Heavy Quark Physics and CP Violation (III)

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$$\begin{bmatrix} u \\ \ \end{bmatrix} \begin{bmatrix} c \\ s \end{bmatrix} \begin{bmatrix} \ \\ b \end{bmatrix}$$

TM

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Outline

- **Lecture 3**
  - **Comments on blind analysis**
  - **The Cabibbo-Kobayashi-Maskawa (CKM) matrix**
  - **Phenomenology of meson oscillations**
  - **Measuring sin2β from time-dependent CP violation in *B* decays**
  - **Conclusions**

Blind Analysis

- Basic principle: it's OK to be stupid.
  It's not OK to be biased!

- Translation: if an analysis isn't perfectly optimized, it's OK. But it's not OK to perform an analysis that will give a non-reproducible result when more data are obtained.

- All studies are performed in such a way as to *hide* information on the value of the final answer.

- Avoids any subconscious experimenter bias
  - e.g. agreement with the Standard Model!

- Not needed for certain kinds of "easy" analyses.

An unblinding party in BaBar

You should worry if you hear these

- “My answer agrees with the previous result, so it must be right.”
- “Something must be wrong with the data...the answer isn’t coming out right.”
- “We don’t need to perform a blind analysis, because we already know the answer.”
- “If this is right, we could win the...”
- “Correlations?”
- “He needs to graduate now.”
- “The conference is in two weeks. This will have to be good enough.”
- “Let’s see if we can enhance the significance of our signal by changing the selection requirements.”
- “If it turns out to be true, we can say we saw it first.”

Good practices in data analysis

- **Verify data quality using processes separate from those that are critical for discoveries.**
  - **Very bad practice: reject data samples as bad because they don't confirm hypothesis**
- **Don't tune analysis cuts on the data. This can result in sensitivity to statistical fluctuations that will not be reproducible with future data samples.**

The CKM matrix and its mysterious pattern

(Wolfenstein parametrization)

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

origin in SM:
Higgs sector

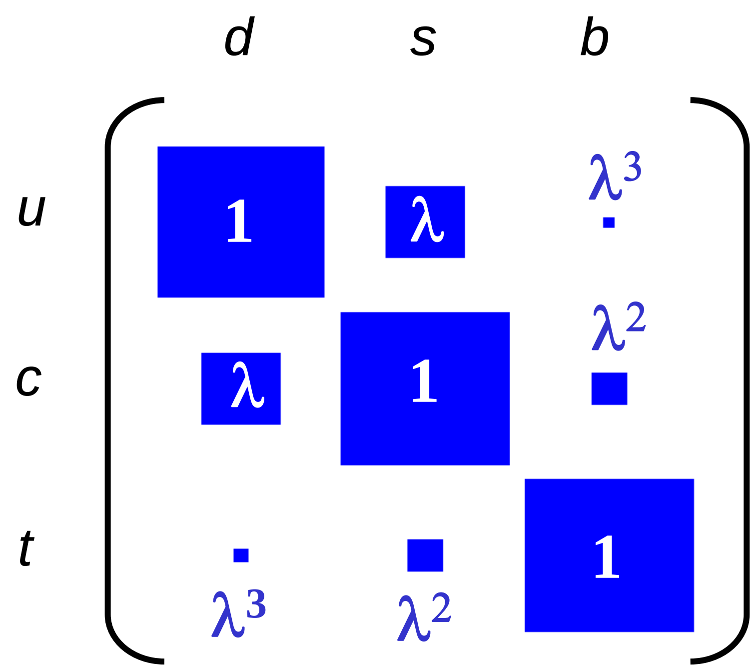
$$\simeq \begin{pmatrix} 0.97 & 0.23 & 0.004 \\ -0.23 & 0.97 & 0.04 \\ 0.004 & -0.04 & 1 \end{pmatrix}$$

(magnitudes only)

- The SM offers no explanation for this numerical pattern.
- But SM framework is <u>highly predictive</u>:
  - ❑ Unitarity triangle: (Col 1)(Col 3)* =0 etc.
  - ❑ Only 4 independent parameters: A, λ, ρ, η
  - ❑ One independent *CP*-violating phase parameter

A simplified picture of the CKM matrix

Magnitudes of CKM elements



Largest phases in the Wolfenstein parametrization

$$\begin{pmatrix} 1 & 1 & e^{-i\gamma} \\ 1 & 1 & 1 \\ e^{-i\beta} & 1 & 1 \end{pmatrix}$$

Note: all terms in the inner product between columns 1 and 3 are of order λ^3. This produces a unitarity triangle of roughly equal sides.

CP asymmetries in the *B* decays can be large

Unitarity

[Column i][Column j]*=0

[Row i][Row j]*=0

$$V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0$$

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

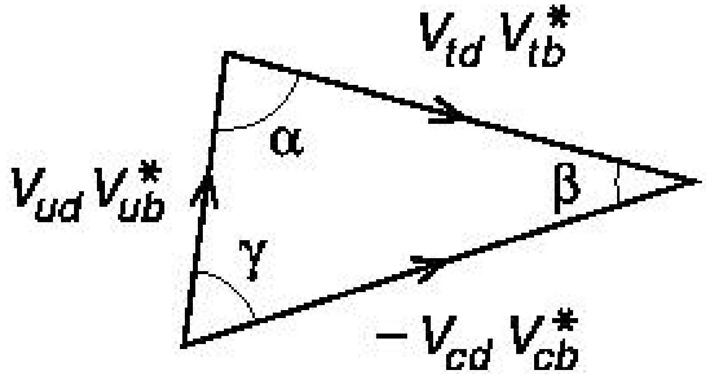
$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$

$$O(\lambda) + O(\lambda) + O(\lambda^5) = 0$$

$$O(\lambda^3) + O(\lambda^3) + O(\lambda^3) = 0$$

$$O(\lambda^4) + O(\lambda^2) + O(\lambda^2) = 0$$

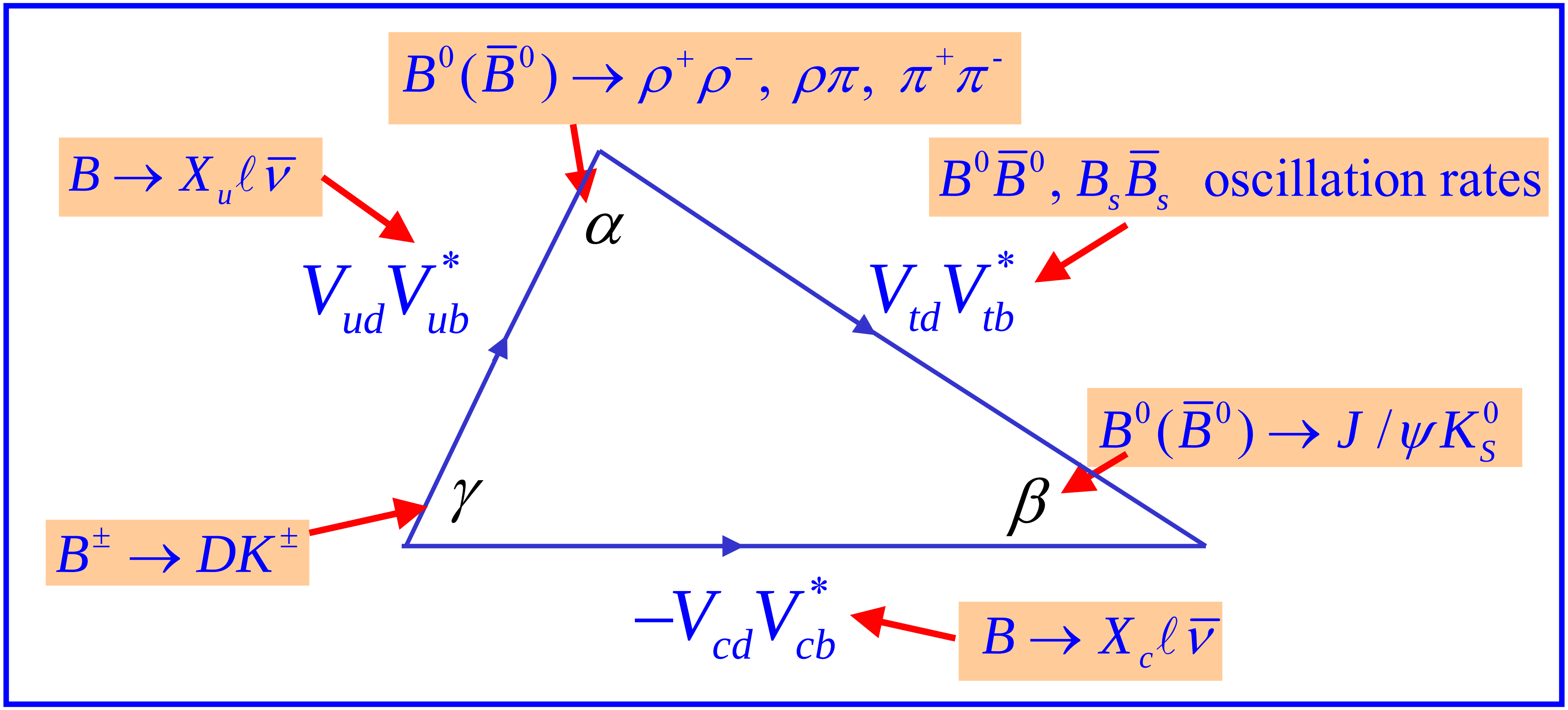
(Col 1)(Col 3)* =0



Overall orientation of the triangle has no physical significance.

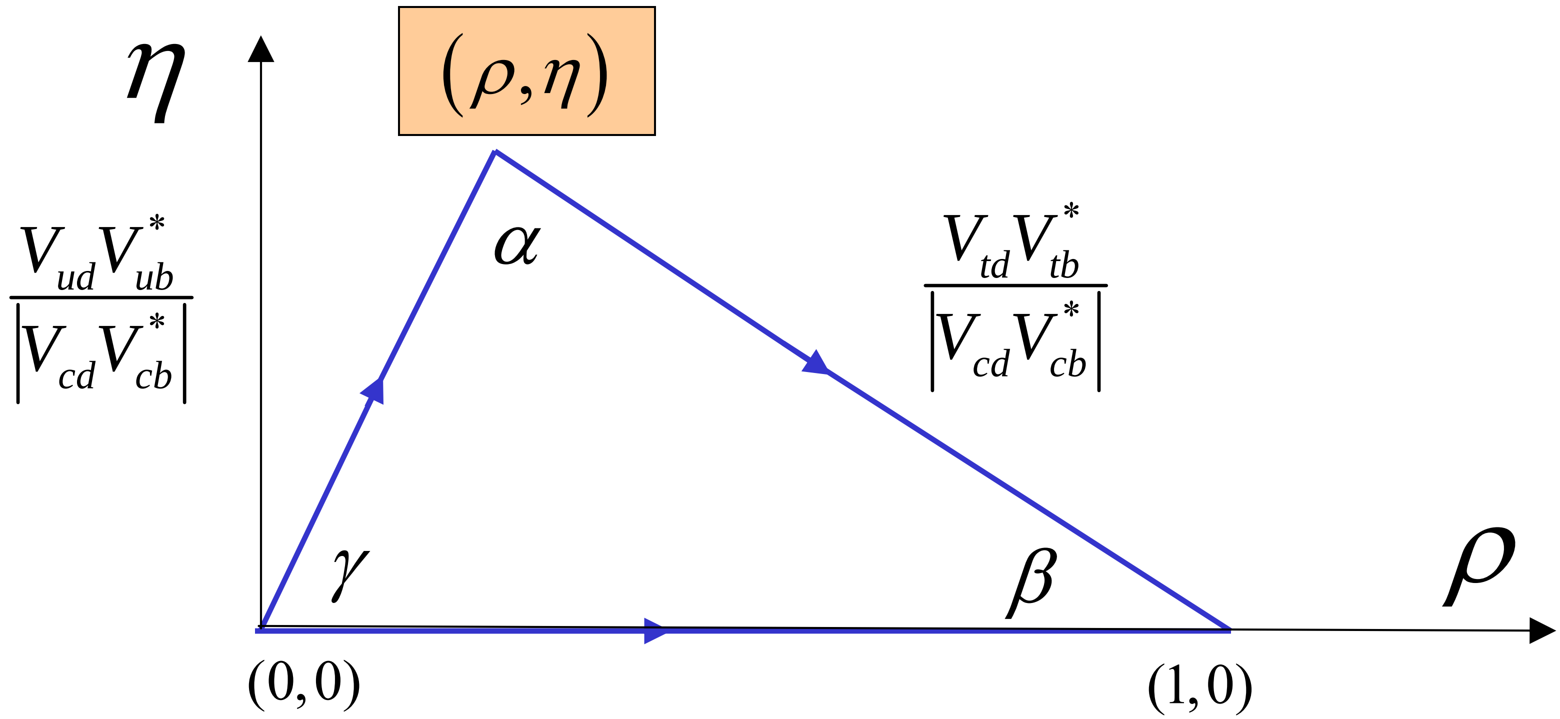
Fat unitarity triangle
➔large angles
➔large CP asymmetry
But only certain decays have interfering amps!

SM prediction: ALL measurements of *W*-mediated quark processes must be consistent with the CKM framework.



- **Angles** of triangle: measure from CP **asymmetries** in *B* decay
- **Sides** of triangle: measure **rates** for b→ulν, $B^0\overline{B}^0$ mixing
- **Other constraints** in ρ,η plane from CP violation in *K* decay

Form of the CKM Constraints in the ρ, η plane



$$V_{ub} = A\lambda^3(\rho - i\eta)$$

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

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

$$\left|\frac{V_{cb}}{V_{us}}\right|^2 = A$$

$$\left|V_{ub}^*/V_{cd}V_{cb}\right| = \sqrt{\rho^2+\eta^2}$$

$$\left|V_{td}\right|^2 = A^2\lambda^6\left[(1-\rho)^2+\eta^2\right]$$

Angles of the unitarity triangle

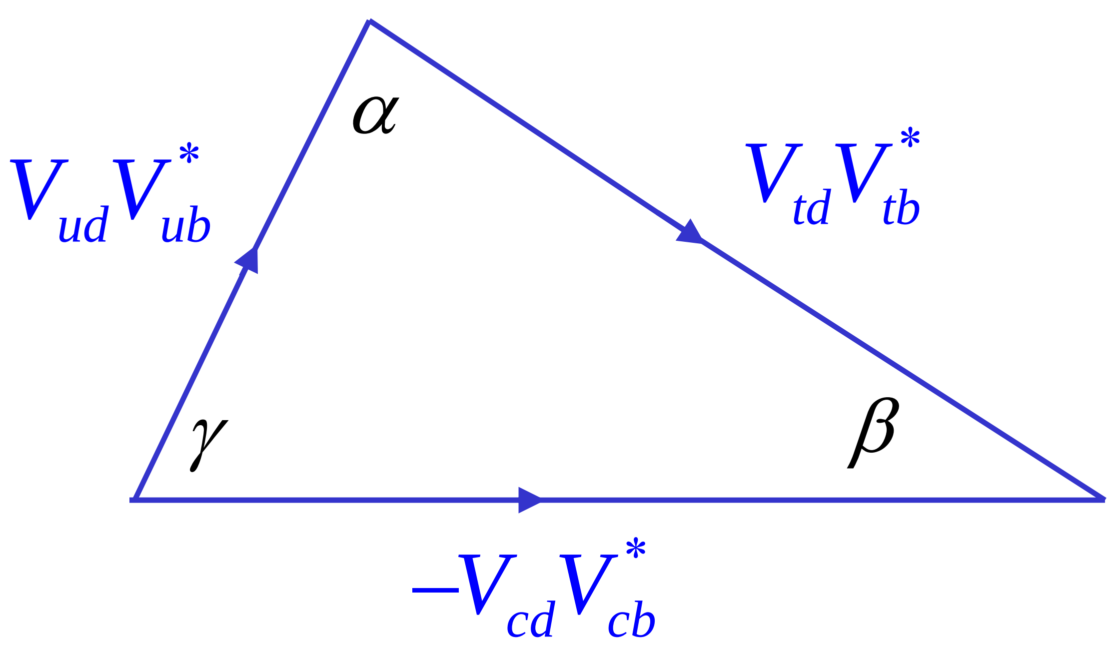
Consider two complex numbers z_1 and z_2.

$$z_1 = |z_1| e^{i\theta_1} \qquad z_2 = |z_2| e^{i\theta_2} \quad \Rightarrow \quad \frac{z_2/|z_2|}{z_1/|z_1|} = e^{i(\theta_2-\theta_1)} \qquad \arg\left(\frac{z_2}{z_1}\right) = \theta_2 - \theta_1$$

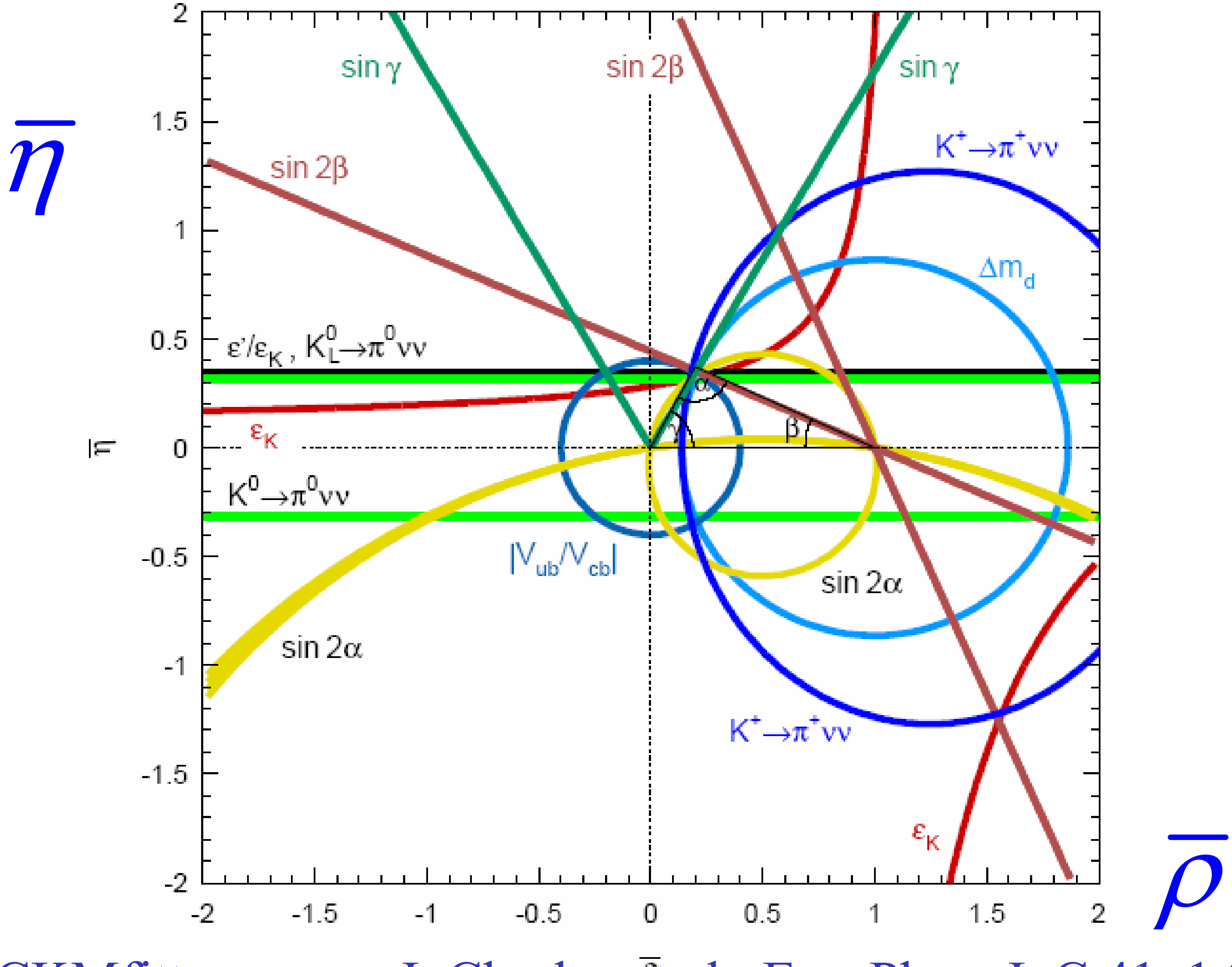
$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$$\beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

$$\gamma = \arg\left(\frac{-V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

