Belle II

Karlsruhe Institute of Technology

Measurements of *CP* Violation at Belle II

Pablo Goldenzweig

On behalf of the Belle II Collaboration

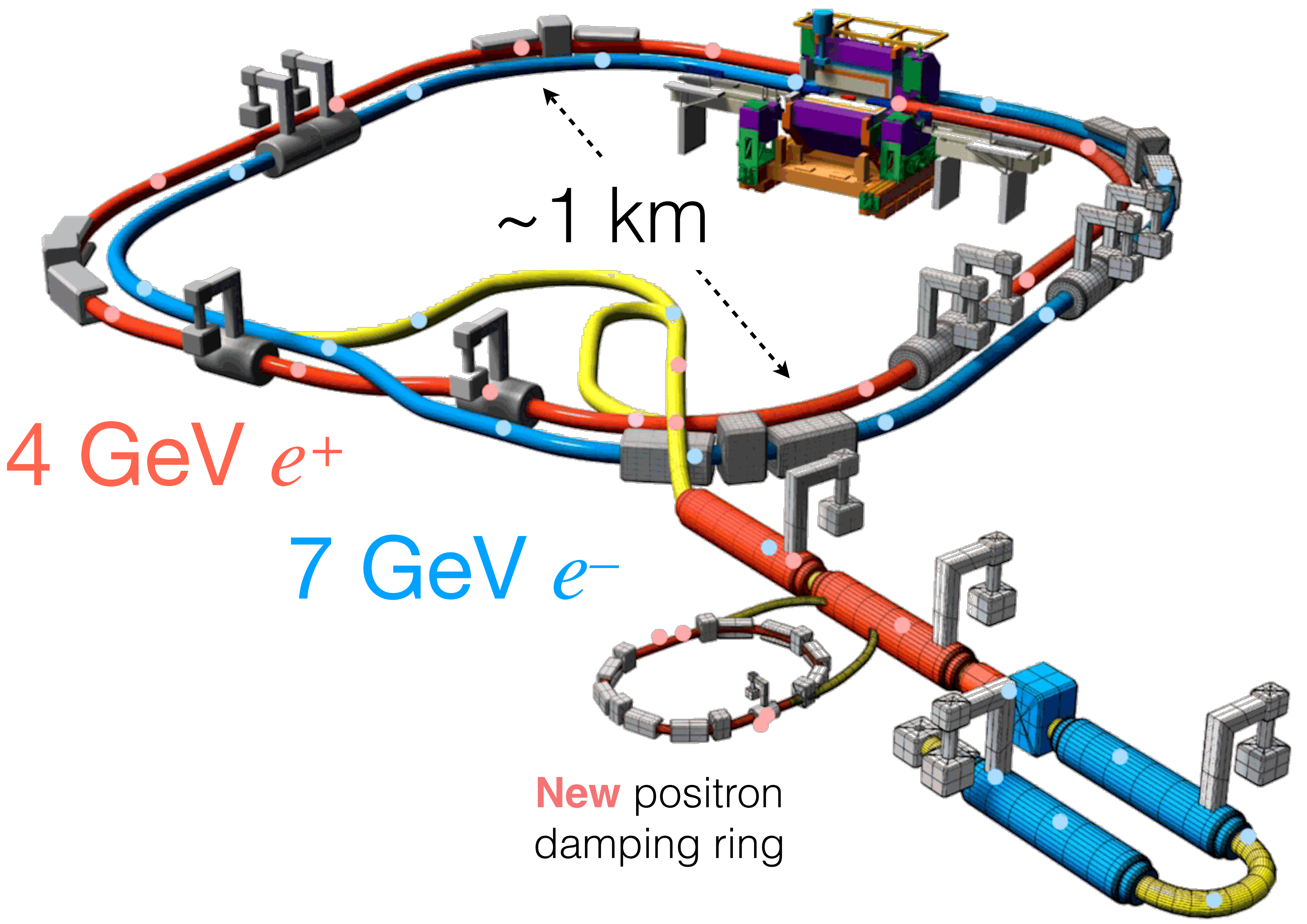
DISCRETE 2022

7-11 Nov. 2022

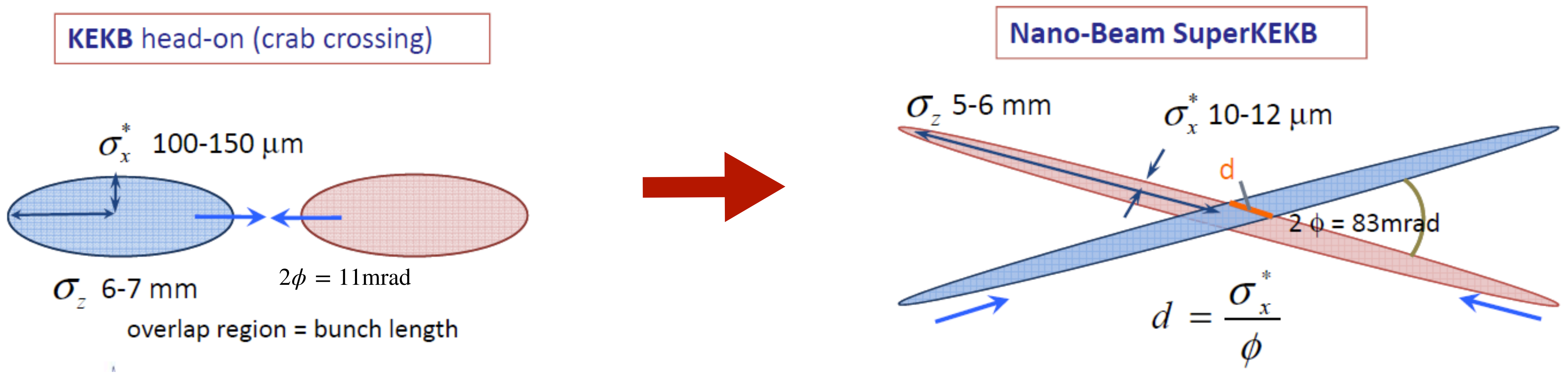
Baden-Baden

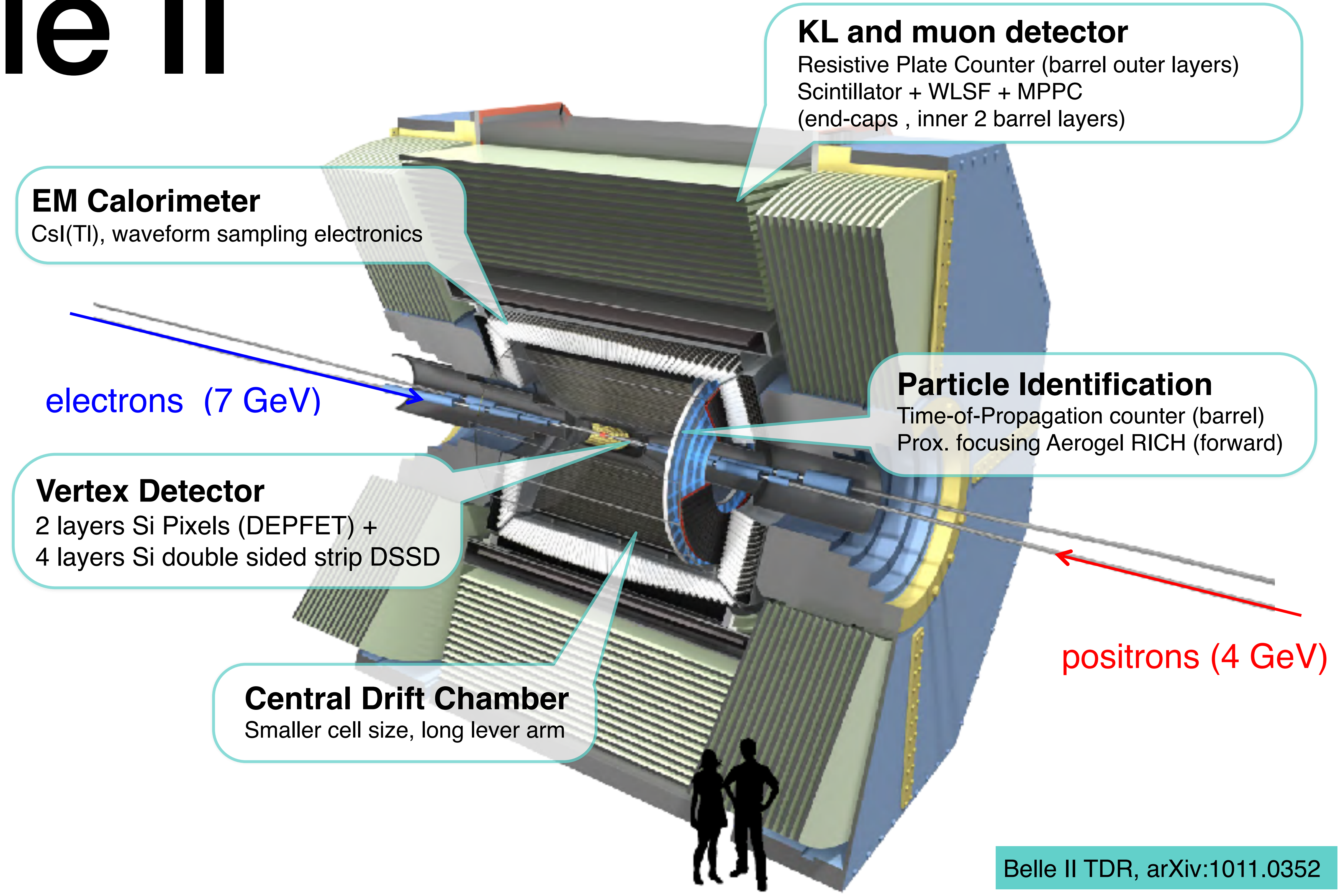
SuperKEKB and Belle II

Upgrade to achieve 40x peak $\mathscr{L}$ under 20x background

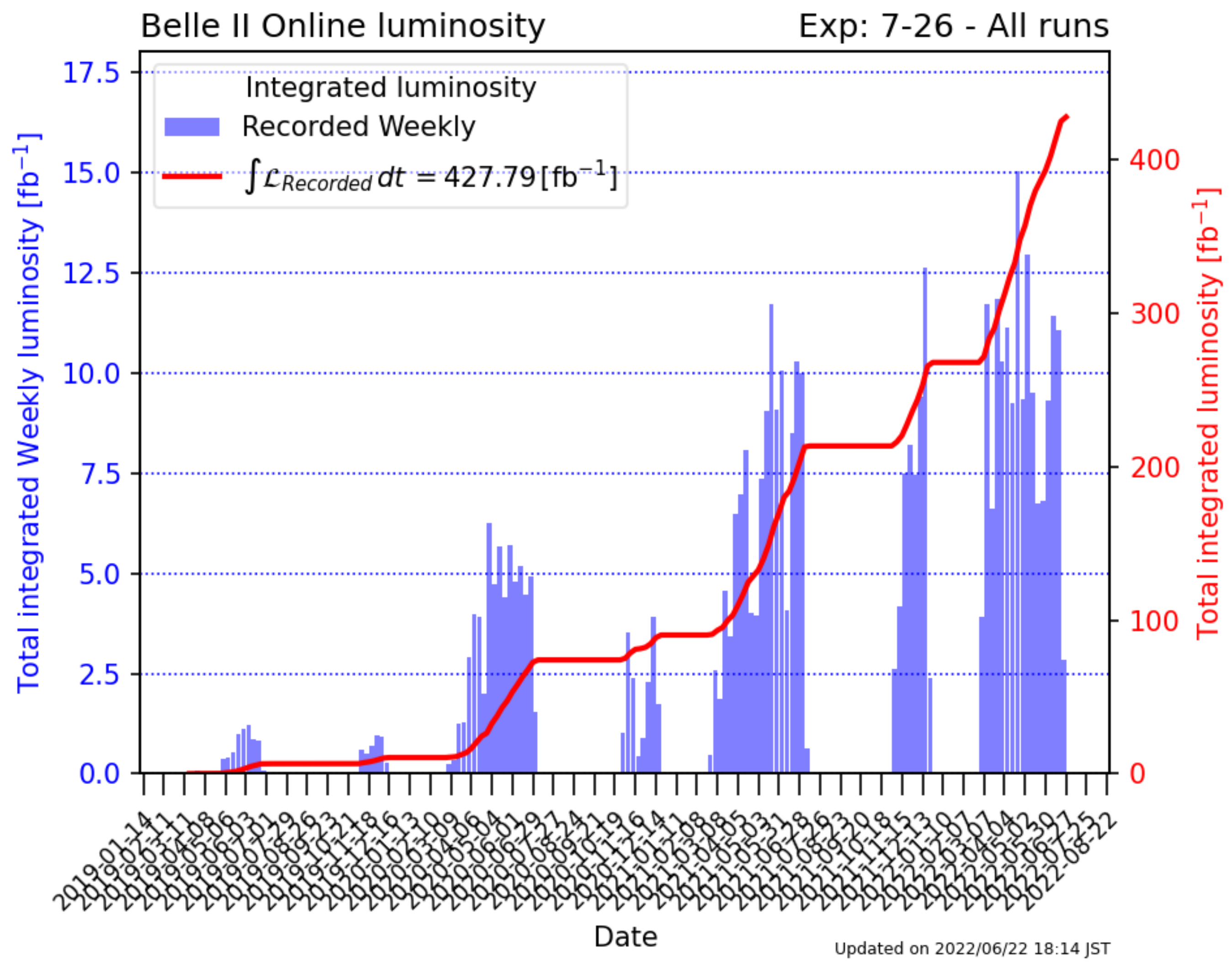


Animation © KEK





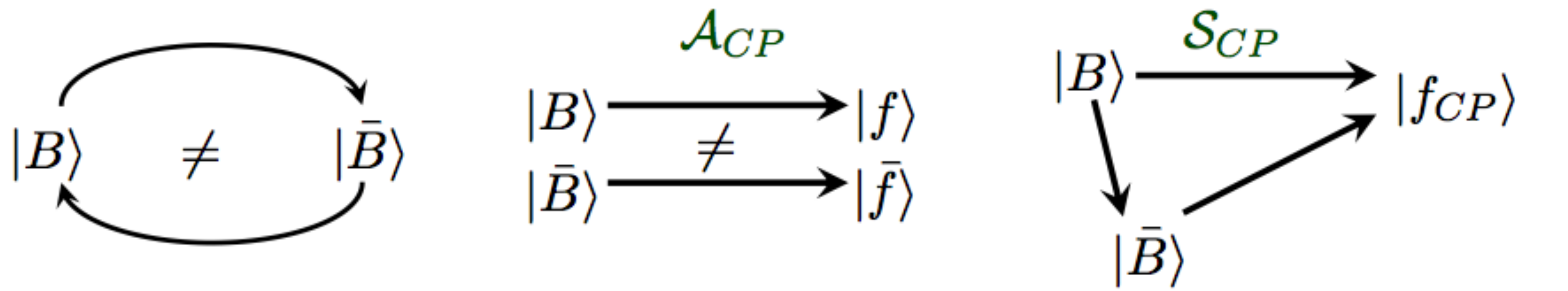
Belle II TDR, arXiv:1011.0352



- *World record $\mathscr{L}_{\text{inst}}$.*
- *High resolution hermetic detector.*
- *Efficient reconstruction of neutrals (π^0, η).*
- *Tagged events to measure absolute $\mathscr{B}$.*

