Recent results of Belle II

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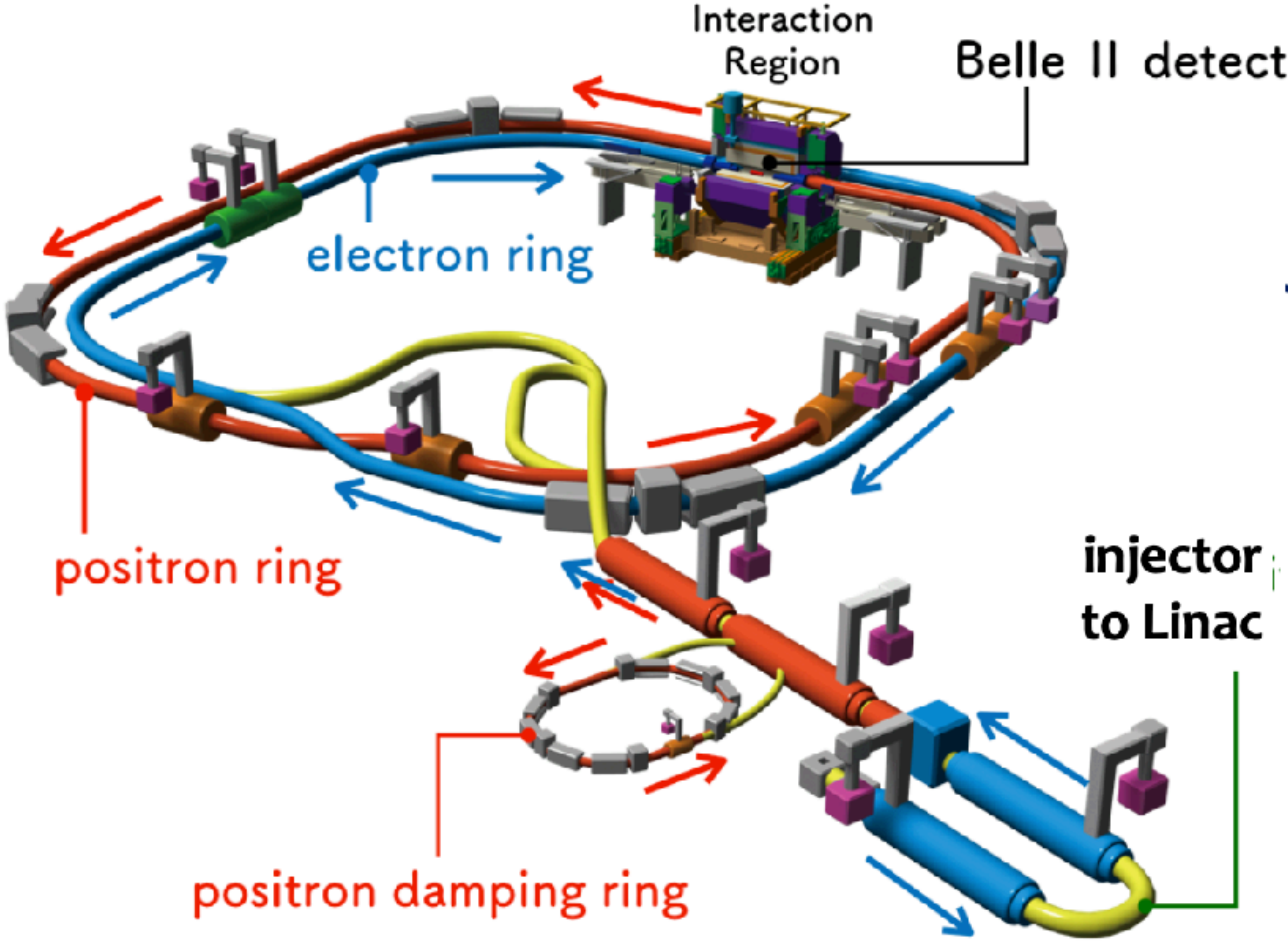
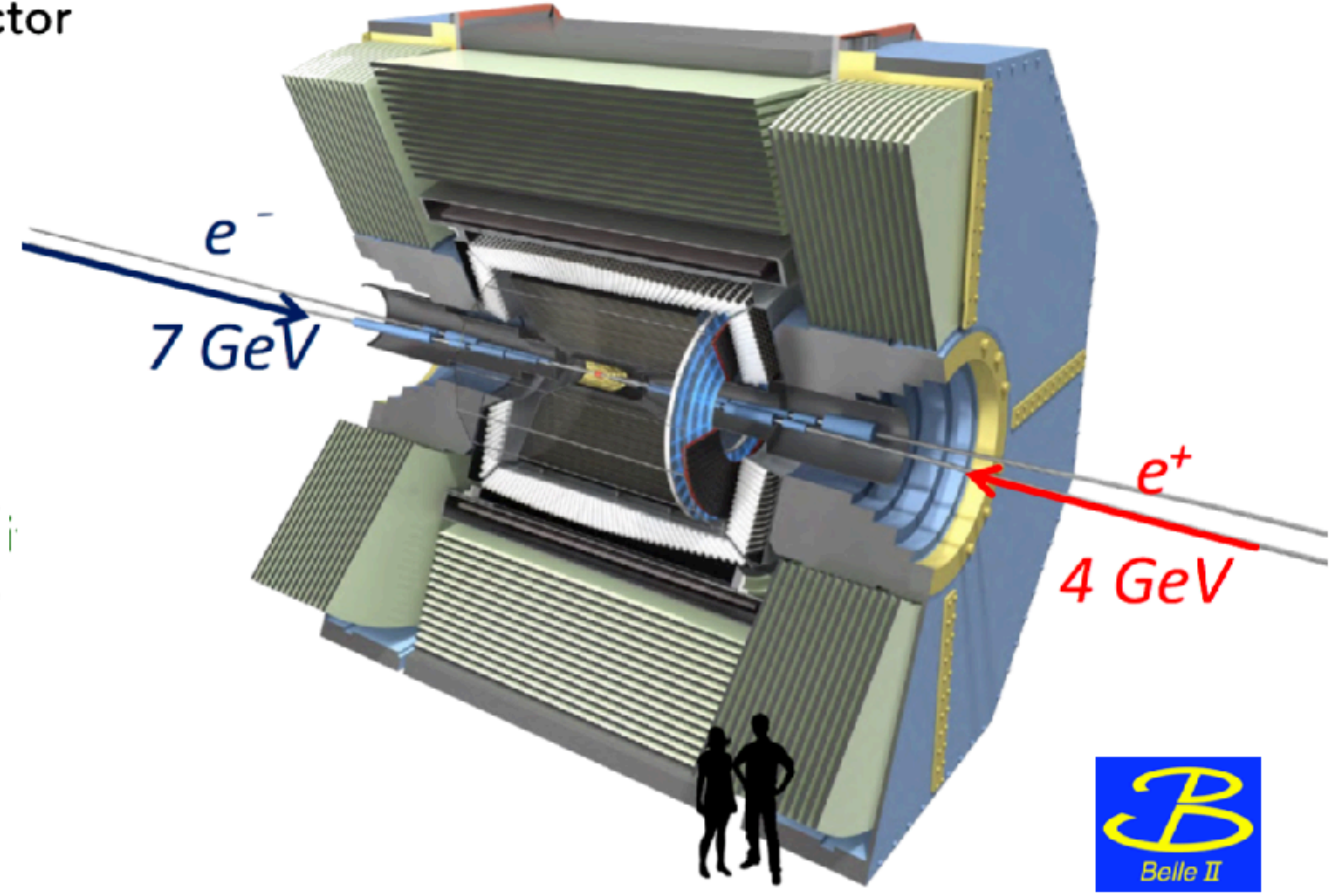
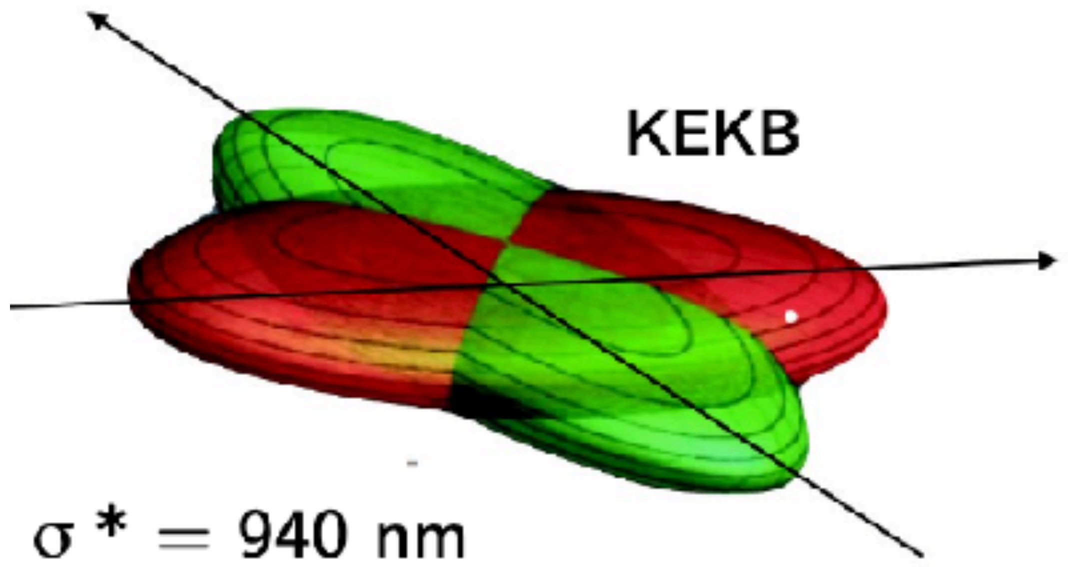
SuperKEKB $e^- \xrightarrow{7\text{ GeV}} (\star) \xleftarrow{4\text{ GeV}} e^+$ Belle II



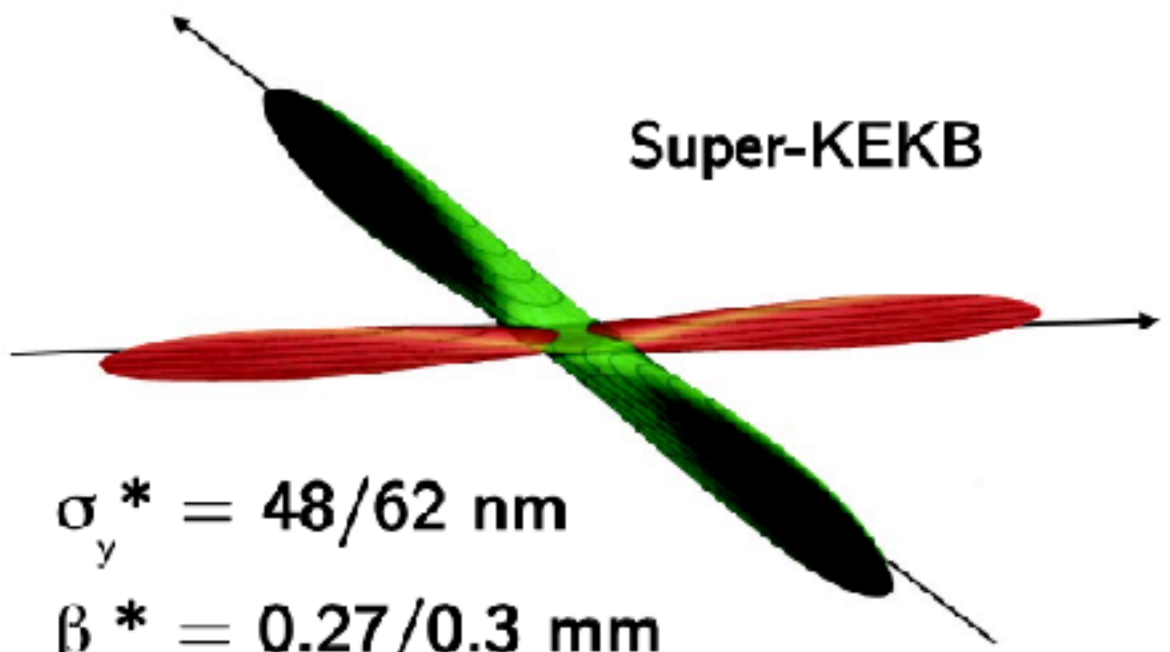




$\sigma_y^* = 940$ nm

$\beta_y^* = 5.9$ mm

$\sigma_x^* = 147/170$ µm



$\sigma_y^* = 48/62$ nm

$\beta_y^* = 0.27/0.3$ mm

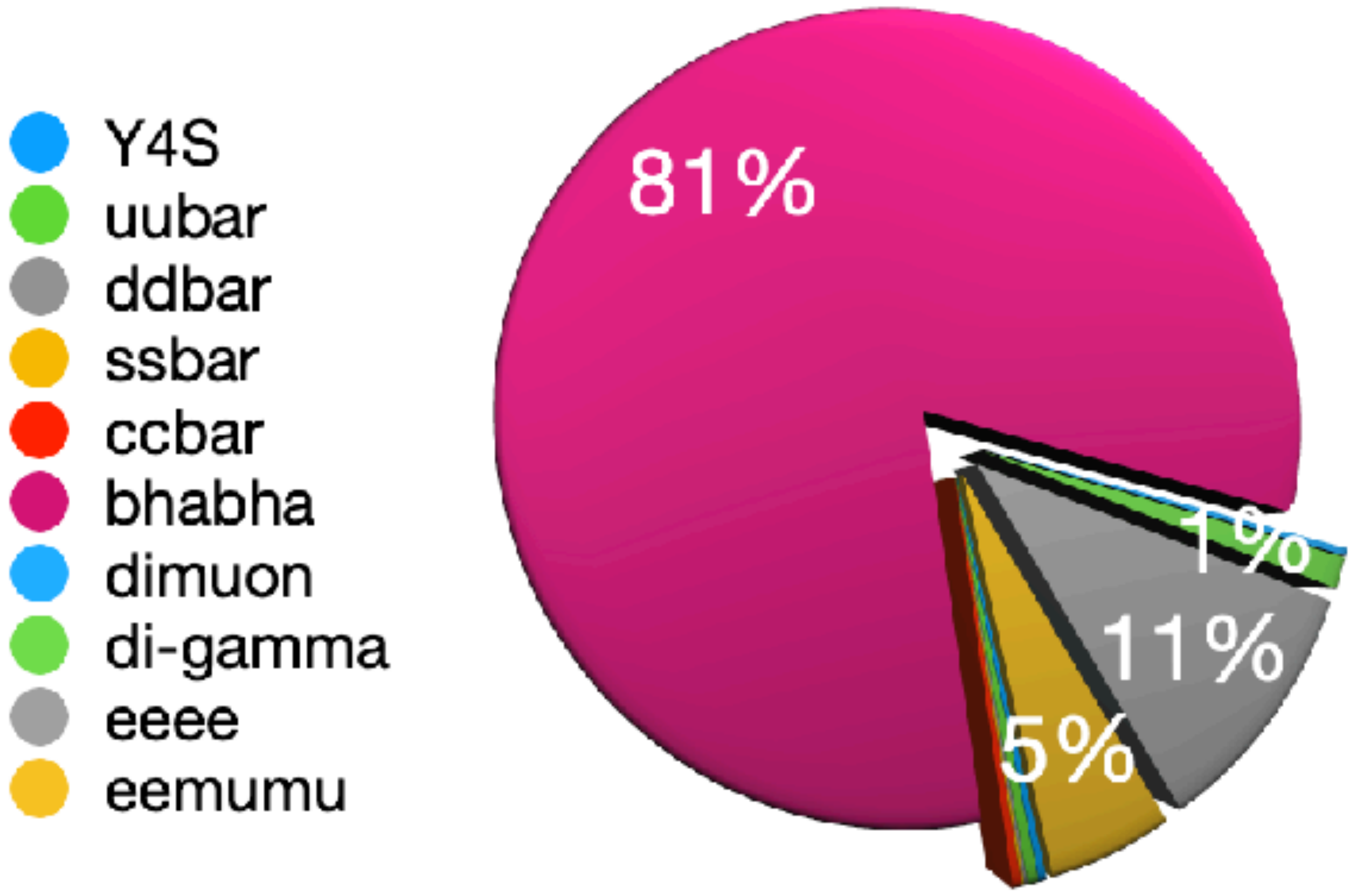
$\sigma_x^* = 10.1/10.7$ µm

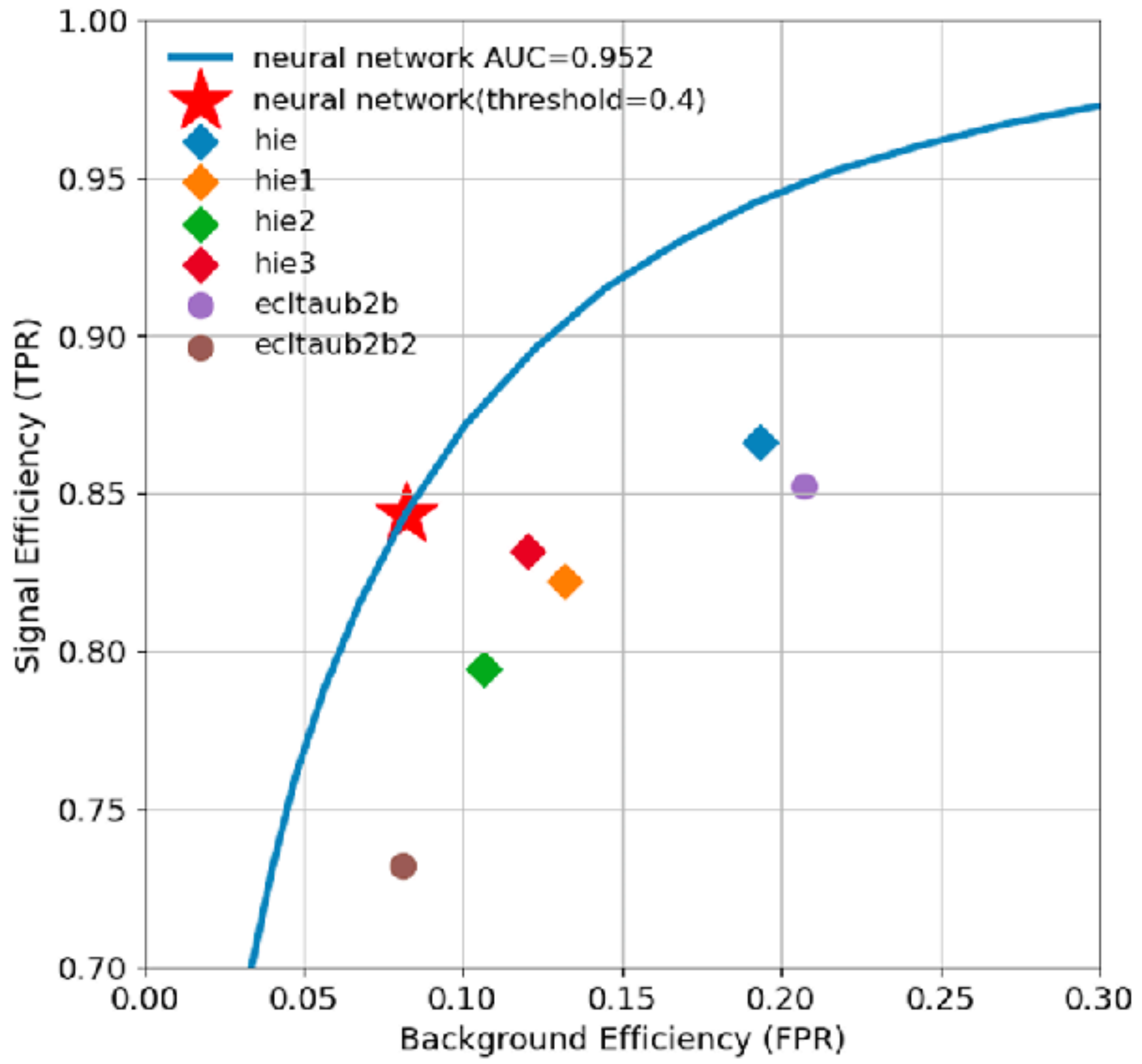
$$\mathcal{L}_{\mathrm{II}}^{\mathrm{peak}} \approx 30 \times \mathcal{L}_{\mathrm{I}}^{\mathrm{peak}}$$

$$\int^{\mathrm{goal}} \mathcal{L}_{\mathrm{II}}\, dt = 50\ \mathrm{ab}^{-1} \approx 50 \int \mathcal{L}_{\mathrm{I}}\, dt$$

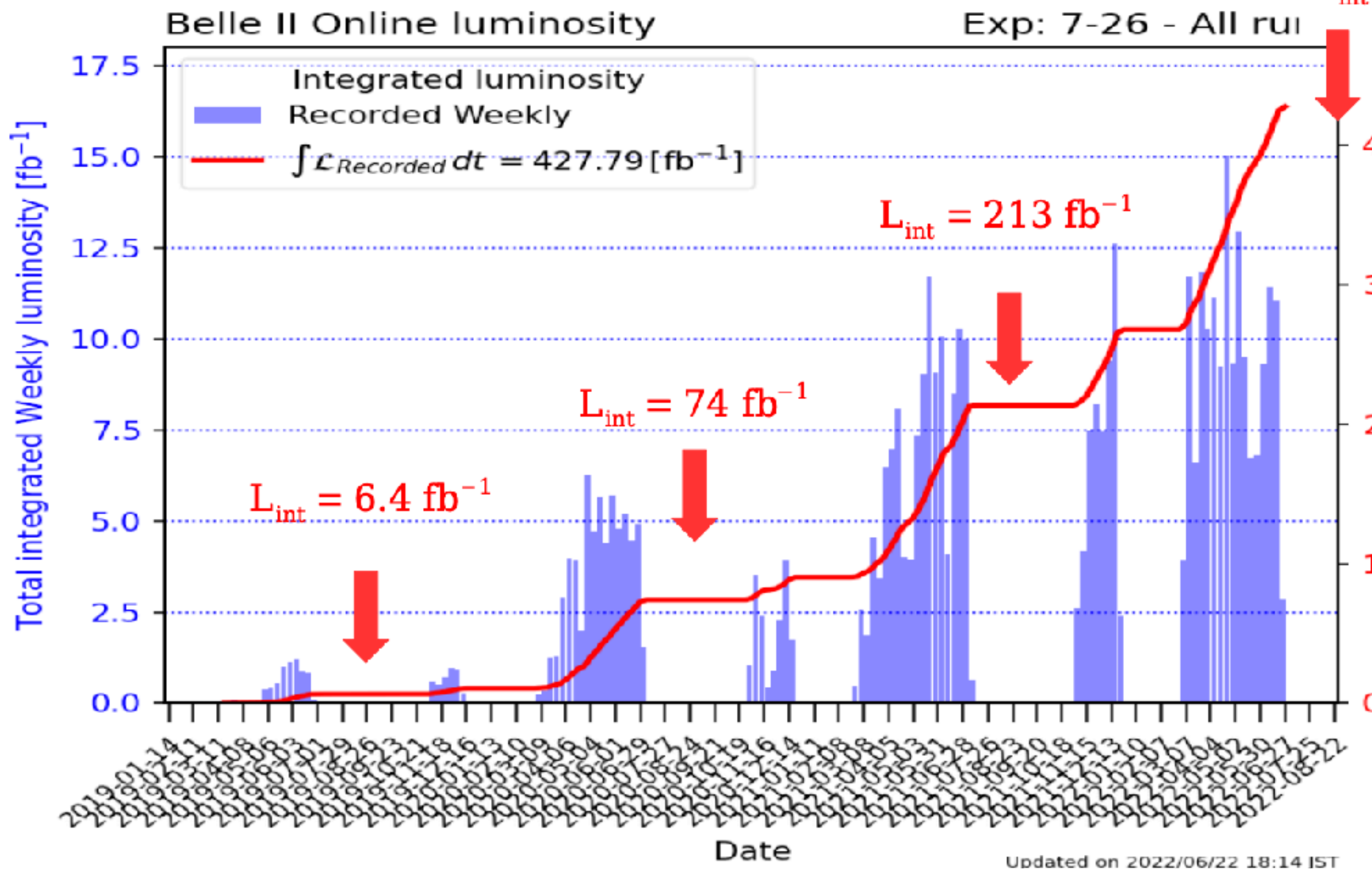
Trigger Challenges

- High luminosity, high background
  - Total physics trigger rate: 15 kHz @ $8.0 \times 10^{35}/cm^2/s$ (designed)
  - Large beam-related; QED background, ***Huge*** bhabha
- Two levels of triggers
  - Hardware trigger — Level 1 trigger
  - Software trigger — High level trigger
- Predefined selections to various physics processes
  - $\Upsilon(4S)$ + continuum, ~100% efficiency
  - Individual designed for low multiplicity process
    - Selection criteria, *i.e.* $E_{ECL} > 2.0$ GeV for ISR processes
    - Neural network based, *i.e.* $e^+e^- \to \tau^+\tau^-$





Belle II RUN-I (2019-2022)



$5 \times 10^{34}/\text{cm}^2/\text{s}$
~ 1 BaBar/year

- (364 ± 2) fb^{-1} $\Upsilon(4S)$ on resonance data
- (42.6 ± 0.3) fb^{-1} $\Upsilon(4S)$ off resonance data
- (19.7 ± 0.1) fb^{-1} $\Upsilon(10753)$ scan data

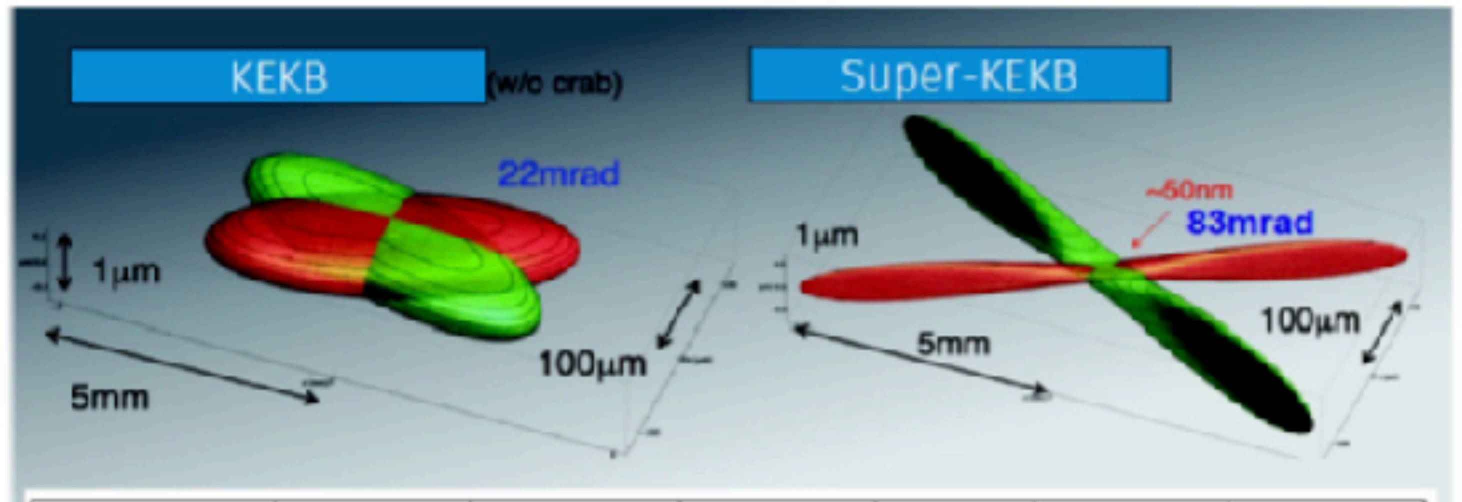
luminosity: $4.7 \times 10^{34}/\text{cm}^2/\text{s}$! > 2 fb^{-1} per day !

June, 2022

06/07 23:59:36 - 06/08 23:59:36, 2022 JST

$\mathcal{L}_{peak}$	4.653 $\times 10^{34}$ cm^{-2}s^{-1} @ 22:58:08 06/08	HER I_{peak}	1127	mA	n_b	2249	β^*_x / β^*_y	60	/ 1	mm
int. $\mathcal{L}$/day	1253 / 1681 pb^{-1}	LER I_{peak}	1405	mA	n_b	2249	β^*_x / β^*_y	80	/ 1	mm

record of KEKB/Belle
$2 \times 10^{34}/\text{cm}^2/\text{s}$; currents > 1 A
record of PEPII/BaBar
$1 \times 10^{34}/\text{cm}^2/\text{s}$; currents > 2 A



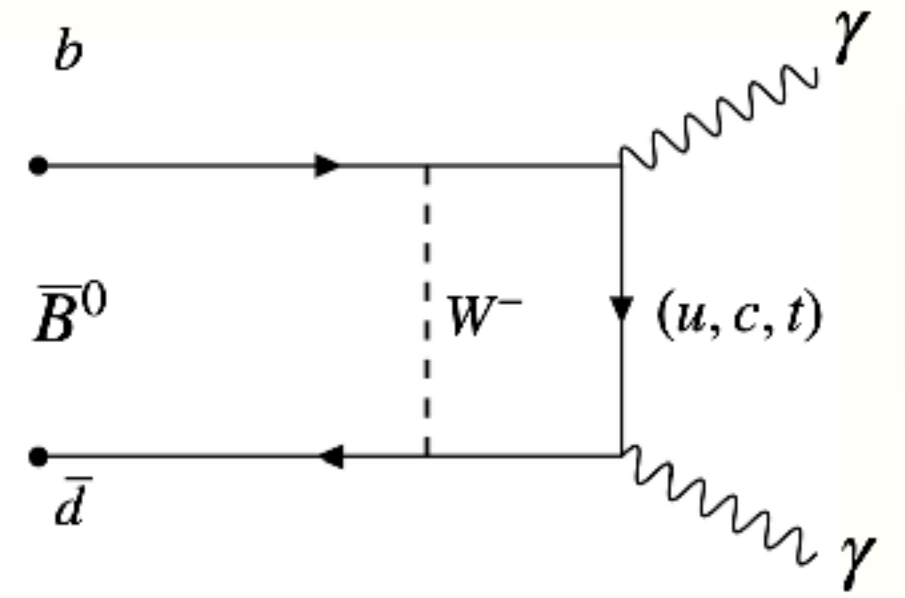
	E (GeV) LER/HER	β^*_y (mm) LER/HER	β^*_x (cm) LER/HER	φ (mrad)	I (A) LER/HER	L (cm^{-2}s^{-1})
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1 x 10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80 x 10^{34}

factor 20   factor 2-3

squeezing further β^*_y (→ 0.6 mm)
doubling (or more) the currents
⇒ L > $10^{35}/\text{cm}^2/\text{s}$ after LS1

Search for $B \to \gamma\gamma$

Belle + Belle II, Preliminary



Very rare in SM with $\mathscr{B}(B \to \gamma\gamma) = (1.4^{+1.4}_{-1.8}) \times 10^{-8}$ *(Y. L. Shen, et. al, JHEP12, 169(2020))*

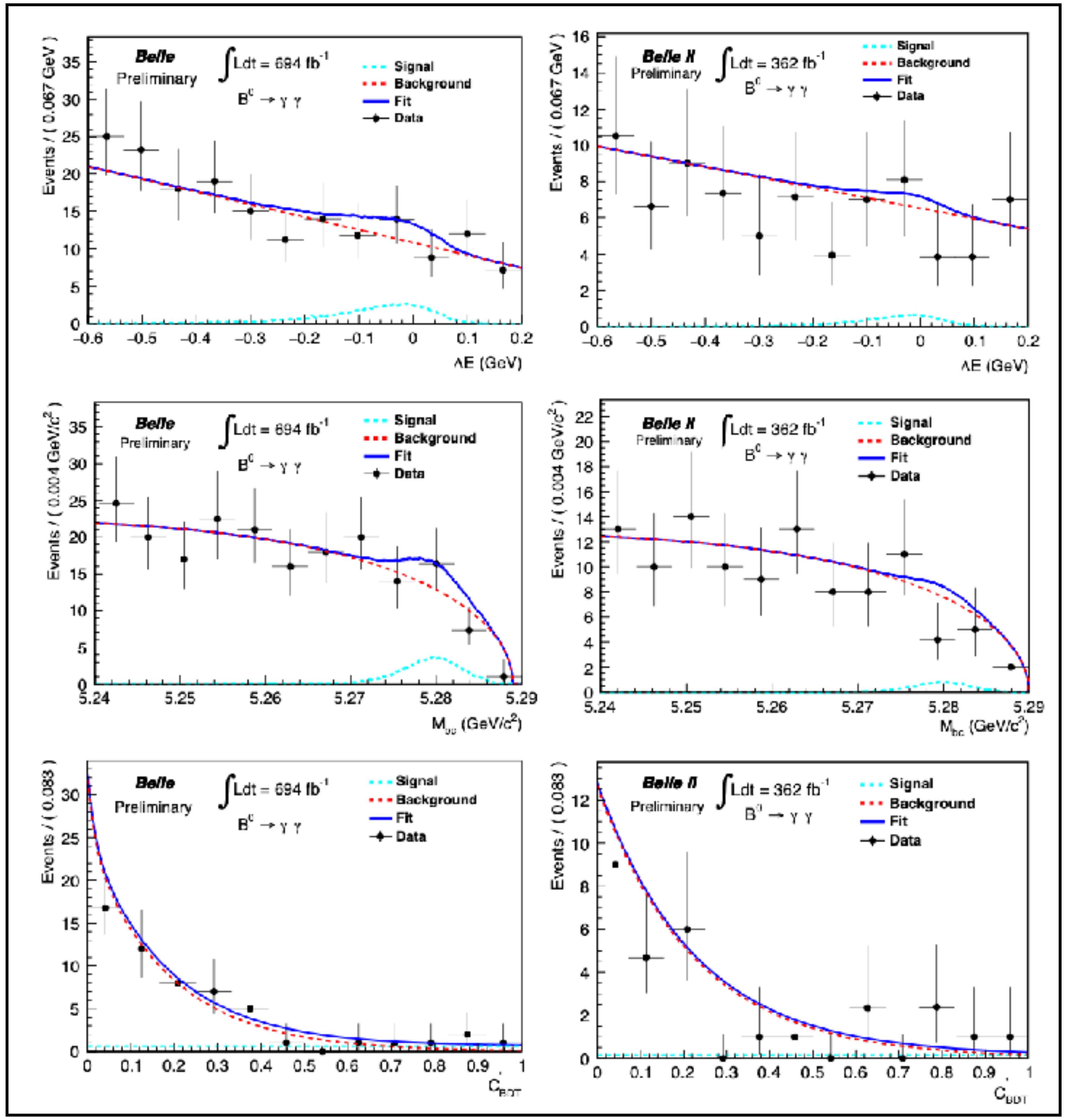
Previous searches	Limits
L3 (73 pb^{-1})	$< 3.9 \times 10^{-5}$
Belle (104 fb^{-1})	$< 6.2 \times 10^{-7}$
BaBar (426 fb^{-1})	$< 3.2 \times 10^{-7}$

Big challenge due to large background.

- Simultaneous 3D fit to M_{bc}, ΔE, and C'_{BDT}.
- Combined signal yield: $11.0^{+6.48}_{-5.48}$ with significance of 2.5σ

	$\mathcal{B}(B^0 \to \gamma\gamma)$	$\mathcal{B}(B^0 \to \gamma\gamma)$ (at 90% CL)
Belle	$(5.4^{+3.3}_{-2.6} \pm 0.5) \times 10^{-8}$	$< 9.9 \times 10^{-8}$
Belle II	$(1.7^{+3.7}_{-2.4} \pm 0.3) \times 10^{-8}$	$< 7.4 \times 10^{-8}$
Combined	$(3.7^{+2.2}_{-1.8} \pm 0.7) \times 10^{-8}$	$< 6.4 \times 10^{-8}$

× 5 improvement over previous best UL.



CP and isospin asymmetries in $B \to \rho\gamma$

Belle + Belle II, Preliminary

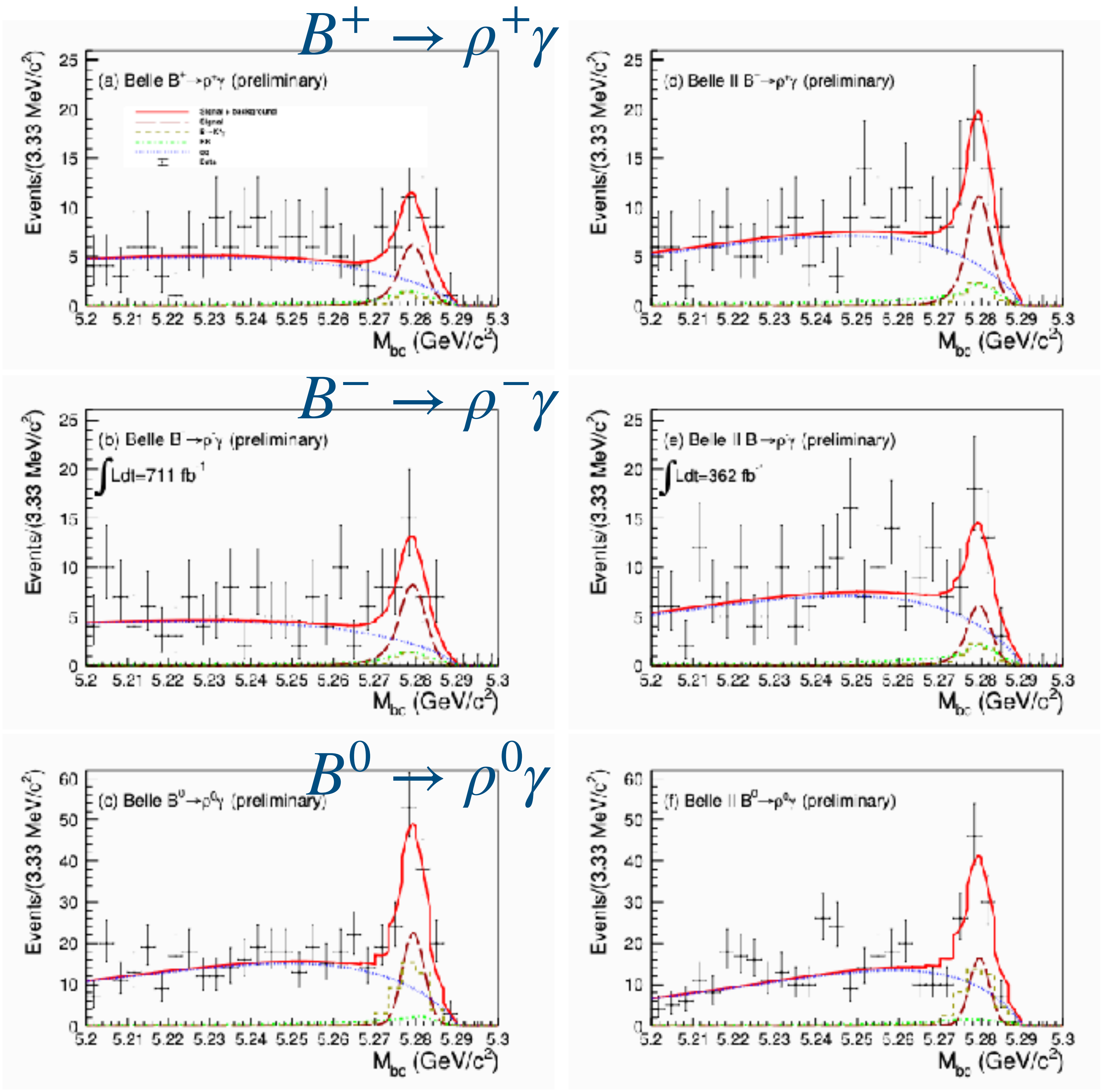
- Clean environment to search for BSM physics
- SM expect CP-average isospin asymmetry as $\bar{A}_{\mathrm{I}}^{\mathrm{SM}} = (5.2 \pm 2.8)\,\%$

$$A_{\mathrm{I}} = (A_{\mathrm{I}}^{\bar{0}-} + A_{\mathrm{I}}^{0+})/2, \text{ with } A_{\mathrm{I}}^{\bar{0}-} = \frac{c_\rho^2\Gamma(\bar{B}^0 \to \rho^0\gamma) - \Gamma(B^- \to \rho^-\gamma)}{c_\rho^2\Gamma(\bar{B}^0 \to \rho^0\gamma) + \Gamma(B^- \to \rho^-\gamma}$$

- Current world average $A_{\mathrm{I}}^{\mathrm{exp}} = (30^{+16}_{-13})\,\%$.

$$\mathcal{B}\left(B^+ \to \rho^+\gamma\right) = \left(12.85^{+2.02+1.38}_{-1.92-1.13}\right) \times 10^{-7},$$
$$\mathcal{B}\left(B^0 \to \rho^0\gamma\right) = \left(7.45^{+1.33+0.97}_{-1.27-0.79}\right) \times 10^{-7},$$
$$A_{\mathrm{CP}}\left(B^+ \to \rho^+\gamma\right) = \left(-7.1^{+15.3+1.4}_{-15.2-1.3}\right)\%,$$
$$A_{\mathrm{I}}\left(B \to \rho\gamma\right) = \left(14.2^{+11.0+6.6+6.0}_{-11.7-6.4-6.5}\right)\%,$$

- *Consistent with the SM prediction.*
- *Highest precision to date; supersede the previous measurements from Belle*



