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SUMMER SCHOOL ON PARTICLE PHYSICS

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CP Violation and Rare Decays in the Standard Model and Beyond

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CP Violation and Rare Decays in the Standard Model and Beyond

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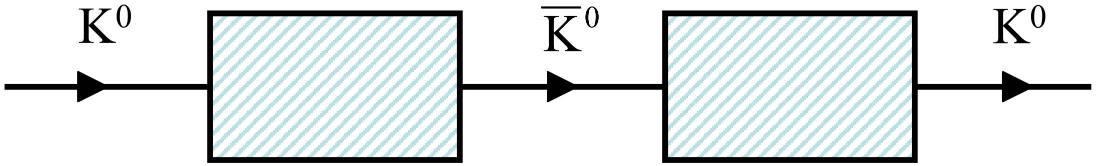
Overture 1

$K^0 - \bar{K}^0$ Mixing (Oscillations)

$K^0 = d\bar{s}$

$\bar{K}^0 = \bar{d}s$



(discovered in 1960)

K^0 and $\bar{K}^0$ are not Mass Eigenstates

Mass Eigenstates :

$$K_L = \frac{K^0 + \bar{K}^0}{\sqrt{2}} \qquad K_S = \frac{K^0 - \bar{K}^0}{\sqrt{2}}$$

(L = Long) (S = Short)

$M(K_L) \cong M(K_S) = 0.5\ \text{GeV}$

★ $M(K_L) - M(K_S) = 3.5 \cdot 10^{-15}\ \text{GeV}$

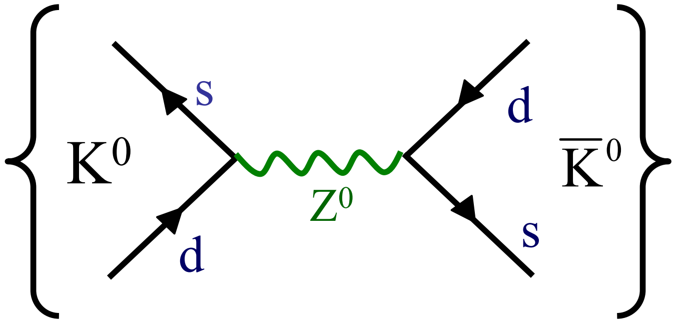
$$\equiv \Delta M_K$$

$$\frac{\tau(K_L)}{\tau(K_S)} \cong 600$$ ★

$M \equiv$ mass

$\tau \equiv$ Life Time

Could ordinary Weak Interactions explain ΔM_K ?



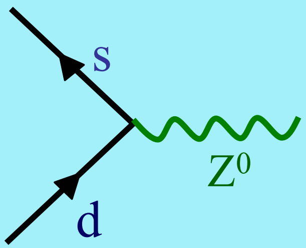
$$\Delta M_K = \left[2\cdot 10^{-2}\,\mathrm{GeV}^3\right] G_F \left[\frac{M_W^2}{M_Z^2}\right]$$

$$G_F \cong 1.1\cdot 10^{-5}\,\mathrm{GeV}^{-2}$$

$M_Z \cong 90$ GeV

$$\Delta M_K \cong 2\cdot 10^{-7}\,\mathrm{GeV}$$

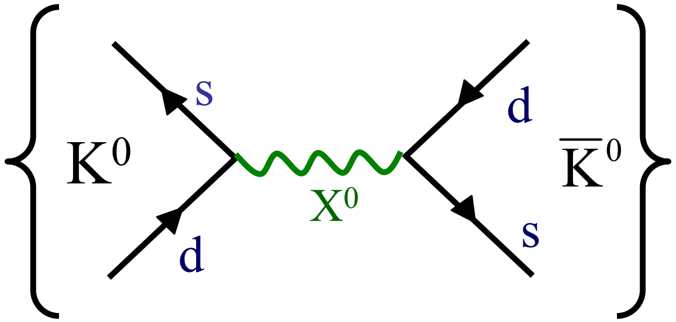
Disaster !!!
Missed by
8 orders of
magnitude !!!



$= 0$

GIM Mechanism

(1971)



$$\Delta M_K \cong 2\cdot 10^{-7}\left[\frac{M_Z^2}{M_X^2}\right]\mathrm{GeV} = 3.5\cdot 10^{-15}\,\mathrm{GeV}$$

$$\left\{M_X \cong 10^6\,\mathrm{GeV}\right\}$$

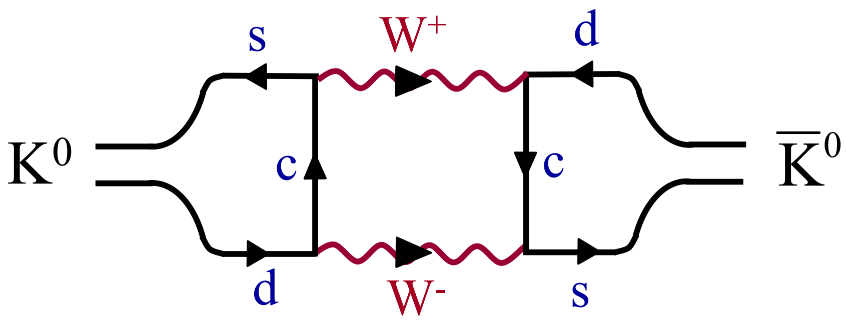
Testing
10^{-22}m !

New very heavy neutral boson !

ΔM_K in the Standard Model

Gaillard-Lee (March 1974)

$\lambda \cong 0.22$



$$\left\{ \begin{array}{l} \Delta M_K = \left[1.4\ \mathrm{GeV}^5\right] G_F^2 \lambda^2 \left[\dfrac{m_c^2}{M_W^2}\right] \\ G_F \cong 1.2 \cdot 10^{-5}\,\mathrm{GeV}^{-2} \end{array} \right\}$$

$$\Delta M_K = 10^{-11}\,\mathrm{GeV}\left[\frac{m_c^2}{M_W^2}\right] = 3.5 \cdot 10^{-15}\,\mathrm{GeV}$$

$$m_c = \sqrt{3.5} \cdot 10^{-2} M_W = 1.5\ \mathrm{GeV}$$

(Prediction !!)

November Revolution
1974
Discovery of $\overline{c}c$ State
(SLAC, Brookhaven)

$M_{\overline{c}c} \cong 3.1\ \mathrm{GeV}$

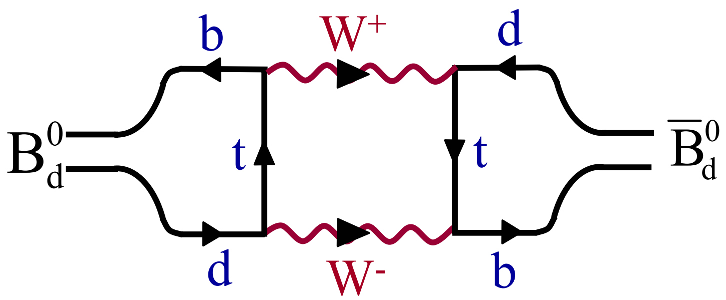
$m_c \cong 1.5\ \mathrm{GeV}$!!

Prediction confirmed !

Similar Studies: 1974-1994

$B_d^0 - \overline{B}_d^0$ Oscillations

DESY 87



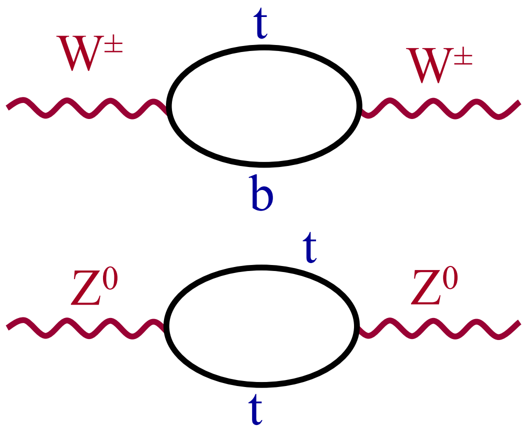
$+$ $\Delta M_{B_d} \cong 4 \cdot 10^{-13}\,\mathrm{GeV}$ ⇒

(Prediction)

$m_t \approx 150\ \mathrm{GeV}$
± 30

Electroweak Precision Studies

CERN, SLAC (1989-1994)



⇒ $m_t \approx 150\ \mathrm{GeV}$
± 20

(Prediction)

1994 Discovery of the Top Quark (Fermilab)

$m_t = 178 \pm 4\ \mathrm{GeV}$

First Lessons

1. Very rare processes allow to probe very short distance scales.

2. Before claiming New Physics it is essential to make precise calculations (higher order corrections).

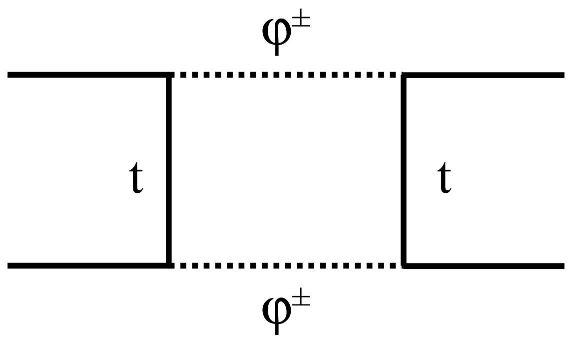
3. Low Energy Processes can give information about heavy particles prior to their discovery.

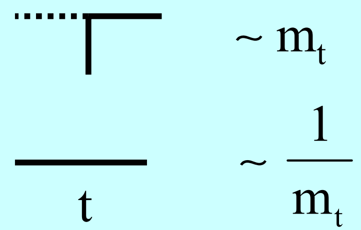
Non-Decoupling of the Top Quark from Low Energy Processes

In QCD and QED very heavy particles ($m_H \to \infty$) do not influence low energy processes: Appelquist-Carazzone Decoupling Theorem

In the $SU(2)_L \otimes U(1)_Y$ the decoupling can be violated by couplings of heavy particles that increase with the heavy particle mass.

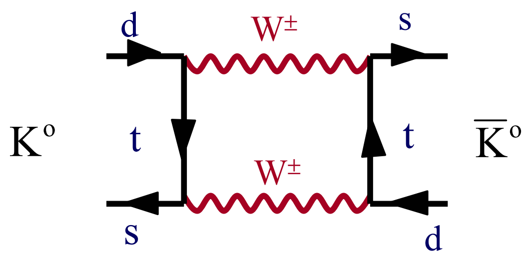
Goldstone-Boson

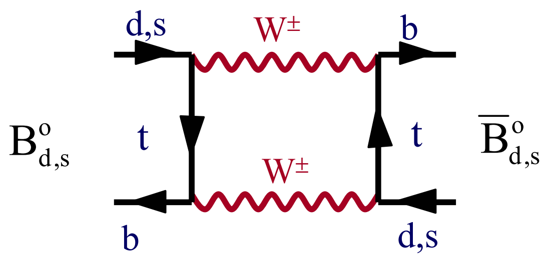




$$m_t^4 \cdot \frac{1}{m_t^2} = m_t^2$$

View at Short Distance Scales

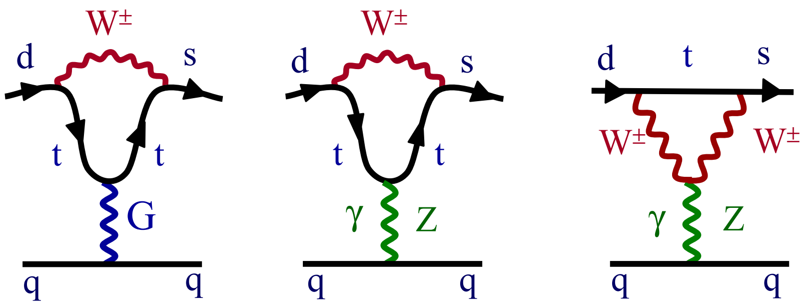




~~CP~~ ε_K-Parameter
ΔM (K_L-K_S)

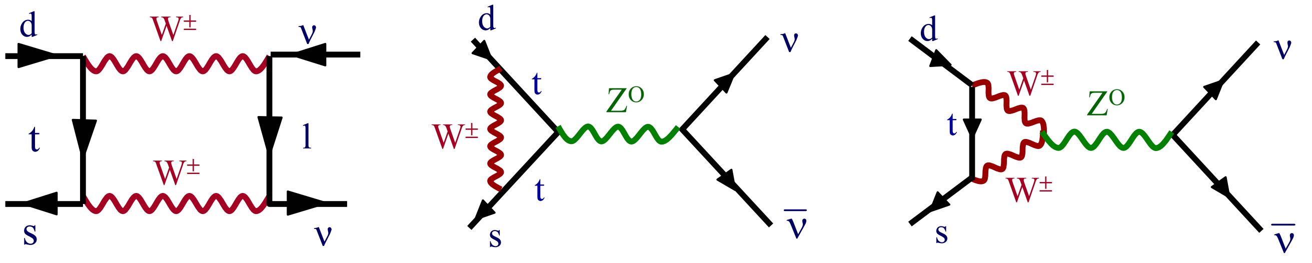
$B^o_d - \overline{B}^o_d$ Mixing

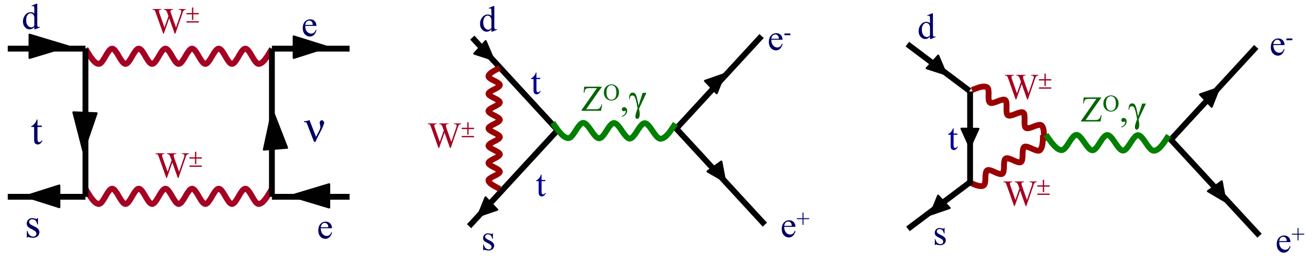
ε'



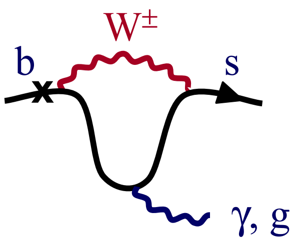
View at Short Distance Scales

$K^+ \to \pi^+ \nu\bar{\nu}$, $K_L \to \pi^0 \nu\bar{\nu}$ $K_L \to \mu\bar{\mu}$, $B \to \mu\bar{\mu}$, $B \to X_S \nu\bar{\nu}$





$K_L \to \pi^0 e^+ e^-$ $B \to X_s e^+ e^-$, $X_s \mu\bar{\mu}$



$B \to X_s \gamma$ $B \to K^* \gamma$

$B \to X_d \gamma$ $b \to s$ gluon

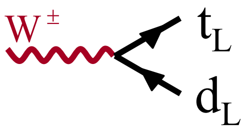
Goals for these Lectures

1. Develop Formalism for Rare Processes:
   CP-Violating Transitions, CP-Asymmetries and
   Rare Decays within Gauge Theories
2. Apply this Formalism to the Standard Model and its simplest Extensions
3. Develop a systematic Procedure for Probing New Physics with these Processes
4. Identify most interesting Problems and Questions

Overture 2

Four Basic Properties in the SM

1. Charged Current Interactions only between left-handed Quarks



$$\frac{g_2}{2\sqrt{2}}\gamma_\mu(1-\gamma_5)\cdot V_{td}$$

2. Quark Mixing

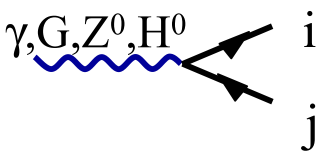
{ Weak Eigenstates } ≠ {Mass Eigenstates }

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{ub} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

(Weak Eigenstates) (Unitarity CKM-Matrix) (Mass Eigenstates)

3. GIM Mechanism

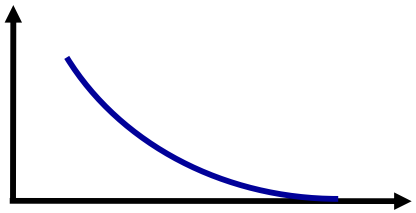
Natural suppression of FCNC

{ 

$= 0$ } ➡ {Loop Induced Decays, sensitive to short distance flavour dynamics}

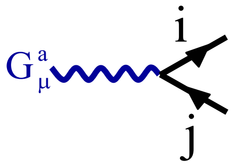
4. Asymptotic Freedom

α_{QCD}



LD ⇦ RG ⇨ SD

Q



$$g_{QCD}\, T^a_{ij} \gamma_\mu$$

$$\alpha_{QCD} = \frac{g^2_{QCD}}{4\pi}$$

$$\alpha_{QCD}(Q) = \frac{4\pi}{\beta_0 \ln\left(Q^2/\Lambda^2_{\overline{MS}}\right)}\left[1 - \frac{\beta_1}{\beta_0^2}\frac{\ln\ \ln\left(Q^2/\Lambda^2_{\overline{MS}}\right)}{\ln\left(Q^2/\Lambda^2_{\overline{MS}}\right)} + \ldots\right]$$

$$\Lambda^{(5)}_{\overline{MS}} = 225 \pm 40 \text{ MeV} \qquad \alpha^{(5)}_{\overline{MS}}(M_Z) = 0.118 \pm 0.003$$

SD = Short Distances (Perturbation Theory)

⇧

RG = Renormalization Group Effects

⇩

LD = Long Distances (Non-Perturbative Physics)

Kobayashi-Maskawa Picture of CP Violation

CP Violation arises from a single phase δ
in $W^{\pm}$ interactions of Quarks

ud $c_{12}c_{13}$	us $s_{12}c_{13}$	ub $s_{13}e^{-i\delta}$
cd $-s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta}$	cs $c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta}$	cb $s_{23}c_{13}$
td $s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta}$	ts $-s_{23}c_{12}-s_{12}s_{23}s_{13}e^{i\delta}$	tb $c_{23}c_{13}$

Four Parameters: $(\theta_{12} \approx \theta_{cabibbo})$

$$s_{12} = |V_{us}|, \quad s_{13} = |V_{ub}|, \quad s_{23} = |V_{cb}|, \quad \delta$$

$$c_{ij} \equiv \cos\theta_{ij} \ ; \ s_{ij} \equiv \sin\theta_{ij} \ ; \ c_{13} \cong c_{23} \cong 1$$

Wolfenstein Parametrization

Parameters: λ, A, ρ, η

	d	s	b
u	$1-\frac{\lambda^2}{2}$	λ	V_{ub}
c	$-\lambda$	$1-\frac{\lambda^2}{2}$	V_{cb}
t	V_{td}	V_{ts}	1

$\lambda=0.22$

$V_{us}=\lambda+0(\lambda^7)$

$V_{cb}=A\lambda^2+0(\lambda^8)$

$V_{ts}=-A\lambda^2+0(\lambda^4)$

$(A=0.83\pm0.02)$

$$V_{ub} \equiv A\lambda^3(\rho - i\eta) \qquad V_{td} = A\lambda^3(1-\bar{\rho}-i\bar{\eta})$$

$$\bar{\rho} = \rho\left(1-\frac{\lambda^2}{2}\right) \qquad \bar{\eta} = \eta\left(1-\frac{\lambda^2}{2}\right)$$

(AJB, Lautenbacher, Ostermaier, 94)

$$R_b \equiv \sqrt{\bar{\rho}^2+\bar{\eta}^2} = \left(1-\frac{\lambda^2}{2}\right)\frac{1}{\lambda}\left|\frac{V_{ub}}{V_{cb}}\right|$$

Circle around $(\bar{\rho},\bar{\eta}) = (0,0)$

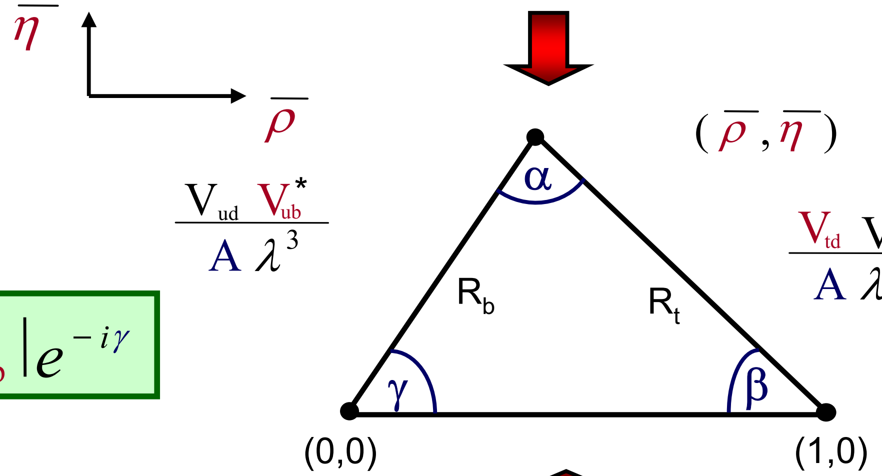
$$R_t \equiv \sqrt{(1-\bar{\rho})^2+\bar{\eta}^2} = \frac{1}{\lambda}\left|\frac{V_{td}}{V_{cb}}\right|$$

Circle around $(\bar{\rho},\bar{\eta}) = (1,0)$

Unitarity Triangle

$$V_{ud} V_{ub}^{*} + V_{cd} V_{cb}^{*} + V_{td} V_{tb}^{*} = 0$$

$\bar{\eta} \neq 0$ Signals CP Violation



$$V_{ub} = |V_{ub}| e^{-i\gamma}$$

$$V_{td} = |V_{td}| e^{-i\beta}$$

An Important Target of Particle Physics

$$J_{CP} = \lambda^2 |V_{cb}|^2 \bar{\eta} = 2 \cdot \triangle$$

Area of unrescaled UT

Particular Definition of λ, A, ρ, η

$$s_{12} \equiv \lambda$$
$$s_{23} \equiv A\,\lambda^2$$
$$s_{13}e^{i\delta} \equiv A\,\lambda^3(\rho - i\eta)$$

BLO: Phys.Rev. (94); (Schmidtler, Schubert)

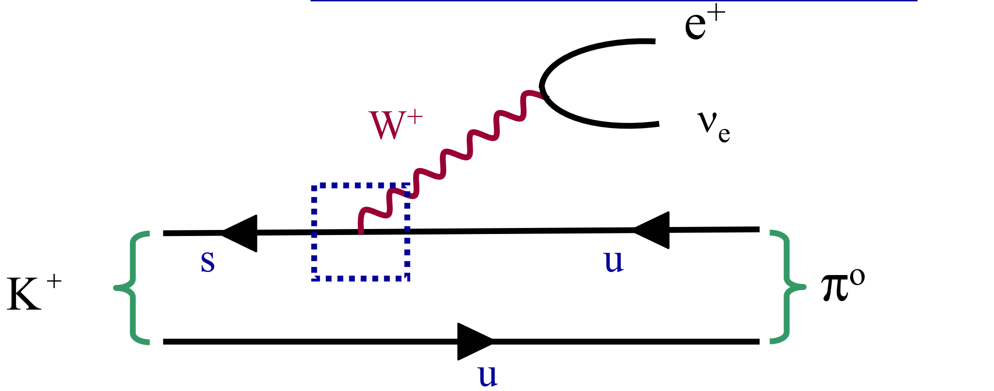
At $0(\lambda^5)$ equivalent to (Branco, Lavoura, 88)

Basic Virtues of this Definition:

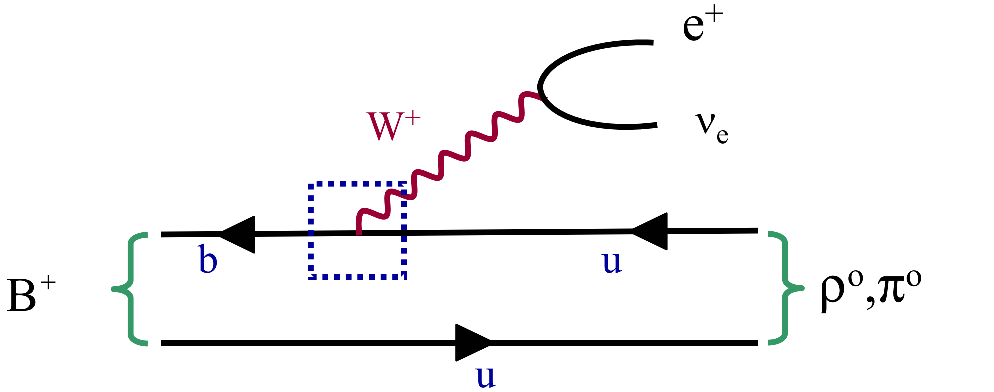
$$V_{us} = \lambda + 0\left(\lambda^7\right)$$
$$V_{ub} = A\lambda^3\left(\rho - i\eta\right)$$
$$V_{cb} = A\lambda^2 + 0\left(\lambda^8\right)$$
$$V_{td} = A\lambda^3\left(1 - \bar{\rho} - i\bar{\eta}\right)$$

The apex of UT given by $\left(\bar{\rho}, \bar{\eta}\right)$ (BLO)

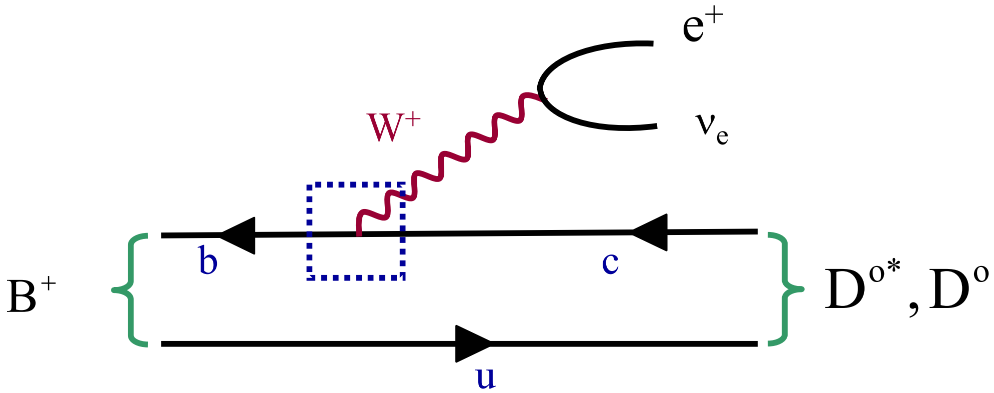
Tree Level Decays



V_{us}



V_{ub}



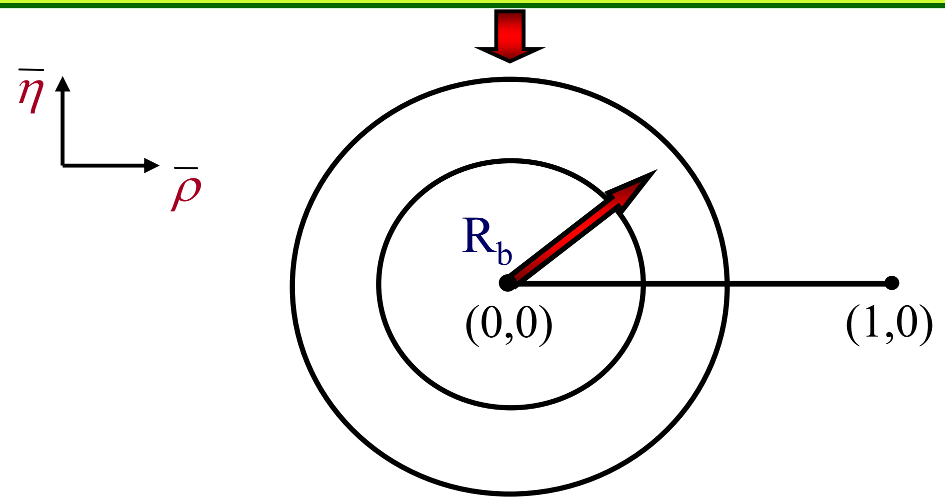
V_{cb}

Information from Tree Level Decays

$$|V_{us}| = 0.225 \pm 0.002 \qquad = \lambda$$

$$|V_{cb}| = (41.5 \pm 0.8)\cdot 10^{-3} \qquad (A = 0.83 \pm 0.02)$$

$$\left|\frac{V_{ub}}{V_{cb}}\right| = 0.092 \pm 0.012 \qquad (R_b = 0.40 \pm 0.06)$$



Apex of Unitarity Triangle somewhere on this Band

To find it **GO TO**

Loop Induced Decays

CP-Violation in K-Decays

CP-Violation in B-Decays

$$F_1^{th}(\lambda, A, \overline{\eta}, \overline{\rho}) = F_1^{exp}$$

$$F_2^{th}(\lambda, A, \overline{\eta}, \overline{\rho}) = F_2^{exp}$$

$$F_3^{th}(\lambda, A, \overline{\eta}, \overline{\rho}) = F_3^{exp}$$

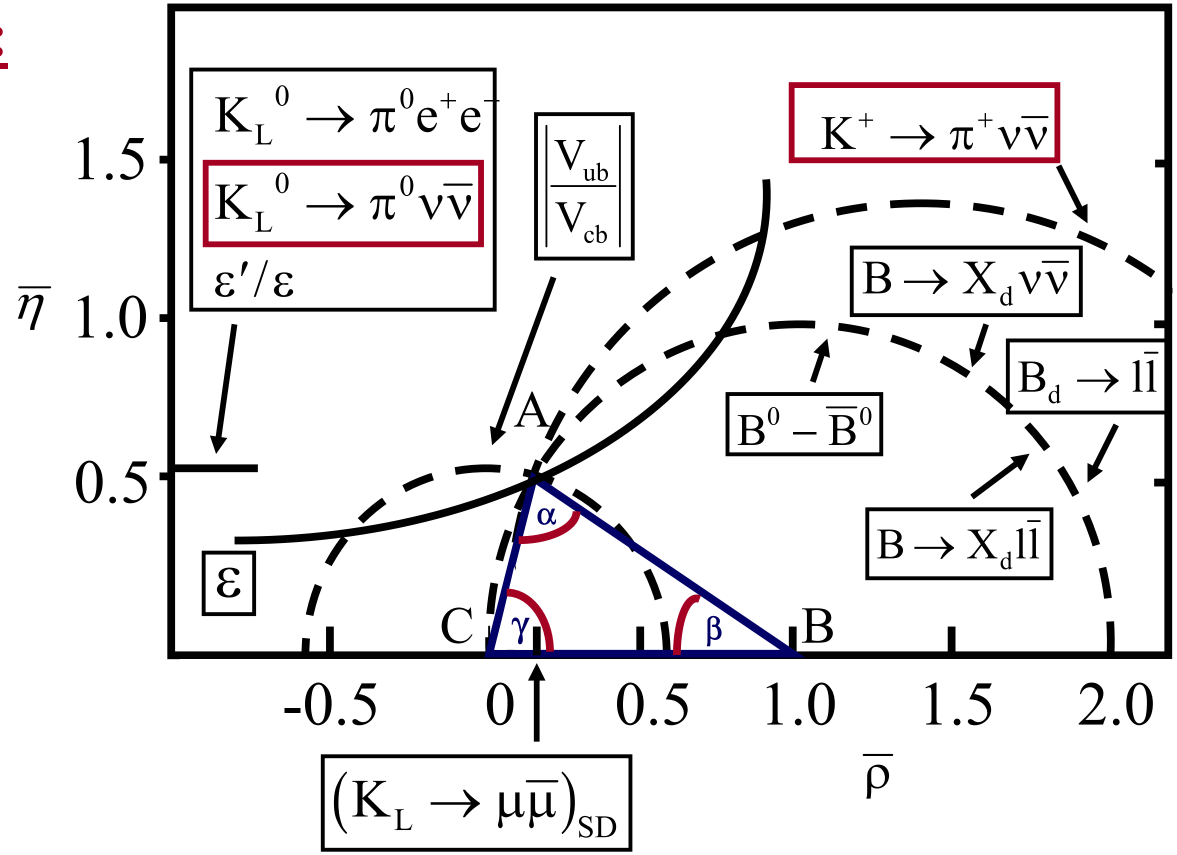
etc.

↓

Determination of
the Unitarity Triangle

Hunting Δ with Rare and ~~CP~~ Decays

2012:



★ **Quark Mixing and CP Violation closely related in the St. Model**

★ $\left\{\begin{array}{l}\text{CP Asymmetries} \\ \text{in} \\ \text{B-Decays}\end{array}\right\} \Rightarrow \left\{\begin{array}{c}\alpha \\ \beta \\ \gamma\end{array}\right\}$

Lecture I

1. TH Framework
2. Various Types of ~~CP~~

Lecture II

3. Standard Analysis of Δ
4. α, β, γ from B´s
5. $K^+ \to \pi^+ \nu\bar{\nu}$, $K_L \to \pi^0 \nu\bar{\nu}$

Lecture III

6. Rare B- and K-Decays
7. Models with MFV

Lecture IV

8. Going Beyond MFV
9. Probing New Physics in 10 Steps
10. Outlook

Literature

Buchalla, AJB, Lautenbacher

Rev. Mod. Phys. 68 (1996) 1125

AJB, Fleischer

in Heavy Flavours II (World Scientific) (1998) (hep-ph / 9704376)

AJB

★ Les Houches Lectures (1997) (hep-ph / 9806471)
Erice Lectures (2000) (hep-ph / 0101336)
★ Spain Lectures (2004) (hep-ph / 0505175)

Y. Nir

Scottish Universities Summer School (hep-ph / 0109090)

The BABAR Physics Book

B-Physics at the LHC (hep-ph / 0003238)

Books: Branco, Lavoura, Silva;
Bigi, Sanda

B Physics at the Tevatron (Run II and Beyond) (hep-ph/0201071)

Fleischer:

Physics Reports (hep-ph/0207108)

1.

Theoretical Framework

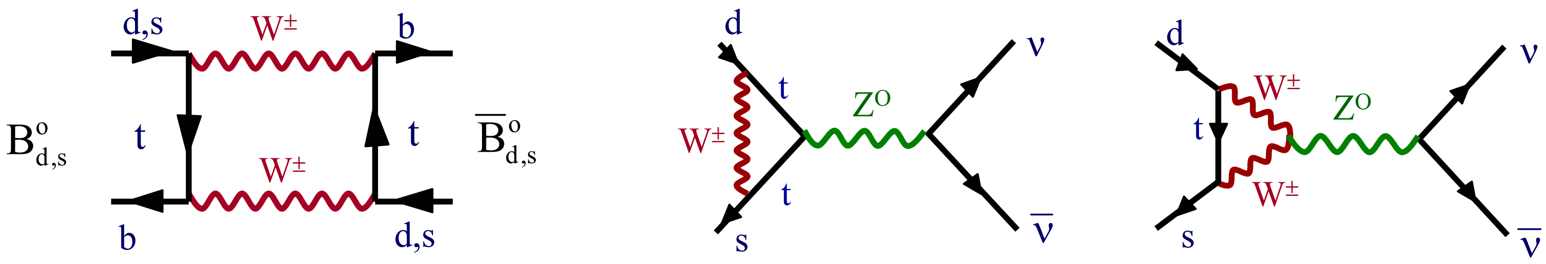
Starting Point :

$$\mathcal{L} = \mathcal{L}_{SM}\left(g_i, m_i, V^i_{CKM}\right) + \mathcal{L}_{NP}\left(g_i^{NP}, m_i^{NP}, V^i_{NP}\right)$$

Goal :

Identify the effects of $\mathcal{L}_{NP}$ in weak decays in the presence of the background from $\mathcal{L}_{SM}$

First Implication from $\mathcal{L}$: Feynman Diagrams



+ NP

$B^o_d - \overline{B}^o_d$ Mixing

$K^+ \to \pi^+ \nu\overline{\nu}, \;\; K_L \to \pi^0 \nu\overline{\nu}$

Two challenges :

1. Theory formulated in terms of quarks but experiments involve their bound states (K, B, D)

2. NP takes place at very short distance scales (10^{-19}-10^{-18}m), while K, B, D live at 10^{-16}-10^{-15}m.

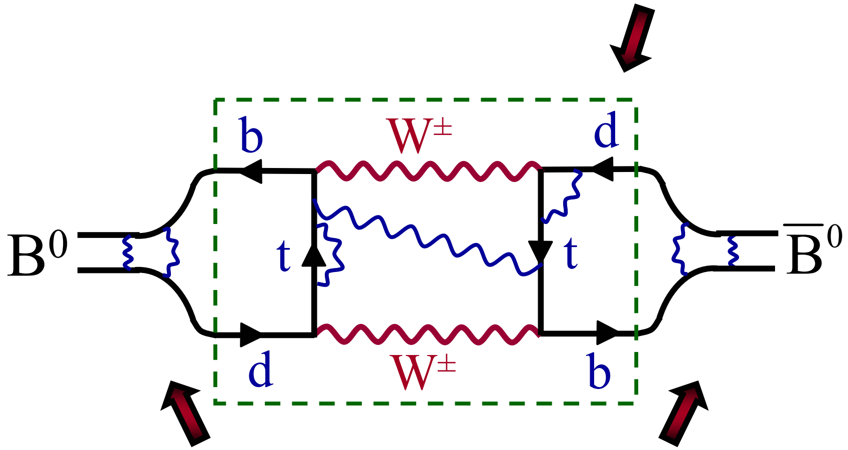
Solution : Effective Theories, OPE, Renormalization Group

⇒ Separation of SD from LD
+ Summation of large $\log(\mu_{SD} / \mu_{LD})$

The Problem of Strong Interactions

$B_d^0 - \overline{B}_d^0$ Mixing (SM)

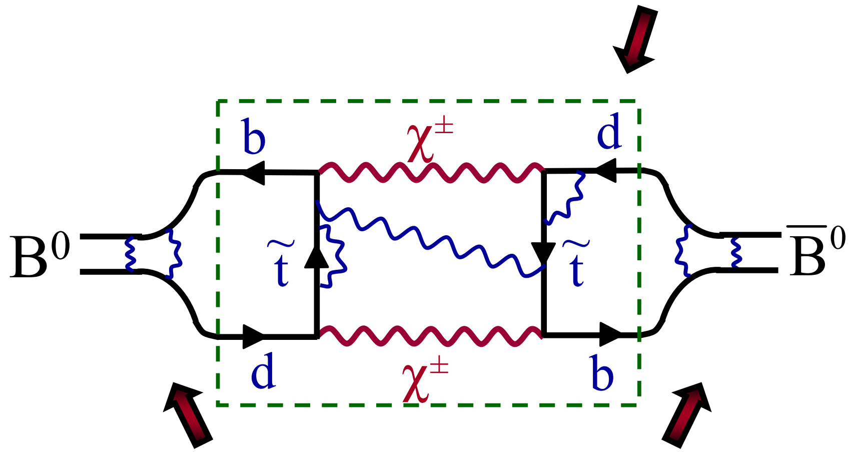
Short Distance



Long Distance

$B_d^0 - \overline{B}_d^0$ Mixing (MSSM)

Short Distance



Long Distance

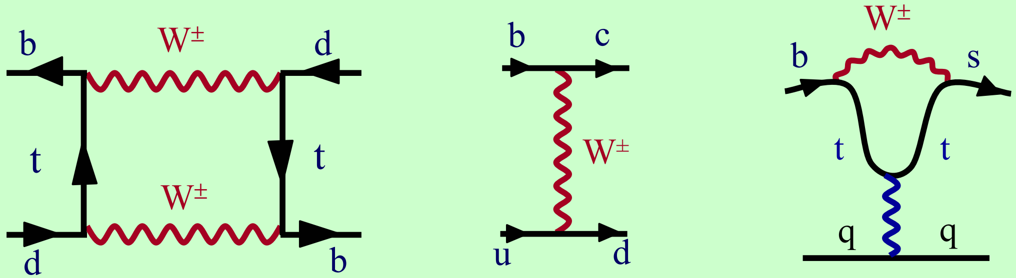
SD : Perturbative
(Asymptotic Freedom)

LD : Non-Perturbative
(Confinement)

Effective Field Theory

Full Theory

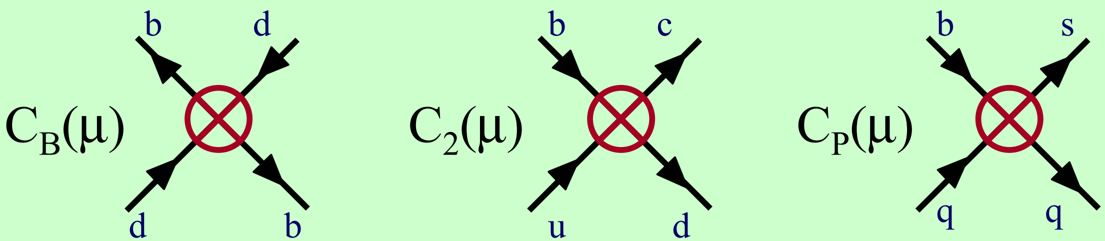
($W^{\pm}$, Z^0, G, γ, t, H^0, b, u, d, s, c, l)



$\mu \geq M_W$

Effective Theory

(G, γ, b, u, d, s, c, l)



$\mu \cong 0(m_b)$

"Generalized Fermi Theory" with calculable "couplings" $C_B(\mu)$, $C_2(\mu)$,...

Operator Product Expansion

{Wilson Coefficients} {Local Operators}

$$H_{eff} = \frac{G_F}{\sqrt{2}} V_{CKM} \sum_i C_i(\mu)\, Q_i$$

Q_i ⟺ Four Quark Interaction Vertex $(\bar{s}d)_{V-A}(\bar{s}d)_{V-A}$

$C_i(\mu)$ ⟺ **Coupling Constants** $C(\mu) = \left[\frac{\alpha_s(M_W)}{\alpha_s(\mu)}\right]^{\frac{6}{23}}$

{K, B, D,...}

$$A(M \to F) = \frac{G_F}{\sqrt{2}} V_{CKM} \sum_i C_i(\mu) \langle F | Q_i(\mu) | M \rangle$$

$\{\pi\pi,\ \pi\nu\bar{\nu},\ \mu\bar{\mu},\ K^*\gamma, \ldots\}$

M_W — $\mu = 0(1\ \text{GeV}, m_b)$ — 0

Short | RG | Long Distance

{Top, SUSY, $H^{\pm}$...}

{Renormalization Group $\sum\left(\alpha_s \log\frac{M_w}{\mu}\right)^n$}

{Lattice, 1/N, HQET, QCDS, ChPTh}

$$\langle \bar{K}^0 | (\bar{s}d)_{V-A}(\bar{s}d)_{V-A} | K^0 \rangle = \frac{8}{3} \hat{B}_K F_K^2 m_K^2 [\alpha_s(\mu)]^{2/9}$$

Operators

Current-Current

$$Q_1 = \left(\bar{s}_\alpha u_\beta\right)_{V-A}\left(\bar{u}_\beta d_\alpha\right)_{V-A} \qquad Q_2 = \left(\bar{s}u\right)_{V-A}\left(\bar{u}d\right)_{V-A}$$

QCD-Penguins

$$Q_3 = \left(\bar{s}d\right)_{V-A}\sum_{q=u,d,s}\left(\bar{q}q\right)_{V-A} \qquad Q_4 = \left(\bar{s}_\alpha d_\beta\right)_{V-A}\sum_{q=u,d,s}\left(\bar{q}_\beta q_\alpha\right)_{V-A}$$

$$Q_5 = \left(\bar{s}d\right)_{V-A}\sum_{q=u,d,s}\left(\bar{q}q\right)_{V+A} \qquad Q_6 = \left(\bar{s}_\alpha d_\beta\right)_{V-A}\sum_{q=u,d,s}\left(\bar{q}_\beta q_\alpha\right)_{V+A}$$

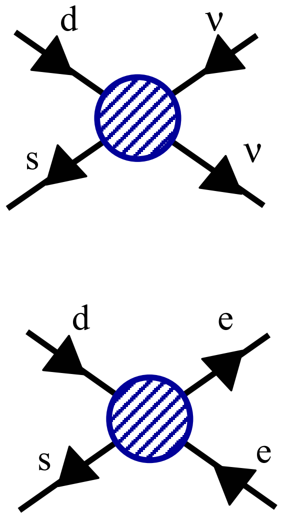
Electroweak-Penguins

$$Q_7 = \frac{3}{2}\left(\bar{s}d\right)_{V-A}\sum_{q=u,d,s} e_q\left(\bar{q}q\right)_{V+A} \qquad Q_8 = \frac{3}{2}\left(\bar{s}_\alpha d_\beta\right)_{V-A}\sum_{q=u,d,s} e_q\left(\bar{q}_\beta q_\alpha\right)_{V+A}$$

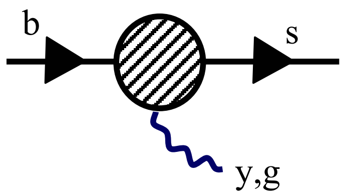
$$Q_9 = \frac{3}{2}\left(\bar{s}d\right)_{V-A}\sum_{q=u,d,s} e_q\left(\bar{q}q\right)_{V-A} \qquad Q_{10} = \frac{3}{2}\left(\bar{s}_\alpha d_\beta\right)_{V-A}\sum_{q=u,d,s} e_q\left(\bar{q}_\beta q_\alpha\right)_{V-A}$$

View at Long Distance Scales

$K^+ \to \pi^+ \nu\bar{\nu}$, $K_L \to \pi^0 \nu\bar{\nu}$ $K_L \to \mu\bar{\mu}$, $B \to \mu\bar{\mu}$, $B \to X_S \nu\bar{\nu}$



$K_L \to \pi^0 e^+ e^-$ $B \to X_S e^+ e^-$, $X_S \mu\bar{\mu}$

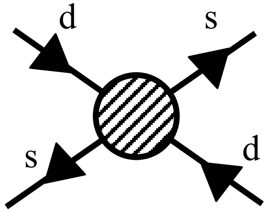


$B \to X_S \gamma$ $B \to K^* \gamma$

$B \to X_d \gamma$ $b \to s$ gluon

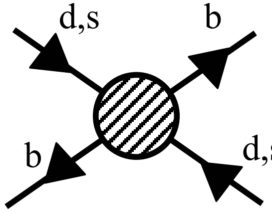
View at Long Distance Scales

K^o



$\overline{K}^o$

$B^o_{d,s}$

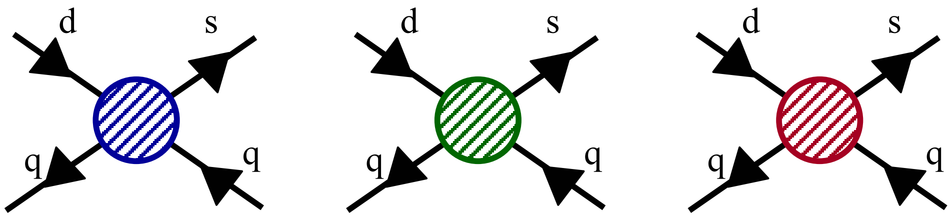


$\overline{B}^o_{d,s}$

~~CP~~ ε_K-Parameter
$\Delta M\ (K_L\text{-}K_S)$

$B^o_d - \overline{B}^o_d$ Mixing

ε'



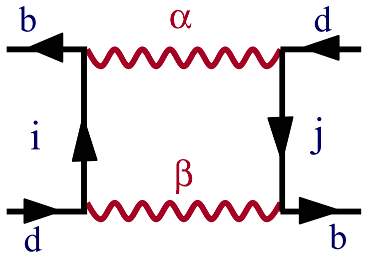
$K^+ \rightarrow \pi^+ \nu\bar{\nu}$, $K_L \rightarrow \pi^0 \nu\bar{\nu}$ $K_L \rightarrow \mu\bar{\mu}$, $B \rightarrow \mu\bar{\mu}$, $B \rightarrow X_S \nu\bar{\nu}$

Deriving $H_{eff}\left(B_d^0 - \bar{B}_d^0\right)$ and $\Delta M_d\left(B_d^0 - \bar{B}_d^0\right)$ in 7 Steps

Step 1 : Calculate Box Diagrams

$\Phi^{\pm}$ - Goldstone Bosons Must be taken into account except in a Unitarity Gauge

$$\sum_{i,j=u,c,t} \sum_{\alpha,\beta=W^{\pm},\Phi^{\pm}}$$



$$\equiv \sum_{i,j=u,c,t} F\left(x_i, x_j\right)\left(V_{ib}^* V_{id}\right)\left(V_{jb}^* V_{jd}\right)Q$$

UG : see AJB, Poschenrieder, Uhlig; hep-ph/0410309

Step 2 : Use

$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$$

Multiply by i and keep only $V_{td}V_{tb}^*$ part

$$x_i \equiv \frac{m_i^2}{M_W^2}$$

$$H_{eff}^{(\Delta B=2)} = \frac{G_F^2}{16\pi^2} M_W^2 \left(V_{tb}^* V_{td}\right)^2 \; S_0(x_t) \; Q(\Delta B = 2)$$

$$S_0(x_t) = \tilde{F}(x_t, x_t) + \tilde{F}(x_u, x_u) - 2\tilde{F}(x_t, x_u)$$

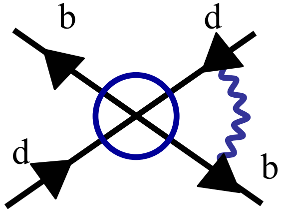
$$Q(\Delta B = 2) = \left(\bar{b}d\right)_{V-A}\left(\bar{b}d\right)_{V-A}$$

$$x_u = 0$$

Step 3 : Include QCD Corrections in the Leading Logarithmic Approximation

 = Gluon

$$\left\{ \right.$$



$$\left. + \ldots \right\} \Rightarrow \left\{ S_0(x_t) \rightarrow \left[\frac{\alpha_s(\mu_W)}{\alpha_s(\mu_b)} \right]^{6/23} S_0(x_t) \equiv C(\mu_b) \right\}$$

