Beauty Physics and *CP* Violation (II)

sin(2β) and the Triumph of the Standard Model

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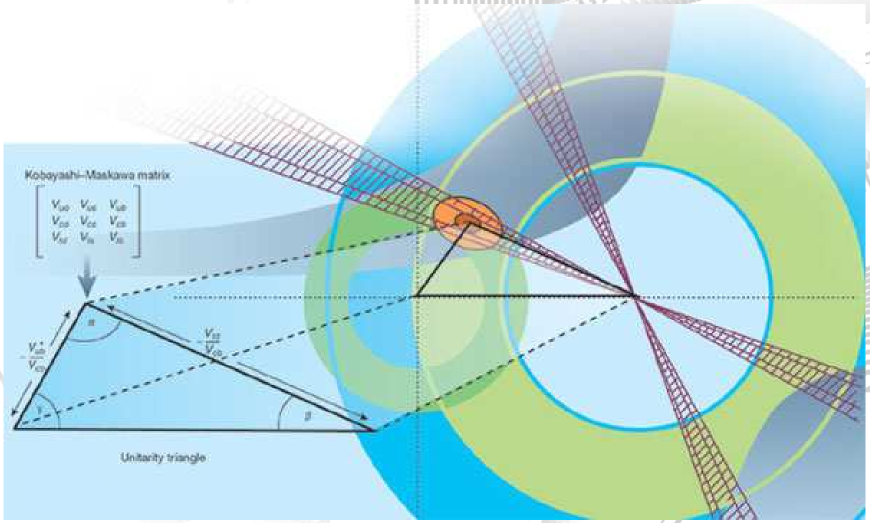


Experimental lecture at the Helmholz School on Heavy Quark Physics

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

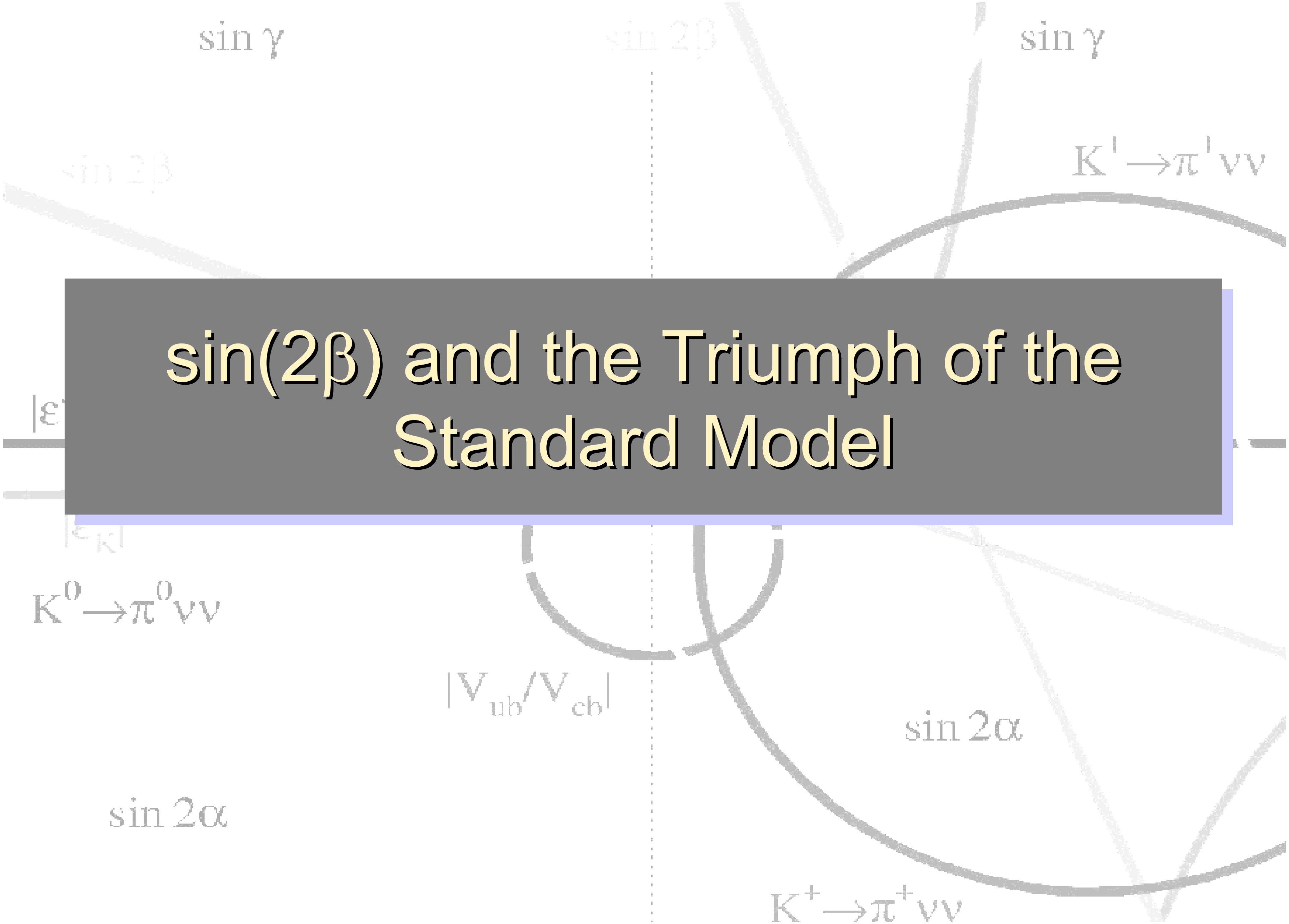
II. sin(2β) and the triumph of the Standard Model

- *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

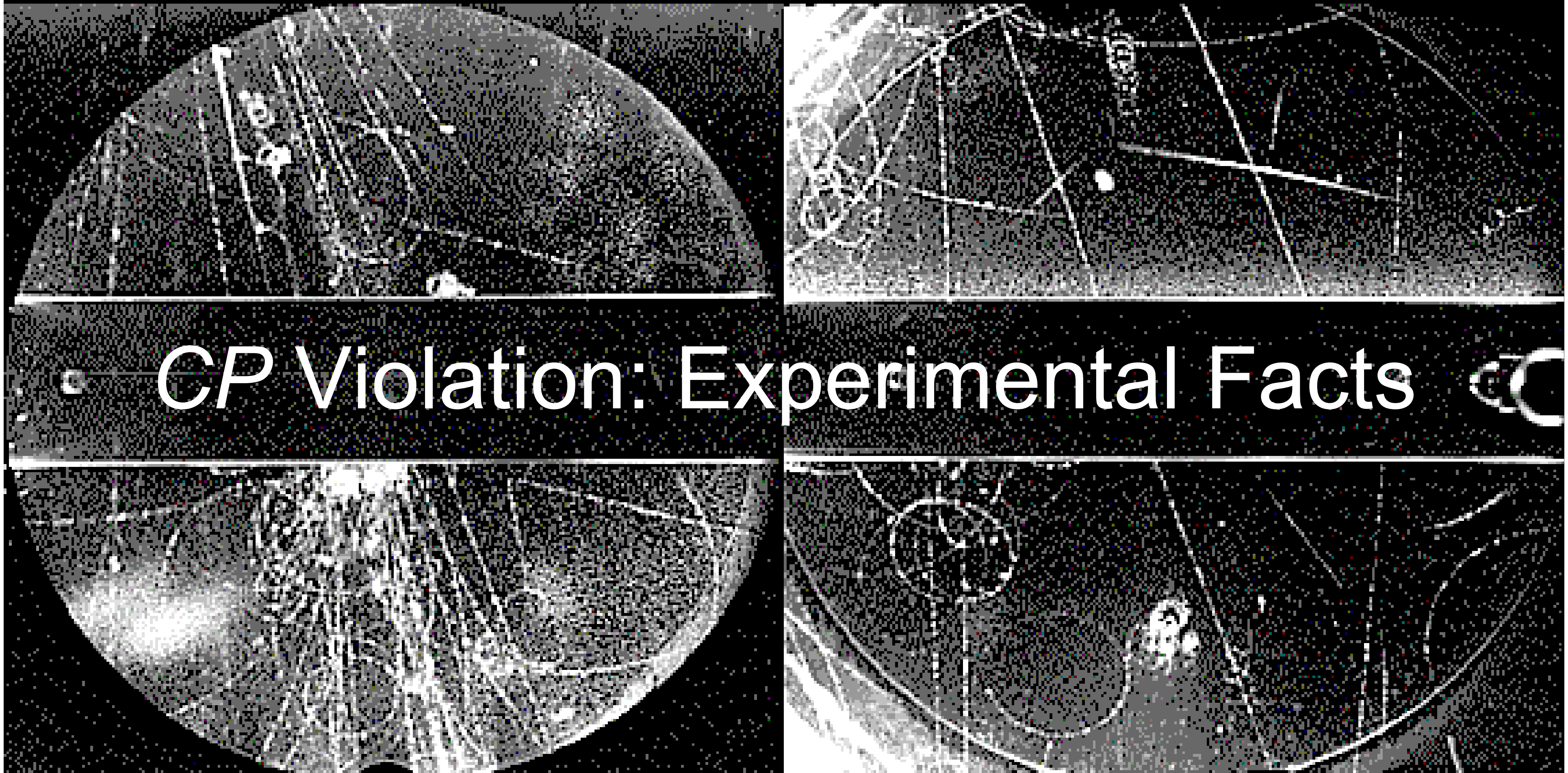
III. Rare *B* decays: towards the full unitarity triangle … and beyond

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

sin(2β) and the Triumph of the Standard Model



CP Violation: Experimental Facts



Experimental Facts (I)

★ The K_L^0 decays into $\pi^+\pi^-$ and $\pi^0\pi^0$

the *CP*-violating parameters are η_{+-} and η_{00}

historically, the way *CP* violation was discovered back in 1964

$$\eta_{+-} = \frac{A(K_L^0 \to \pi^+\pi^-)}{A(K_S^0 \to \pi^+\pi^-)} = (2.286 \pm 0.017) \cdot 10^{-3} \cdot e^{i(43.51^\circ \pm 0.06^\circ)}$$

and the measurement of η_{+-} is consistent with that of η_{00}

The "super-weak" hypothesis: *CP* (time reversal) symmetry violation is confined to $\Delta S = 2$ processes ($K^0\bar{K}^0$ mixing)

The super-weak model was proposed less than one year after the experimental discovery of *CP* violation. A new interaction affecting only kaon mixing seemed a "natural" explanation for the small observed effects of *CP* violation. The Kobayashi-Maskawa model came 9 years later, still before the discovery of charm.

➡ under the super-weak hypothesis: $\eta_{+-} = \eta_{00} = \varepsilon$

$$|K_L^0\rangle \propto (1+\varepsilon)|K^0\rangle - (1-\varepsilon)|\bar{K}^0\rangle$$

Experimental Facts (II)

- Direct measurements of $|\eta_{+-}/\eta_{00}|$ show significant departure from unity

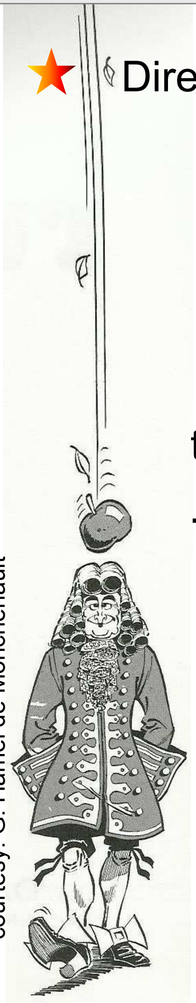
$$\mathrm{Re}(\varepsilon'/\varepsilon) = (1 - |\eta_{00}/\eta_{+-}|)/3 = (16.7 \pm 2.6) \times 10^{-4}$$

$\Rightarrow$ $\mathrm{Re}(\varepsilon') \propto 10^{-6}$ tiny effect !

Average: KTeV & NA48

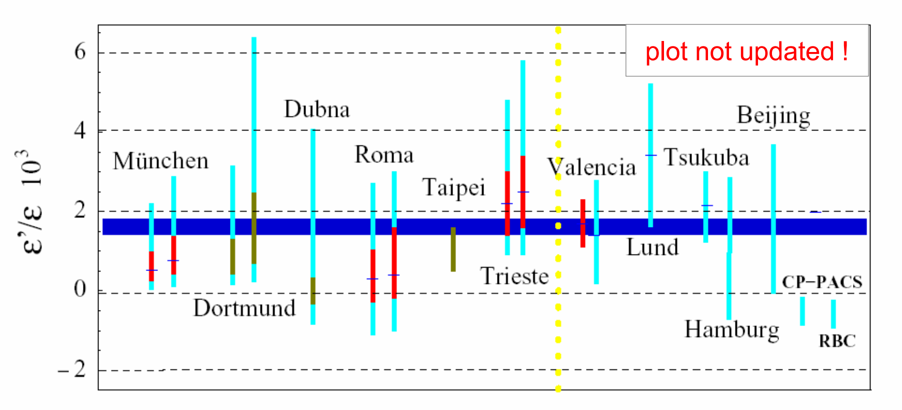
this establishes direct *CP* violation (*i.e.* in a $\Delta S = 1$ decay process)

…and rules out the super-weak model (~30 years after the discovery of *CP* violation!)



courtesy: G. Hamel de Monchenault

Theoretical pre(post)dictions



...the ball is on the theory side

- All observations are consistent with the conservation of the *CPT* symmetry

for instance: $m_{\bar{K}^0} - m_{K^0} = (1.7 \pm 4.2) \cdot 10^{-19}\,\mathrm{GeV}/c^2$

including new preliminary result by NA48/1

Experimental Facts (III)

★ 2001: mixing-induced *CP* violation has been observed in the *B* meson system

from time-dependence of $B^0 \to J/\psi K_S^0$ and similar decays

➡ $\sin(2\beta) = 0.726 \pm 0.037$ BABAR & **Belle**, 2004

first uncontroversial effect of *CP* violation outside the kaon system

The observed *CP* violation effect in the *B* meson system is in excellent agreement with predictions using the Kobayashi & Maskawa framework in the Standard Model

★ 2004: <u>large</u> direct *CP* violation has been observed in the *B* meson system

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

➡ $A_{K^+\pi^-} = -0.109 \pm 0.019$ BABAR & **Belle**, 2004

★ With rising statistics, many more *CP*-violating *B* decays should show up

> 3σ candidates are $B^0 \to \pi^+\pi^-$, $\rho^+\pi^-$

"Popular Misconceptions"

★ *"CP violation is always a small effect, typically of order 10^{-3} or less"*

not completely exact!

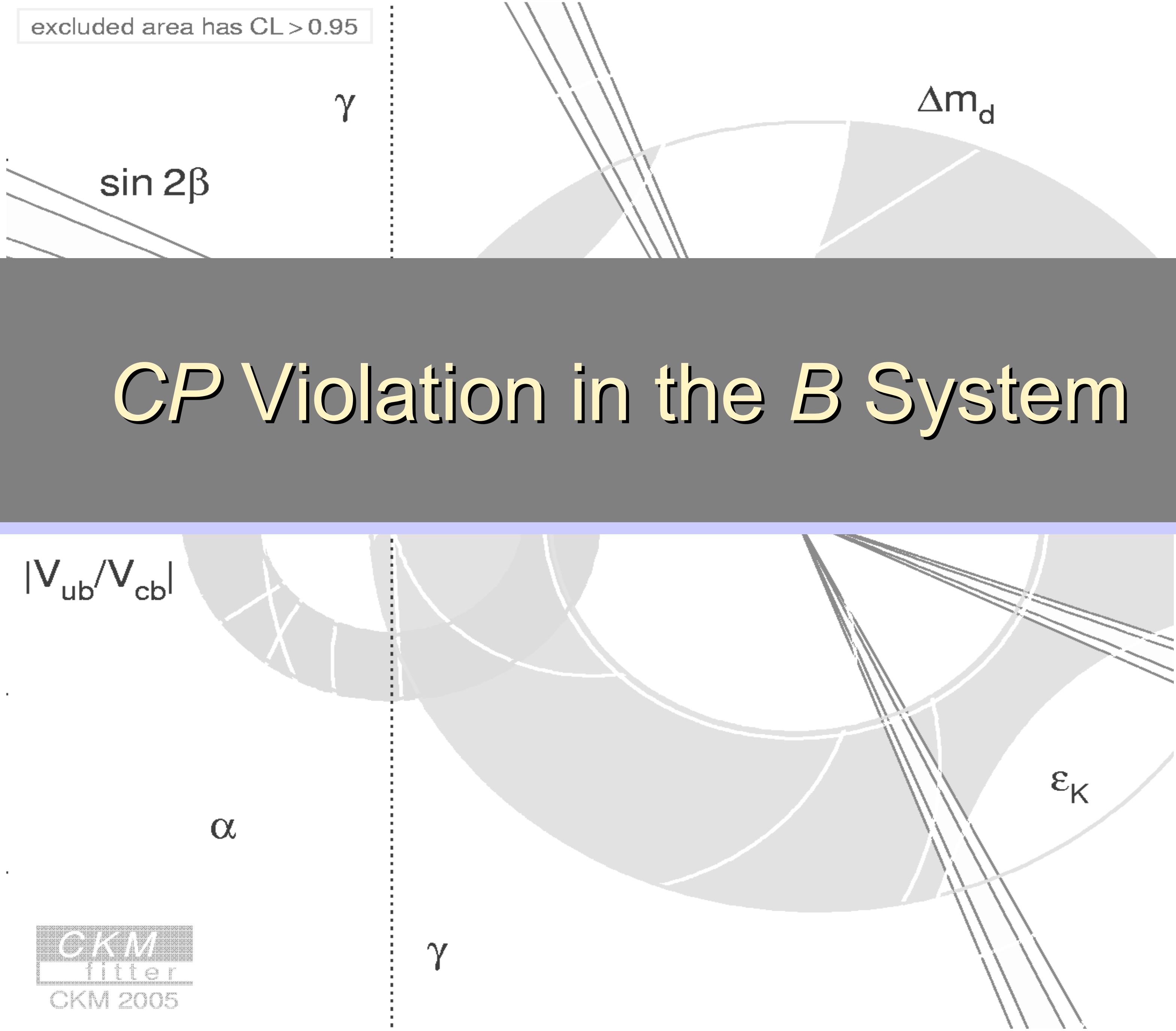
- *CP* asymmetry of 10% observed in neutral *B* decay to $K^+\pi^-$
- Time-dependent *CP* asymmetry of 70% in the decay $B^0, \bar{B}^0 \rightarrow J/\psi K^0_S$
- *CP* asymmetry of 100% expected in the rare decay $K^0_L \rightarrow \pi^0 \nu\bar{\nu}$

