Recent Belle II results on hadronic *B* decays

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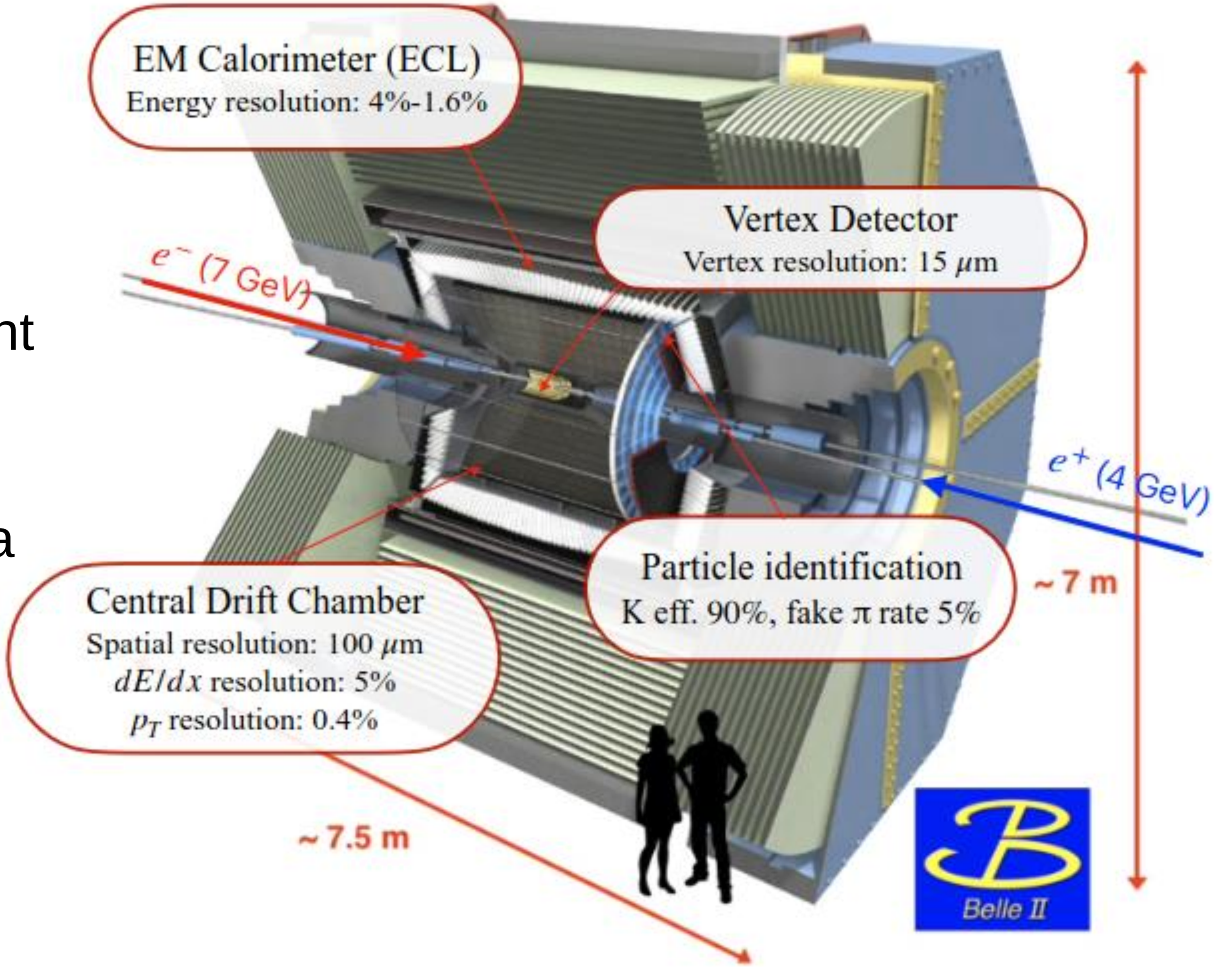
The Belle II detector

- SuperKEKB: asymmetric e^-e^+ collisions at $10.58\ GeV\ (\Upsilon(4S))$
- aim at $700\,\frac{B\bar{B}\ pairs}{s}$ in low-background environment
- $362 fb^{-1}$ ($387 \times 10^6\ B\bar{B}$ pairs) on-resonance data collected
- record peak luminosity: $4.7 \times 10^{34} cm^{-2} s^{-1}$



opens window to final states including multiple $neutrinos$ and $\pi^0/photons$

Hadronic B decays

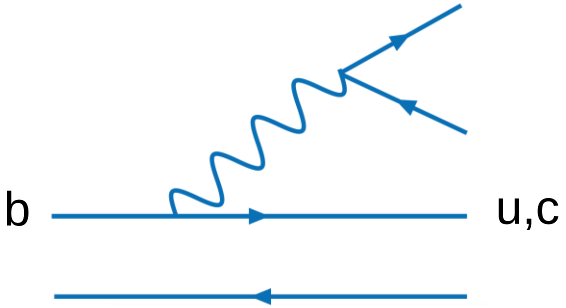
$\boldsymbol{b \to u, c}$ trees and $\boldsymbol{b \to d, s}$ loops

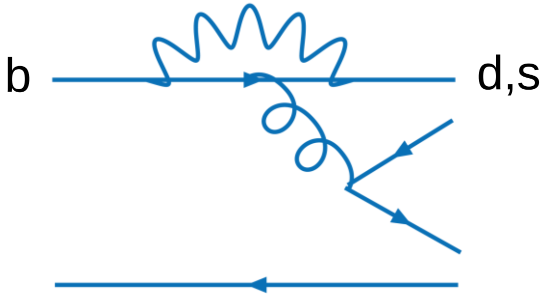
Probe the SM:

- over-constrain CKM triangle
  - $\boldsymbol{\Phi_1}$: via time-dependent analysis of e.g. $K_S^0\pi^0$
  - $\boldsymbol{\Phi_2}$: via isospin analysis of $B \to \rho\rho$, $B \to \pi\pi$
  - $\boldsymbol{\Phi_3}$: via $B \to Dh$, $B \to D^*K$
- via isospin sum rules

<u>Belle II advantages:</u>

- clean environment
- excellent neutral reconstruction



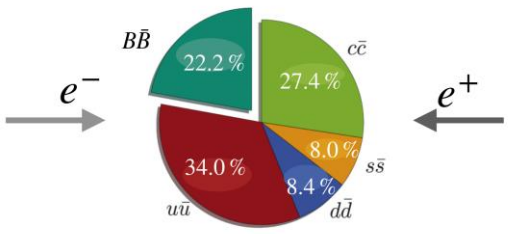


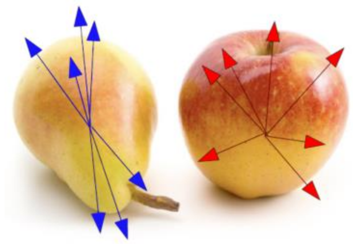
Today:

