CKM phase and CP Violation in B Decays

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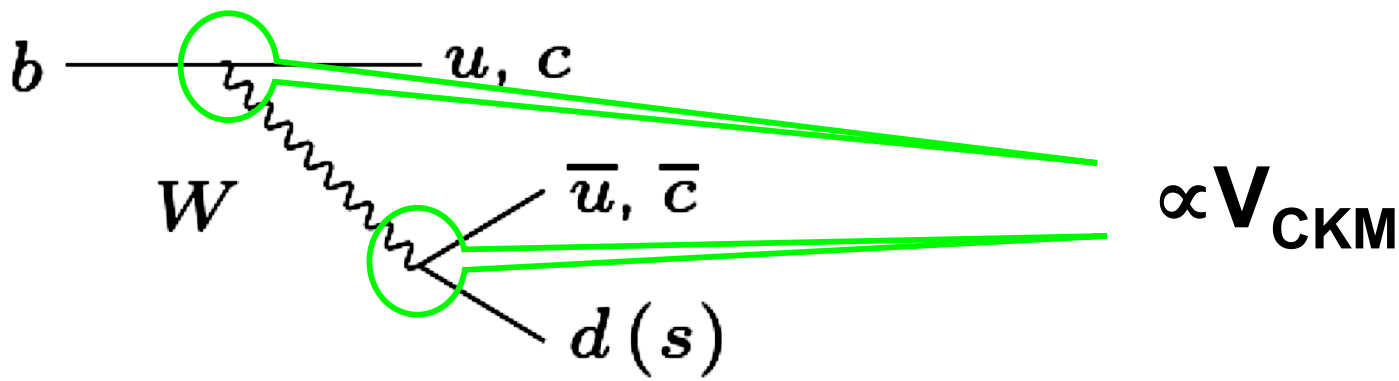
Talk Outline

- Review of CPV in the B system
- Results on the CKM unitarity angle $\beta=\phi_1$
- Results on the CKM unitarity angle $\alpha=\phi_2$
- Results on the CKM unitarity angle $\gamma=\phi_3$
- Results on the B_s phase angle ϕ_s
- Results on Direct CPV
- Conclusions

I will concentrate on (some) New Results

Quark-Sector Flavor in the SM

- 3 known generations of quark doublets
  - (u,d) (c,s) (t,b), EM charge (2/3, -1/3)
  - Origin of families unknown in SM
- Only the charged-current EW interaction can change flavor in the SM
- EW eigenstates aren't mass eigenstates
  - Only SM connection between generations!



The CKM matrix

- Relates EW flavor and quark mass eigenstates
  - No prediction of values within SM
- 3 generations, Unitarity $\Rightarrow$ 3 rotations, 1 phase
  - Non-zero phase implies CPV in flavor transitions
- New Physics (NP) with non-SM flavor couplings would make the CKM description incomplete
  - Eg: 4th generation, SUSY, …

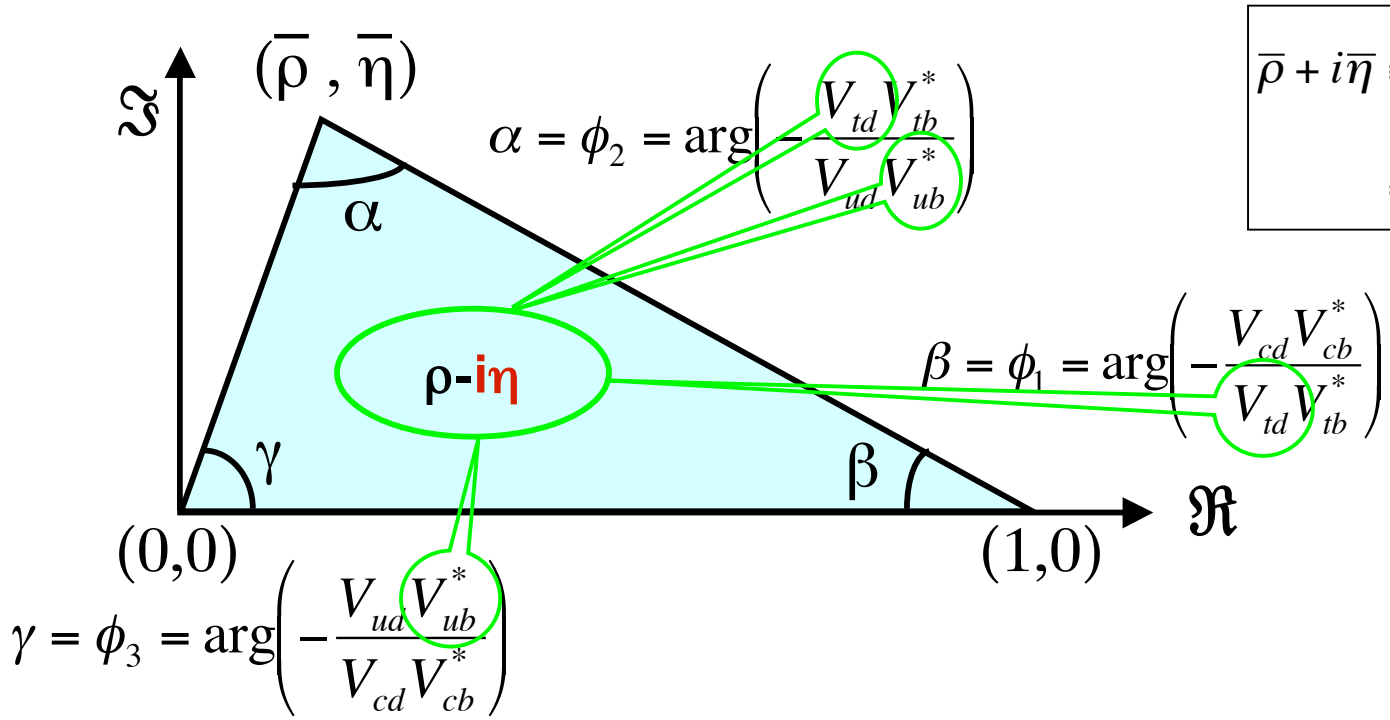
Wolfenstein parameterization

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

$\lambda \approx 0.23$, $A \approx 0.8$, $\rho \approx 0.2$, $\eta \approx 0.4$

The Unitarity Triangle(s)

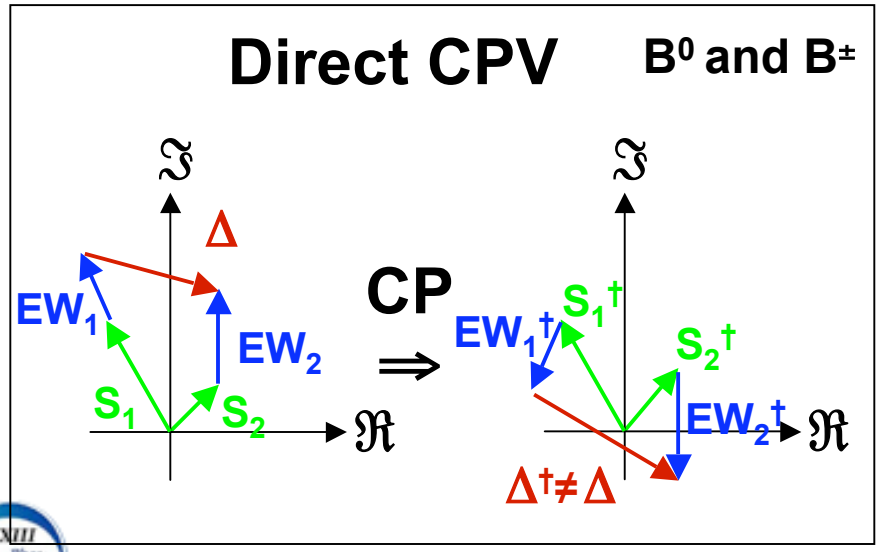
- Graphical expression of unitarity condition(s)
  - 1 triangle has roughly equal-length sides
- CKM Unitarity violation would imply New Physics
  - Test SM + CKM by over-constraining angles and sides

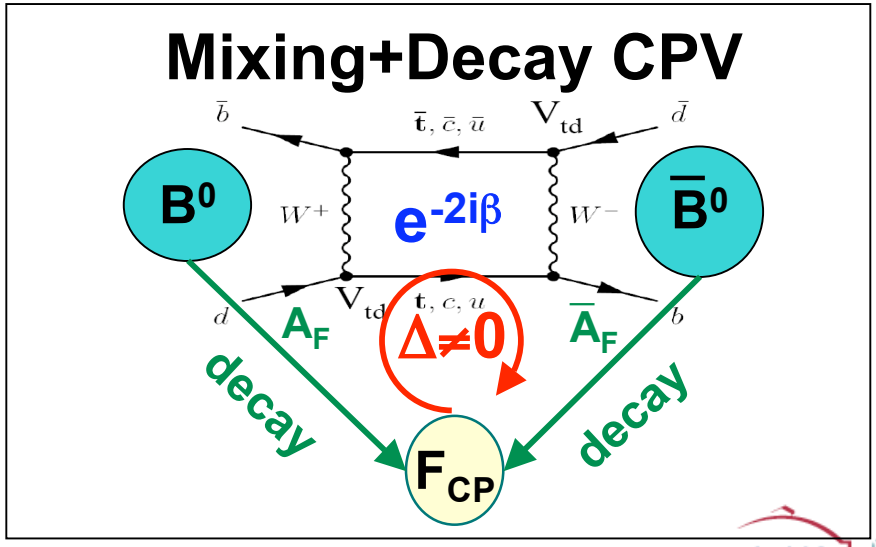


$$\bar{\rho} + i\bar{\eta} \equiv -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} = \rho + i\eta + O(\lambda^2)$$

Consequences of CPV

- CPV can occur when multiple B→F amplitudes interfere
  - CPV in decay (direct CPV)
  - CPV in mixing (original CPV seen in K_S, K_L)
    - Very small for B system (exp. limit $<10^{-2}$, predicted $\sim 10^{-3}$ in SM)
  - CPV in mixing + decay (indirect CPV)
- B system uniquely situated for CPV studies
  - Mixing, long lifetime, large production X-section, rich decay set, heavy quarks⇒theoretically accessible, …

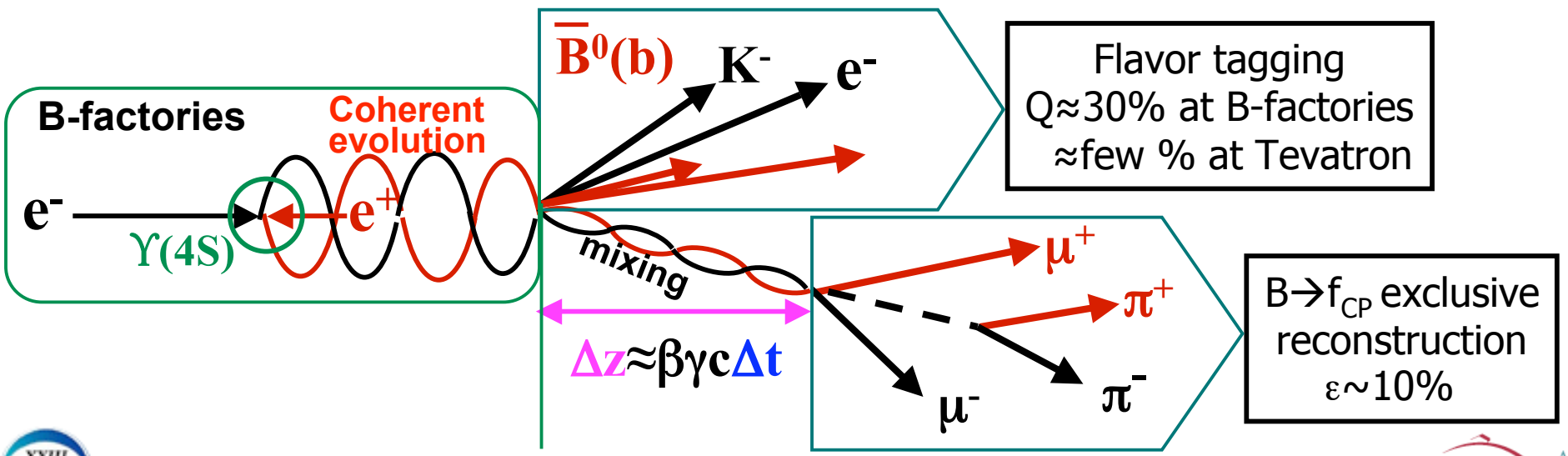




Detecting Indirect CPV in B-decays

$$A_{CP}(\Delta t) = \frac{N(\overline{B}^0(\Delta t) \to f_{CP}) - N(B^0(\Delta t) \to f_{CP})}{N(\overline{B}^0(\Delta t) \to f_{CP}) + N(B^0(\Delta t) \to f_{CP})}$$
$$= S_f \sin(\Delta m \bullet \Delta t) - C_f \cos(\Delta m \bullet \Delta t)$$

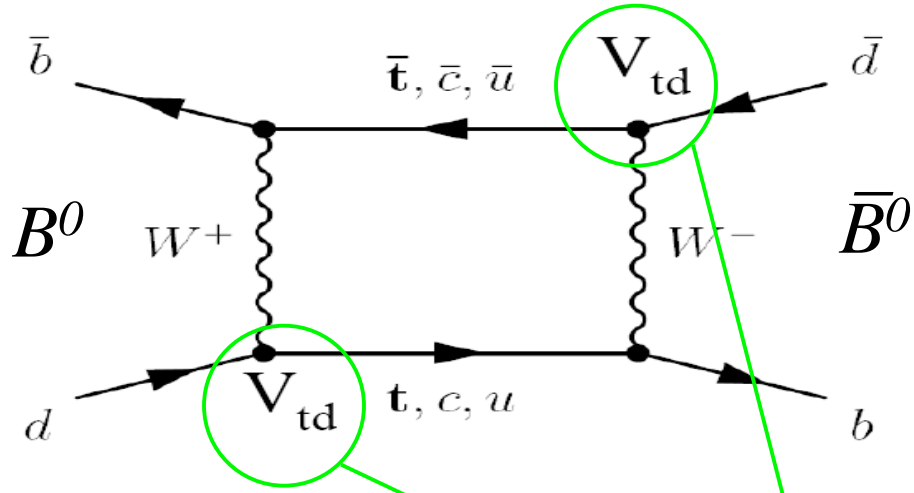
$$\lambda_f \approx \frac{\overline{A}_f}{A_f} e^{-2i\beta} \quad S_f = \frac{2\Im(\lambda_f)}{1+|\lambda_f|^2} \quad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$$

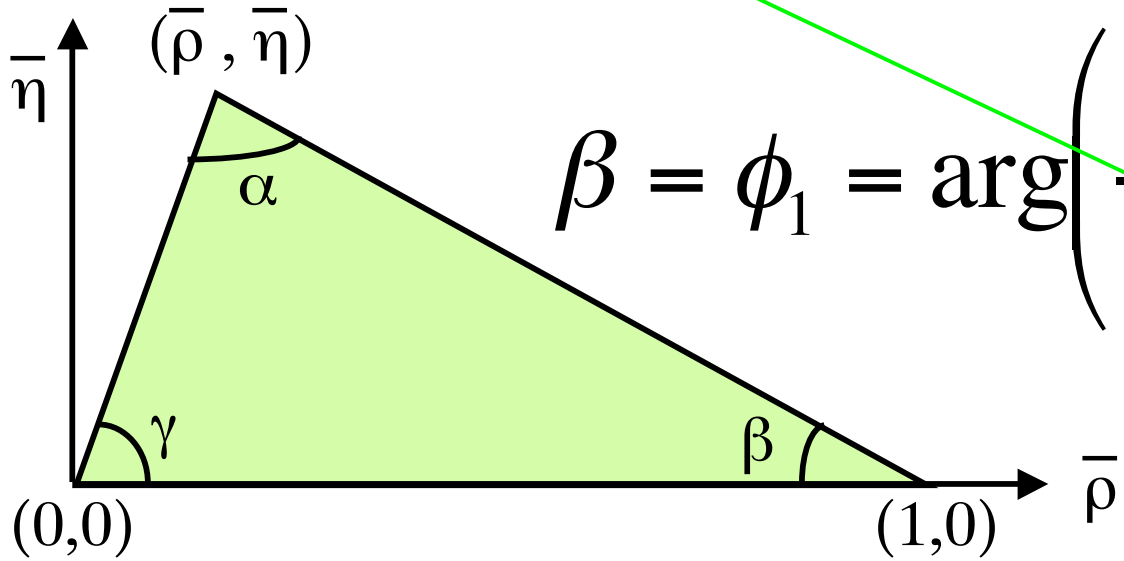


The B-factories

- Asymmetric e^+e^- colliders make boosted $\Upsilon(4S)$
  - $\beta\gamma c\tau_B$~200 μm in the lab frame
- General-purpose detectors
  - Tracking EM calorimetery, muon system, PID,…
- BaBar/PEP-II **Total Sample ≈ 450 fb^{-1}**
- KEK-B/Belle **Total Sample ≈ 700 fb^{-1}**
- Data sets have increased ~10% in the last year
  - Many new results from data 'backlog'!
- Tevatron Run2 results on **≥1fb^{-1}** coming out now

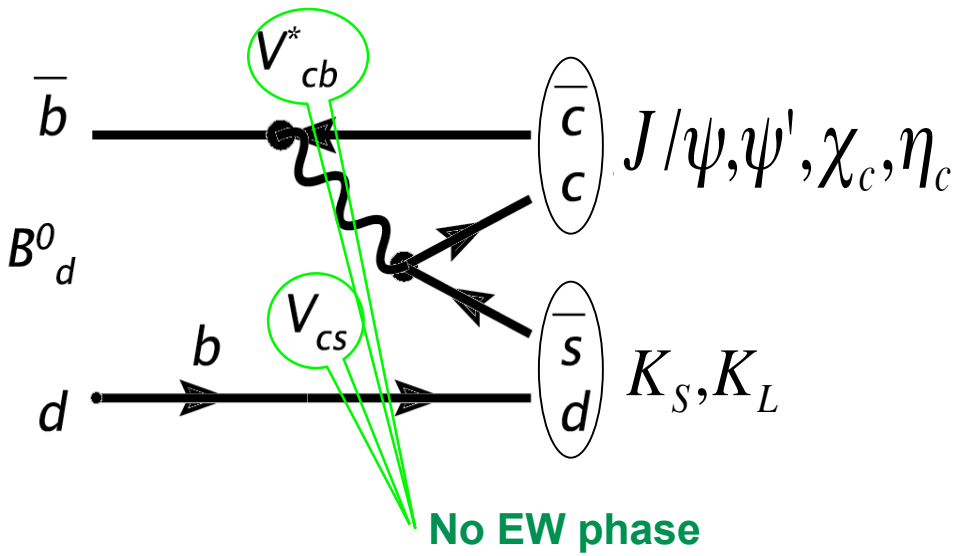
Beta





$$\beta = \phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

$B^0 \rightarrow$ charmonium K^0: $b \rightarrow c\bar{c}s$



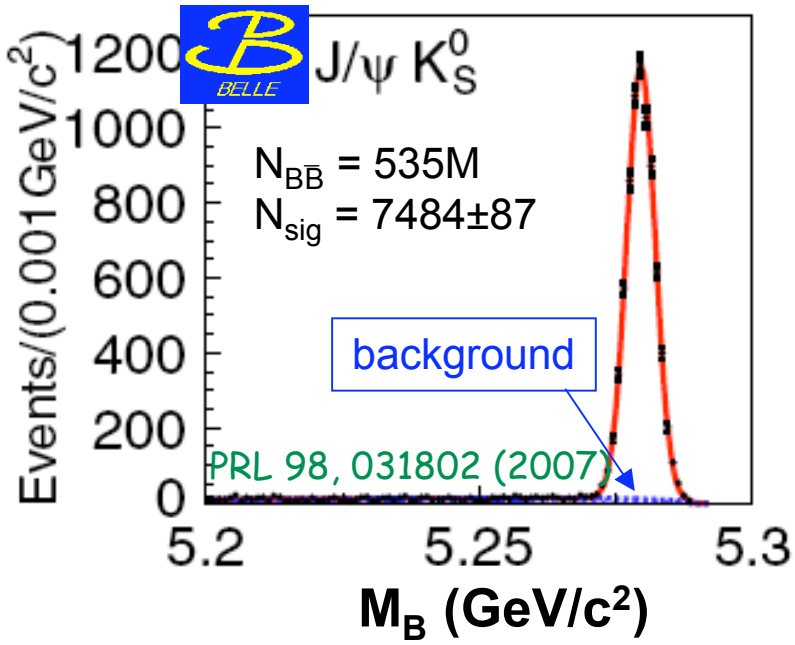
$$\lambda_{gold} = e^{-i\eta_f 2\beta}$$

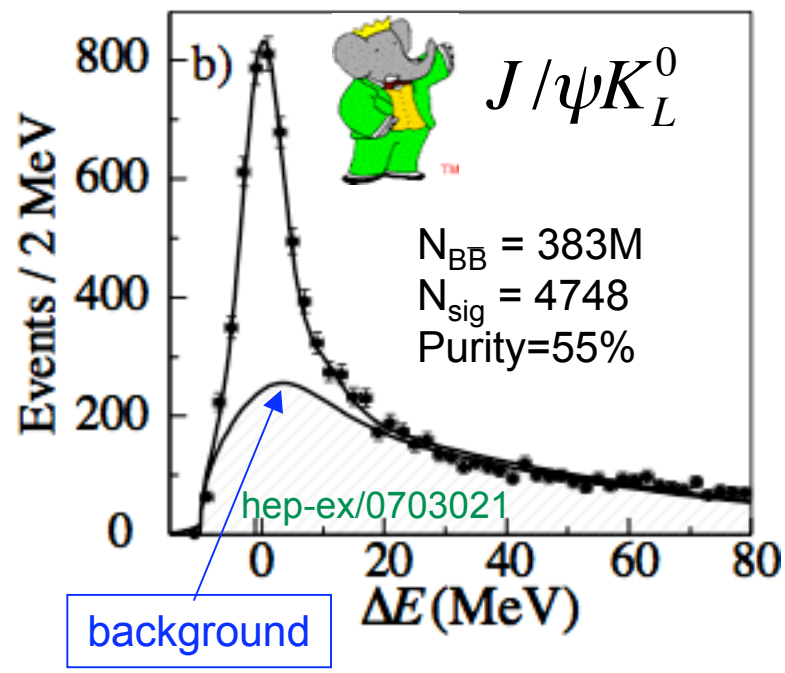
η_f= CP eigenvalue

= -1(K_S),+1(K_L)

- SM decay dominated by a single tree diagram
  - Leading order (Tree) diagram has no weak phase
    - asymmetry directly measures β
  - Higher-order diagrams are smaller by factor ~$O(10^{-2} \rightarrow 10^{-3})$
    - most have same EW phase
  - BF $\approx 10^{-3}$ (color suppressed)
- SM expectation: $S = -\eta_f \sin 2\beta$, $C \approx 0$

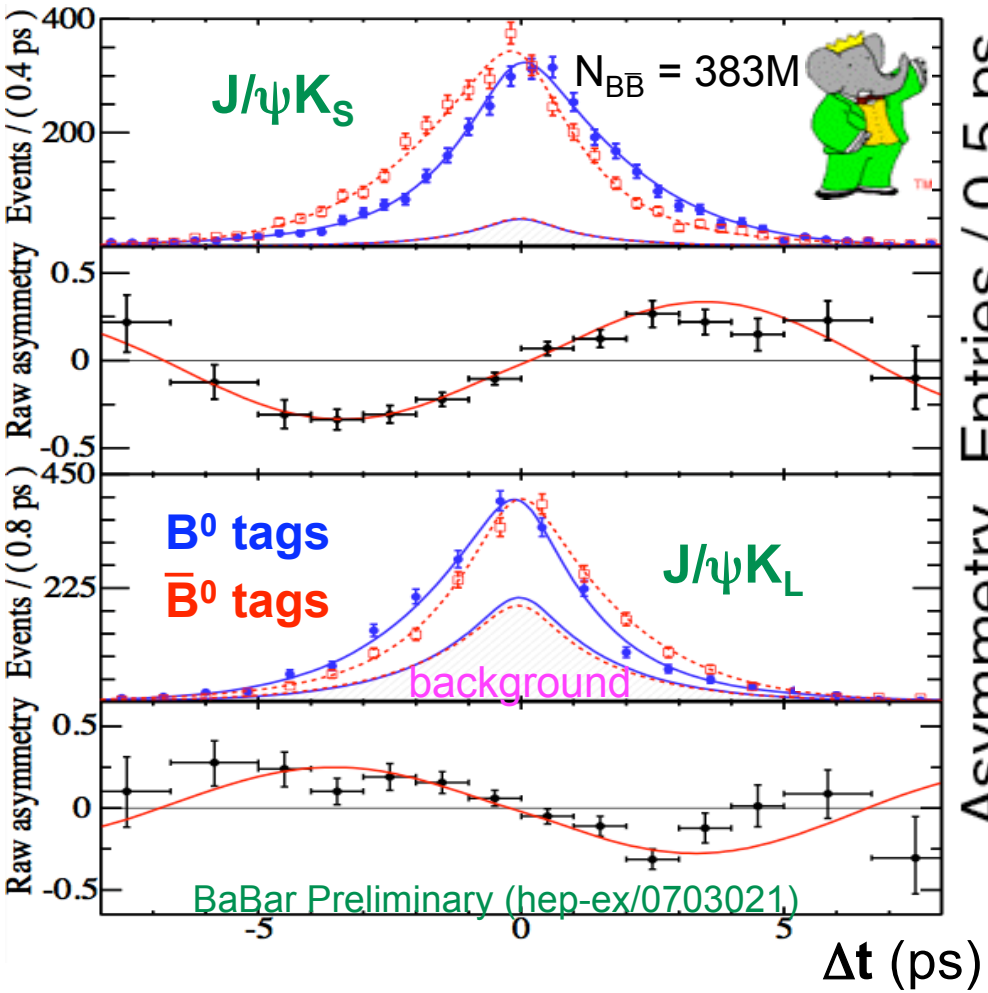
$B^0 \to$ charmonium K^0: $b \to c\bar{c}s$

