# CP Violation

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QMUL

# Overview

- The raison d'etre of the B-factories: testing the CKM mechanism:
  - The story so far: $\beta$, $\alpha$, $\gamma$, and direct CP violation.
- Our efforts in BaBar have led to the two most precise constraints on the CKM mechanism.

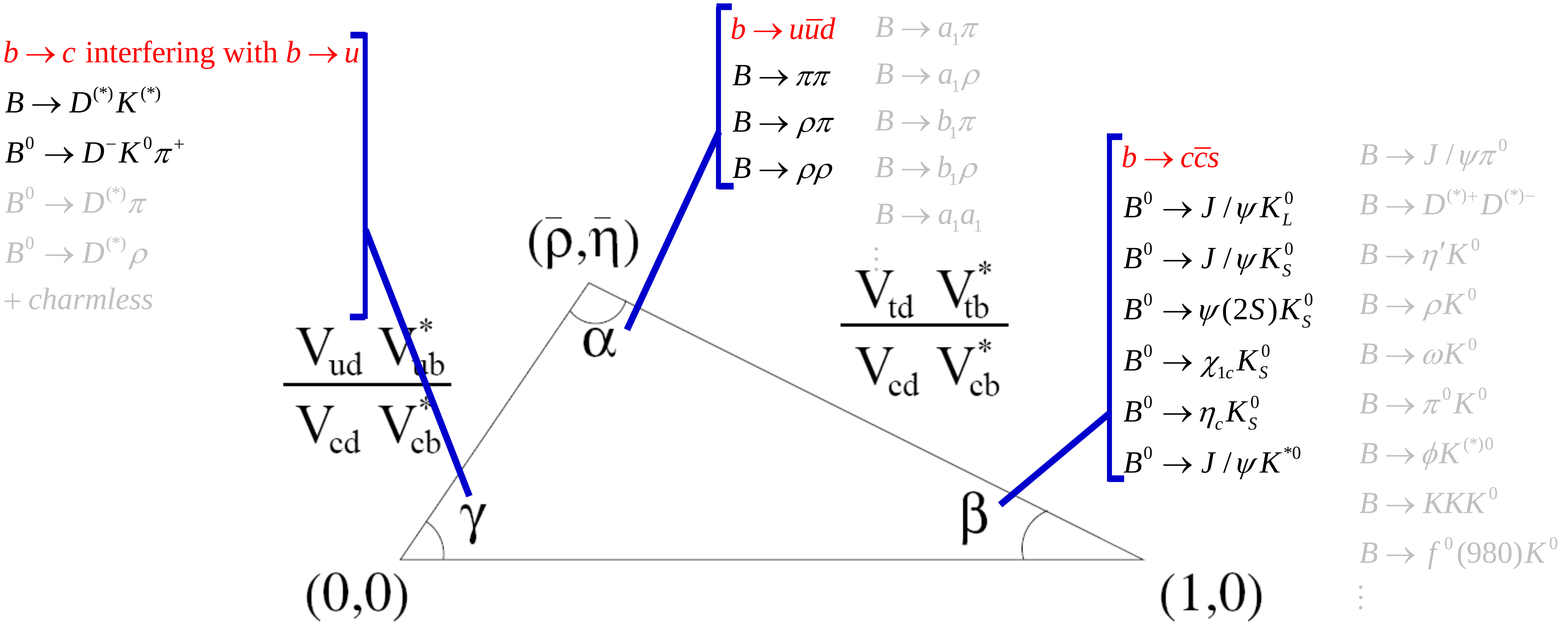
*"Please accept our deepest respect and gratitude for the B factory achievements. In particular, the high-precision measurement of CP violation and the determination of the mixing parameters are great accomplishments, without which we would not have been able to earn the Prize."*

小林誠 *(Makoto Kobayashi)*

益川敏英 *(Toshihide Maskawa)*

# Raison d'etre

- Test the CKM paradigm proposed in the 1973 paper by Kobayashi and Maskawa.
  - Introduces CP violation to the Standard Model of Particle Physics




- This talk will focus on BaBar's results from a few of the main measurements published over the past decade.

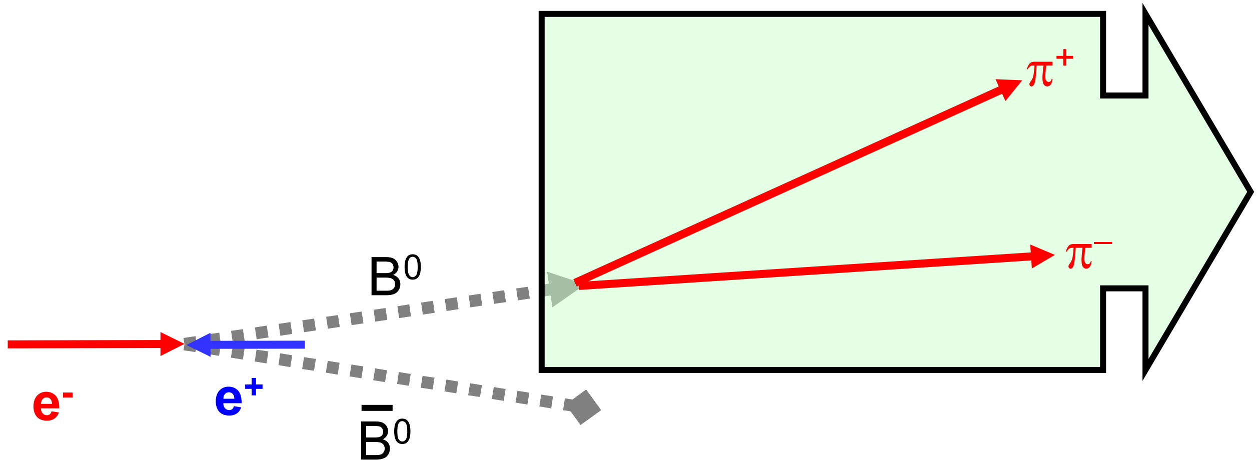
# Raison d'etre

- 1981: Bigi and Sanda realise that large CP violation effects could exist in the decay of B mesons.
  - The golden channel is $B^0 \to J/\psi K^0_S$.
  - Wasn't clear how to measure this effect: need to measure a tiny time difference: $\Delta t$ between B and $\overline{B}$ decays.
- 1987: P. Oddone realizes that PEP can be converted to an asymmetric energy $e^+e^-$ collider:
  - The B-Factories are born:

$$e^+e^- \to \Upsilon(4S) \to B\overline{B}$$

- 1993: President Clinton endorses the SLAC B-Factory
- 1999: First data taken!
- The KEK B-Factory also evolved on a similar timescale to start taking data in 1999.

