Symposium on Prospects in the Physics of Discrete Symmetries

Kai-Feng Chen
National Taiwan University

for the Belle Collaboration

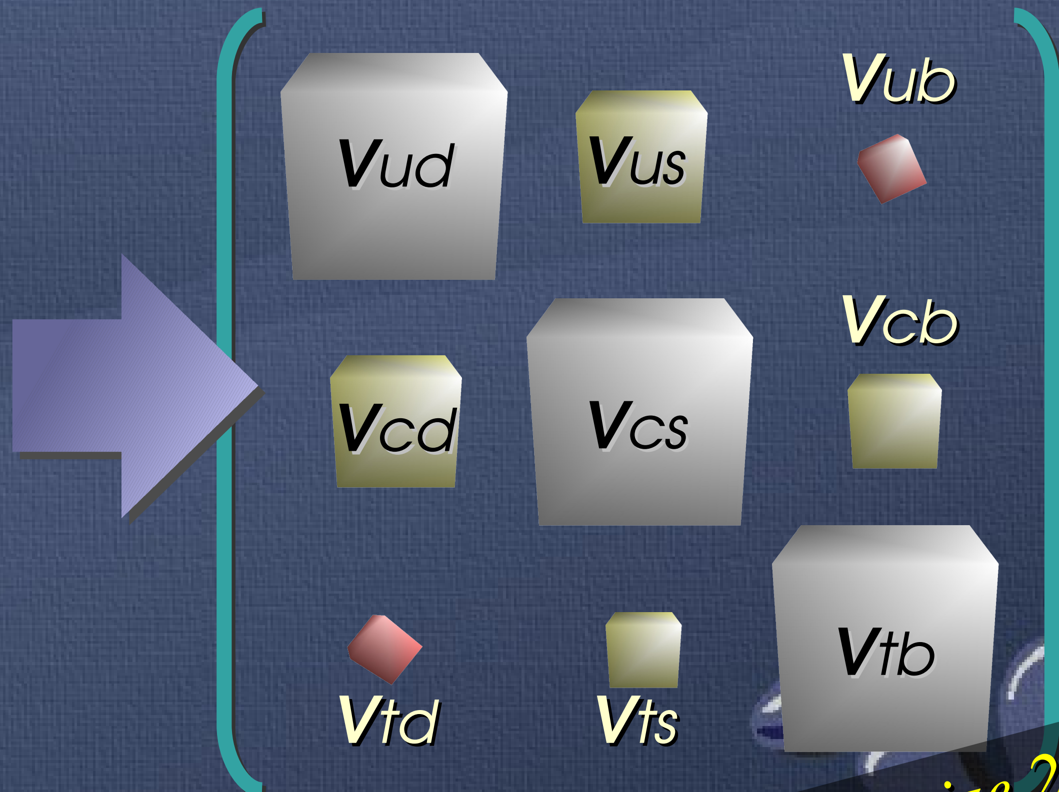
Experimental Review of *CP* Violation & CKM Angles at *B* Factories

11-16 DECEMBER 2008, IFIC, VALENCIA, SPAIN

CP Violation in the Standard Model

The KM Model

The Kobayashi-Maskawa ansatz: We need **THREE** generations of quarks to produce the **ONE** irreducible phase representing for the *CP* violation.



Nobel Prize 2008!

CP Violation in the Standard Model

The Unitarity Triangle for *B*-decays

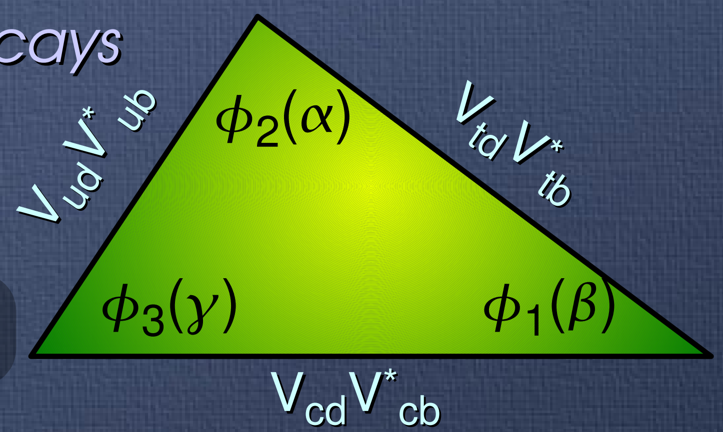
- The unitarity of quark mixing matrix: $V_{ud} V^*_{ub} + V_{cd} V^*_{cb} + V_{td} V^*_{tb} = 0$

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

Take the property of unitarity matrix for B-decays

→ **Unitarity Triangle**

$B \to \pi\pi,\ \rho\pi,\ \rho\rho$



$B \to D^0K$

$B \to J/\psi K_S, \ldots$

$B \to \phi K_S, \eta' K_S, \ldots$

CP Violation in the Standard Model

The *CP*-violating Asymmetries

- CPV is due to the interference between mixing and decay amplitudes.

$$A_{CP}(t) = \frac{\Gamma(\overline{B}^0 \to f_{CP};t) - \Gamma(B^0 \to f_{CP};t)}{\Gamma(\overline{B}^0 \to f_{CP};t) + \Gamma(B^0 \to f_{CP};t)} = \boxed{A_f}\cos(\Delta m t) + \boxed{S_f}\sin(\Delta m t)$$

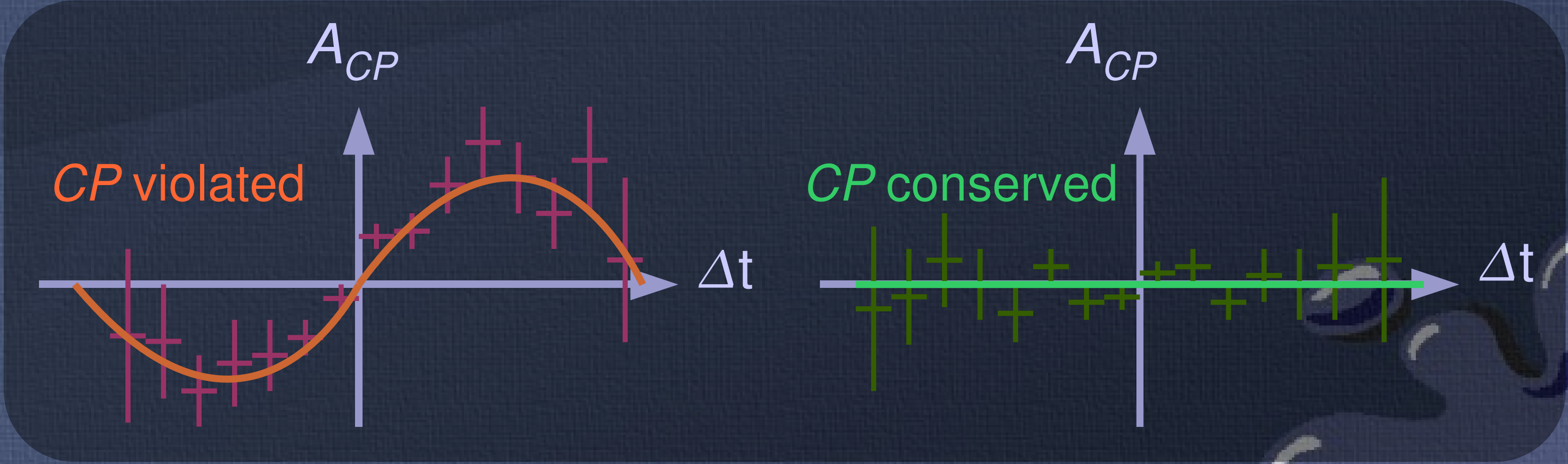
Indicates direct *CP* violation

$A_f = 0$ if $f_{CP} = J/\psi K_S$

($-A_f = C_f$ in BaBar)

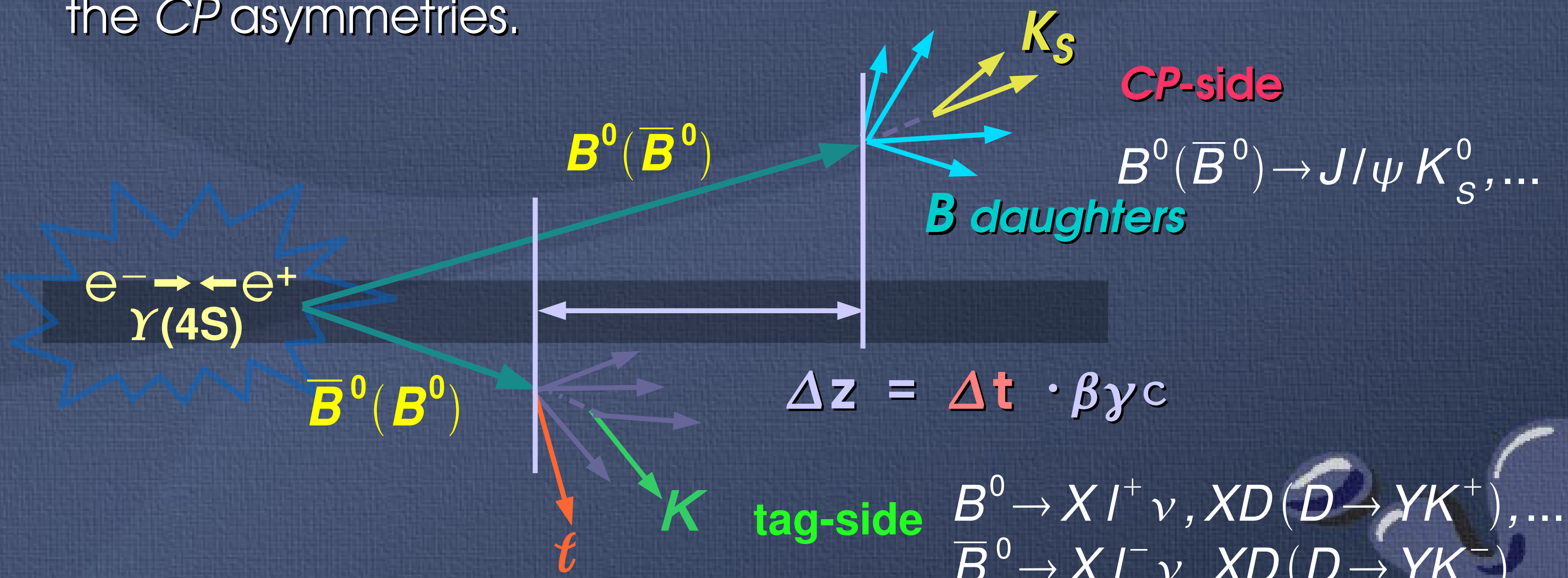
$S_f = \sin 2\phi_1$

if $f_{CP} = J/\psi K_S$



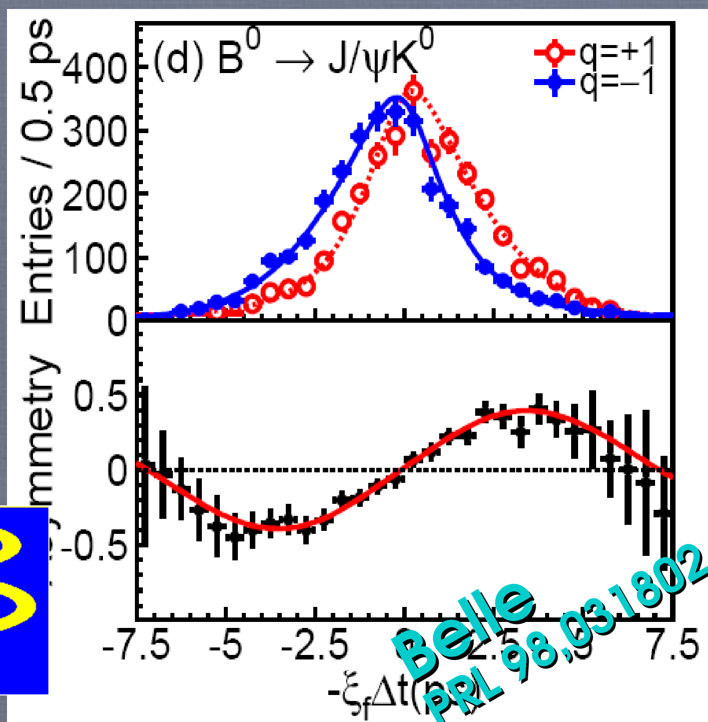
The Measurement in Principle

- The experiments take the advantage of energy-asymmetric collider to produce Lorentz boosted *B* mesons.
- Fully reconstruct a *CP* eigenstate (e.g. $J/\psi K_S$).
- Tags the *B* flavor from the associated *B* meson.
- Measures the proper-time difference (Δt), and extract the *CP* asymmetries.

