CP Violation studies at Belle (including UT angles)

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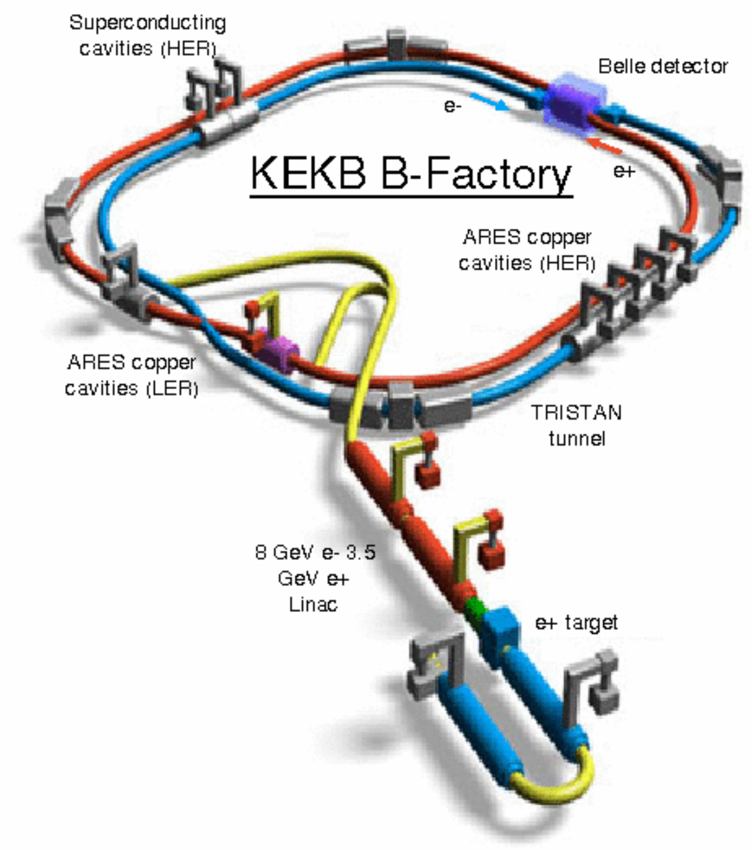
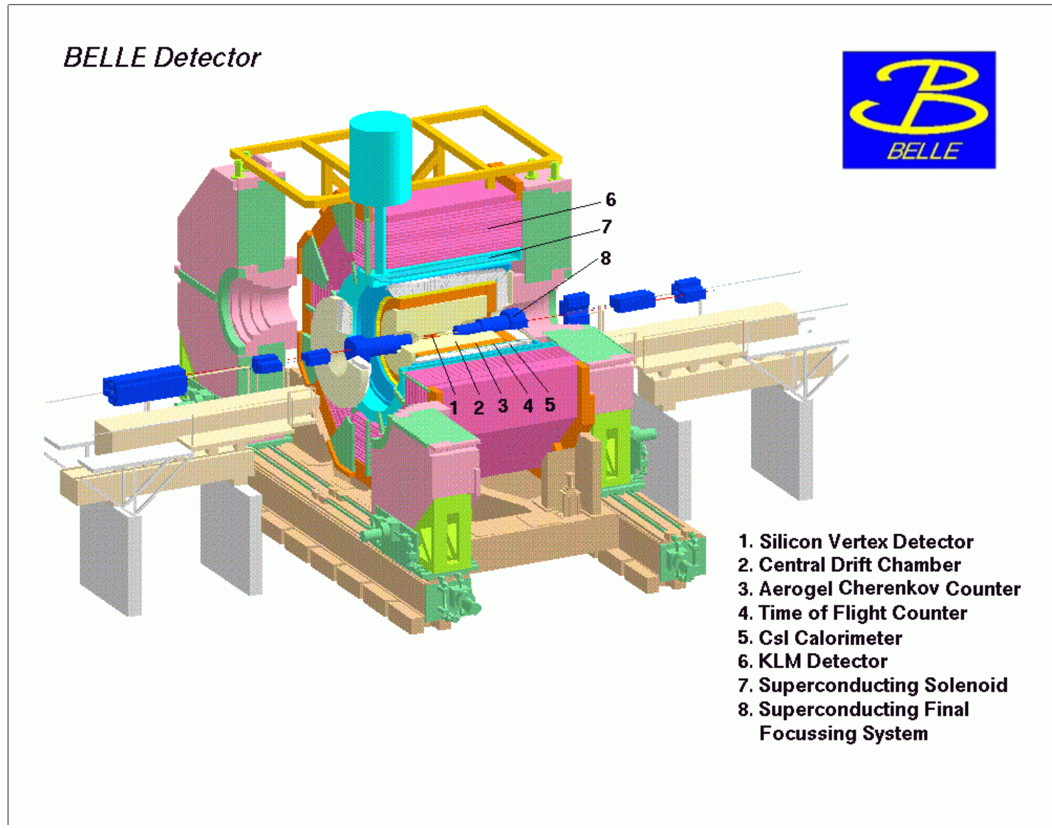
on behalf of the Belle collaboration

XIth International Conference on Heavy Quarks and Leptons
(12, June 2012, Prague, Czech)

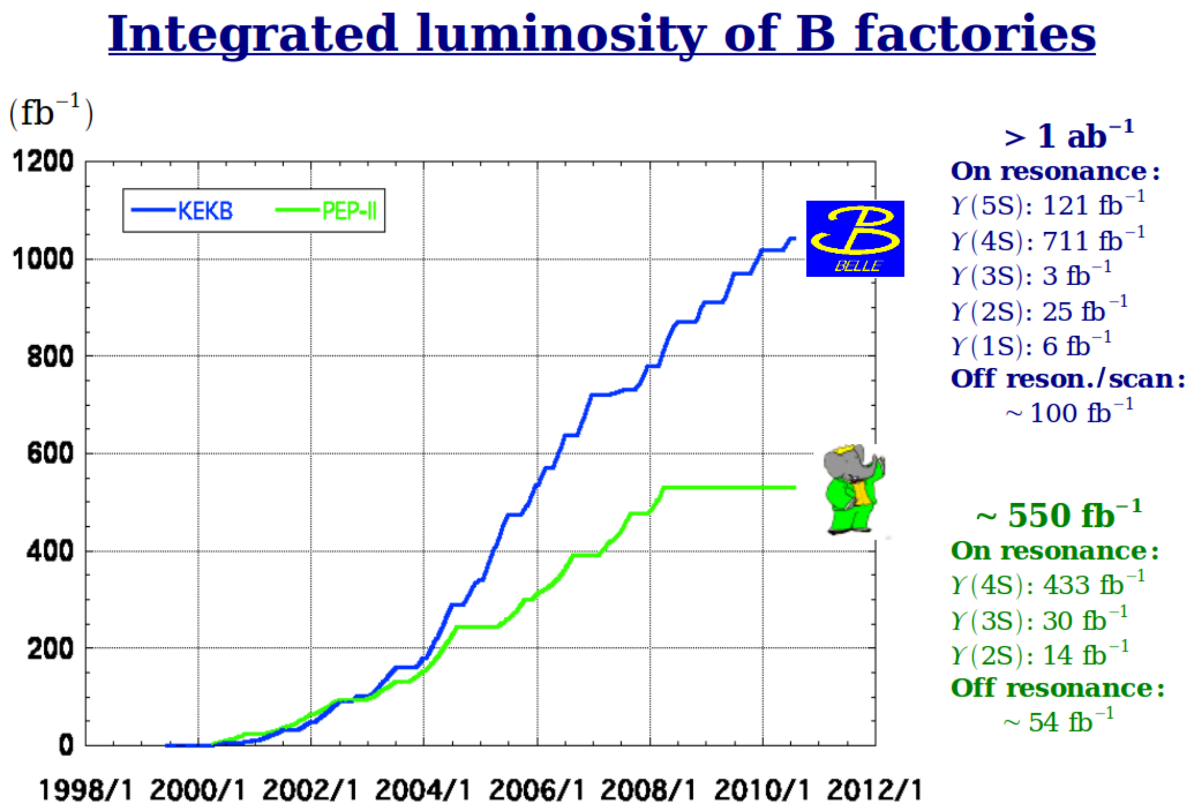
KEKB and Belle





- Belle started in 1999.
  - Experiment designed for ϕ_1 extraction.
  - Data taking is finished at 2010.