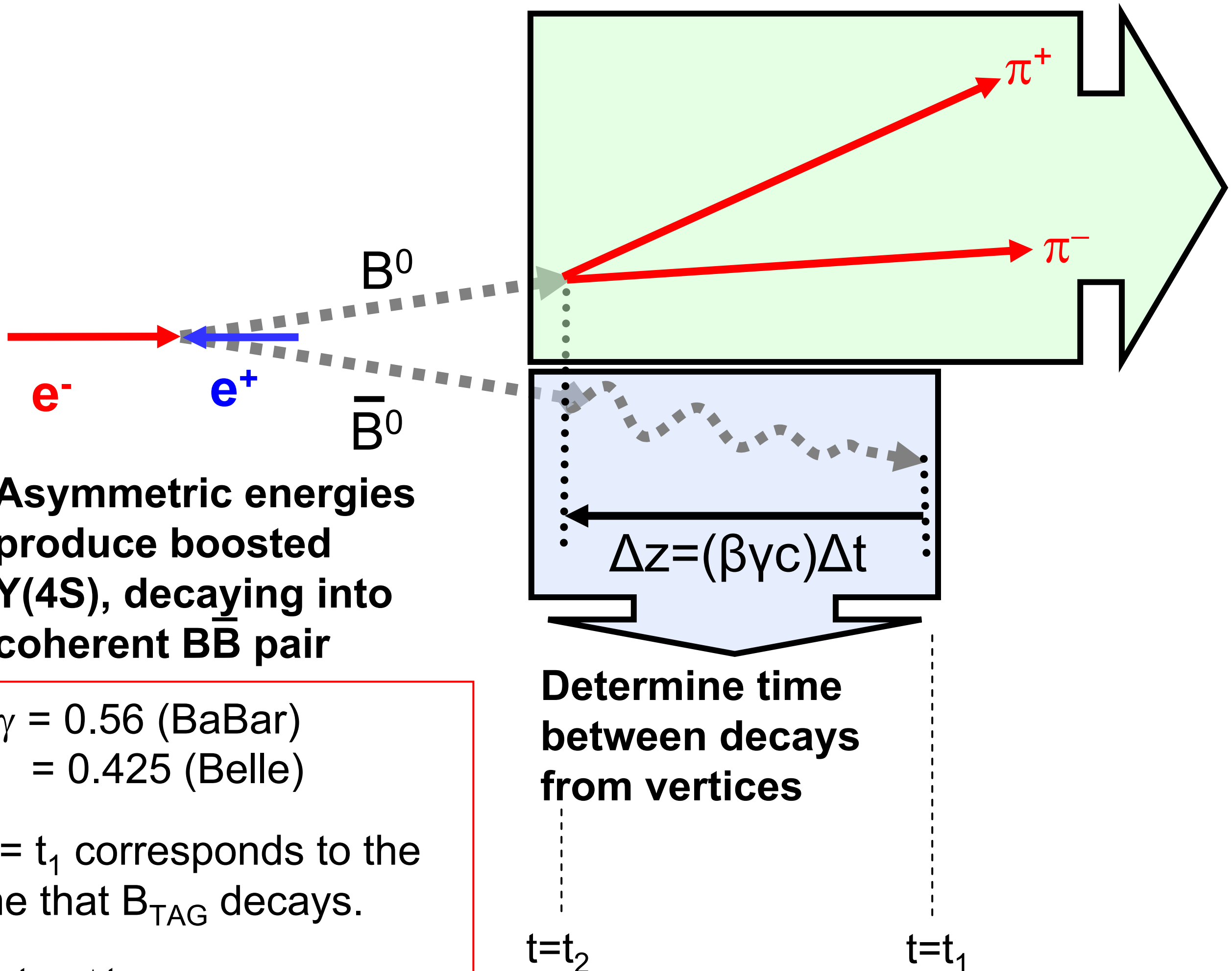
# Measuring Δt and B-tagging




**Fully reconstruct decay to state or admixture under study ($B_{REC}$)**

**Asymmetric energies produce boosted Υ(4S), decaying into coherent $B\bar{B}$ pair**

# Measuring Δt and B-tagging

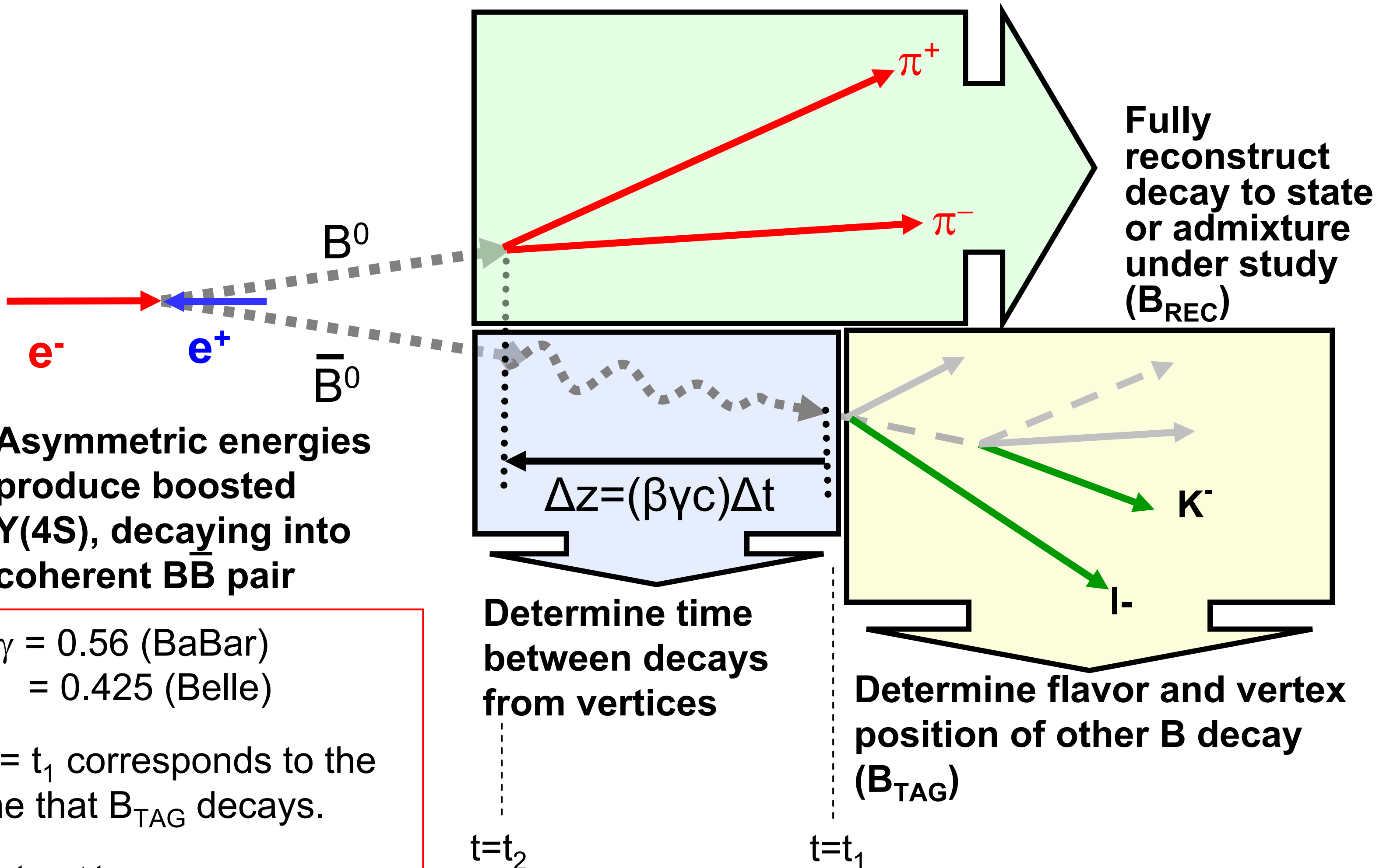



**Fully reconstruct decay to state or admixture under study ($B_{REC}$)**

**Asymmetric energies produce boosted Υ(4S), decaying into coherent $B\bar{B}$ pair**

- $\beta\gamma$ = 0.56 (BaBar)