Wilson Coefficient of $Q(\Delta B=2)$

$$\mu_W = 0(M_W) \qquad \mu_b = 0(m_b)$$

Problems with LO ≡ LLA : Sensitivity to the choices of

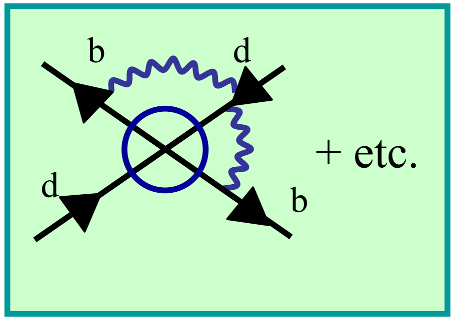
i)	μ_W	$80\ \text{GeV} < \mu_W < 300\ \text{GeV}$
ii)	μ_b	$2.5\ \text{GeV} < \mu_b < 5\ \text{GeV}$
iii)	μ_t	$x_t = \frac{m_t^2(\mu_t)}{M_W^2}$
		$80\ \text{GeV} < \mu_t < 300\ \text{GeV}$

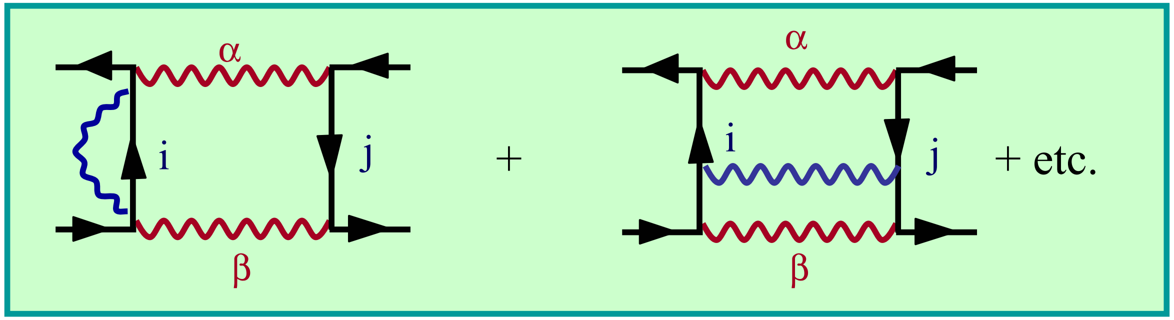
Step 4 : Include Next to Leading QCD Corrections

(AJB, Jamin, Weisz 1990)

Requires:

= Gluon





Pages 101-103 Les Houches Lectures

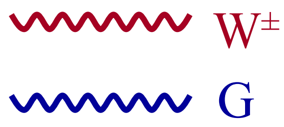
$$H_{\text{eff}}^{(\Delta B=2)} = \frac{G_F^2}{16\pi^2} M_W^2 \left(V_{tb}^* V_{td}\right)^2 \underbrace{S_0(x_t)\ \tilde{\eta}_B^{QCD} \left[\frac{\alpha_S(\mu_W)}{\alpha_S(\mu_b)}\right]^{6/23} \left(1 + J_5 \frac{\alpha_S(\mu_b) - \alpha_s(\mu_W)}{4\pi}\right)} Q(\Delta B = 2)$$

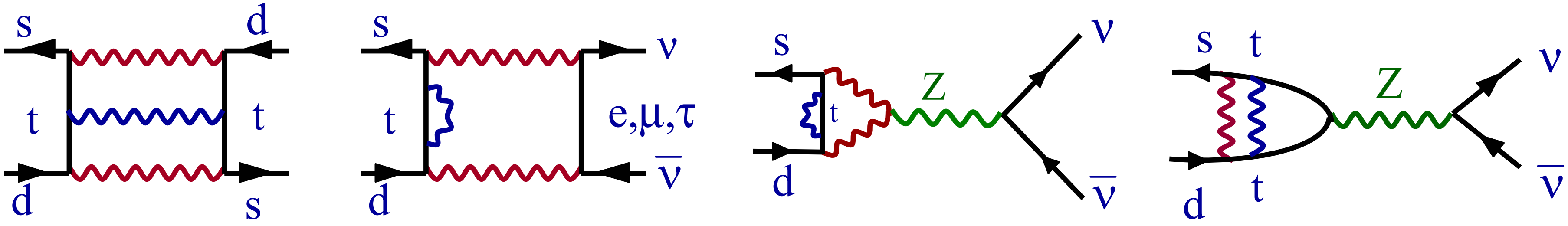
Independent of μ_W and μ_t but still dependent on μ_b

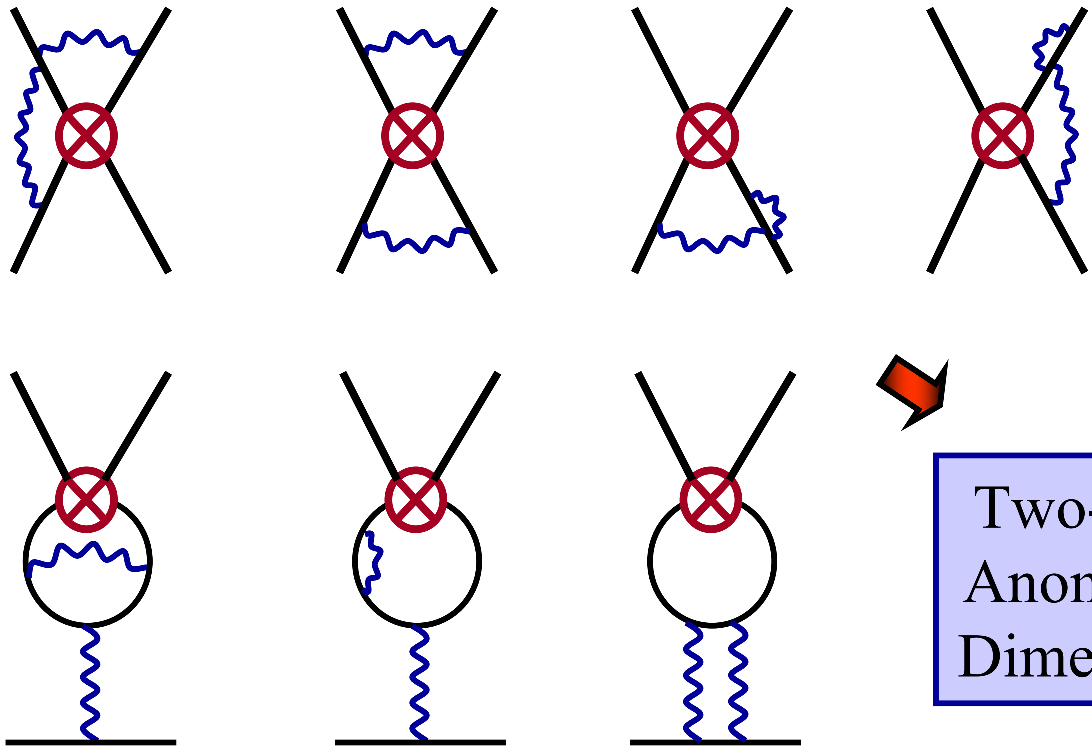
$$\tilde{\eta}_B^{QCD} = 1 + \frac{\alpha_s(\mu_W)}{4\pi} G(\mu_W, \mu_t)$$

$$J_5 = 1.627$$

Typical Two-Loop Diagrams







Two-Loop
Anomalous
Dimensions

Step 5 : Calculate the Matrix Element $\langle Q(\Delta B = 2) \rangle$

$$\langle \overline{B}_d^0 | Q(\Delta B = 2) | B_d^0 \rangle = \frac{8}{3} B_B(\mu_b) F_B^2 m_B^2$$

F_B = B-Meson Decay Constant

This μ_b – dependence cancels the one in $H_{eff}^{\Delta B=2}$

Step 6 : Put $\langle H_{eff}^{\Delta B=2} \rangle$ in a manifestly μ_w, μ_t, μ_b Form

$$\eta_B^{QCD} \equiv \tilde{\eta}_B^{QCD} [\alpha_s(\mu_w)]^{6/23} \left(1 - J_5 \frac{\alpha_s(\mu_w)}{4\pi} \right)$$

with $\mu_t = m_t$
μ_w - independent

$$\hat{B}_B \equiv B_B(\mu_b) [\alpha_s(\mu_b)]^{-6/23} \left(1 + J_5 \frac{\alpha_s(\mu_b)}{4\pi} \right)$$

μ_b – independent

$S_0(x_t)$ evaluated at $\mu_t = m_t$

Step 7 : Calculation of $\Delta M_d \left(B_d^0 - \overline{B}_d^0\right)$

Use $$\Delta M_d = \frac{1}{m_b} \left| \left\langle \overline{B}_d^0 \right| H_{eff}^{(\Delta B=2)} \left| B_d^0 \right\rangle \right|$$

$$\Rightarrow \quad \Delta M_d = \frac{G_F^2}{6\pi^2} m_b M_w^2 \underbrace{\left(\hat{B}_d F_{B_d}^2\right)}_{\text{independent of } \mu_b} \underbrace{\eta_B^{QCD} \; S_0(x_t)}_{\text{independent of } \mu_w,\, \mu_t} \left|V_{td}\right|^2$$

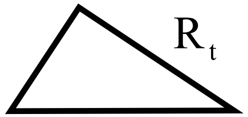
$$\sqrt{\hat{B}_d} F_{B_d} = \left(235 {}^{+33}_{-41}\right) \text{MeV}$$

$$\eta_B^{QCD} = 0.551 \pm 0.006$$

$$S_0(x_t) = \frac{4x_t - 11x_t^2 + x_t^3}{4(1-x_t)^2} - \frac{3x_t \log x_t}{2(1-x_t)^3}$$

$$\approx 2.46 \left(\frac{m_t}{170\text{GeV}}\right)^{1.52}$$

$(\Delta M)_{d,s}$, $|V_{td}|/|V_{ts}|$ and R_t



$$(\Delta M)_d = \frac{0.50}{ps}\left[\frac{\sqrt{\hat{B}_d}F_{Bd}}{230MeV}\right]^2\left[\frac{|V_{td}|}{7.8\cdot 10^{-3}}\right]^2\left[\frac{\eta_B}{0.55}\right]\left[\frac{S(x_t)}{2.34}\right]$$

$$(\Delta M)_s = \frac{18.4}{ps}\left[\frac{\sqrt{\hat{B}_s}F_{Bs}}{270MeV}\right]^2\left[\frac{|V_{ts}|}{0.040}\right]^2\left[\frac{\eta_B}{0.55}\right]\left[\frac{S(x_t)}{2.34}\right]$$

$$S(x_t) = 2.42 \pm 0.12$$

$$\eta_B = 0.55 \pm 0.01$$

AJB, Jamin, Weisz

$$|V_{td}| = \lambda |V_{cb}| R_t$$

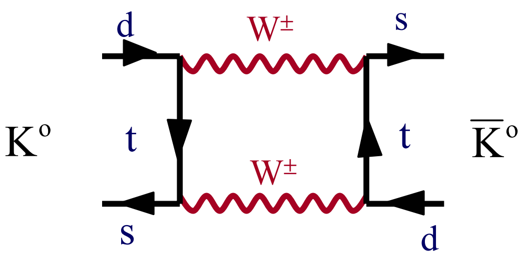
$$|V_{ts}| = |V_{cb}|\left(1 - \frac{\lambda^2}{2} + \bar{\rho}\lambda^2\right)$$

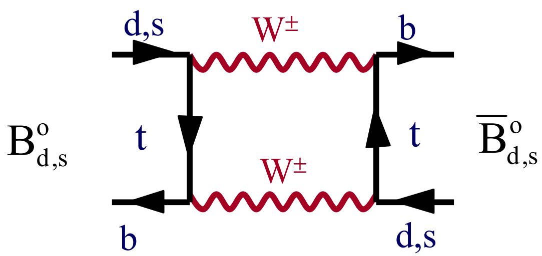
$$\xi = \frac{\sqrt{\hat{B}_s}F_{B_s}}{\sqrt{\hat{B}_d}F_{B_d}} = 1.22 \pm 0.07$$

$$\frac{|V_{td}|}{|V_{ts}|} = 1.01\,\xi\sqrt{\frac{\Delta M_d}{\Delta M_s}}$$

$$R_t = 0.90\sqrt{\frac{\Delta M_d}{0.50/ps}}\sqrt{\frac{18.4/ps}{\Delta M_s}}\left[\frac{\xi}{1.22}\right]$$

View at Short Distance Scales



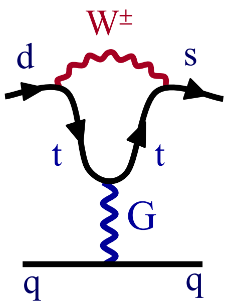


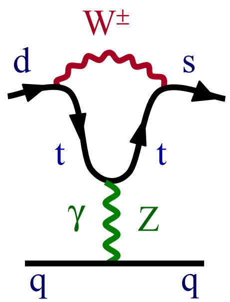
~~C~~P ε_K-Parameter

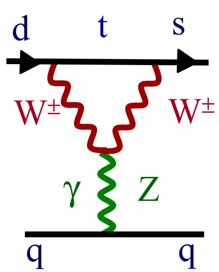
ΔM (K_L-K_S)

$B^o_d - \overline{B}^o_d$ Mixing

ε'

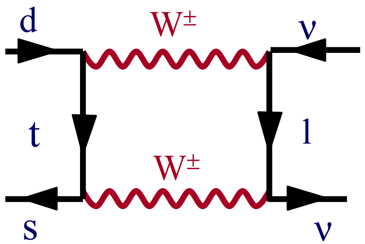


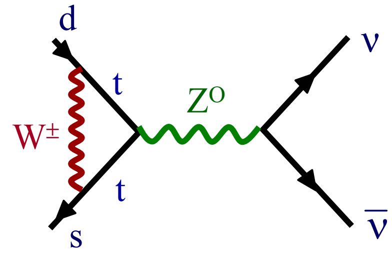


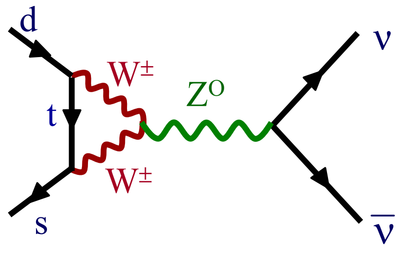


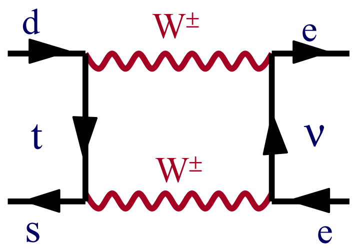
View at Short Distance Scales

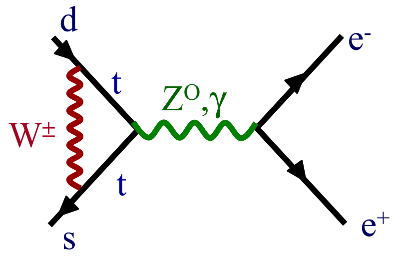
$K^+ \to \pi^+ \nu\bar{\nu}$, $K_L \to \pi^0 \nu\bar{\nu}$ $K_L \to \mu\bar{\mu}$, $B \to \mu\bar{\mu}$, $B \to X_S \nu\bar{\nu}$

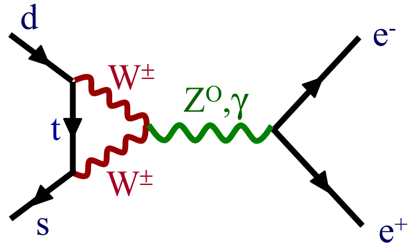




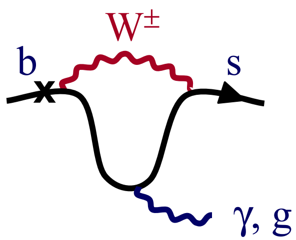








$K_L \to \pi^0 e^+ e^-$ $B \to X_s e^+ e^-$, $X_s \mu\bar{\mu}$



$B \to X_s \gamma$ $B \to K^* \gamma$

$B \to X_d \gamma$ $b \to s$ gluon

Penguin-Box Expansion (SM)

Buchalla, AJB, Harlander (90)

The m_t dependence of all K and B Decays resides in 7 Basic Universal Functions $F_i(x_t)$

$$x_t = \frac{m_t^2}{M_W^2}$$

$$A(\text{Decay}) = \sum_i B_i \eta^i_{QCD} V^i_{CKM} F_i(x_t)$$

F_i : S, X, Y, Z, E, E', D'

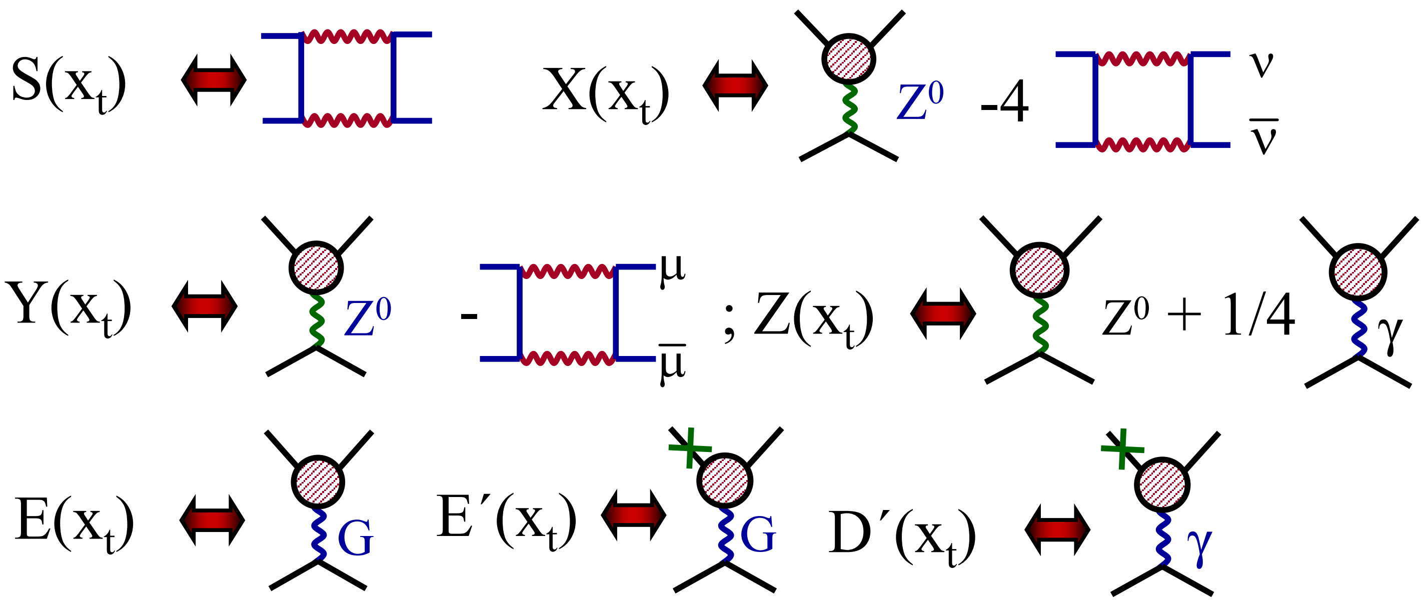
(Gauge Invariant set of functions)

Relation to OPE:

RG

$$C_i(\mu) = \sum_j U_{ij}(\mu, M_W)\underbrace{\left[\sum_r H_{jr} F_r(x_t)\right]}_{C_j(M_W)} = \sum_r \eta^{QCD}_{ir} F_r(x_t)$$

Decay	Contributing Functions
$B_d^0 - \bar{B}_d^0,\ B_s^0 - \bar{B}_s^0,\ \varepsilon$	$S(x_t)$
$K \to \pi\nu\bar{\nu},\ B \to X_s\nu\bar{\nu}$	$X(x_t)$
$K_L \to \mu\bar{\mu},\ B \to l\bar{l}$	$Y(x_t)$
ε'	$Z(x_t),\ X(x_t),\ Y(x_t),\ E(x_t)$
$K_L \to \pi^0 e^+ e^-$	$Y(x_t),\ Z(x_t),\ E(x_t)$
$B \to X_s e^+ e^-$	$Y(x_t),\ Z(x_t),\ D'(x_t), E'(x_t), E(x_t)$
$B \to X_s\gamma$	$D'(x_t),\ E'(x_t)$



m_t Dependence of Basic Universal Functions

$$S(x_t) \equiv S_0(x_t) = 2.46\left[\frac{m_t}{170\mathrm{GeV}}\right]^{1.52}$$

$$X(x_t) = 1.57\left[\frac{m_t}{170\mathrm{GeV}}\right]^{1.15} \qquad Y(x_t) = 1.02\left[\frac{m_t}{170\mathrm{GeV}}\right]^{1.56}$$

$$Z(x_t) = 0.71\left[\frac{m_t}{170\mathrm{GeV}}\right]^{1.86} \qquad E(x_t) = 0.26\left[\frac{m_t}{170\mathrm{GeV}}\right]^{-1.02}$$

$$D'(x_t) = 0.38\left[\frac{m_t}{170\mathrm{GeV}}\right]^{0.60} \qquad E'(X_t) = 0.19\left[\frac{m_t}{170\mathrm{GeV}}\right]^{0.38}$$

Master Formula for Weak Decays

AJB (2001)
hep-ph/0101336
hep-ph/0109197

Non-Perturbative Factors in the SM

QCD RG Factors

Short Distance Loop Functions (Penguins, Boxes)

New Flavour-Changing Parameters

Represent different Dirac and Colour Stuctures

$$A(\text{Decay}) = B_i \; \eta^i_{QCD} \; V^i_{CKM} \left[F^i_{SM} + F^i_{New} \right] + B^{New}_i \left[\eta^i_{QCD} \right]^{New} V^i_{New} \left[G^i_{New} \right]$$

(Summation over i)

New ≡ NP

Non-Perturbative Factors beyond SM

Short Distance Loop Functions Penguins, Boxes

F^i_{SM}, F^i_{New}, G^i_{New} : **Fully calculable in Perturbation Theory**

η^i_{QCD}, $\left[\eta^i_{QCD}\right]^{New}$: **Fully calculable in RG improved Perturbation Theory**

B_i, B^{New}_i : **Require Non-Perturbative Methods or can be extracted from leading decays**

(represent $\langle Q_i \rangle$)

Fully calculable in the SM

Possible Dirac Structures in $K^0 - \bar{K}^0$ and $B^0_{d,s} - \bar{B}^0_{d,s}$

SM:

$$\gamma_\mu(1-\gamma_5) \otimes \gamma^\mu(1-\gamma_5)$$

Beyond SM:

$$\gamma_\mu(1-\gamma_5) \otimes \gamma^\mu(1+\gamma_5)$$

$$(1-\gamma_5) \otimes (1+\gamma_5)$$

$$(1-\gamma_5) \otimes (1-\gamma_5)$$

$$\sigma_{\mu\nu}(1-\gamma_5) \otimes \sigma^{\mu\nu}(1-\gamma_5)$$

MSSM with large tanβ
General Supersymmetric Models
Models with complicated Higgs System

NLO $\left[\eta^i_{QCD}\right]^{New}$: Ciuchini, Franco, Lubicz, Martinelli, Scimemi, Silvestrini

AJB, Misiak, Urban, Jäger

Three Simple Scenarios

Inami Lim Functions

SM :

$$A(\text{Decay}) = \sum_i B_i \, \eta^i_{QCD} \, V^i_{CKM} \underbrace{F^i_{SM}}_{\text{real}}(m_t)$$

MFV :

(Minimal Flavour Violation)

$$A(\text{Decay}) = \sum_i B_i \, \eta^i_{QCD} \, V^i_{CKM} \underbrace{\left[F^i_{SM} + F^i_{New} \right]}_{\text{real}}$$

AJB, Gambino, Gorbahn, Jäger, Silvestrini
D'Ambrosio, Giudice, Isidori, Strumia

Enhanced Z^0-Penguins :

$$A(\text{Decay}) = \sum_i B_i \, \eta^i_{QCD} \, V^i_{CKM} \left[\underbrace{F^i_{SM}}_{\text{real}} + \underbrace{\Delta^i_{New}}_{} \right]$$

Dominated by Z^0-Penguins with a New Complex Phase

AJB, Colangelo, Isidori, Romanino, Silvestrini
Buchalla, Hiller, Isidori; Atwood, Hiller
AJB, Fleischer, Recksiegel, Schwab

Two more complicated Scenarios

MSSM (MFV)
(large tanβ)

(Higgs penguin)

$$A(\text{Decay}) = \sum_i B_i\, \eta^i_{QCD}\; V^i_{CKM} \Big[F^i_{SM} + \overbrace{F^i_{New}}^{\text{real}} \Big] + \sum_i B^{New}_i \big[\eta^i_{QCD}\big]^{New} V^i_{CKM} \underbrace{\big[G^i_{New}\big]}_{\text{real}}$$

General MSSM

Z'-Models
L-R Models
Multi-Higgs Models

$$A(\text{Decay}) = \sum_i B_i\, \eta^i_{QCD}\; V^i_{CKM} \Big[F^i_{SM} + \overbrace{F^i_{New}}^{\text{complex}} \Big] + \sum_i B^{New}_i \big[\eta^i_{QCD}\big]^{New} V^i_{New} \underbrace{\big[G^i_{New}\big]}_{\text{complex}}$$

Inclusive Decays

(Generally TH cleaner than Exclusive Decays)

Examples: $B \to X_s\gamma,\ B \to X_s\mu^+\mu^-,\ B \to X_s\nu\bar{\nu}$

$X_s \equiv$ all final states with $\Delta S = 1$ quantum number

1. Construction of H_{eff} as in the case of Exclusive Decays
2. The branching ratios calculated perturbatively from b-quark decay diagrams
3. Non-Perturbative Effects $\sim \Lambda^2_{QCD} / m_b^2$ (~ 5%)

Heavy Quark Expansions:

Chay, Georgi, Grinstein (1990)
Bigi, Shifman, Uraltsev, Vainshstein (1992)
Manohar, Wise (1993); Mannel (1993)

2.

Particle Mixing and Various Types of CP Violation

Express Review of $B^0 - \overline{B}^0$ Mixing

Flavour Eigenstates

$$B^0 = \left(\overline{b}d\right)$$

$$\overline{B}^0 = \left(b\overline{d}\right)$$

$$CP\left|B^0\right\rangle = -\left|\overline{B}^0\right\rangle$$

$$CP\left|\overline{B}^0\right\rangle = -\left|B^0\right\rangle$$

In the absence of $B^0 - \overline{B}^0$ Mixing:

$$\left|B^0(t)\right\rangle = \left|B^0(0)\right\rangle \exp[-i\,Ht]$$

$$\left|\overline{B}^0(t)\right\rangle = \left|\overline{B}^0(0)\right\rangle \exp[-i\,Ht]$$

$$H = M - i\frac{\Gamma}{2}$$

Mass (M), Width (Γ)

Time Evolution in the Presence of Mixing

$$i\frac{d\psi(t)}{dt} = \hat{H}\,\psi(t) \qquad \psi(t) = \begin{pmatrix} \left|B^0(t)\right\rangle \\ \left|\overline{B}^0(t)\right\rangle \end{pmatrix}$$

Hermitian Matrices with positive (real) eigenvalues

$$\hat{H} = \hat{M} - i\frac{\hat{\Gamma}}{2} = \begin{pmatrix} M_{11} - i\frac{\Gamma_{11}}{2} & M_{12} - i\frac{\Gamma_{12}}{2} \\ M_{21} - i\frac{\Gamma_{21}}{2} & M_{22} - i\frac{\Gamma_{22}}{2} \end{pmatrix}$$

M_{ij}-transition with virtual intermediate states

Γ_{ij}- transition with physical intermediate states

$$M_{21} = M_{12}^* \qquad \Gamma_{21} = \Gamma_{12}^*$$

Express Review of B^0-$\overline{B}^0$ Mixing

- **Flavour Eigenstates**

$$B_d^0 = \left(\overline{b}d\right)$$
$$\overline{B}_d^0 = \left(b\overline{d}\right)$$
$$B_s^0 = \left(\overline{b}s\right)$$
$$\overline{B}_s^0 = \left(b\overline{s}\right)$$

see:
Erice (2000)
Spain (2004)
$\left(K^0 - \overline{K}^0\right)$

- **Mass Eigenstates**

$$B_{H,L} = p\,B^0 \pm q\,\overline{B}^0$$

$$p = \frac{\left(1+\overline{\varepsilon}_B\right)}{\sqrt{2\left(1+\left|\overline{\varepsilon}_B\right|^2\right)}} \qquad q = \frac{\left(1-\overline{\varepsilon}_B\right)}{\sqrt{2\left(1+\left|\overline{\varepsilon}_B\right|^2\right)}}$$

$$\frac{q}{p} = \frac{2M_{12}^* - i\Gamma_{12}^*}{\Delta M - i\,\frac{\Delta\Gamma}{2}}$$

$$\Delta M = M\left(B_H\right) - M\left(B_L\right)$$

$$\Delta\Gamma = \Gamma\left(B_H\right) - \Gamma\left(B_L\right)$$

All exact formulae from $K^0 - \overline{K}^0$ system apply but now:

$$\left|M_{12}\right| >> \left|\Gamma_{12}\right|$$

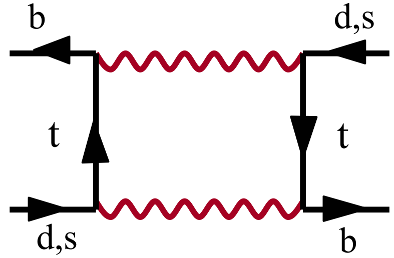
Master Formulae $(B^0\text{-}\bar{B}^0)$

$$\Delta M = 2|M_{12}|$$

$$\Delta\Gamma = 2\frac{\mathrm{Re}(M_{12}\Gamma^*_{12})}{|M_{12}|}$$

$$\frac{q}{p} \cong \frac{M^*_{12}}{|M_{12}|}\left[1-\frac{1}{2}\mathrm{Im}\left(\frac{\Gamma_{12}}{M_{12}}\right)\right]$$

$$M^*_{12} = \langle \overline{B}^0|H_{eff}|B^0\rangle \approx$$



$$(M^*_{12})_d \sim (V_{td}V^*_{tb})^2 \qquad (M^*_{12})_s \sim (V_{ts}V^*_{tb})^2$$

$$V_{td} = |V_{td}|e^{-i\beta} \qquad V_{ts} = |V_{ts}|e^{-i\beta_s} \qquad (\beta_s \cong 0)$$

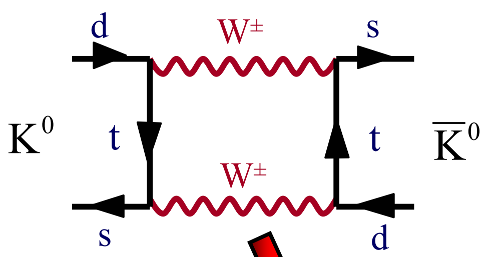
$$\frac{q}{p} \cong e^{i2\varphi_M} \qquad \varphi_M = \begin{cases} -\beta & B^0_d - \overline{B}^0_d \\ -\beta_s & B^0_s - \overline{B}^0_s \end{cases}$$

(Pure Phase)

Indirect and Direct $\not{C}\!P$ in $K_L \to \pi\pi$

$$K_{1,2} = \frac{K^0 \mp \overline{K}^0}{\sqrt{2}}$$

$$CP\,|K^0\rangle = -|\overline{K}^0\rangle$$



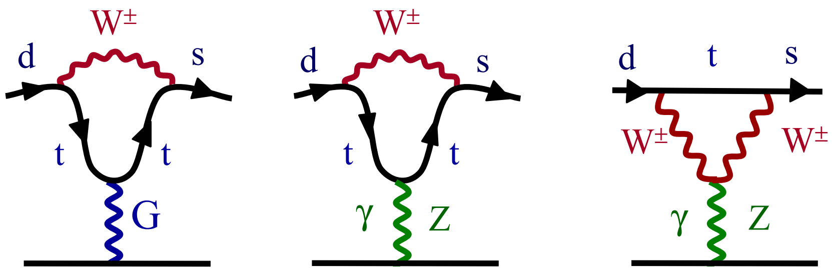
$(K^0 - \overline{K}^0$ Mixing$)$

Mass Eigenstates are not CP Eigenstates

indirect CP violation (ε)

$$K_L = \overset{(-)}{K}_2 + \varepsilon \overset{(+)}{K}_1 \xrightarrow{\varepsilon} \overbrace{\pi^+\pi^-,\ \pi^0\pi^0}^{CP\,(+)}$$

direct CP-Violation (ε')



$$\eta_{+-} \equiv \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} = \varepsilon + \varepsilon'$$

$$\eta_{00} \equiv \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} = \varepsilon - 2\varepsilon'$$

$\varepsilon'=0$ in Superweak Models
Wolfenstein (64)

$$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = \frac{1}{6}\left(1 - \left|\frac{\eta_{00}}{\eta_{+-}}\right|^2\right)$$

June 2005

$$\Delta M_K = (0.5301 \pm 0.0016) \cdot 10^{-2} / \text{ps}$$

$$\Delta M_d = (0.503 \pm 0.006) / \text{ps}$$

$$\Delta M_s > 14.4 / \text{ps} \quad (95\% \text{ C.L.})$$

$$1/\text{ps} = 6.582 \cdot 10^{-13} \text{GeV}$$

$$\varepsilon = (2.280 \pm 0.013) \cdot 10^{-3} e^{i\pi/4}$$

$$\text{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = (16.6 \pm 1.6) \cdot 10^{-4}$$

Modern Classification of CP Violation

We have:

Particle-Antiparticle Mixing

and

Decay

→

1. CP Violation in Mixing
2. CP Violation in Decay
3. CP Violation in the Interference of Mixing and Decay

Classification of $\not{CP}$ in B- and K-Decays

(Nir 99),...

1. CP Violation in Mixing

$$B_{H,L} = p\left|B^0\right\rangle \pm q\left|\overline{B}^0\right\rangle$$

Mass Eigenstates

$\not{CP}$: $|q/p| \neq 1$ ⇒ (Not CP Eigenstates)

$$a_{SL} = \frac{\Gamma\left(\overline{B}^0(t) \to l^+\nu X\right) - \Gamma\left(B^0(t) \to l^-\nu X\right)}{\Gamma\left(\overline{B}^0(t) \to l^+\nu X\right) + \Gamma\left(B^0(t) \to l^-\nu X\right)}$$

$$a_{SL} = \frac{1-|q/p|^4}{1+|q/p|^4} = \operatorname{Im}\frac{\Gamma_{12}}{M_{12}}$$

$$\hat{H} = \hat{M} - i\frac{\hat{\Gamma}}{2}$$

Observed in K-system: $\operatorname{Re}\varepsilon_K \neq 0$

$$\overline{B}^0 \to B^0 \to l^+\nu X$$

(Phase Difference)

$$B^0 \to \overline{B}^0 \to l^-\nu X$$

"wrong charge" leptons

$$a_{SL} \approx 0\left(10^{-3}\right)$$

Hadronic Uncertainties in Γ_{12}, M_{12}

2. CP Violation in Decay

$$A_f = \langle f | H^{weak} | B \rangle \quad \bar{A}_{\bar{f}} = \langle \bar{f} | H^{weak} | \bar{B} \rangle$$

$$\not{CP}: \quad \left| \bar{A}_{\bar{f}} / A_f \right| \neq 1 \qquad f \xrightarrow{CP} \bar{f}$$

$$a_{f^\pm}^{Decay} = \frac{\Gamma\left(B^+ \to f^+\right) - \Gamma\left(B^- \to f^-\right)}{\Gamma\left(B^+ \to f^+\right) + \Gamma\left(B^- \to f^-\right)} = \frac{1 - \left| \bar{A}_{f^-} / A_{f^+} \right|^2}{1 + \left| \bar{A}_{f^-} / A_{f^+} \right|^2}$$

Requires at least two different contibutions with different weak (φ_i) and strong (δ_i) phases

$$A_f = \sum_i A_i e^{i(\delta_i + \varphi_i)} \qquad \bar{A}_{\bar{f}} = \sum_i A_i e^{i(\delta_i - \varphi_i)} \qquad \left(A_2 << A_1 \right) \qquad r \equiv \frac{A_2}{A_1} << 1$$

$$i = 1,\ 2$$

$$a_{f^\pm}^{Decay} \approx -2r \sin\left(\delta_2 - \delta_1\right) \sin\left(\varphi_2 - \varphi_1\right)$$

Observed in K-system: $\mathrm{Re}\ \varepsilon'_K \neq 0$

Hadronic Uncertainties in A_i , δ_i

B^0-Decays into CP-Eigenstate

$B^0 \to \overline{B}^0$ → f
$B^0 \to B^0$ → f

ΔM = Difference between Mass Eigenstates in $(B^0, \overline{B}^0)$ System

$f \equiv f_{CP}$ = CP eigenstate
η_f = CP-parity = ± 1

Time-dependent asymmetry:

$$a_{CP}(t,f) = \frac{\Gamma\left(B^0(t) \to f\right) - \Gamma\left(\overline{B}^0(t) \to f\right)}{\Gamma\left(B^0(t) \to f\right) + \Gamma\left(\overline{B}^0(t) \to f\right)}$$

$$a_{CP}(t,f) = a_{CP}^{Decay} \cos(\Delta M t) + a_{CP}^{"mix-ind"} \sin(\Delta M t)$$

$$a_{CP}^{Decay} = \frac{1-|\xi_f|^2}{1+|\xi_f|^2} \equiv C_f \qquad a_{CP}^{"mix-ind"} = \frac{2\,\mathrm{Im}\,\xi_f}{1+|\xi_f|^2} \equiv -S_f$$

$$\xi_f = \underbrace{\exp[i2\varphi_M]}_{\text{Mixing}} \frac{\overline{A}_f\left(\overline{B}^0 \to f\right)}{A_f\left(B^0 \to f\right)}$$

Decay Amplitudes

For a **single** decay contribution or sum of contributions with **the same weak phase**

$$\xi_f = -\eta_f \exp[i2\varphi_M] \cdot \exp[-i2\varphi_D]$$

$|\xi_f|^2 = 1$ $\quad \varphi_D$: weak phase in the B^0 decay

⇒ ξ_f = given only in terms of CKM phase

$$a_{CP}^{decay} = 0$$

Dominance of a single CKM Amplitude

A_{Tree}, A_P - hadronic matrix elements
δ_T, δ_P - final state interaction phases
φ_T, φ_P - weak CKM phases

$$\frac{\overline{A}_f\left(\overline{B}^0 \to f\right)}{A_f\left(B^0 \to f\right)} = -\eta_f\left[\frac{A_{Tree}e^{i(\delta_T-\varphi_T)} + A_P e^{i(\delta_P-\varphi_P)}}{A_{Tree}e^{i(\delta_T+\varphi_T)} + A_P e^{i(\delta_P+\varphi_P)}}\right]$$

Tree Dominance

$$\frac{\overline{A}_f\left(\overline{B}^0 \to f\right)}{A_f\left(B^0 \to f\right)} = -\eta_f e^{-i2\varphi_T}$$

(Pure Phase)
Very Clean !

Penguin Dominance

$$\frac{\overline{A}_f\left(\overline{B}^0 \to f\right)}{A_f\left(B^0 \to f\right)} = -\eta_f e^{-i2\varphi_P}$$

(Pure Phase)
Very Clean !

Also pure phase if $\varphi_T=\varphi_P$!! (Example: $B_d^0 \to J/\psi\, K_S$)

3. CP Violation in the Interference of Mixing and Decay

Misnomer: ("Mixing induced CP-Violation")

$$a_{CP}(t,f) = \mathrm{Im}\,\xi_f \sin(\Delta M t)$$

$$\mathrm{Im}\,\xi_f = \eta_f \sin(2\varphi_D - 2\varphi_M) \equiv -S_f$$

Very clean TH

Measures the difference between the phases of B^0-$\bar{B}^0$ mixing ($2\varphi_M$) and of decay amplitude ($2\varphi_D$)

Examples:

$B_d^0 \to \psi K_S$: $\varphi_D = 0 \quad \varphi_M = -\beta \quad \eta_f = -1$

$$\mathrm{Im}\,\xi_{\psi K_S} = -\sin 2\beta$$

$B_d^0 \to \pi^+\pi^-$: $\varphi_D = \gamma \quad \varphi_M = -\beta \quad \eta_f = +1$

$$\mathrm{Im}\,\xi_{\pi\pi} = \sin(2(\gamma+\beta)) = -\sin 2\alpha$$

$K_L \to \pi^0 \nu\bar{\nu}$: Measures the difference between the phases in K^0-$\bar{K}^0$ mixing and $\bar{s} \to \bar{d}\nu\bar{\nu}$ amplitude

B^0-Decays into CP Eigenstates

$$\left(\text{Two Contributions} \quad r = \frac{A_2}{A_1} << 1 \right)$$

$$a_{CP}(t,f) = C_f \cos(\Delta M t) - S_f \sin(\Delta M t)$$

$$C_f = -2r \sin(\varphi_1 - \varphi_2) \sin(\delta_1 - \delta_2)$$

$$S_f = -\eta_f \left[\sin 2(\varphi_1 - \varphi_M) + 2r \cos 2(\varphi_1 - \varphi_M) \sin(\varphi_1 - \varphi_2) \cos(\delta_1 - \delta_2) \right]$$

φ_i = weak phases $\qquad$ δ_i = strong phases

$$\{r = 0\} \Rightarrow \quad C_f = 0 \qquad S_f = -\eta_f \sin 2(\varphi_1 - \varphi_M)$$

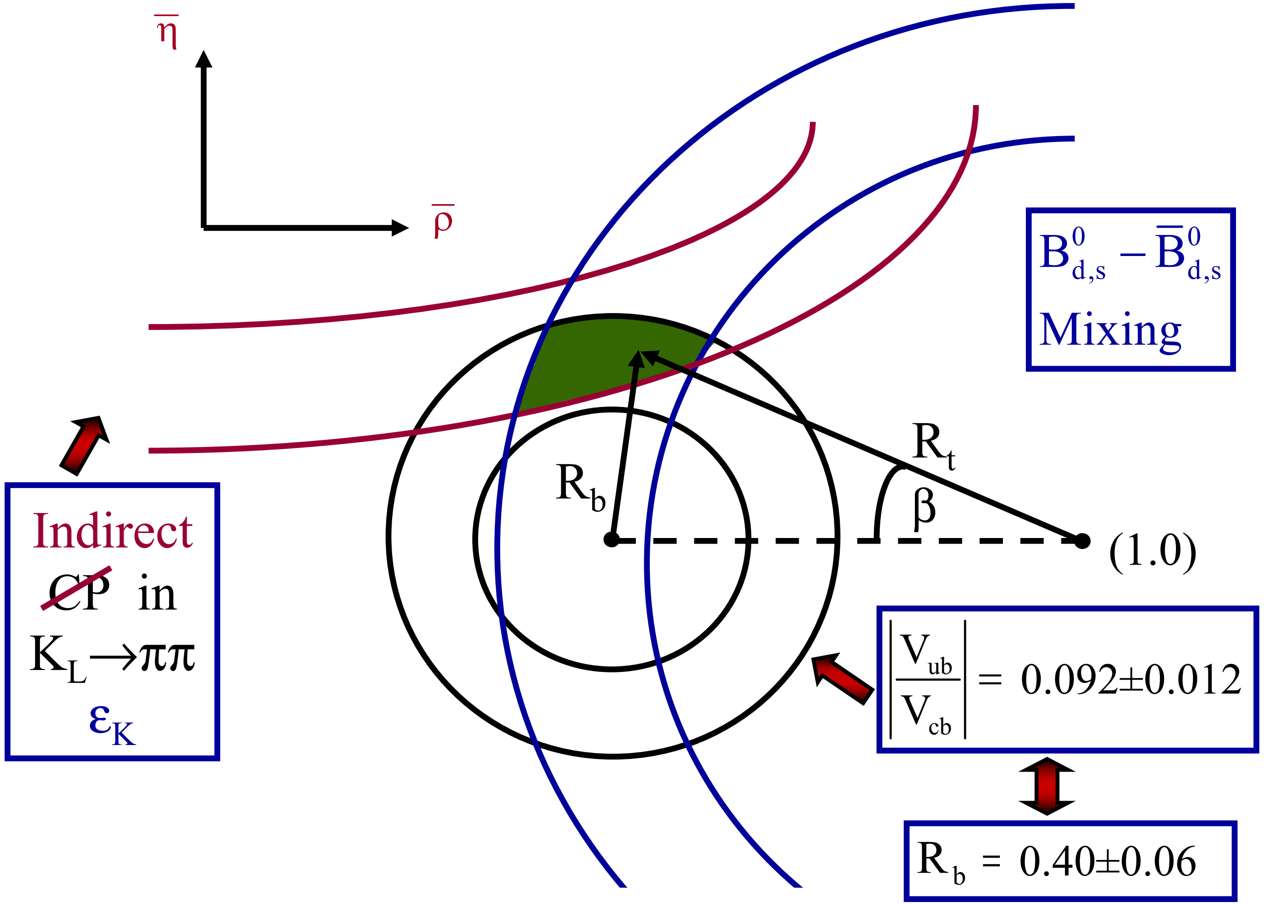
Comparison of Two-Languages

CP violation in mixing	≡	Manifestation of indirect $\not{CP}$
CP violation in decay	≡	Manifestation of direct $\not{CP}$
CP violation in interference of mixing and decay	≡	With a single decay it is impossible to state whether $\not{CP}$ in mixing or decay. But $\mathrm{Im}\,\xi_{f_1} \neq \mathrm{Im}\,\xi_{f_2}$ signals CP violation in decay (Direct $\not{CP}$)

3.

