Measurement of ϕ_2 at Belle II

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KEK Flavor Factories workshop 2023

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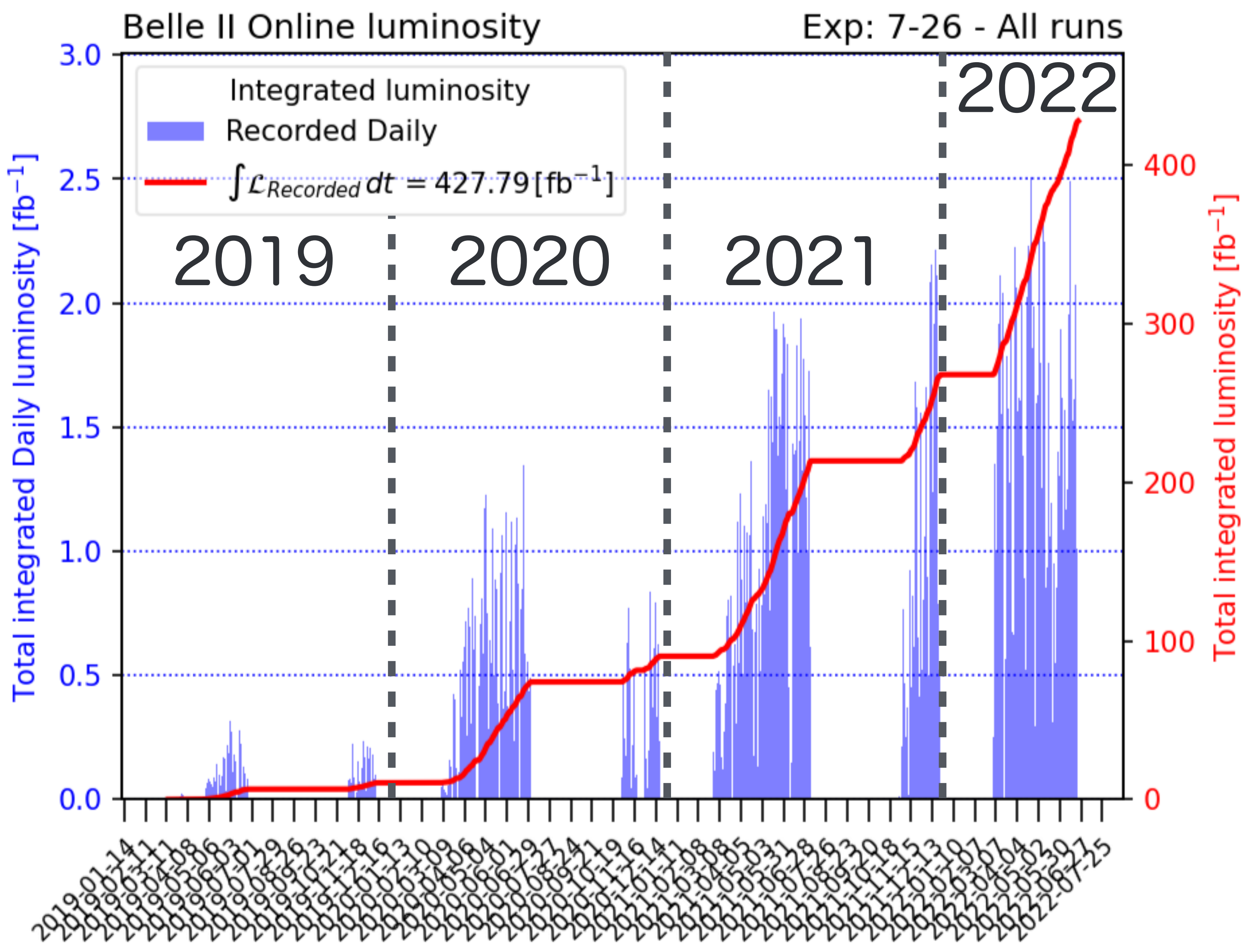
Belle II @ SuperKEKB

- asymmetric e^+-e^- collider ($\sqrt{s}$ = 10.58 GeV)
  - $e^+e^- \to \Upsilon(4S) \to B\bar{B}$
- Four-momenta of B are well known.
- Determination of the decay position allows time-dependent analysis.

Luminosity	Design	Accomplished
Integrated	50 /ab (Belle x50)	428 /fb
Peak	6.5×10^{35} /cm^2/s	4.7×10^{34} /cm^2/s

World Record!!



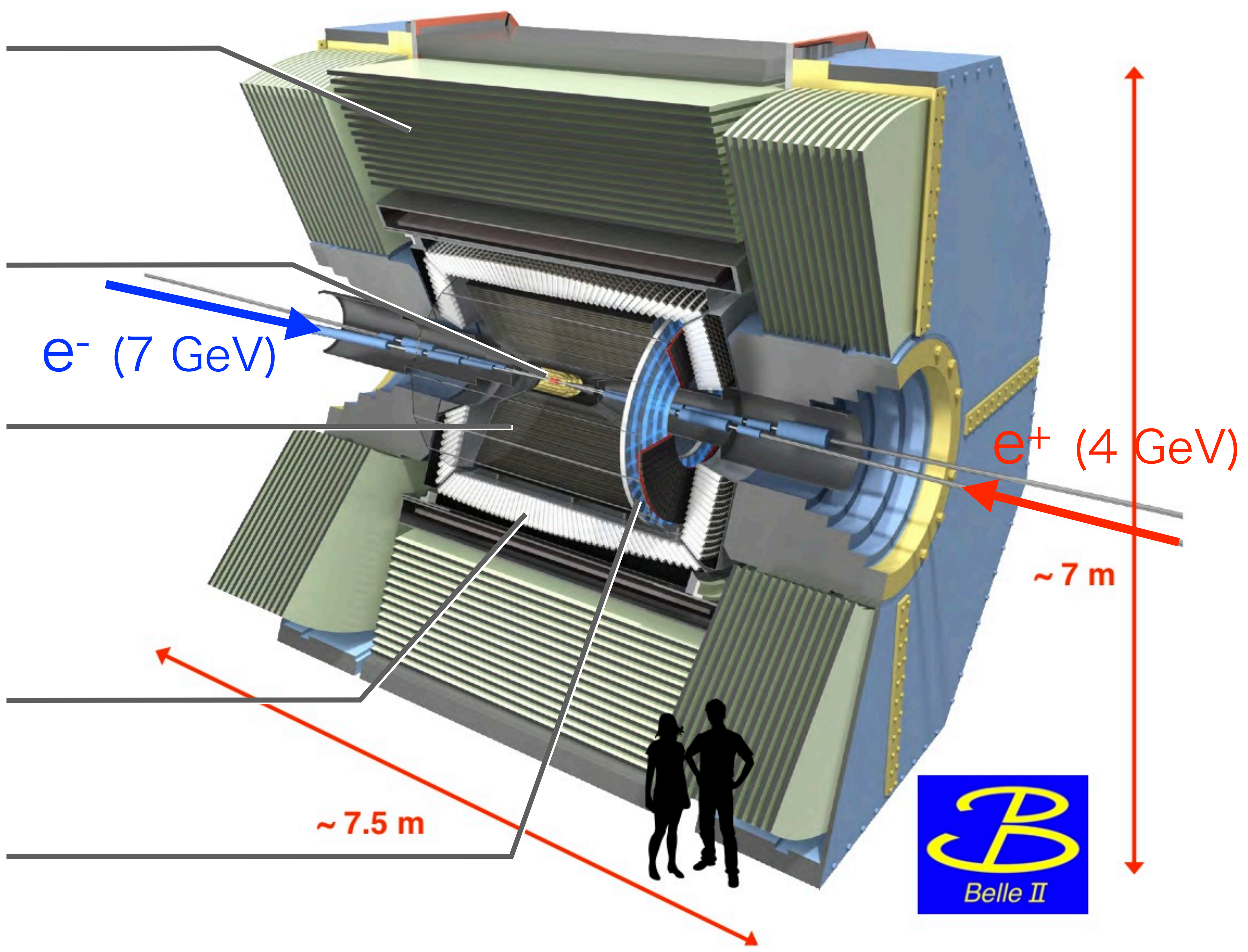
K$_L$ and μ Detection
K$_L^0$ p resolution: 15 MeV
μ identification eff.: ~90%

Vertex Detector
vertex resolution: 15 μm

Central Drift Chamber
spatial resolution: 100 μm
dE/dx resolution: 5%
P$_T$ resolution: 0.4%

EM Calorimeter (CsI)
energy resolution: 1.6%-4%

Particle Identification
K eff.: 90%, fake π rate: 5%



Determination of CKM parameters at Belle II

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$\phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) = (22.2 \pm 0.7)^\circ$$

$$\phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right) = \left(85.2^{+4.8}_{-4.3}\right)^\circ$$

$$\phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right) = \left(65.9^{+3.3}_{-3.5}\right)^\circ$$

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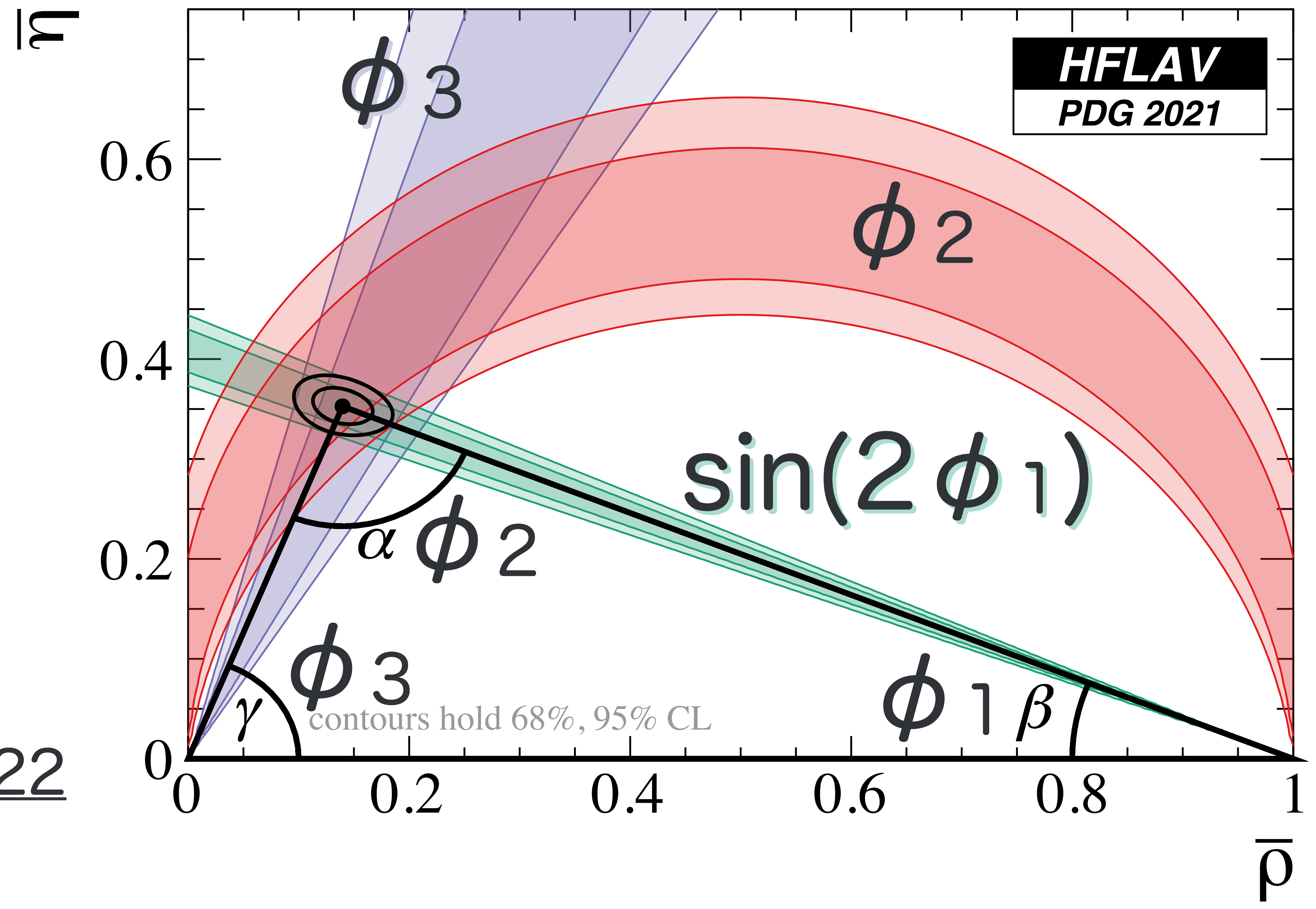


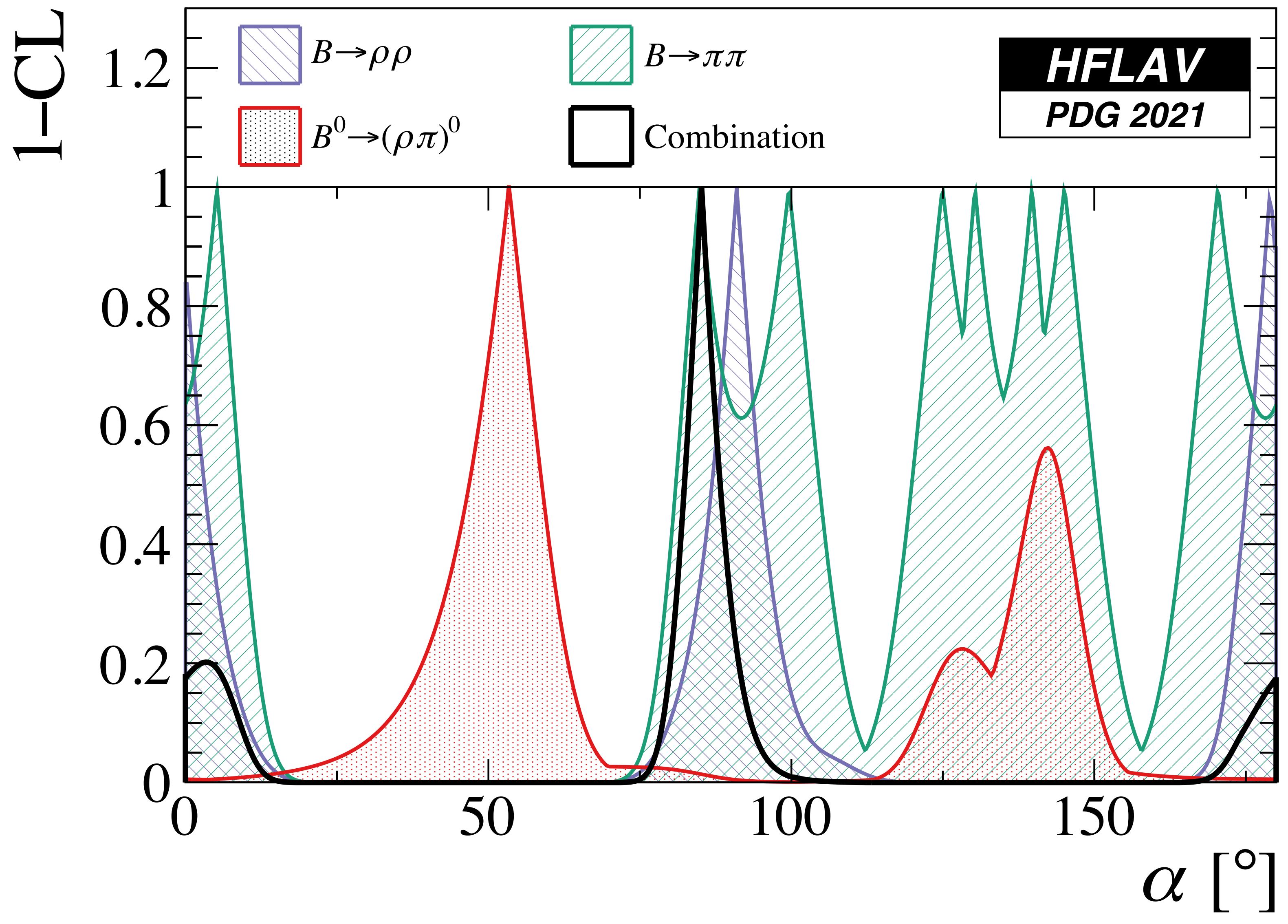
Belle II has the potential to measure more accurately all angles and sides of the unitarity triangle (UT).

