Review of
β , α and γ measurements
(ϕ_1 , ϕ_2 and ϕ_3)

on behalf of the BaBar and Belle collaborations

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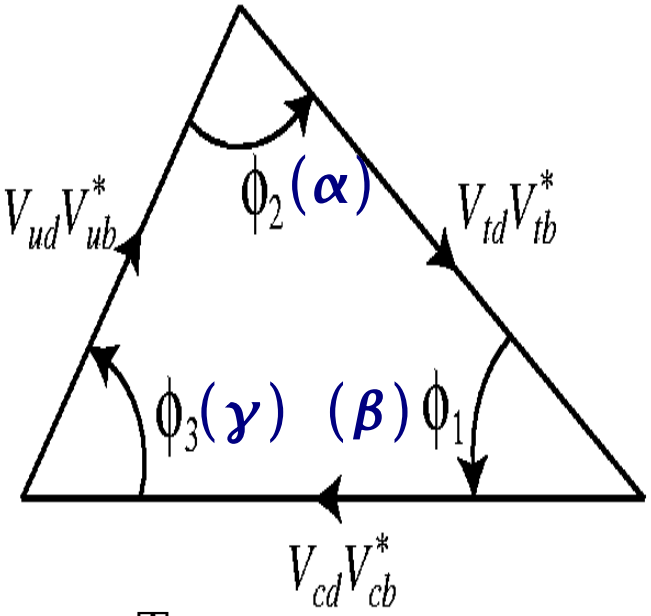
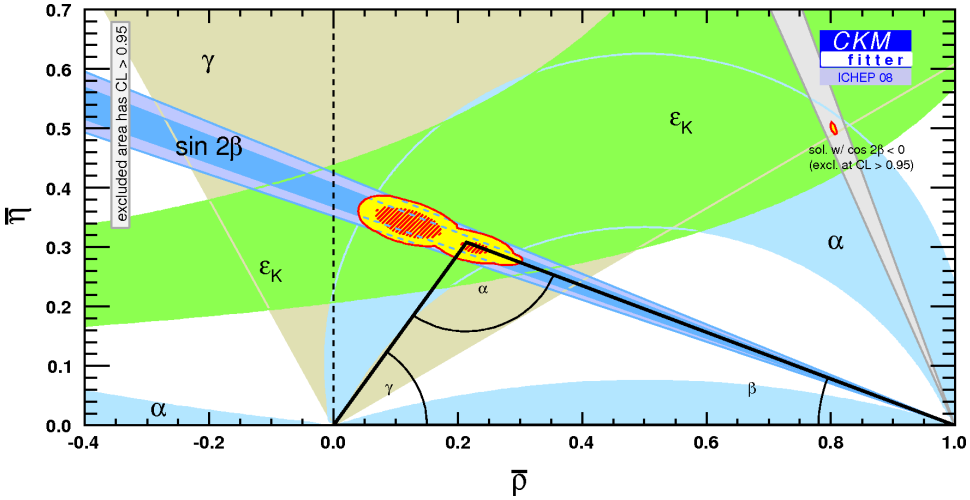
Electroweak Session, La Thuile, March 7-14, 2009

Motivations

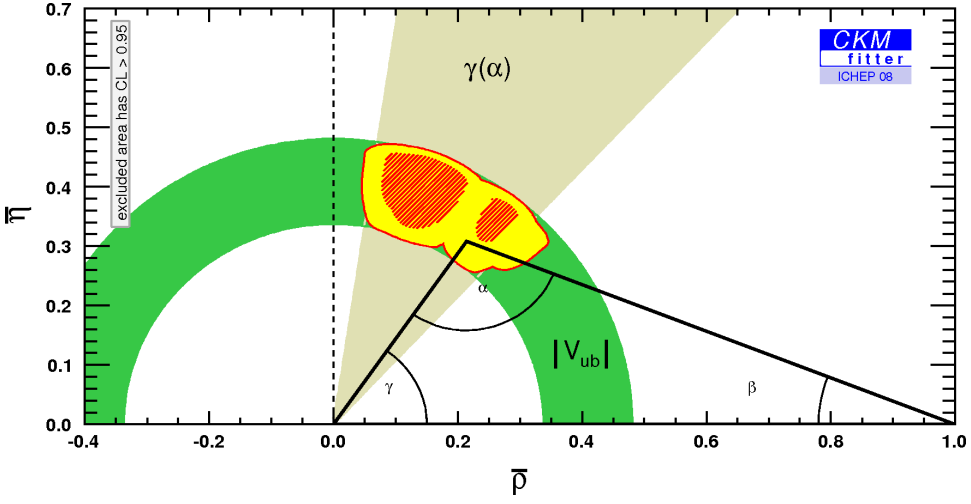
- Overconstrain the CKM matrix: measure fundamental parameters, constrain new physics effects
- Measure the 4 free paremeters in various ways:
  - CP conserving $\{|V_{us}|, |V_{cb}|, |V_{td}|, |V_{ub}|\}$
  - CP violating $\{\epsilon_K, \phi_s, \beta, \gamma\}$
  - Tree level $\{\ldots, \ldots, |V_{ub}|, \gamma\}$
  - Loop level $\{\ldots, \ldots, |V_{td}|, \beta\}$
  - ...



CP violating



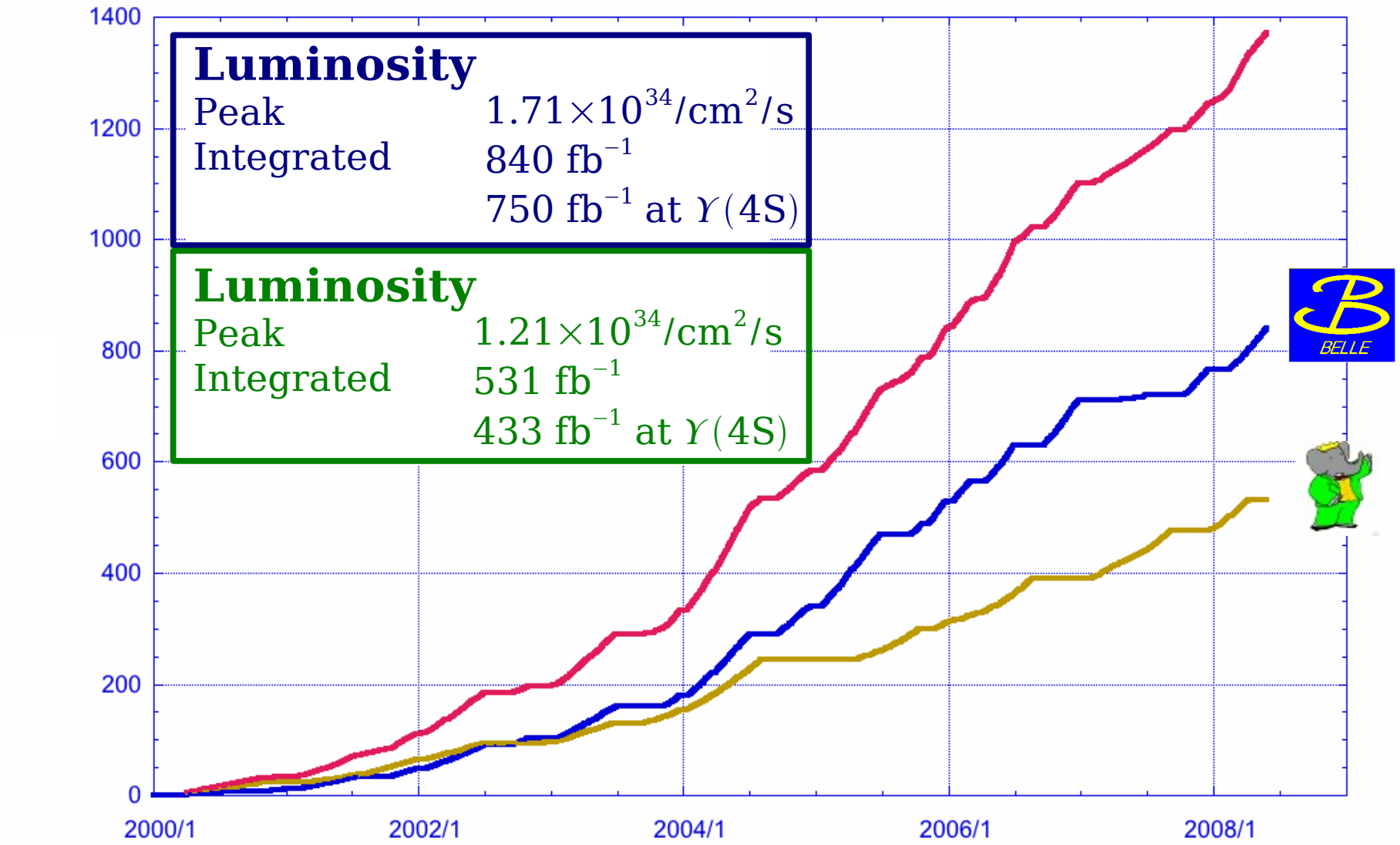
Tree



B factories: BaBar and Belle

Luminosity (fb^{-1})

cumulated stat: $\sim$**1400 fb^{-1} !!**

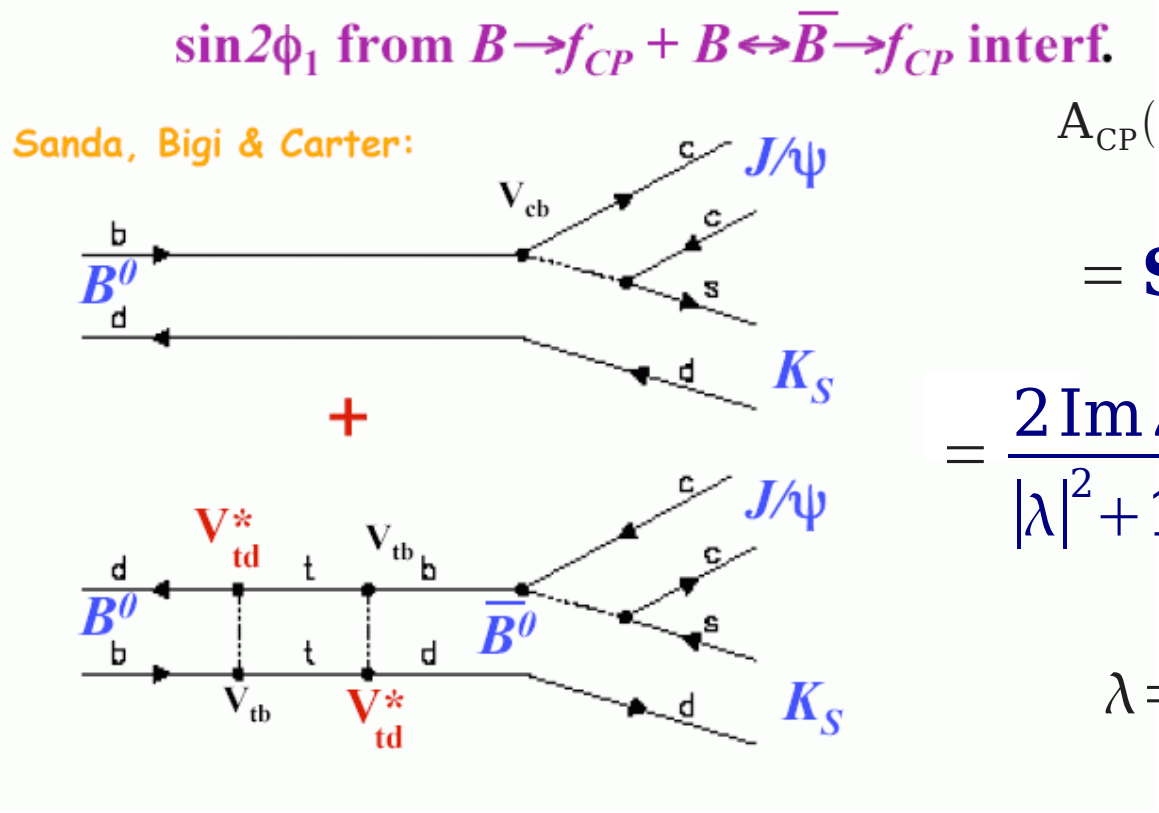


$>$ 250 publications for each experiment

BaBar: $\sim 465 \times 10^6\, B\bar{B}$ pairs = final sample

Belle: $\sim 657 \times 10^6\, B\bar{B}$ pairs = max. current sample (final sample will probably be $\sim 800 \times 10^6\, B\bar{B}$ pairs)

Time−dependent CP asymmetries in decays to CP eigenstates



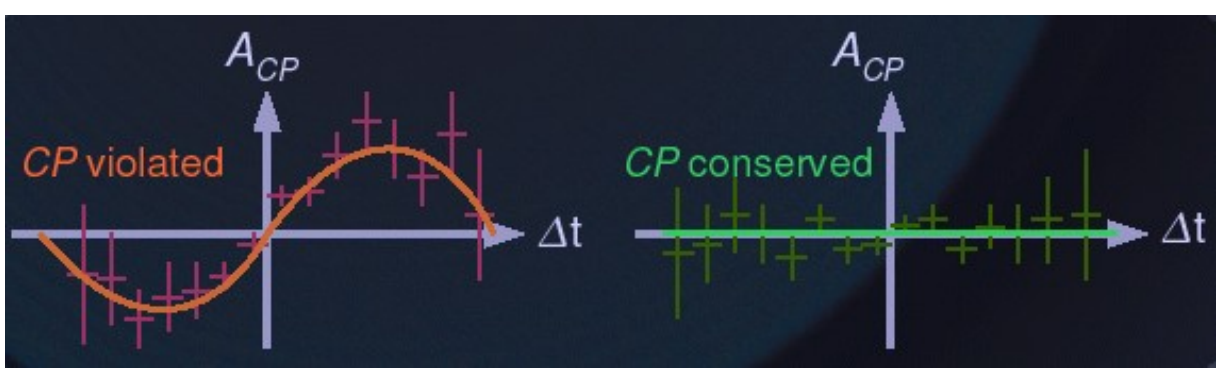
$$A_{CP}(f;t) = \frac{N(\overline{B}^0(t)\to f) - N(B^0(t)\to f)}{N(\overline{B}^0(t)\to f) + N(B^0(t)\to f)}$$

$$= \mathbf{S}\,\sin\Delta m_d t + \mathbf{A}\,\cos\Delta m_d t$$

$$= \frac{2\,\mathrm{Im}\,\lambda}{|\lambda|^2+1}\sin\Delta m_d t + \frac{|\lambda|^2-1}{|\lambda|^2+1}\cos\Delta m_d t$$

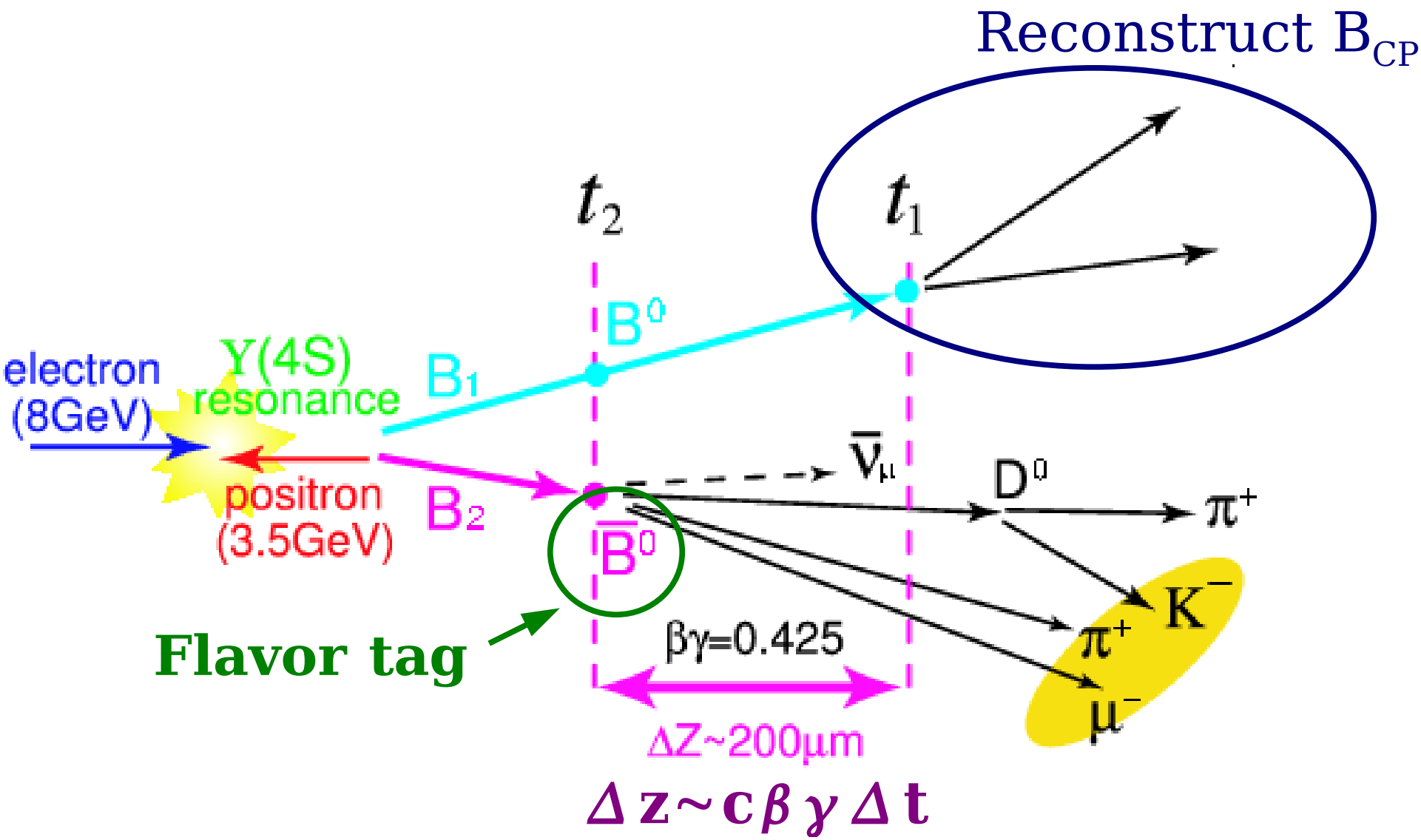
$$\lambda = \frac{q}{p}\,\frac{A(\overline{B}^0\to f)}{A(B^0\to f)} = e^{-i2\phi_i}\,\frac{\overline{A}_f}{A_f}$$

- $\mathbf{A} = 0$ and $\mathbf{S} = -\xi_f \sin 2\beta$ for $(c\bar{c})K_{S/L}$ $(\xi_f = \mp 1)$
- $\mathbf{A} = 0$ and $\mathbf{S} = \sin 2\alpha$ for $\pi^+\pi^-$ (if tree only)



$\mathbf{C} = -\mathbf{A}$

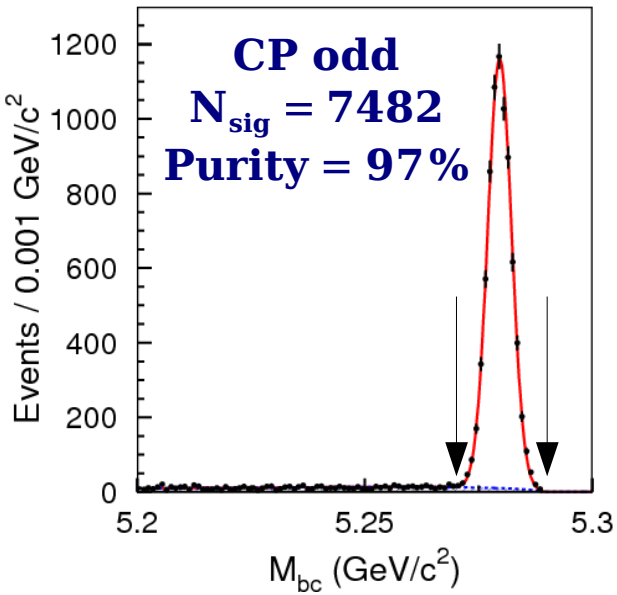
Measuring the CP parameters **S** and **A**

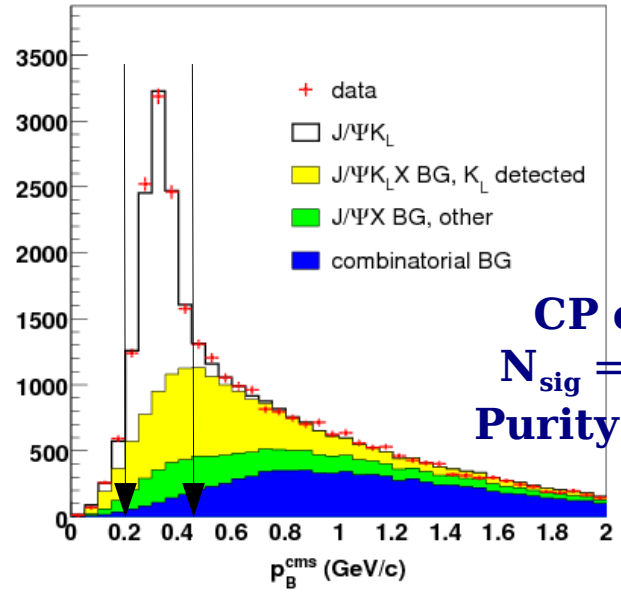


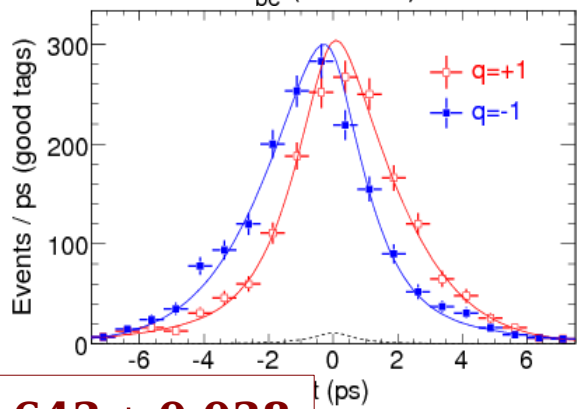
$$\frac{dP_{sig}}{dt}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_B}}{4\tau_B}(1 + q(S\sin(\Delta m_d \Delta t) + A\cos(\Delta m_d \Delta t)))$$

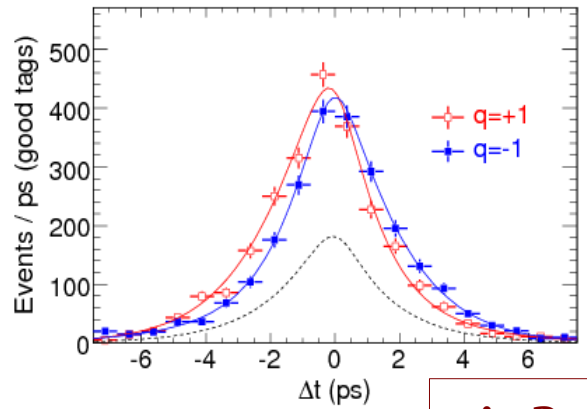
$J/\psi\ K_S$ and $J/\psi\ K_L$

535×10^6 $B\bar{B}$ pairs
[PRL98 (2007) 031802]

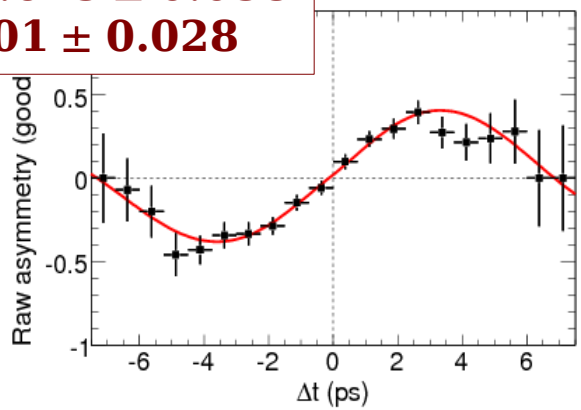




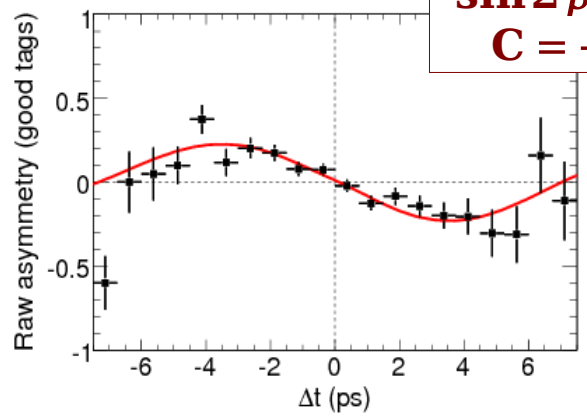




$\sin 2\beta = 0.643 \pm 0.038$
$C = 0.001 \pm 0.028$

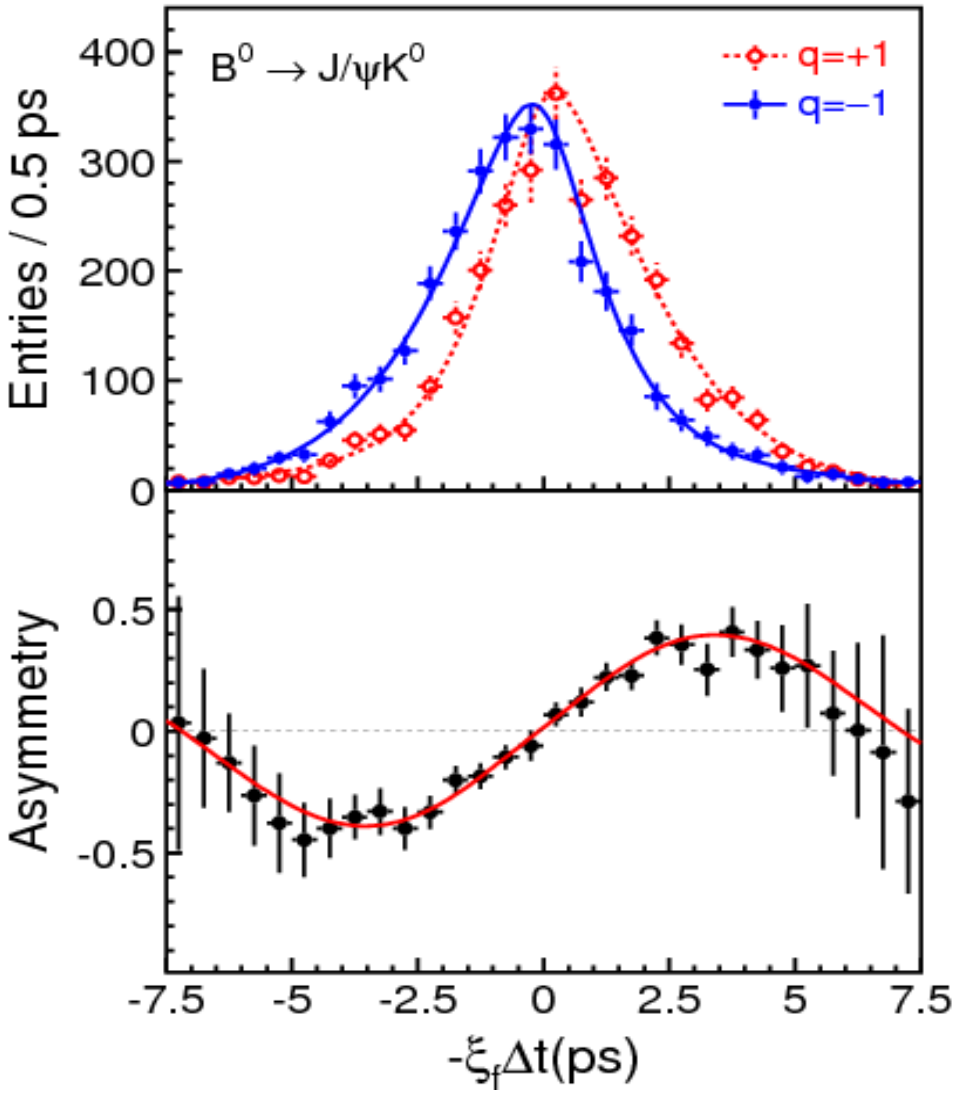


$\sin 2\beta = 0.641 \pm 0.057$
$C = -0.045 \pm 0.033$



$\sin 2\beta$ in $J/\psi K^0$ ...

