Semileptonic decays and tests of lepton flavour universality at Belle II

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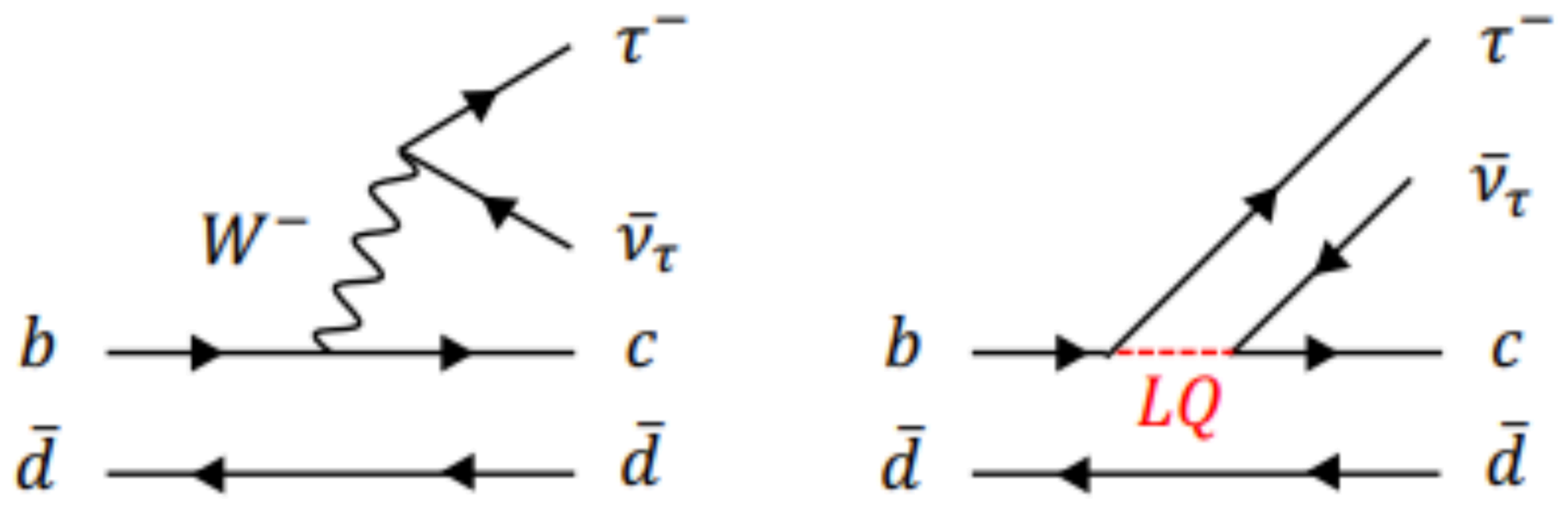
Representing the collaboration

21st Lomonosov Conference on Elementary Particle Physics
August 24-30, 2023, Moscow State University

Search for LFU violation

Motivation



- Physics beyond the Standard Model can spoil the universality of lepton flavour couplings
  - Probing lepton flavour universality (LFU) is thus a promising, theoretically clean avenue for searching for New Physics
- Semileptonic B meson decays combine high rate and low experimental background
  - They thus present an excellent tool for LFU searches
  - There is a long-standing 3σ LFU anomaly in semitauonic B decays

Outline

Belle II results covered in this presentation

- Measurement of $R(X)$
  [189/fb, EPS-HEP 2023]

$$R(X) = \frac{\mathcal{B}(B \to X\tau\nu_\tau)}{\mathcal{B}(B \to X\ell\nu_\ell)}$$

- Measurement of $R(D^*)$
  [189/fb, Lepton Photon 2023]

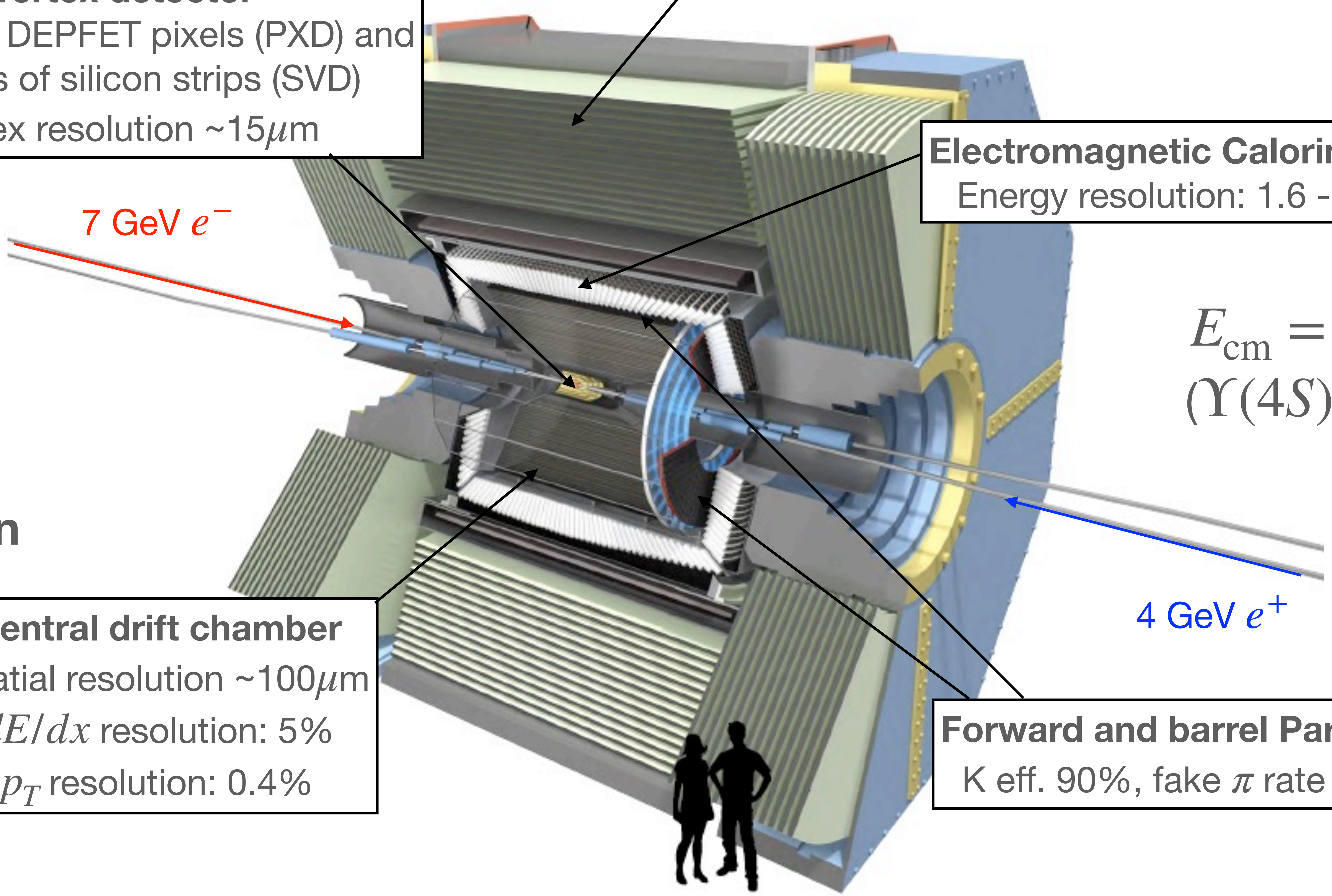
$$R(D^*) = \frac{\mathcal{B}(B \to D^*\tau\nu_\tau)}{\mathcal{B}(B \to D^*\ell\nu_\ell)}$$

- Tests of light-lepton universality in angular asymmetries of $B \to D^*\ell\nu$
  [189/fb, arXiv:2308.02023, submitted to Phys. Rev. Lett.]

- Test of light-lepton universality in inclusive semileptonic B meson decays
  [189/fb, arXiv:2301.08266, Phys. Rev. Lett. 131, 051804 (2023)]

The Belle II detector

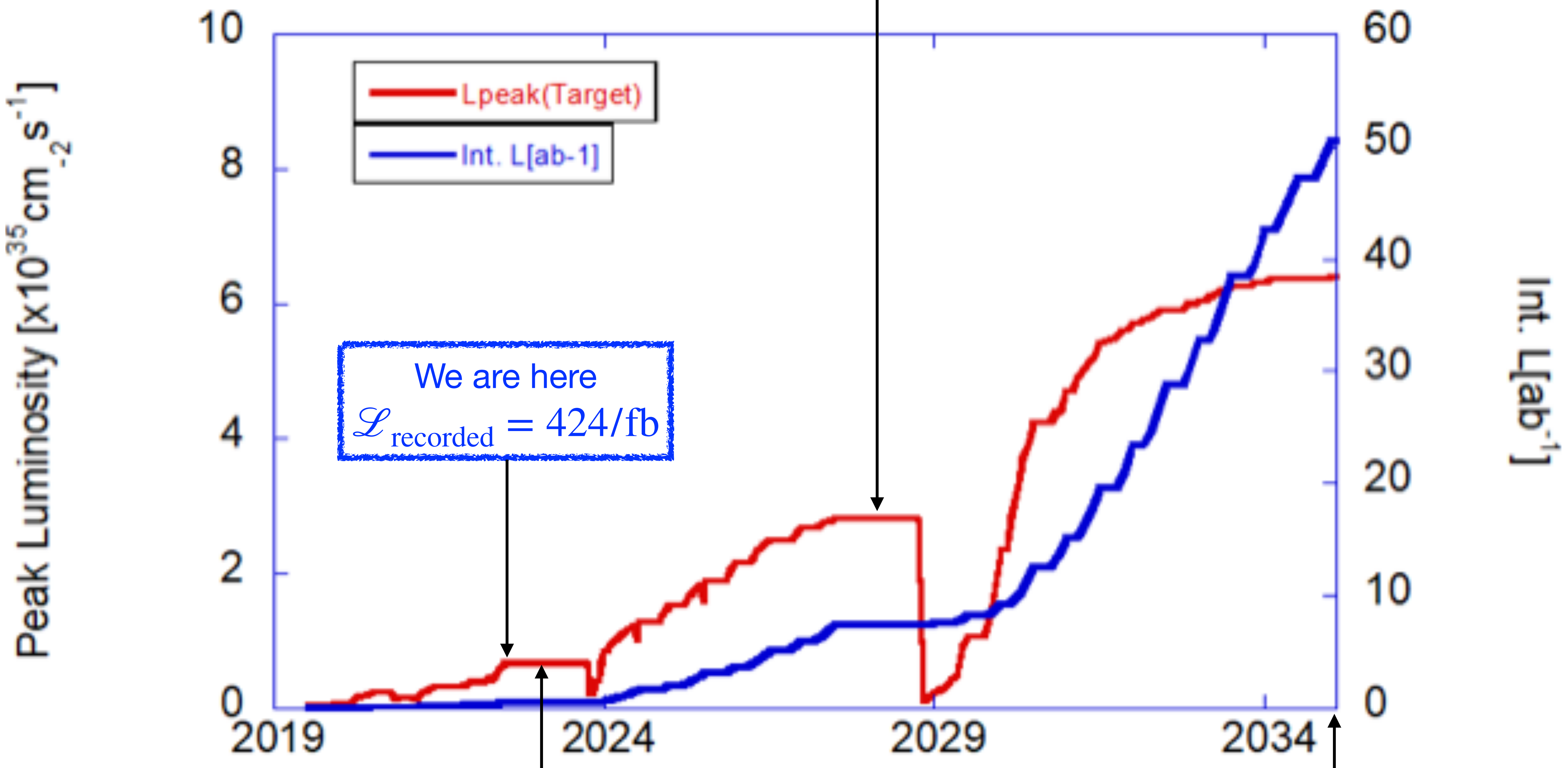
KEK
Tsukuba, Japan



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

Belle II timeline

Luminosity projection



We are here
$\mathscr{L}_{\text{recorded}} = 424/\text{fb}$

LS2 (2026-27):
SKB IR upgrade
VTX installation?

