Time-dependent CPV and hadronic *B* decays at Belle II

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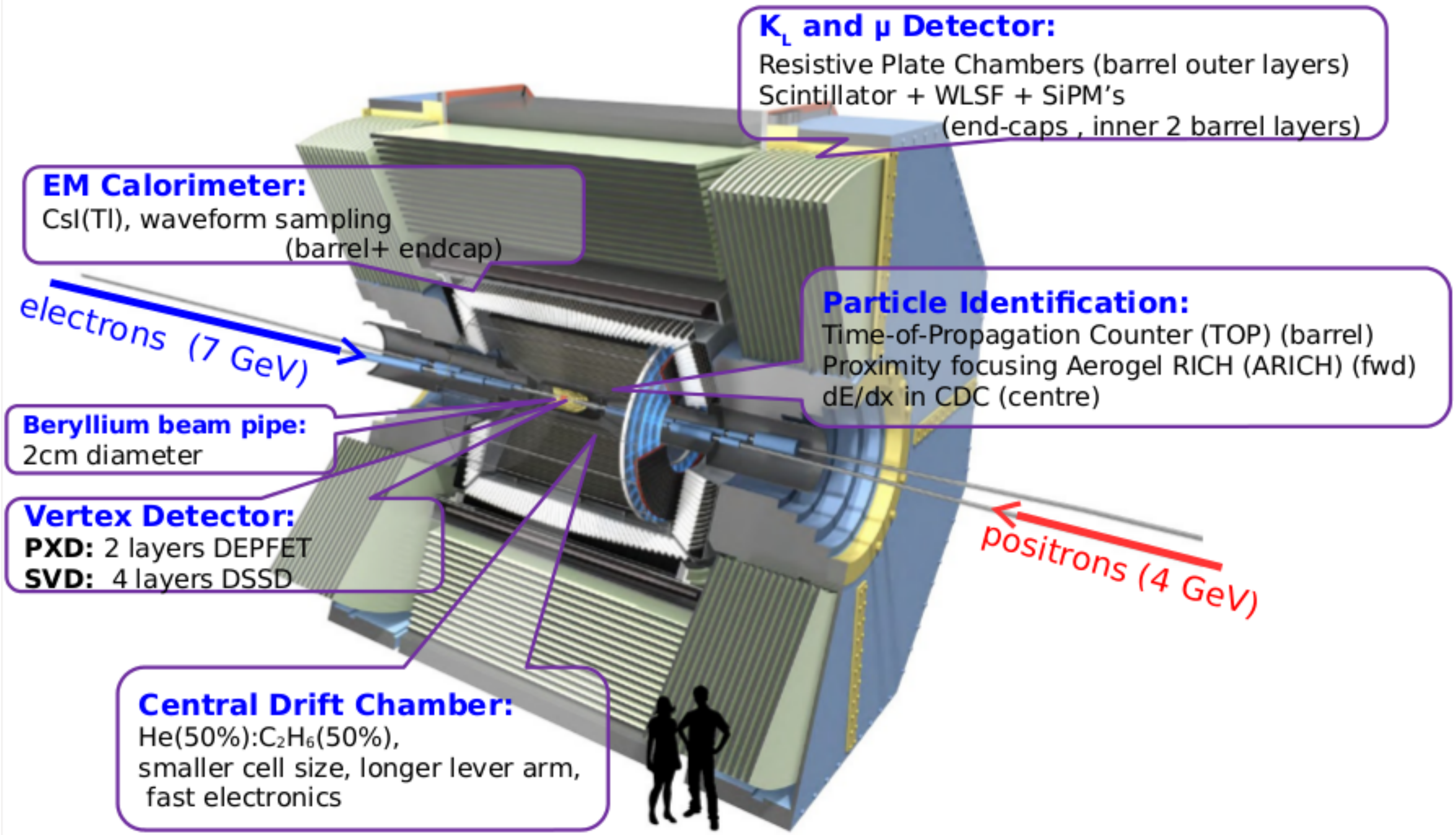
(On behalf of the Belle II collaboration)

Workshop on status and perspective of physics at high intensity, Frascati
10th November, 2022

The Belle II detector

- Higher beam background
- Higher trigger rate
- New tracking system and improved vertexing capability
- New particle identification systems
- Better time resolution at calorimeter
- Unique capability to reconstruct final states with multiple neutrinos and π^0/ photons

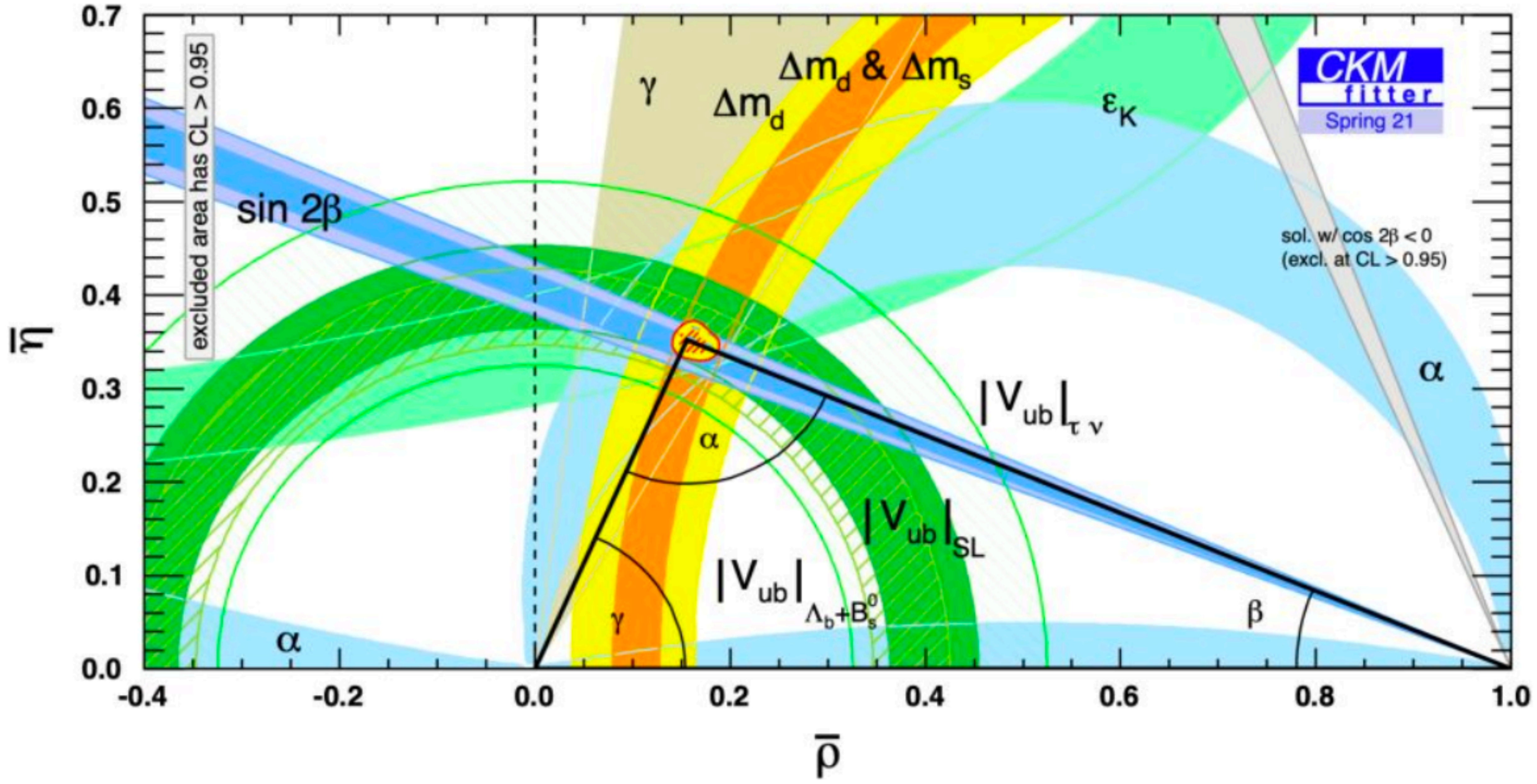


So far 424 fb^{-1} of data collected, today's results are based on 190 fb-1 of $\Upsilon(4S)$ data

Today's talk

- **Time dependent measurements**
  - B^0 lifetime and mixing
  - ϕ_1/β
  - CPV in $B^0 \to K_S^0 K_S^0 K_S^0$
- **Charmless *B* decays**
  - $K\pi$ puzzle: $B \to K_S^0 \pi^0, K^+\pi^0$
  - $\phi_2/\alpha : B \to \pi^0\pi^0, \rho\rho$
- **ϕ_3/γ: combined Belle + Belle II analysis**

The primary goal of Belle II is to probe non-SM physics as well as improve existing precision measurements on CKM Unitarity triangle by over constraining it.

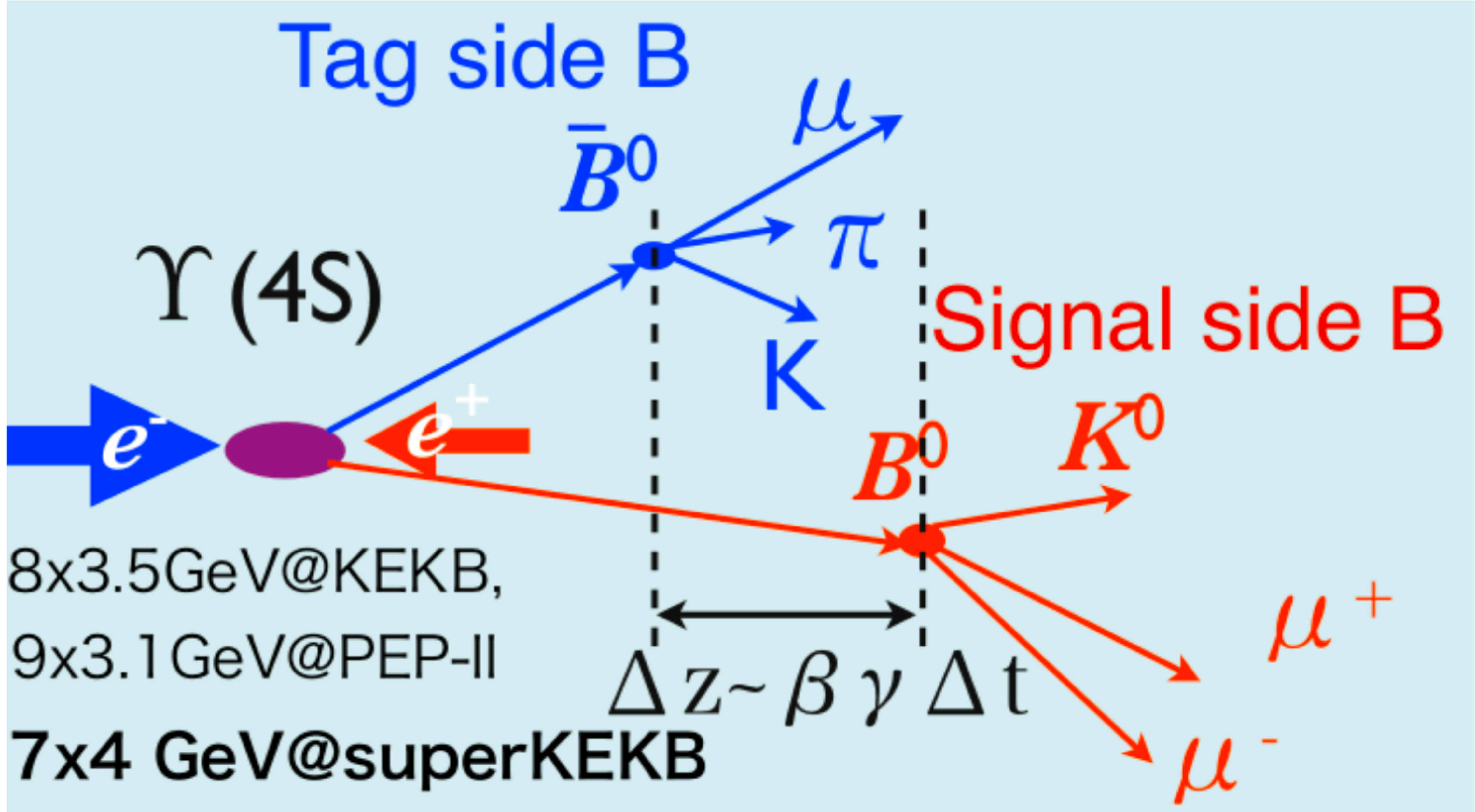


TDCPV measurements

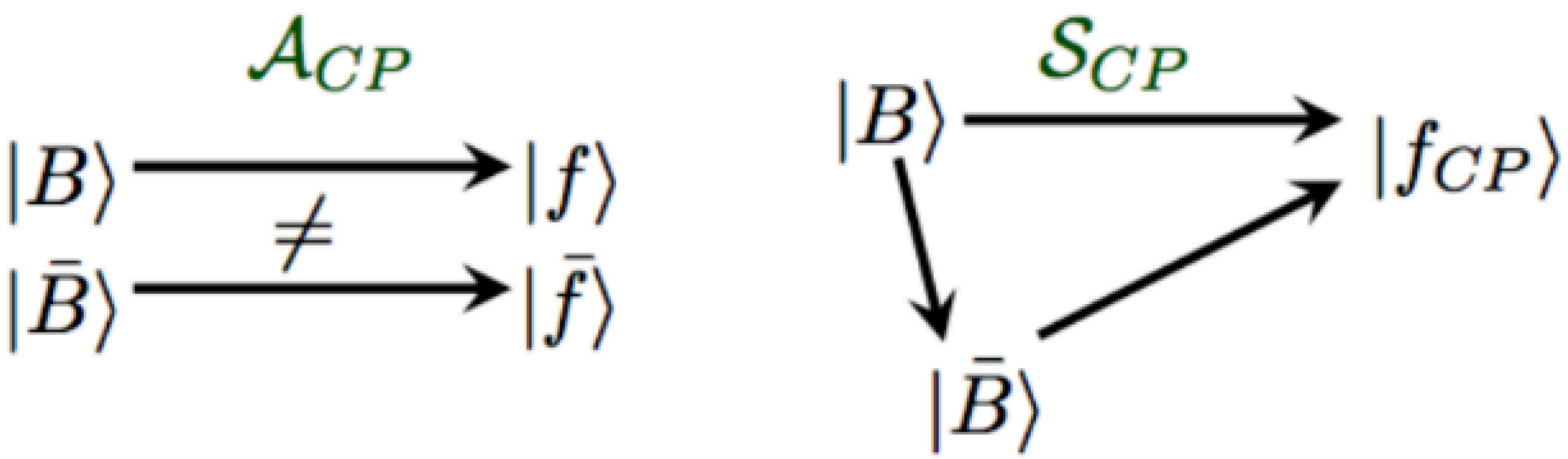
Decay rate of B^0 meson to *CP* eigenstate:

$$\mathcal{P}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left[1 + q\left(\mathcal{A}_{CP}\cos\Delta m_d \Delta t + \mathcal{S}_{CP}\sin\Delta m_d \Delta t\right)\right]$$

Direct CPV — Mixing induced CPV



$< \Delta Z > = 130\ \mu$m at Belle II



Key elements

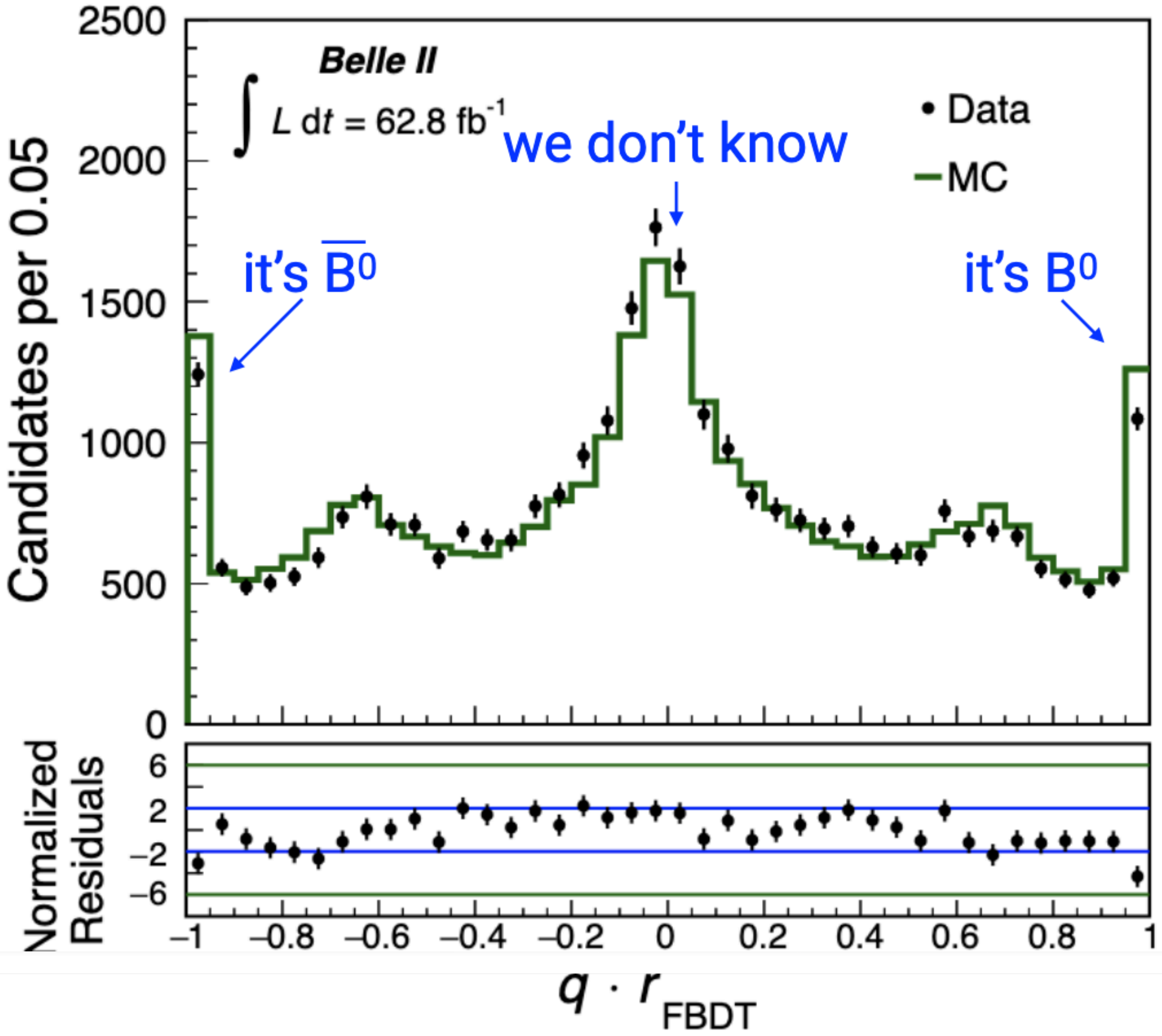
- Vertex position measurement
- B meson flavour tagging