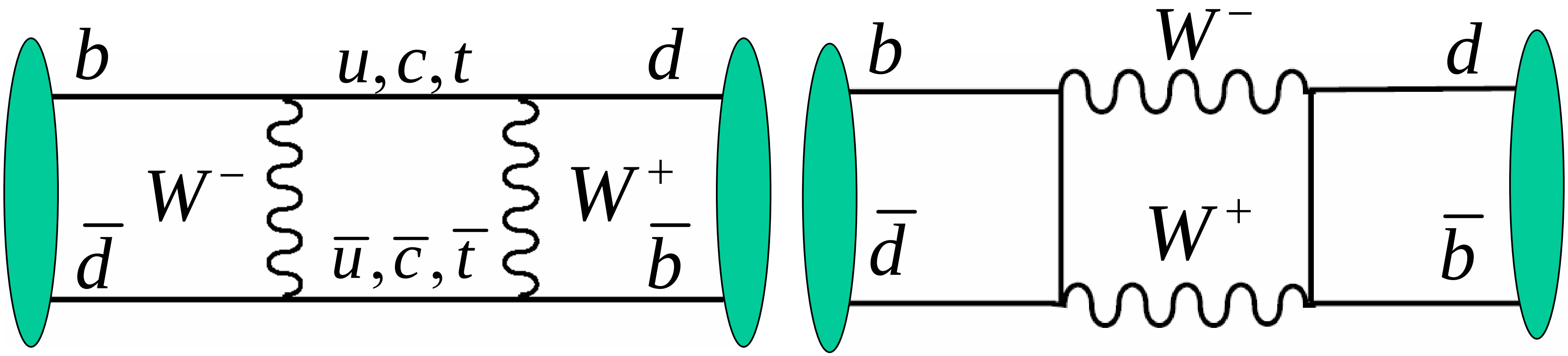


Form of the CKM Constraints in the ρ, η plane



CKMfitter group: J. Charles et al., Eur. Phys. J. C 41, 1 2005)

Weak transitions underlying $B^0\,\overline{B}^0$ oscillations



$$\left|B^0(t)\right\rangle = e^{-\frac{\Gamma}{2}t}e^{-iMt}\left(\cos\frac{\Delta M\cdot t}{2}\left|B^0\right\rangle + i\alpha\cdot\sin\frac{\Delta M\cdot t}{2}\left|\overline{B}^0\right\rangle\right)$$

$$\left|\overline{B}^0(t)\right\rangle = e^{-\frac{\Gamma}{2}t}e^{-iMt}\left(\frac{i}{\alpha}\sin\frac{\Delta M\cdot t}{2}\left|B^0\right\rangle + \cos\frac{\Delta M\cdot t}{2}\left|\overline{B}^0\right\rangle\right)$$

B^0 and $\overline{B}^0$ spontaneously evolve into each other. More precisely, a particle that is initially a B^0 evolves into a superposition of B^0 and $\overline{B}^0$.

Common formalism for $P^0\bar{P}^0$ oscillations

$$H = H_0 + H_w$$

Weak interactions (perturbation) induce
$$\begin{cases} P^0 \leftrightarrow \bar{P}^0 \\ P^0 \to f \\ \bar{P}^0 \to \bar{f} \end{cases}$$

Strong and EM interactions (create bound states)

$$\left|\Psi(t)\right\rangle = a(t)\left|P^0\right\rangle + b(t)\left|\bar{P}^0\right\rangle + \sum_f c_f(t)\left|f\right\rangle$$

We can **recast** the formalism in terms of a 2-dimensional vector space in which we only include P^0 and $\bar{P}^0$.

$$\left|P^0\right\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \qquad \left|\bar{P}^0\right\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

← important!

see my Les Houches lectures

$$\boldsymbol{H}\begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix}\begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = i\frac{\partial}{\partial t}\begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

$$\boldsymbol{H}^\dagger \neq \boldsymbol{H}$$

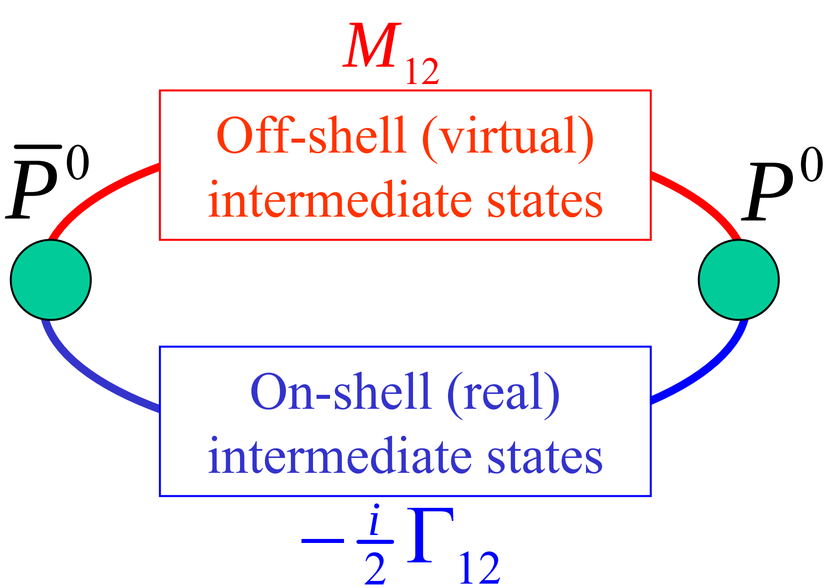
The two classes of transitions in mixing

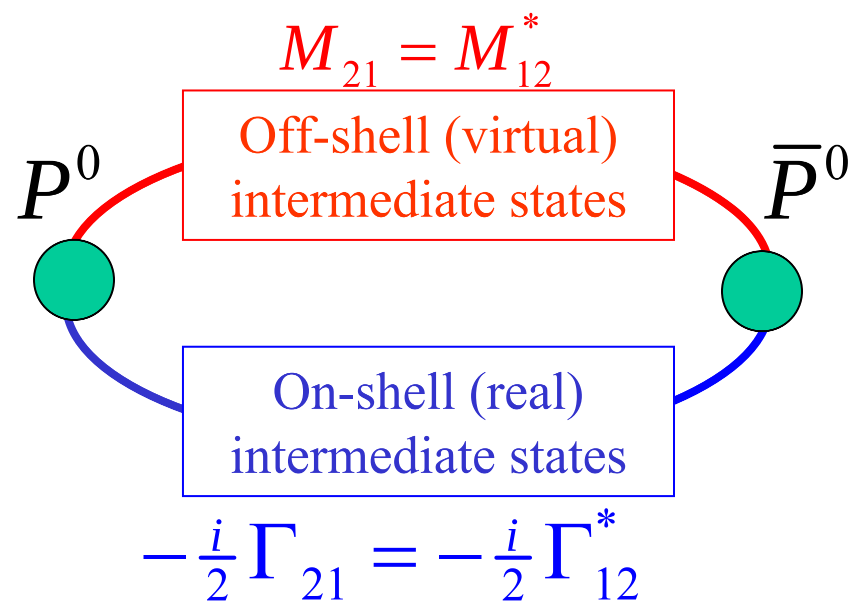
Get specific form of $\boldsymbol{H}$ in terms of matrix elements of H_w.

$$H = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix} = \underbrace{\begin{pmatrix} M & M_{12} \\ M^{*}_{12} & M \end{pmatrix}}_{\text{mass matrix}} - \frac{i}{2} \underbrace{\begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma^{*}_{12} & \Gamma \end{pmatrix}}_{\text{decay matrix}}$$

$H_{21} \neq H^{*}_{12}$

crucial factor!





Implications of a small Γ_{12} in $B^0\overline{B}^0$ oscillations

$$\alpha = \frac{q}{p} = \frac{H_{21}}{H_{12}} = \left(\frac{M_{12}^* \cancel{- \frac{i}{2}\Gamma_{12}^*}}{M_{12} \cancel{- \frac{i}{2}\Gamma_{12}}} \right)^{1/2} = \left(\frac{M_{12}^*}{M_{12}} \right)^{1/2} \quad \Rightarrow |\alpha| = 1$$

$$\Gamma_1 = \Gamma_2 = \Gamma$$

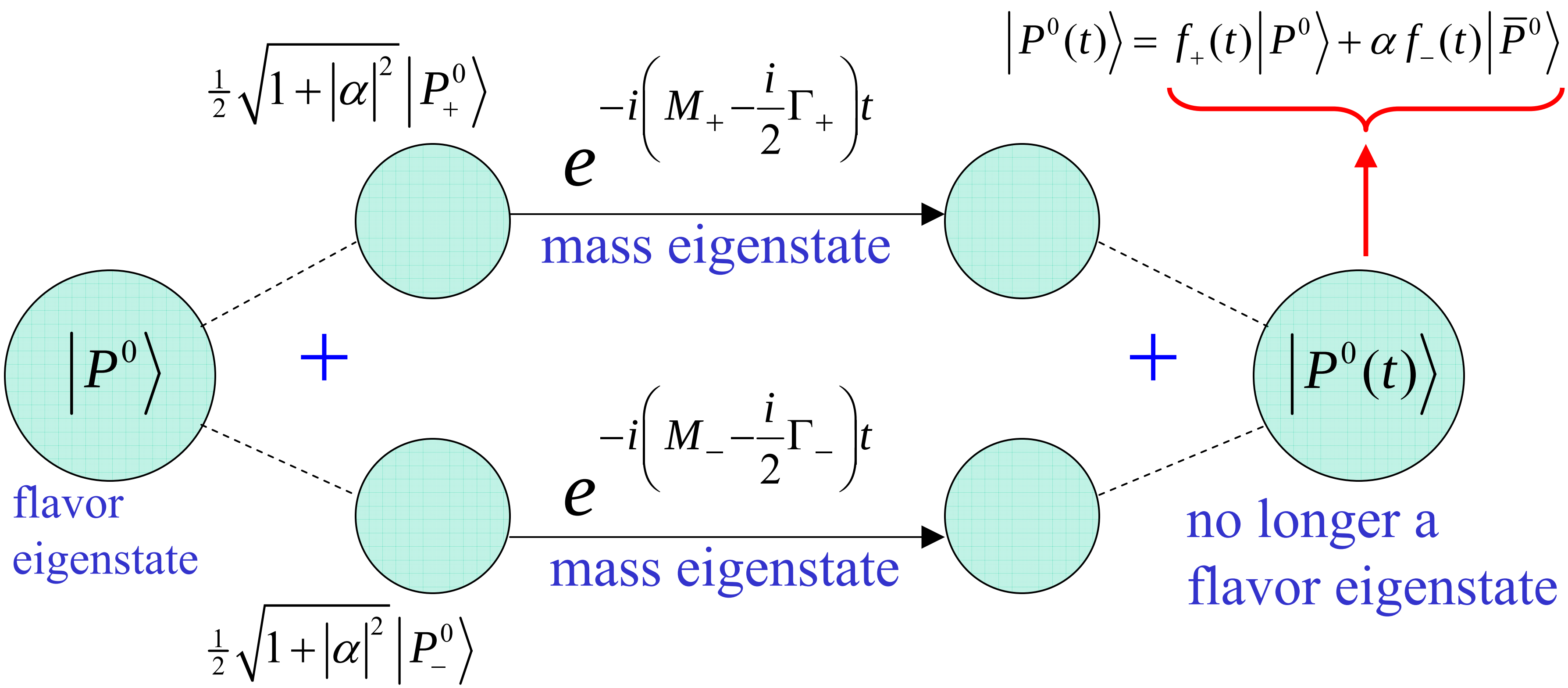
No CP violation in mixing since don't have second amplitude with non-zero CP-conserving relative phase.

$$\text{Prob}\left(P^0 \text{ at } t \,|\, P^0 \text{ at } t=0\right) = \frac{1}{2} e^{-\Gamma t}\left[1 + \cos(\Delta M t)\right]$$

$$\left.\begin{aligned} &\text{Prob}\left(\overline{P}^0 \text{ at } t \,|\, P^0 \text{ at } t=0\right) = \frac{1}{2} e^{-\Gamma t}\left[1 - \cos(\Delta M t)\right] \\ &\text{Prob}\left(P^0 \text{ at } t \,|\, \overline{P}^0 \text{ at } t=0\right) = \frac{1}{2} e^{-\Gamma t}\left[1 - \cos(\Delta M t)\right] \end{aligned}\right\} \text{used to have } |\alpha|^2,\ 1/|\alpha|^2$$

$$\text{Prob}\left(\overline{P}^0 \text{ at } t \,|\, \overline{P}^0 \text{ at } t=0\right) = \frac{1}{2} e^{-\Gamma t}\left[1 + \cos(\Delta M t)\right]$$

Time evolution of states that are initially flavor eigenstates (general case)



$$\left|P^0(t)\right\rangle = f_+(t)\left|P^0\right\rangle + \alpha f_-(t)\left|\bar{P}^0\right\rangle$$

$$\left|\bar{P}^0(t)\right\rangle = f_+(t)\left|\bar{P}^0\right\rangle + \frac{1}{\alpha} f_-(t)\left|P^0\right\rangle$$

$$f_+(t) = \frac{1}{2}\left(e^{-iM_+t}e^{-\Gamma_+t/2} + e^{-iM_-t}e^{-\Gamma_-t/2}\right)$$

$$f_-(t) = \frac{1}{2}\left(e^{-iM_+t}e^{-\Gamma_+t/2} - e^{-iM_-t}e^{-\Gamma_-t/2}\right)$$

Probabilities vs. time: master equations

$$\text{Prob}\left(P^0 \text{ at } t \mid P^0 \text{ at } t=0\right) = \frac{1}{4}\left[e^{-\Gamma_+ t} + e^{-\Gamma_- t} + 2e^{-\Gamma t}\cos(\Delta M t)\right]$$

$$\text{Prob}\left(\overline{P}^0 \text{ at } t \mid P^0 \text{ at } t=0\right) = |\alpha|^2 \frac{1}{4}\left[e^{-\Gamma_+ t} + e^{-\Gamma_- t} - 2e^{-\Gamma t}\cos(\Delta M t)\right]$$

$$\text{Prob}\left(P^0 \text{ at } t \mid \overline{P}^0 \text{ at } t=0\right) = \left|\frac{1}{\alpha}\right|^2 \frac{1}{4}\left[e^{-\Gamma_+ t} + e^{-\Gamma_- t} - 2e^{-\Gamma t}\cos(\Delta M t)\right]$$

$$\text{Prob}\left(\overline{P}^0 \text{ at } t \mid \overline{P}^0 \text{ at } t=0\right) = \frac{1}{4}\left[e^{-\Gamma_+ t} + e^{-\Gamma_- t} + 2e^{-\Gamma t}\cos(\Delta M t)\right]$$

Notes:

$$\Delta M \equiv M_- - M_+ \qquad \Gamma = \tfrac{1}{2}(\Gamma_+ + \Gamma_-)$$

To calculate, need 5 numbers: $M_+, M_-, \Gamma_+, \Gamma_-, |\alpha|$

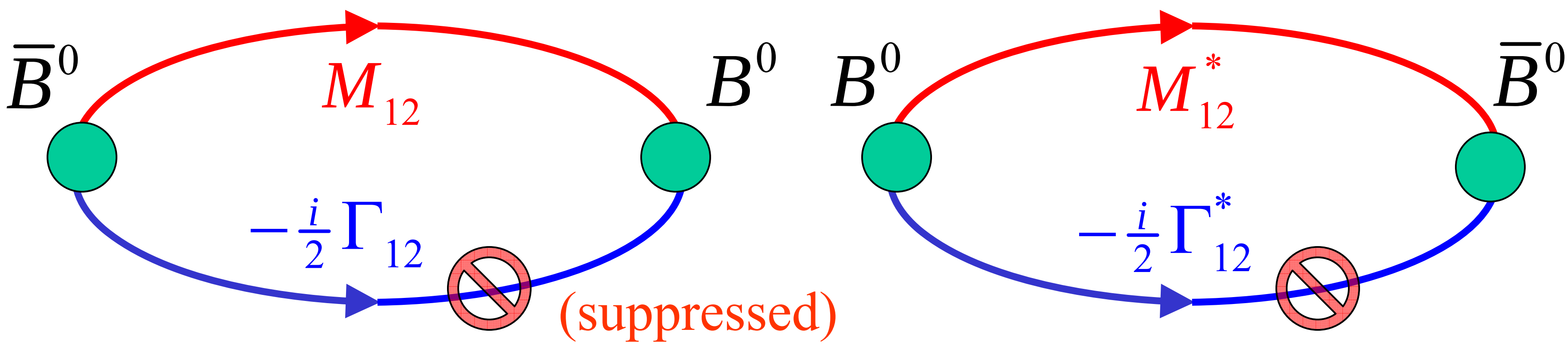
$$|\alpha| \neq 1 \quad \Rightarrow \quad \text{Prob}\left(\overline{P}^0 \text{ at } t \mid P^0 \text{ at } t=0\right) \neq \text{Prob}\left(P^0 \text{ at } t \mid \overline{P}^0 \text{ at } t=0\right)$$

$$\text{CPT} \quad \Rightarrow \quad \text{Prob}\left(\overline{P}^0 \text{ at } t \mid \overline{P}^0 \text{ at } t=0\right) = \text{Prob}\left(P^0 \text{ at } t \mid P^0 \text{ at } t=0\right)$$

Phenomenology of $B^0\overline{B}^0$ Oscillations

Oscillations in the $B\overline{B}$ and $K\overline{K}$ systems have very different parameters! This is due to different CKM factors and different intermediate states in the mixing diagrams.

$\mathrm{Amp}(\overline{B}^0 \to B^0)$ $\mathrm{Amp}(B^0 \to \overline{B}^0)$



M_{12}: Dominated by $t\bar{t}$ intermediate states; can be calculated reasonably well using input from lattice QCD

Γ_{12}: Small! Few on-shell intermediate states that both B and $\overline{B}$ can reach. (These are the states both can actually decay into.)