LS1 (2022-23):
PXD2 installation and
other maintenance/upgrade
of detector & machine

Goal in the mid 2030ies:
$\mathscr{L}_{\text{recorded}} \approx 50/\text{ab}$

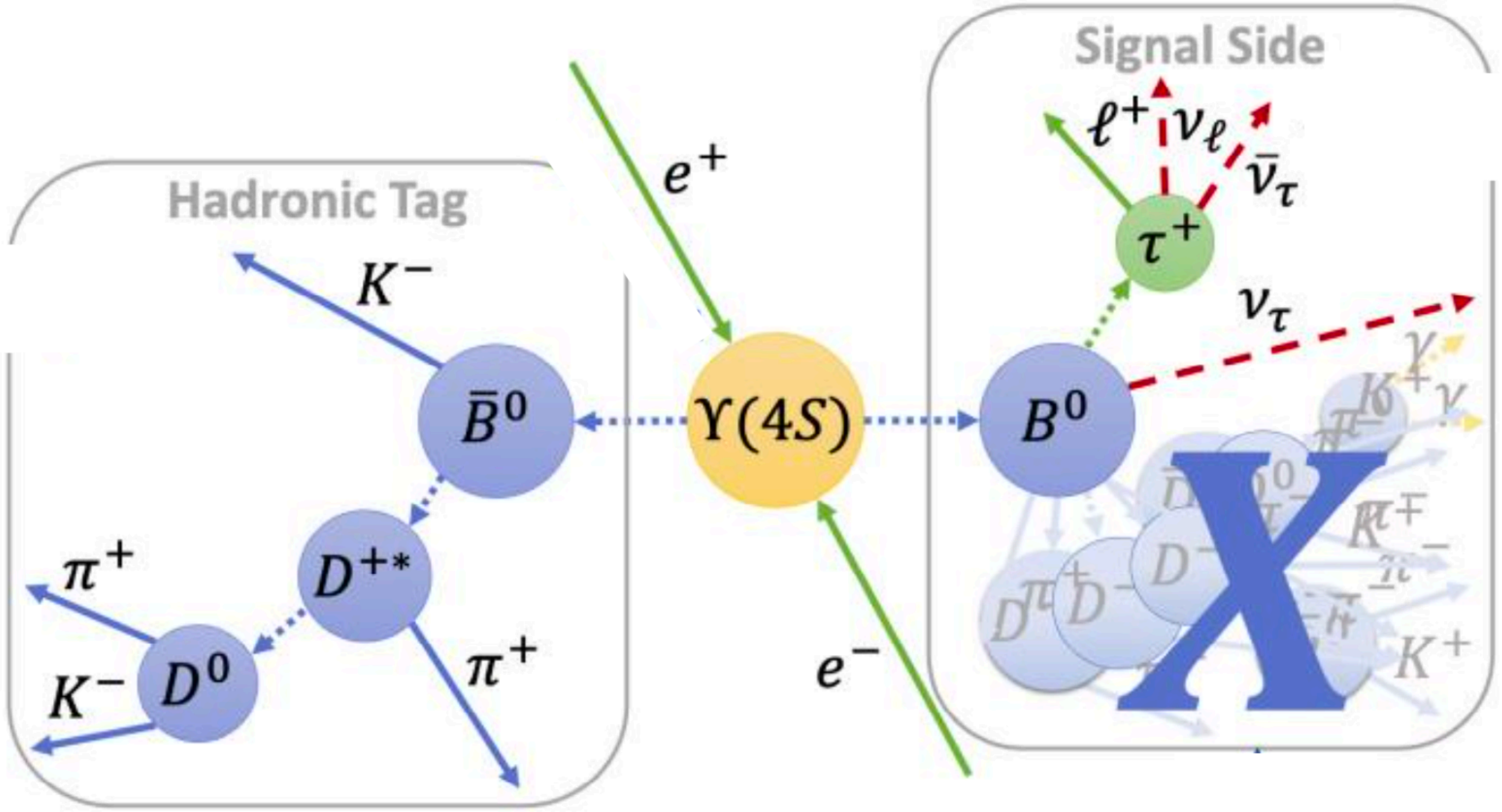
New !

Measurement of $R(X)$

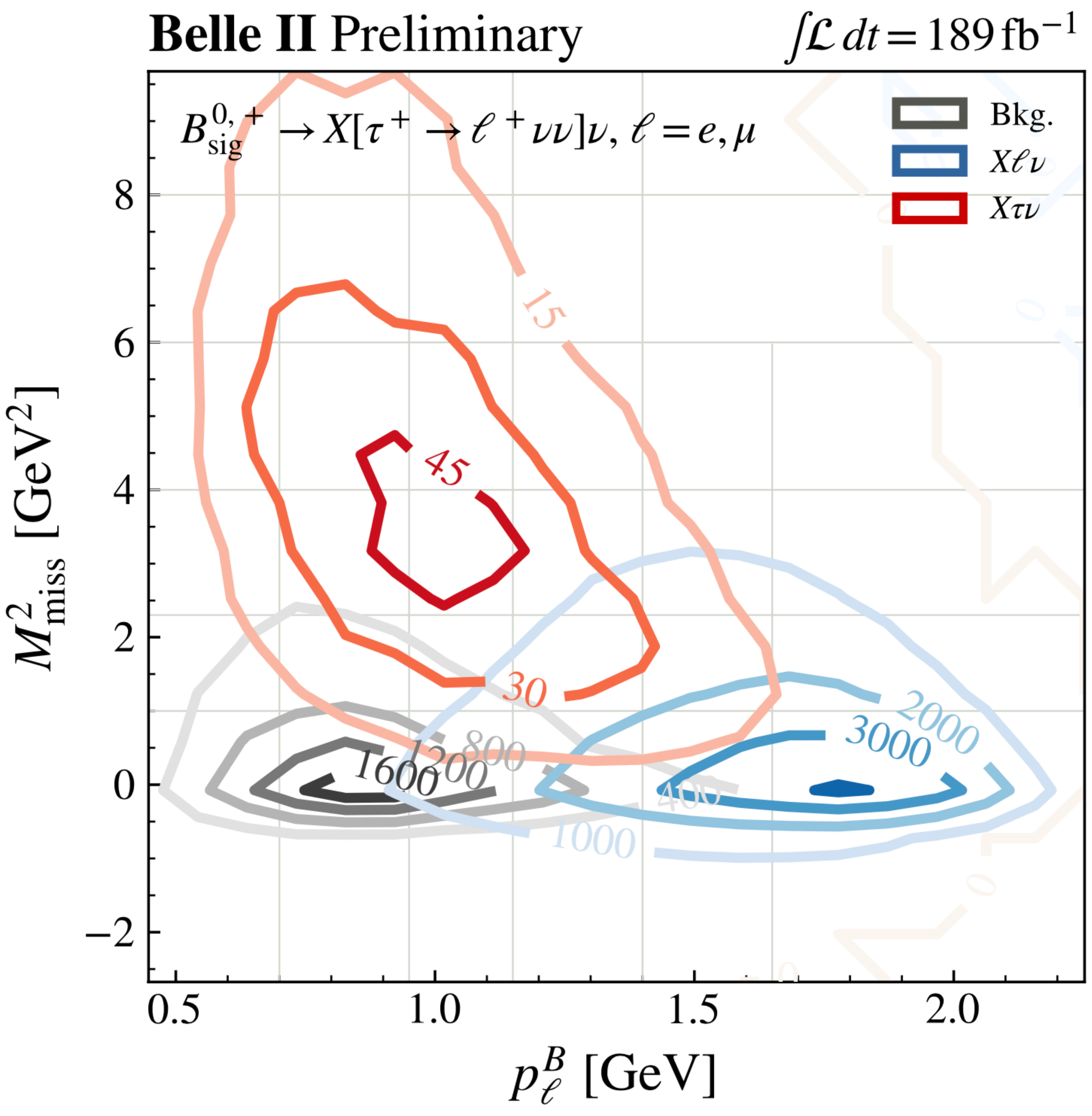
[189/fb, EPS-HEP 2023]

Reconstruction

- Reconstruct one B meson in a hadronic decay mode (B_{tag})
- Reconstruct a leptonic τ within remaining particles ($\tau \to e\nu\nu, \mu\nu\nu$)
  - $p_{T,\text{lab}}(e) > 0.3/0.5$ GeV, $p_{T,\text{lab}}(\mu) > 0.4/0.7$ GeV
- The remaining particles on the signal side are collectively referred to as X
- Main challenge: correct model of backgrounds
  - Data-driven $X\ell\nu$ re-shaping using the M_X distribution in the $p_\ell^B > 1.4$ GeV region



Signal extraction



- From the p_ℓ^B vs. M^2_{miss} distribution, separately for e and μ events
  - 34 bins in p_ℓ^B vs. M^2_{miss}
  - 2×4 fit components: $X\tau\nu$, $X\ell\nu$, $B\bar{B}$ background (fakes and secondaries), continuum (off-resonance data, yield constrained)

Results

preliminary

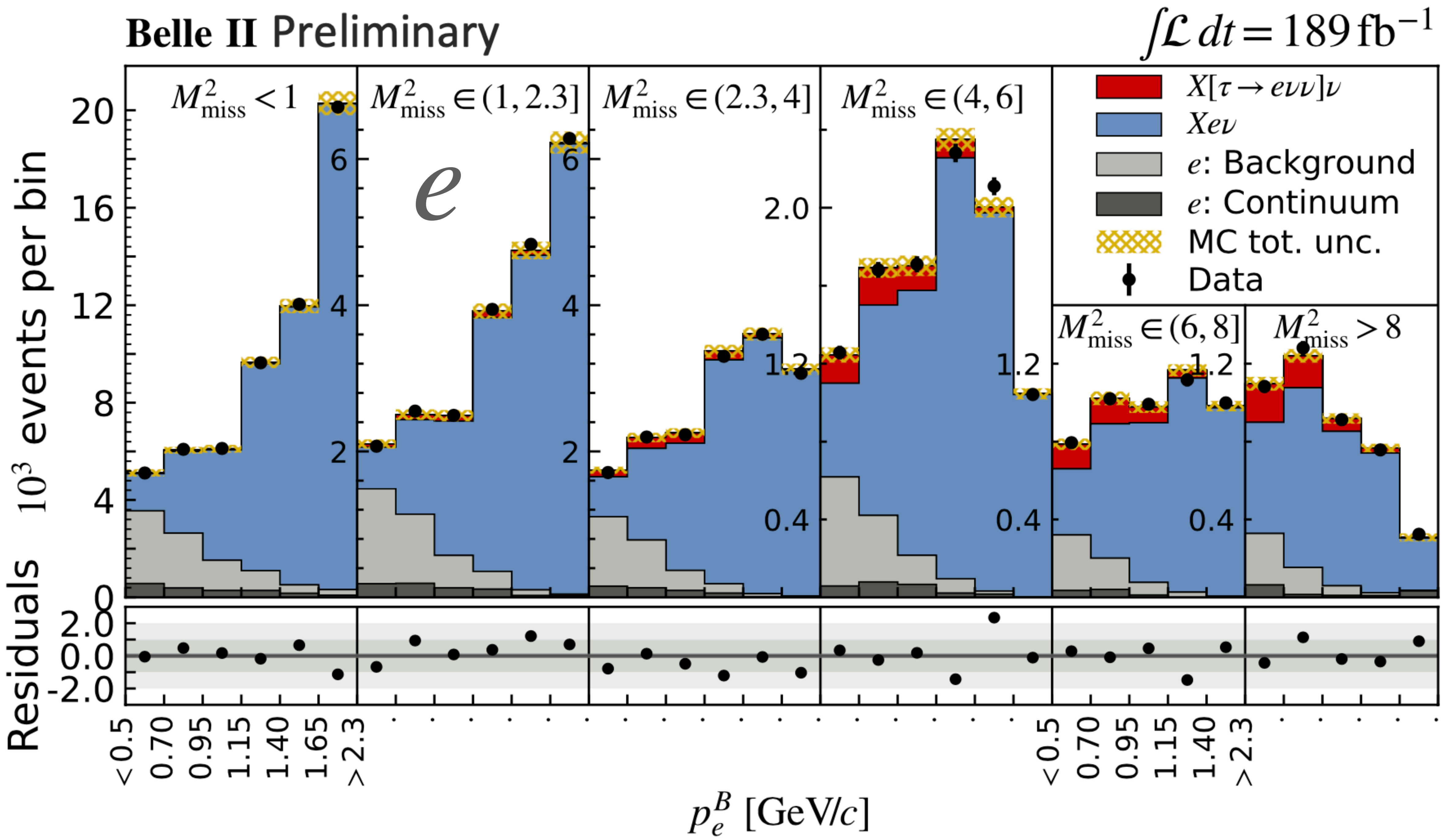
$$R(X) = \frac{\mathcal{B}(B \to X\tau\nu_\tau)}{\mathcal{B}(B \to X\ell\nu_\ell)}$$

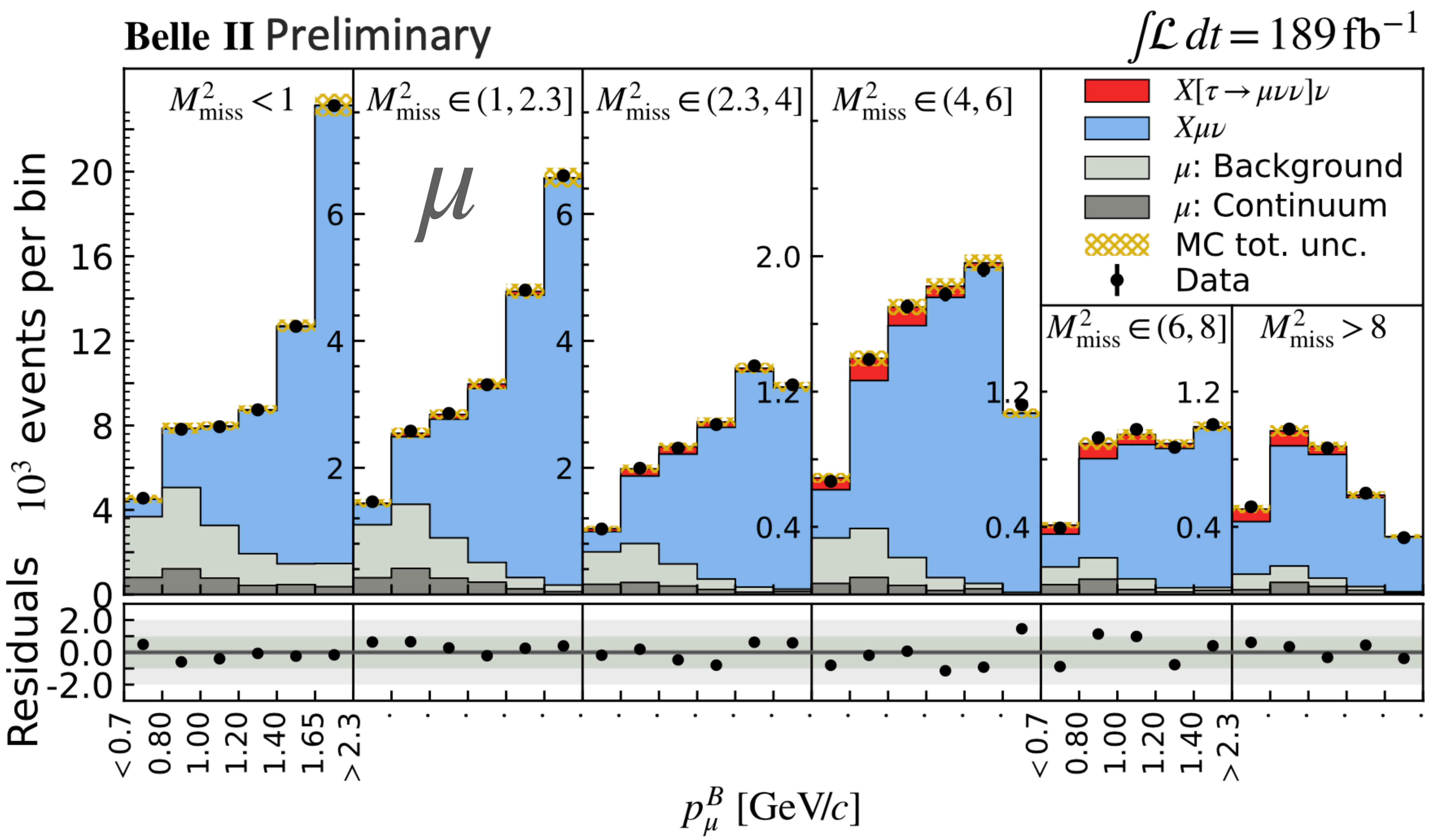
$$R(X_{\tau/e}) = 0.232 \pm 0.042,\ [0.020\ (\text{stat}), 0.037\ (\text{syst})]$$

$$R(X_{\tau/\mu}) = 0.222 \pm 0.057,\ [0.027\ (\text{stat}), 0.050\ (\text{syst})]$$

$$R(X_{\tau/\ell}) = 0.228 \pm 0.039,\ [0.016\ (\text{stat}), 0.036\ (\text{syst})]$$