Standard Analysis of Unitarity Triangle

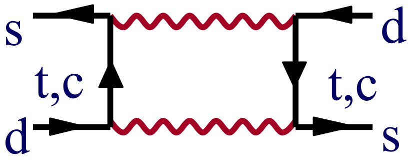
Standard Analysis of UT



Relevant Parameters

$$\hat{B}_K, \; F_{B_d}\sqrt{\hat{B}_{B_d}}, \quad \xi = F_{B_s}\sqrt{\hat{B}_{B_s}} \,/\, F_{B_d}\sqrt{\hat{B}_{B_d}} \quad \Leftrightarrow \quad \varepsilon_K \qquad \Delta M_d \qquad \Delta M_s / \Delta M_d$$

Indirect CP in $K_L \to \pi\pi$

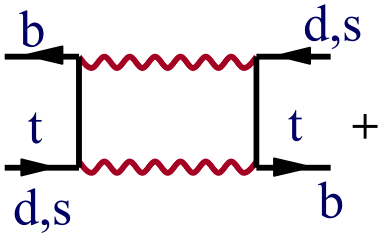
$\left\{ \text{Im} \right.$ 

$\left. + \text{QCD} \right\} \Rightarrow \varepsilon_K \Leftarrow \{\text{Experiment}\}$

exp:

$$\varepsilon_K = (2.280 \pm 0.013) \cdot 10^{-3} e^{i\frac{\pi}{4}}$$

$B^0_{d,s} - \overline{B}^0_{d,s}$ Mixing

$\{$ 

$+ \text{QCD} \} \Rightarrow (\Delta M)_{d,s} \Leftarrow$ {CLEO, ARGUS, 4*LEP,SLD, BaBar, Belle}

$$(\Delta M)_{d,s} \equiv M(B^0_H)_{d,s} - M(B^0_L)_{d,s}$$

Mass Eigenstates

exp: ★

$$(\Delta M)_d = (0.503 \pm 0.006)/\text{ps}$$

$$(\Delta M)_s > 14.4/\text{ps} \quad (95\%\ \text{C.L.}) \qquad (\text{LEP}/\text{SLD})$$

Basic Formulae

1. ε_K - Hyperbola

$$\bar{\eta}\left[\left(1-\bar{\rho}\right)A^2F_{tt}\eta_{QCD}^{tt}+P_c\left(\varepsilon\right)\right]A^2\hat{B}_K=0.213$$

$$\eta_{QCD}^{tt}=0.57\pm0.01;\quad P_C\left(\varepsilon\right)=0.28\pm0.05;\quad F_{tt}=2.42\pm0.12$$

$$\left(F_{tt}\equiv S\left(x_t\right)\right)$$

2. $B_d^0-\bar{B}_d^0$ Mixing Constraint

$$R_t=0.86\left[\frac{0.041}{\left|V_{cb}\right|}\right]\sqrt{\frac{2.34}{F_{tt}}}\sqrt{\frac{\Delta M_d}{0.50/ps}}\left[\frac{230MeV}{\sqrt{\hat{B}_d}F_{B_d}}\right]\sqrt{\frac{0.55}{\eta_B^{QCD}}}$$

$$\left|V_{cb}\right|=0.041\pm0.001;\quad \Delta M_d=\left(0.503\pm0.006\right)/ps;\quad \eta_B^{QCD}=0.55\pm0.01$$

3. $B_s^0-\bar{B}_s^0$ Mixing Constraint ($\Delta M_d/\Delta M_s$)

$$R_t=0.90\sqrt{\frac{\Delta M_d}{0.50/ps}}\sqrt{\frac{18.4/ps}{\Delta M_s}}\left[\frac{\xi}{1.22}\right]$$

$$\xi=\frac{\sqrt{\hat{B}_s}F_{B_s}}{\sqrt{\hat{B}_d}F_{B_d}}$$

$\Delta M_s > 14.4$ / ps (95% C.L.) LEP (SLD)

4. $\sin 2\beta$ from $A_{CP}(\psi K_S)$

$$A_{CP}(\psi K_S) \equiv -a_{\psi K_S} \sin(\Delta M_d t)$$

$$a_{\psi K_S} = \sin 2\beta \qquad \text{(SM)}$$

$$\sin 2\beta_{\psi K_S} = \begin{cases} 0.79 \pm {}^{0.41}_{0.44} & \text{(CDF)} \\ 0.741 \pm \underset{\text{(stat)}}{0.067} \pm \underset{\text{(syst)}}{0.033} & \text{(BaBar)} \\ 0.719 \pm 0.074 \pm 0.035 & \text{(Belle)} \end{cases}$$

$$\left(\text{ALEPH}: 0.84\ {}^{+0.82}_{-1.04} \pm 0.16\right)$$

⇓

$$\sin 2\beta = 0.726 \pm 0.037 \quad (a_{\psi K_s})$$

⇓

$$\beta = \begin{cases} (23.3 \pm 1.6)^{O} \\ (66.7 \pm 1.6)^{O} & \text{(excluded in the SM)} \end{cases} \qquad (\sin\beta \cong 0.40 \pm 0.03)$$

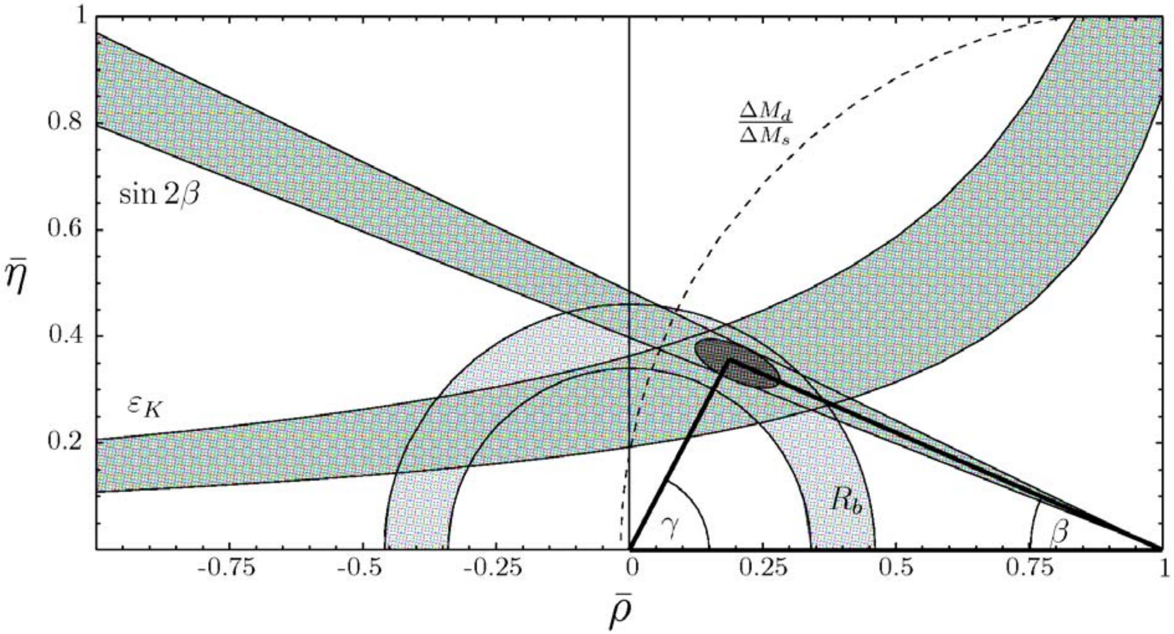
Crucial Parameters in SM and Beyond

$\lvert V_{us}\rvert = \lambda$	0.2240 ± 0.0036	
$\lvert V_{ub}\rvert$	$(3.81 \pm 0.46)\cdot 10^{-3}$	
$\lvert V_{cb}\rvert$	$(41.5 \pm 0.8)\cdot 10^{-3}$	★
$\left\lvert \frac{V_{ub}}{V_{cb}} \right\rvert$	0.092 ± 0.012	★
$m_t(m_t)$	(168 ± 4) GeV	
$\hat{B}_K$	0.86 ± 0.15	(ε_K)
$\sqrt{\hat{B}_d} F_{Bd}$	$(235 {}^{+33}_{-41})$ MeV	(ΔM_d)
$\xi = \frac{\sqrt{\hat{B}_s} F_{Bs}}{\sqrt{\hat{B}_d} F_{Bd}}$	1.24 ± 0.08	$\left(\frac{\Delta M_s}{\Delta M_d}\right)$

Valid for all extensions of SM !!

Unitarity Triangle 2004

AJB, Schwab, Uhlig



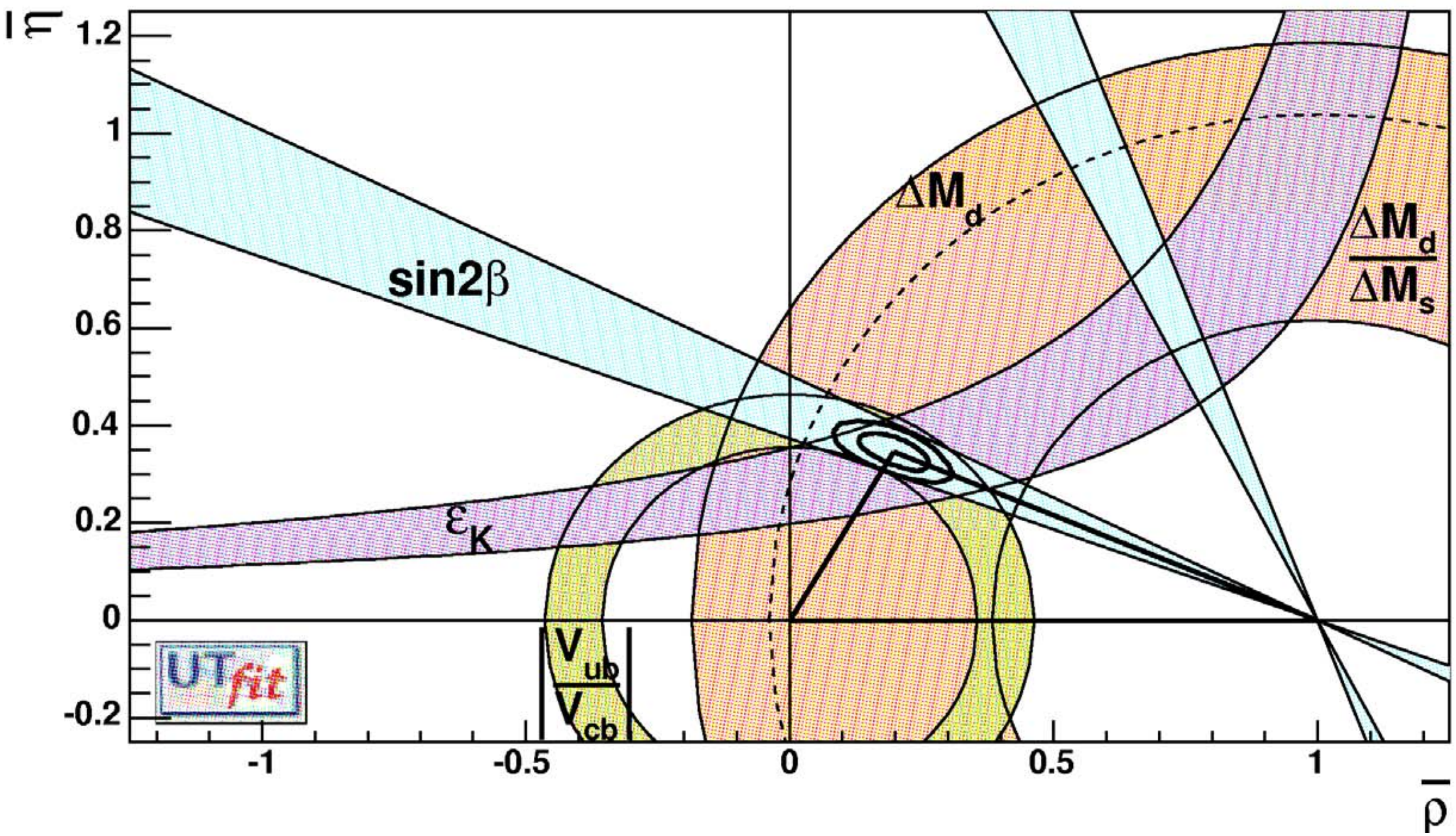
$$\bar{\eta} = 0.354 \pm 0.027$$
$$\bar{\rho} = 0.187 \pm 0.059$$

$$\gamma = (62.2 \pm 8.2)^{o}$$
$$R_t = 0.887 \pm 0.059$$
$$R_b = 0.400 \pm 0.039$$
$$|V_{td}| = (8.24 \pm 0.54) \cdot 10^{-3}$$

$$\mathrm{Im}\,\lambda_t = (1.40 \pm 0.12) \cdot 10^{-4}$$
$$\lambda_t = V_{ts}^{*} V_{td}$$

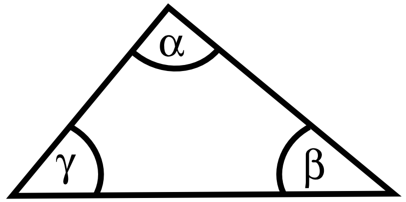
Unitarity Triangle 2005

UTfit collaboration : Bona et al.



4.

α, β, γ from B-Decays



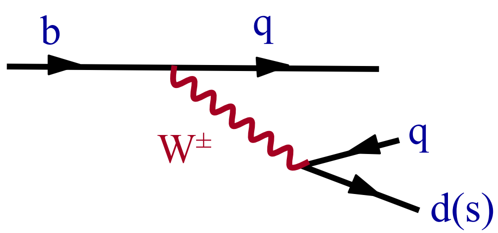
$$V_{td} = |V_{td}| e^{-i\beta}$$

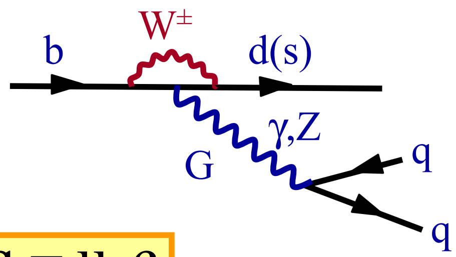
$$V_{ts} = |V_{ts}| e^{-i\beta_s}$$

$$V_{ub} = |V_{ub}| e^{-i\gamma}$$

Basic Contributions

Class I Decays with Trees and Penguins

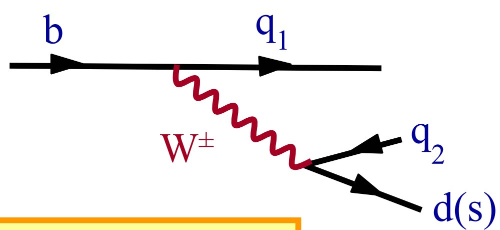




$q = u, c$

$b \to c\bar{c}s$
$b \to c\bar{c}d$
$b \to u\bar{u}s$
$b \to u\bar{u}d$

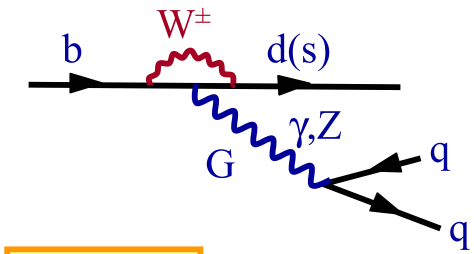
Class II Trees only



$b \to c\bar{u}s$
$b \to c\bar{u}d$
$b \to u\bar{c}s$
$b \to u\bar{c}d$

$q_1 \neq q_2 \in \{u, c\}$

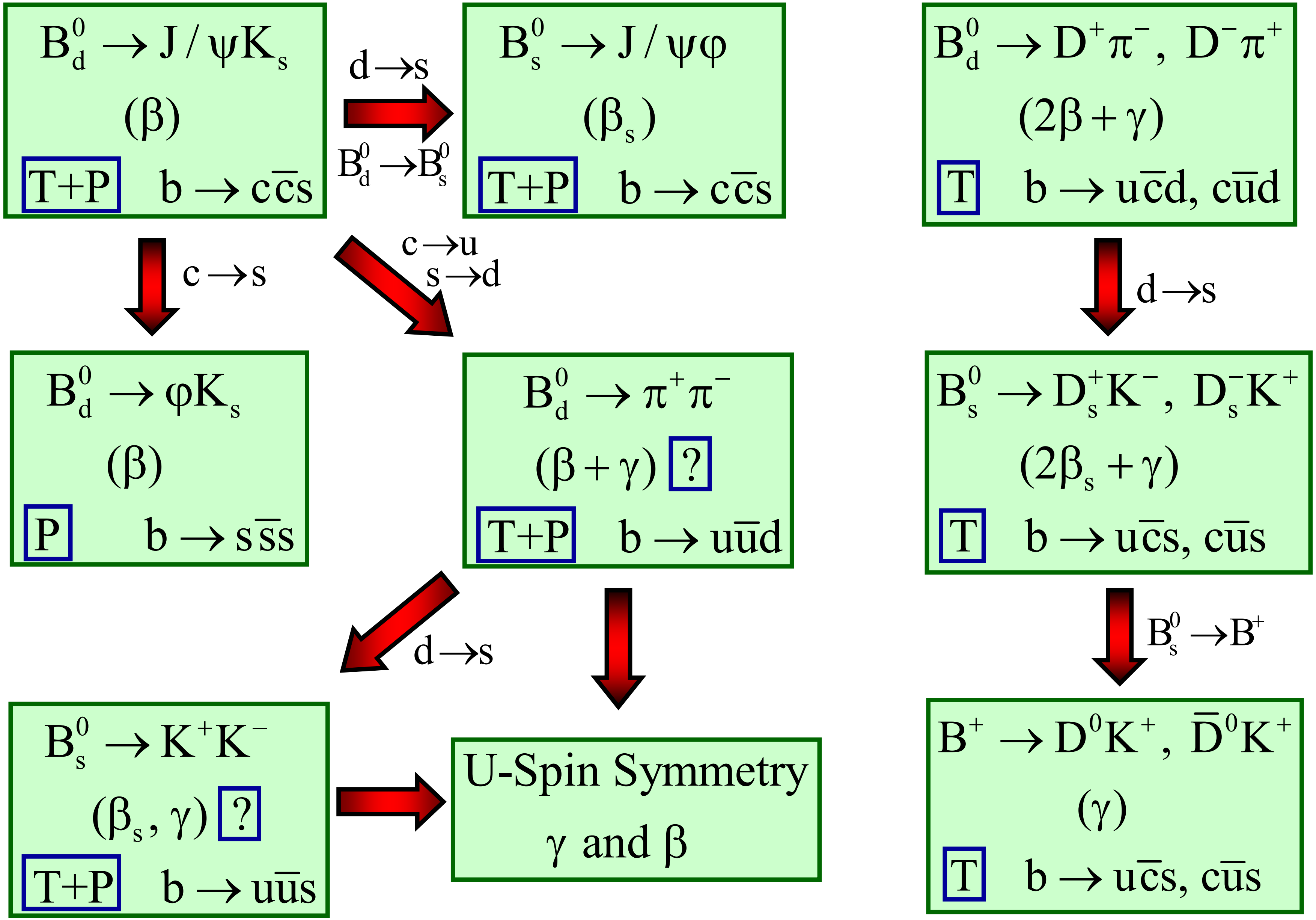
Class III Penguins only



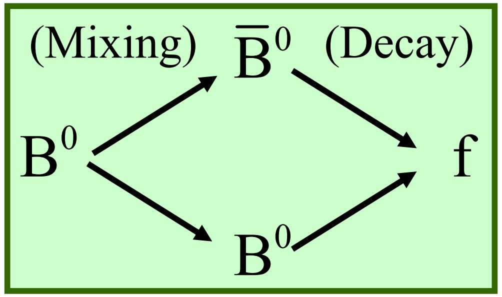
$b \to s\bar{s}s$
$b \to s\bar{s}d$
$b \to d\bar{d}s$
$b \to d\bar{d}d$

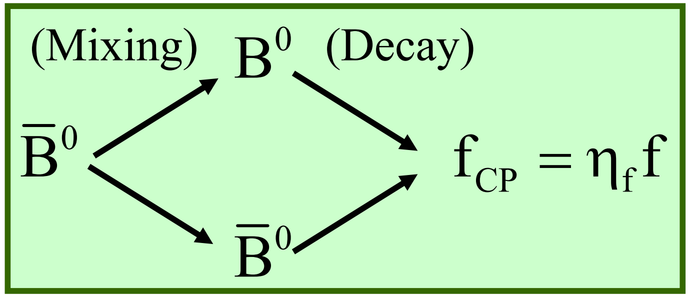
$q = d, s$

α, β, γ from B-Decays



$B^0(\bar{B}^0)$-Decays into CP-Eigenstates





$\eta_f = \pm 1$ CP Parity

Basic dynamical quantity:

$$\xi_f \equiv \underbrace{\exp(i2\varphi_M)}_{\text{Mixing}} \underbrace{\frac{\bar{A}_f(\bar{B}^0 \to f)}{A_f(B^0 \to f)}}_{\text{Decay Amplitudes}}$$

Weak phase in B^0 Decay : $\varphi_D = 0,\ \beta,\ \gamma$

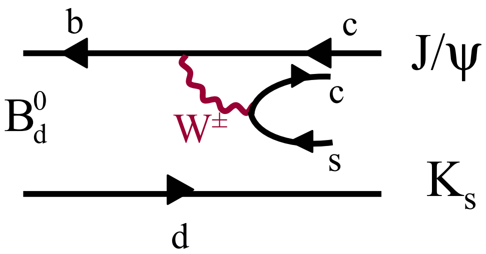
$$= -\eta_f \exp(i2\varphi_M) \cdot \exp(-i2\varphi_D)$$

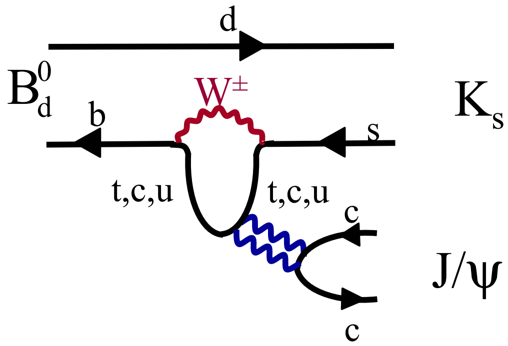
In the case of a single decay contribution or contributions with the same weak phase

$$\varphi_M = \begin{cases} -\beta & (B^0_d - \bar{B}^0_d \text{ mixing}) \\ \underbrace{-\beta_s}_{\approx 1^0} & (B^0_s - \bar{B}^0_s \text{ mixing}) \end{cases}$$

EXP ➡ $\mathrm{Im}\,\xi_f = \eta_f \sin 2(\varphi_D - \varphi_M)$ ★

$B_d^0 \to J/\psi K_S$ and β





$$V_{td} = \left|V_{td}\right| e^{-i\beta}$$

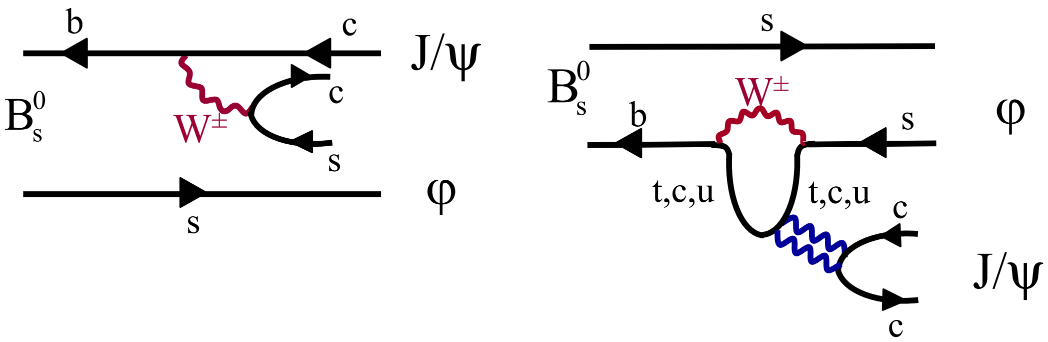
$$V_{cs}V_{cb}^* \cong A\lambda^2$$
$$V_{us}V_{ub}^* \cong A\lambda^4 R_b e^{i\gamma}$$
$$V_{ts}V_{tb}^* = -V_{cs}V_{cb}^* - V_{us}V_{ub}^*$$

$$\begin{aligned} A\left(B_d^0 \to J/\psi K_S\right) &= V_{cs}V_{cb}^*\left(A_T + P_c\right) + V_{us}V_{ub}^* P_u + V_{ts}V_{tb}^* P_t \\ &= V_{cs}V_{cb}^*\left(A_T + P_c - P_t\right) + V_{us}V_{ub}^*\left(P_u - P_t\right) \end{aligned}$$

(Dominance of a single phase)

$$\left\{ \begin{array}{l} \left|\dfrac{V_{us}V_{ub}^*}{V_{cs}V_{cb}^*}\right| \le 0.02 \\ \dfrac{P_u - P_t}{A_t + P_c - P_t} << 1 \end{array} \right\} \Rightarrow \left\{ \begin{array}{l} \varphi_D = 0 \\ \varphi_M = -\beta \\ \left|\xi_{\psi K_S}\right| = 1 \end{array} \right\} \Rightarrow \left\{ \begin{array}{l} a_{CP}^{mix}\left(\psi K_S\right) = \eta_{\psi K_S} \sin 2\left(\varphi_D - \varphi_M\right) = -\sin 2\beta \\ a_{CP}^{dir}\left(\psi K_S\right) = 0 \qquad a_{CP}\left(\psi K^+\right) \cong 0 \\ \boxed{C_{\psi K_S} = 0} \qquad \boxed{S_{\psi K_S} = \sin 2\beta} \end{array} \right\}$$

$B_s^0 \to J/\psi\varphi$ and β_s



$$V_{ts} = \left|V_{ts}\right| e^{-i\beta_S}$$

Differs from

$B_d^0 \to J/\psi K_S$ only by

"spectator" quark $d \to s$

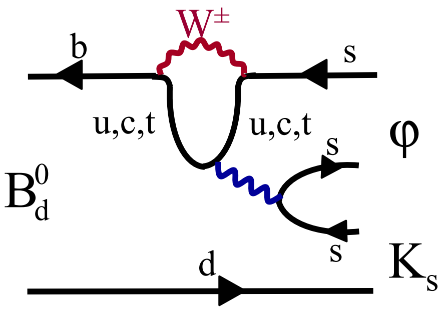
$$(\varphi_D = 0)$$

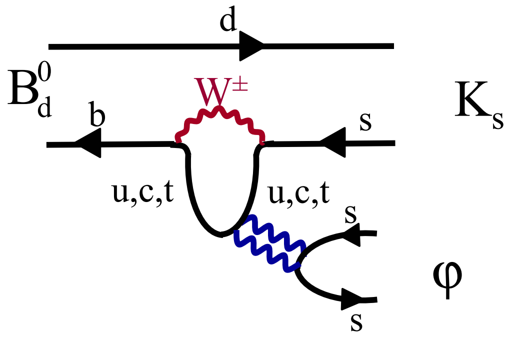
Complication: $(J/\psi\varphi)$ admixture of CP = + and CP = −

(Can be resolved: see Page 40: "B-Decays at the LHC ")

$$\left\{ \begin{array}{l} \varphi_D = 0 \\ \varphi_M = -\beta_S \cong -\lambda^2\eta \\ \left|\xi_{\psi\varphi}\right| = 1 \end{array} \right\} \Rightarrow \left\{ \begin{array}{l} a_{CP}^{mix} = \sin 2(\varphi_D - \varphi_M) \cong \underbrace{2\lambda^2\eta}_{2\beta_S} \cong 0.03 \\ a_{CP}^{dir} \cong 0 \\ \text{A lot of room for New Physics!} \end{array} \right\}$$

$B_d^0 \to \varphi K_S$ and β (Pure Peguin Decay)





$$V_{cs}V_{cb}^* \cong A\lambda^2$$
$$V_{us}V_{ub}^* \cong A\lambda^4 R_b e^{i\gamma}$$
$$V_{ts}V_{tb}^* = -V_{cs}V_{cb}^* - V_{us}V_{ub}^*$$

$$\begin{aligned} A\left(B_d^0 \to \varphi K_S\right) &= V_{cs}V_{cb}^* P_c + V_{us}V_{ub}^* P_u + V_{ts}V_{tb}^* P_t \\ &= V_{cs}V_{cb}^*\left(P_c - P_t\right) + V_{us}V_{ub}^*\left(P_u - P_t\right) \end{aligned}$$

(Dominance of a single phase)

$$\left\{ \begin{array}{l} \left|\dfrac{V_{us}V_{ub}^*}{V_{cs}V_{cb}^*}\right| \le 0.02 \\ \dfrac{P_u - P_t}{P_c - P_t} \approx O(1) \end{array} \right\} \Rightarrow \left(\begin{array}{c}\text{neglecting} \\ V_{us}V_{ub}^*\end{array}\right) \left\{ \begin{array}{l} a_{CP}^{mix}\left(\varphi K_S\right) = -\sin 2\beta = a_{CP}^{mix}\left(\psi K_S\right) \\ C_{\varphi K_S} \approx 0 \qquad S_{\psi K_S} = S_{\varphi K_S} = \sin 2\beta \\ \left|S_{\psi K_S} - S_{\varphi K_S}\right| \le 0.04 \ (SM) \end{array} \right\}$$

Grossman, Isidori, Worah, London, Soni

First Results for $B_d^0 \to \varphi K_S$

$$(\sin 2\beta)_{\phi K_S} = \begin{cases} +0.45 \pm 0.43 \pm 0.07 & \text{(BaBar)} \\ -0.96 \pm 0.50 \begin{smallmatrix} +0.11 \\ -0.09 \end{smallmatrix} & \text{(Belle)} \end{cases}$$

World Averages

$$S_{\phi K_S} = -0.05 \pm 0.24$$
$$C_{\psi K_S} = -0.15 \pm 0.33$$

(Belle)

$$S_{\eta' K_S} = 0.76 \pm 0.36$$
$$C_{\eta' K_S} = -0.26 \pm 0.22$$

(BaBar)

$$S_{\eta' K_s} = 0.02 \pm 0.35$$

(fully consistent with SM)

$$\left|S_{\varphi K_S} - S_{\psi K_S}\right| \cong 0.88 \pm 0.34$$

(Violation of SM by 2.6σ)

but $S_{\varphi K_S} \neq S_{\eta' K_S}$ possible as non-leading terms could be different

Grossman, Isidori Worah

Ciuchini Silvestrini

New Physics:

Enhanced QCD Penguins
Z^0 Penguins, ..

Hiller, Raidal, Ciuchini + Silvestrini
Fleischer, Mannel

Present Results for $B_d^0 \to \varphi K_s$

$$(\sin 2\beta)_{\phi K_s} = \begin{cases} 0.50 \pm 0.25 \pm 0.06 & \text{(BaBar)} \\ 0.06 \pm 0.33 \pm 0.09 & \text{(Belle)} \end{cases}$$

World Averages: $S_{\varphi K_s} = 0.34 \pm 0.20$ $C_{\varphi K_s} = -0.04 \pm 0.17$

To be compared with $S_{\psi K_s} \approx 0.73$

New Physics?

Decays to CP non-eigenstates and γ

$\overset{(-)}{B}{}^0_d \to D^{\pm}\pi^{\mp}$
(Dunietz+Sachs)

$d \to s$

$\overset{(-)}{B}{}^0_s \to D_s^{\pm}K^{\mp}$
Aleksan, Dunietz, Kayser

- $B_d^0\left(B_s^0\right)$ and $\overline{B}_d^0\left(\overline{B}_s^0\right)$ can decay to the same final state
- Requires full time-dependent analysis: 4 time dependent rates

  $B_{d,s}^0(t) \to f, \quad \overline{B}_{d,s}^0(t) \to f,$

  $B_{d,s}^0(t) \to \overline{f}, \quad \overline{B}_{d,s}^0(t) \to \overline{f},$
- Tree diagrams only

$$\xi_f = e^{i2\varphi_M}\frac{A\left(\overline{B}^0 \to f\right)}{A\left(B^0 \to f\right)}$$

$$\begin{array}{l} \overline{B}^0 \searrow \\ \updownarrow \qquad f \\ B^0 \nearrow \end{array}$$

$$\xi_{\overline{f}} = e^{i2\varphi_M}\frac{A\left(\overline{B}^0 \to \overline{f}\right)}{A\left(B^0 \to \overline{f}\right)}$$

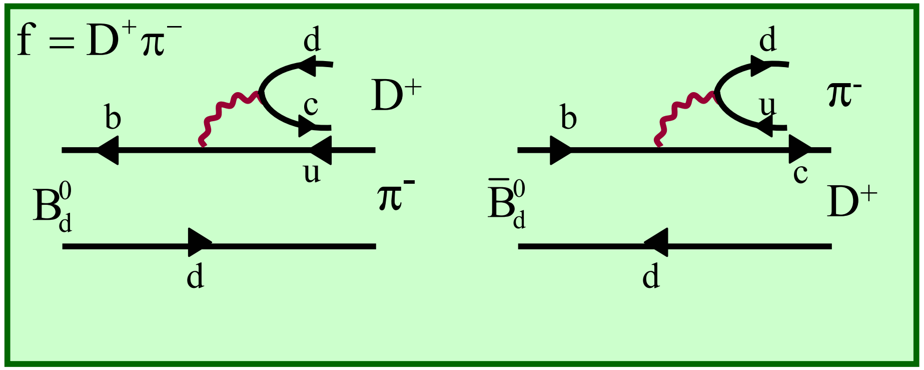
$$\begin{array}{l} \overline{B}^0 \searrow \\ \updownarrow \qquad \overline{f} \\ B^0 \nearrow \end{array}$$

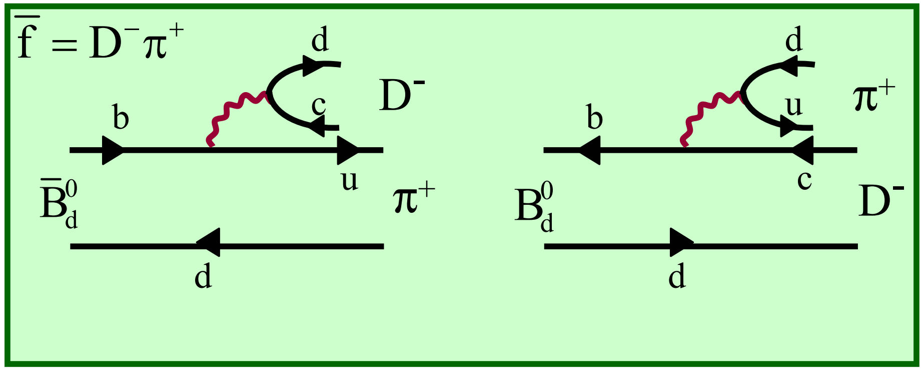
$$\varphi_M = \begin{cases} -\beta & B_d^0 \\ -\beta_s & B_s^0 \end{cases}$$

$$\xi_f \cdot \xi_{\overline{f}} = F\left(\gamma, \beta_{(s)}\right)$$

(Dunietz, Sachs)

$B_d^0 \to D^\pm \pi^\mp,\ \bar{B}_d^0 \to D^\pm \pi^\mp$ and γ





$\left(M_f A\lambda^4 R_b e^{i\gamma}\right)$ $\left(\bar{M}_f A\lambda^2\right)$ $\left(\bar{M}_{\bar{f}} A\lambda^4 R_b e^{-i\gamma}\right)$ $\left(M_{\bar{f}} A\lambda^2\right)$

$$\xi_f^{(d)} = e^{-i2\beta}\frac{A\left(\bar{B}_d^0 \to f\right)}{A\left(B_d^0 \to f\right)} = e^{-i(2\beta+\gamma)}\frac{1}{\lambda^2 R_b}\frac{\bar{M}_f}{M_f}$$

$$\xi_{\bar{f}}^{(d)} = e^{-i2\beta}\frac{A\left(\bar{B}_d^0 \to \bar{f}\right)}{A\left(B_d^0 \to \bar{f}\right)} = e^{-i(2\beta+\gamma)}\lambda^2 R_b\frac{\bar{M}_{\bar{f}}}{M_{\bar{f}}}$$

$\bar{M}_f = M_{\bar{f}}$ $\qquad$ $M_f = \bar{M}_{\bar{f}}$

Hadronic Matrix Elements

$$\xi_f^{(d)} \cdot \xi_{\bar{f}}^{(d)} = e^{-i2(2\beta+\gamma)}$$

$2\beta+\gamma$ without hadronic uncertainties

(β known)

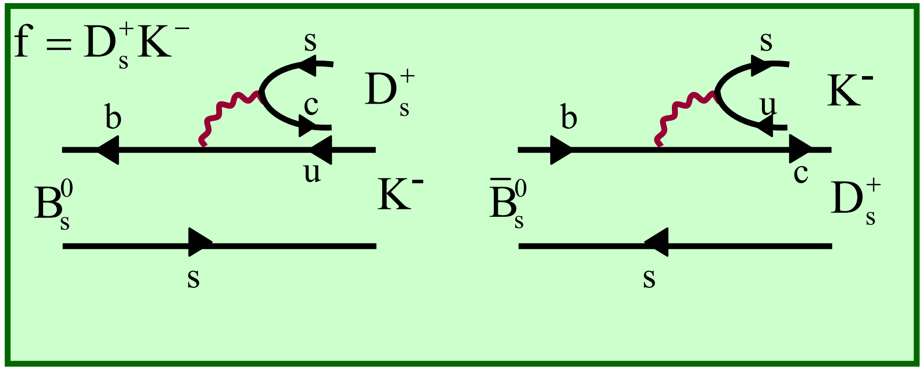
γ

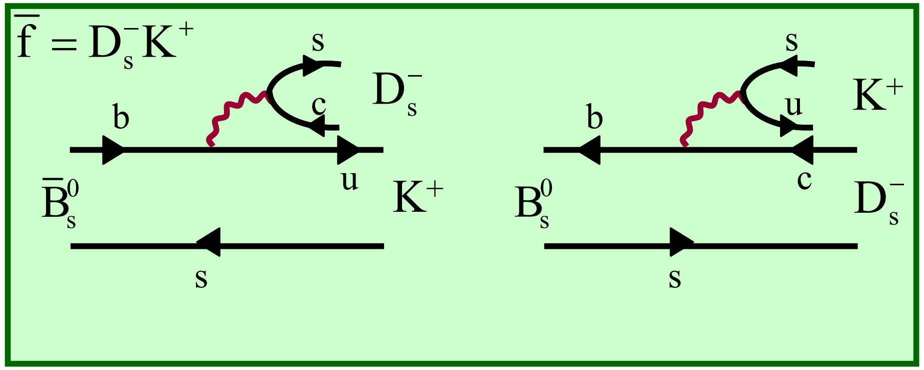
Small Interference: difficult exp. task

Aleksan
Dunietz
Kayser

$B_s^0 \to D_s^{\pm} K^{\mp},\ \bar{B}_s^0 \to D_s^{\pm} K^{\mp}$ and γ

Directly obtained from $B_d^0,\ \bar{B}_d^0 \to D^{\pm}\pi^{\mp}$ through $d \to s$





$\left(M_f A\lambda^3 R_b e^{i\gamma}\right)$ $\left(\bar{M}_f A\lambda^3\right)$ $\left(\bar{M}_{\bar{f}} A\lambda^3 R_b e^{-i\gamma}\right)$ $\left(M_{\bar{f}} A\lambda^3\right)$

In analogy to $B_d^0,\ \bar{B}_d^0 \to D^{\pm}\pi^{\mp}$

$$\xi_f^{(s)} \cdot \xi_{\bar{f}}^{(s)} = e^{-i2(2\beta_s+\gamma)}$$

β_s – phase in $B_s^0 - \bar{B}_s^0$

$2\beta_s + \gamma$ without hadronic uncertainties

β_s from $B_s^0 \to \varphi\psi$

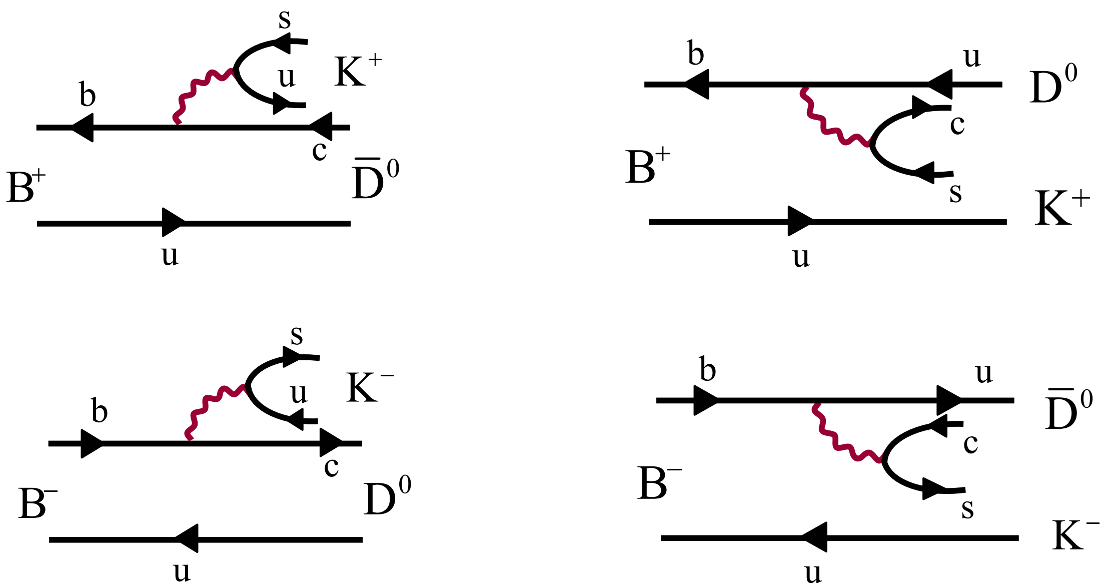
γ

Much bigger interference than in $B_d^0,\ \bar{B}_d^0 \to D^{\pm}\pi^{\mp}$

$B^{\pm} \to D^0 K^{\pm},\ \bar{D}^0 K^{\pm}$ and γ

(Gronau + Wyler)

Directly obtained from $B_s^0,\ \bar{B}_s^0 \to D_s^{\pm} K^{\pm}$ through $B_s \to B^{\pm}$



$K^+\bar{D}^0 \neq K^+ D^0$

Need

$B^+ \to D_+^0 K^+$

$$D_+^0 = \frac{1}{\sqrt{2}}\left(D^0 + \bar{D}^0\right)$$

To each process only single diagram contributes

$$A\left(B^+ \to \bar{D}^0 K^+\right) = A\left(B^- \to D^0 K^-\right)$$

$$A\left(B^+ \to D^0 K^+\right) = A\left(B^- \to \bar{D}^0 K^-\right) e^{2i\gamma}$$

$0\left(A\lambda^3\right)$

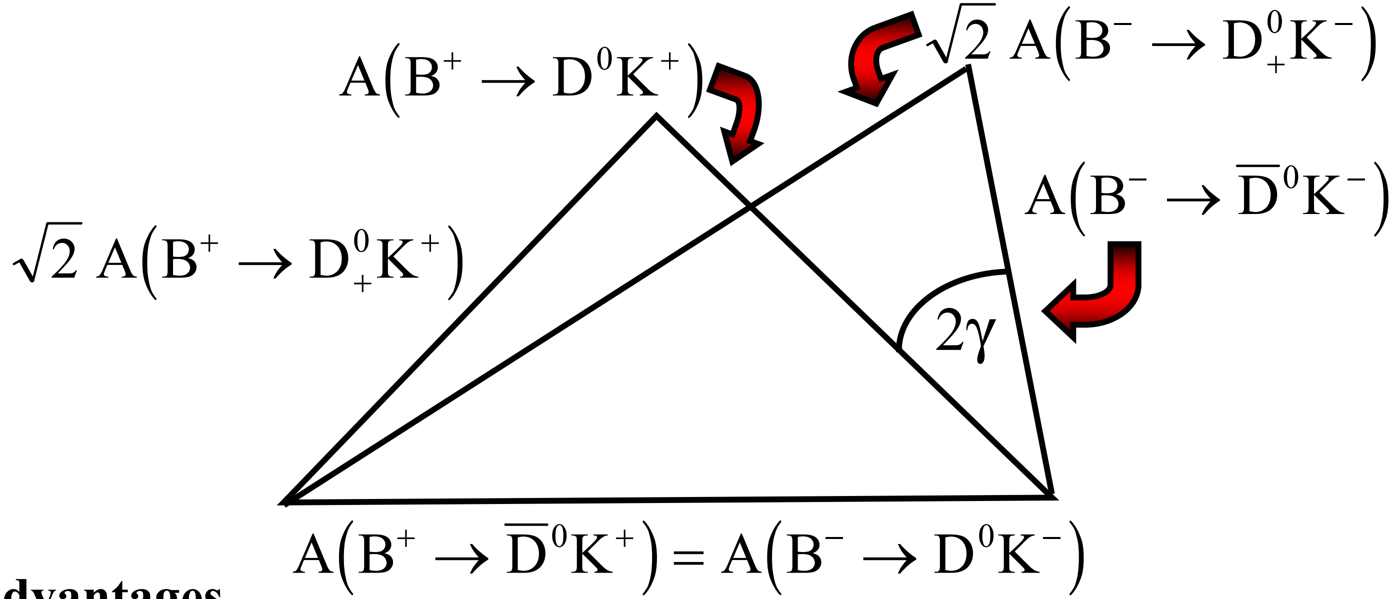
$0\left(A\lambda^3 R_b\right)$ Colour suppressed

Gronau-Wyler Method for γ

$$\sqrt{2}\,A\left(B^+ \to D_+^0 K^+\right) = A\left(B^+ \to D^0 K^+\right) + A\left(B^+ \to \overline{D}^0 K^+\right)$$

$$\sqrt{2}\,A\left(B^- \to D_+^0 K^-\right) = A\left(B^- \to \overline{D}^0 K^-\right) + A\left(B^- \to D^0 K^-\right)$$

$$D_+^0 = \frac{1}{2}\left(\left|D^0\right\rangle + \left|\overline{D}^0\right\rangle\right) \qquad CP = +$$



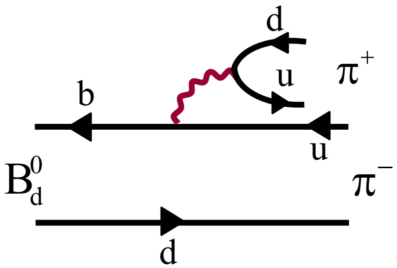
Advantages

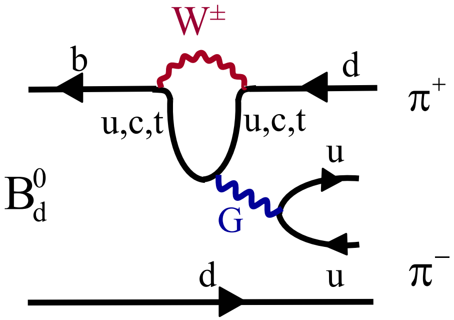
- Pure Trees
- No tagging
- No time dependent measurements
- Only rates

Disadvantages

- $Br\left(B^+ \to D^0 K^+\right) \sim 0\left(10^{-6}\right)$
- $Br\left(B^+ \to \overline{D}^0 K^+\right) \sim 0\left(10^{-4}\right)$
- Detection of D_+^0

$B_d^0 \to \pi^+\pi^-$ and α





$$V_{ub}^* V_{ud} = A\lambda^3 R_b e^{i\gamma}$$
$$V_{cb}^* V_{cd} = A\lambda^3$$
$$V_{tb}^* V_{td} = -V_{ub}^* V_{ud} - V_{cb}^* V_{cd}$$

$$A\left(B_d^0 \to \pi^+\pi^-\right) = V_{ub}^* V_{ud}\left(A_T + P_u\right) + V_{cb}^* V_{cd} P_c + V_{tb}^* V_{td} P_t$$
$$= V_{ub}^* V_{ud}\left(A_T + P_u - P_t\right) + V_{cb}^* V_{cd}\left(P_c - P_t\right)$$

$$\left|\frac{V_{cb}^* V_{cd}}{V_{ub}^* V_{ud}}\right| = \frac{1}{R_b} \approx 0(2)$$
$$\frac{P_c - P_t}{A_T + P_u - P_t} = \frac{P_{\pi\pi}}{T_{\pi\pi}} \quad ?$$

Assuming

$$\frac{P_{\pi\pi}}{T_{\pi\pi}} << 1$$

$$\varphi_D = \gamma \qquad \varphi_M = -\beta \qquad \left|\xi_{\pi\pi}\right| = 1$$

$$a_{CP}^{mix} = \eta_{\pi\pi} \sin 2\left(\varphi_D - \varphi_M\right) = \sin 2\left(\gamma + \beta\right) = -\sin 2\alpha$$

$$a_{CP}^{dir} = 0 \qquad C_{\pi\pi} = 0 \qquad S_{\pi\pi} = \sin 2\alpha$$

Dominance of a
single amplitude uncertain

Results for $B_d^0 \to \pi^+\pi^-$

$$C_{\pi\pi} = \begin{cases} -0.09 \pm 0.15 \pm 0.04 & \text{(BaBar)} \\ -0.58 \pm 0.15 \pm 0.07 & \text{(Belle)} \end{cases}$$

Consistent with 0

$\not{CP}$

$$S_{\pi\pi} = \begin{cases} -0.30 \pm 0.17 \pm 0.03 & \text{(BaBar)} \\ -1.00 \pm 0.21 \pm 0.07 & \text{(Belle)} \end{cases}$$

Consistent with 0

$\not{CP}$

World Average: $C_{\pi\pi} = -0.37 \pm 0.11 \qquad S_{\pi\pi} = -0.61 \pm 0.16$

Isospin analysis (Gronau + London)
Model independent determination of α

Model independent upper bound
(Grossman, Quinn; Charles)

$$\sin^2(\alpha_{\text{eff}} - \alpha) \leq \frac{Br(B^0 \to \pi^0\pi^0)}{Br(B^+ \to \pi^+\pi^0)}$$

$$\sin 2\alpha_{\text{eff}} \equiv \frac{\operatorname{Im}\xi_{\pi\pi}}{|\xi_{\pi\pi}|}$$

Model dependent determination
of α using $(P_{\pi\pi}/T_{\pi\pi})_{TH}$

Beneke, Buchalla, Neubert, Sachrajda: small $C_{\pi\pi}$

Keum,Li,Sanda: large $C_{\pi\pi}$

Most recent:
Buchalla, Safir;
AJB, Fleischer, Recksiegel, Schwab
Gronau, Rosner et al.
Ali, Lunghi, Parkhomenko

U-Spin Strategies

($d \leftrightarrow s$)

Fleischer:

$$\left\{\begin{array}{l} B_d^0 \to \pi^+\pi^- \\ B_s^0 \to K^+K^- \end{array}\right\} \Rightarrow \beta, \gamma$$

$$\left\{\begin{array}{l} B_d^0 \to J/\psi K_s \\ B_s^0 \to J/\psi K_s \end{array}\right\} \Rightarrow \gamma$$

$$\left\{\begin{array}{l} B_d^0 \to D^+D^- \\ B_s^0 \to D_s^+D_s^- \end{array}\right\} \Rightarrow \gamma$$

Uncertainty from
U-Spin breaking

Gronau + Rosner; Chiang Wolfenstein:

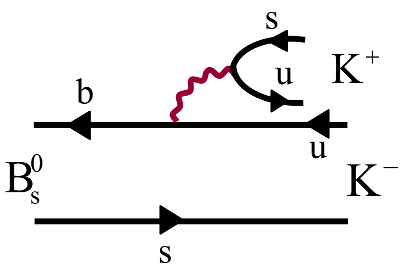
$$\left\{\begin{array}{l} B_d^0 \to \pi^-K^+ \\ B_s^0 \to \pi^+K^- \end{array}\right\} \Rightarrow \gamma$$

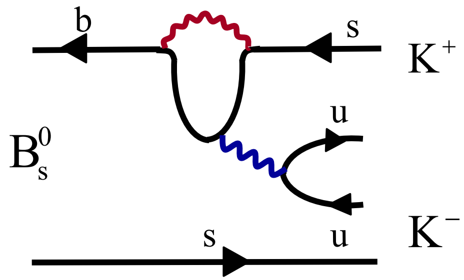
Uncertainty from U-Spin breaking,
rescattering, colour suppressed
EW-Penguins