  = 0.425 (Belle)
- $t = t_1$ corresponds to the time that $B_{TAG}$ decays.
- $t_2 - t_1 = \Delta t$

# Measuring $\Delta t$ and B-tagging

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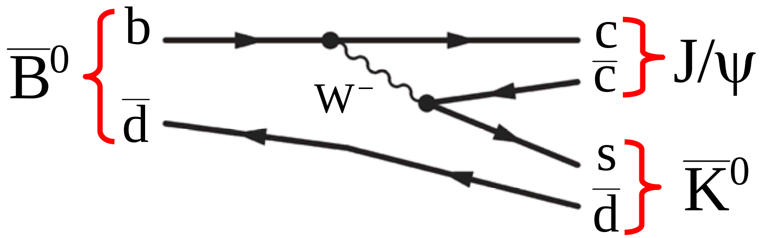
# $\beta$

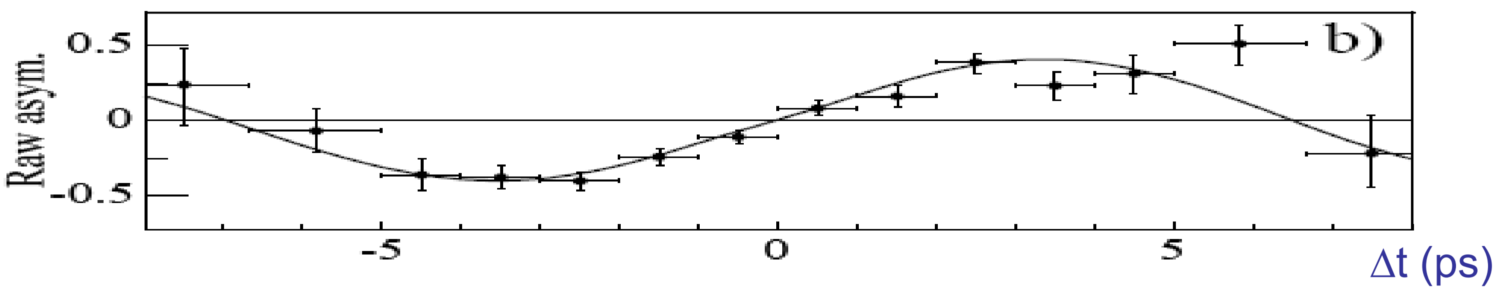
- Theoretically clean $c\bar{c}s$ decays to final states like $J/\psi K_S$




  - Interference with $B^0$-$\bar{B}^0$ mixing amplitude means this decay is sensitive to $\beta$.