- Total uncertainty: 17.5%
- Largest systematics: signal and background model
- Consistent with previous measurements from LEP, the SM expectation and constraints from $R(D^{(*)})$



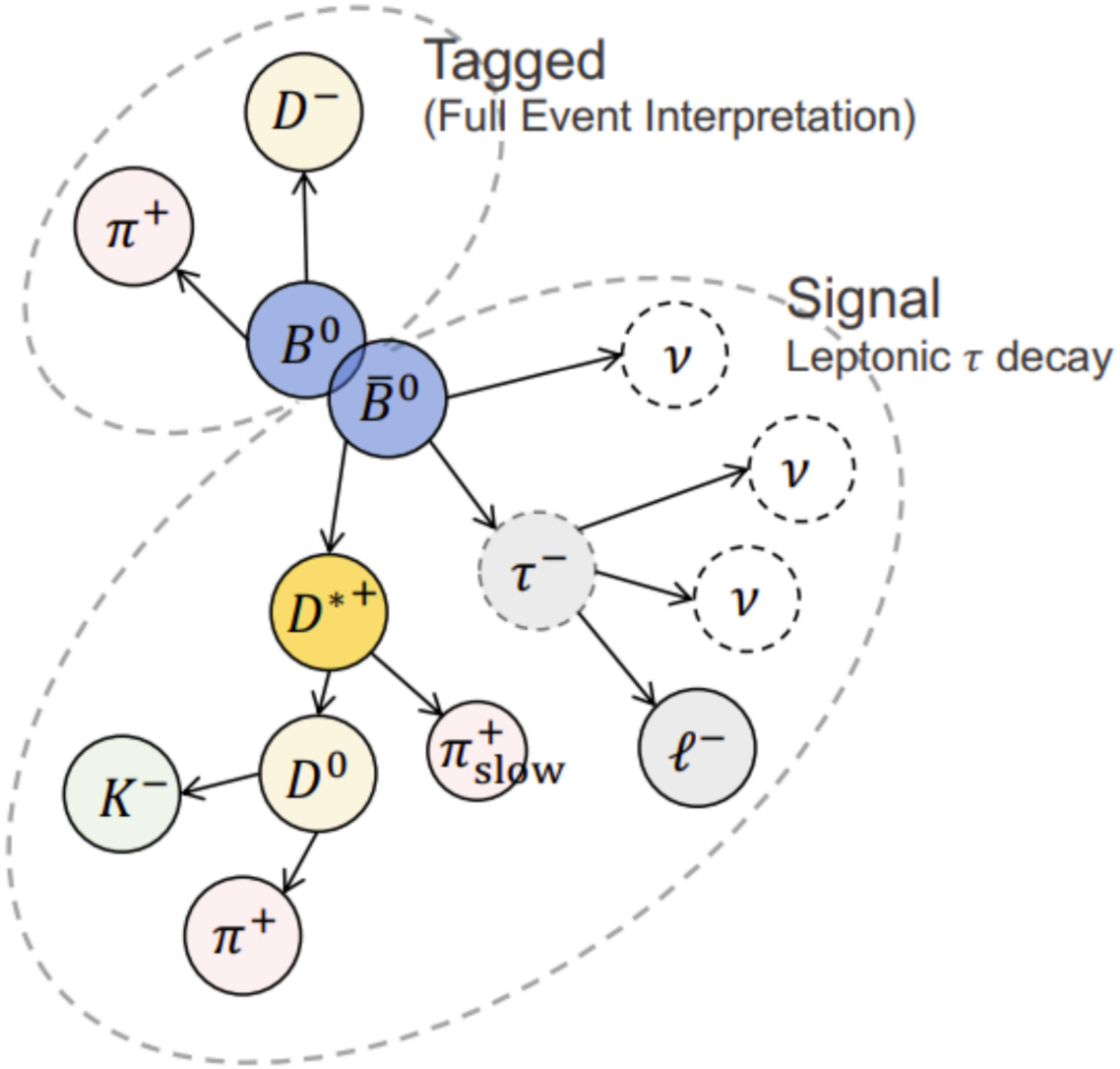


New !

Measurement of $R(D^*)$

[189/fb, Lepton Photon 2023]

Reconstruction



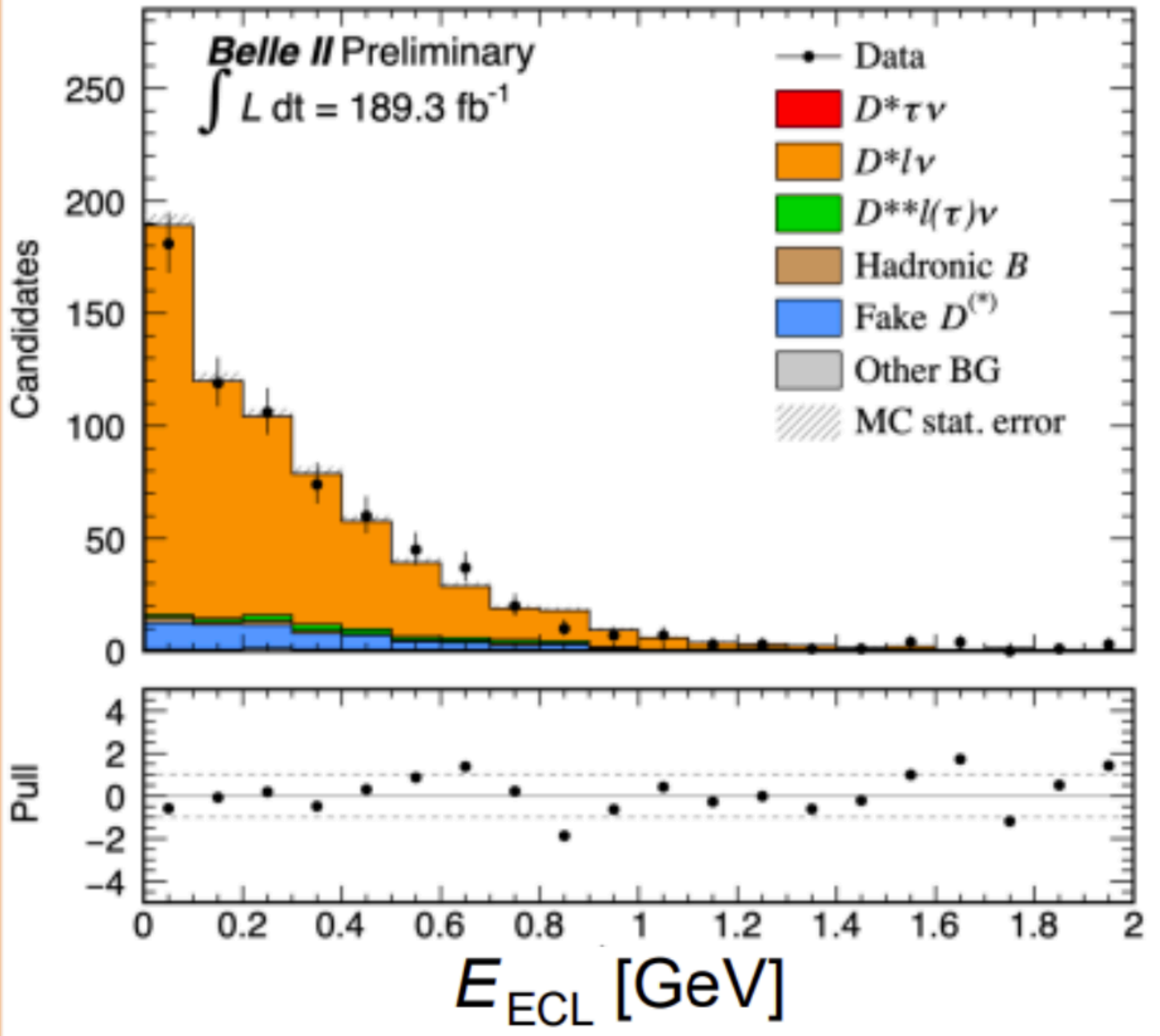
- Reconstruct one B meson in a hadronic decay mode (B_{tag})
- Reconstruct a D^* and a leptonic τ decay ($\tau \to e\nu\nu, \mu\nu\nu$) on the signal-side within remaining particles
    - Three D^* modes: $D^{*+} \to D^0\pi^+, D^+\pi^0$, $D^{*0} \to D^0\pi^0$
- Rest of the event: no charged tracks, no π^0 candidates
- Main challenge: three neutrinos in the final state → significant, sometimes poorly understood ($D^{**}\ell\nu$) backgrounds

Data-driven validation of the background model

Using different side bands

q^2 side band for $\bar{B} \to D^* \ell^- \bar{\nu}_\ell$

$q^2 \equiv (p_\ell + p_\nu)^2 < 3.5\ \mathrm{GeV}/c$ below m_τ^2 threshold

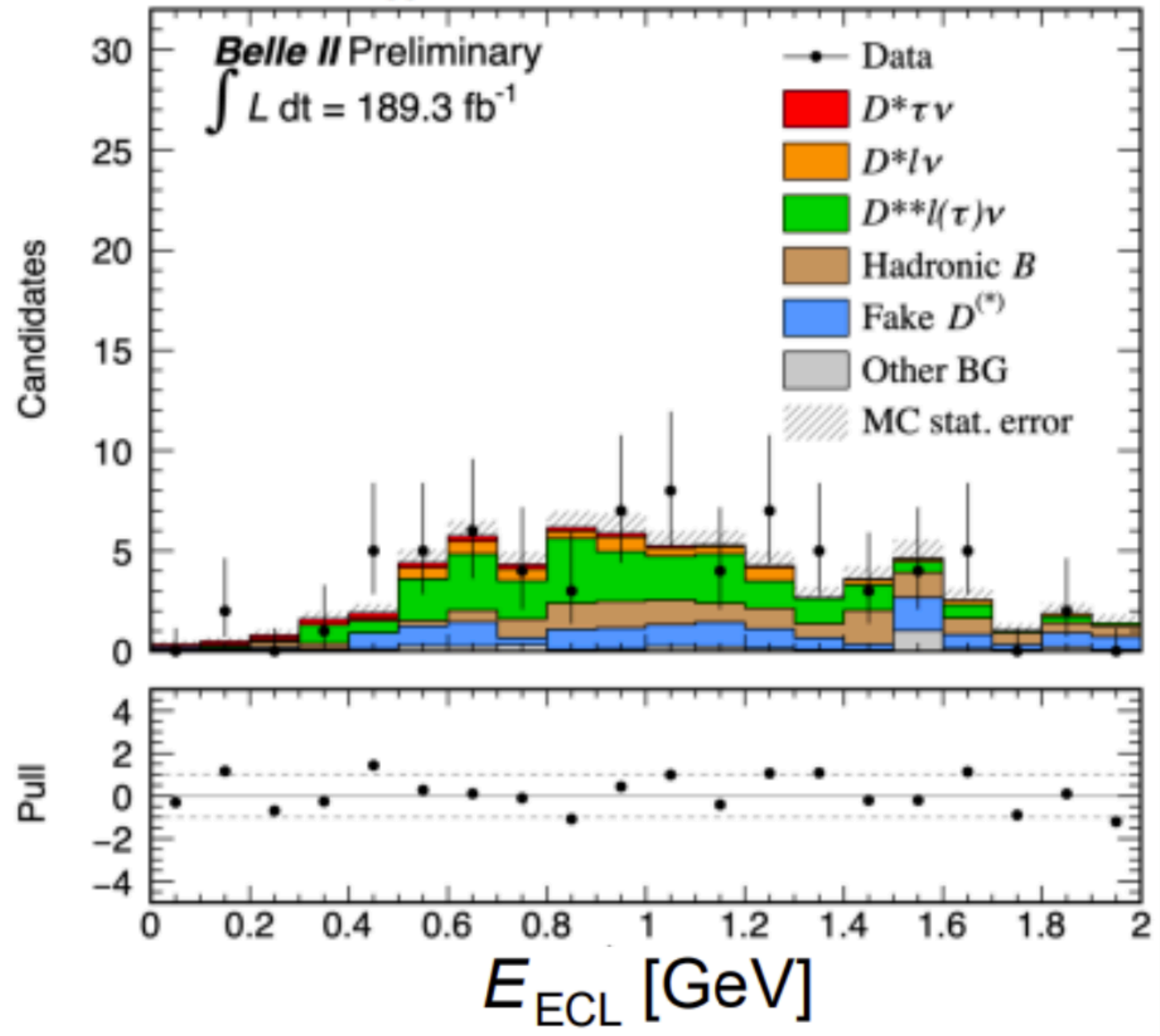


$\bar{B} \to D^{**} \ell^- \bar{\nu}_\ell$-enhanced side band

An additional π^0 is require to $B\bar{B}$.

