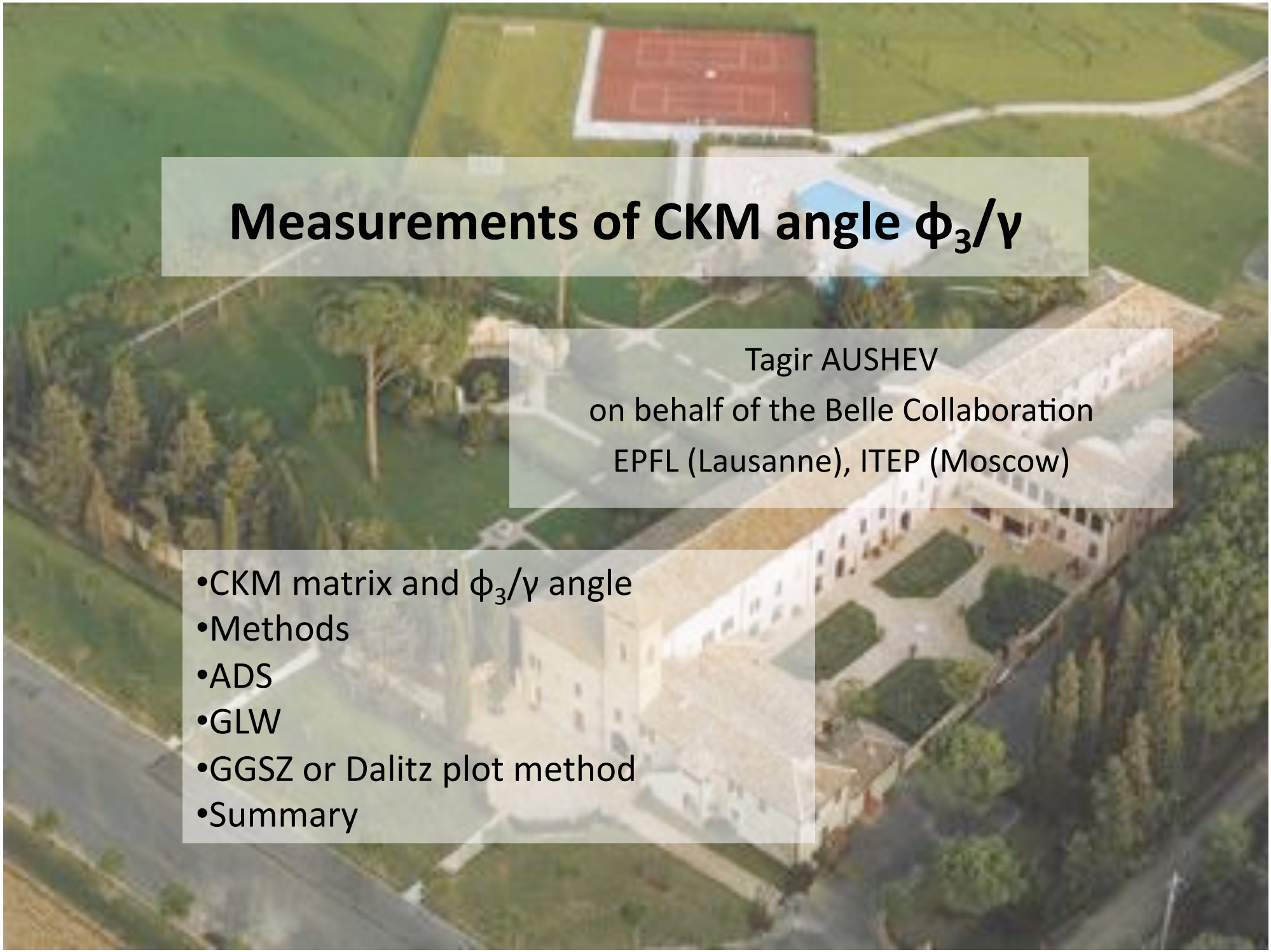


Measurements of CKM angle ϕ_3/γ

Tagir AUSHEV
on behalf of the Belle Collaboration
EPFL (Lausanne), ITEP (Moscow)

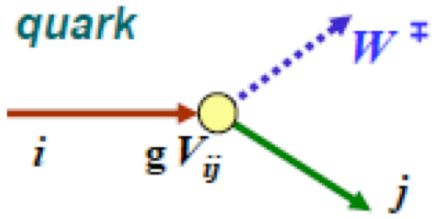
- CKM matrix and ϕ_3/γ angle
- Methods
- ADS
- GLW
- GGSZ or Dalitz plot method
- Summary

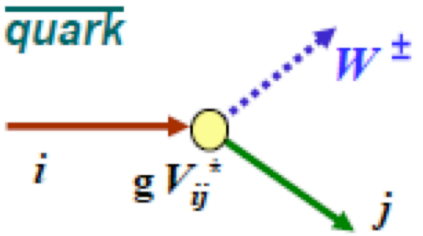
CKM matrix & ϕ_3/γ

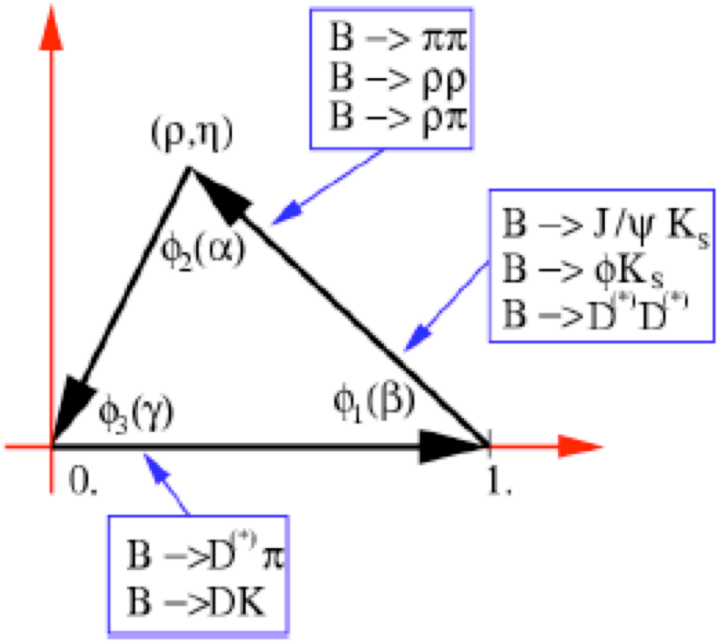
Cabibbo-Kobayashi-Maskawa quark mixing matrix (CKM):

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

$\sim e^{i\varphi_3}$







CKM unitarity leads to triangle in complex plane:

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

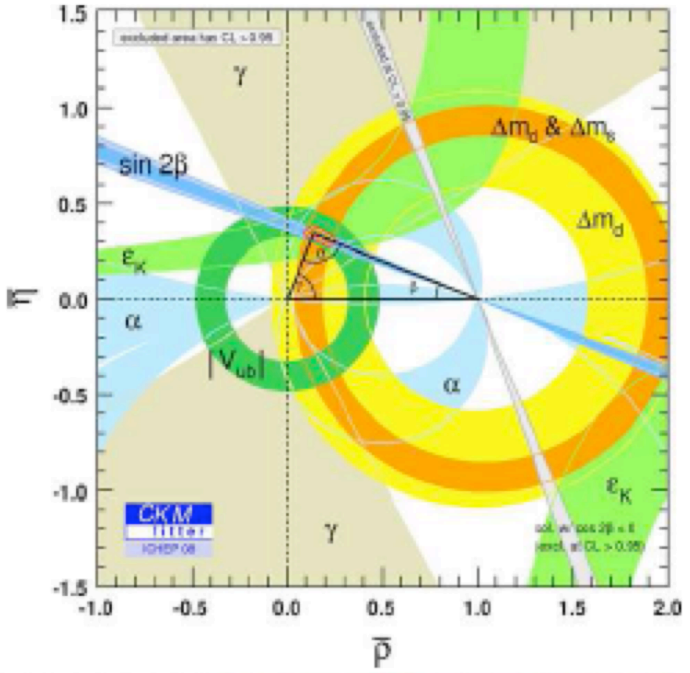
$$\Rightarrow \frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + 1 + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0$$