Measuring the $B^0\bar{B}^0$ oscillation frequency

$$\left(\frac{dN}{dt}\right)_{\text{nomix}} = \frac{1}{4\tau_B} \cdot e^{-\Gamma t} \cdot \left[1+\cos(\Delta m_d \cdot t)\right]$$

$$\left(\frac{dN}{dt}\right)_{\text{mix}} = \frac{1}{4\tau_B} \cdot e^{-\Gamma t} \cdot \left[1-\cos(\Delta m_d \cdot t)\right]$$

$$\Rightarrow \mathrm{A}_{\text{mix}} = \frac{\left(\frac{dN}{dt}\right)_{\text{nomix}} - \left(\frac{dN}{dt}\right)_{\text{mix}}}{\left(\frac{dN}{dt}\right)_{\text{nomix}} + \left(\frac{dN}{dt}\right)_{\text{mix}}} = \cos(\Delta m \cdot t)$$

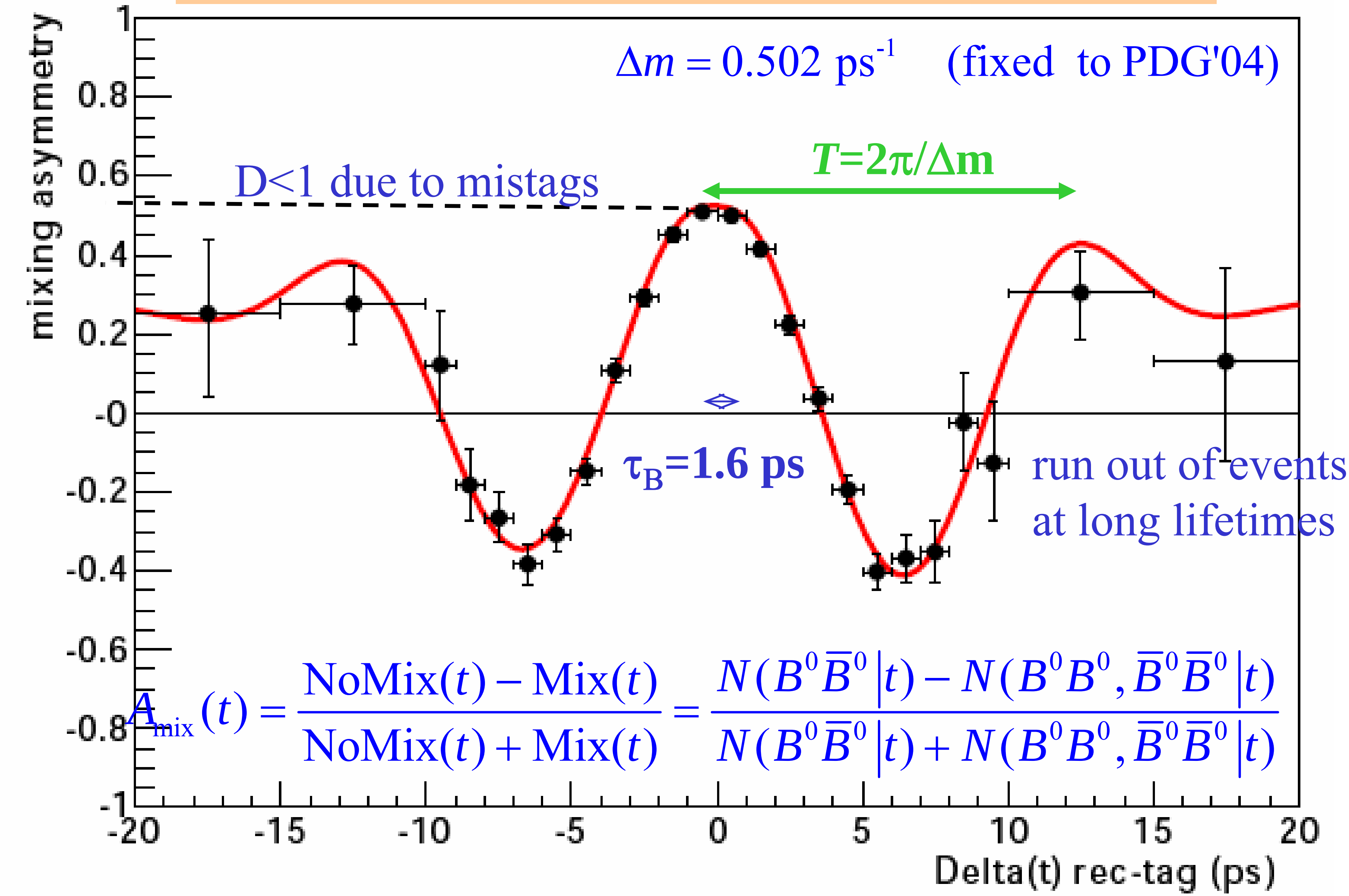
very simple!

amplitude=1

How do you actually do this measurement? Basic question: did the B oscillate or not? Need to know this as a function of time!

1. When it was produced, was the meson a B^0 or $\bar{B}^0$?
2. When it decayed, was the meson a B^0 or a $\bar{B}^0$?
3. What is the time difference between production and decay?

Mixing asymmetry vs. Δt



$$A_{mix}(t) = \frac{\text{NoMix}(t) - \text{Mix}(t)}{\text{NoMix}(t) + \text{Mix}(t)} = \frac{N(B^0\overline{B}^0|t) - N(B^0B^0,\overline{B}^0\overline{B}^0|t)}{N(B^0\overline{B}^0|t) + N(B^0B^0,\overline{B}^0\overline{B}^0|t)}$$

Does a mass really have units of s^{-1} ?

$$A_{mix} = \cos(\Delta m \cdot t)$$

1. Put in c^2

$$(\Delta m)c^2 \cdot t \sim ET$$

2. Divide by $\hbar \sim ET$ since phase must be dimensionless

$$\frac{(\Delta m)c^2 \cdot t}{\hbar} \sim \text{dimensionless!}$$

$$\frac{(\Delta m)c^2}{\hbar} = 0.5 \text{ ps}^{-1} \qquad B^0 \overline{B}^0$$

$$(\Delta m)c^2 = (0.5 \cdot 10^{12} \text{ s}^{-1}) \cdot (66 \cdot 10^6 \text{ eV} \cdot 10^{-23} \text{ s}) \approx 3 \cdot 10^{-4} \text{ eV}$$

Explains why we don’t worry about B_H and B_L in most analyses!

Ingredients of the CP Asymmetry Measurement

1. Determine initial state: "tag" using other *B*

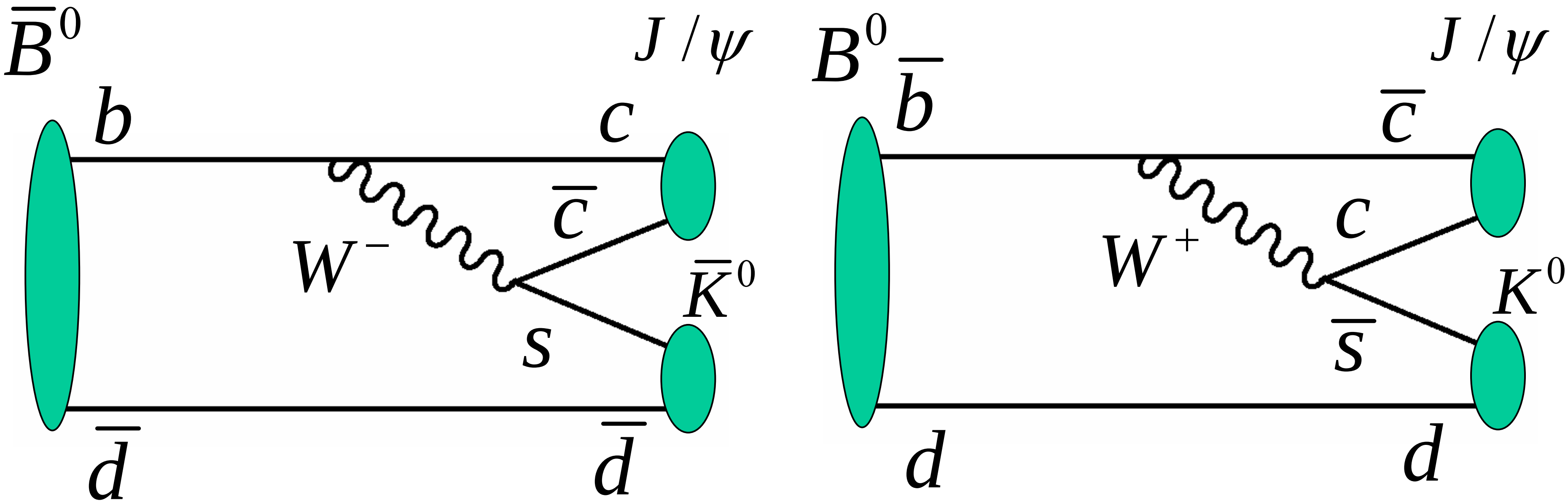
$$A_{CP}(\Delta t) \equiv \frac{\Gamma\left(\overline{B}^0(\Delta t) \to f_{CP}\right) - \Gamma\left(B^0(\Delta t) \to f_{CP}\right)}{\Gamma\left(\overline{B}^0(\Delta t) \to f_{CP}\right) + \Gamma\left(B^0(\Delta t) \to f_{CP}\right)}$$

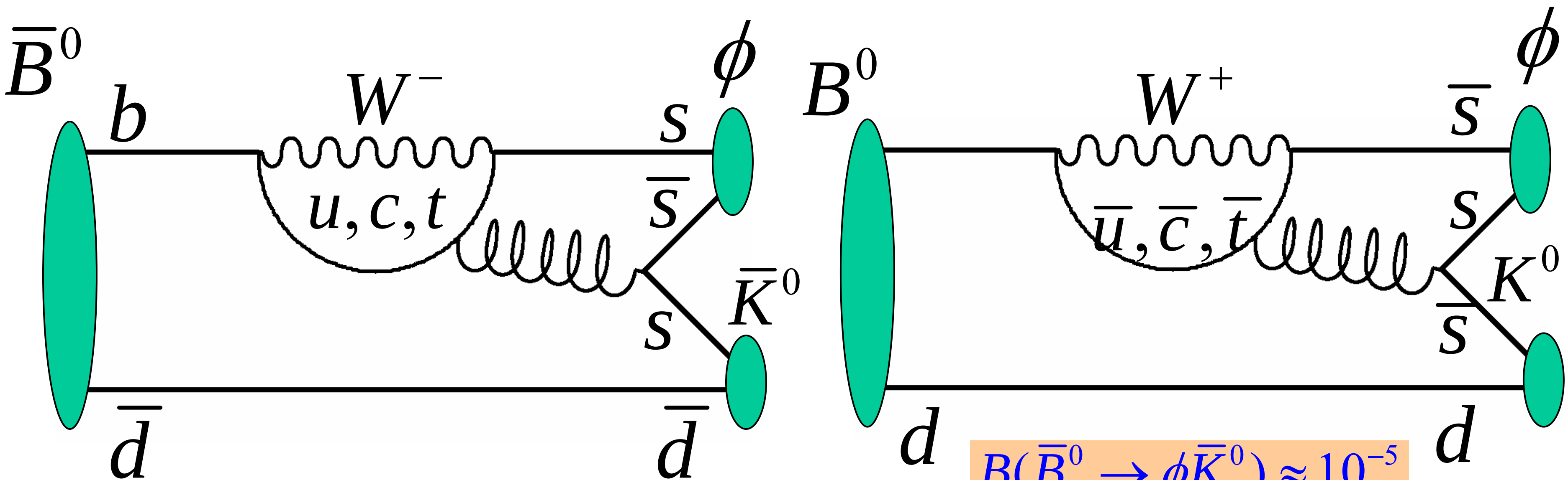
2. Reconstruct the final state system.

3. Measure Δt dependence

Different final states f_{CP} provide access to different CKM elements and hence different CP-violating phases.
Reason for time dependence: one of the amplitudes is due to mixing.

