First measurements of the ϕ_3-sensitive decay $B^{\pm} \to D(K_S^0\pi^+\pi^-\pi^0)K^{\pm}$ with Belle

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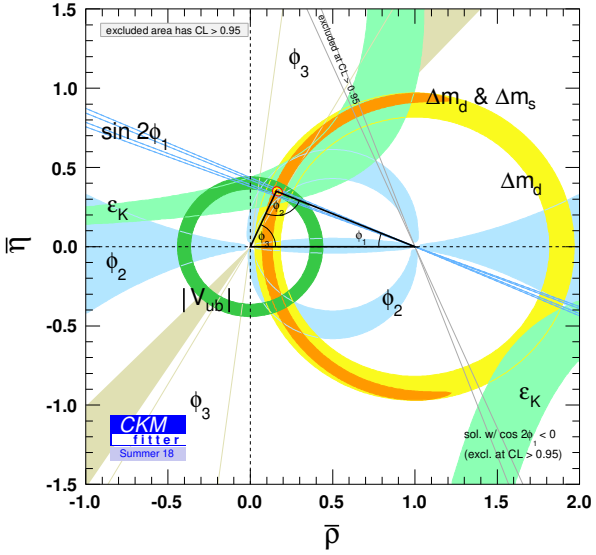
Outline

- Introduction
- $B^{\pm} \to D(K_S^0\pi^+\pi^-\pi^0)K^{\pm}/\pi^{\pm}$ decays at Belle
- Determination of K_i and $\bar{K}_i$ from D^* tagged D decays
- Measurement of ϕ_3-sensitive parameters $x_{\pm}$ and $y_{\pm}$
- Estimation of ϕ_3, r_B, and δ_B
- Summary

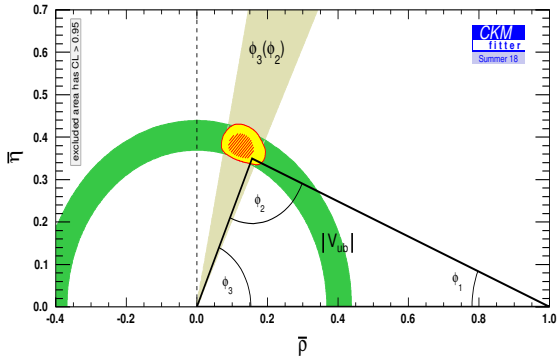
CKM angles - current status



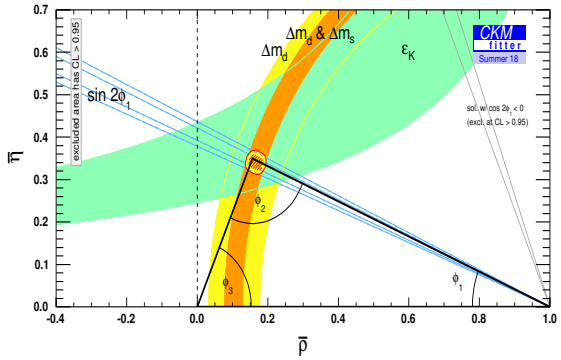
Constraints on CKM parameters [1].

Current best results for CKM angles [2]

- $\phi_1^{\text{measured}} = (22.2^{+0.7}_{-0.7})^\circ$
- $\phi_3^{\text{measured}} = (73.5^{+4.2}_{-5.1})^\circ$
- $\phi_3^{\text{predicted}} = (65.8^{+1.0}_{-1.7})^\circ$ [1]



Constraints from tree quantities.



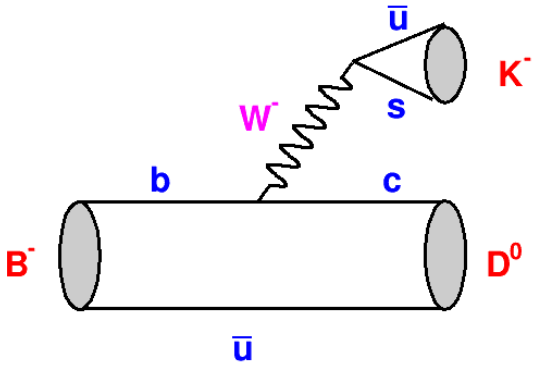
Constraints from loop quantities.

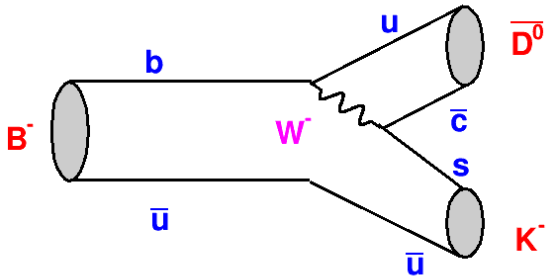
[1] http://ckmfitter.in2p3.fr

[2] http://www.slac.stanford.edu/xorg/hflav/triangle/moriond2018/index.shtml

ϕ_3 measurements from $B^\pm \to DK^\pm$ decays

- ϕ_3 from the interference between $B^- \to D^0 K^-$ and $B^- \to \bar{D}^0 K^-$, tree-level diagrams $\Rightarrow 10^{-7}$ theoretical uncertainty [3]





colour allowed $B^- \to D^0 K^- \approx V_{cb} V_{us}^*$ $\mathbf{A_1}$

colour suppressed $B^- \to \bar{D}^0 K^- \approx V_{ub} V_{cs}^*$ $\mathbf{A_1 r_B e^{i(\delta_B - \phi_3)}}$

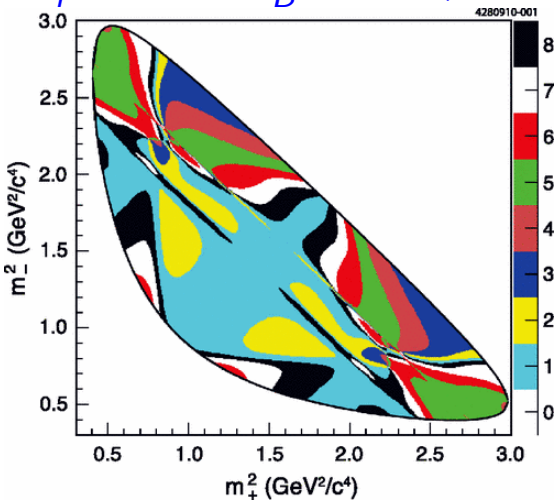
- Statistically limited due to small branching fractions of decays involved
- The statistical uncertainty on $\phi_3 \propto 1/r_B$
- $r_B^{DK} \approx 0.1$ and $r_B^{D\pi} \approx 0.005$; $B^\pm \to D\pi^\pm$ decays are not very sensitive!
- But they serve as good calibration modes due to similar topology and sample $\left(\frac{\mathcal{B}(B^\pm \to D\pi^\pm)}{\mathcal{B}(B^\pm \to DK^\pm)} \approx 10\right)$

