# Latest results on $B \to DK/D\pi$ decays from Belle

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# Outline

- Introduction
- Belle results
  - $B \to D(K_S\pi^+\pi^-)K$
  - $B \to D^{*0}K$ GLW and ADS
  - $B \to D(K^+\pi^-\pi^0)K$
  - $B^0 \to D^0(K\pi)K^{*0}$
  - $B^0 \to D^0(K_S\pi^+\pi^-)K^{*0}$
  - $B \to D(K_S\pi^+\pi^-\pi^0)K$
  - $B \to D^*\rho$
- Rediscoveries from Belle II data
- Summary

sensitivity studies only

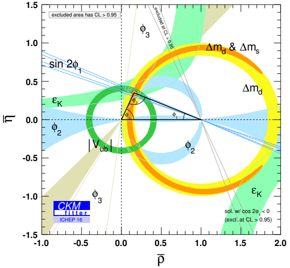



Figure : Constraints on CKM parameters [1].

## Current best results for CKM angles [2]

- $\phi_1^{measured} = (21.9^{+0.7}_{-0.7})^\circ$
- $\phi_3^{measured} = (73.5^{+4.2}_{-5.1})^\circ$
- $\phi_3^{predicted} = (65.3^{+1.0}_{-2.5})^\circ$

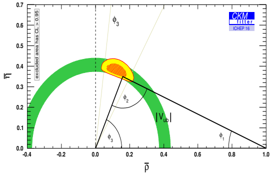



Figure : Constraints from tree quantities.

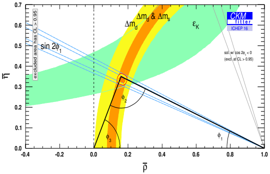


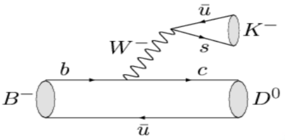

Figure : Constraints from loop quantities.

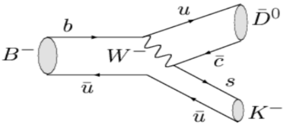
1 http://ckmfitter.in2p3.fr

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

# $\phi_3$ measurements from $B \to DK$ decays

- Determine $\phi_3$ via 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**

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

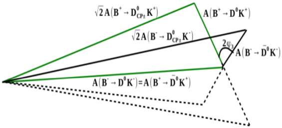
$\mathbf{A_1 r_B e^{i(\delta_B - \phi_3)}}$

- The only $CP$-violating parameter that can be measured solely in tree-level processes.
- The results are statistically limited due to small branching fractions of decays involved.

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

# $\phi_3$ measurements : GLW method [4]

- Both $D^0$ and $\bar{D}^0$ decay to the same $CP$-eigenstate.
  - $CP$-even: $D_1 = K^+K^-,\ \pi^+\pi^-$
  - $CP$-odd: $D_2 = K_S^0\pi^0,\ K_S^0\omega,\ K_S^0\eta$




- The charge-averaged rate

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

- The partial-rate asymmetry

$$A_{CP} = \frac{\mathcal{B}(B^- \to D_{1,2}K^-) - \mathcal{B}(B^+ \to D_{1,2}K^+)}{\mathcal{B}(B^- \to D_{1,2}K^-) + \mathcal{B}(B^+ \to D_{1,2}K^+)} = \frac{\pm 2r_B \sin\delta_B \sin\phi_3}{R_{CP}}$$

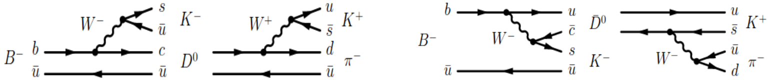
- For a multibody $D$ decay, $CP$ content $F_+$ needs to be considered; a dilution factor of $(2F_+ - 1)$ on the asymmetry parameters [5].