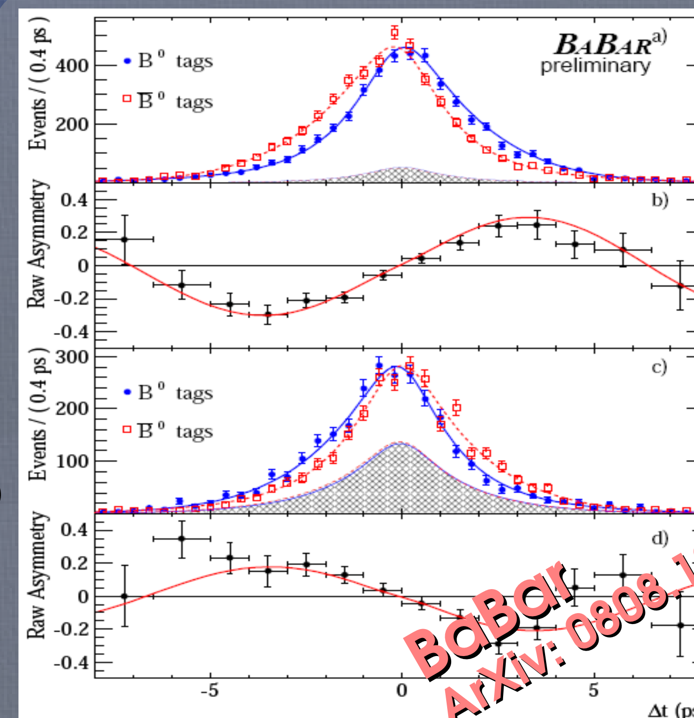


Measurements of ϕ_1/β

The Golden Channel, $b \to ccs$ Decays



Belle
PRL 98,031802 (2007)



BaBar
ArXiv: 0808.1903

$S = 0.642 \pm 0.031 \pm 0.017$

$S = 0.691 \pm 0.029 \pm 0.014$

CP Violation in *B* system
is already established within
the Standard Model.

HFAG ($b \to ccs$): $S_{ccs} = 0.672 \pm 0.024$
($A_{ccs} = 0.005 \pm 0.020$, consists of no *DCPV*)

The Grand Puzzle

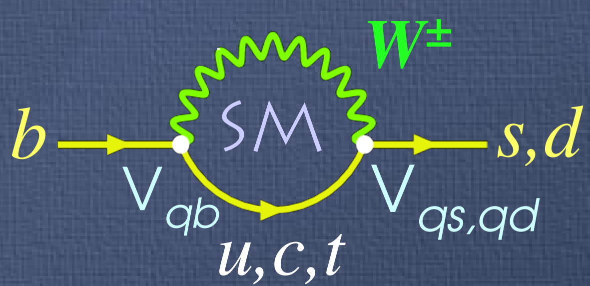
- Q: What is the source of *CP* violation?
- A: The **Kobayashi-Maskawa phase** is the source!

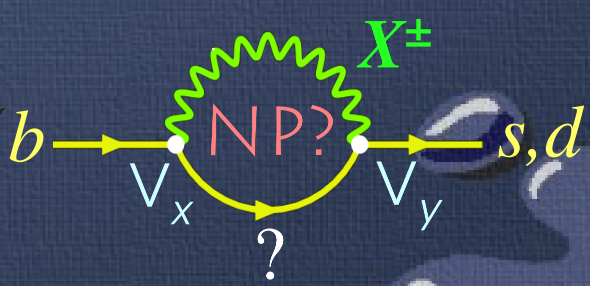
- Q: That's all?
- A: **NOT YET CLEAR!** Since: $\frac{n(B)}{n(\gamma)} = (5.1^{+0.3}_{-0.2}) \times 10^{-10}$ (WMAP)

KM phase only contributes ~10^{-20}

New source of CPV is required.

Search for non-SM particles with higher order diagrams:
e.g. ***b→s,d* penguin loops,** $B \to \phi K_S$, $\eta' K_S$,...

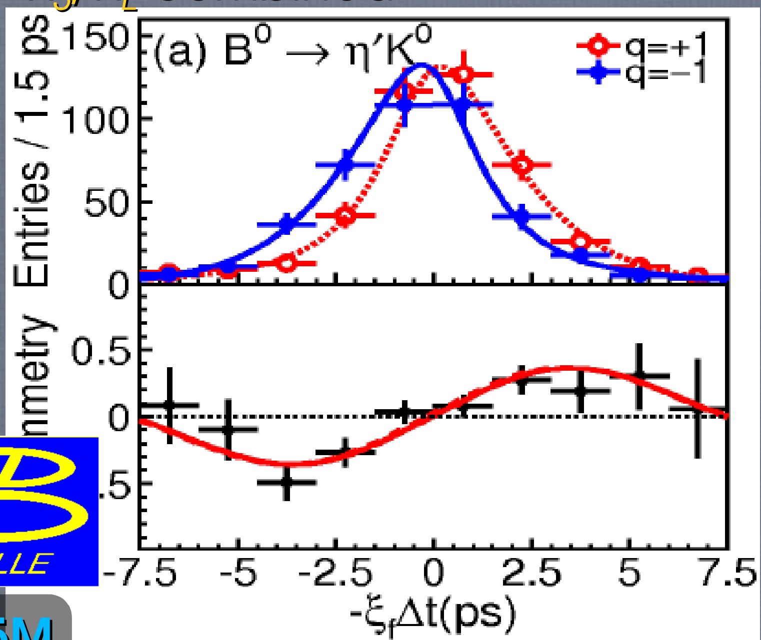




Measurements of ϕ_1/β with Penguins

Single Mode with the Highest Precision: $B \to \eta' K^0$

K_S/K_L combined

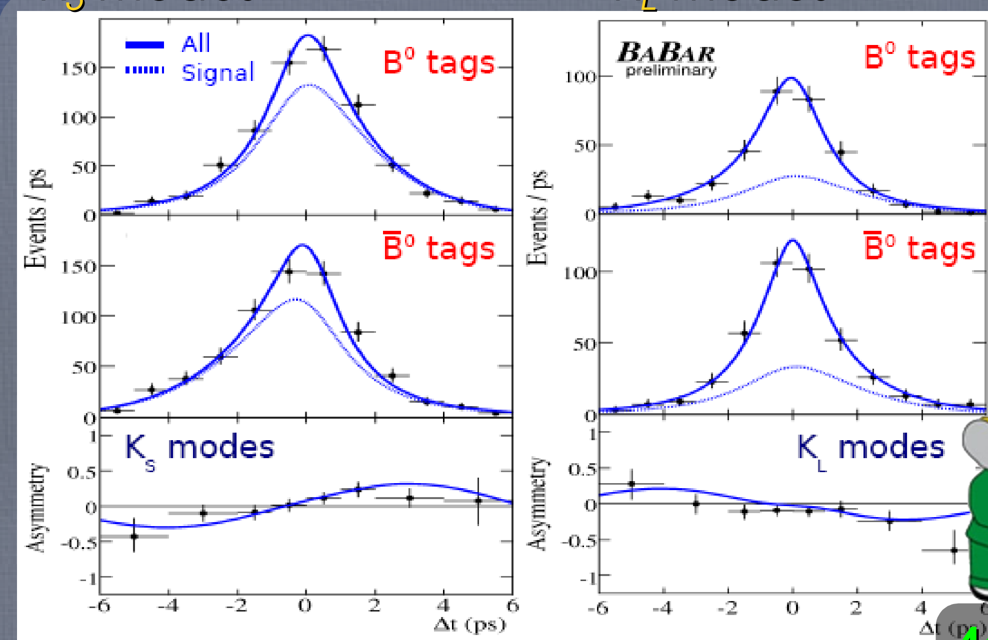


BELLE

535M

Ref. PRL 98: 031802 (2007)

K_S modes K_L modes



467M

Ref. arXiv: 0809.1174

$S(\eta' K^0) = 0.64 \pm 0.10 \pm 0.04$
$A(\eta' K^0) = -0.01 \pm 0.07 \pm 0.05$

$S(\eta' K^0) = 0.57 \pm 0.08 \pm 0.02$
$-C(\eta' K^0) = 0.08 \pm 0.06 \pm 0.02$

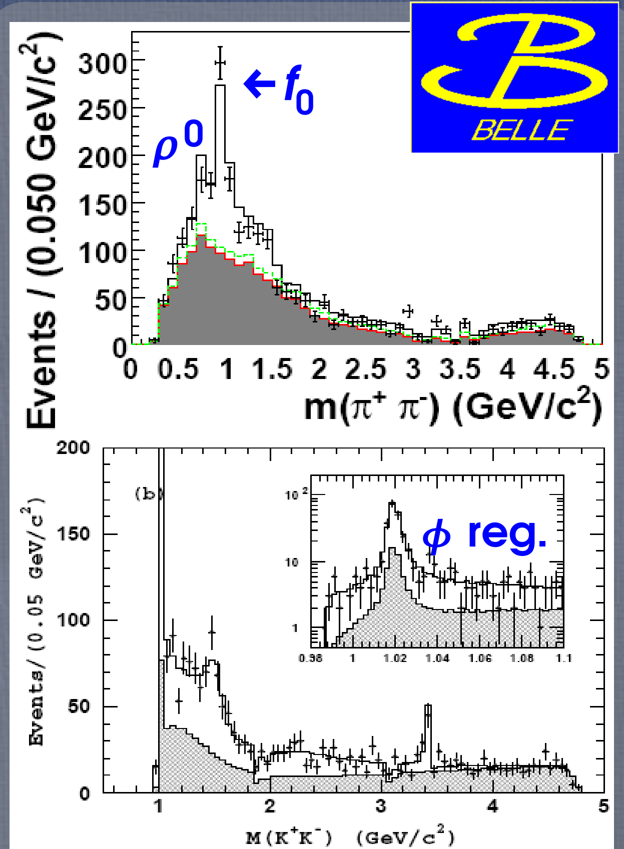
- Observation of TCPV in a single well-defined penguin mode!
- Results are consistent with $J/\psi K$ average.

