The Abdus Salam International Centre for Theoretical Physics

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Workshop on the original of P, CP and T Violation

2 - 5 July 2008

CP violation and CKM measurements in B decays.

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CANADA

CP violation and CKM measurements in B decays

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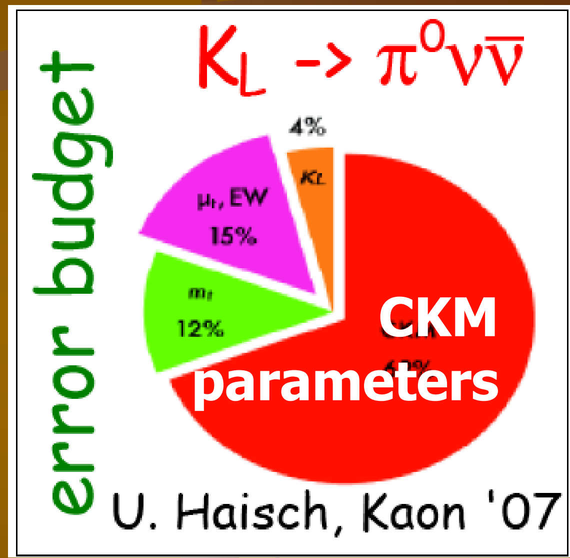
Importance of CKM measurements

- Need to pin down "standard" physics for many "new physics" searches, e.g. $K_L \rightarrow \pi^0 \nu\nu$:



- Improved precision translates directly into increased NP reach

- NP signal will be more credible if seen in multiple observables → need precise measurements of many quantities

CKM in B physics

- B decays allow *direct* access to 2 elements and *indirect* access to 2 others via loops

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- Can determine 2 angles and the phase in CKM
- $|V_{cb}|$ now known to ~2.5%; only $\sin\theta_C$ is known better

Unitarity relation of interest

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

Choice of parameters:

$\lambda,\ A,\ \bar{\rho}$ and $\bar{\eta}$

At the 1% level : $|V_{us}|$

$$\lambda = |V_{us}| = \sin\theta_c$$

$$\lambda = 0.2257 \pm 0.0021$$

At the 3% level : $|V_{cb}|$

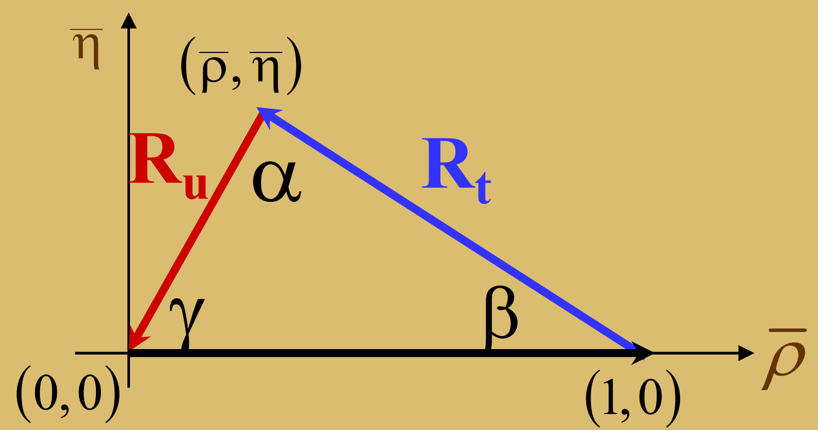
$$A = |V_{cb}|/\lambda^2$$

$$A = 0.809 \pm 0.024$$

$|V_{ub}|$ **and** $|V_{td}|$

$\rightarrow \bar{\rho}$ **-** $\bar{\eta}$ **plane**

Unitarity: $\mathbf{1 + R_t + R_u = 0}$



$$R_u = \frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}} \approx -\sqrt{\bar{\rho}^2+\bar{\eta}^2}\ e^{i\gamma}$$

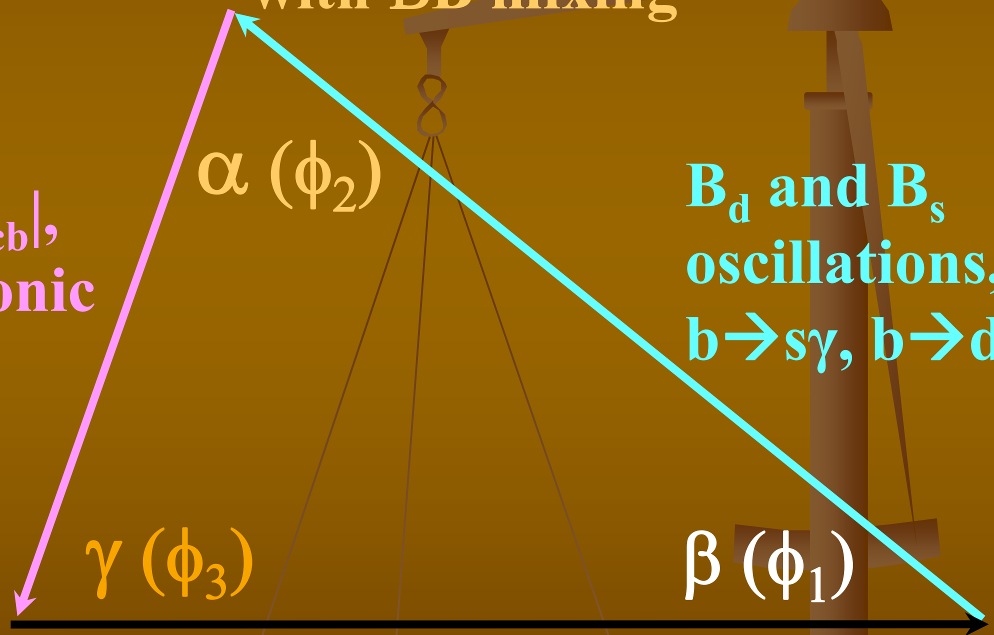
$$R_t = \frac{V_{td}V_{tb}^{*}}{V_{cd}V_{cb}^{*}} \approx -\sqrt{(1-\bar{\rho})^2+\bar{\eta}^2}\ e^{-i\beta}$$

$$\gamma = \arg V_{ub}^{*}\,,\quad \alpha = \pi-\gamma-\beta$$

Observables

In all cases many different modes accessible in e^+e^-

CP asmmetries in $b \rightarrow u\bar{q}q$ transitions with $\bar{B}B$ mixing



$|V_{ub}| / |V_{cb}|$, semileptonic B decays

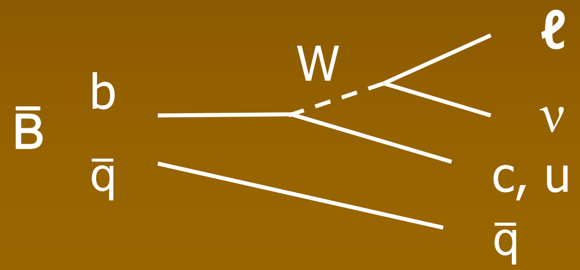
B_d and B_s oscillations, $b \rightarrow s\gamma$, $b \rightarrow d\gamma$

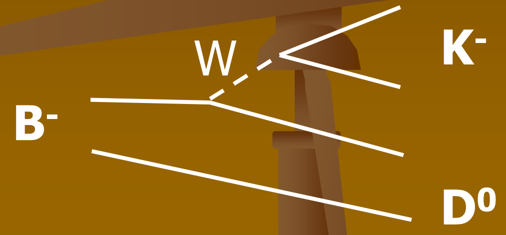
Direct CP asmmetries, e.g. $B^+ \rightarrow D^0K^+/\bar{D}^0K^+$

CP asmmetries in $b \rightarrow c\bar{c}s$ transitions with $\bar{B}B$ mixing

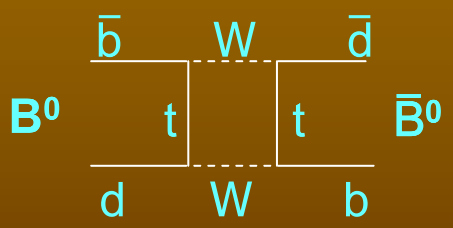
Trees and loops

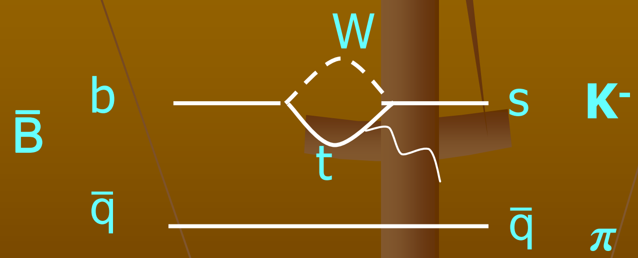
- Tree-dominated processes are ~free of new physics





- New physics, even at a high mass scale, can induce effects in loop-dominated processes (e.g. $W^+ \rightarrow H^+$)

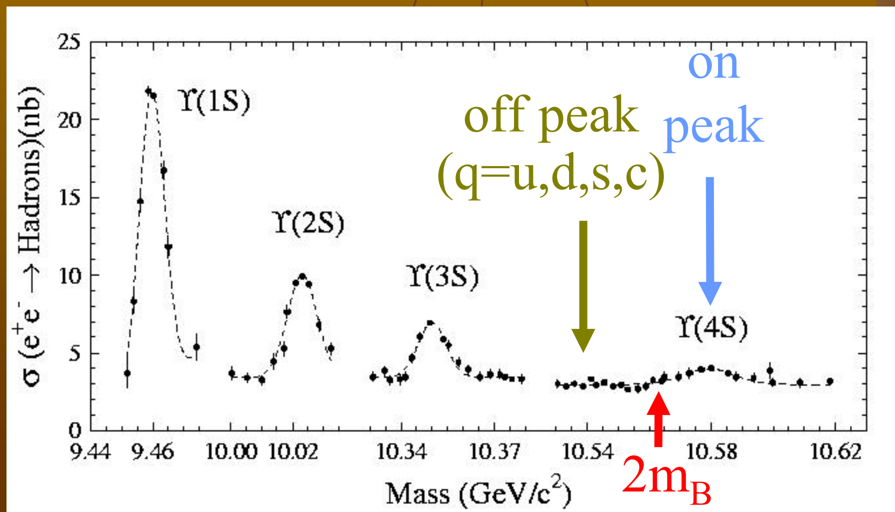


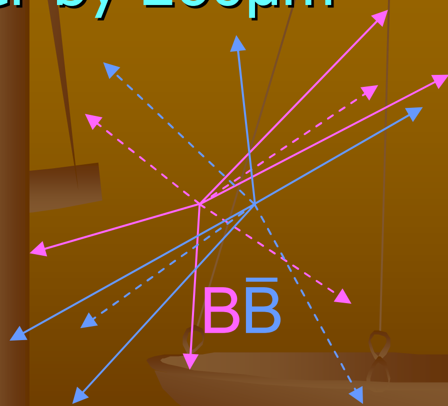


- Compare CKM parameters from tree and loop processes

Experimental setting: $e^+e^- \to Y(4S) \to B\bar{B}$

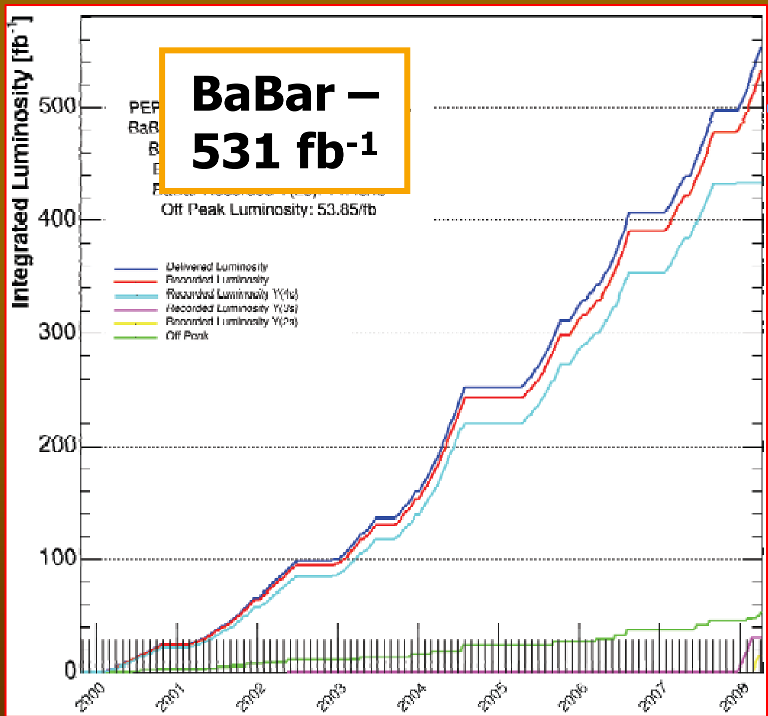
- 20 MeV above $B\bar{B}$ threshold; no additional pions
- B mesons have small speed $\beta \sim 0.06$ in Y(4S) frame
- Decay products of B and $\bar{B}$ overlap in detector
- $e^+e^- \to q\bar{q}$ continuum decays also produced
- At asymmetric B factories, B vertices differ by 260μm