535×10^6 $B\bar{B}$ pairs
[PRL98 (2007) 031802]



$$\sin 2\beta = 0.642 \pm 0.031 \pm 0.017$$

$$C = -0.018 \pm 0.021 \pm 0.014$$

...and $\psi(2S)K_S$

$\sin 2\beta$ in $\psi(2S)K_S^0$

$\psi(2S) \to l^+ l^-$
$\psi(2S) \to J/\psi\, \pi^+ \pi^-$

657×10^6 $B\bar{B}$ pairs
[PRD77 (2008) 091103]

$$\sin 2\beta = 0.72 \pm 0.09 \pm 0.03$$

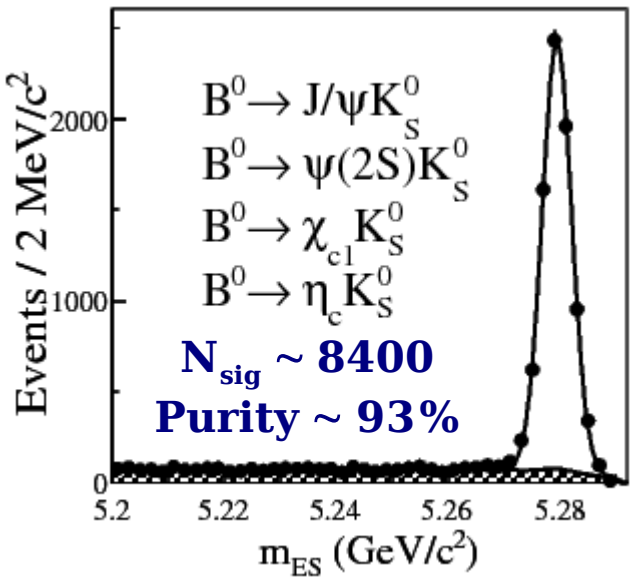
$$C = -0.04 \pm 0.07 \pm 0.05$$

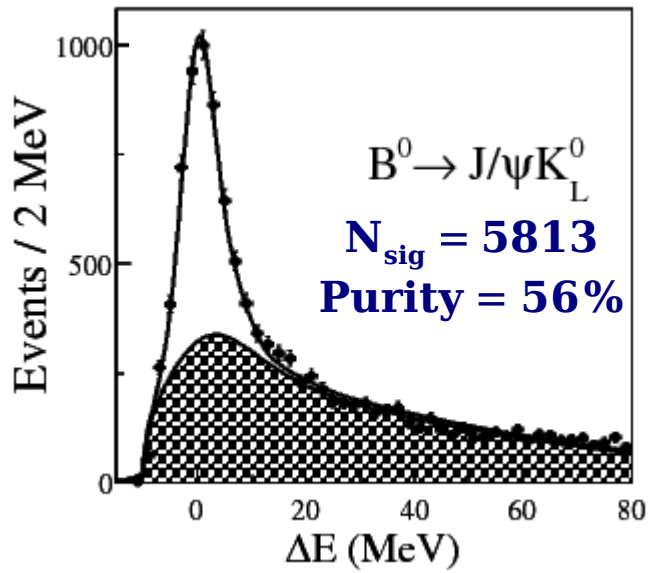
soon other charmonium modes
$\chi_{c1} K_S$, $\eta_c K_S$ ...

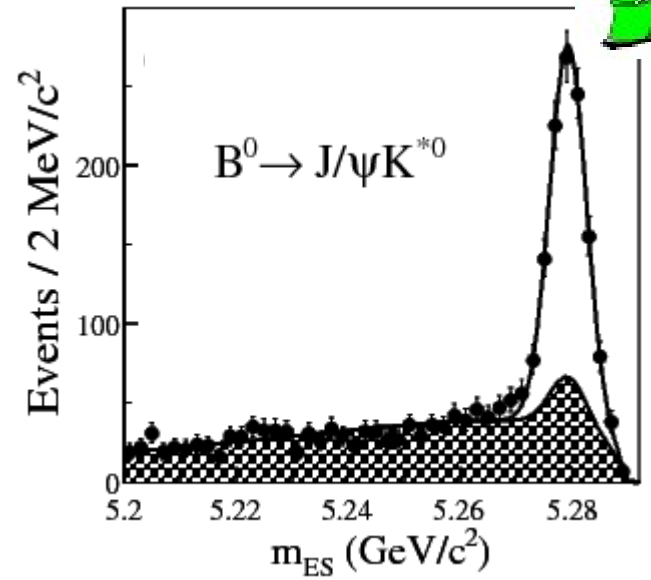
- anchor point of the SM
- still statistically limited !
  irreducible syst ~ 0.013

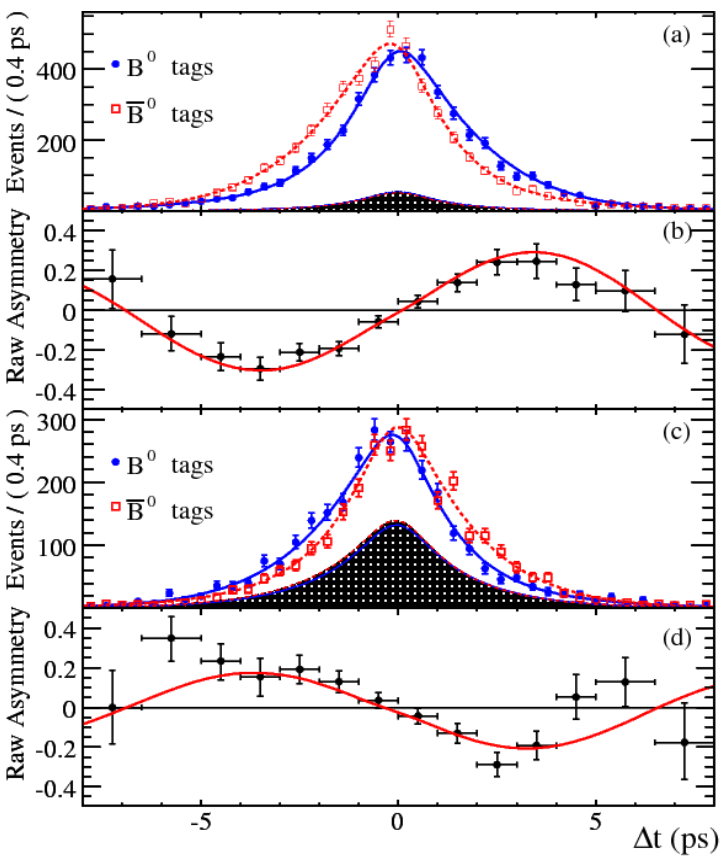
$\sin 2\beta$ in $(c\bar{c})\,K^{(*)0}$

465×10^6 $B\bar{B}$ pairs
[ArXiv:0902.1708]





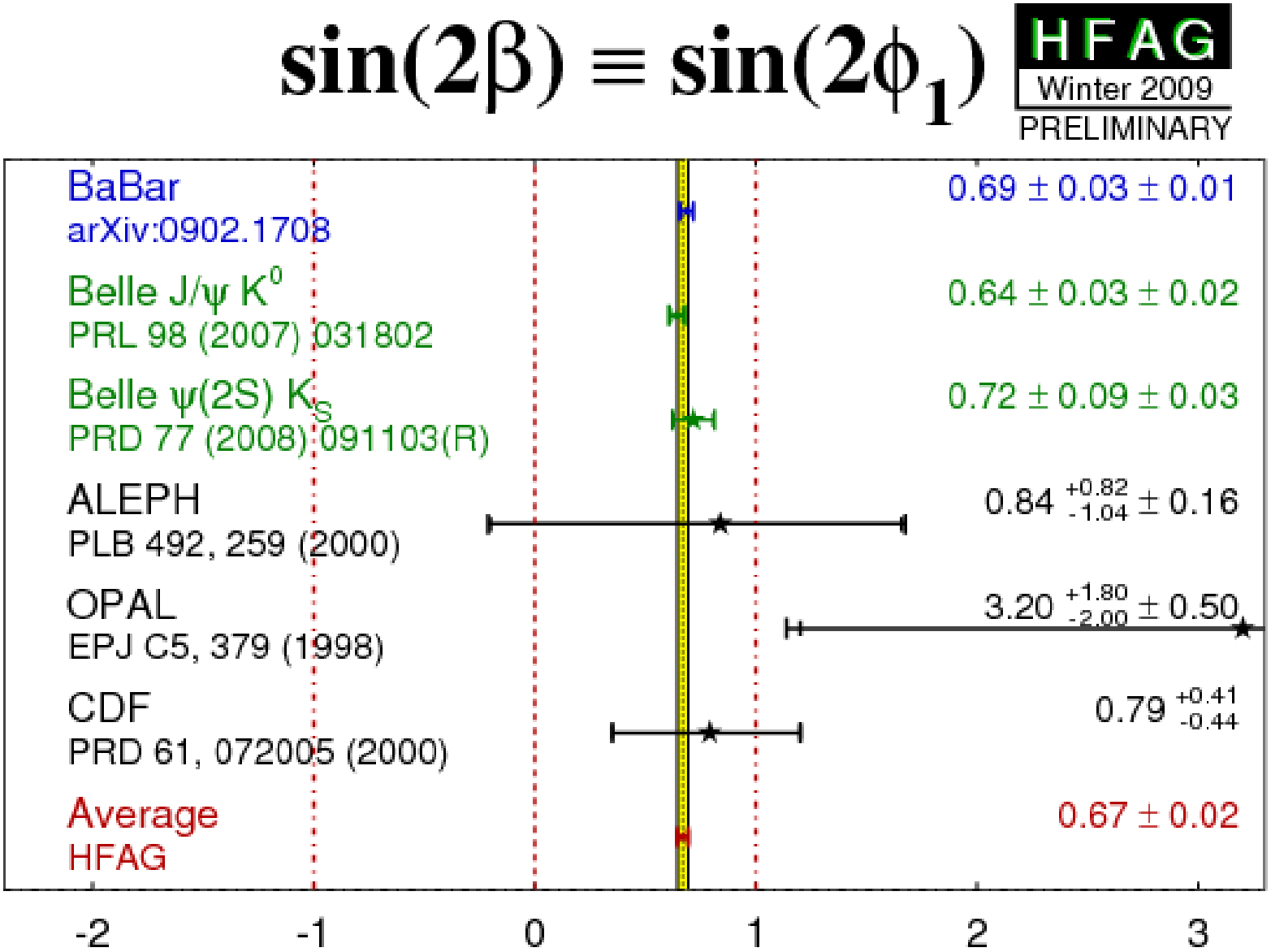




Mode	$\sin 2\beta$
$J/\psi K_S$	$0.657 \pm 0.036 \pm 0.012$
$J/\psi K_L$	$0.694 \pm 0.061 \pm 0.031$
$J/\psi K^0$	**$0.666 \pm 0.031 \pm 0.013$**
$\psi(2S) K_S$	$0.897 \pm 0.100 \pm 0.036$
$\chi_{c1} K_S$	$0.614 \pm 0.160 \pm 0.040$
$\eta_c K_S$	$0.925 \pm 0.160 \pm 0.057$
$J/\psi K^{*0}$	$0.601 \pm 0.239 \pm 0.087$
$c\bar{c} K^{(*)0}$	**$0.687 \pm 0.028 \pm 0.012$**

La raison d'être of the B factories

$$\sin(2\beta) \equiv \sin(2\phi_1)$$

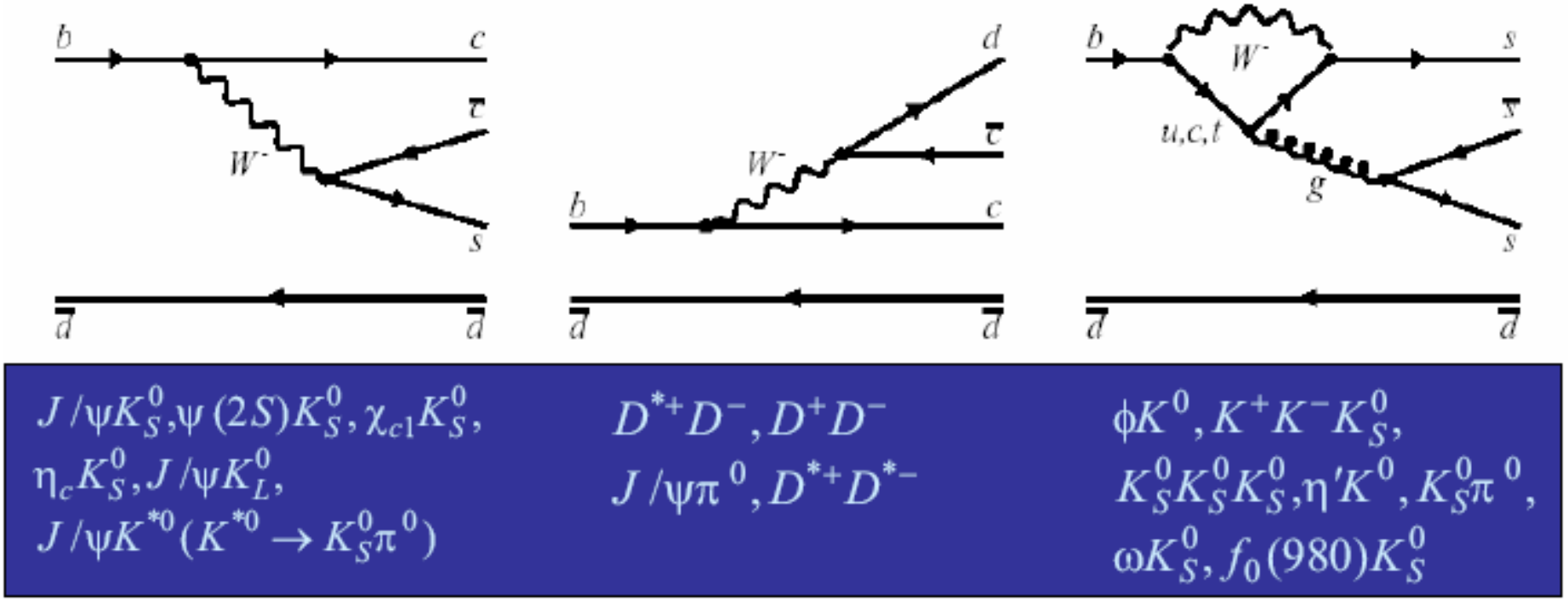


$$\boxed{\beta = (21.0 \pm 0.9)^\circ}$$

What is the source of CP violation ?

The Kobayashi-Maskawa phase is the source

β in other modes



$J/\psi K_S^0, \psi(2S)K_S^0, \chi_{c1}K_S^0,$	$D^{*+}D^-, D^+D^-$	$\phi K^0, K^+K^-K_S^0,$
$\eta_c K_S^0, J/\psi K_L^0,$	$J/\psi\pi^0, D^{*+}D^{*-}$	$K_S^0K_S^0K_S^0, \eta' K^0, K_S^0\pi^0,$
$J/\psi K^{*0}(K^{*0} \to K_S^0\pi^0)$		$\omega K_S^0, f_0(980)K_S^0$

increasing tree diagram amplitude

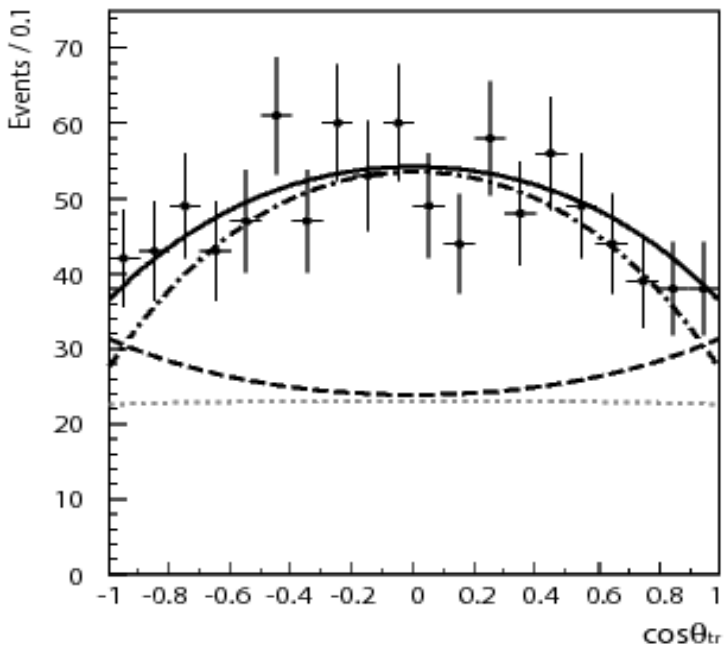
increasing sensitivity to new physics

possible new sources of CPV ?

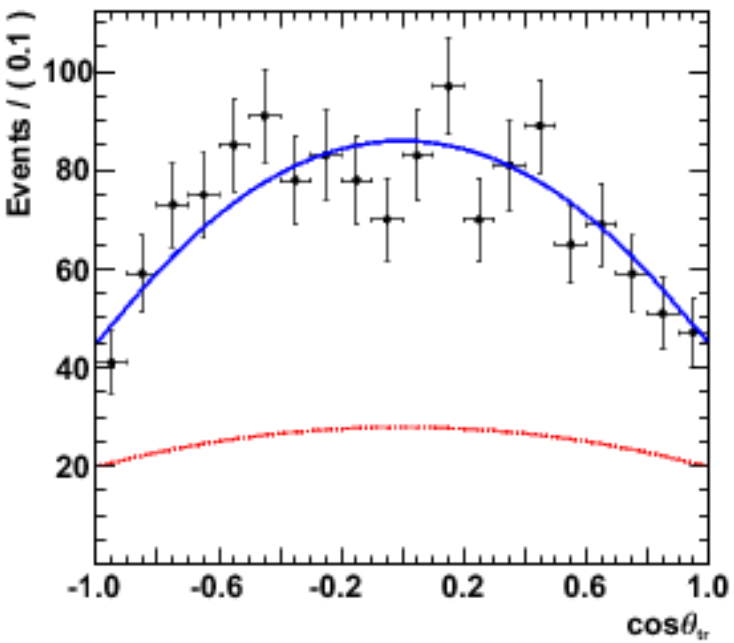
$D^{*+}D^{*-}$

2 vector mesons in the final state: admixture of CP-even and CP-odd states

657×10^6 $B\bar{B}$ pairs
[ArXiv:0901.4057]



467×10^6 $B\bar{B}$ pairs
[PRD79, 032002 (2009)]



CP-odd fraction

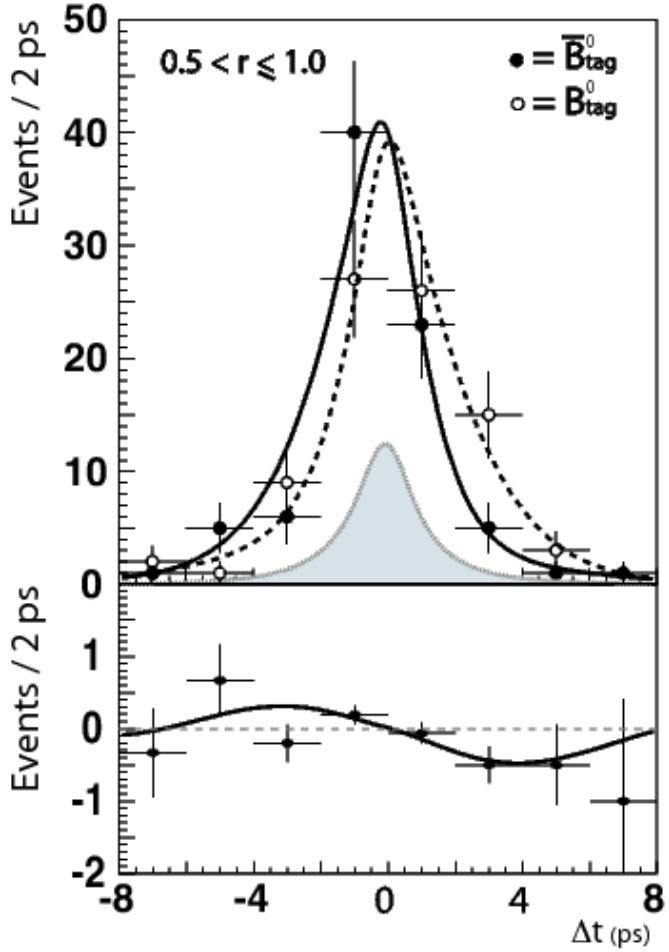
$R_\perp = 0.125 \pm 0.043 \pm 0.023$

$R_\perp = 0.158 \pm 0.028 \pm 0.006$

$D^{*+}D^{*-}$

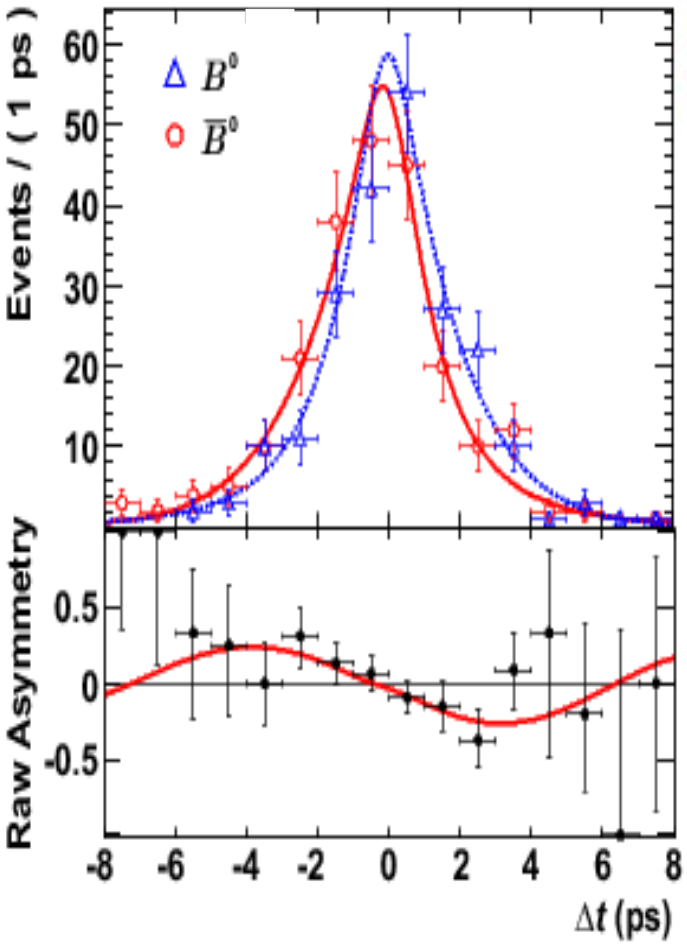
2 vector mesons in the final state: admixture of CP-even and CP-odd states

657×10^6 $B\bar{B}$ pairs
[ArXiv:0901.4057]



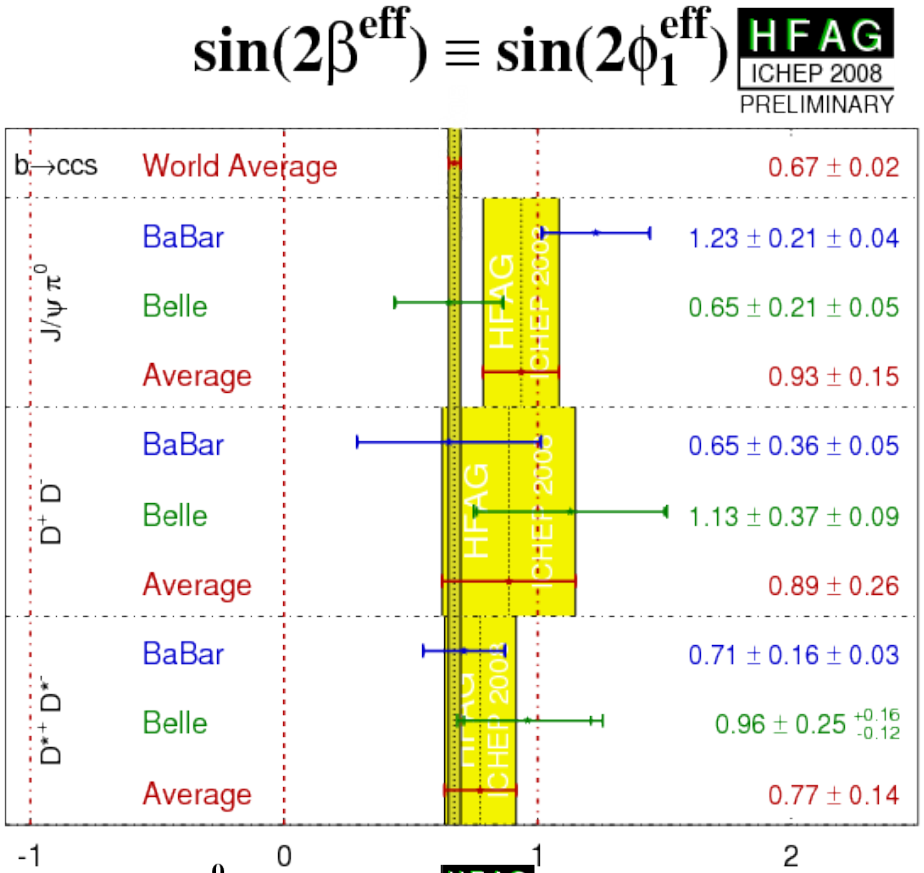
$$C = -0.15 \pm 0.13 \pm 0.04$$
$$S = -0.96 \pm 0.25^{+0.12}_{-0.16}$$

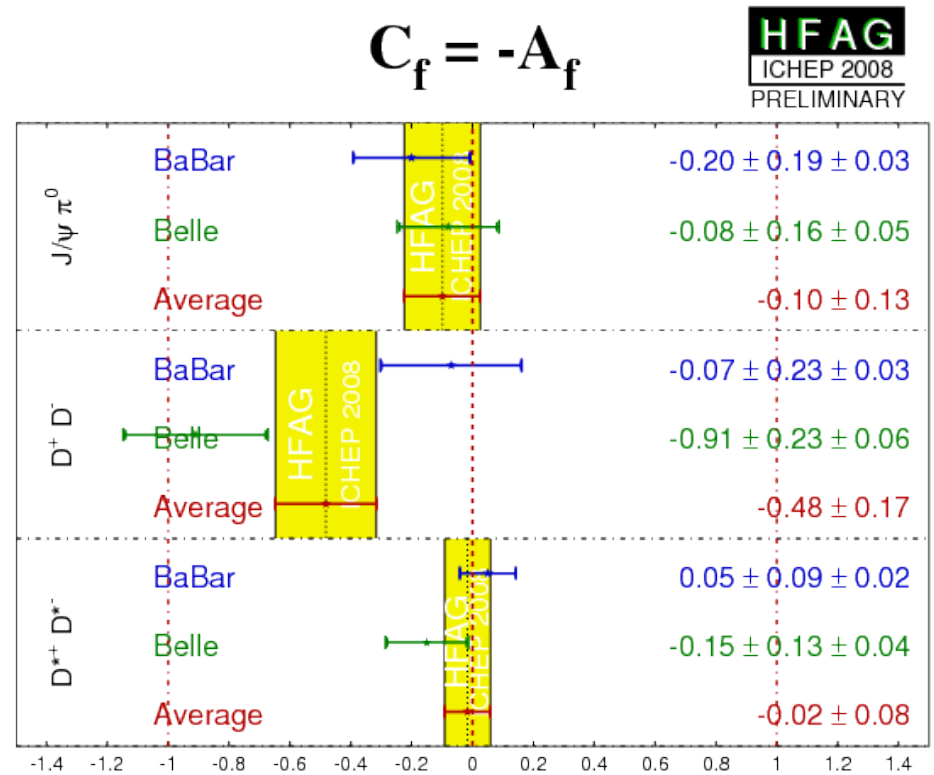
467×10^6 $B\bar{B}$ pairs
[PRD79, 032002 (2009)]

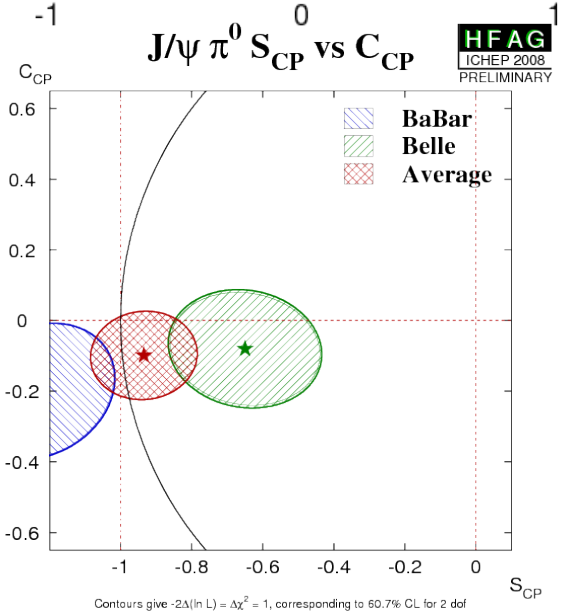


$$C = +0.05 \pm 0.09 \pm 0.02$$
$$S = -0.70 \pm 0.16 \pm 0.03$$

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



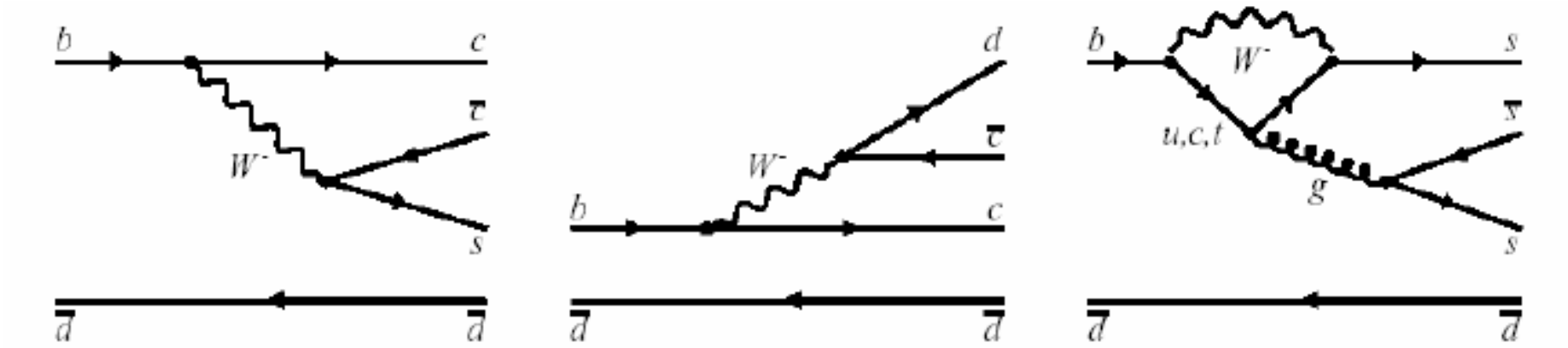




good agreement with $b \to c\bar{c}s$ modes result

$S = -\sin 2\beta, \quad C = 0$

more info needed for C in D^+D^- mode



$J/\psi K_S^0, \psi(2S)K_S^0, \chi_{c1}K_S^0,$	$D^{*+}D^-, D^+D^-$	$\phi K^0, K^+K^-K_S^0,$
$\eta_c K_S^0, J/\psi K_L^0,$	$J/\psi\pi^0, D^{*+}D^{*-}$	$K_S^0K_S^0K_S^0, \eta' K^0, K_S^0\pi^0,$
$J/\psi K^{*0}(K^{*0}\to K_S^0\pi^0)$		$\omega K_S^0, f_0(980)K_S^0$

