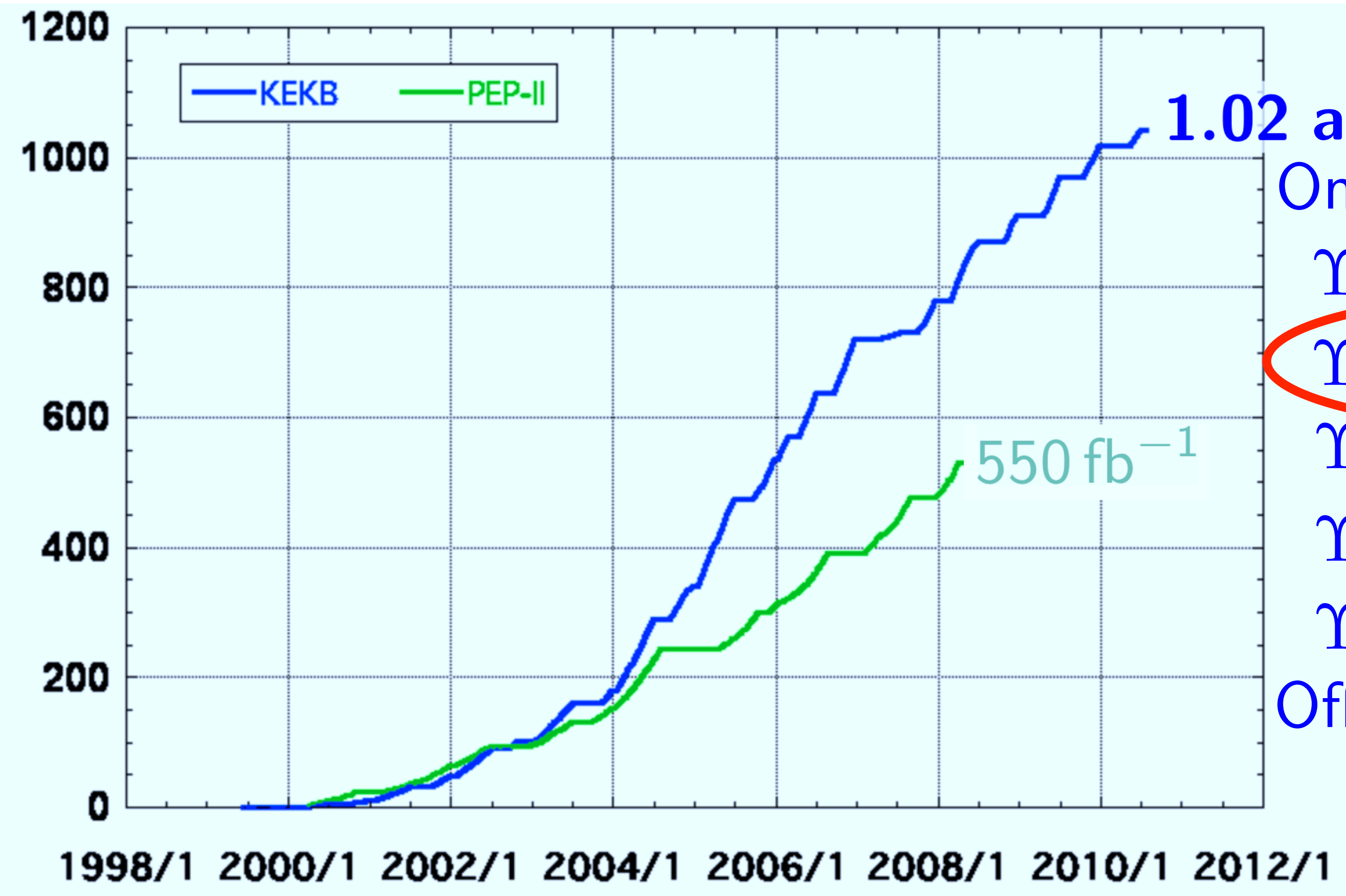
Measurement of the CKM Angle ϕ_3 / γ at Belle

Leo Piilonen, Virginia Tech
on behalf of the Belle Collaboration

DPF Brown University Providence RI August 2011

Integrated luminosity at the B factories



1.02 ab^{-1}

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 25 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off resonance/scan:

155 fb^{-1}

The quark-mixing matrix contains one irreducible phase that is responsible for all $\not{CP}$ in quark transitions

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$


Kobayashi


Maskawa

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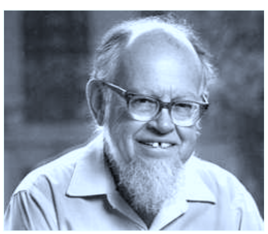
Wolfenstein

$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\boldsymbol{\rho}-i\boldsymbol{\eta}) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\boldsymbol{\rho}-i\boldsymbol{\eta}) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

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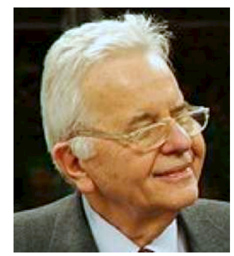
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

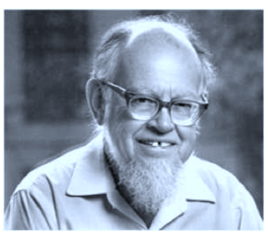
Kobayashi

Maskawa



Cabibbo

$\sin\theta_C$

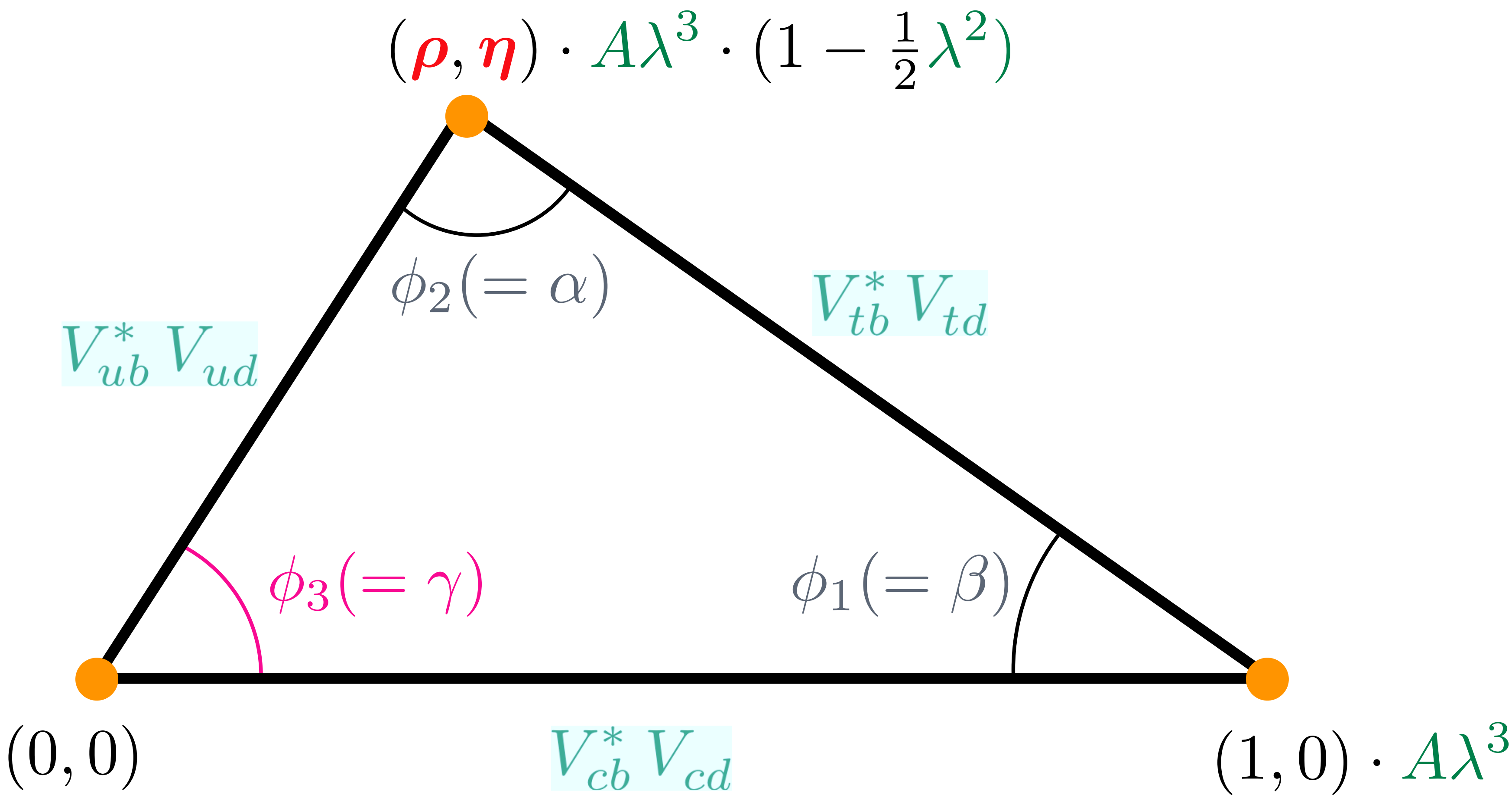


Wolfenstein

$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\boldsymbol{\rho}-i\boldsymbol{\eta}) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\boldsymbol{\rho}-i\boldsymbol{\eta}) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

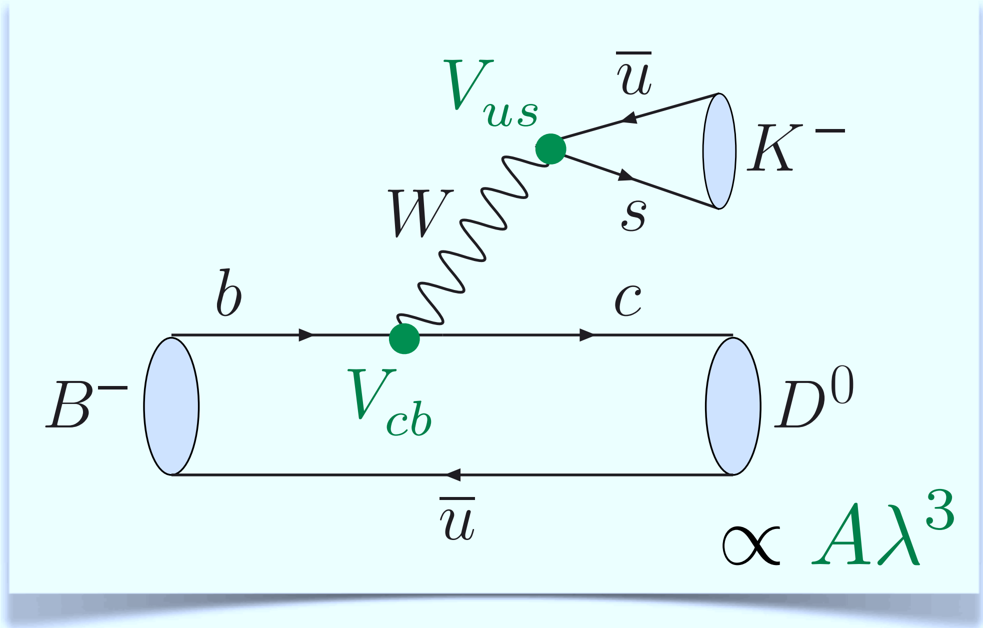
Unitarity $\Rightarrow$ 6 triangle relations in the complex plane,