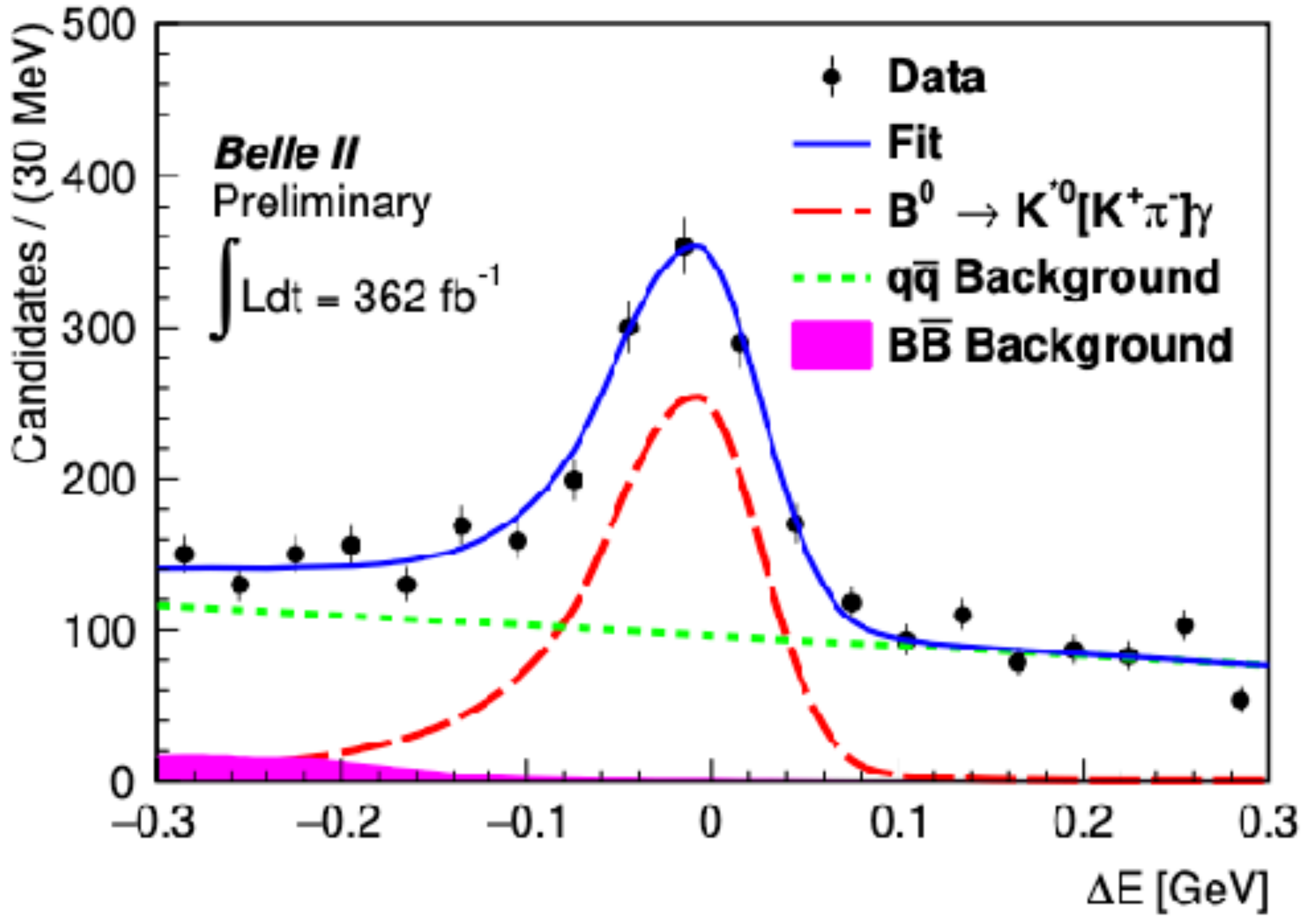
Measurement of $B \to K^*\gamma$

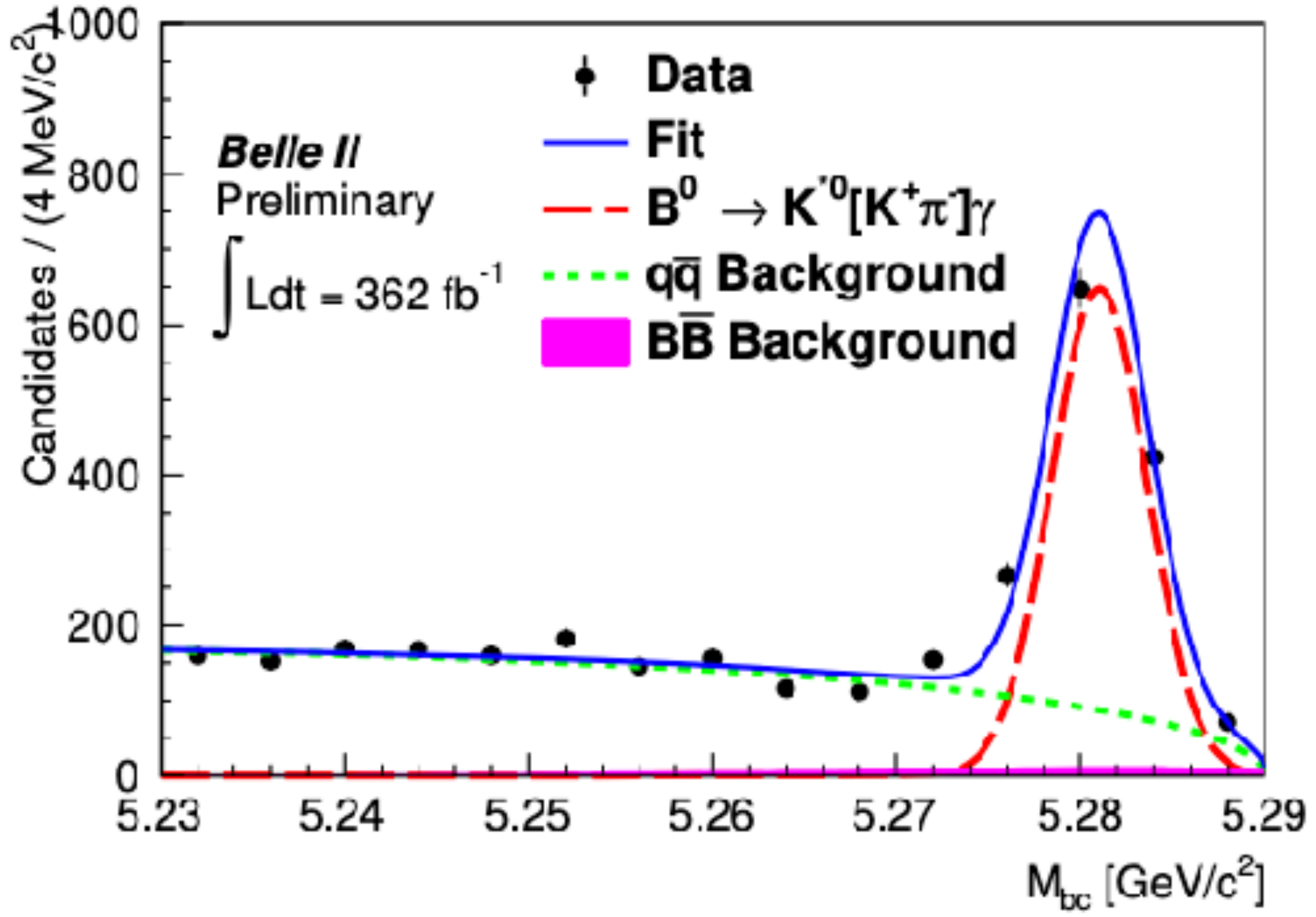
Belle II, Preliminary

$$\mathcal{A}_{CP} = \frac{\Gamma(\overline{B} \to \overline{K}^*\gamma) - \Gamma(B \to K^*\gamma)}{\Gamma(\overline{B} \to \overline{K}^*\gamma) + \Gamma(B \to K^*\gamma)}$$

$$\Delta_{0+} = \frac{\Gamma(B^0 \to K^{*0}\gamma) - \Gamma(B^+ \to K^{*+}\gamma)}{\Gamma(B^0 \to K^{*0}\gamma) + \Gamma(B^+ \to K^{*+}\gamma)},$$

- CP and isospin asymmetries are theoretically clean to cancellation of form factor uncertainties.
- Sensitive to NP.
- Simultaneous fit to M_{bc} and ΔE for different modes





Results:

$$\mathcal{B}[B^0 \to K^{*0}\gamma] = (4.16 \pm 0.10 \pm 0.11) \times 10^{-5},$$

$$\mathcal{B}[B^+ \to K^{*+}\gamma] = (4.04 \pm 0.13 \pm 0.13) \times 10^{-5},$$

$$\mathcal{A}_{CP}[B^0 \to K^{*0}\gamma] = (-3.2 \pm 2.4 \pm 0.4)\%,$$

$$\mathcal{A}_{CP}[B^+ \to K^{*+}\gamma] = (-1.0 \pm 3.0 \pm 0.6)\%,$$

$$\Delta\mathcal{A}_{CP} = (2.2 \pm 3.8 \pm 0.7)\%, \text{ and}$$

$$\Delta_{0+} = (5.1 \pm 2.0 \pm 1.5)\%,$$

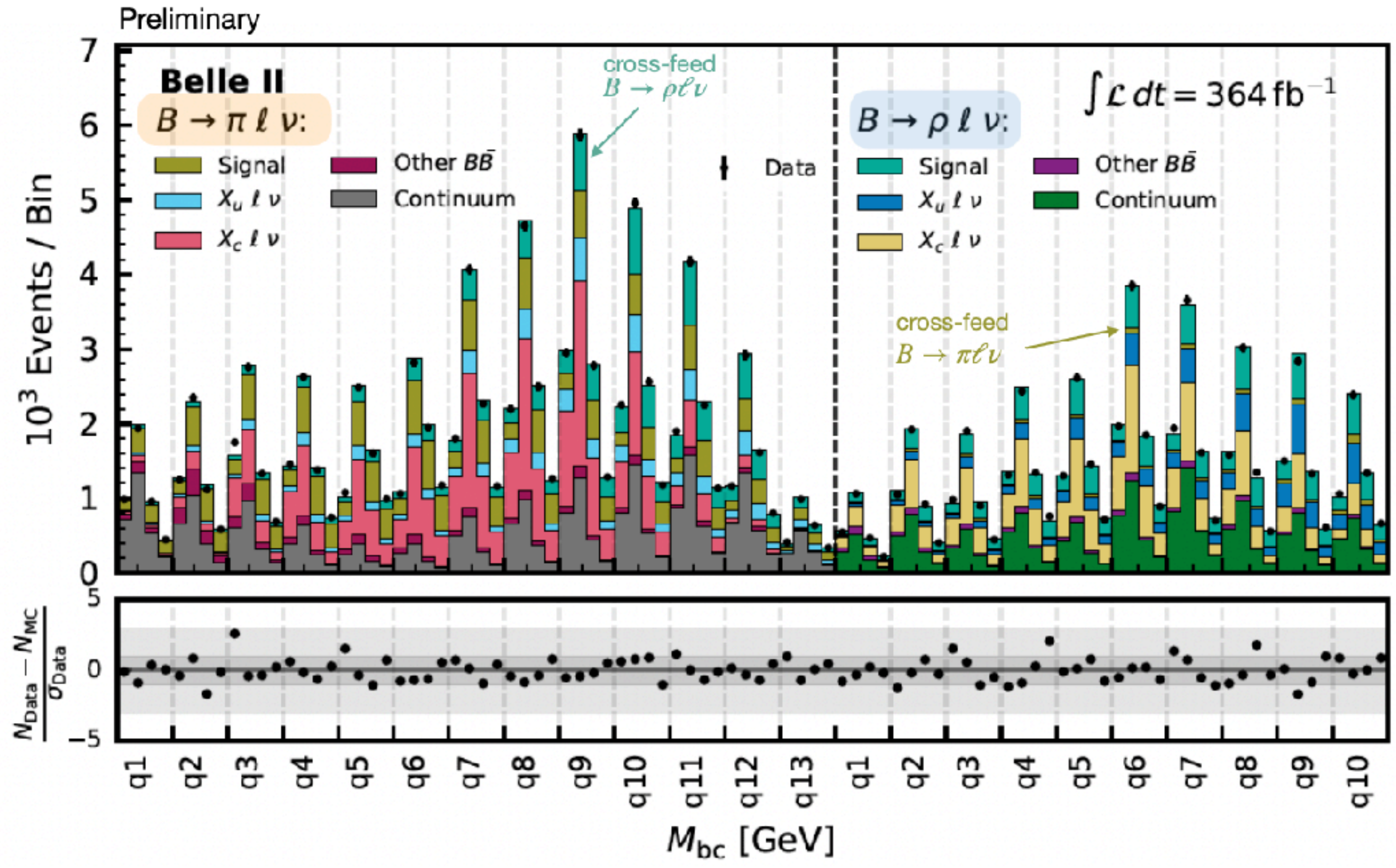
$|V_{ub}|$ using $B^0 \to \pi^- l^+ \nu_l$, $B^+ \to \rho^0 l^+ \nu_l$

Preliminary

NEW!!

Simultaneous fit in 2D grid of M_{bc} and ΔE for each bin of q^2:

13 bins for $B^0 \to \pi^- l^+ \nu_l$ mode, 10 bins for $B^+ \to \rho^0 l^+ \nu_l$ mode.



$$M_{bc} = \sqrt{E^{*2}_{\mathrm{beam}} - |\vec{p}^{\,*}_B|^2} = \sqrt{\left(\frac{\sqrt{s}}{2}\right)^2 - |\vec{p}^{\,*}_B|^2}$$

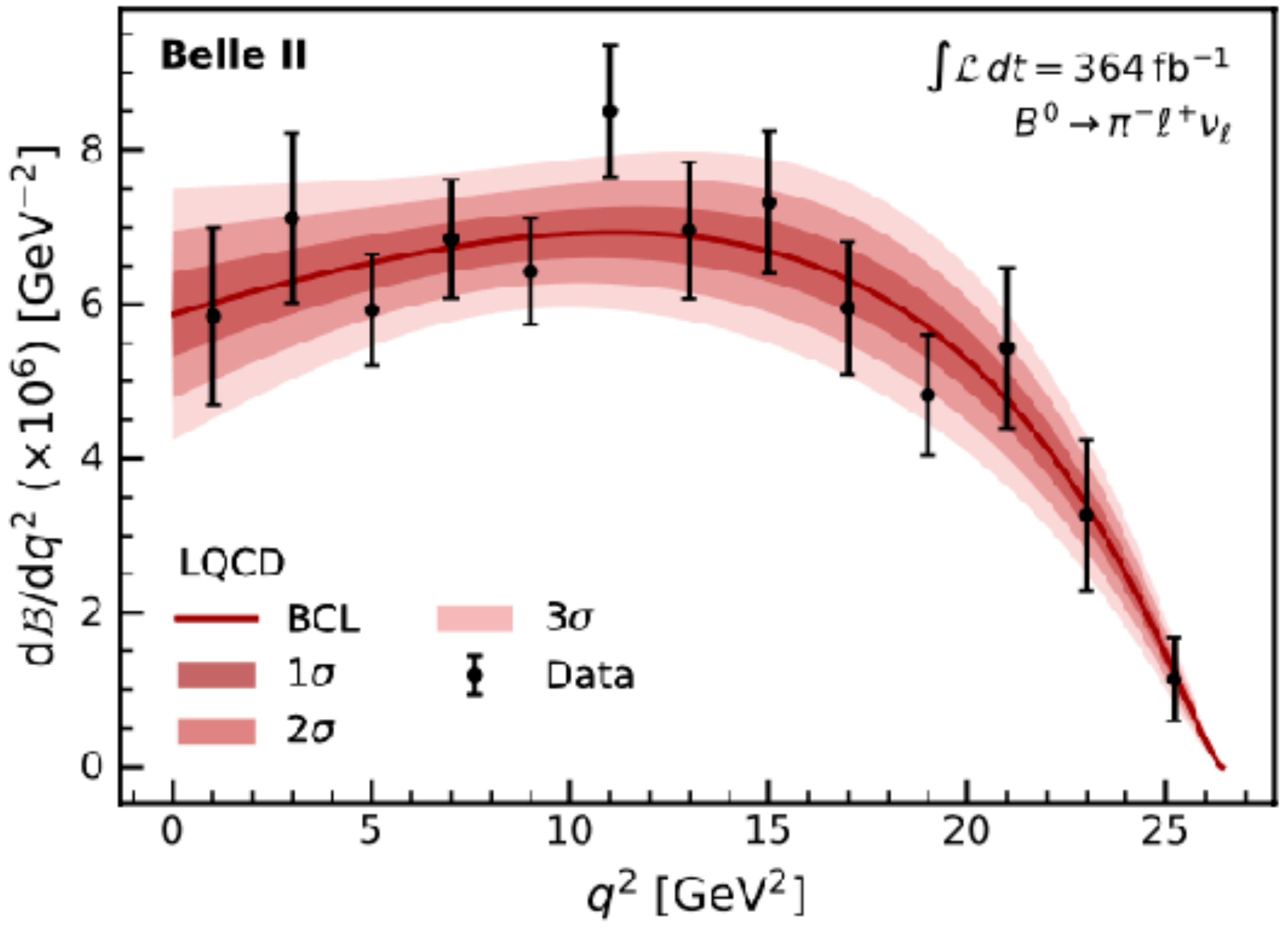
$$\Delta E = E^*_B - E^*_{\mathrm{beam}} = E^*_B - \frac{\sqrt{s}}{2}$$

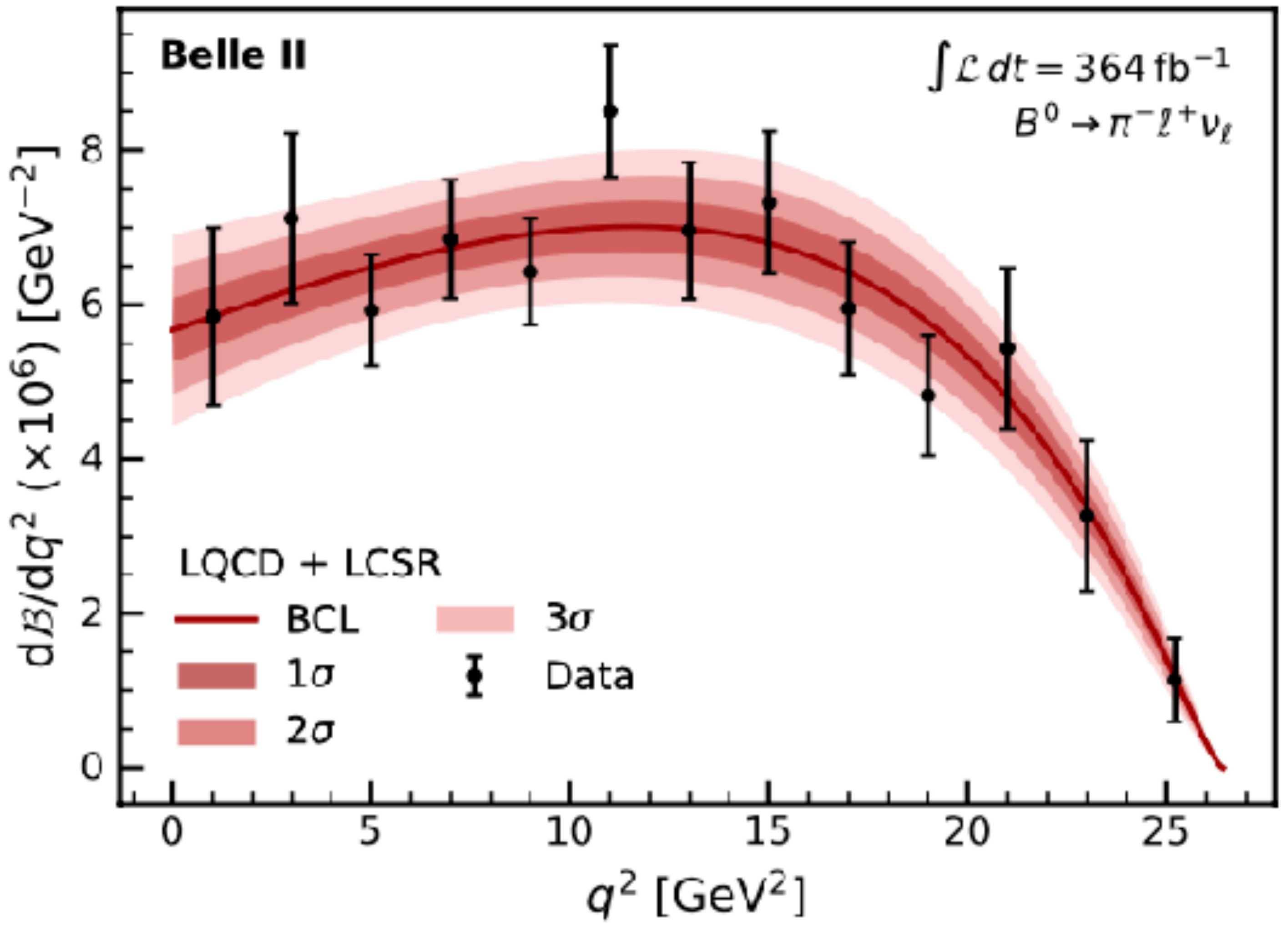
$$\mathcal{B}(B^0 \to \pi^- \ell^+ \nu_\ell) = (1.516 \pm 0.042 \pm 0.059) \times 10^{-4}$$

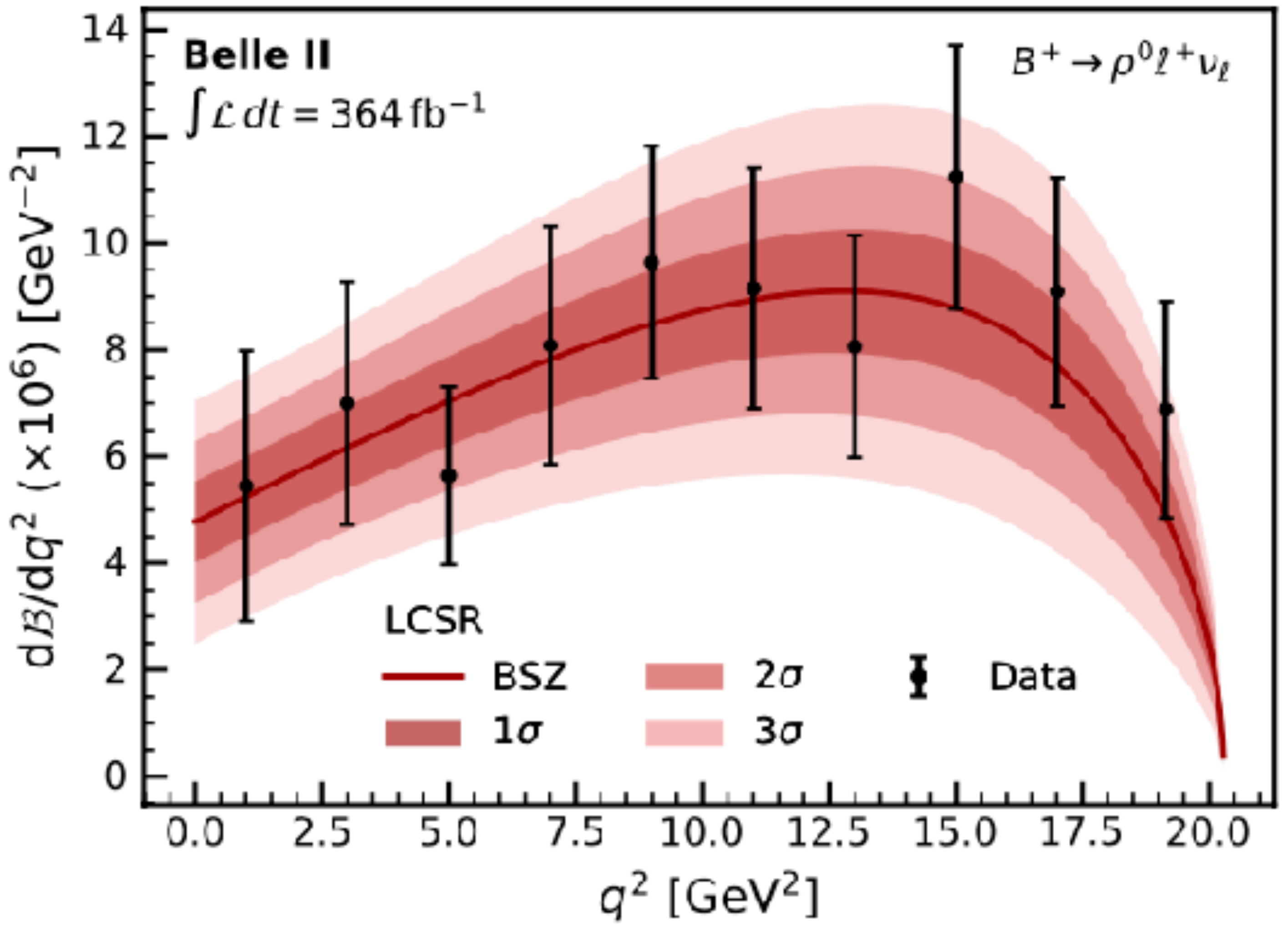
$$\mathcal{B}(B^+ \to \rho^0 \ell^+ \nu_\ell) = (1.625 \pm 0.079 \pm 0.180) \times 10^{-4}$$

stat syst

Consistent with world average.







Extracted |Vub| with lattice QCD and/or light-cone sum rules (LCSR) constraints of form factors

$$|V_{ub}|_{B\to\pi\ell\nu} = (3.93 \pm 0.09(\mathrm{stat}) \pm 0.13(\mathrm{syst}) \pm 0.19(\mathrm{theo})) \times 10^{-3}, \text{ (LQCD)}$$

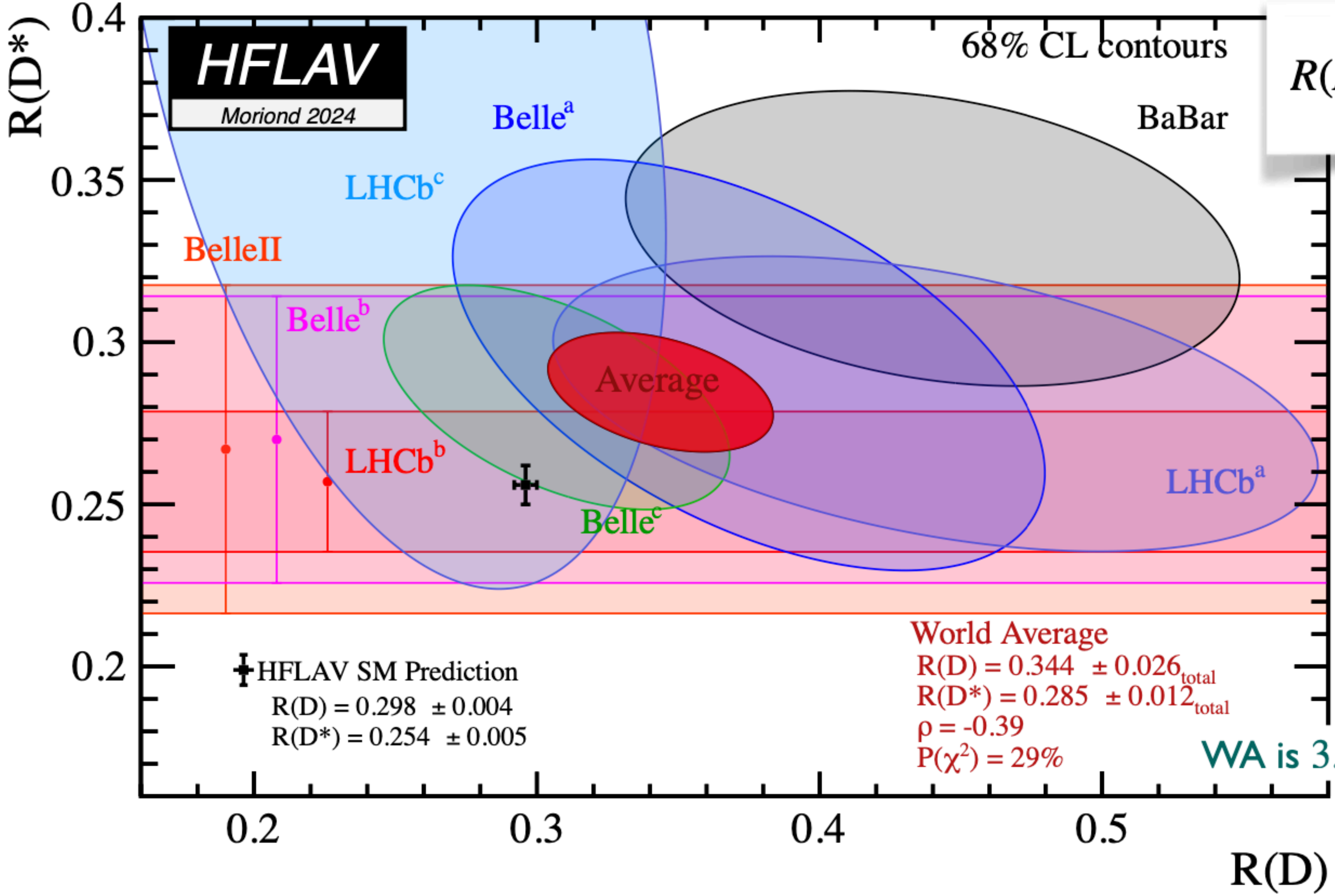
$$= (3.73 \pm 0.07(\mathrm{stat}) \pm 0.07(\mathrm{syst}) \pm 0.16(\mathrm{theo})) \times 10^{-3}, \text{ (LQCD+LCSR)}$$

$$|V_{ub}|_{B\to\rho\ell\nu} = (3.19 \pm 0.12(\mathrm{stat}) \pm 0.18(\mathrm{syst}) \pm 0.26(\mathrm{theo})) \times 10^{-3}, \text{ (LCSR)}$$

Preliminary

NEW!!

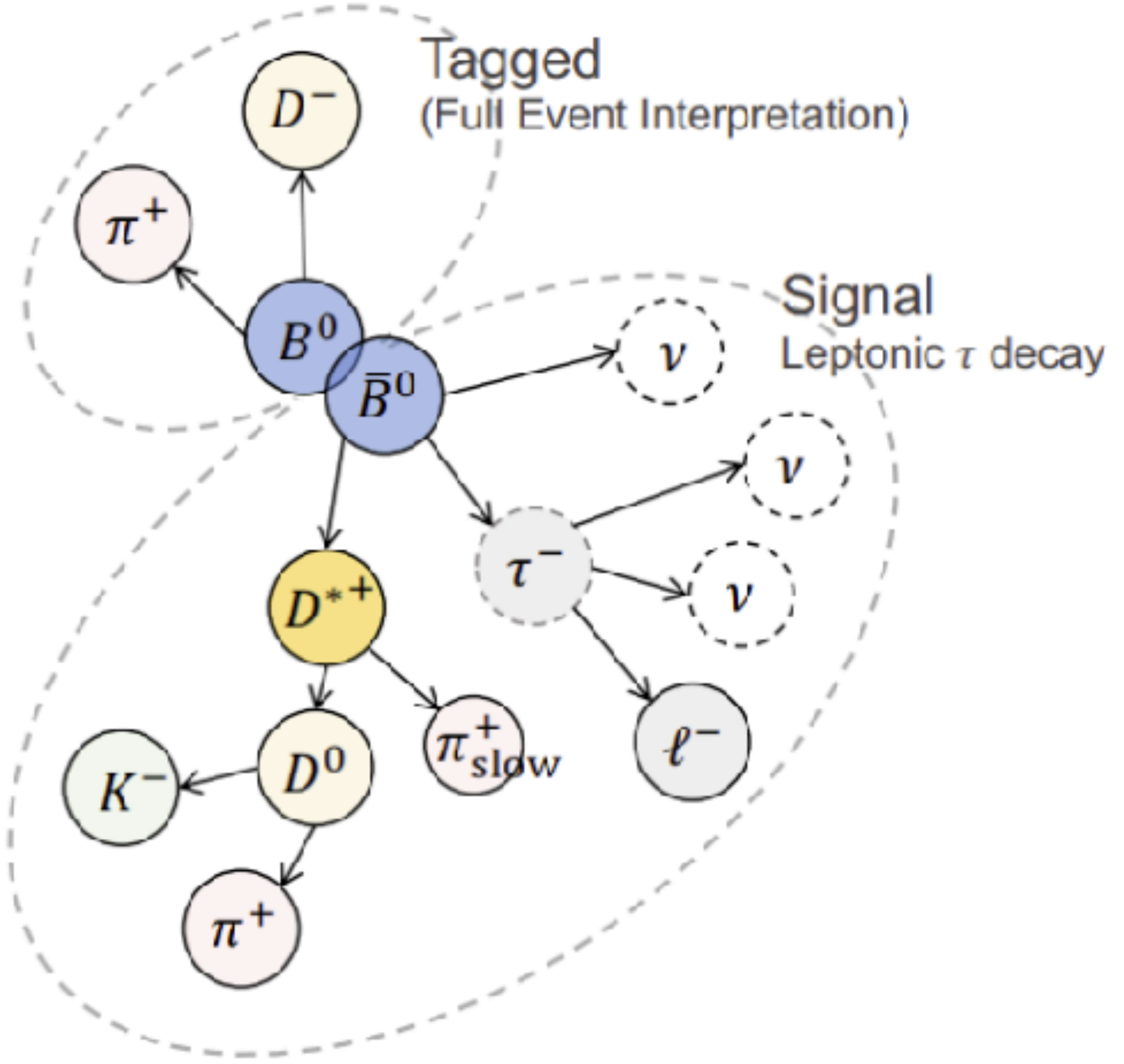
LFU test via $R(D)$ vs. $R(D^*)$



$$R(D^*) \equiv \frac{\mathscr{B}(B \to D^*\tau^+\nu)}{\mathscr{B}(B \to D^*\ell^+\nu)}$$

WA is 3.17σ from SM.

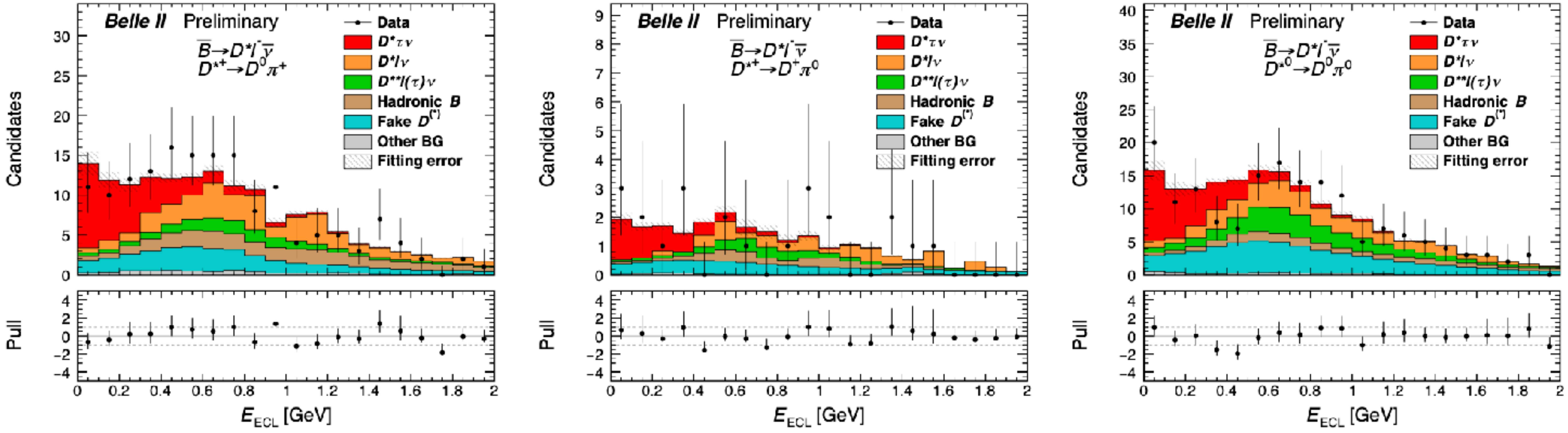
Measurement of $R(D*)$ Preliminary



First $R(D*)$ measurement on Belle II

$B \to D^*\tau\nu$ and $B \to D^*\ell\nu$ measured by 2D binned likelihood fit to:

- Missing mass of undetected neutrinos
- Sum of energy from extra photons in ECL (E_{ECL})



Signal enhanced region

$M^2_{\mathrm{miss}} \in [1.5,\ 6.0]\ \mathrm{GeV}^2$

$$R(D^*) = 0.267\ ^{+0.041}_{-0.039}(\mathrm{stat.})\ ^{+0.028}_{-0.033}(\mathrm{syst.})$$

Consistent with the SM and previous measurements.

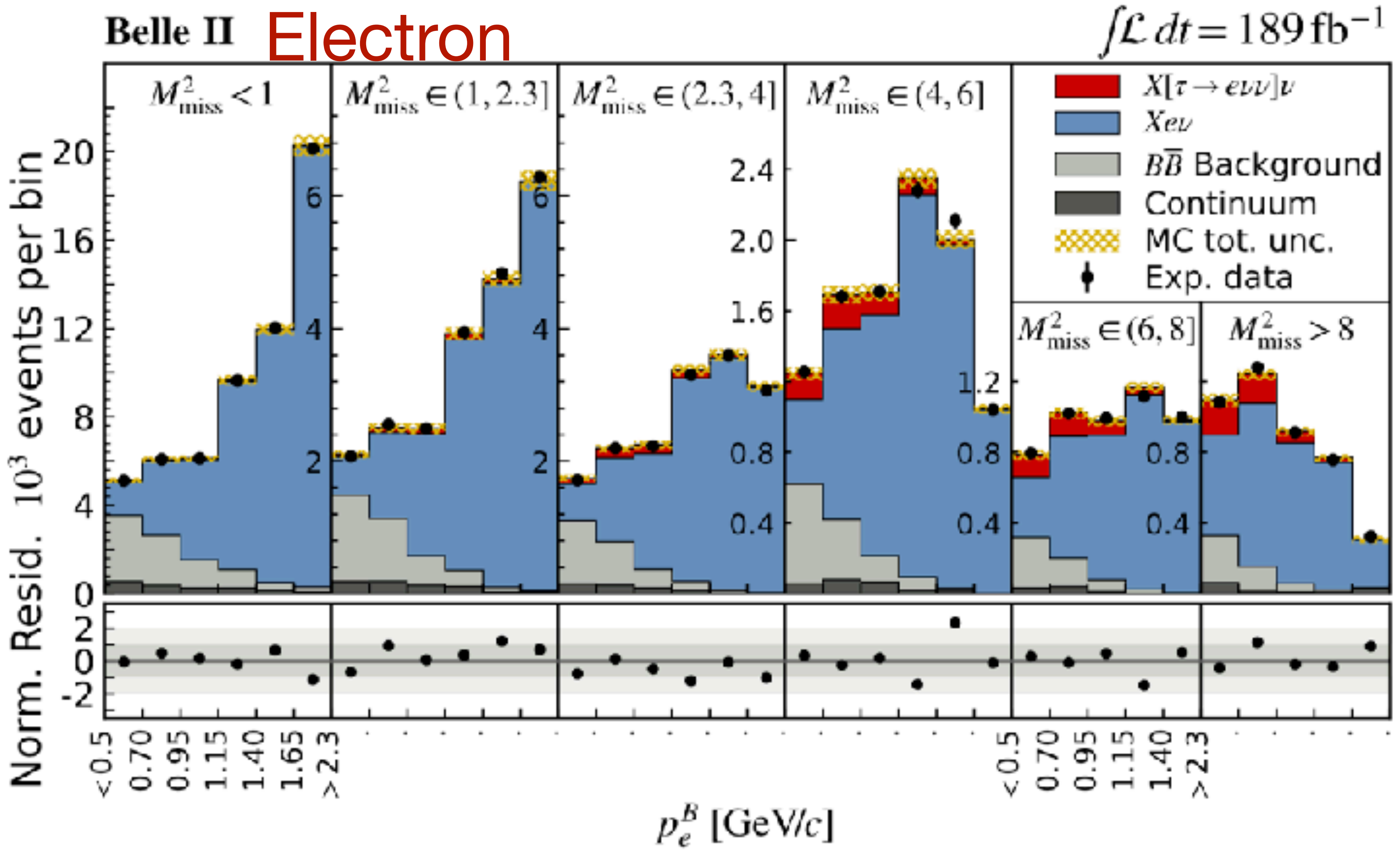
First measurement of $R(X_{\tau/\ell})$

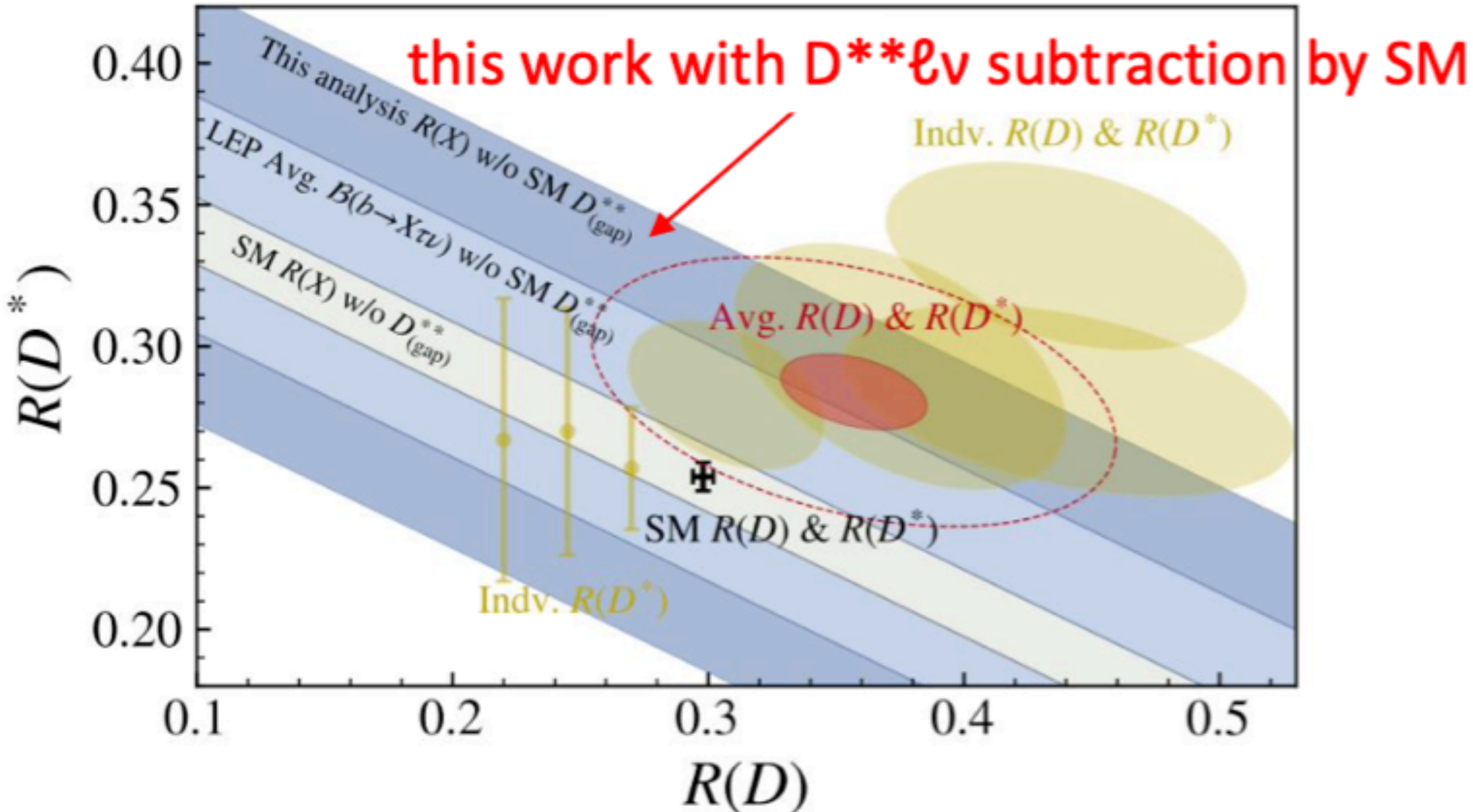
$$R(X_{\tau/\ell}) = \frac{\mathscr{B}(B \to X\tau\nu_\tau)}{\mathscr{B}(B \to X\ell\nu_\ell)}$$

- First measurement at B factories.
  - Different systematic uncertainties from $R(D^{(*)})$
- X reconstructed from remaining tracks and neutrals
- 2D-fit to M^2_{miss} and p^B_ℓ
  - $R(X_{\tau/e}) = 0.232 \pm 0.020(\text{stat.}) \pm 0.037(\text{syst.})$
  - $R(X_{\tau/\mu}) = 0.222 \pm 0.027(\text{stat.}) \pm 0.050(\text{syst.})$
- Combining:
  - $R(X_{\tau/\mu}) = 0.228 \pm 0.016(\text{stat.}) \pm 0.036(\text{syst.})$

