ϕ_3 measurements at B factories

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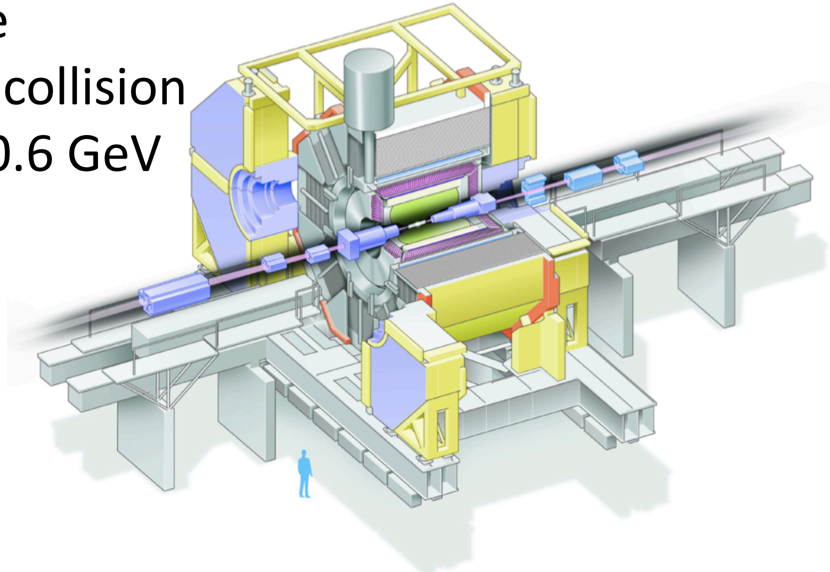
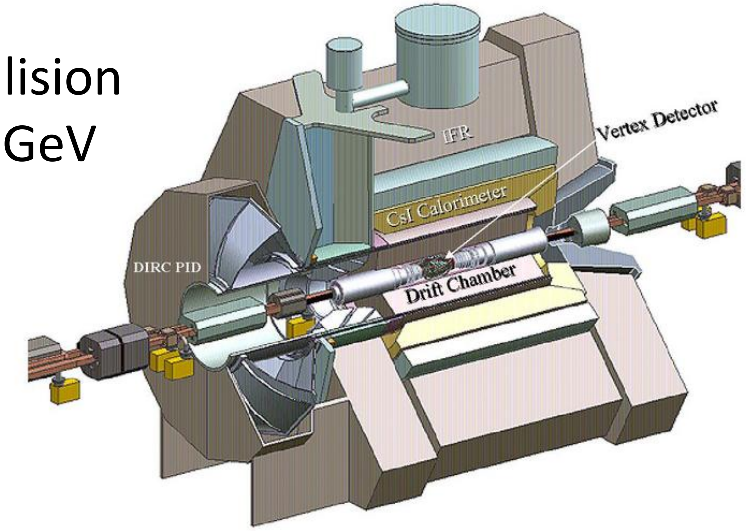
Epiphany Conference, Cracow, 9th Jan. 2012

Experiments Contributing to ϕ_3 Determination

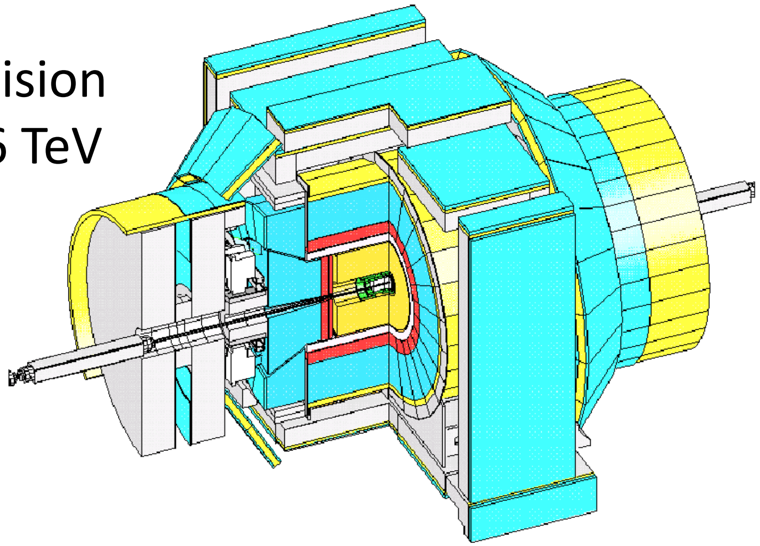
Belle
e^+e^- collision
at 10.6 GeV



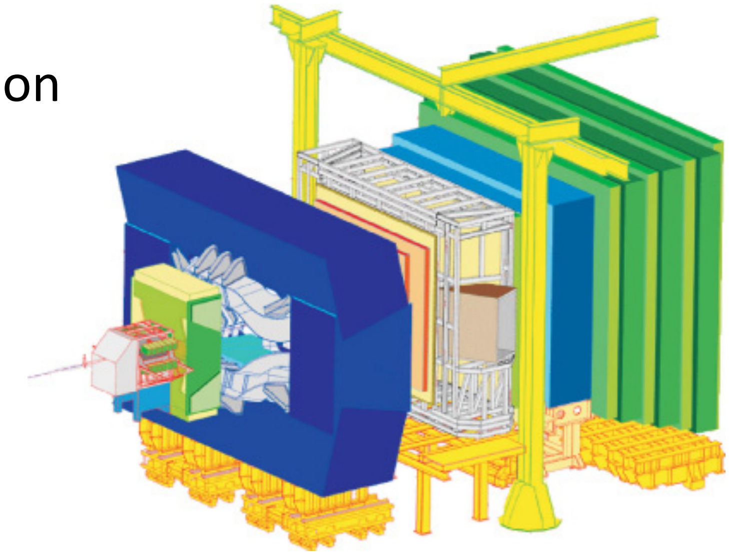
BaBar
e^+e^- collision
at 10.6 GeV



CDF
$p\bar{p}$ collision
at 1.96 TeV



LHCb
pp collision
at 7 TeV



With charm inputs by CLEO, etc.

CKM Matrix and Unitary Triangle

- Charged-current interaction Lagrangian:

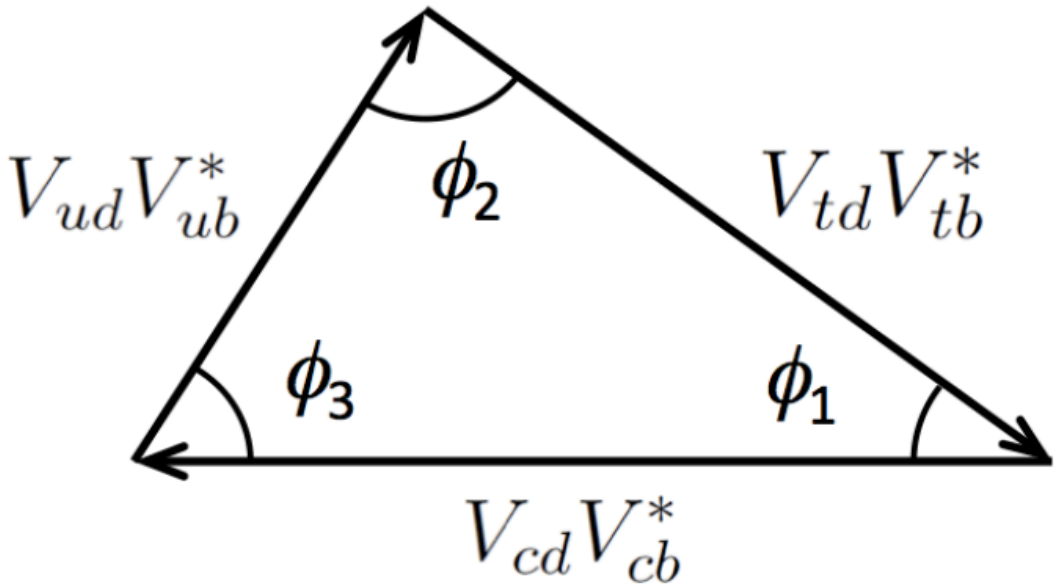
$$\mathcal{L}_{\mathrm{int},qW} = -\frac{g}{\sqrt{2}}\left[\left(\overline{U}_L\gamma^\mu \boldsymbol{V} D_L\right) W_\mu^+ + \left(\overline{D}_L\gamma^\mu \boldsymbol{V}^\dagger U_L\right) W_\mu^-\right]$$

- CKM matrix and unitary triangle:

$$\boldsymbol{V} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

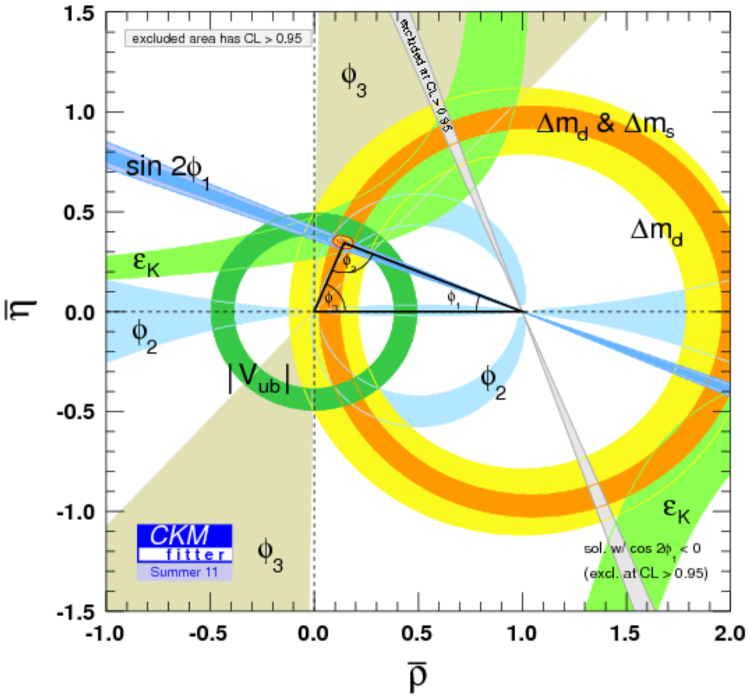
orthogonal

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



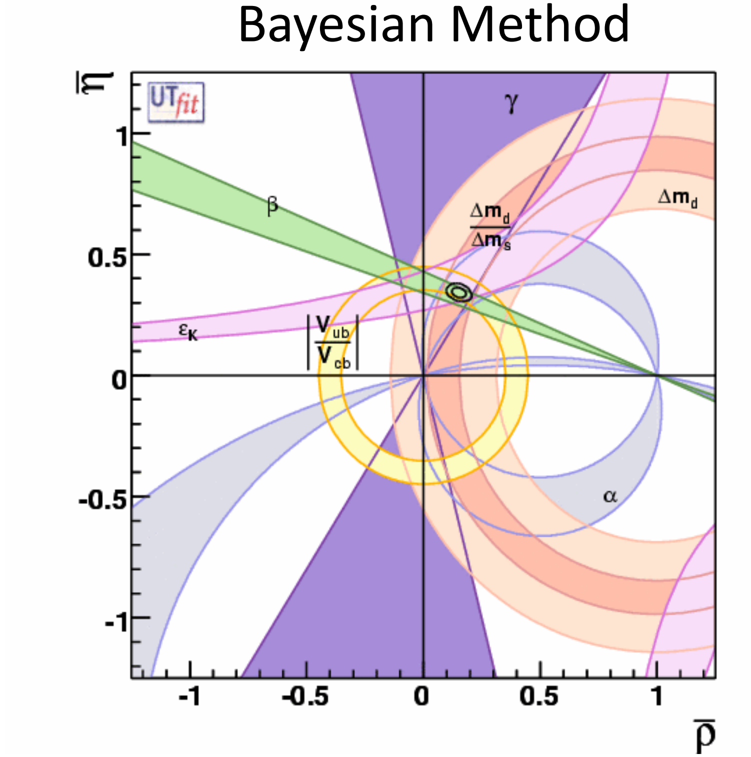
CKM Parameters and ϕ_3

Recent Result by CKMfitter
Full Frequentist Method



$\phi_3 = 68°^{+10°}_{-11°}$

Recent Result by UTfit
Bayesian Method



$\phi_3 = 74°\pm11°$

- Precision on ϕ_3 has been improved in recent years (20°→10°).
- Good agreement with measurements of other CKM parameters.