- observation of new $\boldsymbol{B \to D^{(*)}KK_S^0}$ modes
- $\boldsymbol{\Phi_3}$ measurements with two methods
- towards $\boldsymbol{\Phi_2}$ with $B \to \rho\rho, \pi\pi$ decays
- $\boldsymbol{K\pi}$ isospin sum rule

Analysis Workflow

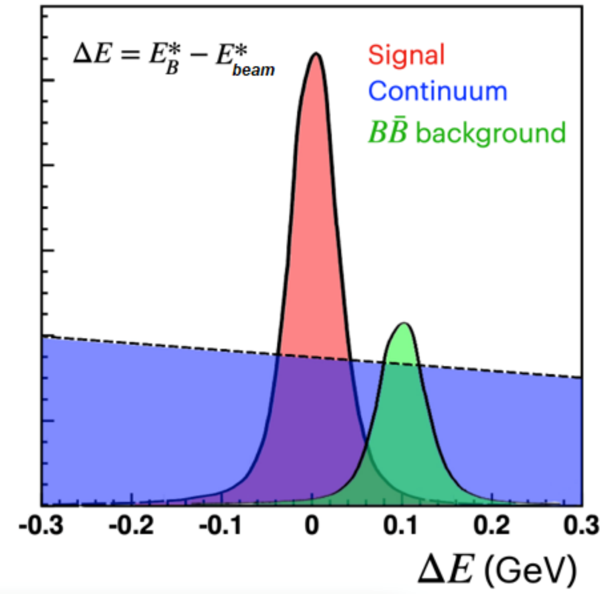
1. **Reconstruction**
   - combine final state particle candidates in kinematic fits to form *B* candidates
2. **Selection**
   - optimize event-shape multivariate classifier + particle ID criteria

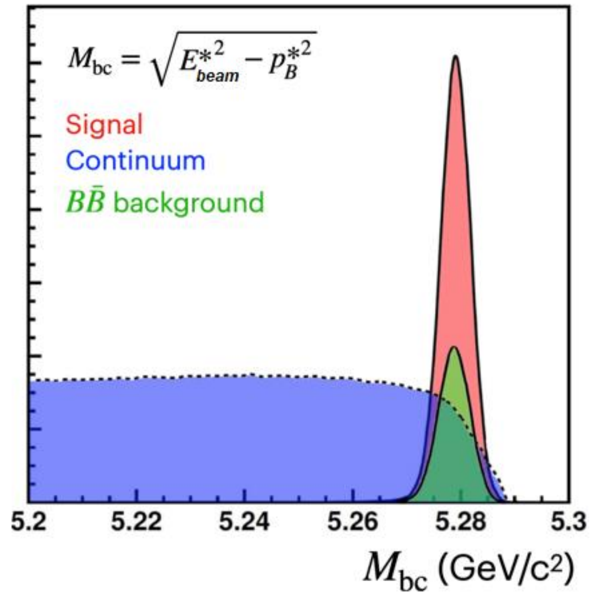




3. **Modelling + Fit**
   - extract models from simulation (+calibrate on data)
   - fit to data to extract physics quantities
4. **Systematic uncertainties**
   - toy studies + control modes

Challenges: small BR, high backgrounds, neutrals





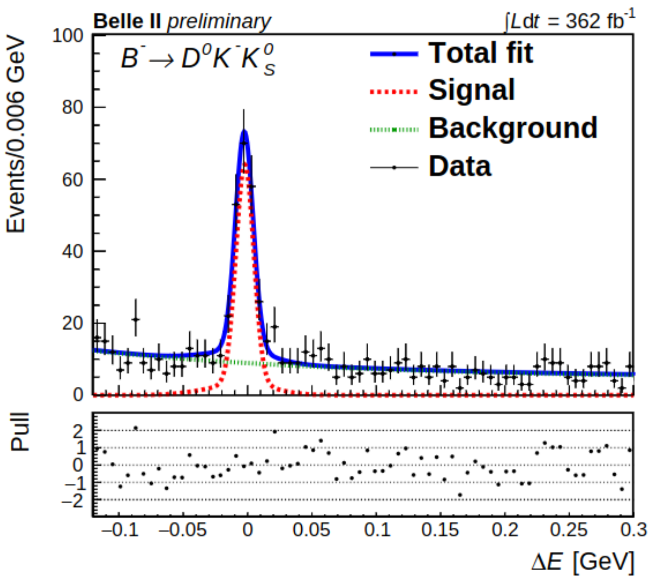
$B \to D^{(*)} K^- K_S^0$ decays

$B \to D^{(*)} K^- K^0_S$ decays

$\boldsymbol{B \to D^{(*)} K^- K^0_S}$ make up a few % of hadronic BR, but only small fraction of it is measured

serves as input for simulation and tagging techniques
- ➢ improving our knowledge will improve other analyses

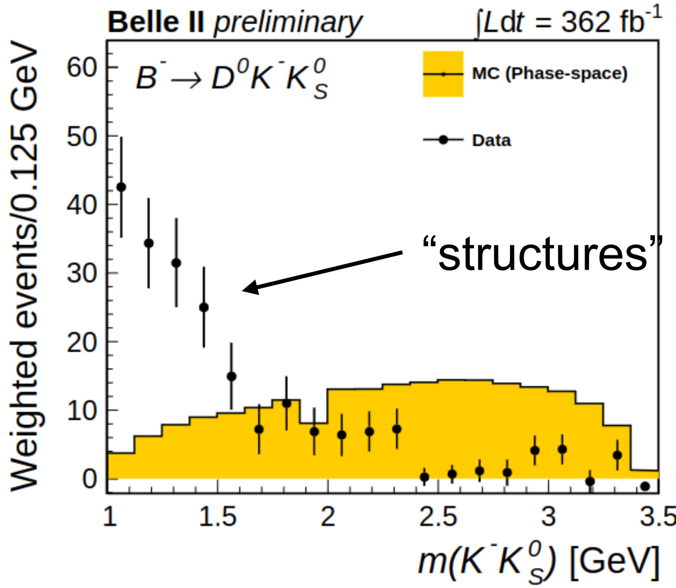
search for possible intermediate states $\boldsymbol{B \to D^{(*)} X^- [K^- K^0_S]}$
- ➢ Fit ΔE to obtain 'background' free invariant mass distributions