[3] J. Brod, J. Zupan, JHEP **01**, 051 (2014)

Model-independent determination

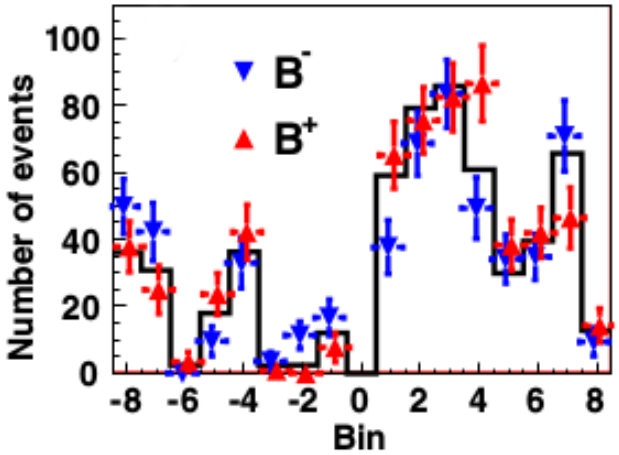
- Binned Dalitz plot analysis of multibody D final states like $K^0_S\pi^+\pi^-$, $K^0_S K^+K^-$, $K^0_S\pi^+\pi^-\pi^0$[4]
- For the B^- decay, the signal yield in each bin is represented as

  $\Gamma_i^- = K_i + r_B^2\bar{K}_i + 2\sqrt{K_i\bar{K}_i}(c_i x_- + s_i y_-)$, and similarly for the B^+ decay



Dalitz plot binning for $K^0_S\pi^+\pi^-$.

PRD**82**, 112006(2010)



B^+ and B^- yields for D final state $K^0_S\pi^+\pi^-$ at Belle.

PRD**85**, 112014(2012)

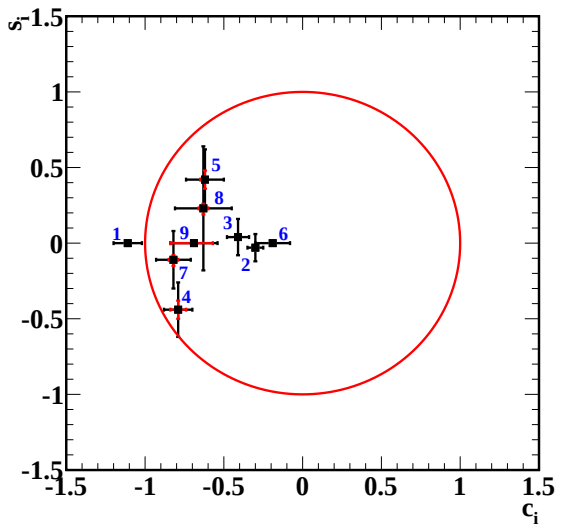
- $\mathbf{x}_\pm = r_B\cos(\delta_B \pm \phi_3)$; $\mathbf{y}_\pm = r_B\sin(\delta_B \pm \phi_3)$.
- $\mathbf{c_i}$, $\mathbf{s_i}$ - cosine and sine of the strong phase difference between D^0 and $\bar{D}^0$ averaged over the ith region of phase space (bin) $\Rightarrow$ input from CLEO-c or BESIII
- $\mathbf{K_i}$ and $\mathbf{\bar{K}_i}$ - fraction of flavour-tagged D events $\Rightarrow$ from $D^{*\pm} \to D\pi^\pm$ decays.

[4] A. Giri, Yu. Grossman, A. Soffer and J. Zupan, PRD **68**, 054018 (2003)

$D \to K_S^0\pi^+\pi^-\pi^0$ decays

- The dominant mode in ϕ_3 measurements using model-independent formalism is $K_S^0\pi^+\pi^-$ owing to high sensitivity from ADS and GLW like regions in the Dalitz.
- The decay $D \to K_S^0\pi^+\pi^-\pi^0$ has a relatively large branching fraction of 5.2% [5] which is almost twice that of $D \to K_S^0\pi^+\pi^-$. 750k events in Belle dataset[6]
- Interesting resonance substructures.
  - $K_S^0\omega$ - *CP* eigenstate - GLW like.
  - $K^{*-}\pi^+\pi^0$ - Cabibbo-favored state - ADS like.

Bin	Bin region
1	$m(\pi^+\pi^-\pi^0) \approx m(\omega)$
2	$m(K_S^0\pi^-) \approx m(K^{*-})$ & $m(\pi^+\pi^0) \approx m(\rho^+)$
3	$m(K_S^0\pi^+) \approx m(K^{*+})$ & $m(\pi^-\pi^0) \approx m(\rho^-)$
4	$m(K_S^0\pi^-) \approx m(K^{*-})$
5	$m(K_S^0\pi^+) \approx m(K^{*+})$
6	$m(K_S^0\pi^0) \approx m(K^{*0})$
7	$m(\pi^+\pi^0) \approx m(\rho^+)$
8	$m(\pi^-\pi^0) \approx m(\rho^-)$
9	Remainder

