Charmless B decays at Belle II

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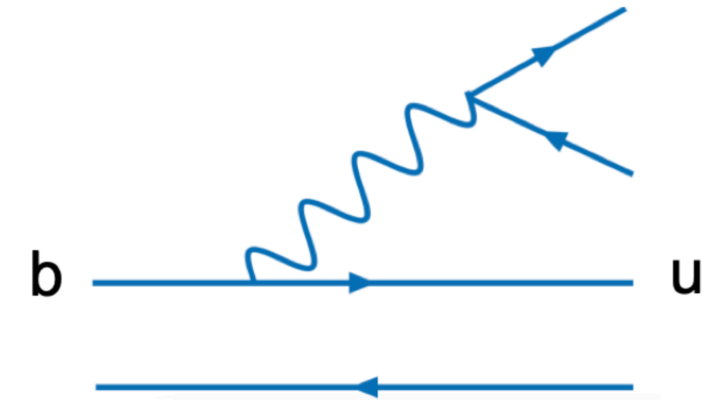
for the Belle II Collaboration

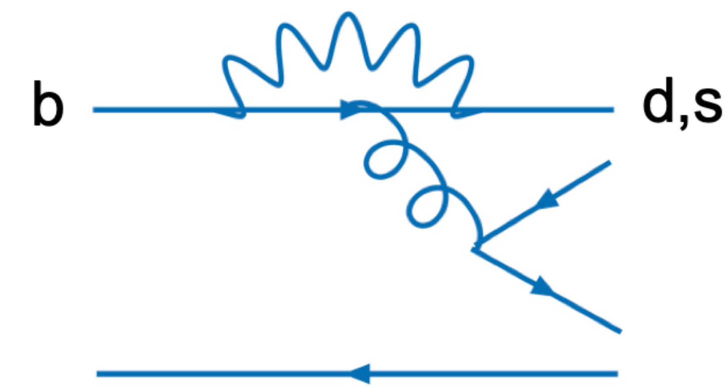
12th CKM Workshop - Santiago de Compostela - Sept 18–22, 2023

Charmless

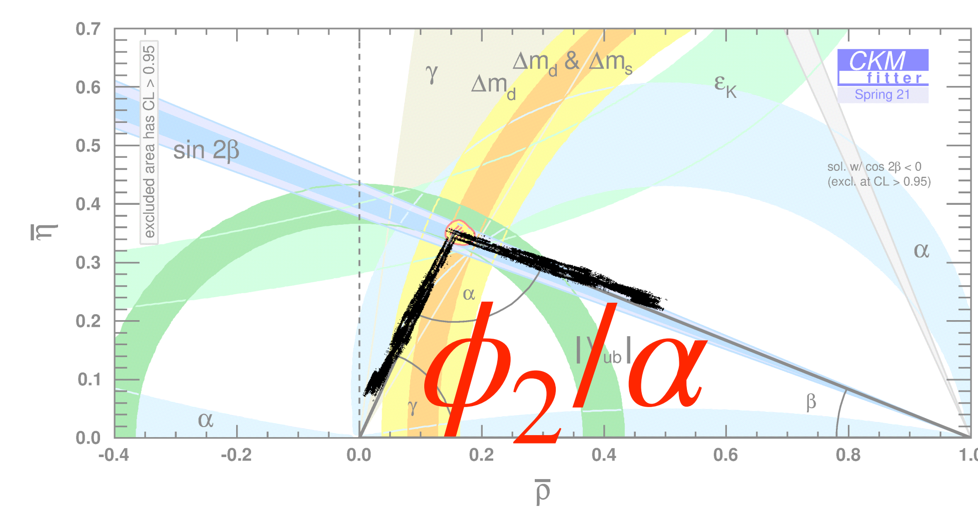
Suppressed decays, $O(10^{-6})$ branching fractions. Non-negligible contribution of loop transitions gives sensitivity to non-SM physics.



Fully hadronic final states, non-factorizable amplitudes. Difficult application of perturbation theory: predictions tend to have large uncertainties. [Nucl.Phys.B 675 (2003) 333-415; Chin.Phys.C 46 (2022) 12, 123103]



Resort to symmetries: combined analysis of decays related by isospin symmetry to suppress theoretical uncertainties to O(1%) [Phys.Rev.Lett. 65 (1990) 3381-3384; Phys.Rev.D 59 (1999) 113002; Phys.Lett.B 627 (2005) 82-88]



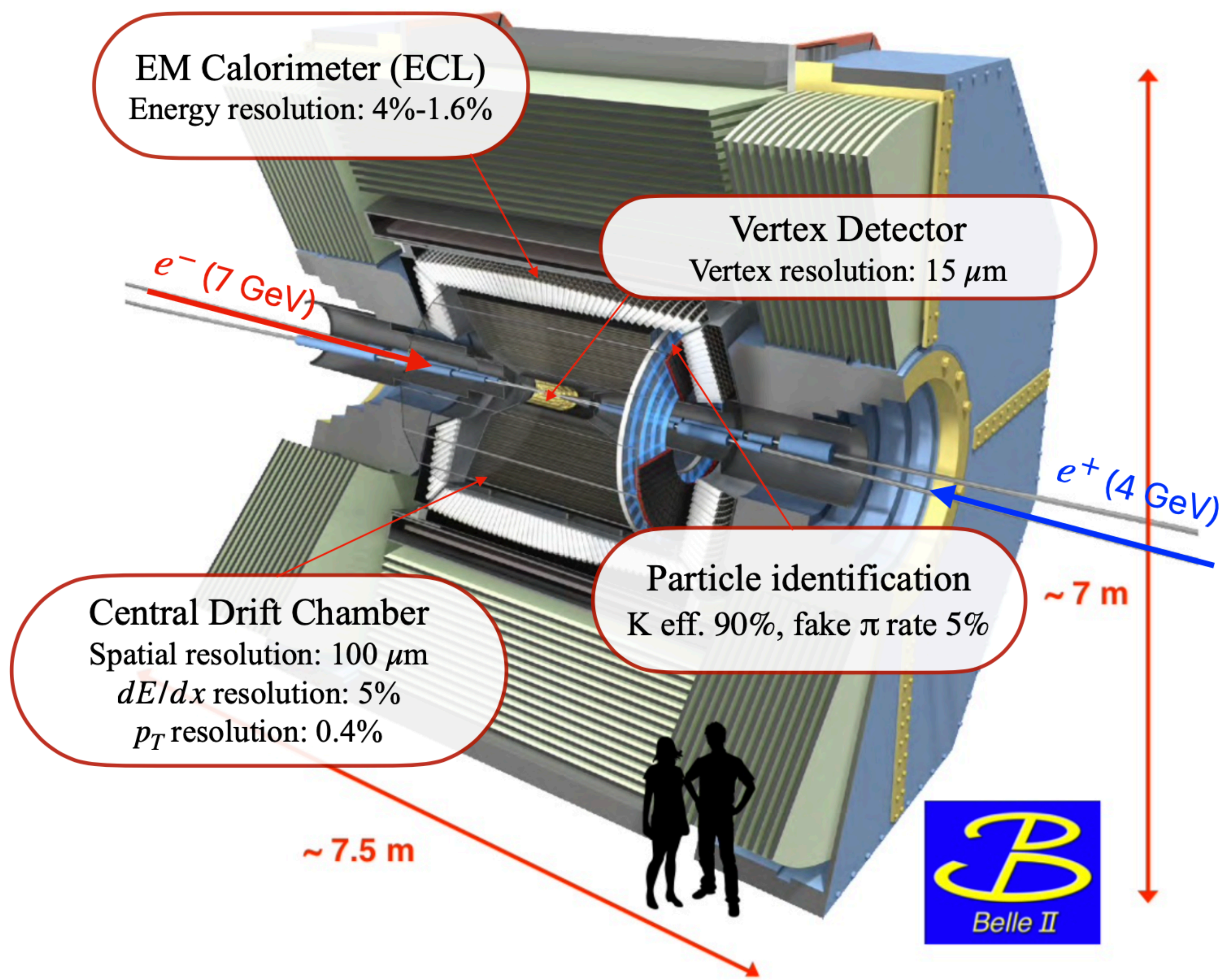
Allow to measure CKM angle ϕ_2/α and to test SM with sum rules

Unique access

Belle II can access within the same experimental environment all relevant final states of isospin-related charmless decays.

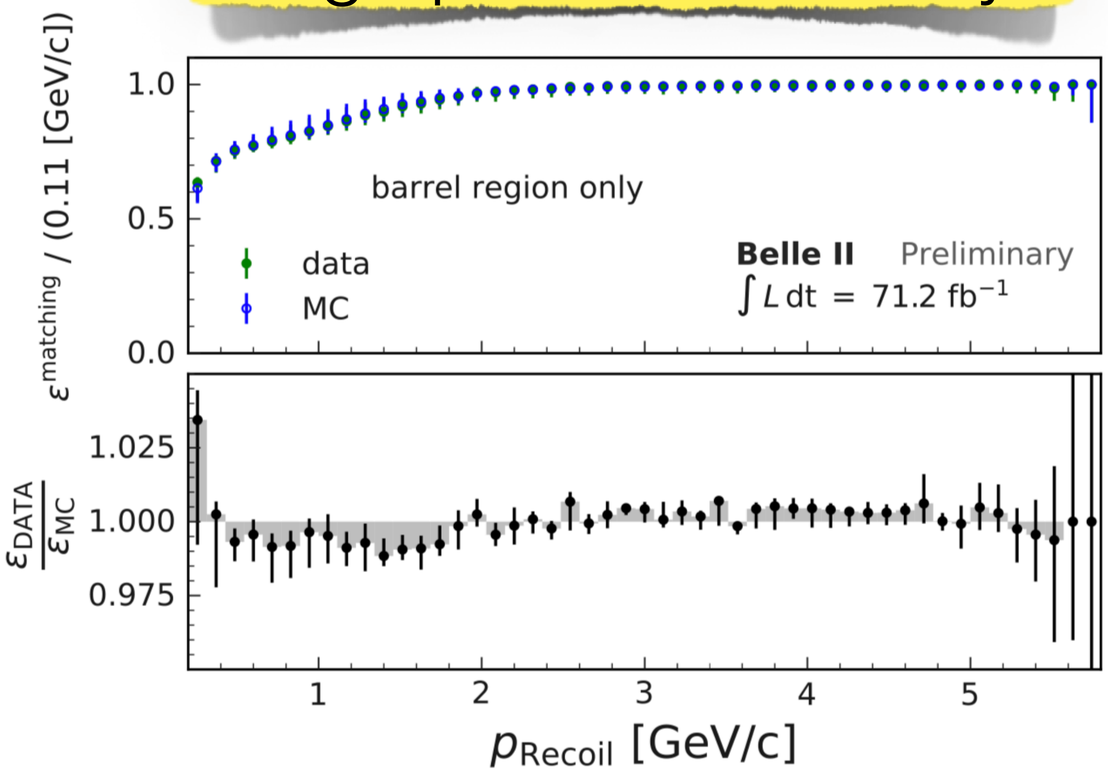
Efficiency for reconstructing tracks, π^0, K_S are similar across the board. Performance pretty uniform over any final state and kinematic regime.

