CP violation in charmless B decays

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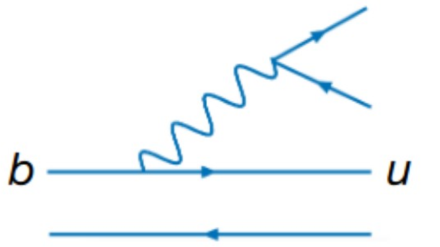
On behalf of the Belle II and LHCb collaborations

Heavy Quarks and Leptons (HQL2023)

Mumbai, 2.12.2023

Charmless B decays



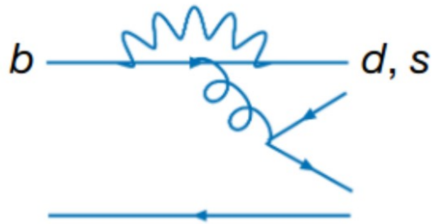
- b→u tree and b→d,s loop transitions are rare → charmless $\mathcal{B} \sim 10^{-6}$

- relatively large loop contributions give sensitivity to NP

- probe the SM via:

→ over-constraining the CKM triangle: ϕ_1/β via TDCPV in b→s decays
(→see S. BAHINIPATI talk, Friday @ 12.15)

→ via isospin sum rules ϕ_2/α via isospin analyses $B \to \pi\pi/\rho\rho$



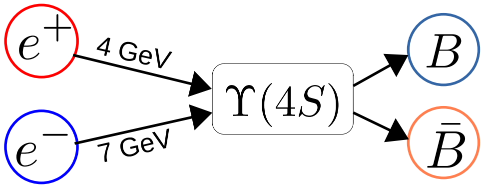
- in decays to fully hadronic final states often poor theory predictions due to non-factorizable amplitudes
→ suppress theory uncertainties by performing measurements of isospin related modes

Showing today

- recent results related to $B \to \pi\pi/\rho\rho$ @ Belle II
- recent test of isospin sum rule in $B \to K\pi$ @ Belle II
- recent measurement of CP violation in three-body charmless B decays @ LHCb

Belle II @ SuperKEKB – B factory of 2nd generation

- **SuperKEKB:** asymmetric e^+e^- collider operating
  nominally at $\Upsilon(4S) = 10.58$ GeV



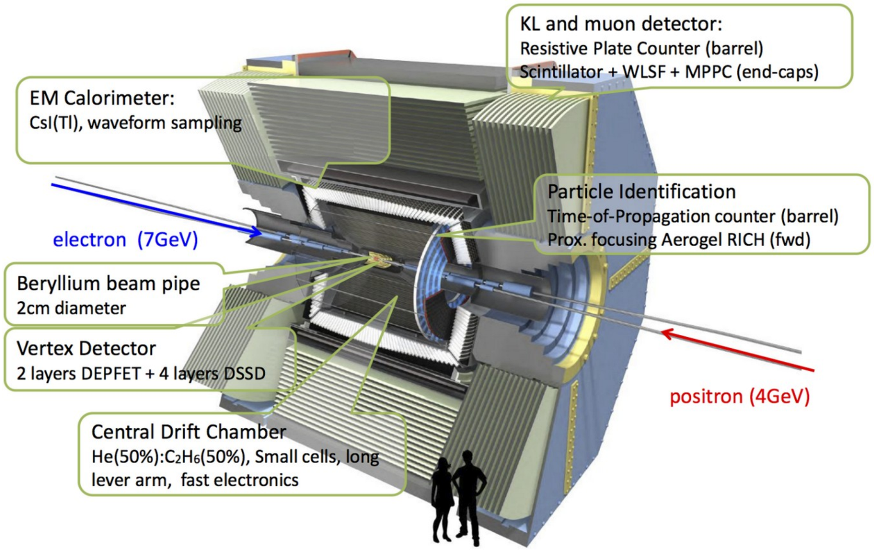
(+ large number of D, τ !)

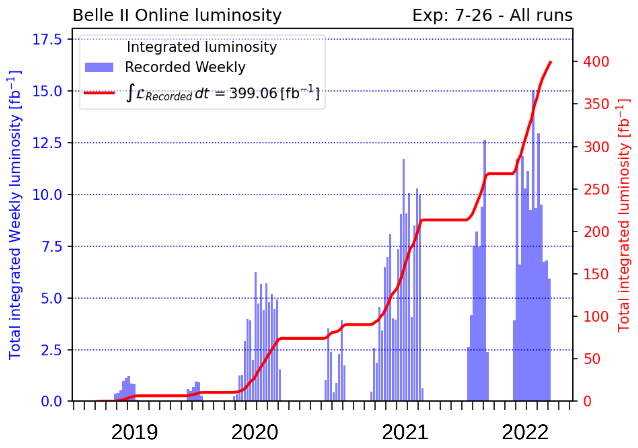
- **Belle II:** general purpose spectrometer
  → 4π coverage
  → clean e^+e^- environment with known initial state!
  → good charged track reconstruction efficiency, excellent particle identification, gamma reconstruction
  → excellent vertexing ($\sigma \sim 60\mu$m, for B,D vertices)

Up to now collected ~362 fb^{-1} of data @ $\Upsilon(4S)$

(~BaBar, ~1/2 of Belle)

