Recent Belle and Belle II results on hadronic B decays

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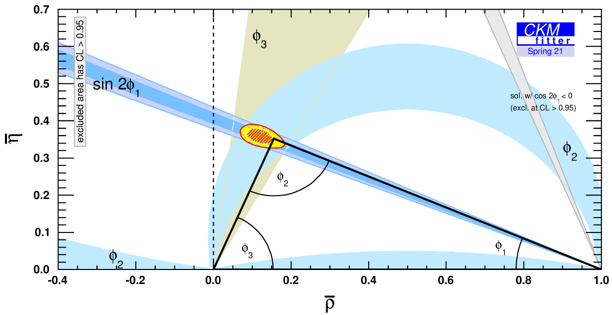
THE UNIVERSITY OF MELBOURNE

Belle II

Motivation

- Unitarity triangle observables point to a single apex with a precision of $\mathcal{O}(10)\%$ - possible non-SM physics amplitudes of the same order.
- CKM angles ϕ_2 and ϕ_3 are significantly less well measured than CKM angle ϕ_1.



Strength of Belle II: can access a wide variety of decays, in particular final states with neutrals (π^0, ρ, K_L...), which can be used to precisely determine ϕ_2 and ϕ_3.

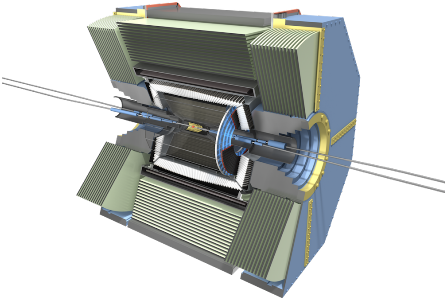
SuperKEKB and Belle II

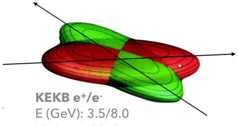
Belle II: general purpose detector situated at the interaction point of SuperKEKB.

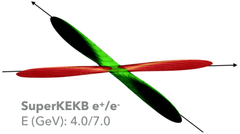
SuperKEKB: asymmetric $e^+ - e^-$ collider operating at $\Upsilon(4S)$ resonance.

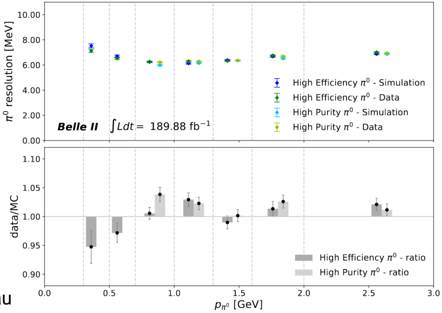
Operation:

- Recorded $\approx$ 424 fb^{-1}
- Achieved world record: $\mathcal{L} = 4.7 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$ (more than twice of KEKB/Belle)





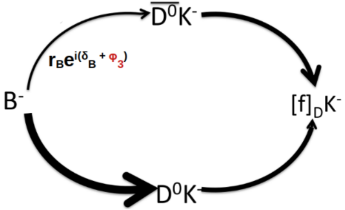




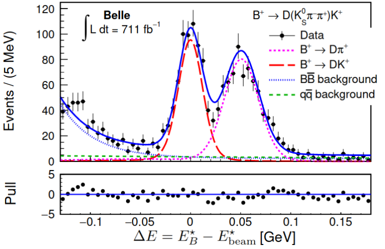
Measurement of ϕ_3 in $B^+ \to D(K^0_S h^+ h^-)K^+$

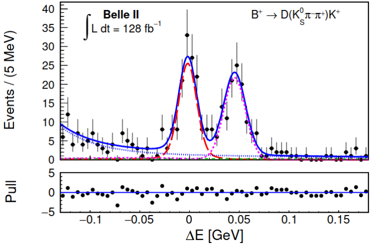
JHEP02 (2022) 063

Measure ϕ_3 via interference of $b \to c$ and $b \to u$ transition.