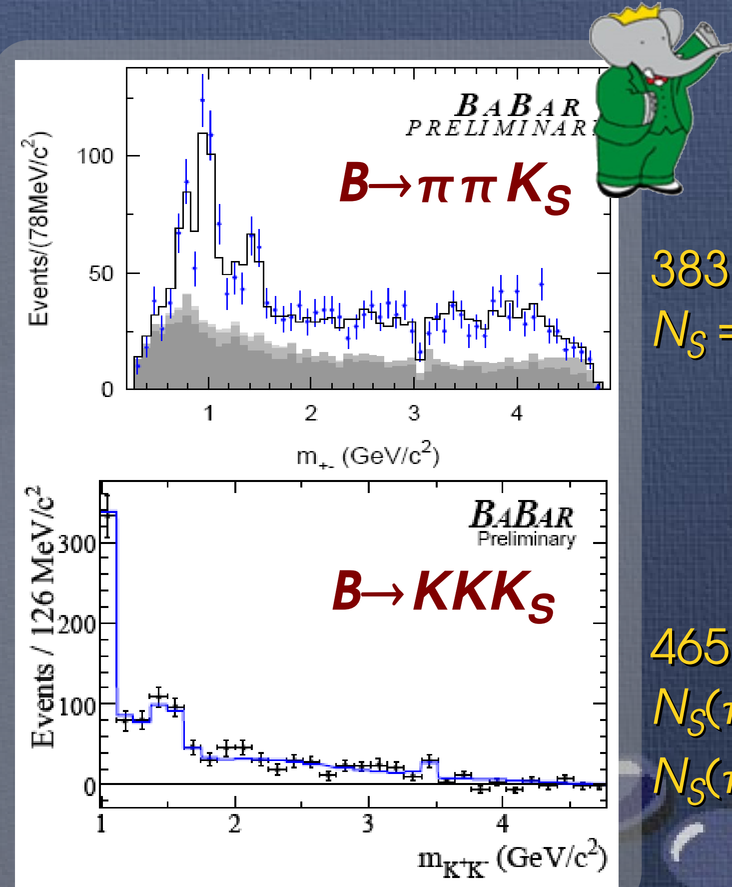
Dalitz Analysis: $B \to \pi\pi K_S, B \to KKK_S$

- Obtain *CP* parameters (ϕ_1/β) directly for 2-body and 3-body modes by time-dependent simultaneous Dalitz fits.
- The 2-fold ambiguity of "$\sin 2\phi_1$" could be resolved.

657M
$N_S = 1944 \pm 98$

657M
$N_S = 1269 \pm 51$





383M
$N_S = 2172 \pm 70$

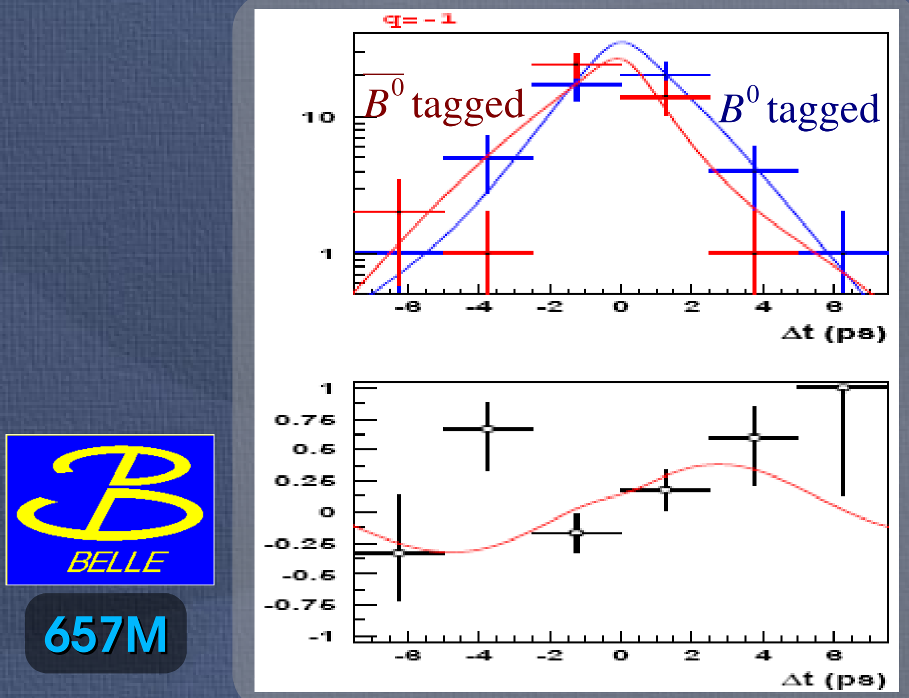
465M
$N_S(\pi^\pm) = 1268 \pm 43$
$N_S(\pi^0) = 160 \pm 19$

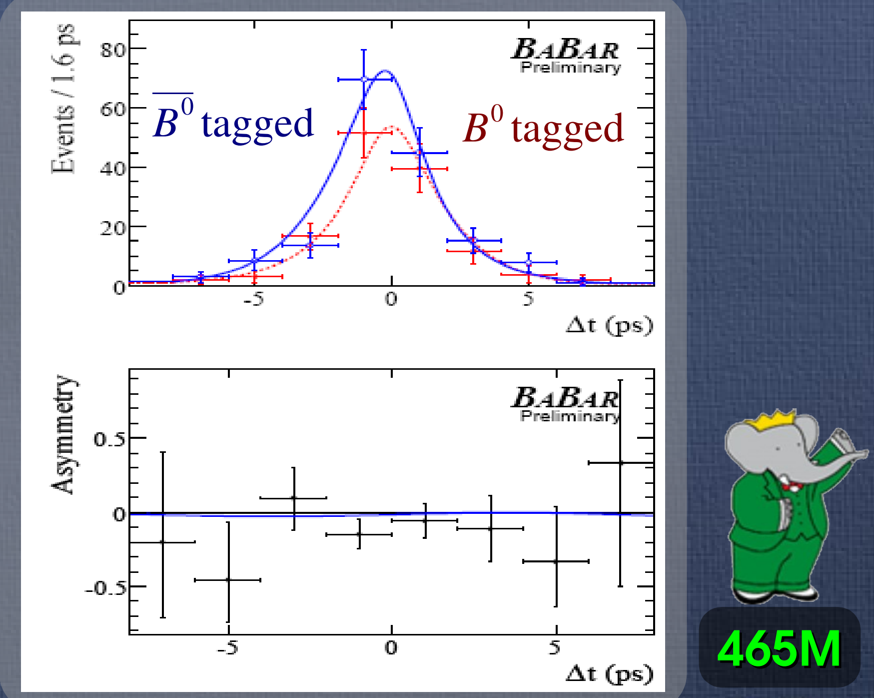
J. Dalseno's talk at ICHEP2008 Ref. arXiv: 0808.0700, 0708.2097

Dalitz Analysis: $B \to \pi\pi K_S, B \to KKK_S$

The Golden Channel: $B \to \phi K_S$

- Focus on the low M(*KK*) region, and Extract the *CP* parameters:





$A_{CP} = +0.31^{+0.21}_{-0.23} \pm 0.04 \pm 0.09$

$\phi_1^{eff} = 21.2^{+9.8}_{-10.4} \pm 2.0 \pm 2.0°$

($\sin 2\phi_1^{eff} = 0.67 + 0.22/-0.32$)

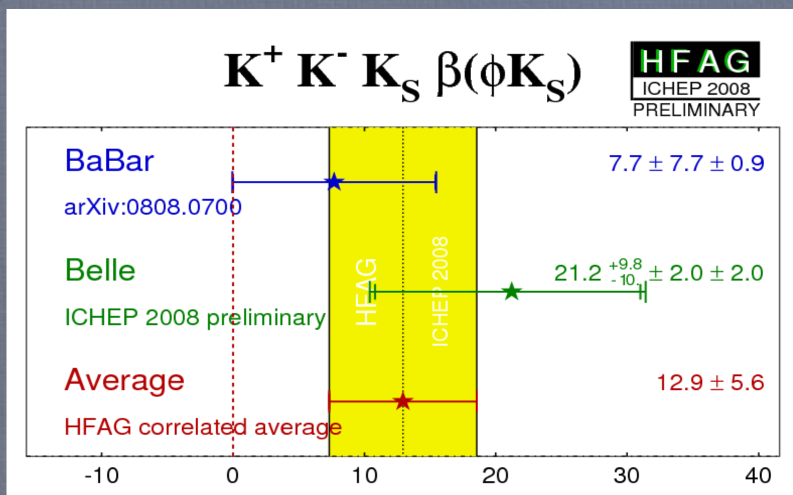
$A_{CP} = +0.14 \pm 0.19 \pm 0.02$

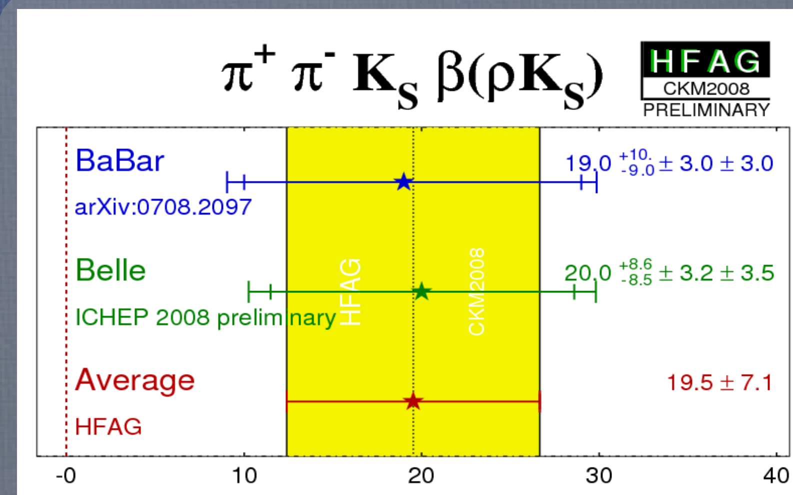
$\phi_1^{eff} = 7.4 \pm 7.4 \pm 1.1°$

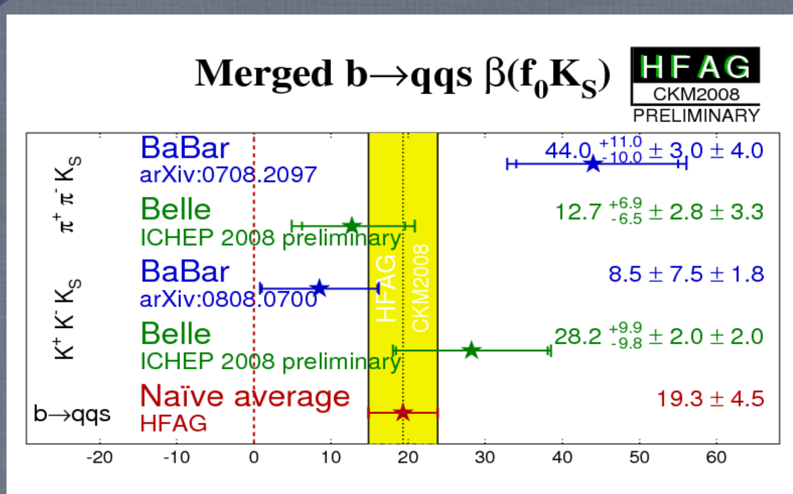
($\sin 2\phi_1^{eff} = 0.26 \pm 0.26 \pm 0.03$)