Belle data set



Belle has ~772 M $B\bar{B}$ pairs data as the final sample

KM unitarity triangle and CPV parameter convention

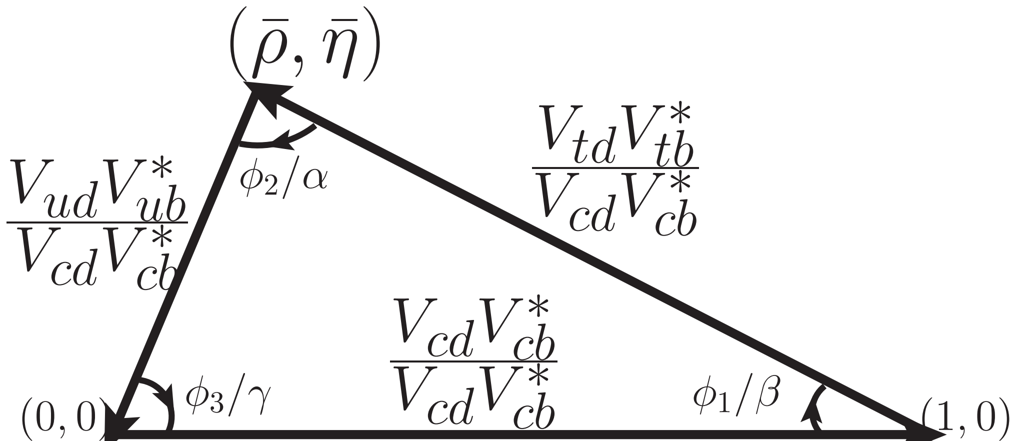
$$V_{KM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

by Wolfenstein parameterization

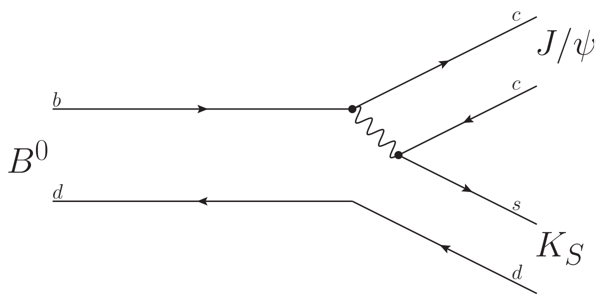
Irreducible complex phase causes CP Violation!

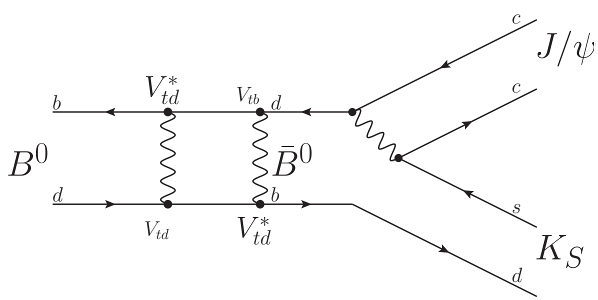
Comprehensive test; measure all the angles and sides.

B system : very good place, all the angles are O(0.1)!



Time-dependent CPV in decays to CP eigenstates





$$A_{\mathrm{CP}}(f_{\mathrm{CP}};t) = \frac{\mathrm{N}(\bar{B}^0(t) \to f_{\mathrm{CP}}) - \mathrm{N}(B^0(t) \to f_{\mathrm{CP}})}{\mathrm{N}(\bar{B}^0(t) \to f_{\mathrm{CP}}) + \mathrm{N}(B^0(t) \to f_{\mathrm{CP}})}$$

$$= \mathbf{S} \sin \Delta m_{\mathrm{d}} t + \mathbf{A} \cos \Delta m_{\mathrm{d}} t$$

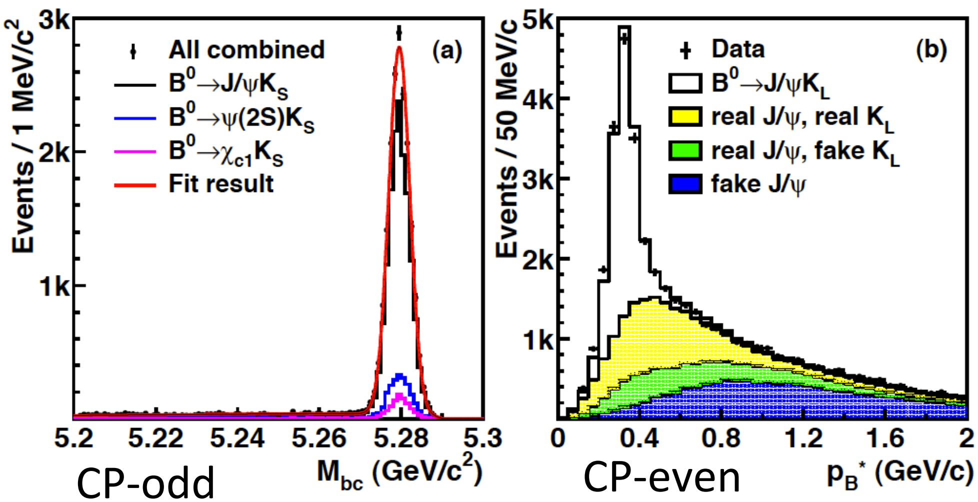
$$\mathbf{S} = \frac{2\mathrm{Im}\lambda}{|\lambda|^2 + 1} \qquad \mathbf{A} = \frac{|\lambda|^2 - 1}{|\lambda|^2 + 1}$$

$$\lambda = \frac{q}{p} \frac{A(\bar{B}^0 \to f_{\mathrm{CP}})}{A(B^0 \to f_{\mathrm{CP}})}$$

$$= e^{-i2\phi_i} \frac{\bar{A}_f}{A_f}$$

- **(S, A)**
  - $(-\xi \sin 2\phi_1, 0)$ for $(c\bar{c})K_{S/L}$ ($\xi = \pm 1$)
  - $(\ \sin 2\phi_2, 0)$ for ππ (if tree only)

$\sin 2\phi_1$ at Belle (772 M BB, final sample)



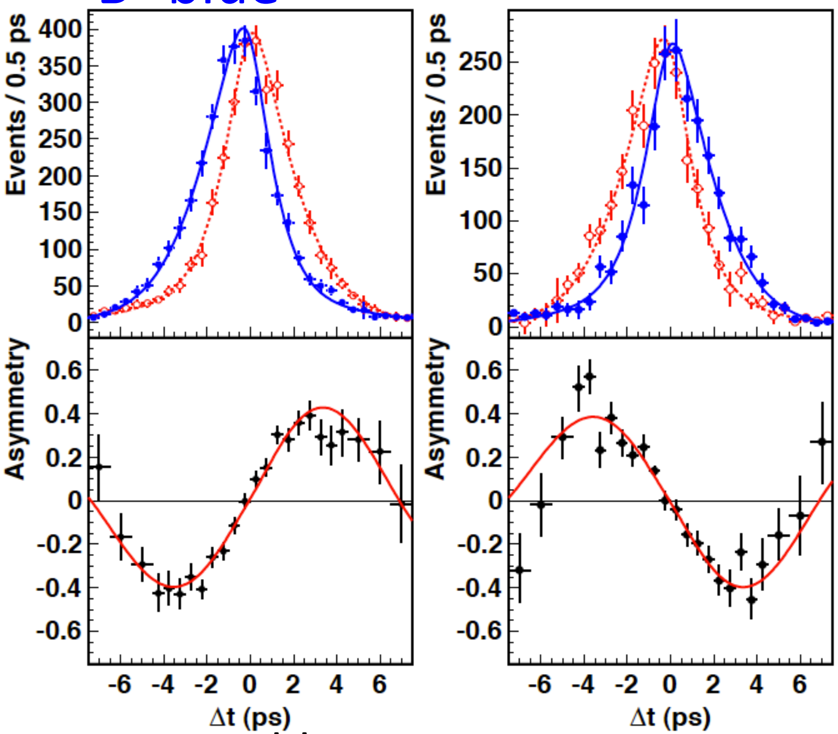
PRL 108 (2012) 171802

- Signal yield increased more than N_{BB} compared to the previous publication (PRL 98, 031802), thanks to the data reprocessing with improved tracking.

	$J/\psi\ K_S$	$J/\psi\ K_L$	$\psi(2S)\ K_S$	$\chi_{c1}\ K_S$	N_{BB}
$N_{sig.}$	12727 ± 115	10087 ± 154	1981 ± 46	943 ± 33	772 M
Purity(%)	97	63	93	89	
$N_{sig.}$(prev.)	7484 ± 87	6512 ± 123			535 M
Purity(%) (prev.)	97	59			

$\sin 2\phi_1$ at Belle (772 M BB)

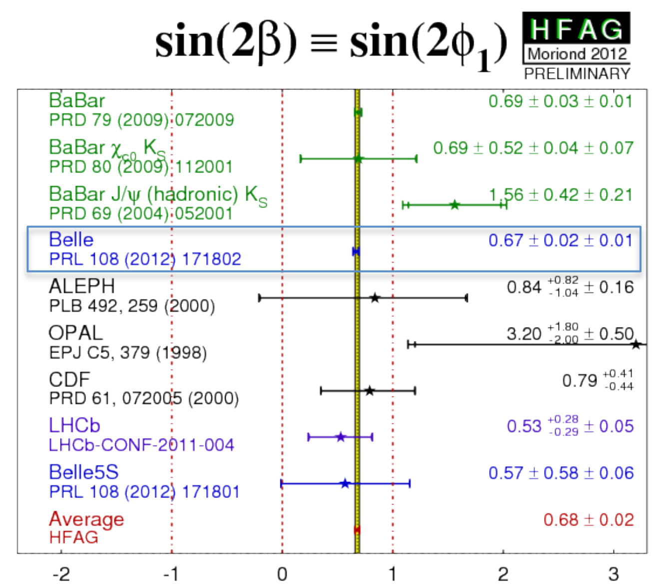
B^0 red
$\bar{B}^0$ blue



CP-odd CP-even

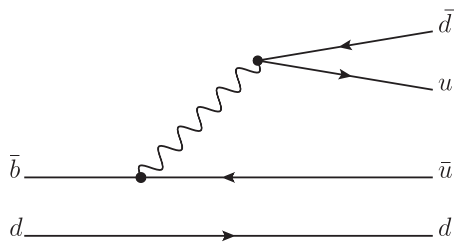
	S	A
$J/\psi\ K_S$	0.671 ± 0.029	-0.014 ± 0.021
$\psi(2S)\ K_S$	0.739 ± 0.079	0.103 ± 0.055
$\chi c1\ K_S$	0.636 ± 0.117	-0.023 ± 0.083
$J/\psi\ K_L$	-0.641 ± 0.047	0.019 ± 0.026