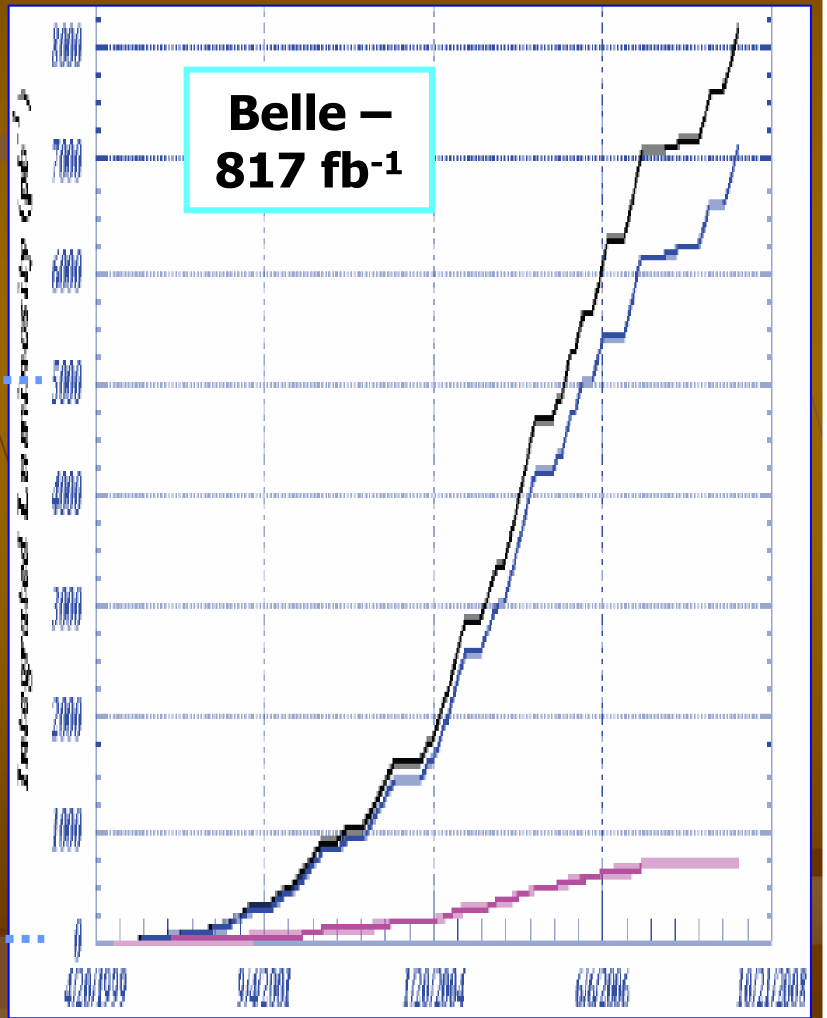




Belle and BaBar

- World’s highest luminosities - corresponds to 800 (500) 10^6 $B\bar{B}$ events for Belle (BaBar)

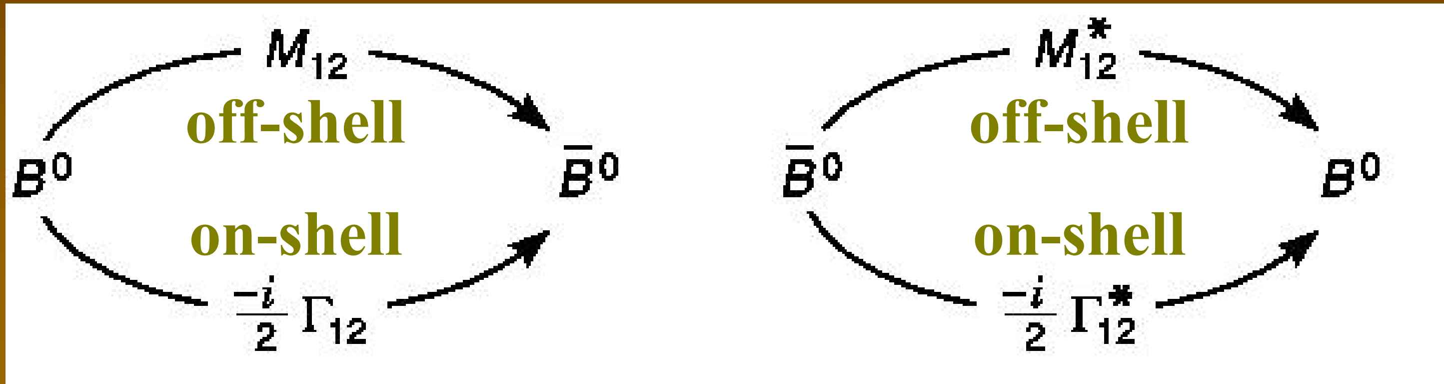




CP violation in B decay

- Need interference between competing amplitudes
  - B^0 Decay to CP eigenstate + $B\bar{B}$ mixing
    - Only neutral B mesons
    - Clean CKM info if 1 decay amplitude dominates
  - CP violation in interfering decay amplitudes
    - Need strong interaction phase shift information
    - Can exploit D^0 decays to CP eigenstates, DCSD
  - CP violation in $B\bar{B}$ mixing process – tiny in SM
- Several mechanisms can be present

CP Violation in Mixing



$$CP\left|B^0\right\rangle = e^{+2i\theta_{CP}}\left|\bar{B}^0\right\rangle$$
$$CP\left|\bar{B}^0\right\rangle = e^{-2i\theta_{CP}}\left|B^0\right\rangle$$

arbitrary phase

$$H_{eff} = \begin{pmatrix} M - \frac{i}{2}\Gamma & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & M - \frac{i}{2}\Gamma \end{pmatrix}$$

$$\text{CP violation } \textit{iff} \quad \left|\frac{q}{p}\right| \neq 1 \quad \text{where} \quad \left|\frac{q}{p}\right|^2 = \frac{\left\langle \bar{B}^0 \middle| H_{eff} \middle| B^0 \right\rangle}{\left\langle B^0 \middle| H_{eff} \middle| \bar{B}^0 \right\rangle} = \left|\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}\right|$$

HFAG average: $|q/p|$ = 1.0025± 0.0019

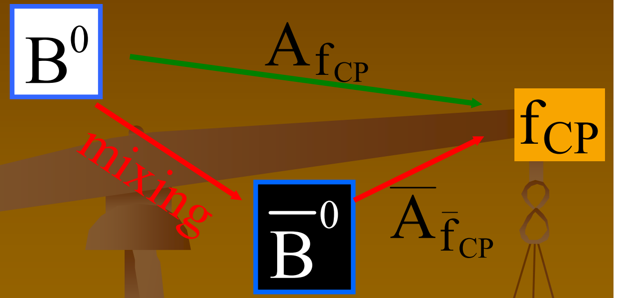
CP violation in the interference between mixing and decay

$$\lambda_{f_{CP}} = \eta_{f_{CP}} \frac{q}{p} \cdot \frac{\bar{A}_{\bar{f}_{CP}}}{A_{f_{CP}}}$$

CP eigenvalue

amplitude ratio

$\frac{q}{p} \approx e^{-2i\beta}$



$$\left|\bar{B}^0_{phys}(t)\right\rangle = e^{-iMt} e^{-\Gamma t/2} \left[\cos(\Delta m t/2)\left|\bar{B}^0\right\rangle + i(p/q)\sin(\Delta m t/2)\left|B^0\right\rangle\right]$$

$$\lambda_{f_{CP}} \neq \pm 1 \quad \Rightarrow \quad \mathrm{Prob}(\bar{B}^0_{phys}(t) \to f_{CP}) \neq \mathrm{Prob}(B^0_{phys}(t) \to f_{CP})$$

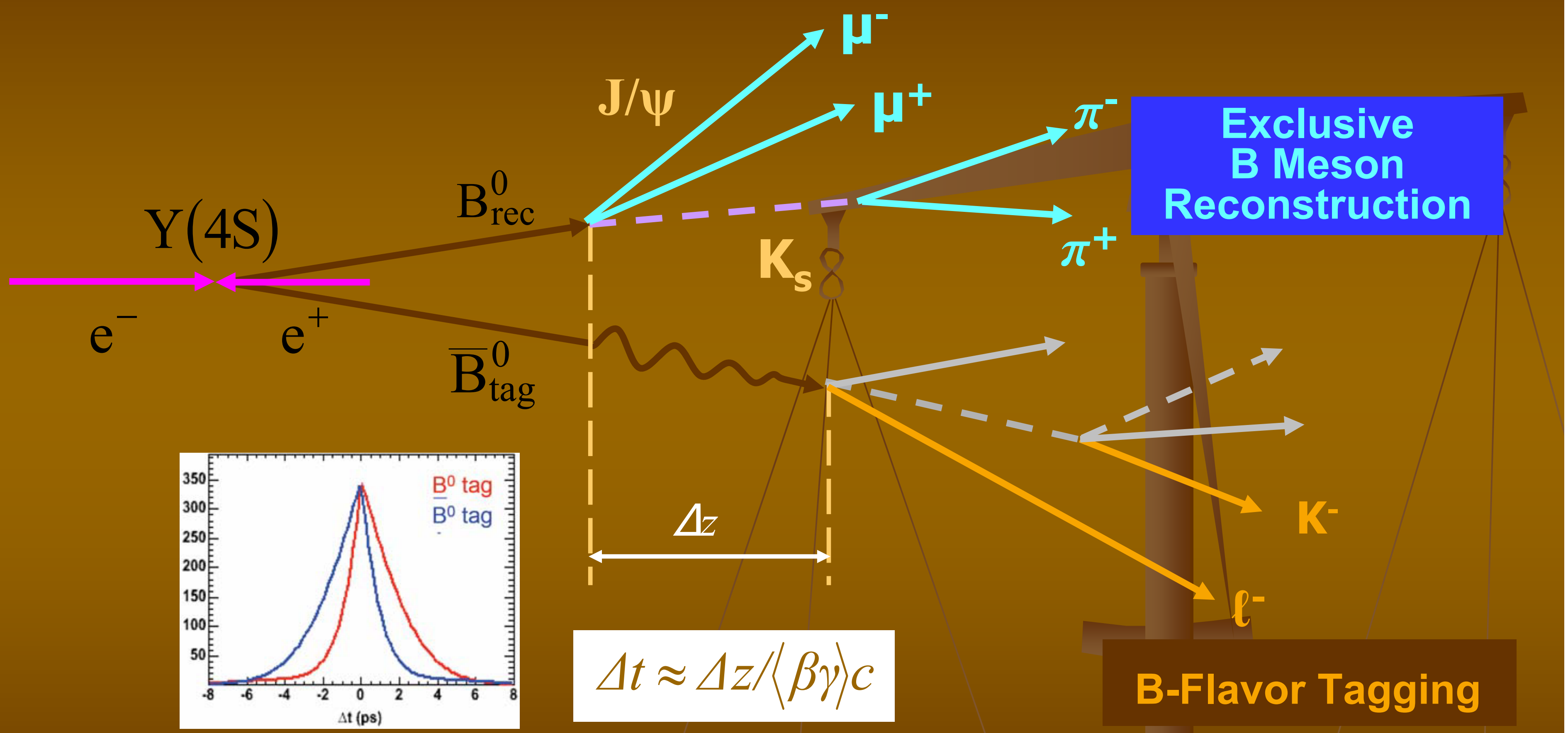
$$a_{f_{CP}}(t) = \frac{\Gamma(\bar{B}^0_{phys}(t) \to f_{CP}) - \Gamma(B^0_{phys}(t) \to f_{CP})}{\Gamma(\bar{B}^0_{phys}(t) \to f_{CP}) + \Gamma(B^0_{phys}(t) \to f_{CP})}$$
$$= C_{f_{CP}} \cdot \cos(\Delta m_{B_d} t) + S_{f_{CP}} \cdot \sin(\Delta m_{B_d} t)$$

$$C_{f_{CP}} = \frac{1 - |\lambda_{f_{CP}}|^2}{1 + |\lambda_{f_{CP}}|^2}$$

$$S_{f_{CP}} = \frac{2\,\mathrm{Im}\lambda_{f_{CP}}}{1 + |\lambda_{f_{CP}}|^2}$$

We have $|q/p| \approx 1$. If one amplitude dominates, $|\bar{A}/A| \approx 1$, but $\mathrm{Im}(\lambda) \neq 0$