Definition and Golden Mode for ϕ_3

- Definition:

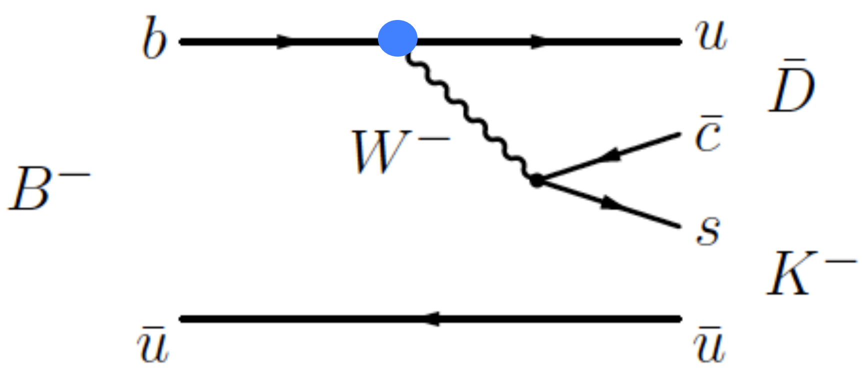
$$\phi_3 \equiv \arg\left(\frac{V_{ud}V_{ub}^*}{-V_{cd}V_{cb}^*}\right) \sim -\arg(V_{ub})$$

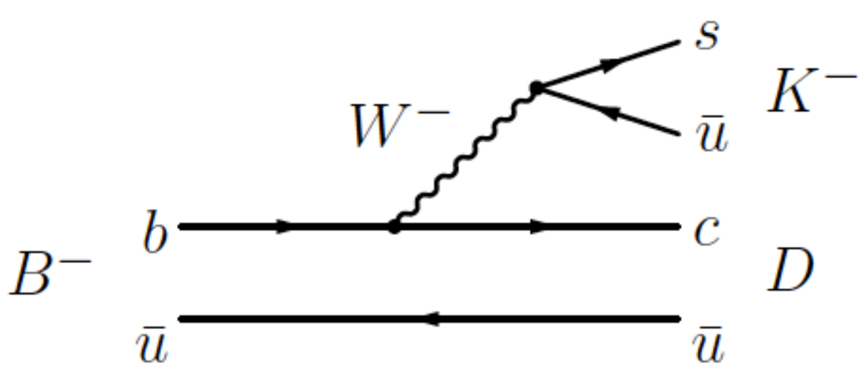
Only large complex element.
L. Wolfenstein,
PRL 51, 1945 (1983)

- Golden mode: B→DK

Tree processes

ϕ_3 ~ $-\arg(V_{ub})$





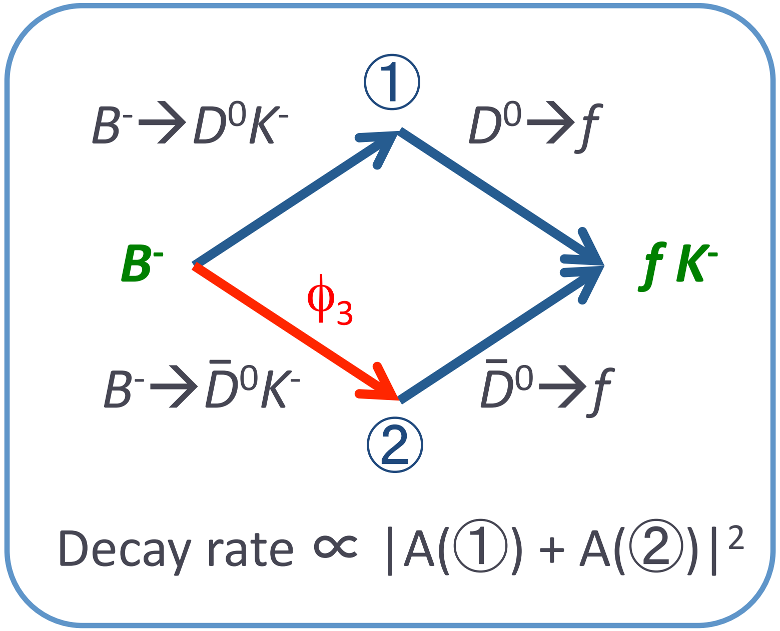
- Color suppressed.
- Final state contains D̄.

- Color allowed.
- Final state contains D.

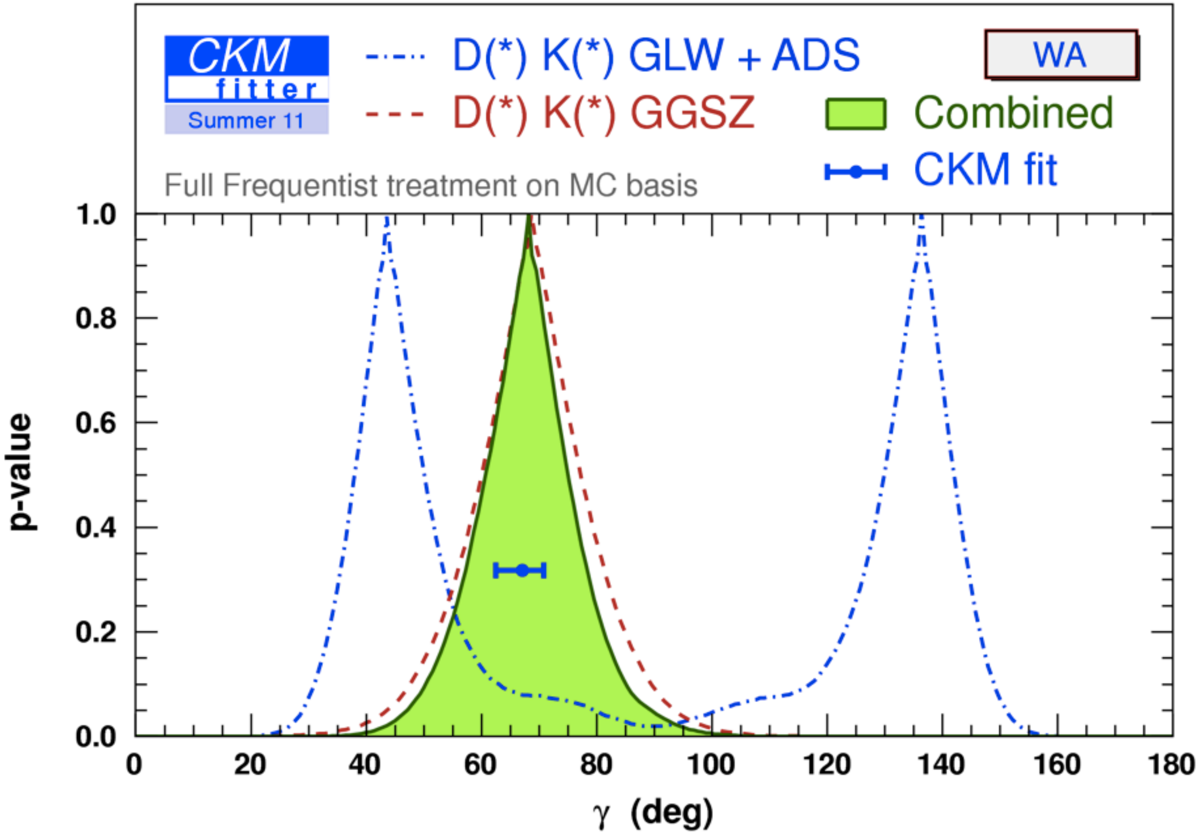
Method of ϕ_3 Measurement

- Exploit the interference between the decay chains through D and $\bar{D}$.
  - Angle ϕ_3 (as well as strong phases) appears in the decay rates.

If no interference, angle disappears.



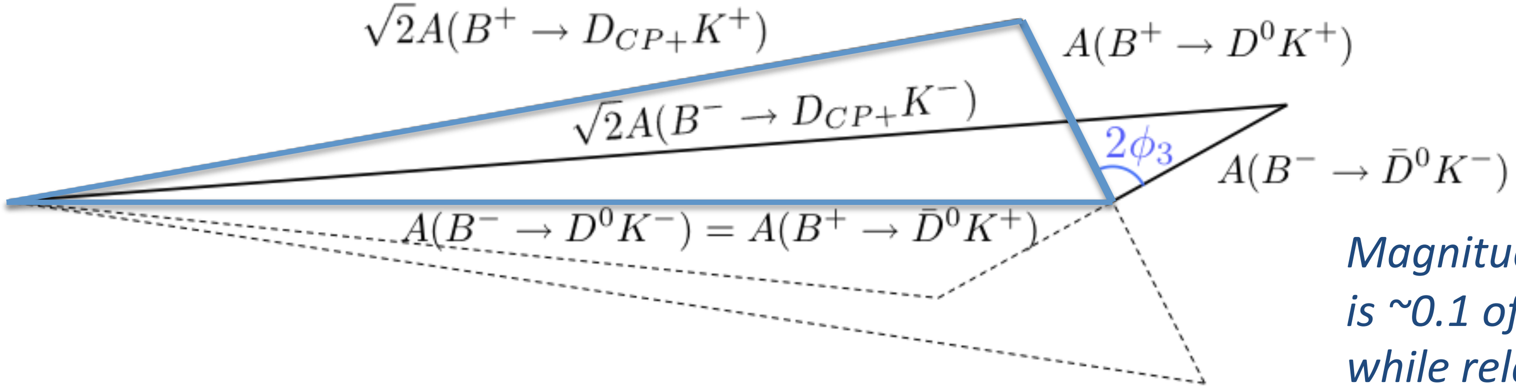
- Several choices of the D decays:
  - $D \to KK$, $\pi\pi$, $K_S\pi^0$, $K_S\phi$, $K_S\omega$, … (Gronau, London, and Wyler)
  - $D \to K\pi$, $K\pi\pi^0$, … (Atwood, Dunietz, and Soni)
  - $D \to K_S\pi\pi$, K_SKK, … (*Bondar*, Giri, Grossman, Soffer, and Zupan)



- Current constraint on ϕ_3 mainly obtained by GGSZ while additional improvement is provided by GLW and ADS.

GLW: Amplitude Triangles and Observables

- Amplitude triangles:



Magnitude of one side is ~0.1 of the others while relative magnitude of the others help ϕ_3 constraint.

