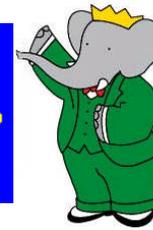


Measurement of the UT angle $\varphi_2(\alpha)$



Gagan Mohanty
Tata Institute, India



TECHNION
The Technological High Energy
Physics Group

INDIAN INSTITUTE OF TECHNOLOGY
The Raymond and Beatrix Sackler
Faculty of Exact Sciences

THE MAURICE AND GABRIELA GOLDIE HIGER
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Flavor Physics & CP Violation

To integrate past results with recent developments in flavor physics and CP violation, both in theory and experiment. Among the topics discussed will be bottom, charm, and kaon decays and mixing, top production and decay, determination of CKM matrix elements, neutrino masses and mixing, new spectroscopy, flavor at the energy frontier and beyond the Standard Model, and future facilities.

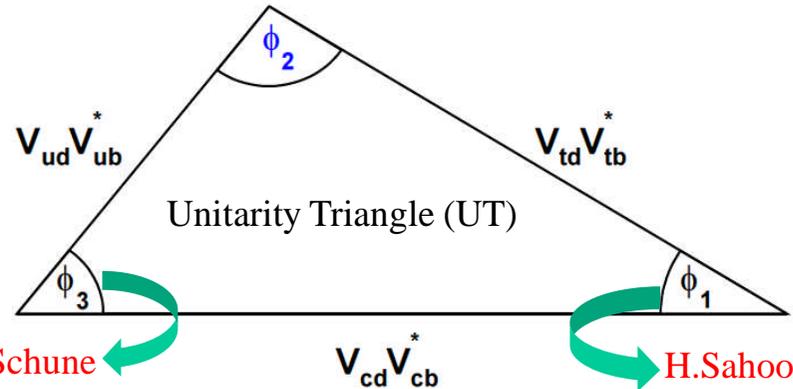
May 23-27, 2011
Maale Hachamisha, Israel

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Talk Outline



BABAR notation:

$$\phi_1 = \beta$$

$$\phi_2 = \alpha$$

$$\phi_3 = \gamma$$

- The UT Angle ϕ_2
 - $B \rightarrow \pi\pi$
 - $B^0 \rightarrow (\rho\pi)^0$
 - $B \rightarrow \rho\rho$
 - World Average
- The $B \rightarrow K\pi$ 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 $b \rightarrow u$ tree-dominated decays

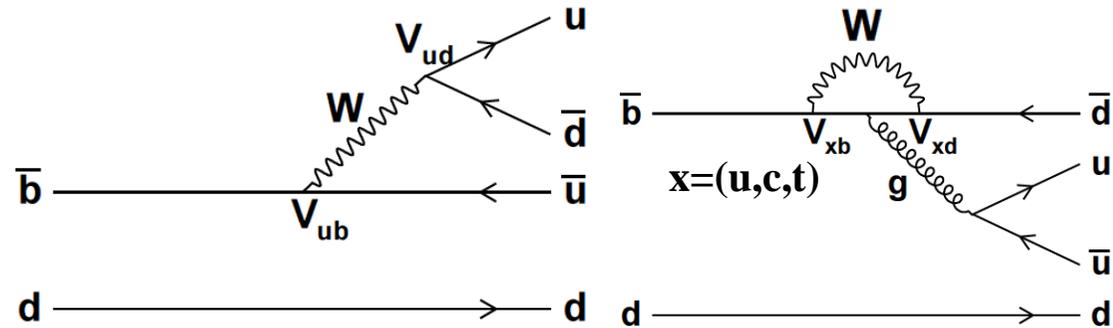
$$A_{CP}(f; t) \equiv \frac{\Gamma[\bar{B}(t) \rightarrow f] - \Gamma[B(t) \rightarrow f]}{\Gamma[\bar{B}(t) \rightarrow f] + \Gamma[B(t) \rightarrow f]} \equiv S_f \sin(\Delta m t) + A_f \cos(\Delta m t)$$

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

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

BABAR notation:
 $C_f = -A_f$

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

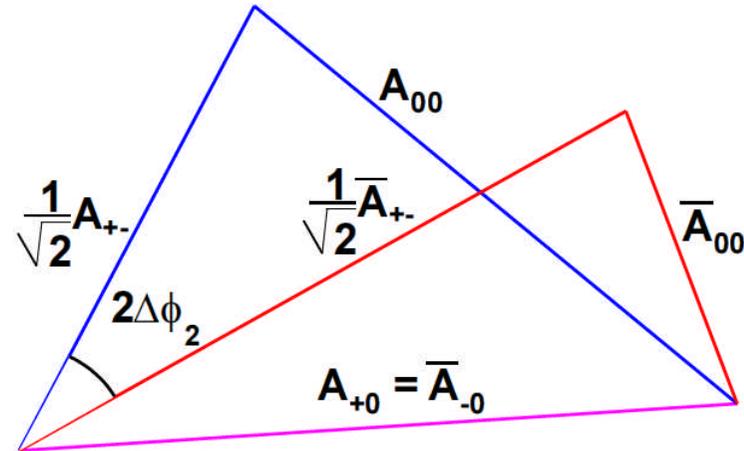


➤ Measure $S_f = \sqrt{1 - A_f^2} \sin 2\phi_2^{\text{eff}}$ \rightarrow $\phi_2^{\text{eff}} = \phi_2 + \Delta\phi_2$

Measuring φ_2 in $B \rightarrow \pi\pi$

- 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:
 - $B^+ \rightarrow \pi^+\pi^0$ is a pure tree mode \rightarrow 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

$$\mathcal{B}(B^0 \rightarrow \pi^+\pi^-)$$

$$\mathcal{B}(B^+ \rightarrow \pi^+\pi^0)$$

$$\mathcal{B}(B^0 \rightarrow \pi^0\pi^0)$$

$$A_f(B^0 \rightarrow \pi^+\pi^-)$$

$$S_f(B^0 \rightarrow \pi^+\pi^-)$$

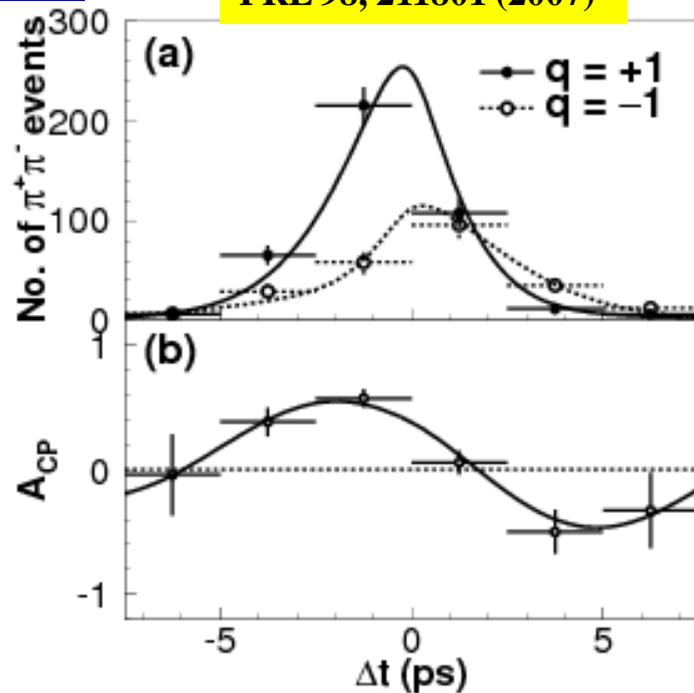
$$A_f(B^0 \rightarrow \pi^0\pi^0)$$

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



$535 \times 10^6 B\bar{B}$

PRL 98, 211801 (2007)