However, it is true that *CP* violation is a very rare phenomenon

- either sizeable after several mean lifetimes
- or suppressed by very small branching fractions
- or both

★ Direct *CP* "theorem":

- don't expect direct *CP* violation in copious decays
- rather look into rare modes



CP Violation in the *B* System

The *CP* Operator

The *CP* eigenstates of the $|P^0\rangle|\bar{P}^0\rangle$ system are:

$$|P^0_{CP=+1}\rangle \equiv \frac{1}{\sqrt{2}}\left(|P^0\rangle + CP|P^0\rangle\right)$$
$$|P^0_{CP=-1}\rangle \equiv \frac{1}{\sqrt{2}}\left(|P^0\rangle - CP|P^0\rangle\right)$$

with, by construction:

$$CP|P^0_{CP=+1}\rangle = +|P^0_{CP=+1}\rangle$$
$$CP|P^0_{CP=-1}\rangle = -|P^0_{CP=-1}\rangle$$

Note: arbitrary phase ξ in the definition of the *CP* operator

final state of P^0 decay

$$\begin{cases} CP|P^0\rangle = e^{2i\xi_P}|\overline{P}^0\rangle \\ CP|\overline{P}^0\rangle = e^{-2i\xi_P}|P^0\rangle \end{cases}$$ and $$CP|f\rangle = e^{2i\xi_f}|\bar{f}\rangle$$

Real eigenvalue for a *CP* final state: $CP|f_{CP}\rangle = \sigma_{f_{CP}}|f_{CP}\rangle$ with $\sigma_{f_{CP}} = \pm 1$

Decay Amplitudes

★ Decay amplitudes of flavor states into the same final state:

$$\begin{cases} A_f \equiv \mathcal{A}(P^0 \to f) = \langle f|H|P^0\rangle \\ \overline{A}_f \equiv \mathcal{A}(\overline{P}^0 \to f) = \langle f|H|\overline{P}^0\rangle \end{cases}$$

note: decay amplitudes are phase-convention dependent

define

$$\lambda_f \equiv \frac{q}{p}\frac{\overline{A}_f}{A_f}$$

phase convention independent parameter

note: for flavor eigenstates $A_f = 0$ or $\overline{A}_f = 0$

★ Decay amplitudes of mass states:

$$\begin{cases} A_{L\,f} \equiv \langle f|H|P_L\rangle = p\,A_f + q\,\overline{A}_f = p\,A_f\,(1+\lambda_f) \\ A_{H\,f} \equiv \langle f|H|P_H\rangle = p\,A_f - q\,\overline{A}_f = p\,A_f\,(1-\lambda_f) \end{cases}$$

define

$$\eta_f \equiv \frac{A_{H\,f}}{A_{L\,f}} = \frac{1-\lambda_f}{1+\lambda_f}$$

Why Different Notations ?

- In *B* physics, the physical (= mass) states cannot be isolated.

  One starts with pure $|B^0\rangle$ or $|\bar{B}^0\rangle$ initial states, identified thanks to flavor tagging

  ➡ therefore the natural parameter is λ_f

- In *K* physics, the physical (=mass) states are well-isolated, thanks to very different lifetimes

  ➡ therefore the natural parameter is η_f

Time Evolution of Neutral B Meson System

★ Recall that: the time evolution of the physical states $|B^0(t)\rangle$ ($|\bar{B}^0(t)\rangle$) is given by

$$|B^0(t)\rangle = g_+(t)|B^0\rangle + \frac{q}{p} g_-(t)|\bar{B}^0\rangle$$
$$|\bar{B}^0(t)\rangle = \frac{p}{q} g_-(t)|B^0\rangle + g_+(t)|\bar{B}^0\rangle$$

where:
(assuming $\Delta\Gamma = 0$)

$$g_+(t) = e^{-i(\mu_L+\mu_H)t/2} \cdot \cos(\Delta m t/2)$$
$$g_-(t) = i \cdot e^{-i(\mu_L+\mu_H)t/2} \cdot \sin(\Delta m t/2)$$

★ so that one finds for the time-dependent rates of an initially pure flavor state

$$|\langle f|H|B^0(t)\rangle|^2 = |A_f|^2 \cdot |g_+(t) + \lambda_f g_-(t)|^2 \quad \text{and} \quad |\langle f|H|\bar{B}^0(t)\rangle|^2 = \left|\frac{p}{q}\right|^2 \cdot |A_f|^2 \cdot |g_-(t) + \lambda_f g_+(t)|^2$$

and after some trigonometry and assuming CPV in mixing is absent ($|q/p| = 1$)

$$|\langle f|H|B^0(t)\rangle|^2 = e^{-t/\tau_B} \cdot |A_f|^2 \frac{1+|\lambda_f|^2}{2}\left[1 + C_f \cos(\Delta m_d t) - S_f \sin(\Delta m_d t)\right]$$
$$|\langle f|H|\bar{B}^0(t)\rangle|^2 = e^{-t/\tau_B} \cdot |A_f|^2 \frac{1+|\lambda_f|^2}{2}\left[1 - C_f \cos(\Delta m_d t) + S_f \sin(\Delta m_d t)\right]$$

CP observables

$$C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$$
$$S_f = \frac{2\mathrm{Im}[\lambda_f]}{1+|\lambda_f|^2}$$

Case of *CP* Eigenstate

- Condition for *CP* invariance : $\left|\langle f_{CP}|H|B^0(t)\rangle\right|^2 = \left|\langle f_{CP}|H|\bar{B}^0(t)\rangle\right|^2, \quad \forall t$

- Definition of "*CP* parameter" :

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

← decay amplitude ratio

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

- *CP* invariance requires :

Note that the q/p parameter is not an observable, because its argument depends on phase conventions, but its modulus $|q/p|$ is !

→ $|q/p| = 1$ $\quad \{|B_L\rangle, |B_H\rangle\} = \{|B_{CP=+1}\rangle, |B_{CP=-1}\rangle\}$

→ $|\bar{A}_{f_{CP}} / A_{f_{CP}}| = 1$

→ $\mathrm{Im}\,\lambda_{f_{CP}} = 0$

$\Rightarrow \lambda_{f_{CP}} = \pm 1$

- Classification of *CP* violation :

CP-violating phenomena:

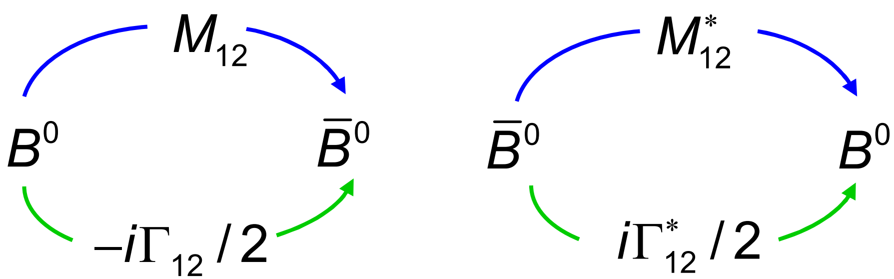
- *CP* violation in mixing ("indirect") : $|q/p| \neq 1$
- *CP* violation in the decay ("direct") : $|\lambda_{f_{CP}}| \neq 1$
- *CP* violation in interference between mixing and decay : $\mathrm{Im}\,\lambda_{f_{CP}} \neq 0$

CP Violation in Mixing (1st type)

The condition for *CP* conservation in mixing is:

$$\mathrm{Im}\left[M_{12}\Gamma_{12}^{*}\right]=0$$

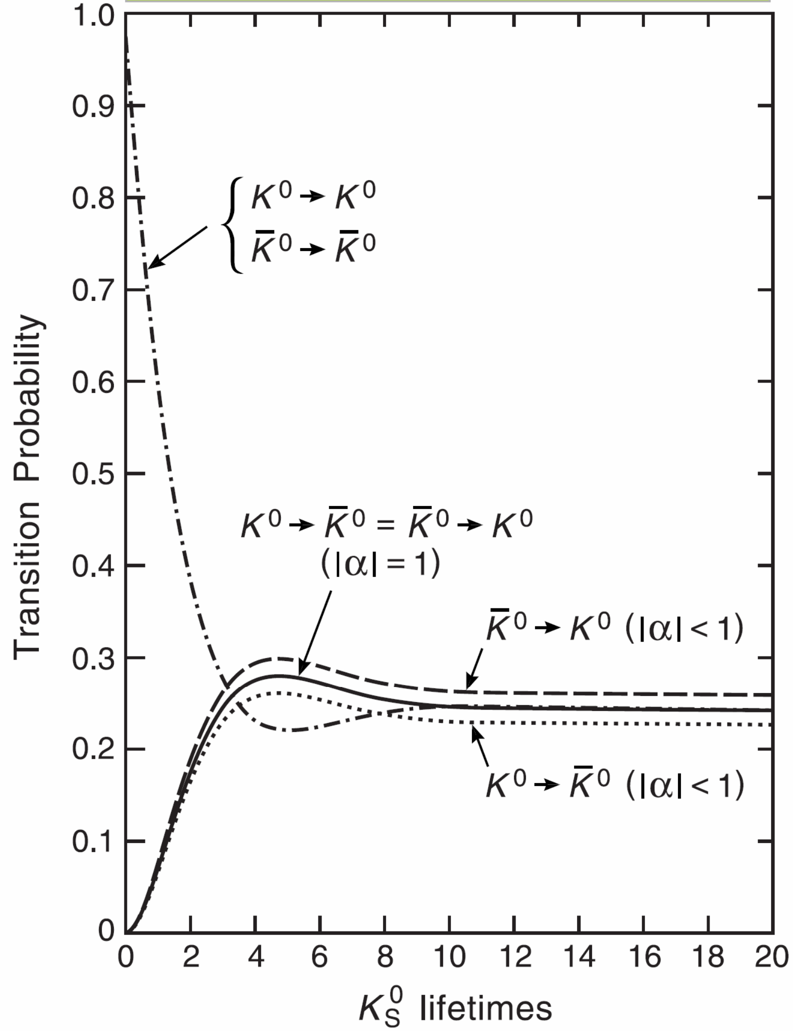
CP violation in mixing can be understood as being due to interference between the set of amplitudes with virtual intermediate states and the set of amplitudes with on-shell intermediate states



Indirect *CP* violation is small if either

- the two amplitudes are almost relatively real
- one of the two amplitudes is small

CPV in mixing in K^0 System



Small CPV in mixing in B^0 System

CP Violation in the Decay (2nd type)

★ *CP*-conjugated amplitudes : $\begin{cases} A_f = A(B \to f) \\ \bar{A}_{\bar{f}} = A(\bar{B} \to \bar{f}) \end{cases}$ ... *CP* invariance implies : $|A_f| = |\bar{A}_{\bar{f}}|$

define

$$A_{CP} \equiv \frac{\Gamma(\bar{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\bar{B} \to \bar{f}) + \Gamma(B \to f)} = \frac{|\bar{A}_{\bar{f}}|^2 - |A_f|^2}{|\bar{A}_{\bar{f}}|^2 + |A_f|^2}$$

CP

$$A_f = \sum_j a_j \cdot e^{i\theta_j} e^{i\phi_j}$$

$$\bar{A}_{\bar{f}} = e^{-2i(\xi_B - \xi_f)} \sum_j a_j \cdot e^{i\theta_j} e^{-i\phi_j}$$

ϕ_j alters sign under *CP* (weak phase)

θ_j *CP* invariant (strong phase)

$$A_{CP} = \frac{\sum_{ij} a_i a_j \cdot \sin(\theta_i - \theta_j) \cdot \sin(\phi_i - \phi_j)}{\sum_{ij} a_i a_j \cdot \cos(\theta_i - \theta_j) \cdot \cos(\phi_i - \phi_j)}$$

Direct *CP* violation requires at least two amplitudes with different weak *and* strong phases

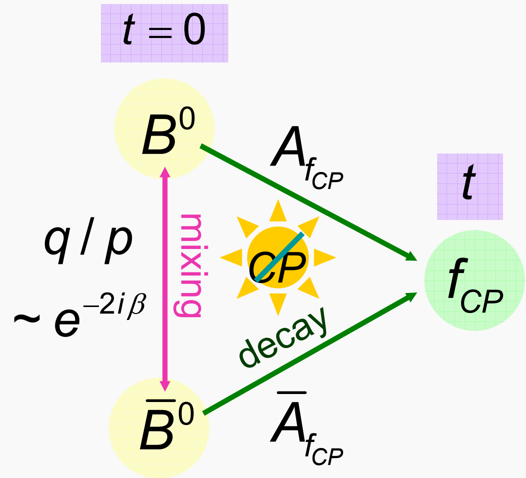
Mixing-Induced CP Violation (3rd type)

★ CP Violation due to the interference of decays with and without mixing

$$\lambda_{f_{CP}} \neq \pm 1 \;\Leftrightarrow\; \text{Prob}(\bar{B}^0(t) \to f_{CP}) \neq \text{Prob}(B^0(t) \to f_{CP})$$

★ Time-dependent asymmetry observable

$$A_{f_{CP}}(t) = \frac{\Gamma(\bar{B}^0(t) \to f_{CP}) - \Gamma(B^0(t) \to f_{CP})}{\Gamma(\bar{B}^0(t) \to f_{CP}) + \Gamma(B^0(t) \to f_{CP})}$$
$$= S_{f_{CP}} \sin(\Delta m_d t) - C_{f_{CP}} \cos(\Delta m_d t)$$



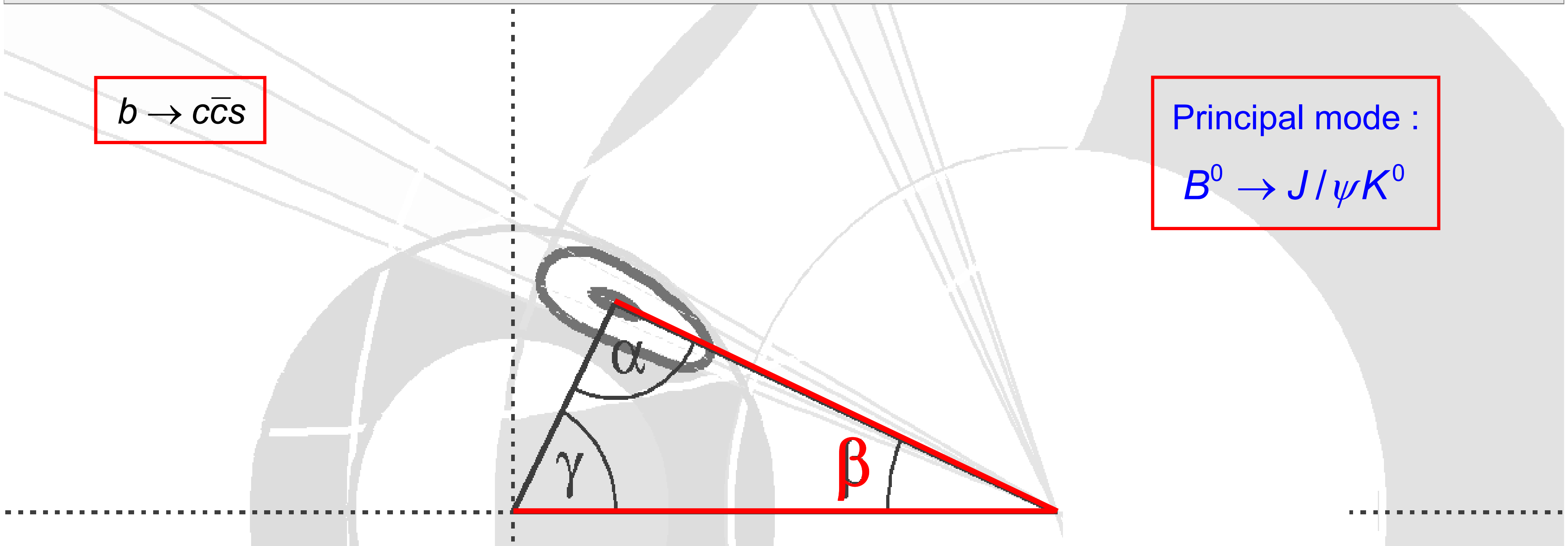
recall:

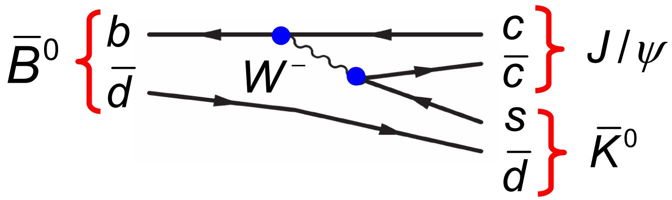
CP observables

$$C_f = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2}$$

$$S_f = \frac{2\,\text{Im}[\lambda_f]}{1 + |\lambda_f|^2}$$

sin(2β)