- Usually-measured observables:

$$\mathcal{R}_{CP\pm} \equiv \frac{\mathcal{B}(B^- \to D_{CP\pm}K^-) + \mathcal{B}(B^+ \to D_{CP\pm}K^+)}{\mathcal{B}(B^- \to D^0 K^-) + \mathcal{B}(B^+ \to \bar{D}^0 K^+)}$$
$$= 1 + r_B^2 \pm 2r_B \cos\delta_B \cos\phi_3,$$
$$\mathcal{A}_{CP\pm} \equiv \frac{\mathcal{B}(B^- \to D_{CP\pm}K^-) - \mathcal{B}(B^+ \to D_{CP\pm}K^+)}{\mathcal{B}(B^- \to D_{CP\pm}K^-) + \mathcal{B}(B^+ \to D_{CP\pm}K^+)}$$
$$= \pm 2r_B \sin\delta_B \sin\phi_3 / R_{CP\pm},$$

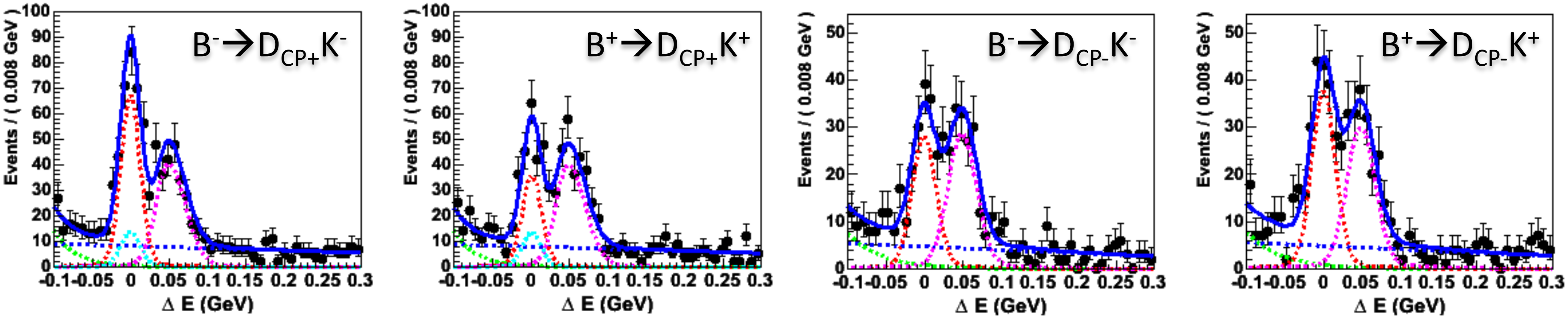
$$r_B = \left| \frac{A(B^- \to \bar{D}^0 K^-)}{A(B^- \to D^0 K^-)} \right|$$

δ_B : strong phase

GLW by Belle

LP 2011 preliminary,
772M BB

CP+ (K^+K^-, $\pi^+\pi^-$): 582 ± 40 events CP− ($K_S\pi^0$, $K_S\eta$): 476 ± 37 events



Red: signal
Magenta: B→Dπ
Green: BB BG
Blue: qq BG (q=u, d, s, c)
Light blue: peaking BG

$$R_{CP+} = 1.03 \pm 0.07 \pm 0.03$$
$$R_{CP-} = 1.13 \pm 0.09 \pm 0.05$$

$$A_{CP+} = +0.29 \pm 0.06 \pm 0.02$$
$$A_{CP-} = -0.12 \pm 0.06 \pm 0.01$$

Systematics dominated by peaking BG.

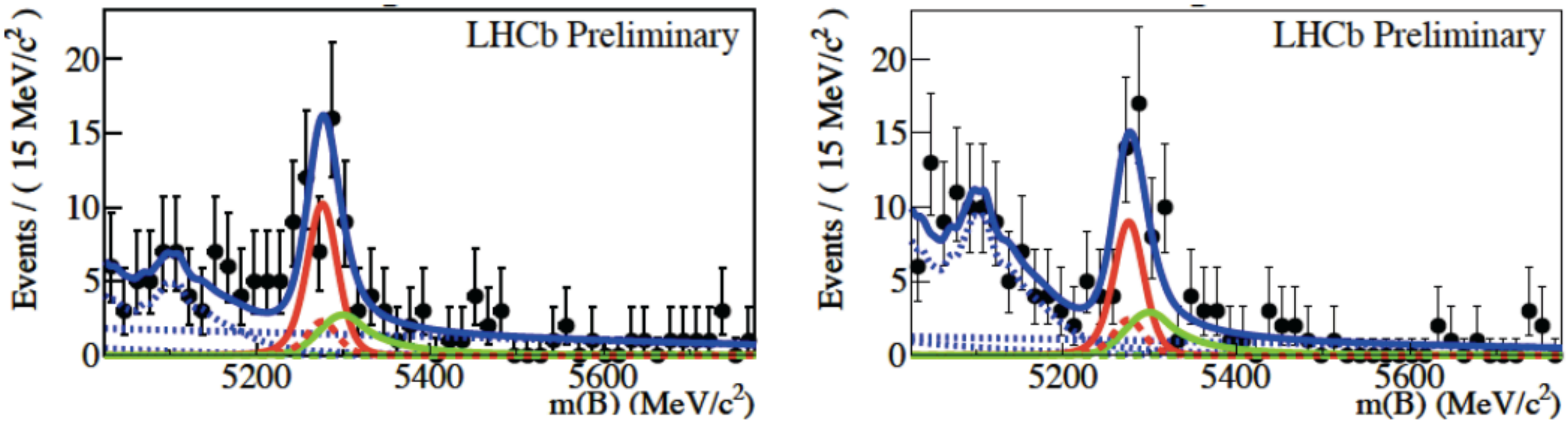
Significant CP asymmetry for CP+ mode.
Opposite asymmetry btw CP+ and CP−.

GLW by LHCb

EPS 2011 preliminary, 35.6 pb^{-1}

- Result obtained by using data taken in 2010.

$B^- \rightarrow (KK)_D K^-$ $\qquad$ $B^+ \rightarrow (KK)_D K^+$



Yields

	$D^0 \rightarrow K^+K^-$
$B^- \rightarrow DK^-$	44
$B^+ \rightarrow DK^+$	40

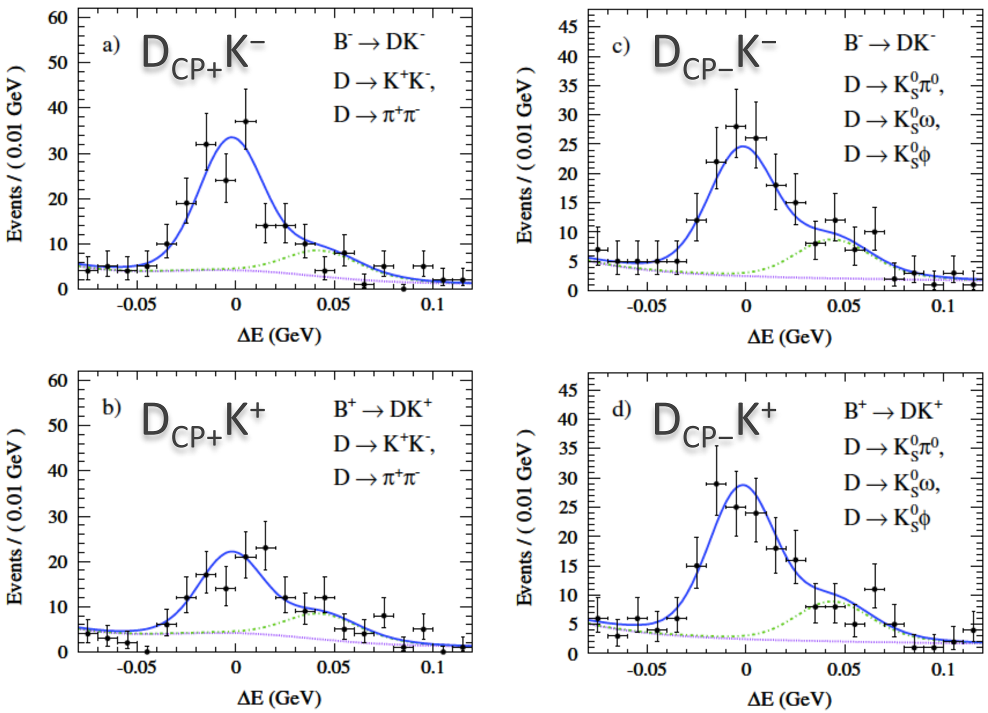
$$R_{CP+} = 1.48 \pm 0.31(stat.) \pm 0.12(syst.)$$

$$A_{CP+} = 0.07 \pm 0.18(stat.) \pm 0.07(syst.)$$

Signal clearly seen. Promising result for obtaining nice R_{CP+}/A_{CP+} at higher statistics.

GLW up to 2010

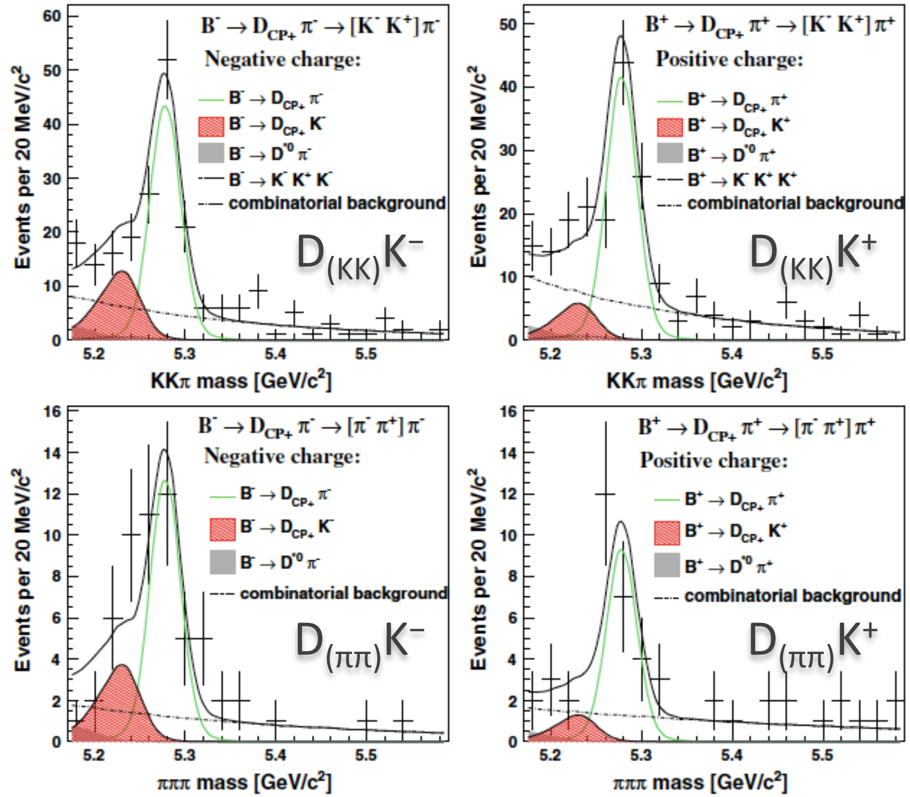
BaBar, 467M BB, PRD82, 072004 (2010)



$$A_{CP+} = 0.25 \pm 0.06(\text{stat}) \pm 0.02(\text{syst})$$
$$A_{CP-} = -0.09 \pm 0.07(\text{stat}) \pm 0.02(\text{syst})$$

Opposite asymmetry btw CP+ and CP−.
Consistent with the results of Belle.