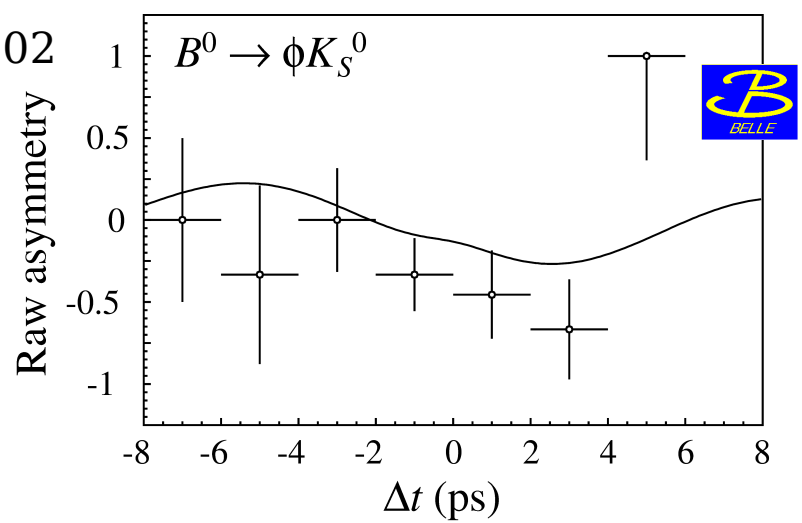
increasing tree diagram amplitude

increasing sensitivity to new physics

first reported in Moriond EW 2002

''$\sin 2\beta$'' $= -0.73 \pm 0.64 \pm 0.22$

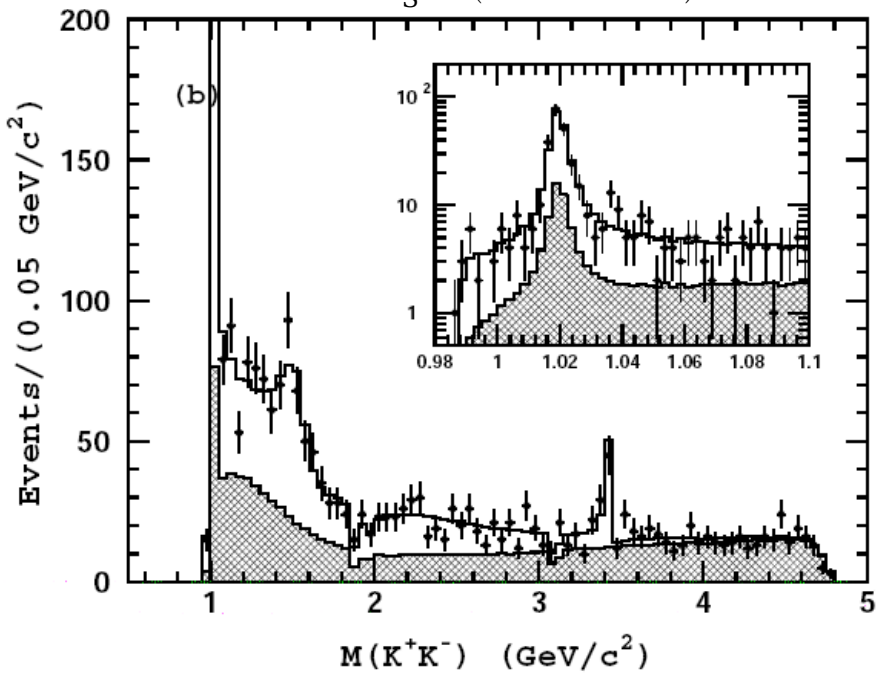
[PRD 67, 031102 (2003)]



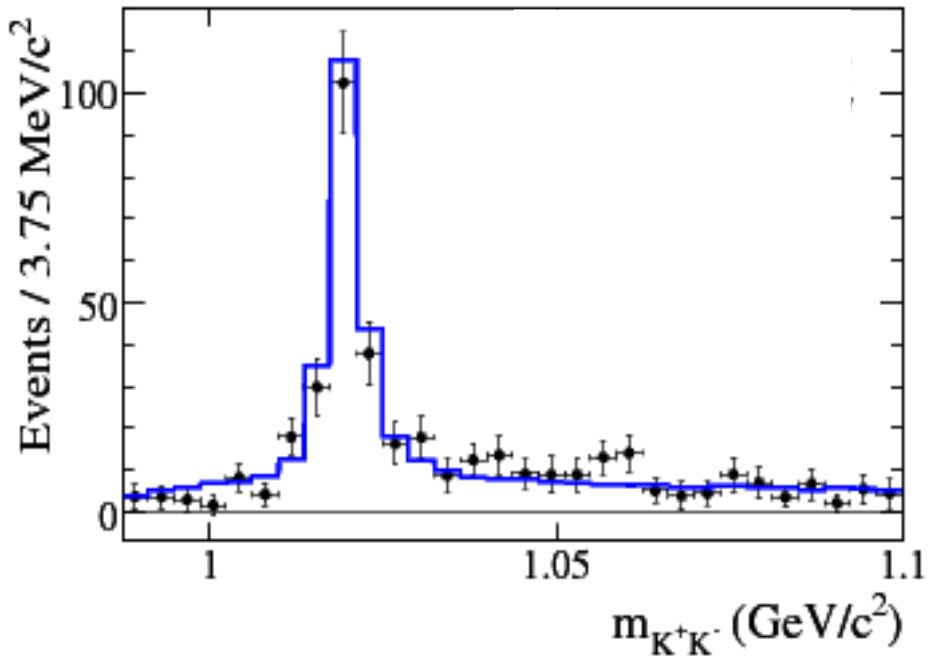
Time-dependent Dalitz plot analysis $K_S K^+ K^-$

657×10^6 $B\bar{B}$ pairs [ICHEP 08]

$N_S = (1269 \pm 51)$ evts



465×10^6 $B\bar{B}$ pairs [ArXiv:0808.0700]



ϕK_S

$$\beta_{eff} = (21.2\,^{+9.8}_{-10.4} \pm 2.0 \pm 2.0)^\circ$$
$$A_{CP} = +0.31\,^{+0.21}_{-0.23} \pm 0.04 \pm 0.09$$

$$\beta_{eff} = (7.7 \pm 7.7 \pm 0.9)^\circ$$
$$A_{CP} = +0.14 \pm 0.19 \pm 0.02$$

$f_0(980) K_S$

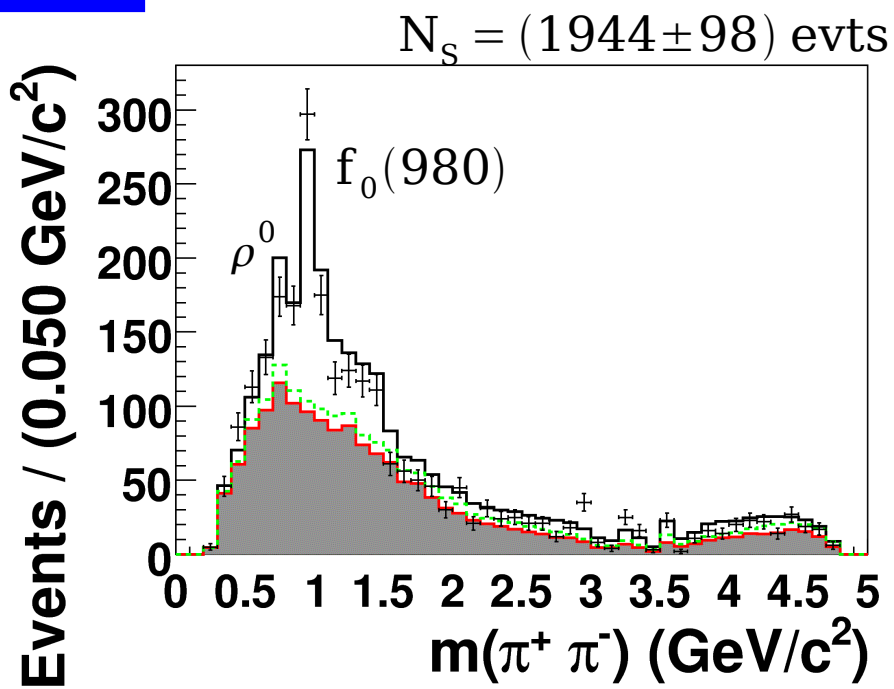
$$\beta_{eff} = (28.2\,^{+9.9}_{-9.8} \pm 2.0 \pm 2.0)^\circ$$
$$A_{CP} = -0.02 \pm 0.34 \pm 0.08 \pm 0.09$$

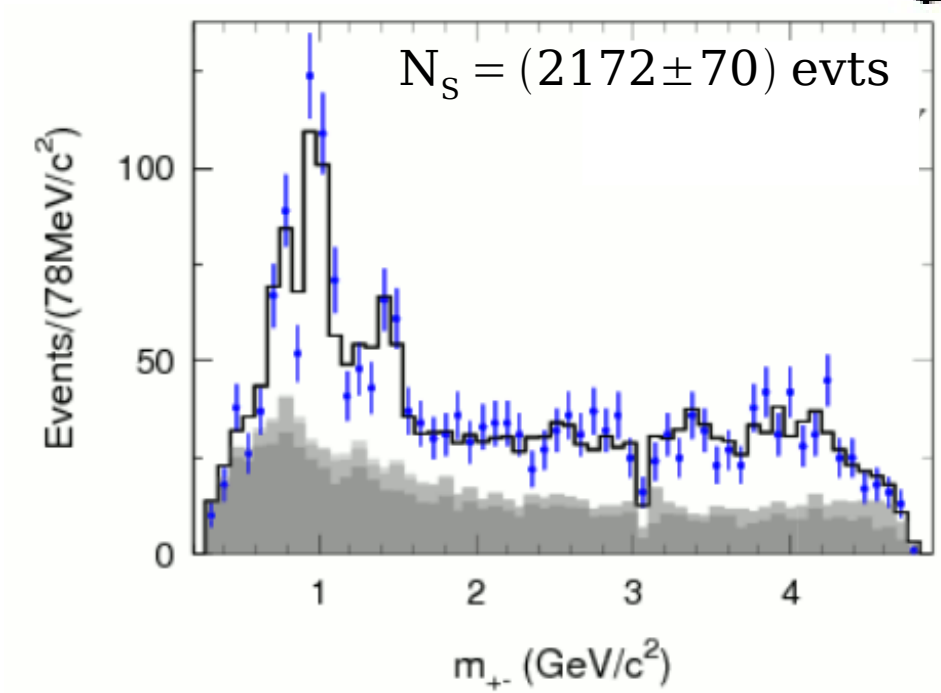
$$\beta_{eff} = (8.5 \pm 7.5 \pm 1.8)^\circ$$
$$A_{CP} = +0.01 \pm 0.26 \pm 0.07$$

Time-dependent Dalitz plot analysis $K_S \pi^+ \pi^-$

657×10^6 $B\bar{B}$ pairs
[ArXiv:0811.3665]

383×10^6 $B\bar{B}$ pairs
[ArXiv:0708.2097]





$\rho^0 K_S$

$$\beta_{\rm eff} = (20.0\,^{+8.6}_{-8.5} \pm 3.2 \pm 3.5)^\circ$$
$$A_{CP} = +0.03\,^{+0.23}_{-0.24} \pm 0.11 \pm 0.10$$

$$\beta_{\rm eff} = (19\,^{+10}_{-9} \pm 3 \pm 3)^\circ$$
$$A_{CP} = -0.02 \pm 0.27 \pm 0.08 \pm 0.06$$

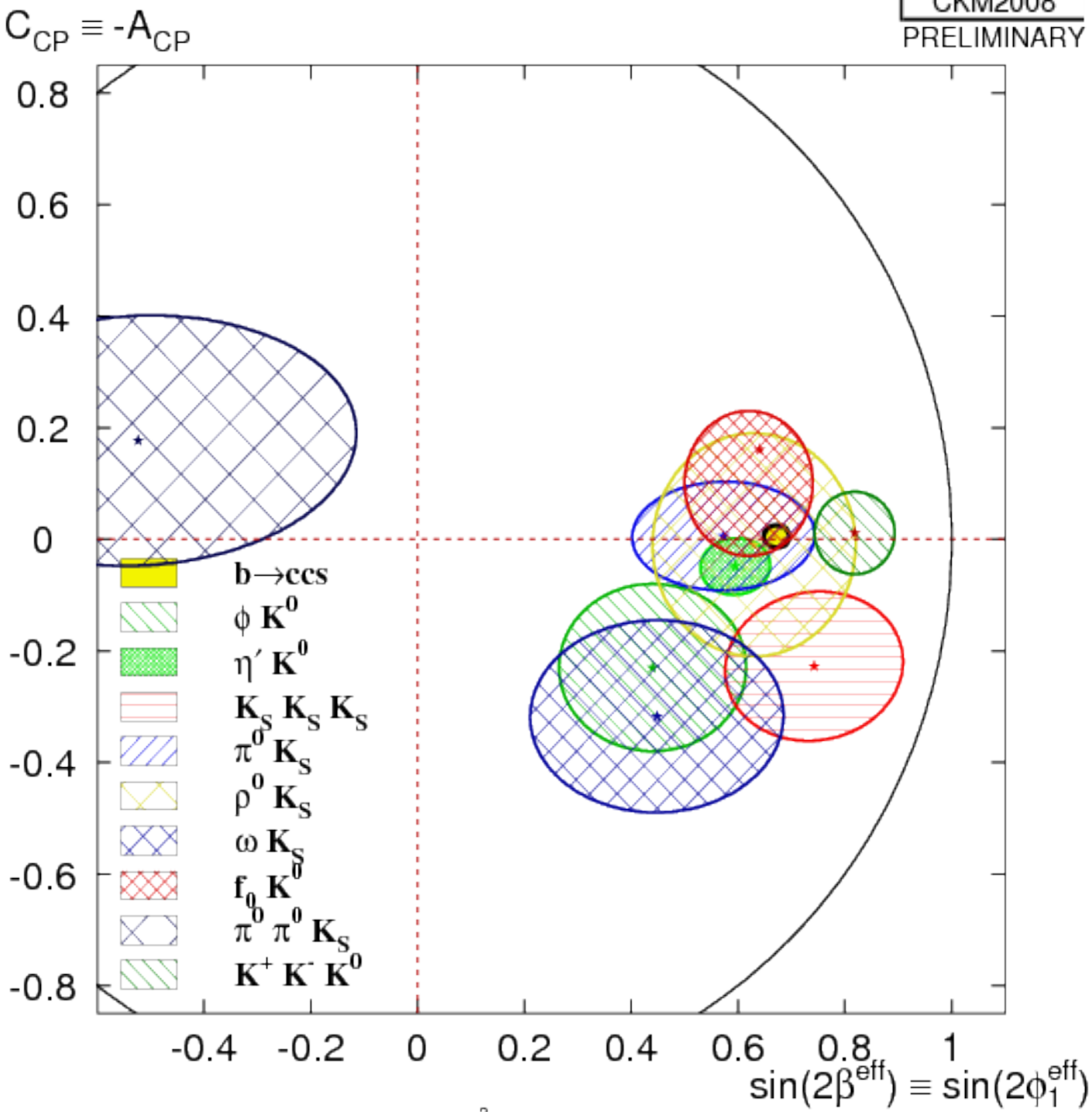
$f_0(980) K_S$

$$\beta_{\rm eff} = (12.7\,^{+6.9}_{-6.5} \pm 2.8 \pm 3.3)^\circ$$
$$A_{CP} = -0.06 \pm 0.17 \pm 0.07 \pm 0.09$$

$$\beta_{\rm eff} = (44\,^{+11}_{-10} \pm 3 \pm 4)^\circ$$
$$A_{CP} = -0.35 \pm 0.27 \pm 0.07 \pm 0.04$$

$\sin(2\beta^{eff}) \equiv \sin(2\phi_1^{eff})$ vs $C_{CP} \equiv -A_{CP}$

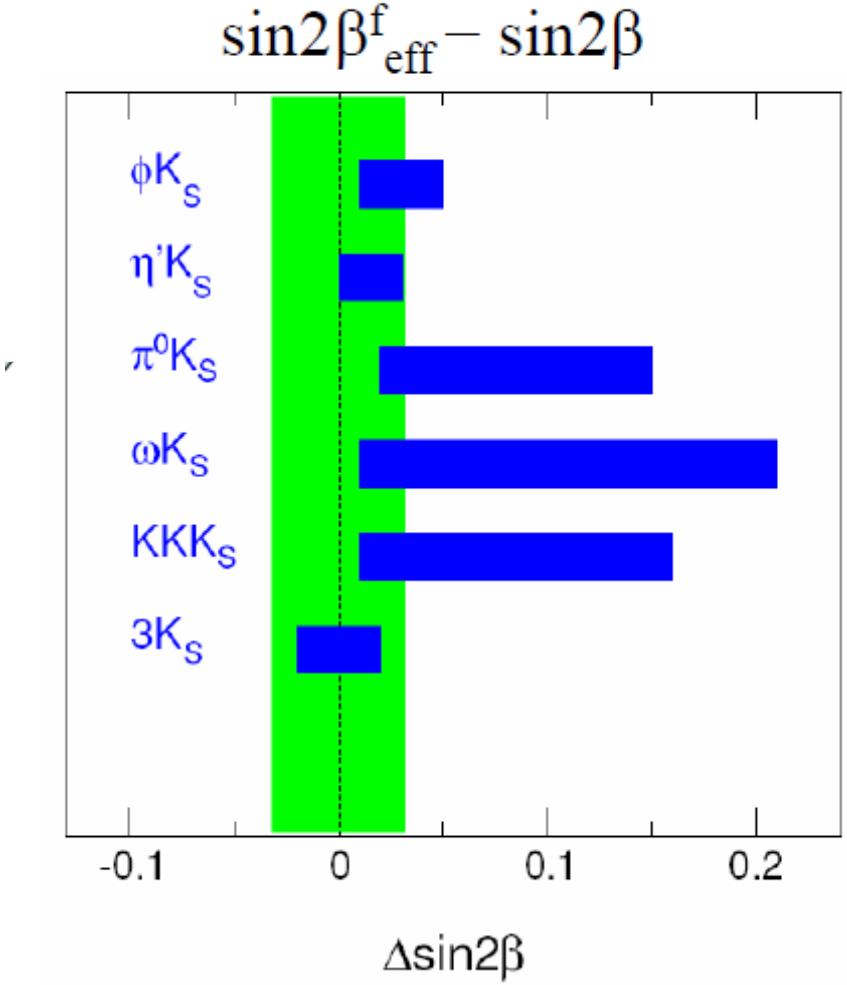
HFAG
CKM2008
PRELIMINARY



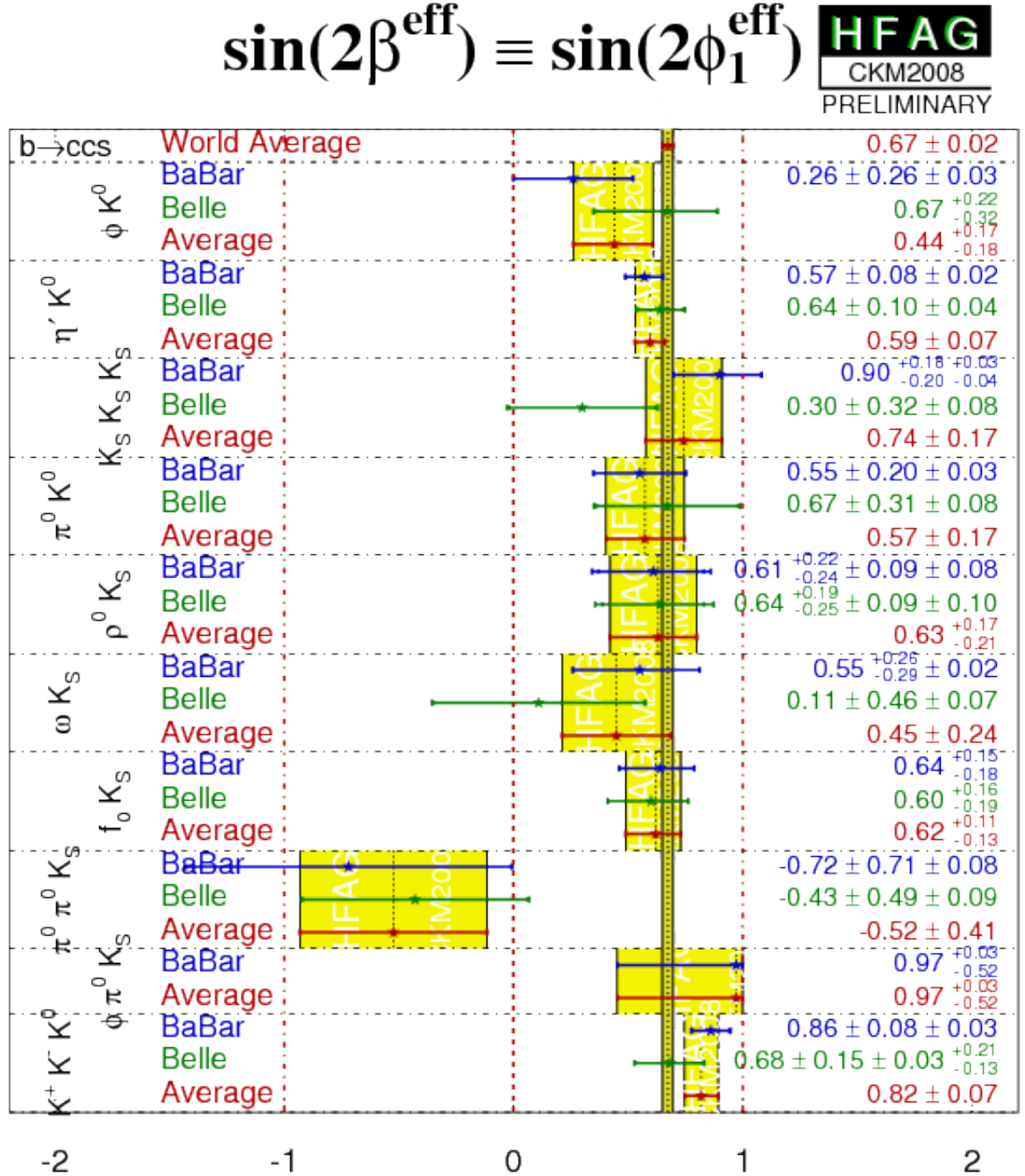
Contours give $-2\Delta(\ln L) = \Delta\chi^2 = 1$, corresponding to 60.7% CL for 2 dof

β with b→s penguins

some of recent QCDF estimates



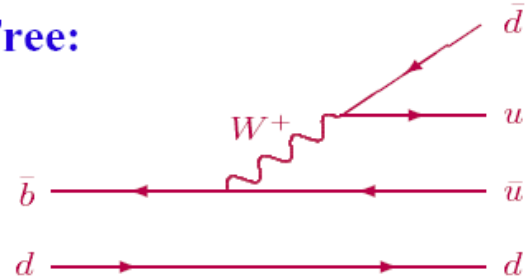
$$\sin(2\beta^{eff}) \equiv \sin(2\phi_1^{eff})$$



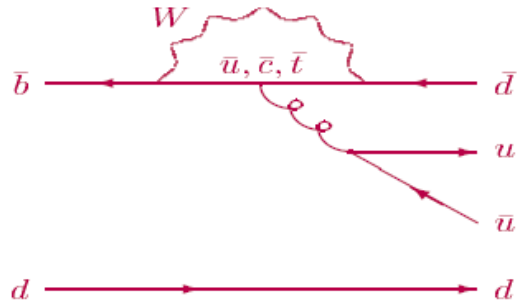
More statistics crucial
for mode-by-mode studies

α determination

Tree:



Penguin:



$$A(B^0 \to \pi^+\pi^-) = T\, e^{i\gamma} + P\, e^{i\delta}$$

$$\begin{aligned} A(t) &= S_{\pi^+\pi^-} \sin(\Delta m t) - C_{\pi^+\pi^-} \cos(\Delta m t) \\ &= \sqrt{1 - A^2_{\pi^+\pi^-}}\, \sin 2\alpha_{eff} \sin(\Delta m t) - C_{\pi^+\pi^-} \cos(\Delta m t) \end{aligned}$$

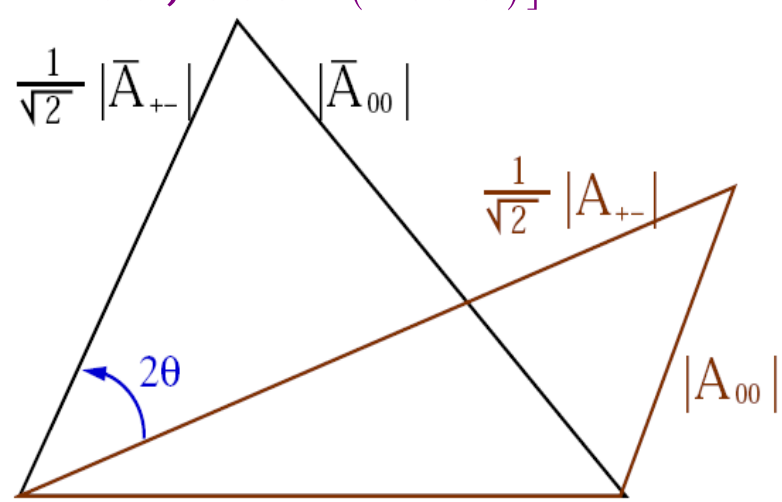
from time dependent CP, we can measure α_{eff}, but we want α !

$$\mathbf{S}_{\pi^+\pi^-} = \mathbf{\sin 2\alpha} + 2r\cos\delta \sin(\beta+\alpha)\cos 2\alpha + O(r^2) \qquad r = P/T$$

Isospin analysis [Gronau-London, PRL65, 3381 (1990)]

$$A_{+-} + \sqrt{2}A_{00} = \sqrt{2}A_{+0}$$
$$\bar{A}_{+-} + \sqrt{2}\bar{A}_{00} = \sqrt{2}\bar{A}_{+0}$$

α can be resolved up to an 8−fold ambiguity



A_{+0} pure tree $\quad |\bar{A}_{+0}| = |A_{+0}|$

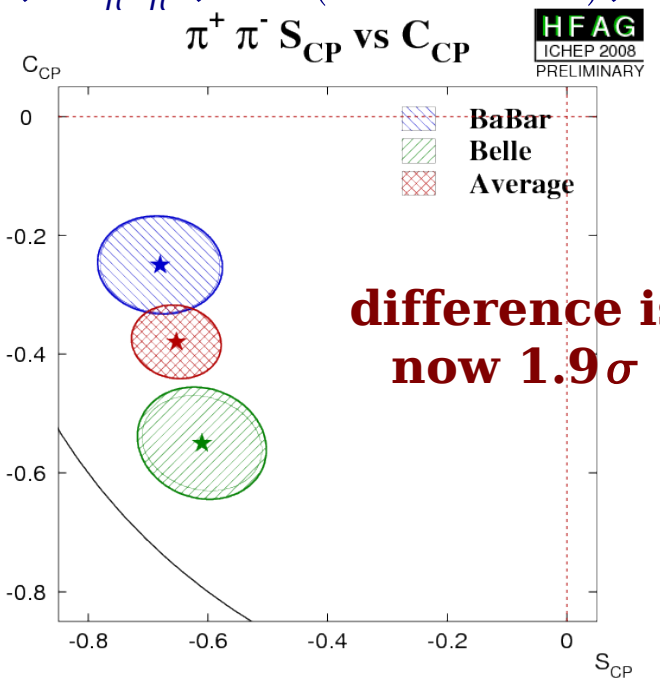
$\underline{\alpha}$: $\pi\pi$ system (6 observables for 6 parameters)

$\mathrm{Br}(B\to\pi^+\pi^-)$, $S_{\pi^+\pi^-}$, $C_{\pi^+\pi^-}$, $\mathrm{Br}(B\to\pi^+\pi^0)$, $\mathrm{Br}(B\to\pi^0\pi^0)$, $C_{\pi^0\pi^0}$

535×10^6 $B\overline{B}$ pairs
PRL 98, 221801 (2007)

$$C = -0.55 \pm 0.08 \pm 0.05$$
$$S = -0.61 \pm 0.10 \pm 0.04$$

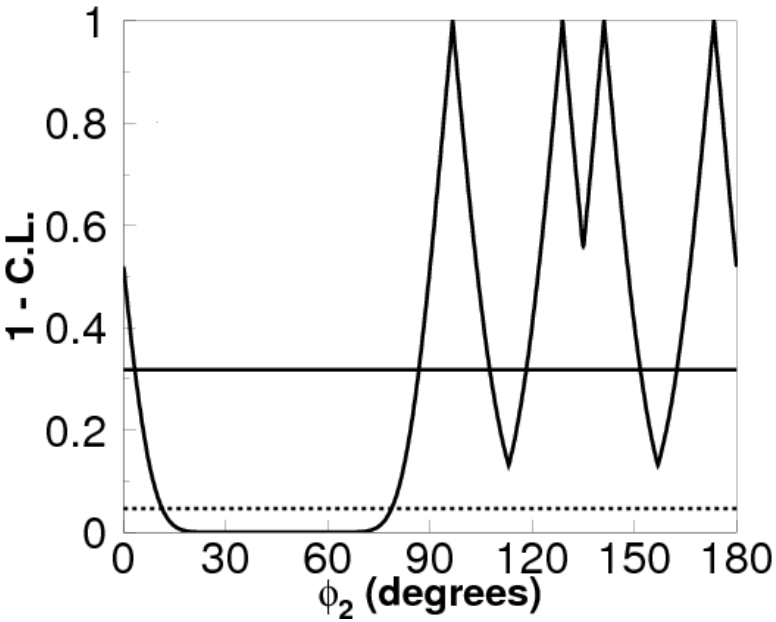
direct CPV @ 5.5σ



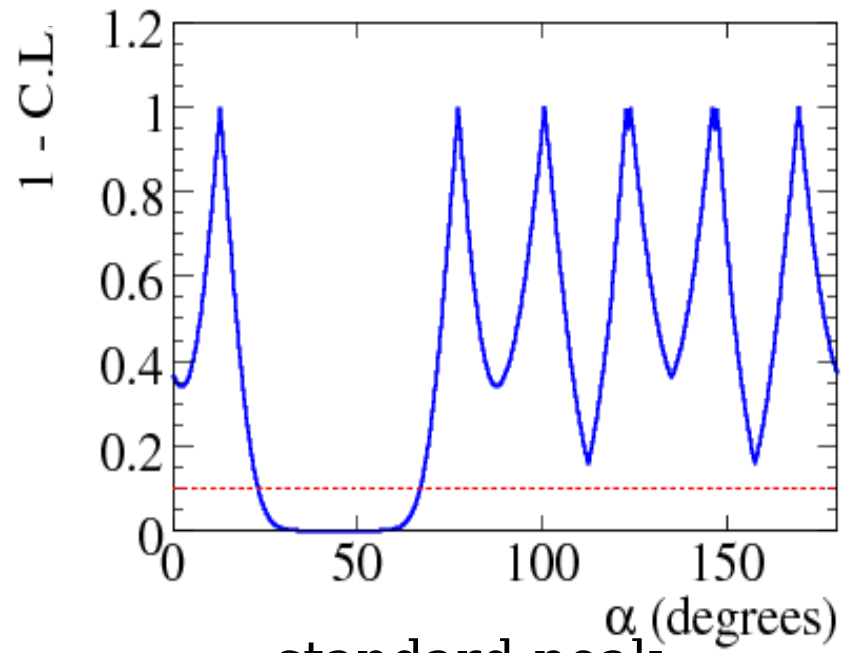
difference is now 1.9σ

467×10^6 $B\overline{B}$ pairs
ArXiv:0807.4226

$$C = -0.25 \pm 0.08 \pm 0.02$$
$$S = -0.68 \pm 0.10 \pm 0.03$$



standard peak
$[86^\circ, 108^\circ]$ @ 68% C.L.