CP Violation Measurements

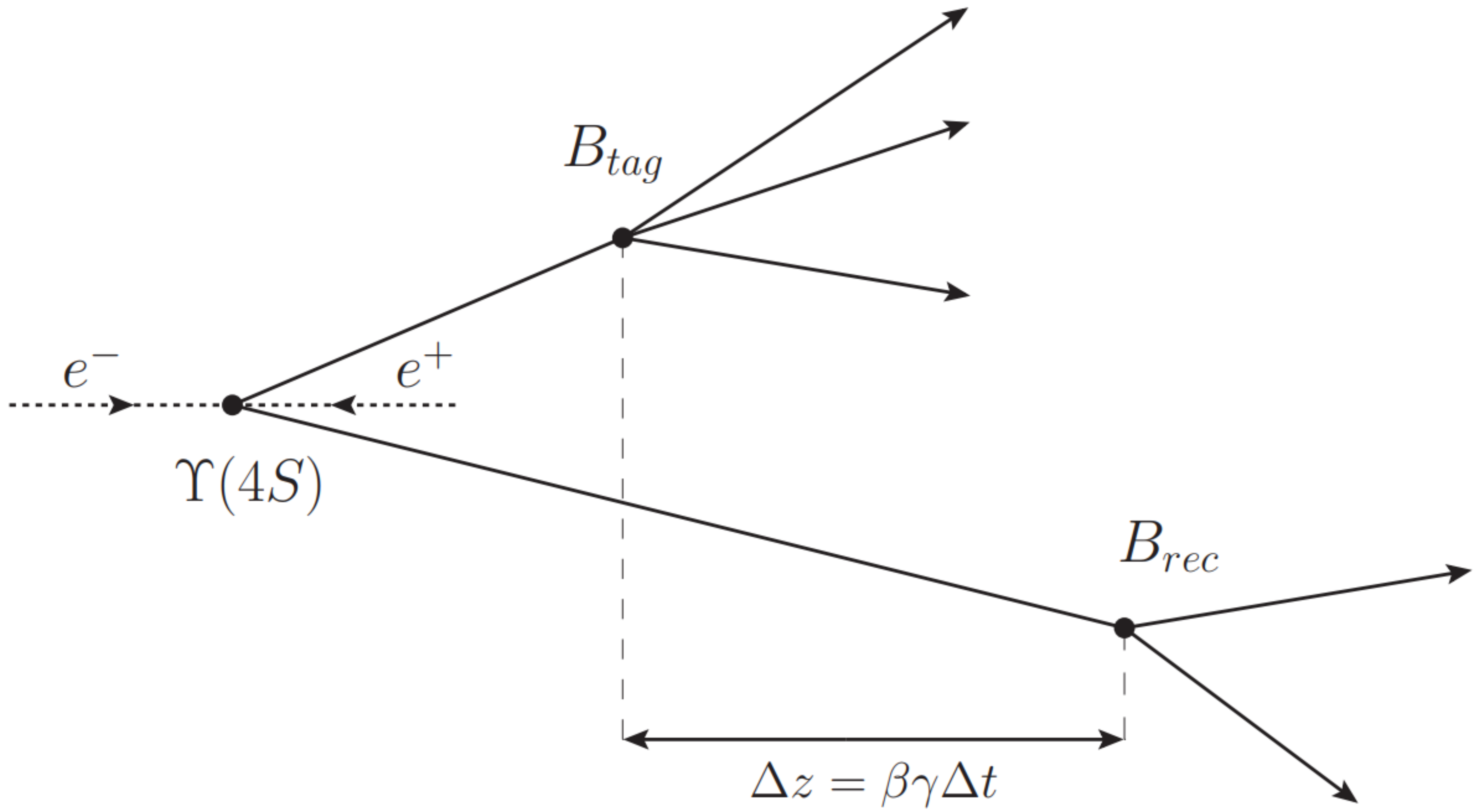
CPV in mixing | Direct CPV in Decay | CPV in the interference between mixing and decay



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

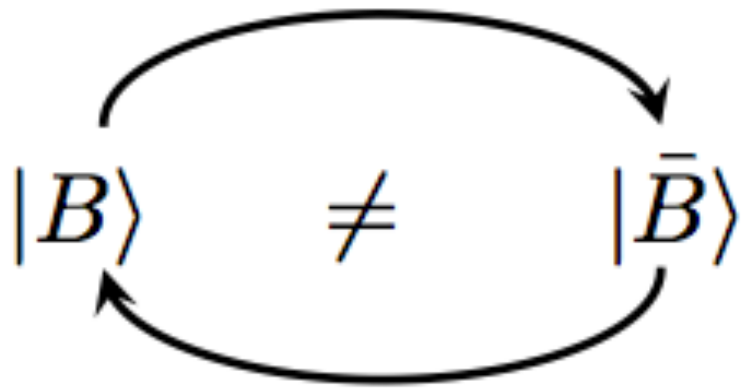
Key ingredients:

- Vertex position measurement.
- B meson flavor tagging.

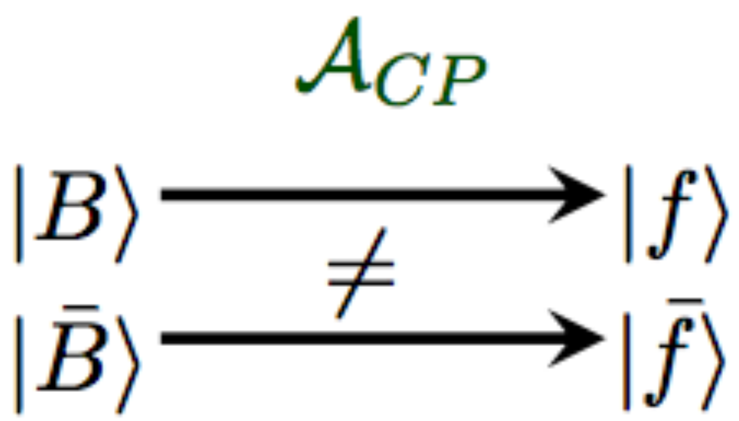


CP Violation Measurements

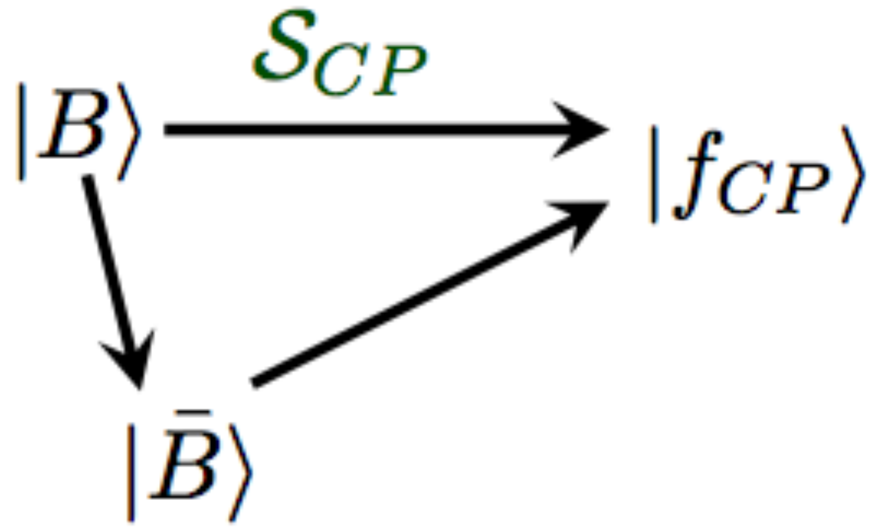
CPV in mixing



Direct CPV in Decay



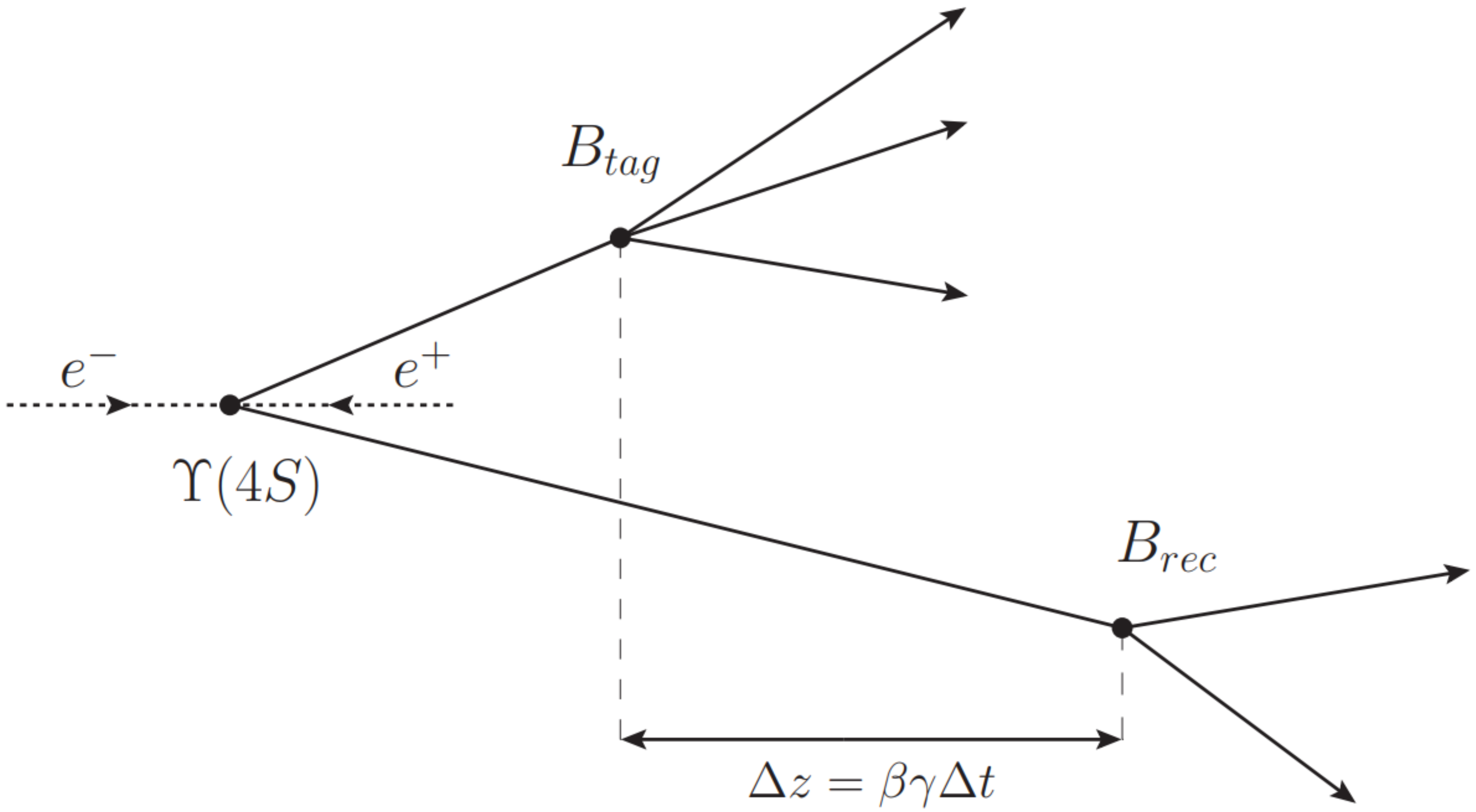
CPV in the interference between mixing and decay



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

Key ingredients:

- Vertex position measurement.
- B meson flavor tagging.



Flavor tagging

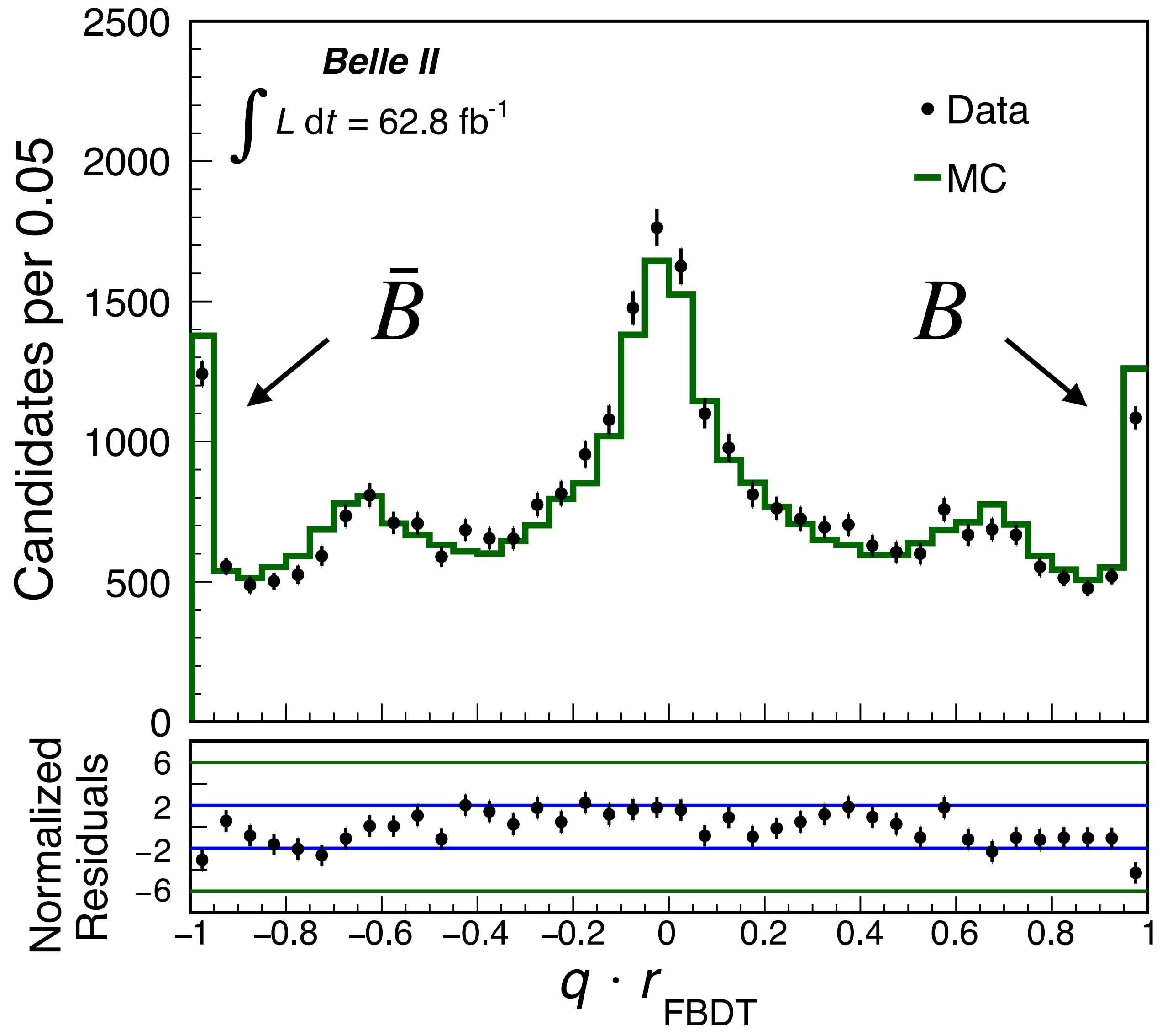
Eur. Phys. J. C 82, 283(2022)

Determination of the B_{tag} with an MVA technique using all particles not belonging to B_{sig}.

Dilution factor: $r_{\text{FBDT}} \approx (1 - 2w)$
Flavor tag: $q = \pm 1$.