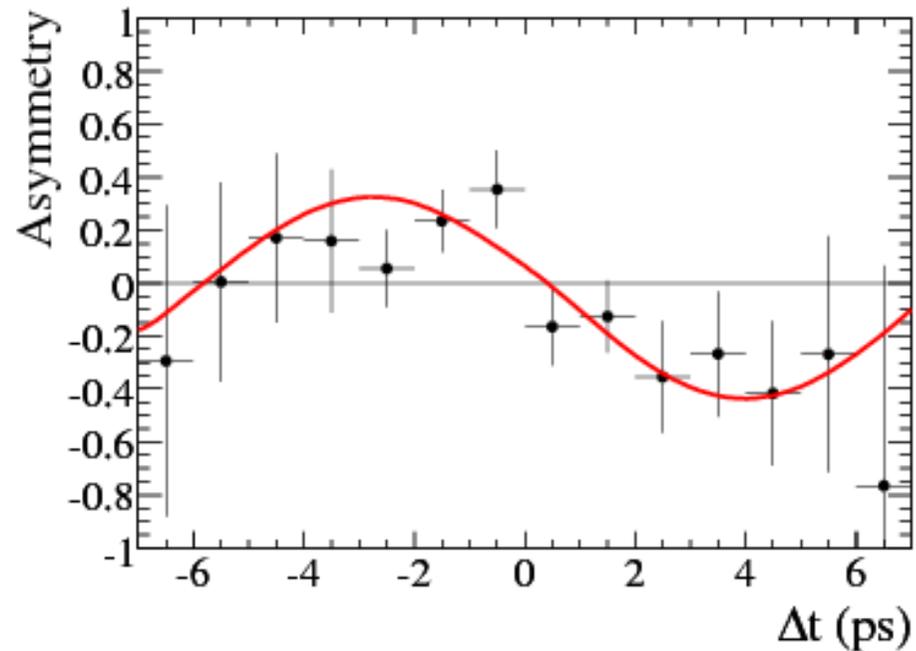


$$A_{\pi\pi} = +0.55 \pm 0.08 \pm 0.05$$

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

$467 \times 10^6 B\bar{B}$

arXiv:0807.4226 (2008)



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

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

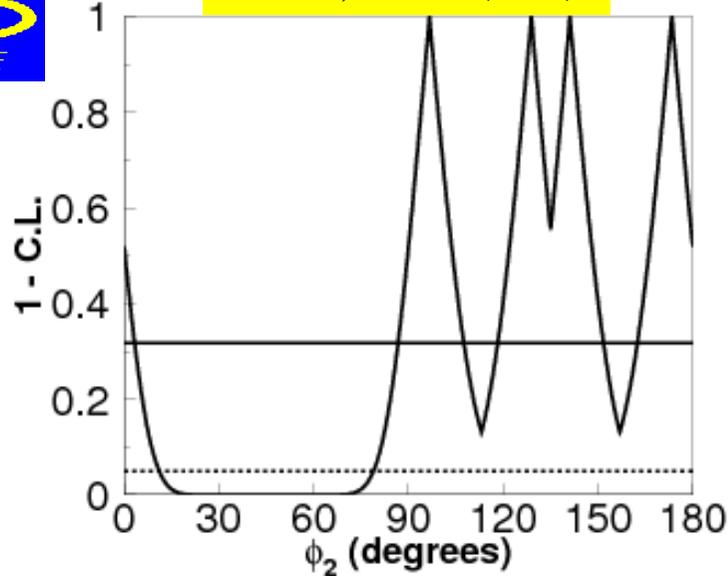
- Both find clear evidence for mixing-induced CP violation (S); for A ($-C$) the significance of Belle (BABAR) is 5.5σ (3.0σ)

Results on φ_2 from $B \rightarrow \pi\pi$

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

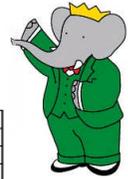
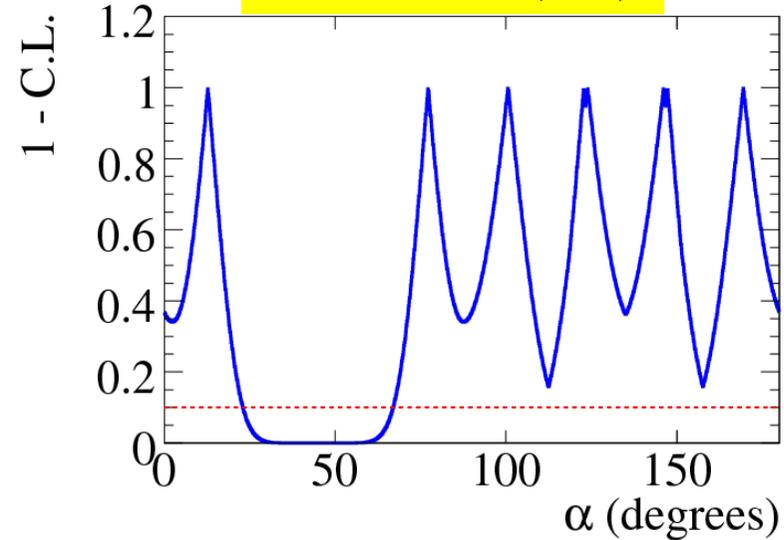


PRL 98, 211801 (2007)



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

arXiv:0807.4226 (2008)



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

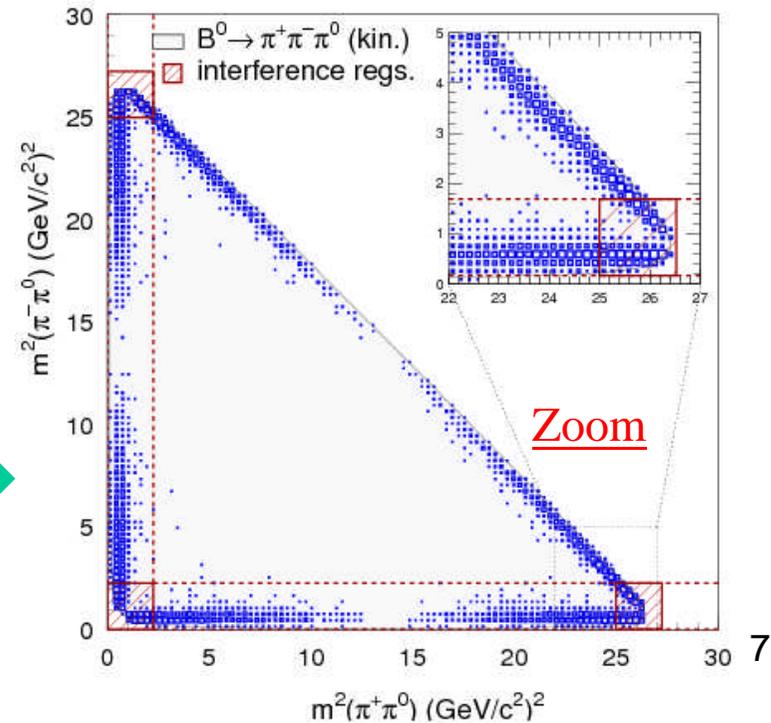
Measuring φ_2 in $B^0 \rightarrow (\rho\pi)^0$