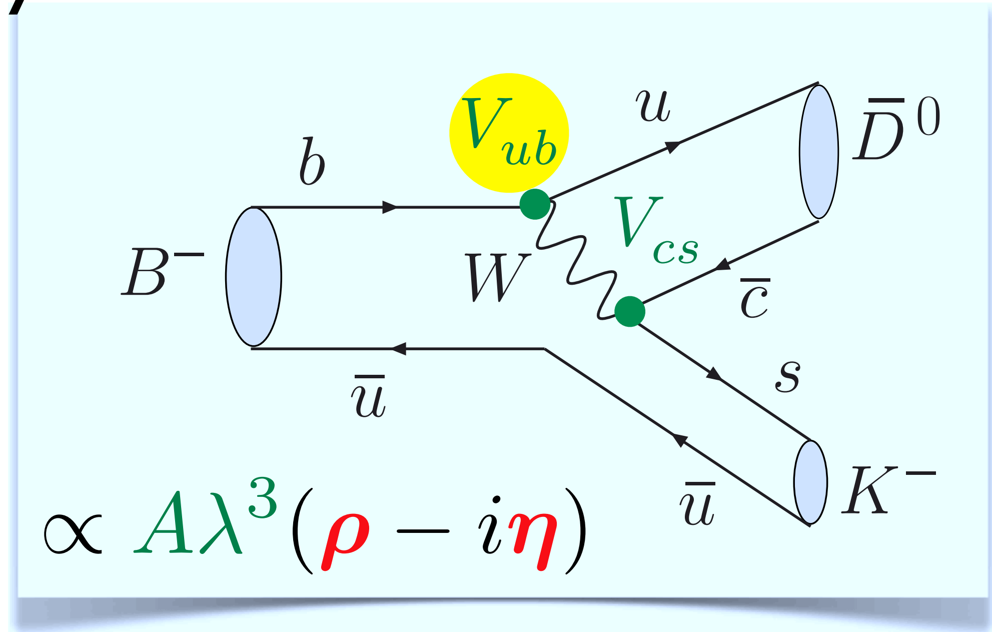
e.g., $V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$



The weak phase $\phi_3 \equiv \arg \frac{i\eta}{\rho}$ can be measured ...

The weak phase ϕ_3 is measured in $B^- \to D^{(*)}K^{(*)-}$ decays by the interference between two amplitudes if both $D^{(*)0}$ and $\overline{D}^{(*)0}$ decay to a common final state





Then $B^- \to \overline{\widetilde{D}}K^-$ *with* $|\overline{\widetilde{D}}\rangle \propto |D^0\rangle + r_B e^{i(\delta_B - \phi_3)}|\overline{D}^0\rangle$

and $B^+ \to \widetilde{D}K^+$ *with* $|\widetilde{D}\rangle \propto |D^0\rangle + r_B e^{i(\delta_B + \phi_3)}|\overline{D}^0\rangle$

where $r_B = \left| \dfrac{\mathcal{A}(B^- \to \overline{D}^0 K^-)}{\mathcal{A}(B^- \to D^0 K^-)} \right| \approx \mathcal{O}(0.1)$ **including colour suppression**

Three techniques to measure ϕ_3 all use rare decays of the form $B^- \to \overset{(-)}{D}{}^0 K^-$

✓ GLW: use CP eigenstates $|D\rangle_{1,2} \propto |D^0\rangle \pm \bar{D}^0\rangle$

Gronau and London, PLB 253, 483 (1991)

Gronau and Wyler, PLB 265, 172 (1991)

Gronau, PRD 58, 037301 (1998)

Gronau, PLB 557, 198 (2003)

✓ ADS: use $|K^+\pi^-\rangle$ state (CF for $\bar{D}^0$; DCS for D^0)

Atwood, Dunietz and Soni, PRL 78, 3257 (1997)

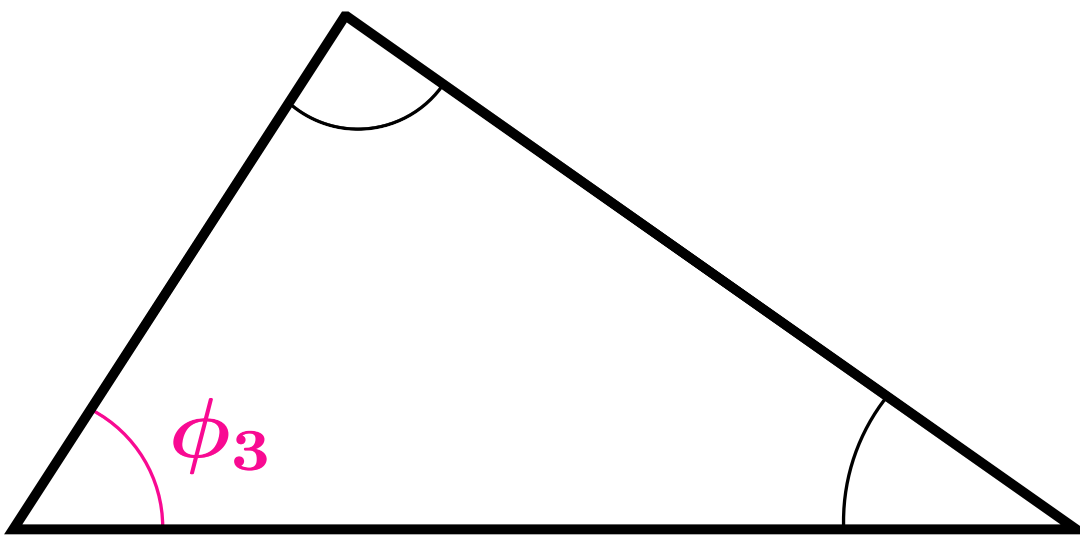
✓ GGSZ: use Dalitz analysis of $|K_S\pi^+\pi^-\rangle$ state

Giri, Grossman, Soffer and Zupan, PRD 68, 054018 (2003)

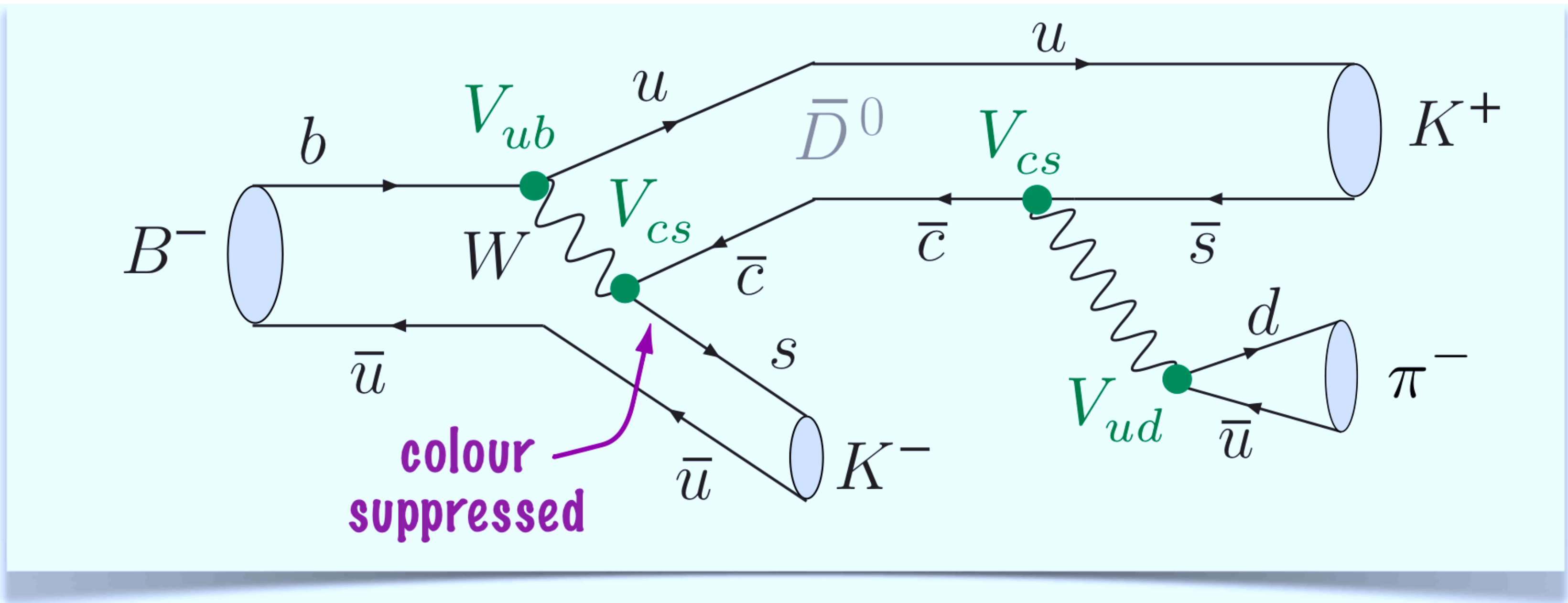
Bondar, Proc BINP Dalitz Analysis Meeting (2002) (unpublished)

Atwood – Dunietz – Soni method (ADS)

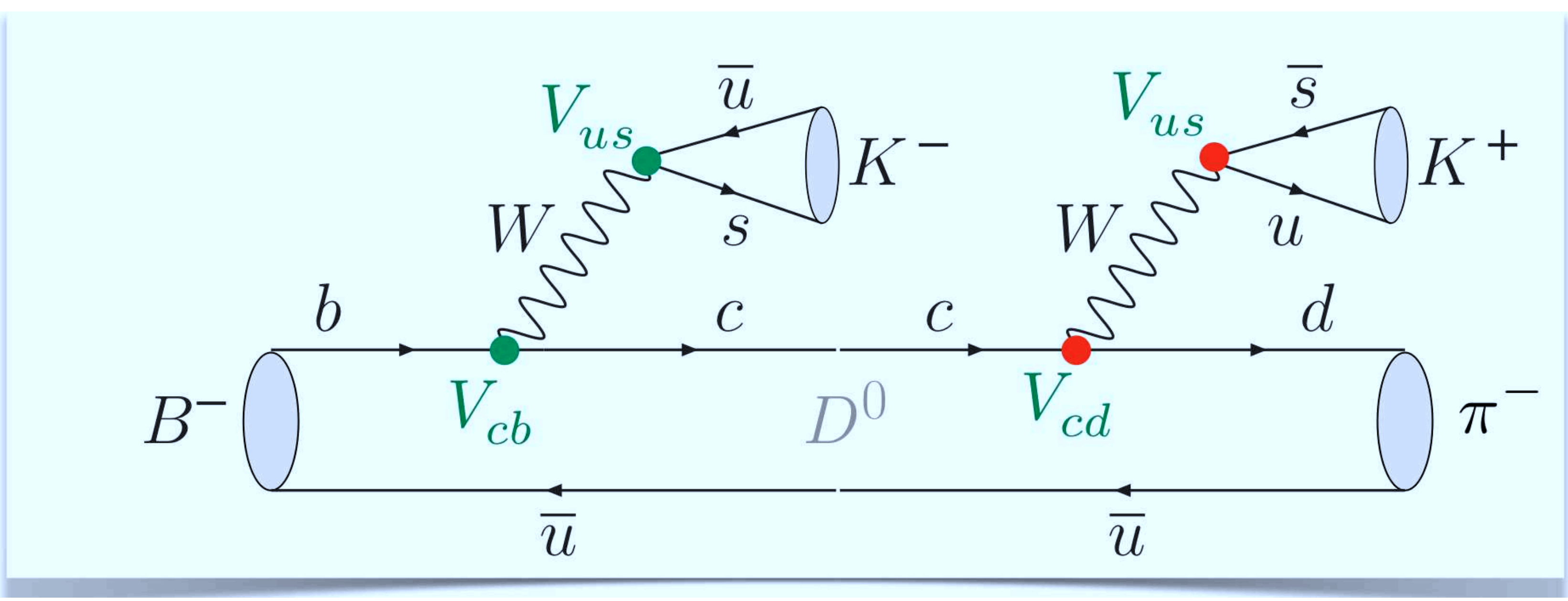
Atwood, Dunietz and Soni, PRL 78, 3257 (1997)
Atwood, Dunietz and Soni, PRD 63, 036005 (2001)



