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SMR.1317 - 30

SUMMER SCHOOL ON PARTICLE PHYSICS

18 June - 6 July 2001

CP VIOLATION AND B-PHYSICS

Lectures II, III & IV

i.e. Lectures 3, 4 and 5 (Quinn numbering)

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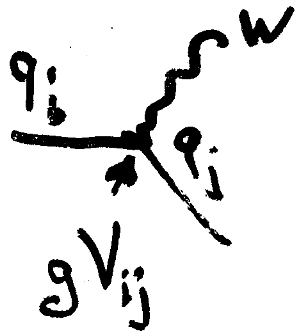
Lecture 3.

Standard Model Predictions for CP Violation in B decays.

CKM Matrix of weak couplings

$$V = \begin{bmatrix} V_{ud} & V_{us} & \underline{V_{ub}} \\ V_{cd} & V_{cs} & V_{cb} \\ \underline{V_{td}} & V_{ts} & V_{tb} \end{bmatrix}$$



$V_{us} \equiv \lambda \cong 0.2$

$\hat{=}$ Wolfenstein Parameterization

$\Leftrightarrow$ <u>choice of phase convention</u>

$$\begin{bmatrix} 1-\lambda^2/2 & \lambda & \underline{A\lambda^3(\rho-i\eta)} \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ \underline{A\lambda^3(1-\rho-i\eta)} & -A\lambda^2 & 1 \end{bmatrix} + \mathcal{O}(\lambda^4)$$

Unitarity of V

$$\Rightarrow \quad \overset{\lambda}{V_{ud}V_{us}^*} + \overset{\lambda}{V_{cd}V_{cs}^*} + \overset{\lambda^5}{V_{td}V_{ts}^*} = 0 \qquad (a)$$

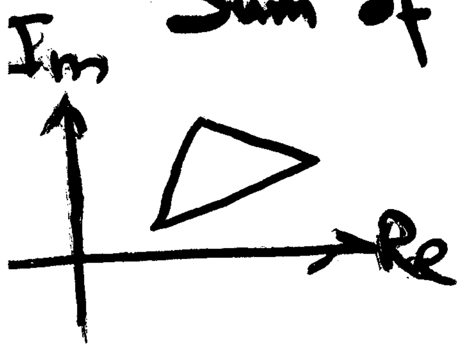
$$\overset{\lambda^4}{V_{us}V_{ub}^*} + \overset{\lambda^2}{V_{cs}V_{cb}^*} + \overset{\lambda^2}{V_{ts}V_{tb}^*} = 0 \qquad (b)$$

All angles order 1 $\Rightarrow$

$$\overset{\lambda^3}{V_{ud}V_{ub}^*} + \overset{\lambda^3}{V_{cd}V_{cb}^*} + \overset{\lambda^3}{V_{ts}V_{tb}^*} = 0 \qquad (c)$$

+ 6 more relationships, 3 of each type.

Sum of 3 complex #s = 0



$\Rightarrow$ triangle in complex plane

"Unitarity Triangles"

Also
$$\mathrm{Im}\left[V_{ij}V_{kl}V_{il}^*V_{kj}^*\right] = J\sum_{m,n=1}^{3} \epsilon_{ikm}\epsilon_{jln}$$

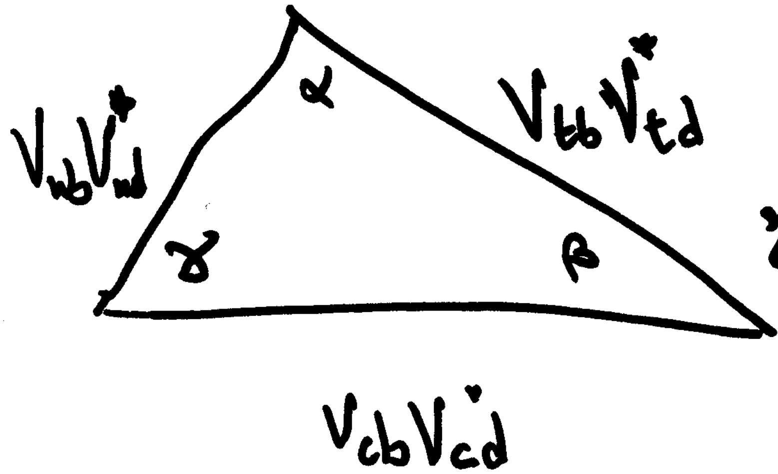
for any $ijkl = 1,2,3$

antisymmetric
$\epsilon_{123} = 1$
$\epsilon_{213} = -1$
etc.

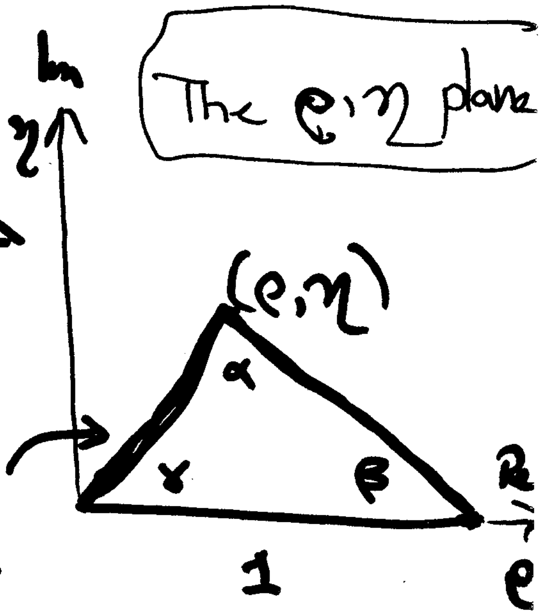
$\Rightarrow$ All triangles have area $J/2$

J = Jarlskog Invariant $\Leftrightarrow$ CP Violating quantity

What do we measure in B decays ?



$\hookrightarrow$ rescale by $V_{cb}V_{cd}^*$



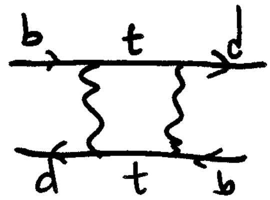
Measure sides

$|V_{cb}|$ $\quad B \to D^* \ell \nu$

$|V_{ub}|$ $\quad B \to (\text{no charm})\, \ell \nu$ 'inclusive'

$B \to \underset{\pi}{\rho}\, \ell \nu$

$|V_{td}|$ $\quad B - \overline{B}$ mixing



OR $\quad \boxed{\dfrac{B_d \Leftrightarrow \overline{B}_d}{B_s \Leftrightarrow \overline{B}_s} \Rightarrow \dfrac{V_{td}}{V_{ts}}}$

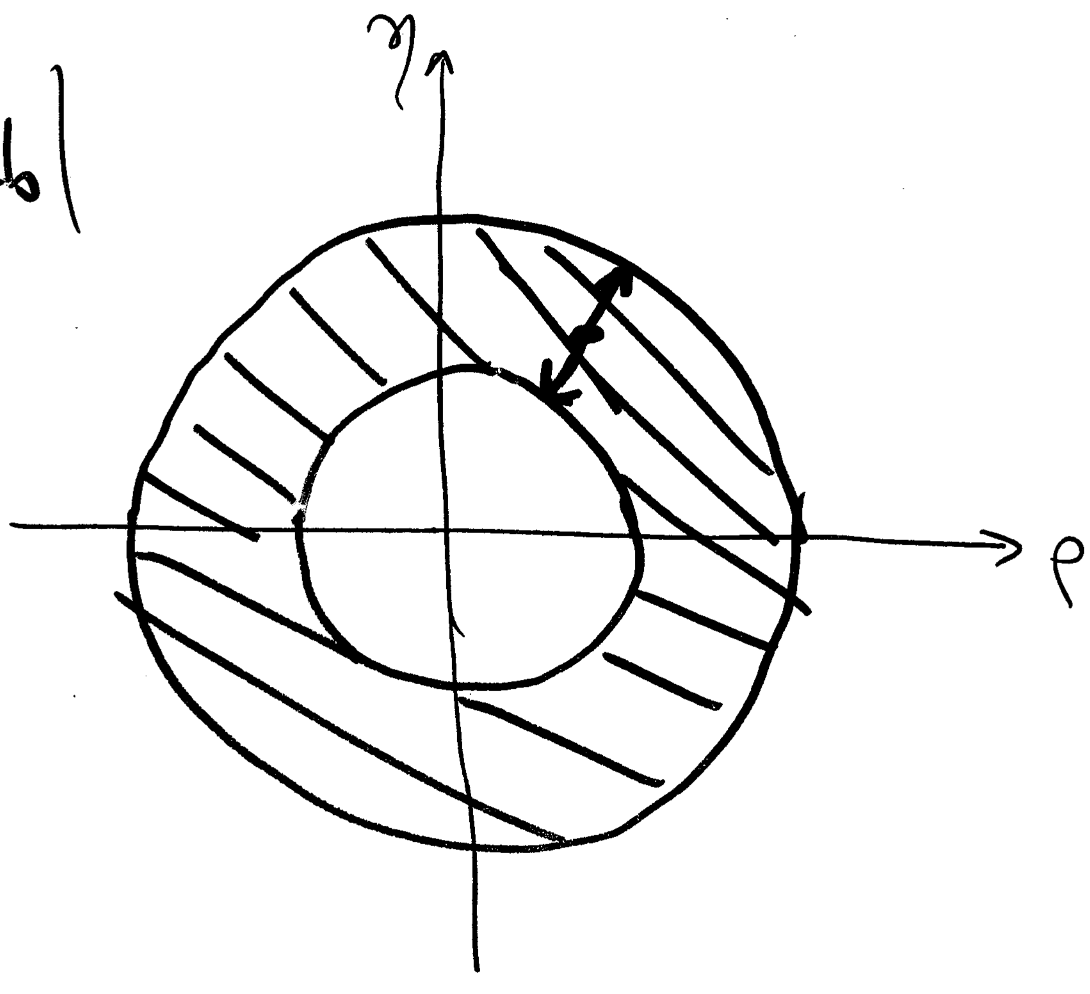
- For each such measurement ⟺ Experimental uncertainties
  - Calculation of expected rate