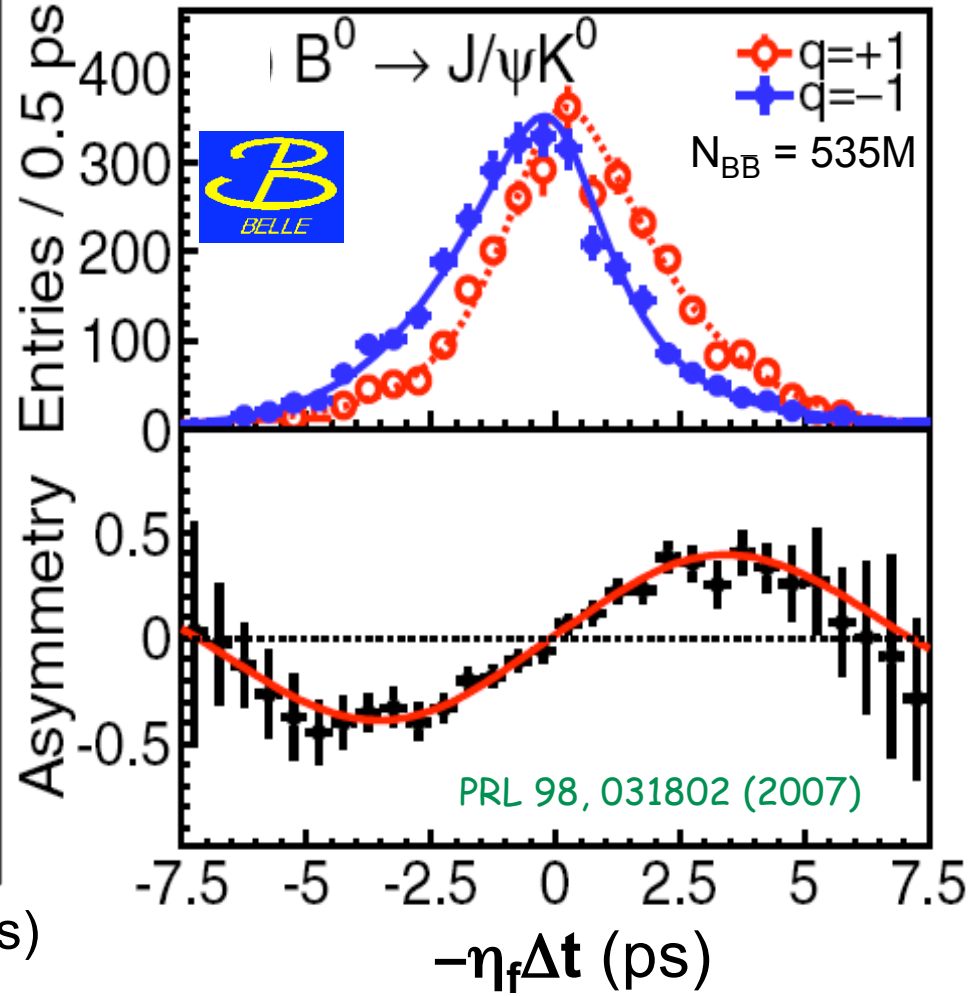




- Easily reconstructed final states
  - Charmonium $\to \ell^+\ell^-$ has high efficiency, low background
  - $K_S \to \pi^+\pi^-$ easily recognized in tracking detectors
- Strong kinematic variables separate B from background
  - M_B constrained to known beam energies to improve resolution
  - $\Delta E \equiv E_B - E_{beam}$ is an independent kinematic variable

$\sin 2\beta$ in $B^0 \to$ charmonium K^0 : $b \to c\bar{c}s$



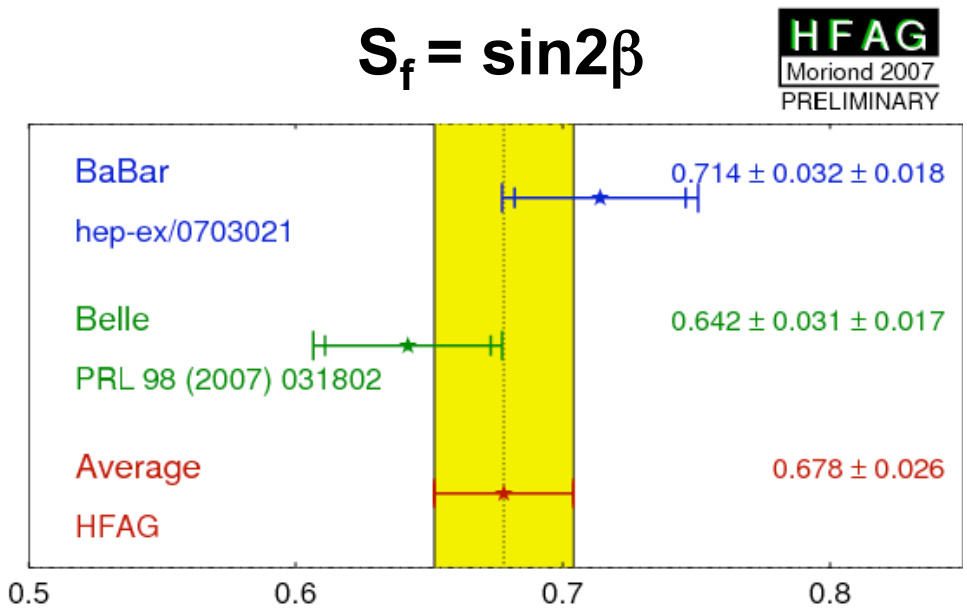


$$S = 0.714 \pm 0.032 \pm 0.018$$
$$C = 0.049 \pm 0.022 \pm 0.017$$

$$S = 0.642 \pm 0.031 \pm 0.017$$
$$C = 0.018 \pm 0.021 \pm 0.014$$

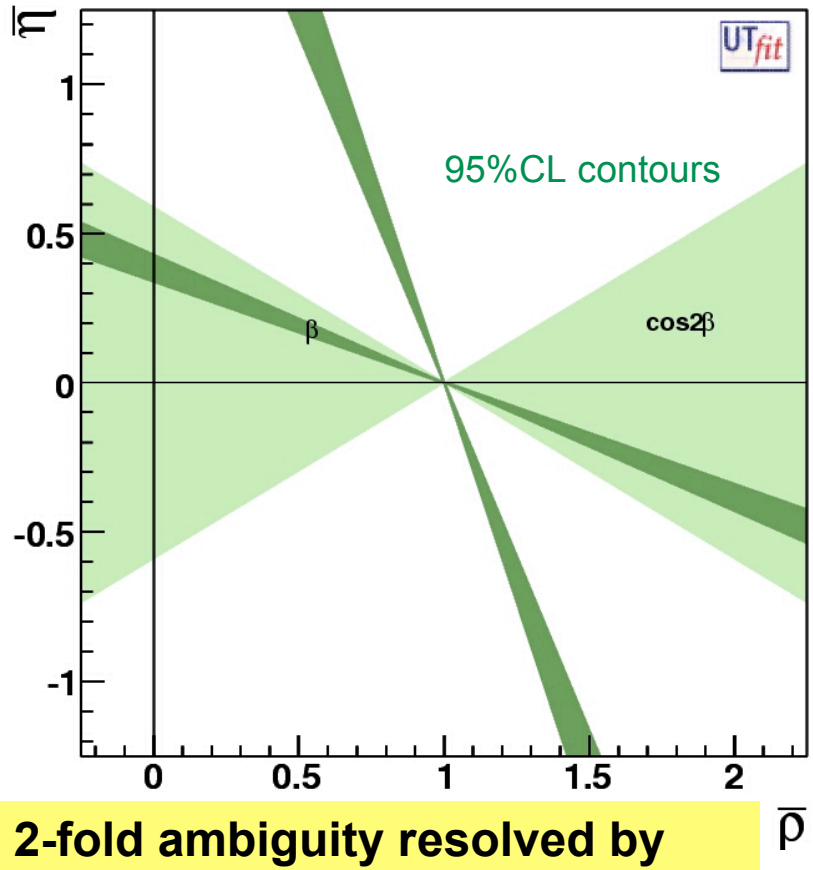
β from $B^0 \to$ charmonium K^0 : $b \to c\bar{c}s$

$S_f = \sin 2\beta$

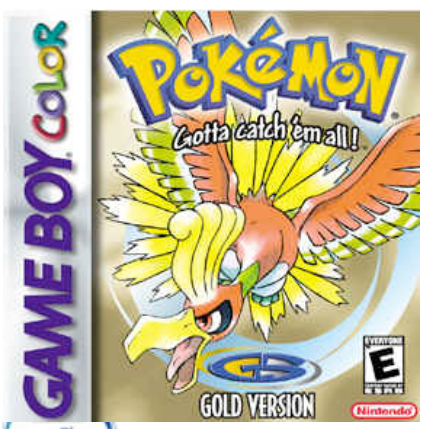


$\sin 2\beta = 0.678 \pm 0.026$

New world average



2-fold ambiguity resolved by several cos2β, β measurements



Sets the gold standard for CPV measurements

new

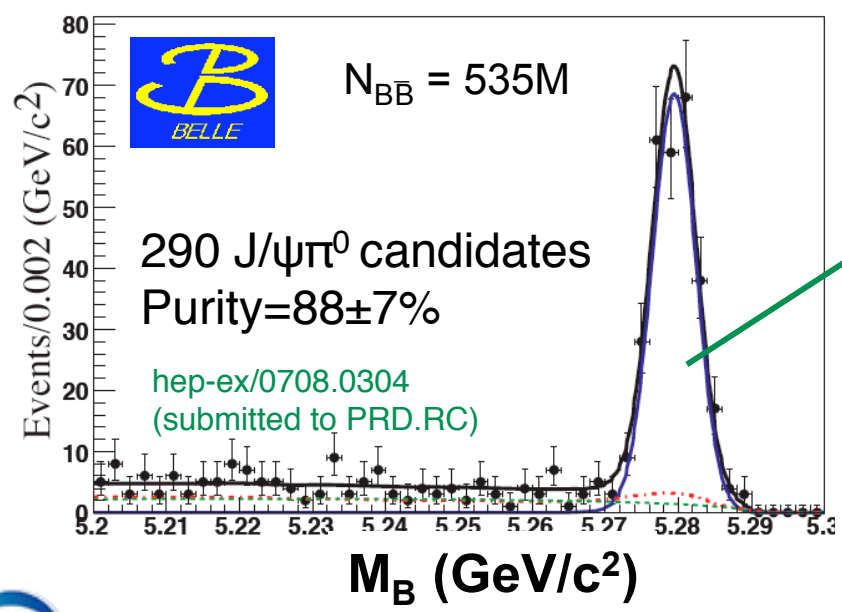
- $B^0 \to D^0_{3\text{-body}} h^0$ Dalitz Analysis (BaBar)
- $B^0 \to K_S \pi^+ \pi^-$ Dalitz Analysis (BaBar)
- $B^0 \to K_S K^+ K^-$ Dalitz Analysis (BaBar)

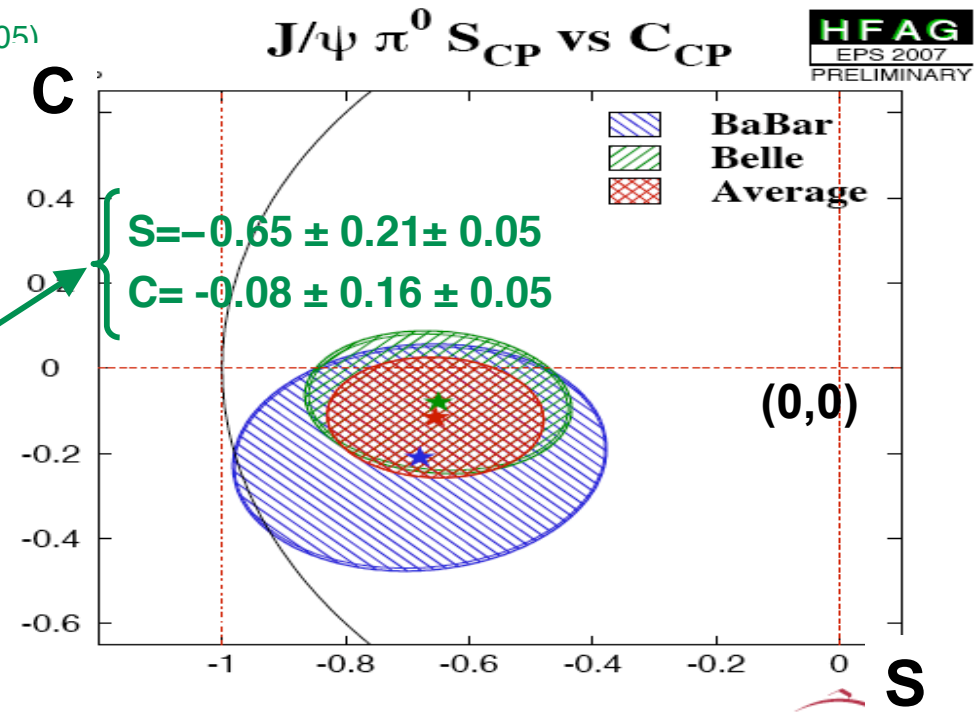
+ older results on $B^0 \to J/\psi K^*$, …

$B^0 \to J/\psi\pi^0$: $b \to c\bar{c}d$

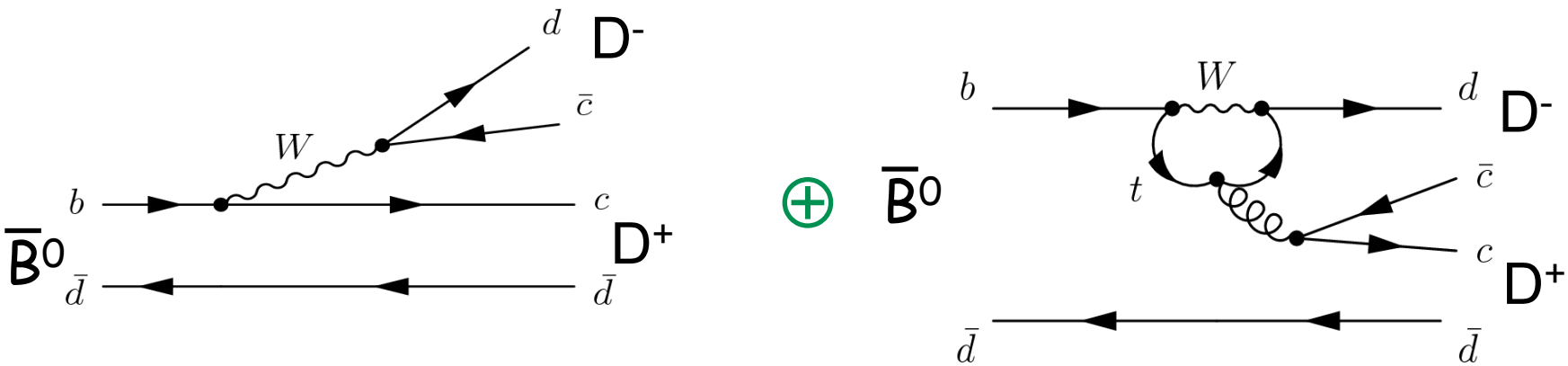
- Enhanced sensitivity to higher-order (penguin) diagrams
  - Cross-check on assumption that $C_{gold} \approx 0$

M.Ciuchini,M.PieriniandL.Silvestrini,Phys.Rev.Lett**95**,221804(2005)





$B^0 \to D^+D^- : b \to c\bar{c}d$



- Two decay amplitudes interfere
  - $b \to c$ tree diagram with $S = -\sin 2\beta$
  - $b \to d$ penguin diagram with $S \sim 0$
- Penguin is expected to be small
  - ~2-10% (PRD 61, 014010, 2001)
- Larger backgrounds

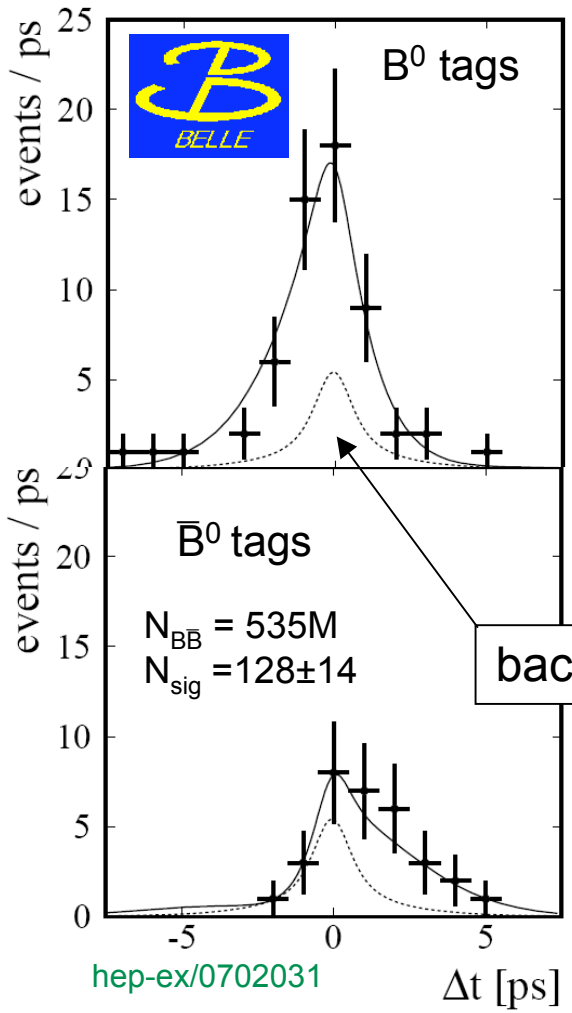
Standard Model predicts:

$$S = -\sin 2\beta$$

$$C \sim < 10\%$$

Y. Grossman and M. Worah, Phys. Lett. B 395, 241 (1997)

S and C in $B^0 \to D^+D^-$: $b \to c\bar{c}d$



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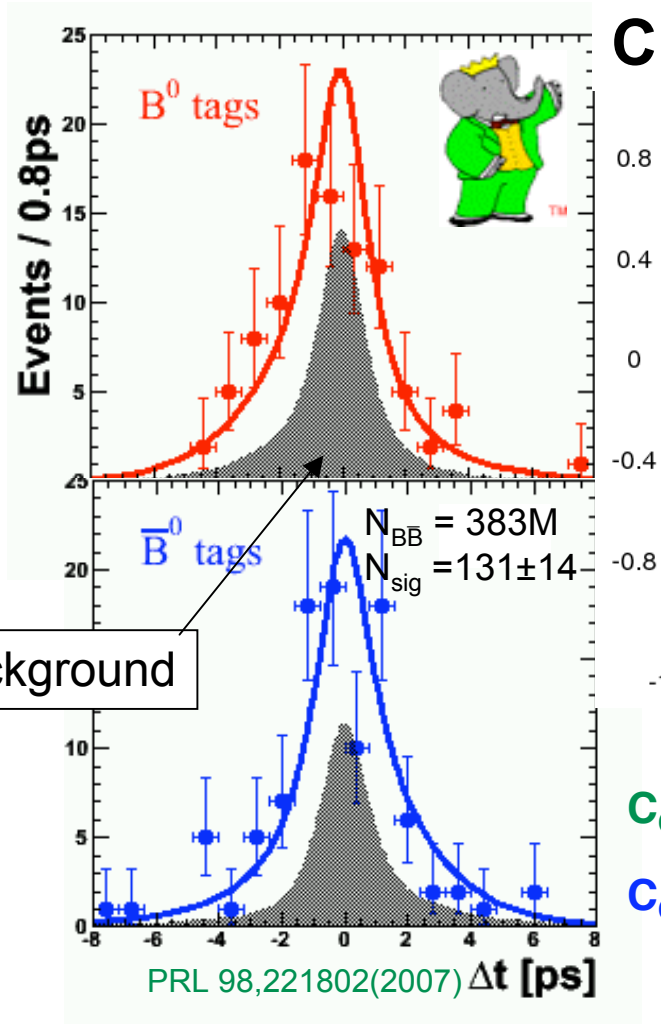
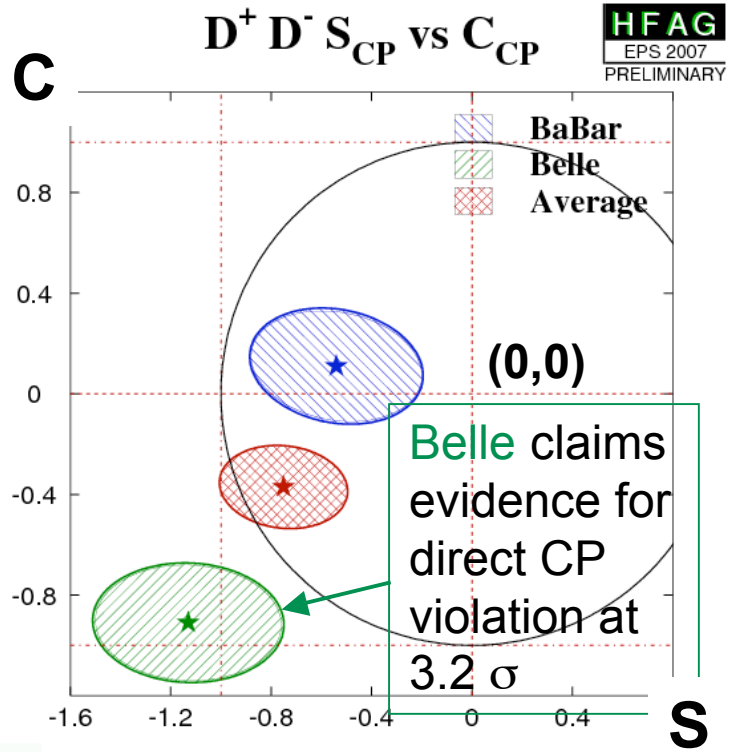


PRL 98,221802(2007)

background



$C_{CP}(B^0 \to D^+D^-) = -0.91 \pm 023 \pm 0.06$

$C_{CP}(B^0 \to D^+D^-) = +0.11 \pm 022 \pm 0.07$

Agreement on C has CL=0.003

$\Rightarrow$ **>3.0σ discrepancy**

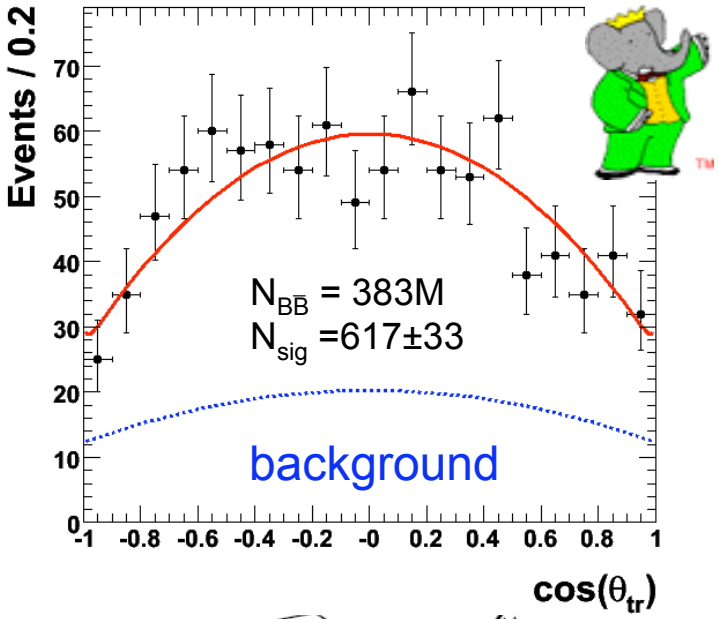
New Belle Result:

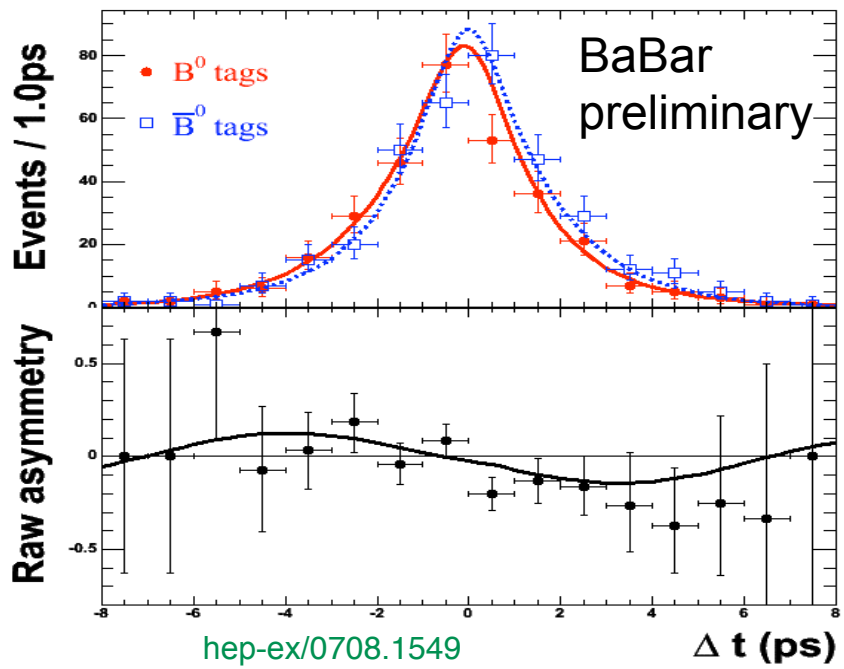
$A_{CP}(B^+ \to D^+D^0) = 0.01 \pm 0.08 \pm 0.02$

BELLE-CONF-0762 Preliminary

CPV in $B^0 \to D^{*+}D^{*-}$: $b \to c\bar{c}d$

- Same diagram as $B^0 \to D^+D^-$,but Vector-Vector final state
  - η_f **(CP)** depends on helicity, analyzed using D* decay angles





