Recent Belle II results related to lepton-flavor universality and violation

Marco Milesi
on behalf of the Belle II collaboration

The Dark Side of The Universe, Sydney
5-9 December 2022

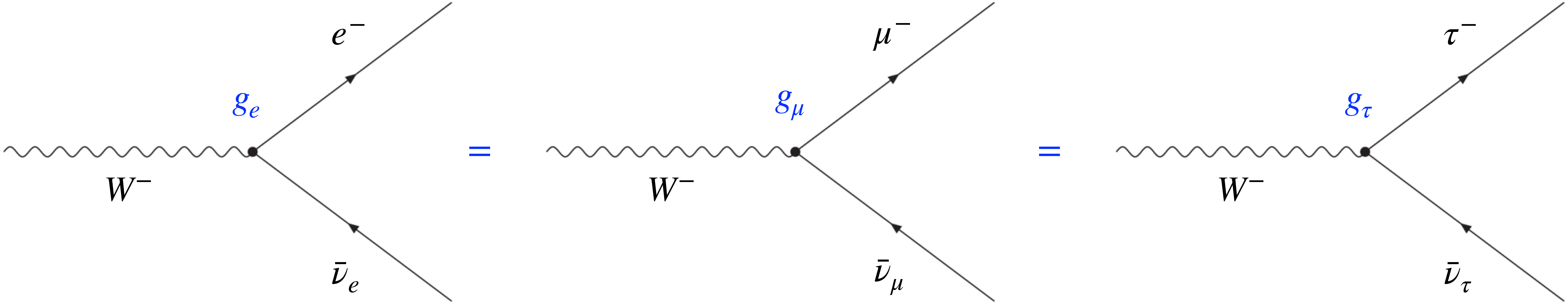
THE UNIVERSITY OF MELBOURNE

Belle II

(Prelude)
Anomalies in lepton flavour universality tests at flavour experiments

Lepton Flavour Universality in the Standard Model

- The Standard Model postulates that electroweak couplings of gauge bosons $(Z, W^{\pm})$ to leptons (e, μ, τ) are independent of lepton flavour $\rightarrow$ Lepton Flavour Universality (LFU)

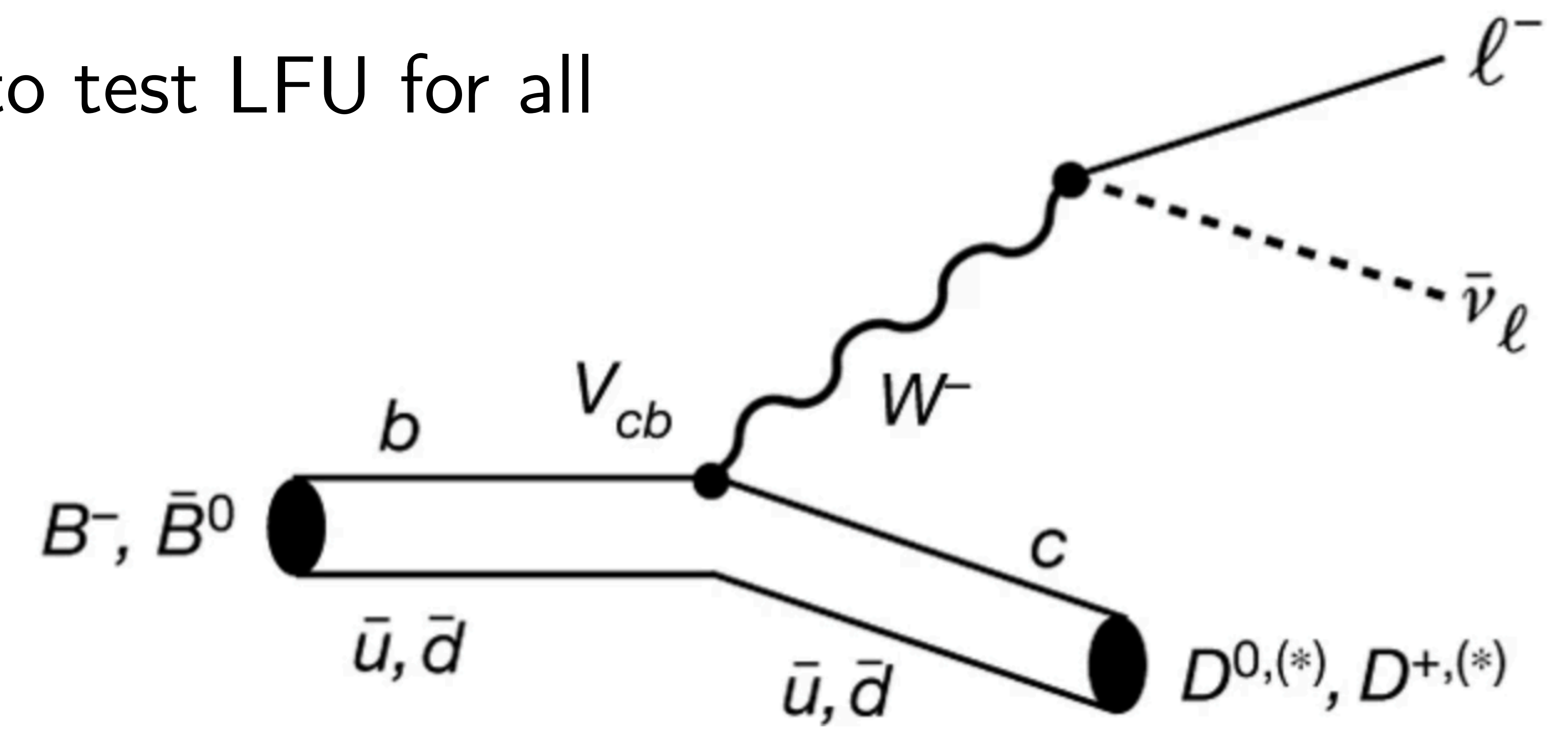


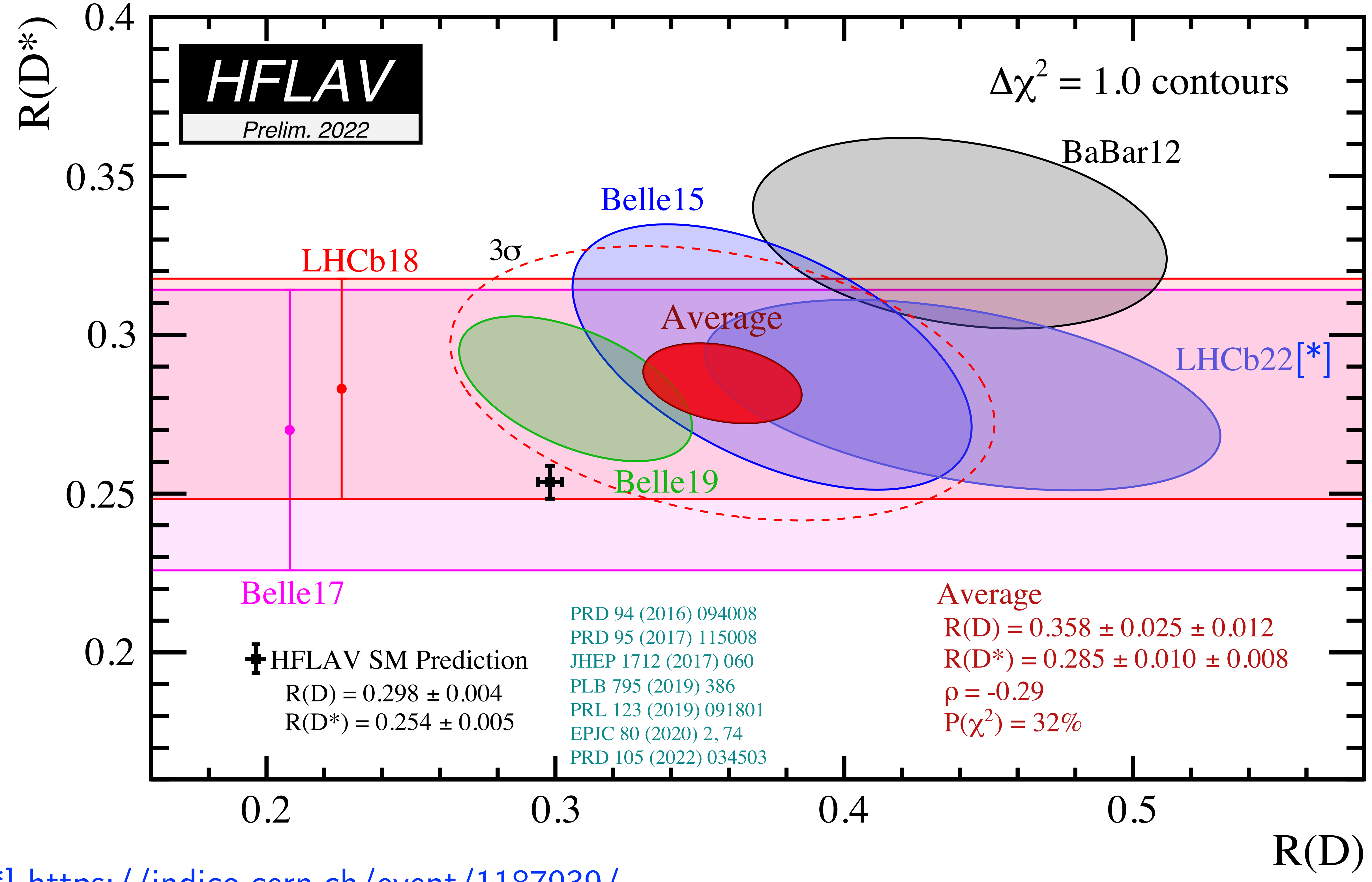
- Observation of LFU violation would clearly indicate existence of physics beyond the Standard Model.

LFU anomalies in $b \to c\tau\nu$ transitions

- Semileptonic B decays via $b \to c$ *tree-level* transition → excellent probe to test LFU for all three lepton generations.

- Branching fractions of *exclusive* decays to charmed mesons $B \to D^{(*)}\ell\nu$ calculated in the SM with high precision, $\mathcal{O}(0.1\%)$.



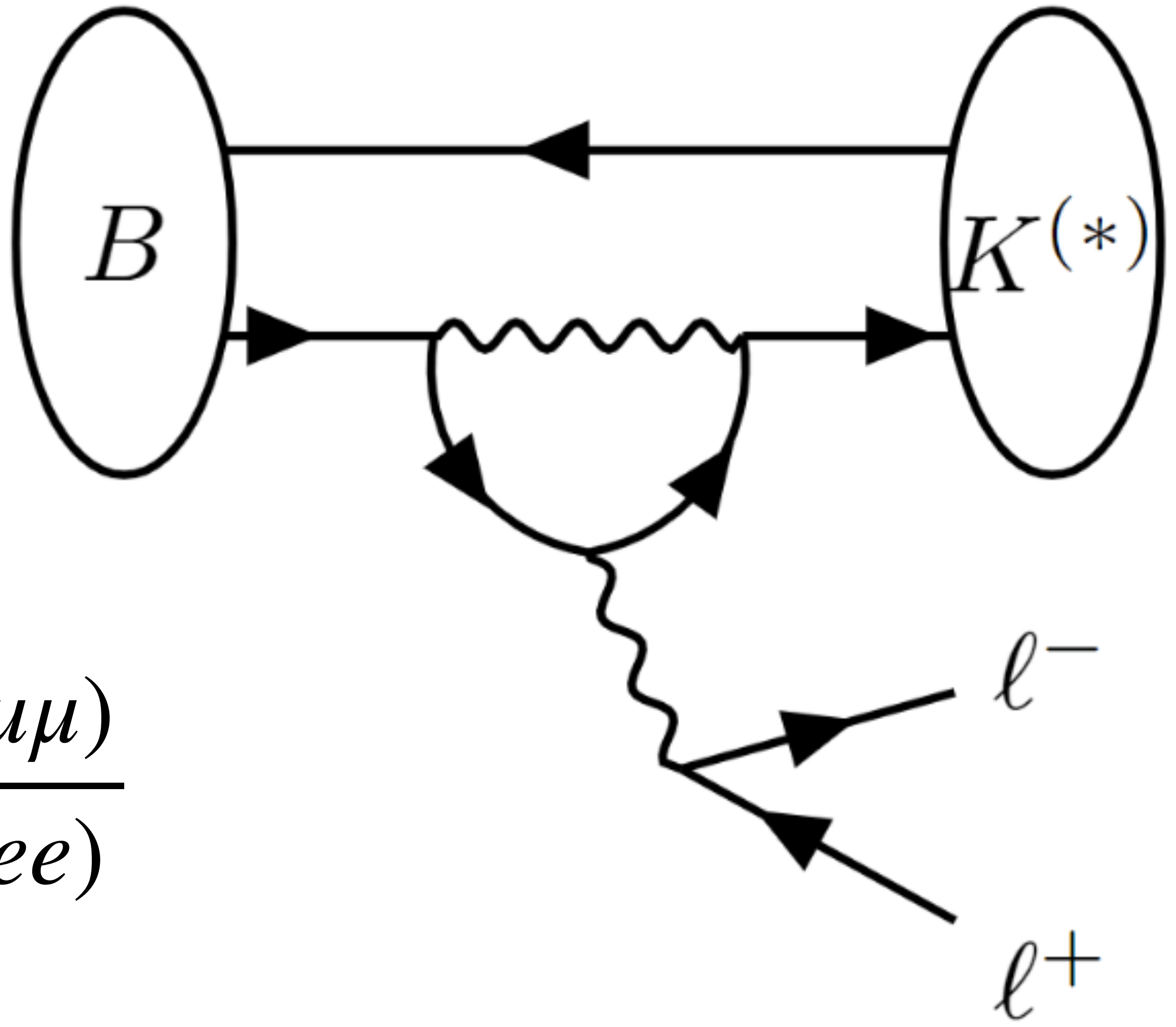


[*] https://indico.cern.ch/event/1187939/

- Rate of $b \to c\tau\nu$ transitions may be enhanced wrt. $b \to c(e,\mu)\nu$ in several beyond-SM scenarios.

- Combined measurements of the ratio of branching fractions $R(D^{(*)})$, by Belle, BaBar, LHCb presently in tension with the SM at $\approx 3\sigma$.

