Recent Belle results related to pion-kaon interactions

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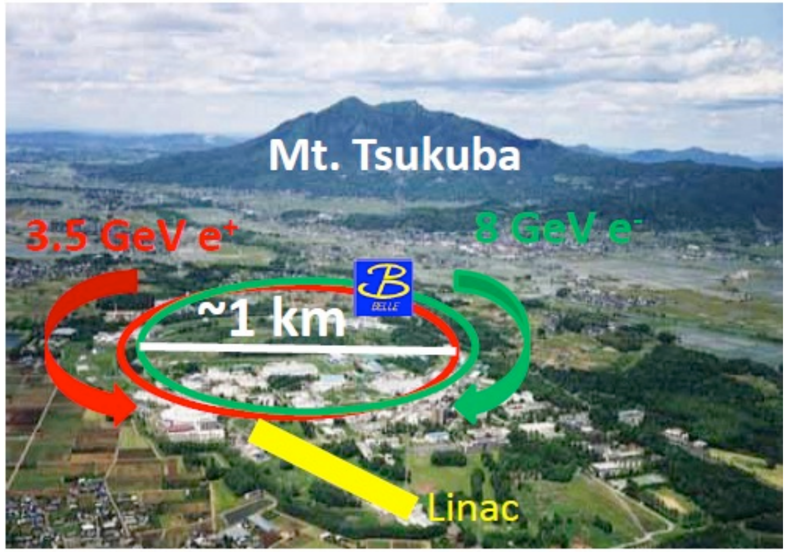
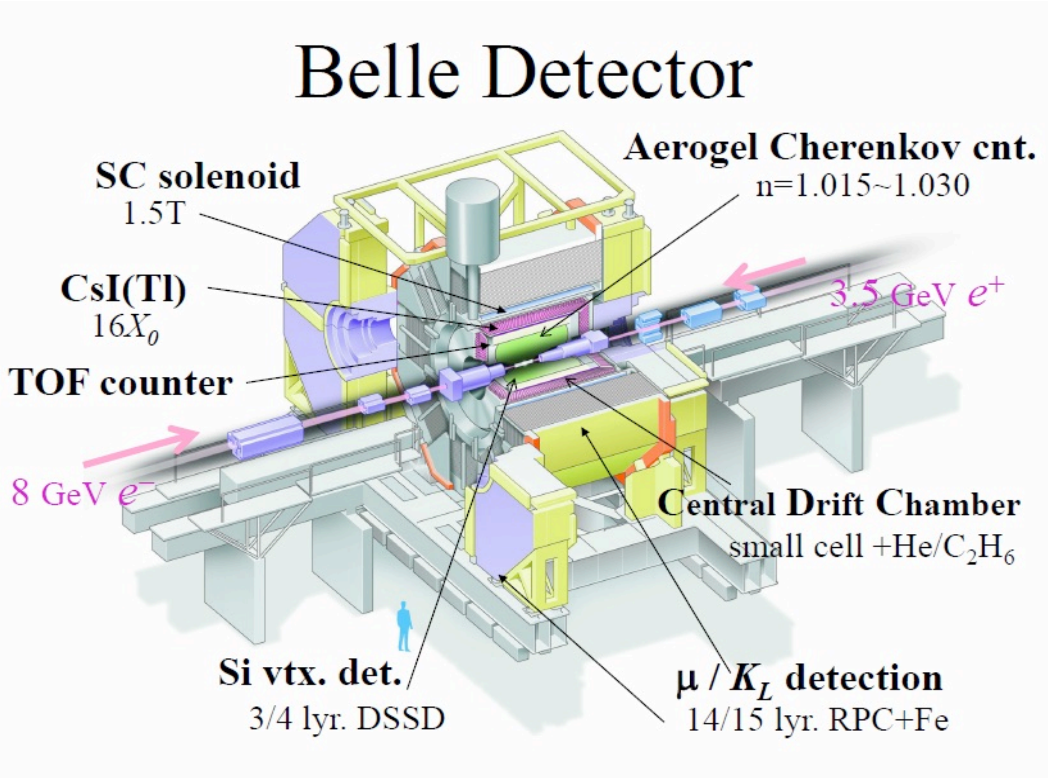
Talk Outline

- Belle experiment at KEKB
- $B^+ \to K^+K^-\pi^+$
- $\Lambda_c^+ \to \phi p\pi^0,\ K^-\pi^+p\pi^0$
- $\Lambda_c^+ \to pK^+\pi^-$
- ϕ_3 from $B^\pm \to DK^\pm, D \to K_S^0\pi^+\pi^-$
- Summary

Belle Experiment



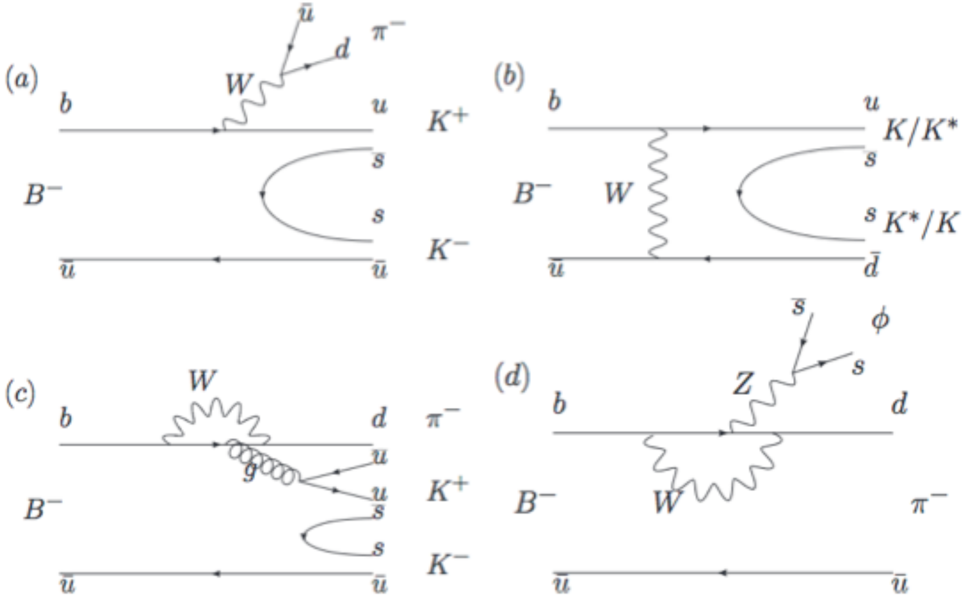


- Asymmetric energy electron-positron collider
- Runtime: 1999-2010
- Total integrated luminosity ~ 1000 fb^{-1}

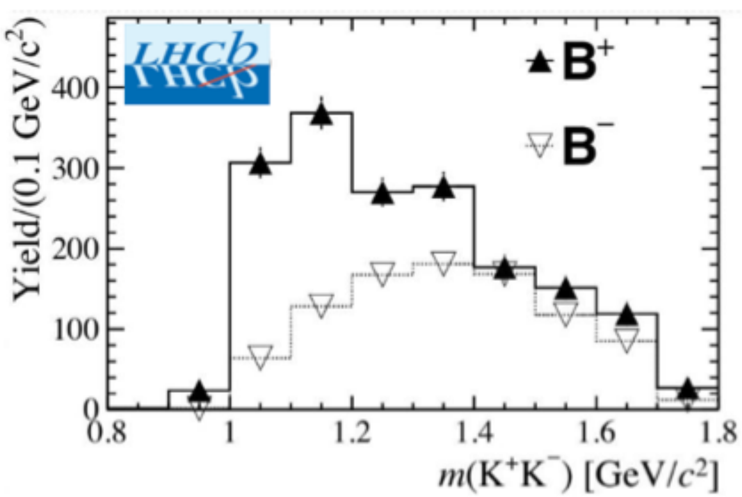
On resonance:	$\Upsilon(5S)$:	121 fb^{-1}
	$\Upsilon(4S)$:	711 fb^{-1}
	$\Upsilon(3S)$:	3 fb^{-1}
	$\Upsilon(2S)$:	25 fb^{-1}
	$\Upsilon(1S)$:	6 fb^{-1}
Off resonance/ scan:		~100 fb^{-1}

$B^+ \to K^+K^-\pi^+$

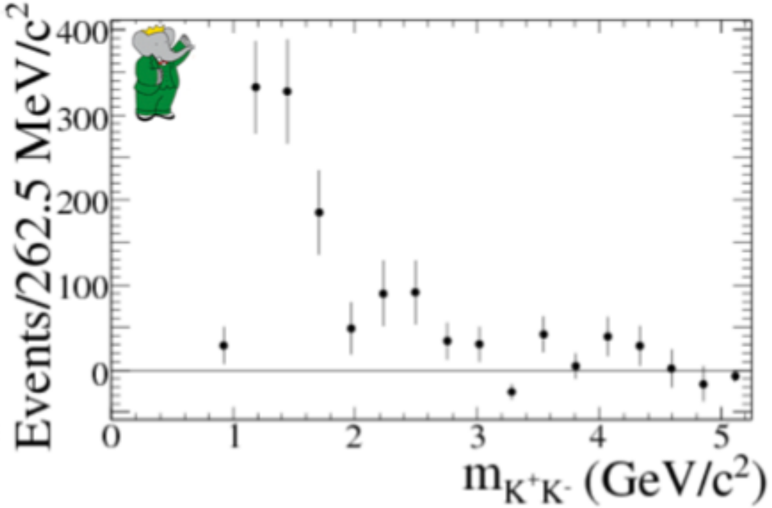
- Suppressed in Standard Model
- Unidentified structure in $M_{KK} < 1.5$ GeV is seen: only presents in B^+, which give rise to a large local CP asymmetry in this region.