Issues at hand:

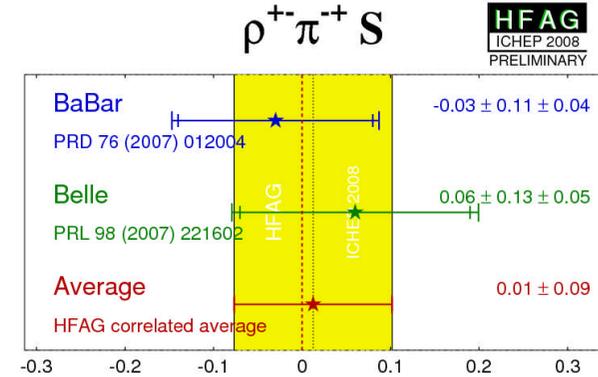
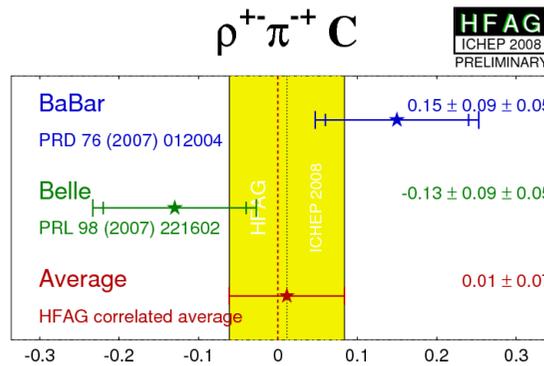
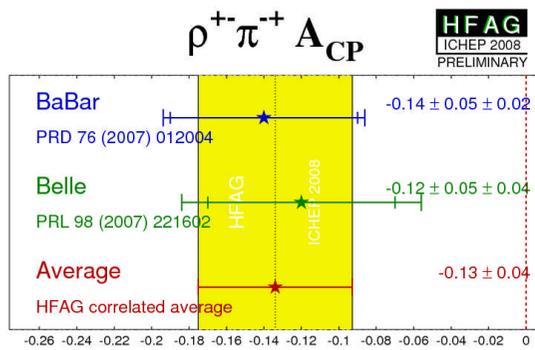
- Not a CP eigenstate $\rightarrow S_f$ and A_f also contain a CP conserving part
- Has four isospin (0,1 and 2) amplitudes
 - 12 unknowns in the isospin pentagon

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

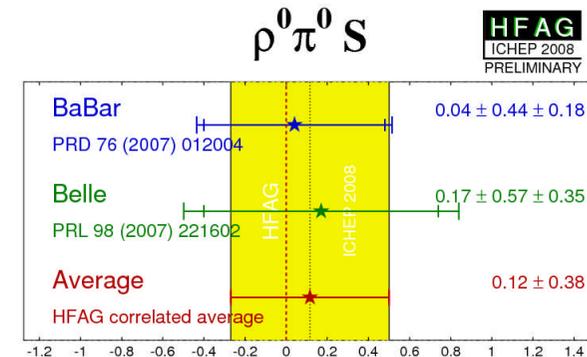
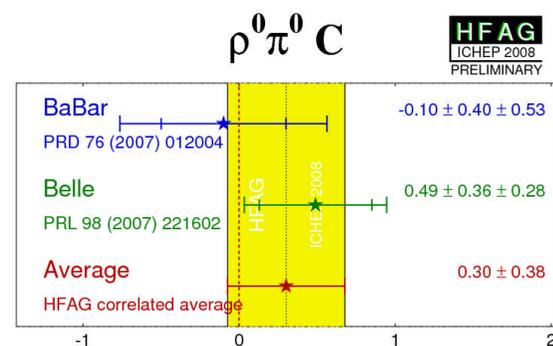
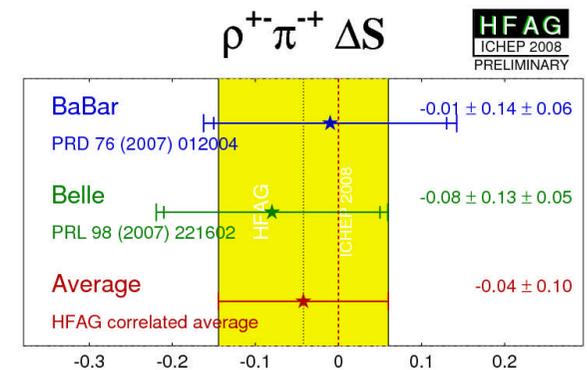
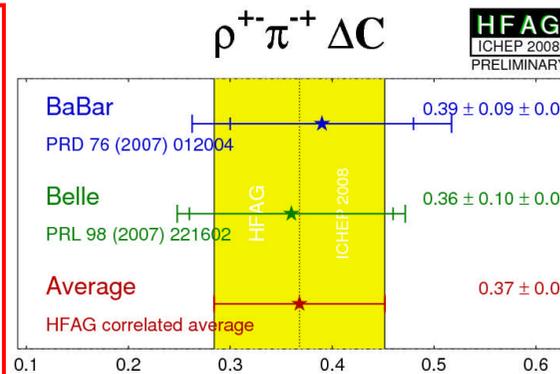
- Time-dependent Dalitz plot analysis (TDPA) of $B^0 \rightarrow \rho\pi \rightarrow \pi^+\pi^-\pi^0$ to constrain φ_2 without any discrete ambiguity
 - Exploit the variation of the strong phase of interfering ρ resonances over the Dalitz plot



Results from Belle and BABAR



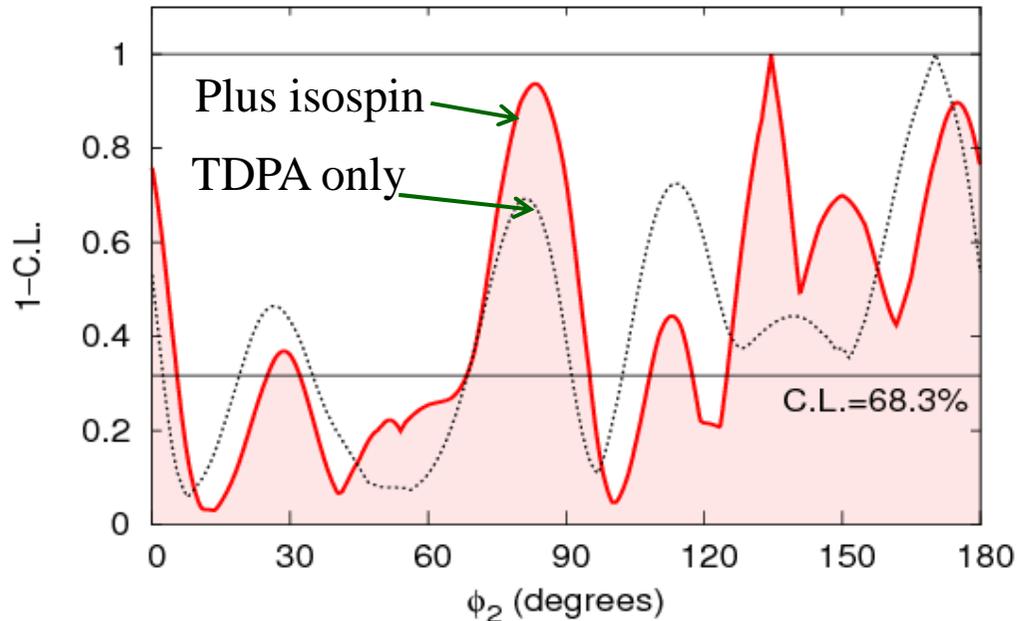
- Good agreement between the two experiments
- 3σ evidence for time- and flavor-integrated CP asymmetry (see the top left plot)
- ΔS and ΔC are CP conserving part of S and C ($-A$)