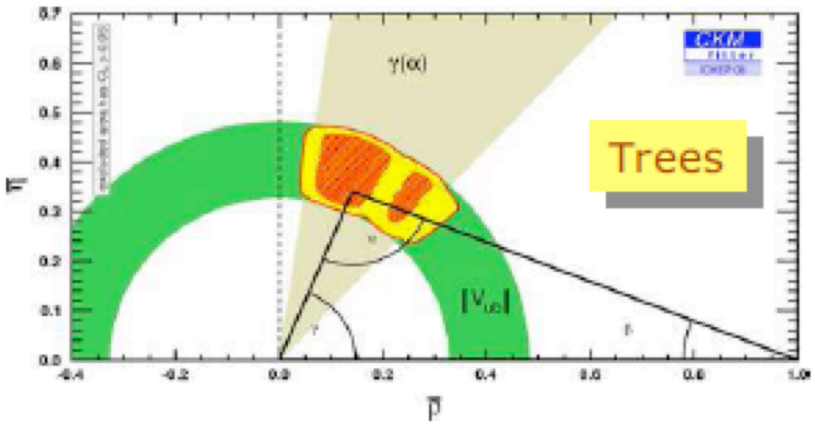
Constraints on CKM parameters

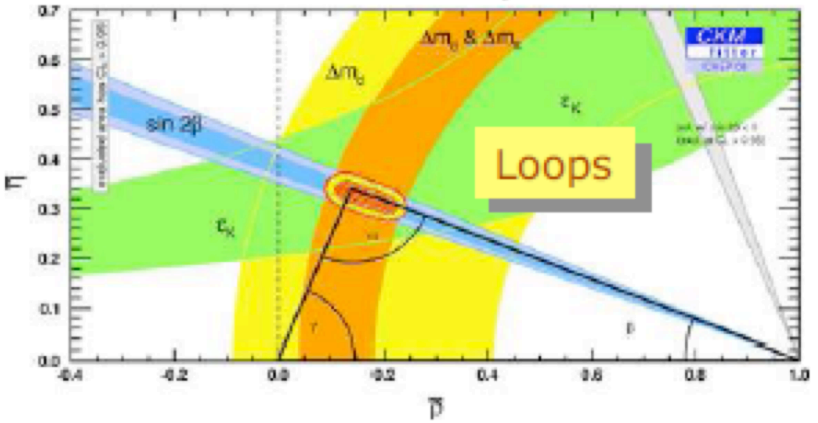
Direct angle measurements
[CKM World averages, 2009]:

$\phi_1 = 21.1° \pm 0.9°$
$\phi_2 = 89° \pm 4°$
$\phi_3 = 70°^{+27°}_{-30°}$

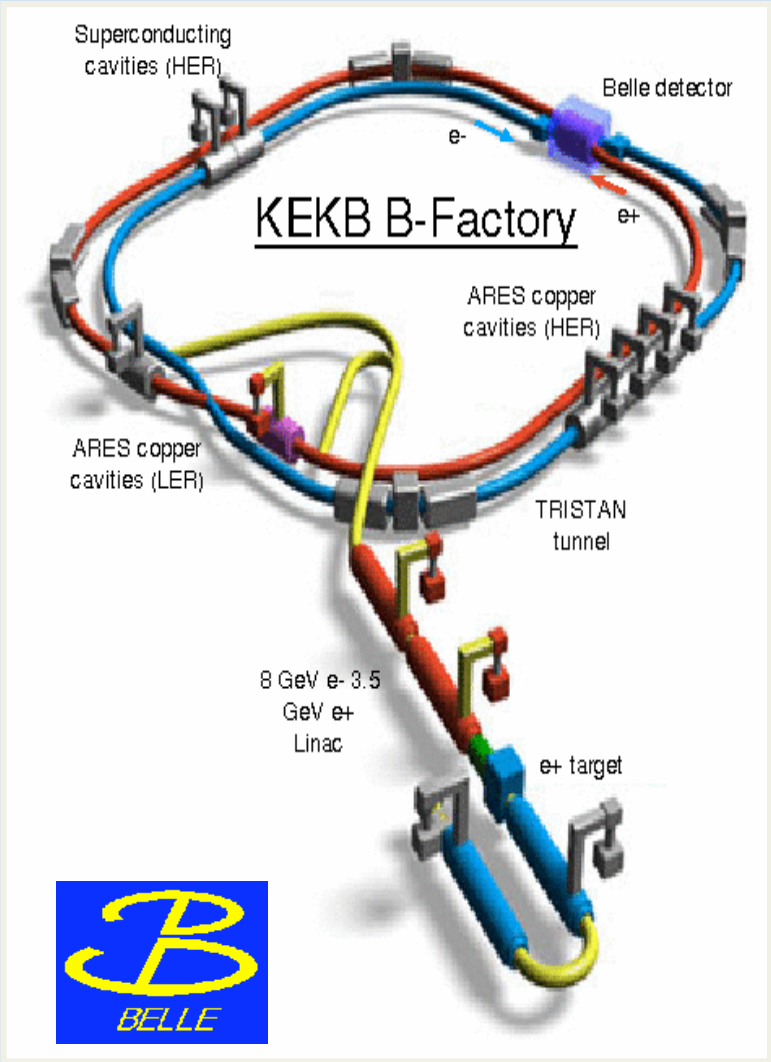
ϕ_3/γ is measured in tree decays
Together with $|V_{ub}|$ provides a SM reference for new physics searches

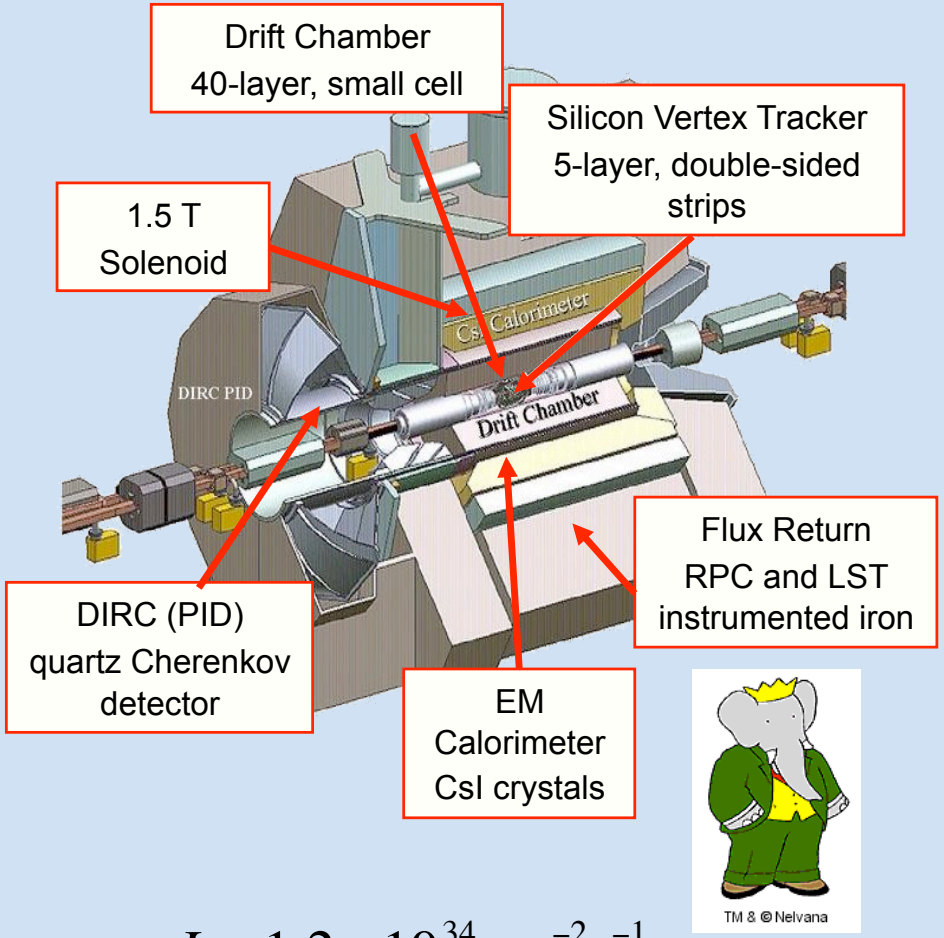






Belle & BaBar B-factories





$L = 2.1 \times 10^{34}\, cm^{-2} s^{-1}$ (World record)

$\int Ldt \sim 710\, fb^{-1} @ Y(4S)$

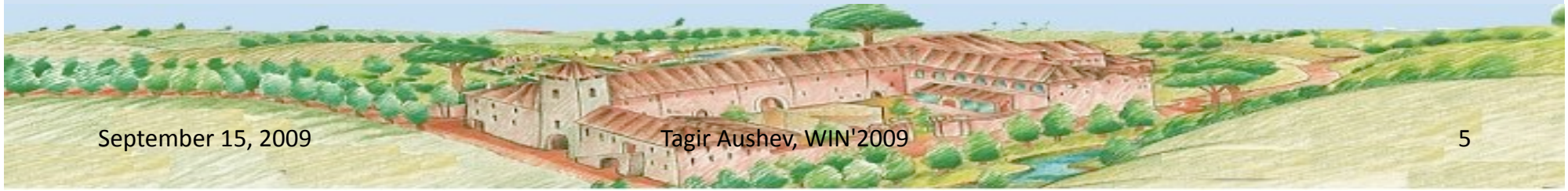
$L = 1.2 \times 10^{34}\, cm^{-2} s^{-1}$

$\int Ldt \sim 433\, fb^{-1} @ Y(4S)$

Methods of ϕ_3/γ measurement

- Based on $B \to DK$ decay with D^0-$\overline{D^0}$ interference:
  - GLW (CP eigenstates: $D^0 \to \pi\pi$, KK, $K_S\phi$, $K_S\omega$)
  - ADS (CF and DCS states: $D^0 \to K\pi$, $K\pi\pi^0$)
  - GGSZ or Dalitz (multibody states: $D^0 \to K_S\pi\pi$, K_SKK, $\pi\pi\pi^0$)

- Based on B^0 decays (measurement of $2\phi_1+\phi_3$)
  - $B^0 \to D^{(*)-}\pi^+$, $D\rho$ full rec.
  - $B^0 \to D^{*-}\pi^+$ partial rec.