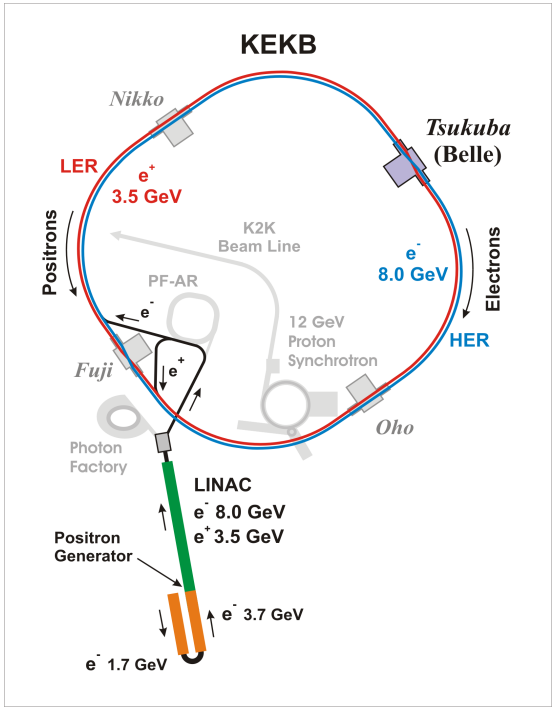


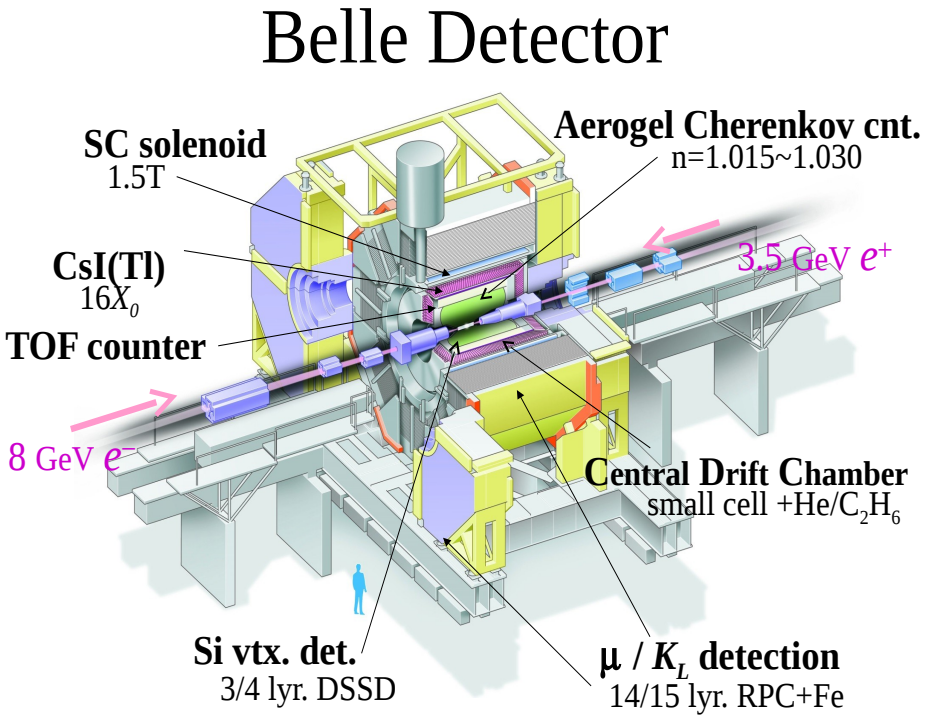
c_i and s_i results in 9 bins using CLEO-c data [7].

[5] M. Tanabashi *et al.* (PDG), PRD. **98**, 030001 (2018).
[6] K. Prasanth *et al.* (Belle Collaboration), PRD. **95**, 091101(R) (2017).
[7] P. K. Resmi, J. Libby, S. Malde, and G. Wilkinson, J. High Energ. Phys. **01**, 82 (2018).

KEKB and Belle

- KEKB is an asymmetric e^+e^- collider with 8.0 GeV e^- and 3.5 GeV e^+.





- Belle detector comprises of tracking systems, particle identification (PID) detectors and electromagnetic calorimeter (ECL).
- 772×10^6 $B\bar{B}$ pairs produced from collisions at $\Upsilon(4S)$ resonance $\Rightarrow$ 711 fb^{-1} data during 1999–2010.

$B^{\pm} \to D(K^0_S\pi^+\pi^-\pi^0)K^{\pm}/\pi^{\pm}$ decays at Belle

- Events are selected with
  - track quality criteria
  - K/π separation using PID info
  - $|M_i - M_{\rm PDG}| < 3\sigma$; $i = D, K^0_S, \pi^0$

$$M_{bc} = c^{-2}\sqrt{E^{*2}_{beam} - |\vec{p^*_B}|^2 c^2}$$

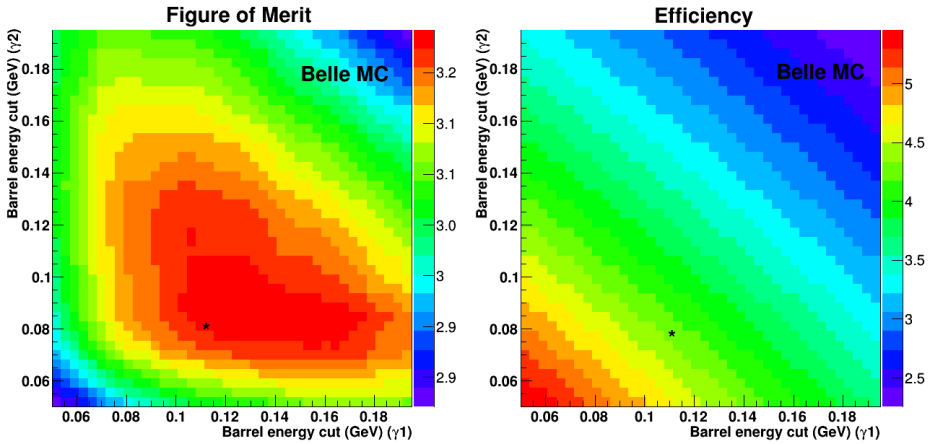
$$\Delta E = E^*_B - E^*_{beam}$$

- $M_{\rm bc} > 5.27$ GeV$/c^2$
- $-0.13 < \Delta E < 0.3$ GeV

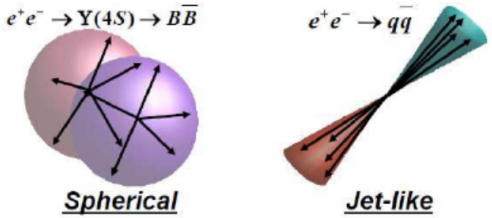
- Misreconstructed π^0 causes more random combinations of final state particles.
- Optimised selection of E_γ done by looking at the position of γ in ECL and good π^0 candidates are chosen.

γ_1	γ_2	$E_{\gamma 1}$ (MeV)	$E_{\gamma 2}$ (MeV)
Barrel	Barrel	70	65
FWD ec	Barrel	220	65
Barrel	BWD ec	65	95
FWD ec	FWD ec	150	210