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

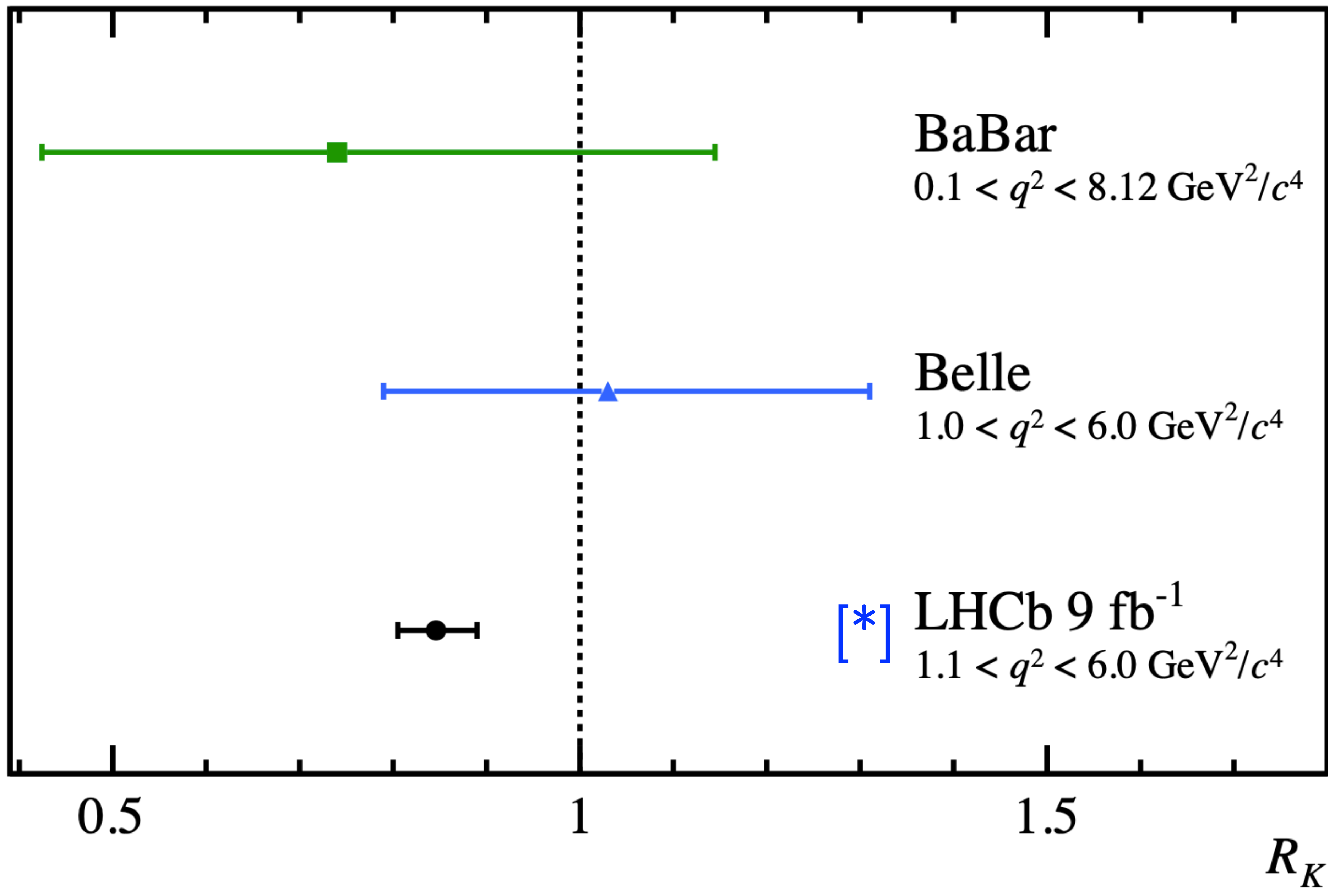


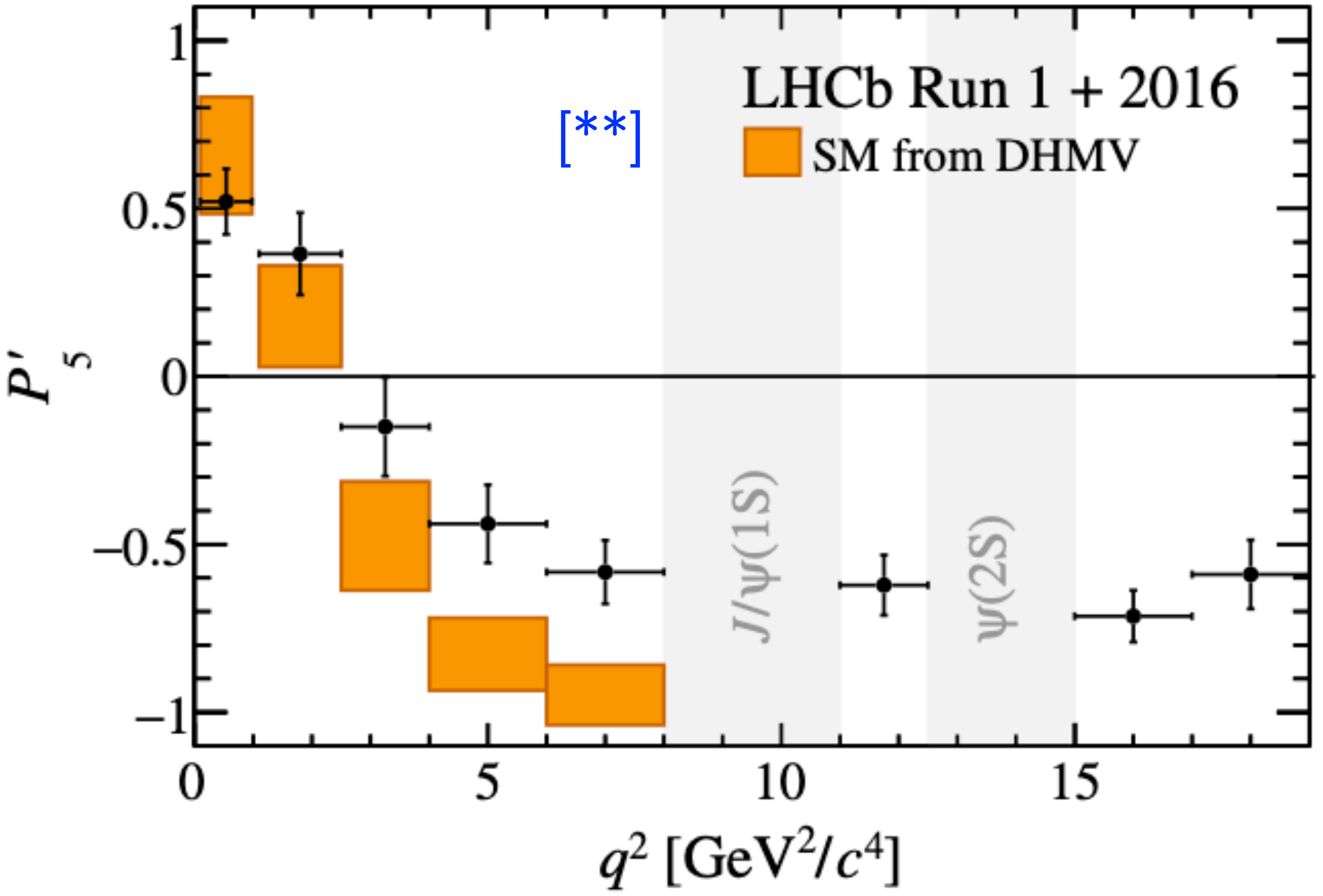
- Loop-induced, Cabibbo-suppressed Flavour-Changing Neutral Current decays $\to$ highly sensitive to non-SM contributions in loop.

- Recent measurement of $R(K)$ from LHCb [*] found 3.1σ tension with the SM.

- Anomalies at $\approx 2\sigma$ level also seen in angular observables (e.g. $B^0 \to K^{*0}\mu^+\mu^-$ [**]) and $R(K^*)$ [***] at LHCb.

$$R(K) = \frac{\mathscr{B}(B^+ \to K^+\mu\mu)}{\mathscr{B}(B^+ \to K^+ee)}$$





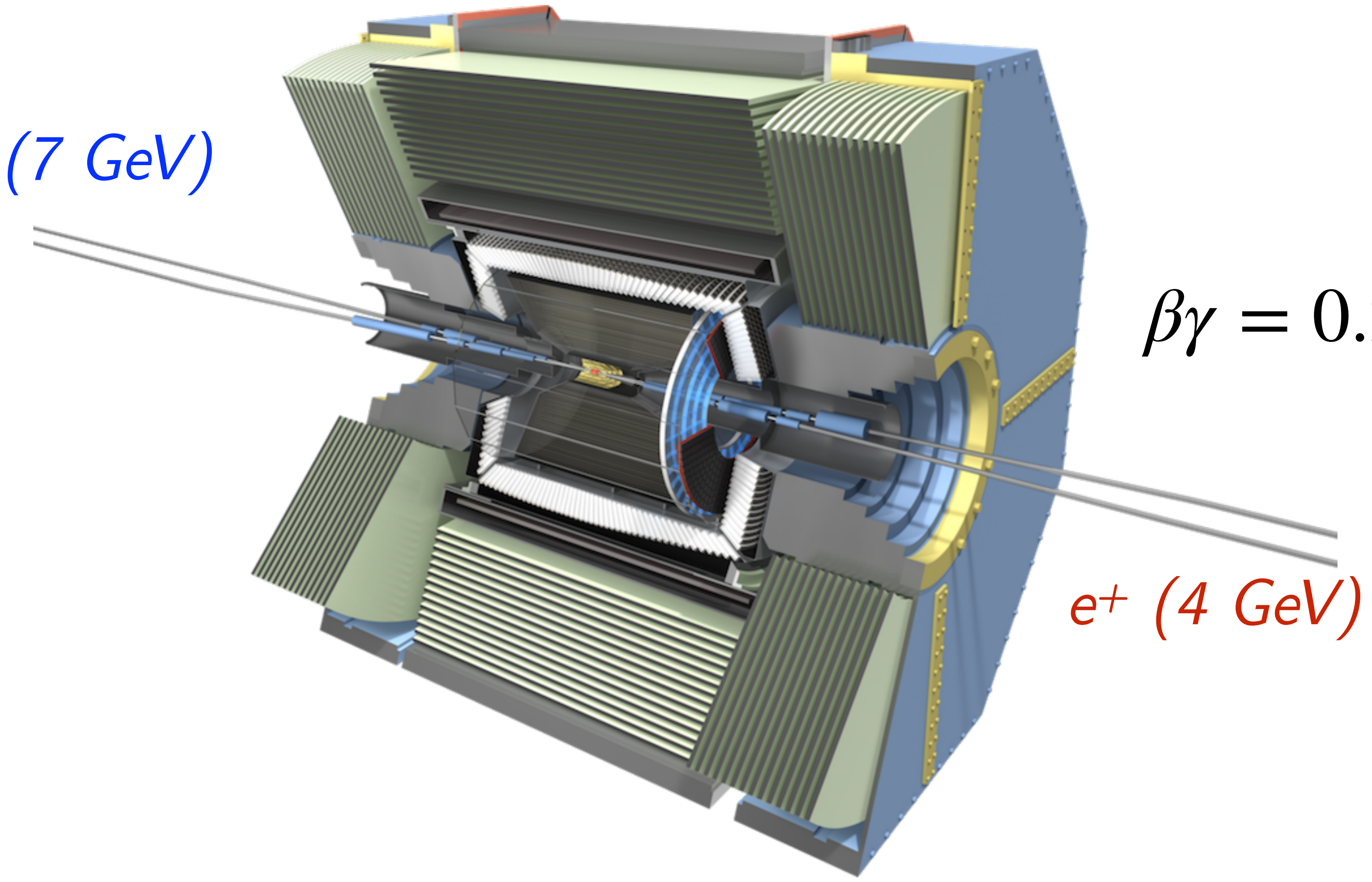
[*] LHCb, Nature Phys, vol. 18, pp. 277–282 (2022)

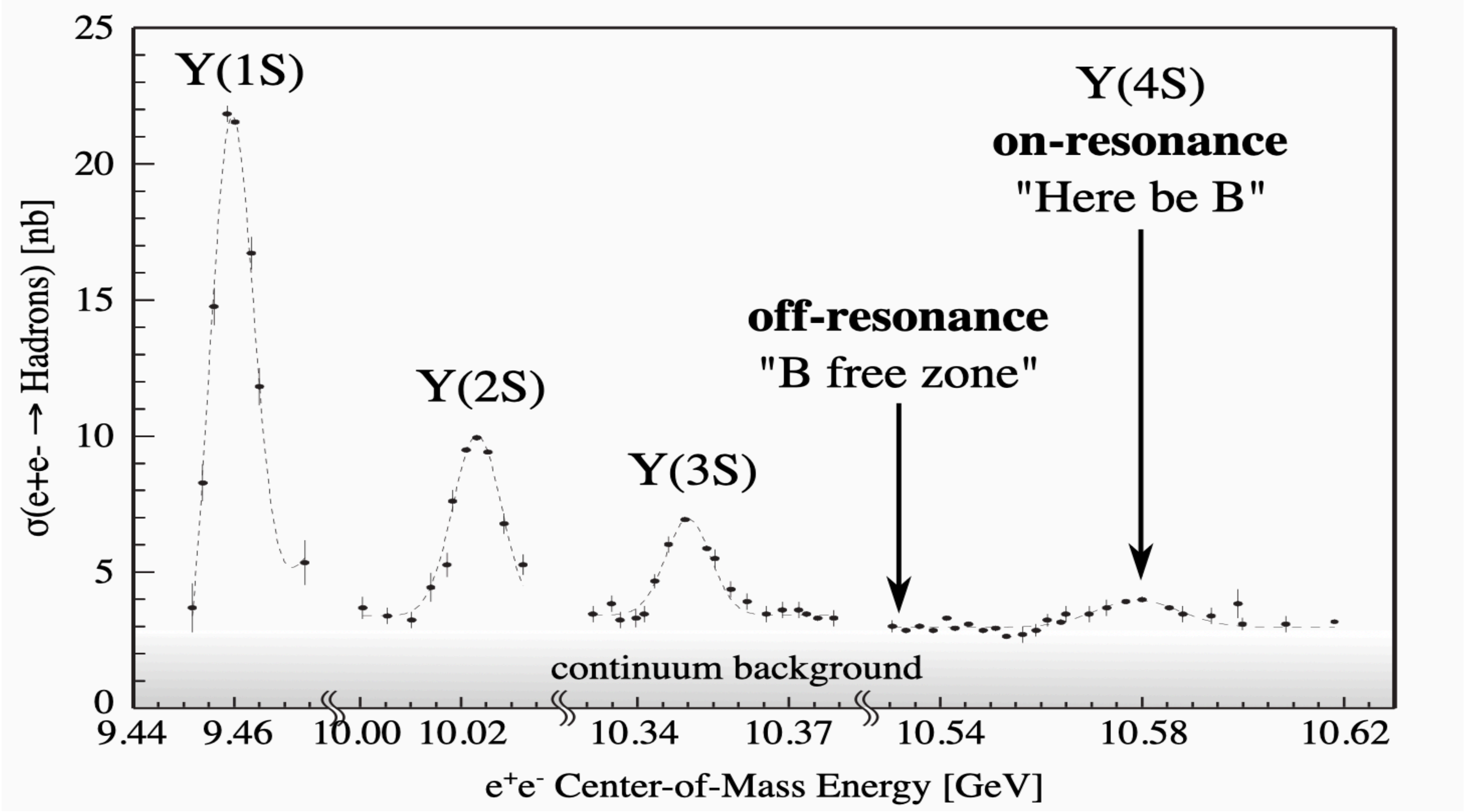
[**] LHCb, PRL 125 (2020) 011802

[***] LHCb, JHEP 2017, 55 (2017)

Where does Belle II stand?

