Beauty Physics and *CP* Violation (III)

Rare *B* decays: towards the full UT … and beyond

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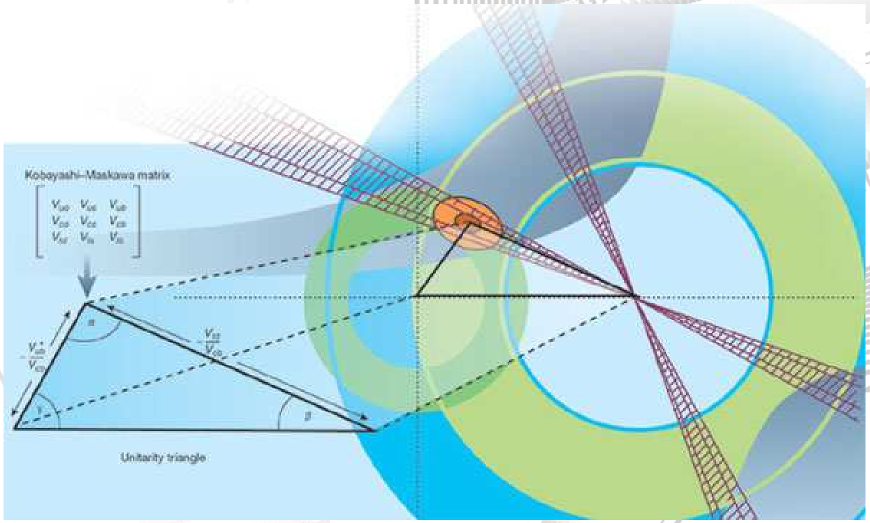


Experimental lecture at the Helmholz School on Heavy Quark Physics

Dubna, June 6-16, 2005

Themes

I. Beauty Physics and *CP* Violation – the experimental program

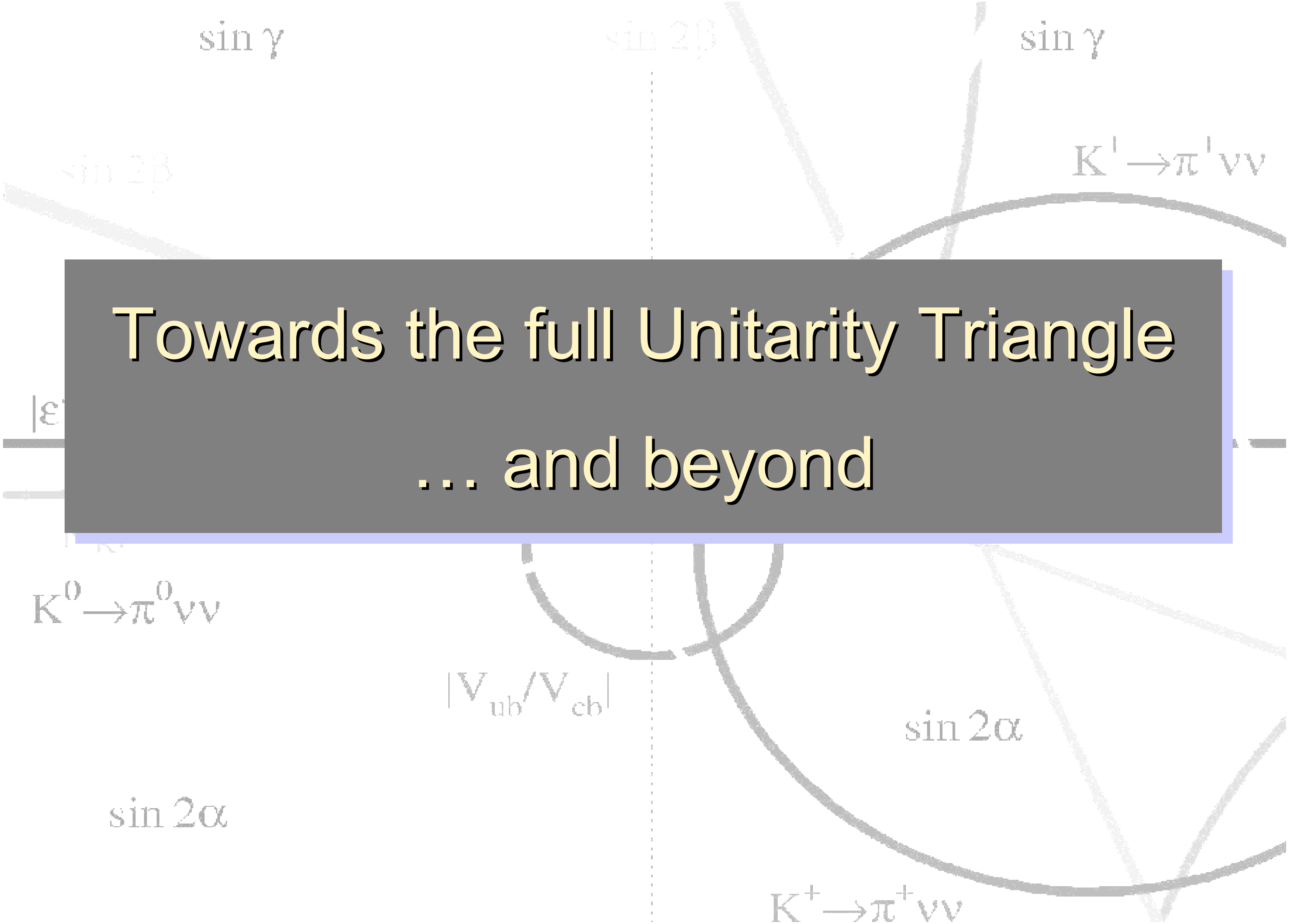
- Heavy meson production and decay
- *B* Physics and *CP* Violation
- The *B* Factories
- Physics at the $\Upsilon(4S)$: time-integrated and time-dependent measurements

II. sin(2β) and the triumph of the Standard Model

- *CP* violation: experimental facts
- *CP* violation in the *B* system
- The measurement of sin(2β) in tree and loop (penguin) decays
- Briefing on radiative *B* decays

III. Rare *B* decays: towards the full unitarity triangle … and beyond

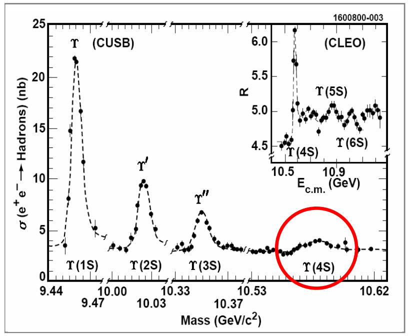
- Leptonic *B* Decays
- Charmless *B* decays and the measurement of α
- $B \rightarrow K\pi$ decays (direct *CP* violation) and other charmless modes
- Towards γ
- Flavor, CPV and CKM: the present picture and the experimental future



Towards the full Unitarity Triangle

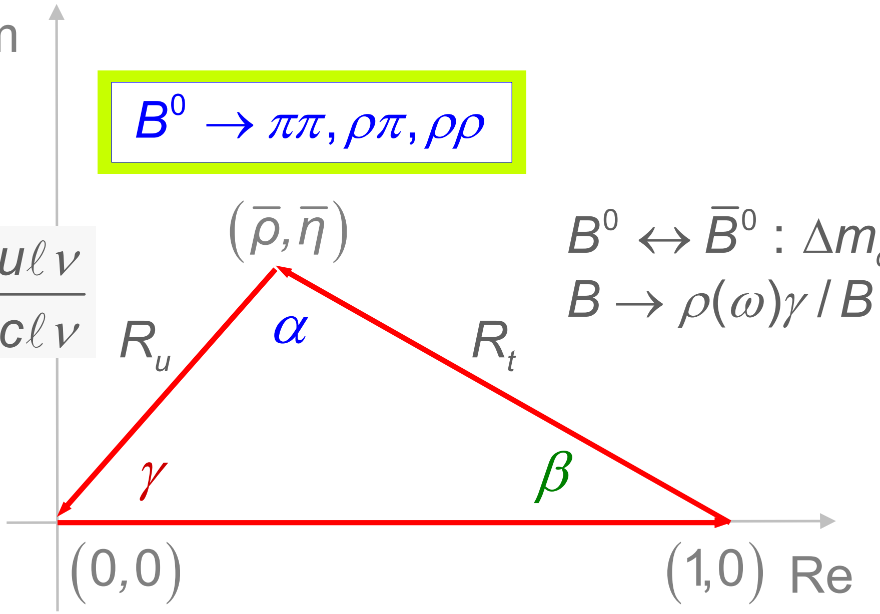
… and beyond

The B_d System ($e^+e^- \to \Upsilon(4S)$ factories)



the B_d is also produced by the hadron machines

$$B^0 \to \pi\pi, \rho\pi, \rho\rho$$



$$\frac{b \to u \ell \nu}{b \to c \ell \nu}$$

$B^0 \leftrightarrow \bar{B}^0 : \Delta m_d$

$B \to \rho(\omega)\gamma \,/\, B \to K^{(*)}\gamma$

$B \to D^{(*)} K^{(*)}$

$B \to D_{K_S^0 \pi^+ \pi^-} K^{(*)}$

$B^0 \to D K_S^0, \ldots$

$B^0 \to D^* \pi(\rho)$

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

$B^0 \to J/\psi K_S^0, \ldots$

$B^0 \to J/\psi \pi^0$

$B^0 \to D_{(s)}^{(*)+} D^{(*)-}$

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

$B^0 \to \phi K_S^0, \ldots$

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

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

Rare Charmless *B* Decays

We distinguish three main categories:

today's lecture

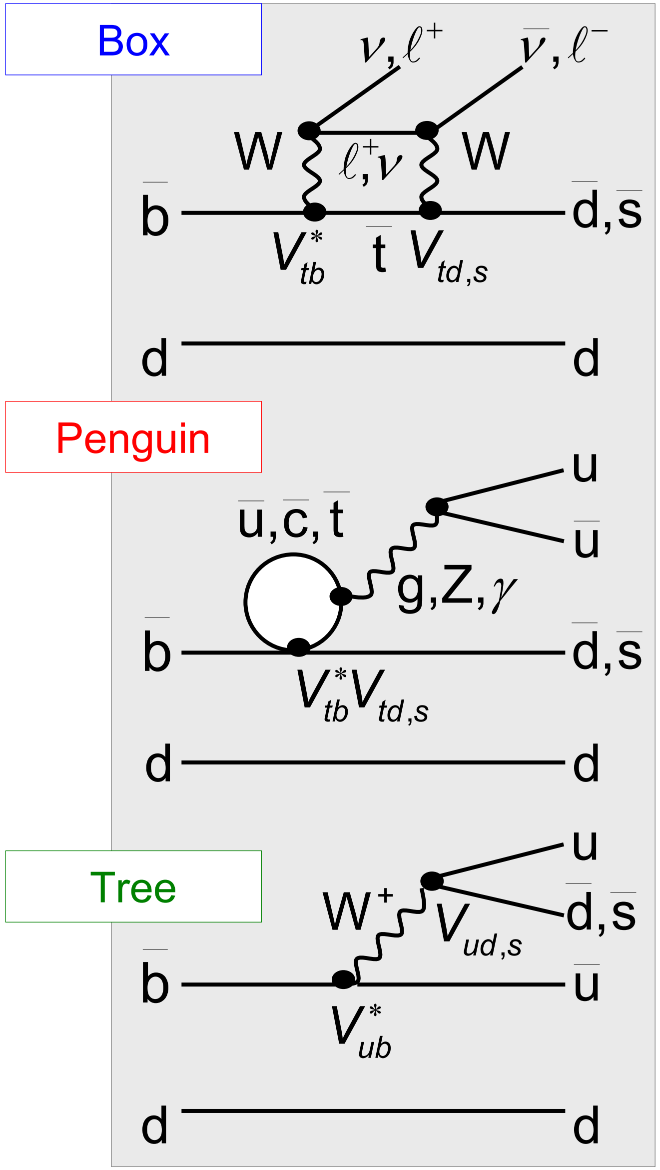
- Hadronic $b \to u(d)$ decays
  - Measurement of CPV
  - Determination of UT angle α
  - Test of *B* decay dynamics (Factorization)

yesterday's lecture

- Semileptonic, FCNC and radiative decays
  - Tree decays used to measure $|V_{ub}|$
  - Penguins and boxes sensitive to new physics
  - Penguins used to determine $|V_{td}/V_{ts}|$
  - Search for direct *CP,* FB asym. or ratios of BRs

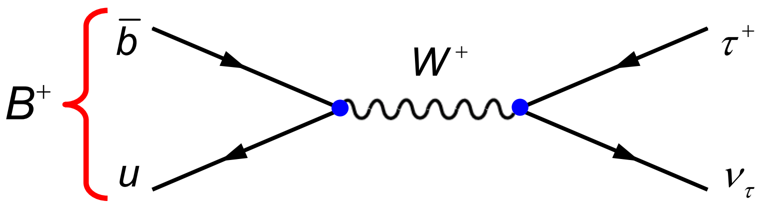
today

- Leptonic *B* decays
  - Measurement of $|V_{ub}|$, $|V_{td}/V_{ts}|$
  - Search for new physics

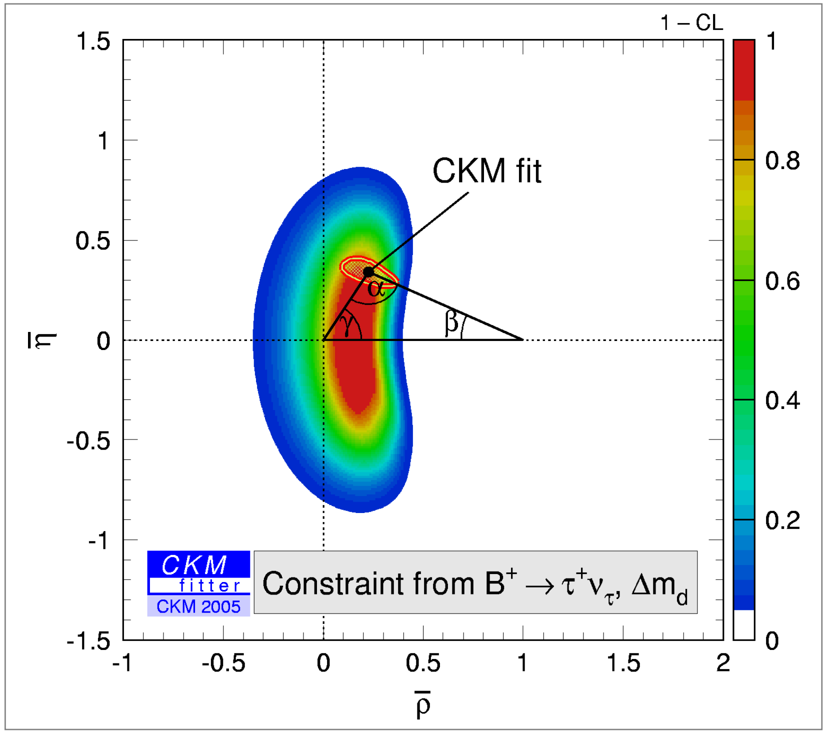


$B^+ \to \tau^+\nu_\tau$

- Helicity-suppressed annihilation decay sensitive to $(f_B \times |V_{ub}|)^2$
- Powerful <u>together</u> with Δm_d : removes f_B (Lattice QCD) dependence
- Sensitive, *e.g.*, to charged Higgs replacing the W propagator



$$\mathrm{BR}(B^+ \to \tau^+\nu) = \frac{G_F^2 m_B \tau_B}{8\pi} m_\tau^2 \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 \left|V_{ub}\right|^2$$



- Best current limit from BABAR :

$$\mathrm{BR}(B^+ \to \tau^+\nu) = 13\,^{+10}_{-9} \times 10^{-5}$$
$$< 26 \times 10^{-5} \text{ at 90\% CL}$$

Datta, SLAC seminar 2005

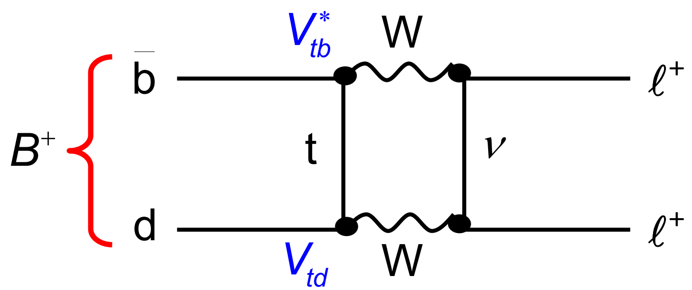
- Prediction from global CKM fit :

$$\mathrm{BR}(B^+ \to \tau^+\nu) = 8.9\,^{+3.9}_{-1.7} \times 10^{-5}$$

CKMfitter Group, CKM'05

$B_{d/s} \to \ell^+\ell^-$

- Box diagram with top exchange $(f_B \times |V_{td}|)^2$ dominates in SM : $\mathrm{BR}_{[\mathrm{SM}]}\left(B_d \to \tau^+\tau^-\right) \sim 3 \times 10^{-8}$
- Penguin diagrams suppressed
- Helicity enhancement : $\propto (m_\tau / m_\ell)^2$
- Best current limits (from BABAR):



$$\mathrm{BR}\left(B_d \to e^+e^-\right) < 6 \times 10^{-8}$$

$$\mathrm{BR}\left(B_d \to \mu^+\mu^-\right) < 8 \times 10^{-8}$$

$$\mathrm{BR}\left(B_d \to \tau^+\tau^-\right) \sim 10^5 \times 10^{-8}$$

expected sensitivity; mode not yet measured

- Sensitive to flavor changing new physics

(2 Higgs doublet models, SUSY, Leptoquarks, …)

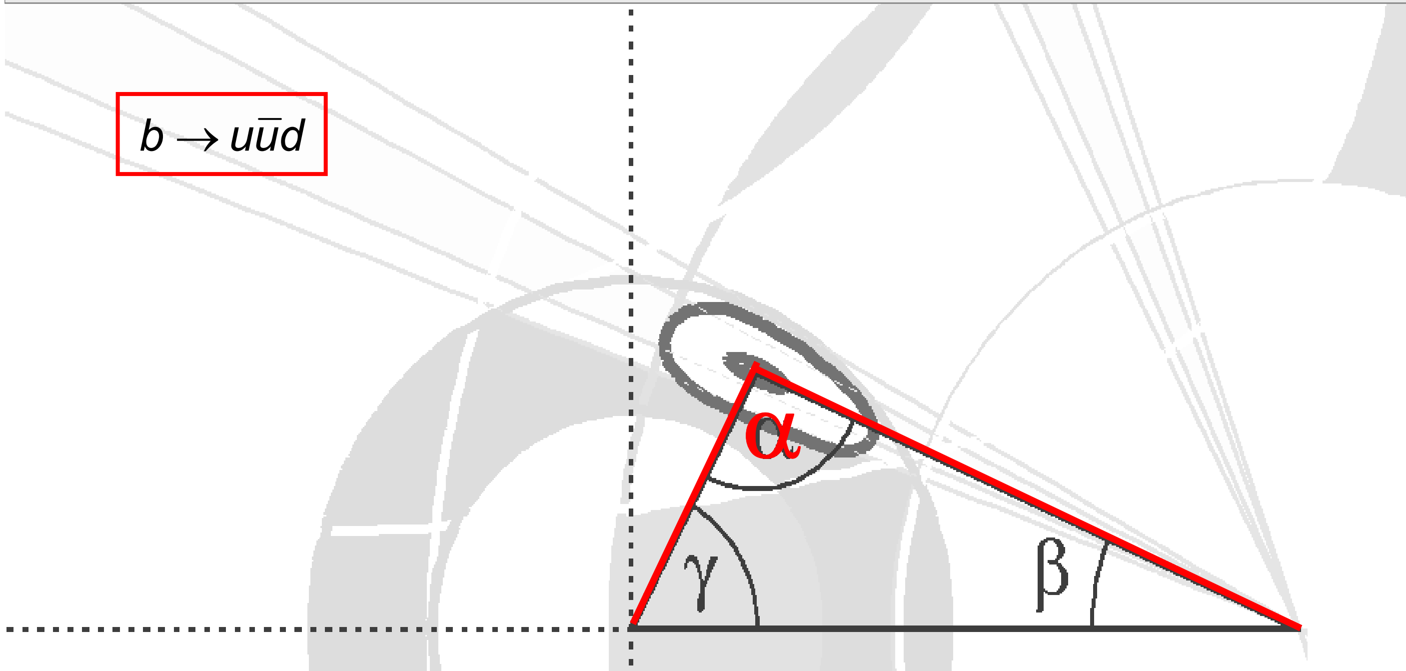
$$\mathrm{BR}_{[\mathrm{MSSM}]}\left(B_d \to \tau^+\tau^-\right) \propto \left(\tan\beta\right)^6 \times f\left(m_{\mathrm{SUSY}}\right)$$

$$\mathrm{BR}_{[\mathrm{2HDM}]}\left(B_d \to \tau^+\tau^-\right) \propto \left(\tan\beta\right)^4 \times \log^2\left(m_H^2 / m_t^2\right)$$

- *B* Factories not sensitive to SM value ➔ domain of LHC experiments ($B_{d/s} \to \mu^+\mu^-$)

α

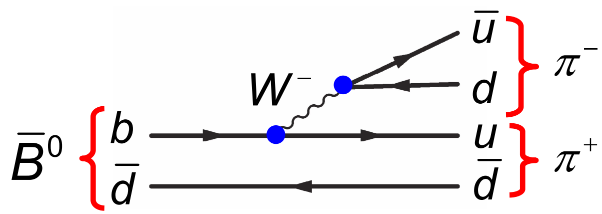
$b \to u\bar{u}d$



Principal modes :

- $B^0 \to \pi^+\pi^-$
- $B^0 \to \rho^\pm\pi^\mp$
- $B^0 \to \rho^+\rho^-$

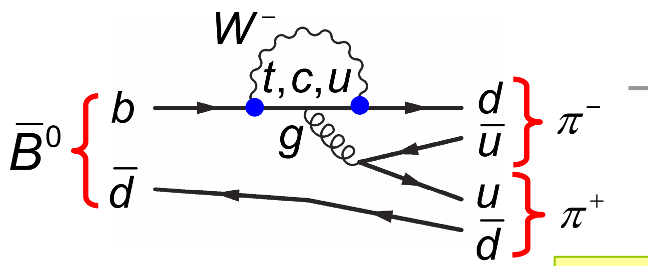
Not a *CP* eigenstate



Tree : dominant

$\propto V_{ub}V_{ud}^*$

$\propto \lambda^3$



Penguin : competitive ?