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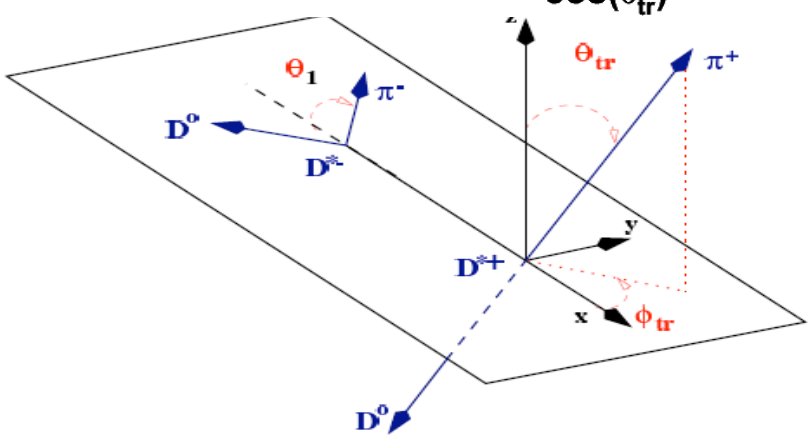
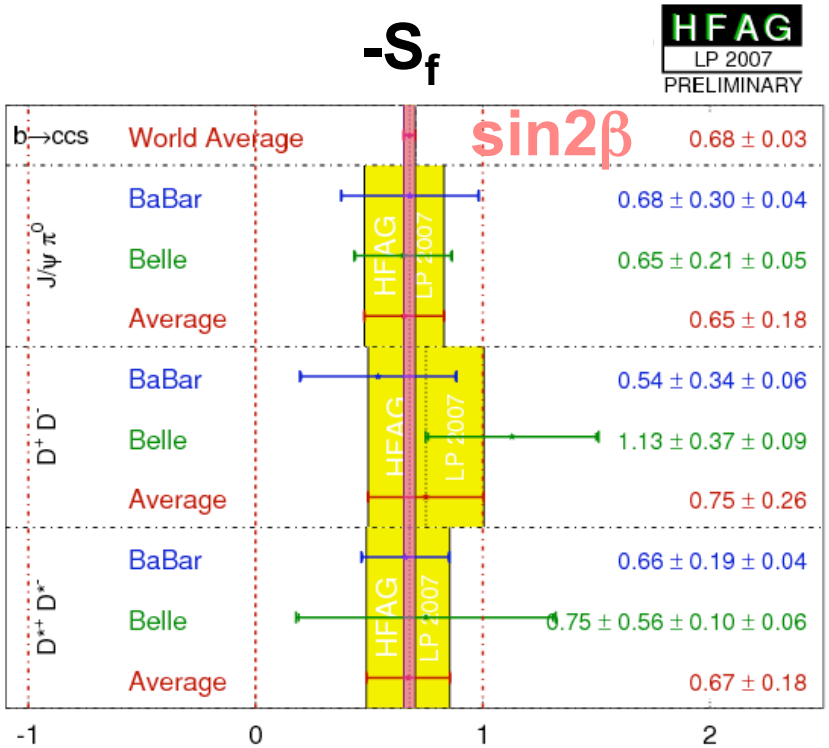
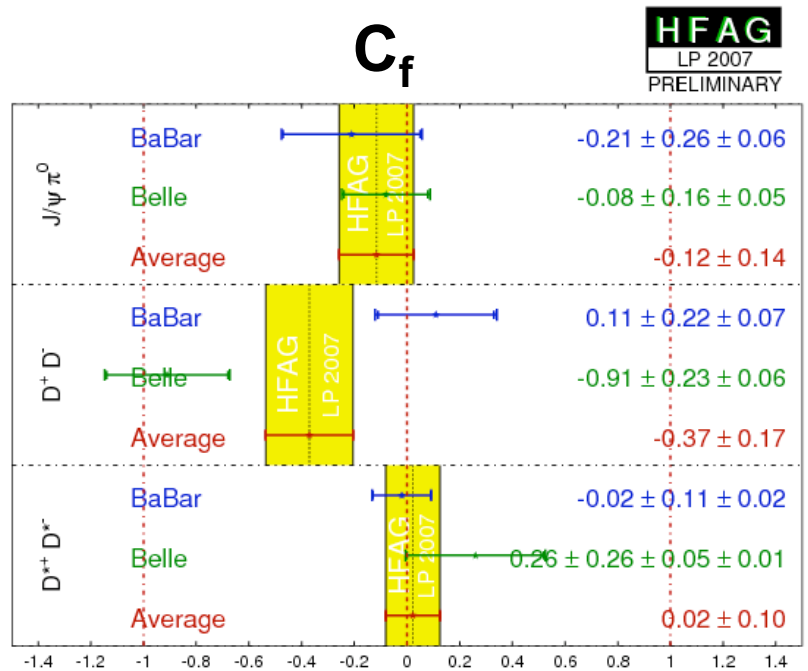


$$R_\perp = 0.143 \pm 0.034 \pm 0.008$$
$$S = -0.66 \pm 0.19 \pm 0.04$$
$$C = -0.02 \pm 0.11 \pm 0.02$$

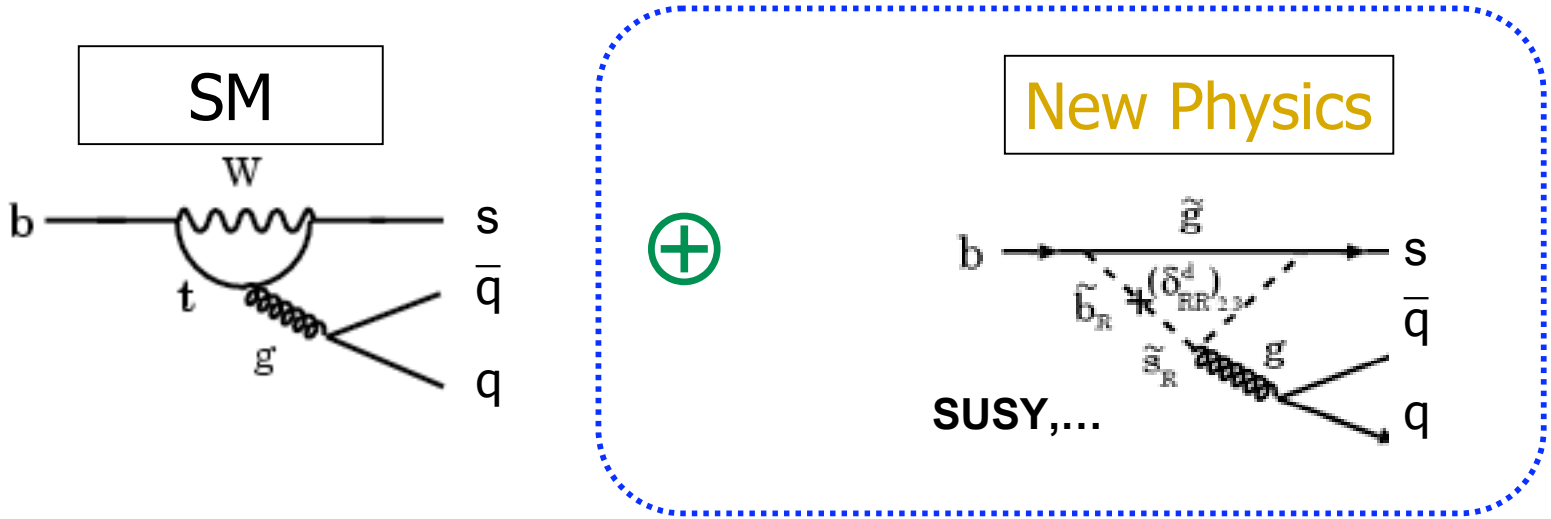
S and C in $b \to c\bar{c}d$





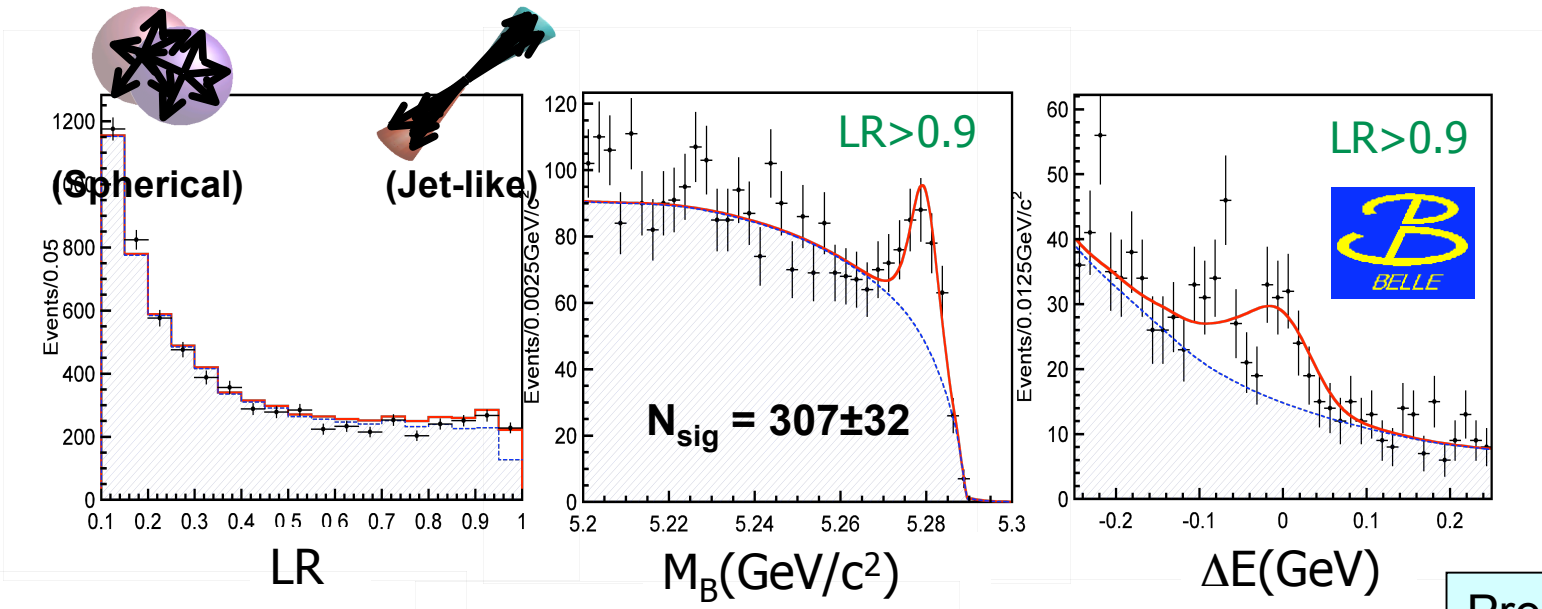
Silver modes: generally good agreement with golden mode S= sin2β, C=0

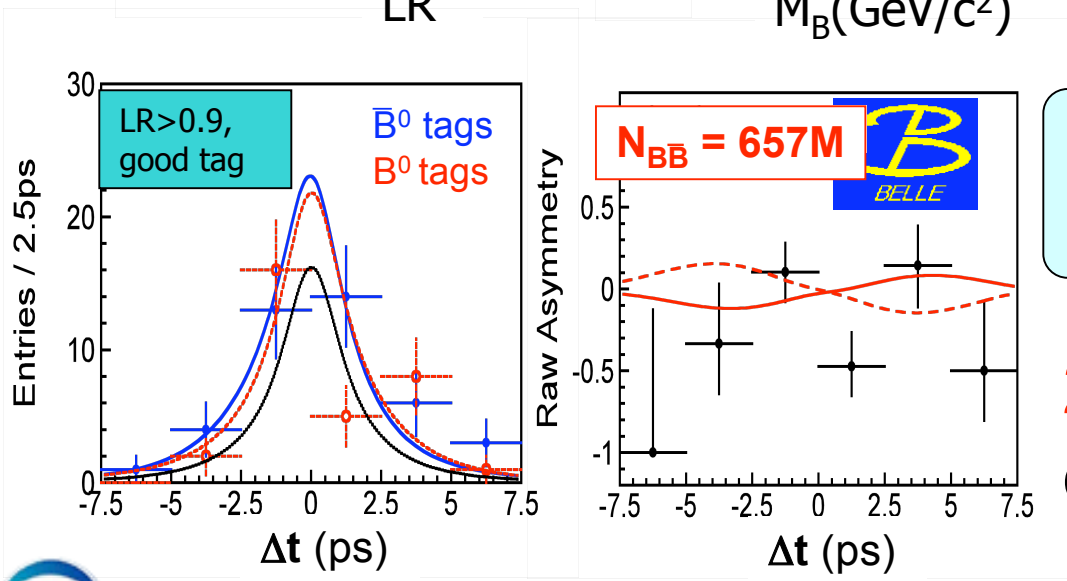
Purely Penguin decays: $b \to s\bar{q}q$



- No tree-level contributions
  - New Physics can enter at equal order as SM
- SM predicts same EW phase as $b \to cW^-$
  - Comparison with charmonium $\sin 2\beta$ provides a direct test for NP
- Many accessible modes
  - NP might couple to some or all
- More challenging experimentally
  - BF ~10^{-5}, large backgrounds from continuum

$B^0 \to K_S\pi^0\pi^0 : b \to s\bar{q}q$





Preliminary

S =+0.43 ± 0.49 ± 0.09

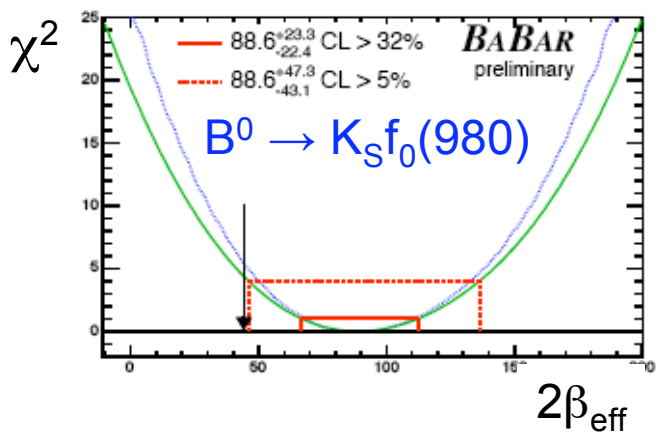
C=+0.17 ± 0.24 ± 0.06

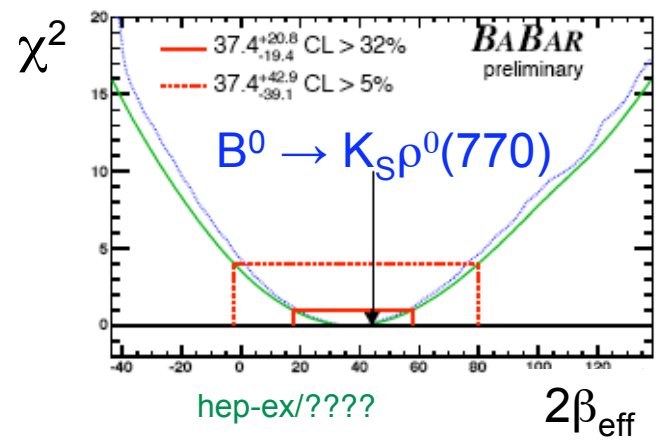
BELLE-CONF-0723

2.0 σ from the SM expectation S= -sin2β

$B^0 \to K_S\pi^+\pi^- : b \to s\bar{q}q$

- Measure TDCPA at each point on the Dalitz plot
  - Include interference between $\pi^+\pi^-$, $K_S\pi^\pm$ resonances
    - ρ^0, f^0, K^*, …
- Supersedes previous results on $B^0 \to K_S\rho^0, K_S f^0$
- + Direct CPV in $B^0 \to K^{*+}\pi^-$, relative phases





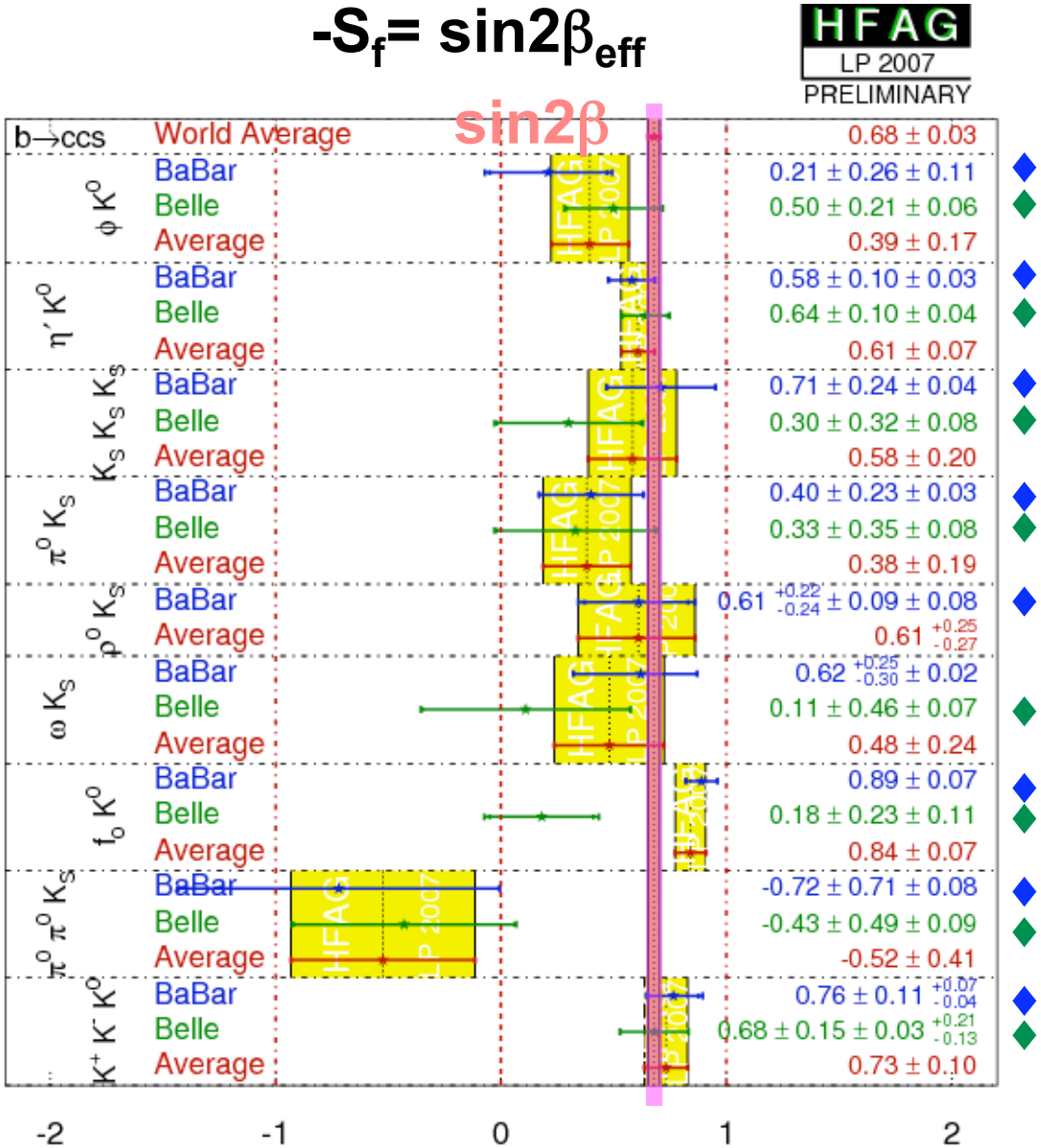
$$B^0 \to K_S f_0(980) : 2\beta_{eff} = 88.6^{+22.0}_{-20.2} \pm 5.1 \pm 7.8^\circ$$
$$B^0 \to K_S \rho^0(770) : 2\beta_{eff} = 37.4^{+19.2}_{-17.4} \pm 5.3 \pm 5.9^\circ$$
$$B^0 \to K^*(892)\pi : A_{CP} = -0.18 \pm 0.1 \pm 0.03 \pm 0.03$$

2.1σ > 2β from charmonium

2-fold β ambiguity (partially) resolved

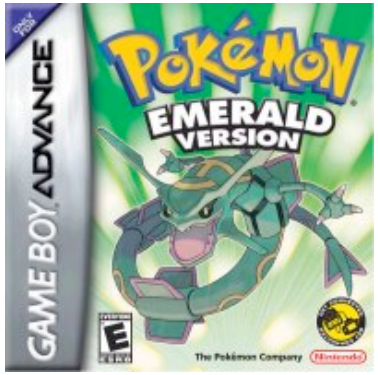
sin2β in b→s$\bar{q}$q Penguins

$-S_f = \sin 2\beta_{eff}$



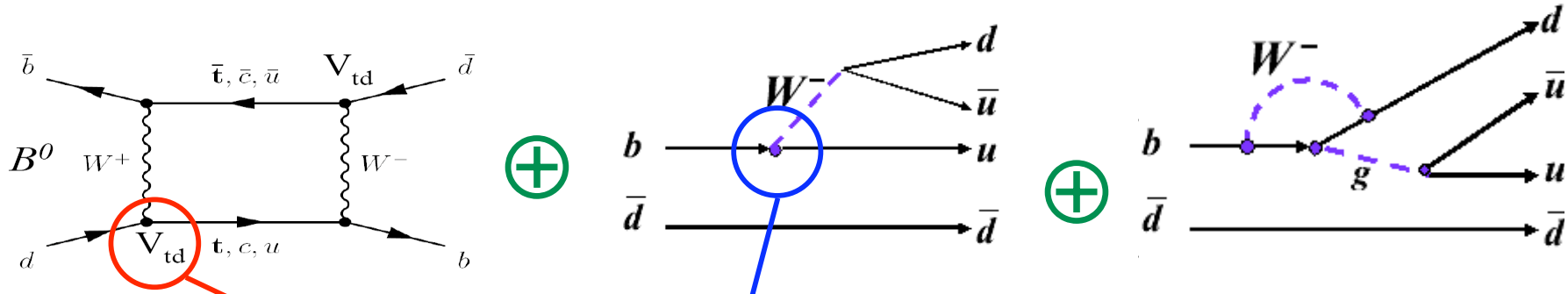
$$\left\langle \sin 2\beta_{eff} \right\rangle = 0.67 \pm 0.04$$

New naïve HFAG average <1σ from the naïve golden mode sin2β value

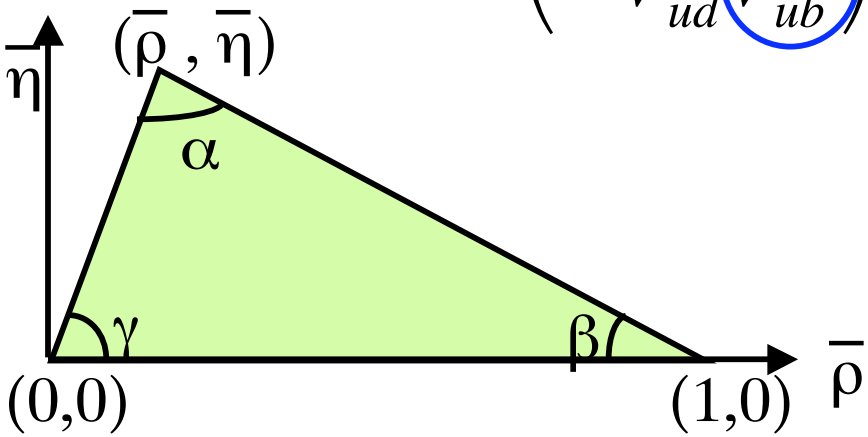


♦≡ New/Updated BaBar/Belle Result

Alpha

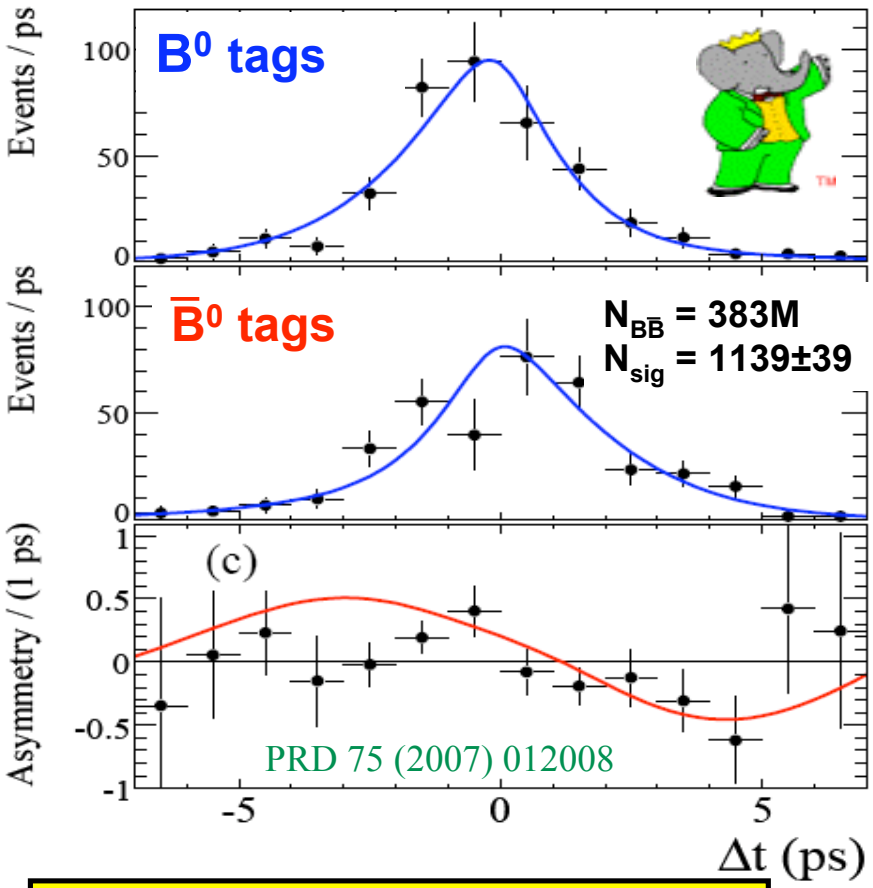


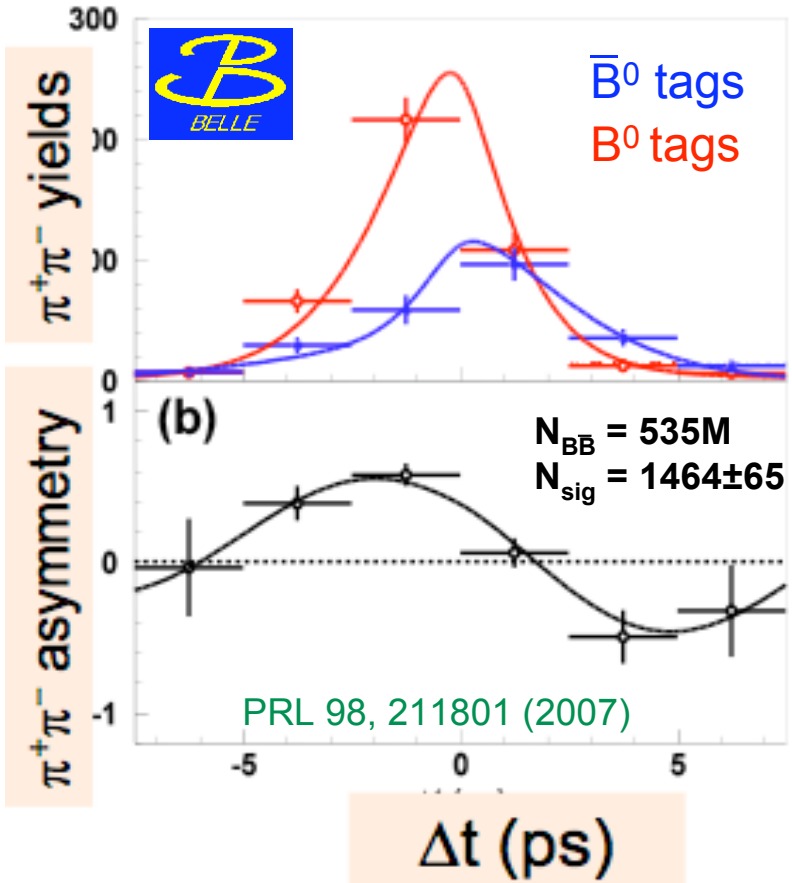
$$\alpha = \phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$



- In principle measurable using any b→u dominated $B^0 \to f_{CP}$
  - Very rare decays! BF~10^{-6}
- In practice, penguin modes have similar magnitude, different EW phase ⇒ extracting α is a challenge!