ADS method measures ϕ_3 via the interference in rare $B^- \to [K^+\pi^-]_D\, K^-$ decays

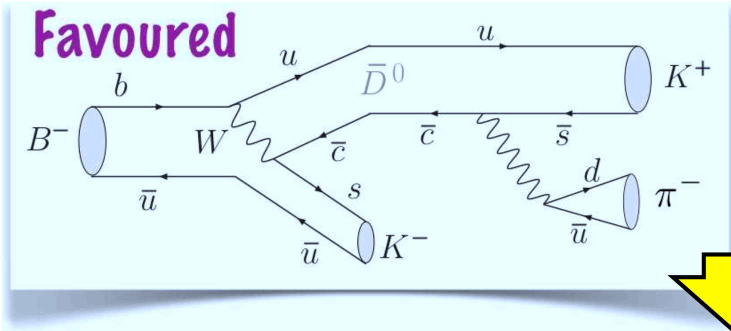


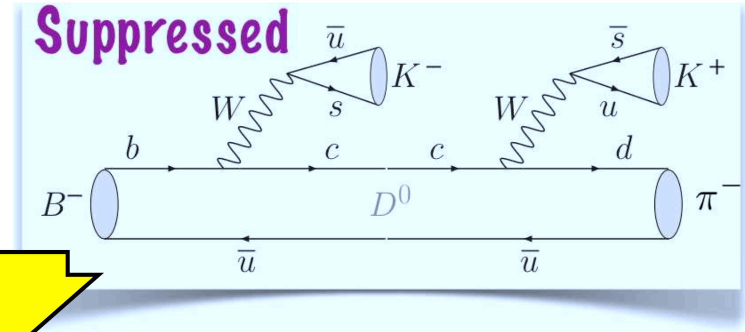
Cabibbo favoured D decay

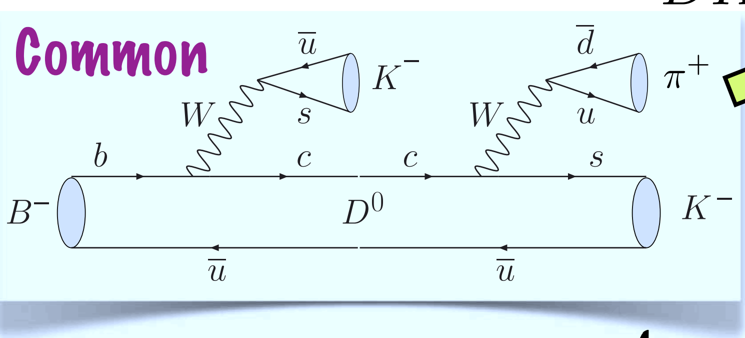


doubly Cabibbo suppressed D decay

ADS rate and asymmetry (relative to the common decay):







$$\mathcal{R}_{DK} = \frac{\Gamma([K^+\pi^-]\,K^-) + \Gamma([K^-\pi^+]\,K^+)}{\Gamma([K^-\pi^+]\,K^-) + \Gamma([K^+\pi^-]\,K^+)}$$

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

$$\mathcal{A}_{DK} = \frac{\Gamma([K^+\pi^-]\,K^-) - \Gamma([K^-\pi^+]\,K^+)}{\Gamma([K^-\pi^+]\,K^-) + \Gamma([K^+\pi^-]\,K^+)}$$

$$= 2\, r_B r_D \sin(\delta_B + \delta_D) \sin \phi_3 \,/\, \mathcal{R}_{DK}$$

where $r_D = \left| \frac{\mathcal{A}(D^0 \to K^+\pi^-)}{\mathcal{A}(\bar{D}^0 \to K^+\pi^-)} \right| = 0.0613 \pm 0.0010$

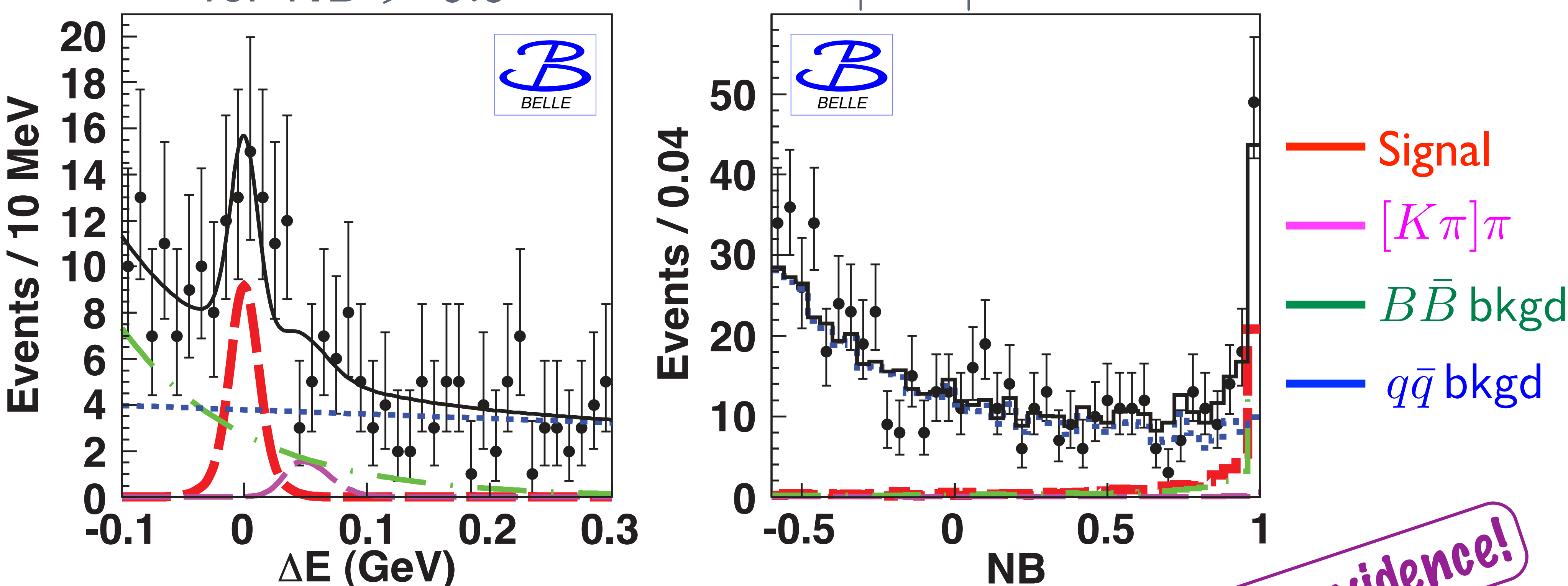
and r_B *was defined on p. 5*

Yields for the ADS mode $B^- \to [K^+\pi^-]_D K^-$ from 772 million $B\bar{B}$ events:

PRL 106, 231803 (2011)

- Continuum background is suppressed by NeuroBayes (NB) neural network based on event shape
- Fit ΔE and NB distributions together to extract signal

for NB > 0.9   for $|\Delta E| < 0.03$ GeV

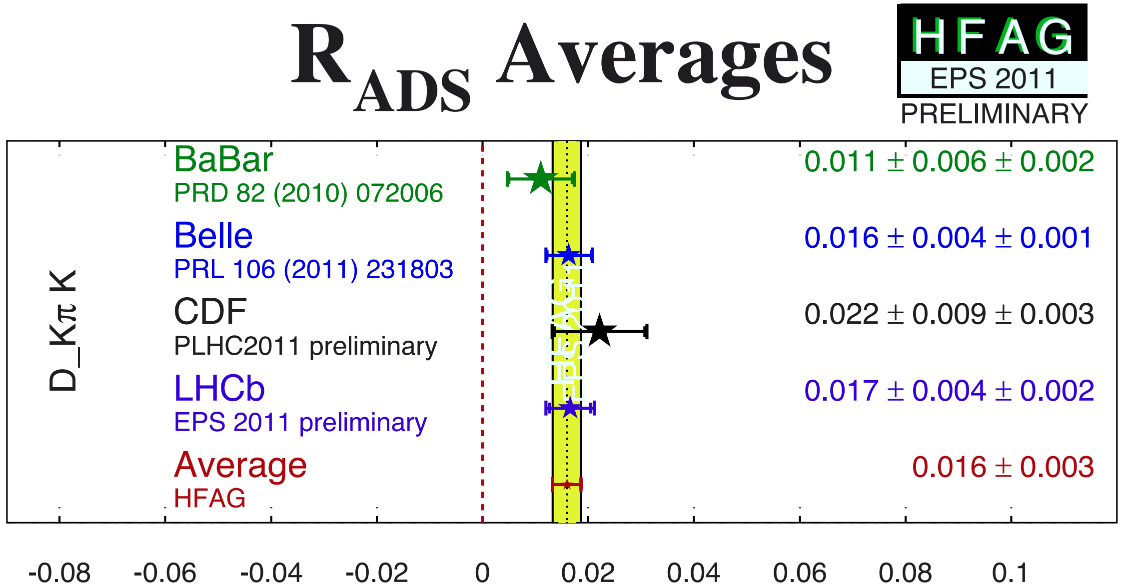


$56.0 \pm ^{15.1}_{14.2}$ events $(\mathcal{S} = 4.1\sigma)$

First evidence!