$\propto V_{tb}V_{td}^*$

$\propto \lambda^3$

Charmless $b \to u$ Decays

- Tree "*T*" amplitude dominates :

$$\lambda_{h^+h^-} = \eta_{h^+h^-} \left(\frac{q}{p}\right)_B \left(\frac{e^{-i\gamma} T^{+-}}{e^{+i\gamma} T^{+-}}\right)$$

$$= \eta_{h^+h^-} e^{2i\alpha}$$

No direct *CP* violation :

$$\left|\lambda_{h^+h^-}\right| = 1$$

$$C_{f_{CP}} = \frac{1 - \left|\lambda_{h^+h^-}\right|^2}{1 + \left|\lambda_{h^+h^-}\right|^2} = 0$$

- Time-dependent CP observable :

ideal scenario

$$A_{h^+h^-}(t) = S_{h^+h^-} \sin(\Delta m_d t) - C_{h^+h^-} \cos(\Delta m_d t)$$

$$= \sin(2\alpha) \cdot \sin(\Delta m_d t)$$

Charmless $b \to u$ Decays

- "*T*" and "*P*" are of the same order of magnitude :
  [Note that *T* and *P* are *complex* amplitudes !]

$$\lambda_{h^+h^-} = \eta_{h^+h^-}\left(\frac{q}{p}\right)_B \left(\frac{e^{-i\gamma}T^{+-} + e^{+i\beta}P^{+-}}{e^{+i\gamma}T^{+-} + e^{-i\beta}P^{+-}}\right)$$

$$= \eta_{h^+h^-} e^{2i\alpha}\left(\frac{1-|P^{+-}/T^{+-}|\,e^{-i(\alpha-\delta_{+-})}}{1-|P^{+-}/T^{+-}|\,e^{+i(\alpha+\delta_{+-})}}\right)$$

$$\equiv \left|\lambda_{h^+h^-}\right| e^{2i\alpha_{\rm eff}}$$

where $\delta_{+-} \equiv \theta_{P^{+-}} - \theta_{T^{+-}}$
is the relative strong phase

Direct *CP* violation can occur :

$$\left|\lambda_{h^+h^-}\right| \neq 1$$

$$C_{f_{CP}} = \frac{1-\left|\lambda_{h^+h^-}\right|^2}{1+\left|\lambda_{h^+h^-}\right|^2} \overset{!}{\neq} 0$$

- Time-dependent CP observable :

realistic scenario

$$A_{h^+h^-}(t) = S_{h^+h^-}\sin(\Delta m_d t) - C_{h^+h^-}\cos(\Delta m_d t)$$

$$= \sqrt{1-C^2_{h^+h^-}}\,\sin(2\alpha_{\rm eff})\cdot\sin(\Delta m_d t) - C_{h^+h^-}\cos(\Delta m_d t)$$

digression: what is the meaning of "*T*" and "*P*" ?

- Example :

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

unitarity $=$

	Convention
$V_{cd}V_{cb}^*(P_c - P_u - T) + V_{td}V_{tb}^*(P_t - P_u - T)$	U - convention
$V_{ud}V_{ub}^*(T + P_u - P_c) + V_{td}V_{tb}^*(P_t - P_c)$	C - convention
$V_{ud}V_{ub}^*(T + P_u - P_t) + V_{cd}V_{cb}^*(P_c - P_t)$	T - convention

"Tree" — $(T + P_u - P_c)$, $(T + P_u - P_t)$

"Penguin" — $(P_t - P_c)$, $(P_c - P_t)$

➡ The "tree" in the (most popular) C - and T - conventions has penguin contributions !

“Taming Penguins” J. Charles

- Time-dependent *CP* analysis of $B^0 \to \pi^+\pi^-$ alone determines α_{eff} : but, we need α !
- Fortunately, SU(2) and SU(3) symmetries provides the additional constraints to deduce the unknown amplitudes
- Consider the decay $B \to pq$, where p,q are isovectors of the iso-multiplet:

$$\{pq\} = \{p^+q^-, p^-q^+, p^+q^0, p^0q^+, p^-q^0, p^0q^-, p^0q^0\}$$

consider the matrix elements of neutral and charged *B* decays:

$$\langle (p,q)^0 | H_s | u\bar{u}\bar{d}, d \rangle \qquad \langle (p,q)^+ | H_s | u\bar{u}\bar{d}, u \rangle$$

H_s – strong Hamiltonian

Example: isospin decomposition yields for $B^0 \to p^+q^-$:

$$A^{+-} = \langle p^+, q^- | H_s | u\bar{u}\bar{d}, d \rangle$$

$$= \langle 1,1 | \otimes \langle 1,-1 | H_s | 3/2, 1/2 \rangle \otimes | 1/2, -1/2 \rangle + \langle 1,1 | \otimes \langle 1,-1 | H_s | 1/2, 1/2 \rangle \otimes | 1/2, -1/2 \rangle$$

$$= \frac{1}{2}\frac{1}{\sqrt{3}} A_{3/2,2} - \frac{1}{2} A_{3/2,1} + \frac{1}{2} A_{1/2,1} - \frac{1}{\sqrt{6}} A_{1/2,0}$$

Clebsch-Gordon coefficients

where: $A_{\Delta I, I_f} \equiv \langle I_f, I_{f,3} | H_s | I_i, I_{i,3} \rangle_{\Delta I}$

- Doing the same for all the other charge combinations leads to the “pentagon” relation:

$$\sqrt{2}\left(A^{+0} + A^{0+}\right) = 2A^{00} + A^{+-} + A^{-+}$$

in the complex plane

“Taming Penguins” (cont.)

- Penguins: since gluons decay with $\Delta I = 0$, penguins can only mediate $\Delta I = 1/2$ transitions:

$$P^{+0} = -P^{0+} = \left(P^{+-} - P^{-+}\right)/\sqrt{2}$$
$$P^{00} = -\left(P^{+-} + P^{-+}\right)/2$$

- Simplification for identical $p=q$, *e.g.*, for $B^0 \to \pi^+\pi^-$, $\rho^+\rho^-$: pentagon ➡ triangle

$$A^{+0} = A^{00} + A^{+-}/\sqrt{2}$$

and same for $A \leftrightarrow \bar{A}$

and for the penguin amplitudes:

$$P^{+0} = -P^{0+} = 0 \quad \Rightarrow \quad \left|A^{+0}\right| = \left|A^{-0}\right|$$
$$P^{00} = -P^{+-}/\sqrt{2}$$

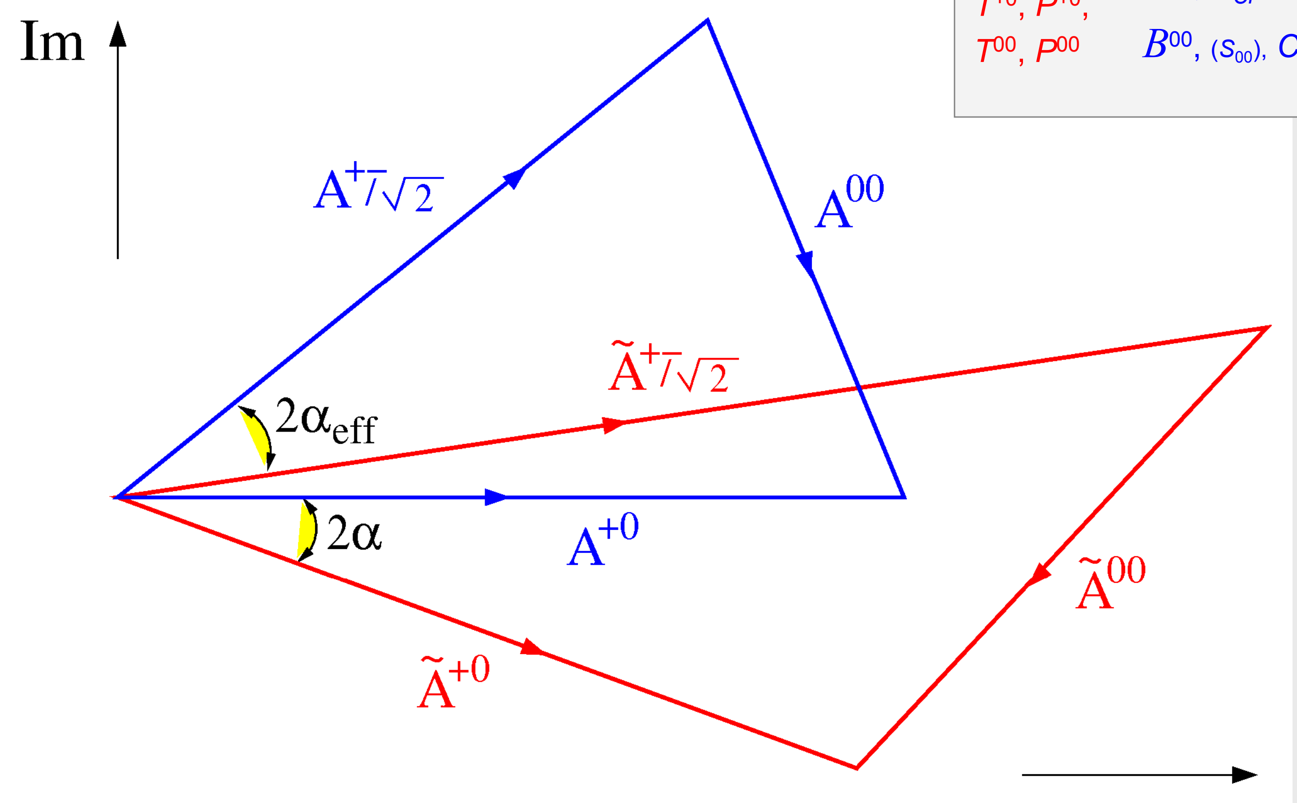
➡ P^{00} measures the penguin pollution in $B^0 \to \pi^+\pi^-$!

since: $\mathrm{B}(B^0 \to \pi^0\pi^0) = \left|T^{00}e^{-\alpha} + P^{00}\right|^2 + \left|T^{00}e^{+\alpha} + P^{00}\right|^2$ the branching fraction provides an upper limit on P^{00}, if $\alpha \neq 0$

Refs. for SU(2) analyses : Gronau-London, PRL, 65, 3381 (1990), Lipkin *et al.*, PRD 44, 1454 (1991), a.o.

Isospin Analysis for $B \to \pi\pi, \rho\rho$

Unknowns	Observables	Constraints	Account
α, T^{+-}, P^{+-}, T^{+0}, P^{+0}, T^{00}, P^{00}	B^{+-}, $S_{\pi\pi}$, $C_{\pi\pi}$ B^{+0}, A_{CP} B^{00}, (S_{00}), C_{00}	2 isospin triangles and one common side	13 unknowns – 7 observ. – 5 constraints – 1 glob. phase = 0 ☺



α can be resolved up to an 8-fold ambiguity within $[0,\pi]$

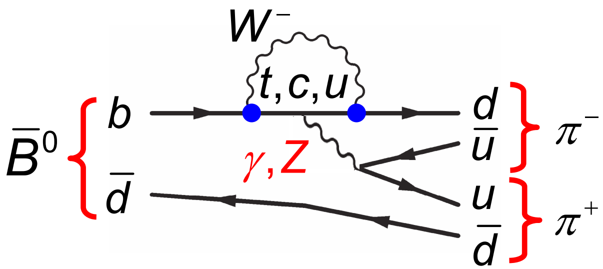
Assumptions:

- neglect EW penguins (shifts α by ~ +2°) penguins
- neglect SU(2) breaking
- in $\rho\rho$: Q2B approx. (neglect interference)

Refs. for SU(2) analyses : Gronau-London, PRL, 65, 3381 (1990), Lipkin *et al.*, PRD 44, 1454 (1991), a.o.

digression: Electroweak (EW) Penguins

- EW penguins can mediate $\Delta I = 3/2$ transitions and hence violate the SU(2) relations



$\propto V_{tb}V_{td}^*$
$\propto \lambda^3$

- Use "Fiertz" trick : the effective weak Hamiltonian of the decay $B \to \pi\pi$ reads:

$$H_{\rm eff} = \frac{G_F}{\sqrt{2}}\left[V_{ub}V_{ud}^*\left(c_1O_1 + c_2O_2\right) - \sum_{i=3}^{10} V_{tb}V_{td}^* c_i O_i\right] + \text{h.c.}$$

where O_1 and O_2 are $(V\!-\!A)\times(V\!-\!A)$ tree operators and $O_{7\text{-}10}$ EW penguins operators

O_7 and O_8 have Lorentz structure $(V\!-\!A)\times(V\!+\!A)$ while O_9 and O_{10} are $(V\!-\!A)\times(V\!-\!A)$

but: $c_7, c_8 \ll c_9, c_{10}$ so that one can Fiertz-relate the EW O_9, O_{10} to the tree O_1, O_2 :

$$P_{\rm EW}^{+-} = \left(T^{+-}/\sqrt{2} + T^{00}\right)\left|V_{tb}^*V_{td}/V_{ub}^*V_{ud}\right| \cdot f\left(\frac{c_9 + c_{10}}{c_1 + c_2}\right)$$

Neubert-Rosner,
PLB 441, 403 (1998)
PRL 81, 5076 (1998)

- Hence, if $f(\ldots)$ real, $A_{CP}(\pi^+\pi^0)$ not sensitive to $P_{\rm EW}$!

Bounds on Penguins

- Once the penguin is bound, one can compute a bound on $|\alpha - \alpha_{\rm eff}|$:

$$\sin^2(\alpha - \alpha_{\rm eff}) \le \frac{\mathrm{B}(B^0 \to \pi^0\pi^0)}{\mathrm{B}(B^+ \to \pi^+\pi^0)} \equiv \frac{\mathrm{B}^{00}}{\mathrm{B}^{+0}}$$

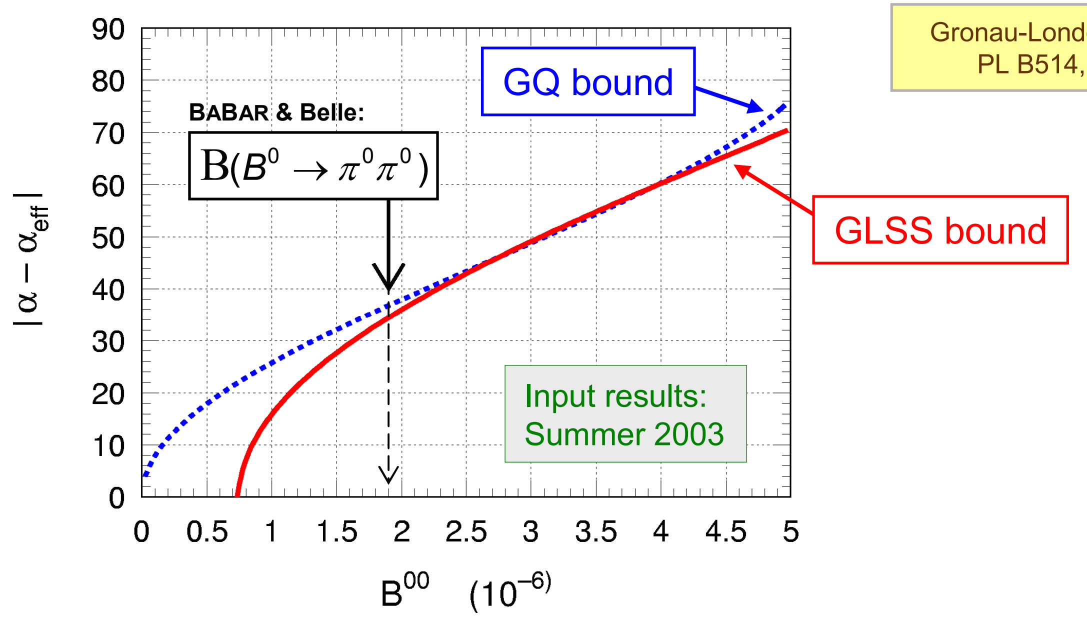
Grossman-Quinn, PRD 58, 017504 (1998)

- This first limit does not unite all the information from the SU(2) triangle. This one does:

$$\sin^2(\alpha - \alpha_{\rm eff}) \le \frac{\mathrm{B}^{00}}{\mathrm{B}^{+0}} + \left(\frac{1}{\sqrt{1-C^2_{h^+h^-}}} - 1\right)\left(\frac{\mathrm{B}^{00}}{\mathrm{B}^{+0}} - \frac{1}{2}\right) - \frac{\left(\mathrm{B}^{00} + \mathrm{B}^{+-}/2 - \mathrm{B}^{+0}\right)^2}{2\mathrm{B}^{+0}\mathrm{B}^{+-}\sqrt{1-C^2_{h^+h^-}}}$$

Gronau-London-Sinha-Sinha PL B514, 315 (2001)

GLSS bound and numerical solution of isospin analysis give same bound on $|\alpha - \alpha_{\rm eff}|$

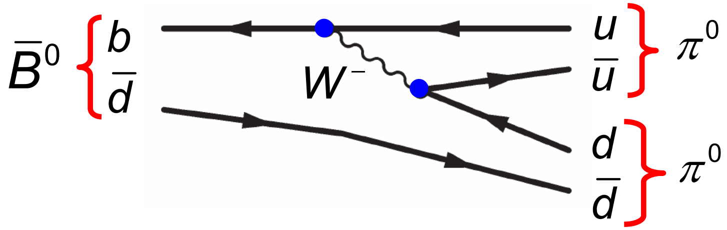


Color-suppressed $b \to u$ Decays

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

$\propto V_{ub}V_{ud}^{*}$

$\propto \lambda^{3}$



famous modes:

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

$B^0 \to \rho^0\pi^0$

$B^0 \to \rho^0\rho^0$

- Internal tree decays must have a neutral particle in the final state

  The quarks from the virtual W decay must match the color of the decaying B meson to produce color-singlet final state mesons ➡ internal diagrams are suppressed by ~ $1/N_c$

  Naive color suppression ≈ verified in $\mathcal{B}(B^0 \to D^0\pi^0)/\mathcal{B}(B^0 \to D^-\pi^+) = (1/10.4)_{exp} \sim (1/N_c)^2$

  Some color-suppressed diagrams are in addition isospin-suppressed (*e.g.*, $\pi^+\pi^-$ vs. $\pi^0\pi^0$)

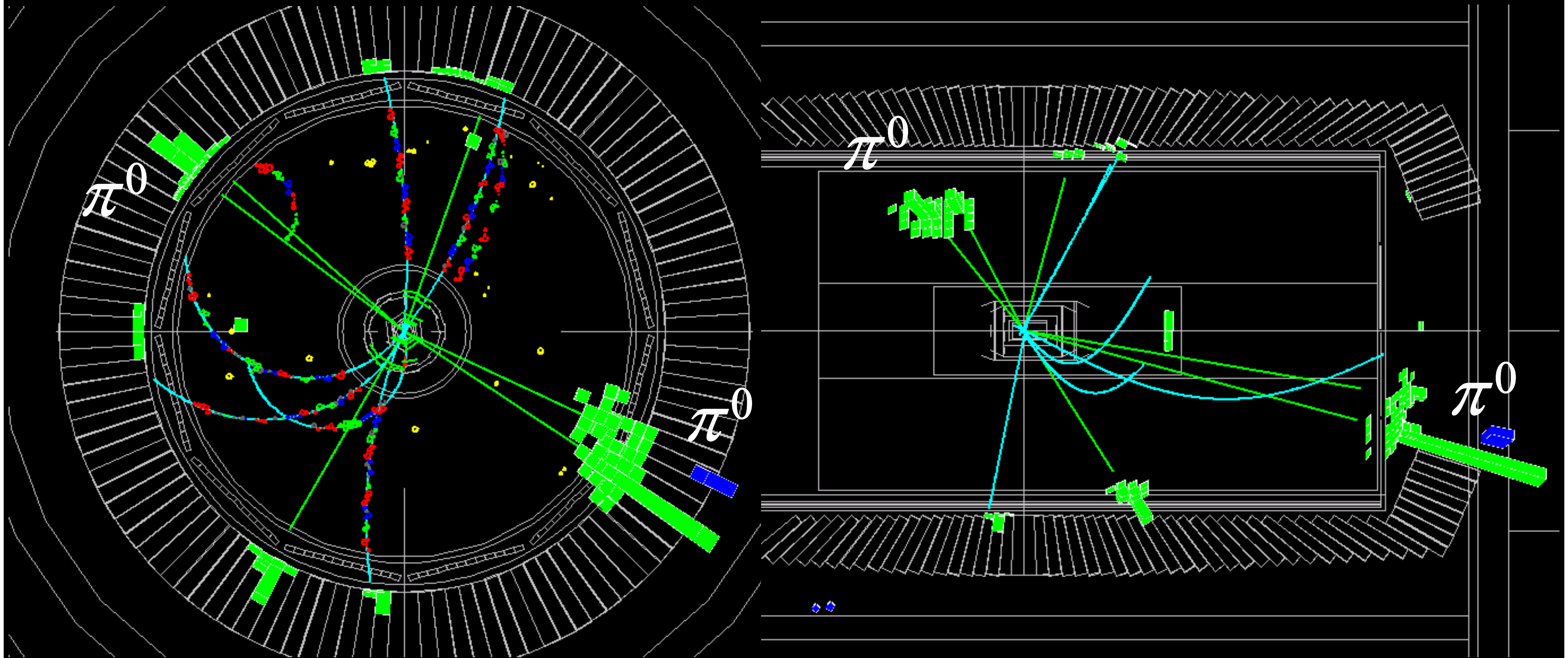
- Final state interaction (rescattering) and non-factorizable contributions can substantially modify the color-suppression

- Since the tree amplitude is suppressed, internal tree decays are sensitive to the penguin amplitude ➡ will see later

SU(2) – Crucial Ingredient : $B \to \pi^0\pi^0$ (color-suppressed)

A $B^0 \to \pi^0\pi^0$ candidate

BABAR



$B(B^0 \to \pi^0\pi^0) = (1.51 \pm 0.28) \times 10^{-6}$ $\quad$ $C(B^0 \to \pi^0\pi^0) = -0.28 \pm 0.39$

BABAR, hep-ex/0412037
Belle, hep-ex/0408100

Analysis Techniques for Charmless *B* Decays

- Strong DIRC Particle ID to separate pions from kaons.

- Event shape monomials (L_0,L_2), and *B* kinematics optimally combined in Multivariate Analyzer [MVA] (Neural Network (NN) or Fisher Discriminant).
- New NN-based *B*-flavor tagging with "*Q*" of 30.5 %
- Unbinned maximum-likelihood fit using beam-energy-substituted *B* mass (m_{ES}), *B*-energy difference (ΔE), the resonance mass and helicity angle, the MVA, and Δt.
- Likelihood components are signal, continuum background, charmed and charmless *B*-related backgrounds; as many likelihood-model parameters as possible are determined simultaneously from the fit to reduce systematic errors.
- Tagging-performance parameters and Δt resolution parameters determined simultaneously from fit to fully reconstructed *B* decays to charm.