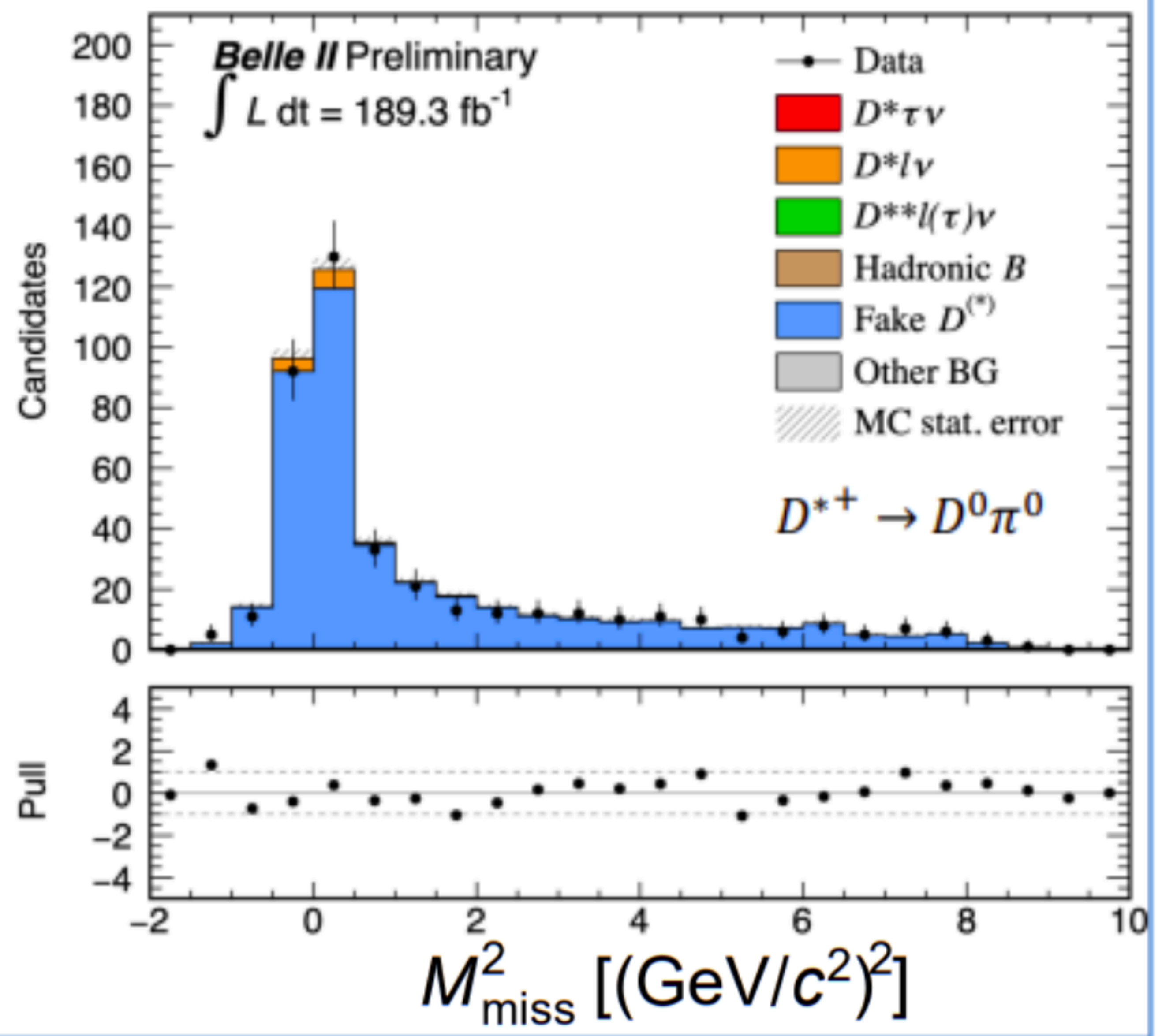
$\bar{B} \to D^{**} \ell^- \bar{\nu}_\ell$ have unknown rates and can mimic $\bar{B} \to D^* \tau^- \bar{\nu}_\tau$.

$1.0 < M_{\mathrm{miss}}^2 < 5.0\ (\mathrm{GeV}/c^2)^2$



$\Delta M_{D^*} (\equiv M_{D^*} - M_D)$ side bands for fake D^*

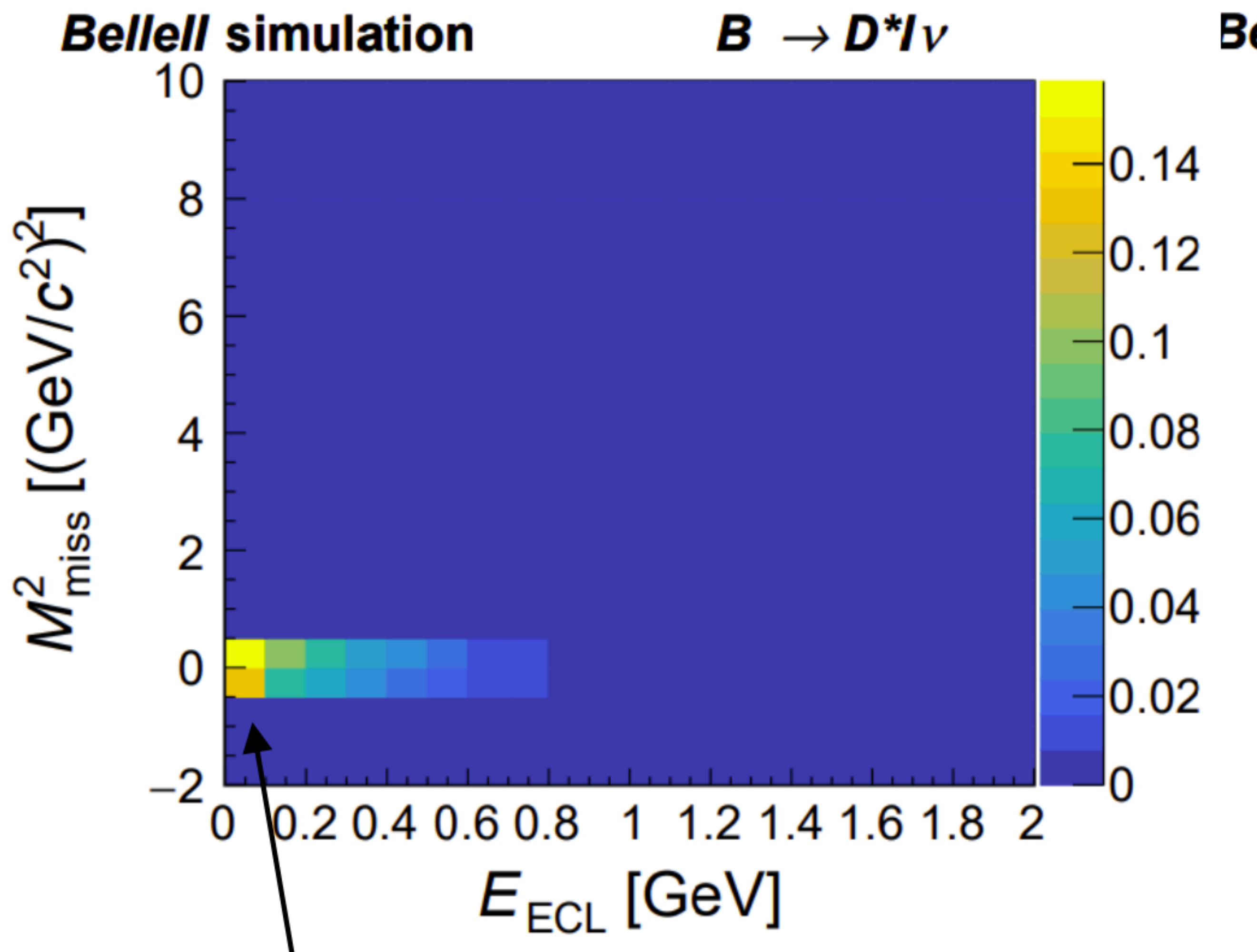
Constrain the fake D^* yields in the signal regions with calibration factors at the ΔM_{D^*} side bands.



$R(D^*)$ signal extraction

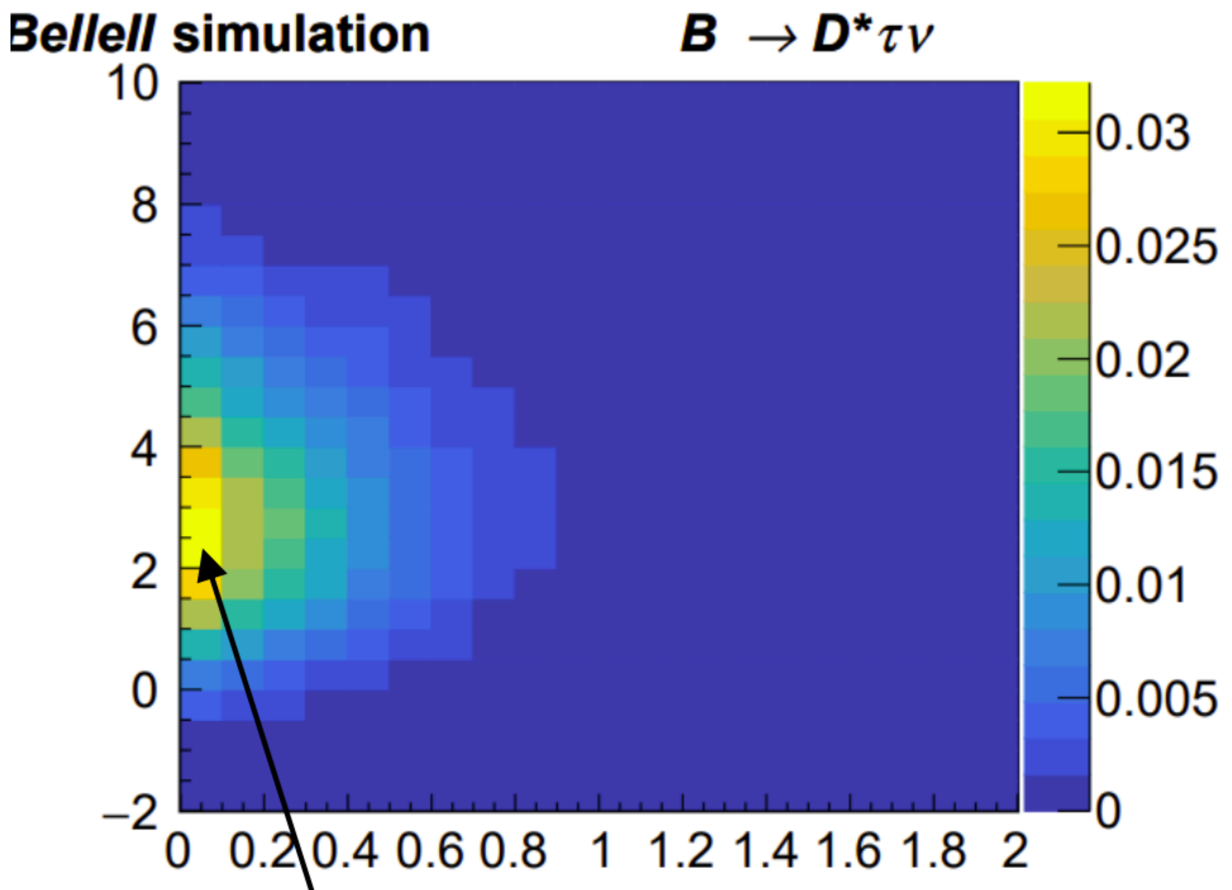
- Two-dimensional binned likelihood fit to
  - E_{ECL}: energy remaining in the calorimeter after removing all reconstructed particles
  - $M^2_{\mathrm{miss}} = (p_{e^+e^-} - p_{B_{\mathrm{tag}}} - p_{D^*} - p_\ell)^2$: missing mass of the event