In agreement with SM prediction and $R(D^{(*)})$ expectation

SM: 0.223 ± 0.005





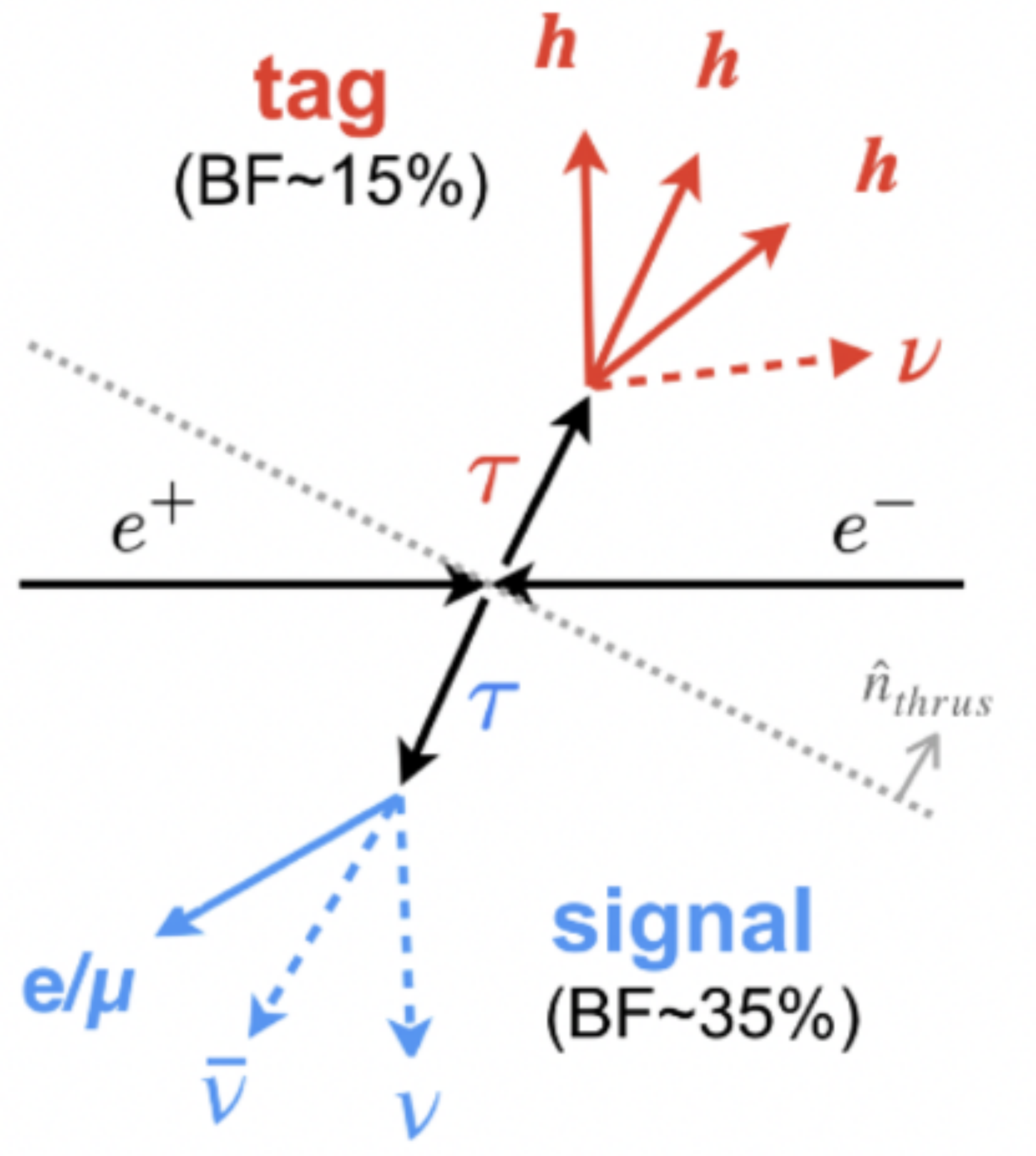
arXiv:2311.07248

τ Lepton Flavor Universality Violation

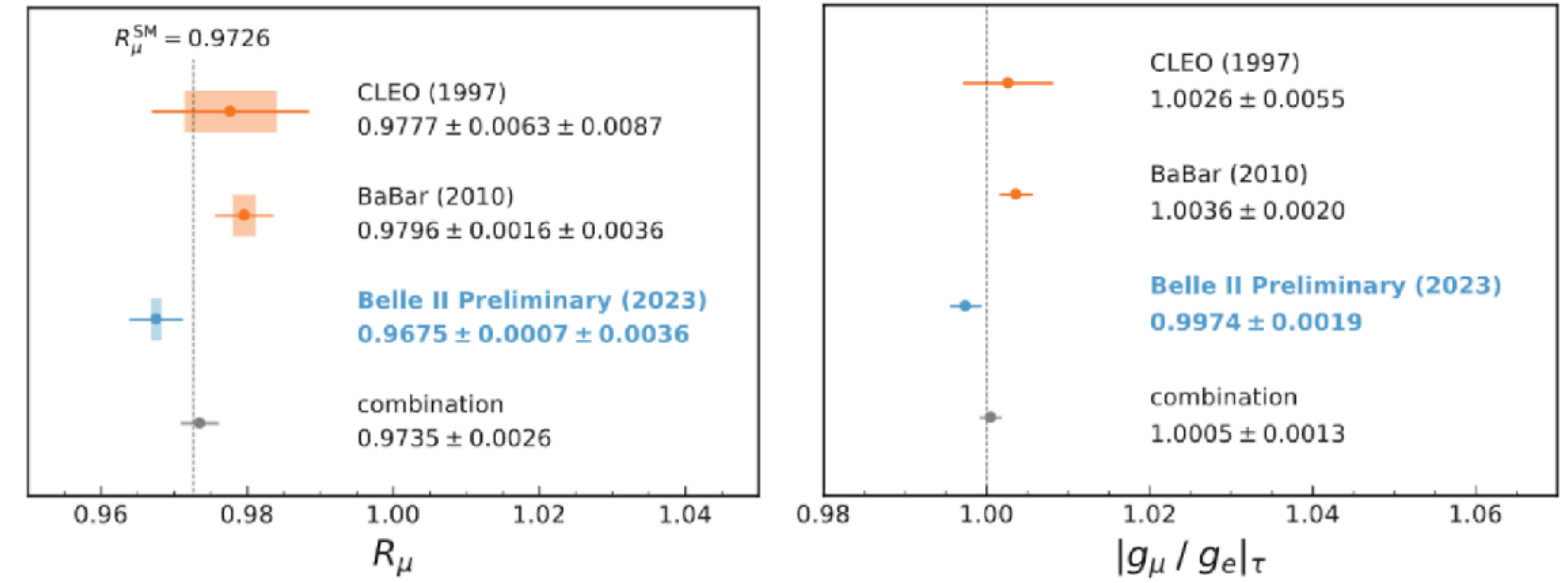
preliminary

$$\left(\frac{g_\mu}{g_e}\right)_\tau = \sqrt{\frac{BF\left[\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau\right]}{BF\left[\tau^- \to e^-\bar{\nu}_e\nu_\tau\right]}\frac{f\left(m_e^2/m_\tau^2\right)}{f\left(m_\mu^2/m_\tau^2\right)}}$$

In the SM: $\left(\frac{g_\mu}{g_e}\right)_\tau = 1$



Tests with 3x1 topology: same method as Babar



$$R_\mu = \frac{\mathcal{B}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)}{\mathcal{B}(\tau^- \to e^-\bar{\nu}_e\nu_\tau)} = 0.9675 \pm 0.0007 \pm 0.0036.$$

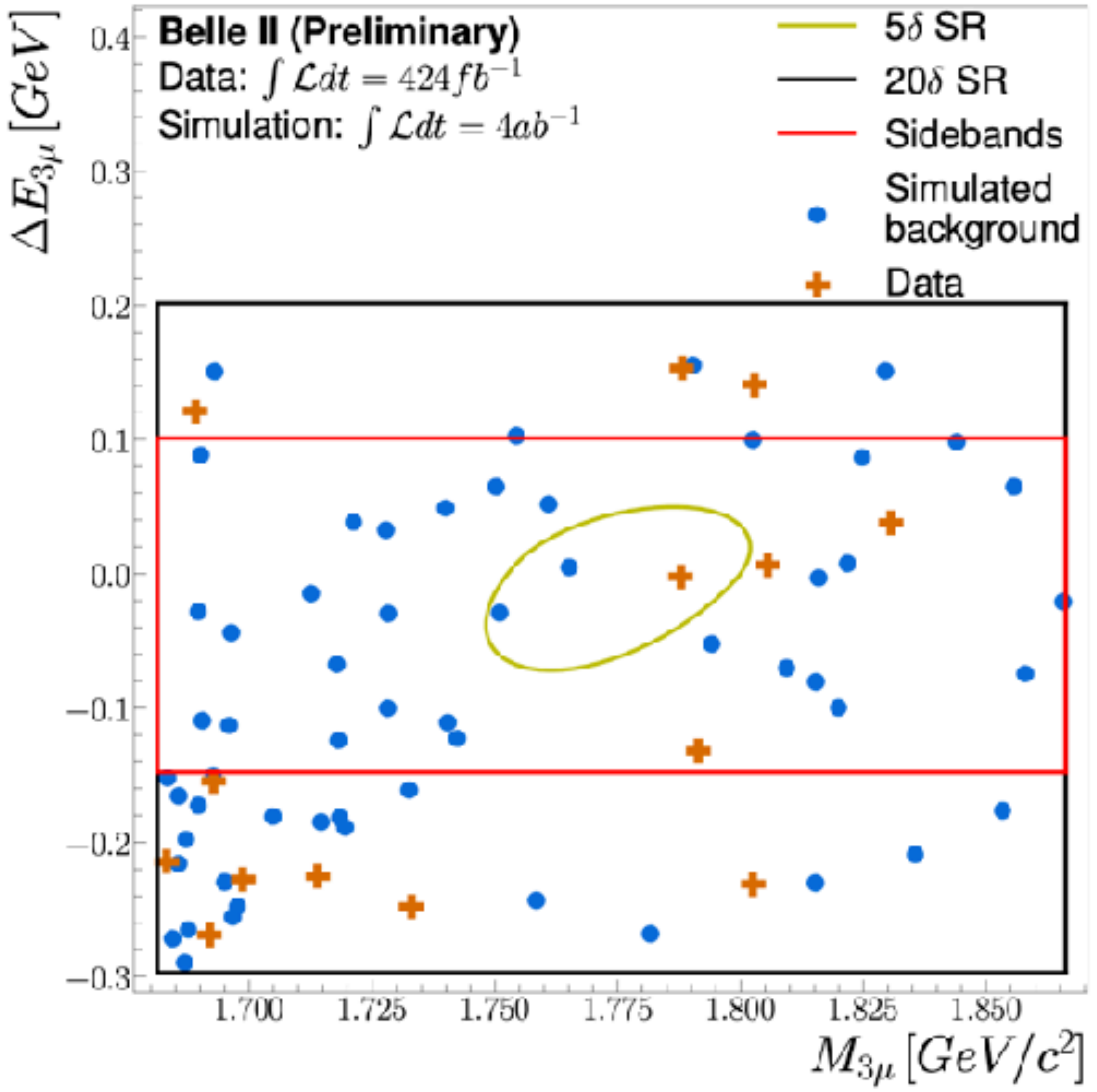
Consistent with previous measurements

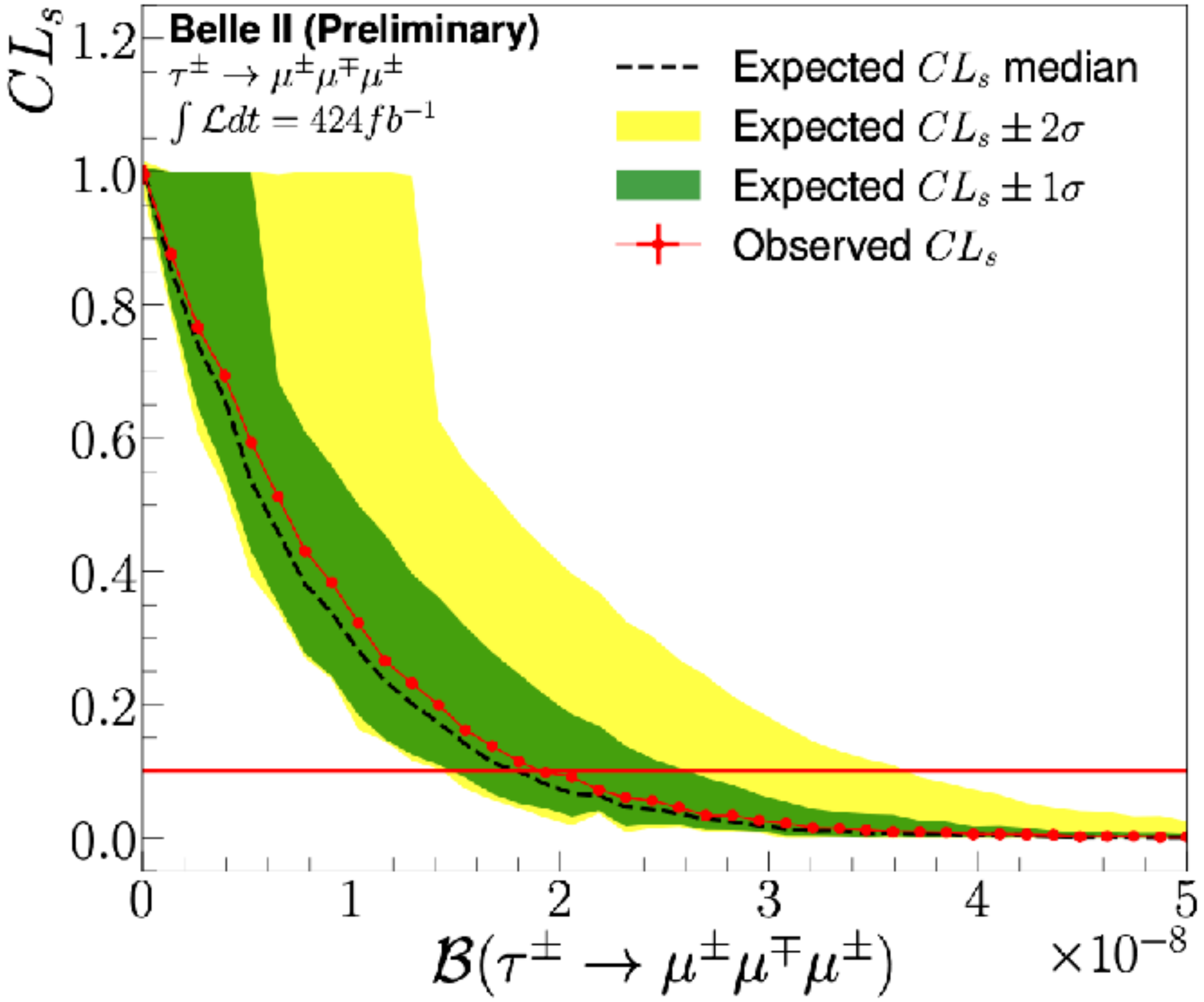
Most precise to date

τ Lepton Flavor Violation

preliminary

- A search for the charged-lepton-flavour violating decay $\tau \to \mu\mu\mu$
- Provide indisputable evidence of physics beyond the SM.





- Novel inclusive tagging followed by a BDT-based selection.
  - 2.5 times higher efficiency than Belle and 37% higher efficiency than 1-prong tagging
- One event in signal region:
  - $B(\tau^- \to \mu^-\mu^+\mu^-) = (3.1 + 8.7 \pm 0.1) \times 10^{-9}$
- $< 1.9(1.8) \times 10^{-8}$ for observed (expected) limit at 90% C.L.
- Less data, more restrictive than Belle

Cross section measurement of $e^+e^- \to \pi^+\pi^-\pi^0$

- Background, 0.5% at omega peaks.

Unfolded signal spectrum

Cross section

$$\sigma_{ee\to 3\pi}(M_i(3\pi)) = \frac{N_{\text{unfolded},i}}{\varepsilon(M_i(3\pi)) \cdot L_{\text{eff}}(M_i(3\pi)) \cdot r_{\text{rad}}}$$

3π mass at i-th bin

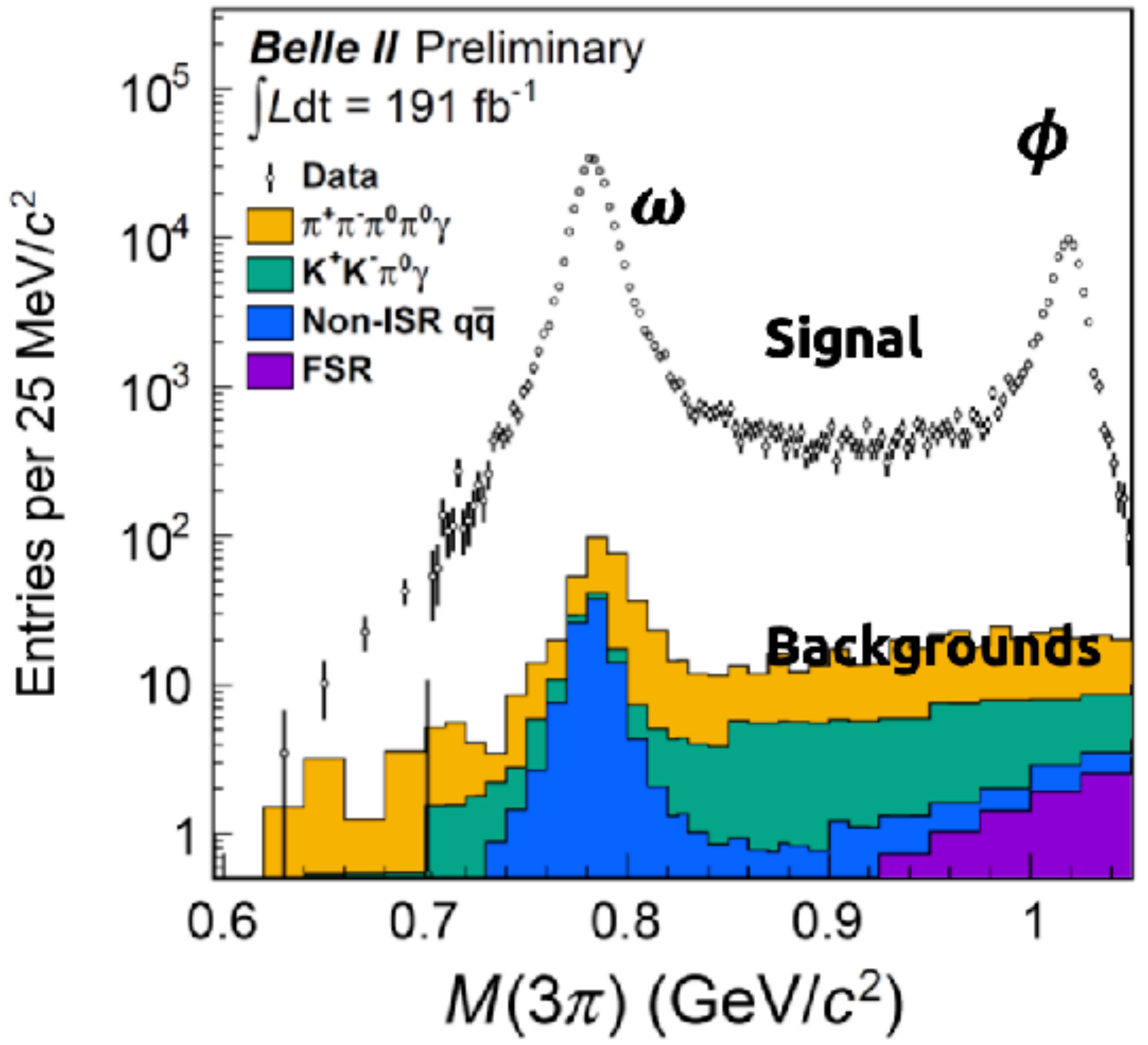
Corrected Efficiency

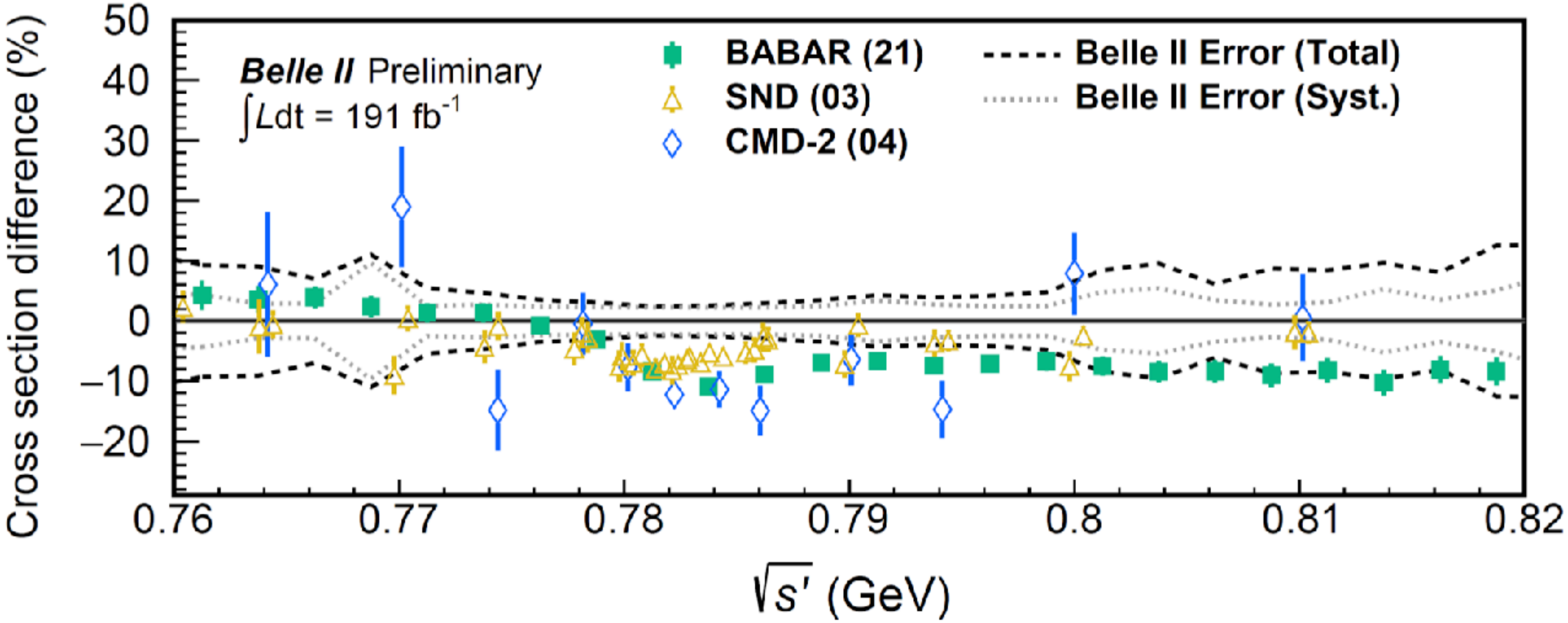
Effective luminosity

Radiative correction

$$r_{rad} = 1.0080 \pm 0.0007$$

Correction is <1 %.





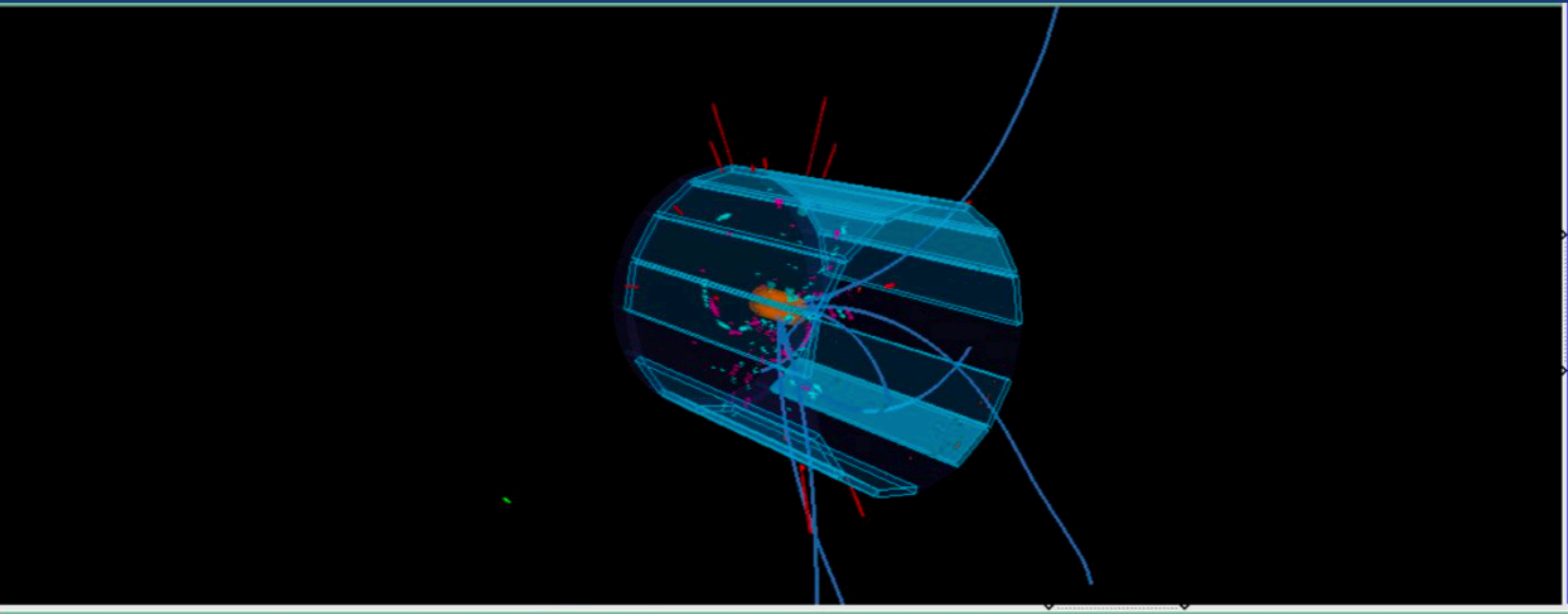
Cross section at ω resonance is 5-10% higher than SND, BABAR, and CMD-2.

$$a_\mu^{\mathrm{LO,HVP},3\pi}(0.62\text{-}\ 1.8\ \mathrm{GeV}) = (48.91 \pm 0.25_{\mathrm{stat}} \pm 1.07_{\mathrm{syst}}) \times 10^{-10}$$

	$a_\mu(3\pi)\times10^{10}$	Difference$\times10^{10}$
BABAR alone [PRD104 11 (2021)]	45.86 ± 0.14 ± 0.58	-2.5σ (6.9%)
Global fit [JHEP08 208 (2023)]	45.91 ± 0.37 ± 0.38	-2.5σ (6.5%)

For further improvement, QED NNLO MC generators are crucial.

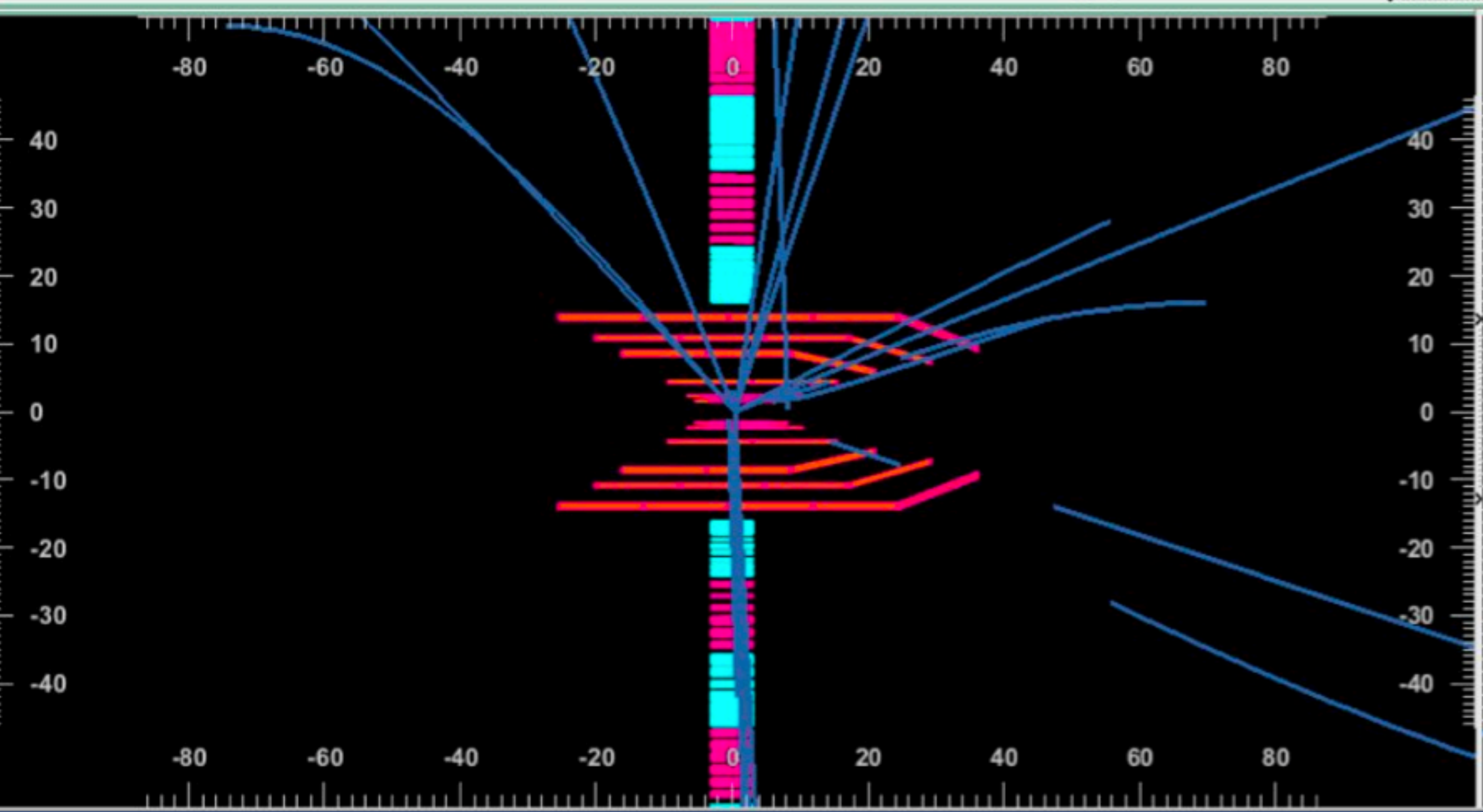
Plan to make precise measurements on the cross sections in other ISR processes $e^+e^- \to \pi^+\pi^-$.

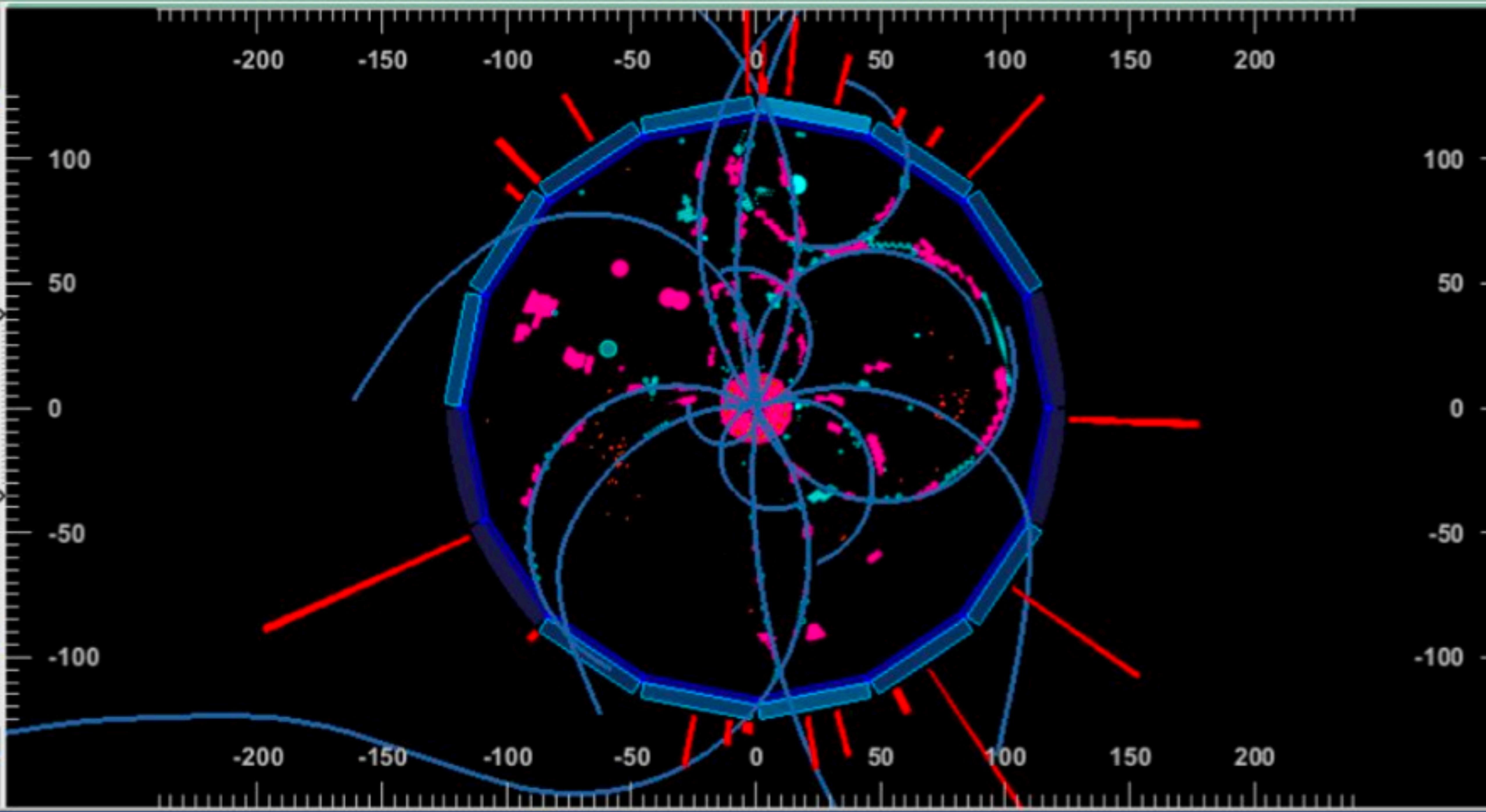


Belle II

First Collisions of Run 2

20th February 2024





Summary

- Belle II has collected 424/fb data before Long Shutdown 1.
- Provide crucial test for SM
    - Rare B decays, B anomalies…
- Smaller data, but more or equivalent accuracy for many analyses
    - Special trigger for individual physics procedure
    - Advanced software tools, FEI, flavor tagger, etc.
    - …
- Unique data provide unique results
    - Spectroscopy, charm baryons (Sen's talk)
- LS1 is finished and new run has started Feb. this year.
    - More data, more new results

BACK UP

Reconstruction and background suppression

Charged particles:
- p_t>0.1 GeV/c
- close to collision point
- in central region

Neutral particles:
- E>100 MeV
- in central region

Signal candidate:
- **charged particle**
- Kaon identification
- Minimal q^2_{rec}

Event (pre-selection):
- $4 \le N_{track} \le 10$
- E_{total}>4 GeV
- $17^o < \vartheta_{miss} < 160^o$

→

BDT$_1$ (first filter):
- 12 event-shape based kinematic variables

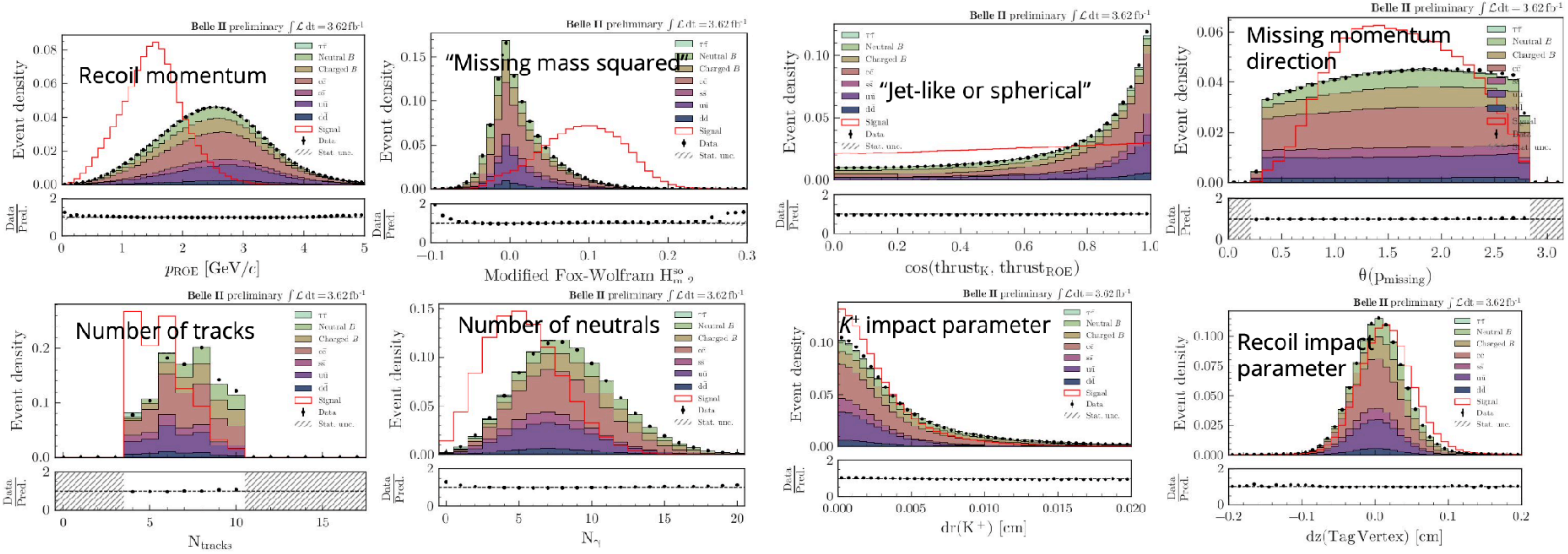
→

BDT$_2$ (final selection):
- *35 input variables*: using signal, event, and their correlations

- Selection criteria for particles to ensure high and well-measured efficiency
- Signal candidate selected using mass of the neutrino pair q^2_{rec} (computed as K^+ recoil)
- Three-step filter: basic event cuts, BDT-based filter (BDT$_1$) and final selection (BDT$_2$). BDT$_2$ improves performance in terms of s/√s+b by almost factor 3

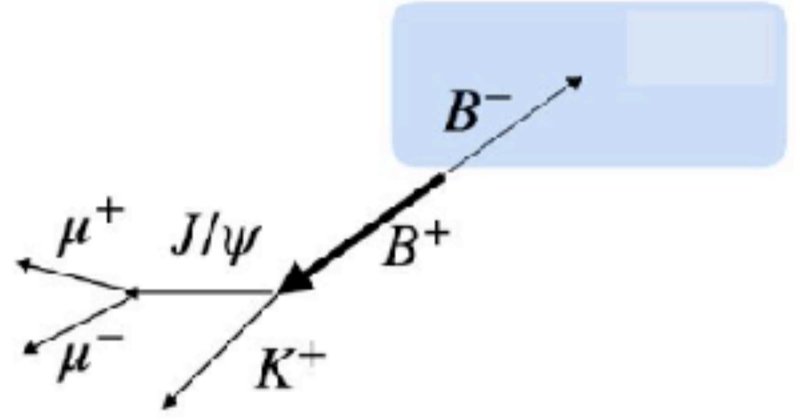
*Missing momentum is reconstructed using beam and all reconstructed particle 4-momenta

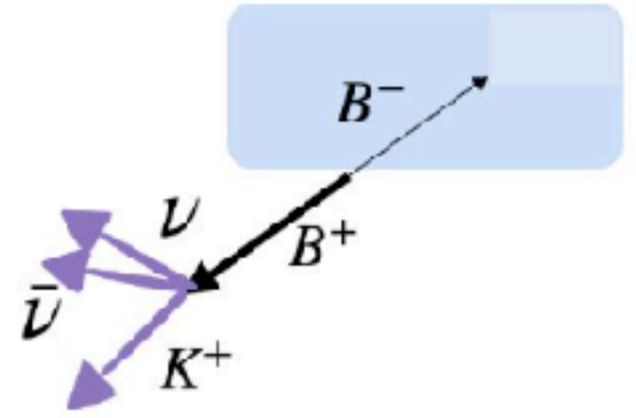
Examples of input variables for BDT_1 and BDT_2

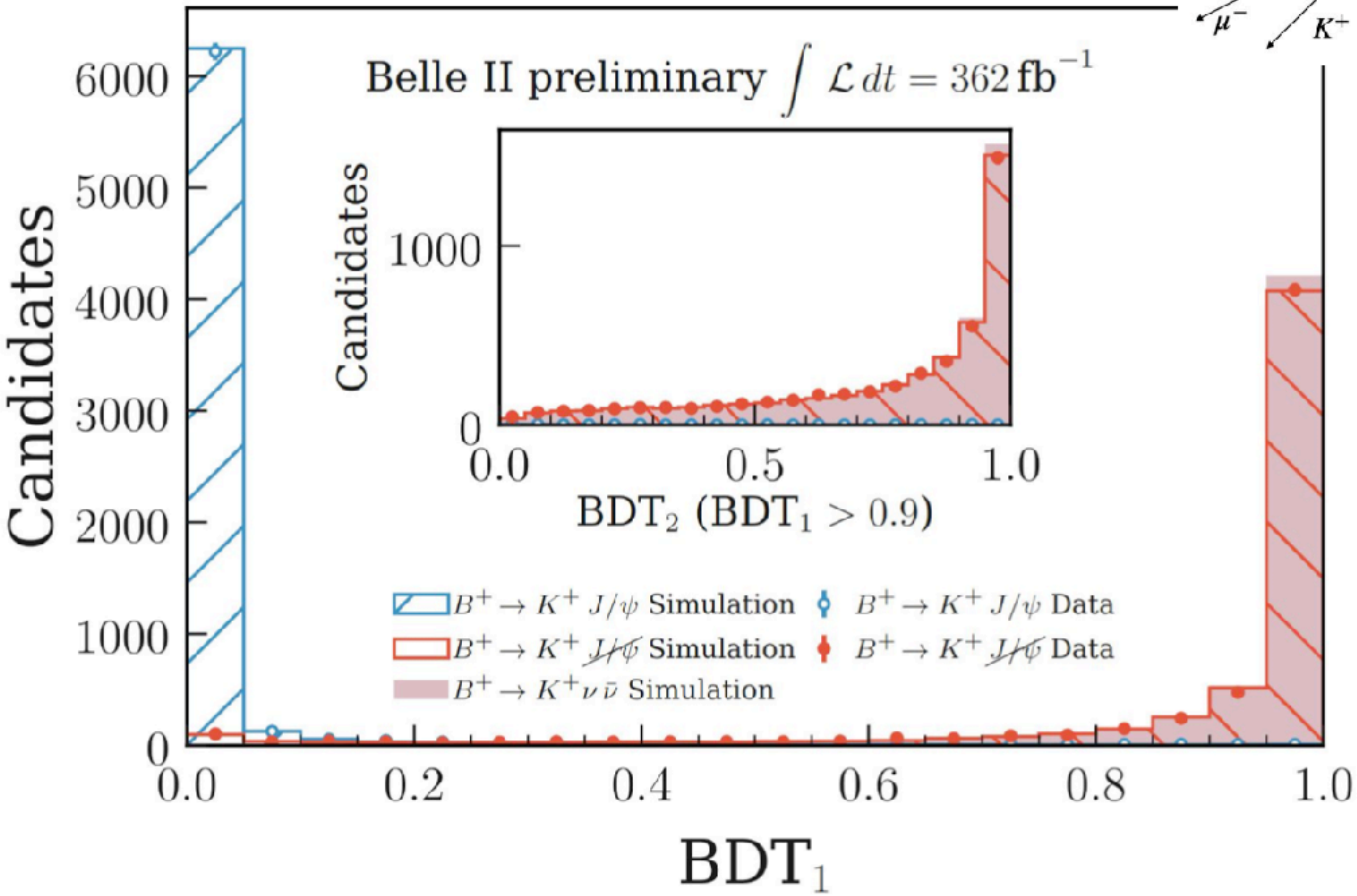


- Example of input distributions at pre-selection level, 1% of data, with detector-level corrections applied but no physics modeling corrections
- Each variable is examined to have reasonable description by simulation and significant separation power