Mistag fraction

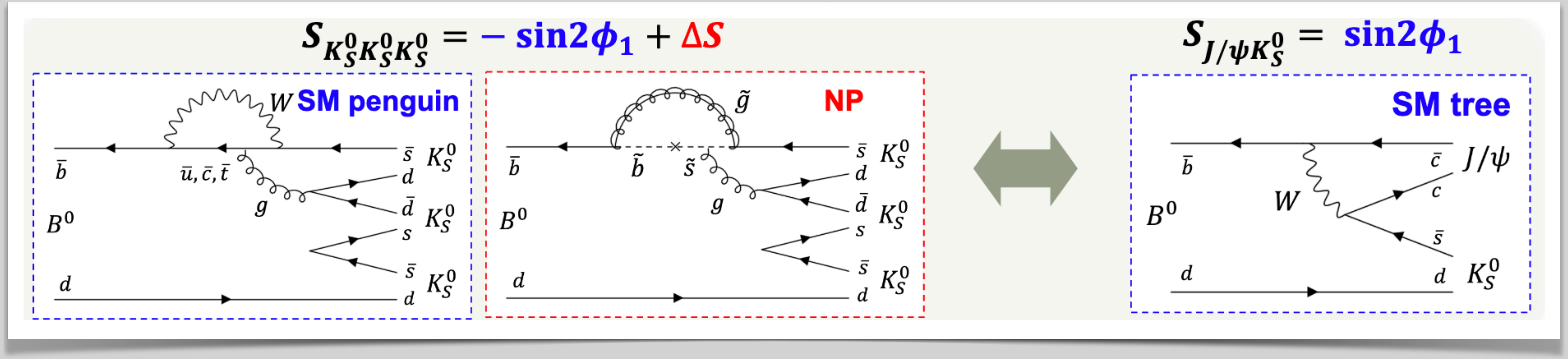
Efficiency evaluated from $BB/B\bar{B}$ in 7 $|q \cdot r|$ bins.



$$\epsilon = (30.0 \pm 1.2 \pm 0.4)\,\%$$

Measurement of $\sin 2\phi_1$

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



$B^0 \to J/\psi K_S^0$

- Golden mode for $\sin 2\phi_1$, almost background free.
- K_L and other $c\bar{c}$ to be added.
- Using resolution function developed for lifetime and mixing analysis on $B^0 \to D^{(*)-}h^+$decays.
- Validation with $B^+ \to J/\psi K^+$.

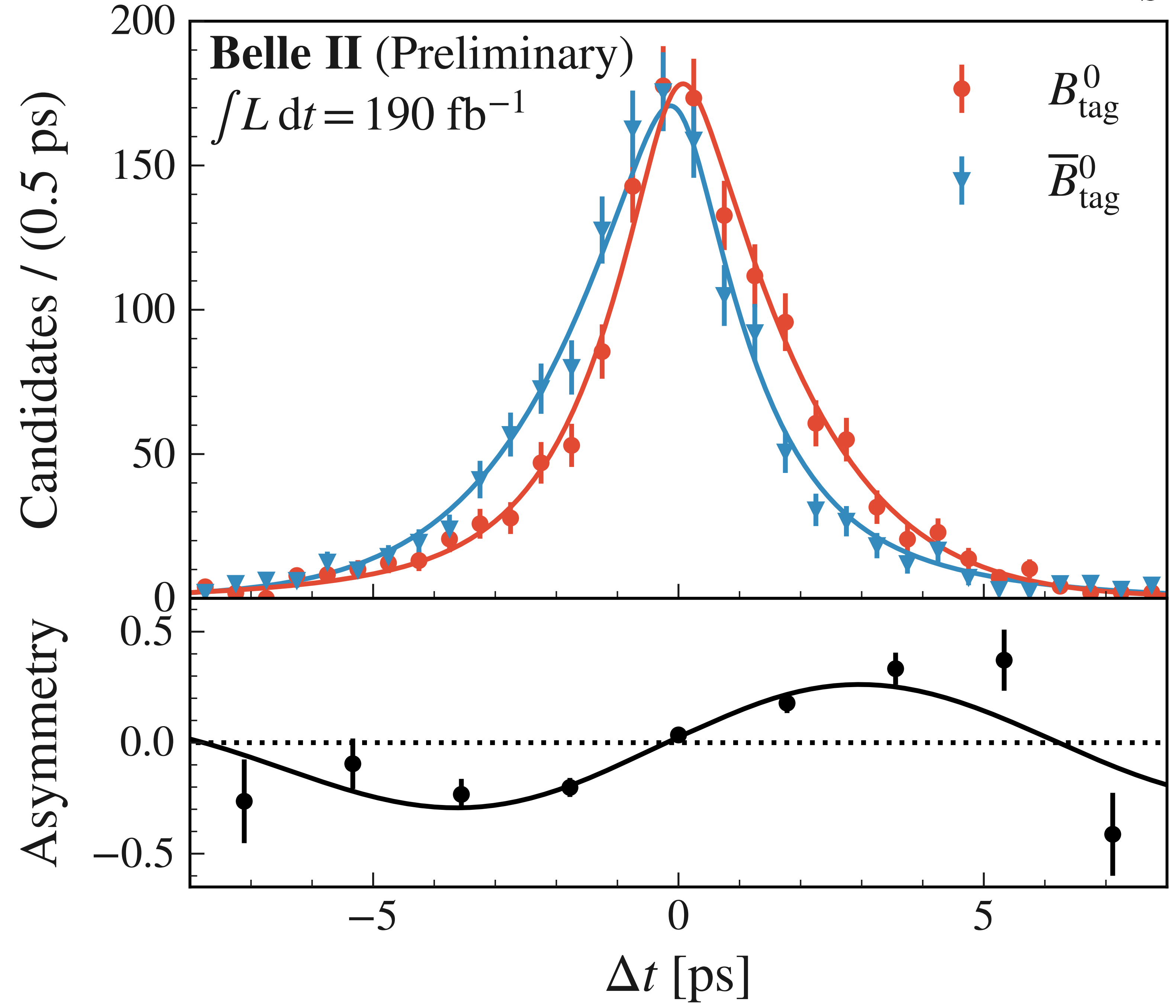
WA (K_S^0 channel):
$A_{CP} = 0.000 \pm 0.020$
$S_{CP} = 0.695 \pm 0.019$

Dominant: Tag-side interference & charge asymmetry

$$A_{CP} = 0.094 \pm 0.044(\text{stat})^{+0.042}_{-0.017}(\text{syst})$$
$$S_{CP} = 0.720 \pm 0.062(\text{stat}) \pm 0.016(\text{syst})$$

Dominant: Size of control samples

ICHEP talk

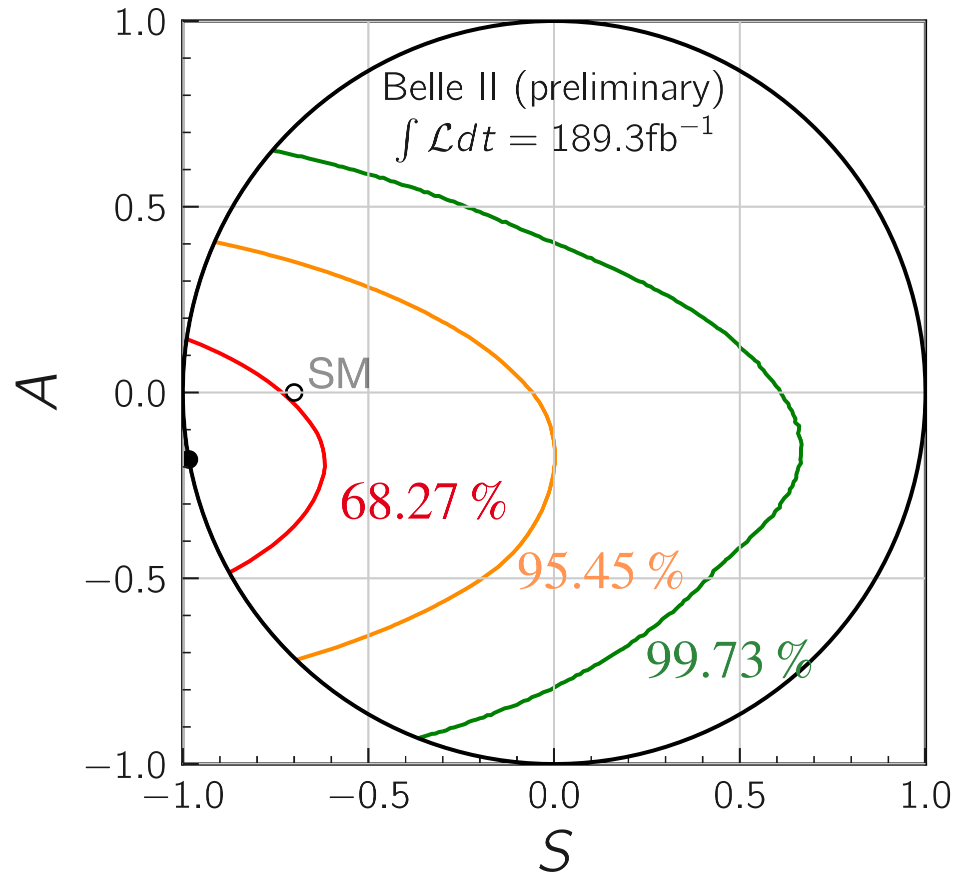


$B^0 \to K_S^0 K_S^0 K_S^0$

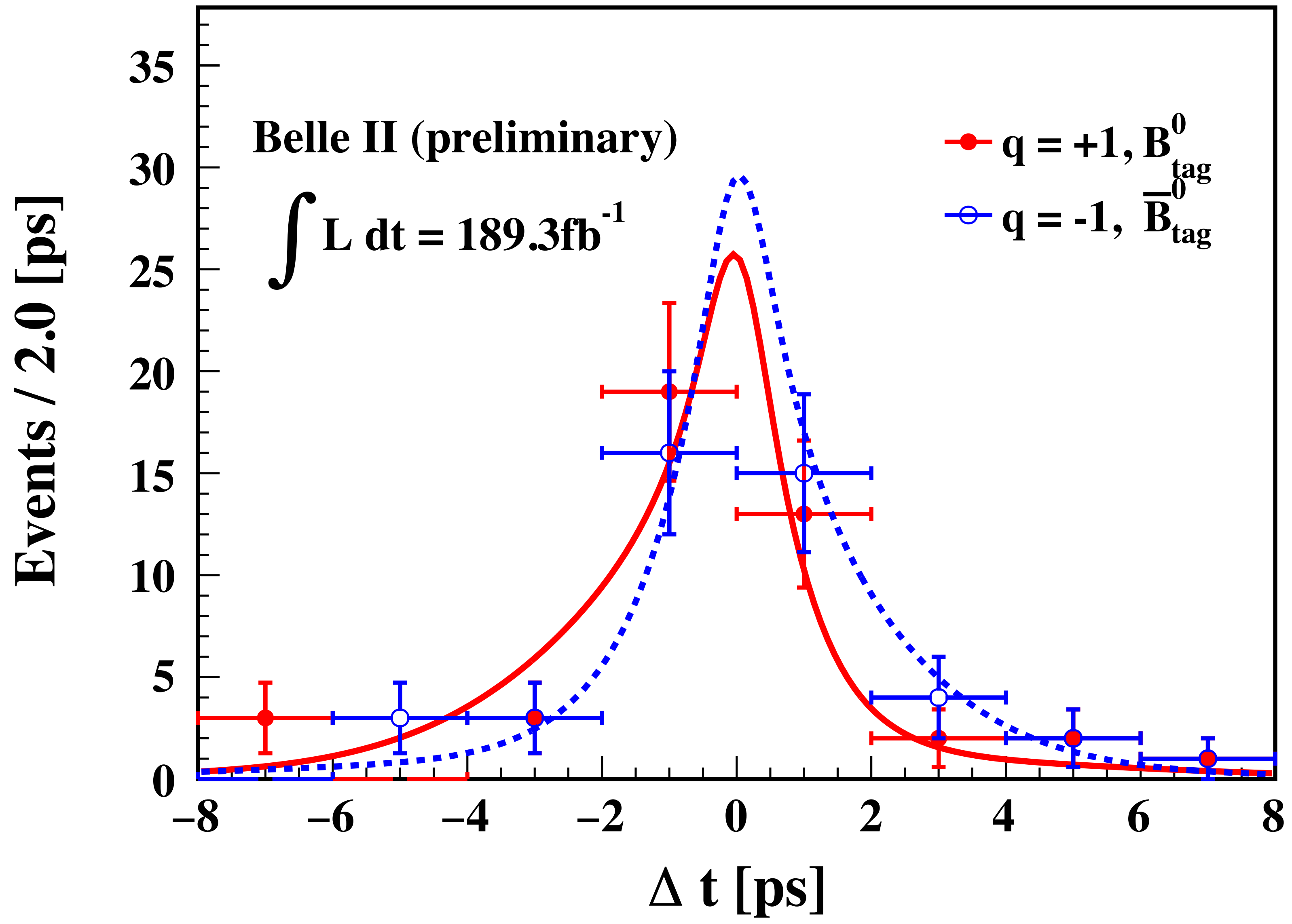
- Challenging vertex reconstruction: *only reconstructed $K_S^0 \to \pi^+\pi^-$ extrapolated back.*
- Two BDT classifiers: *to reduce fake K_S^0 and $e^+e^- \to q\bar{q}$* continuum background *.*
- Validated with $B^+ \to K^+K_S^0K_S^0$.

$$A_{CP} = -0.22 \pm 0.29(\text{stat}) \pm 0.04(\text{syst})$$
$$S_{CP} = -1.86 \pm 0.83(\text{stat}) \pm 0.09(\text{syst})$$