- Loop amplitudes provide sensitive probe to new physics.
  e.g.) B^0-$\bar{B}^0$ mixing ← Time-dependent CP asymmetry measurement

ϕ_2 / α is the least known UT angle

- affected by the penguin contribution in b→d
- uncertainty: 5.6%

$B \to \pi\pi$
$B \to \rho\rho$
$(B^0 \to (\rho\pi)^0)$



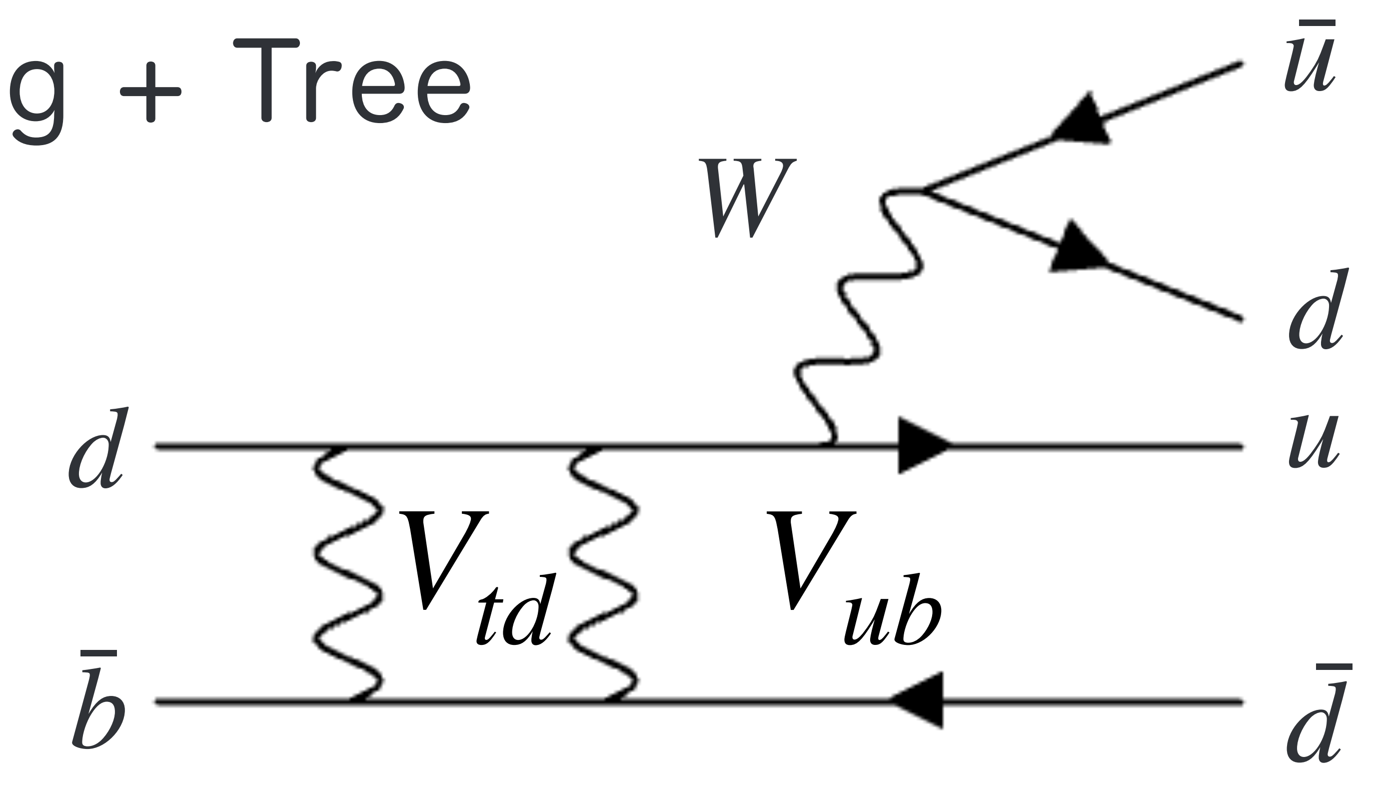
Time-Dependent CP asymmetry measurement

Compare decay widths to determine CP asymmetry

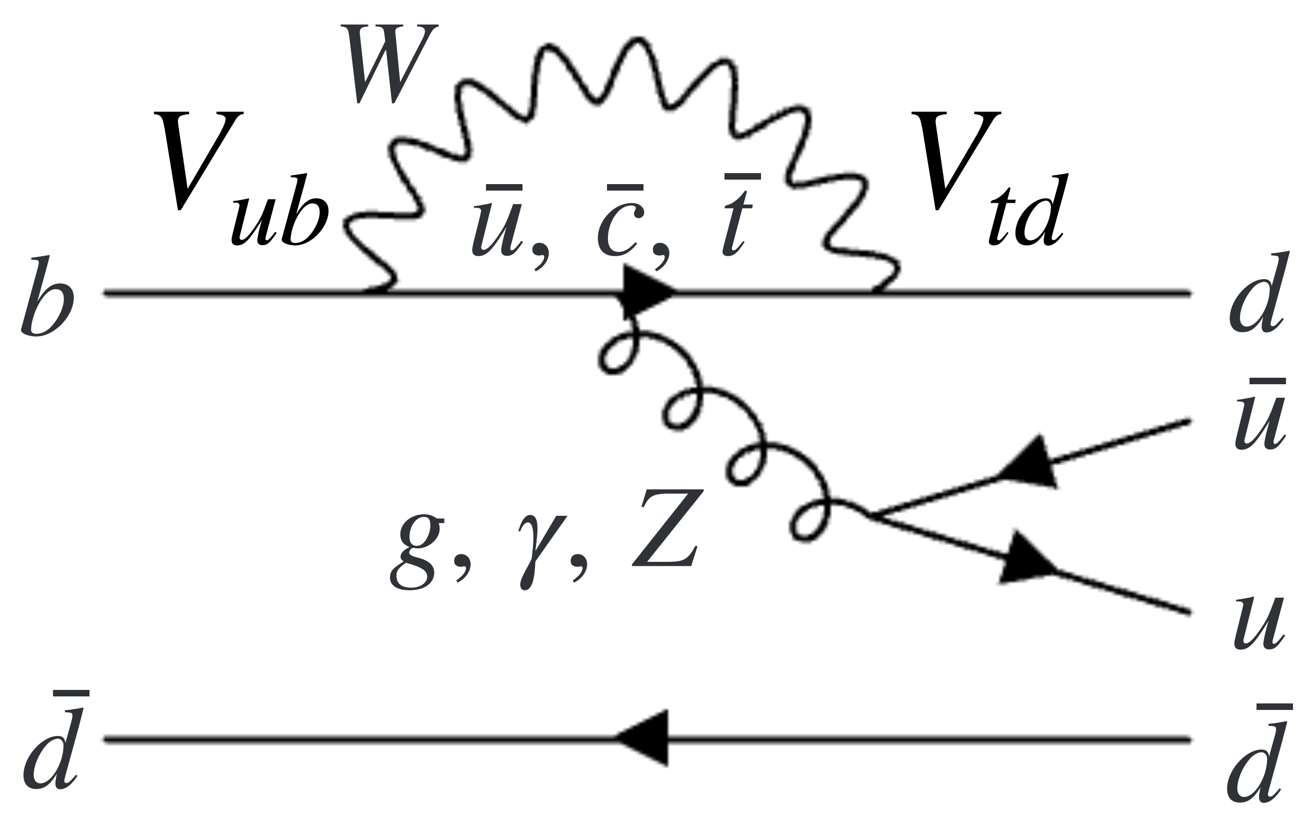
$$\frac{\Gamma(B^0(\Delta t) \to f) - \Gamma(\bar{B}^0(\Delta t) \to f)}{\Gamma(B^0(\Delta t) \to f) + \Gamma(\bar{B}^0(\Delta t) \to f)} = \mathcal{S}^{B\to f} \sin(\Delta m_d \Delta t) + \mathcal{A}^{B\to f} \cos(\Delta m_d \Delta t)$$

mixing-induced CPA   direct CPA

Mixing + Tree



Penguin
(new-physics sensitive)



B→ππ / ρρ = [b→u$\bar{u}$d] + [d or u]

b→u$\bar{u}$d: Tree and Penguin processes interfere

- Electro-weak penguin is negligible small.

Result in $\mathcal{A}^{B\to f} \neq 0$ $\mathcal{S}^{B\to f} \propto \sin(2\phi_2 + 2\Delta\phi_2)$ ϕ_2 is not explicitly determined...

Need to eliminate the contribution of the penguin process → Isospin analysis

Isospin analysis in B→$\pi\pi$

<u>3 decay modes in B→$\pi\pi$</u> (A_2: tree only, A_0: tree + penguin)

$\pi^+\pi^-$: $1/\sqrt{2}\,A^{+-} = A_2 - A_0$

$\pi^0\pi^0$: $A^{00} = 2A_2 + A_0$

$\pi^+\pi^0$: $A^{+0} = 3A_2$

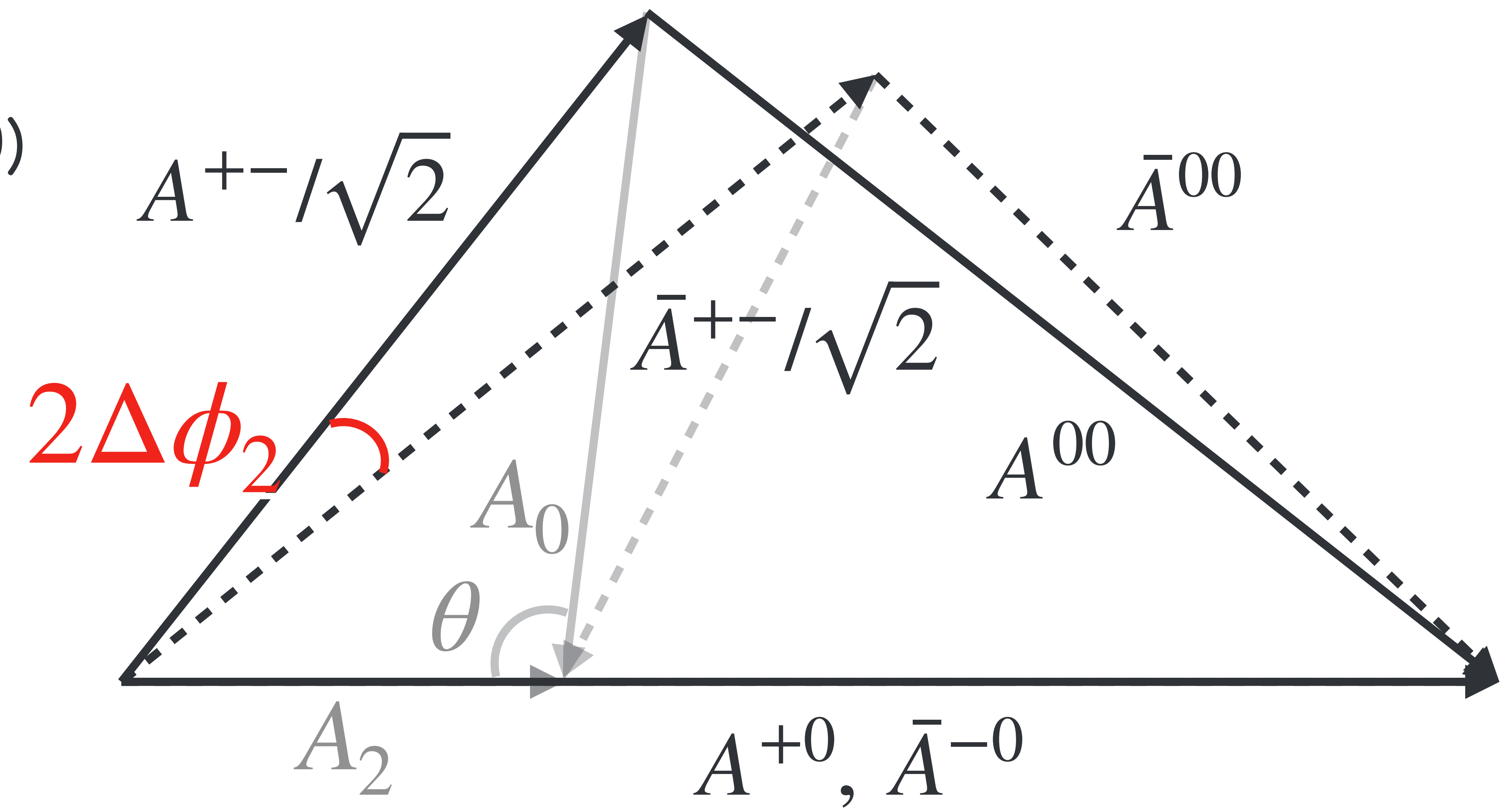
(Penguin for $\pi^+\pi^0$ is not allowed.)

$$1/\sqrt{2}A^{+-} + A^{00} = A^{+0}$$

CP conjugate: $\left(1/\sqrt{2}\bar{A}^{+-} + \bar{A}^{00} = \bar{A}^{+0}\right)$

<u>Isospin triangle</u> (PRL 65, 3381, 1990)

devised by M. Gronau and D. London



By using $\mathcal{S}^{B\to f}$, $\mathcal{A}^{B\to f}$, and BFs, the magnitude of θ is determined, <u>its sign is not</u>.