Signal efficiency validation

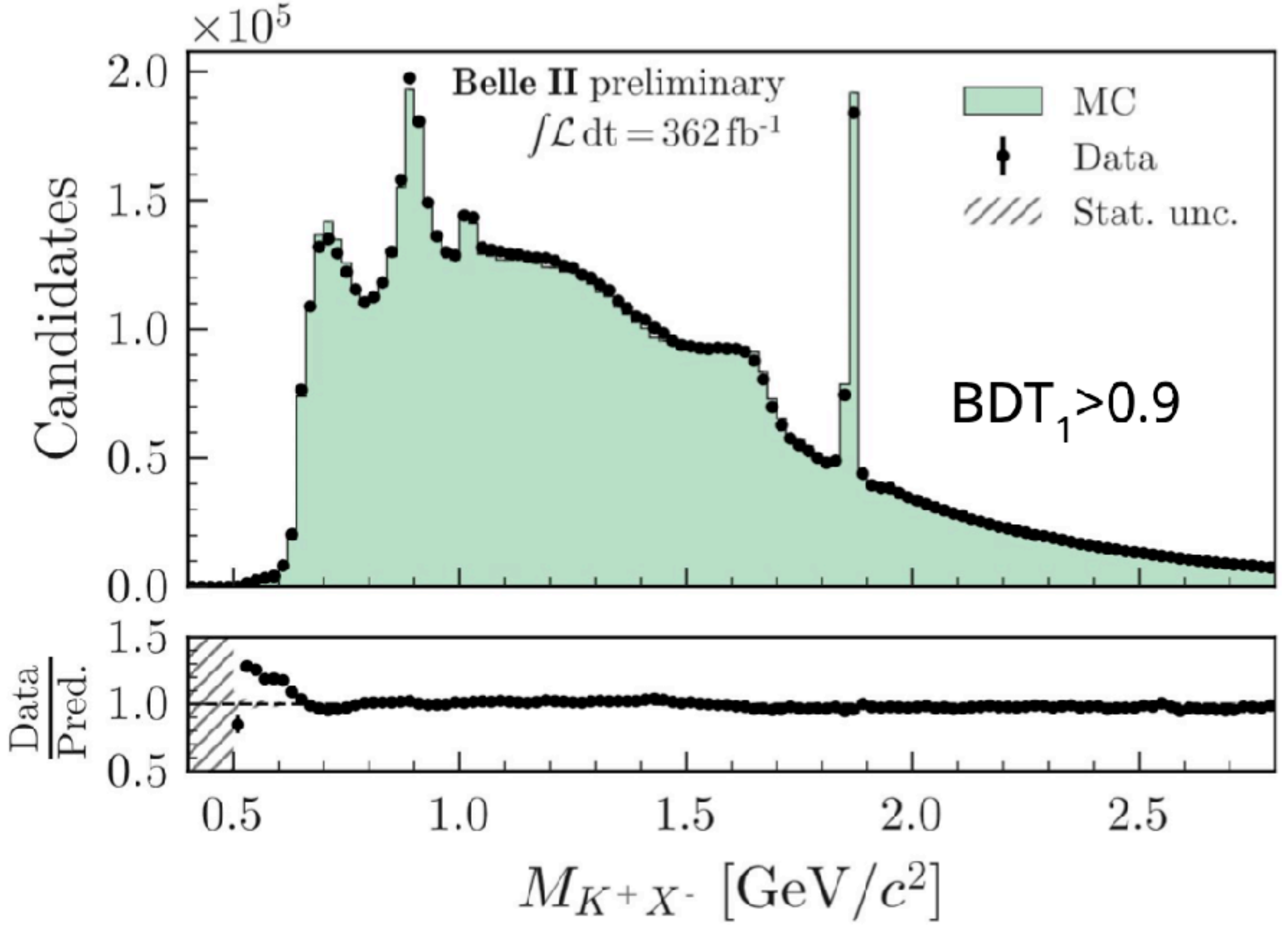


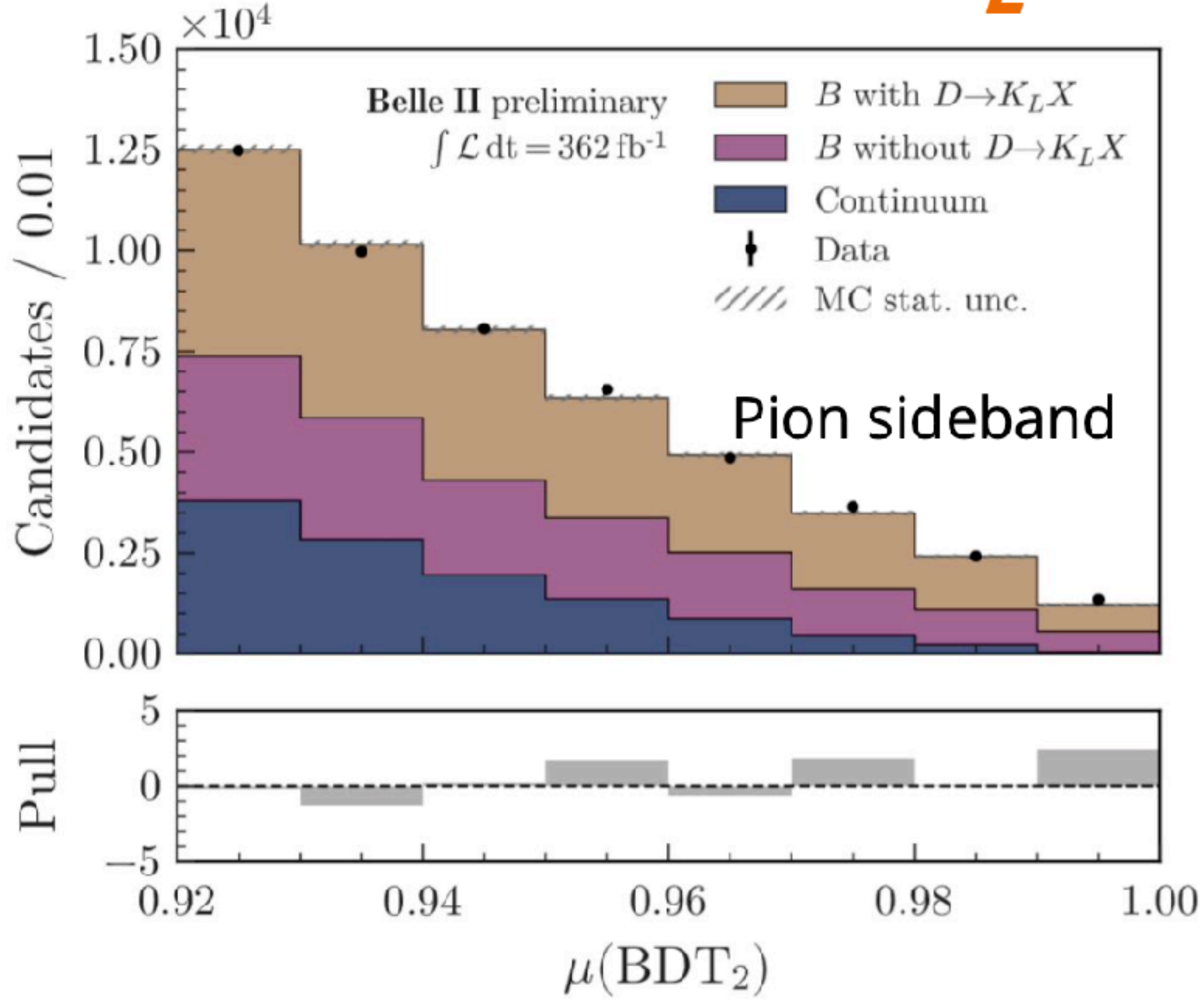




- Use cleanly reconstructed $B^+ \to K^+ J/\psi(\to \mu^+\mu^-)$ decays with $\mu^+\mu^-$ pair removed and K^+ kinematics adjusted to validate the signal efficiency in simulation. The ratio of data/simulation efficiency in the signal region is **1.00±0.03**

Background from $B \to D(\to K^+ X) l\nu$ and $B \to K^+ D(\to K_L X)$

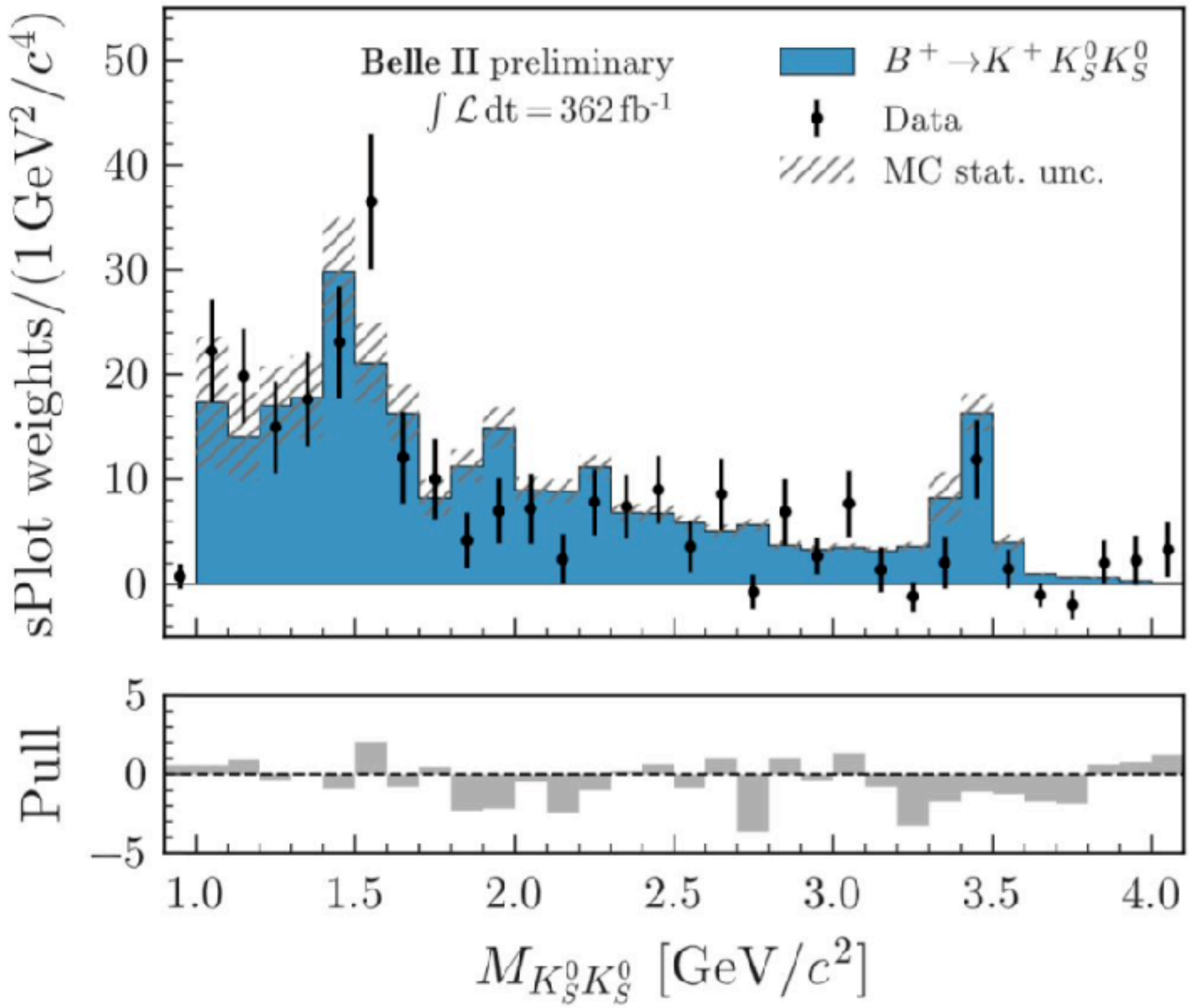




- Main backgrounds: semileptonic $B \to D(\to K^+ X) l\nu$ decays and prompt $B \to K^+ X$ production (>90%)
- Semileptonic decays suppressed by several MVA variables, checked at each selection step
- Prompt K^+ production studied using prompt π^+ from $B^+ \to \pi^+ X$ (and l^+ from $B^+ \to l^+ X$) decays
- Systematic uncertainties on decay branching fractions, enlarged for $D(\to K_L X)$ and $B \to D^{**} l \nu$

Background from $B^+ \to K^+ K^0 K^0$

Most signal-like backgrounds

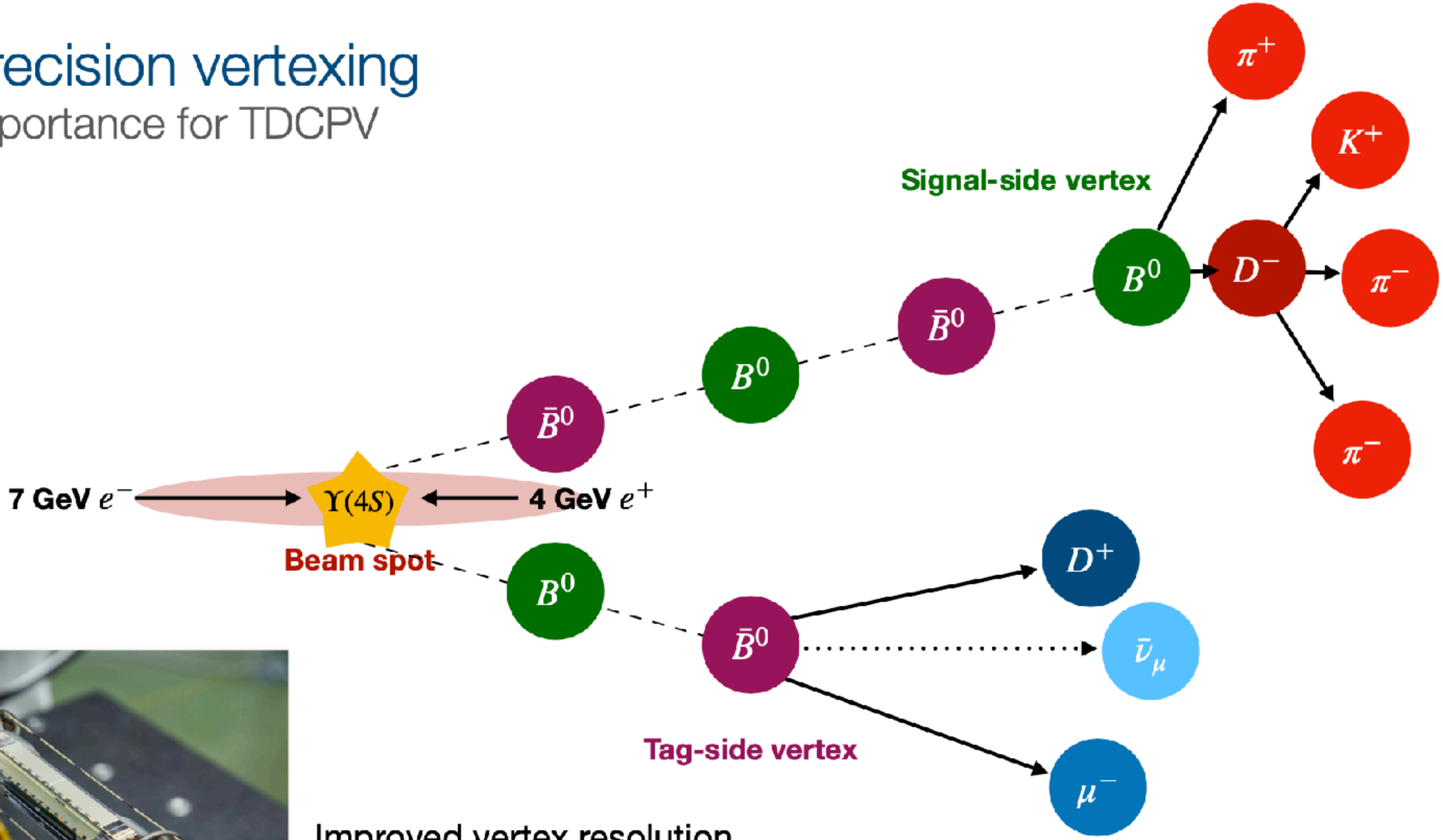


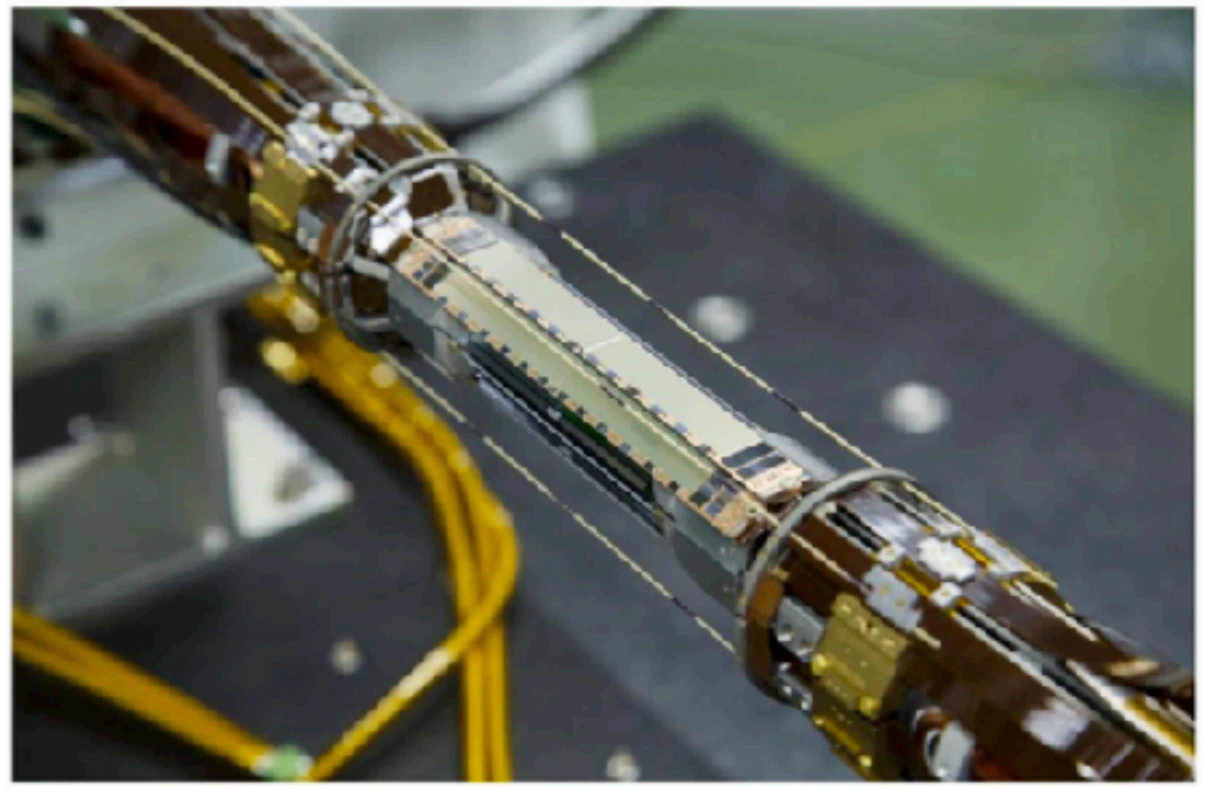
$\leftarrow B^+ \to K^+ K_S K_S$ decays

- Backgrounds from $B^+ \to K^+ nn$ and $B^+ \to K^+ K^0 K^0$ have branching fractions of few x 10^{-5}, however K_L and neutrons can escape EM calorimeter
- $B^+ \to K^+ K^0 K^0$ modeled based on BaBar analysis (arXiv:1201.5897)
- Dedicated checks of K_L performance in calorimeter using radiative φ production
- Dedicated checks using $B^+ \to K^+ K_S K_S$ and $B^0 \to K_S K^+ K^-$ control channels

High-precision vertexing

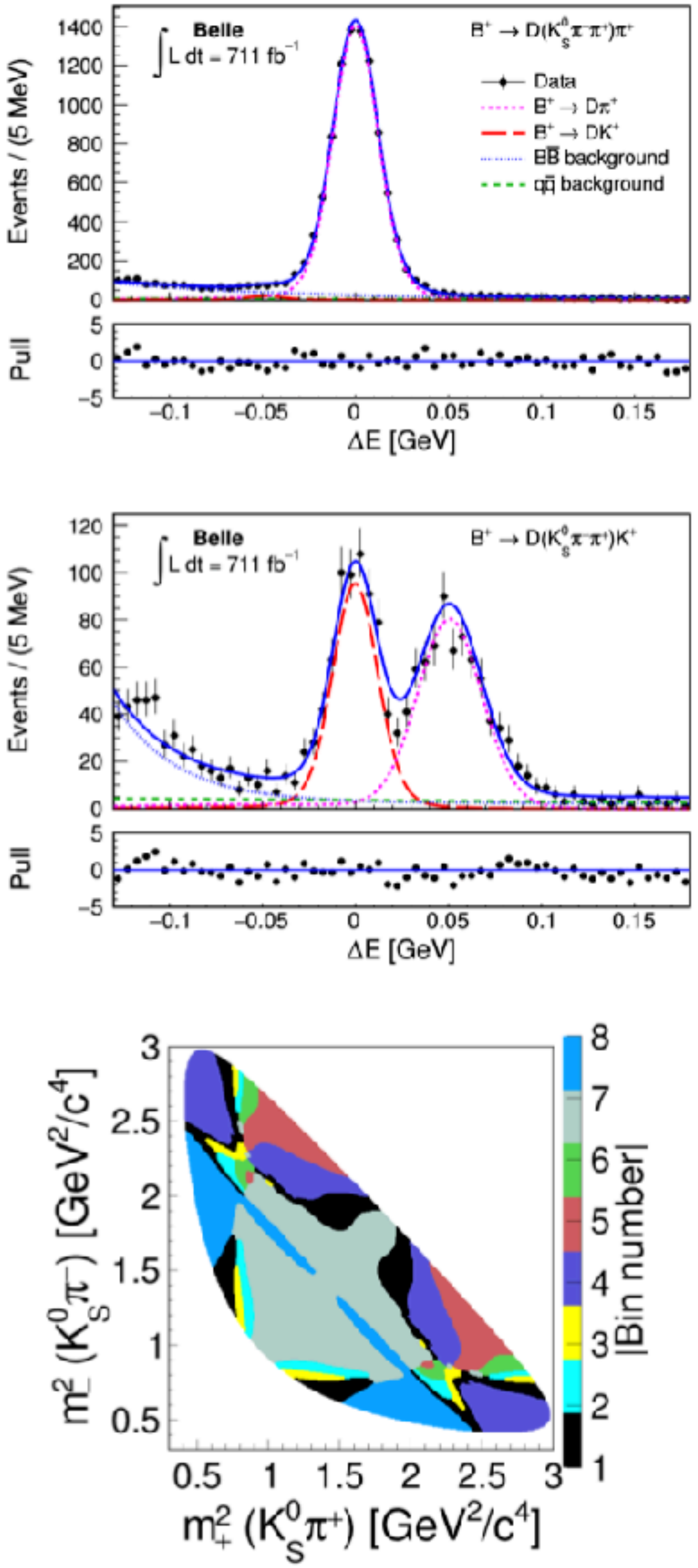
and its importance for TDCPV



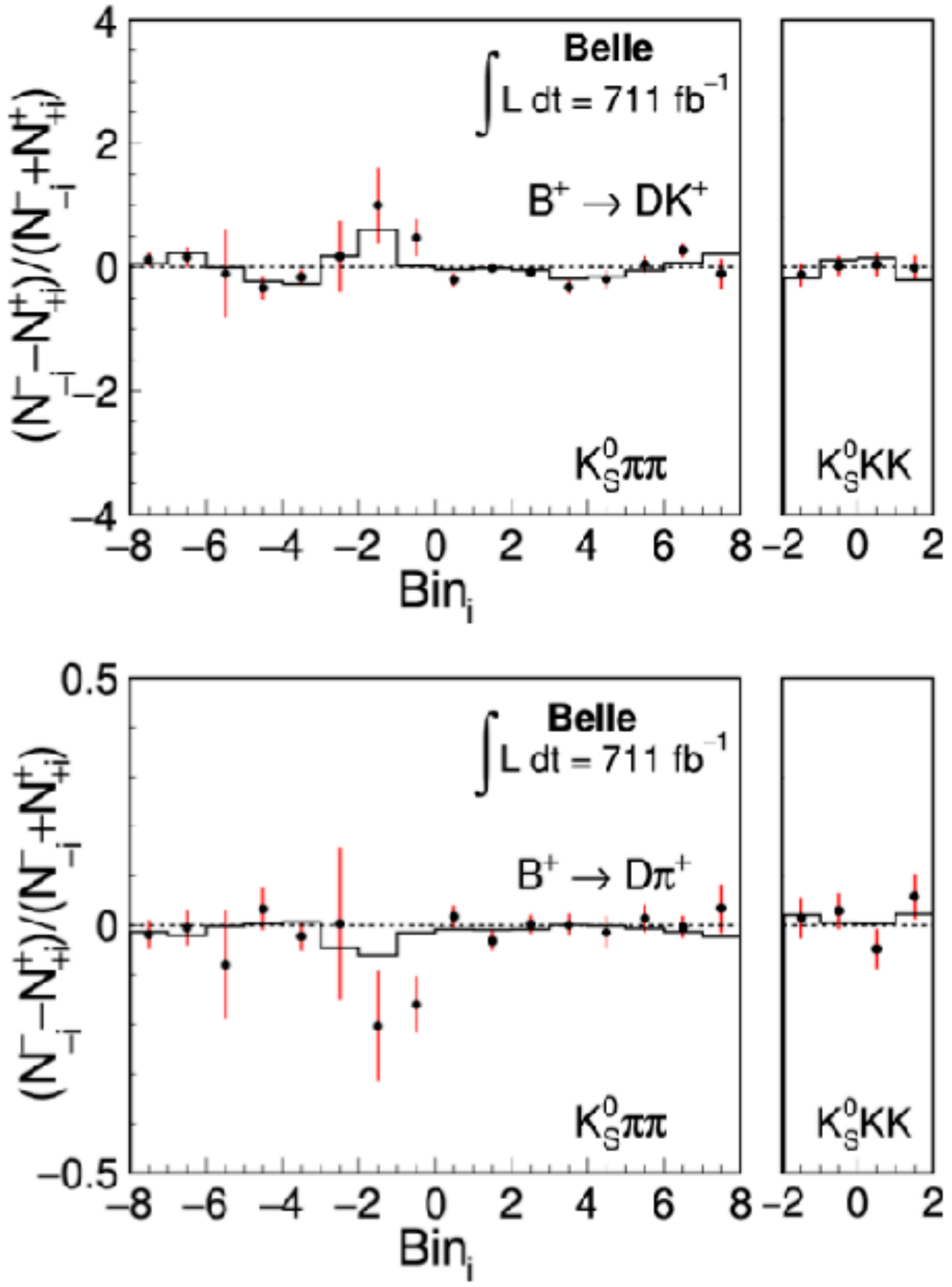


Improved vertex resolution
due to pixel detector
(despite lower boost)

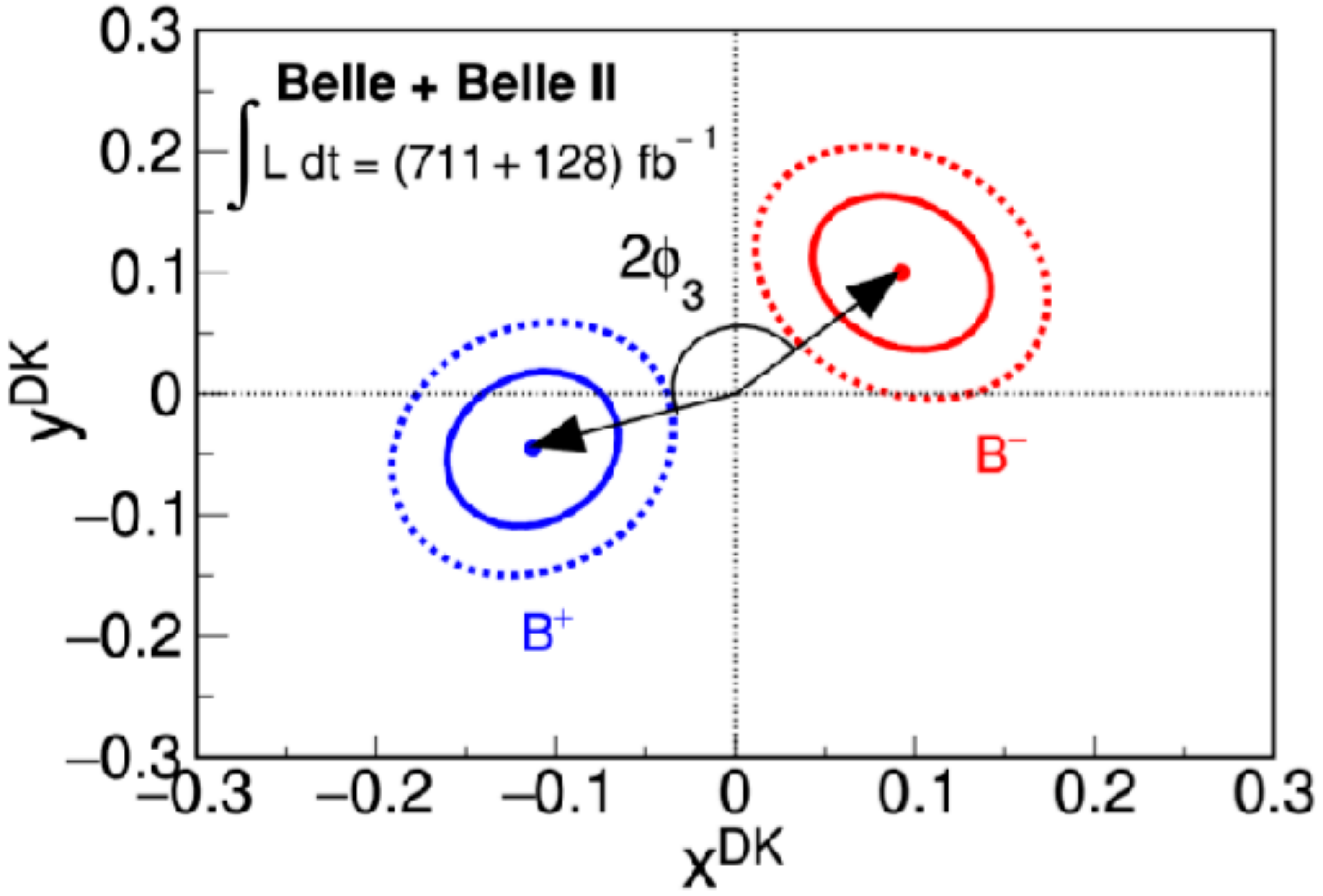
γ measurement in $B^+ \to D(K_S^0 h^+ h^-)h^+$ with Belle and Belle II data



Determine bin-by-bin asymmetries
$(N_-^{-i} - N_+^{+i})/(N_-^{-i} + N_+^{+i})$
in each Dalitz plot bin i



$$x_\pm^{DK} = r_B^{DK} \cos(\delta_B^{DK} \pm \phi_3)$$
$$y_\pm^{DK} = r_B^{DK} \sin(\delta_B^{DK} \pm \phi_3)$$



$$\phi_3 = (78.4 \pm 11.4 \pm 0.5 \pm 1.0)^\circ ,$$
$$r_B^{DK} = 0.129 \pm 0.024 \pm 0.001 \pm 0.002,$$
$$\delta_B^{DK} = (124.8 \pm 12.9 \pm 0.5 \pm 1.7)^\circ ,$$
$$r_B^{D\pi} = 0.017 \pm 0.006 \pm 0.001 \pm 0.001,$$
$$\delta_B^{D\pi} = (341.0 \pm 17.0 \pm 1.2 \pm 2.6)^\circ .$$

Measurement of $B^{\pm} \to D_{CP\pm} K^{\pm}$ with Belle and Belle II data

- Simultaneous fit to $B^{\pm} \to DK^{\pm}$ and $B^{\pm} \to D\pi^{\pm}$ with D decays to CP eigenstates

$$\mathcal{R}_{CP\pm} \equiv \frac{\mathcal{B}(B^- \to D_{CP\pm}K^-) + \mathcal{B}(B^+ \to D_{CP\pm}K^+)}{(\mathcal{B}(B^- \to D_{\text{flav}}K^-) + \mathcal{B}(B^+ \to \overline{D}_{\text{flav}}K^+))/2}$$

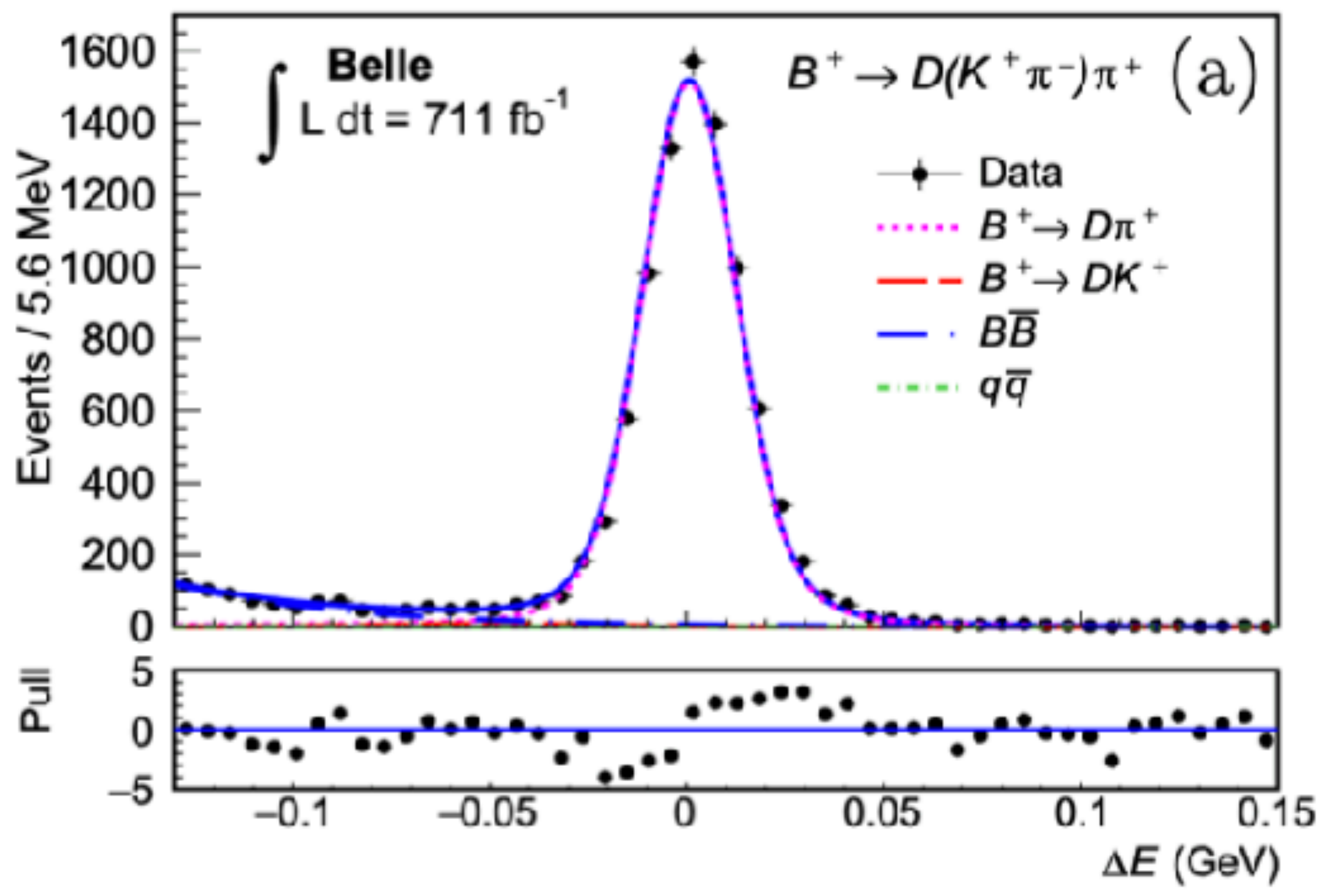
$$\mathcal{A}_{CP\pm} \equiv \frac{\mathcal{B}(B^- \to D_{CP\pm}K^-) - \mathcal{B}(B^+ \to D_{CP\pm}K^+)}{\mathcal{B}(B^- \to D_{CP\pm}K^-) + \mathcal{B}(B^+ \to D_{CP\pm}K^+)}$$

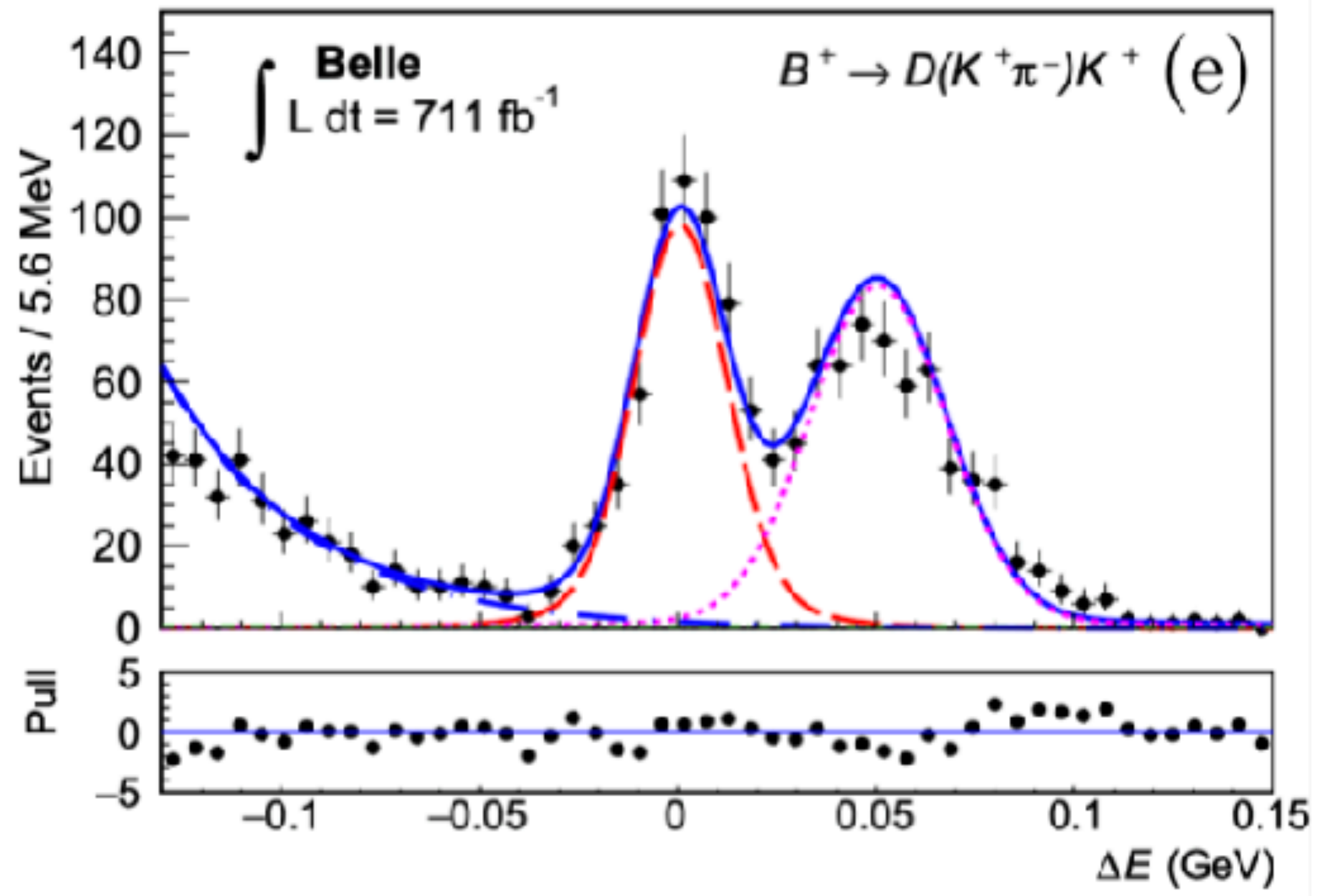
$$\mathcal{R}_{CP\pm} \approx \frac{R_{CP\pm}}{R_{\text{flav}}}$$

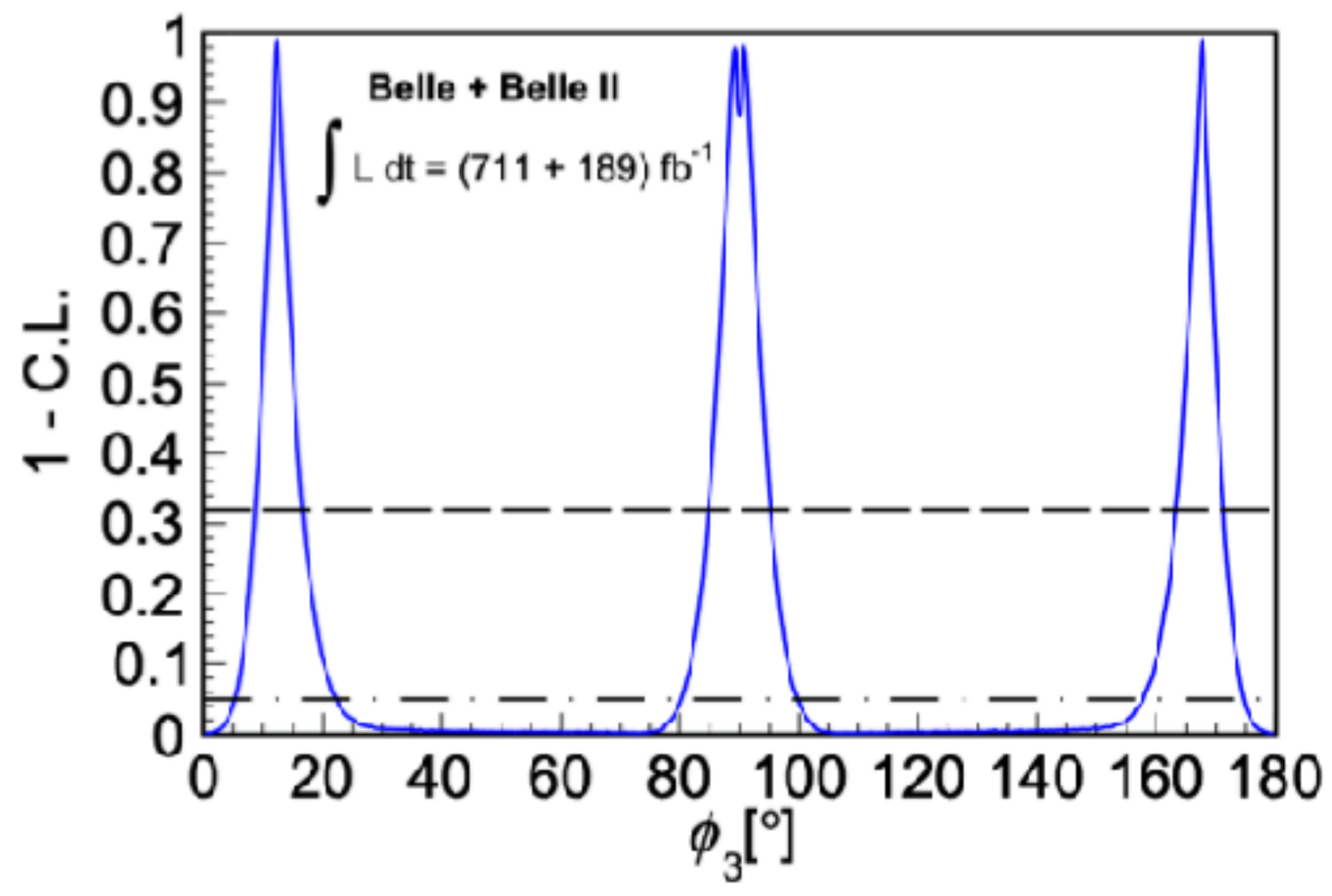
$$\mathcal{R}_{CP\pm} = 1 + r_B^2 \pm 2 r_B \cos\delta_B \cos\phi_3$$