FoM / Efficiency Vs E_γ threshold



Background studies

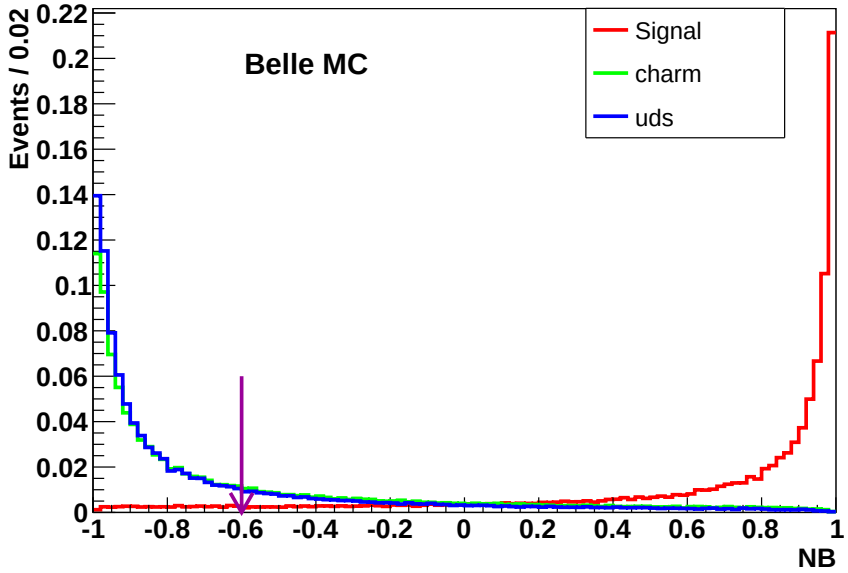


- 67% background reduction at the cost of 5% signal efficiency loss, with NB > -0.6 selection.

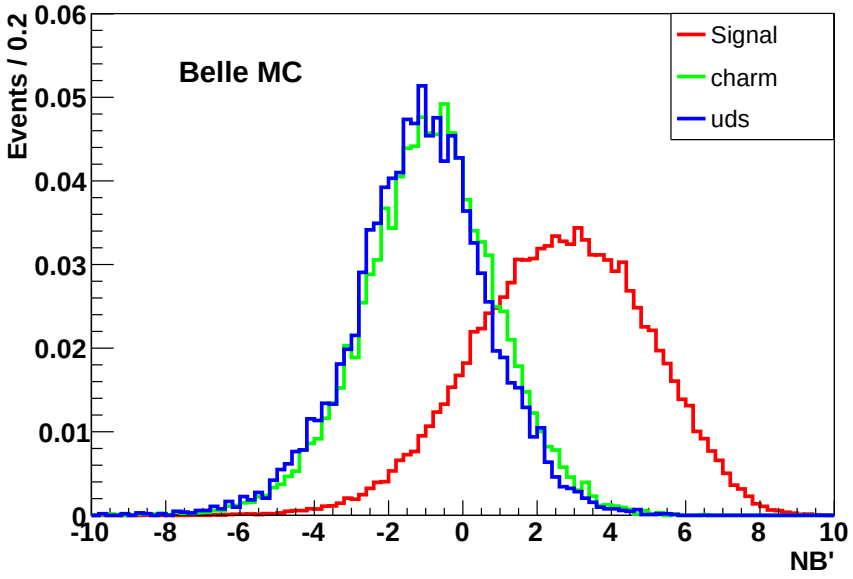
- Event shape variables and other discriminating variables including angular, vertex and flavour tag observables using a Neural Network (NN).
- Transformed NN output

$$NB' = \log\left(\frac{NB - (-0.6)}{0.9985 - NB}\right)$$

is a fit variable



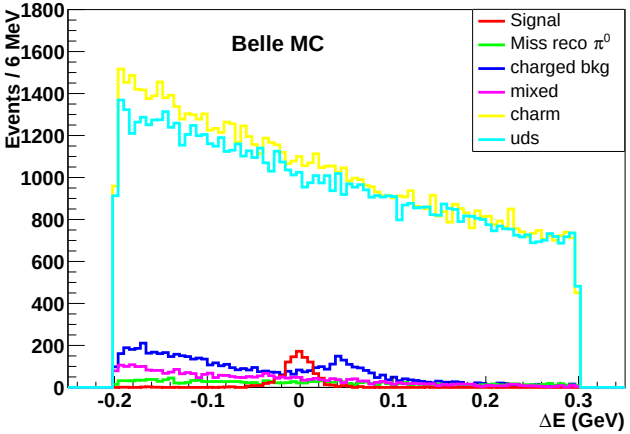
$\Rightarrow$



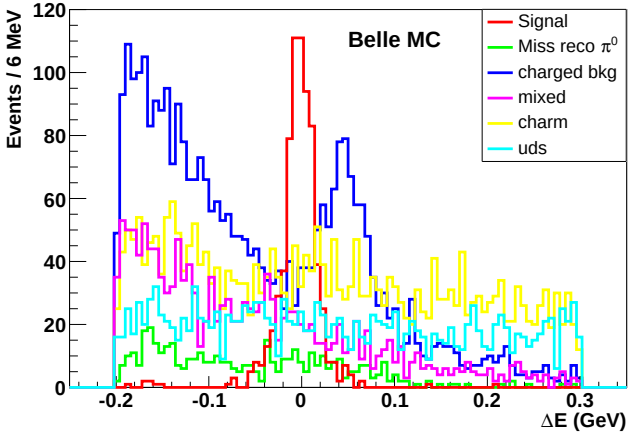
Effect of optimized selection

- The effect of optimized selection to reduce the backgrounds is illustrated in $B^{\pm} \to DK^{\pm}$ MC sample.