Results for the ADS mode $B^- \to [K^+\pi^-]_D K^-$ from 772 million $B\bar{B}$ events:

PRL 106, 231803 (2011)

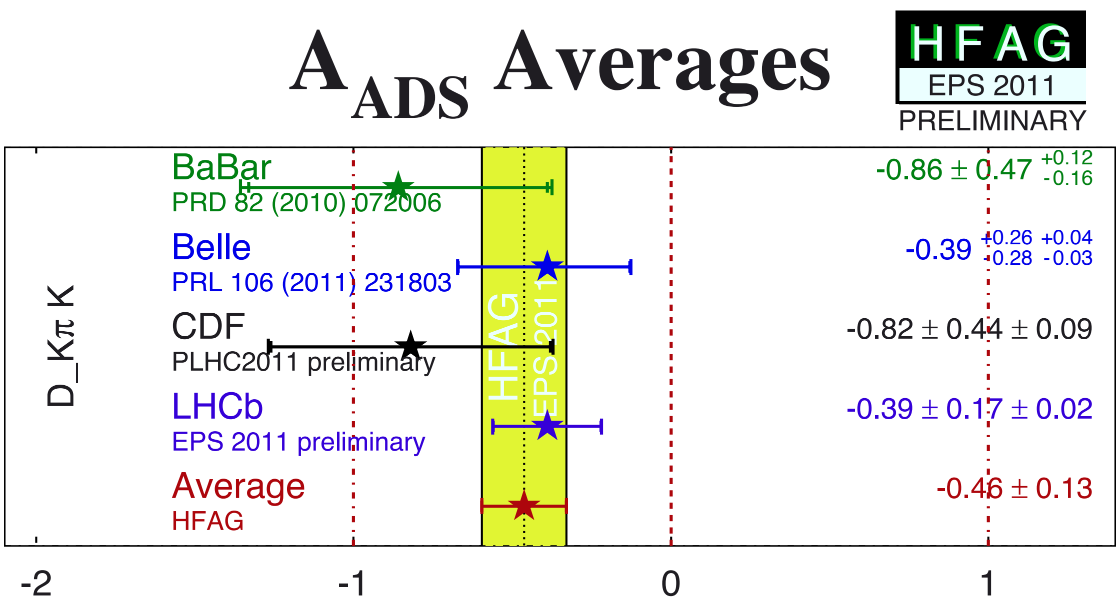


$[1.63 \pm ^{0.44}_{0.41} \pm ^{0.07}_{0.13}] \times 10^{-2}$

stat syst

BELLE

$\Rightarrow r_B \neq 0$



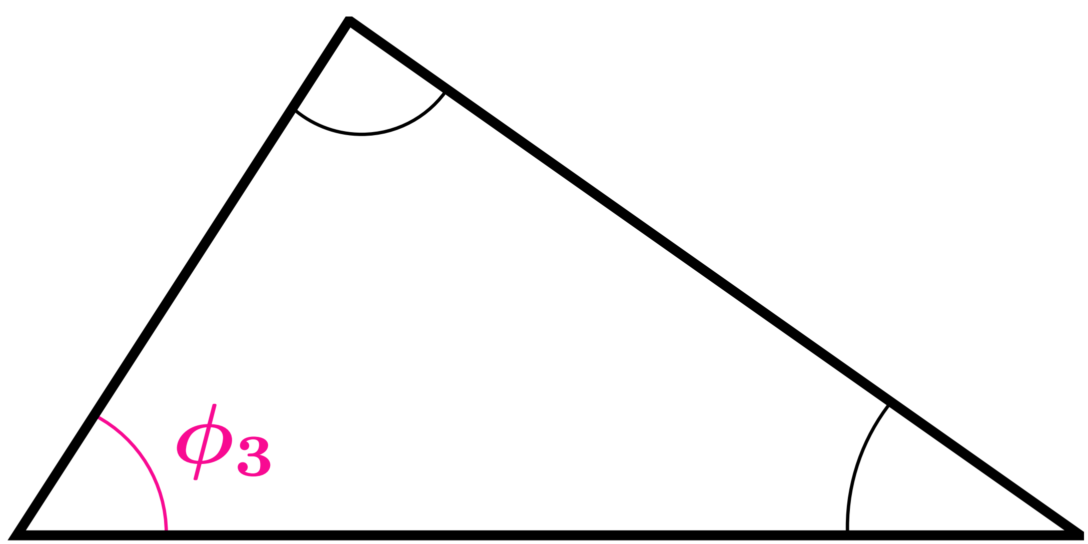
$-0.39 \pm ^{0.26}_{0.28} \pm ^{0.04}_{0.03}$

stat syst

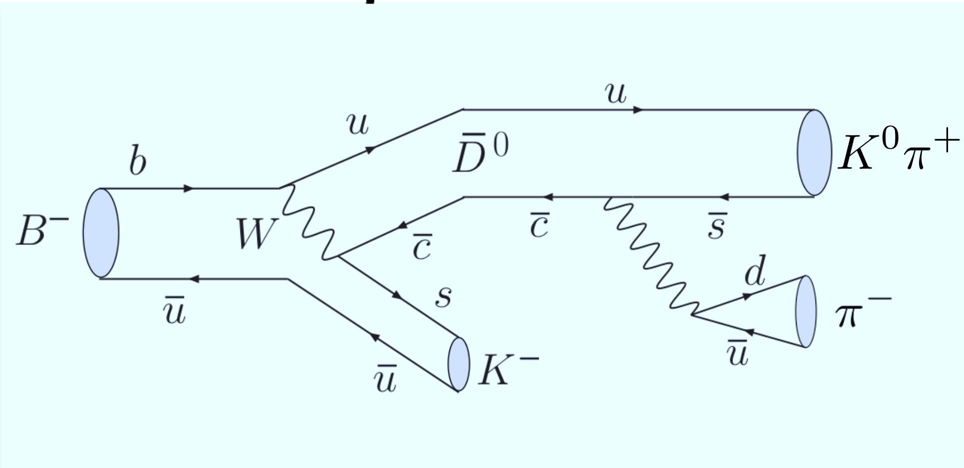
BELLE

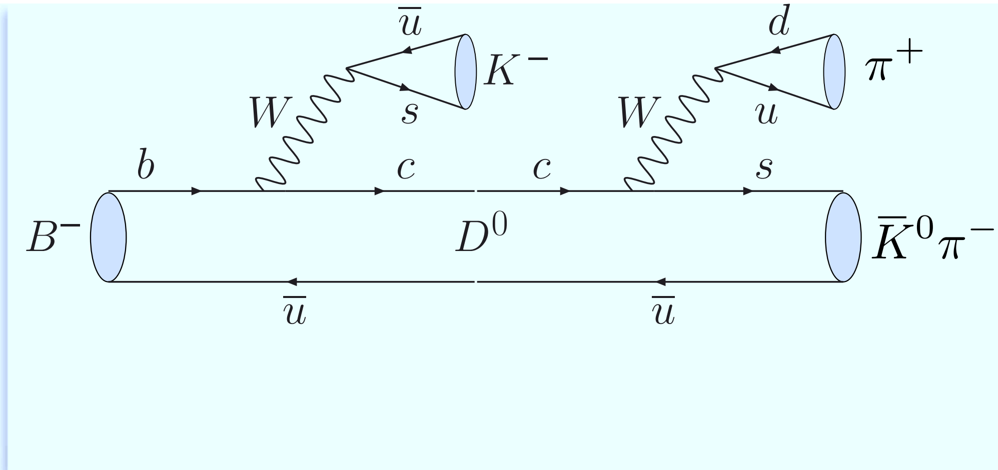
Giri–Grossman–Soffer–Zupan method (GGSW)

Giri, Grossman, Soffer and Zupan, PRD 68, 054018 (2003)
Bondar, Proc BINP Dalitz Analysis Meeting (2002) (unpublished)



GGSW method measures ϕ_3 via the interference in $B^- \to [K_S\pi^+\pi^-]_D K^-$ decays at every point in the D Dalitz plot





Using mixed states $\widetilde{D}$ and $\overline{\widetilde{D}}$ defined on p. 5, matrix elements are

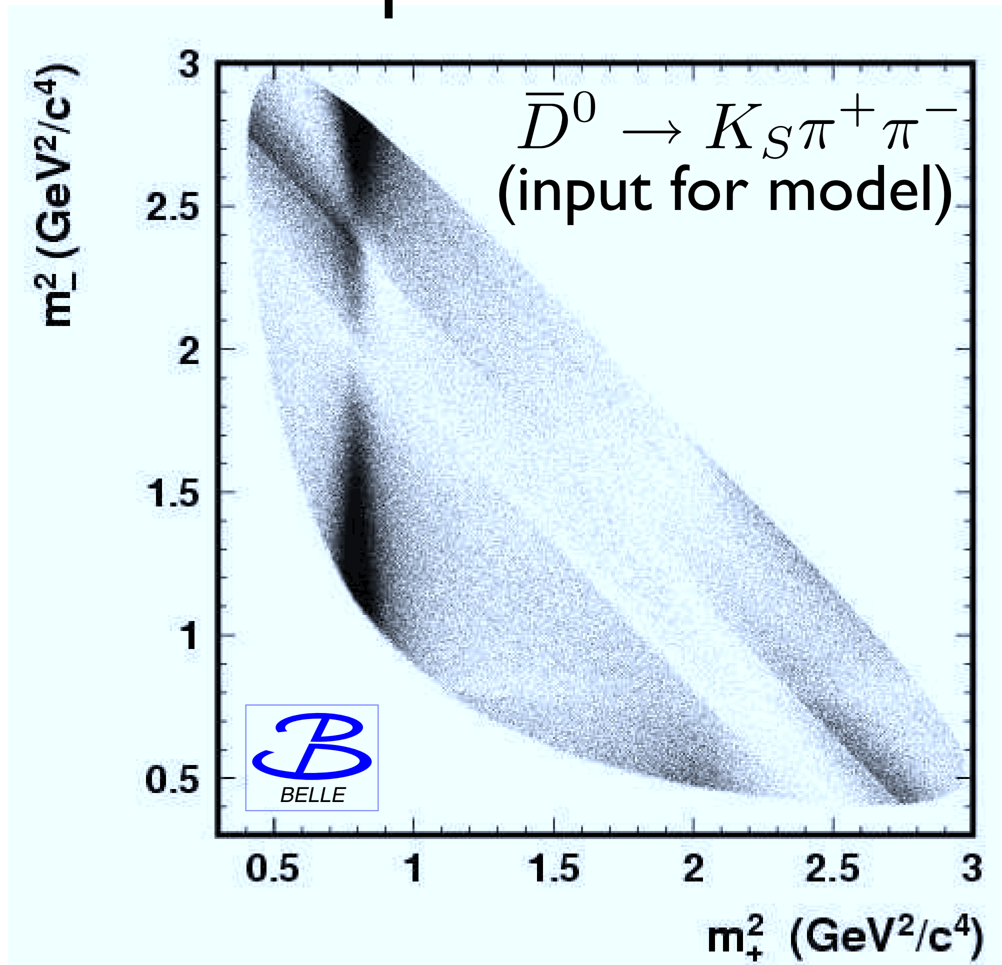
$$B^- \to \overline{\widetilde{D}}K^- : \quad \mathcal{M}_- = f(m_-^2, m_+^2) + r_B e^{i(\delta_B - \phi_3)} f(m_+^2, m_-^2)$$

$$B^+ \to \widetilde{D}K^+ : \quad \mathcal{M}_+ = f(m_+^2, m_-^2) + r_B e^{i(\delta_B + \phi_3)} f(m_-^2, m_+^2)$$

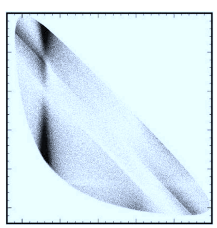
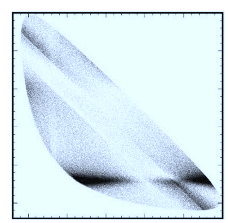
from $D \to K_S\pi^+\pi^-$ production in continuum

$$m_\pm \equiv m(K_S\pi^\pm)$$

Unbinned Dalitz method: model the amplitudes $f(m_\pm^2, m_\mp^2)$ using a sum of known two-body resonances and a non-resonant term to get the best fit to continuum $D^* \to D\pi \to [K_S\pi\pi]\pi$ data