Belle: $N(K^0_S\pi\pi) = 1467 \pm 53, N(K^0_S KK) = 194 \pm 17$





Belle II: $N(K^0_S\pi\pi) = 280 \pm 21,\ N(K^0_S KK) = 34 \pm 7$

Measurement dependent on D decay physics:

- Bin D Dalitz plot (model-independent)
- Require external input (BESIII, CLEO)

$$\phi_3 = (78.4 \pm 11.4\ \text{(stat.)}\ \pm 0.5\ \text{(syst.)}\ \pm 1.0\ \text{(ext.)})^\circ$$

WA: $\phi_3 = 65.9^{+3.3}_{-3.5}$

First joint Belle (711 fb^{-1}) and Belle II (128 fb^{-1}) analysis!

$K\pi$ puzzle

$K\pi$ puzzle: unexpected large difference between $\mathcal{A}^{\mathrm{CP}}_{K^+\pi^-}$ and $\mathcal{A}^{\mathrm{CP}}_{K^+\pi^0}$.

Sum rule allows to test SM in loop decays at 1% precision and provides an important consistency test:

$$I_{K\pi} = \mathcal{A}^{\mathrm{CP}}_{K^+\pi^-} + \mathcal{A}^{\mathrm{CP}}_{K^0\pi^+}\frac{\mathcal{B}_{K^0\pi^+}}{\mathcal{B}_{K^+\pi^-}}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}^{\mathrm{CP}}_{K^+\pi^0}\frac{\mathcal{B}_{K^+\pi^0}}{\mathcal{B}_{K^+\pi^-}}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}^{\mathrm{CP}}_{K^0\pi^0}\frac{\mathcal{B}_{K^0\pi^0}}{\mathcal{B}_{K^+\pi^-}} \approx 0$$

Deviations can be caused by an enhancement of color-suppressed tree amplitudes, or by contributions from non-SM physics

Belle II is a unique place to measure all involved decays!

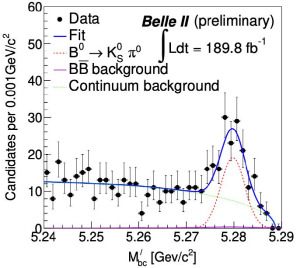
$B^0 \to K_s^0 \pi^0$ Analysis

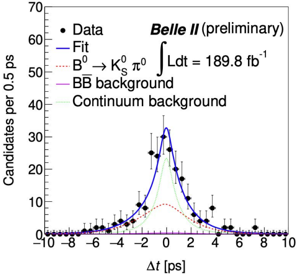
arXiv:2206.07453

- The sum rule has a 10% experimental uncertainty dominated by $\mathcal{A}^{\mathrm{CP}}_{K^0\pi^0}$. This time-dependent measurement is only feasible at Belle II.
- Key challenge is the determination of $B^0 \to K_s\pi^0$ decay vertex
- Signal yield and $\mathcal{A}^{\mathrm{CP}}_{K^0\pi^0}$ from a 4D fit (M_{bc}, ΔE, Δt, continuum suppression BDT output), with $\mathcal{S}_{\mathrm{CP}}$, Δm_d, and τ_{B^0} fixed to their known values

$$\mathcal{A}^{\mathrm{CP}}_{K^+\pi^0} = -0.41 \ {}^{+0.30}_{-0.32}\ (\mathrm{stat}) \pm 0.09\ (\mathrm{syst})$$
$$\mathcal{B}_{K^0\pi^0} = (11.0 \pm 1.2\ (\mathrm{stat}) \pm 1.0\ (\mathrm{syst})) \cdot 10^{-6}$$

WA: $\mathcal{A}^{\mathrm{CP}} = 0.01 \pm 0.10$, $\mathcal{B} = (9.9 \pm 0.5) \cdot 10^{-6}$