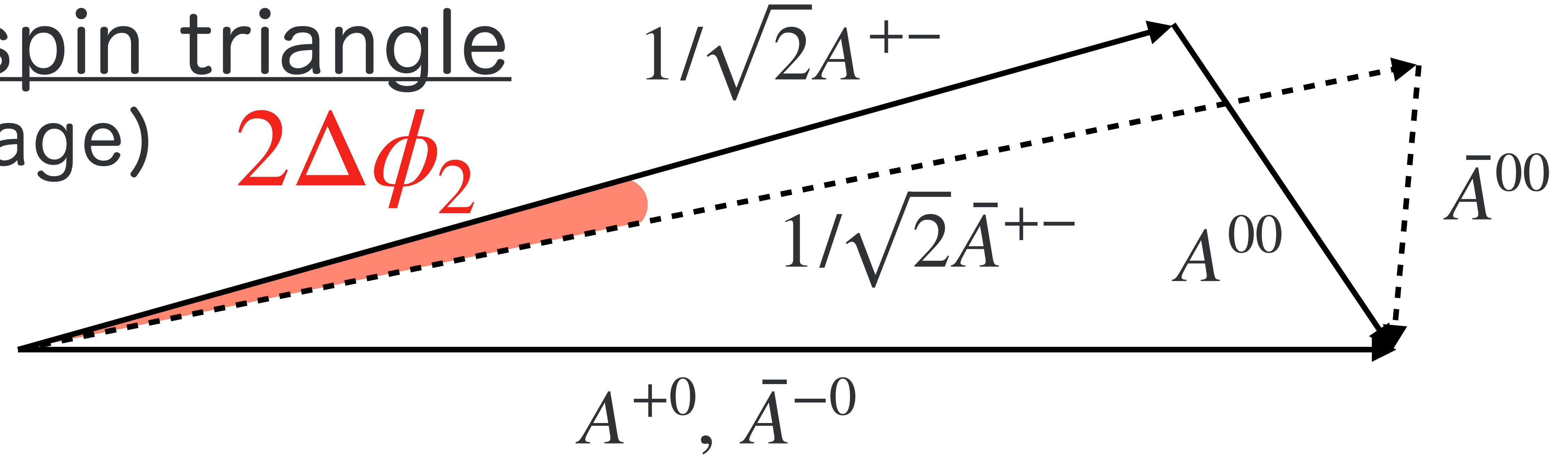
⇒ Multiple candidates of ϕ_2 are available. (8th-fold ambiguity for $\pi\pi$)

Isospin analysis in B→ρρ

Mode	Process: Tree	Process: Penguin	CP conversion preserves amplitude.	BF ($\times 10^{-6}$)
$\rho^+\rho^-$	○	○	no	27.7 ± 1.9
$\rho^0\rho^0$	○	○	no	0.96 ± 0.15
$\rho^+\rho^0$	○	X	yes	24.0 ± 1.9

~1/25

Isospin triangle
(image)



BF($\rho^0\rho^0$) is extremely small.

- $A^{+0} \sim A^{+-}/\sqrt{2}$ → small $\Delta\phi_2$
- Smallness could be quantitatively evaluated by Babar and Belle.

[Particles detected in experiments]

$\pi^0\pi^0$: 4 photons ⇒ Impossible to measure B vertex for a TD analysis: can't measure $\mathcal{S}^{\pi^0\pi^0}$

- $\mathcal{S}^{B\to f}$ will be measurable by analyzing events with the π^0 Dalitz mode in the future.

$\rho^0\rho^0$: 4 charged pions ⇒ possibly determine $\mathcal{S}^{\rho^0\rho^0}$

- Large error in the latest results: 0.3±0.7(stat.)±0.2(syst.))

Belle II's analyses for ϕ_2 measurement

	$\mathcal{B}$ $(\times 10^{-6})$	A_{CP}	$\mathcal{L}_{\text{int}}$ fb^{-1}
$B^0 \to \pi^+\pi^-$	✓		63
$B^0 \to \pi^0\pi^0$	✓	✓	190
$B^+ \to \pi^+\pi^0$	✓	✓	190
$B^0 \to \rho^+\rho^-$	✓		190
$B^0 \to \rho^0\rho^0$			
$B^+ \to \rho^+\rho^0$	✓	✓	190

The measured results are in good agreement with world averages (WAs), and the systematic uncertainties are well understood.

$B^0 \to \pi^+\pi^-$: BF = (5.8 ± 0.7 (stat.) ± 0.3 (syst.)) x 10^{-6} WA: (5.12 ± 0.19) x 10^{-6}

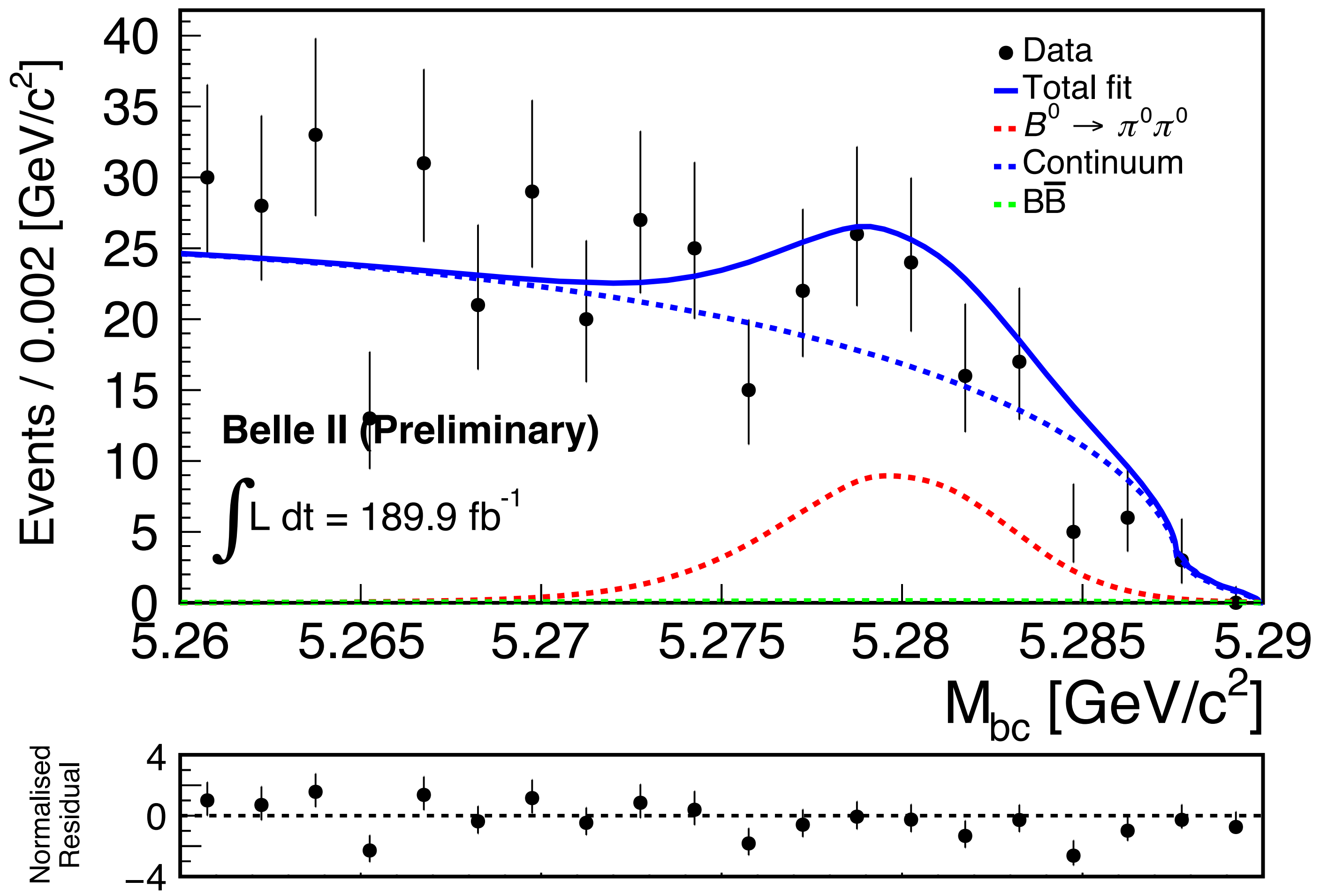
$B^0 \to \rho^0\rho^0$

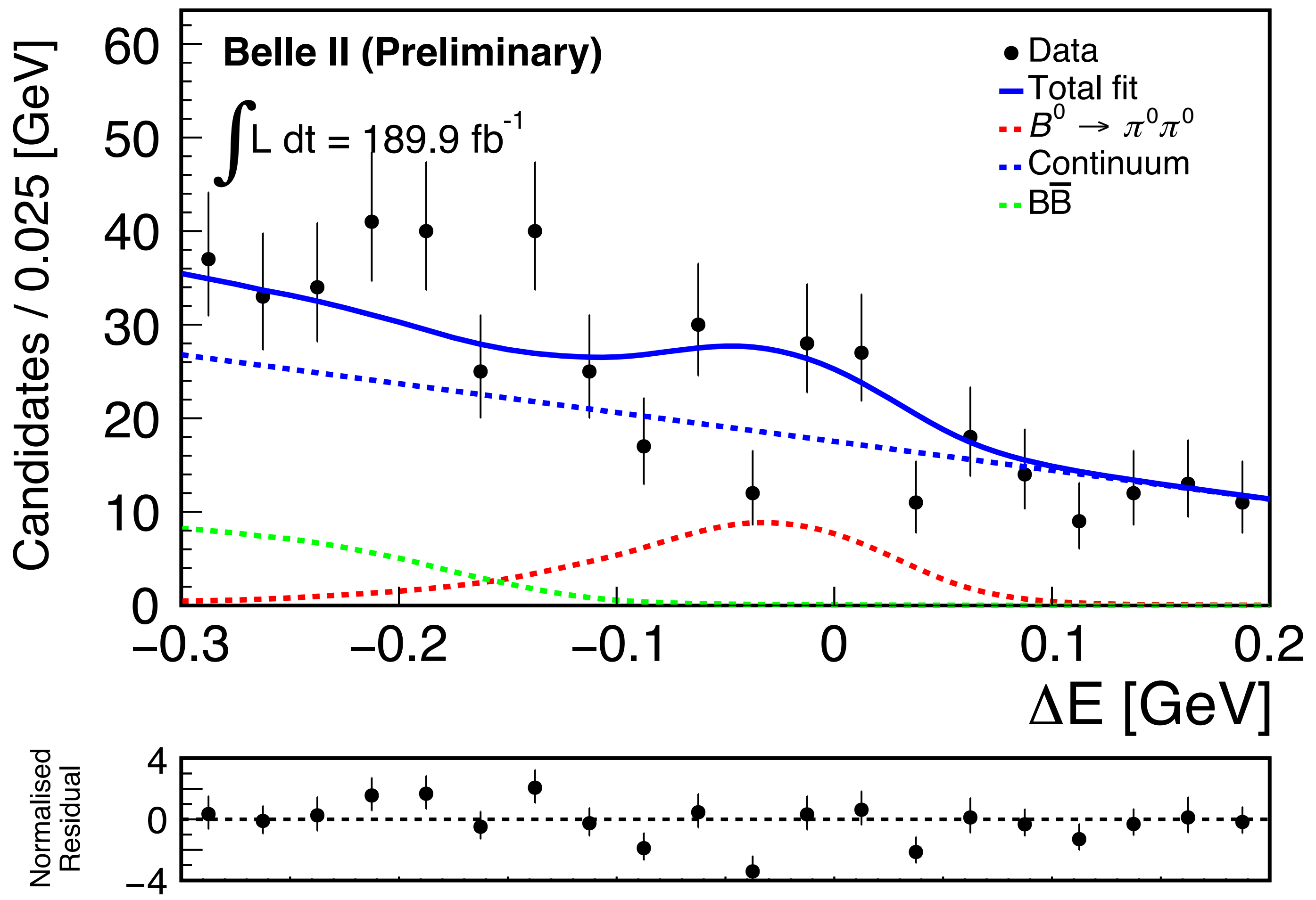
- # of events is currently too small to measure A_{CP} due to the small branching fraction.
- At Belle, 166±59 events w/ 711 fb^{-1}

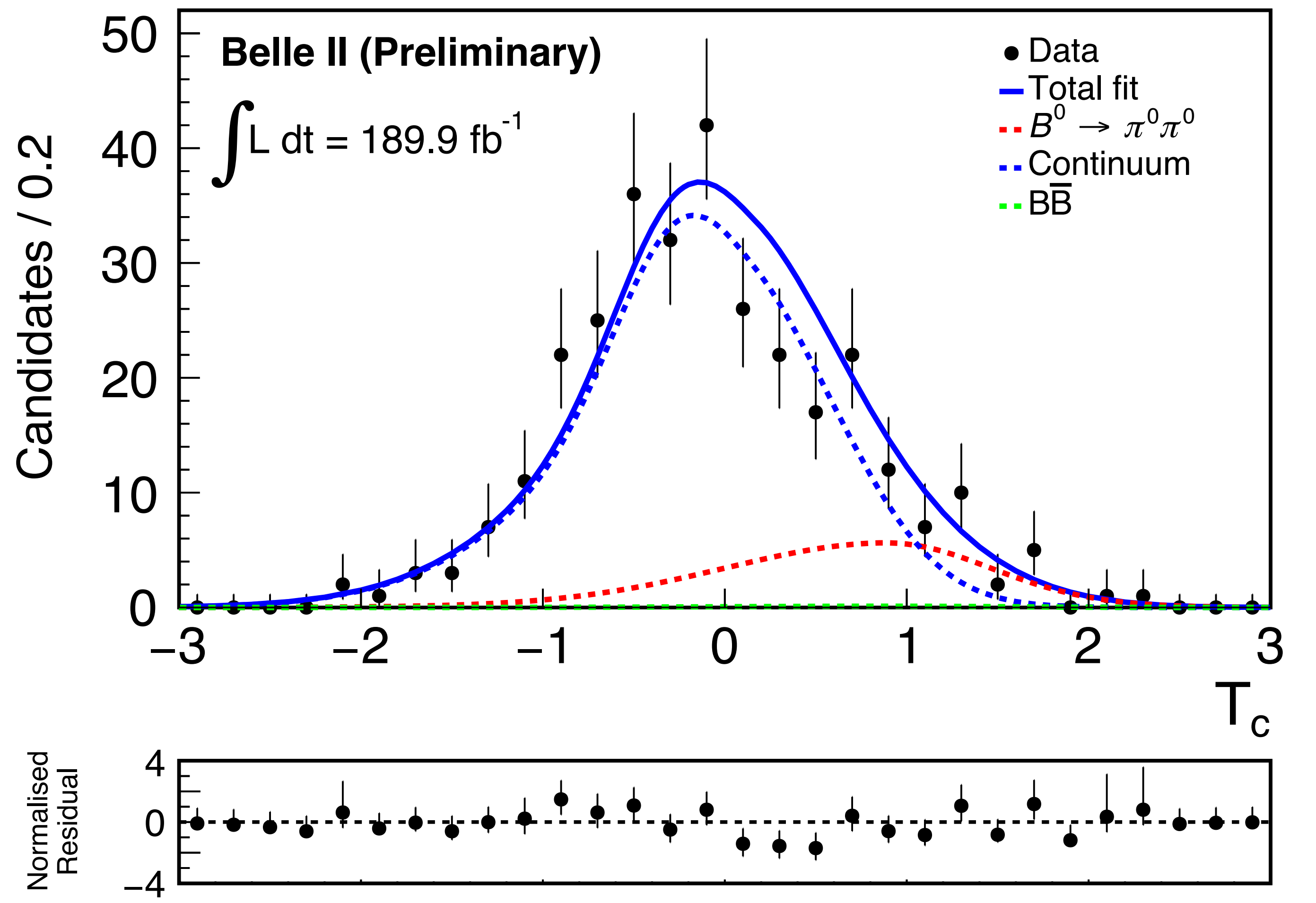
$B^0 \to \pi^0\pi^0$

- Continuum suppression ($e^+e^- \to q\bar{q}$; q=u, d, s, and c)
  - Continuum particles collimated due to the large available momentum for the light-hadron decays.
  - Multivariate analysis (MVA) combining variables associated with event topology
    - Fast Boosted Decision Tree (FBDT): Comput Softw Big Sci 1, 2 (2017)
  - is applied to other analysis modes.
- 4 photons in the final state.
  ⇒ Major backgrounds from fake photons rejected by the additional dedicated FBDT.
- Need to know flavor of B^0 (or $\bar{B}^0$) for A_{CP} ⇒ Flavor classification efficiency: (30.0±1.3%)

arXiv:2110.00790







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

slides at ICHEP 2022

- 3D fit simultaneous in 7 bins of the flavor classification quality

  M_{bc}: invariant mass of B candidates whose energy is replaced by half of collision energy.