Dalitz Analysis: $B\to\pi\pi K_S, B\to KKK_S$

Averages: ϕK_S, $\rho^0 K_S$ and $f_0(980)K_S$







Average $\sin 2\phi_1^{eff}$

$\phi K_S : 0.44^{+0.17}_{-0.18}$

$\rho^0 K_S : 0.63^{+0.17}_{-0.21}$

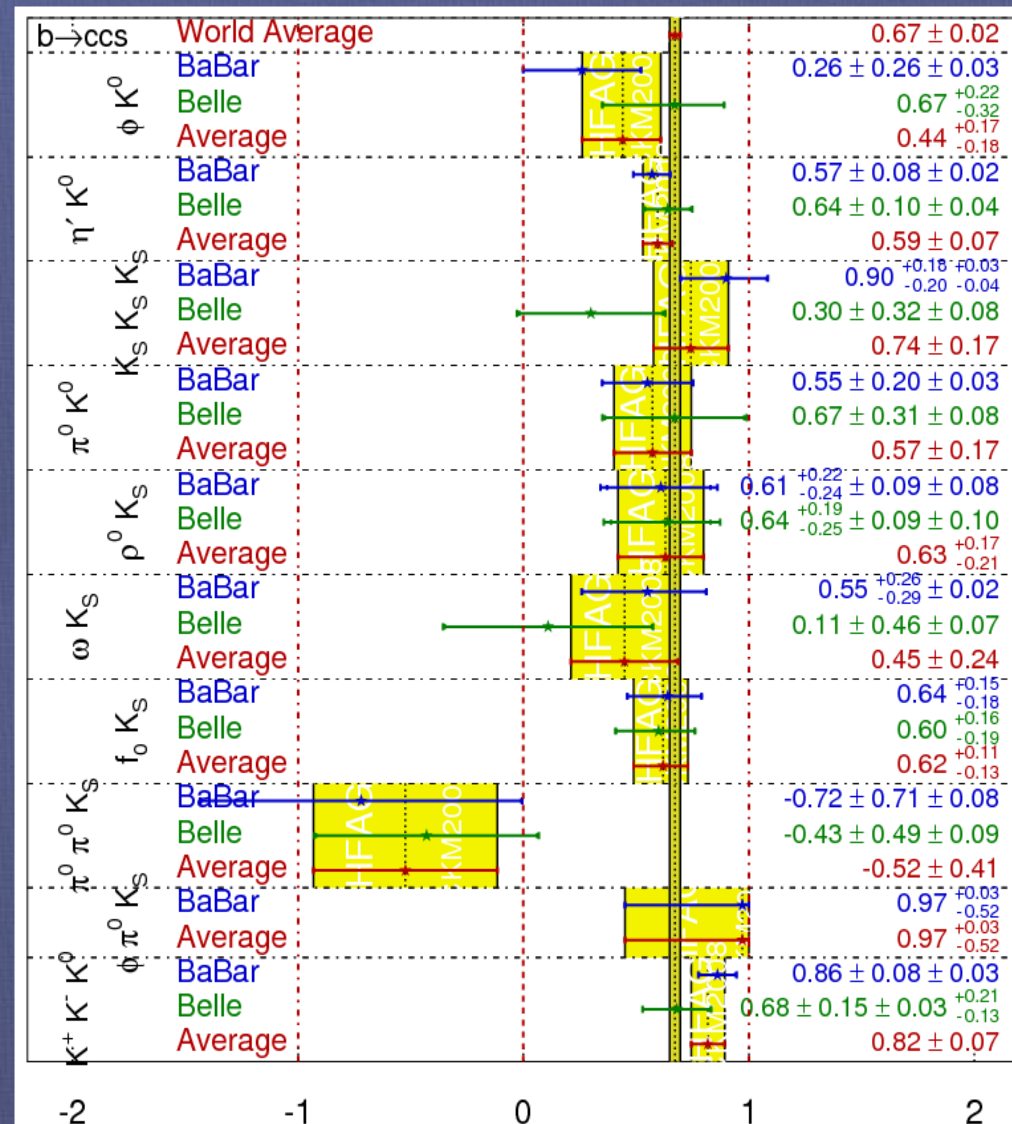
$f_0(980)K_S : 0.62^{+0.11}_{-0.13}$

- More or less consistent with $b\to ccs$ result.

Measurements of ϕ_1/β with Penguins

$b \to sqq$ Penguins Summary

HFAG CKM 2008 results ➔



All measurements now are more or less consistent with the *S* value from $b \to ccs$ decays:

$S(b \to ccs) = 0.672 \pm 0.024$

HFAG naïve average:

$S(\text{penguins}) = 064 \pm 0.04$

- Measurement with penguin modes are still an excellent test for NP.
- More statistics are required for mode-by-mode studies.

Measurements of ϕ_2/α: $\pi\pi$

- We can still extract the *CP* parameters, $A_{\pi\pi}$ & $S_{\pi\pi}$:

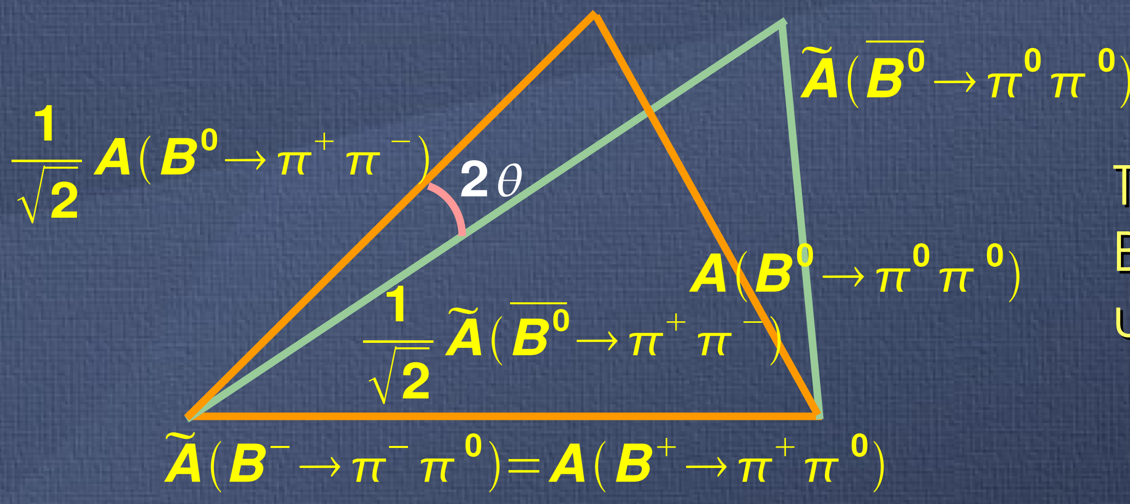
$$A_{CP}(t) = A_{\pi\pi}\cos(\Delta m t) + S_{\pi\pi}\sin(\Delta m t)$$

$$\lambda = e^{2i\phi_2}$$
$$A_{\pi\pi} = 0$$
$$S_{\pi\pi} = \sin 2\phi_2$$

Tree only

$$\lambda = e^{2i\phi_2}\frac{1+|P/T|e^{i\delta}e^{i\gamma}}{1+|P/T|e^{i\delta}e^{-i\gamma}}$$
$$A_{\pi\pi} \propto \sin\delta$$
$$S_{\pi\pi} = \sqrt{1-A_{\pi\pi}}\sin 2\phi_2^{eff}$$

Tree + Penguin Related to ϕ_2



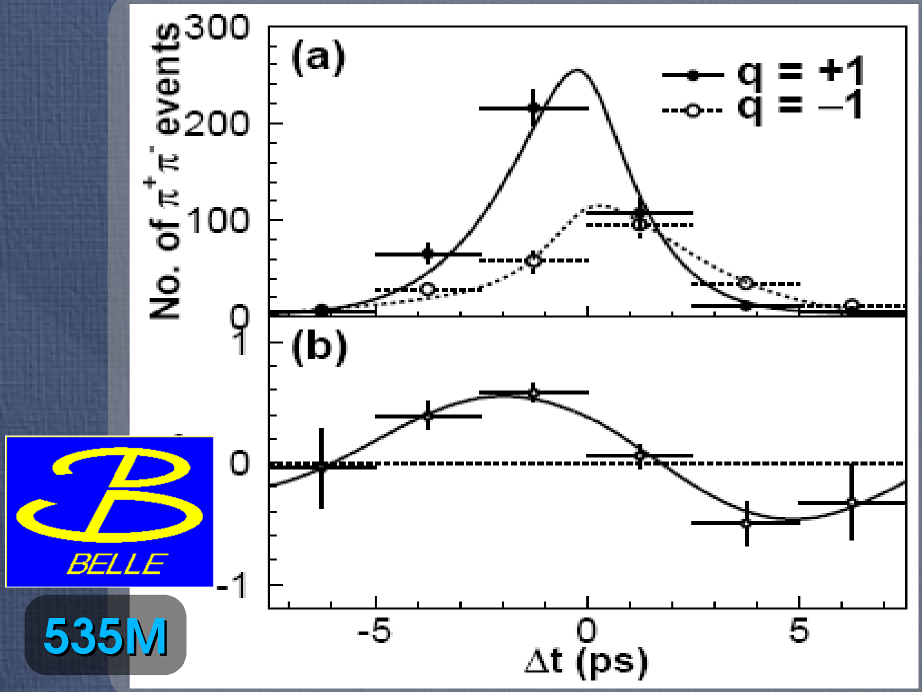
An isospin analysis is required:
Gronau-London PRL 65, 3381 (1990)

The branching fractions of $B\to\pi^+\pi^-/\pi^+\pi^0/\pi^0\pi^0$ can be used to constrain ϕ_2

$$\theta = |\phi_2 - \phi_2^{eff}|$$

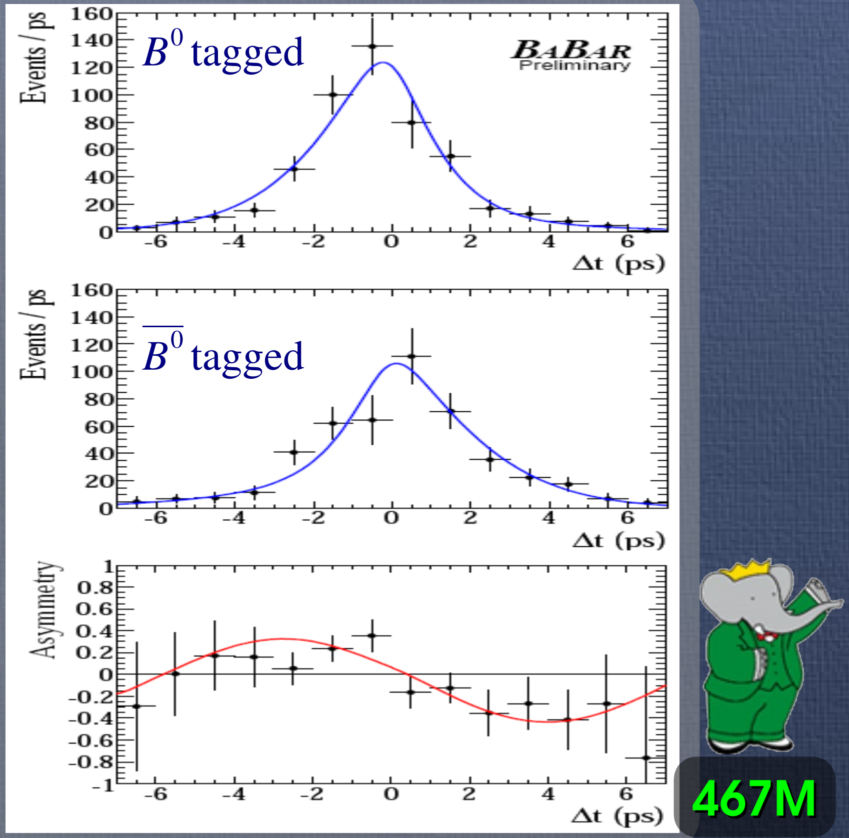
Measurements of ϕ_2/α: $\pi\pi$

- TCPV measurements with $B \to \pi^+\pi^-$ candidates:



Ref. PRL 98: 211801 (2007)

$S(\pi^+\pi^-) = -0.61 \pm 0.10 \pm 0.04$
$A(\pi^+\pi^-) = +0.55 \pm 0.08 \pm 0.05$