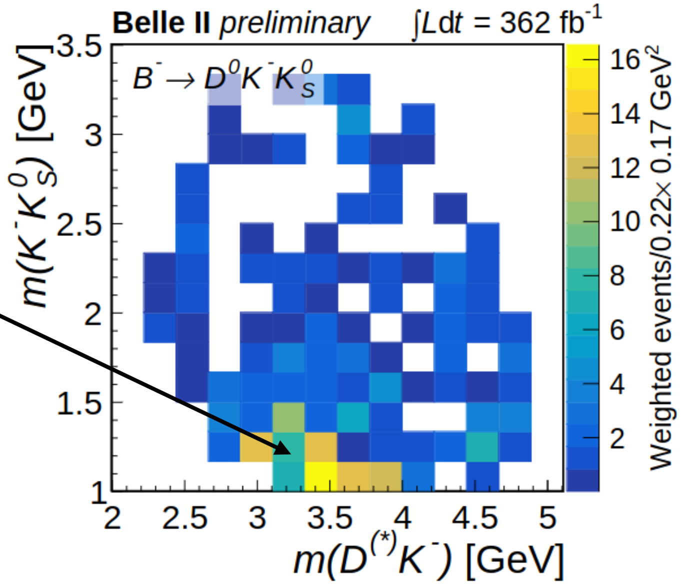


[arXiv:2305.01321](https://arxiv.org/abs/2305.01321)

$$\mathcal{B}(B^- \to D^0 K^- K^0_S) = (1.89 \pm 0.16 \pm 0.10) \times 10^{-4},$$
$$\mathcal{B}(\overline{B}^0 \to D^+ K^- K^0_S) = (0.85 \pm 0.11 \pm 0.05) \times 10^{-4},$$
$$\mathcal{B}(B^- \to D^{*0} K^- K^0_S) = (1.57 \pm 0.27 \pm 0.12) \times 10^{-4},$$
$$\mathcal{B}(\overline{B}^0 \to D^{*+} K^- K^0_S) = (0.96 \pm 0.18 \pm 0.06) \times 10^{-4}$$

first observation



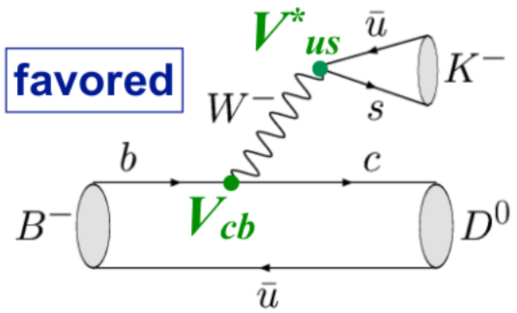


Measurement of Φ_3

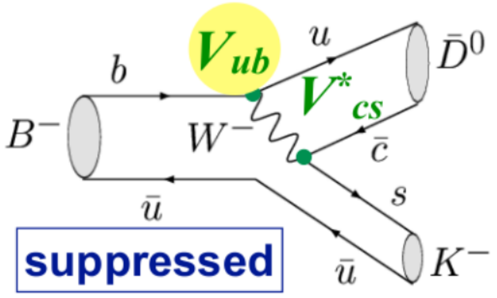
The CKM angle Φ_3

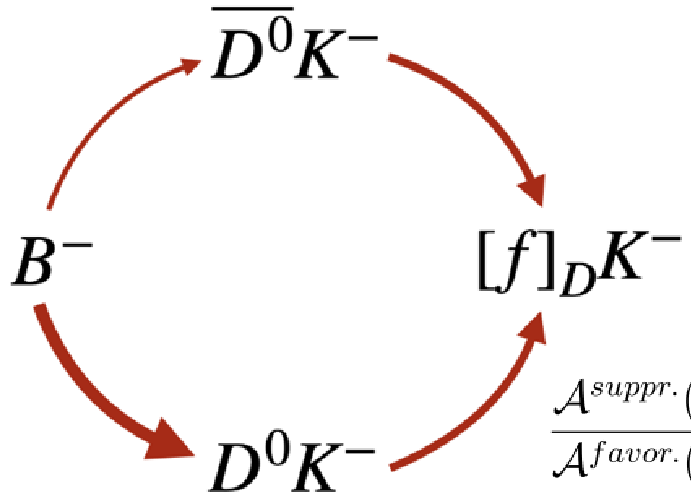
- weak phase between $\boldsymbol{b} \rightarrow \boldsymbol{c}$ and $\boldsymbol{b} \rightarrow \boldsymbol{u}$ tree transitions
- negligible theoretical uncertainty $[\mathcal{O}(10^{-7})]$ arXiv:1308.5663
- current experimental world average
  $\Phi_3[°] = 65.9^{+3.3}_{-3.5}$ HFLAV
- can be compared to other measurements, possibly sensitive to NP

$B^- \rightarrow D^0 K^-$



$B^- \rightarrow \overline{D}^0 K^-$





$$\frac{\mathcal{A}^{suppr.}(B^- \rightarrow \overline{D}^0 K^-)}{\mathcal{A}^{favor.}(B^- \rightarrow D^0 K^-)} = r_B e^{i(\delta_B - \Phi_3)}$$

Different methods to extract Φ_3 depending on D decay mode:
- Cabibbo-suppressed decays, e.g. $\boldsymbol{K^0_S K^\mp \pi^\pm}$ (GLS)
- CP eigenstates, e.g. $\boldsymbol{K^+ K^-}$, $\boldsymbol{K^0_S \pi^0}$ (GLW)
- self-conjugated multibody decays, e.g. $\boldsymbol{K^0_S h^+ h^-}$ (BPGGSZ)

Φ_3 via Cabibbo-suppressed modes

$B^{\pm} \to DK^{\pm}$, $D\pi^{\pm}$ with $D \to K_S^0 K^{\pm}\pi^{\mp}$ (SS: same-sign, OS: opposite-sign)

$711 fb^{-1}$ Belle
$362 fb^{-1}$ Belle II

- measure 4 A_{CP} and 3 BR ratios
  - in full D phase space
  - in $D \to K^*K$ region (large strong phase difference)

$$\mathcal{A}_m^{Dh} \equiv \frac{N_m^{Dh^-} - N_m^{Dh^+}}{N_m^{Dh^-} + N_m^{Dh^+}}$$