$B_d^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ (β and γ)

(Fleischer)

$\left\{\text{Replace in } B_d^0 \to \pi^+\pi^- :\ d \to s\right\}$





$$V_{ub}^* V_{us} = A\lambda^4 e^{i\gamma} R_b$$
$$V_{cb}^* V_{cs} = A\lambda^2$$
$$V_{tb}^* V_{ts} = -V_{ub}^* V_{us} - V_{cb}^* V_{cs}$$

$$A\left(B_s^0 \to K^+K^-\right) = V_{ub}^* V_{us}\left(A'_T + P'_u - P'_t\right) + V_{cb}^* V_{cs}\left(P'_c - P'_t\right)$$

U-Spin Symmetry:
$$\frac{P_{\pi\pi}}{T_{\pi\pi}} = \frac{P_c - P_t}{A_T + P_u - P_t} = \frac{P'_c - P'_t}{A'_T + P'_u - P'_t} = \frac{P_{KK}}{T_{KK}} \equiv d e^{i\delta}$$
strong phase

$a_{CP}^{mix}\left(B_d^0 \to \pi^+\pi^-\right)$ $a_{CP}^{mix}\left(B_s^0 \to K^+K^-\right)$

$a_{CP}^{dir}\left(B_d^0 \to \pi^+\pi^-\right)$ $a_{CP}^{dir}\left(B_s^0 \to K^+K^-\right)$

$(\beta_s$ from $B_s \to J/\psi\varphi)$

$d,\ \delta,\ \beta,\ \gamma$ subject to U-Spin breaking corrections

β present in $B_d^0 - \overline{B}_d^0$ mixing

$V_{td} = |V_{td}| e^{-i\beta}$
$V_{ub} = |V_{ub}| e^{-i\gamma}$
$V_{ts} = |V_{ts}| e^{-i\beta_s}$

Golden Measurements

(Essentially no TH uncertainties)

1. Decays into CP-Eigenstates (time evolution)

$B_d^0 (\overline{B}_d^0) \to \psi K_s$ ➡ β

$B_d^0 (\overline{B}_d^0) \to \psi \varphi$ ➡ β_s

2. Decays into CP non-Eigenstates (time evolution)

$B_d^0 (\overline{B}_d^0) \to D^{\pm} \pi^{\mp}$ ➡ $2\beta + \gamma$

$B_d^0 (\overline{B}_d^0) \to D_s^{\pm} K^{\mp}$ ➡ $2\beta_s + \gamma$

3. $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ (branching ratios)

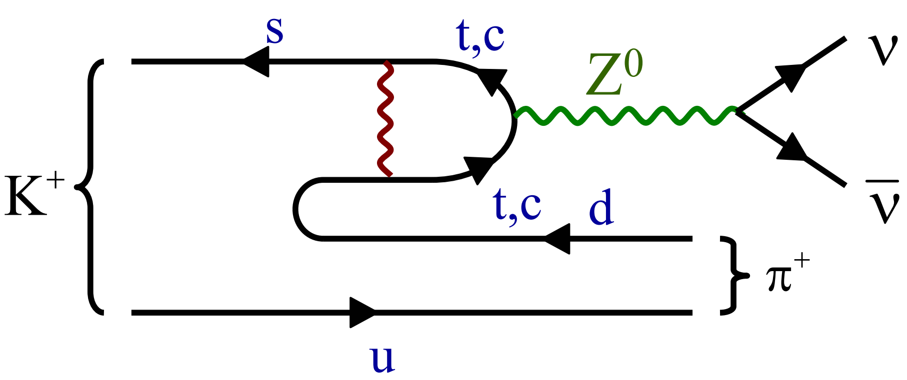
$Br(K^+ \to \pi^+ \nu\bar{\nu})$
$Br(K_L \to \pi^0 \nu\bar{\nu})$
➡ β and γ

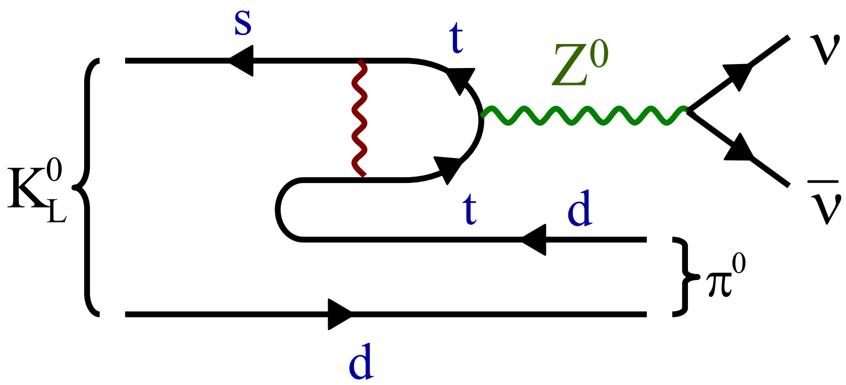
5.

$$K_L \to \pi^0 \nu \overline{\nu}$$

$$K^+ \to \pi^+ \nu \overline{\nu}$$

Decays $K \to \pi\nu\bar{\nu}$





Isospin Symmetry

$$\langle \pi^+ | (\bar{s}d)_{V-A} | K^+ \rangle = \sqrt{2} \langle \pi^0 | (\bar{s}u)_{V-A} | K^+ \rangle$$

$$\langle \pi^0 | (\bar{s}d)_{V-A} | K^0 \rangle = \langle \pi^0 | (\bar{s}u)_{V-A} | K^+ \rangle$$

Leading Decay: $K^+ \to \pi^0 e^+ \nu$

Isospin Breaking:

Marciano, Parsa

K^+(10%) K_L(5%)

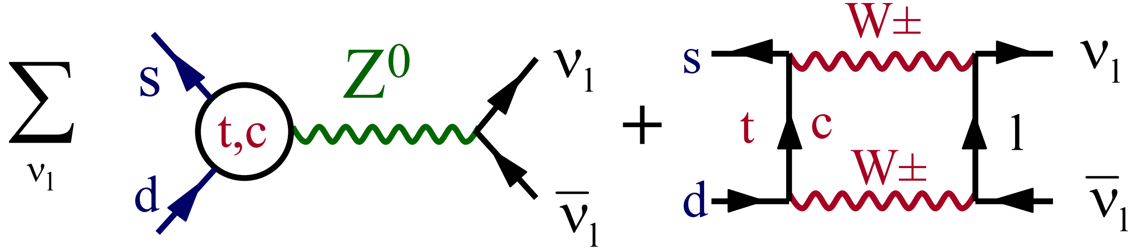
Long Distance:

K^+: +(6±2)% Isidori, Mescia, Smith (2005)

K_L: ≤1% Buchalla, Isidori

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$

V_{td}



+ QCD Corrections:

Dib, Dunietz, Gilman LO (91)

Buchalla + AJB NLO (94)

$x_t = \overline{m}_t^2 / M_W^2$

$$H_{eff} = \frac{G_F}{\sqrt{2}} \frac{\alpha}{2\pi \sin^2 \theta_W} \sum_{\nu_l} \left(\lambda_c X_{NL}^l + \lambda_t X(x_t) \right) Q$$

$$\lambda_c = V_{cs}^* V_{cd} \qquad \lambda_t = V_{ts}^* V_{td} \qquad Q = (\bar{s}d)_{V-A} (\bar{\nu}\nu)_{V-A}$$

$$X(x_t) = X_0(x_t) + \frac{\alpha_s}{4\pi} X_1(x_t) \equiv \eta_x X_0(x_t)$$

$$X_1(x_t) = \tilde{X}_1(x_t) + 8x_t \frac{\partial X_0(t)}{\partial x_t} \ln \frac{\mu_t^2}{M_W^2}$$

Cancels μ_t-dependence in $X_0(x_t(\mu_t))$

$\overline{m}_t(\mu_t)$

For $\mu_t \cong m_t$

$\eta_x = 0.995$

$X_{NL} \approx 10^{-3}$

$X(x_t) = 0.65 \cdot x_t^{0.575}$

$$Br(K^+ \to \pi^+ \nu\bar{\nu})$$

- **Take:** $$H_{eff}(K^+ \to \pi^0 e^+ \nu) = \frac{G_F}{\sqrt{2}} V_{us}^* (\bar{s}u)_{V-A} (\bar{\nu}e)_{V-A}$$
- **Use: Isospin Symmetry**
$$\langle \pi^+ | (\bar{s}d)_{V-A} | K^+ \rangle = \sqrt{2} \langle \pi^0 | (\bar{s}u)_{V-A} | K^+ \rangle$$
- **For single ν with** $m_{\pi^+} = m_{\pi^0}$
$$\frac{Br(K^+ \to \pi^+ \nu\bar{\nu})}{Br(K^+ \to \pi^0 e^+ \nu)} = \frac{\alpha^2}{V_{us}^2 2\pi^2 \sin^4\theta_W} \left| \lambda_C X_{NL} + \lambda_t X(x_t) \right|^2$$
- **Include Isospin breaking corrections** Marciano+ Parsa (95)

$m_{\pi^+} \neq m_{\pi^0}$
Isospin violation in $K \to \pi$ formfactors
Electromagnetic corrections affecting
$\bar{s} \to \bar{u} e^+ \nu$ but not $\bar{s} \to \bar{d} \nu\bar{\nu}$

⇒ Additional Factor $r_{K^+} = 0.901$

Summing over 3 ν's

$$Br(K^+) = \kappa_+ \left[\left(\frac{Im\lambda_t}{\lambda^5} X(x_t) \right)^2 + \left(\frac{Re\lambda_c}{\lambda} P_c + \frac{Re\lambda_t}{\lambda^5} X(x_t) \right)^2 \right]$$

$$\kappa_+ = r_{K^+} \frac{3\alpha^2 Br(K^+ \to \pi^0 e^+ \nu)}{2\pi^2 \sin^4 \theta_W} \lambda^8 = 4.84 \cdot 10^{-11} \left[\frac{\lambda}{0.224} \right]^8$$

$$\alpha = 1/128; \quad \sin^2 \theta_W = 0.23; \quad Br(K^+ \to \pi^0 e^+ \nu) = 4.87 \cdot 10^{-2}$$

$$P_c = \frac{1}{\lambda^4} \left[\frac{2}{3} X_{NL}^e + \frac{1}{3} X_{NL}^\tau \right] = 0.39 \pm \underbrace{0.07}_{(m_c, \mu_c)}$$

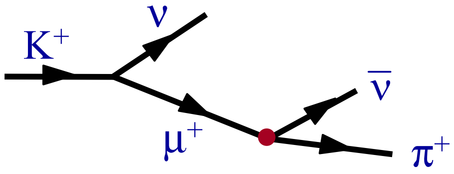
$\left\{ \begin{matrix} \mu_c, \mu_t \text{ Uncertainty} \\ Br, |V_{td}| \end{matrix} \right\}$:

	LO	NLO
Br	± 22%	± 7%
$\lvert V_{td} \rvert$	± 14%	± 4%

$\left\{ \overline{m}_t(\mu_t), \overline{m}_c(\mu_c): 100\text{ GeV} \le \mu_t \le 300\text{ GeV};\ 1\text{ GeV} \le \mu_c \le 3\text{ GeV} \right\}$

LD Effects < 5%
Rein, Sehgal
Hagelin, Littenberg
Lu, Wise; Fajfer

Smallness of LD related to absence of internal γ contributions (present in $K_L \to \pi^0 e^+ e^-, K_L \to \mu\overline{\mu}$)



$$\mathrm{Br}\left(K_L \to \pi^0 \nu\bar{\nu}\right)$$

- **Consider one ν-flavour and denote:**

$$F \equiv \frac{G_F}{\sqrt{2}} \frac{\alpha}{2\pi \sin^2\theta_W}\left(\lambda_c X_{NL} + \lambda_t X(x_t)\right)$$

$$H_{eff} = F(\bar{s}d)_{V-A}(\bar{\nu}\nu)_{V-A} + F^*(\bar{d}s)_{V-A}(\bar{\nu}\nu)_{V-A}$$

- **Now:**

$$K_L = \frac{1}{\sqrt{2}}\left((1+\bar{\varepsilon})\left|K^0\right\rangle + (1-\bar{\varepsilon})\left|\bar{K}^0\right\rangle\right)$$

$$CP\left|K^0\right\rangle = -\left|\bar{K}^0\right\rangle; \qquad C\left|K^0\right\rangle = \left|\bar{K}^0\right\rangle$$

- $$A\left(K_L \to \pi^0 \nu\bar{\nu}\right) = \frac{1}{\sqrt{2}}\Big(F(1+\bar{\varepsilon})\left\langle \pi^0 \right|(\bar{s}d)_{V-A}\left|K^0\right\rangle + F^*(1-\bar{\varepsilon})\left\langle \pi^0 \right|(\bar{d}s)_{V-A}\left|\bar{K}^0\right\rangle\Big)(\bar{\nu}\nu)_{V-A}$$

- $\langle \pi^0 | (\bar{d}s)_{V-A} | \bar{K}^0 \rangle = -\langle \pi^0 | (\bar{s}d)_{V-A} | K^0 \rangle$

$$A(K_L \to \pi^0 \nu\bar{\nu}) = \frac{1}{\sqrt{2}} \underbrace{\left[F(1+\bar{\varepsilon}) - F^*(1-\bar{\varepsilon})\right]}_{\approx 2\,\mathrm{Im}\,\lambda_t X(x_t)} \langle \pi^0 | (\bar{s}d)_{V-A} | K^0 \rangle \cdot (\bar{\nu}\nu)_{V-A}$$

$(\mathrm{Im}\,\lambda_c = -\mathrm{Im}\,\lambda_t)$

$(X_{NL} << X(x_t))$

- $\langle \pi^0 | (\bar{s}d)_{V-A} | K^0 \rangle = \langle \pi^0 | (\bar{s}u)_{V-A} | K^+ \rangle$

- {Isospin Breaking (Marciano, Parsa)} ➡ $\{ r_{K_L} = 0.944 \}$

- **Summing over ν**

$$Br(K_L \to \pi^0 \nu\bar{\nu}) = \kappa_{K_L} \left[\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right]^2$$ ★

$$\kappa_{K_L} = \frac{\tau_{K_L}}{\tau_{K^+}} \frac{r_{K_L}}{r_{K^+}} \kappa_{K^+} = 2.12 \cdot 10^{-10} \left[\frac{\lambda}{0.224} \right]^8$$

Waiting for Precise Measurements of $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$

AJB, Schwab, Uhlig (04)

1. Present Status within SM (TH and Parametric Uncertainties)

2. Impact of Present and Future Measurements of $K \to \pi\nu\bar{\nu}$ on CKM

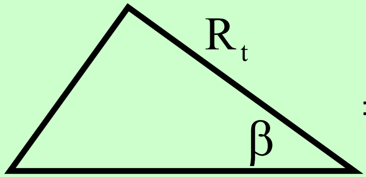
3. $K \to \pi\nu\bar{\nu}$ in Scenarios with New Complex Phases in EWP and $B_d^0 - \bar{B}_d^0$ Mixing

4. Interplay of $K \to \pi\nu\bar{\nu}$ with
   - ~~CP~~ in B Decays
   - $\Delta M_d/\Delta M_s$, Rare Decays

Basic Formulae for $K^+ \to \pi^+ \nu\bar{\nu}$ (SM)

$$X \equiv X(m_t)$$

$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = 4.8 \cdot 10^{-11}\left[A^4 R_t^2 X^2 + 2P_c A^2 R_t X \cos\beta + P_c^2\right]$$



$$= 10^{-11}\Big[\underset{\text{(top)}}{4.1} + \underset{\text{(top-charm)}}{3.0} + \underset{\text{(charm)}}{0.7}\Big]$$

$$A = \frac{|V_{cb}|}{\lambda^2} \cong 0.83$$

Buchalla AJB (94) NLO*)

$$P_c = 0.389 \pm \underbrace{0.033}_{\Delta m_c = 50\,\text{MeV}} \pm \underbrace{0.045}_{\text{scale } \mu_c} \pm \underbrace{0.010}_{\alpha_s} \cong 0.39 \pm 0.07$$

AJB Schwab Uhlig (04)

$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right)_{SM} = \left[7.8 \pm \underbrace{0.8}_{P_c} \pm \underbrace{0.9}_{\text{CKM}}\right] 10^{-11} \cong (7.8 \pm 1.2)\,10^{-11}$$

(Isidori)

$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left[14.7 \begin{array}{l} +13.0 \\ -8.9 \end{array}\right] 10^{-11}$$

E787 (2)
E949 (1)
3 Events

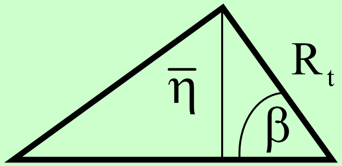
*) NNLO : AJB, Gorbahn, Haisch, Nierste (05 Summer ?)

(Direct $\not{CP}$)

Basic Formulae for $K_L \to \pi^o \nu\bar{\nu}$

(SM) Buchalla
AJB (NLO)

$$Br\left(K_L \to \pi^o \nu\bar{\nu}\right) = 3.0 \cdot 10^{-11} \left[\frac{\bar{\eta}}{0.35}\right]^2 \left[\frac{|V_{cb}|}{41.5 \cdot 10^{-3}}\right]^4 \left[\frac{X}{1.53}\right]^2$$



$$= \left(3.0 \pm \overbrace{0.6}^{\text{CKM}}\right) \cdot 10^{-11}$$

(AJB
Schwab
Uhlig)

KTeV : $Br\left(K_L \to \pi^o \nu\bar{\nu}\right) < 5.9 \cdot 10^{-7}$

Future: E391a, KOPIO, JHF

Model independent bound (Grossman, Nir)

$$Br\left(K_L \to \pi^o \nu\bar{\nu}\right) \le 4.4 \, Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) \le 1.4 \cdot 10^{-9} \, (90\% \, C.L.)$$

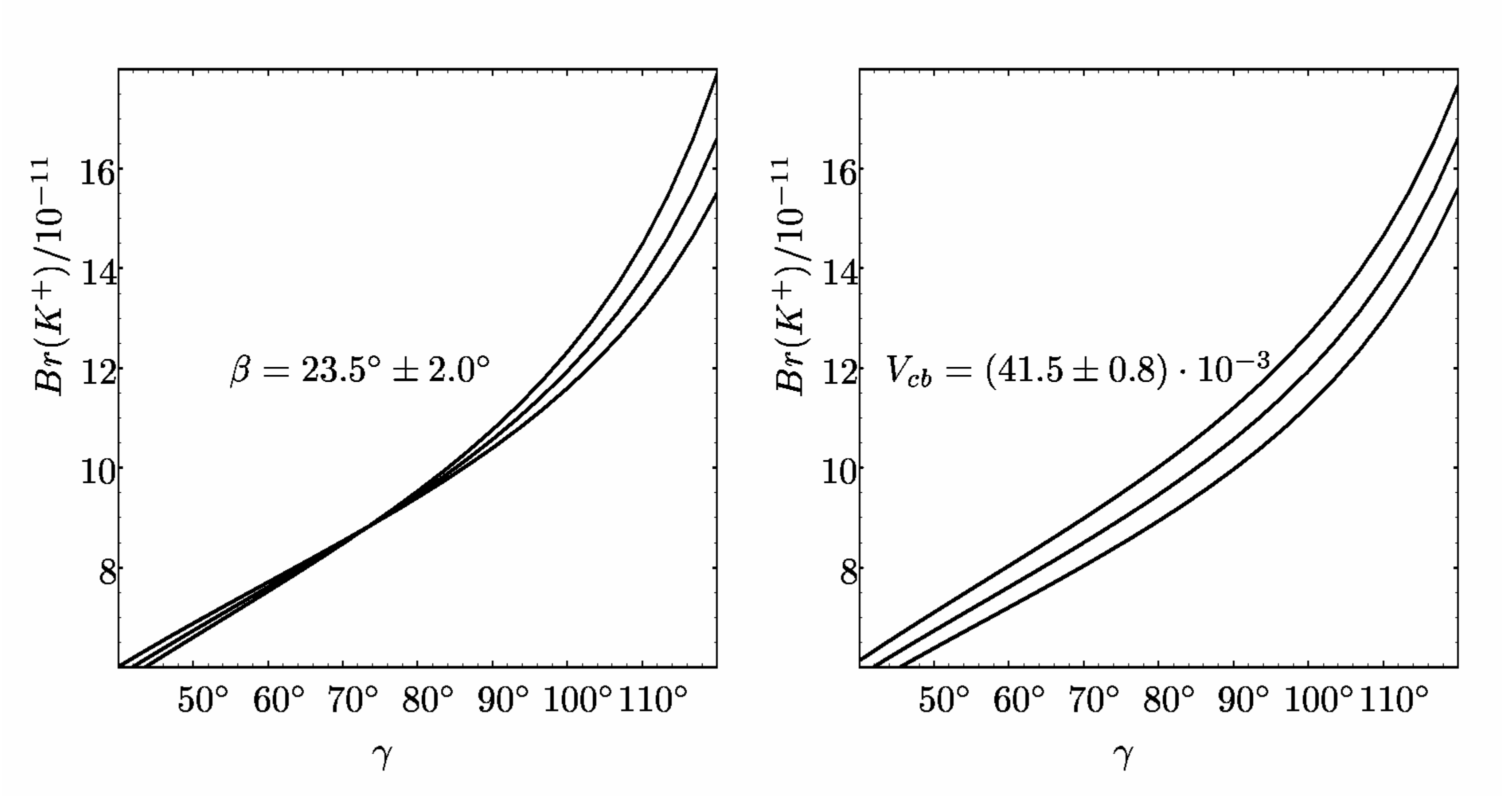
E391a could get the first non-trivial upper bound.

$$\bar{\eta} = R_t \sin\beta$$

KOPIO: ~ 50 Events
E391 (JHF): ~ 1000 Events

β and $|V_{cb}|$ Dependence of $Br(K^+ \to \pi^+ \nu\bar{\nu})$

BSU (04)



Anatomy of $|V_{td}|$ from $K^+ \to \pi^+ \nu\bar{\nu}$

AJB
Schwab
Uhlig

$$\frac{\sigma(|V_{td}|)}{|V_{td}|} = 0.39\frac{\sigma(P_c)}{P_c} + 0.70\frac{\sigma(Br(K^+))}{Br(K^+)} + \frac{\sigma(|V_{cb}|)}{|V_{cb}|}$$

Present:	± 7%	± (Very Large)	± 2%	
$\sigma(Br(K^+)) = 10\%$, $\sigma(P_c) = 0.03$	± 3%	± 7%	± 1.4%	(Scenario I)
$\sigma(Br(K^+)) = 5\%$, $\sigma(P_c) = 0.02$	± 2%	± 3.5%	± 1%	(Scenario II)

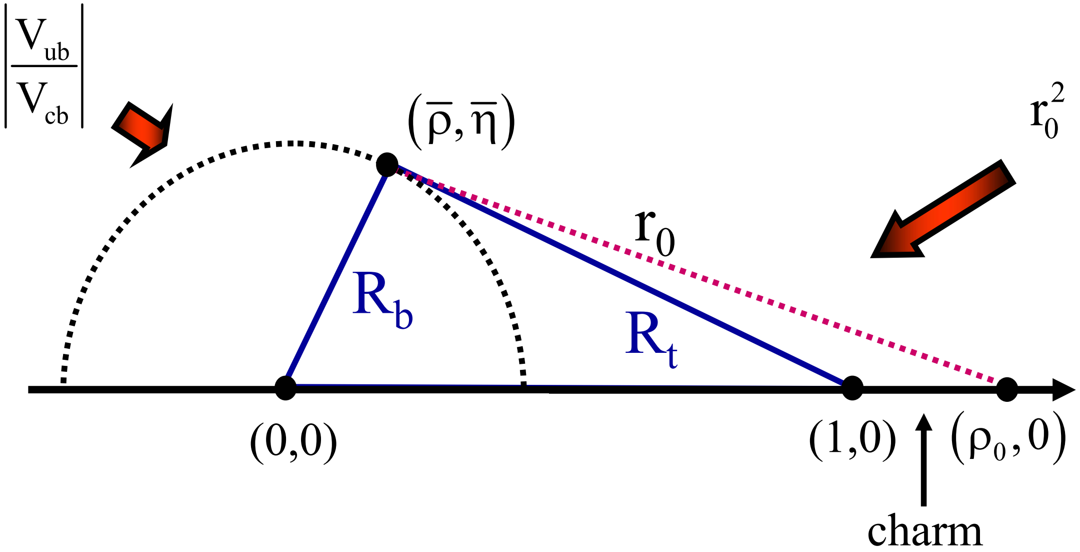
Determination at 4-5% possible

$|V_{td}|$ from UT fit: 6-12% dependently on the error analysis

$K^+ \to \pi^+ \nu\bar{\nu}$ in the $(\bar{\rho}, \bar{\eta})$ Plane

$$\mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = 4.31 \cdot 10^{-11} A^4 X^2(m_t) \frac{1}{\sigma}\left[(\sigma\bar{\eta})^2 + (\rho_0 - \bar{\rho})^2\right]$$

$$\sigma = \frac{1}{\left(1-\lambda^2/2\right)^2} \qquad \rho_0 = 1 + \frac{P_c}{A^2 X(m_t)} \approx 1.4$$



$$r_0^2 = \frac{1}{A^4 X^2(m_t)}\left[\frac{\sigma \mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right)}{4.31 \cdot 10^{-11}}\right]$$

$$R_t = 1 + R_b^2 - 2\bar{\rho}$$

$$V_{td} = A\lambda^3\left(1 - \bar{\rho} - i\bar{\eta}\right)$$

$$|V_{td}| = \lambda |V_{cb}| R_t$$

Theoretically clean Relations

D´Ambrosio + Isidori (02)

$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \bar{\kappa}_+ \left|V_{cb}\right|^4 X^2 \left[R_t^2 \sin^2\beta + \left(R_t \cos^2\beta + \frac{\lambda^4 P_c}{\left|V_{cb}\right|^2 X} \right)^2 \right]$$

$$R_t \sim \xi \frac{\sqrt{\Delta M_d}}{\sqrt{\Delta M_s}} \qquad \bar{\kappa}_+ = 7.64 \cdot 10^{-6} \qquad P_c = 0.39 \pm 0.07$$

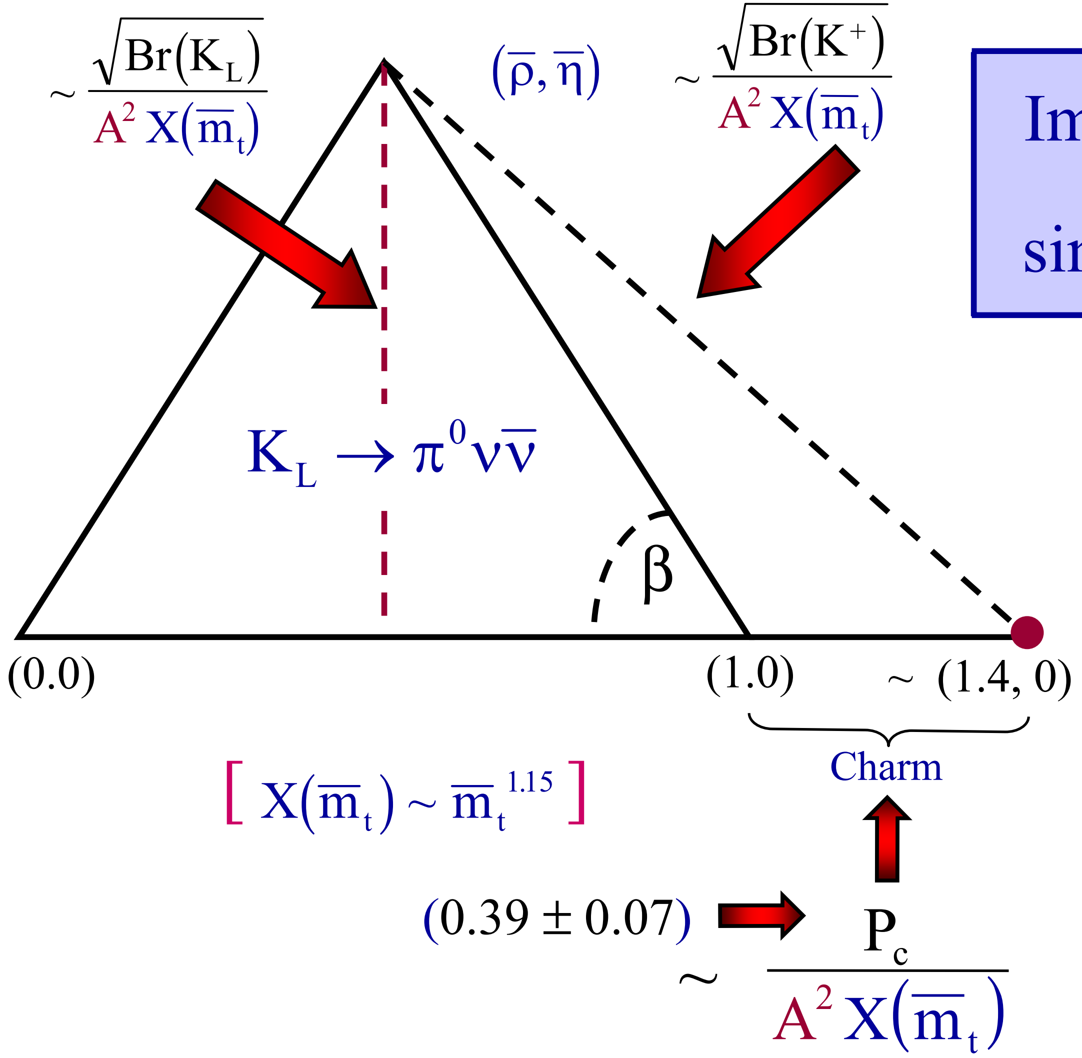
AJB, Schwab, Uhlig (04)

$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \bar{\kappa}_+ \left|V_{cb}\right|^4 X^2 \left[T_1^2 + \left(T_2 + \frac{\lambda^4 P_c}{\left|V_{cb}\right|^2 X} \right)^2 \right]$$

$$T_1 = \frac{\sin\beta \sin\gamma}{\sin(\beta+\gamma)} \qquad T_2 = \frac{\cos\beta \sin\gamma}{\sin(\beta+\gamma)}$$

UT from $K \to \pi\nu\bar{\nu}$

Buchalla
AJB



$$\mathrm{Im}\,\lambda_t = F_1(\overline{m}_t, Br(K_L))$$

$$\sin 2\beta = F_2(P_c, Br(K_L), Br(K^+))$$

$$\lambda_t = V_{ts}^* V_{td}$$

$\sin 2\beta$ $(K \to \pi\nu\bar{\nu})$ ⟺ $\sin 2\beta$ $(B \to J/\psi, K_s)$ $\to \varphi K_s$

K-Physics ⟺ B - Physics

Test of SM and Beyond

Golden Relations

(All involving $K_L \to \pi^0 \nu\bar{\nu}$)

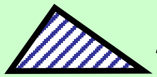
Buchalla, AJB (94)

$$\cot\beta = \frac{\sqrt{B_1 - B_2} - P_c}{\sqrt{B_2}}$$

$$\left(\sin 2\beta\right)_{\pi\nu\bar{\nu}} = \left(\sin 2\beta\right)_{\psi K_S}$$

$$B_1 \sim Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right)$$

$$B_2 \sim Br\left(K_L \to \pi^0 \nu\bar{\nu}\right)$$

$J_{CP} \sim$  $\sim \dfrac{\sqrt{Br\left(K_L \to \pi^0 \nu\bar{\nu}\right)}}{X(m_t)}$

AJB, Schwab, Uhlig (04)

$$\frac{\sin\beta \sin\gamma}{\sin(\beta+\gamma)} = 0.35 \left[\frac{1.53}{X(m_t)}\right]\left[\frac{0.0415}{|V_{cb}|}\right]^2 \sqrt{\frac{Br\left(K_L \to \pi^0 \nu\bar{\nu}\right)}{3 \cdot 10^{-11}}}$$

β from $a_{\psi K_S}$

γ from $B_s^0 \to D_s^\pm K^\mp$, $B_d^0 \to D^\pm \pi^\mp$

The Angle β from $K \to \pi\nu\bar{\nu}$

Buchalla, AJB (94)
AJB, Schwab, Uhlig (04)

BSU:

$$\frac{\sigma(\sin 2\beta)}{\sin 2\beta} = 0.31\frac{\sigma(P_c)}{P_c} + 0.55\frac{\sigma(Br(K^+))}{Br(K^+)} \pm 0.39\frac{\sigma(Br(K_L))}{Br(K_L)}$$

$\sigma(\sin 2\beta) =$	± 0.041	$\pm$?	$\pm$?	(Present)
$\sigma(\sin 2\beta) =$	0.017	± 0.039	± 0.028	(Scenario I) Br´s at 10%
$\sigma(\sin 2\beta) =$	0.011	± 0.020	± 0.014	(Scenario II) Br´s at 5%

TH very clean

$\sigma(\sin 2\beta) \approx 0.02 - 0.03$ requires $\sigma(\text{Br´s}) \leq 5\%$

The Angle γ from $K \to \pi\nu\bar{\nu}$

AJB, Schwab, Uhlig (04)

$$\frac{\sigma(\gamma)}{\gamma} = 0.75\frac{\sigma(P_c)}{P_c} + 1.32\frac{\sigma(Br(K^+))}{Br(K^+)} + 0.07\frac{\sigma(Br(K_L))}{Br(K_L)} + 4.1\frac{\sigma(|V_{cb}|)}{|V_{cb}|}$$

$\sigma(\gamma) =$	$\pm 8.3^\circ$	$\pm ?$	$\pm ?$	$\pm 4.9^\circ$	(Present)
$\sigma(\gamma) =$	$\pm 3.7^\circ$	$\pm 8.5^\circ$	$\pm 0.4^\circ$	$\pm 3.8^\circ$	(Scenario I) Br´s at 10%
$\sigma(\gamma) =$	$\pm 2.5^\circ$	$\pm 4.2^\circ$	$\pm 0.2^\circ$	$\pm 2.5^\circ$	(Scenario II) Br´s at 5%

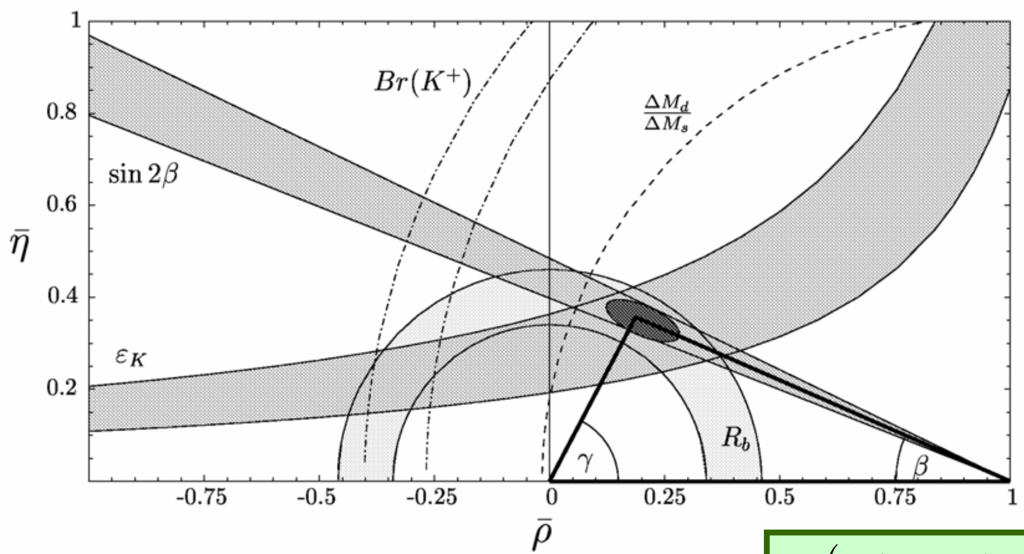
TH very clean

$\sigma(\gamma) \approx \pm 5^\circ$ requires $\sigma(Br(K^+)) \leq 5\%$

Unitarity Triangle 2004

(AJB, Schwab, Uhlig)

$$Br\left(K^+\right) \equiv Br\left(K^+ \to \pi^+\nu\bar{\nu}\right) = 14.7 \cdot 10^{-11}$$



$P_c = \underline{\underline{0.39}} \pm 0.07$

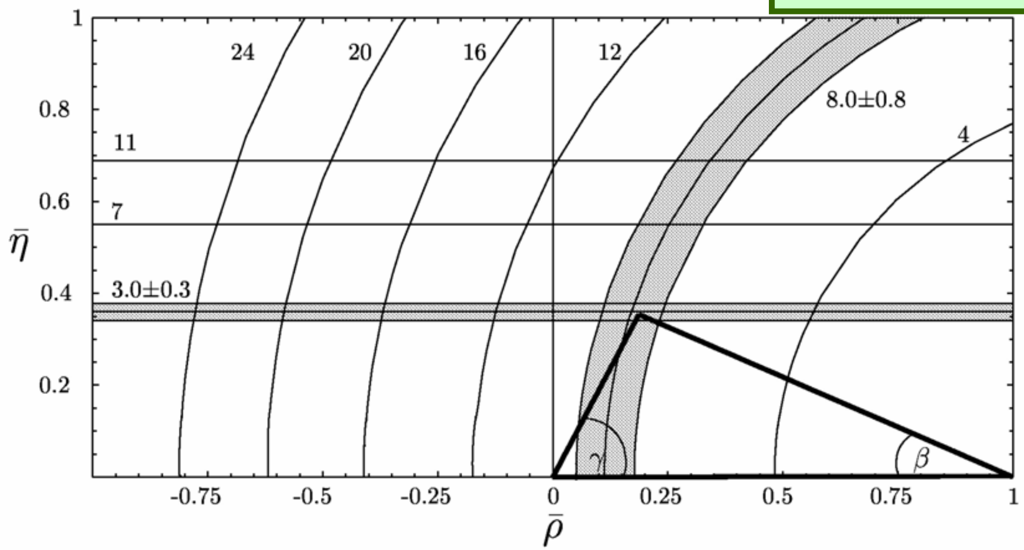
↑

m_c, $V_{cb,}$ μ_c

$Br\left(K^+ \to \pi^+\nu\bar{\nu}\right)$

Unitarity Triangle from $K \to \pi\nu\bar{\nu}$

(2012)



$Br\left(K_L \to \pi^0\nu\bar{\nu}\right)$

Recent News

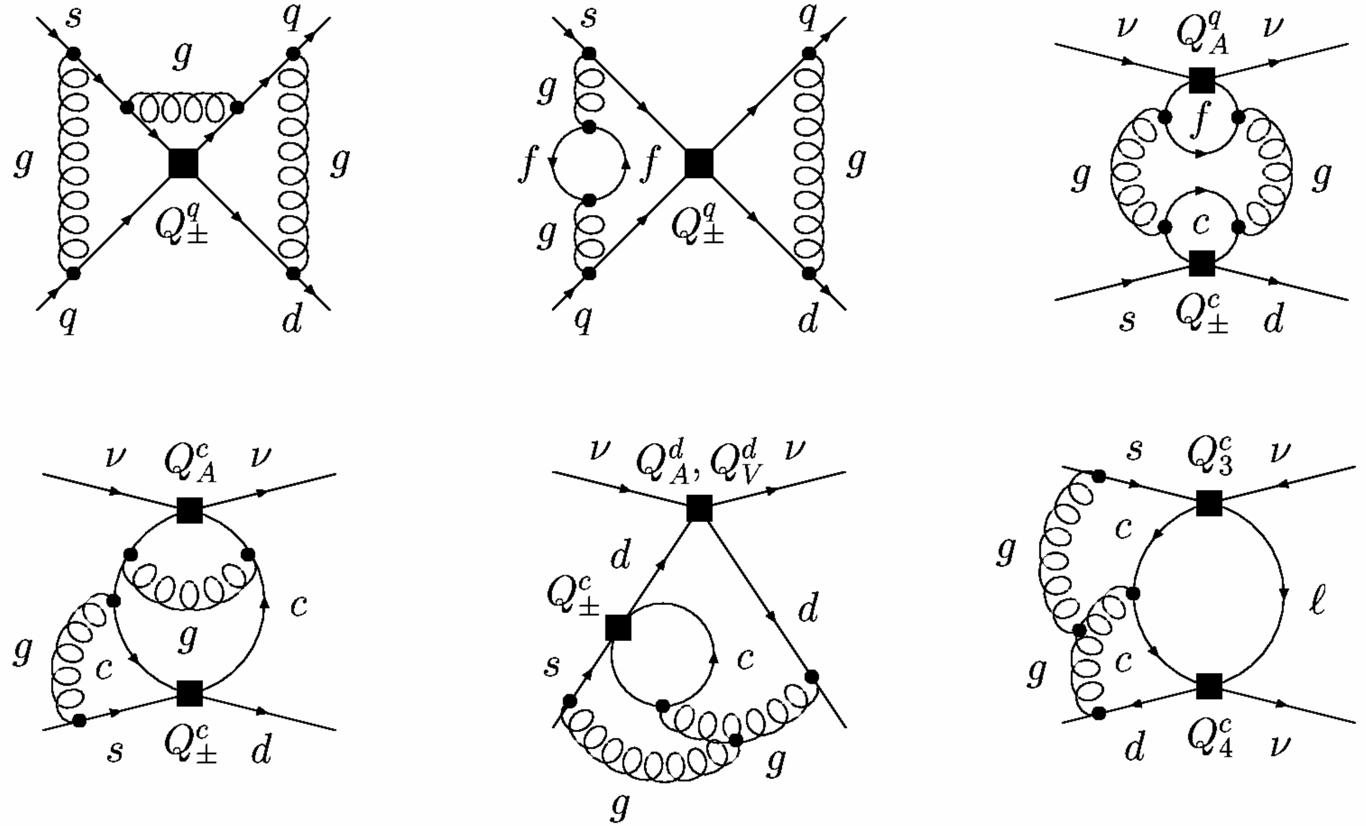
1. Improved Calculation of LD Contributions to the Charm Component in $K^+ \to \pi^+ \nu\bar{\nu}$:

$$P_C = 0.39 \pm 0.07 \;\to\; 0.43 \pm 0.07$$

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) = (7.8 \pm 1.2) \cdot 10^{-11} \to (8.3 \pm 1.2) \cdot 10^{-11}$$

Isidori
Mescia
Smith

2. P_c at NNLO soon available !
(AJB, Gorbahn, Haisch, Nierste)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Q^c_3
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Q^c_4
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6.

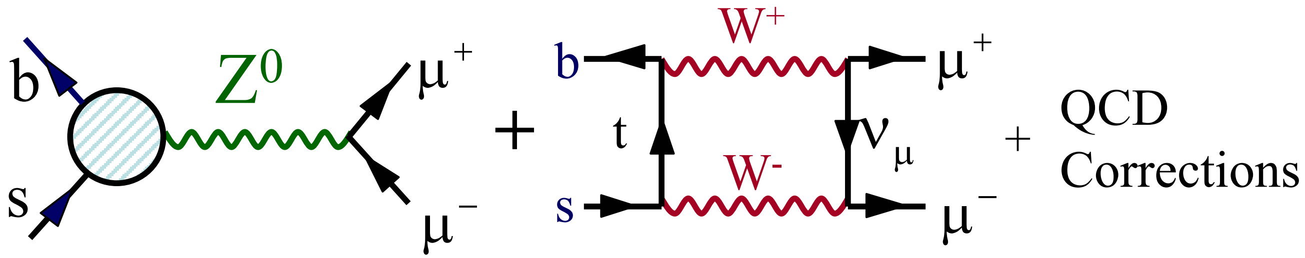
Rare B and K Decays

$$B_{s,d} \to \mu^+\mu^- \qquad B \to X_{s,d}\nu\bar{\nu}$$

$$B \to X_s\gamma \qquad B \to X_s l^+ l^-$$

$$K_L \to \pi^0 l^+ l^-$$

$B_s \to \mu^+\mu^-$



Buchalla, AJB (93)
Misiak, Urban (98)

$$Br(B_s \to \mu^+\mu^-) = 3.8 \cdot 10^{-9} \left[\frac{\tau(B_s)}{1.46\text{ps}}\right]\left[\frac{F_{B_s}}{230\text{MeV}}\right]^2 \left[\frac{|V_{ts}|}{0.040}\right]^2 [Y(x_t)]^2$$

$$Y(x_t) = 1.02\left[\frac{m_t(m_t)}{170\text{GeV}}\right]^{1.56} \approx 1$$

$$F_{B_s} = (230 \pm 30)\text{MeV}$$

$$\tau(B_s) = (1.46 \pm 0.05)\text{ps}$$

(Dominant uncertainty)

SM: $Br(B_s \to \mu^+\mu^-) = (3.7 \pm 1.0)\cdot 10^{-9}$

$Br(B_s \to \mu^+\mu^-) < 5 \cdot 10^{-7}$

DØ, CDF 95% C.L.

$B_d \to \mu^+\mu^-$ (just replace s→d)

$$Br(B_d \to \mu^+\mu^-) = 1.0\cdot 10^{-10}\left[\frac{\tau(B_d)}{1.54\text{ps}}\right]\left[\frac{F_{B_d}}{190\text{MeV}}\right]^2\left[\frac{|V_{td}|}{0.008}\right]^2\left[Y(x_t)\right]^2$$

$\tau(B_d) = (1.540 \pm 0.014)\text{ps}$

$F_{B_d} = (189 \pm 27)\text{MeV}$

$|V_{td}| = (8.24 \pm 0.54)\cdot 10^{-3}$

SM: $Br(B_d \to \mu^+\mu^-) = (1.04 \pm 0.34)\cdot 10^{-10}$

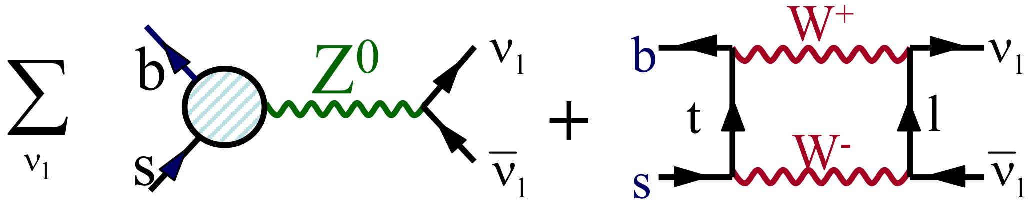
Belle: $Br(B_d \to \mu^+\mu^-) < 1.6\cdot 10^{-7}$ (95% C.L.)

$$\frac{F_{B_s}}{F_{B_d}} = 1.22 \pm 0.06$$

$$\frac{Br(B_s \to \mu^+\mu^-)}{Br(B_d \to \mu^+\mu^-)} = \frac{\tau(B_s)}{\tau(B_d)}\frac{m_{B_s}}{m_{B_d}}\left[\frac{F_{B_s}}{F_{B_d}}\right]^2\left[\frac{|V_{ts}|}{|V_{td}|}\right]^2$$

Useful measurement of $|V_{td}|$

$B \to X_s \nu\bar{\nu}$



+ QCD Corrections

Buchalla, AJB (93)
Misiak, Urban (98)

$$Br(B \to X_s \nu\bar{\nu}) = 1.58 \cdot 10^{-5} \left[\frac{|V_{ts}|}{0.040}\right]^2 \left[X(x_t)\right]^2$$

$$\left[X(x_t)\right] = 1.57 \left(\frac{m_t(m_t)}{170\,GeV}\right)^{1.15}$$

SM: $Br(B \to X_s \nu\bar{\nu}) = (3.66 \pm 0.21) \cdot 10^{-5}$

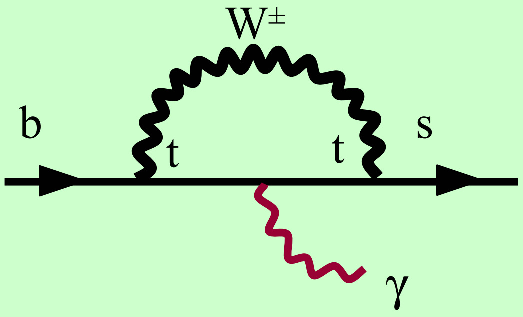
ALEPH: $Br(B \to X_s \nu\bar{\nu}) < 6.4 \cdot 10^{-4}$

$$\frac{Br(B \to X_d \nu\bar{\nu})}{Br(B \to X_s \nu\bar{\nu})} = \frac{|V_{td}|^2}{|V_{ts}|^2}$$

Theoretically cleanest measurement of $|V_{td}| / |V_{ts}|$ ★

Long Distance Effects neglegible: Buchalla, Isidori, Rey

$B \to X_s \gamma$



+ Large SD QCD Corrections

Bertolini, Borzumati, Masiero (1987)
Deshpande, Lo, Trampetic, Eilam, Singer (1987)

γ = on shell

Dominant Operator : $Q_7 = m_b \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$

(Magnetic Penguins)

QCD Enhancement (~ 3) governed by the Mixing of Q_7 with
$Q_2 = (\bar{b}c)_{V-A} (\bar{c}s)_{V-A}$

$$Br(B \to X_s \gamma) = \begin{cases} (3.52 \pm 0.30) \cdot 10^{-4} & \text{CLEO, BaBar, Belle} \\ (3.70 \pm 0.30) \cdot 10^{-4} & \text{SM} \end{cases}$$

Sensitive to New Physics! Important for constraining Supersymmetry !!

