Recent Belle and Belle II results on hadronic *B* decays

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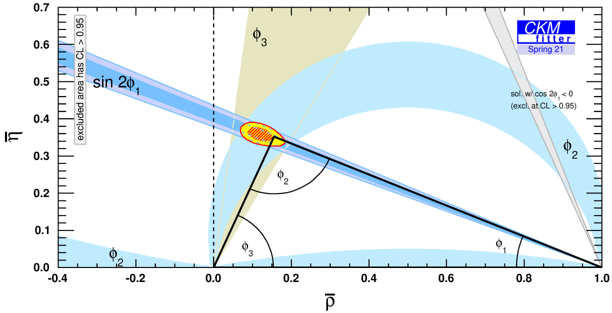
Motivation

- 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.

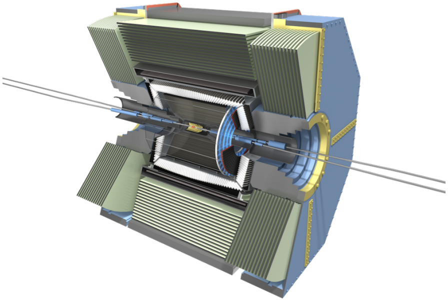
SuperKEKB and Belle II

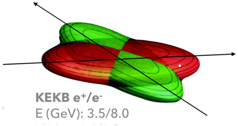
Belle II: general purpose detector situated at the interaction point of SuperKEKB.

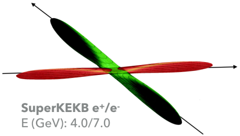
SuperKEKB: asymmetric $e^+ - e^-$ collider operating at $\Upsilon(4S)$ resonance.

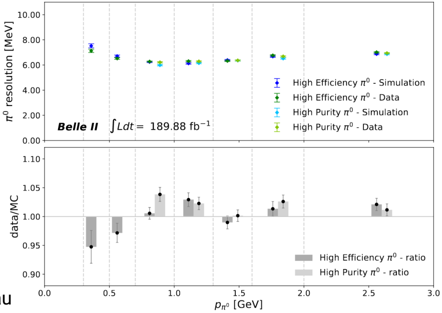
Operation:

- 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)









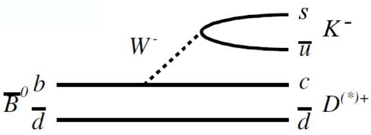
$\bar{B}^0 \to D^{*+}\pi^-$ and $\bar{B}^0 \to D^{*+}K^-$ Analysis

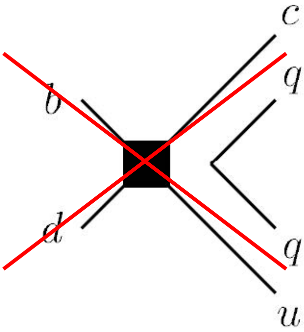
arXiv:2207.00134

- New Belle (711 fb^{-1}) measurement
- Reconstruct $\bar{B}^0 \to D^{*+}h^-$ ($h = \pi, K$), with $D^{*+} \to D^0\pi^+$ and $D^0 \to K^-\pi^+$ or $D^0 \to K^-2\pi^+\pi^-$
- Decays with four different flavors have no penguin or annihilation contribution - theoretically clean
- Decay widths of $B \to D^*h$ can be estimated from their semileptonic counterpart.

$$\Gamma(\bar{B}^0 \to D^{*+}h^-) = 6\pi^2\tau_B|V_{uq}|^2 f_h^2 X_h |a_1(q^2)| \times d\Gamma(\bar{B}^0 \to D^{*+}l^-\bar{\nu}_l)/dq^2|_{q^2=m_h^2}$$

- First measurement of $|a_1|$ with hadronic and semileptonic branching fractions from the same experiment - cancels many systematic uncertainties & strong QCD factorization test