$B^0 \to \pi^+\pi^-$: $b \to u\bar{u}d$





$$S_{\pi\pi} = -0.60 \pm 0.11 \pm 0.03 \ (5.2\sigma)$$
$$C_{\pi\pi} = -0.21 \pm 0.09 \pm 0.02 \ (2.2\sigma)$$

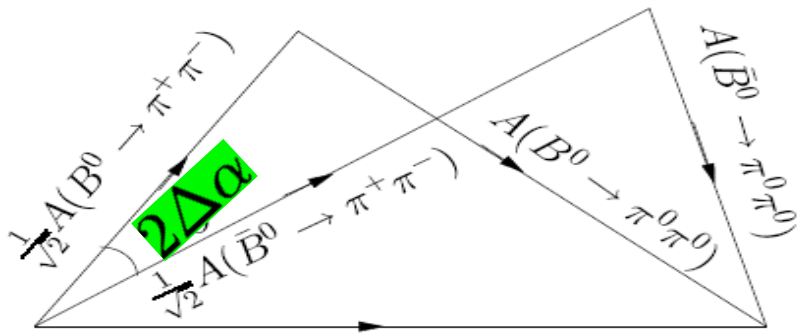
$$S_{\pi\pi} = -0.61 \pm 0.10 \pm 0.04$$
$$C_{\pi\pi} = -0.55 \pm 0.08 \pm 0.05 \ (5.5\sigma)$$

2.1σ tension in Cππ

Extracting α from $B^0 \to \pi^+ \pi^-$

- CPV well established
- Problem: extract α from α_{eff}
- Solution: Isospin
  - Measure isospin-related modes
    - Rates and C/A_{CP} (if possible)
  - Adds another discrete ambiguity

M. Gronau and D. London, Phys Rev. Lett. 65, 3381 (1990)



$$|A(B^- \to \pi^-\pi^0)| = |A(B^+ \to \pi^+\pi^0)|$$

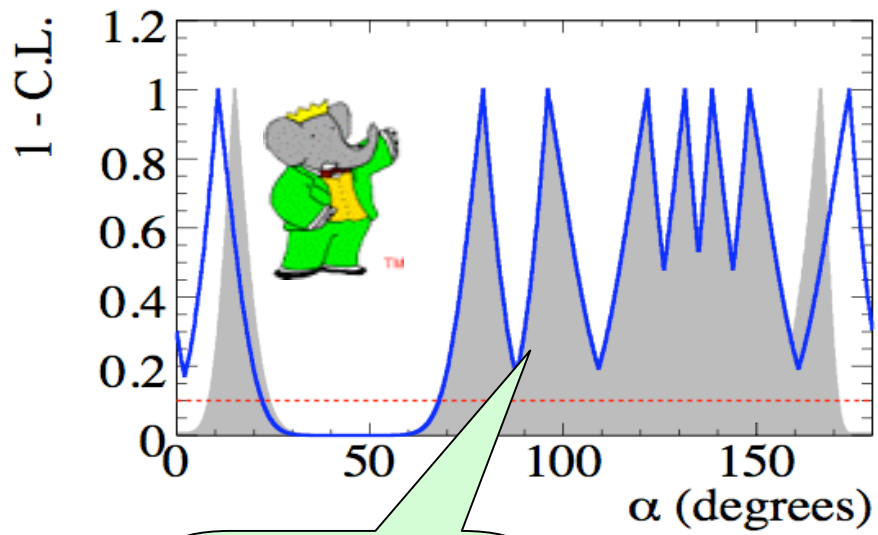
$BR(B^0 \to \pi^0 \pi^0) = (1.47 \pm 0.25 \pm 0.12)\times 10^{-6}$

$C(B^0 \to \pi^0 \pi^0) = -0.49 \pm 0.35 \pm 0.05$

$BR(B^\pm \to \pi^\pm \pi^0) = (5.02 \pm 0.46 \pm 0.29)\times 10^{-6}$

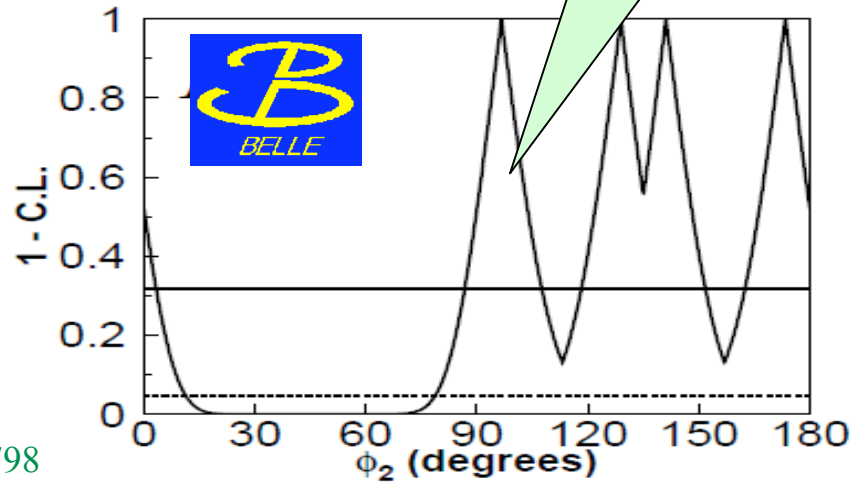
$A(B^\pm \to \pi^\pm \pi^0) = 0.03 \pm 0.08 \pm 0.01$

hep-ex:0707.2798



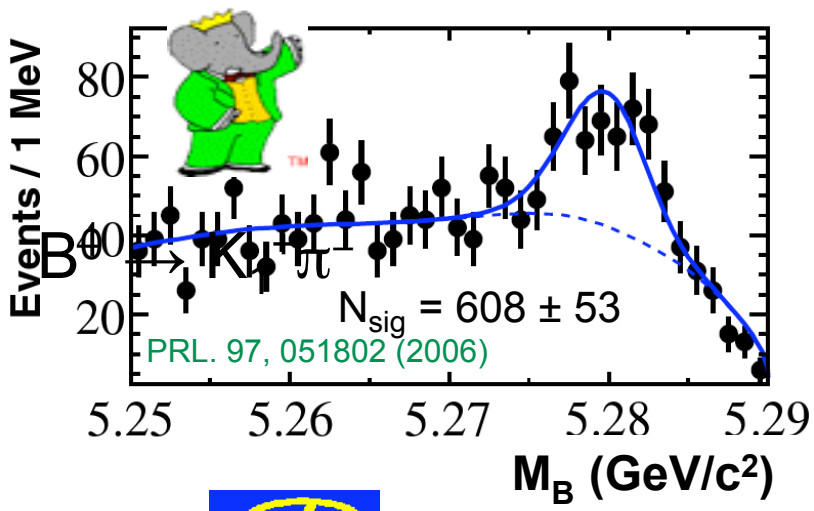
96^{+10}_{-6}°

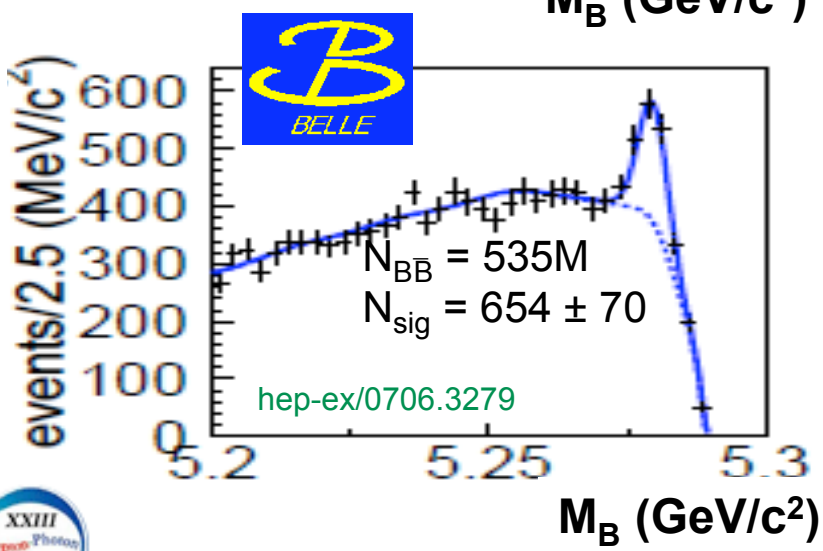
97 ± 11°



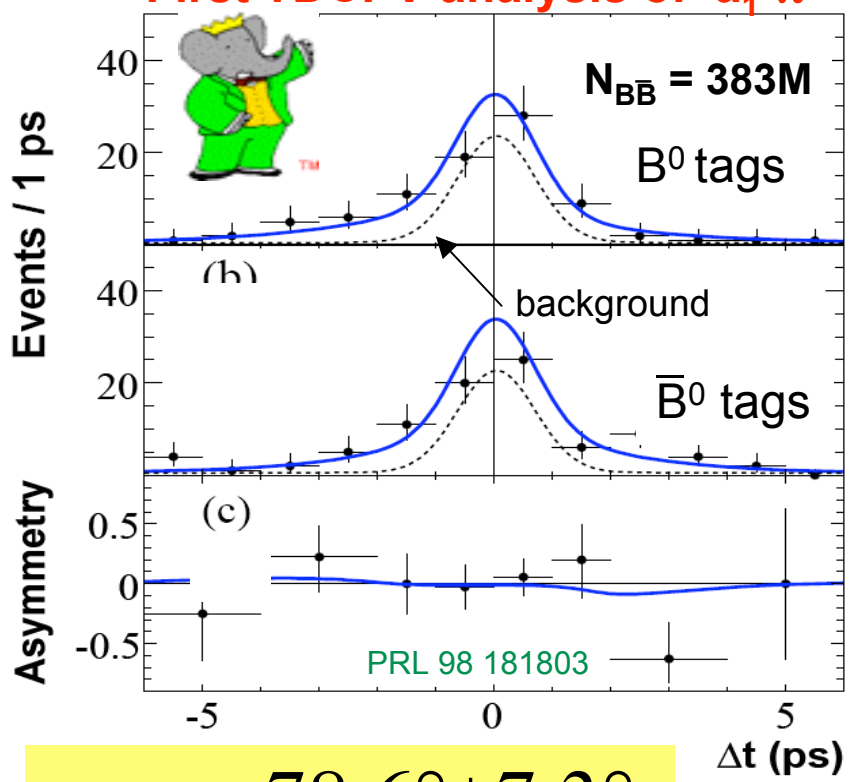
$B^0 \to a_1^+\pi^- : b \to u\bar{u}d$

- **Large signal observed**
  - **significant background**





First TDCPV analysis of $a_1^+\pi^-$

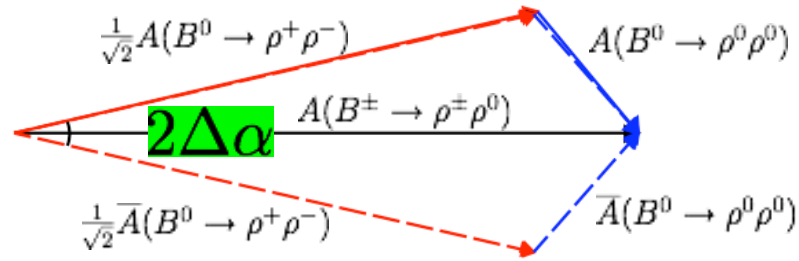


$$\alpha_{eff} = 78.6° \pm 7.3°$$

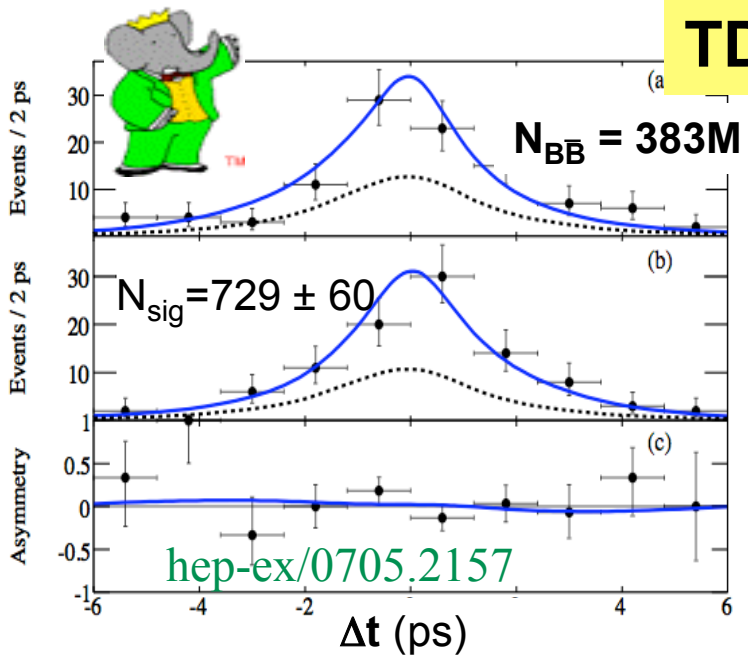
- use SU(3) to relate states
  - BF $B^0 \to K_1^+\pi^-$
  - BF and A_{CP} in $B^0 \to a_1^-K^+$
- Next step: constrain $\Delta\alpha$

$B^0 \to (\rho\rho)^0 : b \to u\bar{u}d$

- Vector+Vector final state
  - Analyze helicity to separate CP admixture as in $B^0 \to D^{*+}D^{*-}$
- Use Isospin triangle to constrain $\Delta\alpha$ as in $\pi\pi$



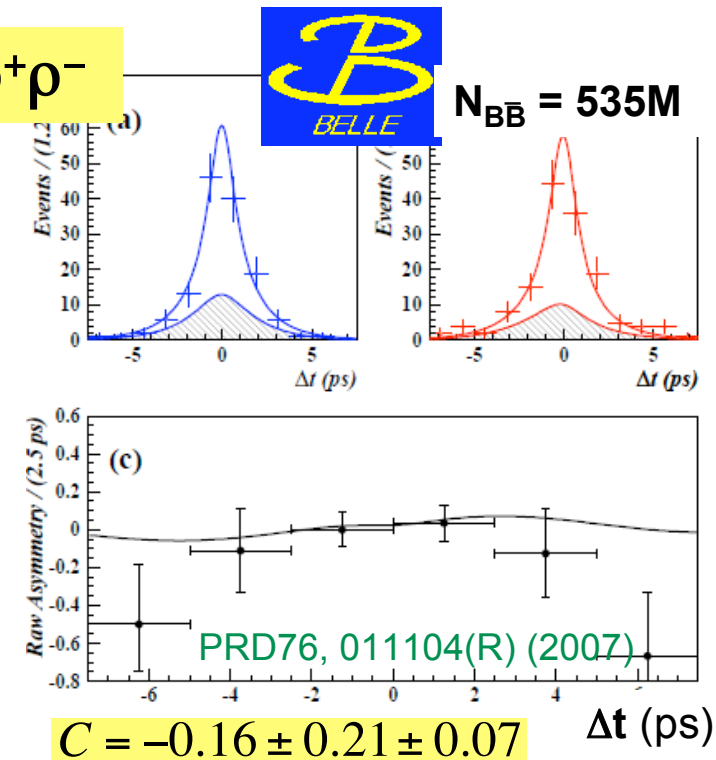
TDCPV in $\rho^+\rho^-$



$C = 0.01 \pm 0.15 \pm 0.06$

$S = -0.17 \pm 0.20$

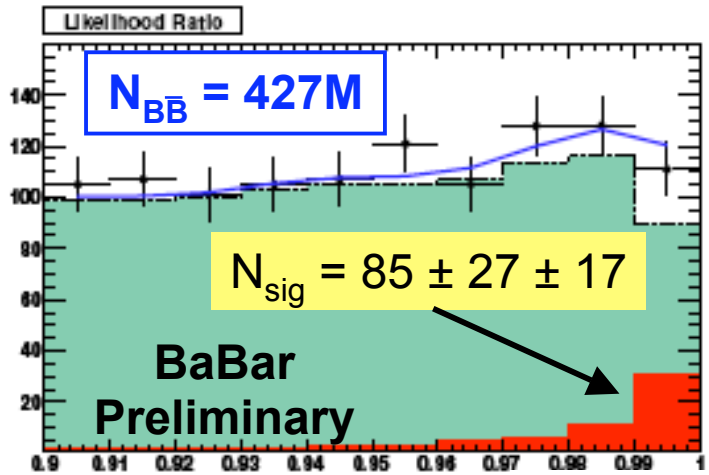
$f_L = 0.992 \pm 0.024$

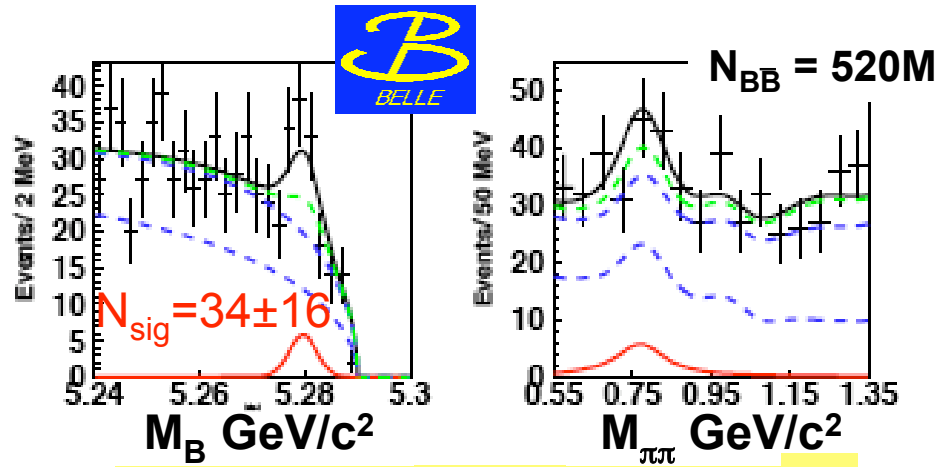


$C = -0.16 \pm 0.21 \pm 0.07$

$S = +0.19 \pm 0.30 \pm 0.07$

The critical side: $B^0 \to \rho^0\rho^0$

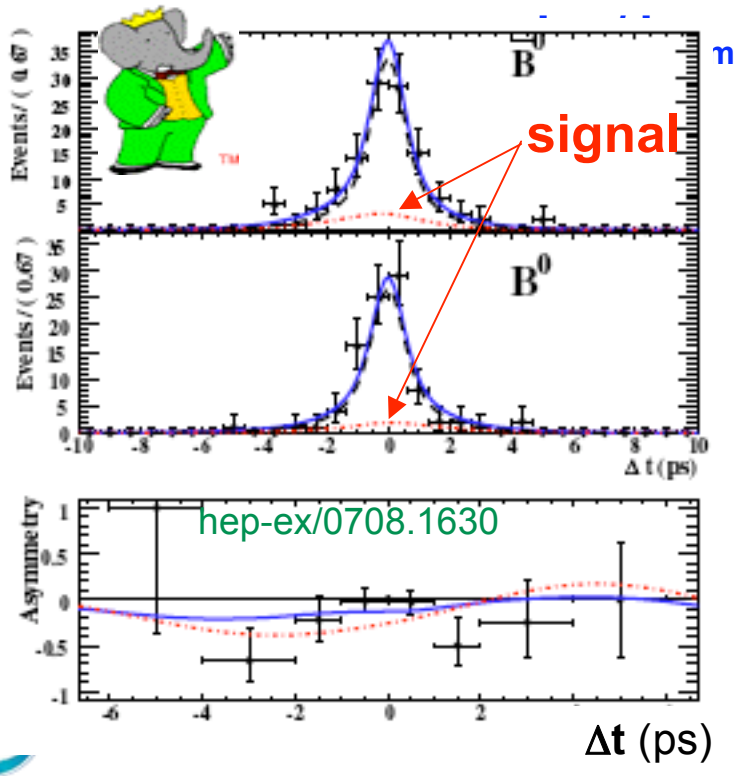




$$B_{\rho^0\rho^0} = (0.9 \pm 0.4^{+0..3}_{-0.4}) \times 10^{-6}$$
$$< 1.6 \times 10^{-6} @ 90\% CL$$
$$f_L = 0.6 \pm 0.2$$

BELLE-CONF-0747

Preliminary

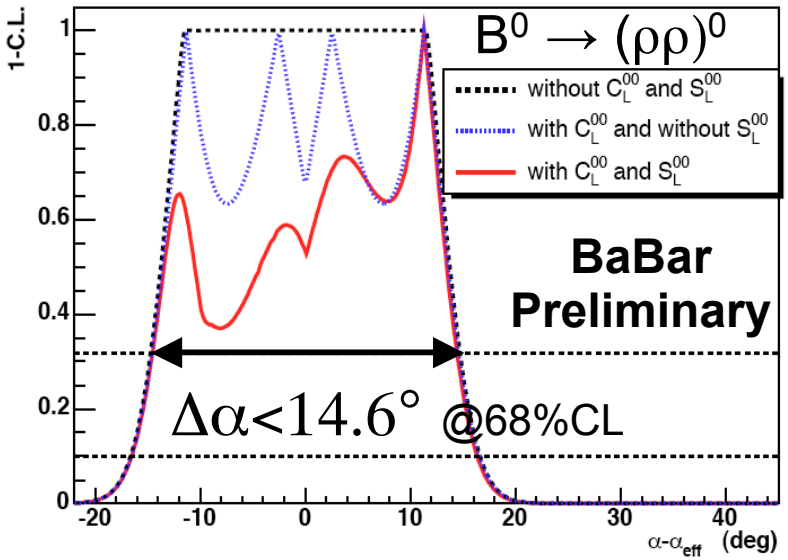


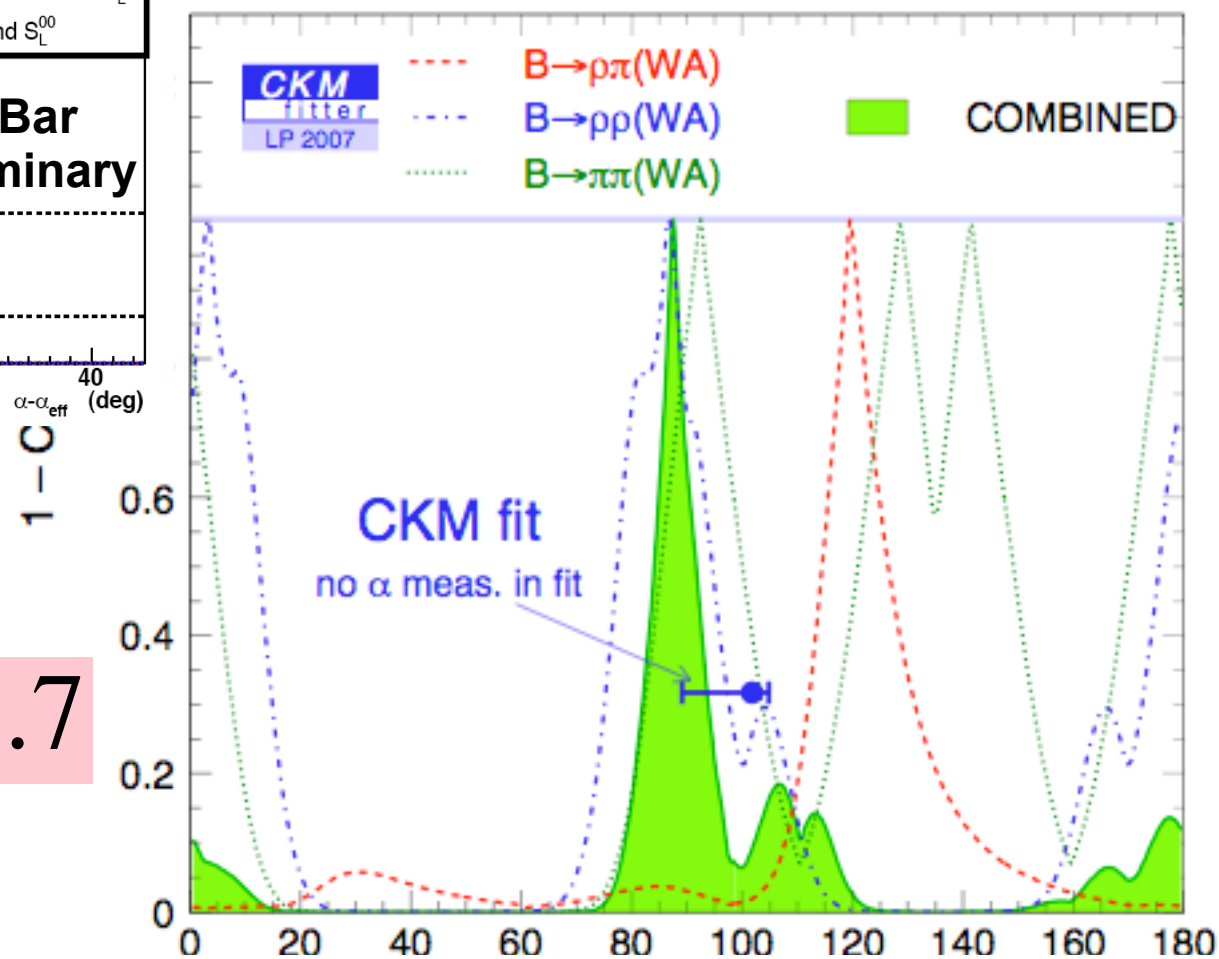
$$B = (0.84 \pm 0.29 \pm 0.17) \times 10^{-6}$$
$$f_L = 0.70 \pm 0.14 \pm 0.05$$
$$S_L^{00} = 0.5 \pm 0.9 \pm 0.2$$
$$C_L^{00} = 0.4 \pm 0.9 \pm 0.2$$

Preliminary

First TDCPV analysis of $\rho^0\rho^0$!