NLO-QCD Corrections Saga 1994-2002

1993 : Identification of strong: Ali, Greub; AJB, Misiak, Münz, Pokorski
μ_b dependence (~ 60%)

Initial Conditions : Adel, Yao (93); Greub, Hurth (97); AJB, Kwiatkowski, Pott (97)
Ciuchini, Degrassi, Gambino, Giudice (97)

Two and Three-Loop Anomalous Dimensions : AJB, Jamin, Lautenbacher, Weisz (92); Ciuchini, Franco, Martinelli, Reina (93)
Misiak, Münz (95) (Two-Loop Mixing of Magnetic Operators)
Chetyrkin, Misiak, Münz (97) (Three-Loop Mixing between Q_7 and Q_2)

Operator Matrix Elements : Greub, Hurth, Wyler (1996)
AJB, Czarnecki, Misiak, Urban (2001)

Review:
AJB, Misiak (2003)

Gluon Bremstrahlung : Ali, Greub (91)
Pott (95)

$B \to X_s\gamma$ beyond NLO $\to$ NNLO

2001: Gambino, Misiak (significant uncertainty due to m_c)

➡ Go beyond NLO

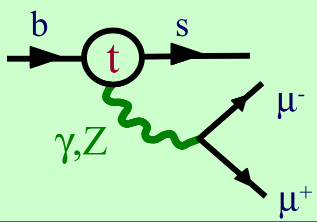
Considerable Progress made:

- Misiak, Steinhauser (2004) — Initial Conditions
- Bieri, Greub, Steinhauser (2003) — Matrix Elements (first steps)
- Gorbahn, Haisch (2005); Gorbahn, Haisch, Misiak (2005) — Three-Loop Mixing of Magnetic Penguins

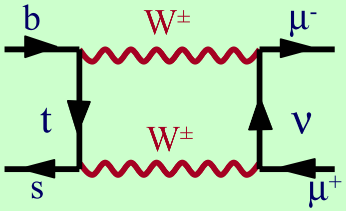
4-Loop Mixing $Q_2 \leftrightarrow Q_7$: Czakon, ...

$B \to X_s \mu^+ \mu^-$

Hou, Willey, Soni (87)



+



+ Smaller Magnetic Penguins

QCD (LO): Grinstein, Savage, Wise (89)

QCD (NLO): Misiak (94)
AJB + Münz (94)

Operators:

$$Q_{9V} = (\bar{s}b)_{V-A}(\bar{\mu}\mu)_V$$
$$Q_{10V} = (\bar{s}b)_{V-A}(\bar{\mu}\mu)_A$$

+

$$Q_7 = m_b \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$$

Known from $B \to X_s\gamma$

$$\frac{d\sigma}{ds} \approx \frac{\alpha^2}{4\pi}(1-s)^2 |V_{ts}|^2 \left[(1+2s)\left(|C_9(s)|^2 + |C_{10}|^2\right) + 4\left(1+\frac{2}{s}\right)|C_7|^2 + 12 C_7 C_9 \right]$$

$$s = \frac{(P_{\mu^+} + P_{\mu^+})^2}{m_b^2}$$

$$C_9(s) = P_0^{NLO}(s) + \frac{Y(x_t)}{\sin^2\theta_W} - 4Z(x_t)$$

$$C_{10} = -\frac{Y(x_t)}{\sin^2\theta_W}$$

$[\ ] = U(s)$

Recent Developments on $B \to X_s \mu^+ \mu^-$

NNLO QCD

Bobeth, Misiak, Urban (2000)
Ghinculov, Hurth, Isidori, Yao (2002-2004)
Asatryan, Asatrian, Greub, Walker (2002-2004)
Asatrian, Asatryan, Hovhannisyan, Poghosyan (2004)
Bobeth, Gambino, Gorbahn, Haisch (2004)

$$\mathrm{Br}\left(B \to X_s l^+ l^-\right) = \begin{cases} (4.5 \pm 1.0) \cdot 10^{-6} & \text{Exp} \\ (4.4 \pm 0.7) \cdot 10^{-6} & \text{SM} \end{cases}$$

(low s region)

(below $c\bar{c}$ resonance)

In order to test better look at $A_{FB}(s) \equiv$ Forward – Backward Asymmetry

(see Section 6)

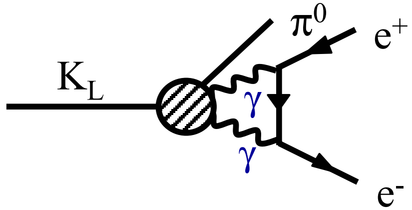
$$A_{FB}(s) = -3C_{10} \frac{\left[sC_9(s) + 2C_7\right]}{U(s)}$$

Vanishes at s_0: $s_0 C_9(s_0) + 2C_7 = 0$

Theoretically clean; sensitive to New Physics.

$K_L \to \pi^0 e^+ e^-$ (3 contributions)

1 $K_L \to \pi^0\gamma\gamma \to \pi^0 e^+ e^-$ ⟸ CP conserving

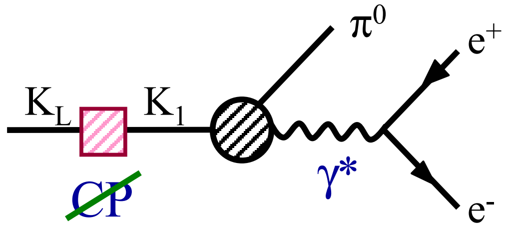


Donoghue, Holstein, Valencia, Ecker, Pich, de Rafael, Flynn, Randall, Seghal, Heiliger, Fajfer (95)
Cohen, Ecker, Pich (93)
Donoghue, Gabbiani (95)
Ambrosio, Portoles (97)

[Using KTeV (99) $K_L \to \pi\gamma\gamma$]

2 $K_L \xrightarrow{K_1} \pi^0\gamma^* \to \pi^0 e^+ e^-$ ⟸ indirect ~~CP~~

$K_L \cong K_2 + \varepsilon K_1$



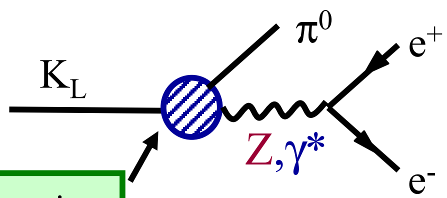
★ ($K_S \to \pi^0 e^+ e^-$ helps here!)

Ecker, Pich, de Rafael (91)
Heiliger, Seghal (93)
Donoghue, Gabbiani (95)
Fajfer (95)

3 $K_L \xrightarrow{K_2} \pi^0\gamma^* \to \pi^0 e^+ e^-$ ⟸ direct ~~CP~~

★ (TH very clean!)

New Physics can enter here



The action of Z^0, γ Penguins

LO: Dib, Dunietz, Gilman; Flynn, Randall; Buchalla, AJB, Harlander

NLO: AJB, Lautenbacher, Misiak, Münz (94)

Present Status on $K_L \to \pi^0 e^+ e^-$, $K_L \to \pi^0 \mu^+ \mu^-$

Buchalla, D´Ambrosio, Isidori; Isidori, Smith, Unterdorfer

$l = e, \mu$

$$Br\left(K_L \to \pi^0 l^+ l^-\right) = \left[C^l_{mix} + C^l_{int}\left(\frac{\mathrm{Im}\lambda_t}{10^{-4}}\right) + C^l_{dir}\left(\frac{\mathrm{Im}\lambda_t}{10^{-4}}\right)^2 + C^l_{CPC} \right] \cdot 10^{-12}$$

- C^l_{mix}: indirect $\not{CP}$
- C^l_{int}: Interference of direct and indirect
- C^l_{dir}: direct
- C^l_{CPC}: CP conserving

$$C^e_{mix} \cong 22.6 \pm 7.0$$
$$C^e_{int} \cong 7.4 \pm 1.5$$
$$C^e_{dir} \cong 2.4 \pm 0.2$$
$$C^e_{CPC} \cong 0$$

$$C^\mu_{mix} \cong 5.3 \pm 1.6$$
$$C^\mu_{int} \cong 1.9 \pm 0.4$$
$$C^\mu_{dir} \cong 1.0 \pm 0.1$$
$$C^\mu_{CPC} \cong 5.2 \pm 1.6$$

$$Br\left(K_L \to \pi^0 e^+ e^-\right) = \left(3.7\,^{+1.1}_{-0.9}\right) \cdot 10^{-11}$$

$$Br\left(K_L \to \pi^0 \mu^+ \mu^-\right) = \left(1.5 \pm 0.3\right) \cdot 10^{-11}$$

7.

Minimal Flavour Violation (MFV)

a) Generalities

b) Model with one Universal Extra Dimension

c) Littlest Higgs Model

d) MSSM at low $\tan\beta$

Review: AJB hep-ph/0310208

Generalities

$$A(\text{Decay}) = \sum_i B_i \eta^i_{QCD} V^i_{CKM} \underbrace{\overbrace{\left[F^i_{SM} + F^i_{New}\right]}^{F_i(v)}}_{\text{real}}$$

AJB, Gambino, Gorbahn, Jäger, Silvestrini
D'Ambrosio, Giudice, Isidori, Strumia

K and B Physics related to each other

1. All flavour changing processes governed by V^i_{CKM} .
2. Only SM Operators are relevant.
3. New Physics enters only through 7 Master Functions

$$F_i(v) = S(v), X(v), Y(v), Z(v), D'(v), E'(v), E(v)$$

$v =$ collects parameters specific to a given MFV model.

SM: $v = x_t$

Universal Unitarity Triangle

AJB, Gambino, Gorbahn, Jäger, Silvestrini (00)

In the full class of MFV-models it is possible to construct quantities that depend on CKM parameters but in which the dependence on new physics parameters cancels out

↓

CKM Matrix determined without "New Physics Pollution"

↓

Universal Unitarity Triangle

Examples

$$R_t = 0.90\sqrt{\frac{\Delta M_d}{0.50/ps}}\sqrt{\frac{18.4/ps}{\Delta M_s}}\left[\frac{\xi}{1.22}\right]$$

$$a_{\psi K_s} = \sin 2\beta$$

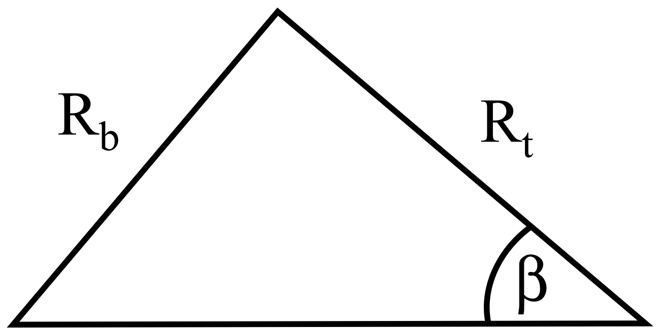
Universal Unitarity Triangle 2004

AJB, Schwab, Uhlig

Use only quantities that are independent of parameters specific to a given Minimal Flavour Violation model

$$\left|\frac{V_{ub}}{V_{cb}}\right| \Rightarrow R_b = \frac{\left(1-\lambda^2/2\right)}{\lambda}\left|\frac{V_{ub}}{V_{cb}}\right|$$

$$\frac{\Delta M_d}{\Delta M_s} \Rightarrow R_t = \frac{\xi_{th}}{\lambda}\sqrt{\frac{\Delta M_d}{\Delta M_s}} \qquad a_{\psi K_s} \Rightarrow \sin 2\beta$$



$$\xi_{th} = \frac{\sqrt{\hat{B}_s}F_{B_s}}{\sqrt{\hat{B}_d}F_{B_d}}$$

SM UT versus UUT of MFV

BSU (04)

SM

$$\bar\eta = 0.354 \pm 0.027$$
$$\bar\rho = 0.187 \pm 0.059$$

$$\gamma = (62.2 \pm 8.2)$$
$$R_t = 0.887 \pm 0.059$$
$$R_b = 0.400 \pm 0.039$$
$$|V_{td}| = (8.24 \pm 0.54) \cdot 10^{-3}$$

$$\mathrm{Im}\lambda_t = (1.40 \pm 0.12) \cdot 10^{-4}$$
$$\lambda_t = V_{ts}^* V_{td}$$

MFV

$$\bar\eta = 0.360 \pm 0.031$$
$$\bar\rho = 0.174 \pm 0.068$$

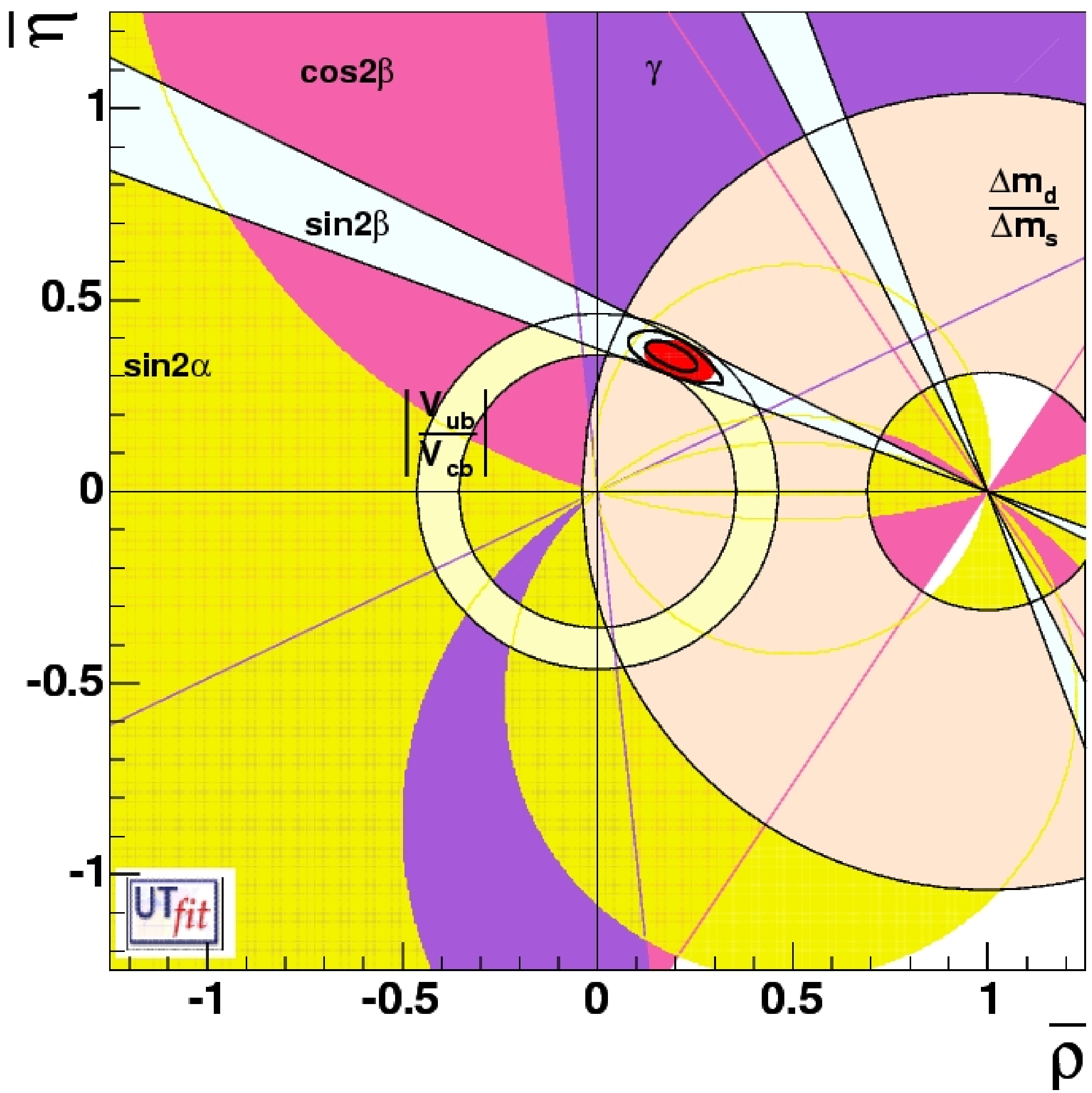
$$\gamma = (64.2 \pm 9.6)$$
$$R_t = 0.901 \pm 0.064$$
$$R_b = 0.400 \pm 0.044$$
$$|V_{td}| = (8.38 \pm 0.62) \cdot 10^{-3}$$

$$\mathrm{Im}\lambda_t = (1.43 \pm 0.14) \cdot 10^{-4}$$

UUT of MFV rather close to SM UT ☆

Universal Unitarity Triangle (MFV)

UTfit Collaboration : Bona et al.



MFV "Sum Rules"

Relations that do not involve the Master Functions X, Y, Z, S, etc.

Violation of these relations signals new flavour (CP) violating interactions beyond CKM or new operators that are strongly suppressed in SM

Examples

$$(\sin 2\beta)_{\pi\nu\bar{\nu}} = (\sin 2\beta)_{\psi K_s}$$

$$\frac{Br(B_s \to \mu^+\mu^-)}{Br(B_d \to \mu^+\mu^-)} = \frac{\tau(B_s)}{\tau(B_d)} \frac{m_{B_s}}{m_{B_d}} \left[\frac{F_{B_s}}{F_{B_d}}\right]^2 \left[\frac{|V_{ts}|}{|V_{td}|}\right]^2$$

$$\frac{\Delta M_d}{\Delta M_s} = \frac{m_{B_d}}{m_{B_s}} \frac{\hat{B}_d}{\hat{B}_s} \frac{F_{B_d}^2}{F_{B_s}^2} \frac{|V_{td}|^2}{|V_{ts}|^2}$$

$$\frac{Br(B \to X_d \nu\bar{\nu})}{Br(B \to X_s \nu\bar{\nu})} = \frac{|V_{td}|^2}{|V_{ts}|^2}$$

Impact of a Modified $|V_{td}|$

$$\left\{\Delta M_d \approx |V_{td}|^2 \cdot \left[S_{SM}(m_t) + \Delta s\right]\right\} \Rightarrow |V_{td}|^2 \approx \frac{\Delta M_d}{\left[S(m_t) + \Delta s\right]}$$

$$Br(B_d \to \mu^+\mu^-) \approx |V_{td}|^2 \cdot \left[Y_{SM}(m_t) + \Delta Y\right]^2 \approx \Delta M_d \frac{\left[Y_{SM}(m_t) + \Delta Y\right]^2}{\left[S(m_t) + \Delta s\right]}$$

But :

$$Br(B_s \to \mu^+\mu^-) \approx |V_{ts}|^2 \cdot \left[Y_{SM}(m_t) + \Delta Y\right]^2$$

$$|V_{ts}| \approx |V_{cb}| \quad \text{(CKM Unitarity)}$$

$$\left\{\begin{array}{l}\Delta S > 0 \\ \text{in most} \\ \text{extensions}\end{array}\right\} \Rightarrow \left(\frac{Br(B_s \to \mu^+\mu^-)}{Br(B_d \to \mu^+\mu^-)}\right)_{NP} > \left(\frac{Br(B_s \to \mu^+\mu^-)}{Br(B_d \to \mu^+\mu^-)}\right)_{SM}$$

Intriguing Property of Models with Minimal Flavour Violation

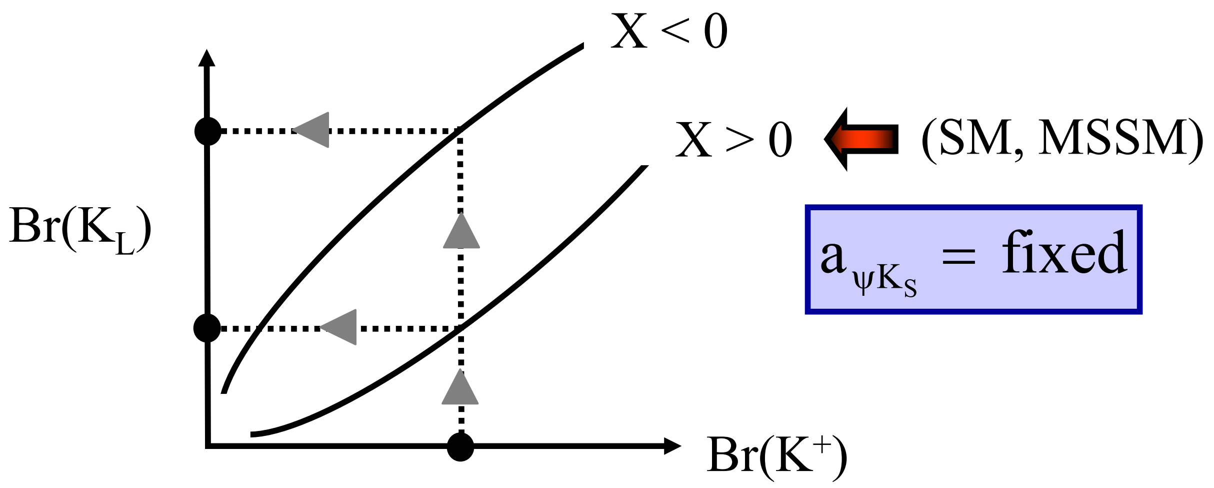
AJB, Fleischer (01)

$$Br(K_L) = F\left(Br(K^+),\ a_{\psi K_S},\ sgn(X)\right)$$

TH very clean

Independently of any parameters, for given $Br(K^+)$ and $a_{\psi K_S}$ only two values of $Br(K_L)$ possible.

X < 0 very unlikely

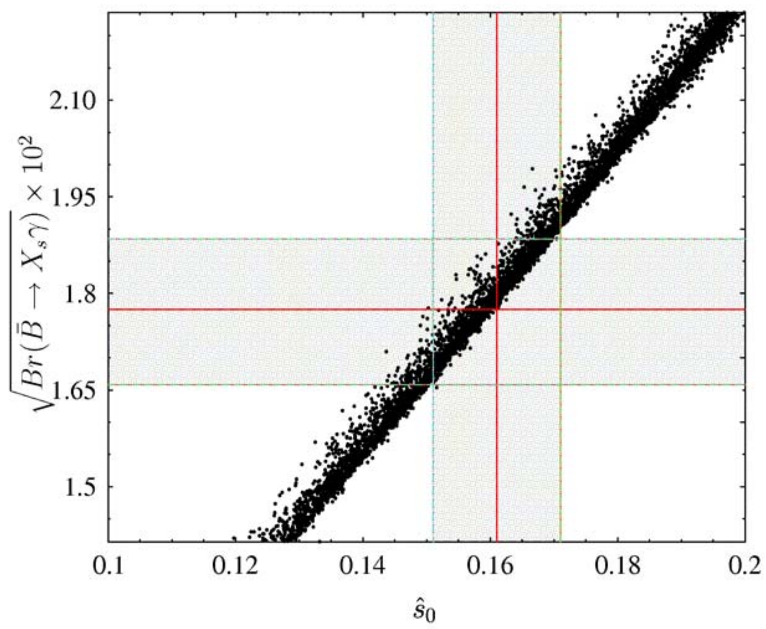


$a_{\psi K_S} = \text{fixed}$

Correlation: $Br(B \to X_s\gamma) \leftrightarrow \hat{s}_0$ in $A_{FB}(B \to X_s l^+ l^-)$

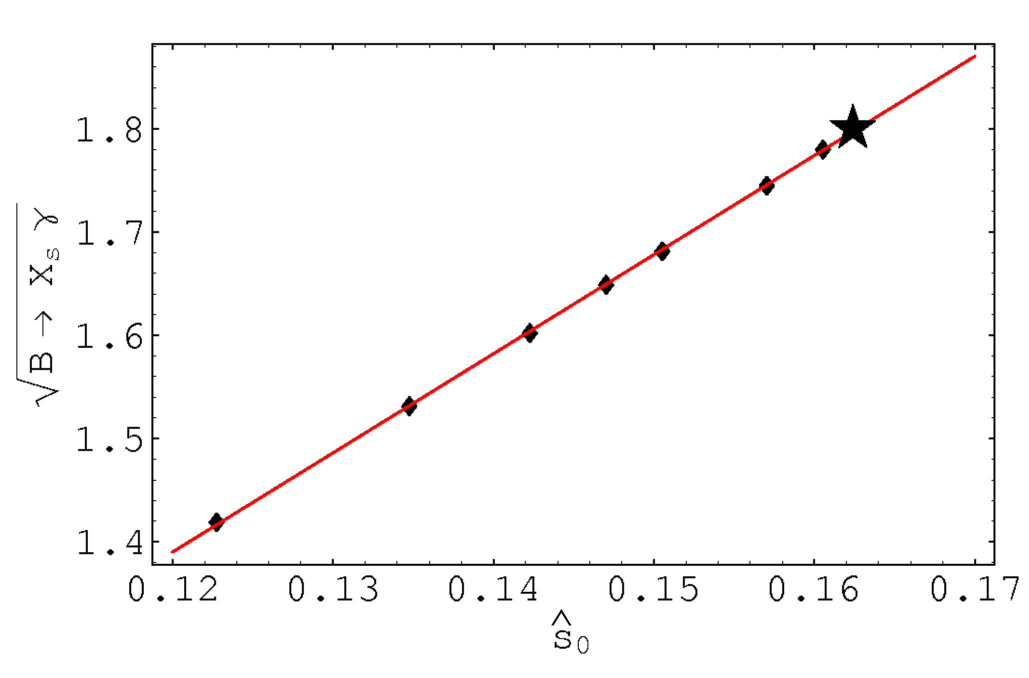
MSSM (MFV)

(Bobeth, AJB, Ewerth)



Universal Extra Dimensions

(AJB, Poschenrieder, Spranger, Weiler)



Relations between $\Delta M_{s,d}$ and $B_{s,d} \to \mu\bar{\mu}$ in Models with Minimal Flavour Violation

(AJB, hep-ph/0303060)

$$\Delta M_q \sim \hat{B}_q F_{B_q}^2 \left|V_{tq}\right|^2 S(x_t, x_{new})$$

$$Br\left(B_q \to \mu\bar{\mu}\right) \sim F_{B_q}^2 \left|V_{tq}\right|^2 Y^2(x_t, \bar{x}_{new})$$

Large hadronic uncertainties due to $F_{B_q}^2$

$$F_{B_d}\sqrt{\hat{B}_d} = \left(235 \pm 33 \begin{array}{c} +0 \\ -24 \end{array}\right) \text{MeV} \qquad F_{B_d} = (189 \pm 27)\ \text{MeV}$$

$$F_{B_s}\sqrt{\hat{B}_d} = \left(276 \pm 38\right) \text{MeV} \qquad F_{B_s} = (230 \pm 30)\ \text{MeV}$$

$$\hat{B}_d = 1.34 \pm 0.12$$

$$\hat{B}_s = 1.34 \pm 0.12 \qquad \frac{\hat{B}_s}{\hat{B}_d} = 1.00 \pm 0.03$$

(No problems with chiral logs and quenching)

$Br\left(B_{s,d} \to \mu\bar{\mu}\right)$ from $\Delta M_{s,d}$

$$Br\left(B_q \to \mu\bar{\mu}\right) = 4.36\cdot 10^{-10}\,\frac{\tau\left(B_q\right)}{\hat{B}_q}\,\frac{Y^2\left(x_t,\bar{x}_{new}\right)}{S\left(x_t,x_{new}\right)}\,\Delta M_q$$

No dependence on $F^2_{B_q}$

SM:

$$Br\left(B_s \to \mu\bar{\mu}\right) = 3.42\cdot 10^{-9}\left[\frac{\tau\left(B_s\right)}{1.46\text{ps}}\right]\left[\frac{1.34}{\hat{B}_s}\right]\left[\frac{\bar{m}_t\left(m_t\right)}{167\ \text{GeV}}\right]^{1.6}\left[\frac{\Delta M_s}{18.0/\text{ps}}\right]$$

$$Br\left(B_d \to \mu\bar{\mu}\right) = 1.00\cdot 10^{-10}\left[\frac{\tau\left(B_d\right)}{1.54\text{ps}}\right]\left[\frac{1.34}{\hat{B}_d}\right]\left[\frac{\bar{m}_t\left(m_t\right)}{167\ \text{GeV}}\right]^{1.6}\left[\frac{\Delta M_d}{0.50/\text{ps}}\right]$$

(Example)

$\Delta M_s = \left(18.0 \pm 0.5/\text{ps}\right)$ ⇒ $Br\left(B_s \to \mu\bar{\mu}\right) = \left(3.42 \pm 0.54\right)\cdot 10^{-9}$

$\Delta M_d = \left(0.503 \pm 0.006/\text{ps}\right)$ ⇒ $Br\left(B_d \to \mu\bar{\mu}\right) = \left(1.00 \pm 0.14\right)\cdot 10^{-10}$

Moreover new Physics Effects can be easier seen

Testing MFV through $B_{s,d} \to \mu\bar{\mu}$ and $\Delta M_{s,d}$

$$\frac{Br(B_s \to \mu\bar{\mu})}{Br(B_d \to \mu\bar{\mu})} = \underbrace{\frac{\hat{B}_d}{\hat{B}_s}}_{(1.00 \pm 0.03)} \underbrace{\frac{\tau(B_s)}{\tau(B_d)} \frac{\Delta M_s}{\Delta M_d}}_{\text{Experiment}}$$

Valid in MFV models in which only SM operators relevant.

Violation of this relation would indicate the presence of new operators and generally of non-minimal flavour violation.

The Impact of Universal Extra Dimensions on FCNC Processes

Based on:

AJB, M. Spranger, A. Weiler ≡ (BSW) (hep-ph/0212143)

AJB, A. Poschenrieder, M. Spranger, A. Weiler (hep-ph/0306158)

The Next Steps

1. ACD Model in D = 5
2. Impact of KK on Inami-Lim Functions
3. Impact on:

   $\Delta, \ \ \varepsilon_K, \ \ \Delta M_{d,s}, \ \ K \to \pi\nu\bar{\nu}$

   $K_L \to \mu\bar{\mu}, \ B \to X_{d,s}\nu\bar{\nu}, \ B_{s,d} \to \mu\bar{\mu}$

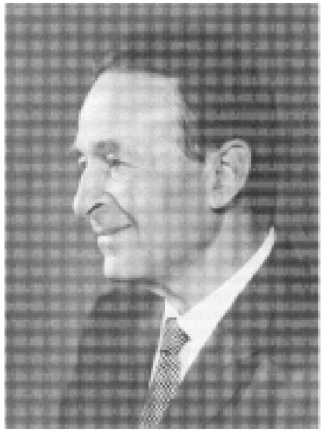
   $B \to X_s\gamma, \ \ B \to X_s\text{gluon}, \ \ \varepsilon'/\varepsilon$

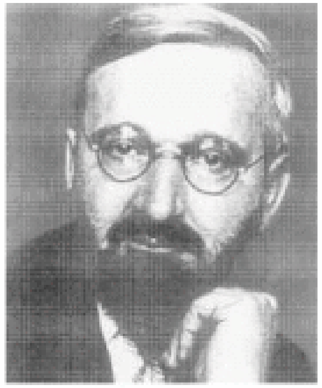
   $B \to X_s\mu\bar{\mu}, \ \ K_L \to \pi^0 e^+ e^-,$

4. Conclusions

Introduction to the Model

Kaluza (1921) and Klein (1926)
Unification of gravity and electrodynamics in $D = 5$ compactified on S^1.





Some extra dimensional Models:

- brane world: SM on brane, gravity in the bulk, localization mechanism
- gravity and gauge bosons in bulk, fermions on brane $R^{-1} >$ few TeV, localization mechanism
- Universal extra dimensions (UED): everything in the bulk, no localization mechanism required, gravity not considered

ACD Model

Appelquist, Cheng, and Dobrescu (ACD)

hep-ph/0012100

- All SM fields live in the bulk $D = 4 + 1$, Gravity not considered.
- Orbifold: Replace S^1 by S^1/Z_2
- Simple extension of SM, 1 extra parameter (R, radius of ED), boundary terms set to zero
- provides excellent dark-matter candidate

  Servant,Tait '02; Cheng,Feng,Matchev '02
- bounds on $1/R$ are rather weak

  $1/R \gtrsim 250$ GeV, $M_H > 250$ GeV,

  $1/R \gtrsim 300$ GeV, $M_H < 250$ GeV. Appelquist,Yee '02

Appelquist, Cheng, Dobrescu Model (ACD)

(D = 5)

Universal Extra Dimensions: All SM fields live in extra dimensions

Particle Content in an Effective D = 4 Theory

SM Fields (n = 0) (Zero Modes)

+

Corresponding KK Models (n = 1, 2, ...) $W^{\pm}_{(n)}$, $Z^{0}_{(n)}$, etc.

+

Additional Physical Scalar Modes $a^{0}_{(n)}$, $a^{\pm}_{(n)}$; $n = 1, 2, \ldots$

Single New Parameter: Compactification Scale $1/R$

$$1/R \geq \begin{array}{l} 250\ \text{GeV}\ (M_H > 250\ \text{GeV}) \\ 300\ \text{GeV}\ (M_H < 250\ \text{GeV}) \end{array}$$

(ACD, AY: Electroweak Precision Observables)

Mass Spectrum

$$M^2_{\gamma(n)} = \frac{n^2}{R^2}$$

$$M^2_{Z(n)} = \frac{n^2}{R^2} + M^2_Z$$

$$M^2_{W(n)} = \frac{n^2}{R^2} + M^2_W$$

$$m^2_{q(n)} = \frac{n^2}{R^2} + m^2_q$$

$$m^2_{l(n)} = \frac{n^2}{R^2} + m^2_l$$

$$m^2_{a^\pm(n)} = \frac{n^2}{R^2} + M^2_W \qquad n \geq 1$$

$$m^2_{a^0(n)} = \frac{n^2}{R^2} + M^2_Z \qquad n \geq 1$$

$(n = 0, 1, 2 \ldots)$

Interactions

1. Full Set of Feynman Rules in BSW
2. Vertices depend on n/R
3. Conservation of KK Parity $\Rightarrow$ Absence of tree level KK contributions
4. Minimal Flavour Violation (CKM Matrix; no new operators)

Properties Relevant for FCNC Processes

$\varepsilon_K, \Delta M_{d,s}$: $S(x_t, 1/R) = S_0(x_t) + \sum_{n=1}^{\infty} S_n\left(x_t, \frac{n}{R}\right)$ $\left(\begin{array}{c}\Delta F=2 \\ \text{Boxes}\end{array}\right)$

$\left(x_t = \frac{m_t^2}{M_W^2}\right)$

$K^+ \to \pi^+ \nu\bar{\nu}$
$K_L \to \pi^0 \nu\bar{\nu}$
$B \to X_{s,d} \nu\bar{\nu}$: $X(x_t, 1/R) = X_0(x_t) + \sum_{n=1}^{\infty} C_n\left(x_t, \frac{n}{R}\right)$

$(C_0\text{-}4B_0)$

SM

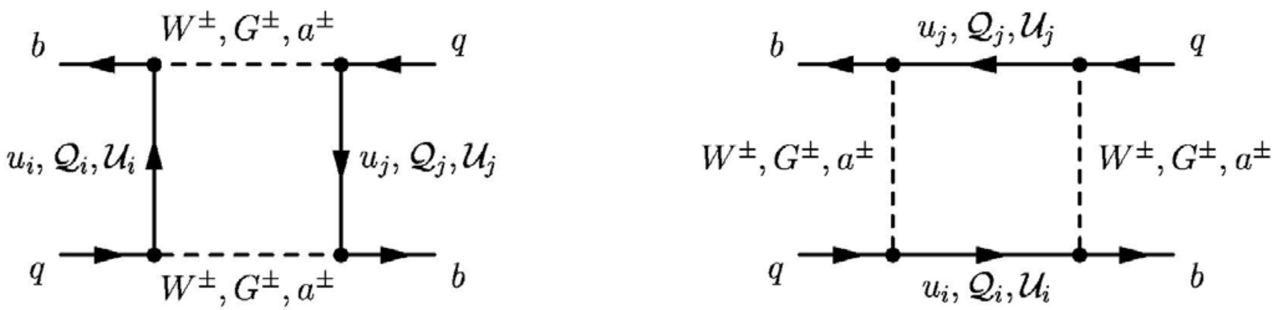
$B_{s,d} \to \mu^+\mu^-$
$K_L \to \mu^+\mu^-$: $Y(x_t, 1/R) = Y_0(x_t) + \sum_{n=1}^{\infty} C_n\left(x_t, \frac{n}{R}\right)$

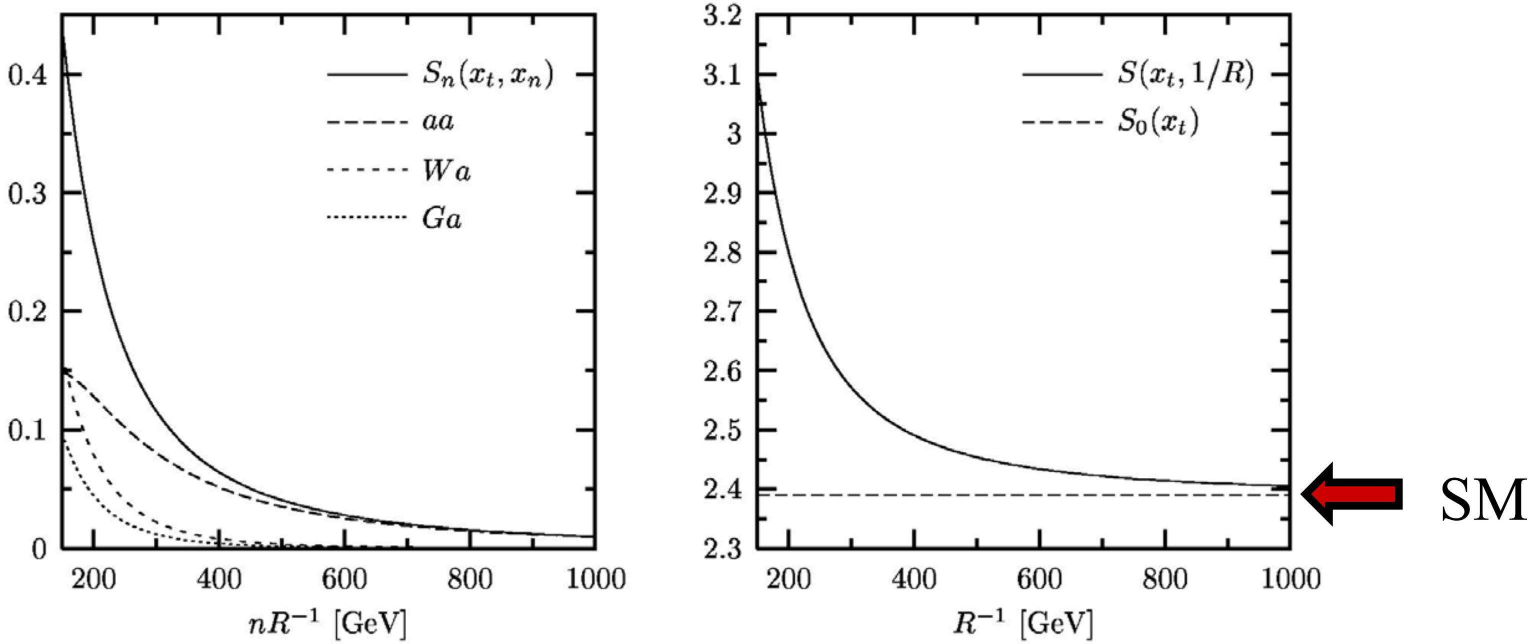
$(C_0\text{-}B_0)$

Z^0 Penguins

GIM mechanism improves significantly the convergence of the sum over the $(KK)_t$ Modes and essentially removes the contributions of $(KK)_{u,c}$ in the first two generations.

Results for the Function S(x_t, 1/R)





(a) (b)

Basic Formulae for UT Analysis

1. ε_K - Hyperbola

$$\bar{\eta}\left[\left(1-\bar{\rho}\right)A^2F_{tt}\eta_{QCD}^{tt}+P_c\left(\varepsilon\right)\right]A^2\hat{B}_K=0.213$$

$$F_{tt}^{SM}=S_0\left(x_t\right)$$
$$F_{tt}^{ACD}=S\left(x_t,1/R\right)$$

$\eta_{QCD}^{tt}=0.57\pm0.01;\quad P_C\left(\varepsilon\right)=0.28\pm0.05;$

2. $B_d^0-\bar{B}_d^0$ Mixing Constraint

$$R_t=0.86\left[\frac{0.041}{\left|V_{cb}\right|}\right]\sqrt{\frac{2.34}{F_{tt}}}\sqrt{\frac{\Delta M_d}{0.50/ps}}\left[\frac{230MeV}{\sqrt{\hat{B}_d}F_{B_d}}\right]\sqrt{\frac{0.55}{\eta_B^{QCD}}}$$

$$\left\{F_{tt}^{ACD}>F_{tt}^{SM}\right\}$$
$$\Downarrow$$
$$\left\{R_t^{ACD}<R_t^{SM}\right\}$$

$\left|V_{cb}\right|=0.041\pm0.001;\quad \Delta M_d=\left(0.503\pm0.006\right)/ps;\quad \eta_B^{QCD}=0.55\pm0.01$

3. $B_s^0-\bar{B}_s^0$ Mixing Constraint ($\Delta M_d/\Delta M_s$)

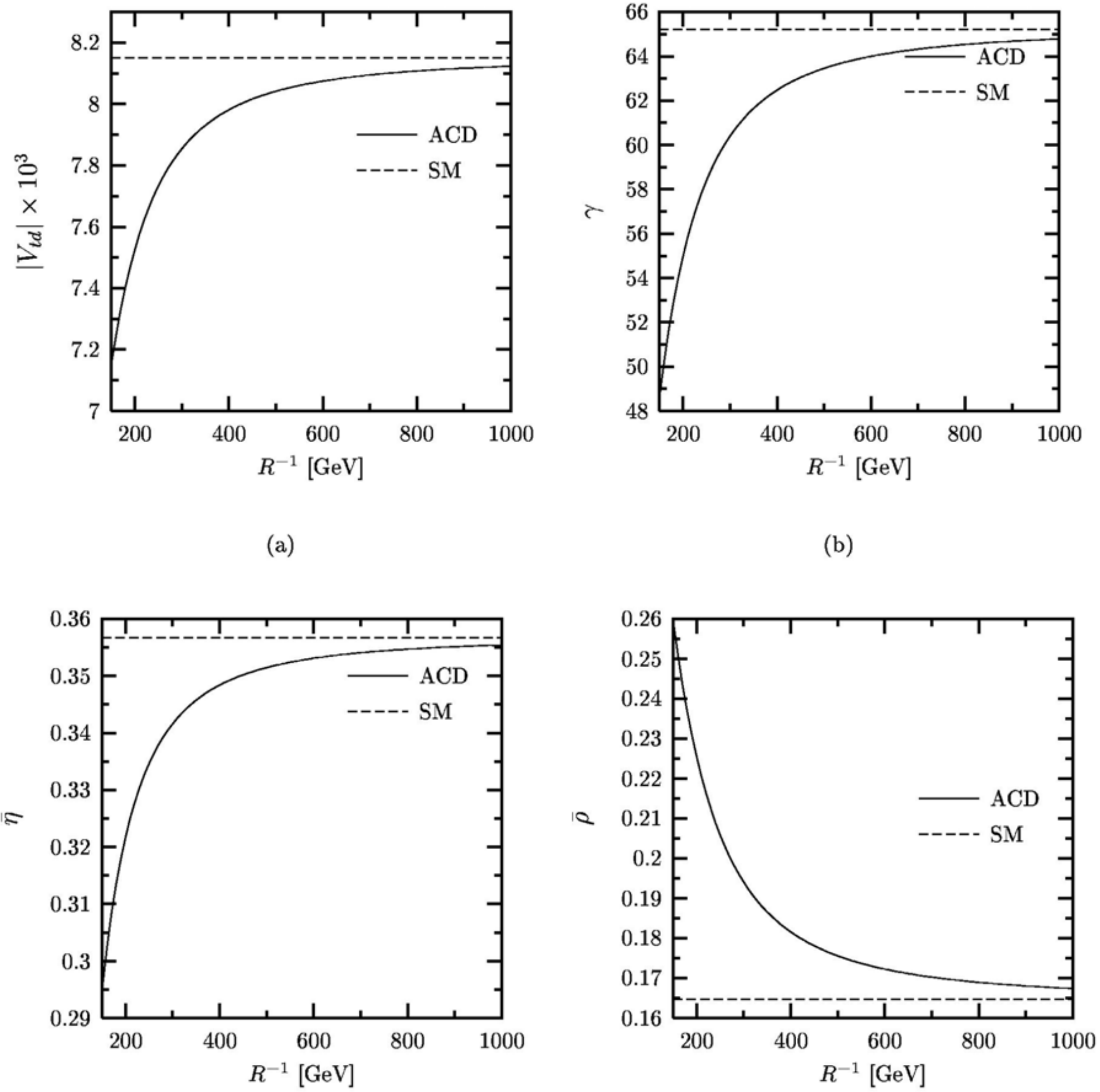
$$R_t=0.90\sqrt{\frac{\Delta M_d}{0.50/ps}}\sqrt{\frac{18.4/ps}{\Delta M_s}}\left[\frac{\xi}{1.22}\right]$$

$$\xi=\frac{\sqrt{\hat{B}_s}F_{B_s}}{\sqrt{\hat{B}_d}F_{B_d}}$$

(No dependence on 1/R)

$\Delta M_s>14.4/ps$ (95% C.L.) LEP (SLD)

Implications for Unitarity Triangle



(c) (d)

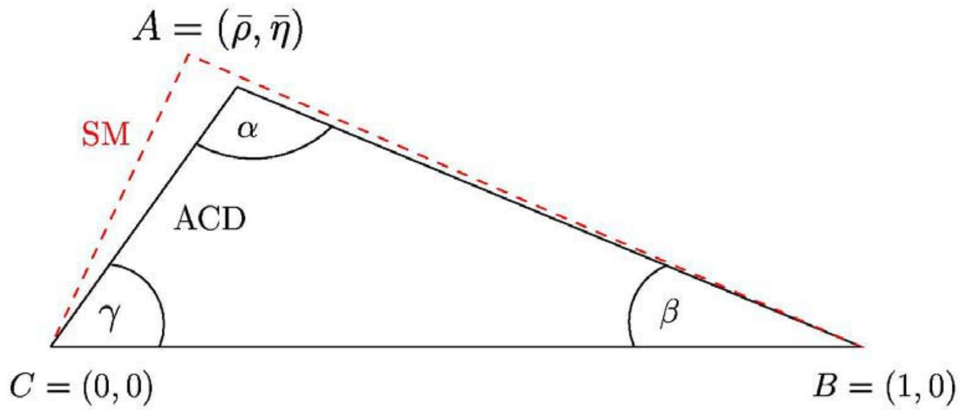
1/R = 200 (300) GeV

Suppressions :

$\lvert V_{td} \rvert$	: 8%	(4%)
$\bar{\eta}$	: 11%	(4.5%)
γ	: 10^o	(5^o)

Unitarity Triangle in the ACD Model

1/R = 200 GeV

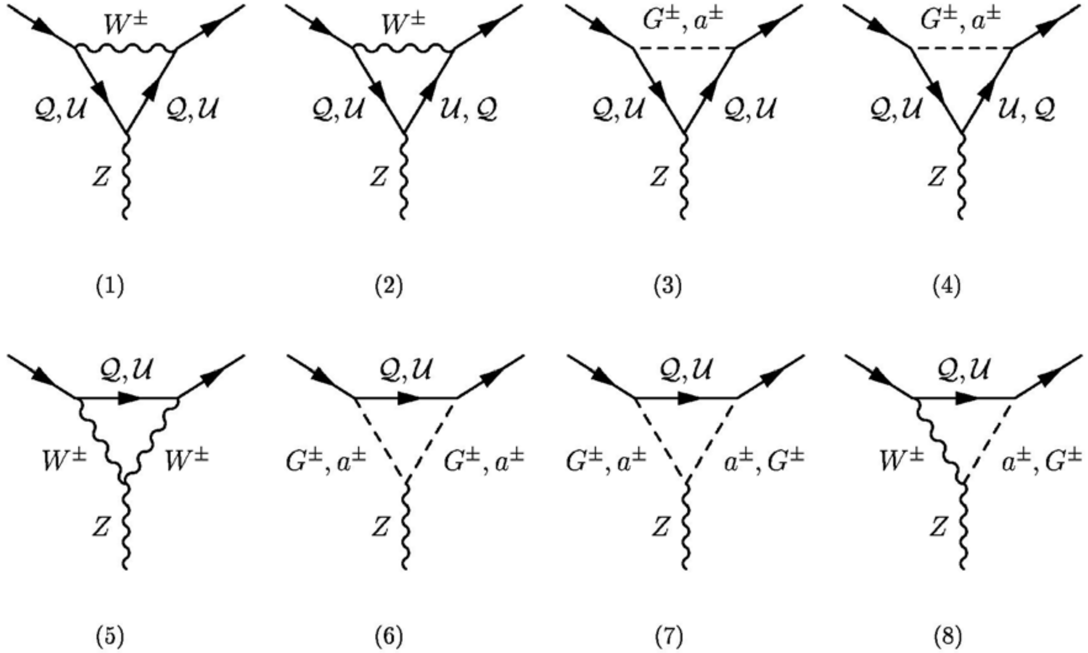


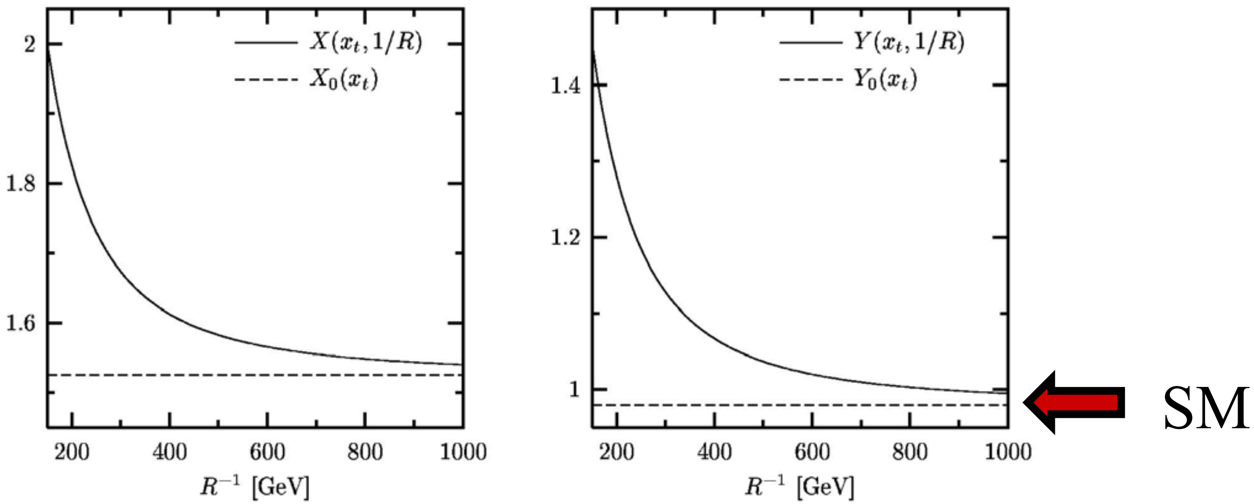
At $1/R = 200$ GeV $\gamma_{SM} = 65^\circ \rightarrow \gamma_{ACD} = 49^\circ$

but at $1/R = 300\ (400)$ GeV $\gamma_{ACD} = 60^\circ (63^\circ)$

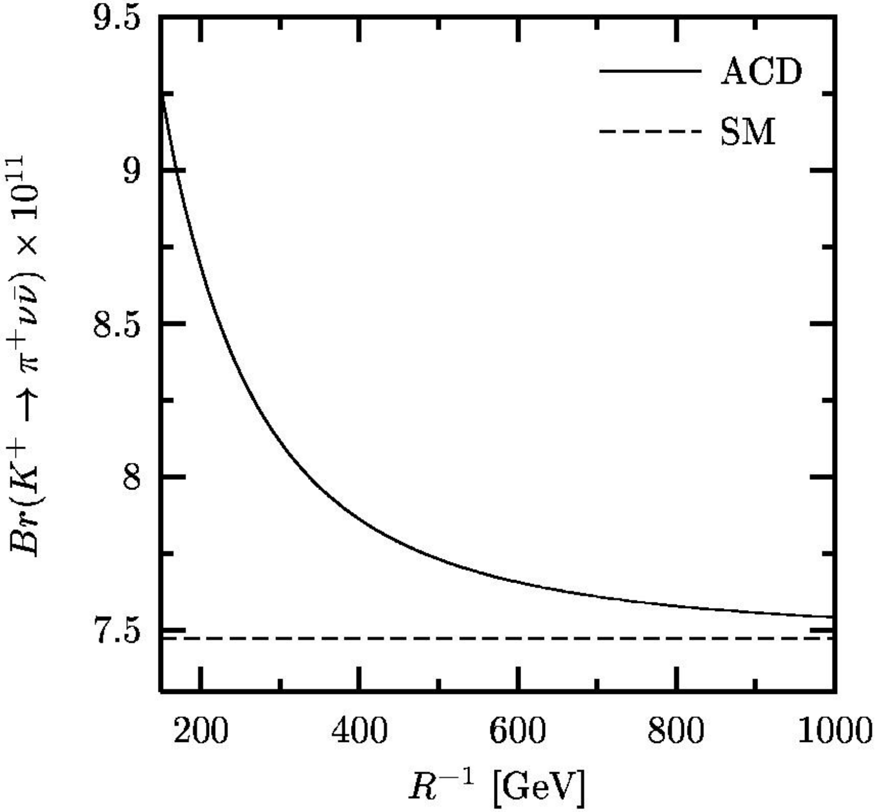
Very difficult to see the difference in view of hadronic uncertainties.

