Measurement of the UT angle $\varphi_2(\alpha)$

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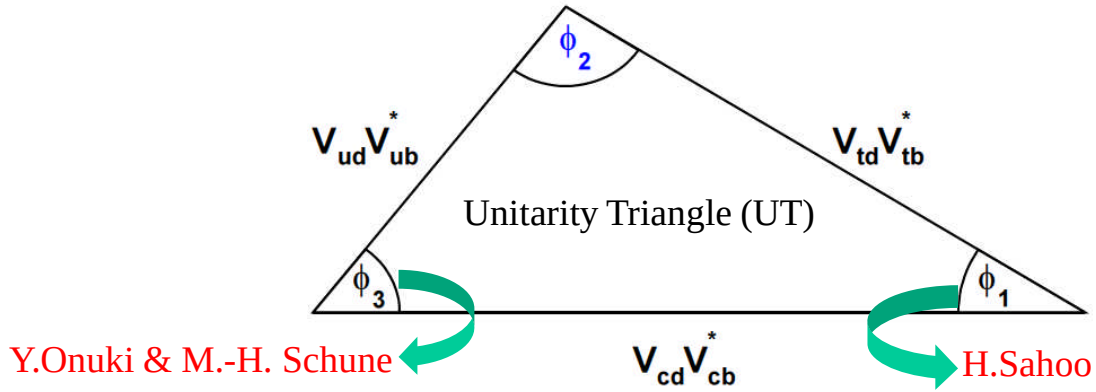
Talk Outline



BaBar notation:

$\varphi_1 = \beta$

$\varphi_2 = \alpha$

$\varphi_3 = \gamma$

- The UT Angle φ_2
  - $B \to \pi\pi$
  - $B^0 \to (\rho\pi)^0$
  - $B \to \rho\rho$
  - World Average
- The $B \to K\pi$ Puzzle
  - Current Status and Possible Way Ahead
- Summary and Prospect

Introduction

- At the *B* factories, measurement of the angle φ_2 derives from the time-dependent *CP* asymmetry in b→ u tree-dominated decays

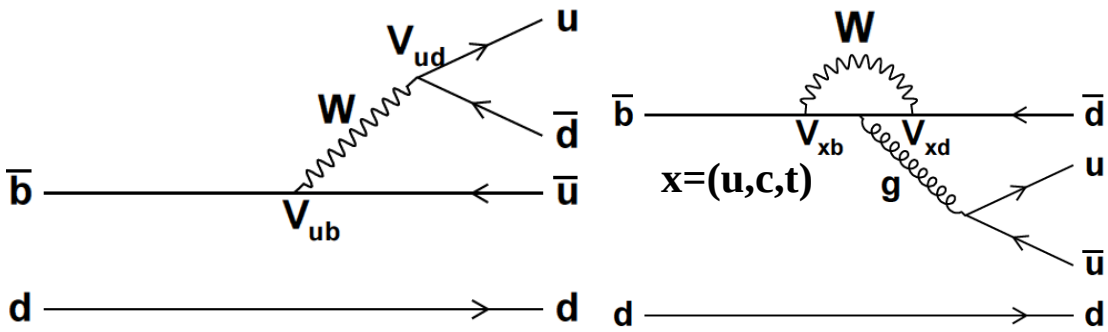
$$A_{CP}(f;t) \equiv \frac{\Gamma[\overline{B}(t)\to f]-\Gamma[B(t)\to f]}{\Gamma[\overline{B}(t)\to f]+\Gamma[B(t)\to f]} \equiv S_f \sin(\Delta m\, t) + A_f \cos(\Delta m\, t)$$

where *f* is a *CP* eigenstate, Δm is the mass difference between the two neutral *B* mesons, and

$$S_f = \frac{2\,\mathrm{Im}(\lambda)}{|\lambda|^2+1},\ A_f = \frac{|\lambda|^2-1}{|\lambda|^2+1} \text{ with } \lambda = e^{-i2\phi_1}\frac{\mathcal{A}(\overline{B}\to f)}{\mathcal{A}(B\to f)}$$

BaBar notation: $C_f = -A_f$

- Complications arise due to possible b→ d penguin contribution
  - Nonzero direct *CP* violation $A_f \neq 0$

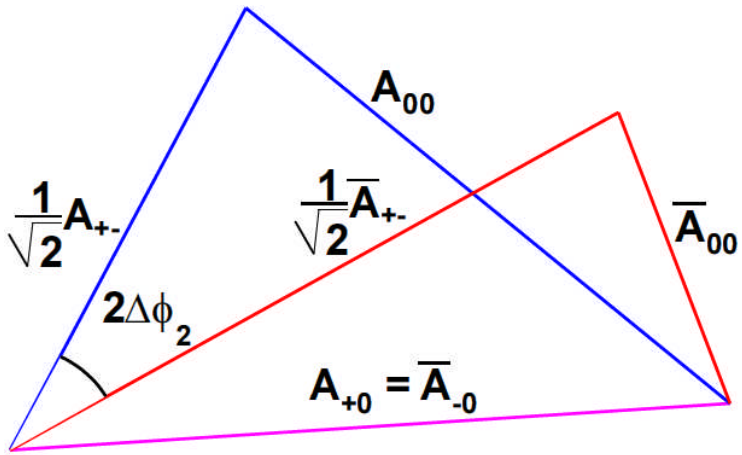


  - Measure $S_f = \sqrt{1-A_f^2}\,\sin 2\phi_2^{\mathrm{eff}}$ → $\phi_2^{\mathrm{eff}} = \phi_2 + \Delta\phi_2$

Measuring φ_2 in $B \to \pi\pi$

- Gronau and London proposed on how to recover φ_2 through an SU(2) isospin analysis

PRL 65, 3381 (1990)



  - Subscripts in A denote amplitudes of various $\pi\pi$ final states
- Few observations:
  - $B^+ \to \pi^+\pi^0$ is a pure tree mode ➡ neglecting electroweak penguin contributions, $A_{+0} = \bar{A}_{-0}$
  - Four-fold discrete ambiguity in the extraction of $2\Delta\varphi_2$
- φ_2 can be determined using the following six observables

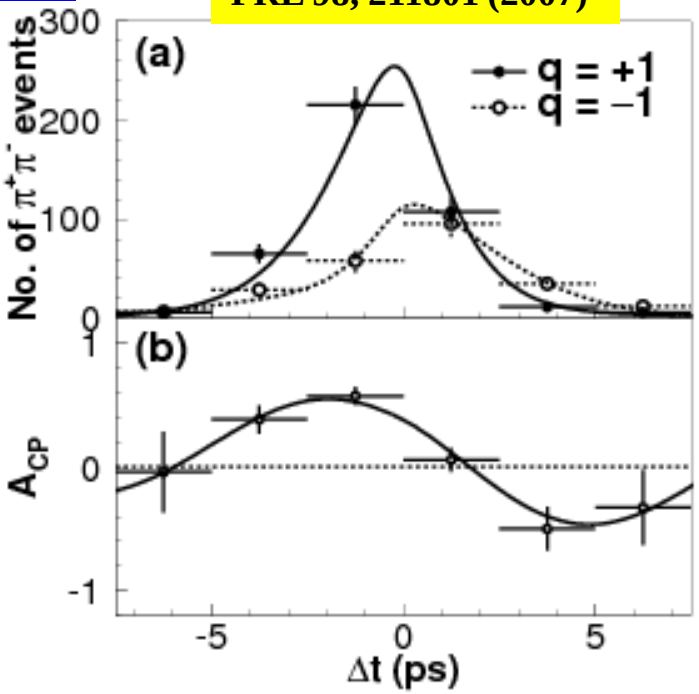
$$\boxed{\mathcal{B}(B^0 \to \pi^+\pi^-)} \quad \boxed{\mathcal{B}(B^+ \to \pi^+\pi^0)} \quad \boxed{\mathcal{B}(B^0 \to \pi^0\pi^0)}$$

$$\boxed{A_f(B^0 \to \pi^+\pi^-)} \quad \boxed{S_f(B^0 \to \pi^+\pi^-)} \quad \boxed{A_f(B^0 \to \pi^0\pi^0)}$$