    depends on parameter to be determined

    × coefficient that has theoretical uncertainties

⇒ allowed region in (ρ, η) plane

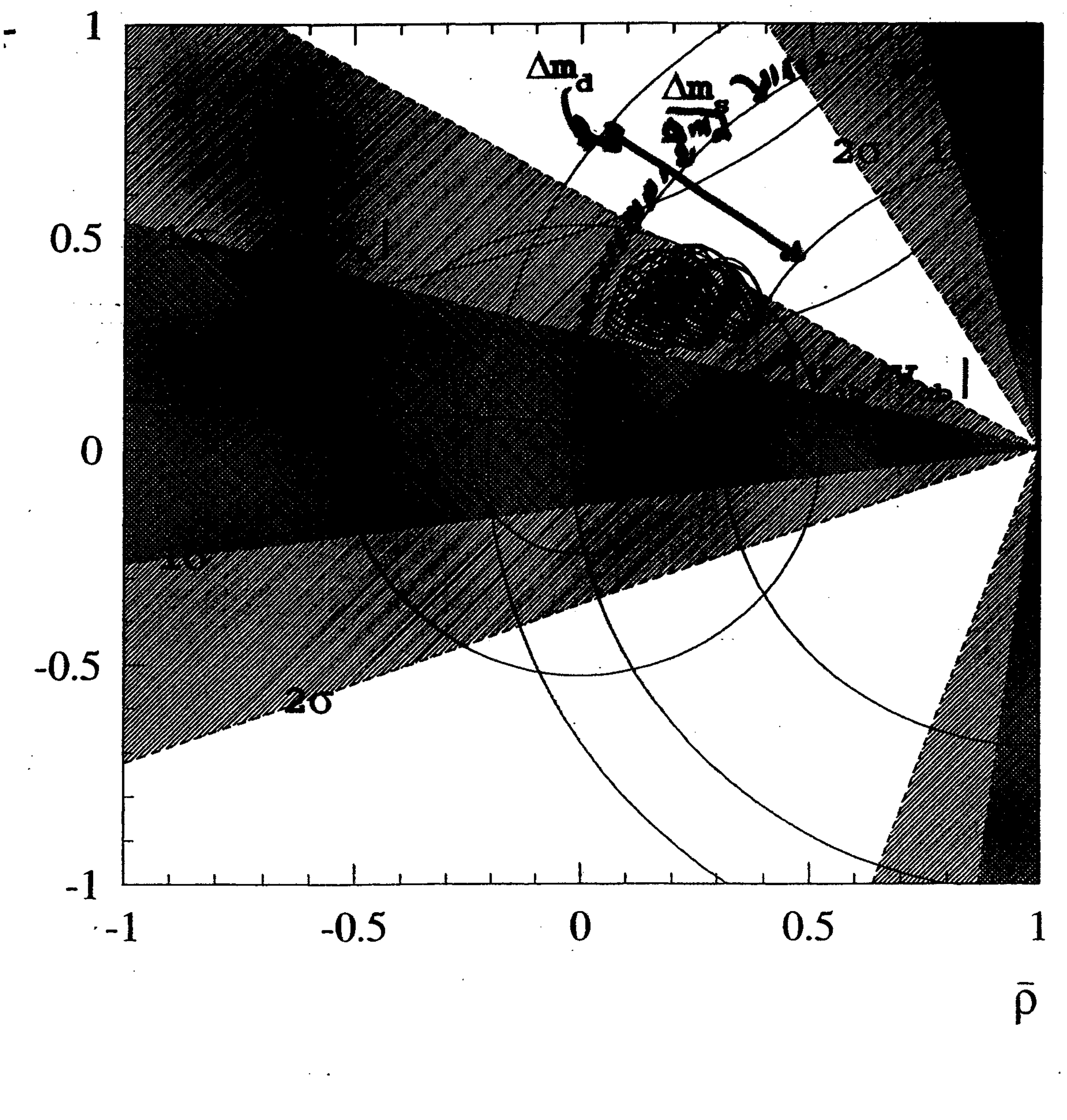
e.g.
$|V_{ub}|$



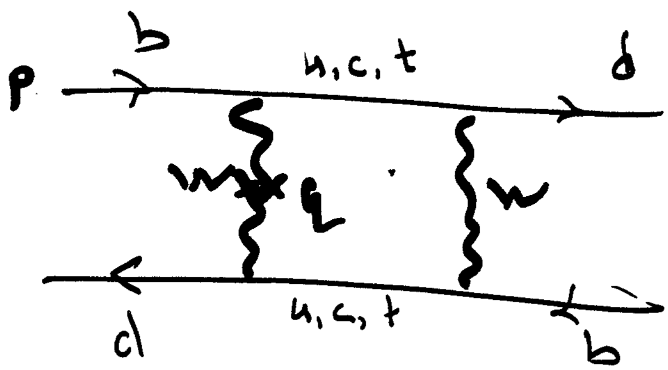
Sample plot from analysis combining all data
(M-H. Schune et al)

For each set of theory parameters
O = 2 sigma experimental region

- Theoretical Uncertainties dominate the picture
- So far ∃ overall consistency with SM within uncertainties

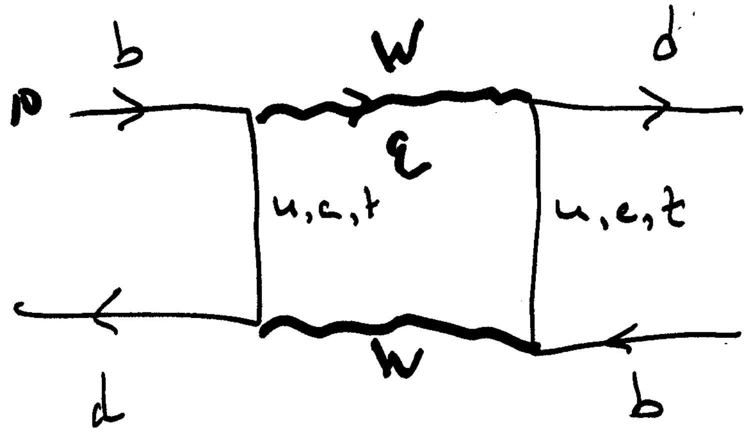


$B_0 \leftrightarrow \bar{B}_0$ mixing – some more detail



"Box" diagrams

\+



Sum of all diagrams $= M_{12} + i\Gamma_{12}/2$

$$\int d^4q \; D_W(q)\, D_W(q') \left[V_{tb}V_{td}^* D_t + V_{cb}V_{cd}^* D_c + V_{ub}V_{ud}^* D_u \right]^2$$

↑ Vanishes by unitarity for $m_t = m_c = m_u$

$\Rightarrow$ Dominated by $V_{tb}V_{td}^*$ terms $m_t >> m_c, m_u$

$$\Delta m_d \longleftrightarrow V_{tb} V_{td}^{*} \langle \bar{B} | O | B \rangle \times \text{known factors}$$

4 quark $O \leftrightarrow \bar{b}\gamma_\mu\gamma_5 d \; \bar{d}\gamma^\mu\gamma_5 b$

Matrix element naive estimate

$$f_B^2 = \langle \bar{B} | \bar{b}\gamma_\mu\gamma_5 d | 0 \rangle \langle 0 | \bar{d}\gamma^\mu\gamma_5 b | B \rangle$$

vacuum insertion approximation

Full Result is usually written as

$$B_K f_B^2$$

correction factor for naive result

Lattice calculation gives best estimate $B_K f_B^2$

For $\dfrac{\Delta m_{B_s}}{\Delta m_{B_d}}$ many uncertainties cancel

SU(3) $s \leftrightarrow d$ corrections only.