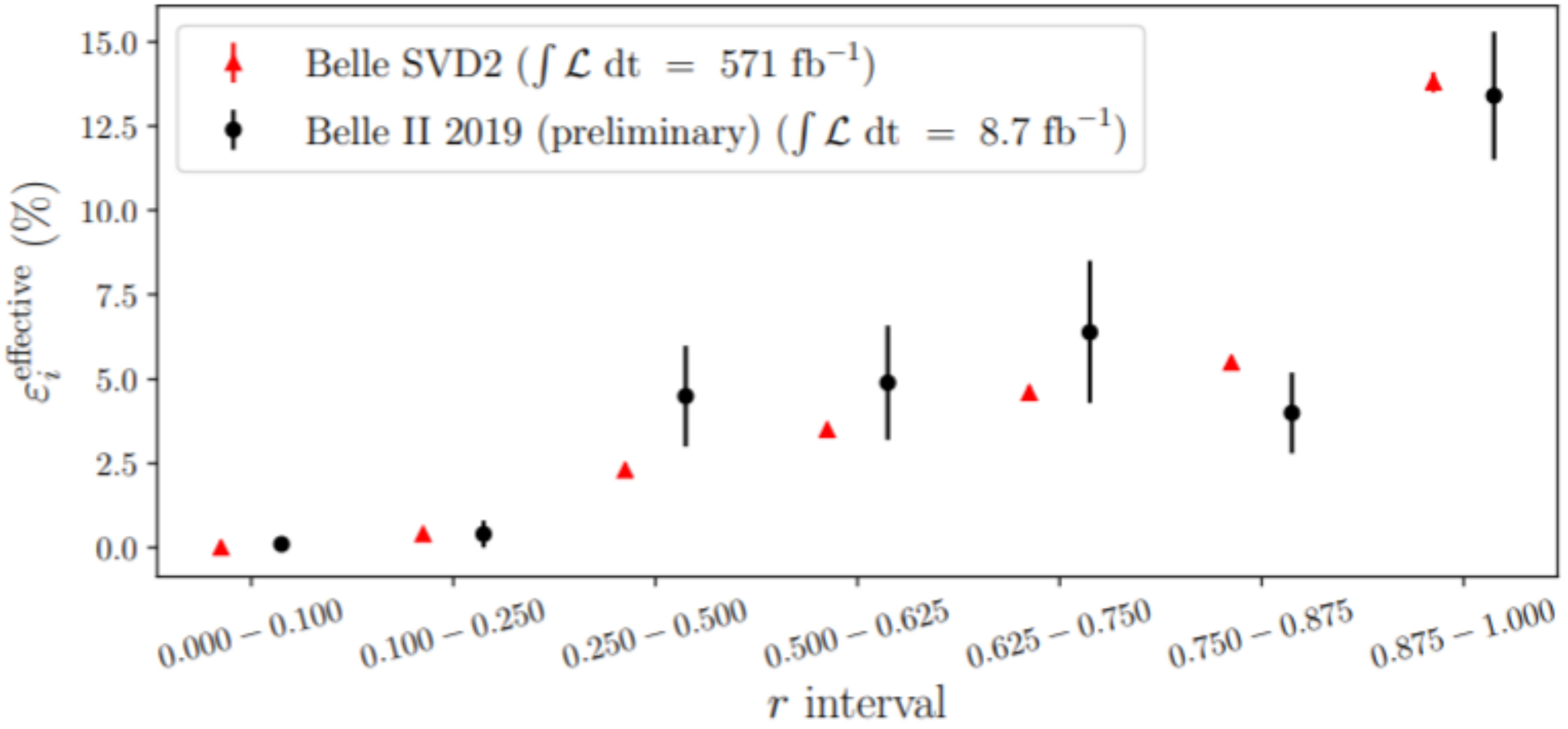
The Flavour Tagger

[Eur. Phys. J. C 82, 283(2022)]

- Crucial to determine the quark-flavour content of *B*-tag

- Multivariate algorithm to infer B-tag flavour from flavour-specific decays. Use information from particles kinematics, track-hit, PID variables etc

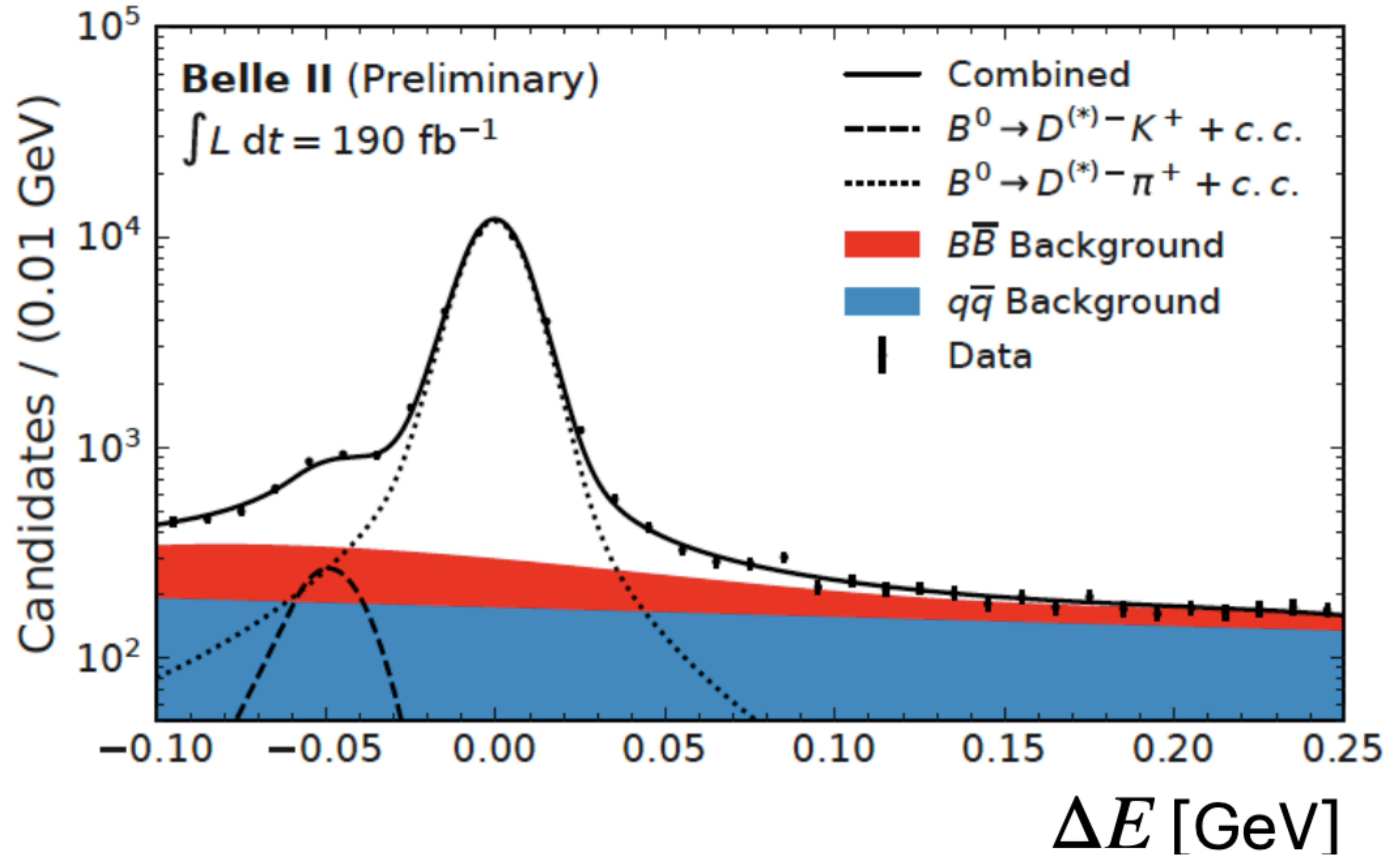




- *Good data-MC agreement*
- *Effective tagging efficiency:* $(30.0 \pm 1.2 \pm 0.4)\ \%$
- *Comparable to best results from Belle and BaBar*

B^0 lifetime and mixing frequency

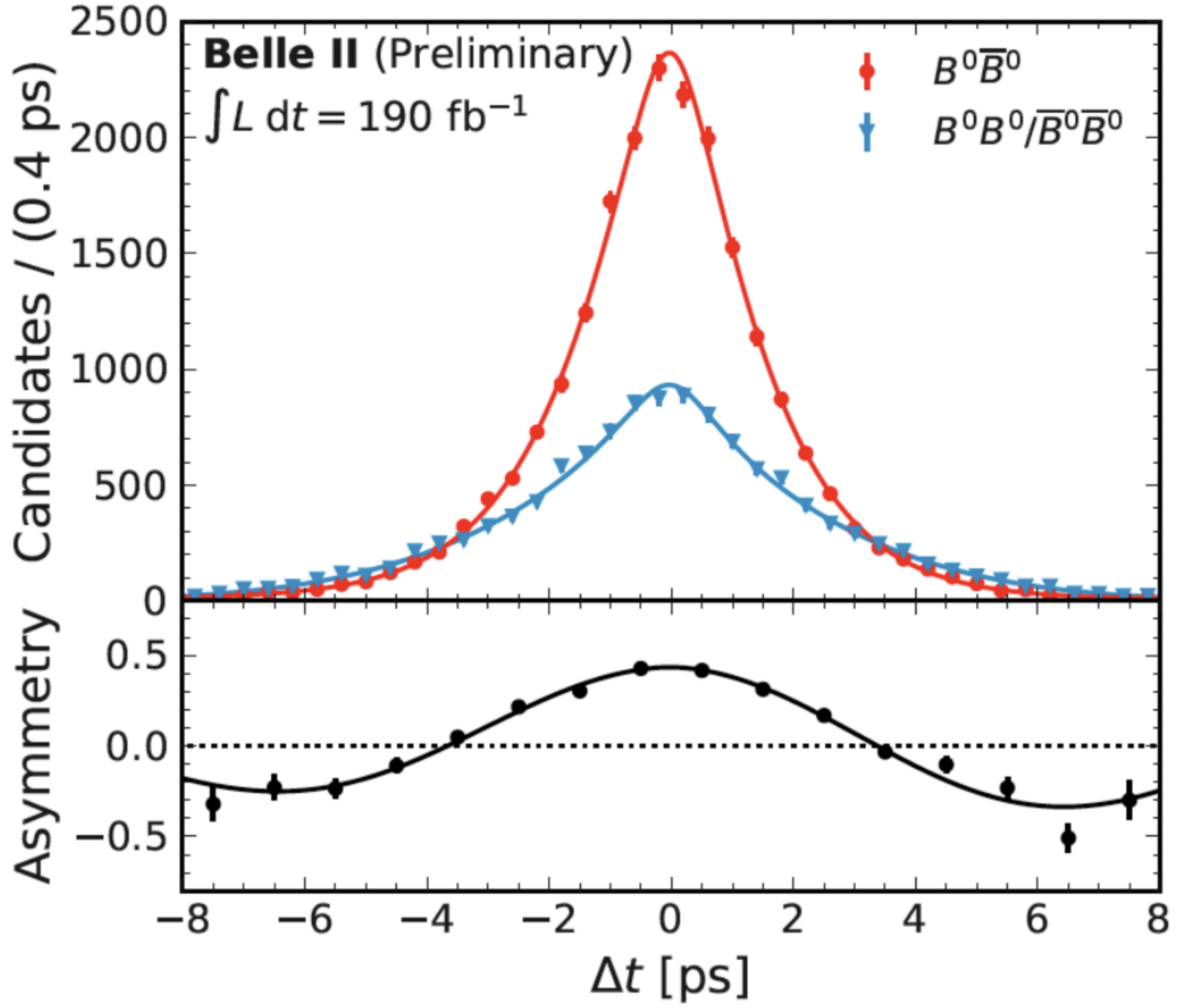
- Goal: validate the Δt resolution function as a key step towards the time-dependent CPV analysis
- Use about 40K $B^0 \to D^{(*)-}\pi^+/K^+$ decays
- Strategy: measure τ_B and Δm_d from the background-subtracted distribution of Δt
  - Background subtracted with sWeights calculated from 2D fit of ΔE and CS output



Good agreement with the WA

$$\tau_{B^0} = 1.499 \pm 0.013(\text{stat}) \pm 0.008(\text{syst})\ \text{ps}$$

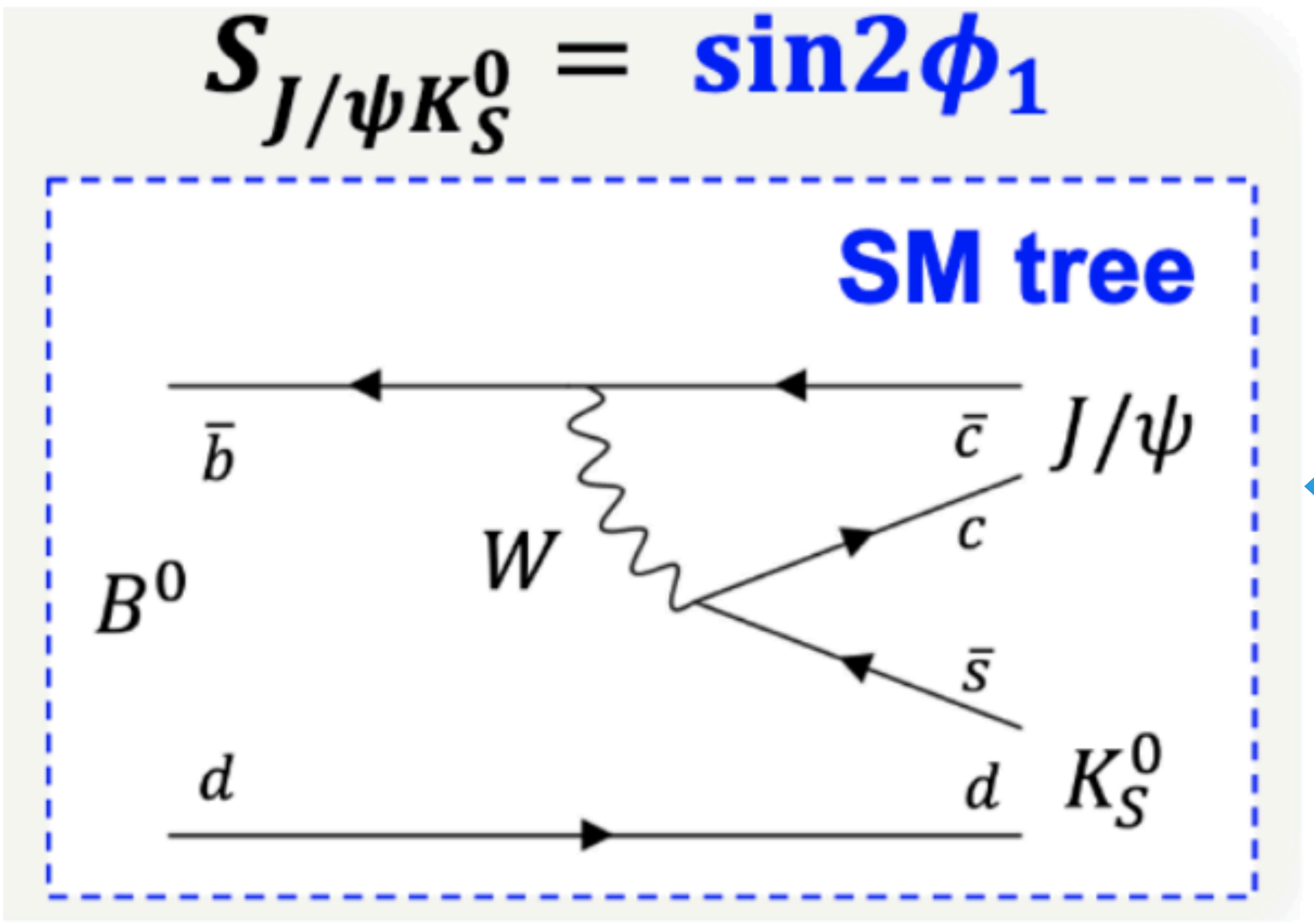
$$\Delta m_d = 0.516 \pm 0.008(\text{stat}) \pm 0.005(\text{syst})\ \text{ps}^{-1}$$

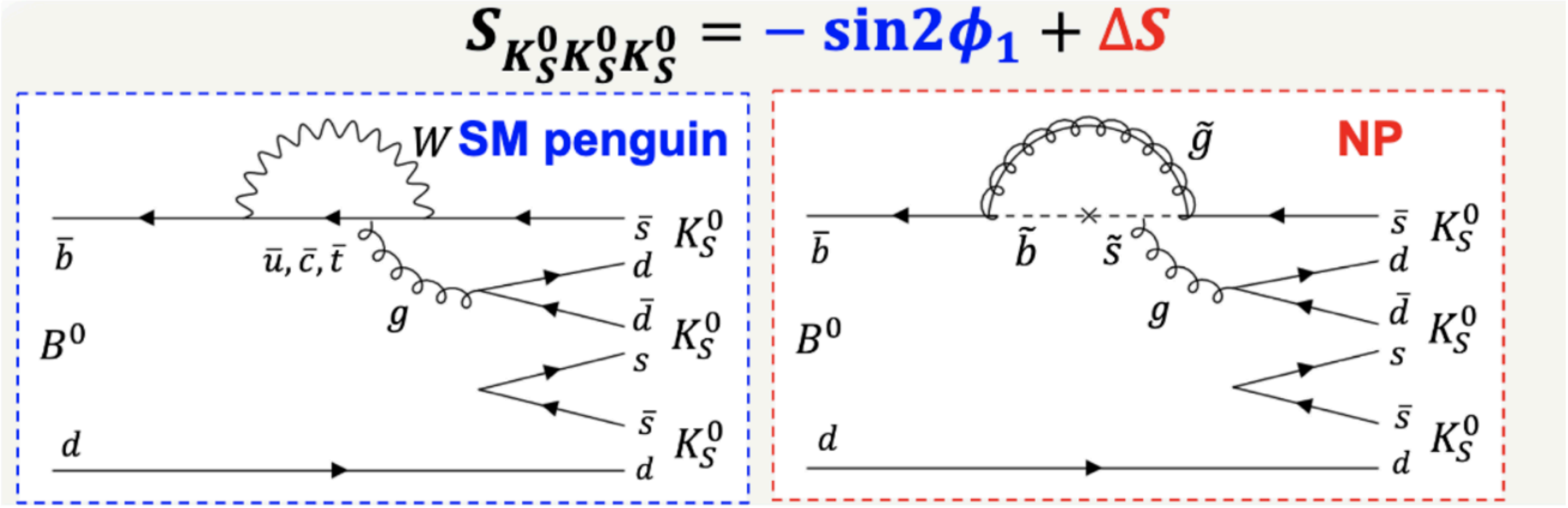


Not yet competitive with global best results (from LHCb), but systematic uncertainties already on par with best Belle/Babar results.