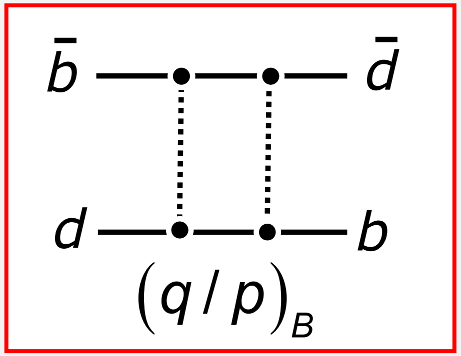
Tree : dominant

$\propto V_{cb}V_{cs}^*$
$\propto \lambda^2$

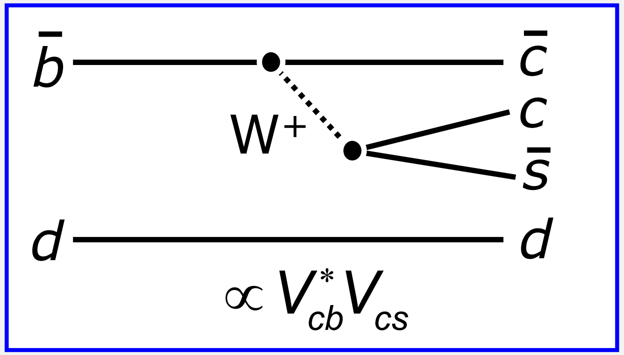
The Golden Channel: $B^0, \bar{B}^0 \rightarrow J/\psi K^0$

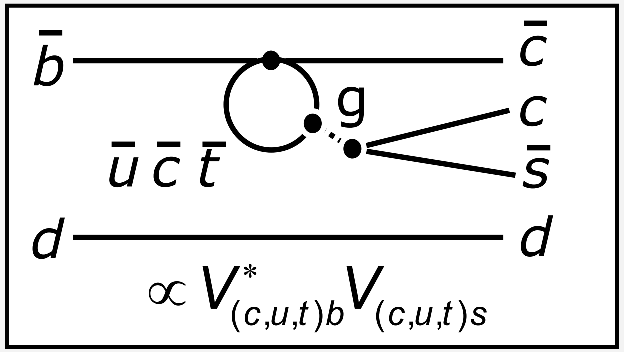
Leading tree : $\frac{q}{p}\frac{\bar{A}}{A} = \eta_{CP}\left(\frac{q}{p}\right)_B \frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}}\left(\frac{q}{p}\right)_K = -e^{-2i\beta}$

B^0 mixing



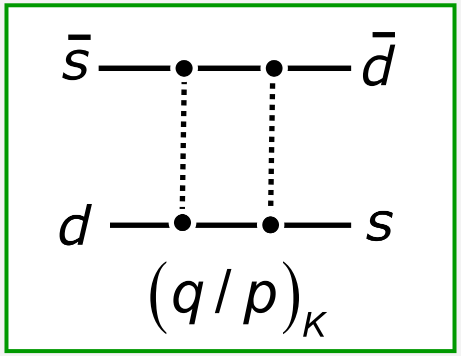
B^0 decay





B^0 decay

K^0 mixing

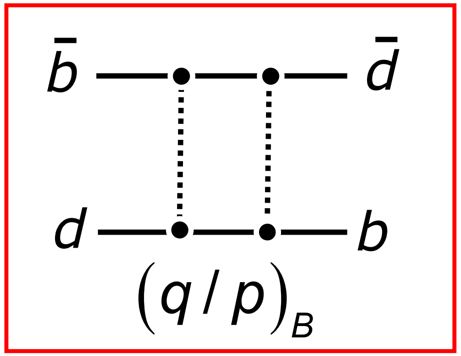


Penguin : $V_{cb}V_{cs}^*$ real , $V_{tb}V_{ts}^*$ real , $V_{ub}V_{us}^* \rightarrow \gamma(\propto A \cdot \lambda^4)$

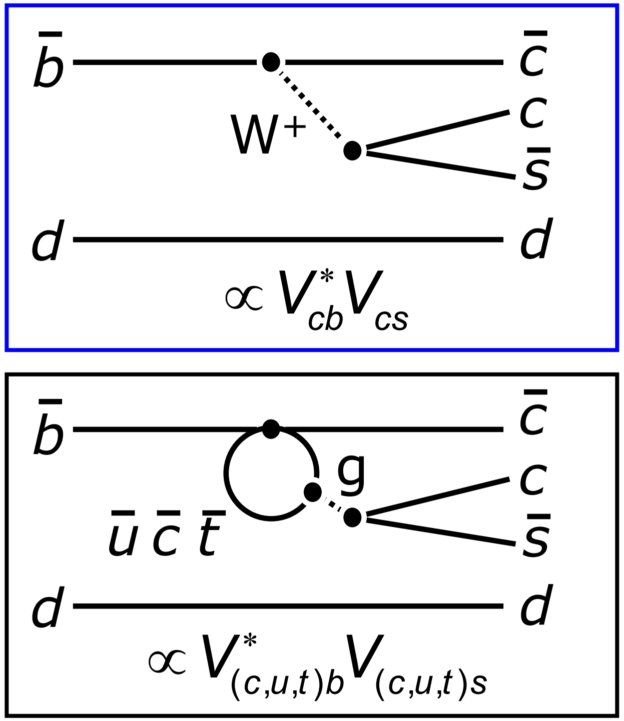
The Golden Channel: $B^0, \bar{B}^0 \to J/\psi K^0$

Leading tree : $\frac{q}{p}\frac{\bar{A}}{A} = \eta_{CP}\left(\frac{q}{p}\right)_B \frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}}\left(\frac{q}{p}\right)_K = -e^{-2i\beta}$

B^0 mixing

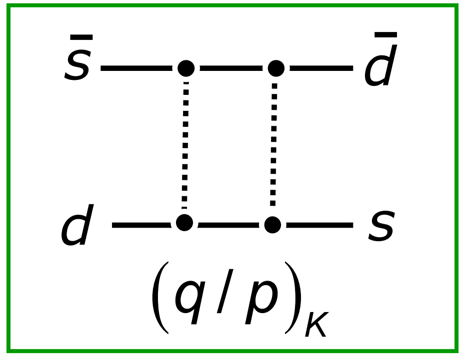


B^0 decay



B^0 decay

K^0 mixing



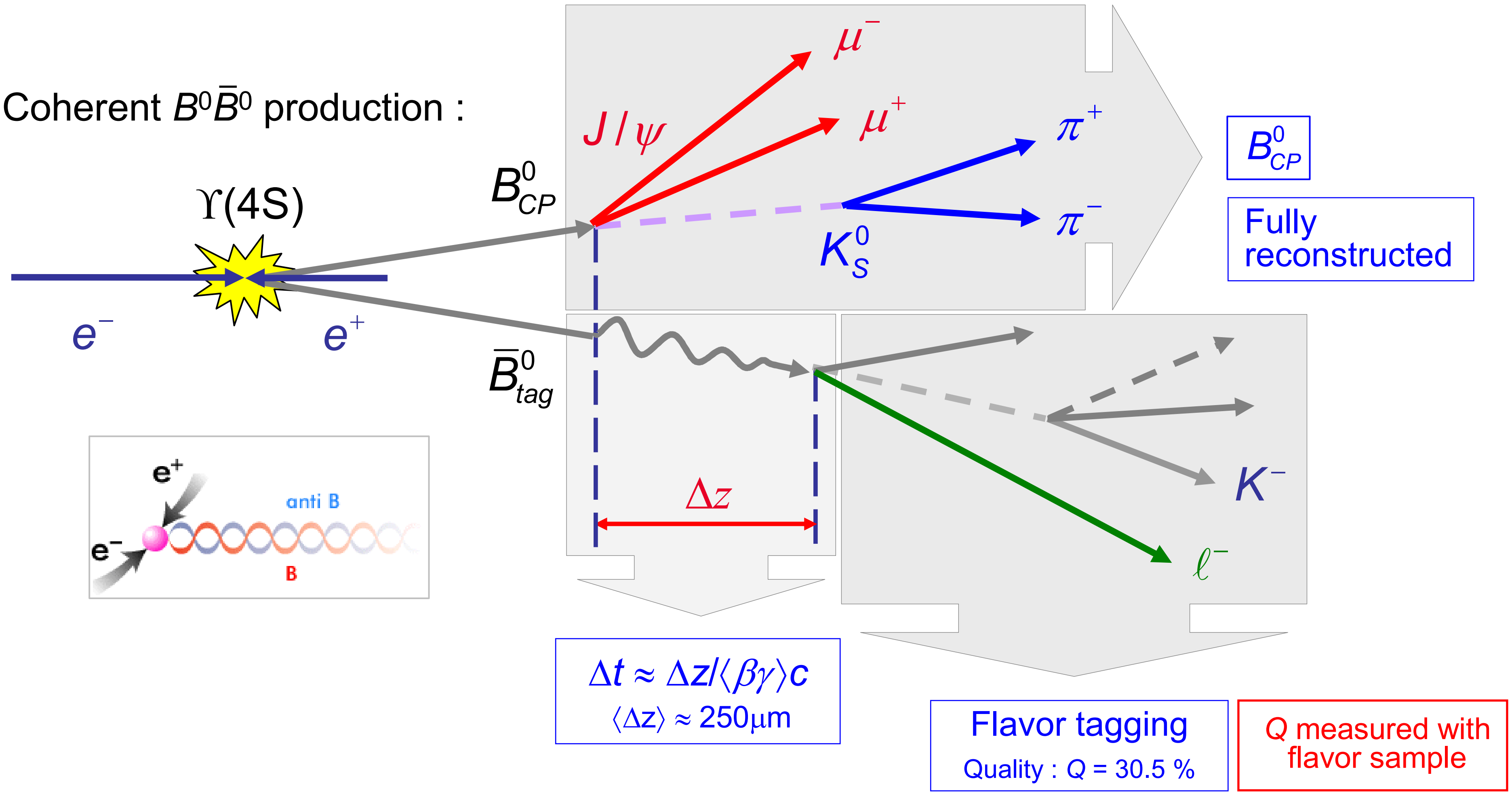
Single weak phase:

- clean *CP* phase
- no direct CPV:

$$A_{J/\psi K^0_{S,L}}(t) = -\eta_{J/\psi K^0_{S,L}} \cdot \sin(2\beta) \cdot \sin(\Delta m_{B_d} t)$$

Experimental Technique

Coherent $B^0\bar{B}^0$ production :



Data Sample

energy-substituted mass

$$m_{ES} \equiv \sqrt{(s/4) - p_B^{*2}}$$

energy difference

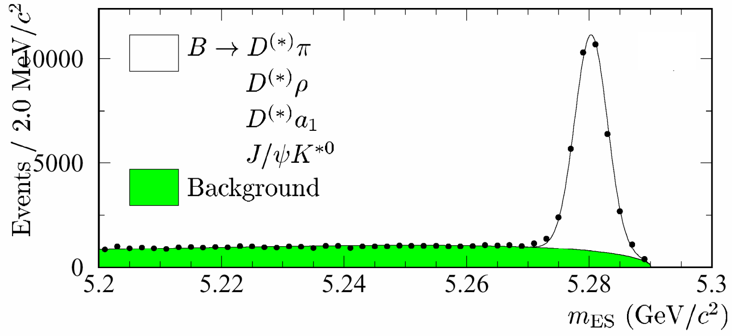
$$\Delta E \equiv \sqrt{s}/2 - E_B^*$$

Nov 1999- July 2004 data

213 fb^{-1} on-peak – 227 million BB pairs

Samples of *B* decays to flavor-specific final states

$$B^0 \to D^{(*)-}\pi^+/\rho^+/a_1^+$$
$$B^0 \to J/\psi\ K^{*0}(\to K^+\pi^-)$$



Samples of *B* decays to *CP* eigenstates with charmonium

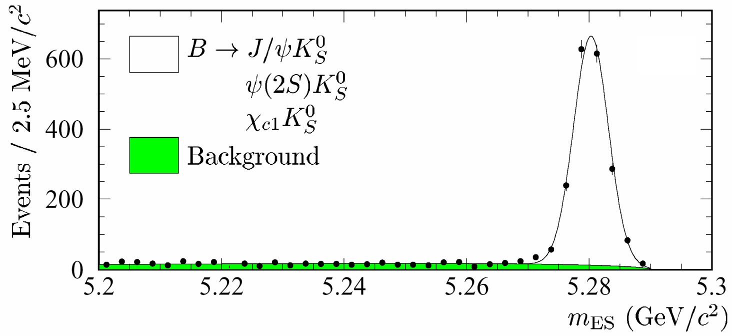
$$B^0_{CP} \to \eta_c(\to K^0_S K^\pm \pi^\mp)\ K^0_S$$ **(not shown)**

$$B^0_{CP} \to J/\psi\,(\to \ell^+\ell^-)\ K^0_S$$

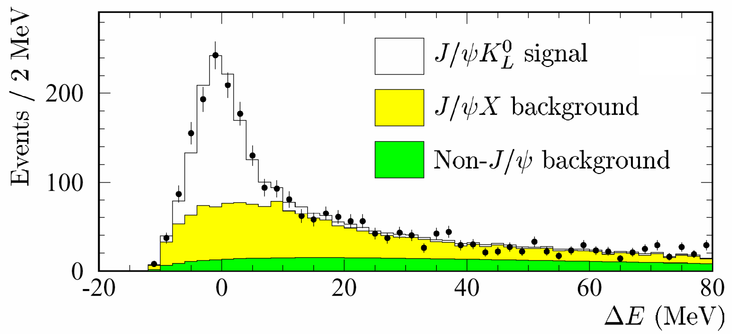
***CP* = –1** $\quad B^0_{CP} \to J/\psi\ K^0_S(\to \pi^0\pi^0)$

$$B^0_{CP} \to \psi(2S)(\to \ell^+\ell^-,\ J/\psi\,\pi\pi)\ K^0_S$$

$$B^0_{CP} \to \chi_{c1}(\to J/\psi\,\gamma)\ K^0_S$$



***CP* = +1** $\quad B^0_{CP} \to J/\psi\ K^0_L$



mixed *CP* $\quad B^0_{CP} \to J/\psi\ K^{*0}_{CP}(\to K^0_S\pi^0)$ **requires angular analysis (not shown)**

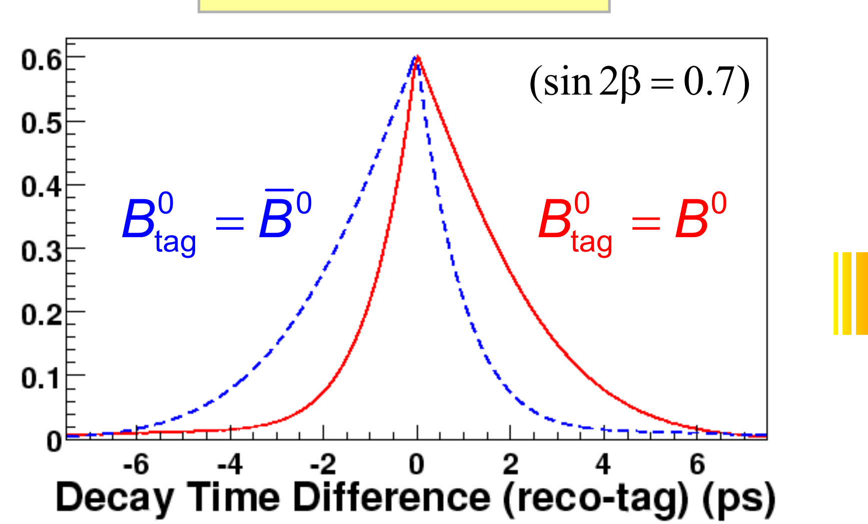
CPV Experimentally: Mistagging and Resolution

Two categories of events:

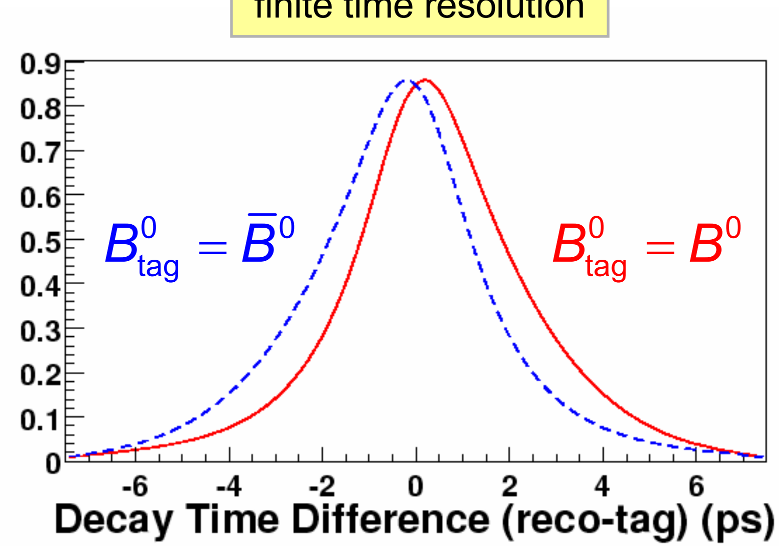
$B^0_{\rm tag} = B^0$ (+) : the "other" (=tag) B is tagged as a B^0

$B^0_{\rm tag} = \bar{B}^0$ (–) : the "other" (=tag) B is tagged as a $\bar{B}^0$