Results on $B^0 \to \pi^+\pi^-$

535×10^6 $B\bar{B}$

PRL 98, 211801 (2007)

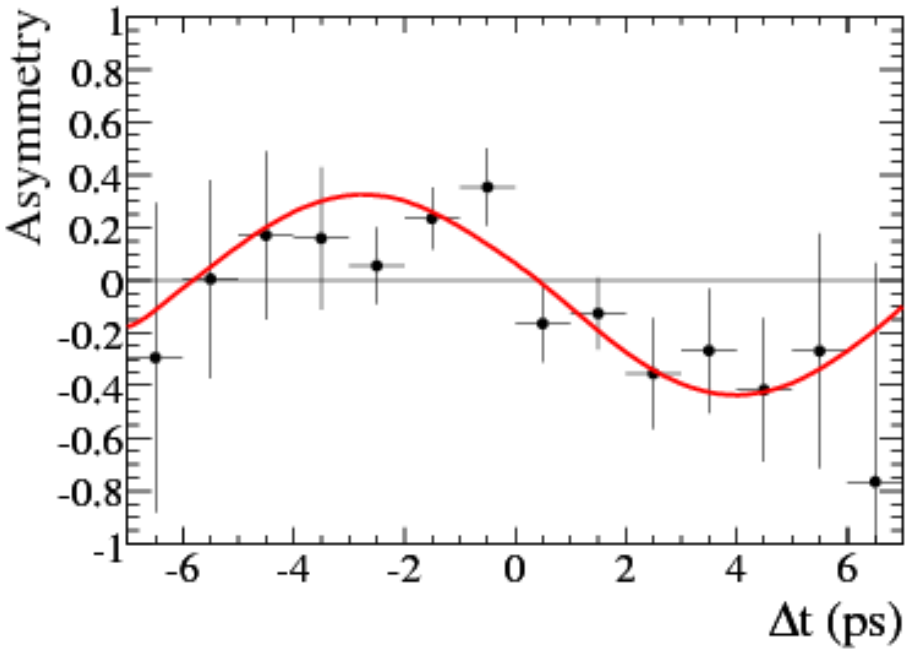


$$A_{\pi\pi} = +0.55 \pm 0.08 \pm 0.05$$

$$S_{\pi\pi} = -0.61 \pm 0.10 \pm 0.04$$

467×10^6 $B\bar{B}$

arXiv:0807.4226 (2008)



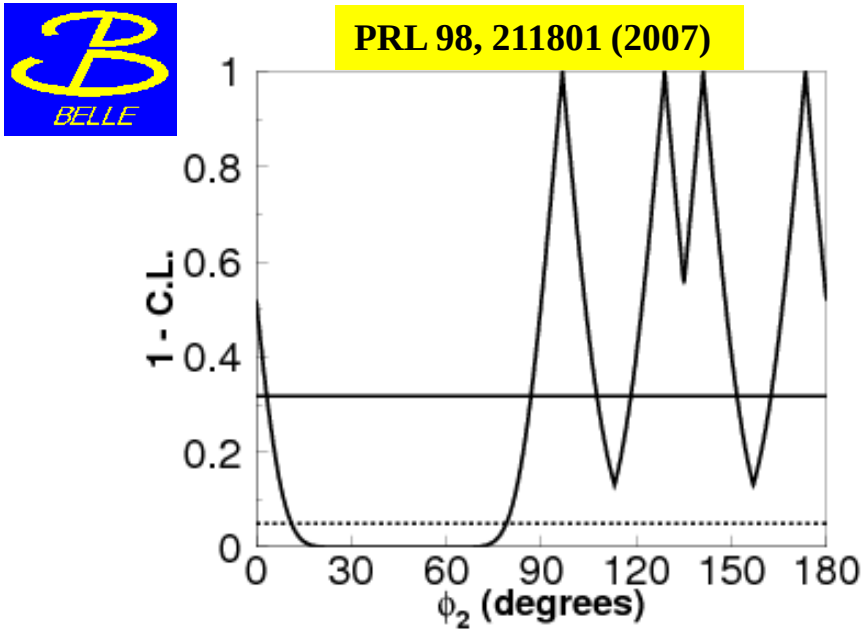
$$C_{\pi\pi} = -0.25 \pm 0.08 \pm 0.02$$

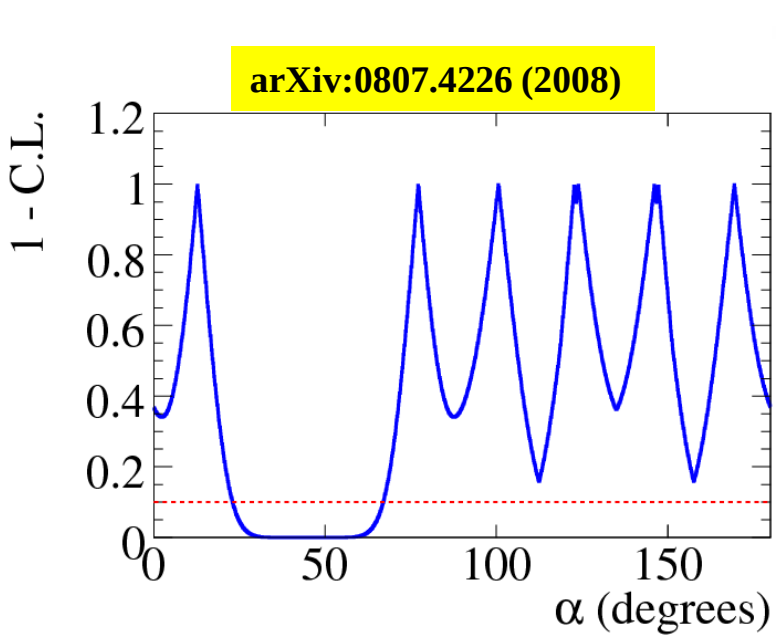
$$S_{\pi\pi} = -0.68 \pm 0.10 \pm 0.03$$

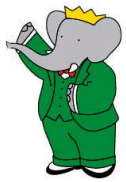
- Both find clear evidence for mixing-induced *CP* violation (*S*); for *A* (−*C*) the significance of Belle (BaBar) is 5.5σ (3.0σ)

Results on φ_2 from $B \to \pi\pi$

- Perform isospin analysis:
  - Scan for φ_2 and calculate χ^2 for the five amplitudes ($\overline{A}_{+-}$, $\overline{A}_{00}$, A_{+0}, A_{+-} and A_{00})







- Out of four different solutions, the one consistent with the SM inferred value is $\varphi_2 = (97\pm11)^o$
- $[11^o,79^o]$ excluded at 95% C.L.

- The range $[23^o,67^o]$ is excluded at the 90% C.L.
- For the SM-preferred solution, the 1σ range for α is $[71^o,109^o]$

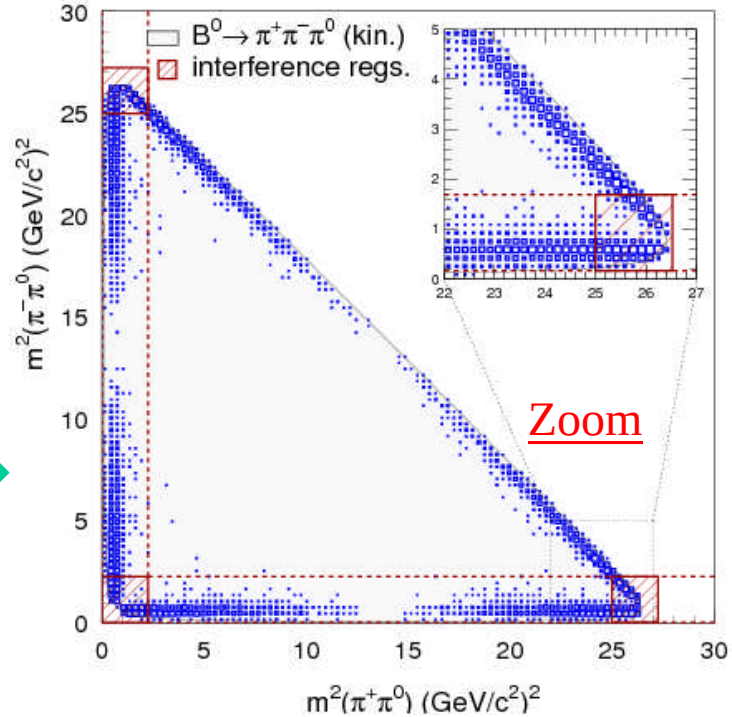
Measuring φ_2 in $B^0 \to (\rho\pi)^0$

Issues at hand:

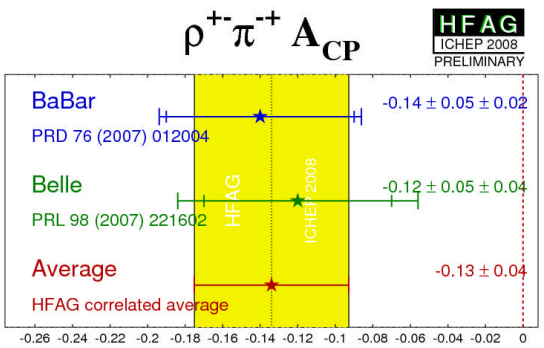
- Not a *CP* eigenstate ➡ S_f and A_f also contain a *CP* conserving part
- Has four isospin (0,1 and 2) amplitudes
  - ➢ 12 unknowns in the isospin pentagon

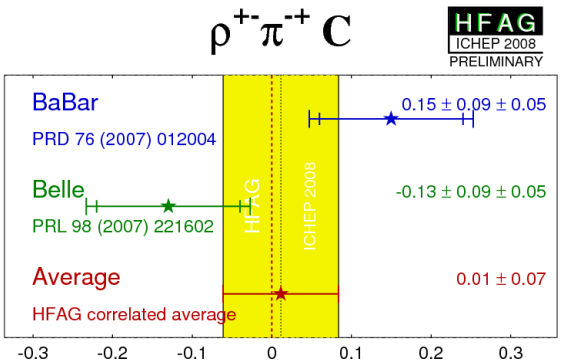
Snyder-Quinn approach: **PRD 48, 2139 (1993)**

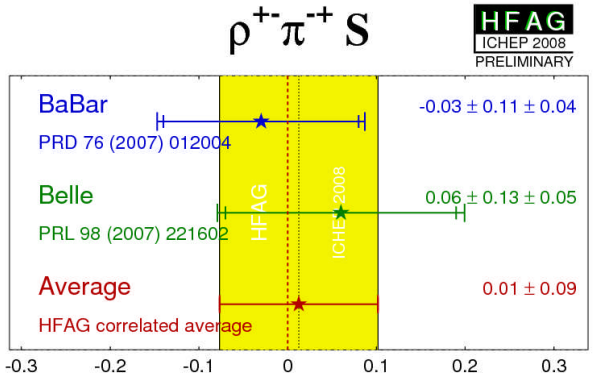
- Time-dependent Dalitz plot analysis (TDPA) of $B^0 \to \rho\pi \to \pi^+\pi^-\pi^0$ to constrain φ_2 without any discrete ambiguity
  - ➢ Exploit the variation of the strong phase of interfering ρ resonances over the Dalitz plot ➡



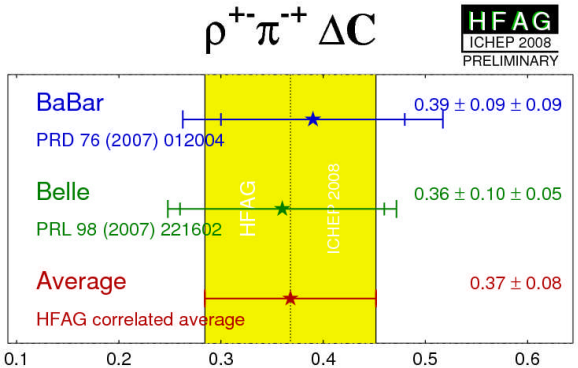
Results from Belle and BABAR

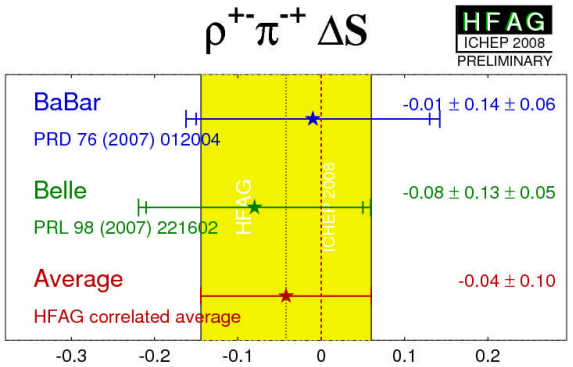


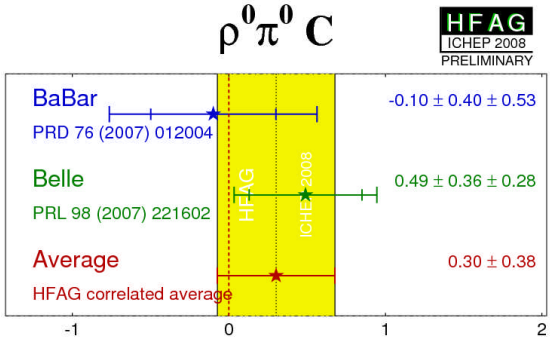


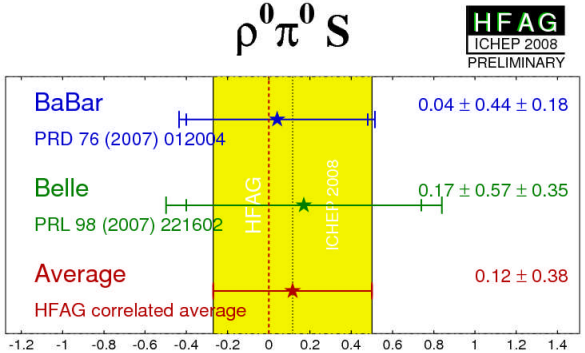


- Good agreement between the two experiments
- 3σ evidence for time- and flavor-integrated *CP* asymmetry (see the top left plot)
- Δ*S* and Δ*C* are *CP* conserving part of *S* and *C* (−*A*)