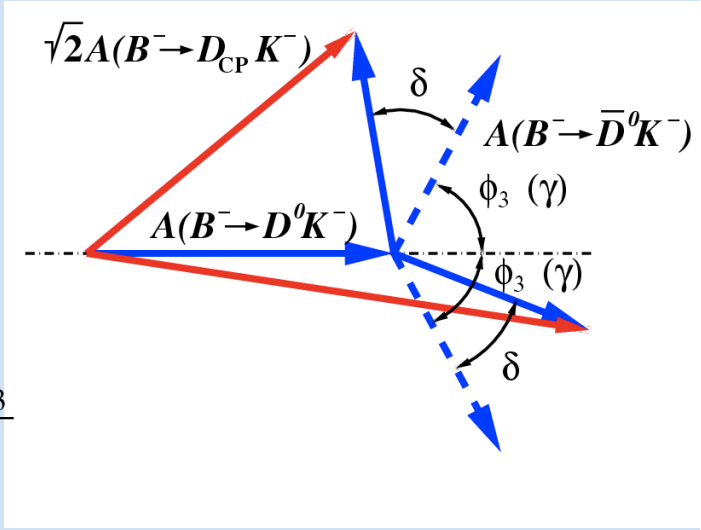
GLW method

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: $D_2 \rightarrow K_S\pi^0, K_S\omega, K_S\phi, K_S\eta, \ldots$

$$R_{1,2} = \frac{Br(B \to D_{1,2}K)/Br(B \to D_{1,2}\pi)}{Br(B \to D^0K)/Br(B \to D^0\pi)} = 1 + r_B^2 + 2r_B \cos\delta'\cos\varphi_3$$

$$A_{1,2} = \frac{Br(B^+ \to D_{1,2}K^+) - Br(B^- \to D_{1,2}K^-)}{Br(B^+ \to D_{1,2}K^+) + Br(B^- \to D_{1,2}K^-)} = \frac{2r_B \sin\delta'\sin\varphi_3}{R_{1,2}}$$



Sensitivity depends on hadronic parameters r_B and δ'

Alternative set of variables: $x_\pm = r_B \cos(\delta \pm \varphi_3) = \frac{R_1(1 \mp A_1) - R_2(1 \mp A_2)}{4}$ $\qquad r_B^2 = \frac{R_1 + R_2 - 2}{2}$

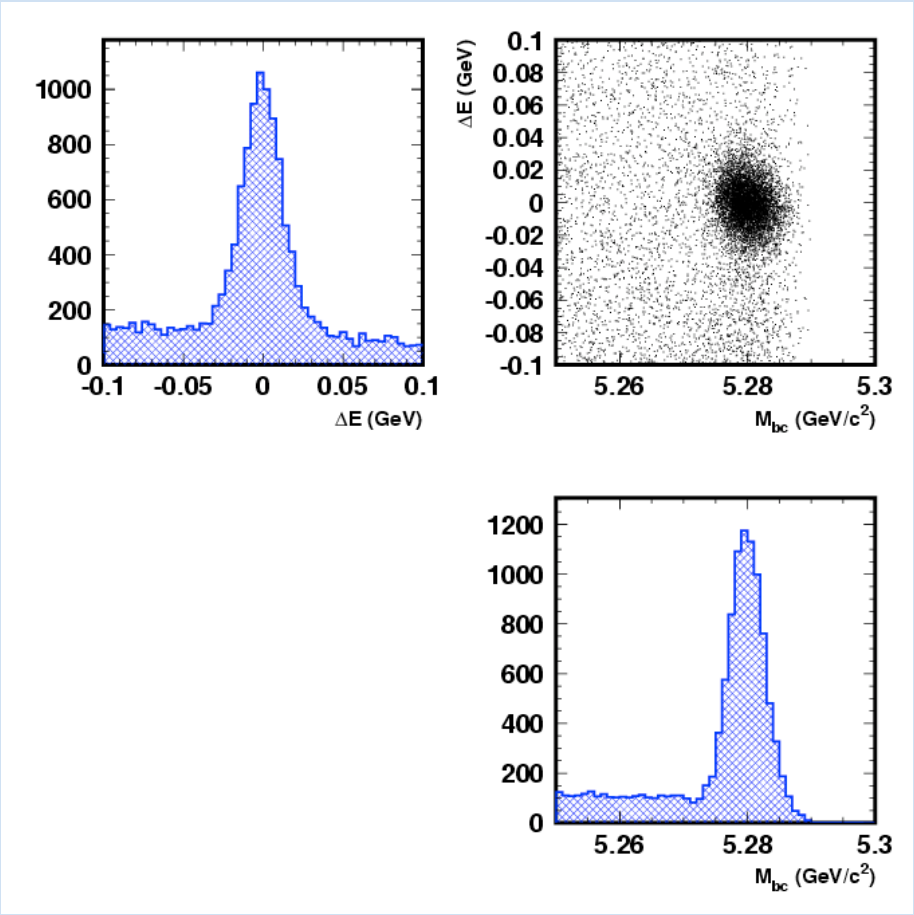
Does not provide direct measurement of ϕ_3/γ, but helps in combination with other methods
Sensitivity depends on strong phase (δ=0 or 180 give no sensitivity)

B meson reconstruction

Y(4S) decays to pair of B-mesons, so in CMS energy of B meson is known:

$$E_B = E_{CM}/2$$

It is used to select B candidates using variables:



•CM energy difference:

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

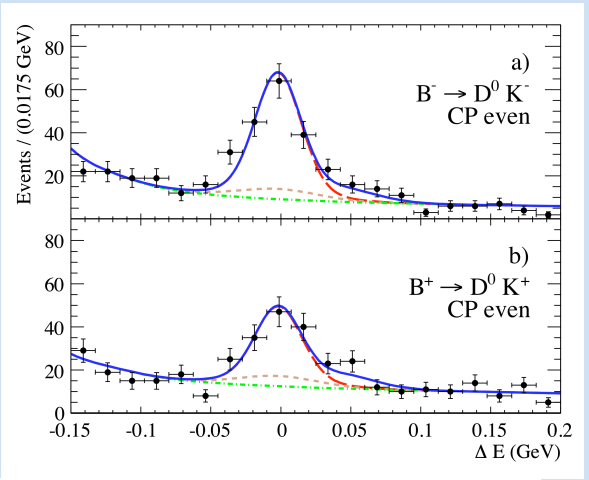
•B-meson "beam-constrained mass" M_{bc} (Belle) or energy substituted mass" M_{ES} (BaBar):

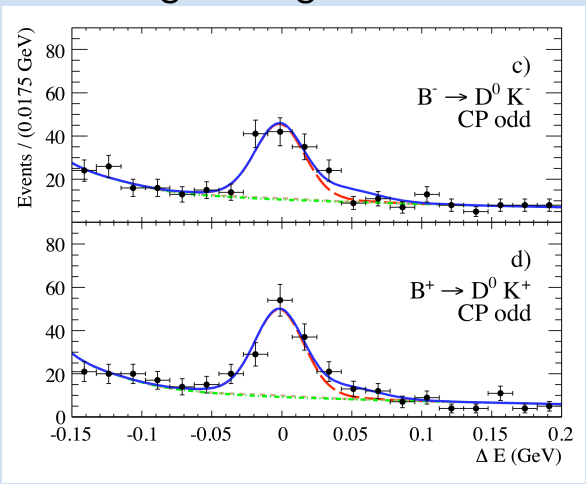
$$M_{bc} = \sqrt{(E_{CM}/2)^2 - (\sum p_i)^2}$$