B→D*ℓν



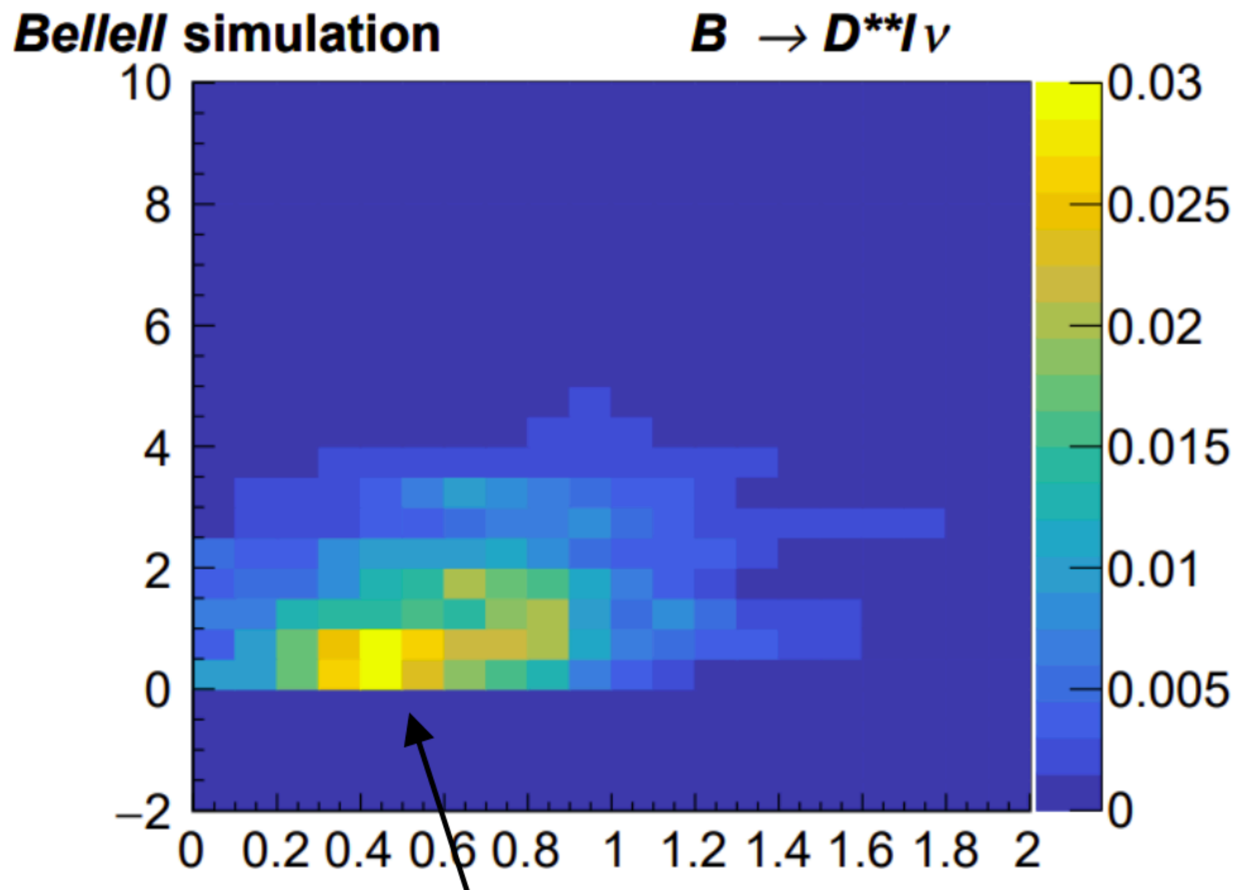
Peaked around E_{ECL}=0, M^2_{miss}=0 with a neutrino

B→D*τν



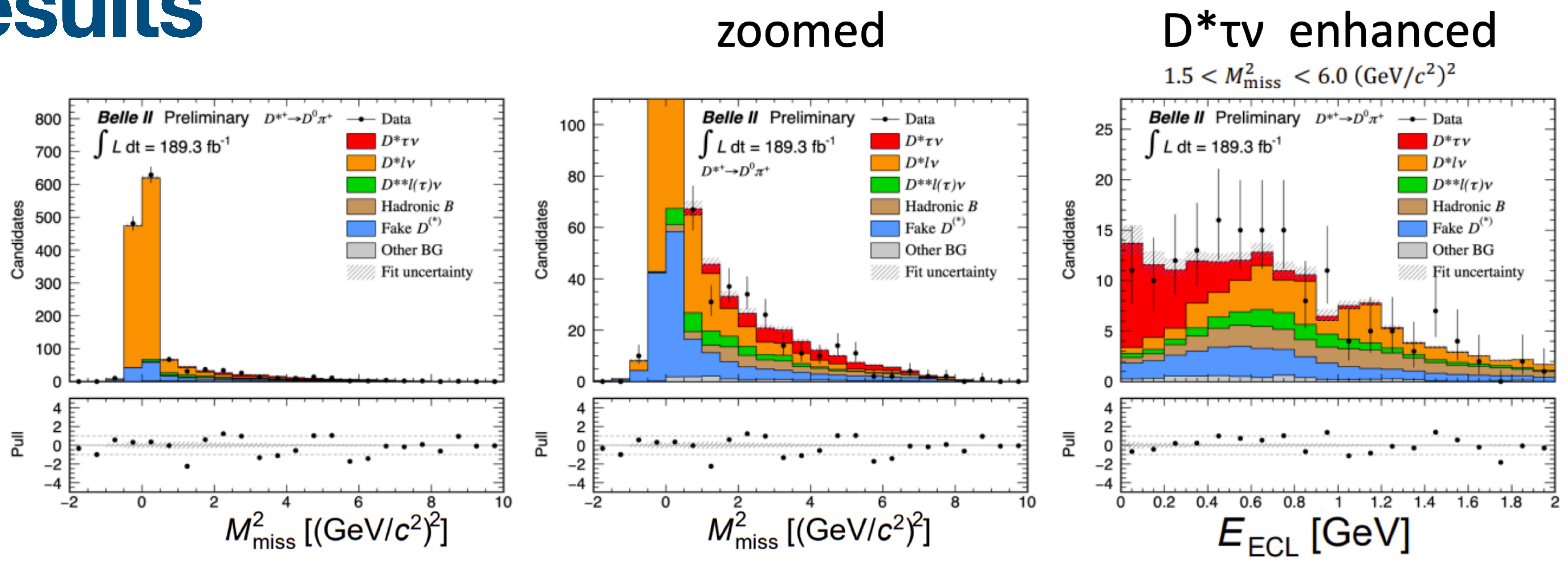
Peaked around E_{ECL}=0, Higher M^2_{miss} with multiple neutrinos

B→ D**ℓν



Higher E_{ECL} and M^2_{miss} with daughters of D** decays

Results



$$R(D^*) = \frac{\mathcal{B}(B \to D^*\tau\nu_\tau)}{\mathcal{B}(B \to D^*\ell\nu_\ell)}$$

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

preliminary

- First $R(D^*)$ result from Belle II data
- Main systematics: MC statistics, shape of E_{ECL}
- Consistent both with the SM and other experimental determinations of $R(D^*)$

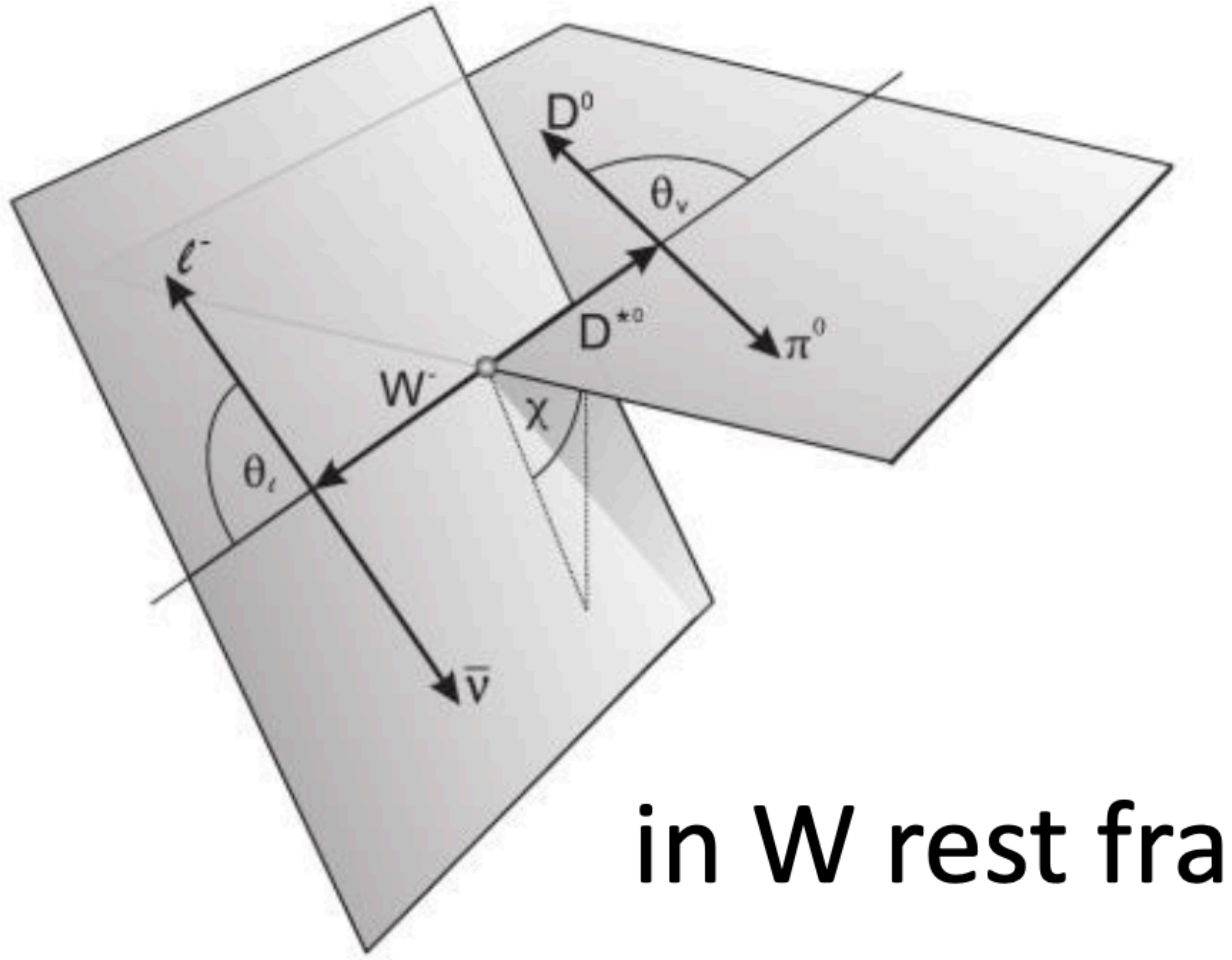
Tests of light-lepton universality in angular asymmetries of $B \to D^* \ell \nu$

[189/fb, arXiv:2308.02023, submitted to Phys. Rev. Lett.]

Definition of angular observables in $B \to D^* \ell \nu$

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

$$\mathcal{A}_x(w) \equiv \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}w}\right)^{-1} \left[\int_0^1 - \int_{-1}^0\right] \mathrm{d}x \frac{\mathrm{d}^2\Gamma}{\mathrm{d}w\mathrm{d}x}$$