The SuperKEKB e^+e^- collider at KEK, Japan, and the Belle II detector



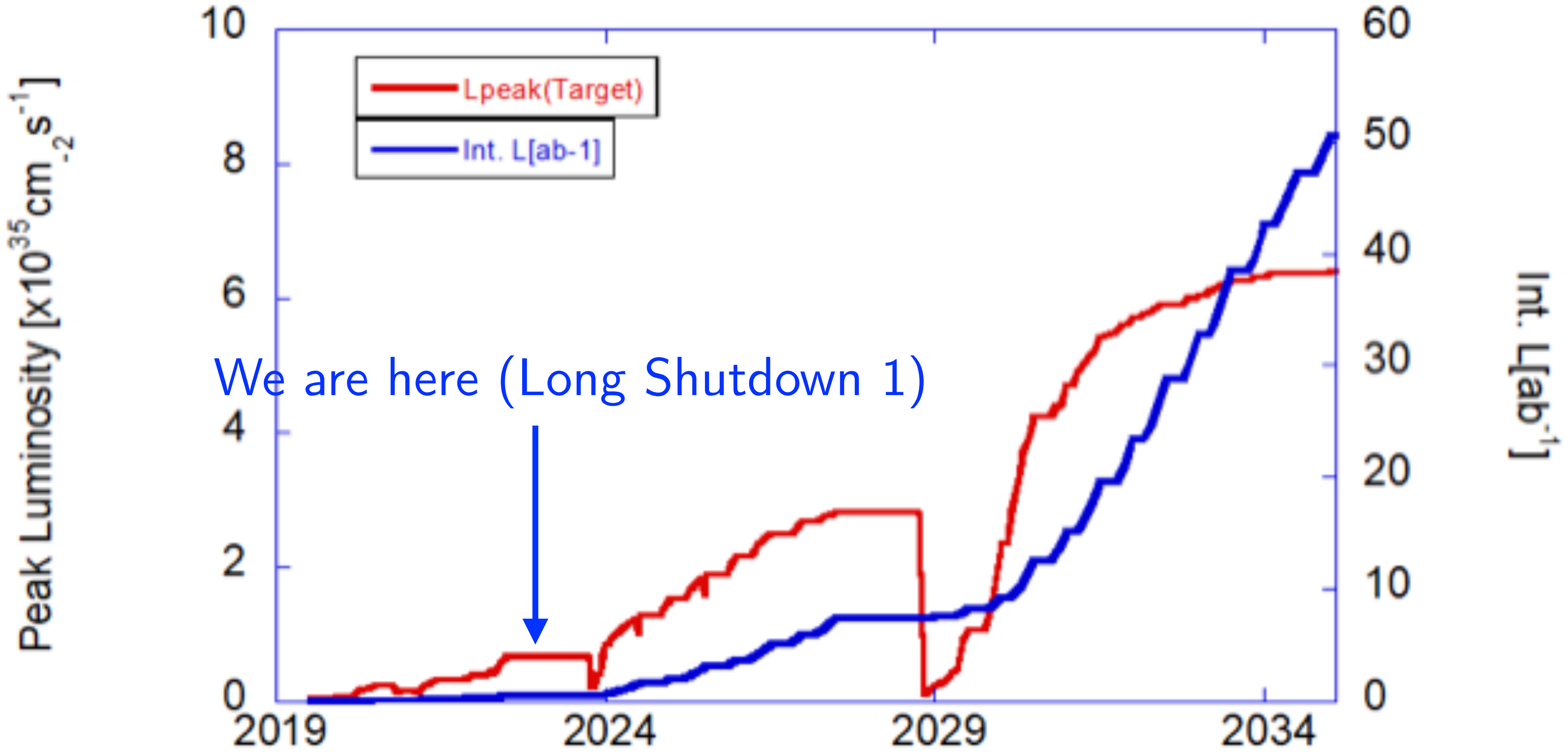


- *SuperKEKB*: asymmetric $e^+ - e^-$ collider at (and near) the $\Upsilon(4S)$ energy.

- *Belle II:* near-hermetic 4π coverage to efficiently reconstruct inclusive final states with missing energy, excellent capability of reconstructing neutral particles (γ, π^0, K_S^0), improved vertexing.

- Collected $\int L\, dt = 363\ \text{fb}^{-1}$ at $\Upsilon(4S)$ (BaBar: $\approx 420\ \text{fb}^{-1}$, Belle: $\approx 700\ \text{fb}^{-1}$).

🏆 *World record on June 22nd 2022*
$L = 4.7 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$



The Belle II detector overview

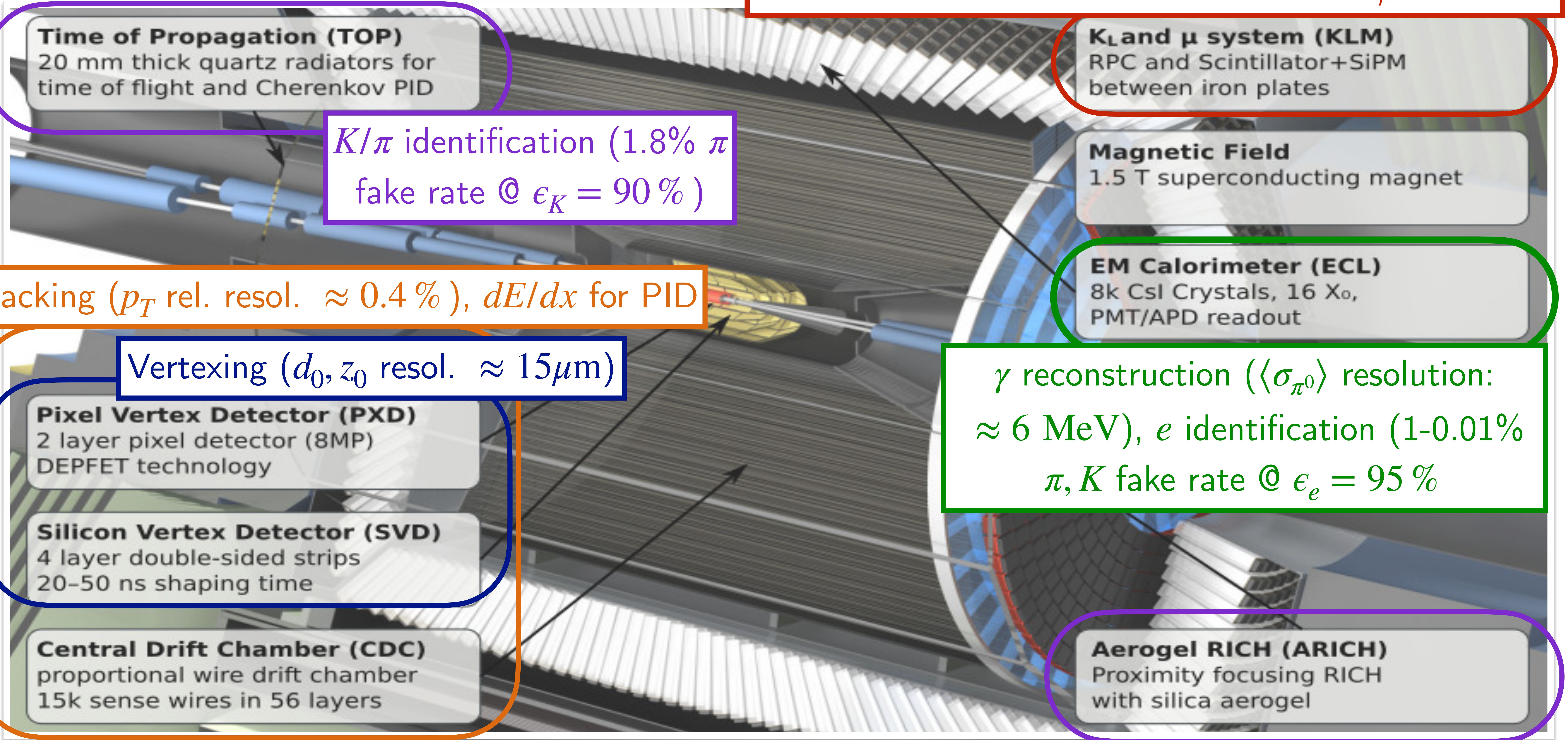
μ identification (2-1% π, K fake rate @ $\epsilon_\mu = 95\,\%$)

K/π identification (1.8% π fake rate @ $\epsilon_K = 90\,\%$)

Tracking (p_T rel. resol. $\approx 0.4\,\%$), dE/dx for PID

Vertexing (d_0, z_0 resol. $\approx 15\mu$m)

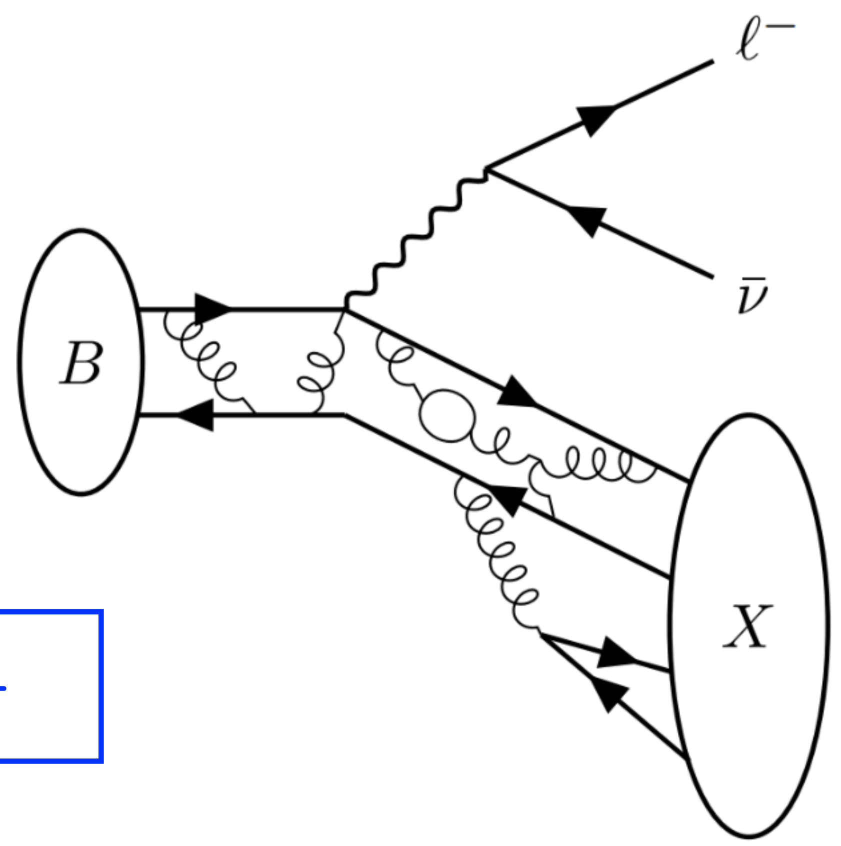
γ reconstruction ($\langle\sigma_{\pi^0}\rangle$ resolution: ≈ 6 MeV), e identification (1-0.01% π, K fake rate @ $\epsilon_e = 95\,\%$



Current Belle II tests of lepton flavour universality: tree-level ($b \to c\ell\nu$)