[4] M. Gronau and D. London, PLB **253**, 483 (1991); M. Gronau and D. Wyler, PLB **265**, 172 (1991)

[5] M. Nayak *et. al.*, Phys. Lett. B **740**, 1 (2015).

# $\phi_3$ measurements : ADS method [6]

- Favoured $B$ decay followed by a DCS $D$ decay, suppressed $B$ decay followed by a CF $D$ decay $\Rightarrow$ comparable amplitudes and max sensitivity. Eg: $D \to K^{\pm}\pi^{\mp}$




- The charge-averaged rate

$$R_{ADS} = \frac{\mathcal{B}(B^- \to [f]_D K^-) + \mathcal{B}(B^+ \to [\bar{f}]_D K^+)}{\mathcal{B}(B^- \to [\bar{f}]_D K^-) + \mathcal{B}(B^+ \to [f]_D K^+)}$$
$$= r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_B + \delta_D) \cos\phi_3$$

- The partial-rate asymmetry

$$A_{ADS} = \frac{\mathcal{B}(B^- \to [f]_D K^-) - \mathcal{B}(B^+ \to [\bar{f}]_D K^+)}{\mathcal{B}(B^- \to [f]_D K^-) + \mathcal{B}(B^+ \to [\bar{f}]_D K^+)}$$
$$= \frac{2 r_B r_D \sin(\delta_B \delta_D) \sin\phi_3}{R_{ADS}}$$

- For multibody $D$ decays (Eg: $K^{\mp}\pi^{\pm}\pi^0$, $K^{\mp}\pi^{\pm}\pi^{\mp}\pi^{\pm}$), the interference term is modulated by coherence factor $\kappa$.

[6] D. Atwood, I. Dunietz and A. Soni, PRL **78**, 3357 (1997)

# $\phi_3$ measurements : GGSZ method [7]

- Binned Dalitz plot analysis of multibody self-conjugate $D$ final states like $K^0_S\pi^+\pi^-$, $K^0_S K^+K^-$, $K^0_S\pi^+\pi^-\pi^0$.
- Avoids modelling error by optimal binning.

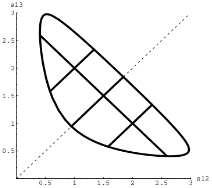



Figure : A typical Dalitz plot binning for a three body $D$ decay.

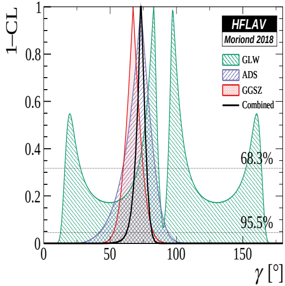
- For the decay $B^\pm \to D(K^0_S h^+ h^-)K^\pm$

$$\Gamma_i^\pm = K_i + r_B^2 \bar{K}_i + 2\sqrt{K_i \bar{K}_i}(c_i x_\pm + s_i y_\pm).$$

- $x_\pm = r_B \cos(\delta_B \pm \phi_3)$;
  $y_\pm = r_B \sin(\delta_B \pm \phi_3)$.
- $K_i$, $\bar{K}_i$ - fraction of flavour-tagged $D^0$ and $\bar{D}^0$ events.
- $c_i$, $s_i$ - cos and sin of the strong phase difference between $D^0$ and $\bar{D}^0$ averaged over the region of phase space.

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

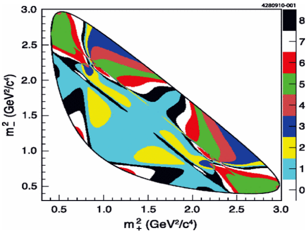
- ADS and GGSZ methods need input from charm:
  - $r_D$, $\delta_D$
  - coherence factor $\kappa$
  - $c_i$, $s_i$
- New $D$ modes can be added for GLW:
  - 3-body final states
  - $CP$-content $F_+$
- Inputs from charm threshold are crucial!
- $e^+e^- \rightarrow \Psi(3770) \rightarrow D^0\bar{D}^0$