$S^2 + A^2 \leq 1$

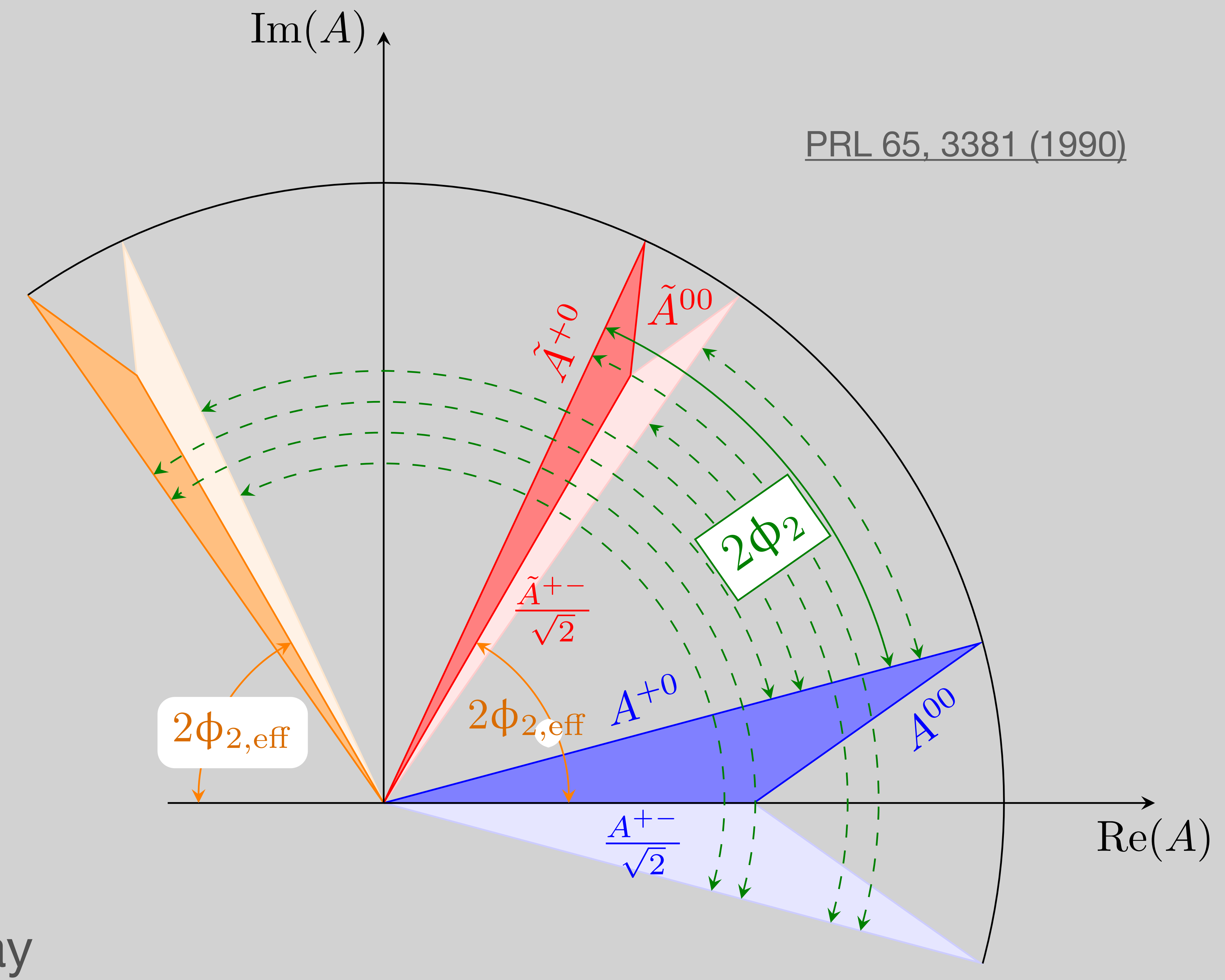


arXiv:2209.09547



Both analyses still statistically limited

ϕ_2 with $B \to \pi\pi$ & $B \to \rho\rho$



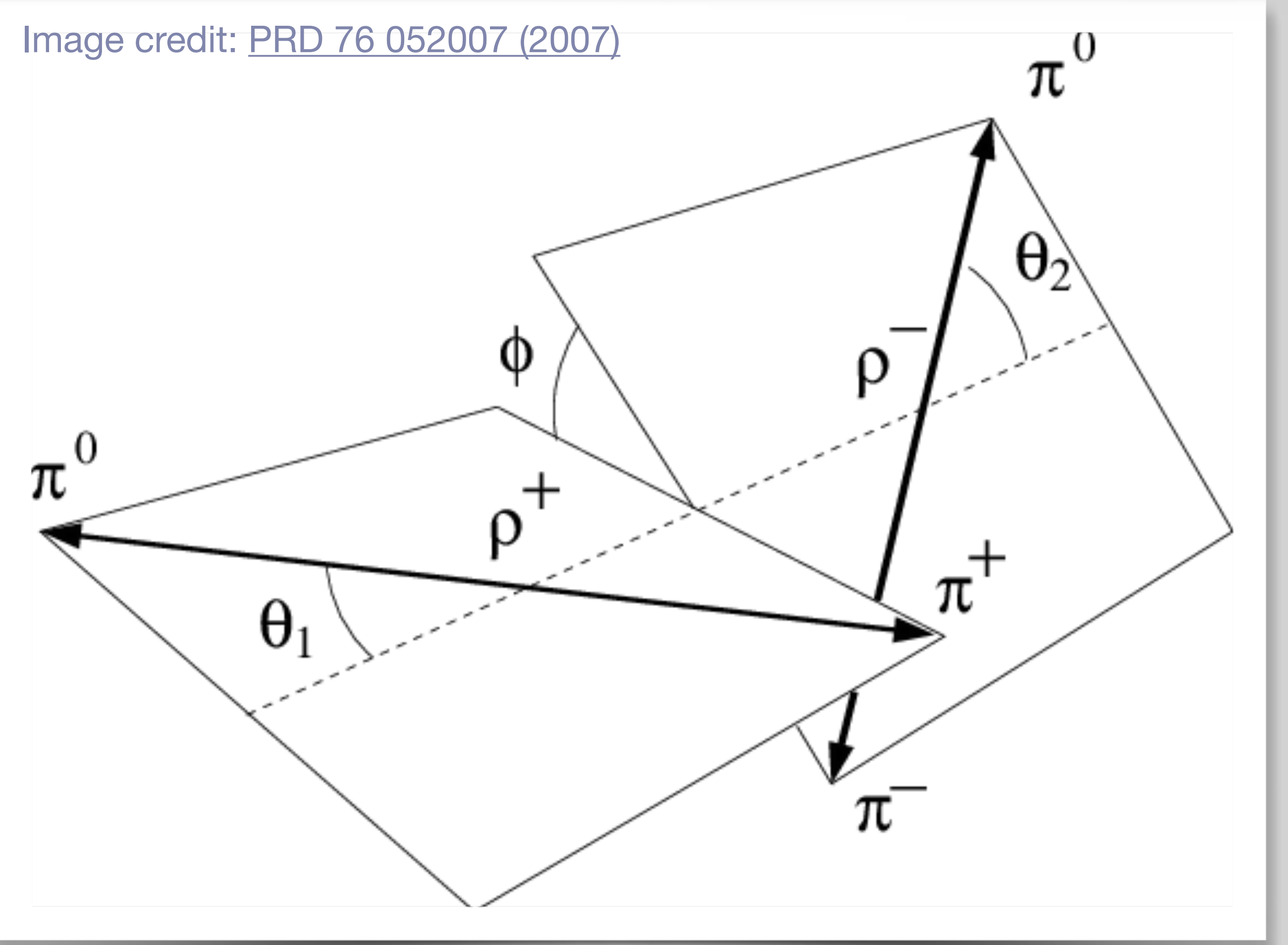
- Penguin pollution complicates extraction of $\phi_2^{\mathrm{eff}} = \phi_2 + \Delta\phi_2$.
- Isospin relations to disentangle tree and penguin contributions.

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

$\overset{(-)}{A}{}^{ij}$ = amplitudes of the (anti)particle decay

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

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



@Belle II:
- $B^0 \to \pi^0\pi^0$ ICHEP talk
- $B^+ \to \pi^+\pi^0$ arXiv:2209.05154
- $B^0 \to \rho^+\rho^-$ arXiv:2208.03554
- $B^+ \to \rho^+\rho^0$ arXiv:2206.12362

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

ICHEP talk

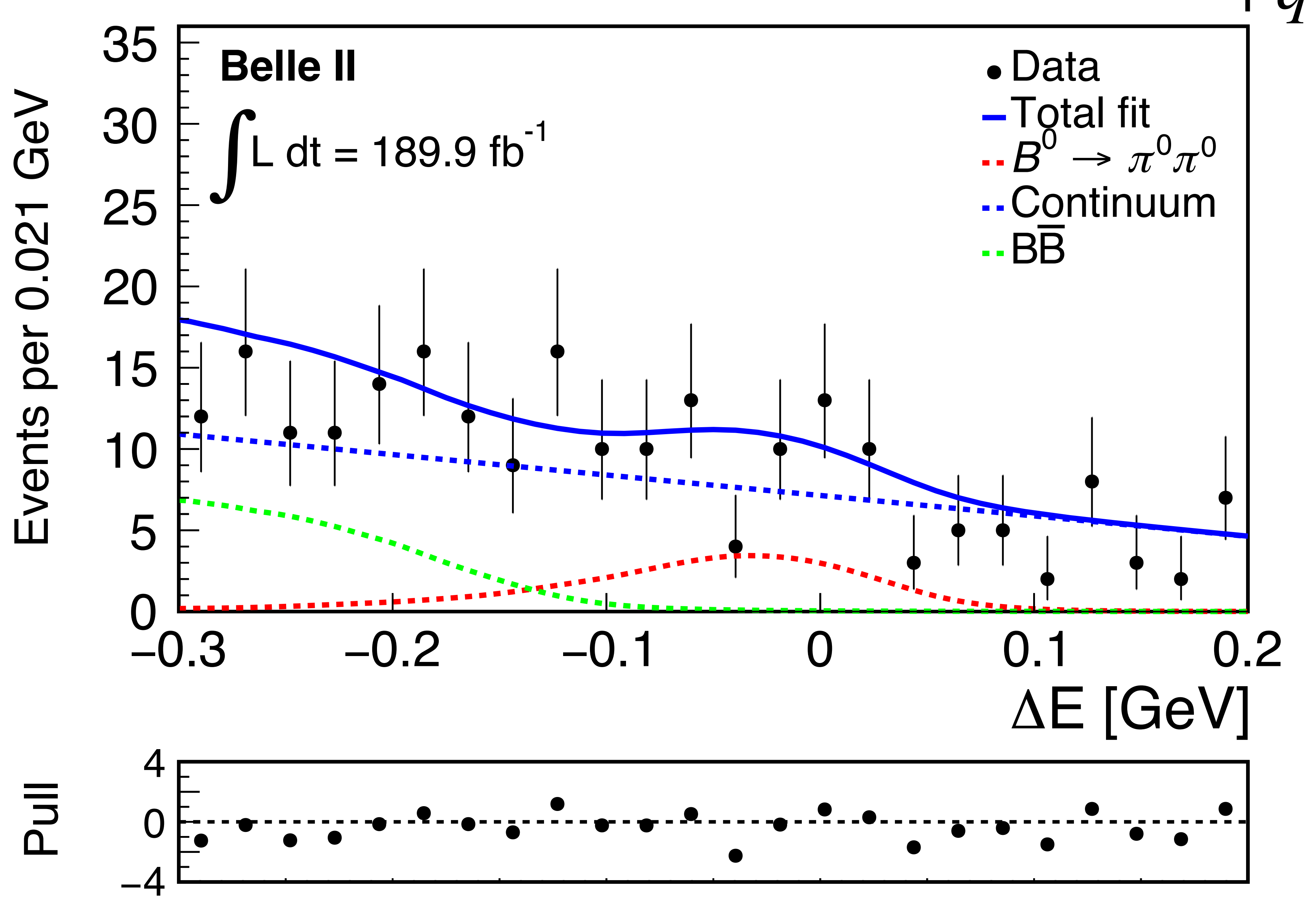
- Limiting input in isospin analysis to determine ϕ_2 from $B \to \pi\pi$ decays. **Belle II unique reach.**
- Dedicated MVA selection to reject fake photons + optimized π^0 selection. ($\epsilon_{\text{Belle II}} = 35.5\,\% > \epsilon_{\text{Belle}} = 22\%$)
- Dedicated continuum suppression BDT algorithm trained on data sideband and signal MC.
- 3D $(M_{bc}, \Delta E, \text{BDT}_{\text{Cont.Supp.}})$ simultaneous fit to 7 bins of flavor tagging quality:

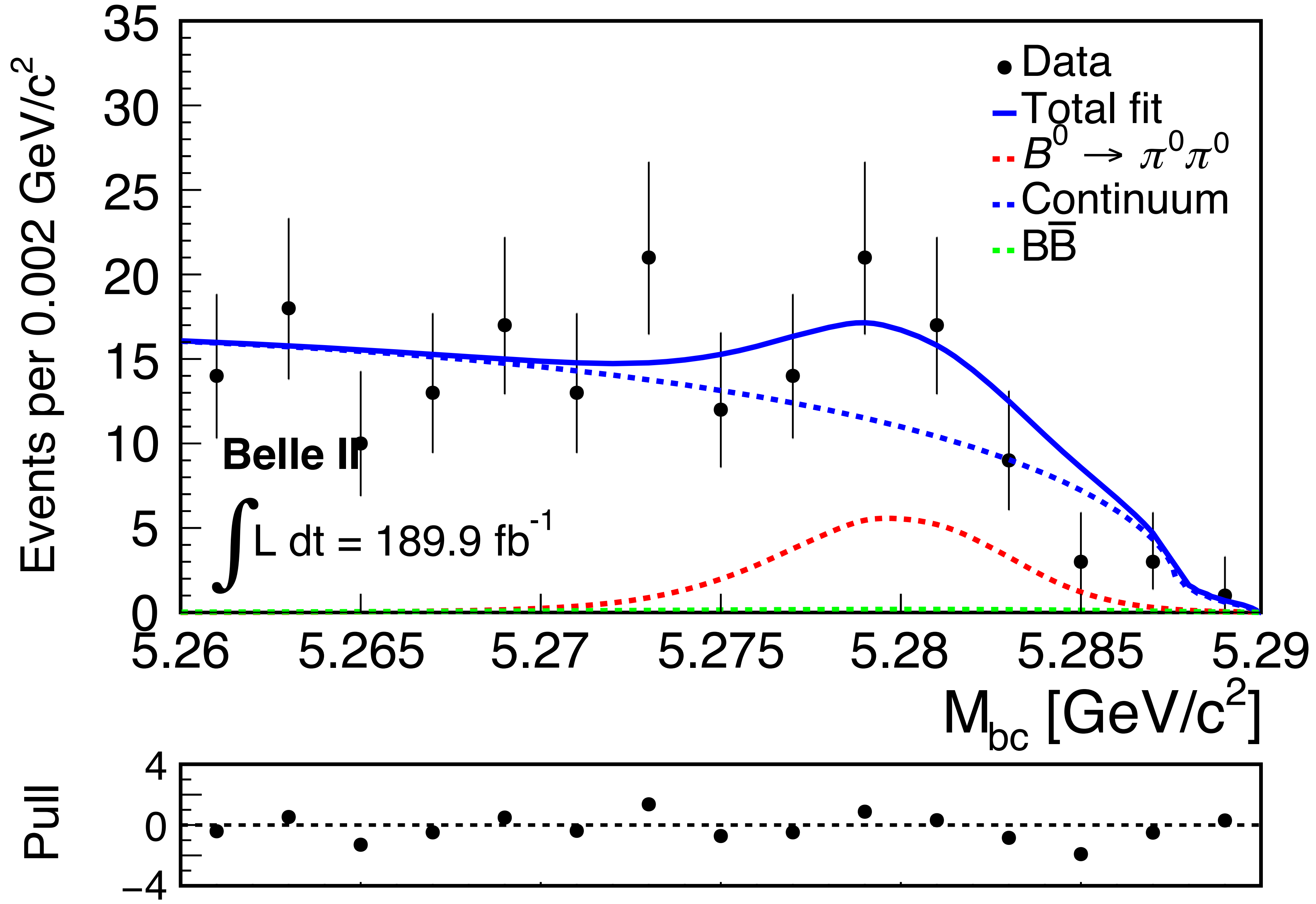
$$\mathcal{B}(B^0 \to \pi^0\pi^0) = (1.36 \pm 0.26 \pm 0.19) \times 10^{-6}$$
$$\mathcal{A}_{CP} = +0.14 \pm 0.46 \pm 0.07$$

Precision not far from Belle with 1/4 the data size

PRD 96 032007 (2017) — PRD 87 052009 (2013)

	Belle ($\times 10^{-6}$)	BaBar ($\times 10^{-6}$)
$\mathcal{B}(B^0 \to \pi^0\pi^0)$	$1.31 \pm 0.19 \pm 0.19$	$1.83 \pm 0.21 \pm 0.13$
$\mathcal{A}_{CP}(B^0 \to \pi^0\pi^0)$	$-0.14 \pm 0.36 \pm 0.10$	$-0.43 \pm 0.26 \pm 0.05$