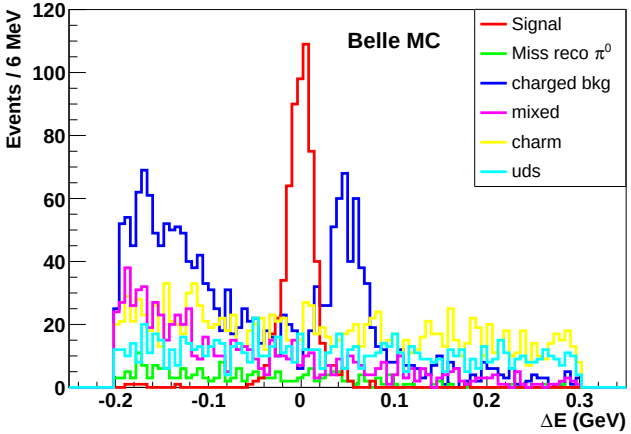
Before optimized selection



After optimizing $q\bar{q}$ background



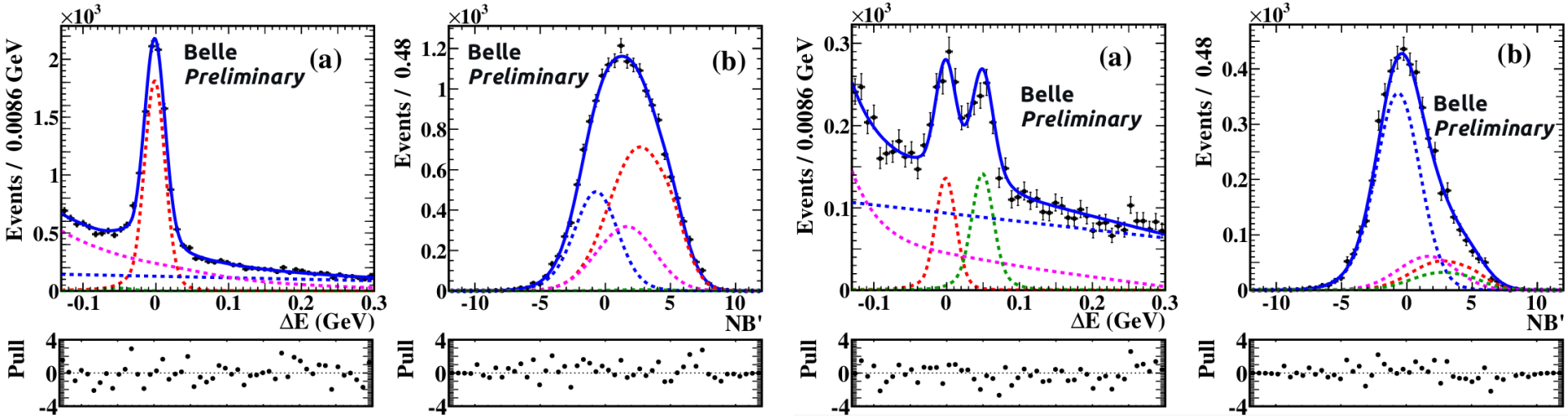
After optimizing $q\bar{q}$ and π^0 backgrounds



- This will be more crucial at Belle II with large statistics sample.

Signal extraction

- Extended maximum likelihood fit to the variables ΔE and NB' simultaneously to $B^{\pm} \to D\pi^{\pm}$ and $B^{\pm} \to DK^{\pm}$ samples.



$B^{\pm} \to D\pi^{\pm}$ data sample $\qquad$ $B^{\pm} \to DK^{\pm}$ data sample

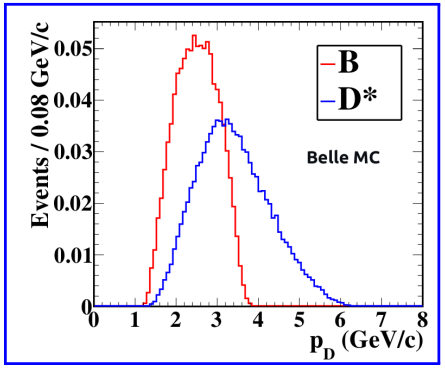
- Signal, $q\bar{q}$ bkg, $B\bar{B}$ bkg and $K-\pi$ cross-feed components are shown.
- Fitter shows no bias: verified with true yields in MC, more MC samples and pseudo experiments.
- Signal yields are shown in the table along with that of $D \to K^0_S\pi^+\pi^-$ mode[8].

	$B^{\pm} \to D\pi^{\pm}$	$B^{\pm} \to DK^{\pm}$
$D \to K^0_S\pi^+\pi^-\pi^0$	**9981 ± 134**	**815 ± 51**
$D \to K^0_S\pi^+\pi^-$	19106 ± 147	1176 ± 43

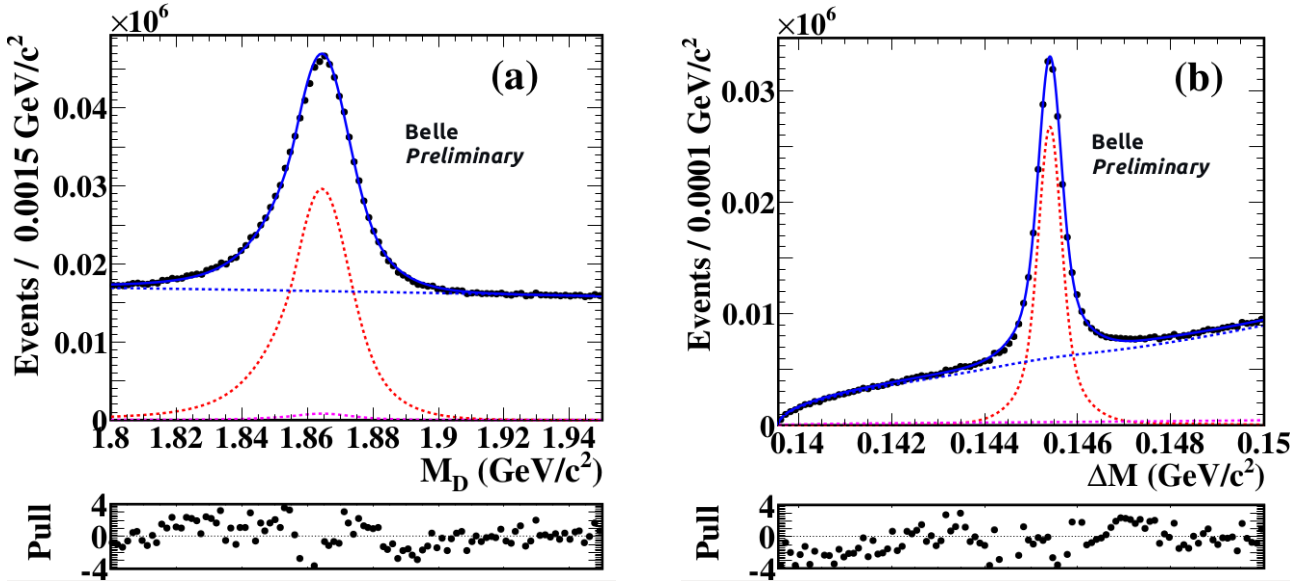
[8] PRD **85**, 112014 (2012)

Determination of K_i and $\bar{K}_i$

- $D^{*\pm} \to D(K^0_S\pi^+\pi^-\pi^0)\pi^\pm_{\rm slow}$ decays are used to extract the fraction of D^0 and $\bar{D}^0$ events in each bin, *i.e.* the K_i and $\bar{K}_i$ values.
- D selection is the same as in $B^\pm \to DK^\pm/\pi^\pm$ sample.
- $\Delta M < 0.15$ GeV$/c^2$; $\Delta M = M_{D^*} - M_D$
- $1 < p_D < 4$ GeV$/c$



- Extended maximum likelihood fit to the variables ΔM and M_D for signal extraction; signal yield in data is **614870 $\pm$ 2145**