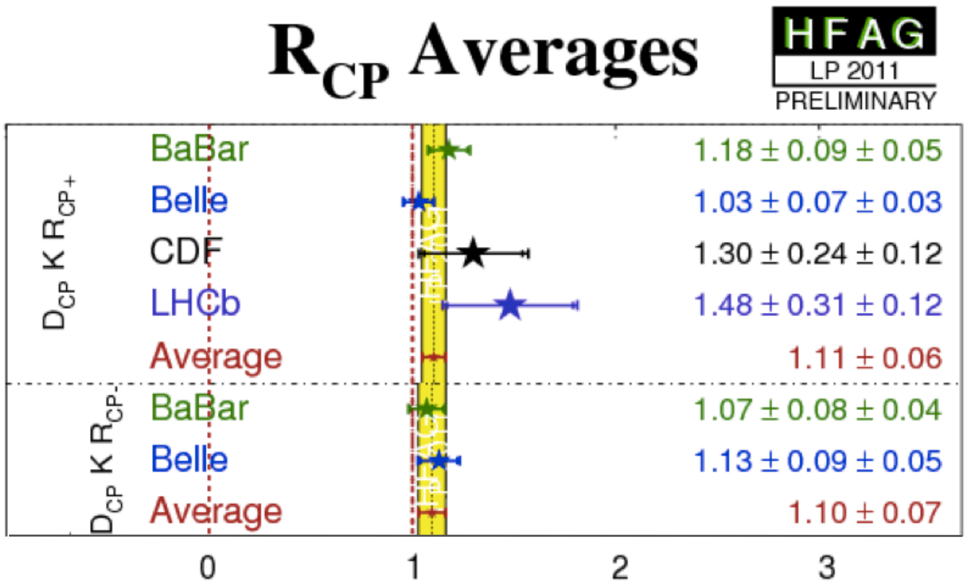
CDF, 1 fb^{-1}, PRD81, 031105(R) (2010)

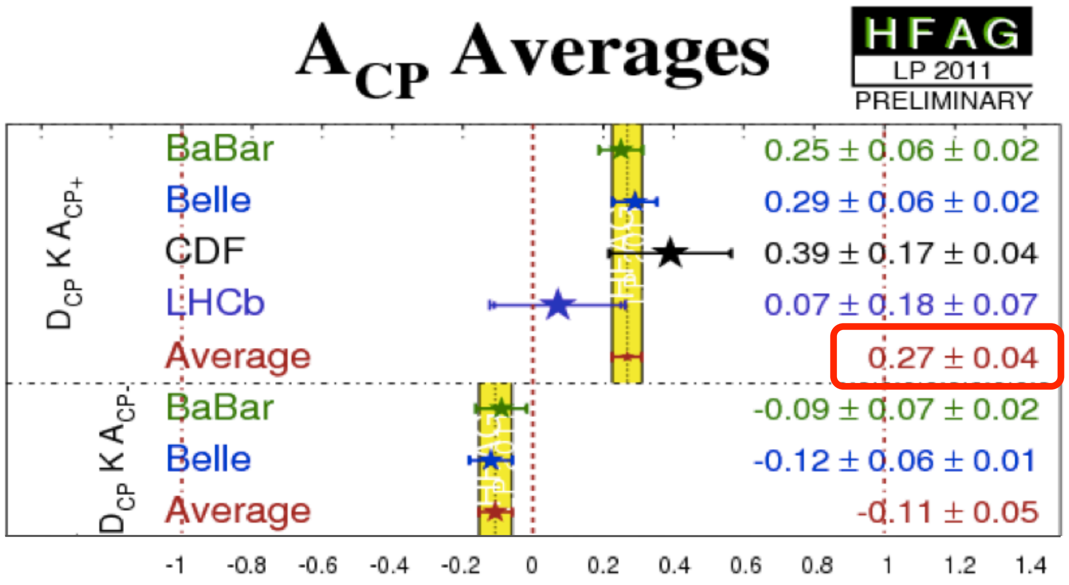


$$A_{CP+} = 0.39 \pm 0.17(\text{stat})$$

Good agreement with other measurements.

Summary for GLW





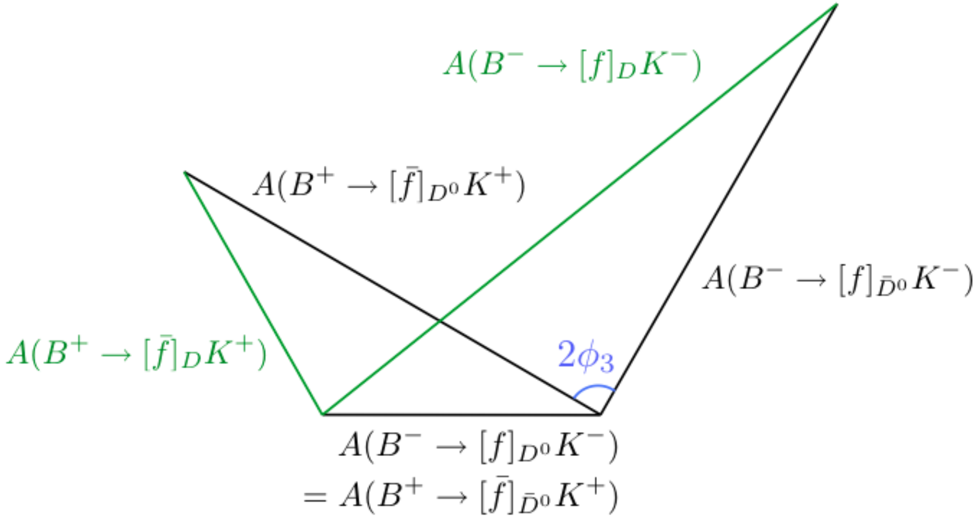
- All results for B→D_{CP}K obtained in 2010-2011.
- Good agreement in measurements by different experiments.
- CP violation clearly established for CP+ (ϕ_3 information).

ADS: Amplitude Triangles and Observables

➢ Amplitude triangles:

*Magnitudes of the sides are small relatively to the GLW ones (**small signal**) while three sides of the triangles have similar magnitudes (**large CPV**).*

Larger contribution from continuum BG.



➢ Usually-measured observables:

$$\mathcal{R}_{\rm ADS} \equiv \frac{\mathcal{B}(B^- \to [f]_D K^-) + \mathcal{B}(B^+ \to [\bar{f}]_D K^+)}{\mathcal{B}(B^- \to [\bar{f}]_D K^-) + \mathcal{B}(B^+ \to [f]_D K^+)}$$

$$= r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_B + \delta_D) \cos\phi_3,$$

$$\mathcal{A}_{\rm ADS} \equiv \frac{\mathcal{B}(B^- \to [f]_D K^-) - \mathcal{B}(B^+ \to [\bar{f}]_D K^+)}{\mathcal{B}(B^- \to [f]_D K^-) + \mathcal{B}(B^+ \to [\bar{f}]_D K^+)}$$

$$= 2 r_B r_D \sin(\delta_B + \delta_D) \sin\phi_3 / R_{\rm ADS},$$

Additional parameters:

$$r_D = \left| \frac{A(D^0 \to f)}{A(\bar{D}^0 \to f)} \right|$$

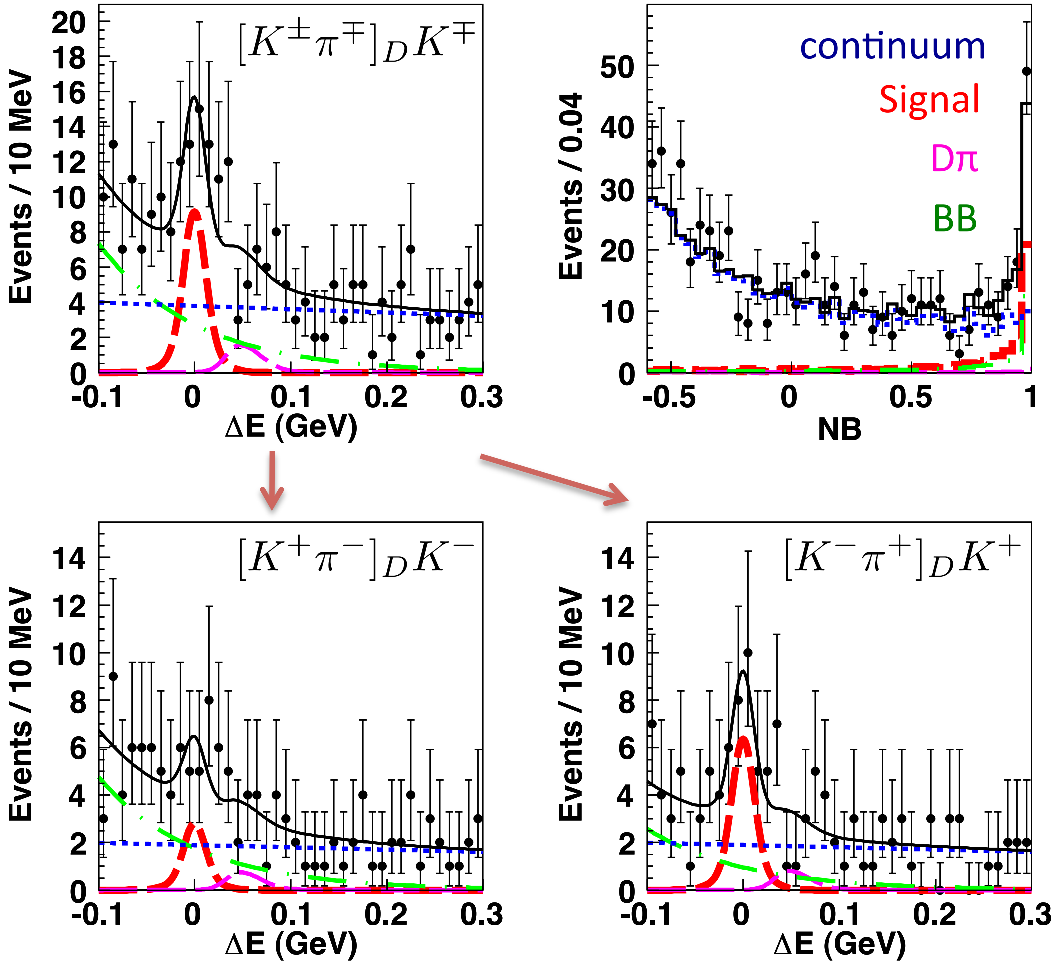
δ_D: strong phase

Inputs from charm factories.

ADS by Belle

PRL106, 231803 (2011), 772M BB

- First evidence is reported by Belle with significance of 4.1σ.
  - Improved continuum suppression with NeuroBayes neural network.