Two mass eigenstates

$$B_H = p B_0 + q \overline{B}^0 \qquad m_H, \Gamma_H$$

$$B_L = p B_0 - q \overline{B}^0 \qquad m_L, \Gamma_L$$

$$p^2 + q^2 = 1$$

$$q/p = \frac{\Delta m - i \Delta\Gamma/2}{2 (M_{12} + i/2\, \Gamma_{12}}$$

$M = \frac{m_H + m_L}{2}$ $\qquad$ $\Gamma = \frac{\Gamma_H + \Gamma_L}{2}$

$\Delta m = m_H - m_L$ $\qquad$ $\Delta\Gamma = \Gamma_H - \Gamma_L$

No CP violation $\qquad$ $q/p \equiv 1$

eigenstates are CP $\begin{cases} \text{even} \\ \text{odd} \end{cases}$

$\Gamma_{12} << M_{12}$ $\quad |q/p| \cong 1$

Time-evolution of an initial ($t=0$) pure B_0 state

⇒ production always gives definite quark content.

⇒ propagation governed by mass eigenstates

$$B_0(t=0) = \frac{B_H + B_L}{2p}$$

$$B_0(t) = \frac{1}{2p}\left[e^{(-im_H t - \Gamma_H t/2)} B_H + e^{(-im_L t - \Gamma_L t/2)} B_L \right]$$

2 mass states evolve differently

$$= g_+(t)\, B_0 + q/p\; g_-(t)\, \overline{B}_0$$

$$g_\pm(t) = \frac{1}{2}\left[e^{(-im_L t - \Gamma_L t/2)} \pm e^{(-im_H t - \Gamma_H t/2)} \right]$$

$$= \frac{1}{2} e^{-iMt - \Gamma t/2} \left[e^{(i\Delta m + \Delta\Gamma/2)t} \pm e^{-(i\Delta m + \Delta\Gamma/2)t} \right]$$

Similarly $\bar{B}(t) = \frac{p}{q}\, g_-(t)\, B + g_+(t)\, \bar{B}$

Thus if f is any final state

CP eigenstate

and $\bar{f}$ its CP conjugate $\boxed{= \pm f}$

η_f

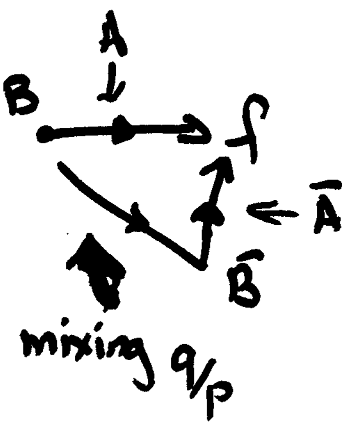
$$A(B(t)\to f) = A(B\to f)\Big\{ |g_+|^2 + |\lambda_f|^2 |g_-|^2 + 2\,\mathrm{Re}\big[\lambda_f\, g_+^*(t)\, g_-(t)\big]\Big\}$$

where

$$\lambda_f = q/p\, \frac{\bar{A}(\bar{B}\to f)}{A(B\to f)}$$

for $\bar{f} = \eta_f f$
CP eigenstates

$$= \eta_f\, \frac{q}{p}\, \frac{A(\bar{B}\to \bar{f})}{A(B\to f)}$$



CP eigenvalue of f.
$\eta_f = \pm 1$

CP conjugate amplitudes

$$\mathrm{Re}\left[\lambda_f \; g_+^*(t)\, g_-(t)\right]$$

$$= \mathrm{Re}\,\lambda_f \; \mathrm{Re}\; g_+^*(t)\, g_-(t)$$

$$- \boxed{\mathrm{Im}\,\lambda_f}\;\mathrm{Im}\; g_+^*(t)\, g_-(t)$$

$\sim \sin \Delta m t$ for $|q/p| \simeq 1$ or $\Delta\Gamma \ll \Delta m$

CP violating

Most interesting case

$$|q/p| = 1 \qquad \left|\frac{A(\bar{B}\to\bar{f})}{A(B\to f)}\right| = 1$$

good approximation for B_d

final states with 1 weak phase in decay

no CP violating decay rate asymmetry

$$\boxed{\mathrm{Im}\,\lambda = \arg\left(q/p\right) + \arg\frac{\bar{A}}{A}} = 2\phi_{\text{mixing}} - 2\phi_{\text{Dec}}$$

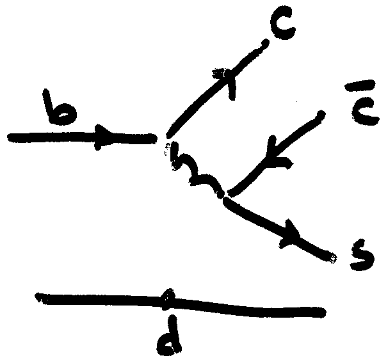
- Convention Independent
- Depends only on CKM phases

Example

$$B_d \to \psi K_s$$

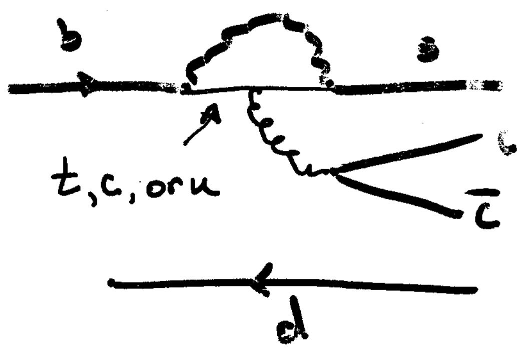
quark level $\qquad b \to c\bar{c}s$

Tree diagram



$$\underline{V_{cb}V_{cs}^*}\, f_{tree}$$

" Penguin diagram $\qquad$ loop $\Leftrightarrow$ $\alpha_s(m_b)/4\pi$



$$\begin{aligned} & V_{tb}V_{ts}^*\, f_p(m_t) \leftarrow O(\lambda^2) \\ + & \underline{V_{cb}V_{cs}^*}\, f_p(m_c) \leftarrow O(\lambda^2) \\ + & V_{ub}V_{us}^*\, f_p(m_u) \leftarrow O(\lambda^4) \end{aligned}$$

USING $\to$ UNITARITY $\quad \underline{V_{cb}V_{cs}^*}\left[f_p(m_c) - f_p(m_t)\right] + V_{ub}V_{us}^*\left[f_p(m_u) - f_p(m_t)\right]$

SIZES

In general for 1st estimate look at 3 factors

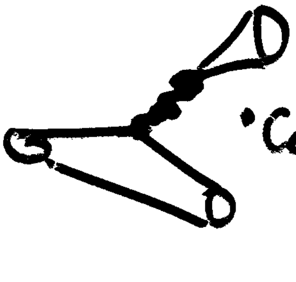
- $f_{tree} > f_{penguin}$

$\uparrow$ loop diagrams

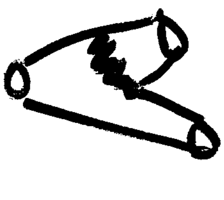
$$\frac{\alpha_s(m_b\ ?)}{4\pi} \sim 0.3 \text{ (or so)}$$