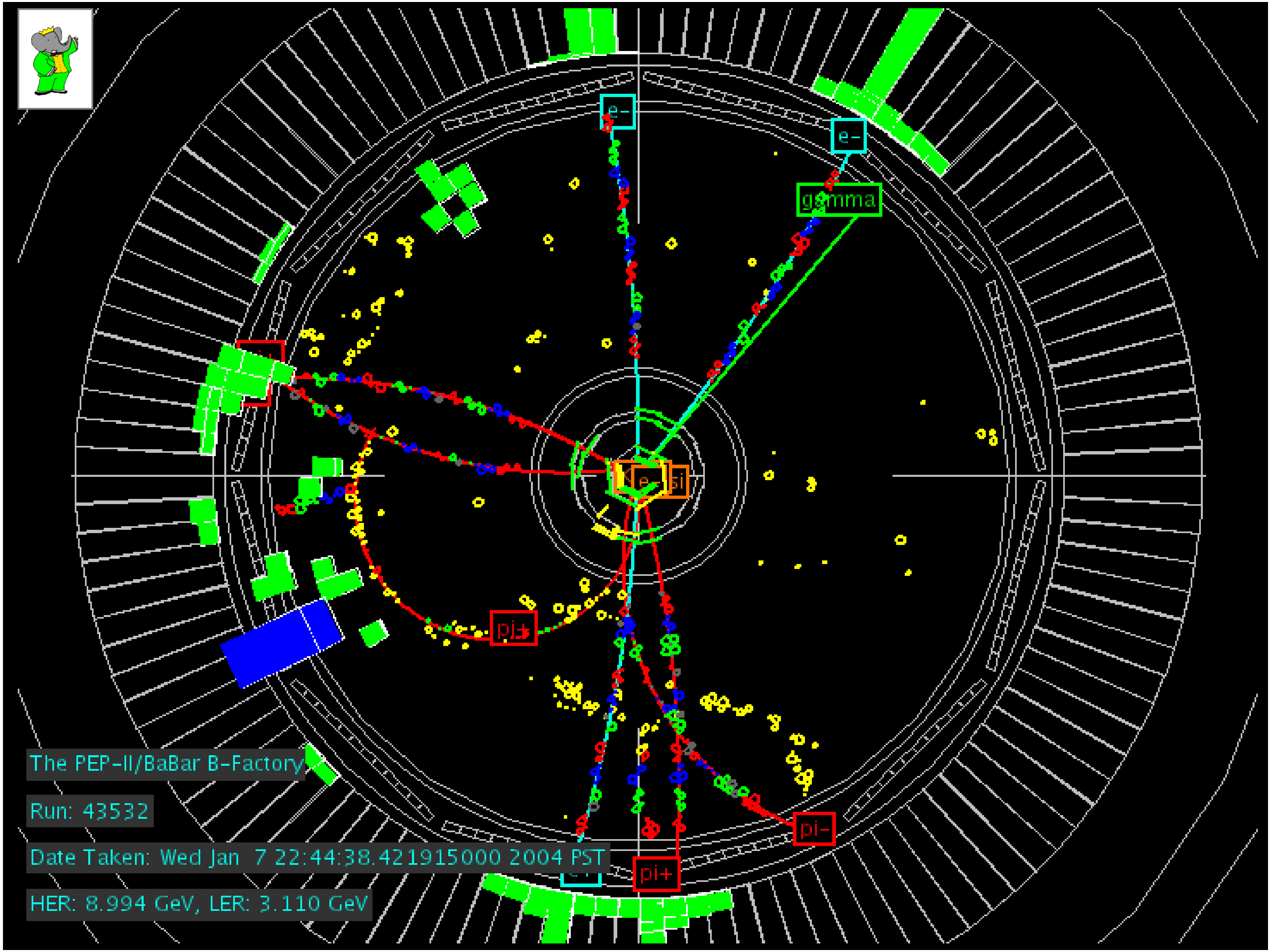
perfect
flavor tagging & time resolution



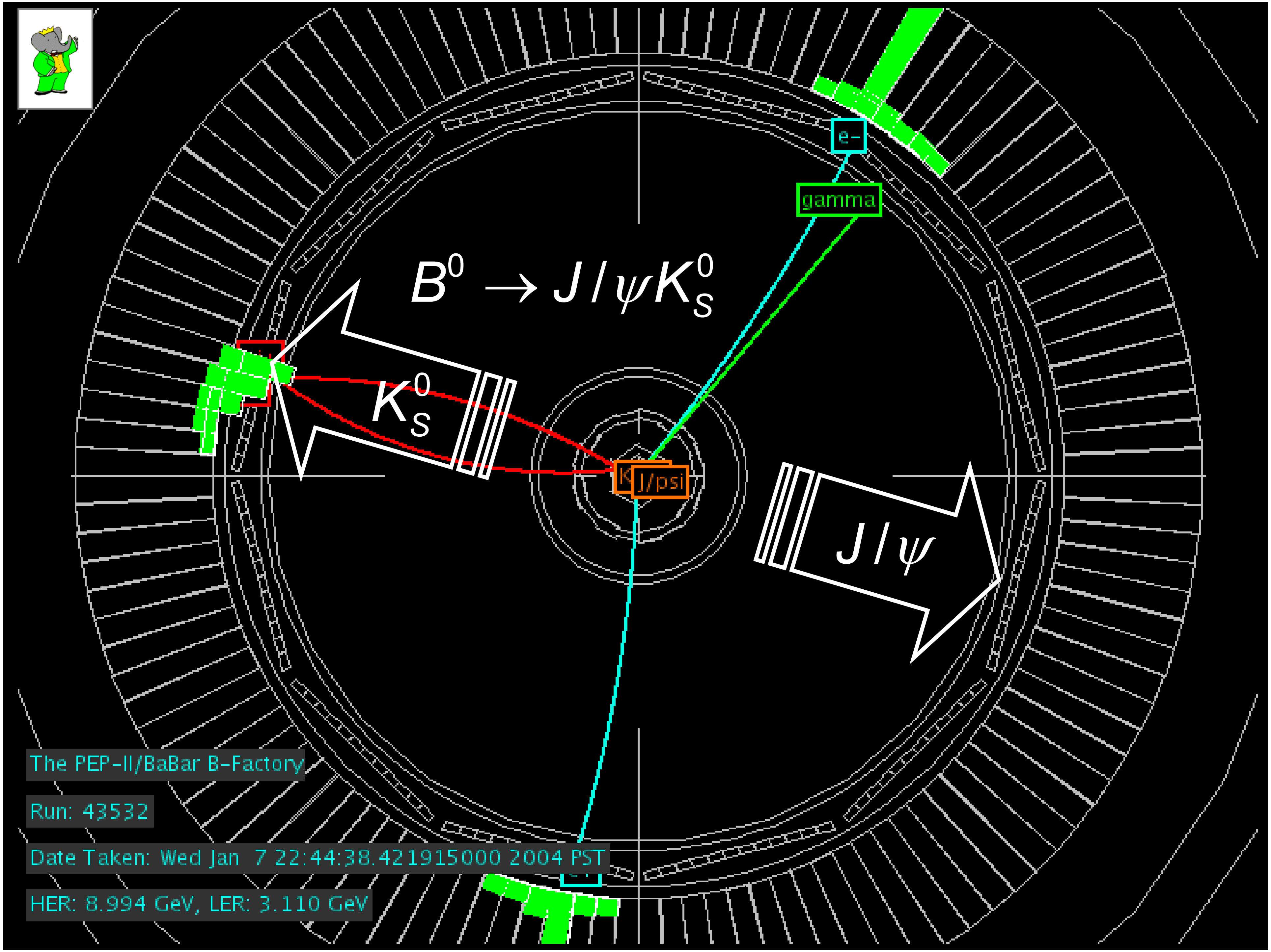
realistic
mistag probability & finite time resolution



$$A_{J/\psi K^0_{S,L}}(t) = -\eta_{J/\psi K^0_{S,L}}(1-2\omega)\cdot\sin(2\beta)\cdot\sin(\Delta m_{B_d} t')\otimes R(t'-t)$$



e-
e-
gamma
e-
pi
pi+
pi-
pi+
The PEP-II/BaBar B-Factory
Run: 43532
Date Taken: Wed Jan 7 22:44:38.421915000 2004 PST
HER: 8.994 GeV, LER: 3.110 GeV



$B^0 \to J/\psi K_S^0$
K_S^0
J/ψ
e-
gamma
J/psi
The PEP-II/BaBar B-Factory
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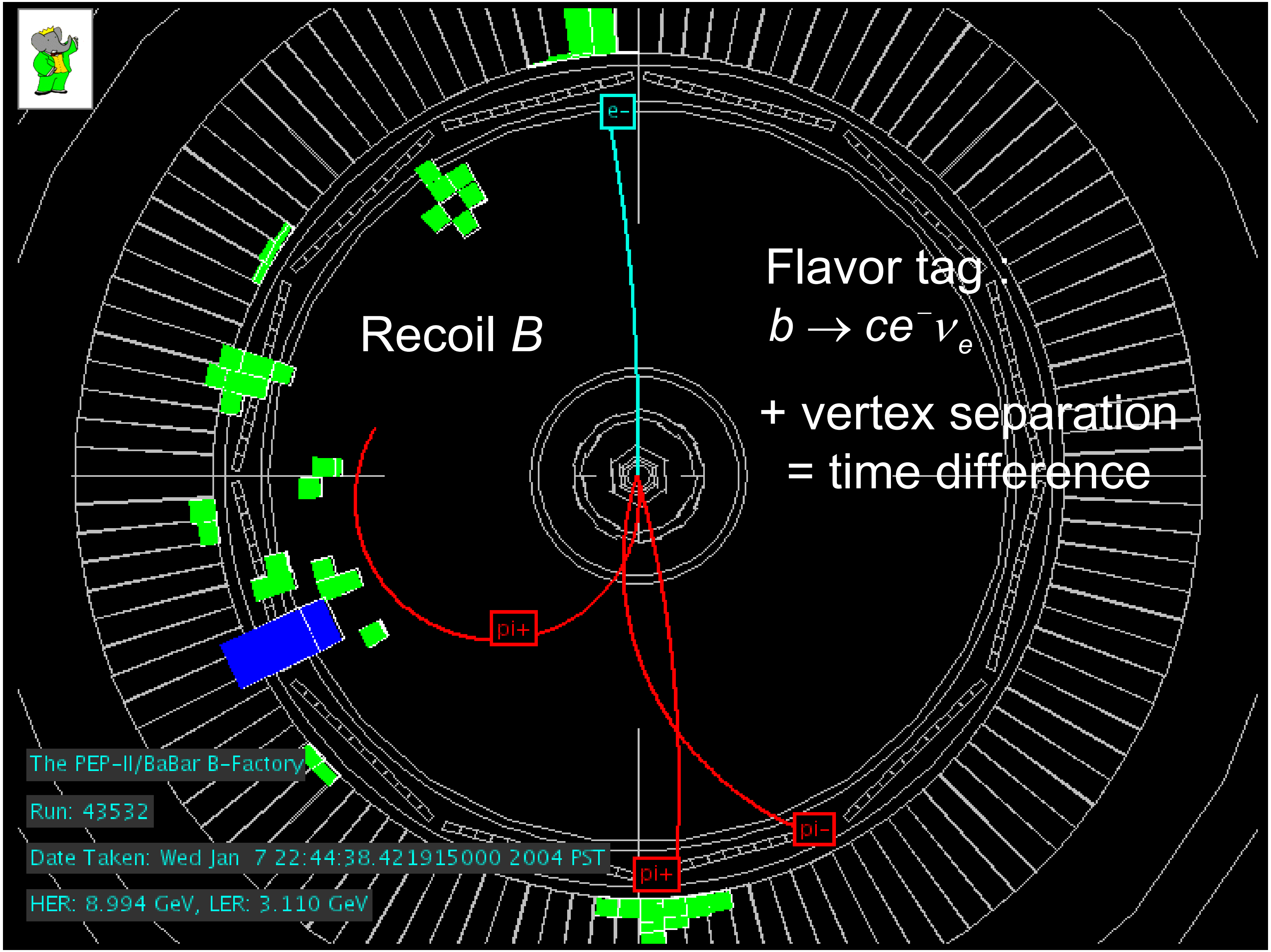
Recoil B
Flavor tag :
$b \to c e^- \nu_e$
+ vertex separation
= time difference
e-
pi+
pi-
pi+
The PEP-II/BaBar B-Factory
Run: 43532
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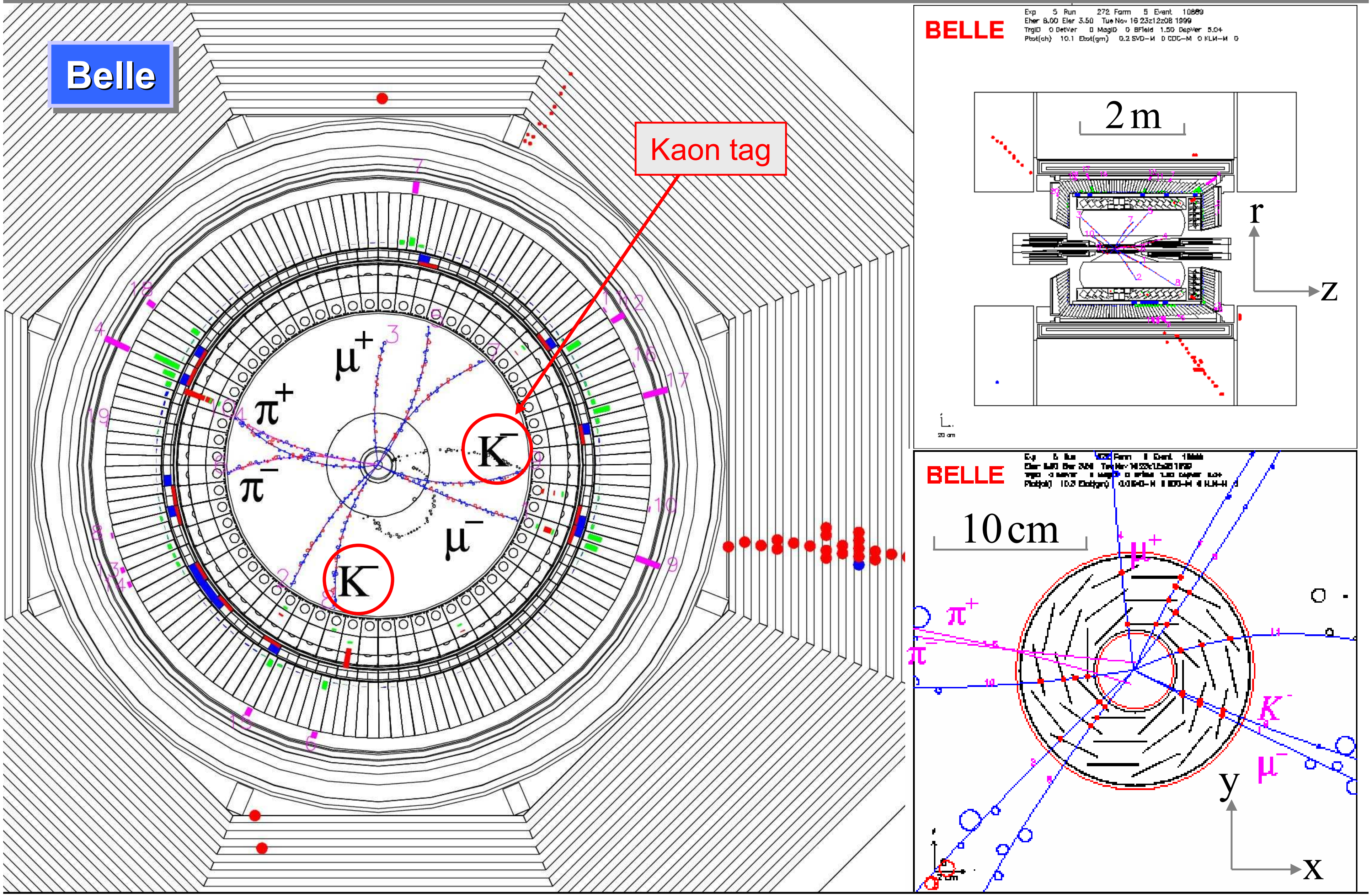
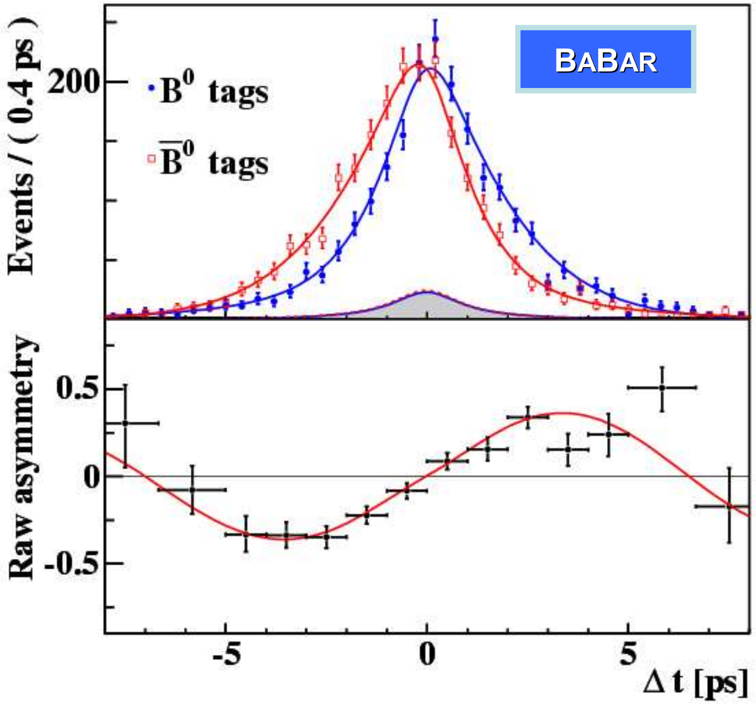
HER: 8.994 GeV, LER: 3.110 GeV

A $B \to \psi(\to\mu^+\mu^-)\, K_S$ Event as seen by Belle

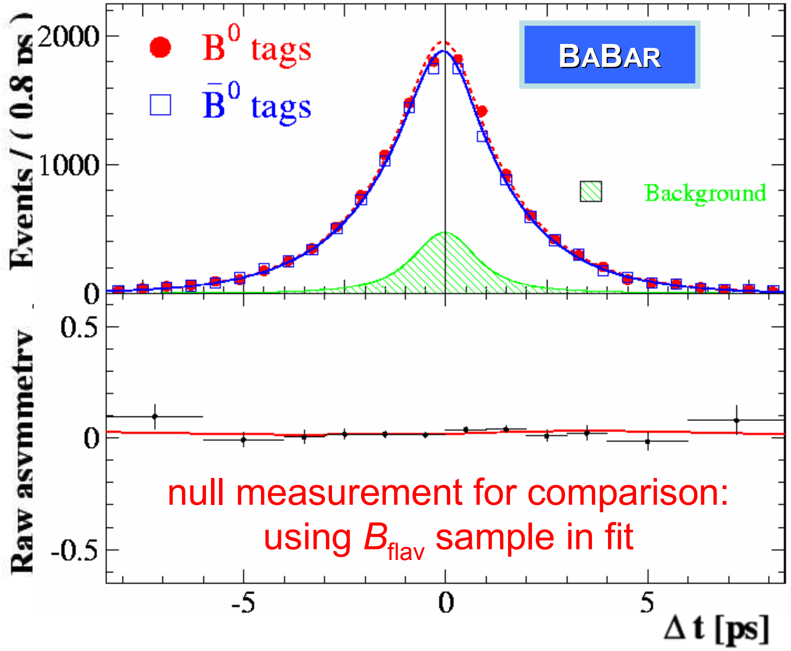


$\sin(2\beta)$ with B^0 to charmonium

CP-odd ($J/\psi\, K_S$ …)



B flavor states



$$\sin 2\beta = 0.726 \pm 0.037$$
$$C = 0.031 \pm 0.029$$

BABAR & **Belle**, ICHEP, 2004

compatible with the Standard Model (CKM fit) :

$$\sin 2\beta_{[\mathrm{CKM}]} = 0.73 \pm 0.08$$

$\sin(2\beta)$ with B^0 to charmonium

CP-odd ($J/\psi\, K_S$ ...)