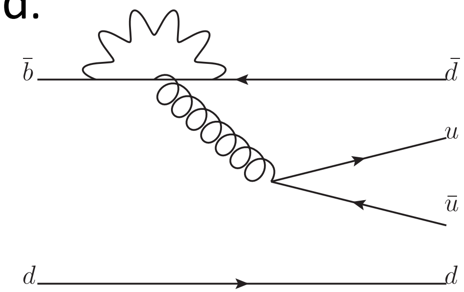
$$\sin 2\phi_1 = 0.667 \pm 0.023 \pm 0.012$$
$$A = +0.006 \pm 0.016 \pm 0.012$$



ϕ_2 determination

B→ππ is used.





$$A(B^0 \to \pi^+\pi^-) = T^{+-}e^{i\phi_3} + P$$

$$A(t) = \mathbf{S}_{\pi^+\pi^-}\sin(\Delta m t) - \mathbf{A}_{\pi^+\pi^-}\cos(\Delta m t)$$
$$= \sqrt{1-\mathbf{A}_{\pi^+\pi^-}}\sin 2\phi_{2,\mathrm{eff}}\sin(\Delta m t) - \mathbf{A}_{\pi^+\pi^-}\cos(\Delta m t)$$

- From time dependent CP Violation, we can measure $\phi_{2,\mathrm{eff}}$ instead of ϕ_2.

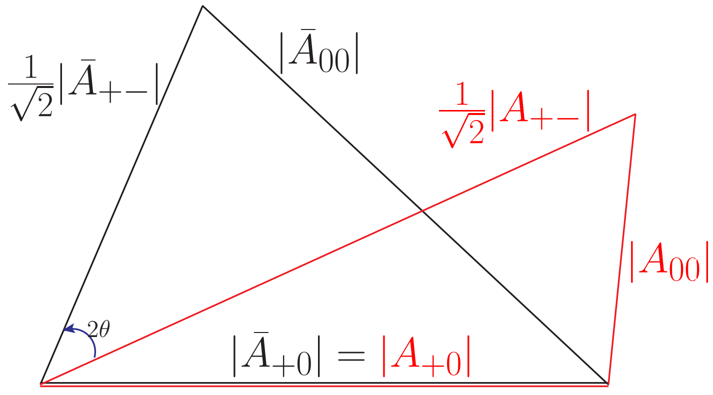
$$\mathbf{S}_{\pi^+\pi^-} = \sin 2\phi_2 + 2r\cos\delta\sin(\phi_1+\phi_2)\cos 2\phi_2 + O(r^2)$$

r = |P|/|T|

Additional inputs required to determine the penguin pollution.

Isospin analysis

$$A_{+-} = A(B^0 \to \pi^+\pi^-) = e^{-i\phi_2}T^{+-} + P$$
$$\sqrt{2}A_{00} = \sqrt{2}A(B^0 \to \pi^0\pi^0) = e^{-i\phi_2}T^{00} + P$$
$$\sqrt{2}A_{+0} = \sqrt{2}A(B^+ \to \pi^+\pi^0) = e^{-i\phi_2}(T^{00} + T^{+-})$$

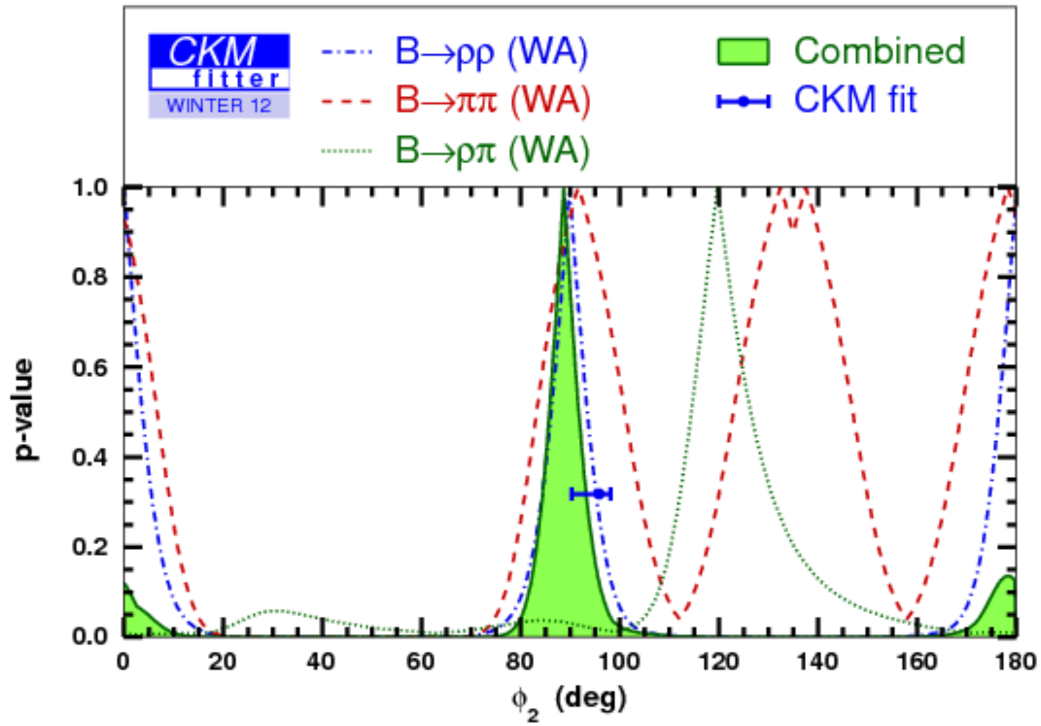


$$A_{+-} + \sqrt{2}A_{00} = \sqrt{2}A_{+0}$$
$$\bar{A}_{+-} + \sqrt{2}\bar{A}_{00} = \sqrt{2}\bar{A}_{+0}$$

- EWP is neglected→ A_{+0} pure tree
  $|A_{+0}| = |\bar{A}_{+0}|$
- ϕ_2 can be resolved with up to the 8-fold ambiguity ($\phi_2 \in [0, \pi]$)

Combined (ππ, ρπ, ρρ) measurements for ϕ_2 determination

dominated by the B → ρρ measurements (though flat isospin triangles)



- $\phi_2 = (88.7^{+4.6}_{-4.2})^\circ$

$B \to a_1^{\pm}\pi^{\mp}$, $a_1^{\pm} \to (\pi^+\pi^-)\pi^{\pm}$

- $B \to a_1^{\pm}\pi^{\mp}$ can be used to determine $\phi_{2,\mathrm{eff}}$.
  - $a_1\pi$ is not CP-eigenstate.
    - 2 interferences are observed
      $(B^0 \to a_1^+\pi^-, \bar{B}^0 \to a_1^+\pi^-)$ $(B^0 \to a_1^-\pi^+, \bar{B}^0 \to a_1^-\pi^+)$

$$\mathcal{P}(\Delta t, q, c) \equiv (1 + c\mathbf{A}_{\mathrm{CP}})\frac{e^{-\frac{|\Delta t|}{\tau_{B^0}}}}{8\tau_{B^0}}\{1 + q[(\mathbf{S}_{\mathrm{CP}} + c\Delta\mathbf{S})\sin\Delta m_d \Delta t - (\mathbf{S}_{\mathrm{CP}} + c\Delta\mathbf{C})\cos\Delta m_d \Delta t]$$

$a_1^+ : c = +1$; $a_1^- : c = -1$
$B^0 : q = +1$; $B^0 : q = -1$

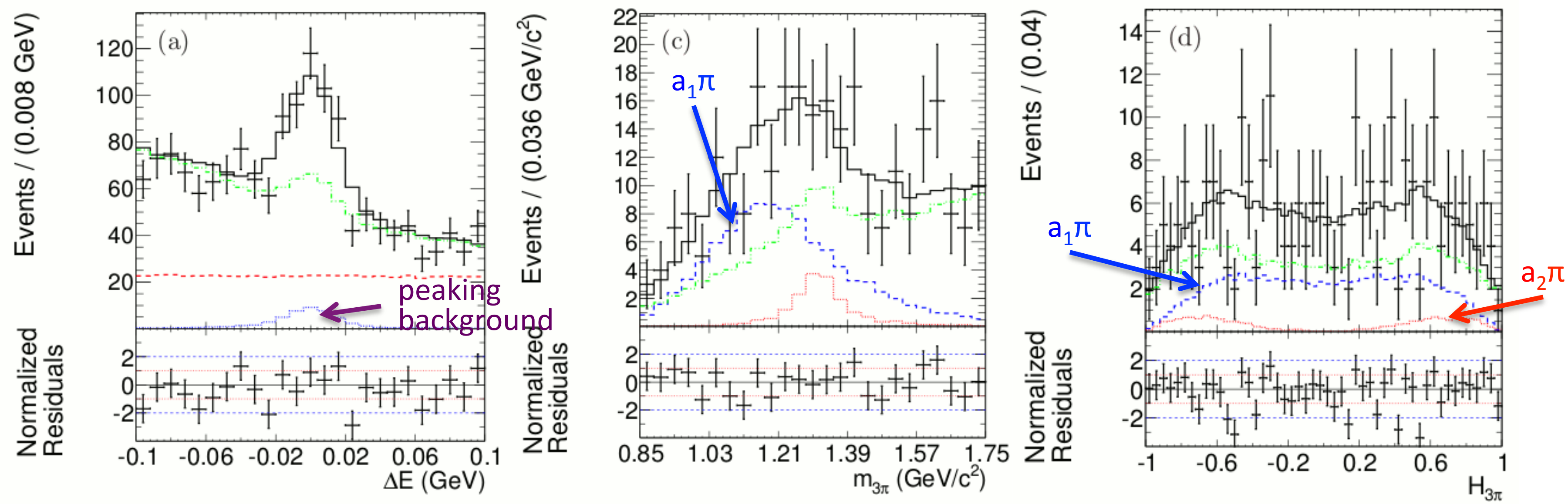
- 5 CPV parameters
  A_{CP} : time and flavor integrated direct CPV par.
  C_{CP} : flavor-dependent direct CPV par.
  S_{CP} : mixing-induces CPV par.
  ΔC : rate difference between the decay channels
  ΔS : strong phase difference between the decay channels

