B and τ physics at e^+e^- collider experiments

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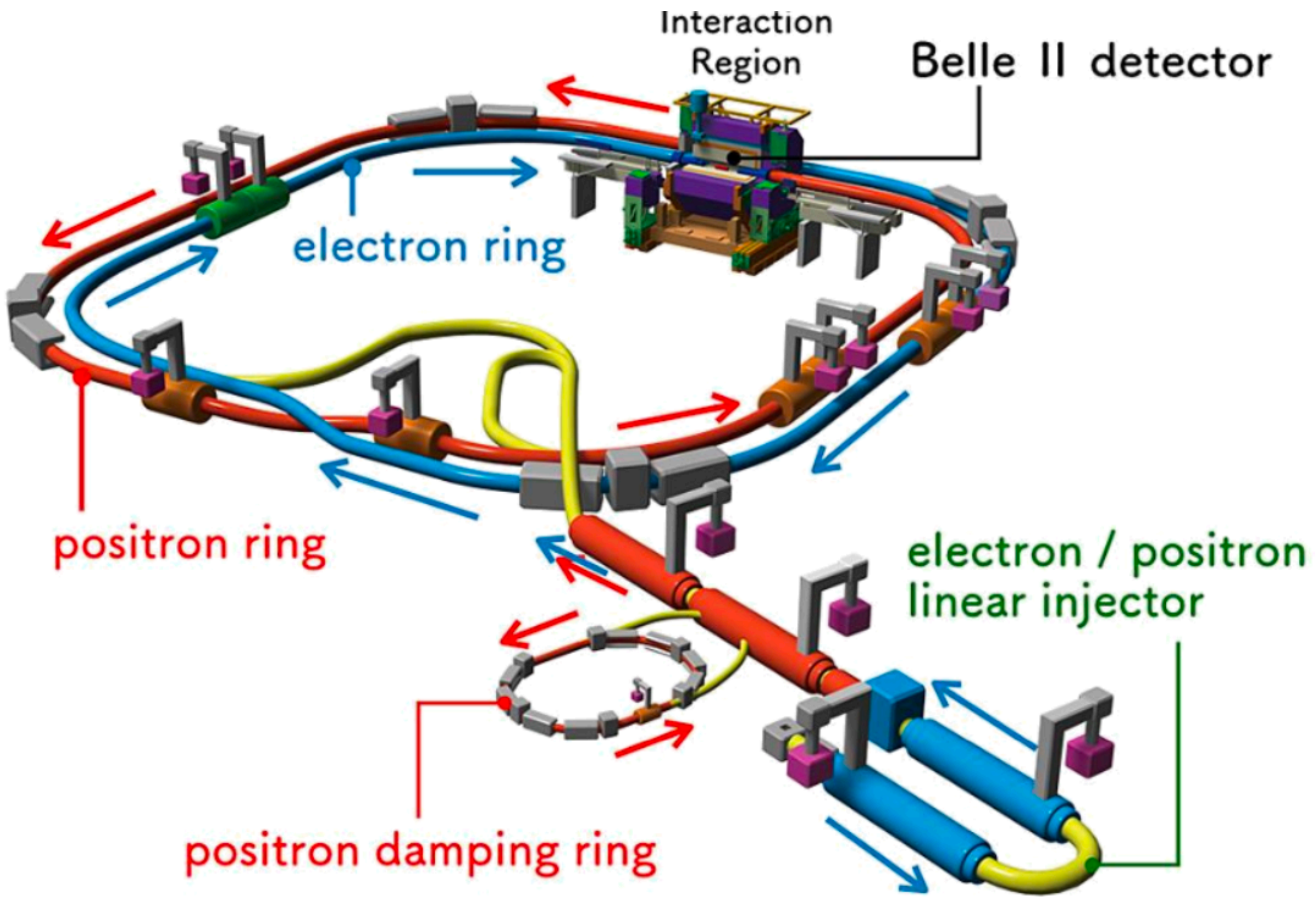
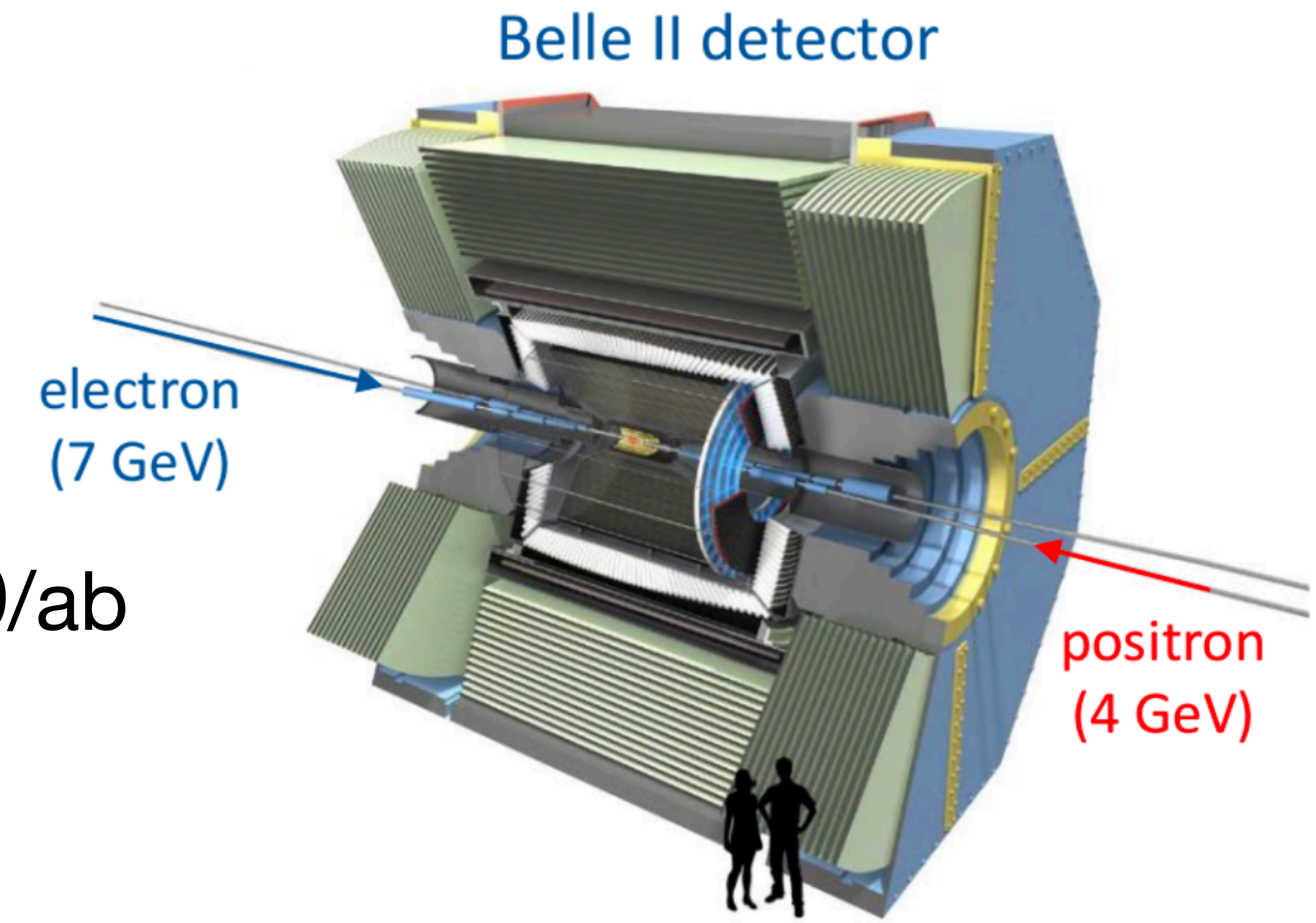
Representing the collaboration

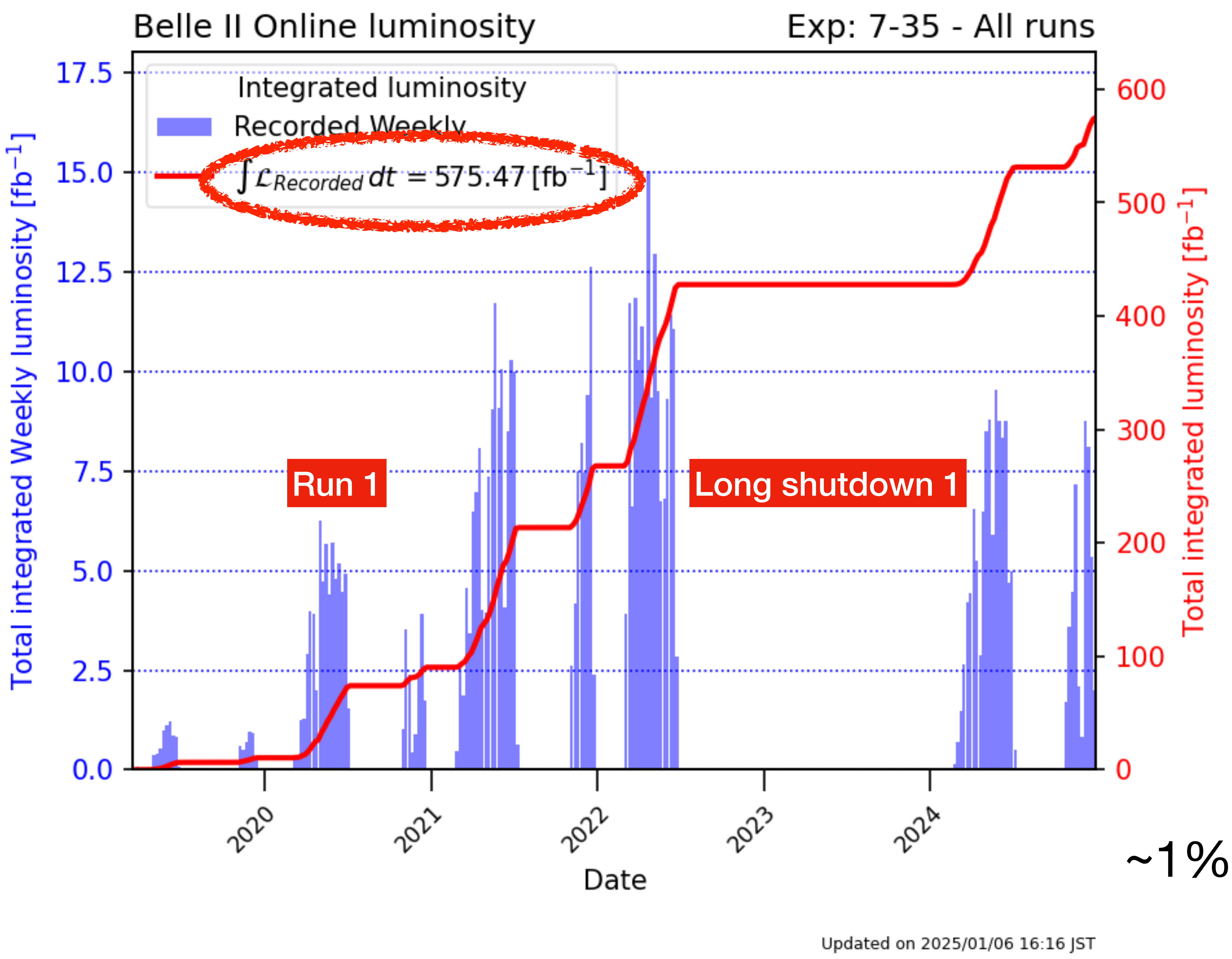
66th ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e^+e^- Colliders (eeFACT 2025)
March 3-7, 2025, Tsukuba International Congress Center

Belle II @ SuperKEKB

- Luminosity frontier experiment to search for Physics beyond the Standard Model
  - e^+e^- asymmetric collision at the $\Upsilon(4S)$
  - High current / nano-beams, challenging background conditions
- Luminosity targets to achieve physics goals:
  - $\mathscr{L} = 6 \times 10^{35}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}, \int \mathscr{L} dt = 50/\mathrm{ab}$