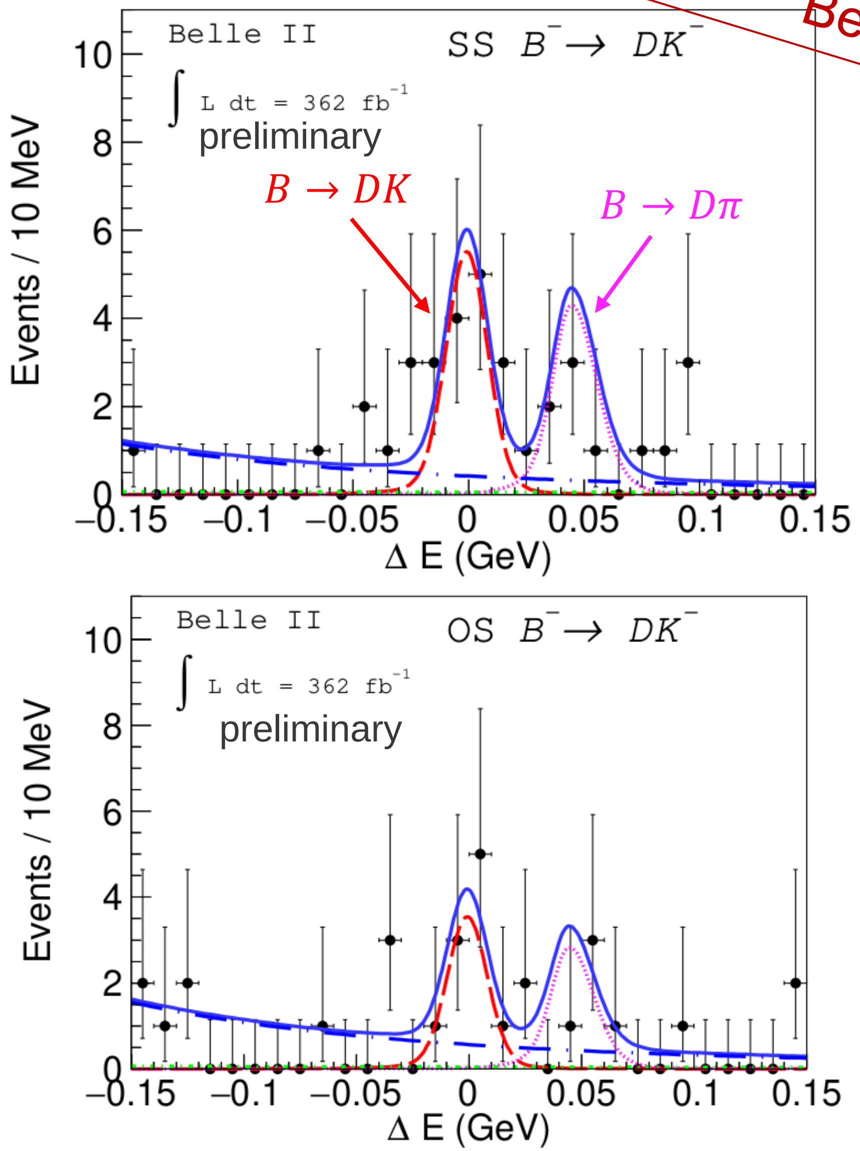
$$\mathcal{R}_m^{DK/D\pi} \equiv \frac{N_m^{DK^-} + N_m^{DK^+}}{N_m^{D\pi^-} + N_m^{D\pi^+}}$$

$$\mathcal{R}_{SS/OS}^{D\pi} \equiv \frac{N_{SS}^{D\pi^-} + N_{SS}^{D\pi^+}}{N_{OS}^{D\pi^-} + N_{OS}^{D\pi^+}}$$

in K^*K region

$$A_{SS}^{DK} = 0.055 \pm 0.119 \pm 0.020,$$
$$A_{OS}^{DK} = 0.231 \pm 0.184 \pm 0.014,$$
$$A_{SS}^{D\pi} = 0.046 \pm 0.029 \pm 0.016,$$
$$A_{OS}^{D\pi} = 0.009 \pm 0.046 \pm 0.009,$$
$$R_{SS}^{DK/D\pi} = 0.093 \pm 0.012 \pm 0.005,$$
$$R_{OS}^{DK/D\pi} = 0.103 \pm 0.020 \pm 0.006,$$
$$R_{SS/OS}^{D\pi} = 2.412 \pm 0.132 \pm 0.019,$$

arXiv:2306.02940



in agreement with LHCb determinations, but less precise
contributes to Φ_3 determination with other Belle and Belle II results

Φ_3 via CP eigenstates

711 fb^{-1} Belle
189 fb^{-1} Belle II

$B^{\pm} \to DK^{\pm}$, $D\pi^{\pm}$ with $D \to K^+K^-$ (CP-even) or $D \to K_S^0\pi^0$ (CP-odd)

unique to Belle(II)

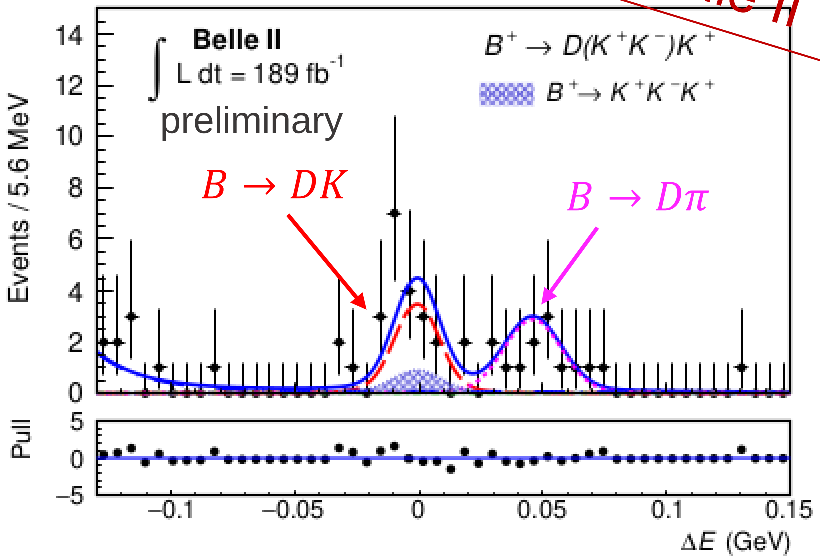
measure 2 A_{CP} and 2 BR ratios

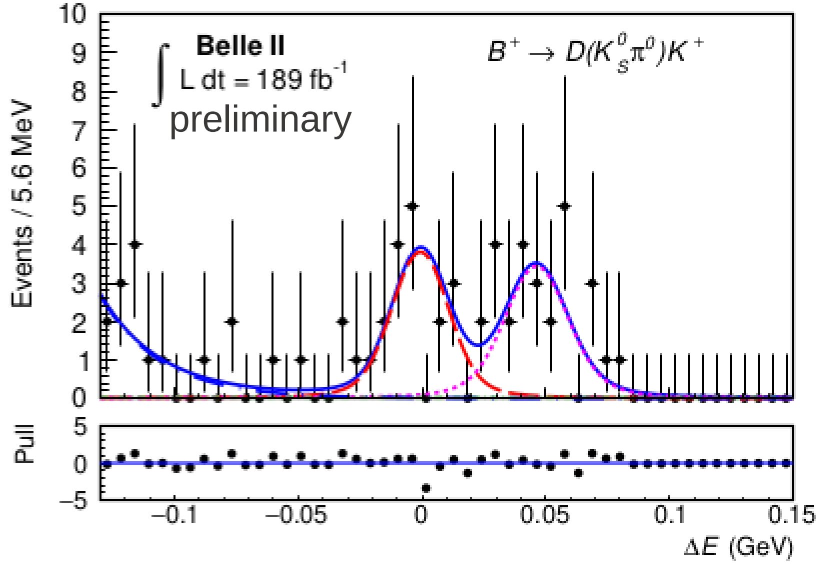
$$\mathcal{R}_{CP\pm} \equiv \frac{\mathcal{B}(B^- \to D_{CP\pm}K^-) + \mathcal{B}(B^+ \to D_{CP\pm}K^+)}{(\mathcal{B}(B^- \to D_{\text{flav}}K^-) + \mathcal{B}(B^+ \to \overline{D}_{\text{flav}}K^+))/2} \quad \mathcal{A}_{CP\pm} \equiv \frac{\mathcal{B}(B^- \to D_{CP\pm}K^-) - \mathcal{B}(B^+ \to D_{CP\pm}K^+)}{\mathcal{B}(B^- \to D_{CP\pm}K^-) + \mathcal{B}(B^+ \to D_{CP\pm}K^+)}$$