Constraining α using b→uūd

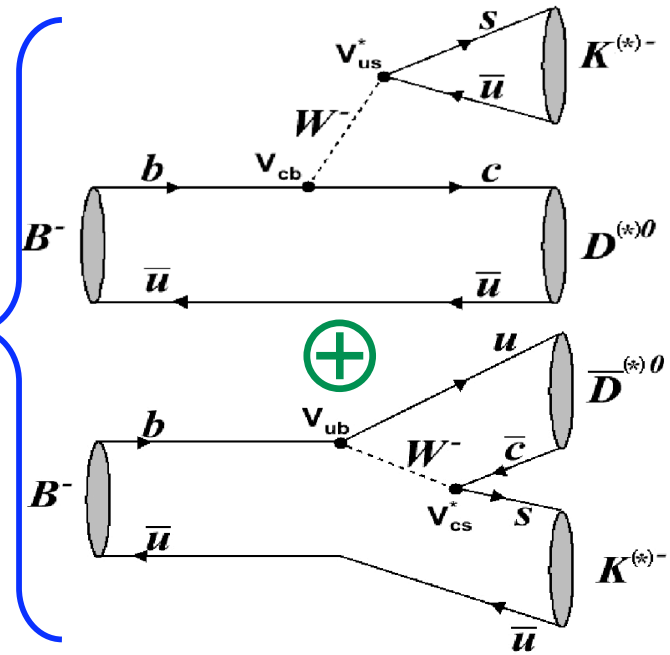


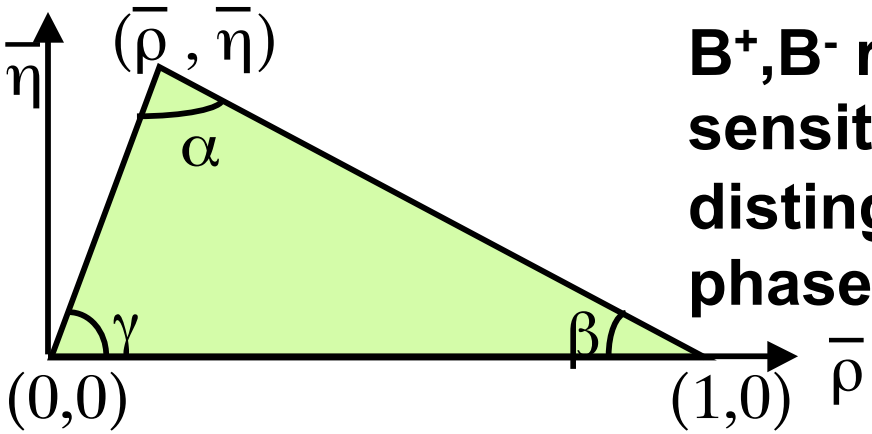


$$\alpha_{WA} = 87.7 \pm 5.7$$

Gamma

$$\gamma = \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$





B^+,B^- rate asymmetry (DCPV) is sensitive to γ. The problem: How to distinguish EW phase from strong phase?

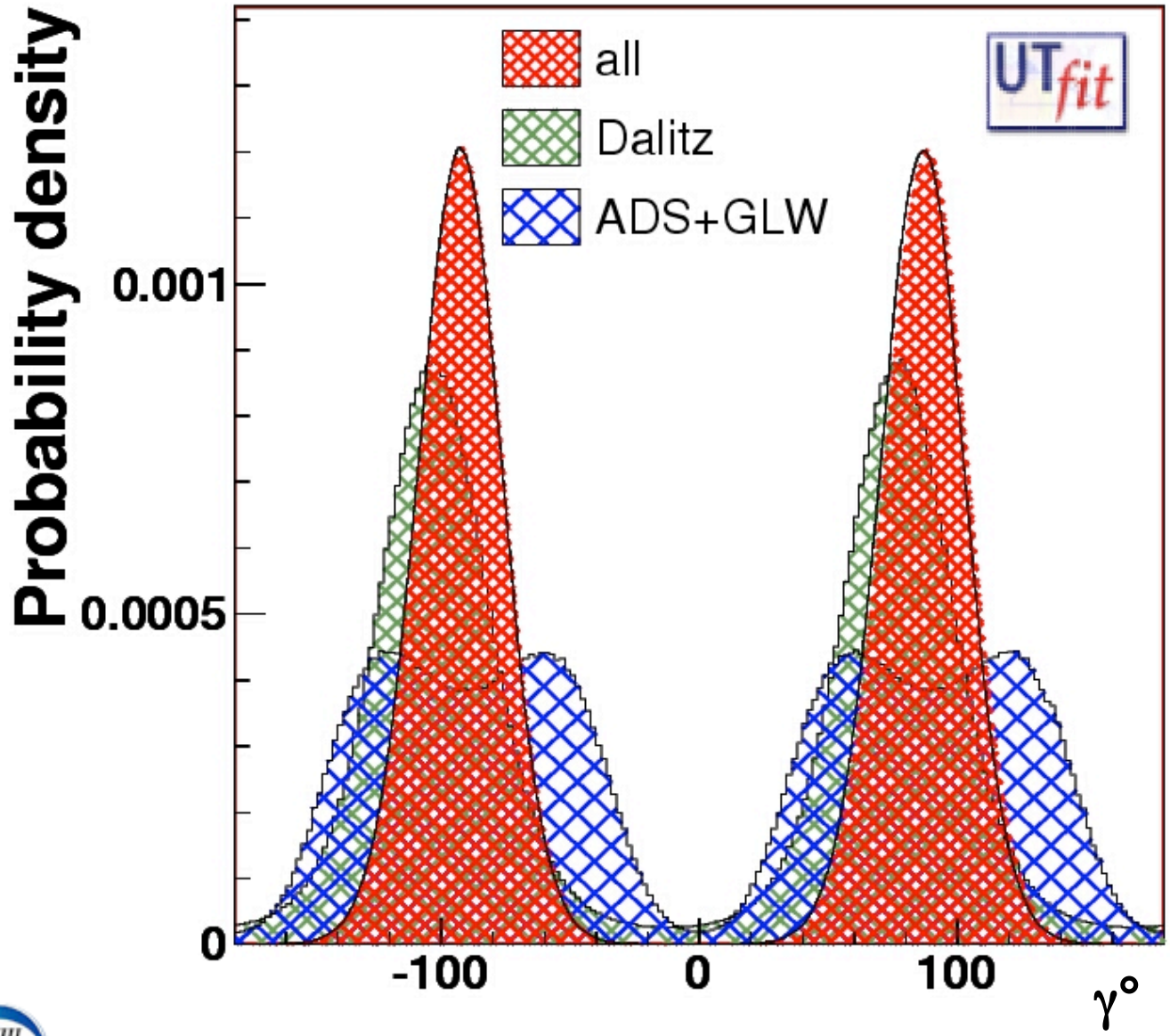
Can also measure $2\beta+\gamma$ via TDCPV in $B^0 \rightarrow D^{(*)+,-}\pi^{-,+}$

γ from $B^{\pm} \rightarrow D^0 K^{\pm}$

- Three Answers
  - D^0 decays to 2-body CP eigenstates (K^+K^-, $\pi^+\pi^-$,…) **GLW**
    - large + unknown asymmetry in B^+,B^- BFs
  - D^0 decays to non-CP eigenstates ($K^+\pi^-$, $K^+\pi^-\pi^0$,…) **ADS**
    - Better match in rates (Cabbio suppression enhances interference)
  - D^0 decays to 3-body ($K^0_S\pi^+\pi^-$) **GGSZ**
    - Uses (~known) variation of resonance strong phase across Dalitz plot
    - Requires detailed model of resonant substructure
- All methods have (varying) weakness due to unknown or under-constrained parameters
- $\Rightarrow$ Constrain γ by combining results from all methods

GLW ≡Gronau, London (1991),Gronau, Wyler (1990)
ADS ≡ Atwood, Danietz, Soni (1997)
GGSZ ≡Giri, Grossman, Soffer, Zupan (2003)

Combined constraint on γ

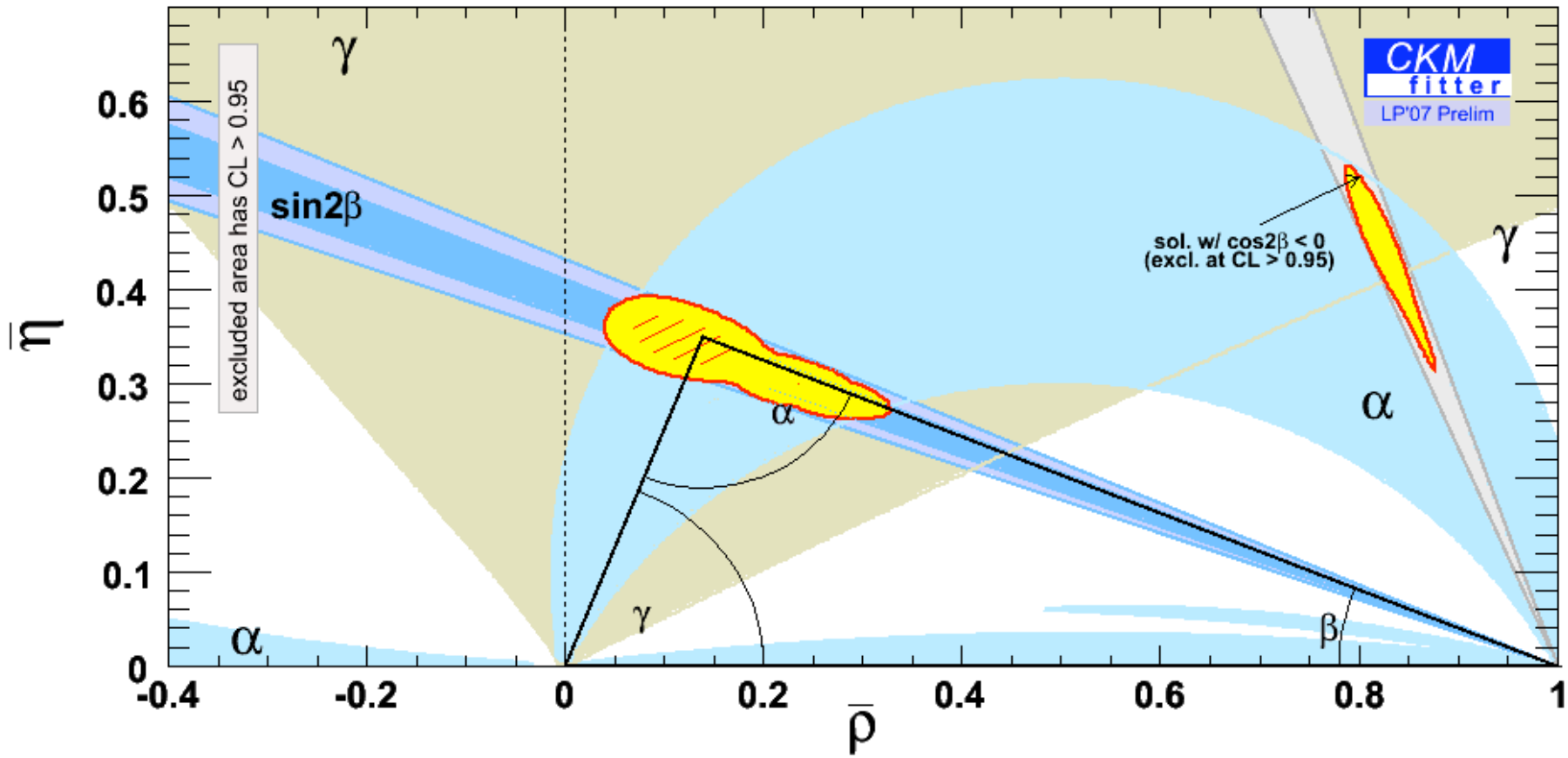


$\gamma = 88 \pm 16\ °$

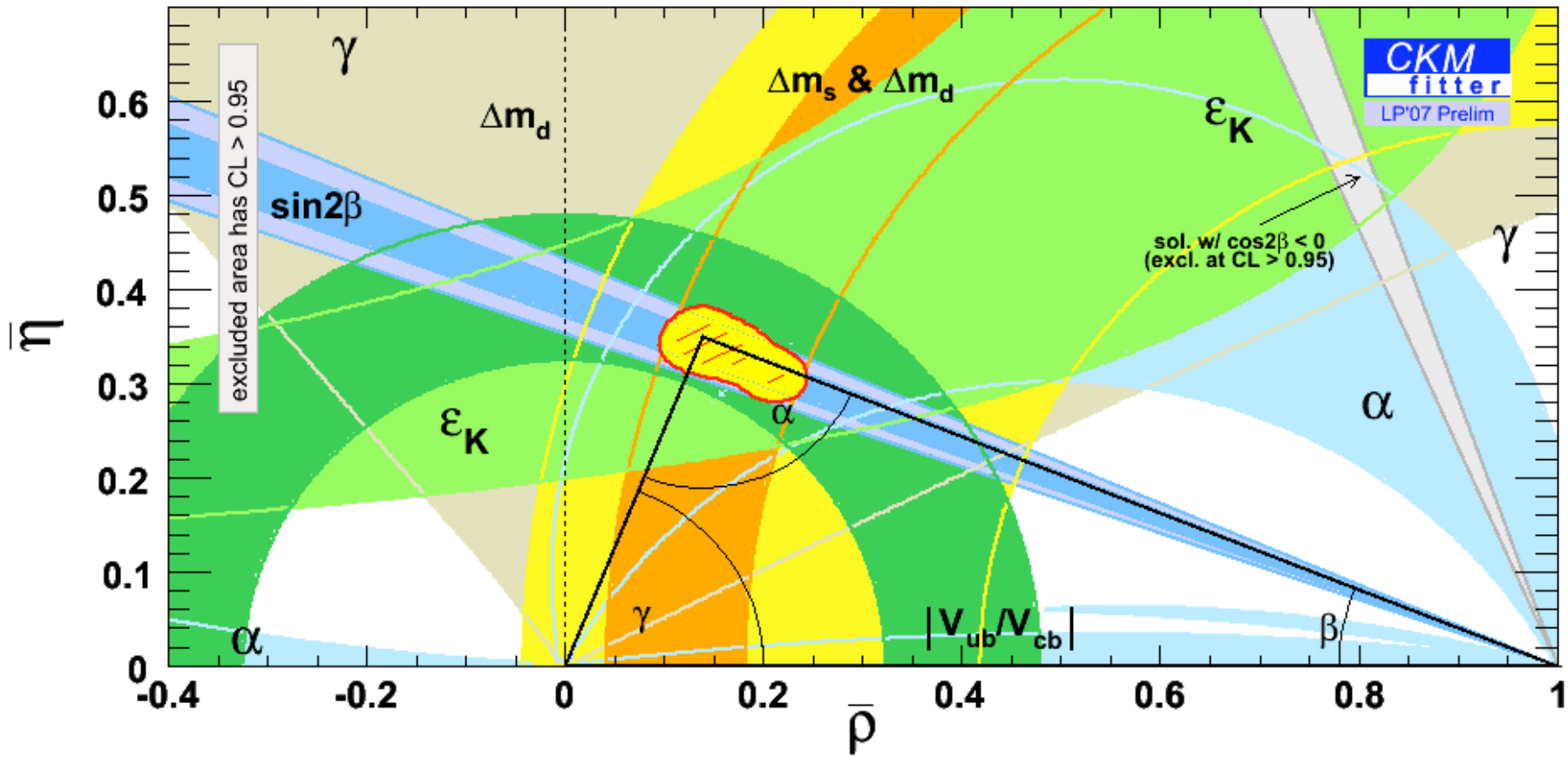
Includes a new preliminary result:

$B^{\pm} \rightarrow D^0 K^{\pm}$ **GLW (BaBar)**

The Unitarity Triangle: angles only



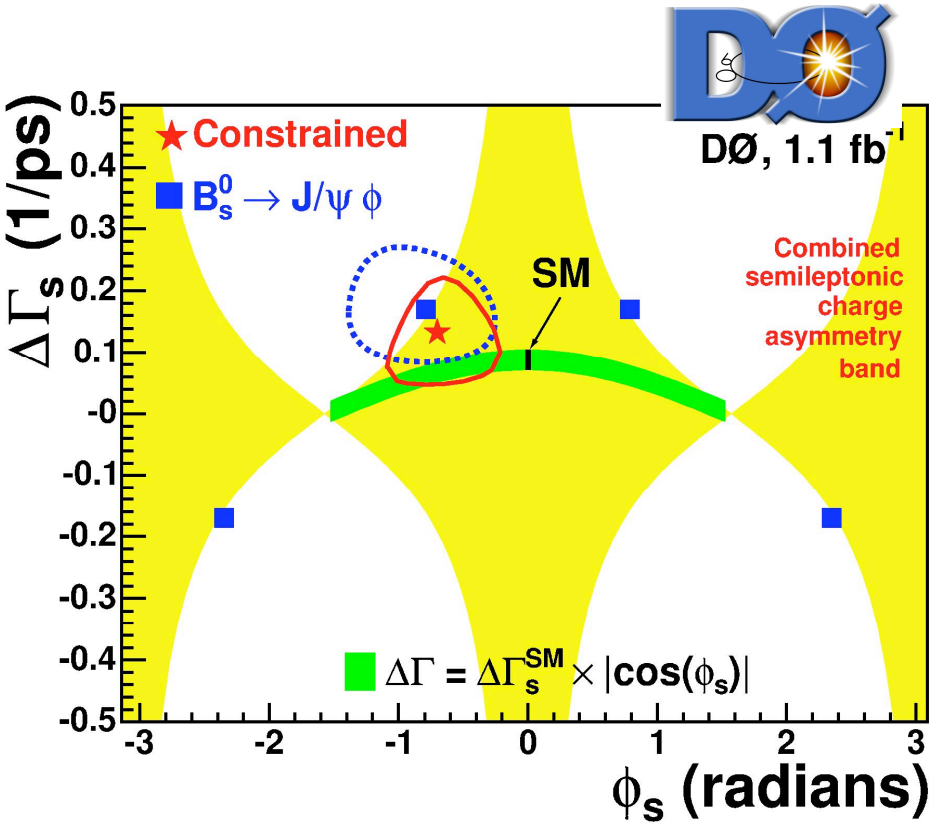
The Unitarity Triangle: all constraints



A consistent picture across a huge array of measurements

$B_s \rightarrow J/\psi\phi$ (ϕ_s): $b \rightarrow c\bar{c}s$

- Same quark decay as $B^0 \rightarrow$ charmonium K^0
- B_s mixing goes as $V_{ts} \Rightarrow$ no CPV phase as in B_d mixing
- SM prediction of $\phi_s = 4.2 \pm 1.4 \times 10^{-3}$ Hep-ph/0612167

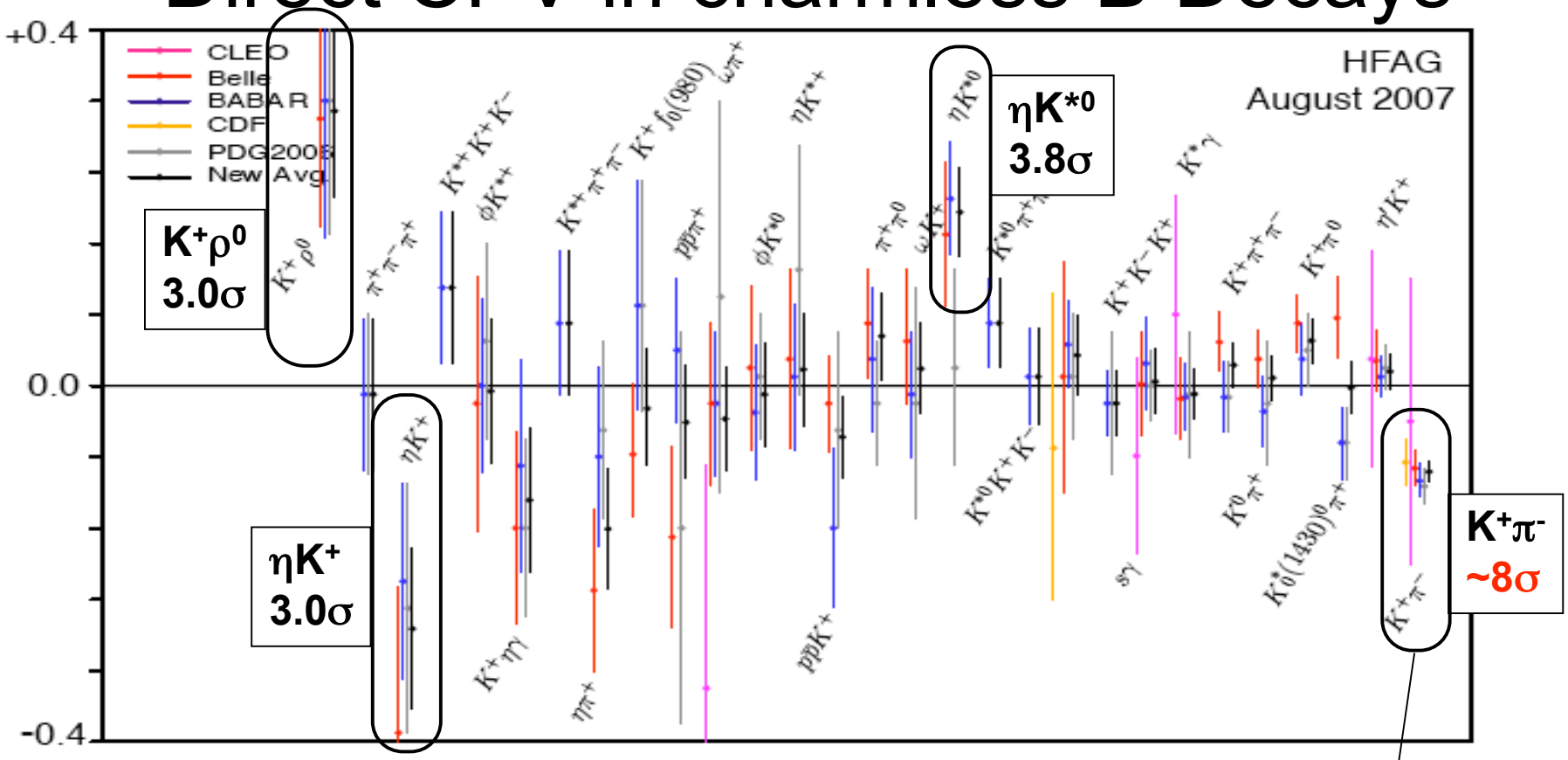


Simultaneous fit to ϕ_s, $\Delta\Gamma_s$

$$\phi_s = -0.70^{+0.47}_{-0.39}$$

Consistent with SM

Direct CPV in charmless B Decays



Isospin analogs

$A_{K\pi}(B^+ \to K^0\pi^+) = 0.009 \pm 0.025$

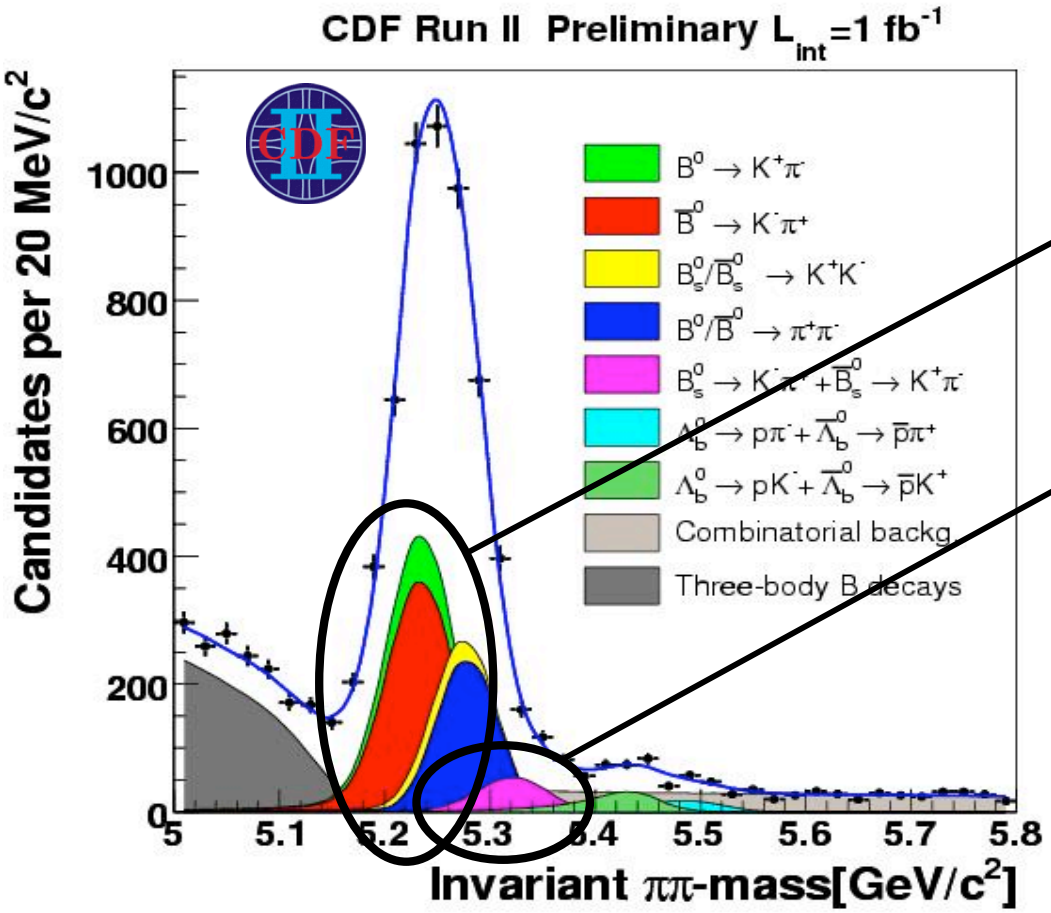
$A_{K\pi}(B^+ \to K^+\pi^0) = 0.050 \pm 0.025$

$\Leftrightarrow$

$A_{K\pi}(B_d) = -0.095 \pm 0.012$ (WA)

Effect from EW penguins?