Measurement of $\sin 2\phi_1$

- B^0 mixing phase $\phi_1 = \arg[-V_{cb}^* V_{cd}/(V_{td}^* V_{tb})]$ from:
  - **Tree decays**: further constrain possible non-SM physics in mixing
  - **Penguin decays**: probe non-SM in decay by comparison with tree measurements





$\sin 2\phi_1$ from $B^0 \to J/\psi K^0_S$

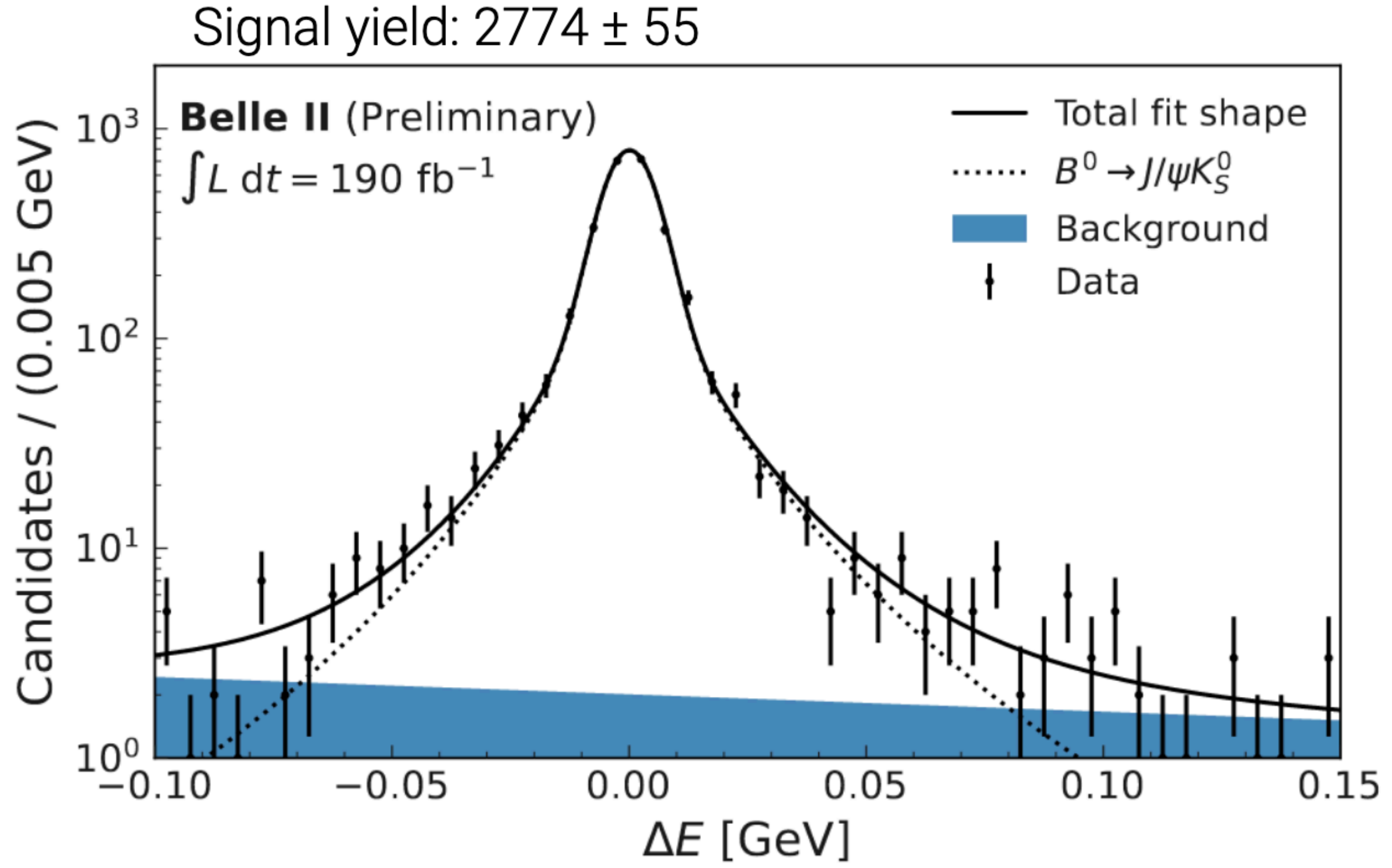
- Tree dominated $b \to c\bar{c}s$ golden mode; theoretically and experimentally clean
- Time resolution and flavour-tagger calibrated with $B^0 \to D^{(*)-}\pi^+/K^+$ decays and validated in control sample $B \to J/\psi K$
- Results:

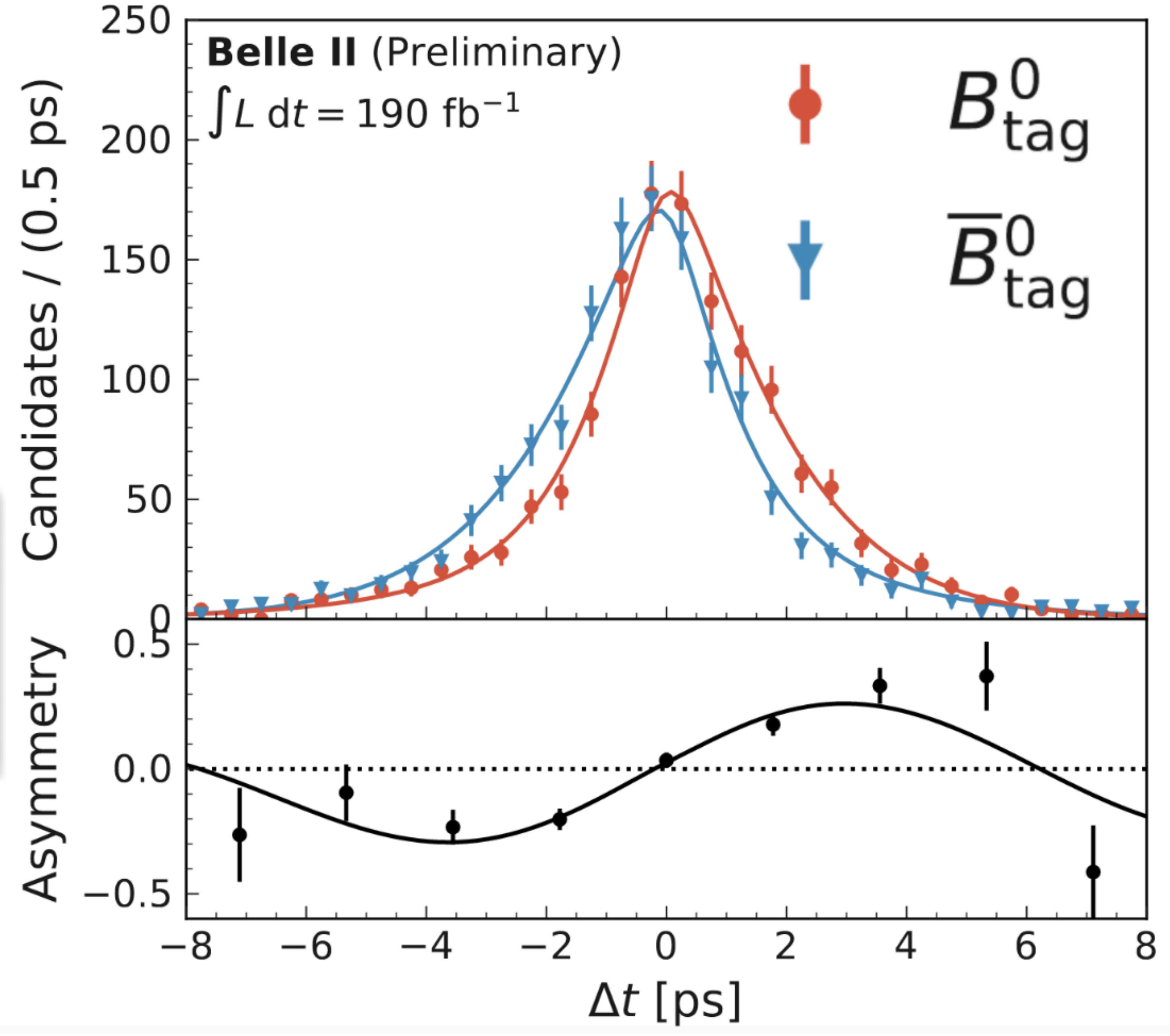
S_{CP} = 0.720 ± 0.062 (stat.) ± 0.016 (syst.)

A_{CP} = 0.094 ± 0.044 (stat.) $^{+0.042}_{-0.017}$ (syst.)

- *Dominant systematics:*
  - *Size of the control sample: S_{CP}*
  - *Tag-side interference and charge-asymmetry: A_{CP}*

Tools are ready for an impactful $\sin 2\phi_1$ measurement





CPV in $B^0 \to K^0_S K^0_S K^0_S$

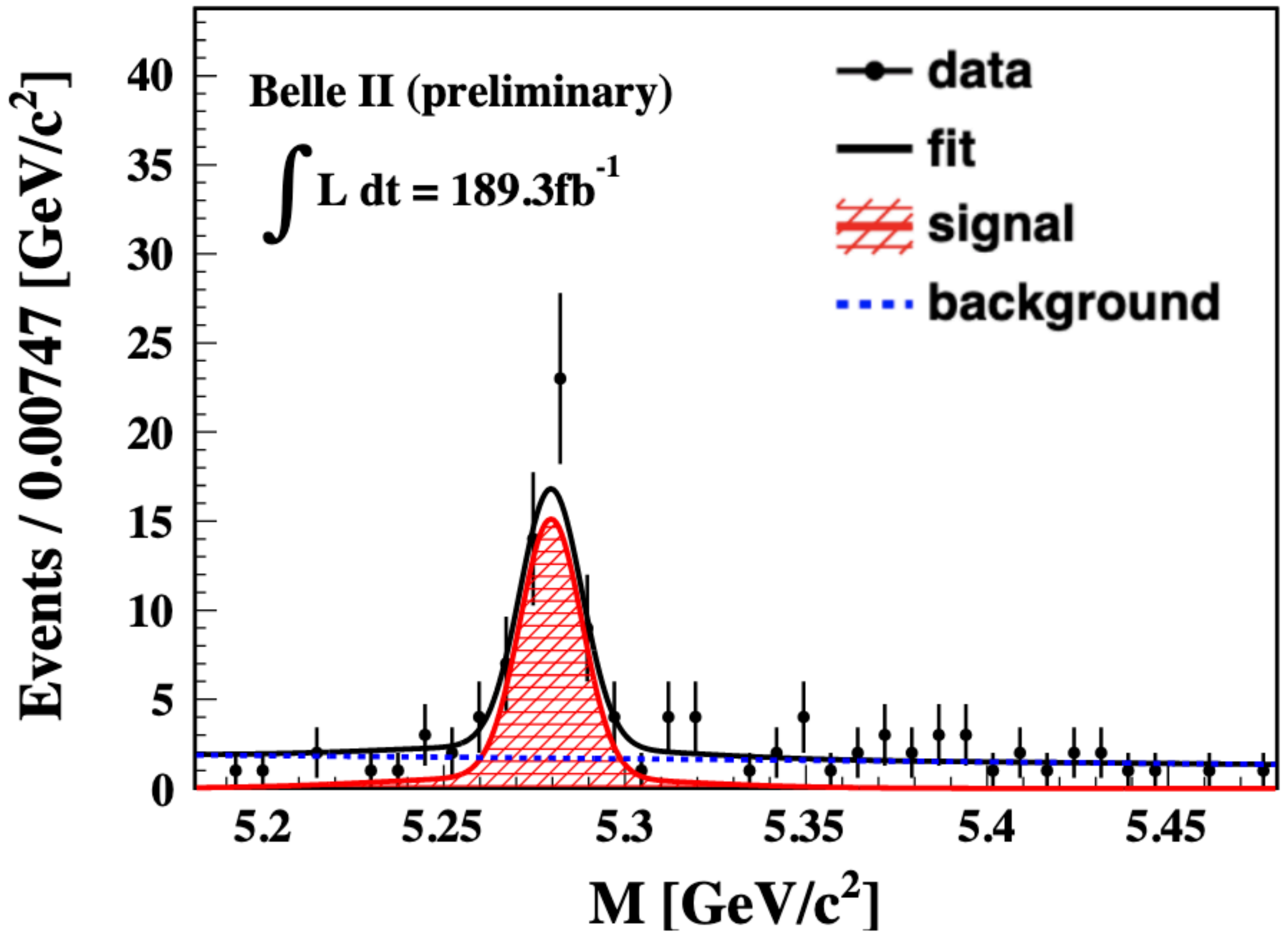
[arXiv:2209.09547]

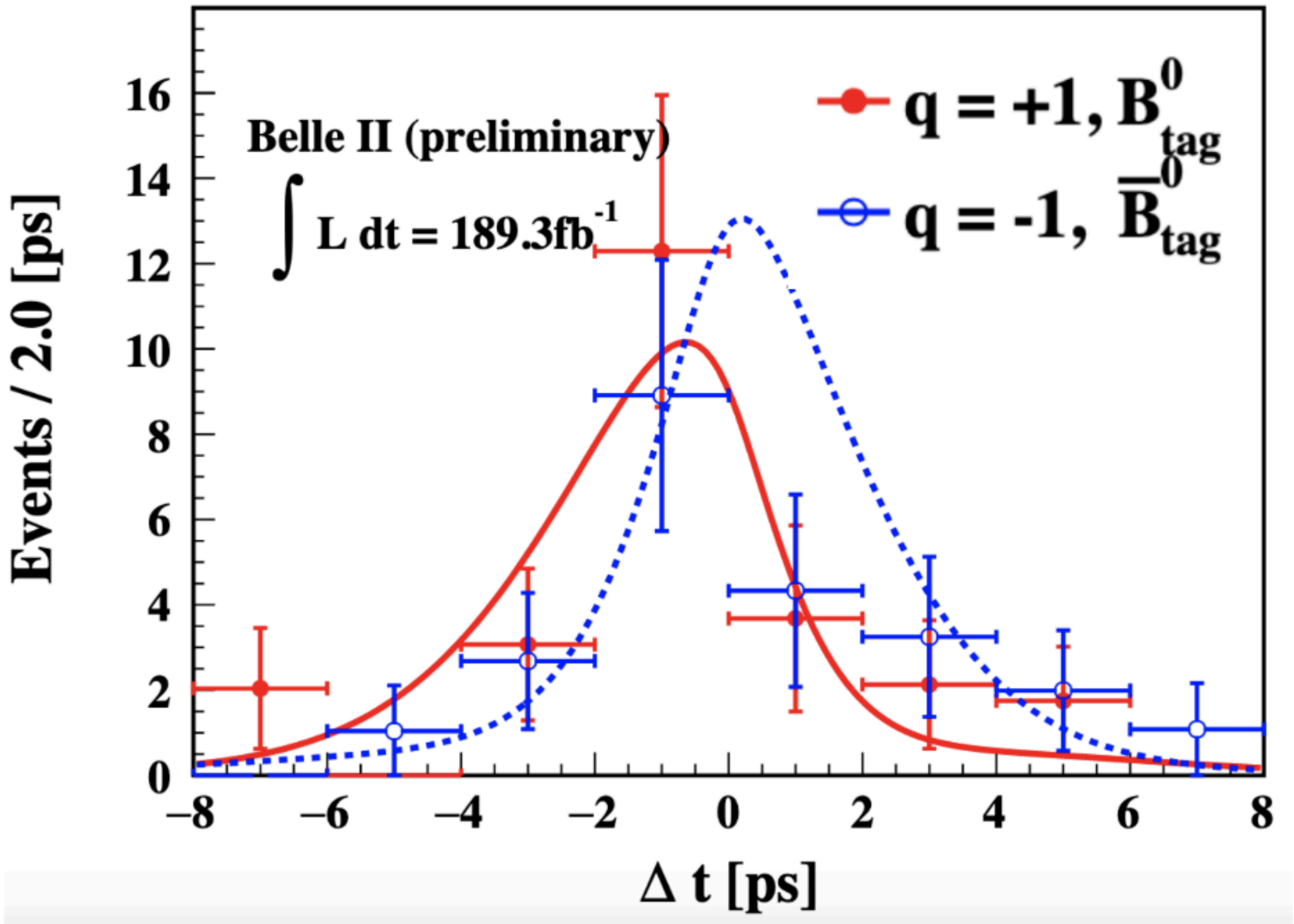
- $b \to s$ transition mediated by penguin loop: potentially sensitive to new physics
- Challenge: B vertexing as there is no prompt track; only $K^0_S \to \pi^+\pi^-$ tracks are extrapolated back
- Signal extraction fit with 3 variables: $\Delta E, M_{K^0_S K^0_S K^0_S}$ and CS output
- Control sample: $B^+ \to K^+ K^0_S K^0_S$

Signal yield: 53 ± 8

$S_{CP} = -1.86\,^{+0.91}_{-0.46}$ (stat.) ± 0.09 (syst.)

$A_{CP} = -0.22\,^{+0.30}_{-0.27}$ (stat.) ± 0.04 (syst.)