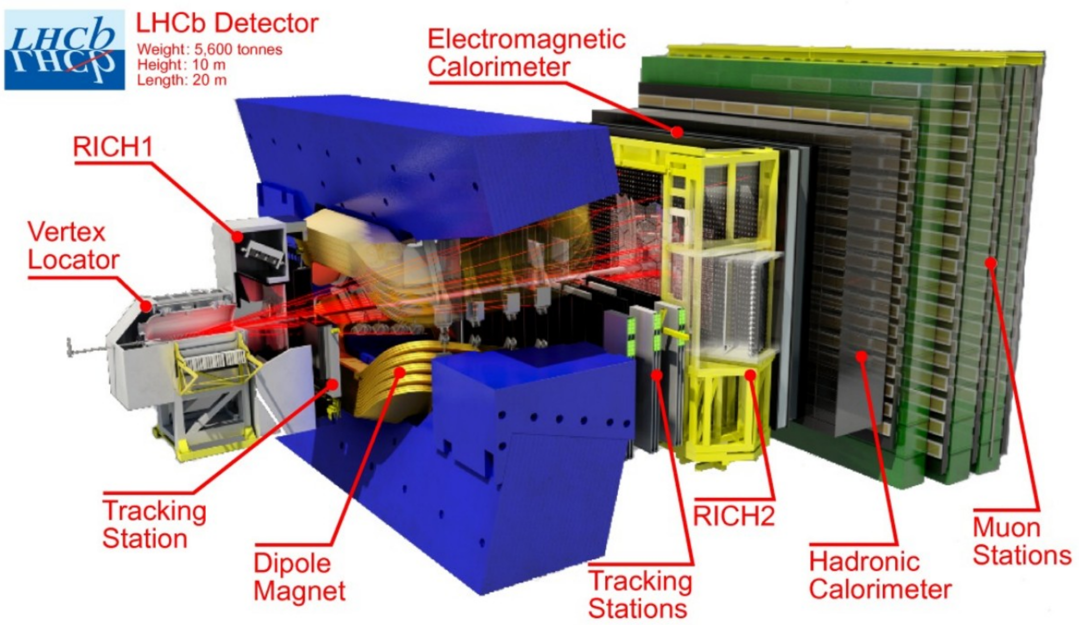
→ some results based on 190 fb^{-1} only

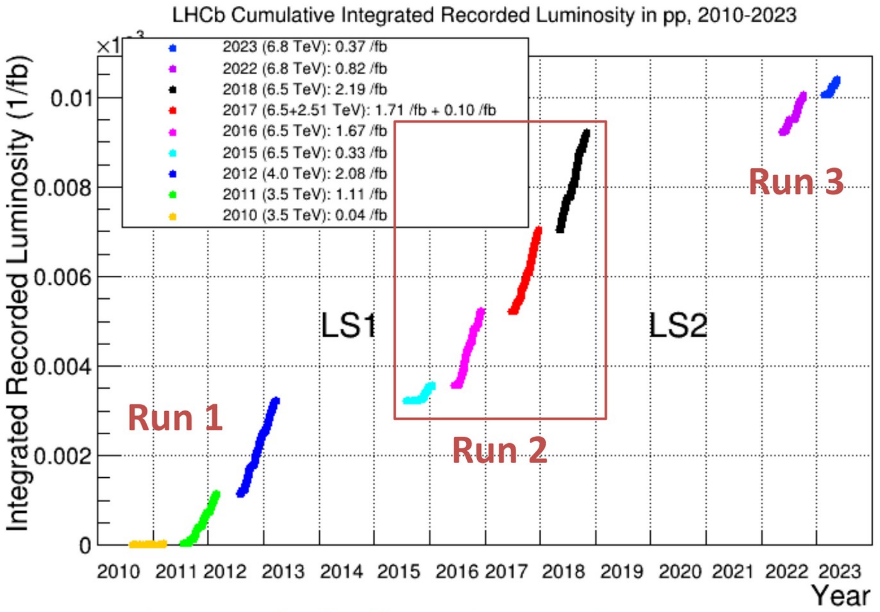




LHCb experiment

- single arm spectrometer @ LHC
  → high-precision tracking → particle identification → decay vertex system



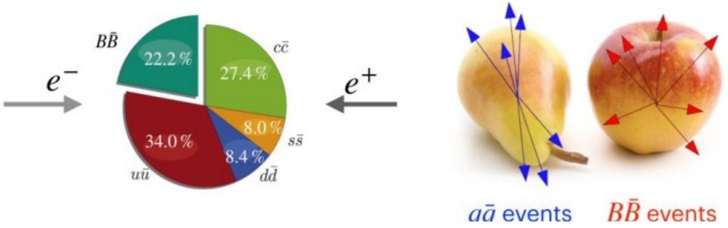


→ analyses presented today based on RUN 2 data

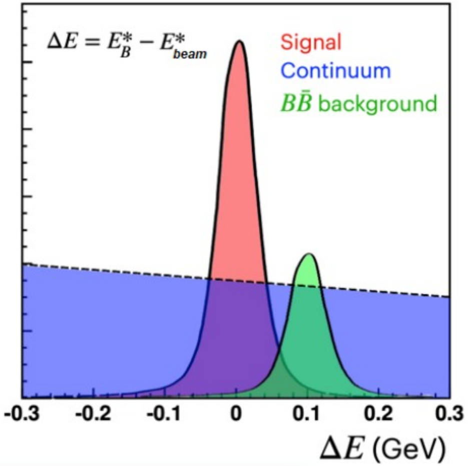
$\mathcal{L} = 5.9\ \mathrm{fb}^{-1}$ p-p collisions @ 13 TeV CM energy (2015-2018)

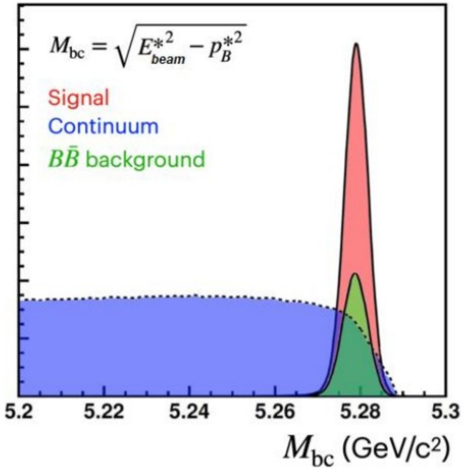
Analysis workflow @ Belle II

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**
   - base fit templates on the distributions from MC (+ calibrate on data)
   - fit to data to extract physics quantities
4. **Systematic uncertainties**
   - toy studies + control modes