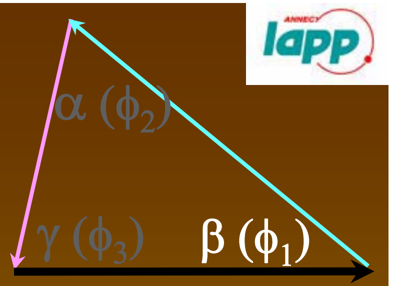
Outline of the measurement



(flavor eigenstates) ➡ lifetime, mixing analyses

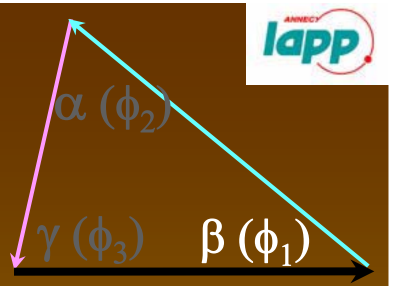
(CP eigenstates) ➡ CP analysis

β (ϕ_1) determination



- Time-dependent CP asymmetries in b→c transitions
- Golden mode for theory and experiment: $B^0 \to X_{cc} K_{S,L}$
- Tree amplitude dominates
  - ~no additional weak phases
  - error on S=sin2β: estimates from 0.001 to 0.017
- Charmonium X_{cc} decays to lepton pairs
  - Easy to reconstruct; good definition of decay vertex
  - ~all K^0_S decays can be reconstructed
  - Even K^0_L can be used due to kinematic constraints

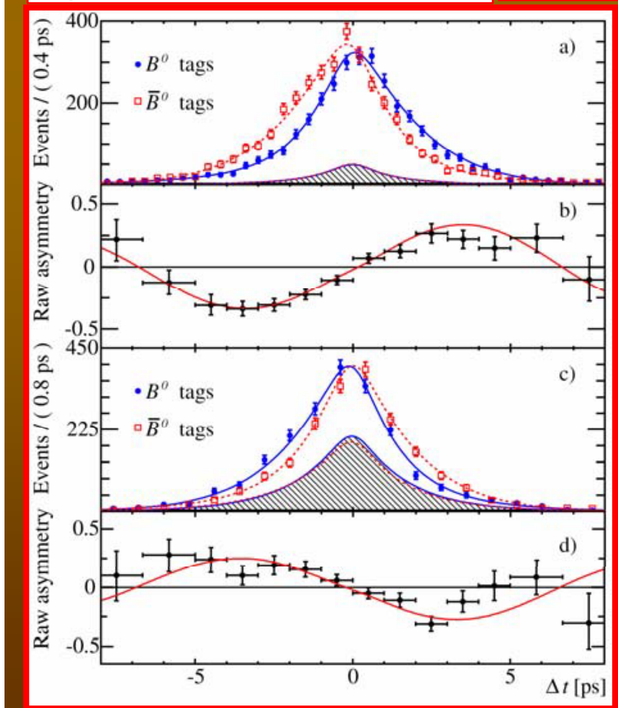
Golden modes for β (ϕ_1)



- $B^0 \rightarrow X_{cc} K^{(*)0}$ (X_{cc} = J/ψ, ψ(2S), χ_{c1}, η_c; K^0 or $K^{*0} \rightarrow K^0\pi^0$)
- Results compiled by HFAG

sin2β= 0.714±0.032±0.018
C=-A= 0.049±0.022±0.017

Phys. Rev. Lett. **99**, 171803 (2007)

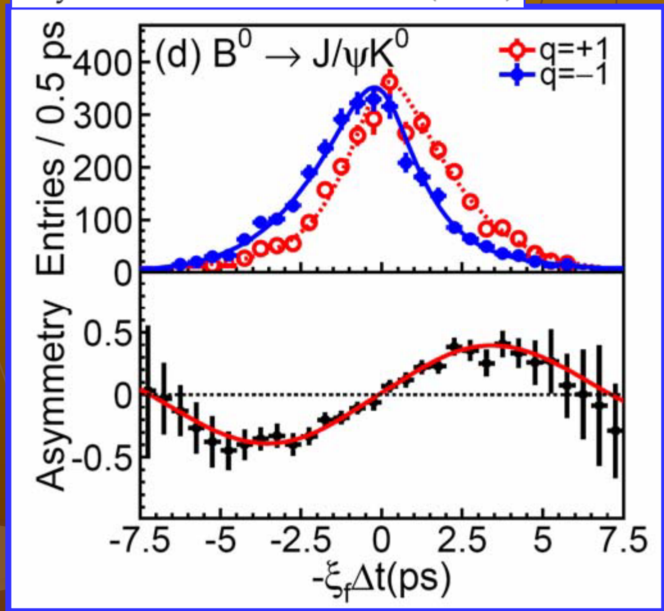


HFAG average:

sin2β= 0.680±0.025
C=-A= 0.012±0.020

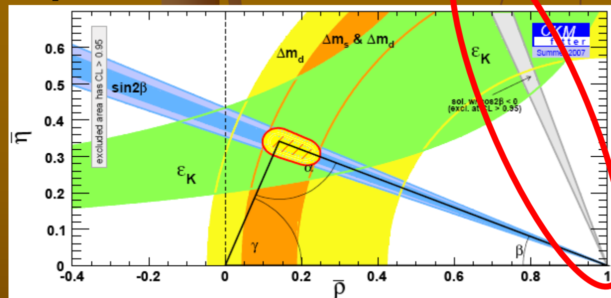
sin2β= 0.650±0.029±0.018
C=-A=-0.018±0.021±0.014

Phys. Rev. Lett. **98**, 031802 (2007)



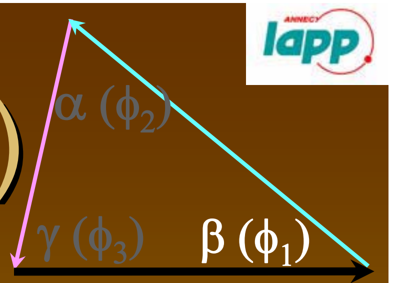
Other β measurements

- Many other modes exhibit Time-dependent CP violation (TDCPV) yielding β:
  - $B^0 \rightarrow D\bar{D}K_S$, $D_{CP}h^0$, $D_{Dalitz}h^0$, $K^+K^-K^0$, …
- Analyses of decays involving different spin or Dalitz amplitudes give sensitivity to cos2β: rules out mirror solution for β

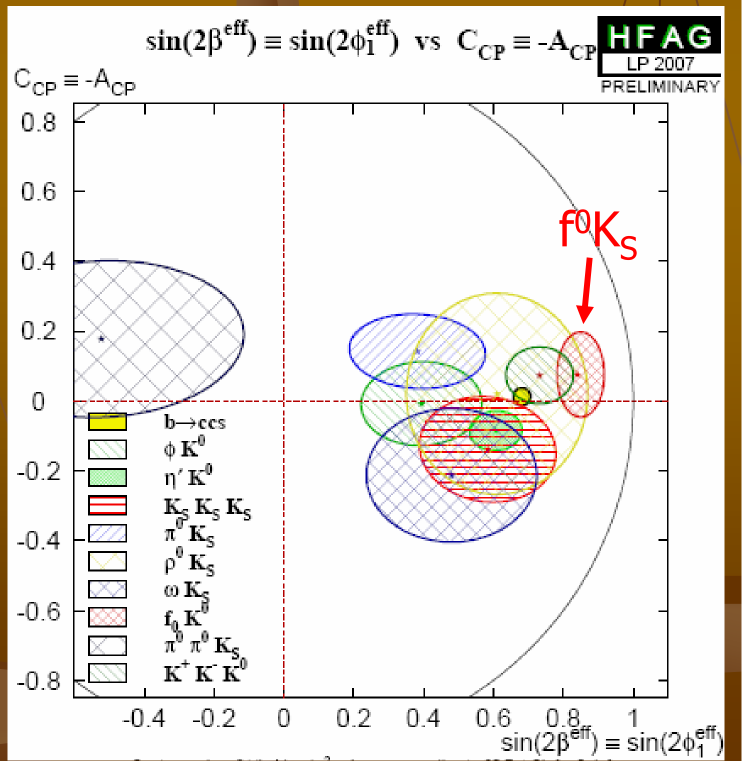


- Too many measurements to mention here; significant (>3σ) CP asymmetries in 11 individual modes

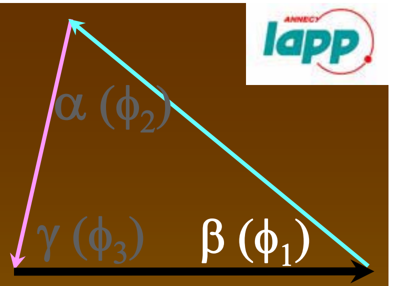
Penguin modes for β (ϕ_1)



- TDCPV in $b \rightarrow q\bar{q}s$ penguin decays measures β_{eff} in SM; e.g. modes $B^0 \rightarrow \phi K^0$, $\eta^{(\prime)} K^0$, $\pi^0 K^0$, $f^0 K^0$, $K^0 K^0 K^0$, etc.
- $\beta_{eff} \neq \beta$ due to additional EW phase; $\delta\beta$ varies per mode
- Interest in $b \rightarrow q\bar{q}s$ continues, consistency with golden modes depends on data selection, estimate of theory uncertainties

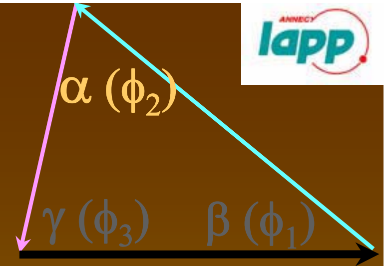


Prospects for β (ϕ_1)



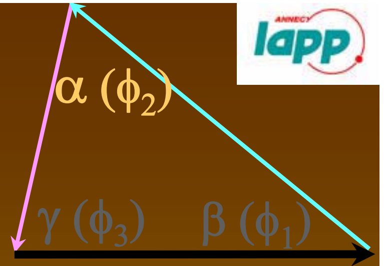
- Super-B with 10^{36} luminosity (assume 75 ab^{-1} dataset)
  [projections taken from arXiv:0709.0451]
  - sin2β from charmonium: ±0.005 (detector syst)
  - Uncertainties of few % in b→cūd modes (stat)
  - Uncertainties of few % in b→ss̄s modes (theory)
- Self-consistency of above modes constrains NP
- Highly accurate knowledge of β pins down CKM

Measuring α (ϕ_2)



- TDCPV in b→u transitions
- Many final states have contributions from >1 amplitude (tree, Penguin, color-suppressed tree)
- Asymmetries proportional to α_{eff}; differs from α by a mode-dependent offset
- Full isospin amplitude analysis needed to determine $\delta\alpha$
- Most useful modes in practice:
  - $B^0 \rightarrow \rho^0\rho^0$, $\rho^+\rho^-$, $B^+ \rightarrow \rho^+\rho^0$
  - $B^0 \rightarrow \pi^0\pi^0$, $\pi^+\pi^-$, $B^+ \rightarrow \pi^+\pi^0$
  - $B^0 \rightarrow \pi^+\pi^-\pi^0$ Dalitz