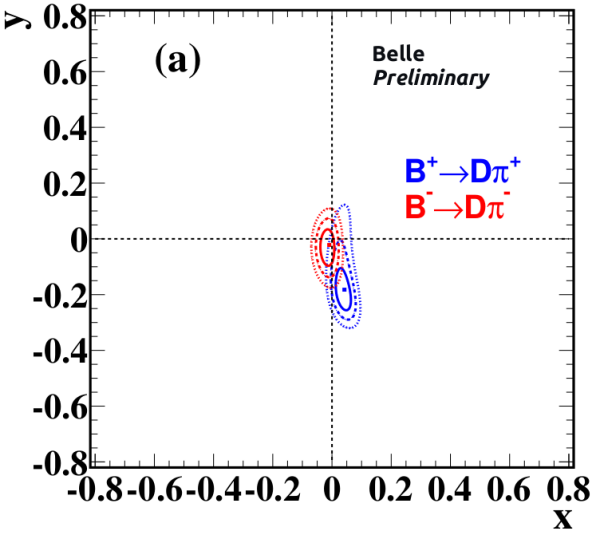


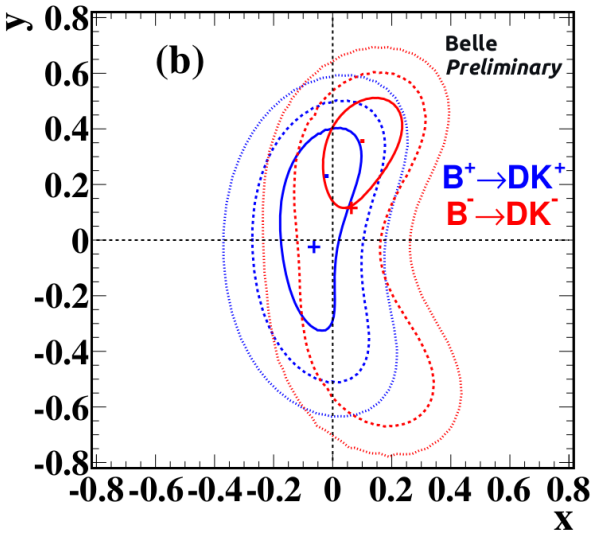
Measurement of $x_\pm$ and $y_\pm$

- $x_\pm$, $y_\pm$ parameters are directly extracted from the simultaneous fit.
- There can be migration of events between the bins due to finite momentum resolution. This is corrected for in the fit via a 9×9 migration matrix.
- Efficiency correction is applied to $D^{*\pm} \to D\pi^\pm$ and $B^\pm \to DK^\pm/\pi^\pm$ samples.

	$B^\pm \to D\pi^\pm$	$B^\pm \to DK^\pm$
x_+	$0.039 \pm 0.024\,^{+0.018}_{-0.013}\,^{+0.014}_{-0.012}$	$-0.030 \pm 0.121\,^{+0.017}_{-0.018}\,^{+0.019}_{-0.018}$
y_+	$-0.196\,^{+0.080}_{-0.059}\,^{+0.038}_{-0.034}\,^{+0.032}_{-0.030}$	$0.220\,^{+0.182}_{-0.541} \pm 0.032\,^{+0.072}_{-0.071}$
x_-	$-0.014 \pm 0.021\,^{+0.018}_{-0.010}\,^{+0.019}_{-0.010}$	$0.095 \pm 0.121\,^{+0.017}_{-0.016}\,^{+0.023}_{-0.025}$
y_-	$-0.033 \pm 0.059\,^{+0.018}_{-0.019}\,^{+0.019}_{-0.010}$	$0.354\,^{+0.144}_{-0.197}\,^{+0.015}_{-0.021}\,^{+0.032}_{-0.049}$

The uncertainties are statistical, systematic and due to c_i, s_i inputs, respectively.



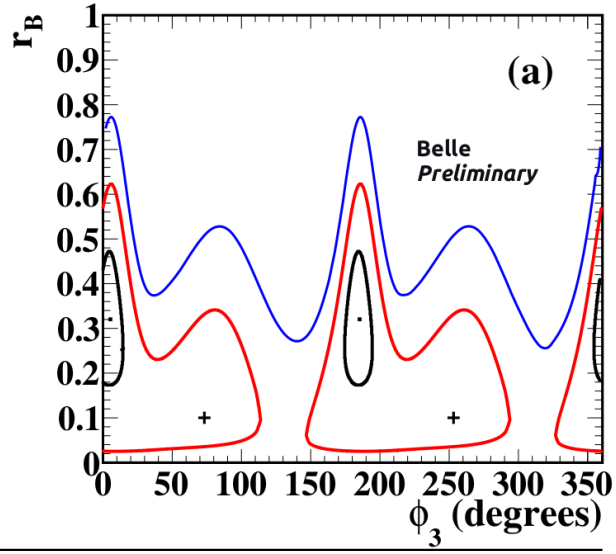


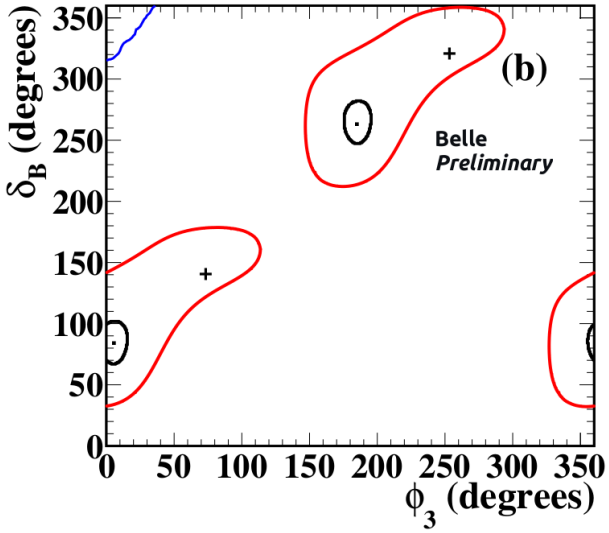
Determination of ϕ_3, r_B, and δ_B

- The physical parameters $\mu = (\phi_3, r_B, \delta_B)$ obtained from the measured parameters $z = (x_+, y_+, x_-, y_-)$ using the frequentist treatment with the Feldman-Cousins ordering[9].

Parameter	Results	2σ interval
ϕ_3 (°)	$5.7\ ^{+10.2}_{-8.8} \pm 3.5 \pm 5.7$	$(-29.7\ ,\ 109.5)$
δ_B (°)	$83.4\ ^{+18.3}_{-16.6} \pm 3.1 \pm 4.0$	$(35.7\ ,\ 175.0)$
r_B	$0.323 \pm 0.147 \pm 0.023 \pm 0.051$	$(0.031\ ,\ 0.616)$

- The current world-average values are $\phi_3 = (71.1^{+4.6}_{-5.3})^\circ$, $\delta_B = (129.6^{+5.0}_{-6.0})^\circ$ and $r_B = 0.099 \pm 0.005$ indicated by "+" in the Fig.