B flavor states

A Triumph for the Standard Model

It establishes the KM mechanism as

dominant source of *CP* violation at the electroweak scale

-5 0 5 Δt [ps]

Δt [ps]

$$\sin 2\beta = 0.726 \pm 0.037$$
$$C = 0.031 \pm 0.029$$

BABAR & **Belle**, ICHEP, 2004

compatible with the Standard Model (CKM fit) :

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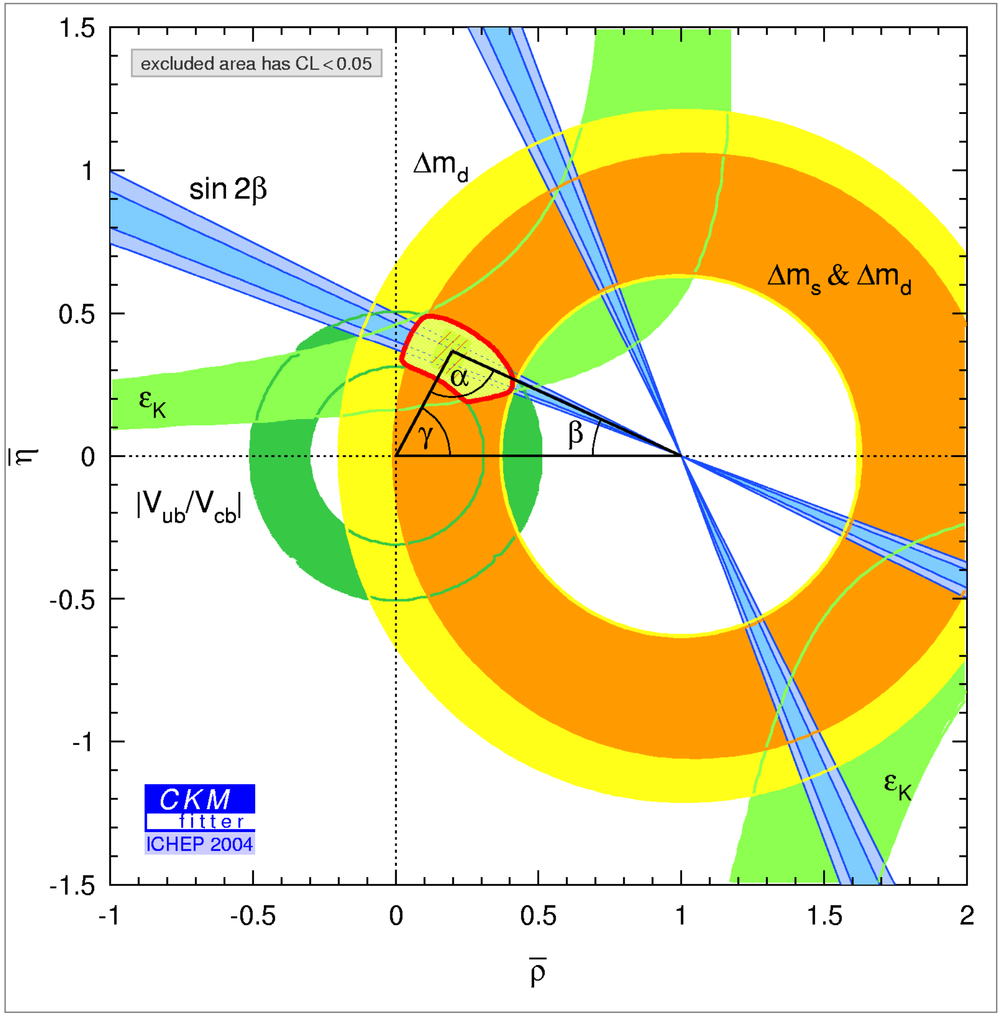
Comparison with CKM Fit

- Precision measurement :

$$\beta = \left[23.3\,^{+1.6}_{-1.5}\right]^{\circ}$$



CKMfitter, EPJ C41, 1-131,2005 [hep-ph/0406184 (2004)]
UTfit, hep-ph/0408079 (2004)
and others !

Comparison with CKM Fit

Precision measurement :

$$\beta = \left[23.3\,^{+1.6}_{-1.5}\right]^\circ$$

- Measurement of the sign of cos2β is a direct test of the SM : if SM $\Rightarrow$ cos2β > 0
- cos2β accessible through time-dependent angular correlations in

$$B^0 \to J/\psi K^{*0}\left(K^{*0} \to K_S^0 \pi^0\right)$$

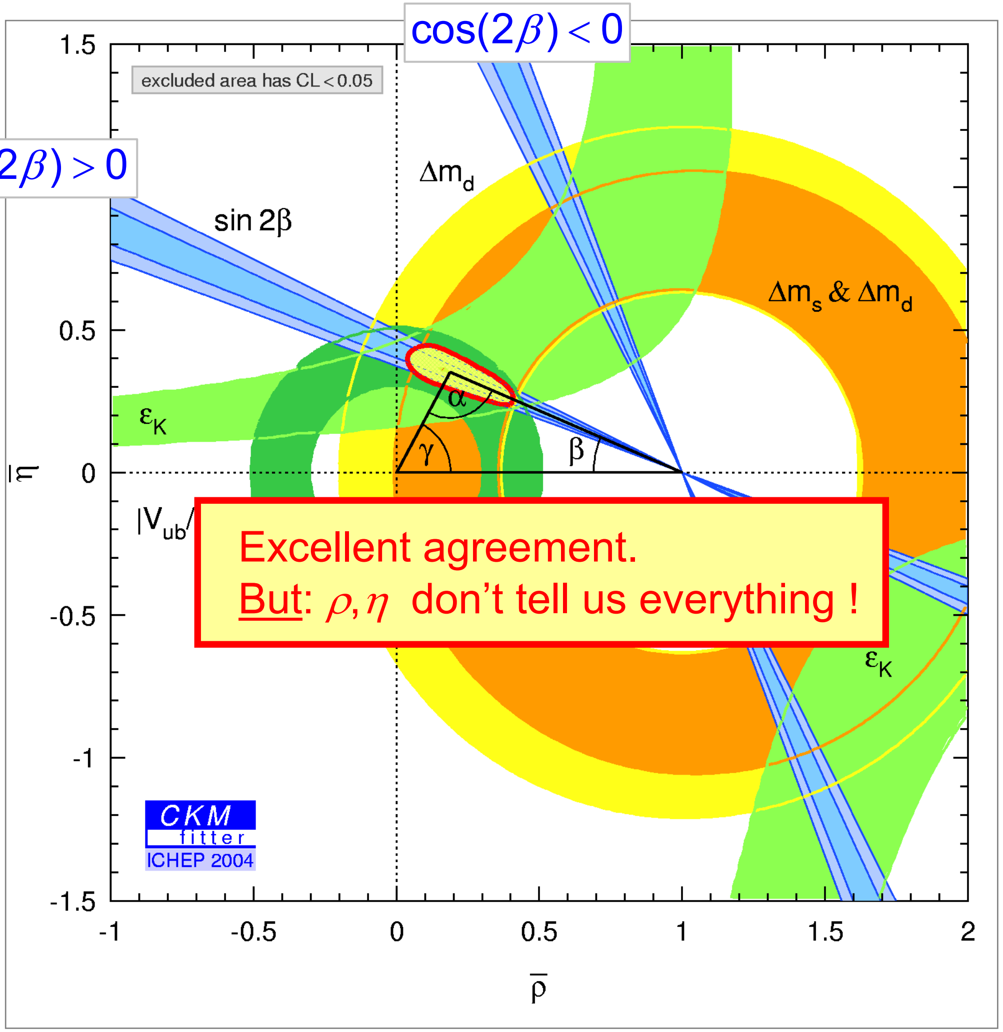
- But :

  with one ambiguity on sign … ☹

  induced by ambiguity on strong phase

- Ambiguity can be lifted with analysis of interference pattern between S and P wave in ($K\pi$) system.

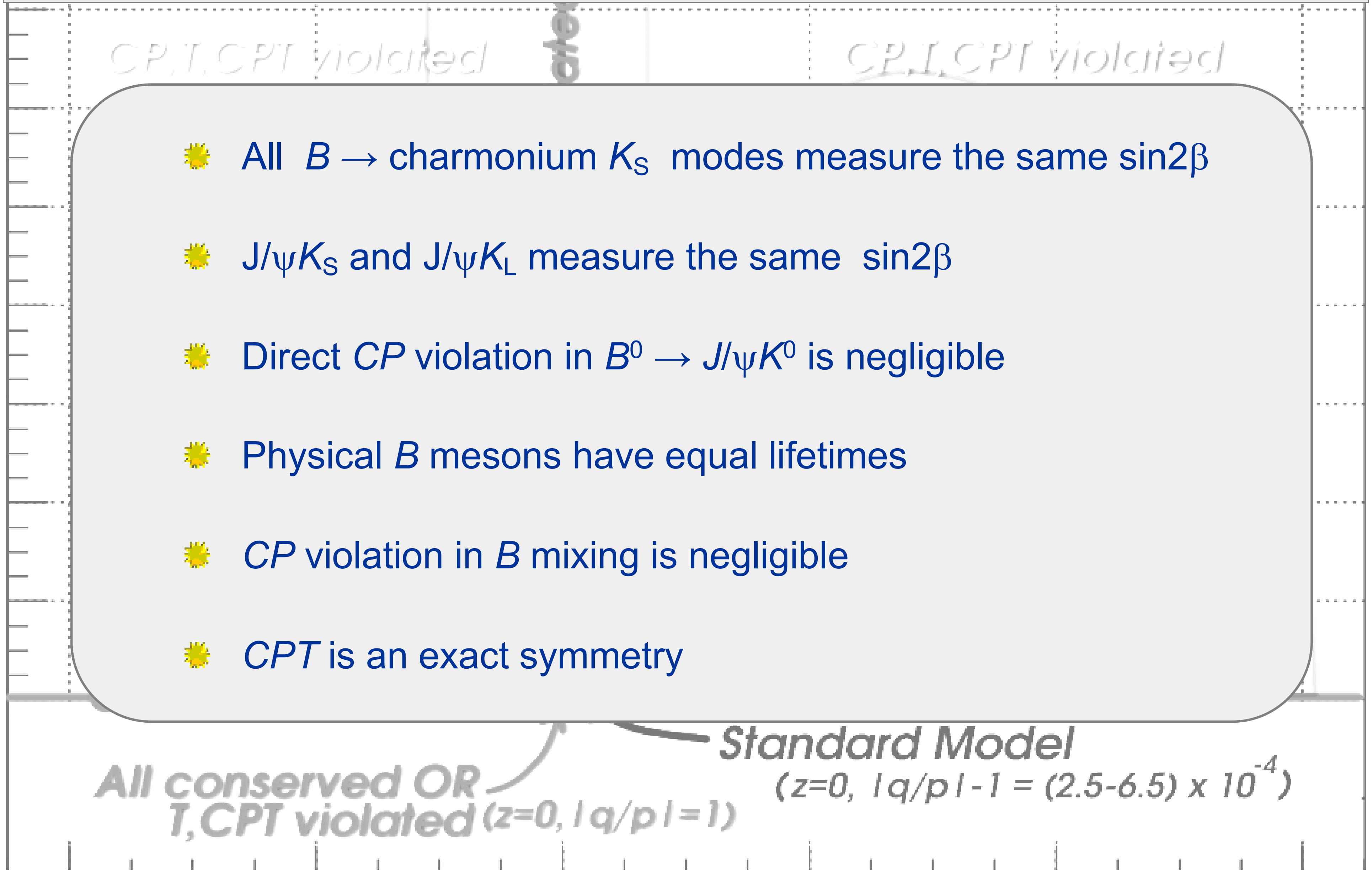
➡ $\cos(2\beta) > 0$ at 89% C.L.



Excellent agreement.
But: ρ, η don't tell us everything !

CKMfitter, EPJ C41, 1-131,2005 [hep-ph/0406184 (2004)]
UTfit, hep-ph/0408079 (2004)
and others !

Measurement of sin2β: Trivial Assumptions ???

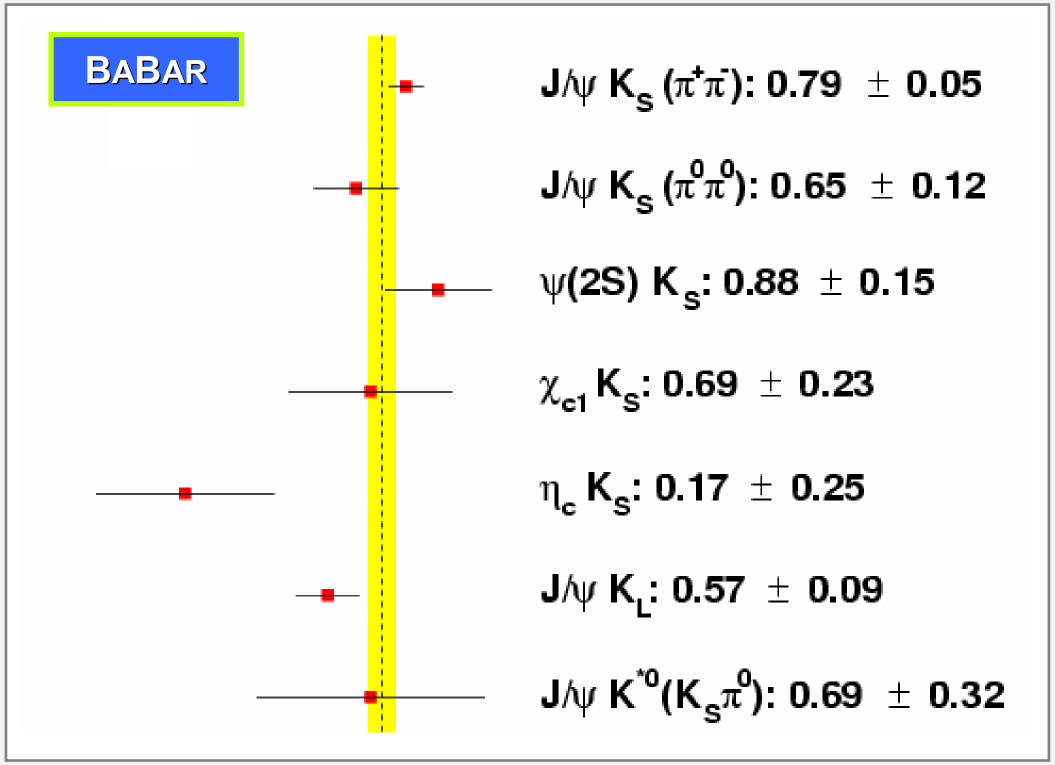


- All $B \rightarrow$ charmonium K_S modes measure the same sin2β
- $J/\psi K_S$ and $J/\psi K_L$ measure the same sin2β
- Direct *CP* violation in $B^0 \rightarrow J/\psi K^0$ is negligible
- Physical *B* mesons have equal lifetimes
- *CP* violation in *B* mixing is negligible
- *CPT* is an exact symmetry

Trivial Assumptions ?

Example: all $B \to$ charmonium K_S modes measure the same $\sin 2\beta$

Compare sin(2β) among charmonium modes



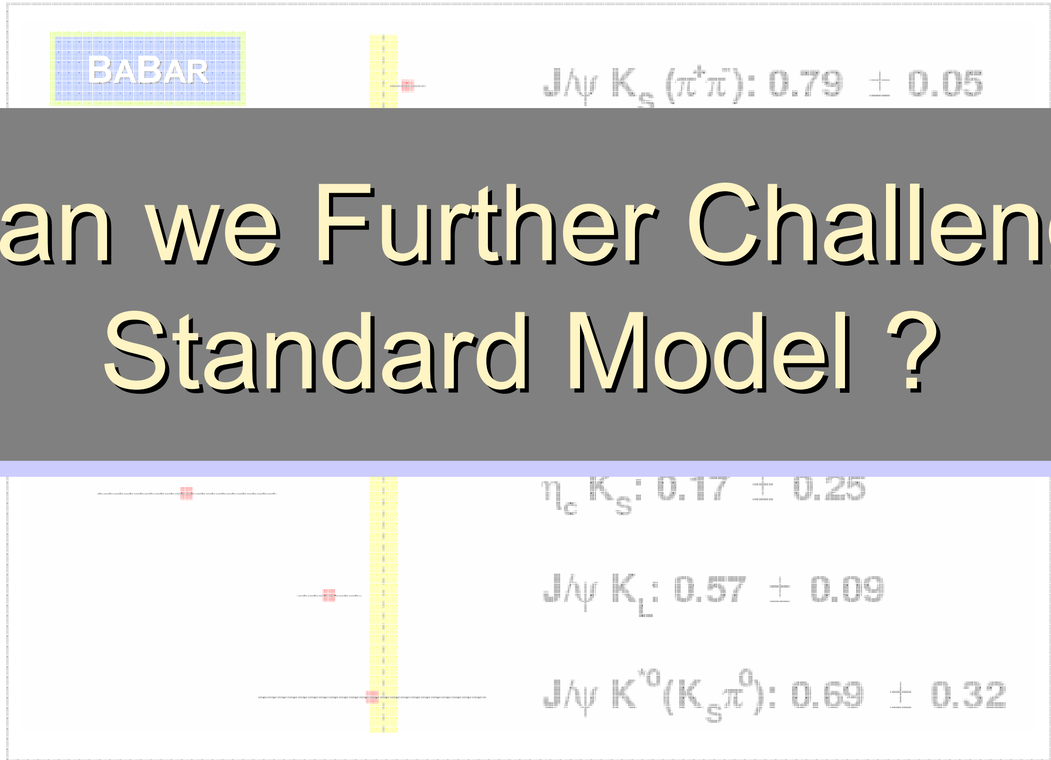
χ^2=11.7/6 d.o.f.
Prob (χ^2)=7%

→ reasonable consistency among the various charmonium modes

Trivial Assumptions ?