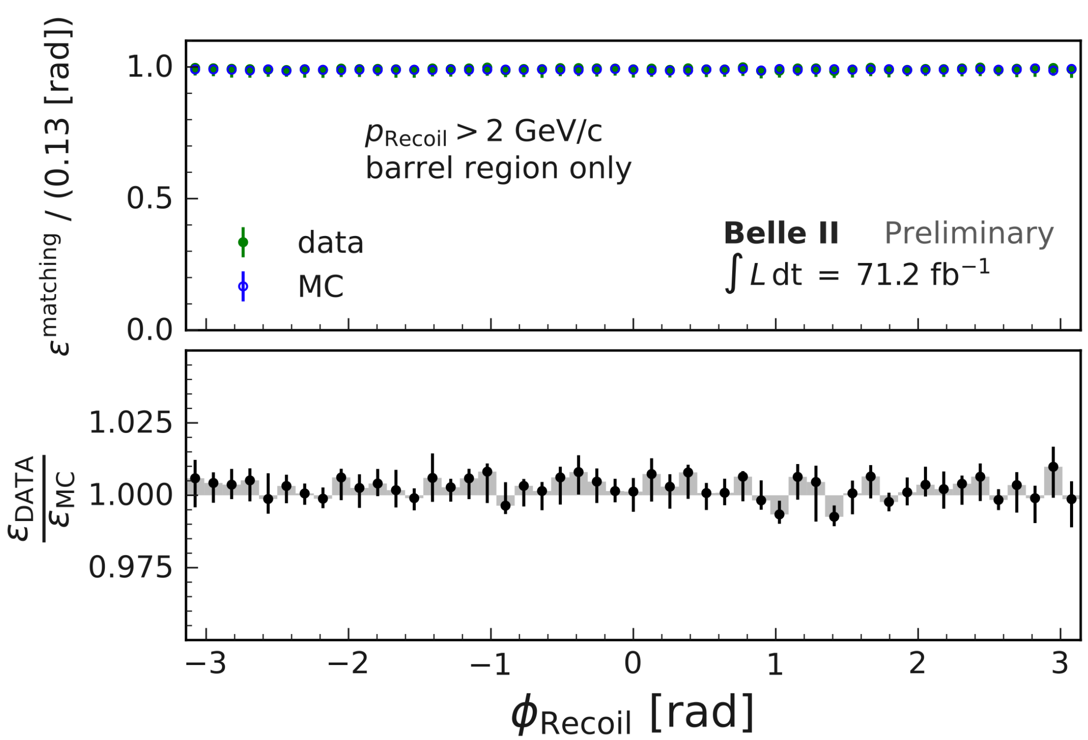
362 fb^{-1} of Υ(4S) data. Comparable to Babar's. Half of Belle's.



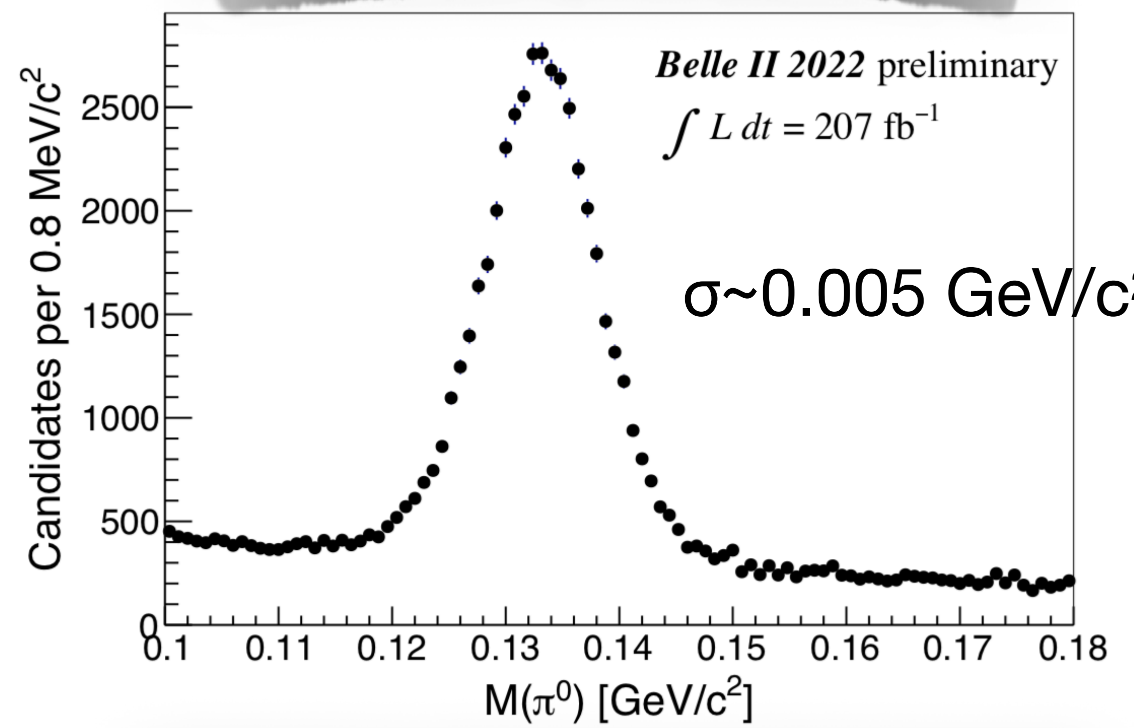
Fit for neutrals

High photon efficiency

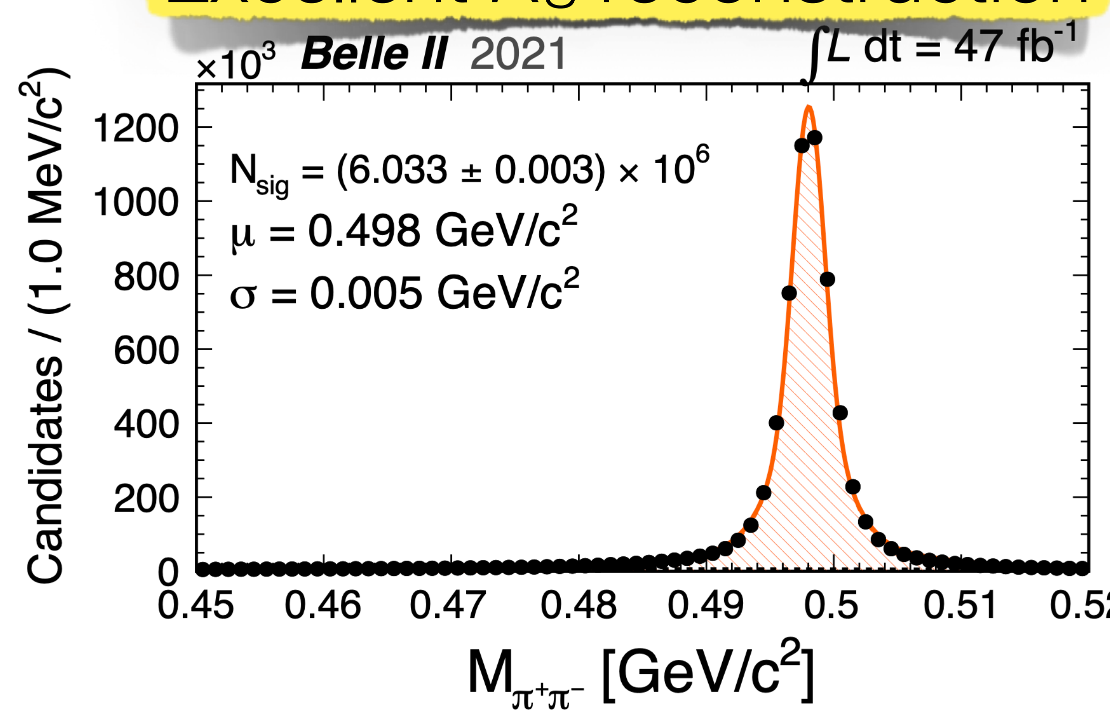




Good π^0 reconstruction

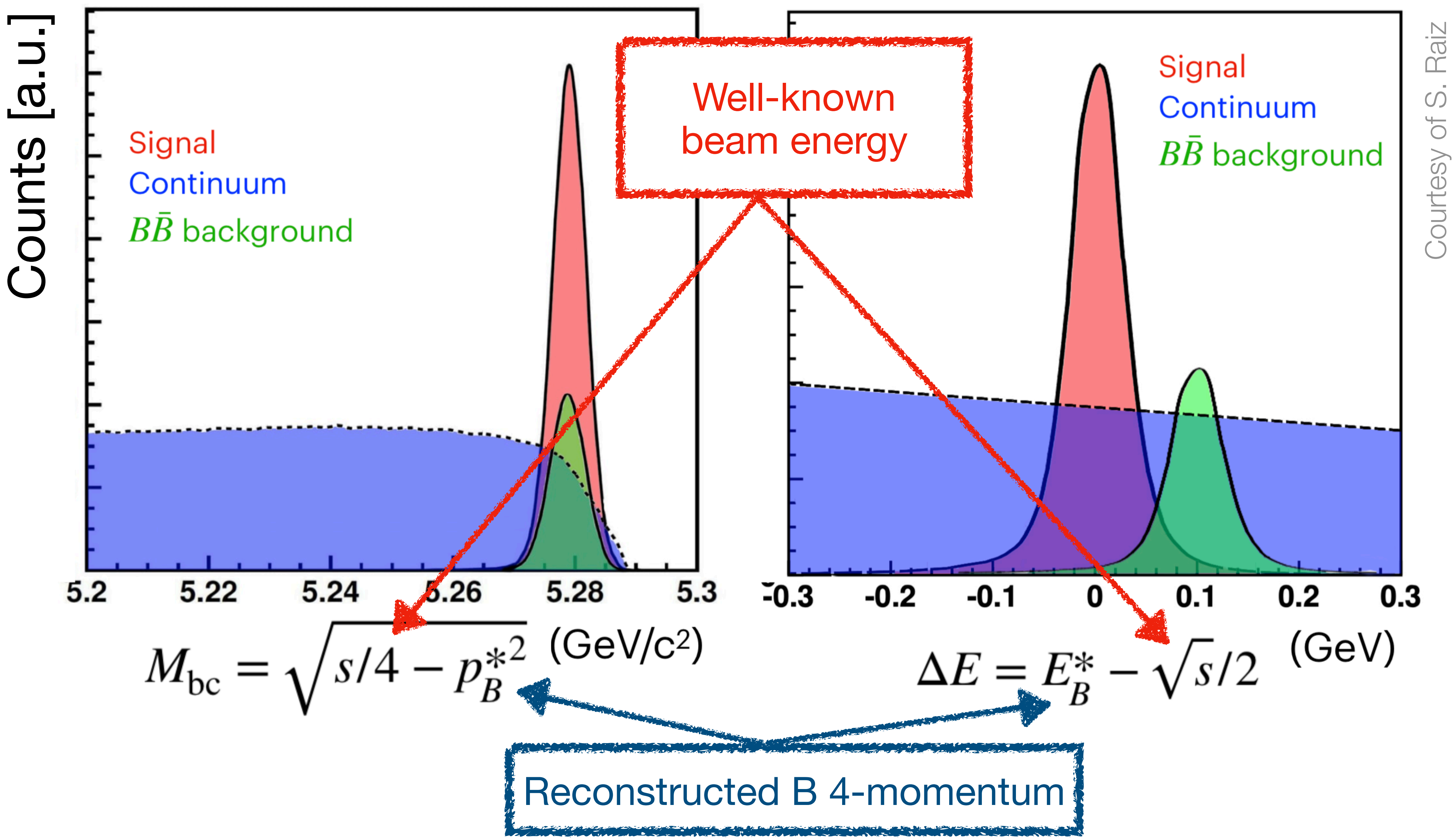


Excellent K_S reconstruction



B-factory basics

Threshold production from point-like colliding particles, $e^+e^- \rightarrow Y(4S) \rightarrow B\bar{B}$.
Low background and knowledge of initial state: kinematic well constrained to extract the signal.