  ΔE: difference between half of collision energy and observed B energy

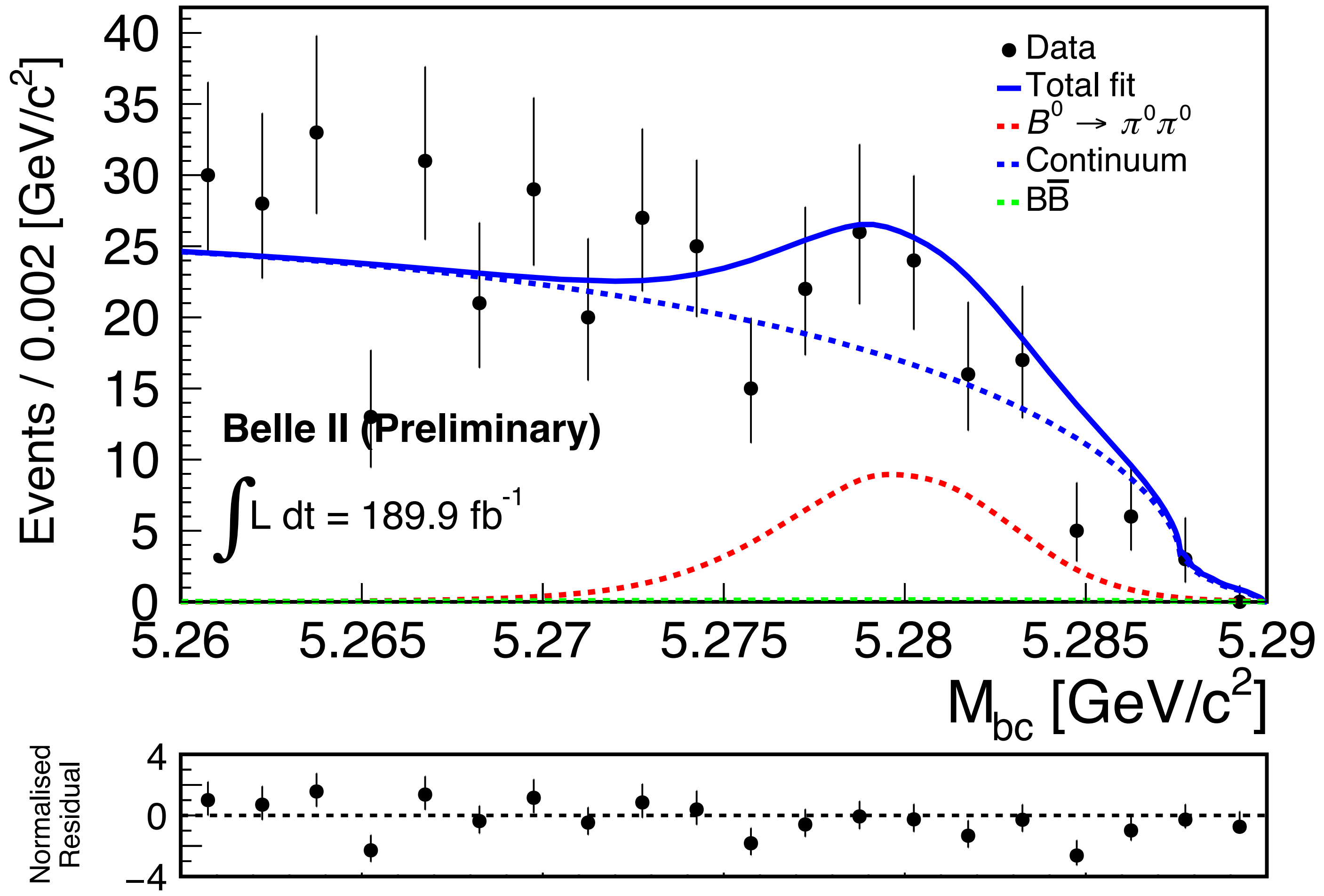
  T_c: converted MVA output

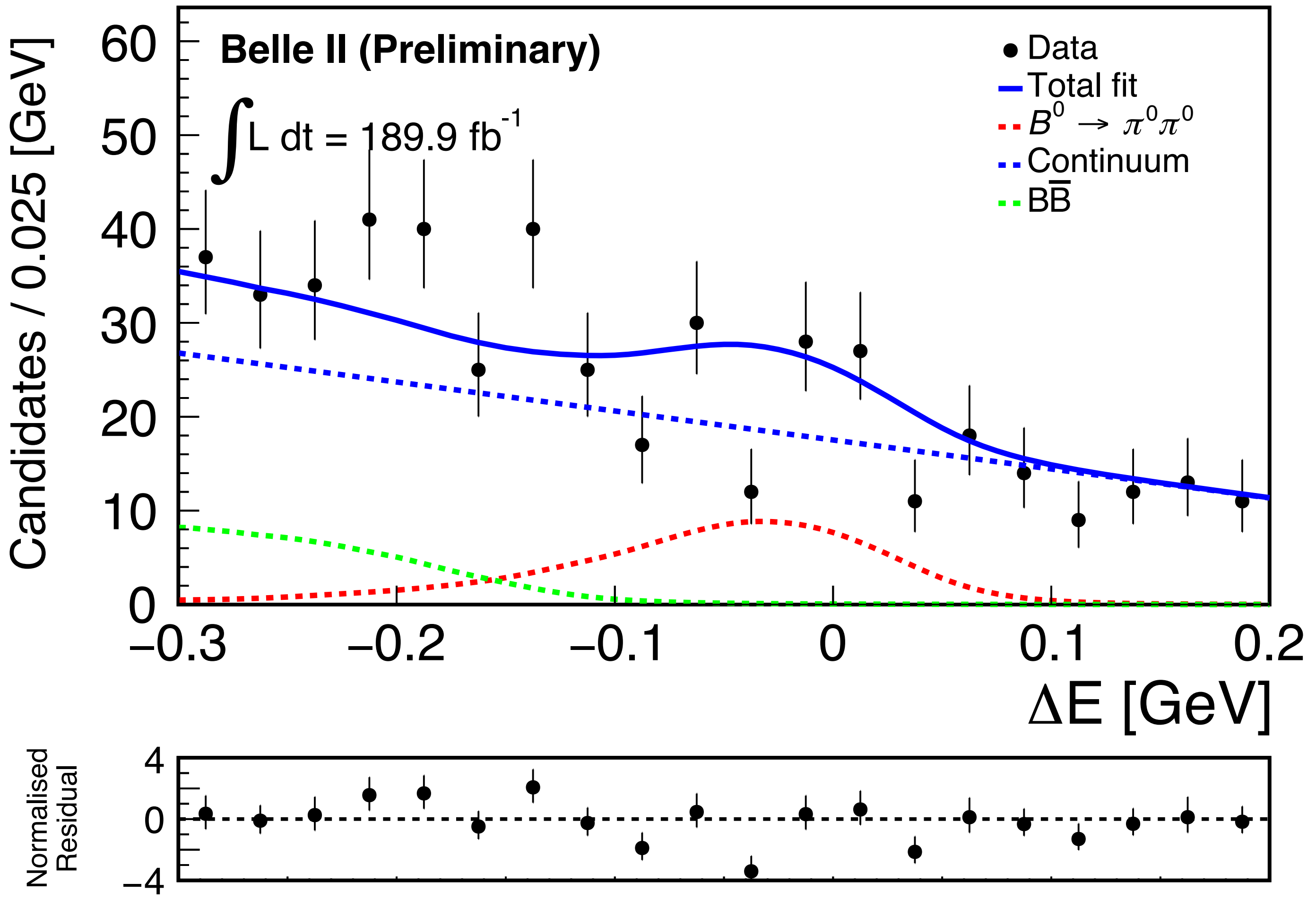
- Results competitive with Belle
  - ~1/3 of Belle's data set
  - statistical error dominant

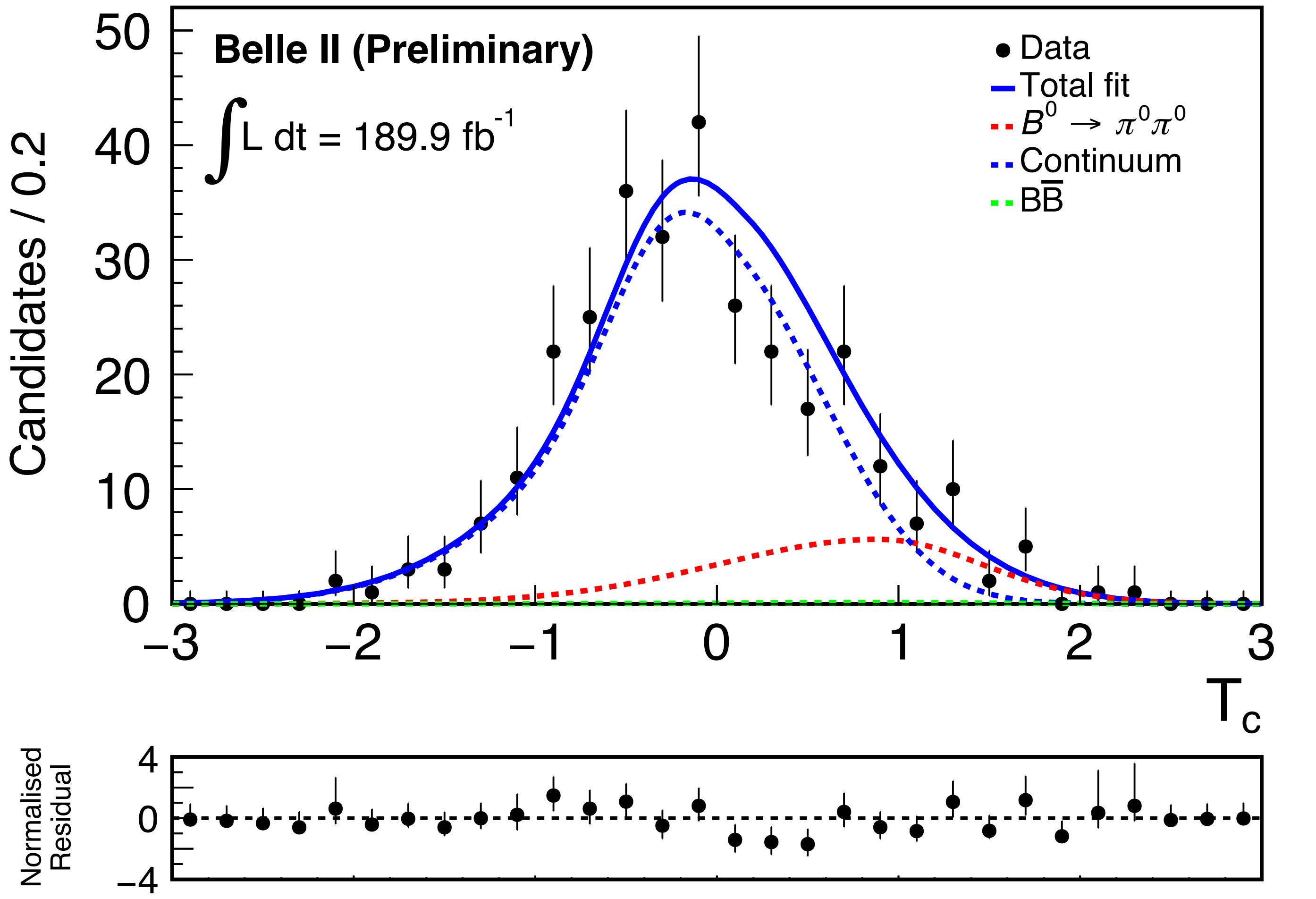
$$\mathcal{A}^{\mathrm{CP}} = 0.14 \pm 0.46(\mathrm{stat.}) \pm 0.07(\mathrm{syst.})$$
$$\mathcal{B} = (1.27 \pm 0.25(\mathrm{stat.}) \pm 0.17(\mathrm{syst.})) \times 10^{-6}$$