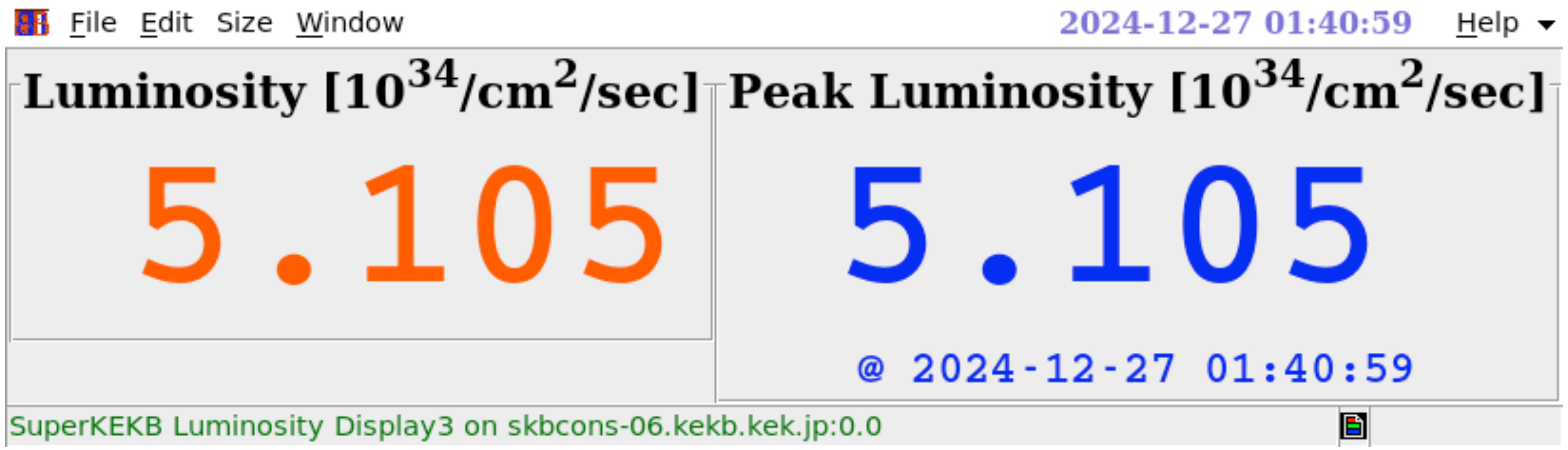




~1% of 50/ab target

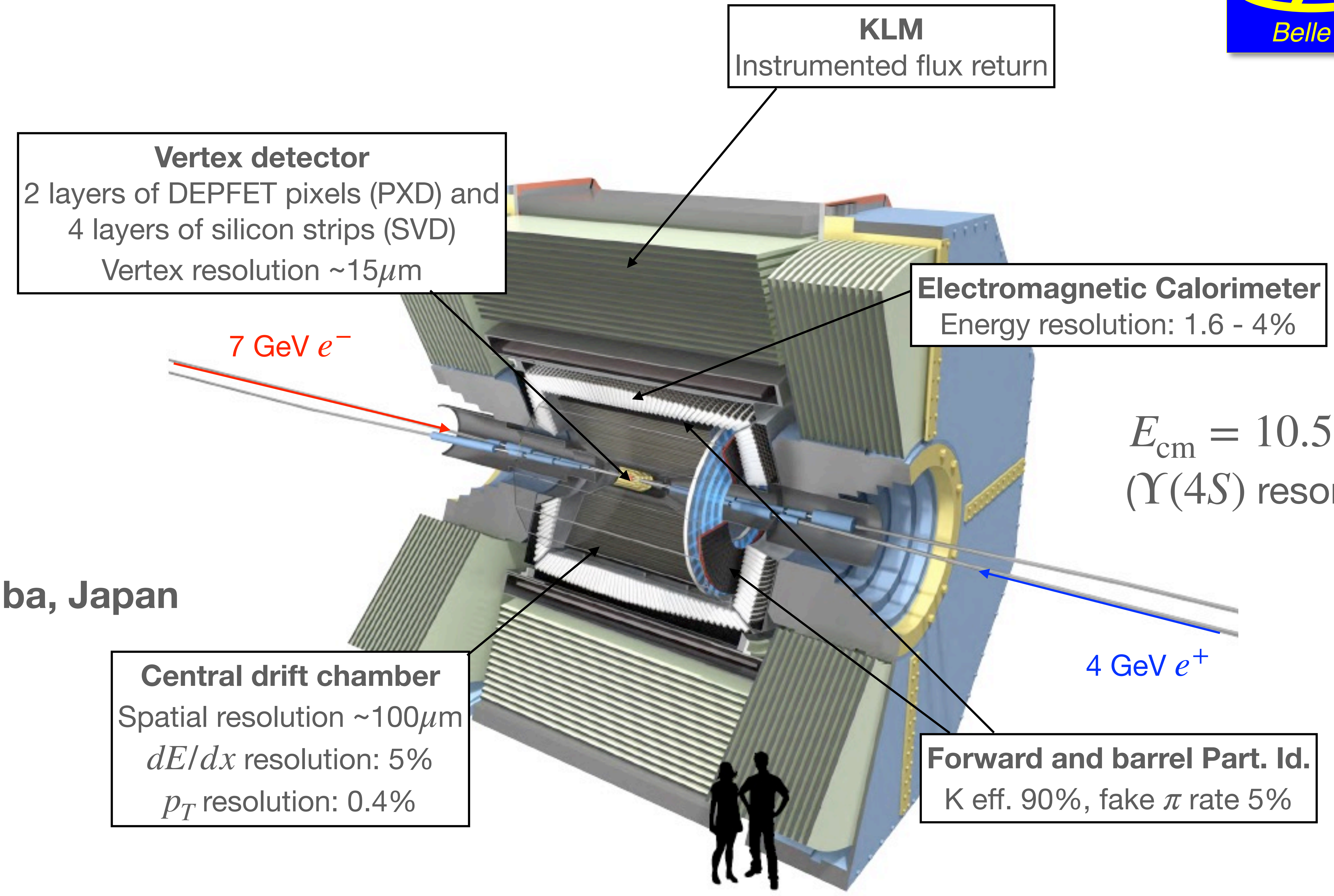
New luminosity record

Dec 27, 2024



The Belle II detector

KEK
Tsukuba, Japan

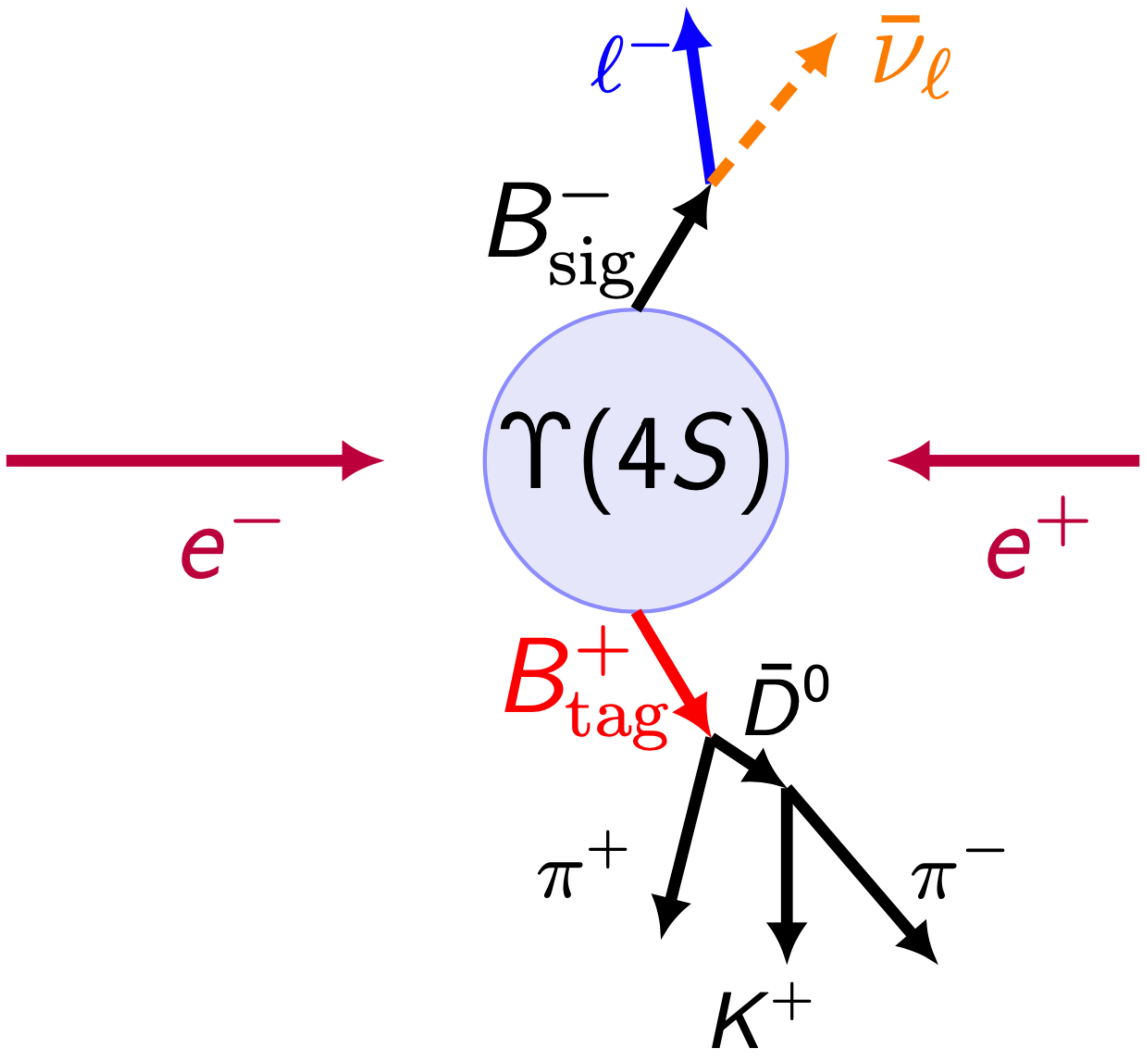


$E_{cm} = 10.58$ GeV
($\Upsilon(4S)$ resonance)

Untagged vs. Tagged

Untagged:
only B_{sig} is reconstructed

high signal yield (+)
high backgrounds (-)
poor neutrino reconstruction (-)