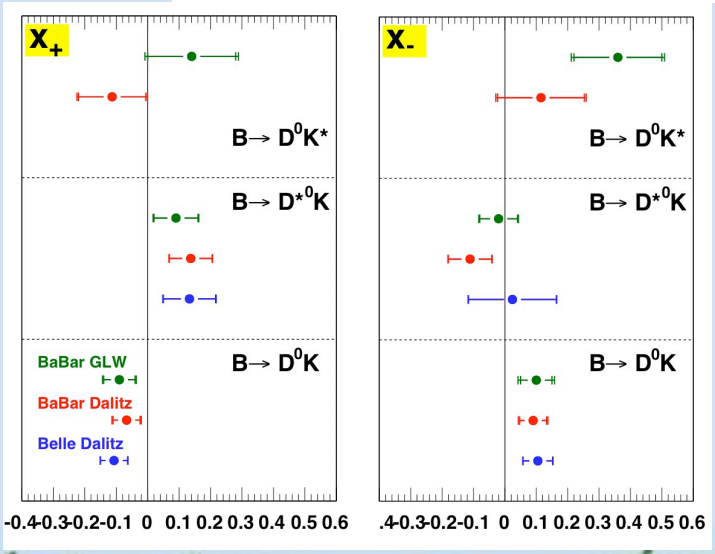
GLW: BaBar results

BaBar: 382M BB pairs
DK: PRD 77, 111102 (2008)
D*K: PRD 78, 092002 (2008)

$B^- \to D_{CP} K^-$ $D^0 \to \pi^+\pi^-, K^+K^-$ $D^0 \to K_S\pi^0, K_S\omega$







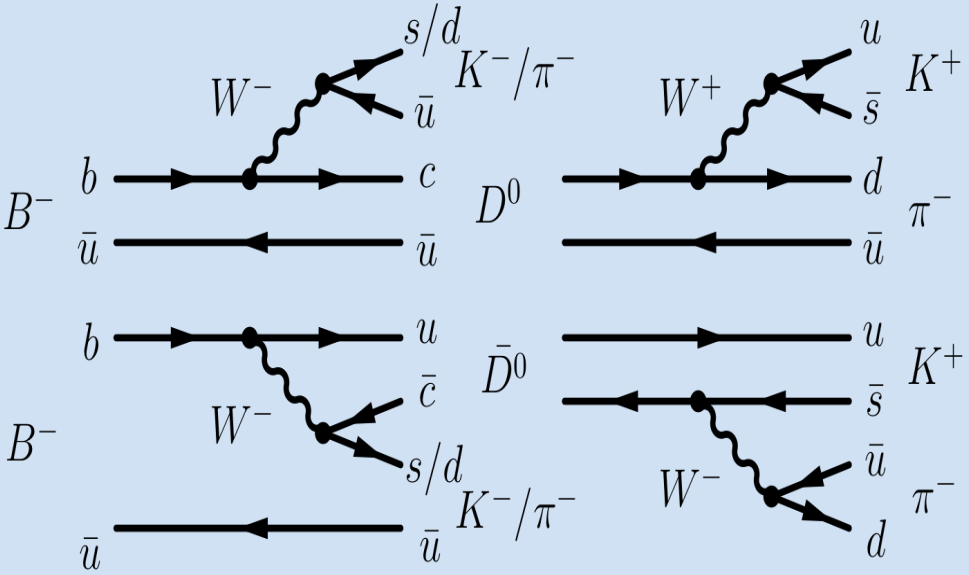
ϕ_3/γ	$=61.5^{\circ}{}^{+29.0^{\circ}}_{-19.2^{\circ}}$
$r_B(D^0K)$	$=0.092^{+0.028}_{-0.028}$
$r^*_B(D^{*0}K)$	$=0.108^{+0.054}_{-0.041}$
$r_s(D^0K^*)$	$0.179^{+0.087}_{-0.098}$

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

ADS method: $B^- \to DK^-$ with $D \to K^+\pi^-$

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

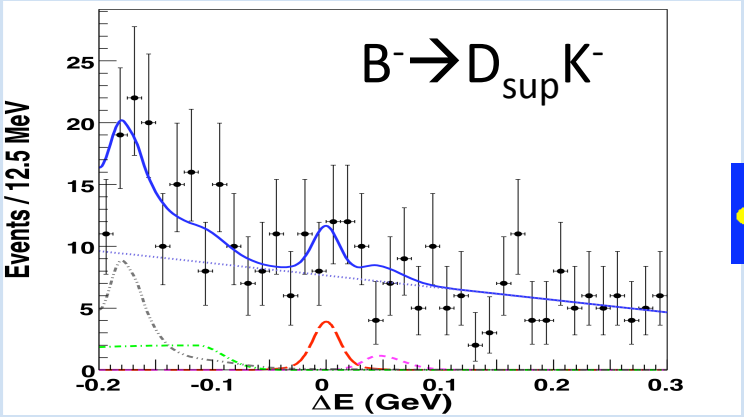
Enhance magnitude of CP violation by using Doubly Cabibbo-suppressed *D* decays



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

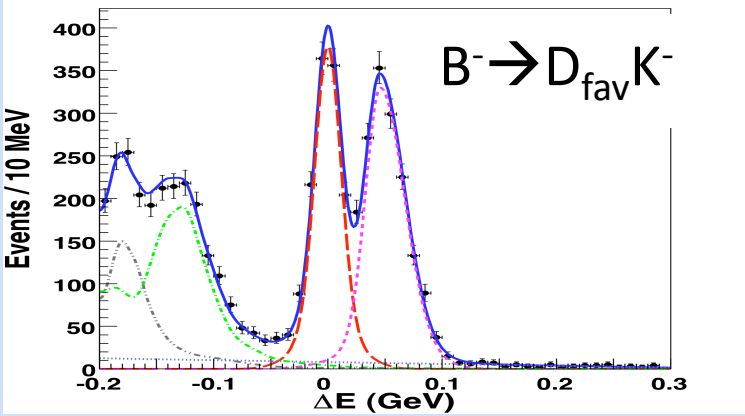
$$\delta = \delta_B + \delta_D, r_D = \left| \frac{A(D^0 \to K^-\pi^+)}{A(D^0 \to K^+\pi^-)} \right| = 0.0578 \pm 0.0008$$

ADS method: $B^- \rightarrow DK^-$ with $D \rightarrow K^+\pi^-$



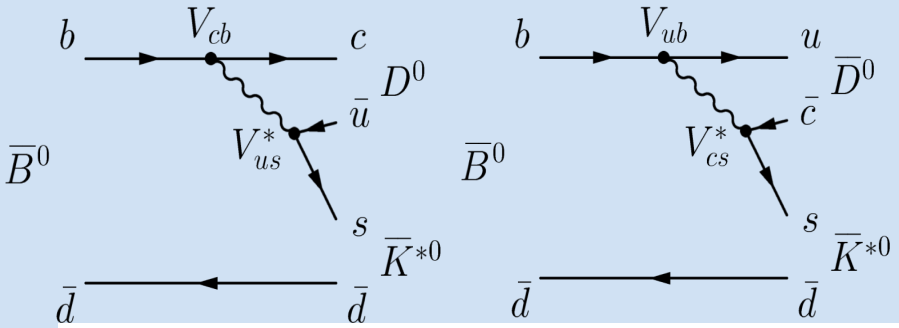
PRD 78, 071901 (2008)

657M BB

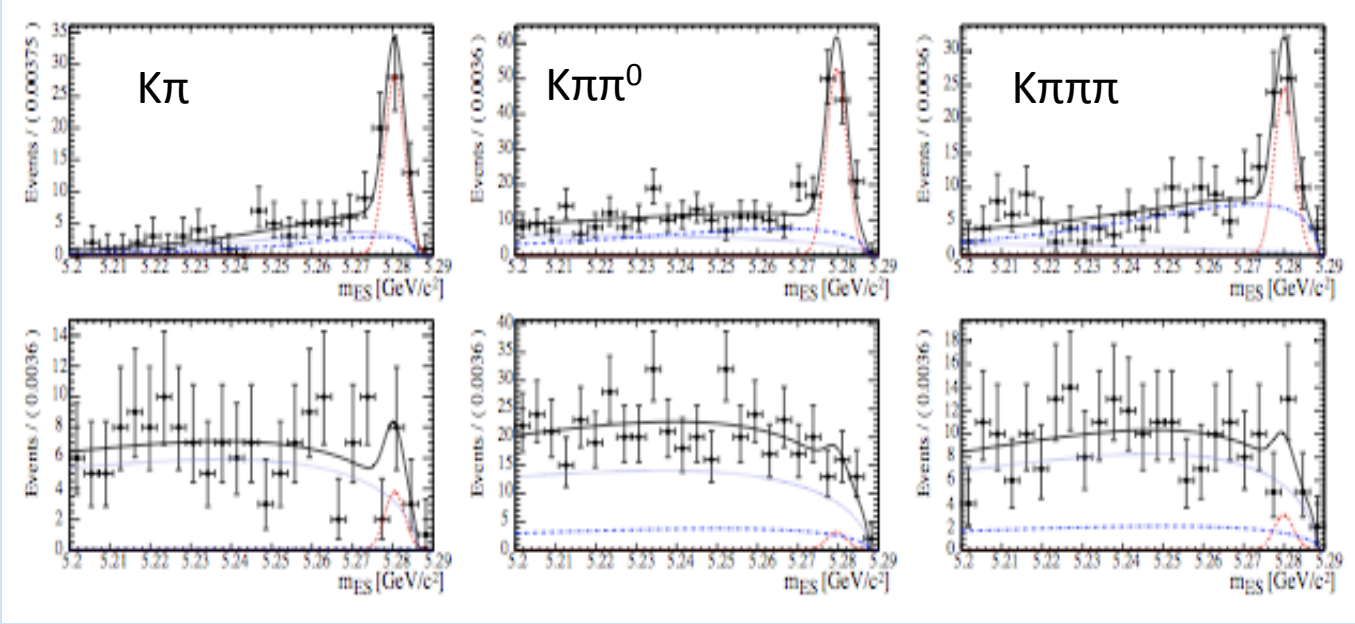


In the absence of the signal:
$R_{DK} < 1.8 \times 10^{-2}$ @ 90% C.L.
which corresponds to: $r_B < 0.19$