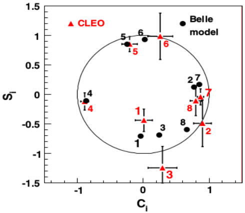



$$\frac{\left(|D^0\rangle\,|\bar{D}^0\rangle - |\bar{D}^0\rangle\,|D^0\rangle\right)}{\sqrt{2}}$$

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

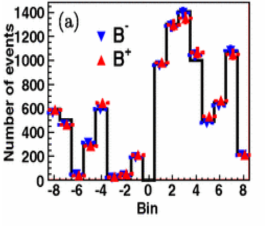
- Golden mode to determine $\phi_3$ via GGSZ formalism at $B$ factories.
- A model-independent Dalitz analysis needs $D$ decay inputs.
- Optimal binning of Dalitz plot guided by amplitude model.
- $c_i$ and $s_i$ in each bin measured from quantum correlated $D$ mesons at CLEO-c [8].

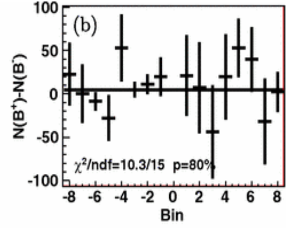



[8] PRD **82**, 112006 (2010)

- Full Belle data set of 711 $fb^{-1}$.
- First model-independent Dalitz analysis : $\phi_3 = (77^{+15.1}_{-14.9} \pm 4.1 \pm 4.3)^\circ$ [9].
- In this approach, the model uncertainty is replaced by statistical uncertainty from CLEO-c.
- Model-dependent analyses have model uncertainty $3^\circ - 9^\circ$
- Latest model-dependent result (with $D^*K$) : $\phi_3 = (78.4^{+10.8}_{-11.6} \pm 3.6 \pm 8.9)^\circ$ [10].
- For future model-independent measurements, inputs from BES III will be imperative.

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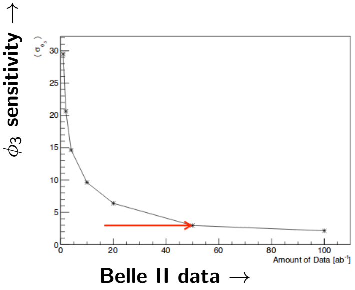
[9] PRD **85**, 112014 (2012)
[10] PRD **81**, 112002 (2010)

# $B \to D(K_S^0\pi^+\pi^-)K$ (GGSZ) - Belle II prospects

- Simulations with $B \to D(K_S^0 hh)K$ (GGSZ)
- More improvements needed:
  - Continuum suppression
  - Particle ID.
- $\sigma_{\phi_3}^{50\ \mathrm{ab}^{-1}} = \mathbf{3.0^\circ}$ by GGSZ (with 10 fb$^{-1}$ BES III data)




- Overall precision improvement as expected.
- These are conservative estimates; more studies are going on.

# $B \to D^{*0}K$ (GLW and ADS)

- Full Belle data set of 711 $\mathrm{fb}^{-1}$.
- GLW modes : $KK, \pi\pi, K_S^0\pi^0, K_S^0\eta$
- ADS mode : $K\pi$

GLW

- With the $CP$ modes for $D^* \to D\pi^0, D\gamma$ decays combined,
  - $A_{CP+} = -0.14 \pm 0.10 \pm 0.01$
  - $A_{CP-} = +0.22 \pm 0.11 \pm 0.01$

ADS

- $R_{D^*K,D\pi^0} = [1.0^{+0.8}_{-0.7}(\mathrm{stat})^{+0.1}_{-0.2}(\mathrm{syst})]\times 10^{-2}$
- $R_{D^*K,D\gamma} = [3.6^{+1.4}_{-1.2}(\mathrm{stat}) \pm 0.2(\mathrm{syst})]\times 10^{-2}$
- To be published...