- Measure asymmetry as a function of $\Delta t$:

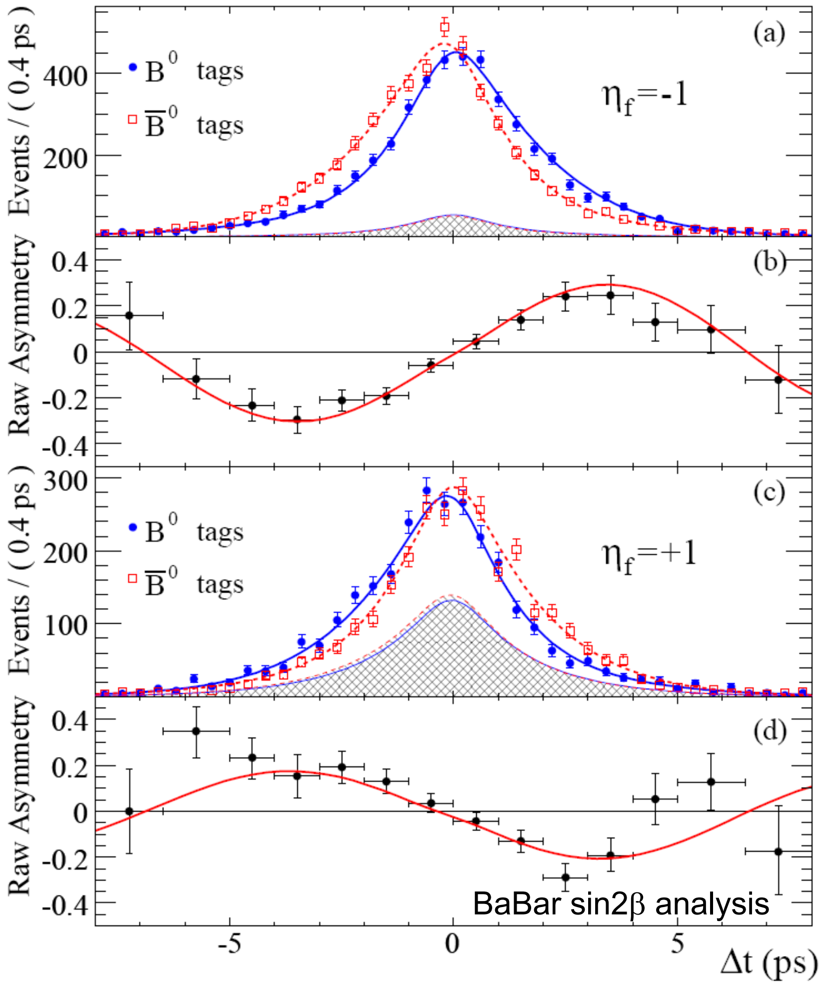
$$\mathcal{A}(\Delta t) = \frac{\Gamma(\Delta t) - \overline{\Gamma}(\Delta t)}{\Gamma(\Delta t) + \overline{\Gamma}(\Delta t)} = S\sin(\Delta m_d \Delta t) - C\cos(\Delta m_d \Delta t)$$



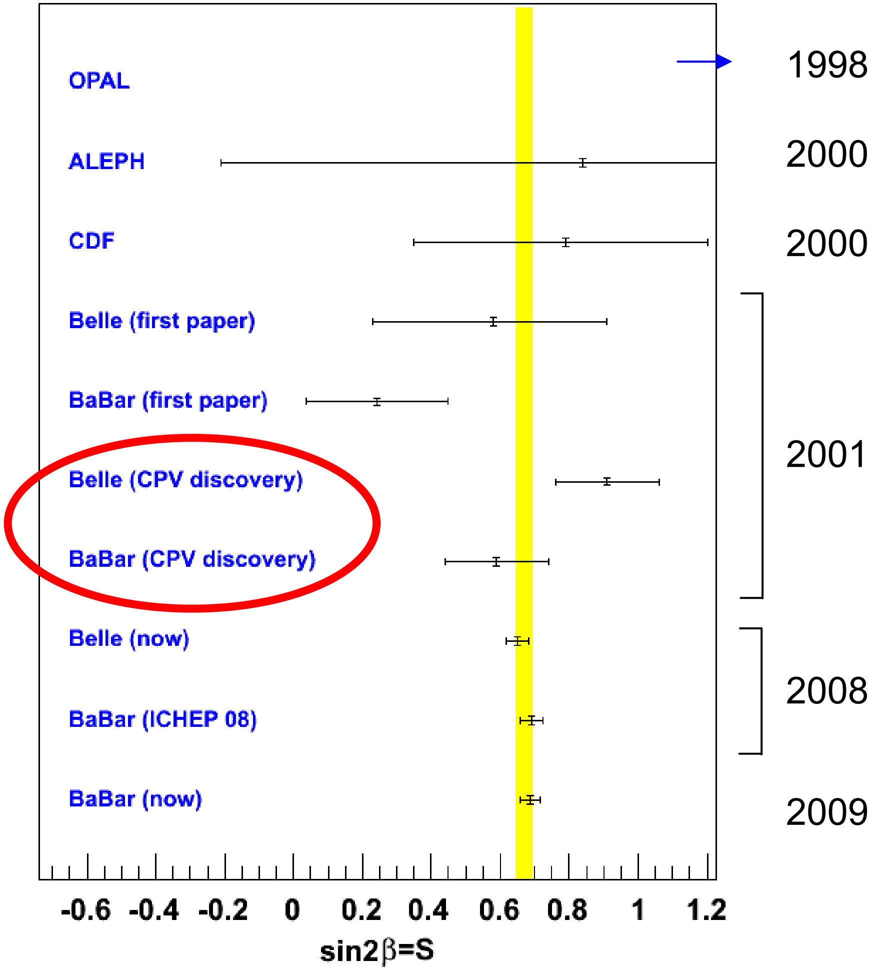

- A non-zero asymmetry is a sign of CP violation: $S \neq 0$, $C \neq 0$.

$$S = \sqrt{1 - C^2}\sin 2\beta$$

- CP Violation established in B decays in 2001!




$$\sin 2\beta = 0.687 \pm 0.028 \pm 0.012$$




Belle Collaboration, **98**, 031802 (2007)
Belle Collaboration, Phys. Rev. Lett. D **77**, 091103 (2008)
BaBar Collaboration, arXiv:0902.1708 (submitted to PRD)

# β

- Lunghi & Soni **Phys.Lett.B666:162-165,2008.**
  - Need to compare sin2β with theory prediction.
  - Is this a 2.1 – 2.7σ hint for new physics?