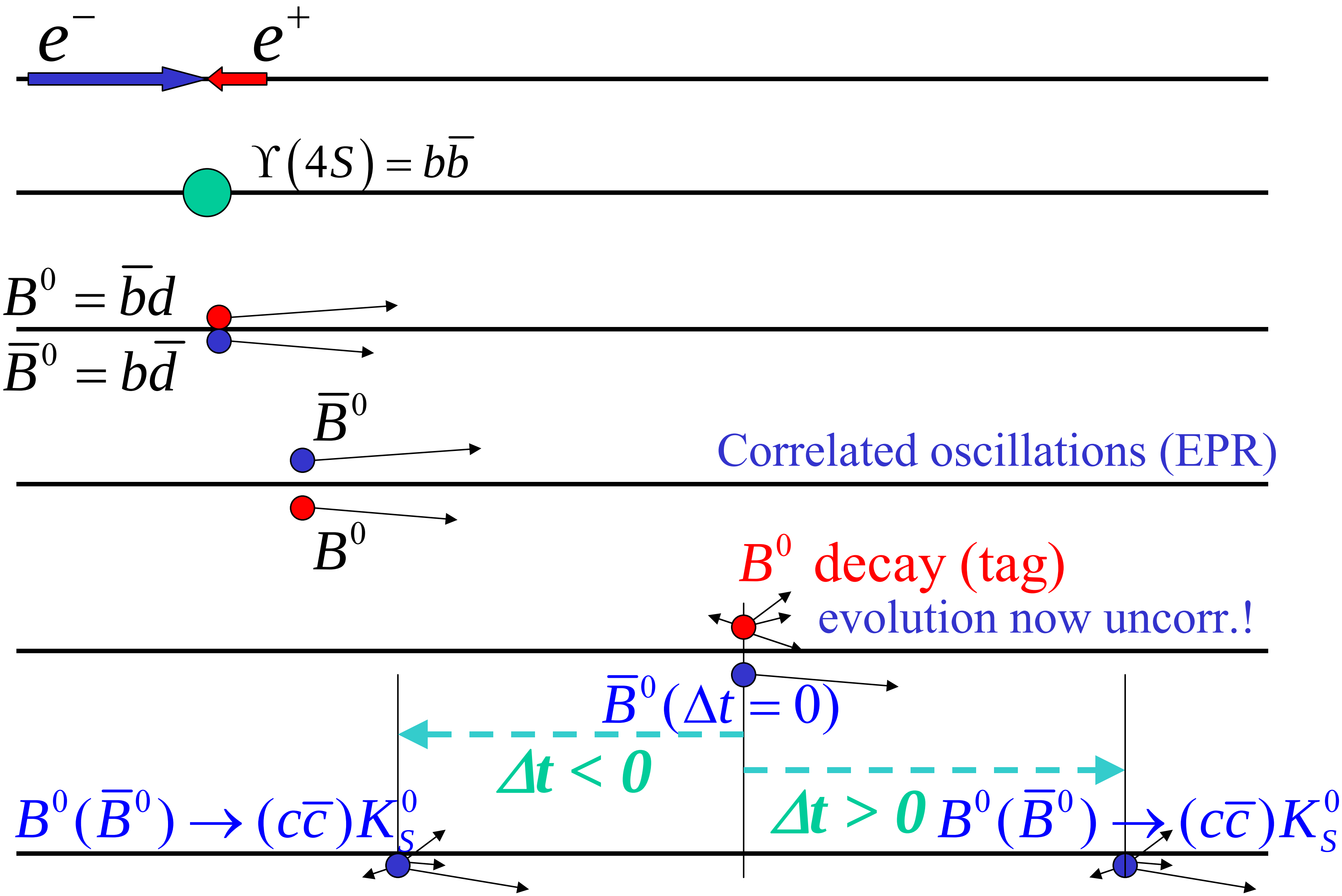
Examples of decays to CP eigenstates



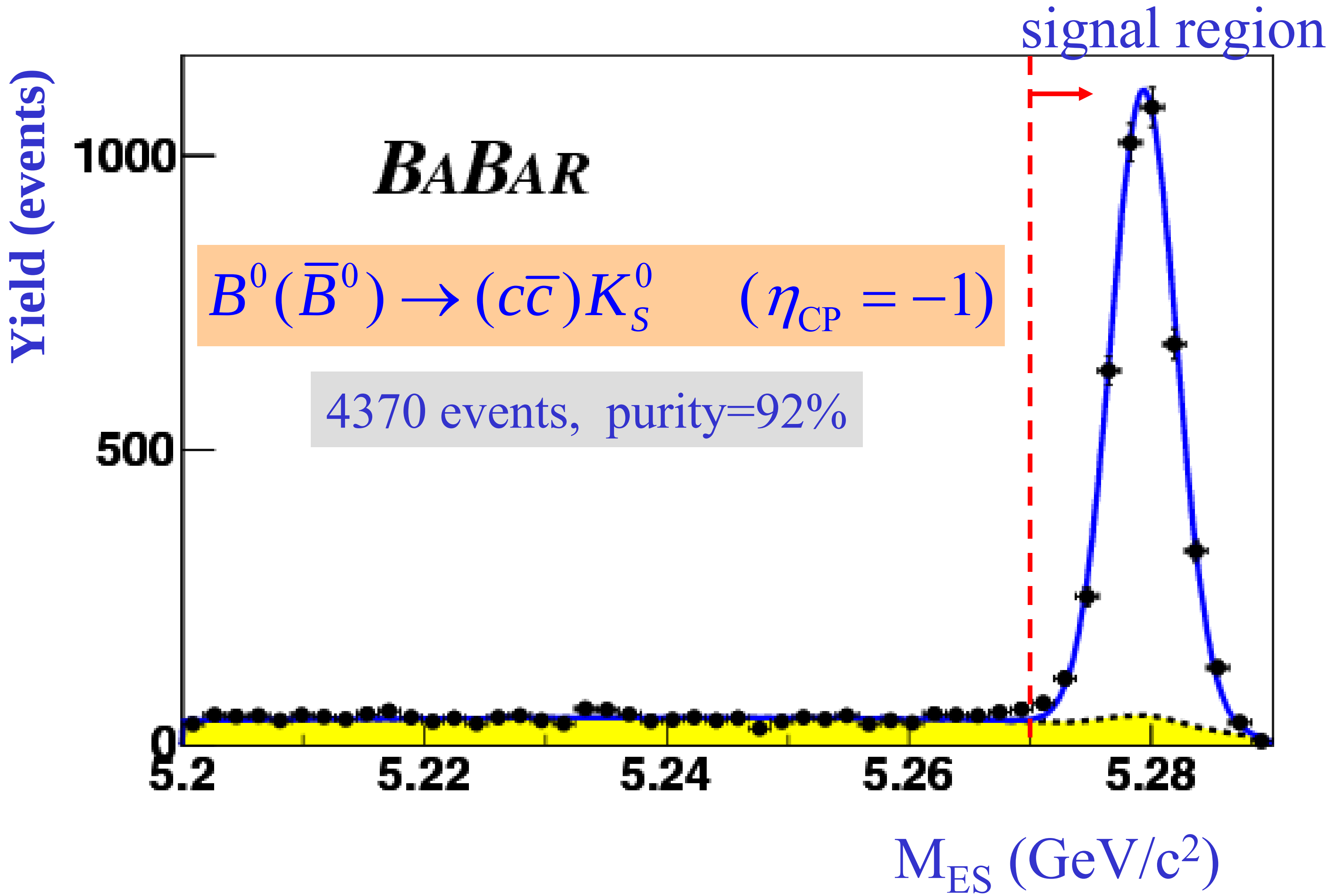


$B(\overline{B}^0 \to \phi\overline{K}^0) \approx 10^{-5}$

Time-dependent CP asymmetry measurement



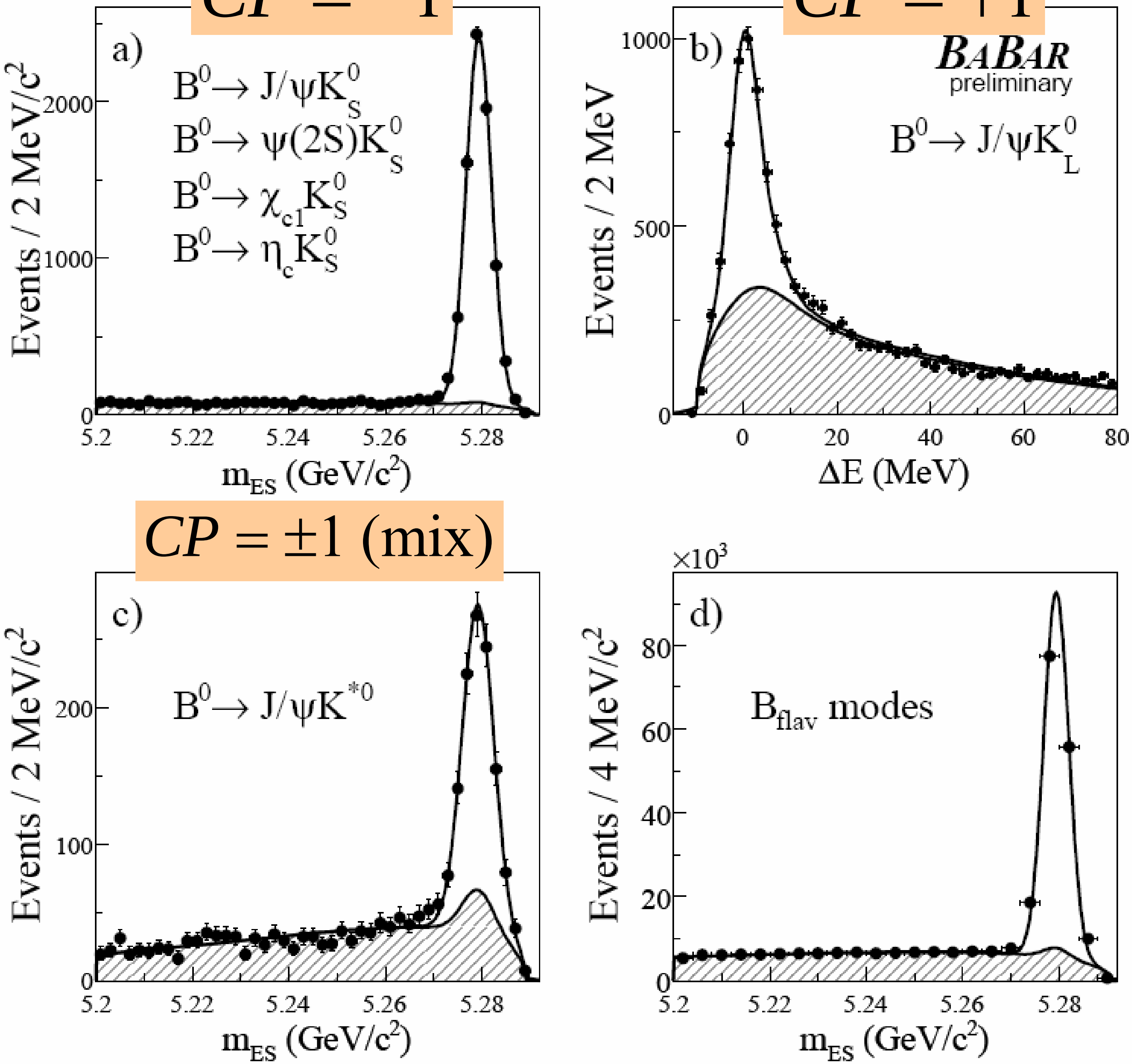
Data: tagged signal events for $B \rightarrow J/\psi\ K_s$ and other $\eta_{CP}= -1$ $\sin 2\beta$ modes



$CP = -1$

$CP = +1$

$CP = \pm 1$ (mix)



$465 \times 10^6\ B\bar{B}$

Control sample for measuring experimental effects (mistag, resolution).

Computing the CP asymmetry for final states common to B^0 and $\bar{B}^0$

Time evolution of tagged states

$$\left|B^0(t)\right\rangle = \quad e^{-\frac{\Gamma}{2}t}e^{-iMt}\left(\cos\frac{\Delta M\cdot t}{2}\left|B^0\right\rangle \ \text{-}\ i\cdot\alpha\cdot\sin\frac{\Delta M\cdot t}{2}\left|\bar{B}^0\right\rangle\right)$$

$$\left|\bar{B}^0(t)\right\rangle = \quad e^{-\frac{\Gamma}{2}t}e^{-iMt}\left(\cos\frac{\Delta M\cdot t}{2}\left|\bar{B}^0\right\rangle \ \text{-}\ i\cdot\frac{1}{\alpha}\cdot\sin\frac{\Delta M\cdot t}{2}\left|B^0\right\rangle\right)$$

We have used $\Delta\Gamma/\Gamma \ll 1$ and set $\Gamma \cong \Gamma_1 \cong \Gamma_2 \qquad M = \frac{1}{2}(M_+ + M_-)$

Goal: calculate $\begin{cases} \left\langle f_{CP}\middle|H\middle|B^0(t)\right\rangle \\ \left\langle f_{CP}\middle|H\middle|\bar{B}^0(t)\right\rangle \end{cases}$

f_{CP} = CP eigenstate

$\underbrace{\langle f_{CP}|H|}$ Simply project above eq'ns onto this!

Decay amplitudes for $B^0(t) \rightarrow f_{CP}$ vs. $\bar{B}^0(t) \rightarrow f_{CP}$

$$\langle f_{CP} | H | B^0(t) \rangle = e^{-\frac{\Gamma}{2}t} e^{-iMt} \langle f_{CP} | H | B^0 \rangle \left(\cos\frac{\Delta M \cdot t}{2} - i \cdot \alpha \cdot \frac{\langle f_{CP} | H | \bar{B}^0 \rangle}{\langle f_{CP} | H | B^0 \rangle} \sin\frac{\Delta M \cdot t}{2} \right)$$

$$\langle f_{CP} | H | \bar{B}^0(t) \rangle = e^{-\frac{\Gamma}{2}t} e^{-iMt} \langle f_{CP} | H | \bar{B}^0 \rangle \left(\cos\frac{\Delta M \cdot t}{2} - i \cdot \frac{1}{\alpha} \cdot \frac{\langle f_{CP} | H | B^0 \rangle}{\langle f_{CP} | H | \bar{B}^0 \rangle} \sin\frac{\Delta M \cdot t}{2} \right)$$

blue: mixing   green: decay

The key quantity in these CP asymmetries is:

$$\lambda \equiv \alpha \cdot \frac{\langle f_{CP} | H | \bar{B}^0 \rangle}{\langle f_{CP} | H | B^0 \rangle} = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}} \cdot \frac{\langle f_{CP} | H | \bar{B}^0 \rangle}{\langle f_{CP} | H | B^0 \rangle}$$

Calculating λ

$$\lambda = \sqrt{\frac{M_{12}^{*} - \frac{i}{2}\Gamma_{12}^{*}}{M_{12} - \frac{i}{2}\Gamma_{12}}} \cdot \frac{\left\langle f_{CP} \middle| H \middle| \overline{B}^{0} \right\rangle}{\left\langle f_{CP} \middle| H \middle| B^{0} \right\rangle} = \frac{q}{p} \cdot \frac{\overline{A}_f}{A_f}$$

Factor from mixing

$$\alpha \cong \sqrt{\frac{M_{12}^{*}}{M_{12}}}$$

$$\simeq \frac{V_{tb}^{*} V_{td}}{V_{tb} V_{td}^{*}} \cdot e^{i\theta_{CP}}$$

$$\simeq e^{i(\theta_{CP} + 2\phi_M)}$$

Factor from decay

assuming 1 decay amplitude:

$$\left\langle f_{CP} \middle| H \middle| B^{0} \right\rangle = |a| e^{i(\delta + \phi_D)}$$

$$\left\langle f_{CP} \middle| H \middle| \overline{B}^{0} \right\rangle = \eta_{CP}(f) e^{-i\theta_{CP}} |a| e^{i(\delta - \phi_D)}$$

$$\frac{\left\langle f_{CP} \middle| H \middle| \overline{B}^{0} \right\rangle}{\left\langle f_{CP} \middle| H \middle| B^{0} \right\rangle} = \eta_{CP}(f) e^{-i(\theta_{CP} + 2\phi_D)}$$

$$\Rightarrow \quad \lambda = \eta_{CP}(f) e^{2i(\phi_M - \phi_D)}$$

(the unphysical phase, the strong phase, and |a| ALL cancel)

Calculating λ for specific final states

$$B^0 \to \pi^+\pi^- \qquad (b \to u\bar{u}d)$$

$$\lambda = \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} \cdot \frac{V_{ud}^* V_{ub}}{V_{ud} V_{ub}^*} \qquad \mathrm{Im}(\lambda) = \sin(2\alpha)$$

(assuming only tree diagram for illustration)

$$B^0 \to J/\psi K_S^0 \quad \lambda = (-1) \cdot \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} \cdot \frac{V_{cs}^* V_{cb}}{V_{cs} V_{cb}^*} \cdot \frac{V_{cd}^* V_{cs}}{V_{cd} V_{cs}^*} \qquad \mathrm{Im}(\lambda) = \sin(2\beta)$$

$$(b \to c\bar{c}s) \times (K^0 \to K_S^0)$$

$$B^0 \to J/\psi K_L^0 \quad \lambda = (+1) \cdot \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} \cdot \frac{V_{cs}^* V_{cb}}{V_{cs} V_{cb}^*} \cdot \frac{V_{cd}^* V_{cs}}{V_{cd} V_{cs}^*} \qquad \mathrm{Im}(\lambda) = -\sin(2\beta)$$

$$(b \to c\bar{c}s) \times (K^0 \to K_L^0)$$

Calculation of the time-dependent CP asymmetry

$$A_{f_{CP}}(t) = \frac{\left|\langle f_{CP} | H | \overline{B}^0(t) \rangle\right|^2 - \left|\langle f_{CP} | H | B^0(t) \rangle\right|^2}{\left|\langle f_{CP} | H | \overline{B}^0(t) \rangle\right|^2 + \left|\langle f_{CP} | H | B^0(t) \rangle\right|^2}$$

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

$$A_{f_{CP}}(t) = S \cdot \sin(\Delta m \cdot t) - C \cdot \cos(\Delta m \cdot t)$$

$$S = \frac{2 \cdot \mathrm{Im}(\lambda)}{1 + |\lambda|^2} \qquad C = \frac{1 - |\lambda|^2}{1 + |\lambda|^2}$$

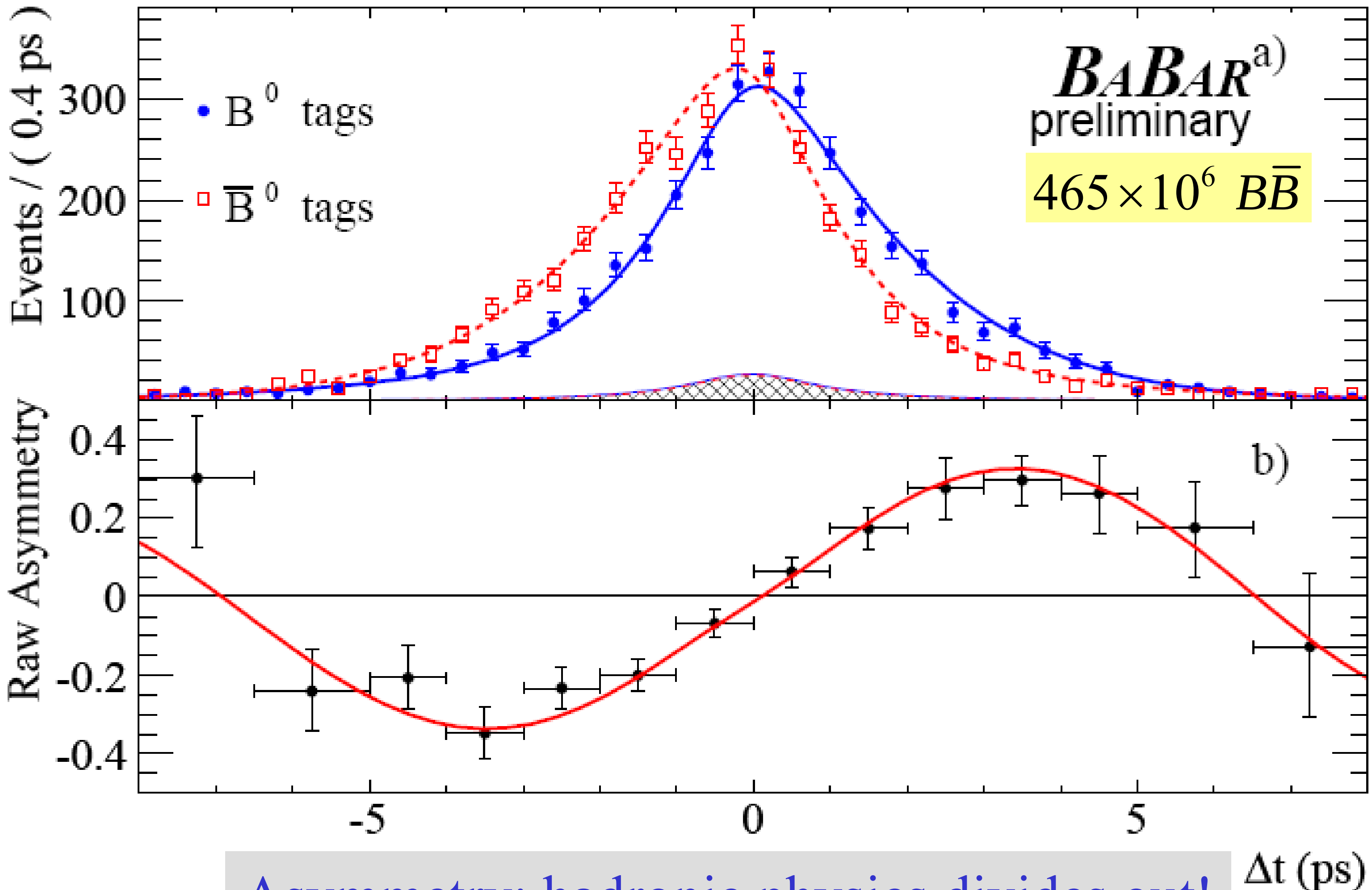
1 decay amplitude:

$$|\lambda| = 1 \quad \Rightarrow \quad S = \mathrm{Im}\left(\lambda\right), \quad C = 0$$

$$A_{f_{CP}}(t) = \mathrm{Im}(\lambda) \cdot \sin(\Delta m \cdot t)$$

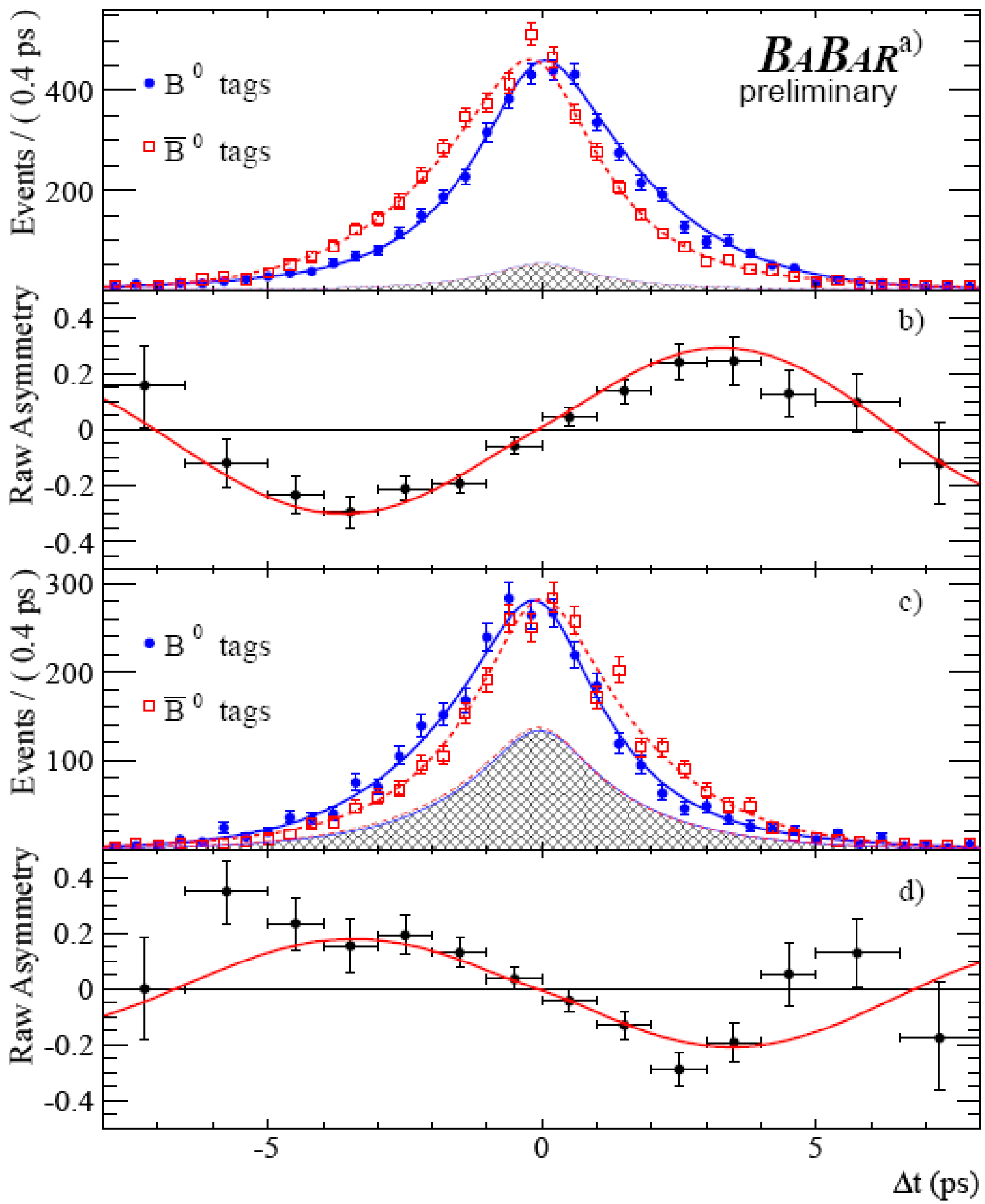
Comparison of decay rates for B^0(t) and $\bar{B}^0$(t)

$B^0 \to J/\psi K_S^0$ $\quad$ $A_{f_{CP}}(t) = S \cdot \sin(\Delta m \cdot t) - C \cdot \cos(\Delta m \cdot t)$



Asymmetry: hadronic physics divides out!