PRD 90, 112004 (2014)

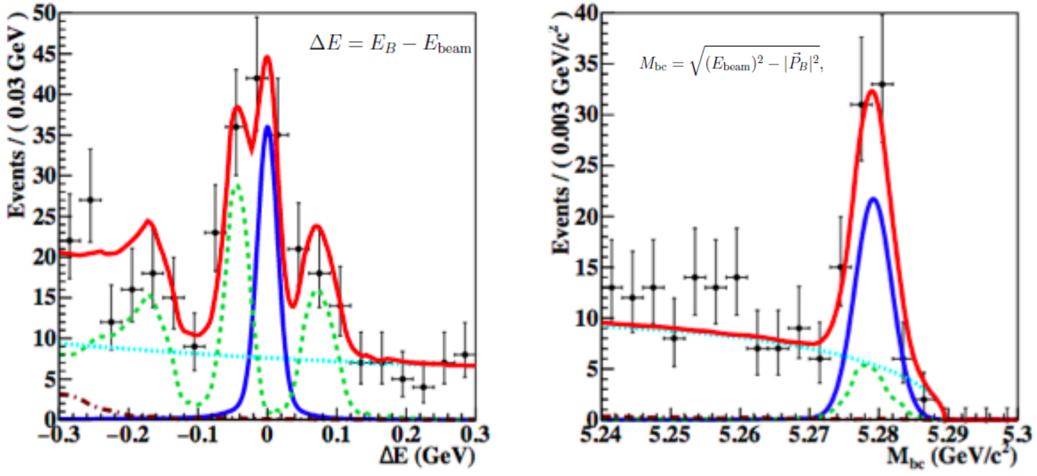


PRL 99, 221801 (2007)

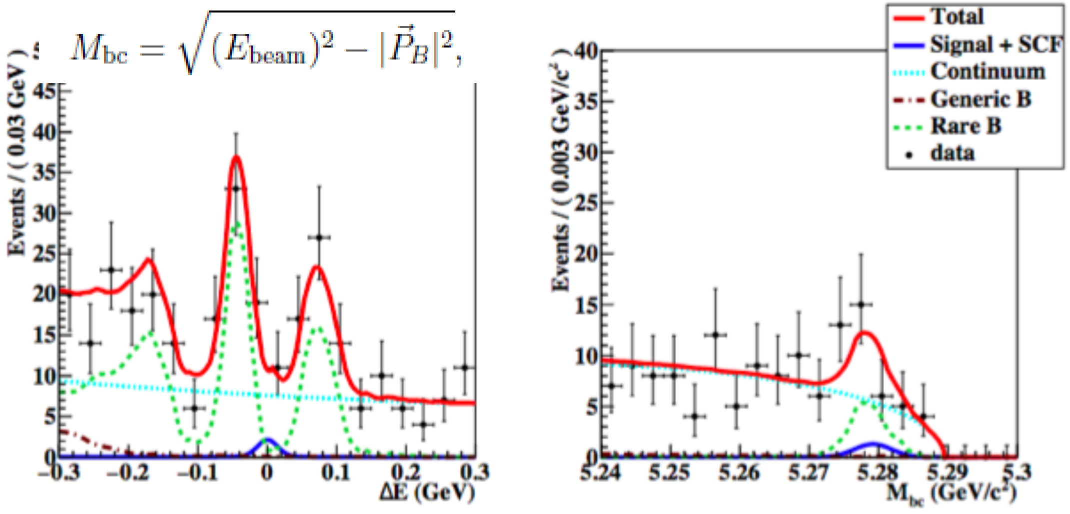


Final-state interaction may contribute to CP-violation.
[B. Bhattacharya, M. Gronau, J. Rosner, PLB 726, 337 (2013); I. Bediaga, T. Frederico, O. Lourenco, PRD 89, 094013 (2013)]

$B^+ \to K^+K^-\pi^+$



(a) $B^+ \to K^+K^-\pi^+$

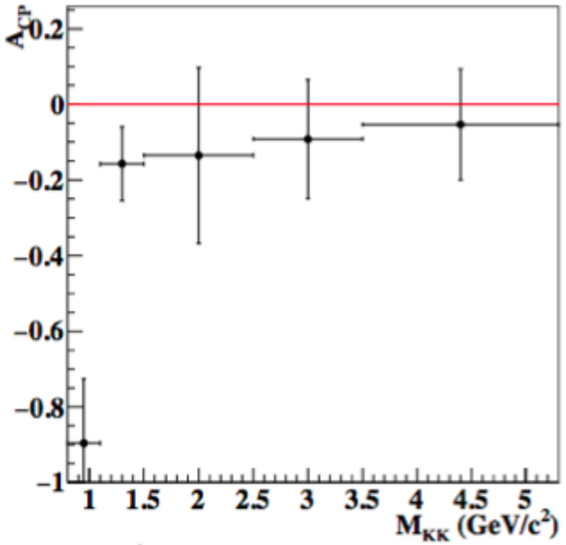


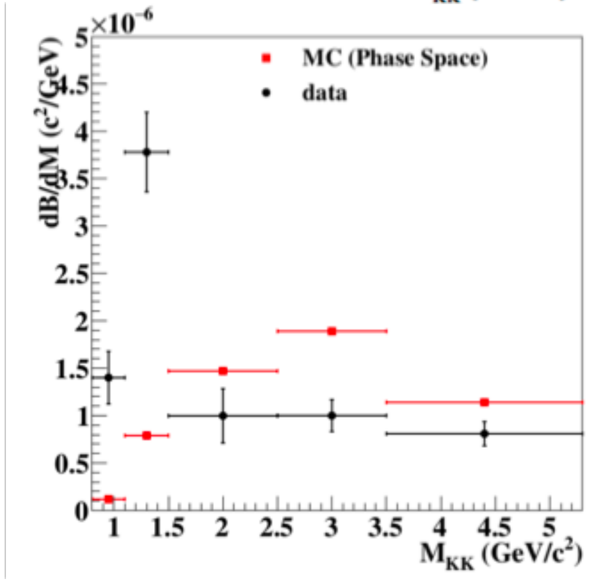
(b) $B^- \to K^-K^+\pi^-$

- Rare B background shows peak structure both in M_{bc} and ΔE; this is due to K-pi misidentification, which includes $B^+ \to K^+K^-K^+$, $B^+ \to K^+\pi^-\pi^+$, and their intermediate states!
- Charm veto is used to reject $b \to c$ background
- Neural Network (NN) is used to suppress the continuum background; input of the NN are the event shape variables
- This analysis uses 711/fb of Y(4S) data

C.L. Hsu et al,
PRD 96, 031101 (R) (2017)

$B^+ \rightarrow K^+ K^- \pi^+$





$M_{K^+K^-}$ (GeV/c^2)	$N_{\rm sig}$	Eff. (%)	$d\mathcal{B}/dM$ ($\times 10^{-7}$)	$\mathcal{A}_{CP}$
0.8 – 1.1	$59.8 \pm 11.4 \pm 2.6$	19.7	$14.0 \pm 2.7 \pm 0.8$	$-0.90 \pm 0.17 \pm 0.04$
1.1 – 1.5	$212.4 \pm 21.3 \pm 6.7$	19.3	$37.8 \pm 3.8 \pm 1.9$	$-0.16 \pm 0.10 \pm 0.01$
1.5 – 2.5	$113.5 \pm 26.7 \pm 18.6$	15.6	$10.0 \pm 2.3 \pm 1.7$	$-0.15 \pm 0.23 \pm 0.03$
2.5 – 3.5	$110.1 \pm 17.6 \pm 4.9$	15.1	$10.0 \pm 1.6 \pm 0.6$	$-0.09 \pm 0.16 \pm 0.01$
3.5 – 5.3	$172.6 \pm 25.7 \pm 7.4$	16.3	$8.1 \pm 1.2 \pm 0.5$	$-0.05 \pm 0.15 \pm 0.01$

4.8 σ

An excess of events and a large CP-asymmetry at $M_{KK} < 1.5$ GeV confirm the previous findings of BaBar and LHCb