Direct CPV in B_s Decays



$A_{K\pi}(B_d)$=-0.086 ± 0.023 ± 0.009
3.5σ significance

$A_{K\pi}(B_s)$=0.39 ± 0.15 ± 0.08
2.3σ significance

Comparing $A_{K\pi}(B_d, B_s)$

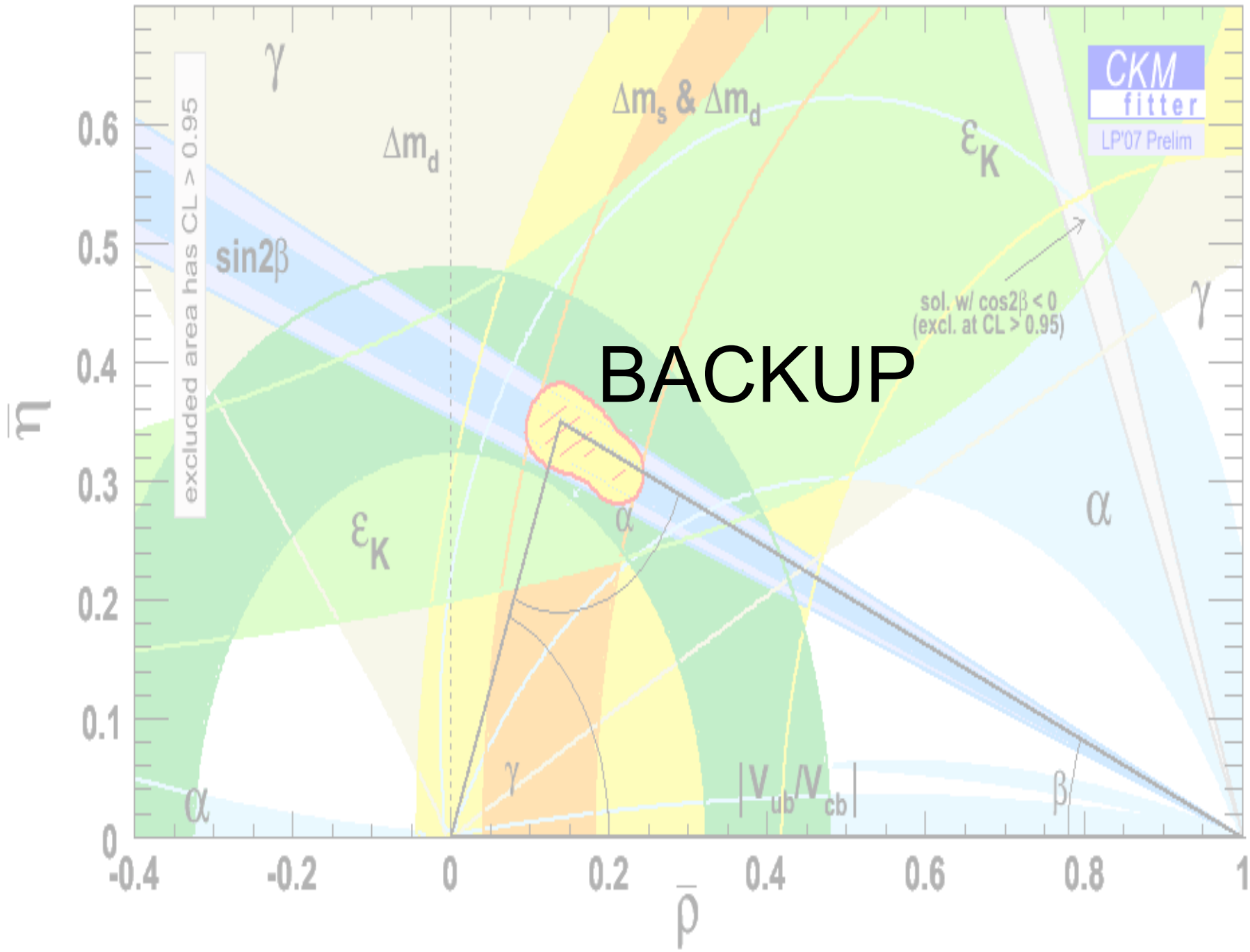
$$\frac{|A(\overline{B}^0 \to K^-\pi^+)|^2 - |A(B^0 \to K^+\pi^-)|^2}{|A(B_s^0 \to K^-\pi^+)|^2 - |A(\overline{B}_s^0 \to K^+\pi^-)|^2} = 0.84 \pm 0.42\ (stat.) \pm 0.15(sys.)$$

Consistent with SM prediction ≈1.0

H.J.Lipkin, Phys. Lett. B 621, 126 (2005)

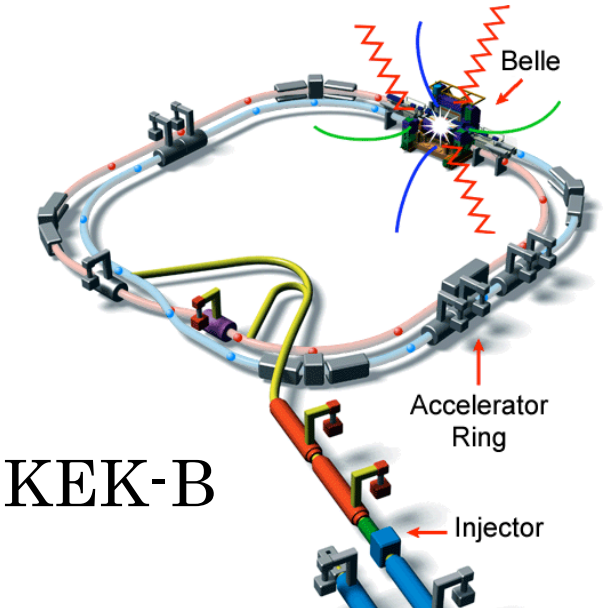
Conclusions

- Standard Model CKM CPV is well established
  - Confirmed by many analyses, several experiments
- Unitarity angle precision continues to improve
  - Sin2β is still statistics limited!
  - New, innovative techniques are still being developed
- CPV provides a unique window on the SM
  - The mysteries of flavor, generations, matter-anti-matter asymmetry remain unsolved
- The existing B-factories will soon be turned off
  - BaBar,Belle complete in ~2008,Tevatron in ~2009
  - Look for final analyses in 2009-2010!
- Future flavor physics depends on future facilities
  - LHCB, super-B, super-Belle, …

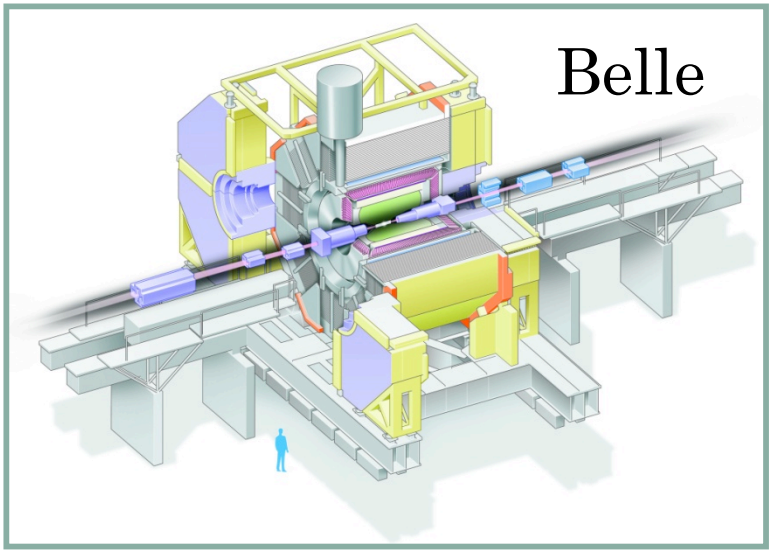

CKM fitter
LP'07 Prelim
excluded area has CL > 0.95
γ
Δm_d
Δm_s & Δm_d
ε_K
sin2β
sol. w/ cos2β < 0
(excl. at CL > 0.95)
α
|V_ub/V_cb|
β
η̄
ρ̄
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

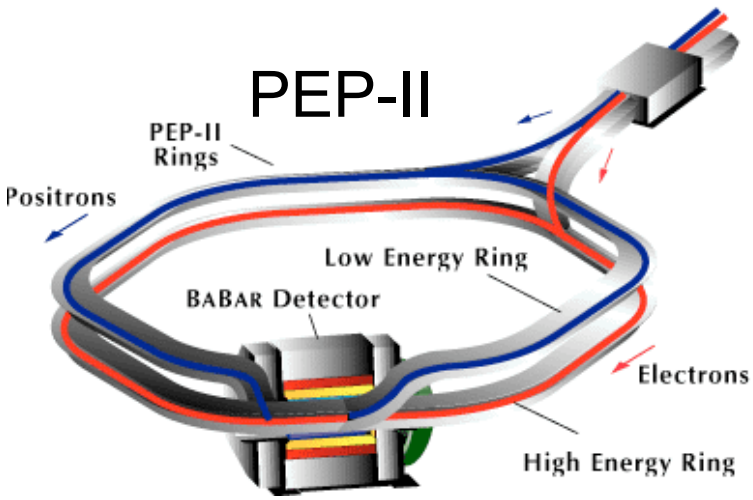
BACKUP

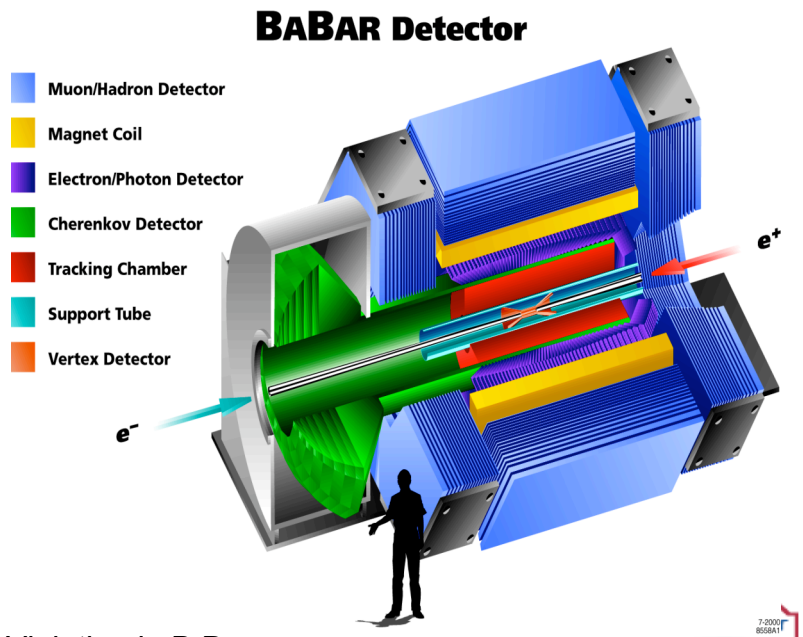
The B-factories



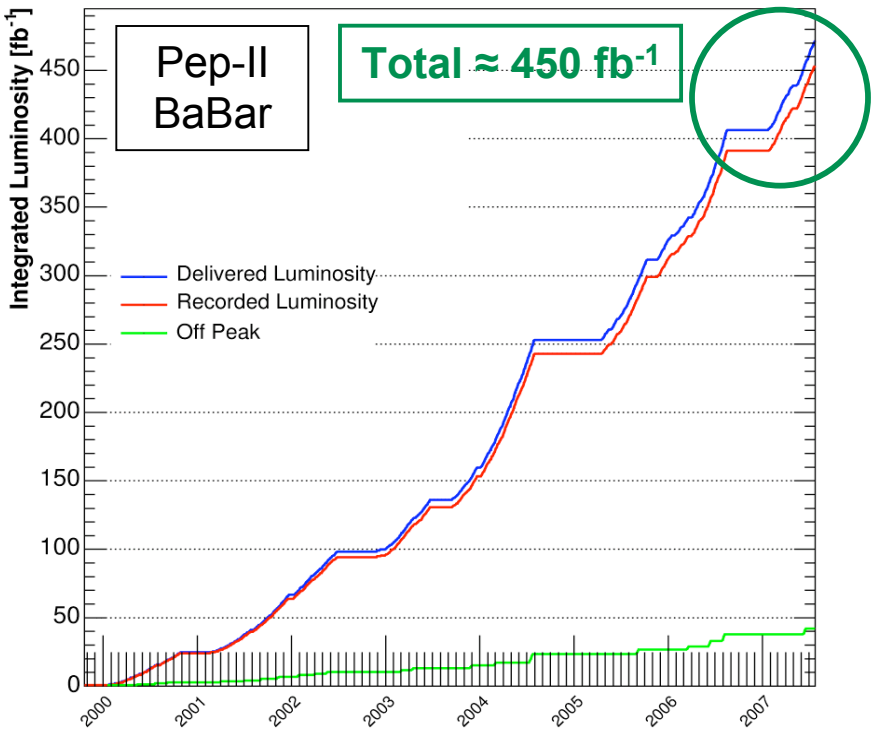
KEK-B

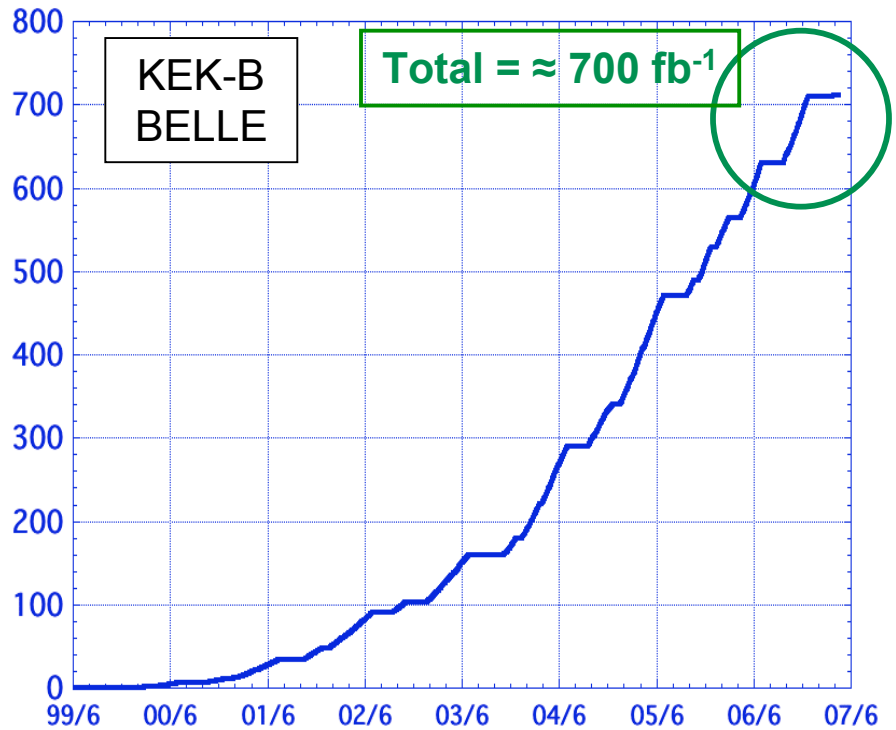






Datasets


Pep-II
BaBar
Total ≈ 450 fb-1
Integrated Luminosity [fb-1]
Delivered Luminosity
Recorded Luminosity
Off Peak
0
50
100
150
200
250
300
350
400
450
2000
2001
2002
2003
2004
2005
2006
2007


KEK-B
BELLE
Total = ≈ 700 fb-1
0
100
200
300
400
500
600
700
800
99/6
00/6
01/6
02/6
03/6
04/6
05/6
06/6
07/6

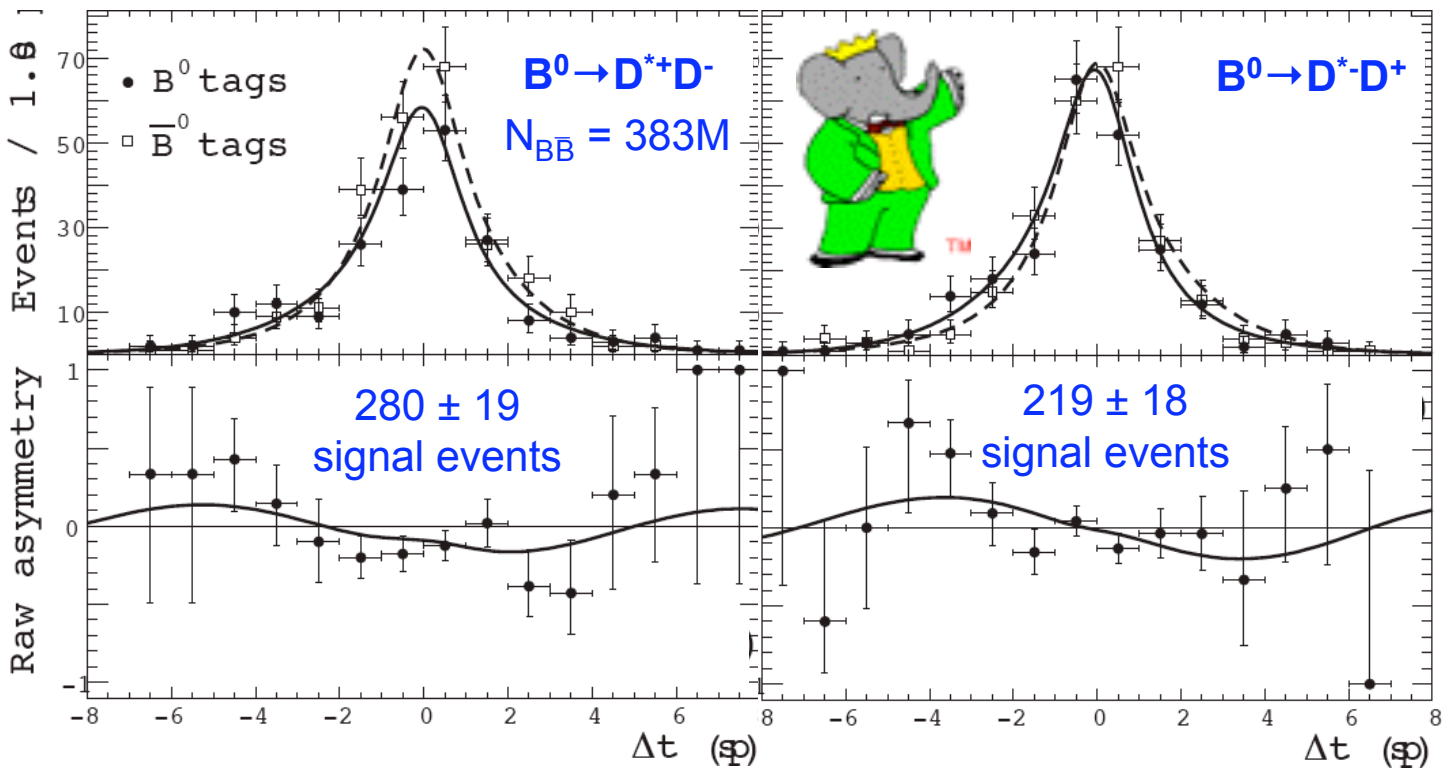
$B^0 \to D^{*+-} D^{-+} : b \to c\bar{c}d$

- Final state not a CP eigenstate
  - Could show time-integrated charge asymmetry
  - TDCPA modified by strong phase difference ($S_{+-} \neq S_{-+}$, $C_{+-} \neq C_{-+}$)
- If penguin contribution is zero, $C_{-+} = -C_{+-}$, $\beta_{eff}=\beta$
- If $S_{-+}= -S_{+-}$,No CPV$\Leftrightarrow$ $\sin(2\beta_{eff}) = 0$

$$\mathcal{A}_{D^{*\pm}D^{\mp}} = \frac{N_{D^{*+}D^{-}} - N_{D^{*-}D^{+}}}{N_{D^{*+}D^{-}} + N_{D^{*-}D^{+}}}$$

$$S_{D^{*\pm}D^{\mp}} = -\sqrt{1 - C^2_{D^{*\pm}D^{\mp}}}\,\sin(2\beta_{\rm eff} \pm \delta)$$

S and C in $B^0 \to D^{*+-} D^{-+}$: $b \to c\bar{c}d$



$$\mathcal{A}_{D^{*\pm}D^{\mp}} = 0.12 \pm 0.06 \pm 0.02$$

$$C_{D^{*+}D^{-}} = 0.18 \pm 0.15 \pm 0.04$$

$$S_{D^{*+}D^{-}} = -0.79 \pm 0.21 \pm 0.06$$

$$C_{D^{*-}D^{+}} = 0.23 \pm 0.15 \pm 0.04$$

$$S_{D^{*-}D^{+}} = -0.44 \pm 0.22 \pm 0.06$$

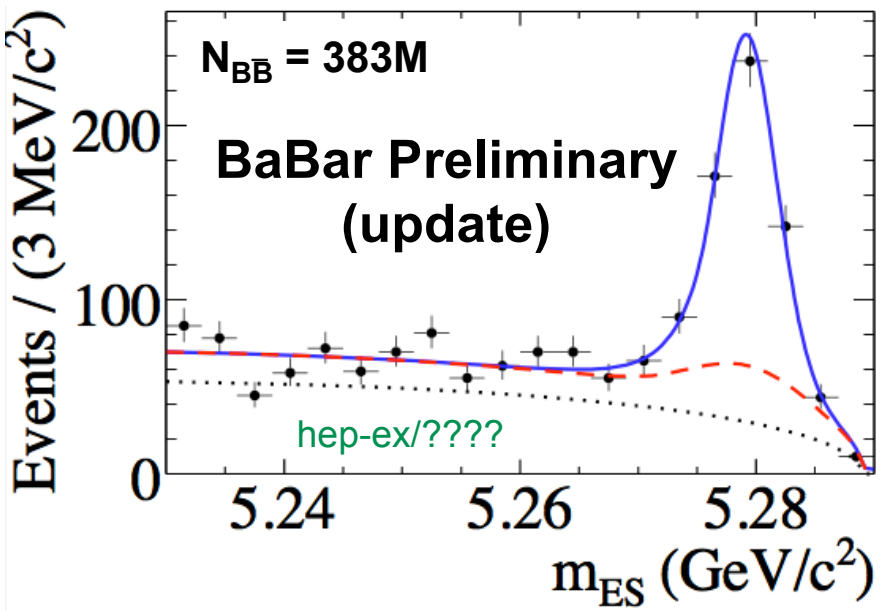
Time-integrated asymmetry consistent with 0

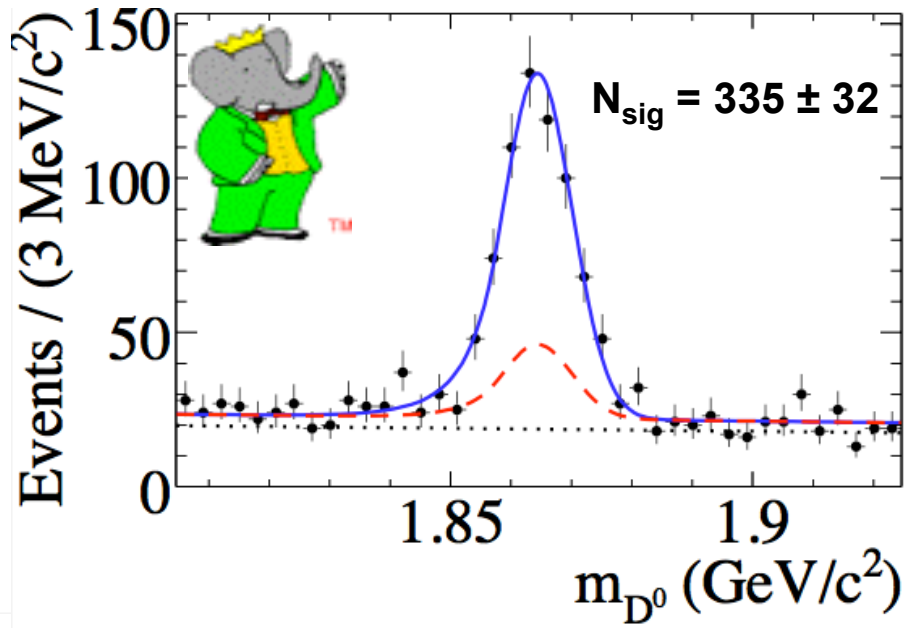
$\sin(2\beta)\cos\delta \neq 0$ @ 4σ

No significant direct CPV

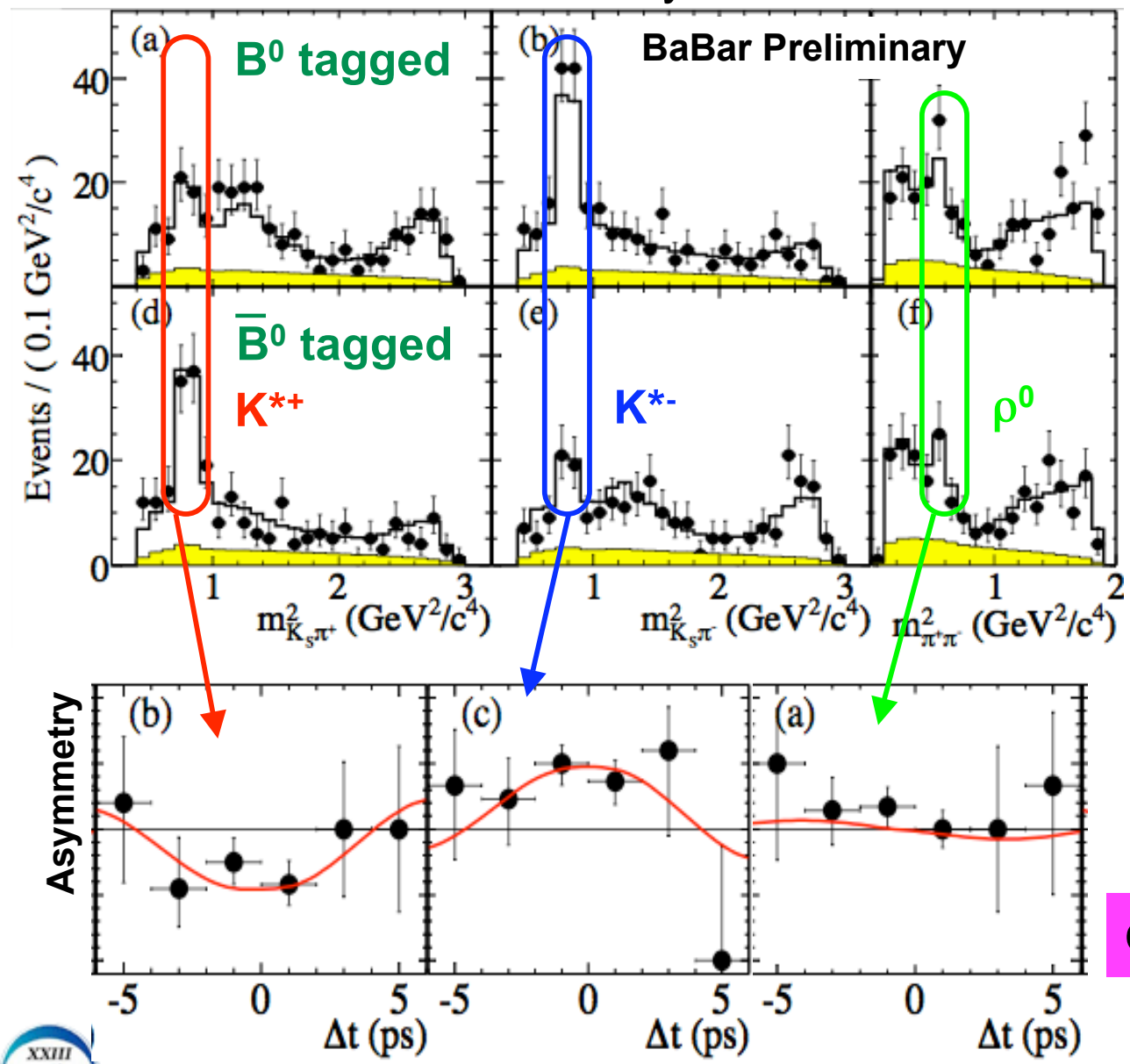
$B^0 \to D^0_{3\text{-body}} h^0 : b \to c\bar{u}d$

- $D^0 \to K_S \pi^+ \pi^-$ = coherent ensemble of quasi 2-body decays
- (Known) variation of strong phase over Dalitz plot allows extraction of strong and weak phase differences!
  - Must measure TDCPA at all points in the Dalitz plot
  - 2-fold ambiguity on β can (in principle) be resolved