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

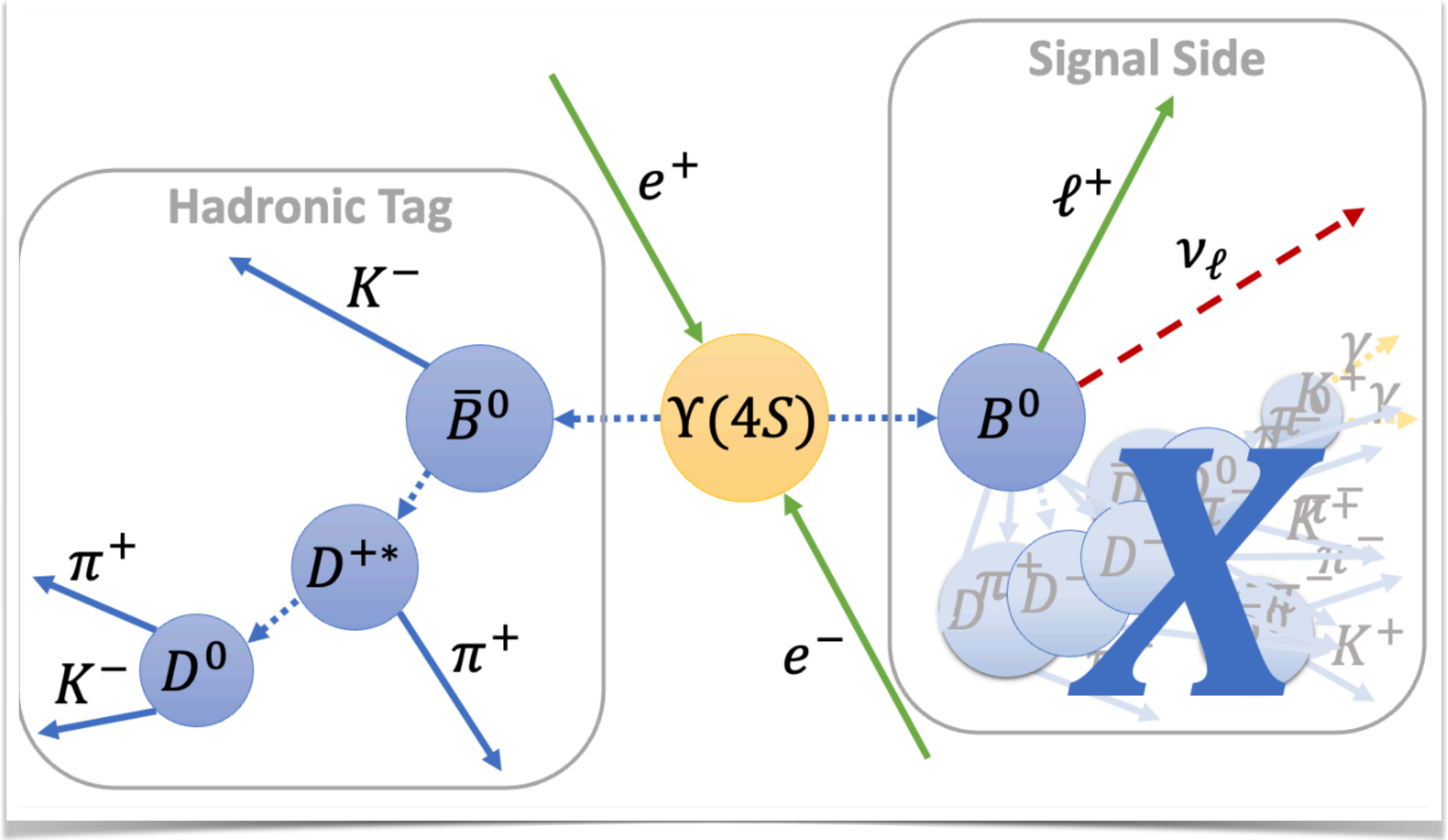
- Test LFU with *inclusive* semileptonic B decays by measuring the ratio: $R(X_{e/\mu}) = \dfrac{\mathcal{B}(B \to Xe\nu)}{\mathcal{B}(B \to X\mu\nu)}$



✔ *Tag* one B (from $\Upsilon(4S) \to B\bar{B}$) in fully hadronic decays to enhance purity and constrain final-state kinematics.

@ICHEP 2022, **189 fb[-1]**

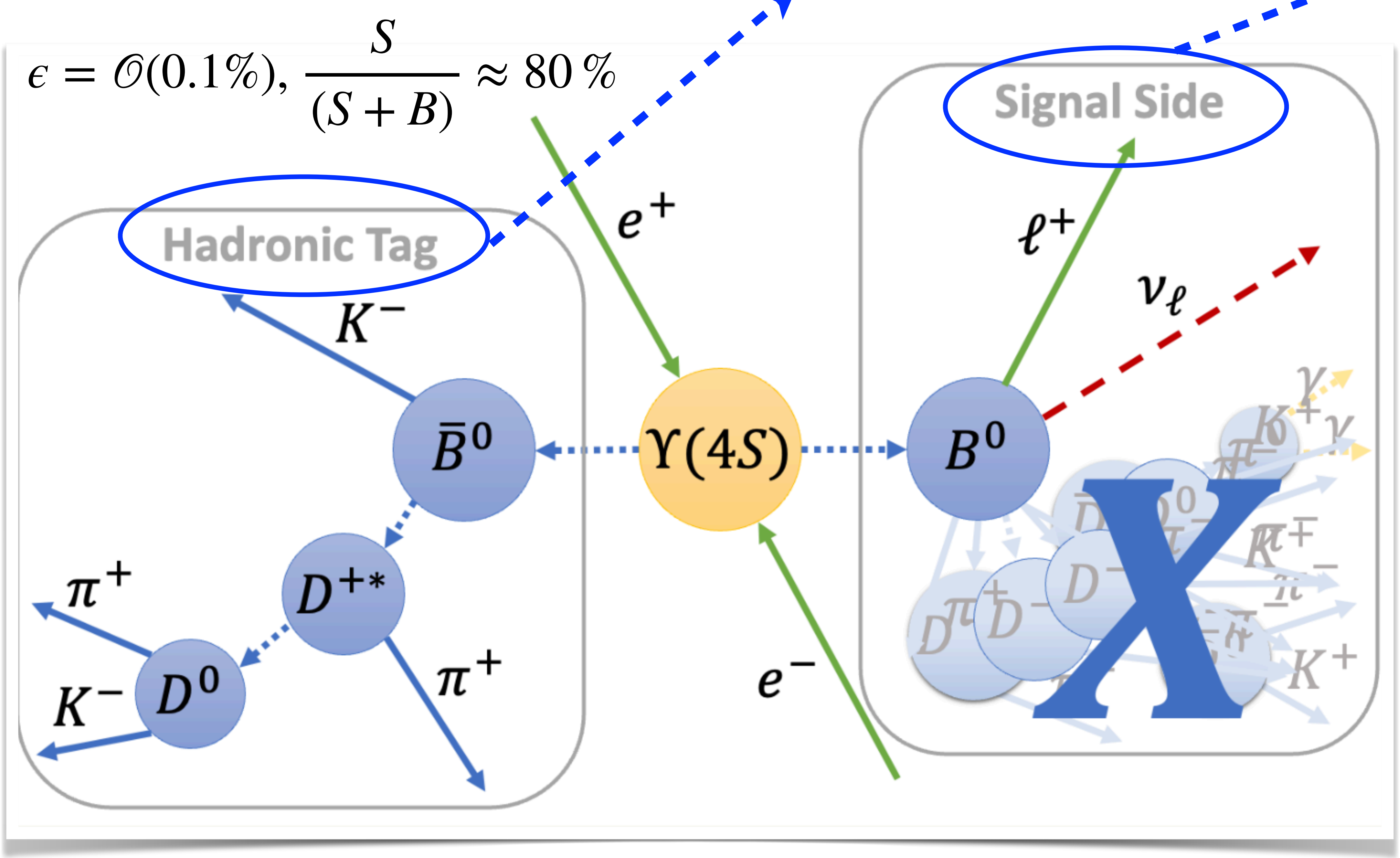
✔ Rely mostly on precise reconstruction of the "signal side" lepton. Only minimal selection applied on the decay products of the (complex) hadronic system X.



Backgrounds→ *continuum* $e^+e^- \to q\bar{q}$ ($q \in \{u, d, s, c\}$), hadrons faking leptons, secondary leptons from $b \to c \to (\ell, s)$ cascades.

$R(X_{e/\mu})$ - Analysis strategy

- Tight selection on B_{tag} quality using kinematic constraints and output of Full Event Interpretation [*] BDT classifier.



- Electron 4-momentum corrected for bremsstrahlung.
    - Validated in $J/\psi \to e^+e^-$control channel.
- Lepton identification requirements (see next slide).
- $p^*_\ell > 1.3\ \mathrm{GeV}/c^2$ (in B_{sig} rest frame)$\to$ reject most $B \to X\tau\nu$, suppress fakes & secondaries.

- Continuum background suppressed via BDT based on observables describing event symmetries.

[*] Comput.Softw.Big Sci. 3 (2019) 1, 6

$R(X_{e/\mu})$ - Lepton identification

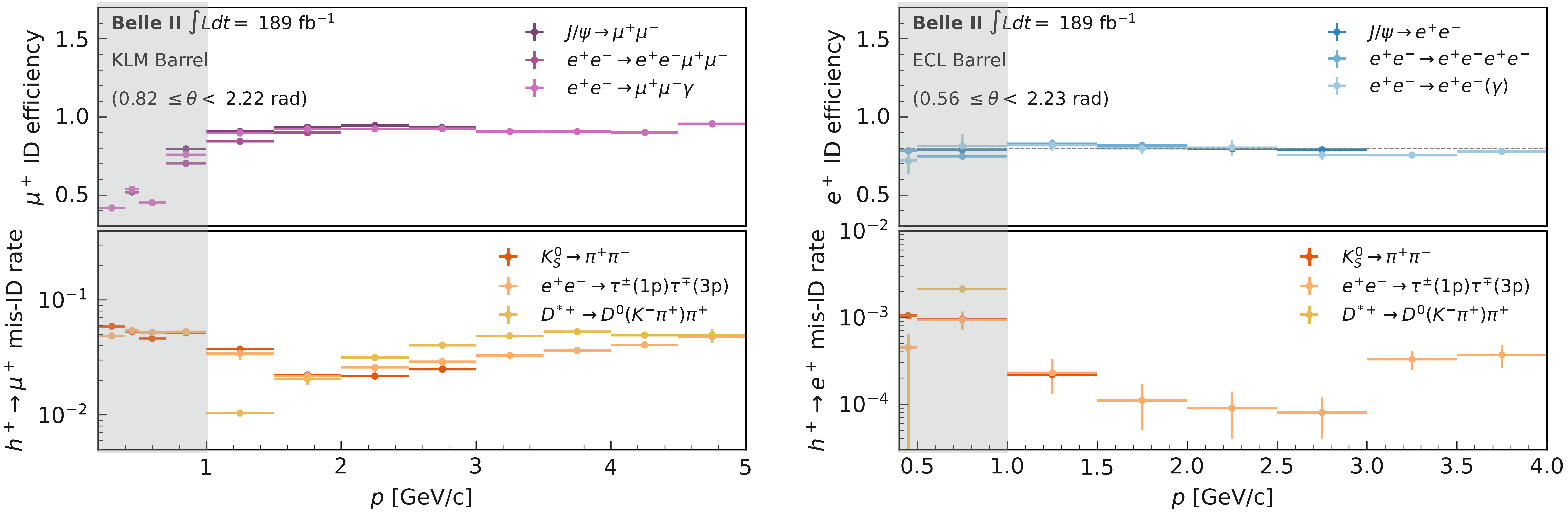
- Muon ID via likelihood ratio: $\text{PID}_\mu = \frac{\mathcal{L}_\mu}{\sum_i \mathcal{L}_i}, \quad \mathcal{L}_i = \prod_d^{d \in D} \mathcal{L}_i^d$

D={central drift chamber (dE/dx), Cherenkov+ToP, EM calorimeter (E/p), muon detector}

- Electron ID via BDT with calorimetric shower shapes [*].
  - $h(\pi, K) \rightarrow e$ mis-ID probability reduced by $>$ x2 wrt. likelihood ratio.

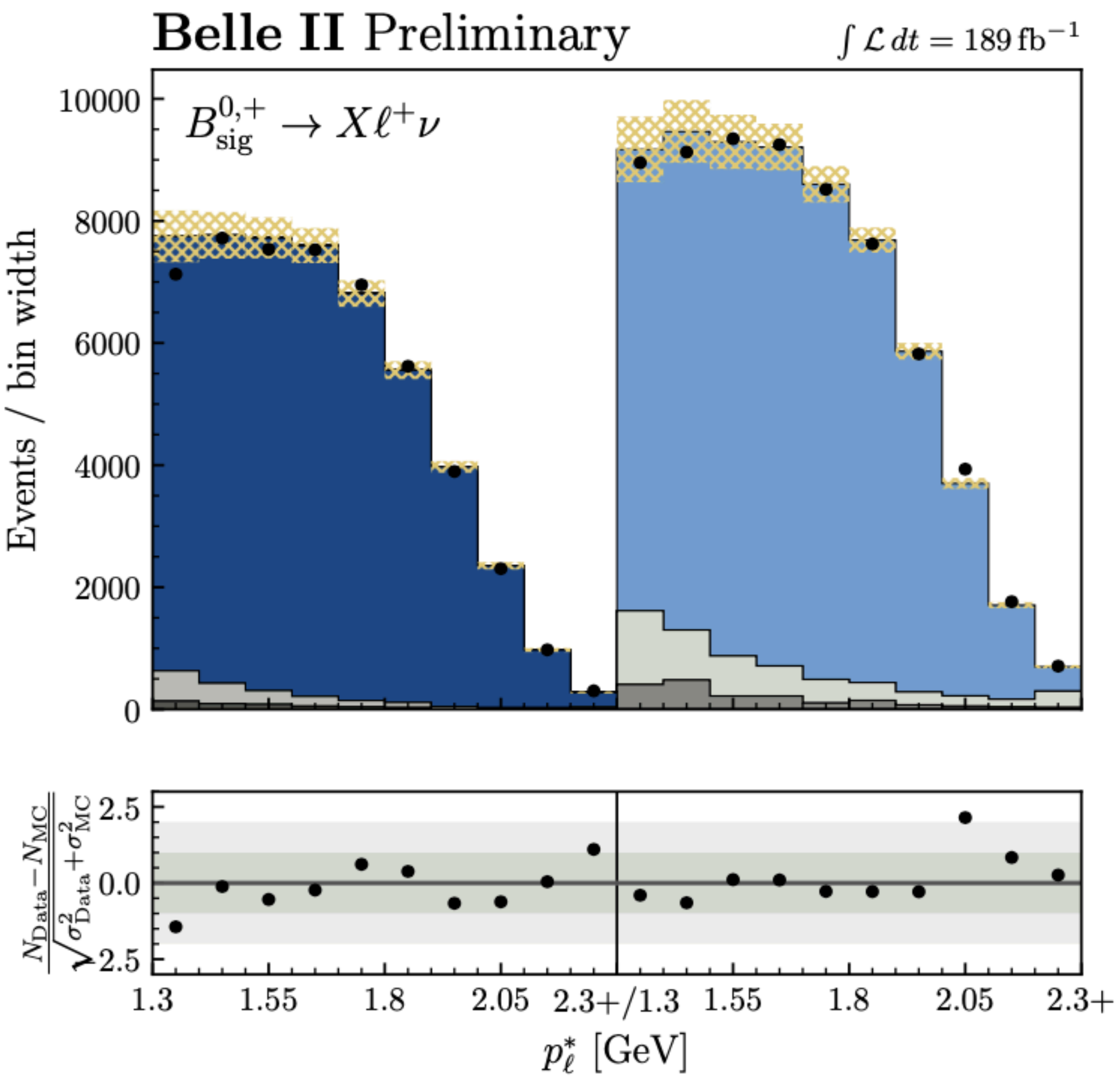
[*] M. M., J. Tan, P. Urquijo, EPJ Web Conf. 245 06023 (2020).