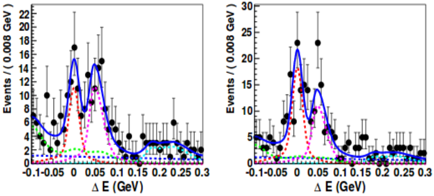



Figure : $B^-$ and $B^+$ for $D_{CP+}$

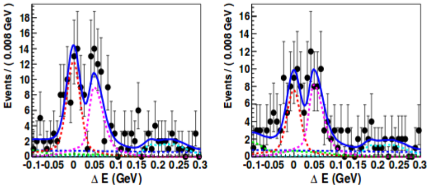



Figure : $B^-$ and $B^+$ for $D_{CP-}$

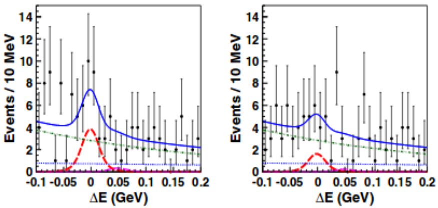



Figure : $B^-$ and $B^+$

- Full Belle data set of 711 $\text{fb}^{-1}$.
- First evidence for suppressed $B \to DK$ decay with $\mathbf{3.2\sigma}$ significance [11].
- Coherence factor $\kappa$ close to 1 $\Rightarrow$ dilution due to strong phase from $D$ decay multi-particle phase space is quite small.
  - $R_{DK} = (1.98 \pm 0.62 \pm 0.24) \times 10^{-2}$
  - $A_{DK} = (0.41 \pm 0.30 \pm 0.05) \times 10^{-2}$

[11] PRD **88**, 091104(R) (2013)

# $B^0 \to D^0(K\pi)K^{*0}$ (ADS)

- Full Belle data set of 711 $fb^{-1}$.
- Self-tagging due to $K^{*0} \to K^+\pi^-$ decay.

$$R_{DK^{*0}} = (4.1^{+5.6}_{-5.0}(\mathrm{stat})^{+2.8}_{-1.8}(\mathrm{syst}))\times 10^{-2}$$ [12]

- As the value is not significant, an upper limit is established.
- $R_{DK^{*0}} < 0.16$ (95% C.L.)

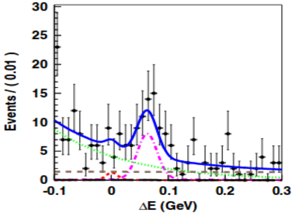


Figure : Suppressed mode

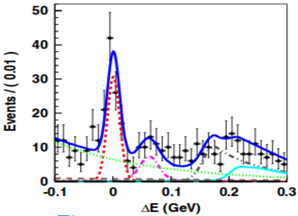


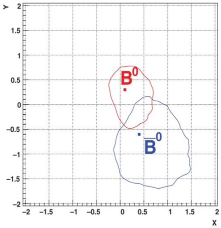
Figure : Favoured mode

[12] PRD **86**, 011101(R) (2012)

# $B^0 \to D^0(K^0_S\pi^+\pi^-)K^{*0}$ (GGSZ)

- Full Belle data set of 711 $fb^{-1}$.
- First model-independent Dalitz analysis of $B^0 \to D^0 K^{*0}$ [13].
  - $x_- = +0.4^{+1.0}_{-0.6}\,^{+0.0}_{-0.1} \pm 0.0$
  - $y_- = -0.6^{+0.8}_{-1.0}\,^{+0.1}_{-0.0} \pm 0.1$
  - $x_+ = +0.1^{+0.7}_{-0.4}\,^{+0.0}_{-0.1} \pm 0.1$
  - $y_+ = +0.3^{+0.5}_{-0.8}\,^{+0.0}_{-0.1} \pm 0.1$
- $r_s < 0.87$ 68% C.L.