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

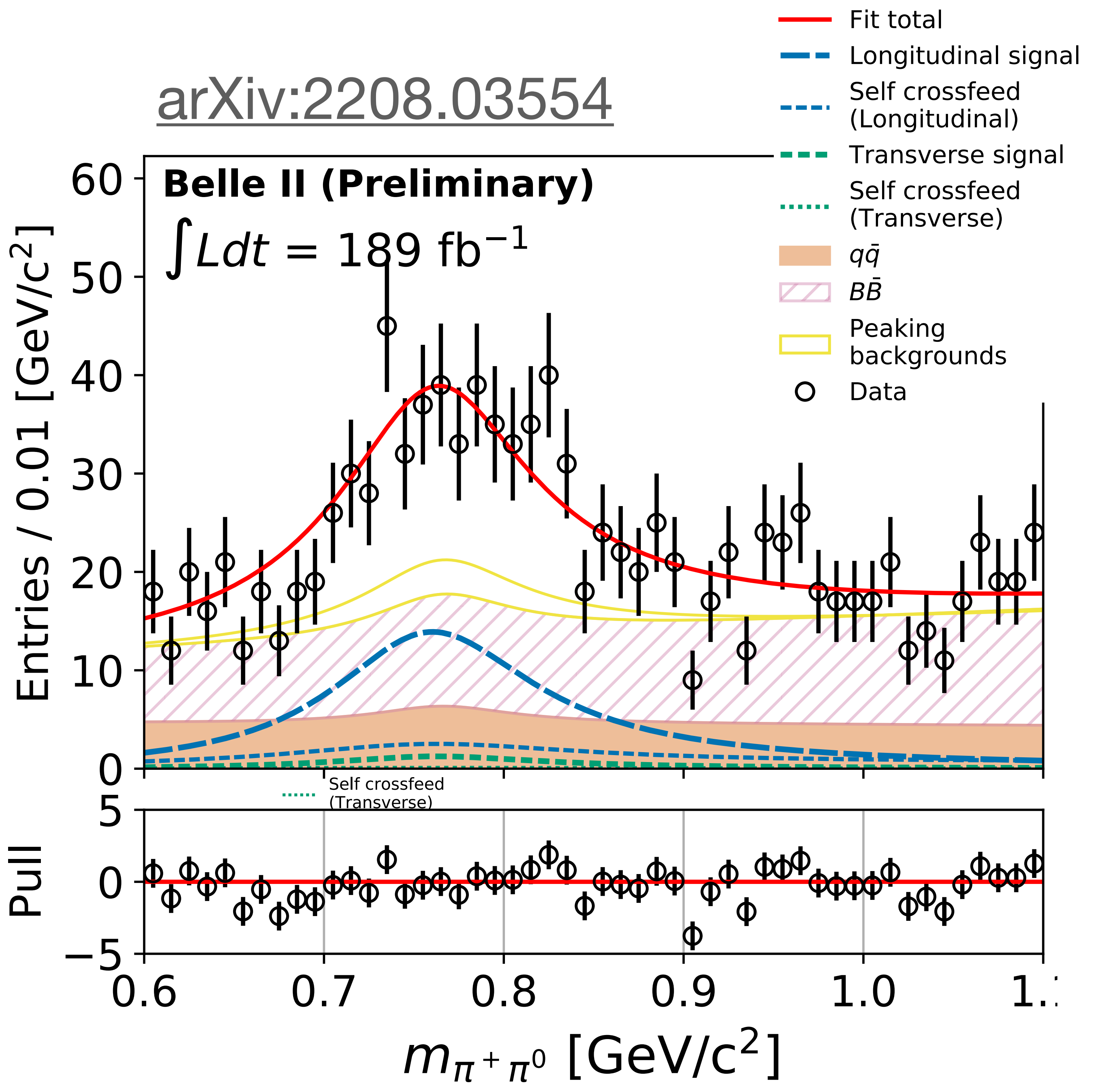
- 6D (ΔE, $m_{\pi^\pm\pi^0}$, $\cos\theta_{\rho^\pm}$, $\mathrm{BDT}_{\mathrm{Cont.Supp.}}$) fit taking correlations into account to extract $\mathscr{B}$ and f_L.
- Yields of measured peaking backgrounds fixed in fit (similar final state $2\pi^0, \pi^+, h^+$).
- $\mathscr{B}$ measurement limited by systematic uncertainty. Largest systematic associated to π^0 reconstruction.

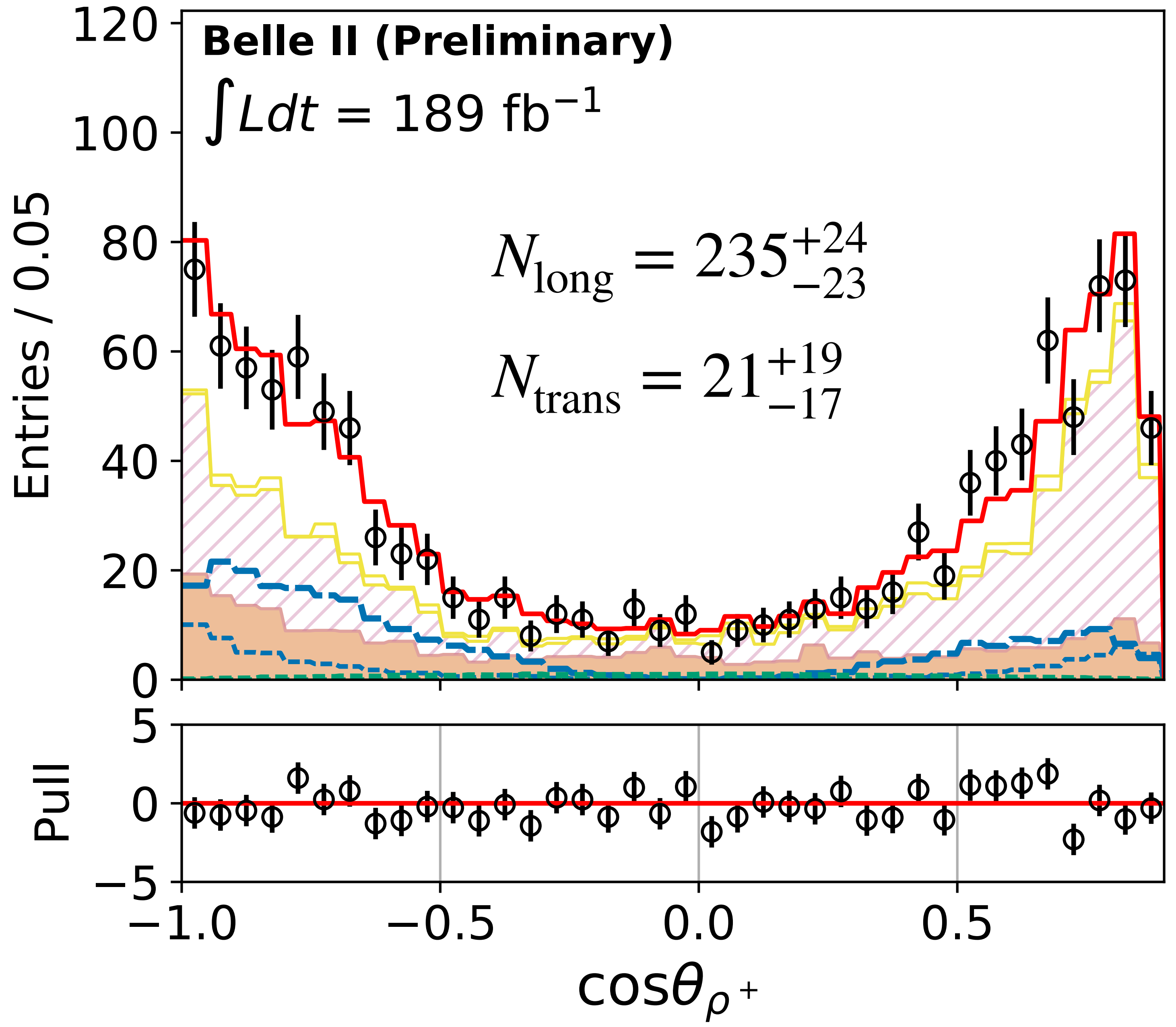
$$\mathcal{B}(B^0 \to \rho^+\rho^-) = [2.67 \pm 0.28\,(\mathrm{stat}) \pm 0.28\,(\mathrm{syst})] \times 10^{-5},$$
$$f_L = 0.956 \pm 0.035\,(\mathrm{stat}) \pm 0.033\,(\mathrm{syst}),$$

WA: $\mathscr{B} = (2.77 \pm 0.19) \cdot 10^{-5}$, $f_L = 0.990^{+0.021}_{-0.019}$

- TDCPV analysis underway.

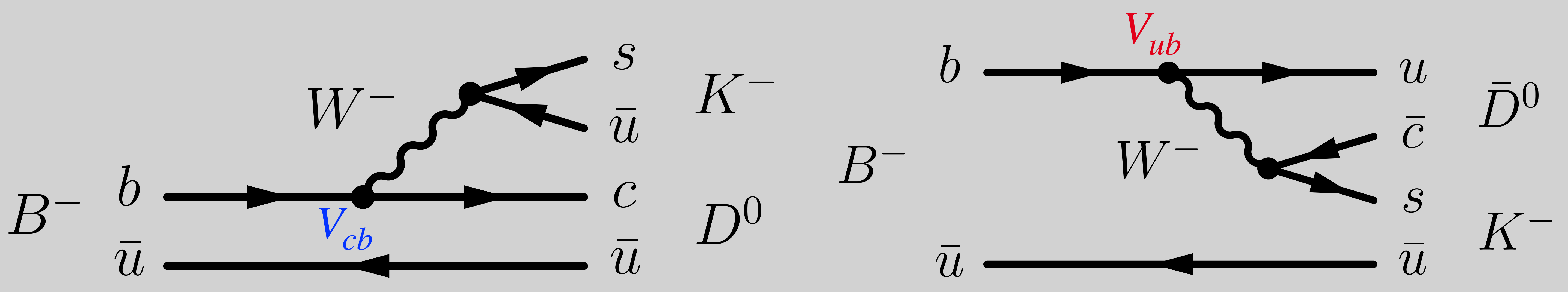
arXiv:2208.03554





ϕ_3

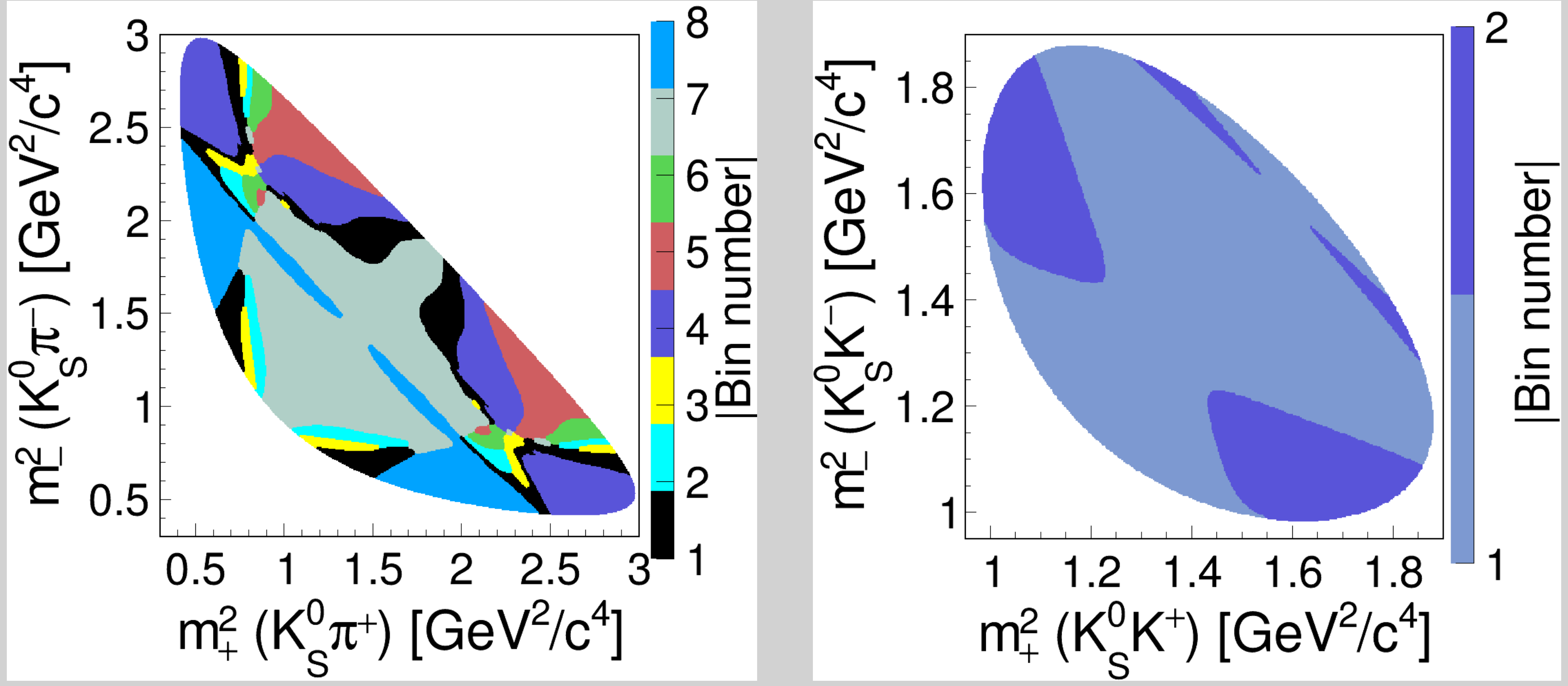
- Measured from interference of $b \to c\bar{u}s$ and $b \to u\bar{c}s$ tree amplitudes in $B^{\pm}$ meson decays to open-charm final states.



First combined Belle and Belle II analysis

JHEP 02, 063 (2022)

- $B^+ \to D^0(K_S^0 h^+ h^-)h^+$
- Simultaneous analysis of both final states.
- BPGGSZ technique: model-independent Dalitz plot



Invariant mass $m_{\pm} = m(K_S^0 h^{\pm})$

Decay amplitude in the point of the Dalitz plot

$$A_{B^+}\left(m_-^2, m_+^2\right) \propto A_{\bar{D}}\left(m_-^2, m_+^2\right) + r_B^{DK} e^{i\left(\delta_B^{DK} - \phi_3\right)} A_D\left(m_-^2, m_+^2\right)$$

Ratio: Suppressed to favored

Relative strong-phase difference

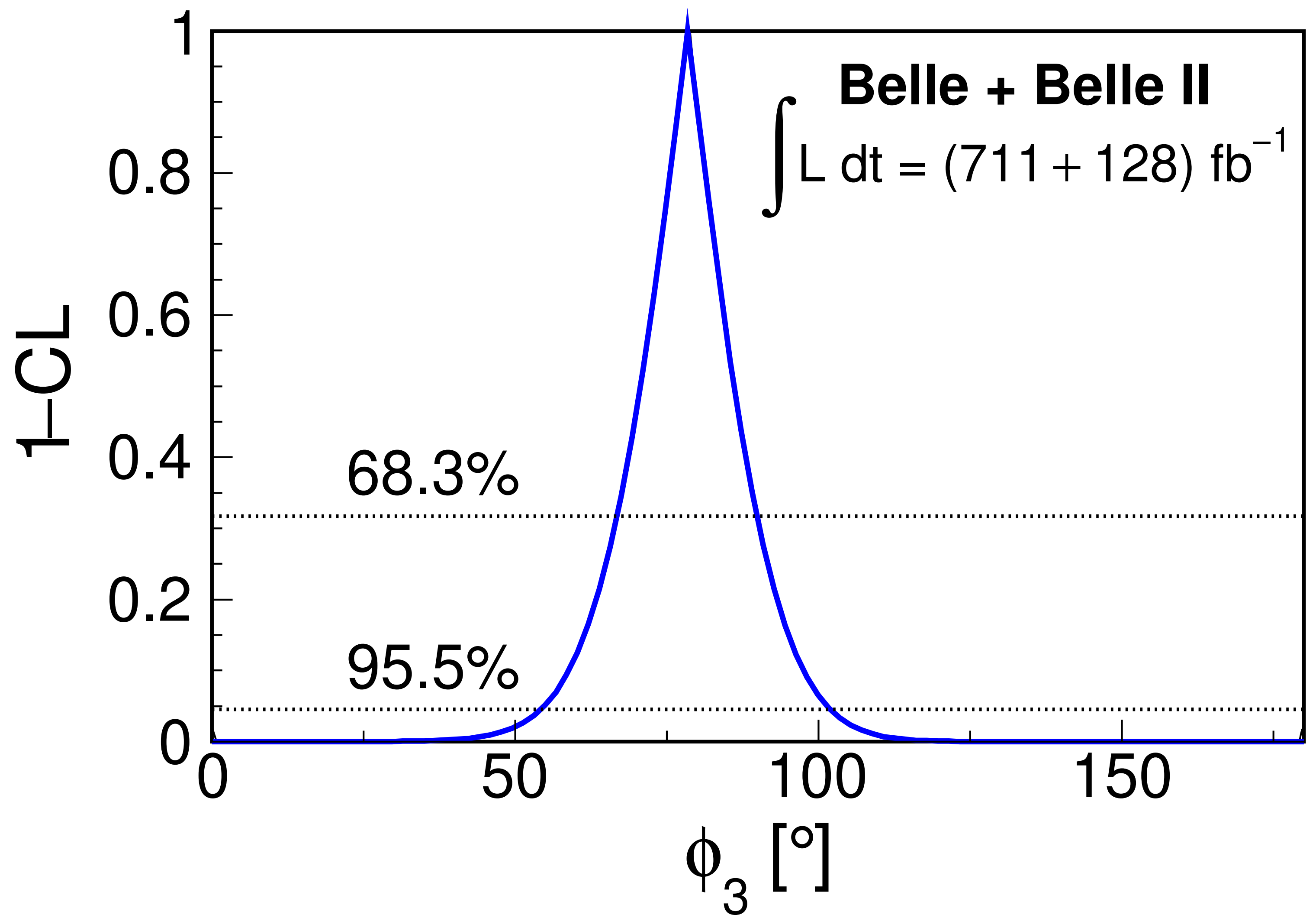
$B^+ \to D^0(K_S^0 h^+ h^-)h^+$

JHEP 02, 063 (2022)

- Improvement wrt previous Belle analysis (PRD85, 112014 (2012)):
  - NN-based MVA for K_S^0 reconstruction;
  - Increased statistics from $D \to K_S^0 K^+ K^-$, in addition to $D \to K_S^0 \pi^+ \pi^-$;
  - Improved background rejection method.