- Efficiencies calibrated in data with several, independent control samples. Corrections to simulation close to unity, measured to a precision of $\mathcal{O}(0.1 - 2\%)$ for both lepton flavours.

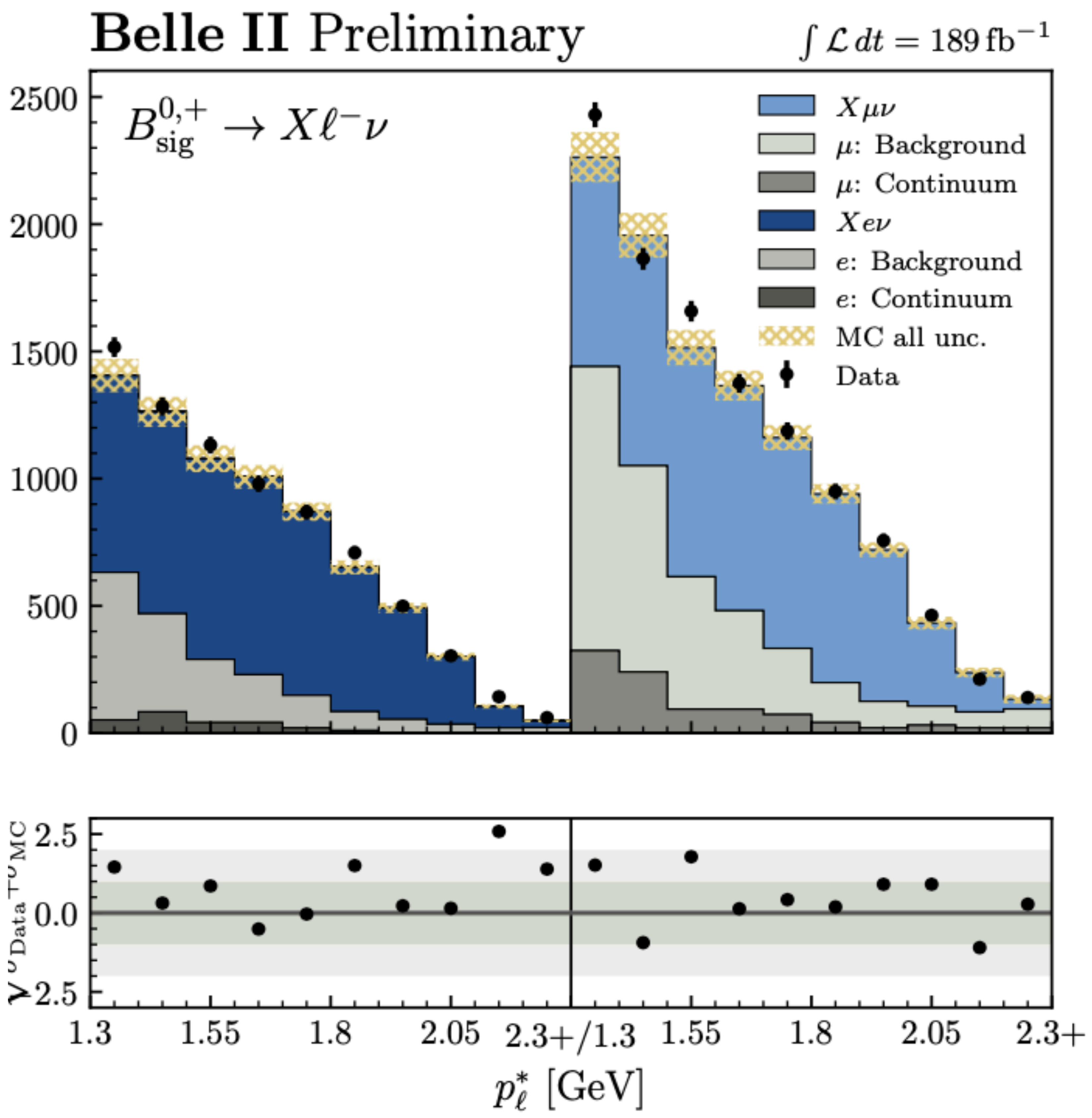


$R(X_{e/\mu})$ - Signal extraction

SR (correct ℓ charge), pre-fit



CR (wrong ℓ charge)



- $B \to X\ell\nu$: $X = D, D^{*}, D^{**}$, non resonant hadronic decays.
- Continuum background normalisation constrained with 18 fb^{-1} of off-resonance data.
- Normalisation of fakes and secondaries constrained in control regions with "wrong lepton charge" $(\Upsilon(4S) \to B^{+,0}_{\mathrm{tag}}, B_{sig} \to X\ell^{+}\nu + \mathrm{c.c.})$

- Electron and muon channels are fitted simultaneously in 10 p^{*}_{ℓ} bins each via maximum likelihood template fit, with $B \to X\ell\nu$ yields free floating parameters.

$$R(X_{e/\mu}) = \frac{\epsilon_{X\mu\nu} N_{Xe\nu}}{\epsilon_{Xe\nu} N_{X\mu\nu}}$$

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

Source	$R(X_{e/\mu})$ uncertainty [%]
Statistical	1.0
Lepton identification	1.8
$X_c \ell \nu$ branching fractions	0.1
$X_c \ell \nu$ form factors	0.2
Total	2.2

$$R(X_{e/\mu}) = 1.033 \pm 0.010\ (\text{stat.}) \pm 0.020\ (\text{sys.})$$

✔ Theory uncertainties largely cancel in ratio.

⚠ Precision limited by systematic uncertainties related to lepton ID.

- Compatible with the Standard Model prediction [*] of $R(X_{e/\mu})_{\text{SM}} = 1.006 \pm 0.001$ within 1.2σ.
- Also consistent with Belle result [**] using $B \to D^* \ell \nu$ decays: $R(D^*_{e/\mu}) = 1.01 \pm 0.01\ (\text{stat.}) \pm 0.03\ (\text{sys.})$

This is the most precise LFU test with semileptonic B decays to date.

[*] M. Rahimi, K. Vos, JHEP 11, 007 (2022)

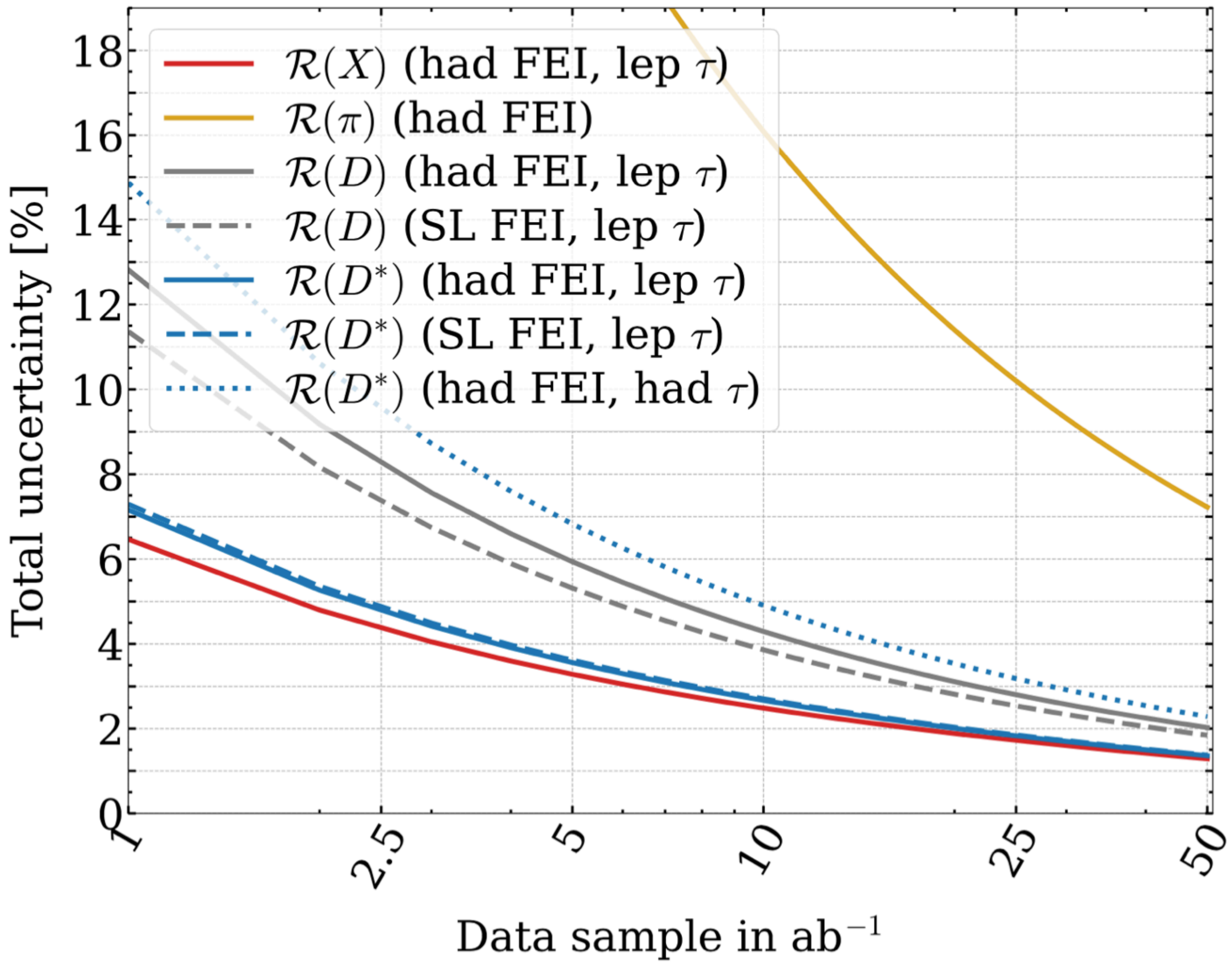
[**] Phys. Rev. D 100, 052007 (2019), **711 fb^{-1}**

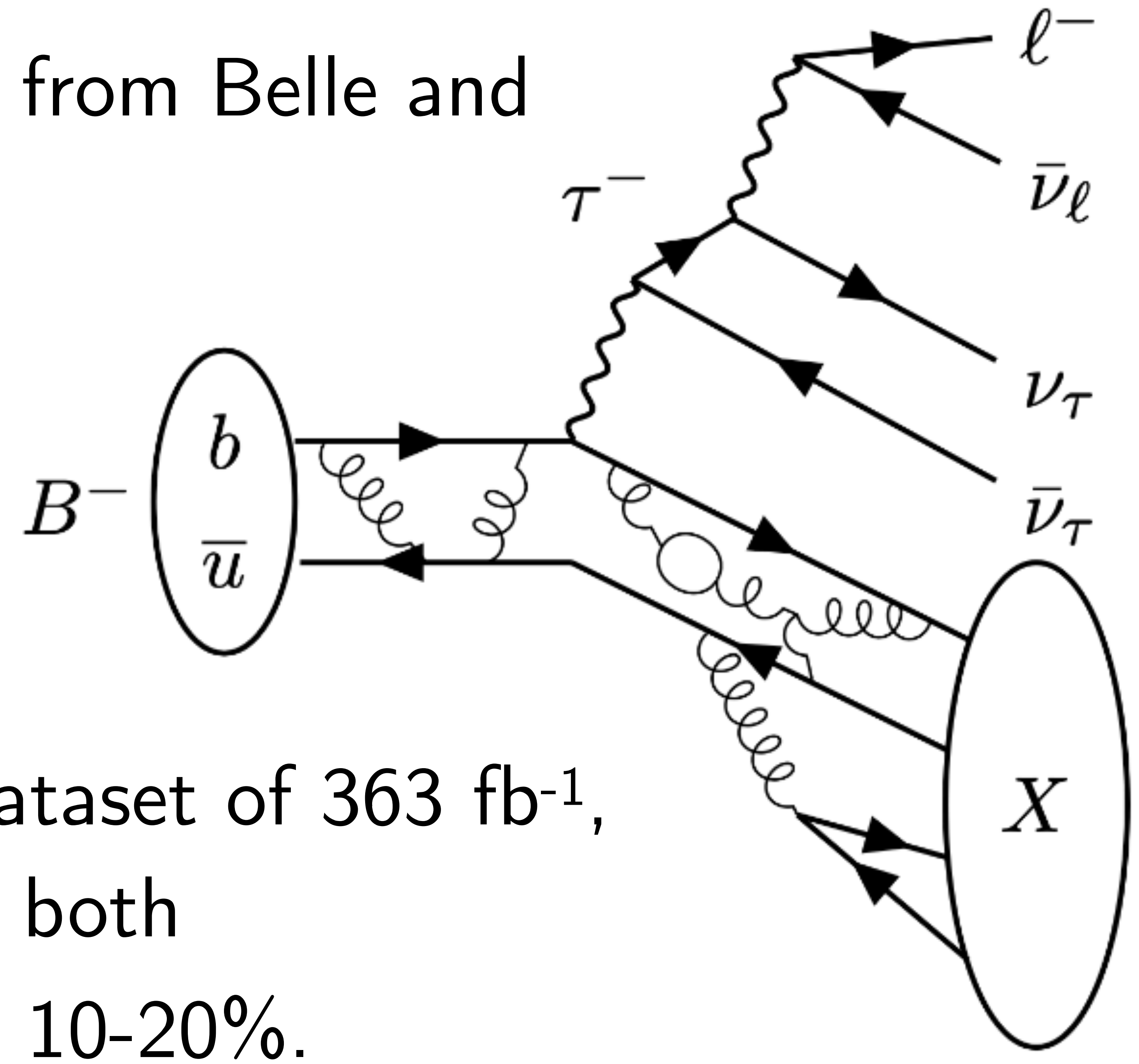
Prospects for Belle II

- Alongside $R(D^{(*)})$, Belle II has unique capability for an *inclusive* measurement: $R(X)$.