ADS method: $B^0 \to D^0 K^{*0}$



$$R_{ADS} \equiv \frac{\Gamma(\bar{B}^0 \to [f]_D \bar{K}^{*0}) + \Gamma(B^0 \to [\bar{f}]_D K^{*0})}{\Gamma(\bar{B}^0 \to [\bar{f}]_D \bar{K}^{*0}) + \Gamma(B^0 \to [f]_D K^{*0})}$$

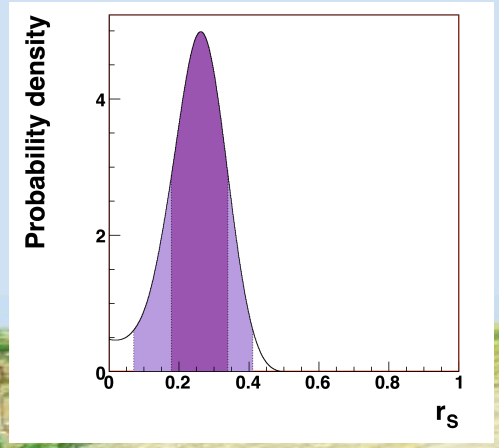


465M BB

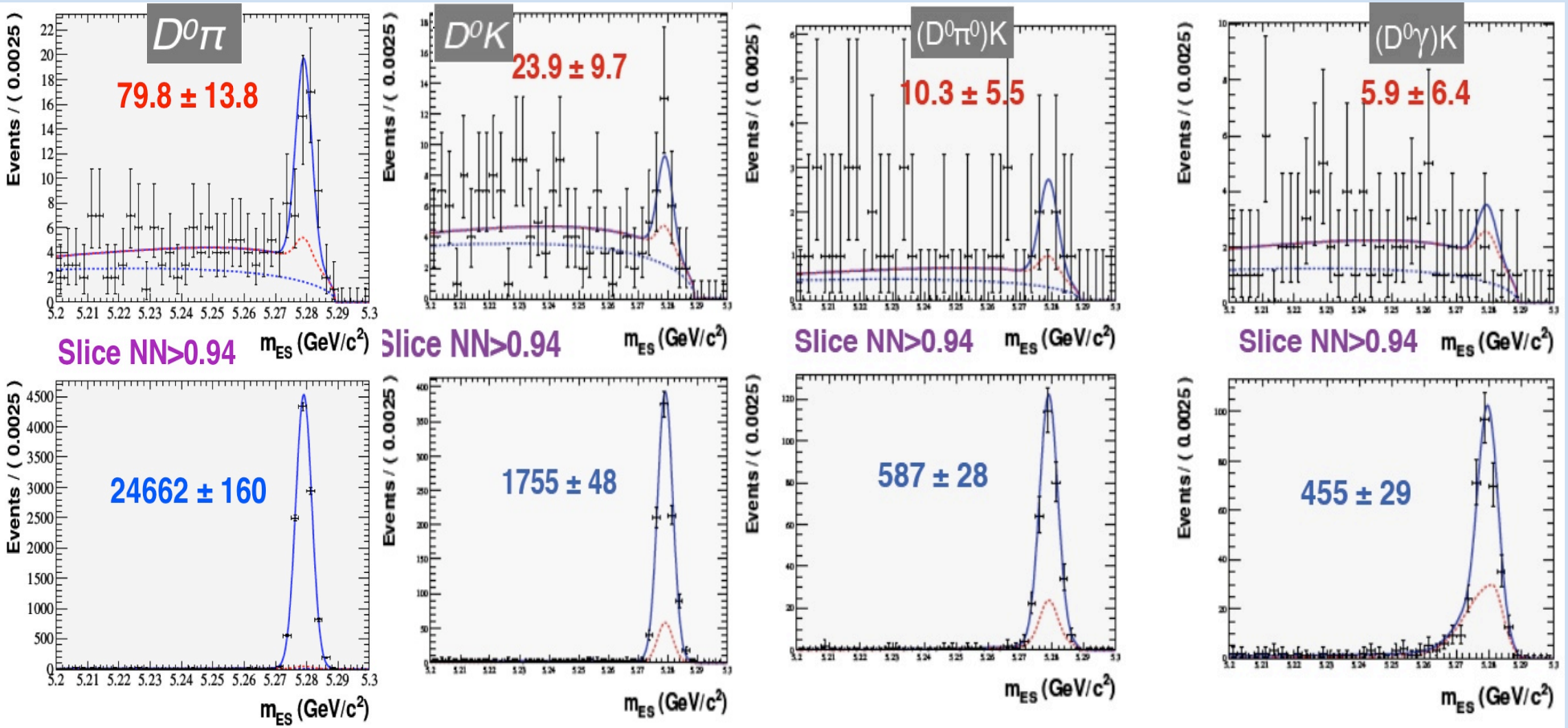
arXiv: 0904.2112

Neglecting K^{*0} final states interference the combined result for three modes is:

$$R_{ADS} \sim r_S^2 = \frac{\Gamma(B^0 \to D^0 K^+ \pi^-)}{\Gamma(B^0 \to \bar{D}^0 K^+ \pi^-)} = 0.26$$



ADS: BaBar



$R_{ADS}(DK)=0.0136\pm0.0055\pm0.0027$

$R_{ADS}([D\gamma]K)=0.013\pm0.014\pm0.007$

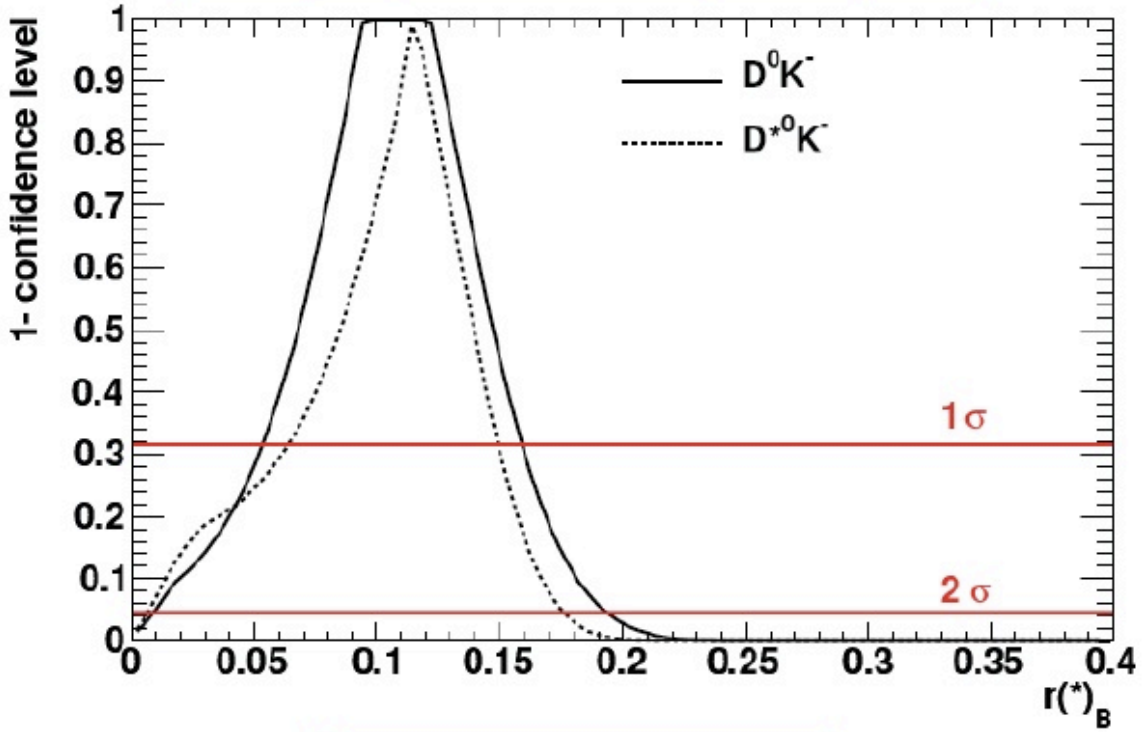
$R_{ADS}(D\pi)=(3.30\pm0.57\pm0.35)\times10^{-3}$