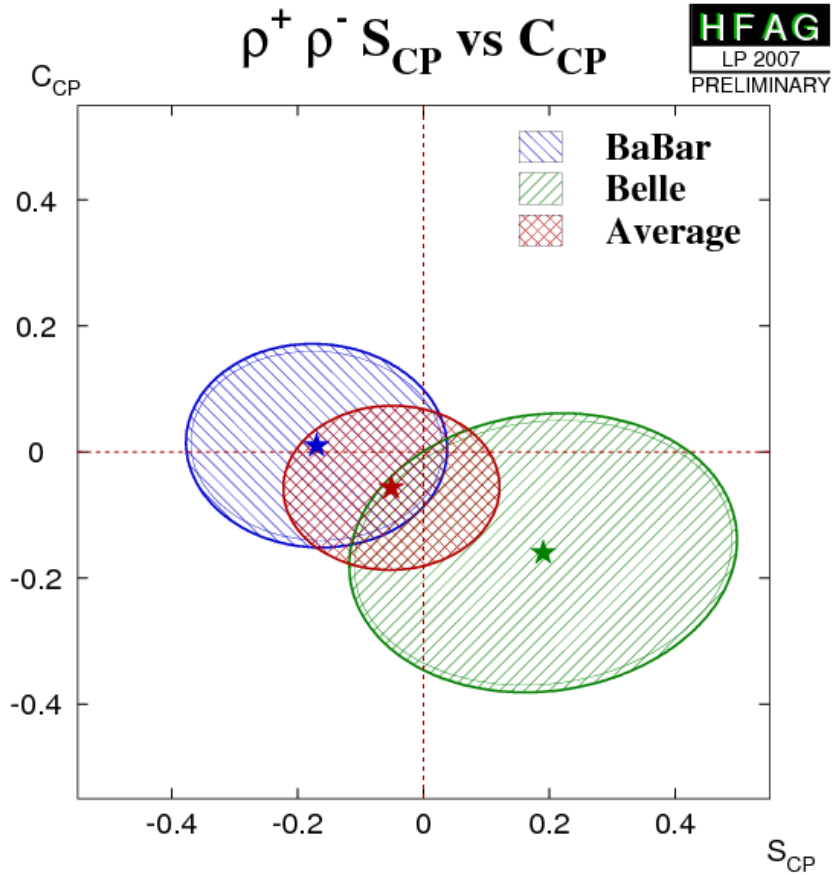


standard peak
$[71^\circ, 109^\circ]$ @ 68% C.L.

$\rho\rho$ system (5 observables for 6 parameters)

$(\mathrm{Br}(B\to\rho^+\rho^-),\ S_{\rho^+\rho^-},\ C_{\rho^+\rho^-},\ \mathrm{Br}(B\to\rho^+\rho^0),\mathrm{Br}(B\to\rho^0\rho^0)) + f_L$

$\rho^+\rho^-$: ~ 100% longitudinally polarized (similar isospin analysis)



387×10^6 $B\bar{B}$ pairs
PRD76, 052007(R)(2007)

$C = +0.01 \pm 0.15 \pm 0.06$

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

535×10^6 $B\bar{B}$ pairs
PRD76, 011104(R)(2007)

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

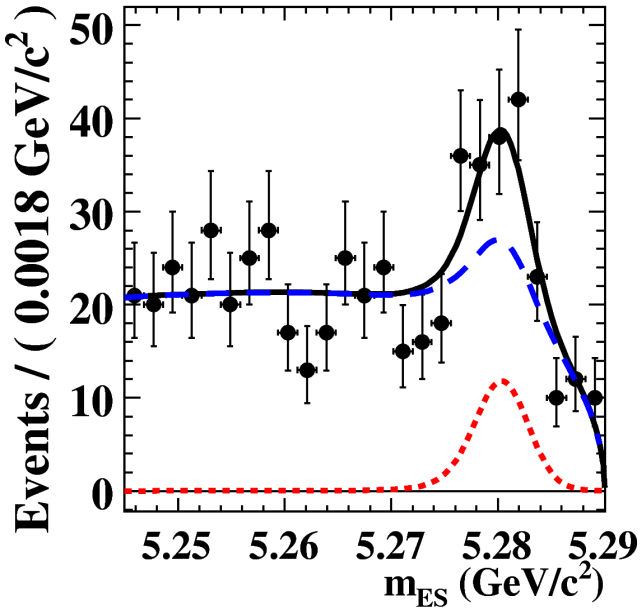
$S = +0.19 \pm 0.30 \pm 0.07$

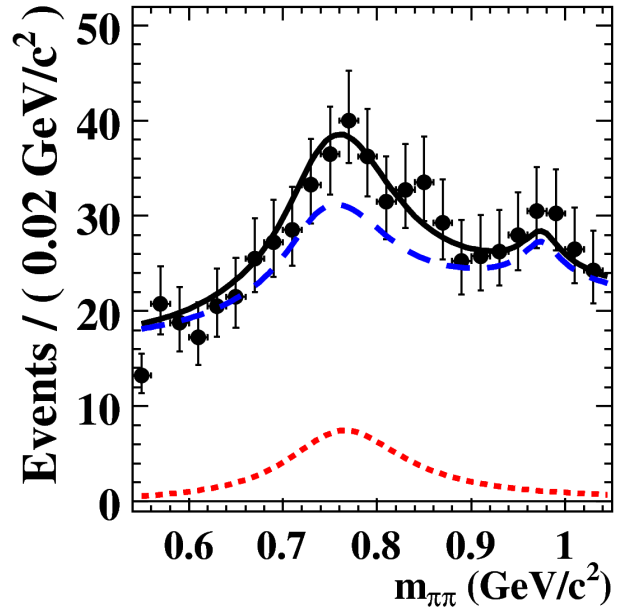
$\rho^0\rho^0$ mode

465×10^6 $B\bar{B}$ pairs
[PRD78, 071104(R)]

10-dim fit to extract yields, f_L, C_L^{00}, S_L^{00}:

$$N_S(\rho^0\rho^0) = 99^{+35}_{-34} \pm 15$$
$$(\Sigma = 3.1\ \sigma)$$





$$\mathrm{Br}(B^0 \to \rho^0\rho^0) = (0.92 \pm 0.32 \pm 0.14) \times 10^{-6}$$

$$N_S(\rho^0\pi^+\pi^-) = -12^{+39}_{-35} \pm 52$$
$$\mathrm{Br}(B^0 \to \rho^0\pi^+\pi^-) < 8.7 \times 10^{-6} \text{ @ } 90\%\text{C.L.}$$

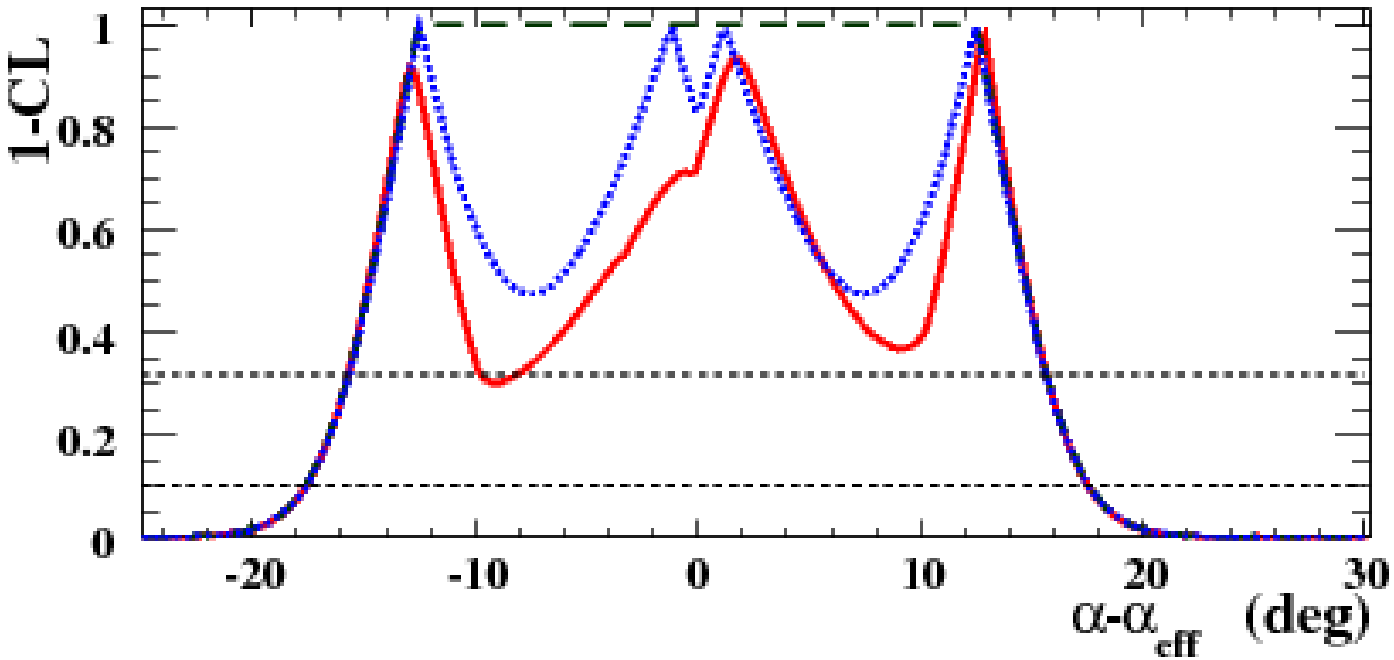
$$N_S(4\pi^\pm) = 8^{+30}_{-25} \pm 6$$
$$\mathrm{Br}(B^0 \to 4\pi^\pm) < 21.1 \times 10^{-6} \text{ @ } 90\%\text{C.L.}$$

$\rho^0\rho^0$ mode

465×10^6 $B\bar{B}$ pairs
[PRD78, 071104(R)]

$$f_L = 0.75^{+0.11}_{-0.14} \pm 0.04$$

$$S_L^{00} = 0.3 \pm 0.7 \pm 0.2 \quad C_L^{00} = 0.2 \pm 0.8 \pm 0.3$$



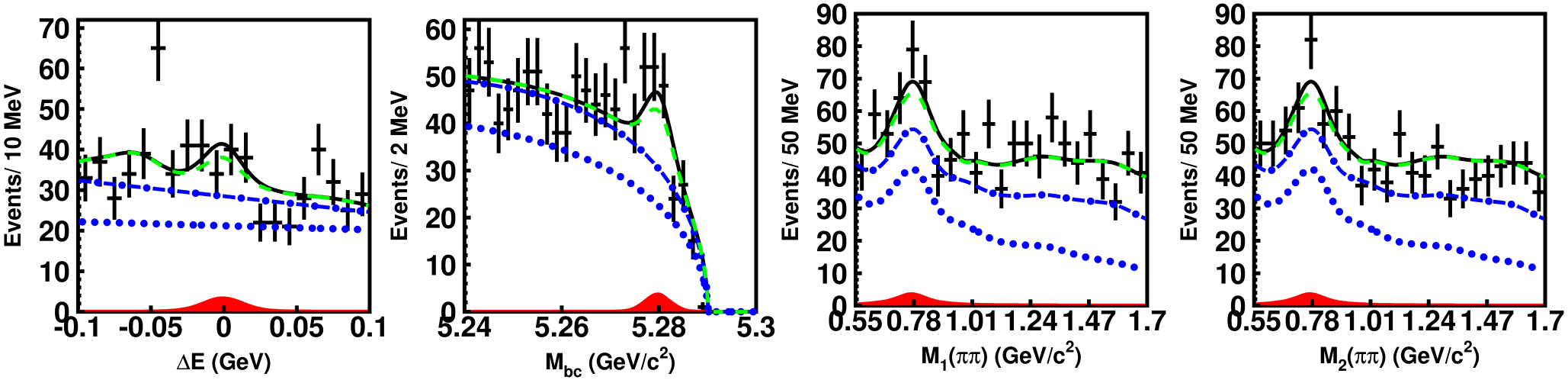
with C^{00}

with C^{00} & S^{00}

$\rho^0\rho^0$ mode

657×10^6 $B\bar{B}$ pairs
[PRD78, 111102(R)]

4-dim (ΔE, M_{bc}, $M_{\pi\pi}$, $M_{\pi\pi}$) fit:



$N_S(\rho^0\rho^0) = 24.5^{+23.6\,+10.1}_{-22.1\,-16.2}$ $(\Sigma = 1.0\ \sigma)$

$$\mathrm{Br}(B^0\to\rho^0\rho^0) < 1.0\times10^{-6}\ @\ 90\%\,\mathrm{C.L.}$$
$$= (0.4\pm0.4^{+0.2}_{-0.3})\times10^{-6}$$

$N_S(\rho^0\pi^+\pi^-) = 113^{+67}_{-66}\pm52$ $(\Sigma = 1.3\ \sigma)$

$\mathrm{Br}(B^0\to\rho^0\pi^+\pi^-) < 12.0\times10^{-6}$ @ 90%C.L.
$= (5.9^{+3.5}_{-3.4}\pm2.7)\times10^{-6}$

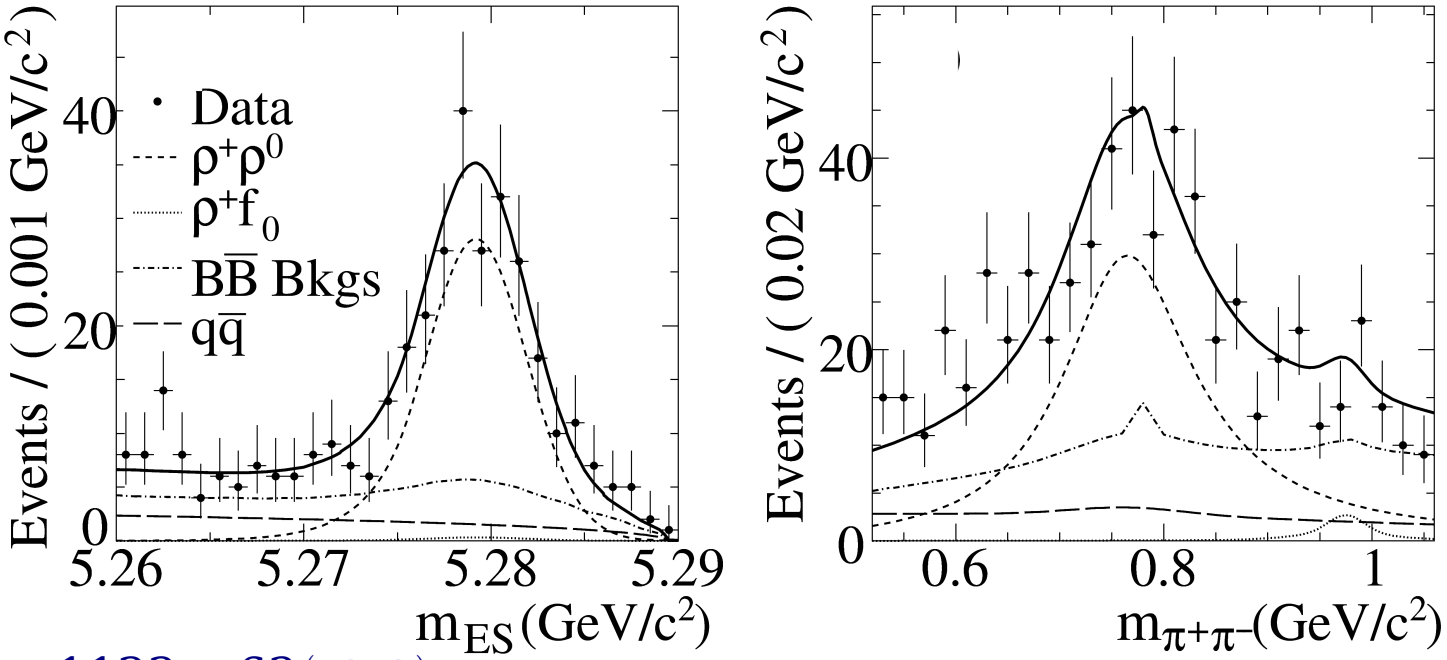
$N_S(4\pi^\pm) = 161^{+61\,+28}_{-59\,-25}$ $(\Sigma = 2.5\ \sigma)$

$\mathrm{Br}(B^0\to4\pi^\pm) < 19.3\times10^{-6}$ @ 90%C.L.
$= (12.4^{+4.7+2.1}_{-4.6-1.9})\times10^{-6}$

$\mathrm{Br}(\rho^0\rho^0)$ is small ! SU(2) triangle even more squashed

$\rho^+\rho^0$ mode

465×10^6 $B\bar{B}$ pairs
[ArXiv:0901.3522]



$N_S(\rho^+\rho^0) = 1122 \pm 63(\text{stat})$

$$\mathrm{Br}(B^+ \to \rho^+\rho^0) = (23.7 \pm 1.4 \pm 1.4) \times 10^{-6}$$

$$f_L = 0.950 \pm 0.015 \pm 0.006$$

Previous results:

232×10^6 $B\bar{B}$ pairs [PRL97, 261801 (2006)]

$\mathrm{Br}(B^+ \to \rho^+\rho^0) = (16.8 \pm 2.2 \pm 2.3) \times 10^{-6}$

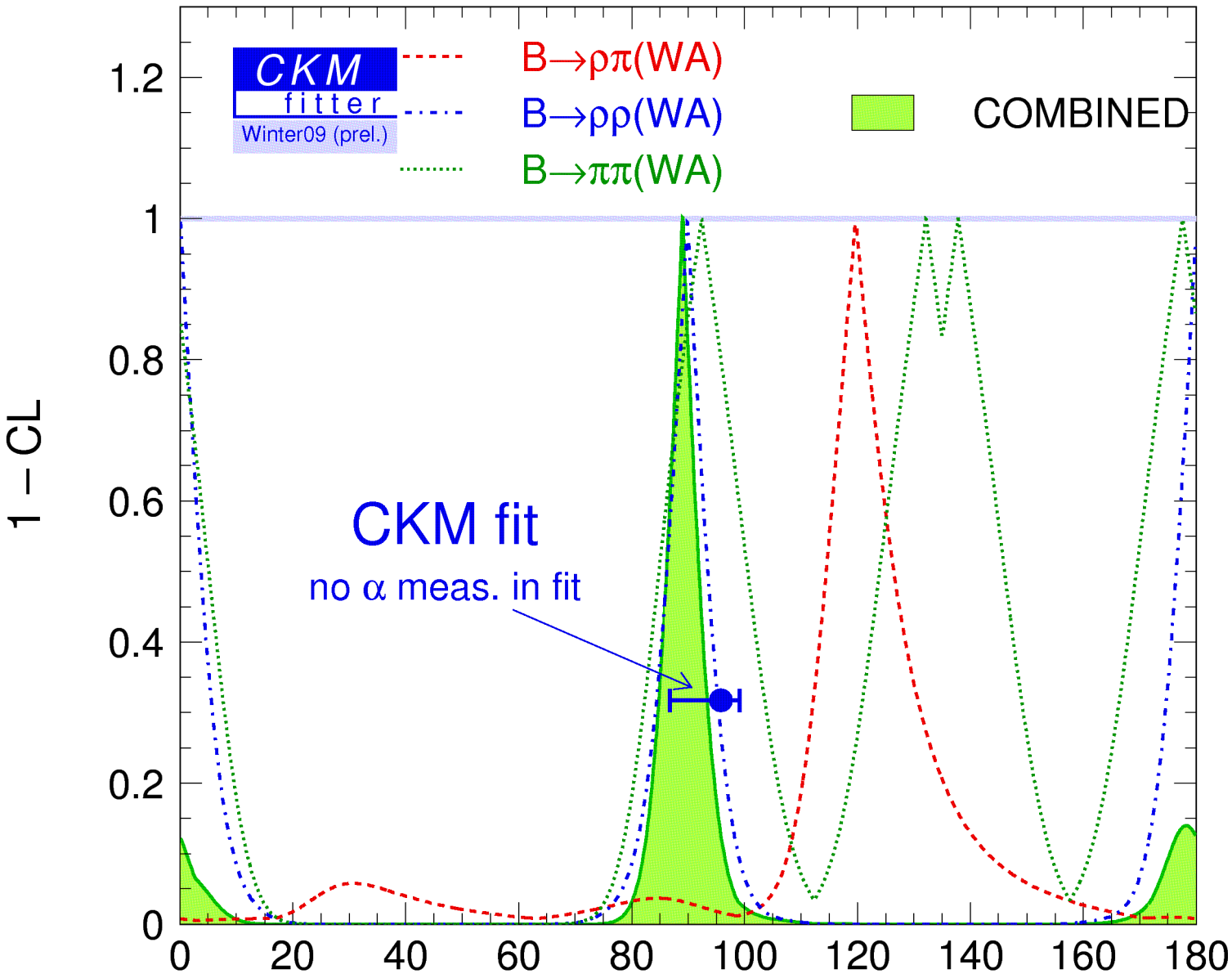
$f_L = 0.905 \pm 0.042 \; ^{+0.023}_{-0.027}$

85×10^6 $B\bar{B}$ pairs [PRL91, 221801 (2003)]

$\mathrm{Br}(B^+ \to \rho^+\rho^0) = (31.7 \pm 7.1^{+3.8}_{-6.7}) \times 10^{-6}$

$f_L = 0.948 \pm 0.106 \; \pm 0.021$

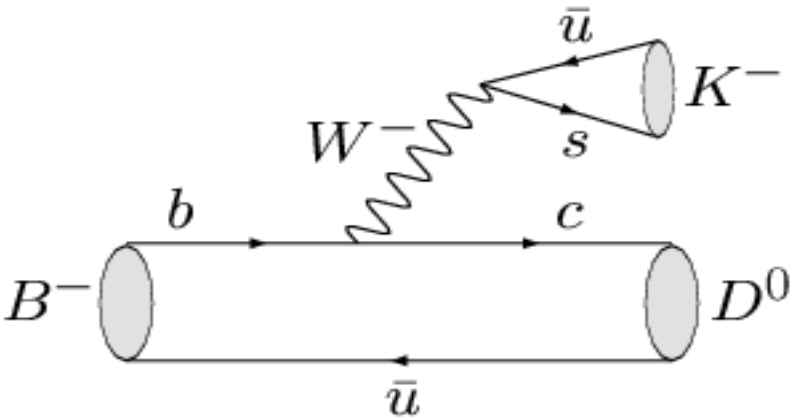
α determination



68% C.L. interval: $\alpha = (89.0^{+4.4}_{-4.2})^{\circ}$

γ measurements from $B^{\pm} \to DK^{\pm}$

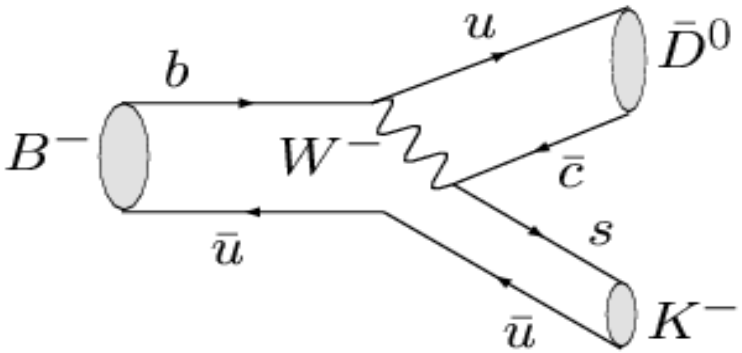
- Theoretically pristine $B \to DK$ approach
- Access γ via interference between $B^- \to D^0 K^-$ and $B^- \to \bar{D}^0 K^-$



color allowed

$B^- \to D^0 K^- \sim V_{cb} V_{us}^*$

$\sim \mathbf{A\lambda^3}$



color suppressed

$B^- \to \bar{D}^0 K^- \sim V_{ub} V_{cs}^*$

$\sim \mathbf{A\lambda^3(\rho + i\eta)}$

relative magnitude of suppressed amplitude is r_B

$$r_B = \frac{|A_{suppressed}|}{|A_{favoured}|} \sim \frac{|V_{ub} V_{cs}^*|}{|V_{cb} V_{us}^*|} \times [\text{color supp}] = 0.1\text{-}0.2$$

relative weak phase is γ, relative strong phase is δ_B

γ measurements from $B^{\pm} \to DK^{\pm}$

- Reconstruct D in final states accessible to both D^0 and $\overline{D}^0$
  - $D = D_{CP}$, CP eigenstates as K^+K^-, $\pi^+\pi^-$, $K_S\pi^0$

    GLW method (Gronau-London-Wyler)
  - $D = D_{sup}$, Doubly-Cabbibo suppressed decays as $K\pi$

    ADS method (Atwood-Dunietz-Soni)
  - Three-body decays as $D \to K_S\pi^+\pi^-$, $K_S K^+ K^-$

    GGSZ (Dalitz) method (Giri-Grossman-Soffer-Zupan)

- Largest effects due to
  - charm mixing
  - charm CP violation

  } negligible

  Y.Grossman, A.Soffer, J.Zupan
  [PRD 72, 031501 (2005)]

- Different B decays (DK, D^*K, DK^*)
  - different hadronic factors (r_B, δ_B) for each