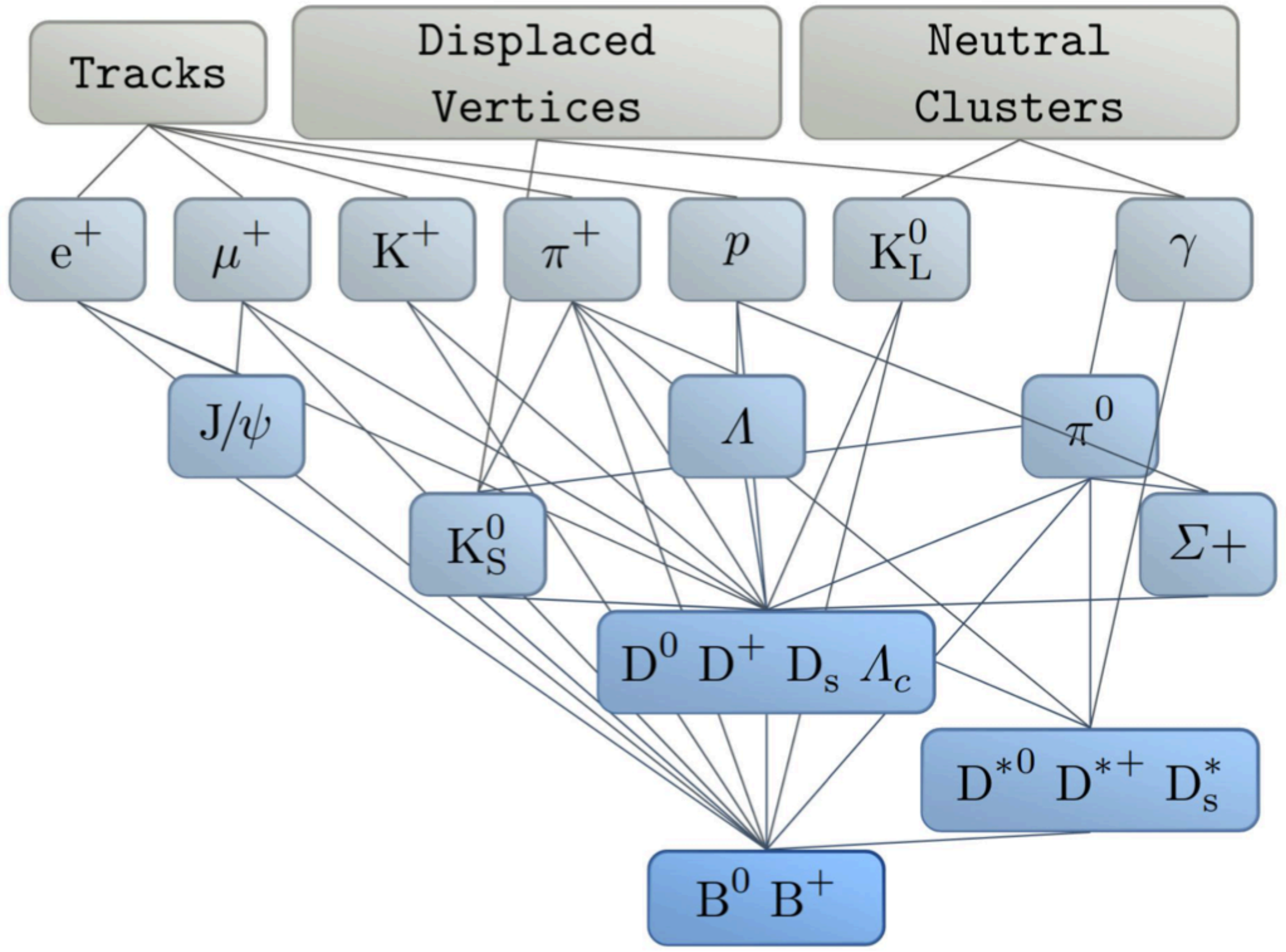


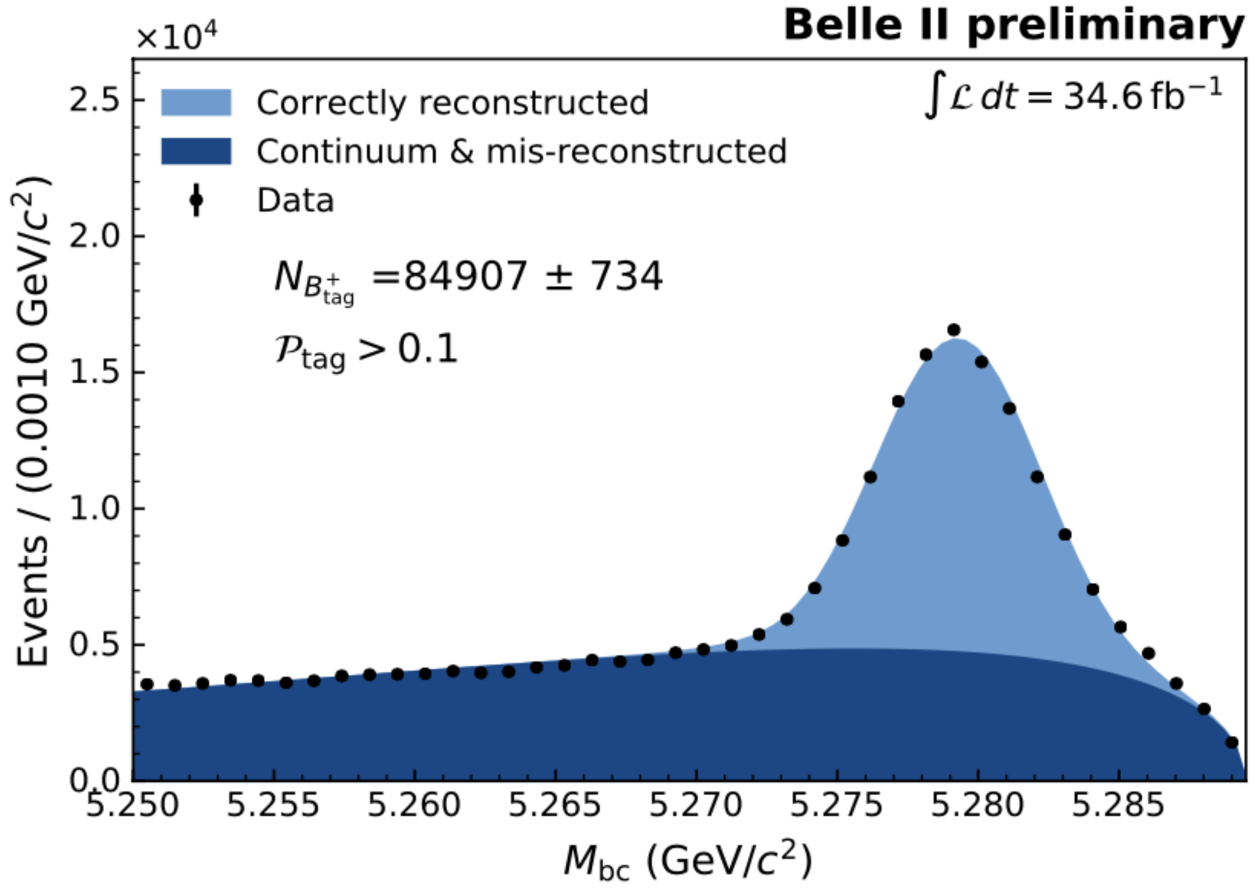
Tagged:
B_{sig} and B_{tag} are reconstructed

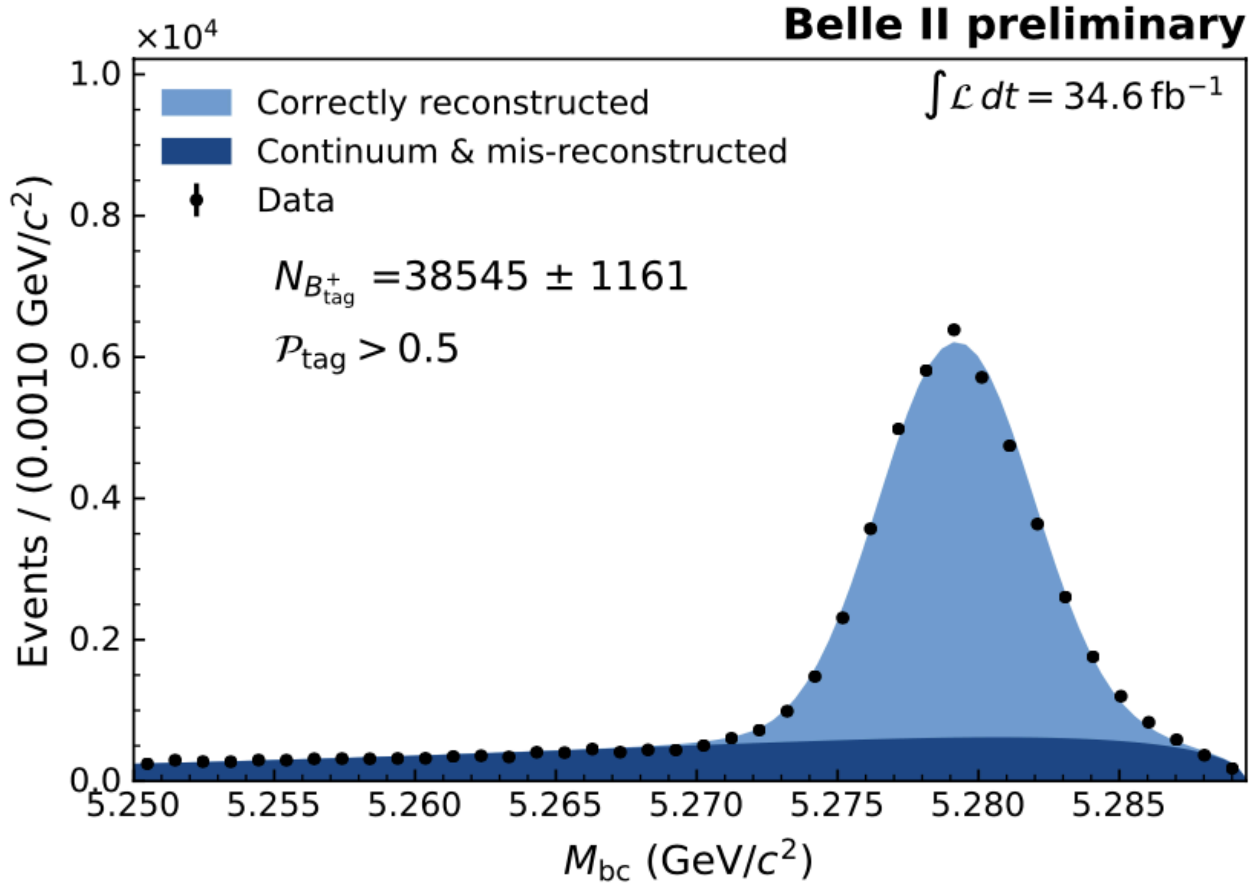
signal yield $O(10^3)$ lower (-)
low backgrounds (+)
good neutrino reconstruction (+)
tag calibration (-)

Hadronic tagging at Belle II

Comput Softw Big Sci (2019) 3: 6.







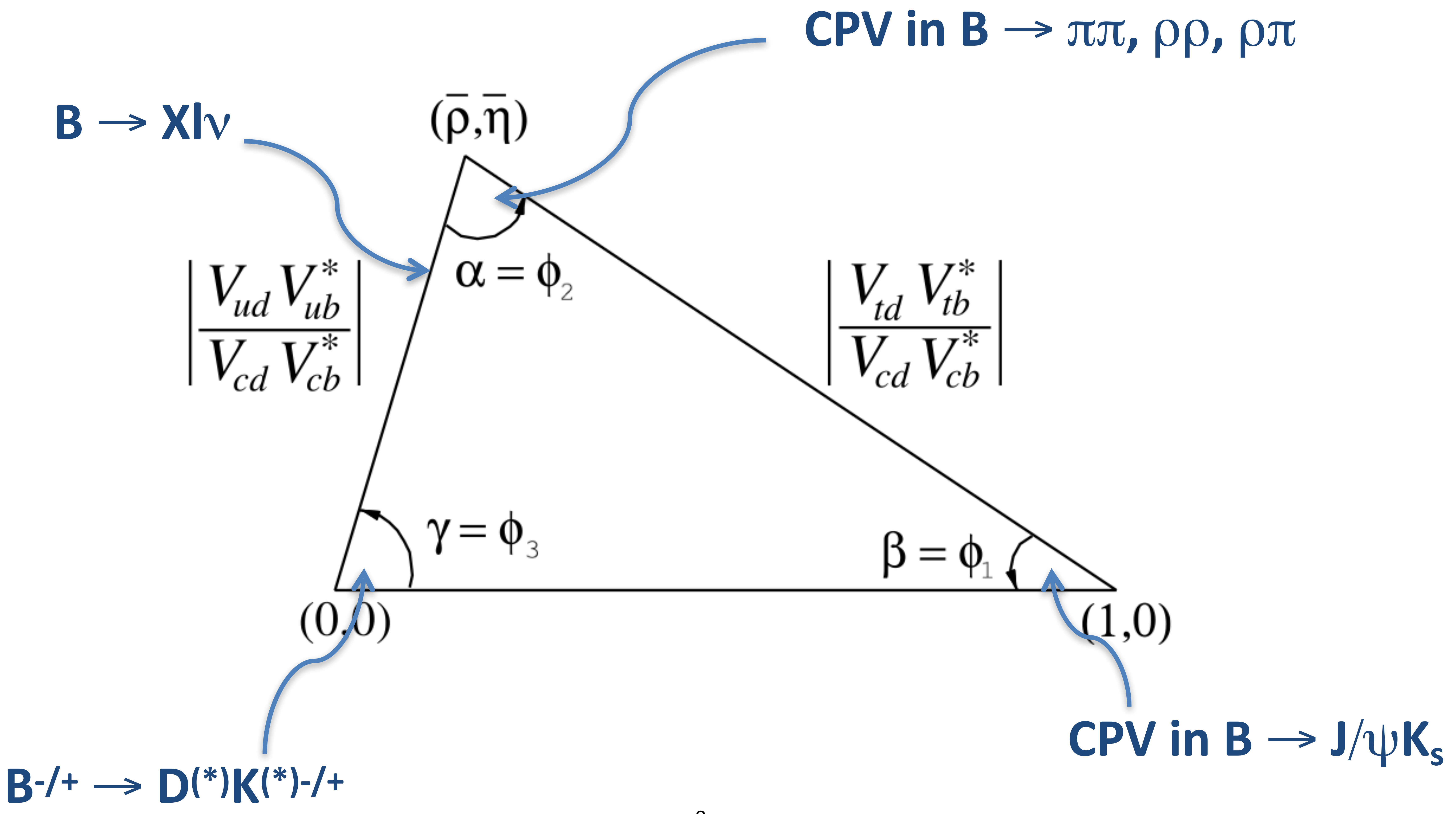
$$M_{bc} = \sqrt{E^2_{beam}/4 - (p^{cm}_{B_{tag}})^2} > 5.27\ \mathrm{GeV}/c^2$$