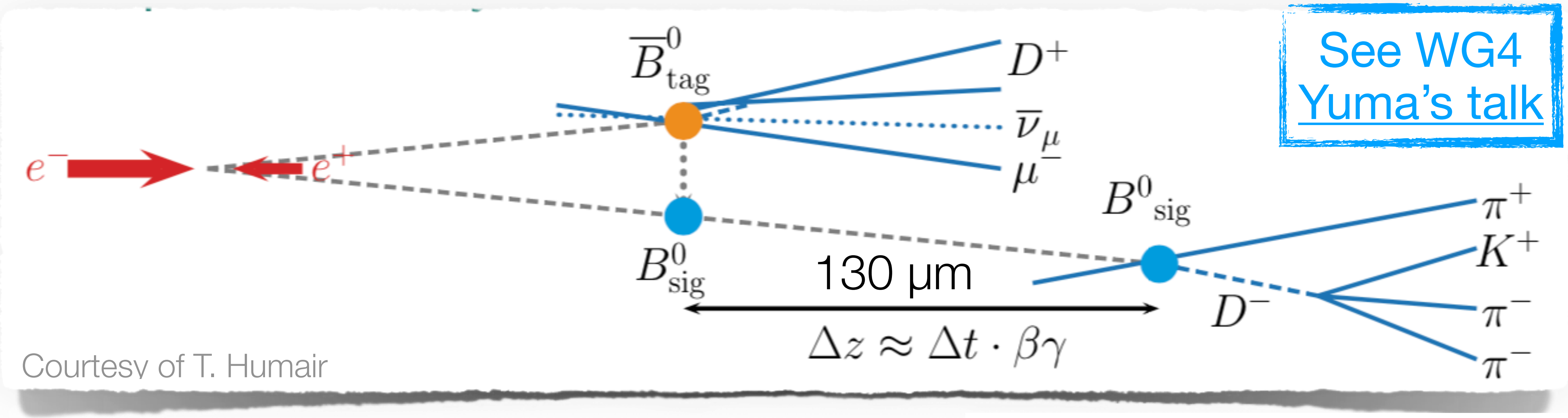


Displacement and tagging

Asymmetric-energy collision gives the boost to measure displacement.

B mesons flight only 130 µm on average (200 µm at Belle).

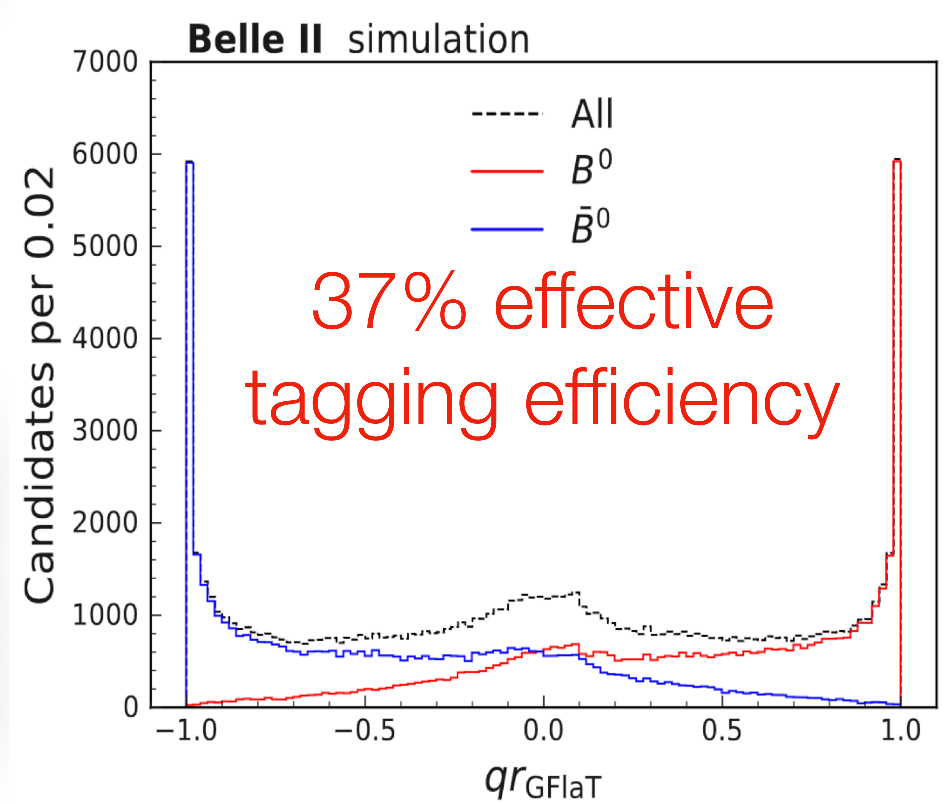
PXD to recover decay-time resolution.



See WG4 Yuma's talk

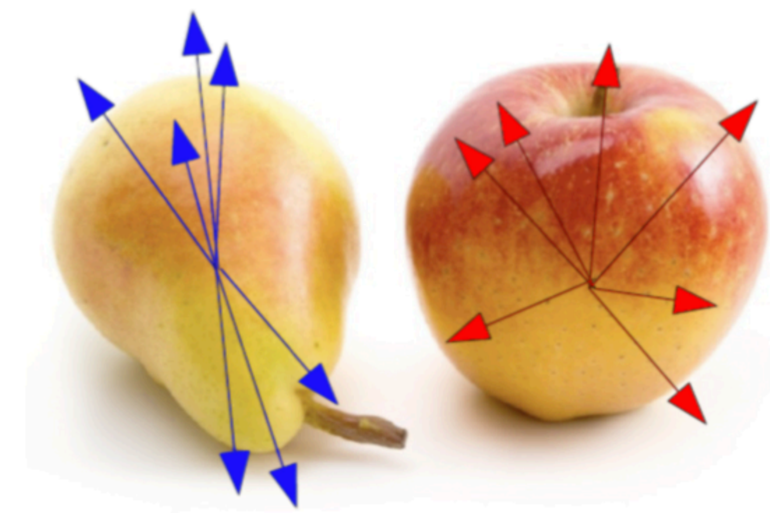
Tag the flavour of the signal with the other *B* decay: 30% effective tagging efficiency with traditional algorithms [EPJC 82 (2022) 83]

New development with graph neural-network enhances efficiency by additional relative 20%, as measured in data!



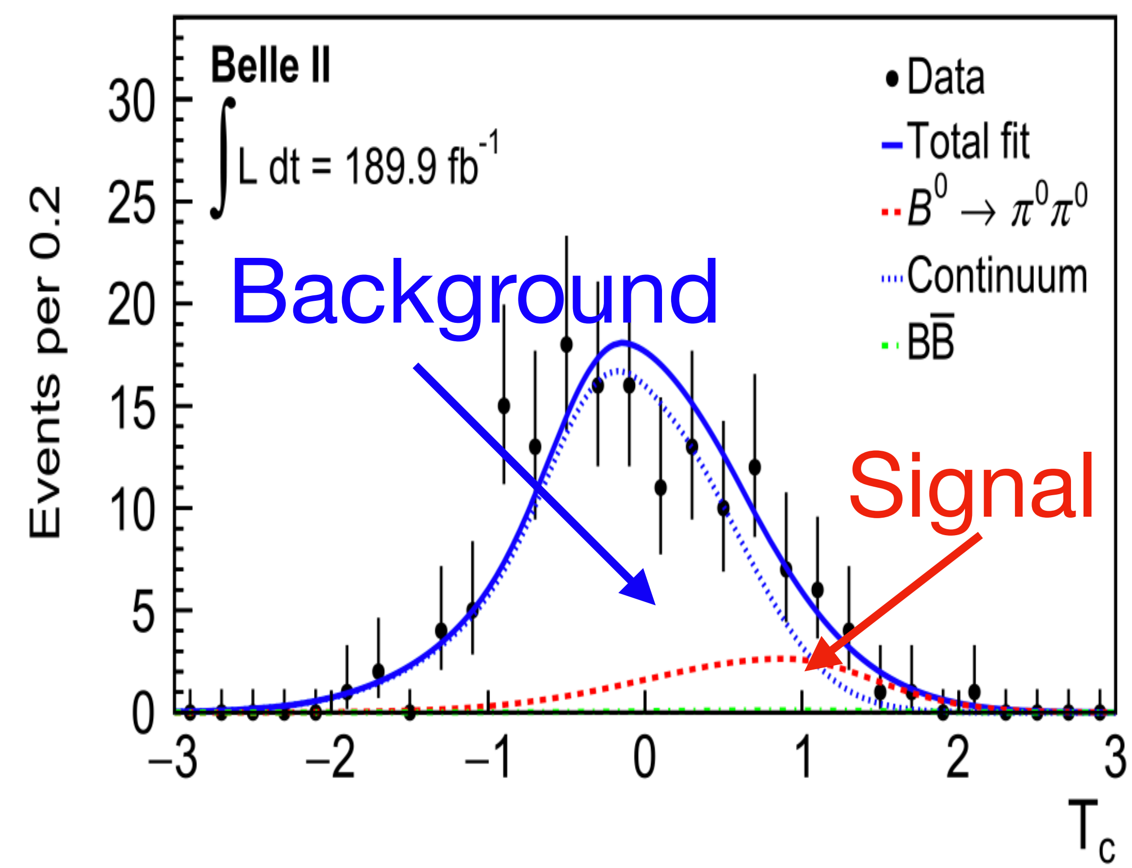
Light-quark background

Fully-hadronic final state:
need to fight against dominant "*continuum*" light-quark production.
Background O(10^6) larger than signal.



Exploit discriminating event topology: continuum features a jet-like structure, while *B* decay isotropically at rest.
Boost event-classification with machine learning algorithms (BDT).