BF ($B^+ \rightarrow K^+K^-\pi^+$) = $(5.38 \pm 0.40 \pm 0.35) \times 10^{-6}$

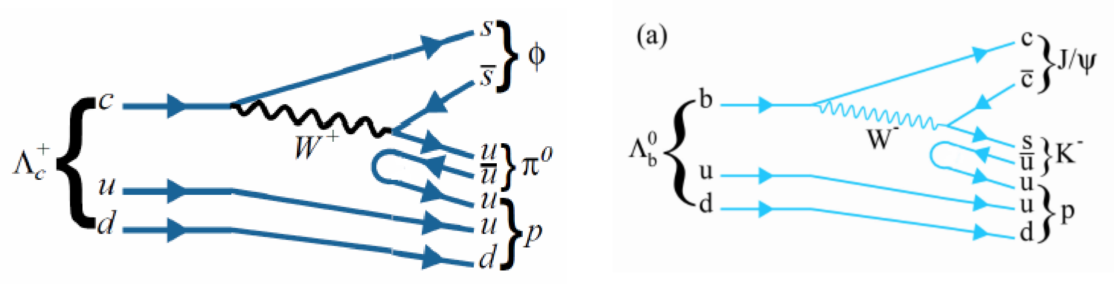
$A_{CP} = -0.182 \pm 0.071 \pm 0.016$

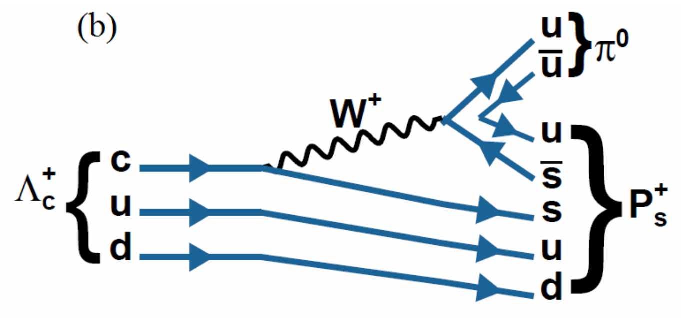
Consistent with previous measurements!

To understand the low mass dynamics, a full Dalitz analysis with sizeable dataset is required. Belle II and LHCb should resolve this!

Search for $\Lambda_c^+ \longrightarrow \phi p \pi^0$ decays

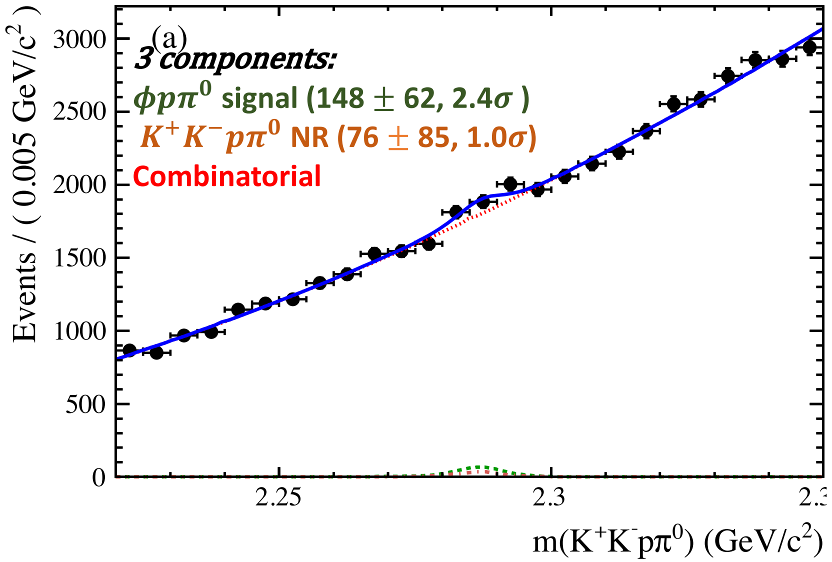
- The decay is similar to the decay of LHCb's hidden-charm penta-quark (P_c^+) discovery channel $\Lambda_b \rightarrow J/\psi p K^-$. [PRL 115, 072001 (2015)]
- Hidden-strangeness penta-quark (P_s^+) may appear in the intermediate state of ϕp, assuming the underlying mechanism creating the P_c^+ also holds for P_s^+, independent of the flavor and mass of P_s^+ is smaller than 2.151 GeV. [PRD 92, 114030 (2015)]

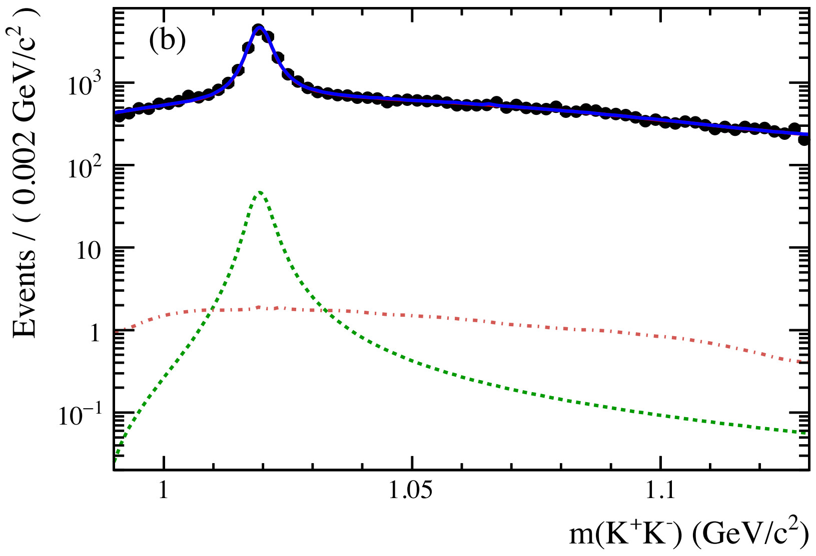




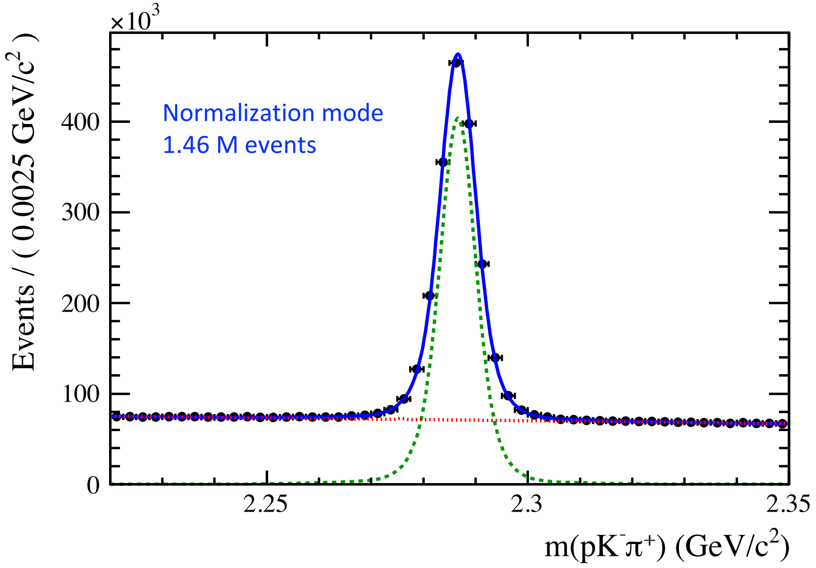
- LEPS & CLAS collaborations observed a bump at $\sqrt{s} \approx 2.0$ GeV in ϕ photo-production. [PRL 95, 182001(2005); PRC 89, 055208(2014); PRC 90, 019901 (2014)]
- This analysis uses 915/fb of Belle data collected at and near $\Upsilon(4S)$ and $\Upsilon(5S)$ resonances.

Search for $\Lambda_c^+ \longrightarrow \phi p \pi^0$ decays





- Two dimensional fit is performed to $K^+K^-p\pi^0$ and K^+K^- invariant masses, in order to extract the Λ_c^+ signal yield.
- Cabibbo-favored $\Lambda_c^+ \to \phi\Sigma^+(\to p\pi^0)$ decay has the same final state and is suppressed by rejecting the events in which $p\pi^0$ system has an invariant mass within 10 MeV of Σ^+ mass.
- Branching fraction is measured with respect to well measured CF decay $\Lambda_c^+ \to \pi^+K^-p$



$$\mathcal{B}(\Lambda_c^+ \to \text{final state}) = \frac{Y_{\text{Sig}}/\varepsilon_{\text{Sig}}}{Y_{\text{Norm}}/\varepsilon_{\text{Norm}}} \times \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$$