- $\lambda \sim 0.2$ CKM factor counting

- Color flow $\Rightarrow$ $1/N_c$ factors $\sim 1/3$



"Color allowed"
$\mathcal{O}(1)$



color supressed
$\mathcal{O}(1/N_c)$

For $B \to \psi K_s$

Up to small $\underline{\lambda^4}$ part of <u>penguin</u> term

tree and penguin have

Same WEAK PHASE

i.e. same CKM element structure

$$\Rightarrow \quad |\bar{A}| = |A|$$

$$A = a e^{i(\varphi + \delta)}$$

$$\bar{A} = a e^{i(-\varphi + \delta)}$$

φ = weak phase

δ = strong phase = absorbtive part of Amplitude

$\Rightarrow$ $B_d \to \psi K_s$

$$|q/p| = 1 \qquad |\bar{A}/A| = 1$$

(to % level)

$$\to \quad \mathrm{Im}\,\lambda = \sin\left[\arg\left(q/p\,\bar{A}/A\right)\right]$$

$$= \sin 2\beta$$

$\left\{ \begin{array}{l} B \text{ mixing} \\ B\text{-decay} \\ K\text{-}~~[illegible]~~ \text{ to } \pi\pi \end{array} \right.$

f = state of definite CP

Examples

$B \to \psi K_s$ Vector + Pseudoscalar

spin 0 $\ell = 1$

$B \to \pi^+\pi^-$ 2 pseudoscalars

$\ell = 0$

But

$B \to \rho^+\rho^-$ 2 vectors

$B \to \psi K^*$ $\ell = 0,2$ $\ell = 1$

$\eta = +1$ $\eta = -1$.

CP even CP odd

Remember $\lambda = \eta_f \, q/p \, \frac{\bar{A}}{A}$ partial cancellation of asymmetry *lc*

Table 1: $B \to q\bar{q}s$ decay modes

Quark process	Leading term	Secondary term	Sample B_d modes	B_d angle	Sample B_s modes	B_s angle
$b \to c\bar{c}s$	$V_{cb}V_{cs}^* = A\lambda^2$ tree + penguin$(c-t)$	$V_{ub}V_{us}^* = A\lambda^4(\rho - i\eta)$ penguin only$(u-t)$	$J/\psi\ K_S$	β	$J/\psi\eta$ $D_s\overline{D}_s$	0
$b \to s\bar{s}s$	$V_{cb}V_{cs}^* = A\lambda^2$ penguin only$(c-t)$	$V_{ub}V_{us}^* = A\lambda^4(\rho - i\eta)$ penguin only$(u-t)$	ϕK_S	β	$\phi\eta'$	0
$b \to u\bar{u}s$ $b \to d\bar{d}s$	$V_{cb}V_{cs}^* = A\lambda^2$ penguin only$(c-t)$	$V_{ub}V_{us}^* = A\lambda^4(\rho - i\eta)$ tree + penguin$(u-t)$	$\pi^0\ K_S$ ρK_S	competing terms	$\phi\pi^0$ $K_S\overline{K}_S$	competing terms

Table 2: $B \to q\bar{q}d$ decay modes

Quark process	Leading term	Secondary term	Sample B_d modes	B_d angle	Sample B_s modes	B_s angle
$b \to c\bar{c}d$	$V_{cb}V_{cd}^* = -A\lambda^3$ tree + penguin$(c-u)$	$V_{tb}V_{td}^* = A\lambda^3(1-\rho+i\eta)$ penguin only$(t-u)$	D^+D^-	$^*\beta$	$J/\psi K_S$	$^*\beta_s$
$b \to s\bar{s}d$	$V_{tb}V_{td}^* = A\lambda^3(1-\rho+i\eta)$ penguin only$(t-u)$	$V_{cb}V_{cd}^* = A\lambda^3$ penguin only$(c-u)$	$\phi\pi$ $K_S\overline{K}_S$	competing terms	ϕK_S	competing terms
$b \to u\bar{u}d$ $b \to d\bar{d}d$	$V_{ub}V_{ud}^* = A\lambda^3(\rho - i\eta)$ tree + penguin$(u-c)$	$V_{tb}V_{td}^* = A\lambda^3(1-\rho+i\eta)$ penguin only$(t-c)$	$\pi\pi;\ \pi\rho$ πa_1	$^*\alpha$	$\pi^0 K_S$ $\rho^0 K_S$	competing terms
$b \to c\bar{u}d$	$V_{cb}V_{ud}^* = A\lambda^2$	0	$D^0\pi^0$, $D^0\rho^0$ $\hookrightarrow$ CP eigenstate	β	D^0K_S $\hookrightarrow$ CP eigenstate	0

*Leading terms only, large secondary terms shift asymmetry.

p. 630 Particle Data Book

Predictions for other channels (2 BODY)

$b \to q\bar{q}'s$ OR $q\bar{q}'d$

$\Rightarrow$ Quark level decay catalogue

- If $q, \bar{q}'$ are up type (u or c) $\Rightarrow$ TREE CONTRIBUTIO[N]
- If $q = q'$ $\rightarrow$ 3 PENGUIN DIAGRAMS (t, c, u)

  Use unitarity to write as sum of two terms (s) $V_{cb}V_{cs}^*(\ ) + V_{ub}V_{us}^*(\ )$

  or (d) $V_{tb}V_{td}^*(\ ) + V_{ub}V_{ud}^*(\ )$

- Combine quarks to get 2 mesons

  Some channels get contribution from more than 1 quark content

  e.g. $\pi^0 = \frac{u\bar{u} + d\bar{d}}{\sqrt{2}} \Leftrightarrow u\bar{u}q$ and $d\bar{d}q$

Continue the catalogue

$B_d \to \phi K_s$

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

Diagrams ?

CKM structure ?

Modes ?

Expected CP asymmetry ?

An interesting (but hard to measure) case

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

Diagrams

CKM structure

Modes

Possible
Interference if $\quad D^0 \to f$ and $\bar{D}^0 \to f$

where f is a CP eigenstate

even though $D \leftrightarrow \bar{D}$ mixing is small

Similar analysis $B_d \to D\pi$ $\quad$ $b \to c\bar{u}d$, $u\bar{c}d$

OR $B_s \to DK$

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

$V_{cb}V_{us}^*$

$A\lambda^3$

$\Uparrow$

phase $= 0$

$B \to f$

$a_1 e^{i\delta_1}$

CP conjugate $\bar{B} \to f$

$a_1 e^{i\delta_1}$

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

$V_{ub}V_{cs}^*$

$A\lambda^3(\rho - i\eta)$

$\uparrow$

phase $\Rightarrow e^{i\gamma}$ $|V_{ub}|$

$a_2 e^{i\delta_2 + \gamma}$

$a_2 e^{i\delta_2 - \gamma}$

$\rightarrow$ Interference $\propto \sin(\delta_2 - \delta_1)\sin\gamma$

Measure
$$\boxed{\begin{array}{l} B(t) \to D_{CP} K_S \\ \bar{B}(t) \to D_{CP} K_S \end{array}}$$

Rate $= (\ )1 + (\ )\cos\Delta m t \pm (\ )\sin\Delta m t$

<u>Homework</u>:

Show that you can extract

γ , $\delta_1 - \delta_2$

Assume $|q/p| = 1$ up to ambiguity (which is which)

Lecture 4.

B Physics _ Tools of the Trade
for calculation of rates

All methods are approximations

based on $\frac{\Lambda}{m_b} \ll 1$ ← QCD Λ-scale

← b quark mass

& $\alpha_s(m_b) \ll 1$

⇒ Intuitive picture of B meson

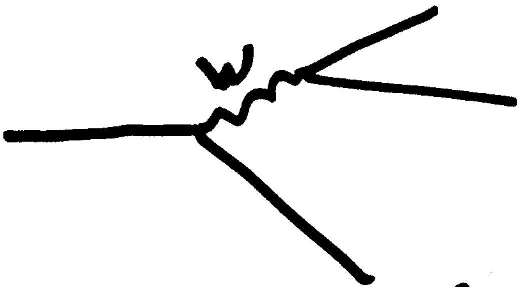
essentially static heavy b quark

"brown muck"
⇒ light quark wavefunction

B decay
Weak decay of b quark
→ hadronization of remnants

Weak decay of b-quark

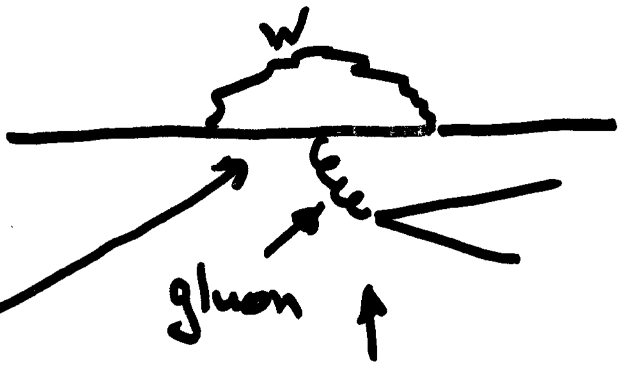
2 classes of diagrams



"Tree"