Maximise efficiency with loose cuts and include BDT output in the fit to gain signal-to-background discrimination



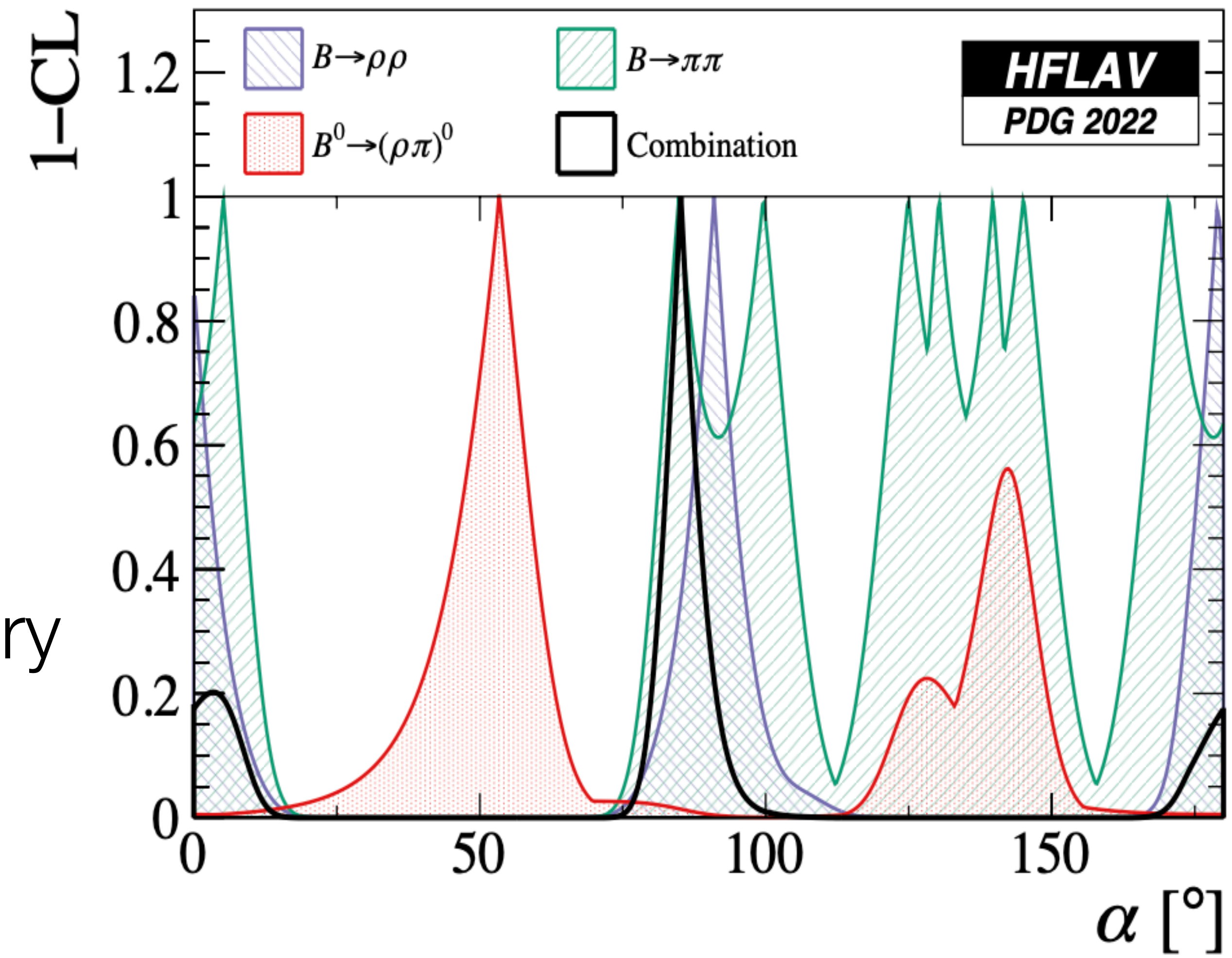
$$\phi_1/\beta \qquad \phi_2/\alpha \qquad \phi_3/\gamma$$

$$22.2^\circ_{\pm 0.7^\circ} + 85.2^{\circ\,+4.8^\circ}_{\;\;-4.3^\circ} + 66.2^{\circ\,+3.4^\circ}_{\;\;-3.6^\circ} = 173.6^{\circ\,+5.9^\circ}_{\;\;-5.6^\circ}$$

Isospin for ϕ_2/α

ϕ_2/α least known angle of the UT, current precision of ~4.5 degrees.

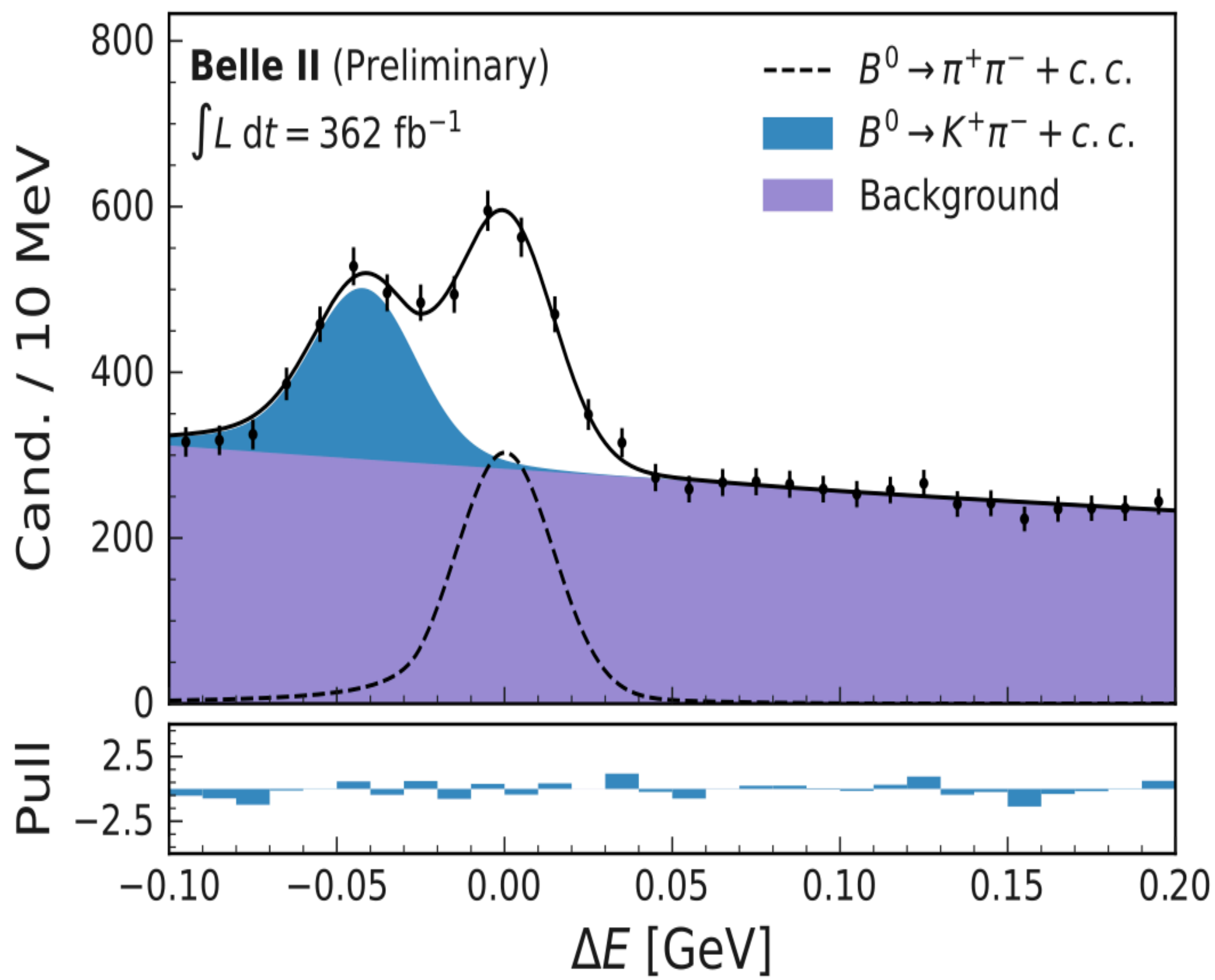
Determined from an isospin analysis [Phys.Rev.Lett. 65 (1990) 3381-3384], remove penguin shift from decay-time dependent CP asymmetry of $B^0 \to \pi^+\pi^-$ by using BR and A_{CP} of $B^+ \to \pi^0\pi^+$ and $B^0 \to \pi^0\pi^0$. Have 8th-fold ambiguity.



Similar for $B \to \rho\rho$ system [Eur.Phys.J.C 77 (2017) 8, 574], better sensitivity (smaller penguin pollution), but requires measurement of helicity states (polarisation). Four pions yield more background. $B^0 \to \rho^0\rho^0$ further suppressed.