Dalitz

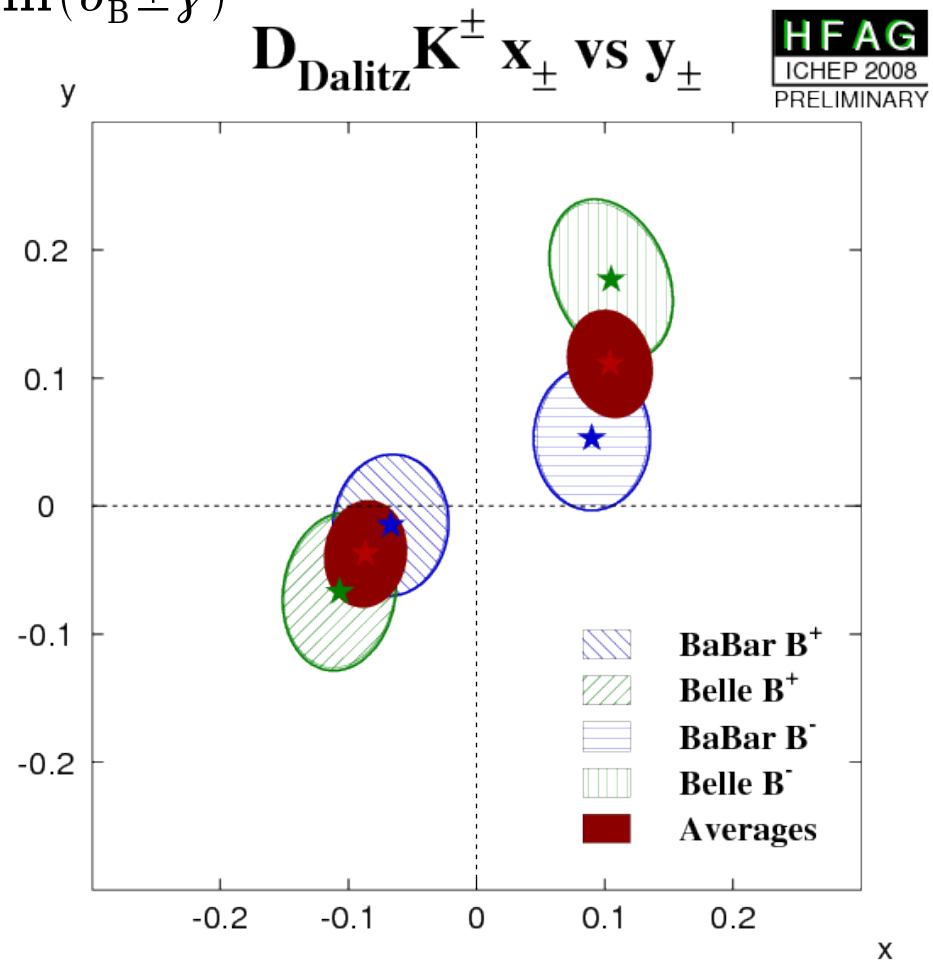
$$x_\pm = r_B \cos(\delta_B \pm \gamma)$$
$$y_\pm = r_B \sin(\delta_B \pm \gamma)$$

657×10^6 $B\bar{B}$ pairs
[arXiv:0803.3375]

$D \to K_S \pi\pi$

$N_S(DK) \simeq 530\pm30$

$N_S(D^*[D\pi^0]K) \simeq 120\pm15$



383×10^6 $B\bar{B}$ pairs
[PRD78, 034023 (2008)]

$D \to K_S \pi\pi$

$N_S(DK) = 600\pm31$

$N_S(D^*[D\pi^0]K) = 133\pm15$

$N_S(D^*[D\gamma]K) = 129\pm16$

$N_S(DK^*) = 118\pm18$

$D \to K_S KK$

$N_S(DK) = 112\pm13$

$N_S(D^*[D\pi^0]K) = 32\pm7$

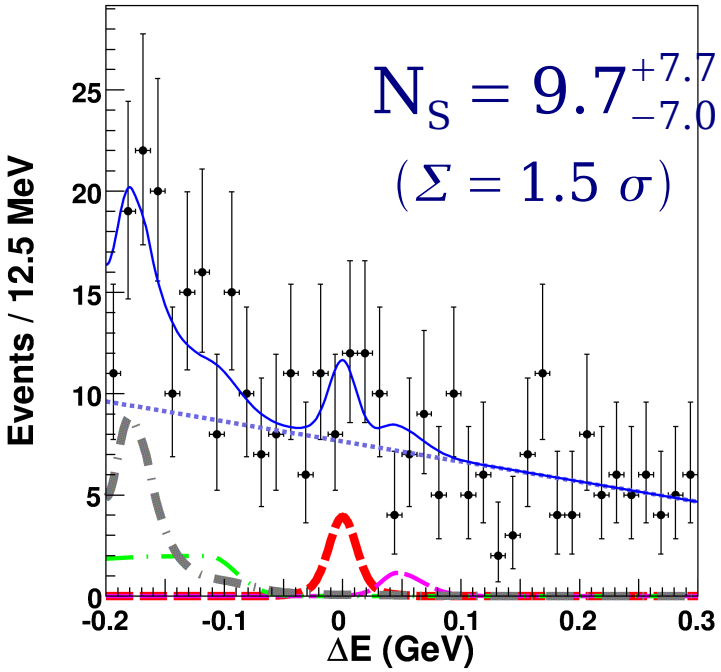
$N_S(D^*[D\gamma]K) = 21\pm7$

$\gamma = 80.8^\circ{}^{+13.1^\circ}_{-14.8^\circ}\pm5.0^\circ\pm8.7^\circ$	DK	$\gamma \simeq (63\pm28)^\circ$
$r_B = 0.161^{+0.040}_{-0.038}\pm0.011\pm0.049$		$r_B = 0.086\pm0.035\pm0.010\pm0.011$
$\delta_B = 137.4^\circ{}^{+13.0^\circ}_{-15.7^\circ}\pm4.0^\circ\pm22.9^\circ$		$\delta_B = 109^\circ{}^{+28^\circ}_{-31^\circ}\pm4^\circ\pm7^\circ$

combining the 2 modes:
$\boldsymbol{\gamma = (76^{+12}_{-13}\pm4\pm9)^\circ}$

combining all these modes:
$\boldsymbol{\gamma = (76 \pm 22 \pm 5 \pm 5)^\circ}$

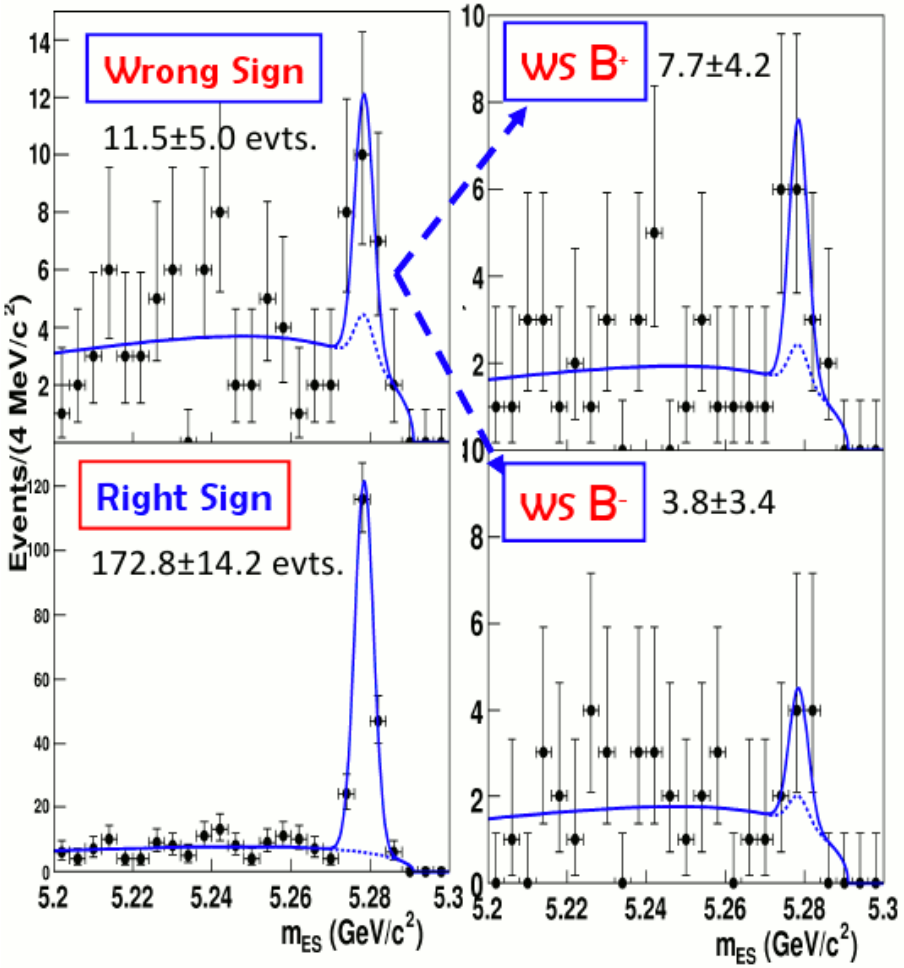
ADS method



$B \to D(K\pi)K$

657×10^6 $B\bar{B}$ pairs
[PRD 78, 071901 (2008)]

No significant signal observed yet,
limit on r_B: < 0.19 @ 90% C.L.

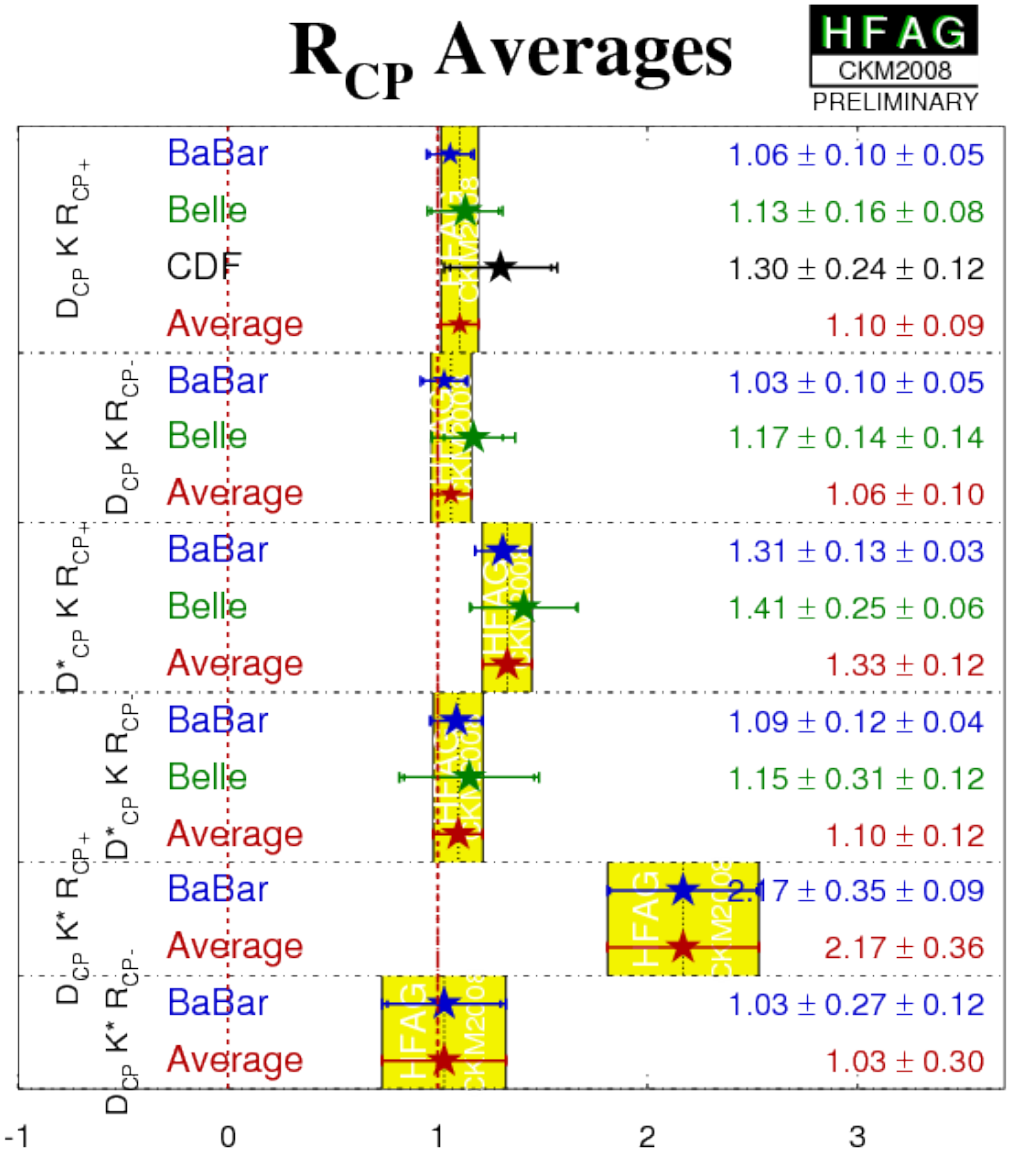


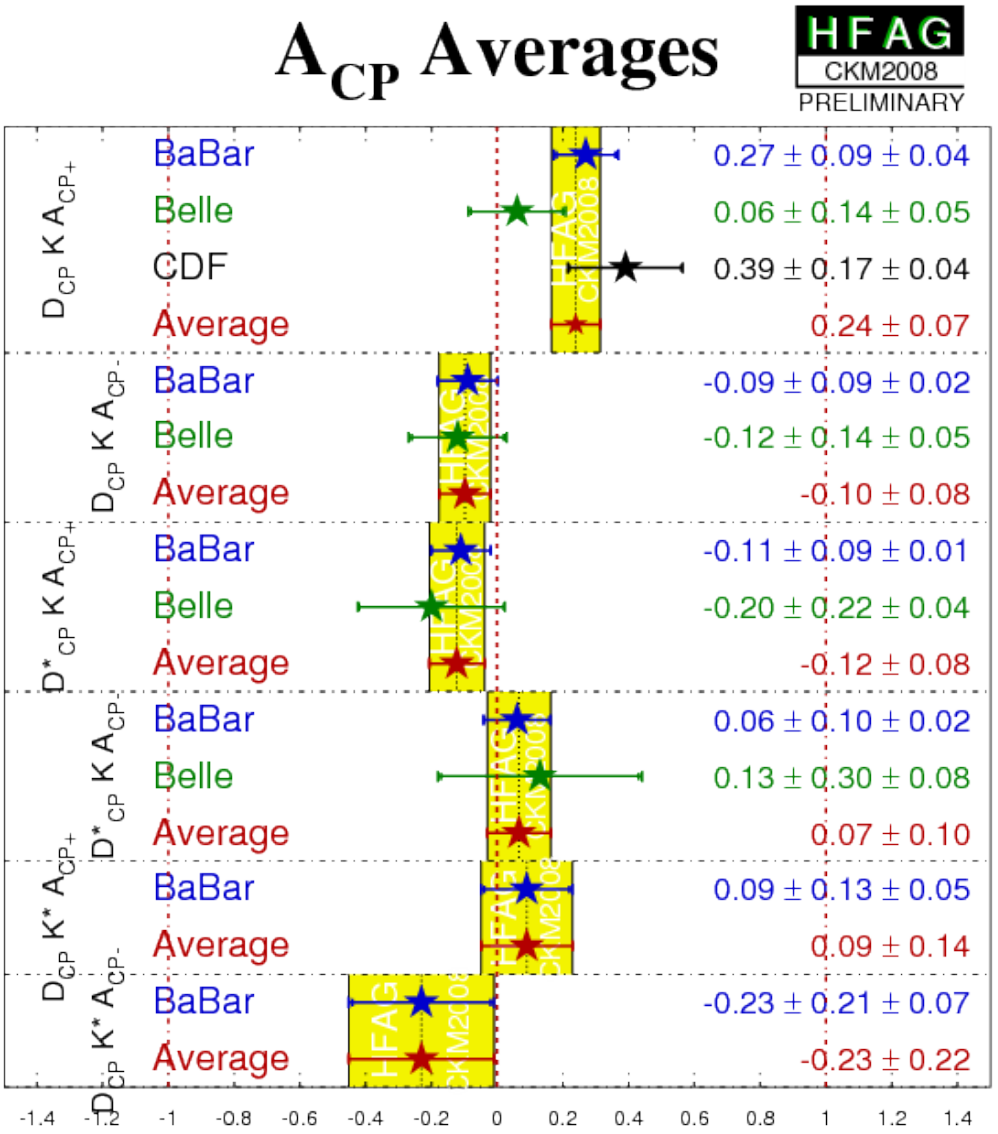
$B \to D(K\pi)K^*$

379×10^6 $B\bar{B}$ pairs
[CKM008 preliminary]

GLW method $D^{(*)}K^{(*)\pm}$, $D\to KK$, $\pi^+\pi^-$, $K_S\pi^0$...

observables $R_{CP^\pm}$, $A_{CP^\pm}$



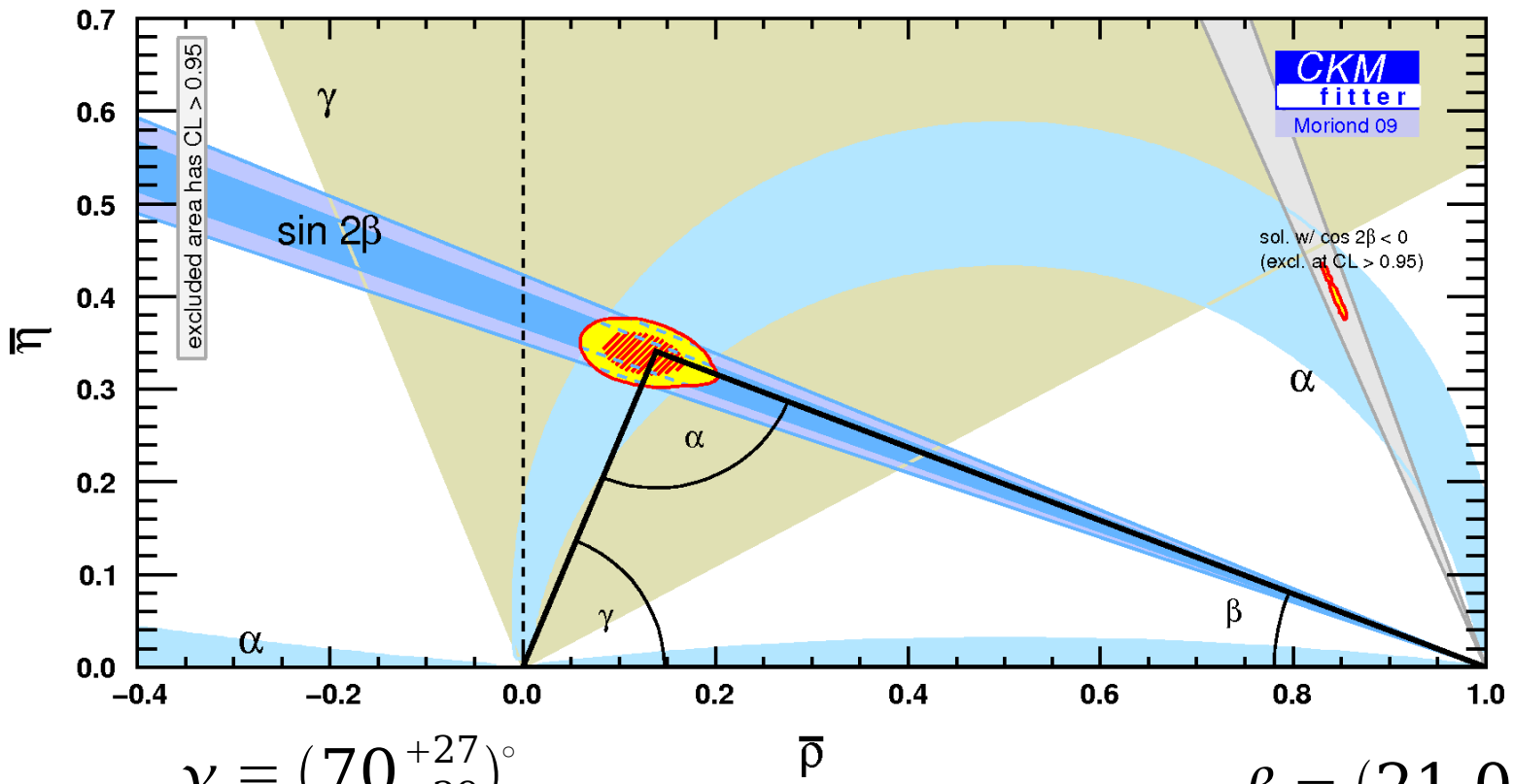


- first result from CDF **1 fb^{-1}, [ArXiv:0809.4809]**
- BaBar ($\sim$350 fb^{-1}), Belle ($\sim$250 fb^{-1})
- no charge asymmetry yet observed

Summary for the Angles

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

(WA, CKMfitter, Winter09)



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

(WA, CKMfitter, CKM08)

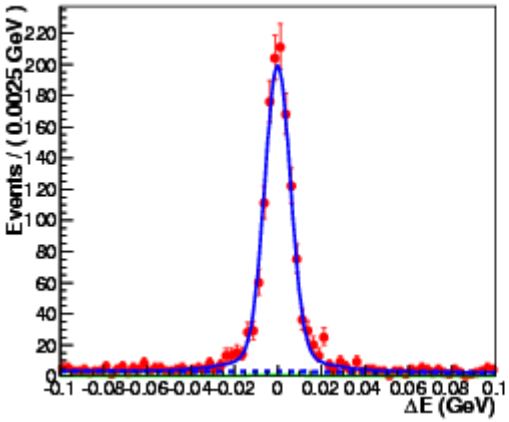
$$\beta = (21.0 \pm 0.9)^\circ$$

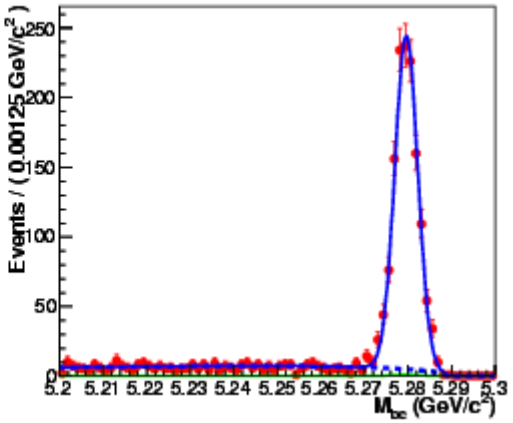
(WA, HFAG, Winter09)

$\sin 2\beta$ in $\psi(2S)K_S^0$

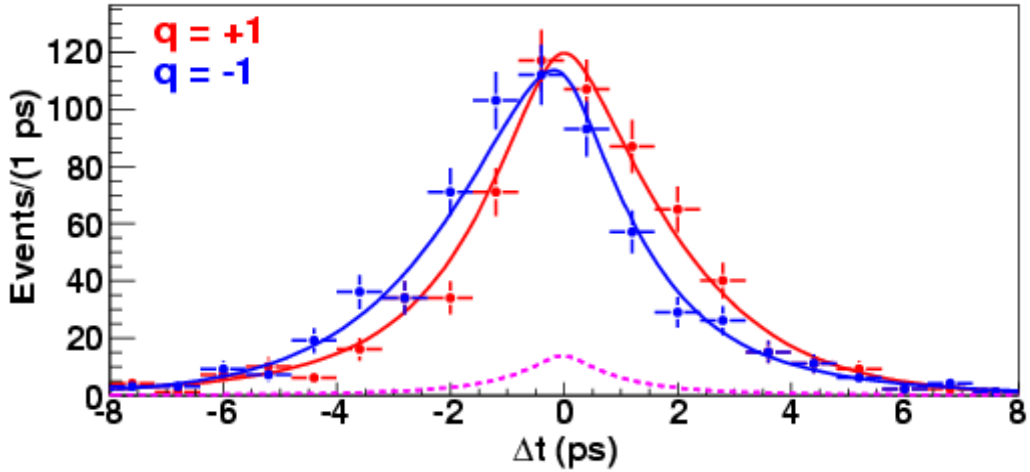
657×10^6 $B\bar{B}$ pairs
[PRD77 (2008) 091103]

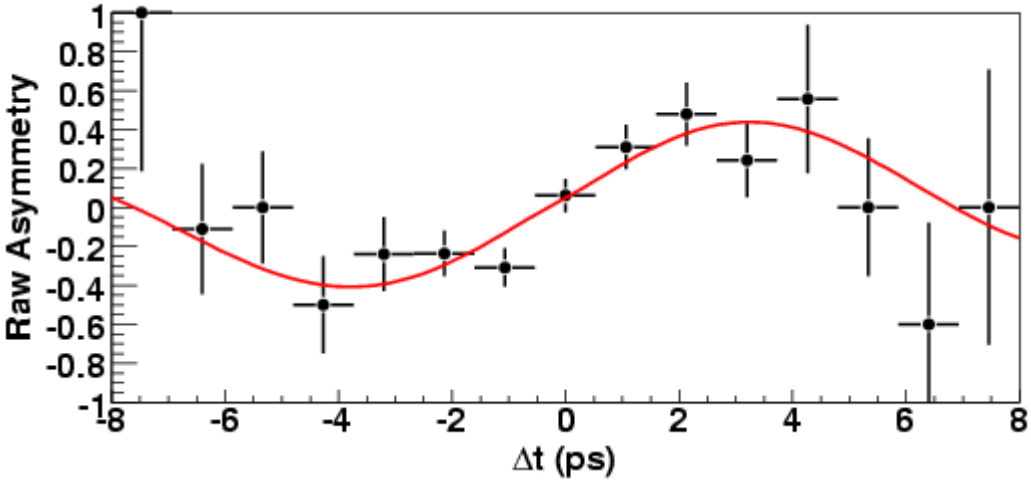
$\psi(2S) \to l^+ l^-$
$\psi(2S) \to J/\psi\, \pi^+ \pi^-$





CP odd
$N_{sig} = 1392$
Purity = 94 %





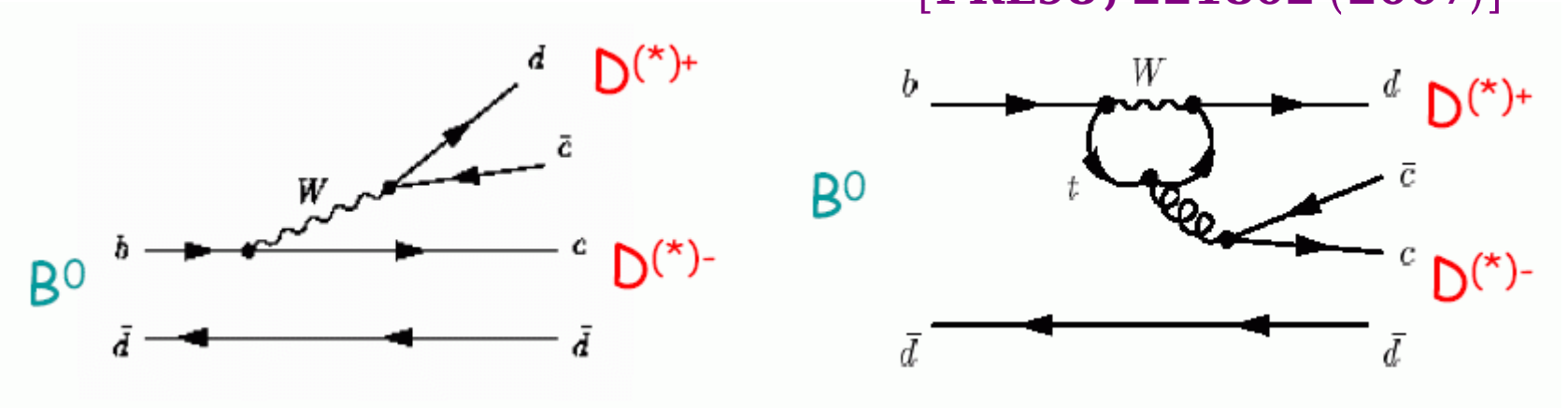
$$\sin 2\beta = 0.72 \pm 0.09 \pm 0.03$$

$$C = -0.04 \pm 0.07 \pm 0.05$$

soon other charmonium modes
$\chi_{c1} K_S$, $\eta_c K_S$ ...

