
Measurement of CKM angle γ/φ_3

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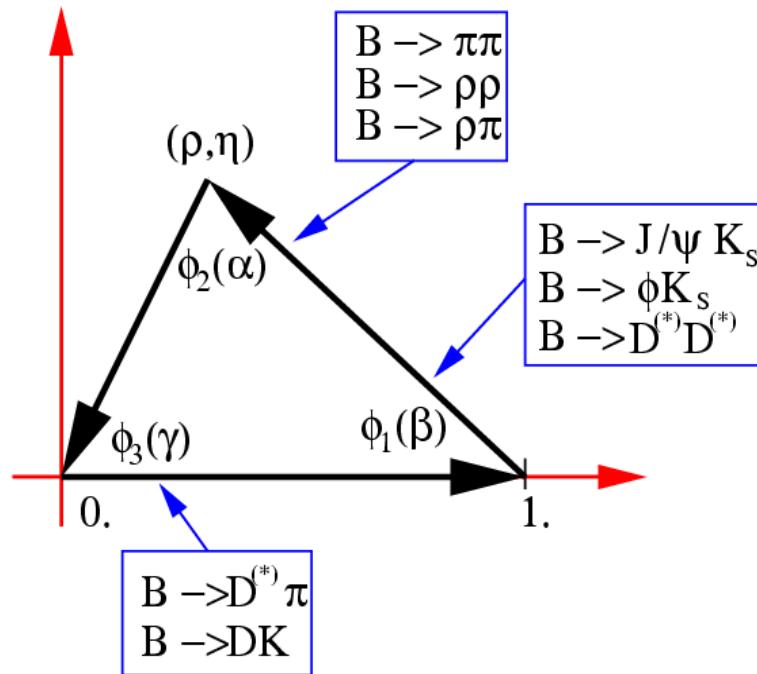
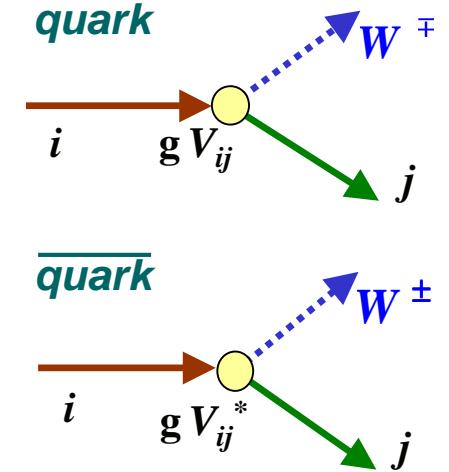
- What is γ/φ_3 ?
- Why measure γ/φ_3 ?
- How to measure γ/φ_3 ?
- What γ/φ_3 is equal to?
- How to make γ/φ_3 more precise?

What is ϕ_3/γ ?

Cabibbo-Kobayashi-Maskawa quark mixing matrix (CKM):

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

$e^{i\phi_3}$



CKM unitarity leads to triangle in complex plane:

$$\{i=1, j=3\}: V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

$$\Rightarrow \frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + 1 + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0$$

Why measure φ_3/γ ?

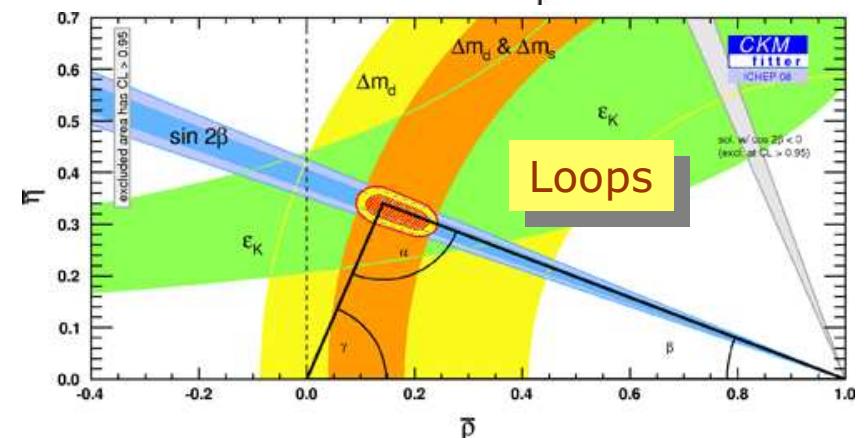
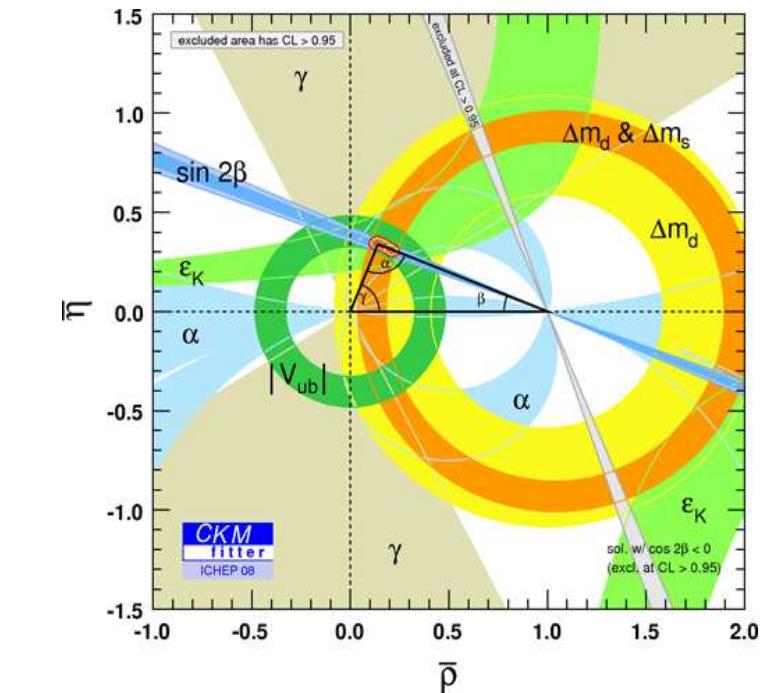
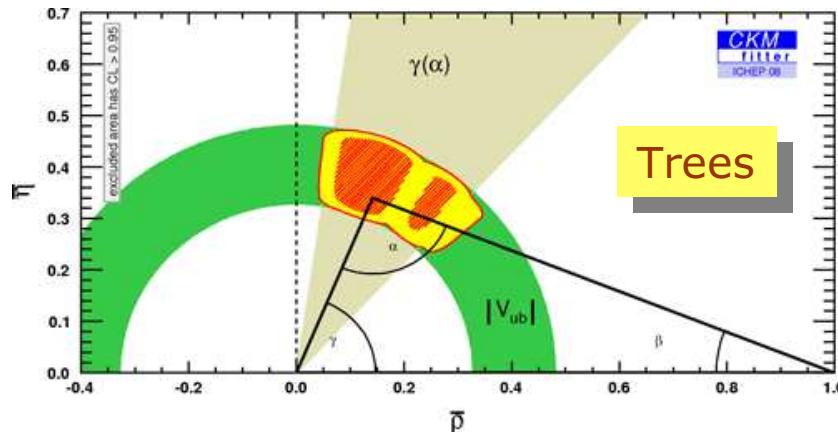
Direct angle measurements

[CKMfitter world averages, 2008]:

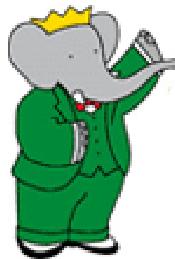
- $\varphi_1/\beta = 21.2 \pm 0.9^\circ$ ($B \rightarrow J/\psi K^0$)
- $\varphi_2/\alpha = 88.3^{+5.7}_{-4.8}^\circ$ ($B \rightarrow \rho\rho$)
- $\varphi_3/\gamma = 67^{+32}_{-25}^\circ$ ($B \rightarrow D\bar{K}$)

φ_3/γ is measured in tree decays.

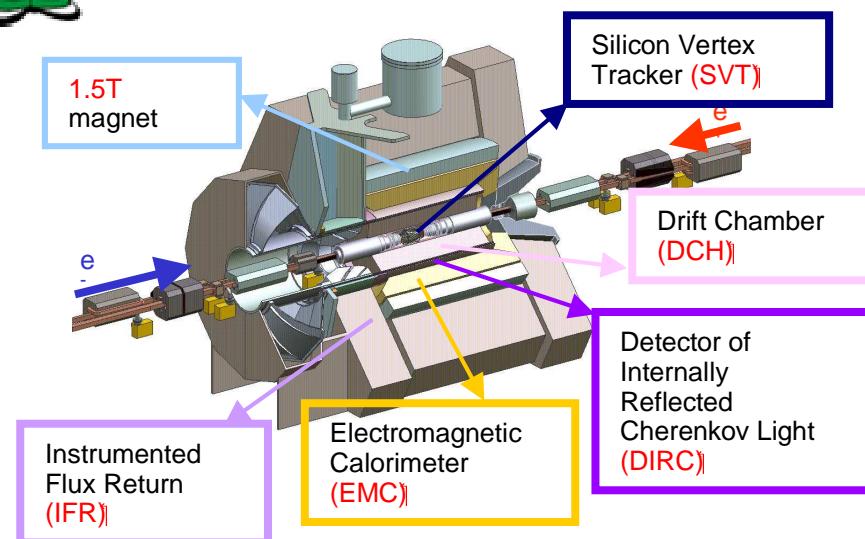
Together with $|V_{ub}|$ provides a SM reference
for new physics searches.



B-factories and detectors



BaBar experiment,
PEP-II, SLAC



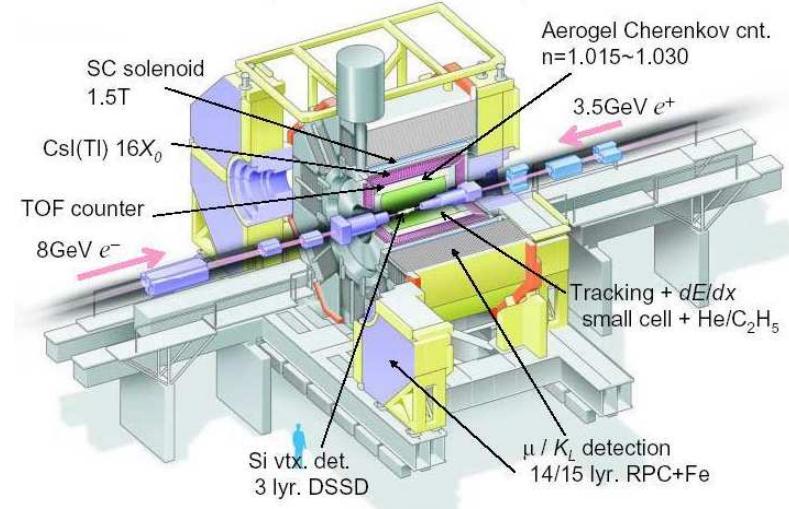
3.1 GeV e^+ & 9 GeV e^- beams

$L = 1.2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

$\int L dt = 530 \text{ fb}^{-1}$ @ $Y(4S)+\text{off}$ ($\sim 10\%$)



Belle experiment,
KEKB, KEK, Japan



3.5 GeV e^+ & 8 GeV e^- beams

$L = 1.7 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ (**world record**)

$\int L dt \sim 850 \text{ fb}^{-1}$ @ $Y(4S)+\text{off}$ ($\sim 10\%$)

More than 1 billion of $B\bar{B}$ pairs accumulated at B factories

How to measure φ_3/γ ?

CP violation enters the Standard Model as a complex phase \Rightarrow only observable in the interference.

To measure φ_3/γ , use interference of amplitudes with and without V_{ub} . Two possibilities:

- Based on $B \rightarrow DK$. Different D^0 modes can be used:

- GLW (CP eigenstates: $D^0 \rightarrow \pi\pi, KK, K\varphi, K\omega$)

Belle: 275M BB pairs ($B \rightarrow D_{CP}K, B \rightarrow D_{CP}^*K$: PRD 73 051106 (2006))

BaBar: 382M BB pairs ($B \rightarrow D_{CP}K$: arXiv:0802.4052,

$B \rightarrow D_{CP}^*K$: arXiv:0807.2408, $B \rightarrow D_{CP}K^*$: 2008 preliminary)

CDF: 1 fb⁻¹

($B \rightarrow D_{CP+}K$: arXiv:0809.4809)

- ADS (CF and DCS states: $D^0 \rightarrow K\pi, K\pi\pi, K\pi\pi\pi$)

Belle: 657M BB pairs ($B \rightarrow DK$: arXiv:0804.2063)

BaBar: 232M BB pairs ($B \rightarrow DK, B \rightarrow D^*K, B \rightarrow DK^*$ with $D \rightarrow K\pi$: PRD 72 032004 (2005))

- Dalitz (multibody states: $D^0 \rightarrow K\pi\pi, KKK, \pi\pi\pi$)

Belle: 657M BB pairs ($B \rightarrow DK, B \rightarrow D^*K$ with $D^* \rightarrow D\pi^0, D^0 \rightarrow K_S\pi^+\pi^-$: arXiv:0803.3375)

BaBar: 382M BB pairs ($B \rightarrow DK, B \rightarrow D^*K$ with $D^* \rightarrow D\pi^0, D\gamma$,

$D^0 \rightarrow K_S\pi^+\pi^-, K_SK^+K^-$: arXiv:0804.2089)

371M BB pairs ($B^0 \rightarrow D^0K^0$: Moriond EW 2008)

- Time-dependent measurement with B^0 decays ($2\varphi_1 + \varphi_3$)

Belle: 386M BB pairs ($B \rightarrow D^*\pi$ partial, $B \rightarrow D^{(*)}\pi$ full rec.: PRD 73 092003 (2006))

BaBar: 232M BB pairs ($B \rightarrow D^*\pi$ partial: PRD 71 112003 (2005),

$B \rightarrow D^{(*)}\pi, D\rho$ full rec.: PRD 73 111101 (2006))