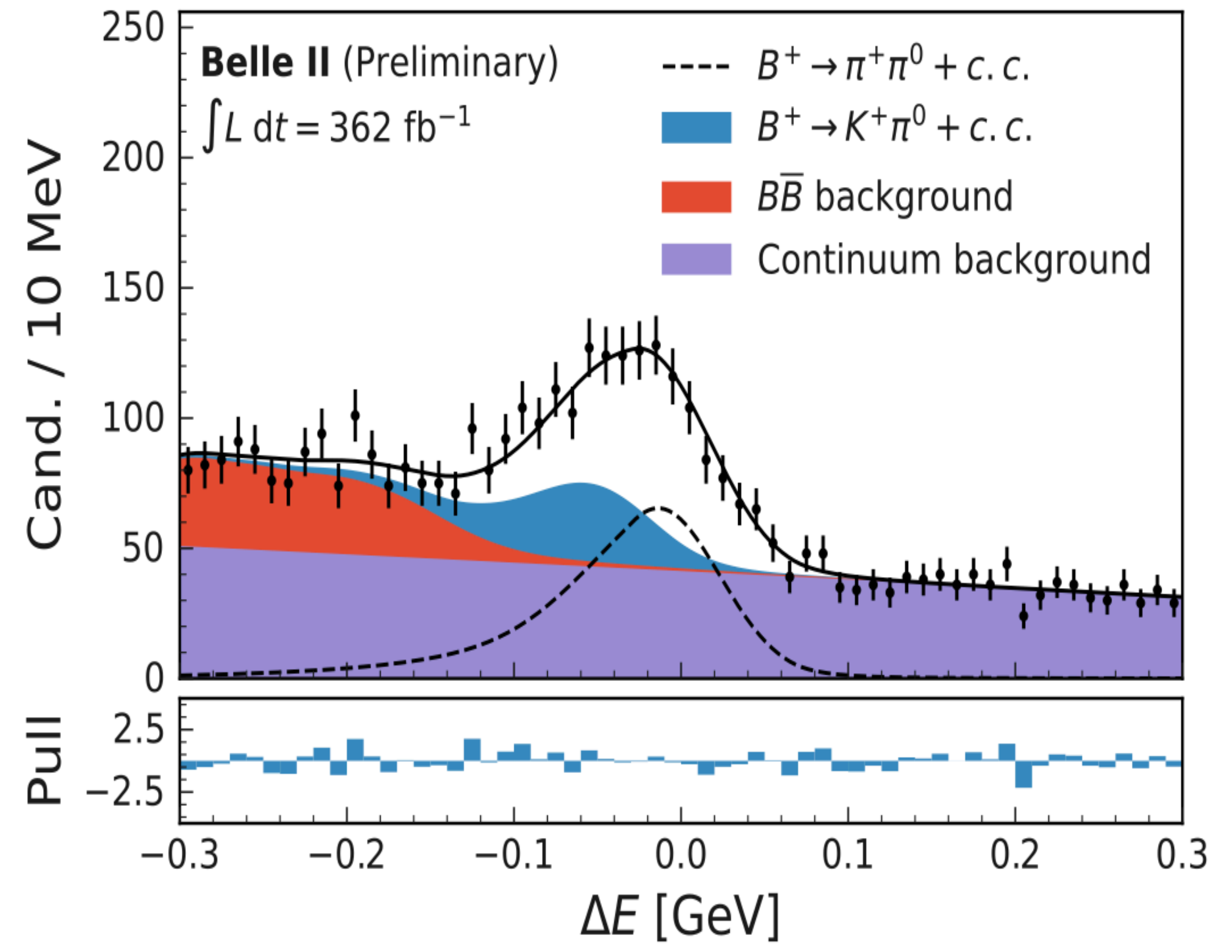
$B \to \pi\pi$ decays

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



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

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



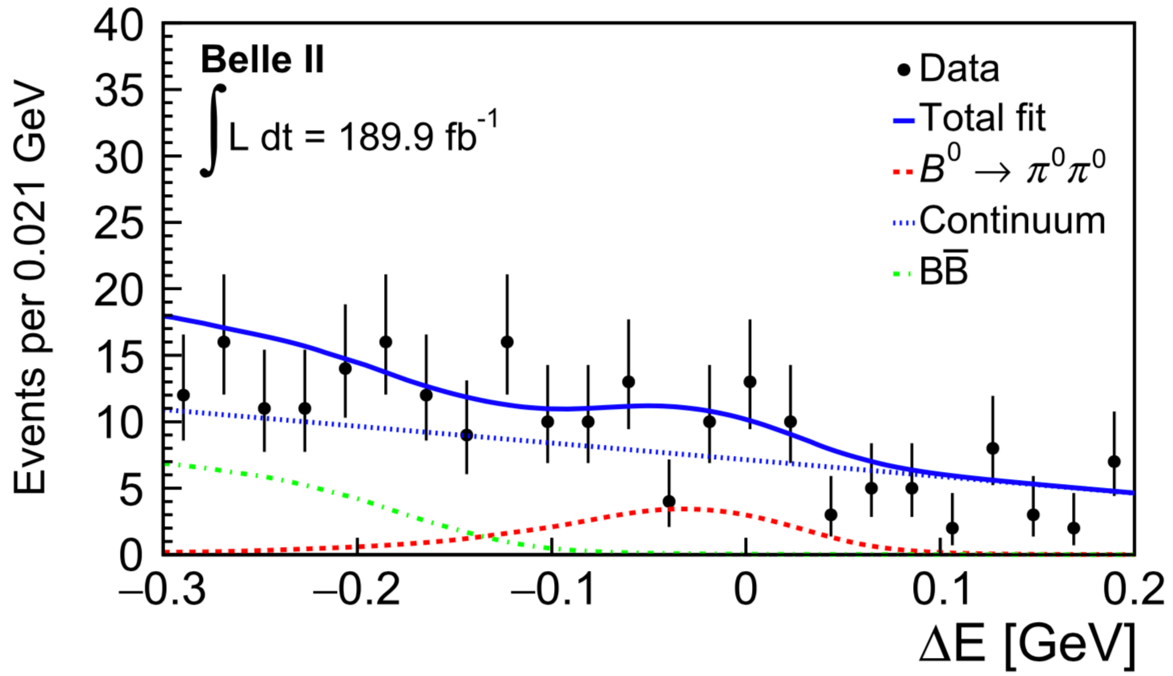
$$\mathscr{B}(\pi^+\pi^0) = (5.10 \pm 0.29 \pm 0.32) \times 10^{-6}$$

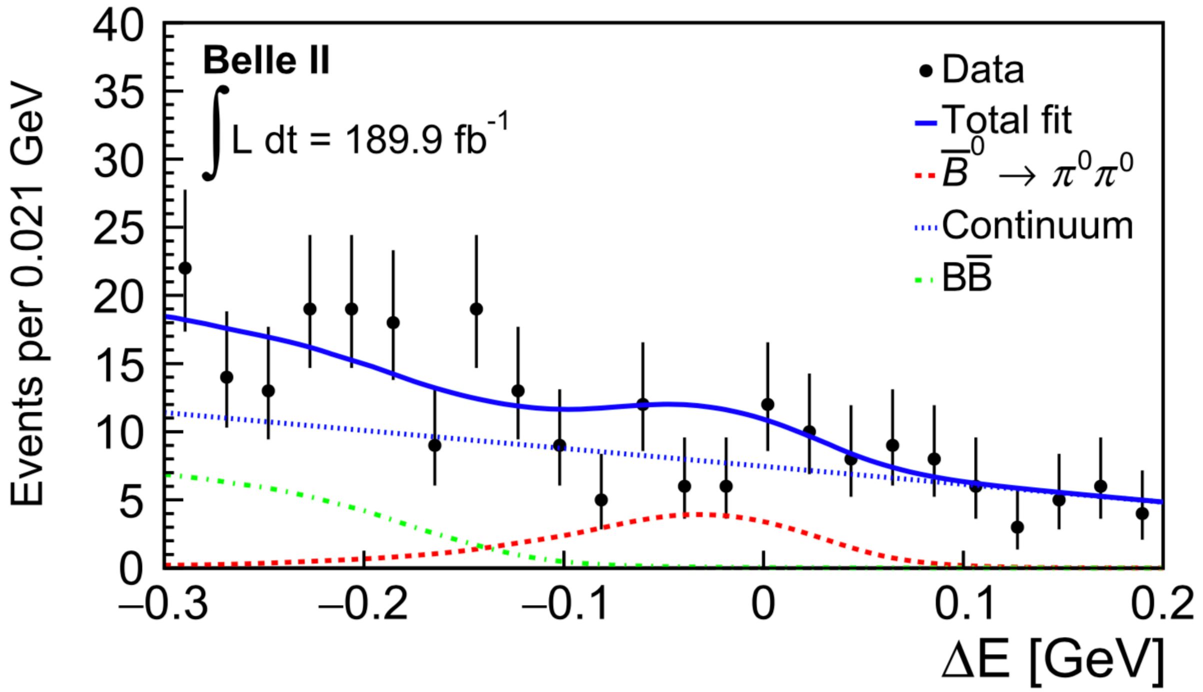
$$\mathscr{A}(\pi^+\pi^0) = -0.081 \pm 0.54 \pm 0.008$$

Competitive with world's best results.
Major systematic uncertainty on BR($B^+ \to \pi^+\pi^0$) from π^0 efficiency.

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

Most challenging charmless decay. Only photons in the final state, completely swamped by continuum from real π^0.
With a 4D fit we find 90 signal candidates [PRD107 (2023) 112009]





$$\mathcal{B}(B^0 \to \pi^0\pi^0) = (1.38 \pm 0.27 \pm 0.22) \times 10^{-6}$$

$$\mathcal{A}_{CP}(B^0 \to \pi^0\pi^0) = 0.14 \pm 0.46 \pm 0.07$$

Achieved Belle precision on BF with 1/3 of Belle sample size thanks to improved photon selection and continuum suppression

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

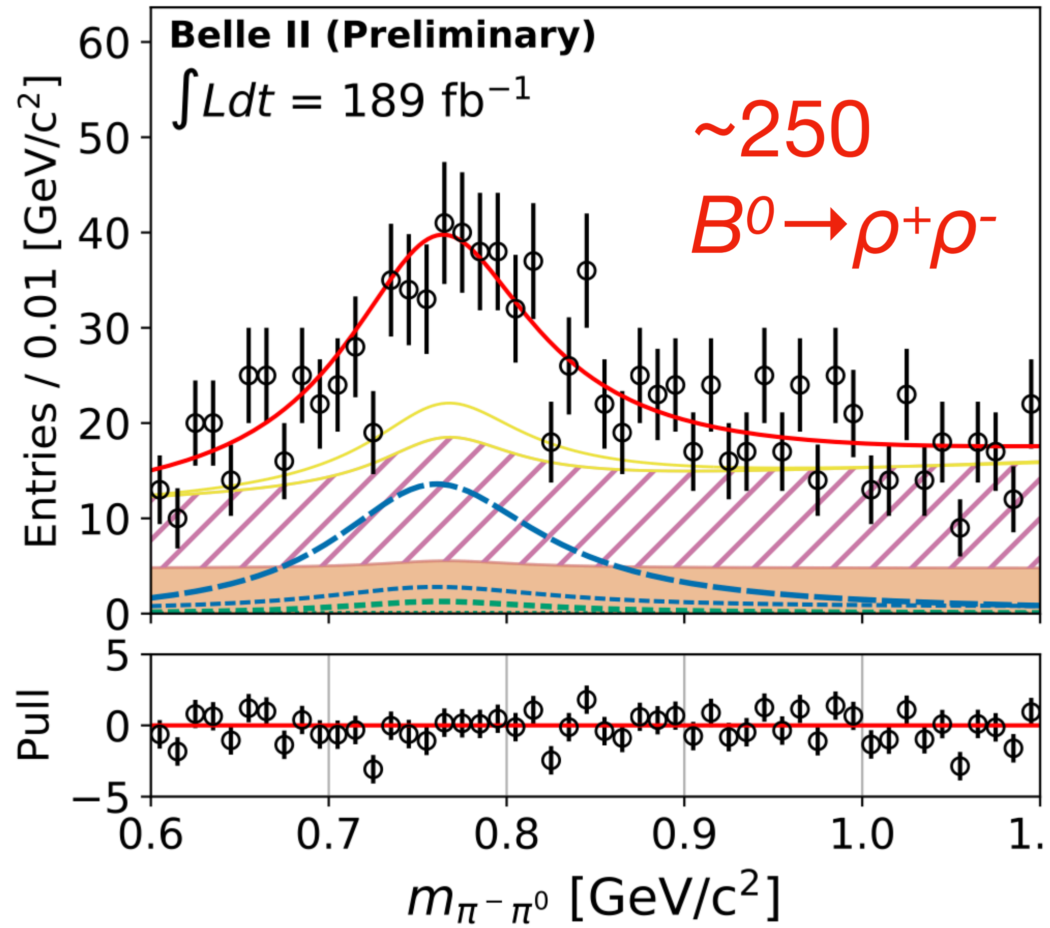
Broad ρ width doesn't provide good signal-to-background separation. Developed ad-hoc selection to suppress misreconstructed photons at low energy. Multitude of peaking background due to 4-pions final state.