Towards Belle II $\mathrm{I}_{K\pi}$

- $K\pi$ puzzle: unexpected difference of A_{CP} in isospin related decays $B^0 \to K\pi, B^+ \to K^+\pi^0$
- Propose to examine the anomaly through a sum-rule:

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

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

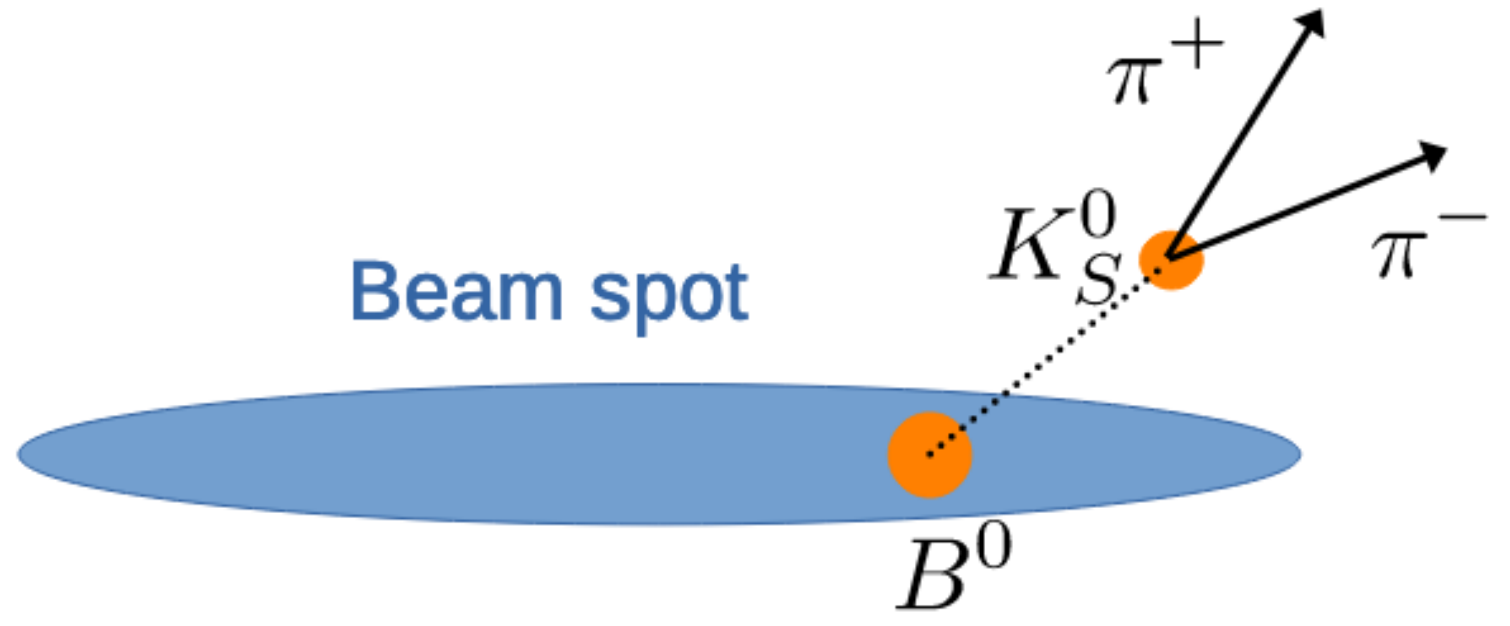
- Belle II is unique to most of the final states involved
- $I_{K\pi}$ sensitivity limited by the large uncertainty on $A_{CP}\,(B \to K^0\pi^0)$

@Belle II:
$B^0 \to K_S^0\pi^0$ [arXiv:2206.07453]
$B^+ \to K^+\pi^0$ [arXiv:2209.05154]
$B \to K^+\pi^-, K_S\pi^+$ [arXiv:2106.03766]

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

[arXiv:2206.07453]

- Main challenge: decay vertex resolution from $K_S^0 \to \pi^+\pi^-$ and IP constraint

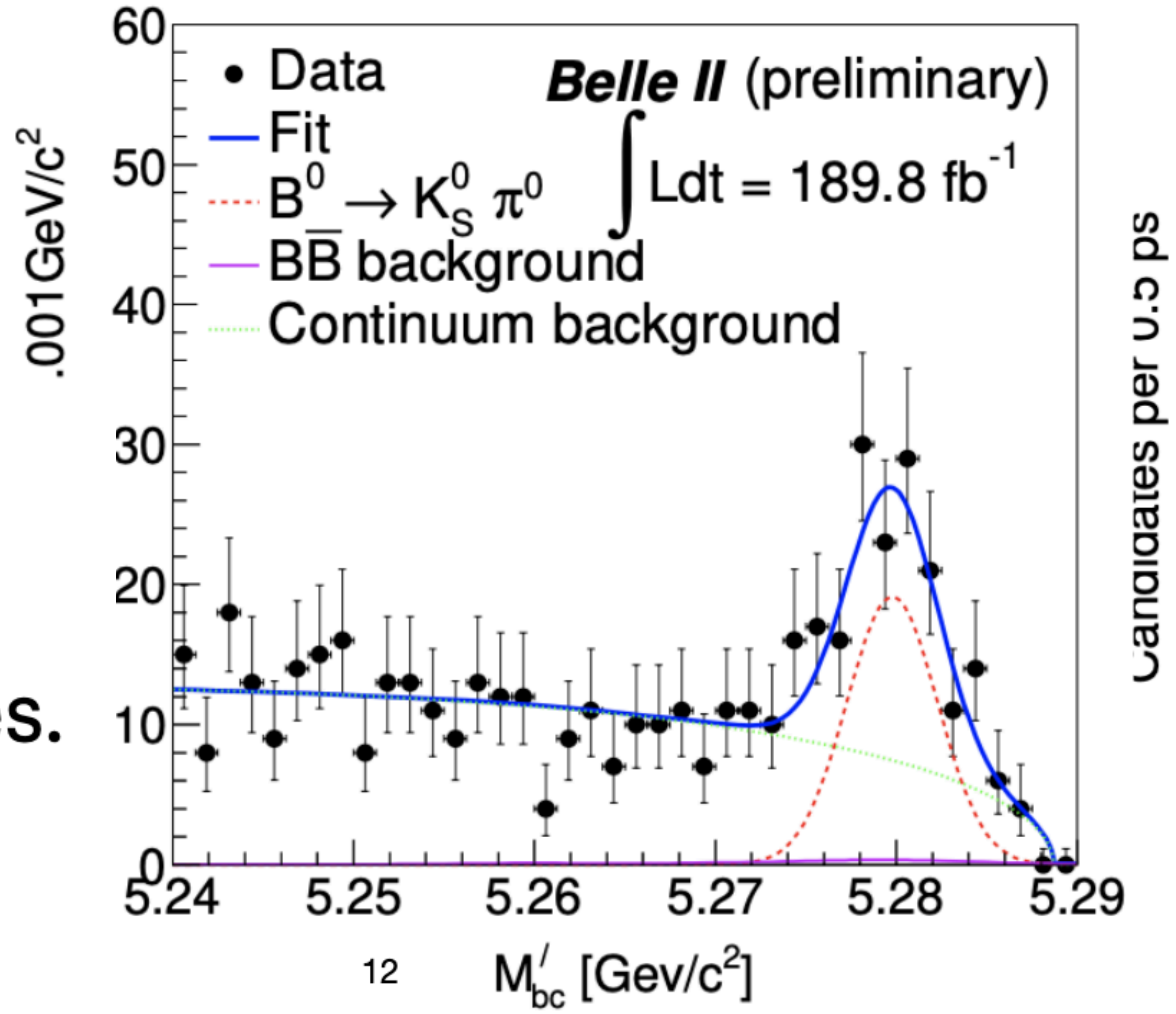


Strategy:

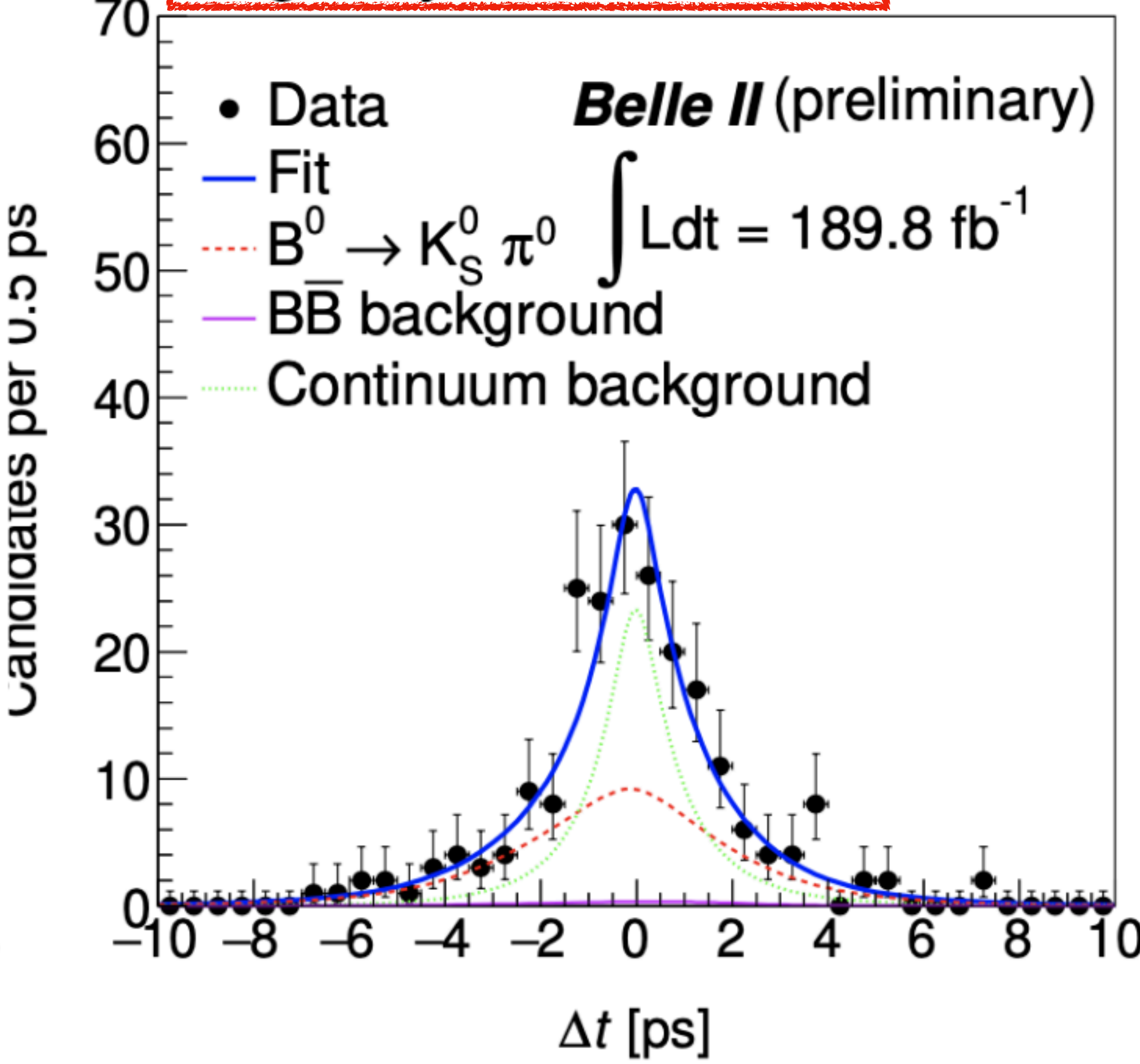
Perform 4D fit (ΔE, M_{bc}, Δt, and CS).

Use $B^0 \to J/\psi K_S^0$ to calibrate Δt shapes.

Constrain $\tau_{B_{sig}}$, Δm_d, and S_{CP} from WA.



Signal yield: 135^{+16}_{-15}



$$\mathscr{B}(B^0 \to K^0\pi^0) = [11.0 \pm 1.2(\text{stat}) \pm 1.0(\text{syst})] \times 10^{-6}$$

$$A_{CP}(B^0 \to K^0\pi^0) = -0.41^{+0.30}_{-0.32}(\text{stat}) \pm 0.09(\text{syst})$$

Towards measurement of ϕ_2/α

Least known angle of the UT, limiting the global test of the CKM unitarity

$$\phi_2[^o] = 85.2^{+4.8}_{-4.3}$$

[HFLAV]

- Penguin pollution complicates extraction of $\phi_2^{eff} = \phi_2 + \Delta\phi_2$
- Isospin relations to disentangle tree and penguin contributions
- Use isospin symmetry to get rid of $\Delta\phi_2$ combining BR and A_{CP} measurements from $B \to \pi\pi$ and $B \to \rho\rho$ decays
- **Belle II can access all isospin-related decays**

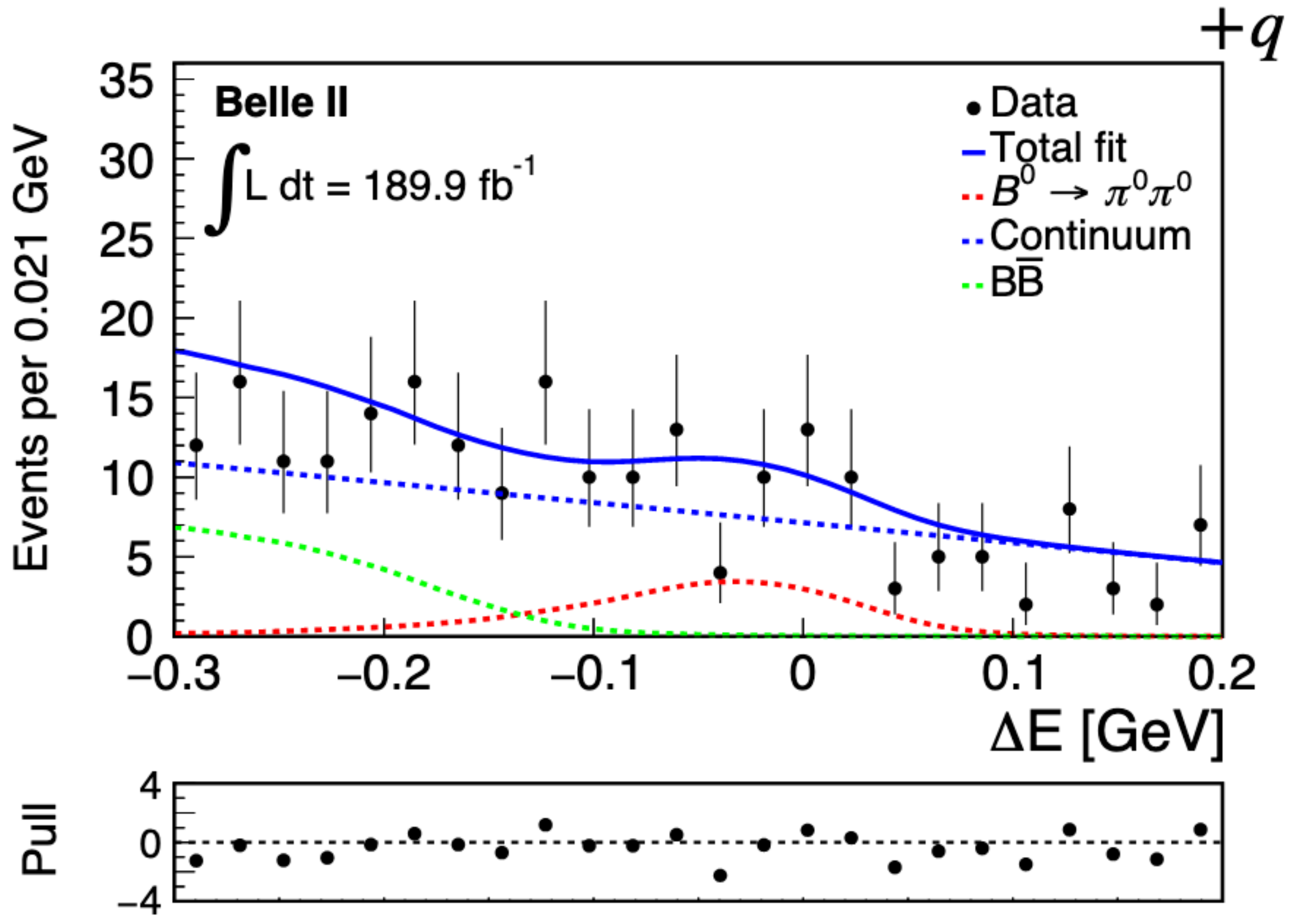
$B^0 \to \pi^0\pi^0$

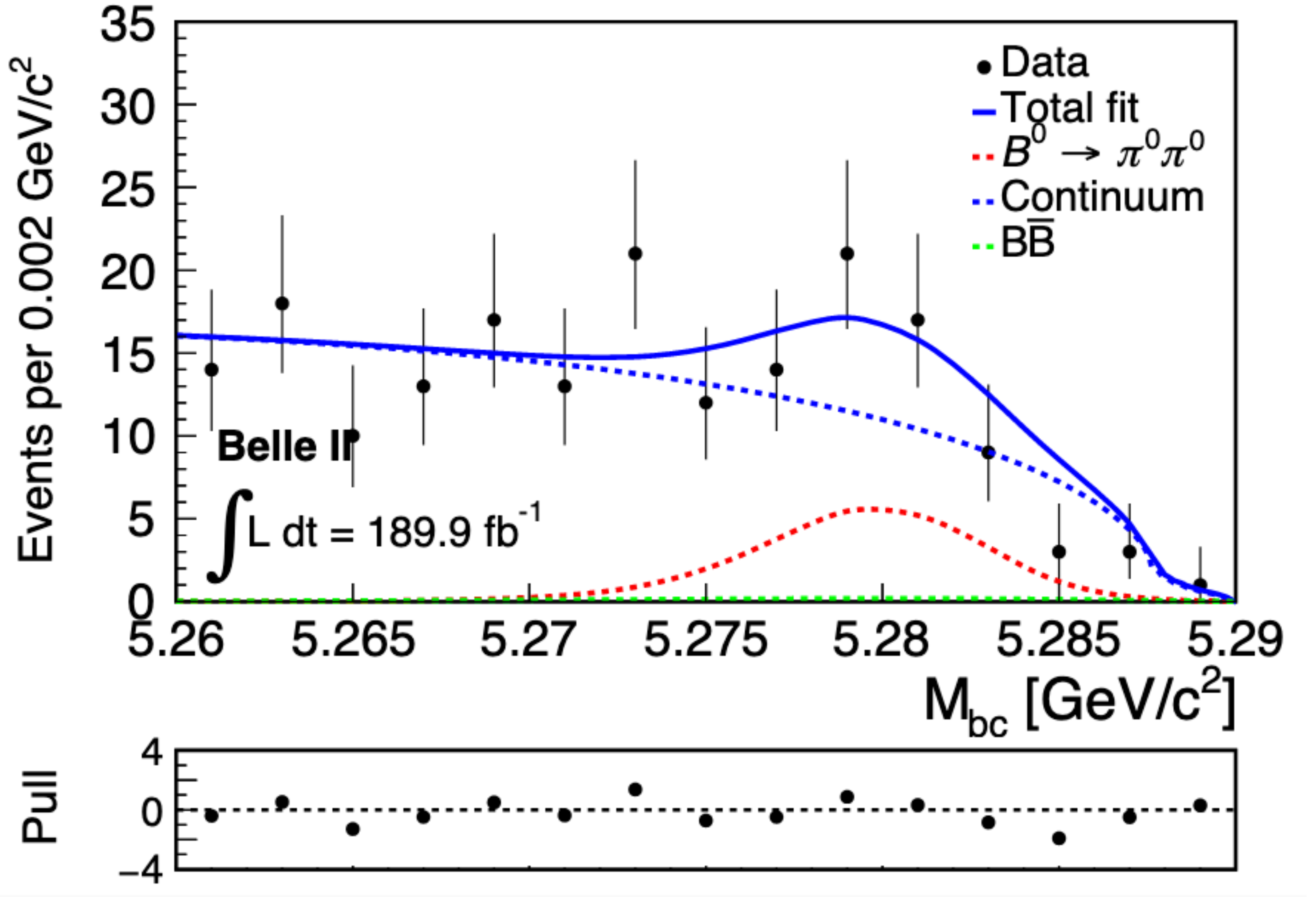
- Most challenging final state, very difficult for LHCb and unique for Belle II
- Multivariate algorithm is used to reject fake photons and increase purity
- Control channel: $B \to D(K\pi\pi^0)\pi^0$
- Using flavour tagger to obtain direct CP asymmetry

$$\mathscr{B}(B^0 \to \pi^0\pi^0) = (1.36 \pm 0.26\ (\text{stat.}) \pm 0.19\ (\text{syst.})) \times 10^{-6}$$

$$\mathscr{A}_{\text{cp}} = +0.14 \pm 0.46\ (\text{stat.}) \pm 0.07\ (\text{syst.})$$