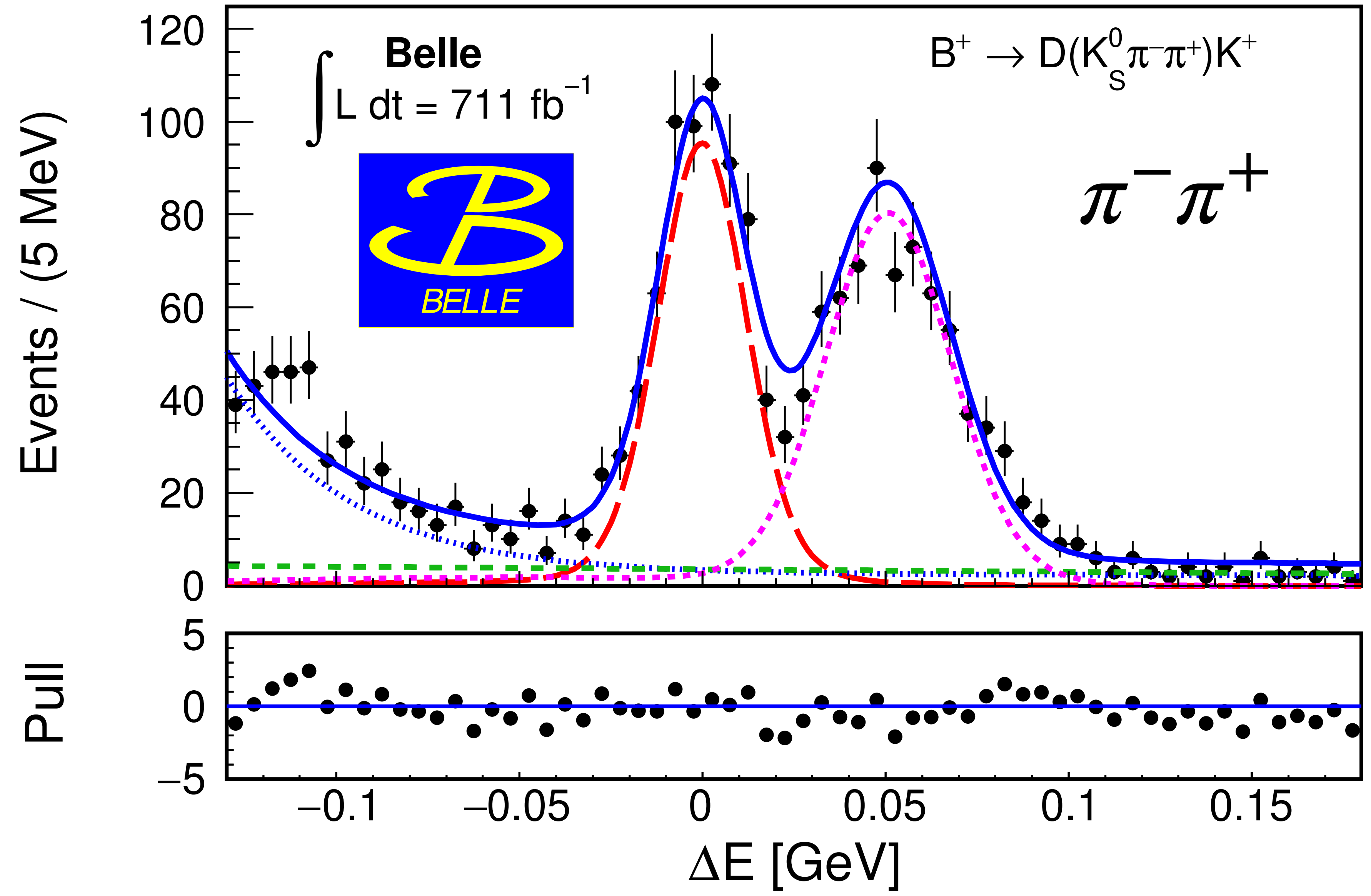
$$\phi_3 = (78.4 \pm 11.4(\text{stat}) \pm 0.5(\text{syst}) \pm 1.0(\text{ext}))^\circ$$

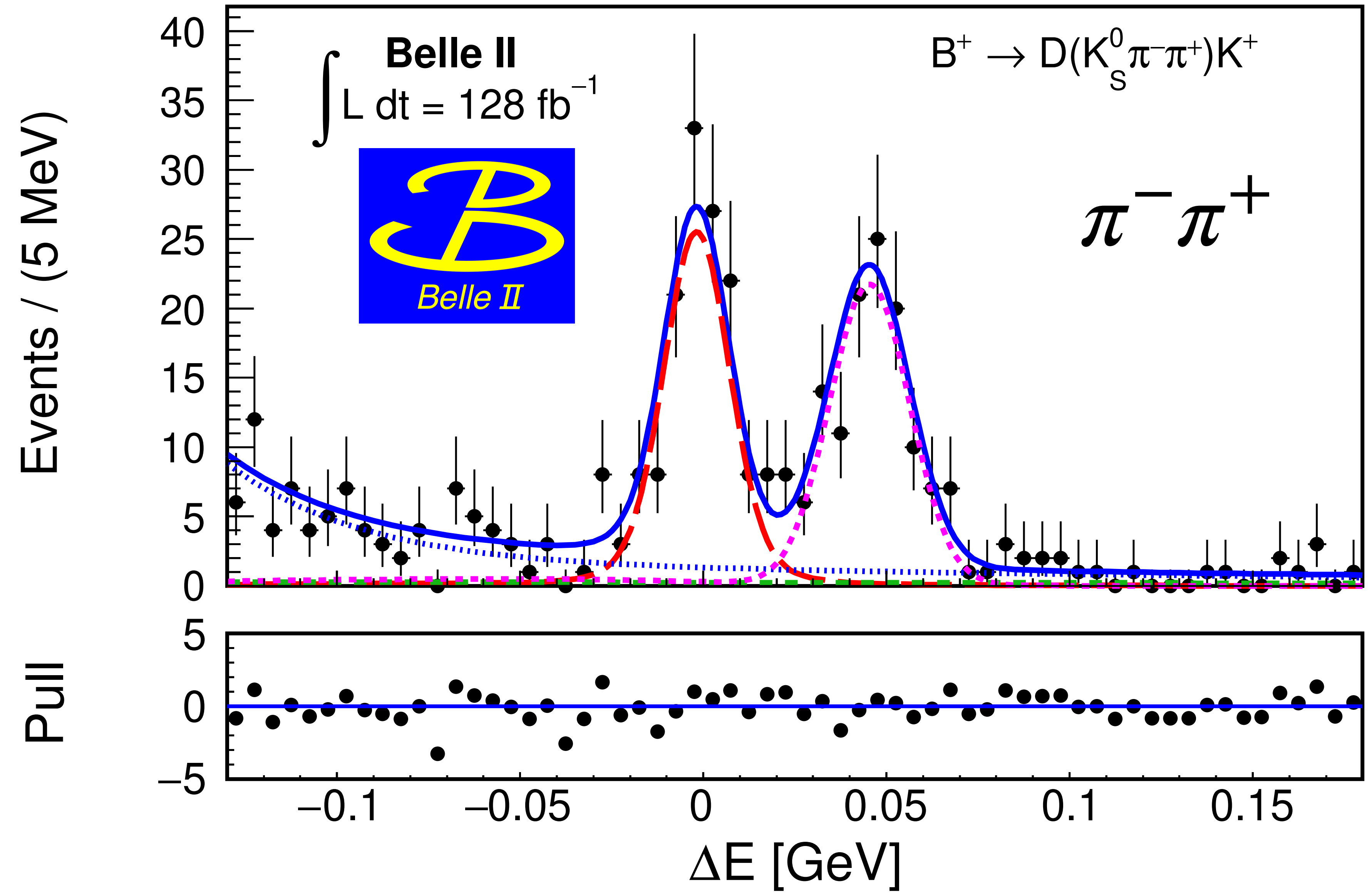
uncertainty in input from CLEO & BESIII



$$\phi_3^{HFLAV} = \left(65.9^{+3.3}_{-3.5}\right)^\circ$$

Yield increased by 40% (Belle) + additional 17% (Belle II)





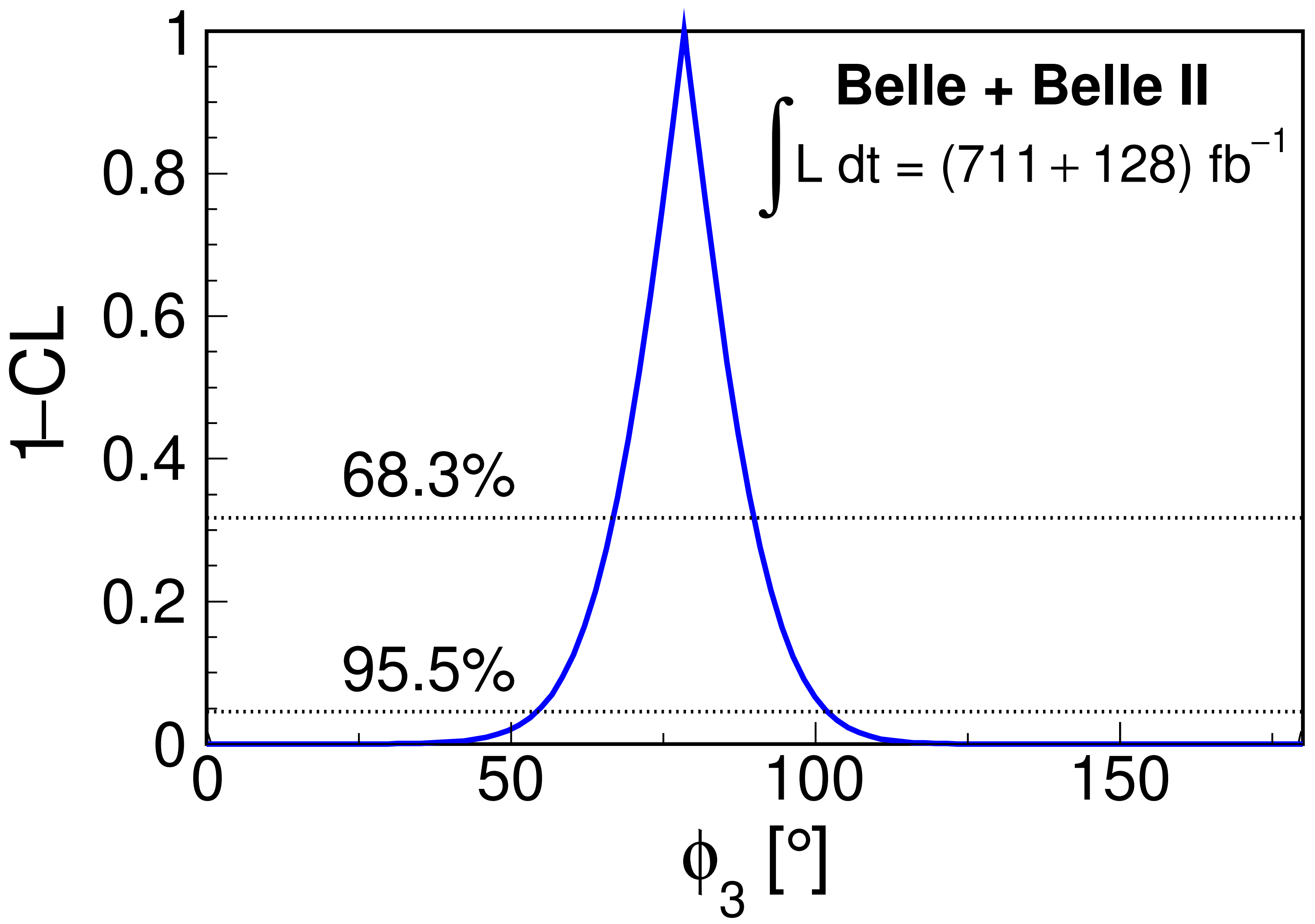
$B^+ \to D^0(K_S^0 h^+ h^-)h^+$

JHEP 02, 063 (2022)

- Improvement wrt previous Belle analysis (PRD85, 112014 (2012)):
  - NN-based MVA for K_S^0 reconstruction;
  - Increased statistics from $D \to K_S^0 K^+ K^-$, in addition to $D \to K_S^0 \pi^+ \pi^-$;
  - Improved background rejection method.