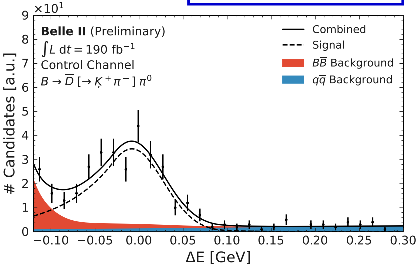


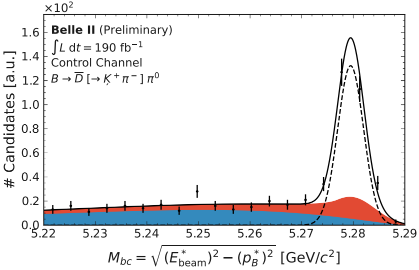
$N(\mathrm{sig}) = 135^{+16}_{-15}$

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

New for Belle II

- Reconstruct $B^+ \to K^+\pi^0$ and $B^+ \to \pi^+\pi^0$ events using common selection
- Divide into pion- and kaon-enhanced sample
- Large background from $e^+e^- \to q\bar{q}$
  $\Rightarrow$ Reduced with machine learning algorithm
- Simultaneous fit to both samples
  $\Rightarrow$ All fit shapes but $B\bar{B}$ are controlled from data using off-resonance data and $B \to \bar{D}\pi$ decays





CONTROL MODE

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

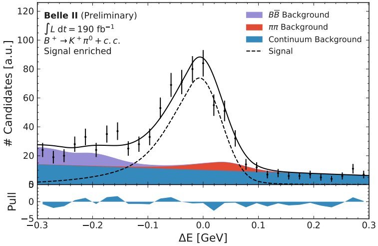
New for Belle II

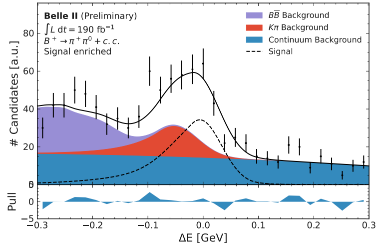
$N(K^+\pi^0) = 887 \pm 43$, $N(\pi^+\pi^0) = 422 \pm 37$

$$\begin{aligned}
\mathcal{A}^{CP}_{K^+\pi^0} &= \quad 0.014 \pm 0.047 \text{ (stat)} \pm 0.010 \text{ (syst)} \\
\mathcal{B}_{K^+\pi^0} &= (14.30 \pm 0.69 \text{ (stat)} \pm 0.79 \text{ (syst)}) \cdot 10^{-6} \\
\mathcal{A}^{CP}_{\pi^+\pi^0} &= -0.085 \pm 0.085 \text{ (stat)} \pm 0.019 \text{ (syst)} \\
\mathcal{B}_{\pi^+\pi^0} &= (6.12 \pm 0.53 \text{ (stat)} \pm 0.53 \text{ (syst)}) \cdot 10^{-6}
\end{aligned}$$

WA: $\mathcal{A}^{CP}_{K^+\pi^0} = 0.030 \pm 0.013$, $\mathcal{A}^{CP}_{\pi^+\pi^0} = 0.03 \pm 0.04$

- Distinguish pions and kaons kinematically via ΔE
- $\mathcal{B}$ and $\mathcal{A}^{CP}$ precision limited by systematic uncertainties associated to size of control samples.





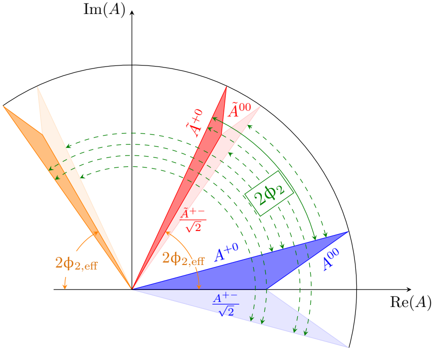
SIGNAL MODES

Measurement of ϕ_2 in charmless hadronic B decays

Access ϕ_2 in $b \to u$ transition of charmless hadronic B decays ($B \to \rho\rho$, $B \to \pi\pi$).
$\Rightarrow$ Significant penguin pollution complicates determination $\phi_{2,eff} = \phi_2 + \Delta\phi_2$
$\Rightarrow$ Isospin relations to disentangle the tree and penguin contributions

$$A^{+0} = \frac{1}{\sqrt{2}}A^{+-} + A^{00}, \quad \bar{A}^{-0} = \frac{1}{\sqrt{2}}\bar{A}^{+-} + \bar{A}^{00},$$

where A^{ij} and $\bar{A}^{ij}$ are the amplitudes of the particle and antiparticle decay respectively