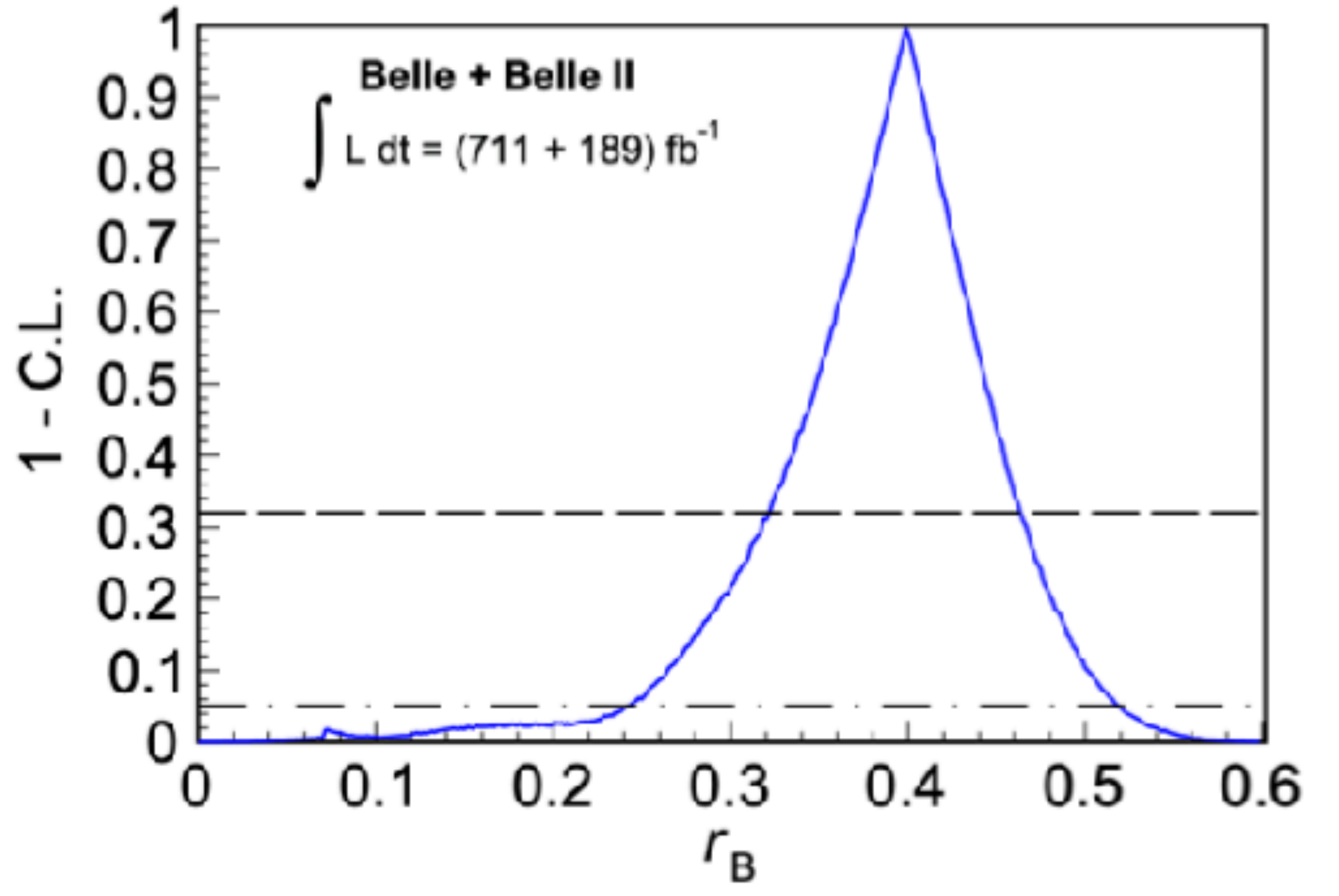
$$\mathcal{A}_{CP\pm} = \pm 2 r_B \sin\delta_B \sin\phi_3 \,/\, \mathcal{R}_{CP\pm}$$

	68.3% CL	95.4% CL
	[8.5, 16.5]	[5.0, 22.0]
ϕ_3 (°)	[84.5, 95.5]	[80.0, 100.0]
	[163.3, 171.5]	[157.5, 175.0]
r_B	[0.321, 0.465]	[0.241, 0.522]









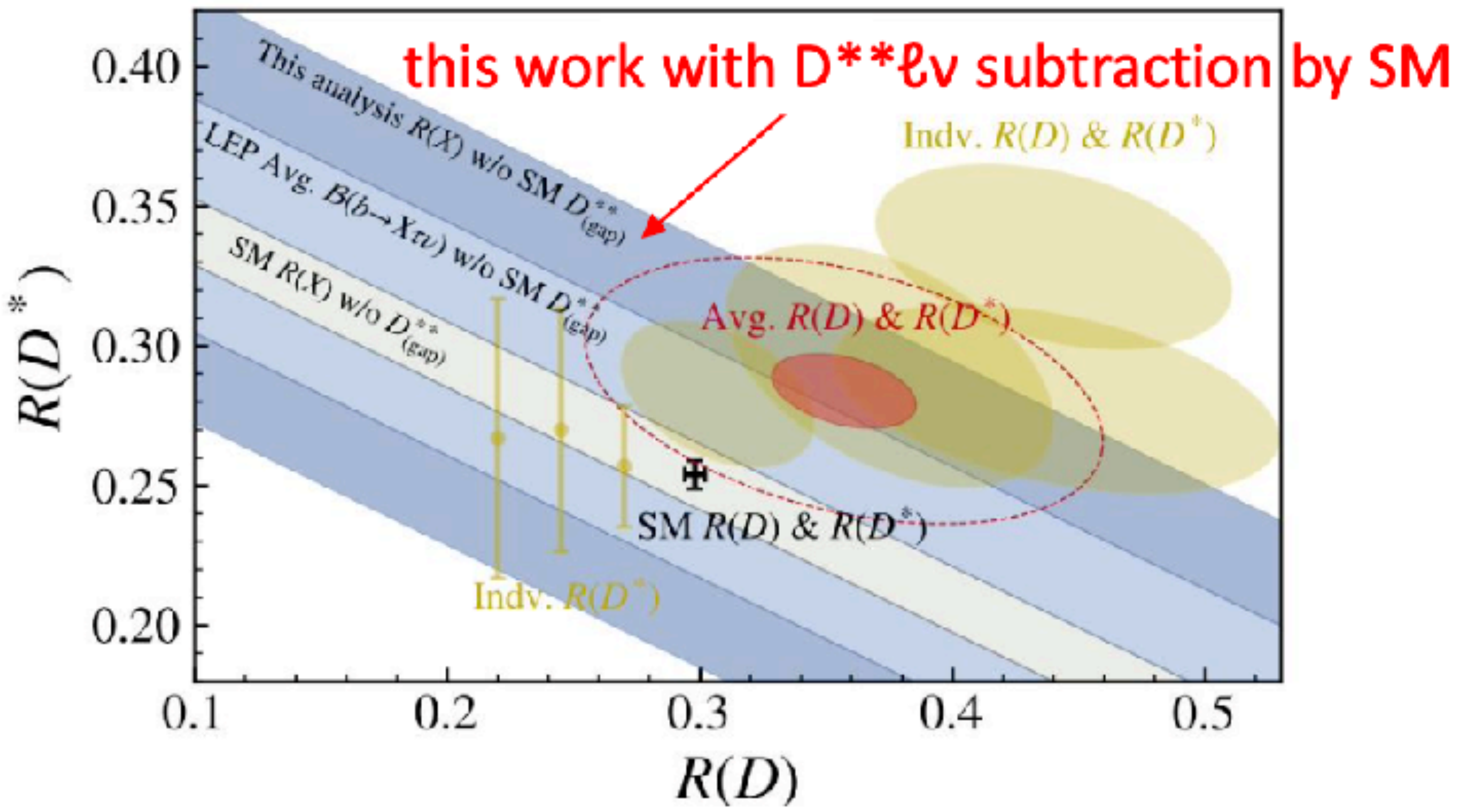
R(X) Result

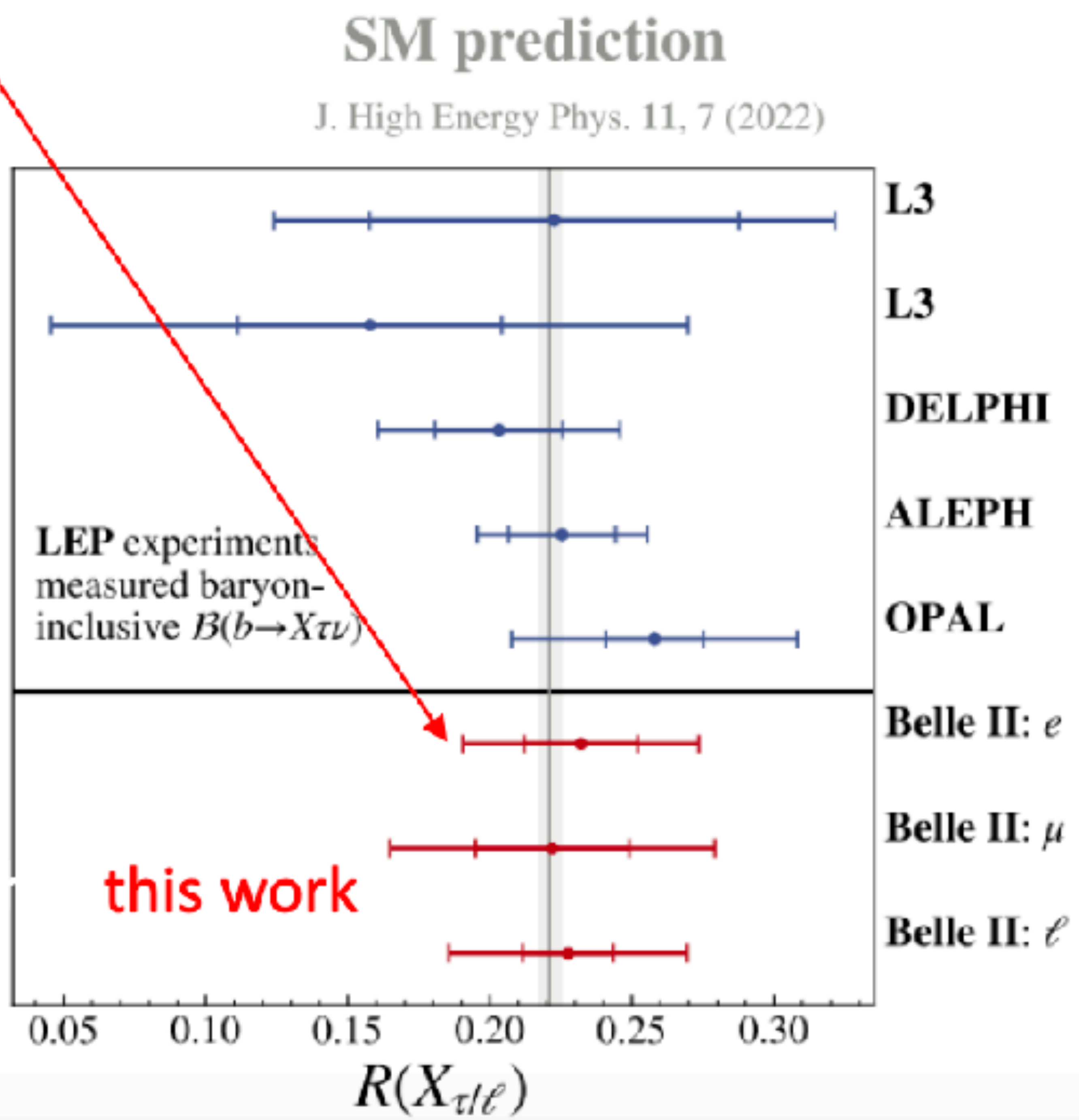
-The first results of $R(X) = \frac{\mathcal{B}(B \to X\tau\nu_\tau)}{\mathcal{B}(B \to X\ell\nu_\ell)}$ at B factory:

$$R(X_{\tau/e}) = 0.232 \pm 0.042, [0.020\,(\text{stat}), 0.037\,(\text{syst})]$$
$$R(X_{\tau/\mu}) = 0.222 \pm 0.057, [0.027\,(\text{stat}), 0.050\,(\text{syst})]$$
$$R(X_{\tau/\ell}) = 0.228 \pm 0.039, [0.016\,(\text{stat}), 0.036\,(\text{syst})]$$

Major systematics: MC statistics, PDF shape, BR of B→D**ℓν

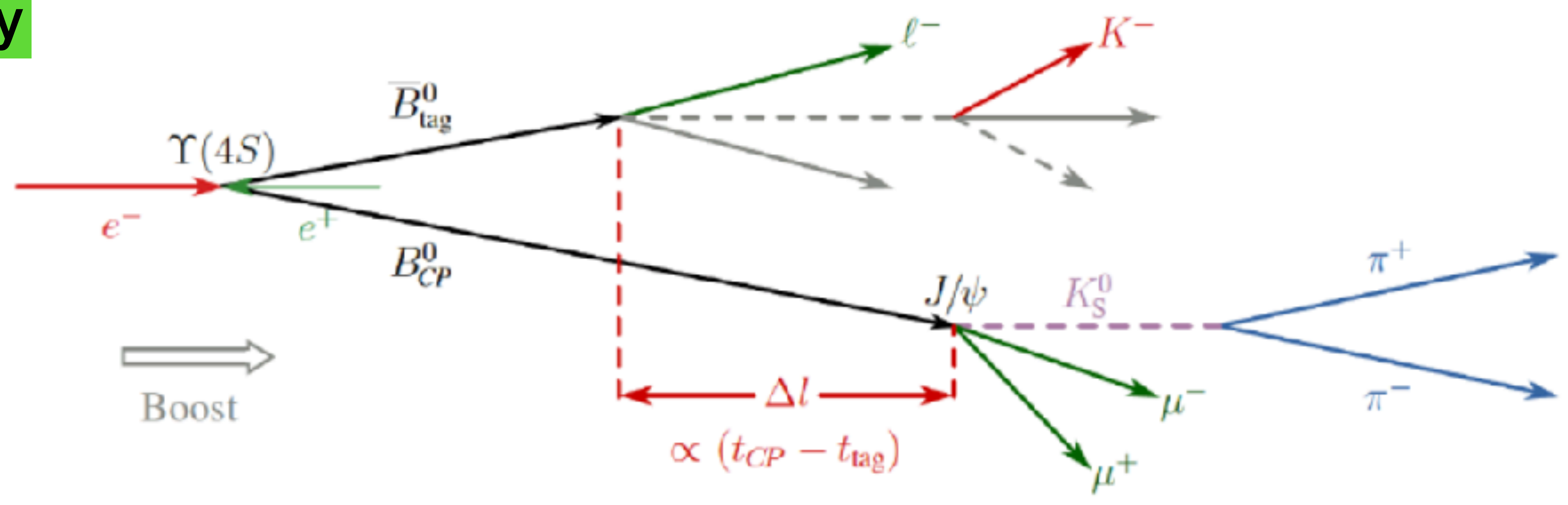
-Consistent with SM prediction





$\sin 2\phi_1$ using $B^0 \to K_S^0 J/\psi$

preliminary

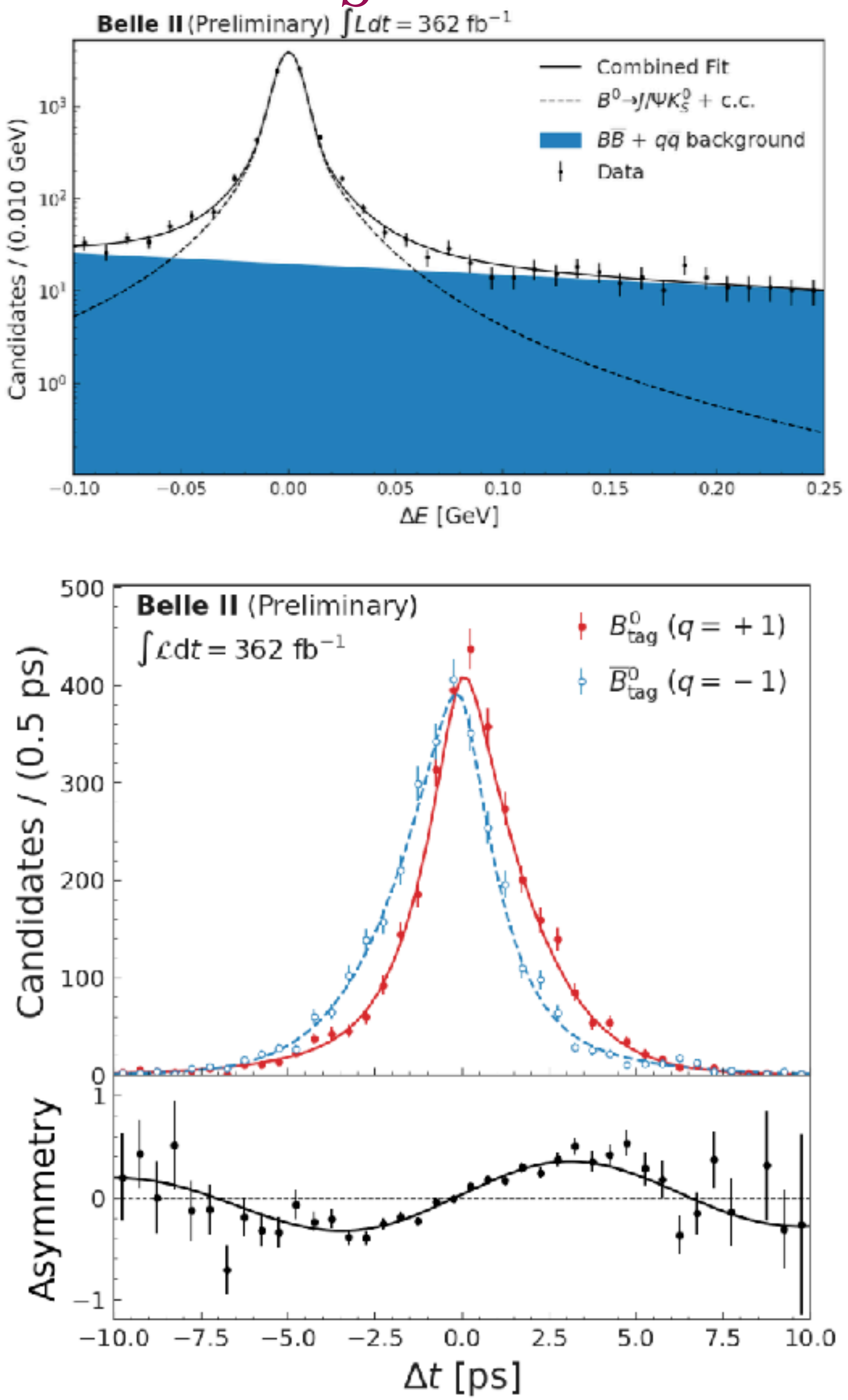


- Use $J/\psi \to e^+e^-, \mu^+\mu^-, K_S^0 \to \pi^+\pi^-$
- Analysis method:
  - Employ Graph Flavor tagger based on Dynamic Graph Convolution Neural Network (GFlaT)
  - Determine signal yields and subtract background using sWeights from ΔE fit
  - Fit Δt to extract S_{CP} and C_{CP}:

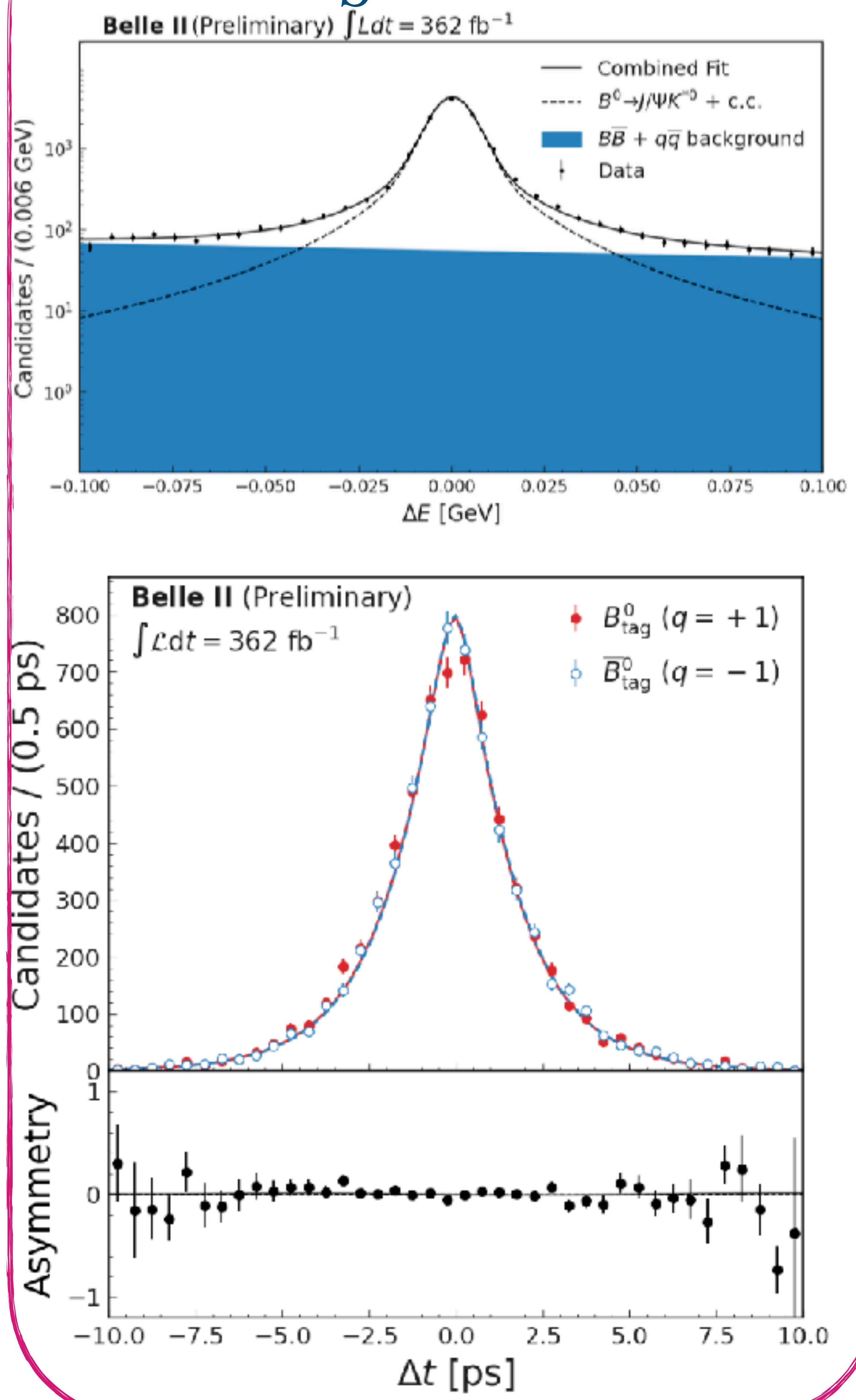
$$f_{CP}^{\rm true} = \frac{1}{4\tau_B^0} e^{-|\Delta t|/\tau_B^0}(1 + q[S_{CP}\sin(\Delta m \Delta t) - C_{CP}\cos(\Delta m \Delta t)])$$

  - SM expectation: $S_{CP} = \sin 2\phi_1$, and $C_{CP} = 0$
  - Flavor resolution effect and resolution function taken from calibration with $B^0 \to D^{(*)+}\pi^-$

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



$B^0 \to K_S^{*0} J/\psi$



cross check:

SM expectation: $S_{cp} = C_{CP} = 0$

$$S_{cp} = 0.008 \pm 0.019$$

$$C_{cp} = -0.018 \pm 0.026$$

$$C_{CP} = -0.035 \pm 0.026\,(\text{stat}) \pm 0.012\,(\text{syst})$$
$$S_{CP} = \quad 0.724 \pm 0.035\,(\text{stat}) \pm 0.014\,(\text{syst})$$

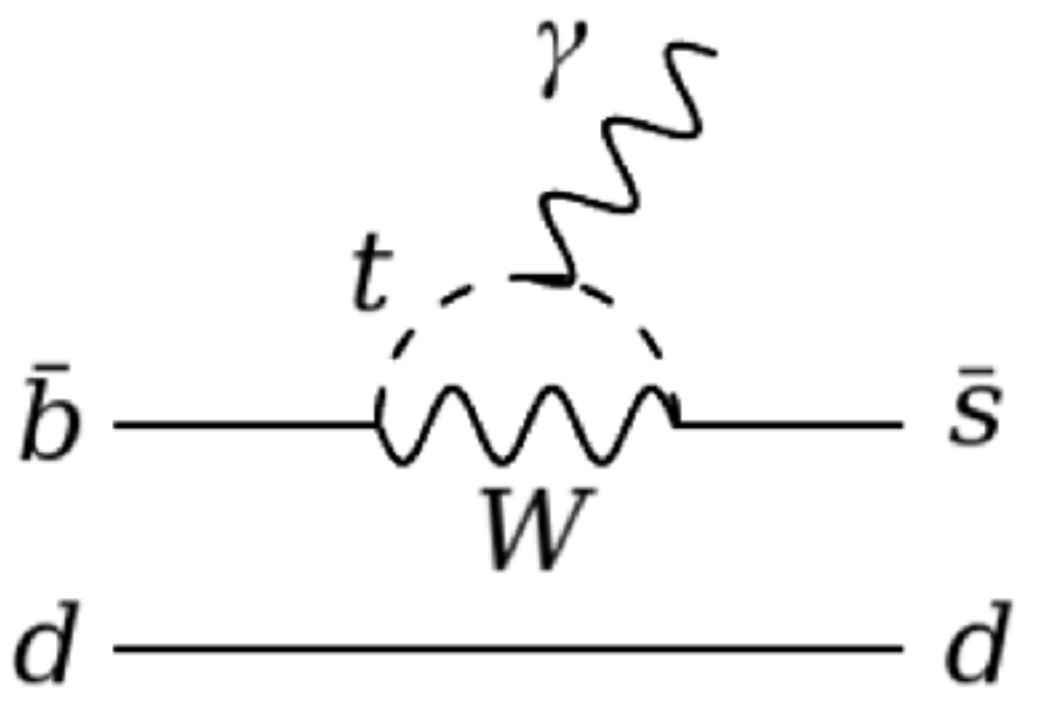
Previous stat. uncertainties:
Belle II ICHEP22: σS_{CP} =0.062 (improvement equivalent to 3.1X larger dataset)

Previous results (JPsi KS **only**):
Belle 2012: σS_{CP} = 0.029
BaBar 2009: σS_{CP} = 0.036
LHCb 2023: σS_{CP} = 0.015

GFlaT established as standard tool for forthcoming TDCPV analyses

CP asymmetries in $B^0 \to K_S^0 \pi^0 \gamma$

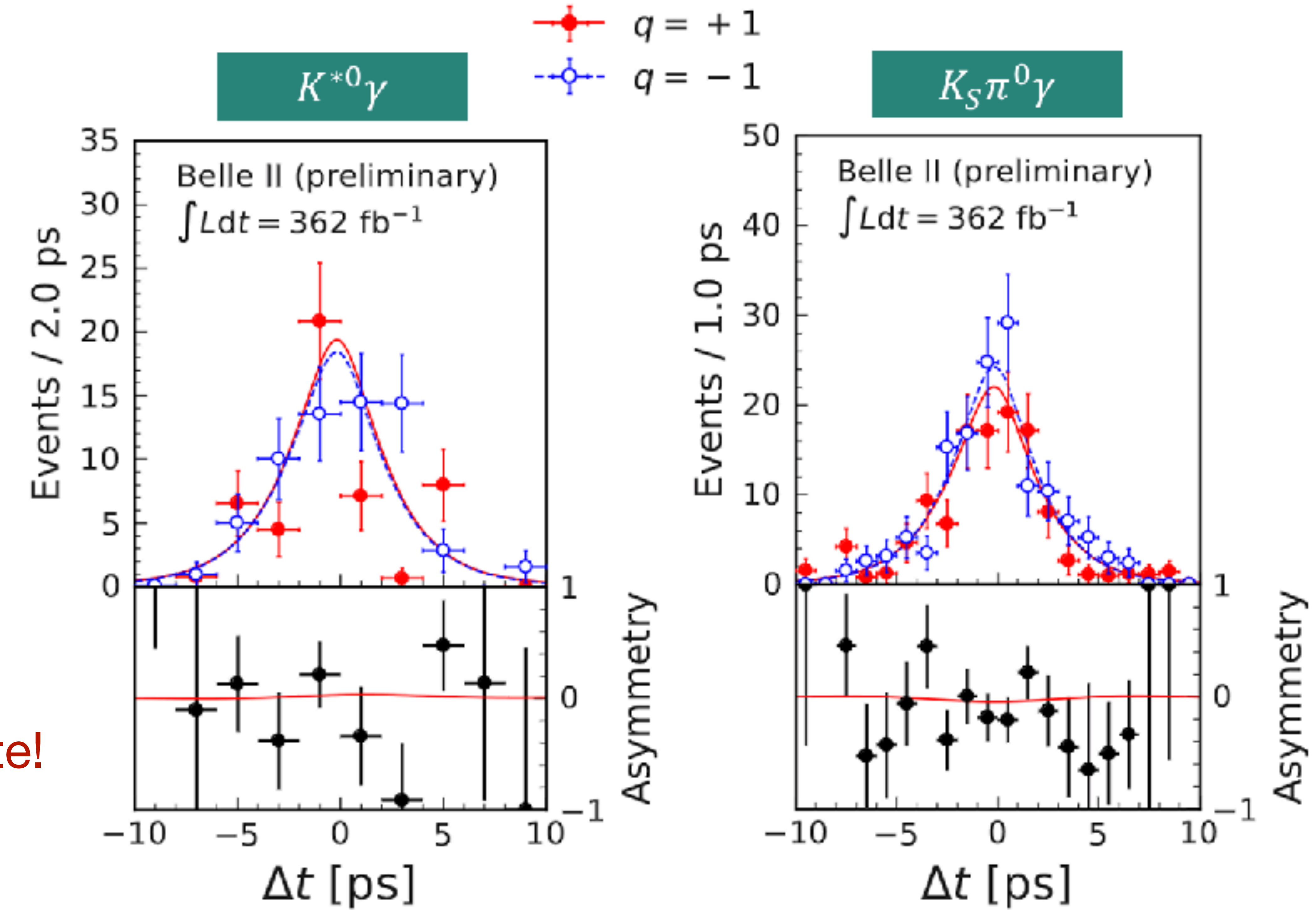
preliminary



- $b \to s\gamma$ proceeds via one-loop diagrams
  - Sensitive to BSM physics
- Mixing-induced time-dependent CP asymmetries (S) are expected to be small
  - $S_{CP} = -0.035 \pm 0.017$(arXiv:hep-ph/0406055)

$$S(K^{*0}\gamma) = 0.00^{+0.27+0.03}_{-0.26-0.04},$$
$$C(K^{*0}\gamma) = 0.10 \pm 0.13 \pm 0.03,$$
$$S(K^0_S\pi^0\gamma) = 0.04^{+0.45}_{-0.44} \pm 0.10,$$
$$C(K^0_S\pi^0\gamma) = -0.06 \pm 0.25 \pm 0.07,$$

Most precise result up to date!

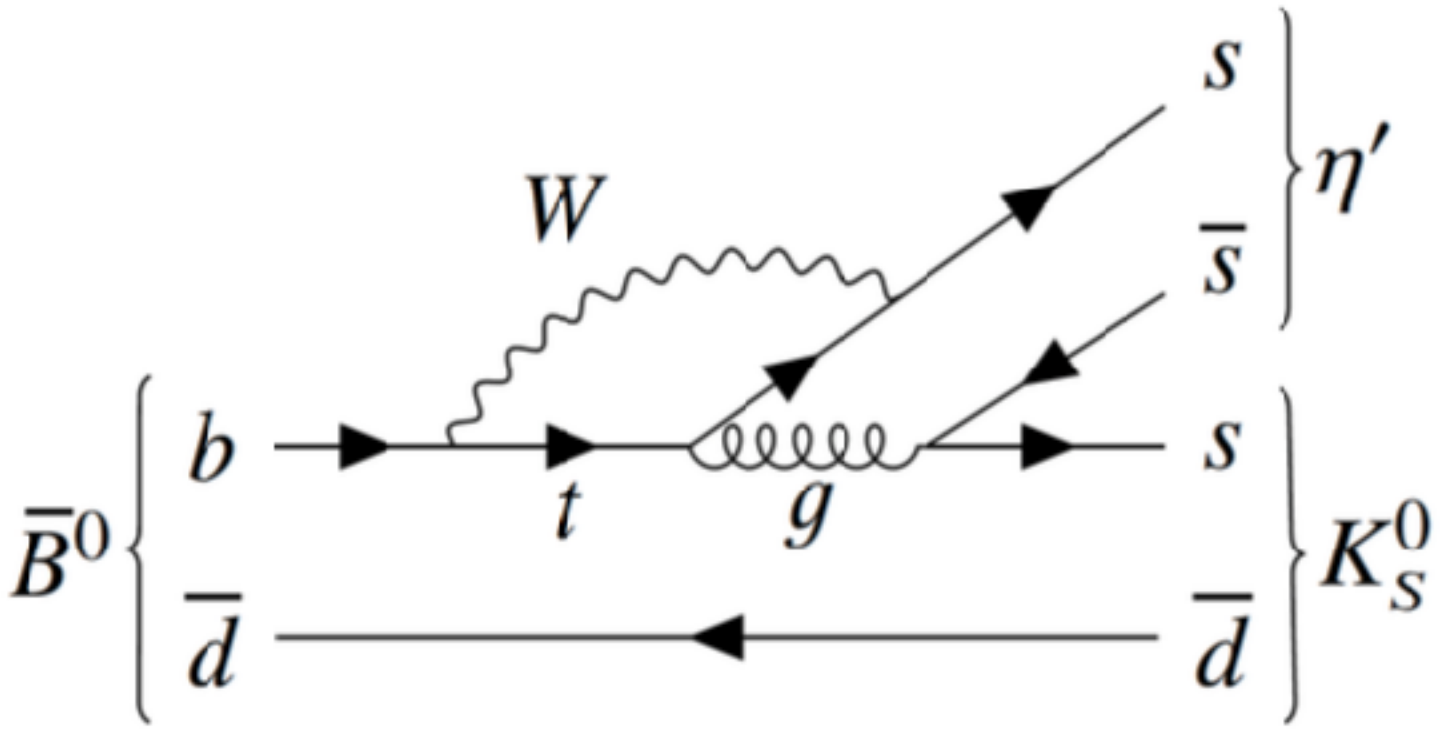


HFLAV:
$K^{*0}\gamma$: $C_{CP} = -0.04 \pm 0.14$ $S_{CP} = -0.16 \pm 0.22$
$K_S\pi^0\gamma$: $C_{CP} = -0.07 \pm 0.12$ $S_{CP} = -0.15 \pm 0.20$

22.08.2023 *The HFLAV $K_S\pi^0\gamma$ values include $K^{*0}\gamma$

CP asymmetries in $B^0 \to \eta' K_S^0$

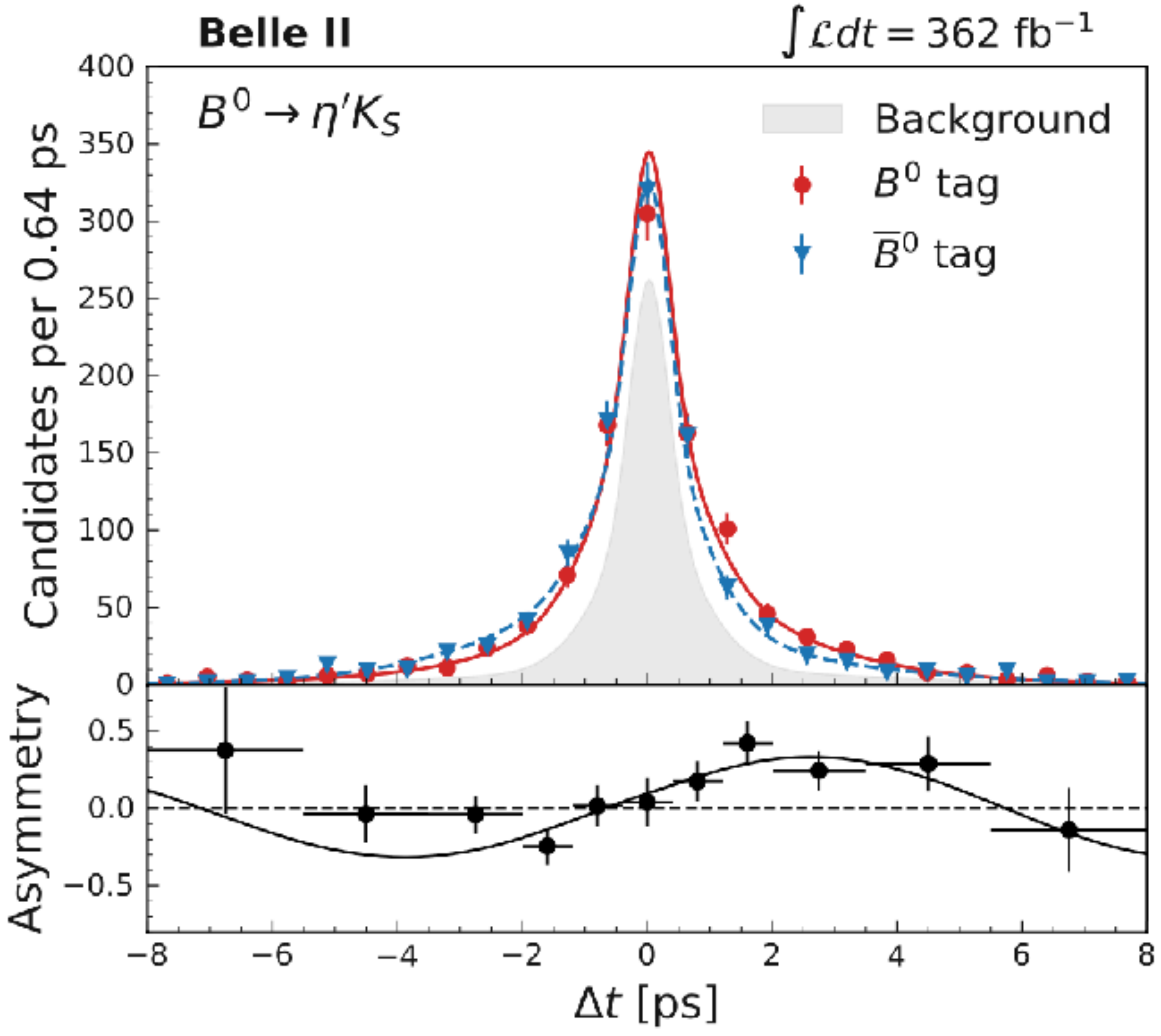
preliminary



- Process $b \to sq\bar{q}$ via loop amplitude
- High transition rate relative to other gluonic penguins
- Addition source BSM could be involved
- Deviation from $\sin 2\phi_1$ would suggest BSM physics
- Cross checked with $B^+ \to \eta' K^+$, where no CP asymmetry is expected

$$C_{\eta' K_S^0} = -0.19 \pm 0.08 \pm 0.03,$$
$$S_{\eta' K_S^0} = 0.67 \pm 0.10 \pm 0.04,$$

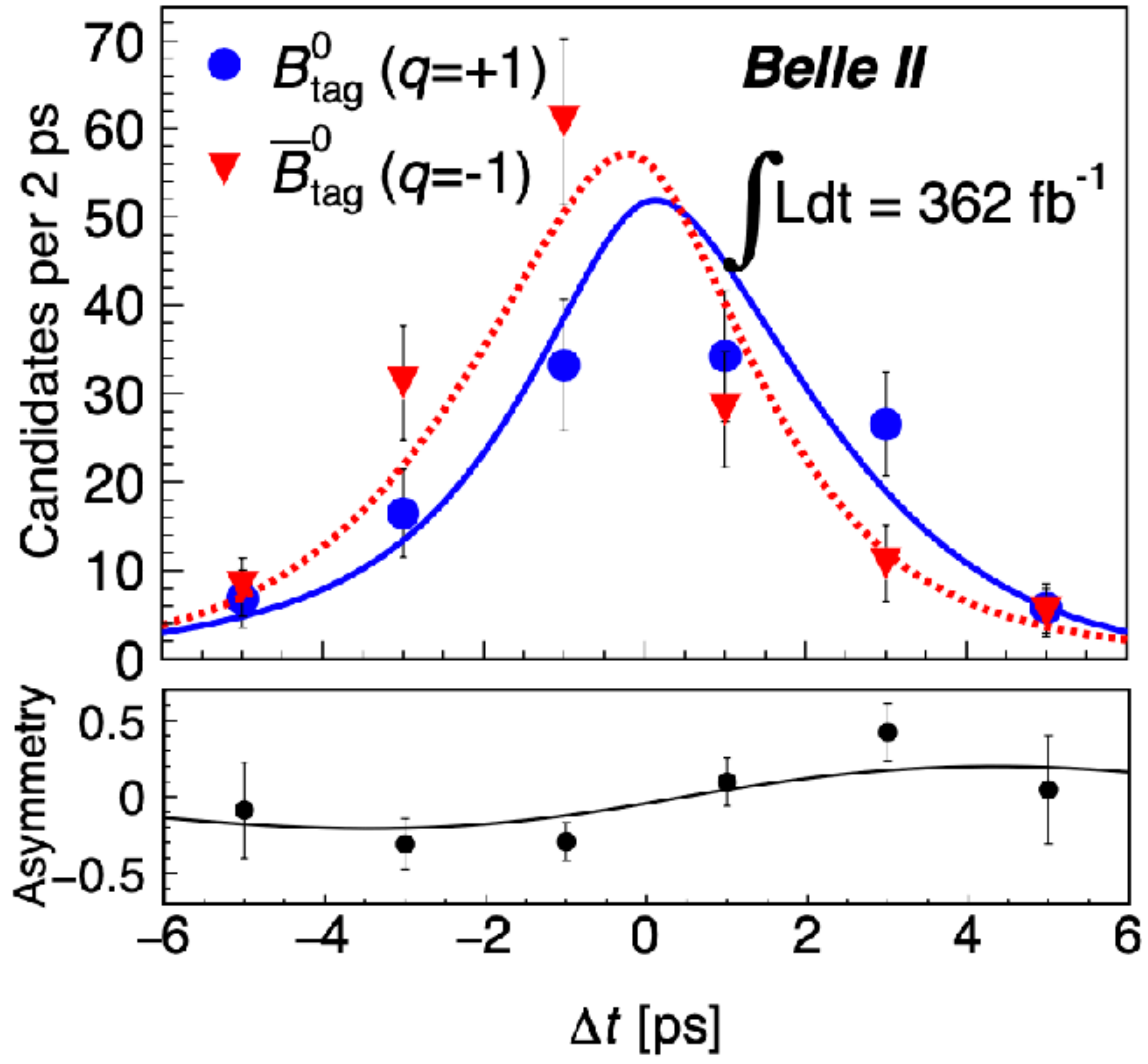
$C = -0.05 \pm 0.04$ and $S = 0.63 \pm 0.06$ from HFLAV



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

PRL 131, 111803 (2023)

- Process $b \to sd\bar{d}$ via loop amplitude
- High transition rate relative to other gluonic penguins
- Addition source BSM could be involved
- Deviation from $\sin 2\phi_1$ would suggest BSM physics
- Cross checked with $B^+ \to \eta' K^+$, where no CP asymmetry is expected



Time dependent CPV using $B^0 \to K_S^0 K_S^0 K_S^0$

preliminary

- Current world average:

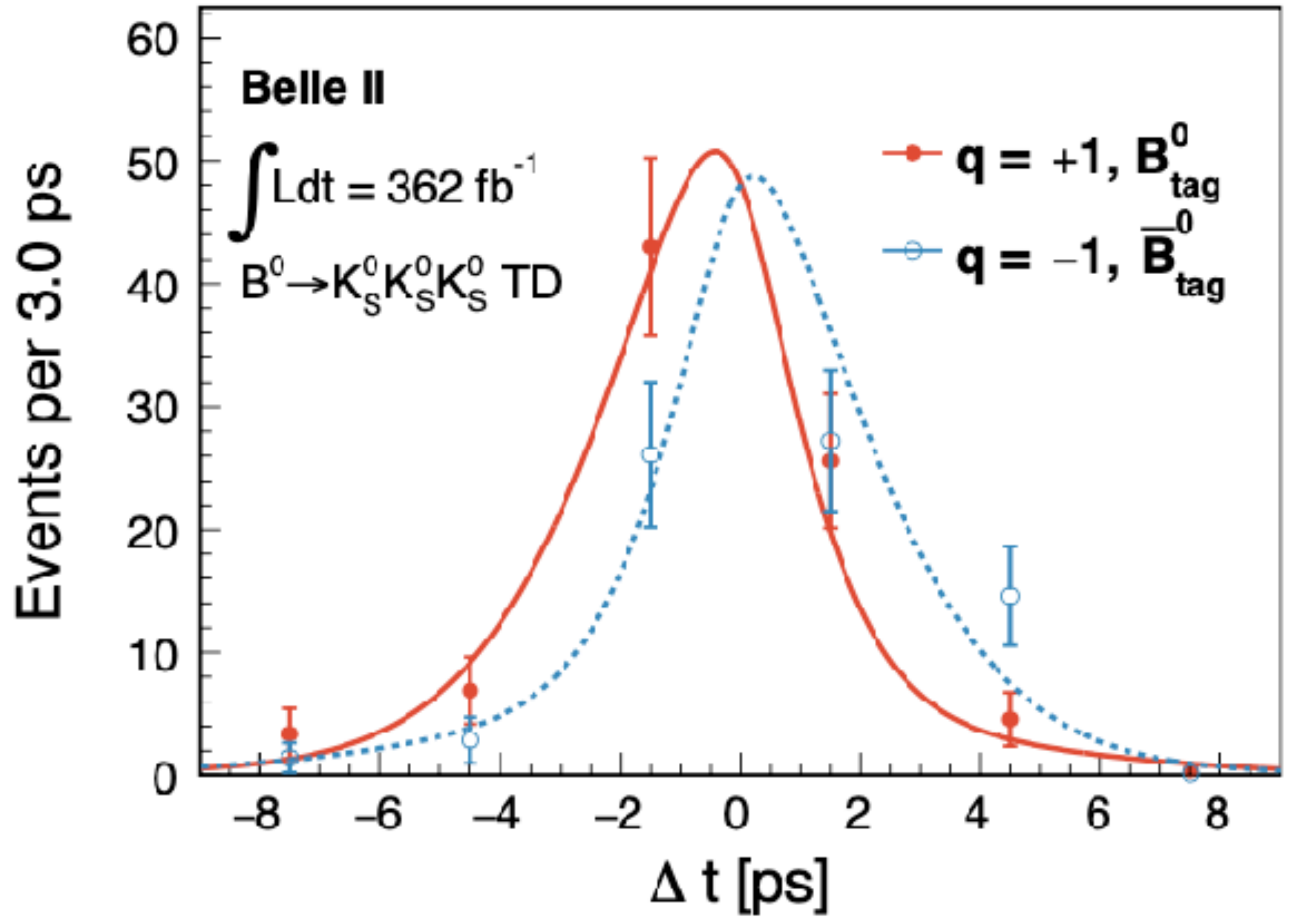
$$C = -0.15 \pm 0.12$$

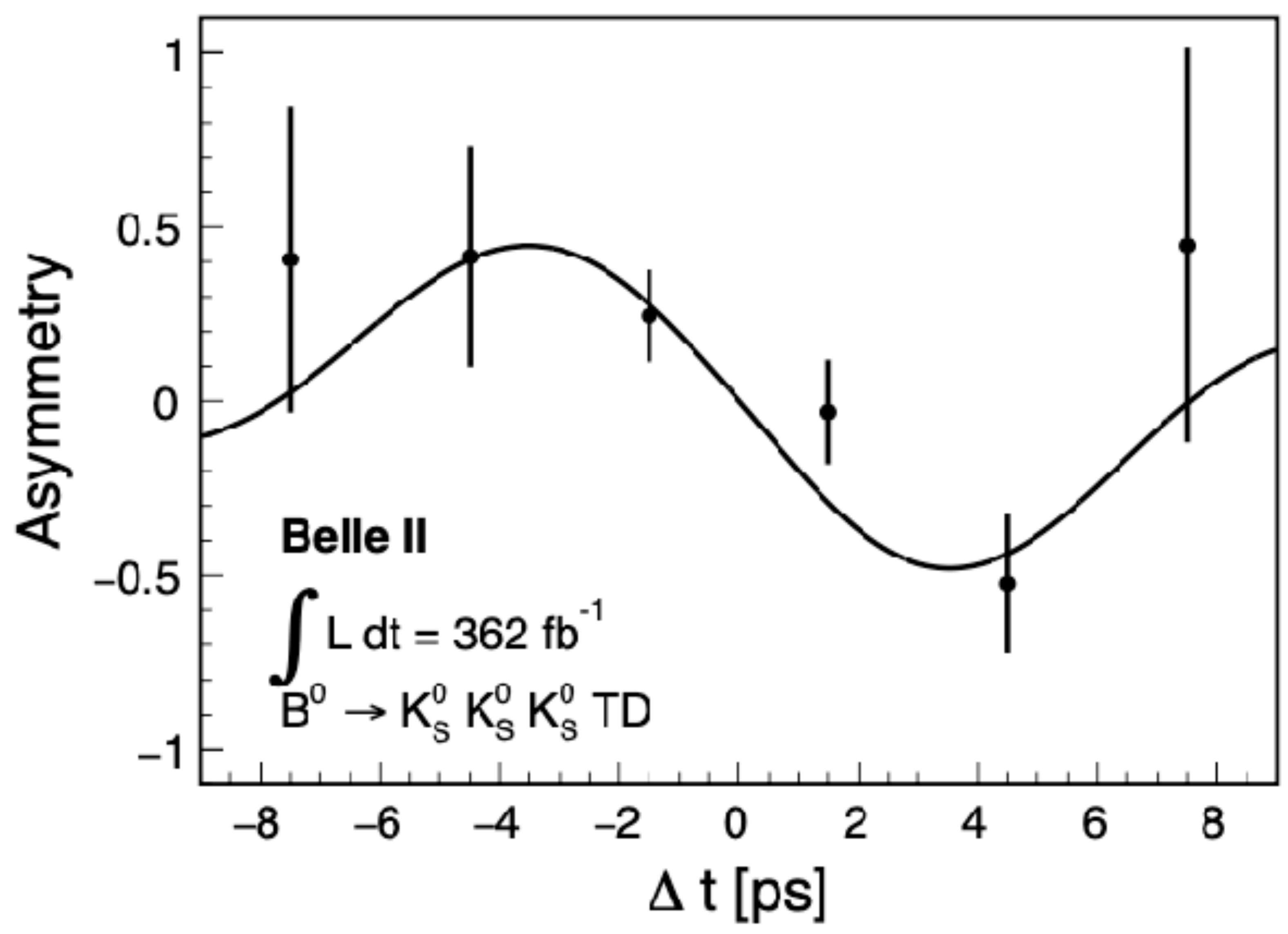
$$S = -0.83 \pm 0.17$$

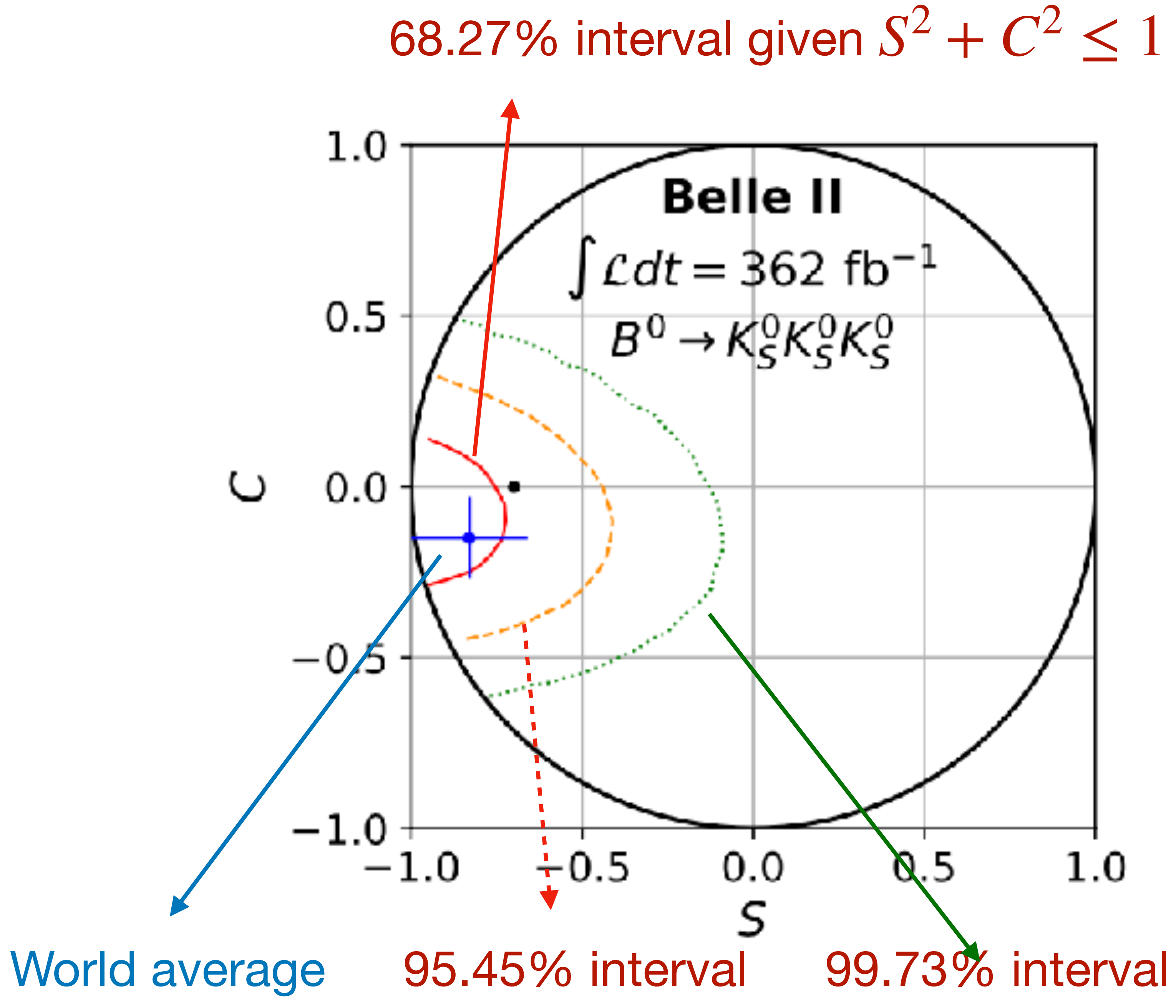
Need improvement on uncertainties.

Use the likelihood from the fit,

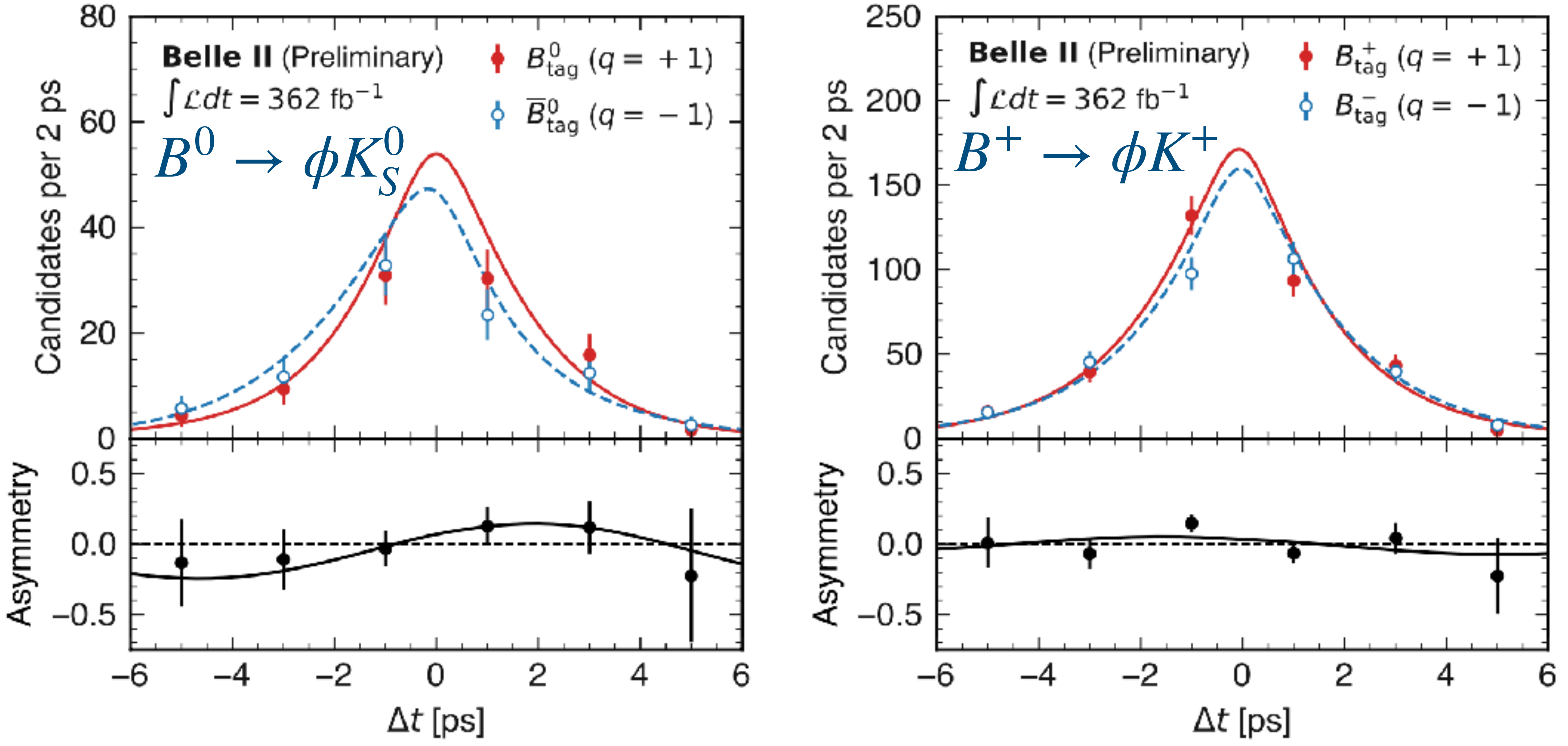
resulting 2D confidence intervals







$B^0 \to \phi K_S^0$ PRD 108, 072012 (2023)



- Current world average:

$$C = 0.01 \pm 0.14$$

$$S = 0.74^{+0.11}_{-0.13}$$

whereas C is expected to be zero in SM, with $S = 0.02 \pm 0.01$

- Cross checked with $B^+ \to \phi K^+$, resulting $C = -0.12 \pm 0.10$ and $S = -0.09 \pm 0.12$

$$C = -0.31 \pm 0.20 \pm 0.05$$

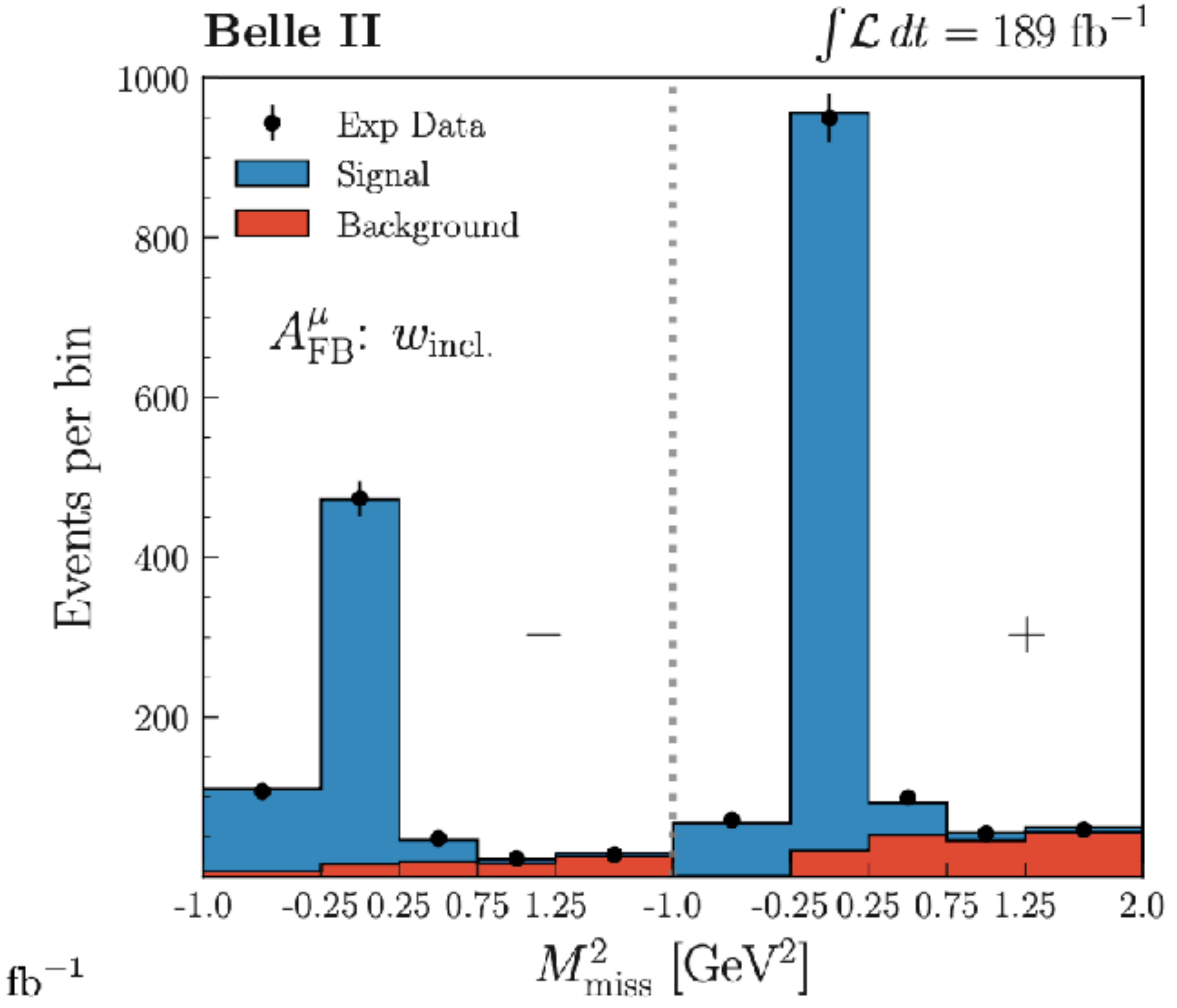
$$S = 0.54 \pm 0.26^{+0.06}_{-0.08}$$

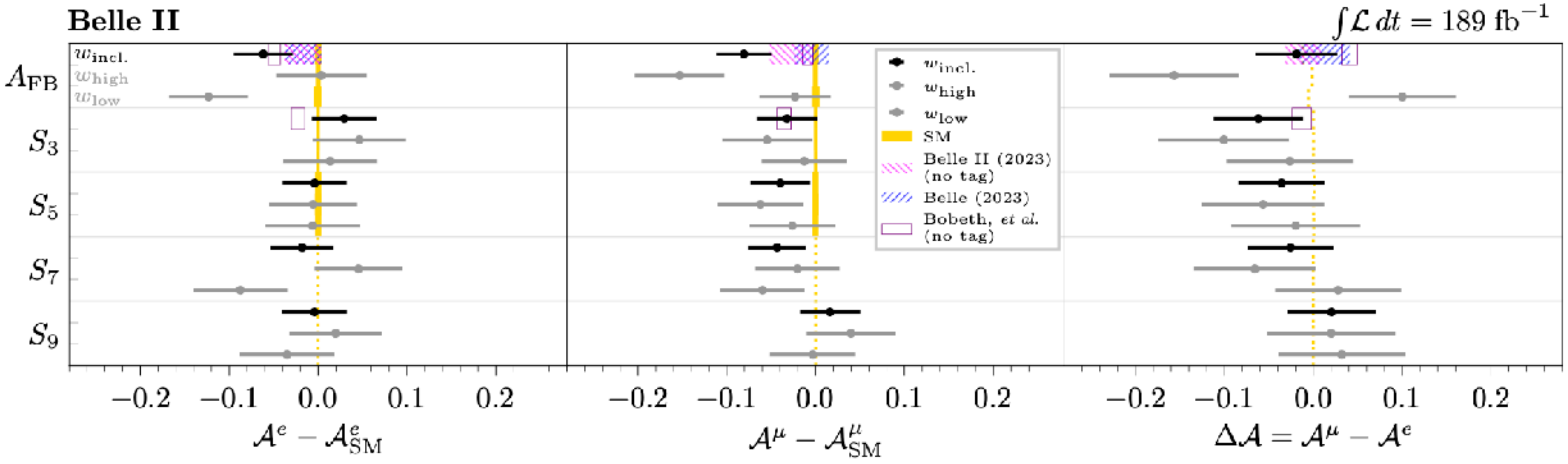
- *Compatible with previous determinations from Belle and BABAR.*
- *Similar uncertainty on C despite of smaller data sample.*
- *Improvement on the statistical uncertainty on S for the same number of signal events.*

Angular asymmetries using $B^0 \to D^{*-}\ell^+\nu_\ell$

PRL 131, 181801 (2023)

- $B^0 \to D^{*-}\ell\nu$ is mediated in the SM via W-boson exchange.
- Characterized in terms of a recoil parameter and 3 helicity angles.
- Calculate the asymmetry: $\mathscr{A}_x(w) = \dfrac{N_x^+ w - N_x^-(w)}{N_x^+ w + N_x^-(w)}$
- Difference $\Delta A_x(w) = A_x^\mu(w) - A_x^e(w)$, is sensitive to LUV.
- Separate signal candidates into angular categories + and – based on the measured value of x.





First comprehensive tests of LU in the angular distributions of semileptonic B decays.

Agrees well with SM.

Direct CPV using $B \to K\pi$ and $B \to \pi\pi$

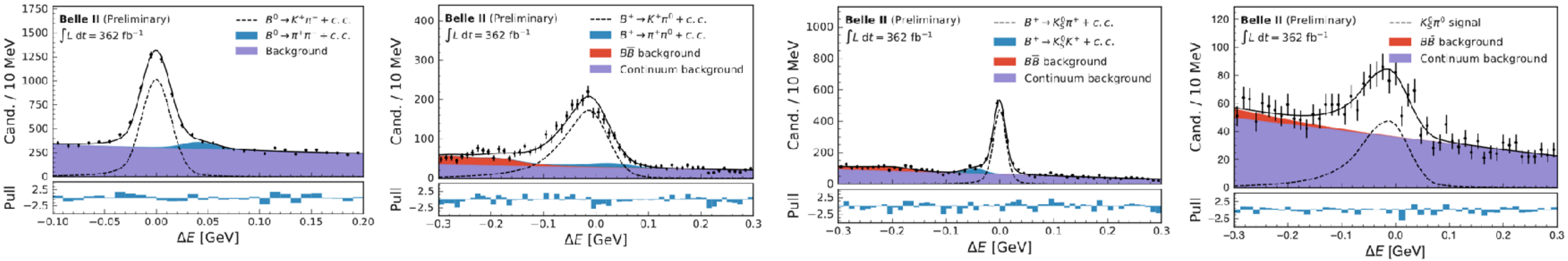
arXiv:2310.06381

- Charmless hadronic B meson decays feature non-negligible contributions from loop amplitudes.
- Sensitive to contributions from non-SM physics.

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

- Belle II measures all modes in coherent way with unique access to $B^0 \to K_S^0\pi^0$

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



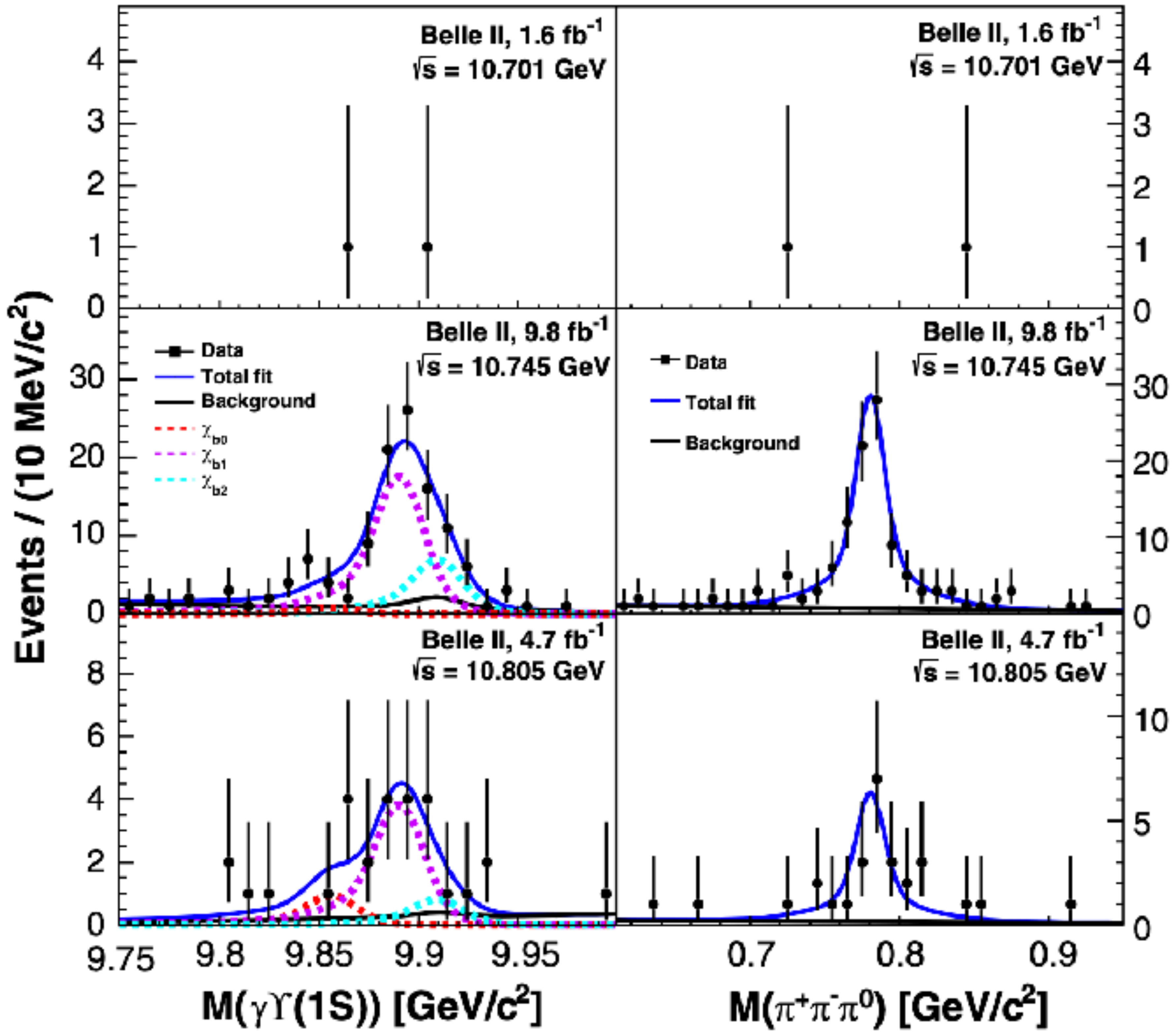
$I_{K\pi} = -0.03 \pm 0.13 \pm 0.05$ (world average: $I_{K\pi} = 0.13 \pm 0.11$)

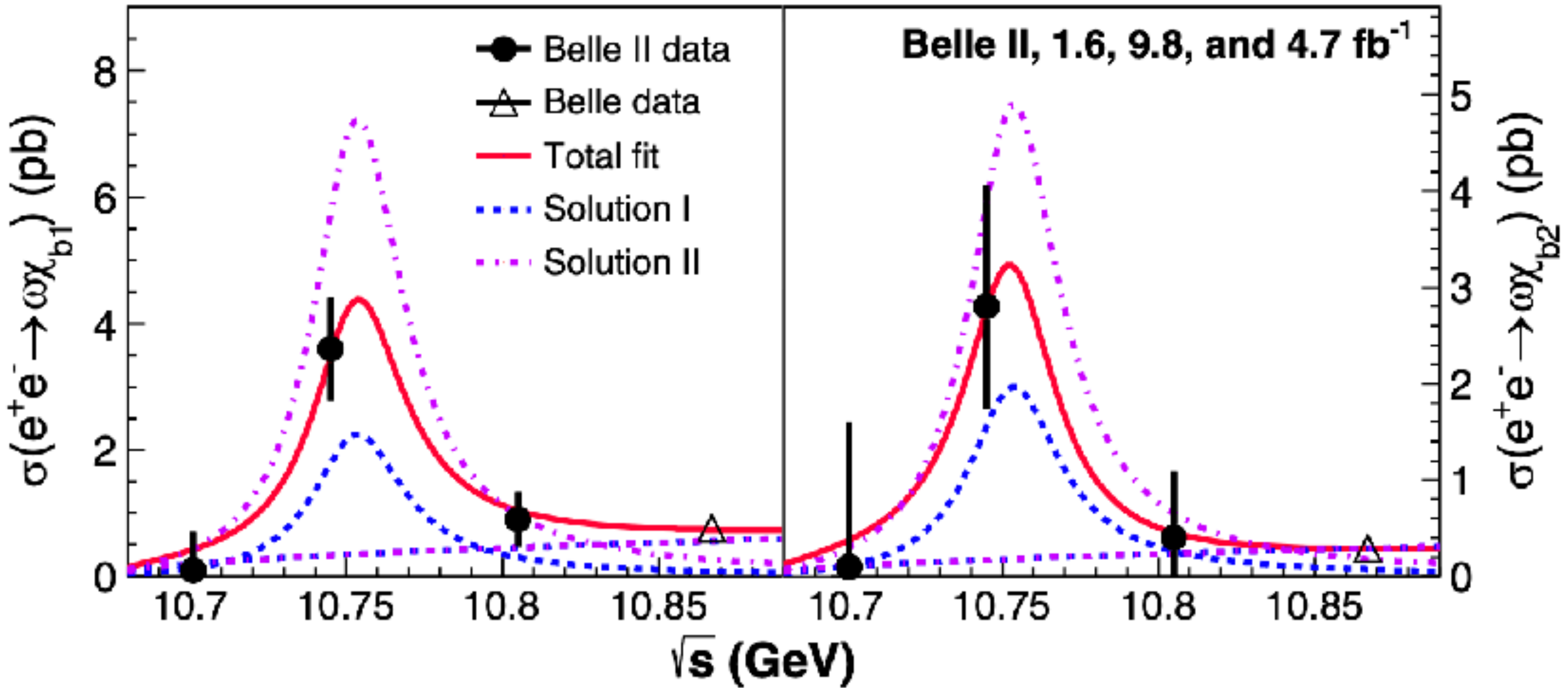
competitive with world average with $362 fb^{-1}$

Observation of $Y(10753) \to \omega\chi_{bJ}$ in $e^+e^- \to \gamma\omega\Upsilon(1S)$

PRL 130, 091902 (2023)

Clear $\omega\chi_{bJ}$ signals at $\sqrt{s} = 10.745$ and 10.805 GeV





$\Gamma_{ee}\mathcal{B}_f$	Solution I	Solution II
$\Gamma_{ee}\mathcal{B}(\Upsilon(10753) \to \omega\chi_{b1})$	$(0.63 \pm 0.39 \pm 0.20)$ eV	$(2.01 \pm 0.38 \pm 0.76)$ eV
$\Gamma_{ee}\mathcal{B}(\Upsilon(10753) \to \omega\chi_{b2})$	$(0.53 \pm 0.46 \pm 0.15)$ eV	$(1.32 \pm 0.44 \pm 0.55)$ eV

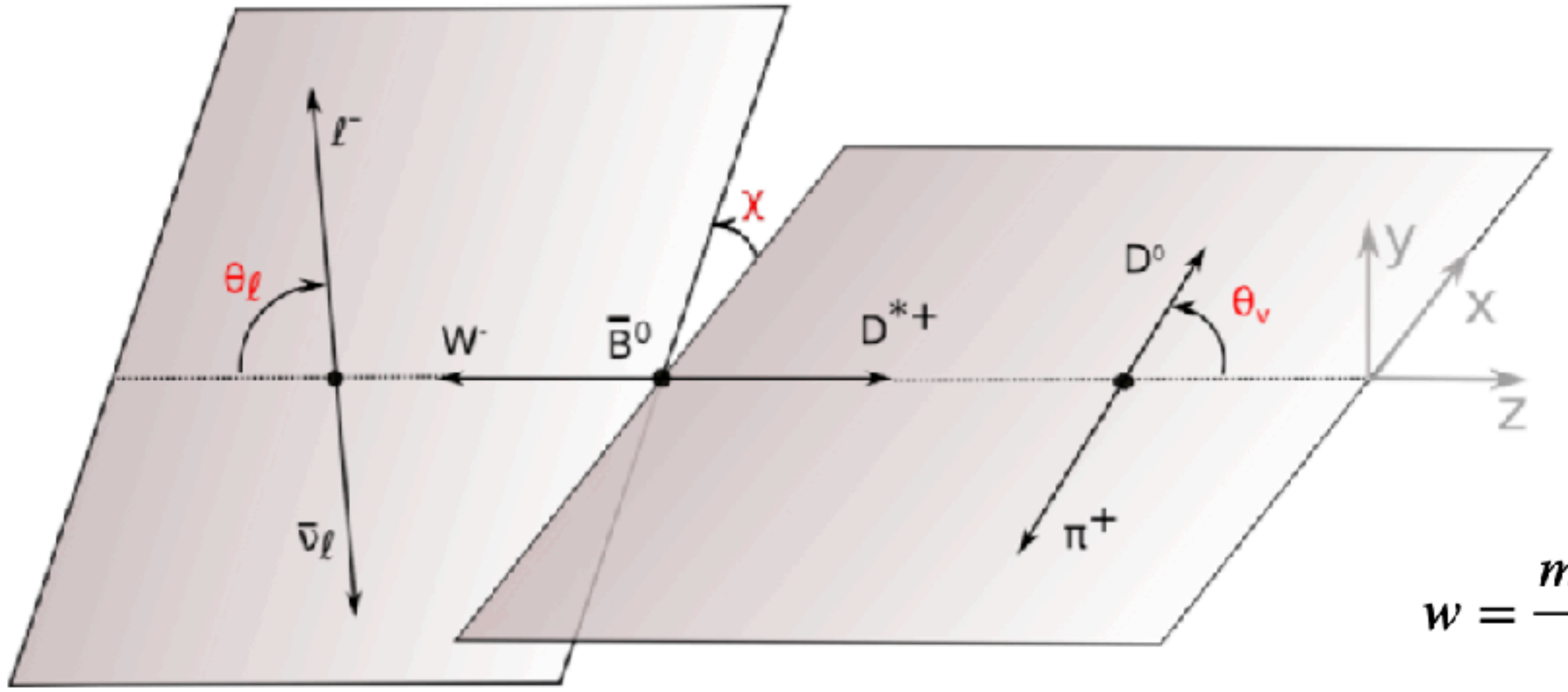
- $\dfrac{\Gamma_{ee}\mathcal{B}(\Upsilon(10753) \to \omega\chi_{b1})}{\Gamma_{ee}\mathcal{B}(\Upsilon(10753) \to \omega\chi_{b2})} \sim 1.0$ agrees with the expectation for HQET[3]
- $\dfrac{\Gamma_{ee}\mathcal{B}(\omega\chi_{b1/2})}{\Gamma_{ee}\mathcal{B}(\pi^+\pi^-\Upsilon(2S))^{[2]}} \sim 1.5$ for $\Upsilon(10753)$ and ~ 0.1 for $\Upsilon(10870)$

[1]PRL 113, 142001(2014); [2]. JHEP 10, 220(2019); [3]. arXiv:hep-ph/9908366;

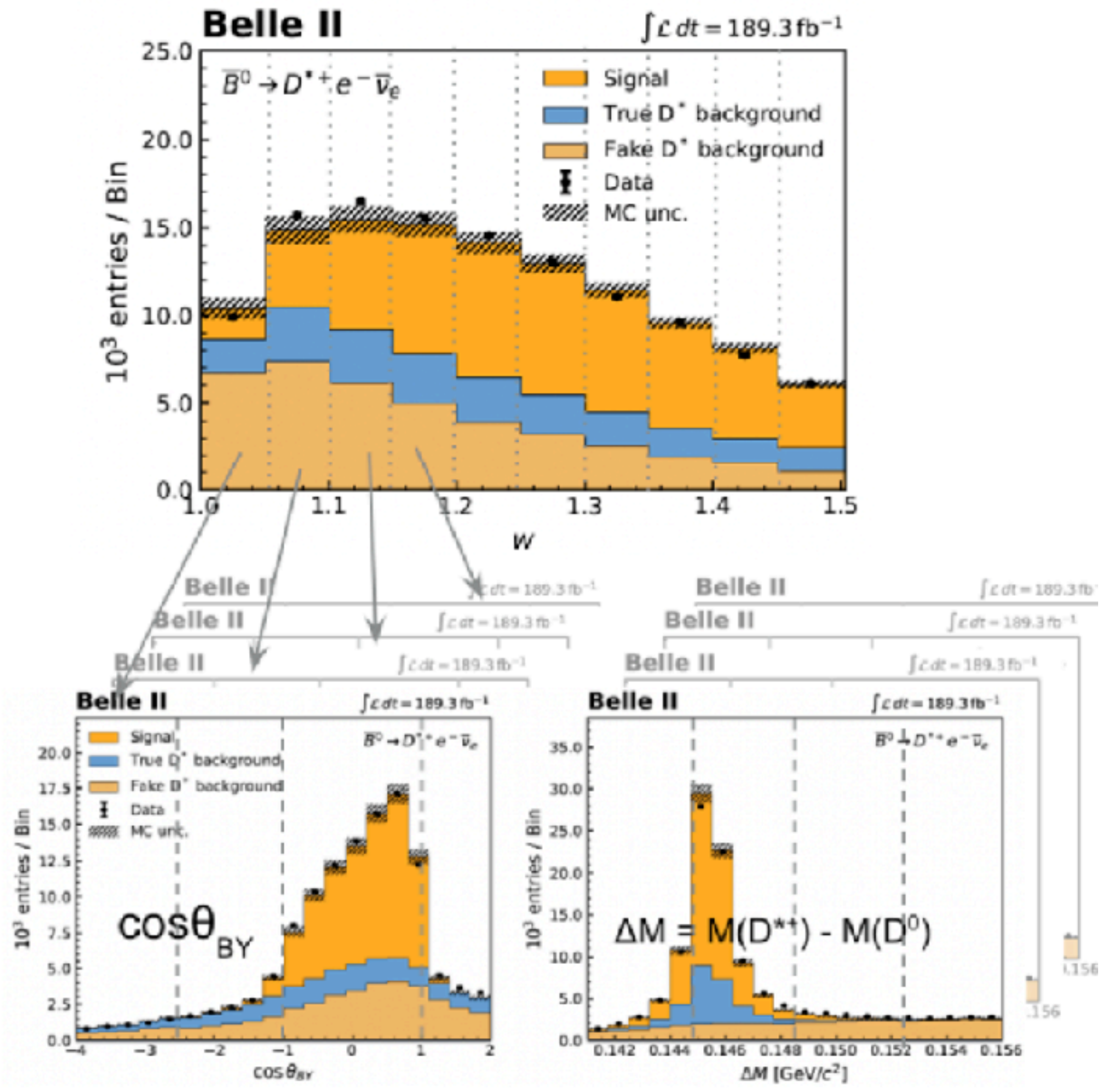
- Confirm the existence of $\Upsilon(10753)$.
- Large difference of $\dfrac{\mathcal{B}(\omega\chi_{bJ})}{\mathcal{B}(\pi^+\pi^-\Upsilon(nS))}$ between $\Upsilon(10753)$ and $\Upsilon(10870)$.