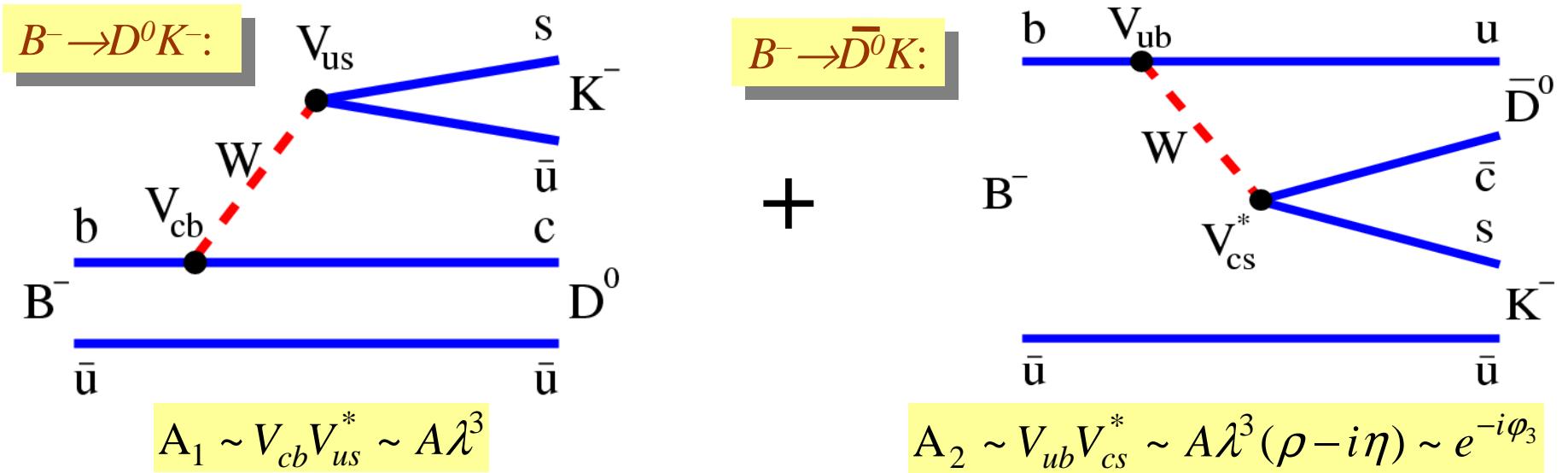
347M BB pairs ($B \rightarrow DK\pi$ time-dependent Dalitz: arXiv:0712.3469)

Interference in final state
(D^0 and \bar{D}^0)

Interference in production
(B^0 - \bar{B}^0 mixing)

How to measure φ_3/γ ? $B^+ \rightarrow D^0 K^+$ decay

Use interference on V_{ub} and V_{cb} amplitudes in B decay final state:



Amplitudes interfere if D^0 and \bar{D}^0 decay into the same final state $|D^0\rangle + re^{i\theta}|\bar{D}^0\rangle$

Relative phase: $\theta_- = -\varphi_3 + \delta$ ($B^- \rightarrow D K^-$), $\theta_+ = \varphi_3 + \delta$ ($B^+ \rightarrow D K^+$) includes weak (φ_3/γ) and strong (δ) phase.

Magnitude of CP violation given by:

$$r_B = \left| \frac{\mathcal{A}(B^- \rightarrow D^0 K^-)}{\mathcal{A}(B^- \rightarrow \bar{D}^0 K^-)} \right| = \left| \frac{V_{ub}^* V_{cs}}{V_{cb}^* V_{us}} \right| \times [\text{color supp.}] \sim 0.1$$

B-meson selection

In $\Upsilon(4S)$ decays, pairs of B -mesons are produced (near $B\bar{B}$ threshold)

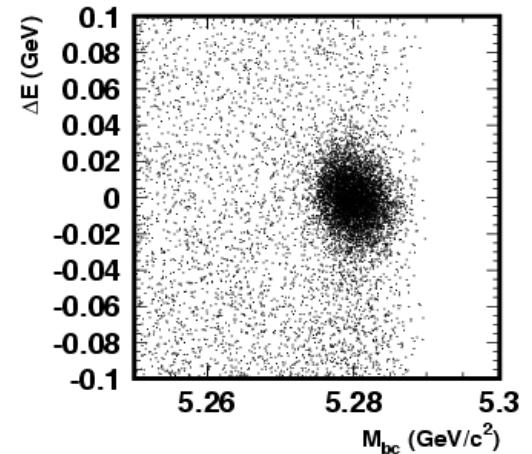
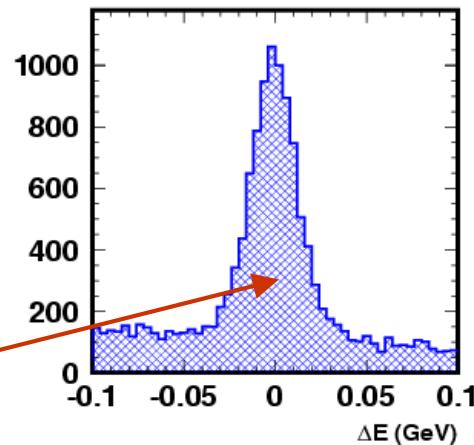
$$\Rightarrow E_B = E_{cm} / 2$$

small CM momentum (300 MeV/c)

Selection variables:

- CM energy difference:

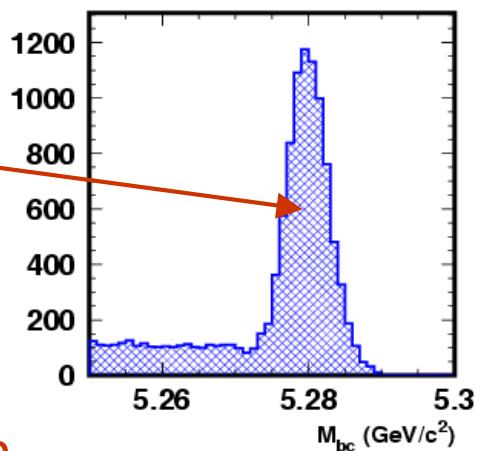
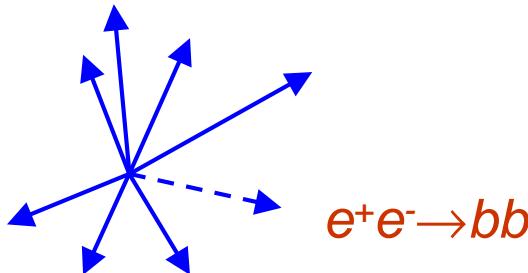
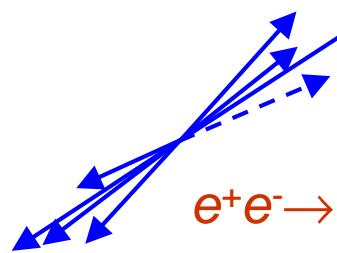
$$\Delta E = \sum E_i - (E_{cm} / 2)$$



- B -meson “beam-constrained mass” M_{bc} (Belle) or
“energy substituted mass” M_{ES} (BaBar):

$$M_{bc} = \sqrt{(E_{cm} / 2)^2 - (\sum p_i)^2}$$

- Event shape ($e^+e^- \rightarrow bb$ and $e^+e^- \rightarrow uu, dd, ss, cc$ separation):



GLW analysis: CP-eigenstates

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

CP eigenstate of D -meson is used (D_{CP}).

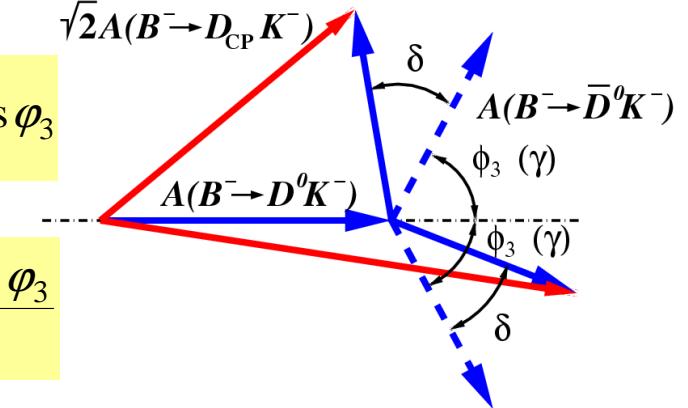
CP-even: $D_1 \rightarrow K^+ K^-$, $\pi^+ \pi^-$, CP-odd: $D_2 \rightarrow K_S \pi^0$, $K_S \omega$, $K_S \varphi$, $K_S \eta \dots$

Double ratio:

$$R_{1,2} = \frac{\text{Br}(B \rightarrow D_{1,2} K) / \text{Br}(B \rightarrow D_{1,2} \pi)}{\text{Br}(B \rightarrow D^0 K) / \text{Br}(B \rightarrow D^0 \pi)} = 1 + r_B^2 + 2r_B \cos \delta' \cos \phi_3$$

CP-asymmetry:

$$A_{1,2} = \frac{\text{Br}(B^+ \rightarrow D_{1,2} K^+) - \text{Br}(B^- \rightarrow D_{1,2} K^-)}{\text{Br}(B^+ \rightarrow D_{1,2} K^+) + \text{Br}(B^- \rightarrow D_{1,2} K^-)} = \frac{2r_B \sin \delta' \sin \phi_3}{R_{1,2}}$$



Sensitivity depends on hadronic parameters r_B and δ'

Alternative set of variables: $x_{\pm} = r_B \cos(\delta \pm \phi_3) = \frac{R_1(1 \mp A_1) - R_2(1 \mp A_2)}{4}$ $r_B^2 = \frac{R_1 + R_2 - 2}{2}$

BaBar collaboration, 382M BB pairs [arXiv: 0802.4052, 0807.2408]

$B \rightarrow D K$, $B \rightarrow D^* K$ modes ($D^* \rightarrow D \pi^0$, $D^* \rightarrow D \gamma$)

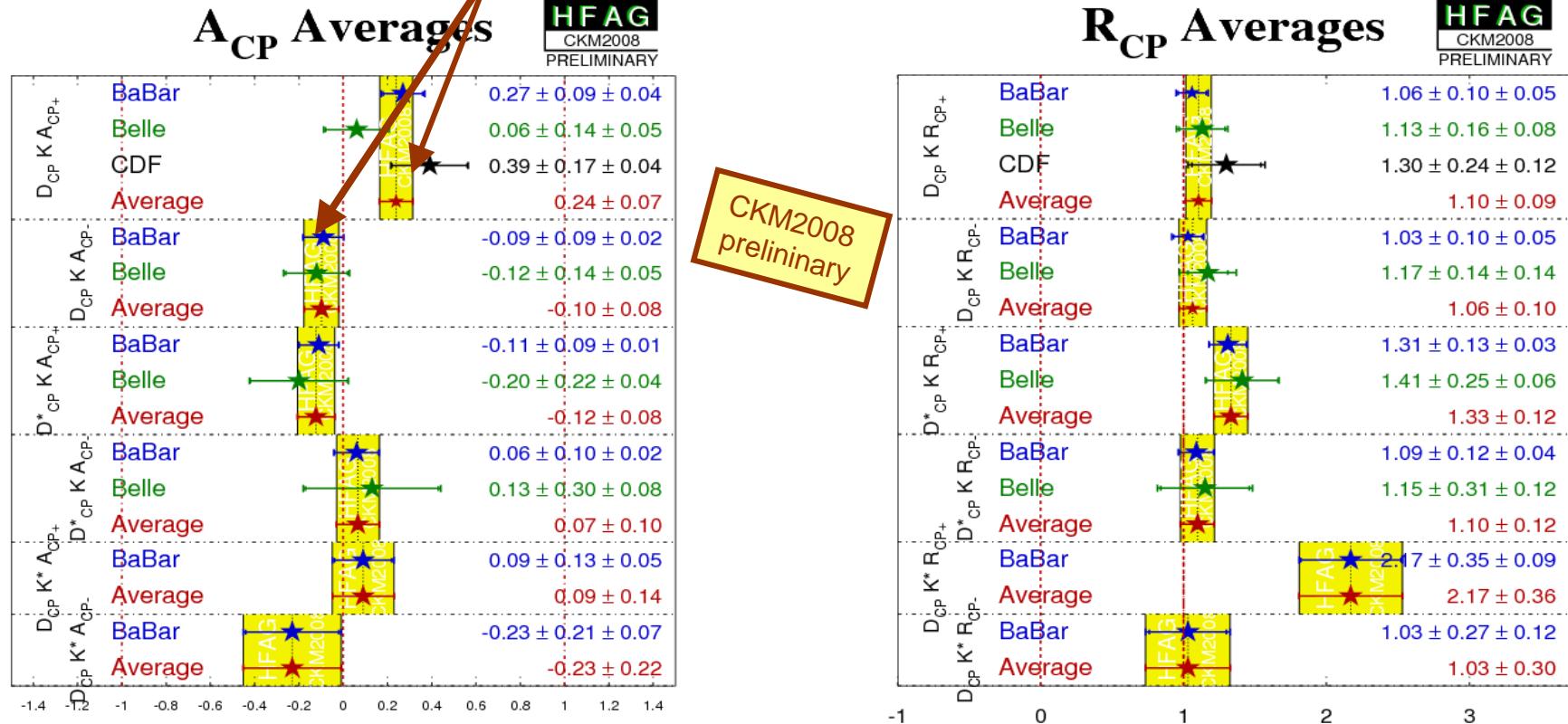
Belle collaboration, 275M BB pairs [PRD **73**, 051106 (2006)]

$B \rightarrow D K$, $B \rightarrow D^* K$ modes ($D^* \rightarrow D \pi^0$ only)

CDF collaboration, 1 fb⁻¹ [arXiv: 0809.4809] $B \rightarrow D K$ mode (only CP-even: $D \rightarrow K^+ K^-$, $\pi^+ \pi^-$)

GLW analysis: results

$$\delta' = \begin{cases} \delta & \text{for } D_1 \\ \delta + \pi & \text{for } D_2 \end{cases} \Rightarrow A_{1,2} \text{ have opposite signs}$$



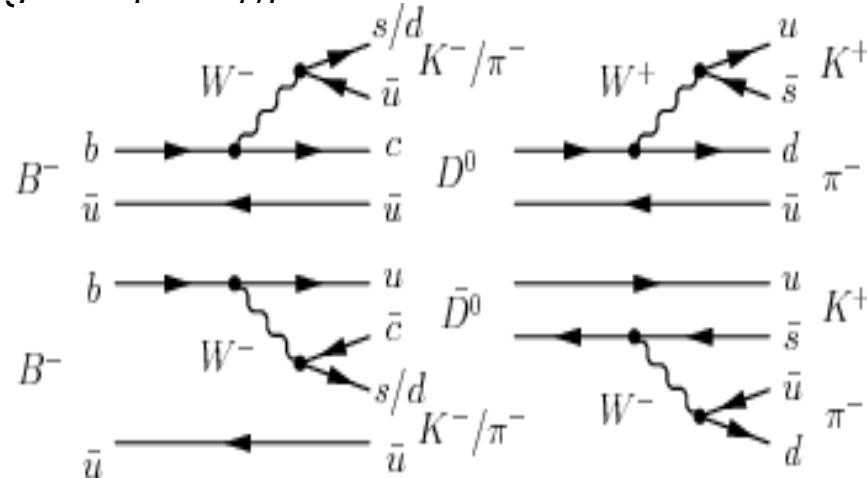
Does not provide direct measurement of φ_3/γ , but helps in combination with other methods.
Sensitivity to φ_3/γ depends on strong phase ($\delta=0, 180^\circ \Rightarrow$ no sensitivity)