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

Yield: 93 ± 18







arXiv:2209.05154

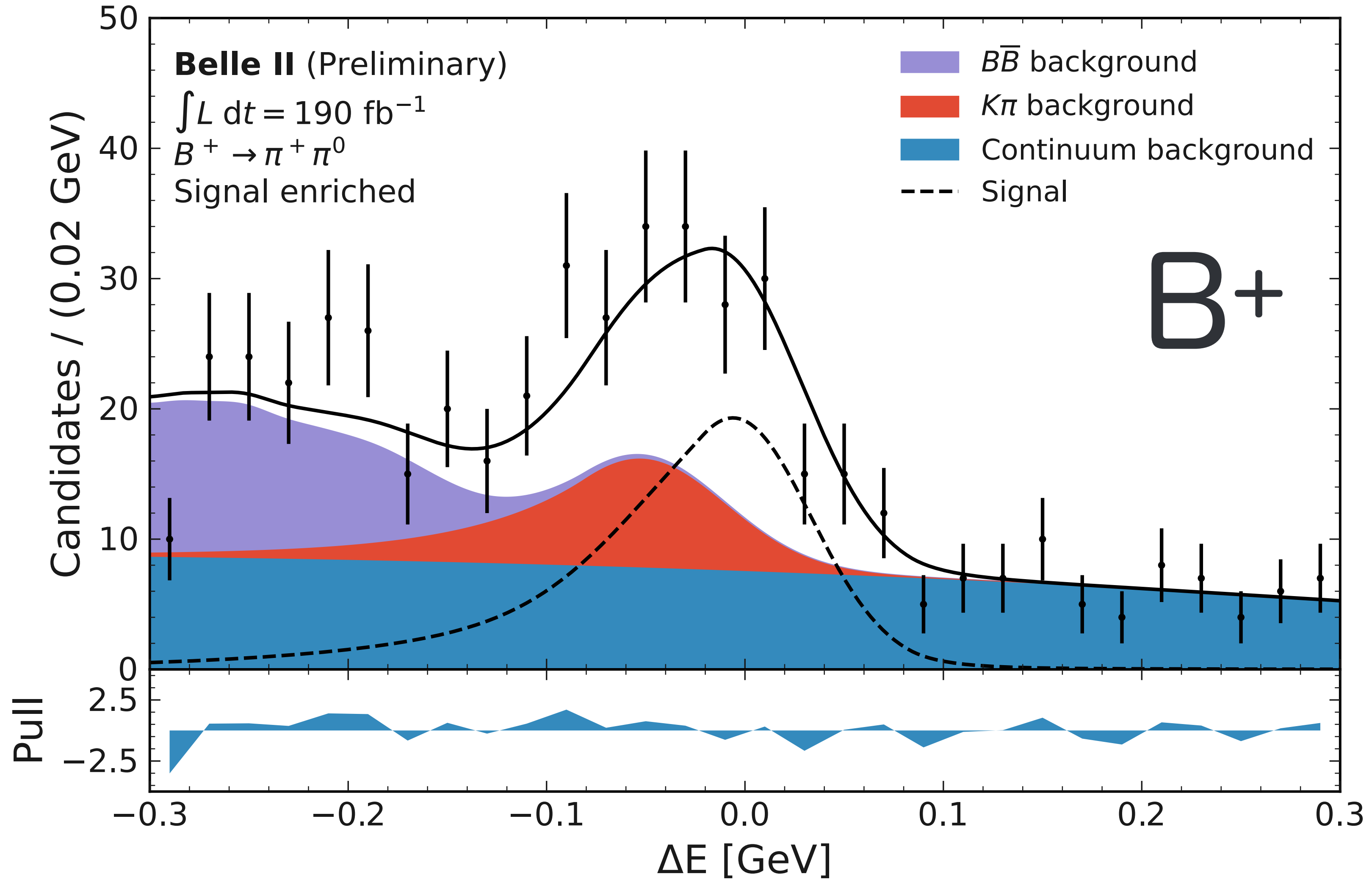
$B^+ \to \pi^+\pi^0$

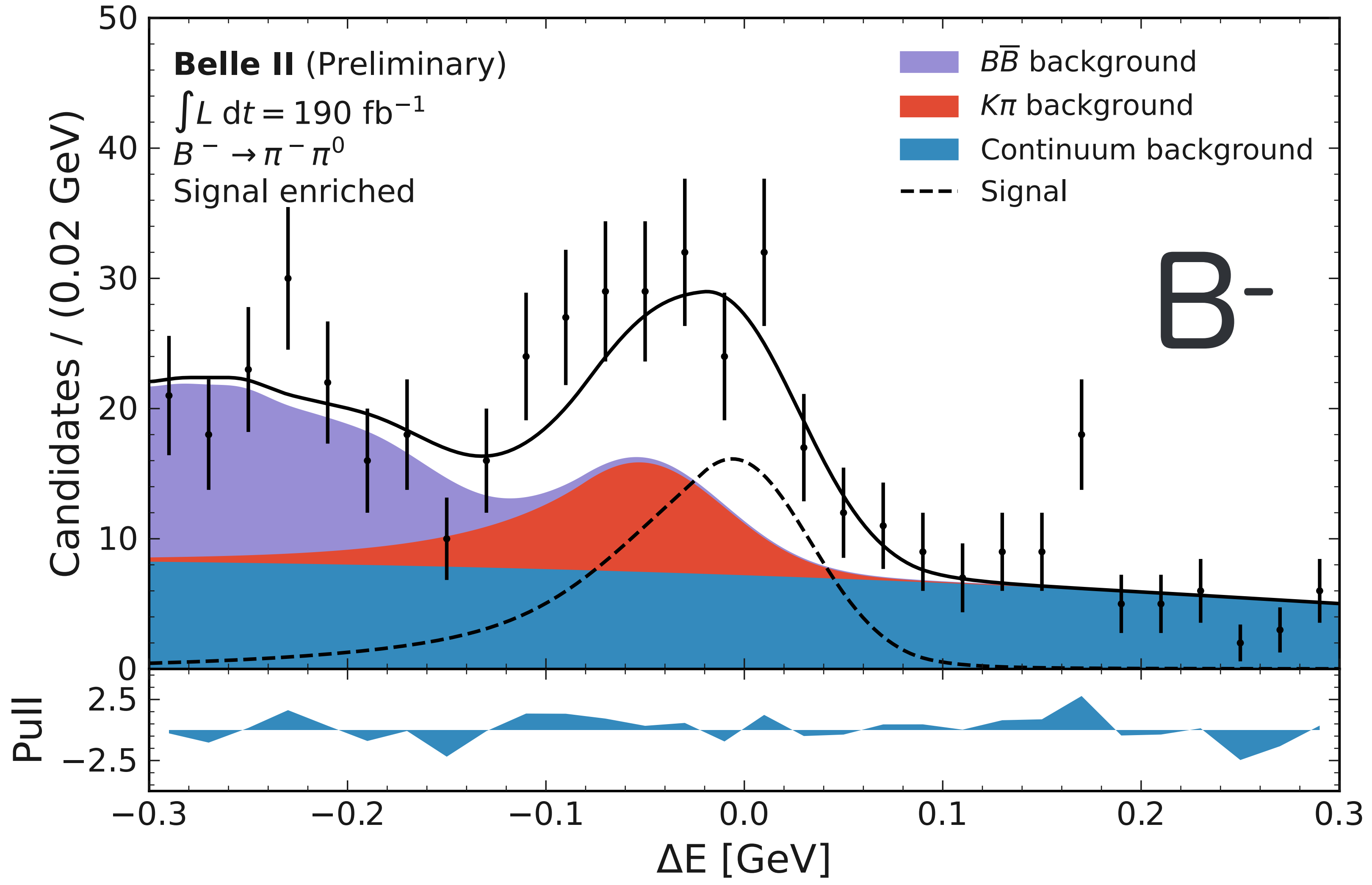
- Reconstruct $B^+ \to K^+\pi^0$ and $B^+ \to \pi^+\pi^0$ events using common selection.
  - $B^+ \to K^+\pi^0$: $K\pi$ puzzle
- Divide into pion- and kaon-enhanced samples.
- 3D charge-specific simultaneous fitting
  - To determine the CP asymmetry
  - Mbc, ΔE, converted MVA output
- K-π mis-identification negatively shifts the peak of ΔE.
  - $B \to \pi\pi$ can be clearly separated from $B \to K\pi$

$$\mathcal{A}^{\mathrm{CP}} = -0.085 \pm 0.085(\mathrm{stat.}) \pm 0.019(\mathrm{syst.})$$
$$\mathcal{B} = (6.12 \pm 0.53(\mathrm{stat.}) \pm 0.53(\mathrm{syst.})) \times 10^{-6}$$

WA: $\mathscr{A}^{CP} = 0.03 \pm 0.04$, $\mathscr{B} = (5.5 \pm 0.4) \times 10^{-6}$

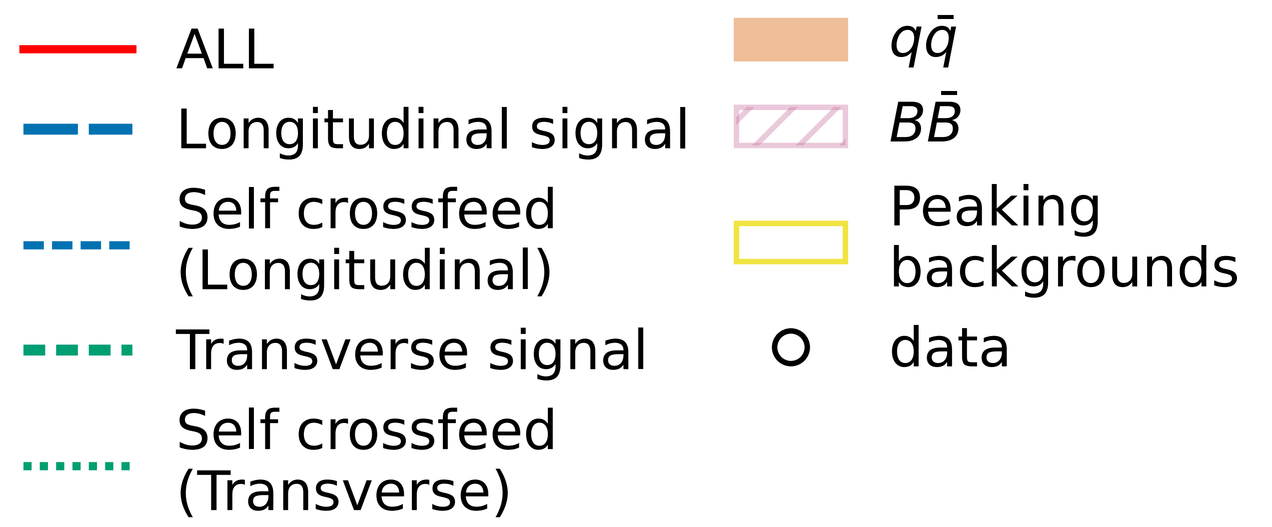
Yield: 422 ± 37





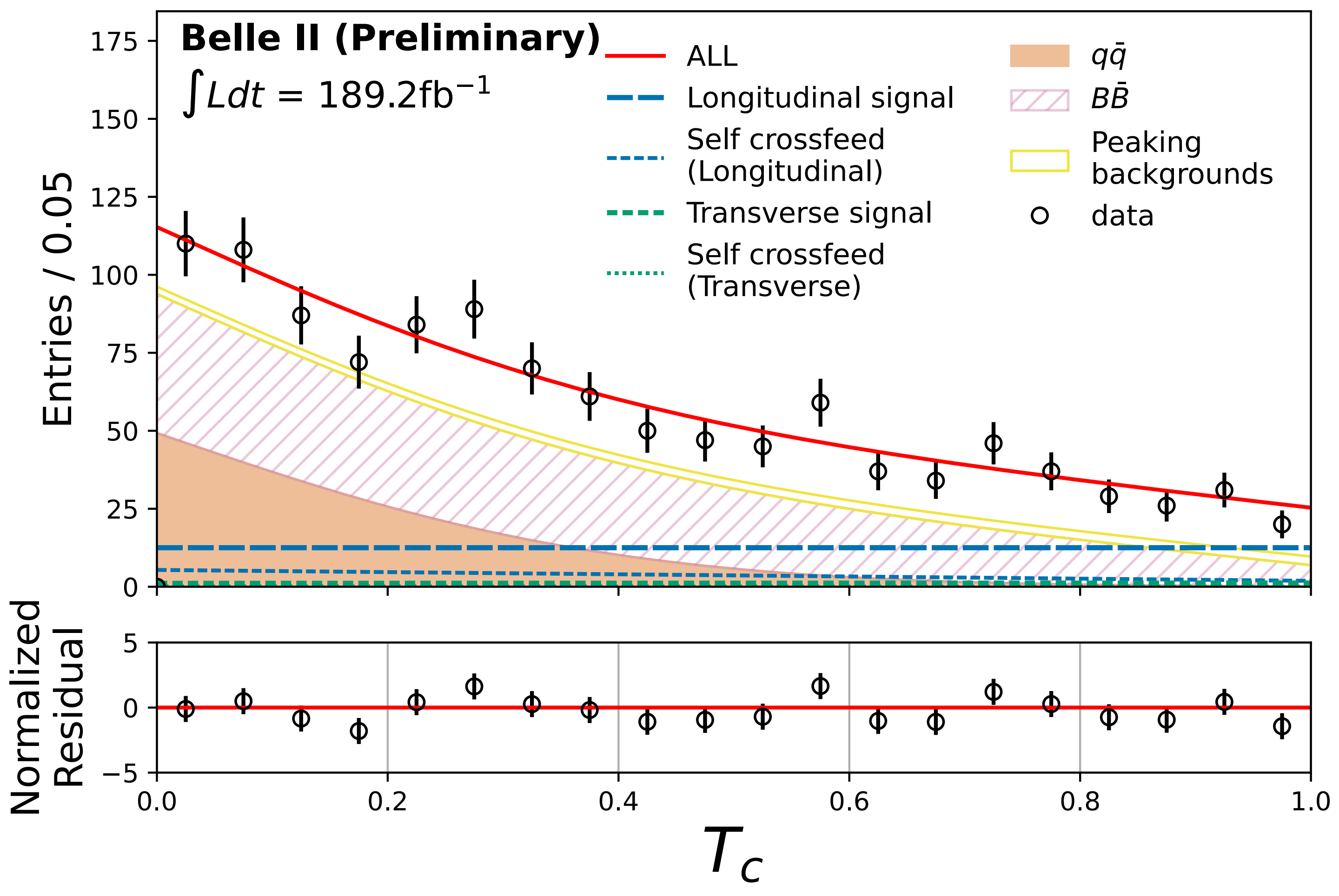
$B^0 \to \rho^+\rho^-$

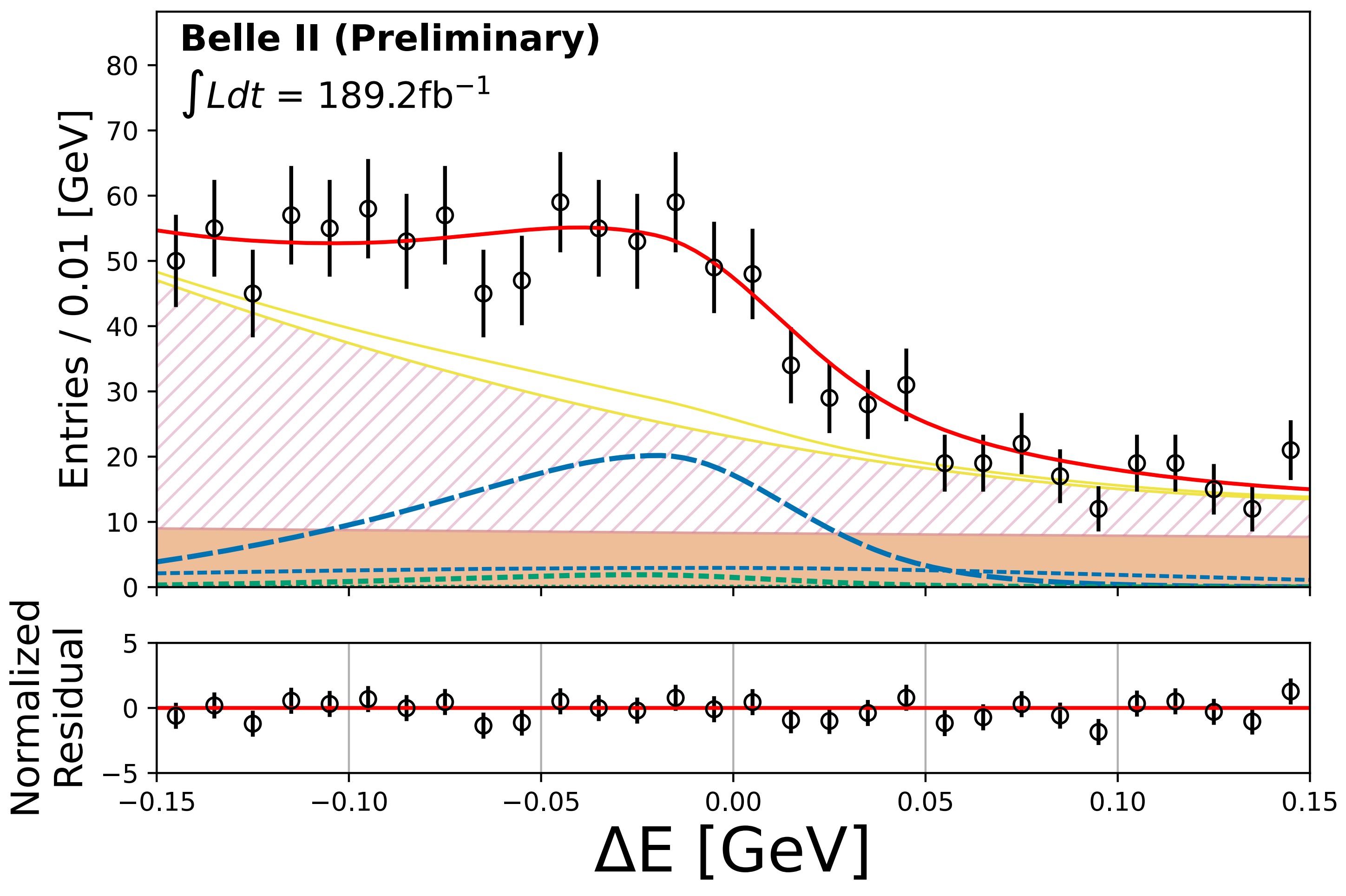
[arXiv:2208.03554]