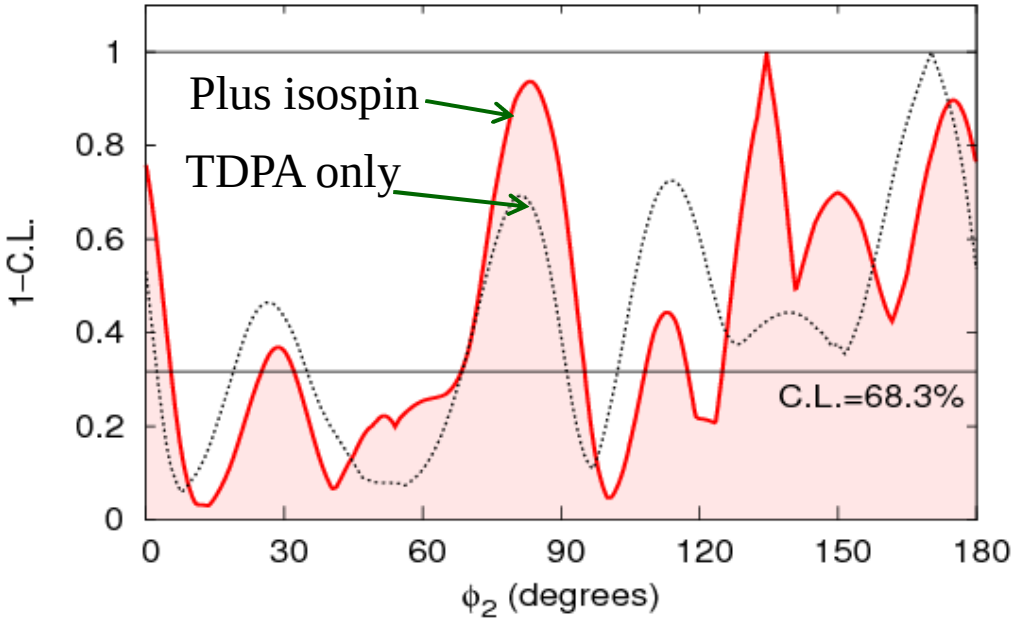




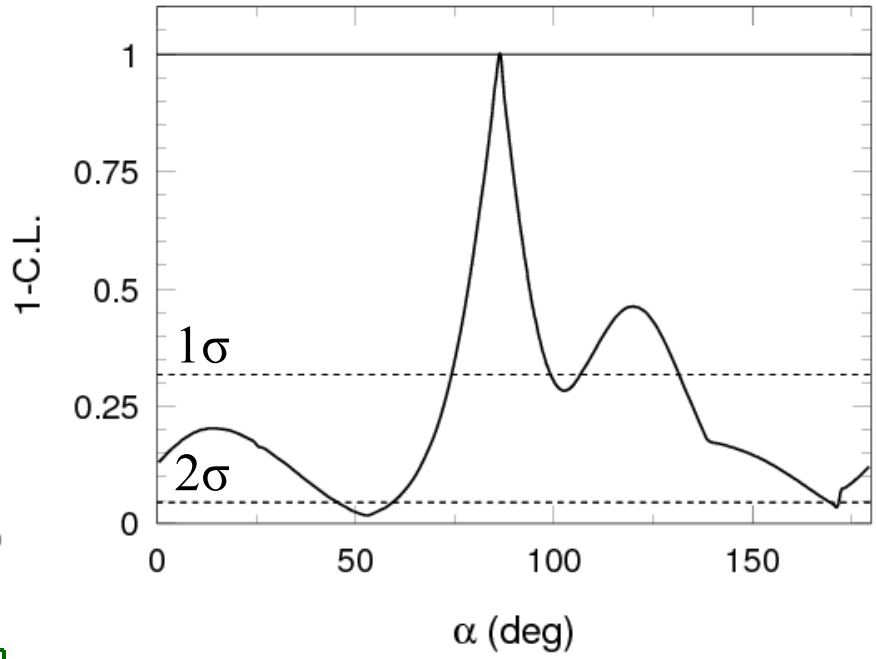


Results on φ_2 from $B^0 \to (\rho\pi)^0$

PRD 77, 072001 (2008)



PRD 76, 012004 (2007)

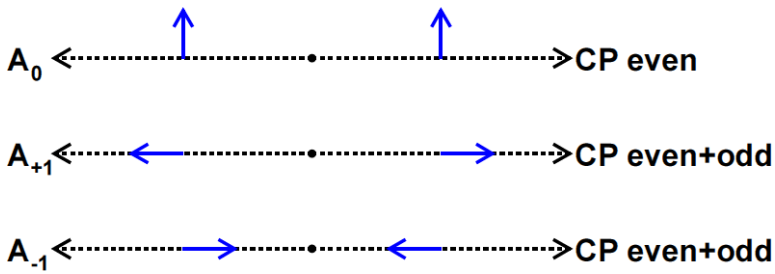


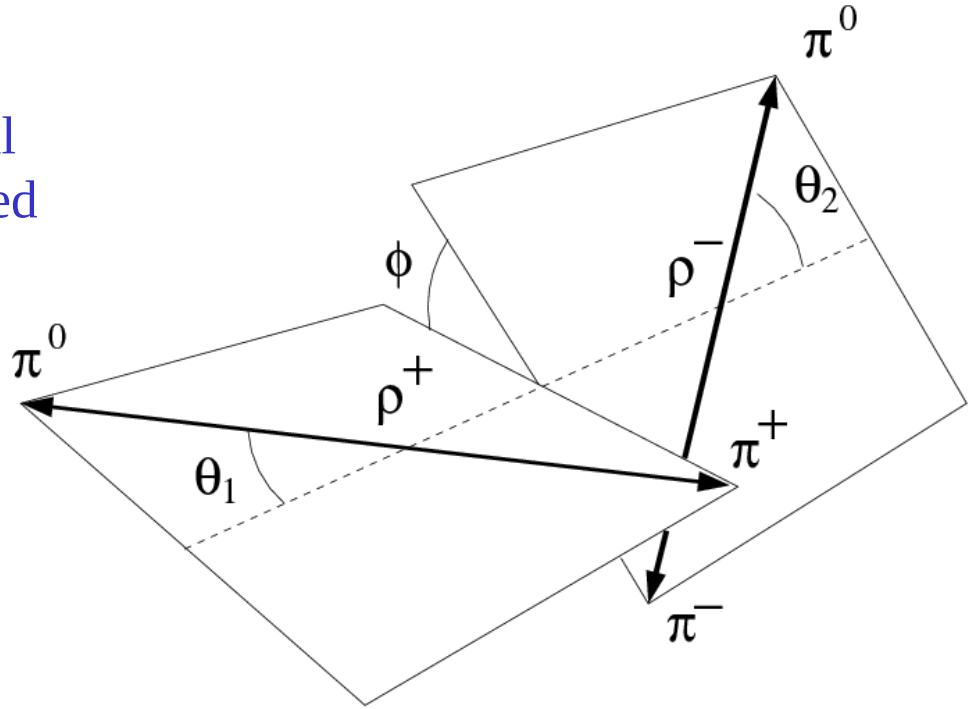
- For Belle:
  - $68^o < \varphi_2 < 95^o$ at 68.3% C.L.
  - Using world-average BF and A_{CP} values of $B^+ \to \rho^0\pi^+$ and $\rho^+\pi^0$
- BaBar measures:
  - $\alpha = \left(87^{+45}_{-13}\right)^\circ$
- Promising method (no discrete ambiguity), but don't have enough data for a compelling result ➡ no constraint on φ_2 at 2σ level

Measuring φ_2 in $B \to \rho\rho$

Pseudoscalar → Vector Vector

- Final state contains one longitudinal (*CP* even) and two transverse (mixed *CP*) amplitudes in the helicity basis





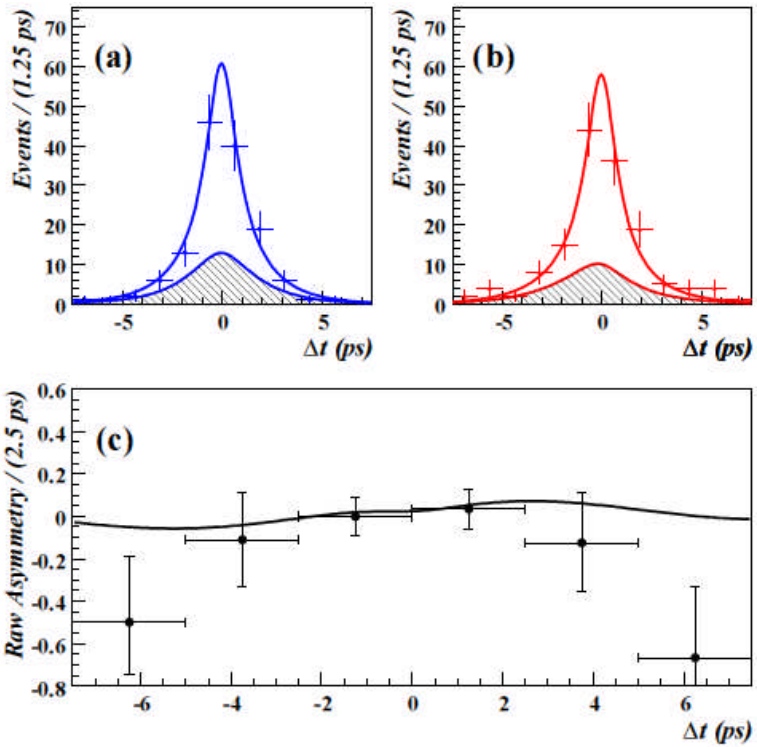
Integrating over ϕ, the angular decay rate:

$$\frac{d^2N}{d\cos\theta_1\, d\cos\theta_2} = \underbrace{4 f_L \cos^2\theta_1 \cos^2\theta_2}_{\text{Longitudinal}} + \underbrace{(1-f_L)\sin^2\theta_1 \sin^2\theta_2}_{\text{Transverse}}$$