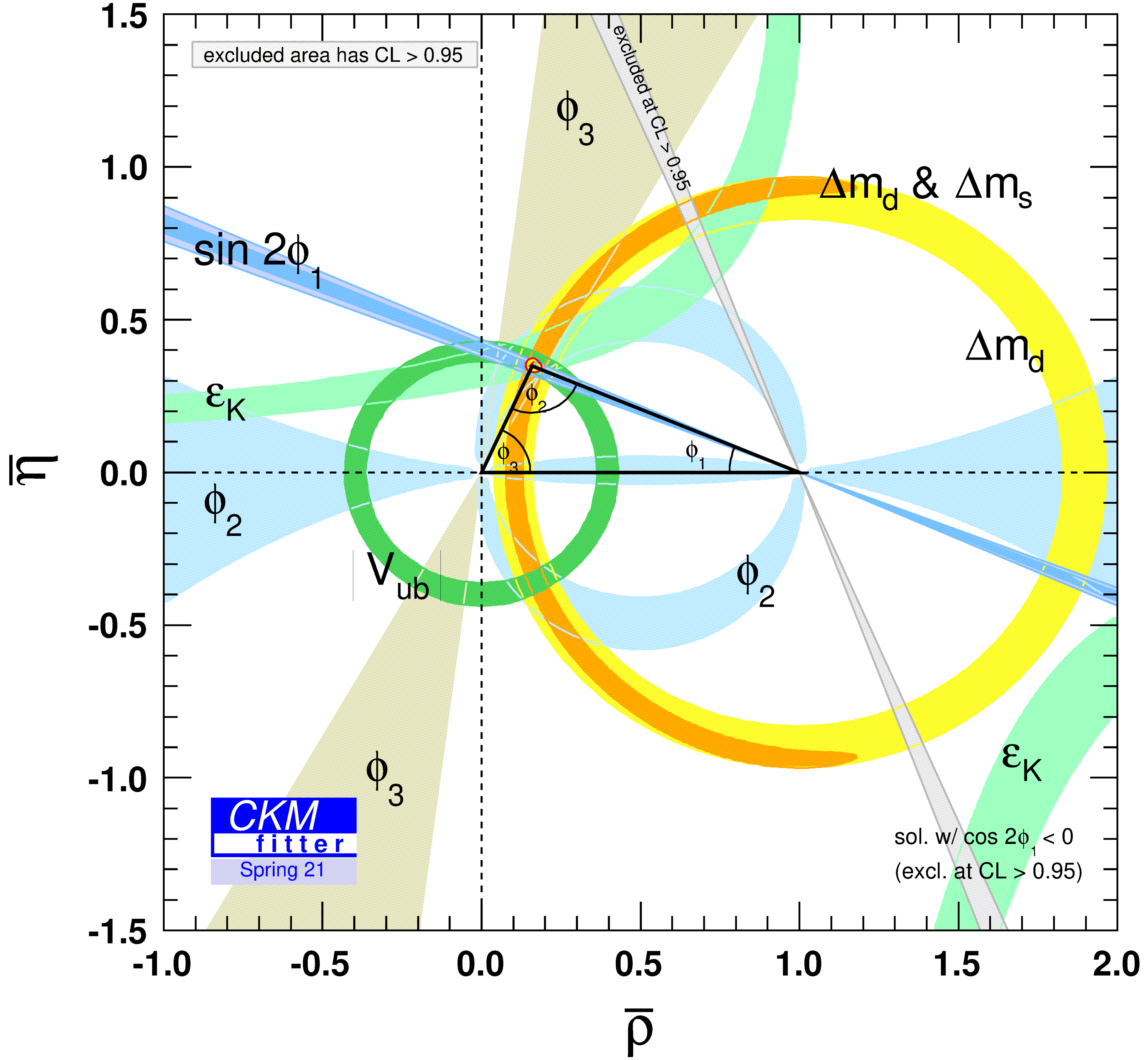
- The hadronic FEI employs over 200 boosted decision trees to reconstruct 10000 B decay chains
  - $\epsilon_{B^+} \approx 0.5\ \%$, $\epsilon_{B^0} \approx 0.3\ \%$ at low purity (about 50% increase with respect to the Belle tag)

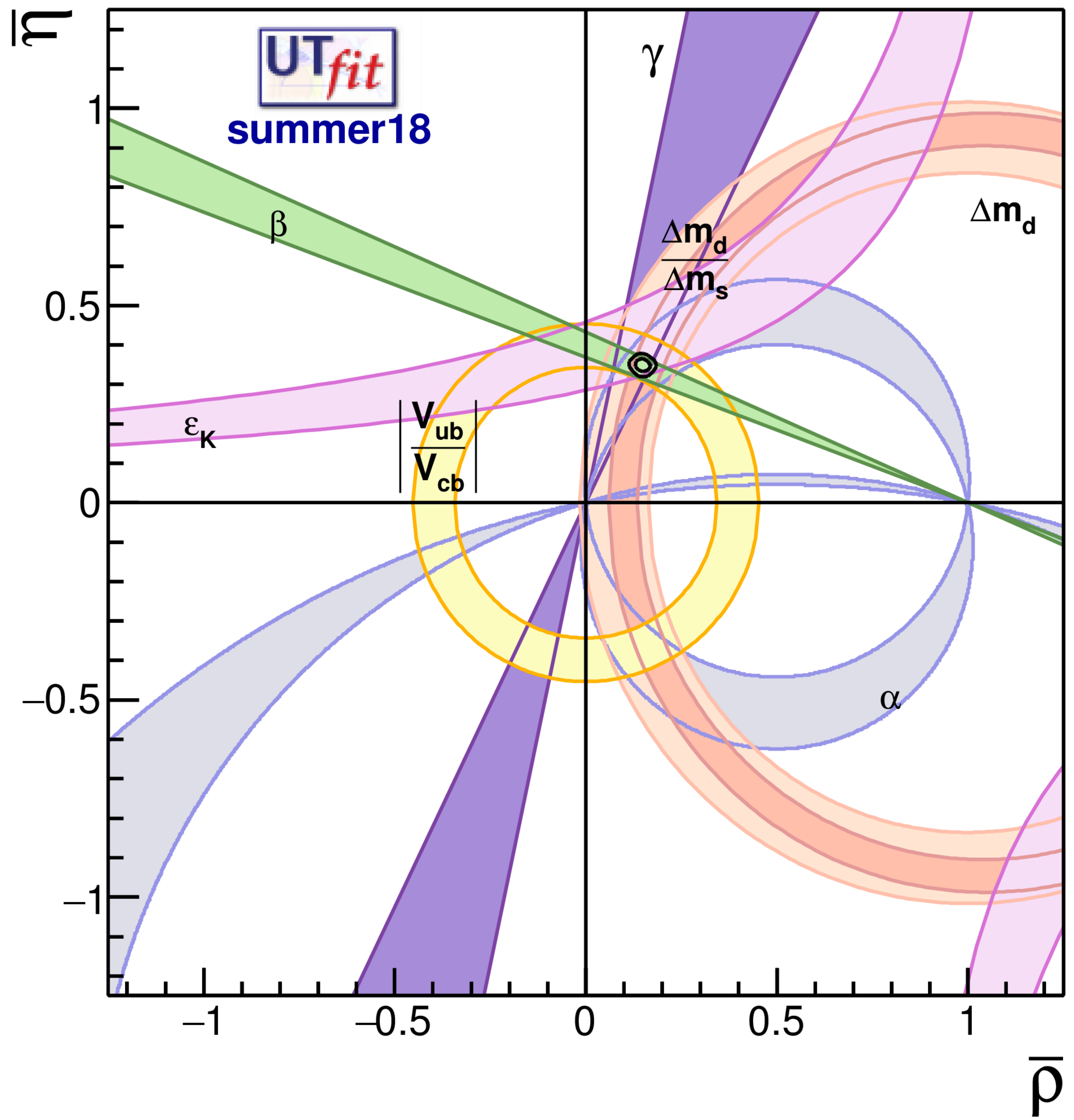
The CKM unitarity triangle

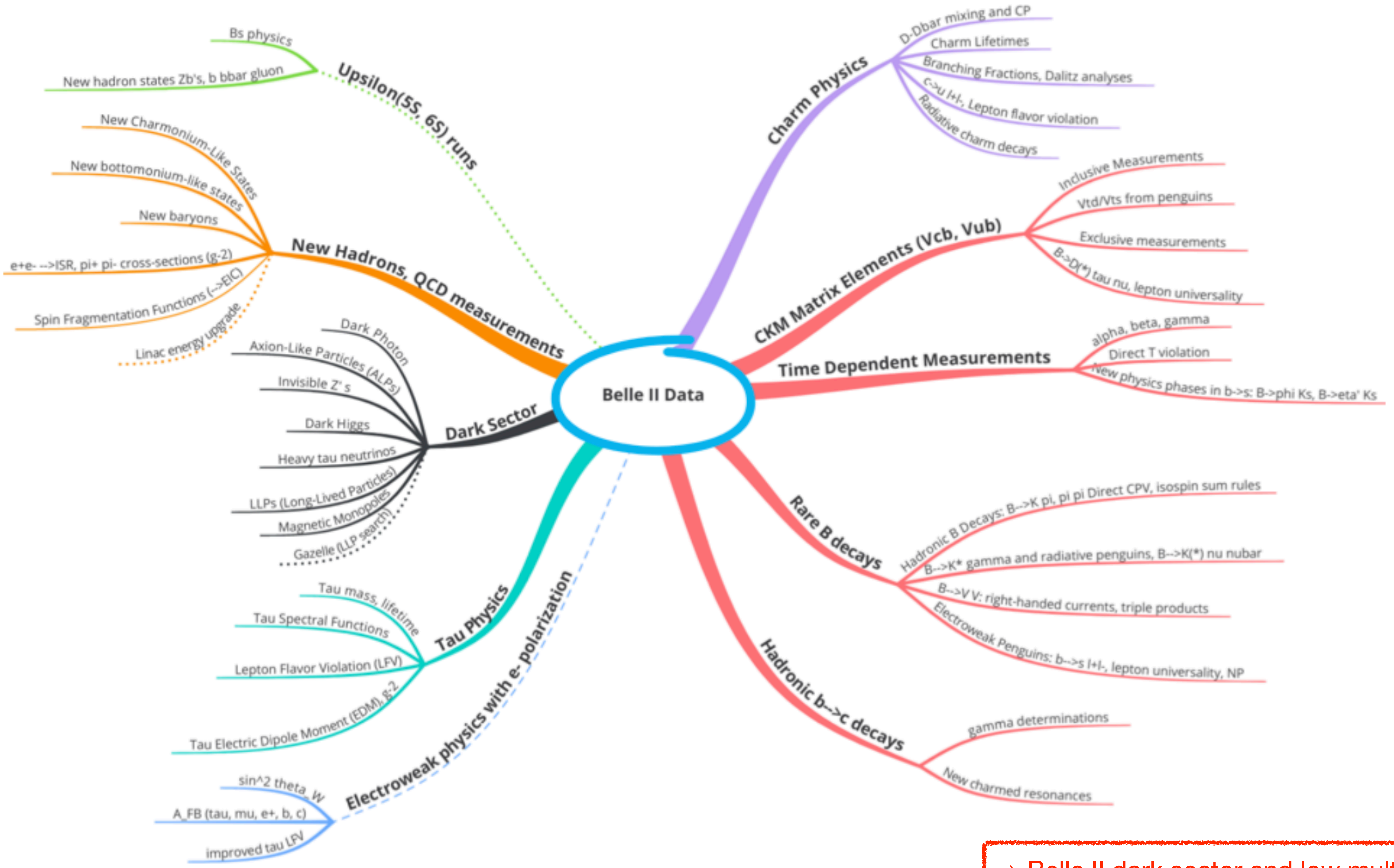
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

…and how to probe it with B mesons




excluded area has CL > 0.95
excluded at CL > 0.95
ϕ_3
Δm_d & Δm_s
sin $2\phi_1$
Δm_d
ε_K
ϕ_2
ϕ_1
ϕ_3
$|V_{ub}|$
ϕ_2
ϕ_3
ε_K
CKM fitter
Spring 21
sol. w/ cos $2\phi_1$ < 0
(excl. at CL > 0.95)
$\bar{\eta}$
$\bar{\rho}$


UTfit
summer18
γ
β
Δm_d
$\frac{\Delta m_d}{\Delta m_s}$
ε_K
$\left|\frac{V_{ub}}{V_{cb}}\right|$
α
$\bar{\eta}$
$\bar{\rho}$



→ Belle II dark sector and low multiplicity physics will be covered in Enrico's talk