← c, or u quark

<u>CKM favored</u> V_{cb}



"Penguin"

, c, t
ntributions

\+ photon or Z — electroweak penguin

→ Operators ⊗ Coefficients

Weak decay of B Meson

= Weak decay of b quark
+ "spectator" light quark

$\Downarrow$ hadronises

Typical final states have
~ 5 light mesons

For CP studies want states of
<u>definite CP</u>

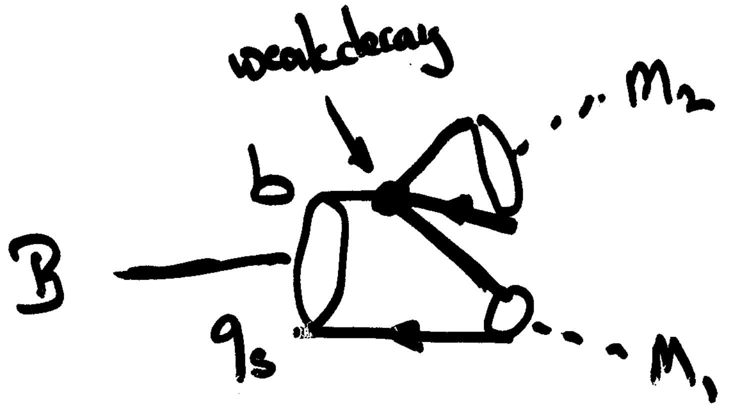
$\Rightarrow$ 2 body (or quasi 2 body) states

PP , PV , or VV + angular analysis
$(-1)^{\ell}$ factors

Hadronization

Simpest picture for 2 body decays

= factorization ; "uninvolved" spectator



$b\bar{q}_s \to (q\bar{q}')(q''q_s)$

Physical Picture

Weak decay is a short-distance (instantaneous) process

$q\bar{q}'$ formed at a point in color-singlet travelling with large momentum

$\Rightarrow$ escape without interaction

If $\quad \bar{q}'_\alpha O_{n2} q''^\alpha$ is color singlet

$\Rightarrow$ "color allowed" matrix element

If $\quad \bar{q}'_\alpha O_{n2} q''^\beta$ is color unmatched

$\Rightarrow \frac{1}{N_c}$ factor to pull out

$\nearrow$ "color supressed"

color-matched $\Leftrightarrow$ color singlet overlap

$\alpha = \beta$

If M_2 contains q instead of q''

$\Rightarrow$ Fierz transformation

+ factorization

More Formal Version

Operator Product Expansion

$\Rightarrow$ expand weak amplitudes as

$\sum_n c_n O_n$ a sum of local 4-quark operators

$$O_n = \bar{b}\, O_{n1}\, q_L\, \bar{q}'_L\, O_{n2}\, q''_L$$

Coefficients c_n are calculable

$\mathcal{O}(\alpha_s)$ corrections

$\Rightarrow$ operator evolution

$$c_n(m_W) \to c_n(\mu)$$

Matrix elements

$$\mathcal{M}_n = \langle m_1 m_2 | O_n | B \rangle$$

$\uparrow$ 2 body final state

"factorization"

$$\mathcal{M}_n \cong \langle m_1 | \bar{q}' O_{n2}\, q''_2 | 0 \rangle \langle m_2 | \bar{b}\, O_{n1}\, q | B \rangle$$

Problem of $\boxed{\text{Unphysical}}$ Scale μ

Feynman diagram

↳ Coefficient c_n ⊗ Operator O_n

↑

CKM factors * numbers * weak coupling

QCD corrections

$$c_n \to c_n(\mu)$$

↑

scale of hard/soft separation for QCD effects

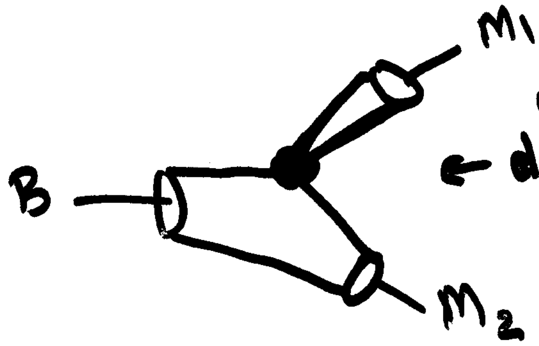
Problem : $\langle f | O_n | B \rangle$ estimates do not give correct compensating μ- dependence

e.g. naive factorization

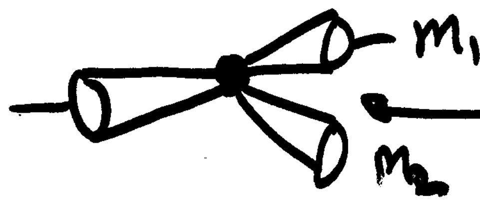
More refined versions of factorization

- Beneke, Buchalla, Neubert + Sachrajda
- Sanda, Li + Keum

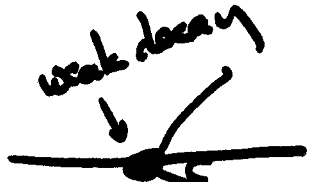
Add explicit QCD calculation

1. 

← QCD dressed weak vertex with 1 gluon connections
but not just to C_n coefficients
need also ↓

2. 

← Hard 6-quark vertex

eg 

with ~ = hard gluon

Need to input

1. $B \to M_2$ transition
   M_1 wave function
2. B, M_1, and M_2 wavefunction ← including scale dependence

Results for 2 groups differ

— different input assumptions

- Wavefunctions

$e^{-(\;)^{b}}$ from collinear gluons $\longleftrightarrow$ • Sudakov suppression

Hard quark + spectator $\Rightarrow$ meson

$x \to 1$ (hard quark), $x \to 0$ (spectator)

$\Rightarrow$ Light cone formalism for meson wavefunction

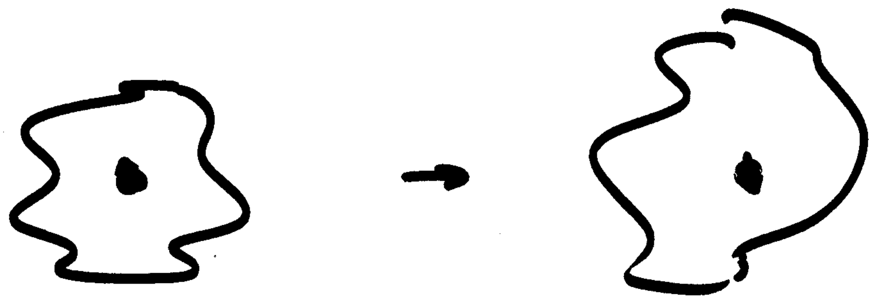
x = fraction of meson momentum carried by quark in question

μ-scale dependence also adds ambiguity

Heavy Quark Expansion

Systematic $\left(\Lambda/m_Q\right)^n$ calculation

e.g. $B \to D^* \ell \nu$



$+ \ell \nu$

If D is at rest in B rest frame

and $\Lambda/m_b << 1$ $\boxed{\Lambda/m_c << 1}$?