- Measure the branching fraction (BF) and the fraction of longitudinal polarization (f_L) simultaneously

Results on $B^0 \to \rho^+\rho^-$

$535\times10^6\ B\bar{B}$ **PRD 76, 011104 (2007)**

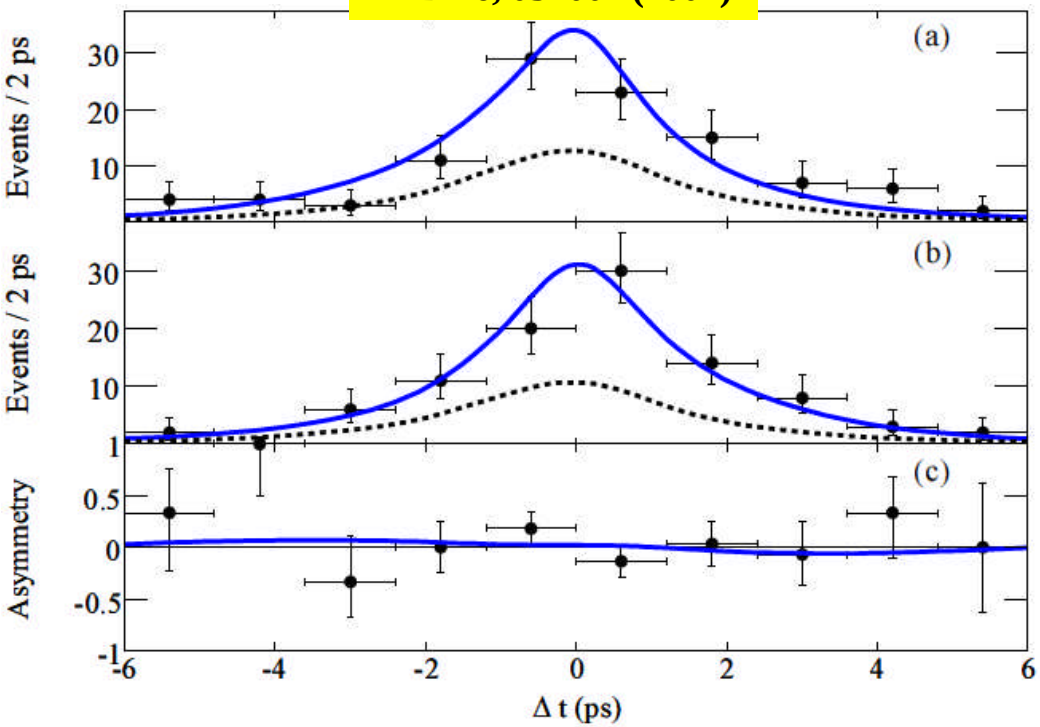


$$A_{\rho^+\rho^-} = +0.16 \pm 0.21 \pm 0.07$$

$$S_{\rho^+\rho^-} = +0.19 \pm 0.30 \pm 0.07$$

$384\times10^6\ B\bar{B}$

PRD 76, 052007 (2007)



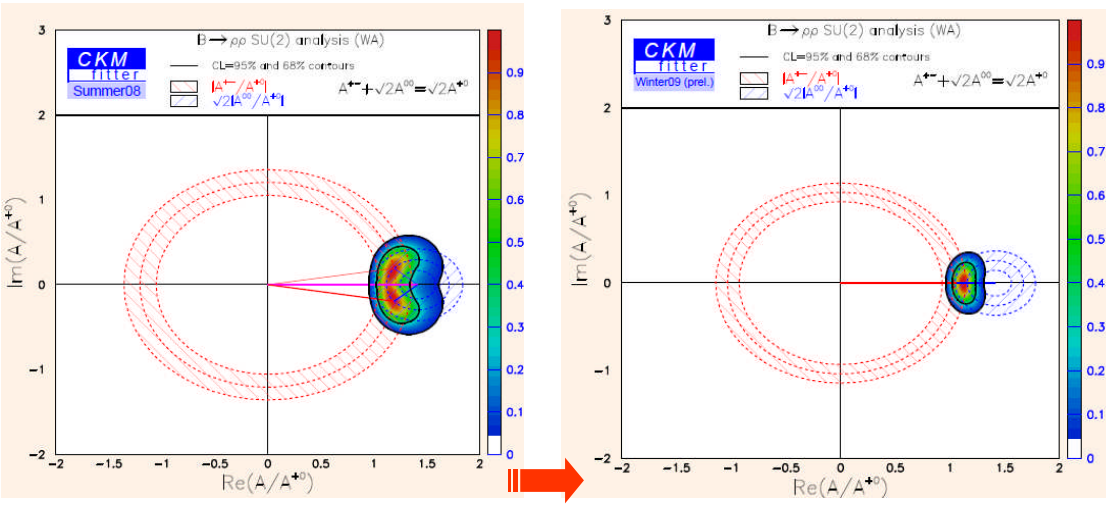
$$C_{\rho^+\rho^-} = +0.01 \pm 0.15 \pm 0.06$$

$$S_{\rho^+\rho^-} = -0.17 \pm 0.20^{+0.05}_{-0.06}$$

➢ $A\ (-C) \approx 0$ ➡ small penguin contribution

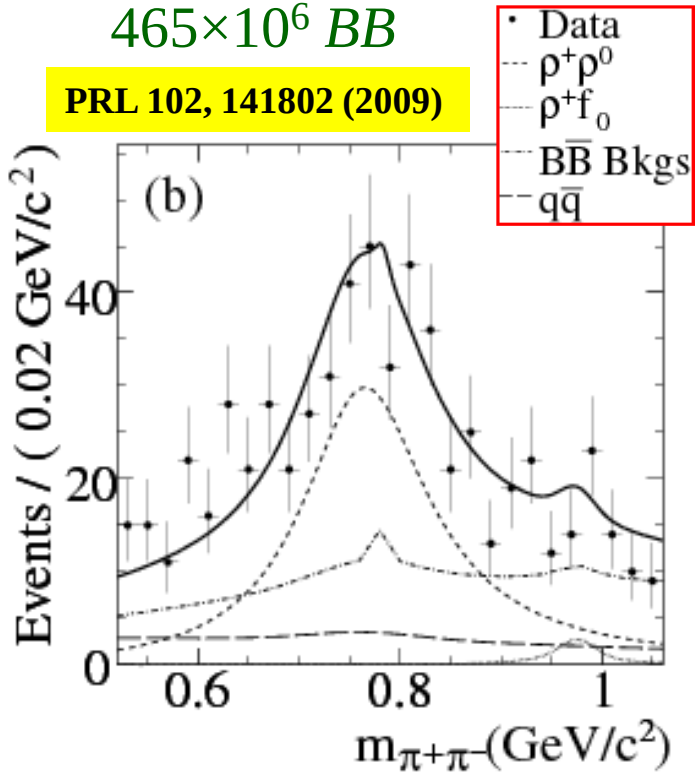
Results on $B^+ \to \rho^+\rho^0$

- BF($B^+ \to \rho^+\rho^0$) = (23.7±1.4±1.4)×10^{-6}
- Large value stretches the base of the two isospin triangles, making them degenerate



465×10^6 $B\bar{B}$

PRL 102, 141802 (2009)



- f_L = (95.0±1.5±0.6)% ➡ Dominantly longitudinally polarized; situation similar for the $B^0 \to \rho^+\rho^-$ case

$$f_L = (94.1^{+3.4}_{-4.0} \pm 3.0)\%: \text{ Belle}$$
$$(99.2 \pm 2.4^{+2.6}_{-1.3})\%: \text{ BaBaR}$$