- Observables:

$$\mathcal{R}_{\mathrm{ADS}} = [1.63^{+0.44}_{-0.41}(\mathrm{stat})^{+0.07}_{-0.13}(\mathrm{syst})] \times 10^{-2}$$

$$\mathcal{A}_{\mathrm{ADS}} = -0.39^{+0.26}_{-0.28}(\mathrm{stat})^{+0.04}_{-0.03}(\mathrm{syst})$$

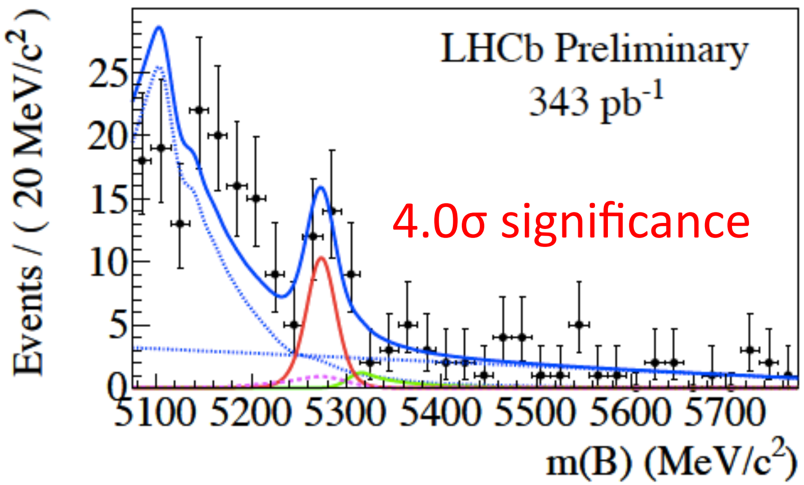
- Indication of important information for ϕ_3 measurement:

R_{ADS} and A_{ADS} varies in [0.2, 2.5] x 10^{-2} and [-0.9, 0.9], respectively, depending on ϕ_3 and strong phases (assuming r_B = 0.1).

ADS by LHCb

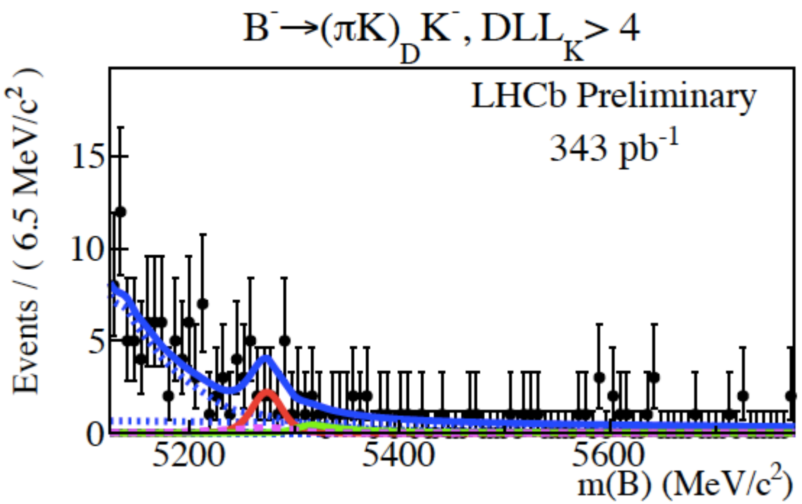
EPS 2011 Preliminary, 343 pb^{-1}

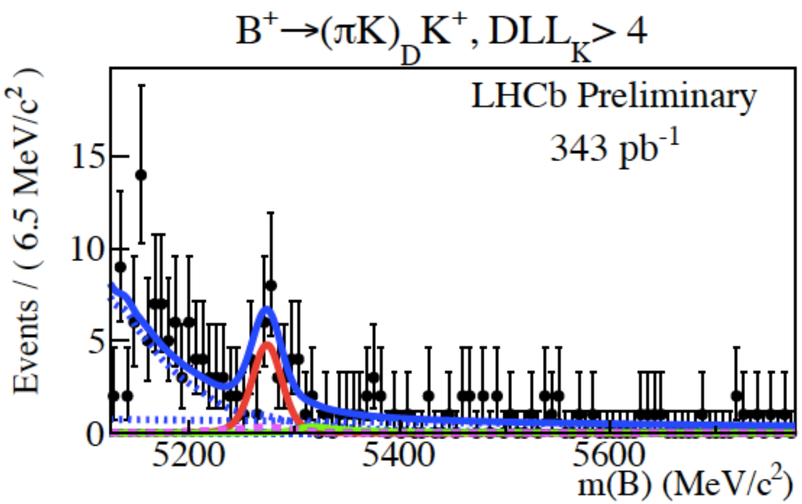
➢ LHCb also obtain evidence of ADS signal:



$$R_{ADS} = (1.66 \pm 0.39 \pm 0.24) \times 10^{-2}$$
$$A_{ADS} = -0.39 \pm 0.17 \pm 0.02$$

Good agreement with the results of Belle.

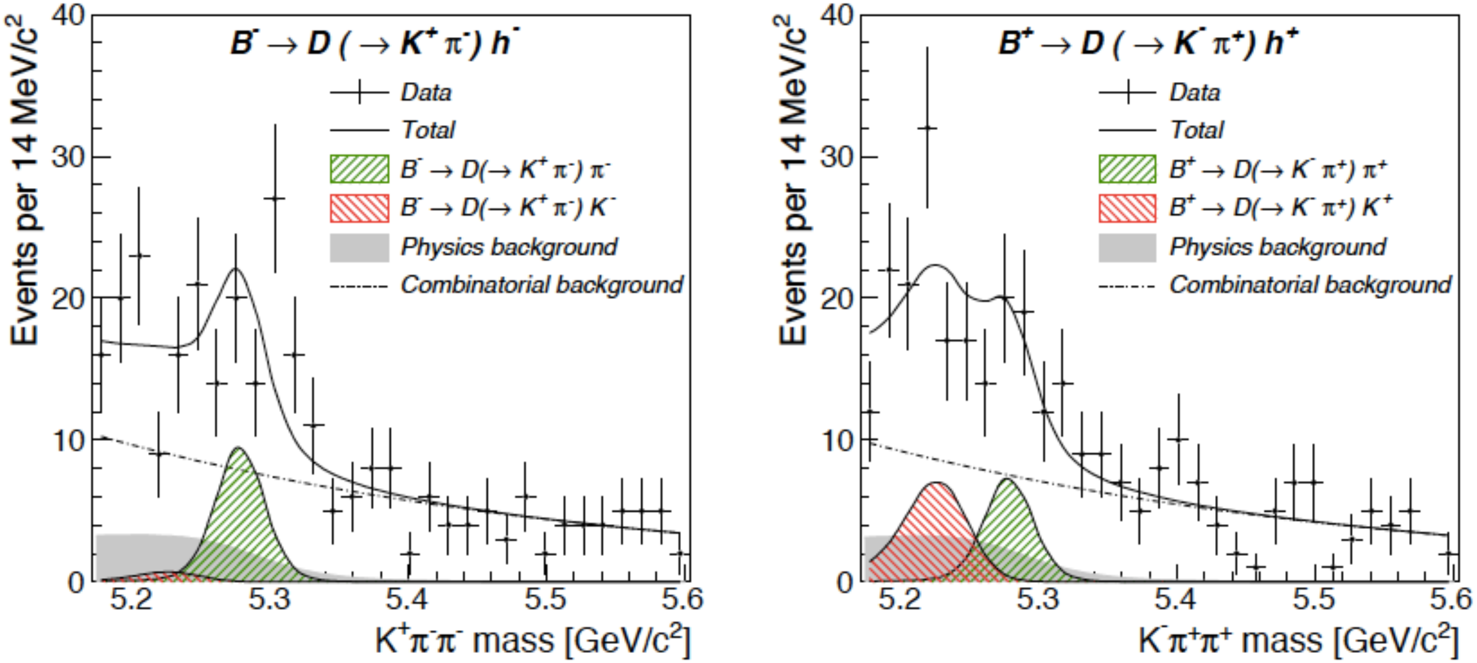




ADS by CDF

Accepted by PRD(RC) in 2011, 7 fb^{-1}

- CDF also obtain evidence of ADS signal (3.2σ):



$$R_{\text{ADS}} = (2.20 \pm 0.86 \pm 0.26) \times 10^{-2}$$

$$A_{\text{ADS}} = -0.82 \pm 0.44 \pm 0.09$$

Good agreement with other measurements.

ADS D^*K by Belle

LP 2011 preliminary,
772M BB

- Continuum suppression with:

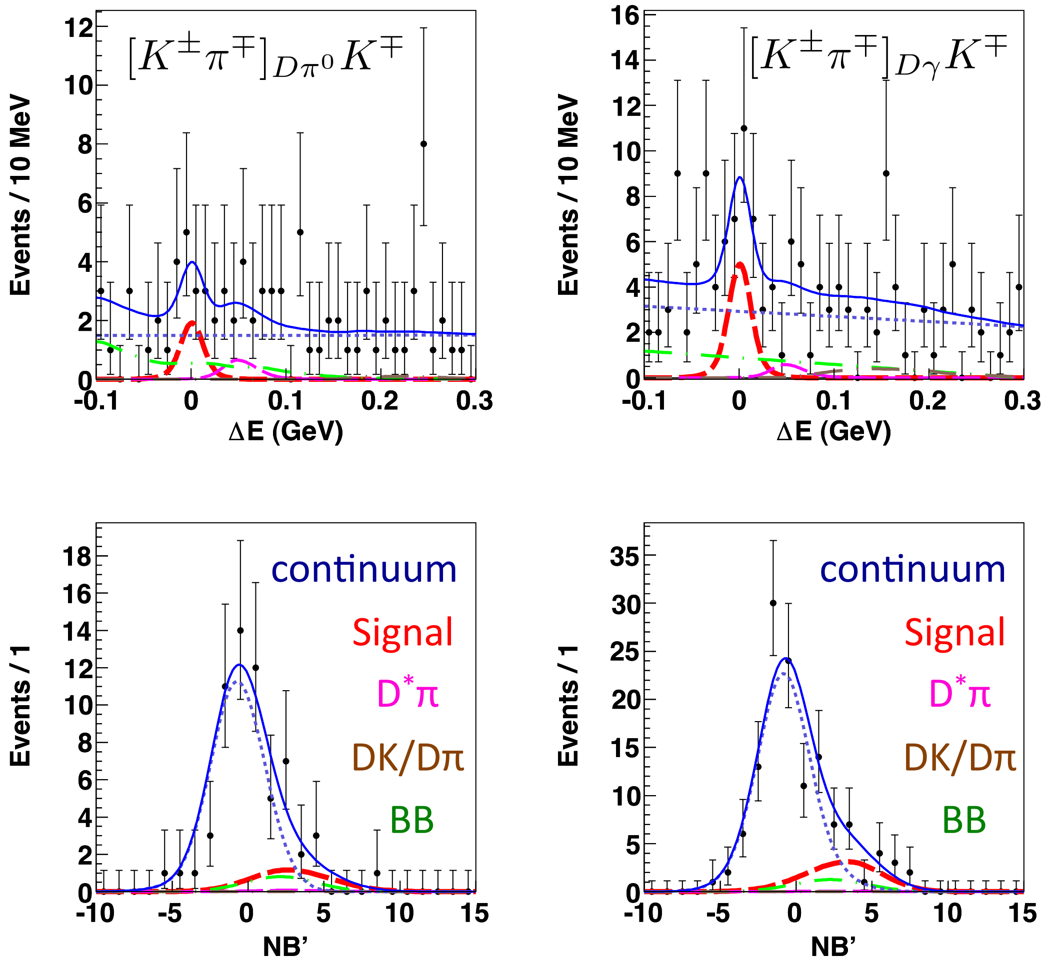
$$NB' \equiv \frac{NB - (-0.6)}{1.0 - NB}$$

- Signal seen with 3.5σ significance for $D^* \to D\gamma$ mode.