$B \to a_1^{\pm} \pi^{\mp}, a_1^{\pm} \to (\pi^+\pi^-)\pi^{\pm}$

arXiv: 1205, 5957
772 M BB

Fisher : for continuum suppression

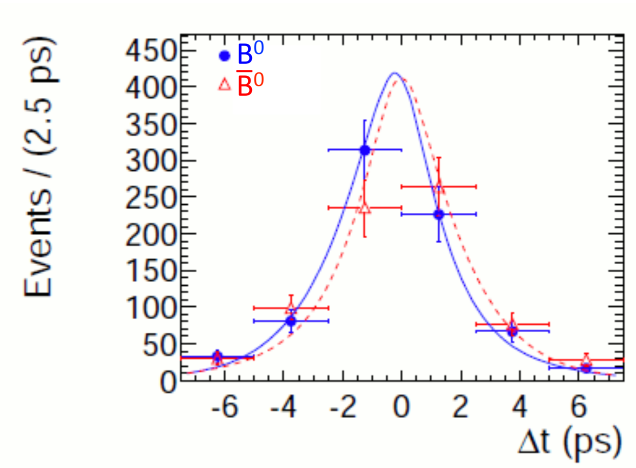
- Signal extracted from a 4D(ΔE, F, $m_{3\pi}$, $H_{3\pi}$) fit

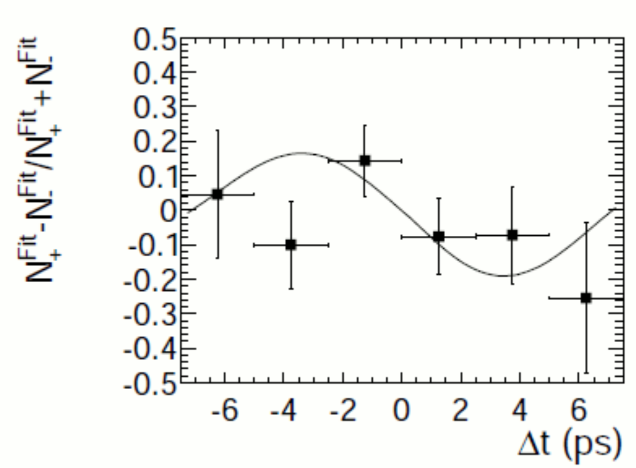


$N_{sig.} = 1445 \pm 101$

$Br(B^0 \to a_1^{\pm}(1260)\pi^{\mp}) \times Br(a_1^{\pm} \to \pi^+\pi^-\pi^{\pm}) = (11.1 \pm 1.0 \pm 1.4) \times 10^{-6}$

$B \to a_1^{\pm} \pi^{\mp}$





$A_{CP} = -0.06 \pm 0.05 \pm 0.07$

$C_{CP} = -0.01 \pm 0.11 \pm 0.09$

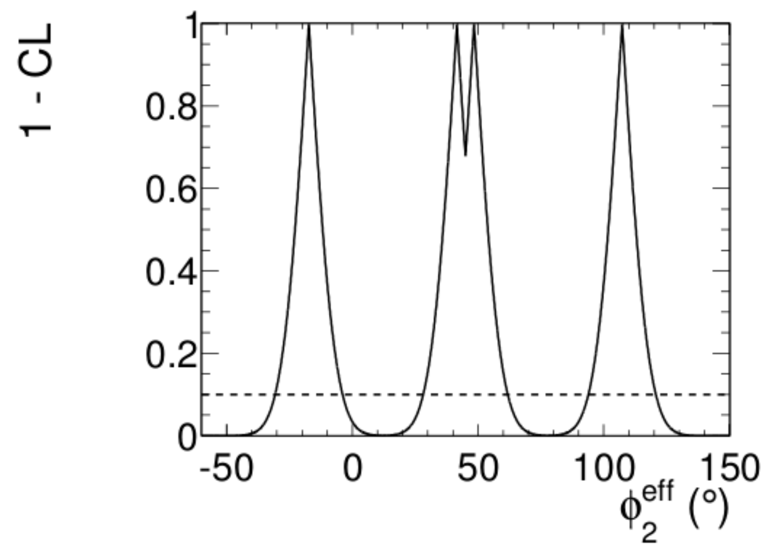
$S_{CP} = -0.51 \pm 0.14 \pm 0.08$

$\Delta C = +0.54 \pm 0.11 \pm 0.07$

$\Delta S = -0.09 \pm 0.14 \pm 0.06$

- **First evidence of mixing-induced CPV with 3.1σ in $B \to a_1\pi$.**
- $\phi_{2,\mathrm{eff}}$ determined with a 4-fold ambiguity :

$$\phi_{2,\mathrm{eff}} = \frac{1}{4}\left[\arcsin\left(\frac{\mathbf{S}_{\mathrm{CP}} + \Delta\mathbf{S}}{\sqrt{1-(\mathbf{C}_{\mathrm{CP}}+\Delta\mathbf{C})^2}}\right) + \arcsin\left(\frac{\mathbf{S}_{\mathrm{CP}} - \Delta\mathbf{S}}{\sqrt{1-(\mathbf{C}_{\mathrm{CP}}-\Delta\mathbf{C})^2}}\right)\right]$$



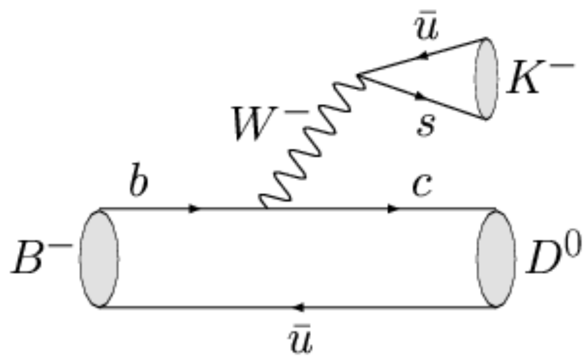
[-25.5˚, -9.1˚]
[34.7˚, 55.3˚]
[99.1˚, 115.5˚]

This is “effective” ϕ_2. So “true” ϕ_2 will be shifted.

→ ϕ_2 using isospin analysis
[M.Gronau and D.London, PRL 65 (1990) 3381]
using SU(3) flavour symmetry
[M.Gronau and J.Zupan, PRD 73 (2006) 057502]

ϕ_3 measurements from B→DK

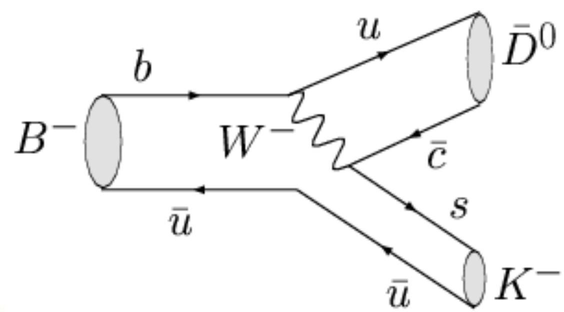
- Access ϕ_3 via interference between B→DK and B→$\bar{D}$K



color allowed

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

$\sim A\lambda^3$



color suppressed

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

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

relative weak phase is ϕ_3,

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

relative strong phase is δ_B.

ϕ_3 measurements from B→DK

- Reconstruct D in final states accessible to both D^0 and $\bar{D}^0$
  - D = D_{CP}, CP eigenstates as K^+K^-, $\pi^+\pi^-$, $K_S\pi^0$
    - GLW method (Gronau-London-Wyler)
  - D = D_{sup}, Doubly-Cabbibo-suppressed decay as Kπ
    - ADS method (Atwood-Dunietz-Soni)
  - Three-body decay as $D \to K_S\pi^+\pi^-$, $K_SK^+K^-$
    - GGSZ (Dalitz) method (Giri-Grossman-Soffer-Zupan)

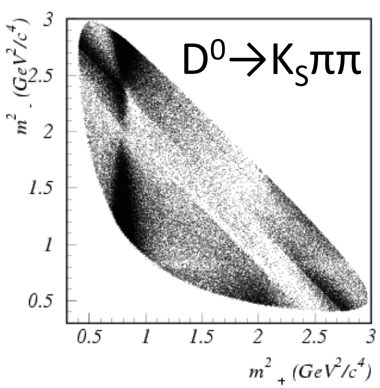
- Largest effects due to
  - charm mixing
  - charm CP violation

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

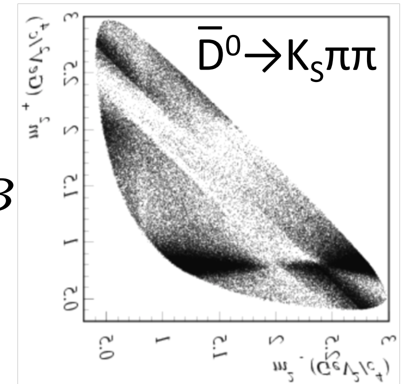
- Different B decay modes (DK, D*K, DK*)
  - different hadronic factor (r_B, δ_B) for each.