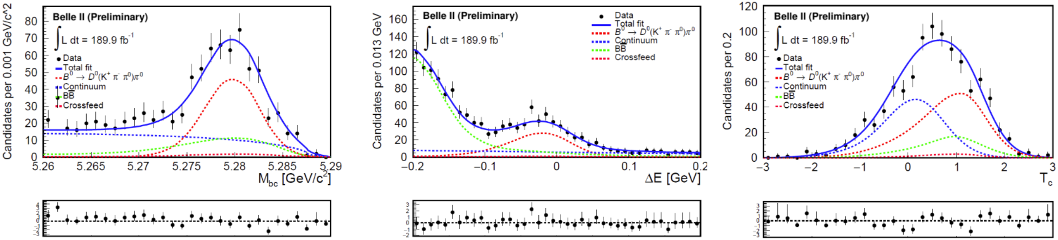


$B^0 \to \pi^0\pi^0$ Analysis

New for Belle II

- Background from fake photons, e.g. beam background
- Dominated by continuum background, signal-to-background ratio of $\approx 1/350$
  $\Rightarrow$ Dedicated machine learning algorithm
- Need to know flavor of B for $\mathcal{A}^{\mathrm{CP}}$
  $\Rightarrow$ Belle II's flavor tagger $\epsilon_{\mathrm{tag}} = (30.0 \pm 1.3)\%$
- 3D fit simultaneous in 7 bins of the flavor tagger quality
- Extract data-simulation correction factors using $B^0 \to D^0(\to K^-\pi^+\pi^0)\pi^0$

Control channel:



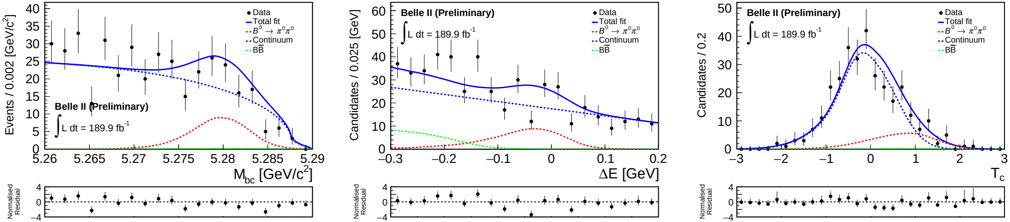
$B^0 \to \pi^0\pi^0$ Result

New for Belle II

Results competitive with Belle with a data set of less than one third!

$$\mathcal{A}^{CP} = 0.14 \pm 0.46\ \text{(stat)} \pm 0.07\ \text{(syst)}$$
$$\mathcal{B} = (1.32 \pm 0.25\ \text{(stat)} \pm 0.18\ \text{(syst)}) \cdot 10^{-6}$$

WA: $\mathcal{A}^{CP} = 0.33 \pm 0.22$, $\mathcal{B} = (1.59 \pm 0.26) \cdot 10^{-6}$



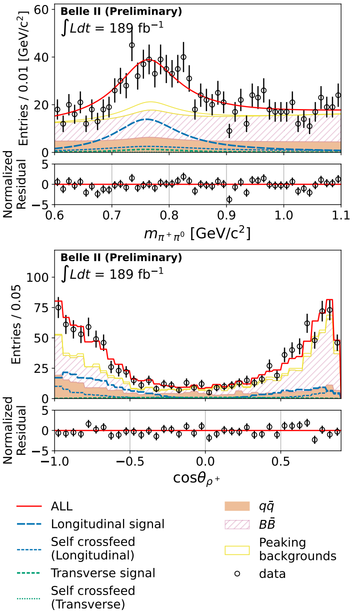
Signal enhanced $N(\text{sig}) = 93 \pm 18$