- Ratio to favored mode:

$$\mathcal{R}_{D\pi^0} = [1.0^{+0.8}_{-0.7}(\text{stat})^{+0.1}_{-0.2}(\text{syst})] \times 10^{-2}$$

$$\mathcal{R}_{D\gamma} = [3.6^{+1.4}_{-1.2}(\text{stat}) \pm 0.2(\text{syst})] \times 10^{-2}$$



- Difference between $R_{D\pi 0}$ and $R_{D\gamma}$: indication of the effect of the interference term $2r_B{}^*r_D \cos(\delta_B{}^*+\delta_D) \cos \phi_3$ (opposite sign for $R_{D\pi 0}$ and $R_{D\gamma}$).

ADS D*K by Belle

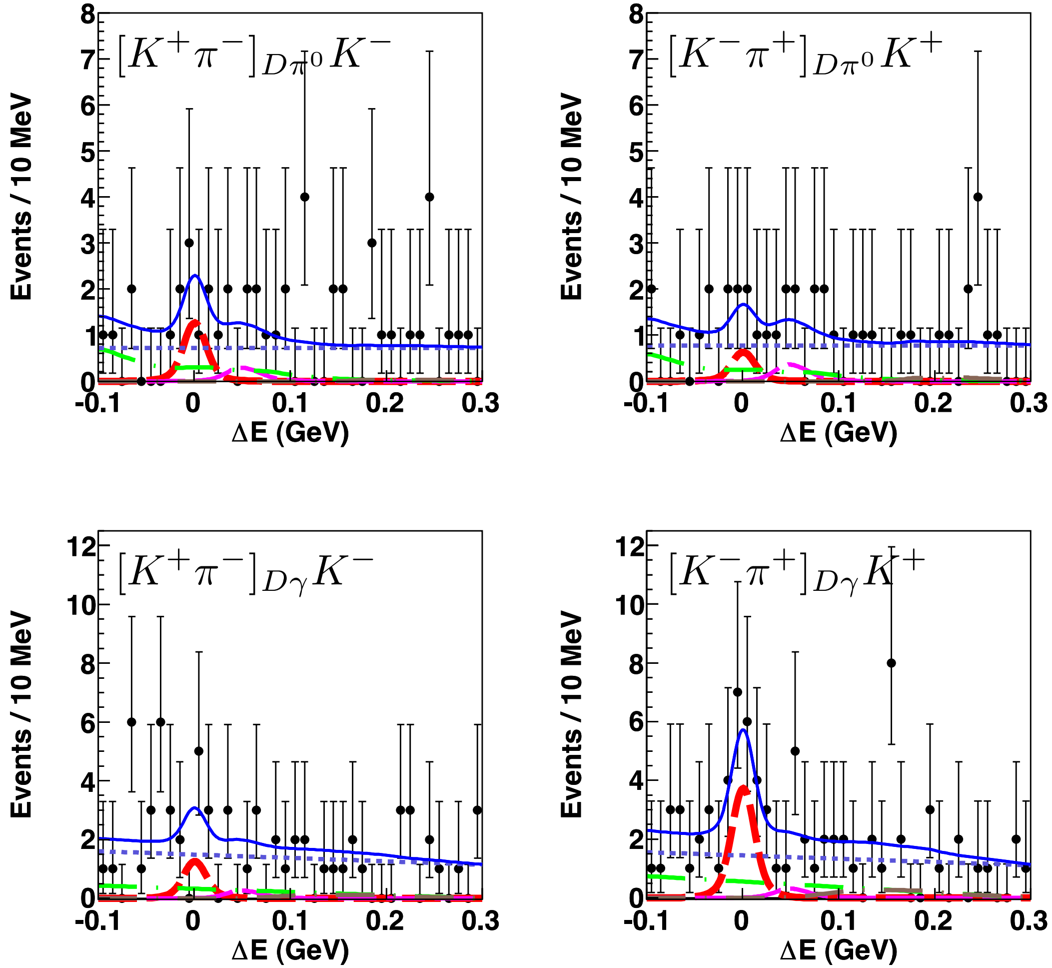
LP 2011 preliminary, 772M BB

- Asymmetry:

$$\mathcal{A}_{D\pi^0} = 0.4^{+1.1}_{-0.7}(\text{stat})^{+0.2}_{-0.1}(\text{syst})$$

$$\mathcal{A}_{D\gamma} = -0.51^{+0.33}_{-0.29}(\text{stat}) \pm 0.08(\text{syst})$$

- Indication of opposite sign for $A_{D\pi 0}$ and $A_{D\gamma}$: consistent with expectation. (Opposite strong phase between $D^* \rightarrow D\pi^0$ and $D^* \rightarrow D\gamma$.)

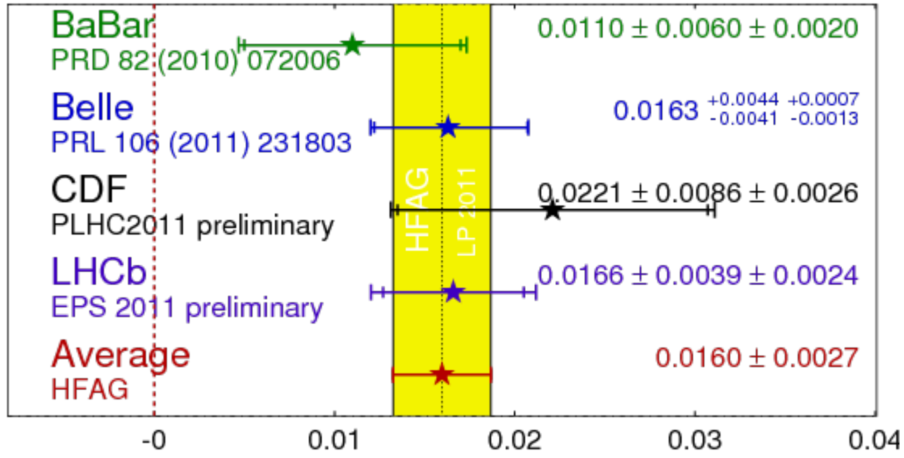


- Combining $R_{D\pi 0}$, $R_{D\gamma}$, $A_{D\pi 0}$, and $A_{D\gamma}$: indication of negative $\cos(\delta_B{}^*+\delta_D)\cos\phi_3$ and positive $\sin(\delta_B{}^*+\delta_D)\sin\phi_3$. Consistent with $B \rightarrow D^{(*)}K$ GGSZ result.

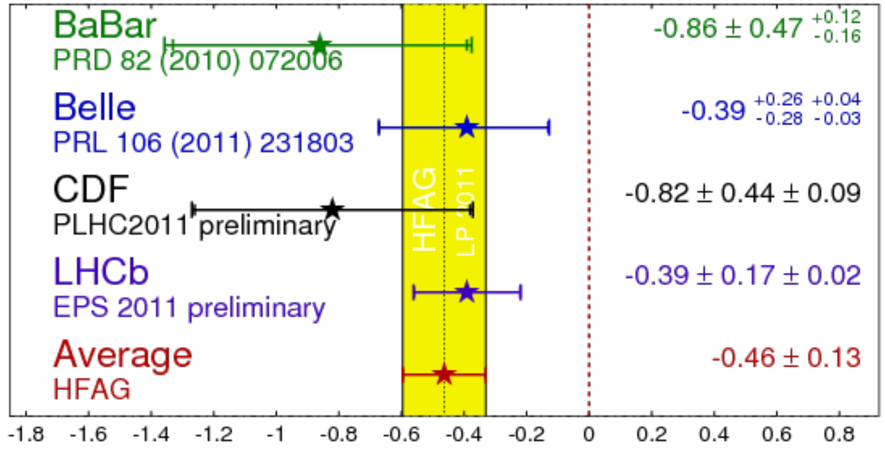
Summary for ADS

HFAG
LP2011
PRELIMINARY

R_{ADS} for DK

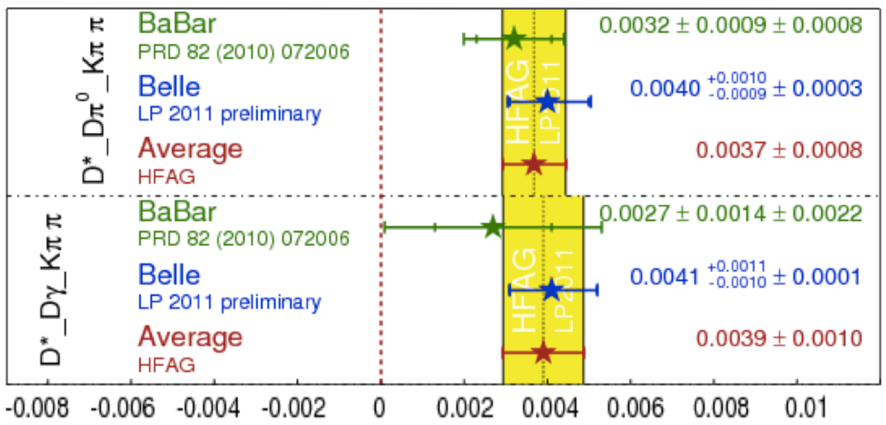


A_{ADS} for DK

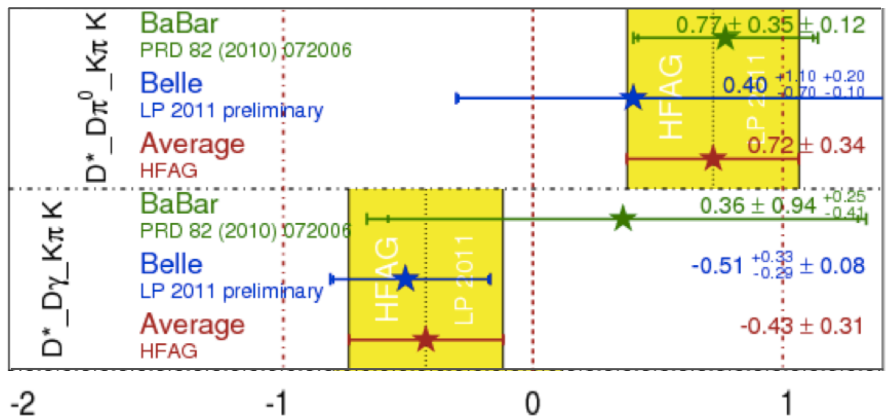


Signal established. Negative asymmetry. Promising for ϕ_3 determination.