Dalitz ($B^- \rightarrow [K_S\pi\pi]_D K^-$)

PRD 81, 112002 (2010)
657 M BB



$$+ r_B e^{\pm i\phi_3 + i\delta_B}$$



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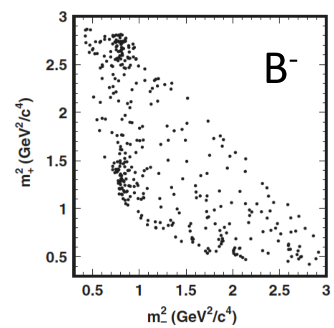
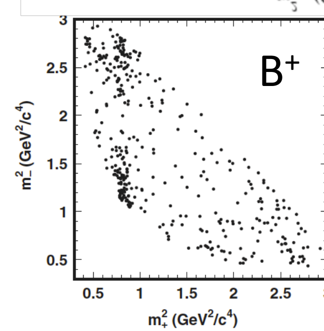
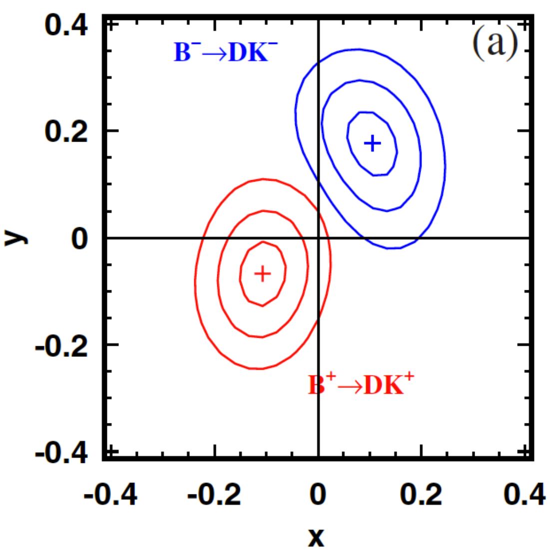




old model dependent analysis



$x_\pm = r_B \cos(\delta_B \pm \phi_3)$
$y_\pm = r_B \sin(\delta_B \pm \phi_3)$

- $K_S\pi\pi$ plane model ← error!!

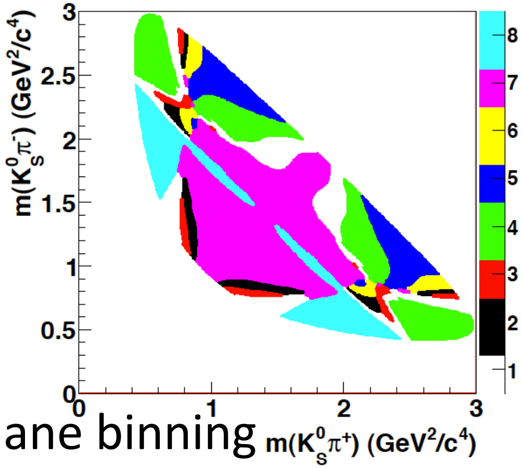
$\phi_3 = (80.8 \,^{+13.1}_{-14.8} \pm 5.0 \pm 8.9)^\circ$

$r_B = 0.161 \,^{+0.040}_{-0.038} \pm 0.011 \,^{+0.050}_{-0.010}$

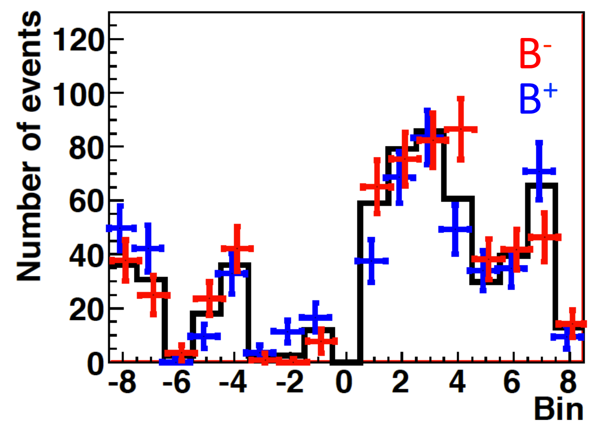
$\delta_B = (137.4 \,^{+13.0}_{-15.7} \pm 4.0 \pm 22.9^\circ$

Binned Dalitz ($B^- \to [K_S\pi\pi]_D K^-$)

arXiv: 1204.6561
772M BB



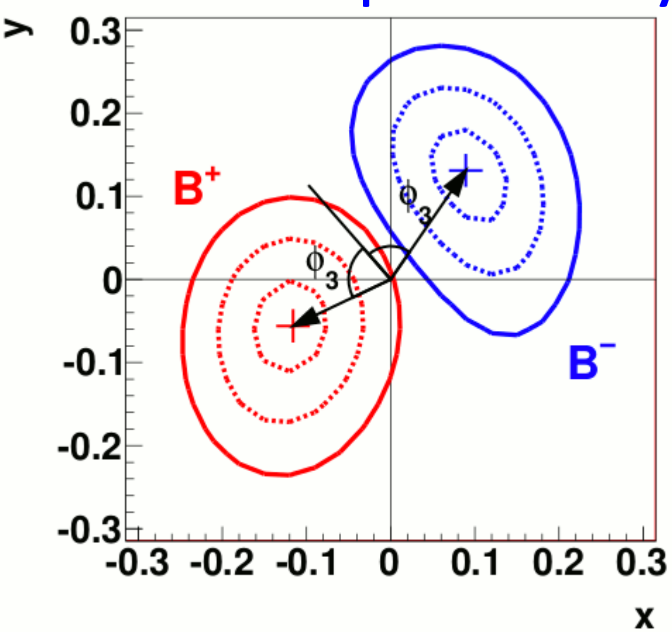
$K_S\pi\pi$ plane binning



events projection for each bin

- Avoid the modeling error by optimal binning of the Dalitz($K_S\pi\pi$) plot

new model independent analysis

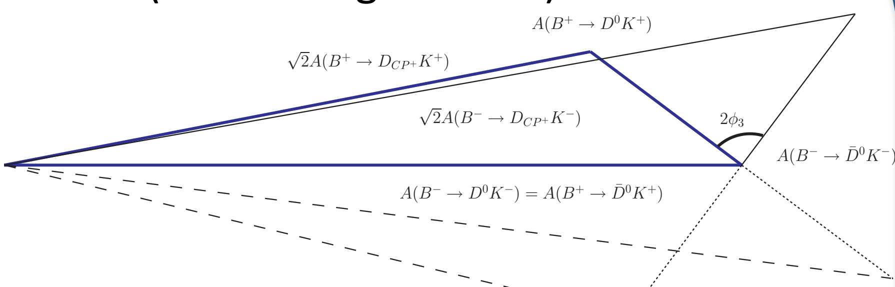


$$\phi_3 = (77.3\ ^{+15.1}_{-14.9} \pm 4.1 \pm 4.3)^\circ$$
$$r_B = 0.145 \pm 0.030 \pm 0.010 \pm 0.011$$
$$\delta_B = (129.9 \pm 15.0 \pm 3.8 \pm 4.7)^\circ$$

The 3rd errors come from binning in Dalitz plane.
It can be reduced by using future BES-III data.
In the Super B-Factory era,
no more model error is dominant.

GLW and ADS

GLW (D → CP-eigenstates)



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

- Larger event.