Results are competitive with Belle with just 1/4th of data set size





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

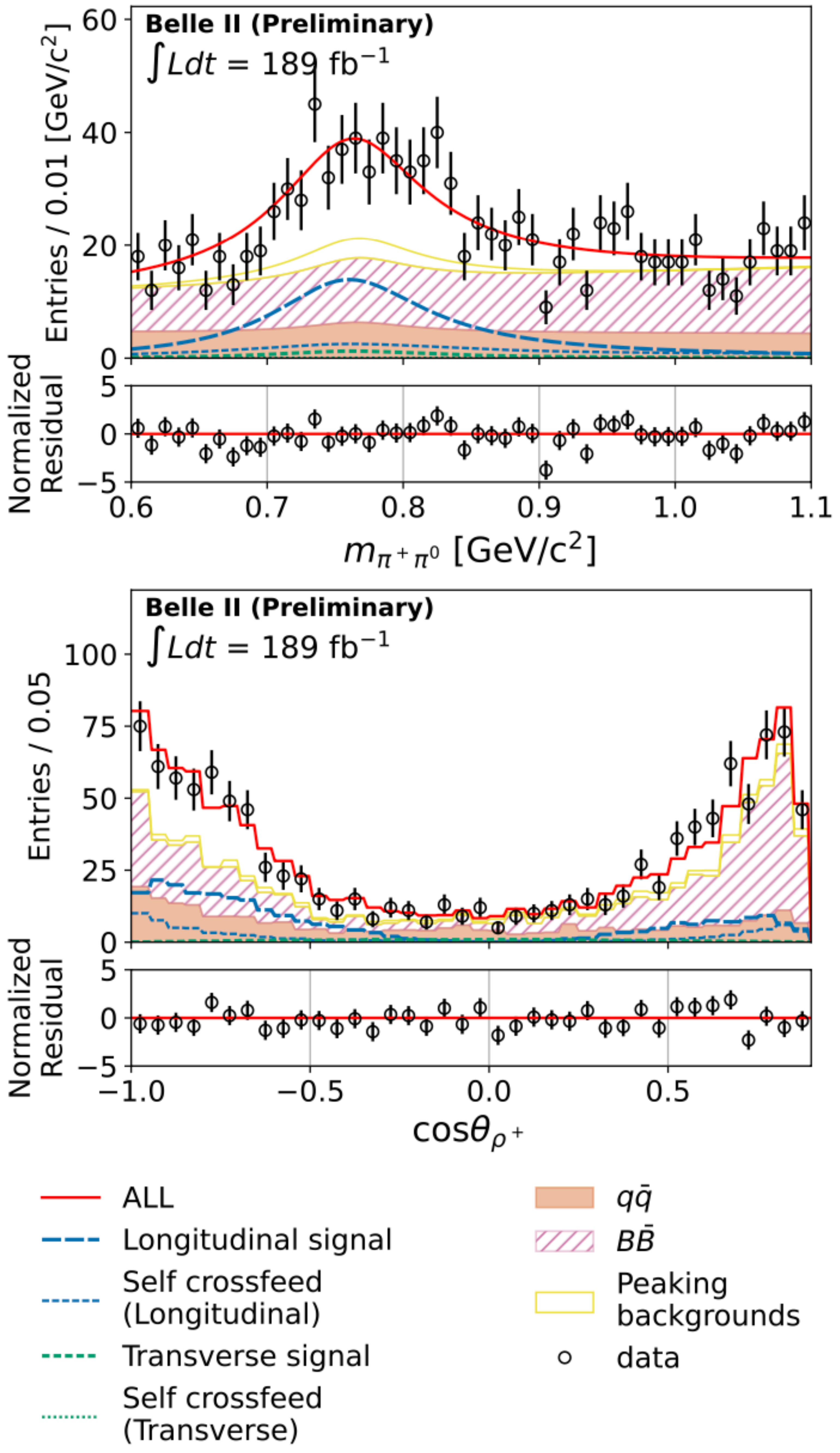
[arXiv:2208.03554]

- Broad resonance of the vector meson and a π^0 in the final state
- Measurement of longitudinal polarisation is necessary for CP analysis
- Angular analysis using helicity angles of ρ's
- 6D fit to the variables: 2*M($\pi\pi$), 2*helicity angles, ΔE and CS output
- Results: $N_{\text{long.}} = 235^{+24}_{-23}$ $N_{\text{trans.}} = 21^{+19}_{-17}$

$$\mathscr{B} = (2.67 \pm 0.28\ (\text{stat.}) \pm 0.28\ (\text{syst.})) \times 10^{-5}$$

$$f_L = 0.956 \pm 0.035\ (\text{stat.}) \pm 0.033\ (\text{syst.})$$

Measurement of BR limited by systematic uncertainty; largest contribution from the π^0 reconstruction efficiency.



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

[arXiv:2206.12362]

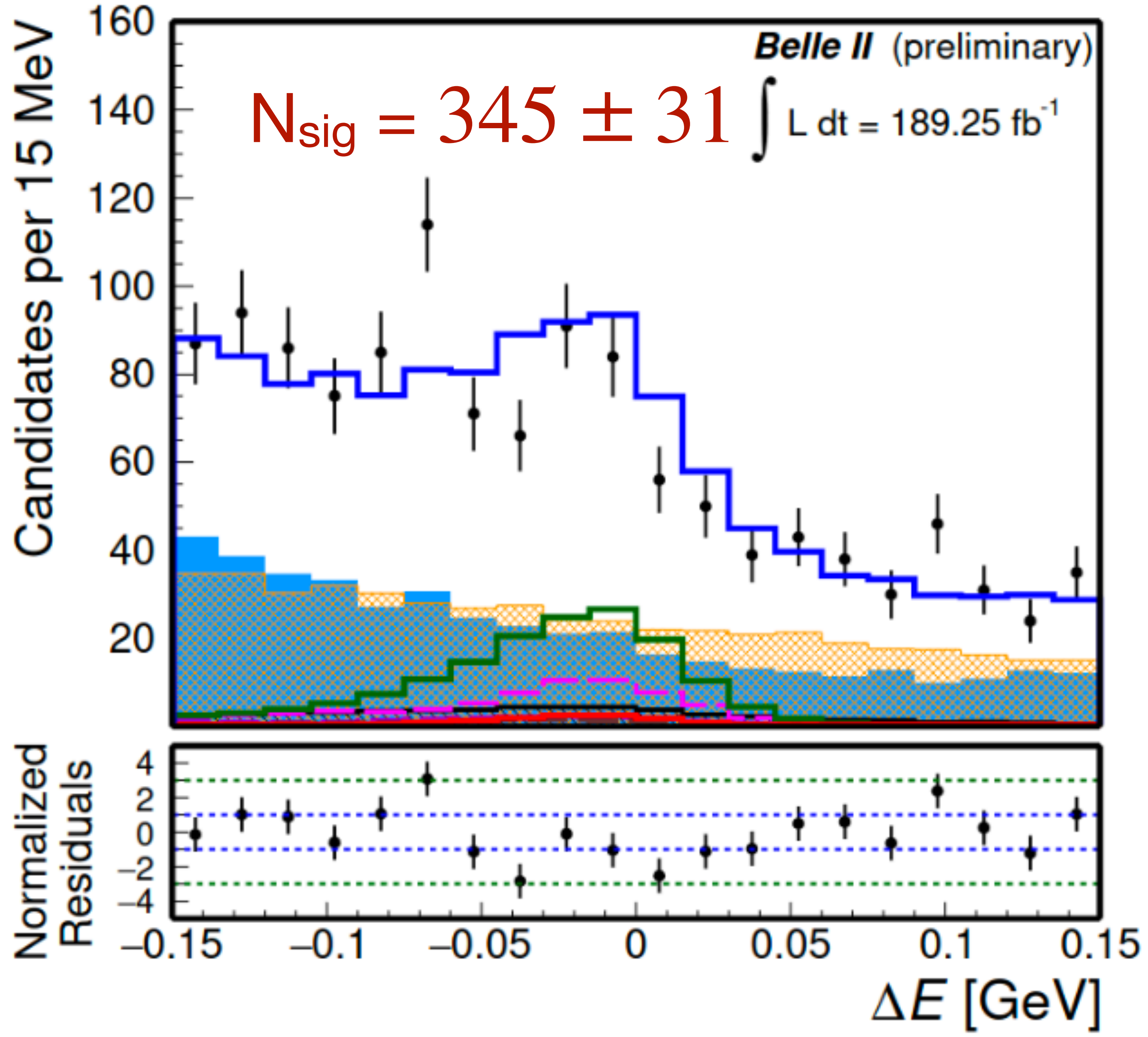
- Similar analysis strategy as $B^+ \to \rho^+\rho^0$
- 6D (ΔE, CS, 2*M($\pi\pi$), 2*cos(helicity angles)) template fit taking correlations into account
  - Fit distribution of helicity angles of π^+

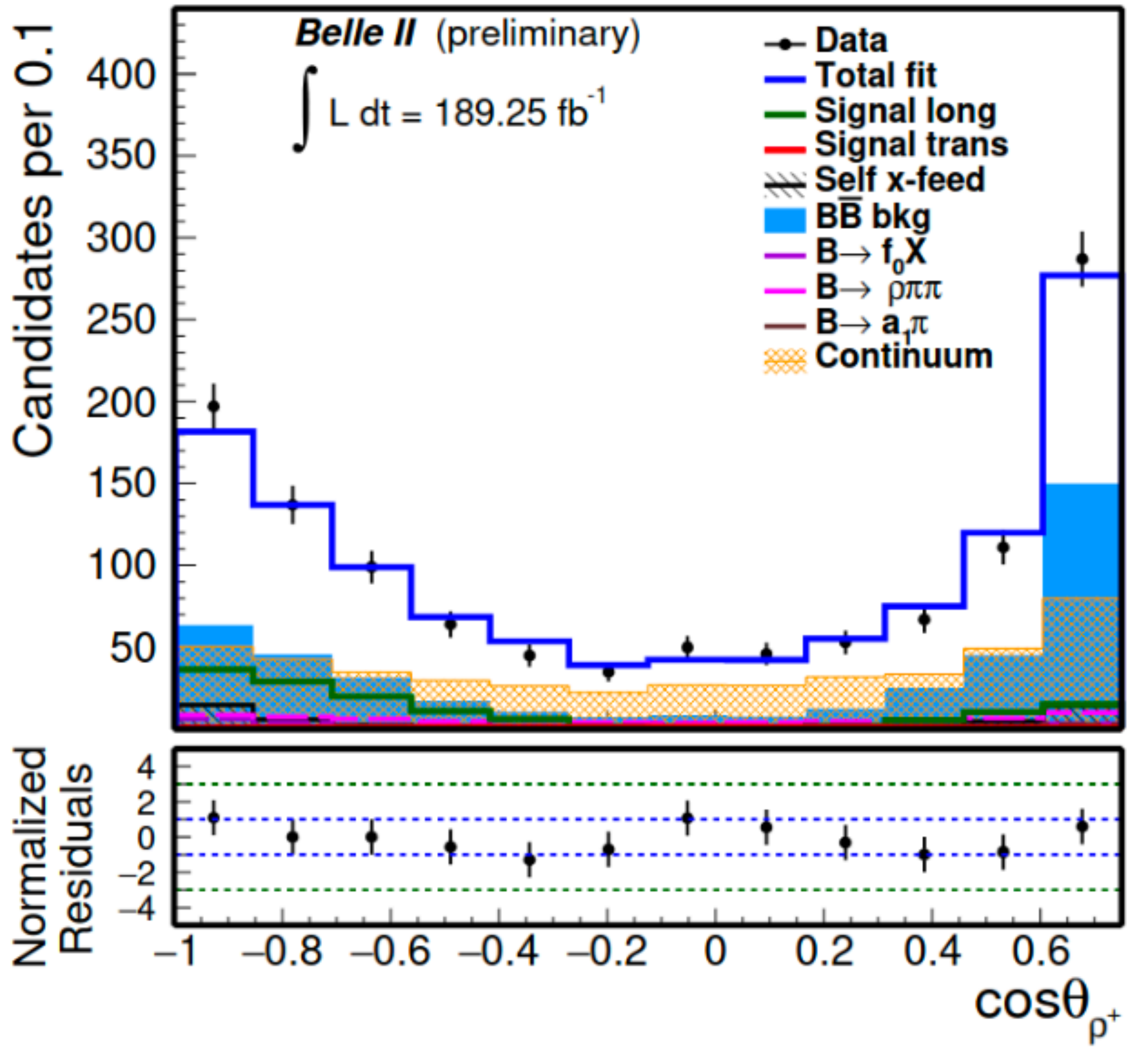
$$\mathscr{A}_{\mathrm{CP}} = -0.069 \pm 0.068\ (\mathrm{stat.}) \pm 0.060\ (\mathrm{syst.})$$

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

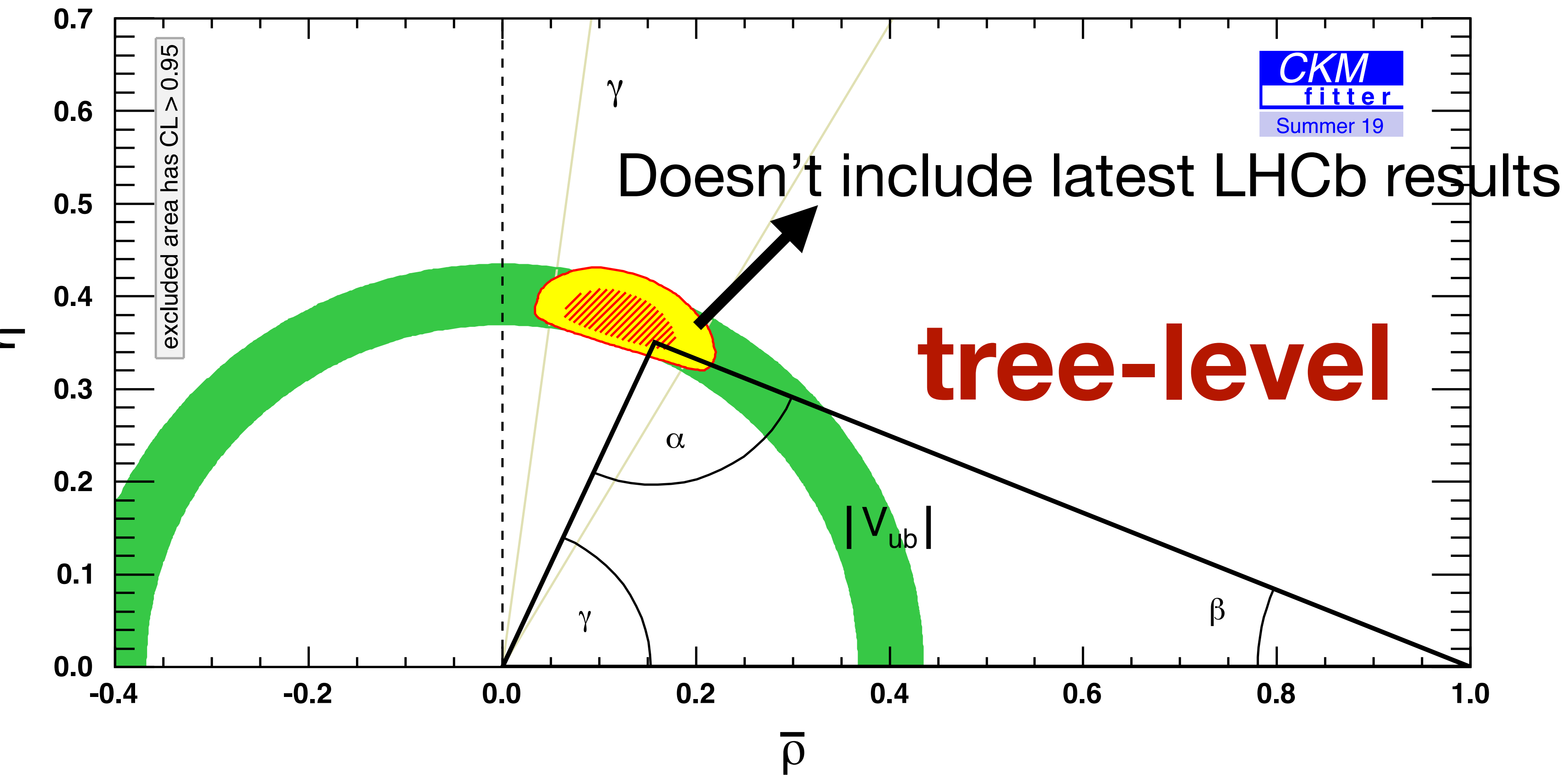
$$f_L = 0.943^{+0.035}_{-0.033}\ (\mathrm{stat.}) \pm 0.027\ (\mathrm{syst.})$$