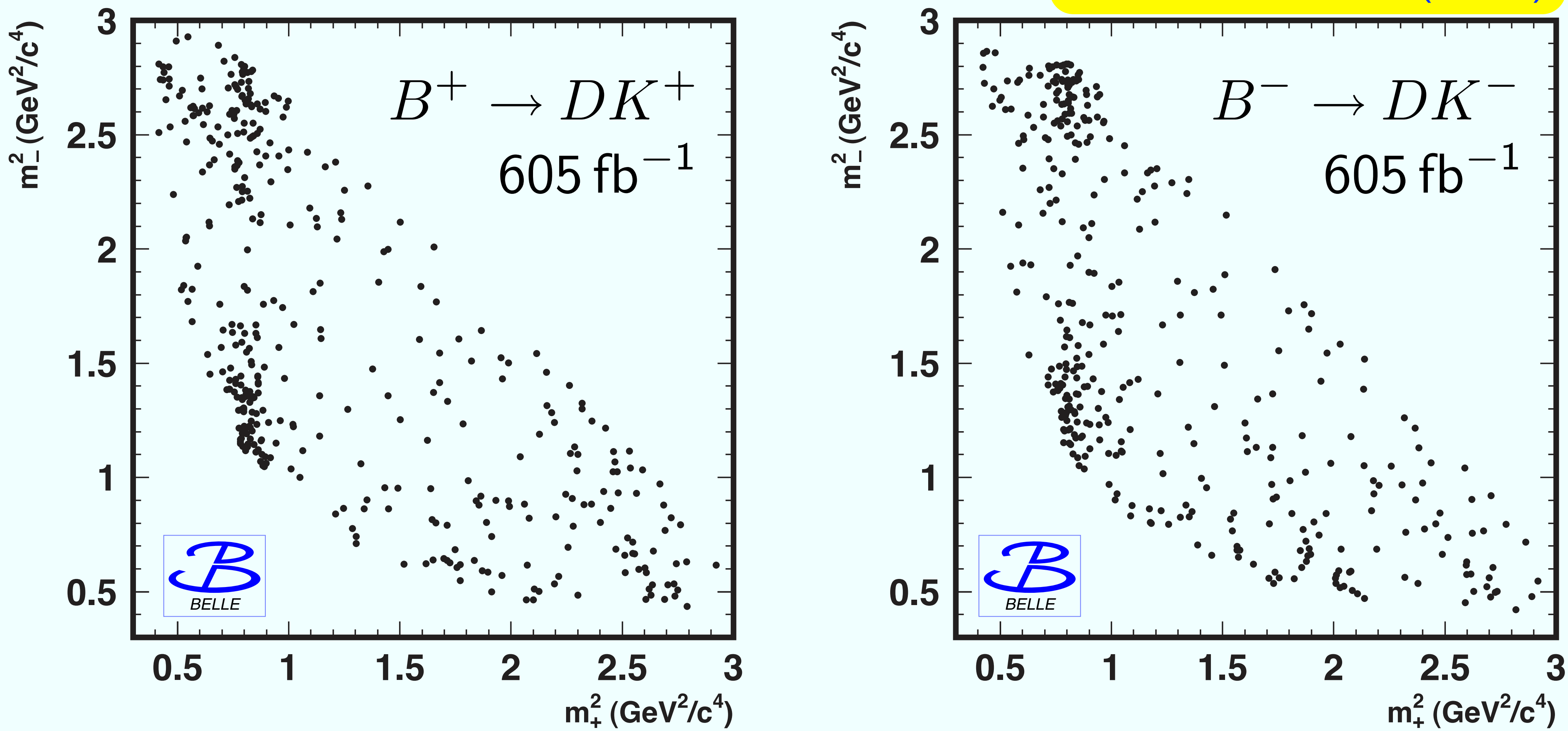
Fit: Match $B^\pm$ data to

$|\mathcal{M}_\pm|^2 = \Big|$  $+\ r_\pm\, e^{i(\delta_B \pm \phi_3)}$  $\Big|^2$

and extract best-fit values of ϕ_3, δ_B and $r_\pm$.

Unbinned Dalitz method: fit the $B^{\pm}$ distributions using m_+, m_-, $M_{\rm bc}$, ΔE, $\cos\theta_{\rm thr}$, and $\mathcal{F}_{\rm shape}$

PRD 81, 112002 (2010)

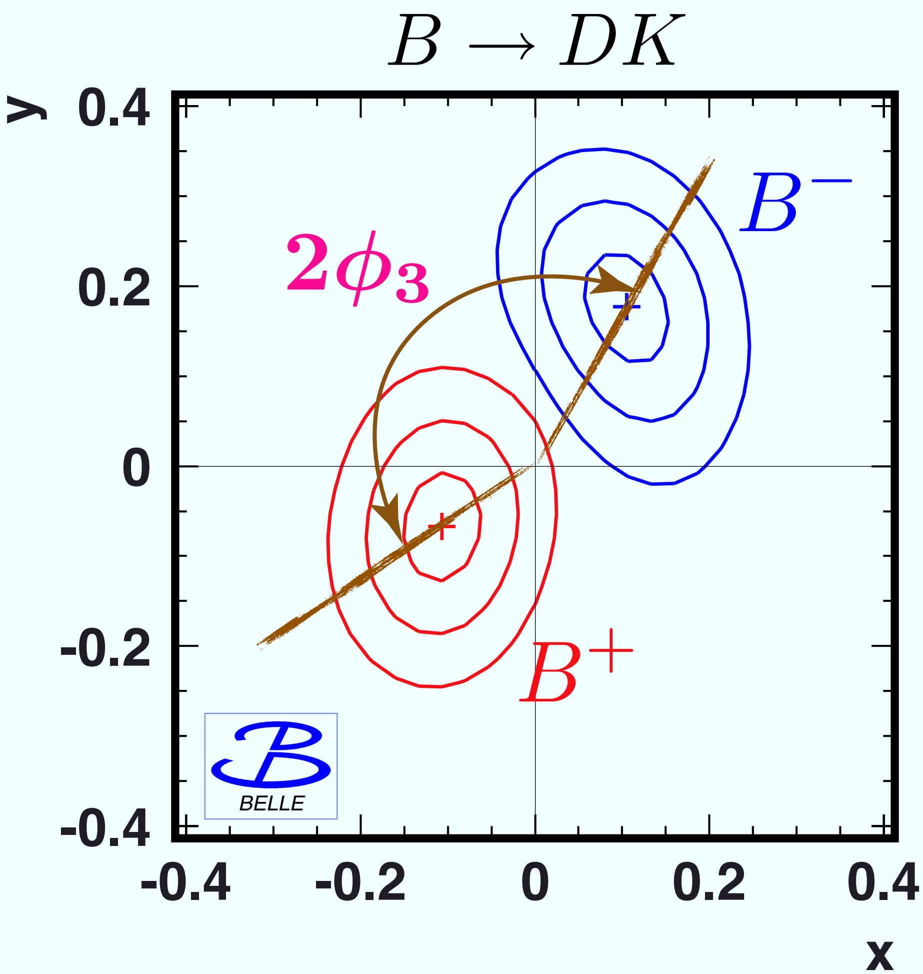


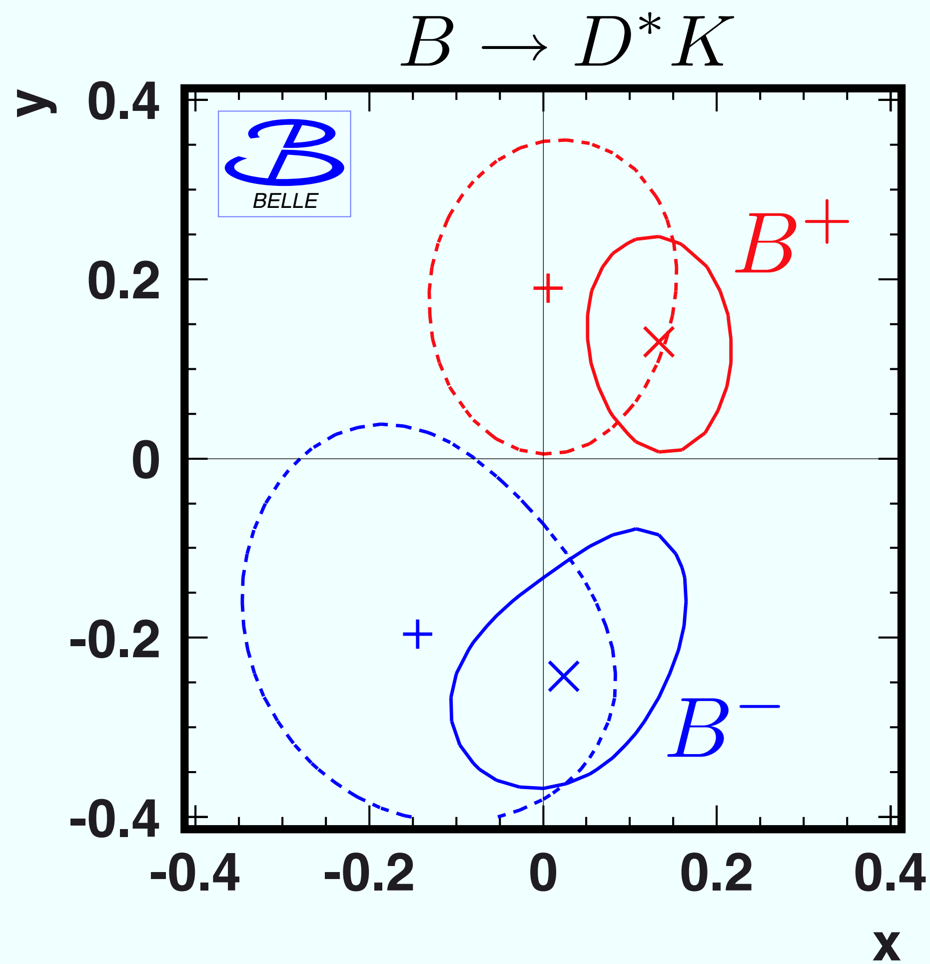
The fits use the "Cartesian" CP-sensitive parameters

$x_\pm = r_\pm \cos(\delta \pm \phi_3)$ and $y_\pm = r_\pm \sin(\delta \pm \phi_3)$

Results for the unbinned Dalitz analysis for $B \to D^{(*)}K$ from 657 million $B\bar{B}$ events:

PRD 81, 112002 (2010)





$$x_\pm = r_\pm \cos(\delta \pm \phi_3)$$
$$y_\pm = r_\pm \sin(\delta \pm \phi_3)$$

——— $B \to [D\pi^0]_{D^*} K$

- - - - - $B \to [D\gamma]_{D^*} K$ with $\Delta\delta = 180^\circ$

Results for the unbinned Dalitz analysis for $B \to D^{(*)}K$ from 657 million $B\bar{B}$ events:

PRD 81, 112002 (2010)