R_{ADS} for D^*K



A_{ADS} for D^*K

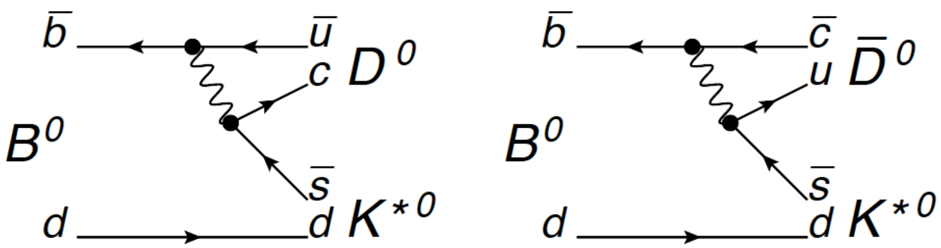


*Signal seen also for B→D*K ADS. Encouraging for improving ϕ_3 measurement.*

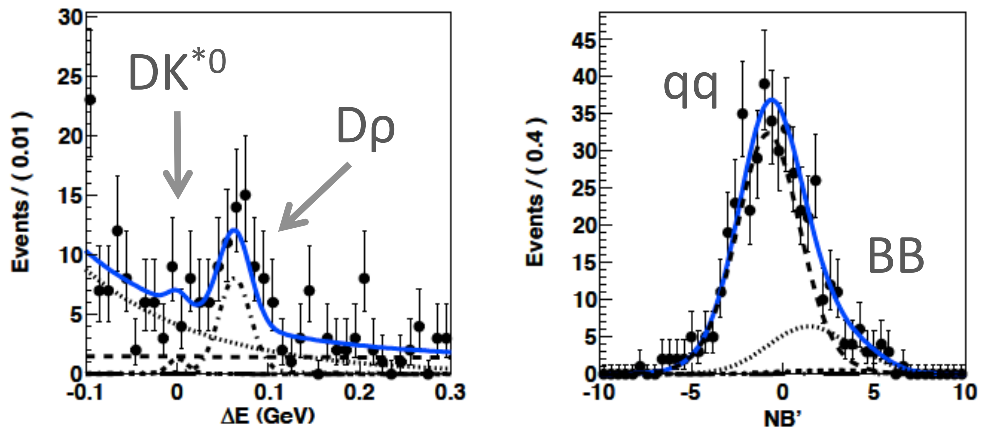
Additional Update: $B^0 \rightarrow DK^{*0}$ ADS by Belle

New
772M BB

- ADS method can be extended to $B^0 \rightarrow DK^{*0}$ by tagging B^0 from K^{*0}.



Both color suppressed.

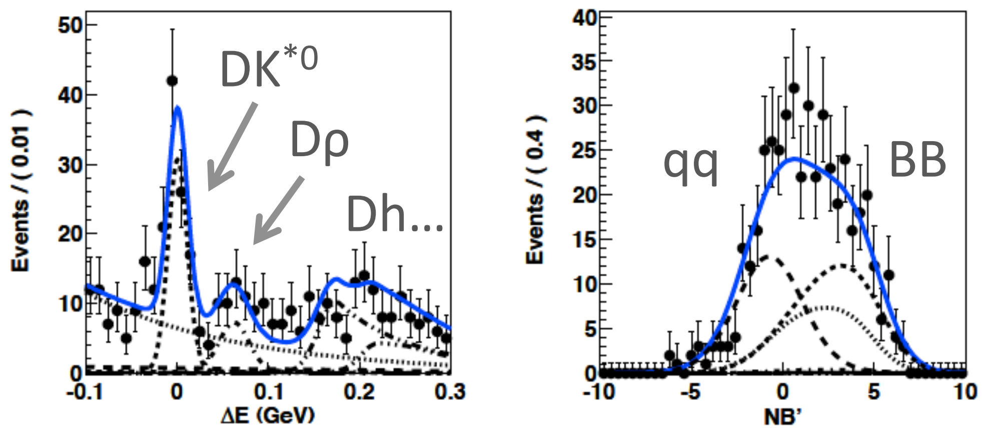


No significant signal for main mode: $7.7^{+10.6}_{-9.5}$.

- K^{*0} cannot be separated by $K^+\pi^-$ and effective parameters r_S and δ_S are included in 'ADS fit'.
- Result:

$$\mathcal{R}_{DK^{*0}} = (4.1^{+5.6+2.8}_{-5.0-1.8}) \times 10^{-2}$$

$$\mathcal{R}_{DK^{*0}} < 0.16 \text{ (95\% C.L.)}$$



Signal seen for calibration mode: 190^{+22}_{-21}.

(NB': variable for continuum suppression.)

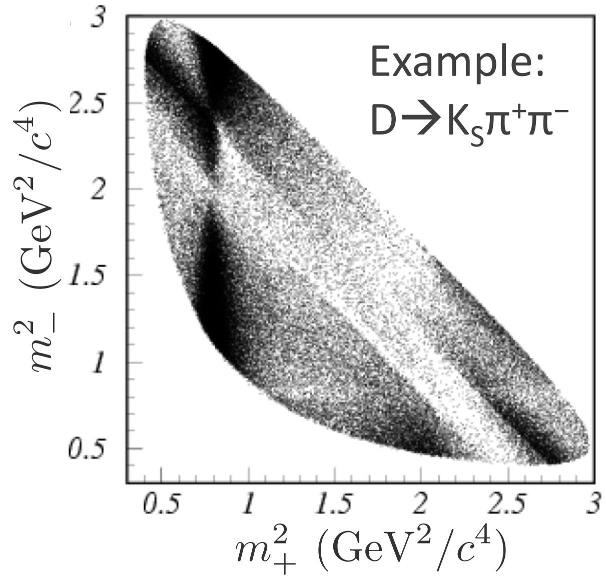
GGSZ, Model-Dependent Approach

- Amplitude of $B^{\pm} \rightarrow DK^{\pm}$ process can be expressed by

$$M_{\pm} = \underline{f(m_{\pm}^2, m_{\mp}^2)} + r_B e^{\pm i\phi_3 + i\delta_B} \underline{f(m_{\mp}^2, m_{\pm}^2)}$$

$$m_{\pm}^2 = m_{K_S h^{\pm}}^2$$

Amplitude of $D \rightarrow K_S h^+ h^-$ decay
determined from Dalitz plot of large continuum data
(Flavor is tagged by soft-pion charge in $D^{*\pm} \rightarrow D\pi^{\pm}_{soft}$).
Isobar-model assumption with BW for resonances.



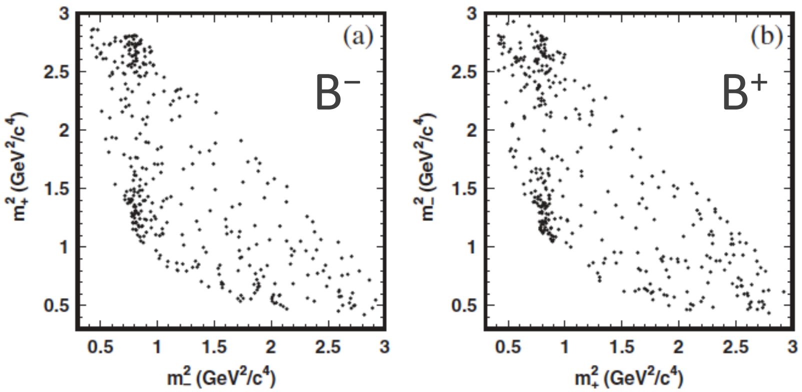
- Procedure of analysis:

1. Fit to $m_{\pm}$ by $M_{\pm}$ to obtain $x_{\pm} = r_B\cos(\pm\phi_3+\delta_B)$ and $y_{\pm} = r_B\sin(\pm\phi_3+\delta_B)$.
2. Extract ϕ_3 (as well as r_B and δ_B) from $x_{\pm}$ and $y_{\pm}$.

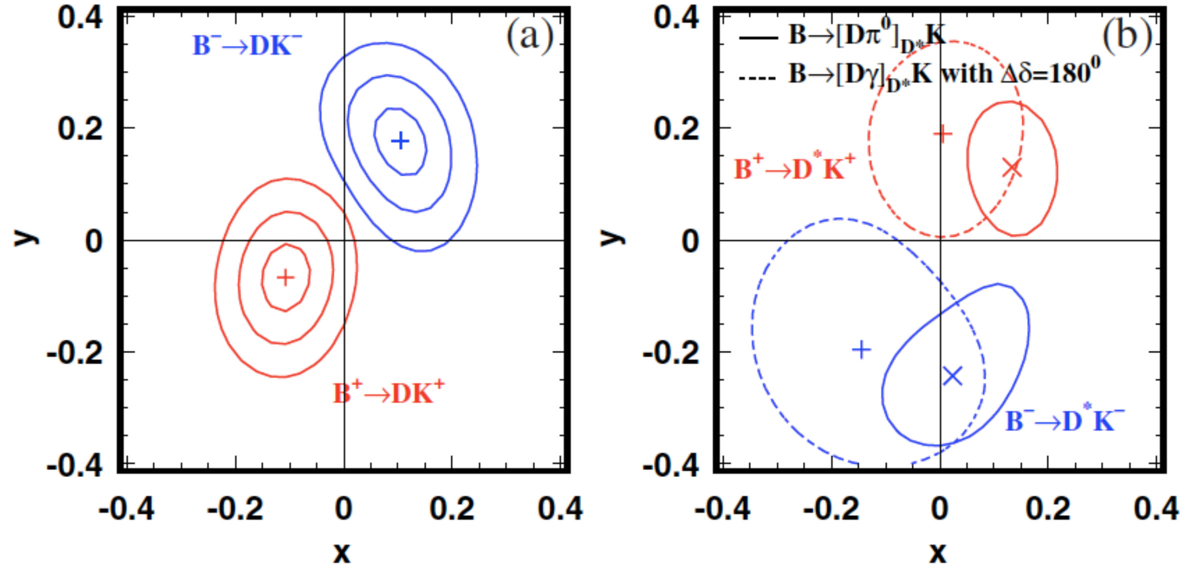
GGSZ by Belle

PRD81, 112002 (2010), 657M BB

- Examples of Dalitz plots and confidence contours on x and y:



Dalitz plots for B→DK.



- Result on ϕ_3 obtained by combining DK and D^*K:

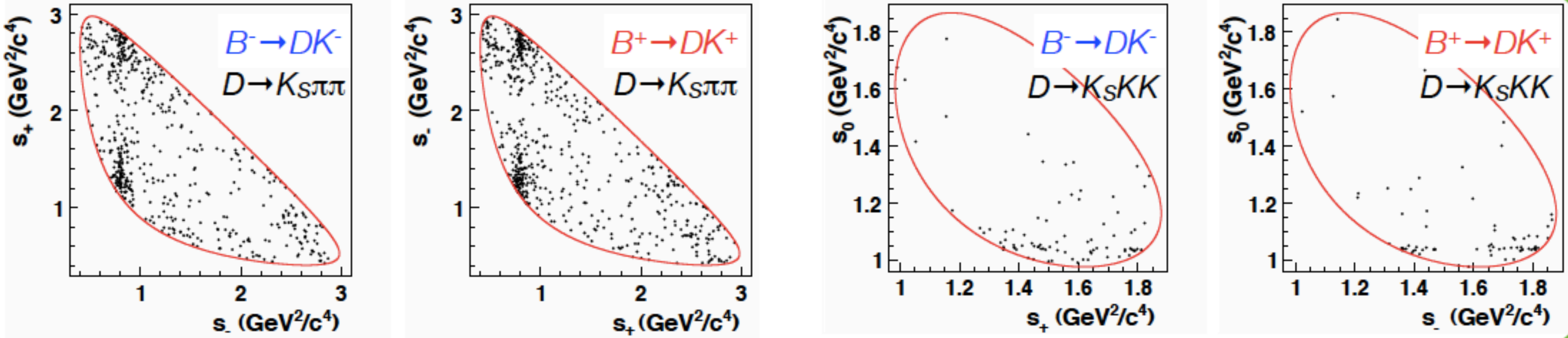
$$\phi_3 = 78.4^\circ\ {}^{+10.8^\circ}_{-11.6^\circ} \pm 3.6^\circ(\text{syst}) \underline{\pm 8.9^\circ(\text{model})}$$

D decay modeling (isobar model)