Example: all $B \to$ charmonium K_S modes measure the same $\sin 2\beta$

Compare $\sin(2\beta)$ among charmonium modes

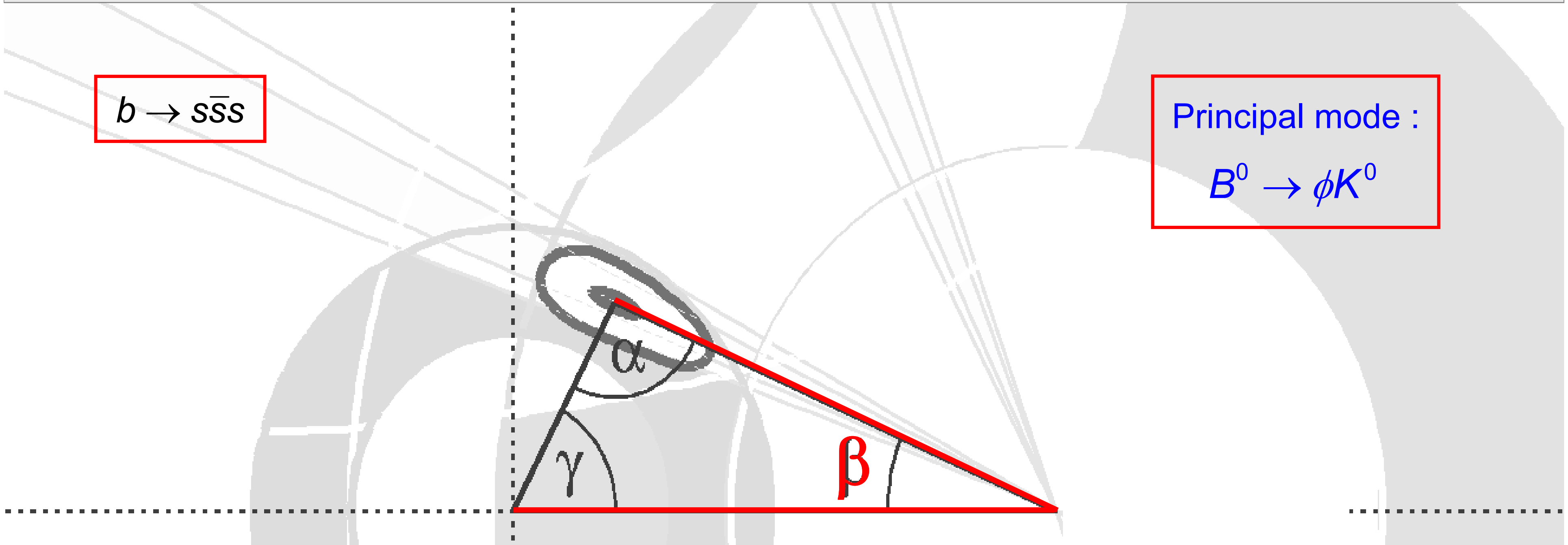


How can we Further Challenge the Standard Model ?

χ^2=11.7/6 d.o.f.
Prob (χ^2)=7%

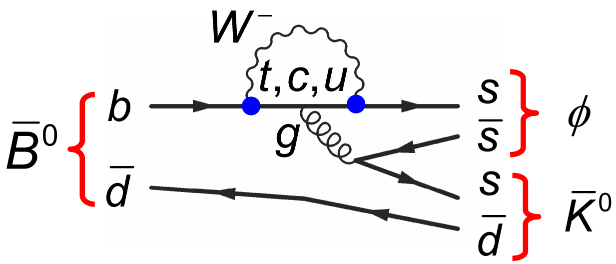
→ reasonable consistency among the various charmonium modes

Use the *Penguins* to Measure sin($2\beta_{eff}$)



Principal mode :

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



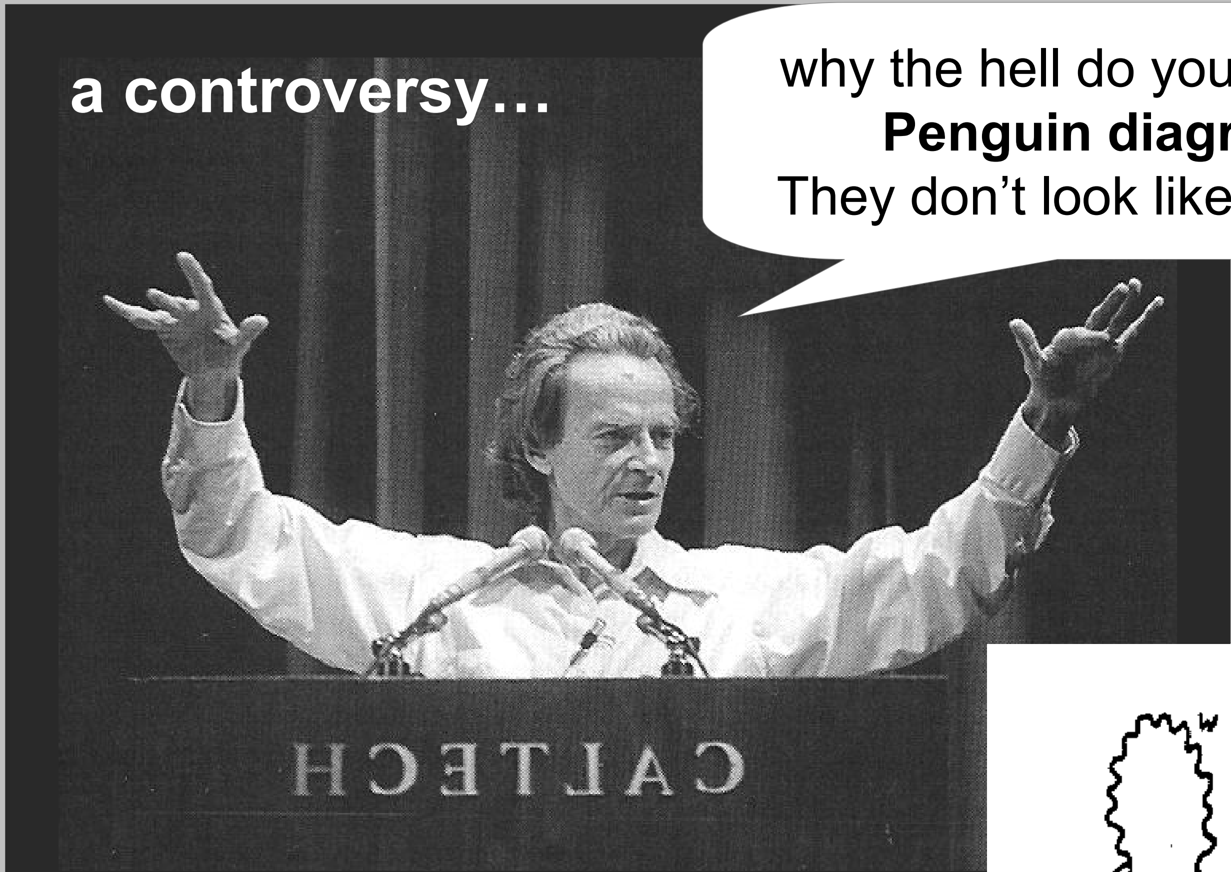
Penguin : dominant

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

$\propto \lambda^2$

BUT …

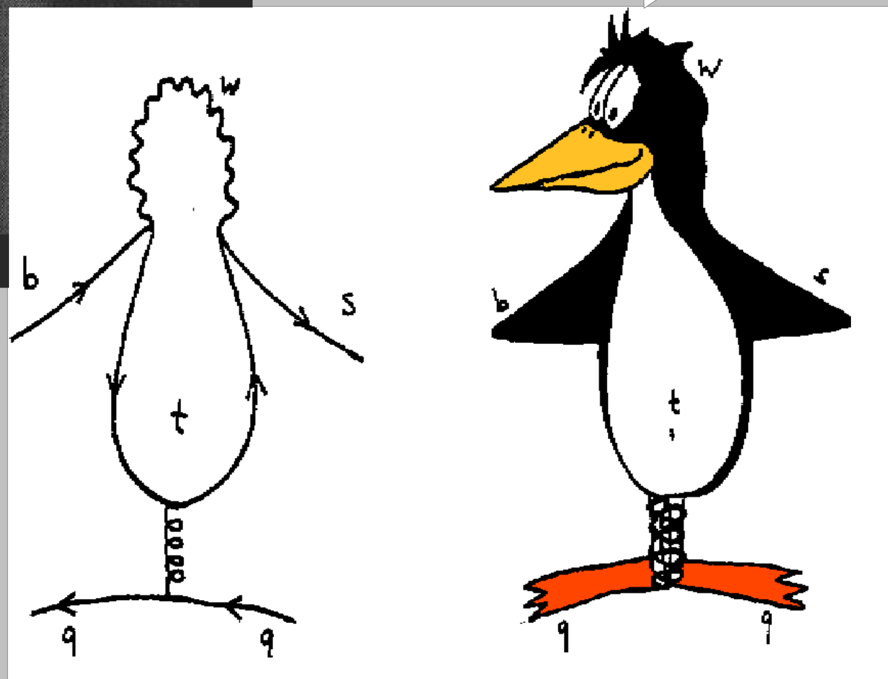
a controversy…



mirror image of Richard Feynman

why the hell do you call these **Penguin diagrams**? They don't look like penguins!

I've never seen a **Feynman diagram** that looks like **you** ☺

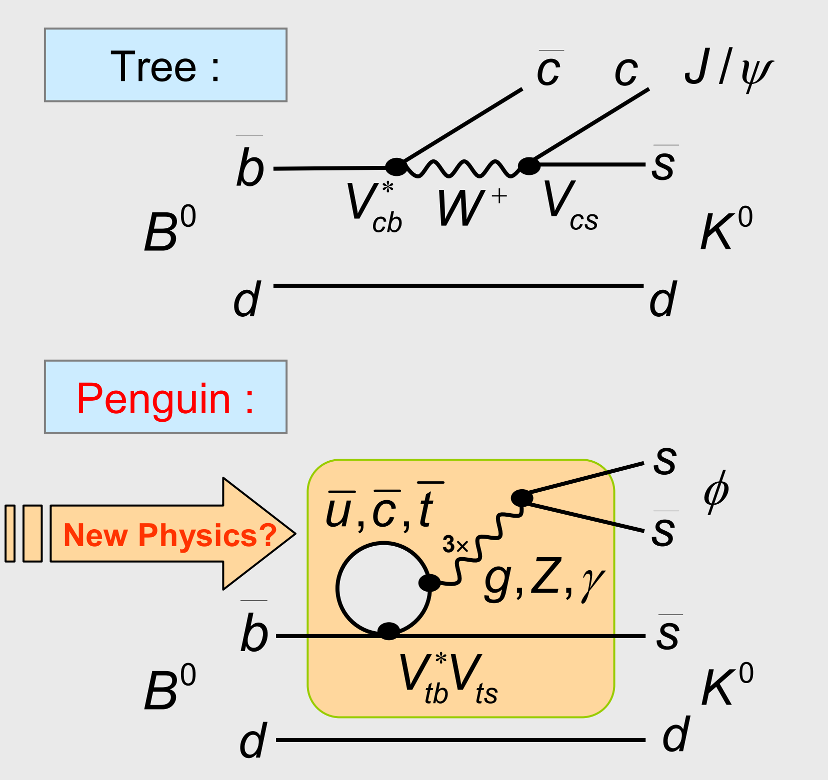


courtesy: G. Hamel de Monchenault

Confronting Loop and Tree Decays

- $b \to c\bar{c}s$ decays are tree and penguin diagrams, with equal dominant weak phases
- $b \to s\bar{s}s$ decays are pure "internal" and "flavor-singlet" penguin diagrams
  - ➡ High virtual mass scales involved: believed to be sensitive to New Physics

Both decays dominated by single weak phase



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

$$\lambda_{J/\psi K^0_{S,L}} = \eta_{J/\psi K^0_{S,L}} \left(\frac{q}{p}\right)_B \cdot \left(\frac{V_{cb}V^*_{cs}}{V^*_{cb}V_{cs}}\right) \cdot \left(\frac{q}{p}\right)_K = \eta_{J/\psi K^0_{S,L}} e^{-2i\beta}$$

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

$$\lambda_{\phi K^0_{S,L}} = \eta_{\phi K^0_{S,L}} \left(\frac{q}{p}\right)_B \cdot \left(\frac{V_{cb}V^*_{cs}}{V^*_{cb}V_{cs}}\right) \cdot \left(\frac{q}{p}\right)_K \simeq \eta_{\phi K^0_{S,L}} e^{-2i\beta}$$

$\sin 2\beta$ [charmonium] $\stackrel{?}{=}$ $\sin 2\beta$ [s-pingouin]

(7000 tagged events) (1500 tagged events)

Naïve Classification of the penguins

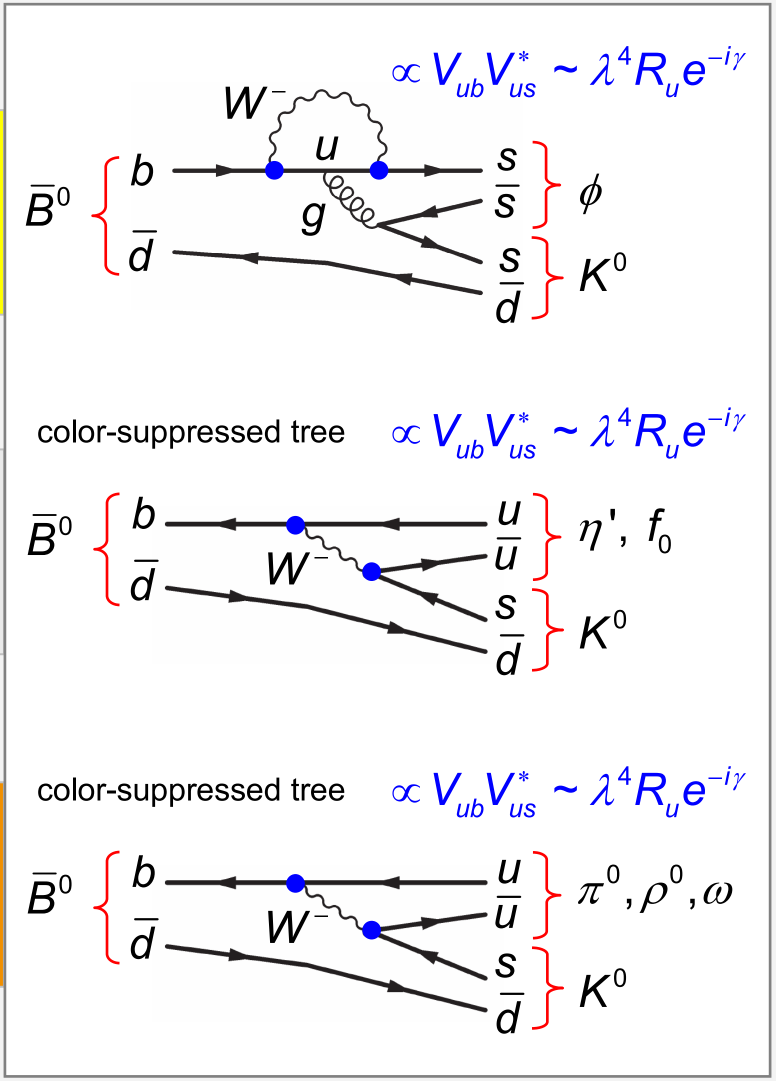
- Can we identify golden, silver and bronze-plated *s*-penguin modes ?