$R_{ADS}([D\pi^0]K)=0.0176\pm0.0093\pm0.0042$

ADS: BaBar results

inputs

$r_D = (5.78 \pm 0.08)\%$ (HFAG) $\delta_D = (22.7\ ^{+11.4}_{-12.3})^o$ (CLEO-C)



$r_B(D^0K) = 0.109\ ^{+0.049}_{-0.056}$

$r_B(D^{*0}K) = 0.116\ ^{+0.033}_{-0.051}$

$r_B < 0.18$ at 90% C.L
467M $B\bar{B}$

$r_B < 0.19$ at 90% C.L
657M $B\bar{B}$

Dalitz plot + GLW combination:

$r_B(D^0K) = 0.092\ ^{+0.027}_{-0.028}$

$r_B(D^{*0}K) = 0.108\ ^{+0.052}_{-0.041}$

Dalitz analysis: three-body decays

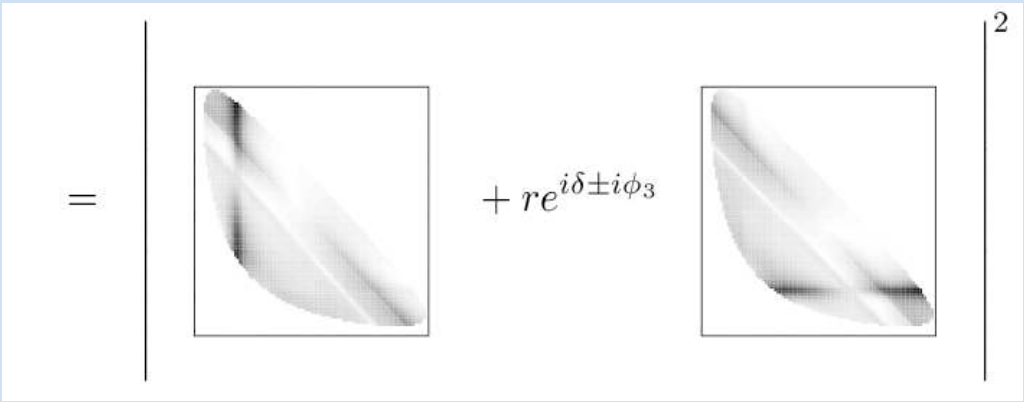
A.Giri, Yu.Grossman, A.Soffer, J.Zupan, PRD 68, 054018 (2003)
A.Bondar, Proc. of Belle Dalitz analisis meeting, 24-26 Sep 2002

$\left|D^0\right\rangle + re^{i\theta}\left|\overline{D}^0\right\rangle$ Using 3-body final state, identical for D^0 and anti-D^0: $K_S\pi^+\pi^-$

Dalitz distribution density:

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

$$\left|f_B(m^2_{K_S\pi^+}, m^2_{K_S\pi^-})\right|^2 =$$

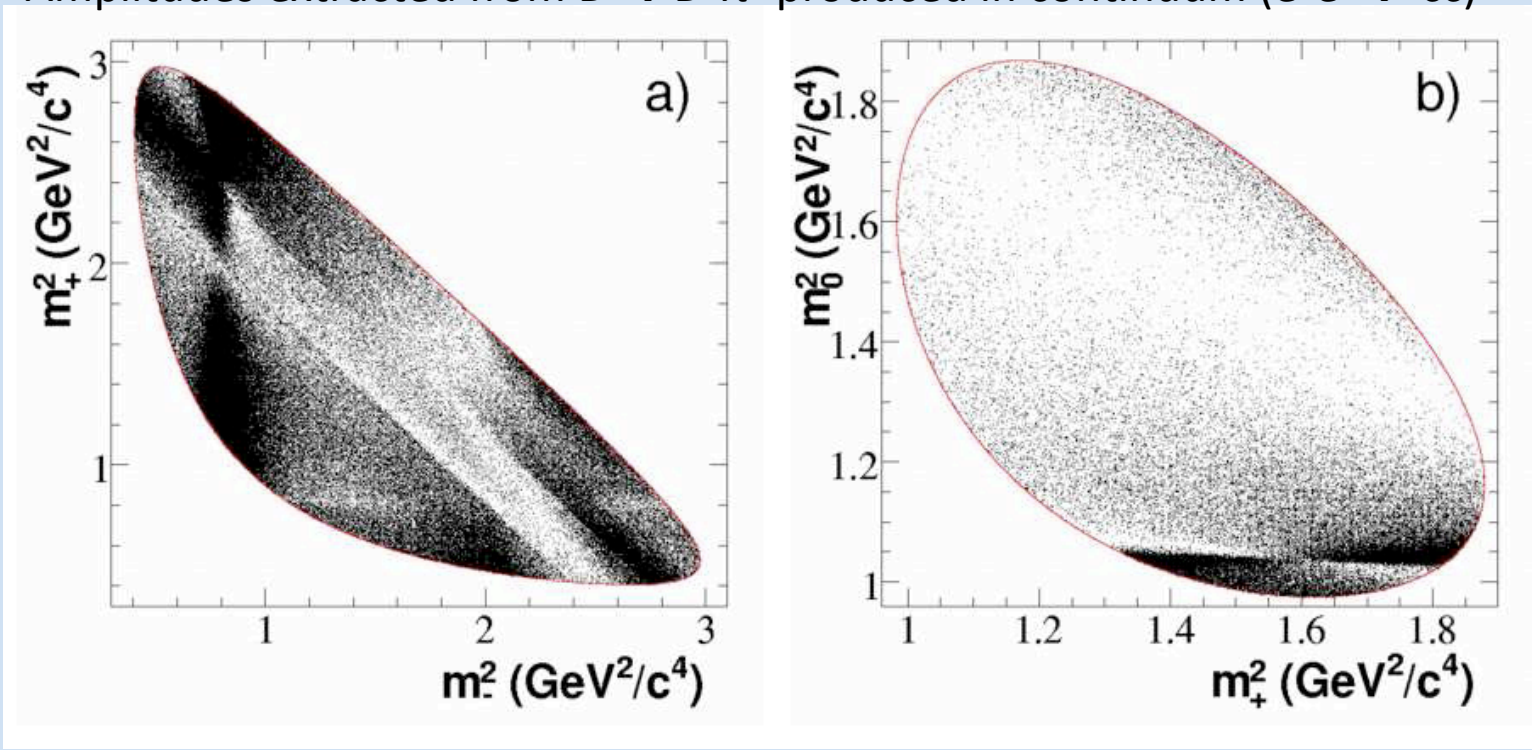


(Assuming CP-conservation in D^0 decays)

If $f_B(m^2_{K_S\pi^+}, m^2_{K_S\pi^-})$ 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.

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

Amplitudes extracted from $D^* \to D^0\pi^+$ produced in continuum ($e^+e^- \to c\bar{c}$)



$K^*(892)^\pm$, $K_0^*(1430)^\pm$, $K_2^*(1430)^\pm$,
$K^*(1680)^\pm$, $\rho(770)$, $\omega(782)$, $f_2(1270)$,

$a_0(980)^0$, $\phi(1020)$, $f_0(1370)$, $f_2(1270)$,
$a_0(1450)^0$, $a_0(980)^\pm$, $a_0(1450)^\pm$

S-wave: K-matrix (BaBar)

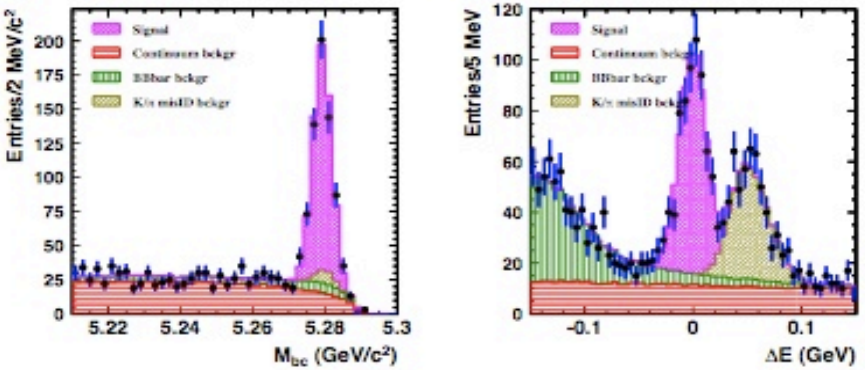
Scalar resonances σ,f_0, K^*_0 (Belle)