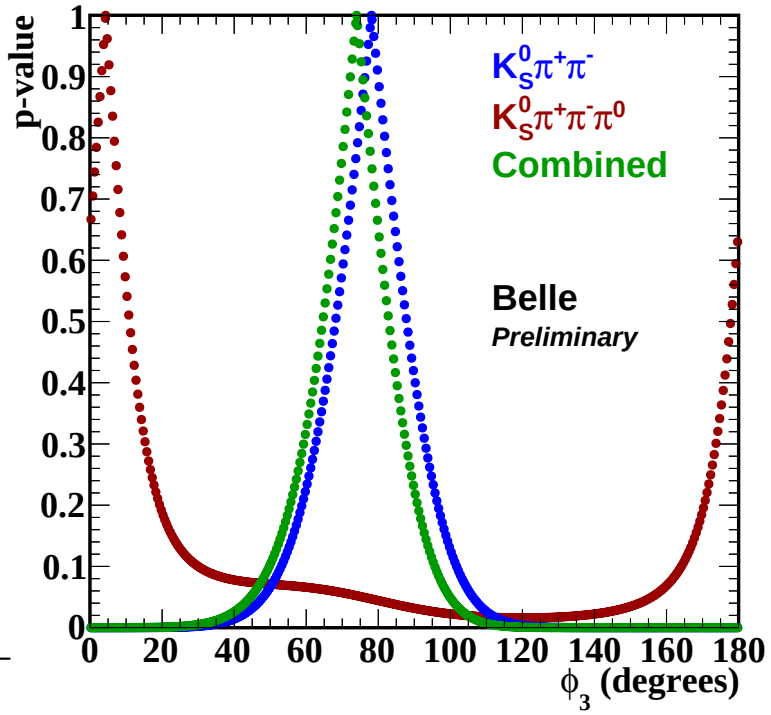


[9] G. J. Feldman and R. D. Cousins, PRD **57**, 3873 (1998)

Belle average

- The averages of the following ϕ_3 measurements performed at Belle
  - $B^{\pm} \to D(K^0_S\pi^+\pi^-)K^{\pm}$ model-independent[8]
  - $B^0 \to D(K^0_S\pi^+\pi^-)K^{*0}$ model-dependent[10]
  - $B^{\pm} \to D(K^0_S\pi^+\pi^-\pi^0)K^{\pm}$ model-independent this result

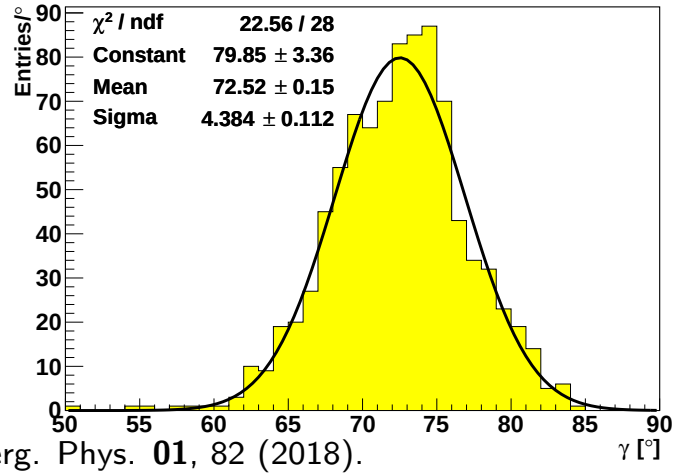
- ϕ_3 without this measurement = $(78^{+14}_{-15})^{\circ}$
- ϕ_3 including this measurement = $\mathbf{(74^{+13}_{-14})^{\circ}}$



[8] PRD **85**, 112014 (2012)
[10] PTEP **2016**, 043C01 (2016)

Summary

- Measuring the CKM angle ϕ_3 more precisely is important to further test the standard model description of CP violation.
- $D \to K_S^0\pi^+\pi^-\pi^0$ is a promising candidate to measure ϕ_3 due to larger branching fraction and resonance substructures.
- For the **first time**, $B^\pm \to D(K_S^0\pi^+\pi^-\pi^0)K^\pm$ decays are analysed at Belle.
- The ϕ_3 sensitive parameters $x_\pm$ and $y_\pm$ are measured in $B^\pm \to D(K_S^0\pi^+\pi^-\pi^0)K^\pm$ data sample.
- The physical parameter ϕ_3 is determined via frequentist method.
- The paper will soon be submitted to the journal!
- Estimates of ϕ_3 sensitivity with $B^\pm \to D(K_S^0\pi^+\pi^-\pi^0)K^\pm$ give $\sigma_{\phi_3} = \mathbf{4.4}^\circ$ with 50 ab^{-1} data from Belle II[7].