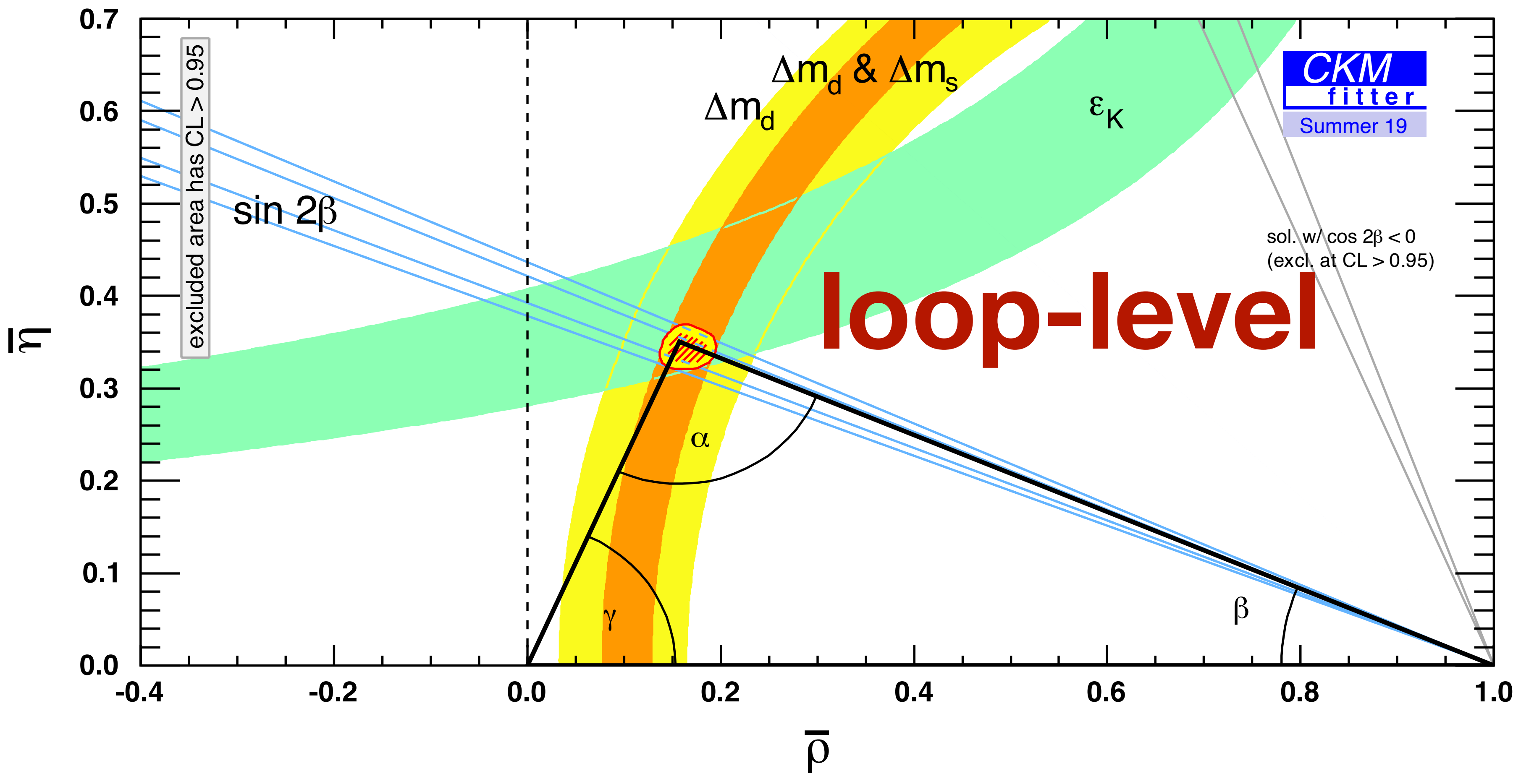
Comparable with the WA values and the largest systematics comes from data-MC discrepancy

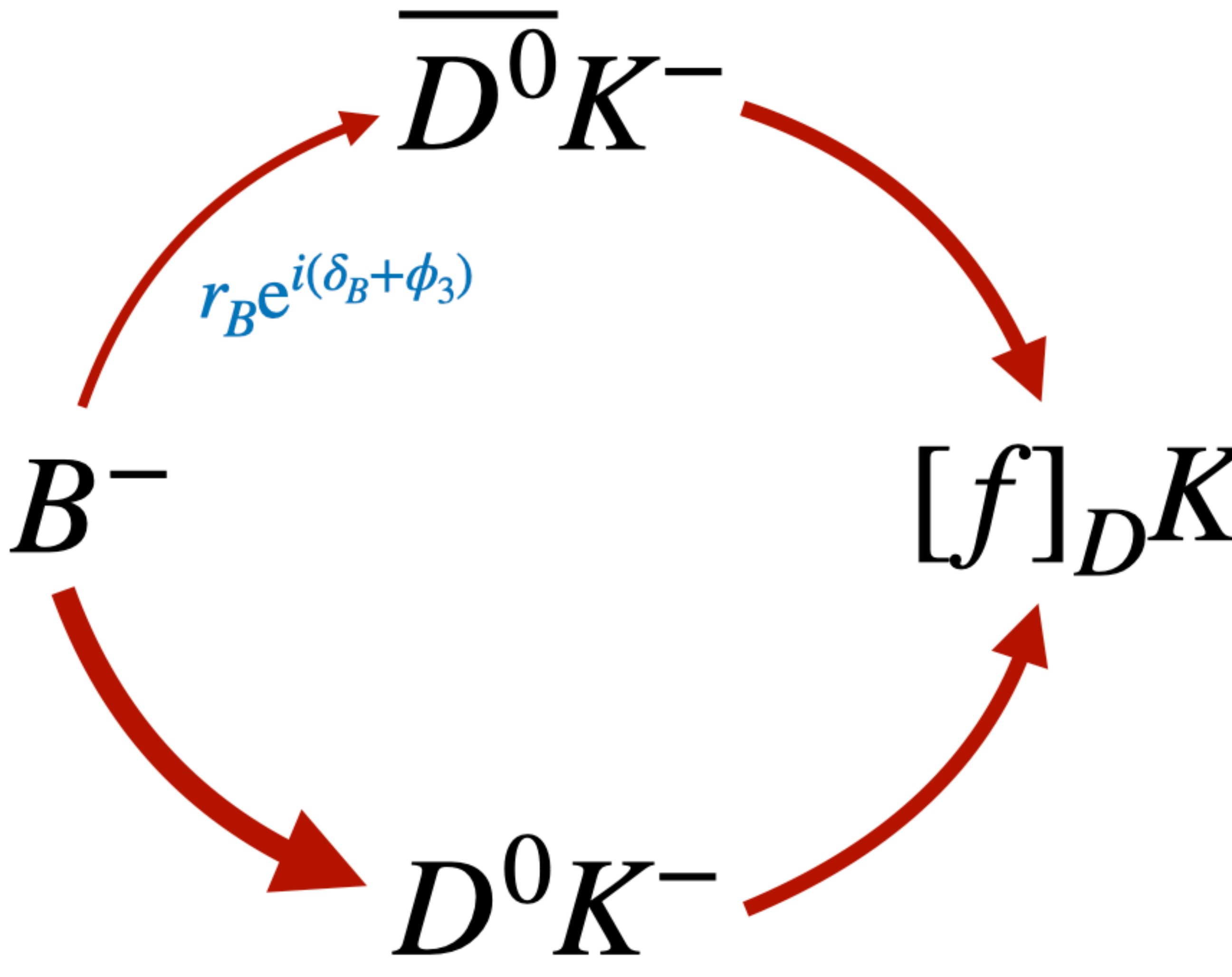




Towards measurement of ϕ_3/γ







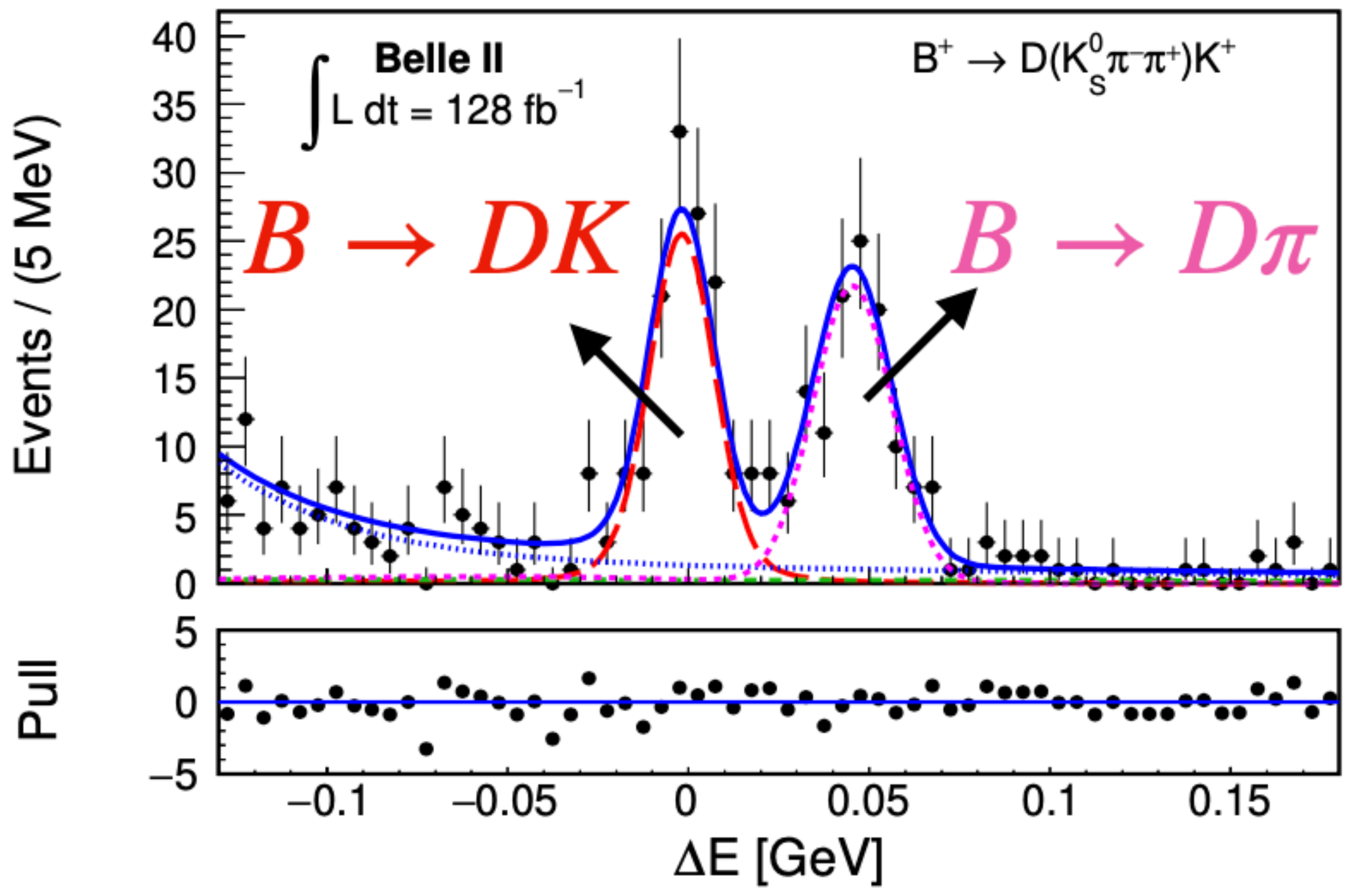
- The direct measurement of γ is a SM benchmark
- Very precise theoretical predictions [$\mathcal{O}(10^{-7})$]
- Testing direct vs indirect extrapolation can serve as an excellent probe for new physics
- Direct experimental measurements are statistically dominated

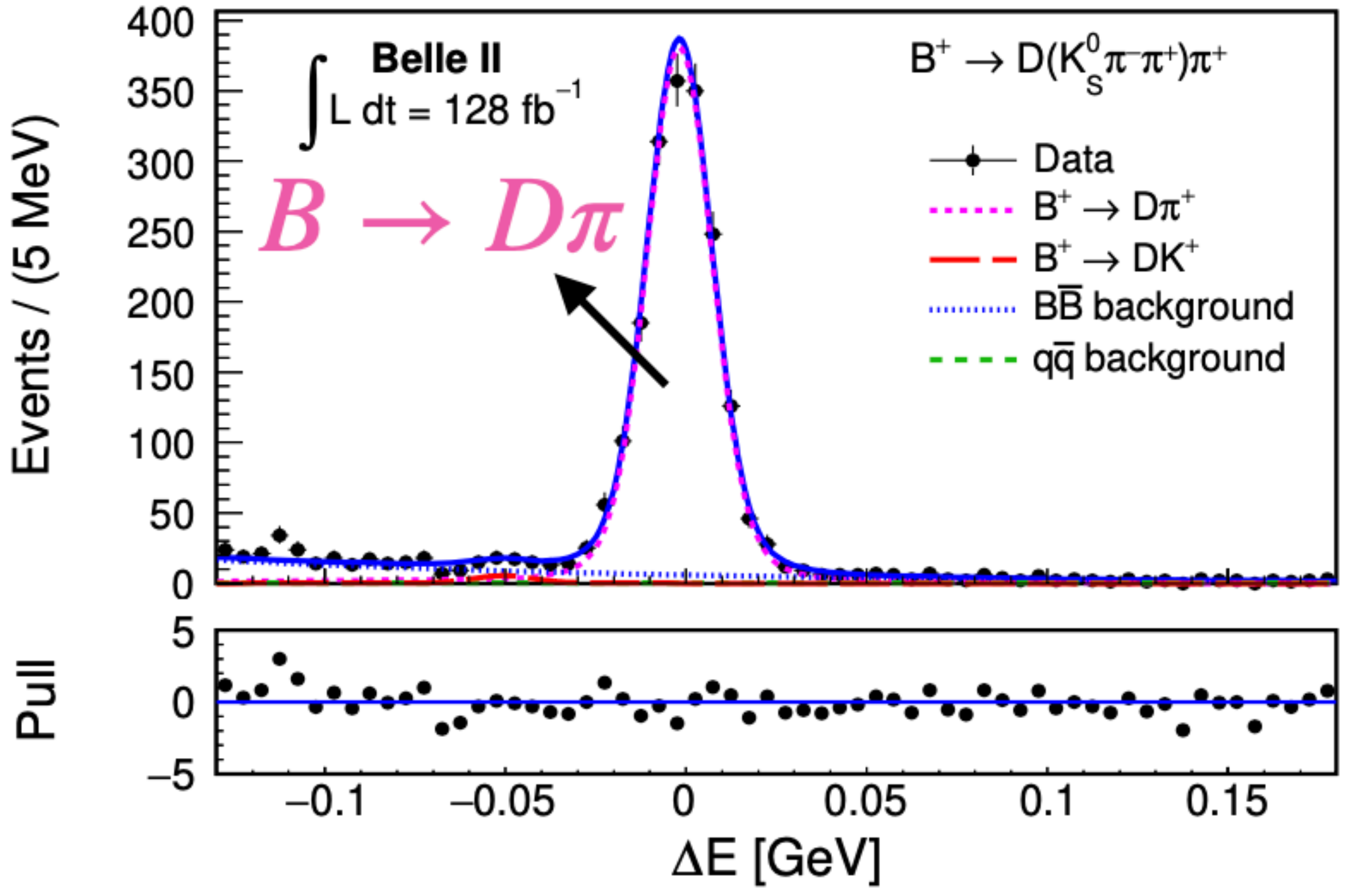
$$\frac{\mathcal{A}^{\text{suppr.}}(B^- \to \overline{D^0}K^-)}{\mathcal{A}^{\text{favor.}}(B^- \to D^0K^-)} = r_B e^{i(\delta_B+\phi_3)}$$