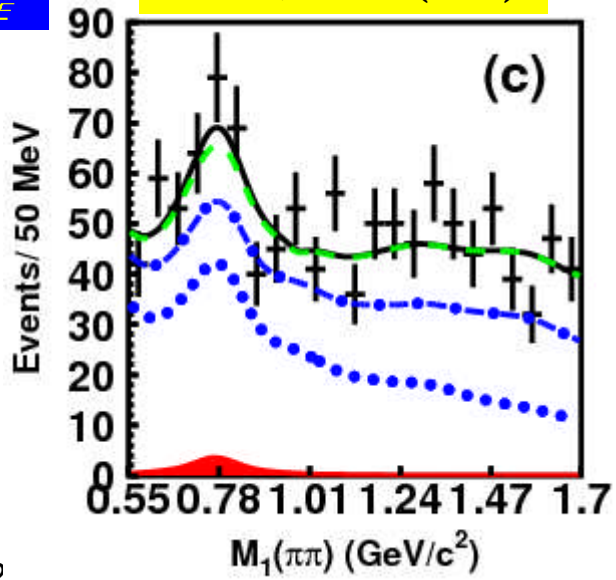
- A_{CP} = +0.054±0.055±0.010 ➡ No evidence for electroweak penguins

Results on $B^0 \to \rho^0\rho^0$

- Although involves four charged tracks (experimentally easy to tag), suffers from small BF and large background
- In absence of a statistically significant (1σ) signal yield, Belle set BF($B^0 \to \rho^0\rho^0$) < 1.0×10^{-6} at 90% C.L.
- BABAR finds a 3σ evidence for signal and reports BF($B^0 \to \rho^0\rho^0$) = $(0.92\pm0.32\pm0.14)\times10^{-6}$.

$657\times10^6\ B\bar{B}$

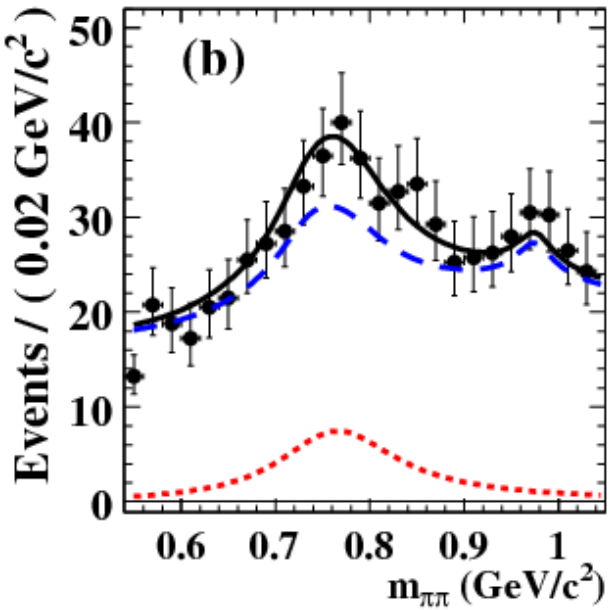
PRD 78, 111102 (2008)



$465\times10^6\ B\bar{B}$

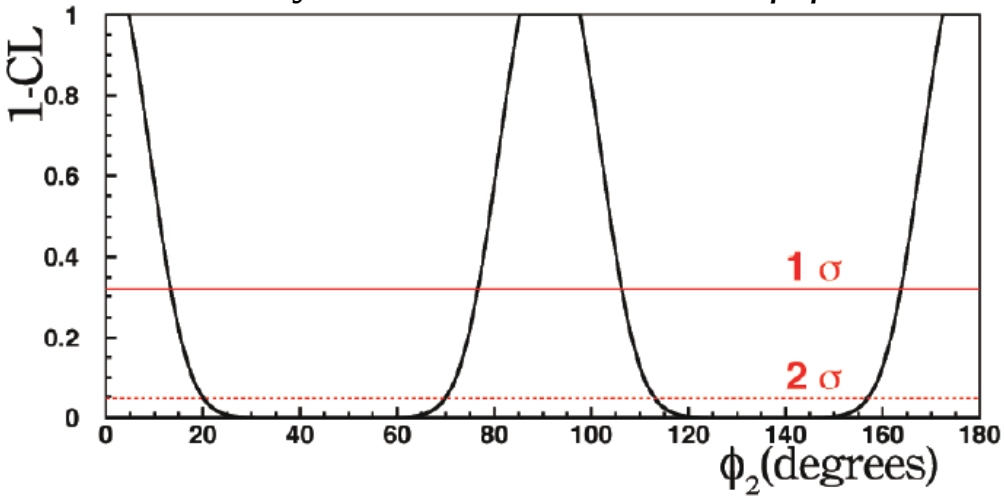
PRD 78, 071104 (2008)

$$C = +0.2 \pm 0.8 \pm 0.3$$
$$S = +0.3 \pm 0.7 \pm 0.2$$



Results on φ_2 from $B \to \rho\rho$

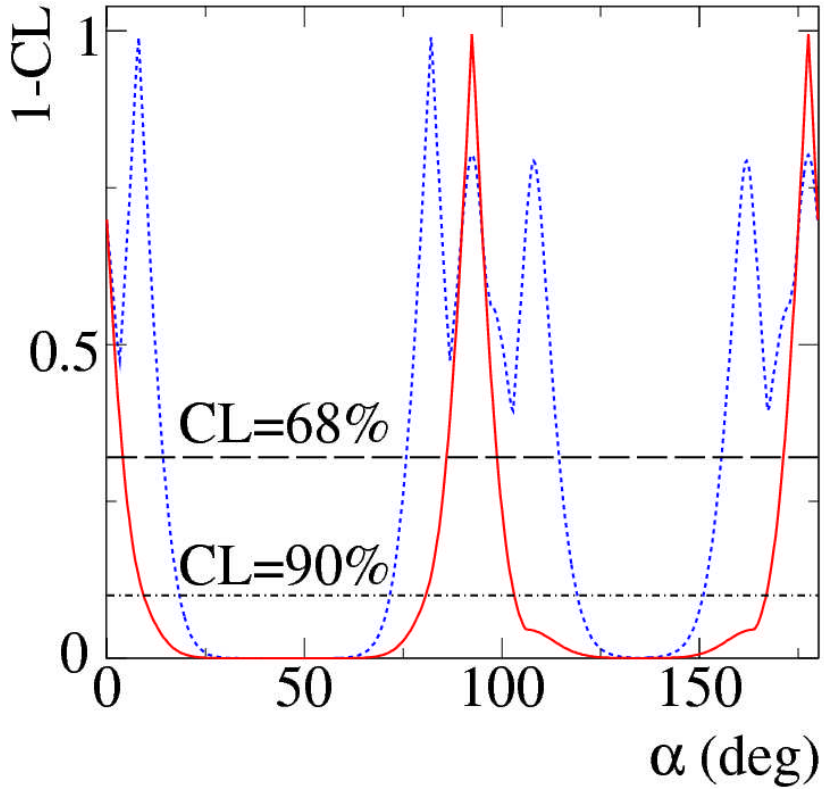
Only Belle's result on $B^0 \to \rho^0\rho^0$ used



- Plateau due to no constraint on $A_{CP}(\rho^0\rho^0)$
- The 1σ interval consistent with unitarity yields

$$\varphi_2 = (91.7 \pm 14.9)^o$$

PRL 102, 141802 (2009)