Outline

Recent Belle II results covered in this presentation

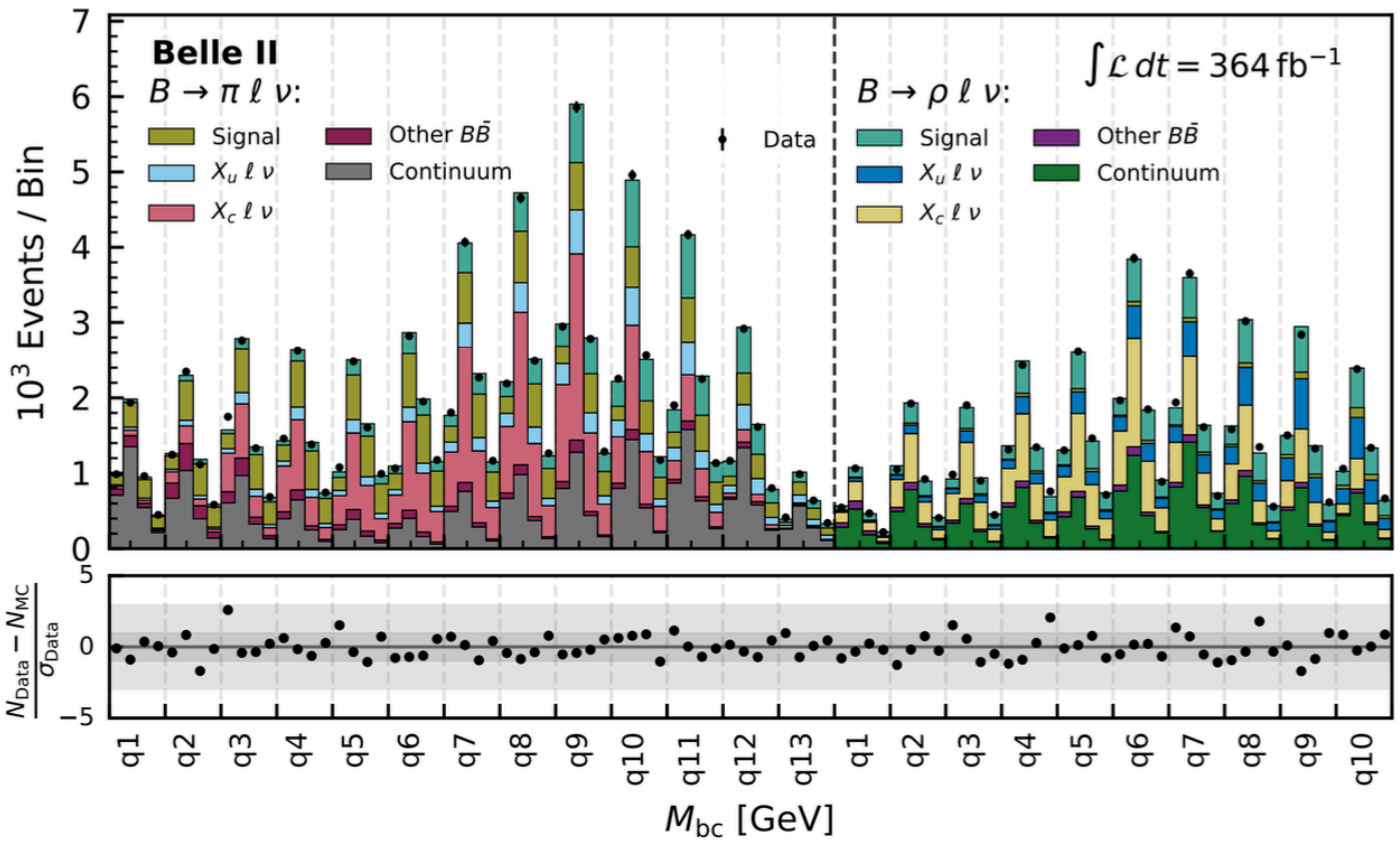
- $|V_{ub}|$ from $B^0 \to \pi^- \ell^+ \nu$ and $B^+ \to \rho^0 \ell^+ \nu$ [arXiv:2407.17403] submitted to Phys. Rev. D
- Branching fraction of $B^+ \to \tau^+ \nu$ [arXiv:2502.04885]
- Branching fraction and CP asymmetry in $B^0 \to \pi^0 \pi^0$ [arXiv:2412.14260]
- CKM phase ϕ_2 (α) from $B^0 \to \rho^+ \rho^-$ [arXiv:2412.19624]
- Search for $B^0 \to K^{*0} \tau^+ \tau^-$

$|V_{ub}|$ from $B^0 \to \pi^- \ell^+ \nu$ and $B^+ \to \rho^0 \ell^+ \nu$

[arXiv:2407.17403] submitted to Phys. Rev. D

- Run 1 dataset (364/fb), untagged analysis, $\pi^- \ell^+$ and $\rho^0 \ell^+$ are reconstructed, neutrino is inferred from the missing energy and momentum in th event
- Background suppression with multivariate methods (BDTs)
- Signal extraction from a simultaneous fit in bins of q^2

$$q^2 = (p_B - p_{\pi/\rho})^2$$



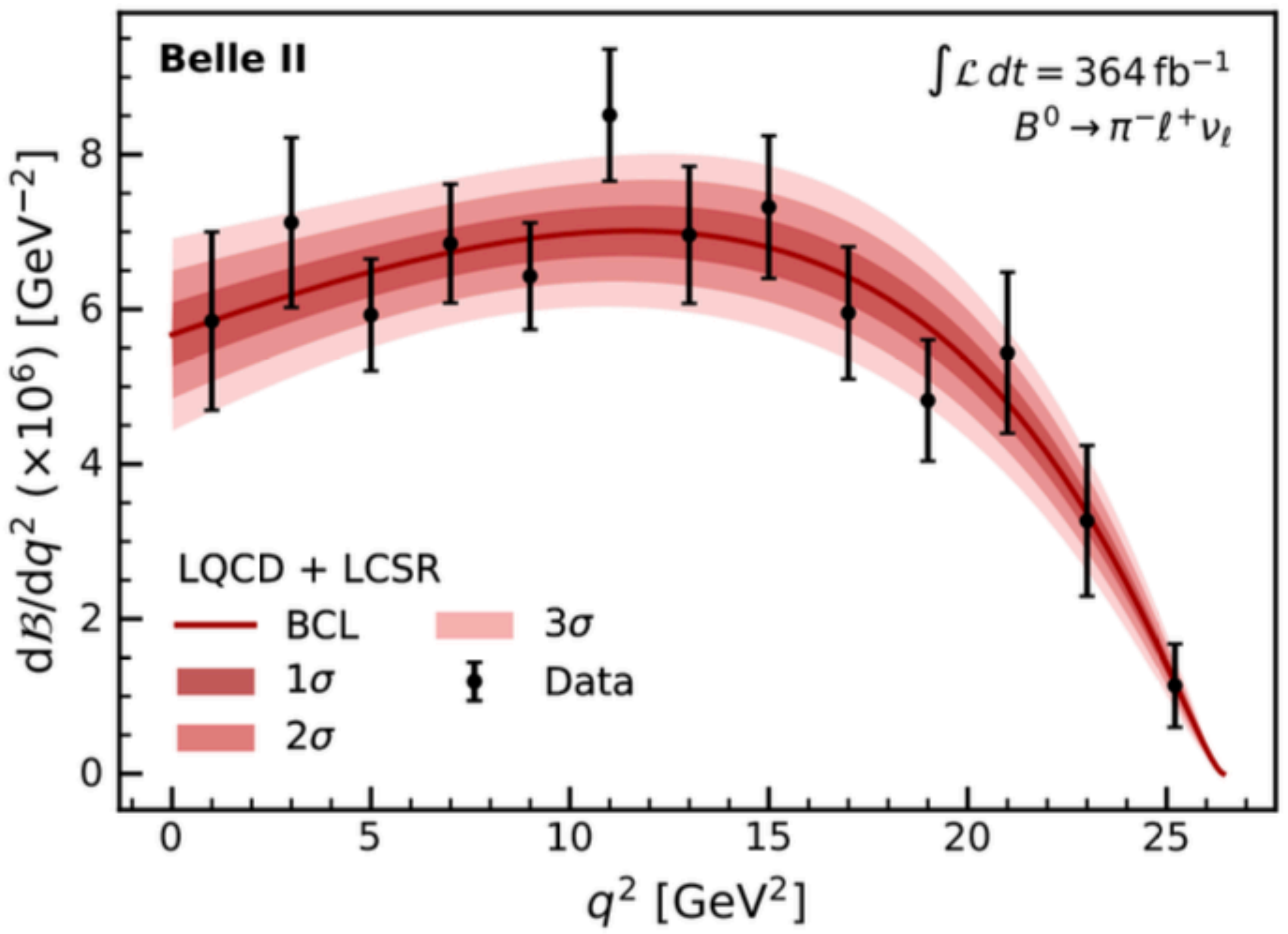
$$\mathscr{B}(B^0 \to \pi^- \ell^+ \nu_\ell) = (1.516 \pm 0.042 \pm 0.059) \times 10^{-4}$$

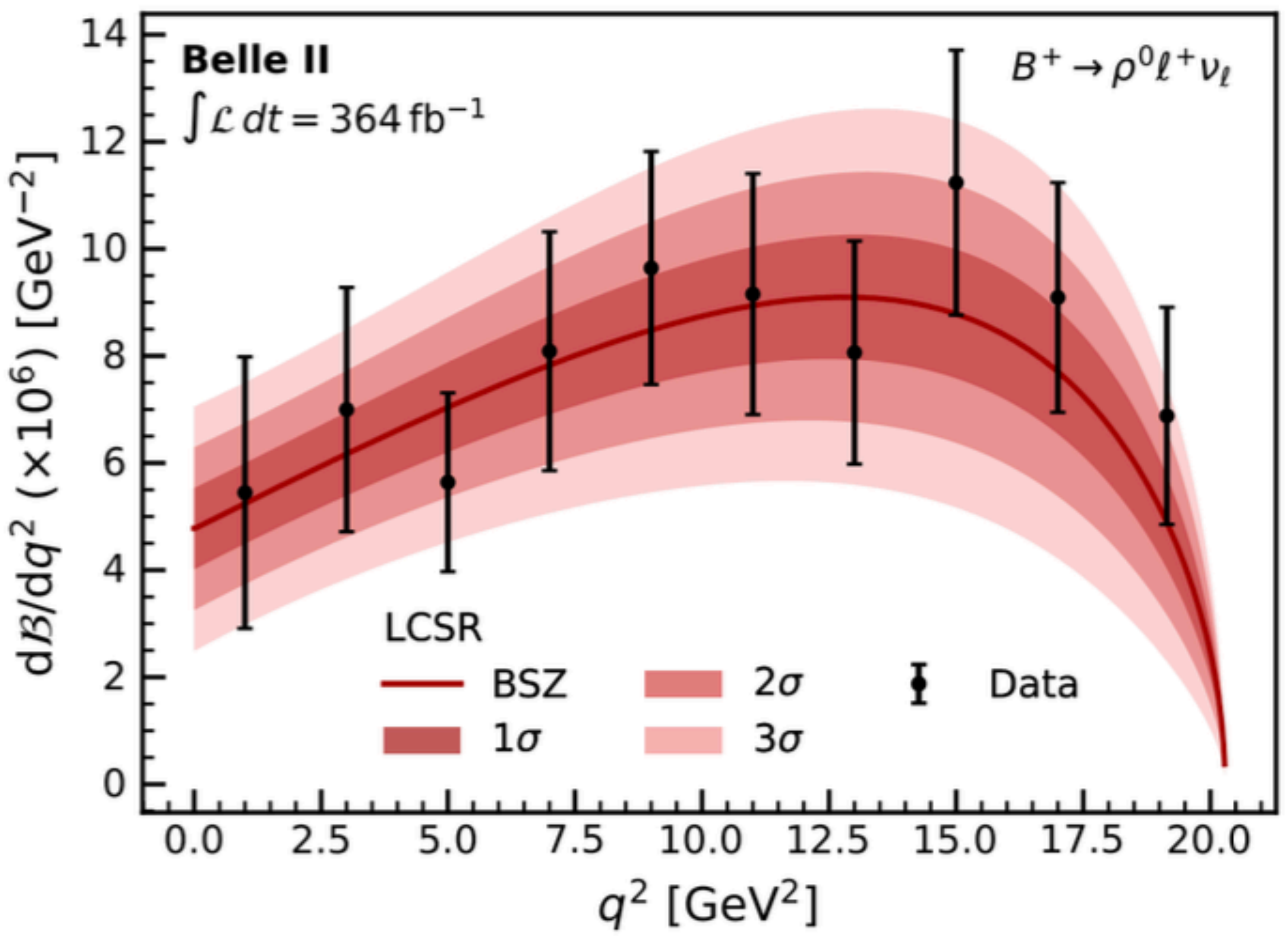
$$\mathscr{B}(B^+ \to \rho^0 \ell^+ \nu_\ell) = (1.625 \pm 0.079 \pm 0.180) \times 10^{-4}$$

$|V_{ub}|$ from $B^0 \to \pi^- \ell^+ \nu$ and $B^+ \to \rho^0 \ell^+ \nu$

[arXiv:2407.17403] submitted to Phys. Rev. D

- $|V_{ub}|$ is extracted from a combined fit to lattice QCD and light-cone sum rule calculations
  - Lattice QCD (LQCD) [Eur. Phys. J. C 82, 869 (2022)]
  - Light-cone sum rule (LCSR) [J. High Energ. Phys. 2021, 36 (2021), J. High Energ. Phys. 2016, 98 (2016)]





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

(stat.) (syst.) (theo.)

$$|V_{ub}|^{\mathrm{LQCD+LCSR}}_{B\to\pi\ell\nu} = (3.73 \pm 0.07 \pm 0.07 \pm 0.16) \times 10^{-3}$$

$$|V_{ub}|^{\mathrm{LCSR}}_{B\to\rho\ell\nu} = (3.19 \pm 0.12 \pm 0.17 \pm 0.26) \times 10^{-3}$$