Results on sin2β from charmonium modes



$\eta_f(CP) = -1$

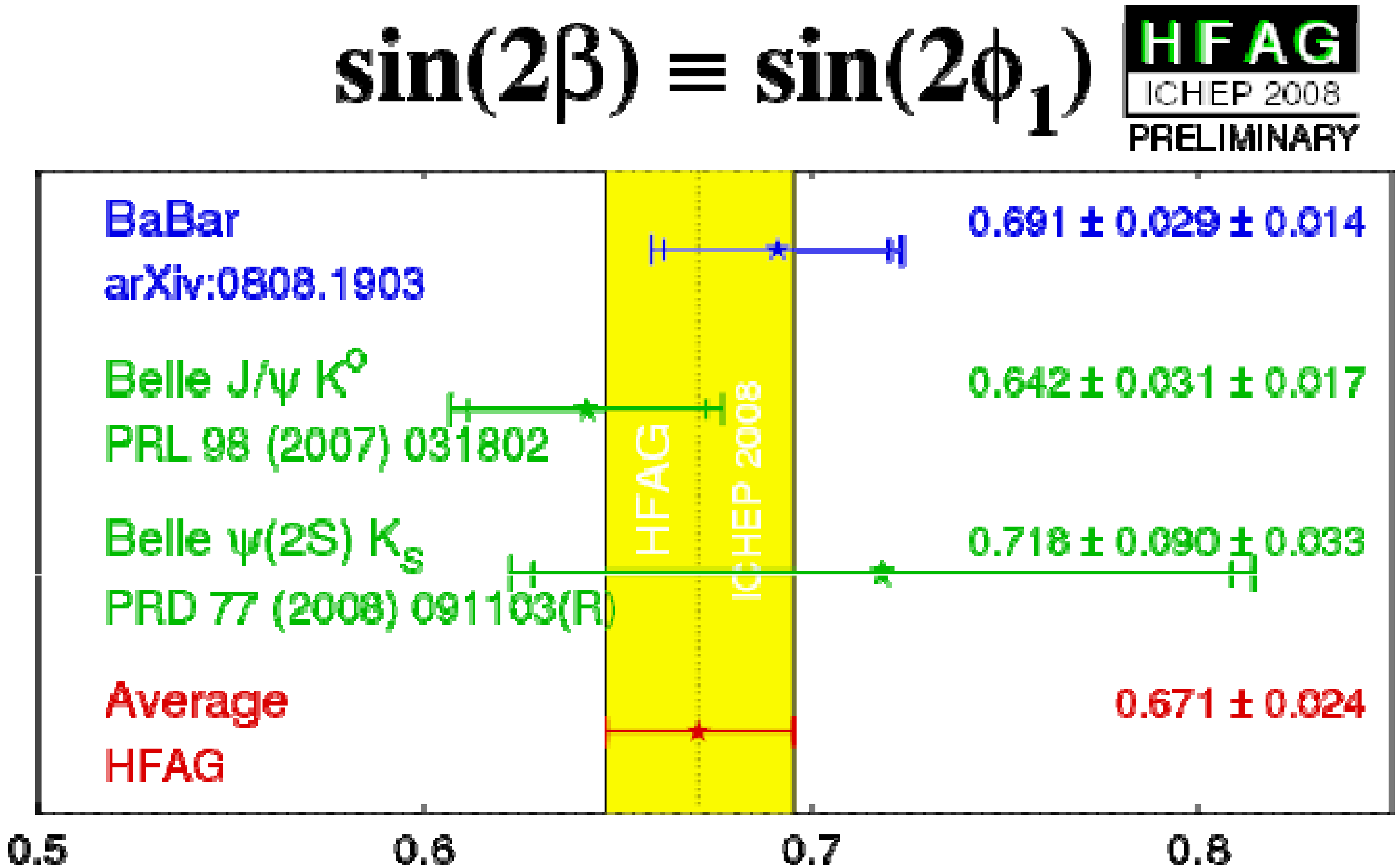
stat sys

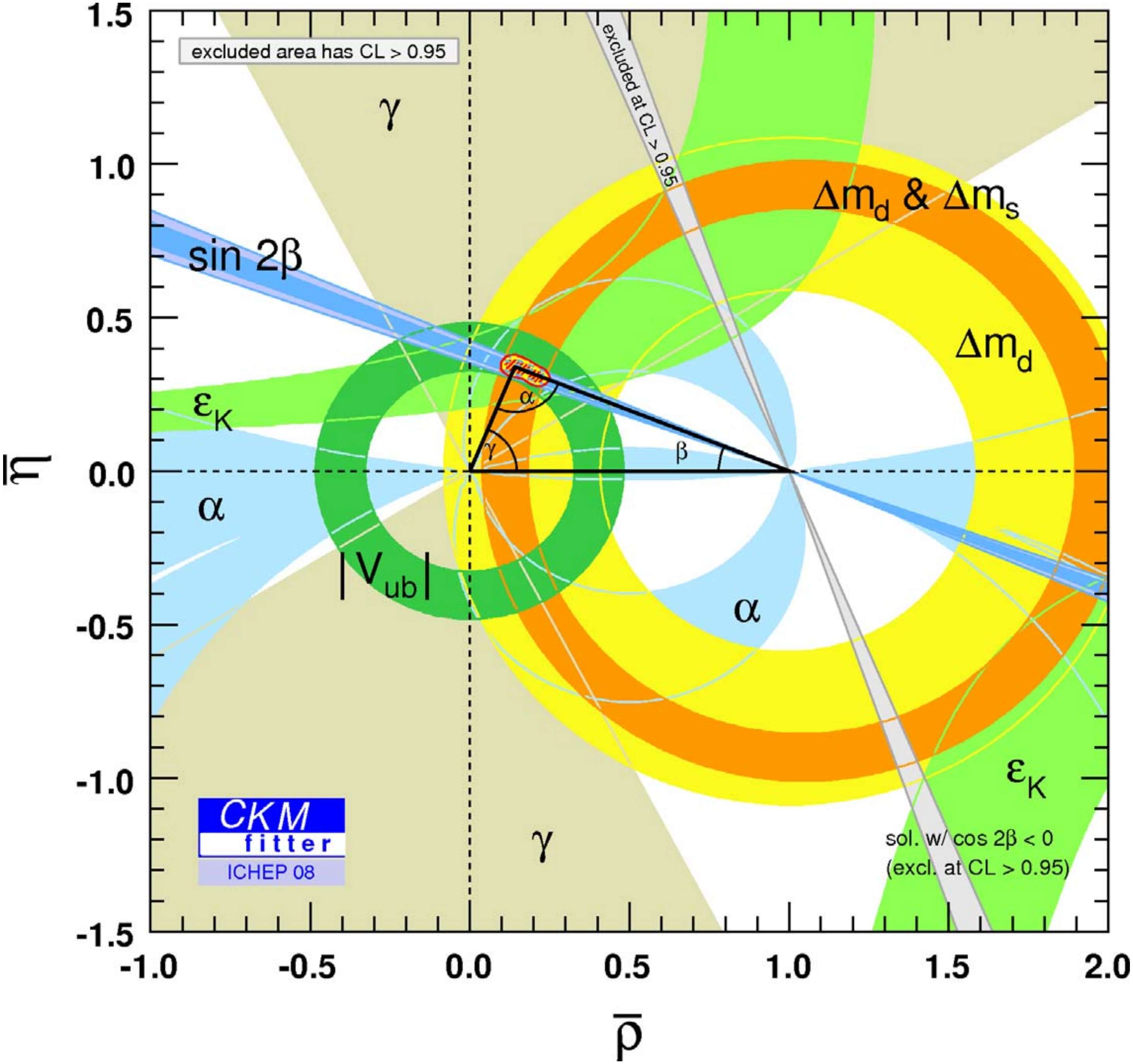
$$S_f = 0.691 \pm 0.029 \pm 0.014$$

$$C_f = 0.026 \pm 0.020 \pm 0.016$$

$\eta_f(CP) = +1$

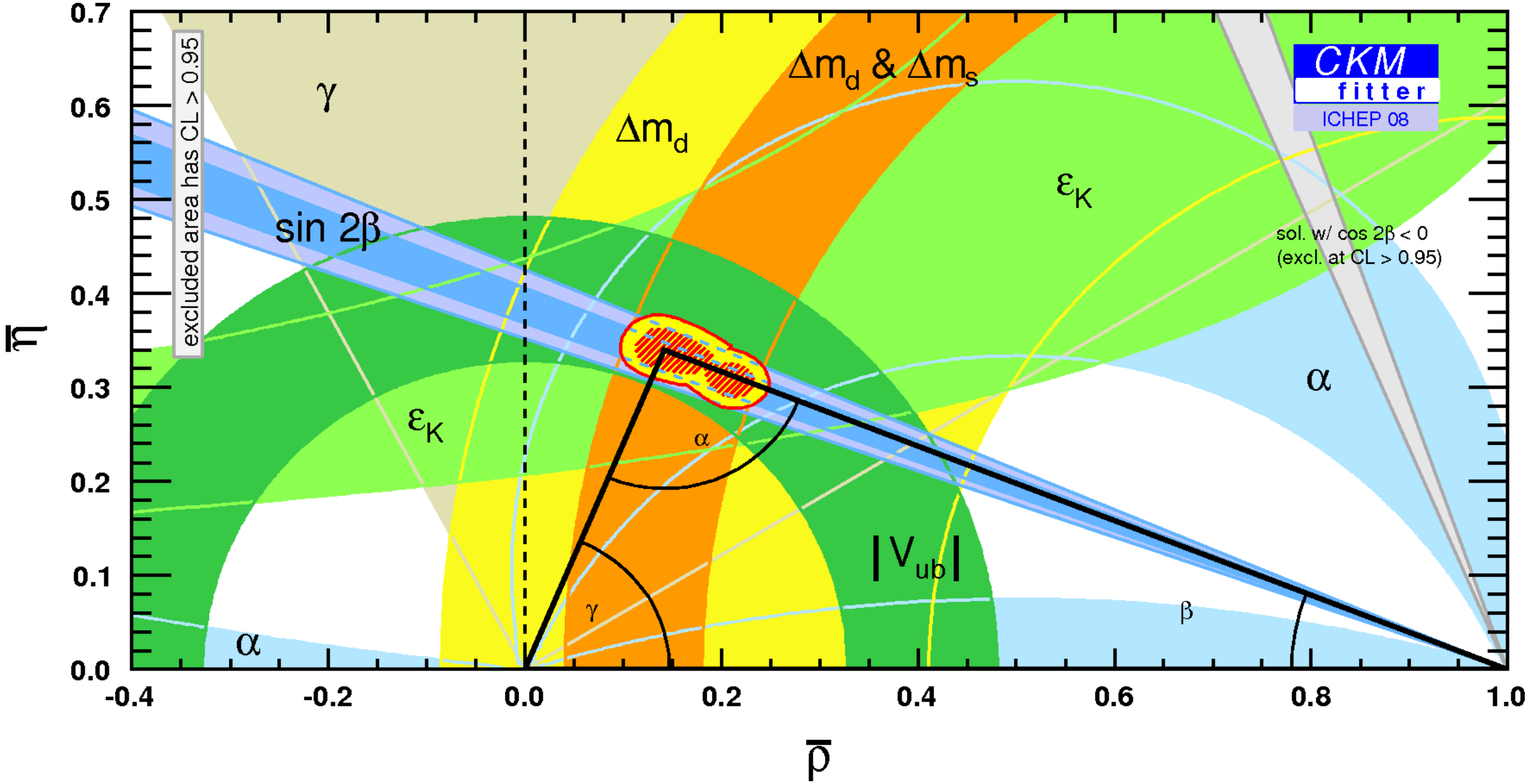
$$\sin(2\beta) \equiv \sin(2\phi_1)$$

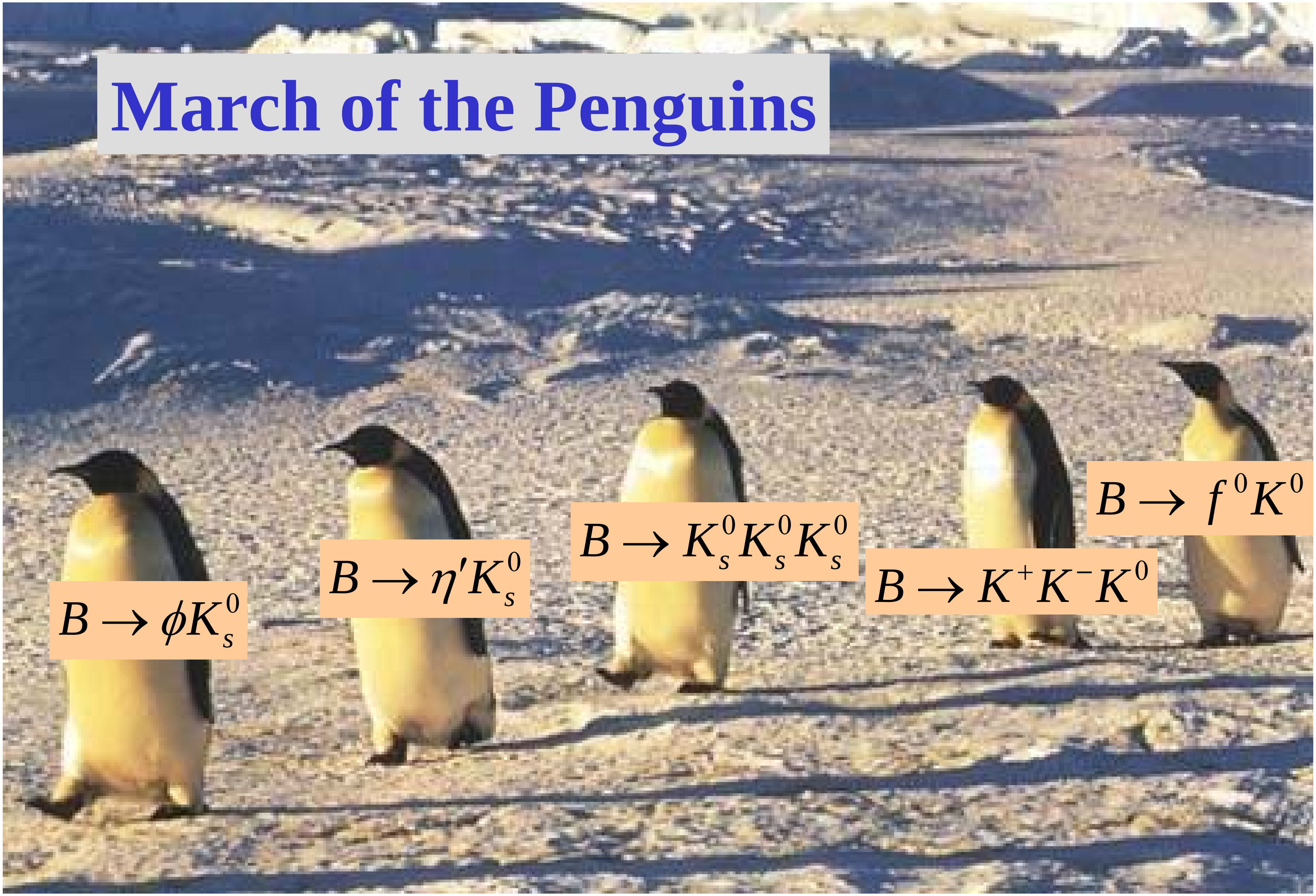




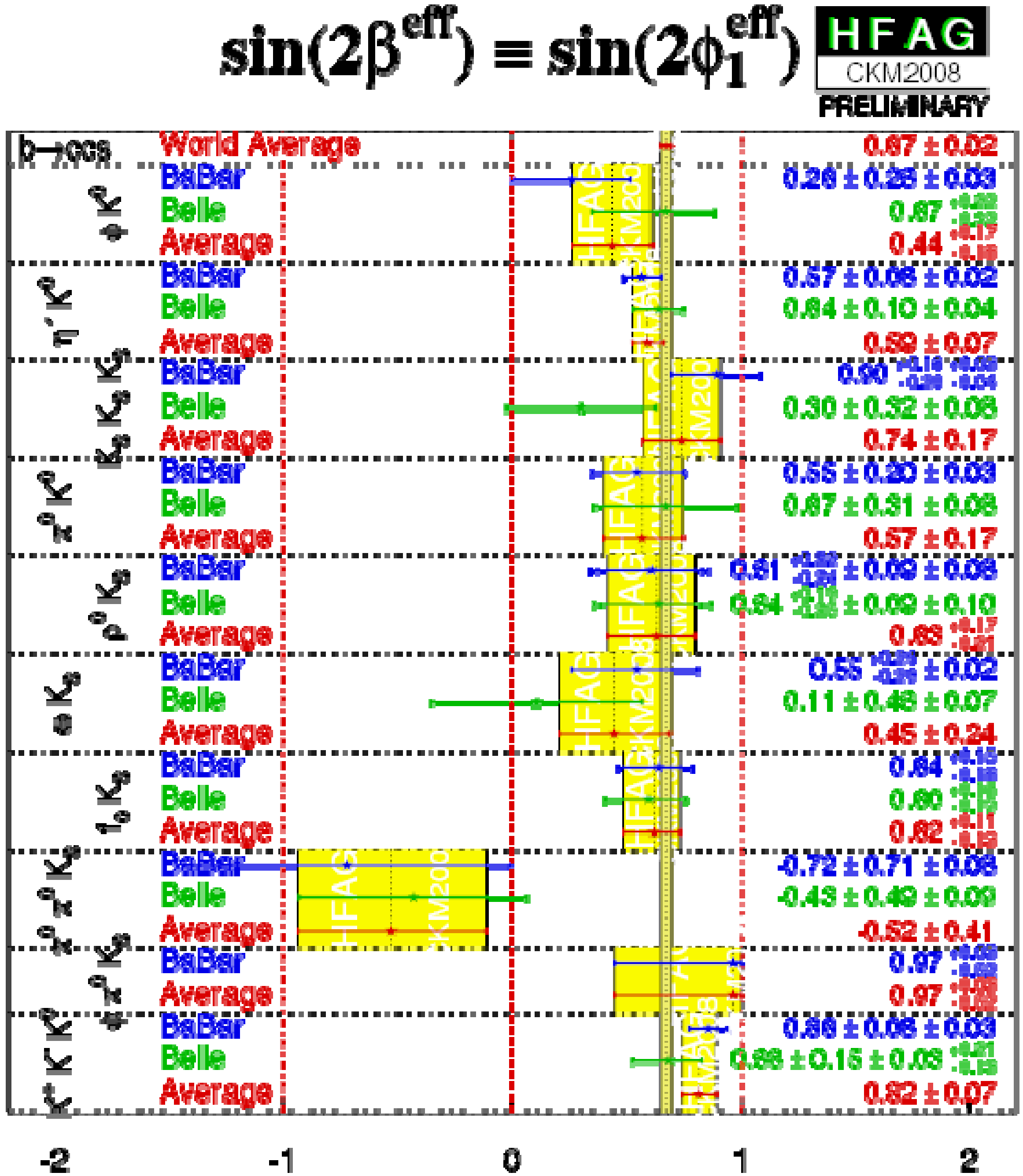
excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
γ
β
α
$|V_{ub}|$
α
ε_K
CKM fitter
ICHEP 08
γ
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
$\bar\eta$
$\bar\rho$
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0

Are the CKM measurements consistent?




March of the Penguins
$B \to \phi K_s^0$
$B \to \eta' K_s^0$
$B \to K_s^0 K_s^0 K_s^0$
$B \to K^+ K^- K^0$
$B \to f^0 K^0$

sin2β from tree diagrams



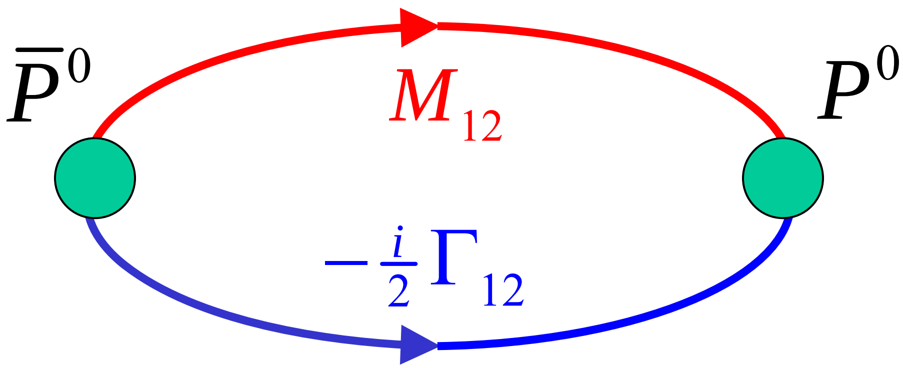
Conclusions (I)

- CP violation arises from interfering amplitudes that have both a CP-violating and a CP-conserving *relative* phase.
  - only certain decay modes are useful; most of them have small branching fractions; need lots of data.
  - *B* factories deliver O(10^9) *B* mesons
- The CKM framework, together with measurements of non-CP violating observables, predicted large CP violation in B decays.
  - O(0.1-1) CP violation in *B* decays vs. O(10^{-3}) in *K* decays are all part of the same picture!
  - Predictions confirmed!
- CKM matrix requires that CP violating and non-CP violating observations be described by 4 independent parameters. So far, confirmed by measurement.