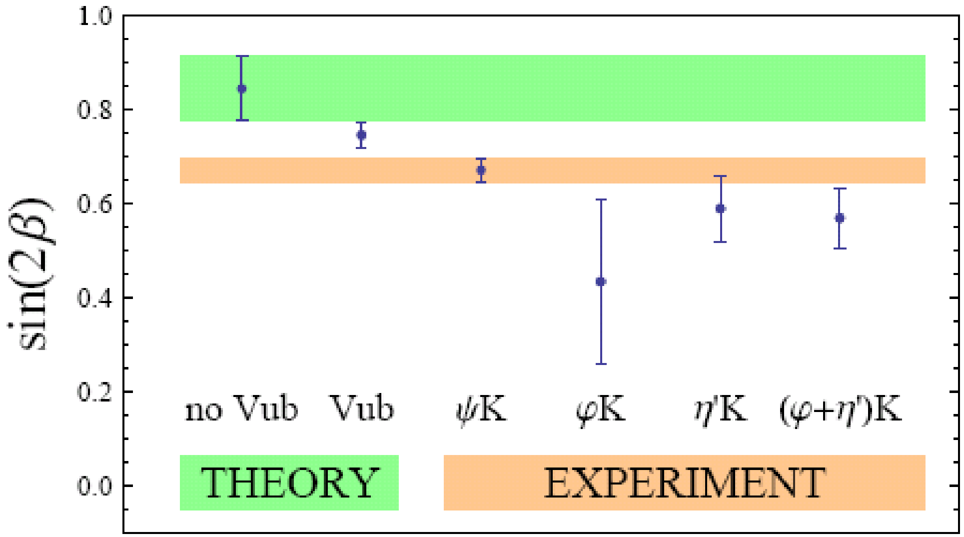
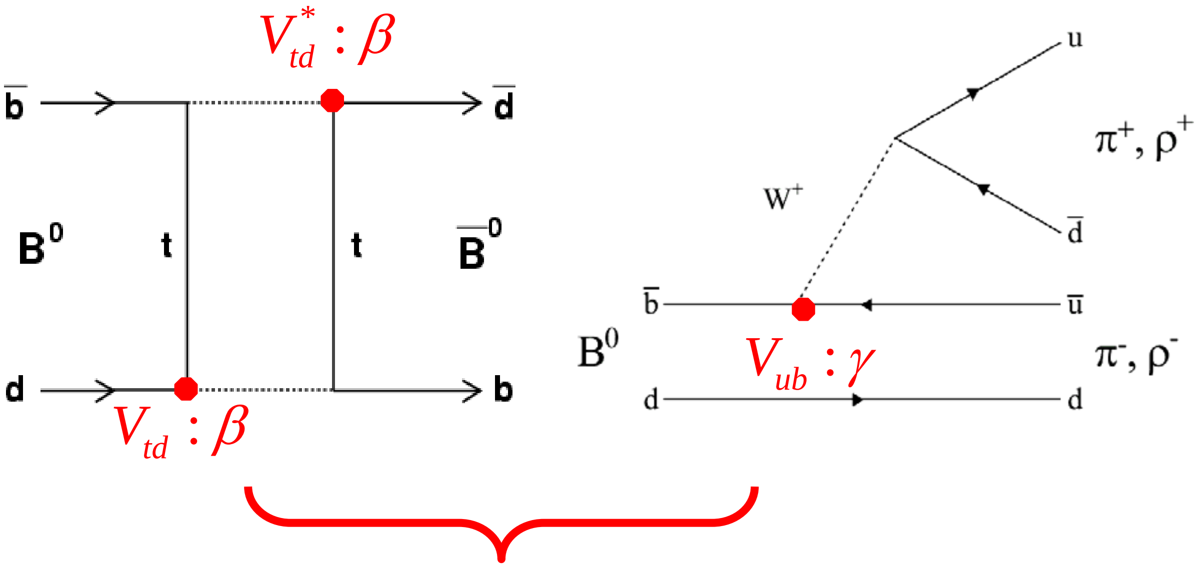



**Figure 2:** Comparison between the SM predictions Eq. (2.5) and the direct determinations in $b \to c\bar{c}s$ and $b \to s$ penguin modes.

- Complicated by significant loop contribution:




$$C_{hh} = 0$$

$$S_{hh} = \sin(2\alpha)$$

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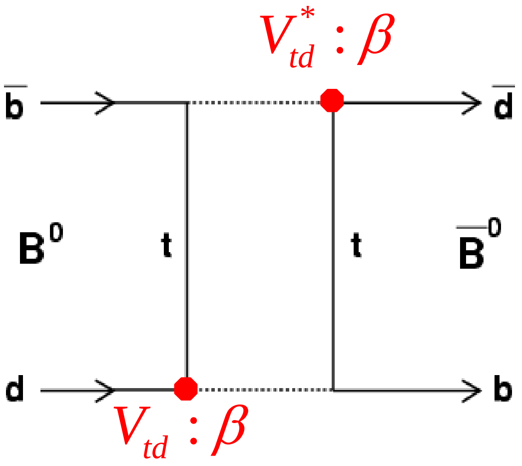
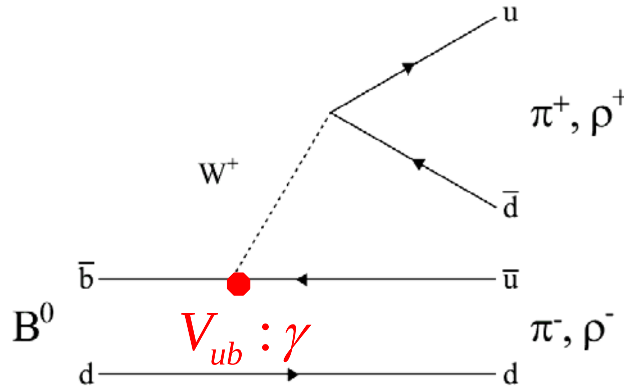
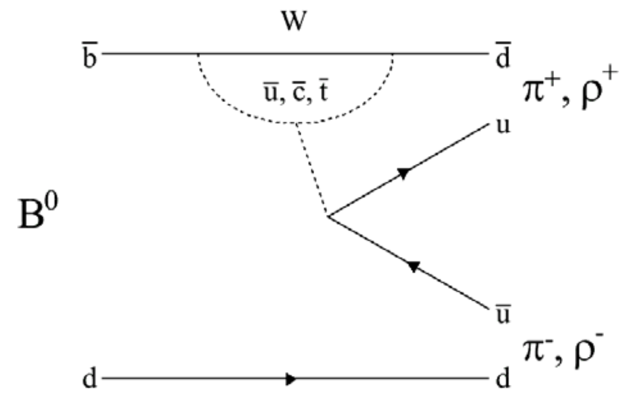