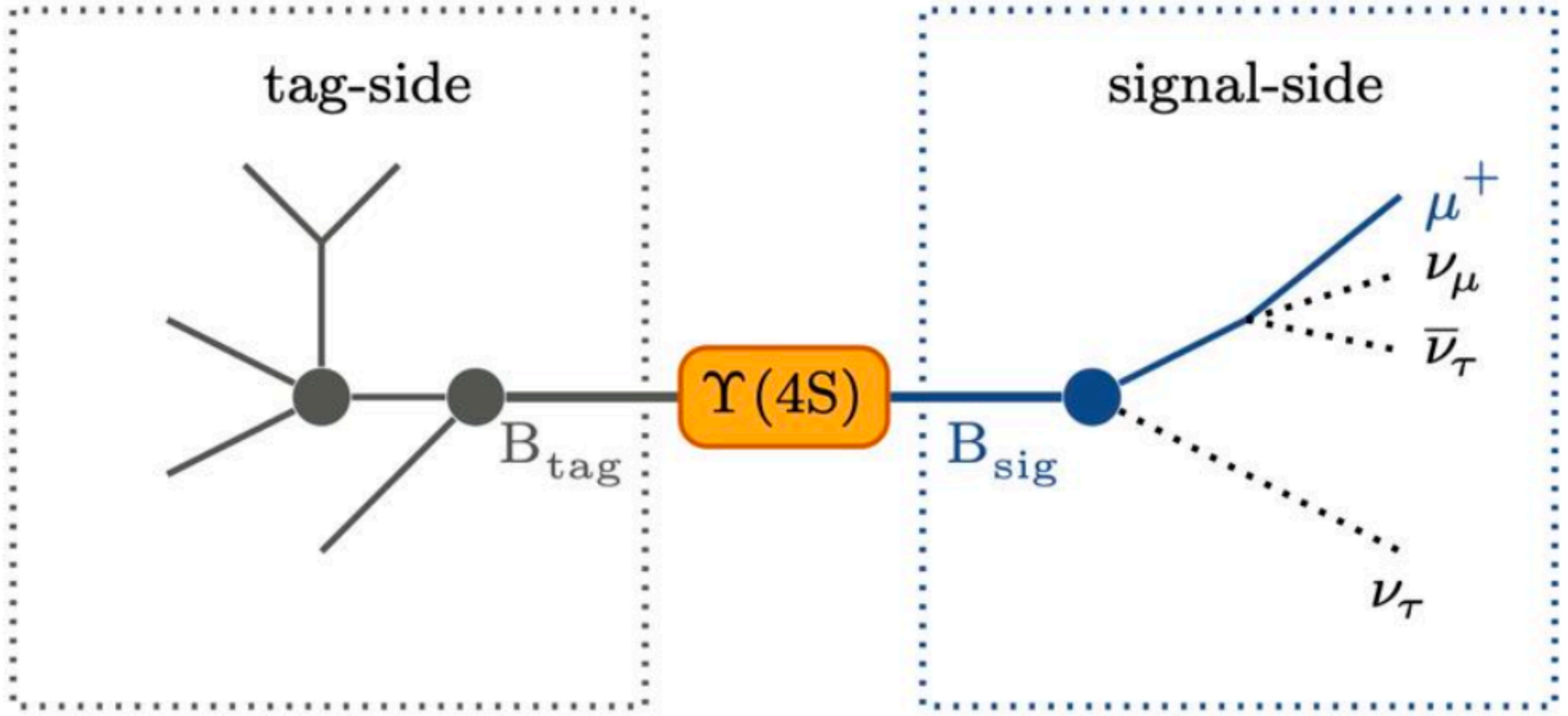
$B^+ \to \tau^+ \nu$

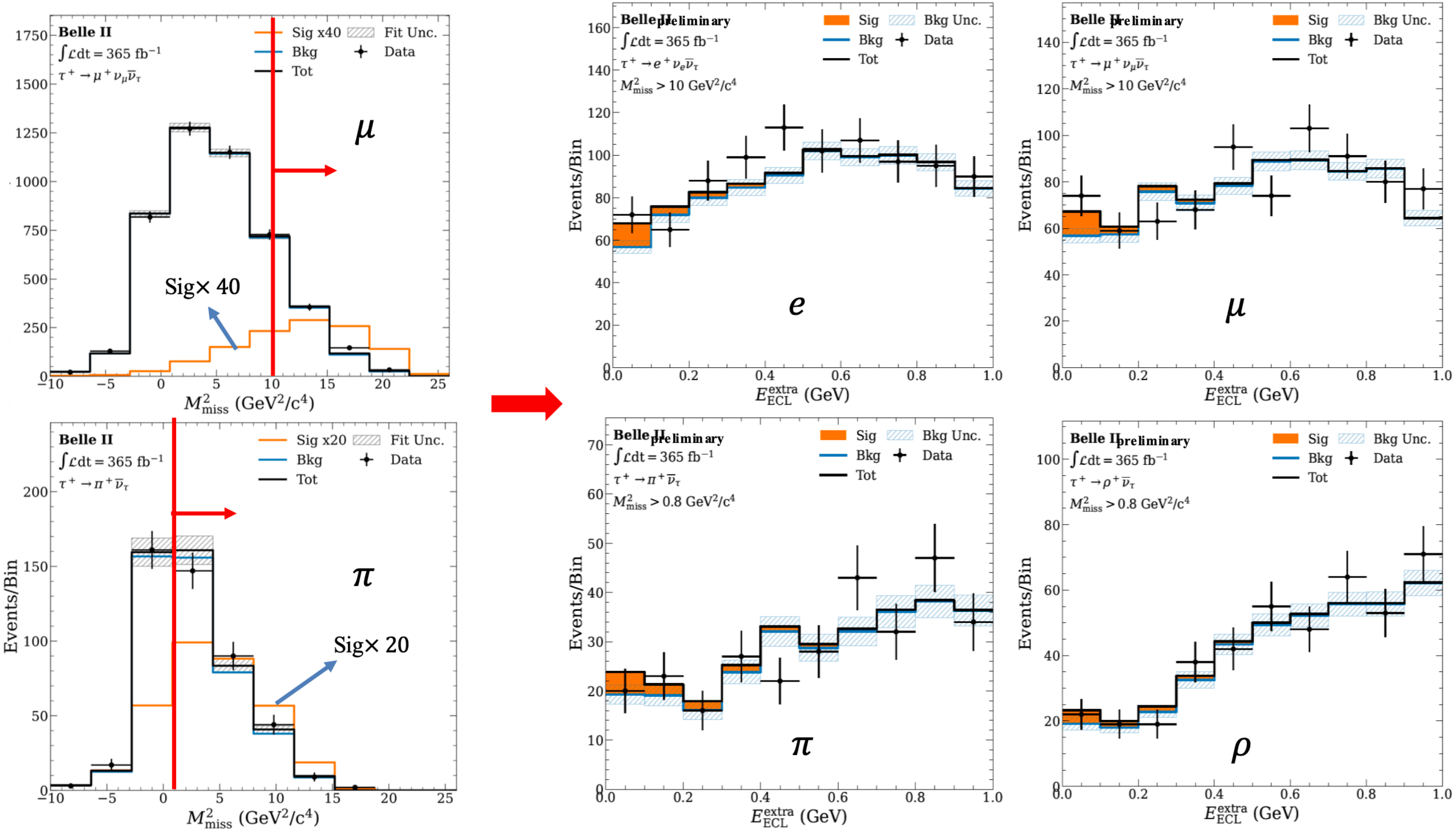
[arXiv:2502.04885], submitted to Phys. Rev. D

- Leptonic B decay with the largest branching fraction that might be affected by New Physics

$$\mathcal{B}(B^+ \to \tau^+ \nu_\tau) = \frac{G_F^2 m_B m_\tau^2}{8\pi} \left[1 - \frac{m_\tau^2}{m_B^2}\right]^2 f_B^2 |V_{ub}|^2 \tau_B$$

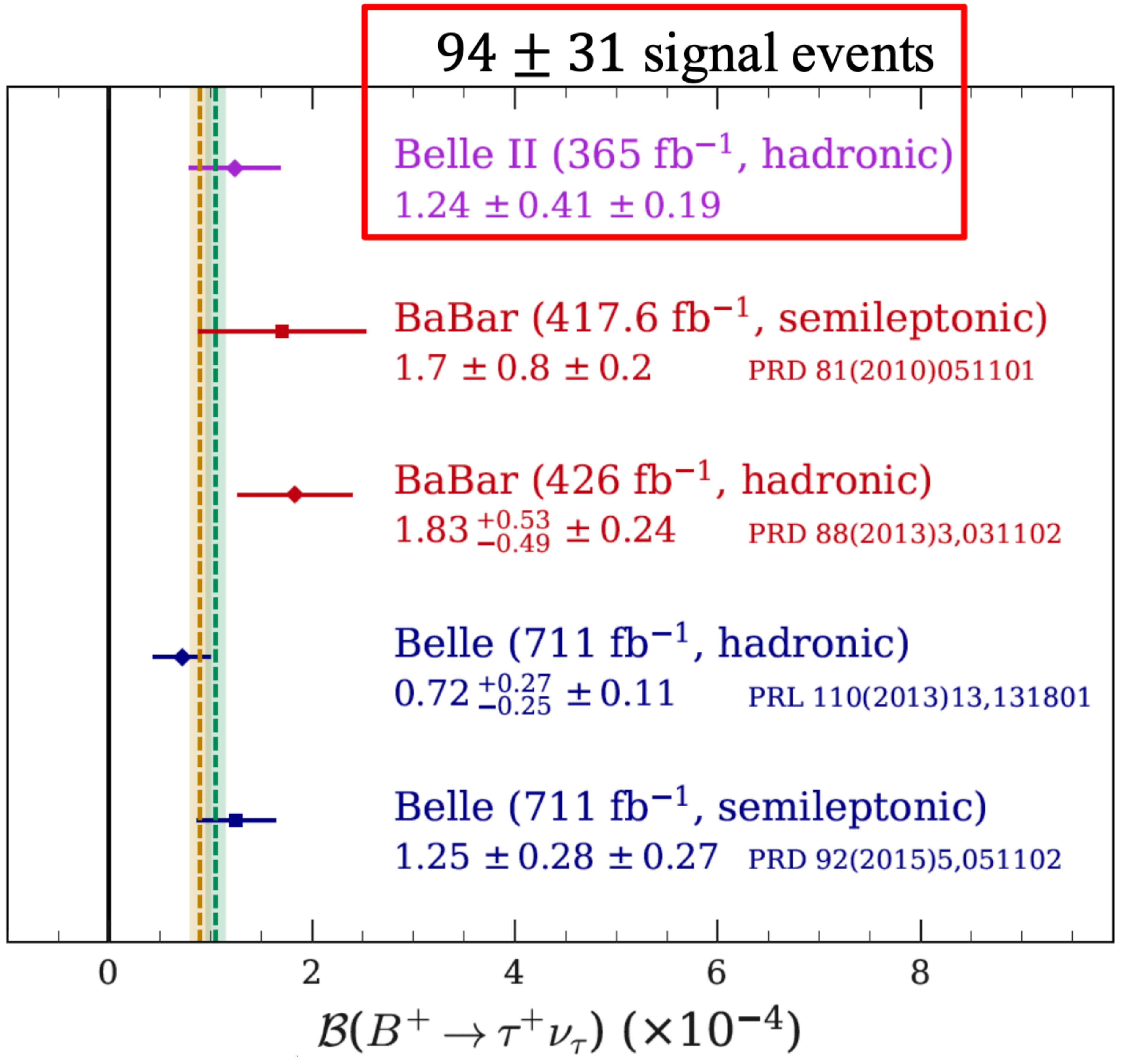
- Tagged analysis using 365/fb, on the signal side e^+, μ^+, π^+ or $\rho^+ \to \pi^+\pi^0$ are reconstructed
- Discriminating variables
  - $E_{\text{ECL}}^{\text{extra}}$ — residual energy in the em. calorimeter
  - M_{miss}^2 — missing mass squared in the event




Belle II
∫ℒdt = 365 fb⁻¹
τ⁺ → μ⁺ ν_μ ν̄_τ
Sig x40
Fit Unc.
Bkg
Data
Tot
μ
Sig× 40
M²_miss (GeV²/c⁴)
τ⁺ → π⁺ ν̄_τ
Sig x20
π
Sig× 20
Events/Bin
Belle II preliminary
Sig
Bkg Unc.
τ⁺ → e⁺ ν_e ν̄_τ
M²_miss > 10 GeV²/c⁴
e
E^extra_ECL (GeV)
M²_miss > 0.8 GeV²/c⁴
τ⁺ → ρ⁺ ν̄_τ
ρ

$B^+ \to \tau^+ \nu$

[arXiv:2502.04885], submitted to Phys. Rev. D



World average BR goes from

$$(1.09 \pm 0.24) \times 10^{-4}$$

to

$$(1.12 \pm 0.21) \times 10^{-4}$$

Leads to:

$$V_{ub}^{\tau\nu} = \left(4.19 \begin{array}{c} +0.38 \\ -0.41 \end{array}\right) \times 10^{-3}$$

Relative uncertainty: $^{+9\%}_{-10\%}$

Determination of the CKM angle ϕ_2/α

- Probability for $B \to CP$-Eigenstate

C: CP violation (CPV) in decay
S: CPV in mixing-decay interference

$$P(q, \Delta t) \propto 1 \pm S \sin \Delta m \Delta t - C \cos \Delta m \Delta t$$

$$q = \begin{cases} +1 & B_{\text{tag}} = B^0 \\ -1 & B_{\text{tag}} = \bar{B}^0 \end{cases}$$