Current WA dominated by LHCb:

$$\gamma[^\circ] = 65.9 \begin{array}{l} +\,3.3 \\ -\,3.5 \end{array}$$ HFLAV

Belle + Belle II combined analysis





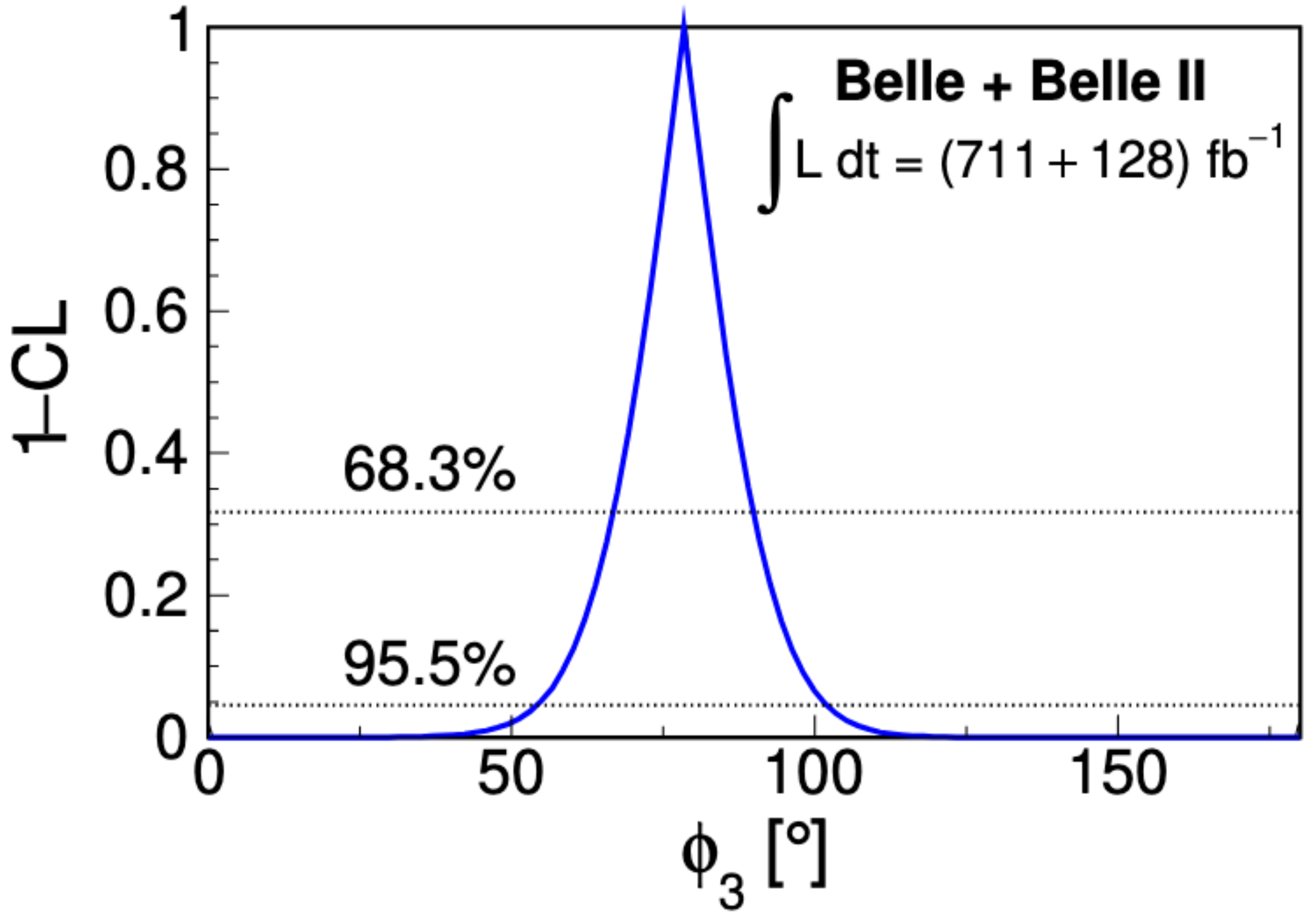
Signal yields

Belle:	Belle II :
$K_S^0\pi\pi$: 1467 ± 53	$K_S^0\pi\pi$: 280 ± 21
K_S^0KK: 194 ± 17	K_S^0KK: 34 ± 7

[JHEP 02 (2022) 063]

$\delta_B(^\circ)$	124.8 ± 12.9 (stat.) ± 0.5 (syst.) ± 1.7 (ext. input)
r_B^{DK}	0.129 ± 0.024 (stat.) ± 0.001 (syst.) ± 0.002 (ext. input)
$\phi_3(^\circ)$	78.4 ± 11.4 (stat.) ± 0.5 (syst.) ± 1.0 (ext. input)

- This result is most precise to date from the *B*-factory experiments
- New inputs from BESIII on strong-phase has significant impact on systematic uncertainty
- Use of $B \to Dh$ decay mode to incorporate efficiency effects reduces the experimental systematic uncertainty

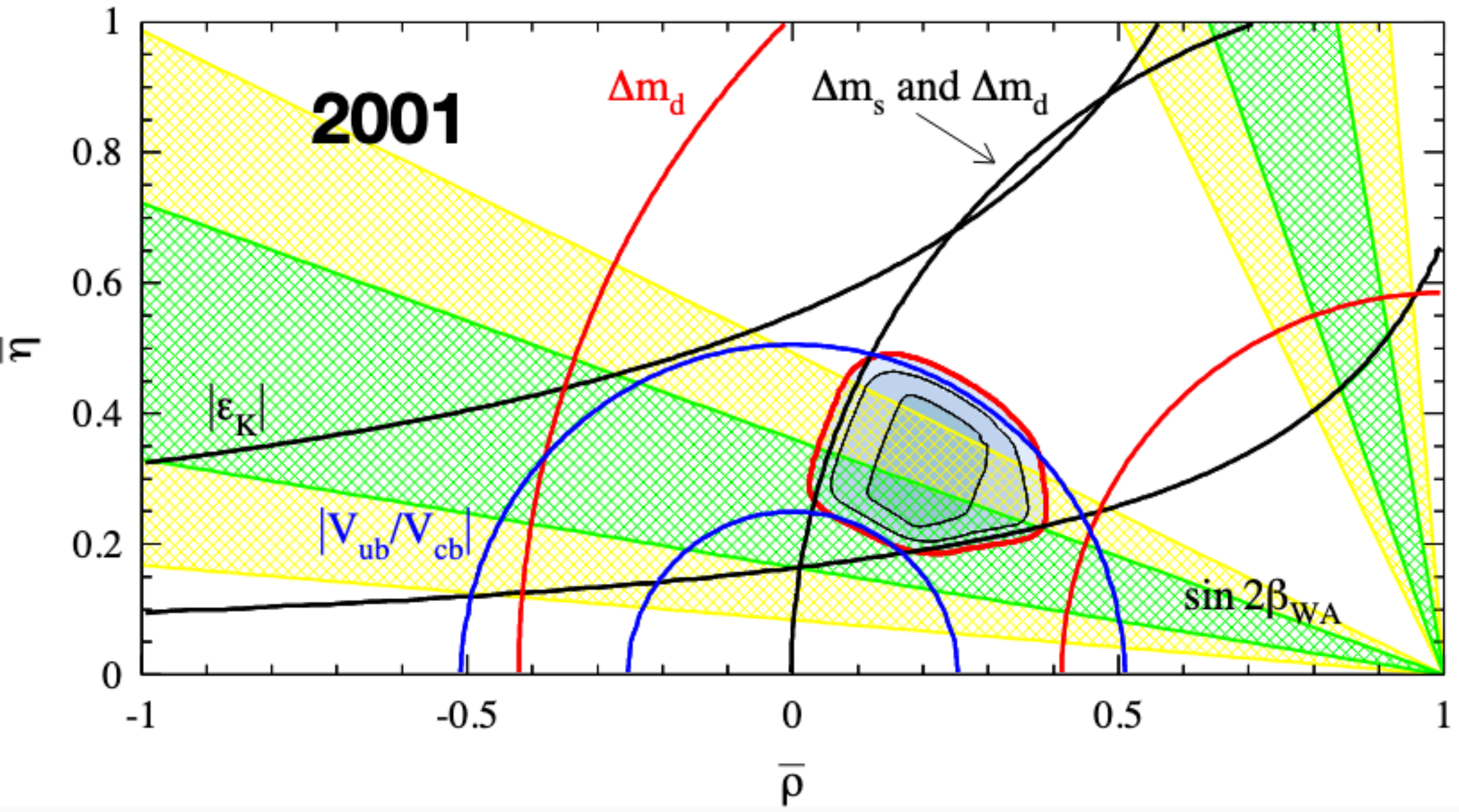


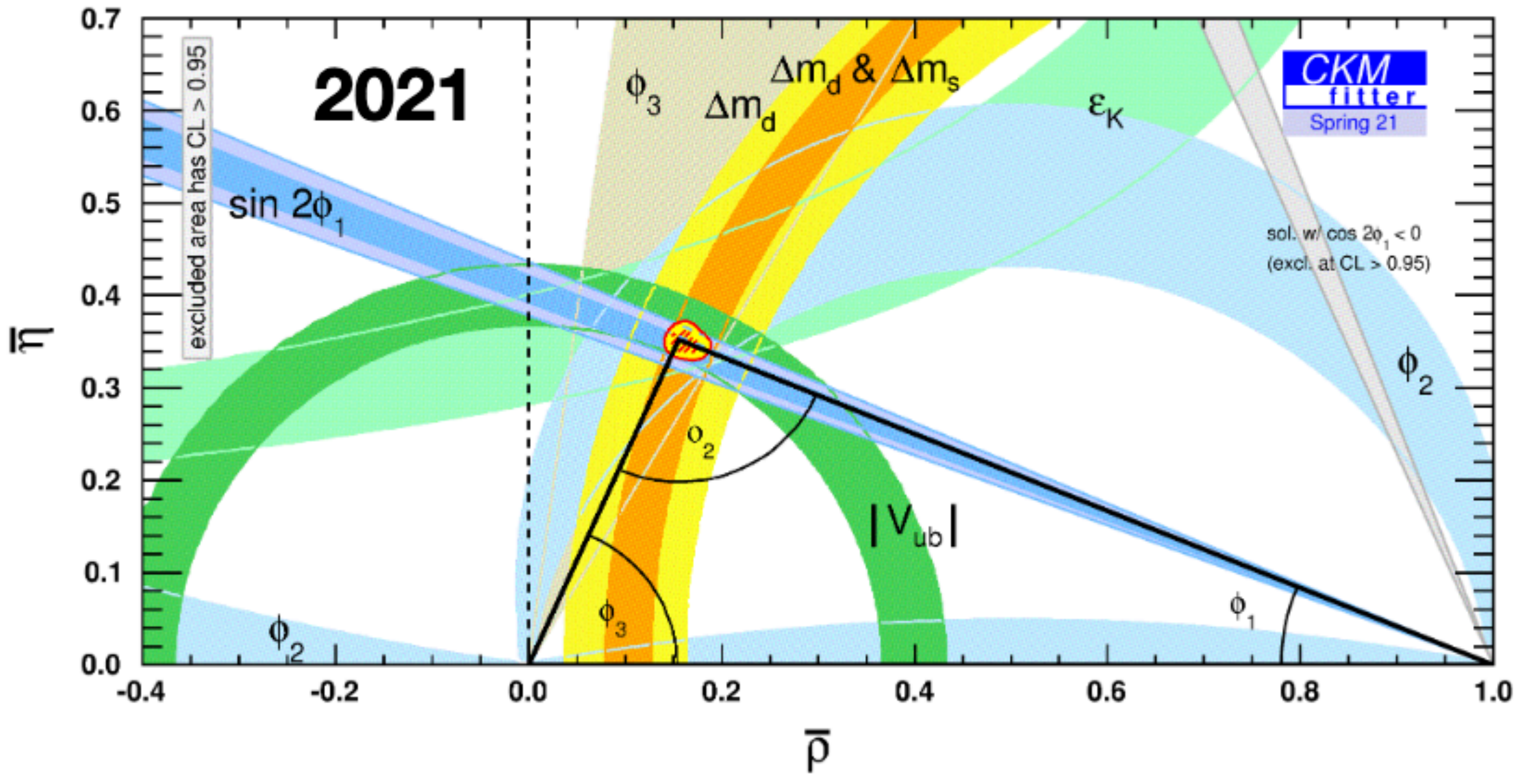
Summary and Outlook

- **Presented several results that showcase Belle II rich program**
  - Based on 190/fb. Have twice the data on tape, a sample as large as that of BaBar but with an improved detector
- **Exploiting Belle + Belle II combined analyses too**

arXiv:2203.11349

Observable	2022 Belle(II), BaBar	Belle-II $5\ ab^{-1}$	Belle-II $50\ ab^{-1}$	Belle-II $250\ ab^{-1}$
$\sin 2\beta/\phi_1$	0.03	0.012	0.005	0.002
γ/ϕ_3 (Belle+BelleII)	11°	4.7°	1.5°	0.8°
α/ϕ_2 (WA)	4°	2°	0.6°	0.3°





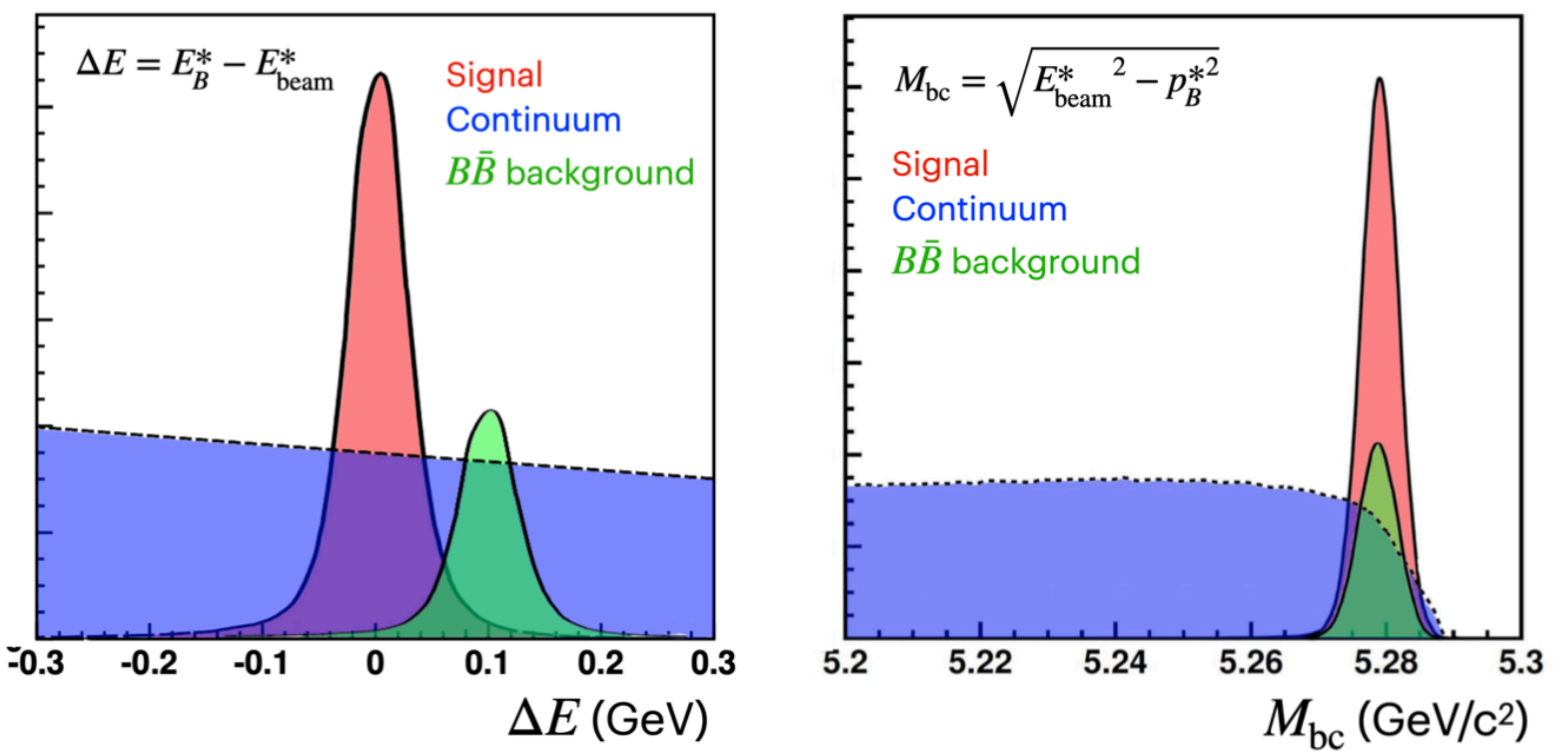
Potential for Belle II to go much further

THANK YOU

Backup

B-factory variables

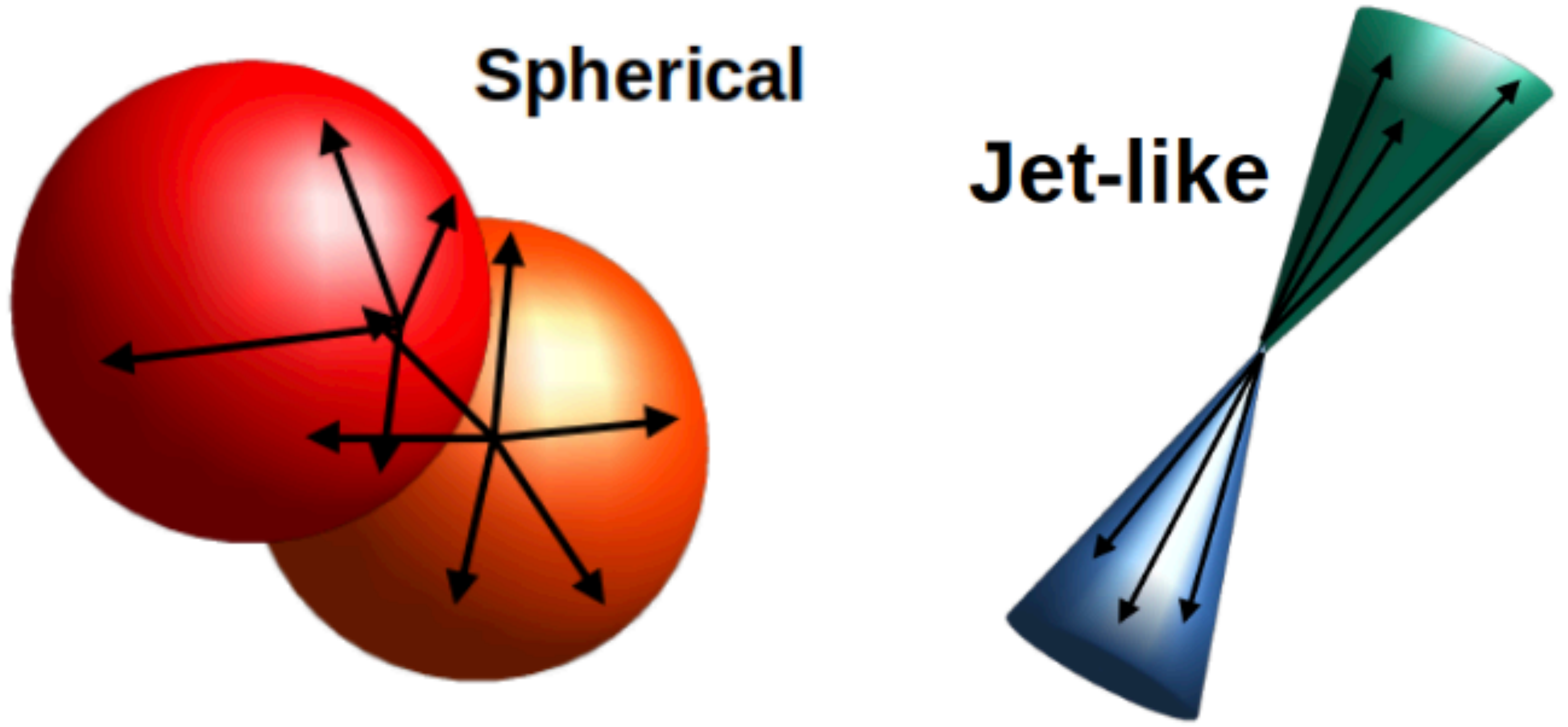
Two key variables discriminate against background for fully reconstructed hadronic final states



Separate signal from $q\bar{q}$ and misidentified B's.