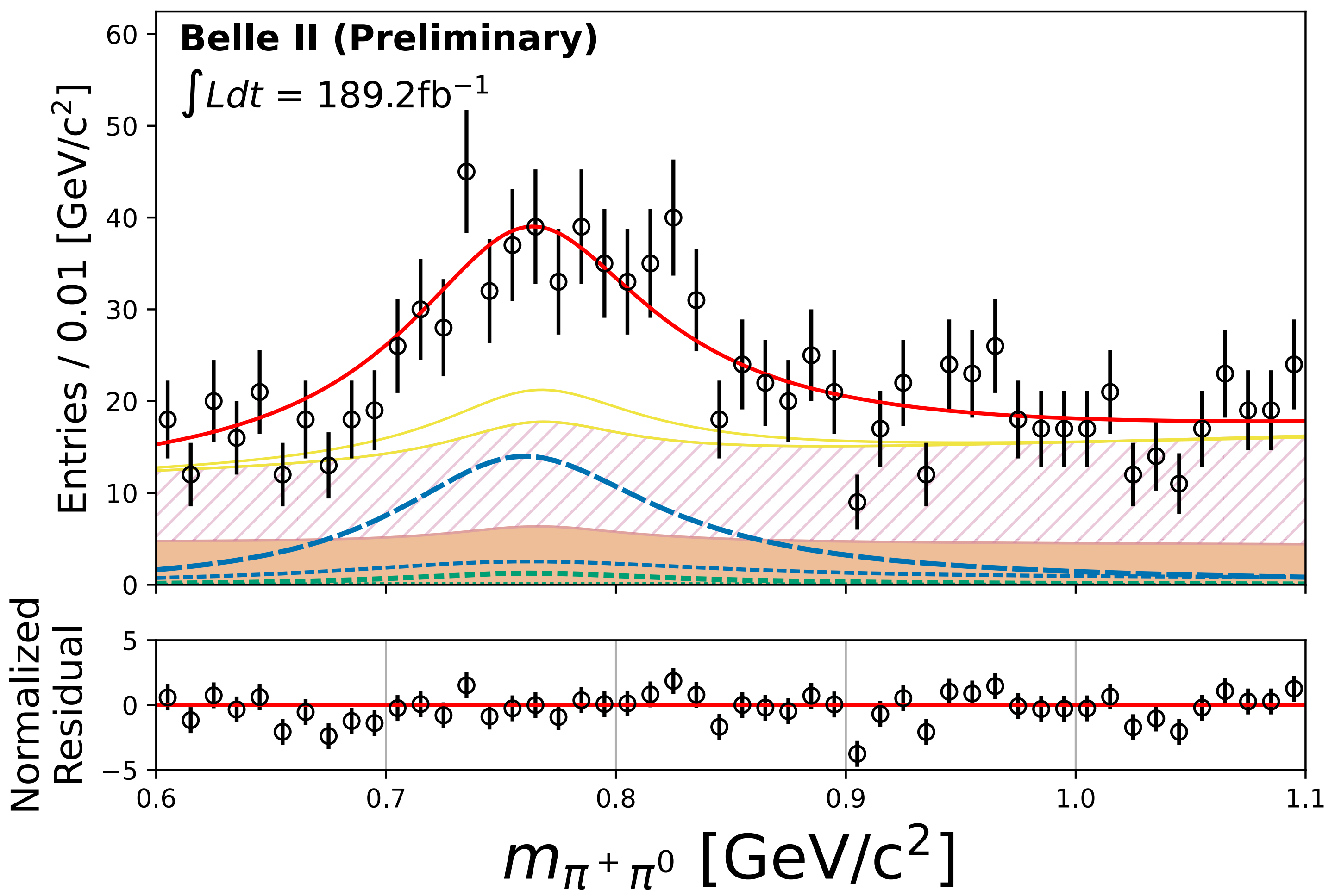


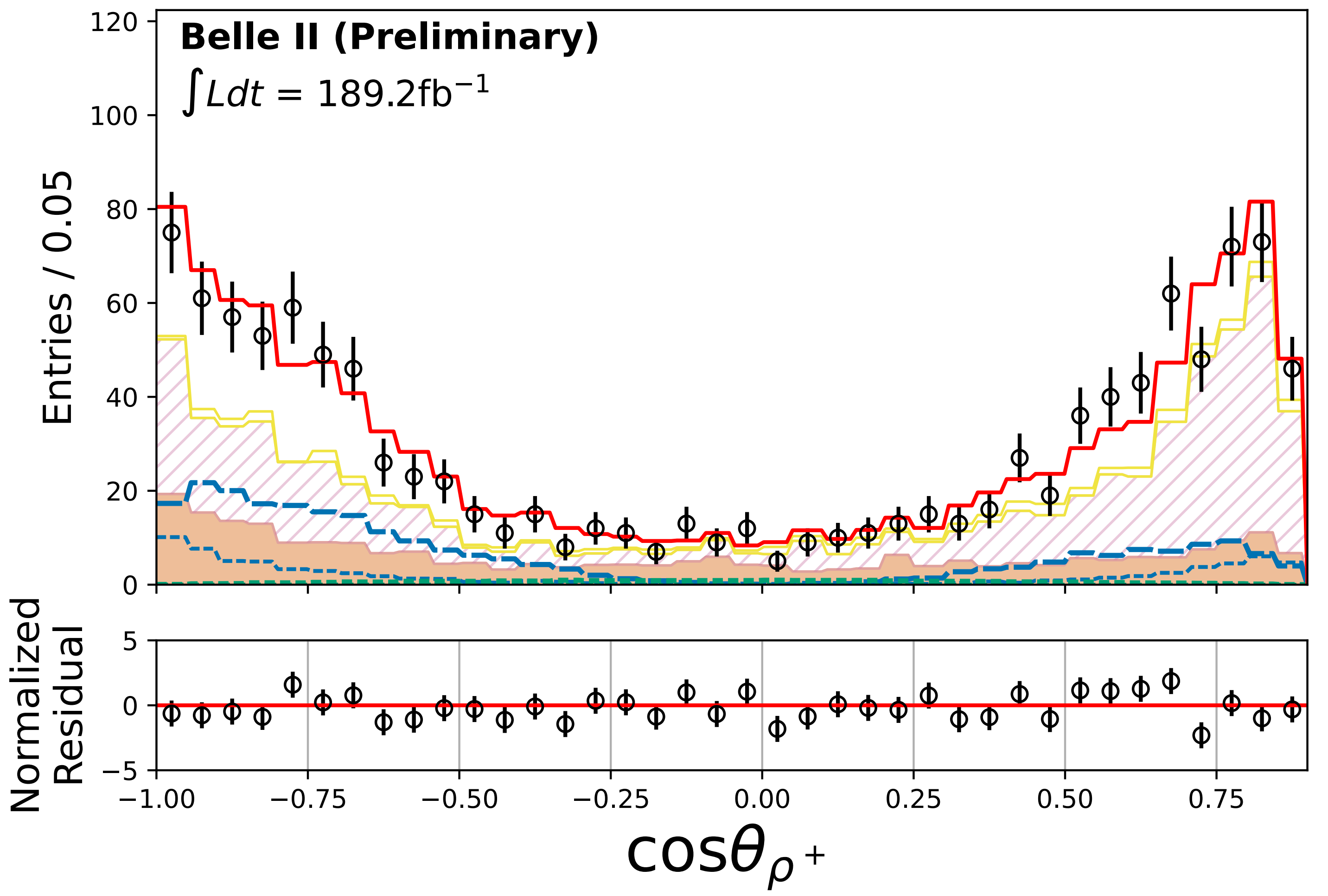
- P→VV decay
  ⇒ need angular analysis to separate different polarizations
  ⇒ fit helicity angle of $\rho^{\pm} \to \pi^{\pm}\pi^{0}$

- 6D (ΔE, T_c, $m_{\pi^{\pm}\pi^{0}}$, $\cos\theta_{\rho^{\pm}}$) fit taking correlations into account
  - 6 modes of peaking backgrounds have a similar final state as signal ($2\pi^0$, $1\pi^+$+1h^-)