in W rest frame

with $x = \cos\theta_\ell$ for A_{FB}

$\cos 2\chi$ for S_3

$\cos\chi \cos\theta_V$ for S_5

$\sin\chi \cos\theta_V$ for S_7

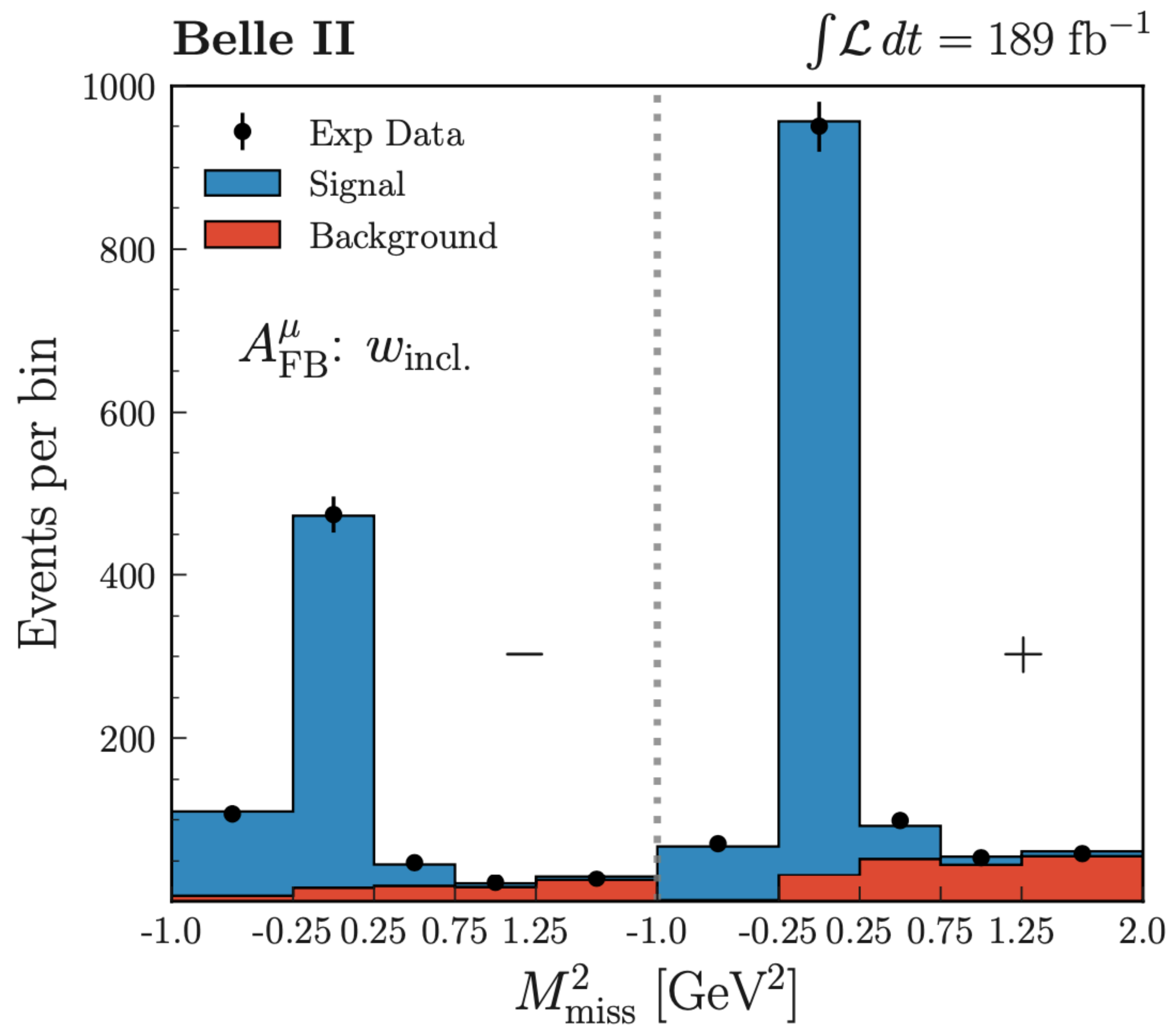
$\sin 2\chi$ for S_9

$$\Delta\mathcal{A}_x(w) \equiv \mathcal{A}_x^\mu(w) - \mathcal{A}_x^e(w)$$

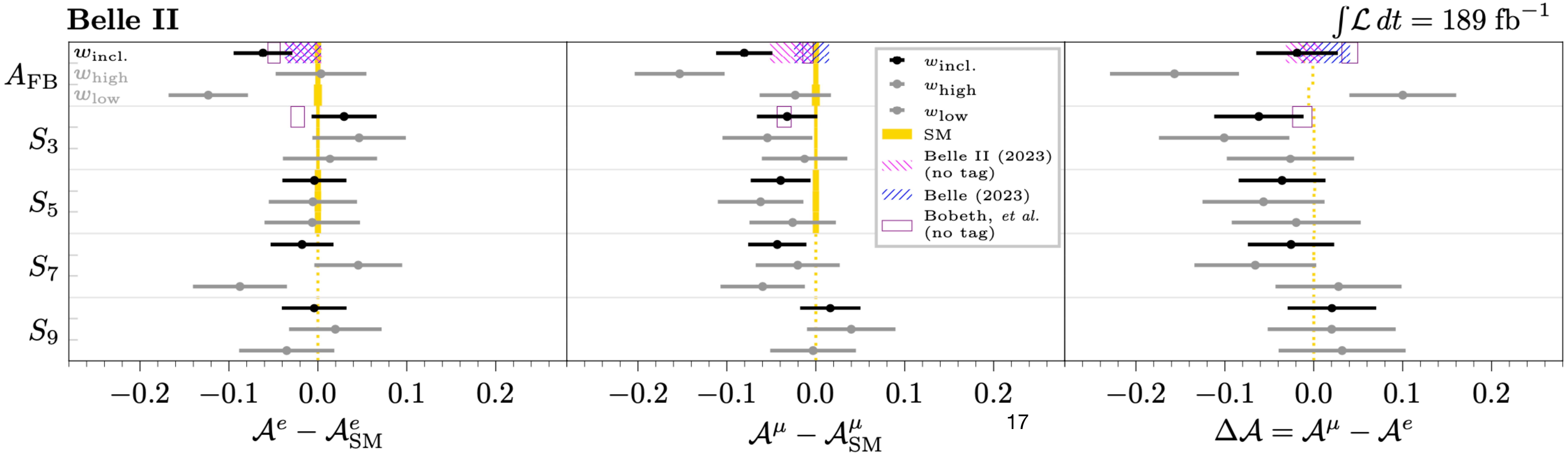
- 4σ tension in ΔA_{FB} seen in Belle $B \to D^* \ell \nu$ data: Eur. Phys. J. C 81, 984 (2021), arXiv:2104.02094 [hep-ph]
- Correlation between angular observables: Phys. Rev. D 107 (2023) 1, 015011, arXiv:2206.11283 [hep-ph]

Angular asymmetries in $B \to D^* \ell \nu$

- Reconstruction
  - $B^0 \to D^{*-}\ell^+\nu_\ell$ decays are reconstructed in hadronically tagged $\Upsilon(4S)$ events
  - Signal is extracted from the M^2_{miss} distributions
  - Asymmetries are extracted in the full w region ($w_{\text{incl.}}$), in w_{low} $(1 < w < 1.275)$ and in w_{high} $(1.275 < w < 1.503)$



- Result



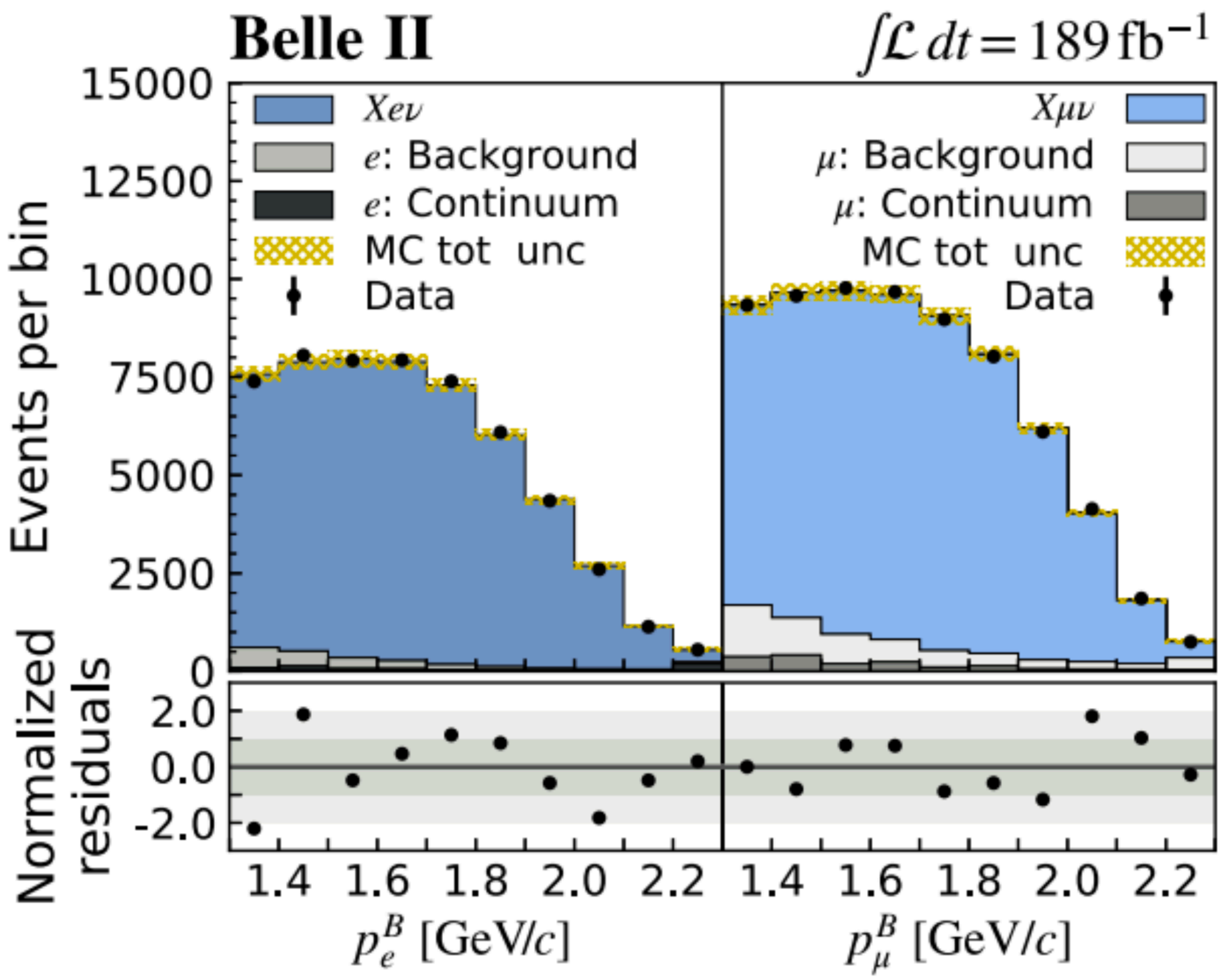
preliminary

Test of light-lepton universality in inclusive semileptonic B meson decays

[189/fb, arXiv:2301.08266, Phys. Rev. Lett. 131, 051804 (2023)]

$R(X_{e/\mu})$

- Analysis and background correction technique is shared with the $R(X)$ measurement
- The ratio of inclusive semileptonic decays to e and to μ is obtained in the region $p_\ell^B > 1.3$ GeV
- Result