$B^0 \to \pi\pi$

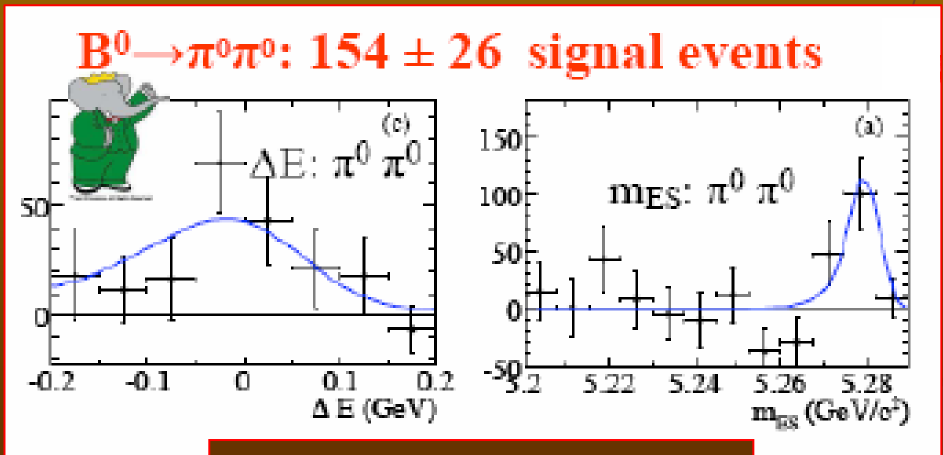


- $B \to \pi\pi$; easy experimentally (except $\pi^0\pi^0$, for which time-dependent asymmetry can't readily be measured)
- In each case need isospin analysis (Gronau, London PRL**65:**3381(1990)) to determine δα; hope for $A_{hh}^{00} \ll A_{hh}^{+-}$
- 8-fold ambiguities in solution for α

HFAG

$BF(B^0 \to \pi^+\pi^-) = (5.2 \pm 0.2) \times 10^{-6}$

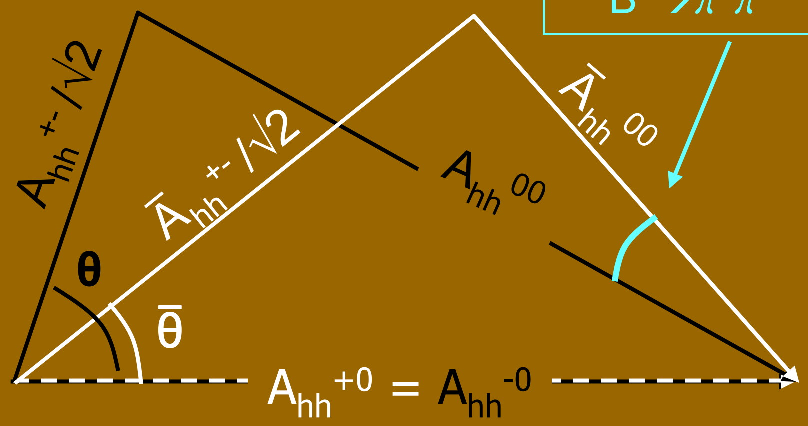
$BF(B^0 \to \pi^0\pi^0) = (1.3 \pm 0.2) \times 10^{-6}$ (**big!**)



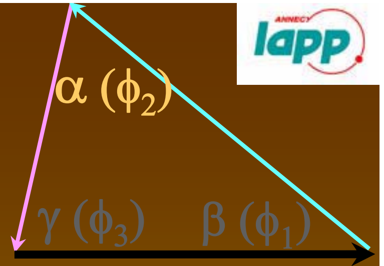
BaBar, PRD**76**:091102(2007)

$\theta - \bar{\theta} = 2\,\delta\alpha$

No TDCPV input in $B^0 \to \pi^0\pi^0$



$B^0 \rightarrow \rho\rho$

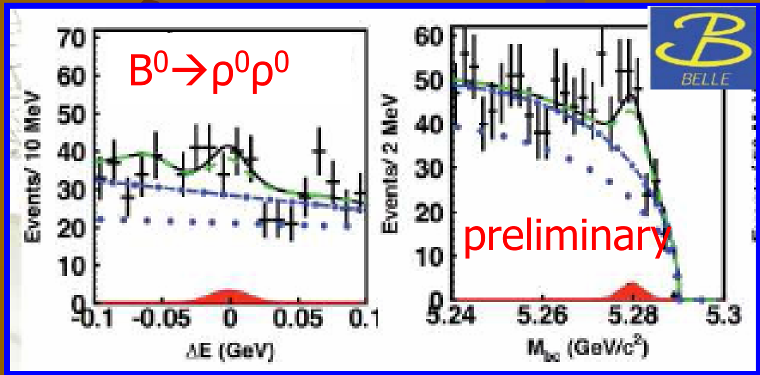


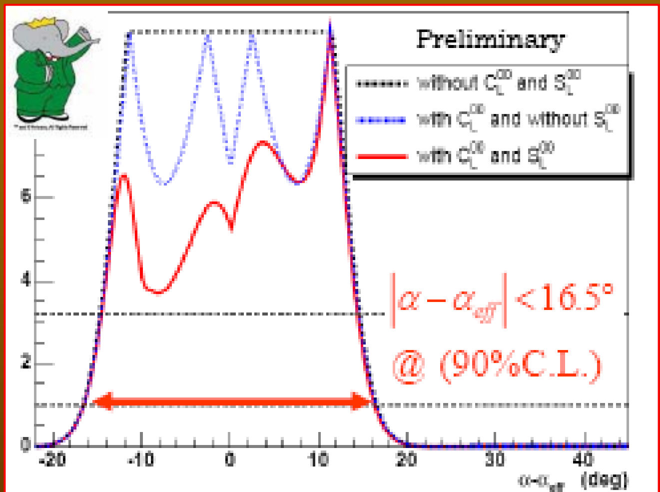
- $B \rightarrow \rho\rho$; polarization determines CP eigenvalue
  - experiment: ~full longitudinal polarization (CP even)
- Isospin analysis as for $\pi\pi$, but $\rho^0\rho^0$ easier, smaller

HFAG

$BF(B^0 \rightarrow \rho^+\rho^-) = (24.2 \pm 3.2) \times 10^{-6}$

$BF(B^0 \rightarrow \rho^0\rho^0) = (\ 1.1 \pm 0.4) \times 10^{-6}$



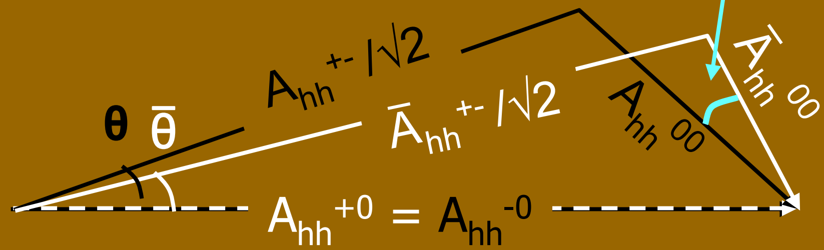


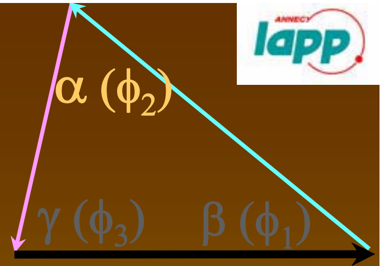
Impact of $A(B^0 \rightarrow \rho^0\rho^0)$

arXiv:0708.1630

$\theta - \bar{\theta} = 2\,\delta\alpha$

Angle constrained by TDCP in $B^0 \rightarrow \rho^0\rho^0$





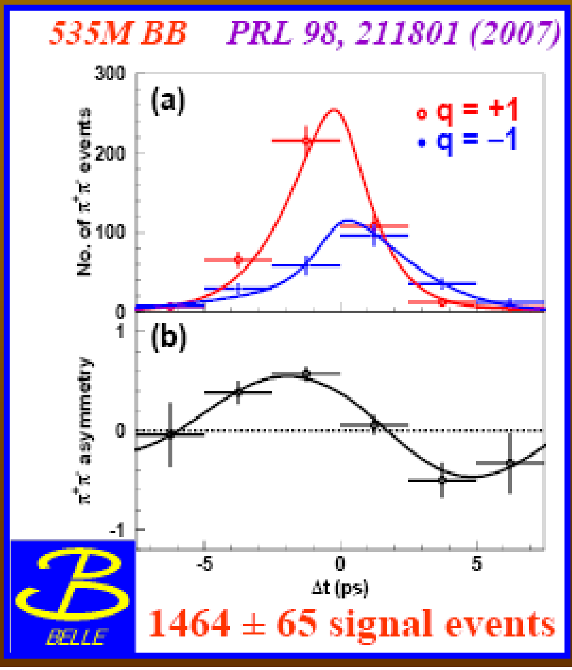
Main input for α (ϕ_2)

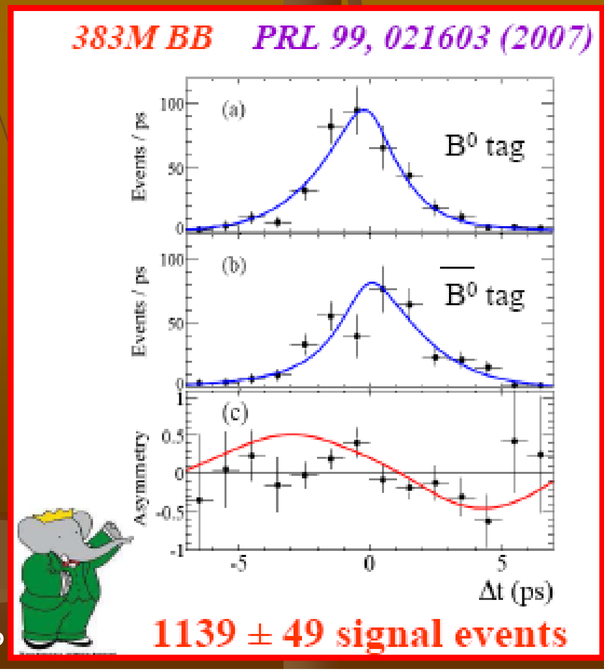
- $B \rightarrow \pi^+\pi^-$:

	S_{+-}	C_{+-}
Belle	-0.61±0.10±0.04	-0.55±0.08±0.05
BaBar	-0.60±0.11±0.03	-0.21±0.09±0.02

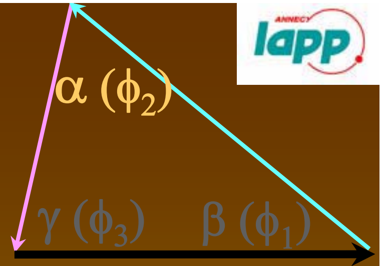
- $B \rightarrow \rho^+\rho^-$:

	S_L^{+-}	C_L^{+-}	f_L
Belle	0.19±0.30±0.08	-0.16±0.21±0.08	0.941±0.037±0.030
BaBar	-0.17±0.20±0.06	0.01±0.15±0.06	0.992±0.024±0.026





Constraints on α (ϕ_2)



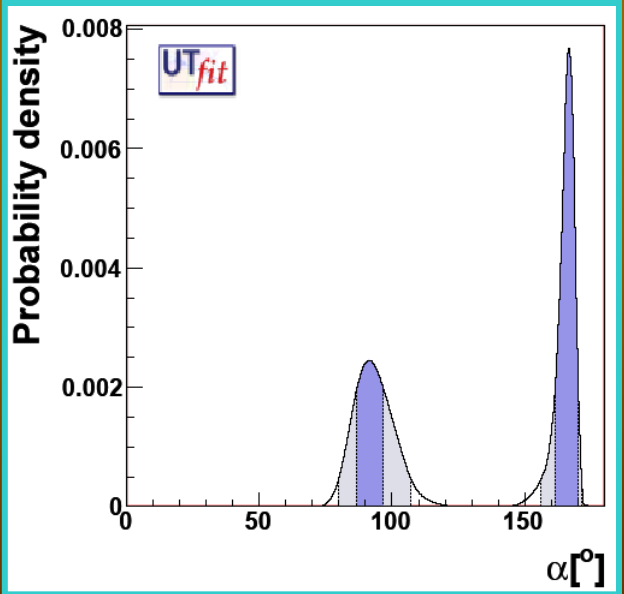
- Isospin analyses on $\pi\pi$, ρρ; Dalitz analysis on ρπ
- Combined result is