Challenges: small branching fractions ($\mathcal{B}$), high backgrounds, neutral particles

Determination of ϕ_2/α from $B \to \pi\pi$ / $\rho\rho$

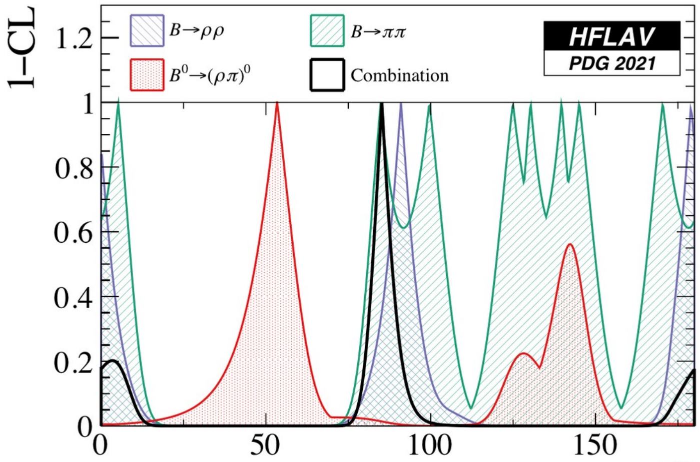
Belle II

→ ϕ_2 can be determined from TDCPV in $B^0 \to \pi^+\pi^- / \rho^+\rho^-$
but due to sizable b→d penguin contribution
$S \propto \sin(2\phi_2 + 2\Delta\phi_2)$

→ $\Delta\phi_2$ can be accessed based on the isospin relations

→ $\mathcal{B},\ \mathcal{A}_{CP}$ in $B^+ \to \pi^0\pi^+,\ B^0 \to \pi^0\pi^0$

→ $\mathcal{B},\ \mathcal{A}_{CP},\ f_L$ in $B^+ \to \rho^0\rho^+,\ B^0 \to \rho^0\rho^0$



$\alpha[^\circ] = 85.2 \,^{+4.8}_{-4.3}$

HFLAV

→ $\rho\rho$ less ambiguity in ϕ_2 due to smaller penguin contribution

→ possible to measure TDCPV in $\rho^0\rho^0$

→ low $\mathcal{B}$: $10^{-6} - 10^{-5}$ (+ large contributions from continuum backgrounds)

Several recent measurements @ Belle II providing new inputs for ϕ_2

$$\mathcal{A}_{CP} = \frac{\Gamma(\bar{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\bar{B} \to \bar{f}) + \Gamma(B \to f)}$$

$$f_L = \frac{|H_0|^2}{|H_0|^2 + |H_+|^2 + |H_-|^2}$$

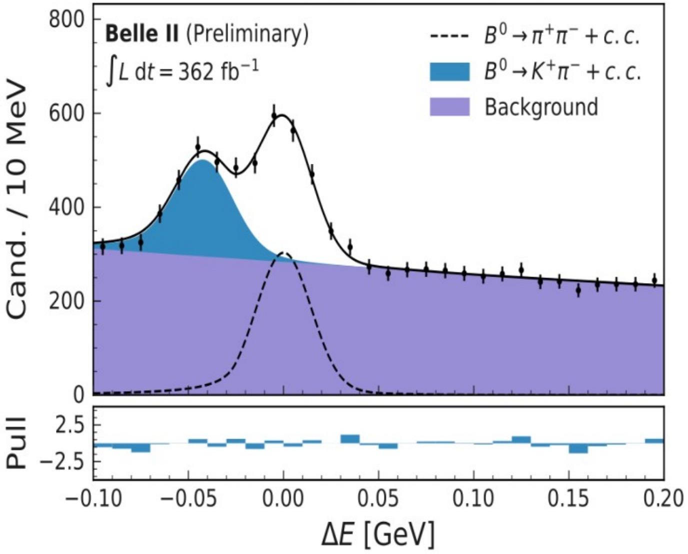
longitudinal transverse

Phys. Lett. B 601, 151–163 (2004)

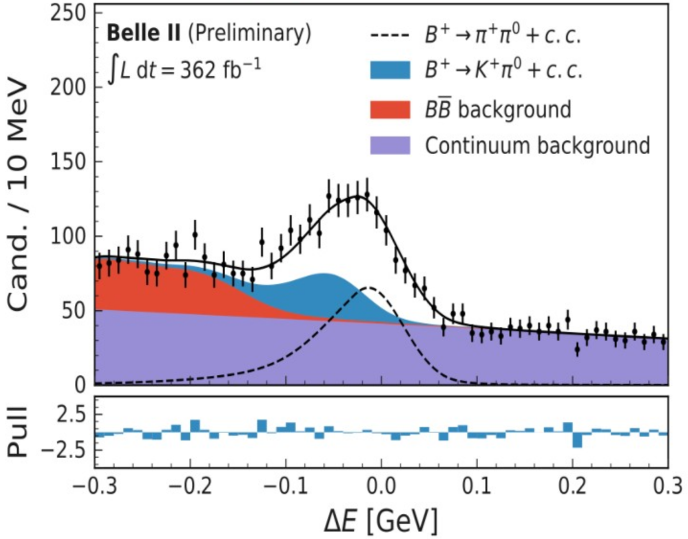
$B \to \pi\pi$ decays

[arxiv: 2310.06381] (with 362 fb^{-1})

~1500 $B^0 \to \pi^+\pi^-$



~900 $B^+ \to \pi^+\pi^0$



$$\mathcal{B}(\pi^+\pi^-) = (5.83 \pm 0.22 \pm 0.17) \times 10^{-6}$$

world's best

$$\mathcal{B}(\pi^+\pi^0) = (5.10 \pm 0.29 \pm 0.32) \times 10^{-6}$$

$$\mathcal{A}_{CP}'(\pi^+\pi^0) = -0.081 \pm 0.54 \pm 0.008$$

→ compatible and competitive with W.A.