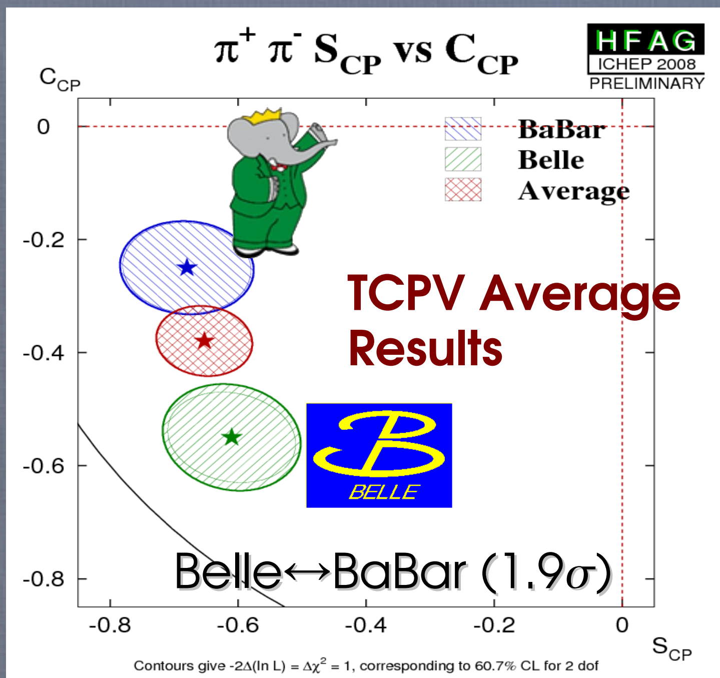


Ref. arXiv: 0807.4226

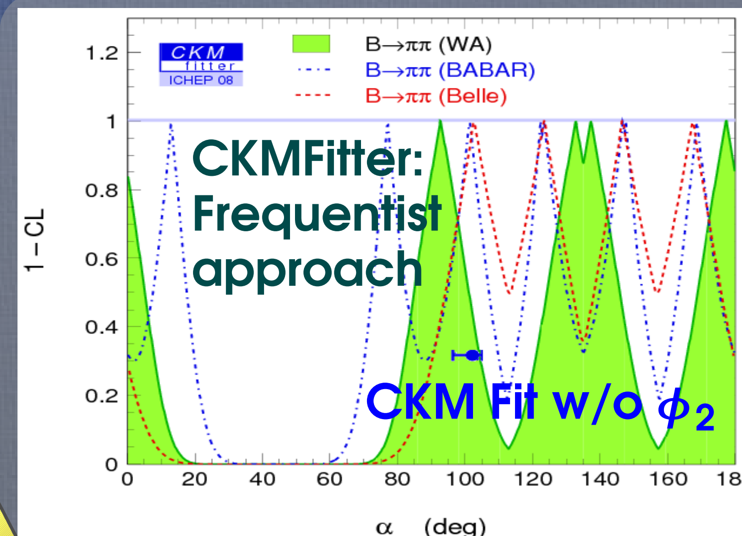
$S(\pi^+\pi^-) = -0.67 \pm 0.10 \pm 0.03$
$-C(\pi^+\pi^-) = +0.25 \pm 0.08 \pm 0.02$

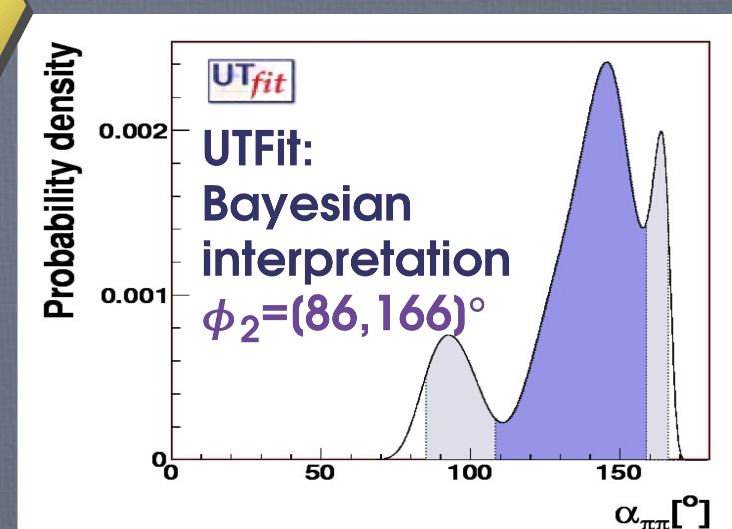
Observation of TCPV & DCPV!

Measurements of ϕ_2/α: $\pi\pi$



$$Bf(\pi^+\pi^-) = 5.16 \pm 0.22 \times 10^{-6}$$
$$Bf(\pi^+\pi^0) = 5.59 \pm 0.41 \times 10^{-6}$$
$$Bf(\pi^0\pi^0) = 1.55 \pm 0.19 \times 10^{-6}$$
$$A_{CP}(\pi^+\pi^0) = 0.06 \pm 0.05$$
$$A_{CP}(\pi^0\pi^0) = 0.43^{+0.25}_{-0.24}$$

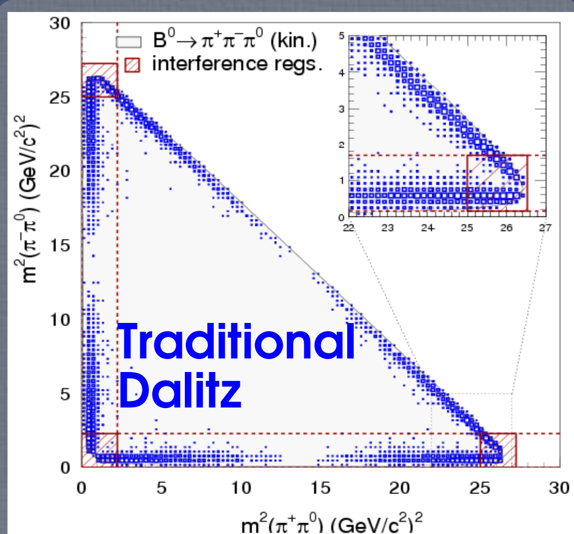




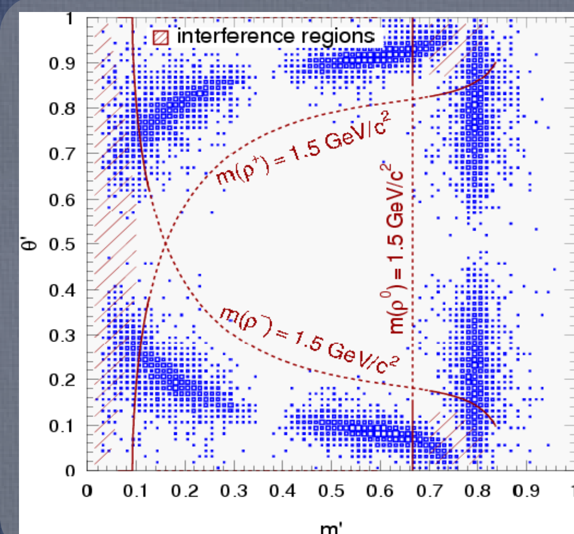
HFAG *Bf* & A_{CP}

Measurements of ϕ_2/α: $\rho\pi$

- Not a pure *CP*-eigenstate!
- Experimental approach: Time-dependent Daltiz analysis to constrain the ϕ_2 angle without discrete ambiguity (Snyder-Quinn).
- Model the events through a **square Dalitz plot**:



Zoom in to the interference region.

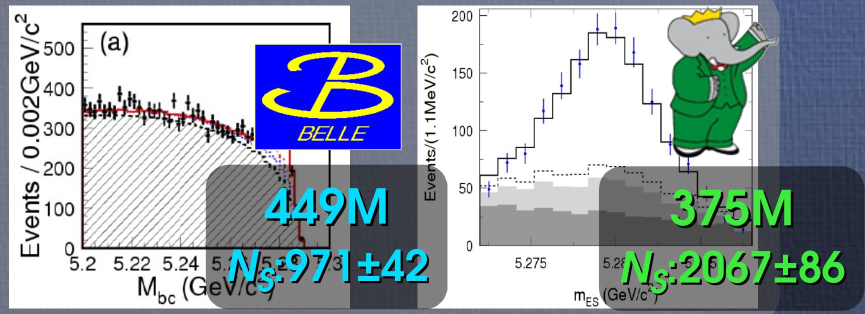


- Starting from the 3-body decay amplitudes, and fits to the events with **27** form factor bilinear coefficients.

(Translate these coefficients to quasi-2-body parameters for easy interpretations)

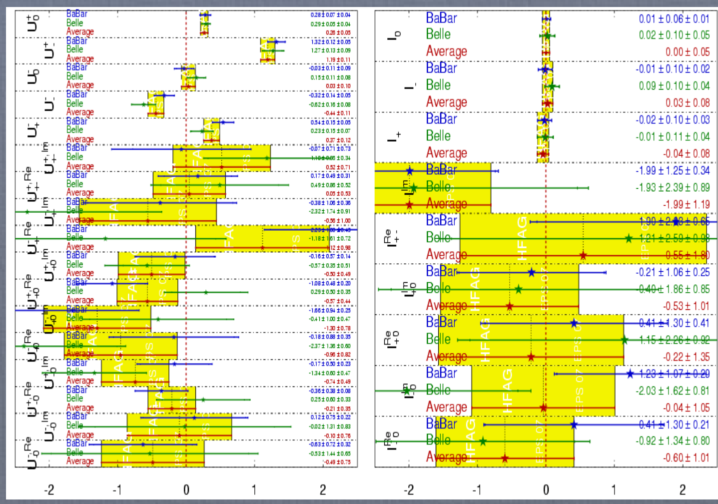
Measurements of ϕ_2/α: $\rho\pi$

B-factory data

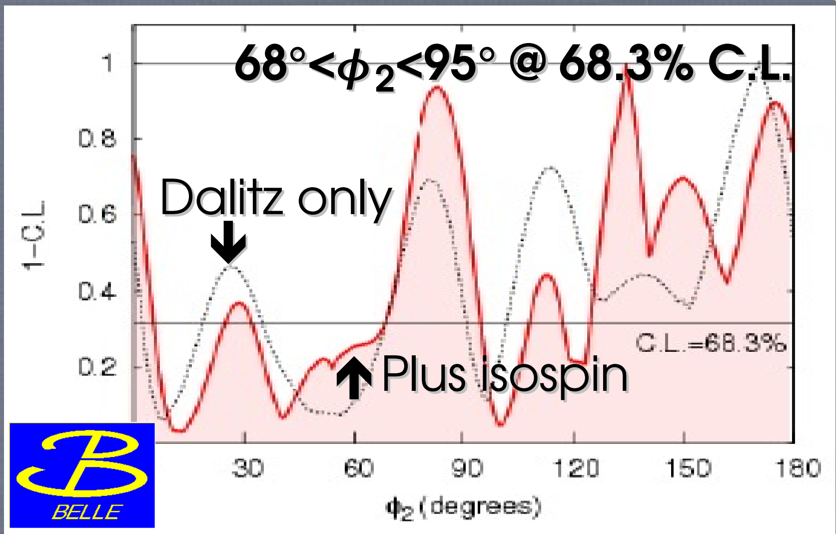


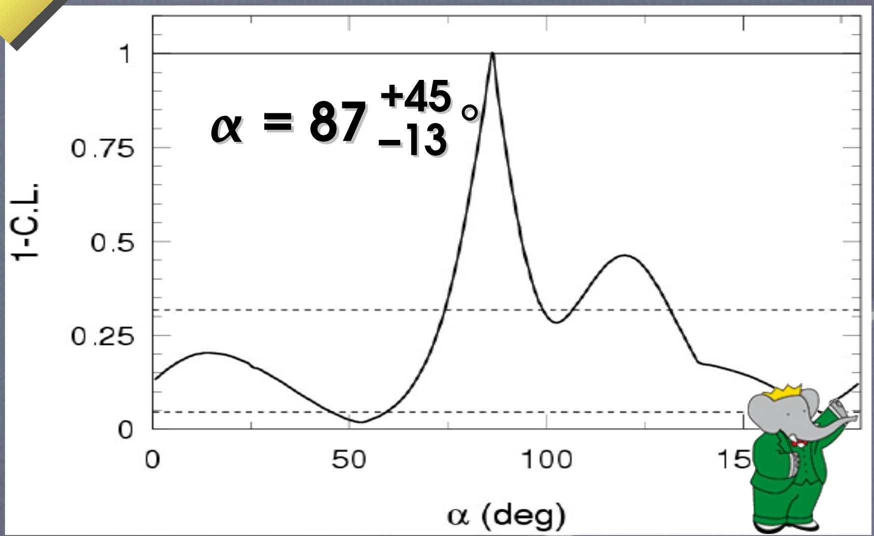
Ref. PRL 98: 221602 (2007)
Ref. PRD 76: 012004 (2007)