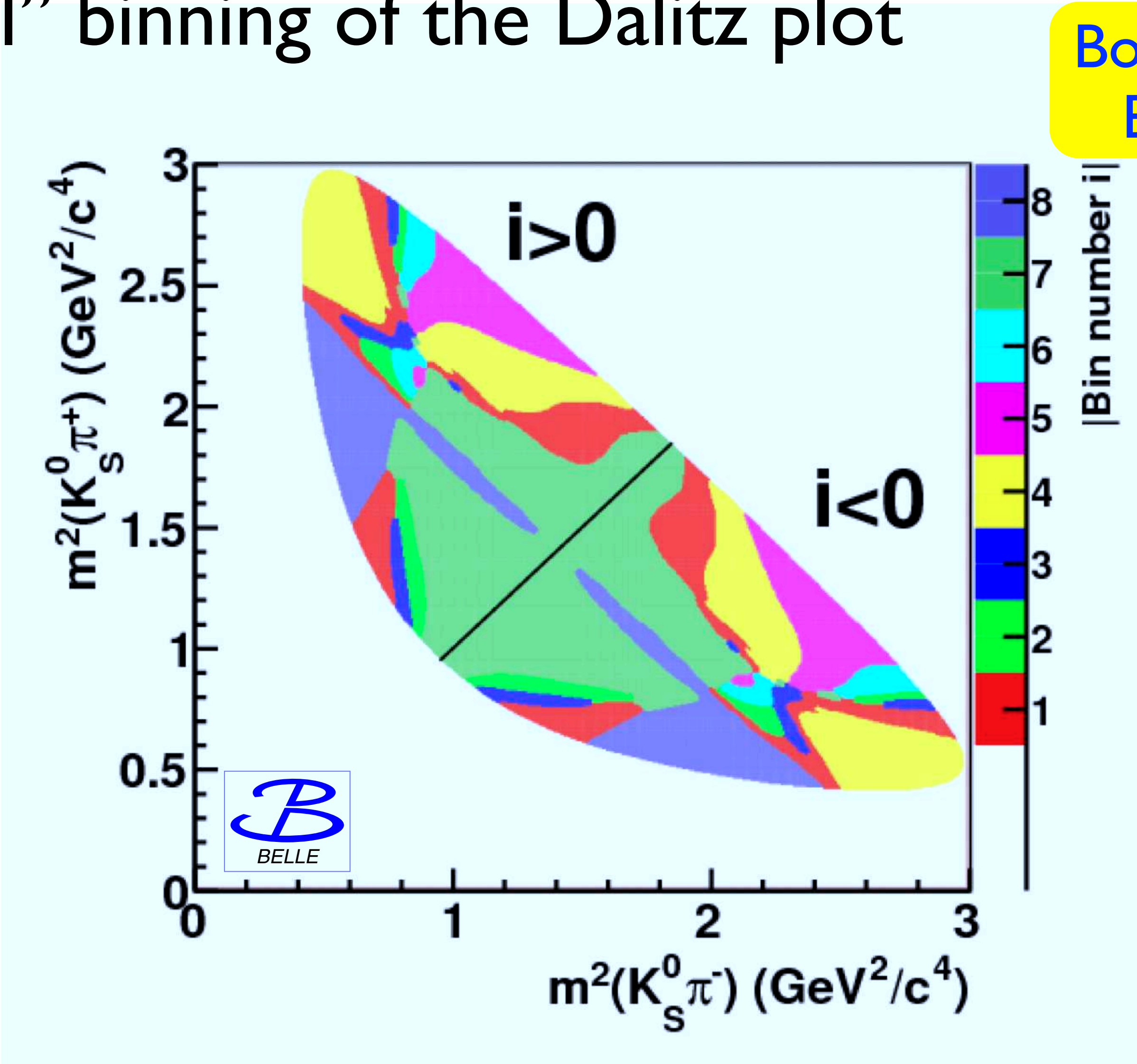
Parameter	$B^+ \to DK^+$	$B^+ \to D^*K^+$, $D^* \to D\pi^0$	$B^+ \to D^*K^+$, $D^* \to D\gamma$
x_-	$+0.105 \pm 0.047 \pm 0.011$	$+0.024 \pm 0.140 \pm 0.018$	$+0.144 \pm 0.208 \pm 0.025$
y_-	$+0.177 \pm 0.060 \pm 0.018$	$-0.243 \pm 0.137 \pm 0.022$	$+0.196 \pm 0.215 \pm 0.037$
x_+	$-0.107 \pm 0.043 \pm 0.011$	$+0.133 \pm 0.083 \pm 0.018$	$-0.006 \pm 0.147 \pm 0.025$
y_+	$-0.067 \pm 0.059 \pm 0.018$	$+0.130 \pm 0.120 \pm 0.022$	$-0.190 \pm 0.177 \pm 0.037$

Parameter	$B^+ \to DK^+$ mode	$B^+ \to D^*K^+$ mode
ϕ_3	$(80.8^{+13.1}_{-14.8} \pm 5.0 \pm 8.9)^\circ$	$(73.9^{+18.9}_{-20.2} \pm 4.2 \pm 8.9)^\circ$
r	$0.161^{+0.040}_{-0.038} \pm 0.011^{+0.050}_{-0.010}$	$0.196^{+0.073}_{-0.072} \pm 0.013^{+0.062}_{-0.012}$
δ	$(137.4^{+13.0}_{-15.7} \pm 4.0 \pm 22.9)^\circ$	$(341.7^{+18.6}_{-20.9} \pm 3.2 \pm 22.9)^\circ$

model-dependent error will limit the viability of this approach

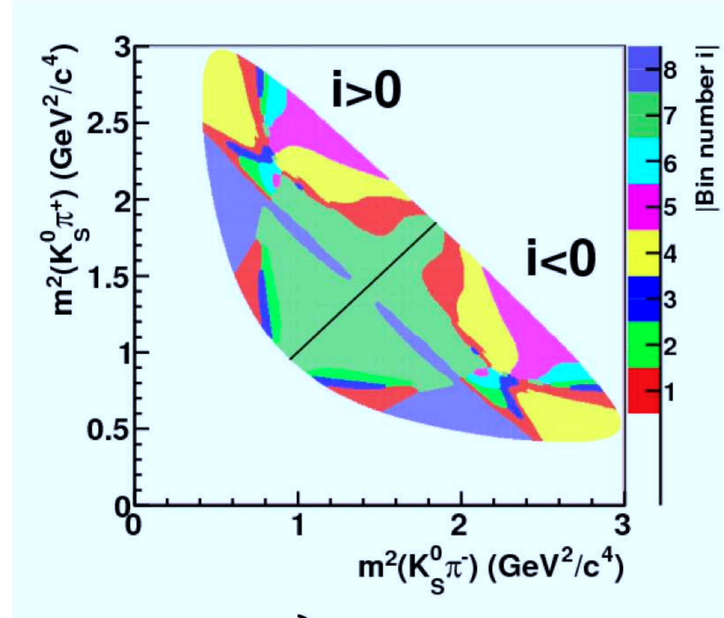
Binned Dalitz method: avoid the modeling error by "optimal" binning of the Dalitz plot

Bondar and Poluektov, EPJ C55, 51 (2008)



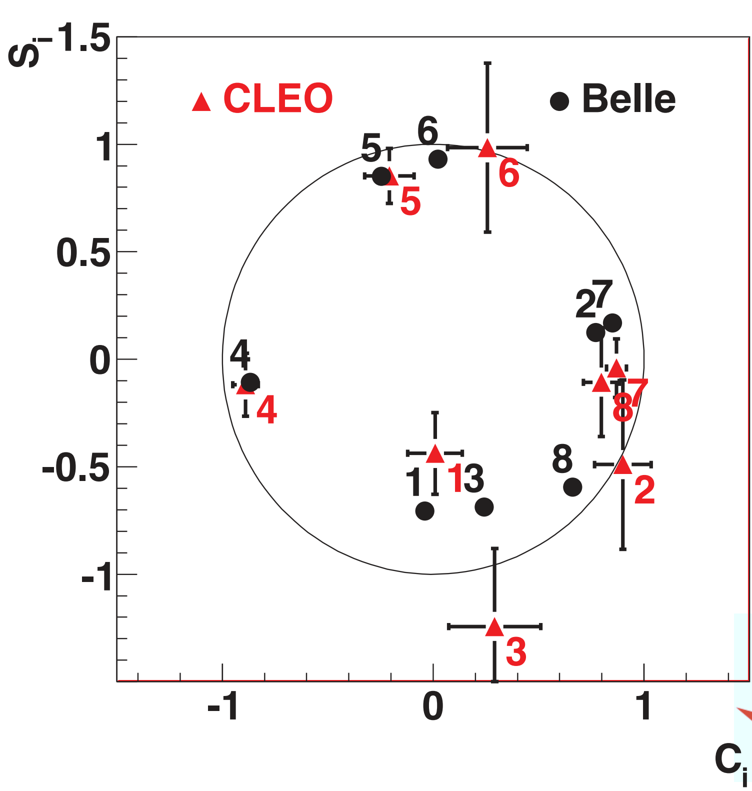
Choice of bins guided by model, but extracted ϕ_3 is not biased by this choice.

Binned Dalitz method: minimize χ^2 in fit to all bins for each mode



Expected number of $B^\pm \to DK^\pm$ events in bin i is:

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

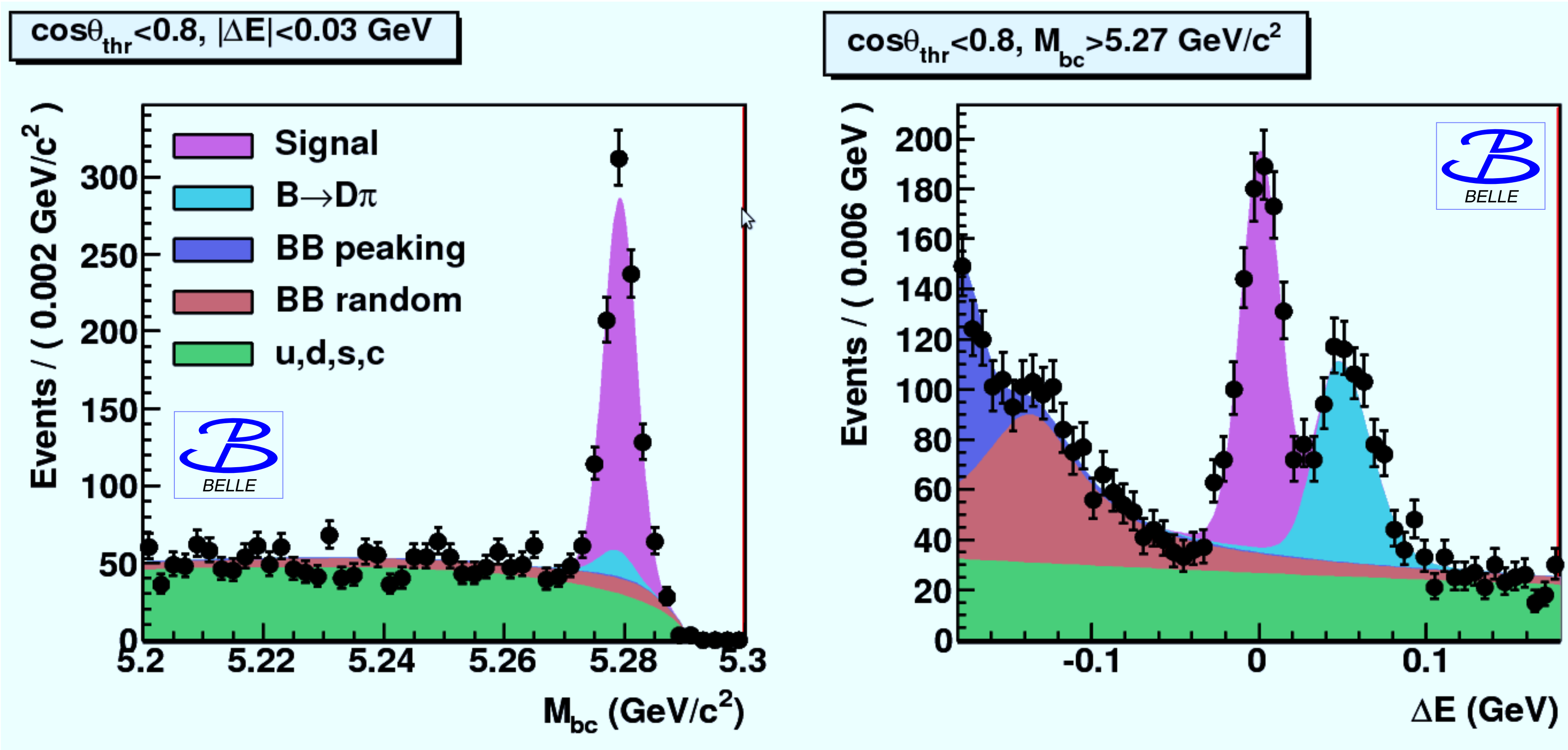


K_i is the # of events in bin i from a flavour-tagged sample $(D^{*\pm} \to D\pi^\pm)$

c_i and s_i contain information about the strong-phase difference in bin i (use CLEO data for $\psi(3770) \to D^0\overline{D}^0$ here; can be measured by BES-III too)