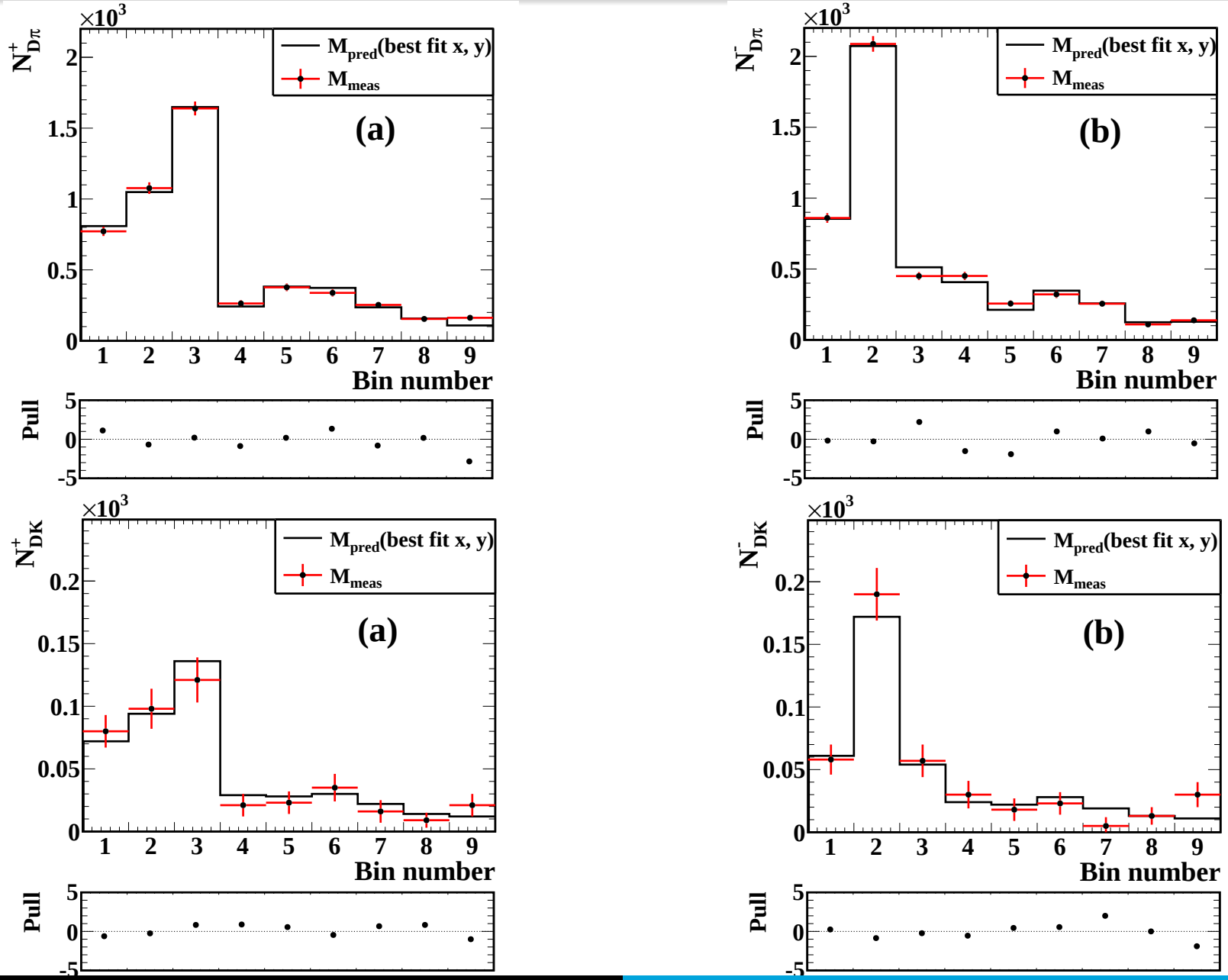
[7] P. K. Resmi, J. Libby, S. Malde, and G. Wilkinson, J. High Energ. Phys. **01**, 82 (2018).

Back-up slides

Systematic uncertainties

Source	$B^{\pm} \to D\pi^{\pm}$				$B^{\pm} \to DK^{\pm}$			
	x_+	y_+	x_-	y_-	x_+	y_+	x_-	y_-
Efficiency	$+0.013$	$+0.030$	$+0.012$	$+0.012$	$+0.012$	$+0.022$	$+0.012$	$+0.013$
uncertainty	-0.009	-0.027	-0.008	-0.013	-0.013	-0.023	-0.012	-0.016
Migration matrix	$+0.011$	$+0.021$	$+0.011$	$+0.013$	$+0.007$	$+0.015$	$+0.007$	$+0.006$
uncertainty	-0.004	-0.019	-0.003	-0.014	-0.008	-0.016	-0.007	-0.012
$m_{\pi\pi\pi^0}$ resolution	0.003	0.001	0.004	0.001	0.001	0.001	0.001	0.003
K_i, $\overline{K_i}$	$+0.004$	$+0.007$	$+0.004$	$+0.002$	$+0.001$	$+0.001$	$+0.002$	$+0.001$
uncertainty	-0.001	-0.006	-0.001	-0.002	-0.002	-0.001	-0.002	-0.001
PDF shape	$+0.004$	$+0.004$	$+0.004$	$+0.001$	$+0.009$	$+0.017$	$+0.009$	$+0.001$
	-0.008	-0.003	-0.004	-0.001	-0.008	-0.016	-0.007	-0.005
Fit bias	0.000	0.001	0.000	0.000	0.001	0.001	0.001	0.003
PID	0.001	0.001	0.001	0.000	0.002	0.001	0.002	0.001
Total systematic	$+0.018$	$+0.038$	$+0.018$	$+0.018$	$+0.017$	$+0.032$	$+0.017$	$+0.015$
uncertainty	-0.013	-0.034	-0.010	-0.019	-0.018	-0.032	-0.016	-0.021
c_i, s_i	$+0.014$	$+0.032$	$+0.010$	$+0.019$	$+0.019$	$+0.072$	$+0.023$	$+0.032$
uncertainty	-0.012	-0.030	-0.006	-0.010	-0.018	-0.071	-0.025	-0.049
Total statistical	$+0.024$	$+0.080$	$+0.021$	$+0.059$	$+0.121$	$+0.182$	$+0.121$	$+0.144$
uncertainty	-0.024	-0.059	-0.021	-0.059	-0.121	-0.541	-0.121	-0.197

Measured and expected bin yields



Migration matrix

Bin no.	1	2	3	4	5	6	7	8	9
1	0.93	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.01
2	0.01	0.96	0.02	0.00	0.00	0.00	0.00	0.00	0.00
3	0.01	0.02	0.95	0.00	0.00	0.00	0.00	0.00	0.00
4	0.04	0.03	0.02	0.90	0.00	0.00	0.00	0.00	0.01
5	0.04	0.01	0.03	0.01	0.91	0.01	0.00	0.00	0.01
6	0.02	0.02	0.01	0.01	0.01	0.92	0.01	0.00	0.00
7	0.01	0.03	0.02	0.00	0.01	0.02	0.91	0.00	0.01
8	0.01	0.02	0.02	0.01	0.00	0.01	0.01	0.88	0.02
9	0.06	0.02	0.02	0.01	0.01	0.01	0.01	0.00	0.86

Table : Migration matrix for $B^+ \to DK^+$ decays estimated from signal MC sample. The rows correspond to the true bins and columns show the reconstructed bins.

Migration matrix

Bin no.	1	2	3	4	5	6	7	8	9
1	0.93	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.01
2	0.01	0.96	0.01	0.00	0.00	0.00	0.00	0.00	0.00
3	0.01	0.02	0.95	0.01	0.00	0.01	0.00	0.00	0.00
4	0.03	0.02	0.02	0.92	0.00	0.01	0.00	0.00	0.00
5	0.03	0.02	0.02	0.01	0.91	0.01	0.00	0.00	0.01
6	0.03	0.02	0.01	0.01	0.00	0.93	0.00	0.01	0.00
7	0.01	0.03	0.01	0.00	0.00	0.01	0.92	0.00	0.01
8	0.00	0.01	0.03	0.00	0.01	0.01	0.01	0.92	0.01
9	0.05	0.01	0.01	0.01	0.00	0.02	0.01	0.01	0.88

Table : Migration matrix for $B^+ \to D\pi^+$ decays estimated from signal MC sample. The rows correspond to the true bins and columns show the reconstructed bins.