$$C_{hh} = 0$$

$$S_{hh} = \sin(2\alpha)$$

$$C_{hh} \propto \sin(\delta)$$

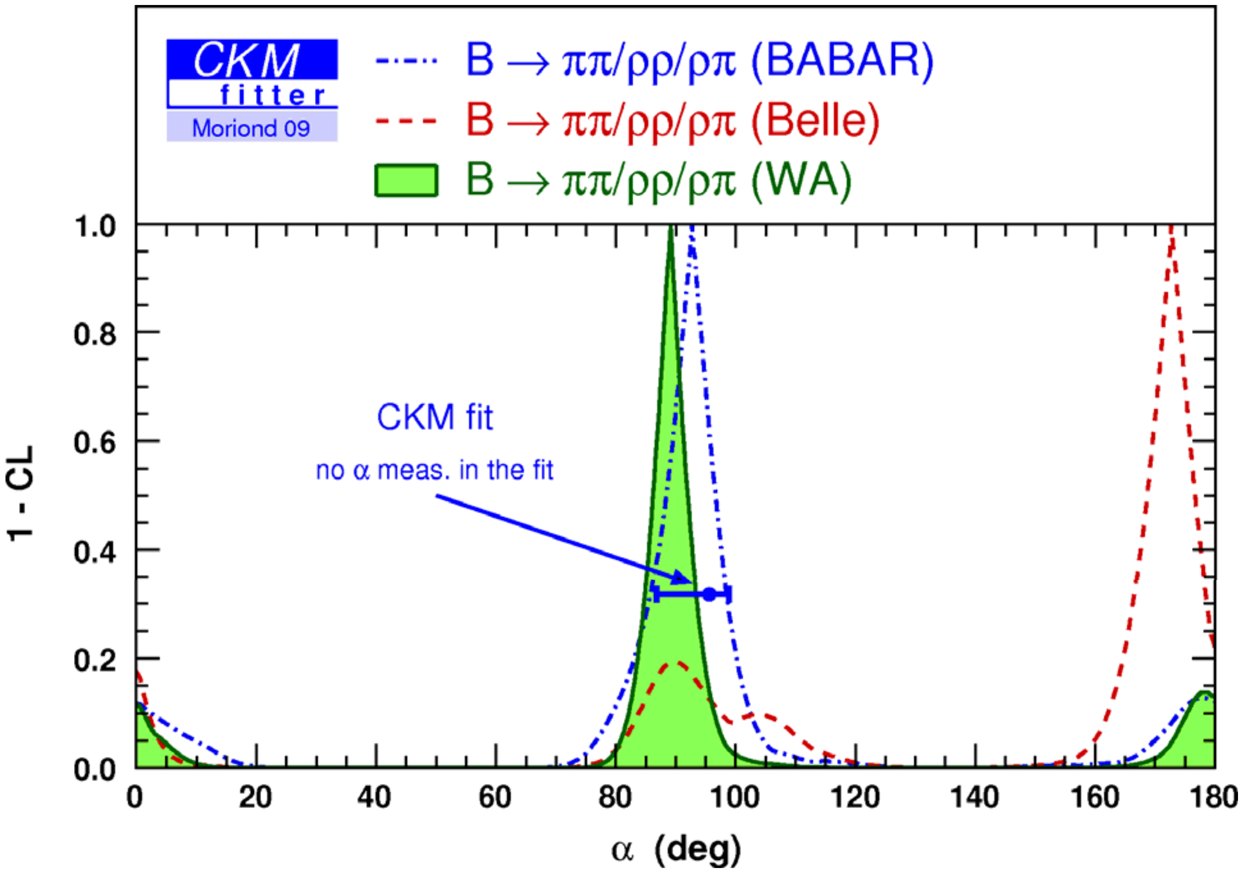
$$S_{hh} = \sqrt{1 - C_{hh}^2}\,\sin(2\alpha_{\mathrm{eff}})$$

$$\delta = \delta_P - \delta_T$$

- Have to constrain $\alpha - \alpha_{\mathrm{eff}}$
- Need to use ππ, ρπ, ρρ final states to measure this angle.

# α

- Two independent ways to interpret data SU(2) constraint shown




$$\alpha_{SU(2)} = \left(89.0^{+4.4}_{-4.2}\right)^{\circ} \qquad \alpha_{SU(3)} = \left(89.8^{+7.0}_{-6.4}\right)^{\circ}$$

# γ

- GGSZ ("Dalitz") Method: Study $D^{(*)0}K^{(*)}$ using the $D^{(*)0} \to K_s h^+ h^-$ Dalitz structure to constrain γ. (h = π, K)
  - Self tagging: use charge for $B^{\pm}$ decays or $K^{(*)}$ flavour for $B^0$ mesons.