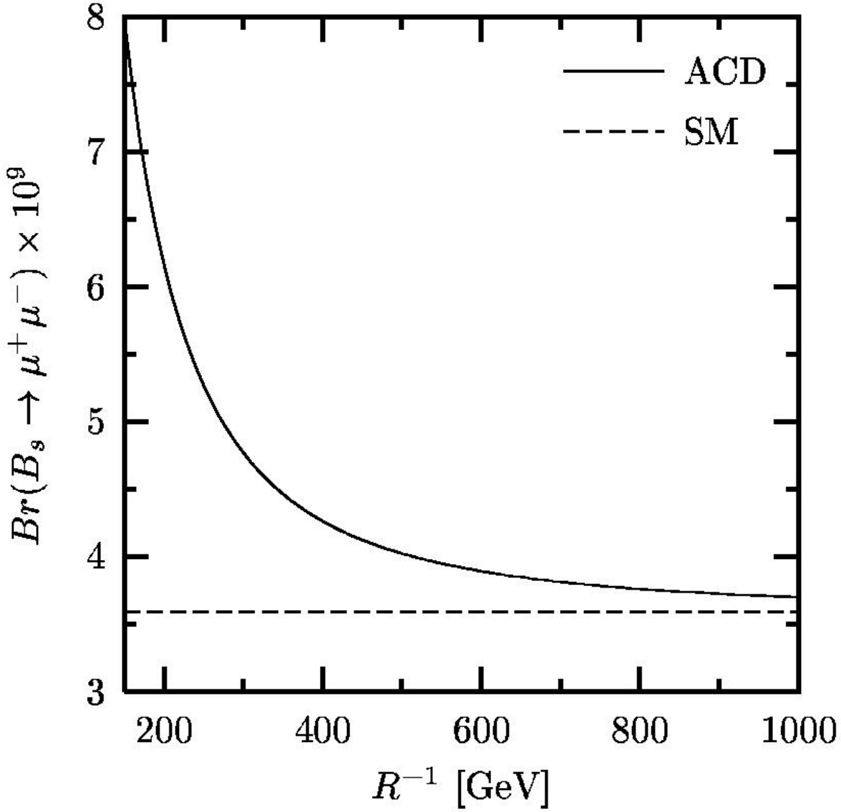
Results for the Functions $X(x_t, 1/R)$, $Y(x_t, 1/R)$





Implications for Rare K and B Decays

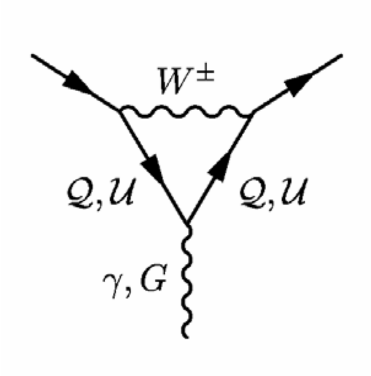


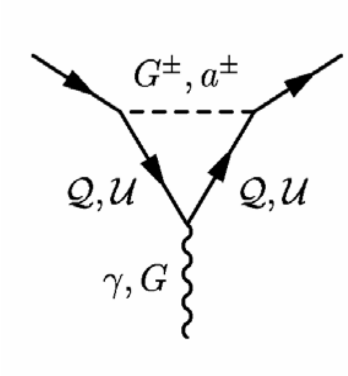


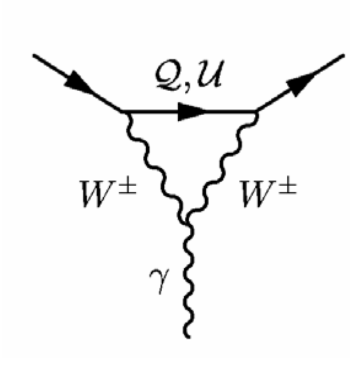
The Impact of Universal Extra Dimensions on $B \to X_s\gamma$, $B \to X_s\mu^+\mu^-$, $K_L \to \pi^0 e^+ e^-$

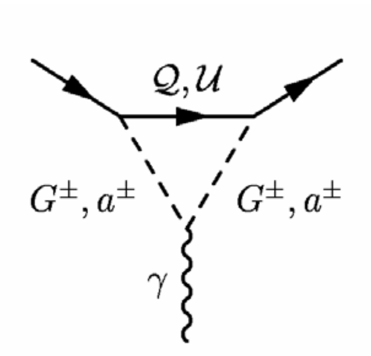
Andrzej J. Buras, Anton Poschenrieder,
Michael Spranger, Andreas Weiler

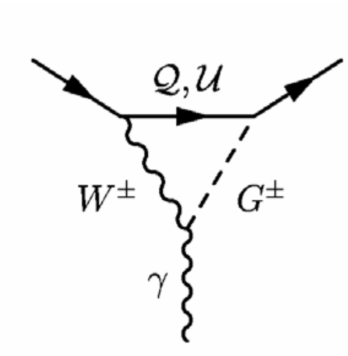
Diagrams Contributing to D, E, D', E'

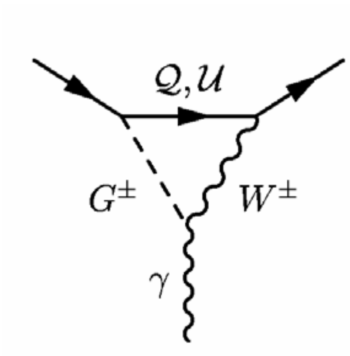




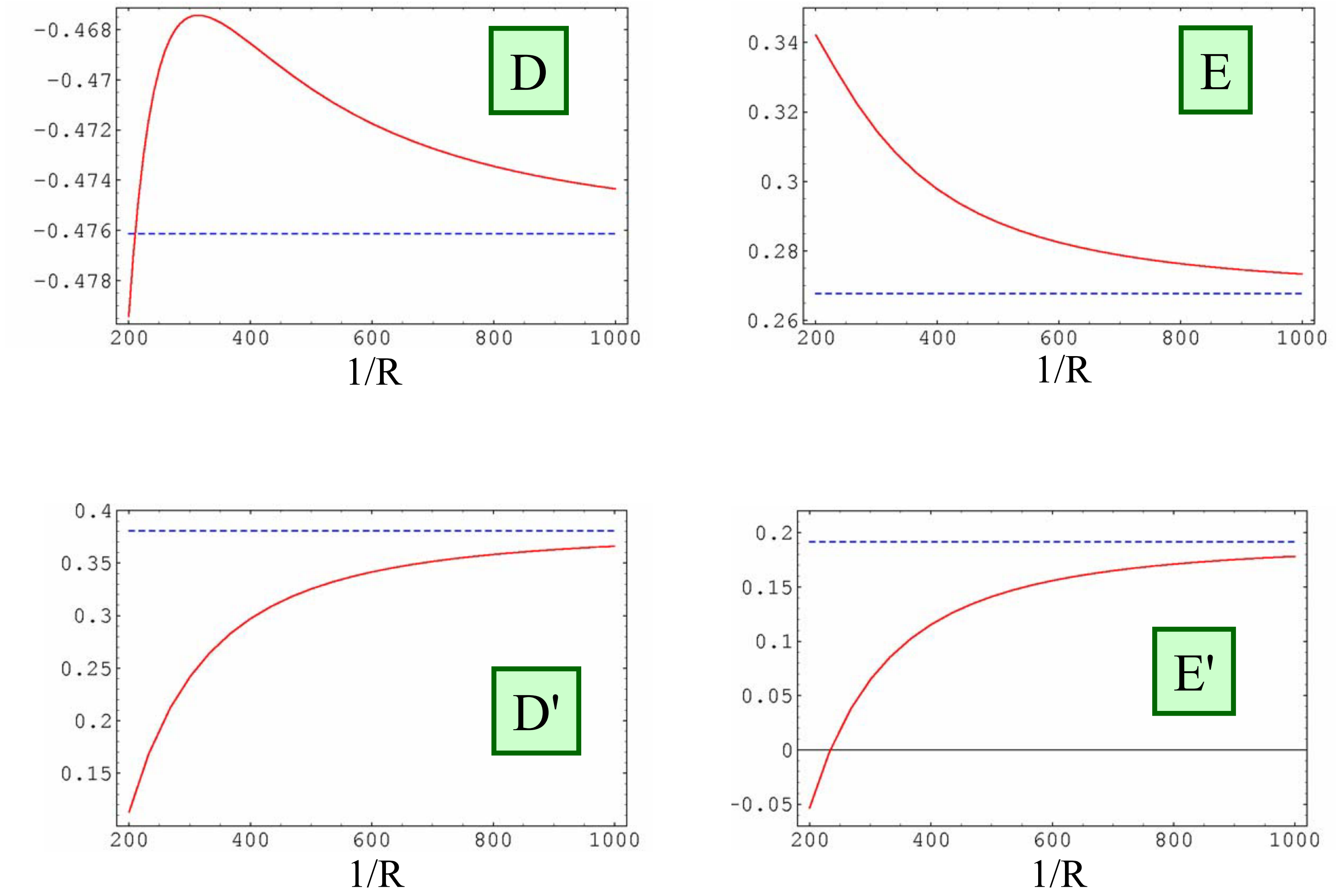








Results for D, E, D', E'



Impact of KK on $B \to X_s\gamma$

CLEO, ALEPH, BaBar, Belle:

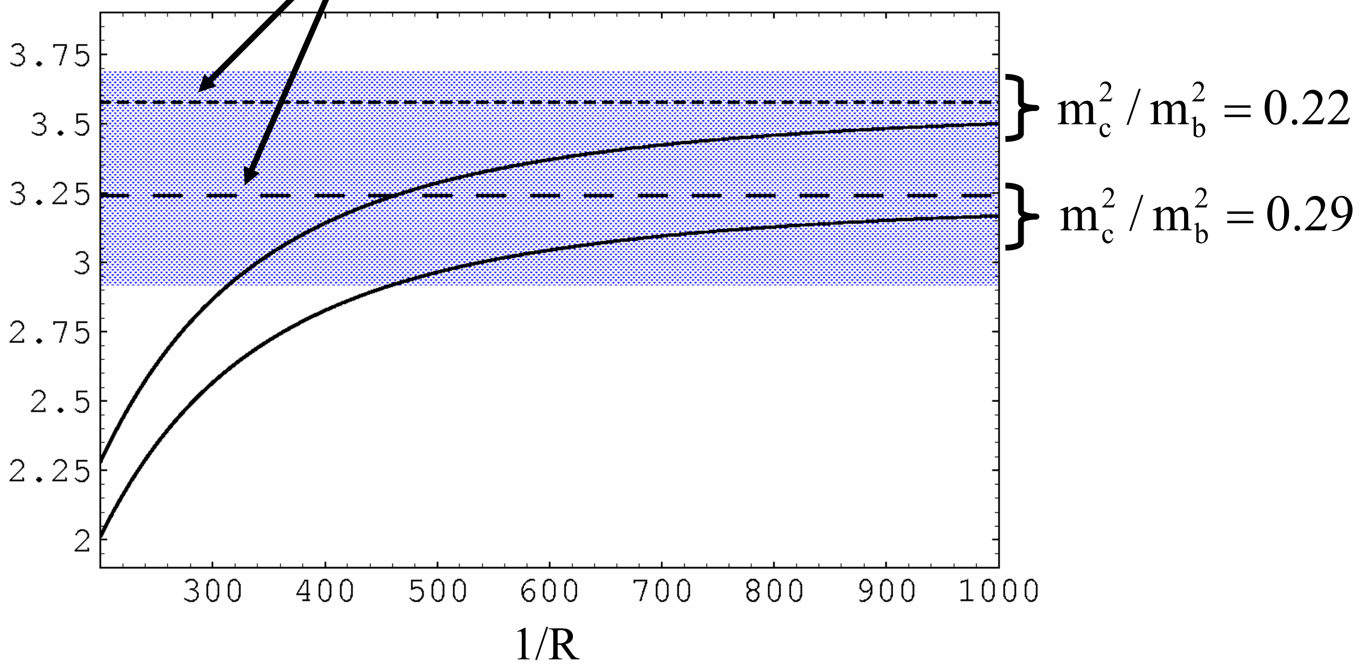
$$Br(B \to X_s\gamma) = \left(3.28 \begin{array}{c} +0.41 \\ -0.36 \end{array}\right) \cdot 10^{-4}$$

SM

$$(3.57 \pm 0.30) \cdot 10^{-4}$$

Gambino + Misiak $\left(\frac{m_c^2}{m_b^2} = 0.22\right)$

SM



$Br(B \to X_s\gamma)$ $[10^{-4}]$

Impact of KK on $B \to X_s\mu\bar{\mu}$

$$\left\{\begin{array}{c}\text{Integration}\\ \text{over}\\ \text{full dileption}\\ \text{mass spectrum}\end{array}\right\}$$

$$\mathrm{Br}\left(B \to X_s\mu\bar{\mu}\right) = \left(7.9 \pm 2.1 \begin{array}{c}+2.0\\ -1.5\end{array}\right)\cdot 10^{-6} \quad (\text{Belle})$$

$$\text{SM}: \quad (4.1 \pm 0.7)\cdot 10^{-6} \quad (\text{Ali, Lunghi, Greub, Hiller})$$

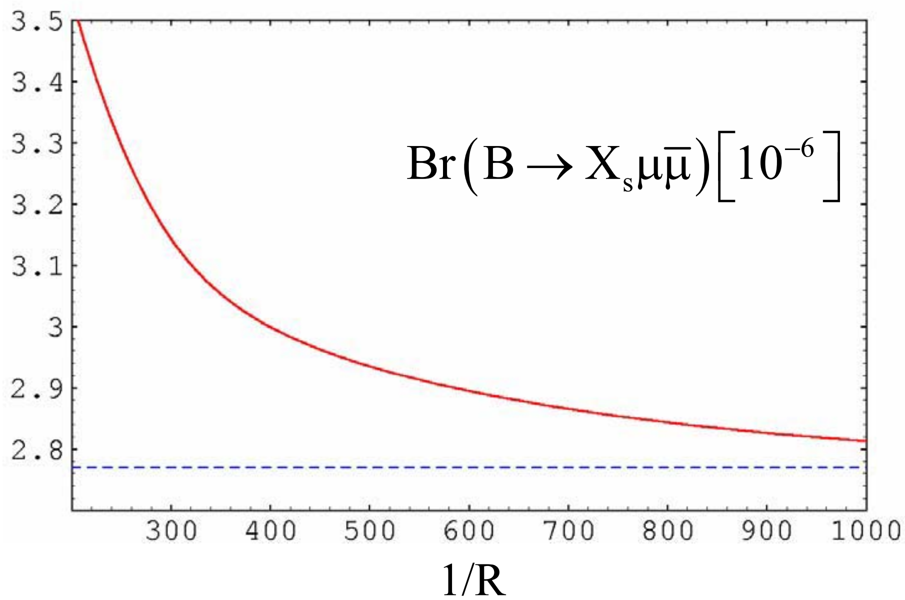
$$\text{ACD}: \quad (4.8 \pm 0.8)\cdot 10^{-6} \quad (\text{BPSW; } 1/R{=}300\text{GeV})$$

$$\hat{s} = \frac{\left(P_{\mu_+} + P_{\mu_-}\right)^2}{m_b^2}$$

$$\left\{\begin{array}{c}\text{Integration}\\ \text{over}\\ \text{low dileption}\\ \text{mass spectrum}\end{array}\right\}$$

$$0.05 \lesssim \hat{s} \lesssim 0.25$$

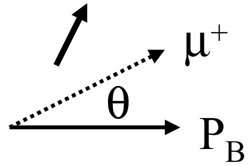
$$\text{SM}: \quad (2.75 \pm 0.45)\cdot 10^{-6}$$



Forward-Backward Asymmetry in $B \to X_s \mu^+ \mu^-$ (SM)

$$A_{FB}(\hat{s}) = \frac{1}{\Gamma(b \to c e \bar{\nu})} \int_{-1}^{+1} d\cos\theta_L \frac{d^2\Gamma(b \to s \mu^+ \mu^-)}{d\hat{s}\, d\cos\theta_L} \mathrm{sgn}(\cos\theta_L)$$

$$A_{FB}(\hat{s}) = -3\tilde{C}_{10} \frac{\left[\hat{s}\,\mathrm{Re}\,\tilde{C}_9^{eff}(\hat{s}) + 2C_{7\gamma}^{(0)eff}\right]}{U(\hat{s})}$$



$$\hat{s}_0 \cong -\frac{2C_{7\gamma}^{(0)eff}}{\mathrm{Re}\,\tilde{C}_9^{eff}(\hat{s}_0)}$$

$$C_9 \leftrightarrow (\bar{s}b)_{V-A}(\bar{\mu}\mu)_V$$
$$C_{10} \leftrightarrow (\bar{s}b)_{V-A}(\bar{\mu}\mu)_A$$
$$C_{7\gamma} \leftrightarrow B \to X_s \gamma$$

SM :

$$\mathrm{NLO}: \quad \hat{s}_0 \cong 0.14 \pm 0.02$$

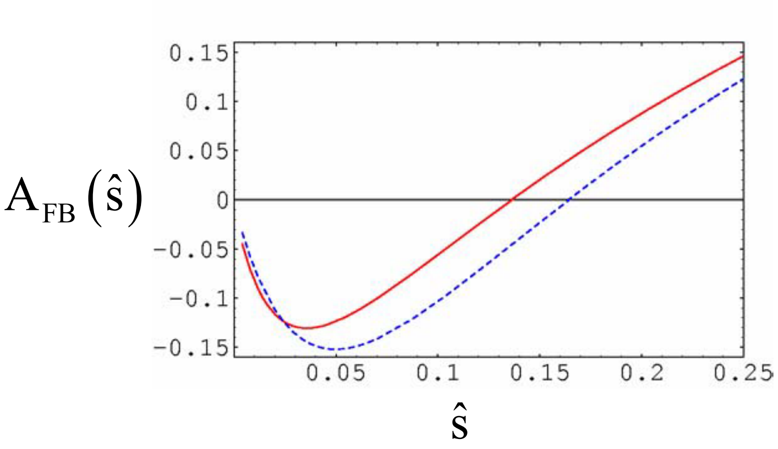
Ali Mannel Morozumi

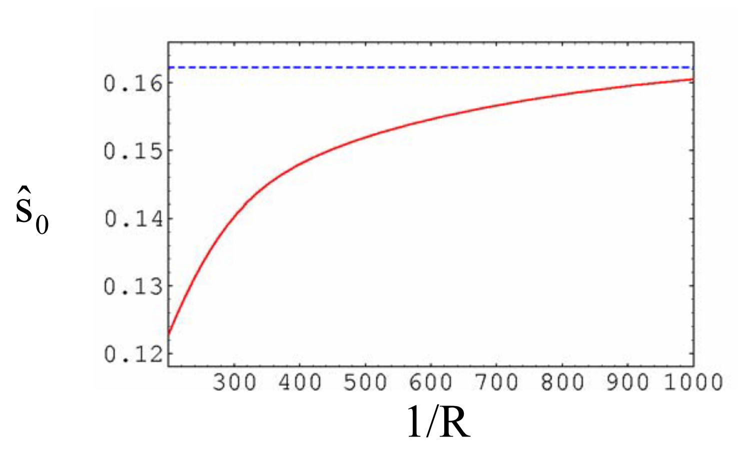
$$\mathrm{NNLO}: \quad \hat{s}_0 \cong 0.162 \pm 0.008$$

Asatrian, Asatrian, Greub, Walker, Bieri Hovhannisyan

Ghinculov, Hurth, Isidori, Yao

Impact of KK on $A_{FB}(\hat{s})$

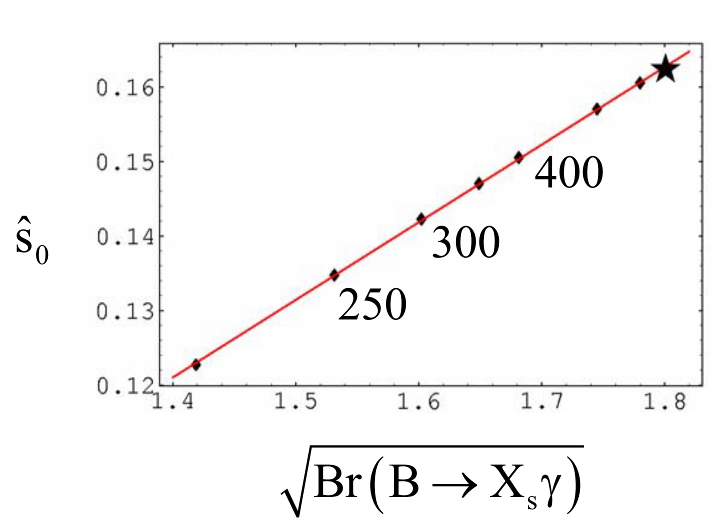




$$\left\{ \begin{array}{c} \widetilde{C}_9^{eff} \text{ very} \\ \text{weakly affected} \end{array} \right\}$$

⇓

$$\hat{s}_0 \sim \sqrt{Br(B \to X_s \gamma)}$$



Summary

1. ACD Model consistent with the data on FCNC Processes with $1/R \cong 300$ GeV

2. Only small impact on UT relative to the SM

3. Enhancements : $K^+ \to \pi^+ \nu\bar{\nu}(9\%)$, $K_L \to \pi^0 \nu\bar{\nu}(10\%)$
   $1/R = 300$ GeV
   $B \to X_s \mu\bar{\mu}(12\%)$, $B \to X_d \nu\bar{\nu}(12\%)$
   $B \to X_s \nu\bar{\nu}(21\%)$, $K_L \to \mu^+\mu^-(20\%)$
   $B_d \to \mu^+\mu^-(23\%)$, $B_s \to \mu^+\mu^-(33\%)$

4. Suppressions : $B \to X_s \gamma(20\%)$, $B \to X_s \mathrm{gluon}(40\%)$
   $\hat{s}_0 : 0.162 \to 0.142$; ε'/ε

5. With improved Exp+Th for $B \to X_s \gamma$ and $\hat{s}_0$ strong lower bound on $1/R$ could be obtained.

FCNC Processes in the "Littlest" Higgs Model

LH Model : Arkani-Hamed, Cohen, Katz, Nelson (2002)

FCNC Processes : AJB, Poschenrieder, Uhlig : hep-ph/0410309 $B^0_{d,s} - \bar{B}^0_{d,s}$ Mixing
0501230 Rare Decays
05xxyyy Technical Details

New Effect generally below 30%

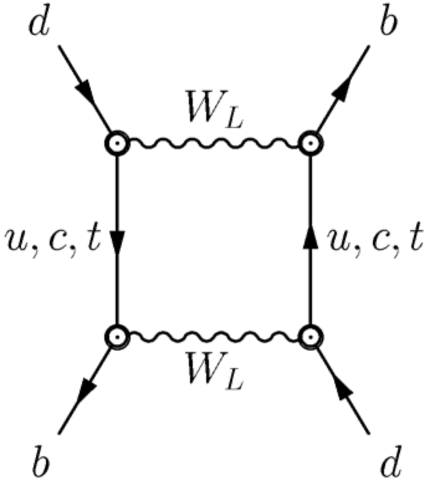
A symphony of penguin and box diagrams with

SM	New Particles	
$W_L^\pm,\ Z_L^0$	$W_H^\pm,\ Z_H^0,\ A_H^0$	(new Gauge Bosons)
t	$T,\ \Phi^\pm$	(new heavy top, charged scalar)

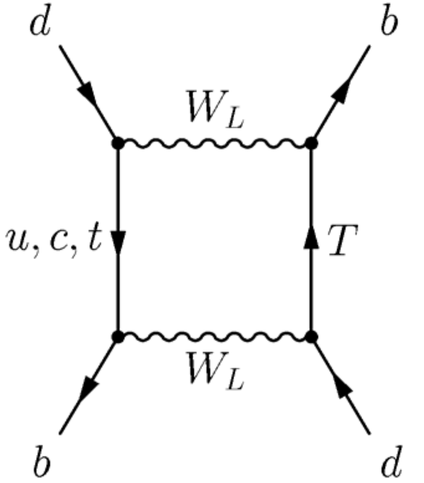
New Particles $m_i > 1$ TeV

Related work: Choudhury, Gaur, Goyal, Mahajan, 0407050 (confirmed our results)
Choudhury, Gaur, Joshi, McKellar, 0408125 (?)

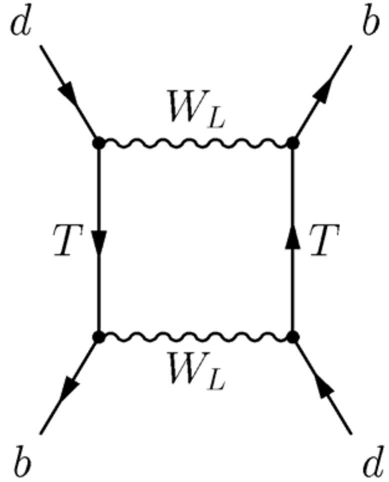
Movement 1



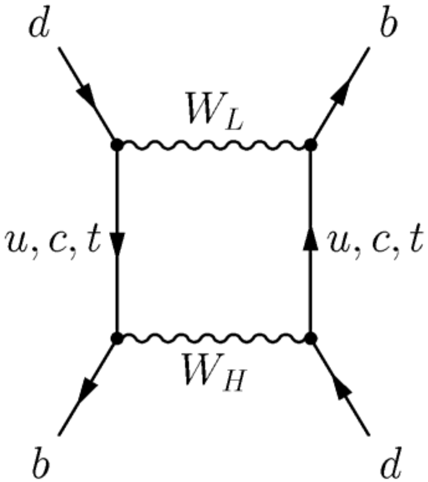
d
b
W_L
u, c, t
u, c, t
W_L
b
d



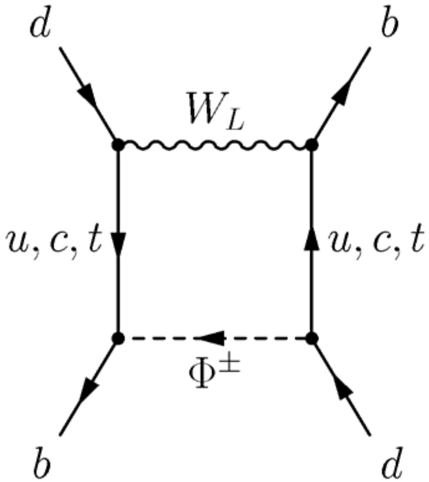
d
b
W_L
u, c, t
T
W_L
b
d



d
b
W_L
T
T
W_L
b
d

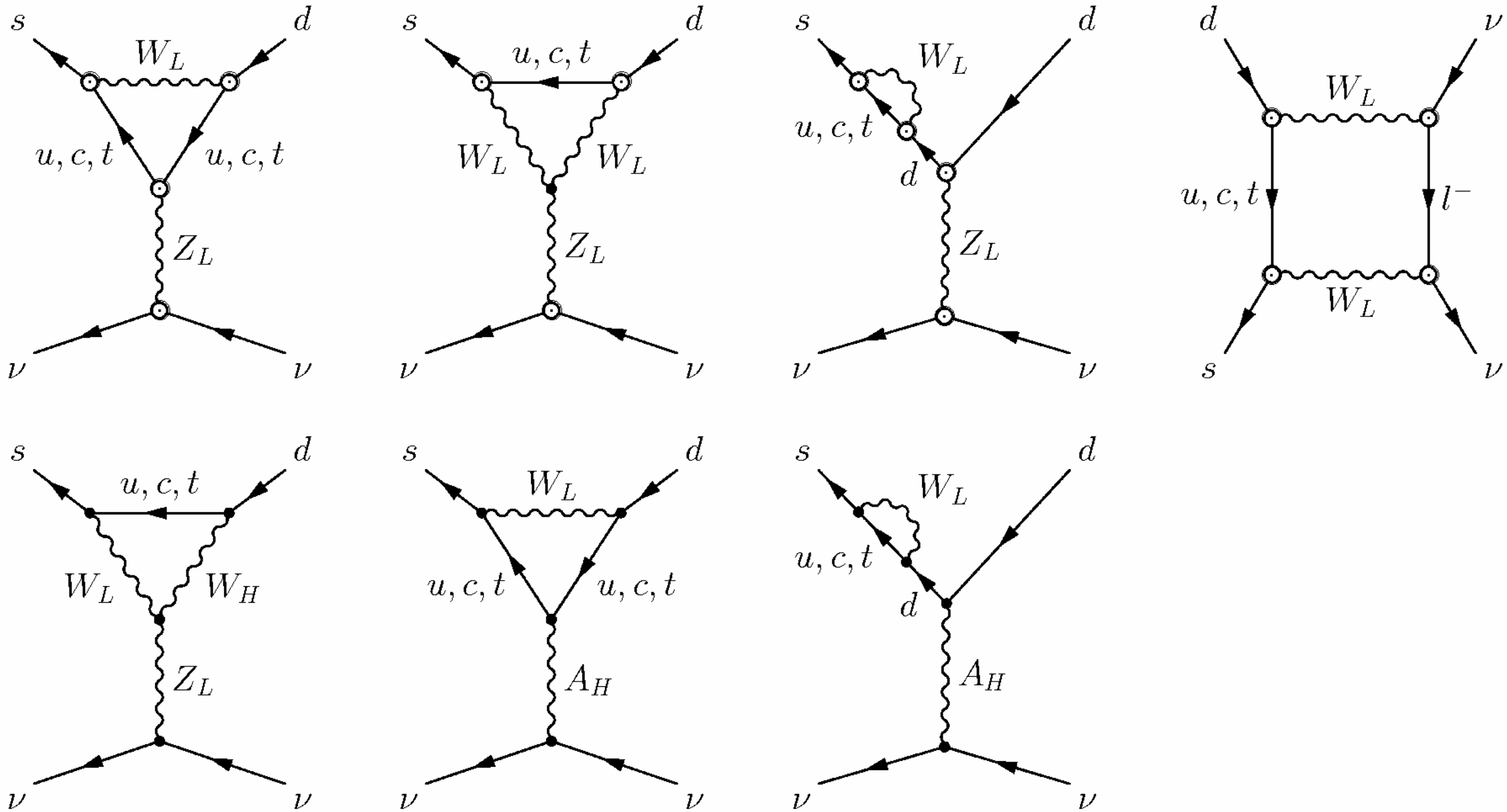


d
b
W_L
u, c, t
u, c, t
W_H
b
d



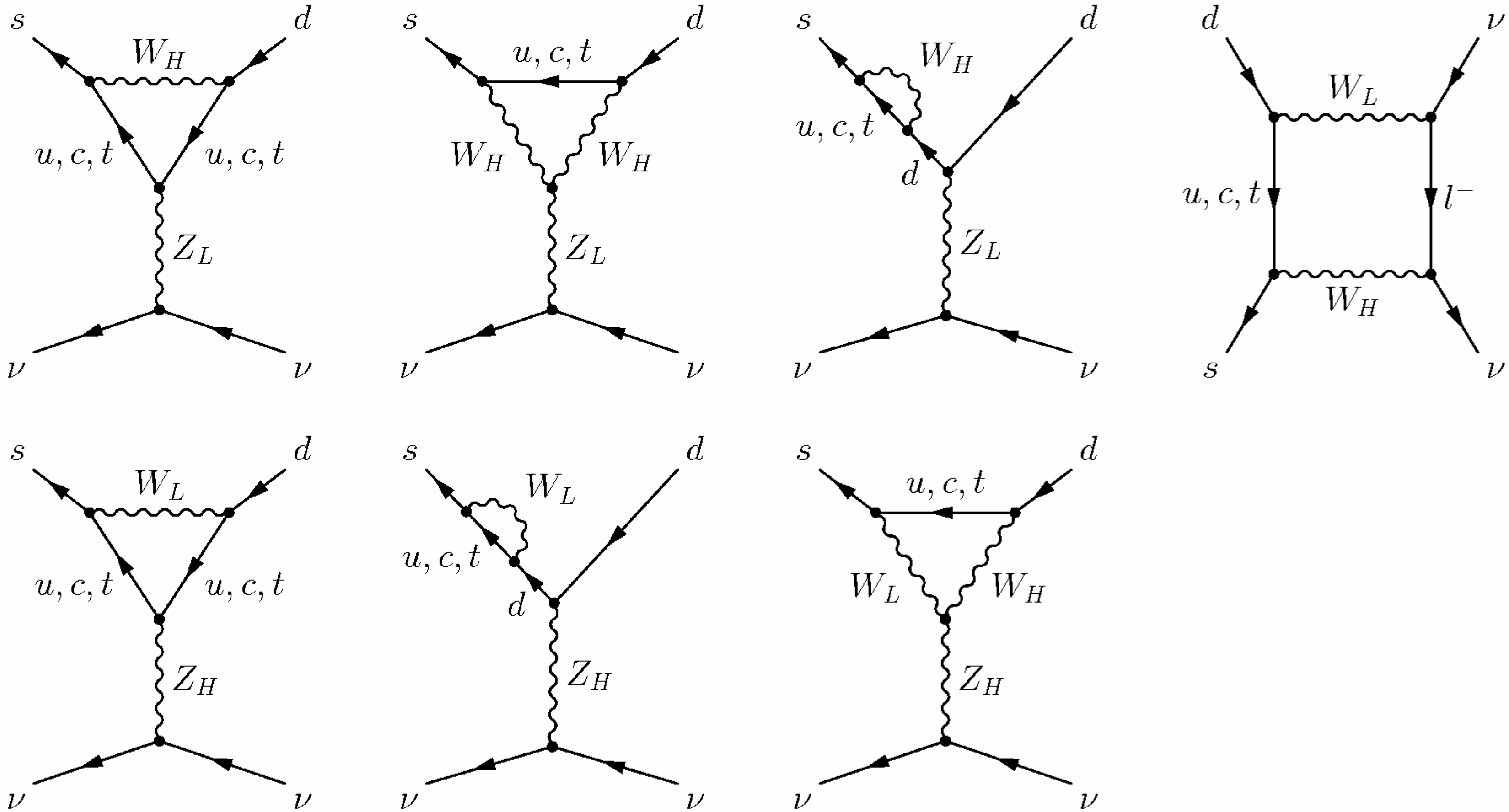
d
b
W_L
u, c, t
u, c, t
$\Phi^{\pm}$
b
d

Movement 2



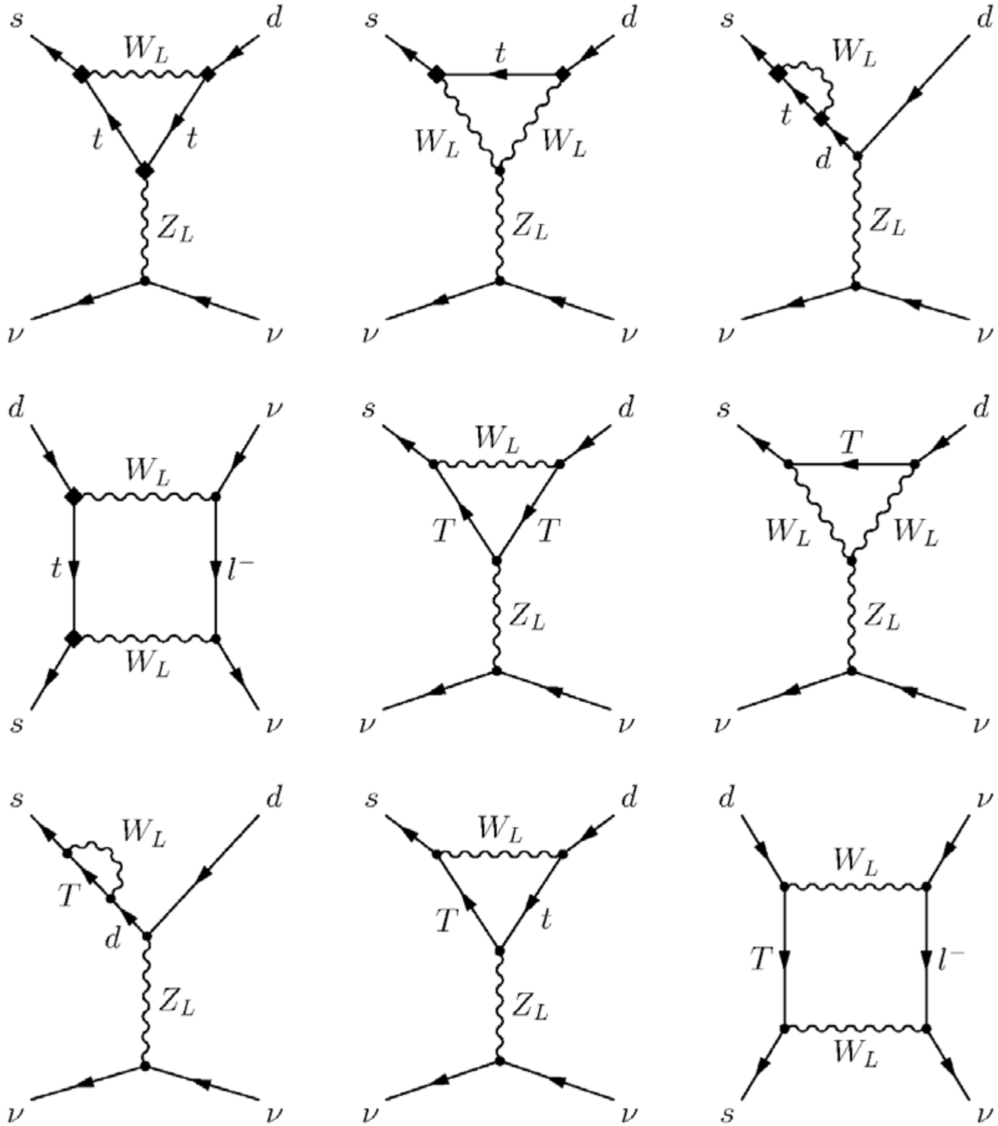
s d W_L u,c,t u,c,t Z_L ν ν
s d u,c,t W_L W_L Z_L ν ν
s d W_L u,c,t d Z_L ν ν
d ν W_L u,c,t l^- W_L s ν
s d u,c,t W_L W_H Z_L ν ν
s d W_L u,c,t u,c,t A_H ν ν
s d W_L u,c,t d A_H ν ν

Movement 3



s
d
W_H
u, c, t
u, c, t
Z_L
ν
ν
s
d
u, c, t
W_H
W_H
Z_L
ν
ν
s
d
W_H
u, c, t
d
Z_L
ν
ν
d
ν
W_L
u, c, t
l^-
W_H
s
ν
s
d
W_L
u, c, t
u, c, t
Z_H
ν
ν
s
d
W_L
u, c, t
d
Z_H
ν
ν
s
d
u, c, t
W_L
W_H
Z_H
ν
ν

Movement 4


s d W_L t t Z_L ν ν
s d t W_L W_L Z_L ν ν
s d W_L t d Z_L ν ν
d ν W_L t l⁻ W_L s ν
s d W_L T T Z_L ν ν
s d T W_L W_L Z_L ν ν
s d W_L T d Z_L ν ν
s d W_L T t Z_L ν ν
d ν W_L T l⁻ W_L s ν

FCNC Processes in MSSM (MFV)

Classic Paper : Bertolini, Borzumati, Masiero, Ridolfi (1991)

Last Analysis : AJB, Gambino, Gorbahn, Jäger, Silvestrini (2000)

$$T(Q) \equiv \frac{Q_{MSSM}}{Q_{SM}}$$

$$0.65 \le T\left(K^+ \to \pi^+ \nu\bar{\nu}\right) \le 1$$

$$0.41 \le T\left(K_L \to \pi^0 \nu\bar{\nu}\right) \le 1$$

$$0.73 \le T\left(B \to X_s \nu\bar{\nu}\right) \le 1.34$$

$$0.68 \le T\left(B_s \to \mu\bar{\mu}\right) \le 1.53$$

Governed by the modification of $\underbrace{X(v)}_{\text{enhanced or suppressed}}$ and $V_{td} \Downarrow$

Governed by the modification of the functions $\underbrace{X(v)\,,\,Y(v)}_{\text{enhanced or suppressed}}$

V_{ts} not modified

MFVfit Collaboration

(BBBEPSW)
hep-ph/0505110

Use the existing results for

1. UUTfit
2. $B \to X_s \gamma$
3. $B \to X_s l^+ l^-$
4. $K^+ \to \pi^+ \nu \bar{\nu}$

$\Rightarrow$

$X_{max}(v) = 1.95$ $\quad$ $Y_{max}(v) = 1.43$

$(X_{SM} \cong 1.53)$ $\quad$ $(Y_{SM} \cong 0.99)$

$\Downarrow$

Model Independent
Upper Bounds
within MFV Scenario

Conclusion : Large Departures from SM within MFV not possible

Upper Bounds on Rare K and B Decays from MFV

Bobeth, Bona, AJB, Ewerth, Pierini, Silvestrini, Weiler   hep-ph/0505110

Branching Ratios	MFV (95%)	SM (95%)	SM (68%)	Exp
$Br(K^+ \to \pi^+ \nu\bar{\nu}) \cdot 10^{11}$	<11.9	<10.9	8.3±1.2	$14.7^{+13.0}_{-8.9}$
$Br(K_L \to \pi^0 \nu\bar{\nu}) \cdot 10^{11}$	<4.6	<4.2	3.1±0.6	$<5.9 \cdot 10^4$
$Br(B \to X_S \nu\bar{\nu}) \cdot 10^5$	<5.2	<4.1	3.7±0.2	<64
$Br(B_s \to \mu^+\mu^-) \cdot 10^9$	<7.4	<5.9	3.7±1.0	$<5.0 \cdot 10^2$
$Br(B_d \to \mu^+\mu^-) \cdot 10^{10}$	<2.2	<1.8	1.1±0.4	$<1.6 \cdot 10^3$

8.