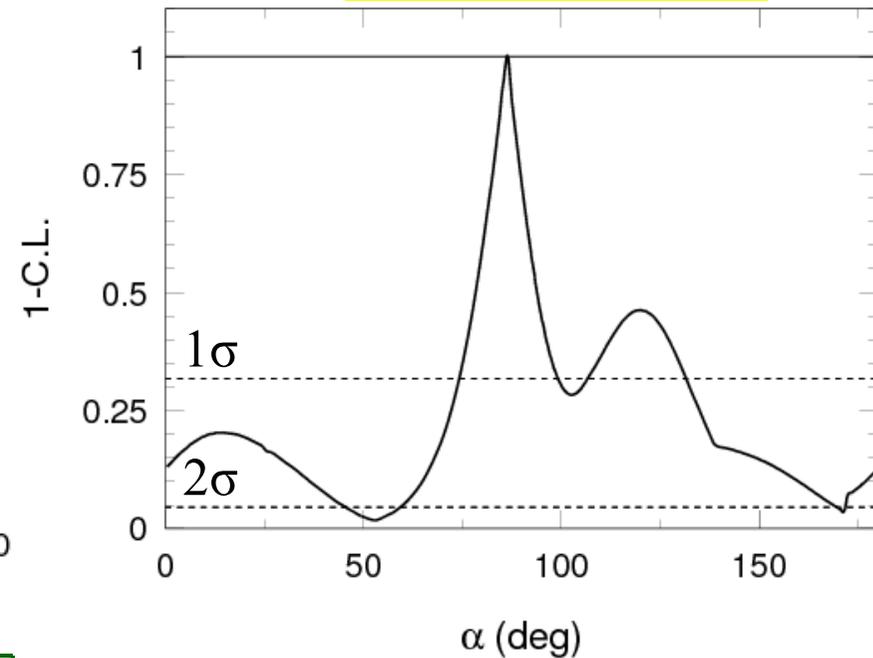
Results on φ_2 from $B^0 \rightarrow (\rho\pi)^0$



PRD 77, 072001 (2008)



PRD 76, 012004 (2007)



- For Belle:

- $68^\circ < \varphi_2 < 95^\circ$ at 68.3% C.L.
- Using world-average BF and A_{CP} values of $B^+ \rightarrow \rho^0\pi^+$ and $\rho^+\pi^0$

- BABAR measures:

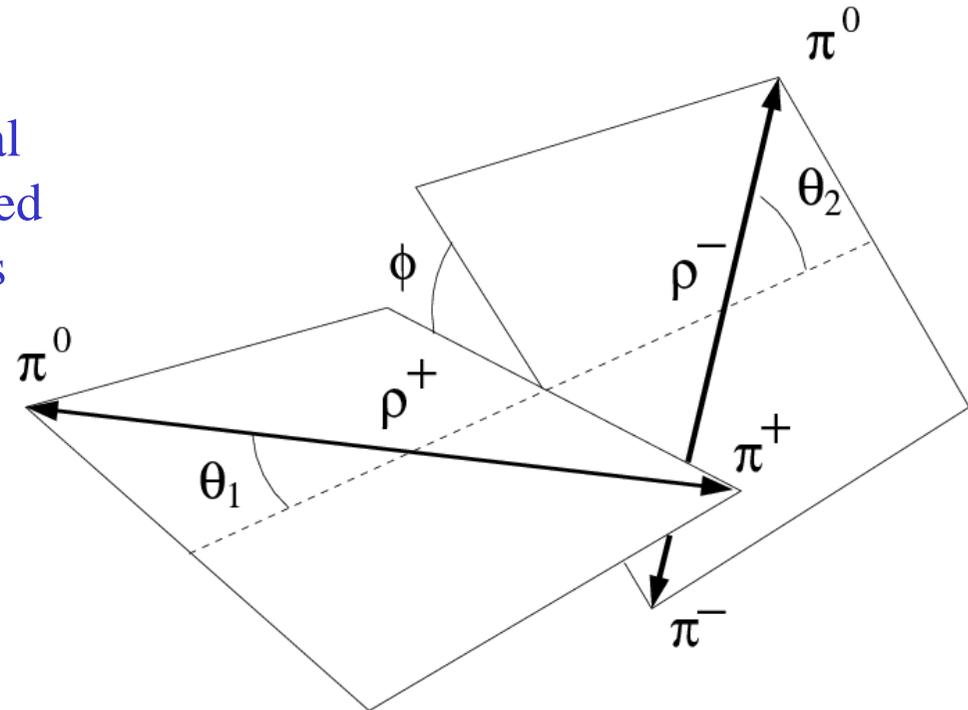
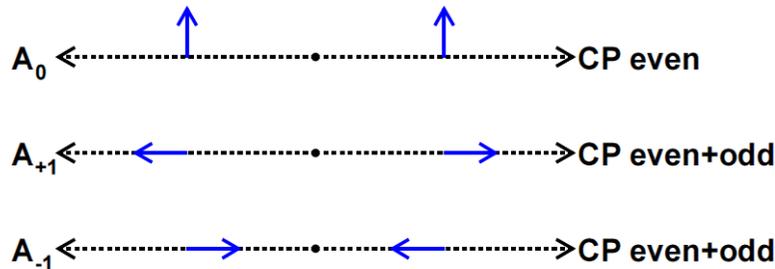
- $\alpha = \left(87^{+45}_{-13} \right)^\circ$

- 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 $B \rightarrow \rho\rho$

Pseudoscalar \rightarrow 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:

$$\frac{d^2 N}{d \cos \theta_1 d \cos \theta_2} = 4f_L \cos^2 \theta_1 \cos^2 \theta_2 + (1 - f_L) \sin^2 \theta_1 \sin^2 \theta_2$$