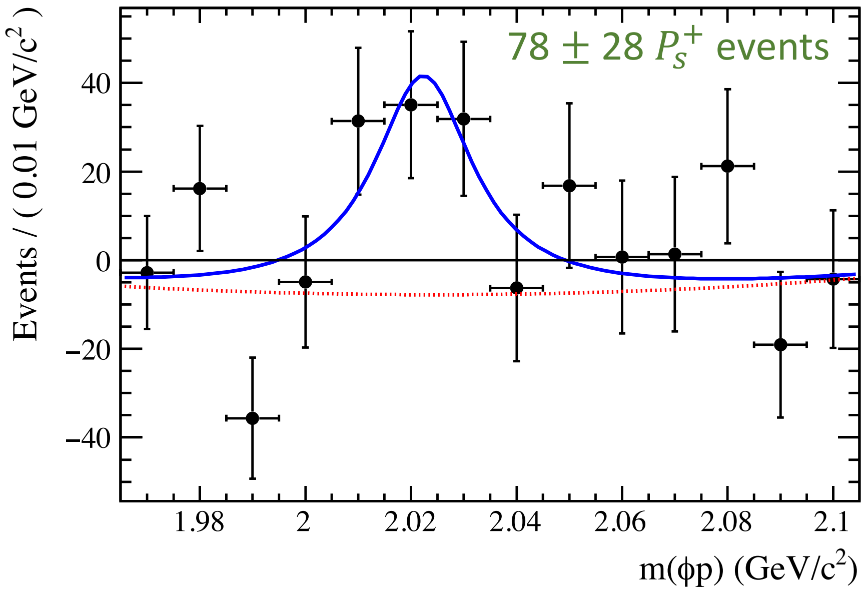
90% CL Upper limits on branching fractions

$$\mathcal{B}(\Lambda_c^+ \to \phi p\pi^0) < 15.3 \times 10^{-5},$$
$$\mathcal{B}(\Lambda_c^+ \to K^+K^-p\pi^0)_{\text{NR}} < 6.3 \times 10^{-5},$$

B. Pal et. al., PRD 96, 051102(R) (2017)

Search for hidden-strangeness pentaquark

- 2D fits (slide # 6) are performed in bins of $\mathrm{m}(\phi p)$ for the background-subtracted $\mathrm{m}(\phi p)$ distribution.
- The distribution is then fitted with a RBW for P_s^+ and a phase space contribution obtained from MC simulation.
- The data shows (**no**) clear evidence of a P_s^+ state



M = 2.025 ± 0.005 GeV
Γ = 0.022 ± 0.012 GeV

90% CL Upper limits on product branching fractions

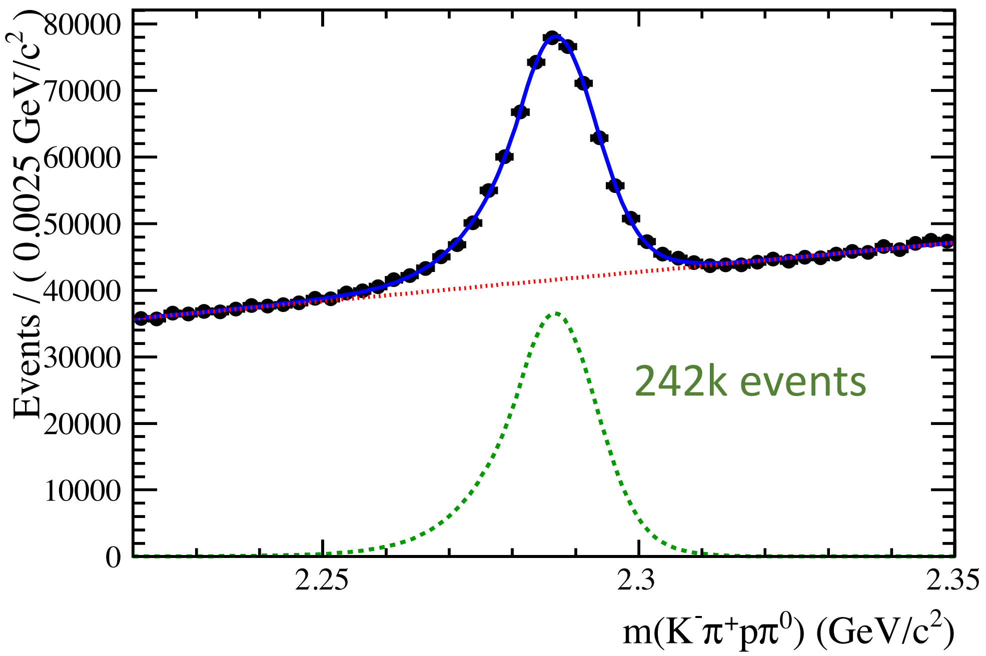
$$\mathcal{B}(\Lambda_c^+ \to P_s^+\pi^0) \times \mathcal{B}(P_s^+ \to \phi p) \ < \ 8.3 \times 10^{-5}$$

B. Pal et. al., PRD 96, 051102(R) (2017)

This limit is a factor of 6 higher than the product branching measured by LHCb for an analogous hidden-charm pentaquark states $P_c^+(4450)$ [$(1.3 \pm 0.4)\times10^{-5}$]

Branching fraction of $\Lambda_c^+ \to K^-\pi^+ p\pi^0$

- CF decay $\Lambda_c^+ \to K^-\pi^+ p\pi^0$ has the same final state topology and is used to adjust the MC-data differences in $\phi p\pi^0$ and $K^+K^- p\pi^0$ decays.



$$\frac{\mathcal{B}(\Lambda_c^+ \to K^-\pi^+ p\pi^0)}{\mathcal{B}(\Lambda_c^+ \to K^-\pi^+ p)} = (0.685 \pm 0.007 \pm 0.018)$$

Absolute branching fraction

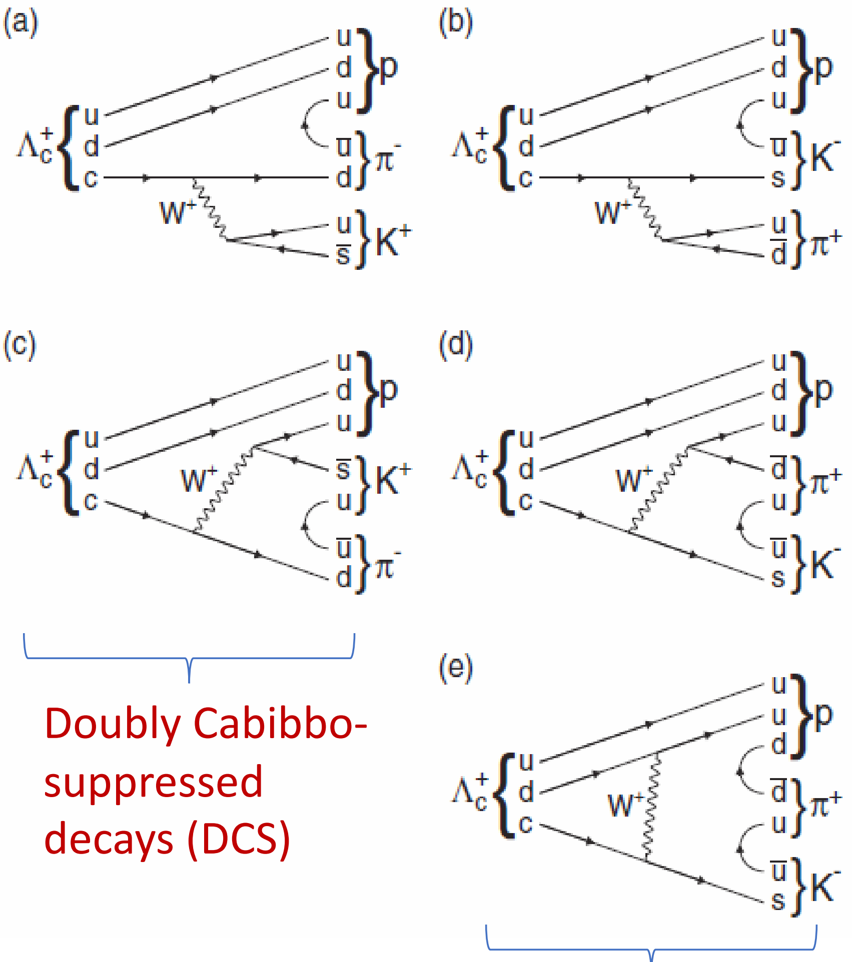
$$\mathcal{B}(\Lambda_c^+ \to K^-\pi^+ p\pi^0) = (4.42 \pm 0.05 \pm 0.12 \pm 0.16)\%,$$

B. Pal et. al., PRD 96, 051102(R) (2017)

This is the most precise measurement to date.