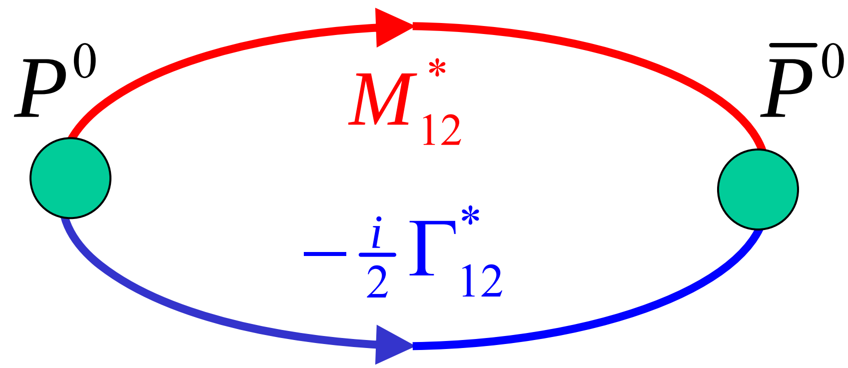
Conclusions (II)

- Observed time dependence of CP violating asymmetries in B decays
  - confirms prediction of interference between mixing and decay
  - different from predominant CP violation in K decays (mixing: interference between on-shell and off-shell amps).
- Many B decay modes with quantum loops (penguins). Because these modes are suppressed in the SM, and new particles can appear in the intermediate state, they are a good place to search for new physics.
- Measurements of sin2β in penguin modes are (so far) consistent with measurements based on tree diagrams.
- LHCb and possibly Super-B factories will extend these investigations!

CP Violation in Oscillations



$\mathrm{Amp}(\overline{P}^0 \to P^0)$



$\mathrm{Amp}(P^0 \to \overline{P}^0)$

M_{12} = transition amplitude via intermediate states that are virtual (off-shell)

Γ_{12} = transition amplitude via intermediate states are are real (on-shell: both P^0 and $\overline{P}^0$ can decay into these!)

- The "-i" is a CP conserving phase factor. It doesn't change sign!
- M_{12} and Γ_{12} behave like CP-violating phase factors, as long as they are not relatively real.

Solving the eigenvector problem in time-dependent perturbation theory

Eigenvectors of unperturbed Hamiltonian; notation

$$H_0\left|P^0\right\rangle = m_0\left|P^0\right\rangle$$

$$H_0\left|\bar{P}^0\right\rangle = m_0\left|\bar{P}^0\right\rangle$$

$$\underbrace{H_0\left|f\right\rangle = E_f\left|f\right\rangle}$$

Unperturbed energies of these states depend on quark masses, strong interations, and EM interactions that bind quarks into mesons.

$$CP\left|P^0\right\rangle = e^{i\theta_{CP}}\left|\bar{P}^0\right\rangle$$

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

$$\underbrace{(CP)^2\left|P^0\right\rangle = \left|P^0\right\rangle}$$

Work in arbitrary phase convention; keep unphysical phases explicit. physical results must not depend on them!

$$H_{11} = \left\langle P^0\right|H\left|P^0\right\rangle$$

$$H_{12} = \left\langle P^0\right|H\left|\bar{P}^0\right\rangle$$

$$H_{21} = \left\langle \bar{P}^0\right|H\left|P^0\right\rangle$$

$$H_{11} = \left\langle P^0\right|H\left|P^0\right\rangle$$

$$H = H_0 + H_w$$

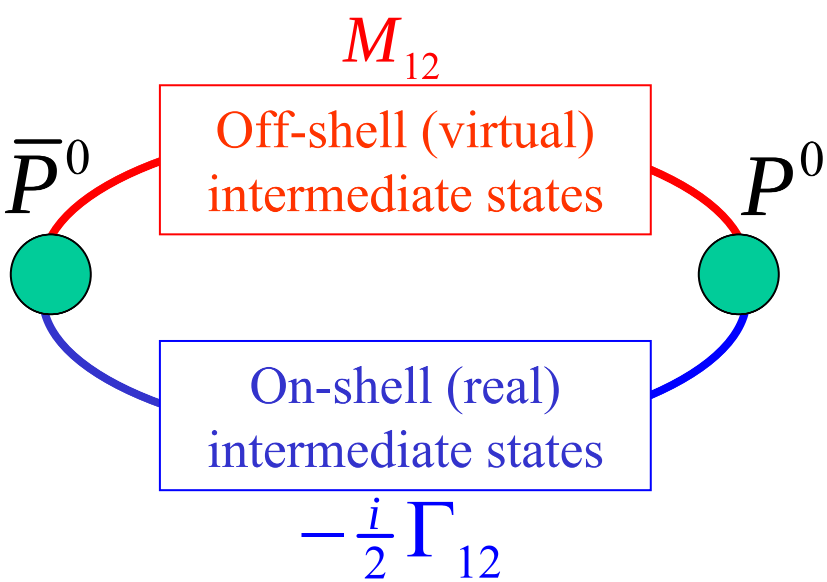
The two classes of transitions in mixing

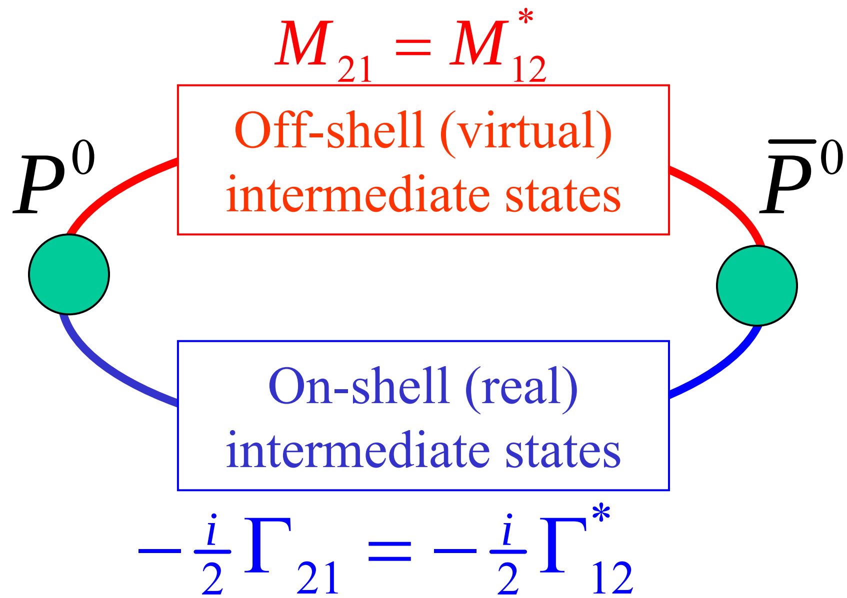
Get specific form of ***H*** in terms of matrix elements of H_w.

$$H = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix} = \underbrace{\begin{pmatrix} M & M_{12} \\ M^*_{12} & M \end{pmatrix}}_{\text{mass matrix}} - \frac{i}{2} \underbrace{\begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma^*_{12} & \Gamma \end{pmatrix}}_{\text{decay matrix}}$$

$$H_{21} \neq H^*_{12}$$

crucial factor!





Solution to the eigenvalue problem

$$\boldsymbol{H} = H_{11}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \begin{pmatrix} 0 & H_{12} \\ H_{21} & 0 \end{pmatrix} = H_{11}\boldsymbol{I} + \boldsymbol{K}$$

H, ***K*** have same eigenvectors.

$$\begin{pmatrix} 0 & H_{12} \\ H_{21} & 0 \end{pmatrix}\begin{pmatrix} p \\ q \end{pmatrix} = \mu\begin{pmatrix} p \\ q \end{pmatrix} \quad \Rightarrow \mu^2 = H_{12}H_{21}$$

easy!

$$\Rightarrow \alpha \equiv \frac{q}{p} = \left(\frac{H_{21}}{H_{12}}\right)^{1/2} = \left(\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}\right)^{1/2}$$

To get eigenvalues of ***H***, just add H_{11} to μ

$$\mu_\pm = H_{11} \pm (H_{12}H_{21})^{1/2}$$

$$= M_\pm - \tfrac{i}{2}\Gamma_\pm$$

$$M_\pm = M \pm \mathrm{Re}(H_{12}H_{21})^{1/2}$$

$$\Gamma_\pm = \Gamma \mp \mathrm{Im}(H_{12}H_{21})^{1/2}$$

$$\Delta M = -2\,\mathrm{Re}(H_{12}H_{21})^{1/2} \qquad \Delta\Gamma = 4\,\mathrm{Im}(H_{12}H_{21})^{1/2}$$

M_{ij}, Γ_{ij}, and the story of the factor $-i$

Results from time-dependent perturbation theory

$$M_{ij} = m_0\delta_{ij} + \underbrace{\langle i|H_w|j\rangle}_{\text{0 in SM}} + P\sum_f \frac{\langle i|H_w|f\rangle\langle f|H_w|j\rangle}{m_0 - E_f}$$

$$\Gamma_{ij} = 2\pi\sum_f \langle i|H_w|f\rangle\langle f|H_w|j\rangle\ \delta(m_0 - E_f)$$

Real/virtual separation comes from $i\varepsilon$

odd func of m_0-E_f

$$\lim_{\varepsilon\to0^+}\frac{1}{(m_0-E_f)+i\varepsilon} = \lim_{\varepsilon\to0^+}\left[\frac{m_0-E_f}{(m_0-E_f)^2+\varepsilon^2} - i\frac{\varepsilon}{(m_0-E_f)^2+\varepsilon^2}\right]$$

$$= P\left(\frac{1}{m_0-E_f}\right) - i\pi\delta(m_0-E_f)$$

even func

Matrix form of the CP operator for 2-state system

$$[CP, H] = 0 \qquad (CP \text{ is conserved})$$

What does this statement imply for CP violation in oscillations?

$$CP\left|P^0\right\rangle = e^{i\theta_{CP}}\left|\bar{P}^0\right\rangle$$

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

$$CP \rightarrow \begin{pmatrix} 0 & e^{-i\theta_{CP}} \\ e^{i\theta_{CP}} & 0 \end{pmatrix}$$

CP conservation is equivalent to $(CP)^{-1}H(CP) = H$

$$\begin{pmatrix} 0 & e^{-i\theta_{CP}} \\ e^{i\theta_{CP}} & 0 \end{pmatrix}\begin{pmatrix} 0 & H_{12} \\ H_{21} & 0 \end{pmatrix}\begin{pmatrix} 0 & e^{-i\theta_{CP}} \\ e^{i\theta_{CP}} & 0 \end{pmatrix} = \begin{pmatrix} 0 & e^{-2i\theta_{CP}}H_{21} \\ e^{2i\theta_{CP}}H_{12} & 0 \end{pmatrix}$$

$$= \begin{pmatrix} 0 & H_{12} \\ H_{21} & 0 \end{pmatrix}$$

(Only need to look at off-diag components of **H**.)

Condition for CP Violation in Oscillations

CP conservation ([H,CP]=0) therefore implies

$$e^{2i\theta_{CP}} H_{12} = H_{21} \qquad \Rightarrow \qquad \frac{H_{21}}{H_{12}} = e^{i2\theta_{CP}}$$

Conversely, there will be observable CP violation in the oscillations if

$$\left|\frac{\mathrm{Amp}(P^0 \to \overline{P}^0)}{\mathrm{Amp}(\overline{P}^0 \to P^0)}\right| = \left|\frac{H_{21}}{H_{12}}\right| = \left|\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}\right| = |\alpha|^2 = \left|\frac{q}{p}\right|^2 \neq 1$$

Key point: for CP violation to occur in mixing, both M_{12} and Γ_{12} must be non-zero. CP violation in mixing will not occur due to interference of the amplitudes within M_{12} (or Γ_{12}). This is why the formalism is so simple!

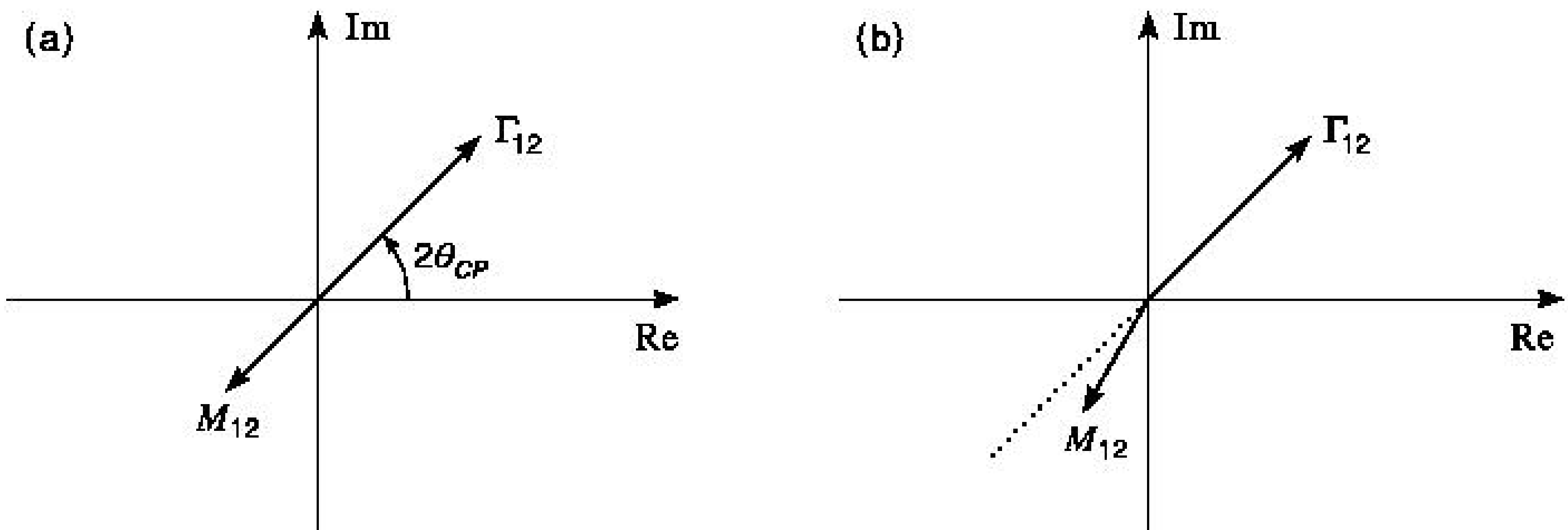
CP Violation in Oscillations: Visualization

Equivalent statement of condition for CP violation in mixing: M_{12} and Γ_{12} must not be collinear and both must be nonzero.

$$\mathrm{Im}(M_{12}\Gamma_{12}^{*}) = |M_{12}||\Gamma_{12}|\sin(\theta_{M_{12}} - \theta_{\Gamma_{12}}) \neq 0$$

no CP violation in mixing

CP violation in mixing



Overall rotation is merely a non-physical phase convention.

Γ_{12} is small in $B^0\overline{B}^0$ oscillations

- In the neutral B-meson system, the common modes that both B^0 and $\overline{B}^0$ can decay into have small branching fractions, since

$$b \to c \qquad \text{and} \qquad \overline{b} \to \overline{c}$$

- These decays usually lead to different final states. There are some exceptions, but the branching fractions are small. Examples:

$$(B^0, \overline{B}^0) \to c\overline{c}d\overline{d}$$ Cabibbo suppressed

$$(B^0, \overline{B}^0) \to u\overline{u}d\overline{d}$$ $b \to u$ is CKM suppressed

SM predicts

$$\left|\frac{\Gamma_{12}}{M_{12}}\right| = O(m_b^2 / m_t^2) \ll 1$$

Expect CP violation in $B^0\overline{B}^0$ mixing to be $O(10^{-3})$. not yet observed

Time evolution of the mass eigenstates

The ratio α=q/p determines the eigenstates of ***H*** in terms of superpositions of the original flavor-eigenstates:

$$\left|P_+^0\right\rangle = \frac{1}{\sqrt{1+|\alpha|^2}}\left(\left|P^0\right\rangle + \alpha\left|\bar{P}^0\right\rangle\right)$$

$$\left|P_-^0\right\rangle = \frac{1}{\sqrt{1+|\alpha|^2}}\left(\left|P^0\right\rangle - \alpha\left|\bar{P}^0\right\rangle\right)$$

$$\alpha \equiv \frac{q}{p} = \left(\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}\right)^{1/2}$$

Since these are the eigenstates of ***H***, their time dependence is simple!

$$\left|P_+^0(t)\right\rangle = \frac{1}{\sqrt{1+|\alpha|^2}} e^{-i(M_+ - \frac{i}{2}\Gamma_+)t}\left(\left|P^0\right\rangle + \alpha\left|\bar{P}^0\right\rangle\right)$$

$$\left|P_-^0(t)\right\rangle = \frac{1}{\sqrt{1+|\alpha|^2}} \underbrace{e^{-i(M_- - \frac{i}{2}\Gamma_-)t}}_{\text{exponential time dependence}}\left(\left|P^0\right\rangle - \alpha\left|\bar{P}^0\right\rangle\right)$$

CP violation and the $K_S K_L$ lifetime splitting

CP violation is a small effect in K^0K^0 oscillations.

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

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

$$\varepsilon = \frac{1-\alpha}{1+\alpha} \qquad |\varepsilon| = (2.284 \pm 0.014)\times 10^{-3}$$

K_S^0 Mostly CP=+1 → can decay to $\pi^+\pi^-$, $\pi^0\pi^0$
→ <u>faster decay rate</u>

K_L^0 Mostly CP=-1 → decays to $\pi^0\pi^0\pi^0$, $\pi^+\pi^-\pi^0$, $\pi e\nu$, $\pi\mu\nu$
→ 3 body decays: <u>slower decay rate</u>

Apply the condition for CP violation in mixing

What are the implications of CP violation for the state vectors?

$$\langle P_-^0 | P_+^0 \rangle = \frac{|p|^2 - |q|^2}{|p|^2 + |q|^2} = \frac{1-|\alpha|^2}{1+|\alpha|^2} \neq 0$$

Mass eigenstates not orthogonal! (***H*** not hermitian).