$$\begin{aligned} \mathcal{R}_{CP+} &= 1.164 \pm 0.081 \pm 0.036, \\ \mathcal{R}_{CP-} &= 1.151 \pm 0.074 \pm 0.019, \\ \mathcal{A}_{CP+} &= (+12.5 \pm 5.8 \pm 1.4)\%, \\ \mathcal{A}_{CP-} &= (-16.7 \pm 5.7 \pm 0.6)\% \end{aligned}$$

arXiv:2308.05048

3.5σ evidence for $\mathcal{A}_{CP+} \neq \mathcal{A}_{CP-}$



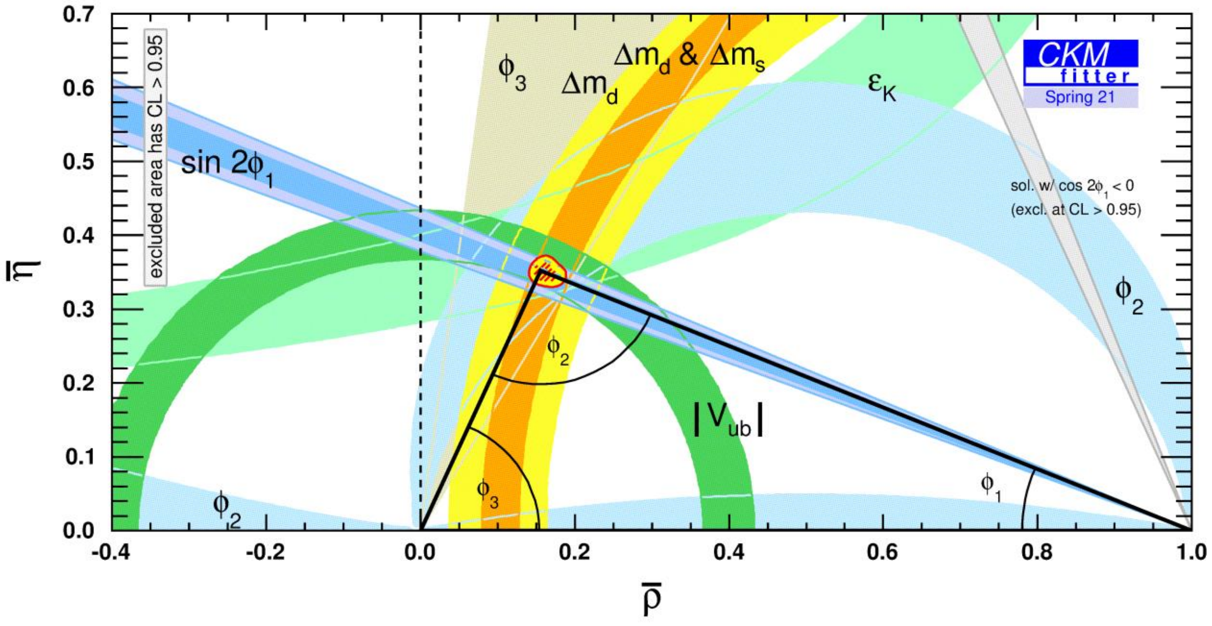


in agreement with world average
contributes to Φ_3 determination with other Belle and Belle II results

Towards Φ_2

The CKM angle Φ_2

- least known angle of the CKM
- current experimental world average
  $\Phi_2[°] = 85.2^{+4.8}_{-4.3}$ HFLAV
- $\sin(2\Phi_2)\sim$ TDCPV $b \to u\bar{u}d$ transitions (if only tree contributions)
- loop contributions introduce shift
- tree and loop contributions can be disentangled exploiting $B \to \pi\pi, \rho\rho$ isospin relations



$$\Phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

- need to measure BR and A_{CP} of all $B \to \pi^+\pi^-, \pi^+\pi^0, \pi^0\pi^0$ modes
  $\to \rho^+\rho^-, \rho^+\rho^0, \rho^0\rho^0$

unique to Belle II

$B \to \pi\pi$ results

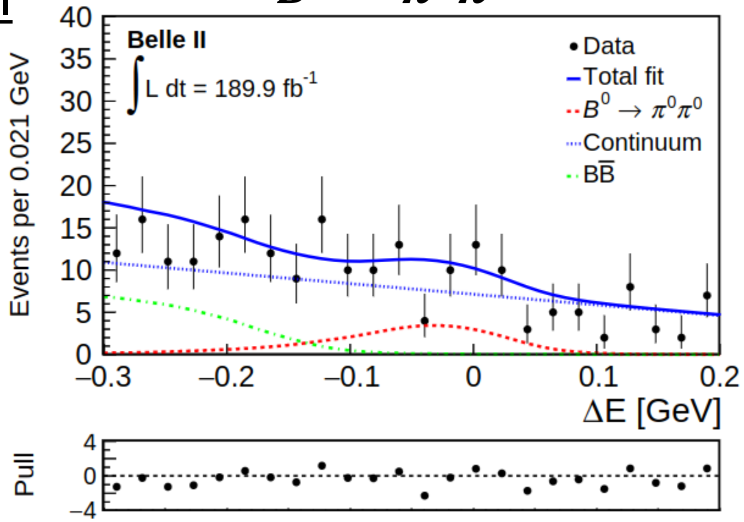
<u>First measurement of $B^0 \to \pi^0\pi^0$ at Belle II</u>

- unique channel to Belle II
- 4 photons in final state
- large background

$$\mathcal{B}(B^0 \to \pi^0\pi^0) = (1.38 \pm 0.27 \pm 0.22) \times 10^{-6}$$
$$\mathcal{A}_{CP}(B^0 \to \pi^0\pi^0) = 0.14 \pm 0.46 \pm 0.07$$