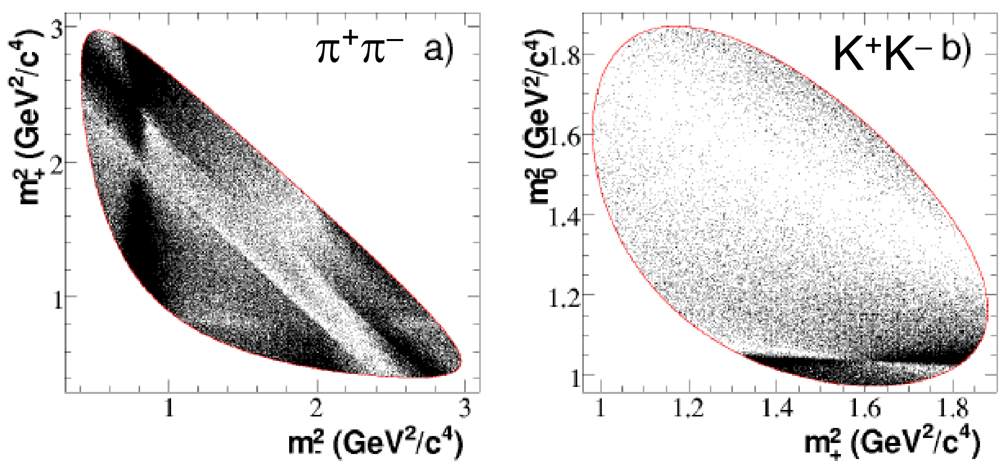
$$A(B^{\pm} \to (K_S^0 h^+ h^-)_D K^{\pm}) \propto f(m_+^2, m_-^2) + f(m_-^2, m_+^2) r_B e^{i(\delta_B \pm \gamma)}$$

where $m_{\pm} = m_{K_S^0 h^{\pm}}$

  - Need a detailed model of the amplitudes in the D meson Dalitz plot.

- Use a control sample (CLEO-c data or $D^{*+} \to D^0 \pi^+$) to measure the Dalitz plot.

$$D^{*+} \to D^0 \pi^-$$
$$\hookrightarrow D^0 \to K_S^0 h^+ h^-$$



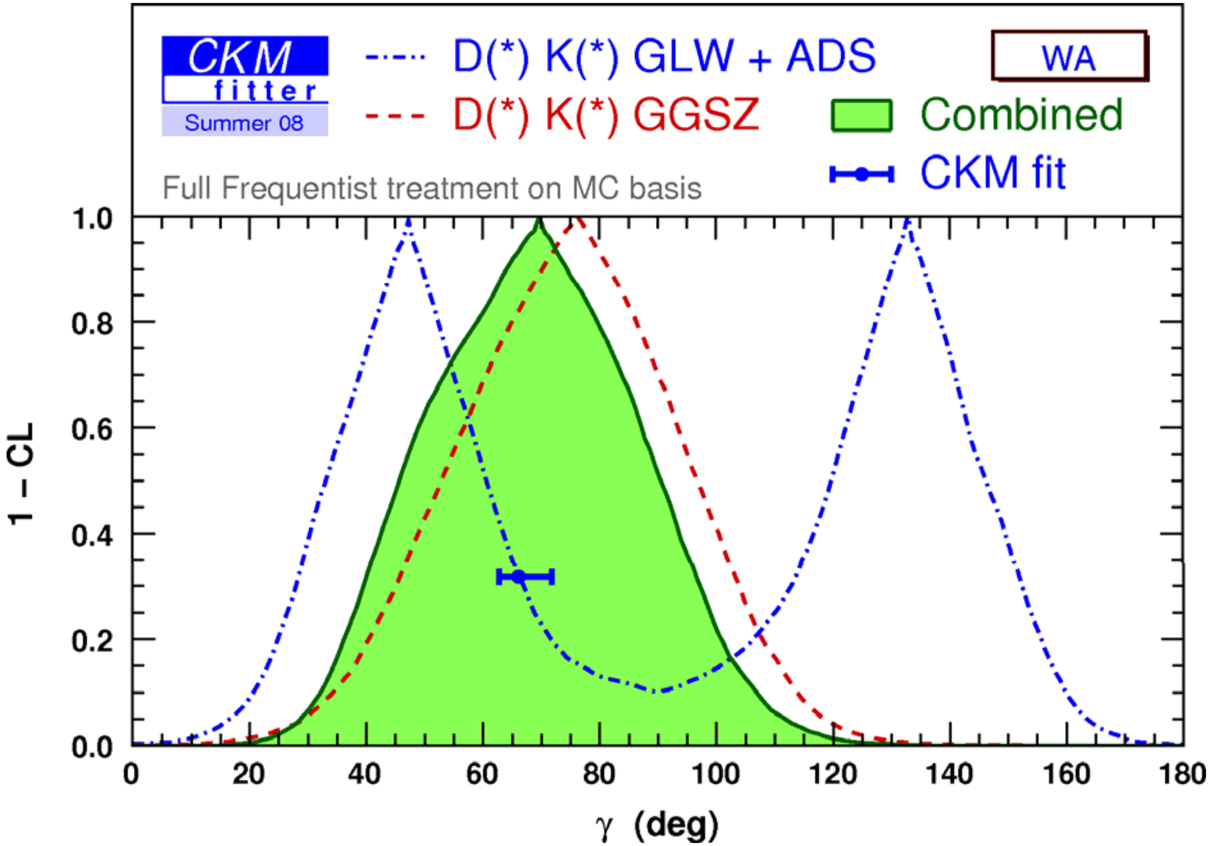

Control sample plots from BaBar GGSZ paper

- Other DK based methods important.