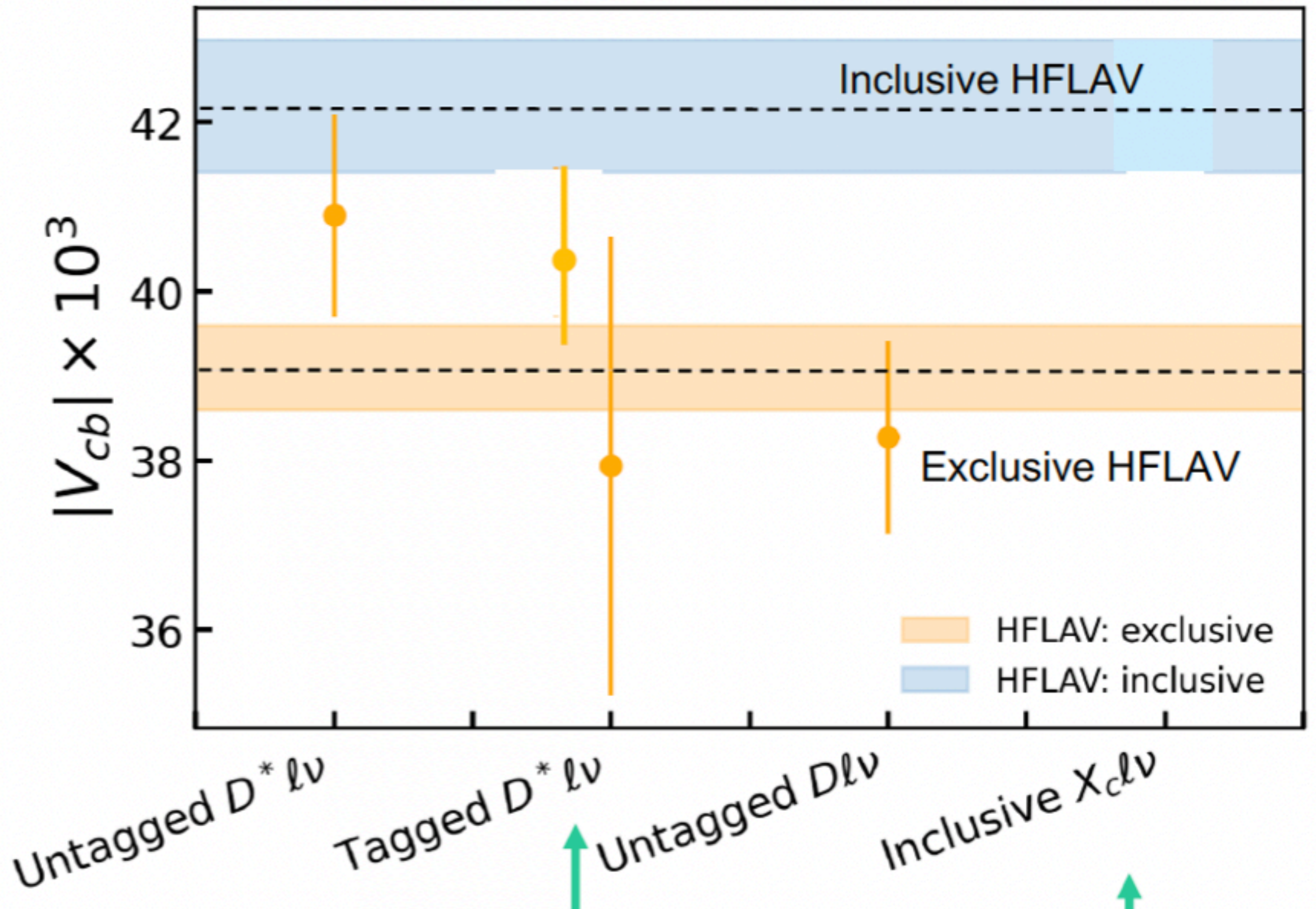


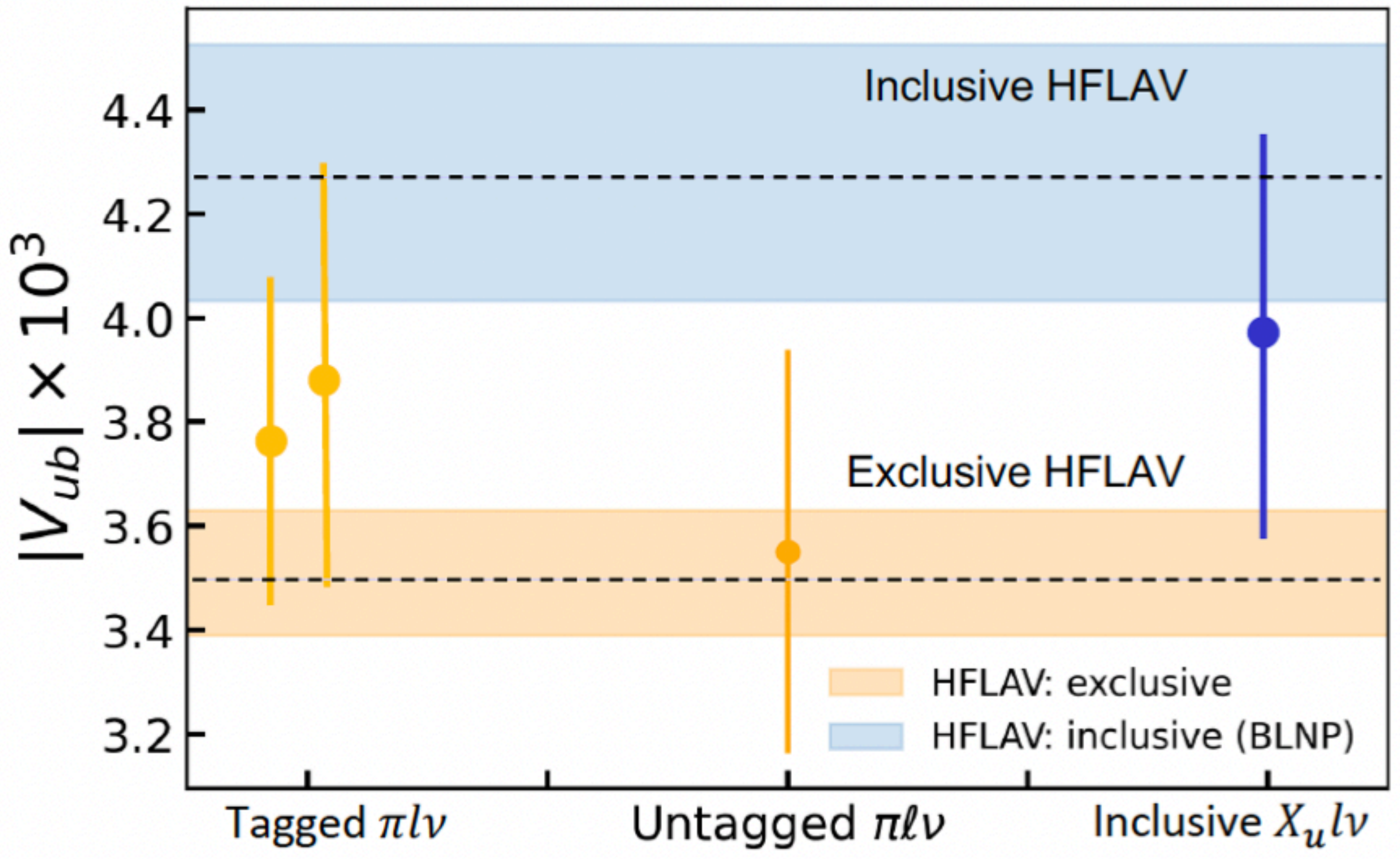
$$R(X_{e/\mu}) = 1.007 \pm 0.009(\mathrm{stat}) \pm 0.019(\mathrm{syst})$$

$$R(X_{e/\mu}) = \frac{\mathcal{B}(B \to X e \nu_e)}{\mathcal{B}(B \to X \mu \nu_\mu)}$$

- Main systematics: lepton identification
- Most precise LFU test so far (2%), consistent with SM

Semileptonic decays and $|V_{cb}|, |V_{ub}|$





Belle, [arXiv: 2301.07529]
BelleII, [arXiv:2301.04716]

BelleII, [arXiv:2210.13143]

Belle II, PRD107,072002(2023) [arXiv: 2301.04716]
Moment measurement only, extraction of V_{cb} with Belle result
Belle PRD104,112011(2021) by F.Bernlocher, et.al,
JHEP10(2022)068

BelleII, [arXiv:2206.08102]

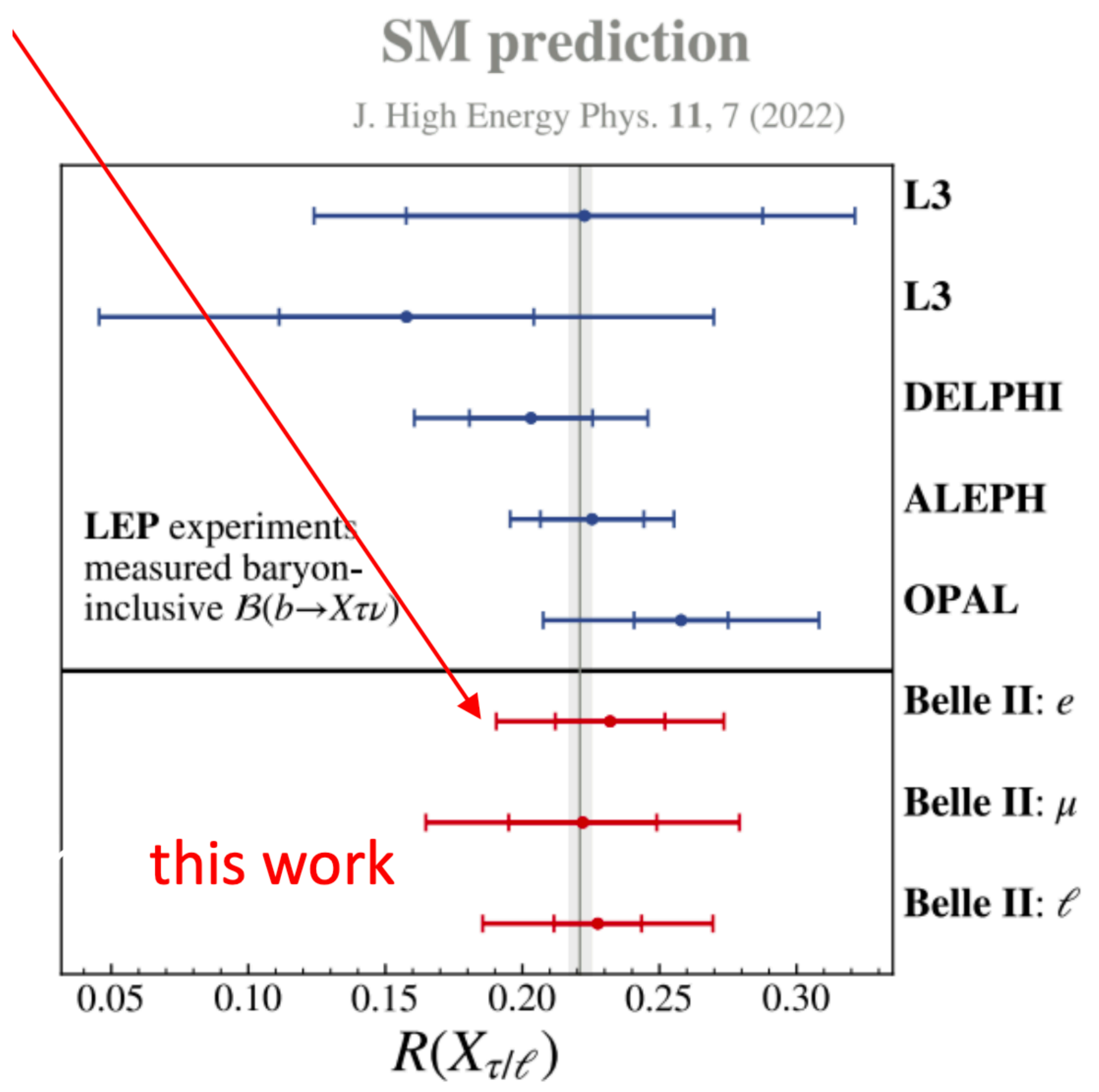
Belle, [arXiv: 2303.17309]
Simultaneous determination of
Exclusive and inclusive V_{ub}

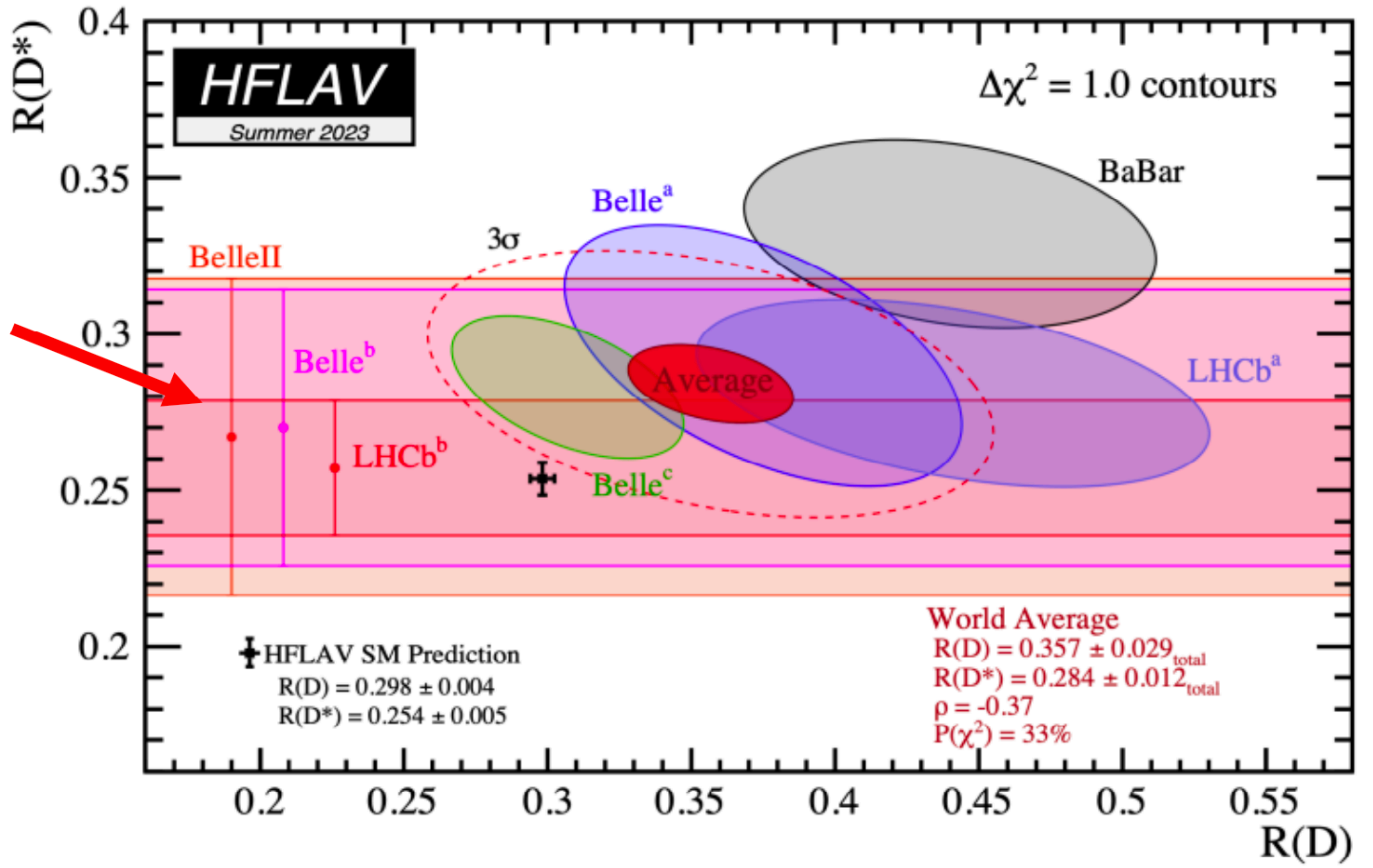
BelleII, [arXiv:2210.04224]

Belle, [arXiv: 2303.17309]
Simultaneous determination of
Exclusive and inclusive V_{ub}

Summary and conclusion

- Belle II has probed lepton flavour universality (LFU) in semileptonic B meson decays
  - First measurement of inclusive semitauonic B decays at the $\Upsilon(4S)$ – $R(X)$
  - First measurement of $B \to D^* \tau\nu$ at Belle II – $R(D^*)$
  - Forward-backward asymmetry (and other angular observables) in $B \to D^*\ell\nu$ separately for $\ell = e, \mu$
  - Most precise test of light lepton universality in inclusive semileptonic B decays
- So far, results are consistent with the SM and previous experimental findings. There is still large room for improvement as more Belle II data is collected