CLEOc data are necessary to make model independent analyses

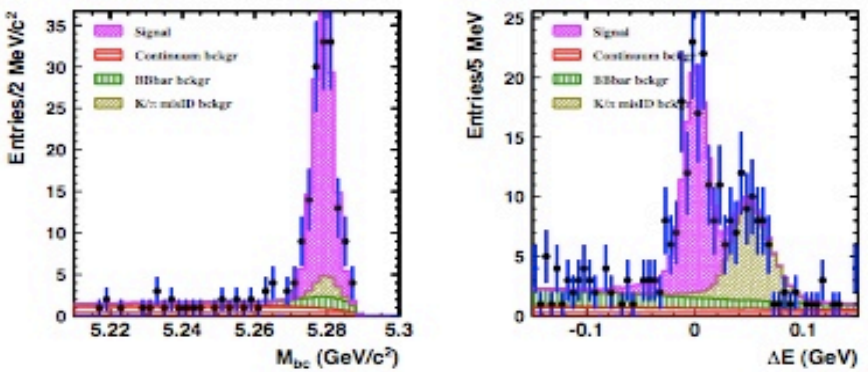
Dalitz: signal selection (Belle)

605 fb^{-1} data sample. [arXiv:0803.3375]

$B^{\pm} \to DK^{\pm}$



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



Signal selections:

$|M_{K_S\pi\pi} - M_D| < 11$ MeV/c^2

$144.9 < \Delta M < 145.9$ MeV/c^2 (for $B^{\pm} \to D^*K^{\pm}$)

$|\Delta E| < 30$ MeV

$M_{\rm bc} > 5.27$ MeV/c^2

$B^{\pm} \to DK^{\pm}$:	756 events, 29% background
$B^{\pm} \to D^*(D\pi^0)K^{\pm}$:	149 events, 20% background

In the "clean" regio

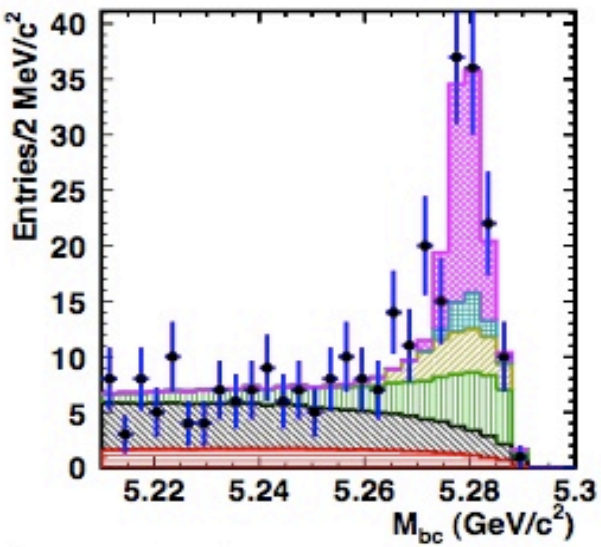
$|\cos\theta_{\rm thr}| < 0.8, \mathcal{F} > -0.7$

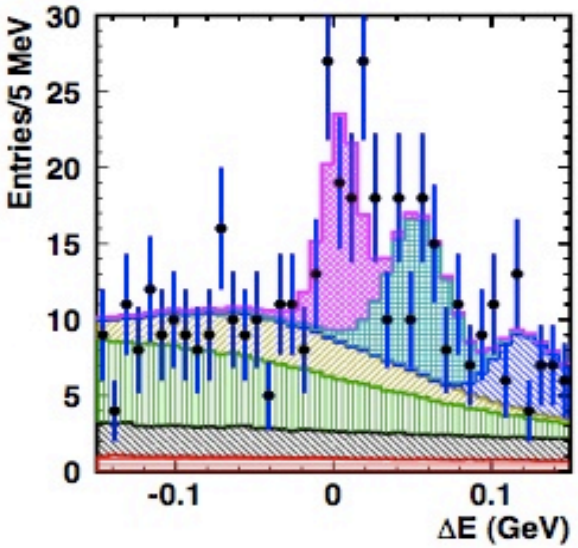
Whole $\cos\theta_{\rm thr}$, $\mathcal{F}$ range used in Dalitz plot fit.

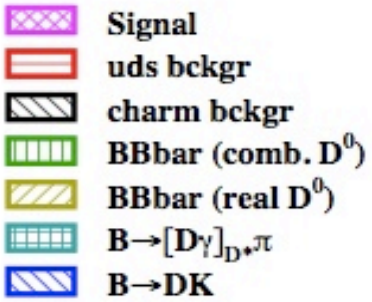
B±→D*K± , D*→Dγ mode

605 fb^{-1} data sample.

Belle preliminary







Signal selections:

$|M_{K_S\pi\pi} - M_D| < 11$ MeV/c^2

$\Delta M < 152$ MeV/c^2

$E_\gamma > 100$ MeV

141 events, 58% background.

$|\Delta E| < 30$ MeV

$M_{\rm bc} > 5.27$ MeV/c^2

In the "clean" region

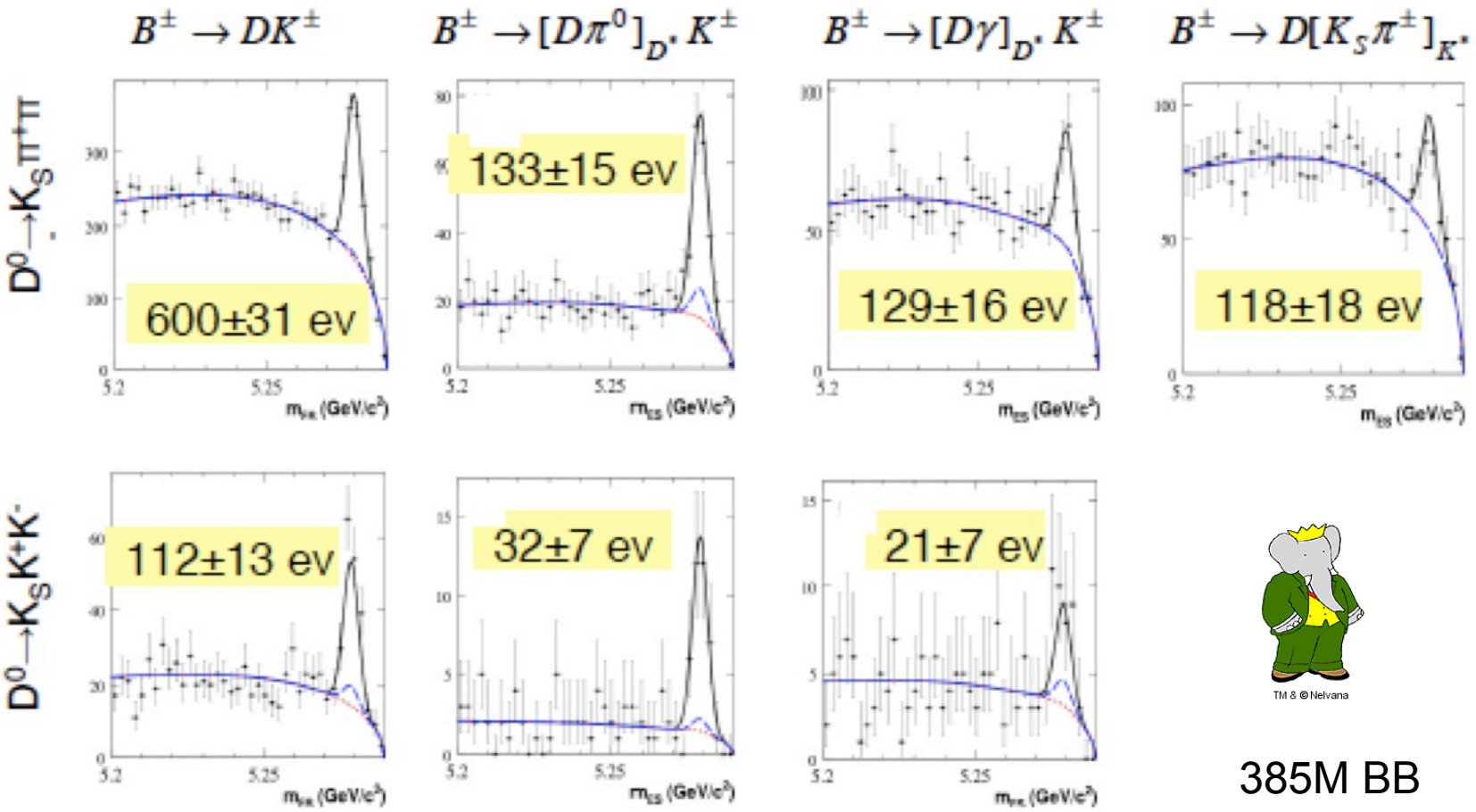
$|\cos\theta_{\rm thr}| < 0.8, \mathcal{F} > -0.7$

Dalitz: signal selection (BaBar)

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

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

PRD 78, 034023 (2008)