$\Rightarrow$ 100% wavefunction overlap

i.e. B B^* D D^* mesons

differ only by STATIC heavy quark

Λ/m treatments "heavy quark effective thy"

Formal expansion

leading corrections

$\left(\Lambda/m\right)^n$ calculable in terms of a few parameters

← same parameters in many processes

higher order corrections

Also
↳ $\alpha_{QCD}^{2n}(m)$

progressively more complicated
more parameters

Issues

Scale - Matching of QCD perturbative correction

$m_b \Rightarrow m_b(\mu)$ ← requires care to define
scheme dependent

M_B is well defined

← where possible replace unphysical m_b by physical M_B to reduce uncertainties

An example

$$B \to D^* \ell \nu$$

$$A = f(q^2) V_{cb} \langle D^* | \bar{b} \gamma_\mu (1-\gamma_5) c | B \rangle$$

known kinematics

$\to 0$ at $q^2 = (m_B - m_D)^2$

want to determine this

Naively $= 1$ at $q^2 = (m_B - m_D)^2$

But rate $\to 0$ at this point

$\Rightarrow$ extrapolate from data away from end-point

$f(q^2)$ assumptions

$\frac{\alpha(m_b)}{4\pi} \to$ QCD corrections

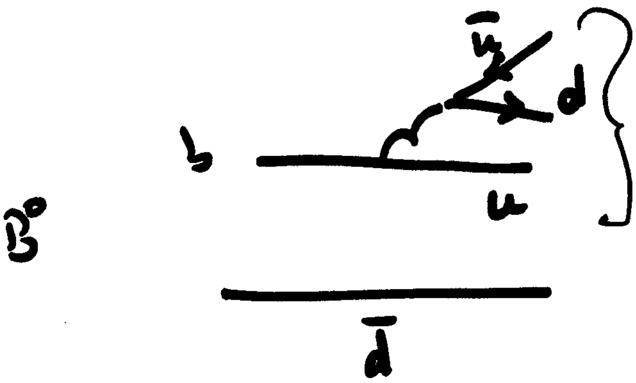
finite quark mass $\to \left(\Lambda/m_b\right)^2$ corrections

$\boxed{\left(\Lambda/m_c\right)^2 \text{ "}}$!

Sources of theoretical uncertainties

Why is isospin relevant in B-decays to light quarks?

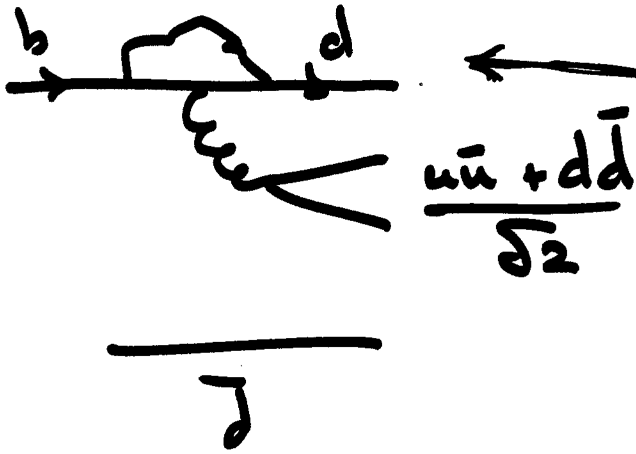
e.g. $b \to u\bar{u}d$ and $b \to d\bar{d}d$



TREE

$\Delta I = 1/2$ or $3/2$

$I_f = 0, 1, 2.$



Gluon has $I = 0$

$\Delta I = 1/2$

$\boxed{I_f = 0, 1 \text{ only}}$

$\Rightarrow$ Isolate $I_f = 2$ part to get "pure" tree process

Electro-weak penguin also

Isospin

- not a spin but SU(2) symmetry of strong interactions

Doublet $\begin{pmatrix} u \\ d \end{pmatrix}$

not quite the same as weak SU(2)

- broken by
  - quark mass terms
  - quark charges $\Leftrightarrow$ electromagnetic effects

N.B. $\frac{m_u - m_d}{m_u + m_d}$ is not small ~ 1

but $\frac{m_u - m_d}{\Lambda_{QCD}}$ is small

Which is the relevant scale? Depends on situation.

Why do we care?

Reminder

3 type of CP Violation

$$\left|q/p\right| \neq 1 \qquad \left|\frac{\bar{A}}{A}\right| \neq 1 \qquad \arg\left(\frac{q}{p}\frac{\bar{A}}{A}\right) \neq 0$$

If $\left|q/p\right| = 1$ and $\left|\bar{A}/A\right| = 1$ then this one directly

measures difference of CKM phases

of $\left(q/p\right)$ and $\left(\bar{A}/A\right)$

mixing decay

for pure tree process $\left|\bar{A}/A\right| = 1$ ← if we can isolate it.

for B_d mixing $\left|q/p\right| = 1$ to high accuracy

Example of Isospin analysis

$\bar{B}_d^0 \to \pi^+\pi^-$
$\qquad\quad \pi^0\pi^0$

$\boxed{\text{Spin}}$

$B^\pm \to \pi^\pm\pi^0$

$S = 0$
for B and both π's
$=$ $\ell = 0$ only

$\boxed{\text{Bose statistics of 2 pions}}$

ℓ even $\Leftrightarrow$ I even

$\boxed{\Rightarrow \text{no } I=1 \text{ final states}}$

$A_{1/2} = \Delta I = 1/2 \quad I_f = 0$

$A_{3/2} = \Delta I = 3/2 \quad I_f = 2$

$A_{1/2}$ has two terms (tree + penguin)

$A_{3/2}$ is pure tree

(modulo isospin breaking corrections)

Each A has form $ae^{i(\delta+\phi)}$

$\uparrow$ strong phase from absorbtive part (fsi)

$\uparrow$ weak phase from CKM

$\bar{A} = ae^{i(\delta-\phi)}$

$\uparrow$ sign change

3 amplitudes 1 overall phase is arbitrary

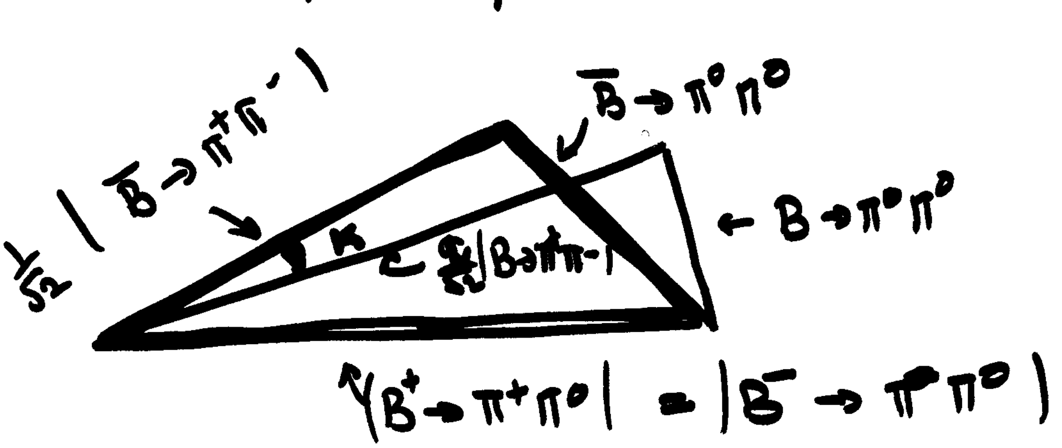
$\Rightarrow$ 3 a's 2 δ's 2 ϕ's

$\uparrow$ same for both tree contributions

Measure

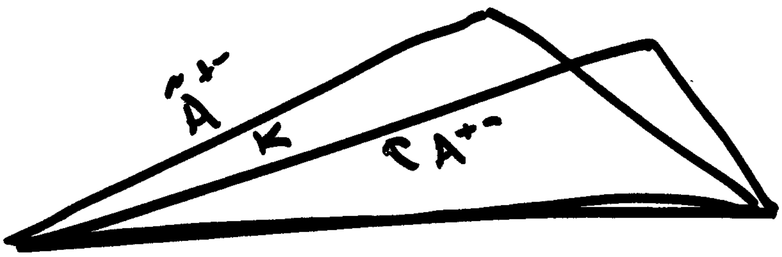
$\left\{ \begin{array}{l} \text{6 rates} \\ \text{time dependent CP violation in } B \to \pi^+\pi^- \\ \quad \Rightarrow \text{one phase} \Rightarrow \text{Im}\,\lambda_{\pi^+\pi^-} \end{array} \right.$

Construct



CKM phase difference

$$\mathrm{Im}\, \lambda_{\pi^+\pi^-} = \mathrm{Im}\left[e^{2i\alpha} \frac{\tilde{A}^{+-}}{A^{+-}} \right]$$



κ - argument is known
- magnitudes measured.