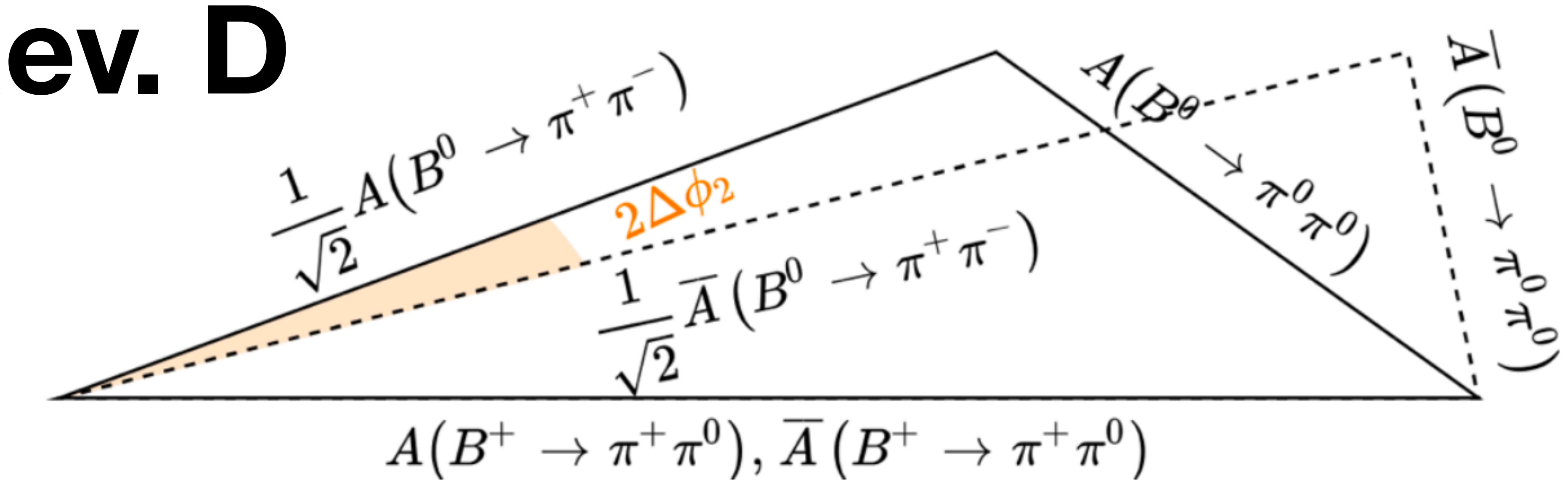
$t_{CP} - t_{\text{tag}}$

$M(B_H) - M(B_L)$

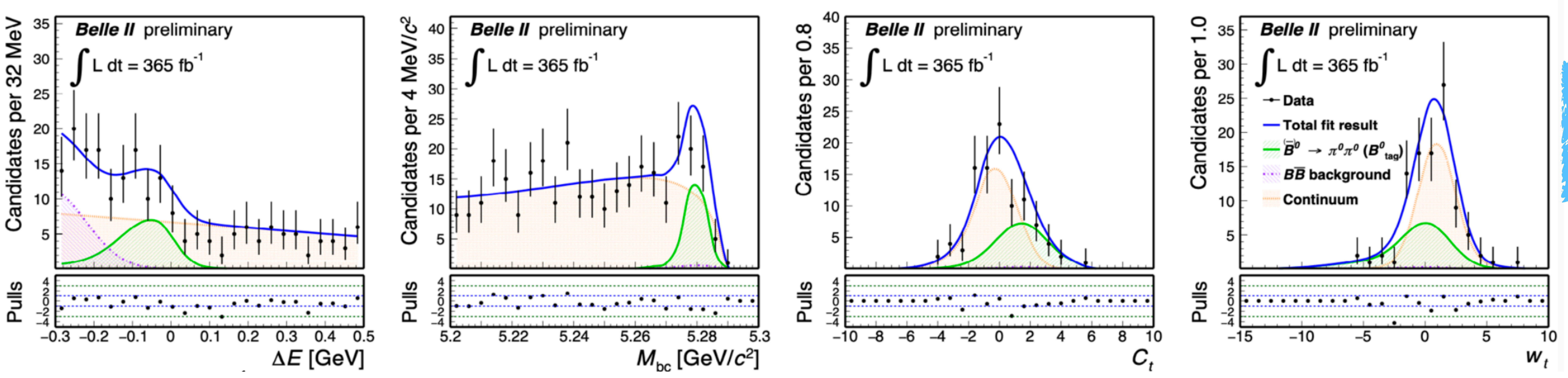
- In tree-level $b \to u\bar{u}d$ transitions to final states $\pi\pi$, $\pi\rho$, $\rho\rho$, πa_1: $S = \sin 2\phi_2$
- But $b \to$ loop contributions change this to $\sqrt{1 - C^2}\,\sin(2\phi_2 + \Delta\phi_2)$

Isospin relations in $B^0 \to \pi^0\pi^0$

[arXiv:2412.14260], submitted to Phys. Rev. D



- Isospin relations are used to disentangle the loop contribution and obtain $\Delta\phi_2$
- Requires measuring branching fractions and CP asymmetries for $\pi^+\pi^-$, $\pi^\pm\pi^0$ and $\pi^0\pi^0$
- Experimentally, $\pi^0\pi^0$ is the most difficult (only photons)



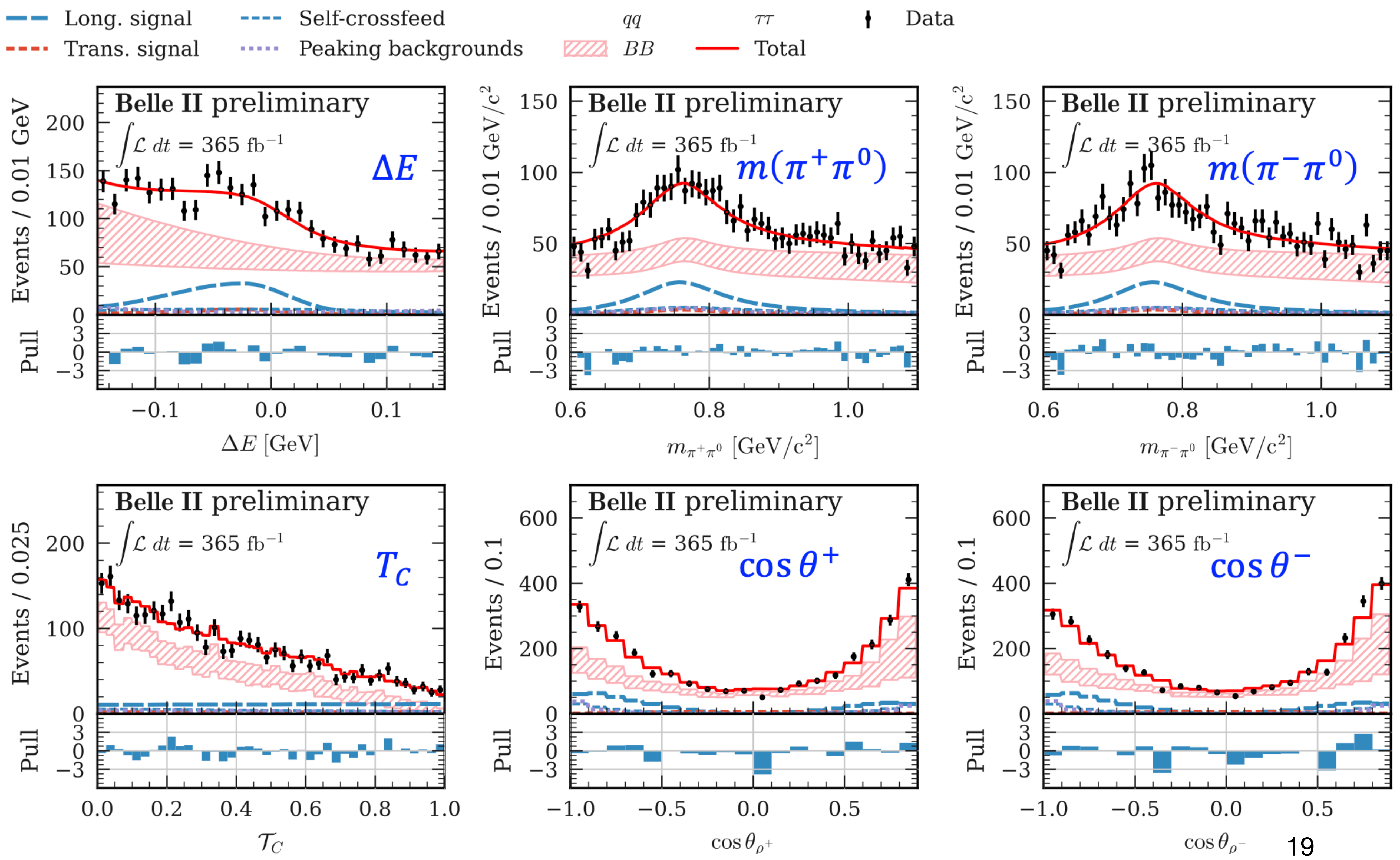
$B(\pi^0\pi^0) = (1.25 \pm 0.23) \times 10^{-6}$

$A_{CP}(\pi^0\pi^0) = 0.03 \pm 0.30$

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

[arXiv:2412.19624], submitted to Phys. Rev. D

- Only small penguin contamination, thus golden mode for ϕ_2
- First, obtain signal BR and longitudinal polarization from a 6D fit



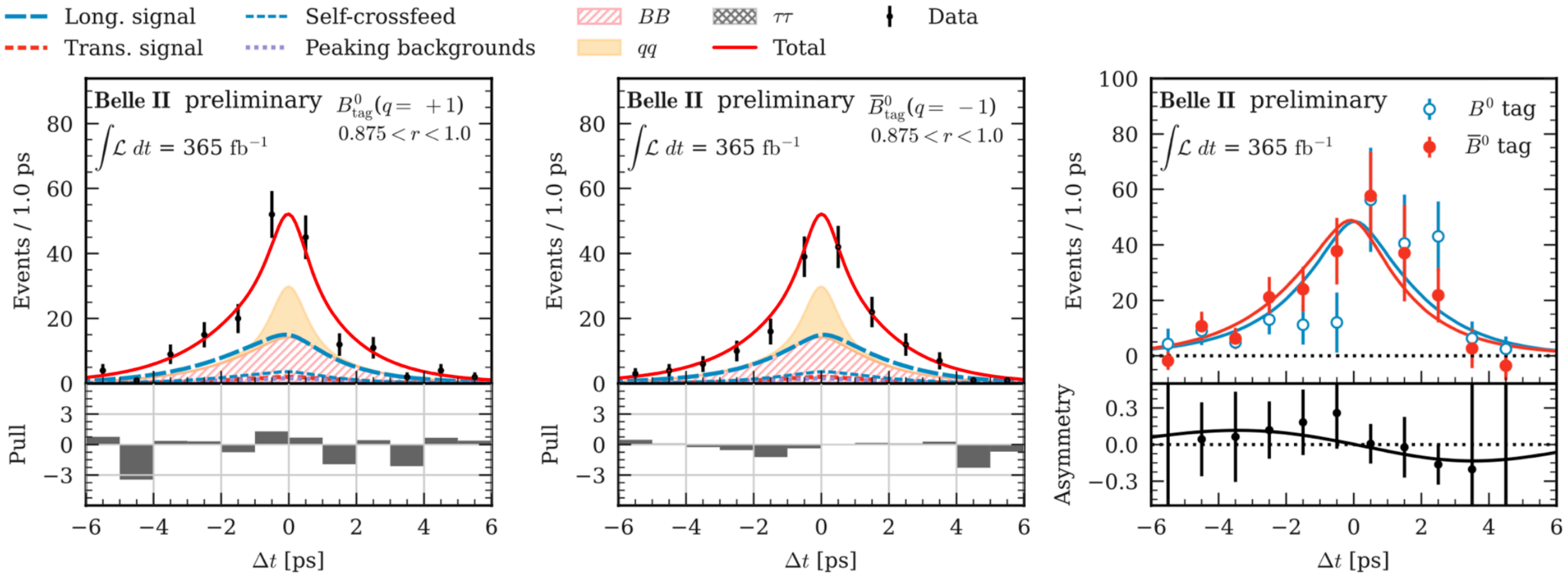
$$\mathcal{B}(B^0 \to \rho^+\rho^-) = (2.88^{+0.23+0.29}_{-0.22-0.27}) \times 10^{-5}$$

$$f_L = 0.921^{+0.024+0.017}_{-0.025-0.015}$$

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

[arXiv:2412.19624], submitted to Phys. Rev. D

- Then perform CP-fit to Δt as both tag flavors q
  - Δt is obtained from the CP- and tag-vertex separation
  - q is inferred from the residual particles in the event