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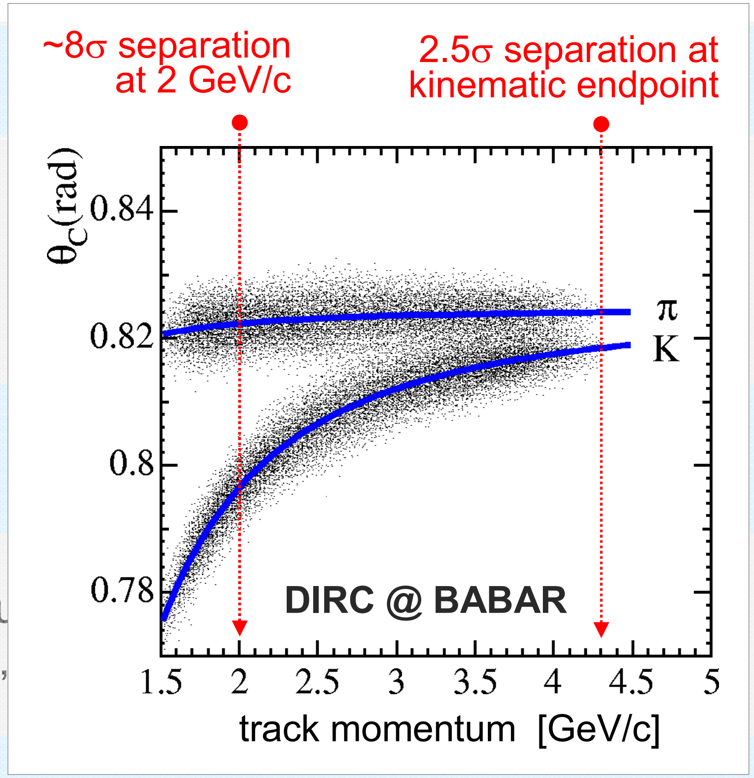

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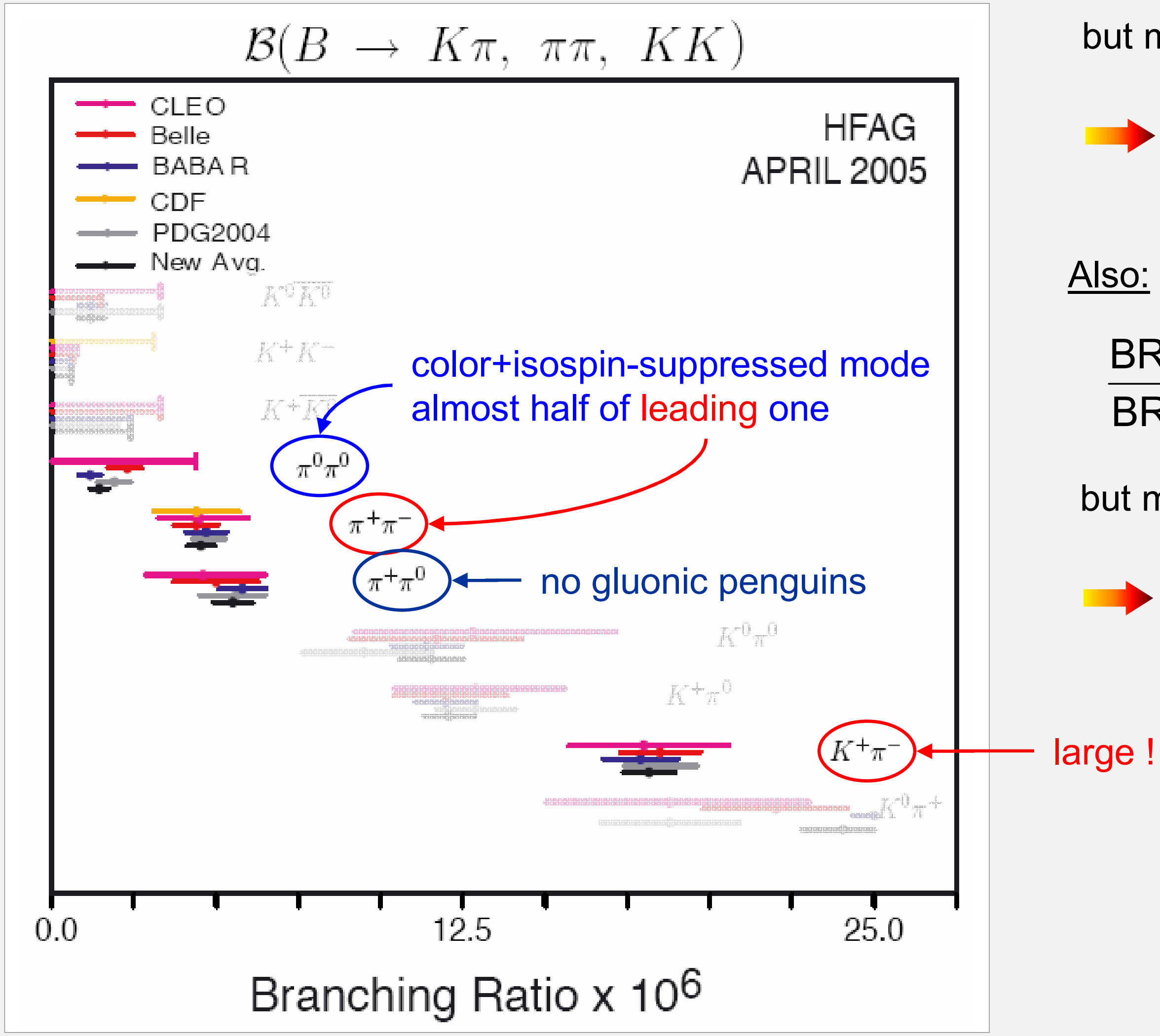
$B \to hh'$ Branching Fractions

Zero penguins and color suppr. predicts the hierarchy: $\mathrm{BR}(\pi^+\pi^-) = 2\times\mathrm{BR}(\pi^+\pi^0) \approx 20\times\mathrm{BR}(\pi^0\pi^0)$



but measurement gives: $\dfrac{B^{+-}}{B^{00}} = 3.1^{+0.8}_{-0.6}$

➡ penguins could be important!

Also: without penguins expect:

$$\frac{\mathrm{BR}(B^0 \to K^+\pi^-)}{\mathrm{BR}(B^0 \to \pi^+\pi^-)} \sim \frac{|V_{us}|^2}{|V_{ud}|^2} \sim 0.05$$

but measurement gives: 4.0 ± 0.4

➡ penguins are important!

CP Results for $B^0 \to \pi^+\pi^-$

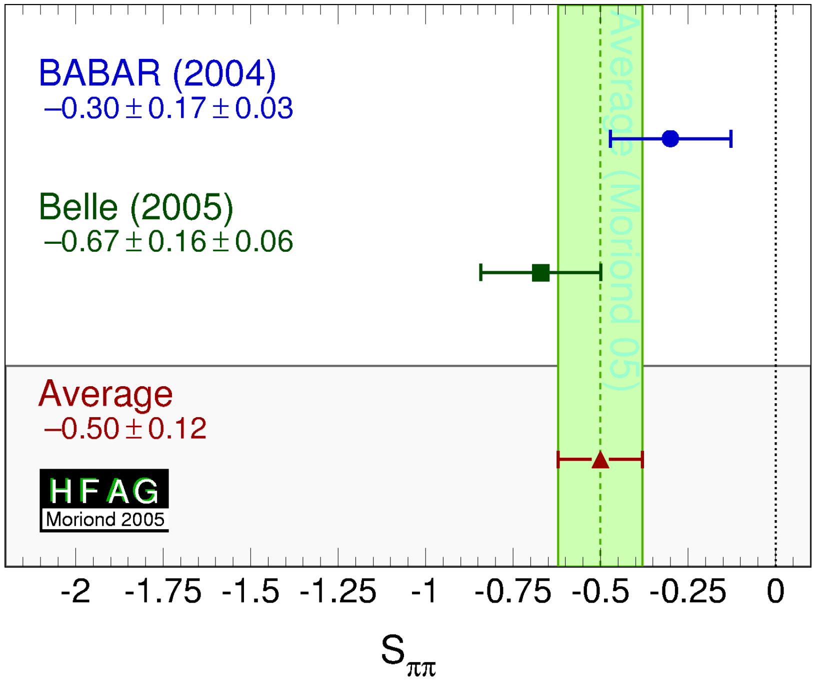
- Results for the time-dependent analysis :

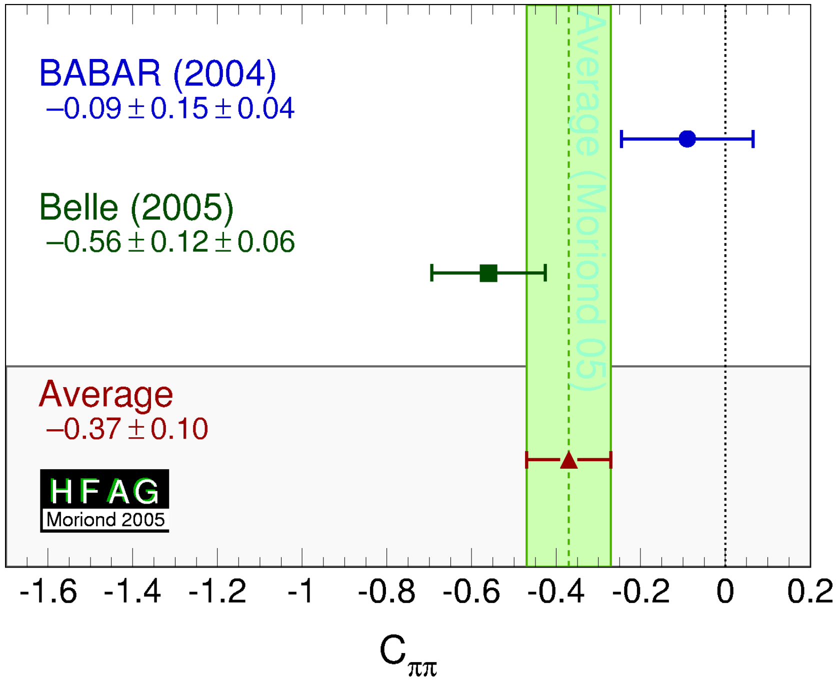
	BABAR (227m)	Belle (275m)	Average
$S_{\pi\pi}$	–0.30 ± 0.17 ± 0.03	–0.67 ± 0.16 ± 0.06	–0.50 ± 0.12
$C_{\pi\pi}$	–0.09 ± 0.15 ± 0.04	–0.56 ± 0.12 ± 0.06	–0.37 ± 0.10

BABAR, hep-ex/0501071
Belle, hep-ex/0502035

Mediocre (but improved) agreement :

χ^2 = 7.9 (CL = 0.019 ⇒ 2.3σ)

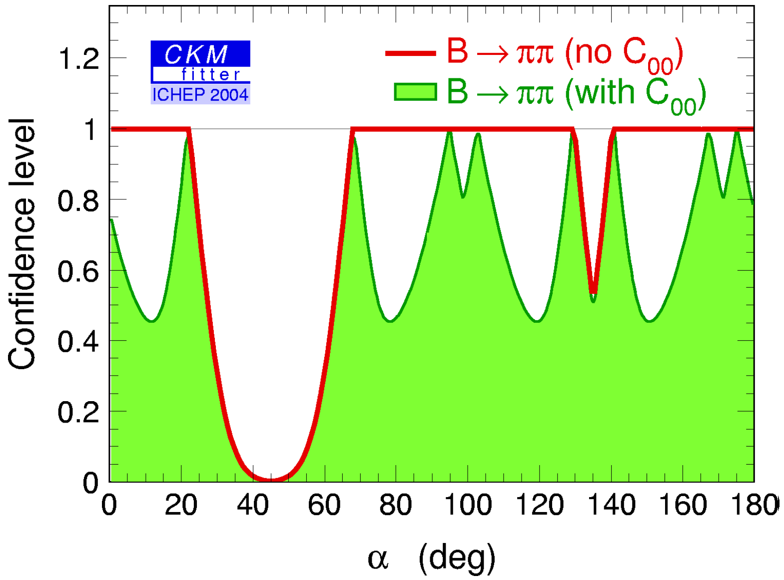




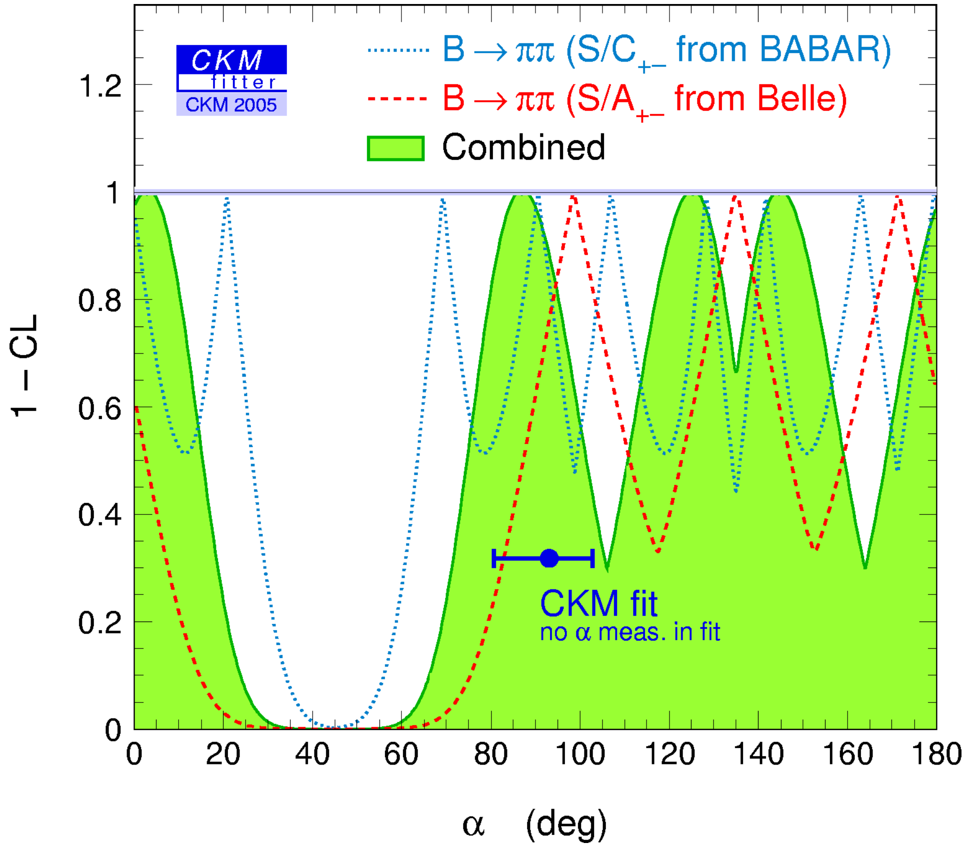
$B \to \pi\pi$ Isospin Analysis

- χ^2 fit of isospin relations to observables: $|\alpha - \alpha_{\text{eff}}| < 38°$ (90% CL)

BABAR



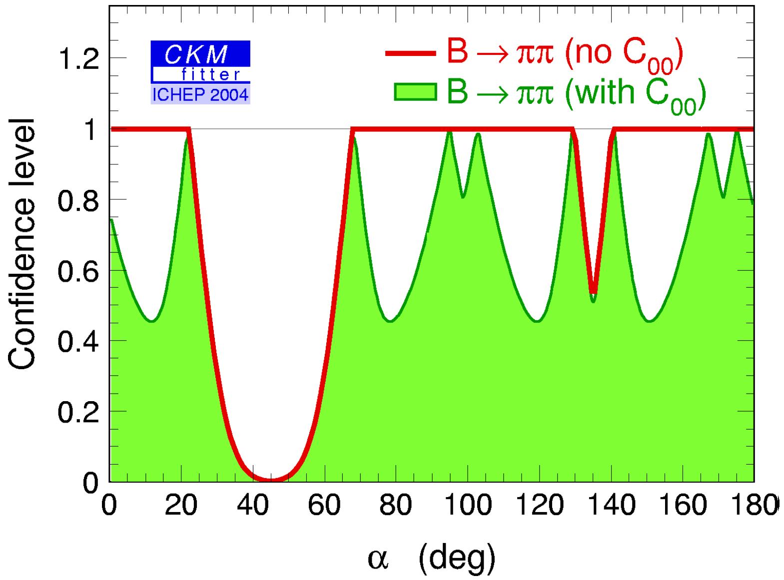
BABAR & Belle

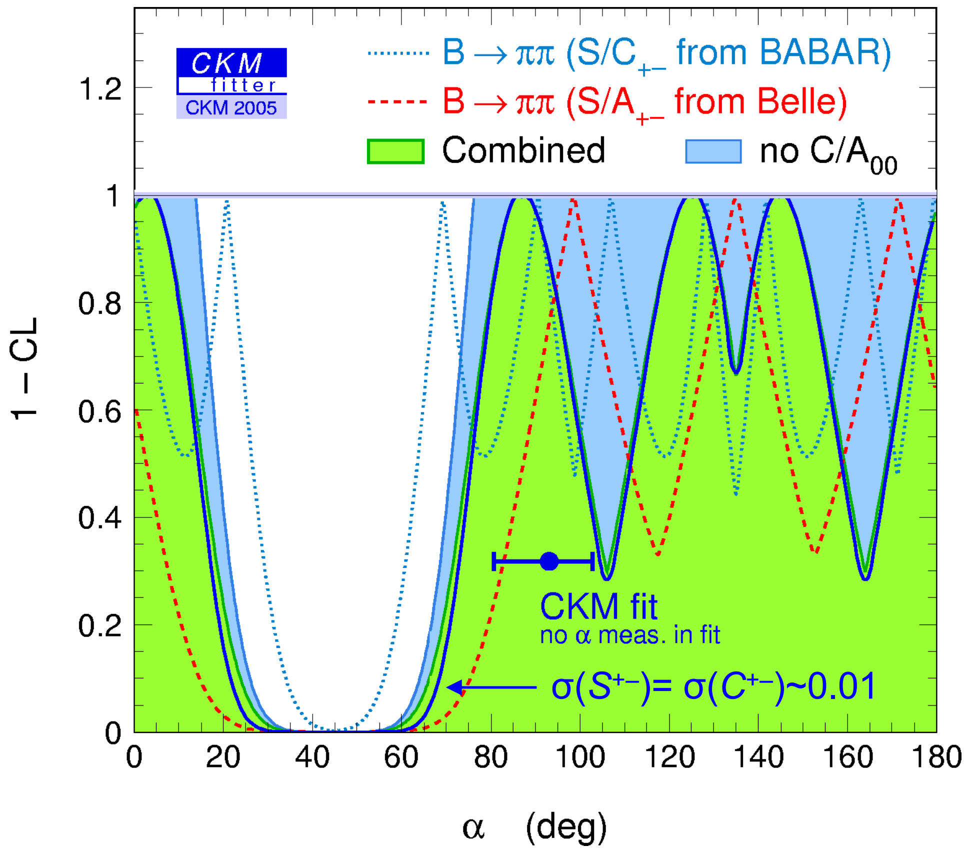


$B \to \pi\pi$ Isospin Analysis

- χ^2 fit of isospin relations to observables: $|\alpha - \alpha_{eff}| < 38°$ (90% CL)

BABAR





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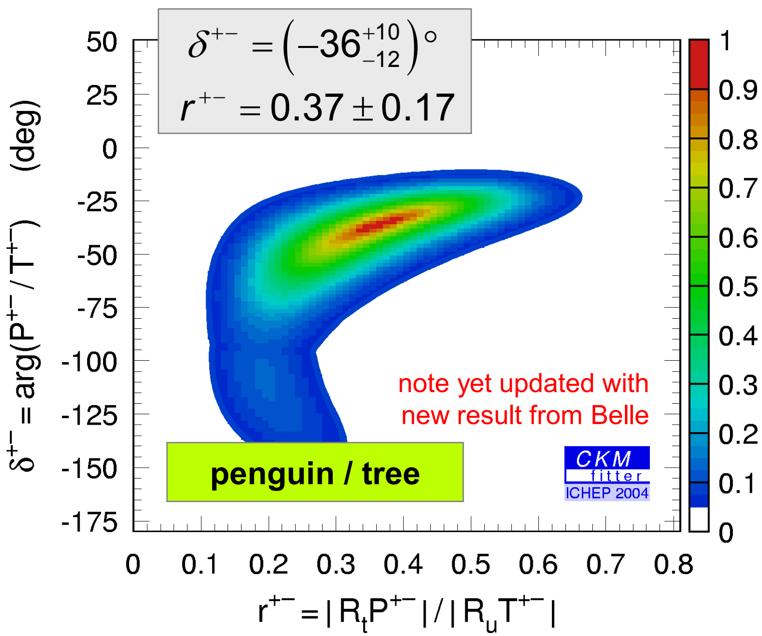
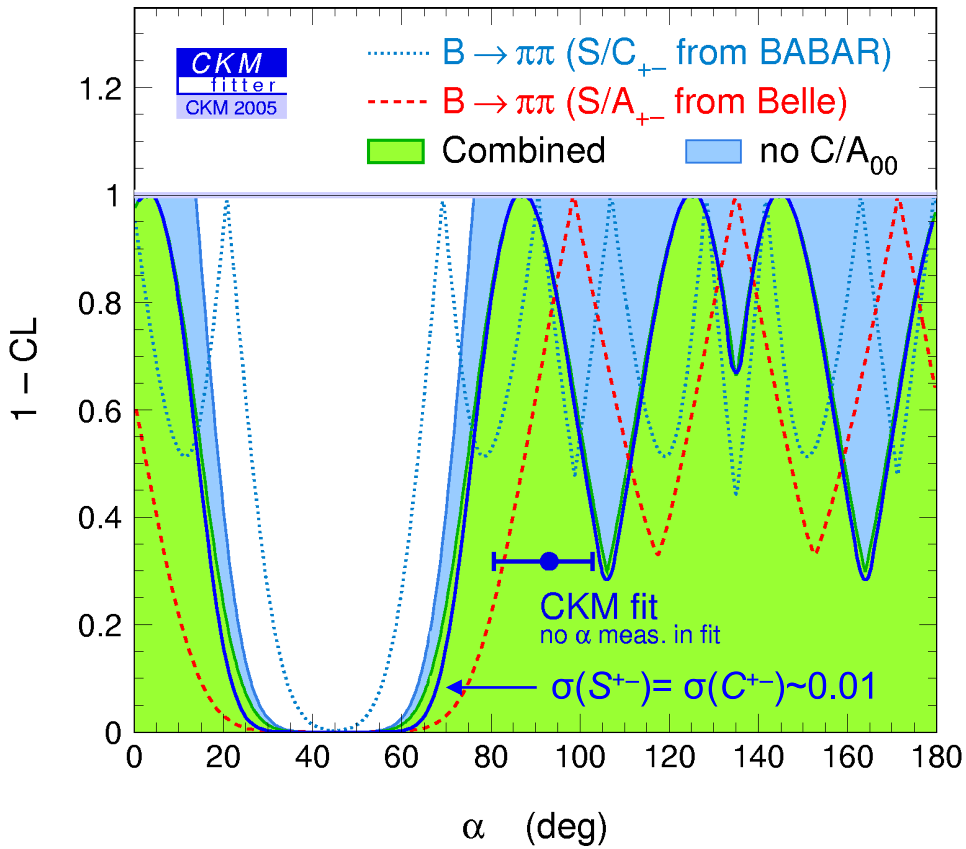




- Study decay dynamics ...

See theory talks !

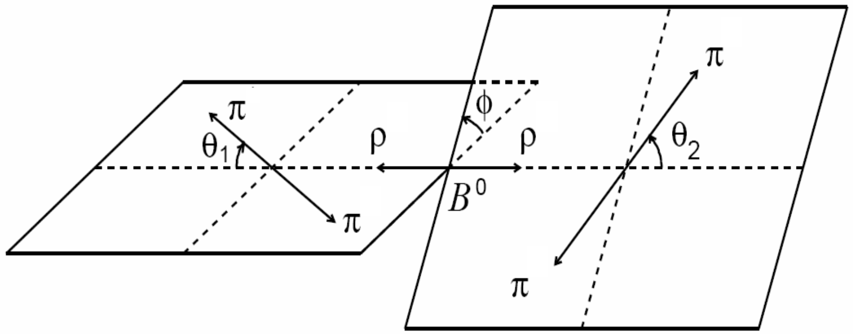
A "surprise" : $B^0 \to \rho^+\rho^-$

★ Branching fractions for the $B \to \rho\rho$ system (WA) :

$\mathcal{B}^{+-} = (30 \pm 6)\times10^{-6}$, $\mathcal{B}^{+0} = (26.4\,^{+6.1}_{-6.4})\times10^{-6}$, $\mathcal{B}^{00} < 1.1\times10^{-6}$ at 90% CL

BABAR, hep-ex/0412067

➡ small penguins !