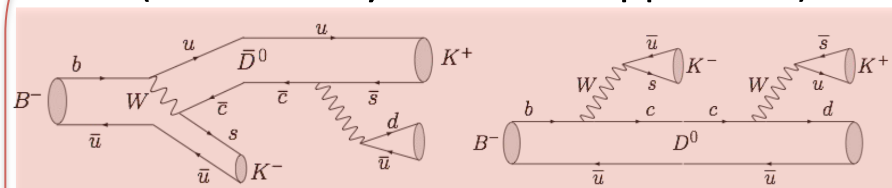
$$R_{CP\pm} = \frac{\Gamma(B^- \to D_{CP\pm} K^-) + \Gamma(B^+ \to D_{CP\pm} K^+)}{\Gamma(B^- \to D^0 K^-) + \Gamma(B^+ \to \bar{D}^0 K^+)}$$

$$= 1 + r_B^2 \pm 2 r_B \cos\delta_B \cos\phi_3$$

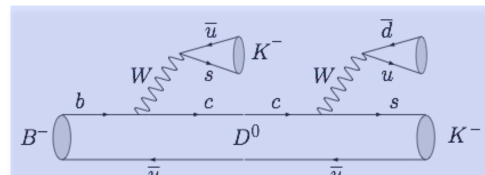
$$A_{CP\pm} = \frac{\Gamma(B^- \to D_{CP\pm} K^-) - \Gamma(B^+ \to D_{CP\pm} K^+)}{\Gamma(B^- \to D_{CP\pm} K^-) + \Gamma(B^+ \to D_{CP\pm} K^+)}$$

$$= \frac{\pm 2 r_B \sin\delta_B \sin\phi_3}{R_{CP\pm}}$$

ADS (D → Doubly-Cabibbo-suppressed)



suppressed mode



favored mode

- Larger asymmetry.

$$R_{DK} = \frac{\Gamma(B^- \to [K^+\pi^-]K^-) + \Gamma(B^+ \to [K^-\pi^+]K^+)}{\Gamma(B^- \to [K^-\pi^+]K^-) + \Gamma(B^+ \to [K^+\pi^-]K^+)}$$

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

$$A_{DK} = \frac{\Gamma(B^- \to [K^+\pi^-]K^-) - \Gamma(B^+ \to [K^-\pi^+]K^+)}{\Gamma(B^- \to [K^+\pi^-]K^-) + \Gamma(B^+ \to [K^-\pi^+]K^+)}$$

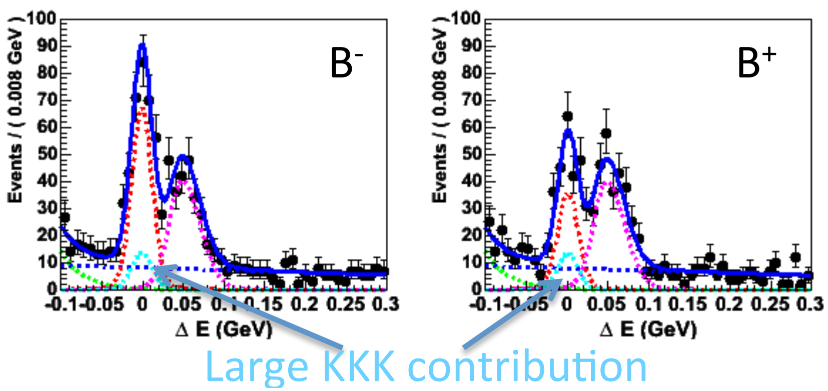
$$= \frac{2 r_B r_D \sin(\delta_B + \delta_D) \sin\phi_3}{R_{DK}}$$

Preliminary (LP2011)
772 M BB

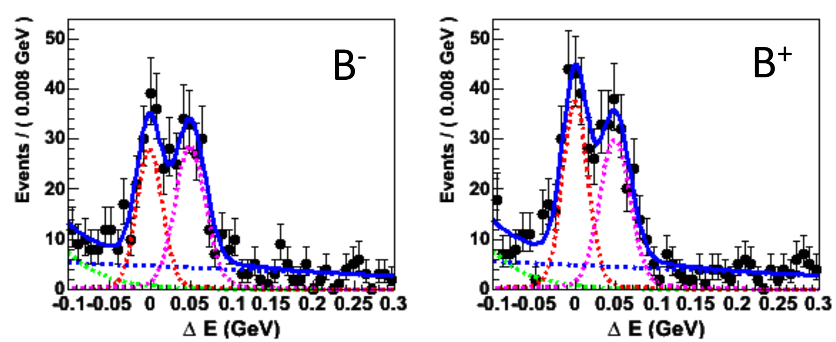
GLW ($B^- \to DK^-$)

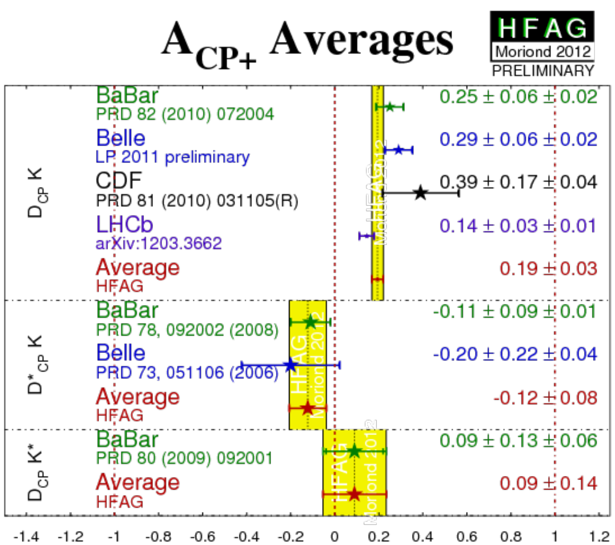
DK Signal
$D\pi$
BB
continuum

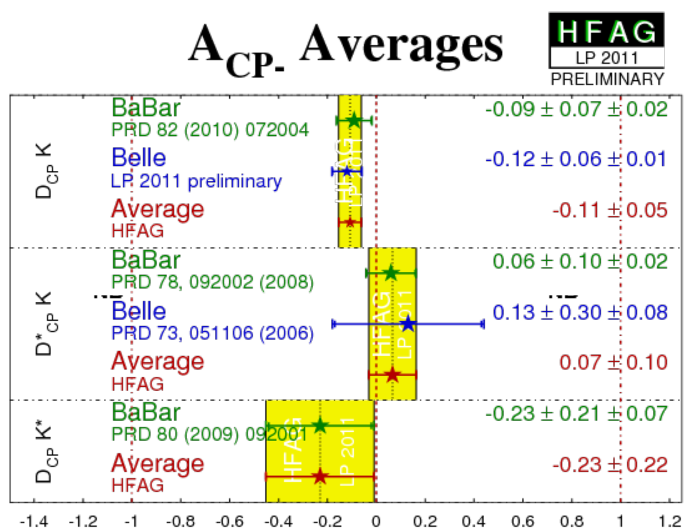
$B \to DK$, $D \to KK$, $\pi\pi$ (CP+)



$B \to DK$, $D \to K_S\pi^0$, $K_S\eta$ (CP-)







$R_{CP+} = 1.03 \pm 0.07 \pm 0.03$

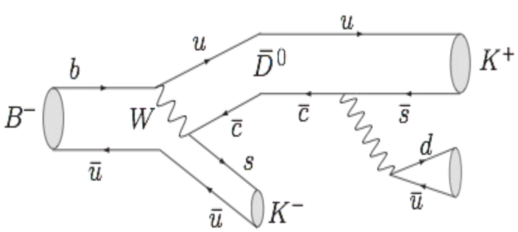
$R_{CP-} = 1.13 \pm 0.09 \pm 0.05$

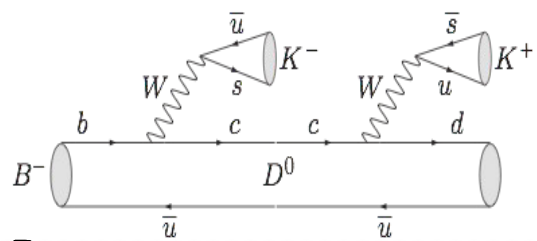
$A_{CP+} = +0.29 \pm 0.06 \pm 0.02$

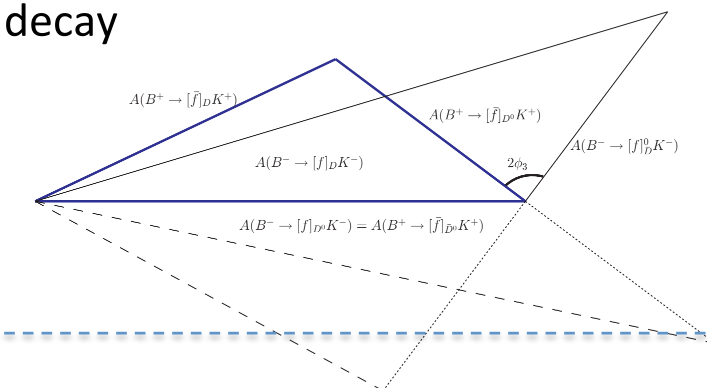
$A_{CP-} = -0.12 \pm 0.06 \pm 0.01$

ADS (comparison charged and neutral B mode)

- ADS in charged B
  - amplitude ratio (r_B)for the two paths is 0.1~0.2
    - Suppressed B decay × Favored D decay × color suppression
    - Favored B decay × Doubly Suppressed D decay

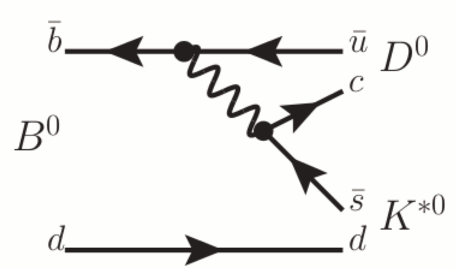


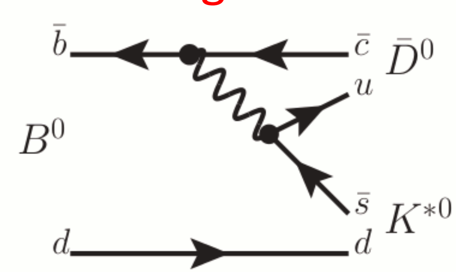




- ADS in neutral B
  - B flavor is tagged by the charge of K from K*.
  - Both path is color suppressed.
    - The amplitude ratio (r_s) can be upto 0.4