- $x_\pm = r_s \cos(\delta_s \pm \phi_3)$
- $y_\pm = r_s \sin(\delta_s \pm \phi_3)$




13 PTEP , 2016(4) (2016)

# $B \to D^0(K^0_S\pi^+\pi^-\pi^0)K$ (GGSZ)

- Relatively large branching fraction of 5.2%
- Interesting resonance substructures.
  - $K^0_S\omega$ - $CP$ eigenstate - GLW like.
  - $K^{*-}\pi^+\pi^0$ - Cabibbo-favored state (CF) - ADS like.
- Binning the phase space around these resonances in the absence of an amplitude model.
- $c_i$, $s_i$ results available with CLEO-c data.

| Bin | Resonance | $c_i$ | $s_i$ |
|---|---|---|---|
| 1 | $\omega$ | $-1.11 \pm 0.09^{+0.02}_{-0.01}$ | 0.00 |
| 2 | $K^{*-}\rho^+$ | $-0.30 \pm 0.05 \pm 0.01$ | $-0.03 \pm 0.09^{+0.01}_{-0.02}$ |
| 3 | $K^{*+}\rho^-$ | $-0.41 \pm 0.07^{+0.02}_{-0.01}$ | $0.04 \pm 0.12^{+0.01}_{-0.02}$ |
| 4 | $K^{*-}$ | $-0.79 \pm 0.09 \pm 0.05$ | $-0.44 \pm 0.18 \pm 0.06$ |
| 5 | $K^{*+}$ | $-0.62 \pm 0.12^{+0.03}_{-0.02}$ | $0.42 \pm 0.20 \pm 0.06$ |
| 6 | $K^{*0}$ | $-0.19 \pm 0.11 \pm 0.02$ | 0.00 |
| 7 | $\rho^+$ | $-0.82 \pm 0.11 \pm 0.03$ | $-0.11 \pm 0.19^{+0.04}_{-0.03}$ |
| 8 | $\rho^-$ | $-0.63 \pm 0.18 \pm 0.03$ | $0.23 \pm 0.41^{+0.04}_{-0.03}$ |
| 9 | remainder | $-0.69 \pm 0.15^{+0.15}_{-0.12}$ | 0.00 |

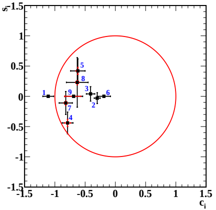
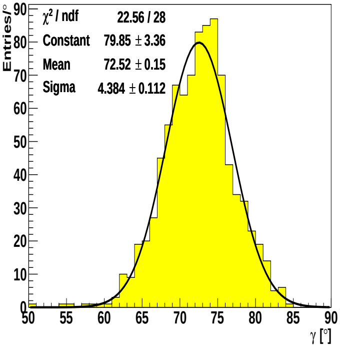



Figure : $c_i$ and $s_i$ results in various bins.

[14] JHEP **01**, 82 (2018)

# $B \to D^0(K^0_S\pi^+\pi^-\pi^0)K$ (GGSZ)

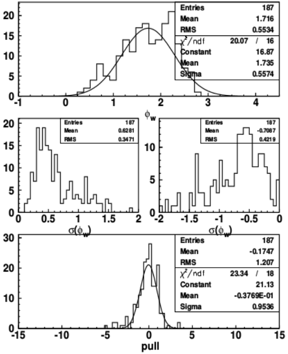
- Estimates of $\phi_3$ sensitivity with $B^\pm \to D(K^0_S\pi^+\pi^-\pi^0)K^\pm$ give
  - $\sigma_{\phi_3} \approx 25^\circ$ with full Belle dataset.
  - $\sigma_{\phi_3} = \mathbf{4.4^\circ}$ with 50 ab$^{-1}$ data from Belle II.
  - Assumed $\epsilon \times BF$ similar to $K^0_S\pi^+\pi^-$.
- Improvements expected with
  - knowledge of an amplitude model,
  - finer binning from a larger statistics (BES III).
- Analysis ongoing with full Belle dataset.