★ Experimental complications (I) :

$B \to VV$ can have L_{VV}=0,1,2, with

$CP(L_{VV}=0,2) = +1$ and $CP(L_{VV}=1) = -1$

Nature's great present : longitudinal polarization dominates ➡ almost no *CP* dilution

★ Experimental complications (II) :

Dominant mode: $B \to \rho^+\rho^- \to \pi^+\pi^-\pi^0\pi^0 \Rightarrow$ large misreconstruction rate (~ 50%)

The large misreconstruction rate makes the fit vulnerable to biases from correlations and backgrounds

4-body mode and broad, light resonance: large amounts of *B*-related backgrounds

$B \to \rho\rho$ Isospin Analysis

- Results from *CP* fit : BABAR, hep-ex/0503049

	BABAR (232m)
$S_{\rho\rho,L}$	$-0.33 \pm 0.24\,^{+0.08}_{-0.14}$
$C_{\rho\rho,L}$	$-0.03 \pm 0.18 \pm 0.09$

- Isospin analysis :

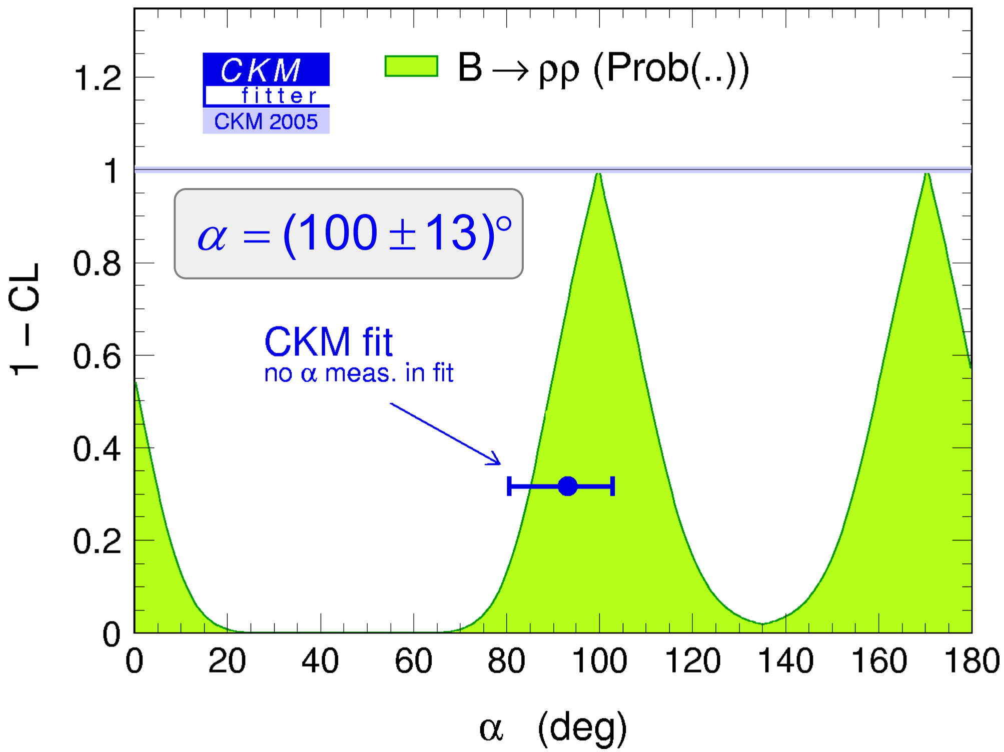
$|\alpha - \alpha_{\text{eff}}| < 11^\circ$ (68% CL)

penguin / tree

$\delta^{+-} = (\ldots)^\circ$

$r^{+-} = 0.07^{+0.14}_{-0.07}$

As expected:
much smaller than in $B \to \pi\pi$



$B \to \rho\rho$ Isospin Analysis

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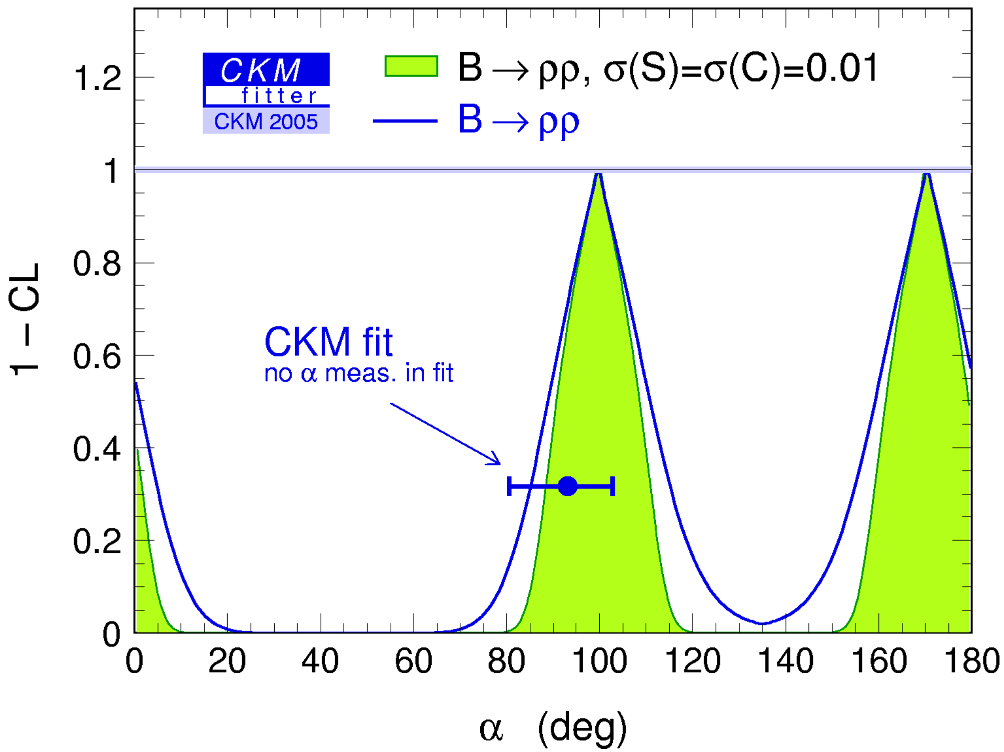
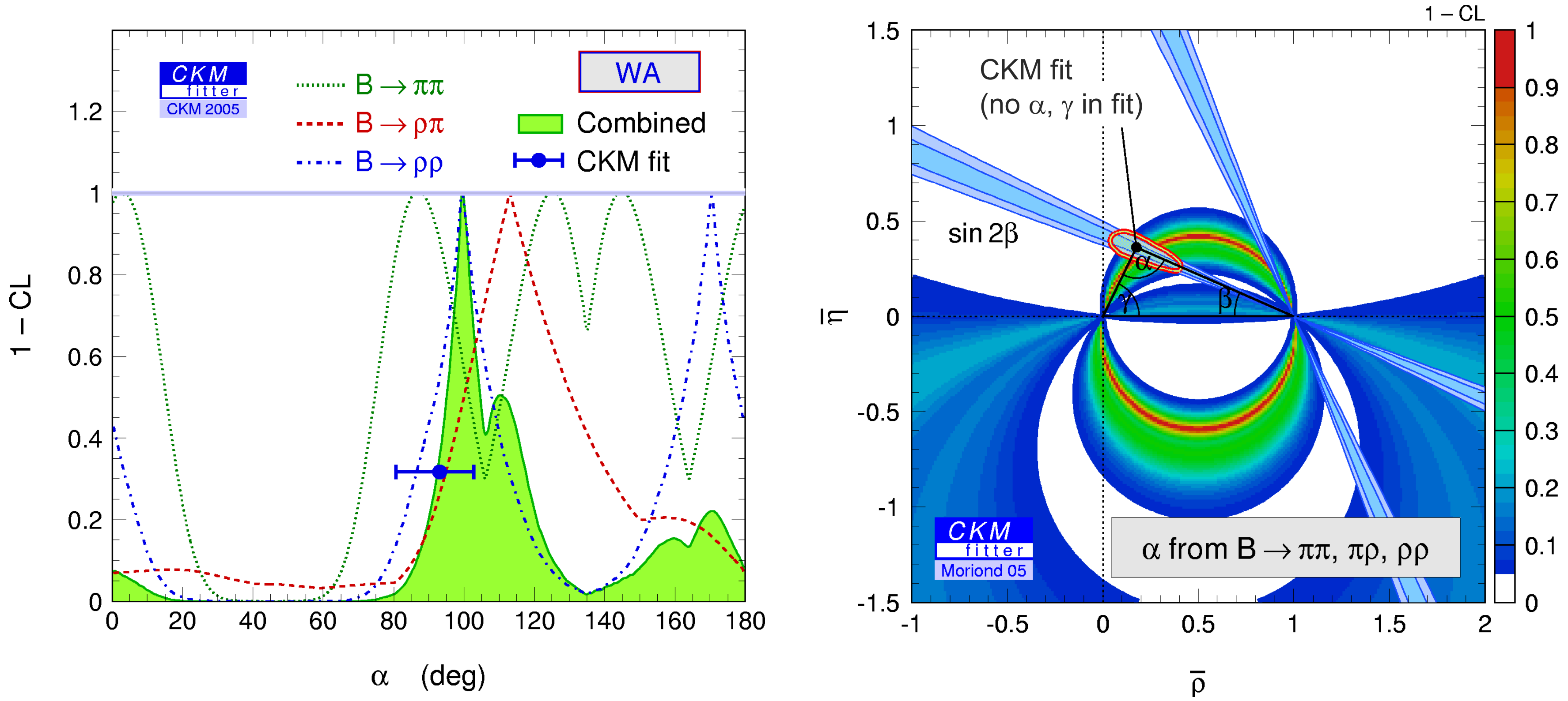


Combination of $\pi\pi$, $\rho\pi$, $\rho\rho$: first measurement of α

- Combining the three analyses ($B \to \rho\rho$ best single measurement) :
  - mirror solution disfavored
  - for the SM solution we find :
  - similar precision as CKM fit :

$$\alpha_{B\text{-Factories}} = \left[101\,^{+16}_{-9}\right]^\circ \quad \Rightarrow \quad \alpha_{\text{CKM}} = \left[93\,^{+10}_{-13}\right]^\circ$$



(1st generation-) *B*-Factories' future on α … till ~ 2008

- Expect ~ 4 times more statistics for both BABAR and Belle

- $\pi\pi$ isospin analysis will "rapidly" improve with better $C(\pi^0\pi^0)$ measurements

- $\rho\rho$ isospin analysis, future unclear:
  - bound on penguin pollution only improves with $\sqrt{B(\rho^0\rho^0)}$
  - if discovered, not enough statistics to well measure $C(\rho^0\rho^0)$ and $S(\rho^0\rho^0)$
  - on the other hands: no Belle results yet !
  - at very large statistics, systematics and model-dependence will become an issue

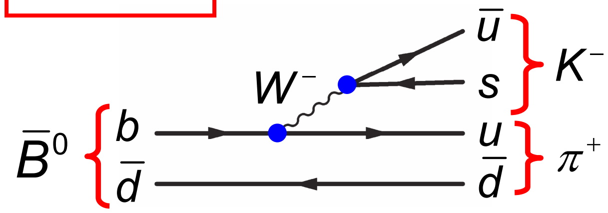
- $\rho\pi$ isospin analysis … not very promising

- $\rho\pi$ Dalitz analysis is just at the beginning: very challenging; still much to learn; no Belle result yet; model-dependence is an issue !

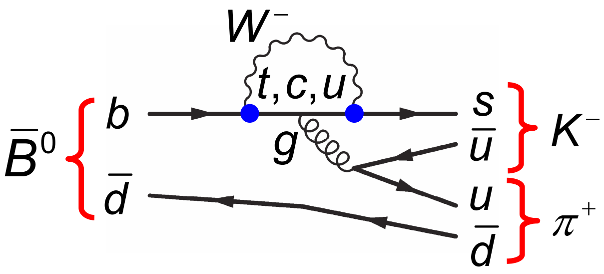
Excursion to
$B \to \pi\pi$, $K\pi$, KK (and more) Decays

Charmless $b \to s$ Decays

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



Tree: Cabibbo-suppressed $\propto V_{ub}V_{us}^*$ $\propto \lambda^4$



Penguin: dominant diagram? $\propto V_{tb}V_{ts}^*$ $\propto \lambda^2$

famous modes:

$B^0 \to K^+\pi^-$

$B^0 \to \rho^-K^+$

$B^0 \to K^{*+}\pi^-$

$B^0 \to \phi K^0$

- Note: no way to produce opposite charge-flavor combination ("self-tagging") :

$$B^0 \not\to K^-\pi^+ \quad \text{and} \quad \bar{B}^0 \not\to K^+\pi^-$$

→ $K^+\pi^-$ is a flavor eigenstate and cannot exhibit mixing-induced *CP* violation

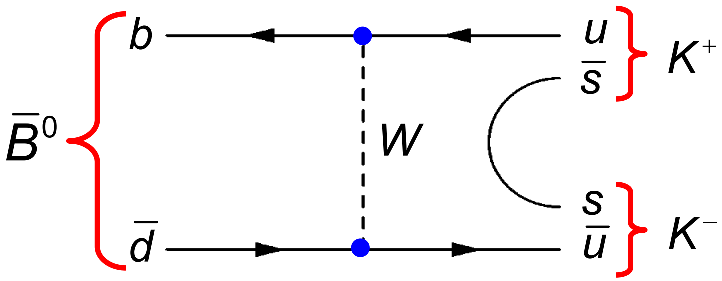
- Since $b \to s$ decays are penguin-enhanced, they provide sensitivity to the penguin pollution in the corresponding $b \to u$ mode, using SU(3) symmetry

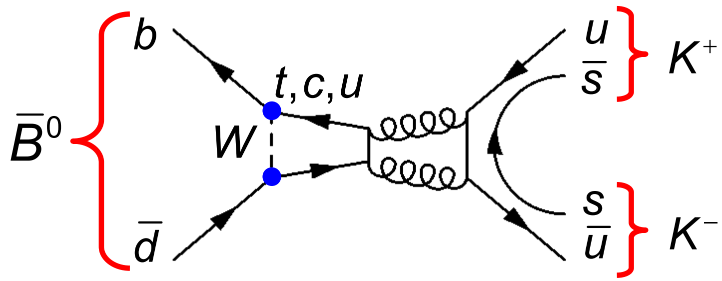
$$P_{\pi\pi}^{+-} \sim P_{K\pi}^{+-}$$

- Could exhibit sensitivity to new physics

Charmless $b \to s$ Decays (cont.)

$b\bar{d} \to u\bar{s}\ \bar{u}s$ are expected to have tiny branching fractions





famous modes:

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

$B^0 \to K^{*-}K^+$

$B^0 \to K^{*+}K^{*-}$

Tree: exchange diagram

$\propto V_{ub}V_{ud}^*$

$\propto \lambda^3$

Penguin: Okubo-Zweig-Iizuka (OZI) - suppressed annihilation ("*disconnected quark lines are suppressed*")

$\propto V_{tb}V_{td}^*$

$\propto \lambda^3$

- Exchange (neutral decays) and annihilation (charged decays) decay rates go with

$$(f_{B_d})^2$$

- Exchange diagrams also contribute to $B^0 \to \pi^+\pi^-$. Their size is an important unknown in the theoretical prediction of its decay dynamics, since the do not "*factorize*"

→ *theory lectures*

Direct *CP* Violation

- We have seen in the first lecture that direct *CP* violation (= *CP* violation in decay) requires at least two decay amplitudes with different weak and strong phases

$$A_{CP} \equiv \frac{\Gamma(\bar{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\bar{B} \to \bar{f}) + \Gamma(B \to f)} = \frac{|\bar{A}_{\bar{f}}|^2 - |A_f|^2}{|\bar{A}_{\bar{f}}|^2 + |A_f|^2} \propto |T||P|\sin(\Delta\phi)\sin(\Delta\theta)$$

convention: A_{CP} if flavor eigenstate (*e.g.*, $K^+\pi^-$, $\pi^+\pi^0$), C_{hh} if flavor mixing occurs

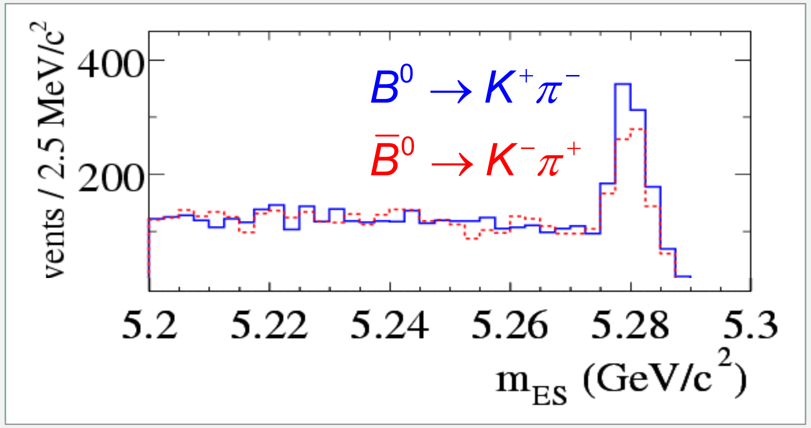
- Occurence of direct *CP* violation thus indicates significant penguin contributions

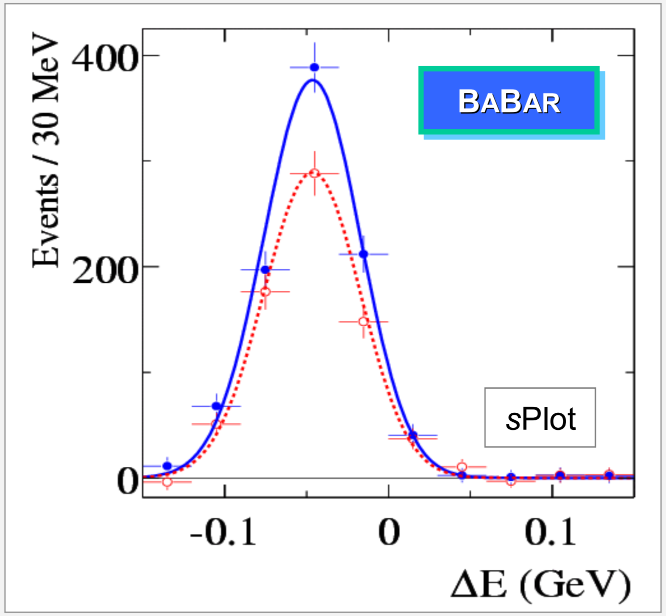
- On the other hand: non-occurrence does not necessarily mean zero penguins, but could be due to vanishing strong phases !

Direct *CP* Violation : $B^0 \to K^+\pi^-$

- Large asymmetry observed by BABAR and Belle in $B^0 \to K^+\pi^-$ decays (Summer 2004) :

$$A_{CP}(B^0 \to K^+\pi^-) = -0.109 \pm 0.019$$





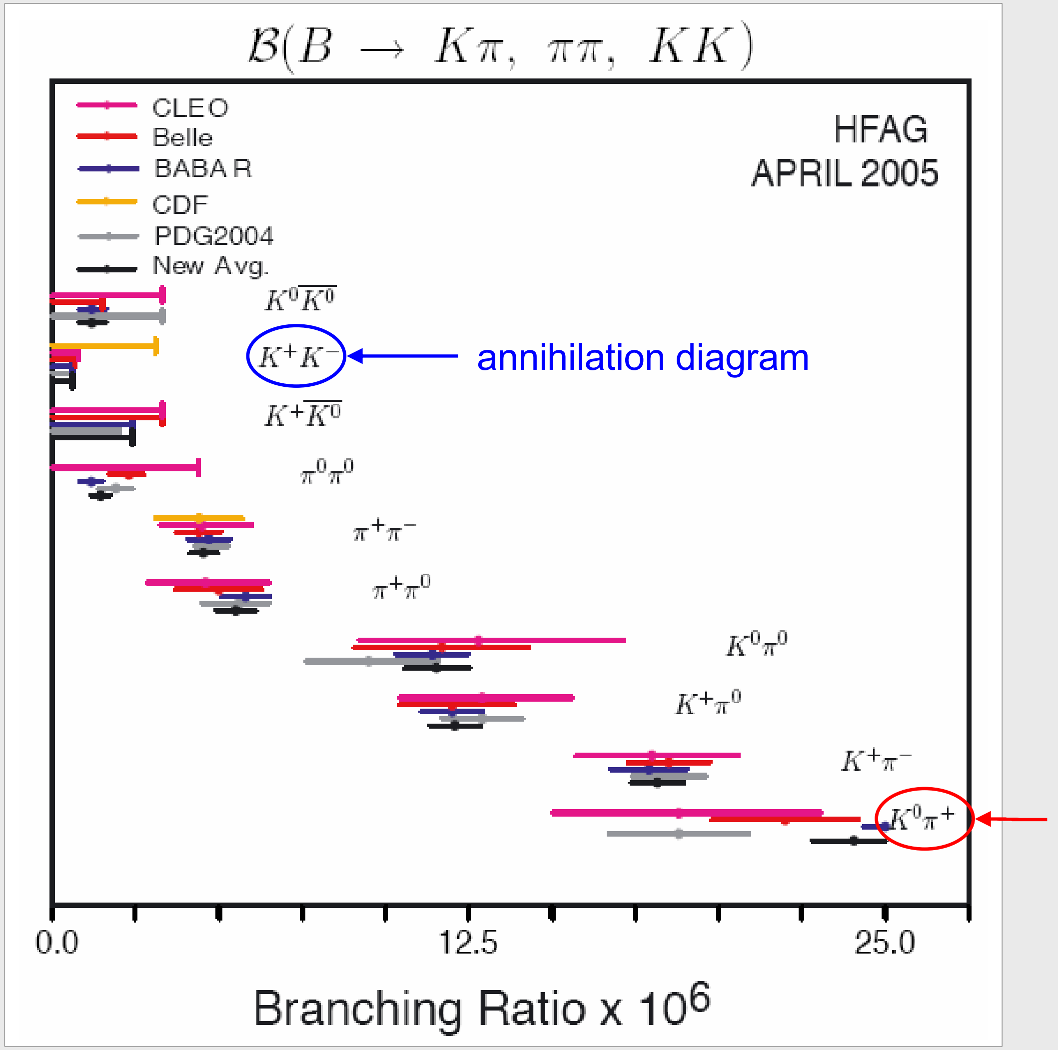
- Expect more *B* decays modes (also charged ones) to soon exhibit direct *CP* violation

- Direct CPV requires interference of amplitudes of similar size and with different weak and strong phases ➡ cannot be reliably predicted (at present) for use in CKM fit

$B \to hh'$ Branching Fractions

Zero trees predict the hierarchy: BR($K^+\pi^-$) ~ BR($K^0\pi^+$) ~ 2×BR($K^+\pi^0$) ~ 2×BR($K^0\pi^0$)

note: lifetime factors omitted here



Without trees expect:

$$\frac{\mathrm{BR}(B^0 \to K^0\pi^+)}{\mathrm{BR}(B^0 \to K^+\pi^-)} \simeq 1.1$$

But measurement gives:

$$\frac{\mathrm{BR}(B^0 \to K^0\pi^+)}{\mathrm{BR}(B^0 \to K^+\pi^-)} = 1.32 \pm 0.09$$

➡ trees are not negligible!

digression: $B \to K\pi$ with Flavor Symmetries

- $B \to K\pi$ decays are related through isospin in quadrangle (4 different final states)
  - neglecting EW penguins system is solvable (9 obs. vs 8 unknowns): determines α
  - needs huge statistics and has many discrete ambiguities
  - if EW penguins are included system underconstrained; ways out:
    - use SU(3) flavor symmetry
    - relate EW penguins to tree via Fiertz transformation
    - neglect exchange/annihilation or color-suppressed EW penguins ☹
    - a mixture of these

- SU(3) flavor symmetry relates ΔB=1 decay amplitudes belonging to a given SU(3) multiplet
  - $B \to PP$ (2 pseudoscalars) has SU(3) singlet and octet relating final states of all charges with the modes π, η, η', K, ...
  - $B \to PV$ (pseudoscalar + vector) has SU(3) octet relating final states of all charges with the modes η, π, K, ... and ρ, K^*, ϕ, ...