$B^0 \to D^0_{3\text{-body}} h^0$ Dalitz Analysis : $b \to c\bar{u}d$



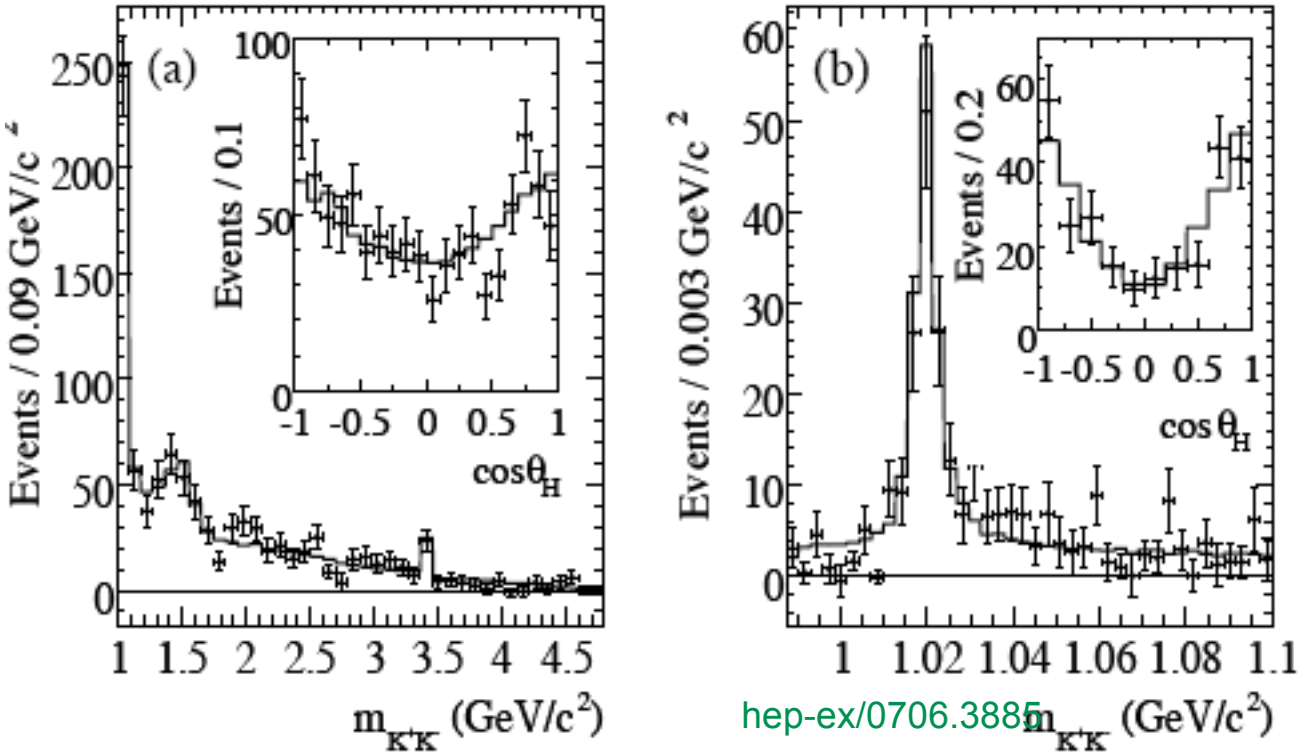
$h^0 = \pi^0, \eta^{(\prime)}, \omega$

$$\sin 2\beta = 0.29 \pm 0.34$$
$$\cos 2\beta = 0.42 \pm 0.49$$
$$|\lambda| = 1.01 \pm 0.08$$

cos2β>0 at 84% CL

$B^0 \to K_S K^+ K^- : b \to s\bar{q}q$

- Measure TDCPA at each point on the Dalitz plot
  - Includes interference between K^+K^-, $K_S K^\pm$ resonances

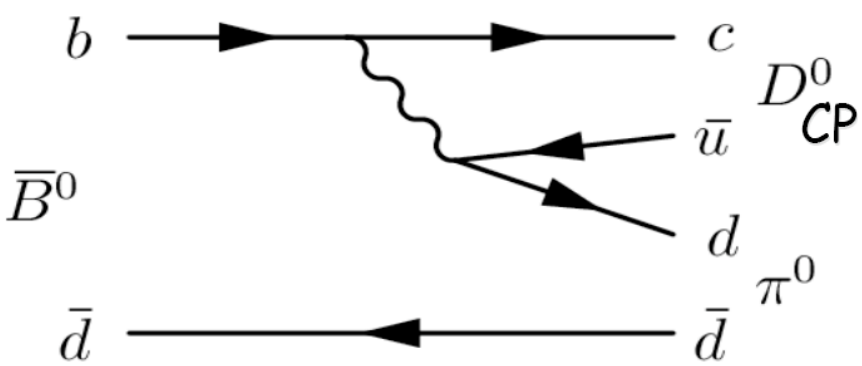


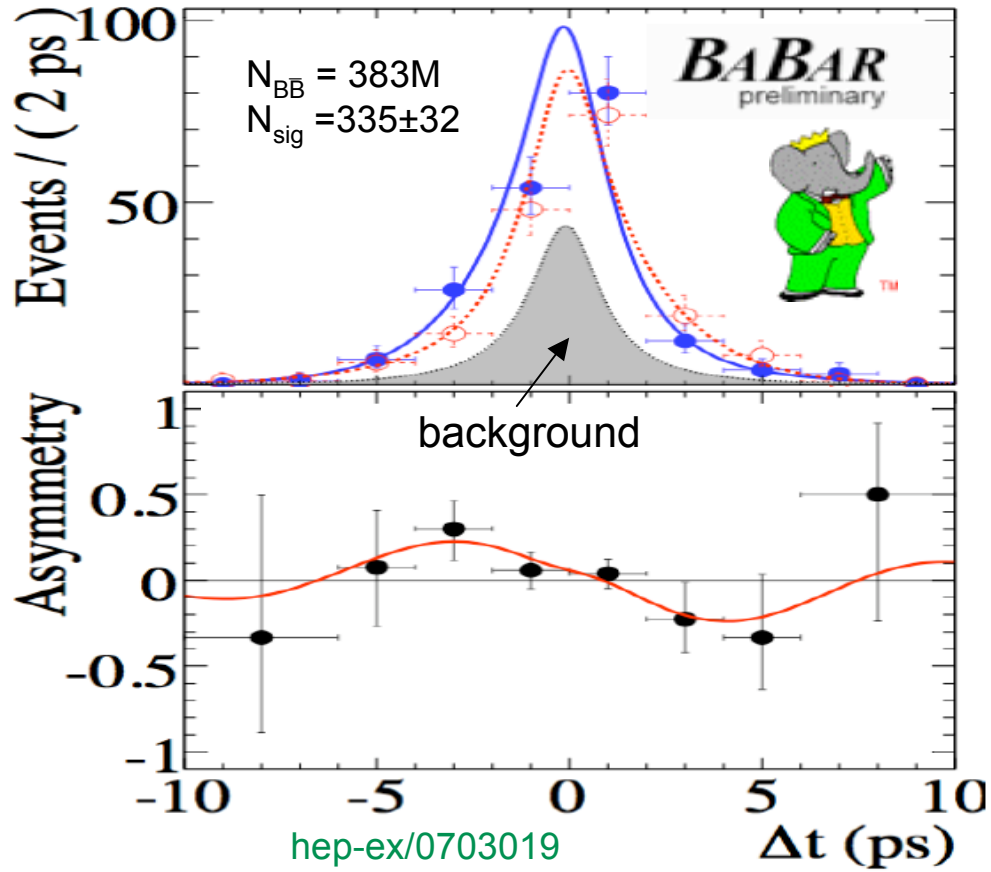
hep-ex/0706.3885

$A_{CP} = -0.015 \pm 0.077 \pm 0.053$
$\beta_{eff} = 0.352 \pm 0.076 \pm 0.026$ rad

4.8σ significance

$B^0 \to D^0_{CP} h^0 : b \to c\bar{u}d$





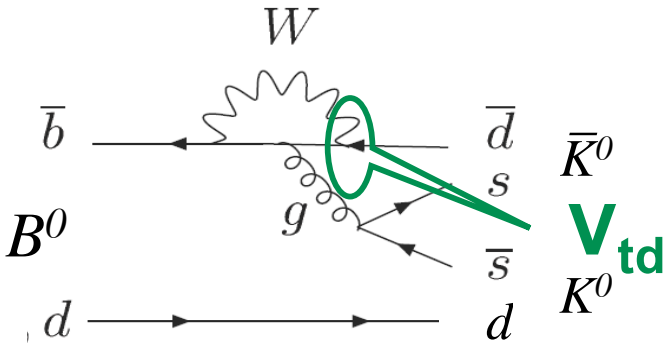
- $b \to c\bar{u}d$ tree dominates
- $b \to u\bar{c}d$ suppressed ~1/50
- $D^0_{CP} \equiv D^0 \to KK, K_S\omega$
  - also $D^{*0} \to D^0_{CP}\pi^0$
- $h^0 \equiv \pi^0, \omega, \eta$

SM predicts S=-sin2β, C≈0

$$S = -0.56 \pm 0.23 \pm 0.05$$
$$C = -0.23 \pm 0.16 \pm 0.04$$

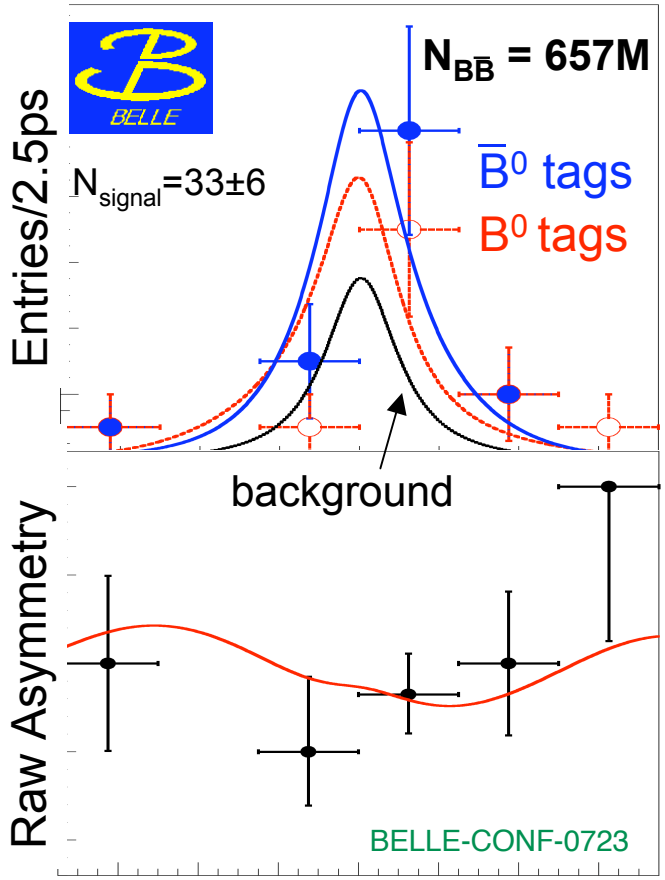
First TDCPA in these modes!

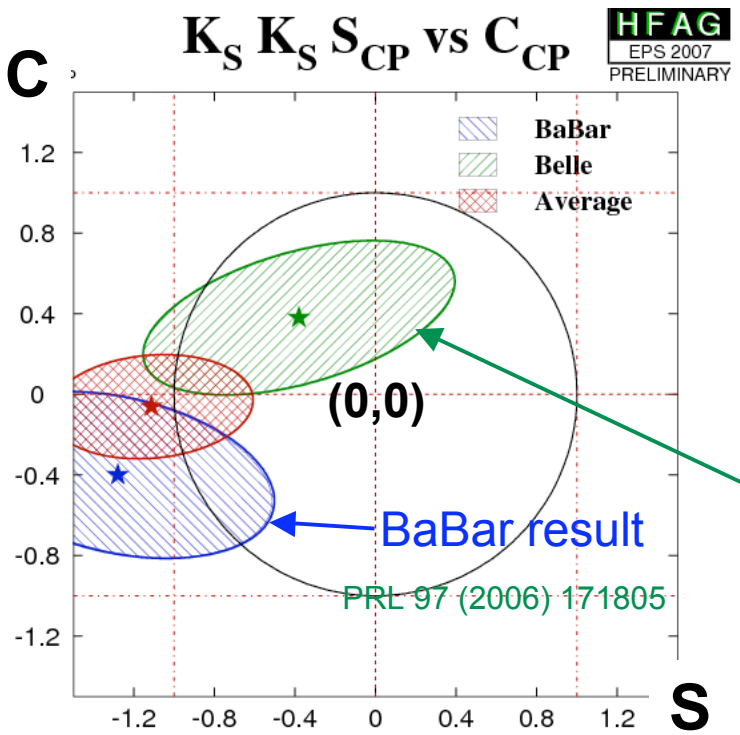
$B^0 \to K_S K_S : b \to d\bar{s}s$



EW decay phase cancels mixing phase ⇒No CPV expected!

R. Fleischer and S. Recksiegel, Eur.Phys.J.C38:251-259,2004





S = - 0.38 ± 0.77 ± 0.08

C = +0.38 ± 0.38 ± 0.05

SM expectation: S≈0, C≈0

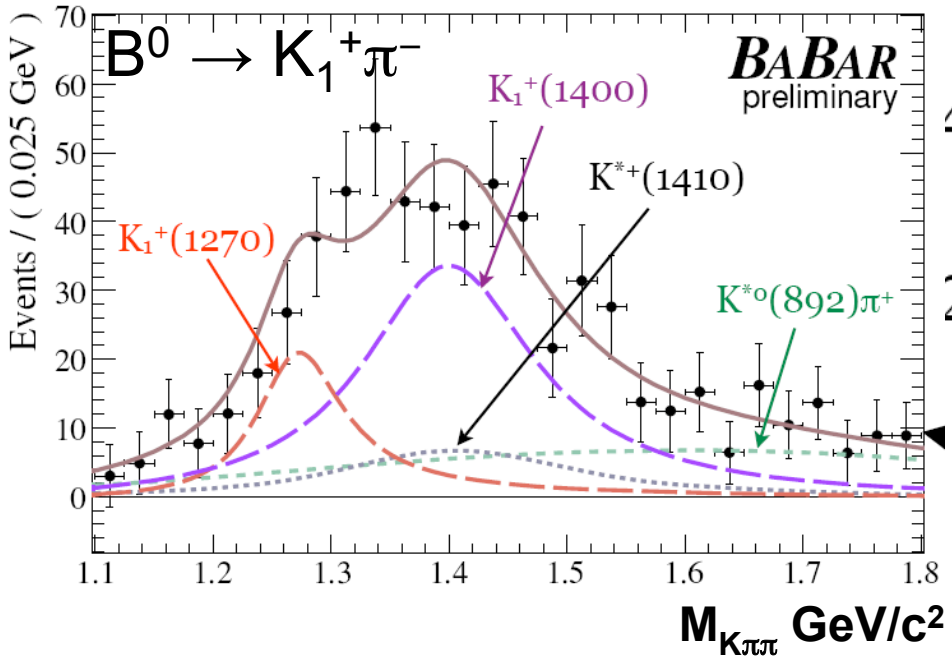
A.K.Giri and R.Mohanta, JHEP,11,084(2004)

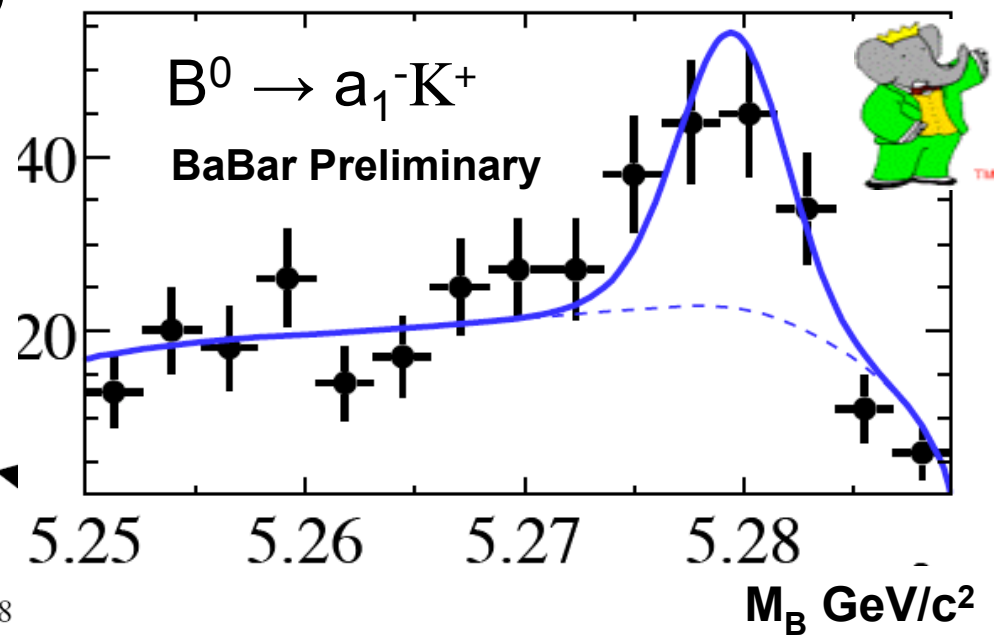
Constraining $\Delta\alpha$ in $B \to a_1\pi$ via SU(3)

- No phase-space overlap between a_1^+, a_1^-, and a_1^0
- Can use SU(3) to relate $p \Leftrightarrow K$ and $a_1 \Leftrightarrow K_{1A}$
- Necessary BFs are measured, $\Delta\alpha$ not yet computed

Gronau & Zupan, Phys. Rev. D73, 057502 (2006)

$$K_{1A} = \cos\theta K_1(1400) + \sin\theta K_1(1270)$$





$BF(B^0 \to K_1^+(1270)\pi^-) = 12.0 \pm 3.1\ ^{+9.3}_{-4.5} \times 10^{-6}$

$BF(B^0 \to K_1^+(1400)\pi^-) = 16.7 \pm 2.6\ ^{+3.5}_{-5.0} \times 10^{-6}$

$BF(B^0 \to a_1^- K^+) \cdot BF(a_1^- \to \pi^+\pi^-\pi^-) = 8.2 \pm 1.5 \pm 1.2 \times 10^{-6}$

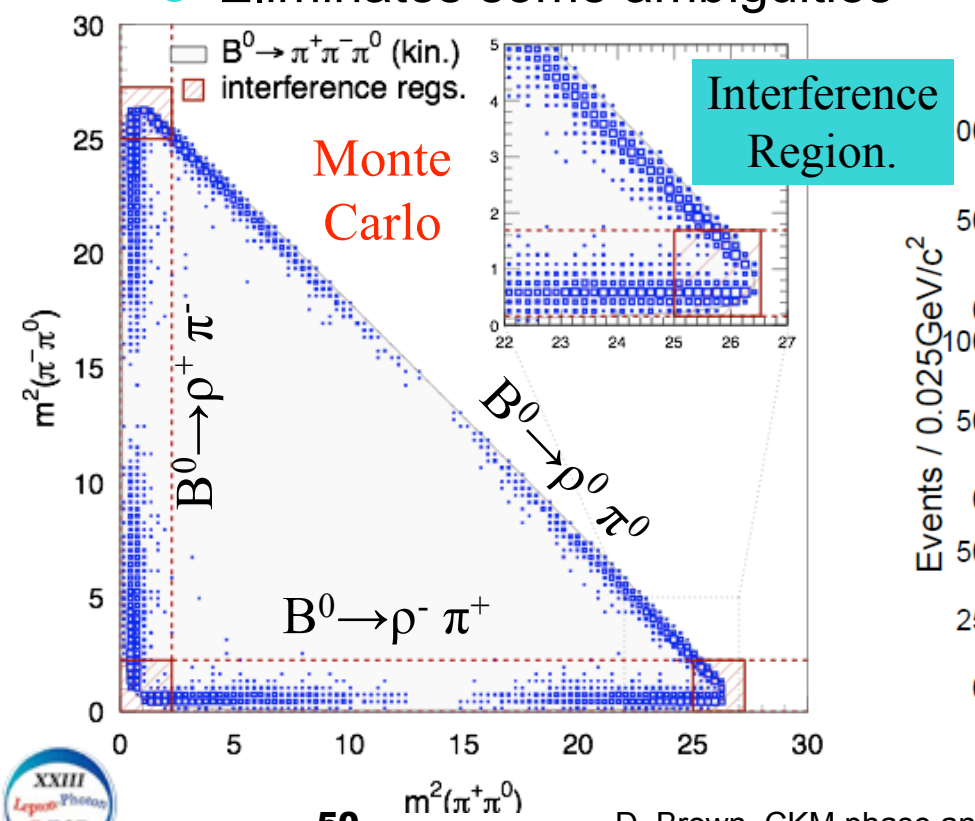
$A_{ch}(B^0 \to a_1^- K^+) = -0.16 \pm 0.12 \pm 0.01$

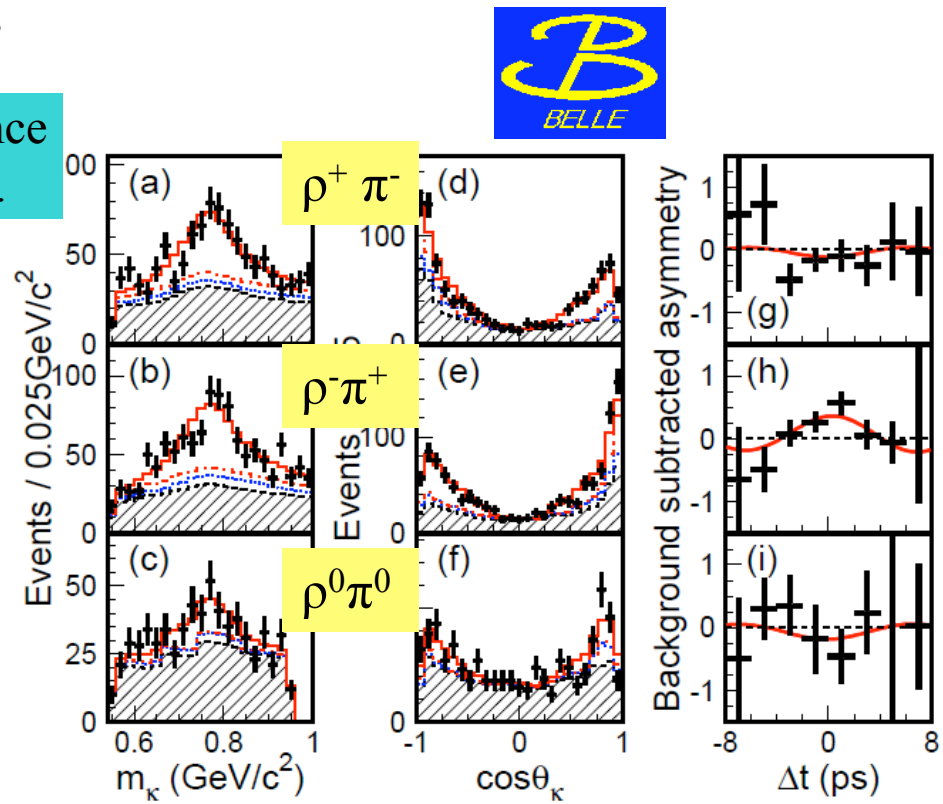
$BF(B^+ \to a_1^+ K^0) \cdot BF(a_1^+ \to \pi^+\pi^+\pi^-) = 17.4 \pm 2.5 \pm 2.2 \times 10^{-6}$

$A_{ch}(B^+ \to a_1^+ K^0) = 0.12 \pm 0.11 \pm 0.02$

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

- Can use Isospin as in $\pi^+\pi^-$
  - 'pentagon' relationship -> more terms to measure
- New method: use (known) resonance phase variation over Dalitz to analyze EW phase
  - Eliminates some ambiguities





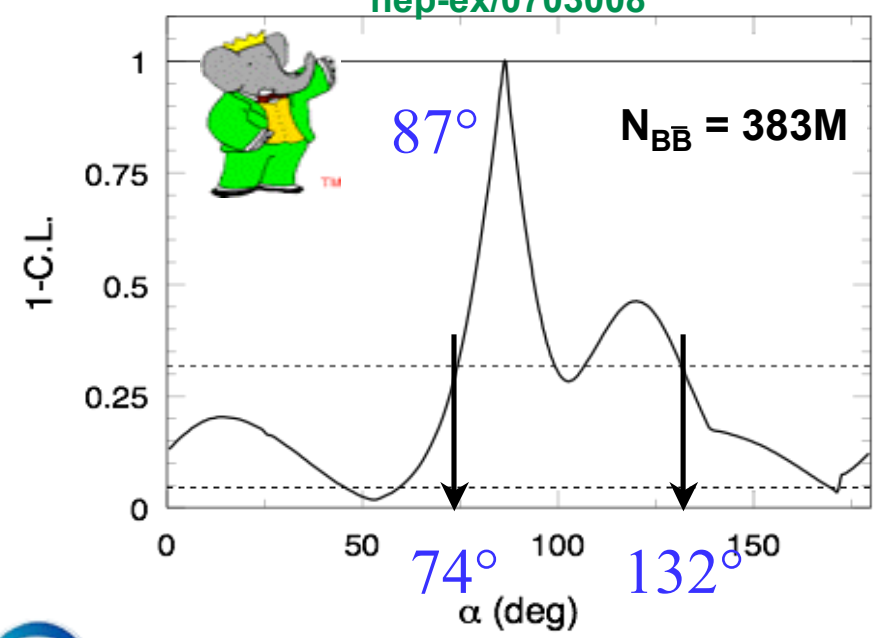
$B^0 \to \pi^+\pi^-\pi^0$ $(\rho\pi)^0$: $b \to u\bar{u}d$