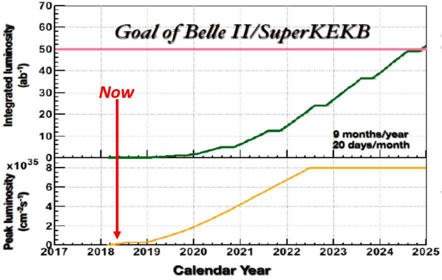

[14] JHEP **01**, 82 (2018)

# Time-dependent measurements

- Time-dependent measurements possible with $B^0 \to D^{(*)}\pi/\rho$ modes.
- CPV induced from mixing.
- All physics parameters can be extracted from data using $B \to VV$ decays like $B \to D^*\rho$.
- 60k $B \to D^*\rho$ events in Belle full dataset.
- With angular time dependent fit, $2\phi_1 + \phi_3$ can be extracted.
- $\sigma(2\phi_1 + \phi_3) \approx 80^\circ$ for Belle.
- $\sigma(2\phi_1 + \phi_3) \approx 11^\circ$ for Belle II at 50 $\mathrm{ab}^{-1}$.
- Analysis ongoing with full Belle dataset.

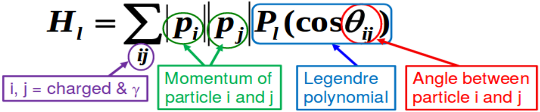


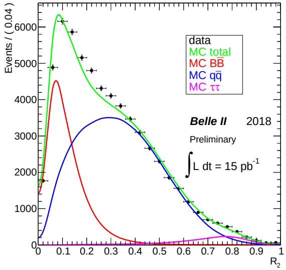
- First collision on 26 April & completed on 17 July 2018.
- Accumulated $\approx 0.5\ \text{fb}^{-1}$ data
- Phase 3 kick-off from early 2019
- Target luminosities :
  - $\mathcal{L}_{\text{int}} = 50\ \text{ab}^{-1}$ (50 $\times$ Belle)
  - $\mathcal{L}_{\text{peak}} = 8 \times 10^{35}\ \text{cm}^{-1}\text{s}^{-1}$ (40 $\times$ KEKB)



# Early Belle II data analysis

- Looked at $R_2$ distribution to check if the collisions happen really at $\Upsilon(4S)$.
- $R_2$ is the ratio of second and zeroth Fox-Wolfram moment. FW moment is similar to multipolar expansion of vector potential.

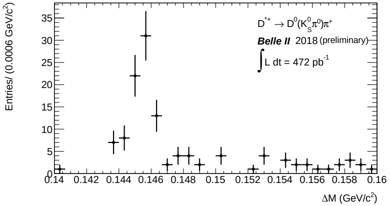


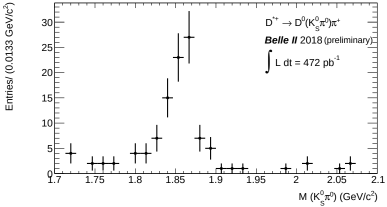




- $B\bar{B}$ events, $R_2 \rightarrow 0$.
- $q\bar{q}$ events, $R_2 \rightarrow$ higher values.
- So the collisions happen at $\Upsilon(4S)$ resonance producing $B\bar{B}$ pairs.

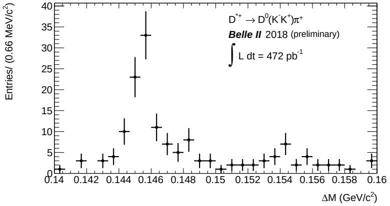
# Rediscovering the **CP modes** from phase 2

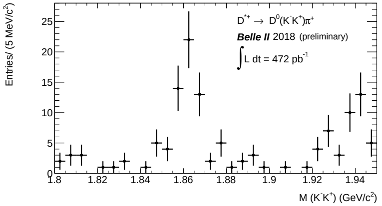
- $D^{*\pm} \to D(K_S^0 \pi^0)\pi^{\pm}_{\rm slow}$ decays