DCS $\Lambda_c^+ \longrightarrow pK^-\pi^+$ decays

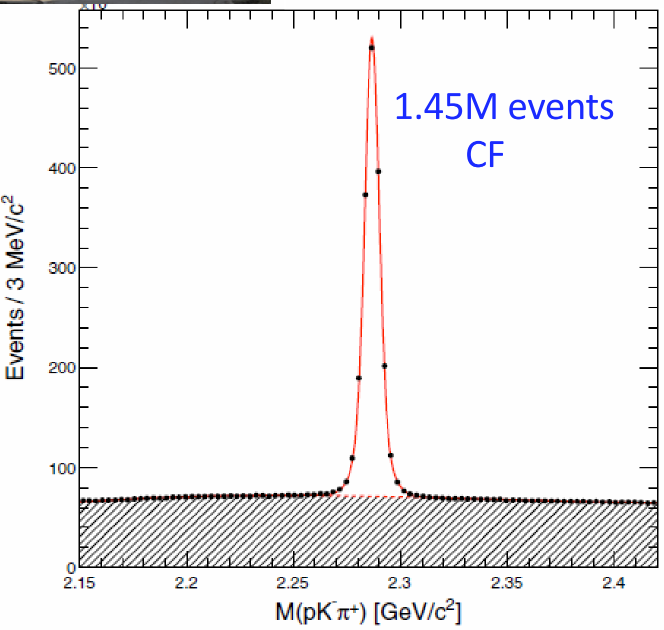
- Double Cabibbo-suppressed (DCS) decays seen in charm mesons, but not previously in baryons.
  - One trial so far: $\frac{\mathrm{B}(\Lambda_c^+\to pK^+\pi^-)}{\mathrm{B}(\Lambda_c^+\to pK^-\pi^+)} < 4.6\times 10^{-3}$ at 90% CL by FOCUS [PLB 624, 166 (2005)]
- Naïve expectation: $\frac{\mathrm{B}(\boldsymbol{DCS})}{\mathrm{B}(\boldsymbol{CF})} = tan^4\theta_c =$ 0.285%
- Since W-exchange diagram is absent in DCS decay, $\frac{\mathcal{B}(DCS)}{\mathcal{B}(CF)}$ may be smaller than the naïve expectation.
- This analysis uses the entire Belle Data.

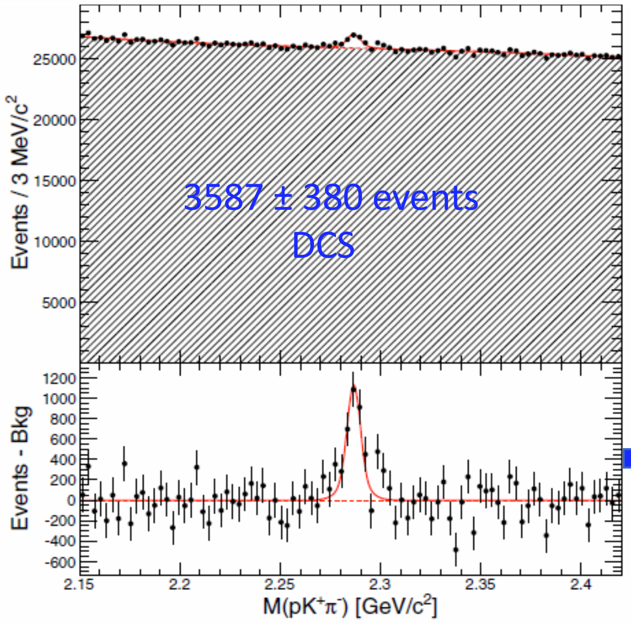


Doubly Cabibbo-suppressed decays (DCS)

Cabibbo-favored decays

DCS $\Lambda_c^+ \longrightarrow pK^-\pi^+$ decays





Residuals of the data with respect to fitted the combinatorial background

- $\Lambda_c^+ \to \Lambda(\to p\pi^-)K^+$ is a singly Cabibbo-suppressed (SCS) decay having the same final state as the DCS decays.
- Most of the SCS decays are suppressed by vertex cut. We estimate the contamination of the remaining SCS decays using $\frac{N(SCS)}{N(CF)} = \frac{\varepsilon(SCS)}{\varepsilon(CF)} \times \frac{B(SCS)}{B(CF)}$
- After subtraction, we observed 3379 ± 380 ± 78 DCS events with a significance > 9σ.

$$\frac{\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = (2.35 \pm 0.27 \pm 0.21)\times 10^{-3}$$
$$= (0.82 \pm 0.12)\, tan^4\, \theta_c$$

(consistent within 1.5σ with the naïve expectation)

After subtracting the contribution $\Lambda^*(1520)$ and Δ isobar intermediates, which only contribute to CF decay, the revised ratio

$$\frac{\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = (1.10 \pm 0.17)\, tan^4\, \theta_c$$

compatible with naïve expectation (within 1.0σ): no large W-exchange contribution in CF decay.

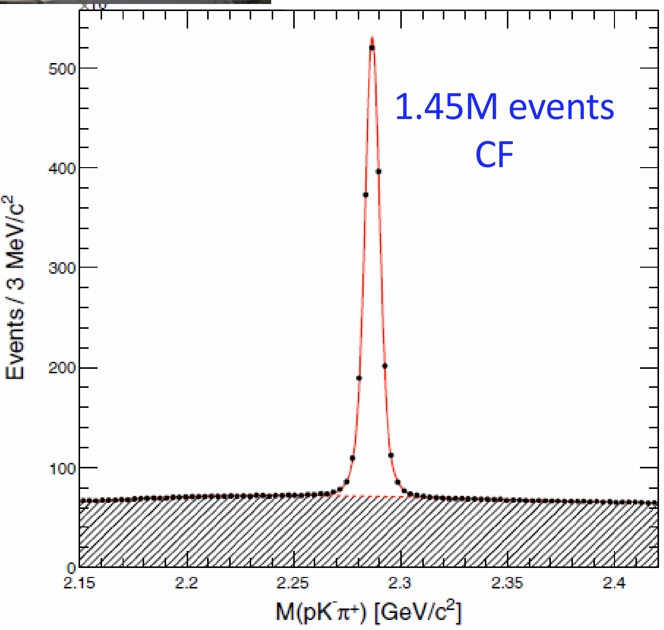
Absolute branching fraction

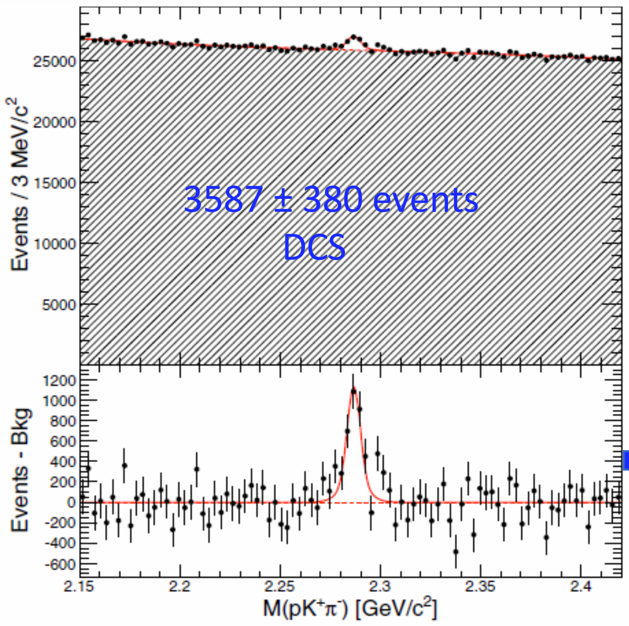
$$\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-) = (1.61 \pm 0.23^{+0.07}_{-0.08})\times 10^{-4}$$

1st Observati on

S.B. Yang et. al., PRL 117, 011801 (2016)

DCS $\Lambda_c^+ \longrightarrow pK^-\pi^+$ decays





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1st Observation

S.B. Yang et. al., PRL 117, 011801 (2016)

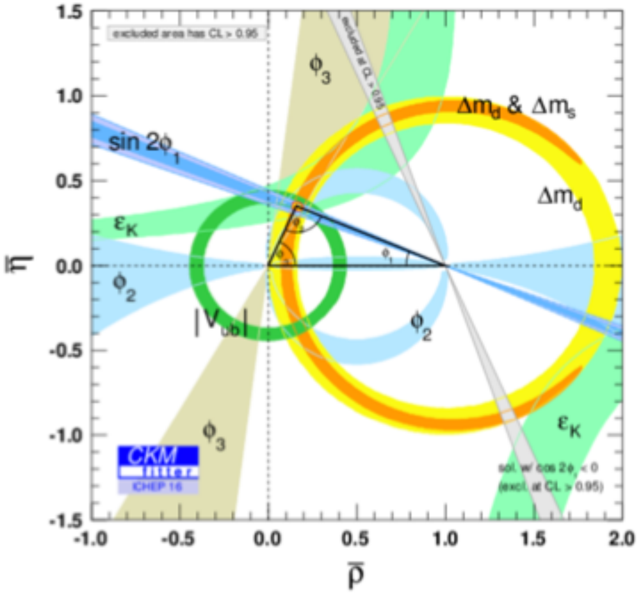
LHCb recently measured the ratio:

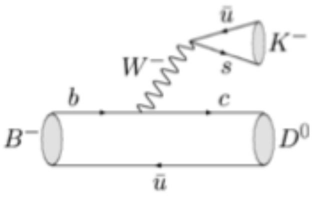
$$\frac{\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = (1.65 \pm 0.15 \pm 0.05)\times 10^{-3},$$

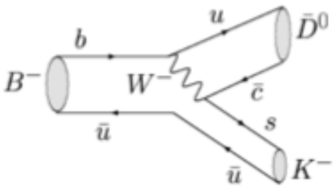
The ratio is 2.0σ lower than that of Belle.

arXiv:1711.01157[hep-ex]