      → larger CPV and higher sensitivity to ϕ_3 are expected!!





$$r_B \sim \frac{V_{ub}V_{cs}^*}{V_{cb}V_{us}^*} \times [\text{color supp.}] \sim 0.1\text{-}0.2$$

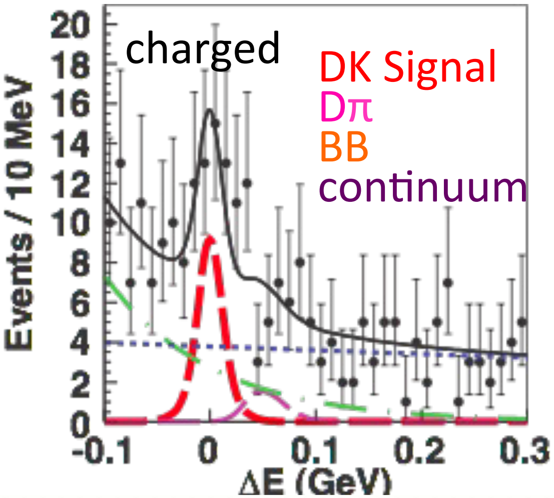
$$r_S \sim \frac{V_{ub}V_{cs}^*}{V_{cb}V_{us}^*} \times [\text{color supp.}] \sim 0.4$$

PRL 106 231803 (2011)
772 M BB

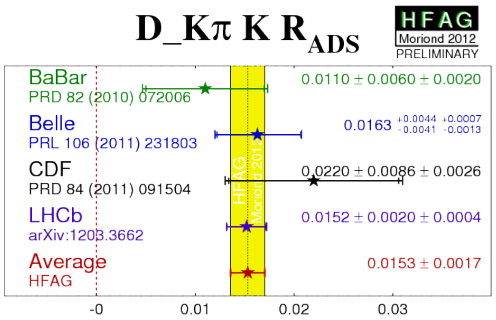
ADS

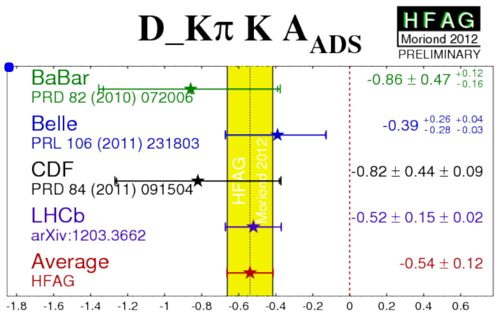
arXiv: 1205, 0422
772 M BB

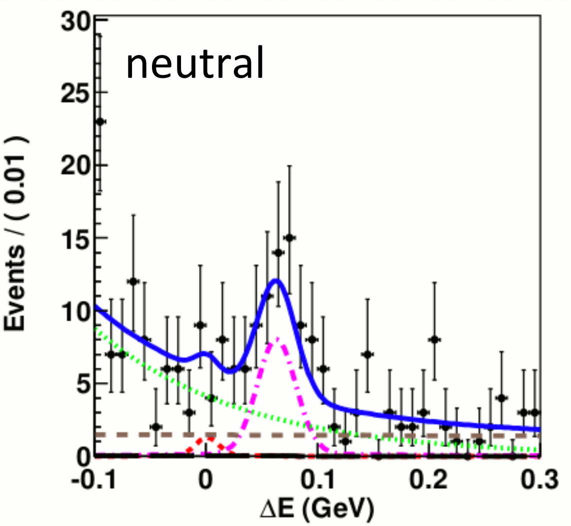
$(B^- \to [K^+\pi^-]_D K^-, \bar{B}^0 \to [K^+\pi^-]_D \bar{K}^{*0})$



- $B^- \to [K^+\pi^-]_D K^-$
  - **First evidence obtained with a significance of 4.1σ.**
    - $R_{DK} = (1.63\ ^{+0.44}_{-0.41}\ ^{+0.07}_{-0.13}) \times 10^{-2}$
    - $A_{DK} = -0.39\ ^{+0.26}_{-0.28}\ ^{+0.04}_{-0.03}$



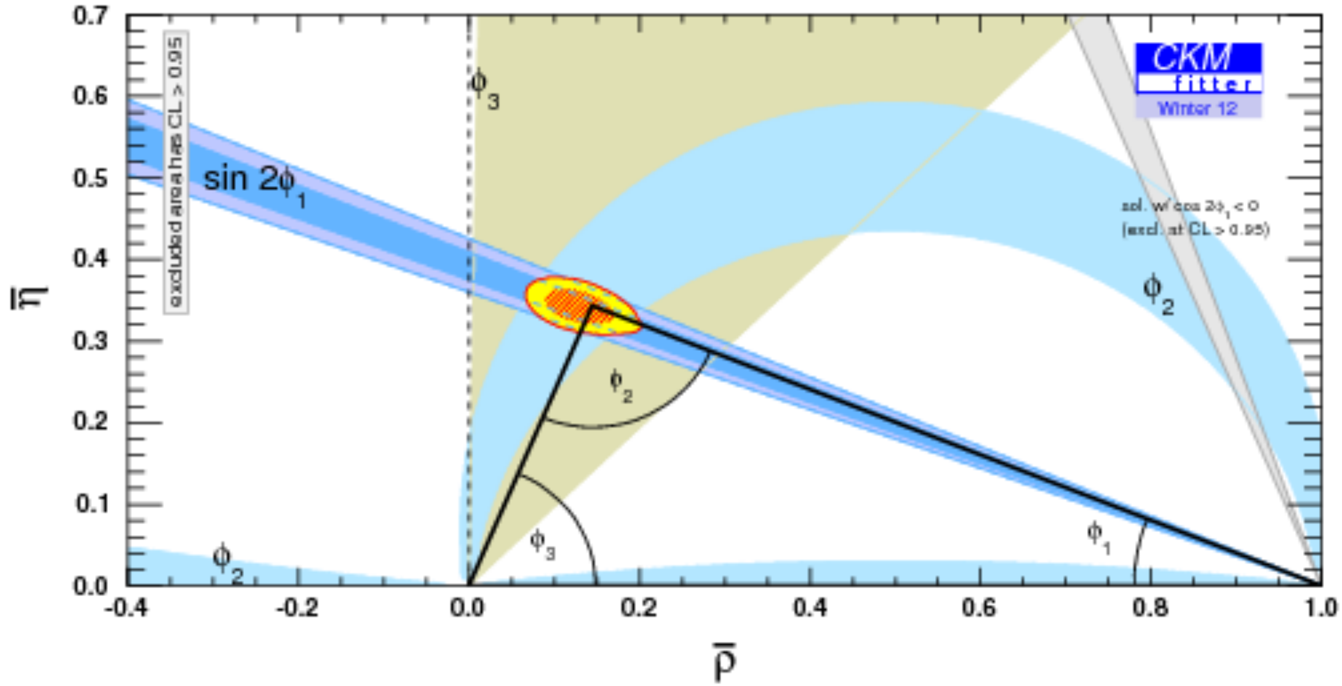




- $B^0 \to [K^-\pi^+]_D K^{*0}$
  - **Most stringent limit on $R_{DK^{*0}}$ to date**
    - $R_{DK^{*0}} = (4.5\ ^{+5.6}_{-5.0}\ ^{+2.8}_{-1.8}) \times 10^{-2}$
      < 0.16 @ 95 % C.L.
    - $r_S < 0.4$ @ 95 % C.L.

Summary

- Now we know CKM precision.