→ modes with π^0 systematically limited by the π^0 reconstruction efficiency systematics (will reduce with more data available)

The case of $B^0 \to \pi^0\pi^0$ [PRD107 (2023) 112009] (with 190 fb^{-1})

Belle II

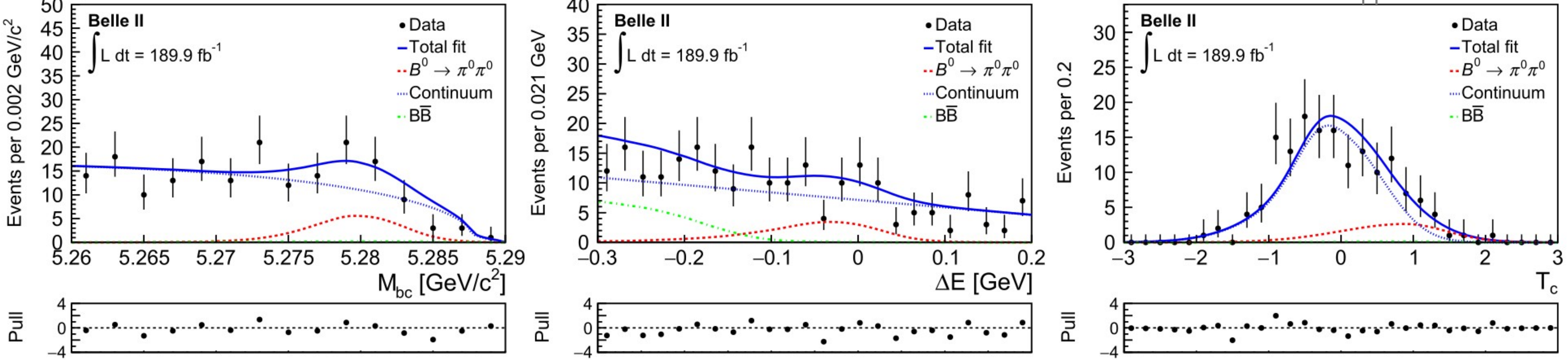
→ very very challenging measurement due to solely 4 photons in the final state
→ signal swamped by large backgrounds (mostly true π^0 combination from $q\bar{q}$ events)
→ still, **uniquely accessible @ Belle II**
→ 4D fit is performed to extract $\mathcal{B}$ and A_{CP}

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

Precision comparable to Belle is achieved using ~1/3 of data size!
→ due to improved π^0 eff. and continuum rejection

Systematics dominated by π^0 eff., followed by continuum modeling

continuum suppression variable

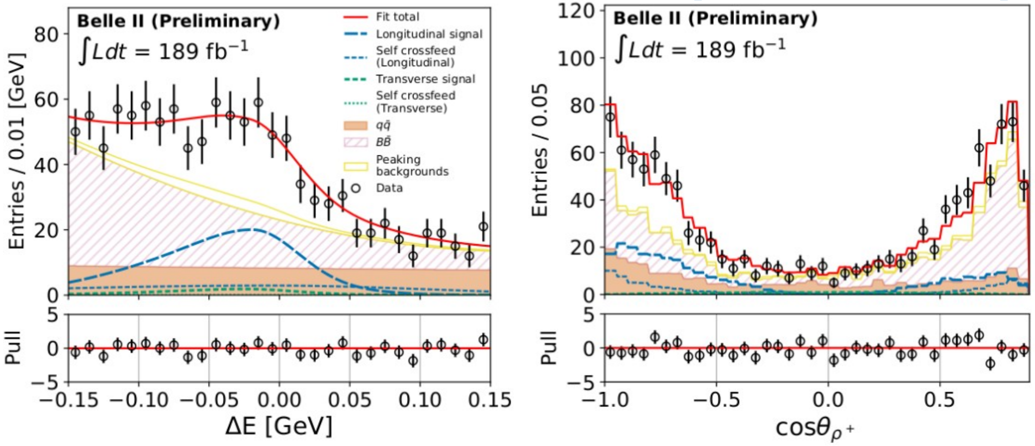


$B \to \rho\rho$ decays (with 190 fb^{-1})

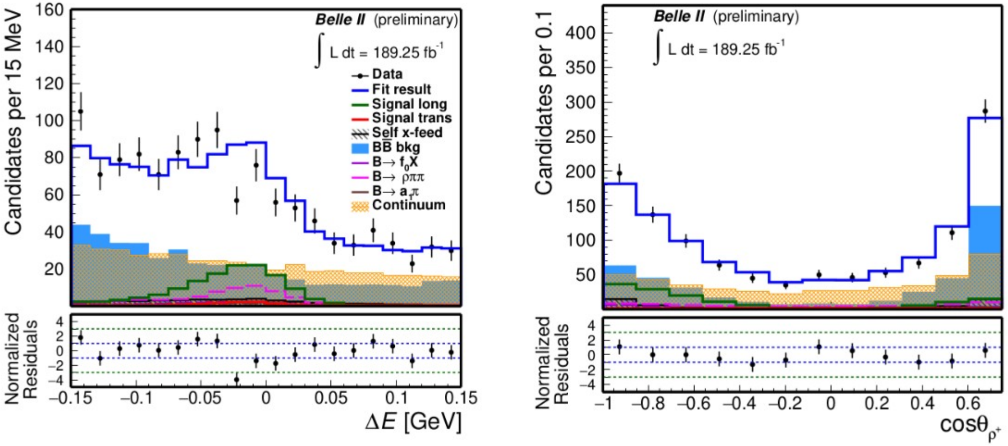
Belle II

→ due to large width of ρ limited signal/background separation capabilities
→ four pions in the final state → multiple non-negligible peaking background contributions
→ angular analysis needed to disentangle longitudinal and transverse polarizations