Ignores $\begin{cases} \text{isospin breaking} & \pi^0 \text{ not exactly } I=1 \text{ state.} \\ \text{electroweak penguin} & Z \text{ and on } \gamma \end{cases}$

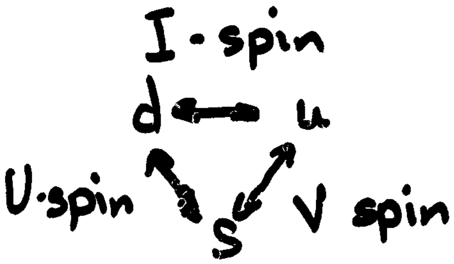
have $I=1$ content

→ significantly reduced theoretical uncertainty for $\boxed{\alpha}$

→ Standard Model test

flavor SU(3)

$\Rightarrow$ 3 quark generalization of Isospin



U spin relates:

$$\begin{array}{ccc} B_d \to \pi\pi & \leftrightarrow & B_s \to \pi K \\ \updownarrow & & \updownarrow \\ B_d \to \pi K & \leftrightarrow & B_s \to K K \end{array}$$

? How big are SU(3) breaking corrections ?

- kinematics $\quad \dfrac{m_s - m_d}{m_B} << 1 \quad$ small (except near a threshold.)

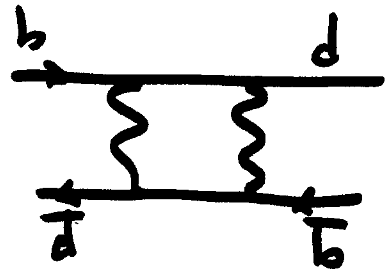
- $f_K / f_\pi \Leftrightarrow \langle M | \bar{\psi} \gamma_\mu (1-\gamma_5) \psi | 0 \rangle$

  $\boxed{\text{known}} \sim 1.2$

- phase differences & other effects ?

Other theory inputs $\boxed{\text{Lattice calculation}}$

e.g. Mixing matrix element



$$\langle B^0 | \bar{d} \gamma_\mu (1-\gamma_5) b \; \bar{b} \gamma^\mu (1-\gamma_5) d | \bar{B}^0 \rangle$$

usually written

$$= B_B \underbrace{\langle B^0 | \bar{d} \gamma_\mu (1-\gamma_5) b | 0 \rangle \langle 0 | \bar{b} \gamma (1-\gamma_5) d | \bar{B}^0 \rangle}_{\text{vacuum insertion approximation}}$$

correction

$$= f_B^2$$

How big is $B_B f_B^2$?

→ lattice calculation gives estimate

How big are uncertainties in estimate ?

Issues in lattice calculations

Statistics ✓

Treatment of heavy quark ✓

Continuum extrapolation / matching ✓

"Quenched" vs unquenched

⇒ inclusion of light quark pairs

COMING SOON

State of the art advances each year

⇒ size of theory uncertainty shrinking

To extract theory parameters from experimental data

For 2 body decays & semi-leptonic decays

NEED • transition matrix element

and/or • form factors

Where do we learn about them?

- measurement e.g. in semi-leptonic decays
- rigorous constraints
  - Regge limit
  - QCD sum rule limits
  - Heavy quark limit relationships
- models

To estimate rates all are useful

To TEST Standard Model

minimize dependence on models for cleanest test

What is idea of each limit

Regge Limit

Regge theory for hadron-hadron scattering in large t limit

Amplitudes $\sim (t)^{\alpha(s)}$

Mandelstam s, t, u

↳ translates into power laws for behavior of hadron structure as $x \to 1$

QCD Sum rules

incorporating heavy quark expansion and non-perturbative aspects of QCD via parameters for "condensates"

$\langle \bar{q} q \rangle$

$\langle \alpha_s G^{\mu\nu} G_{\mu\nu} \rangle$

$\langle g \, \bar{q} \, G^{\mu\nu} q \, G_{\mu\nu} \rangle$

$\vdots$ higher dimensions

$\Rightarrow$ parameterized $q^2 \to$ large behavior of B form factors $\hookrightarrow F_n$

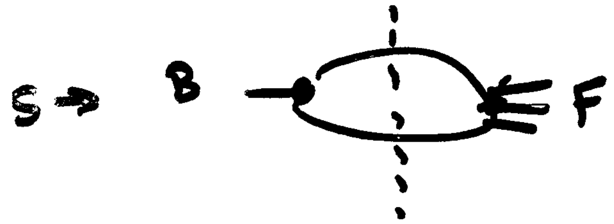
Uses

$$\Pi(\omega) = i \int d^4x \, e^{ik \cdot x} \langle 0 | T \, \bar{q} \gamma_5 h_v(x) \, \bar{h}_v(x) \gamma_5 q \, | 0 \rangle$$

$$= \sum_n \frac{F_n^2}{\nu_n - \omega - i\varepsilon}$$

$\boxed{\text{sum over states } n}$

↘ Quark-Hadron "Duality"



Transition Amplitude ⟺ Σ intermediate states

- quark diagrams, sum over quark states

⇕ ?

- physical discontinuities come from hadron states

When do quark diagrams give correct result?

→ SMEARING (Analytic continuation)   average over range of s e.g. $e^+e^- \to$ hadrons

LONG DISTANCE EFFECTS
e.g. IMAGINARY PART OF $A(s)$ at $s = s_0$

Integral over quark amplitudes at unphysical s   definite energy

But for B-decays

$$E = m_B$$

No energy averaging possible

Yet many possible final states contribute to decay

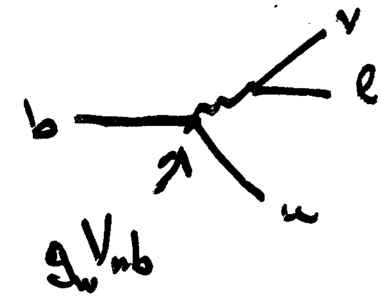
→ quark result <u>may</u> be good for some inclusive quantities

We know it does NOT correctly give every detail of spectrum e.g. end point

An example

Measure $B \to X_{\text{no charm}}\, \ell \nu$

Want to know V_{ub}



Simple to calculate total rate from quark level calculation

BUT

Measurement must cut to **exclude** background from charm decays

2 approaches

- lepton momentum $> m_b - m_c \approx m_B - m_D$
- hadronic invariant mass $< m_c$

Both introduce theoretical uncertainty

How well do we know the fraction excluded by the cut?

Difference in methods

$\Longleftrightarrow$ region of phase space retained

$\Longleftrightarrow$ sensitivity to assumptions about quark spectrum vs hadron spectrum

$\longrightarrow$ Hadron invariant mass cut method

$\Rightarrow$ Smaller theoretical uncertainty

But estimates of such uncertainties are themselves uncertain

<u>Usual game</u> – make variations in model for hadronization

See how fraction discarded by cut varies with model

How (where) can we measure B physics effects

Relatively long B lifetime $V_{cb} \sim \lambda^2 \Leftrightarrow$ Key

$B_{d,s}$ lifetime $\Leftrightarrow$ $e^+e^- \to Z \to b\bar{b}$
B_d mixing

SLD, LEP

B - branching fractions $e^+e^- \to \Upsilon_{4S} \to B^+B^-$
Direct CP Violation Searches $\to B_0\bar{B}_0$

CLEO, BABAR, BELLE

Coherent State

CP Asymmetries in B_d decays
Interference of decay with + without mixing

sin($\Delta m t$) BABAR BELLE

B_s mixing, CP asymmetries in tagged modes

TeVatron - CDF (D0)
→ BTeV

2 "separated" charged tracks

Signature of B events

⇒ vertex of charged tracks

≠ collision point

⇒ requires precision vertex reconstruction

Allows measure of decay time

⟷ separation depends on B momentum $\sim \gamma c \tau$

✓ large at $e^+e^- \to Z \to b\bar{b}$ in c of m

× effectively zero at CLEO (B's almost at rest)

✓ ~200 microns at BaBar & Belle

How do BaBar + Belle differ from CLEO?