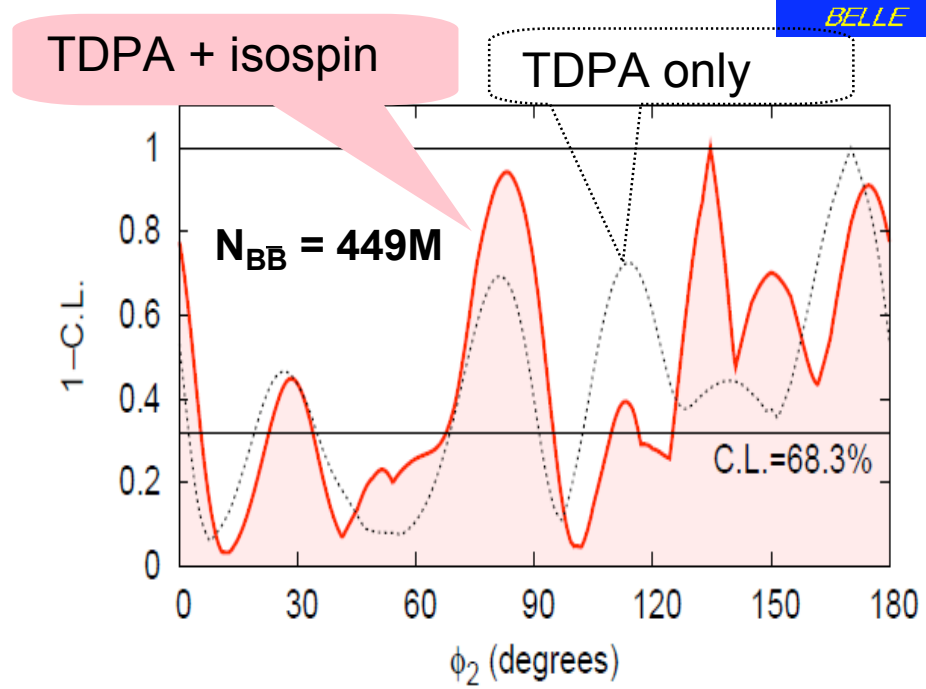
$N(B^0 \to \pi^+ \pi^- \pi^0)$ =	2067 ± 86
$A_{\rho\pi}$ $(\rho^\pm \pi^\mp)$ =	-0.14 ± 0.05 ± 0.02
C $(\rho^\pm \pi^\mp)$ =	0.15 ± 0.09 ± 0.05
S $(\rho^\pm \pi^\mp)$ =	-0.03 ± 0.11 ± 0.04
ΔC $(\rho^\pm \pi^\mp)$ =	0.39 ± 0.09 ± 0.09
ΔS $(\rho^\pm \pi^\mp)$ =	-0.01 ± 0.14 ± 0.06
C_{00} $(\rho^0 \pi^0)$ =	-0.10 ± 0.40 ± 0.53
S_{00} $(\rho^0 \pi^0)$ =	0.02 ± 0.22 ± 0.09

$$A_{\rho^0\pi^0} = -0.45 \pm 0.35(stat) \pm 0.32(syst)$$
$$S_{\rho^0\pi^0} = +0.15 \pm 0.57(stat) \pm 0.43(syst)$$

PRL 98, 221602 (2007)

hep-ex/0703008





GLW results

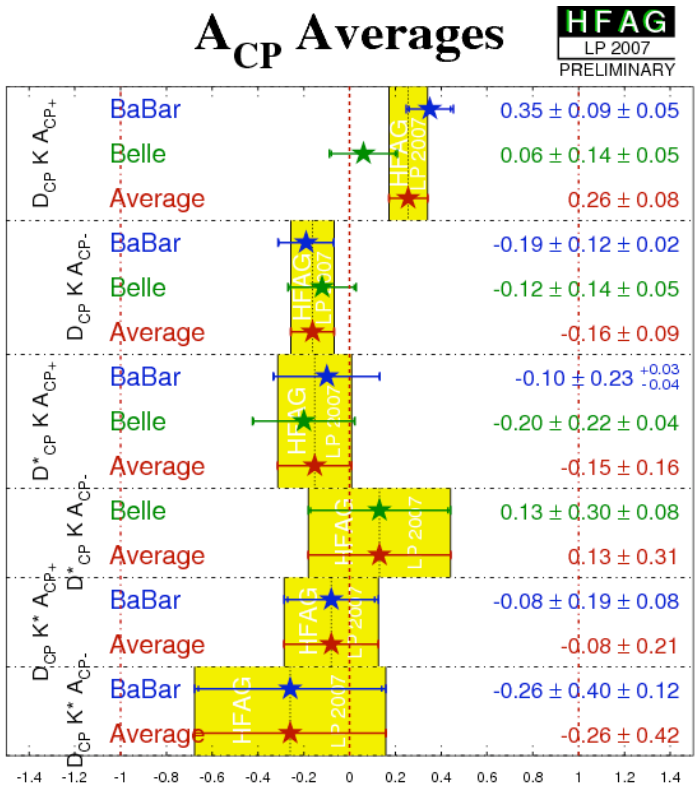
$$\mathcal{A}_{CP\pm} = \frac{\Gamma(B^- \to D^{(*)0}_{CP\pm} K^{(*)-}) - \Gamma(B^+ \to D^{(*)0}_{CP\pm} K^{(*)+})}{\Gamma(B^- \to D^{(*)0}_{CP\pm} K^{(*)-}) + \Gamma(B^+ \to D^{(*)0}_{CP\pm} K^{(*)+})} = \frac{\pm 2 r^{(*)}_{(s)B} \sin\delta^{(*)}_{(s)B} \sin\gamma}{R_{CP\pm}}$$

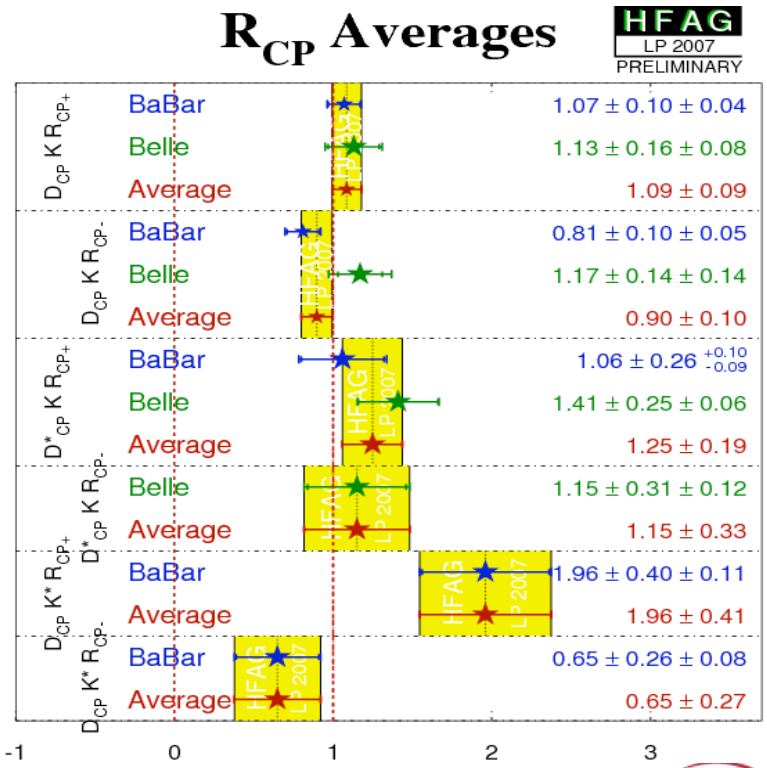
$$R_{CP\pm} = \frac{\Gamma(B^- \to D^{(*)0}_{CP\pm} K^{(*)-}) + \Gamma(B^+ \to D^{(*)0}_{CP\pm} K^{(*)+})}{[\Gamma(B^- \to D^{(*)0} K^{(*)-}) + \Gamma(B^- \to D^{(*)0} K^{(*)-})]/2} = 1 + r^{(*)2}_{(s)B} \pm 2 r^{(*)}_{(s)B} \cos\delta^{(*)}_{(s)B} \cos\gamma$$

CP−even: $D \to K^+K^-, \pi^+\pi^-$

CP−odd: $D \to K_S\pi^0$, $K_S\omega$, $K_S\phi$

4 observables, 3 unknowns





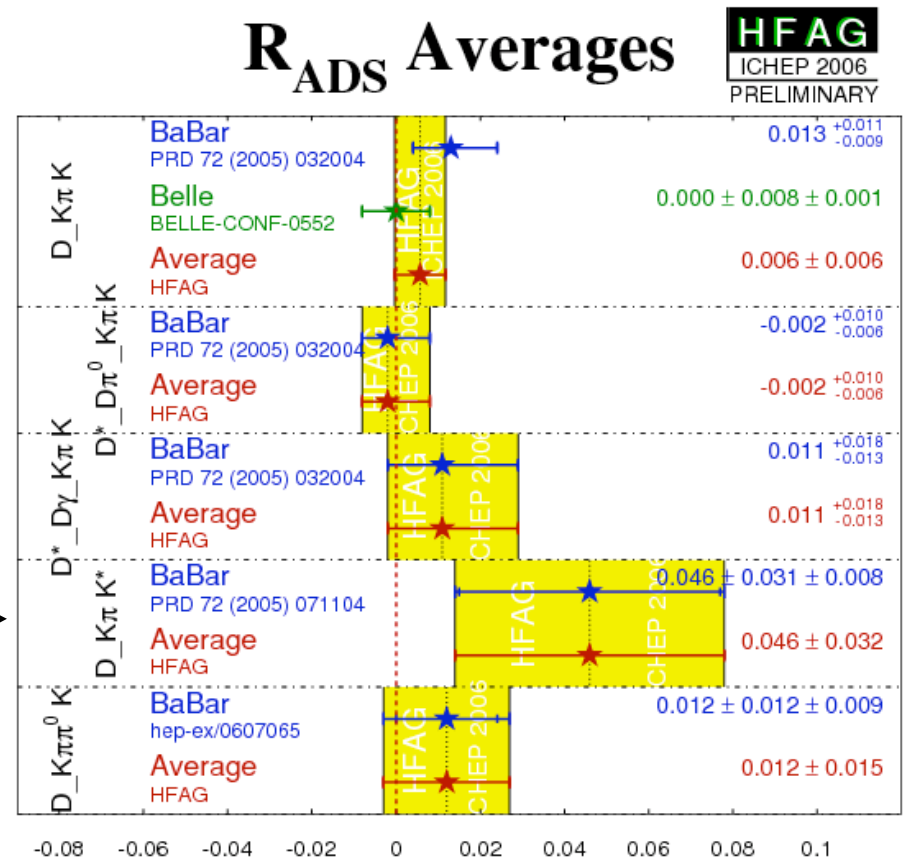
ADS results

$$A_{ADS} = \frac{\Gamma(B^- \to D[K^+\pi^-]K^-) - \Gamma(B^+ \to D[K^-\pi^+]K^+)}{\Gamma(B^- \to D[K^+\pi^-]K^-) + \Gamma(B^+ \to D[K^-\pi^+]K^+)}$$
$$= 2 r_B r_D \sin(\delta_B + \delta_D) \sin\gamma / R_{ADS}$$

$$R_{ADS} = \frac{\Gamma(B^- \to D[K^+\pi^-]K^-) + \Gamma(B^+ \to D[K^-\pi^+]K^+)}{\Gamma(B^- \to D[K^-\pi^+]K^-) + \Gamma(B^+ \to D[K^+\pi^-]K^+)}$$
$$= r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_B + \delta_D) \cos\gamma$$

2 observables, 5 unknowns

$A_{ADS} = -0.22 \pm 0.61 \pm 0.17$



GGSZ Results

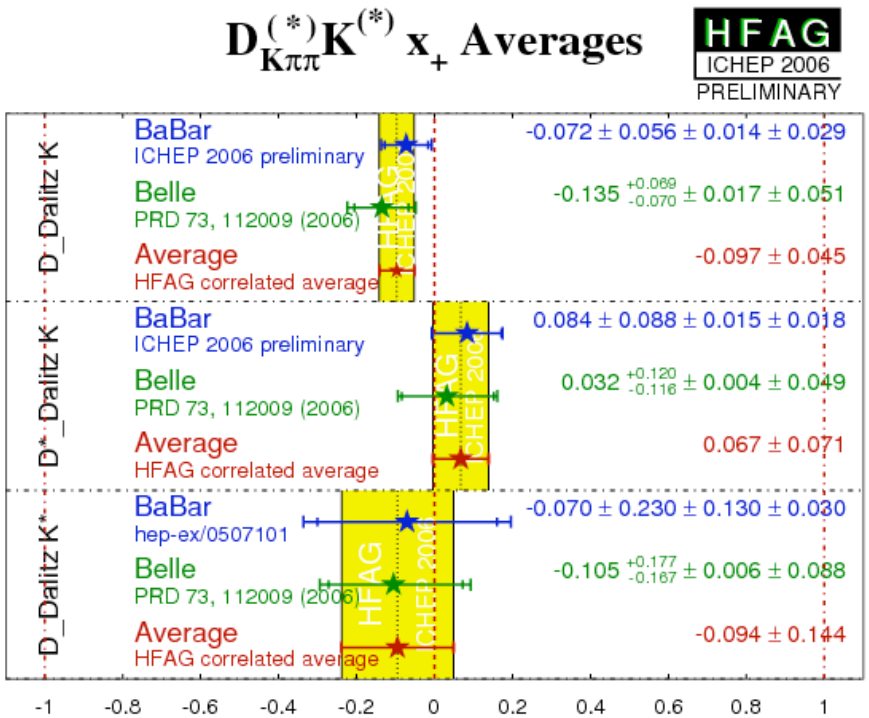
Physical Variables

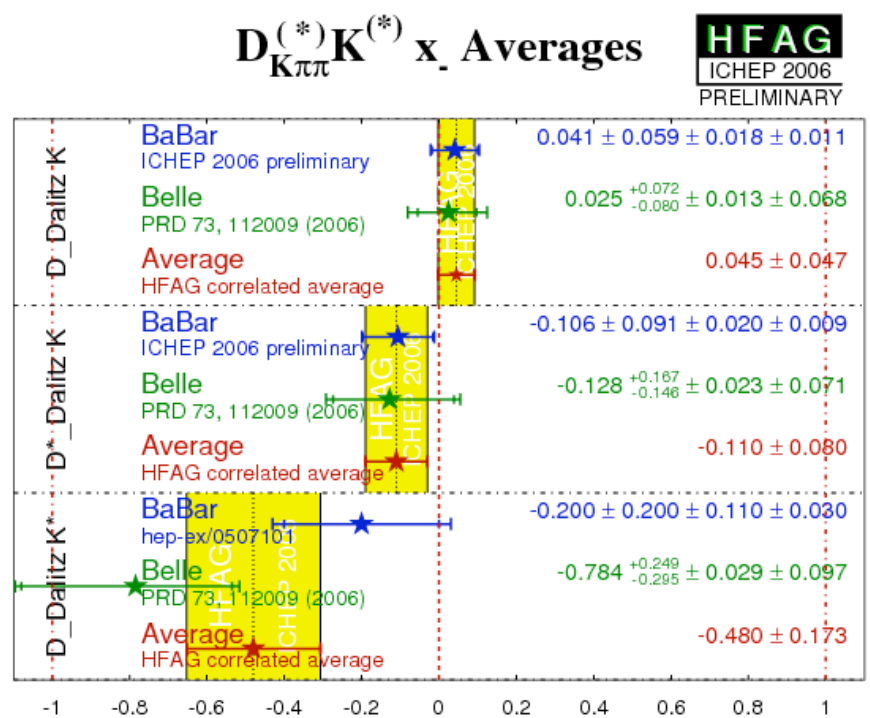
r_B , δ_B ,γ

⇒

Gaussian Variables

$x_+ = r_B \cos(\delta_B+\gamma)$, $y_+ = r_B \sin(\delta_B+\gamma)$
$x_- = r_B \cos(\delta_B-\gamma)$, $y_- = r_B \sin(\delta_B-\gamma)$



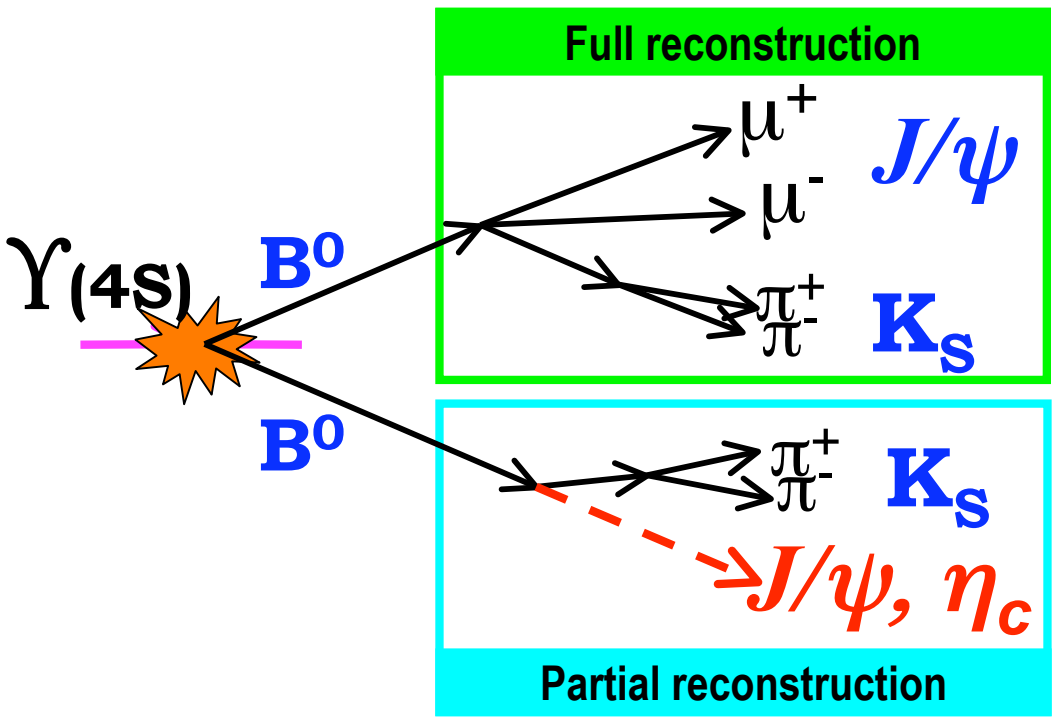


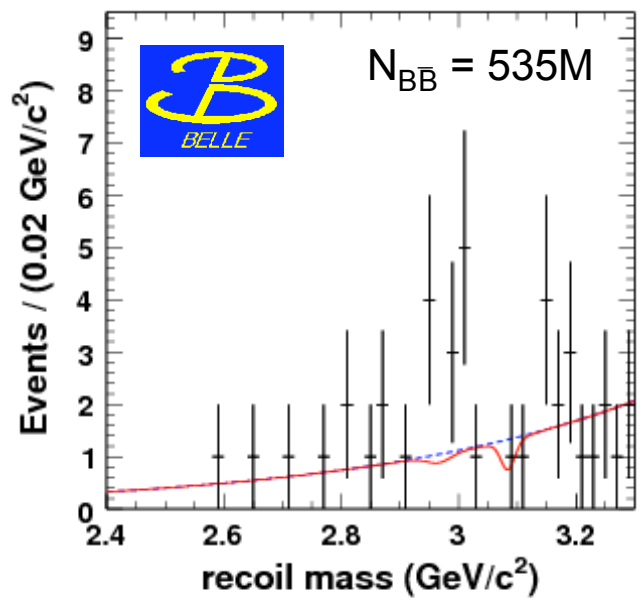
Modes in $D_{KK\pi}{}^{(*)}K^{(*)}$

Similar for Y_+,Y_-

CPV in $\Upsilon(4S)$ Decay

- If large, would invalidate sin2β from TDCPA results
- Method: partial reconstruction





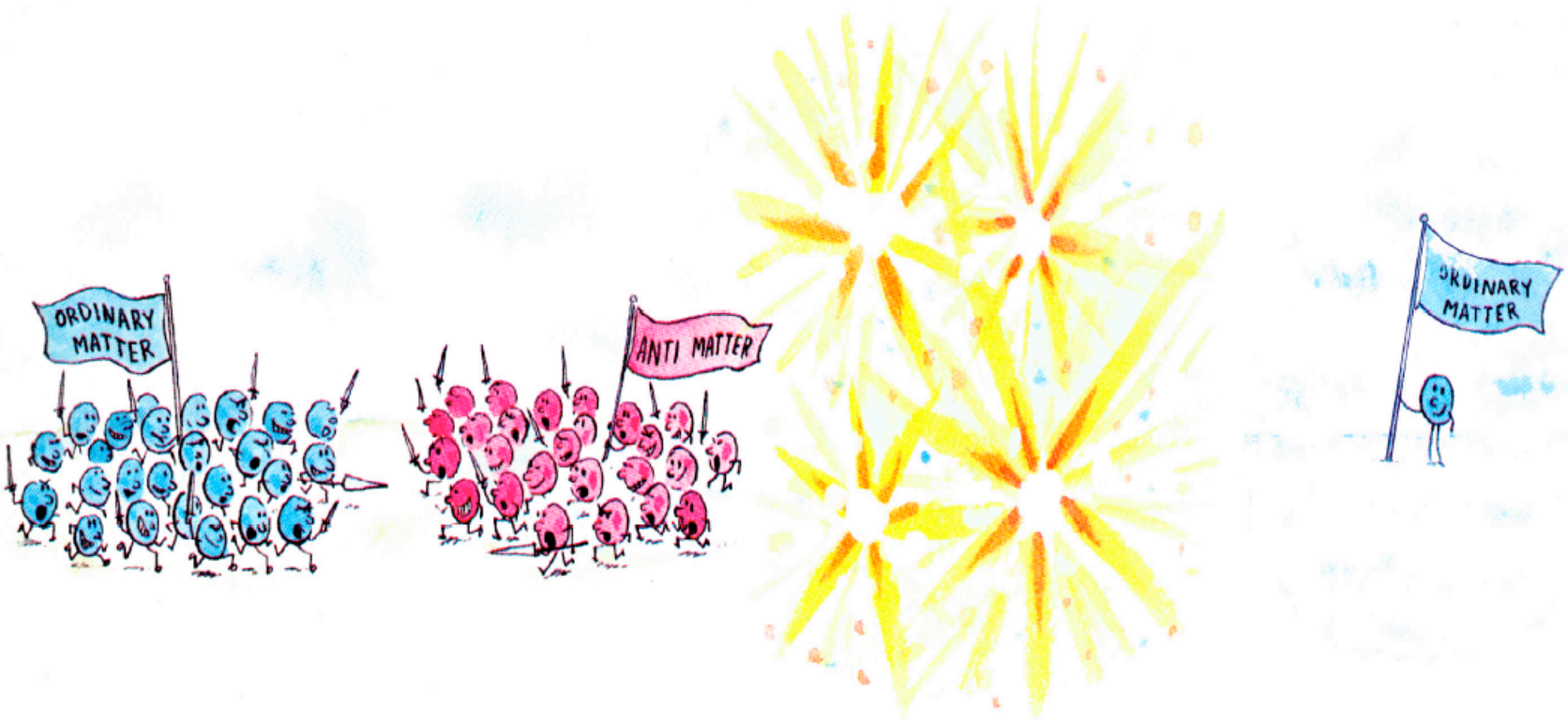
arXiv:0707.4336 (submitted to PRL)

$N_{sig} = -1.5\,^{+3.6}_{-2.8}$ events

Br($\Upsilon(4S) \rightarrow B^0B^0 \rightarrow J/\psi K_S + J/\psi(\eta_c)K_S$) < 4x10^{-7}(90%C.L.)

SM expectation: ~1.4x10^{-7}

How this all started...

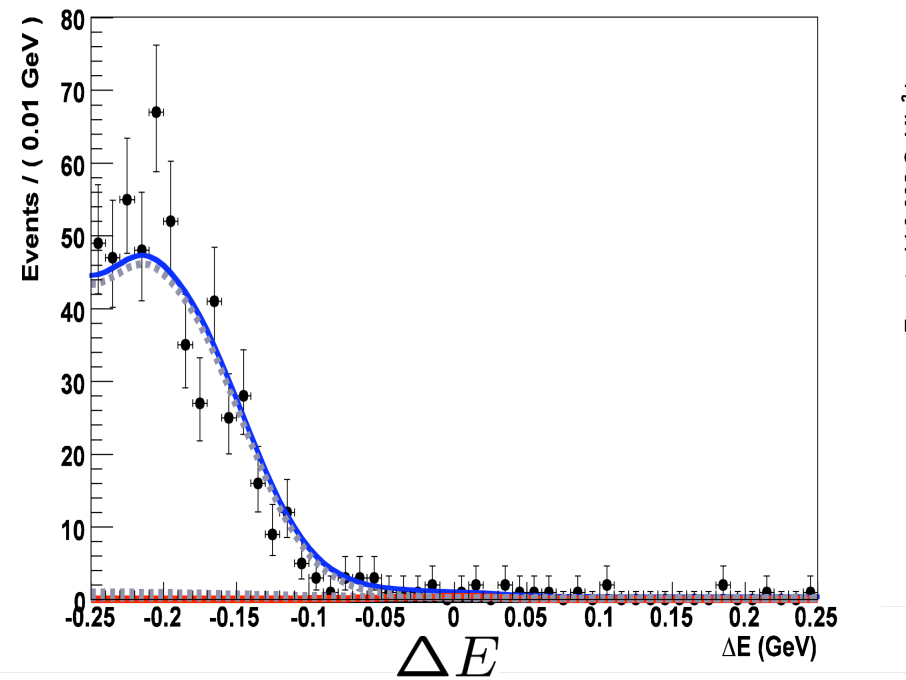


In the early universe, for every billion ordinary particles annihilating with antimatter, one was left standing…

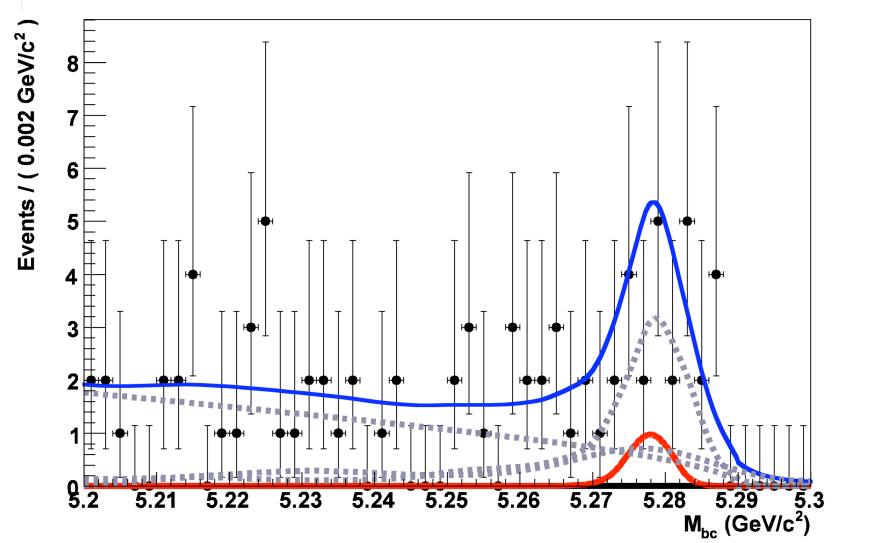
- CKM CPV is too small to account for observed matter/anti-matter asymmetry by a factor of ~10^{-20}
- Due to 'Heavy' Higgs, 12 factors of lambda for simplest process resulting in matter/anti-matter asymmetry

$$\mathcal{S} = \frac{2(-1)^L r \sin(2\phi_1 + \phi_3 + \delta)}{1 + r^2}$$

$$r^2 = \frac{\mathcal{B}(B^0 \to D^{*+}\pi^-)}{\mathcal{B}(B^0 \to D^{*-}\pi^+)} = \frac{2\mathcal{B}(B^+ \to D^{*+}\pi^0)}{\mathcal{B}(B^0 \to D^{*-}\pi^+)}$$



ΔE



M_{bc}

$$\mathcal{B}(B^+ \to D^{*+}\pi^0) < 3.0 \times 10^{-6} \ (90\% \ C.L.)$$