ϕ_3/γ from $B^{\pm} \to DK^{\pm}, D \to K_S^0\pi^+\pi^-$







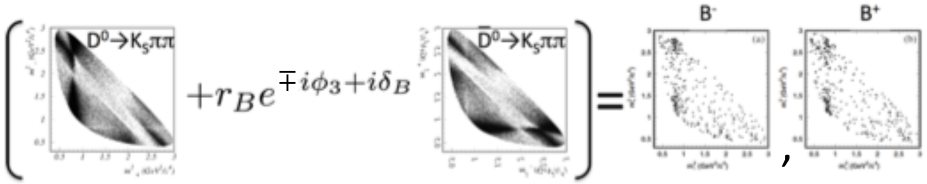
- $\phi_3 \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$
- Currently least constrained CKM angle
- Best theoretically clean way of measuring ϕ_3 is based on the interferences between $b \to \bar{u}cs$ and $b \to u\bar{c}s$ tree level amplitudes. [This is the only CKM angle accessible at tree level.]
- Useful processes are: $B^{\pm} \to D^{(*)}K^{\pm}$ followed by $D \to f$ and $B^{\pm} \to \overline{D^{(*)}}K^{\pm}$ followed by $\overline{D} \to f$, where f is a common final state
- Currently ϕ_3 precision is limited by small branching fractions ~ $\mathcal{O}(10^{-7})$

ϕ_3/γ Extraction methods:

- **GLW** – D meson is reconstructed from CP eigenstate, e.g., $K^+K^-, \pi^+\pi^-, K_S^0\pi^0$ etc. [Gronau & London, PLB 253, 483 (1991); Gronau & Wyler, PLB 265. 172 (1991)]
- **ADS** – DCS D decays involved, e.g., $K^+\pi^-$, $K^+\pi^-\pi^0$ etc. [Atwood, Dunietz & Soni, PRD 63, 036005 (2001)]
- **GGSZ** – For self-conjugate multibody D final states, e.g. $K_S^0\pi^+\pi^-$; involved Dalitz plot analysis of D decays. [Giri, Grossman, Soffer & Zupan, PRD 68, 054018 (2003), Bonder & Poluektov, EPJC 55, 51 (2008)]

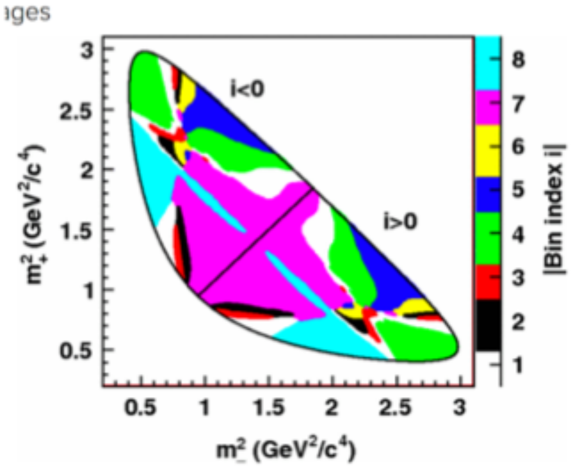
In this talk we present a measurement of ϕ_3 using GGSZ method.

ϕ_3/γ from $B^{\pm} \to DK^{\pm}, D \to K_S^0\pi^+\pi^-$



- r_B is the ratio of the absolute values of $DK^{\pm}$ and $\bar{D}K^{\pm}$ amplitudes and δ_B is the strong phase difference between them.
- In model-dependent approach, one performs the Dalitz plot fit to obtain the observables $x_{\pm} = r_B\cos(\pm\phi_3 + \delta_B)$ and $y_{\pm} = r_B\sin(\pm\phi_3 + \delta_B)$
- ϕ_3 (as well as r_B and δ_B) is then extracted from $x_{\pm}$ and $y_{\pm}$

- In model-independent approach, the Dalitz plot is divided into 2N bins
- The expected number of events in bin *i* is $N_i^{\pm} = h_B\left[K_{\pm i} + r_B^2 K_{\mp i} + 2\sqrt{K_i K_{-i}}(x_{\pm i}c_i \pm y_{\pm i}s_i)\right]$
  - h_B: normalization constant
  - K_i: number of events in ith bin of flavor tagged D decays
  - c_i and s_i: cosine and sine of the strong phase difference between $\bar{D}$ and D amplitudes in ith bin averaged over the bin region.

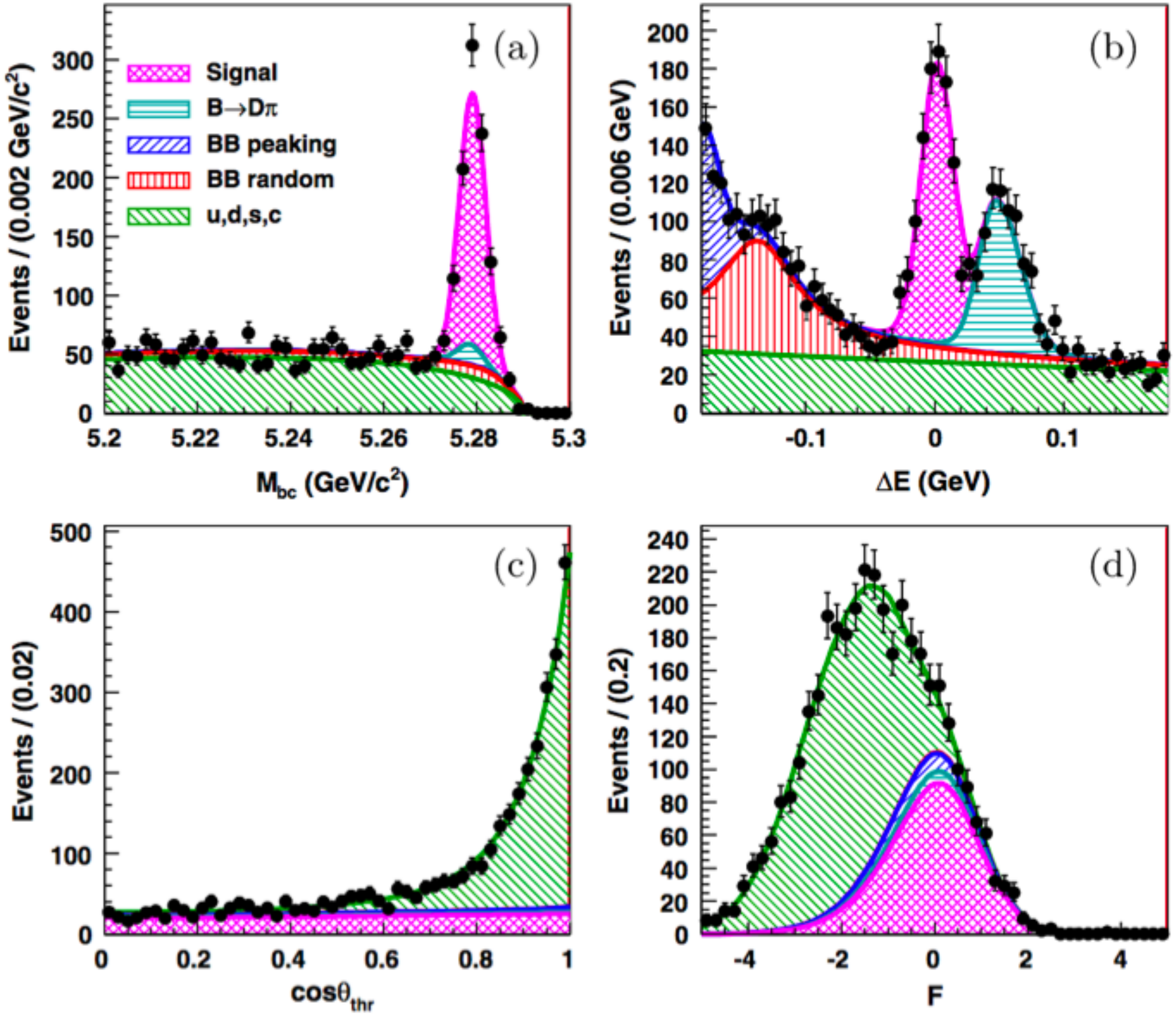


These are taken from CLEO measurement. [PRD 80, 032002 (2009); PRD 82, 112006 (2010)]

- A large systematic error due to Dalitz model enters the model-dependent approach
- In model-independent approach, this error is replaced by the error due to c_i and s_i, which in future can be reduced using BES-III measurement.