$|V_{cb}|$ using $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$

PRD 108, 092013 (2023)



$$w = \frac{m_{\bar{B}^0}^2 + m_{D^*}^2 - q^2}{2m_{B^0}m_{D^*}}$$

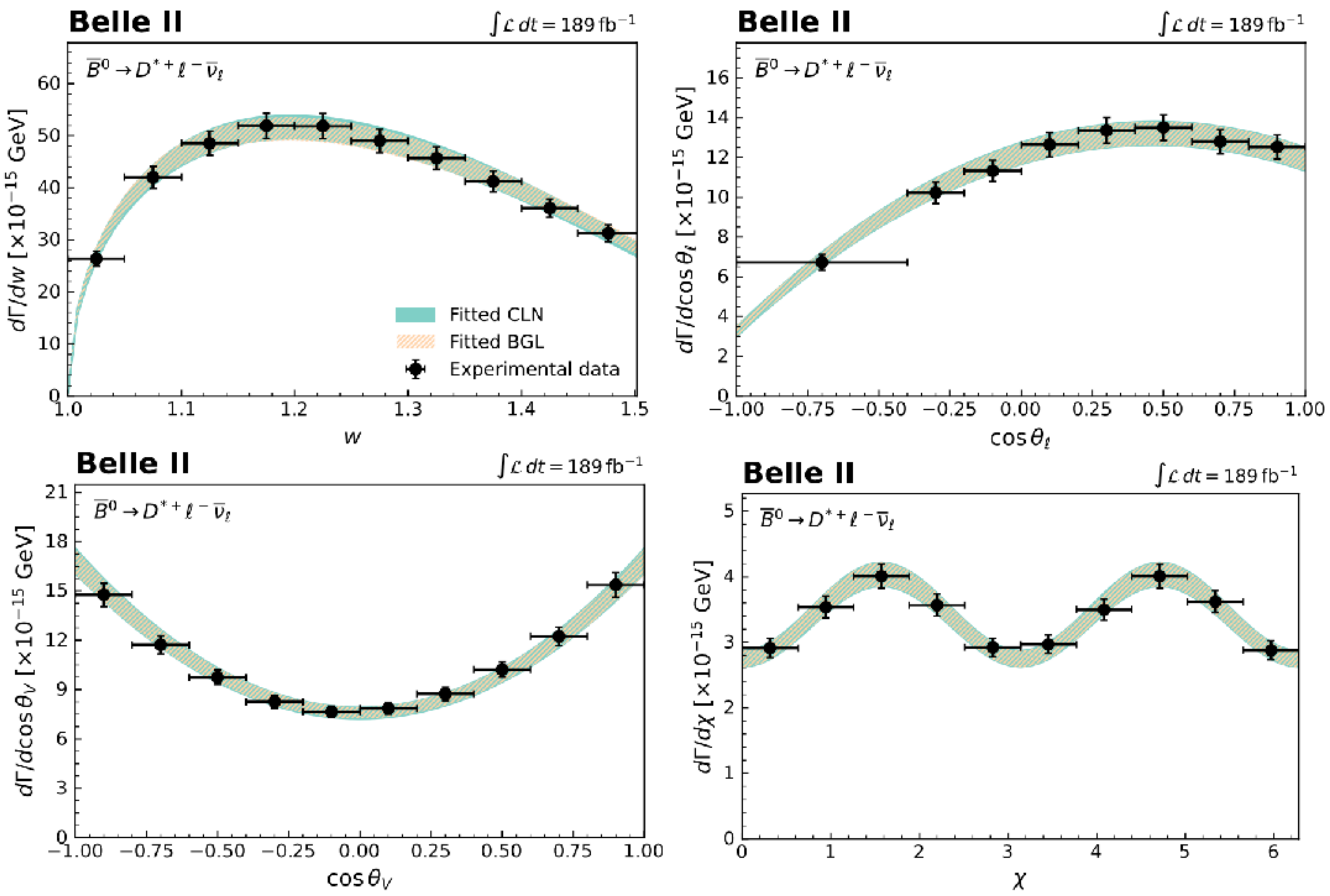


integral projection

- $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ is parameterized by the recoil parameter (w) and three decay angles (θ_l, χ, θ_V)
- 2D-binned likelihood fit to ($\cos\theta_{BY}$, ΔM) for each bin of variables.
    - $\cos\theta_{BY} = \dfrac{2E_B^{CM}E_Y^{CM} - m_B^2 - m_Y^2}{2|p_B^{CM}||p_Y^{CM}|}$, $\Delta M = M(D^{*+}) - M(D)$

- Include all measured w, θ_l, χ, θ_V to extract form factor & |Vcb|

- Fit differential shapes with form factor expansion based on Caprini-Lellouch-Neubert (CLN) [Nucl. Phys. B530, 153 (1998)] & Boyd-Grinstein-Lebed (BGL) parameterisations [Phys. Rev. D56, 6895 (1997)]



$$|V_{cb}|\eta_{\text{EW}}\mathcal{F}(1) = \frac{1}{\sqrt{m_B m_{D^*}}}\left(\frac{|\tilde{b}_0|}{P_f(0)\phi_f(0)}\right)$$

$$|V_{cb}|_{\text{BGL}} = (40.9 \pm 0.3 \pm 1.0 \pm 0.6) \times 10^{-3}$$

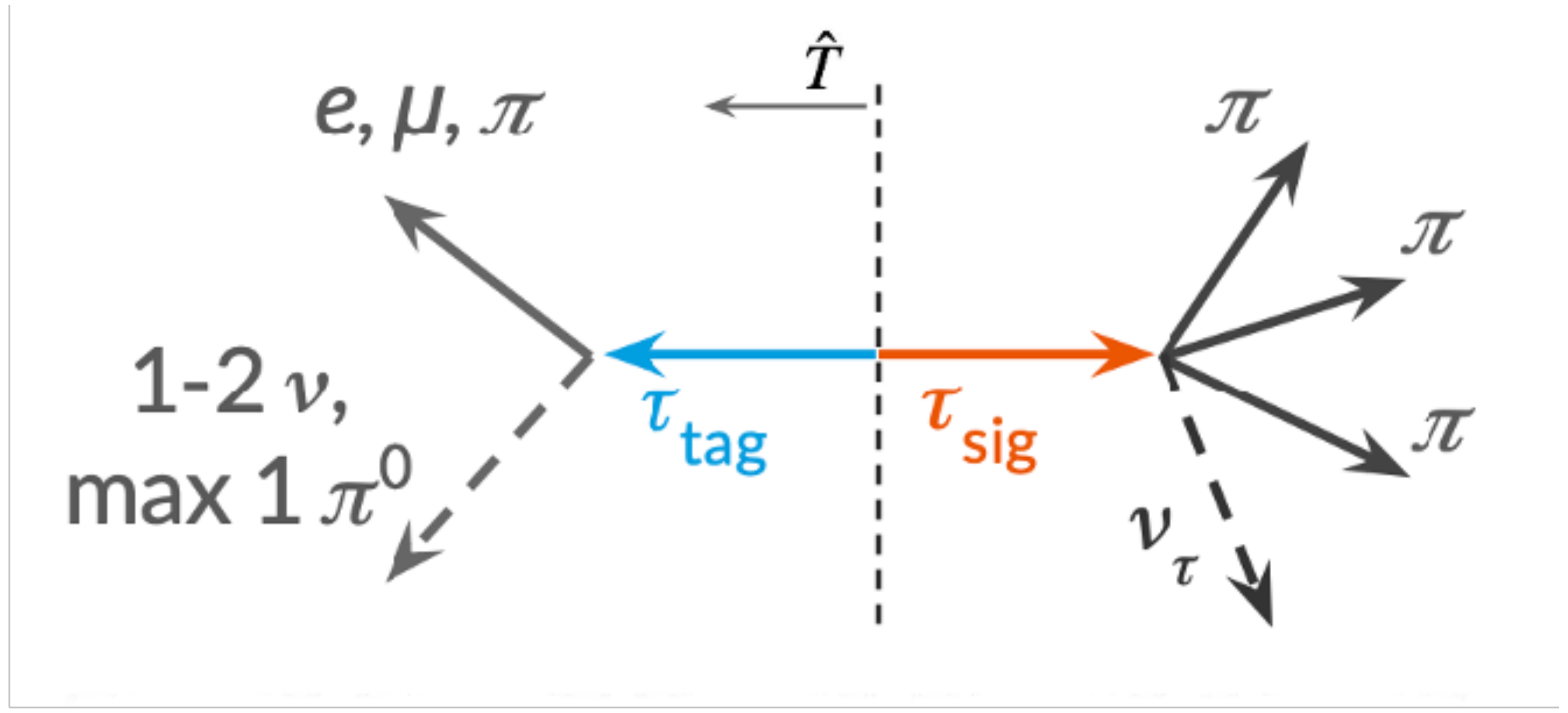
$$|V_{cb}|_{\text{CLN}} = (40.4 \pm 0.3 \pm 1.0 \pm 0.6) \times 10^{-3}$$

Slow pion eff. plays leading role in syst.

Input from LQCD at zero-recoil F(1)

Measurement of τ mass

PRD 108, 032006 (2023)



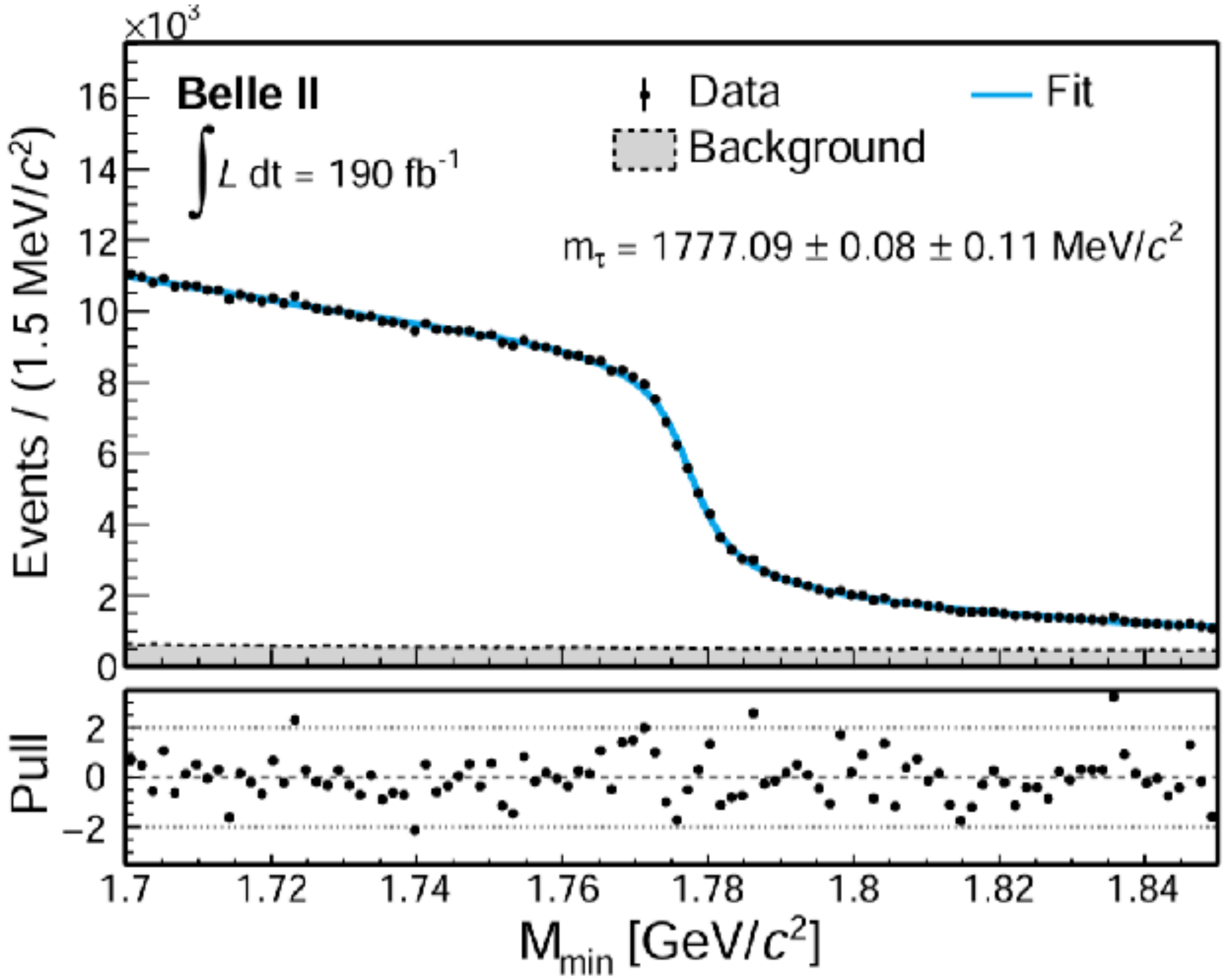
Pseudomass method:

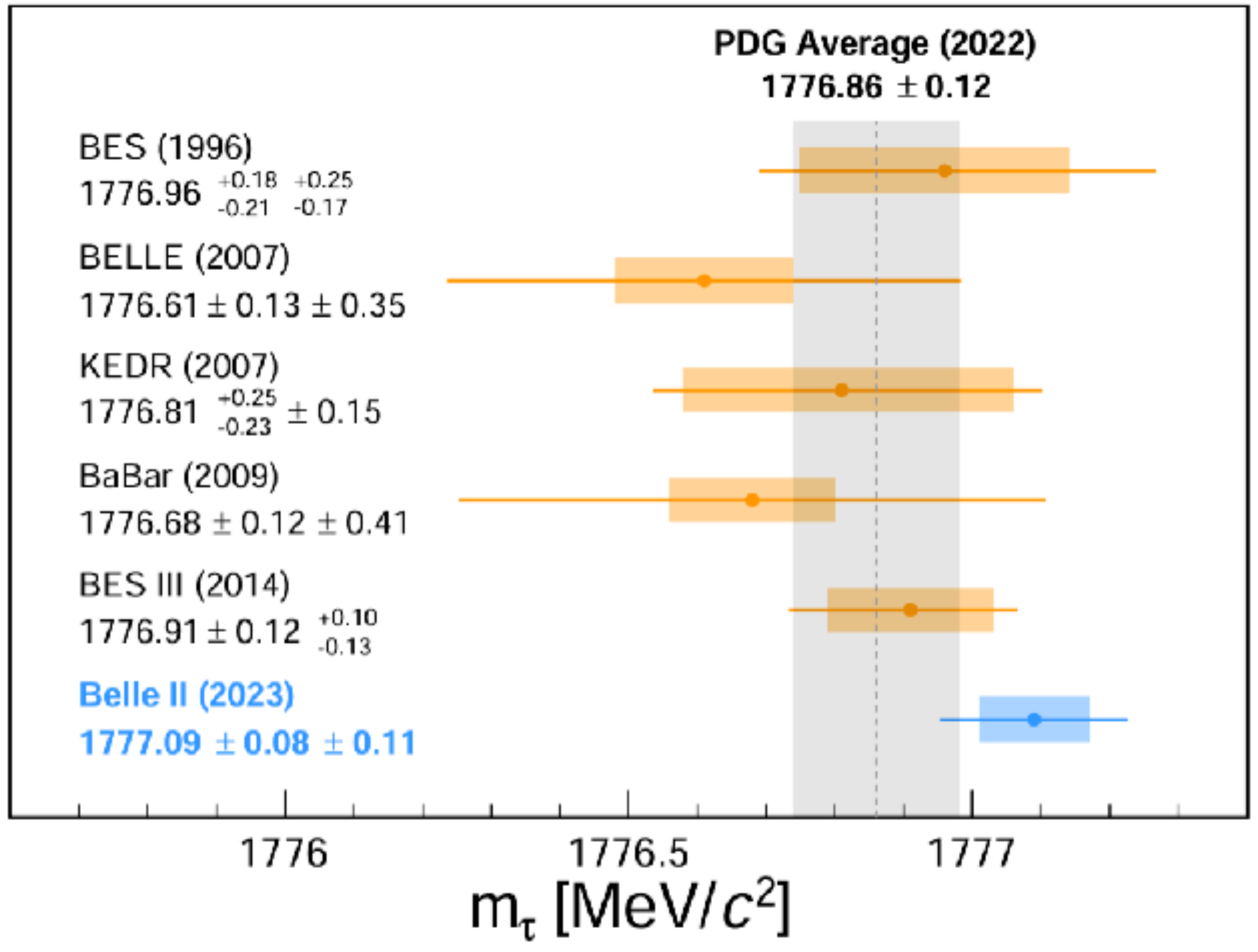
$$m_\tau^2 = (p_h + p_\nu)^2$$

$$= 2\,E_h\,(E_\tau - E_h) + m_h^2 - 2|\vec{p}_h|(E_\tau - E_h)\cos(\vec{p}_h, \vec{p}_\nu)$$

The direction of the neutrino is not known, since $\cos(\vec{p}_h, \vec{p}_\nu) \leq 1$

Pseudomass: $M_{\min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - p_{3\pi}^*)} \leq m_\tau$





$m_\tau = 1777.09 \pm 0.08 \pm 0.11\ \mathrm{MeV}/c^2$

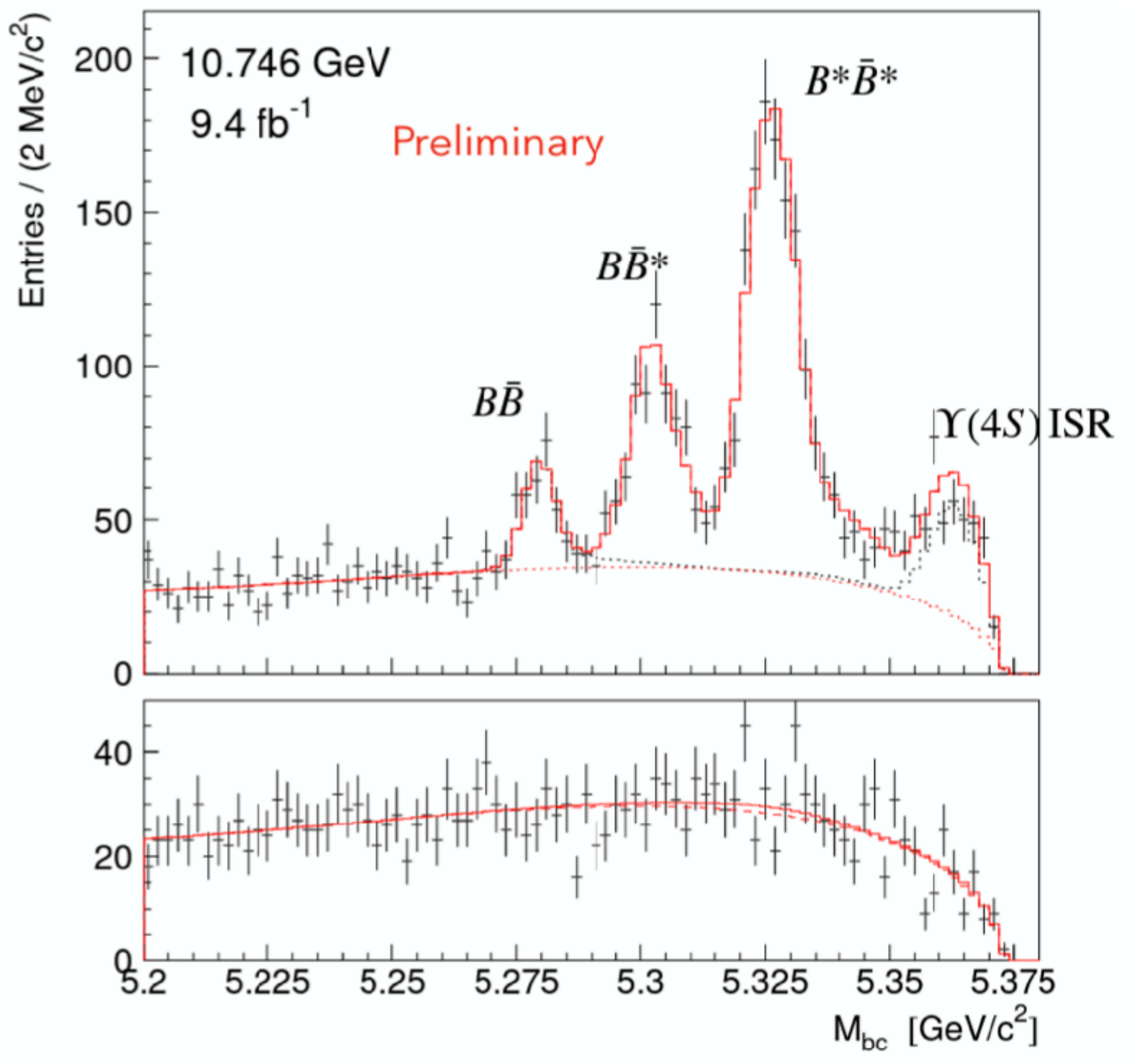
World's best!

Smaller data

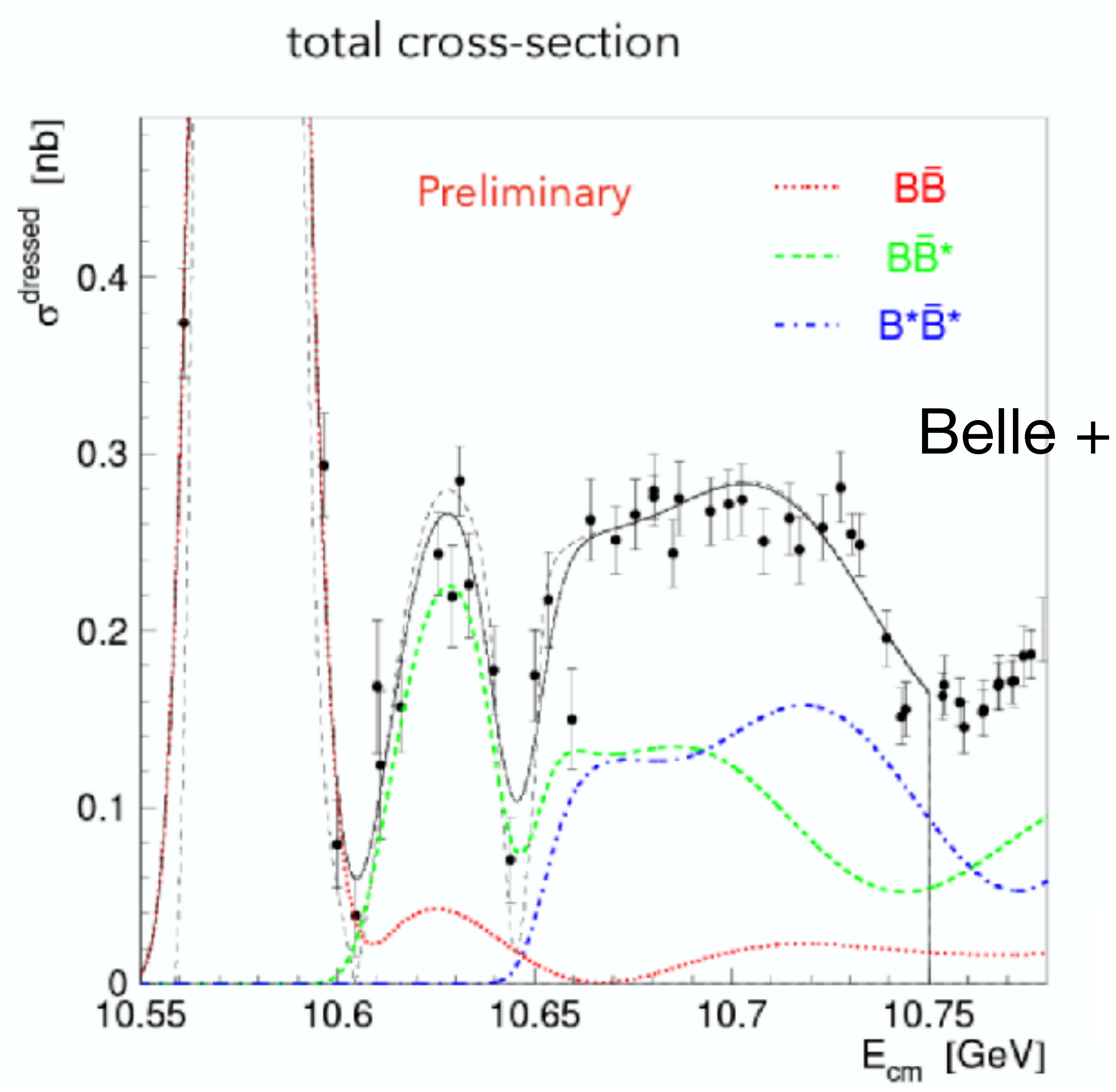
BUT better statistical precision!

Measurement of $e^+e^- \to B^{(*)}\bar{B}^{(*)}$

Preliminary



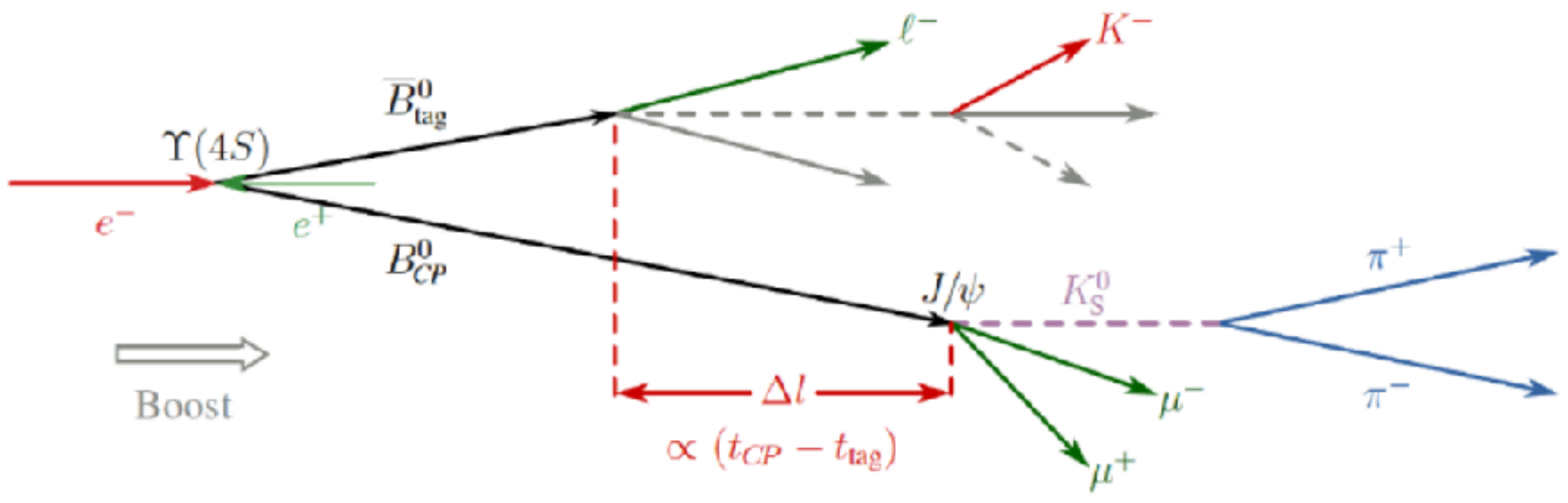
- Reconstruct B_{tag} with FEI
- Yield signals from simultaneous fit to M_{bc} (SR and SB)



Belle + Belle II

Shape increase at $B\bar{B}^*$ threshold. Suggestive of something?

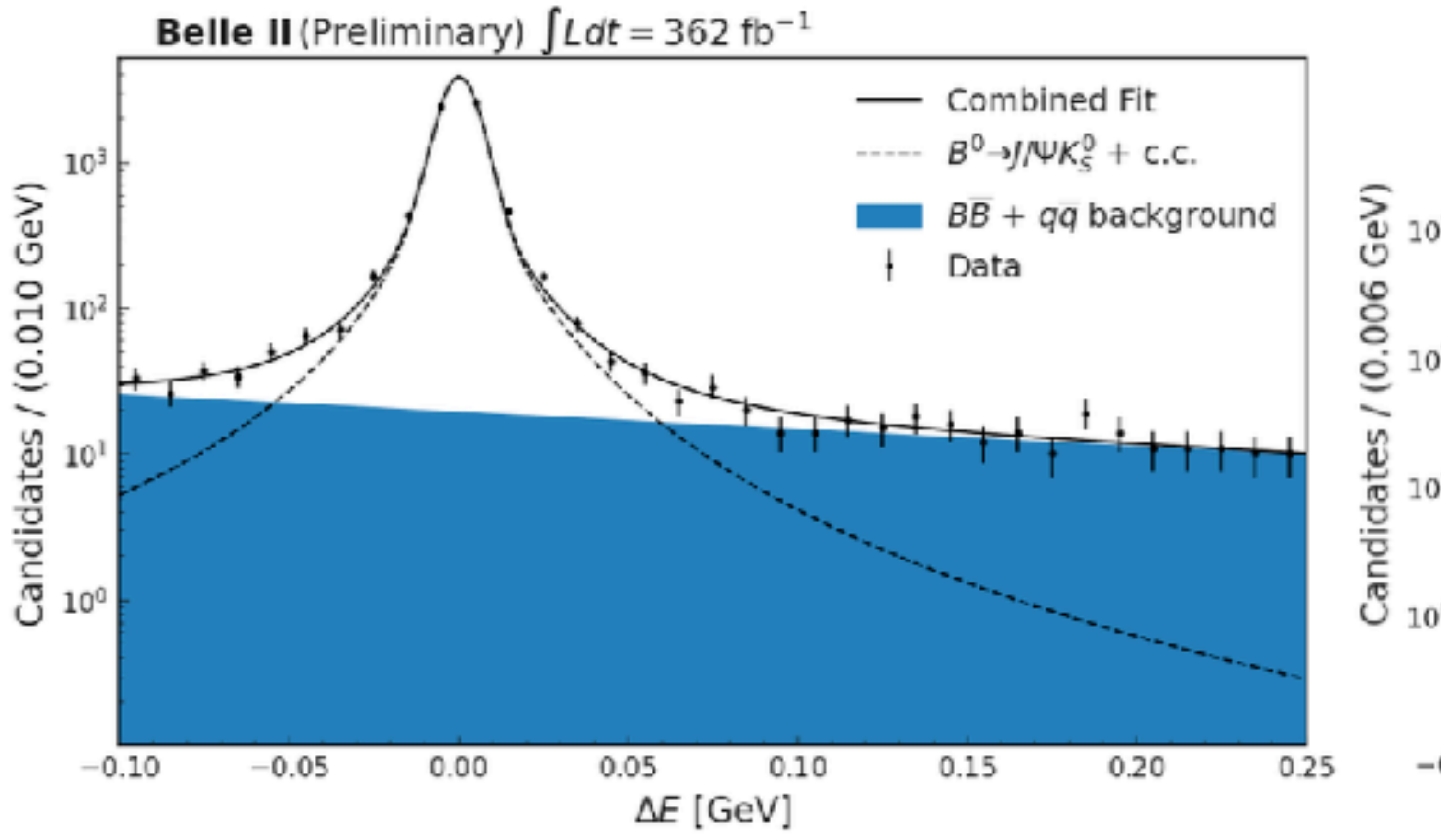
$\sin 2\phi_1$ measurement



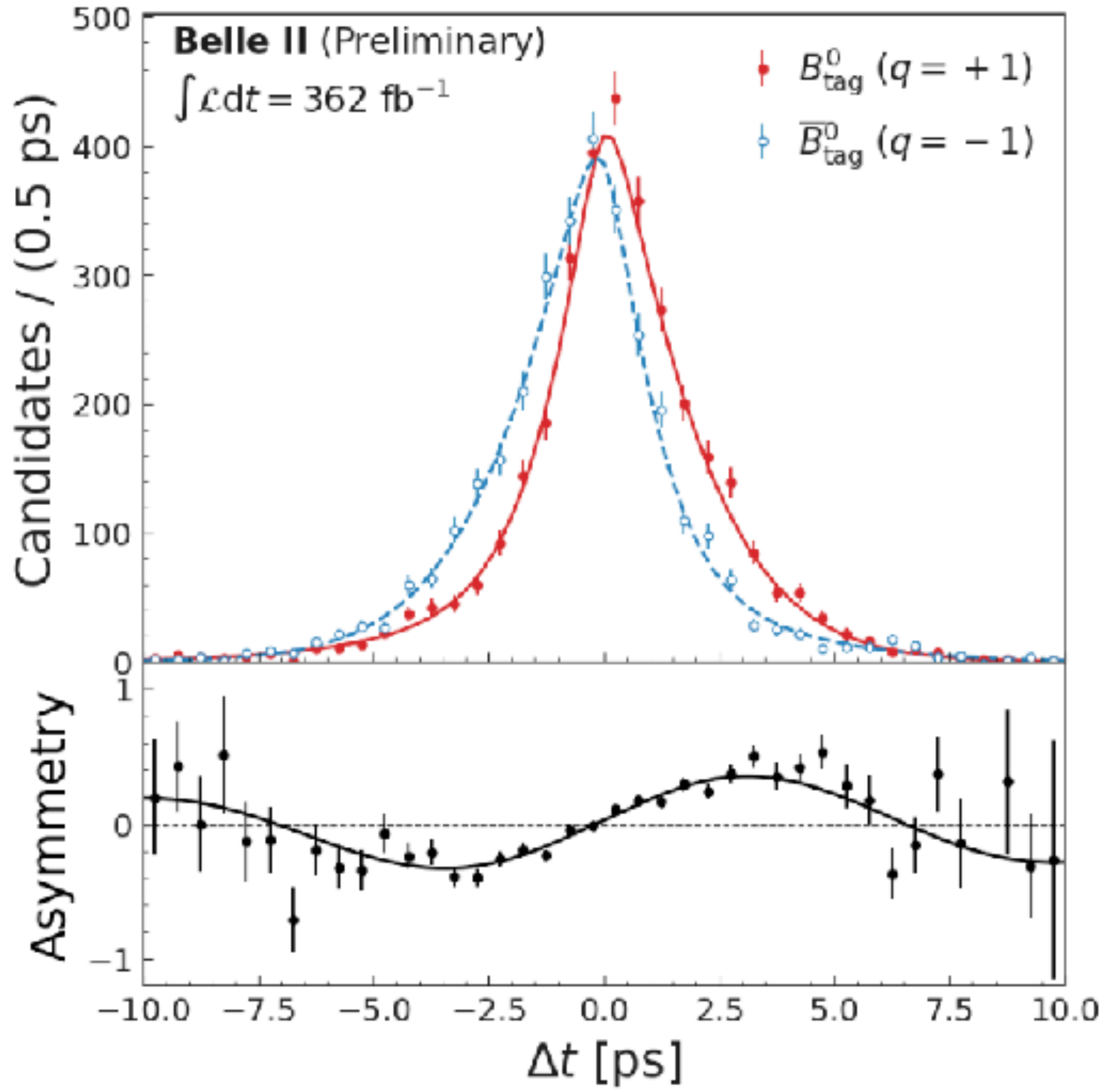
- Sensitive to BSM physics
- Fit Δt to extract S_{CP} and C_{CP}:

$$f_{CP}^{\rm true} = \frac{1}{4\tau_B^0} e^{-|\Delta t|/\tau_B^0}(1 + q[S_{CP}\sin(\Delta m \Delta t) - C_{CP}\cos(\Delta m \Delta t)])$$

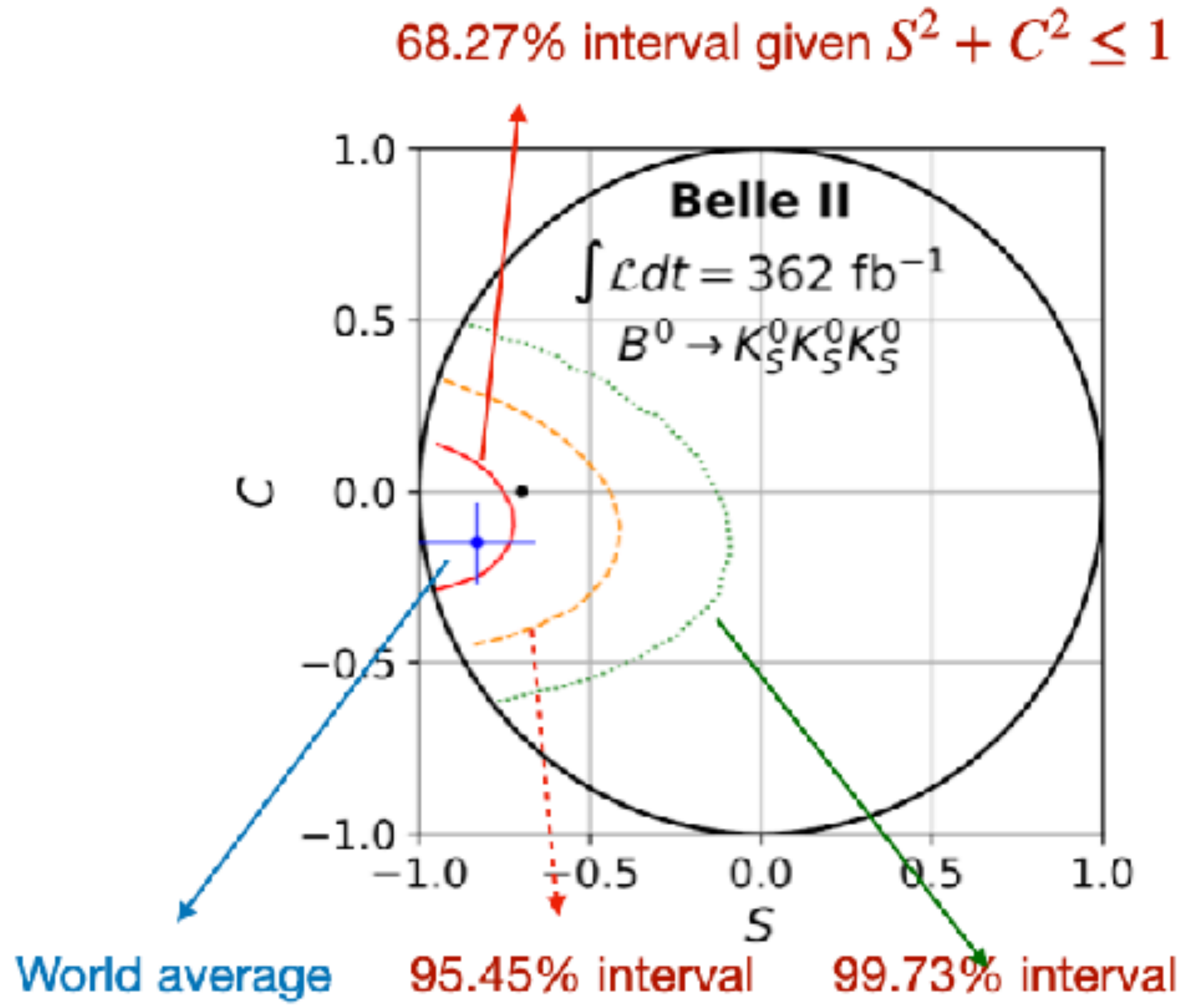
- SM expectation: $S_{CP} = \sin 2\phi_1$, and $C_{CP} = 0$
- Deviation from $\sin 2\phi_1$would suggest BSM physics
- Sensitive to BSM physics in
  - $b \to sq\bar{q}$
  - $b \to s\gamma$



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



channel	S_meas	C_meas	
$B^0 \to K_S^0 J/\psi$	$0.724 \pm 0.035 \pm 0.014$	$-0.035 \pm 0.026 \pm 0.012$	preliminary
$B^0 \to K_S^0 \pi^0 \gamma$	$0.04^{+0.45}_{-0.44} \pm 0.10$	$-0.06 \pm 0.25 \pm 0.07$	preliminary
$B^0 \to \eta' K_S^0$	$0.67 \pm 0.10 \pm 0.04$	$-0.19 \pm 0.08 \pm 0.03$	preliminary
$B^0 \to \pi^0 K_S^0$	$0.75^{+0.20}_{-0.23} \pm 0.04$	$-0.04^{+0.14}_{-0.15} \pm 0.05$	**PRL 131, 111803** (2023)
$B^0 \to \phi K_S^0$	$0.54 \pm 0.26^{+0.06}_{-0.08}$	$-0.31 \pm 0.20 \pm 0.05$	**PRD 108, 072012** (2023)



Pseudo-experiments

- Consistent with world average and SM expectation.
- $B^0 \to \eta' K_S^0$ provides the most sensitive results up to date.
- Smaller data size but equivalent uncertainties, sometimes better.

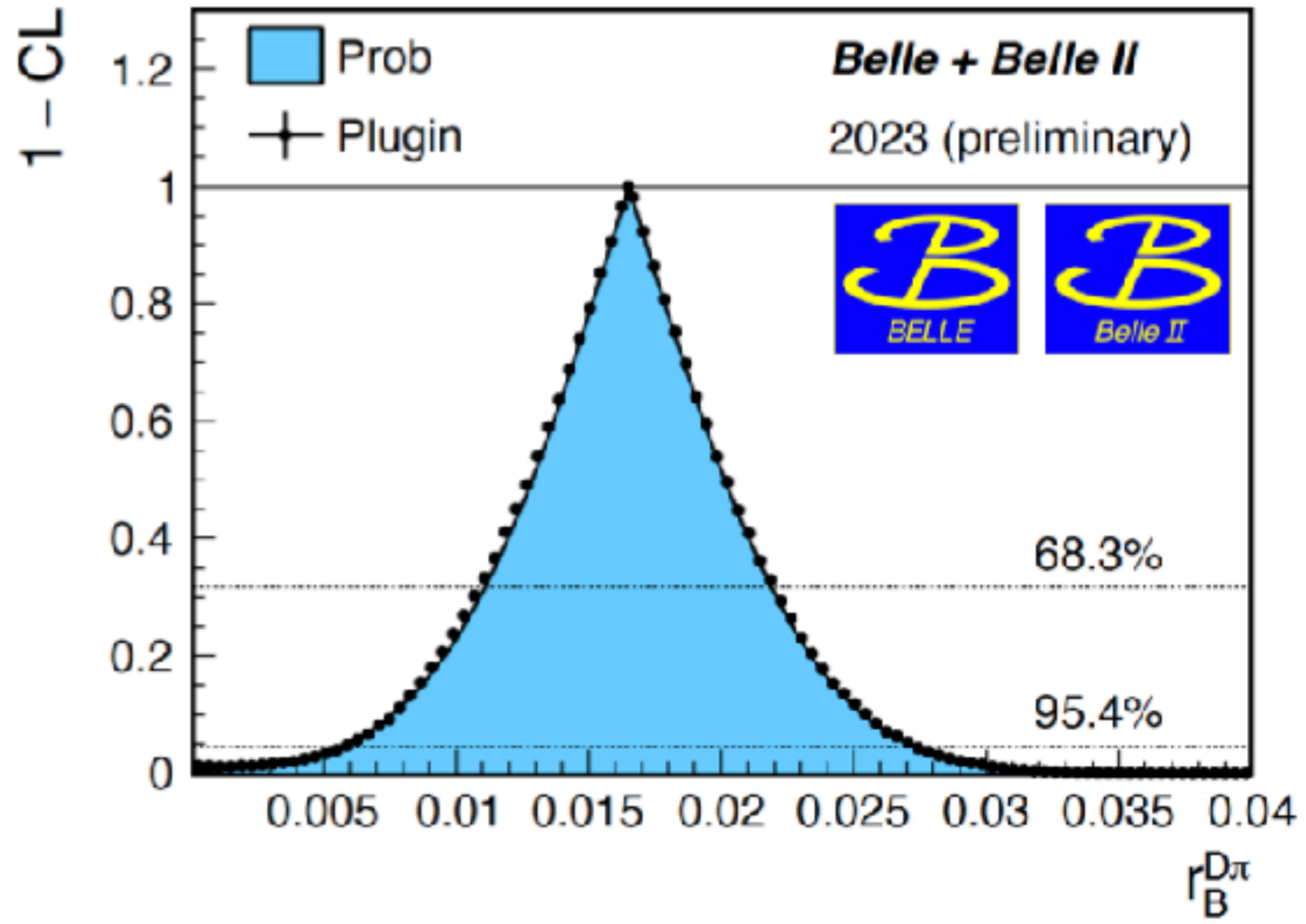
Combined measurement of ϕ_3 with Belle & Belle II

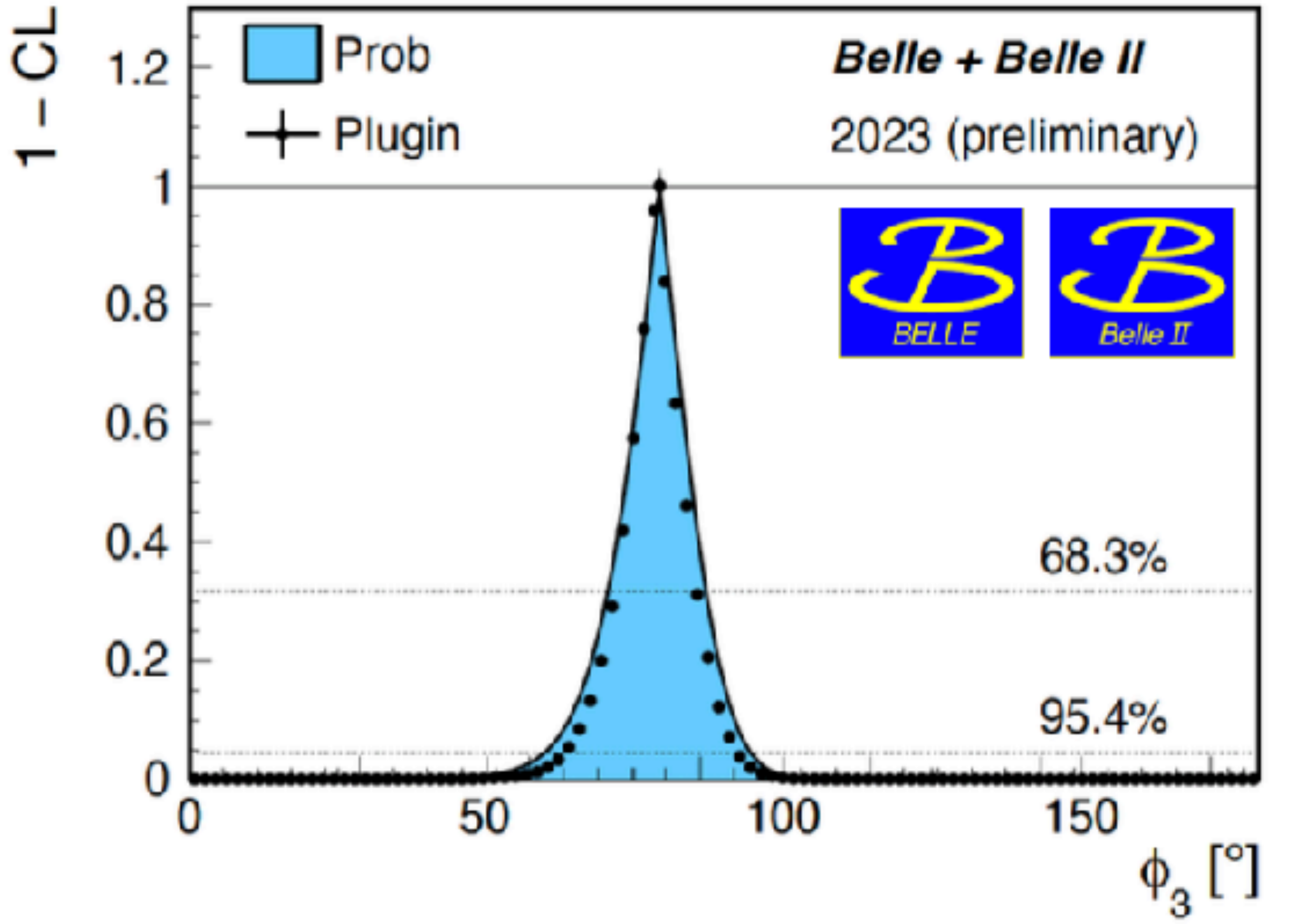
Preliminary

- Four different methods using 17 different final states
- Inputs on D decays dynamics from other experiments
  - r_D (amplitude ratio), δ_D (strong-phase difference), κ_D (coherence factor), etc.