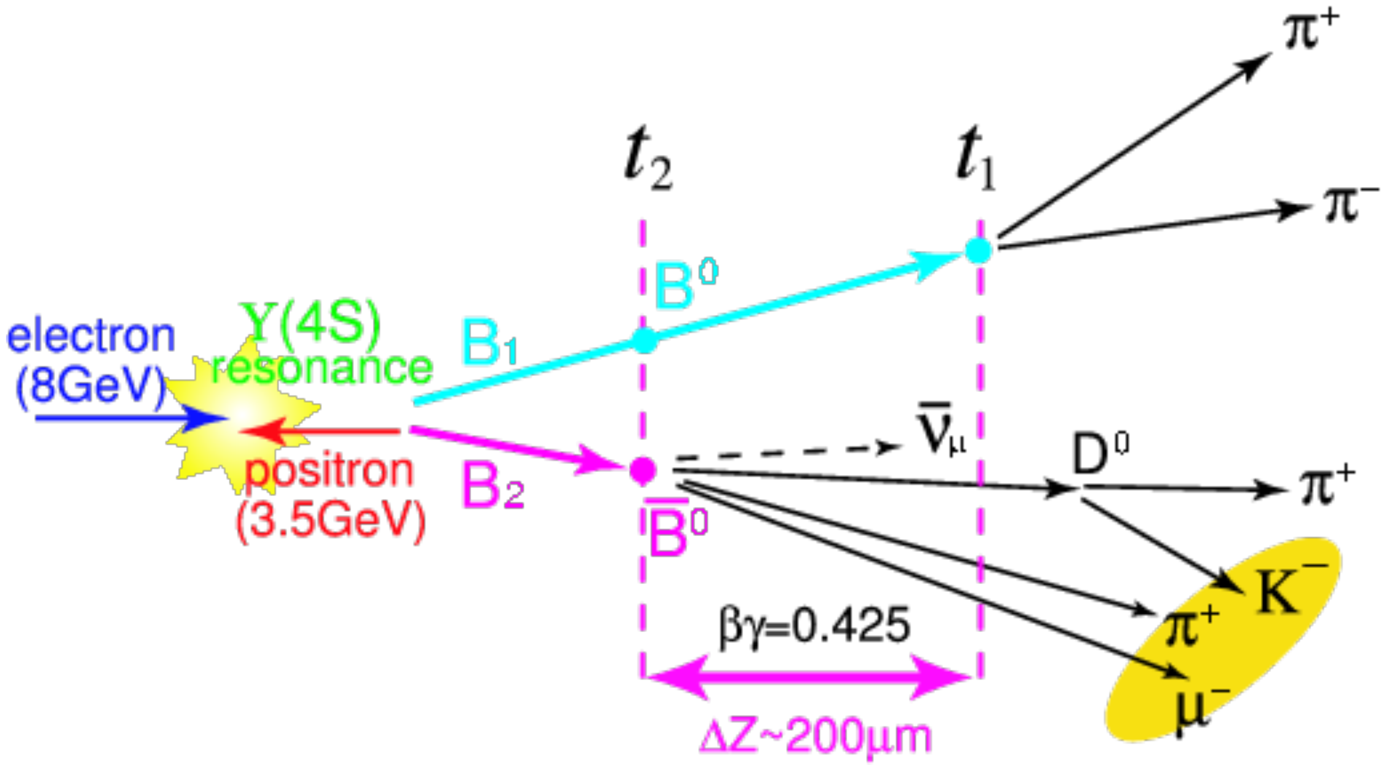


- still interesting updates in the pipeline (especially on ϕ_2 and ϕ_3)
  - new Belle result shown today on $B \to a_1\pi$

Thank you!!

Back up

measuring the CP parameter **S** and **A**

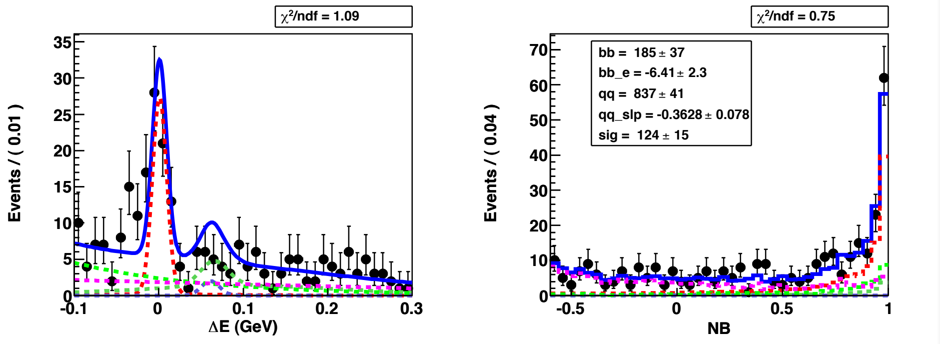


ΔZ ~ cβγΔt

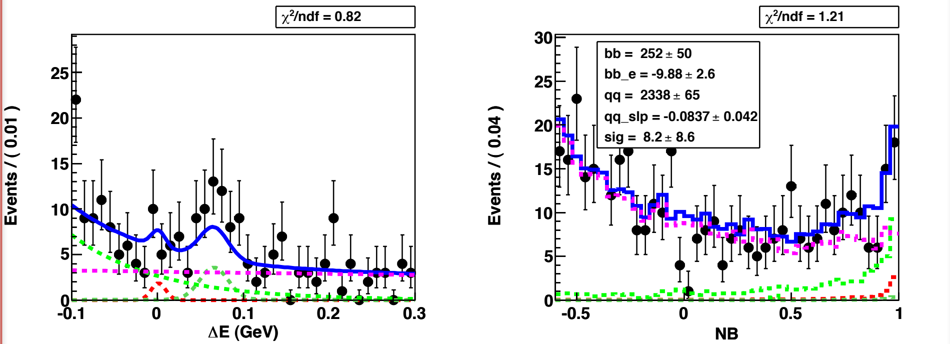
$$\mathcal{P}(\Delta t, q) = \frac{e^{\frac{|\Delta t|}{\tau_B}}}{4\tau_B}(1 + q(\mathbf{S}\sin(\Delta m_d \Delta t) + \mathbf{A}\cos(\Delta m_d \Delta t)))$$

$[K\pi]_D K^{*0}$

favored mode

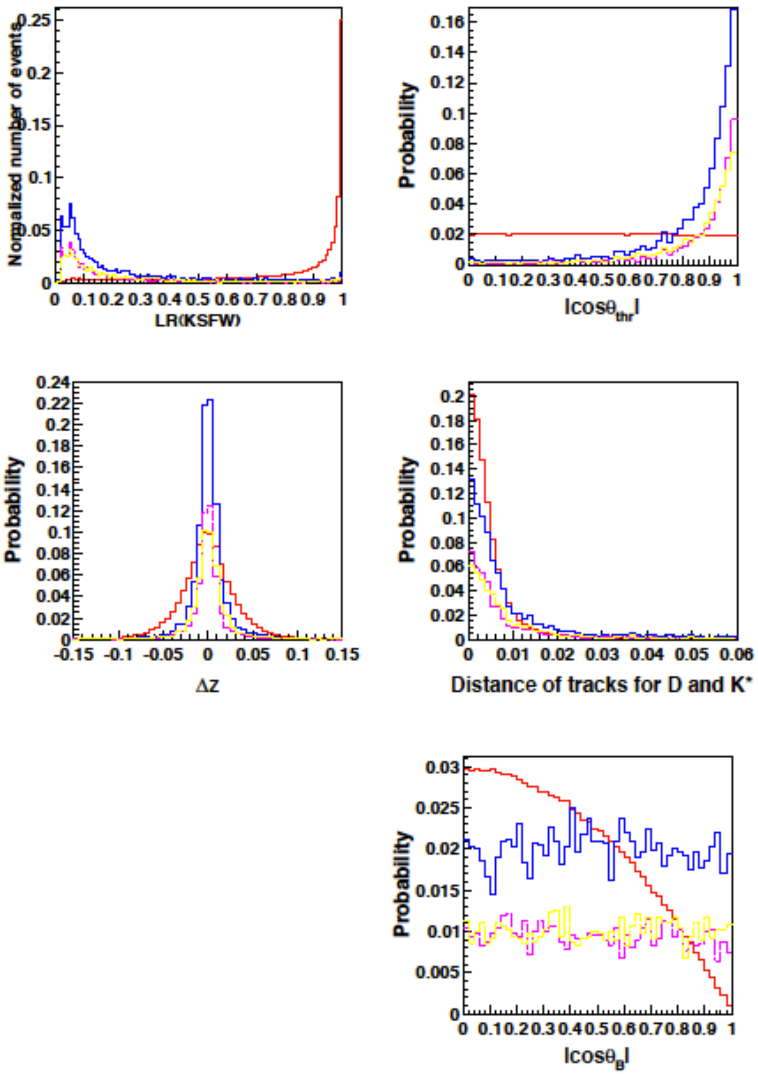


suppressed mode

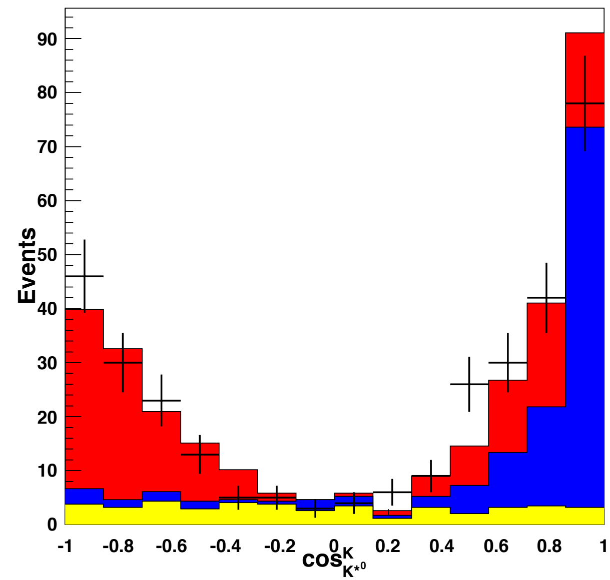


Mode	ϵ (%)	N	$\mathcal{R}_{DK^{*0}}$
$B^0 \to [K^+\pi^-]_D K^{*0}$	21.0 ± 0.3	$190^{+22.3}_{-21.2}$	$(4.5^{+5.6}_{-5.0}) \times 10^{-2}$
$B^0 \to [K^-\pi^+]_D K^{*0}$	20.9 ± 0.3	$7.7^{+10.6}_{-9.5}$	

Source	Uncertainty $[10^{-2}]$
Signal PDFs	+0.1–0.2
$\bar{D}^0\rho^0$ PDFs	+0.0–0.1
Combinatorial $B\bar{B}$ PDFs	+1.8–1.2
Peaking background PDFs	+0.1–0.1
$q\bar{q}$ PDFs	+2.2–1.4
$\bar{D}^0K^+$ and $\bar{D}^0\pi^+$ PDFs	+0.0–0.1
Fit bias	+0.1–0.1
Efficiency	+0.1–0.1
Charmless decay	+0.0–0.3
Total	+2.8–1.8



NeuroBayes inputs



$\cos\theta_{K^*}$