← Longitudinal → ← Transverse →

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



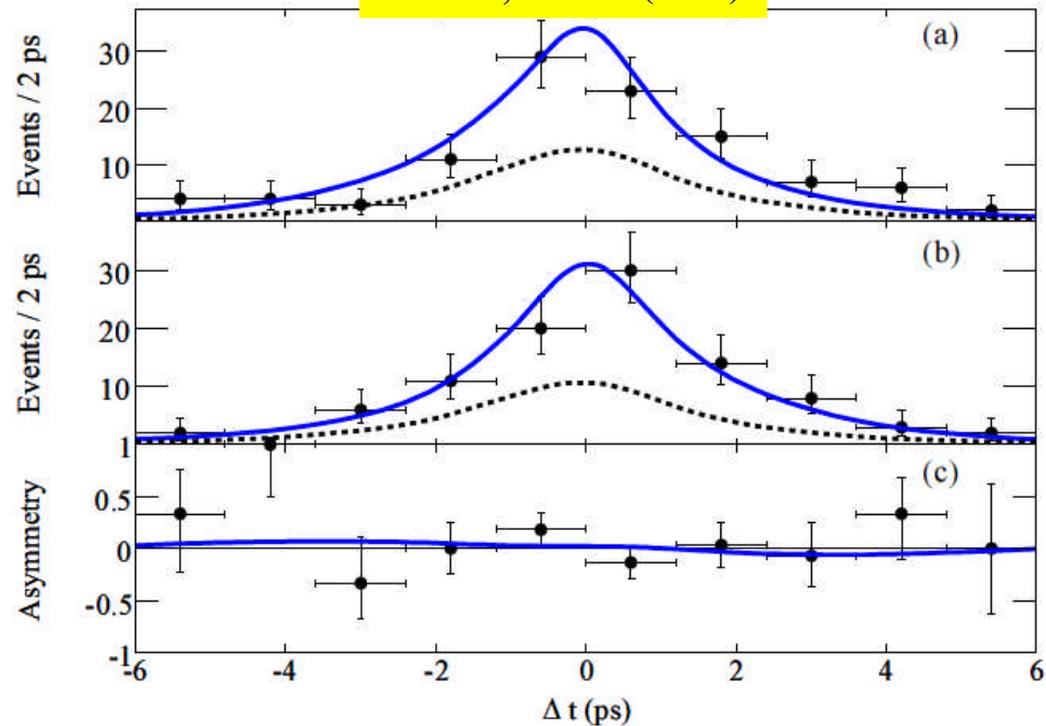
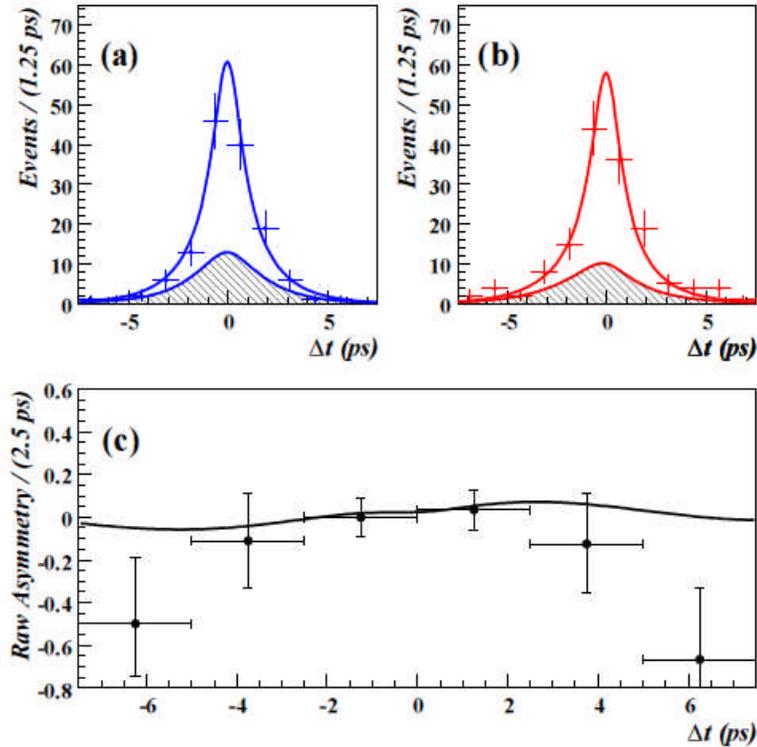
Results on $B^0 \rightarrow \rho^+ \rho^-$

$535 \times 10^6 B\bar{B}$

PRD 76, 011104 (2007)

$384 \times 10^6 B\bar{B}$

PRD 76, 052007 (2007)



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

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

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

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

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



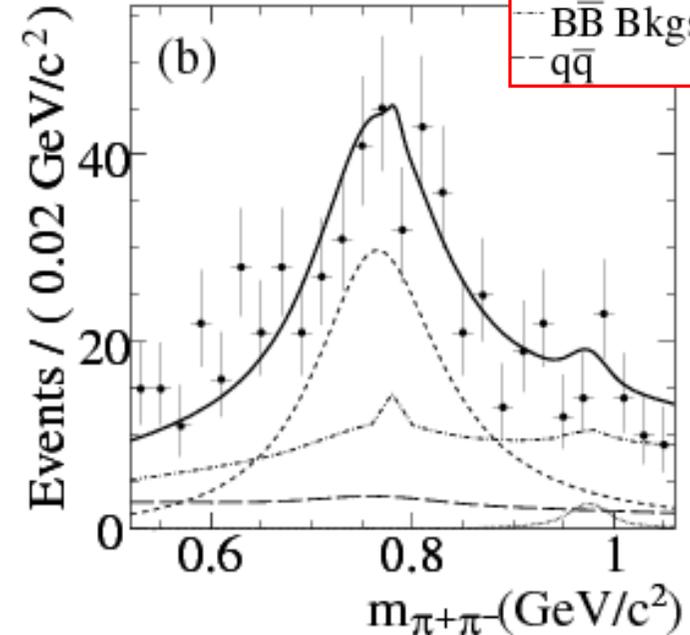
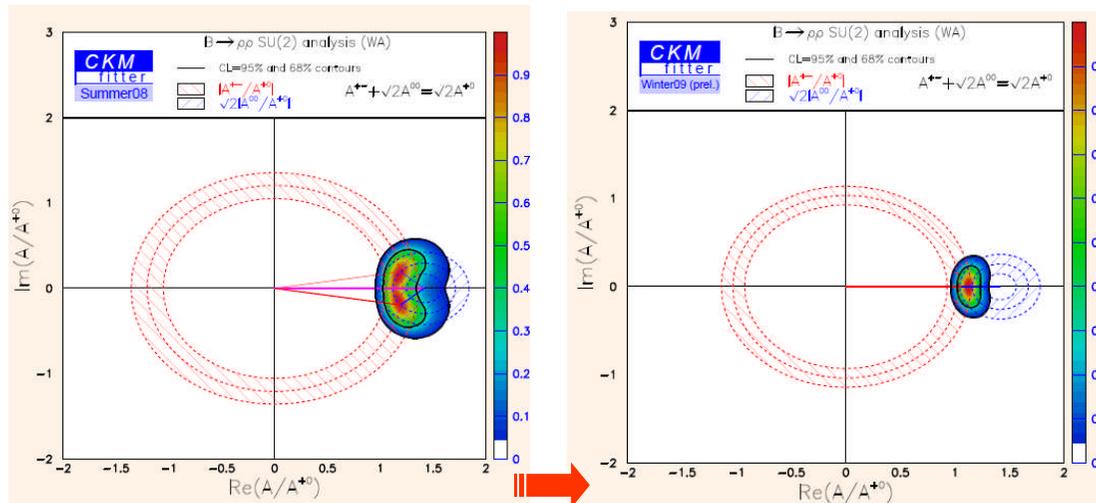
Results on $B^+ \rightarrow \rho^+ \rho^0$

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

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

PRL 102, 141802 (2009)