- Complementary test of LFU w/ semileptonic B decays, no published results from Belle and BaBar.

Belle II Snowmass White Paper (2021) [Link]





- With current Belle II dataset of 363 fb^{-1}, the expected precision of both $R(X), R(D^{(*)})$ is of order 10-20%.

- New results for both analyses are highly anticipated.

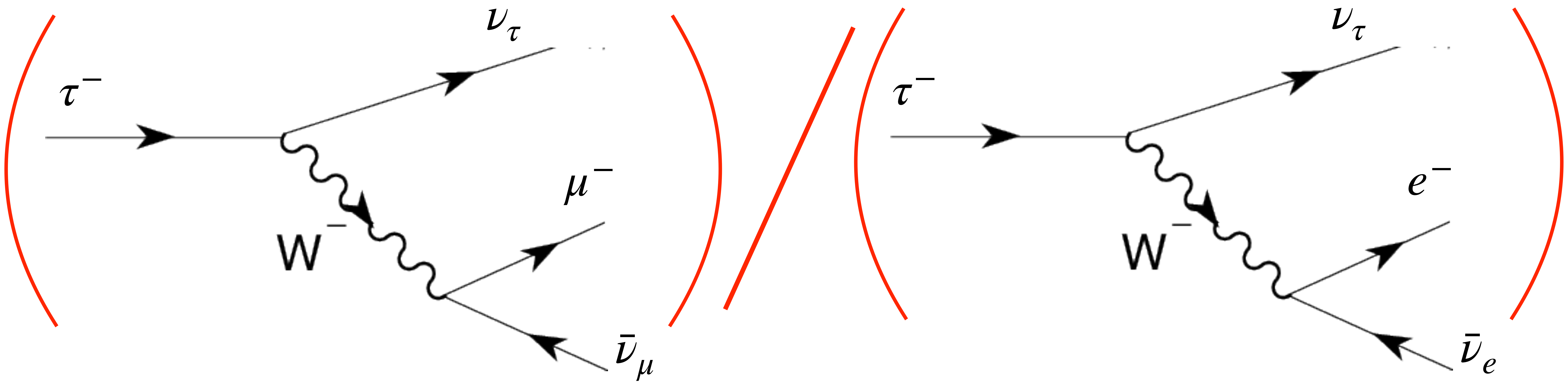
Belle II lepton flavour violation searches with tau lepton decays

LF(U)V at Belle II with τ leptons

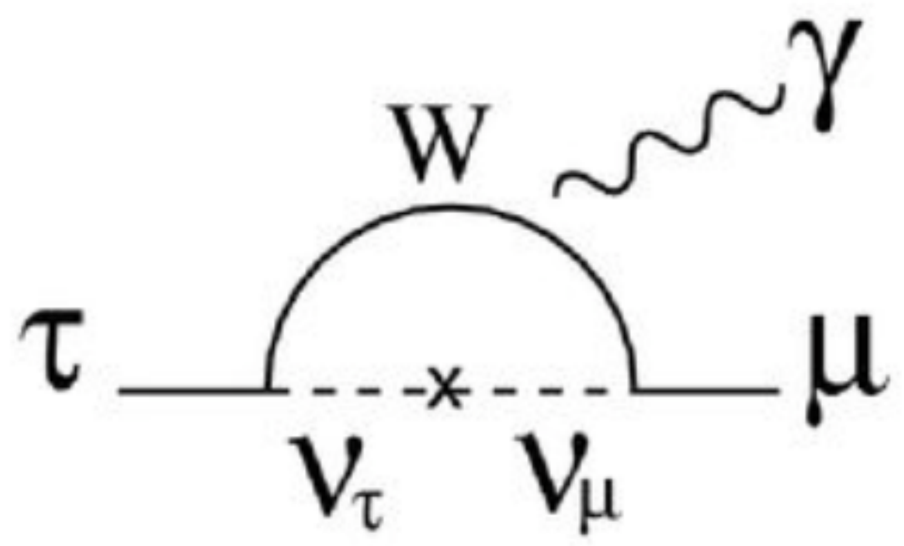
- SuperKEKB is (also) a τ-factory! $\rightarrow \approx 10^6\ e^+e^- \rightarrow \tau^+\tau^-$ pairs/fb-1 $\simeq e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$ pairs/fb-1.

- Abundance of τ lepton pairs can be exploited as a high-precision probe for both:

1) LFU tests.



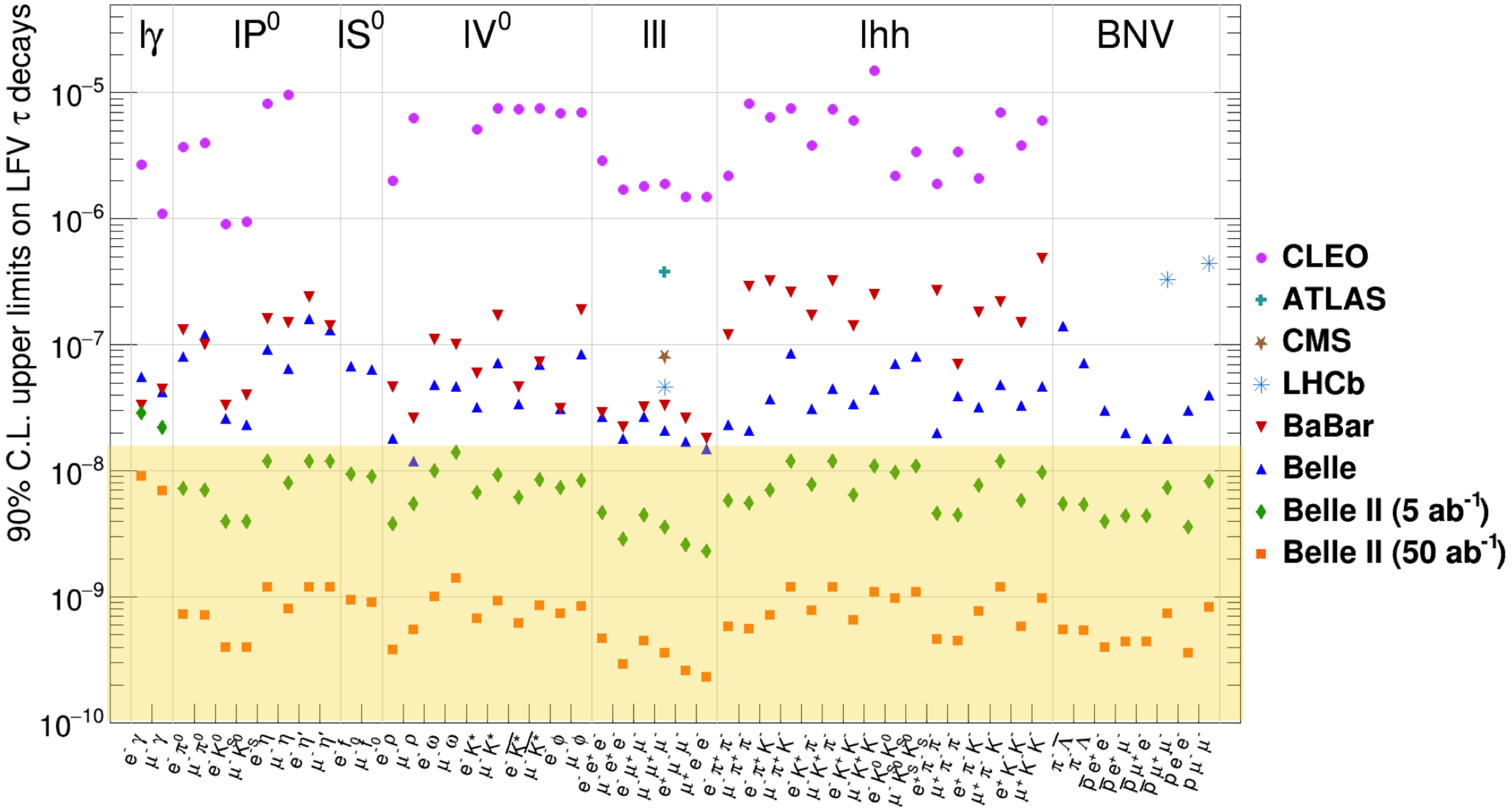
2) Searches for Lepton Flavour (and/or Number) Violating processes, prohibited (or strongly suppressed) in the SM.



LFV in τ decays

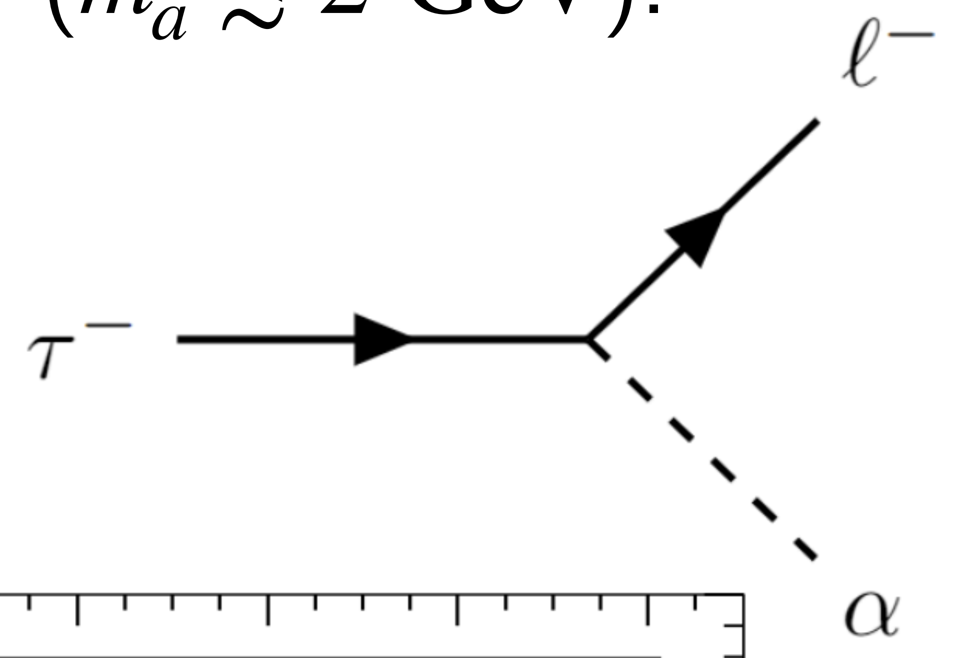
- Any observation of lepton flavour (or number)-violating (LFV) decays $\rightarrow$ direct evidence of beyond-SM physics.
- Many models predict LFV τ decays with branching ratios of $\mathcal{O}(10^{-8} - 10^{-10})$ [*].
- Plenty (>52) of channels accessible at Belle II through dedicated low multiplicity triggers (c.f. Chia-Ling's talk).

[*] S. Banerjee et al., arXiv:2203.14919v2 (2022)