$B^0 \to \rho^+\rho^-$ [arxiv: 2208.03554]



$B^+ \to \rho^+\rho^0$ [arxiv: 2206.12362]



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

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

→ major systematics from data/MC mismodelings
→ update to full dataset and time-dependent CPV in $\rho^+\rho^-$ ongoing

→ on par with Belle precision

Isospin sum rule test

[arxiv: 2310.06381] (with 362 fb^{-1})

Belle II

→ Stringent null test of SM, sensitive to presence of non-SM dynamics.

Gronau (Phys. Lett. B 627 (2005) no.1, 82-88)

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

(within ~1%)

→ experimentally consistent with 0 at 10% level, limited by $K^0_S\pi^0$ mode

→ **Belle II in unique position to measure all observables at single experiment**

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

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

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

$$\mathcal{B}(K^+\pi^0) = (13.93 \pm 0.38 \pm 0.84) \times 10^{-6}$$
$$\mathcal{A}_{CP}(K^+\pi^0) = +0.013 \pm 0.027 \pm 0.005$$

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

$$\mathcal{B}(K^0_S\pi^+) = (24.40 \pm 0.71 \pm 0.86) \times 10^{-6}$$
$$\mathcal{A}_{CP}(K^0_S\pi^+) = +0.046 \pm 0.029 \pm 0.007$$

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

$$\mathcal{B} = (10.50 \pm 0.62 \pm 0.67) \times 10^{-6}$$
$$\mathcal{A}_{CP} = -0.01 \pm 0.12 \pm 0.05$$

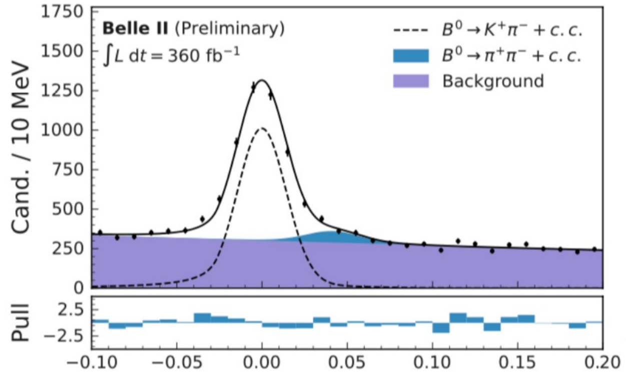
world's best

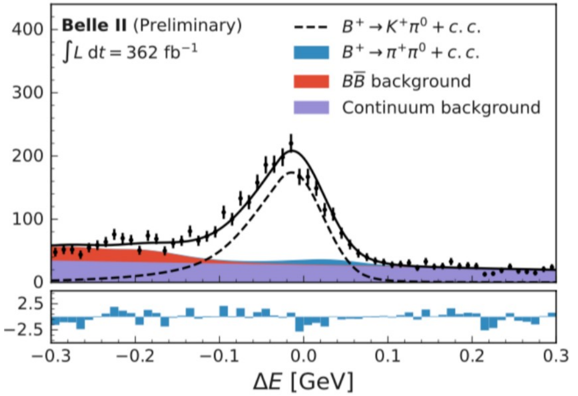
$$I_{K\pi} = -0.03 \pm 0.13 \pm 0.05$$

(world average 0.13 ± 0.11)

precision on par with W/A!

→ 5% uncertainty achievable @ 10 ab^{-1}





Studies of three-body charmless B decays @ LHCb

Studies of three-body charmless B decays @ LHCb

→ two recent measurements, based on the RUN 2 data (5.9 fb^{-1})

Direct CP violation in charmless three-body decays of $B^{\pm}$ mesons

$$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$$
$$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$$
$$B^{\pm} \to \pi^{\pm}K^{+}K^{-}$$
$$B^{\pm} \to K^{\pm}K^{+}K^{-}$$

[PRD.108.012008(2023)]

Search for direct CP violation in charged charmless B → VP decays

$$B^{\pm} \to (\rho^{0} \to \pi^{+}\pi^{-})\pi^{\pm}$$
$$B^{\pm} \to (\rho^{0} \to \pi^{+}\pi^{-})K^{\pm}$$
$$B^{\pm} \to (K^{*0} \to K^{+}\pi^{-})\pi^{\pm}$$
$$B^{\pm} \to (K^{*0} \to K^{+}\pi^{-})K^{\pm}$$
$$B^{\pm} \to (\phi \to K^{+}K^{-})K^{\pm}$$

[PRD.108.012013(2023)]