- Data
- $\rho^+ \rho^0$
- $\rho^+ f_0$
- $B\bar{B}$ Bkgs
- $q\bar{q}$



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

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

$$(99.2 \pm 2.4_{-1.3}^{+2.6})\%: \text{BABAR}$$

- $A_{CP} = +0.054 \pm 0.055 \pm 0.010$ ➔ No evidence for electroweak penguins

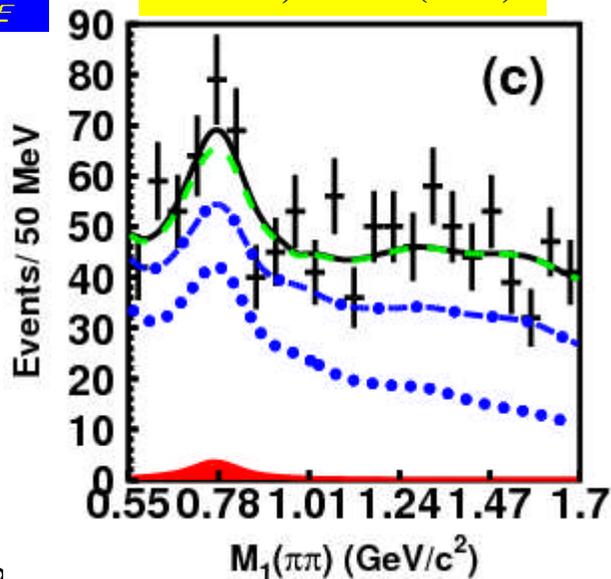
Results on $B^0 \rightarrow \rho^0 \rho^0$

- 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 $\text{BF}(B^0 \rightarrow \rho^0 \rho^0) < 1.0 \times 10^{-6}$ at 90% C.L.
- BABAR finds a 3σ evidence for signal and reports $\text{BF}(B^0 \rightarrow \rho^0 \rho^0) = (0.92 \pm 0.32 \pm 0.14) \times 10^{-6}$.



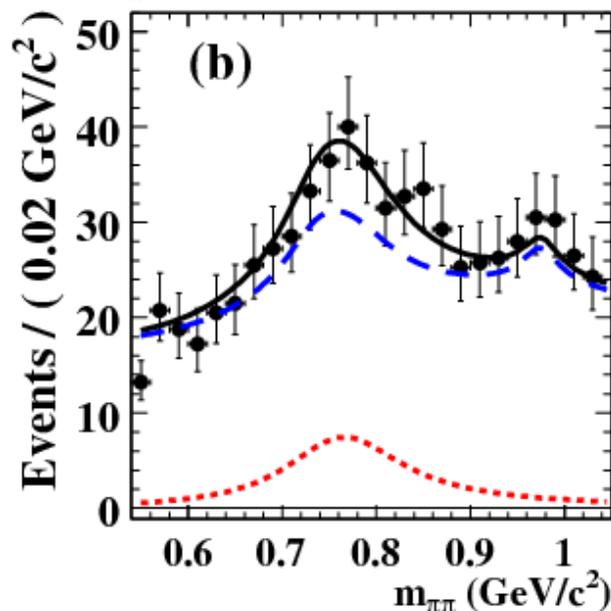
$657 \times 10^6 B\bar{B}$

PRD 78, 111102 (2008)



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

PRD 78, 071104 (2008)



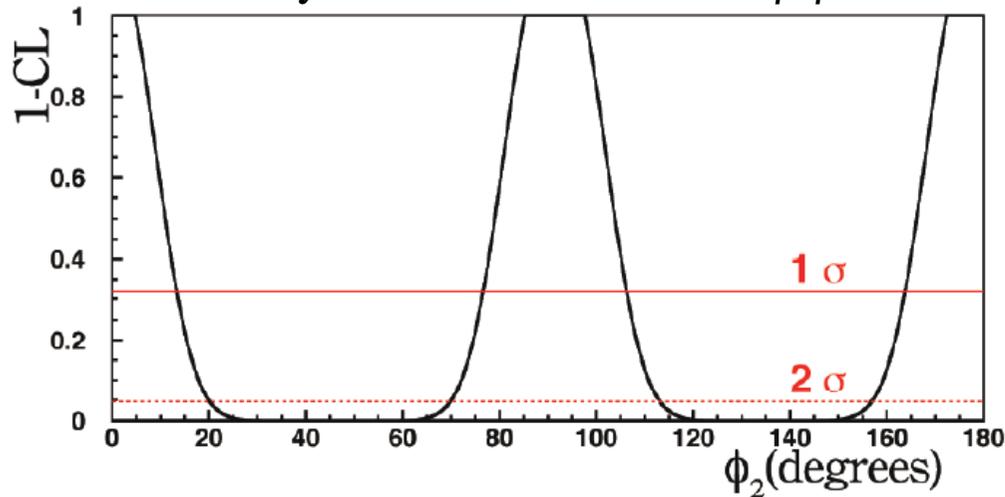
$$C = +0.2 \pm 0.8 \pm 0.3$$

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

Results on φ_2 from $B \rightarrow \rho\rho$



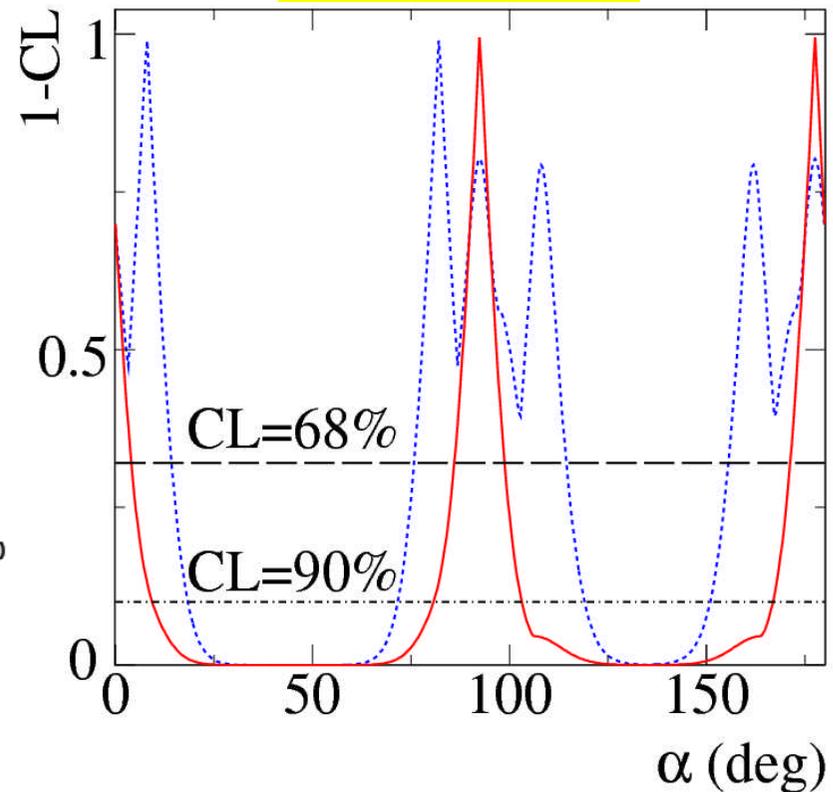
Only Belle's result on $B^0 \rightarrow \rho^0\rho^0$ used



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

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

PRL 102, 141802 (2009)