Giri, Grossman, Soffer, Zupan, PRD **68**, 054018 (2003)

# γ

- No single channel gives a precision measurement.
  - Need to study many channels and combine them:




$$\gamma = \left(70^{+27}_{-29}\right)^{\circ}$$

- Need next generation experiments to perform a precision measurement: e.g. LHCb/SuperB

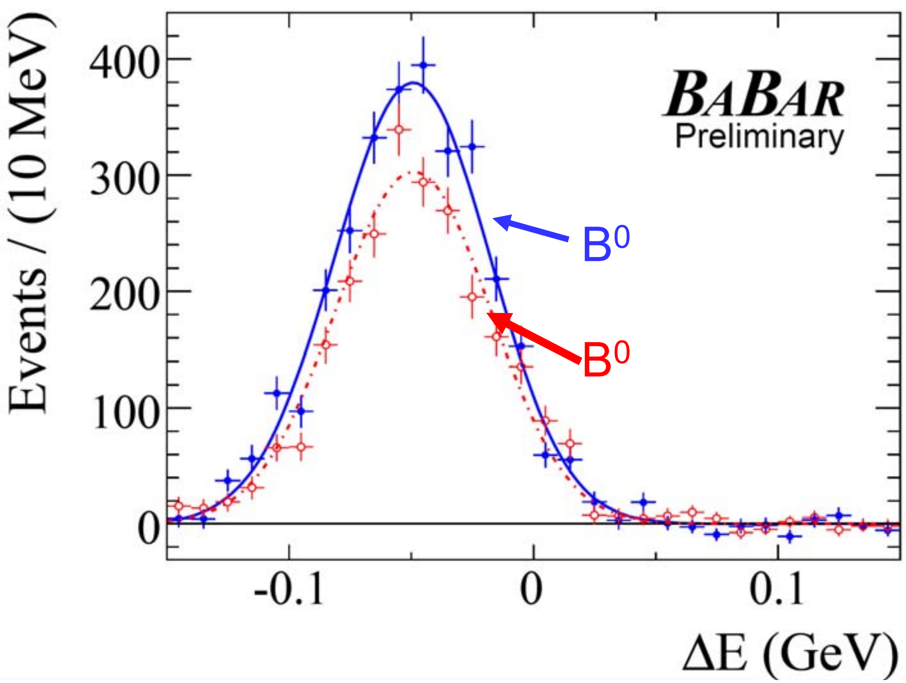
# Direct CP Violation

- This is a time integrated asymmetry:

$$A_{CP} = \frac{\overline{N} - N}{\overline{N} + N}$$

$N$ = # of $B$ decay to $f$
$\overline{N}$ = # of $\overline{B}$ decay to $\overline{f}$

$B \to K^{\pm}\pi^{\mp}$




$$A_{K^{\pm}\pi^{\mp}} = -0.107 \pm 0.016^{+0.006}_{-0.004}$$

(the asymmetry between the blue and red curves)

- This type of CP violation was discovered in 2007.

arXiv:0807.4226v2

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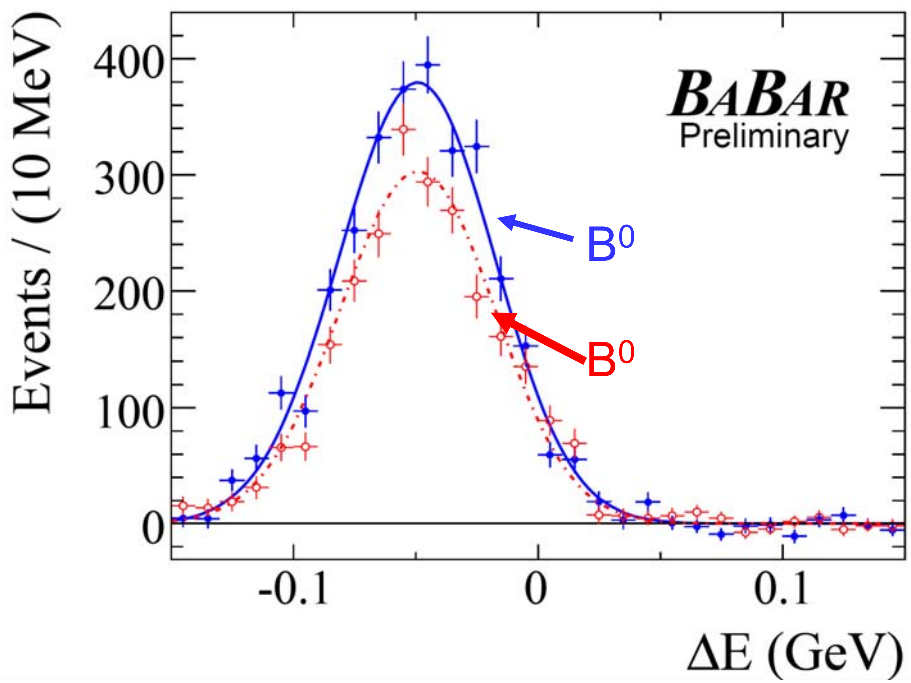


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**Soni/Cheng et al. note that:**

$$\Delta A_{K\pi} = A_{K^{\pm}\pi^{\mp}} - A_{K^{+}\pi^{0}} = (14.4 \pm 2.9)\%$$

This can not be accommodated in the Standard Model today.

**Is this another hint of new physics?**

- This type of CP violation was discovered in 2007.

arXiv:0807.4226v2

# Summary

- The past decade has confirmed that the CKM picture is the dominant contribution to CP violation in meson decay.

  $\alpha+\beta+\gamma=180^{\circ}$

- Precision of CKM tests have surpassed all expectations.
  - The CKM mechanism provides the 1st order description of nature!
  - New physics corrections can be 2nd order $\Rightarrow$ O(10%)!
    - **Are we starting to see these effects?**

- We continue to probe for discrepancies
  - The solution to the universal matter-antimatter asymmetry puzzle still eludes us.

- New physics scenarios have the '*flavour problem*' to solve:
  - How do we reconcile precision EW and FCNC data that prefer vastly different new physics energy scales.

- LHCb (+ upgrade), SuperB and Super-KEKB will take up the challenge of trying to solve this puzzle.