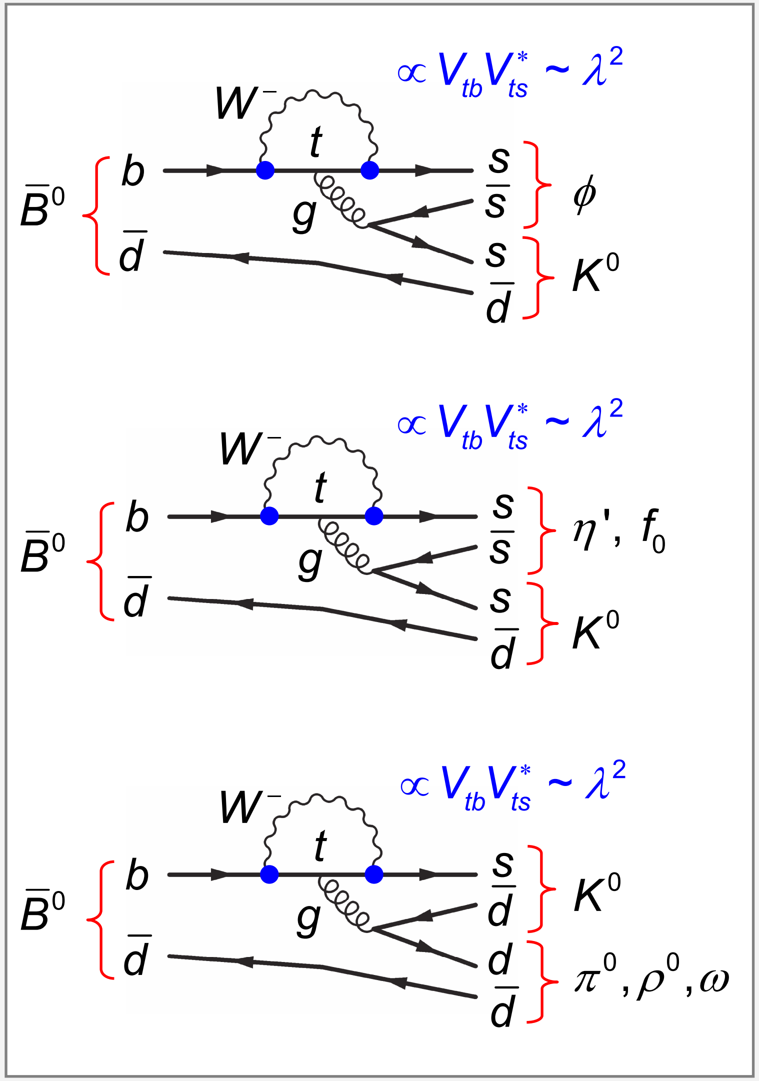
Naïve (dimensional) uncertainties on sin2β

Gold

Silver

Bronze





$O(\lambda^2)$

$\sim 5\%$

$O(\lambda^2(1+f_{q\bar{q}}/\bar{\lambda}))$

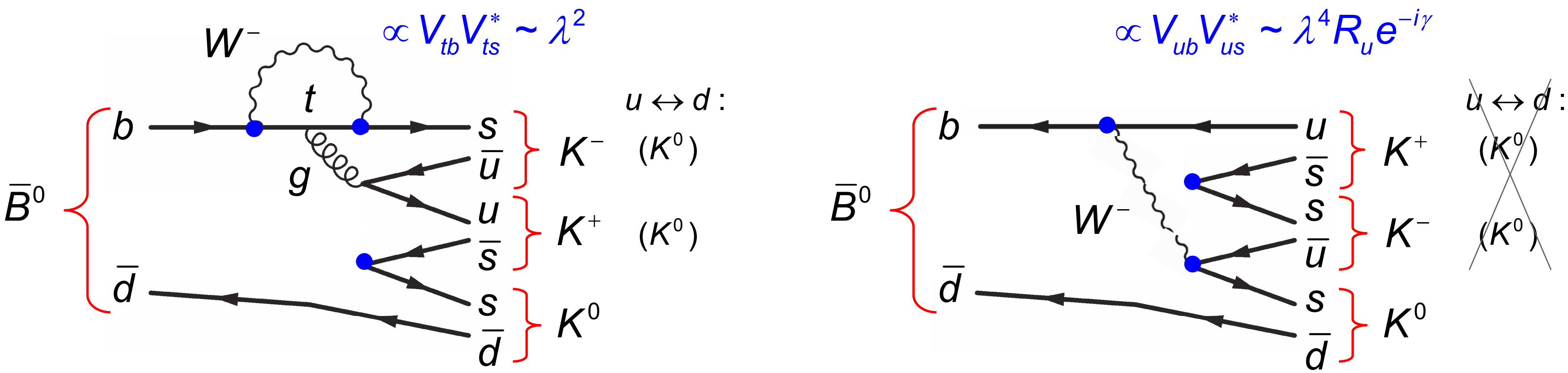
$\sim 10\%$

$O(\lambda^2/\bar{\lambda})$

$\sim 20\%$

KKK^0 Modes

- How about $B^0 \to K^+K^-K^0$ and $B^0 \to K_S K_S K_S$?



$B^0 \to K^+K^-K^0$ bronze and $B^0 \to K_S K_S K_S$ seems to be a new golden mode !

<u>but</u> : « *popup* » *ss*-bar dynamically disvafored with respect to *popup uu*-bar

➡ is $B^0 \to K^+K^-K^0$ silver ?

- Note that

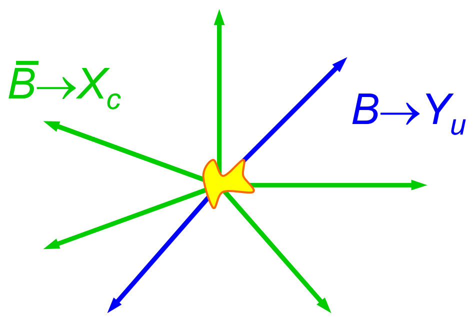
  if NP contributes significantly to CPV in loop decays, we naturally expect it to be different among the modes

  ➡ averaging only meaningful (if at all) in case of SM

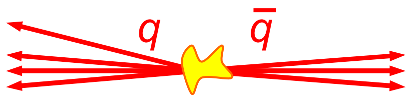
"Rare Modes" → Dedicated Background Fighting (I)

★ Suppress continuum, background using event shape variables

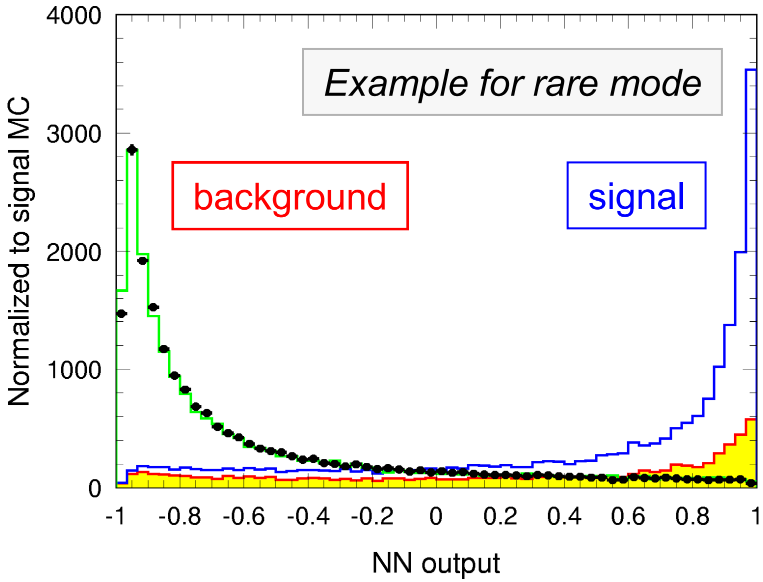
$e^+e^- \to \Upsilon(4s) \to B\bar{B}$
B decay ~ in rest → event shape spherical



Dominant $e^+e^- \to q\bar{q}$
background is jet-like:



Apply multivariate analyzer techniques:
Neural Network or Fisher Discriminants



"Rare Modes" → Dedicated Background Fighting (II)

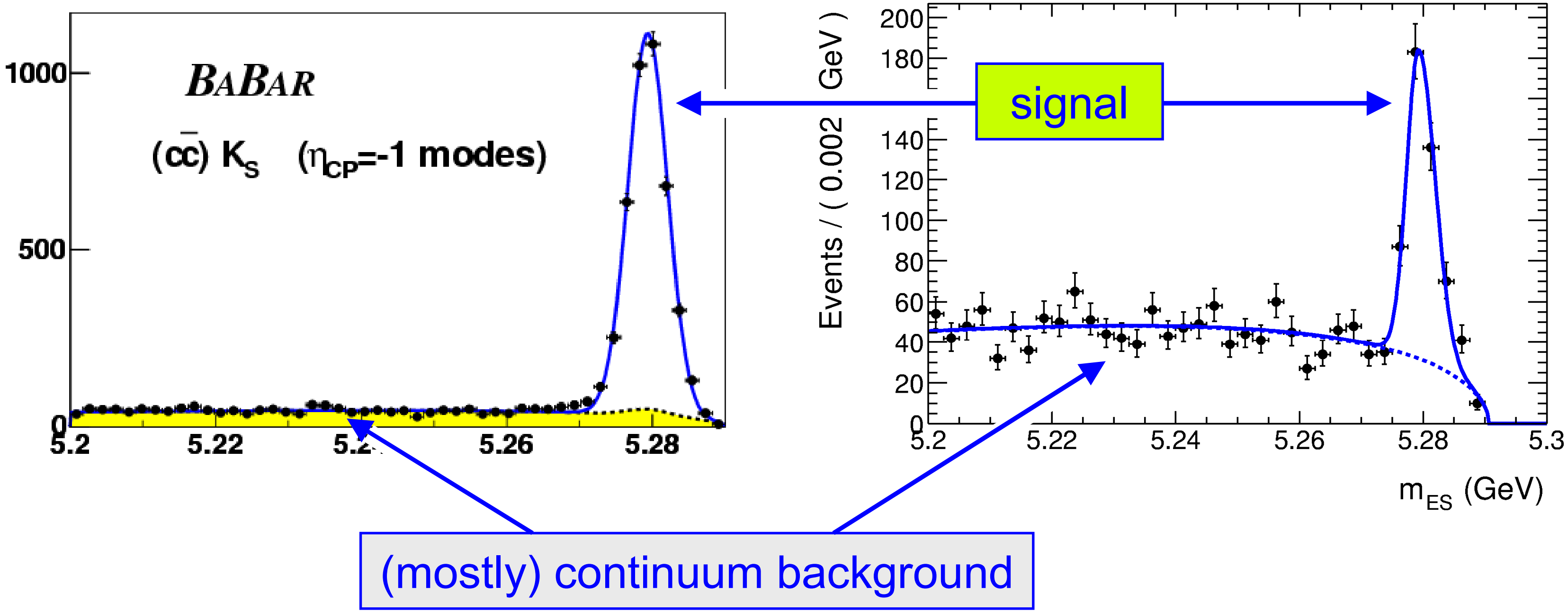
- Also: kinematic variables: ***m***

Typical resolution:

$\sigma(m_{ES}) \approx$ 2.5 MeV/c^2

$\sigma(\Delta E) \approx$ 25 - 40 MeV

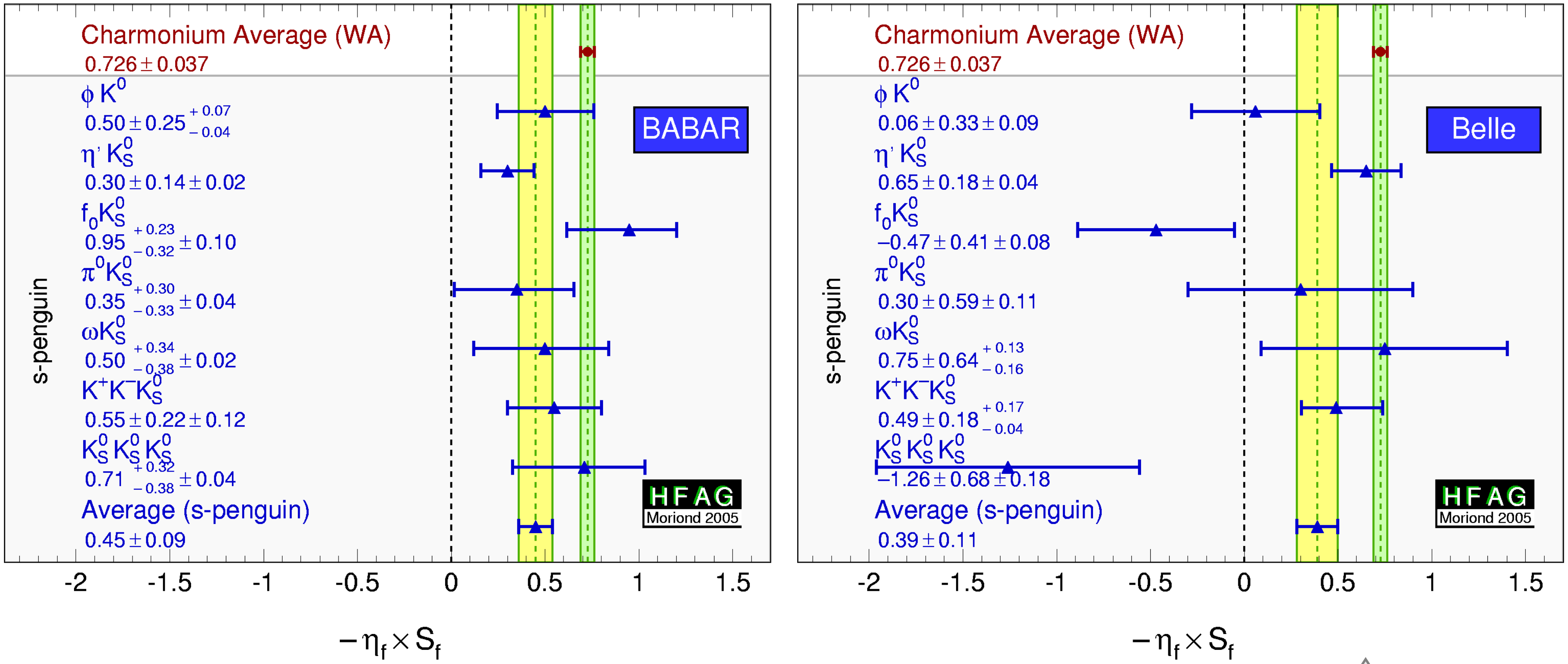
$B^0 \rightarrow (c\bar{c})K_S^0$ $\qquad$ $B^0 \rightarrow K^+K^-K_S^0$



s-penguin : comparison BABAR vs. Belle

Moriond 2005

BABAR : *s*-penguin average at 2.9σ from $\sin 2\beta[c\bar{c}]$ (WA)



Belle : *s*-penguin average at 2.9σ from $\sin 2\beta[c\bar{c}]$ (WA)

Confronting Loop and Tree Decays

- Conflict with $\sin 2\beta_{\text{eff}}$ from *s*-penguin modes ?

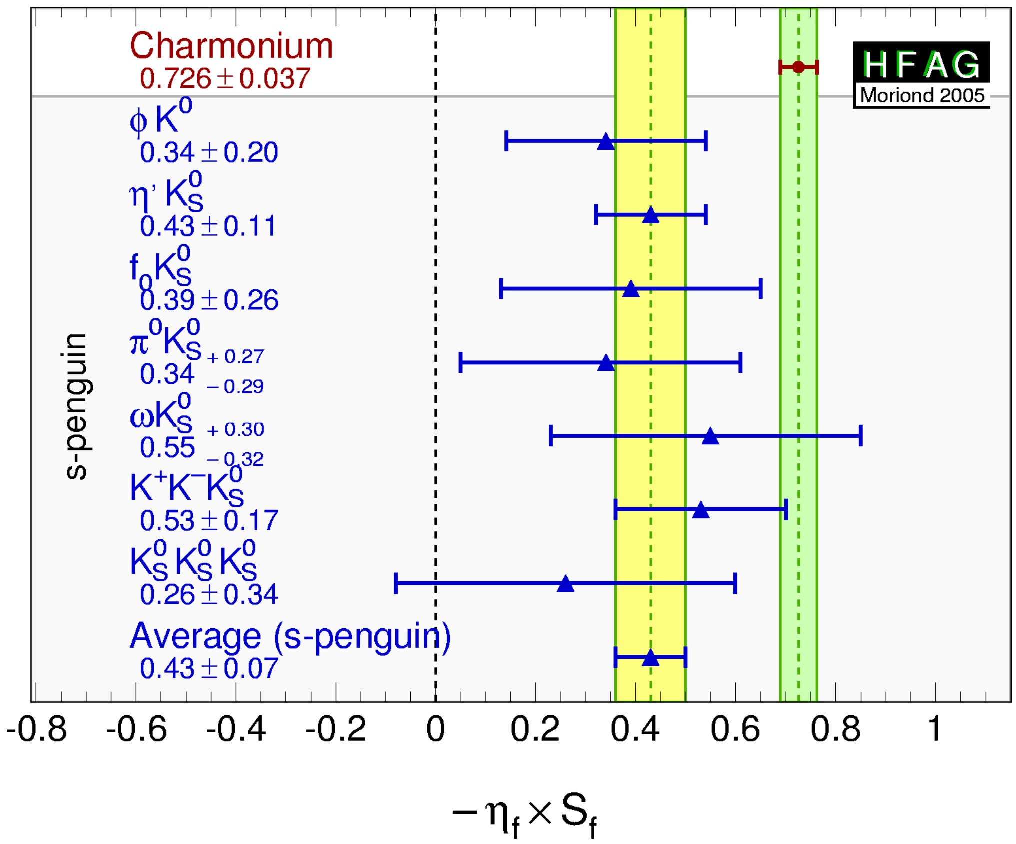
$$\langle \sin 2\beta_{[s\text{-peng}]} \rangle - \sin 2\beta_{[c\bar{c}]} = \underbrace{-0.30 \pm 0.08}_{3.7\sigma}$$

$$\langle \sin 2\beta_{[\phi/\eta'/2K_S]} \rangle - \sin 2\beta_{[c\bar{c}]} = \underbrace{-0.33 \pm 0.10}_{3.3\sigma}$$

- Theory uncertainty ?

  what is $\Delta S_{[s\text{-peng}]}$? positive ?