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

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

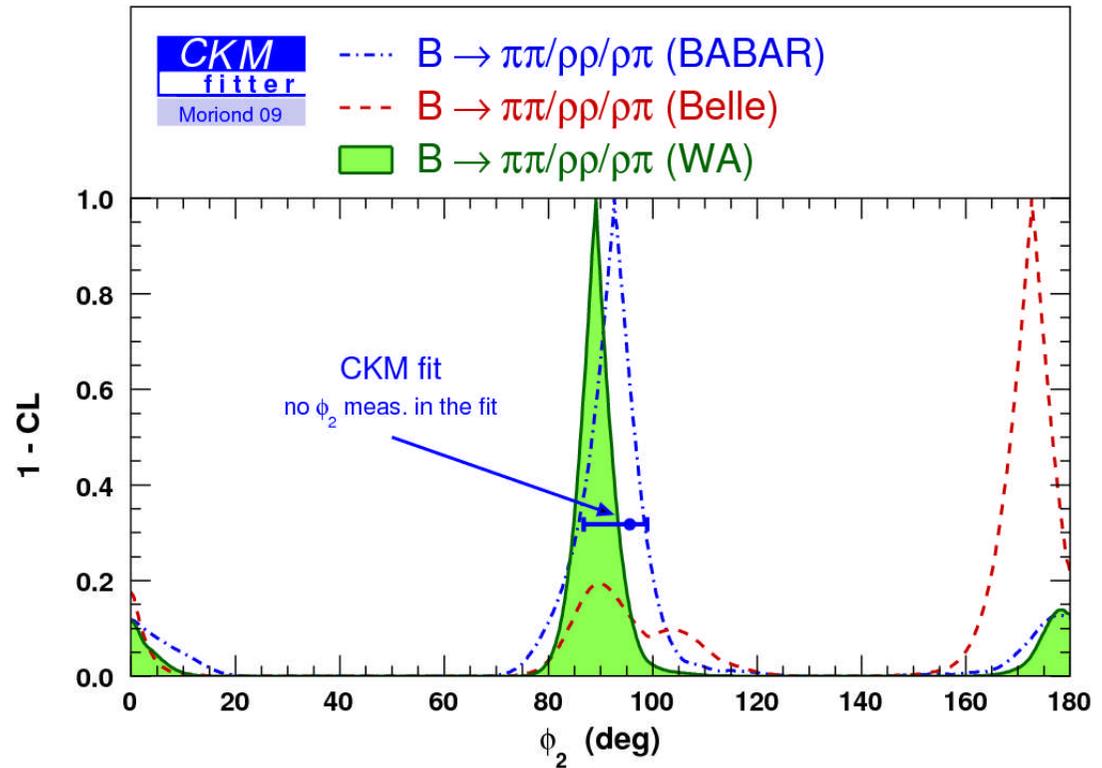
World Average of ϕ_2

- Almost a precision measurement

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

- Dominated by BABAR's new $B^+ \rightarrow \rho^+\rho^0$ results

PRL 102,141802 (2009)

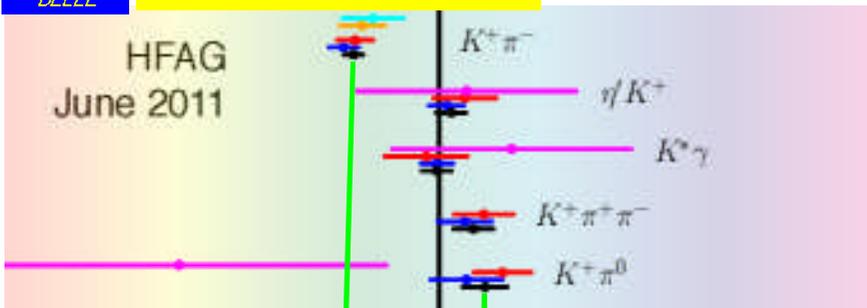


- ❖  final results on $B \rightarrow \rho\rho$, especially $B^+ \rightarrow \rho^+\rho^0$, are eagerly awaited for  9 times more data compared to its last result on $\rho^+\rho^0$



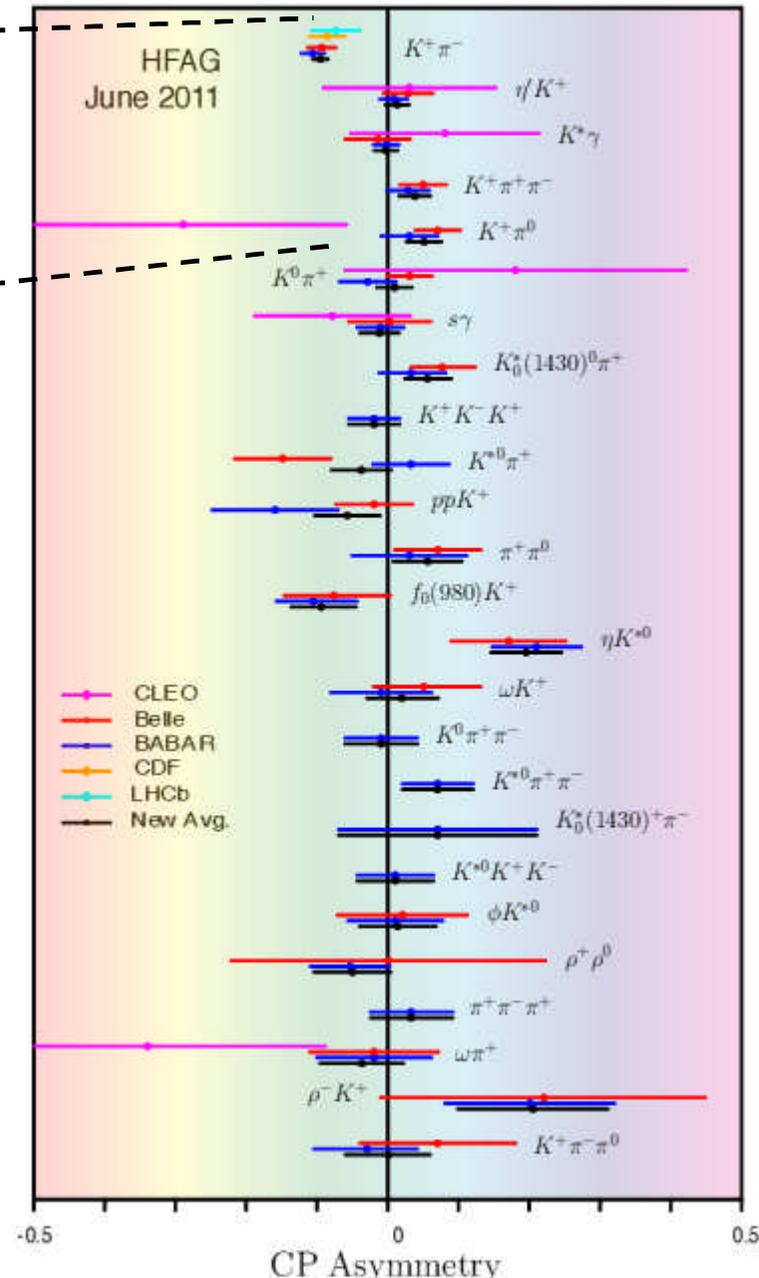
Nature 452, 332 (2008)

The $K\pi$ Puzzle



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

- Both decay channels occur via same diagrams at the tree level $\rightarrow \Delta A_{K\pi}$ 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)