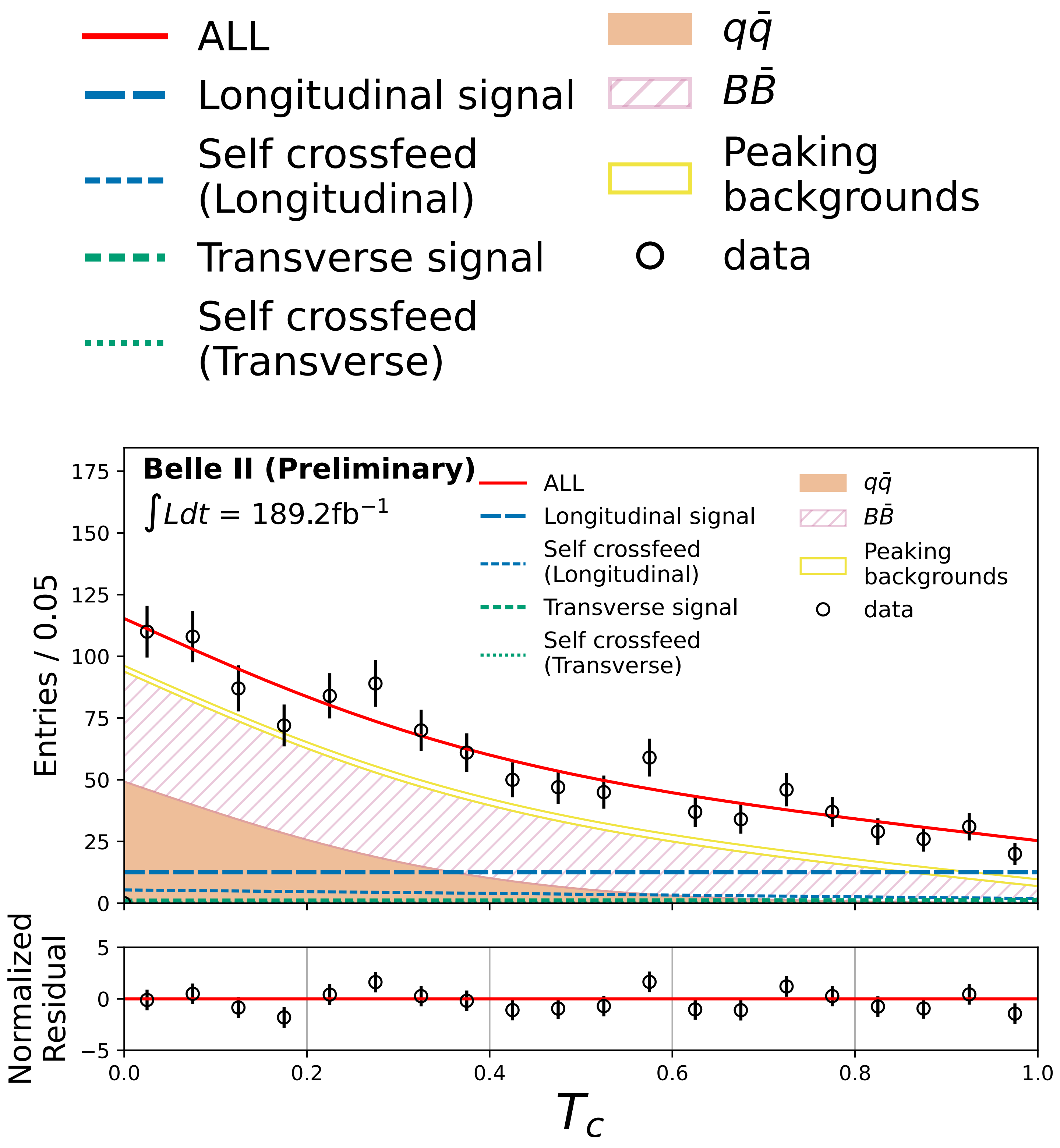
$B^0 \to \rho^+ \rho^-$

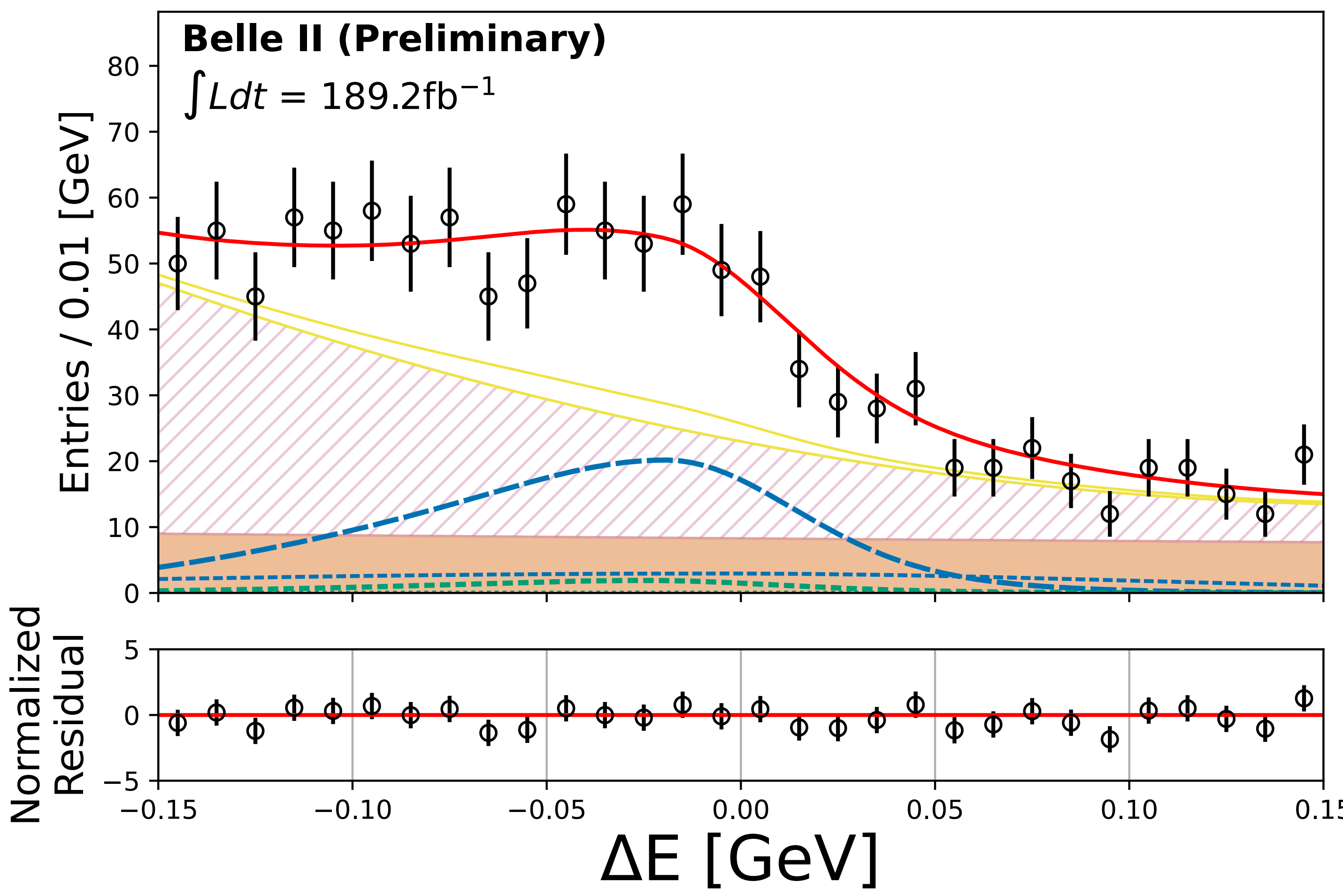
Yield: (long.) $234.6^{+23.7}_{-22.8}$, (trans.) $21.3^{+18.7}_{-17.3}$

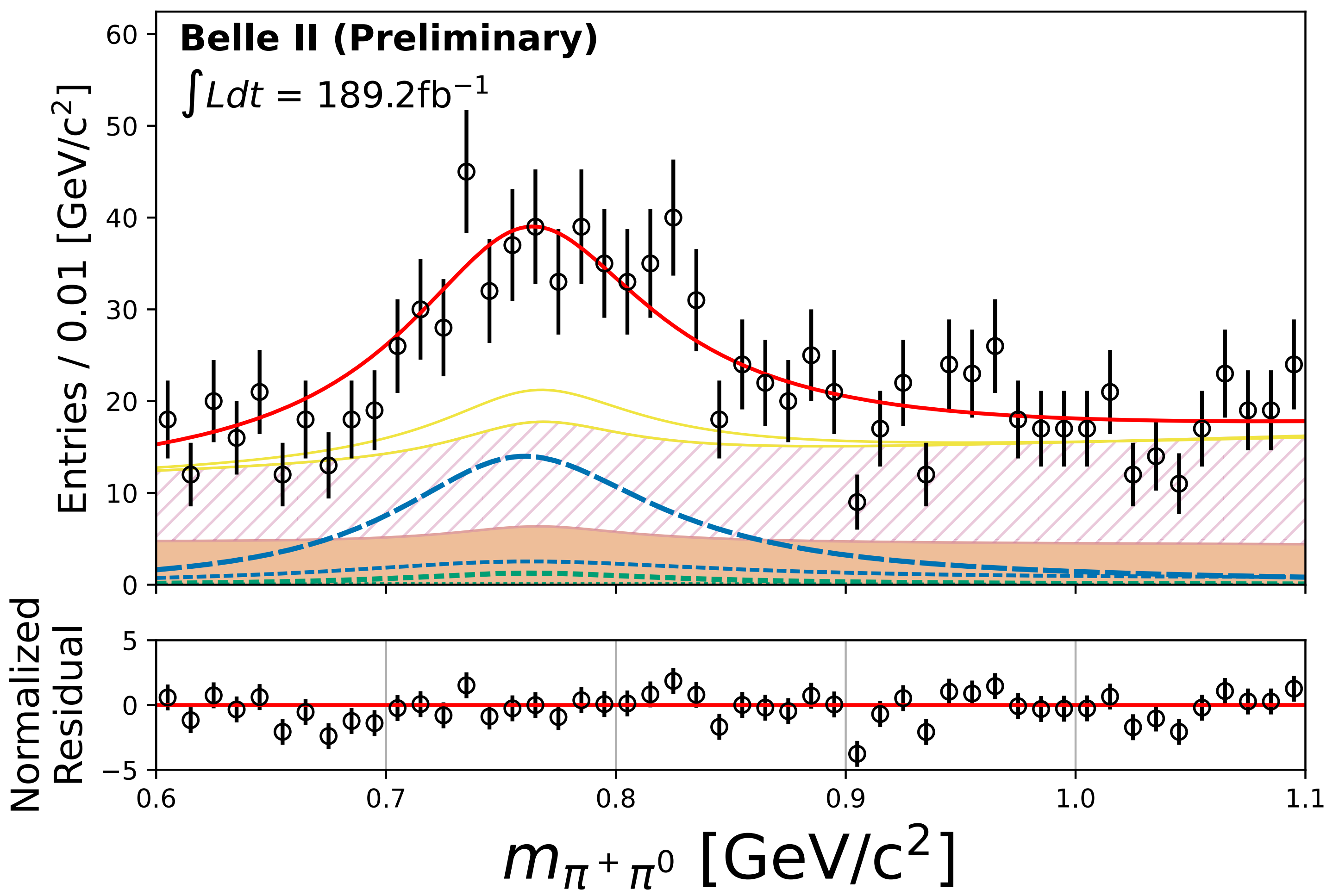
$$\mathcal{B} = (26.7 \pm 2.8(\text{stat.}) \pm 2.8(\text{syst.})) \times 10^{-6}$$
$$f_L = 0.956 \pm 0.035(\text{stat.}) \pm 0.033(\text{syst.})$$

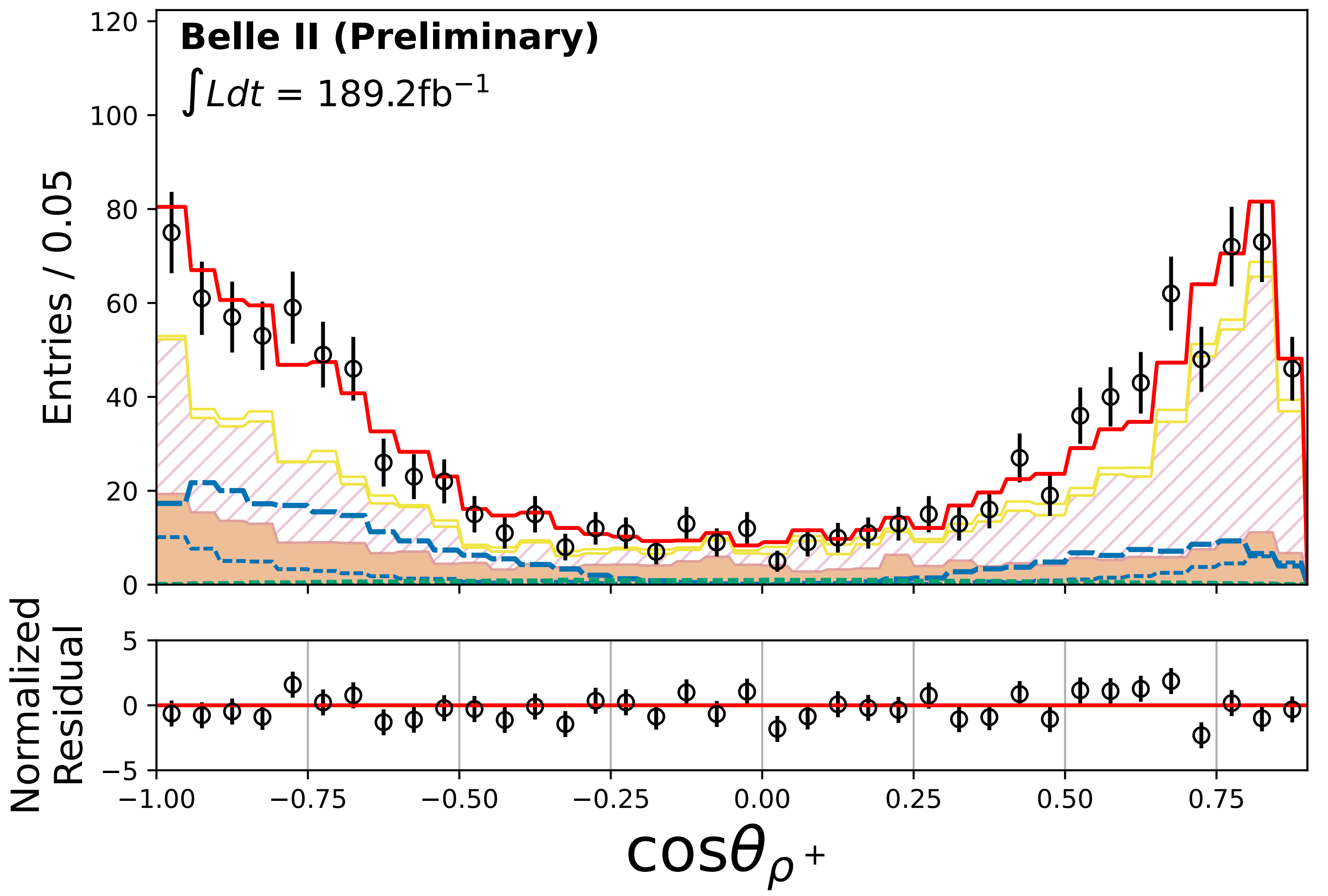
WA: $\mathscr{B} = (27.7 \pm 0.19) \times 10^{-6}$, $f_L = 0.990^{+0.021}_{-0.019}$

- Largest systematic uncertainty associated to π^0 reconstruction: 7.7% for BF









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

arXiv:2206.12362

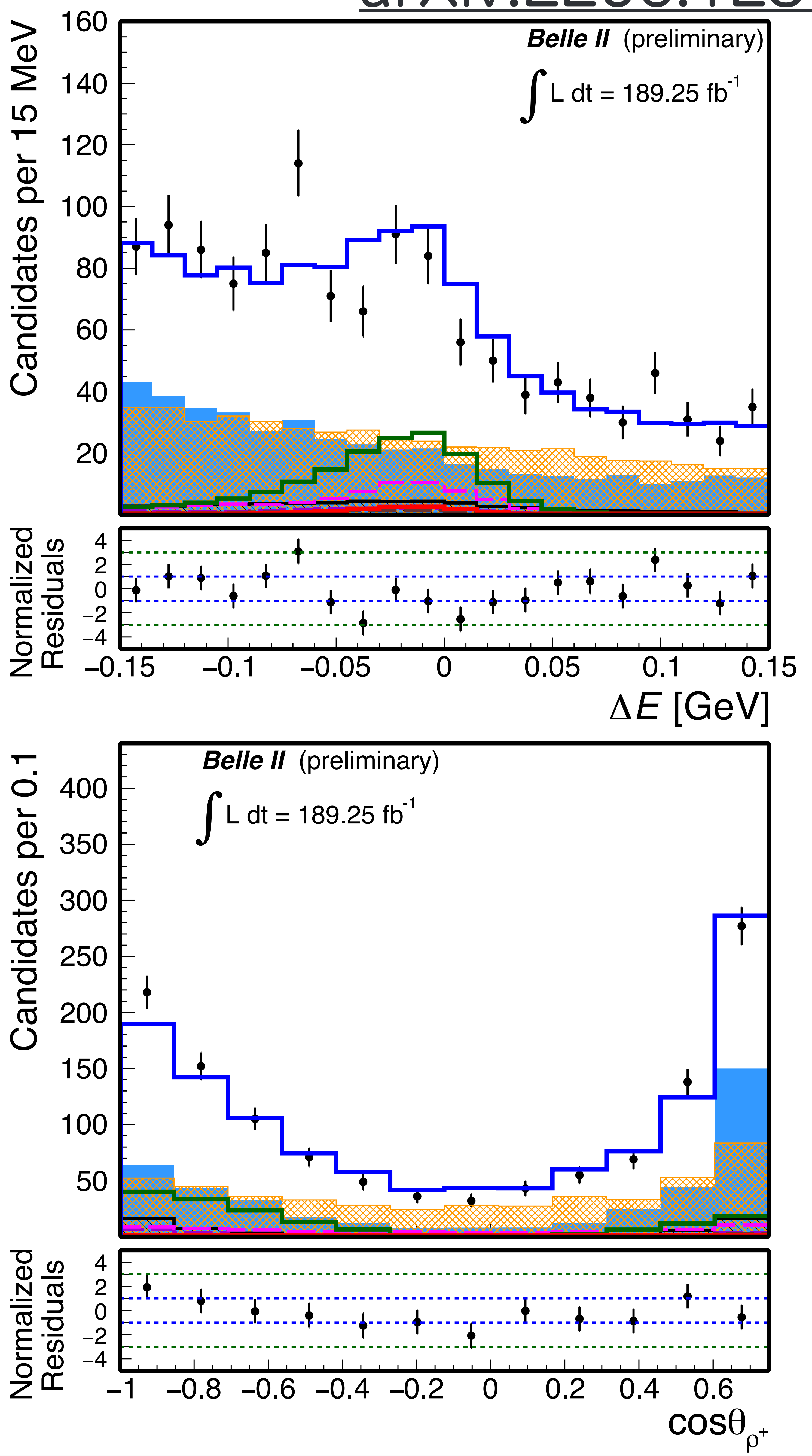
Yield: 345 ± 31

- Similar analysis strategy as $B^0 \to \rho^+ \rho^-$
- Fit helicity angle of $\rho \to \pi\pi$
  ⇒ Determine longitudinal-polarization fraction