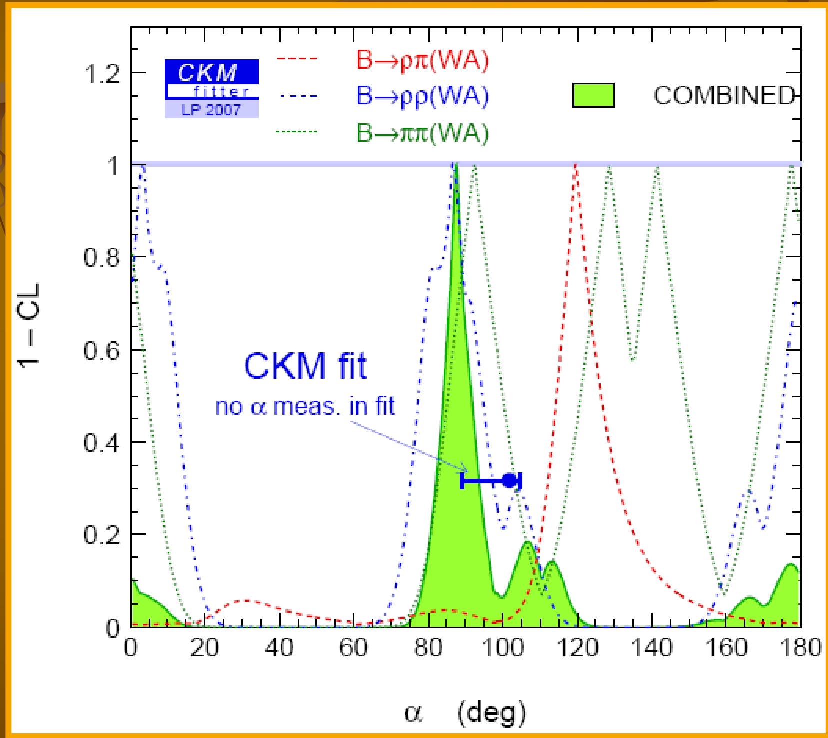
UTfit

$$\alpha = 91 \pm 8^\circ$$

CKMfitter

$$\alpha = \left(87.5^{+6.2}_{-5.3}\right)^\circ$$

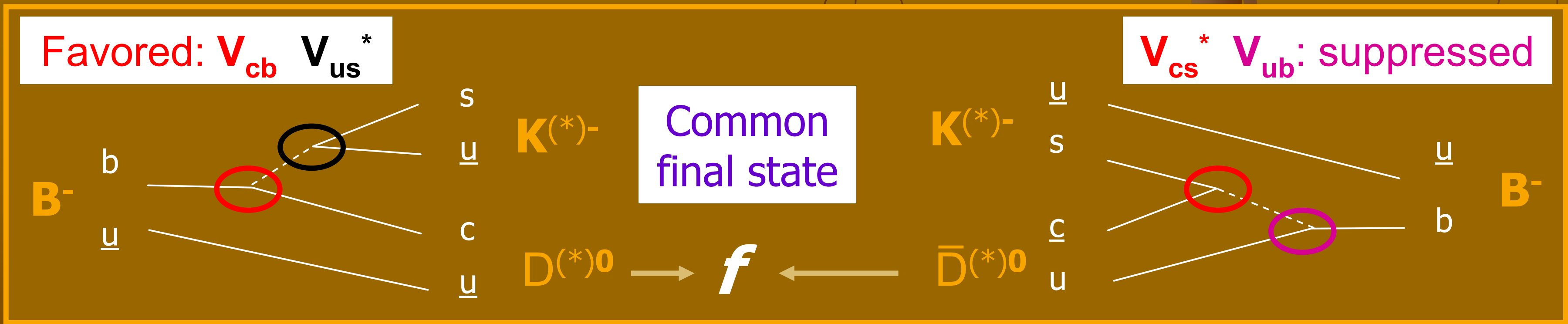




SuperB projects 1-2° in ρρ, 2° in ρπ and 3° in $\pi\pi$; theory limited

Direct CP violation

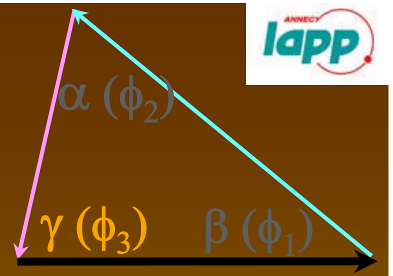
- Interference between competing amplitudes (e.g. tree and penguin) involve strong phase shifts → uncertainty
- Important special case: CP eigenstates or doubly CKM-suppressed decays lead to same final state of D^0 and $\bar{D}^0$.



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

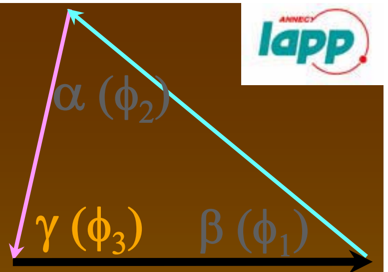
Parameters: γ,
(r_B, δ_B) per mode

Accessing γ (ϕ_3)



- Need interference → common final state for D^0 and $\bar{D}^0$
  - CP eigenstates (GronauLondonWyler): $D^0 \to K^+K^-$, $\pi^+\pi^-$, $K_S\pi^0$…
  - Double CKM-suppressed (AtwoodDunietzSoni): $D^0 \to K^+\pi^-$…
  - 3-body Dalitz (GiriGrossmanSofferZupan, Bondar): $K_S\pi^+\pi^-$…
- Measure asymmetries between B^+ and B^- decays and ratios of average decay rates to gain sensitivity to magnitude (r_B) and phase (δ_B) of amplitude ratio
- These are tree-level decays → insensitive to NP
- Self-tagging $B^0 \to D^{(*)0}K^{*0}$ ($K^{*0} \to K^+\pi^-$) also measure γ
- TDCPV in $B^0 \to D^{(*)+}h^-$ and $D^{(*)-}h^+$ measures $\sin(2\beta+\gamma)$

Observables for γ (ϕ_3)



- GLW: CP +/- eigenstates

r_B, δ_B, γ

8-fold ambiguity on γ

$$\mathcal{A}_{CP\pm} = \frac{\Gamma(B^- \to D_\pm K^-) - \Gamma(B^+ \to D_\pm K^+)}{\Gamma(B^- \to D_\pm K^-) + \Gamma(B^+ \to D_\pm K^+)} = \frac{\pm 2 r_B \sin\delta_B \sin\gamma}{1 + r_B^2 \pm 2 r_B \cos\delta_B \cos\gamma}$$

$$\mathcal{R}_{CP\pm} = \frac{\Gamma(B^- \to D_\pm K^-) + \Gamma(B^+ \to D_\pm K^+)}{\Gamma(B^- \to D^0 K^-) + \Gamma(B^+ \to \overline{D}^0 K^+)} = 1 + r_B^2 \pm 2 r_B \cos\delta_B \cos\gamma$$

- ADS: DCSD

r_B, δ_B, r_D, δ_D, γ

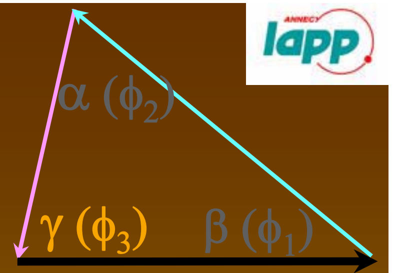
amplitude ratio

$$\frac{A(B^- \to \overline{D}[K^+\pi^-]K^-)}{A(B^- \to D[K^+\pi^-]K^-)} = r_B e^{i\delta_B} e^{-i\gamma} \Big/ r_D e^{-i\delta_D}$$

$$\mathcal{A}_{ADS} = \frac{\Gamma(B^- \to [K^+\pi^-]K^-) - \Gamma(B^+ \to [K^-\pi^+]K^+)}{\Gamma(B^- \to [K^+\pi^-]K^-) + \Gamma(B^+ \to [K^-\pi^+]K^+)} = \frac{2 r_B r_D \sin(\delta_B + \delta_D)\sin\gamma}{\mathcal{R}_{ADS}}$$

$$\mathcal{R}_{ADS} = \frac{\Gamma(B^- \to [K^+\pi^-]K^-) + \Gamma(B^+ \to [K^-\pi^+]K^+)}{\Gamma(B^- \to [K^-\pi^+]K^-) + \Gamma(B^+ \to [K^+\pi^-]K^+)} = r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_B + \delta_D)\cos\gamma$$

Dalitz method for $\gamma\ (\phi_3)$

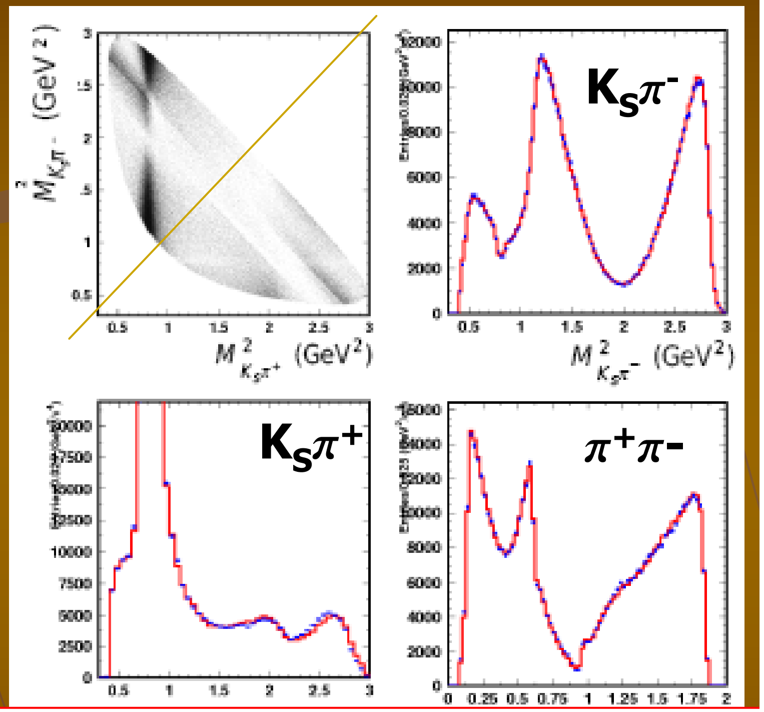


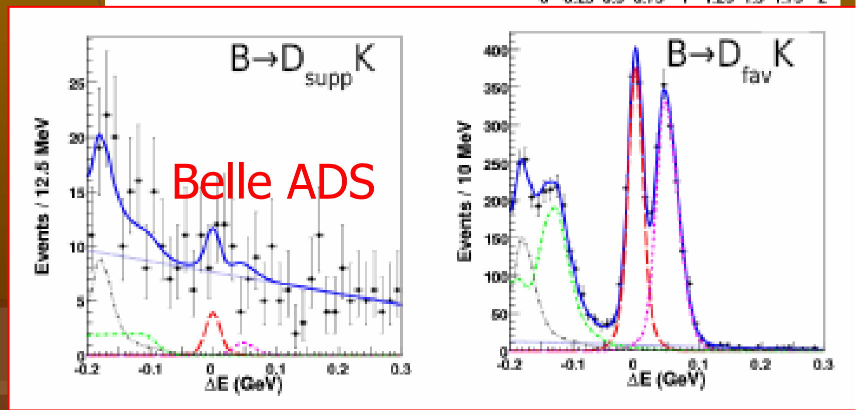
- Most precise results from Dalitz method: $B^- \to [K_S \pi^+ \pi^-] K^{(*)-}$; also use $D^{*0} \to D^0 \pi^0$, $D^0 \gamma$
- Amplitude ($m_+ \leftrightarrow m_-$ ➔ $D^0 \leftrightarrow \bar{D}^0$)

$$A_\pm = f\left(m_+^2, m_-^2\right) + r_B e^{\pm i\gamma} e^{i\delta_B} f\left(m_-^2, m_+^2\right)$$

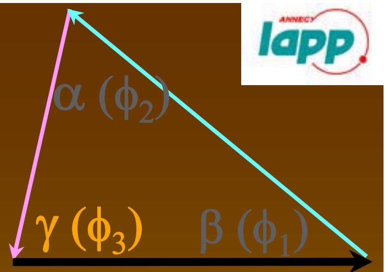
at point $m_\pm^2 \Rightarrow m^2\left(K_s \pi^\pm\right)$

- Determine f in flavor-tagged $D^{*+} \to D^0 \pi^+$ decays
- need D^0 decay model (~18 quasi-2-body states)
- Can remove modeling error using $\psi(3770) \to D\bar{D}$ data (CLEOc, BES)
- BaBar also analyze $D^0 \to K_S K^+ K^-$