ADS analysis: CF and DCS decays

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

Enhance magnitude of CP violation by using Doubly Cabibbo-suppressed D decays

e.g. $B^- \rightarrow [K^+ \pi^-]_D K^-$:

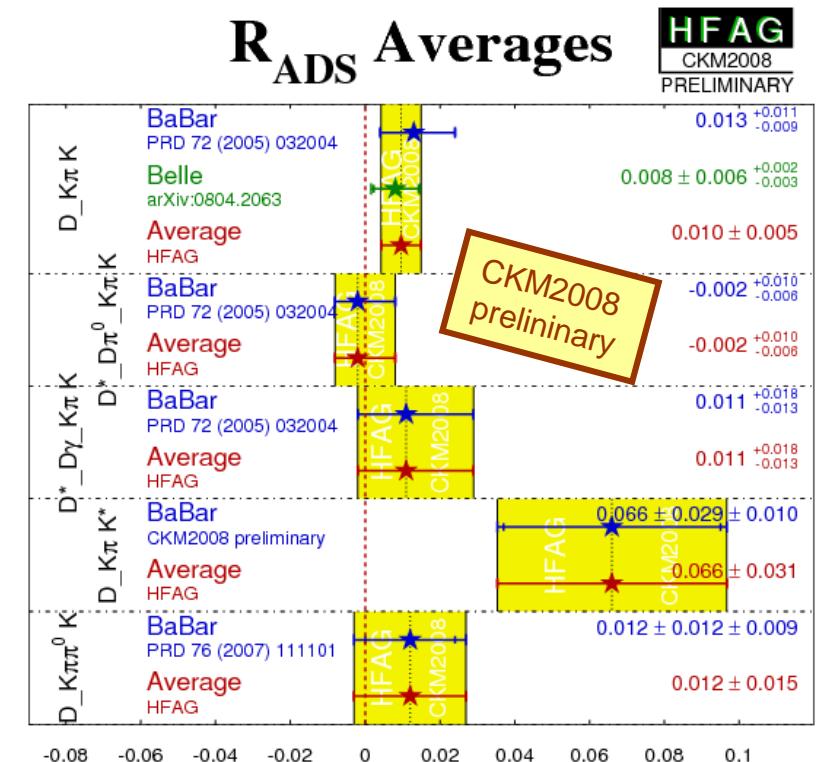


Observable:

$$R_{ADS} = \frac{Br(B \rightarrow D_{\text{supp}} K)}{Br(B \rightarrow D_{\text{fav}} K)} = r_B^2 + r_D^2 + 2r_B r_D \cos \varphi_3 \cos \delta$$

where

$$\delta = \delta_B + \delta_D, \quad r_D = \left| \frac{\mathcal{A}(D^0 \rightarrow K^- \pi^+)}{\mathcal{A}(D^0 \rightarrow K^+ \pi^-)} \right| = 0.0578 \pm 0.0008$$



CP asymmetry not observed yet,
but helpful to constrain r_B

Dalitz analysis: three-body decays

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

A. Bondar, Proc. of Belle Dalitz analysis meeting, 24-26 Sep 2002.

$$|D^0\rangle + re^{i\theta}|\bar{D}^0\rangle$$

Using 3-body final state, identical for D^0 and \bar{D}^0 : $K_s\pi^+\pi^-$ or $K_sK^+K^-$

Dalitz distribution density: $dp(m_{K_s\pi^+}^2, m_{K_s\pi^-}^2) \sim |f_B|^2 dm_{K_s\pi^+}^2 dm_{K_s\pi^-}^2$

$$|f_B(m_{K_s\pi^+}^2, m_{K_s\pi^-}^2)|^2 = \left| \begin{array}{c} \text{Dalitz plot} \\ \text{with } f_D \\ \text{and } re^{i\delta \pm i\phi_3} \end{array} \right|^2$$

complex amplitudes

$$|f_B(m_{K_s\pi^+}^2, m_{K_s\pi^-}^2)|^2 =$$

(assuming CP-conservation in D^0 decays)

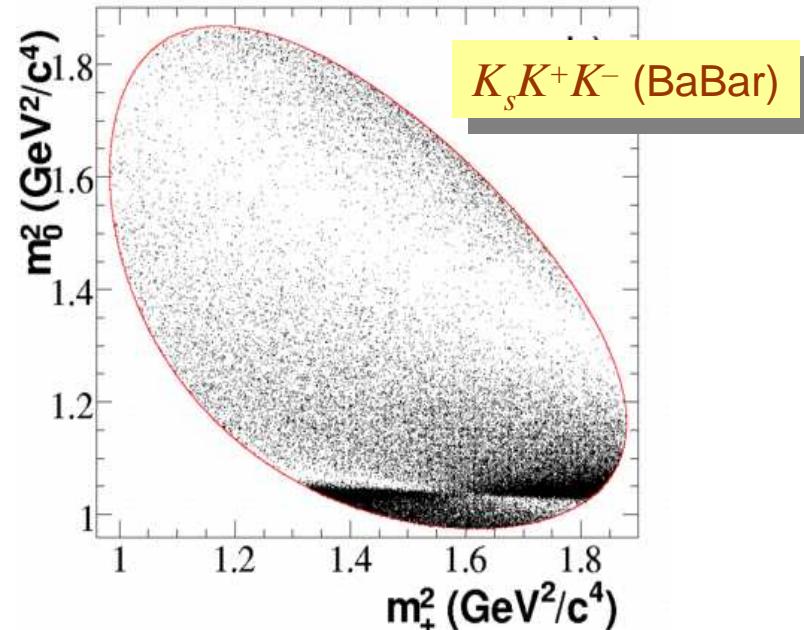
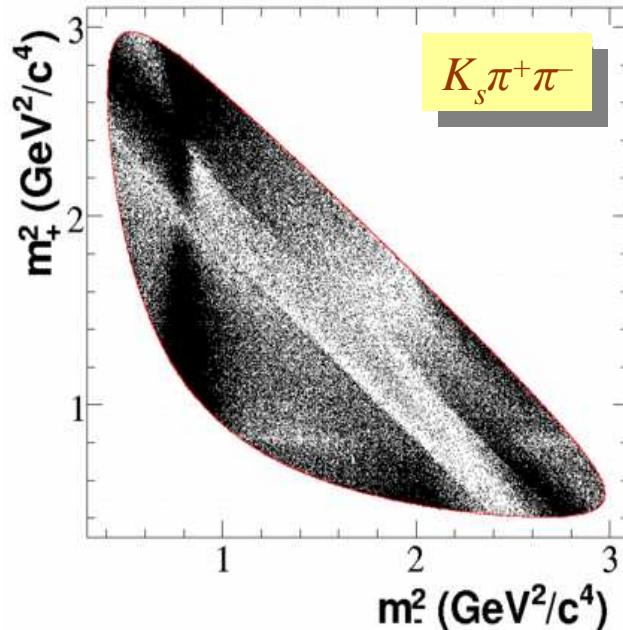
If $f_D(m_{K_s\pi^+}^2, m_{K_s\pi^-}^2)$ is known, parameters $(\phi_3/\gamma, r_B, \delta)$ are obtained from the fit to

Dalitz distributions of $D \rightarrow K_s\pi^+\pi^-$ from $B^\pm \rightarrow DK^\pm$ decays

Need to know a complex form of the D^0 decay amplitude, but only $|f_D|^2$ is obtained from $D^* \rightarrow D\pi$
⇒ Need to use model description, model uncertainty as a result

$D^0 \rightarrow K_S \pi^+ \pi^-$ and $K_S K^+ K^-$ amplitudes

Amplitudes extracted from $D^* \rightarrow D^0 \pi^\pm$ produced in continuum ($e^+ e^- \rightarrow cc$). $>10^5$ decays



$K^*(892)^\pm$, $K_0^*(1430)^\pm$, $K_2^*(1430)^\pm$,

$K^*(1680)^\pm$, $\rho(770)$, $\omega(782)$, $f_2(1270)$,

S-wave: K-matrix (BaBar)

Scalar resonances σ , f_0 , K_0^* (Belle)

$a_0(980)^0$, $\phi(1020)$, $f_0(1370)$, $f_2(1270)$,

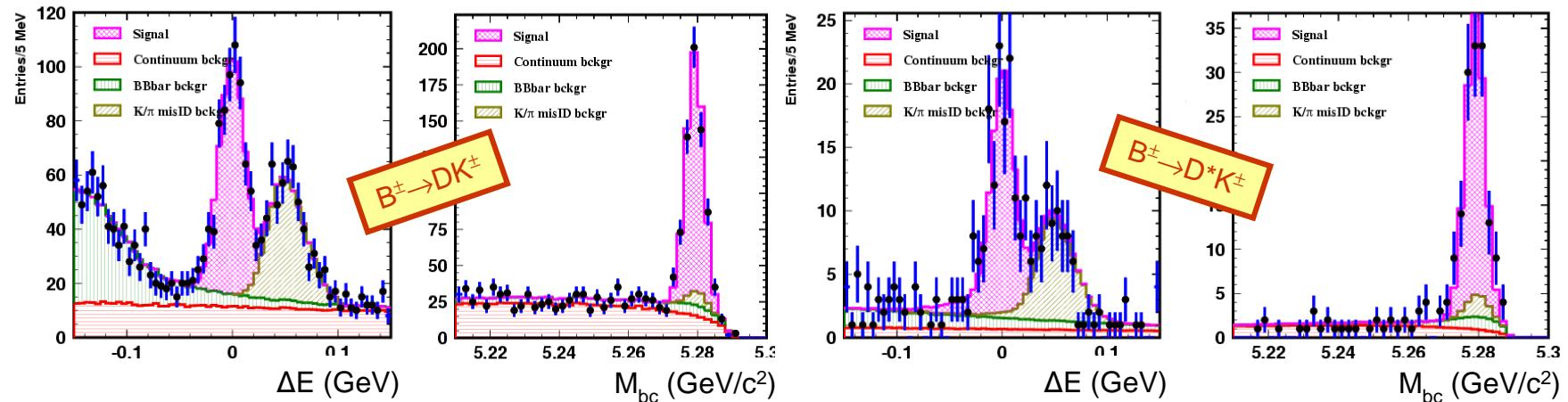
$a_0(1450)^0$, $a_0(980)^\pm$, $a_0(1450)^\pm$

Both CP- and flavor-specific states,
large phase variations across phase space
⇒ Good sensitivity to both x and y

Dalitz: signal selection (Belle)

Belle collaboration, 657M BB pairs [arXiv: 0803:3375]

[preliminary]



- $|\Delta E| < 30 \text{ MeV}$
- $M_{bc} > 5.27 \text{ GeV}/c^2$
- Continuum rejection variables: cuts to determine background composition.

Whole range is used in Dalitz fit, included into likelihood.

756 events, 29% background ($B \rightarrow DK$).
149 events, 20% background ($B \rightarrow D^* K$, $D^* \rightarrow D\pi^0$).

In “clean” signal region
($|\cos\theta_{\text{thr}}| < 0.8$, $\mathcal{F} > -0.7$)

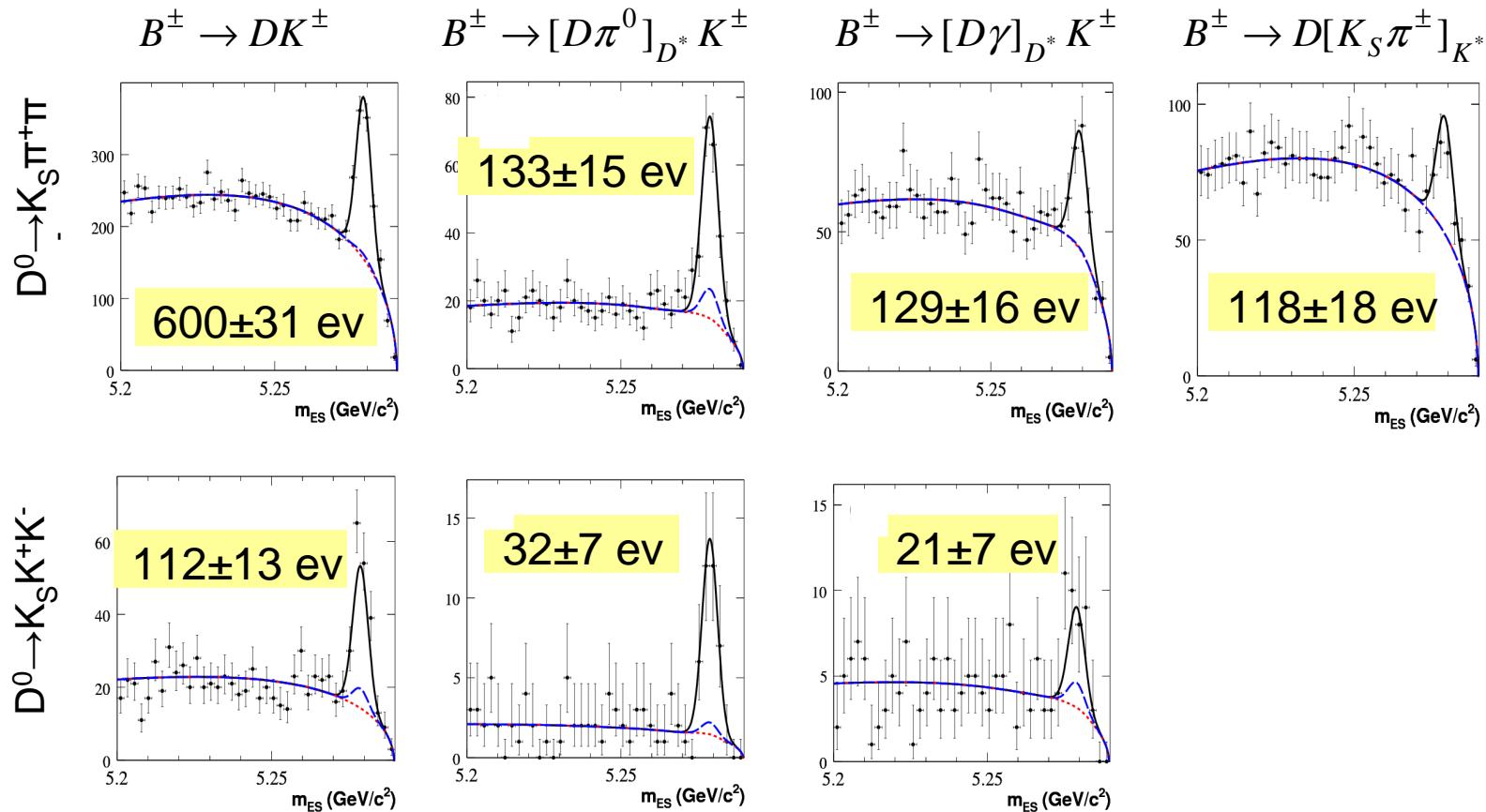
Dalitz: signal selection (BaBar)