Extracting the 27 bilinears



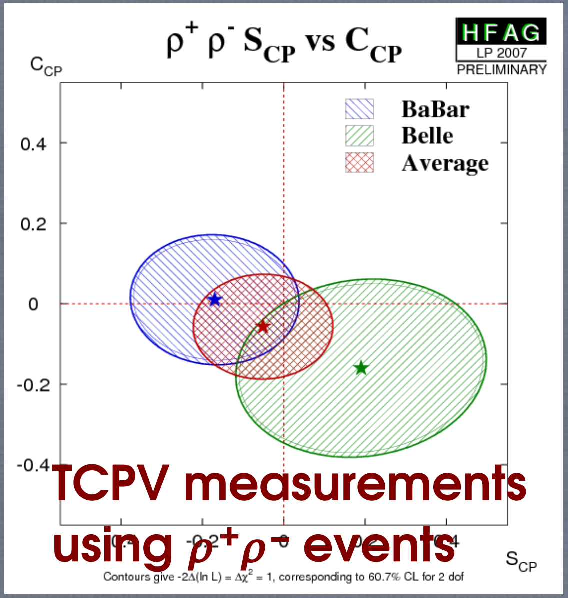
Then, constrain to the ϕ_2 angle

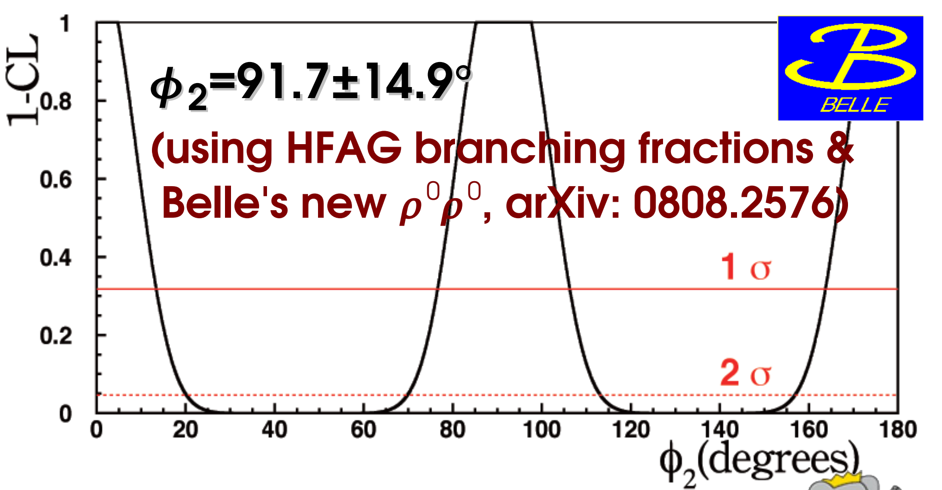


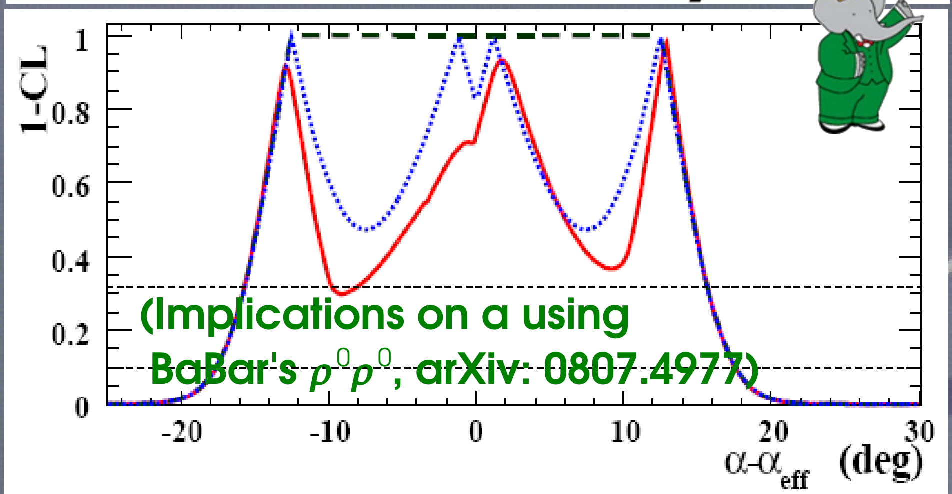


Measurements of ϕ_2/α: $\rho\rho$

- Similar to $\pi\pi$, the ϕ_2 angle can be constrained using an isospin analysis *(including several branching fractions & A_{CP} measurements).*



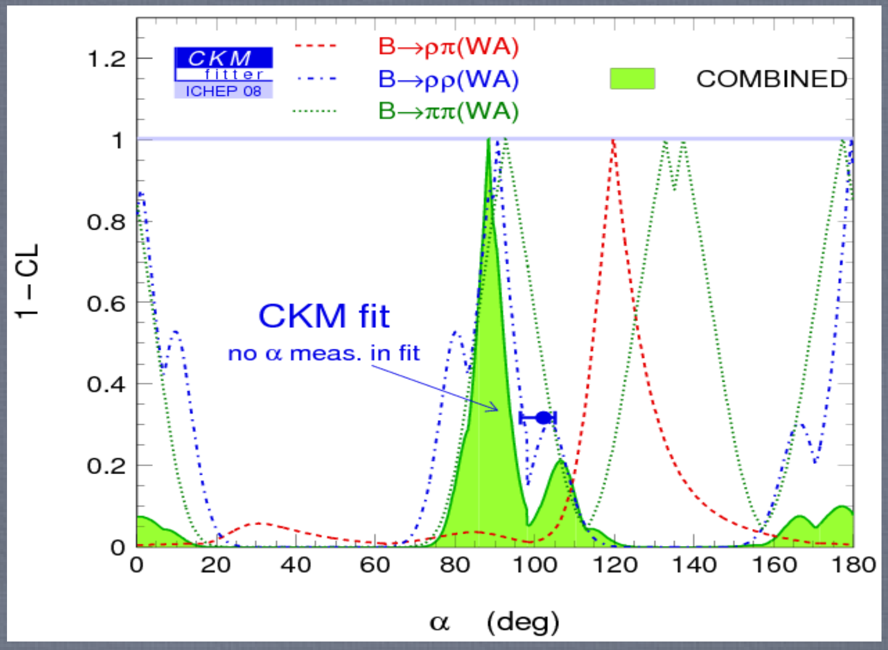


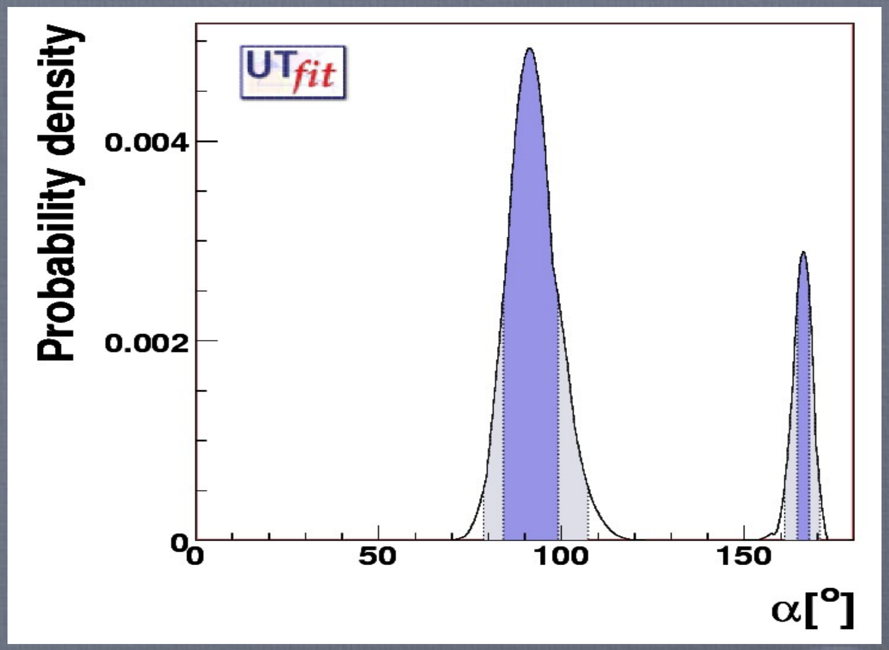


- $\rho\rho$ is ~100% longitudinal polarized ➔ ~*CP* eigenstate.
- Penguin pollution is small (since $\rho^0\rho^0$ is tiny.)

Measurements of ϕ_2/α: Summary

- A global constraint on ϕ_2/α: rely on statistical treatment, CKMFitter (Frequentist) or UTFit (Bayesian).
- Including: $\pi\pi$ (WA), $\rho\pi$ (WA), and $\rho\rho$ (WA) HFAG results.





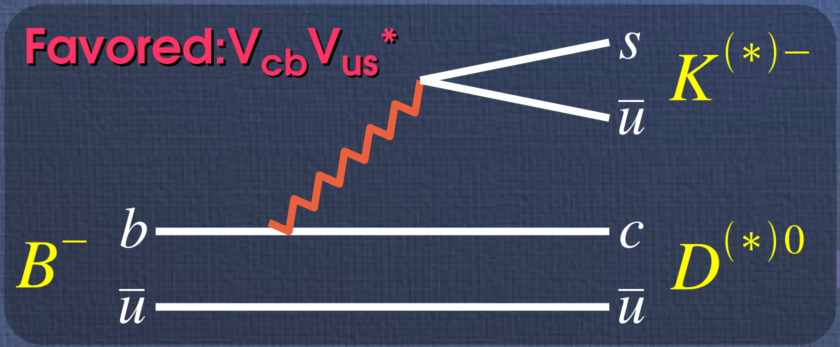
ϕ_2=88.3° (central value)

$\phi_2 \in$ (83.5,94.0)° 1σ interval

$\phi_2 \in$ (92±7)° ∪ (166±2)° @ 68% C.L.

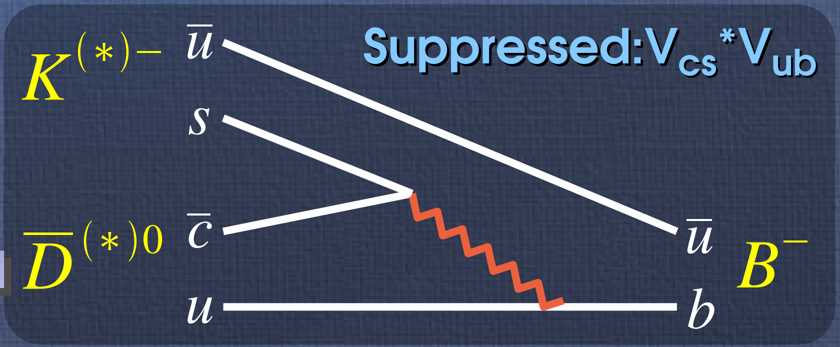
(From the rest of UTFit: ϕ_2=92±4°)

Measurements of ϕ_3/γ



Common Final State

f



$$A\left(\frac{B^- \to \overline{D}^0 K^-}{B^- \to D^0 K^-}\right) = \boxed{r_B} \cdot \exp(i\,\boxed{\delta_B}) \cdot \exp(-i\,\boxed{\phi_3})$$

Mode-by-mode para. Common CKM angle

- Three methods for exploiting the interference (choice of D^0 decays):
  - ➔ Gronau, London, Wyler (GLW): Use CP eigenstates of $D^{(*)0}$ decays,
    e.g. $D^0 \to KK, \pi\pi, K\phi, K\omega$.
  - ➔ Atwood, Dunietz, Soni (ADS): Use doubly Cabibbo-suppressed decays,
    e.g. $D^0 \to K\pi, K\pi\pi$.
  - ➔ Giri, Grossman, Soffer, Zupan (GGSZ): Use Dalitz plot analysis,
    e.g. $D^0 \to K_S\pi\pi, KKK, \pi\pi\pi$.