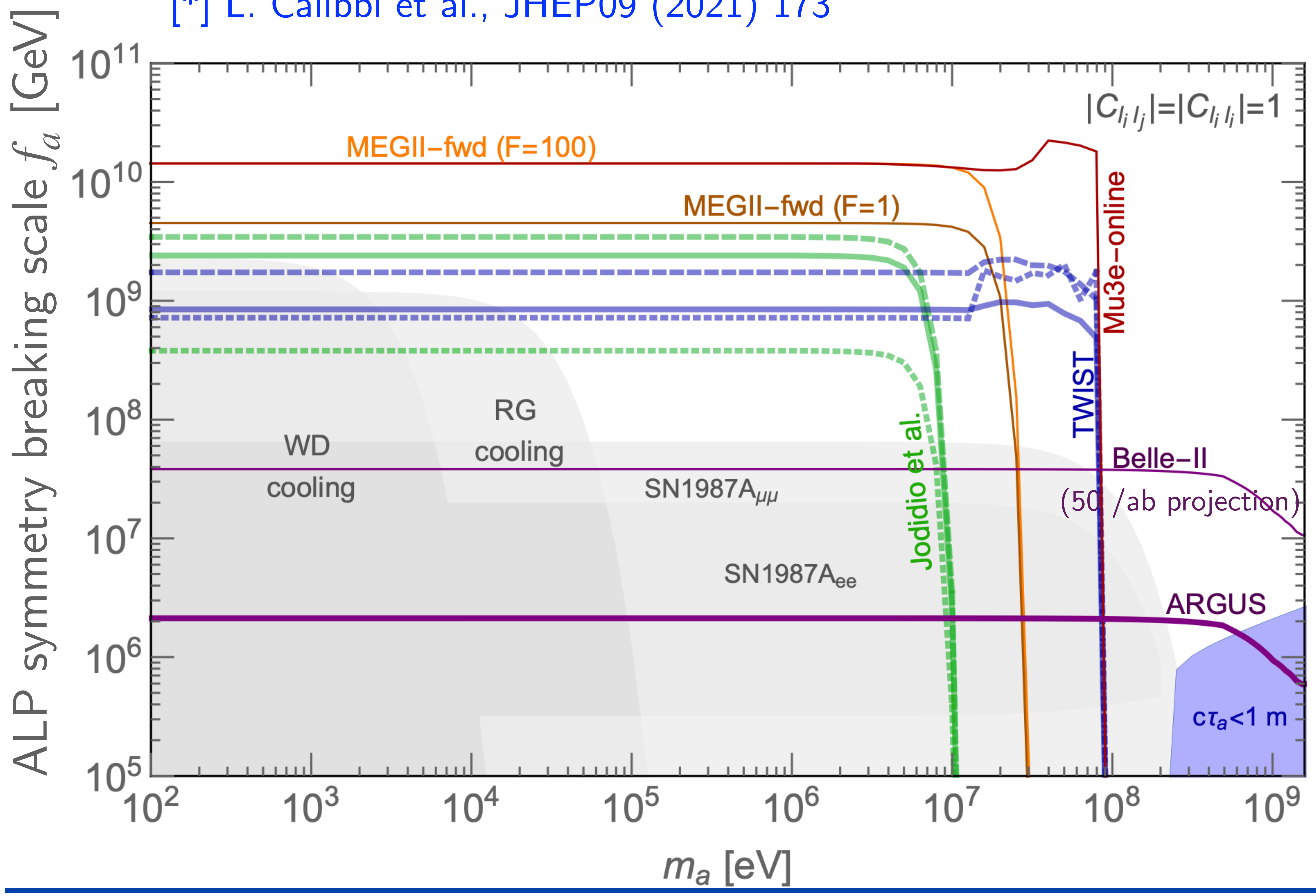


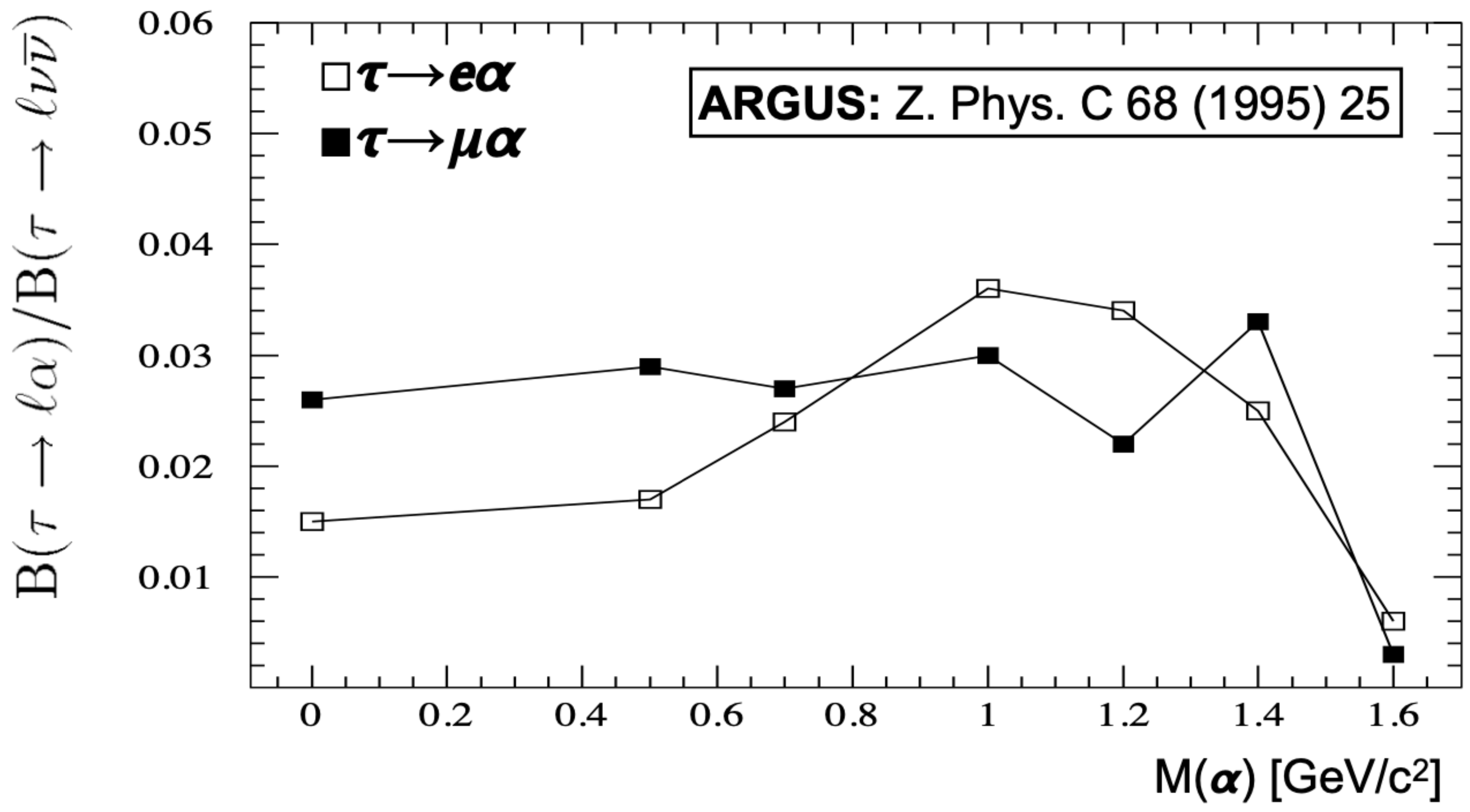
LFV in τ decays

- Missing energy signatures in LFV tau decays may be explained by light bosons such as ALPs [*] ($m_a \lesssim 2$ GeV).
- Best limits on $\frac{\mathscr{B}(\tau \to \ell\alpha)}{\mathscr{B}(\tau \to \ell\nu_\ell\nu_\tau)}$ ($\mathscr{B}(\tau \to \ell\alpha) \propto 1/f_a^2$) set by ARGUS in 1995 (476 pb^{-1}).



[*] L. Calibbi et al., JHEP09 (2021) 173



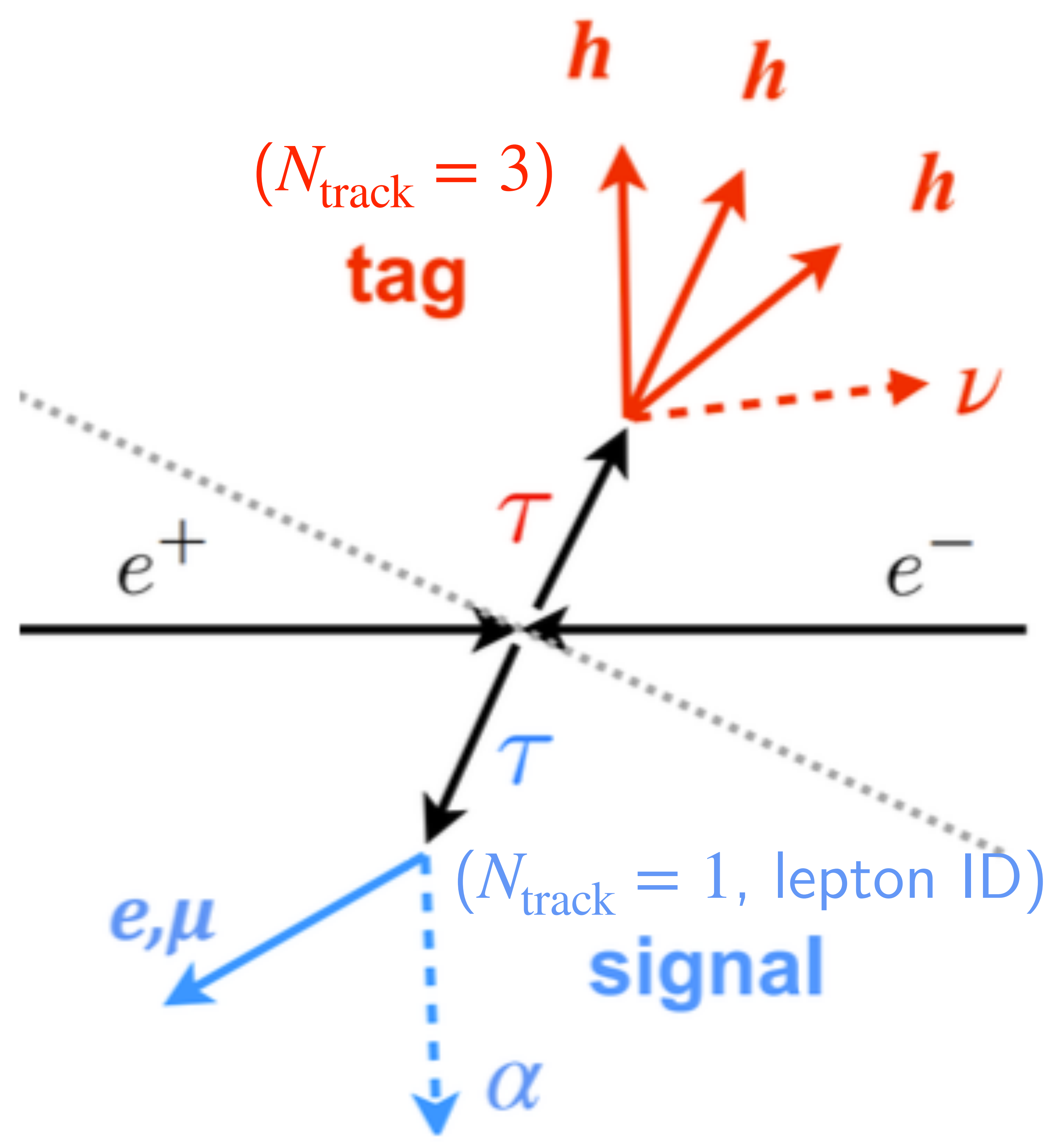


Belle II current dataset can already be used to set more stringent limits.

$\tau \to \ell\alpha$ (invisible), $\ell \in \{e, \mu\}$ - Analysis strategy

- Search for an *invisible* (pseudo)scalar light boson α with $m_\alpha \in (0{,}1.6)$ GeV/c^2.

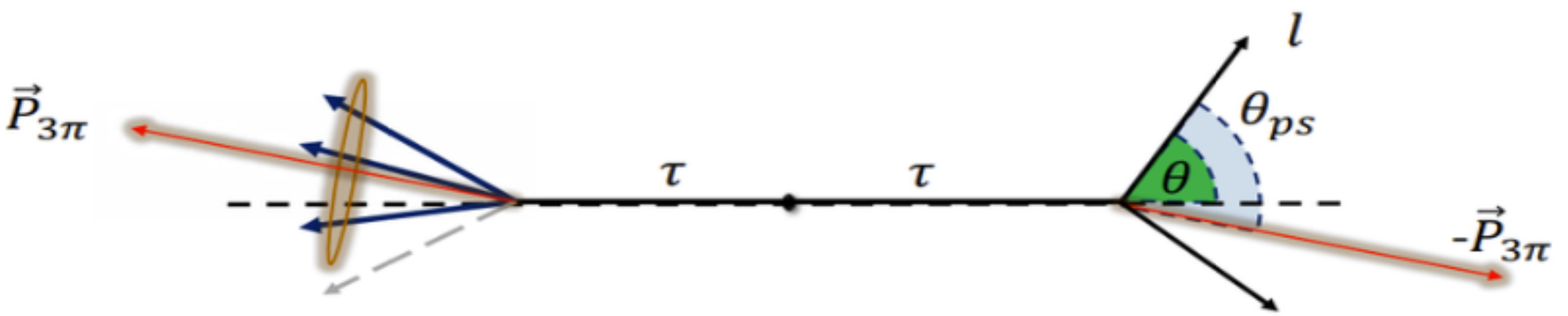
arXiv:2212.03634, to be sub. to PRL , **62.8 fb^{-1}**



- Use plane orthogonal to thrust axis to divide *tag* (3-prong) hemisphere and signal hemisphere.

- 2-body decay → monochromatic lepton momentum peak above $\tau \to \ell\nu_\ell\nu_\tau$ irreducible background in τ_{sig} rest frame, depending on m_α.

- Due to undetected neutrinos, boost to the τ_{sig} *pseudo*-rest frame:



τ_{sig} direction: $-\dfrac{\vec{p}_{3h}}{|\vec{p}_{3h}|}$

τ_{sig} energy: $\approx \dfrac{\sqrt{s}}{2}$ (neglecting ISR)

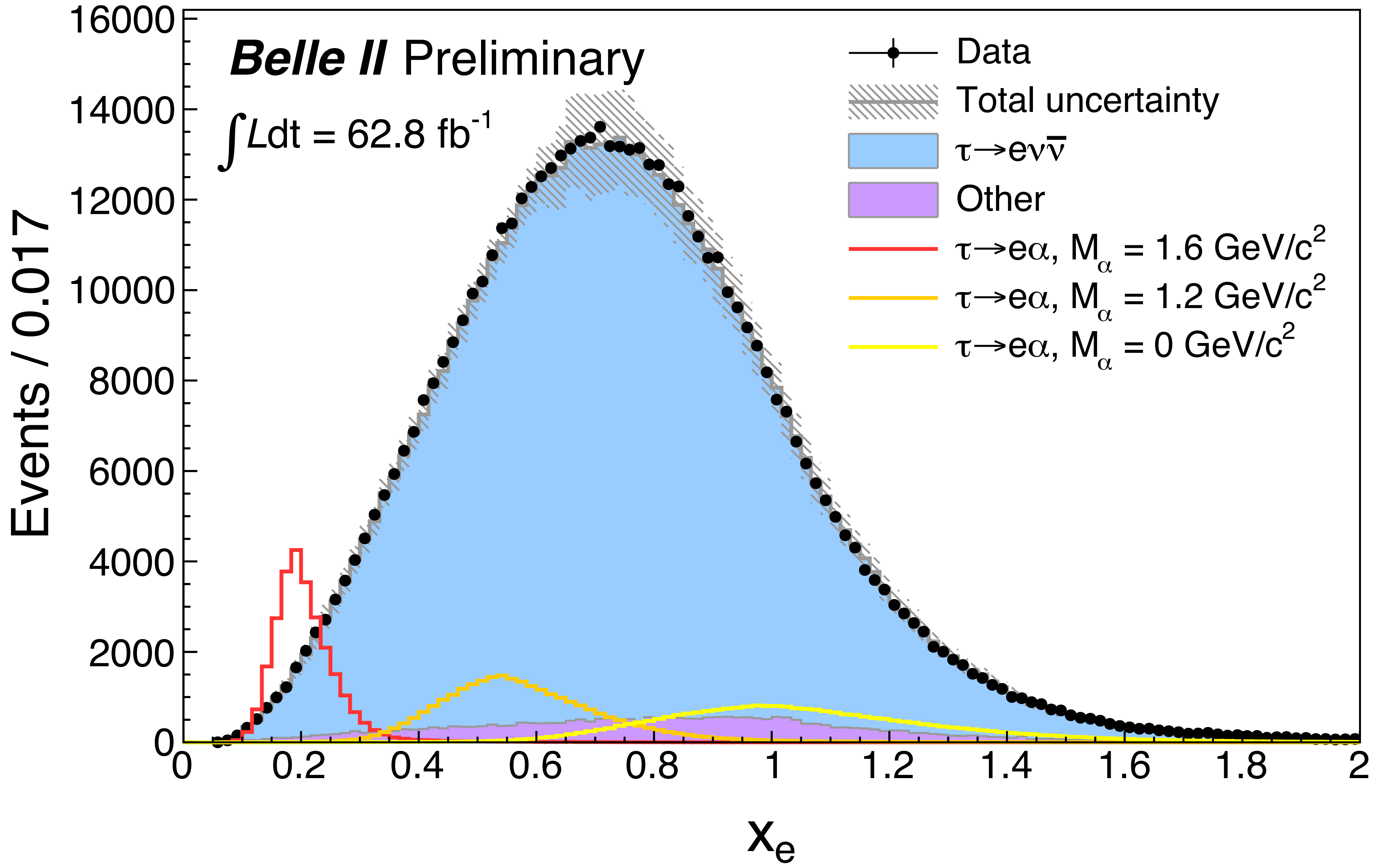
$\tau \to \ell\alpha$ (invisible) - Signal extraction