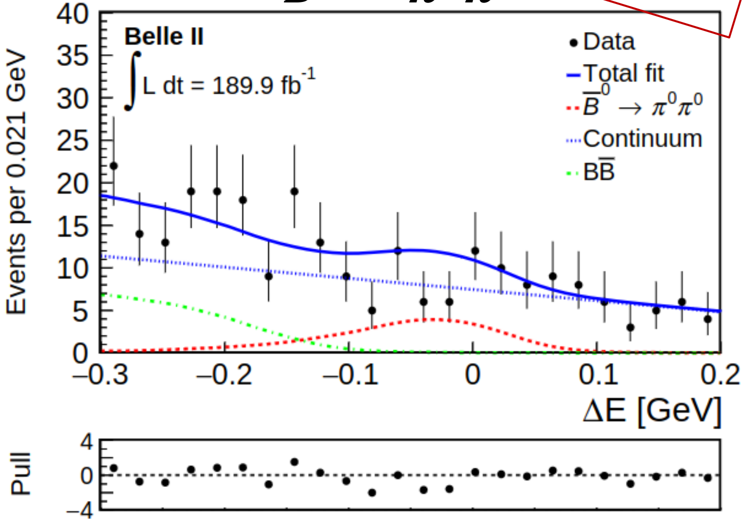
- same BR precision as Belle with 1/3 of data

$B^0 \to \pi^0\pi^0$



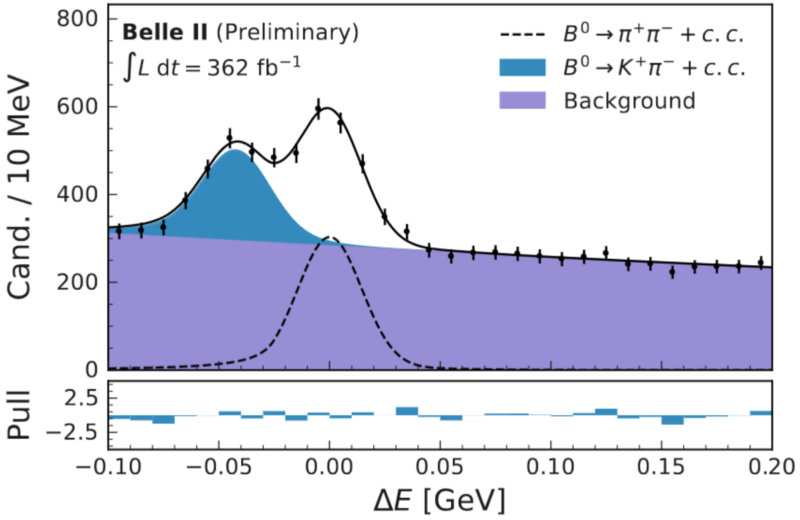
$\bar{B}^0 \to \pi^0\pi^0$

$189 fb^{-1}$



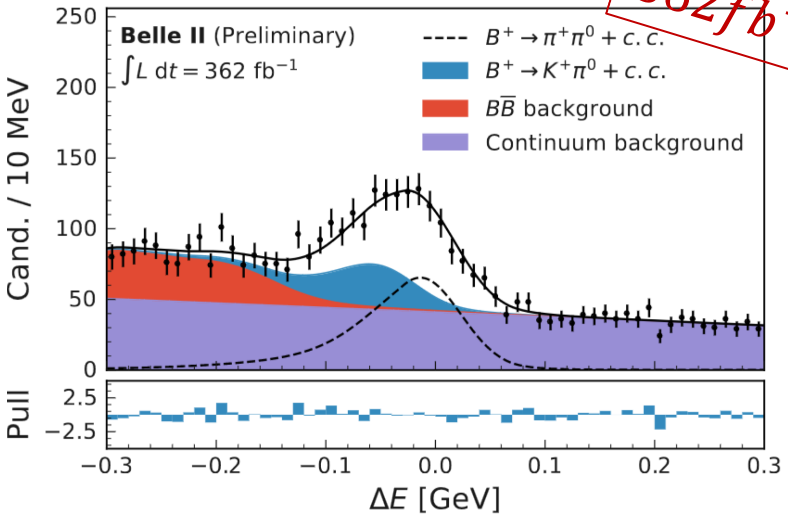
[Phys. Rev. D 107, 112009]

$B^0 \to \pi^+\pi^-$



$B^+ \to \pi^+\pi^0$

$362 fb^{-1}$



$$\mathcal{B}(B^0 \to \pi^+\pi^-) = (5.83 \pm 0.22 \pm 0.17) \times 10^{-6}$$
$$\mathcal{B}(B^+ \to \pi^+\pi^0) = 5.10 \pm 0.29 \pm 0.27 \times 10^{-6}$$
$$\mathcal{A}_{CP}(B^+ \to \pi^+\pi^0) = -0.081 \pm 0.054 \pm 0.008$$

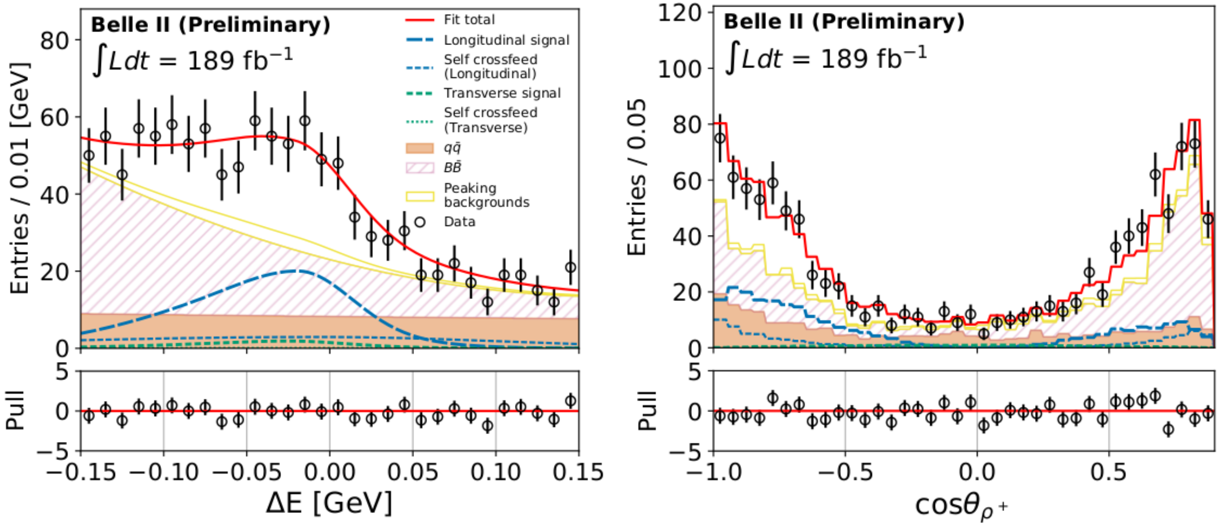
- compatible with world averages
- worlds best $BR(B^0 \to \pi^+\pi^-)$