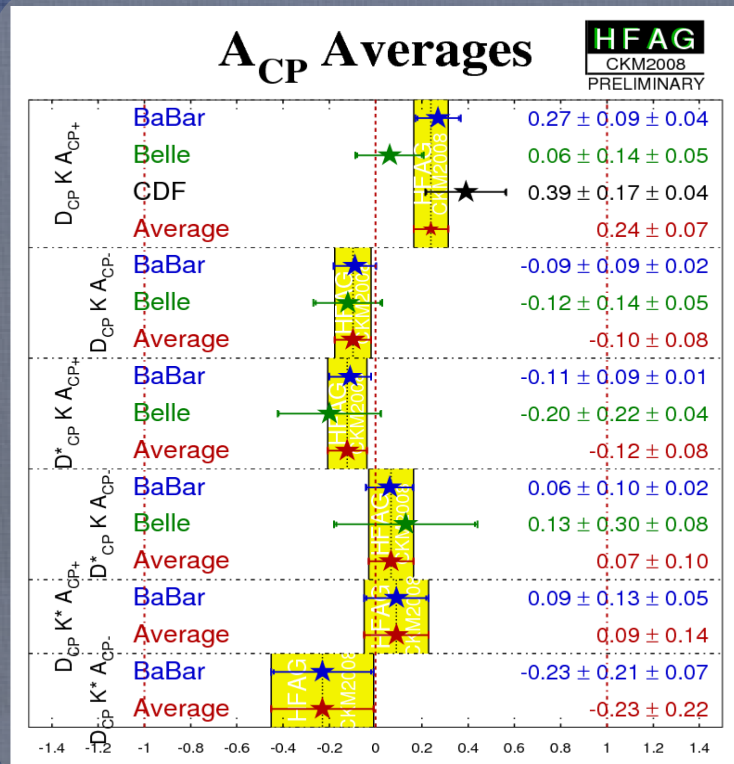
Measurements of ϕ_3/γ: GLW Method

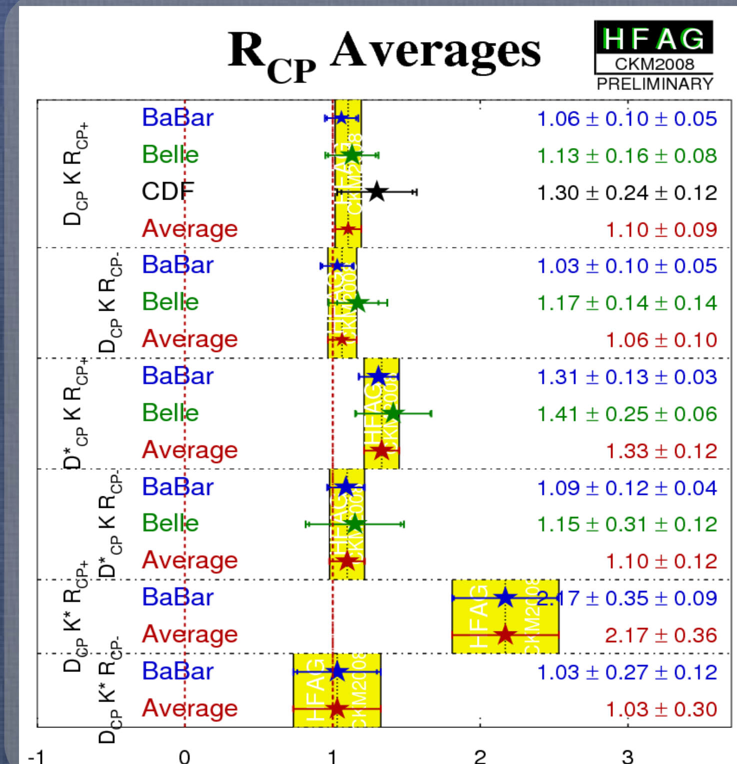
Ref. M. Gronau, D. London, D. Wyler PLB 253, 483 (1991); PLB 265, 172 (1991)

HFAG Averages:

BELLE 275M

~380M





Constrain on ϕ_3:

(ϕ_3 is unique)

$$R_{CP\pm} = 1 + r_B^2 \pm 2 r_B \cos(\delta_B)\cos(\phi_3)$$

$$A_{CP\pm} = \pm 2 r_B \sin(\delta_B)\sin(\phi_3)/R_{CP\pm}$$

Mode dependent parameters:

$$r_B = \left|\frac{A(b\to u)}{A(b\to c)}\right|$$

$$\delta_B = arg\left[\frac{A(b\to u)}{A(b\to c)}\right]$$

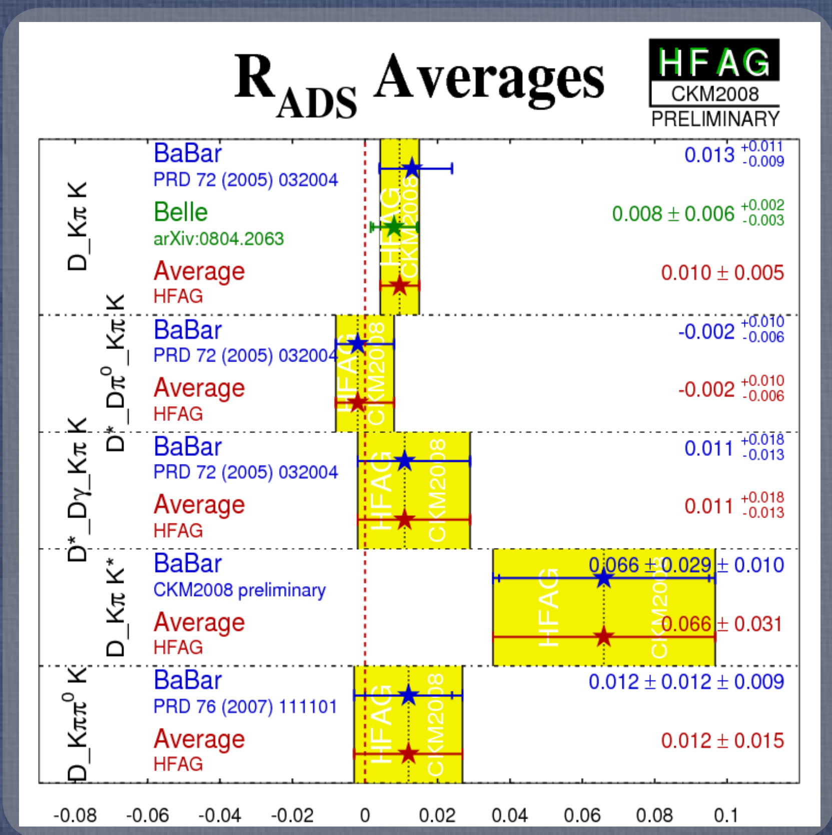
Measurements of ϕ_3/γ: ADS Method

Ref. D. Atwood, I. Dunietz and A. Soni, PRL 78, 3357 (1997).

HFAG Averages:
(mostly from BaBar)

232M
379M

657M



Observables:

$$R_{ADS}=\frac{Bf(B\rightarrow D_{\text{suppressed}}K)}{Bf(B\rightarrow D_{\text{flavored}}K)}$$
$$=r_B^2+r_D^2+2r_Br_D\cos(\phi_3)\cos(\delta)$$
$$A_{ADS}=2r_Br_D\sin(\phi_3)\sin(\delta)/R_{ADS}$$

Where

$$\delta=\delta_B+\delta_D$$
$$r_D=\left|\frac{A(D^0\rightarrow K^-\pi^+)}{A(D^0\rightarrow D^+\pi-[\,])}\right|=0.0613\pm0.0010$$

r_D & δ_D are the corresponding amplitude ratio and strong phase difference of the D meson decays.

Measurements of ϕ_3/γ: Dalitz Analysis

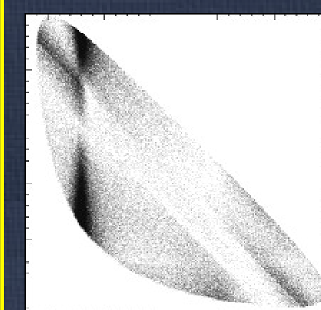
Re.f A. Giri, Yu. Grossman, A. Soffer, J. Zupan, PRD 68, 054018 (2003).

- Using three-body final state (common to D^0 and $\bar{D}^0$): $K_S\,\pi^+\pi^-$.
- The Dalitz distribution density:

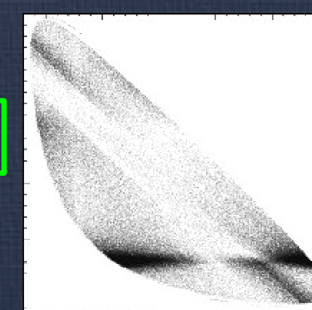
$$dp(m^2_{K_S\pi^+}, m^2_{K_S\pi^-}) \propto |f_D|^2\, dm^2_{K_S\pi^+}\, dm^2_{K_S\pi^-}$$