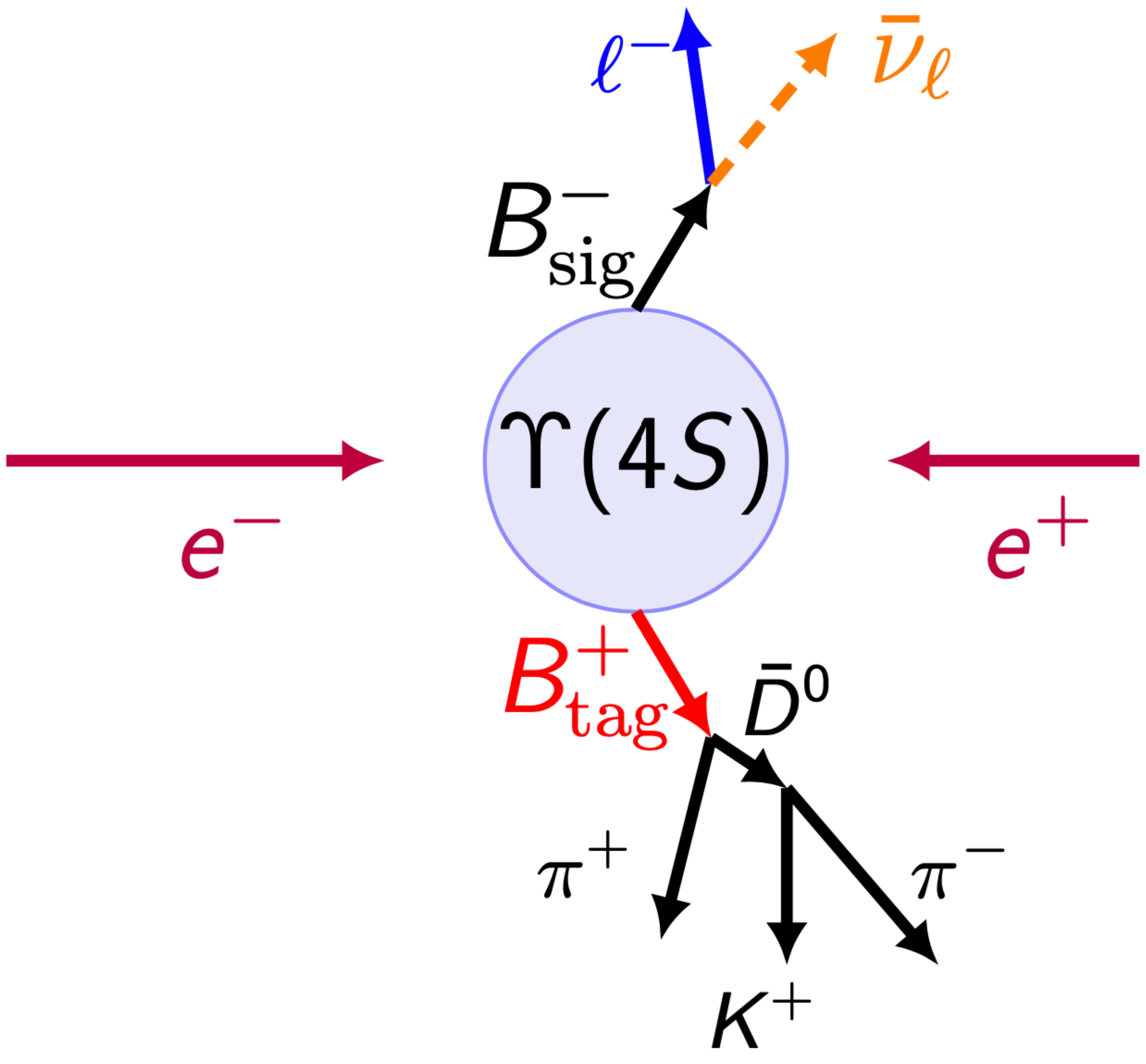
Backup

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

to take advantage of $\Upsilon(4S)$ kinematics

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

Hadronic tagging at Belle II

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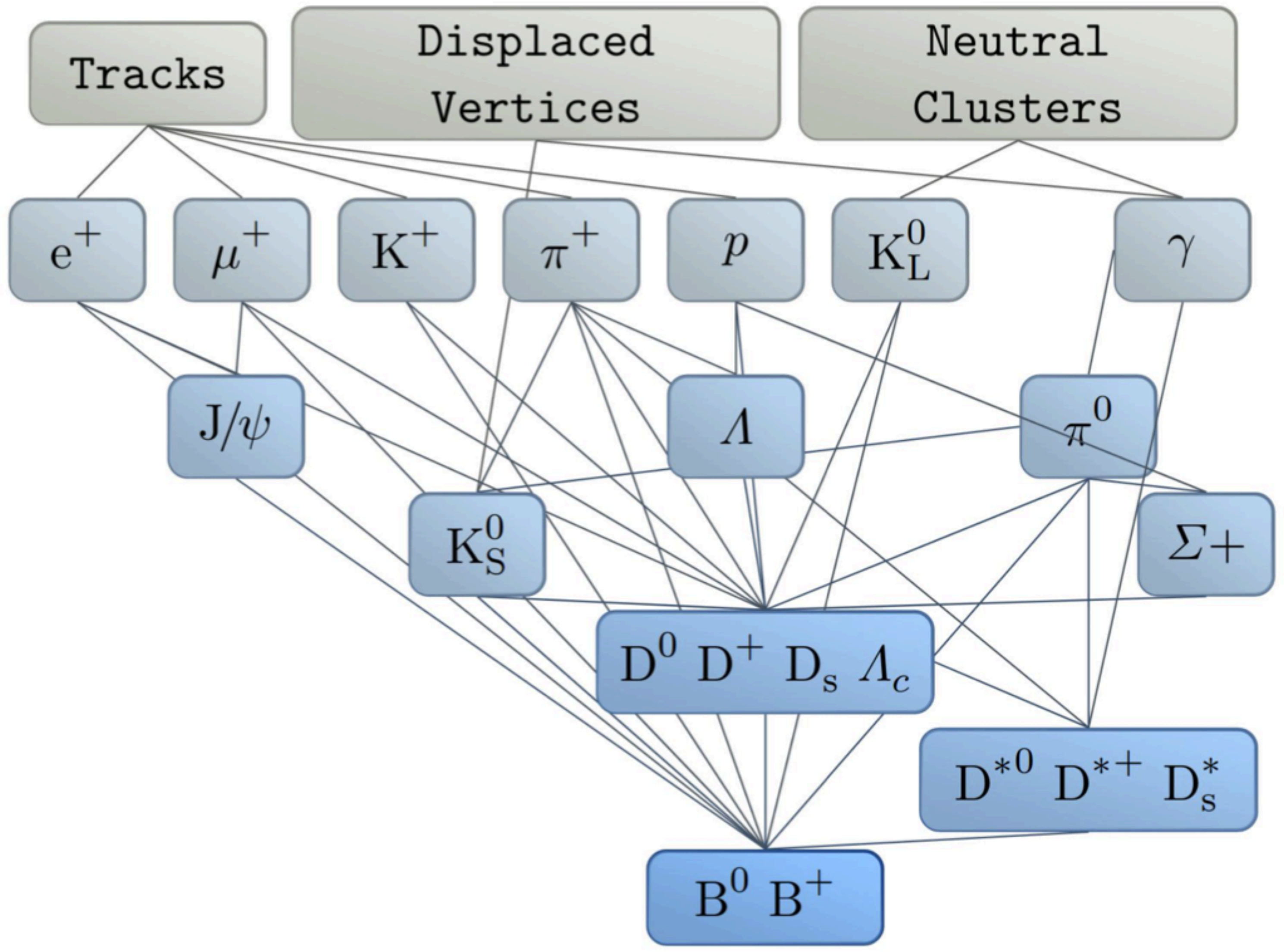

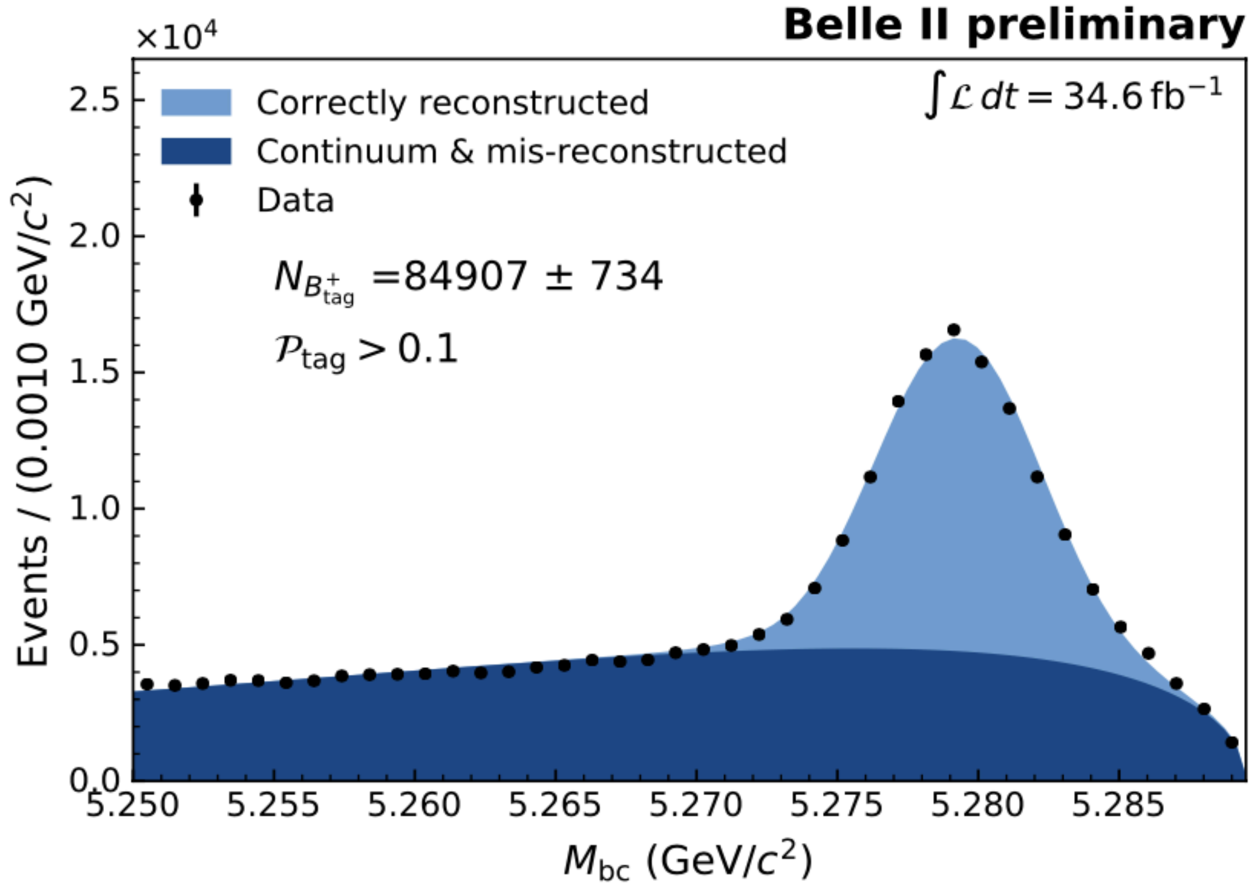

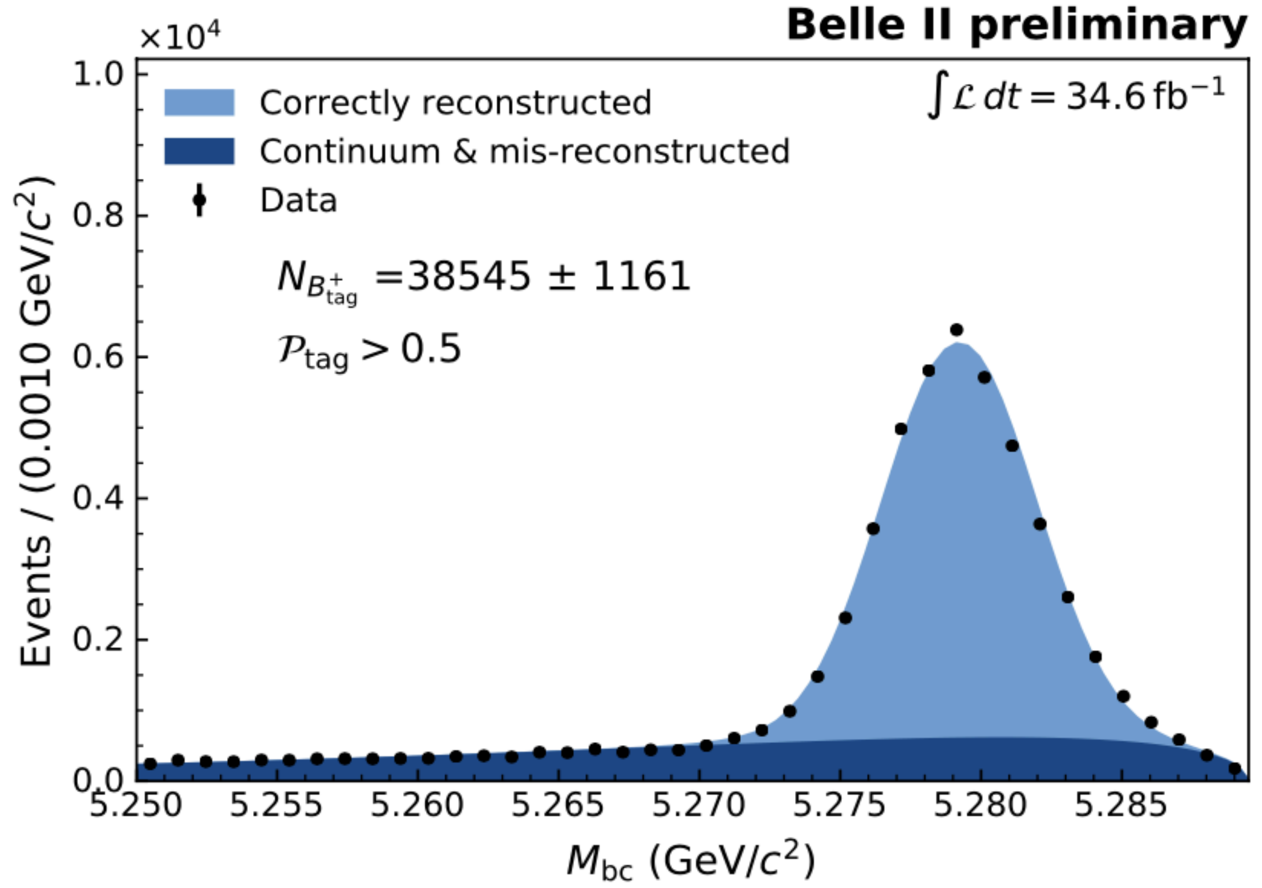

$$M_{bc} = \sqrt{E_{beam}^2/4 - (p_{B_{\mathrm{tag}}}^{\mathrm{cm}})^2} > 5.27\ \mathrm{GeV}/c^2$$

- 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)