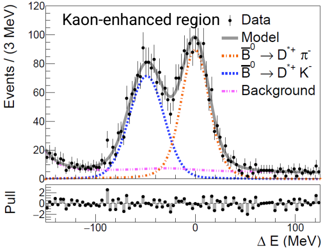




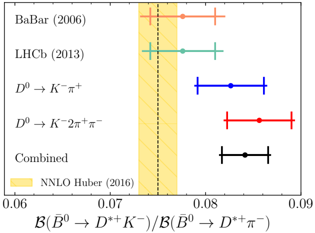
$\bar{B}^0 \to D^{*+}\pi^-$ and $\bar{B}^0 \to D^{*+}K^-$ Analysis

arXiv:2207.00134

- $\mathcal{R}_{K/\pi} = \mathcal{B}_{D^{*+}K^-}/\mathcal{B}_{D^{*+}\pi^-}$ a discrepancy of 2.7σ is found
- $|a_1(h)|$ is (4.7-5.8 for K) or (6.7-8.9 for π) σ smaller than those expected from theoretical predictions
- $|a_1(K)|^2/|a_1(\pi)|^2$ consistent with unity - no evidence for $SU(3)$ breaking effect is found to 5% precision
- Results consistent with Belle and Babar - Tensions suggest large non-factorizable contributions of $\mathcal{O}(15-20\%)$, non-SM physics, or both



$$\mathcal{B}_{D^{*+}\pi^-} = (2.62 \pm 0.02 \text{ (stat)} \pm 0.09 \text{ (syst)}) \cdot 10^{-3}$$
$$\mathcal{B}_{D^{*+}K^-} = (2.22 \pm 0.06 \text{ (stat)} \pm 0.08 \text{ (syst)}) \cdot 10^{-4}$$
$$\mathcal{R}_{K/\pi} = (8.41 \pm 0.24 \text{ (stat)} \pm 0.013 \text{ (syst)}) \cdot 10^{-2}$$
$$a_1(\pi) = 0.884 \pm 0.004 \text{ (stat)} \pm 0.003 \text{ (syst)} \pm 0.016 \text{ (ext)}$$
$$a_1(K) = 0.913 \pm 0.019 \text{ (stat)} \pm 0.008 \text{ (syst)} \pm 0.013 \text{ (ext)}$$



$|a_1(h)| = 1.05$ (QCDF)

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

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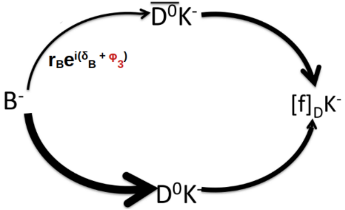
Joint Belle (711 fb^{-1}) and Belle II (128 fb^{-1}) analysis.

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



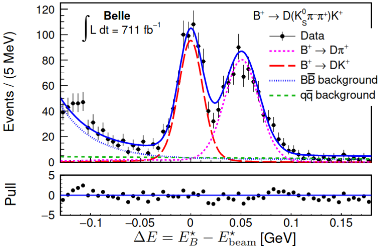
Measurement dependent on D decay physics:

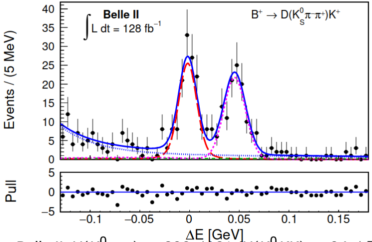
- 2D (ΔE, continuum suppression output) fit
- Bin D Dalitz plot (model-independent)
- Require external input (BESIII, CLEO)

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

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

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





Belle II: $N(K_S^0\pi\pi) = 280 \pm 21$, $N(K_S^0KK) = 34 \pm 5$

$K\pi$ 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:

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

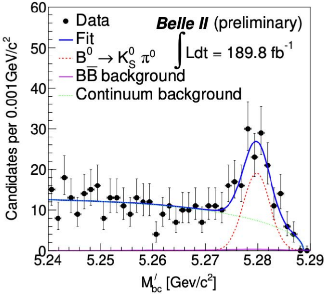
Deviations can be caused by an enhancement of color-suppressed tree amplitudes, or by contributions from non-SM physics

Previous tests of sum rule at Belle II using 62.8 fb^{-1}:

- Measurements of $B^0 \to K^+\pi^-$, $B^+ \to K^0_S\pi^+$ (arXiv:2106.03766), $B^0 \to K^0_S\pi^0$ (arXiv:2104.14871) and $B^+ \to K^+\pi^0$ (arXiv:2105.04111).