Going beyond MFV

1. MSSM at large tanβ

2. New Complex Phase in Z^0 Penguins

Three Simple Scenarios

Inami Lim Functions

SM :

$$A(\text{Decay}) = \sum_i B_i \, \eta^i_{QCD} \, V^i_{CKM} \underbrace{F^i_{SM}}_{\text{real}}(m_t)$$

MFV :

(Minimal Flavour Violation)

$$A(\text{Decay}) = \sum_i B_i \, \eta^i_{QCD} \, V^i_{CKM} \underbrace{\left[F^i_{SM} + F^i_{New}\right]}_{\text{real}}$$

AJB, Gambino, Gorbahn, Jäger, Silvestrini
D'Ambrosio, Giudice, Isidori, Strumia

Enhanced Z^0-Penguins :

$$A(\text{Decay}) = \sum_i B_i \, \eta^i_{QCD} \, V^i_{CKM} \left[\underbrace{F^i_{SM}}_{\text{real}} + \underbrace{\Delta^i_{New}}\right]$$

Dominated by Z^0-Penguins with a New Complex Phase

AJB, Colangelo, Isidori, Romanino, Silvestrini
Buchalla, Hiller, Isidori; Atwood, Hiller
AJB, Fleischer, Recksiegel, Schwab

Two more complicated Scenarios

MSSM (MFV) (large tanβ)

(Higgs penguin)

$$A(\text{Decay}) = \sum_i B_i\, \eta^i_{QCD}\, V^i_{CKM} \Big[F^i_{SM} + \underbrace{}_{}\overbrace{F^i_{New}}^{\text{real}} \Big] + \sum_i B^{New}_i \left[\eta^i_{QCD}\right]^{New} V^i_{CKM} \underbrace{\left[G^i_{New}\right]}_{\text{real}}$$

General MSSM

Z'-Models
L-R Models
Multi-Higgs Models

$$A(\text{Decay}) = \sum_i B_i\, \eta^i_{QCD}\, V^i_{CKM} \Big[F^i_{SM} + \overbrace{F^i_{New}}^{\text{complex}} \Big] + \sum_i B^{New}_i \left[\eta^i_{QCD}\right]^{New} \underbrace{V^i_{New} \left[G^i_{New}\right]}_{\text{complex}}$$

The Case of large tanβ in MSSM

h_i = Yukawa couplings

SM :

$$\begin{cases} m_b = h_b v \\ m_t = h_t v \end{cases} \Rightarrow \{h_b \ll h_t\} \Rightarrow$$

Couplings of b, s, d, μ, τ, e to Higgs particles can be neglected

MSSM :

$$\begin{cases} m_b = h_b v_D \\ m_t = h_t v_U \end{cases} \Rightarrow \begin{cases} h_b \approx h_t \\ \text{if} \\ \tan\beta = \frac{v_U}{v_D} \gg 1 \end{cases} \Rightarrow$$

$$v = \sqrt{v_U^2 + v_D^2}$$

Couplings of b, s, τ, μ to Higgs particles **cannot** be neglected

Implications :

1. Enhancement Factors in Higgs-Fermion Vertices $\sim \tan\beta \cdot m_b$
2. Higgs Penguins cannot be neglected
3. New relevant Vertices imply new Operators

MSSM with MFV but large tanβ

$$\tan\beta = \frac{v_2}{v_1}$$

$$A(\text{Decay}) = \sum_i B_i\, \eta^i_{QCD}\, V^i_{CKM}\left[F^i_{SM} + \overbrace{F^i_{New}}^{\text{real}}\right] + \sum_i B^{New}_i \left[\eta^i_{QCD}\right]^{New} V^i_{CKM} \underbrace{\left[G^i_{New}\right]}_{\text{real}}$$

$B_s \to \mu^+\mu^-$

ΔM_s

$$O_A = \left[\bar{b}\gamma_\mu(1-\gamma_5)s\right]\left[\bar{\mu}\gamma^\mu\gamma_5\mu\right]$$

SM Operators

$$Q^{VLL} = \left[\bar{b}\gamma_\mu(1-\gamma_5)s\right]\left[\bar{b}\gamma^\mu(1-\gamma_5)s\right]$$

$$O_S = m_b\left[\bar{b}(1-\gamma_5)s\right]\left[\bar{\mu}\mu\right]$$

$$O_P = m_b\left[\bar{b}(1-\gamma_5)\right]\left[\bar{\mu}\gamma_5\mu\right]$$

← New Operators →

$$Q_1^{LR} = \left[\bar{b}\gamma_\mu(1-\gamma_5)s\right]\left[\bar{b}\gamma^\mu(1+\gamma_5)s\right]$$

$$Q_2^{LR} = \left[\bar{b}(1-\gamma_5)s\right]\left[\bar{b}(1+\gamma_5)s\right]$$

$$Q_1^{SLL} = \left[\bar{b}(1-\gamma_5)s\right]\left[\bar{b}(1-\gamma_5)s\right]$$

$$Q_2^{SLL} = \left[\bar{b}\sigma_{\mu\nu}(1-\gamma_5)s\right]\left[\bar{b}\sigma_{\mu\nu}(1-\gamma_5)s\right]$$

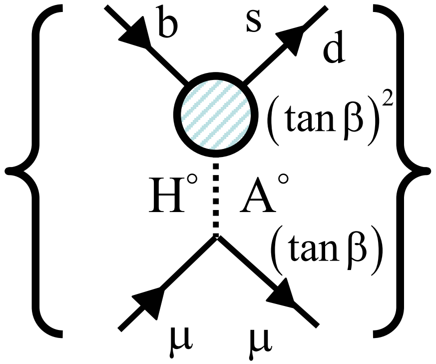
Correlation between ΔM_s and $B^0_{s,d} \to \mu^+ \mu^-$ in Supersymmetry at Large $\tan\beta$

<u>*Based on:*</u> *AJB, Chankowski, Rosiek, Slawianowska*
(hep-ph/0207241)
(hep-ph/0210121)

MSSM at large tanβ $\left(B_{s,d} \to \mu^+\mu^-\right)$

In MSSM at large tanβ
(CKM still the only source of Flavour and CP Violation)

Strong Enhancement



$$\Rightarrow \begin{cases} Br\left(B_{s,d} \to \mu\bar{\mu}\right) \sim \left(\tan\beta\right)^6 \\ 10^{-6}\left(10^{-7}\right) \text{ possible} \\ SM \sim 10^{-9} \end{cases}$$

Babu, Kolda
Chankowski, Slawianowska
Bobeth, Ewerth, Krüger, Urban
Huang, Liao, Yan, Zhu
Isidori, Retico
Dedes, Dreiner, Nierste
Dedes, Pilaftis
Chankowski, Rosiek
Foster, Okumura, Roszkowski

$$Br\left(B_s \to \mu\bar{\mu}\right) < \begin{matrix} 5.0\cdot 10^{-7}\,(D\varnothing) \\ 7.5\cdot 10^{-7}\,(CDF) \end{matrix} \quad 95\%\ \text{C.L.}$$

$$Br\left(B_d \to \mu\bar{\mu}\right) < \begin{matrix} 1.9\cdot 10^{-7}\,(CDF) & 95\%\ \text{C.L.} \\ 8.3\cdot 10^{-8}\,(BaBar) & 90\%\ \text{C.L.} \end{matrix}$$

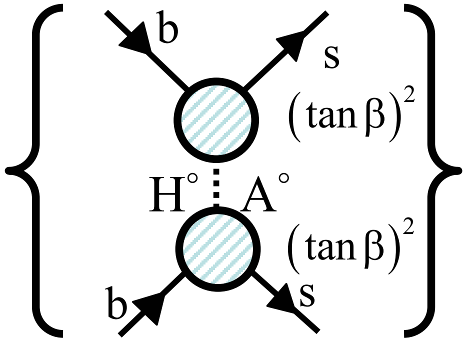
MSSM at large tanβ (cont.)

(ΔM_s)

$B_s^0 - \bar{B}_s^0$ Mixing

(Double-Higgs Peguin)

Suppression



$$\Delta M_s \approx (\Delta M_s)^{SM} - c(\tan\beta)^4$$

AJB, Chankowski, Rosiek
Slawianowska (2001, 2002)

Correlation between
SUSY effects in
$Br(B_{s,d} \to \mu\bar{\mu})$ and ΔM_s

Negligible contributions to $\Delta M_d,\ \varepsilon_K$

Clear violation
of K↔B MFV
relations

Subsequent analyses: D'Ambrosio, Giudice, Isidori, Stumia
Dedes, Pilaftis

$$\begin{Bmatrix} \text{Double} \\ \text{Higgs} - \text{Penguin} \end{Bmatrix} \Rightarrow \left\{ \Delta M_S^{DP} \sim -(\tan\beta)^4 \frac{F_{B_s}^2}{M_A^2} \frac{\varepsilon_Y^2}{(1+\tilde{\varepsilon}_3 \tan\beta)^2 (1+\varepsilon_0 \tan\beta)^2} \right\}$$

$$\left\{ [\text{Higgs} - \text{Penguin}]^2 \right\} \Rightarrow \left\{ Br(B_s \to \mu\bar{\mu}) \sim (\tan\beta)^6 \frac{F_{B_s}^2}{M_A^4} \frac{\varepsilon_Y^2}{(1+\tilde{\varepsilon}_3 \tan\beta)^2 (1+\varepsilon_0 \tan\beta)^2} \right\}$$

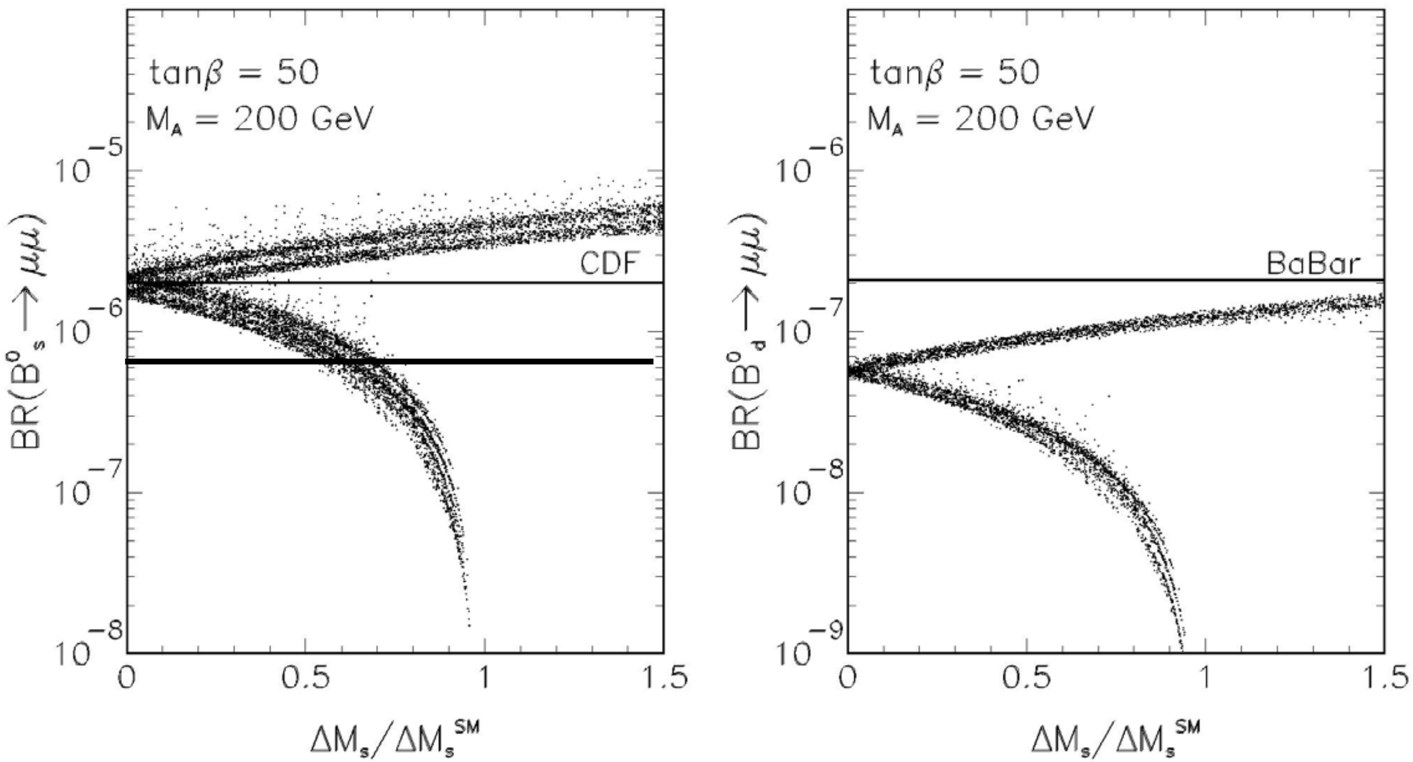
$\varepsilon_Y, \ \varepsilon_0, \ \bar{\varepsilon}_3$ - Functions of SUSY parameters

$$\frac{Br(B_d^0 \to \mu^+\mu^-)}{Br(B_s^0 \to \mu^+\mu^-)} \cong \left[\frac{F_{B_d}}{F_{B_s}}\right]^2 \left|\frac{V_{td}}{V_{ts}}\right|^2 \left|\frac{M_{B_d}}{M_{B_s}}\right|^5$$

$Br\left(B_{s,d} \to \mu^+\mu^-\right)$ vs $\left(\Delta M_s\right)^{exp} / \left(\Delta M_s\right)^{SM}$ in SUSY at Large $\tan\beta$

AJB, Chankowski, Rosiek, Slawianowska, hep-ph/0207241

2002
2004



2002

Numerical Results

$$0.8 \le \frac{(\Delta M_s)^{exp}}{(\Delta M_s)^{SM}} \le 0.95$$

⇒

$$6 \cdot 10^{-7} \ge Br^{max}\left(B_s \to \mu^+\mu^-\right) \ge 3 \cdot 10^{-8}$$

$$1.8 \cdot 10^{-8} \ge Br^{max}\left(B_d \to \mu^+\mu^-\right) \ge 1 \cdot 10^{-9}$$

$$(\Delta M_s)^{exp} > 15/ps$$

⇒

$$Br\left(B_s \to \mu^+\mu^-\right) < 8 \cdot 10^{-7}$$

$$Br\left(B_d \to \mu^+\mu^-\right) < 2 \cdot 10^{-8}$$

$$Br\left(B_s \to \mu^+\mu^-\right)_{exp} < 5 \cdot 10^{-7} \quad \text{(CDF)}$$

$$Br\left(B_d \to \mu^+\mu^-\right)_{exp} < 1.6 \cdot 10^{-7} \quad \text{(BaBar)}$$

Conclusions

1. For $(\Delta M_s)^{exp} \geq (\Delta M_s)^{SM}$ substantial enhancements of $Br(B_{s,d} \to \mu^+\mu^-)$ not possible without new sources of flavour violation (beyond CKM)

2. Observation of $Br(B_s \to \mu^+\mu^-) \geq 10^{-8}$

$$Br(B_d \to \mu^+\mu^-) \geq 10^{-9}$$

will imply either $(\Delta M_s)^{exp} < (\Delta M_s)^{SM}$ and/or new sources of flavour violation (beyond CKM)

3. In order to find out $\dfrac{(\Delta M_s)^{exp}}{(\Delta M_s)^{SM}}$ ⇐ (CDF, DØ) ⇐ F_{B_s}, B_i

News on $B \to \pi\pi$, $B \to \pi K$ and Rare K and B Decays

hep-ph/0312259 hep-ph/0410407
hep-ph/0402112

New Complex Phase in Z^0 Penguins

Enhanced Z^0-Penguins : $$A(\text{Decay}) = \sum_i B_i \, \eta^i_{QCD} \, V^i_{CKM} \left[\underbrace{F^i_{SM}}_{\text{real}} + \underbrace{\Delta^i_{New}} \right]$$

Dominated by Z^0-Penguins with a New Complex Phase

AJB, Colangelo, Isidori, Romanino, Silvestrini
Buchalla, Hiller, Isidori; Atwood, Hiller
AJB, Fleischer, Recksiegel, Schwab

Just replace: $C(x_t) \rightarrow |C(v)| e^{i\varphi_C}$

φ_C = new complex Phase

$$X(x_t) \rightarrow |X(v)| e^{i\theta_X}$$
$$Y(x_t) \rightarrow |Y(v)| e^{i\theta_Y}$$

Basic Structure

BFRS

Basic Scenario : New Physics enters dominantly through EW Penguins including new complex phases

AJB, Colangelo, Isidori, Romanino, Silvestrini (00)
Buchalla, Hiller, Isidori (01)

Simple, Predictive

Step 1. : $B \to \pi\pi$ Decays described within SM
(EW –Penguins small)

→ **Isospin Symmetry**, **$B \to \pi\pi$ Data** → Hadronic Parameters in $B \to \pi\pi$ $(d,\ \theta,\ x,\ \Delta)$ → Sizable Departures from QCDF, PQCD

Step 2. : $d,\ \theta,\ x,\ \Delta$ + $SU(3)_F$ → Hadronic Parameters in $B \to \pi K$ → **$B \to \pi K$ Data** → Enhanced EWP with large New Complex Phase + γ $(65 \pm 7)^\circ$

↕

Step 3. : Correlations between $B \to \pi K$, Rare K and B Decays and other Processes ↔ Implications for Rare K and B Decays sensitive to EWP

The B→πK Puzzle

$$R \equiv \left[\frac{Br(B_d^0 \to \pi^- K^+) + Br(\bar{B}_d^0 \to \pi^+ K^-)}{Br(B^+ \to \pi^+ K^0) + Br(\bar{B}^- \to \pi^- \bar{K}^0)}\right] \frac{\tau(B^+)}{\tau(B_d^0)} = 0.91 \pm 0.07$$

$$R_c \equiv 2\left[\frac{Br(B^+ \to \pi^0 K^+) + Br(B^- \to \pi^0 K^-)}{Br(B^+ \to \pi^+ K^0) + Br(B^- \to \pi^- \bar{K}^0)}\right] = 1.17 \pm 0.12$$

$$R_n \equiv \frac{1}{2}\left[\frac{Br(B_d^0 \to \pi^- K^+) + Br(\bar{B}_d^0 \to \pi^+ K^-)}{Br(B_d^0 \to \pi^0 K^0) + Br(\bar{B}_d^0 \to \pi^0 \bar{K}^0)}\right] = 0.76 \pm 0.10$$

CLEO
Belle
BaBar

Status before ICHEP 04

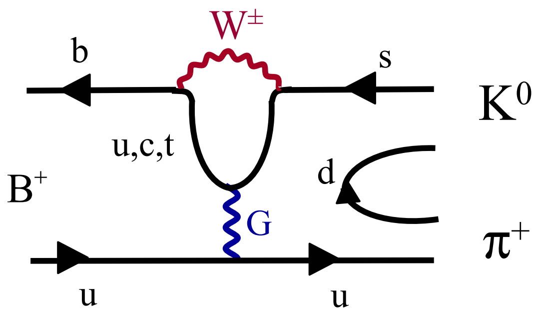
★ Pattern $R_c > 1$ and $R_n < 1$ very puzzling!

seen by all experiments

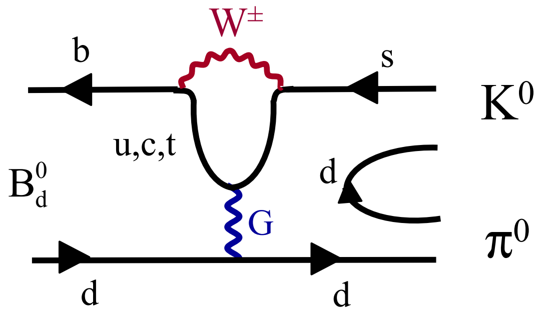
Could it come from enhanced EWP ? AJB + Fleischer (2000)

Recently also: Yoshikawa, Beneke + Neubert, Gronau + Rosner

$B^+ \rightarrow \pi^+ K^0$

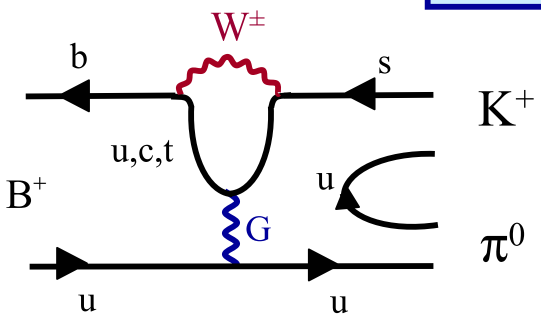


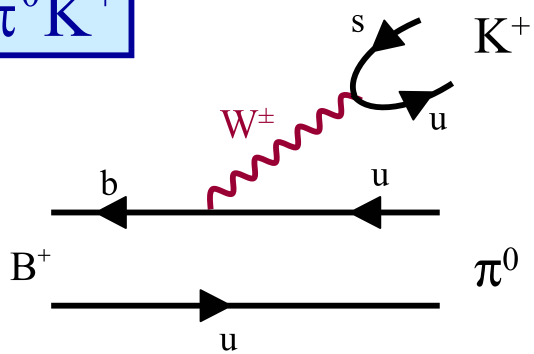
$B_d^0 \rightarrow \pi^0 K^0$



QCD Penguins
at work

$B^+ \rightarrow \pi^0 K^+$

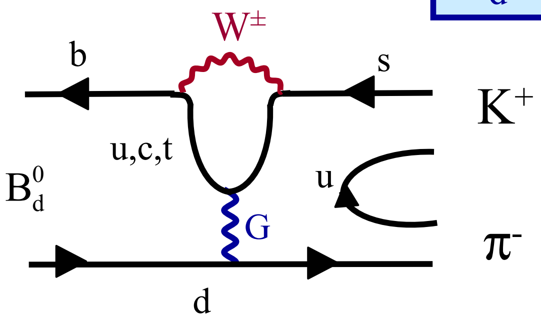


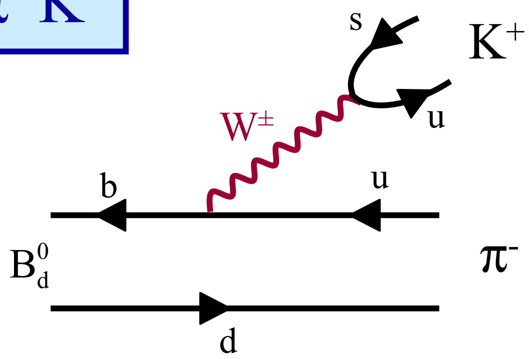


Penguins:	λ^2	(c,t)
(P)	$\lambda^4 e^{i\gamma}$	(u)

Trees: $\lambda^4 e^{i\gamma}$
(T)

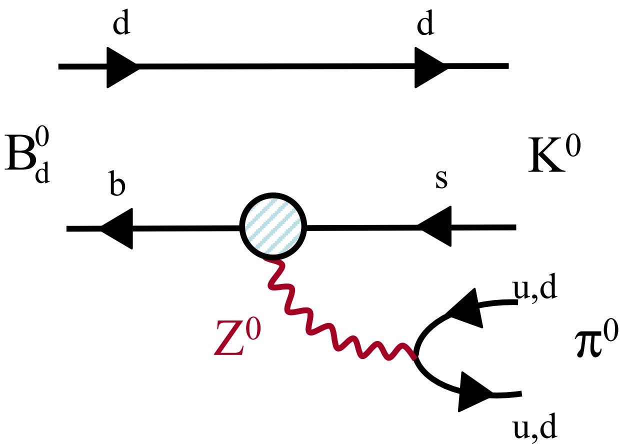
$B_d^0 \rightarrow \pi^- K^+$



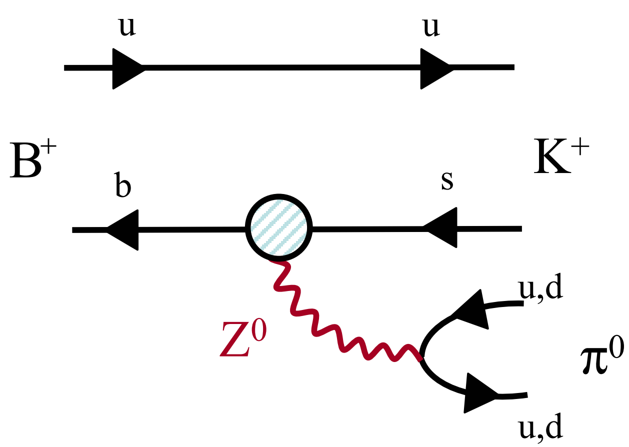


Electroweak Penguins in $B \to \pi K$

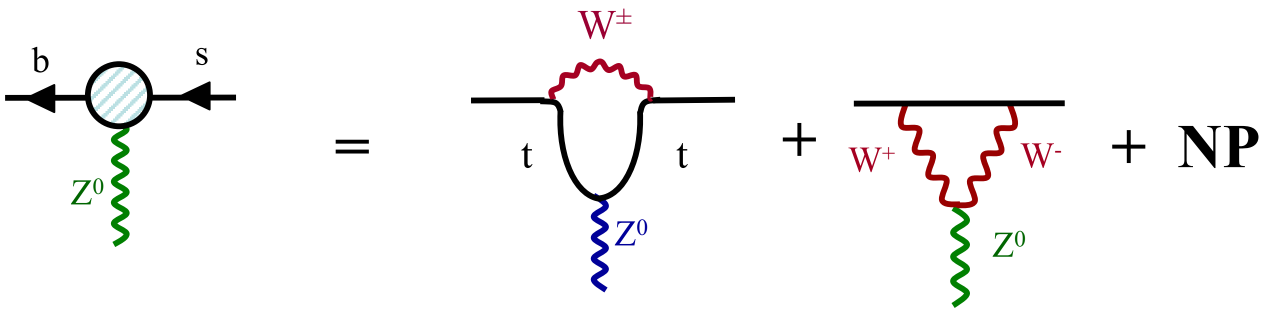
$B_d^0 \to \pi^0 K^0$



$B^+ \to \pi^0 K^+$



$0(\lambda^2)$



EWP's in $B^+ \to \pi^+ K^0$ and $B_d^0 \to \pi^- K^+$ colour suppressed.

$B \to \pi K$ Amplitudes (BFRS 04)

Basic Assumptions : **Neglect colour-suppressed EW penguins**
SU(3) Flavour Symmetry

$$A\left(B_d^0 \to \pi^- K^+\right) = P'\left[1 - r e^{i\delta} e^{i\gamma}\right]$$
$$A\left(B^+ \to \pi^+ K^0\right) = -P' = \text{QCP Penguin}$$

} **colour suppressed EW penguins tiny**

$$\sqrt{2}\ A\left(B_d^0 \to \pi^0 K^0\right) = -P'\left[1 + \rho_n e^{i\theta_n} e^{i\gamma} - r_c e^{i\delta_c} \boxed{q e^{i\varphi}}\right]$$
$$\sqrt{2}\ A\left(B^+ \to \pi^0 K^+\right) = P'\left[1 - \left(e^{i\gamma} - \boxed{q e^{i\varphi}}\right) r_c e^{i\delta_c}\right]$$

} **EW penguins significant**

$r, \delta, \rho_n, \theta_n$
r_c, δ_c
← **SU(3)** $B \to \pi\pi$

Non-Perturbative Parameters

$q e^{i\varphi}$ ← R_n, R_c

EW-Penguin Parameter

$B \to \pi K$ in the SM

SM EWP

$q = 0.69 \qquad \varphi = 0$

Neubert
Rosner (98)

Exp

(BFRS)

$R\big	_{SM} = 0.94 \pm 0.03$	(0.91 ± 0.07)	ok
$R_c\big	_{SM} = 1.14 \pm 0.08$	(1.17 ± 0.12)	ok
$R_n\big	_{SM} = 1.11 \pm 0.07$	(0.76 ± 0.10)	Disagreement!!

Modify EWP: $qe^{i\varphi}$ $\qquad \varphi$ = new ~~CP~~ phase

to fit R_n and R_c

The B →πK Puzzle

(BFRS)

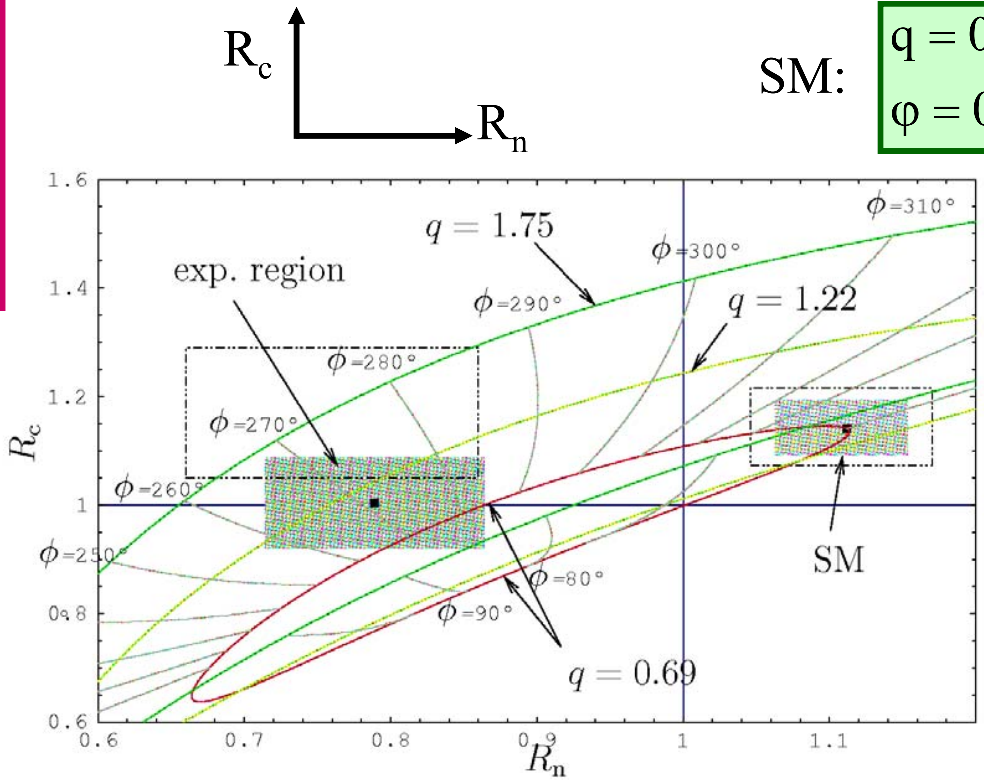
$$R_c = 2\left[\frac{Br(B^\pm \to \pi^0 K^\pm)}{Br(B^\pm \to \pi^\pm K^0)}\right]$$

$$R_n = \frac{1}{2}\left[\frac{Br(B^0 \to \pi^- K^+)}{Br(B^0 \to \pi^0 K^0)}\right]$$

$$(R_c)_{SM} = 1.14 \pm 0.05$$
$$(R_n)_{SM} = 1.11 \pm 0.05$$

$EWP = qe^{i\varphi}$

SM: $q = 0.69$, $\varphi = 0$ — Neubert Rosner



Best Values (including rare decay constraint)

$q \approx 0.92$, $\varphi \approx -85^o$ — BFRS

$$R_c = 1.17 \pm 0.12$$
$$R_n = 0.76 \pm 0.10$$

Exp: before ICHEP 04

Rare Decays →

$$R_c = 1.00\,{}^{+0.12}_{-0.08}$$
$$R_n = 0.82\,{}^{+0.12}_{-0.11}$$

BFRS Expectation of June 04

$$R_c = 1.00 \pm 0.08$$
$$R_n = 0.79 \pm 0.08$$

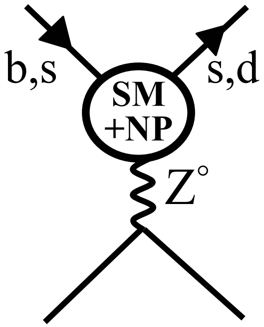
Exp: after ICHEP 04

CLEO
BaBar
Belle

Relation: $B \to \pi K$ ⟺ Rare K and B Decays

BFRS

Fundamental
Short Distance
Physics of EWP
$\mu = 0(m_t)$:



$$\sim X\big(\underbrace{m_t, \tilde{m}, \text{ new phases}}_{v}\big) \qquad \nu\bar{\nu}$$

$$\sim Y\left(m_t, \tilde{m}, \text{ new phases}\right) \qquad \mu\bar{\mu}$$

RG

$B \to \pi K$
(q, φ)
$\mu = 0(m_b)$

⟺

$K \to \pi\nu\bar{\nu},\ B \to X_S\mu^+\mu^-$
$K_L \to \pi^0\mu^+\mu^-,\ B_{d,s} \to \mu^+\mu^-$
$B \to X_{d,s}\nu\bar{\nu}$

Renormalization group :

$$\left|X(v)\right| e^{i\theta_X} = 2.35\ q e^{i\varphi} - 0.09 \approx 2.2 \cdot e^{-i86^o}$$

$$\left|Y(v)\right| e^{i\theta_Y} = 2.35\ q e^{i\varphi} - 0.64 \approx 2.2 \cdot e^{-i100^o}$$

$X_{SM} = 1.53$
$Y_{SM} = 0.98$

Implications for $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^o \nu\bar{\nu}$

$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right)_{SM} = (7.8 \pm 1.2) \cdot 10^{-11}$ ⇒ $(7.5 \pm 2.1) \cdot 10^{-11}$ ⇐ Enhancement of |X| compensated by destructive "top-charm" interference

★ $Br\left(K_L \to \pi^o \nu\bar{\nu}\right)_{SM} = (3.0 \pm 0.6) \cdot 10^{-11}$ ⇒ $(3.1 \pm 1.0) \cdot 10^{-10}$

★ Strong Violation of the "Golden" Relation :

Buchalla, AJB (94)

SM: $(\sin 2\beta)_{\pi\nu\bar{\nu}} = (\sin 2\beta)_{\psi K_S}$

Here: $-\left(0.69\,^{+0.23}_{-0.41}\right) \neq 0.74 \pm 0.05$

$\sin 2\beta_X$

$\beta_X = \beta - \theta_X$

$X = |X| e^{i\theta_X}$

$\beta_X \cong 110^o$

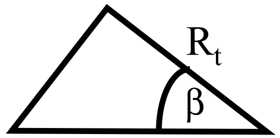
★ Saturation of the model-independent Grossman-Nir bound :

FIG

$$Br\left(K_L \to \pi^o \nu\bar{\nu}\right) \leq 4.4 \; Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right)$$

Here:
$$\frac{Br\left(K_L \to \pi^o \nu\bar{\nu}\right)}{Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right)} \approx 4.4 \; \sin^2(\beta_X) \approx 4.2 \pm 0.2$$

Impact of $X = |X| e^{i\theta_X}$ on $K^+ \to \pi^+ \nu\bar{\nu}$



$(A \approx 0.83)$

$(P_c \approx 0.39)$

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) = 4.8 \cdot 10^{-11} \Big[A^4 R_t^2 |X|^2 + 2 P_c A^2 R_t |X| \cos(\underbrace{\beta - \theta_X}_{\beta_X}) + P_c^2 \Big]$$

SM: $= 10^{-11} [4.1 + 3.0 + 0.7]$ $\quad X = 1.53$

Here: $= 10^{-11} [8.5 - 1.7 + 0.7]$ $\quad X = 2.2 e^{-i86^o}$

(top) (charm-top) (charm) $\quad \beta\text{-}\theta_X \approx 110^o$

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) = (7.8 \pm 1.2) \cdot 10^{-11} \Rightarrow (7.5 \pm 2.1) \cdot 10^{-11}$$

(SM)

Impact of $X = |X| e^{i\theta_X}$ on $K_L \to \pi^o \nu\bar{\nu}$

$$\frac{Br\left(K_L \to \pi^o \nu\bar{\nu}\right)}{Br\left(K_L \to \pi^o \nu\bar{\nu}\right)_{SM}} = \underbrace{\left|\frac{X}{X_{SM}}\right|^2}_{\approx 2} \underbrace{\left[\frac{\sin\left(\beta - \theta_X\right)}{\sin\beta}\right]^2}_{\approx 5}$$

$\beta\text{-}\theta_X \approx 110^o$

$\beta \cong 24^o$

$$Br\left(K_L \to \pi^o \nu\bar{\nu}\right) = \left(3.0 \pm 0.6\right) \cdot 10^{-11} \Rightarrow \left(3.1 \pm 1.0\right) \cdot 10^{-10}$$

(SM) (Here)

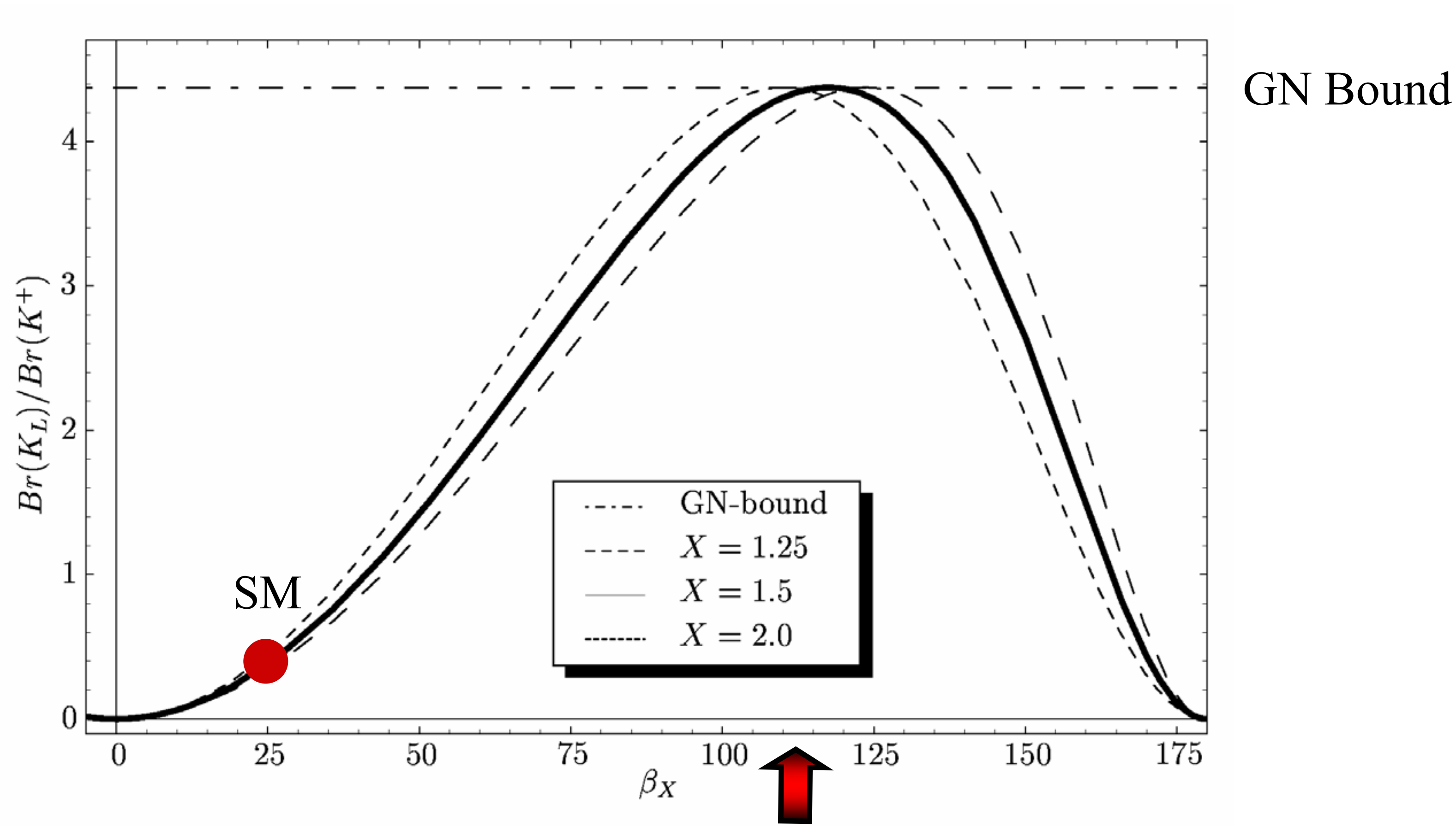
$$\frac{Br\left(K_L \to \pi^o \nu\bar{\nu}\right)}{Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right)} = \underset{(SM)}{0.4} \Rightarrow 4.2$$

< 4.4 Grossman-Nir bound

Order of magnitude enhancement !!

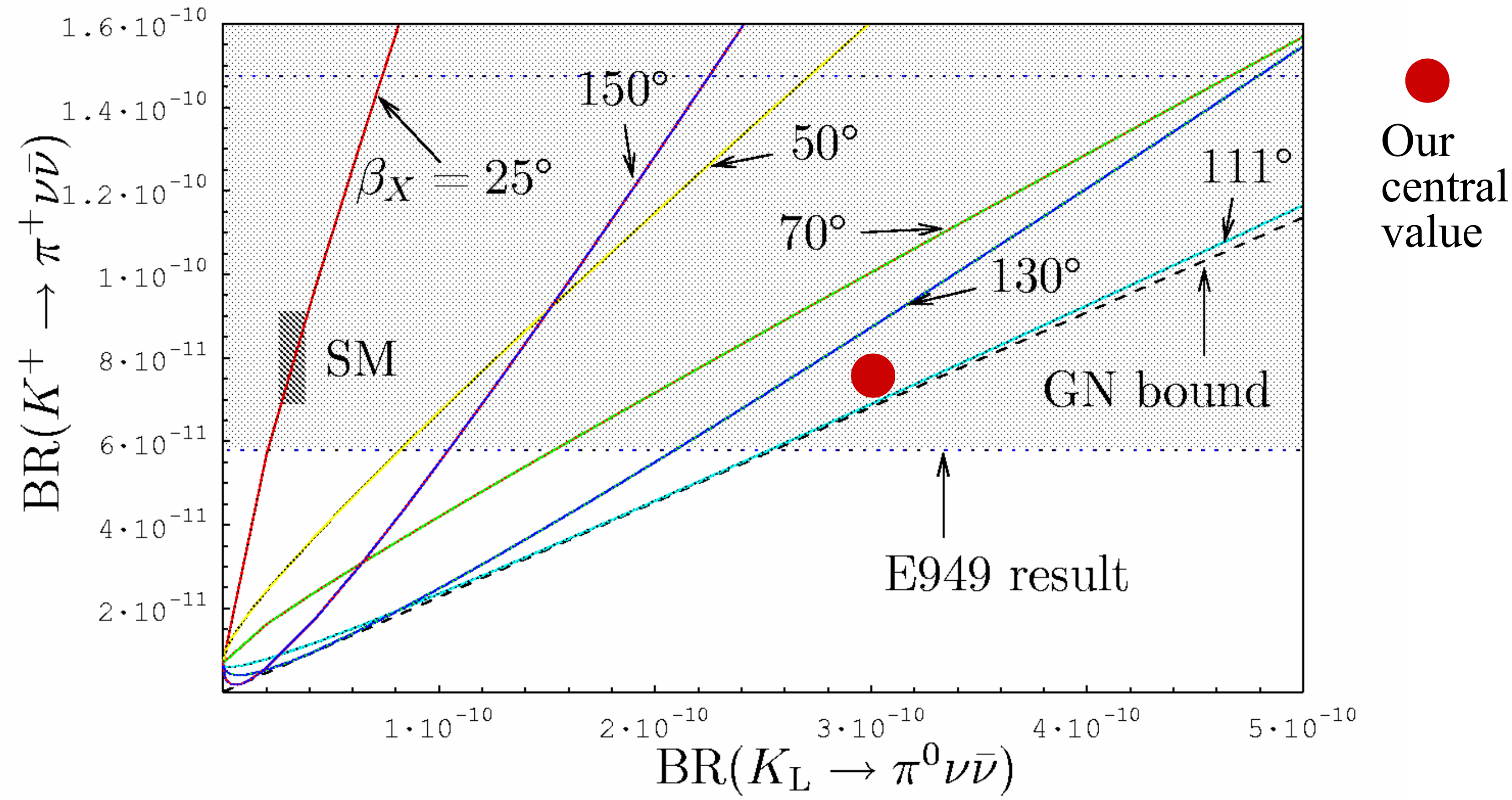
$$\frac{Br\left(K_L \to \pi^0\nu\bar{\nu}\right)}{Br\left(K^+ \to \pi^+\nu\bar{\nu}\right)} \text{ versus } \beta_X$$

BSU (04)



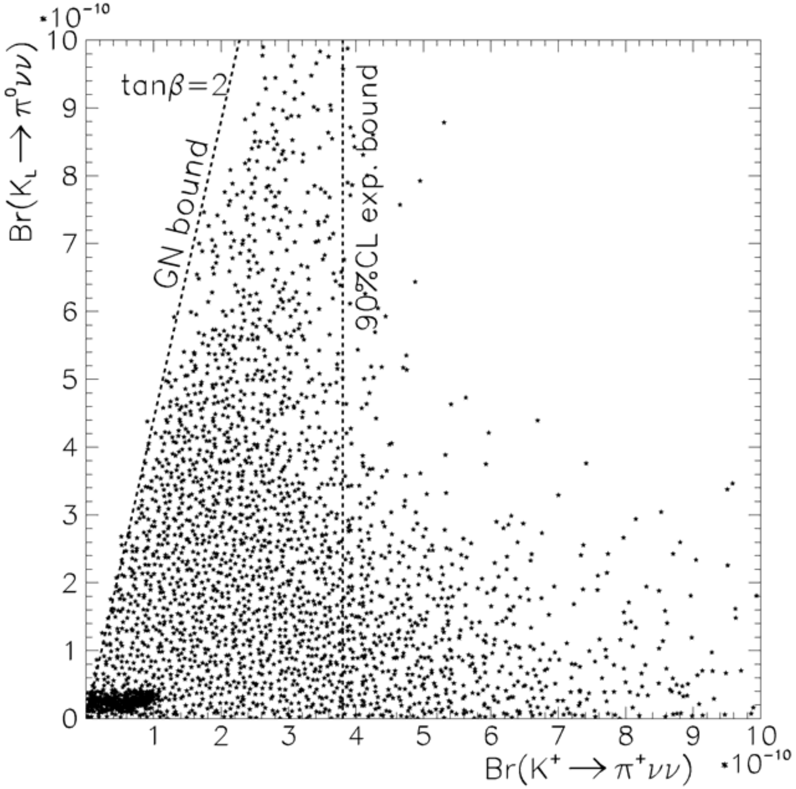
$K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ with $X = |X| e^{i\theta_x}$ (BFRS)

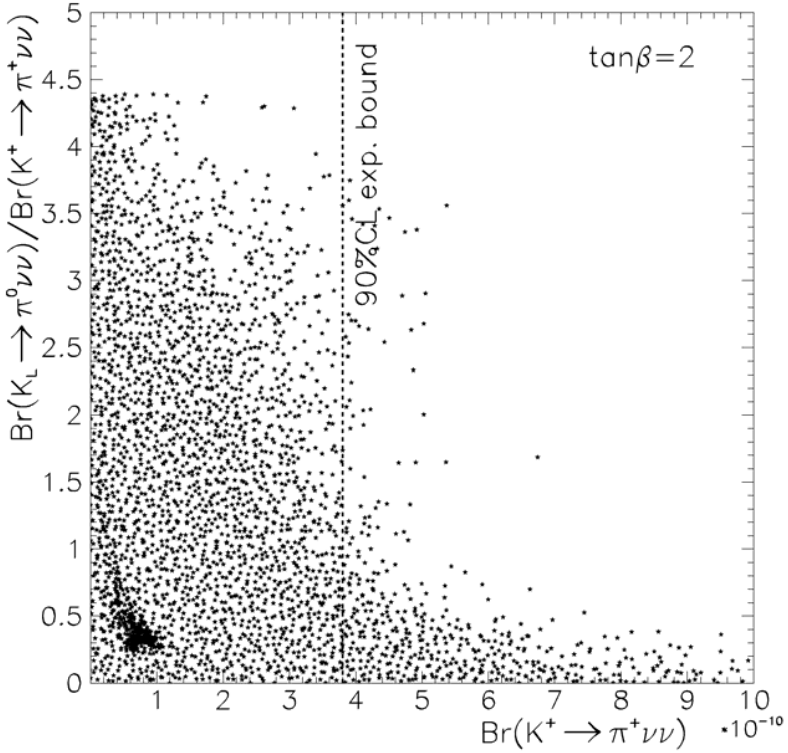
$$\beta_x = \beta - \theta_x$$



$K_L \rightarrow \pi^0 \nu\bar{\nu}$ and $K^+ \rightarrow \pi^0 \nu\bar{\nu}$ from a general MSSM

AJB, Ewerth, Jäger, Rosiek (04)





Other Impacts on Rare K and B Decays

Could it be seen
by Belle, BaBar ?

Could it be seen
at Tevatron ?
Will be seen at LHC!

$$\frac{Br\left(B \to X_{s,d}\nu\bar{\nu}\right)}{Br\left(B \to X_{s,d}\nu\bar{\nu}\right)_{SM}} \approx 2.0$$

$$\frac{Br\left(B_{s,d} \to \mu^+\mu^-\right)}{Br\left(B_{s,d} \to \mu^+\mu^-\right)_{SM}} \approx 2.5$$

$$Br\left(B \to X_s\nu\bar{\nu}\right) \approx 7\cdot 10^{-5}$$

$$Br\left(B_s \to \mu^+\mu^-\right) \approx 1\cdot 10^{-8}$$

$$Br\left(B_d \to \mu^+\mu^-\right) \approx 3\cdot 10^{-10}$$

Spectacular Effects in
FB CP Asymmetry in
$B_d \to K^*\mu^+\mu^-$

Lepton polarization
asymmetries in $b \to s l^+ l^-$
(Choudhury, Gaur, Cornell (04))

BUT: $(\sin 2\beta)_{\varphi K_S} > (\sin 2\beta)_{\psi K_S} \approx 0.73$

Consistent with BaBar (0.50±0.25±0.06)
but

0.06±0.33±0.09 (Belle)

Z'-models can explain both πK and Belle (Barger et al, 0406126)
but no relation to $K \to \pi\nu\bar{\nu}$, $B \to \mu\mu$

Impact on $K_L \to \pi^o e^+ e^-$ and $K_L \to \pi^o \mu^+ \mu^-$

$$\mathrm{Br}\left(K_L \to \pi^o e^+ e^-\right)_{SM} = \left(3.7 \begin{smallmatrix}+1.1\\-0.9\end{smallmatrix}\right) \cdot 10^{-11}$$

Dominated by <u>indirect</u> $\not{C}\not{P}$
(Buchalla, D'Ambrosio, Isidori)
(Friot, Greynat, de Rafael)

⇒

$$\left(9.0 \pm 1.6\right) \cdot 10^{-11}$$

Dominated by <u>direct</u> $\not{C}\not{P}$
BFRS

Isidori
Smith
Unterdorfer

$$\mathrm{Br}\left(K_L \to \pi^o \mu^+ \mu^-\right) = \left(1.5 \pm 0.3\right) \cdot 10^{-11}$$

Dominated by CP-conserving
+ indirect $\not{C}\not{P}$

⇒

$$\left(4.3 \pm 0.7\right) \cdot 10^{-11}$$

Dominated by <u>direct</u> $\not{C}\not{P}$
ISU

KTeV:

$$\mathrm{Br}\left(K_L \to \pi^o e^+ e^-\right) < 2.8 \cdot 10^{-10}$$

$$\mathrm{Br}\left(K_L \to \pi^o \mu^+ \mu^-\right) < 3.8 \cdot 10^{-10}$$

Six messages

1. $B \to \pi\pi$ data described within SM with hadronic parameters differing significantly from QCDF and PQCD

2. $B \to \pi K$ data give a hint for enhanced EWP with new Large <u>negative</u> CP phase.

3. The angle γ found in agreement with UT fits.

4. $\frac{Br(K^+ \to \pi^+ \nu\bar{\nu})}{Br(K^+ \to \pi\nu\bar{\nu})_{SM}} \approx 1$ $\frac{Br(K_L \to \pi^0 \nu\bar{\nu})}{Br(K^+ \to \pi^0 \nu\bar{\nu})_{SM}} \approx 10$ $\frac{Br(B_{s,d} \to \mu^+\mu^-)}{Br(B_{s,d} \to \mu^+\mu^-)_{SM}} \approx 2.5$

5. $(\sin 2\beta)_{\varphi K_S} \geq (\sin 2\beta)_{\psi K_S}$ in disagreement with Belle but consistent with BaBar

6. General MSSM can be made consistent with this pattern (AJB, Ewerth, Jäger, Rosiek)

9.