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

New for Belle II

- Intermediate ρ is a vector meson:
  $\Rightarrow$ Only the longitudinal polarization is usable for time dependent analysis to extract CP violating parameters, hence longitudinal polarization fraction f_L is required
  $\Rightarrow$ Fit helicity angle of $\rho \to \pi\pi^0$

- 6D (ΔE, CS, $2{\cdot}m(\pi\pi)$, $2{\cdot}\cos(\theta_\rho)$) fit taking correlations into account
  $\Rightarrow$ Peaking background has a similar final state as signal ($2\pi^0, 1\pi^+ + 1h^+$)
  $\Rightarrow$ Yields of measured peaking backgrounds are fixed in the fit



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

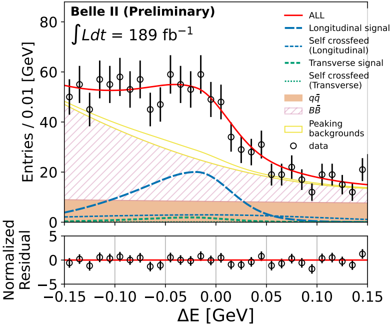
New for Belle II

$N(\text{long.}) = 235^{+24}_{-23}$, $N(\text{trans.}) = 21^{+19}_{-17}$

$$\mathcal{B} = (2.67 \pm 0.28 \ \text{(stat)} \pm \ 0.28 \ \text{(syst)}) \cdot 10^{-5}$$
$$f_L = 0.956 \pm 0.035 \ \text{(stat)} \pm 0.033 \ \text{(syst)}$$

WA: $\mathcal{B} = (2.77 \pm 0.19) \cdot 10^{-5}$, $f_L = 0.990^{+0.021}_{-0.019}$

Measurement of $\mathcal{B}$ limited by systematic uncertainty.
Largest contribution associated to π^0 reconstruction.



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

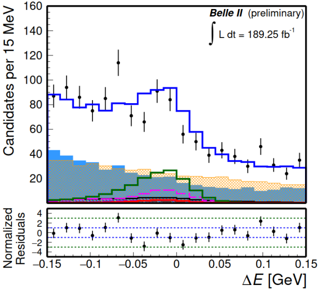
$N(\text{sig}) = 345 \pm 31$ arXiv:2206.12362

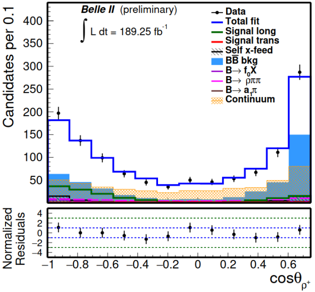
- Similar analysis strategy as $B^+ \to \rho^+\rho^-$
- 6D (ΔE, CS, 2·$m(\pi\pi)$, 2· $\cos(\theta_\rho)$) template fit taking correlations into account
  $\Rightarrow$ Fit distribution of helicity angles of π^+

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

WA: $\mathcal{A}^{CP} = -0.05 \pm 0.05$, $\mathcal{B} = (24.0 \pm 1.9) \cdot 10^{-6}$

- Largest systematic uncertainty from data-simulation discrepancies





Conclusion

- Study of hadronic B decays gives access to ϕ_2 and ϕ_3 and probes non-SM in subleading amplitudes

- Showed six measurements:
  $\Rightarrow$ Measurement of ϕ_3 using $B^+ \to D(K_S^0 h^+ h^-)K^+$
  $\Rightarrow$ Branching ratio and CP asymmetry of $B^0 \to K_S^0 \pi^0$
  $\Rightarrow$ Branching ratio and CP asymmetry of $B^+ \to \pi^+\pi^0$ and $B^+ \to K^+\pi^0$
  $\Rightarrow$ Branching ratio and CP asymmetry of $B^0 \to \pi^0\pi^0$
  $\Rightarrow$ Branching ratio and polarization of $B^0 \to \rho^+\rho^-$
  $\Rightarrow$ Branching ratio and CP asymmetry of $B^+ \to \rho^+\rho^0$

- Results demonstrate Belle II's capability to measure decays with neutrals
  $\Rightarrow$ Belle II is ready to offer key contributions