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

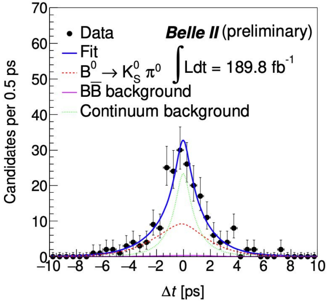
$N(\text{sig}) = 135^{+16}_{-15}$ arXiv:2206.07453



- The sum rule has a 10% experimental uncertainty dominated by $\mathcal{A}^{\text{CP}}_{K^0\pi^0}$. 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 $\mathcal{A}^{\text{CP}}_{K^0\pi^0}$ from a 4D fit ($M_{\text{bc}}, \Delta E, \Delta t$, continuum suppression BDT output), with $\mathcal{S}_{\text{CP}}$, Δm_d, and τ_{B^0} fixed to their known values

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

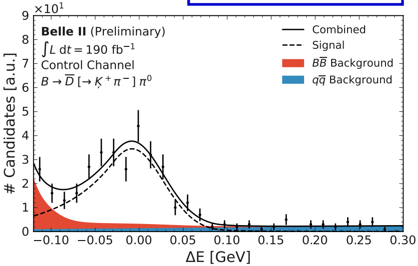
WA: $\mathcal{A}^{\text{CP}} = 0.01 \pm 0.10$, $\mathcal{B} = (9.9 \pm 0.5) \cdot 10^{-6}$

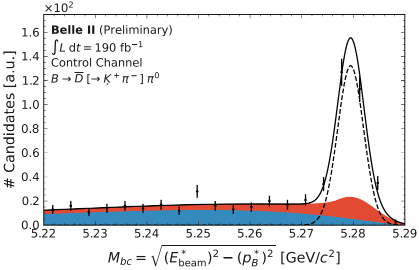


$B^+ \to K^+\pi^0$ and $B^+ \to \pi^+\pi^0$ Analysis

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

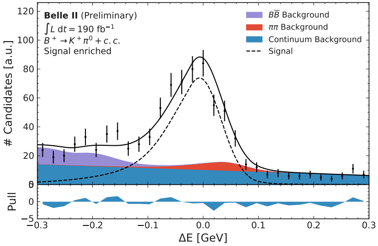
New for Belle II

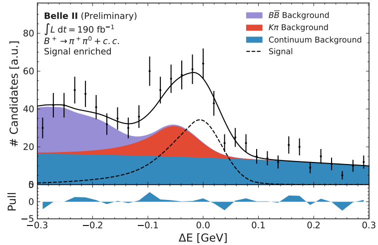
$N(K^+\pi^0) = 887 \pm 43$, $N(\pi^+\pi^0) = 422 \pm 37$

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

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.





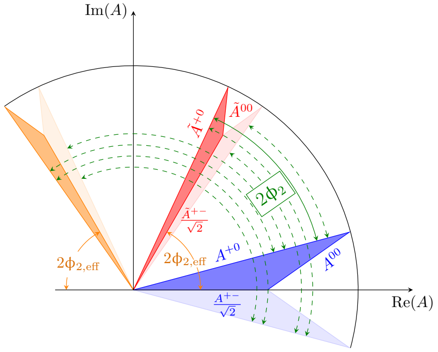
SIGNAL MODES

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
$\Rightarrow$ Previous Belle II measurements using 62.8 fb^{-1}: $B^0 \to \pi^+\pi^-$ (arXiv:2106.03766), $B^0 \to \pi^0\pi^0$ (arXiv:2107.02373) and $B^+ \to \rho^+\rho^0$ (arXiv:2206.12362)

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

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

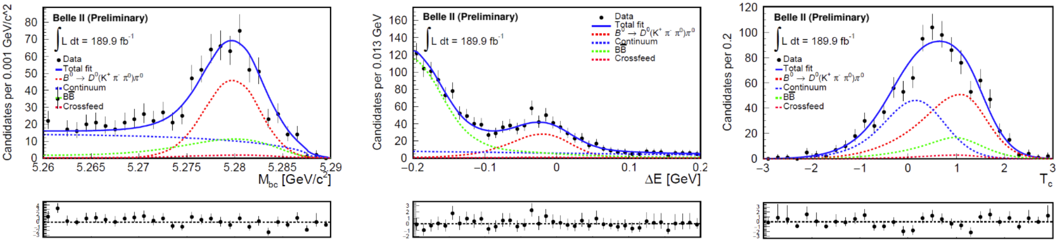


$B^0 \to \pi^0\pi^0$ Analysis

New for Belle II

- QCD-based factorization predicts $\mathcal{B} < 1 \times 10^{-6}$ - experimental disagreement
- 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
- 3D fit simultaneous in 7 bins of the flavor tagger quality