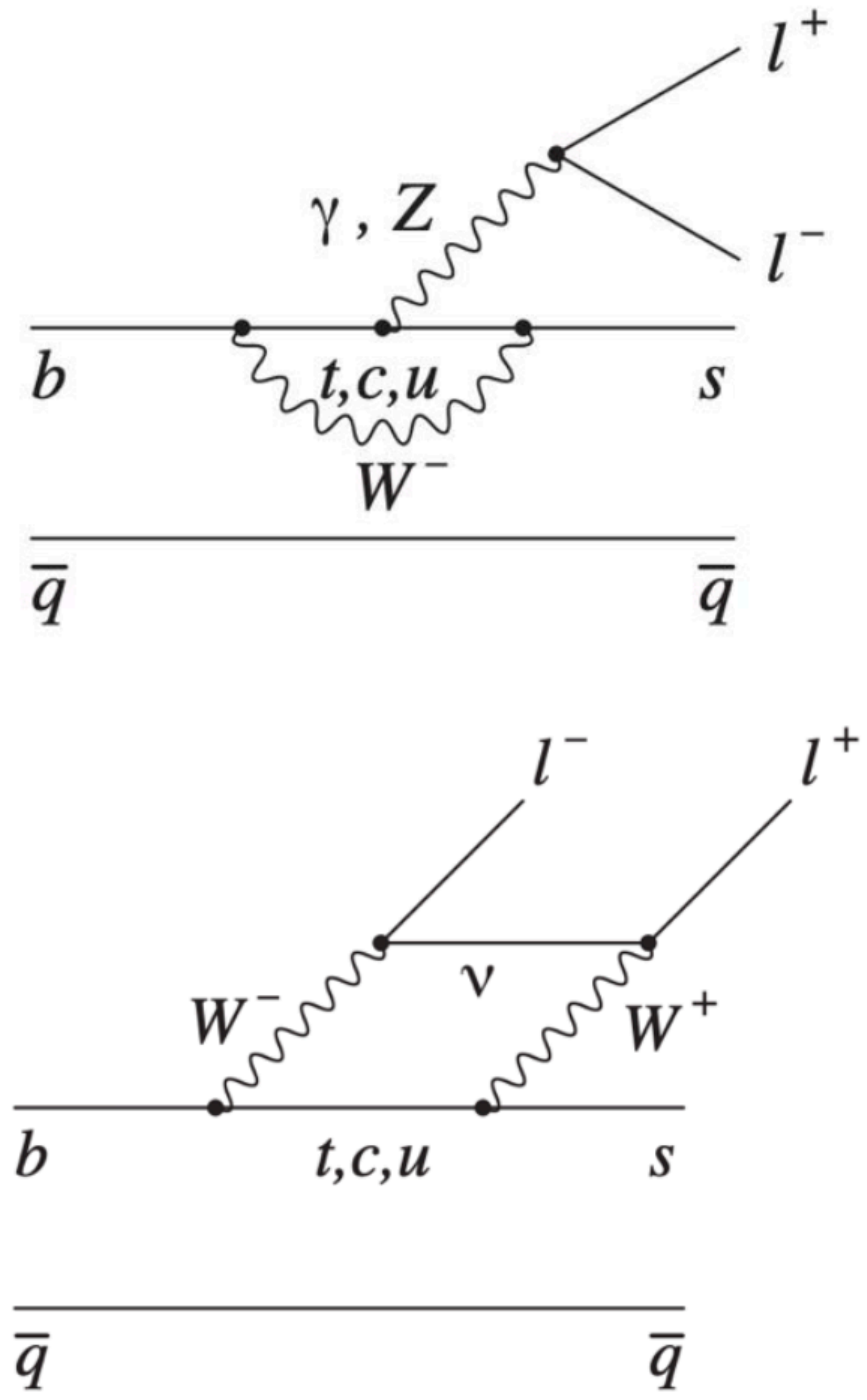


Tag B^0 Tag $\bar{B}^0$ Asymmetry

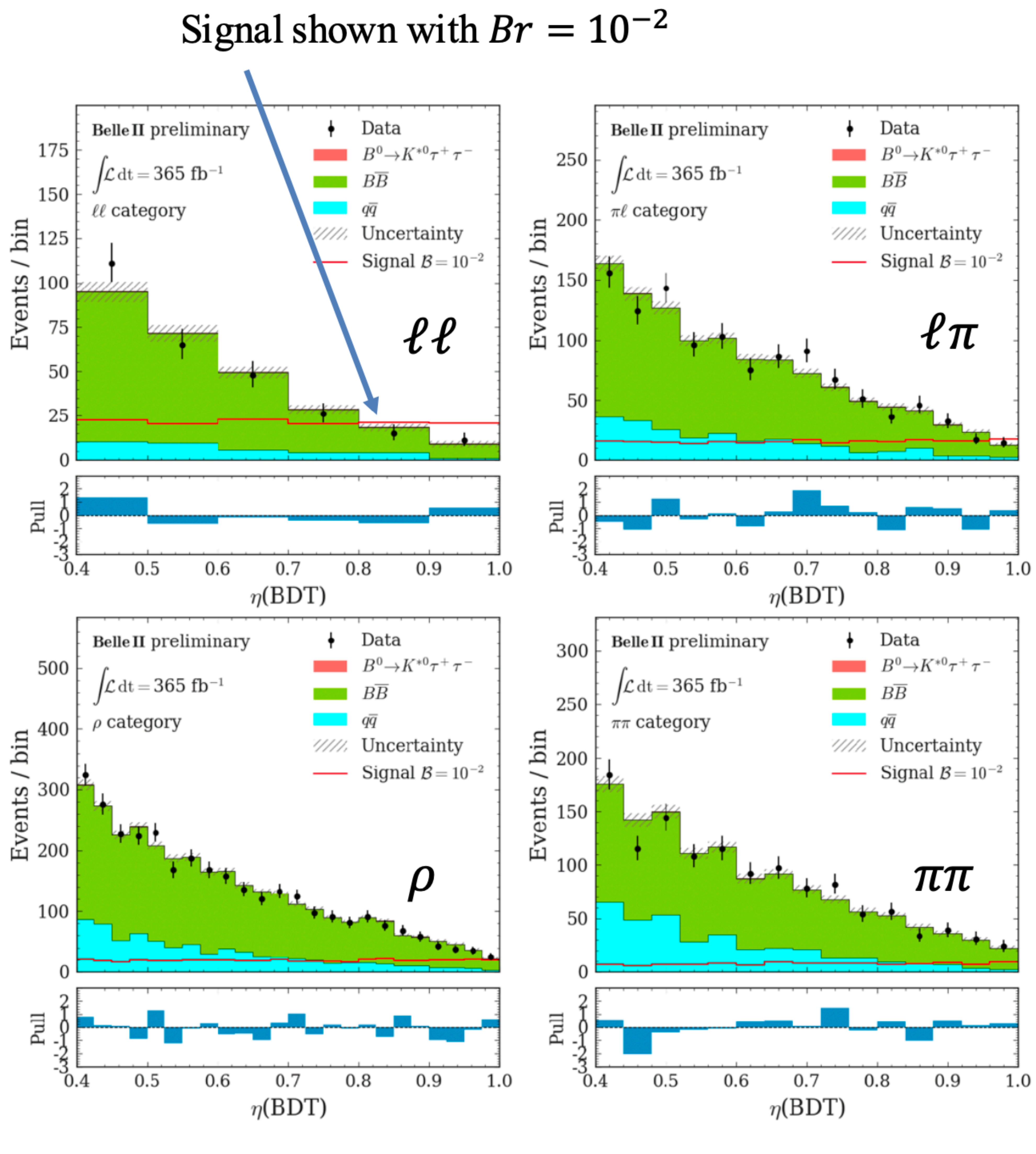
$$S = -0.26 \pm 0.19 \pm 0.08,$$
$$C = -0.02 \pm 0.12^{+0.06}_{-0.05},$$

Search for $B^0 \to K^{*0}\tau^+\tau^-$

- Suppressed FCNC process sensitive to New Physics
- Involving 3rd generation fermions
- SM prediction of the BR: $(0.98 \pm 0.10) \times 10^{-7}$ [PRL 120, 181802 (2018)]
- The $R(D^{(*)})$ anomaly implies that this process could be enhanced to the level of ~10^{-4} [PRL 120, 181802 (2018)]



Search for $B^0 \to K^{*0}\tau^+\tau^-$



- Fit to BDT signal classifier gives
  $\mathscr{B}(B^0 \to K^{*0}\tau^+\tau^-) = (-0.15 \pm 0.86 \pm 0.52) \times 10^{-3}$
- Resulting in the 90% C.L. upper limit
  $\mathscr{B}(B^0 \to K^{*0}\tau^+\tau^-) < 1.8 \times 10^{-3}$
- Previous Belle limit (711/fb)
  [HFLAV: 2411.18639]
  $\mathscr{B}(B^0 \to K^{*0}\tau^+\tau^-) < 3.1 \times 10^{-3}$

Summary

- Belle II has resumed data taking in 2024 after LS1 and accumulated 575/fb on and below the $\Upsilon(4S)$ resonance
- Though only a fraction of the target Belle II sample is available, we follow our physics program and have achieved a number of significant results by using novel analysis techniques and/or combining the Belle II sample with the 711/fb data of Belle
- We are looking forward to the restart of the SuperKEKB run in November 2025!

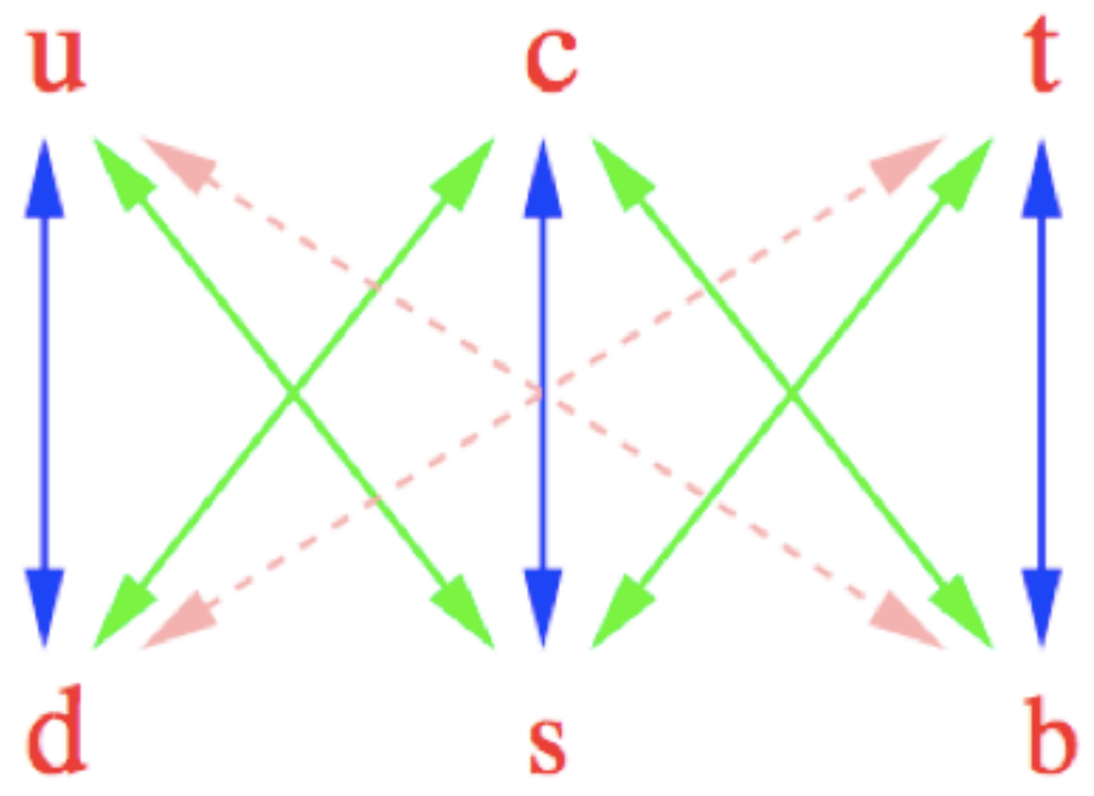
Backup

Cabibbo-Kobayashi-Maskawa quark mixing

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \mathbf{V} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

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

$$\mathbf{V}\,\mathbf{V}^{\dagger} = \mathbf{V}^{\dagger}\,\mathbf{V} = 1$$



- The weak interaction down-type doublet partners are a mixture of the mass (flavour) eigenstates described by the unitary Cabibbo-Kobayashi-Maskawa (CKM) matrix
- The CKM element magnitudes squared determine the rate of quark flavour transitions in charged current processes

$$-\mathcal{L}_{W^{\pm}} = \frac{g}{\sqrt{2}}\,\overline{u_{Li}}\,\gamma^{\mu}\,(V_{\mathrm{CKM}})_{ij}\,d_{Lj}\,W_{\mu}^{+} + \mathrm{h.c.}$$

CP violation

Wolfenstein parametrization of V_{CKM}

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

- However, V_{CKM} also contains a complex phase, responsible for all CP-violating phenomena in the quark sector of the SM, and consistent with observations in K, D and B meson decays so far
- New physics would typically disturb the SM pattern of CPV