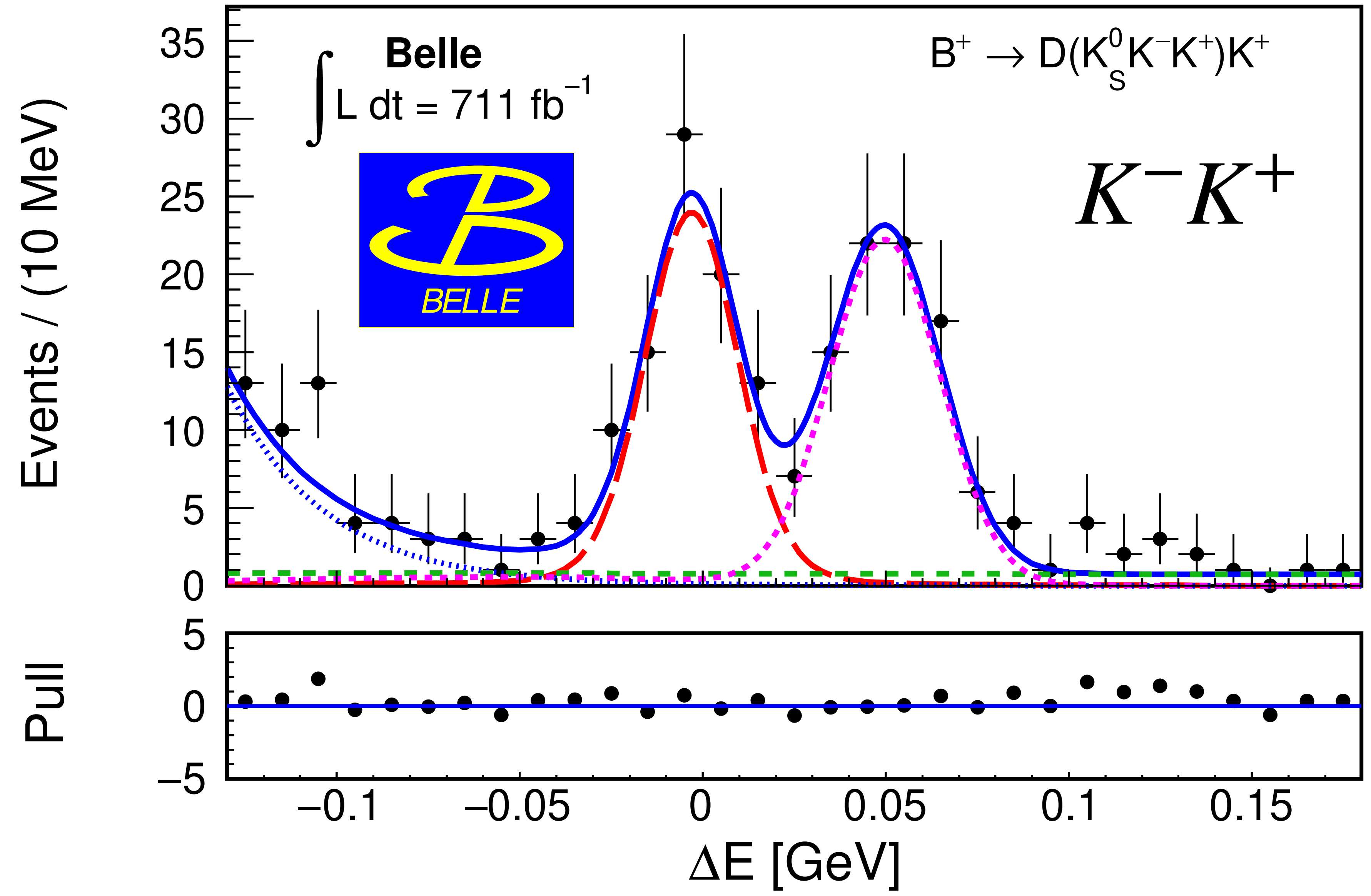
$$\phi_3 = (78.4 \pm 11.4(\text{stat}) \pm 0.5(\text{syst}) \pm 1.0(\text{ext}))^\circ$$

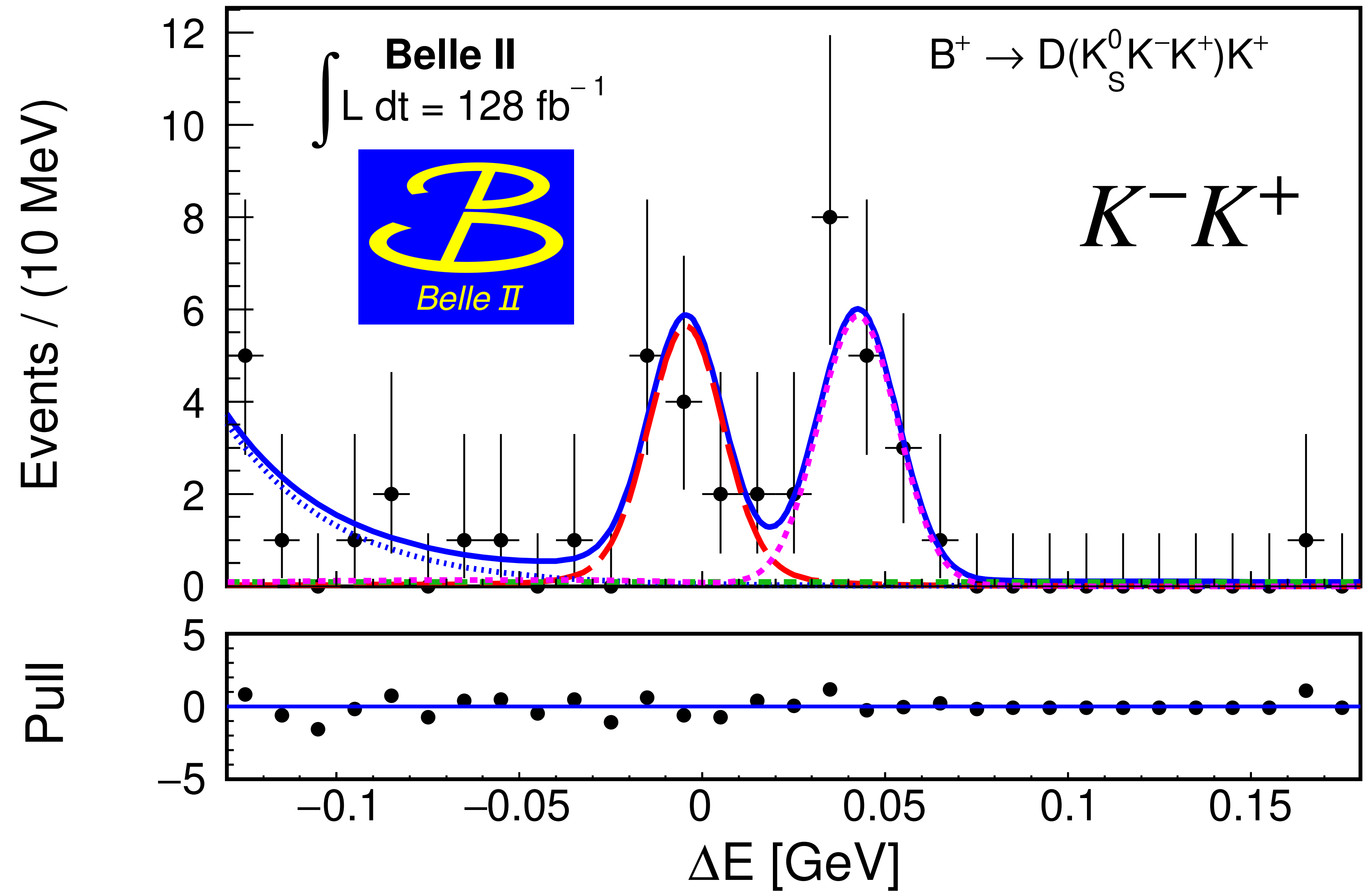
uncertainty in input from CLEO & BESIII



$$\phi_3^{HFLAV} = \left(65.9^{+3.3}_{-3.5}\right)^\circ$$

Yield increased by 40% (Belle) + additional 17% (Belle II)





Towards Belle II $I_{K\pi}$

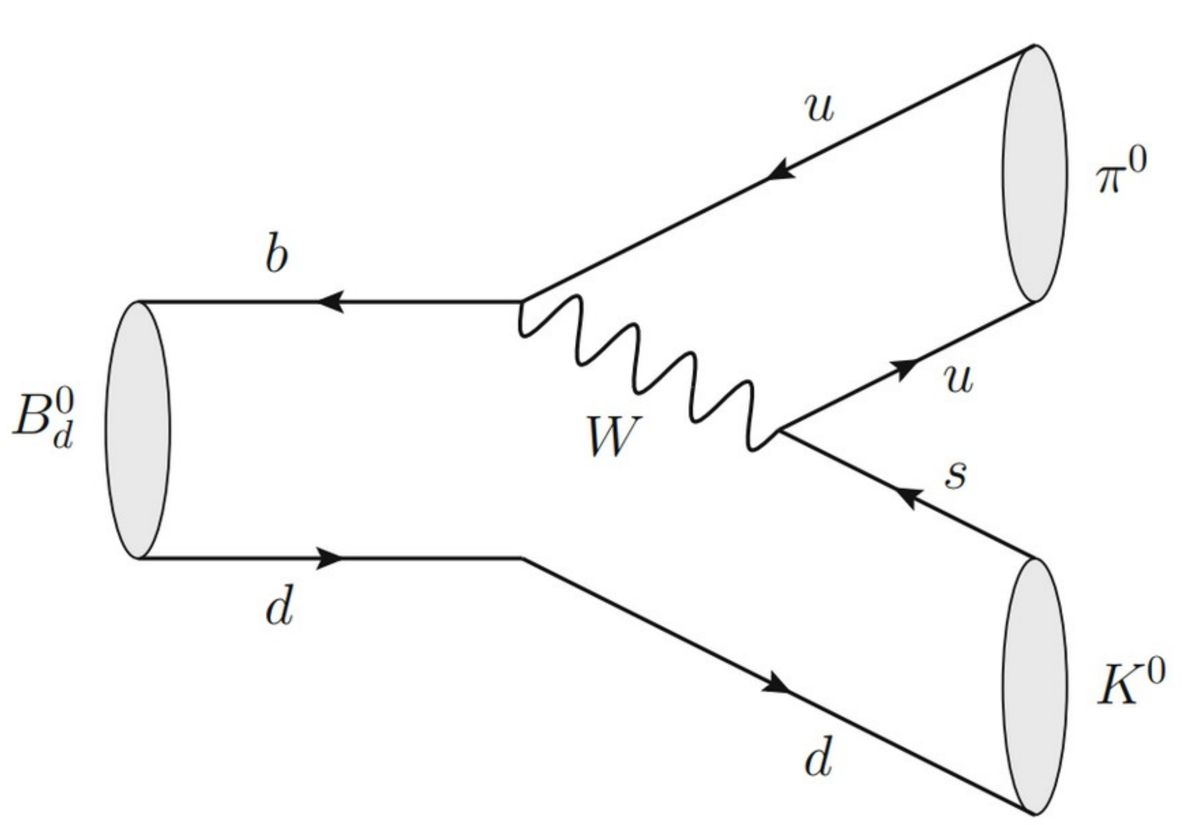
Asymmetry rule for NP nearly free of theoretical uncertainties, where the SM can be tested by measuring all observables: [PLB 627, 82(2005), PRD 58, 036005(1998)]

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

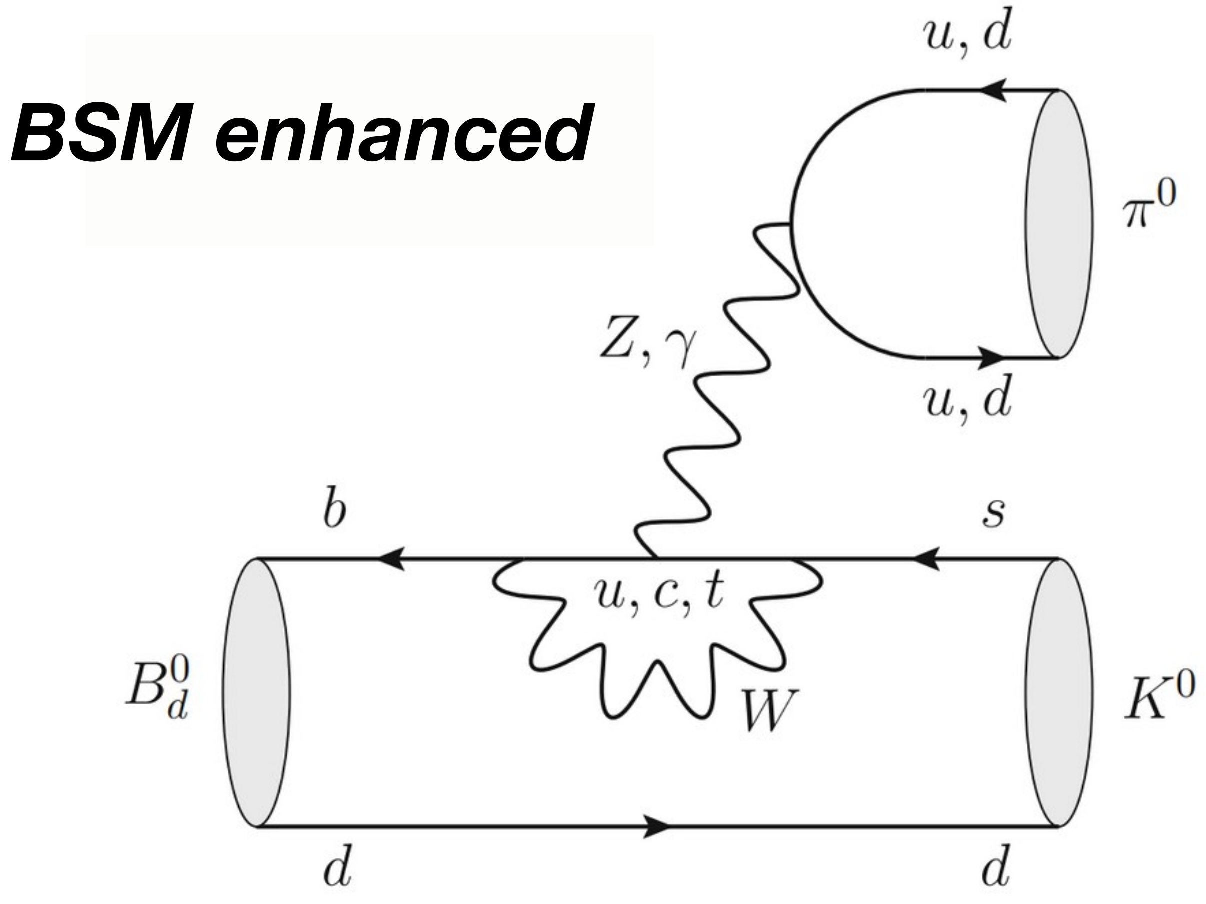
$$\left(I_{K\pi} = -0.0088^{+0.0016+0.0131}_{-0.0017-0.0091}\right)$$ [@NNLO] PLB 750(2015)348-355

$I_{K\pi}$ has a 10% experimental uncertainty dominated by $A_{CP}(K^0_S\pi^0)$

EPJC 78 (2018) 11, 943



Color-suppressed tree



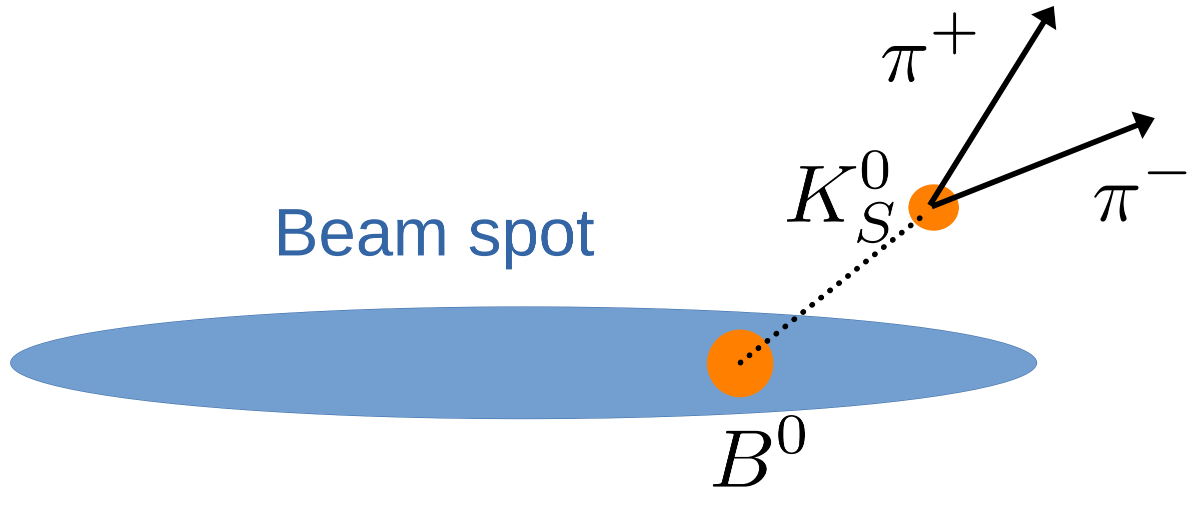
Color-allowed penguin

@Belle II:

- $B^0 \to K^0_S\pi^0$ arXiv:2206.07453
- $B^+ \to K^+\pi^0$ arXiv:2209.05154
- $B \to K^+\pi^-, K_S\pi^+$ arXiv:2106.03766

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

- Measurement is unique to Belle II.
- Main challenge: *Decay vertex resolution from* $K_S^0 \to \pi^+\pi^-$ *and IP constraint.*