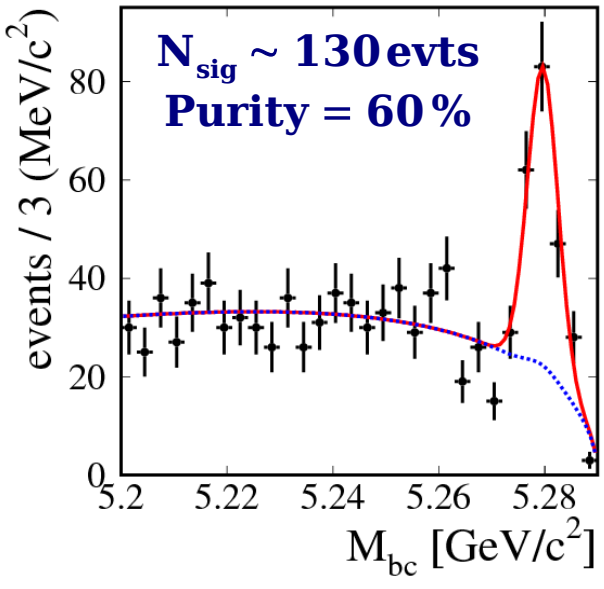
$B^0 \to D^+ D^-$ mode

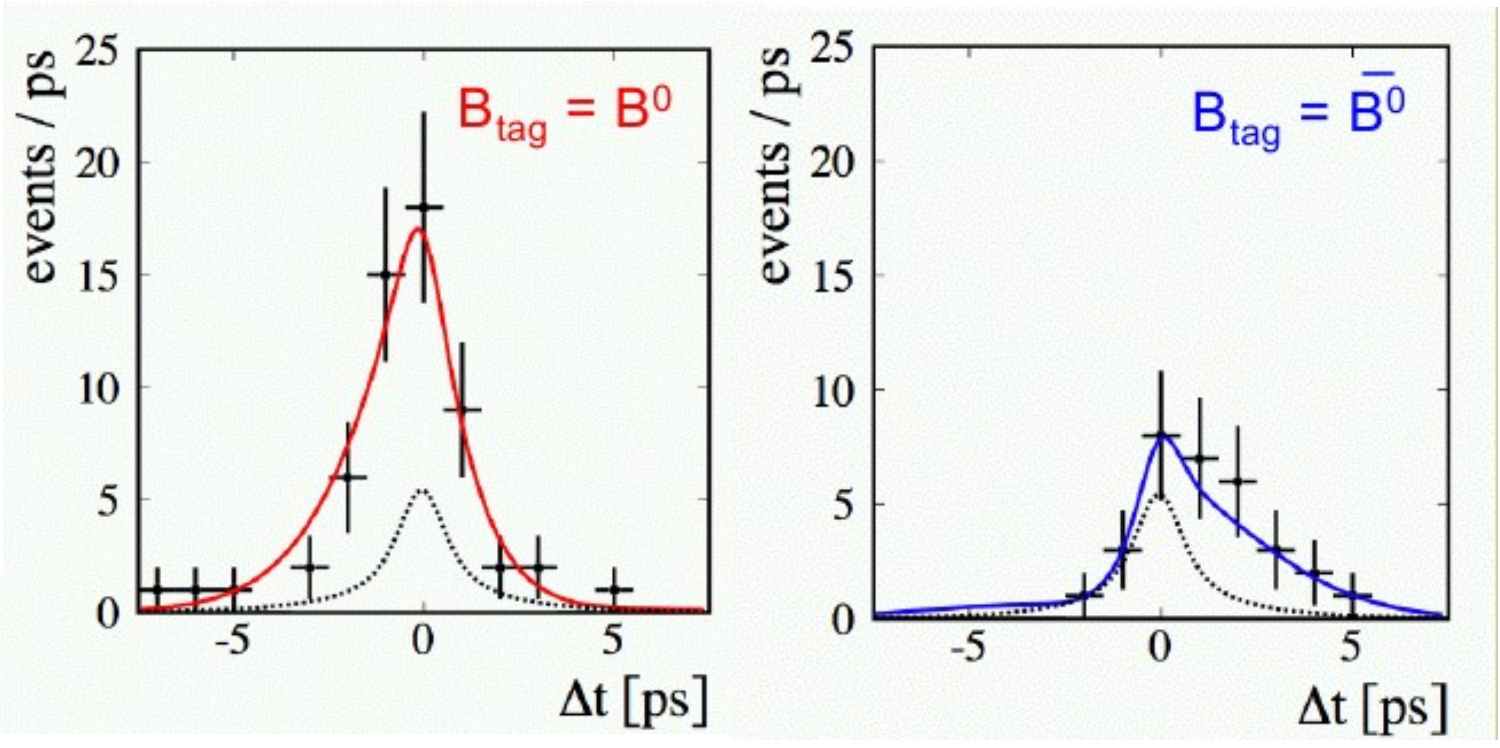
535×10^6 $B\bar{B}$ pairs
[PRL98, 221802 (2007)]



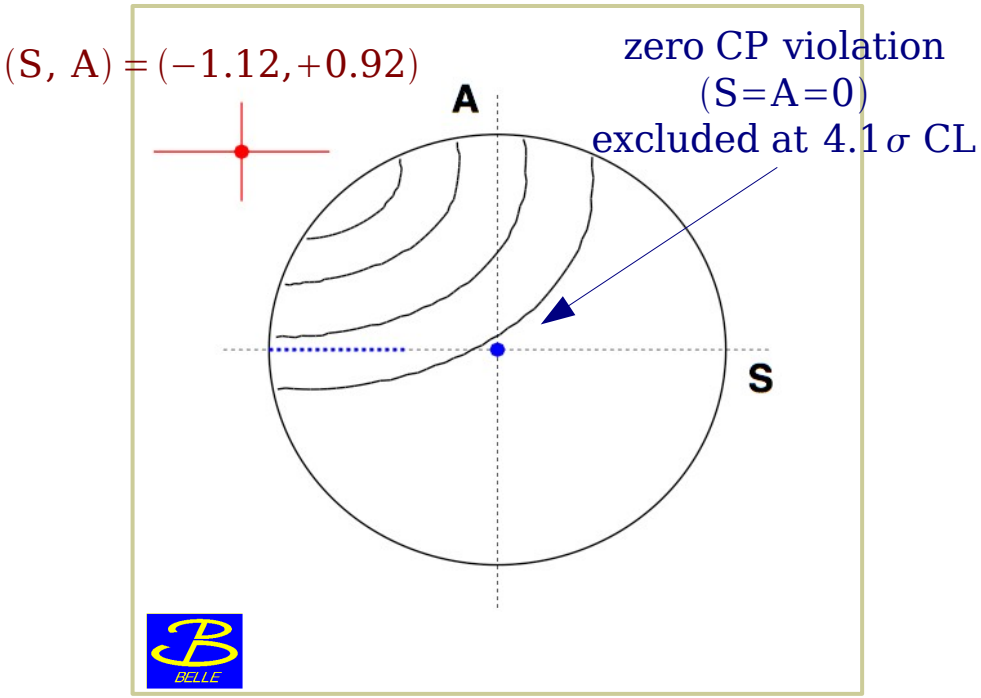
SM expectation: $S \approx -\sin 2\beta$, $C \approx -3\%$
Z.Z.Xing, PRD61 (2000) 014010

$S = -1.13 \pm 0.37 \pm 0.09$
$C = -0.91 \pm 0.23 \pm 0.06$

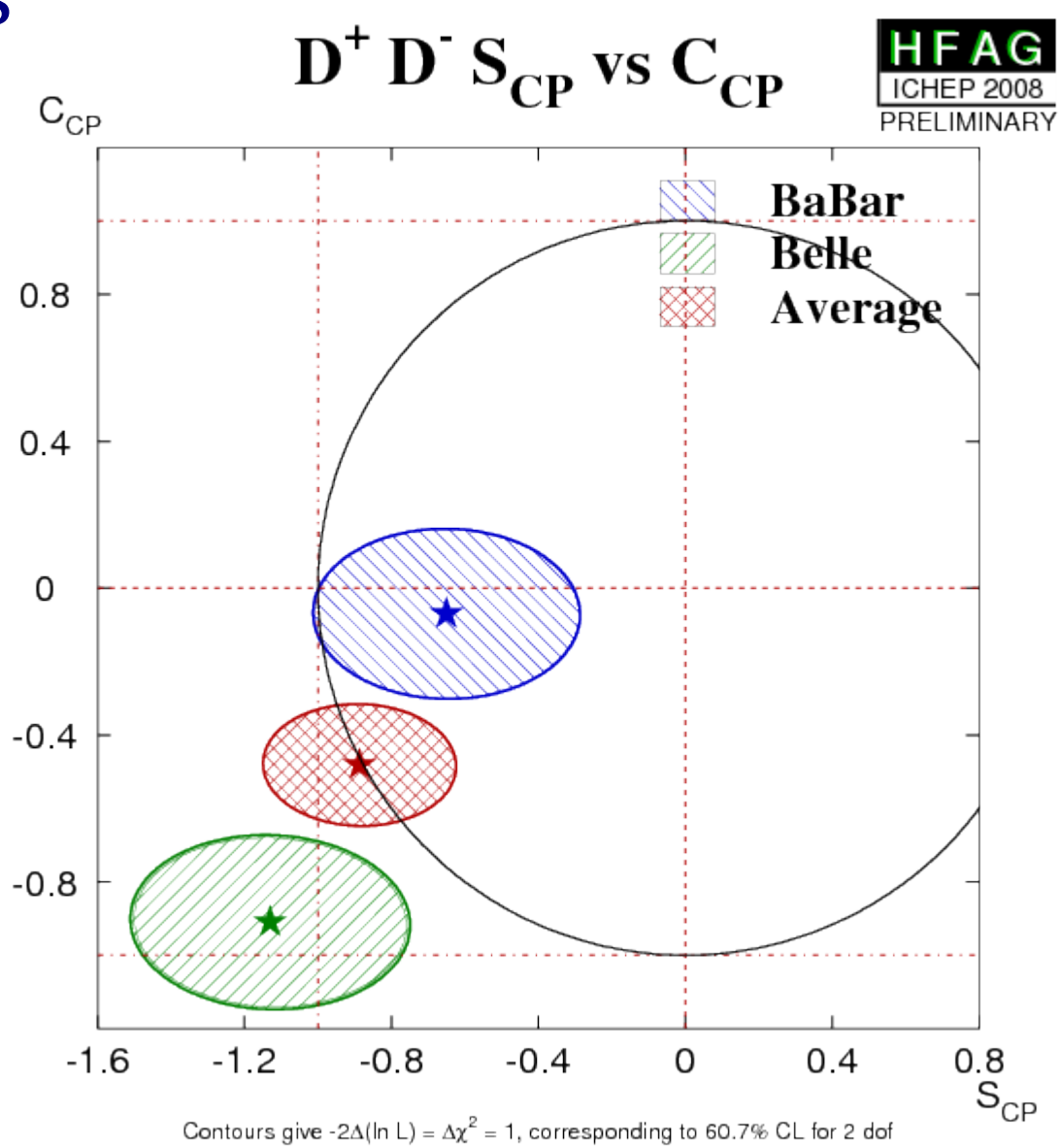




tCPV in D^+D^- decays

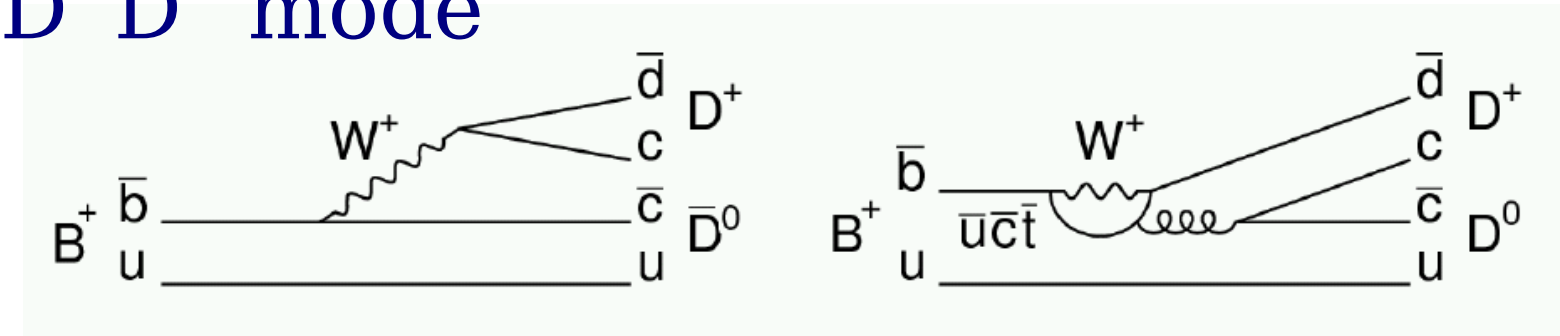


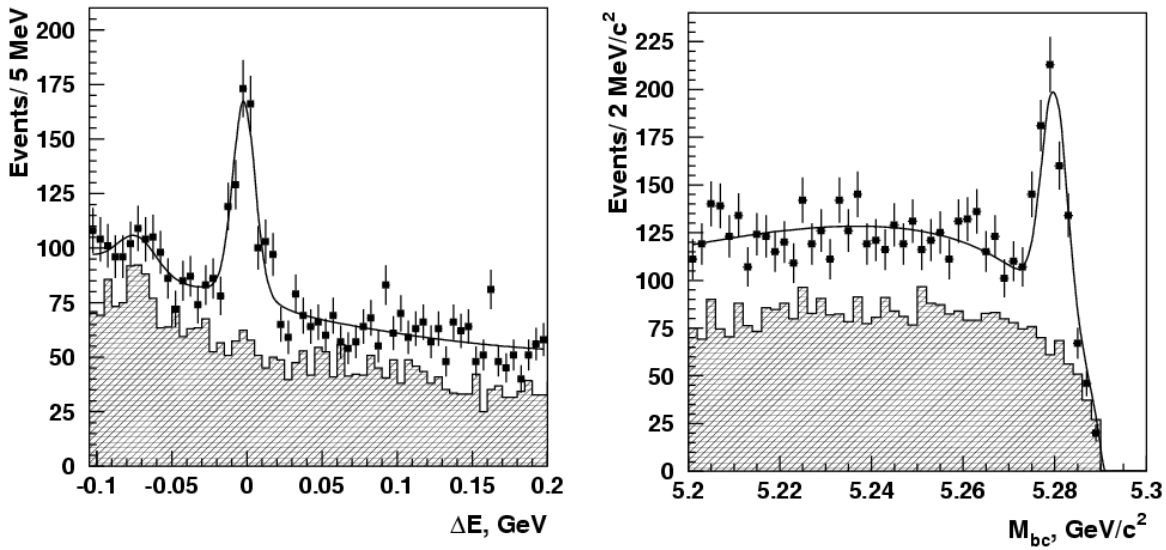
[PRL98, 221802 (2007)]



- First evidence of CP violation in D^+D^- decays
- Evidence (@ 3.2 σ) of direct CPV... but
  not indicated by other measurements
  need to check other modes (D^+D^0 etc...)

$B^+ \to D^+ D^0$ mode

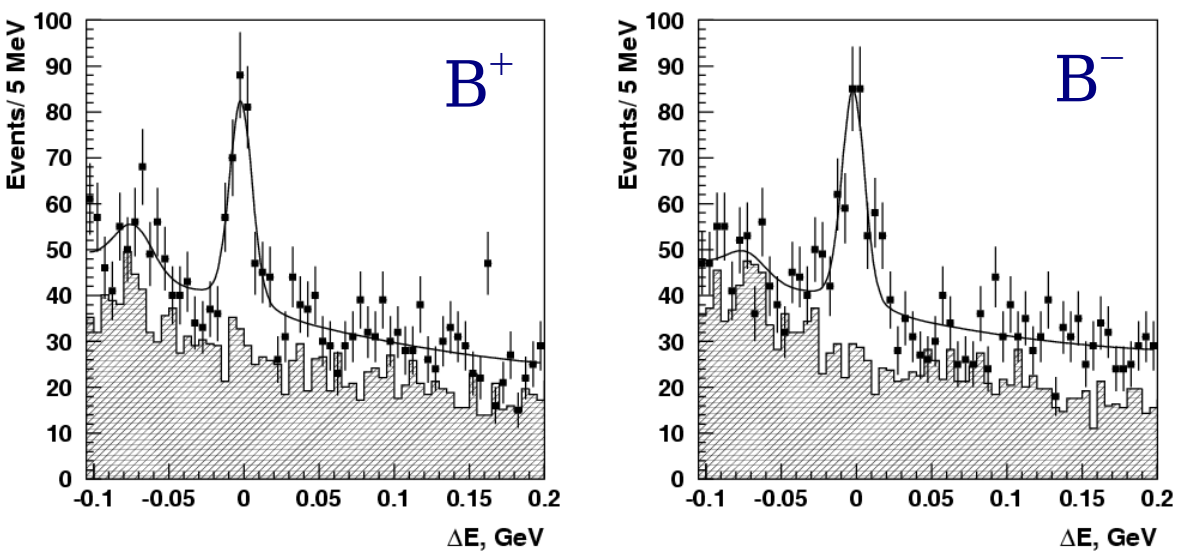




657×10^6 $B\bar{B}$ pairs
[arXiv:0708.1668]

$$Br(B^+ \to D^+ \bar{D}^0) = (3.85 \pm 0.31 \pm 0.38)\times10^{-4}$$

BaBar [PRD73, 112004 (2006)]
$(3.8 \pm 0.6 \pm 0.5)\times10^{-4}$
Belle [PRL95, 041803 (2005)]
$(4.8 \pm 0.8 \pm 0.6)\times10^{-4}$



$$A_{CP}(B^+ \to D^+ \bar{D}^0) = (0.00 \pm 0.08 \pm 0.02)$$

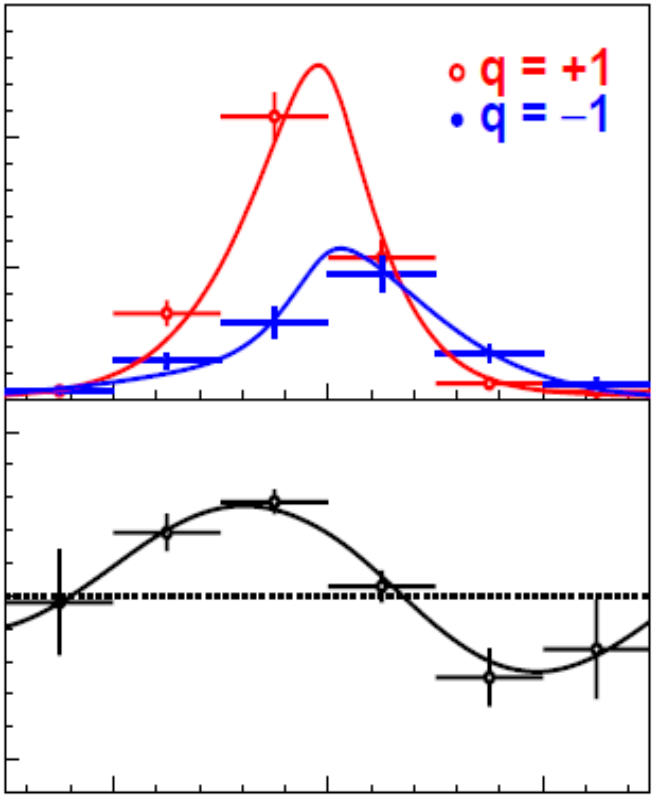
no direct CP observed

$$Br(B^0 \to D^0 \bar{D}^0) < 0.42\times10^{-4} \text{ @ } 90\%\text{C.L.}$$

$\underline{\alpha}$: $\pi\pi$ system (6 observables for 6 parameters)

$Br(B\to\pi^+\pi^-)$, $S_{\pi^+\pi^-}$, $C_{\pi^+\pi^-}$, $Br(B\to\pi^+\pi^0)$, $Br(B\to\pi^0\pi^0)$, $A_{\pi^0\pi^0}$

535×10^6 $B\bar{B}$ pairs
PRL 98, 221801 (2007)

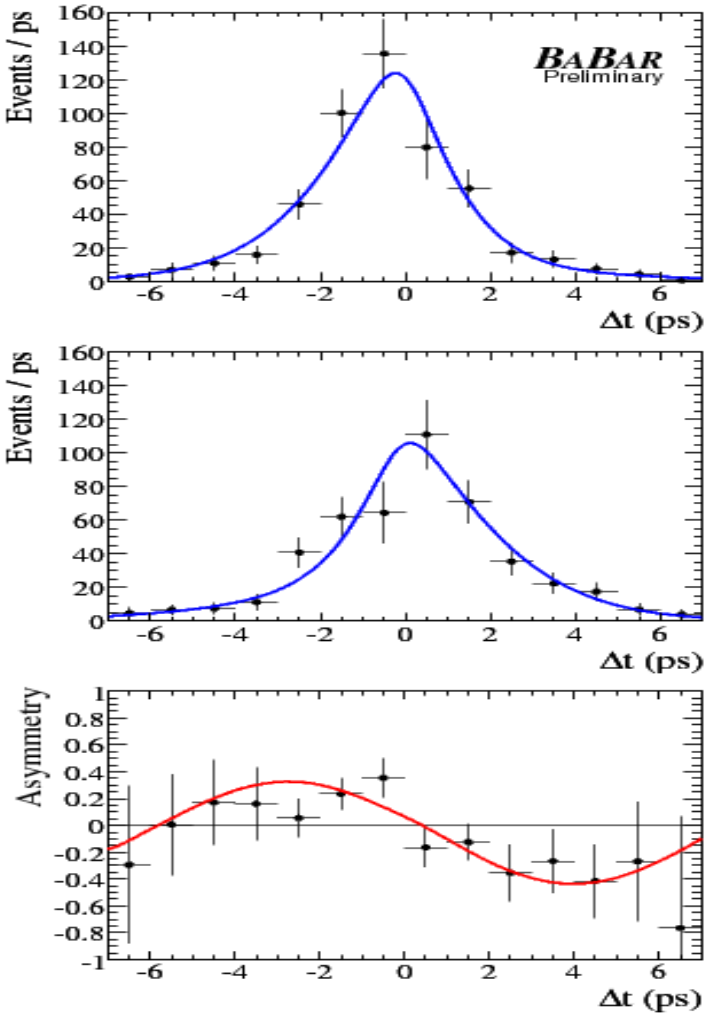


$$C = -0.55 \pm 0.08 \pm 0.05$$

$$S = -0.61 \pm 0.10 \pm 0.04$$

Direct CPV @ 5.5σ

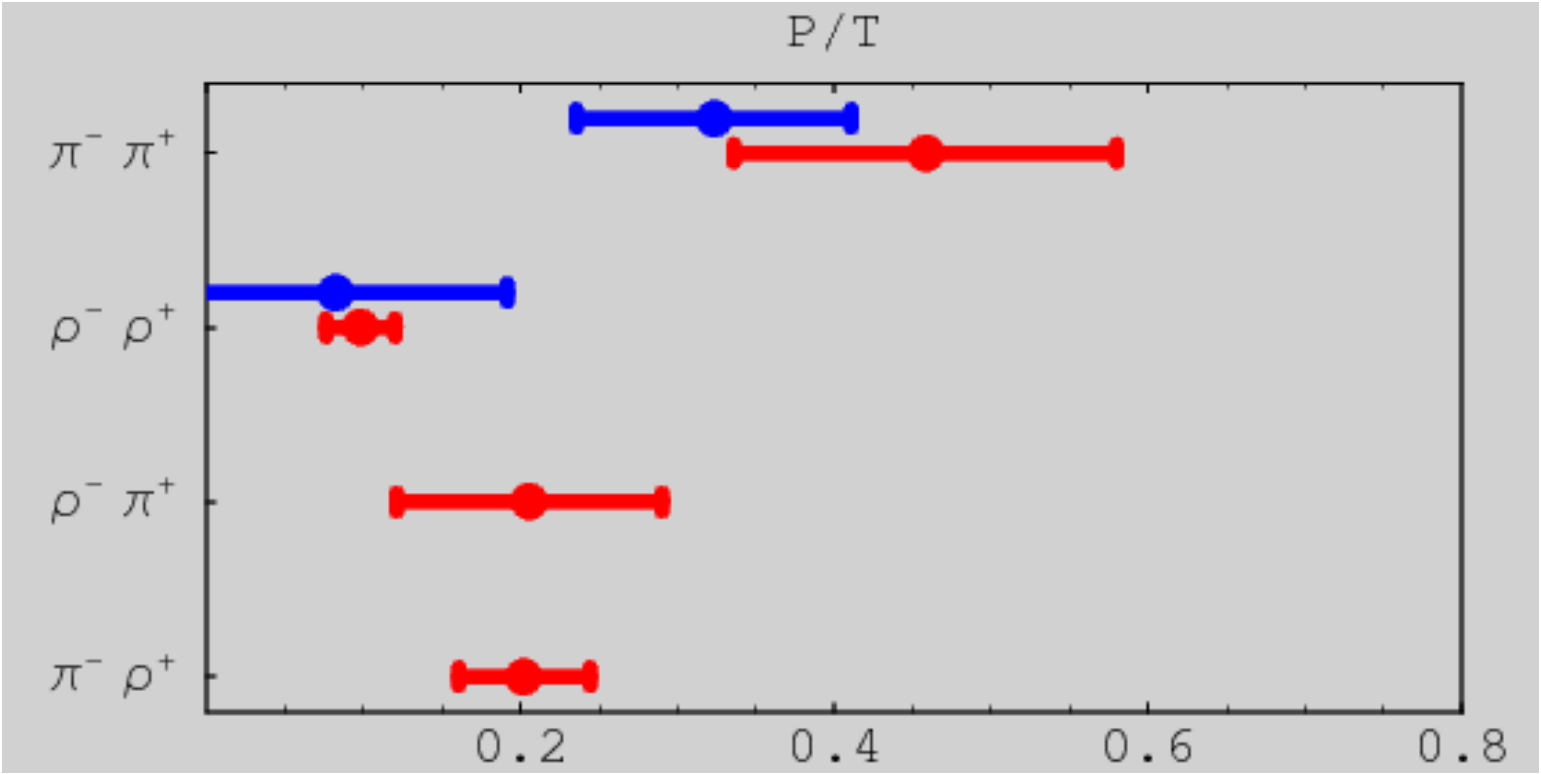
467×10^6 $B\bar{B}$ pairs
ArXiv:0807.4226



$$C = -0.25 \pm 0.08 \pm 0.02$$

$$S = -0.68 \pm 0.10 \pm 0.03$$

Sizes of penguin-to-tree ratios r

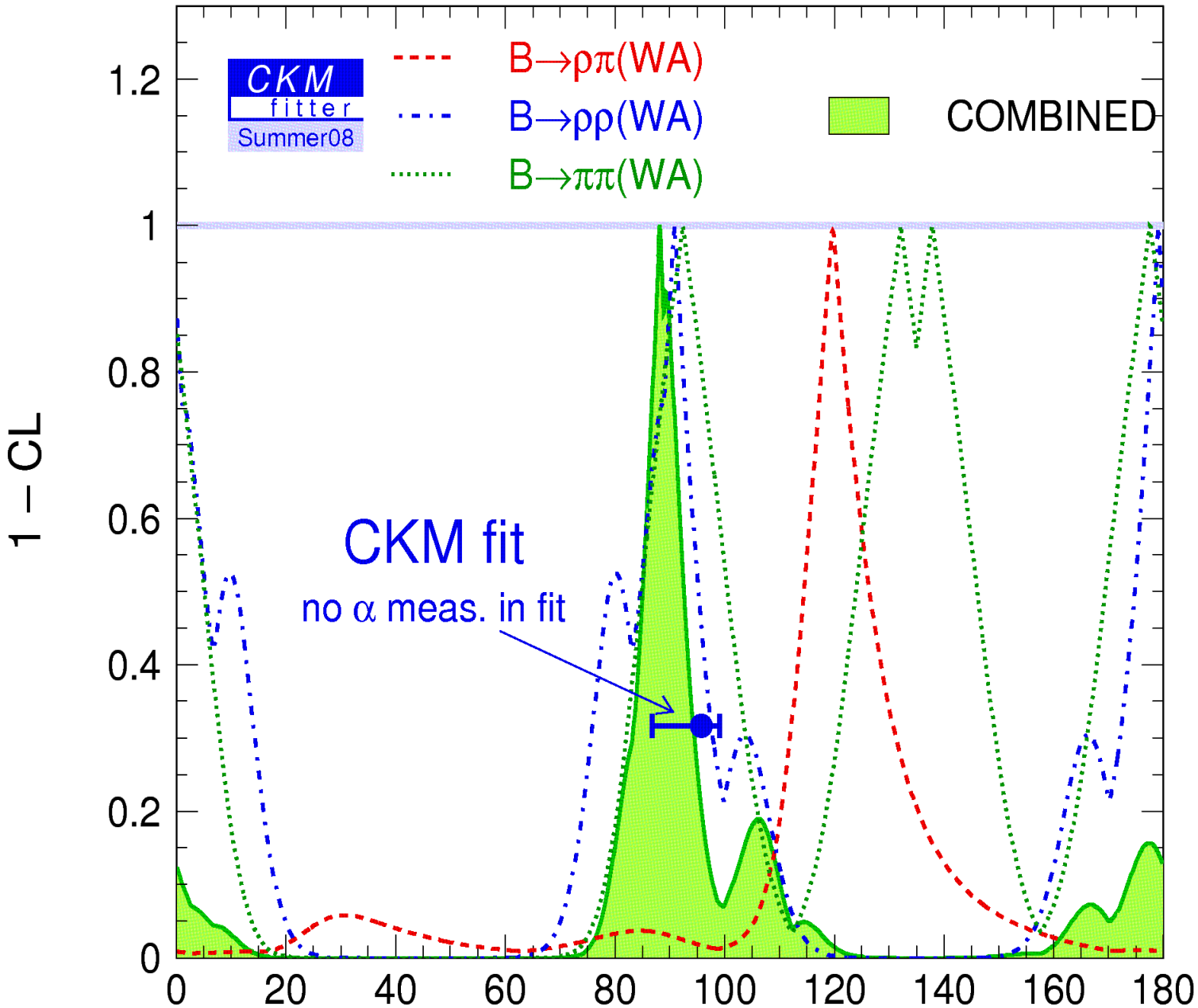


(blue) from isospin decomposition, (red) using SU(3)