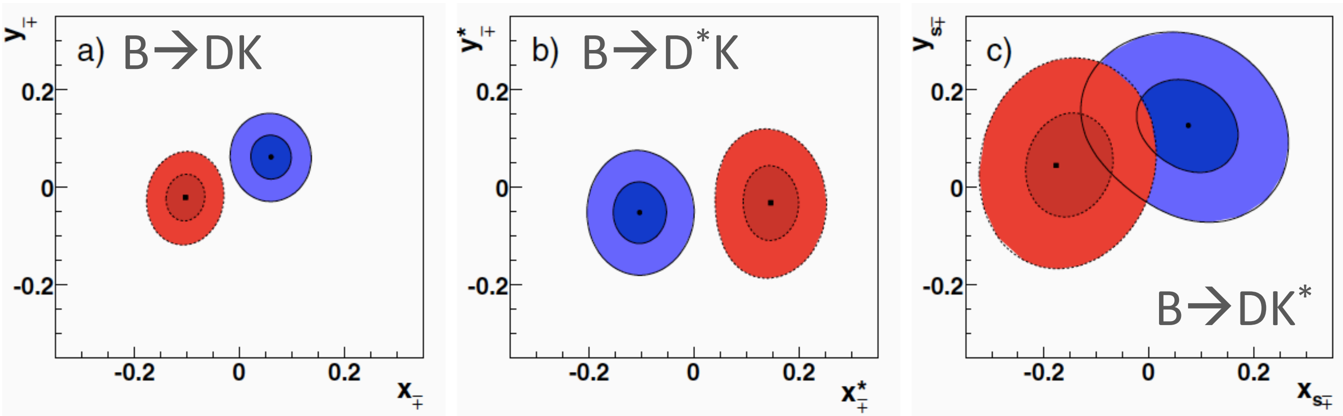
GGSZ by BaBar

PRL105, 121801 (2010),
468M BB

Dalitz plots for B→DK



Contours for x and y

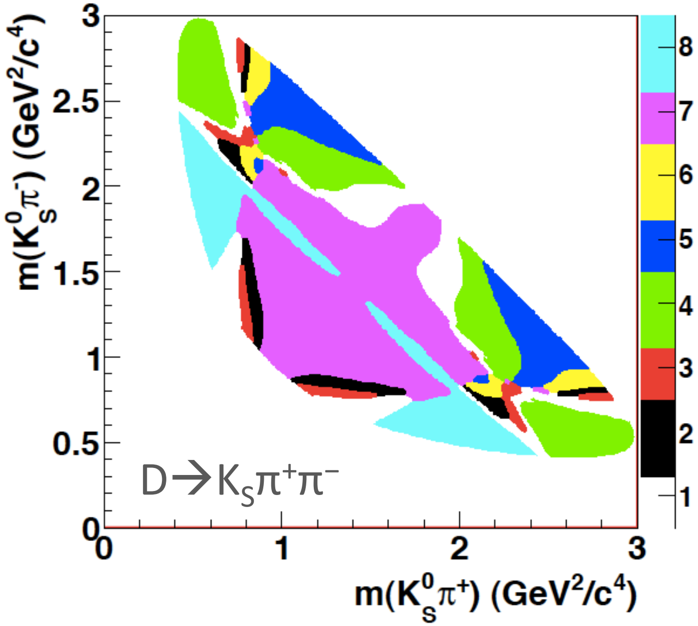


Effective hadronic parameters for B→DK to take interference with other B→DK$_S^0\pi$.*

$$\phi_3 = (68 \pm 14 \pm 4 \pm 3)^\circ$$

GGSZ, Model-Independent Approach

- Divide the Dalitz plot into several regions
  (averaged strong phase of D→$K_S$hh obtained without assuming model).



Optimal binning: uniform division of the strong phase difference.
(Binning is model-dependent while result model-independent.)

Number of events in i^{th} bin is a function of $x_\pm/y_\pm$

$$N_i^\pm = h_B \left[K_{\pm i} + r_B^2 K_{\mp i} + 2\sqrt{K_i K_{-i}}(x_\pm c_i \pm y_\pm s_i) \right]$$

where

h_B : normalization constant

K_i : number of events in $i^{\rm th}$ bin of flavor tagged D decay

c_i and s_i : cosine and sine of strong phase of D decay avegraged in $i^{\rm th}$ bin

ψ(3770) by CLEO

Values of ϕ_3, r_B, and δ_B are extracted from $N_i^\pm$'s (simultaneous equations for ϕ_3, r_B, and δ_B).

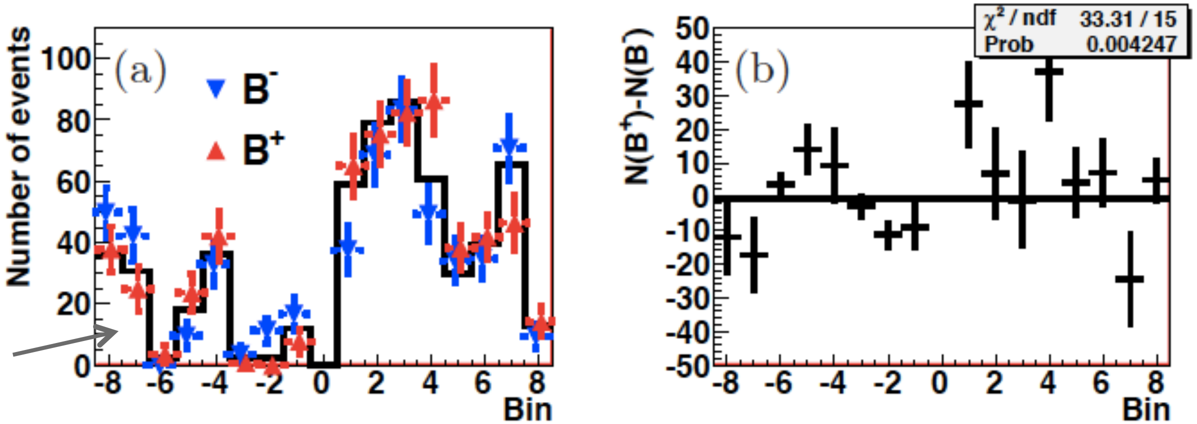
A. Bondar and A. Poluektov, Eur. Phys. J. C **47**, 347 (2006); Eur. Phys. J. C **55**, 51 (2008).

GGSZ Model-Independent by Belle

Moriond 2011
preliminary, 772M BB

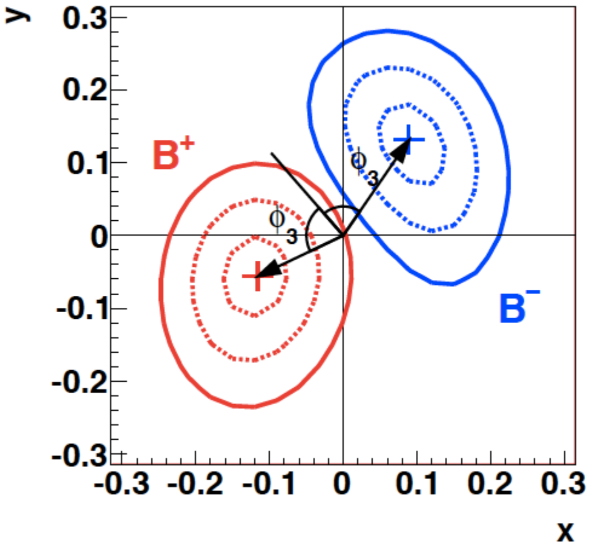
- Result of the fit of $B^{\pm} \rightarrow DK^{\pm}$ sample in each bin:

Black: flavor sample



- Result on ϕ_3 as well as contours on x and y:

$$\phi_3 = (77.3^{+15.1}_{-14.9} \pm 4.1 \pm 4.3)^\circ$$



Third error due to c_i and s_i uncertainty.
Will decrease to 1° or less by BES-III.

Summary

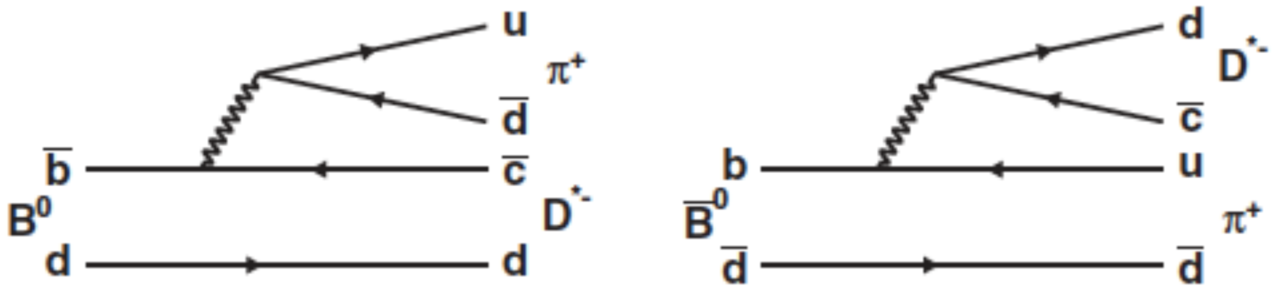
- Recent improvement on ϕ_3 (20°→10°) is achieved by updates on $B \to D^{(*)}K^{(*)}$ by Belle, BaBar, LHCb, and CDF.
  - GLW
    - CP asymmetry for CP+ mode established by BaBar and Belle.
  - ADS
    - Evidence of signal obtained by Belle, CDF, and LHCb.
    - Evidence also obtained for D^*K by Belle.
  - GGSZ
    - First model-independent measurement by Belle.
- Promising to obtain a precision of O(1°) in near future.

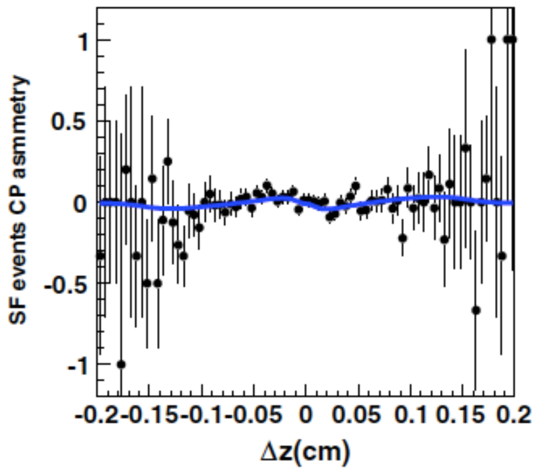
$2\phi_1 + \phi_3$

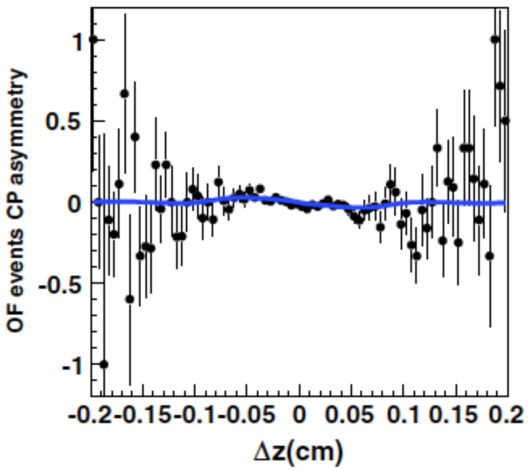
Belle, PRD84, 021101(R) (2011), 657M BB

➢ Result of partial reconstruction for $B \rightarrow D^{*\mp}\pi^{\pm}$ published by Belle. (Preliminary result shown in 2008.)

Mixing-induced CP violation to extract $2\phi_1 + \phi_3$.







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

$$S^{+} = +0.061 \pm 0.018 \pm 0.012,$$

$$S^{-} = +0.031 \pm 0.019 \pm 0.015,$$