$B \to \rho\rho$ results

$189 fb^{-1}$

- 4 final state particles, including π^0
- non-negligible contribution from peaking backgrounds
- need to perform angular analysis to disentangle longitudinal from transversal polarization

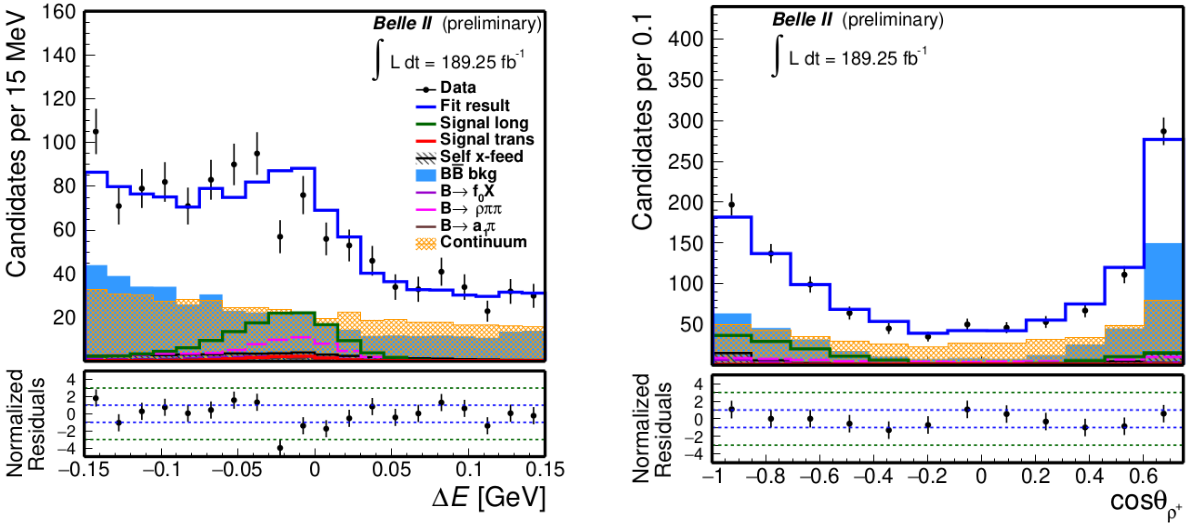
$B^0 \to \rho^+\rho^-$



$$\mathcal{B}(B^0 \to \rho^+\rho^-) = [2.67 \pm 0.28\,(\text{stat}) \pm 0.28\,(\text{syst})] \times 10^{-5},$$
$$f_L = 0.956 \pm 0.035\,(\text{stat}) \pm 0.033\,(\text{syst})$$

arXiv:2208.03554

$B^+ \to \rho^+\rho^0$



$$\mathcal{B}(B^+ \to \rho^+\rho^0) = [23.2^{+\,2.2}_{-\,2.1}(\text{stat}) \pm 2.7(\text{syst})] \times 10^{-6},$$
$$f_L = 0.943^{+\,0.035}_{-\,0.033}(\text{stat}) \pm 0.027(\text{syst}),$$
$$\mathcal{A}_{CP} = -0.069 \pm 0.068(\text{stat}) \pm 0.060(\text{syst})$$

arXiv:2206.12362

extension to full sample promising

$K\pi$ isospin sum rule

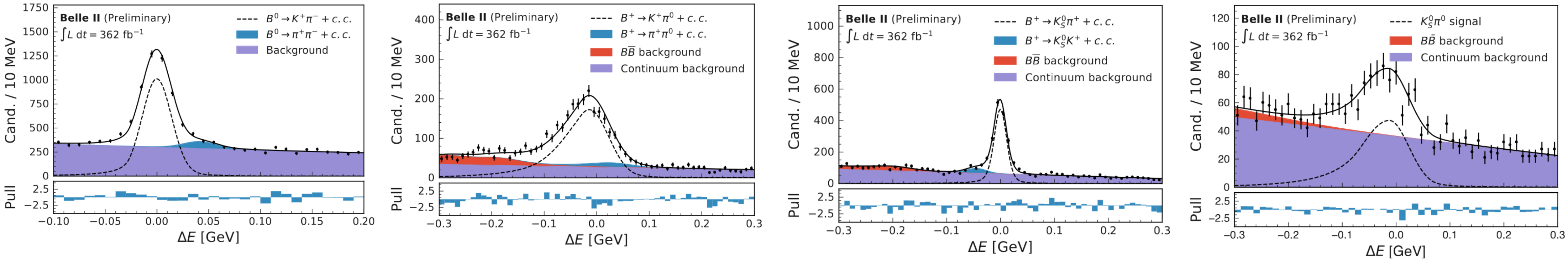
$K\pi$ isospin sum rule

$$I_{K\pi} = A_{K^+\pi^-} + A_{K^0\pi^+}\frac{Br(K^0\pi^+)}{Br(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2A_{K^+\pi^0}\frac{Br(K^+\pi^0)}{Br(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2A_{K^0\pi^0}\frac{Br(K^0\pi^0)}{Br(K^+\pi^-)} \approx 0$$

- direct and precise method to test SM in hadronic *B* decays
- SM prediction: 0 within 1% precision (Phys. Lett. B627 (2005) 82-88)
- provides stringent null test of SM
- Belle II measures all modes in coherent way with unique access to $B^0 \rightarrow K_S^0\pi^0$ (limits $I_{K\pi}$)

$362 fb^{-1}$

$B^0 \rightarrow K^+\pi^-$ $B^+ \rightarrow K^+\pi^0$ $B^+ \rightarrow K_S^0\pi^+$ $B^0 \rightarrow K_S^0\pi^0$



$K\pi$ isospin sum rule

$B^0 \to K^+\pi^-$

$$\mathcal{B}(B^0 \to K^+\pi^-) = (20.67 \pm 0.37 \pm 0.62) \times 10^{-6}$$
$$\mathcal{A}_{CP}(B^0 \to K^+\pi^-) = -0.072 \pm 0.019 \pm 0.007$$

$B^+ \to K^+\pi^0$

$$\mathcal{B}(B^+ \to K^+\pi^0) = (13.93 \pm 0.38 \pm 0.71) \times 10^{-6}$$
$$\mathcal{A}_{CP}(B^+ \to K^+\pi^0) = 0.013 \pm 0.027 \pm 0.005$$

$B^+ \to K_S^0\pi^+$

$$\mathcal{B}(B^+ \to K_S^0\pi^+) = (24.37 \pm 0.71 \pm 0.86) \times 10^{-6}$$
$$\mathcal{A}_{CP}(B^+ \to K_S^0\pi^+) = 0.046 \pm 0.029 \pm 0.007$$

$B^0 \to K_S^0\pi^0$

$$\mathcal{B}(B^0 \to K_S^0\pi^0) = (10.40 \pm 0.66 \pm 0.60) \times 10^{-6}$$
$$\mathcal{A}_{CP}(B^0 \to K_S^0\pi^0) = -0.06 \pm 0.15 \pm 0.05$$

competitive with world averages, BRs limited by systematics ($\pi^0, f^{+-/00}$)