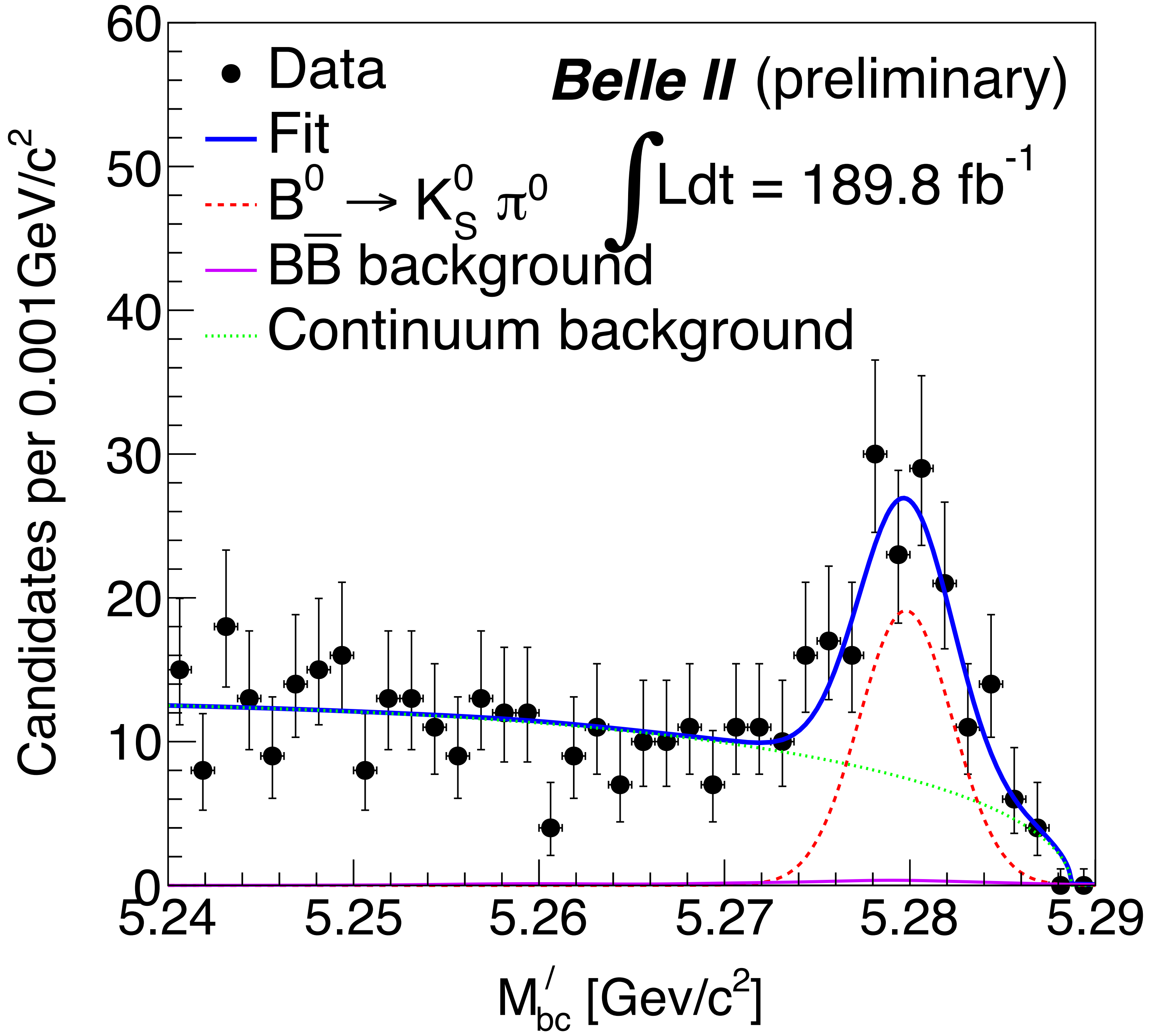
- Control channel: $B^0 \to J/\psi K_S^0$ (with J/ψ excluded for vertexing).
- Time-dependent CPV fit to M_{bc}, ΔE, Δt and $\mathrm{BDT}_{\mathrm{Cont.Supp.}}$, with S_{CP}, Δm_d, and τ_{B^0} fixed.

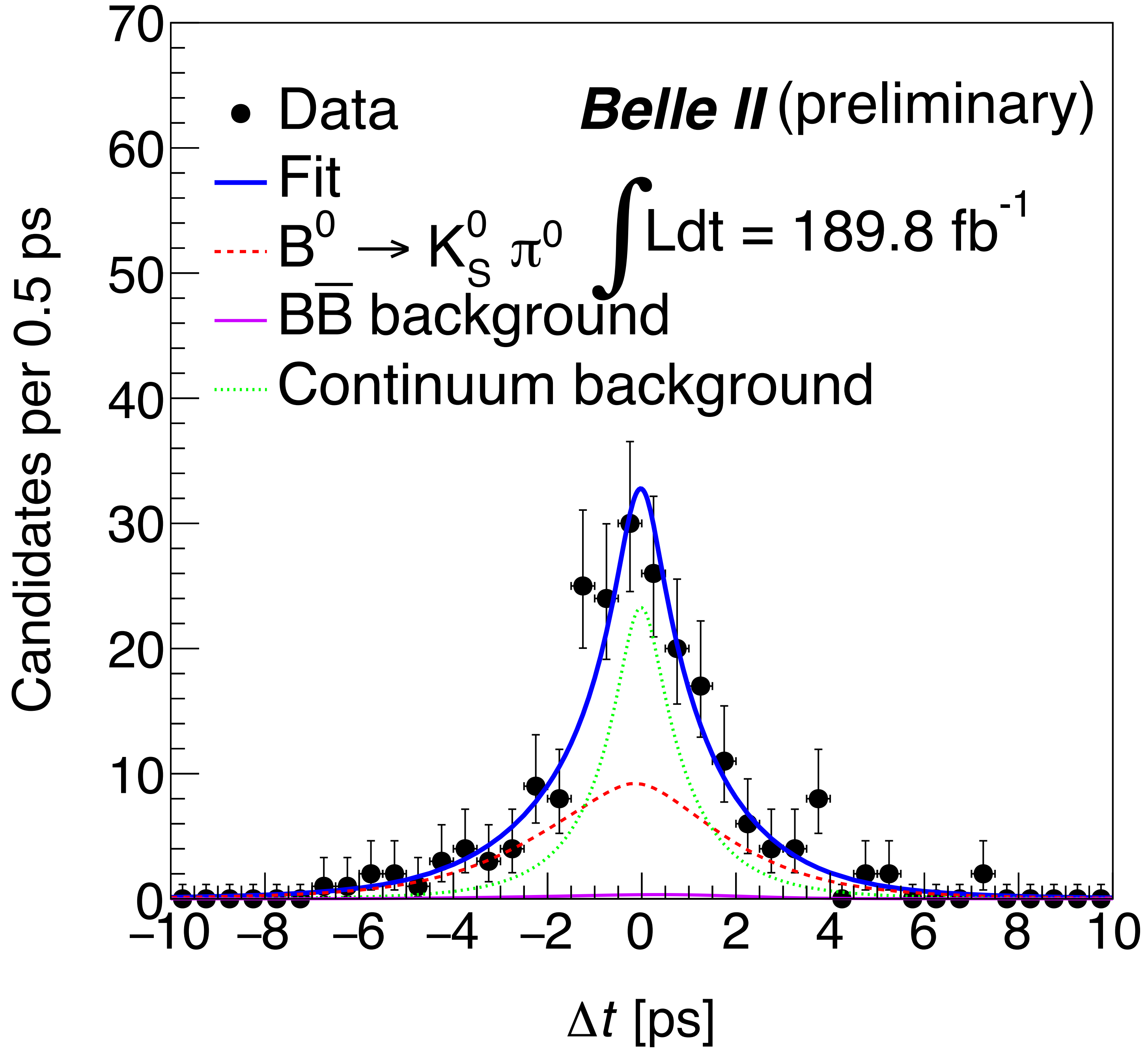
$$\mathcal{B}(B^0 \to K^0\pi^0) = [11.0 \pm 1.2(\mathrm{stat}) \pm 1.0(\mathrm{syst})] \times 10^{-6}$$

$$\mathcal{A}_{CP} = -0.41^{+0.30}_{-0.32}(\mathrm{stat}) \pm 0.09(\mathrm{syst})$$

From isospin
$A_{CP} = -0.14 \pm 0.03$

arXiv:2206.07453



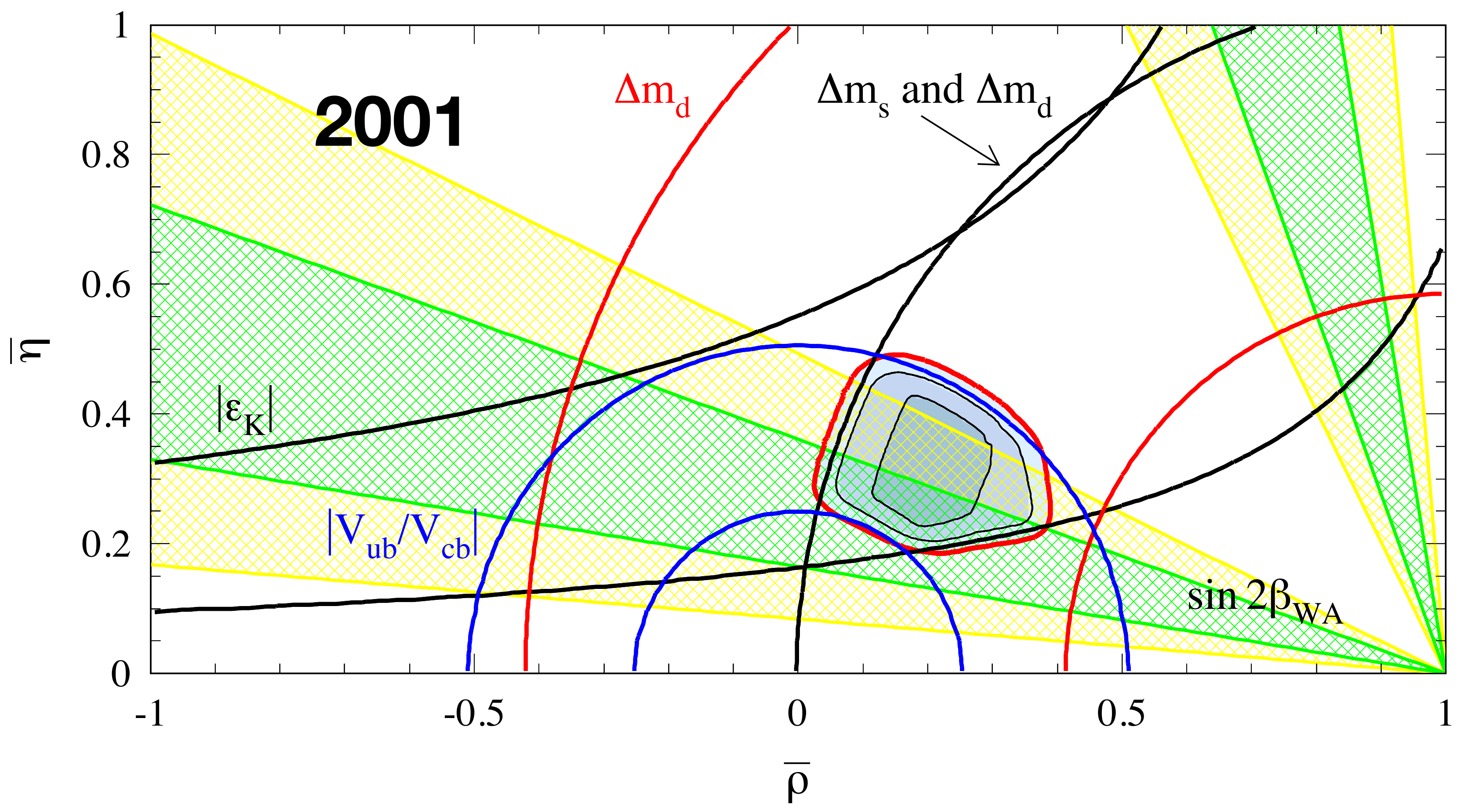


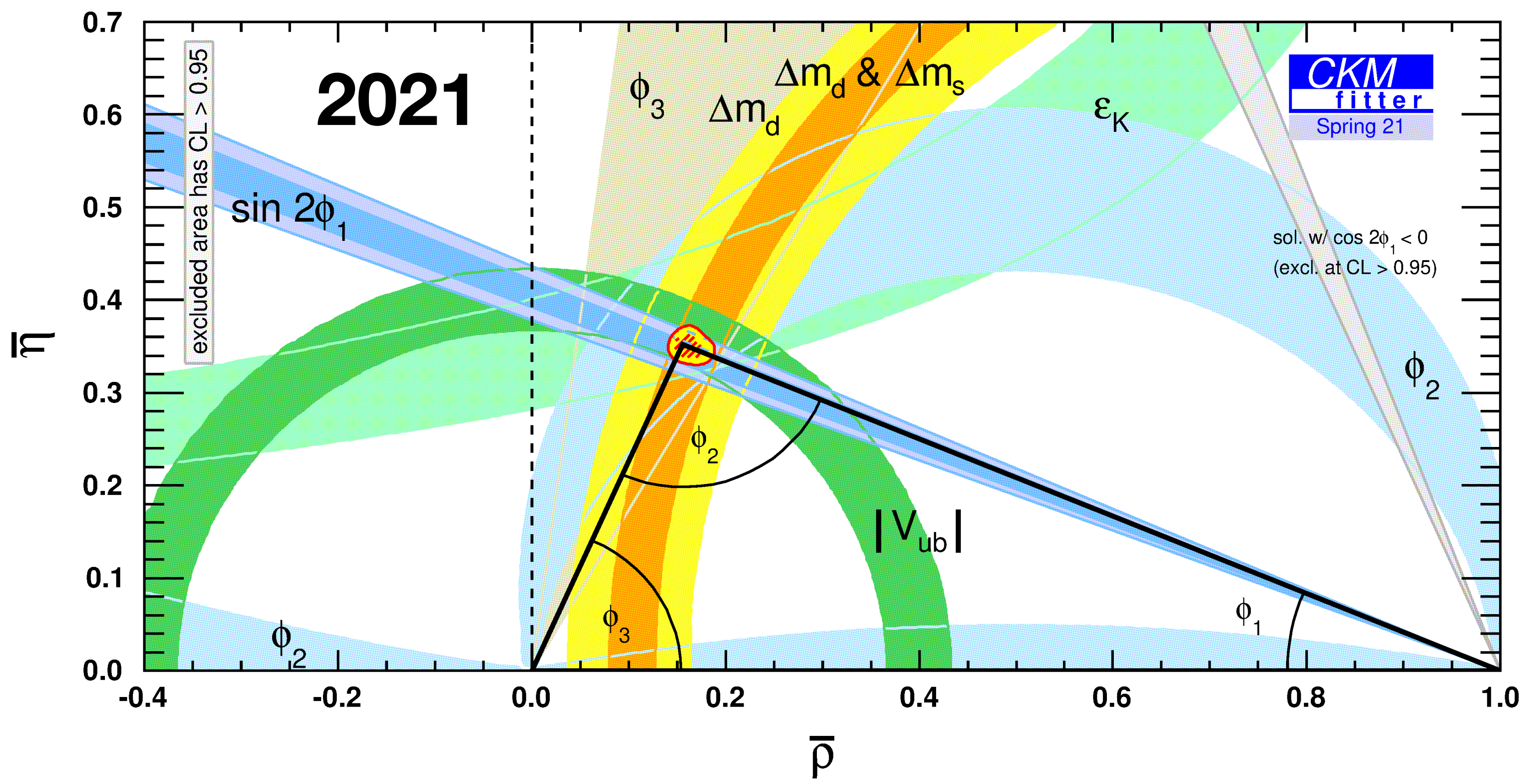
Outlook

- Robust program to measure all angles of the Unitarity Triangle.
- Moving towards penguin decays (ϕK_S^0, $\eta' K_S^0$, ...) after measuring the golden mode.
- Exploiting the full potential of Belle + Belle II analyses.

arXiv:2207.06307, arXiv:2203.11349 (Snowmass)

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





Potential for Belle II to go much further with large dataset with well-controlled kinematics and backgrounds