Summary of $C_{\pi\pi}$

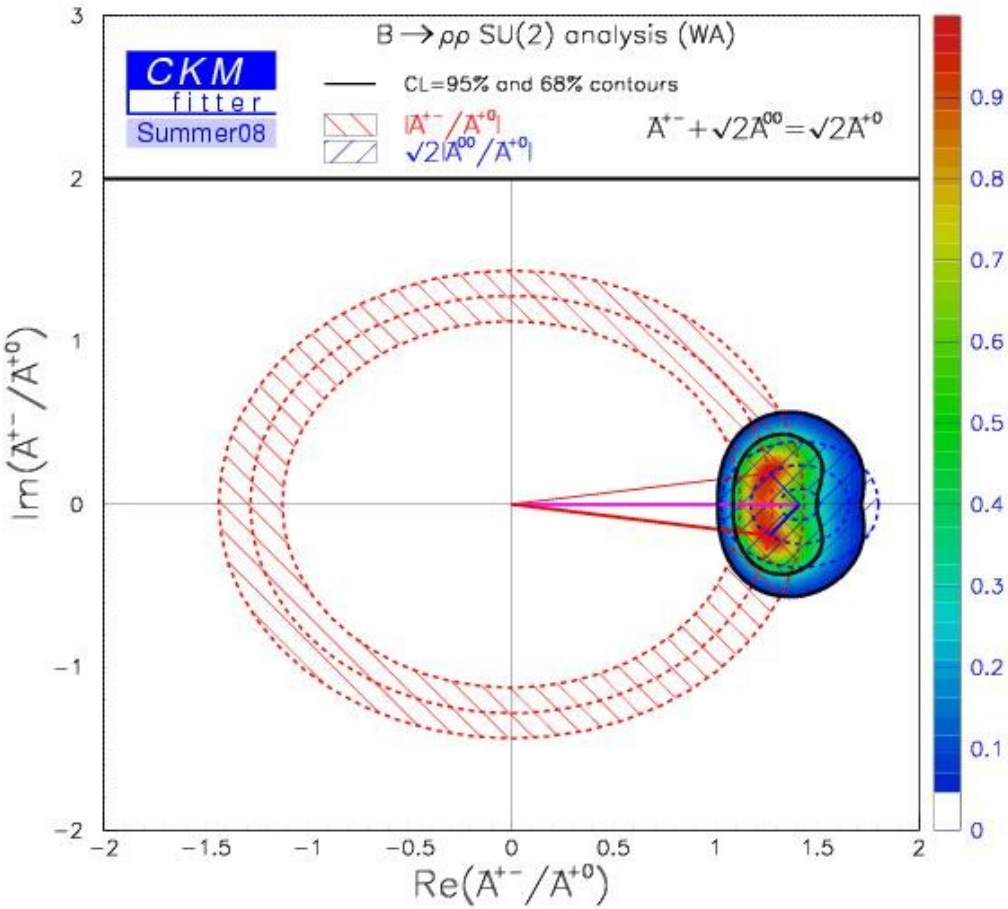
Year	BaBar	Belle	Difference
2001	$-0.25 \pm 0.45 \pm 0.14$		
	PRD 65, 051502 (33M)		
2002	$-0.30 \pm 0.25 \pm 0.04$	$-0.94\,^{+0.25}_{-0.31} \pm 0.09$	
	PRL 89, 281802 (88M)	PRL 89, 071801 (45M)	
2003	$-0.19 \pm 0.19 \pm 0.05$	$-0.77 \pm 0.27 \pm 0.08$	2.0σ
	preliminary LP2003 (123M)	PRD 68, 012001 (85M)	
2004	$-0.09 \pm 0.15 \pm 0.04$	$-0.58 \pm 0.15 \pm 0.07$	3.2σ
	PRL 95, 151803 (227M)	PRL 93, 021601 (152M)	
2005		$-0.56 \pm 0.12 \pm 0.06$	2.3σ
		PRL 95, 101801 (275M)	
2006	$-0.16 \pm 0.11 \pm 0.03$	$-0.55 \pm 0.08 \pm 0.05$	2.3σ
	ArXiv:0607106 (347M)	PRL 98, 211801 (535M)	
2007	$-0.21 \pm 0.09 \pm 0.02$		2.1σ
	PRL 99, 021603 (383M)		
2008	$-0.25 \pm 0.08 \pm 0.02$		1.9σ
	ArXiv:0807.4226 (467M)		

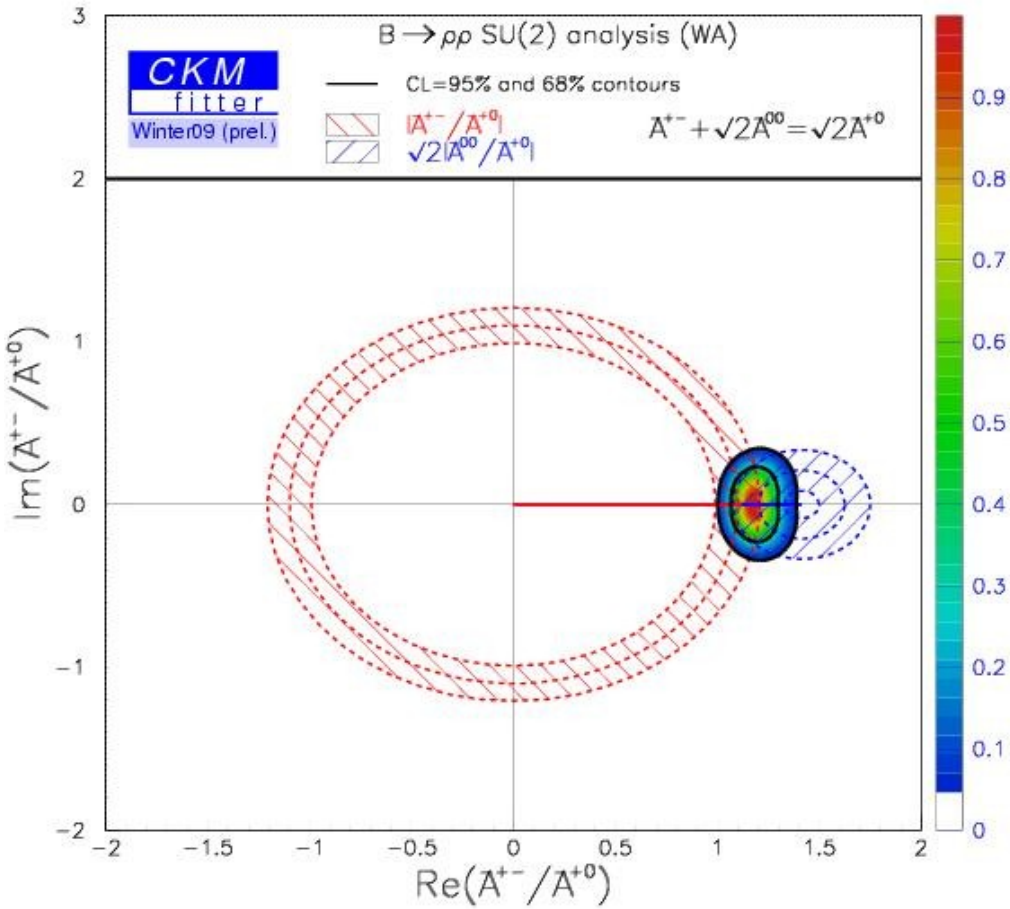
α determination



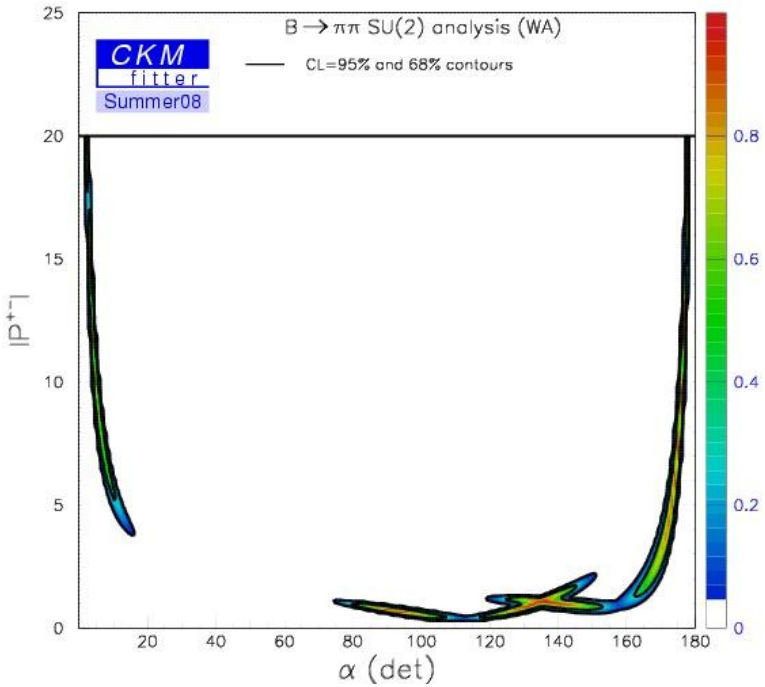
68% C.L. interval: $\alpha = (88.2^{+6.1}_{-4.8})^\circ$

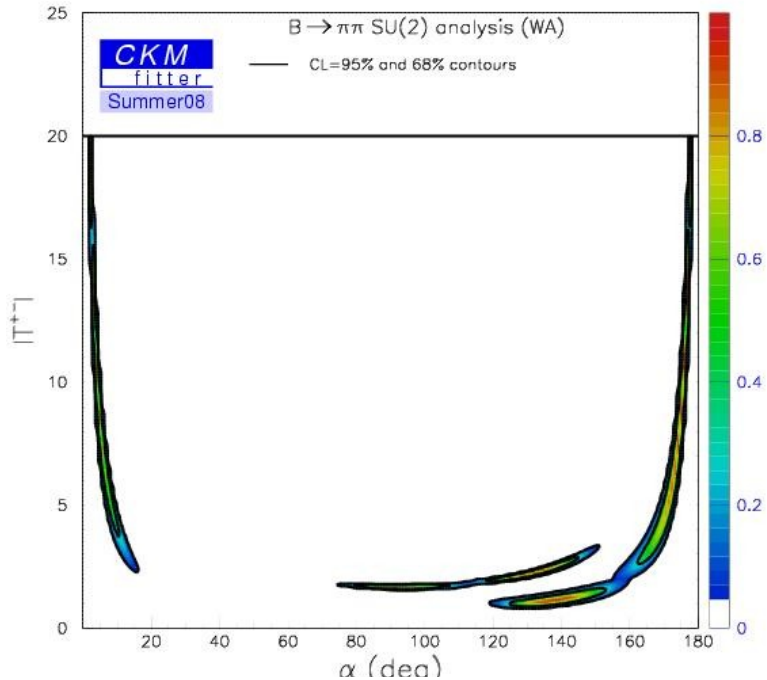
Isospin triangles

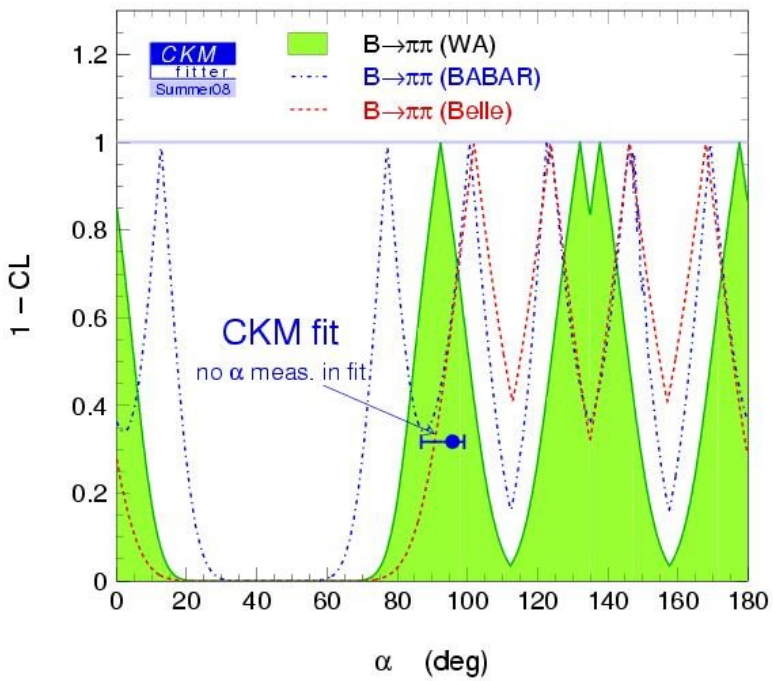


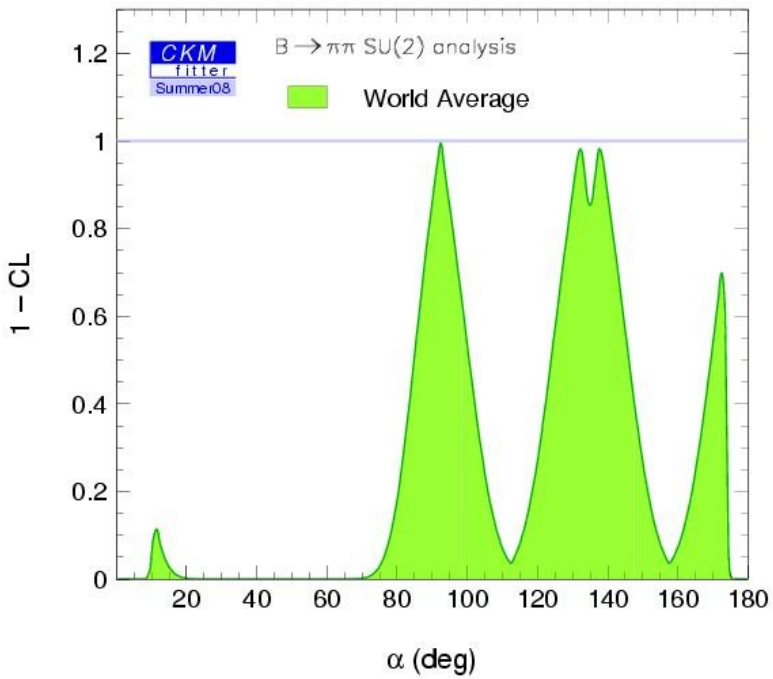


P and T


B→ππ SU(2) analysis (WA)
CKM fitter
Summer08
CL=95% and 68% contours
|P+-|
α (det)


B→ππ SU(2) analysis (WA)
CKM fitter
Summer08
CL=95% and 68% contours
|T+-|
α (deg)


CKM fitter
Summer08
B→ππ (WA)
B→ππ (BABAR)
B→ππ (Belle)
CKM fit
no α meas. in fit
1 – CL
α (deg)

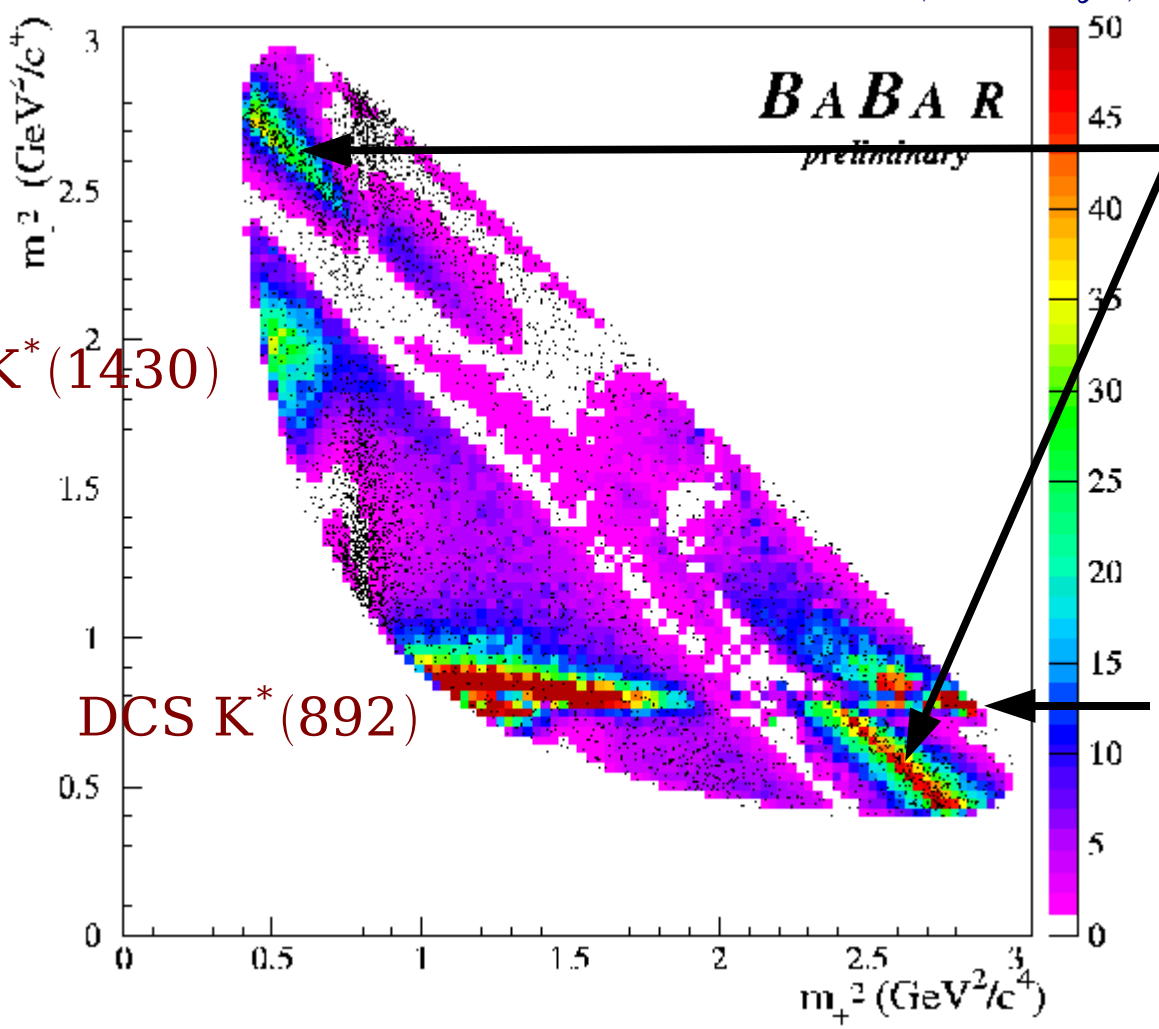

CKM fitter
Summer08
B→ππ SU(2) analysis
World Average
1 – CL
α (deg)

Sensitivity to γ

sensitivity to γ/ϕ_3 varies across the Dalitz plot

$\gamma=75^\circ$, $\delta=180^\circ$, $r_B=0.125$

$w=1/(d^2L/d\gamma^2)$



DCS $K^*(1430)$

DCS $K^*(892)$

GLW like

Interference of

$B^- \to D^0 K^-$, $D^0 \to K^0_S \rho^0$

with

$B^- \to \overline{D}^0 K^-$, $\overline{D}^0 \to K^0_S \rho^0$

ADS like

Interference of

$B^- \to D^0 K^-$, $D^0 \to K^{*+} \pi^-$

with

$B^- \to \overline{D}^0 K^-$, $\overline{D}^0 \to K^{*+} \pi^-$

$B \to D^{(*)} K^{(*)}$ Dalitz analysis

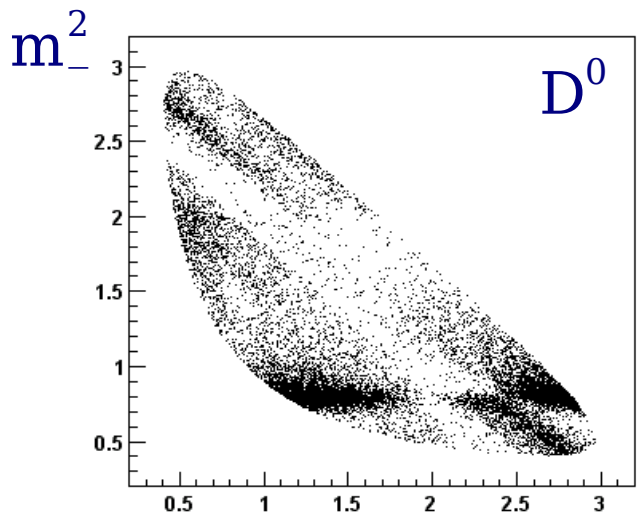
Reconstruction of three−body final states D^0, $\overline{D}^0 \to K_S \pi^+ \pi^-$

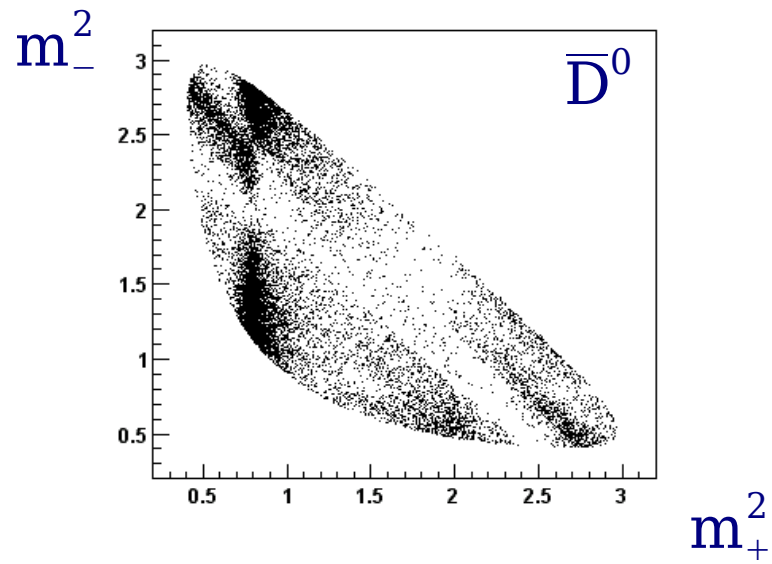
Amplitude for each Dalitz point is described as:

$$\overline{D}^0 \to K_S \pi^+ \pi^- \sim f(m_+^2, m_-^2)$$
$$D^0 \to K_S \pi^+ \pi^- \sim f(m_-^2, m_+^2)$$

$$B^+ \to (K_S \pi^+ \pi^-)_D K^+ : f(m_+^2, m_-^2) + r e^{i(\delta_B + \gamma)} f(m_-^2, m_+^2)$$

$m_- = M(K_S \pi^-)$
$m_+ = M(K_S \pi^+)$





$$B^- \to (K_S \pi^+ \pi^-)_D K^- : f(m_-^2, m_+^2) + r e^{i(\delta - \gamma)} f(m_+^2, m_-^2)$$

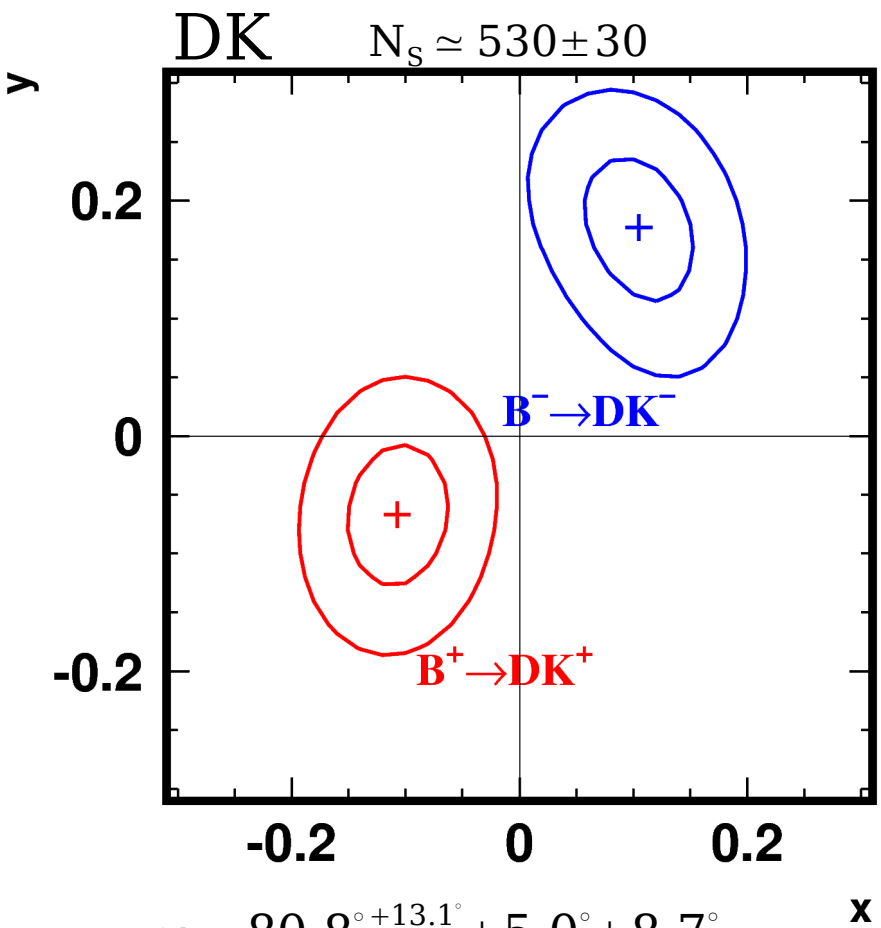
Simultaneous fit of B^+ and B^- to extract parameters r_B, ϕ_3 and δ_B

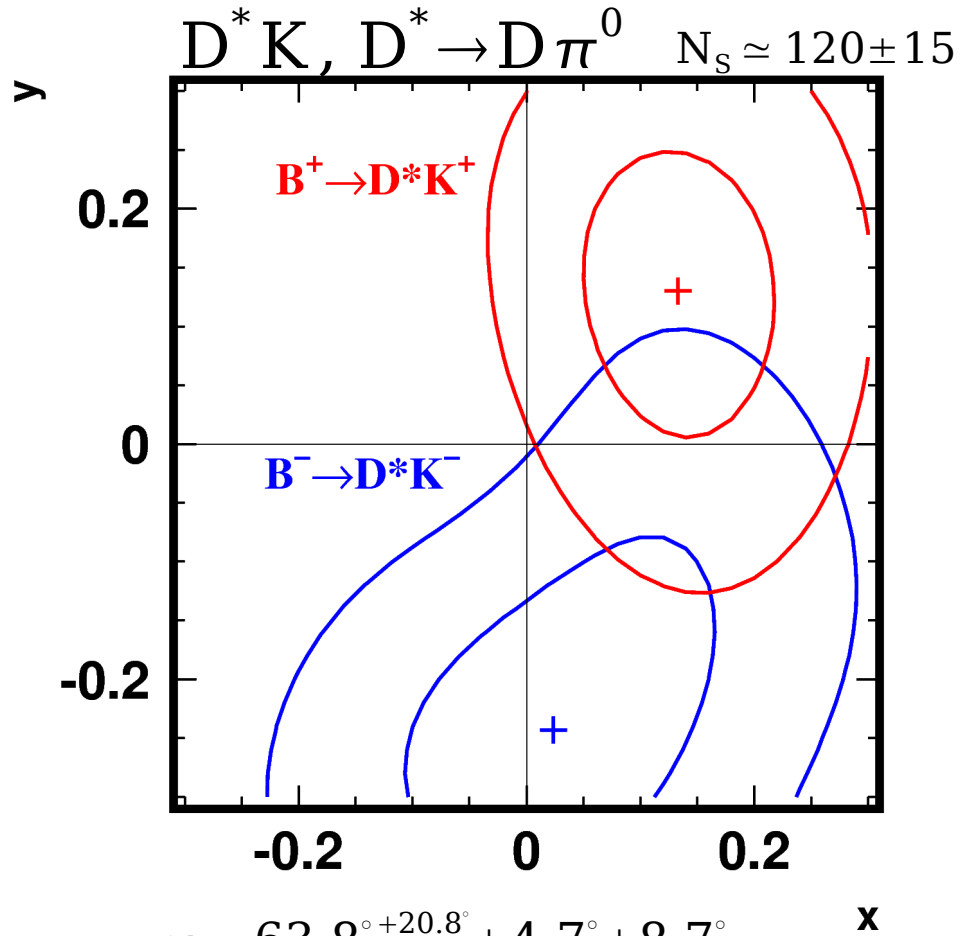
Note: 2 fold ambiguity on γ: $(\gamma, \delta_B) \to (\gamma + \pi, \delta_B + \pi)$

Dalitz $B \to D^{(*)}(K_S \pi\pi)K$

657×10^6 $B\bar{B}$ pairs [arXiv:0803.3375]

$$x_\pm = r_B \cos(\delta_B \pm \gamma)$$
$$y_\pm = r_B \sin(\delta_B \pm \gamma)$$





$$\gamma = 80.8^\circ {}^{+13.1^\circ}_{-14.8^\circ} \pm 5.0^\circ \pm 8.7^\circ$$
$$r_B = 0.161 {}^{+0.040}_{-0.038} \pm 0.011 \pm 0.049$$
$$\delta_B = 137.4^\circ {}^{+13.0^\circ}_{-15.7^\circ} \pm 4.0^\circ \pm 22.9^\circ$$

$$\gamma = 63.8^\circ {}^{+20.8^\circ}_{-22.9^\circ} \pm 4.7^\circ \pm 8.7^\circ$$
$$r_B = 0.208 {}^{+0.085}_{-0.083} \pm 0.015 \pm 0.049$$
$$\delta_B = 342.0^\circ {}^{+21.4^\circ}_{-22.9^\circ} \pm 3.7^\circ \pm 22.9^\circ$$

combining these 2 modes: $\gamma = 76^\circ {}^{+12^\circ}_{-13^\circ}(\text{stat}) \pm 4^\circ(\text{syst}) \pm 9^\circ(\text{model})$