$\boldsymbol{B^0 \to K_S^0\pi^0}$ combined with time-dependent analysis (arXiv:2206.07453)

- world's best $A_{CP}(K_S^0\pi^0) = -0.01 \pm 0.12 \pm 0.05$

$I_{K\pi} = -0.03 \pm 0.13 \pm 0.05$ (world average: $I_{K\pi} = 0.13 \pm 0.11$)

competitive with world average with $362 fb^{-1}$

Summary

- Hadronic *B* decays offer a large and diverse physics program
  - Enable improvement of descriptions in generic *B* simulations
  - Constrain unitarity of the weak interactions of quarks through measurements of Φ_1, Φ_2, Φ_3
  - Offer sensitive SM tests based on flavor symmetries (e.g., isospin sum rules)
- Belle II has unique / competitive reach owing to its efficient performance in reconstruction of neutral particles
- Today shown contributions to the determination of Φ_3, world leading results on isospin sum rules and promising progress toward determination of Φ_2
- Shutdown since July 2022 to replace pixel detector, restart in December

Thank you

Backup

Φ_3 via Cabibbo-suppressed modes

$711 fb^{-1}$ Belle
$362 fb^{-1}$ Belle II

$B^\pm \to DK^\pm, D\pi^\pm$ with $D \to K_S^0 K^\pm \pi^\mp$ (SS: same-sign, OS: opposite-sign)

- 2 $\mathcal{A}_{CP}$ for DK ($D\pi$):

$$\mathcal{A}_{SS}^{DK} \equiv \frac{N_{SS}^- - N_{SS}^+}{N_{SS}^- + N_{SS}^+}$$

$$\mathcal{A}_{OS}^{DK} \equiv \frac{N_{OS}^- - N_{OS}^+}{N_{OS}^- + N_{OS}^+}$$

Physics meanings →

$$\mathcal{A}_{SS}^{DK} = \frac{2r_B r_D \kappa \sin(\delta_B - \delta_D)\sin\phi_3}{1 + r_B^2 r_D^2 + 2r_B r_D \kappa \cos(\delta_B - \delta_D)\cos\phi_3}$$

$$\mathcal{A}_{SS}^{DK} = \frac{2r_B r_D \kappa \sin(\delta_B + \delta_D)\sin\phi_3}{1 + r_B^2 + r_D^2 + 2r_B r_D \kappa \cos(\delta_B + \delta_D)\cos\phi_3}$$

- 3 ratios:

$$\mathcal{R}_{SS}^{DK/D\pi} \equiv \frac{N_{SS}^- + N_{SS}^+}{N_{SS}'^- + N_{SS}'^+}$$

$$\mathcal{R}_{OS}^{DK/D\pi} \equiv \frac{N_{OS}^- + N_{OS}^+}{N_{OS}'^- + N_{OS}'^+}$$

$$\mathcal{R}_{SS/OS}^{D\pi} \equiv \frac{N_{SS}'^- + N_{SS}'^+}{N_{OS}'^- + N_{OS}'^+}$$

Physics meanings →

$$\mathcal{R}_{SS}^{DK/D\pi} = R\frac{1 + r_B^2 r_D^2 + 2r_B r_D \kappa \cos(\delta_B - \delta_D)\cos\phi_3}{1 + r_B'^2 r_D^2 + 2r_B' r_D \kappa \cos(\delta_B' - \delta_D)\cos\phi_3}$$

$$\mathcal{R}_{OS}^{DK/D\pi} = R\frac{r_B^2 + r_D^2 + 2r_B r_D \kappa \cos(\delta_B + \delta_D)\cos\phi_3}{r_B'^2 + r_D^2 + 2r_B' r_D \kappa \cos(\delta_B' + \delta_D)\cos\phi_3}$$

$$\mathcal{R}_{SS}^{DK/D\pi} = \frac{1 + r_B'^2 r_D^2 + 2r_B' r_D \kappa \cos(\delta_B' - \delta_D)\cos\phi_3}{r_B'^2 + r_D^2 + 2r_B' r_D \kappa \cos(\delta_B' + \delta_D)\cos\phi_3}$$

Φ_3 via CP eigenstates

$711fb^{-1}$ Belle
$189fb^{-1}$ Belle II

$B^\pm \to DK^\pm$, $D\pi^\pm$ with $D \to K^+K^-$ (CP-even) or $D \to K_S^0\pi^0$ (CP-odd)

unique to Belle(II)

$$\mathcal{A}_{CP\pm} = \frac{\Gamma(B^- \to D_{CP\pm}K^-) - \Gamma(B^+ \to D_{CP\pm}K^+)}{\Gamma(B^- \to D_{CP\pm}K^-) + \Gamma(B^+ \to D_{CP\pm}K^+)} = \pm \frac{r_B \sin\delta_B sin\phi_2}{1 + r_B^2 \pm 2r_B \cos deltа_B \cos\phi_3},$$

$$\mathcal{R}_{CP\pm} = \frac{\mathcal{B}(B^- \to D_{CP\pm}K^-) + \mathcal{B}(B^+ \to D_{CP\pm}K^+)}{\mathcal{B}(B^- \to D_{flav}K^-) + \mathcal{B}(B^+ \to D_{flav}K^+)} \approx \frac{R_{CP\pm}}{R_{flav}}, \text{ with}$$

$$R_X \equiv \frac{\mathcal{B}(B^- \to D_X K^-) + \mathcal{B}^+ \to D_X K^+)}{\mathcal{B}(B^- \to D_X\pi^-) + \mathcal{B}^+ \to D_X\pi^+)}.$$

$$\Rightarrow \begin{cases} \mathcal{R}_{CP\pm} = 1 + r_B^2 \pm 2\cos\delta_B\cos\phi_3 \\ \mathcal{A}_{CP\pm} = \pm 2r_B \sin\phi_3/\mathcal{R}_{CP\pm} \end{cases}, \text{ assuming } CP \text{ conservation in } B^\pm \to D\pi^\pm$$

- Channels:
  - Signal: $B \to D(\to KK, K_S^0\pi^0)K$
  - R_{flav} control channel: $B \to D(\to K\pi)K$
  - R_X control channel: $B \to D\pi$

Φ_3 via CP eigenstates

$711 fb^{-1}$ Belle
$189 fb^{-1}$ Belle II

$B^\pm \to DK^\pm$, $D\pi^\pm$ with $D \to K^+K^-$ (CP-even) or $D \to K_S^0\pi^0$ (CP-odd)

unique to Belle(II)

$$\mathcal{R}_{CP+} = 1.164 \pm 0.081 \pm 0.036,$$

2.2σ above world average

- large r_B
- stringent constraint Φ_3