Probing New Physics in 10 Steps

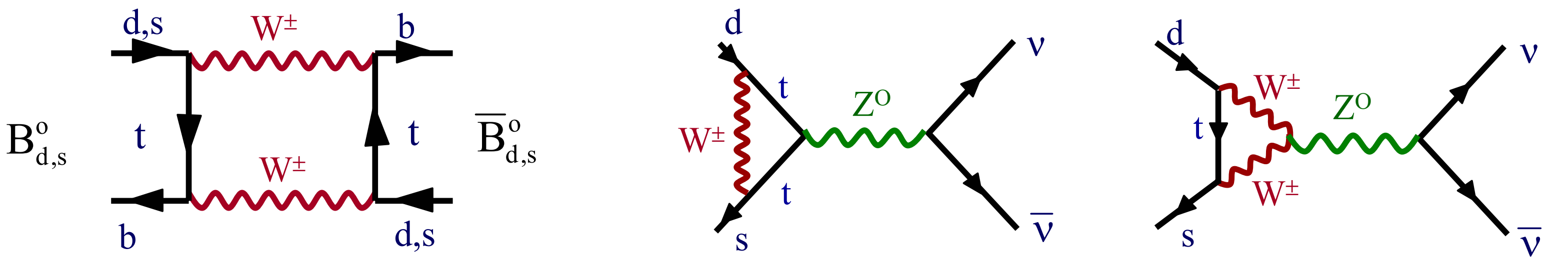
Starting Point :

$$\mathcal{L} = \mathcal{L}_{SM}\left(g_i, m_i, V^i_{CKM}\right) + \mathcal{L}_{NP}\left(g_i^{NP}, m_i^{NP}, V^i_{NP}\right)$$

Goal :

Identify the effects of $\mathcal{L}_{NP}$ in weak decays in the presence of the background from $\mathcal{L}_{SM}$

First Implication from $\mathcal{L}$: Feynman Diagrams



$B^o_d - \bar{B}^o_d$ Mixing

$K^+ \to \pi^+ \nu\bar{\nu}, \; K_L \to \pi^0 \nu\bar{\nu}$

+ NP

Master Formula for Weak Decays

AJB (2001)
hep-ph/0101336
hep-ph/0109197

Non-Perturbative Factors in the SM

QCD RG Factors

Short Distance Loop Functions (Penguins, Boxes)

New Flavour-Changing Parameters

Represent different Dirac and Colour Stuctures

$$A(\text{Decay}) = B_i \ \eta^i_{QCD} \ V^i_{CKM} \left[F^i_{SM} + F^i_{New} \right] + B^{New}_i \left[\eta^i_{QCD} \right]^{New} V^i_{New} \left[G^i_{New} \right]$$

(Summation over i)

New ≡ NP

Non-Perturbative Factors beyond SM

Short Distance Loop Functions Penguins, Boxes

F^i_{SM}, F^i_{New}, G^i_{New} : **Fully calculable in Perturbation Theory**

η^i_{QCD}, $\left[\eta^i_{QCD}\right]^{New}$: **Fully calculable in RG improved Perturbation Theory**

B_i, B^{New}_i : **Require Non-Perturbative Methods or can be extracted from leading decays**

(represent $\langle Q_i \rangle$)

Fully calculable in the SM

Three Simple Scenarios

Inami Lim Functions

SM :

$$A(\text{Decay}) = \sum_i B_i\, \eta^i_{QCD}\, V^i_{CKM} \underbrace{F^i_{SM}}_{\text{real}}(m_t)$$

MFV :

(Minimal Flavour Violation)

$$A(\text{Decay}) = \sum_i B_i\, \eta^i_{QCD}\, V^i_{CKM} \underbrace{\left[F^i_{SM} + F^i_{New}\right]}_{\text{real}}$$

AJB, Gambino, Gorbahn, Jäger, Silvestrini
D'Ambrosio, Giudice, Isidori, Strumia

Enhanced Z^0-Penguins :

$$A(\text{Decay}) = \sum_i B_i\, \eta^i_{QCD}\, V^i_{CKM} \left[\underbrace{F^i_{SM}}_{\text{real}} + \underbrace{\Delta^i_{New}}\right]$$

Dominated by Z^0-Penguins with a New Complex Phase

AJB, Colangelo, Isidori, Romanino, Silvestrini
Buchalla, Hiller, Isidori; Atwood, Hiller
AJB, Fleischer, Recksiegel, Schwab

Two more complicated Scenarios

MSSM (MFV)
(large tanβ)

(Higgs penguin)

$$A(\text{Decay}) = \sum_i B_i\, \eta^i_{QCD}\; V^i_{CKM} \left[F^i_{SM} + \underbrace{}_{} \overbrace{F^i_{New}}^{\text{real}} \right] + \sum_i B^{New}_i \left[\eta^i_{QCD}\right]^{New} V^i_{CKM} \underbrace{\left[G^i_{New}\right]}_{\text{real}}$$

General
MSSM

Z'-Models
L-R Models
Multi-Higgs
Models

$$A(\text{Decay}) = \sum_i B_i\, \eta^i_{QCD}\; V^i_{CKM} \left[F^i_{SM} + \overbrace{F^i_{New}}^{\text{complex}} \right] + \sum_i B^{New}_i \left[\eta^i_{QCD}\right]^{New} V^i_{New} \underbrace{\left[G^i_{New}\right]}_{\text{complex}}$$

Step 1 :

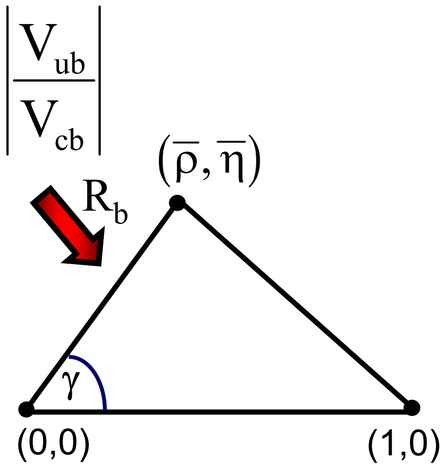
Determine $|V_{us}|, |V_{cb}|, |V_{ub}|, \gamma$
by means of tree level decays insensitive to NP
(requires TH at a certain level)

$$\left\{\begin{matrix}\text{Semi-leptonic} \\ \text{K, B decays}\end{matrix}\right\} \Rightarrow \left\{ |V_{us}|, |V_{cb}|, |V_{ub}| \right\}$$

$$\left\{ B^{\pm} \to D^{0} K^{\pm} \right\} \Rightarrow \left\{ \gamma \right\}$$ (Gronau-London-Wyler)

$$\left\{\begin{matrix} B_d^0 \to D^+\pi^-(2\beta+\gamma) \\ B_d^0 \to \psi K_s(2\beta) \end{matrix}\right\} \Rightarrow \left\{ \gamma \right\}$$ (Dunietz, Sachs)

$$\left\{\begin{matrix} B_s^0 \to D^+K^-(2\beta_s+\gamma) \\ B_s^0 \to \psi\varphi(2\beta_s) \end{matrix}\right\} \Rightarrow \left\{ \gamma \right\}$$ (Aleksan, Dunietz, Sachs)



Reference Unitarity Triangle

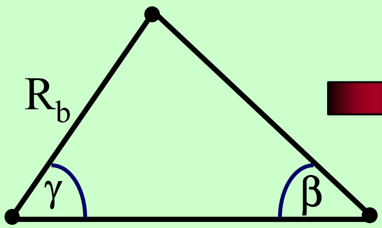
Goto, Kitazawa, Okada, Tanaka
Cohen et al.
Grossman et al.
Ciuchini et al.

<u>Generalizations</u>: Fleischer, Wyler, Gronau, Atwood, Soni, ...

Comment to Step 1

Having γ from tree-level decays allows the first test of SM and NP

Up to discrete ambiguities



Reference UT

→ $\{\beta_{true}\}$

⇔

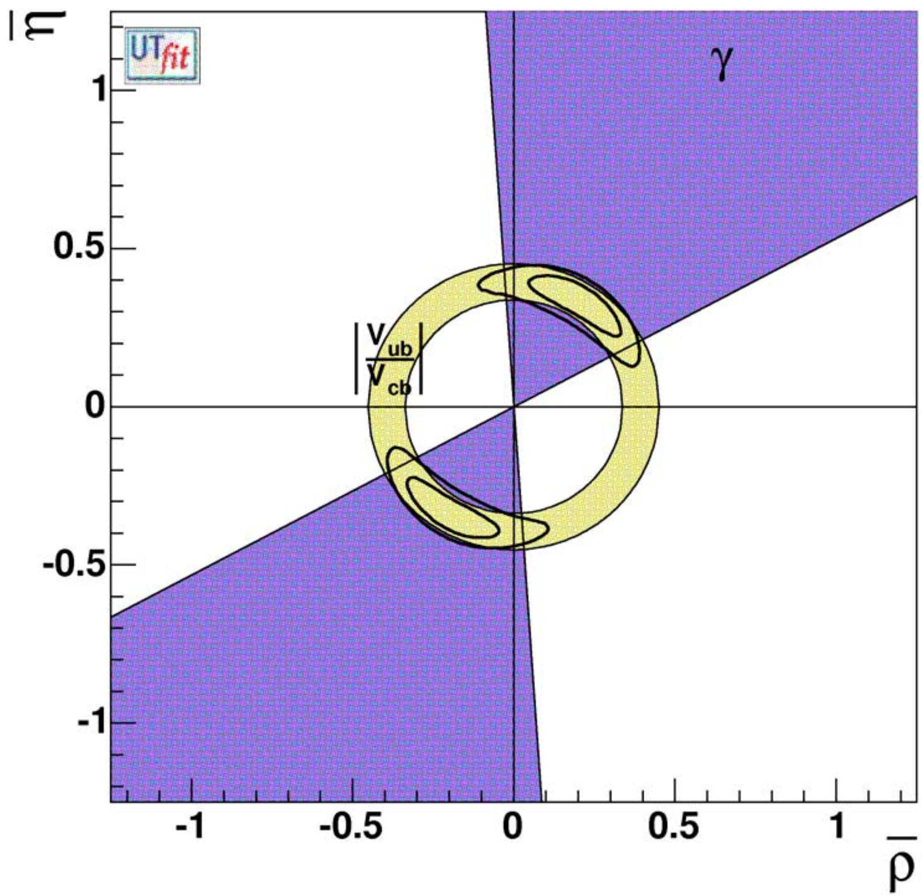
$\beta_{\psi K_s}$ from $A_{CP}^{mix}\left(B_d^0 \to \psi K_s\right)$

$\beta_{\psi K_s} = \beta_{true} + \theta_{NP}$

New Phase in $B_d^0 - \overline{B}_d^0$ mixing

→ $\{$Possible signal of a new phase $\theta_{NP} \neq 0\}$ → $\{$Implications for other A_{CP}^{mix} asymmetries$\}$

First Steps towards RUT



Obtained using only tree-level processes:

$\left|\frac{V_{ub}}{V_{cb}}\right|$ and γ from $B \to D^{(*)}K^{(*)}$

Utfit collaboration: M. Bona et al. hep-ph/0501199.

Step 2

Determine experimentally matrix elements of weak currents in tree-level decays

marginal impact of NP

Ideally:

Calculate these matrix elements by Non-Perturbative Methods

No impact of NP

$$\Rightarrow \quad F_\pi,\ F_K,\ F_{B_d},\ F_{B_s},\ \langle \pi^+ | (\bar{s}d)_{V-A} | K^+ \rangle,\ \langle \pi^0 | (\bar{s}d)_{V-A} | K_L^0 \rangle$$

- F_π, F_K: known very well
- F_{B_d}, F_{B_s}: $\pm$ 15% Lattice, QCDS
- matrix elements: $K^+ \to \pi^0 e^+ \nu_e$ + Isospin Breaking Corrections (Marciano, Parsa) $\pm$ 2-3%

Step 3

use input from Steps 1 and 2

Calculate $Br(K^+ \to \pi^+ \nu\bar{\nu})$, $Br(K_L \to \pi^0 \nu\bar{\nu})$

$Br(B_s \to \mu^+\mu^-)$, $Br(B_d \to \mu^+\mu^-)$

$Br(B \to X_s \nu\bar{\nu})$, $Br(B \to X_d \nu\bar{\nu})$

in the Standard Model

Comparison with experiment will hopefully give hints for NP in a clean TH environment. ★

or

use input from Step 2 to determine

$|V_{td}|$, $|V_{ts}|$

β, γ, $\triangle$

$$\left\{ Br(B_{s,d} \to \mu^+\mu^-) \propto F^2_{B_{d,s}} \right\} \Rightarrow \left\{ \text{Need precise values of } F^2_{B_{d,s}} \right\}$$

Express Review of $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$

AJB
Schwab
Uhlig
hep-ph/0405132

NLO: Buchalla + AJB (94); NNLO: AJB, Gorbahn, Haisch, Nierste (05)

SM: $Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = (7.8 \pm 1.2) \cdot 10^{-11}$ $\quad Br\left(K_L \to \pi^0 \nu\bar{\nu}\right) = (3.0 \pm 0.6) \cdot 10^{-11}$

Exp: $Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(14.7 \begin{smallmatrix} +13.0 \\ -8.9 \end{smallmatrix}\right) \cdot 10^{-11}$ $\quad Br\left(K_L \to \pi^0 \nu\bar{\nu}\right) < 5.9 \cdot 10^{-7}$ (KTeV)

Brookhaven: E787, E949
(CKM, NA48, JPARC, ..)

Soon improved by E391a !!!
(KOPIO, J-PARC, ...)

TH very clean : (With improved CKM parameters ~ 2008) ⇒

$$\sigma\left(Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right)\right) < 5\%$$

$$\sigma\left(Br\left(K_L \to \pi^0 \nu\bar{\nu}\right)\right) < 5\%$$

Very clean determination of Unitarity Triangle

$\sigma(Br) \cong 10\%$	$\sigma(\sin 2\beta \cong 0.04)$	$\sigma(\gamma) = 9^o$	$\sigma(\lvert V_{td} \rvert) = 7\%$
$\sigma(Br) \cong 5\%$	$\sigma(\sin 2\beta \cong 0.025)$	$\sigma(\gamma) = 5^o$	$\sigma(\lvert V_{td} \rvert) = 4\%$

Unitarity Triangle 2004

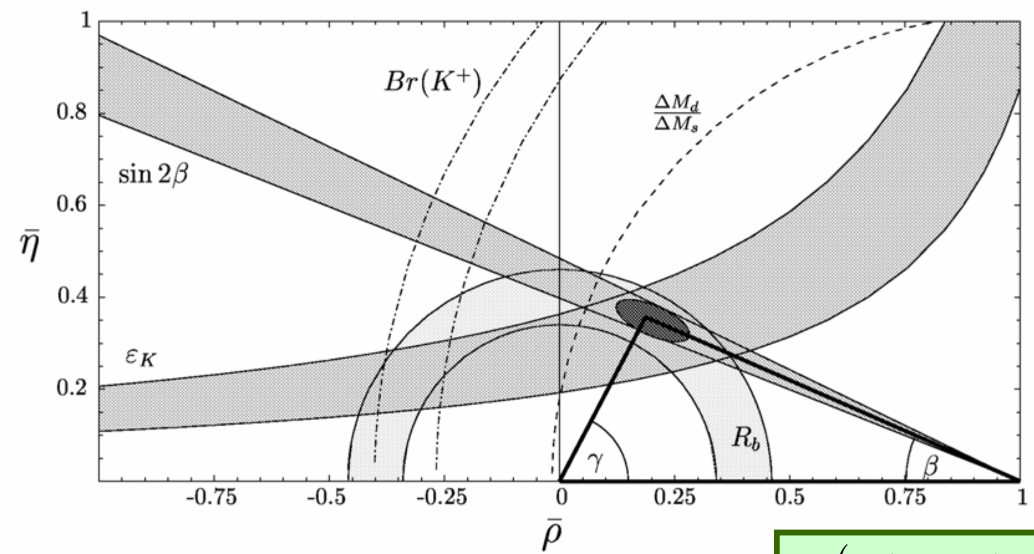
(AJB, Schwab, Uhlig)

$$Br\left(K^+\right) \equiv Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = 14.7 \cdot 10^{-11}$$

$$P_c = \underline{\underline{0.39}} \pm 0.07$$

↑

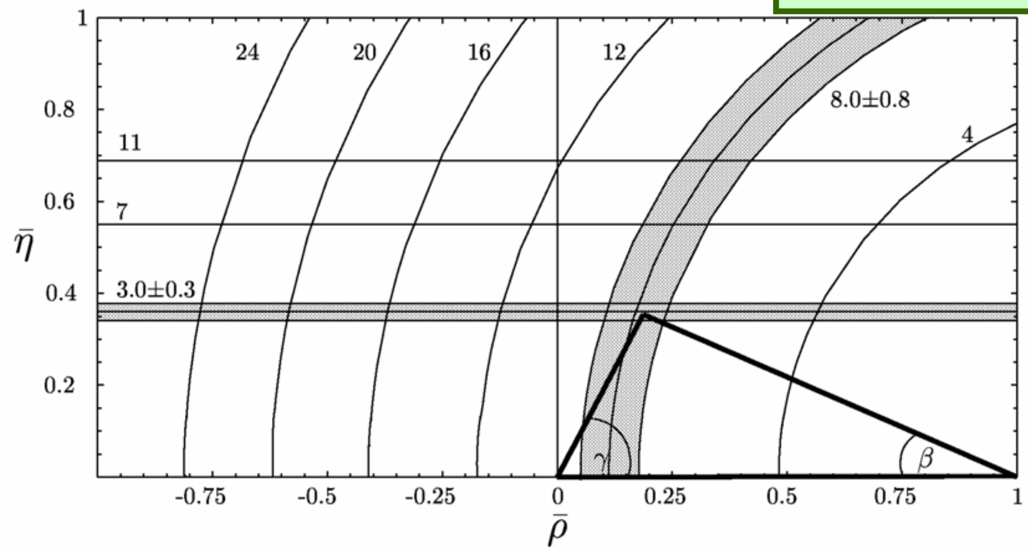
$m_c,\ V_{cb},\ \mu_c$



$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right)$

Unitarity Triangle from $K \to \pi\nu\bar{\nu}$

(2012)



$Br\left(K_L \to \pi^0 \nu\bar{\nu}\right)$

Possible Enhancements

1. MFV : $Br(K^+ \to \pi^+ \nu\bar{\nu})$, $Br(K_L \to \pi^0 \nu\bar{\nu})$, $Br(B \to X_s \nu\bar{\nu})$, $Br(B \to X_d \nu\bar{\nu})$

by at most a factor of 1.5 relative to SM (MFV fit)

$Br(B_s \to \mu^+\mu^-)$, $Br(B_d \to \mu^+\mu^-)$ up to a factor of 2

2. $Br(K_L \to \pi^0 \nu\bar{\nu})$ can be enhanced by 10 in models with enhanced EW penguins with a large complex phase.

$3 \cdot 10^{-10}$

(Hints from $B \to \pi K$) (AJB, Fleischer, Recksiegel, Schwab)

(AJB, Ewerth, Jäger, Rosiek) general MSSM

3. $Br(B_{s,d} \to \mu^+\mu^-)$ can be enhanced by 100 in MSSM with large $\tan\beta \approx 40$ (Higgs penguins)

As high as present experimental bounds

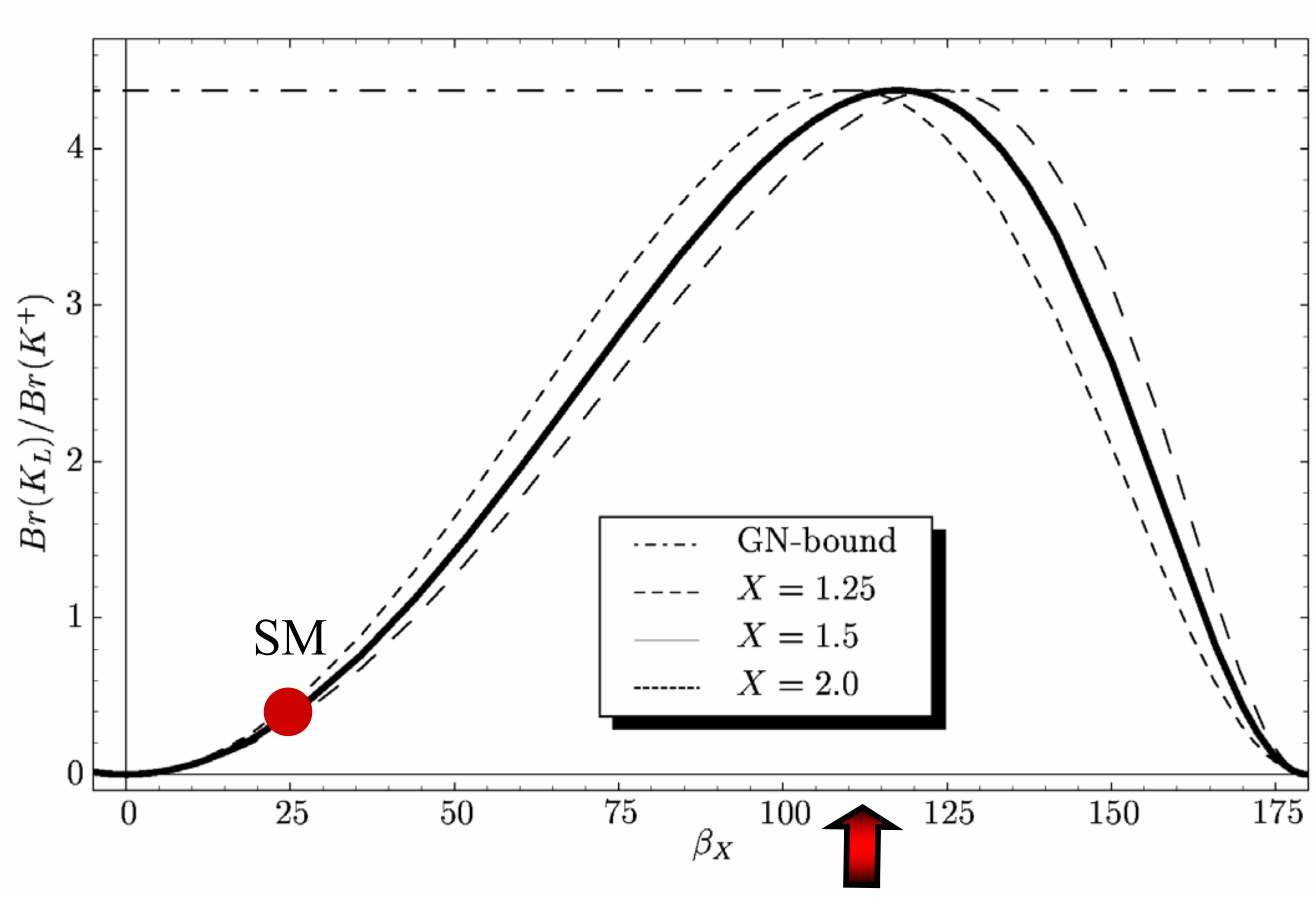
$\sim 10^{-7}$ (10^{-8})

Babu, Kolda
Chankowski, Slawianowska
Bobeth, Ewerth, Krüger, Urban
Huang, Liao, Yan, Zhu
Isidori, Retico
Dedes, Dreiner, Nierste
Dedes, Pilaftis
Chankowski, Rosiek

$$\frac{Br\left(K_L \to \pi^0 \nu\bar{\nu}\right)}{Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right)} \text{ versus } \beta_X$$

BSU (04)

$\beta_x = \beta - \theta_X$ ← New Phase in EWP

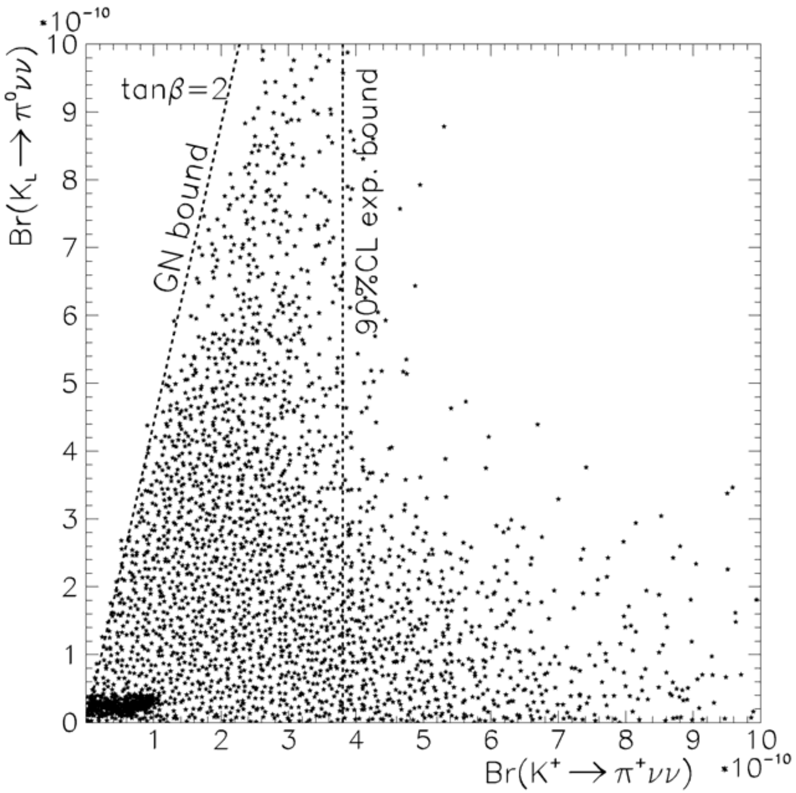


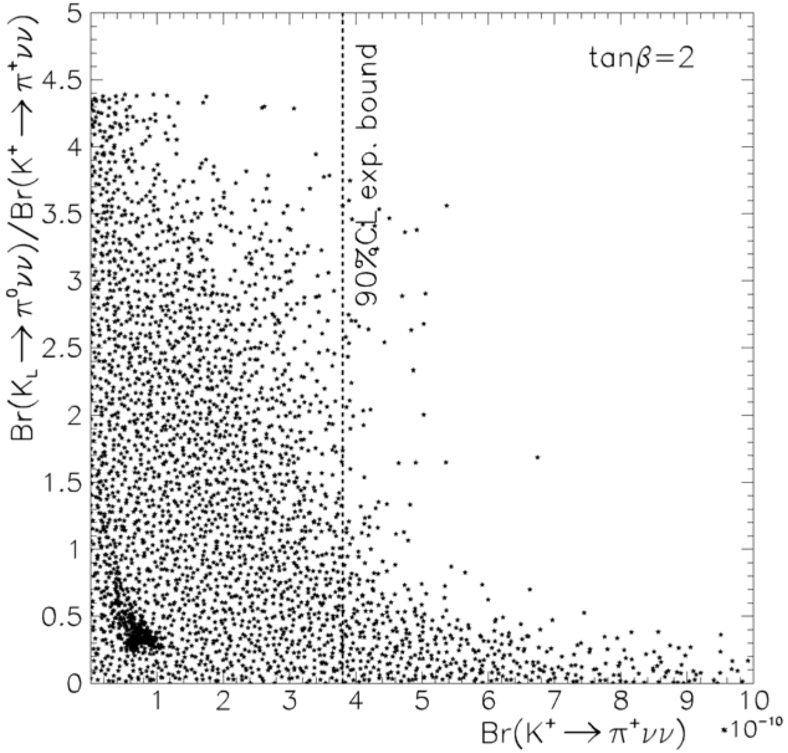
$\theta_X \approx -90^o$

Necessary to fit B→πK data (BFRS)

$K_L \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^0 \nu\bar{\nu}$ from a general MSSM

AJB, Ewerth, Jäger, Rosiek (04)



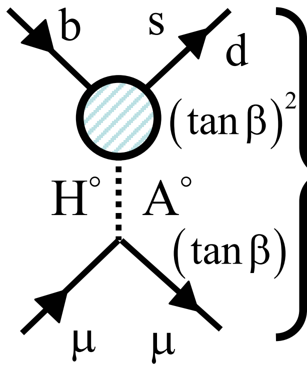


MSSM at large tanβ

$\left(B_{s,d} \to \mu^+\mu^-\right)$

In MSSM at large tanβ
(CKM still the only source of Flavour and CP Violation)

Strong Enhancement



$$\begin{cases} Br\left(B_{s,d} \to \mu\bar{\mu}\right) \sim \left(\tan\beta\right)^6 \\ 10^{-6}\left(10^{-7}\right) \text{ possible} \\ SM \sim 10^{-9} \end{cases}$$

Babu, Kolda
Chankowski, Slawianowska
Bobeth, Ewerth, Krüger, Urban
Huang, Liao, Yan, Zhu
Isidori, Retico
Dedes, Dreiner, Nierste
Dedes, Pilaftis
Chankowski, Rosiek
Foster, Okumura, Roszkowski

$$Br\left(B_s \to \mu\bar{\mu}\right) < \begin{matrix} 5.0\cdot 10^{-7}\,(D\varnothing) \\ 7.5\cdot 10^{-7}\,(CDF) \end{matrix}$$ 95% C.L.

$$Br\left(B_d \to \mu\bar{\mu}\right) < \begin{matrix} 1.9\cdot 10^{-7}\,(CDF) \\ 8.3\cdot 10^{-8}\,(BaBar) \end{matrix}$$ 95% C.L. / 90% C.L.

Step 4

Calculate $\hat{B}_K$, $\hat{B}_{B_d}$, $\hat{B}_{B_s}$
using Lattice or other methods

(no chiral logs present)

Steps 2+ 4 → $\hat{B}_K F_K$ → ε_K; $\hat{B}_{B_d} F_{B_d}$ → ΔM_d; $\hat{B}_{B_s} F_{B_d}$ → ΔM_s

SM Box Diagrams → ε_K, ΔM_d, ΔM_s

UT to be compared with RUT

+ Possible signals of NP in
$\Delta S = 2$, $\Delta B = 2$ Transitions

Possible Effects in ΔM_s

1. MFV : Enhancement by at most 1.4

2. General MSSM and Models with new FCNC sources 2-3

3. MSSM (CKM) with large $\tan\beta$ 0.8
Suppression of ΔM_s correlated with enhancement of $Br(B_{s,d} \to \mu^+\mu^-)$
(AJB, Chankowski, Rosiek, Slawianowska)

4. In a General MSSM this correlation can be avoided.
(Dedes, Pilaftis; Chankowski, Rosiek; Isidori, Retico)

Step 5

CP Asymmetries in $B \to X_{s,d}\gamma$

Calculate $Br(B \to X_{s,d}\gamma)$, $Br(B \to X_{s,d} l^+ l^-)$

$Br(K_L \to \pi^0 \mu^+ \mu^-)$, $Br(K_L \to \pi^0 e^+ e^-)$

and related CP Asymmetries,

FB asymmetries, etc. $K_L \to \mu^+ \mu^-$

$Br(B \to (K^*, \rho)\gamma)$, $Br(B \to (K^* \rho) l^+ l^-)$ (Larger TH uncertainties)

$$Br(B \to X_s \gamma) = \begin{cases} (3.52 \pm 0.30) \cdot 10^{-4} & \text{EXP} \\ (3.70 \pm 0.30) \cdot 10^{-4} & \text{SM} \end{cases}$$

CLEO, BaBar, Belle

GMH, BCMU, GH

$$Br(B \to X_s l^+ l^-) = \begin{cases} (4.5 \pm 1.0) \cdot 10^{-6} & \text{EXP} \\ (4.4 \pm 0.7) \cdot 10^{-6} & \text{SM} \end{cases}$$

Belle, BaBar

BGGH, GHIY, AAGW (NNLO)

ALGH

(low $\hat{s}$ region)

SUSY (NNLO) : BBE

Comments on Step 5

1. Very valuable Constraints on SUSY and other models (Ali, Hiller, Greub, Lunghi, Handoko, Morozumi; Krüger) {Gambino, Haisch, Misiak (2004)} ⇒ $C_7^{NP} = -C_7^{SM}$ essentially excluded!

2. Important Targets : FB-Asymmetries — Burdman, GHIY, ...

$\not{C}\not{P}$ in $B \to X_s \gamma$, $B \to K^* \gamma$ — Kagan, Neubert; ...

FB $\not{C}\not{P}$ Asymmetry — Buchalla, Hiller, Isidori

⟸ Spectacular effects due to new EWP weak phase (BFRS)

3.

$$Br(K_L \to \pi^0 e^+ e^-)_{SM} = (3.7 \pm 1.0) \cdot 10^{-11}$$

$$Br(K_L \to \pi^0 \mu^+ \mu^-)_{SM} = (1.5 \pm 0.3) \cdot 10^{-11}$$

Buchalla, D´Ambrosio, Isidori
Friot, Greyant, de Rafael
Isidori, Smith, Unterdorfer

⇒ **New weak phase from $B \to \pi K$**

$(9.0 \pm 1.6) \cdot 10^{-11}$ (BFRS)

$(4.3 \pm 0.7) \cdot 10^{-11}$ (ISU)

$< 2.8 \cdot 10^{-10}$

$< 3.8 \cdot 10^{-10}$

KTeV

Step 6

Calculate Hadronic Matrix Elements relevant for

$$B \to \pi\pi, \boxed{B \to \pi K}, B \to K\bar{K}, \boxed{B \to \varphi K_s}, \ldots$$

QCDF
PQCD
SCET
LCSR

Many, many papers ....

Study simultaneously many channels using Flavour Symmetries

GHLR
Fleischer (U-Spin)
Rome
BFRS
⋮

CKM input

Input from RUT

Predictions for Branching Ratios and CP asymmetries possible

WICK CONTRACTIONS
Rome; AJB, Silvestrini

New Complex Phase from EWP in $B \to \pi K$?

AJB, Fleischer (2000)
AJB, Fleischer, Recksiegel, Schwab (2003)
Yoshikawa (2003), Gronau + Rosner (2003), Beneke, Neubert (2003)
Barger, Chiang, Langacker, Lee (2004)
He, McKellar (2004)
Wu, Zhou
London, Matias et al. (2004)
Baek, Hamel, London, Datta, Suprun (2004)
Ciuchini et al.
Grossman, Neubert
Kagan (1999)

The B →πK Puzzle

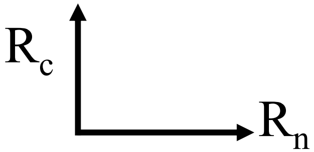
(BFRS)

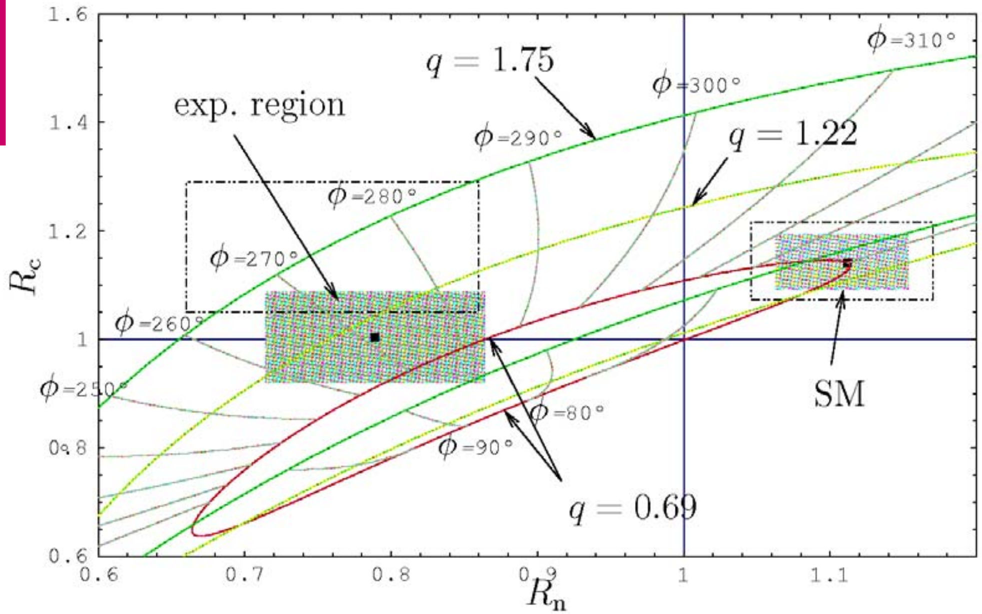
$$R_c = 2\left[\frac{Br(B^{\pm} \to \pi^0 K^{\pm})}{Br(B^{\pm} \to \pi^{\pm} K^0)}\right]$$

$$R_n = \frac{1}{2}\left[\frac{Br(B^0 \to \pi^- K^+)}{Br(B^0 \to \pi^0 K^0)}\right]$$

EWP = $q e^{i\varphi}$

SM: $q = 0.69$, $\varphi = 0$ — Neubert Rosner





$$(R_c)_{SM} = 1.14 \pm 0.05$$
$$(R_n)_{SM} = 1.11 \pm 0.05$$

Best Values (including rare decay constraint)

$q \approx 0.92$, $\varphi \approx -85^{o}$ — BFRS

$$R_c = 1.17 \pm 0.12$$
$$R_n = 0.76 \pm 0.10$$

Exp: before ICHEP 04

Rare Decays ⇒

$$R_c = 1.00 \begin{matrix} +0.12 \\ -0.08 \end{matrix}$$
$$R_n = 0.82 \begin{matrix} +0.12 \\ -0.11 \end{matrix}$$

BFRS Expectation of June 04

$$R_c = 1.00 \pm 0.08$$
$$R_n = 0.79 \pm 0.08$$

Exp: after ICHEP 04

CLEO
BaBar
Belle

Confront the Avalanche of magic Numbers from BaBar and Belle

$$\mathrm{Br}(B^\pm \to \pi^\pm\pi^0)$$
$$\mathrm{Br}(B_d \to \pi^+\pi^-)$$
$$\mathrm{Br}(B_d \to \pi^0\pi^0)$$

$$\mathrm{Br}(B^\pm \to \pi^\pm K)$$
$$\mathrm{Br}(B_d \to \pi^\mp K^\pm)$$
$$\mathrm{Br}(B^\pm \to \pi^0 K^\pm)$$
$$\mathrm{Br}(B_d \to \pi^0 K^0)$$

$$A_{CP}^{dir}(B^\pm \to \pi^\pm K)$$
$$A_{CP}^{dir}(B_d \to \pi^\mp K^\pm)$$
$$A_{CP}^{dir}(B^\pm \to \pi^0 K^\pm)$$
$$A_{CP}^{dir}(B^0 \to \pi^0 K_s)$$
$$A_{CP}^{mix}(B^0 \to \pi^0 K_s)$$

$$A_{CP}^{dir}(B_d \to \pi^+\pi^-)$$
$$A_{CP}^{mix}(B_d \to \pi^+\pi^-)$$
$$A_{CP}^{dir}(B_d \to \pi^0\pi^0)$$
$$A_{CP}^{mix}(B_d \to \pi^0\pi^0)$$

Simultaneous study of all these channels and also of B_s decays (DØ, CDF, LHC) should offer valuable insight into

QCD and Flavour Dynamics $\not{C}\not{P}$

Step 7

Calculate Hadronic Matrix Elements relevant for

$K_L \to \pi\pi$

➡ ε'/ε

NA48
KTeV

$$(\varepsilon'/\varepsilon)_{exp} = (1.6 \pm 0.16) \cdot 10^{-3}$$

and

Large sensitivity to NP in the Electroweak Penguin Sector

Estimates from:

Munich, Rome, Trieste, Dortmund
Lund, Valencia, ...

within the SM, consistent with EXP.

But:

Large hadronic uncertainties in $\langle Q_6 \rangle$, $\langle Q_8 \rangle$ preclude reasonable tests of New Physics at present.

Step 8

Look at Charm Decays

Final Messages

It is essential to study simultaneously as many processes as possible in a given NP scenario.

★ Identify correlations between various quantities that generally depend on fewer parameters. (MFV ″Sum Rules″)

★ In the presence of many quantities already the pattern of enhancements and suppressions relative to the SM can rule out a given NP or give hints for it. (Example)

★ In particular identify quantities that vanish or are tiny in the SM but have a definite sign in a given NP.

Comparison of different Models

	universal extra dimensions	MSSM (CKM) large tanβ	MSSM (CKM) low tanβ	Littlest Higgs
$Br(K^+ \to \pi^+ \nu\bar{\nu})$	↑	No effect	↓	↓
$Br(K_L \to \pi^0 \nu\bar{\nu})$	↑	No effect	↓	↓
$Br(B_s \to \mu\bar{\mu})$	↑	↑↑↑	↑↓	↑
ΔM_s	↑	↓	↑	↑
Collaboration with:	Spranger Weiler (02)	see previous refs.	Gambino Gorbahn Jäger Silvestrini (01)	Poschenrieder Uhlig (04)

10.

Short Outlook

Targets for 2005-2012

$|V_{us}|,\ |V_{cb}|,\ |V_{ub}|,\ \gamma$
from tree level decays

Improved $F_{B_d},\ F_{B_s}$
$\hat{B}_d,\ \hat{B}_s,\ B_i^{NP},\ \xi, \dots$

$K^+ \to \pi^+ \nu\bar{\nu}$
$K_L \to \pi^0 \nu\bar{\nu}$
$B \to X_{d,s} \nu\bar{\nu}$

$B_{d,s} \to l^+ l^-$
ΔM_s

Improved
$Br(B \to X_s \gamma)$
$Br(B \to X_s l^+ l^-)$
+ Exclusive Modes

FB - Asymmetries $(B \to X_s l^+ l^-,\ K^* l^+ l^-)$
$\not{C}\not{P}$ in $B \to X_s \gamma,\ K^* \gamma$
$\not{C}\not{P}$ – FB Asymmetries $(B \to X_s l^+ l^-,\ K^* l^+ l^-)$

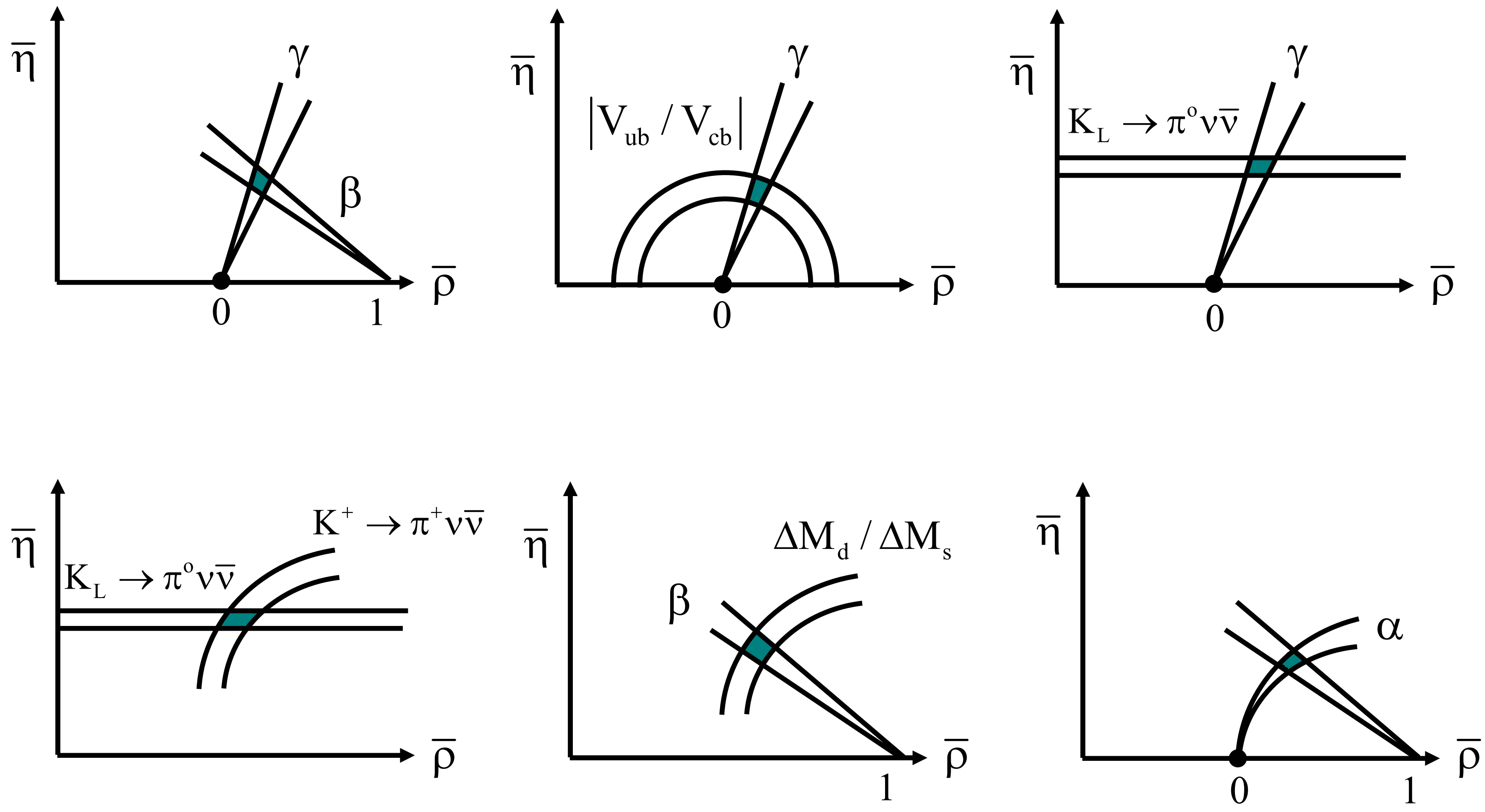
$K_L \to \pi^0 e^+ e^-$
$K_L \to \pi^0 \mu^+ \mu^-$
$K_L \to \mu^+ \mu^-$ (TH)
$\varepsilon' / \varepsilon$ (TH)

Resolution of
$B \to \pi K$ Puzzle
$B \to \pi\pi$ Puzzle
$B \to \varphi K_s$ Puzzle
$B \to \eta' K$ Puzzle

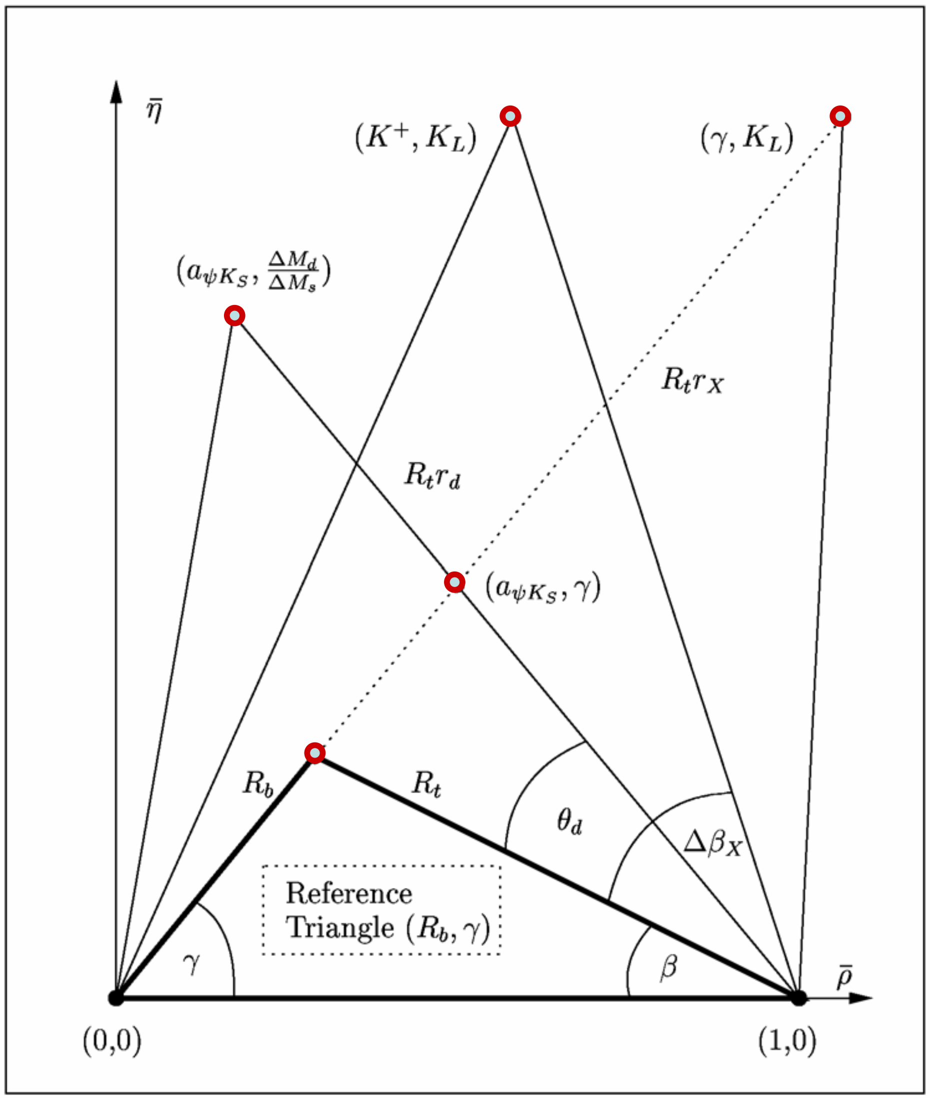
$A_{CP}^{dir},\ A_{CP}^{mix}$
in
2 – Body
$B_{d,s},\ B^{\pm}$
decays

Correlations with
Electric Dipole Moments
$\mu \to e\gamma$
$(g-2)_\mu$
Lepton Flavour Violation

Searching for New Physics



The 2012 Vision of the Unitarity Triangle



AJB
Schwab
Uhlig

The Future until 2012 should be very exciting