385M BB

Dalitz: results

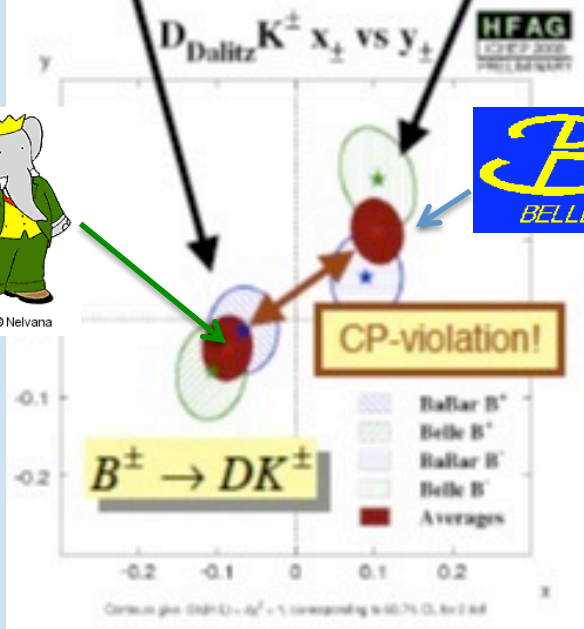
Fit results expressed in Cartesian coordinates $x_\pm = r_B \cos(\pm\gamma+\delta)$, $y_\pm = r_B \sin(\pm\gamma+\delta)$

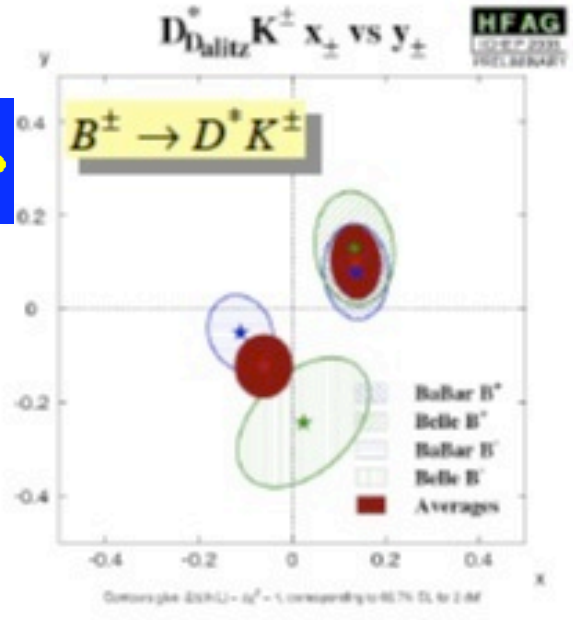
$$|\tilde{D}\rangle = |D^0\rangle + (x+iy)|\overline{D}^0\rangle$$

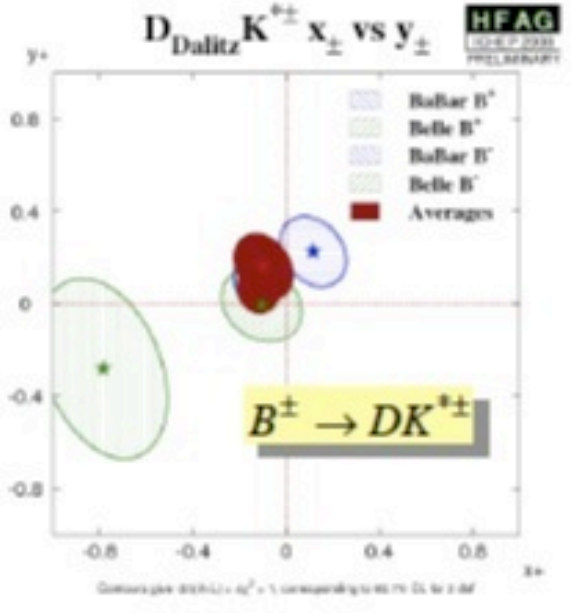
$x_\pm$ is the same as in GLW

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

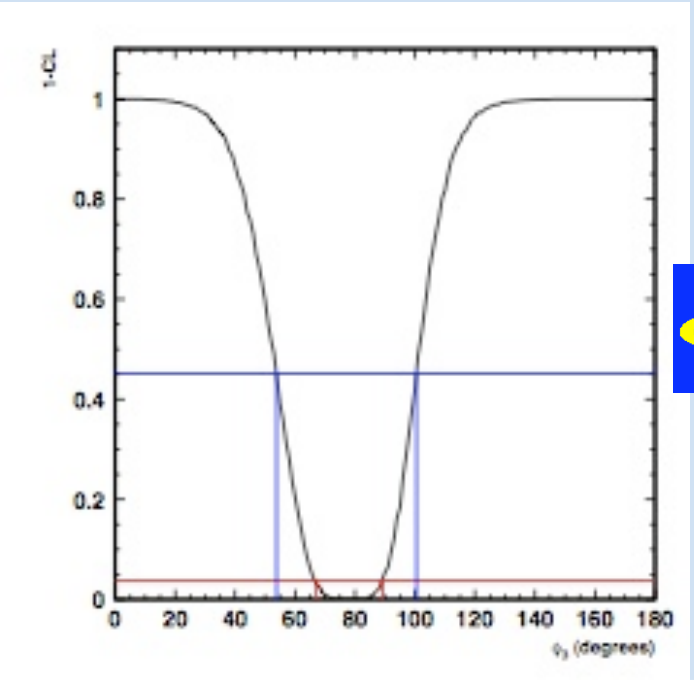
BaBar collaboration, 383M BB pairs **PRD 78, 034023 (2008)**

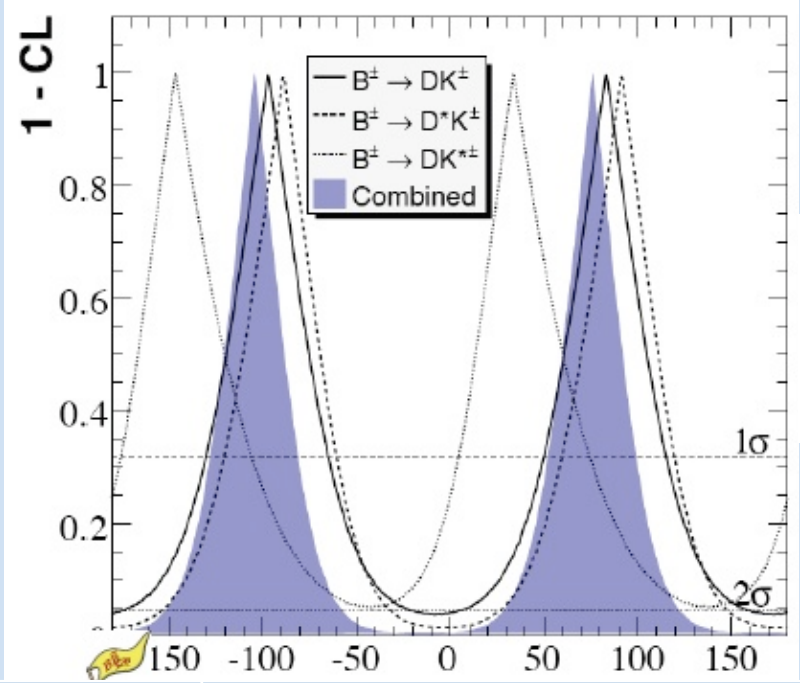






Dalitz: Summary





	Belle	BaBar
ϕ_3/γ	$78.4^{o+10.8o}_{-11.6o}\pm3.6^o\pm8.9^o$	$76^o\pm22^o\pm5^o\pm5^o$
r_{DK}/r_B	$0.160^{+0.040}_{-0.038}\pm0.011^{+0.050}_{-0.010}$	$0.086\pm0.035\pm0.010\pm0.011$
r_{D^*K}/r^*_B	$0.196^{+0.072}_{-0.069}\pm0.012^{+0.062}_{-0.012}$	$0.135\pm0.051\pm0.011\pm0.005$
CPV significance	3.5σ	3.0σ

Summary

- Many results are provided by B-factories in last year:
  - BaBar & Belle ADS
  - Belle Dalitz updated $D^0 \to K_S\pi^+\pi^-$ and new $D^* \to D^0(\pi,\gamma)$
  - BaBar Dalitz updated $D^0 \to K_S\pi^+\pi^-$ and new $D^0 \to K_S K^+ K^-$
- Strong evidence of CP violation combining all results
- Good agreement between different measurements, both in r_{DK}/r_B and ϕ_3/γ:
  - **BaBar: $\gamma = (76 \pm 22 \pm 5 \pm 5)^\circ$ ($61.5^\circ {}^{+29.0^\circ}_{-19.2^\circ}$ using Dalitz+GLW)**
  - **Belle: $\phi_3 = (78.4\ {}^{+10.8}_{-11.6} \pm 3.6 \pm 8.9)^\circ$**