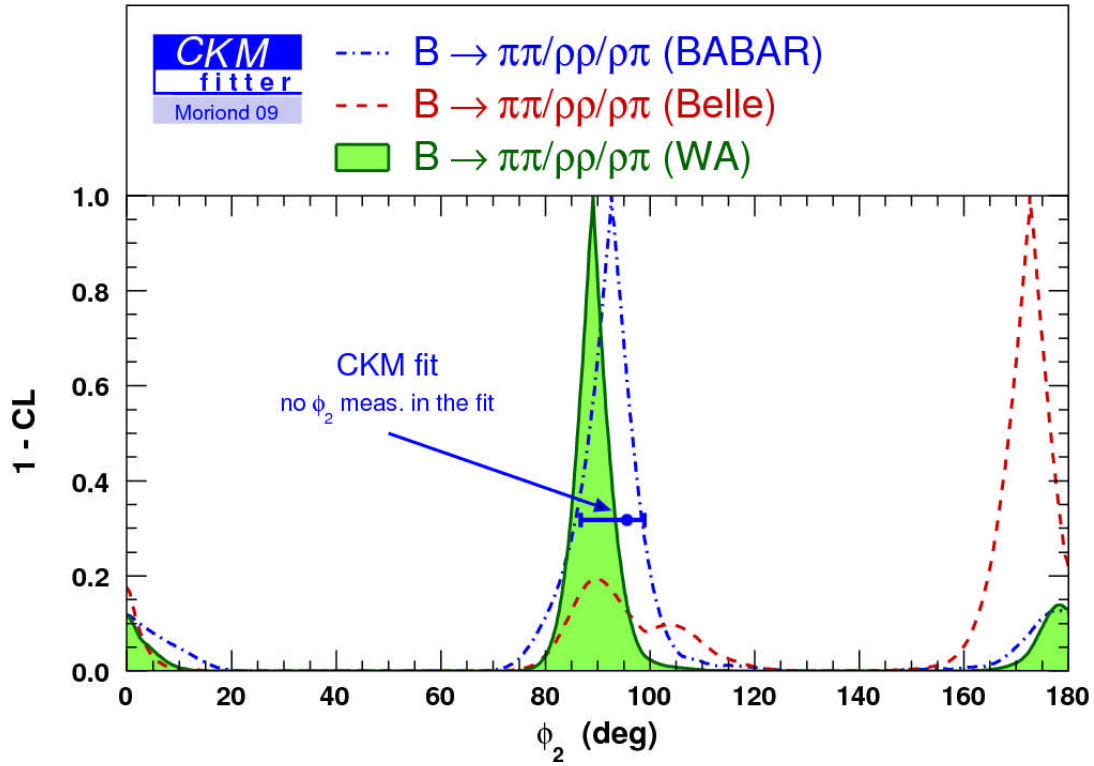
- - - - Prior to BaBar's new $B^+ \to \rho^+\rho^0$ result

$$\alpha = (92.4^{+6.0}_{-6.5})^o$$

World Average of φ_2

- Almost a precision measurement

$$\phi_2 = \left(89.0^{+4.4}_{-4.2}\right)^{\circ}$$



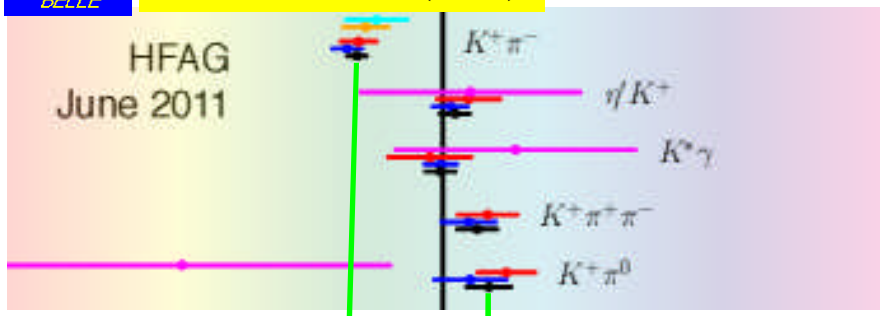
- Dominated by BaBar's new $B^+ \to \rho^+\rho^0$ results

PRL 102,141802 (2009)

- final results on $B \to \rho\rho$, especially $B^+ \to \rho^+\rho^0$, are eagerly awaited for ➡ 9 times more data compared to its last result on $\rho^+\rho^0$

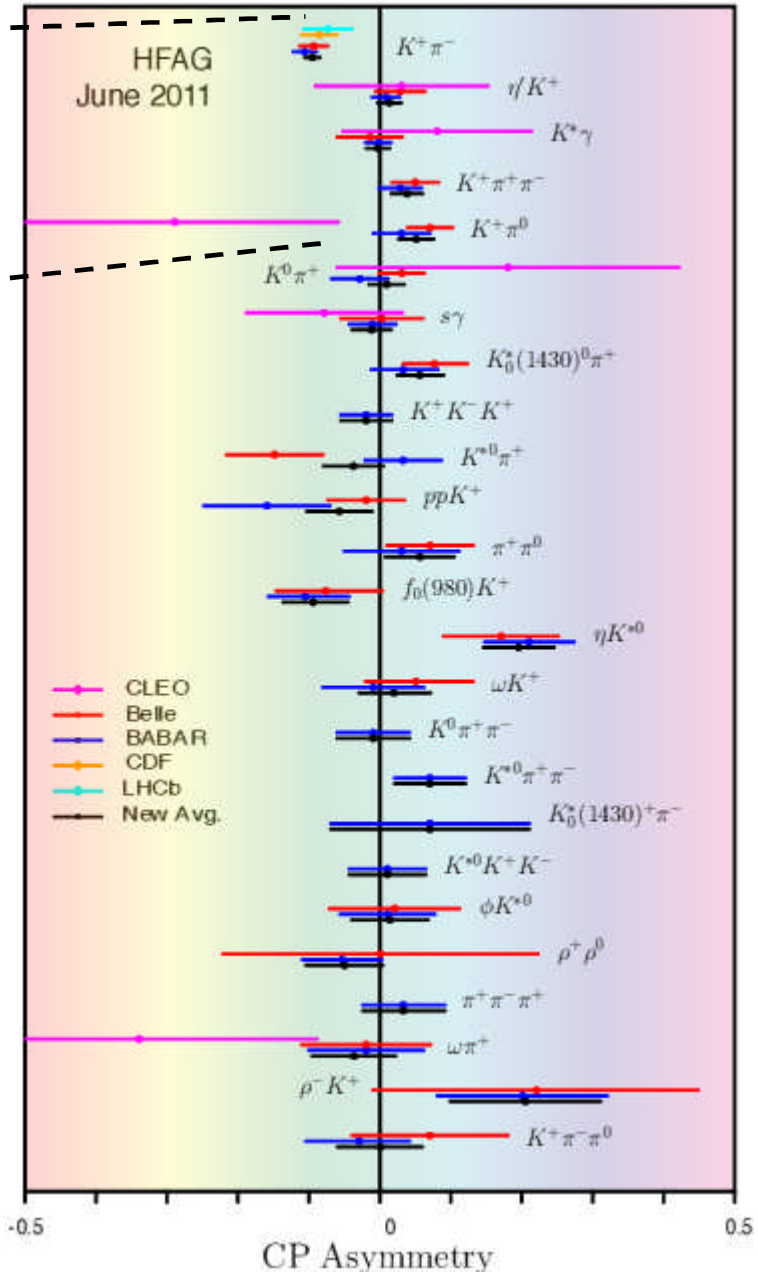
The $K\pi$ Puzzle

Nature 452, 332 (2008)



$\Delta A_{K\pi} = A_{CP}(K^+\pi^-) - A_{CP}(K^+\pi^0) = -0.144 \pm 0.029$

- Both decay channels occur via same diagrams at the tree level ➡ $\Delta A_{K\pi}$ should be zero
- In contrast, measured *CP* asymmetry difference is a 5σ observation
- Possible interpretations
  - Large color-suppressed tree
  - Enhance electroweak penguin
  - Potential new-physics effects