Separate B-events from $q\bar{q}$.

Main backgrounds: $e^-e^+ \to q\bar{q}$ events (collimated jets, very different event shape as compared to $e^-e^+ \to B\bar{B}$ events) and also some misreconstructed $B\bar{B}$ events



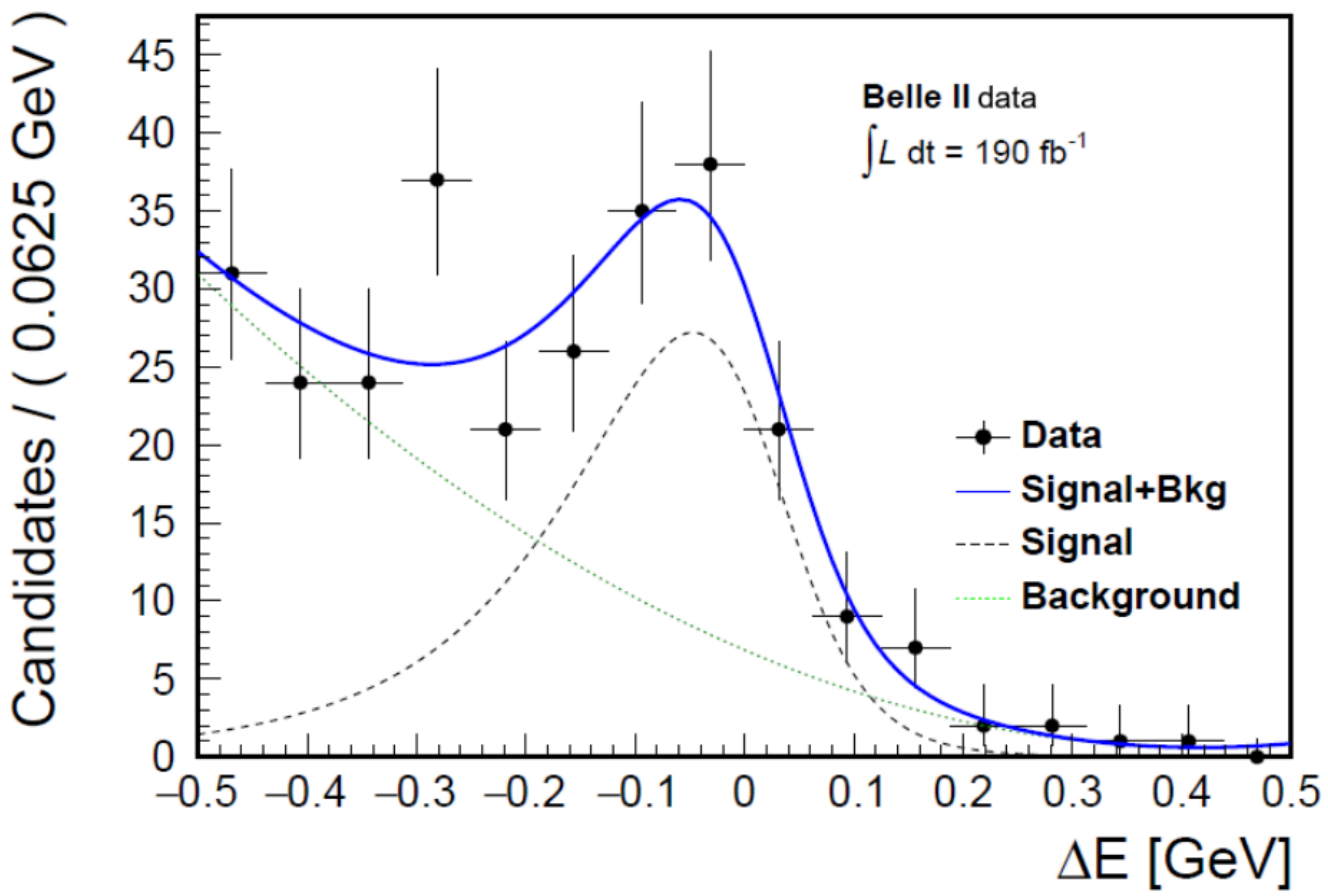
$e^-e^+ \to B\bar{B}$ $e^-e^+ \to q\bar{q}$

$\mathbf{B} \to \mathbf{K_S^0}\pi^0\gamma$

[arXiv:2206.08280]

- $\mathbf{B} \to \mathbf{K_S^0}\pi^0\gamma$ is expected to have small/none mixing induced CPV in SM
  - $b \to s\gamma_R$ is helicity suppressed (m_s/m_b) wrt $b \to s\gamma_L$
  - $B^0 \to s\gamma_L$ vs $B^0 \to \bar{B}^0 \to s\gamma_L$
- First measurement of the BR
- Signal extraction: fit to ΔE

Yield: 121 ± 29



$$\mathcal{B}\left(B^0 \to K_S^0\pi^0\gamma\right) = (7.3 \pm 1.8\,(\mathrm{stat}) \pm 1.0\,(\mathrm{syst})) \times 10^{-6}$$

- Compatible with the known value
- Full TDCPV analysis is ongoing

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

[arXiv:2209.05154]

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

Isospin sum rule provides null test of standard model:

Next slide

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

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

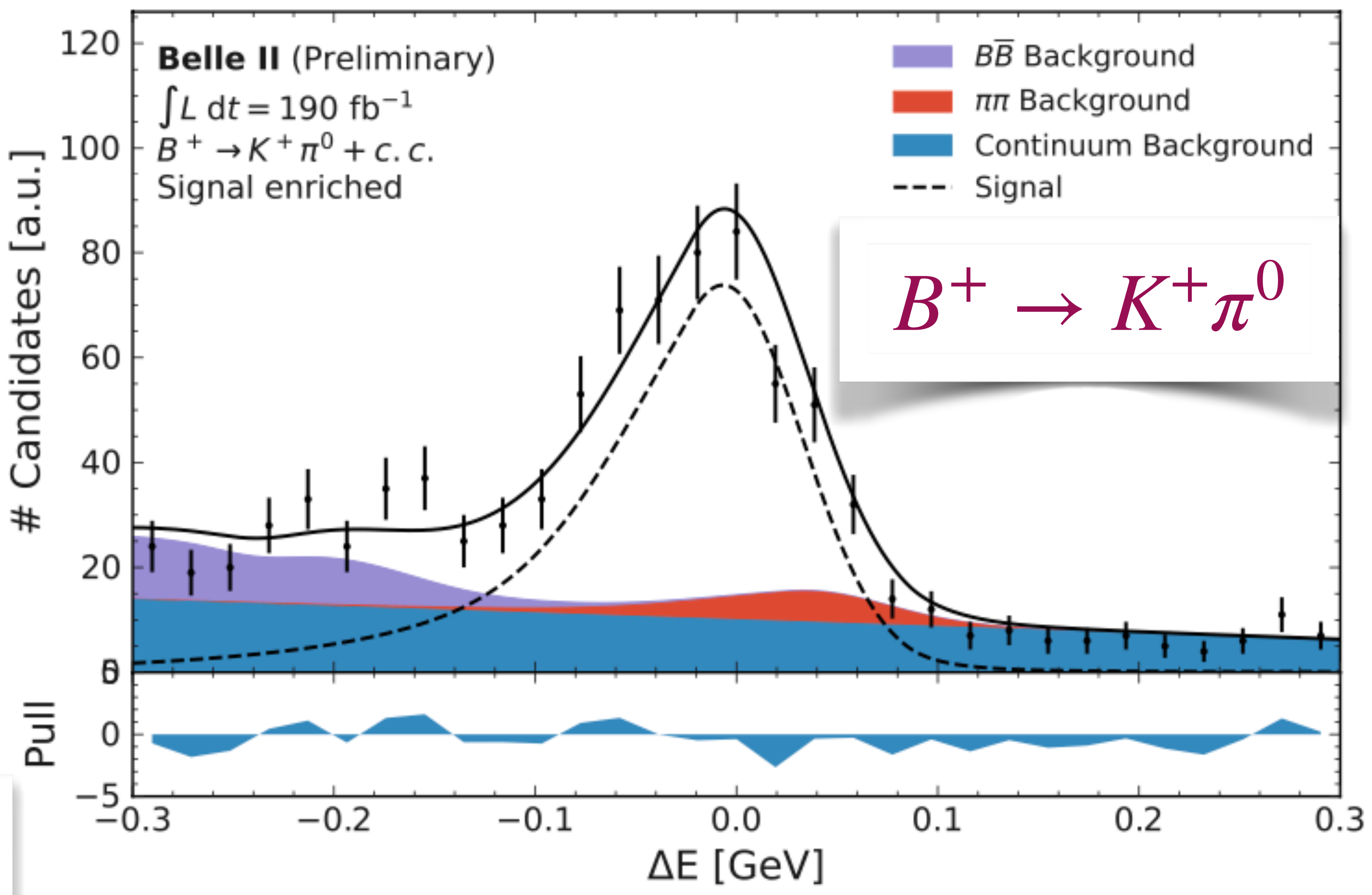
$N(K^+\pi^0) = 887 \pm 43$, $N(\pi^+\pi^0) = 422 \pm 37$

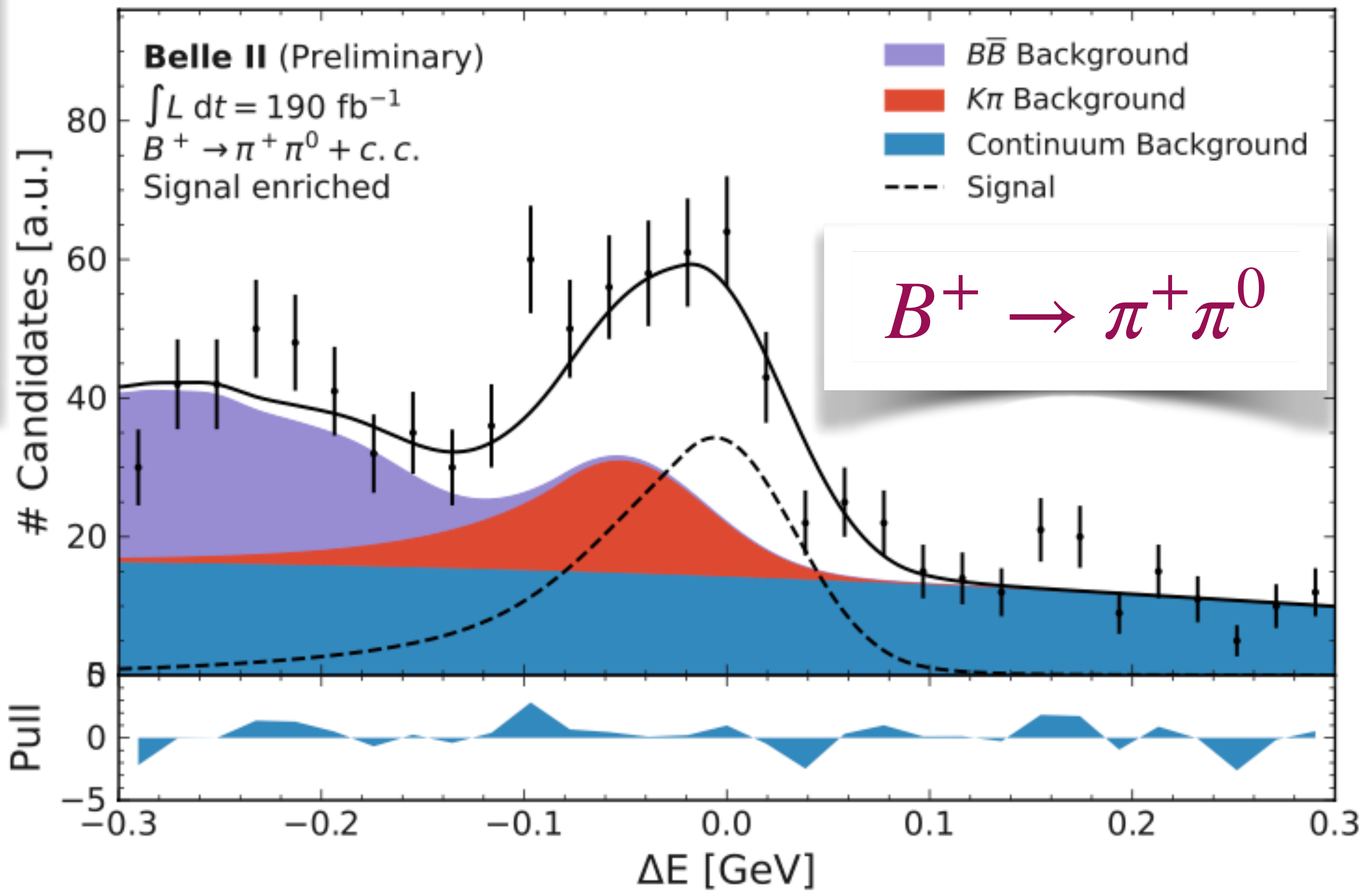
$$\mathcal{A}^{CP}_{K^+\pi^0} = 0.014 \pm 0.047\ (\text{stat.})\ \pm 0.010\ (\text{syst.})$$
$$\mathcal{B}_{K^+\pi^0} = (14.30 \pm 0.69\ (\text{stat.})\ \pm 0.76\ (\text{syst.})) \cdot 10^{-6}$$
$$\mathcal{A}^{CP}_{\pi^+\pi^0} = -0.085 \pm 0.085\ (\text{stat.})\ \pm 0.019\ (\text{syst.})$$
$$\mathcal{B}_{\pi^+\pi^0} = (6.12 \pm 0.54\ (\text{stat.})\ \pm 0.52\ (\text{syst.})) \cdot 10^{-6}$$

- common selection for both the modes
- 3D fit of M_{bc}, ΔE and CS output

WA: $\mathcal{A}^{CP}_{K^+\pi^0} = 0.037 \pm 0.021$, $\mathcal{B}_{K^+\pi^0} = (12.9 \pm 0.5) \cdot 10^{-6}$

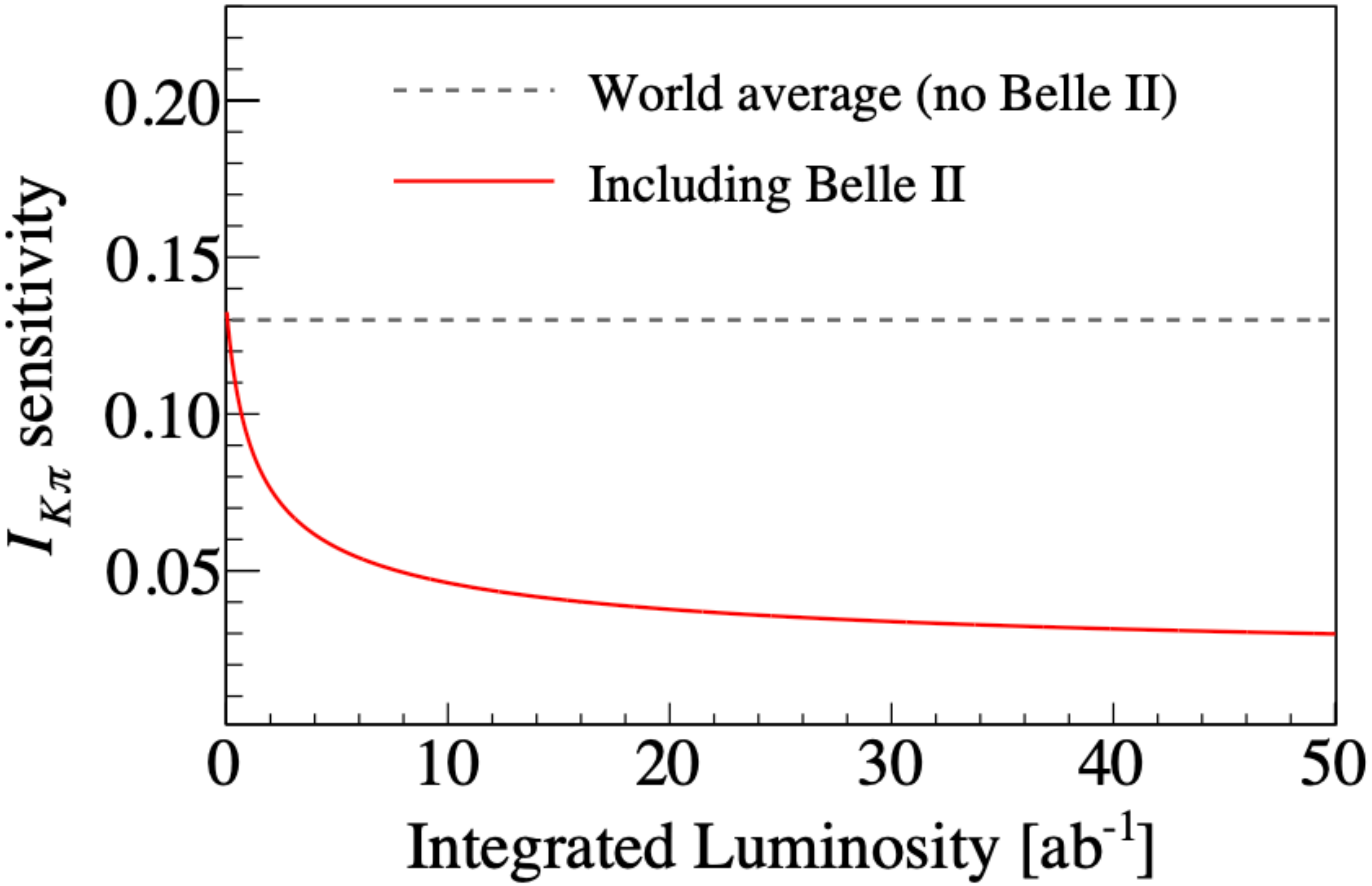
$\mathcal{B}$ precision limited by systematic uncertainties associated to size of control samples.





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

- *Dominant uncertainty comes from* $A_{K^0\pi^0}$
- *Fundamental role of Belle II in precision improvement*



- For statistically limited $B \to VV$ decays, integrate over ϕ and fit helicity angles to extract f_L

$$\frac{1}{\Gamma}\frac{d^2\Gamma}{d\cos\theta_{\rho_1} d\cos\theta_{\rho_2}} \propto f_L \cos^2\theta_1 \cos^2\theta_2 + (1 - f_L)\sin^2\theta_1 \sin^2\theta_2$$

Image credit: PRD 76 052007 (2007)