Studies of three-body charmless B decays @ LHCb

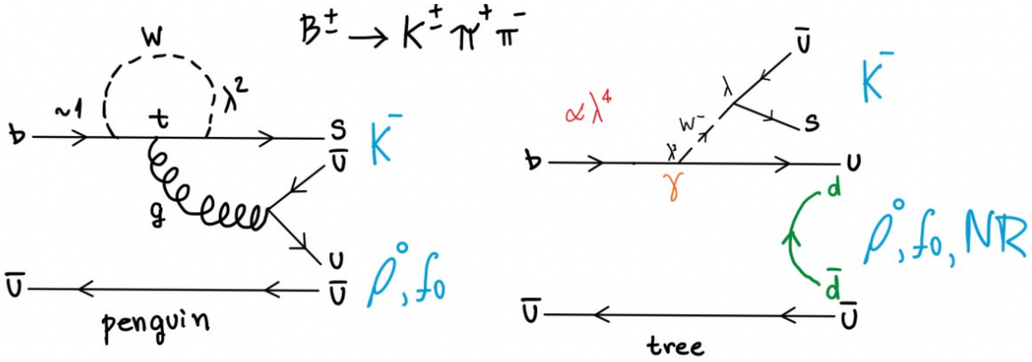
→ motivated by large asymmetries observed in RUN 1 measurements of $B^{\pm} \rightarrow h^{\pm}h^{+}h^{-} (h = K, \pi)$
(PhysRevD.90.112004, PhysRevLett.124.031801(2020), PhysRevLett.123.231802(2019), PhysRevD101012006(2020))

→ condition for direct CPV: interference between amplitudes with different strong and weak phases
(leading to the same final state)

→ in three body charmless decays interference from:

- penguin and tree diagrams
- intermediate resonances
- final-state-interactions (FSI)

hadronic rescattering: $\pi\pi \leftrightarrow KK$
→ coupling final states with same quantum numbers
e.g. $B^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$ & $B^{\pm} \rightarrow \pi^{\pm}K^{+}K^{-}$



→ providing a way to understand the role of short- and long-distance contributions to the strong phase difference needed for CPV

L. Falcão @ CKM 2023

Direct CPV in $B^\pm \to h^\pm h^+ h^-$

[PRD.108.012008(2023)]

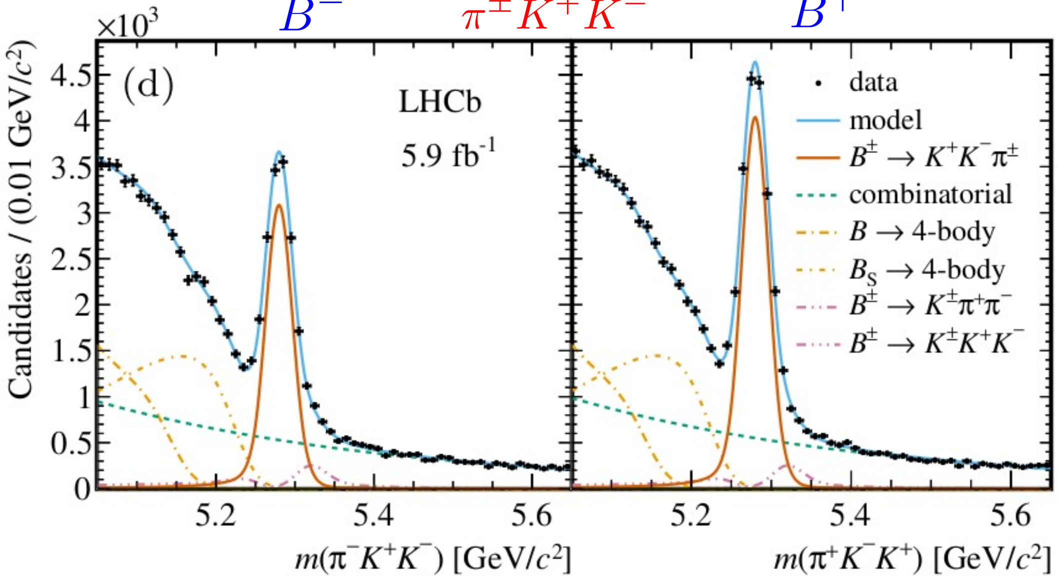
→ event selection:
- multivariate selector (BDT) based on 10 topological/kinematic observables
- stringent PID requirements to reduce cross contamination to % level
- charm vetoes

→ fit $m(h^\pm h^+ h^-)$ distributions to determine signal yields and raw asymmetries

→ raw asymmetries are corrected for reconstruction efficiency and the $B^\pm$ production asymmetry determined from $B^\pm \to J/\psi K^\pm$ control channel

$$A_{CP} = \frac{A_{raw}^{corr} - A_P}{1 - A_{raw}^{corr} A_P}$$

B^- $\pi^\pm K^+ K^-$ B^+



Decay mode	Total yield	A_{raw}
$B^\pm \to K^\pm\pi^+\pi^-$	$499\,200 \pm 900$	$+0.006 \pm 0.002$
$B^\pm \to K^\pm K^+ K^-$	$365\,000 \pm 1000$	-0.052 ± 0.002
$B^\pm \to \pi^\pm\pi^+\pi^-$	$101\,000 \pm 500$	$+0.090 \pm 0.004$
$B^\pm \to \pi^\pm K^+ K^-$	$32\,470 \pm 300$	-0.132 ± 0.007

Direct CPV in $B^{\pm} \to h^{\pm}h^{+}h^{-}$

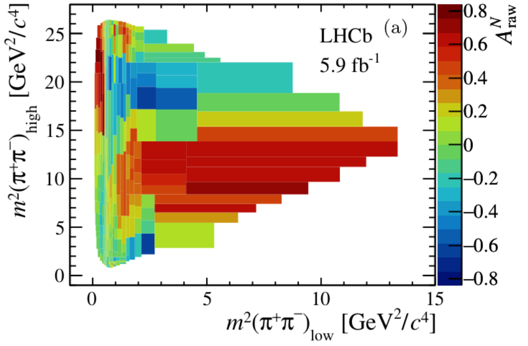
[PRD.108.012008(2023)]

→ obtained phase space integrated asymmetries:

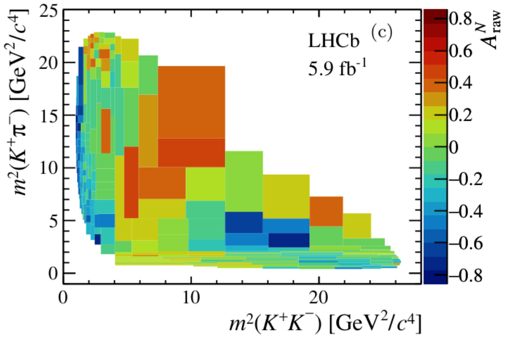
	stat.	syst.	$J/\psi K$	
$A_{CP}(B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}) = +0.011$	$\pm\, 0.002$	$\pm\, 0.003$	$\pm\, 0.003$	$\Longrightarrow 2.4\sigma$
$A_{CP}(B^{\pm} \to K^{\pm}K^{+}K^{-}) = -0.037$	$\pm\, 0.002$	$\pm\, 0.002$	$\pm\, 0.003$	$\Longrightarrow 8.5\sigma$ → **First observation!**
$A_{CP}(B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}) = +0.080$	$\pm\, 0.004$	$\pm\, 0.003$	$\pm\, 0.003$	$\Longrightarrow 14.1\sigma$
$A_{CP}(B^{\pm} \to \pi^{\pm}K^{+}K^{-}) = -0.114$	$\pm\, 0.007$	$\pm\, 0.003$	$\pm\, 0.003$	$\Longrightarrow 13.6\sigma$ → **First observation!**

→ localized asymmetries: using sPlot technique, asymmetry maps in Dalitz space are made

$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$



$B^{\pm} \to \pi^{\pm}K^{+}K^{-}$



→ localized asymmetries ranging from (-80%, 80%), with several asymmetry flips

→ closer look into region $(1.0, 2.25)\ \mathrm{GeV}^2/c^4$ where the S-wave $\pi\pi \leftrightarrow KK$ rescattering effect is seen in elastic scattering experiments confirms large CPV in this region in all four modes

CP violation in charged charmless B → V P decays

[PRD.108.012013(2023)]

→ novel method is used to extract direct CPV in quasi-two-body B → V P decays, which result in three-body final states (due to V decay) $(V = \rho^0, K^{*0}, \phi;\ P = \pi, K)$

→ the method avoids full amplitude analysis, based on the key features of three-body B decays

1) large available phase space
2) dominance of scalar and vector resonances @ ~ 1 GeV/c^2
3) clear signatures of the resonant amplitudes in the Dalitz plot

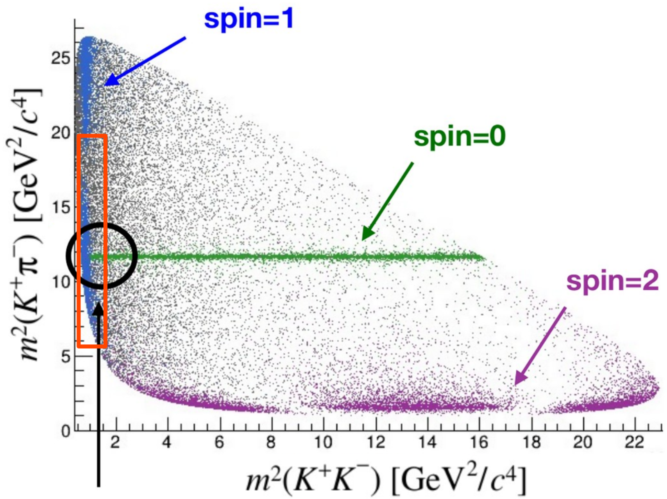
→ method description:

In $B^\pm \to R(\to h_1^- h_2^+) h_3^\pm$ a narrow band in $m^2(h_1^- h_2^+)$ around the resonance is selected

The distribution of $m^2(h_1^- h_3^+)$ in a band reflects the angular distribution of decay products:

Vector: → parabolic (decay width $\propto \cos^2\theta_{hel}$)
Scalar: → uniform (isotropic in $\cos\theta_{hel}$)
V+S inter.: → linear ($\propto \cos\theta_{hel}$)

$B^\pm \to K^\pm K^+ \pi^-$ MC



Overlap between vector and scalar resonances

CP violation in charged charmless B → V P decays

[PRD.108.012013(2023)]

→ in total: $|\mathcal{M}_\pm|^2 = f(\cos\theta(m_V^2, s_\perp)) = \overset{\text{scalar}}{\boxed{p_0^\pm}} + \overset{\text{interference}}{\boxed{p_1^\pm \cos\theta(m_V^2, s_\perp)}} + \overset{\text{vector}}{\boxed{p_2^\pm \cos^2\theta(m_V^2, s_\perp)}}$ $\quad s_\perp \equiv m^2(h_1^- h_3^+)$

→ $m^2(h_1^- h_3^+)$ distribution is therefore fitted (for B^+ and B^-) with the ansatz $f(x) = p_0 + p_1 x + p_2 x^2$

→ finally $\mathcal{A}_{CP}^V$ is determined as $\mathcal{A}_{CP}^V = \dfrac{|\mathcal{M}_-|^2 - |\mathcal{M}_+|^2}{|\mathcal{M}_-|^2 + |\mathcal{M}_+|^2} = \dfrac{p_2^- - p_2^+}{p_2^- + p_2^+}$