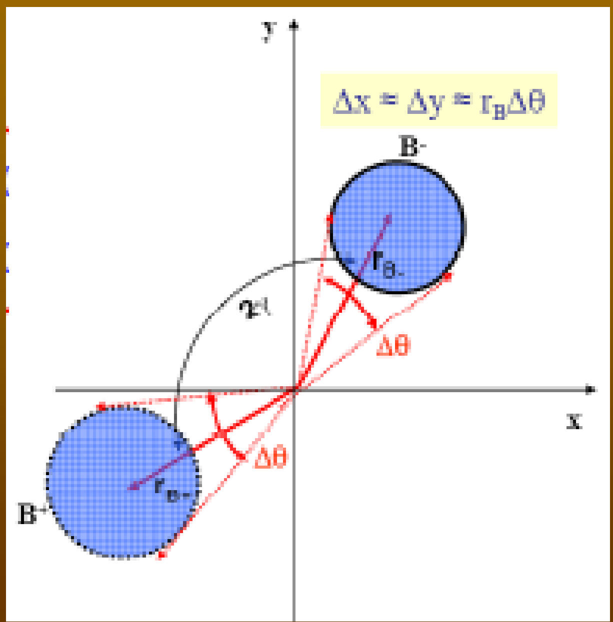
Dalitz method results



- Quote Cartesian variables: $x_\pm = r_B \cos(\pm\gamma+\delta)$, $y_\pm = r_B \sin(\pm\gamma+\delta)$

	BaBar [arXiv : 0804.2089] 383M $B\bar{B}$	Belle [arXiv : 0803.3375] 657M $B\bar{B}$
x_-	$+0.090 \pm 0.043 \pm 0.015 \pm 0.011$	$+0.105 \pm 0.047 \pm 0.011$
y_-	$+0.053 \pm 0.056 \pm 0.007 \pm 0.015$	$+0.177 \pm 0.060 \pm 0.018$
x_+	$-0.067 \pm 0.043 \pm 0.014 \pm 0.011$	$-0.107 \pm 0.043 \pm 0.011$
y_+	$-0.015 \pm 0.055 \pm 0.006 \pm 0.008$	$-0.067 \pm 0.059 \pm 0.018$

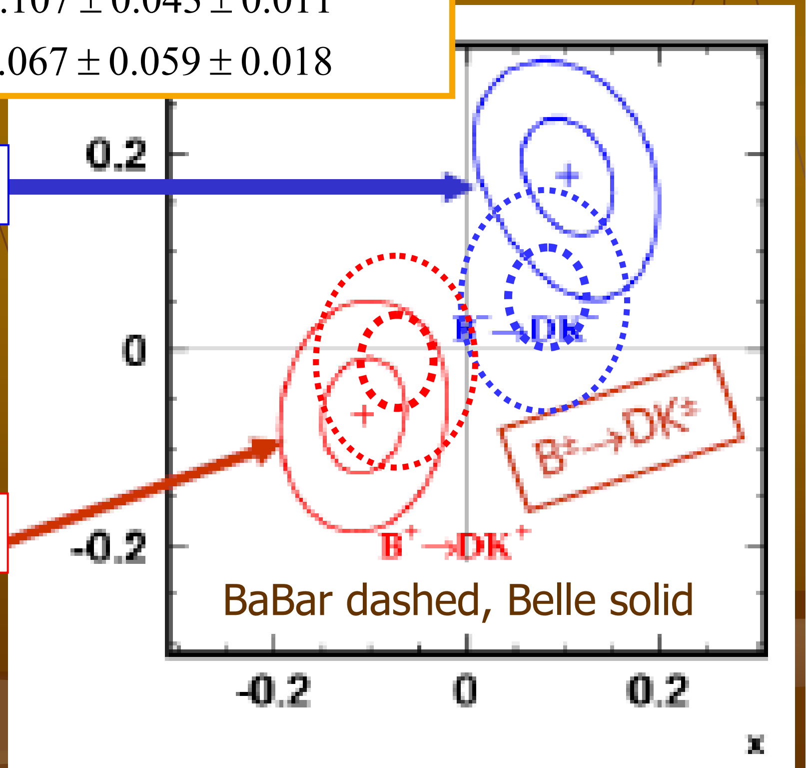
$B^- \to DK^-$



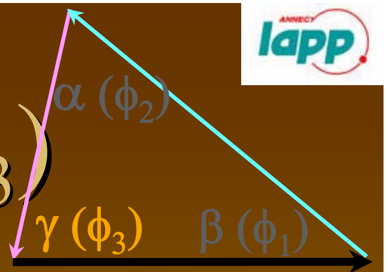
$B^- \to DK^-$

$B^+ \to DK^+$

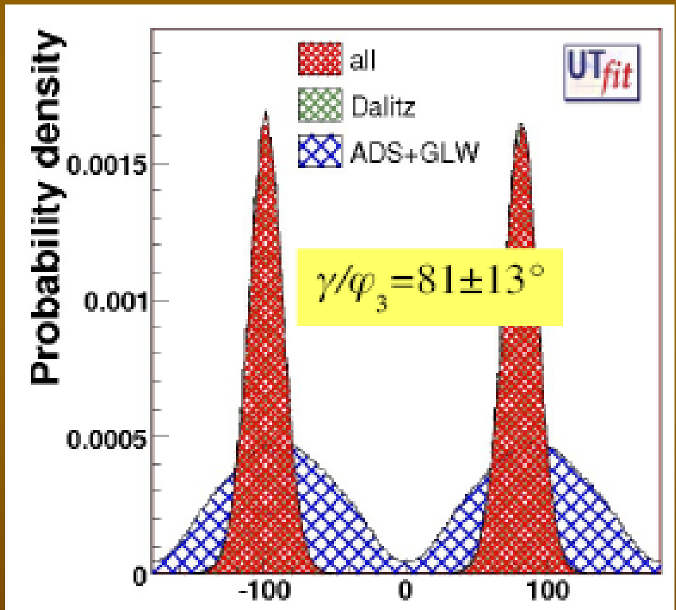
Similar results in D^*K and DK^*

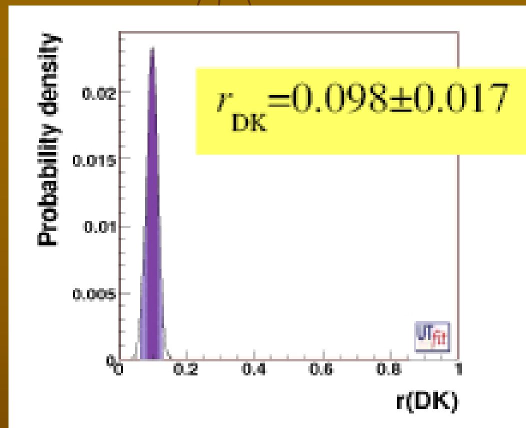


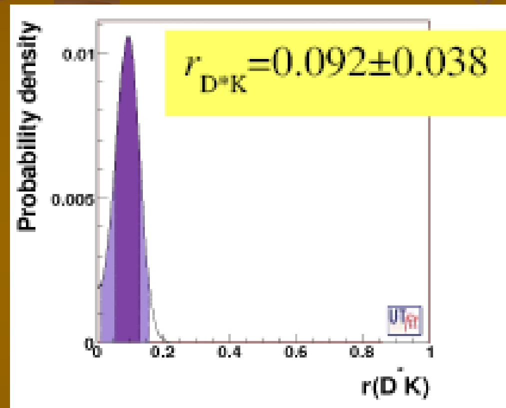
Combined results for γ (ϕ_3)

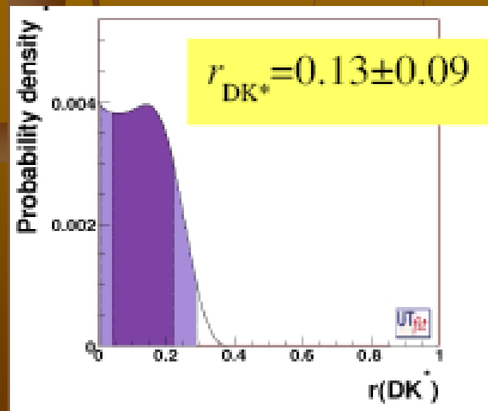


- Three methods (ADS, GLW and Dalitz) can be combined for each of $B^- \rightarrow D^0 K^-$, $B^- \rightarrow D^{*0} K^-$ and $B^- \rightarrow D^0 K^{*-}$



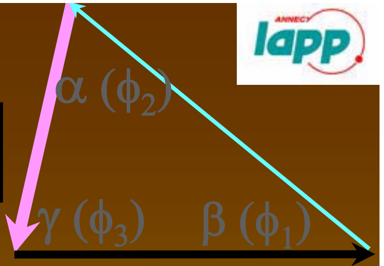




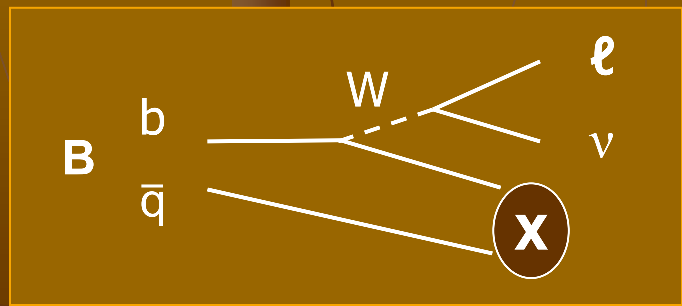


- SuperB: 1-2% from all methods combined; statistics limited

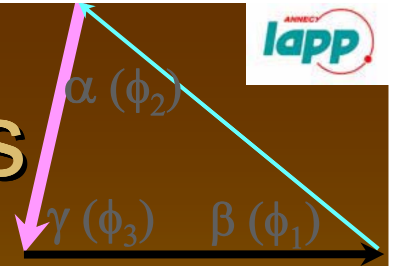
The left side - $|V_{ub}| / |V_{cb}|$



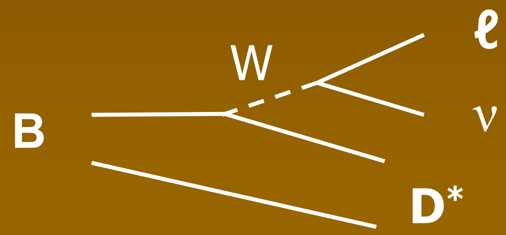
- The determination of the $|V_{ub}|$ and $|V_{cb}|$ relies on semileptonic decays → only one hadronic current
- Tree decays – like γ, insensitive to NP
- Two complementary approaches:
  - **Exclusive**: **X** fully reconstructed
    - Need form factor normalization (non-perturbative)
  - **Inclusive**: sum over many **X** states, with at most partial reconstruction of the **X** system
    - Use OPE in $(1/m_b)^n$



Exclusive semileptonic decays



- Conceptually simple – measure $F(q^2)|V_{cb}|$



$$\frac{d\Gamma\left(B \to D^{*}\ell\nu\right)}{dq^{2}} = \frac{G_F^2 |V_{cb}|^2}{48\pi^3} \left(F(q^2)\right)^2 G(q^2)$$

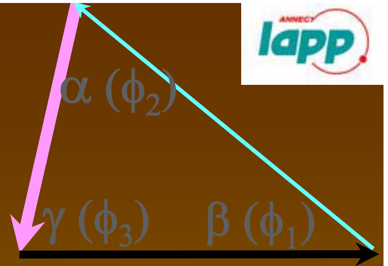
form factors

$q^2 = (p_\ell + p_\nu)^2$

(momentum transfer)^2

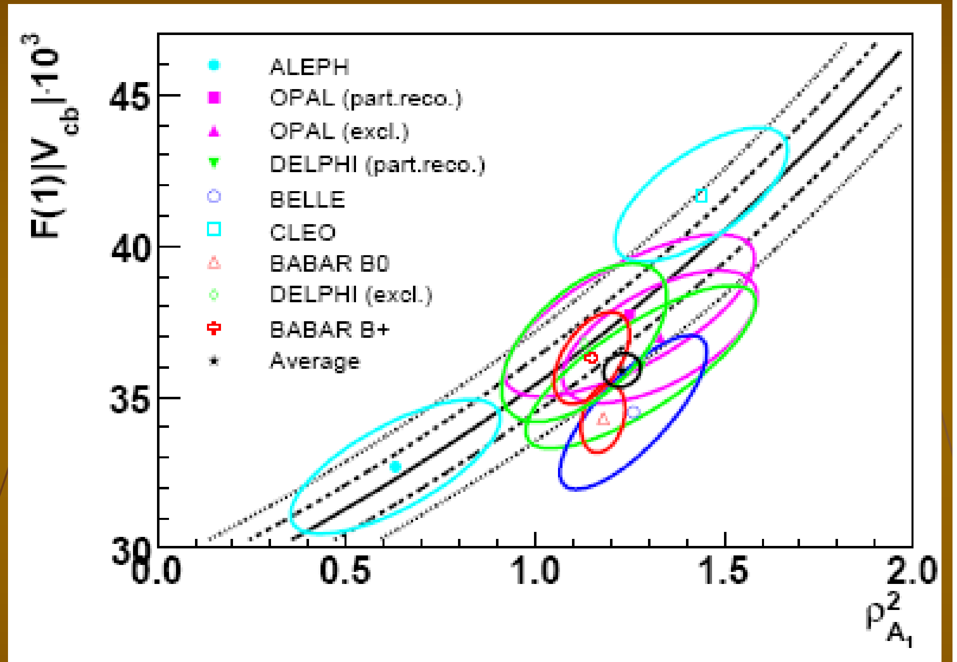
phase space

- QCD uncertainties enter calculation of form-factors F
  - One form-factor per Lorentz structure in amplitude
  - Shapes versus q^2 can be measured
  - Normalization from theory → uncertainty (~2% now)