Since $[H, CP] \neq 0$, expect that mass eigenstates are not simultaneously CP eigenstates.

$$\left| P_{CP=+1}^0 \right\rangle = \tfrac{1}{\sqrt{2}} \left(\left| P^0 \right\rangle + e^{i\theta_{CP}} \left| \overline{P}^0 \right\rangle \right)$$

$$\left| P_{CP=-1}^0 \right\rangle = \tfrac{1}{\sqrt{2}} \left(\left| P^0 \right\rangle - e^{i\theta_{CP}} \left| \overline{P}^0 \right\rangle \right)$$

You can verify that these are

1. CP eigenstates
2. If CP is violated, they are not mass eigenstates.

CP violation in $K^0\bar{K}^0$ oscillations: semileptonic decays

The K^0 has a slightly higher probability of decaying as a K_L than as a K_S.

$$\delta \equiv \frac{\Gamma\left(K_L^0 \to \pi^-\ell^+\nu\right) - \Gamma\left(K_L^0 \to \pi^+\ell^-\nu\right)}{\Gamma\left(K_L^0 \to \pi^-\ell^+\nu\right) + \Gamma\left(K_L^0 \to \pi^+\ell^-\nu\right)} = \frac{\left|\left\langle K^0 \middle| K_L^0\right\rangle\right|^2 - \left|\left\langle \bar{K}^0 \middle| K_L^0\right\rangle\right|^2}{\left|\left\langle K^0 \middle| K_L^0\right\rangle\right|^2 + \left|\left\langle \bar{K}^0 \middle| K_L^0\right\rangle\right|^2}$$

$$= \frac{1-|\alpha|^2}{1+|\alpha|^2} = \left\langle K_L^0 \middle| K_S^0\right\rangle = (3.27 \pm 0.12) \times 10^{-3}$$

$\bar{s}d$ $\quad$ $s\bar{d}$

δ gives direct measure of non-orthogonality of mass eigenstates.

$$|\alpha| \simeq 1 - \delta \simeq 0.9967$$

Time evolution of particles initially tagged as $K^0(\bar{K}^0)$

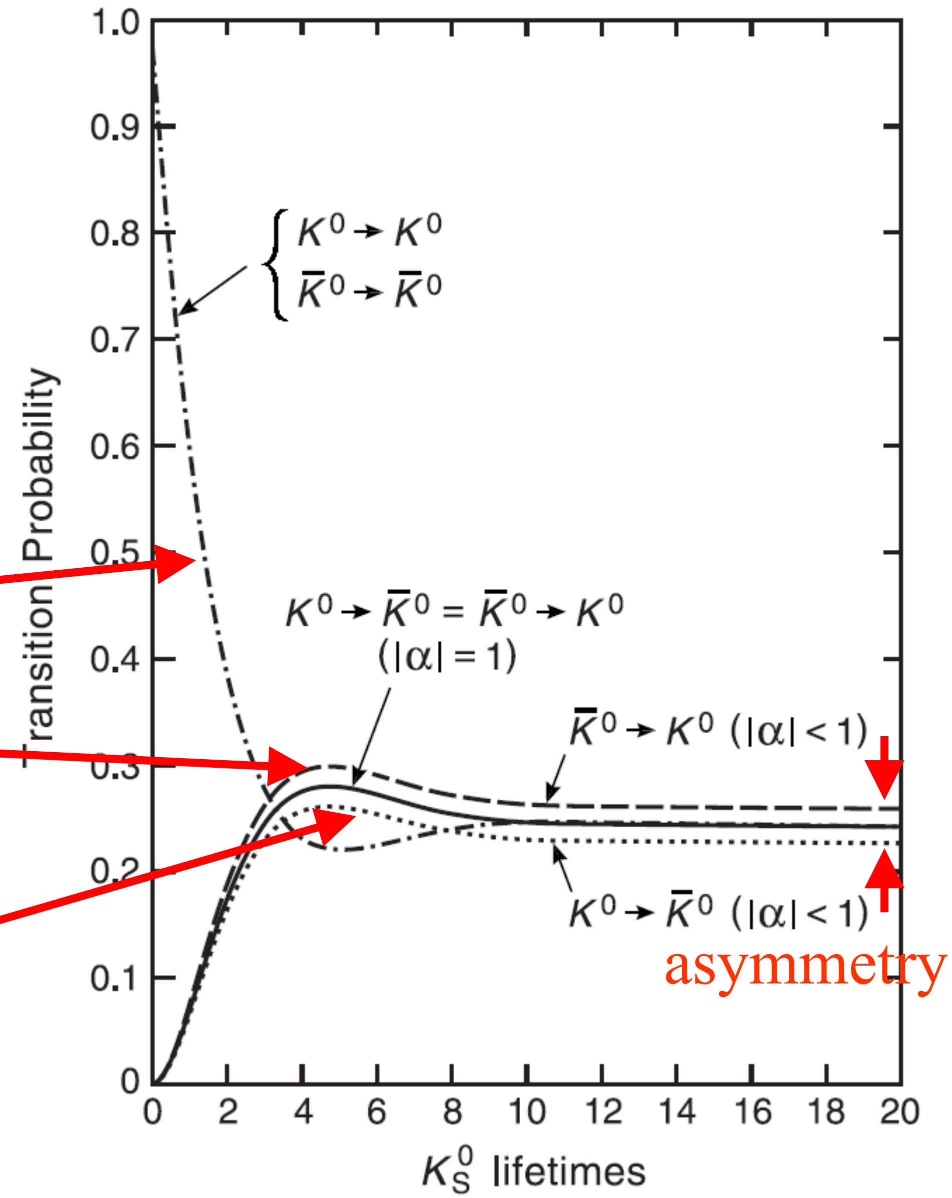
$$|\alpha| \simeq 1 - \delta \simeq 0.9967$$

In fig., increase δ by 10X
→ |α|=0.967

$$\frac{1}{4}\left[e^{-\Gamma_+ t} + e^{-\Gamma_- t} + 2e^{-\Gamma t}\cos(\Delta M t)\right]$$

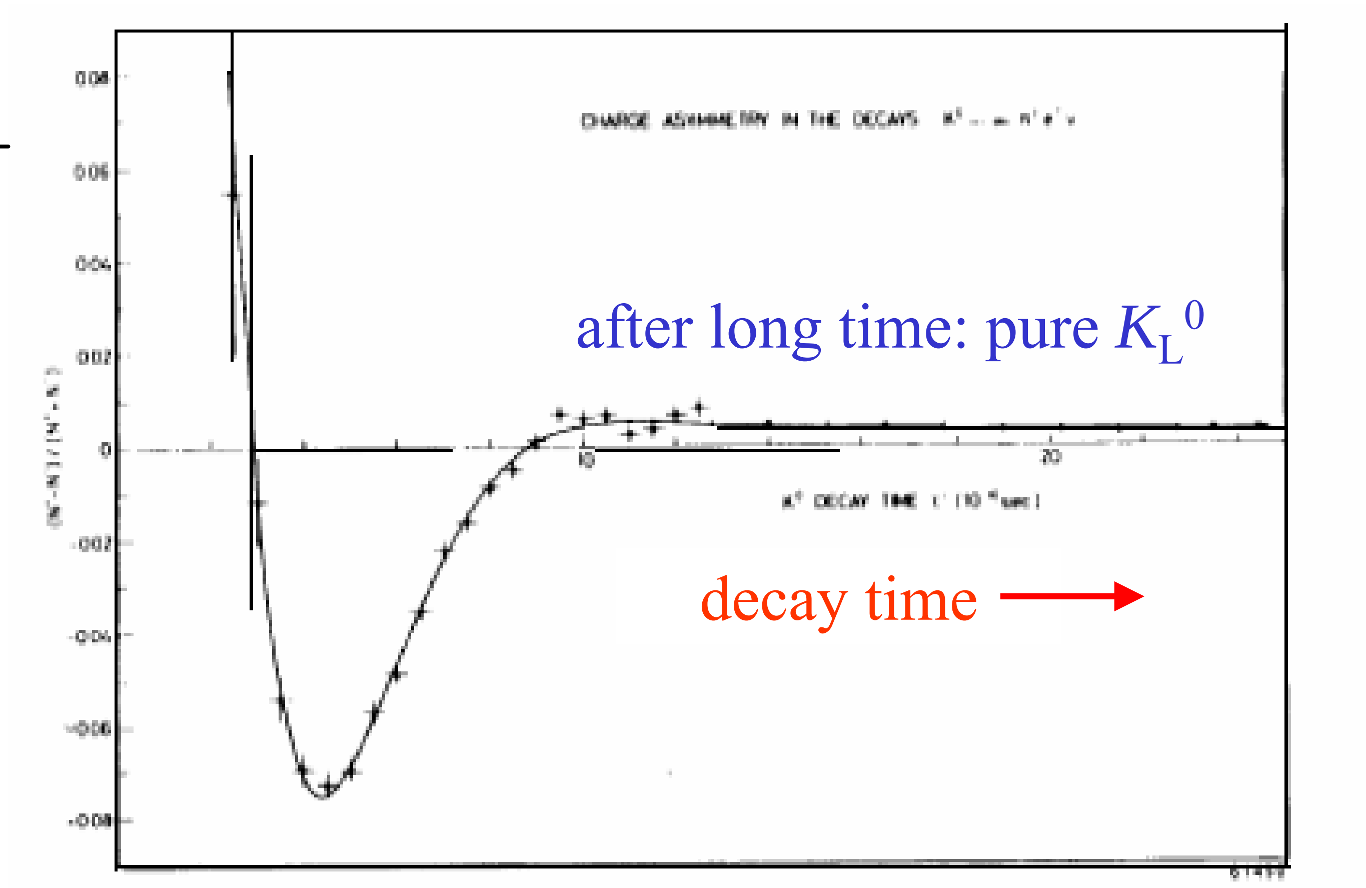
$$\frac{1}{4}|\alpha|^2\left[e^{-\Gamma_+ t} + e^{-\Gamma_- t} - 2e^{-\Gamma t}\cos(\Delta M t)\right]$$

$$\frac{1}{4}\left|\frac{1}{\alpha}\right|^2\left[e^{-\Gamma_+ t} + e^{-\Gamma_- t} - 2e^{-\Gamma t}\cos(\Delta M t)\right]$$



Measurement of the charge asymmetry in K^0 semileptonic decays

$$A = \frac{N^+ - N^-}{N^+ + N^-}$$



CP violation is a small effect in $K^0\bar{K}^0$ oscillations, but it is possible to observe it!

Direct CP violation in *K* decays

In the neutral *K* decays, does CP violation occur only between mixing amplitudes, or does it also occur between decay amplitudes?

Compare two CP violating amplitudes

$$\eta_{+-} \equiv \frac{A\left(K_L^0 \to \pi^+\pi^-\right)}{A\left(K_S^0 \to \pi^+\pi^-\right)} \qquad \eta_{00} \equiv \frac{A\left(K_L^0 \to \pi^0\pi^0\right)}{A\left(K_S^0 \to \pi^0\pi^0\right)}$$

$$\left.\begin{aligned} \eta_{+-} &\simeq \varepsilon + \varepsilon' \\ \eta_{00} &\simeq \varepsilon - 2\varepsilon' \end{aligned}\right\} \quad \begin{aligned} \varepsilon &\simeq \tfrac{2}{3}\eta_{+-} + \tfrac{1}{3}\eta_{00} \\ \varepsilon' &\simeq \tfrac{1}{3}(\eta_{+-} - \eta_{00}) \end{aligned}$$

CP violation from mixing only

CP violation from interference between direct decay amps

$$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = (1.67 \pm 0.26) \times 10^{-3}$$

(Direct CP violation due to tree-penguin interference.)

$B^0\bar{B}^0$ oscillation frequency in the SM

$$\Delta m_d = \frac{G_F^2}{6\pi^2}\eta_B m_{B_d} f_{B_d}^2 B_d m_W^2 S(x_t)\left|V_{td}V_{tb}^*\right|^2$$

Inami-Lim function

pert. QCD correction

B meson decay constant

"Bag" constant

$$\eta_B = 0.551 \pm 0.007$$

$$x_t = (m_t^2 / m_W^2)$$

$$\Delta m_s = \frac{G_F^2}{6\pi^2}\eta_B m_{B_s} \xi^2 f_{B_d}^2 B_d m_W^2 S(x_t)\left|V_{ts}V_{tb}^*\right|^2$$

$$\xi \equiv \frac{f_{B_s}\sqrt{B_s}}{f_{B_d}\sqrt{B_d}}$$

$$\xi = 1.16 \pm 0.05$$

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}}\xi^2\left|\frac{V_{ts}}{V_{td}}\right|^2 \gg 1$$

B_s oscillations are very fast.
Current limit: Δm_s>14.4 ps^{-1}.

17 December 1998

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Physics Letters B 444 (1998) 43–51

First direct observation of time-reversal non-invariance in the neutral-kaon system

CPLEAR Collaboration

Abstract

We report on the first observation of time-reversal symmetry violation through a comparison of the probabilities of $\overline{\mathrm{K}}^0$ transforming into K^0 and K^0 into $\overline{\mathrm{K}}^0$ as a function of the neutral-kaon eigentime t. The comparison is based on the analysis of the neutral-kaon semileptonic decays recorded in the CPLEAR experiment. There, the strangeness of the neutral kaon at time $t=0$ was tagged by the kaon charge in the reaction $\mathrm{p}\overline{\mathrm{p}} \rightarrow \mathrm{K}^{\pm}\pi^{\mp}\mathrm{K}^0(\overline{\mathrm{K}}^0)$ at rest, whereas the strangeness of the kaon at the decay time $t=\tau$ was tagged by the lepton charge in the final state. An average decay-rate asymmetry

$$\left\langle \frac{R\left(\overline{\mathrm{K}}^0_{t=0} \rightarrow \mathrm{e}^+\pi^-\nu_{t=\tau}\right) - R\left(\mathrm{K}^0_{t=0} \rightarrow \mathrm{e}^-\pi^+\overline{\nu}_{t=\tau}\right)}{R\left(\overline{\mathrm{K}}^0_{t=0} \rightarrow \mathrm{e}^+\pi^-\nu_{t=\tau}\right) + R\left(\mathrm{K}^0_{t=0} \rightarrow \mathrm{e}^-\pi^+\overline{\nu}_{t=\tau}\right)} \right\rangle = \left(6.6 \pm 1.3_{\mathrm{stat}} \pm 1.0_{\mathrm{syst}}\right) \times 10^{-3}$$

was measured over the interval $1\,\tau_{\mathrm{S}} < \tau < 20\,\tau_{\mathrm{S}}$, thus leading to evidence for time-reversal non-invariance.

First Observation of T-violation (CP LEAR)

1. Introduction

Since weak interactions do not conserve strangeness, a K^0 meson can transform into a $\overline{K}^0$ in the course of time, and vice-versa, a $\overline{K}^0$ can transform into a K^0. Time-reversal (T) invariance, or microscopic reversibility, would require all details of the second process to be deducible from the first; in particular, the probability ($\mathscr{P}$) that a $K^0(t=0)$ is observed as a $\overline{K}^0$ at time τ should be equal to the probability that a $\overline{K}^0(t=0)$ is observed as a K^0 at the same time τ [1]. Any difference between these two probabilities is a signal for T violation and can be measured through the time-reversal asymmetry

$$\frac{\mathscr{P}(\overline{K}^0 \to K^0) - \mathscr{P}(K^0 \to \overline{K}^0)}{\mathscr{P}(\overline{K}^0 \to K^0) + \mathscr{P}(K^0 \to \overline{K}^0)} . \tag{1}$$

Experimentally this requires knowledge of the strangeness of the neutral kaon at two different times of its life.

A measurement of this asymmetry has become possible with the CPLEAR experiment, which produced K^0s and $\overline{K}^0$s through the strong interactions

$$p\bar{p} \to \begin{cases} K^- \pi^+ K^0 \\ K^+ \pi^- \overline{K}^0 , \end{cases}$$

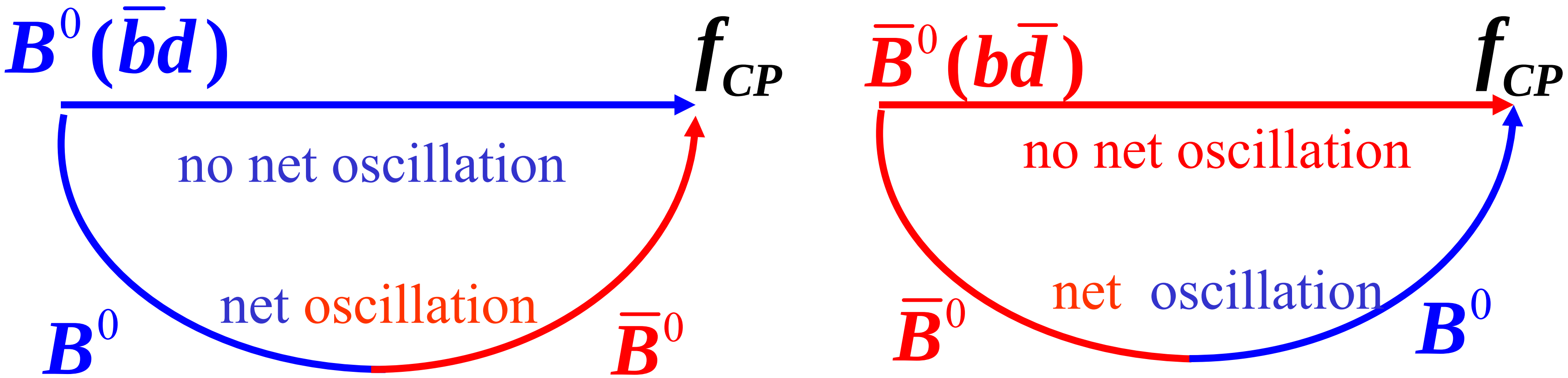
enabling the initial strangeness of the neutral kaon to be tagged by the charge of the accompanying charged kaon. To tag the strangeness of the kaon at the moment of its decay we use semileptonic decays: positive lepton charge is associated to a K^0 and negative lepton charge to a $\overline{K}^0$. We measure, as a function of time, the decay-rate asymmetry

$$\frac{R\left(\overline{K}^0_{t=0} \to e^+ \pi^- \nu_{t=\tau}\right) - R\left(K^0_{t=0} \to e^- \pi^+ \overline{\nu}_{t=\tau}\right)}{R\left(\overline{K}^0_{t=0} \to e^+ \pi^- \nu_{t=\tau}\right) + R\left(K^0_{t=0} \to e^- \pi^+ \overline{\nu}_{t=\tau}\right)} . \tag{2}$$

In the limit of CPT symmetry in the semileptonic decay process and of the validity of the $\Delta S = \Delta Q$ rule, this asymmetry is identical with the time-reversal asymmetry given in (1).

Time-dependent CP asymmetries from the interference between mixing and decay amplitudes

By modifying the mixing measurement, we can observe whole new class of CP-violating phenomena: pick final states that both B^0 and $\bar{B}^0$ can decay into. (Often a CP eigenstate, but doesn't have to be.)



$\Gamma(B^0_{phys}(t) \to f_{CP})$ $\qquad$ $\Gamma(\bar{B}^0_{phys}(t) \to f_{CP})$

Oscillations in the $K^0\overline{K^0}$ System

Most striking feature of $K^0\overline{K}^0$ system: huge lifetime splitting between mass eigenstates. (This is quite different from the $B^0\overline{B}^0$ system, where the mass splitting is very small!)

$$\frac{\tau\left(K_L^0\right)}{\tau\left(K_S^0\right)} \simeq \frac{52\text{ ns}}{0.09\text{ ns}} \simeq \frac{15.5\text{ m}}{2.7\text{ cm}}$$

$$\simeq 580$$

Major experimental implication: a neutral K beam evolves over distance into a nearly pure K_L^0 beam.

$$\Delta\Gamma = \Gamma\left(K_L^0\right) - \Gamma\left(K_S^0\right) \simeq -\Gamma\left(K_S^0\right) \simeq -10^{-10}\ \text{s}^{-1}$$

$$\Delta M = M\left(K_L^0\right) - M\left(K_S^0\right) = (0.5304 \pm 0.0014) \times 10^{10}\ \text{s}^{-1}$$

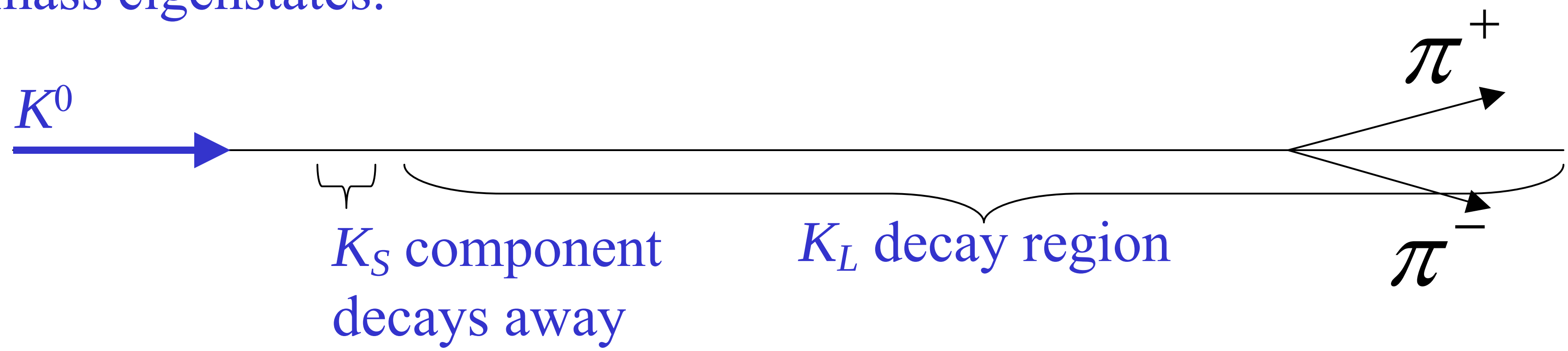
$$\simeq 3.5 \times 10^{-6}\ \text{eV}$$

$$\Delta\Gamma \approx -2\Delta M$$

The mass and lifetime splittings are comparable!