BaBar collaboration, 383M BB pairs [arXiv: 0804:2089]

[preliminary]

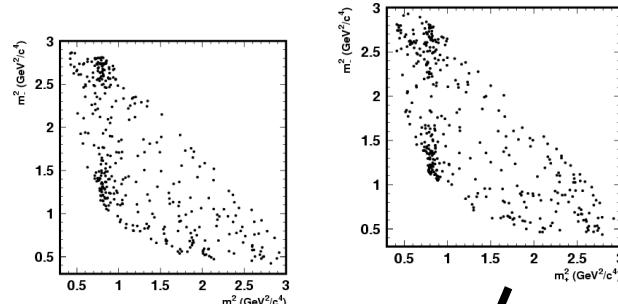
7 modes used: $B \rightarrow DK$, $B \rightarrow D^* K$ with $D^* \rightarrow D\pi^0$ and $D\gamma$, $B \rightarrow DK^*$

$D^0 \rightarrow K_S \pi^+ \pi^-$ and $K_S K^+ K^-$ (except for $B \rightarrow DK^*$)



Dalitz analysis: (x, y) fit results

Fit results expressed in Cartesian coordinates $x_{\pm} = r_B \cos(\pm\gamma + \delta)$, $y_{\pm} = r_B \sin(\pm\gamma + \delta)$

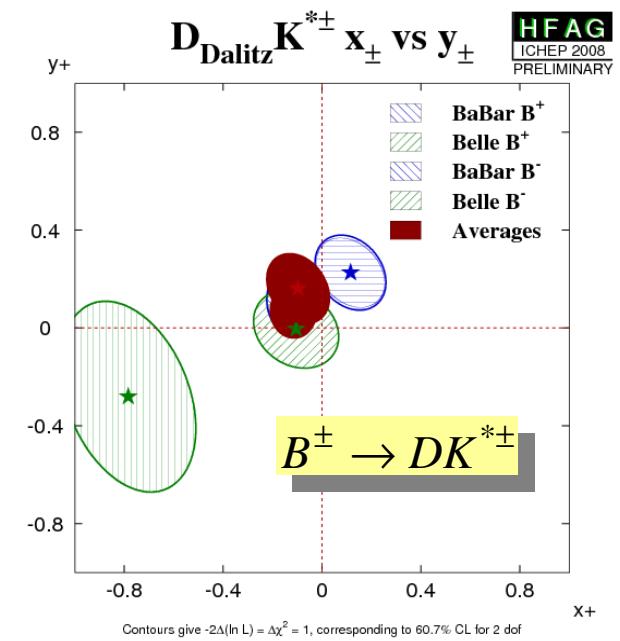
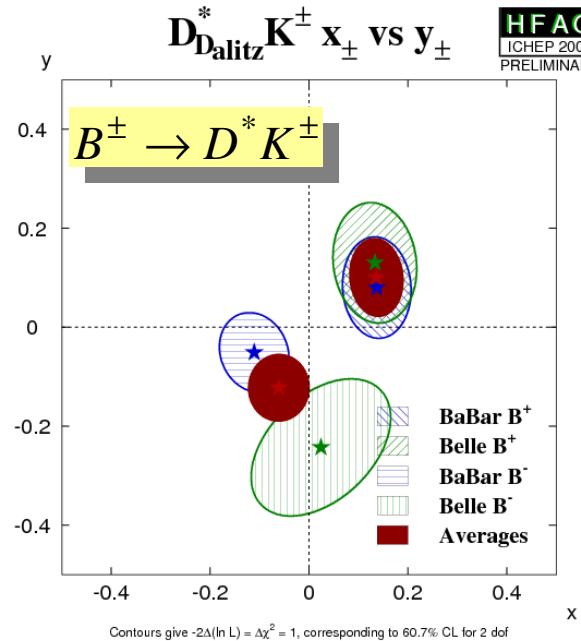
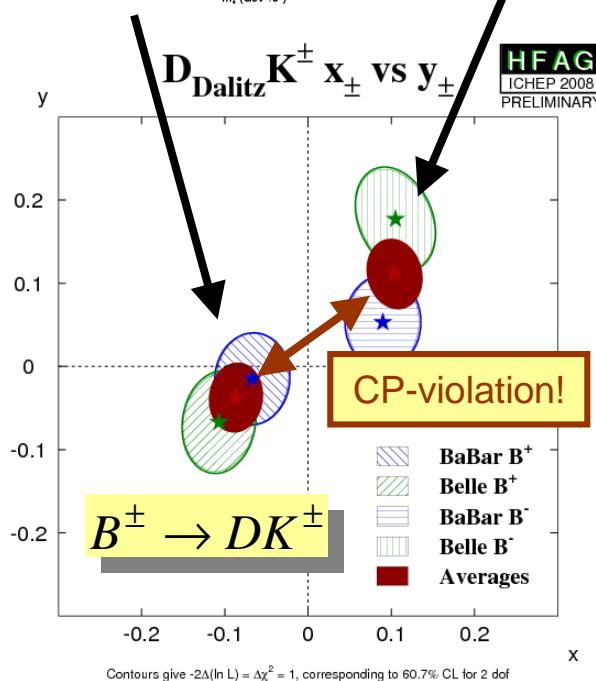


$$|\tilde{D}\rangle = |D^0\rangle + (x + iy)|\bar{D}^0\rangle$$

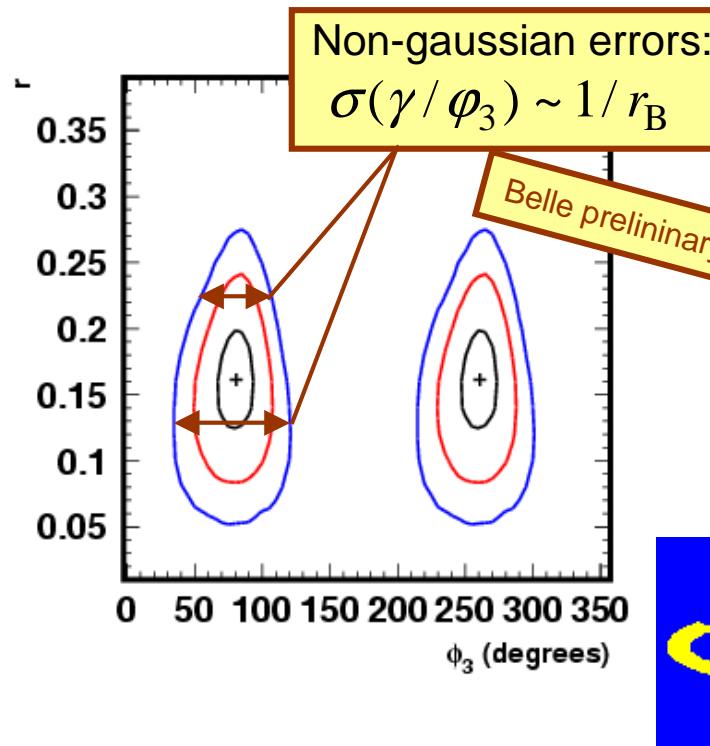
x_{\pm} is the same as in GLW

Belle collaboration, 657M BB pairs [arXiv: 0803:3375]

BaBar collaboration, 383M BB pairs [arXiv: 0804:2089]

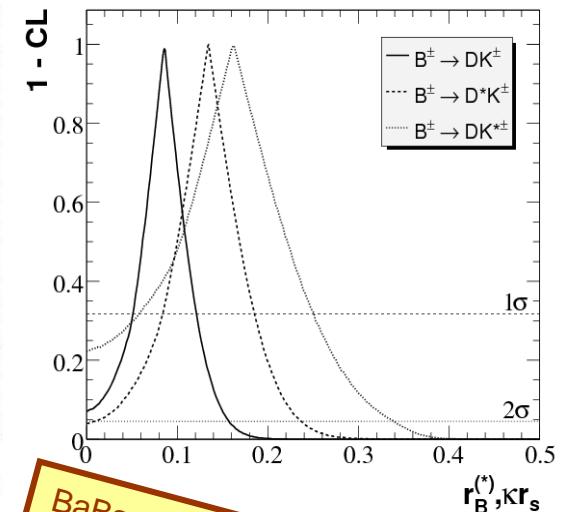
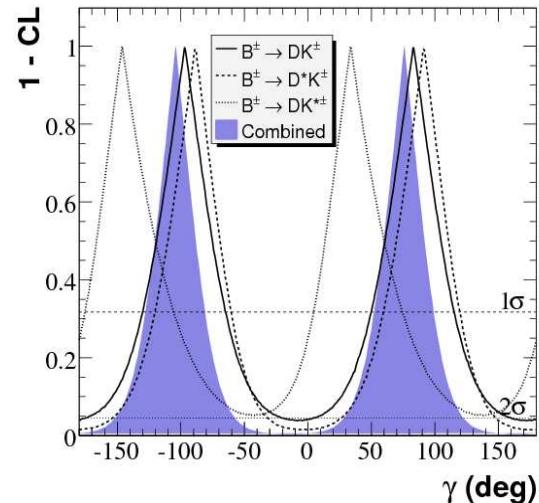


Dalitz analysis: fit results



$\phi_3 = 76^{+12}_{-13}^\circ \pm 4^\circ$ (syst) $\pm 9^\circ$ (model) 3.5σ CPV
 $r_{DK} = 0.16 \pm 0.04 \pm 0.01$ (syst) ± 0.05 (model)
 $r_{D^*K} = 0.21 \pm 0.08 \pm 0.01$ (syst) ± 0.05 (model)

Note $(\phi_3, \delta) \rightarrow (\phi_3 + 180^\circ, \delta + 180^\circ)$ ambiguity. Solution consistent with SM is shown

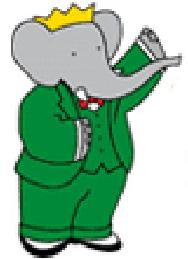


$$\gamma = 76^{+23}_{-24}^\circ \pm 5^\circ \pm 5^\circ \quad 3.0\sigma \text{ CPV}$$

$$r_B = 0.086 \pm 0.035 \pm 0.010 \pm 0.011$$

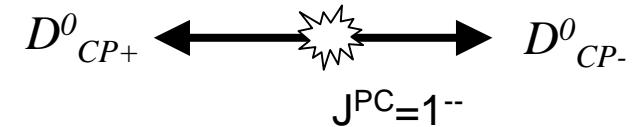
$$r_B^* = 0.135 \pm 0.051 \pm 0.011 \pm 0.005$$

$$k r_s = 0.163^{+0.088}_{-0.105} \pm 0.037 \pm 0.021$$



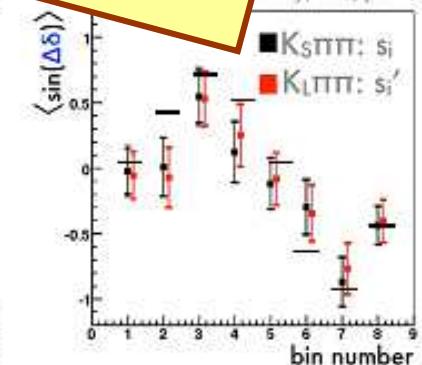
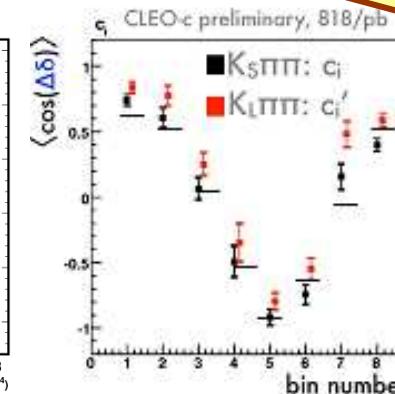
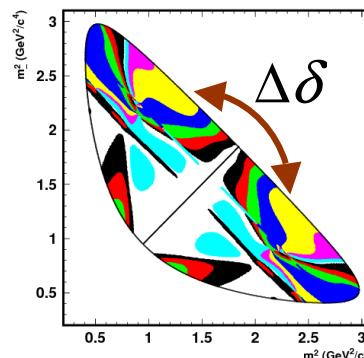
Charm factory impact on φ_3/γ

Quantum coherence in $\psi(3770) \rightarrow DD$ decays provides a unique opportunity to obtain unknown hadronic parameters in D decays needed for φ_3/γ measurement.



- Determination of D^0 amplitude for Dalitz analysis method.

Obtain $\Delta\delta(m_+^2, m_-^2)$ – difference of strong phases between symmetric phase space points
 $\Rightarrow 1-2^\circ D^0$ ampl. error



- Determination of strong phase in $D^0 \rightarrow K^- \pi^+$ in ADS mode.

$$\delta_D = (22^{+11}_{-12} {}^{+9}_{-11})^\circ \quad \text{Improve limits on } r_B$$

- Determination of coherence factors in multibody ADS modes ($D^0 \rightarrow K^- \pi^+ \pi^0, K^- \pi^+ \pi^- \pi^+$).

$$R_{ADS}(B \rightarrow (K\pi\pi\pi)_D K) = r_B^2 + r_D^2 + 2R_{K3\pi}r_B r_D \cos\varphi_3 \cos\delta$$

$$R_{K3\pi} = \begin{cases} 0 - \text{incoherent} \\ 1 - \text{fully coherent} \end{cases}$$

Dalitz: model-independent way

[A. Giri, Yu. Grossman, A. Soffer, J. Zupan, PRD 68, 054018 (2003)]

[A. Bondar, A.P., Eur. Phys. J. C47 347 (2006), Eur. Phys. J. C55 51 (2008)]

Model-independent way: obtain D^0 decay strong phase from $\psi(3770) \rightarrow D\bar{D}$ data

$$P_{B^\pm}(m_+^2, m_-^2) = |f_D + (x + iy)\bar{f}_D|^2 = P_D + r_B^2 \bar{P}_D + 2\sqrt{P_D \bar{P}_D} [x_\pm C + y_\pm S]$$

$$\begin{aligned} P_D(m_+^2, m_-^2) &= |f_D(m_+^2, m_-^2)|^2 & x_\pm &= r_B \cos(\delta \pm \varphi_3) \\ \bar{P}_D(m_+^2, m_-^2) &= |f_D(m_-^2, m_+^2)|^2 & y_\pm &= r_B \sin(\delta \pm \varphi_3) \end{aligned} \quad \left. \right\} \text{Free parameters}$$

$$\begin{aligned} C(m_+^2, m_-^2) &= \cos(\delta_D(m_+^2, m_-^2) - \delta_D(m_-^2, m_+^2)) \\ S(m_+^2, m_-^2) &= \sin(\delta_D(m_+^2, m_-^2) - \delta_D(m_-^2, m_+^2)) \end{aligned} \quad \left. \right\} \text{Unknown, can be obtained from charm data at } \psi(3770):$$

$D_{CP} \rightarrow K_S \pi^+ \pi^-$:

$$P_{CP\pm}(m_+^2, m_-^2) = |f_D \pm \bar{f}_D|^2 = P_D + \bar{P}_D \pm 2\sqrt{P_D \bar{P}_D} C$$

$\psi(3770) \rightarrow (K_S \pi^+ \pi^-)_D (K_S \pi^+ \pi^-)_D$:

$$\begin{aligned} P_{Corr}(m_+^2, m_-^2, m'_+^2, m'_-^2) &= |f_D \bar{f}'_D - \bar{f}_D f'_D|^2 = \\ &= P_D \bar{P}'_D + \bar{P}_D P'_D - 2\sqrt{P_D \bar{P}_D P'_D \bar{P}'_D} (CC' + SS') \end{aligned}$$

Technically: binned fit. Using appropriate binning, the precision comparable to unbinned fit.