- SU(3) violations can be large; correction only possible for factorizable terms

→ *theory lectures*

“Penguin Puzzles”

- Long list of publications on the so-called $B \to K\pi$ puzzle

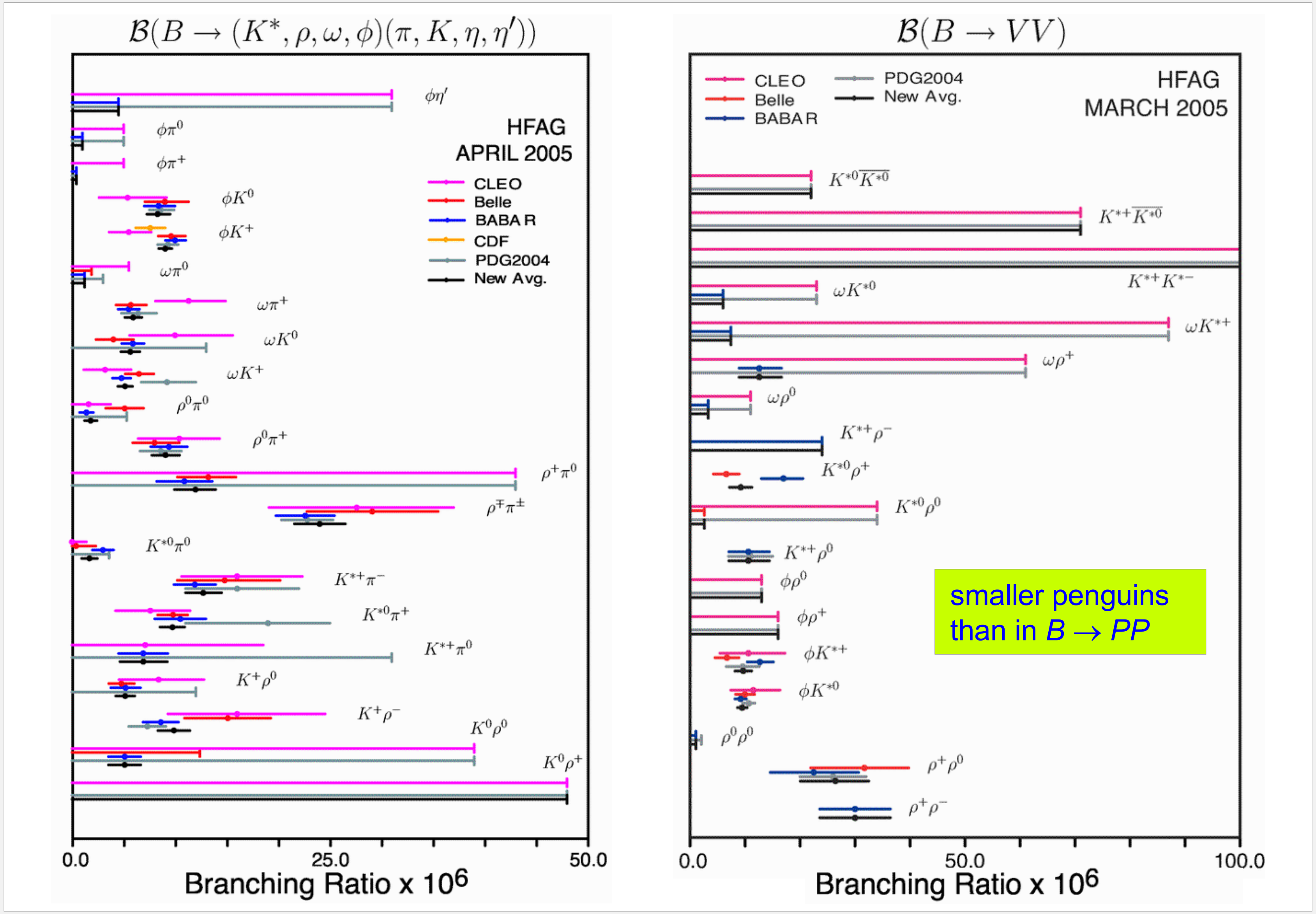
Silva-Wolfenstein, 1993
Benke-Neubert, NP, B675, 333 (2003)
Buras *et al*. (BFRS), EPJ C32, 45 (2003); (+ 2005)
Chiang *et al*, PRD D70, 034020 (2004)
Wu-Zhou, hep-ph/0503077
Charles *et al*., EPJ C41, 1–131 (2005)
apologies to the many other authors on this problem

- There’s more puzzles …

- My personal take on puzzles:
  - there is no puzzle in $B \to \rho\rho$: color suppression works when penguins are small
  - there is a $\pi\pi$ puzzle: why are terms $\sim V_{ub}$ so large ?
  - there is a $K\pi$ puzzle: why are terms $\sim V_{ub}$ so large ?
  - there is an *s*-penguin puzzle: why are terms $\sim V_{ub}$ so large ?

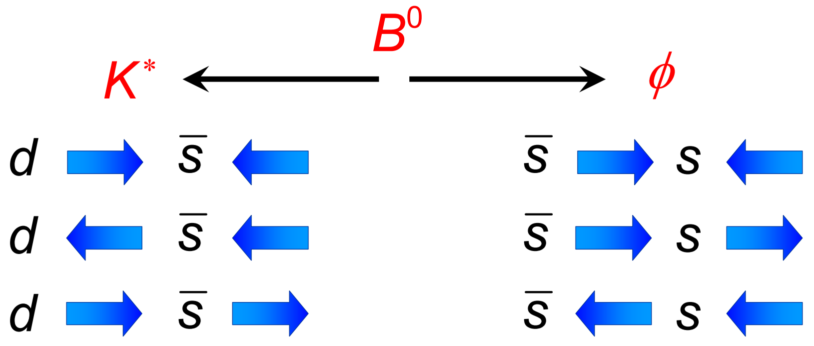
} similar magnitude of “*u*-penguin” enhancement

$B \to PV, VV$ Branching Fractions



Polarization in $B \to VV$ Decays

- Within naïve factorization, transverse polarization suppressed $\propto (m_V / m_B)^2$



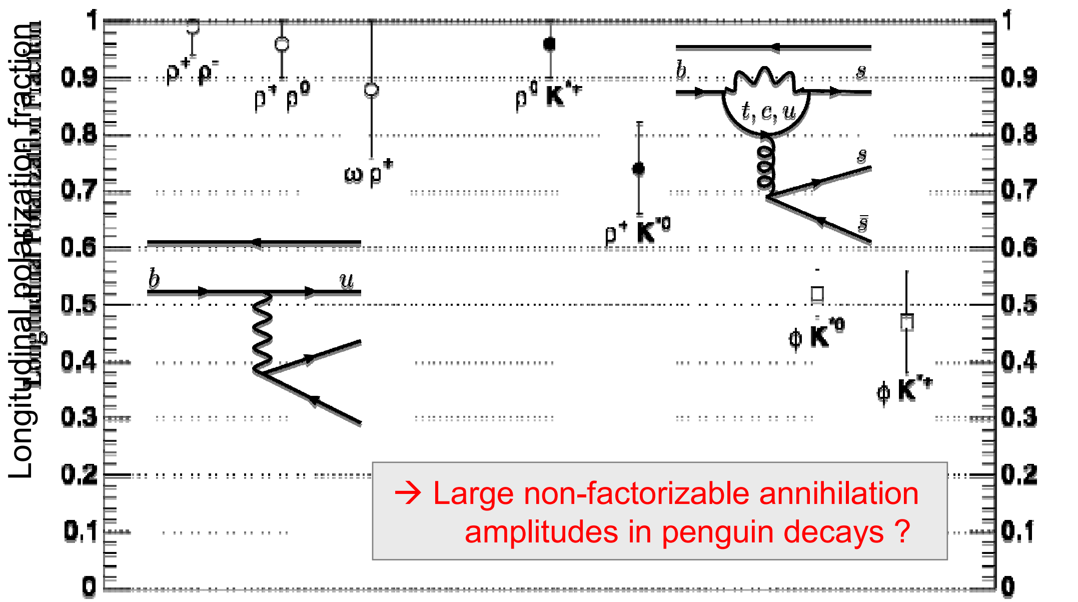
$A_0 \sim 1$

$A_+ \sim m_\phi / m_{B^0}$

$A_- \sim m_\phi \cdot m_{K^*} / m_{B^0}^2$

- Experiment:

BABAR & Belle,
HFAG Moriond 2005



Towards γ [next UT input that is not theory limited]

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

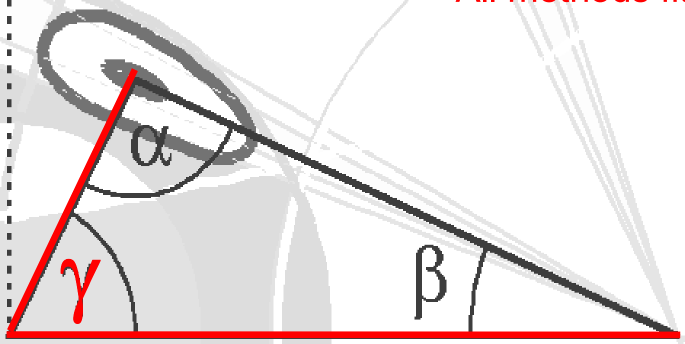
the million dollar Q:

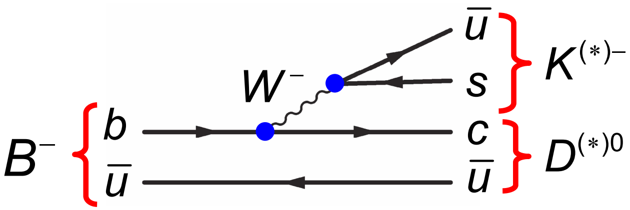
$\left.\begin{matrix} r_B \\ r_B^* \end{matrix}\right\}$ how small ?

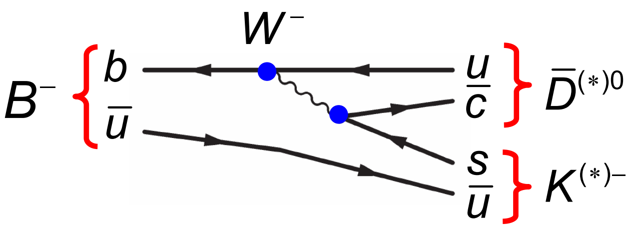
- GLW : D^0 decays into *CP* eigenstate
- ADS : D^0 decays to $K^-\pi^+$ (favored) and $K^+\pi^-$ (suppressed)
- GGSZ : D^0 decays to $K_S\pi^+\pi^-$ (interference in Dalitz plot)

➨ All methods fit simultaneously: γ, r_B and θ

Gronau-London, PL B253, 483 (1991); Gronau-Wyler, PL B265, 172 (1991)
Atwood-Dunietz-Soni, PRL 78, 3257 (1997)
Giri *et al*, PRD 68, 054018 (2003)







No Penguins ☺

Tree: dominant

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

$\propto \lambda^3$

Tree: color-suppressed

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

$\propto \lambda^3\sqrt{\rho^2+\eta^2}$

relative CKM phase : γ

The "GLW" and "ADS" Analyses

GLW : measure branching fraction of $B^- \to D^0{}_{(CP)}K^-$

$D^0{}_{CP\pm}$ reconstructed in $\pm CP$ (for ex., $D^0{}_{CP+}\to K^-K^+$, $D^0{}_{CP-}\to K_S\pi^0$) ➡ $b \to c$ and $b \to u$ interfere

4 observables sensitive to γ :

$$r_B \equiv \left| A(b \to u\bar{c}s) / A(b \to c\bar{u}s) \right|$$

~ 0.1 - 0.3 ??

$$R_{CP\pm} \propto \Gamma(B^- \to D^0_{CP\pm}K^-) + \Gamma(B^+ \to D^0_{CP\pm}K^+) \propto 1 + r_B^2 \pm 2r_B \cos\delta_B \cos\gamma$$

$$A_{CP\pm} \propto \Gamma(B^- \to D^0_{CP\pm}K^-) - \Gamma(B^+ \to D^0_{CP\pm}K^+) \propto \pm 2r_B \sin\delta_B \sin\gamma / R_{CP\pm}$$

strong phase
in decay of B

Problem of GLW : requires interference of amplitudes with rather different sizes

ADS : disfavor favored amplitude and favor disfavored amplitude

$$B^- \to D^0(\to K^+\pi^-)K^- \quad \Longleftrightarrow \quad B^- \to \bar{D}^0(\to K^+\pi^-)K^-$$

2×Cabibbo-suppressed

$$r_D \equiv \left| A(c \to d u\bar{s}) / A(b \to s u\bar{d}) \right|$$

= 0.060 ± 0.003

$$R_{ADS} \equiv (\ldots) = r_D^2 + r_B^2 + 2r_B r_D \cos\gamma \cos(\delta_B + \delta_D)$$

$$A_{ADS} \equiv (\ldots) = 2r_B r_D \sin\gamma \sin(\delta_B + \delta_D) / R_{ADS}$$

strong phase
in decay of D

"ADS+GLW" : Constraint on γ

- BABAR and Belle have measured the observables for GLW and ADS in the modes $B^- \to D^0K^-$, $D^{*0}K^-$ (upcoming: D^0K^{*-})

  - No significant measurement of suppressed amplitude yet ⇒ limit : $r_B^{(*)} \lesssim 0.2$

BABAR, hep-ex/0408082, hep-ex/0408060 hep-ex/0408069, hep-ex/0408028

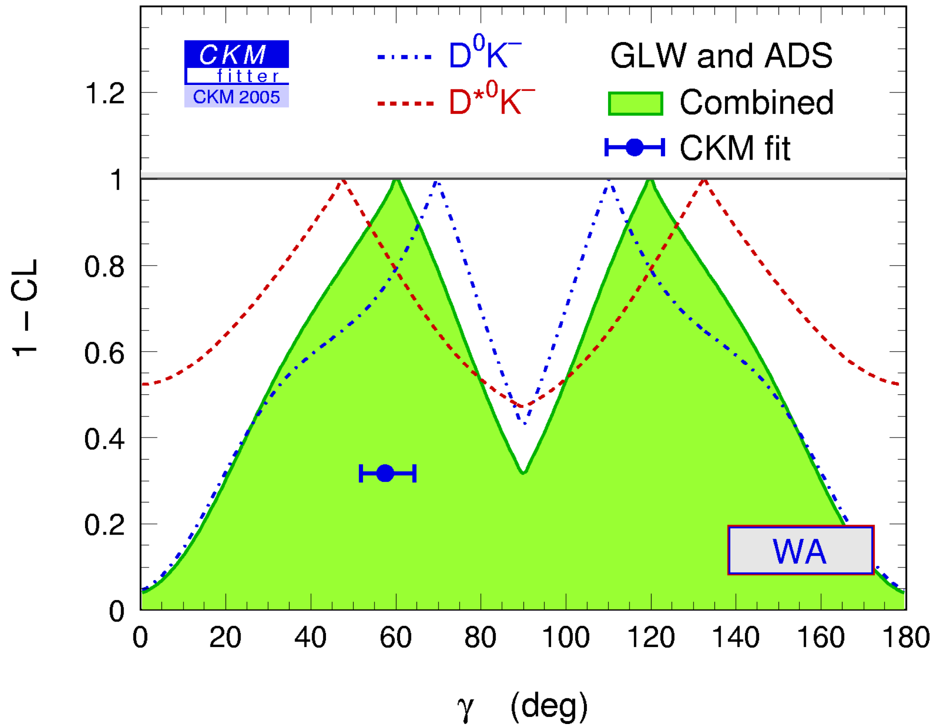
Belle, Belle-CONF-0443, hep-ex/0307074 hep-ex/0408129

  - for the SM solution :

$$\gamma_{\text{meas}} = \left[60\,^{+30}_{-39}\right]^\circ$$

$$\gamma_{\text{CKM}} = \left[58\,^{+7}_{-5}\right]^\circ$$

  - not yet competitive with CKM fit



The “GGSZ” Dalitz Analysis

Promising : Increase B decay interference through D decay Dalitz plot with $D^0 \to K_S\pi^+\pi^-$

Decay amplitudes :

$$A_-\left(m_-^2, m_+^2\right) = \left|A\left(B^- \to D^0 K^-\right)\right| \left[f_{-+} + r_B e^{i(\delta-\gamma)} f_{+-}\right]$$

$$A_+\left(m_-^2, m_+^2\right) = \left|A\left(B^+ \to \bar{D}^0 K^+\right)\right| \left[f_{+-} + r_B e^{i(\delta+\gamma)} f_{-+}\right]$$

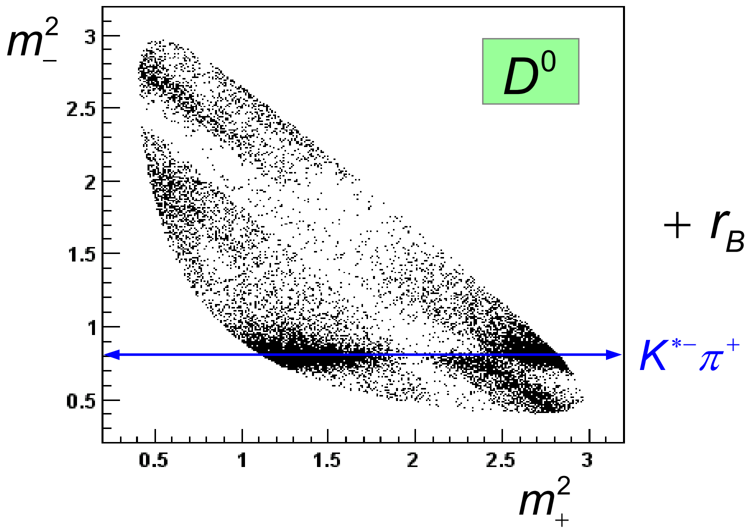
CP

Sum of amplitudes contributing to $D^0 \to K_S\pi^+\pi^-$

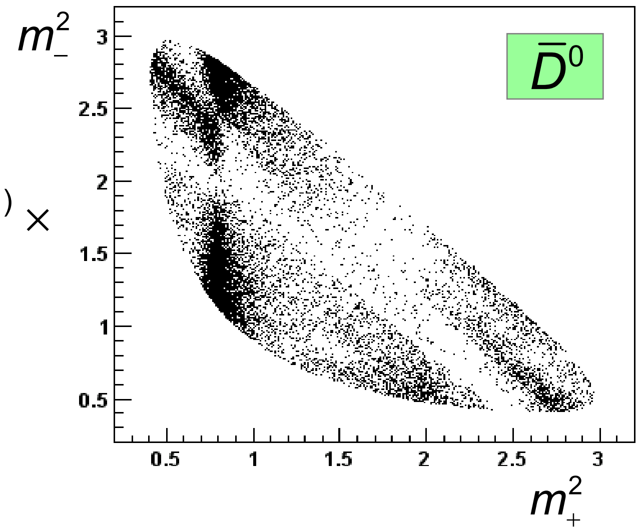
$f_{+-} \equiv f\left(m_+^2, m_-^2\right)$

$m_\pm \equiv m(K_S^0\pi^\pm)$

$|A_-|^2 = \Big|$



$+\ r_B e^{i(\delta-\gamma)} \times$



$\Big|^2$

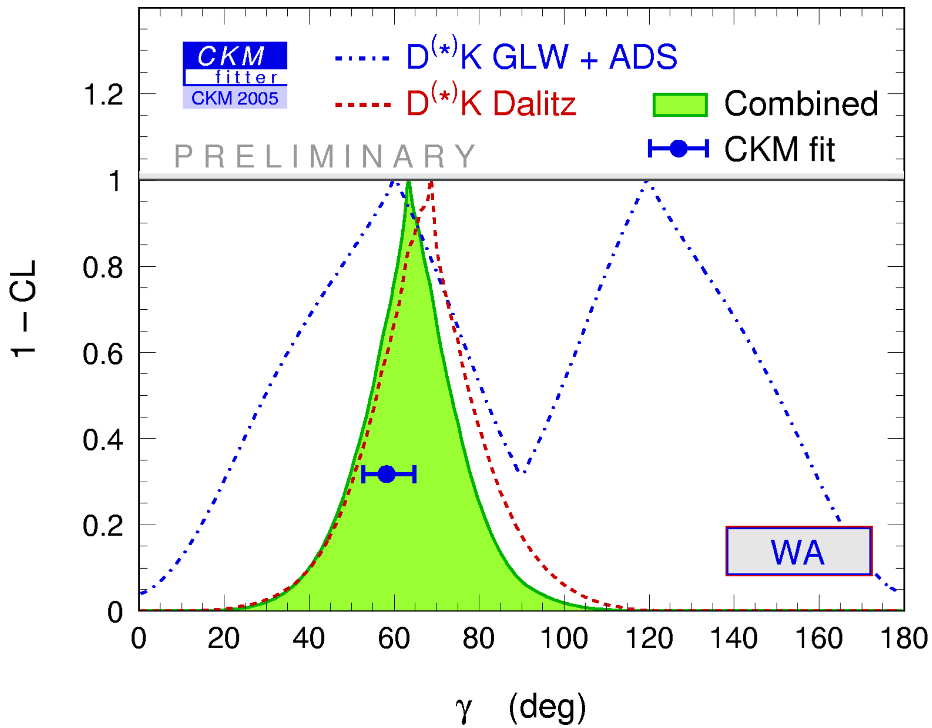
Simultaneous measurement of r_B , δ and γ

BABAR, hep-ex/0408088

"GGSZ" : Constraint on γ

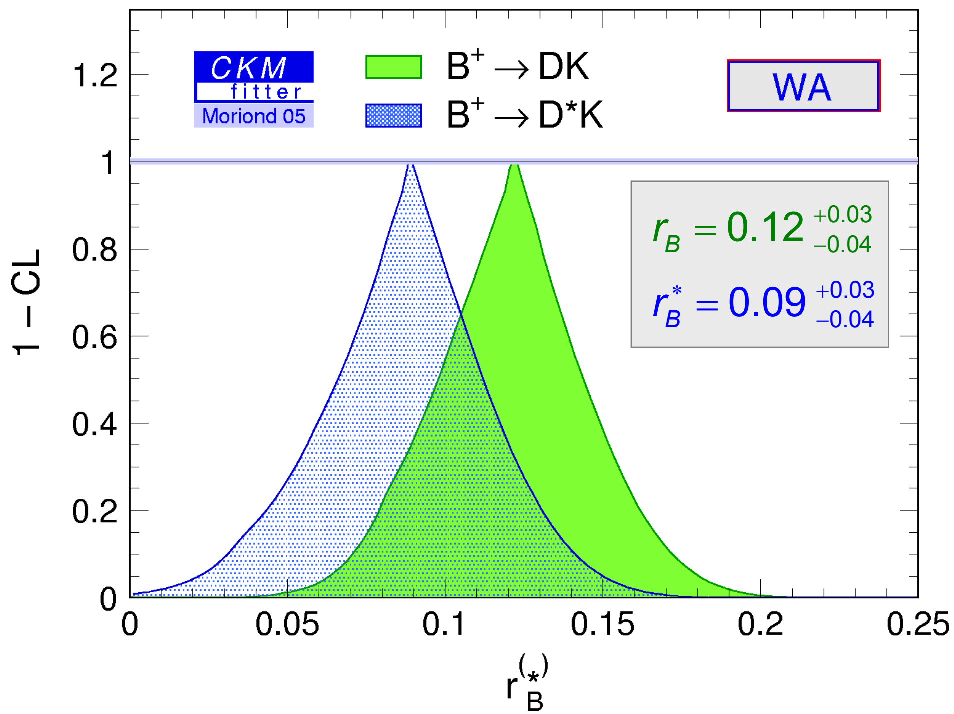
- huge number of resonances in DP: $K^*(892)$, $\rho(770)$, $\omega(782)$, $f_0(980,1370)$, $K_0{}^*(1430)$, ... ☹
- amplitudes of Dalitz plot measured in charm control sample ☺

$$\gamma_{\text{meas}} = \left[63\,^{+15}_{-13}\right]^\circ$$

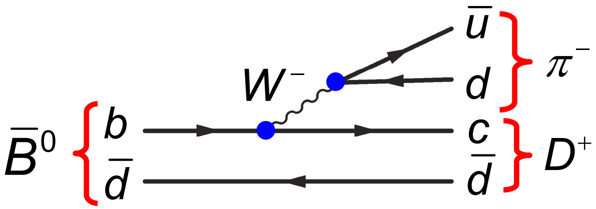


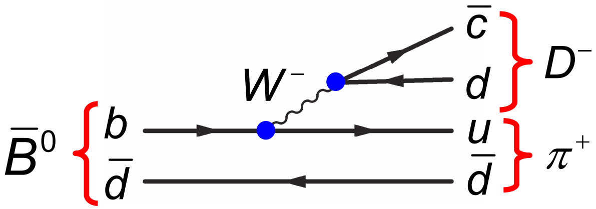
Measurement of amplitude ratio:

[no improved constraint when adding γ from CKM fit]



"sin(2β + γ)"





Similarly: $B_s^0(\bar{B}_s^0) \to D_s^- K^+$ golden γ mode at LHCb

Tree: dominant $\propto V_{cb}V_{ud}^*$ $\propto \lambda^2$

Tree: doubly CKM-suppressed $\propto V_{ub}V_{cd}^*$ $\propto \lambda^4$

- Relative weak phase 2β + γ

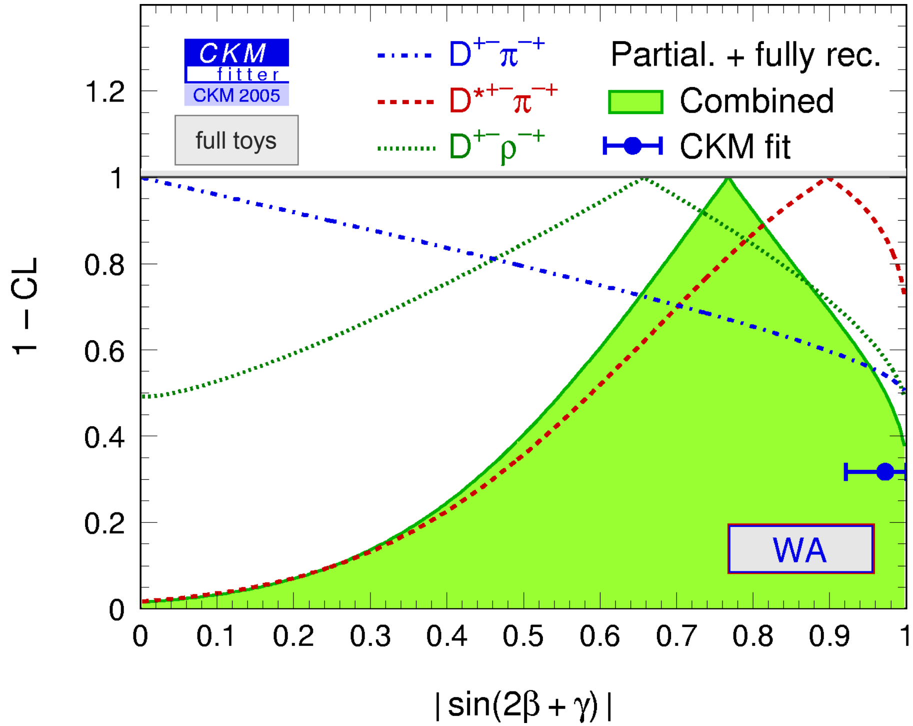
  but : γ dependence of the order of $O(10^{-4})$

- Huge statistics, but small *CP* asymmetry
- Unknowns : r_{B0}, γ and δ ⇒ needs external input
- Use SU(3) to estimate $r_{B0}^{(*)}$ (theory error: 30%)

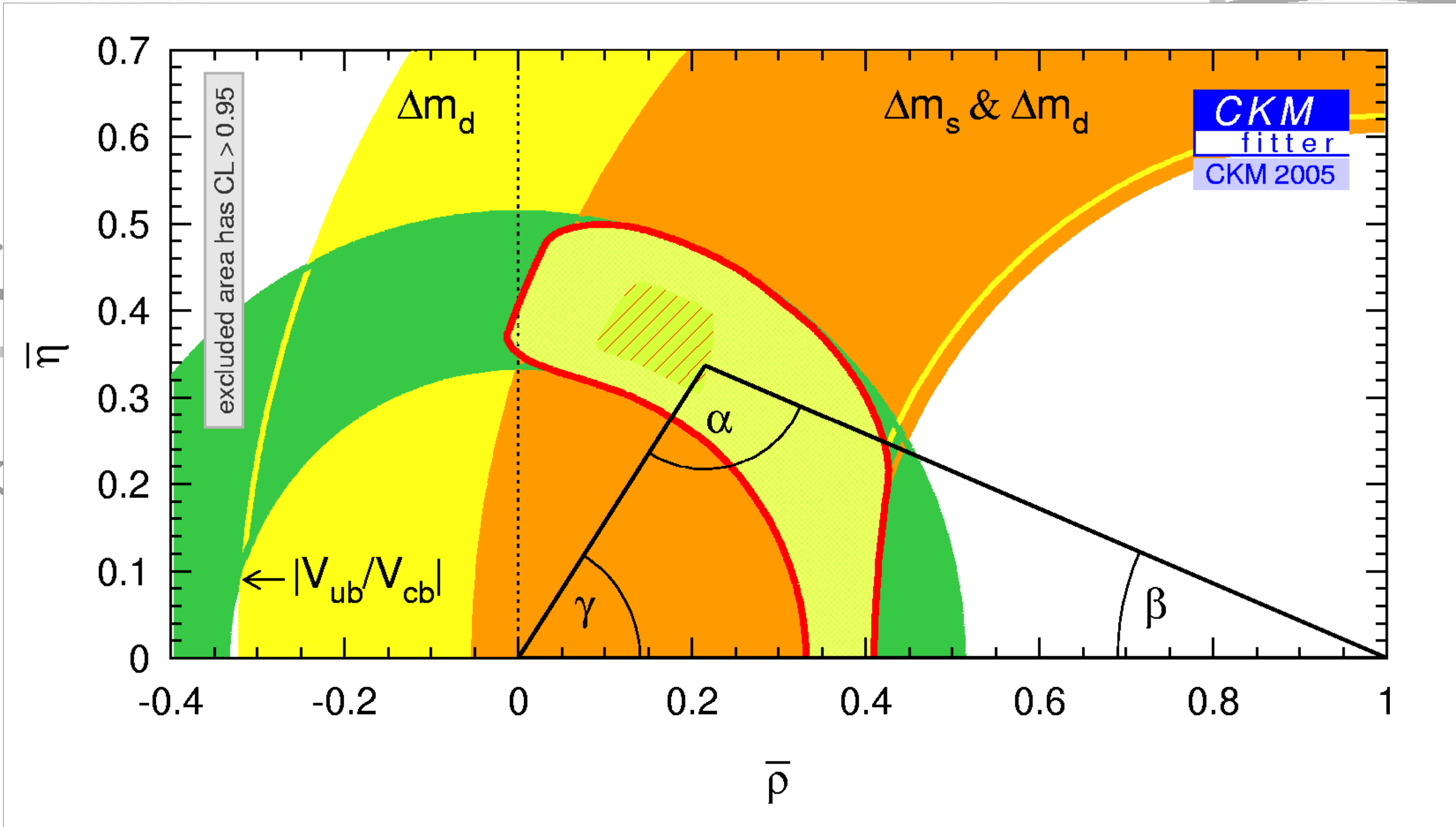
therefore not used in global CKM fit

BABAR, hep-ex/0408038, hep-ex/0408059

Belle, hep-ex/0408106, PRL 93 (2004) 031802; Erratum-ibid. 93 (2004) 059901



Putting it all together — the global CKM fit



Inputs:

$\left|\frac{V_{ub}}{V_{cb}}\right|$

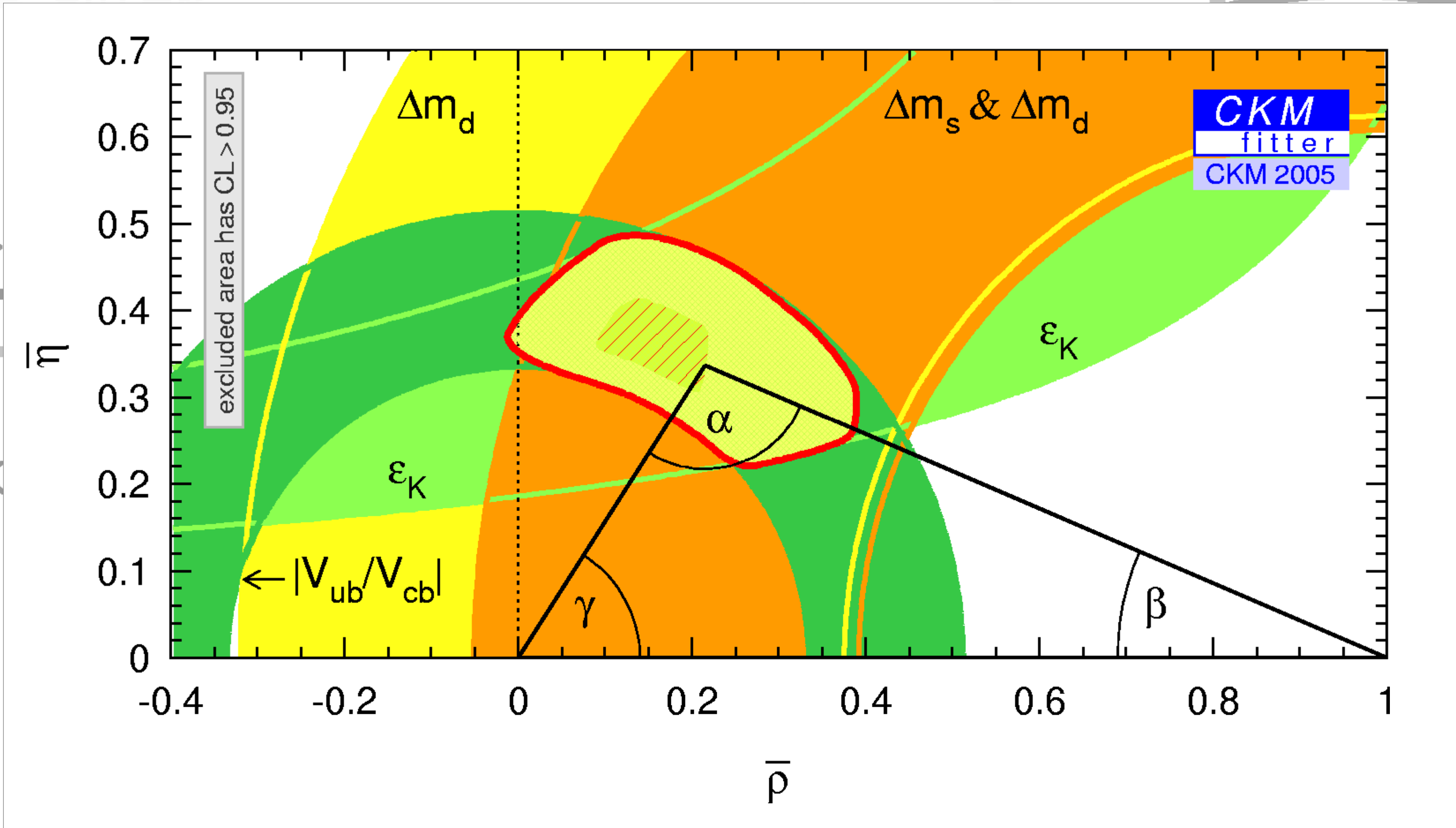
Δm_d

Δm_s

$B \to \tau\nu$

Perfect agreement … if it weren't for the *s*-penguin decays

Putting it all together



Inputs:

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Δm_d

Δm_s

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$|\varepsilon_K|$

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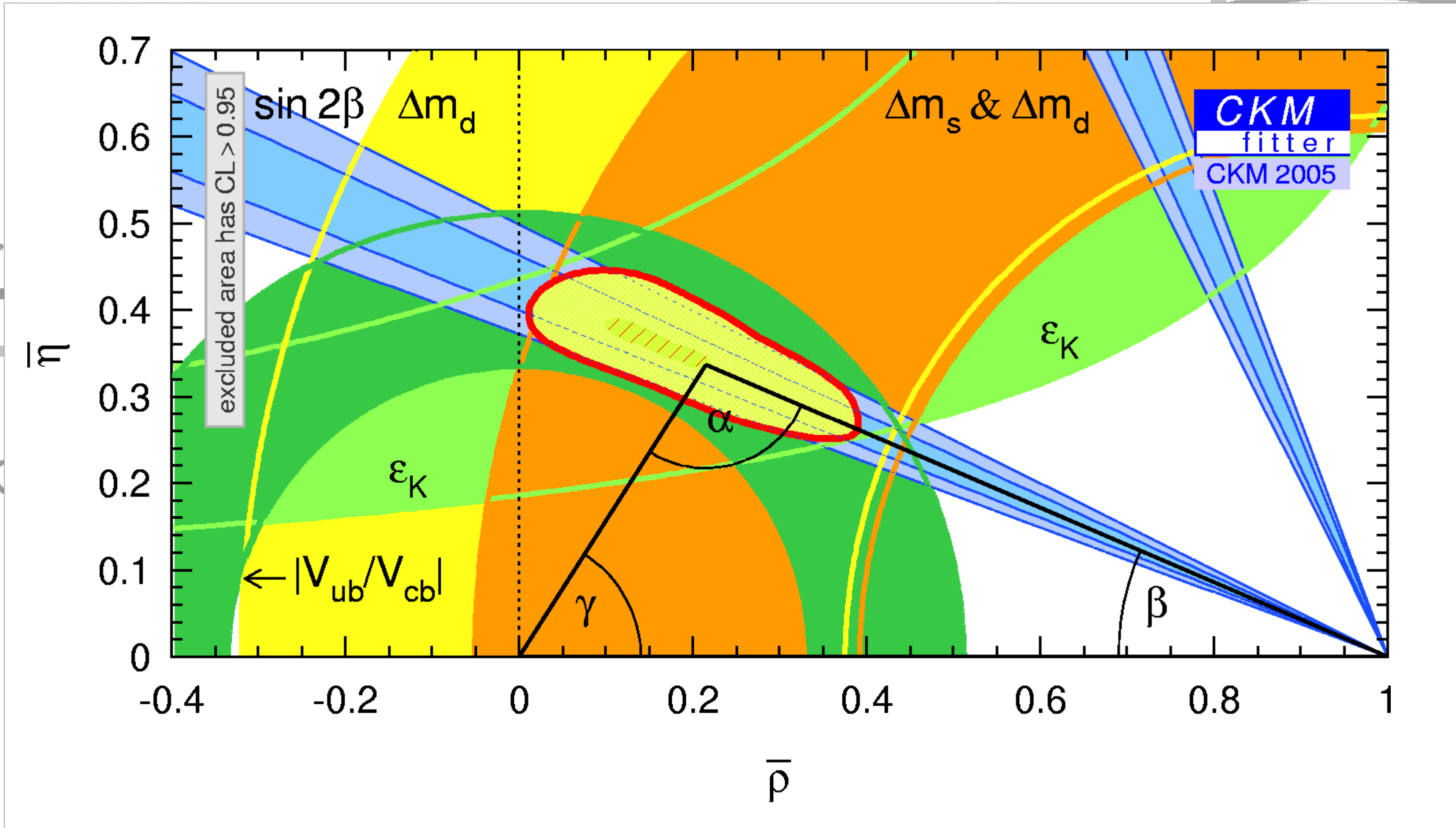
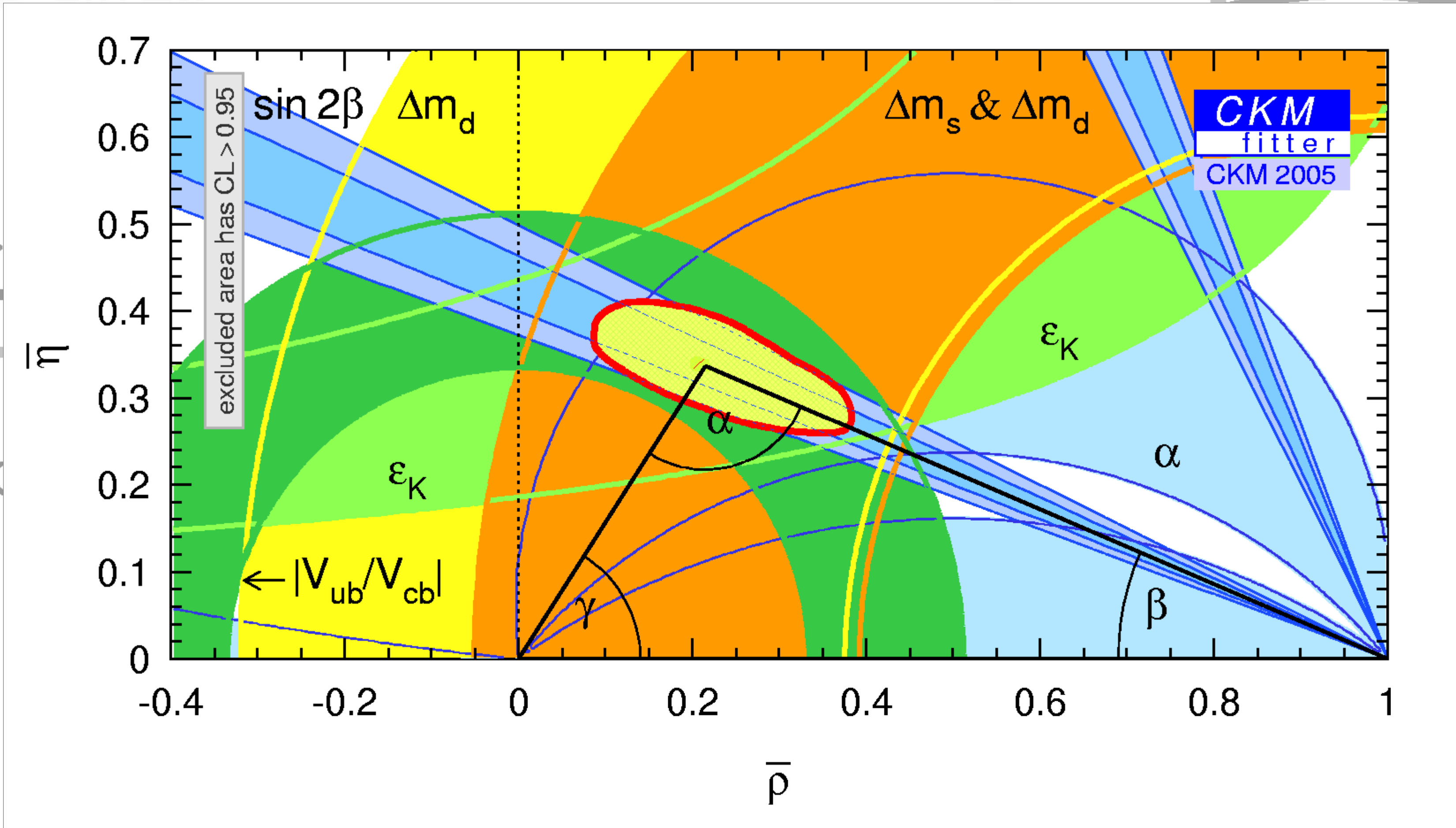


Inputs:

- $\left|\frac{V_{ub}}{V_{cb}}\right|$
- Δm_d
- Δm_s
- $B \to \tau\nu$
- $|\varepsilon_K|$
- $\sin 2\beta$

Perfect agreement … if it weren't for the *s*-penguin decays

Putting it all together — the global CKM fit



Inputs:

$\left|\frac{V_{ub}}{V_{cb}}\right|$

Δm_d

Δm_s

$B \to \tau\nu$

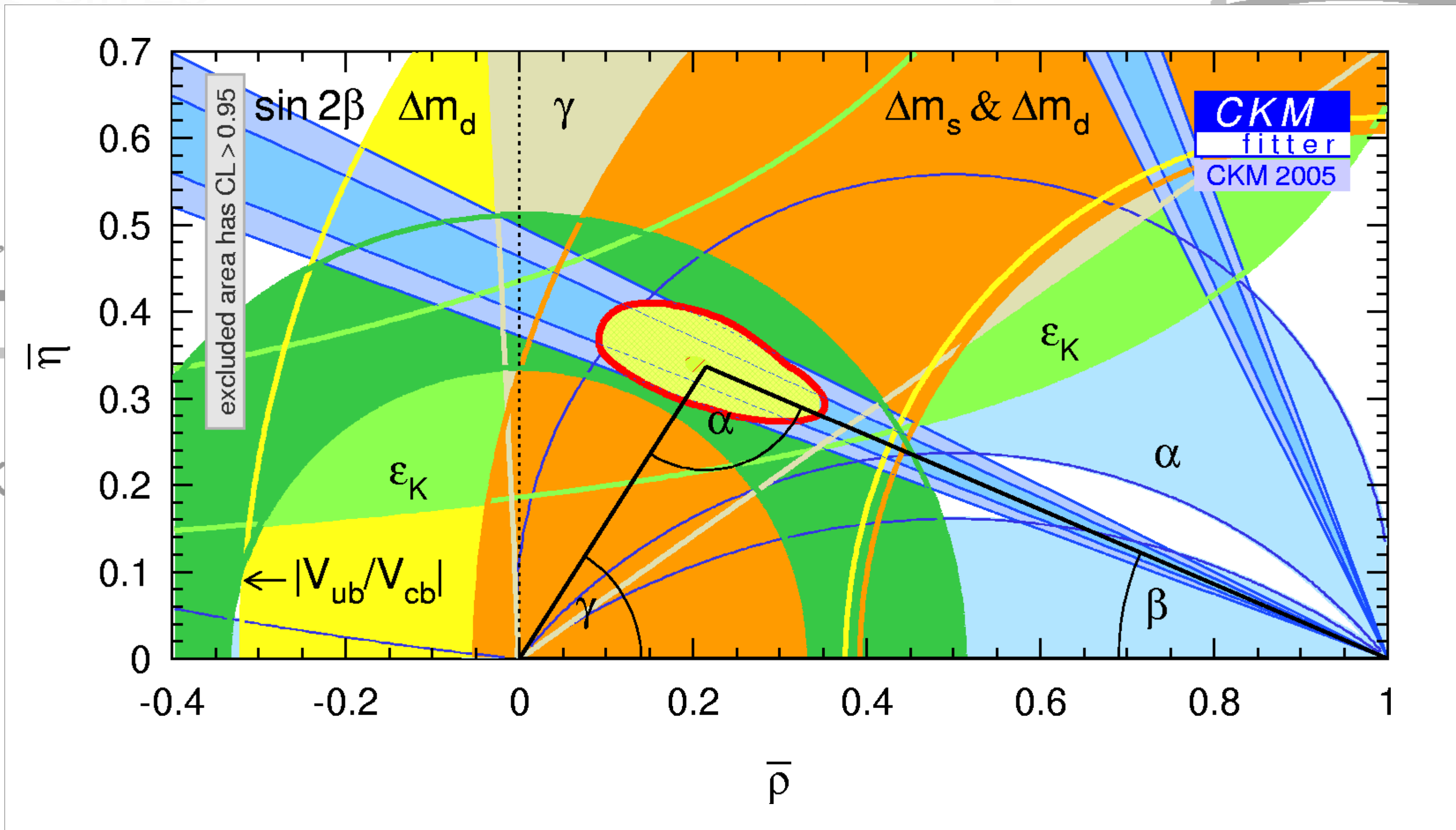
$|\varepsilon_K|$

$\sin 2\beta$

α

Perfect agreement … if it weren't for the *s*-penguin decays

Putting it all together



Inputs:

$\left|\frac{V_{ub}}{V_{cb}}\right|$

Δm_d

Δm_s

$B \to \tau\nu$

$|\varepsilon_K|$

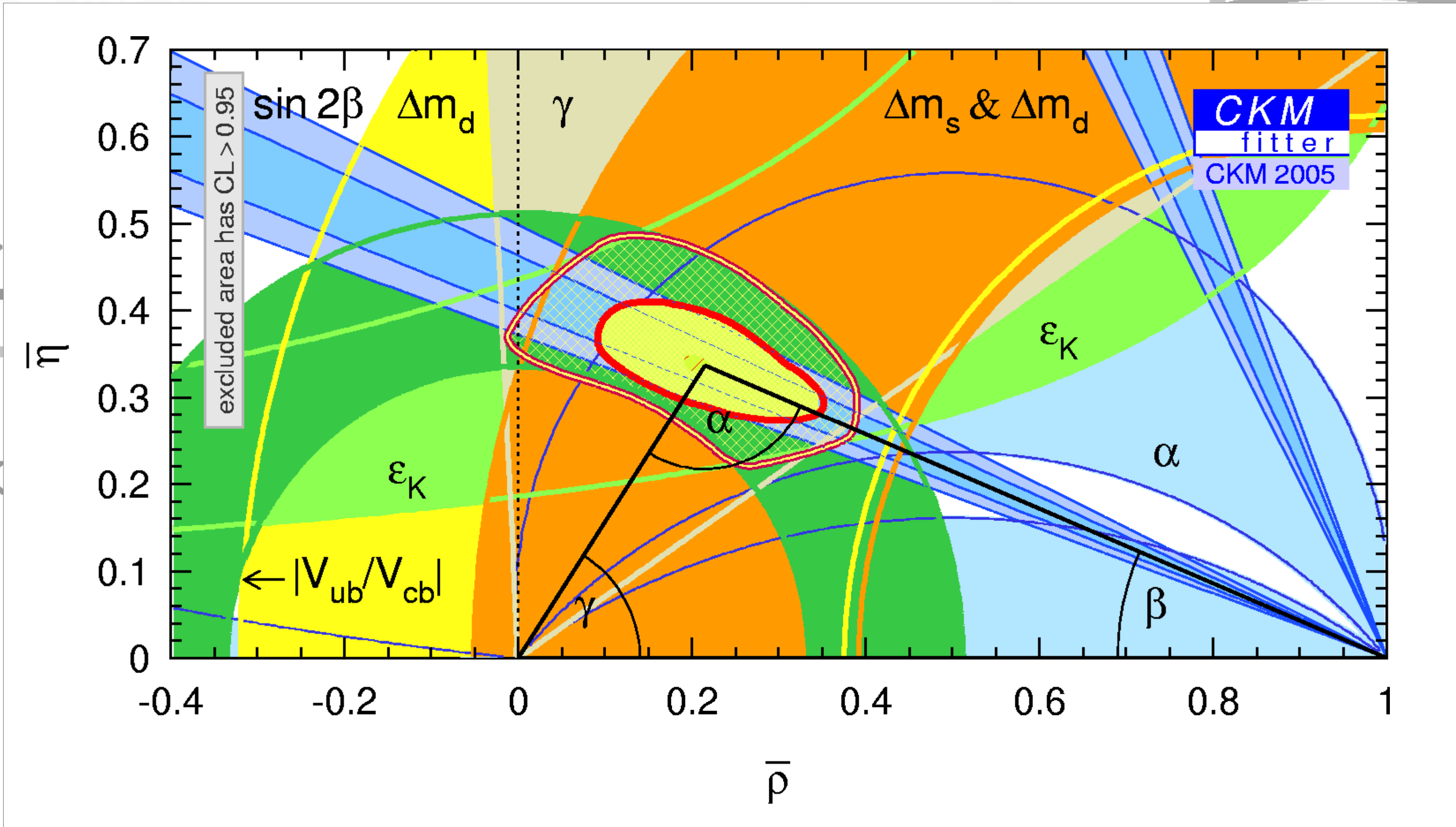
$\sin 2\beta$

α

γ

Perfect agreement … if it weren't for the *s*-penguin decays

Putting it all together



Inputs:

$\left|\frac{V_{ub}}{V_{cb}}\right|$

Δm_d

Δm_s

$B \to \tau\nu$

$|\varepsilon_K|$

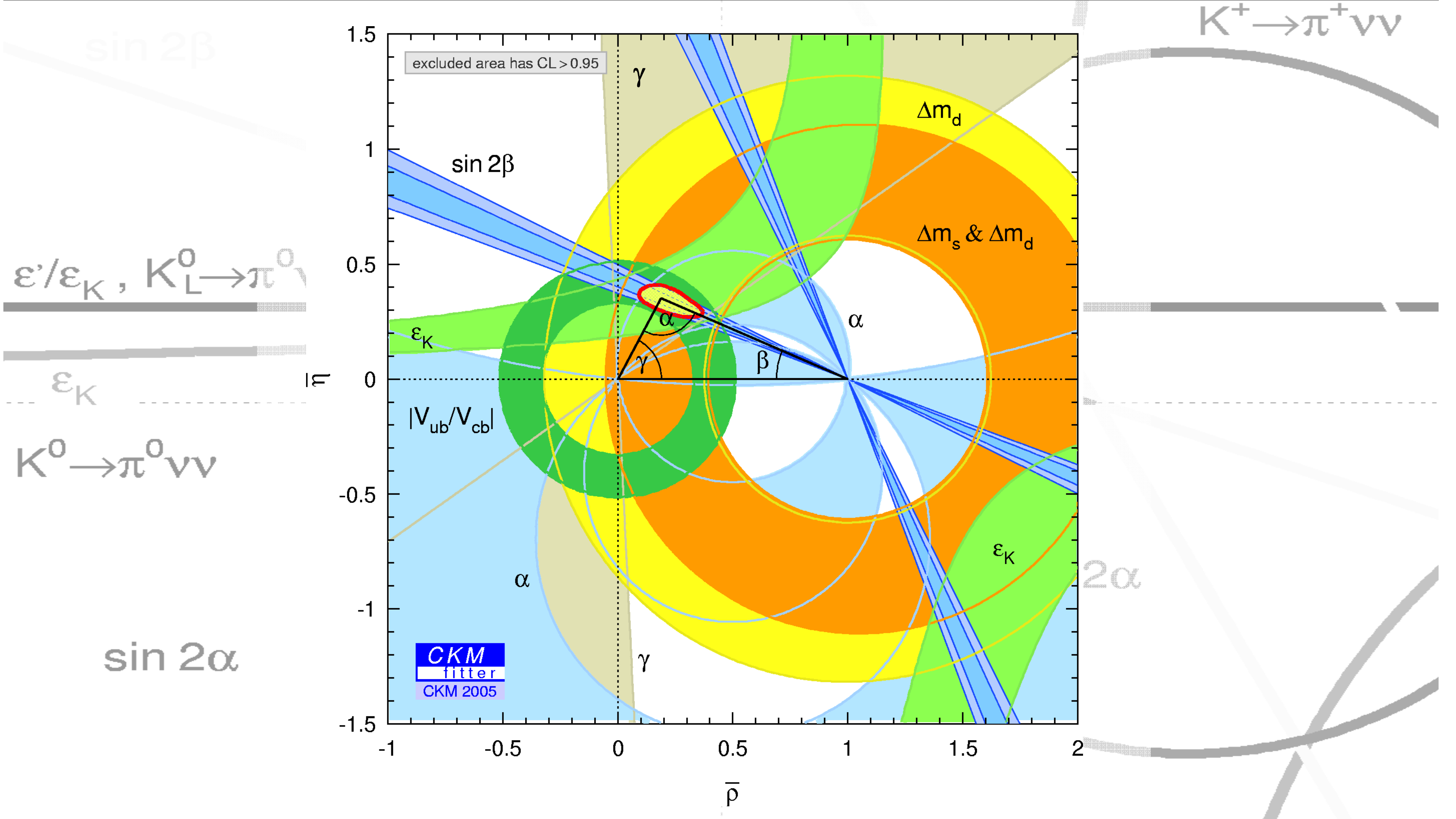
$\sin 2\beta$

α

γ

Perfect agreement … if it weren't for the *s*-penguin decays

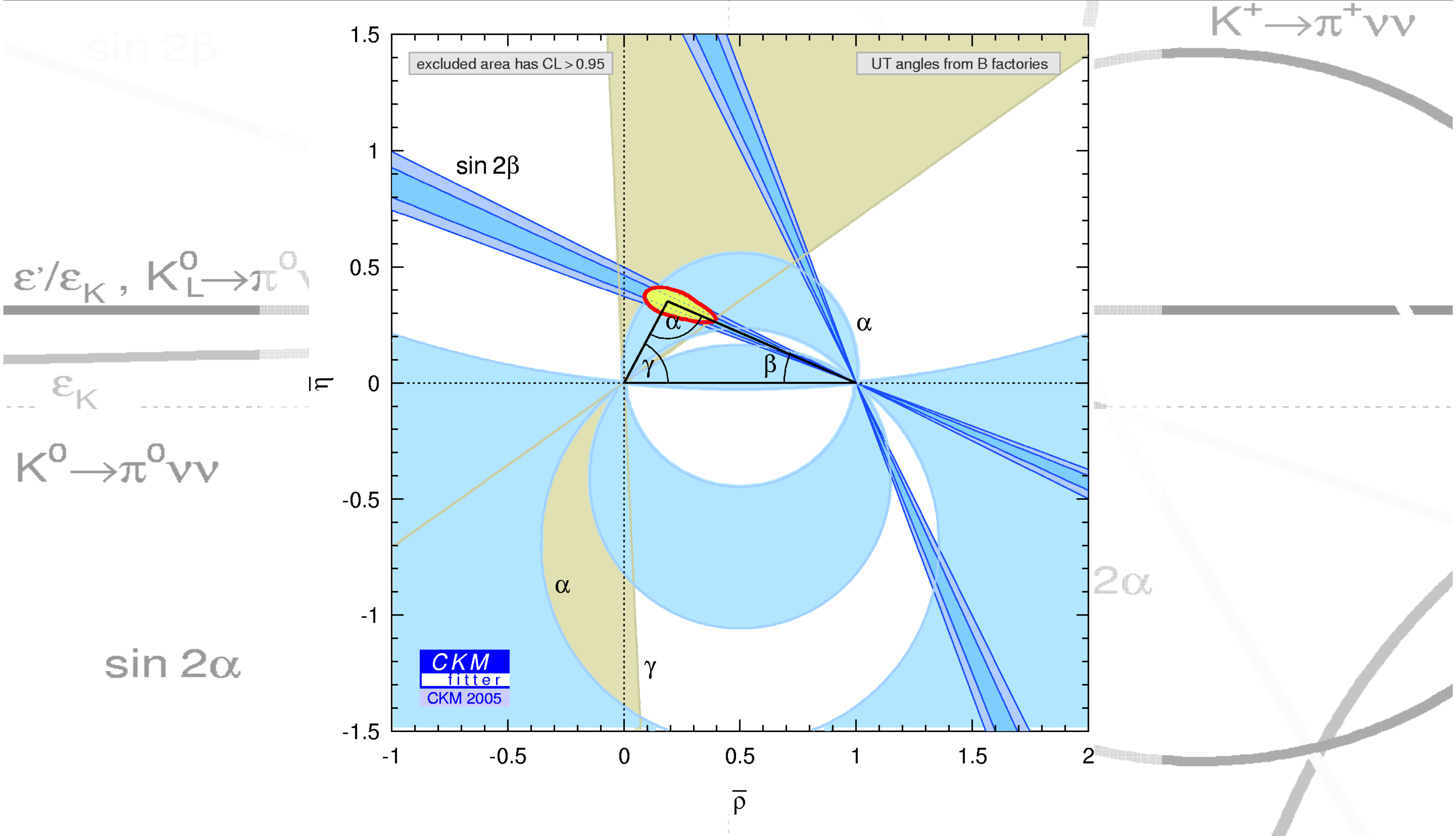
Putting it all together
the impact of the unitarity triangle angles



The angle measurements dominate !

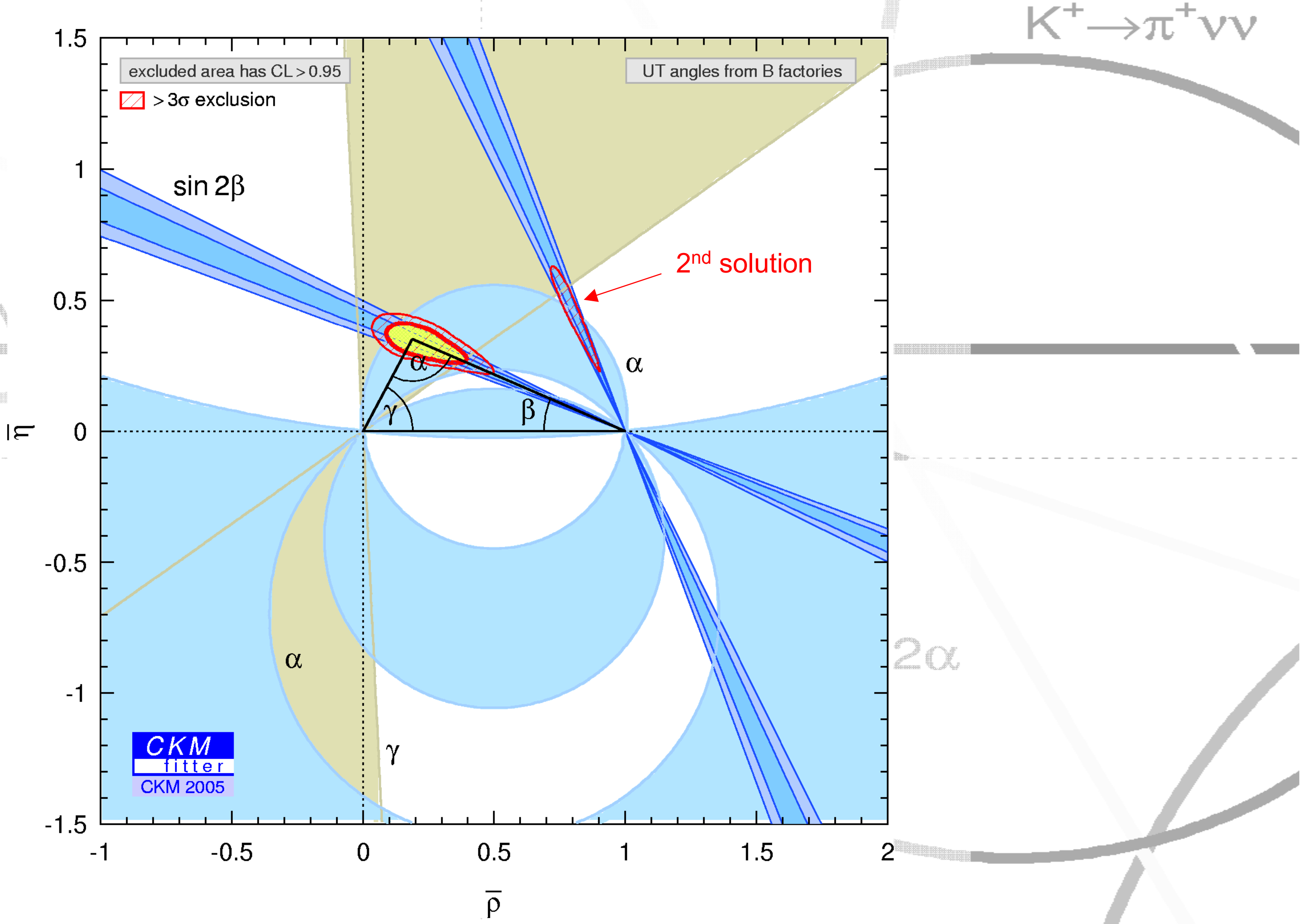
Putting it all together

the impact of the unitarity triangle angles



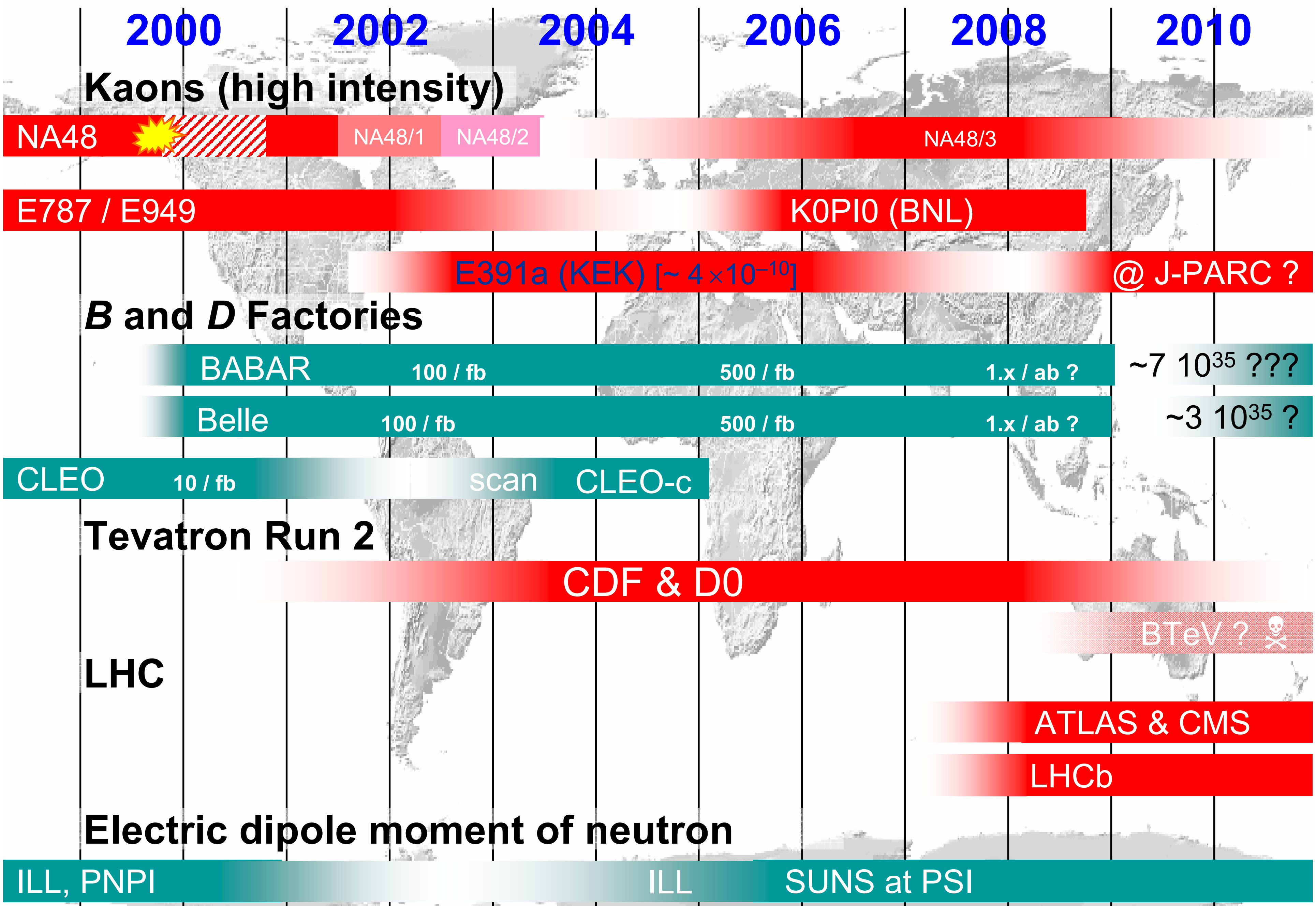
The angle measurements dominate !

Putting it all together — the impact of the unitarity triangle angles

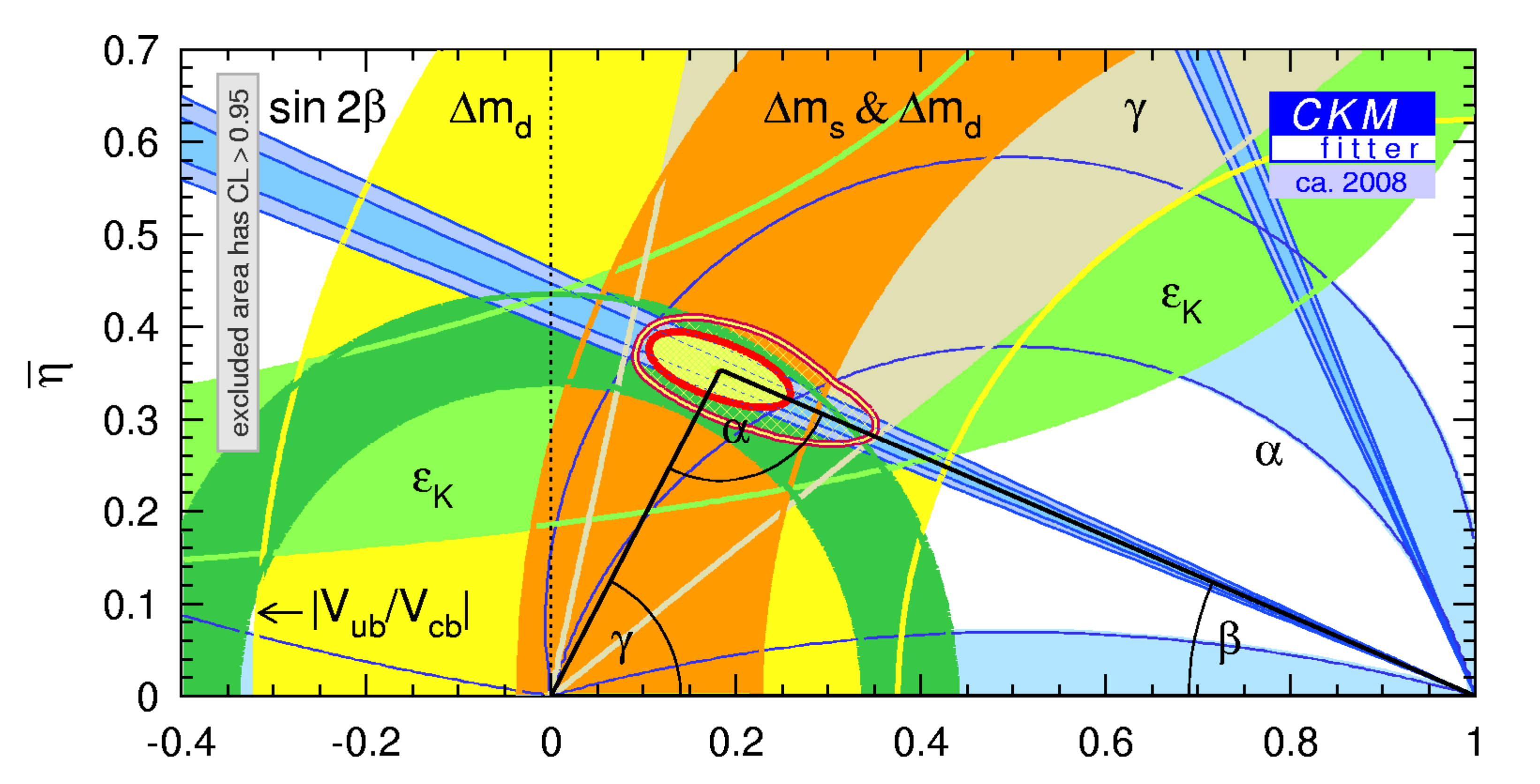


The angle measurements dominate !