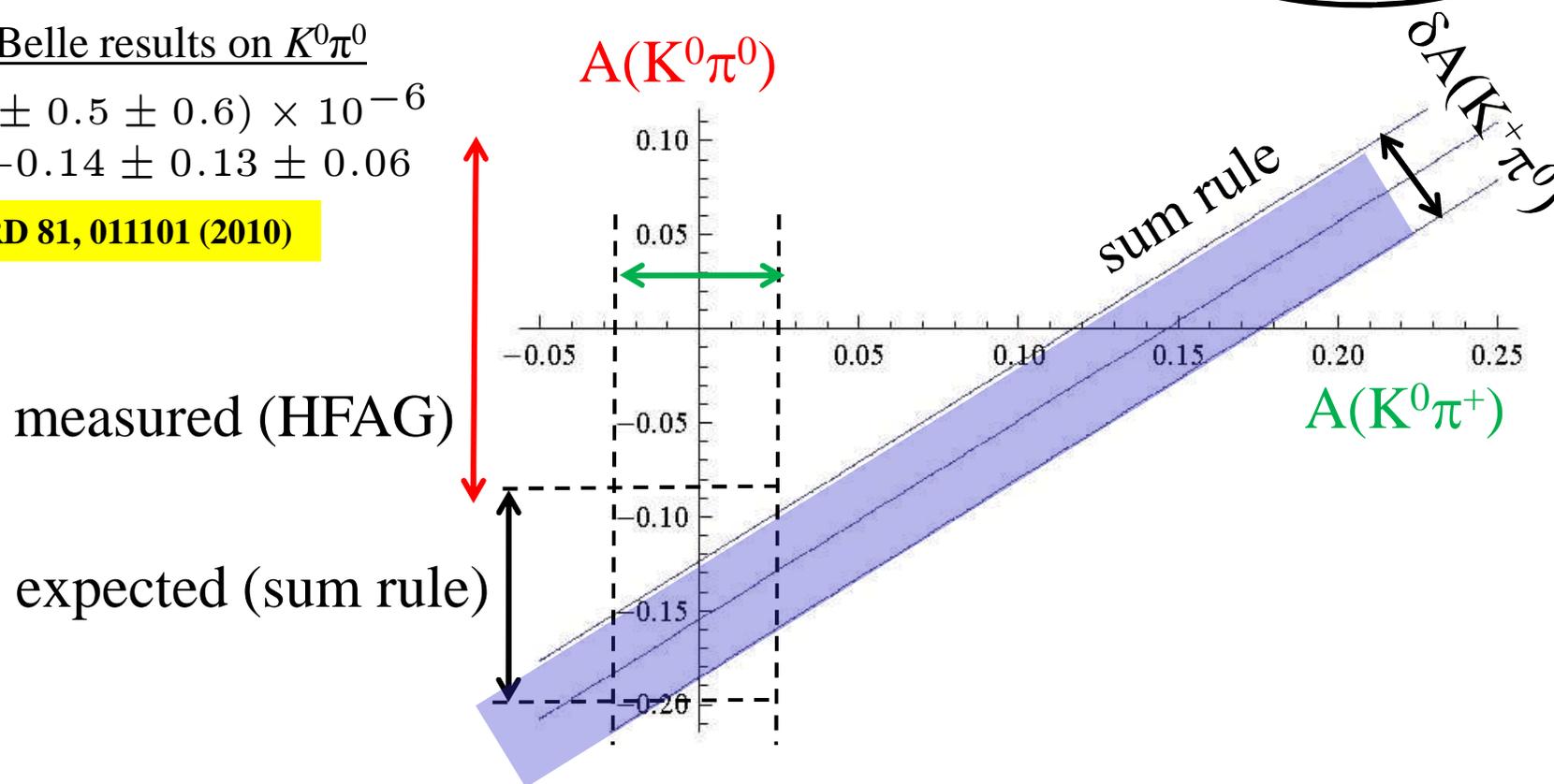
$$\mathcal{A}_{CP}(K^+\pi^-) + \mathcal{A}_{CP}(K^0\pi^+) \frac{\mathcal{B}(K^0\pi^+) \tau_0}{\mathcal{B}(K^+\pi^-) \tau_+} = \mathcal{A}_{CP}(K^+\pi^0) \frac{2\mathcal{B}(K^+\pi^0) \tau_0}{\mathcal{B}(K^+\pi^-) \tau_+} + \mathcal{A}_{CP}(K^0\pi^0) \frac{2\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

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)

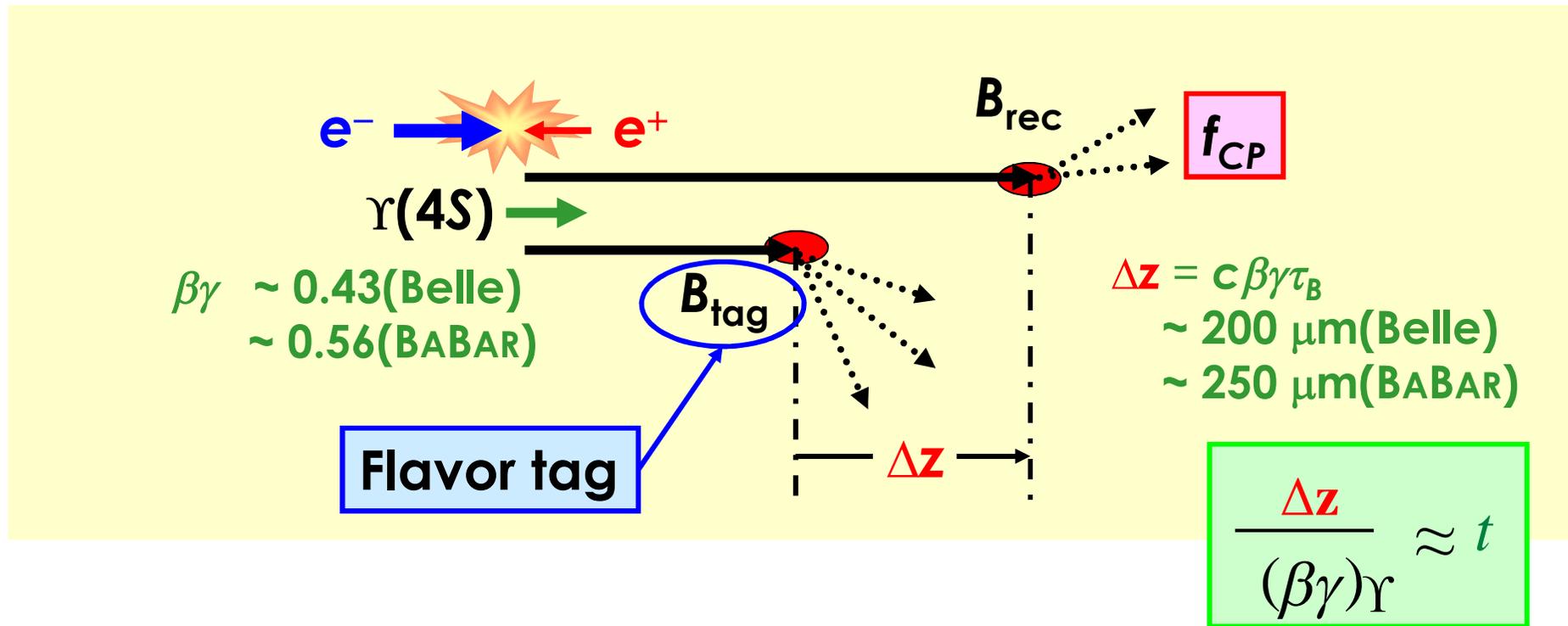


Summary and Prospects

- Measurement of the UT angle φ_2 is slowly getting into the precision phase
- Largely dominated by the constraints coming from $B \rightarrow \rho\rho$
 - Eagerly waiting for Belle's final word on $B^+ \rightarrow \rho^+\rho^0$
- Updates on $B \rightarrow \pi\pi$ 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 $B^0 \rightarrow K^0\pi^0$ 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 $A_{CP}(f; t)$