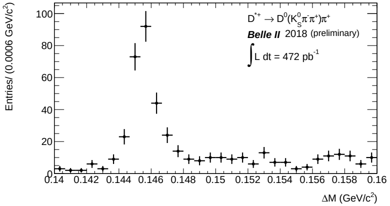

- $D^{*\pm} \to D(K^+K^-)\pi^{\pm}_{\rm slow}$ decays

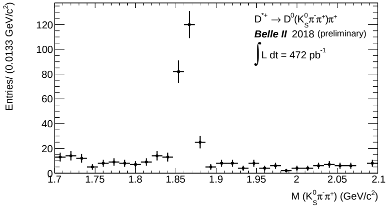


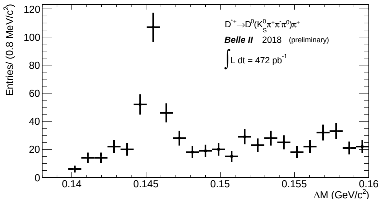
# Rediscovery of $D^{*\pm} \to D(K^0_S\pi^+\pi^-(\pi^0))\pi^{\pm}_{\mathrm{slow}}$ from phase 2

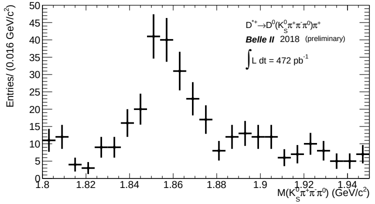
- $D^{*\pm} \to D(K^0_S\pi^+\pi^-)\pi^{\pm}_{\mathrm{slow}}$ decays

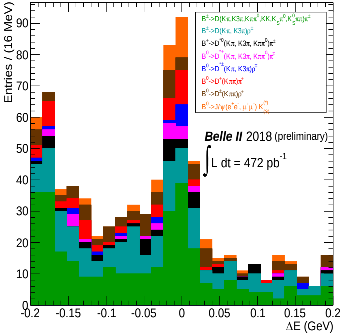


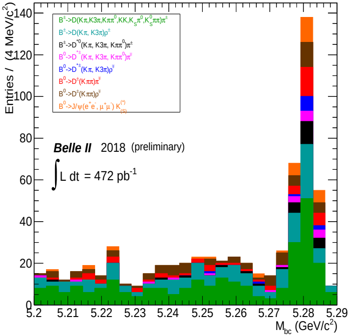




- $D^{*\pm} \to D(K^0_S\pi^+\pi^-\pi^0)\pi^{\pm}_{\mathrm{slow}}$ decays






- Total 245 $B$ candidates were found.
- $B \to D\pi$ decays are good calibration modes for $B \to DK$ for $\phi_3$.

# Summary

- Measuring $\phi_3$ precisely is important to establish the Standard Model description of *CP* violation.
- Interesting analyses ongoing with full Belle dataset now.
- Strong prospects at Belle II.
  - $\mathbf{B^{\pm} \to D(K^0_S \pi^+ \pi^-) K^{\pm}}$:
    $\phi_3$ sensitivity will improve to at least $\mathbf{3.0^\circ}$
  - $\mathbf{B^{\pm} \to D(K^0_S \pi^+ \pi^- \pi^0) K^{\pm}}$:
    $\phi_3$ sensitivity will improve to $\mathbf{4.4^\circ}$
- Motivation to go for $1^\circ$ precision.
- Conservatively, combined sensitivity $\sigma_{\phi_3} = \mathbf{1.6^\circ}$

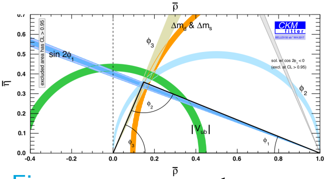



Figure : Future (50 $ab^{-1}$ Belle II data)