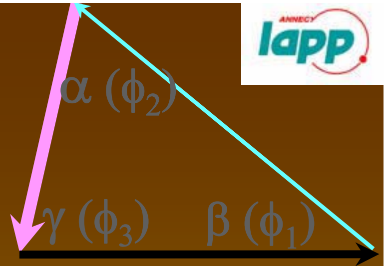


$|V_{cb}|$ from $B \to D^* \ell \nu$

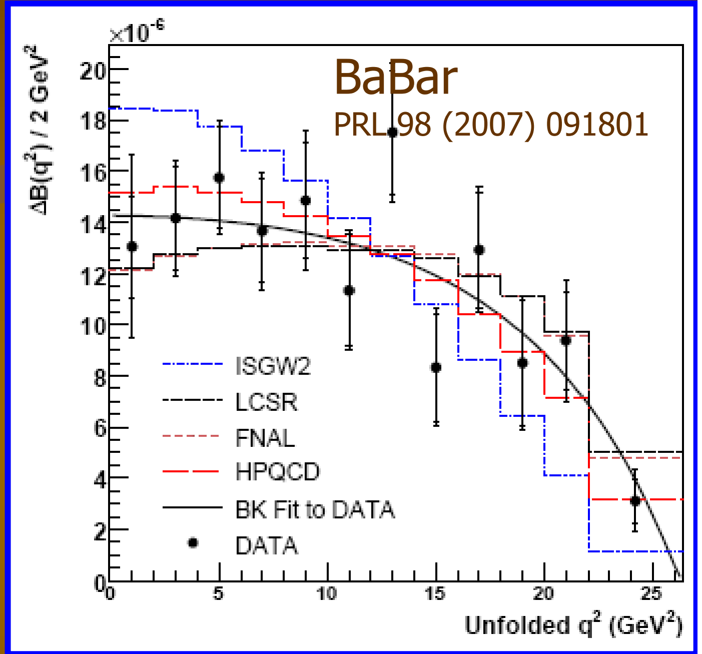
- Measure decay rate versus 4-velocity transfer w and determine $F(1)|V_{cb}|$ and FF slope
  $F(w) = F(1)^* [1 - \rho^2(w-1)+\ldots]$
- Many experiments have done so; average has $P(\chi^2) = 2.6\%$
  → scale errors by $\sqrt{\chi^2/ndf}=1.5$
  so $F(1)|V_{cb}| = (35.9 \pm 0.8)\times 10^{-3}$
- Latest lattice value is[1]
  $F(1) = 0.930 \pm 0.023$
  [1] Laiho et al., arXiv:0710.1111
- Determine $|V_{cb}| = (38.6 \pm 0.9_{\mathbf{exp}} \pm 1.0_{\mathbf{th}}) \times 10^{-3}$



$|V_{ub}|$ from B → $\pi\ell\nu$



- Use analyticity and unitarity constraints plus measured $d\Gamma/dq^2$ to fit FF shape; then normalize at any q^2
- Fit determines $|V_{ub}|\ f_+(q^2=0) = (91 \pm 3_{BF} \pm 6_{shape})*10^{-5}$
- FF normalizations → $|V_{ub}|$ values

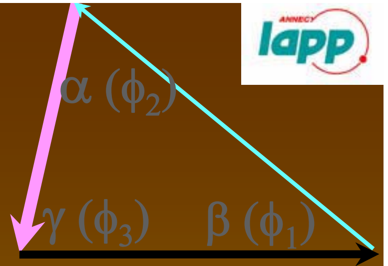


Choose

$$|V_{ub}| = \left(3.5\ ^{+0.6}_{-0.5}\right)\times 10^{-3}$$

	$f_+(0)$	$\lvert V_{ub}\rvert*10^4$
LCSR	0.26 ± 0.04	$35 \pm 3\ ^{+6}_{-5}$
LQCD (FNAL)	0.25 ± 0.03	$36 \pm 3\ ^{+5}_{-4}$
LQCD (HPQCD)	0.27 ± 0.03	$33 \pm 3\ ^{+4}_{-3}$

Inclusive semileptonic decays



- Theoretical tool: Heavy Quark Expansion (OPE)

$$\Gamma(B \to X) = \frac{1}{2m_B} \sum (2\pi)^4 \delta^4 (p_B - p_X) \left| \langle X | L_{eff} | B \rangle \right|^2$$

$$= \frac{G_F^2 m_b^5}{192\pi^3} (1 + A_{EW}) A^{pert} \left\{ 1 + 0 - \frac{\mu_\pi^2 + 3\mu_G^2}{2m_b^2} + \ldots \right\}$$

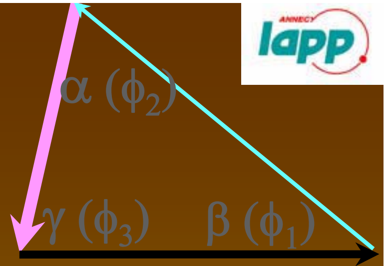
Simplified form for massless X

Quark model result

First correction $\mathcal{O}((\Lambda/m_b)^2)$

- Express decay rate as double expansion in α_s and $1/m_b$
  - Perturbative corrections are calculable
  - Non-perturbative matrix elements (e.g. μ_π^2) arise at each order in $1/m_b$; determine in fits moments

$|V_{cb}|$ from inclusive decays



- Calculate moments (M_x^n, E_e^n) of inclusive processes $b \to c\ell\nu$ and $b \to s\gamma$ for various cuts on lepton (photon) energy:

$$\left\langle M_x^n \right\rangle_{E_l > E_0} = \tau_B \int_{E_0} M_X^n d\Gamma = f_n^x(E_0, m_b, m_c, \mu_G^2, \mu_\pi^2, \rho_D^3, \rho_{LS}^3)$$

e or γ energy cut → E_0

b-quark mass → m_b

c-quark mass → m_c

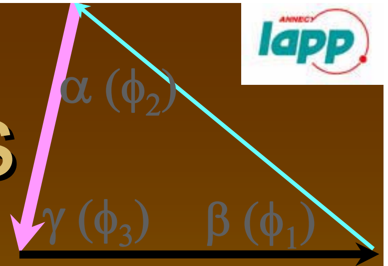
Matrix elements appearing at order $1/m_b^2$ and $1/m_b^3$ → $\mu_G^2, \mu_\pi^2, \rho_D^3, \rho_{LS}^3$

Kinetic scheme
Benson, Bigi, Gambino, Mannel, Uraltsev
(several papers)

1S scheme
Bauer, Ligeti, Luke, Manohar, Trott
PRD 70:094017 (2004)

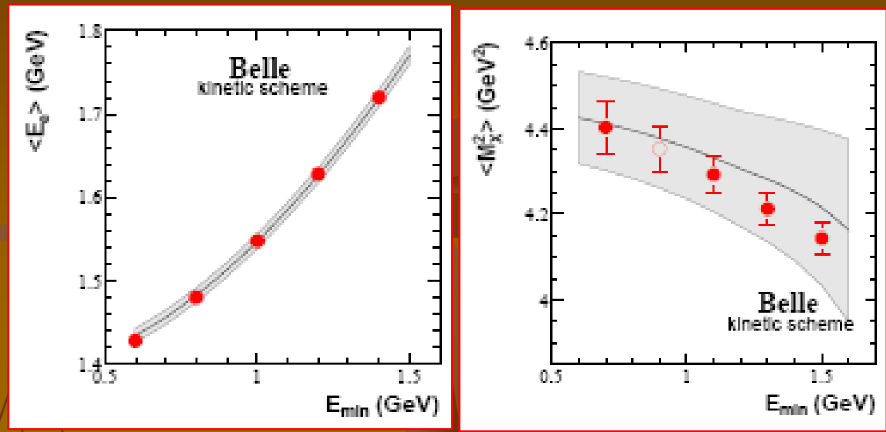
- Fit ~60 measured moments from DELPHI, CLEO, BABAR, BELLE, CDF to determine ~6 parameters

Global moment fit results



Scheme	$\|V_{cb}\|$ (10^{-3})
Kinetic	$41.68 \pm 0.39 \pm 0.58_{\Gamma SL}$
1S	$41.56 \pm 0.39 \pm 0.08_{\tau_B}$

Choose $|V_{cb}| = (41.6 \pm 0.6) \times 10^{-3}$



arXiv:0803.2158

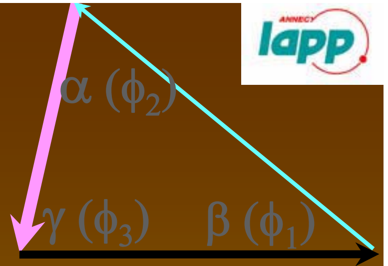
Source	m_b (GeV)
$m_{b[kin]}$ (global fit)	4.61 ± 0.03
$m_{b[kin]}$ (global fit, no $b\to s\gamma$)	4.68 ± 0.05
$m_{b[kin]}$ ($b\bar{b}$ threshold)	4.56 ± 0.06
$m_{b[1S]}$ (global fit)	4.70 ± 0.03
$m_{b[1S]}$ (global fit, no $b\to s\gamma$)	4.75 ± 0.06
$m_{b[1S]}$ ($b\bar{b}$ threshold)	4.69 ± 0.03

χ^2/ndf is too good (e.g. 39/62 for kinetic, 25/63 for 1S); suggests theory errors (included in fit) may be overestimated

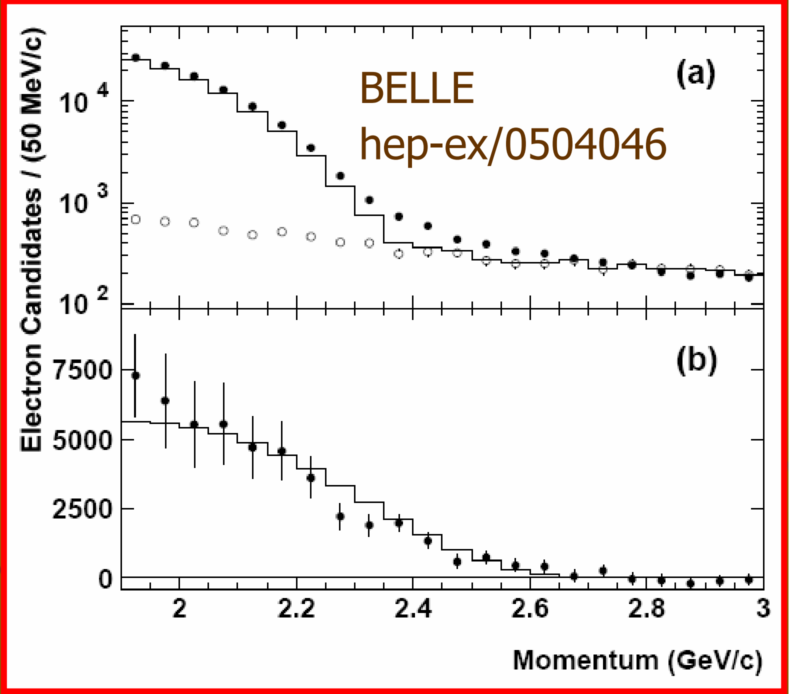
m_b is crucial for $|V_{ub}|$

Use (or not) of $b\to s\gamma$ in global fit still controversial

$|V_{ub}|$ from inclusive decays



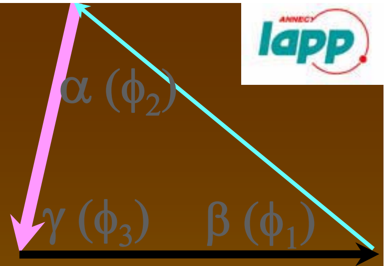
- Measurement of inclusive b→u SL rate requires cuts to suppress large b→c background
  - OPE convergence ruined in limited phase space
  - Non-perturbative distribution fn needed; measure it in b→sγ
  - Other issues: large m_b dependence, weak annihilation
- Measure many partial rates (E_e, M_X, q^2…) and compare with calculated rates →