B decay	D decay	Method	Data set (Belle + Belle II)[fb^{-1}]	
$B^+ \to Dh^+$	$D \to K_S^0 h^- h^+$	BPGGSZ	$711 + 128$	[JHEP 02 063 (2022)]
$B^+ \to Dh^+$	$D \to K_S^0 \pi^- \pi^+ \pi^0$	BPGGSZ	$711 + 0$	[JHEP 10 178 (2019)]
$B^+ \to Dh^+$	$D \to K_S^0 \pi^0, K^- K^+$	GLW	$711 + 189$	[arxiv:2308.05048]
$B^+ \to Dh^+$	$D \to K^+ \pi^-, K^+ \pi^- \pi^0$	ADS	$711 + 0$	[PRL 106 231803 (2011)]
$B^+ \to Dh^+$	$D \to K_S^0 K^- \pi^+$	GLS	$711 + 362$	[JHEP 09 (2023) 146]
$B^+ \to D^* K^+$	$D \to K_S^0 \pi^- \pi^+$	BPGGSZ	$605 + 0$	[PRD 81 112002 (2010)]
$B^+ \to D^* K^+$	$D \to K_S^0 \pi^0, K_S^0 \phi, K_S^0 \omega, K^- K^+, \pi^- \pi^+$	GLW	210+0	[PRD 73 051106 (2006)]

Parameters	$\phi_3 (^\circ)$	r_B^{DK}	$\delta_B^{DK} (^\circ)$	$r_B^{D\pi}$	$\delta_B^{D\pi} (^\circ)$	$r_B^{D^*K}$	$\delta_B^{D^*K} (^\circ)$
Plugin method							
Best fit value	78.6	0.117	138.4	0.0165	347.0	0.234	341
68.3% interval	[71.4, 85.4]	[0.105, 0.130]	[129.1, 146.5]	[0.0109, 0.0220]	[337.4, 355.7]	[0.165, 0.303]	[327,355]
95.5% interval	[63, 92]	[0.092, 0.141]	[118, 154]	[0.006, 0.027]	[322, 366]	[0.10, 0.37]	[307, 369]

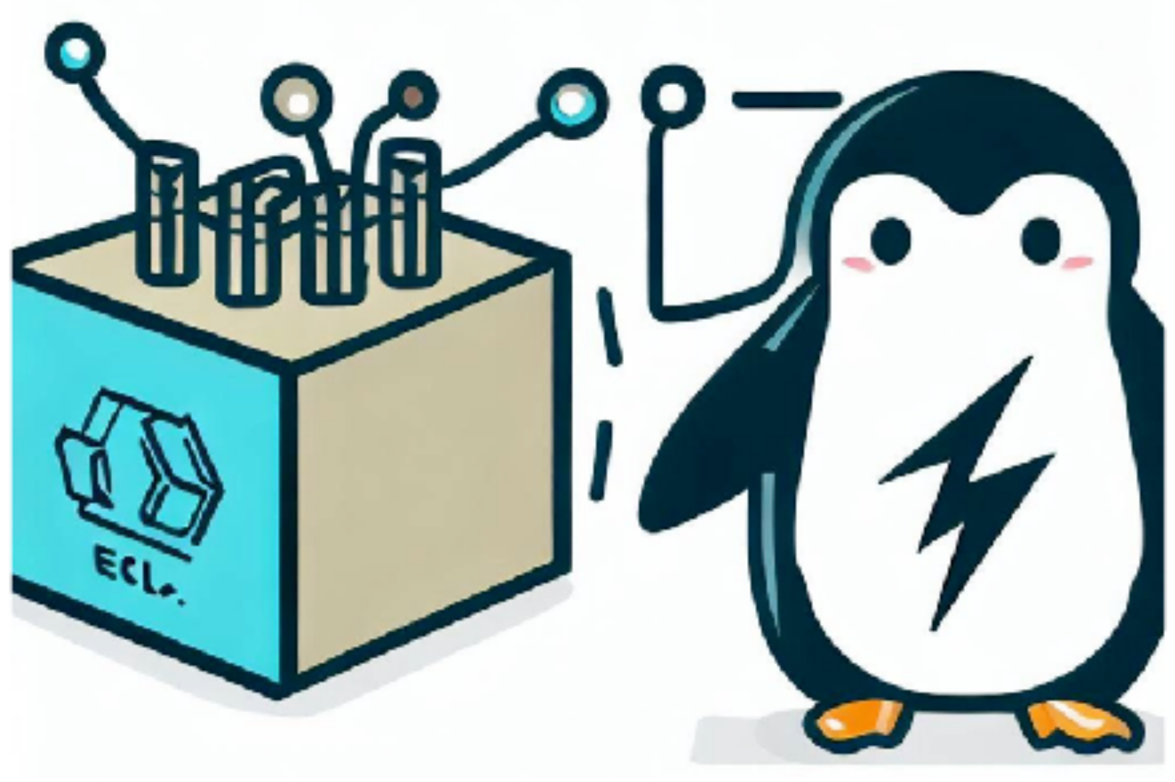




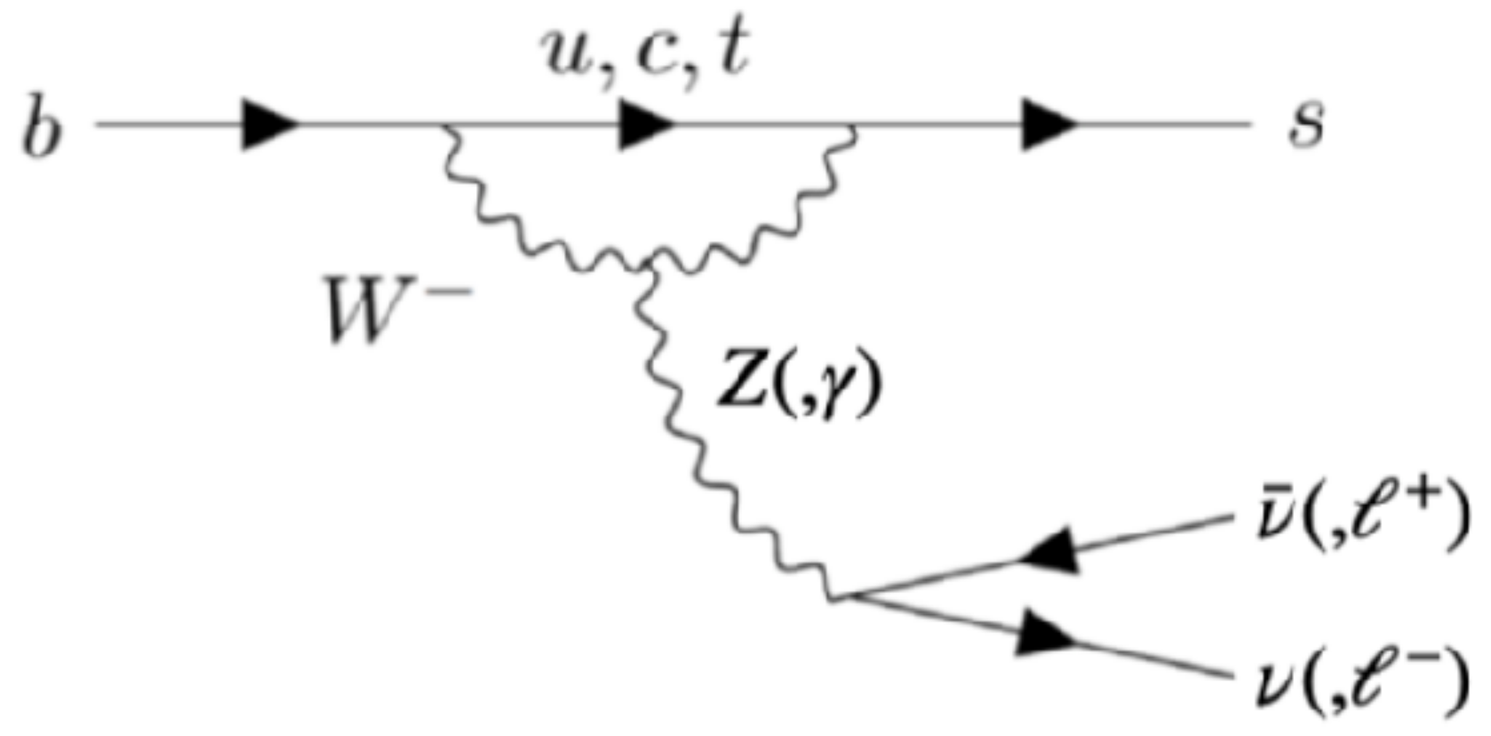
$\phi_3 = (78.6 \pm 7.3)^\circ$, consistent with WA, $\phi_3 = (66.2^{+3.2}_{-3.6})^\circ$, within 2σ

Measurement of branching fraction of $B^+ \to K^+ \nu \bar{\nu}$

arXiv:2311.14647

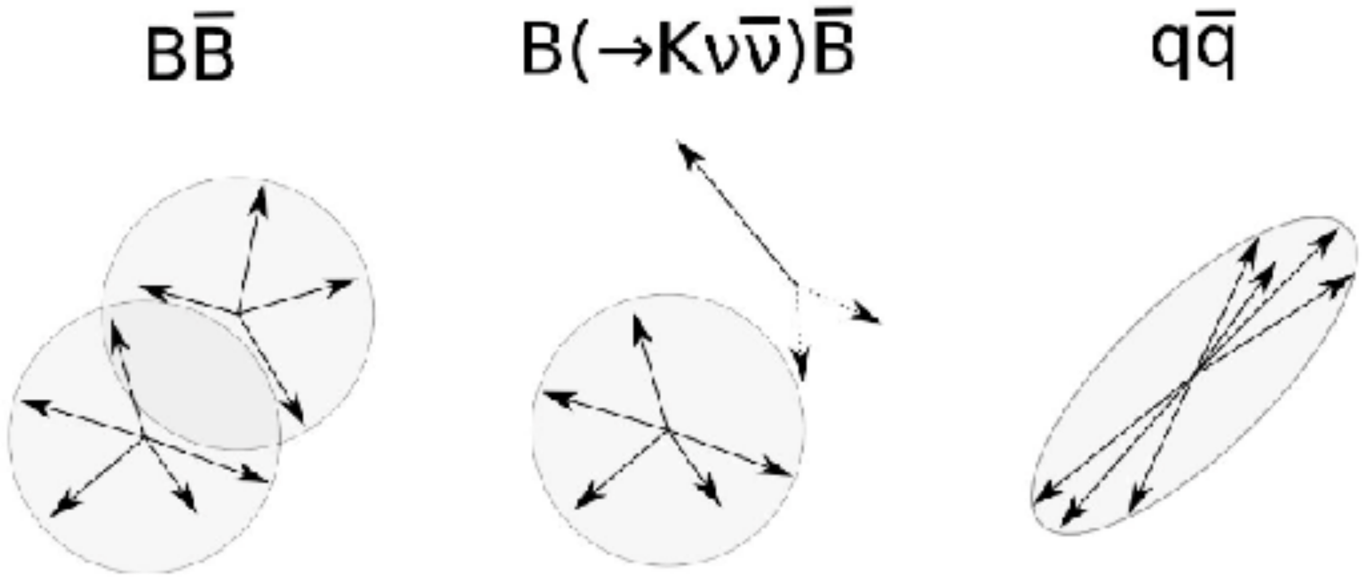


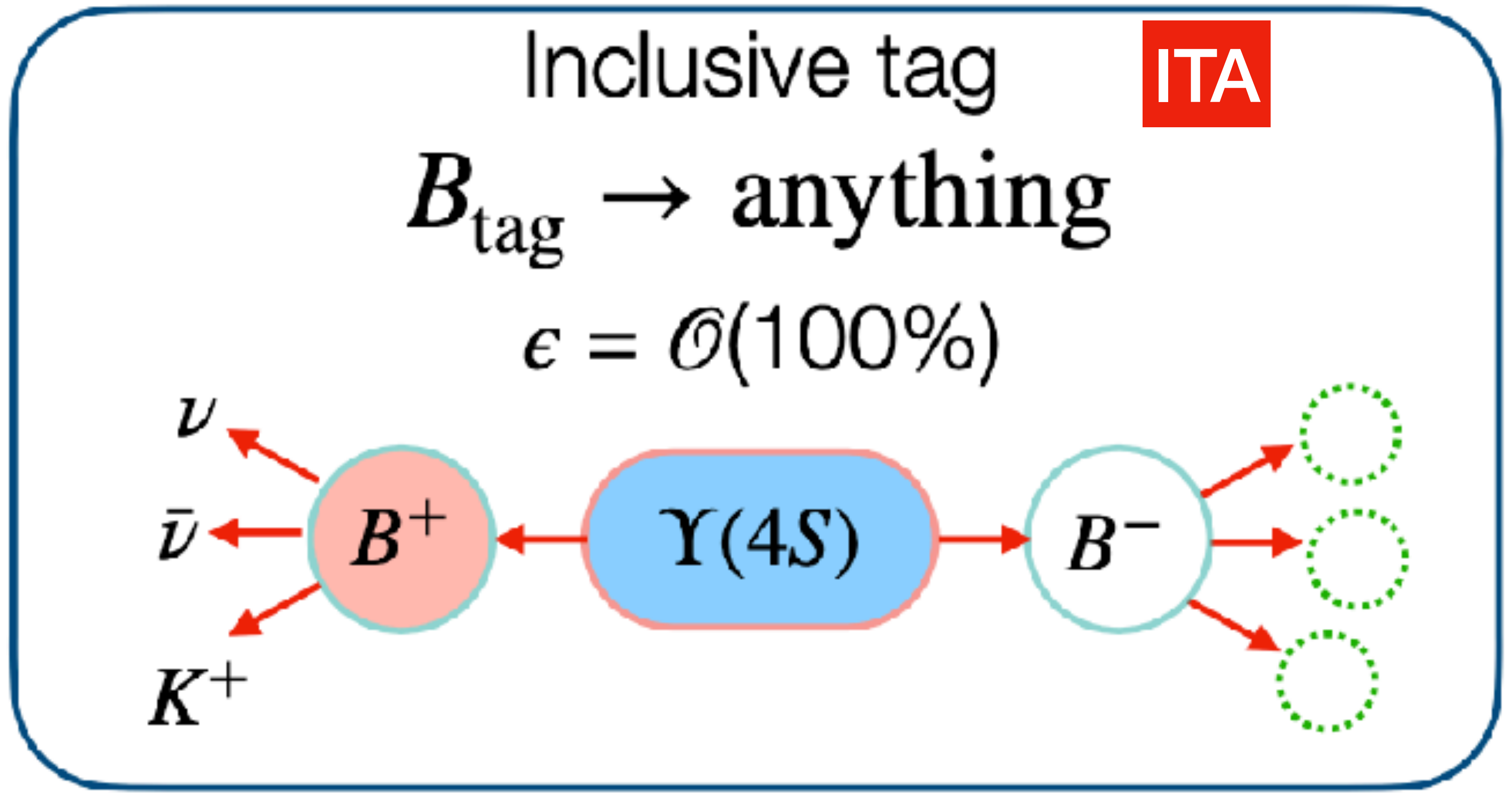
- The $B \to K\nu\nu$ process is known with high accuracy in the SM:
  - $\mathscr{B}(B \to K^+\nu\nu) = (5.6 \pm 0.4) \times 10^{-6}$(arXiv:2207.13371)
  - *We use 4.97×10^{-6} as a reference, after removal of $B \to \tau(K\bar{\nu})\nu$*
- Extensions beyond SM may lead to significant rate increase
- Very challenging experimentally, not yet observed
  - Low branching fraction, high background contributions
  - 3-body kinematics, no good kinematic variable to fit

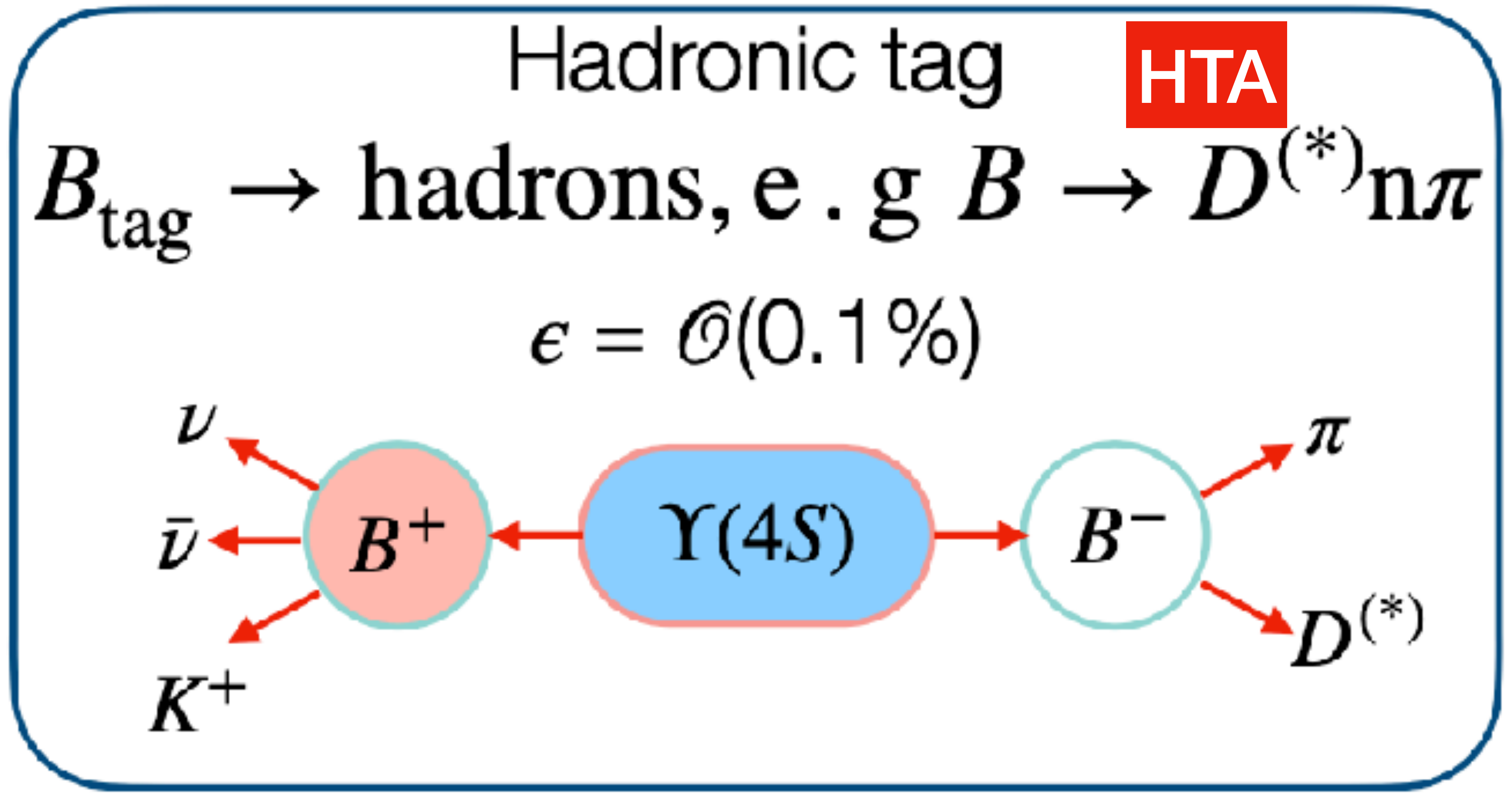


Analysis strategy

arXiv:2311.14647







- Two analyses:
    - More sensitive inclusive tagging (ITA)
    - Conventional hadronic tagging (HTA)
- Kinematic properties to suppress background with MVA
- Use classifier output as (one of) the fit variable(s), use simulation for signal and background templates
- Use multiple control channels to validate simulation with data

FIT

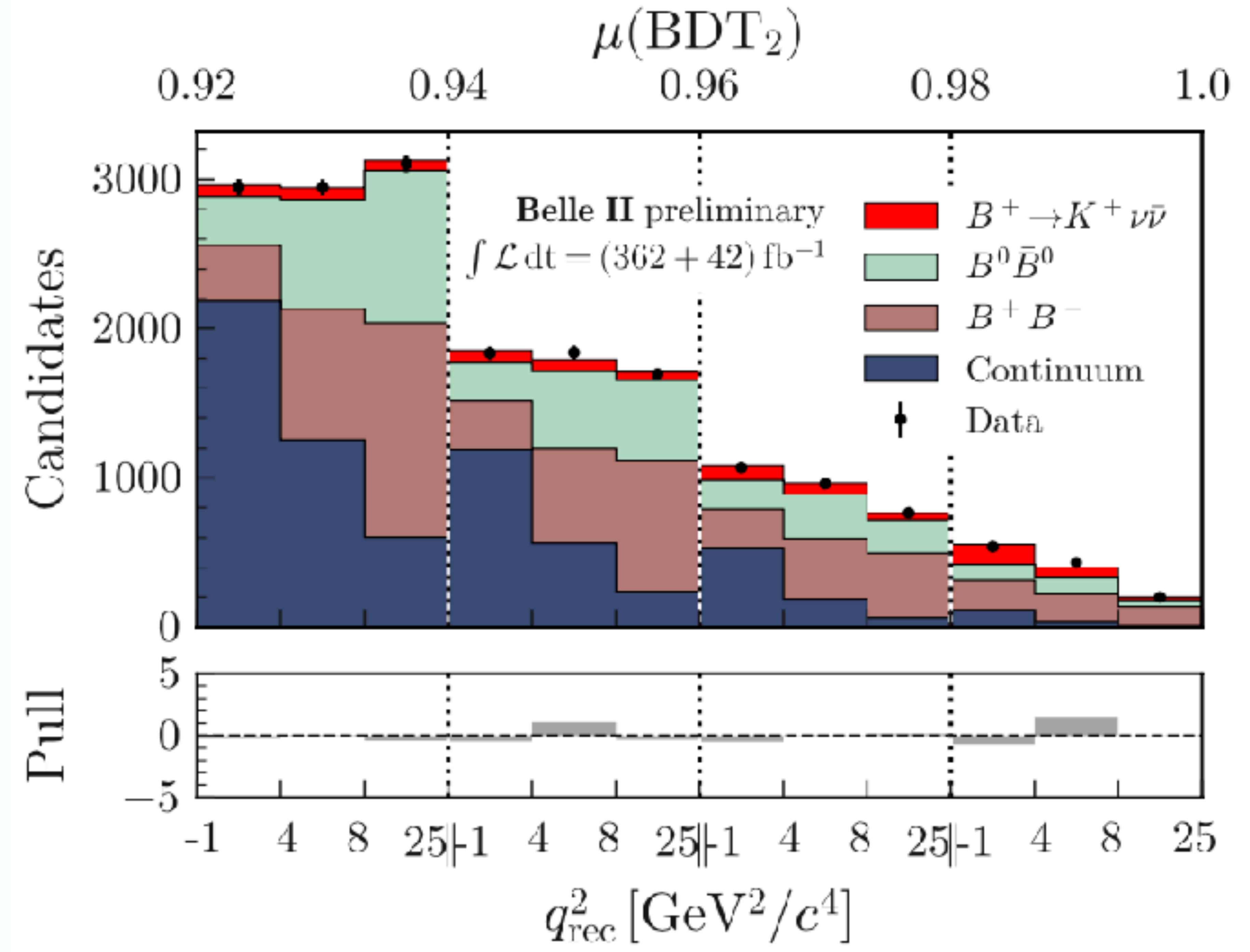
arXiv:2311.14647

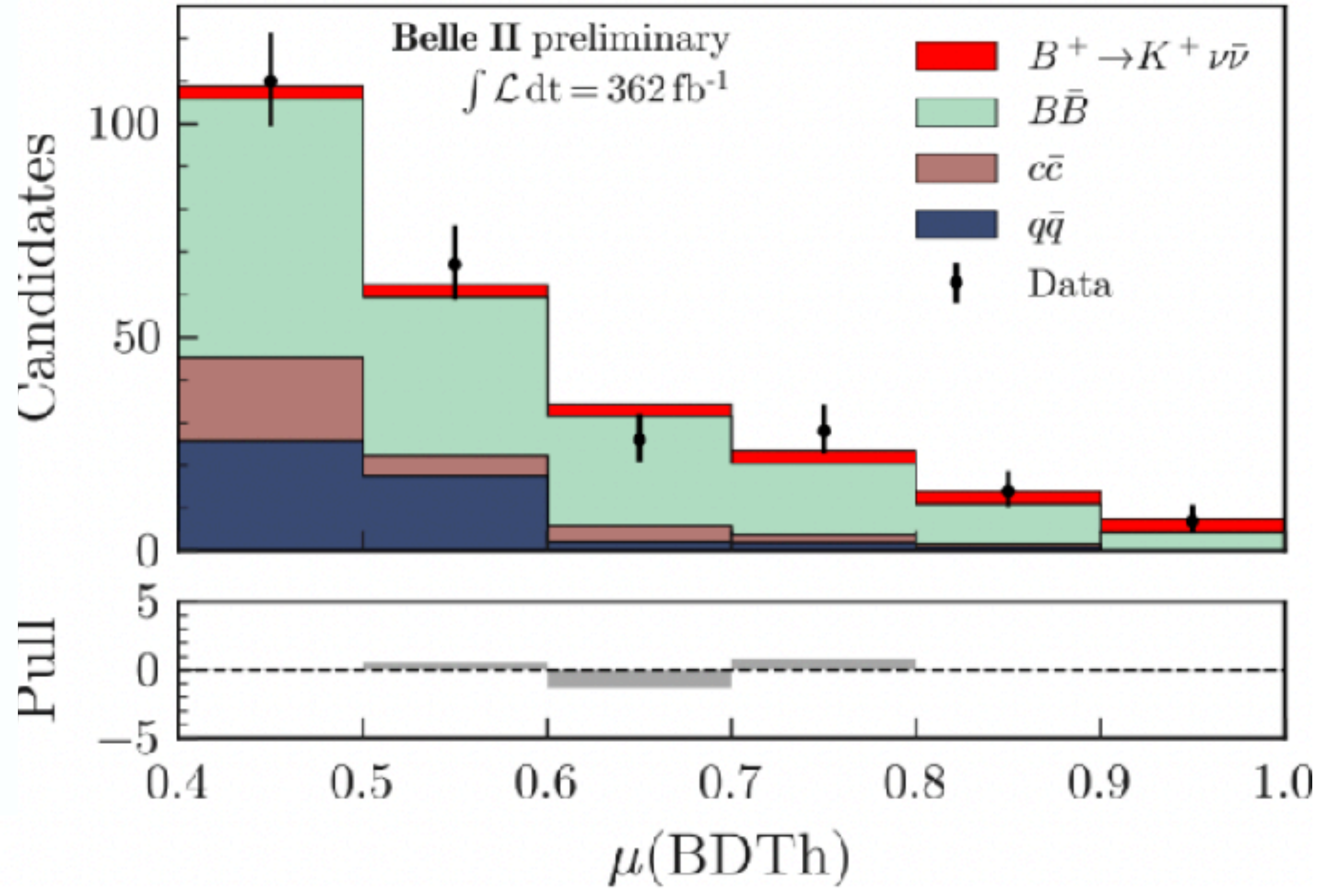
- Extract signal from maximum likelihood fit
  - Inclusive tag: in bins of q^2_{rec} and $\eta(\mathrm{BDT}_2)$
  - Hadronic tag: in bins of $\eta(\mathrm{BDT}_\mathrm{h})$
- Signal is extracted in terms of signal strength μ

signal relative to SM expectation

  - Inclusive tag: $\mu = 5.4 \pm 1.0(\mathrm{stat}) \pm 1.1(\mathrm{syst})$
  - Hadronic tag: $\mu = 2.2^{+1.8}_{-1.7}(\mathrm{stat})^{+1.6}_{-1.1}(\mathrm{syst})$
  - Combined: $\mu = 4.6 \pm 1.0(\mathrm{stat}) \pm 0.9(\mathrm{syst})$

ITA and HTA results are consistent at 1.2σ level





Inclusive tag: $\mathscr{B} = 2.7 \pm 0.5(\mathrm{stat}) \pm 0.5(\mathrm{syst})$

Hadronic tag: $\mathscr{B} = 1.1^{+0.9}_{-0.8}(\mathrm{stat})^{+0.8}_{-0.5}(\mathrm{syst})$

Combined: $\mathscr{B} = 2.3 \pm 0.5(\mathrm{stat})^{+0.5}_{-0.4}(\mathrm{syst})$

For the inclusive tag, significance of the result

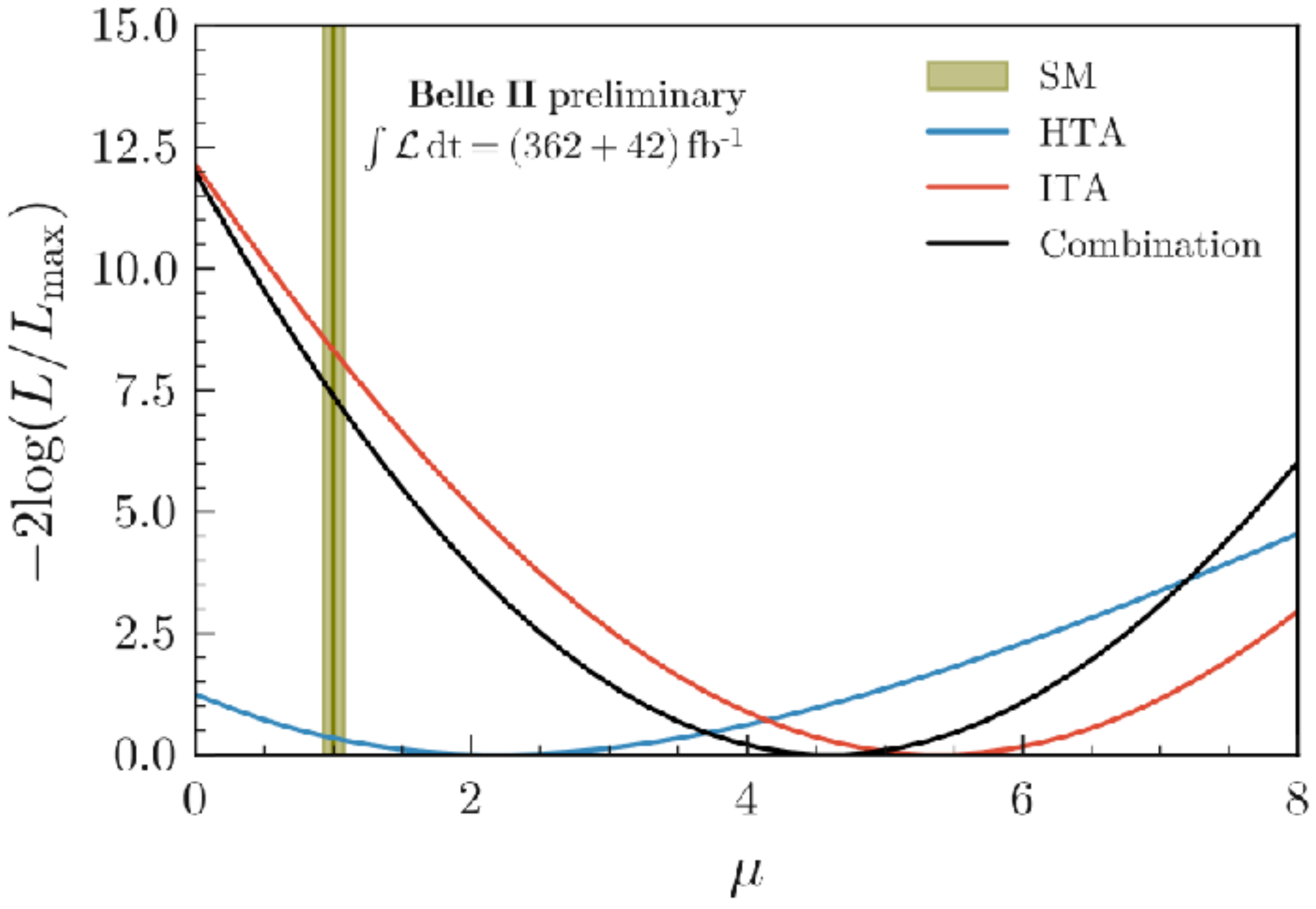
- wrt null hypothesis is 3.5σ
- wrt SM is 2.9σ

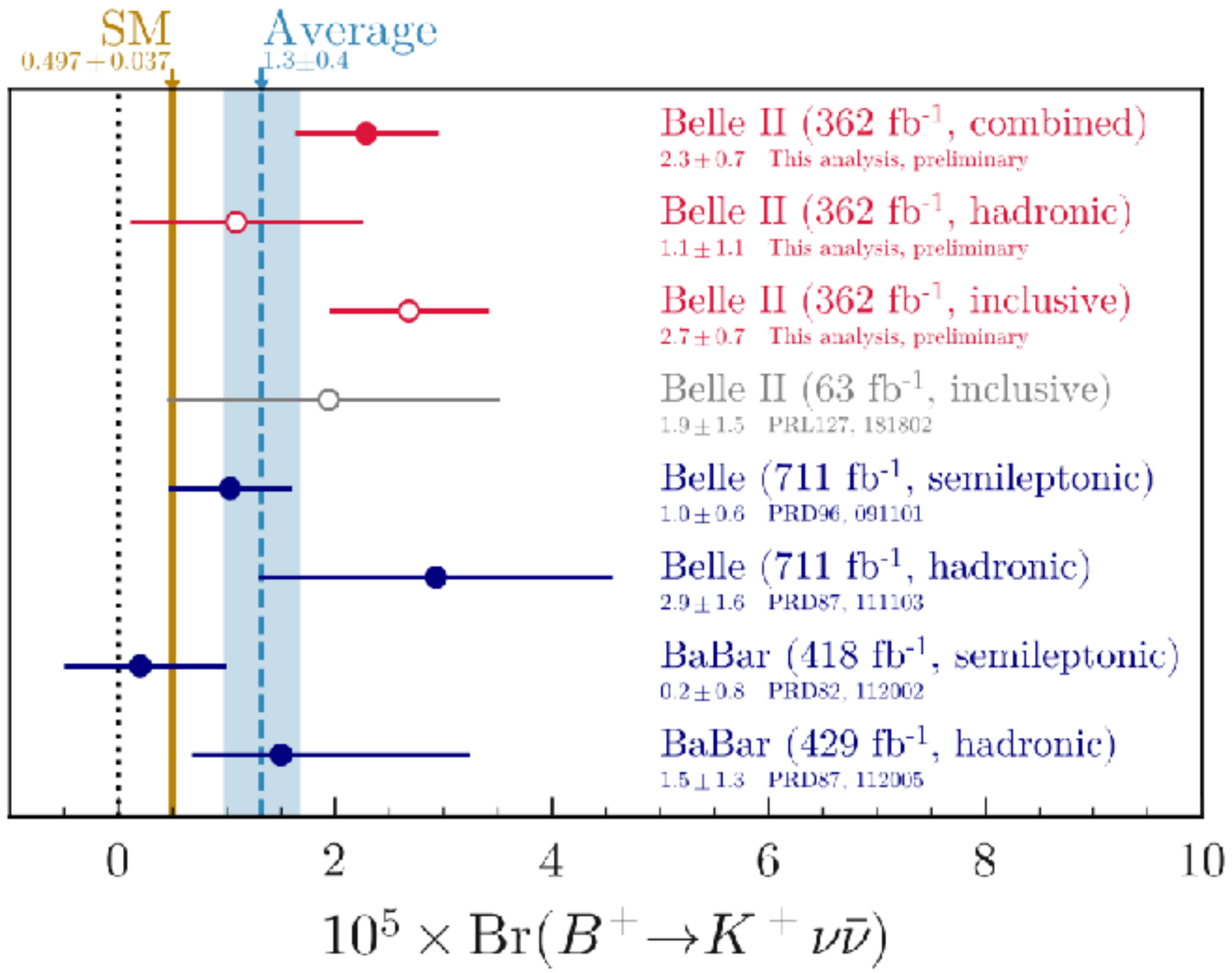
For the hadronic tag, significance of the result

- wrt null hypothesis is 1.1σ
- wrt SM is 0.6σ

For the combination, significance of the result

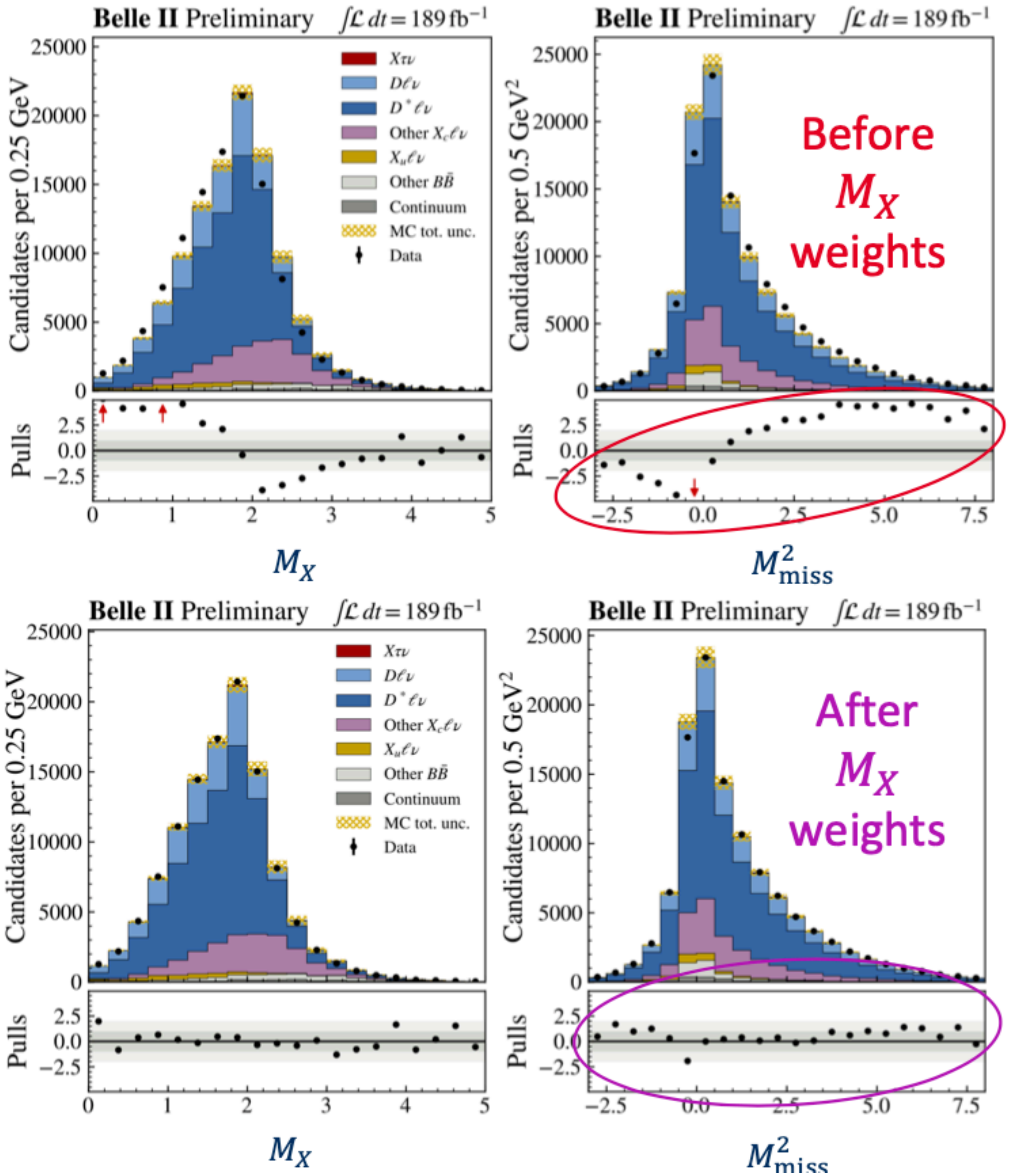
- wrt null hypothesis is 3.5σ
- wrt SM is 2.7σ





First evidence of the $B^+ \to K^+\nu\bar{\nu}$ decay!

$R(X_{\tau/\ell})$, event distributions



- for reliable template shapes for fitting
  - make detailed adjustments to MC (FF's, B and D BF's)
  - corrections by comparing MC to data in control region: low q^2, low M^2_{miss}, high M_X
  - e.g. adjust M_X in p_ℓ > 1.4 GeV sideband; using these weights also improves modeling in M^2_{miss} and q^2

Main sources of systematic uncertainty:

• MC stat	±5.7 %
• Bkg shape	±5.5 %
• M_X modeling	±7.1 %
• $B \to X_c\ell\nu$ BFs	±7.7 %
• $B \to X_c\ell\nu$ FFs	±7.9 %

Search for $b \to d\ell^+\ell^-$

Belle, Preliminary

Sensitive to NP.

First search for the channels of

- $B^{+,0} \to (\omega, \rho^{+,0})e^+e^-$
- $B^{+,0} \to (\omega, \rho^{+,0})\mu^+\mu^-$

Best limits for the channels of

- $B^{+,0} \to (\eta, \pi^{+,0})e^+e^-$
- $B^{+,0} \to (\eta, \pi^{+,0})\mu^+\mu^-$

channel	$N_{\rm sig}$	$N_{\rm sig}^{\rm UL}$	ε (%)	$\mathcal{B}^{\rm UL}$ (10^{-8})	$\mathcal{B}$ (10^{-8})
$B^0 \to \eta e^+e^-$	$0.0^{+1.4}_{-1.0}$	3.1	3.9	< 10.5	$0.0^{+4.9}_{-3.4} \pm 0.1$
$B^0 \to \eta\mu^+\mu^-$	$0.8^{+1.5}_{-1.1}$	4.2	5.9	< 9.4	$1.9^{+3.4}_{-2.5} \pm 0.2$
$B^0 \to \eta\ell^+\ell^-$	$0.5^{+1.0}_{-0.8}$	1.8	4.9	< 4.8	$1.3^{+2.8}_{-2.2} \pm 0.1$
$B^0 \to \omega e^+e^-$	$-0.3^{+3.2}_{-2.5}$	3.7	1.6	< 30.7	$-2.1^{+26.5}_{-20.8} \pm 0.2$
$B^0 \to \omega\mu^+\mu^-$	$1.7^{+2.3}_{-1.6}$	5.5	2.9	< 24.9	$7.7^{+10.8}_{-7.5} \pm 0.6$
$B^0 \to \omega\ell^+\ell^-$	$1.0^{+1.8}_{-1.3}$	3.6	2.2	< 22.0	$6.4^{+10.7}_{-7.8} \pm 0.5$
$B^0 \to \pi^0 e^+e^-$	$-2.9^{+1.8}_{-1.4}$	4.0	6.7	< 7.9	$-5.8^{+3.6}_{-2.8} \pm 0.5$
$B^0 \to \pi^0\mu^+\mu^-$	$-0.5^{+3.6}_{-2.7}$	6.1	13.7	< 5.9	$-0.4^{+3.5}_{-2.6} \pm 0.1$
$B^0 \to \pi^0\ell^+\ell^-$	$-1.8^{+1.6}_{-1.1}$	2.9	10.2	< 3.8	$-2.3^{+2.1}_{-1.5} \pm 0.2$
$B^+ \to \pi^+ e^+e^-$	$0.1^{+2.5}_{-1.6}$	5.0	11.5	< 5.4	$0.1^{+2.7}_{-1.8} \pm 0.1$
$B^0 \to \rho^0 e^+e^-$	$5.6^{+3.5}_{-2.7}$	10.8	3.2	< 45.5	$23.6^{+14.6}_{-11.2} \pm 1.1$
$B^+ \to \rho^+ e^+e^-$	$-4.4^{+2.3}_{-2.0}$	5.3	1.4	< 46.7	$-38.2^{+24.5}_{-17.2} \pm 3.4$
$B^+ \to \rho^+\mu^+\mu^-$	$3.0^{+4.0}_{-3.0}$	8.7	2.9	< 38.1	$13.0^{+17.5}_{-13.3} \pm 1.1$
$B^+ \to \rho^+\ell^+\ell^-$	$0.4^{+2.3}_{-1.8}$	3.0	2.0	< 18.9	$2.5^{+14.6}_{-11.8} \pm 0.2$