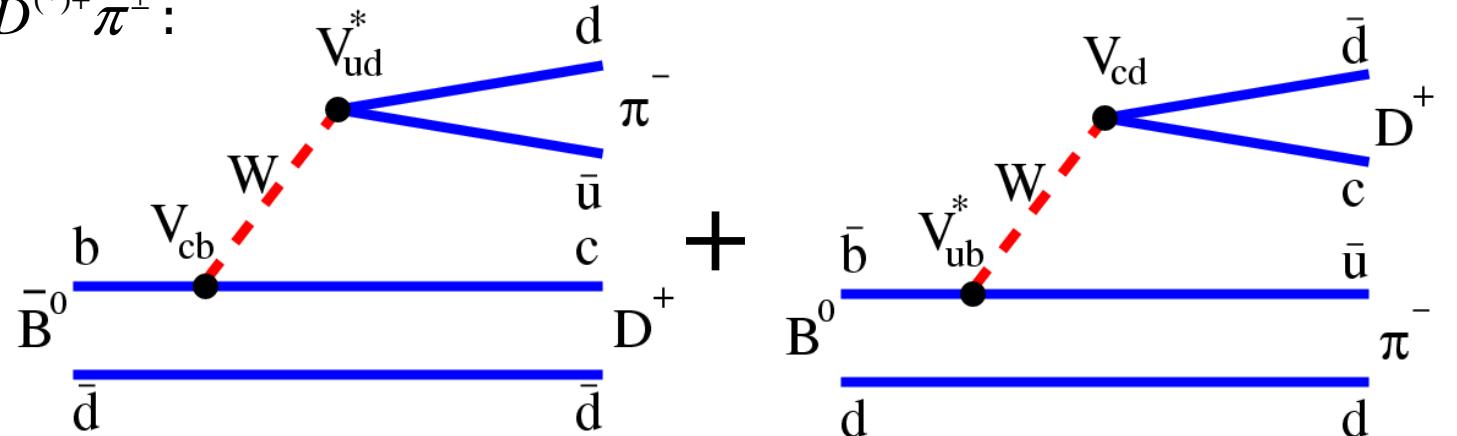
Contribution to φ_3/γ error: 2-5° with CLEO data

(but this is stat. error, more reliable than current model uncertainty)

<1° with BES data (20 fb^{-1})

$\sin(2\phi_1 + \phi_3)$ from $B^0 \rightarrow D^{(*)}\pi$ decay

Decay $B^0(\bar{B}^0) \rightarrow D^{(*)\mp}\pi^\pm$:



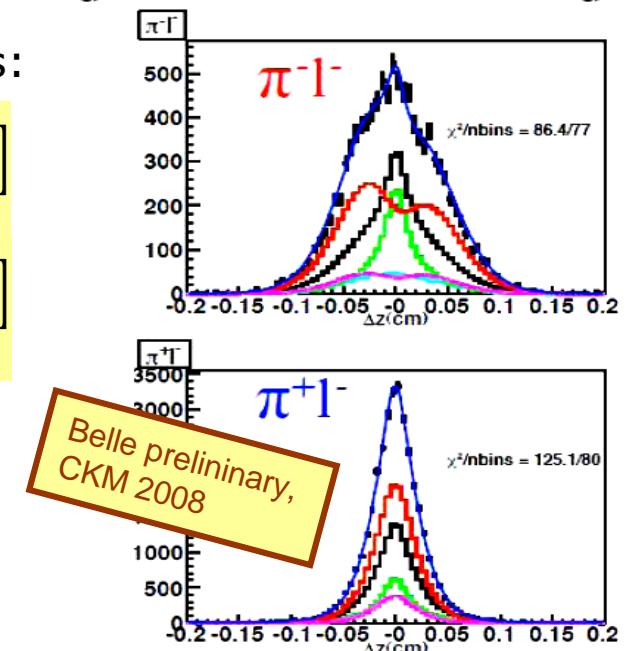
Use B flavor tag, measure time-dependent decay rates:

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

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

where $S^\pm = \frac{2R}{1+R^2} (-1)^L \sin(2\phi_1 + \phi_3 \pm \delta)$,

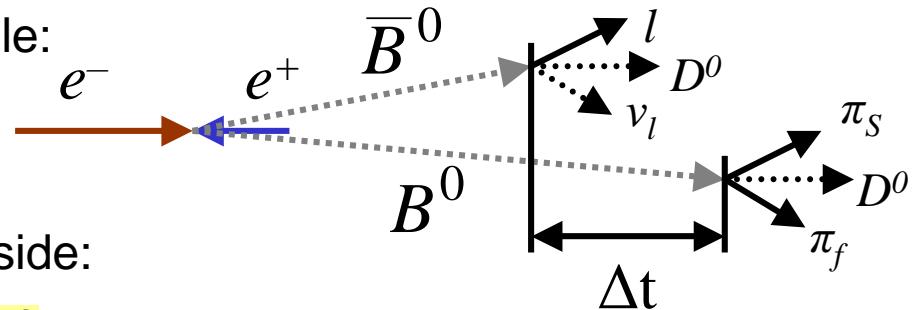
$$C = \frac{1-R^2}{1+R^2} \approx 1 \quad R \approx 0.02$$



$B^0 \rightarrow D^{(*)}\pi$: results

For $B \rightarrow D^*\pi$, partial reconstruction is possible:

For $B \rightarrow D\pi/\rho$ – full reconstruction



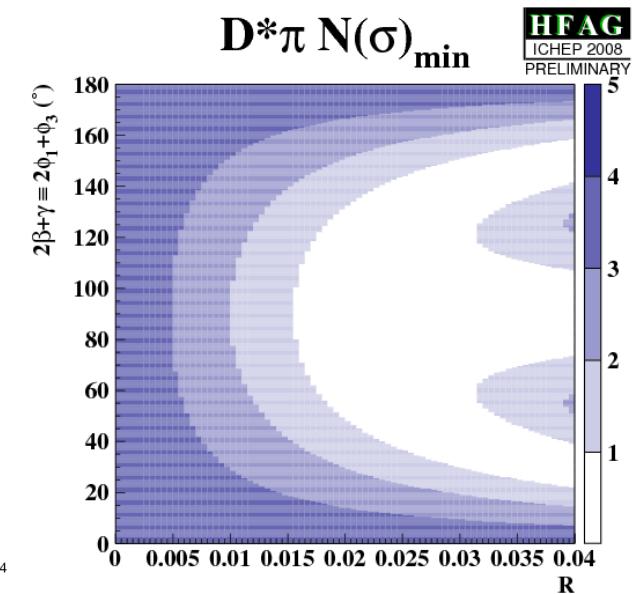
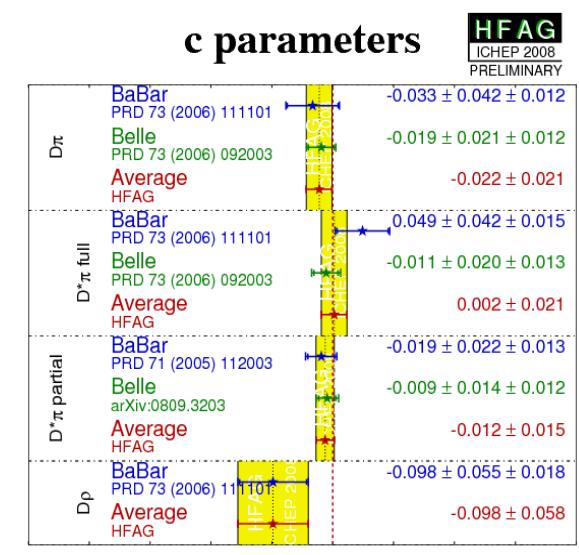
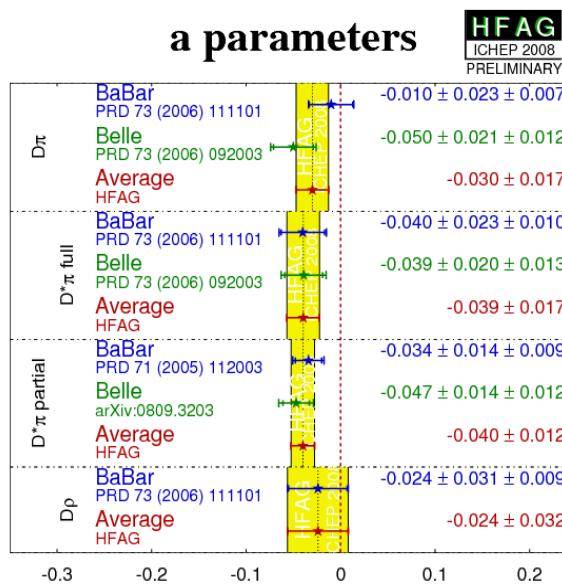
To account for possible CP-violation at tag side:

$$S^\pm = a \pm c, \text{ where}$$

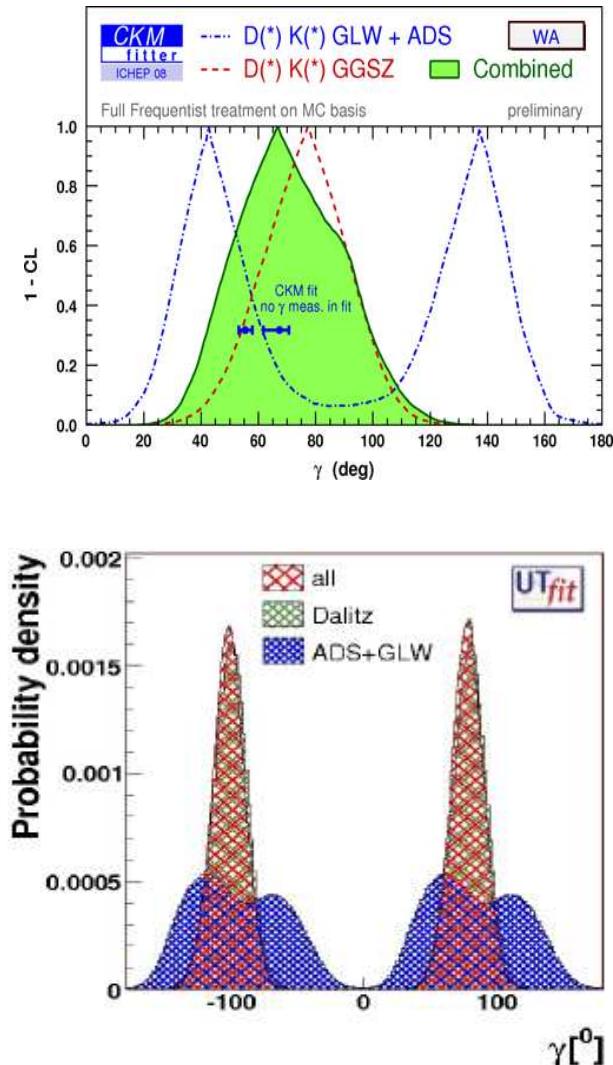
$$a = 2R \sin(2\beta + \gamma) \cos \delta$$

$$c = 2R \cos(2\beta + \gamma) \sin \delta$$

Not affected by tag-side CPV



What φ_3/γ is equal to, after all?



BaBar Dalitz measurement: 3.0σ CPV CL

$$\gamma = 76^{+23}_{-24}^\circ \pm 5^\circ (\text{syst}) \pm 5^\circ (\text{model})$$

Belle Dalitz measurement: 3.5σ CPV CL

$$\varphi_3 = 76^{+12}_{-13}^\circ \pm 4^\circ (\text{syst}) \pm 9^\circ (\text{model})$$

Stat. error difference mostly explained by different measured r_B values. Will become more Gaussian as statistics increases.

CKMfitter average $\varphi_3 / \gamma = 70^{+27}_{-29}^\circ$
(frequentist approach with guaranteed coverage, probably overestimates errors):

UTfit average $\varphi_3 / \gamma = 78 \pm 12^\circ$
(Bayesian intervals, might underestimate errors):

Summary

- γ/φ_3 provides a SM reference for New Physics searches.
- γ/φ_3 is now hard to constrain in a single mode. Combination of many measurements is needed.
- Combining all B-factory results, there is a strong evidence of CP violation in $B \rightarrow DK$. Good agreement between different measurements, both in r_B and γ/φ_3 .
- r_B is shown to be significantly non-zero. Can confidently predict future sensitivity.
- The most significant Dalitz measurement suffers from model uncertainty from D^0 amplitude (5-10%). For $\sim 1^\circ$ precision (LHCb, SuperB), charm data (CLEO-c, BES) will help. Charm factory input is essential in ADS modes, too.