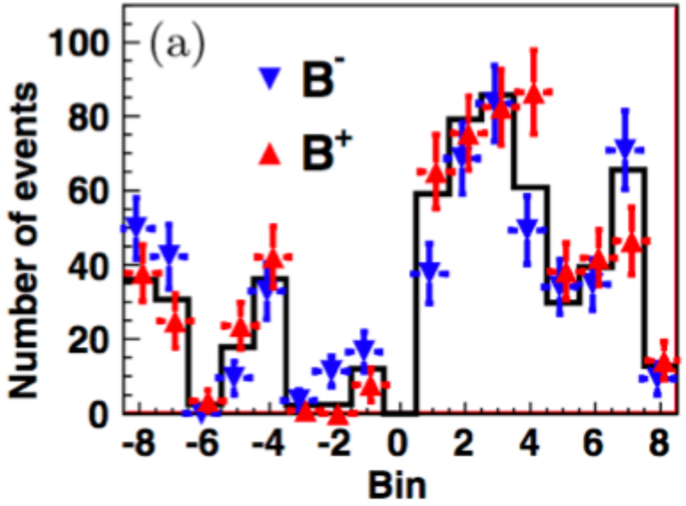
ϕ_3/γ from $B^{\pm} \to DK^{\pm}, D \to K_S^0\pi^+\pi^-$

- This analysis uses 711/fb of Υ(4S) data
- Four dimensional fit is performed to extract the signal yield
- θ_{thr} is the angle between the thrust axis of the B candidate daughters and that of the rest of the events
- F represent the Fisher discriminant: 9 events shape variables as input

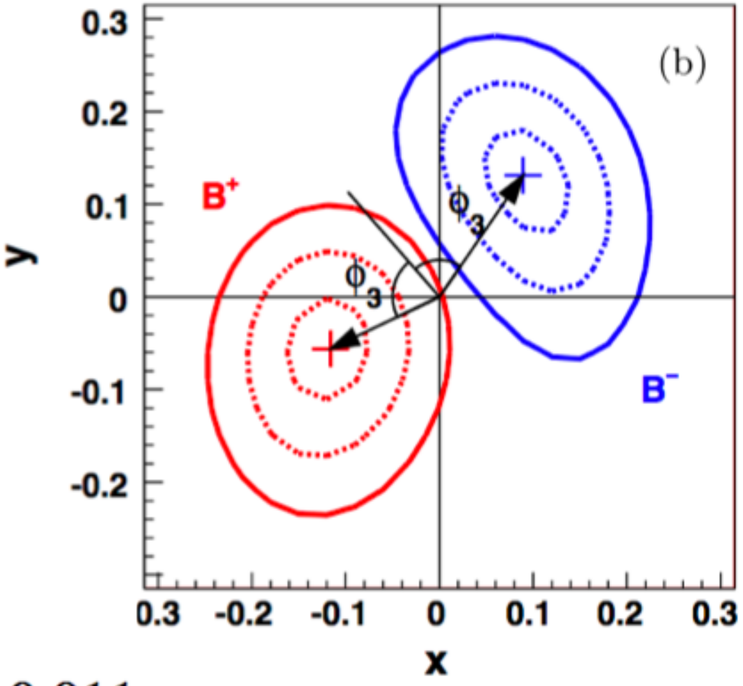


ϕ_3/γ from $B^\pm \to DK^\pm, D \to K_S^0\pi^+\pi^-$

Bin i	N_i^-	N_i^+
−8	49.8 ± 8.2	37.8 ± 7.5
−7	42.2 ± 8.6	24.9 ± 7.2
−6	0.0 ± 1.9	3.4 ± 2.9
−5	9.6 ± 4.5	23.6 ± 6.2
−4	32.9 ± 7.5	42.1 ± 8.3
−3	3.5 ± 2.8	0.7 ± 2.5
−2	11.3 ± 4.1	0.0 ± 1.3
−1	16.6 ± 5.4	7.7 ± 4.4
1	37.6 ± 8.0	65.1 ± 9.9
2	68.6 ± 9.6	75.5 ± 9.8
3	83.4 ± 10.1	82.4 ± 10.2
4	49.3 ± 9.1	86.5 ± 11.4
5	34.0 ± 7.3	38.3 ± 7.6
6	34.8 ± 6.8	41.9 ± 7.5
7	70.8 ± 10.6	46.4 ± 9.0
8	9.4 ± 4.3	14.2 ± 5.1
Total	574.9 ± 29.9	601.6 ± 30.8



Parameter	$B^\pm \to DK^\pm$
x_-	$+0.095 \pm 0.045 \pm 0.014 \pm 0.010$
y_-	$+0.137^{+0.053}_{-0.057} \pm 0.015 \pm 0.023$
$\mathrm{corr}(x_-, y_-)$	-0.315
x_+	$-0.110 \pm 0.043 \pm 0.014 \pm 0.007$
y_+	$-0.050^{+0.052}_{-0.055} \pm 0.011 \pm 0.017$
$\mathrm{corr}(x_+, y_+)$	$+0.059$



H. Aihara et. al., PRD 85, 112014(2012)

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

$$r_B = 0.145 \pm 0.030 \pm 0.010 \pm 0.011$$

$$\delta_B = (129.9 \pm 15.0 \pm 3.8 \pm 4.7)^\circ,$$

Third errors are due to c_i and s_i parameters. With the use of BES-III data, this for ϕ_3 will be decreased to 1° or less

LHCb's results of model-independent GGSZ approach

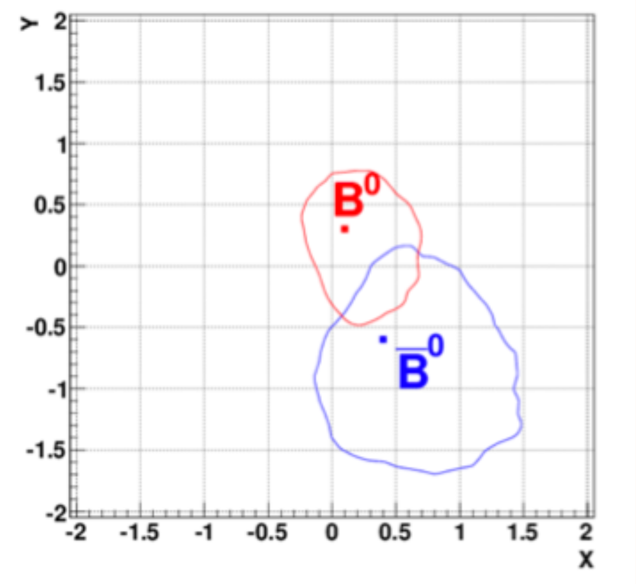
$$\phi_3 = (62^{+15}_{-14})^\circ$$

JHEP 10, 097 (2014)

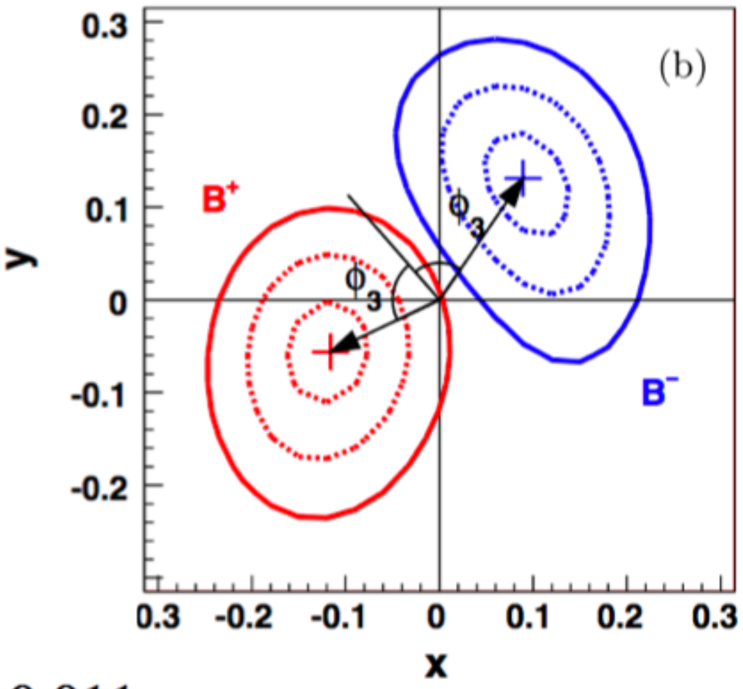
ϕ_3/γ from $B^\pm \to DK^\pm, D \to K_S^0\pi^+\pi^-$

The decay $B^0 \to D(\to K_S^0\pi^+\pi^-)K^{*0}$ is also useful for this purpose. Belle recently perform a model-independent Dalitz plot analysis using this decay mode. [PTEP 043C01 (2016)]

$$x_- = +0.4^{+1.0+0.0}_{-0.6-0.1} \pm 0.0,$$
$$y_- = -0.6^{+0.8+0.1}_{-1.0-0.0} \pm 0.1,$$
$$x_+ = +0.1^{+0.7+0.0}_{-0.4-0.1} \pm 0.1,$$
$$y_+ = +0.3^{+0.5+0.0}_{-0.8-0.1} \pm 0.1,$$
$$r_S < 0.87 \quad \text{at 68\% C.L.},$$



Parameter	$B^\pm \to DK^\pm$
x_-	$+0.095 \pm 0.045 \pm 0.014 \pm 0.010$
y_-	$+0.137^{+0.053}_{-0.057} \pm 0.015 \pm 0.023$
corr(x_-, y_-)	-0.315
x_+	$-0.110 \pm 0.043 \pm 0.014 \pm 0.007$
y_+	$-0.050^{+0.052}_{-0.055} \pm 0.011 \pm 0.017$
corr(x_+, y_+)	$+0.059$