+/– sign corresponding to B+/B–

$$f_D(m^2_{K_S\pi^+}, m^2_{K_S\pi^-}) = \Big|$$



$$+\, r\, e^{i\delta \pm i\phi_3}$$

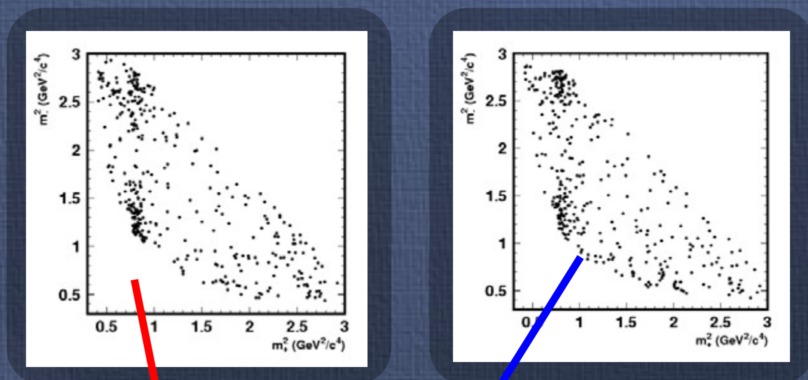


$$\Big|^2$$

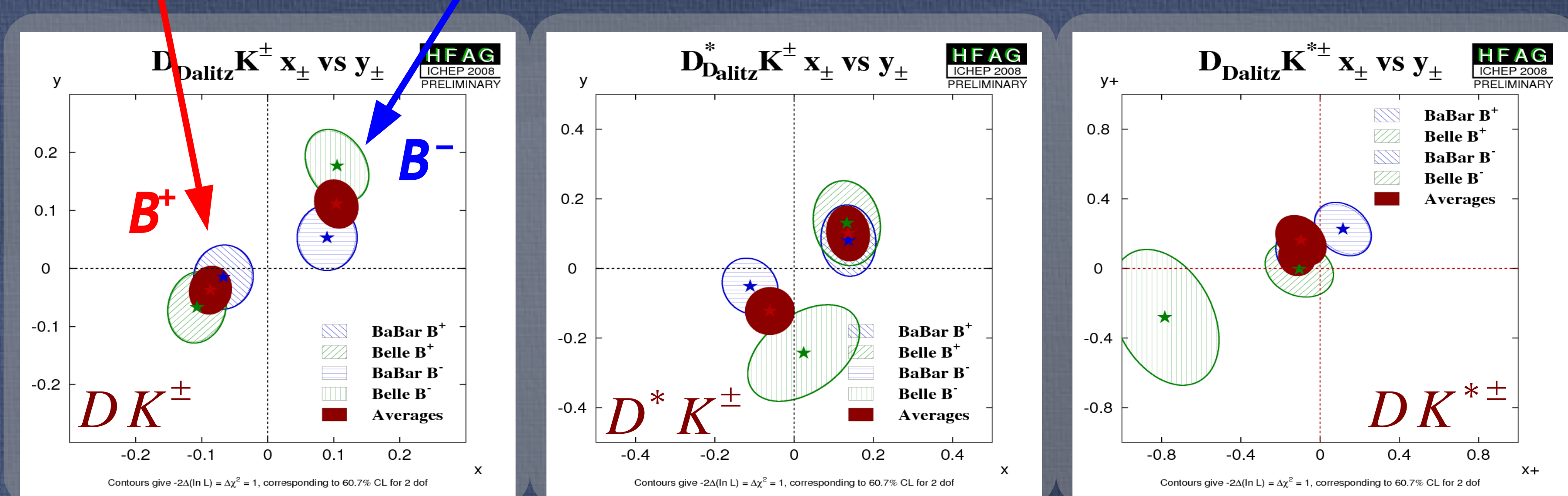
- Measuring B^+/B^- asymmetry across the Dalitz plot.
- If $D^0 \to K_s\pi\pi$ amplitude is known, the parameters, ϕ_3, r_B & δ, can be extracted from the fits to the Dalitz distribution.
- Need to model D^0 decay amplitude ➔ using $D^* \to D^0\pi$ decays.

Measurements of ϕ_3/γ: Dalitz Analysis

- Fitting parameters: $x_{\pm} = r_B \cos(\delta_B \pm \phi_3)$ $y_{\pm} = r_B \sin(\delta_B \pm \phi_3)$
- Maximum likelihood fit with event-by-event background treatment.



Clear evidence of CP violation in $B \to DK$ decays!



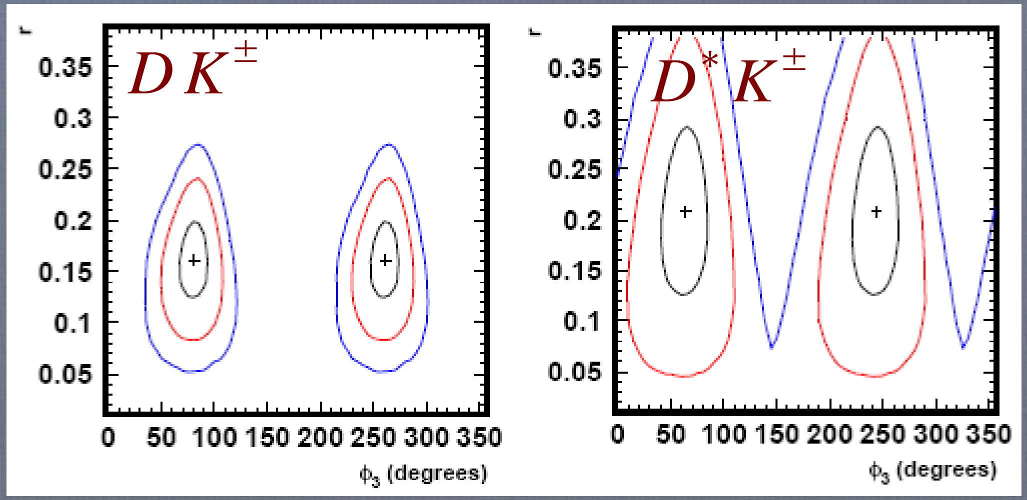
Measurements of ϕ_3/γ: Dalitz Analysis

Belle 657M

Ref. arXiv: 0803.3375

$$\phi_3 = (76^{+12}_{-13} \pm 4 \pm 9)^\circ$$

including DK^- & $D^* K^-$

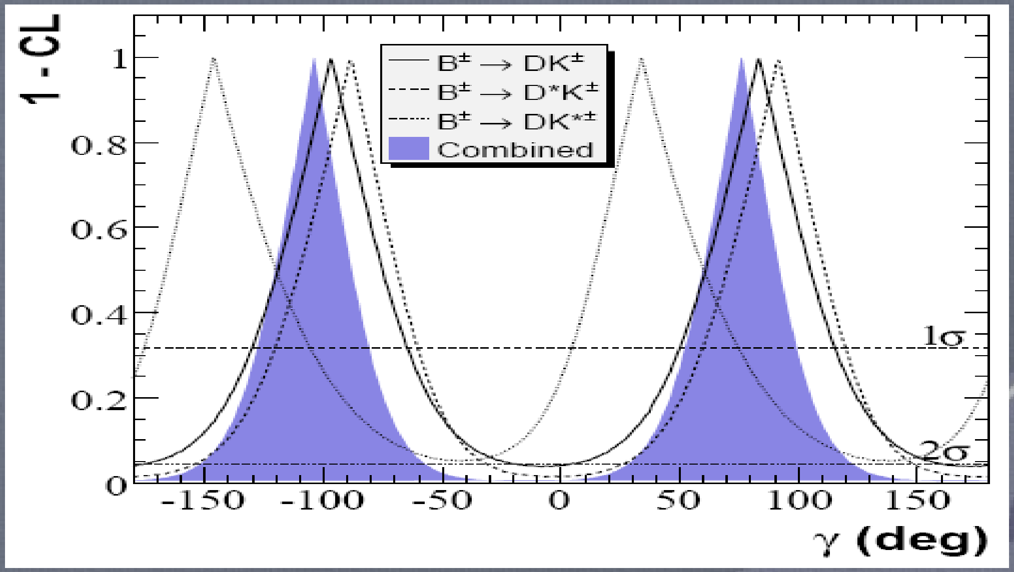


BaBar 383M

Ref. PRD 78:034023 (2008)

$$\gamma = (76 \pm 22 \pm 5 \pm 5)^\circ$$

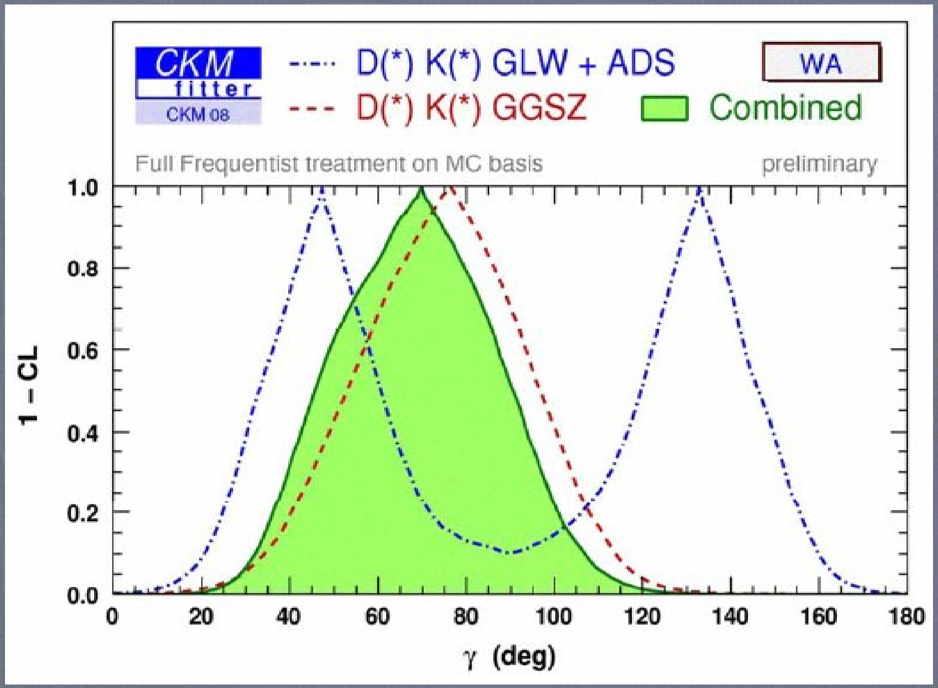
including DK^-, $D^* K^-$, $D K^{*-}$

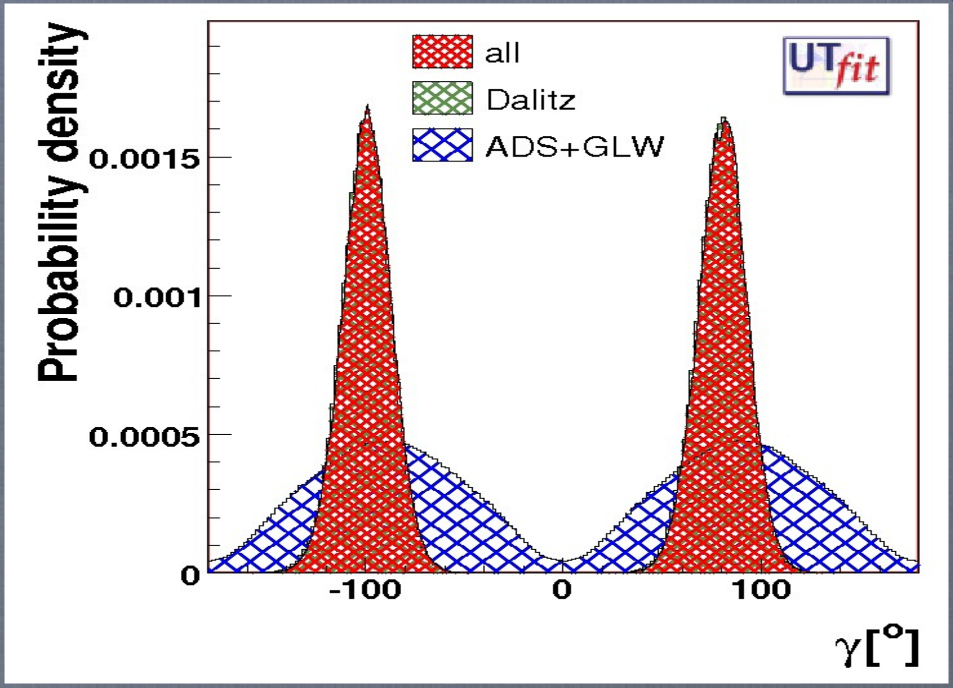


r_B & δ are extracted for each decay channel.

Measurements of ϕ_3/γ: Summary

- Including **GLW**, **ADS**, and **GGSZ** analyses.





CKMFitter : $\phi_3 = 70^{+27}_{-29}\,°$ **UTFit:** $\phi_3 = 81 \pm 13°$

ϕ_3 measurement is still very difficult and is limited by the statistics. Uncertainty is still around 15°~30°. Need new inputs from LHCb & SuperB.

Summary & Conclusion

- The *B*-factories have provided high precision measurements and constraints to the unitary triangle:
  - ➔ ϕ_1/β is precisely measured already, $\delta\sim2°$. Now it becomes an excellent place for NP searches.
  - ➔ ϕ_2/α measurement is limited by the penguin pollution, $\delta\sim10°$.
  - ➔ ϕ_3/γ: $\delta\sim15°–30°$. need much more data, and a good model for the D^0 Dalitz decay.

> Precision measurements of *CP* violation provide important constraints/tests to the physics beyond the Standard Model!

- These measurements are still limited by statistics!
  - ➔ Wait for the final data sets from *B*-factories & Tevatron.
  - ➔ Data from LHCb, and the Super *B* factory in the future.