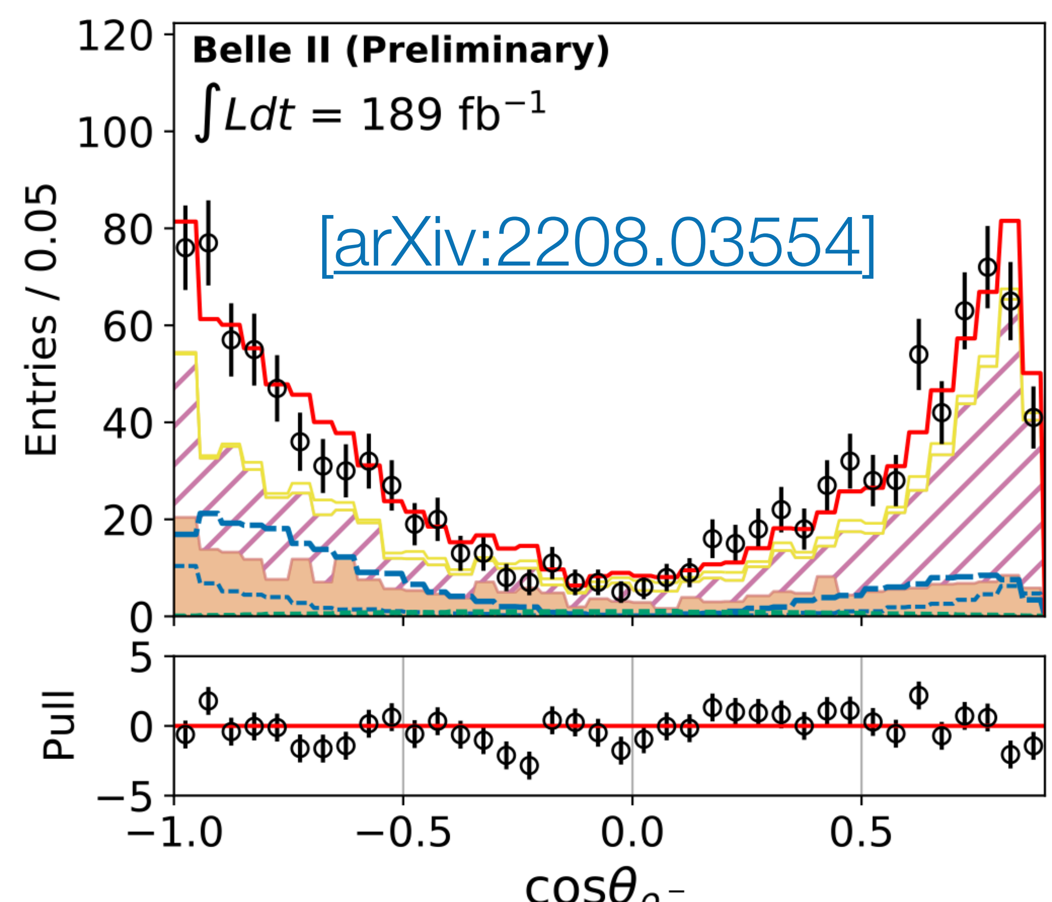
Vector-vector final state, need angular analysis to helicity states (polarisation)

$$\mathscr{B} = (26.7 \pm 2.8 \pm 2.8) \times 10^{-6}$$

$$f_L = 0.956 \pm 0.035 \pm 0.033$$

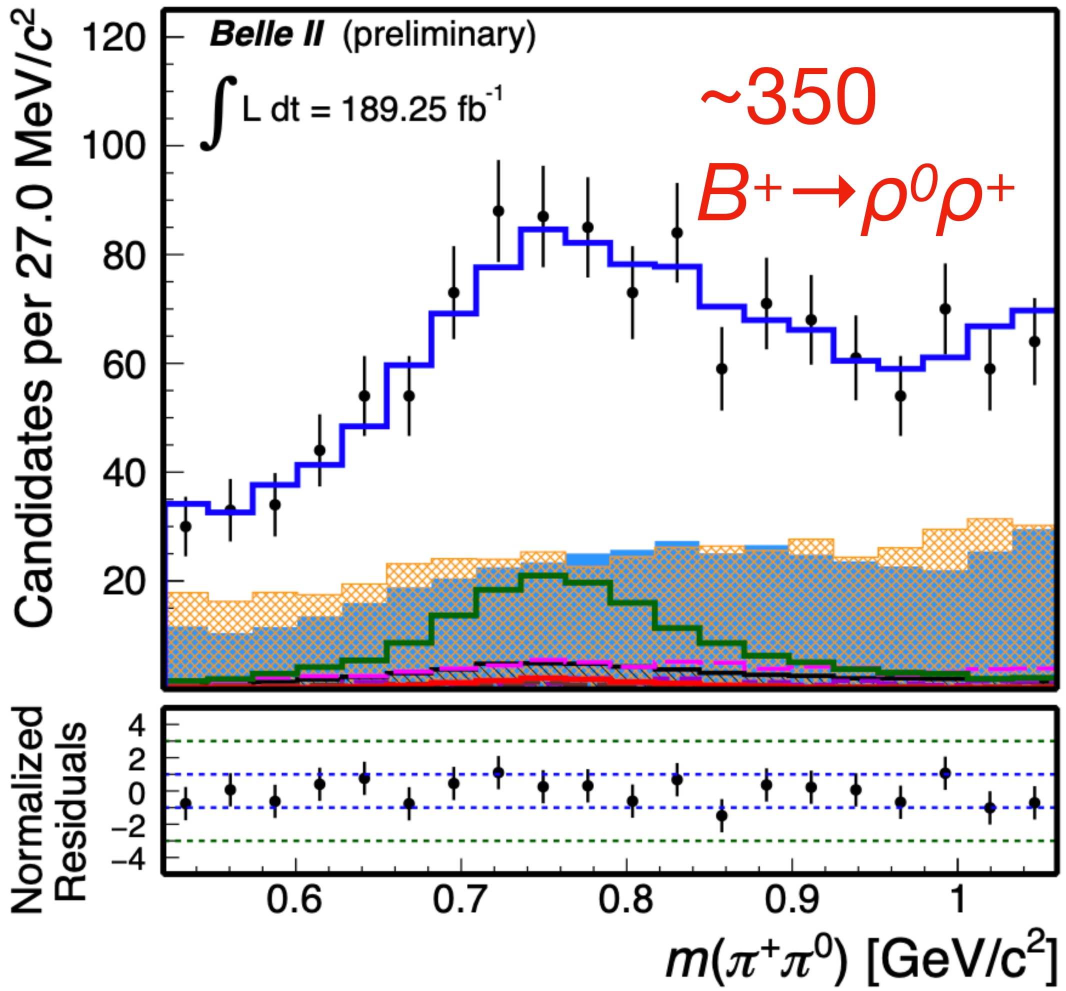
Update to decay-time dependent analysis ongoing.

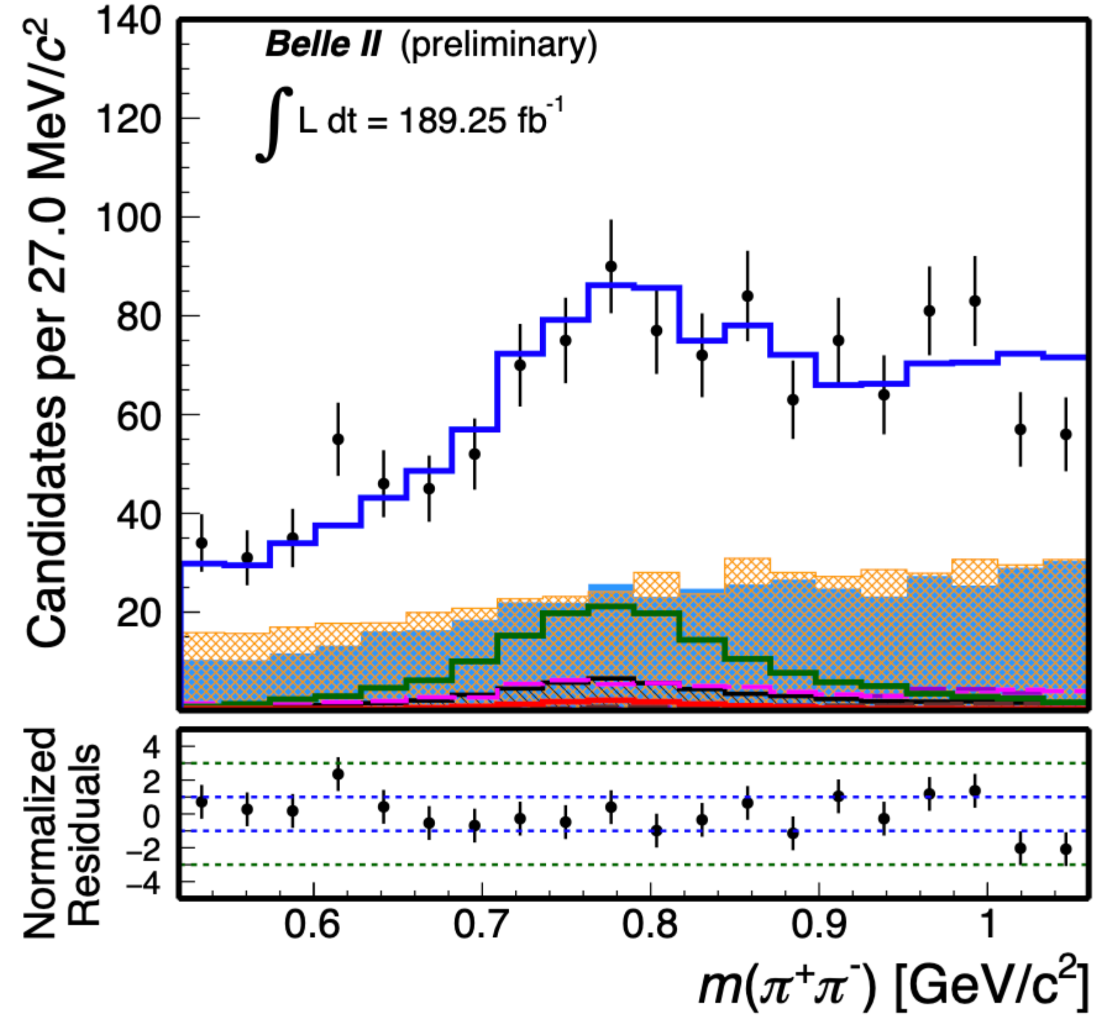




$B^+ \to \rho^0 \rho^+$

[arXiv:2206.12362]





$$\mathscr{B} = (23.2^{+2.2}_{-2.1} \pm 2.7) \times 10^{-6}$$

$$f_L = 0.943^{+0.035}_{-0.033} \pm 0.027$$

$$A_{CP} = -0.069 \pm 0.069 \pm 0.060$$

On par with Belle performance.
Major systematic uncertainty from data-MC mismodelling needs improvement

Sum-rule test

Isospin sum-rule and $K_S\pi^0$

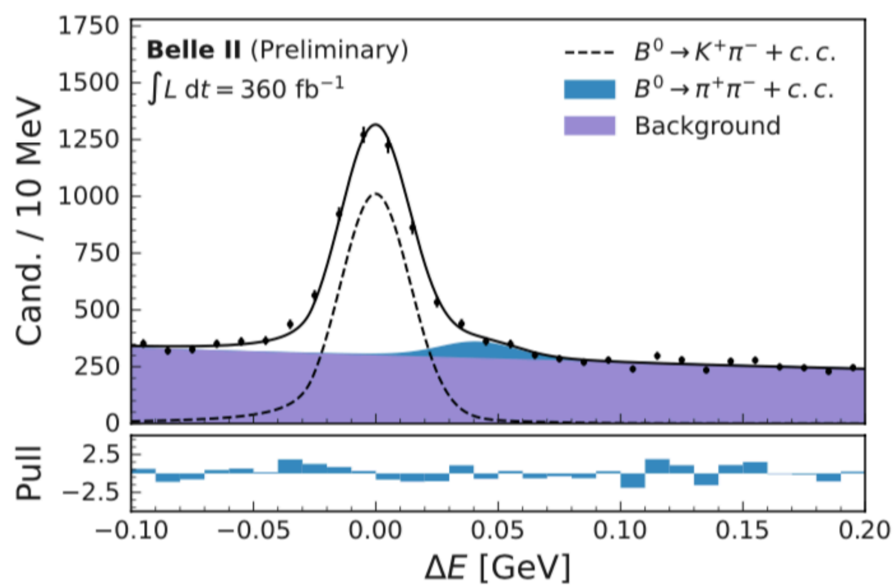
With isospin symmetry, a SM null-test with O(1%) theor. uncertainty

[Phys.Rev.D 59 (1999) 113002; Phys.Lett.B 627 (2005) 82-88]

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

Experimentally consistent with zero with 10% precision limited by $K_S\pi^0$.