The Future Program for Flavor Physics and *CP* Violation


2000
2002
2004
2006
2008
2010
Kaons (high intensity)
NA48
NA48/1
NA48/2
NA48/3
E787 / E949
K0PI0 (BNL)
E391a (KEK) [~ 4×10−10]
@ J-PARC ?
B and D Factories
BABAR
100 / fb
500 / fb
1.x / ab ?
~7 10^35 ???
Belle
100 / fb
500 / fb
1.x / ab ?
~3 10^35 ?
CLEO
10 / fb
scan
CLEO-c
Tevatron Run 2
CDF & D0
BTeV ?
LHC
ATLAS & CMS
LHCb
Electric dipole moment of neutron
ILL, PNPI
ILL
SUNS at PSI

The near Future ? the global CKM fit in 2008



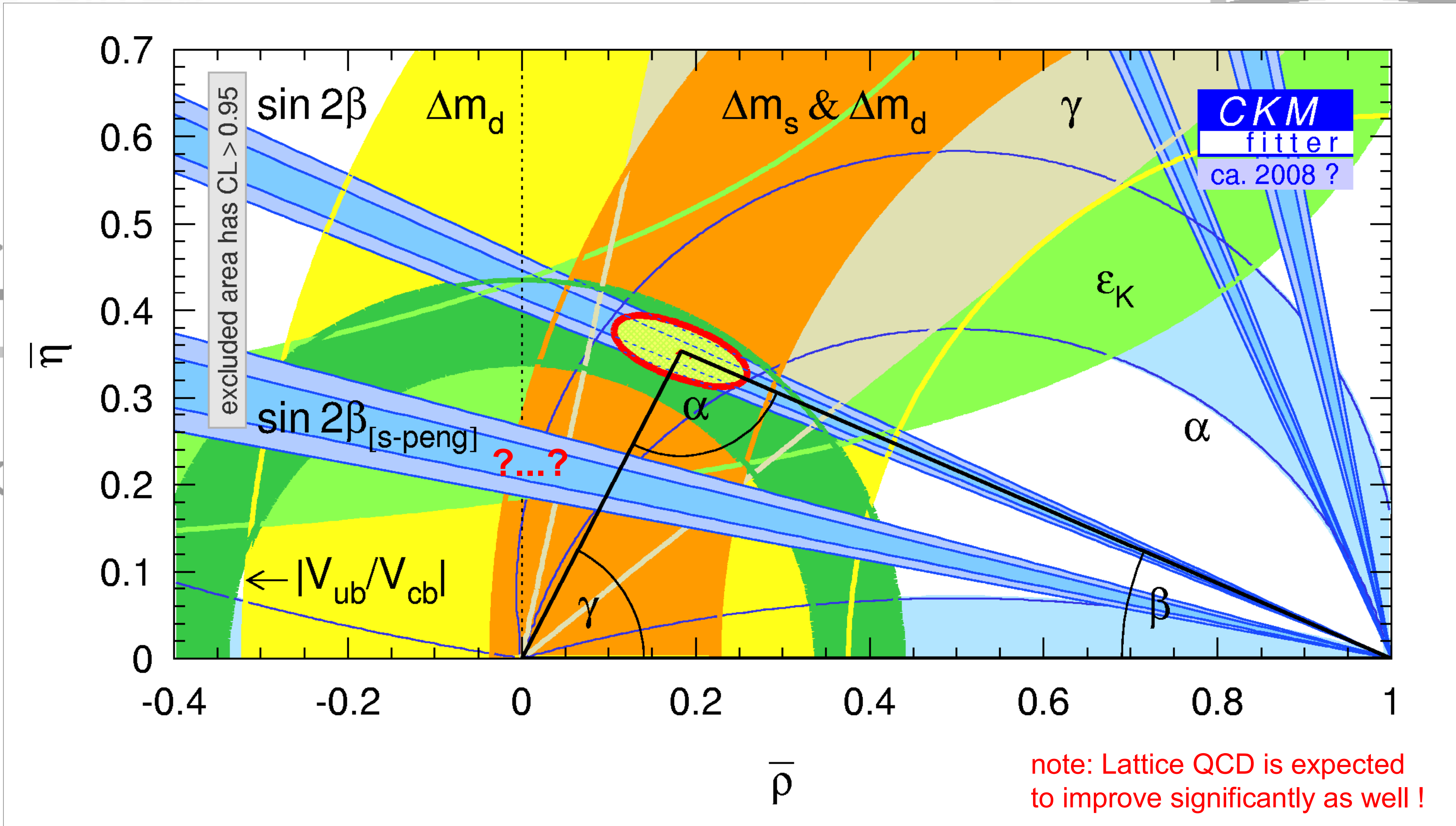
note: Lattice QCD is expected to improve significantly as well !

Inputs:

- $\left|\frac{V_{ub}}{V_{cb}}\right|$
- Δm_d
- Δm_s
- $B \to \tau\nu$
- $|\varepsilon_K|$
- $\sin 2\beta$
- α
- γ

assumptions: $\sigma(V_{ub}) \sim 8\%$ | $\sigma(\Delta m_s) \sim 5\%$ | $\sigma(\sin 2\beta) \sim 0.019$ | $\sigma(\alpha) \sim 6^\circ$ | $\sigma(\gamma) \sim 10^\circ$

The near Future ? the global CKM fit in 2008



note: Lattice QCD is expected to improve significantly as well !

Inputs:

$\left|\frac{V_{ub}}{V_{cb}}\right|$

Δm_d

Δm_s

$B \to \tau\nu$

$|\varepsilon_K|$

$\sin 2\beta$

α

γ

assumptions:	$\sigma(V_{ub}) \sim 8\%$	$\sigma(\Delta m_s) \sim 5\%$	$\sigma(\sin 2\beta) \sim 0.019$	$\sigma(\alpha) \sim 6^\circ$	$\sigma(\gamma) \sim 10^\circ$
			$\sigma(\sin 2\beta_{eff}) \sim 0.04$	?...?	

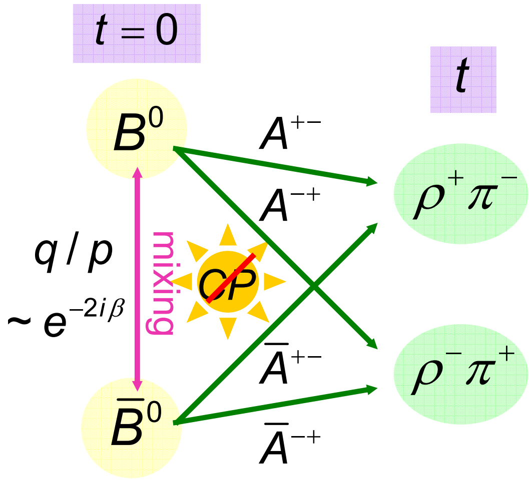
appendix

- SU(3) analysis
- α from $B \to \rho\pi$
- more on γ measurements

The $B \to \rho\pi$ System

- Dominant mode $\rho^+\pi^-$ is not a *CP* eigenstate

Aleksan *et al*, Nucl. Phys. B361, 141 (1991)



$$A_{\rho^\pm\pi^\mp}(t) = \left(1 \pm A_{CP}\right)\cdot\left(-S_\pm \sin(\Delta m_d t) + C_\pm \cos(\Delta m_d t)\right)$$

where: $S_\pm = \dfrac{2\ \mathrm{Im}\ \lambda_{\rho^\pm\pi^\mp}}{1+|\lambda_{\rho^\pm\pi^\mp}|^2}$ $\quad C_\pm = \dfrac{1-|\lambda_{\rho^\pm\pi^\mp}|^2}{1+|\lambda_{\rho^\pm\pi^\mp}|^2}$

mixing-induced CPV — direct CPV

$S \equiv S^+ + S^-$ $\quad \Delta S \equiv S^+ - S^-$ $\quad C \equiv C^+ + C^-$ $\quad \Delta C \equiv C^+ - C^-$

strong phase difference — *CP*-"eigenstateness"

- Pentagon relation between $\rho\pi$ states

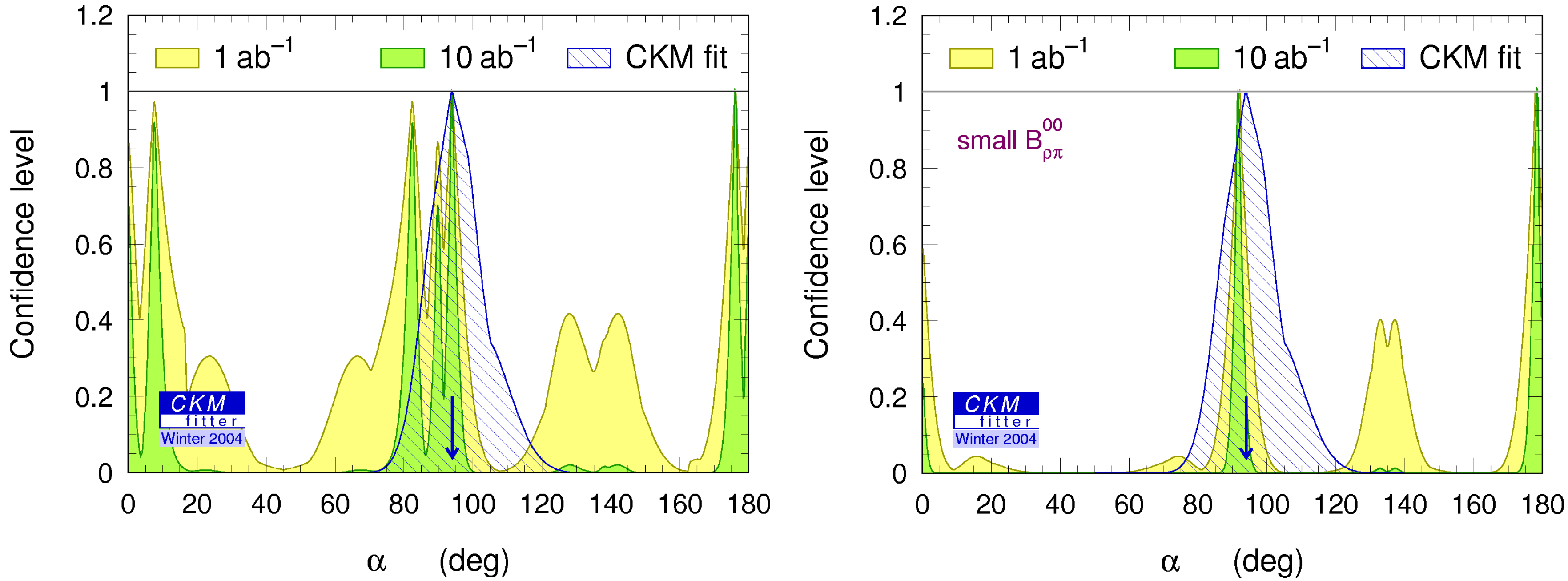
Lipkin et al., PRD 44, 1454 (1991)

Unknowns	Observables	Constraints	Account
α, T^{+-}, P^{+-}, T^{-+}, P^{-+}, T^{+0}, P^{+0}, T^{0+}, P^{0+}, T^{00}, P^{00}	B^{+-}, S, ΔS, C, ΔC, A_{+-} B^{+0}, A_{+0}, B^{0+}, A_{0+} B^{00}, S_{00}, C_{00}	2 SU(2) pentag. $P^{+0} = -P^{0+}$ $P^{+0} \propto f(P^{+-}, P^{-+})$	21 unknowns – 13 observables – 8 constraints – 1 global phase 21 vs. 22 ☺

Isospin analysis for $B \to \rho\pi$?

- At present… no useful constraint. How about the future ?

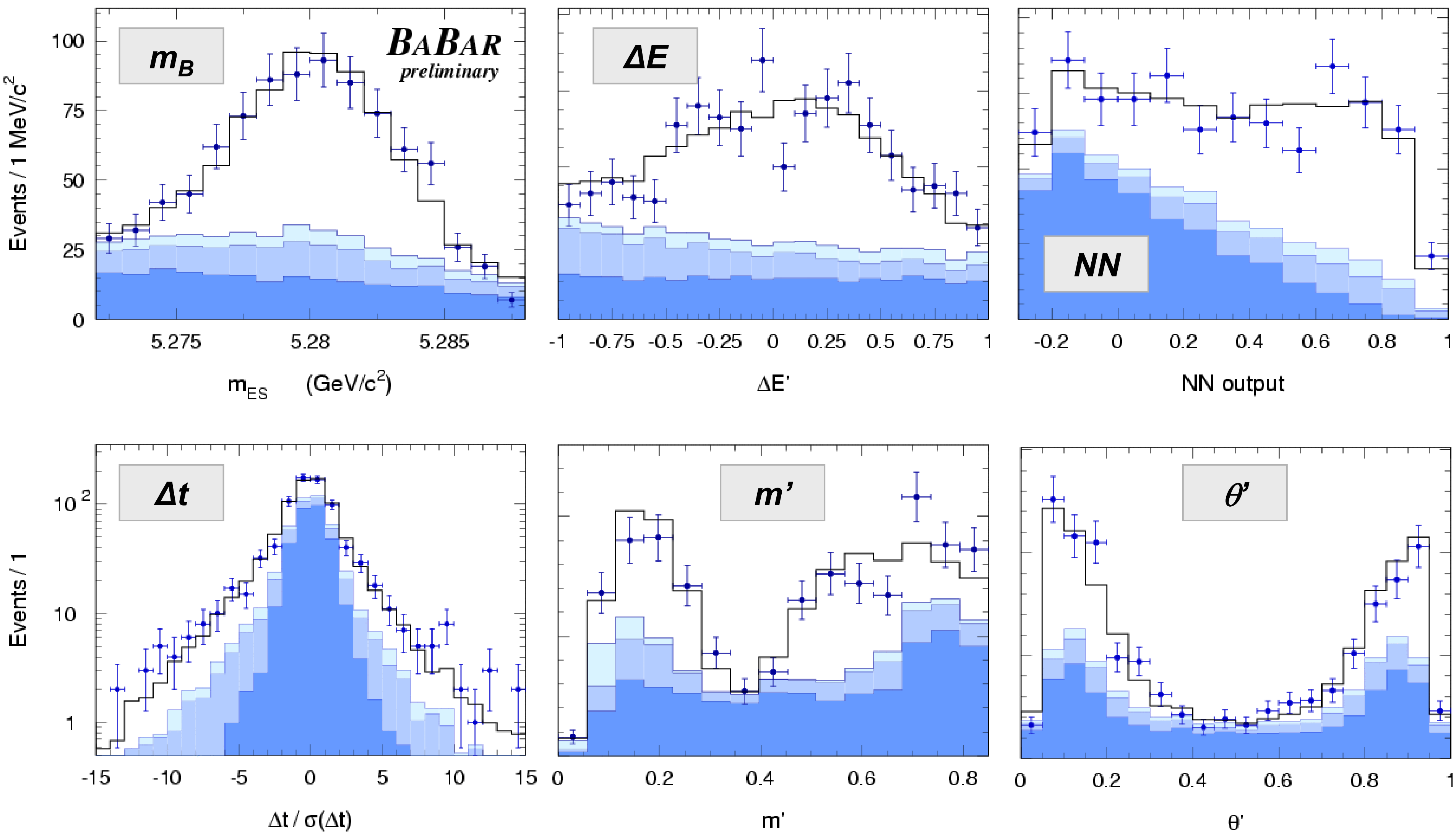
Charles *et al.*, hep-ex/0406184



- Very large statistics needed:
  - *quid* systematic errors ?
  - *quid* goodness of the Q2B approximation ?

Fit Projections

$N_{\pi^+\pi^-\pi^0} = 1064 \pm 51$



Results of $B^0 \to (\rho\pi)^0 \to \pi^+\pi^-\pi^0$ Dalitz analysis

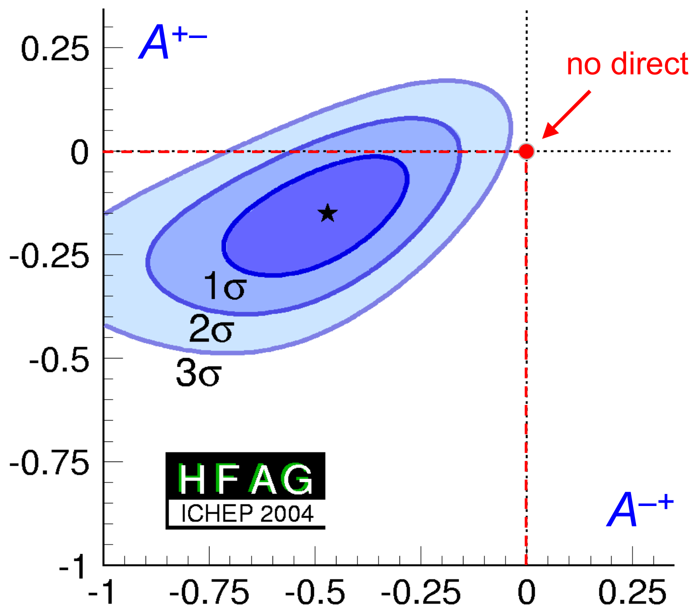
- From the 16 FF coefficients one determines the physical parameters :

- Direct *CP* violation ?

Average : BABAR (213m) & Belle (152m)

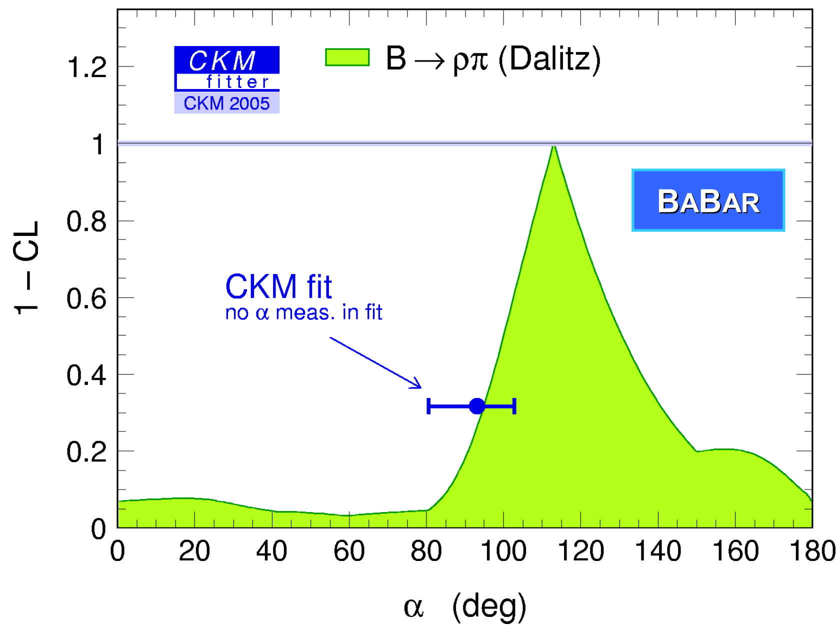
A^{+-} -0.15 ± 0.09	A^{-+} $-0.47\,^{+0.13}_{-0.14}$

$\Delta\chi^2$(no direct CPV) = 14.5 (CL = 0.00070 ⇒ 3.4σ)



- Parameters : α, $|T^{+-}|, T^{-+}, T^{00}, P^{+-}, P^{-+}$

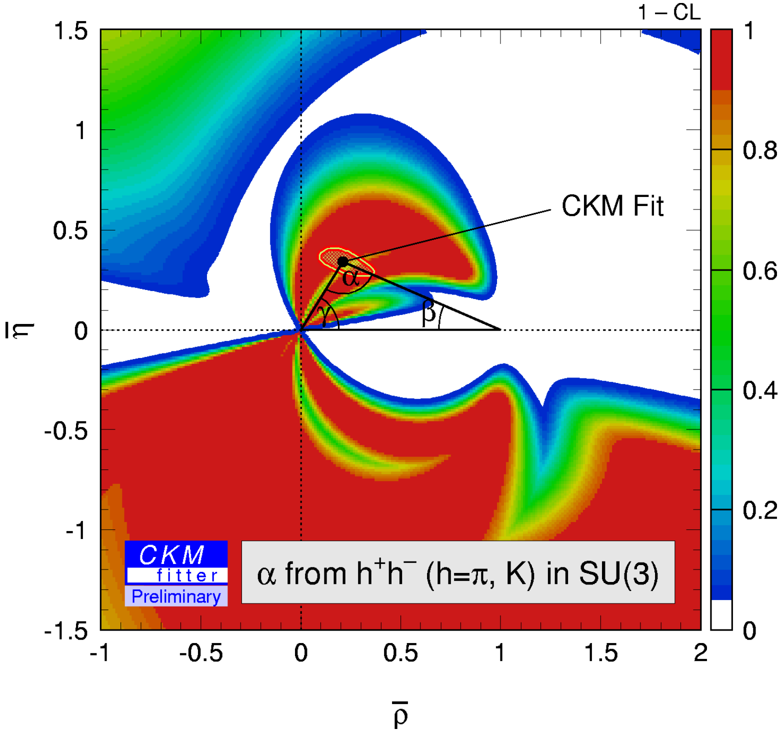
Scan in α using the bilinears :



BABAR, hep-ex/0408099

$B \to \pi\pi$, $K\pi$, KK Decays in SU(3)

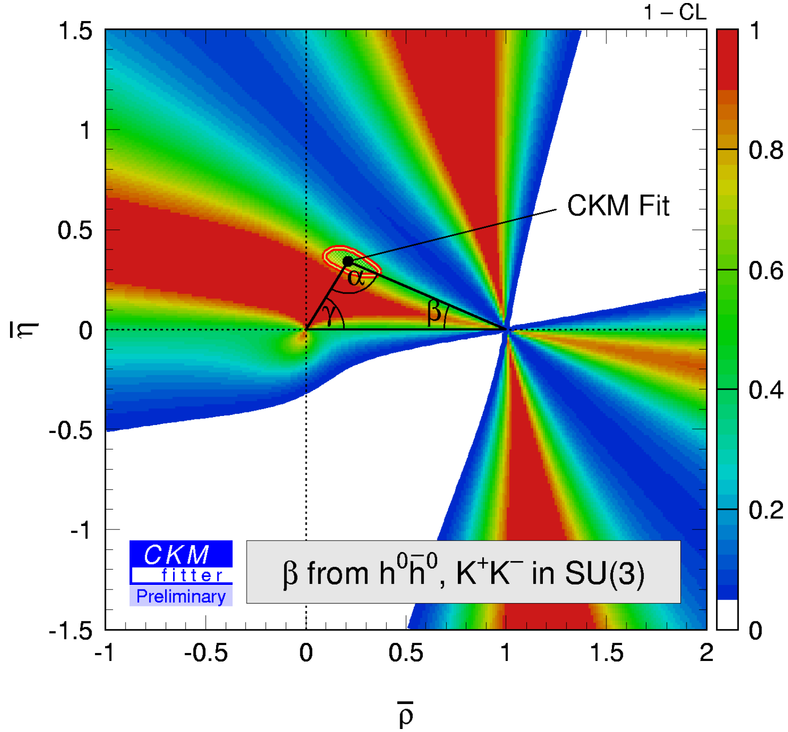
- <u>Complete</u> $B \to \pi\pi$, $K\pi$, KK analysis in SU(3)
  - "α" from $B \to \pi^+\pi^-$, $K^+\pi^-$, K^+K^-



- Global analyses:
  - at present: 13 parameters vs. 19 observables
  - when everything is measured (incl. B_s) :
    15 parameters vs. ~ 50 observables

$B \to \pi\pi$, $K\pi$, KK Decays in SU(3)

- Complete $B \to \pi\pi$, $K\pi$, KK analysis in SU(3)
  - "β" from $B \to \pi^0\pi^0$, $K^0\pi^0$, K^+K^-



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$B \to \pi\pi$, $K\pi$, KK Decays in SU(3)

- Complete $B \to \pi\pi, K\pi, KK$ analysis in SU(3)
  - "α" from $B \to \pi^+\pi^-, K^+\pi^-, K^+K^-$
  - "β" from $B \to \pi^0\pi^0, K^0\pi^0, K^+K^-$
  - interesting combined constraint in (ρ,η) plane

- Global analyses:
  - at present: 13 parameters vs. 19 observables
  - when everything is measured (incl. B_s) :
    15 parameters vs. ~ 50 observables