Yields for Binned Dalitz method from 772 million $B\bar{B}$ events

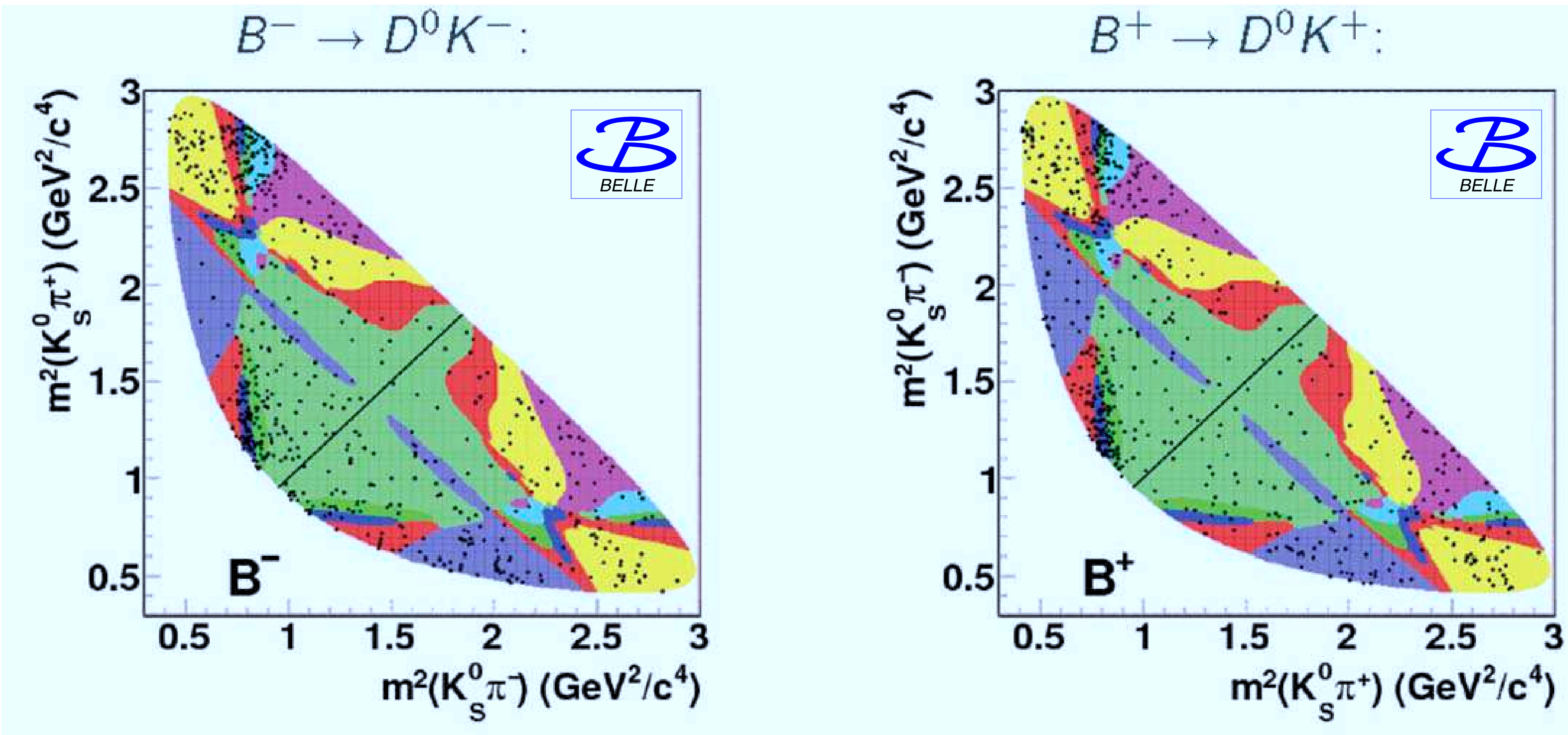
arXiv: 1106.4046



1176 ± 43 events

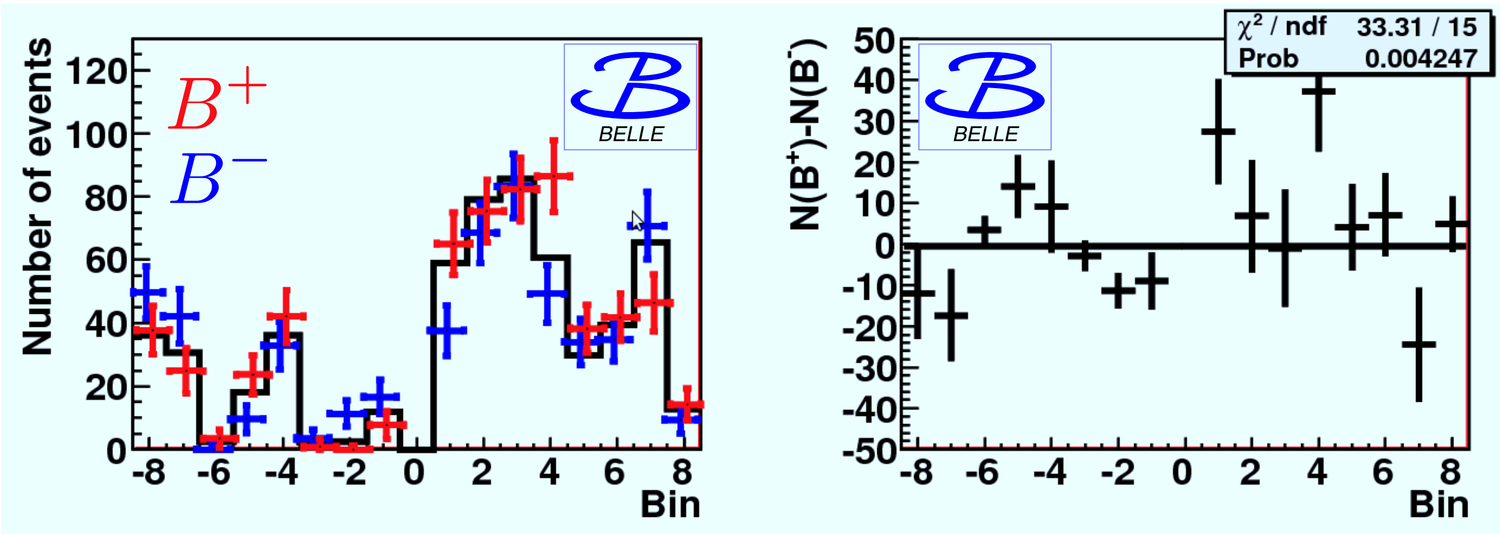
Binned Dalitz distributions from 772 million $B\bar{B}$ events

arXiv: 1106.4046



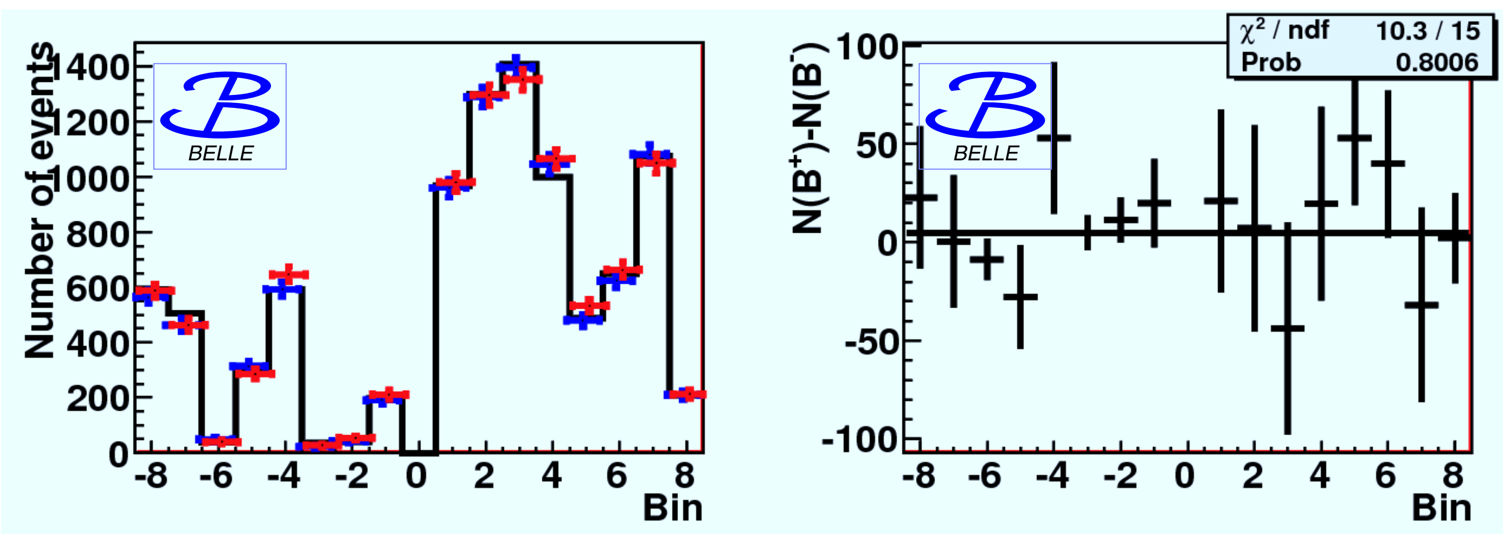
Yields in each Dalitz bin from 772 million $B\bar{B}$ events