Backup

GLW analysis (Belle)

Belle collaboration, 275M BB pairs [PRD 73, 051106 (2006)]

$B \rightarrow DK, B \rightarrow D^* K$ modes ($D^* \rightarrow D\pi^0$ only)

- Cut on m_{ES} , PID, event shape variables
- ΔE fit to extract yields

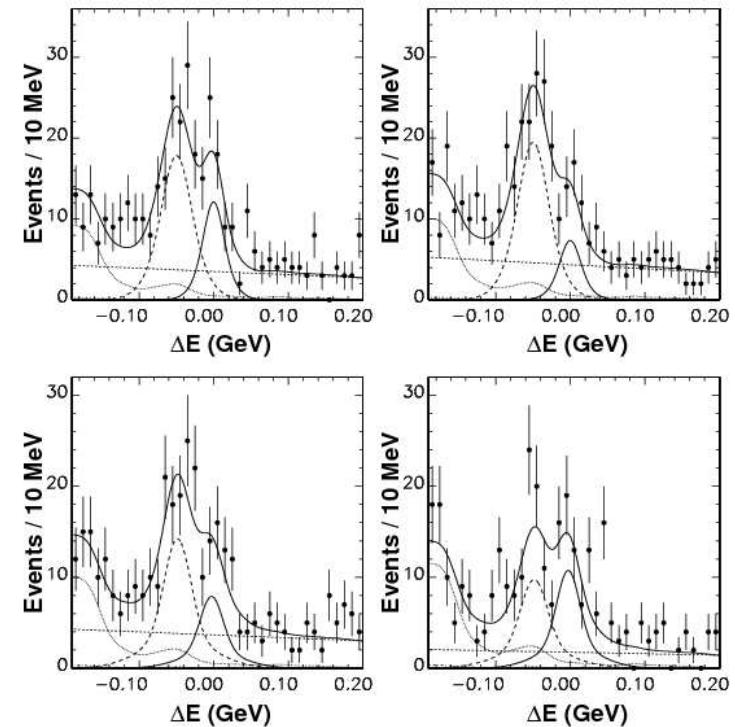
| | |
|-------|---------------------------|
| A_1 | $+0.06 \pm 0.14 \pm 0.05$ |
| A_2 | $-0.12 \pm 0.14 \pm 0.05$ |
| R_1 | $1.13 \pm 0.16 \pm 0.08$ |
| R_2 | $1.17 \pm 0.14 \pm 0.14$ |

| | |
|---------|---------------------------|
| A_1^* | $-0.20 \pm 0.22 \pm 0.04$ |
| A_2^* | $+0.13 \pm 0.30 \pm 0.08$ |
| R_1^* | $1.41 \pm 0.25 \pm 0.06$ |
| R_2^* | $1.15 \pm 0.31 \pm 0.12$ |

The same result expressed in Cartesian variables:

| | |
|-------|---------------------------|
| x_+ | $-0.06 \pm 0.08 \pm 0.05$ |
| x_- | $+0.04 \pm 0.08 \pm 0.04$ |
| r^2 | $0.15 \pm 0.11 \pm 0.08$ |

| | |
|----------|---------------------------|
| x_+^* | $+0.17 \pm 0.15 \pm 0.04$ |
| x_-^* | $-0.04 \pm 0.15 \pm 0.04$ |
| r^{*2} | $0.28 \pm 0.20 \pm 0.07$ |



GLW analysis (BaBar)

BaBar collaboration, 382M BB pairs [arXiv: 0802:4052, 0807:2408]

$B \rightarrow DK, B \rightarrow D^* K$ modes ($D^* \rightarrow D\pi^0, D^* \rightarrow D\gamma$)

- Cut on m_{ES} , event shape variables
- ΔE and Cherenkov angle included into likelihood

| | |
|-----------|---------------------------|
| A_{CP+} | $+0.27 \pm 0.09 \pm 0.04$ |
| A_{CP-} | $-0.09 \pm 0.09 \pm 0.02$ |
| R_{CP+} | $1.06 \pm 0.10 \pm 0.05$ |
| R_{CP-} | $1.03 \pm 0.10 \pm 0.04$ |

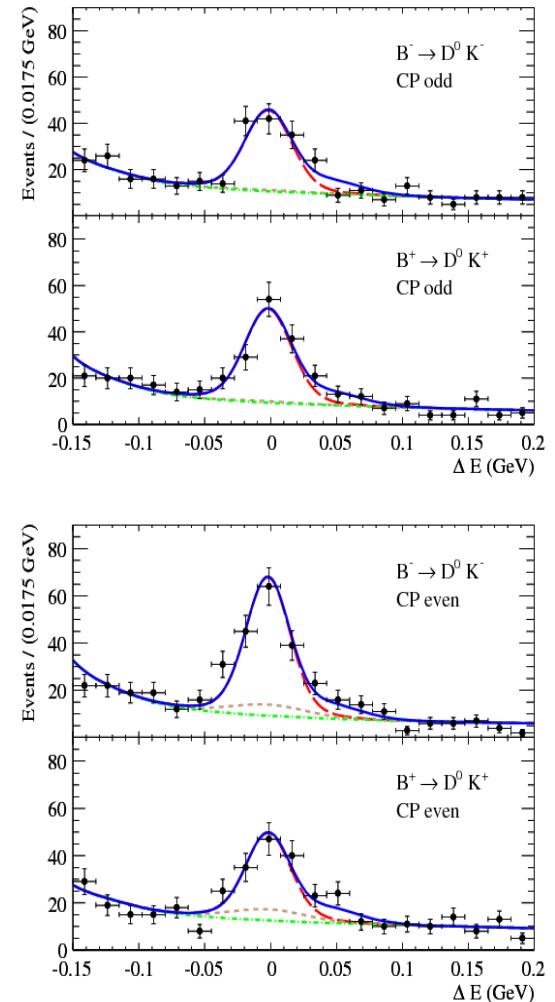
| | |
|-------------|---------------------------|
| A^*_{CP+} | $-0.11 \pm 0.09 \pm 0.01$ |
| A^*_{CP-} | $+0.06 \pm 0.10 \pm 0.02$ |
| R^*_{CP+} | $1.31 \pm 0.13 \pm 0.04$ |
| R^*_{CP-} | $1.10 \pm 0.12 \pm 0.04$ |

The same result expressed in Cartesian variables:

| | |
|-------|---------------------------|
| x_+ | $-0.09 \pm 0.05 \pm 0.02$ |
| x_- | $+0.10 \pm 0.05 \pm 0.03$ |
| r^2 | $0.05 \pm 0.07 \pm 0.03$ |

| | |
|----------|---------------------------|
| x^*_+ | $+0.09 \pm 0.07 \pm 0.02$ |
| x^*_- | $-0.02 \pm 0.06 \pm 0.02$ |
| r^{*2} | $0.22 \pm 0.09 \pm 0.03$ |

x_\pm precision comparable to Dalitz analysis



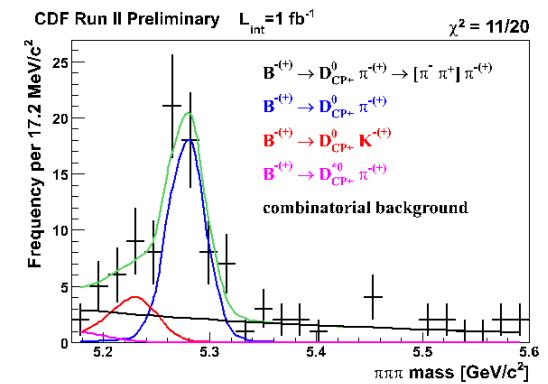
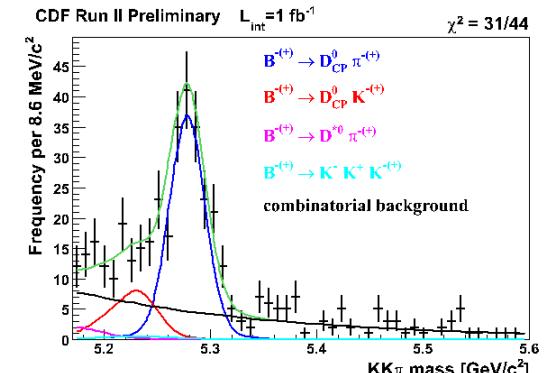
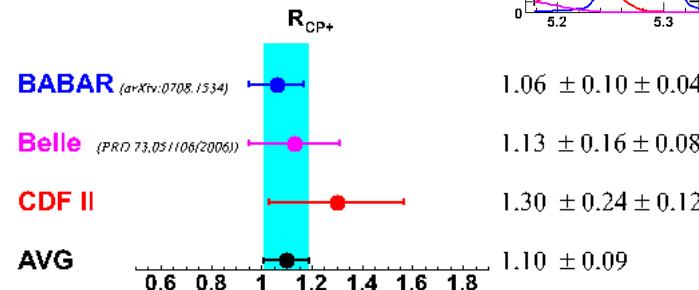
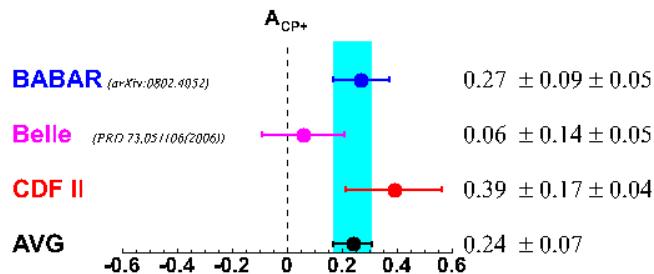
GLW analysis (CDF)

CDF collaboration, 1 fb^{-1} [CDF public note 9109]

$B \rightarrow DK$ mode (only CP-even: $D \rightarrow K^+K^-$, $\pi^+\pi^-$)

| | |
|-----------|---------------------------|
| A_{CP+} | $+0.39 \pm 0.17 \pm 0.04$ |
| R_{CP+} | $1.30 \pm 0.24 \pm 0.12$ |

Precision competitive with B-factories



ADS analysis (Belle)

Belle collaboration, 657M BB pairs [arXiv: 0804:2063, submitted to PRD(RC)]

$B^- \rightarrow [K^-\pi^+]_D K^-$ (suppressed) and $B^- \rightarrow [K^+\pi^-]_D K^-$ (favored) modes are selected.

- Cut on M_{bc} , M_D , PID likelihood, event shape
- Fit ΔE to extract signal yield

$$R_{ADS} = (8.0^{+6.3}_{-5.7} {}^{+2.0}_{-2.8}) \times 10^{-3}$$

CP asymmetry:

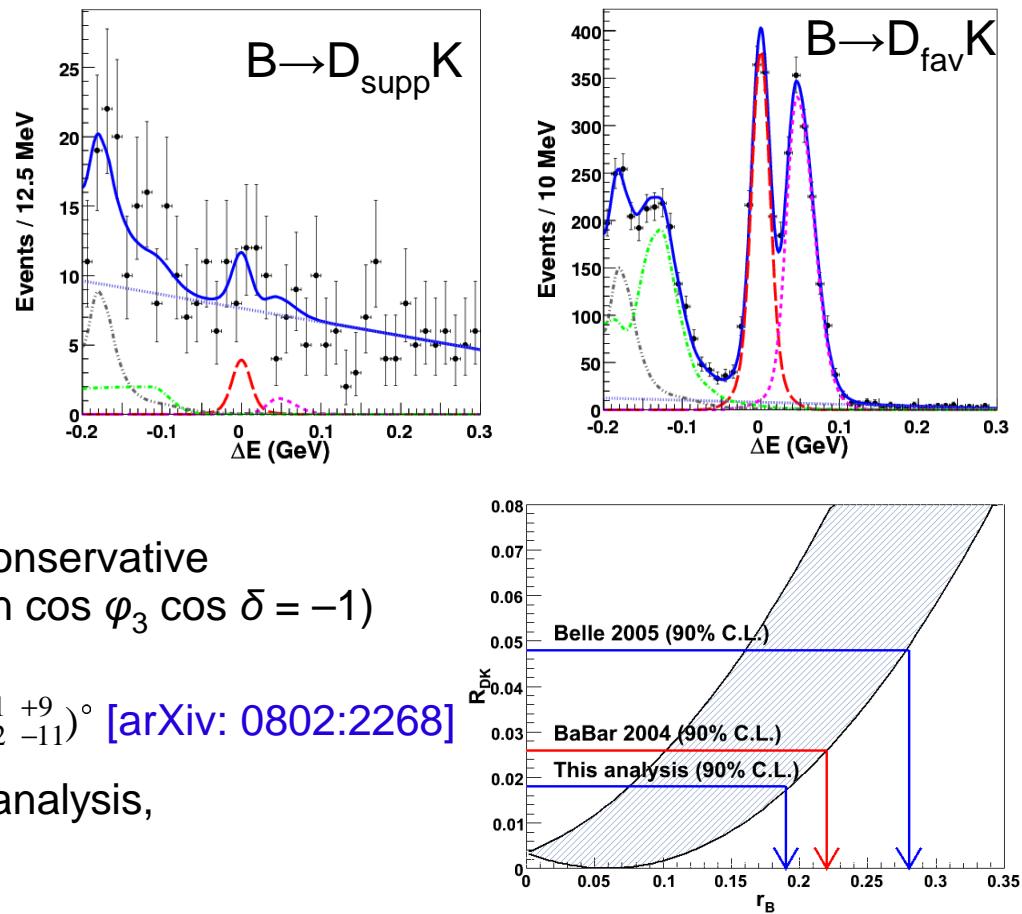
$$A_{ADS} = -0.13^{+0.98}_{-0.88} \pm 0.26$$

$r_B < 0.19$ at 90% CL

(with the conservative assumption $\cos \varphi_3 \cos \delta = -1$)

Using CLEO measurement $\delta_D = (22^{+11}_{-12} {}^{+9}_{-11})^\circ$ [arXiv: 0802:2268]

and φ_3, δ_B measurements from Dalitz analysis, tighter r_B constraint can be obtained.

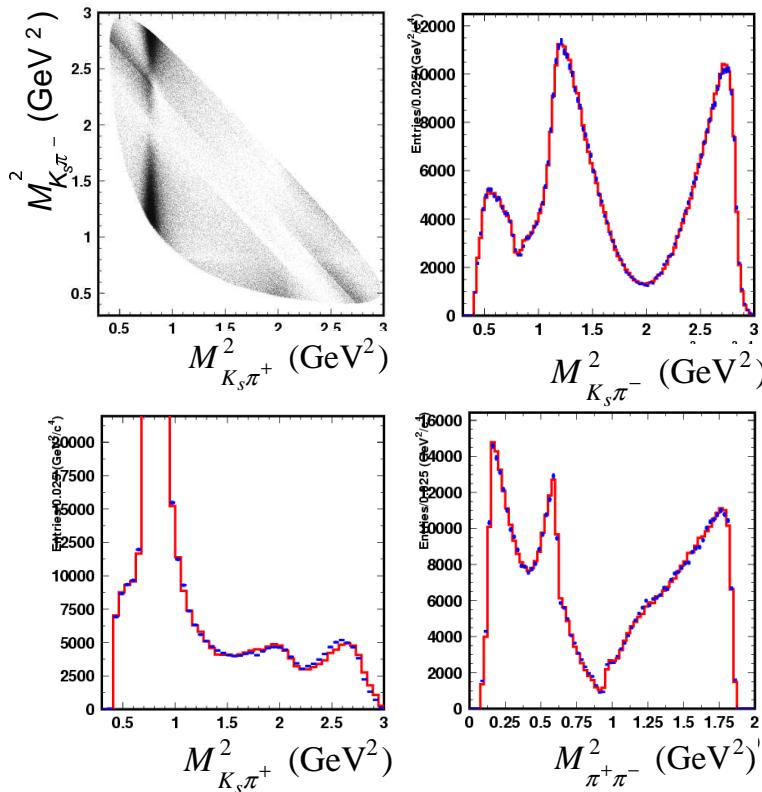


Dalitz: $K_S\pi^+\pi^-$ amplitude

Belle collaboration, 657M BB pairs [arXiv: 0803:3375]

[preliminary]

Isobar model is used as a baseline. K -matrix for systematics test.