Dalitz $B \to D^{(*)}(K_S\pi\pi, K_S KK)K^{(*)}$

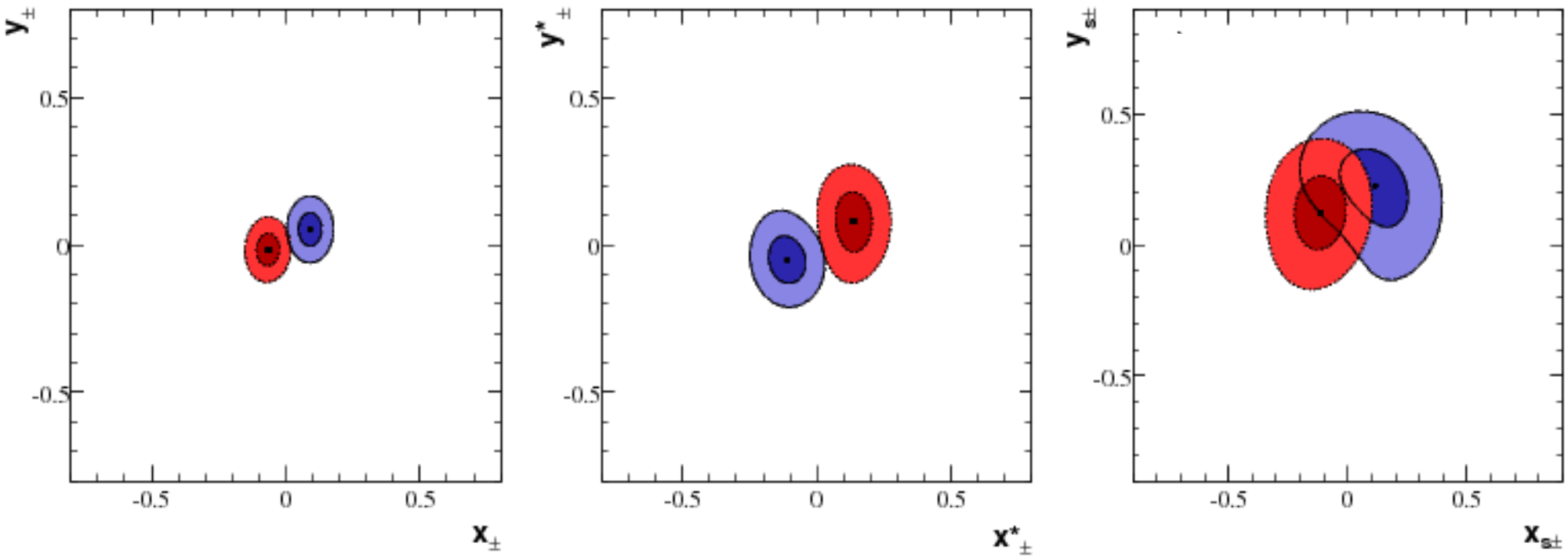
383×10^6 $B\bar{B}$ pairs [PRD78, 034023 (2008)]

$N_S(D^*[D\pi^0]K, K_S\pi\pi) = 133\pm15$

$N_S(DK, K_S\pi\pi) = 600\pm31$ $\quad N_S(D^*[D\gamma]K, K_S\pi\pi) = 129\pm16$ $\quad N_S(DK^*, K_S\pi\pi) = 118\pm18$

$N_S(DK, K_S KK) = 112\pm13$ $\quad N_S(D^*[D\pi^0]K, K_S KK) = 32\pm7$

$N_S(D^*[D\gamma]K, K_S KK) = 21\pm7$



$r_B^* = 0.135\pm0.051\pm0.011\pm0.005$

$\delta_B^* = -63^\circ{}^{+28^\circ}_{-30^\circ}\pm5^\circ\pm4^\circ$

$r_B = 0.086\pm0.035\pm0.010\pm0.011$

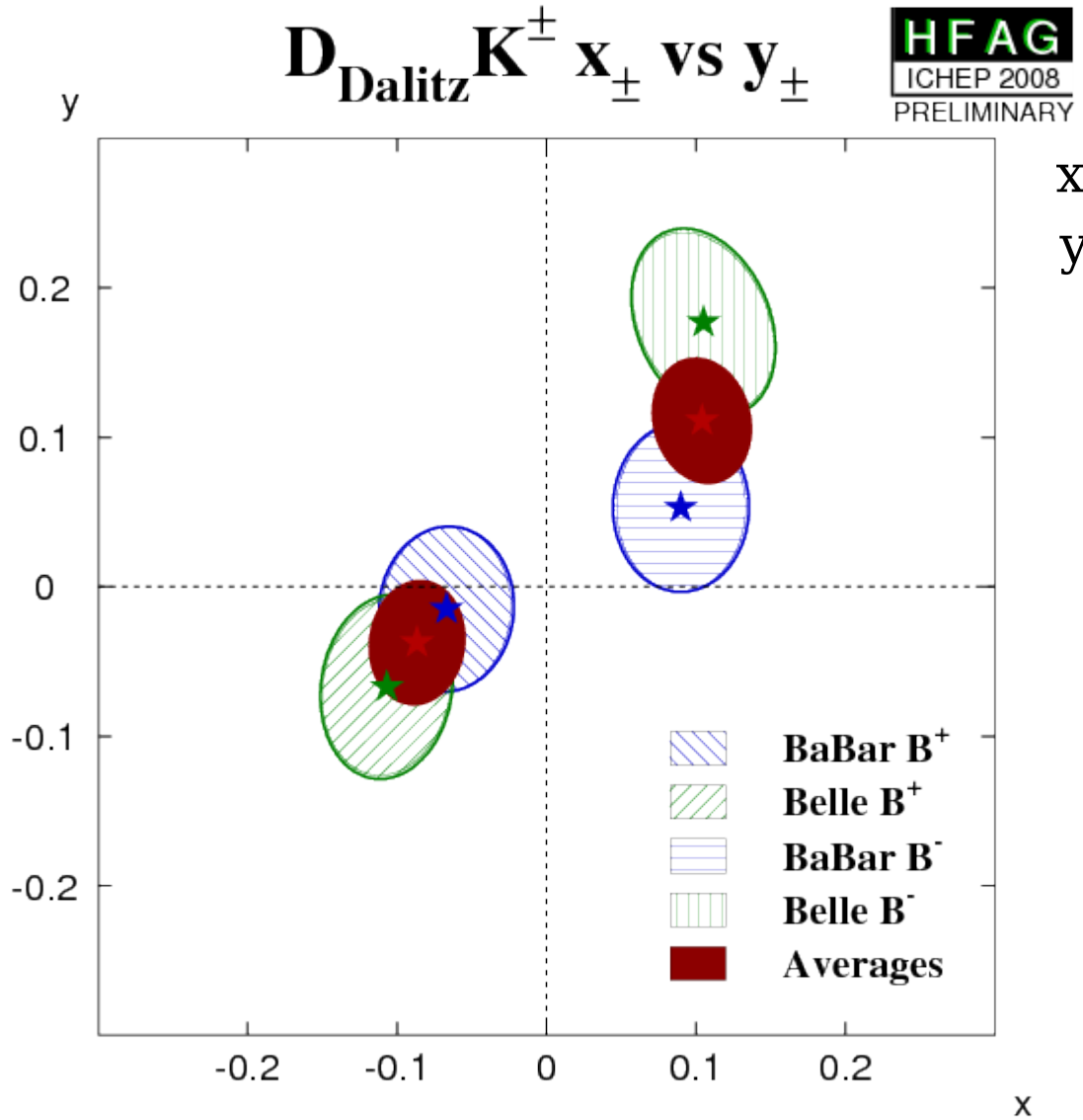
$\delta_B = 109^\circ{}^{+28^\circ}_{-31^\circ}\pm4^\circ\pm7^\circ$

$\kappa r_s = 0.163^{+0.088}_{-0.105}\pm0.037\pm0.021$

$\delta_s = 104^\circ{}^{+43^\circ}_{-41^\circ}\pm17^\circ\pm5^\circ$

combining all these modes: $\gamma = (76 \pm 22 \pm 5 \pm 5)^\circ$

Dalitz B→DK



$$x_{\pm} = r_B \cos(\delta_B \pm \gamma)$$
$$y_{\pm} = r_B \sin(\delta_B \pm \gamma)$$

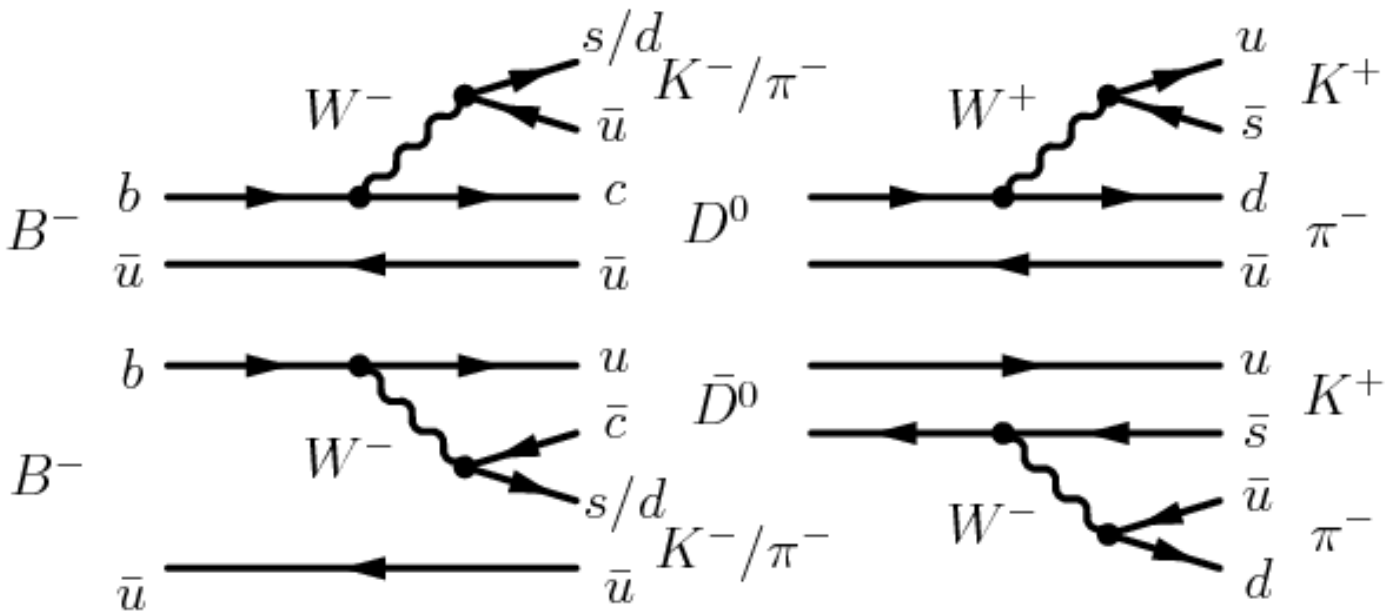
DK, Belle

$$\gamma = 80.8^{\circ}{}^{+13.1^{\circ}}_{-14.8^{\circ}} \pm 5.0^{\circ} \pm 8.7^{\circ}$$
$$r_B = 0.161^{+0.040}_{-0.038} \pm 0.011 \pm 0.049$$
$$\delta_B = 137.4^{\circ}{}^{+13.0^{\circ}}_{-15.7^{\circ}} \pm 4.0^{\circ} \pm 22.9^{\circ}$$

DK, BaBar

$$\gamma \sim 63^{\circ} \pm 28^{\circ}$$
$$r_B = 0.086 \pm 0.035$$
$$\delta_B = 109^{\circ}{}^{+28^{\circ}}_{-31^{\circ}}$$

ADS method: $D \to K\pi$



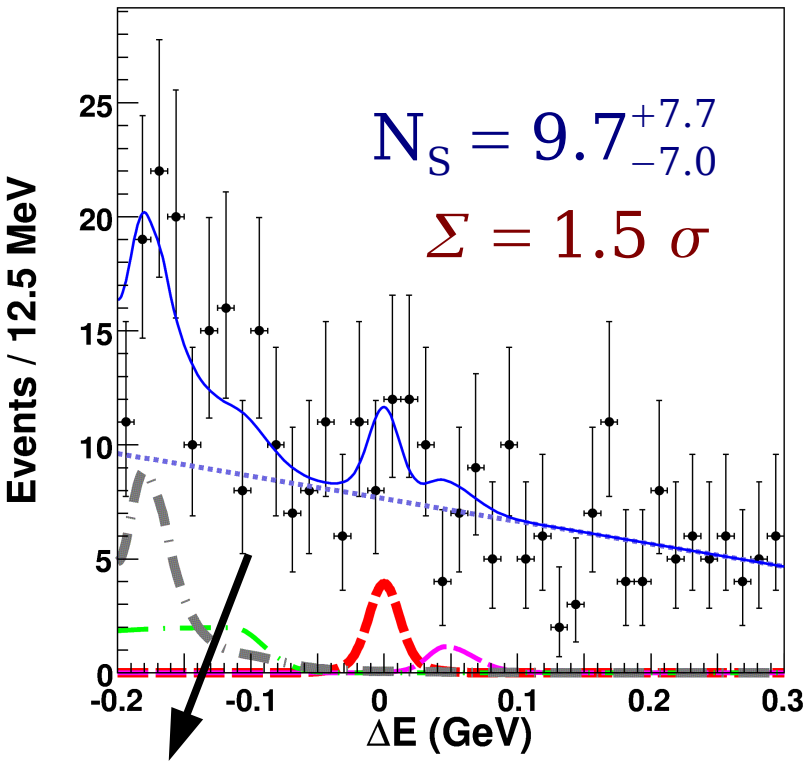
- interfering amplitudes are comparable
- introduce 2 new parameters: r_D, δ_D
- but measured by CLEO ($\to$ BESIII)
- continuum background dominates

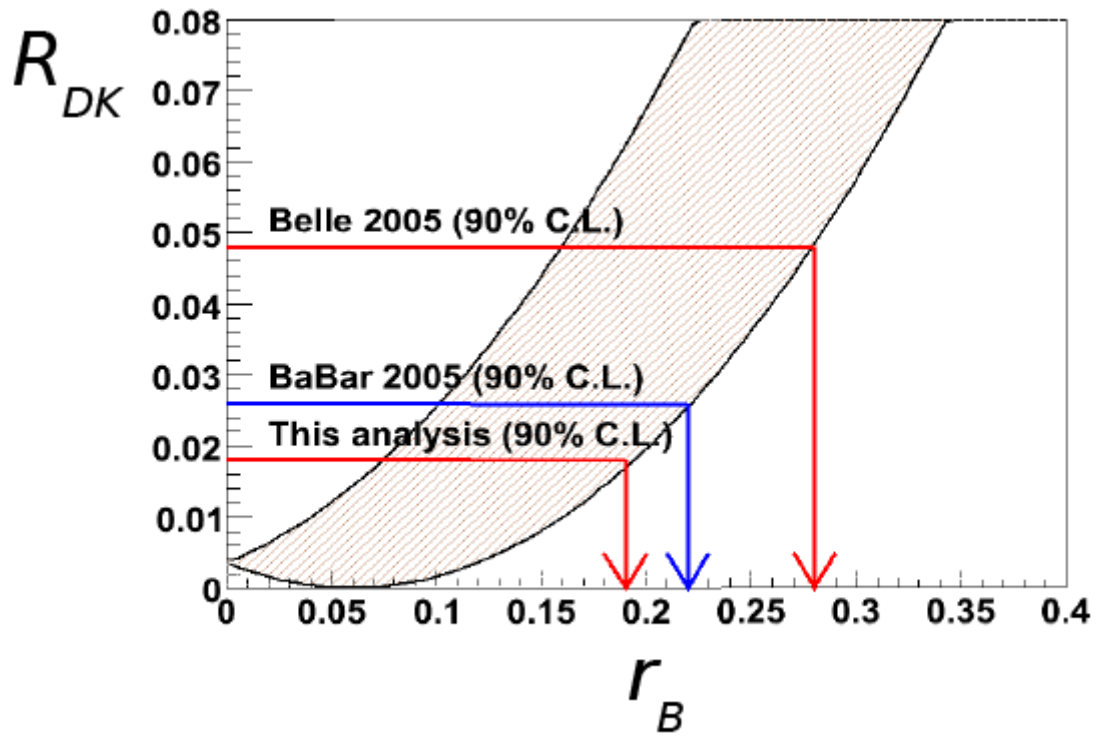
ADS method

$D^0 \to K^+ \pi^-$

657×10^6 $B\bar{B}$ pairs
[PRD 78, 071901 (2008)]

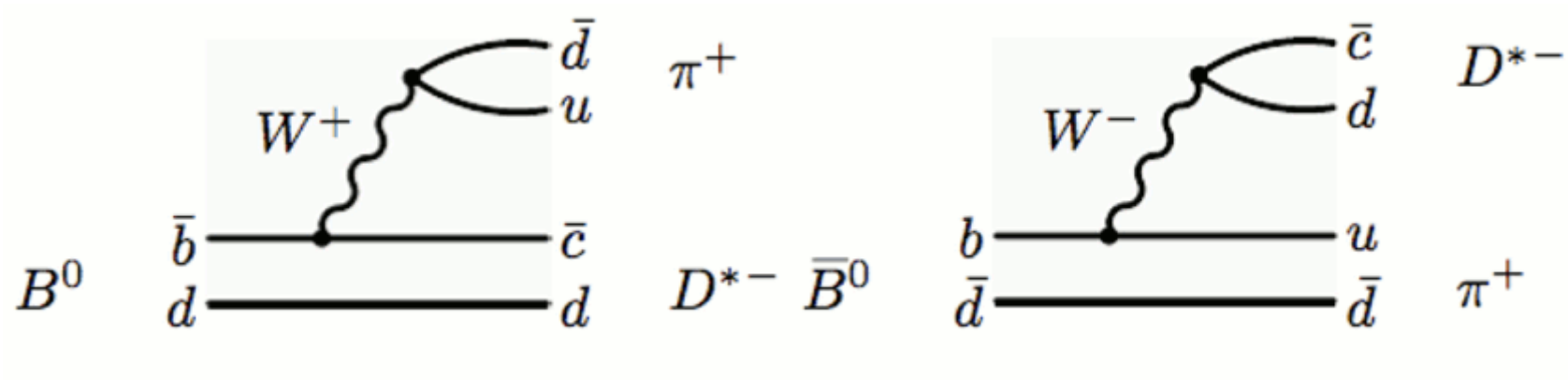
same δ_B, r_B
additional parameters (δ_D, r_D)





No signal observed yet, limit on r_B: < 0.19 at 90% C.L.

$\sin(2\beta+\gamma)$ from $B^0 \to D^{(*)}\pi$ decay



Use B flavor tag, measure time-dependent decay rates

$$P(B^0 \to D^{(*)\pm}\pi^{\mp}) = \frac{1}{8\tau_B} e^{-|\Delta t|/\tau_B}\left[1 \mp \mathbf{C}\cos(\Delta m \Delta t) - \mathbf{S}^{\pm}\sin(\Delta m \Delta t)\right]$$

$$P(\bar{B}^0 \to D^{(*)\pm}\pi^{\mp}) = \frac{1}{8\tau_B} e^{-|\Delta t|/\tau_B}\left[1 \pm \mathbf{C}\cos(\Delta m \Delta t) + \mathbf{S}^{\pm}\sin(\Delta m \Delta t)\right]$$

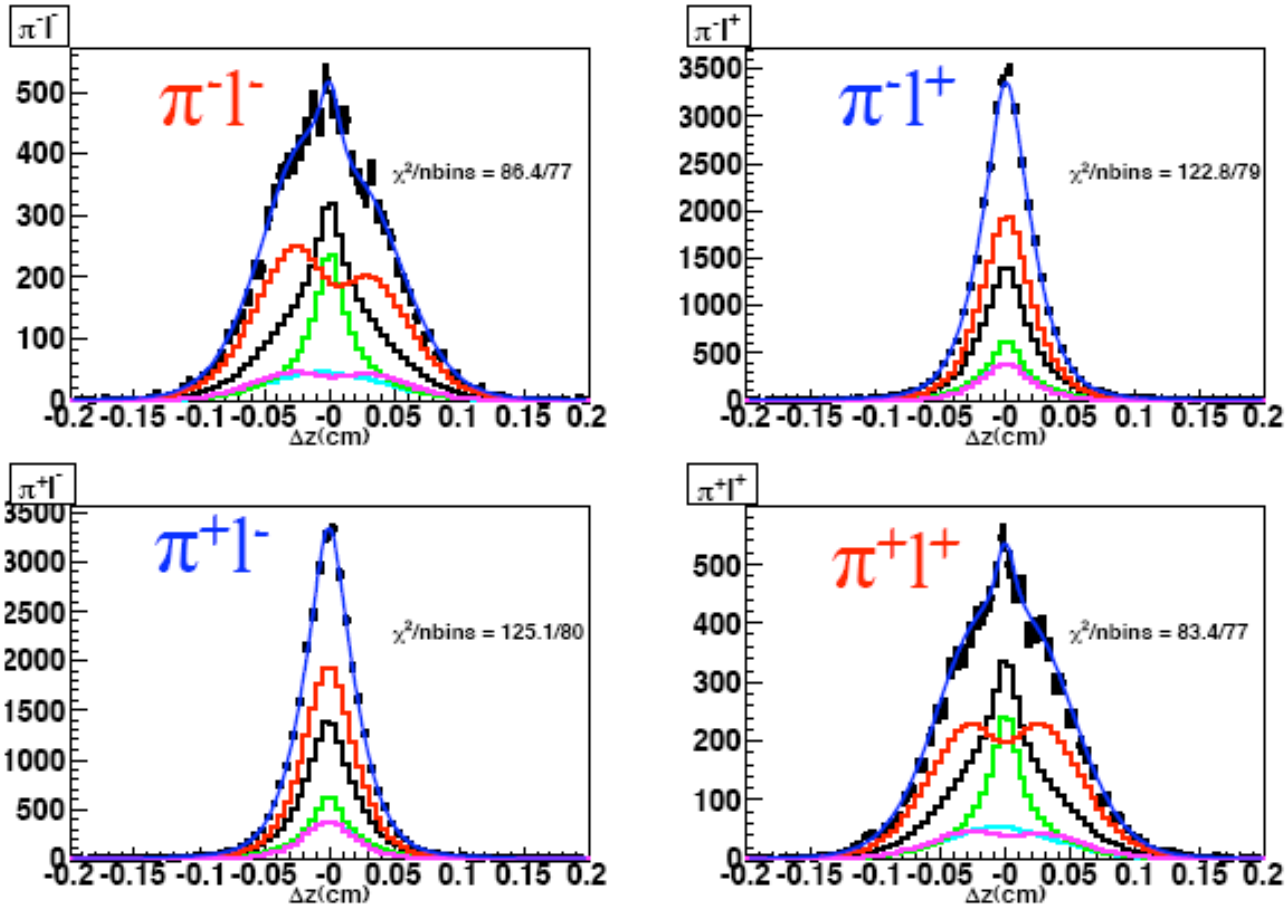
$$\mathbf{S}^{\pm} = -2r\sin(2\beta+\gamma\pm\delta_{D^*\pi}) \qquad \mathbf{C} = \frac{1-r^2}{1+r^2} \approx 1 \qquad r \approx 0.02$$

$\Rightarrow$ large stat available, small CP violation effect

$D^*\pi$ with partial reconstruction

$657\times10^6\,B\bar{B}$ pairs
[ArXiv:0809.3203]

- partial reconstruction helps increase statistics
- lepton tag (50196±286 signal evts)



$D^{*+}\pi^-$
signal
combined
bkg.

$$S^+ = 0.057\pm0.019\pm0.012$$
$$S^- = 0.038\pm0.020\pm0.010$$

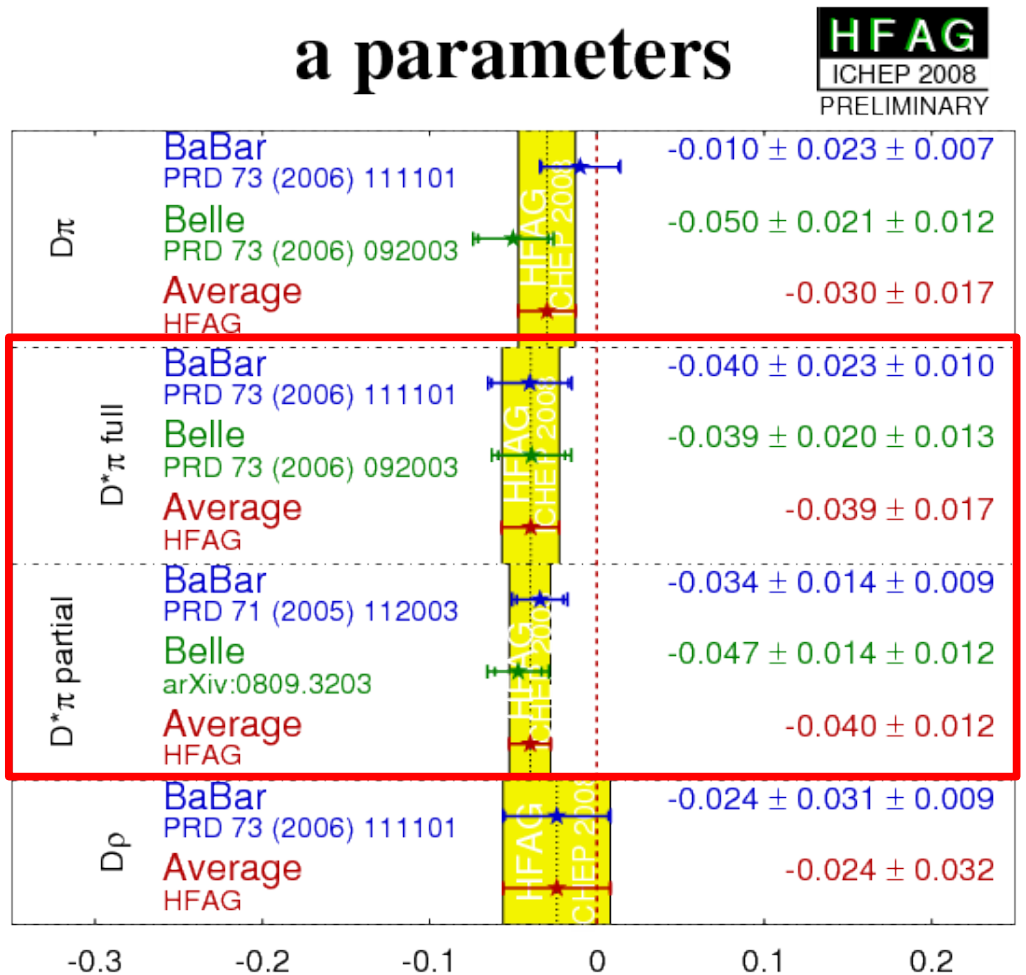
HFAG notation
$$a = -(S^+ + S^-)/2$$
$$c = -(S^+ - S^-)/2$$

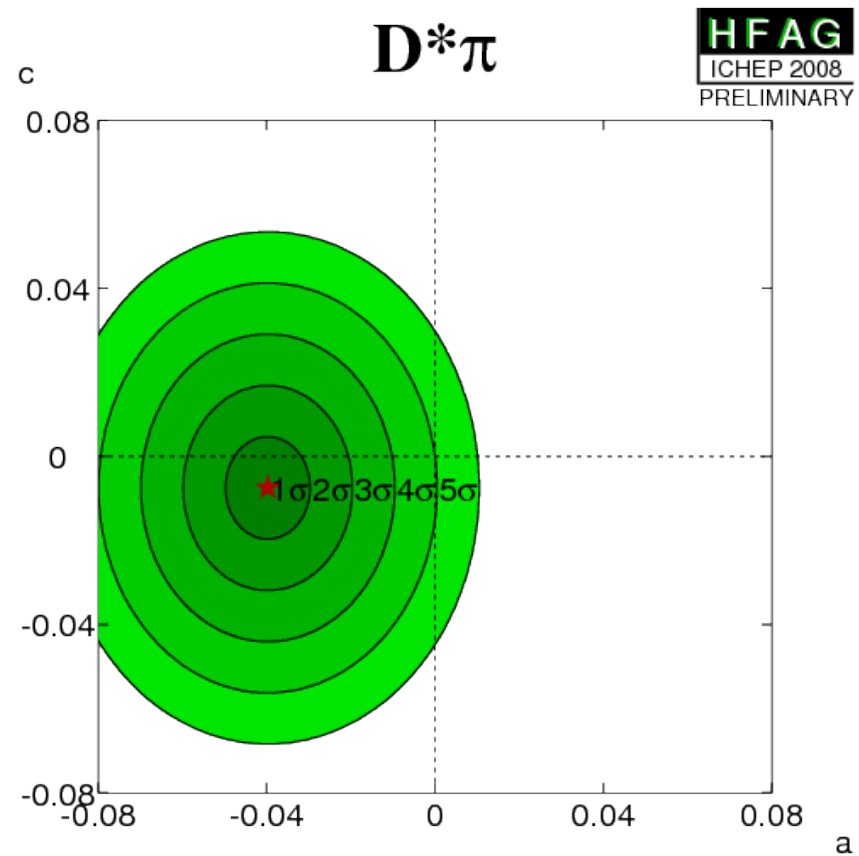
$$a = -0.047\pm0.014\pm0.012$$
$$c = -0.009\pm0.014\pm0.010$$

significance of CPV is 2.6σ

$\sin(2\beta+\gamma)$ from $B^0 \to D^{(*)}\pi$ decay

summary for all measurements (partial and full)





significance of CPV is $\sim 4\sigma$