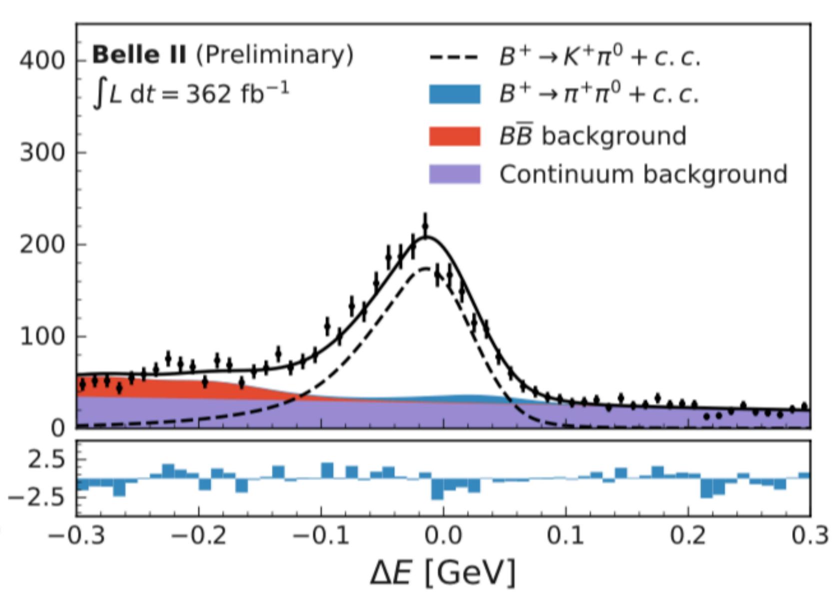
~3900 $B^0 \to K^+\pi^-$



$\mathscr{B} = (20.67 \pm 0.37 \pm 0.62) \times 10^{-6}$

$A_{CP} = (-7.2 \pm 1.9 \pm 0.7)\,\%$

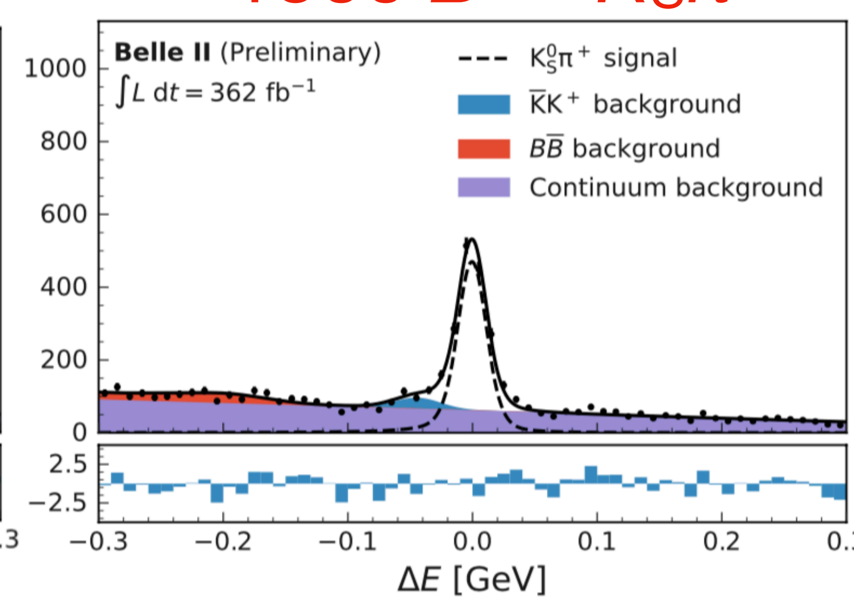
~2100 $B^+ \to K^+\pi^0$



$\mathscr{B} = (14.21 \pm 0.38 \pm 0.85) \times 10^{-6}$

$A_{CP} = (1.3 \pm 2.7 \pm 0.5)\,\%$

~1500 $B^+ \to K_S\pi^+$



$\mathscr{B} = (24.40 \pm 0.71 \pm 0.86) \times 10^{-6}$

$A_{CP} = (4.6 \pm 2.9 \pm 0.7)\,\%$

Pushing the limit to understand K_S and π^0 systematic at 2% and 5%

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

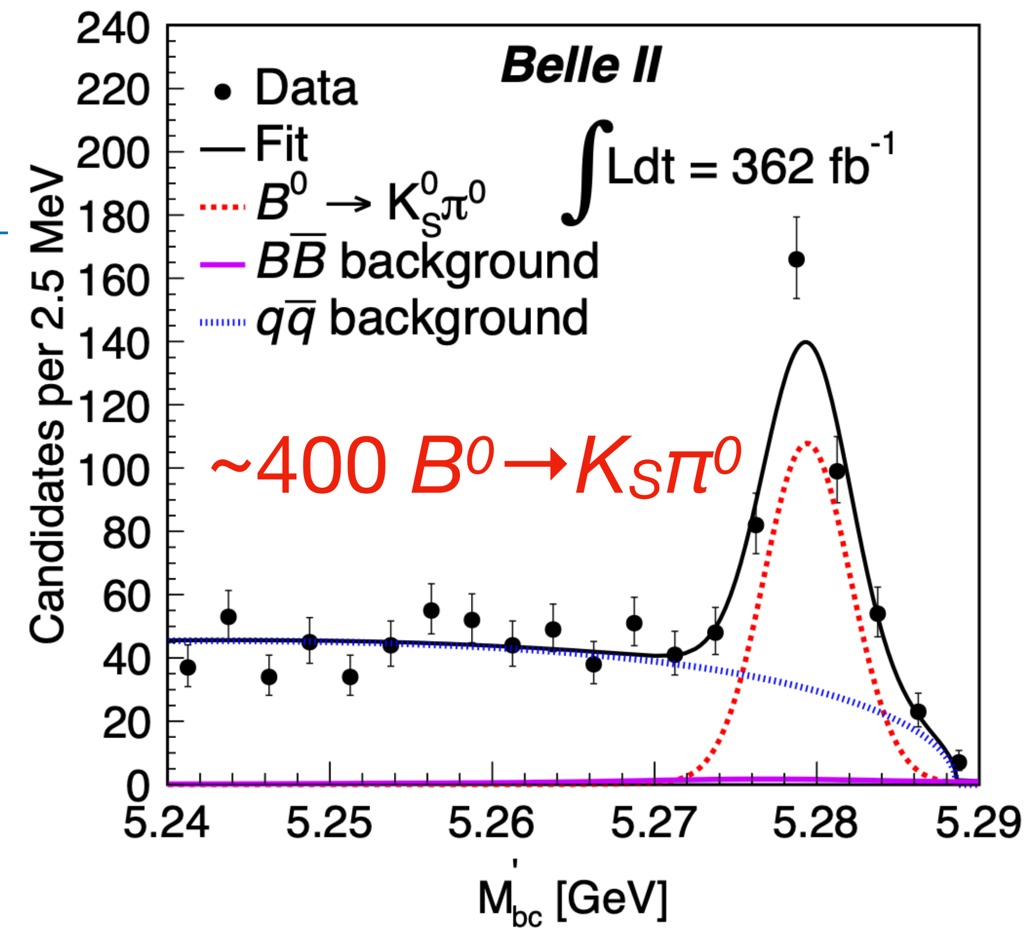
K_S flights 10 cm, decays after first silicon layers: challenging B vertex reconstruction, degraded decay-time resolution. Validate on $B^0 \to J/\psi K_S$ with K_S-only vertexing.
Categorise the events according to decay-time uncertainty to measure time-dependent asymmetries

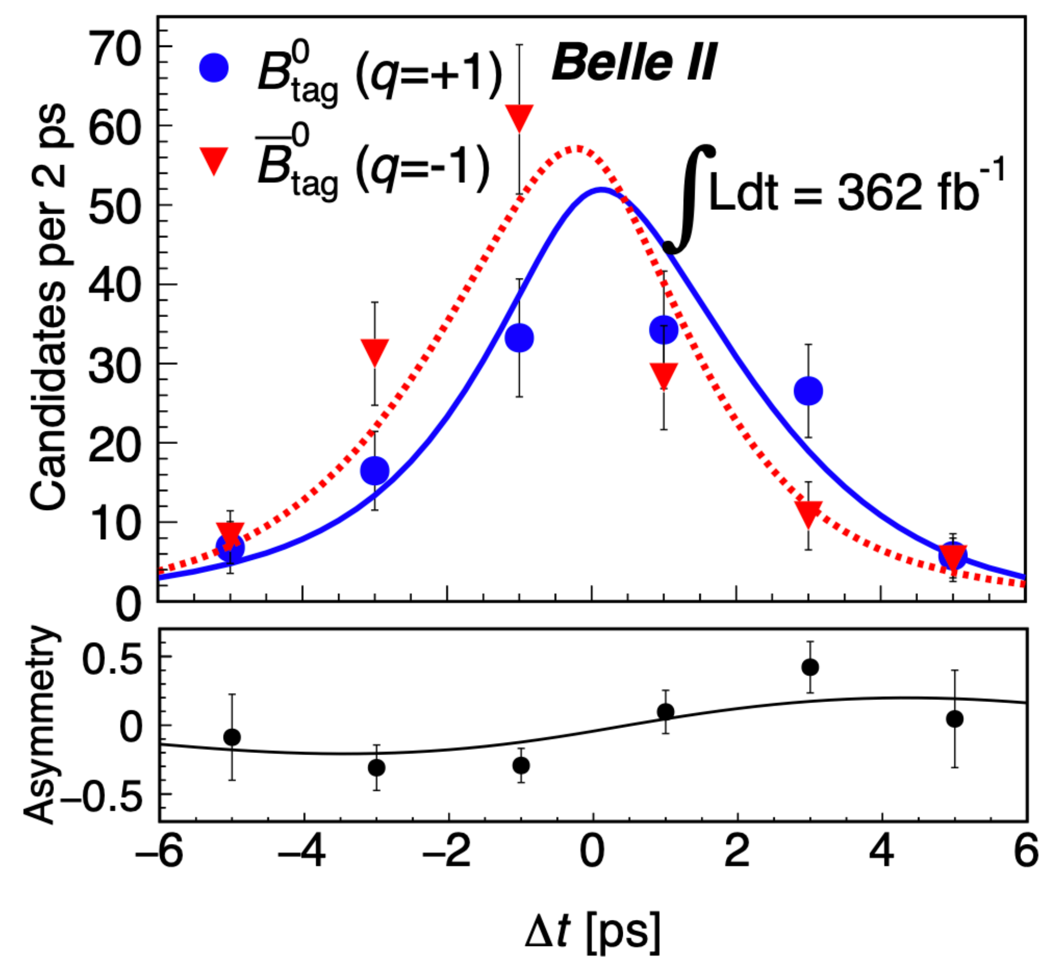
$$A = 0.04^{+0.15}_{-0.14} \pm 0.05$$

$$S = 0.75^{+0.20}_{-0.23} \pm 0.04$$

[arXiv:2305.07555, accepted by PRL]

Improved π^0 reconstruction and enhanced continuum-suppression yield precision competitive with world best results.