Asymmetric Colliders

$e^+e^- \to \Upsilon_{4S} \to B\bar{B}$

Not in center of mass

$\Rightarrow$ 2 storage rings

different energies for e^+ + e^-

$\Rightarrow$ clever geometry to get collisions

2 B decays separated by 1 - 200 microns

$\Rightarrow$ Resolve vertices $\Rightarrow$ measure Δt

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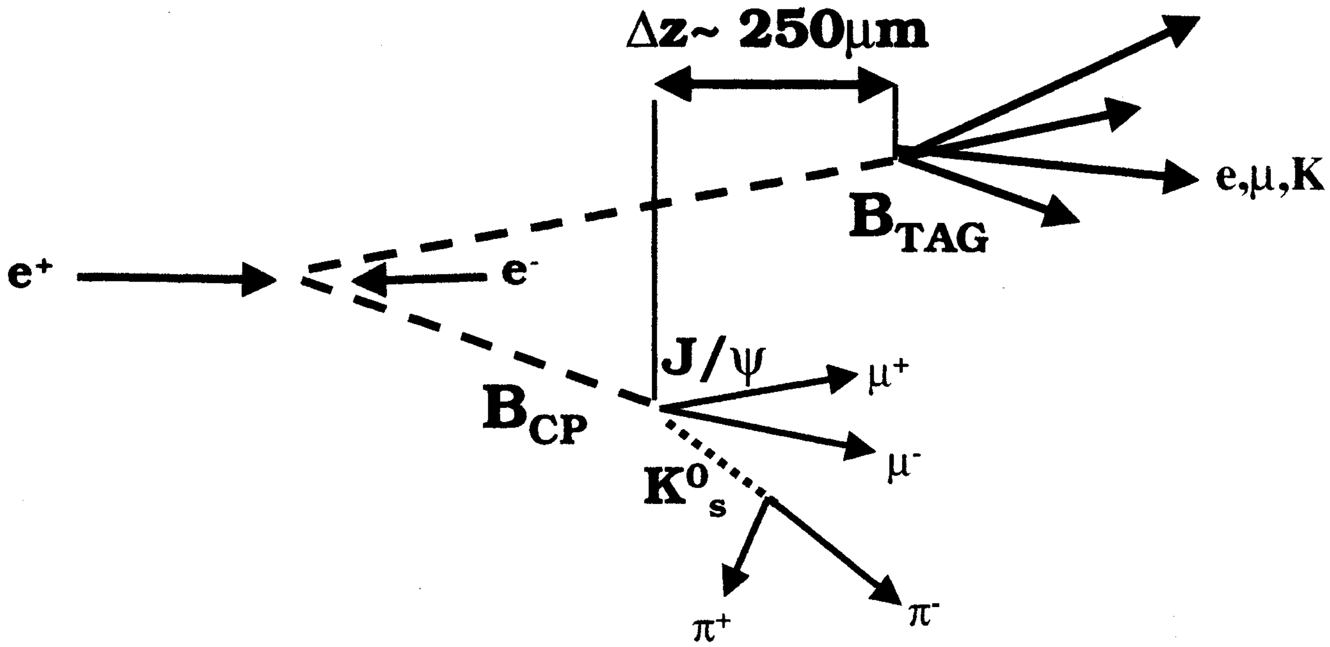
Introduction



- CP violation measurements require:
  - Measurement of time difference between two B decays.
    - Asymmetric machine.
  - High luminosity
    - Interesting decays have low branching ratios
  - Excellent tracking performance and vertex reconstruction.
  - Charged particle identification (e,μ,K,π) over large kinematic range.
  - Neutral particle reconstruction ($\gamma,\pi^0,K_L{}^0$).

Key detector properties

- Precision vertex definition — Silicon Tracker + Drift chamber

- π / K discrimination

  ($\frac{\partial E}{\partial x}$ in drift chamber) good at low momentum

  Cerenkov-type velocity sensitivity

  - CRID
  - DIRC
  - Aerogel

- Segmented calorimeter

  e.g. To Reconstruct $\pi^0 \to \gamma\gamma$

  $\Rightarrow$ neutral hadron and photon detection

- μ-detection system

  (+ K_L decays)

At B factories

$$e^+e^- \rightarrow \text{coherent} \left(B_0 \overline{B}_0 - \overline{B}_0 B_0 \right)$$

Need

- 1 decay to f_{CP} = CP eigenstate
- 1 decay to f_{tag} = flavor "tagging" final state

TAGGING

e.g. $b \rightarrow c \ell^- \nu$
$\bar{b} \rightarrow \bar{c} \ell^+ \nu$ ⇐ lepton tag

w depends on lepton momentum ⇒

$c \hookrightarrow s \ell^-$ ⇐ softer ℓ confuses lepton tag

$\searrow K^-(s\bar{u})$

$\bar{c} \hookrightarrow \bar{s} \ell^+$ K-tag

$\searrow K^+(\bar{s}u)$

⋮

ε efficiency $\qquad$ w : wrong sign fraction

$\varepsilon(1-2w)$ ← figure of merit

CP asymmetry

$$a = \frac{\Gamma(B \to f) - \Gamma(\bar{B}(f))}{\Gamma(B \to f) + \Gamma(\bar{B}(f))}$$

B tags $\quad N_B \propto (1-\omega)\Gamma_B + \omega\Gamma_{\bar{B}}$

$$N_{\bar{B}} \propto (1-\omega)\Gamma_{\bar{B}} + \omega\Gamma_B$$

$$\frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}} = (1-2\omega)\frac{\Gamma_B - \Gamma_{\bar{B}}}{\Gamma_B + \Gamma_{\bar{B}}}$$

measured asymmetry $\qquad$ actual asymmetry

dilution due to wrong tags

ω is calculated on an event-by-event basis

depends on all tagging info

$0 \leq \omega \leq 0.5$

$\omega = 0.5 =$ event with no tagging info

e.g. two decays to CP eigenstates

At hadron collider

TeVatron LHC

Rate of B production $\mathcal{O}(100) \times$ B factories

Challenge is to TRIGGER on these events

↳ record

Key : 2 charged tracks
with separated vertex

e.g. $B \to \psi K_s \to \pi^+\pi^-$
$\quad \hookrightarrow \mu^+\mu^-$

$B \to \pi^+\pi^-$

$B \to \phi K_s$
$\quad \hookrightarrow K^+K^-$

many but not all channels

→ B_s also produced as copiously as $B_d, B^{\pm}$

In hadron collider b or $\bar{b}$ production

is chiefly $g + g \rightarrow b + \bar{b}$

$\boxed{b \text{ and } \bar{b} \text{ hadronize independently}}$

- Tags can come from charge of associated B meson or ~~b~~ baryon-type
- Jet charge $\begin{cases} \text{~~of~~ hadronic jet including B} \\ \text{of opposite hadronic jet} \end{cases}$
- B-decays in opposite jet.

Typically TRIGGER * TAG

$\rightarrow \begin{cases} \text{lower efficiency} \\ \text{larger } \omega \end{cases}$ than for B factories

But remember: starting sample is much larger

$\rightarrow$ competitive in some channels

$\rightarrow$ see additional B_s, B-baryon channels

Homework excercise:

① Consider $\mathcal{L}$ = Standard Model

with
2 generations
1 Higgs doublet

Start with arbitrary <u>complex</u>

Yukawa couplings $Y_{ij}\, \varphi\, \bar{q}_R^i\, \psi_L^j$

where $\varphi = \begin{pmatrix} \varphi^0 \\ \varphi^- \end{pmatrix}$ $\quad \tilde{\varphi} = \begin{pmatrix} \varphi^+ \\ \varphi^{0*} \end{pmatrix}$ $\quad \tilde{Y}_{ij}\, \tilde{\varphi}\, \bar{q}_R^i\, \psi_L^j$

+h.c.

$$\langle \varphi^0 \rangle = v\, e^{i\eta}$$

Show that you can remove all phases

from Y_{ij}, $\tilde{Y}_{ij}$ and $\langle \varphi^0 \rangle$

by successive rephasing of quark & Higgs fields

$\boxed{\text{CDF and D}\emptyset}$

Designed originally for other physics

Upgrades have improved B-physics capability

TRIGGER RATES are an issue

i.e. fraction of pipeline capability available for B trigger events

Run 2 ~~will~~ should produce some interesting B-results

x_s

ψK_S

$\pi\pi$ / $K\pi$

⋮

$\boxed{\text{LHCB (LHC) and BTeV (Tevatron)}}$

Designed to optimize for B physics

⇒ Later start dates (still somewhat uncertain)

Have interesting capabilities

e.g. Rare B_s modes e.g. $B_s \to DK$

Modes needing large data samples

- Angular analysis of VV modes
- Dalitz Plot with multiple contributing channels
  $\rho\pi$, $f_0\pi$, … $\Rightarrow \pi^+\pi^-\pi^0$

Also in the future

Luminosity upgrades for BaBar and/or Belle?

Eventually we may be able to tackle
many rare decay channels
with combined data of all these
experiments

$B \to \pi^+ \pi^- \pi^0$ Dalitz plot analysis

$B_s \to D\pi$, DK, DK^* analyses

$B \to K l^+ l^-$