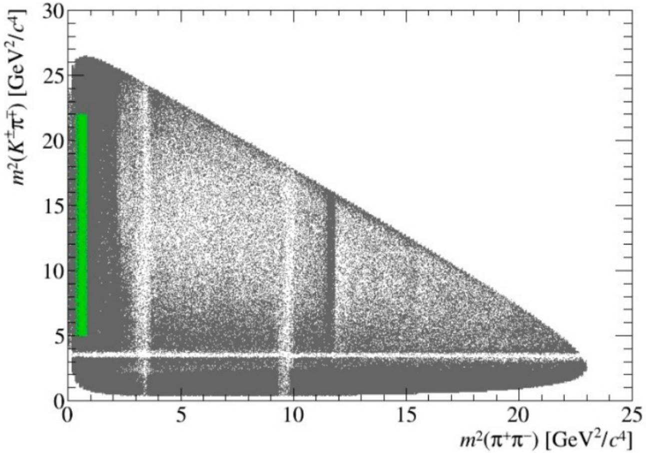
Results

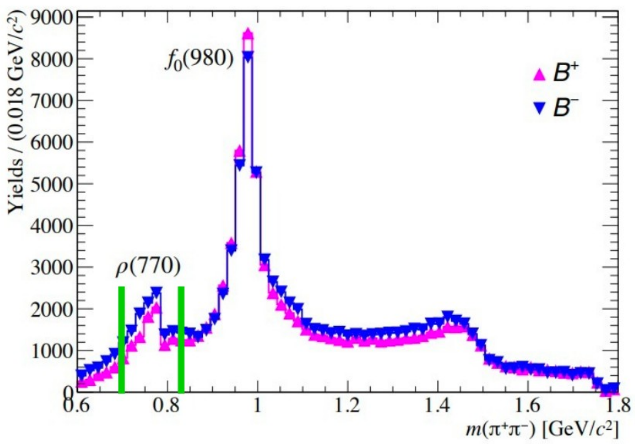
$B^\pm \to (\rho^0 \to \pi^+\pi^-)K^\pm$

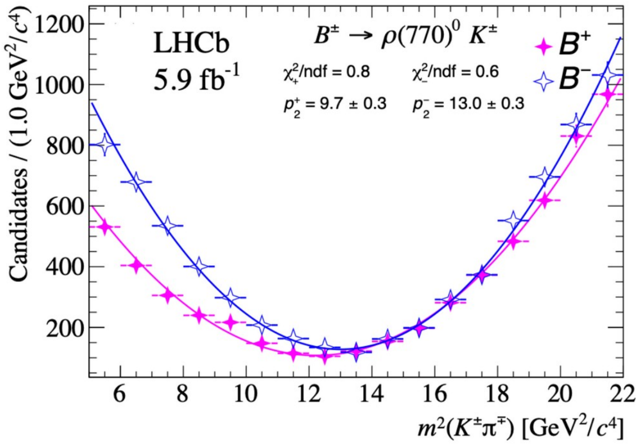
$$\boxed{\mathcal{A}_{CP}^V(\rho(770)^0 K^\pm) = +0.150 \pm 0.019 \pm 0.011} \implies 6.8\sigma$$

First observation!

→ large contribution from $f_0(980)$







CP violation in charged charmless B → V P decays

[PRD.108.012013(2023)]

Complete set of results

Decay channel	$\mathcal{A}_{CP}$ (this work)	Previous measurements
$B^{\pm} \to (\rho(770)^0 \to \pi^+\pi^-)\pi^{\pm}$	$-0.004 \pm 0.017 \pm 0.009$	$+0.007 \pm 0.011 \pm 0.016$ (LHCb)
$B^{\pm} \to (\rho(770)^0 \to \pi^+\pi^-)K^{\pm}$	$+0.150 \pm 0.019 \pm 0.011$	$+0.44 \pm 0.10 \pm 0.04$ (BABAR) $+0.30 \pm 0.11 \pm 0.02$ (Belle)
$B^{\pm} \to (K^*(892)^0 \to K^{\pm}\pi^{\mp})\pi^{\pm}$	$-0.015 \pm 0.021 \pm 0.012$	$+0.032 \pm 0.052 \pm 0.011$ (BABAR) $-0.149 \pm 0.064 \pm 0.020$ (Belle)
$B^{\pm} \to (K^*(892)^0 \to K^{\pm}\pi^{\mp})K^{\pm}$	$+0.007 \pm 0.054 \pm 0.032$	$+0.123 \pm 0.087 \pm 0.045$ (LHCb)
$B^{\pm} \to (\phi(1020) \to K^+K^-)K^{\pm}$	$+0.004 \pm 0.014 \pm 0.007$	$+0.128 \pm 0.044 \pm 0.013$ (BABAR)

→ significantly more precise than previous measurements

→ apart from $B^{\pm} \to \rho^0 K^{\pm}$ other modes consistent with zero, as expected from CPT constraint.
[Phys. Rev. D94 (2016) 054028]

→ in $B^{\pm} \to \rho^0 K^{\pm}$ large $\mathcal{A}_{CP}$ likely due to FSI.

Summary

- recent measurements of observables sensitive to ϕ_2/α @ Belle II
  - → most precise $\mathcal{B}(B^0 \to \pi^+\pi^-)$
  - → on par with world's best in $B^0 \to \pi^0\pi^0$ and $B \to \rho\rho$
  - → updates to LS1 dataset ongoing

- test of $K\pi$ isospin sum rule @ Belle II
  - → in agreement with the SM, still statistically limited (by $K_s^0\pi^0$)
  - → precision competitive to W.A.
  - → world's best result on $\mathcal{A}_{CP}(K_s^0\pi^0)$

- measurement of CPV in three-body charmless B decays @ LHCb
  - → first observation of CPV in $B^\pm \to \pi^\pm\pi^+\pi^-$ and $B^\pm \to K^\pm K^+ K^-$
  - → highly non-uniform asymmetries across the Dalitz space
  - → indication of CPV involving $\pi\pi \longleftrightarrow KK$ rescattering

- measurement of CP asymmetries in B → V P @ LHCb
  - → novel method that allows to extract $\mathcal{A}_{CP}^V$ w/o the full amplitude analysis
  - → first observation of CPV in $B^\pm \to \rho^0(770)K^\pm$