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

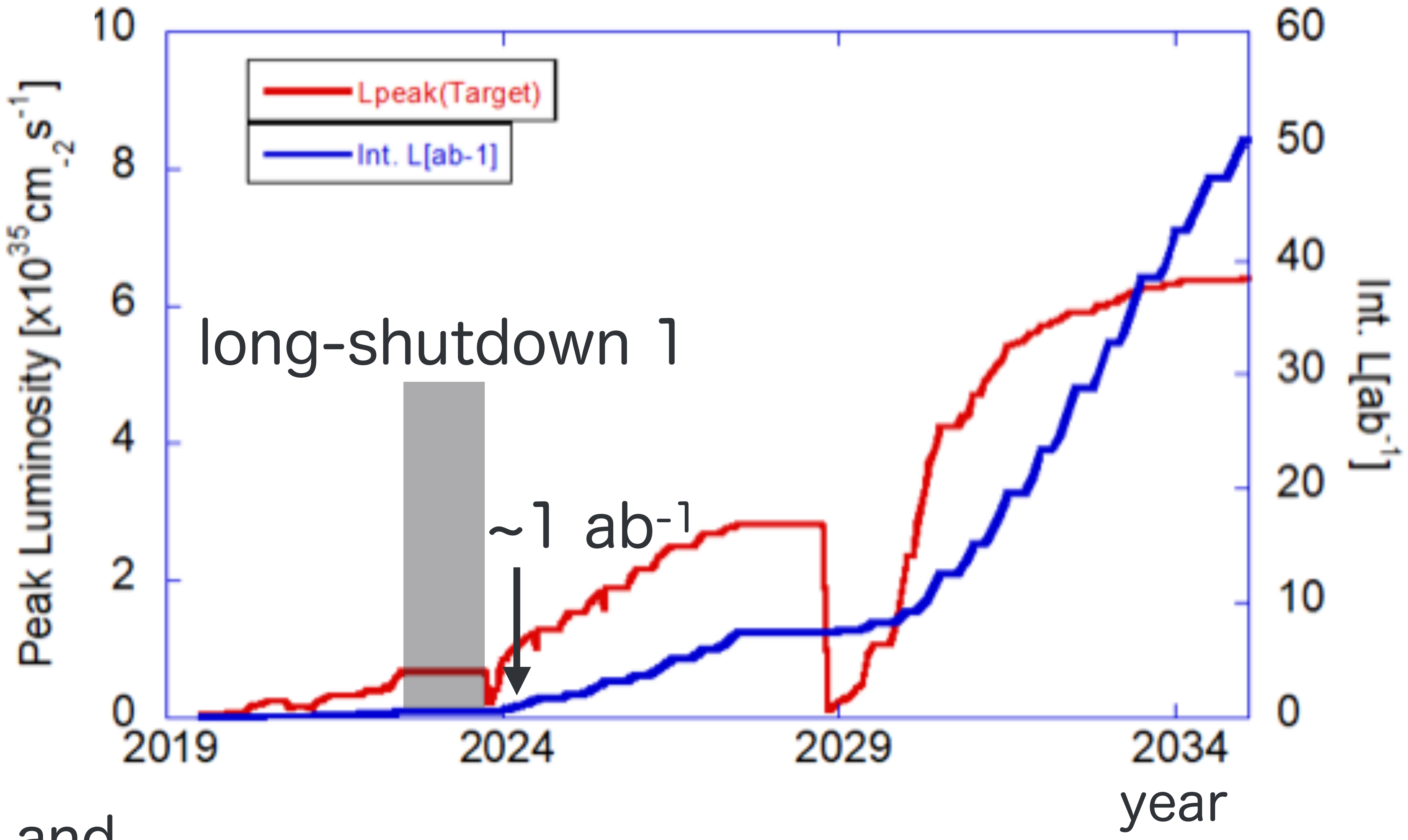
WA: $\mathscr{A}^{CP} = -0.05 \pm 0.05$, $\mathscr{B} = (24.0 \pm 1.9) \times 10^{-6}$
$f_L = 0.950 \pm 0.016$

- Largest systematic uncertainty from data-simulation discrepancies of $\cos\theta_\rho$: 8.0% for BF
  - This is due to mis-modeling of low-p tracks in simulation.
    ⇒ We are trying to reduce this by reweighing on them.

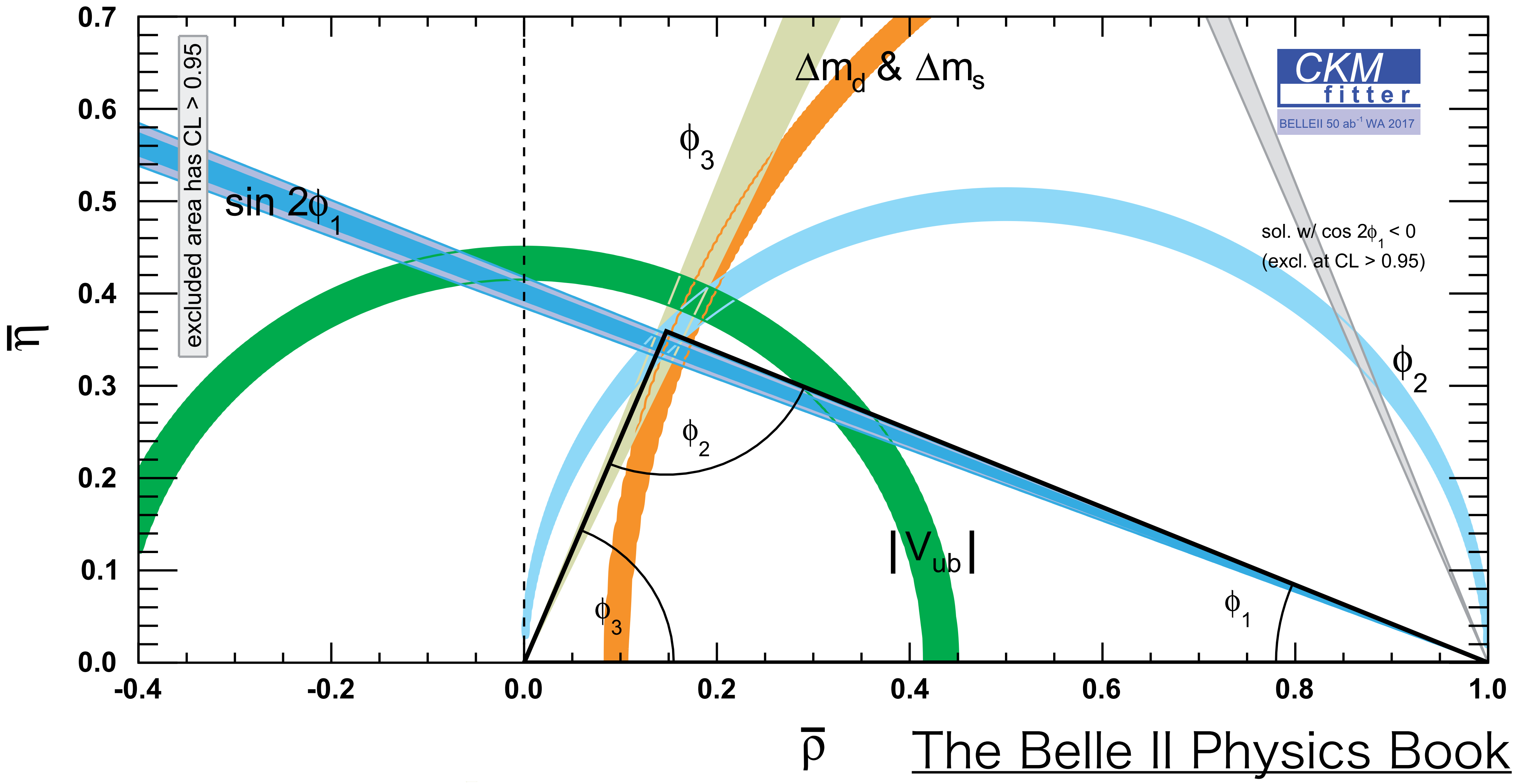


Prospects

- Before the end of 2022: $\mathcal{L}_{\rm int}$ of 363 fb^{-1} at Υ(4S)
  - half of the integrated luminosity at Belle
- Winter and summer 2023: many updates w/ 363 fb^{-1}
- Autumn 2023: resume physics running
  - In about one year, the data size will be the same as Belle's, and
  - the accuracy of the ϕ_2 determination may be improved by applying upgraded analysis technique.
  - Combined analysis of Belle and Belle II data is also available.
- Excellent ϕ_2 precision with 50 ab^{-1}: $\Delta\phi_2$ = 0.6~1.0°
  - Current WA: $(85.2^{+4.8}_{-4.3})^\circ$
  - B→$\pi\pi$: $\Delta\phi_2$ = ~2°
  - B→$\rho\rho$: $\Delta\phi_2$ = 0.7~1.0°



Belle II 50 ab^{-1}



The Belle II Physics Book

Summary

- In CKM, ϕ_2 is the least known parameter due to difficulties in analysis and should be precisely determined.
- Belle II is updating $B \to \pi\pi / \rho\rho$ measurements to determine ϕ_2.
  - Analysis of five of the six modes is ongoing with updated results at Belle II.
  - $B^0 \to \rho^0\rho^0$ will be measured to check its small branching fraction.

	$\mathcal{B}$ $(\times 10^{-6})$	A_{CP}	$\mathcal{L}_{\text{int}}$ fb^{-1}
$B^0 \to \pi^+\pi^-$	$5.8 \pm 0.7 \pm 0.3$ (5.12 ± 0.19)	$(\mathcal{A} = -0.314 \pm 0.030,\ \mathcal{S} = -0.670 \pm 0.030)$	63
$B^0 \to \pi^0\pi^0$	$1.27 \pm 0.25 \pm 0.17$ (1.59 ± 0.26)	$0.14 \pm 0.46 \pm 0.07$ (-0.33 ± 0.22)	190
$B^+ \to \pi^+\pi^0$	$6.12 \pm 0.53 \pm 0.53$ (5.5 ± 0.4)	$0.085 \pm 0.085 \pm 0.019$ (0.03 ± 0.04)	190
$B^0 \to \rho^+\rho^-$	$26.7 \pm 2.8 \pm 2.8$ (27.7 ± 1.9)	$(\mathcal{A} = 0.00 \pm 0.09,\ \mathcal{S} = -0.14 \pm 0.13)$	190
$B^0 \to \rho^0\rho^0$	(0.96 ± 0.15)	$(\mathcal{A} = 0.2 \pm 0.9,\ \mathcal{S} = 0.3 \pm 0.7)$	-
$B^+ \to \rho^+\rho^0$	$23.2^{+2.2}_{-2.1} \pm 2.7$ (24.0 ± 1.9)	$-0.069 \pm 0.068 \pm 0.060$ (-0.05 ± 0.05)	190

PDG2022
(World Averages)

Summary

- In CKM, ϕ_2 is the least known parameter due to difficulties in analysis and should be precisely determined.
- Belle II is updating $B \to \pi\pi / \rho\rho$ measurements to determine ϕ_2.
  - Analysis of five of the six modes is ongoing with updated results at Belle II.
  - $B^0 \to \rho^0 \rho^0$ will be measured to check its small branching fraction.
- Our measurements already show performance equal to or better than the best results from Babar and Belle.
- In the coming years, we plan to achieve the world highest precision measurement.

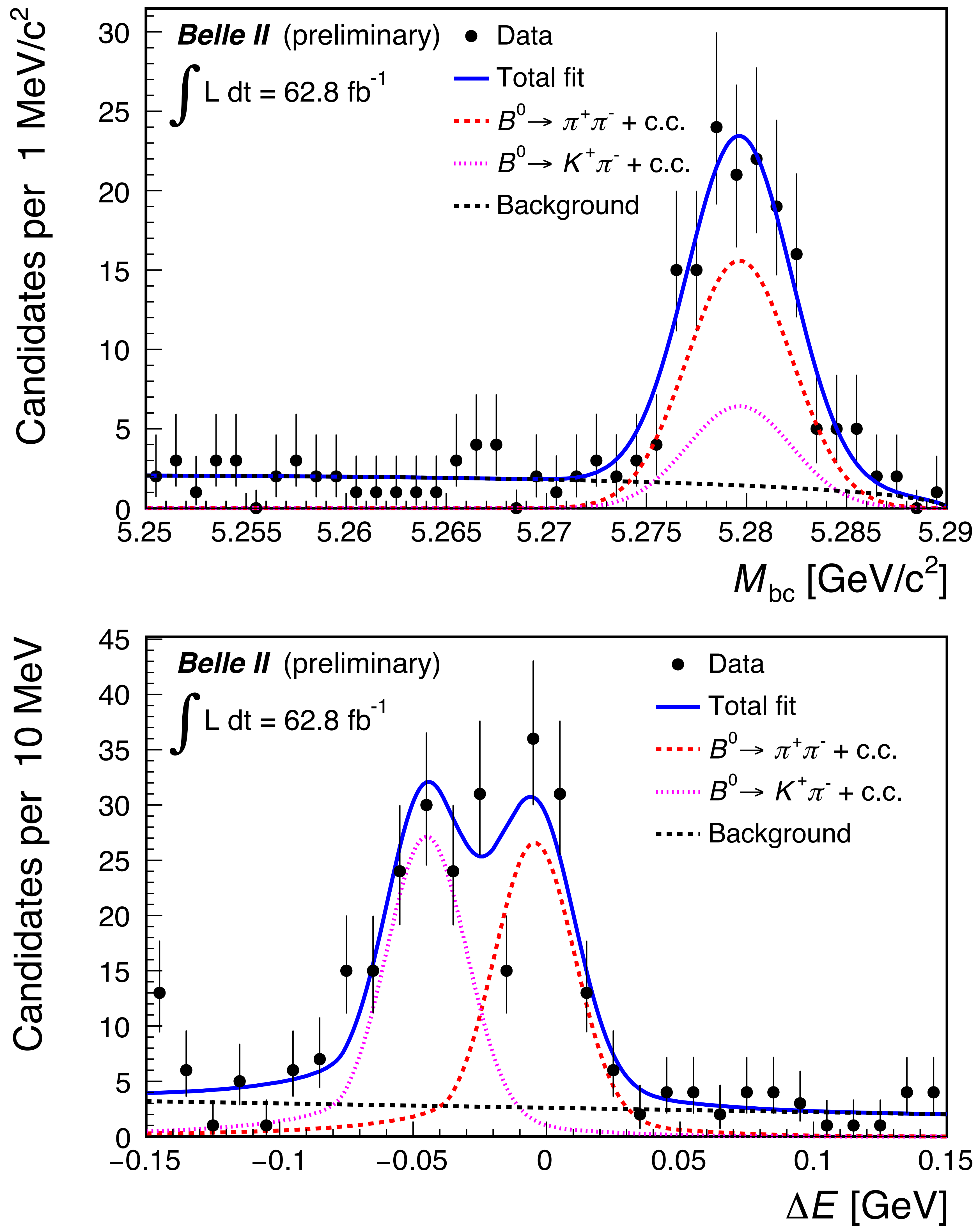
Stay tuned!!

Backup

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

arXiv:2106.03766

Yield: 115^{+14}_{-13}



- 2D fit simultaneously (M_{bc} and ΔE)
- K-π mis-identification negatively shifts a peak position.

$$\mathcal{B} = (5.8 \pm 0.7(\text{stat.}) \pm 0.3(\text{syst.})) \times 10^{-6}$$

WA: $\mathscr{B} = (5.12 \pm 0.19) \times 10^{-6}$