CP Violation in mixing: observation of $K_L \rightarrow \pi^+ \pi^-$

Exploit the large lifetime difference between the two neutral K mass eigenstates.



Demonstrates that $K_L{}^0$ decays into both CP=-1 (usually) and CP=+1 final states→ $K_L{}^0$ is not a CP eigenstate.

$$\eta_{+-} \equiv \frac{A\left(K_L^0 \rightarrow \pi^+\pi^-\right)}{A\left(K_S^0 \rightarrow \pi^+\pi^-\right)} \qquad \eta_{00} \equiv \frac{A\left(K_L^0 \rightarrow \pi^0\pi^0\right)}{A\left(K_S^0 \rightarrow \pi^0\pi^0\right)}$$

both are $2\text{x}10^{-3}$

Key point: K_L beam is "self-tagging." (Tagging = method in which we identify a particle P_1 by studying a particle P_2 that is produced in association with particle P_1.)

Experimental setup used for discovery of $K_L \rightarrow \pi^+\pi^-$

J.H. Christenson, J.W. Cronin, V.L. Fitch, and R.Turlay, Phys. Rev. Lett. 13, 138 (1964).

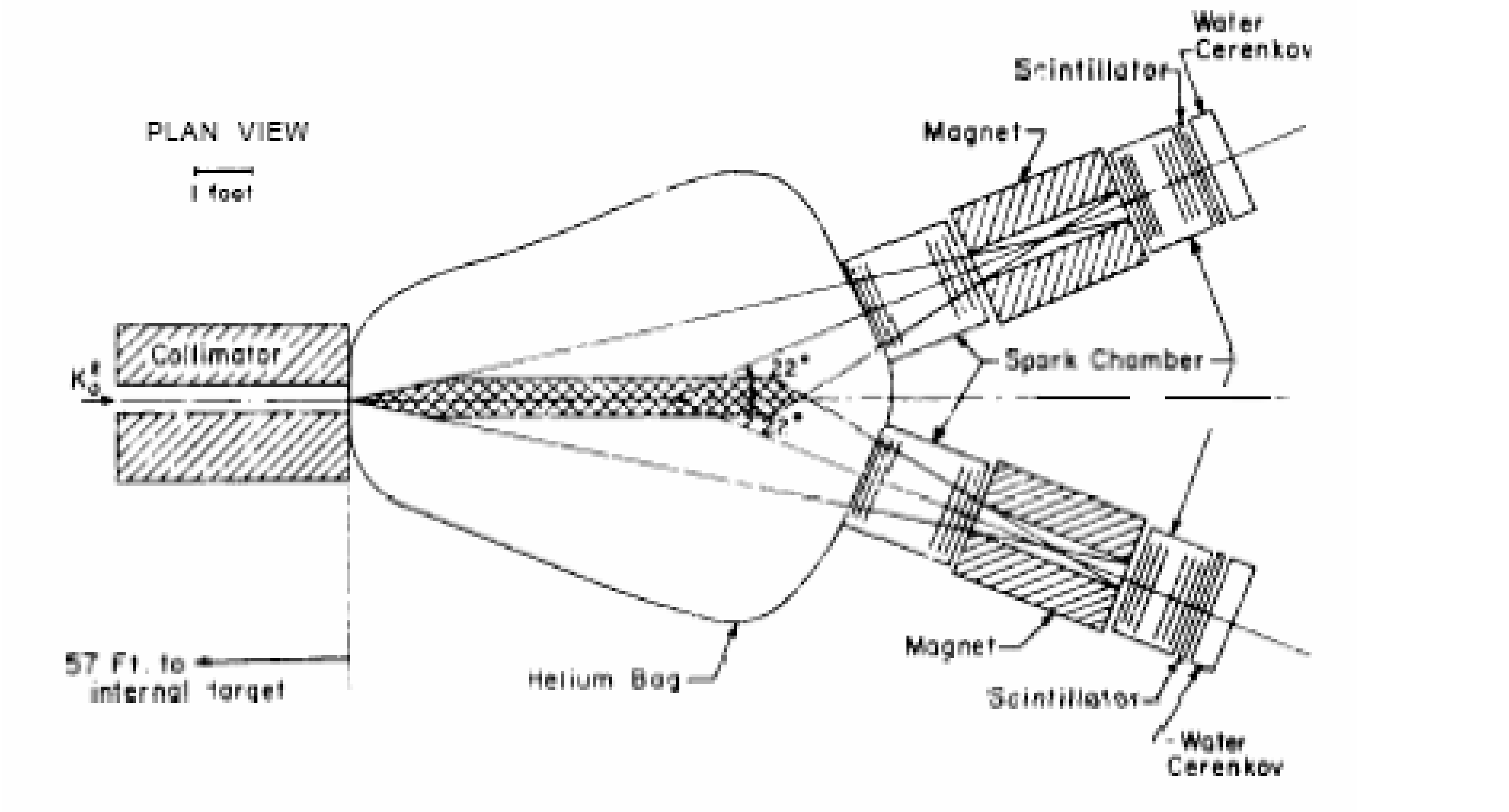


Fig. I. Plan view of the apparatus as located at the A. G. S.

Cosmology: Sakharov's three conditions

A. Sakharov (1967): How to generate an asymmetry between *N*(baryons) and *N*(anti-baryons) in the universe (assuming equal numbers initially)?

1. Baryon-number-violating process
2. Both C and CP violation (particle helicities not relevant to particle populations)
3. Departure from thermal equilibrium

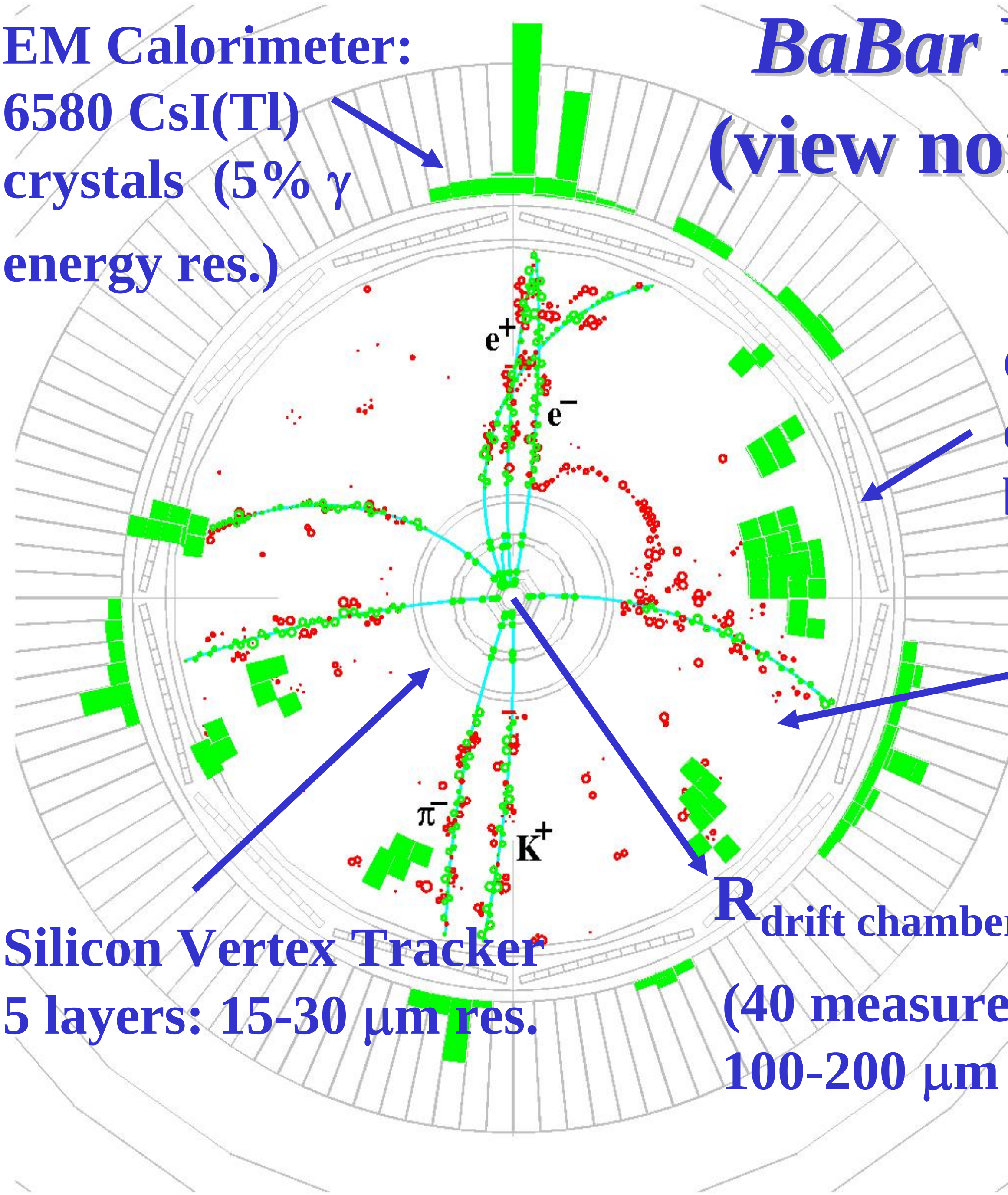
$$\left(N_{\text{bar}} - N_{\text{anti-bar}}\right) \propto \sum_i \left[\Gamma(X \to Y_i) - \Gamma(\bar{X} \to \bar{Y}_i)\right] \cdot \Delta B_i$$

hypothetical heavy particle

We appear to owe our existence to some form of CP violation at work in the early universe.

BaBar Event Display (view normal to beams)

EM Calorimeter:
6580 CsI(Tl) crystals (5% γ energy res.)



Cerenkov ring imaging detectors: 144 quartz bars (measure *velocity*)

Tracking volume:
B=1.5 T

$R_{\text{drift chamber}}$=80.9 cm

(40 measurement points, each with 100-200 μm res. on charged tracks)

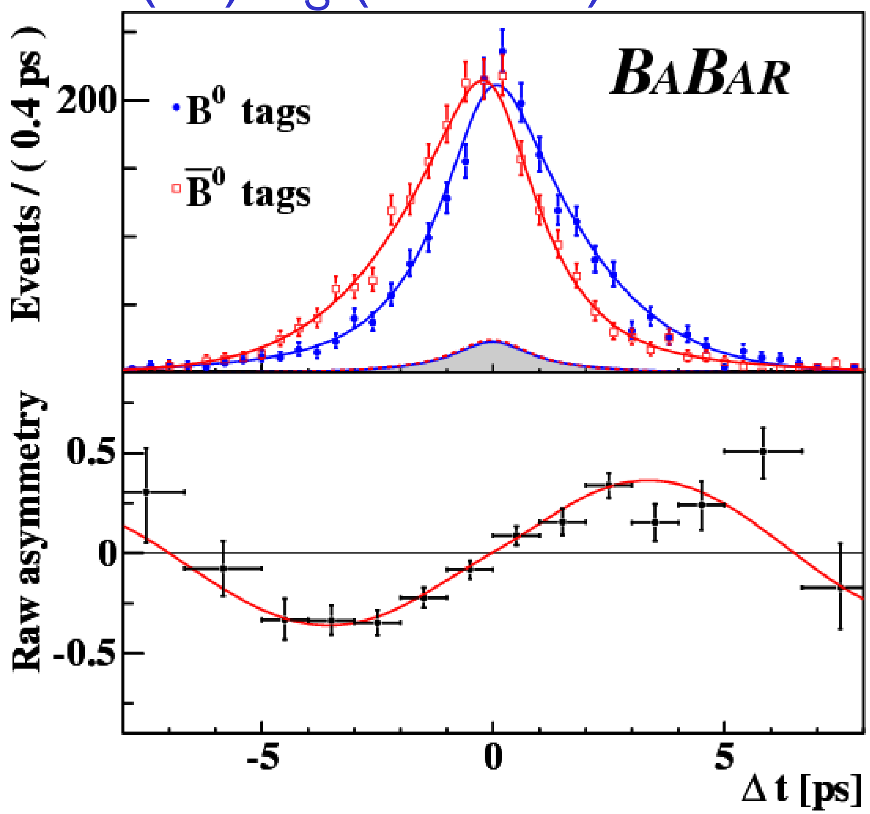
Silicon Vertex Tracker
5 layers: 15-30 μm res.

Systematic Uncertainties: small!

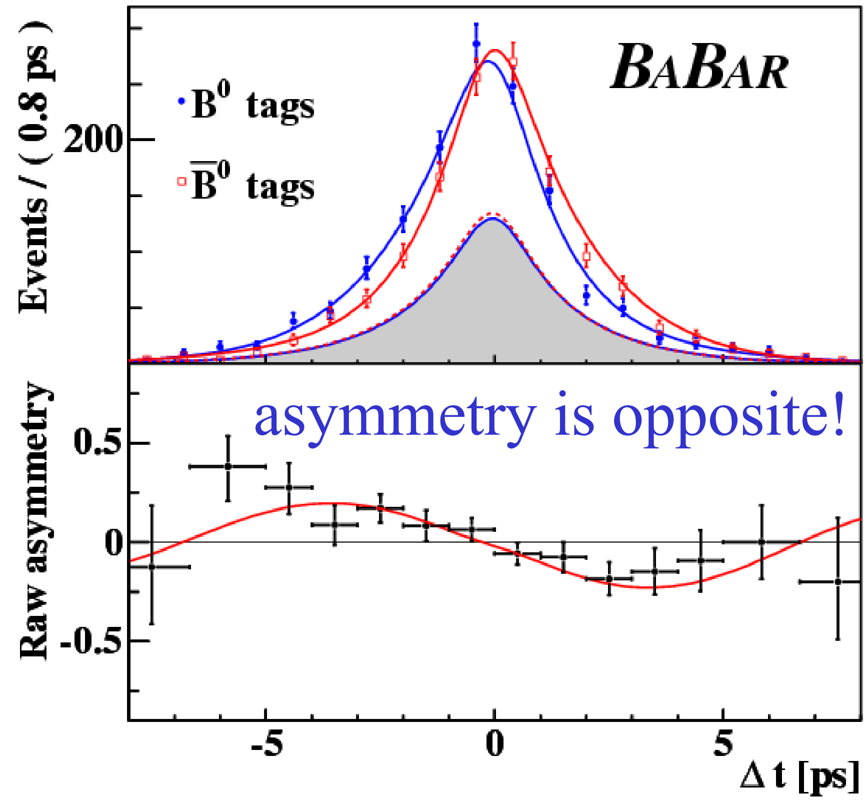
Source/sample		$J/\psi K_S^0(\pi^+\pi^-)$	$J/\psi K_S^0(\pi^0\pi^0)$	$\psi(2S)K_S^0$	$\chi_{c1}K_S^0$	$\eta_c K_S^0$	$J/\psi K^{*0}$
Beamspot	S_f	0.0027	0.0020	0.0078	0.0284	0.0010	0.0058
	C_f	0.0017	0.0032	0.0084	0.0115	0.0001	0.0001
Mistag differences	S_f	0.0075	0.0074	0.0089	0.0065	0.0064	0.0117
	C_f	0.0039	0.0046	0.0052	0.0067	0.0047	0.0019
Δt resolution	S_f	0.0072	0.0074	0.0072	0.0099	0.0163	0.0259
	C_f	0.0030	0.0043	0.0070	0.0039	0.0036	0.0062
$J/\psi K_L^0$ background	S_f	0.0001	0.0000	0.0001	0.0000	0.0001	0.0001
	C_f	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Background fraction	S_f	0.0032	0.0073	0.0156	0.0174	0.0506	0.0564
and CP content	C_f	0.0012	0.0034	0.0056	0.0098	0.0187	0.0256
m_{ES}	S_f	0.0021	0.0089	0.0238	0.0061	0.0023	0.0372
parameterization	C_f	0.0007	0.0063	0.0008	0.0017	0.0005	0.0080
$\Delta m_d, \tau_B, \Delta\Gamma_d/\Gamma_d$	S_f	0.0031	0.0073	0.0157	0.0025	0.0158	0.0140
	C_f	0.0014	0.0013	0.0010	0.0009	0.0020	0.0013
Tag-side interference	S_f	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014
	C_f	0.0143	0.0143	0.0143	0.0143	0.0143	0.0143
Fit bias	S_f	0.0048	0.0040	0.0079	0.0072	0.0073	0.0271
(MC statistics)	C_f	0.0042	0.0030	0.0019	0.0042	0.0070	0.0389
Total	S_f	0.0129	0.0179	0.0365	0.0398	0.0566	0.0876
	C_f	0.0160	0.0187	0.0209	0.0257	0.0271	0.0540

Results on sin2β from charmonium modes

$(c\bar{c})\ K_S$ (CP odd) modes



$J/\psi\ K_L$ (CP even) mode



$\sin 2\beta = 0.722 \pm 0.040\ (\text{stat}) \pm 0.023\ (\text{sys})$

$|\lambda| = 0.950$ +/- 0.031 (stat) +/- 0.013 (sys)

227 M $B\bar{B}$ events

(raw asymmetry shown above must be corrected for the dilution)

$B^0\overline{B}^0$ coherent wave function at the Υ(4S)

The B^0 and B^0 mesons are produced in a coherent quantum state.

$$\Upsilon(4S) \rightarrow \underbrace{B^0\overline{B}^0}$$

must be in a C= -1 state, since the Y(4S) decay is a strong interaction process and conserves C.

$$\left|\Psi(t_1,t_2)\right\rangle_{C=\pm 1} = \frac{1}{\sqrt{2}}\left(\left|B^0(t_1);\vec{p}\right\rangle\left|\overline{B}^0(t_2);-\vec{p}\right\rangle \pm \left|\overline{B}^0(t_1);\vec{p}\right\rangle\left|B^0(t_2);-\vec{p}\right\rangle\right)$$

Major implications

1. The asymmetry between the time-integrated decay rates is zero! At the Y(4S), you must measure Δt to perform a useful CP asymmetry measurement.
2. The two neutral B mesons oscillate coherently until one of them decays. (example of Einstein-Podolsky-Rosen paradox)