Possible Way Ahead

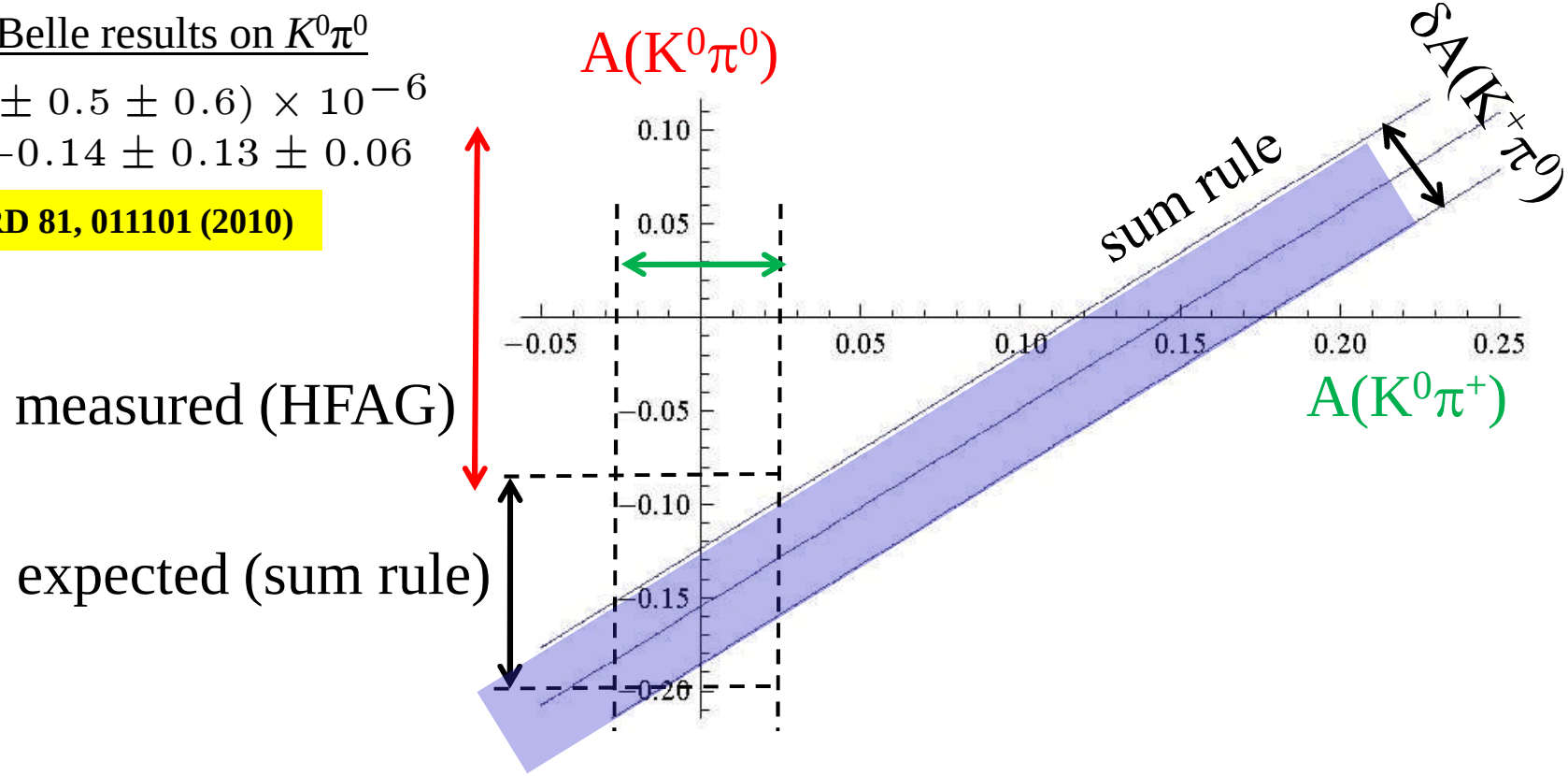
- Sum rule proposed by Gronau, Atwood and Soni **PLB 58, 036005 (1998)**

$$\mathcal{A}_{CP}(K^+\pi^-) + \mathcal{A}_{CP}(K^0\pi^+)\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} = \mathcal{A}_{CP}(K^+\pi^0)\frac{2\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} + \mathcal{A}_{CP}(K^0\pi^0)\frac{2\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

Recent Belle results on $K^0\pi^0$

$$\mathcal{B} = (8.7 \pm 0.5 \pm 0.6) \times 10^{-6}$$
$$\mathcal{A}_{CP} = +0.14 \pm 0.13 \pm 0.06$$

PRD 81, 011101 (2010)



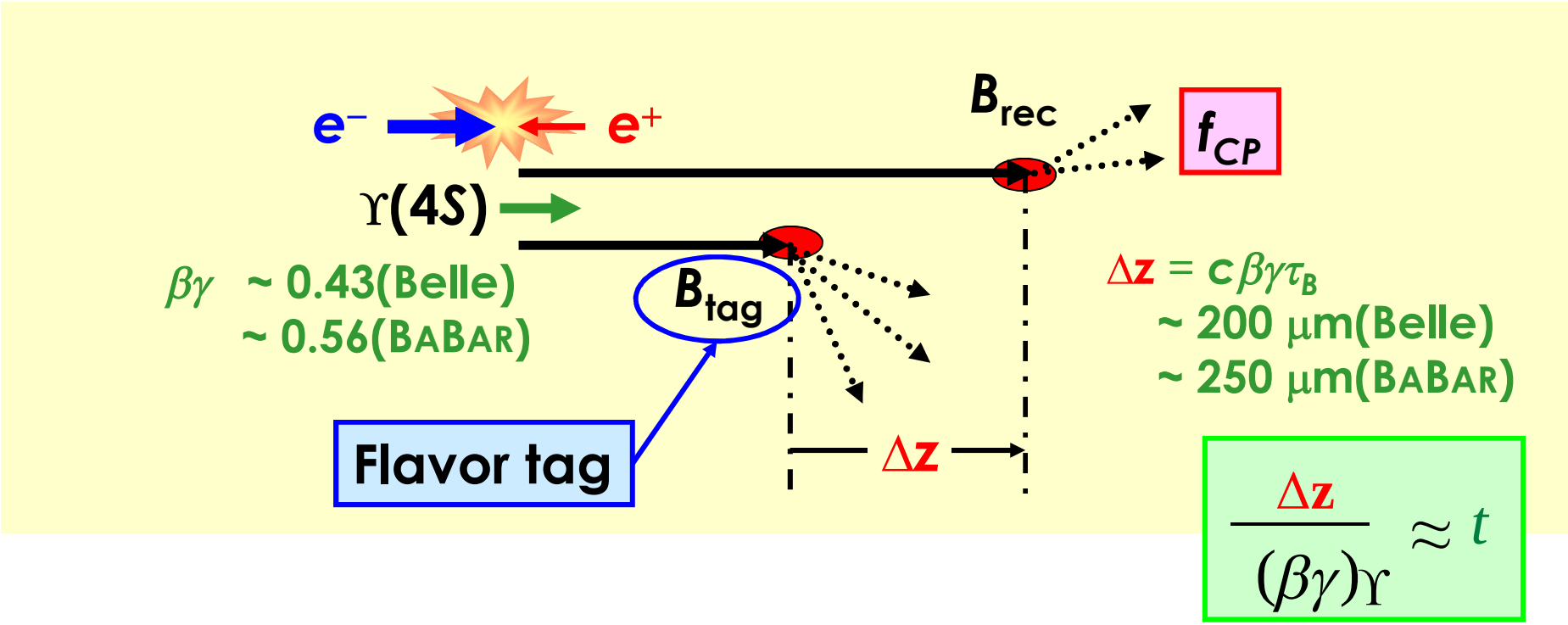
➢ Improved precision on $B^0 \to K^0\pi^0$ will be very useful

Summary and Prospects

- Measurement of the UT angle φ_2 is slowly getting into the precision phase
- Largely dominated by the constraints coming from $B \to \rho\rho$
  - ❑ Eagerly waiting for Belle's final word on $B^+ \to \rho^+\rho^0$
- Updates on $B \to \pi\pi$ and $(\rho\pi)^0$ from both Belle and BABAR with full Y(4S) data would play a good supplementary role
- For the final state involving charged tracks, one expects to have competitive results from LHCb very soon
- So far the $K\pi$ puzzle is concerned, results from $B^0 \to K^0\pi^0$ could be decisive ➡ SuperKEKB and SuperB

Bonus Slides

Principle of Measurement



- Reconstruct the $B \rightarrow f_{CP}$ decay
- Measure proper time difference (t) and find the flavor of B_{tag}
- Evaluate the time-dependent CP asymmetry $A_{CP}(f; t)$