$B^0 \to D^0(\to K^-\pi^+\pi^0)\pi^0$ control channel used to validate procedure and extract data-simulation correction factors:



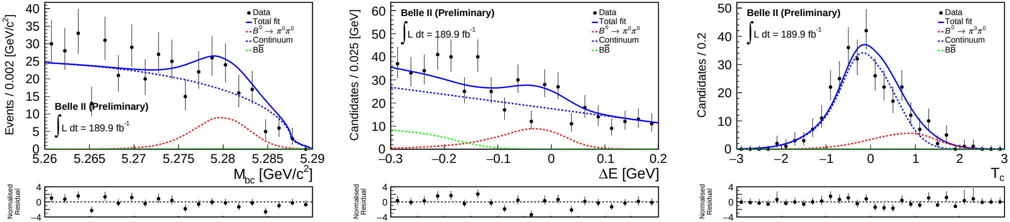
$B^0 \to \pi^0\pi^0$ Result

New for Belle II

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

$$\mathcal{A}^{CP} = 0.14 \pm 0.46\ (\text{stat}) \pm 0.07\ (\text{syst})$$
$$\mathcal{B} = (1.27 \pm 0.25\ (\text{stat}) \pm 0.18\ (\text{syst})) \cdot 10^{-6}$$

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



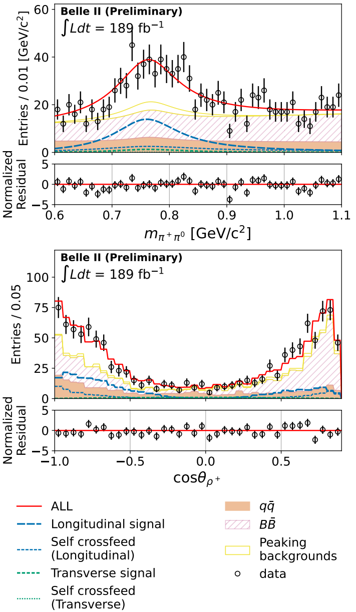
Signal enhanced $N(\text{sig}) = 93 \pm 18$

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

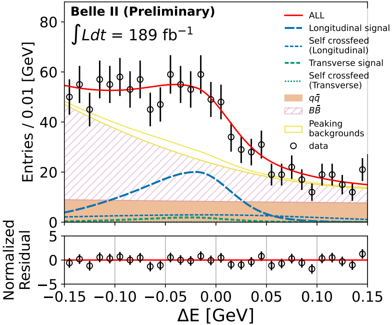
New for Belle II

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

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

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.



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

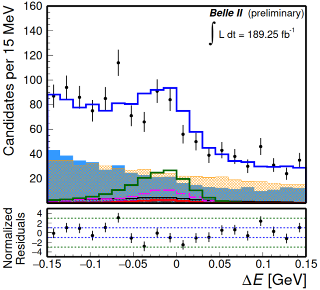
$N(\text{sig}) = 345 \pm 31$ arXiv:2206.12362

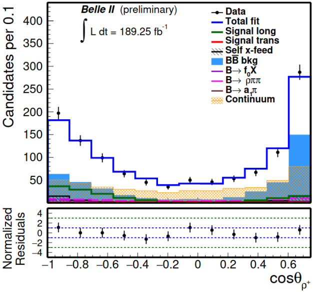
- Similar analysis strategy as $B^+ \to \rho^+\rho^-$
- 6D (ΔE, CS, 2·$m(\pi\pi)$, 2· $\cos(\theta_\rho)$) template fit taking correlations into account
  $\Rightarrow$ Fit distribution of helicity angles of π^+

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

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 seven measurements:
  $\Rightarrow$ Branching ratio, CP asymmetry and $|a_1(h)|$ using $B^0 \to D^{*-}h^+$
  $\Rightarrow$ 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