- Bosch, Lange, Neubert, Paz (BLNP) Phys.Rev.D73,073008(2006)
- Gambino, Giordano, Ossola, Uraltsev (GGOU) JHEP 0710:058(2007)
- Andersen and Gardi (DGE) JHEP 0601:097 (2006)
- Aglietti, Di Lodovico, Ferrera, Ricciardi (AC) arXiv:0711.0860

$$|V_{ub}| = (4.12 \pm 0.15 \pm 0.40) \times 10^{-3}$$

$|V_{ub}|$ and $|V_{cb}|$ summary



- Determinations from inclusive and exclusive decays are independent, both experimentally and theoretically

$$\textbf{Inclusive:}\quad |V_{cb}| = (41.6 \pm 0.6)\times 10^{-3} \qquad |V_{ub}| = (4.12 \pm 0.43)\times 10^{-3}$$

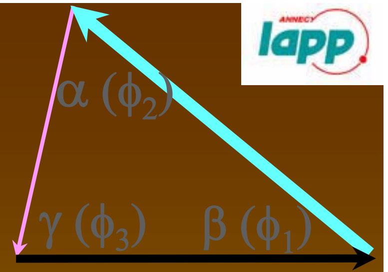
$$\textbf{Exclusive:}\quad |V_{cb}| = (38.6 \pm 1.3)\times 10^{-3} \qquad |V_{ub}| = (3.5\ ^{+0.6}_{-0.5})\times 10^{-3}$$

- $|V_{cb}|$ avg has $P(\chi^2)$=3%; scale error by $\sqrt{\chi^2/\mathrm{ndf}}$=2.1 — $|V_{ub}|$ avg has $P(\chi^2)$=40%

$$|V_{cb}| = (41.2 \pm 1.1)\times 10^{-3} \qquad |V_{ub}| = (3.95 \pm 0.35)\times 10^{-3}$$

- SuperB + theory improvements → ~1% on $|V_{cb}|$, 2-3% on $|V_{ub}|$ for each of inclusive/exclusive determinations

The long side - $|V_{td}|$



- Constraints come from precise experimental knowledge of $B\bar{B}$ mixing:
  - $\Delta m_d = 0.507 \pm 0.005\ ps^{-1}$ (HFAG)
    $\Delta m_s = 17.77 \pm 0.10 \pm 0.07\ ps^{-1}$ (CDF PRL97:242003(2006))
  - Dominant uncertainty in $|V_{td}|$ and $|V_{ts}|$ due to non-perturbative QCD input
    $|V_{td}/V_{ts}| = (0.209 \pm 0.006)*10^{-3}$ (PDG)
- Also accessible in radiative decays $B \rightarrow K^* \gamma$, $B \rightarrow \rho\gamma$
  - Need calculated ratio of form factors
    $|V_{td}/V_{ts}| = (0.21 \pm 0.04)*10^{-3}$ (PDG)

Constraints on UT

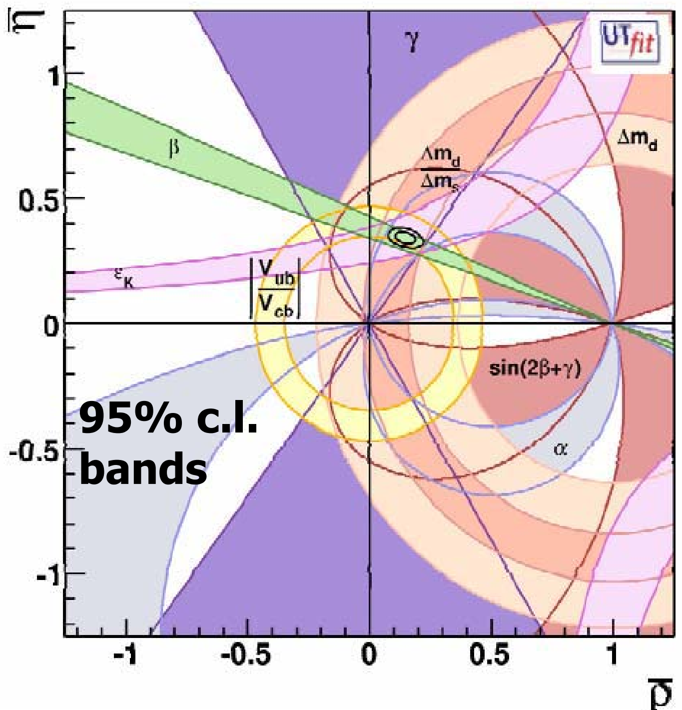
- Putting all constraints together, we determine the apex of the UT as

$\bar{\rho} = 0.141^{+0.029}_{-0.017}$ CKMfitter
$\bar{\eta} = 0.343^{+0.016}_{-0.016}$

$\bar{\rho} = 0.147 \pm 0.029$ UTfit
$\bar{\eta} = 0.342 \pm 0.016$

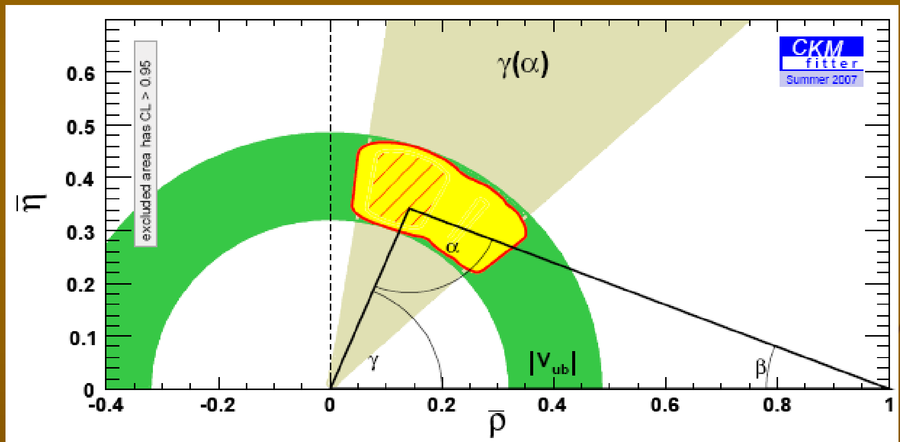
- No significant departure from SM at present

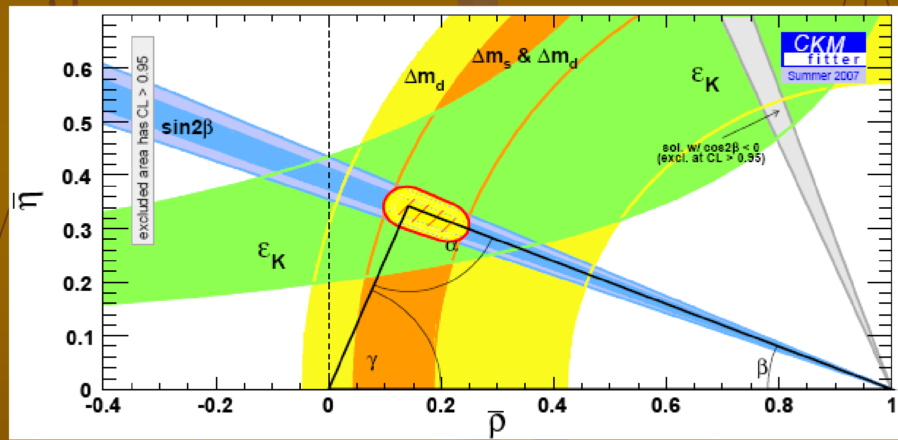
Current results from UTfit



Trees and loops…

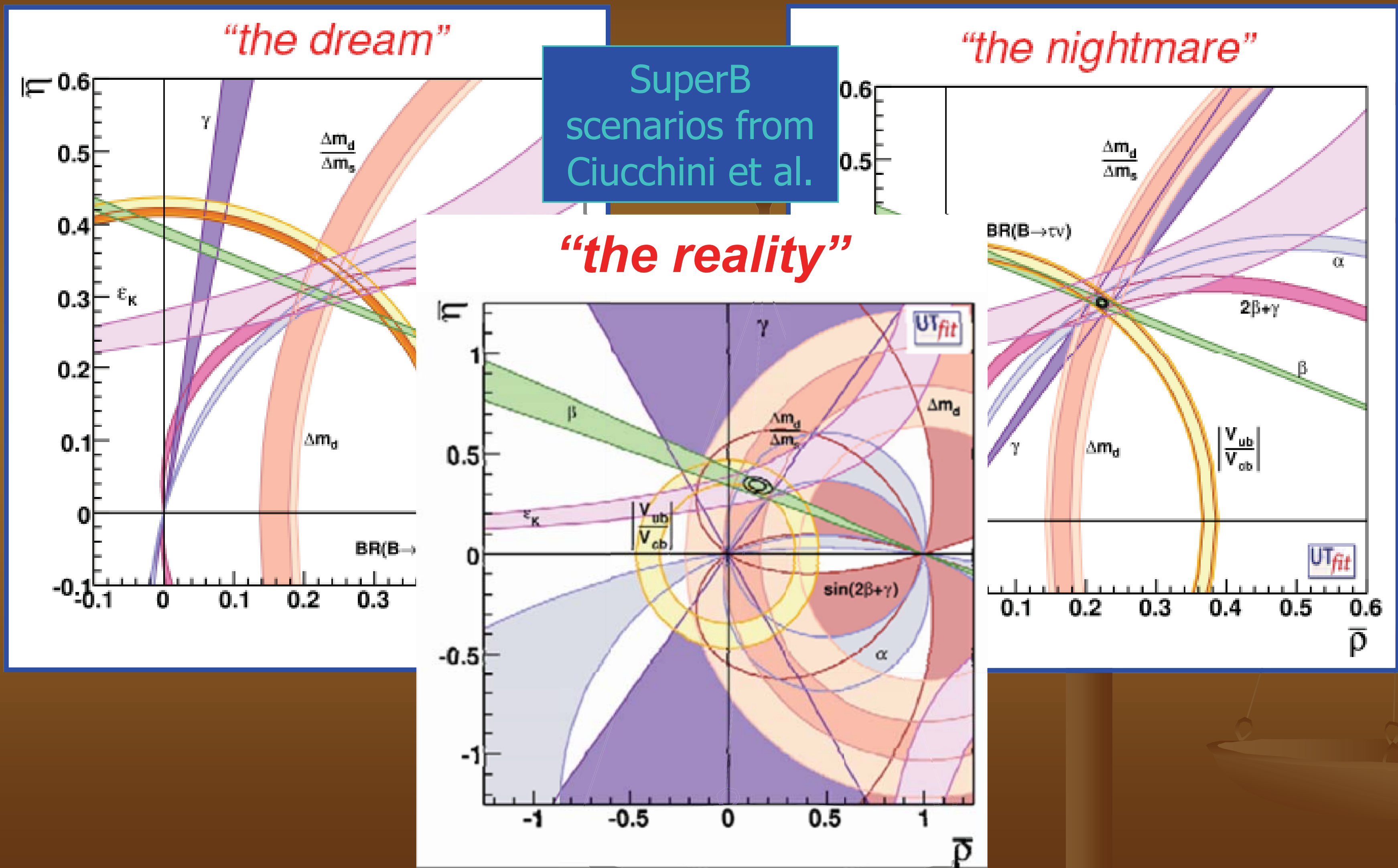
- Recall that some quantities are determined in tree-level processes (e.g. $|V_{ub}|$) while others involve $B\bar{B}$ mixing or “penguin” amplitudes.





- Current accuracy is modest; tests NP amplitudes at the ~100% level

Unitarity triangle outlook



SuperB scenarios from Ciucchini et al.