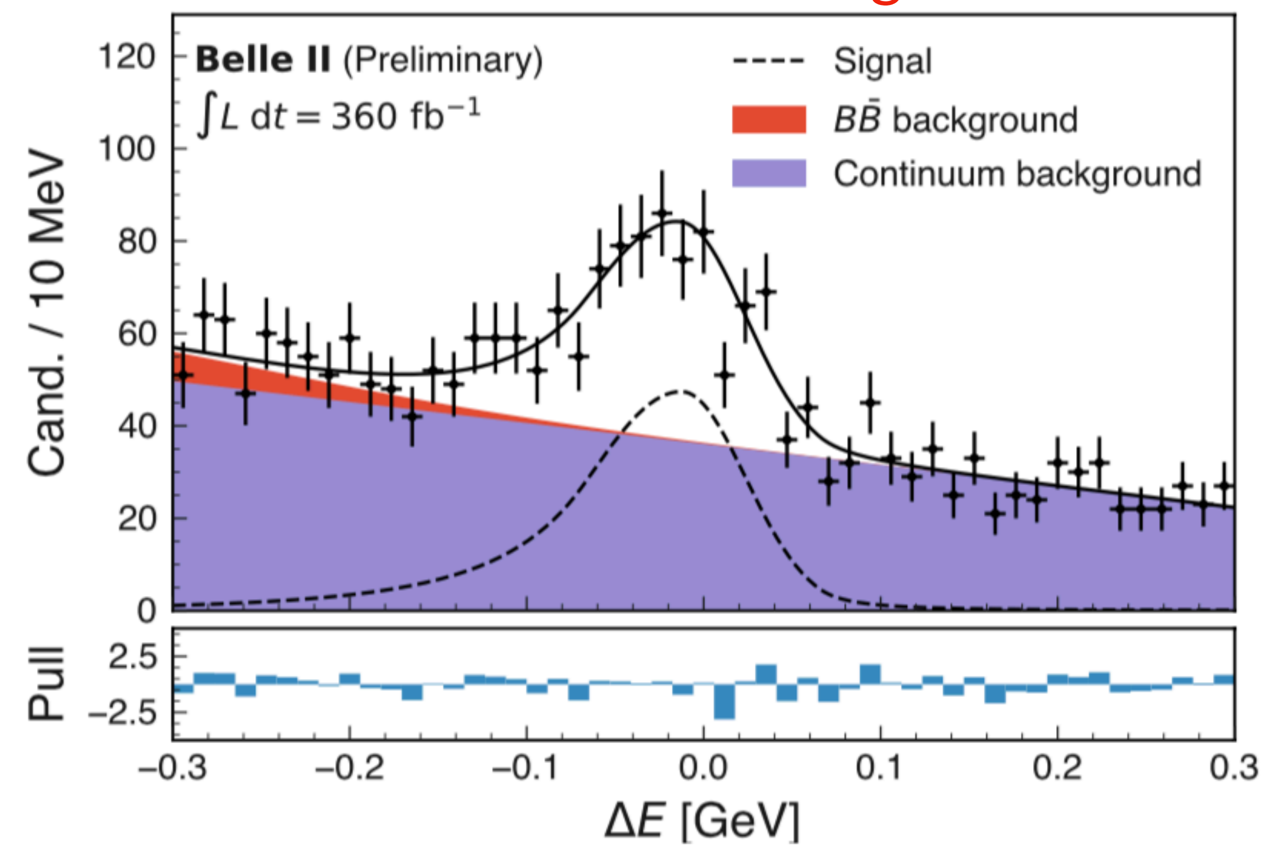
Isospin sum-rule and $K_S\pi^0$

Additional independent decay-time integrated analysis for $B^0 \to K_S\pi^0$, to measure BR and A_{CP}, combine the analyses to enhance sensitivity:

$$\mathscr{B} = (10.50 \pm 0.62 \pm 0.67) \times 10^{-6}$$

$$A_{CP} = -0.01 \pm 0.12 \pm 0.05$$

~500 $B^0 \to K_S\pi^0$



Putting all $K\pi$ results together, *the Belle II isospin sum-rule gives*

$$I_{K\pi} = (-3 \pm 13 \pm 5)\,\%$$

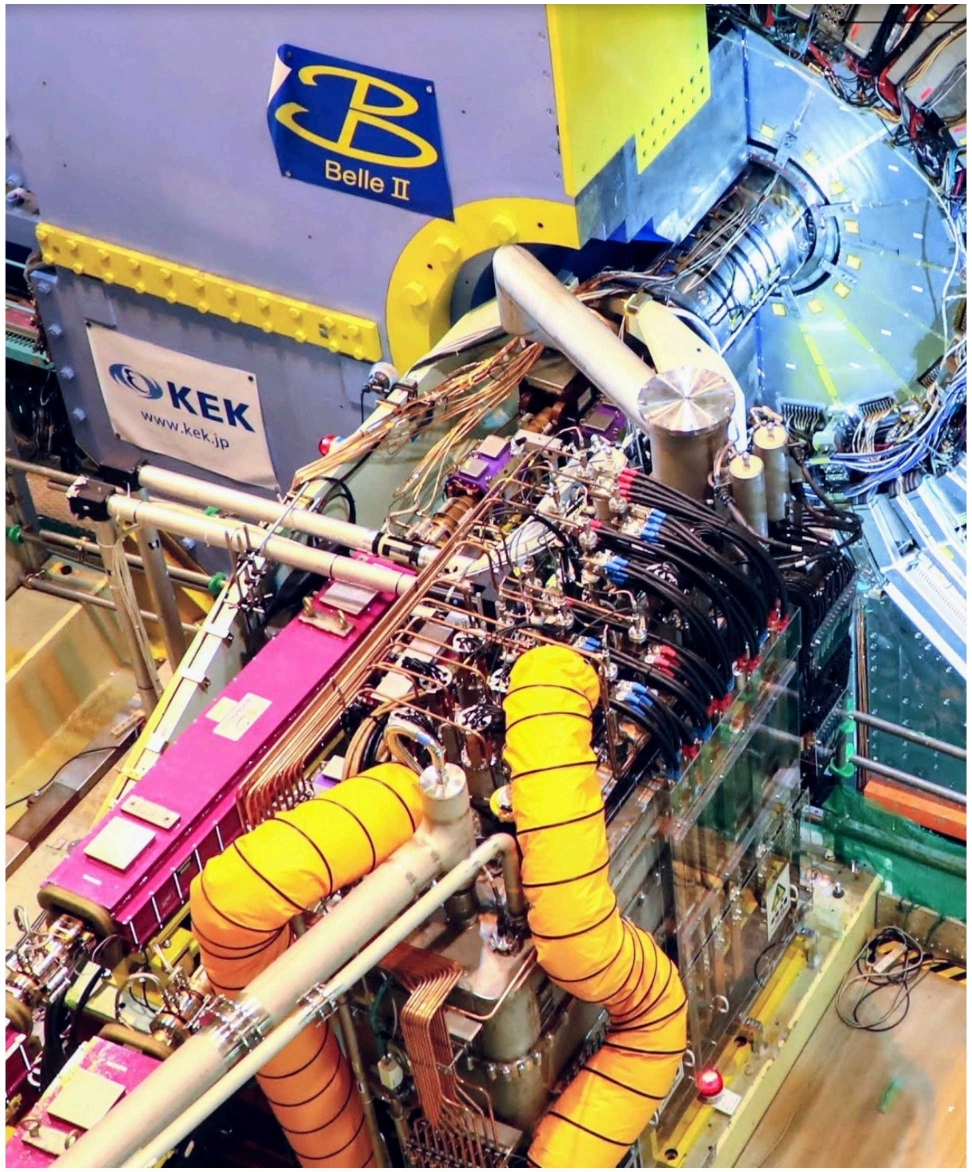
Agrees with SM. Competitive with WA: $(-13 \pm 11)\,\%$
Belle II can reach 5% precision with ~10 ab^{-1}.

Summary

Belle II has unique opportunities for charmless decays by accessing jointly all final states for isospin analyses.

Obtained new results on channels sensitive to ϕ_2/α: exceeded expectations on $B^0 \to \pi^0\pi^0$, on par for $B \to \rho\rho$. Promising for pushing down the uncertainty. Although some measurement already systematically limited, ϕ_2/α still statistically limited.

Obtained new $K\pi$ sum-rule result in agreement with SM, with precision similar to world average.
Statistically limited, $K_S\pi^0$ from Belle II essential to improve the test.



Backup

π^0 efficiency correction

Use $D^{*+} \to (D^0 \to K^-\pi^+\pi^0)\pi^+$ and $D^{*+} \to (D^0 \to K^-\pi^+)\pi^+$ decays: measure the ratio of their yields corrected by their branching fractions

$$\varepsilon(\pi^0) = \frac{N(D^0 \to K^-\pi^+\pi^0)}{N(D^0 \to K^-\pi^+)} \frac{\mathcal{B}(D^0 \to K^-\pi^+)}{\mathcal{B}(D^0 \to K^-\pi^+\pi^0)}$$

uncertainty 3.6%, dominant systematic

Measure it in experimental and simulated data: their ratio is the correction for simulation. Do it as a function of the momentum and polar angle, to account for different kinematic of control sample and signal samples

$$r(p_{\pi^0}, \cos\theta_{\pi^0}) = \frac{\varepsilon(p_{\pi^0}, \cos\theta_{\pi^0})_{\text{data}}}{\varepsilon(p_{\pi^0}, \cos\theta_{\pi^0})_{\text{MC}}},$$ from 0.7 to 1.1 (average 0.99 for $h\pi^0$)

Checked the correction using also $\tau^- \to 3\pi\pi^0\nu$ and $\tau^- \to 3\pi\nu$ decays and found good agreement.

Isospin sum-rule test: Belle II impact

arXiv:2207.06307