H. Aihara et. al., PRD 85, 112014(2012)

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

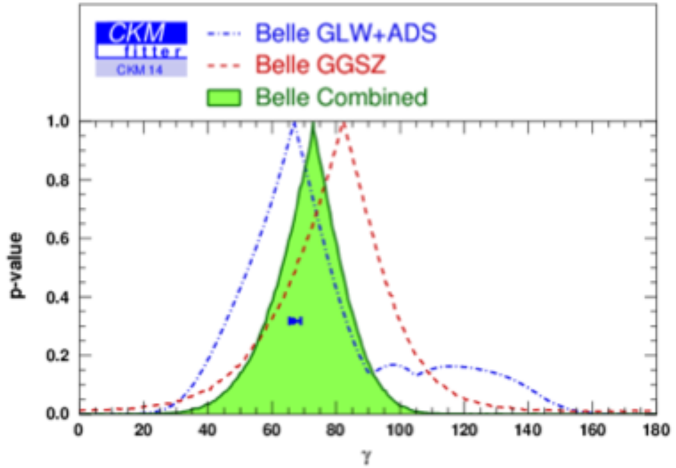
Third errors are due to c_i and s_i parameters. With the use of BES-III data, this for ϕ_3 will be decreased to 1° or less

LHCb's results of model-independent GGSZ approach

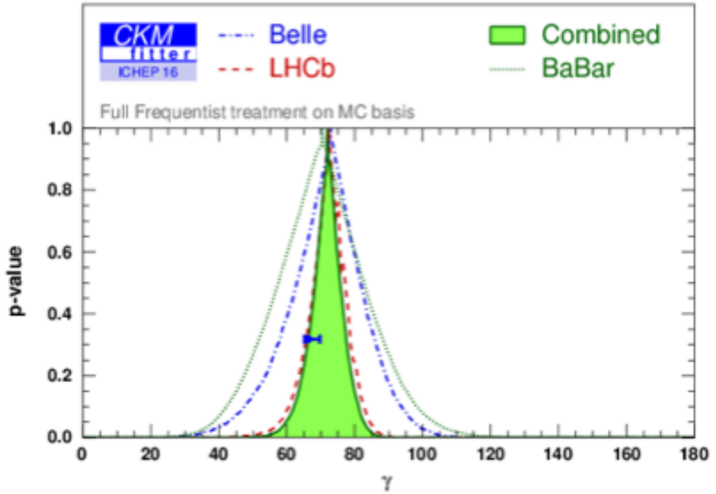
$$\phi_3 = \left(62^{+15}_{-14}\right)^\circ$$

JHEP 10, 097 (2014)

ϕ_3/γ from $B^\pm \to DK^\pm, D \to K_S^0\pi^+\pi^-$

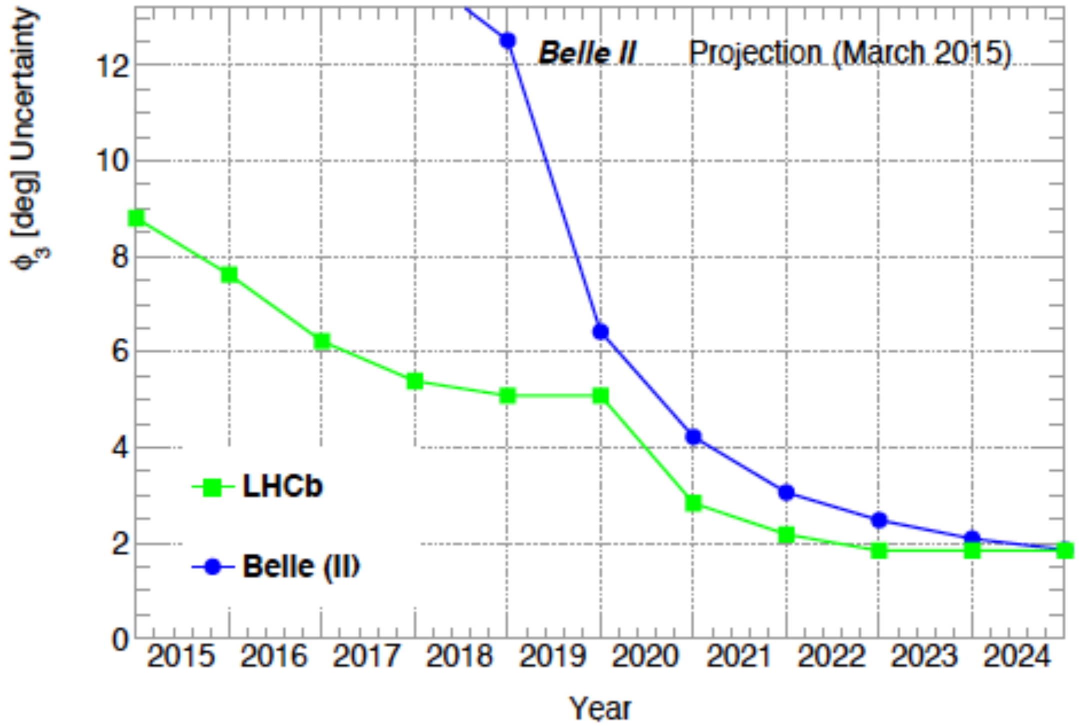


$\phi_3 = (73^{+13}_{-15})^\circ$



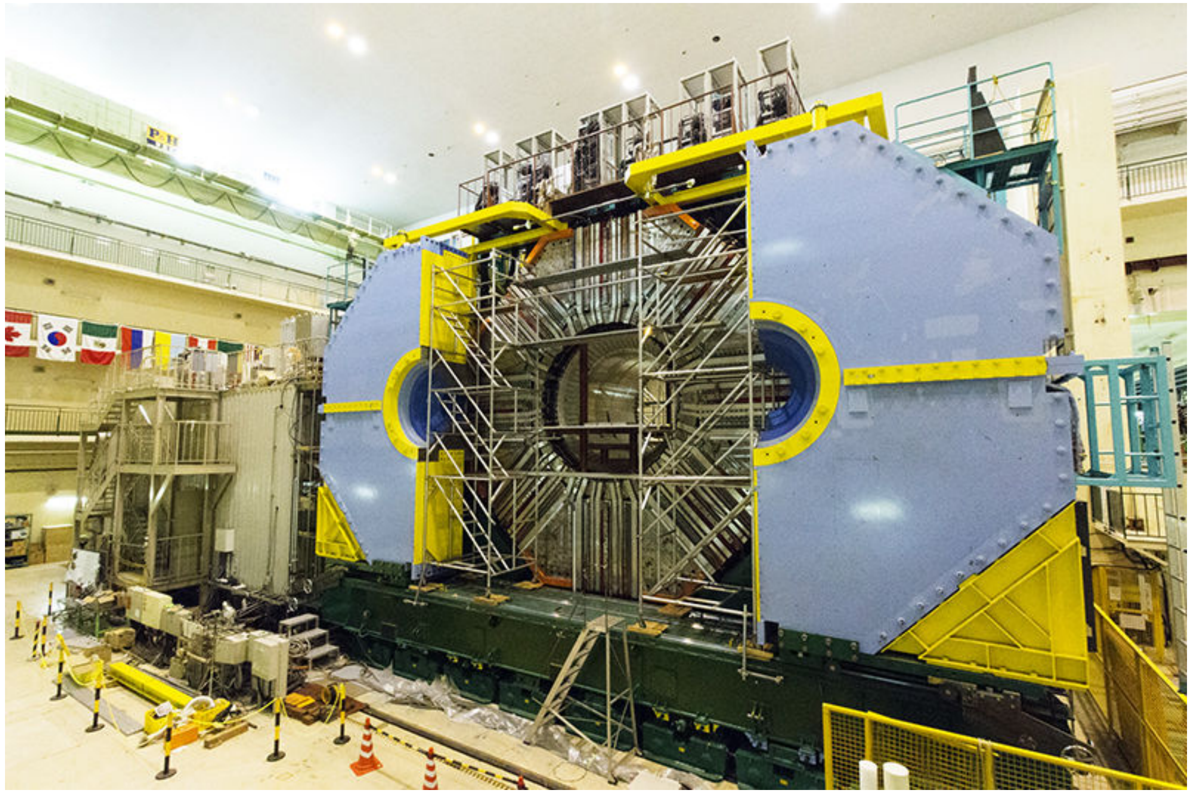
$\phi_3 = (72.2^{+5.3}_{-5.8})^\circ$

ϕ_3 constraint improved much in recent years. LHCb taking more data and exploring new modes. Belle II will start soon to be competitive within few years. Ultimate precision will be a degree in 2025-2029!



Summary

- We have presented some recent results from Belle experiment which involved the interaction of pion and kaon.
- After many years of its shut down, Belle is still producing exciting results
- Belle II is scheduled to start soon and we expect many more interesting/important results in near future!



STAY TUNED...