$\sigma_1(M=522\pm6 \text{ MeV}, \Gamma=453\pm10 \text{ MeV})$

$\sigma_2(M=1033\pm7 \text{ MeV}, \Gamma=88\pm7 \text{ MeV})$

| Intermediate state | Amplitude | Phase, ° |
|----------------------|-------------------|---------------|
| $K_S\sigma_1$ | 1.56 ± 0.06 | 214 ± 3 |
| $K_S\rho(770)$ | 1 (fixed) | 0 ± 0 |
| $K_S\omega$ | 0.0343 ± 0.0008 | 112.0 ± 1.3 |
| $K_Sf_0(980)$ | 0.385 ± 0.006 | 207.3 ± 2.3 |
| $K_S\sigma_2$ | 0.20 ± 0.02 | 212 ± 12 |
| $K_Sf_2(1270)$ | 1.44 ± 0.04 | 342.9 ± 1.7 |
| $K_Sf_0(1370)$ | 1.56 ± 0.12 | 110 ± 4 |
| $K_S\rho(1450)$ | 0.49 ± 0.08 | 64 ± 11 |
| $K^*(892)^+\pi^-$ | 1.638 ± 0.010 | 133.2 ± 0.4 |
| $K^*(892)^-\pi^+$ | 0.149 ± 0.004 | 325.4 ± 1.3 |
| $K^*(1410)^+\pi^-$ | 0.65 ± 0.05 | 120 ± 4 |
| $K^*(1410)^-\pi^+$ | 0.42 ± 0.04 | 253 ± 5 |
| $K^*_0(1430)^+\pi^-$ | 2.21 ± 0.04 | 358.9 ± 1.1 |
| $K^*_0(1430)^-\pi^+$ | 0.36 ± 0.03 | 87 ± 4 |
| $K^*_2(1430)^+\pi^-$ | 0.89 ± 0.03 | 314.8 ± 1.1 |
| $K^*_2(1430)^-\pi^+$ | 0.23 ± 0.02 | 275 ± 6 |
| $K^*(1680)^+\pi^-$ | 0.88 ± 0.27 | 82 ± 17 |
| $K^*(1680)^-\pi^+$ | 2.1 ± 0.2 | 130 ± 6 |
| Nonresonant | 2.7 ± 0.3 | 160 ± 5 |

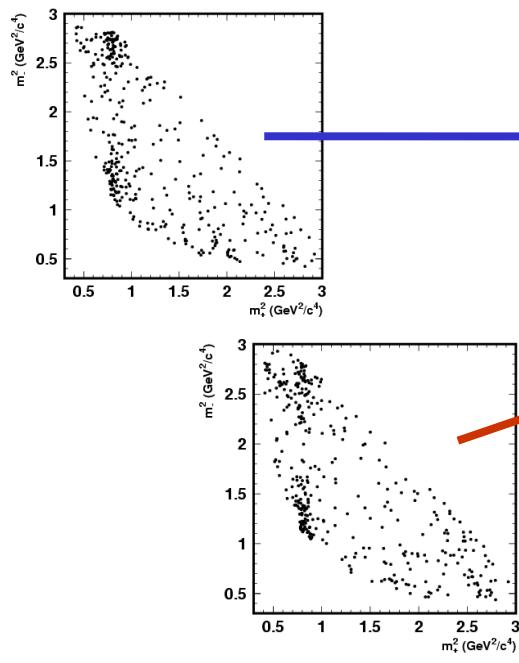
Dalitz: fit results

Fit parameters are $x_{\pm} = r_B \cos(\pm\varphi_3 + \delta)$ and $y_{\pm} = r_B \sin(\pm\varphi_3 + \delta)$

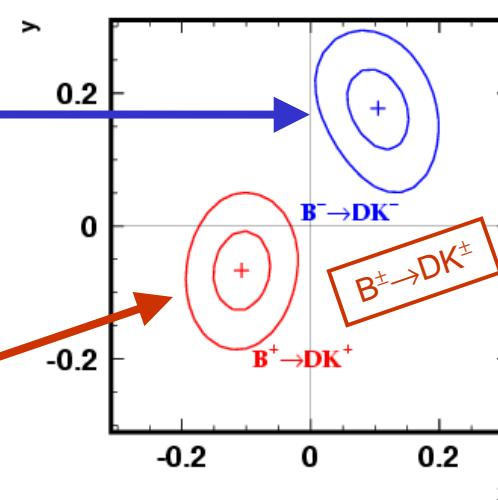
[preliminary]

Unbinned maximum likelihood fit with event-by-event background treatment

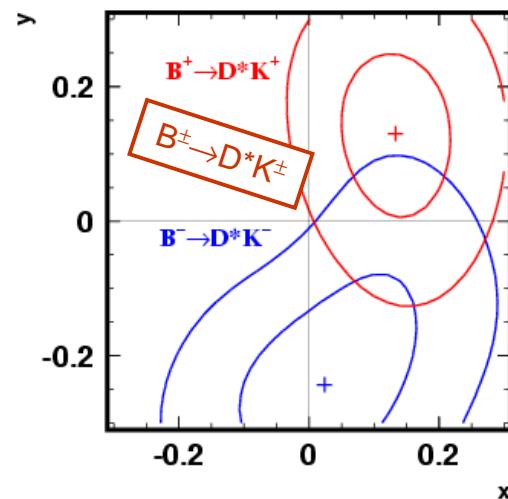
(ΔE , M_{bc} , $|\cos\theta_{thr}|$, \mathcal{F} included into likelihood)



Errors are statistical and experimental systematic.
Model error not included.



$$\begin{aligned}x_- &= +0.105 \pm 0.047 \pm 0.011 \\y_- &= +0.177 \pm 0.060 \pm 0.018 \\x_+ &= -0.107 \pm 0.043 \pm 0.011 \\y_+ &= -0.067 \pm 0.059 \pm 0.018\end{aligned}$$



$$\begin{aligned}x_- &= +0.024 \pm 0.140 \pm 0.018 \\y_- &= -0.243 \pm 0.137 \pm 0.022 \\x_+ &= +0.133 \pm 0.083 \pm 0.018 \\y_+ &= +0.130 \pm 0.120 \pm 0.022\end{aligned}$$

Dalitz: systematic errors

Systematic errors for (x,y) in units of 10^{-2}

| | B \rightarrow DK | | B \rightarrow D * K | |
|----------------------------|--------------------|------|-------------------------------|------|
| | x | y | x | y |
| Signal shape | 0.66 | 1.16 | 0.89 | 1.22 |
| Continuum background shape | 0.34 | 1.10 | 0.94 | 1.63 |
| bb background shape | 0.13 | 0.72 | 0.77 | 0.28 |
| Background fractions | 0.17 | 0.29 | 0.52 | 0.80 |
| Efficiency shape | 0.51 | 0.15 | 0.86 | 0.21 |
| Total | 1.08 | 1.78 | 1.81 | 2.22 |

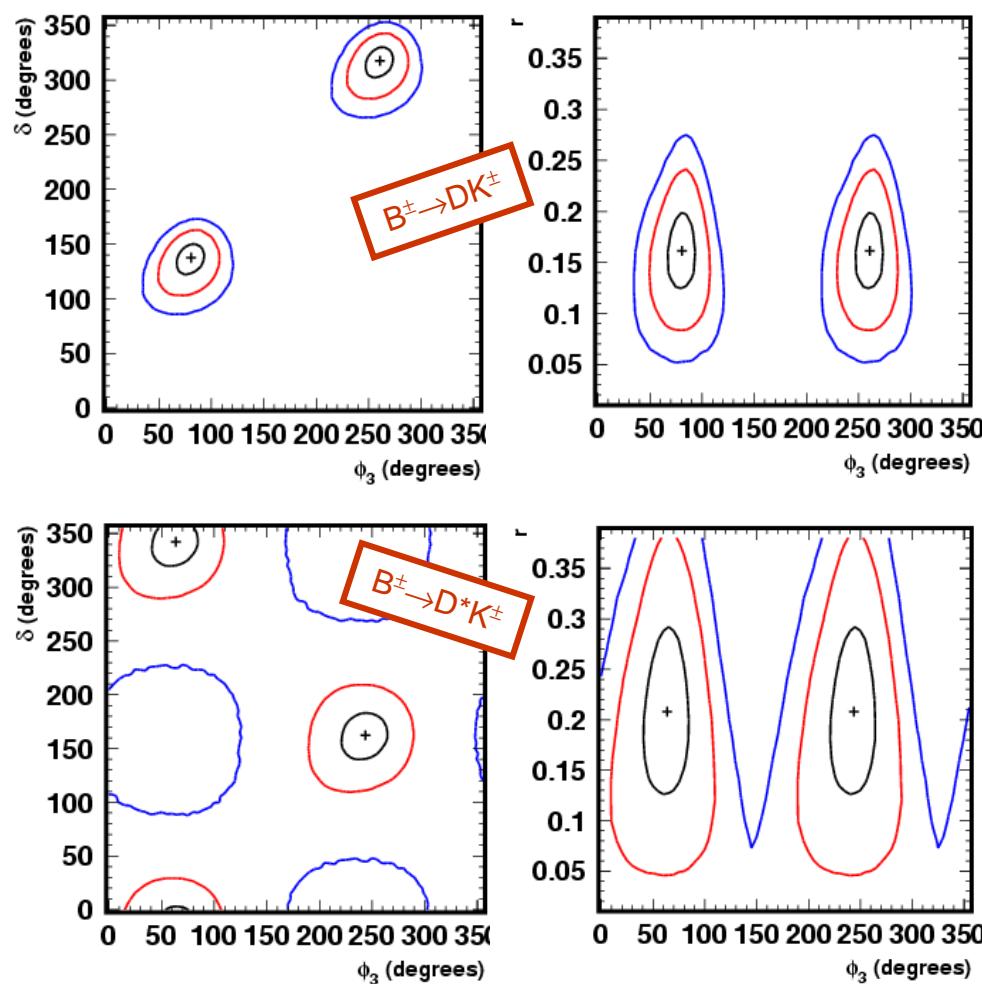
Model uncertainty calculated in terms of (Φ_3, r_B, δ):

$$\Delta\Phi_3 = 9^\circ$$

$$\Delta r_B = 0.05$$

$$\Delta\delta = 23^\circ$$

Dalitz: fit results



$B^\pm \rightarrow DK^\pm$ only: [preliminary]

$$\varphi_3 = 81^{+13}_{-15} \pm 5^\circ \text{ (syst)} \pm 9^\circ \text{ (model)}$$

$B^\pm \rightarrow D^* K^\pm$ only:

$$\varphi_3 = 64^{+21}_{-23} \pm 4^\circ \text{ (syst)} \pm 9^\circ \text{ (model)}$$

$B^\pm \rightarrow DK^\pm, B^\pm \rightarrow D^* K^\pm$ combined:

$$\varphi_3 = 76^{+12}_{-13} \pm 4^\circ \text{ (syst)} \pm 9^\circ \text{ (model)}$$

$$r_{DK} = 0.16 \pm 0.04 \pm 0.01 \text{ (syst)} \pm 0.05 \text{ (model)}$$

$$r_{D^* K} = 0.21 \pm 0.08 \pm 0.01 \text{ (syst)} \pm 0.05 \text{ (model)}$$

$$\delta_{DK} = 136^{+14}_{-16} \pm 4^\circ \text{ (syst)} \pm 23^\circ \text{ (model)}$$

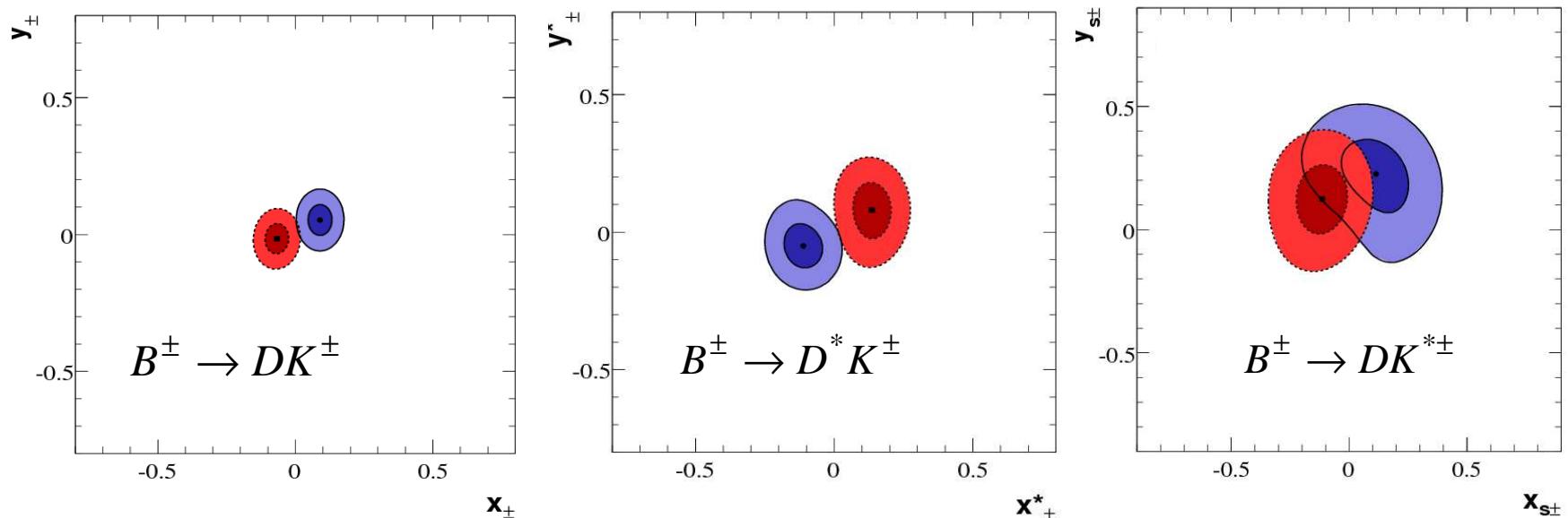
$$\delta_{D^* K} = 343^{+20}_{-22} \pm 4^\circ \text{ (syst)} \pm 23^\circ \text{ (model)}$$

Model error estimate is the same as in previous (385M BB) analysis.