arXiv: 1106.4046



$B^\pm \to DK^\pm$

signal mode

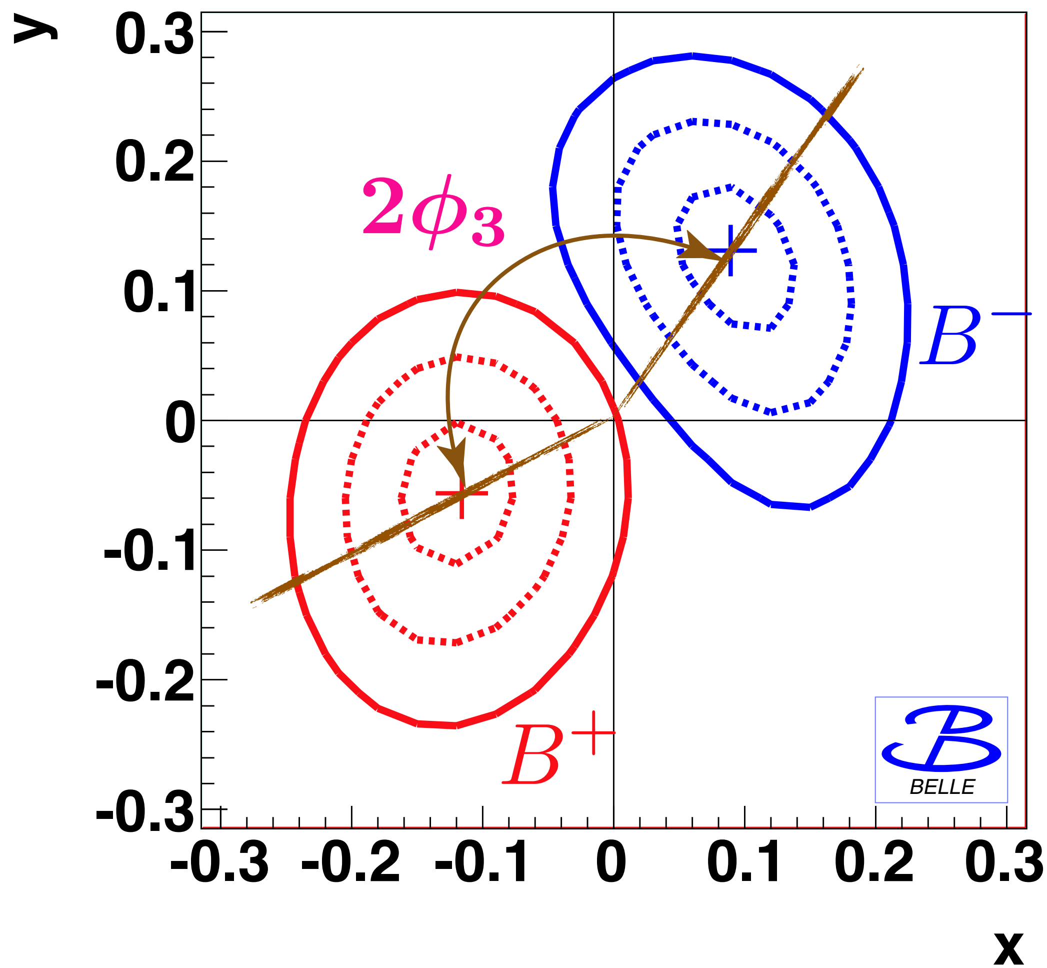


$B^\pm \to D\pi^\pm$

control

Binned Dalitz result from 772 million $B\bar{B}$ events

arXiv: 1106.4046



$B \to DK$

$\phi_3 = (77.3 \pm ^{15.1}_{14.9} \pm 4.2 \pm 4.3)^\circ$

$r_B = 0.145 \pm 0.030 \pm 0.011 \pm 0.011$

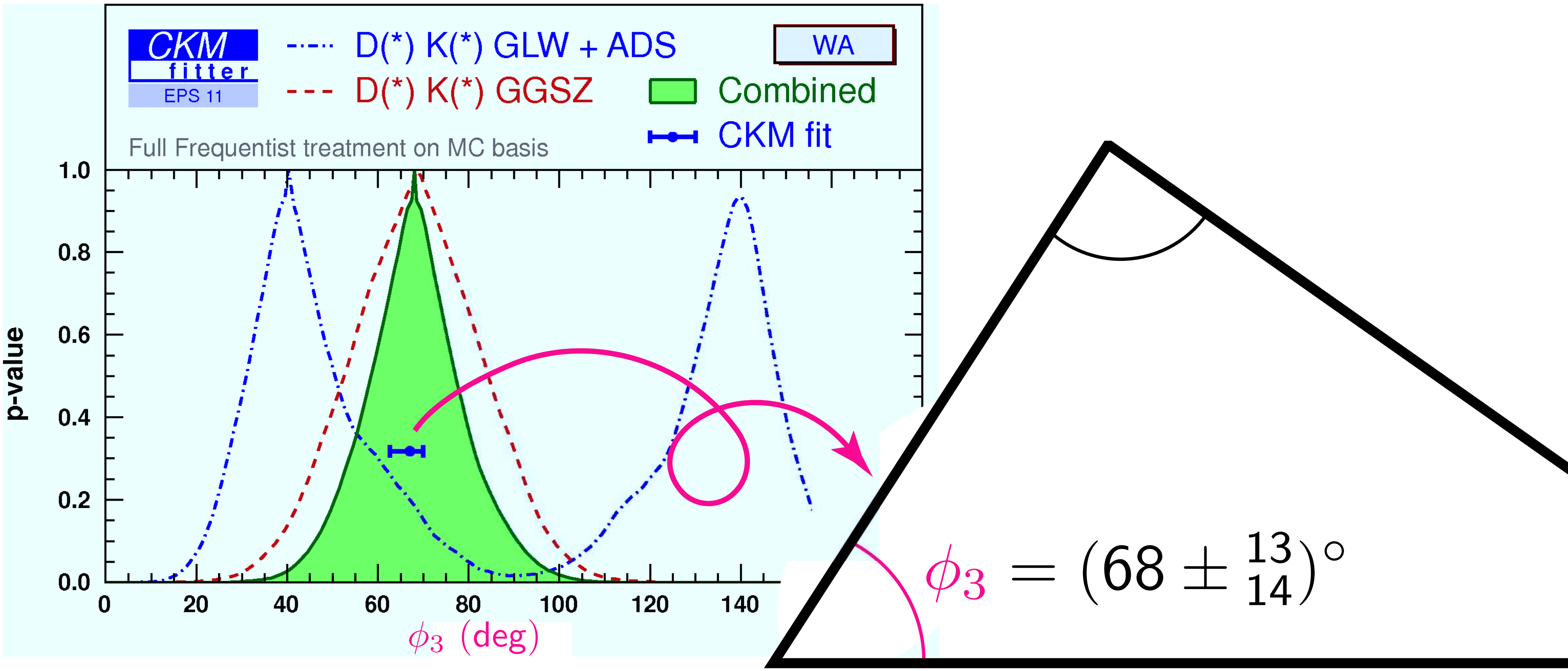
$\delta_B = (129.9 \pm 15.0 \pm 3.9 \pm 4.7)^\circ$

uncertainty in c_i, s_i from CLEO data (can reduce using future BES-III data)

Combined measurements for ϕ_3 from all methods:

except binned Dalitz

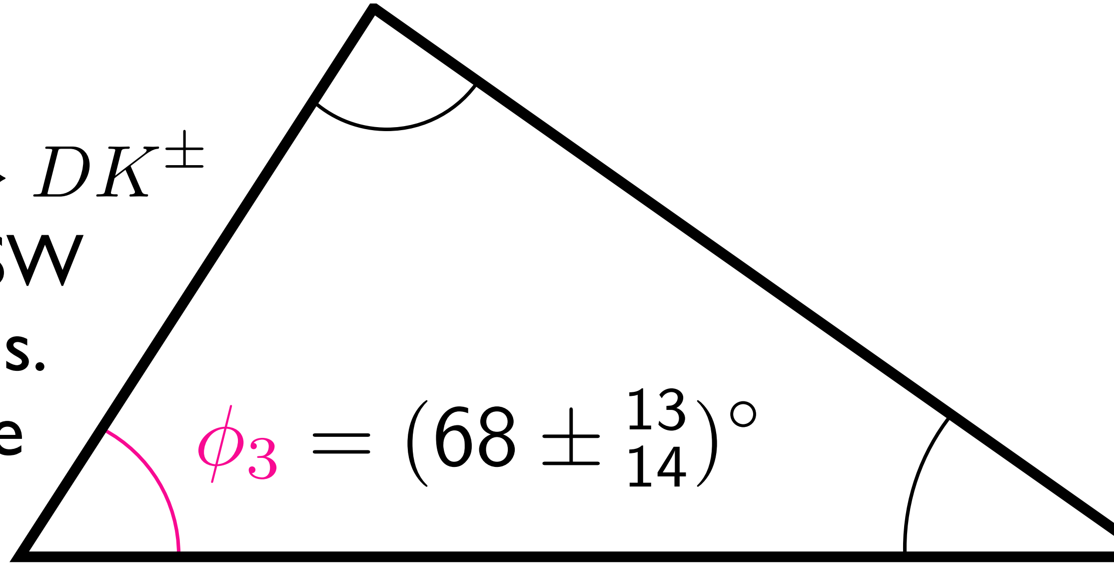
http://ckmfitter.in2p3.fr/



This compilation includes the results reported in this talk <u>other than</u> the binned Dalitz result (arXiv 1106.4046), which is consistent with this world average.

Summary

Belle has new results in $B^{\pm} \to DK^{\pm}$ decays using the ADS and GGSW (unbinned and binned) methods. These provide sensitivity to the CKM angle $\phi_3 (= \gamma)$.



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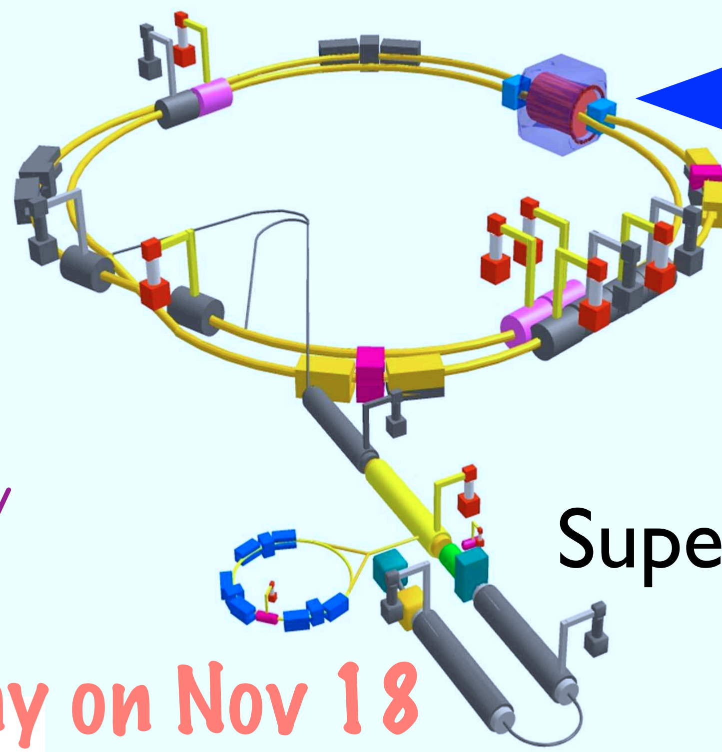
Xth Open Belle II Collaboration Meeting
November 16–20, 2011
KEK, Japan

http://belle2.kek.jp/



SuperKEKB

Groundbreaking ceremony on Nov 18