→ see theory lectures



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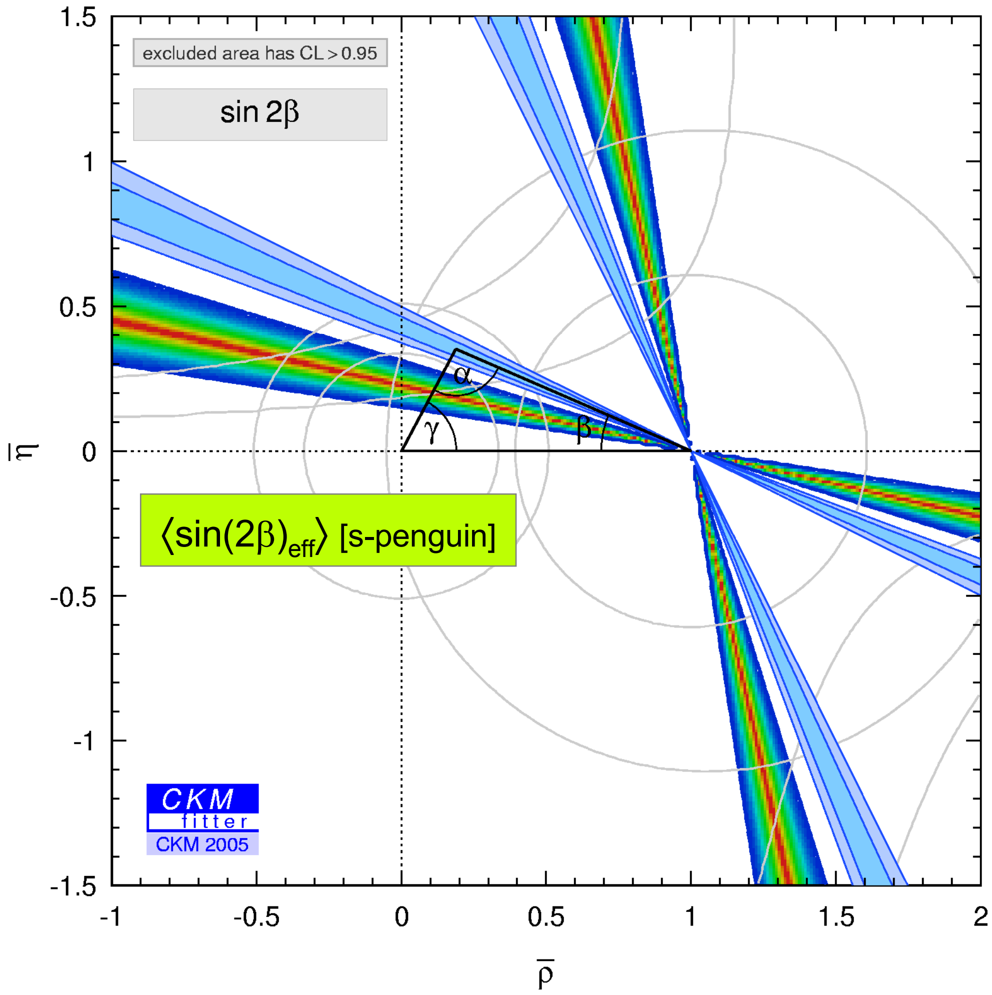
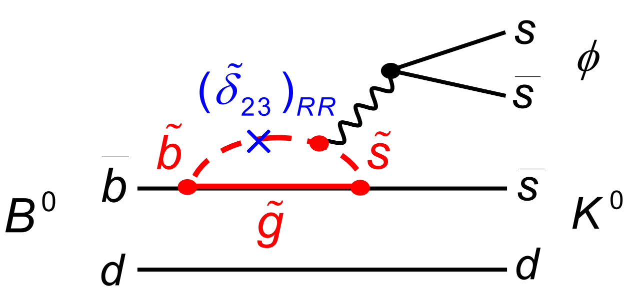
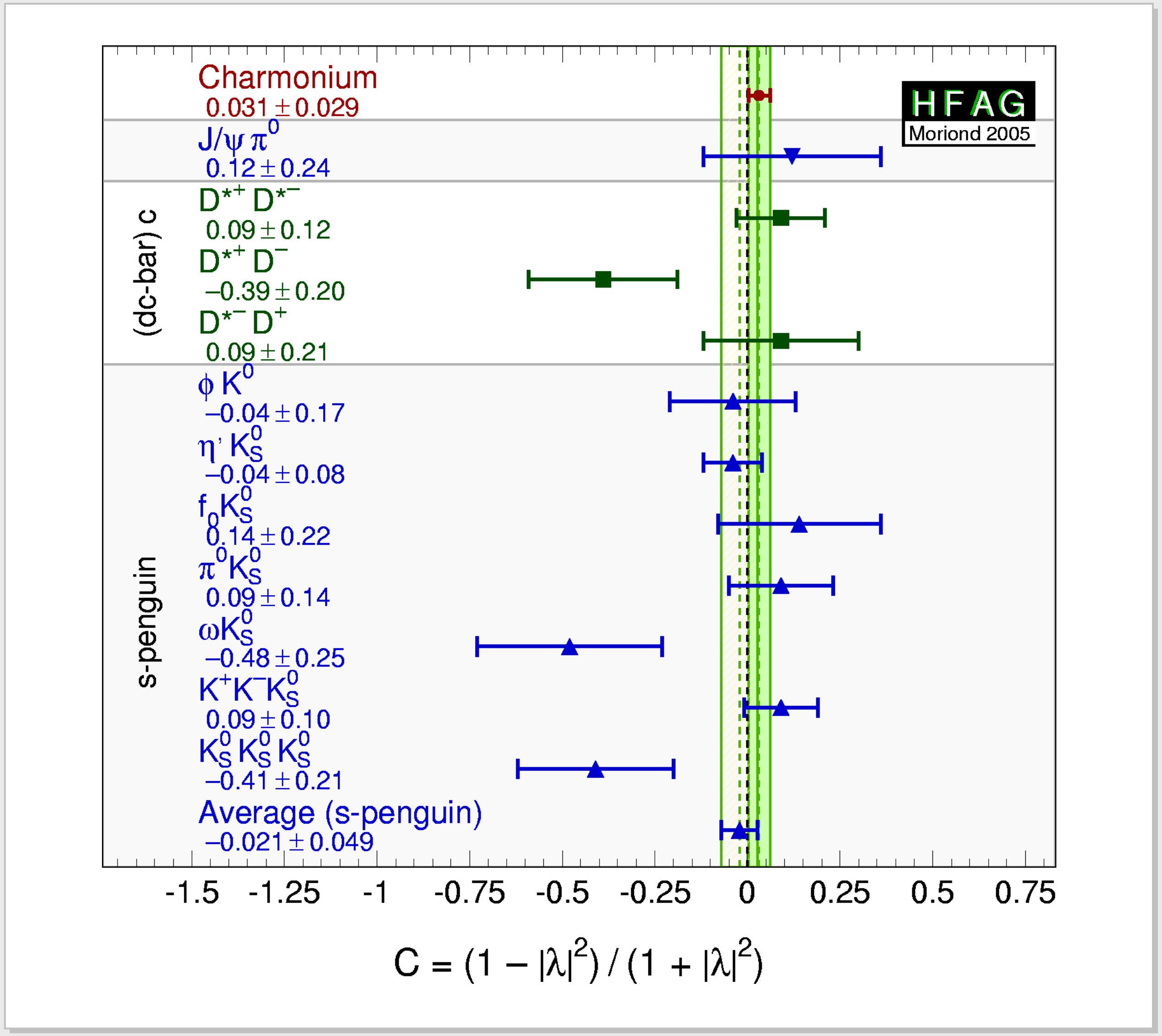


- New Physics in $b \to s$ transitions?



Masiero-Murayama, PRL 83, 907 (1999)

If there were New Physics … how about direct CPV ?

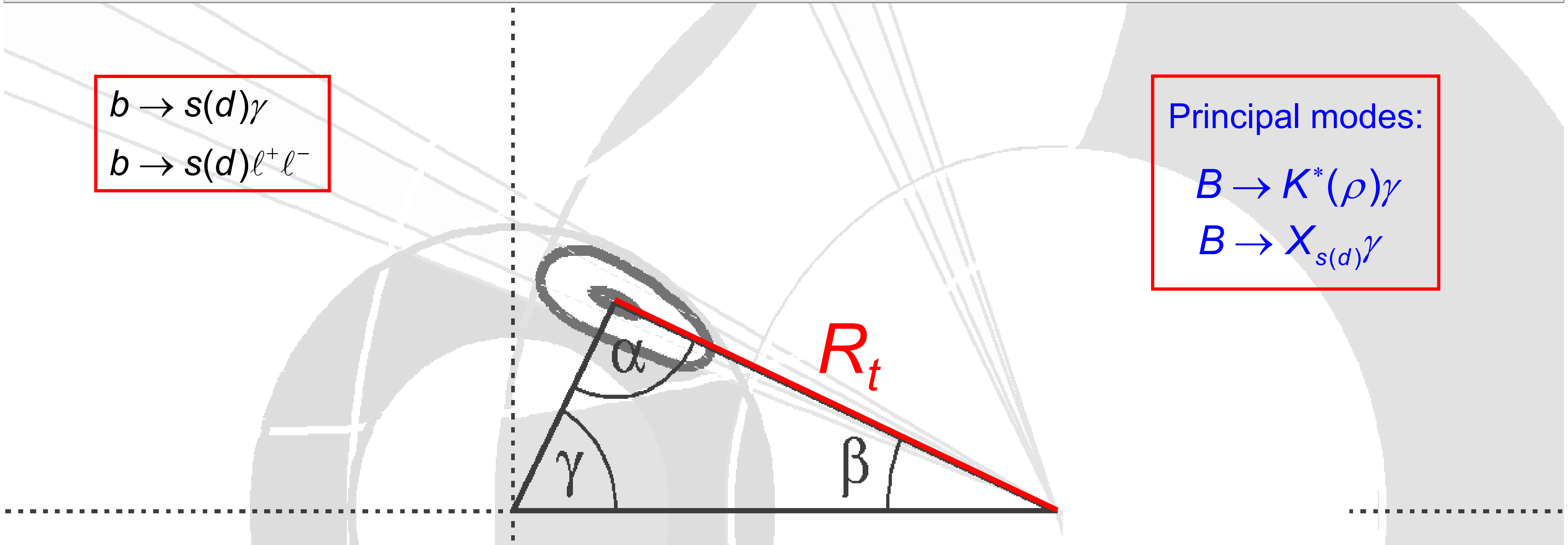


… none.

Radiative Penguin Decays

$b \to s(d)\gamma$

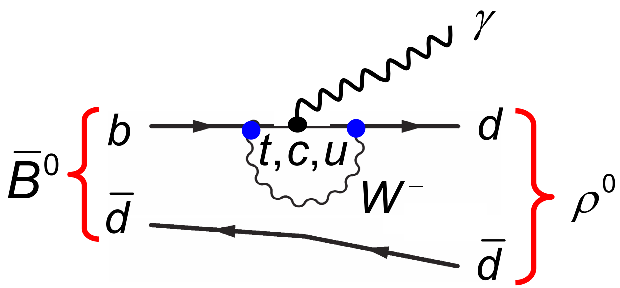
$b \to s(d)\ell^+\ell^-$



Principal modes:

$B \to K^*(\rho)\gamma$

$B \to X_{s(d)}\gamma$



Penguin : dominant

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

$\propto \lambda^3$

Radiative Penguin Decays

- Radiative penguin decays $B \to \rho\gamma$ ($\propto |V_{td}|^2$) and $B \to K^*\gamma$ ($\propto |V_{ts}|^2$) sensitive to New Physics

- Ratio of BRs predicted more cleanly than the individual rates: SU(3) breaking correction

$$\frac{\mathrm{BR}(B^0 \to \rho^0\gamma)}{\mathrm{BR}(B^0 \to K^{*0}\gamma)} \propto \frac{1}{2}\left|\frac{V_{td}}{V_{ts}}\right|^2 \xi^{-2}(1+\Delta)$$

$$\underbrace{\xi = 1.2 \pm 0.1}_{\text{SU(3) breaking}}\ ,\quad \underbrace{\Delta < 0.04}_{\text{NP contrib.}}$$

Ali, Parkhomenko, EPJ C23 (2002) 89
Bosch, Buchalla, NP B621 (2002) 459
(and later papers); errors from CKM 05

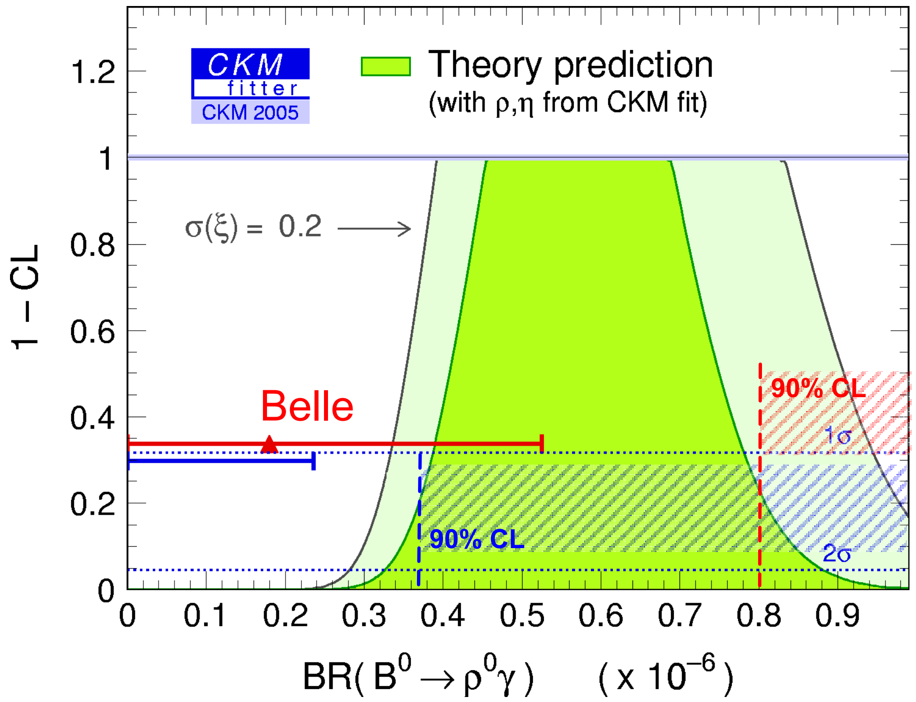
- So far only upper limit for $B \to \rho\gamma$

$$\mathrm{BR}\left(B^0 \to \rho^0\gamma\right) = \left(0.06\,^{+0.19}_{-0.14}\right)\times 10^{-6}$$

$$\mathrm{BR}\left(B^0 \to K^{*0}\gamma\right) = \left(40.1 \pm 2.0\right)\times 10^{-6}$$

BABAR, PRL 94, 011801 (2005)
Belle, hep-ex/0408137 (prelim.)

$B \to \rho\gamma$ observation should be imminent!



Charged modes larger limit: $\mathrm{BR}(B^+ \to \rho^+\gamma) = (1.0 \pm 0.4)\times 10^{-6}$, but less theoretically clean

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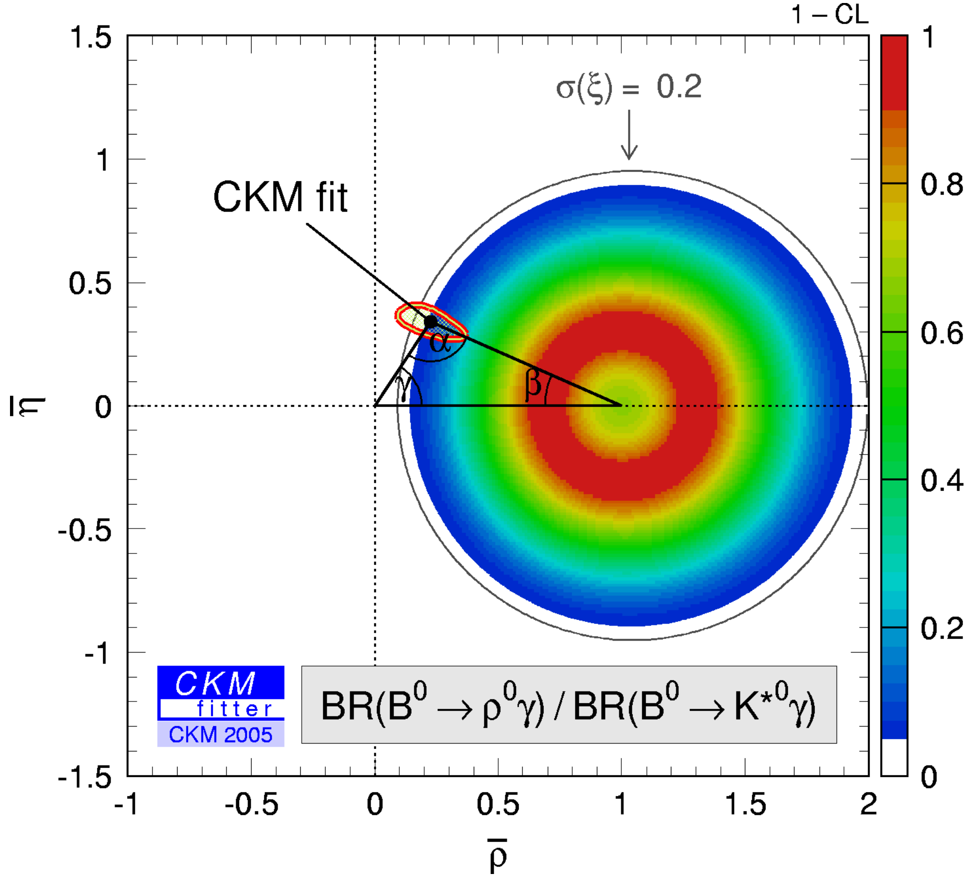

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New Physics in Penguins ?

Penguins being inspected carefully for new physics (J.B.)

appendix

- peguin outlook

The Experimental Program for sin $2\beta_{eff}$

Mode	*CP*	Tot. error Belle $\mathcal{L} \sim 253\ fb^{-1}$	Tot. error BABAR $\mathcal{L} \sim 195\text{-}212\ fb^{-1}$	$\langle\Delta(SM)\rangle$ [in σ]	Error estimate at 2 ab^{-1}	Syste-matics	Max. central value for 5σ deviation at 2 ab^{-1}	Quality [naïve theoretical cleanliness]
ϕK^0	–1	0.34	0.26	– 1.9	0.10	small	0.22	☻ ☻ ☻
$\eta' K^0$	–1	0.18	0.14	– 2.6	< 0.05	small	0.45	☻ ☻ (☻)
$f_0(980)K^0$	+1	0.42	0.29	– 1.3	< 0.12	Q2B	0.12	☻ ☻
$K_S K_S K^0$	±1	0.71	0.36	– 1.4	< 0.16	vertex	– 0.08	☻ ☻ ☻
$K^+K^-K^0$	~+1	0.25	0.25	– 1.1	< 0.08	*CP*	0.31	☻ (☻)
$\pi^0 K_S$	–1	0.60	0.32	– 1.4	0.13	vertex	0.07	☻
ωK^0	–1	0.66	0.36	– 0.6	< 0.15	small	– 0.03	(☻)
$\rho^0 K^0$	–1	-	-	?	?	Q2B	?	(☻)
ηK_S	+1	-	-	?	?	vertex	?	-
Average	-	0.39 ± 0.11	0.45 ± 0.09	– 3.7	< 0.034	ok	0.53	☻ ☻