Stat. CL of CPV: $(1-5.5 \cdot 10^{-4})$ or 3.5σ !

BaBar Dalitz: fit results

Fit results expressed in Cartesian coordinates $x_{\pm} = r_B \cos(\pm\gamma + \delta)$, $y_{\pm} = r_B \sin(\pm\gamma + \delta)$



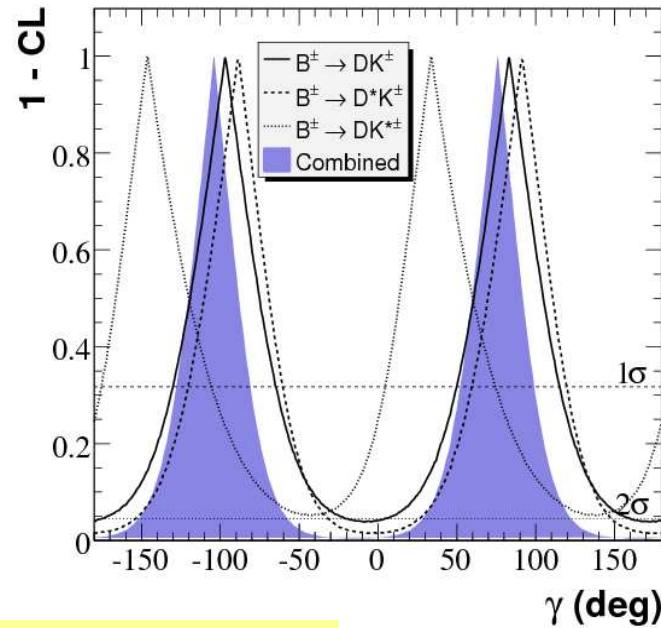
| | $B \rightarrow D^0 K$ | $B \rightarrow D^*{}^0 K$ | $B \rightarrow D^0 K^*$ |
|-------|--|--|--|
| x_- | $+0.090 \pm 0.043 \pm 0.015 \pm 0.011$ | $-0.111 \pm 0.069 \pm 0.014 \pm 0.004$ | $+0.115 \pm 0.138 \pm 0.039 \pm 0.014$ |
| y_- | $+0.053 \pm 0.056 \pm 0.007 \pm 0.015$ | $-0.051 \pm 0.080 \pm 0.009 \pm 0.010$ | $+0.226 \pm 0.142 \pm 0.058 \pm 0.011$ |
| x_+ | $-0.067 \pm 0.043 \pm 0.014 \pm 0.011$ | $+0.137 \pm 0.068 \pm 0.014 \pm 0.005$ | $-0.113 \pm 0.107 \pm 0.028 \pm 0.018$ |
| y_+ | $-0.015 \pm 0.055 \pm 0.006 \pm 0.008$ | $+0.080 \pm 0.102 \pm 0.010 \pm 0.012$ | $+0.125 \pm 0.139 \pm 0.051 \pm 0.010$ |

Statistical

Systematic

D^0 model

BaBar Dalitz: fit results

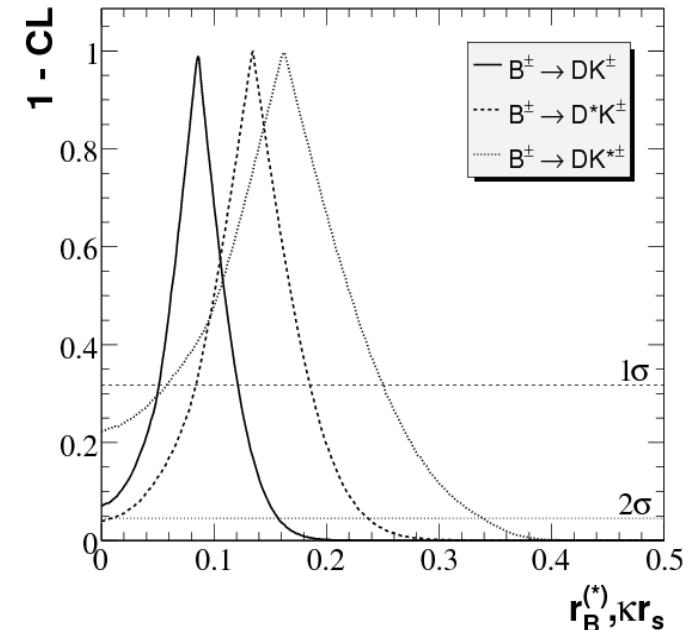


$$\gamma = (76^{+23}_{-24} \pm 5 \pm 5)^\circ$$

$$\gamma = (63^{+30}_{-28} \pm 8 \pm 7)^\circ$$

($D^0 \rightarrow K_S \pi^+ \pi^-$ modes only)

CPV significance is 3.0 σ



$$r_B = 0.086 \pm 0.035 \pm 0.010 \pm 0.011$$

$$r_B^* = 0.135 \pm 0.051 \pm 0.011 \pm 0.005$$

$$K_s^* = 0.163^{+0.088}_{-0.105} \pm 0.037 \pm 0.021$$

Accounts for possible
non-resonant $B \rightarrow DK\pi$

$$\delta_B = (109^{+28}_{-31} \pm 4 \pm 7)^\circ$$

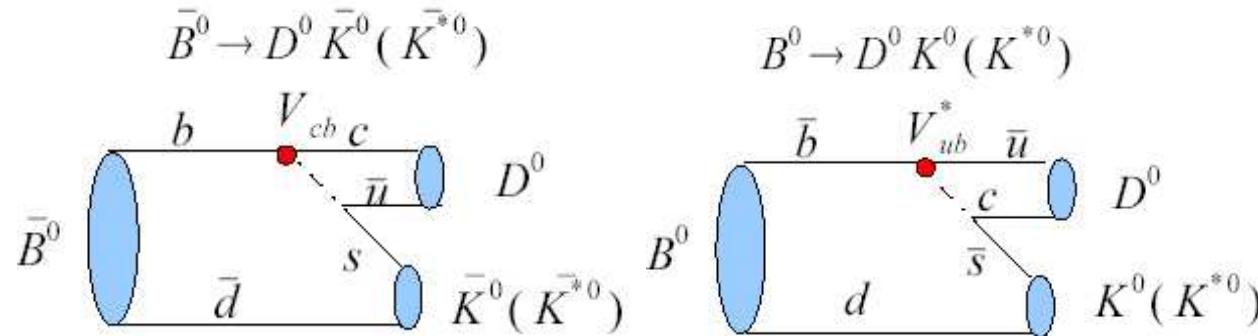
$$\delta_B^* = (-63^{+28}_{-30} \pm 5 \pm 4)^\circ$$

$$\delta_s = (104^{+43}_{-41} \pm 17 \pm 5)^\circ$$

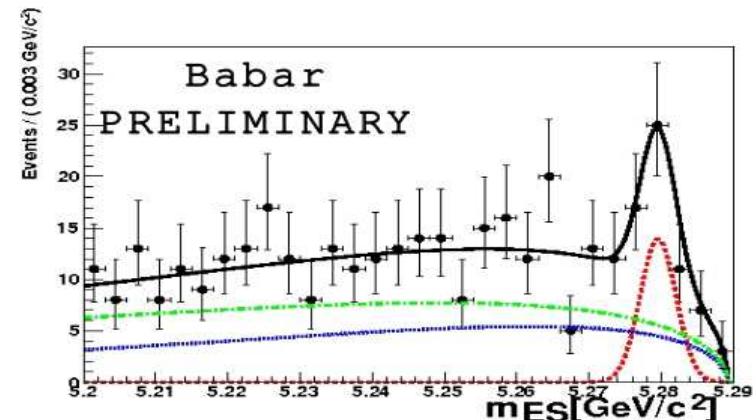
BaBar: Neutral B decays, Dalitz analysis

Decay $B^0 \rightarrow D^0 K^{*0}$:

Both amplitudes are color-suppressed, $r_B \sim 0.4$

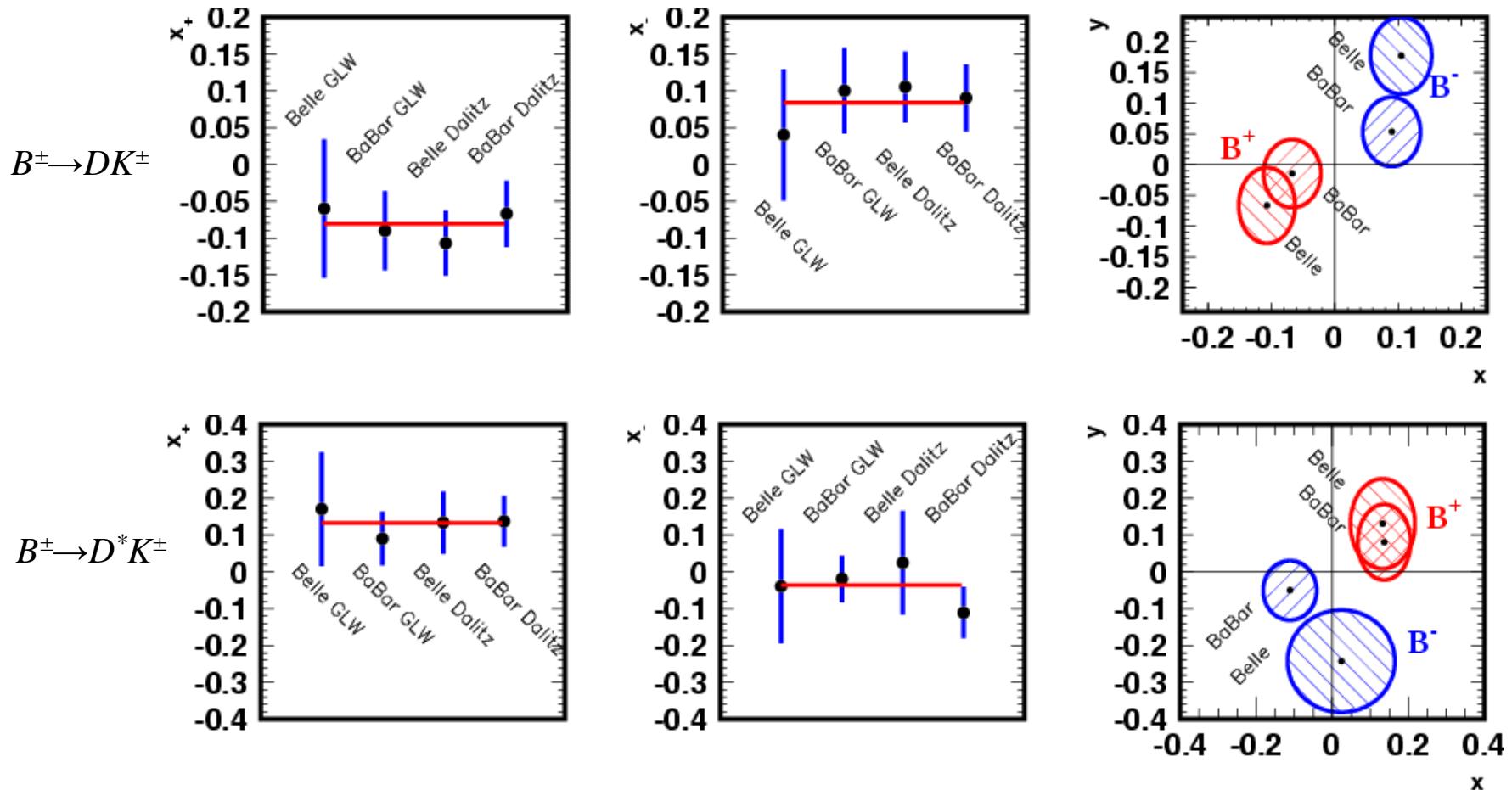


$$\gamma = (162 \pm 56)^\circ$$
$$r(D^0 K^{*0}) < 0.55 \text{ (90% CL)}$$



Comparison of measurements

GLW and Dalitz methods in Cartesian variables (x,y):



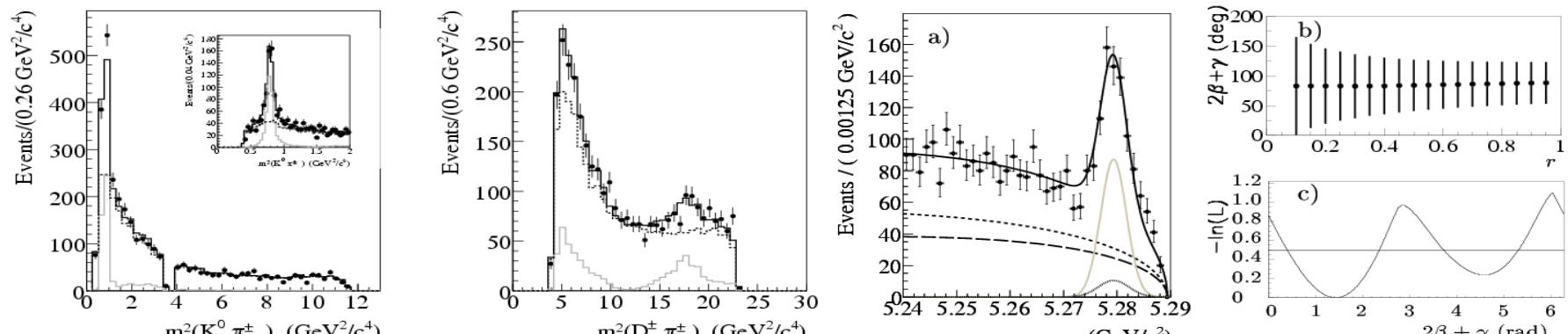
BaBar: Decay $B^0 \rightarrow D^+ K_S \pi^-$

BaBar collaboration, 347M BB pairs [arXiv: 0712:3469]

Decay $B^0 \rightarrow D^+ K_S \pi^-$:

Use B flavor tag, perform time-dependent Dalitz plot analysis. Sensitive to $2\beta + \gamma$

Interference between $B^0 \rightarrow D^{**0} K_S^0$ ($b \rightarrow u$ and $b \rightarrow c$) and $B^0 \rightarrow D^- K^{*+}$ ($b \rightarrow c$)



$$2\beta + \gamma = (83 \pm 53 \pm 20)^\circ$$