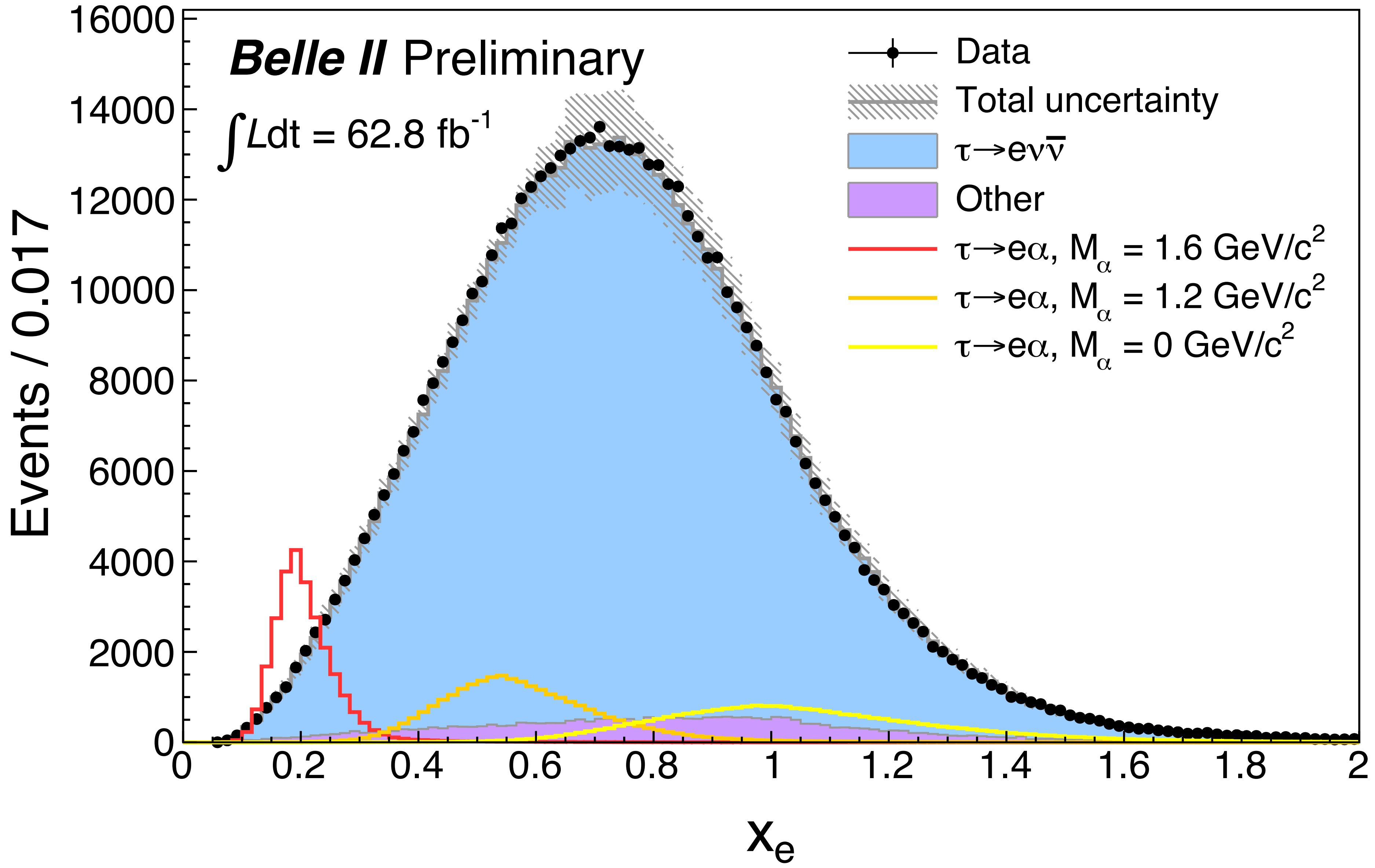
- Reducible backgrounds ($\tau \to \pi\nu$, continuum, $ee\ell\ell, eehh$) suppressed via selection optimised on $\tau \to \ell\nu_\ell\nu_\tau$
$\to$ 96% (e), 92% (μ) purity w/ 9.1-17.9% signal efficiency (m_α-dependent).

- Normalised branching fraction of $\tau \to \ell\alpha$ extracted via maximum likelihood template fit to $x_\ell = \dfrac{E^*_\ell}{m_\tau c^2/2}$ (in τ_{sig} pseudo-rest frame).

$$N(x_\ell) = N_{\ell\bar{\nu}\nu}\frac{\epsilon_{\ell\alpha}}{\epsilon_{\ell\nu\nu}}\frac{\mathcal{B}_{\ell\alpha}}{\mathcal{B}_{\ell\bar{\nu}\nu}}f_{\ell\alpha}(x_\ell) + N_{\ell\bar{\nu}\nu}\,f_{\ell\bar{\nu}\nu}(x_\ell) + N_b\,f_b(x_\ell)$$

free-floating

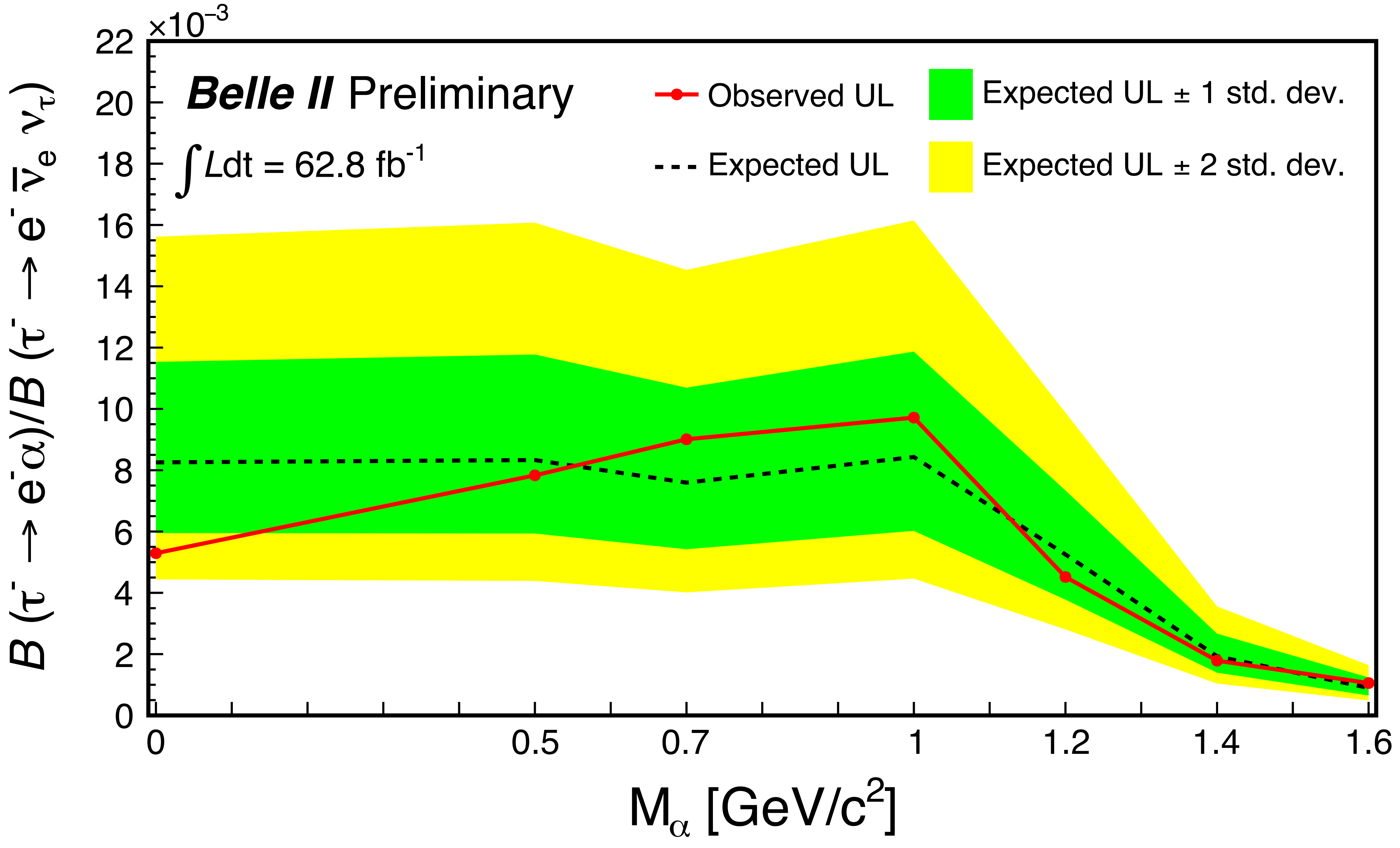


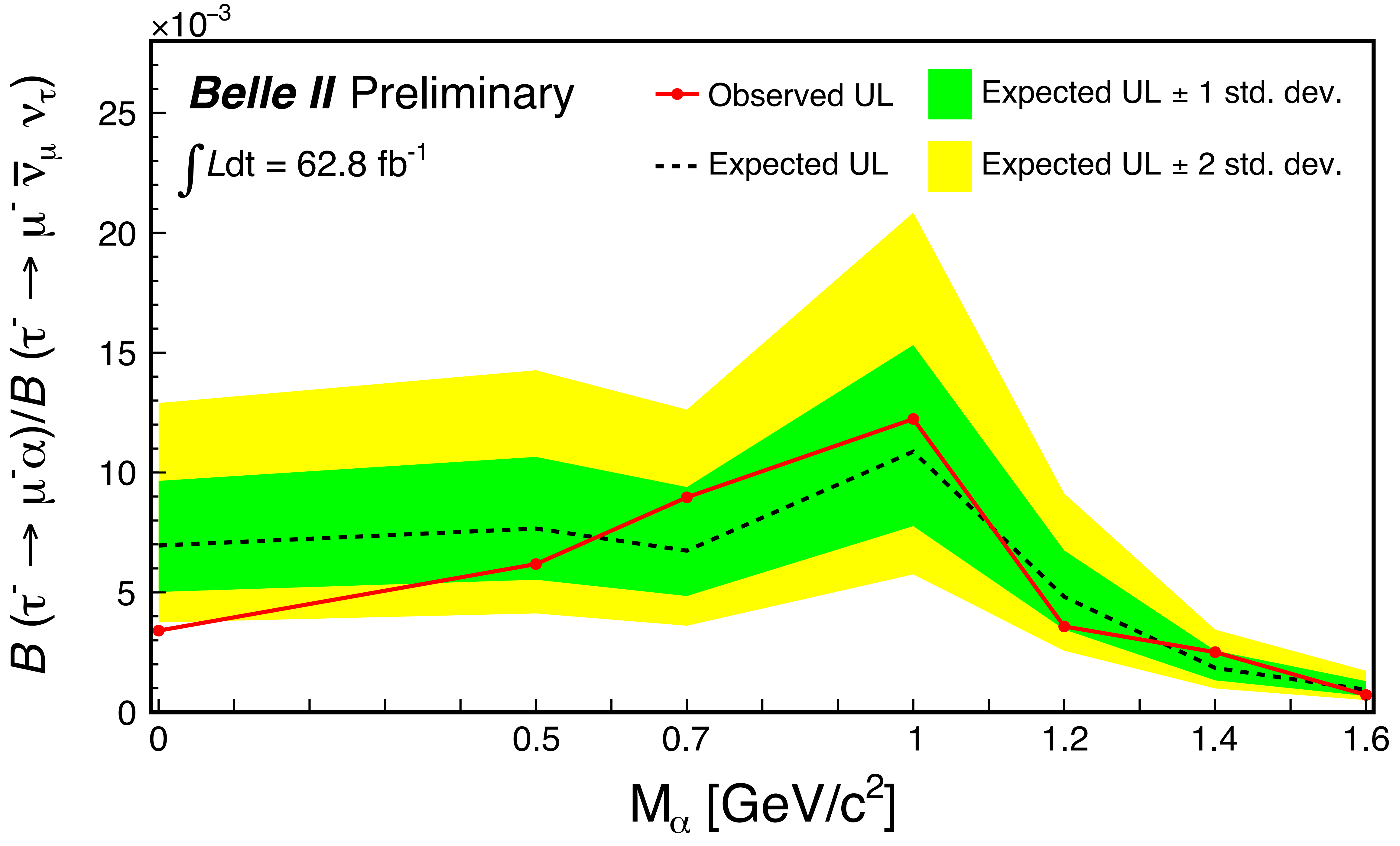


- *Partial* cancellation of lepton ID uncertainties in branching fraction ratio due to differing kinematics.

$\tau \to \ell\alpha$ (invisible) - Results

- No significant signal is observed $\to$ derived 95% CL upper limits on $\dfrac{\mathscr{B}(\tau \to \ell\alpha)}{\mathscr{B}(\tau \to \ell\nu_\ell\nu_\tau)}$ (using CLs method).
- Limits are between 2 and 14 times lower than ARGUS, depending on m_α and lepton flavour.
- Sensitivity degraded by 35% due to systematics (mostly from lepton ID).





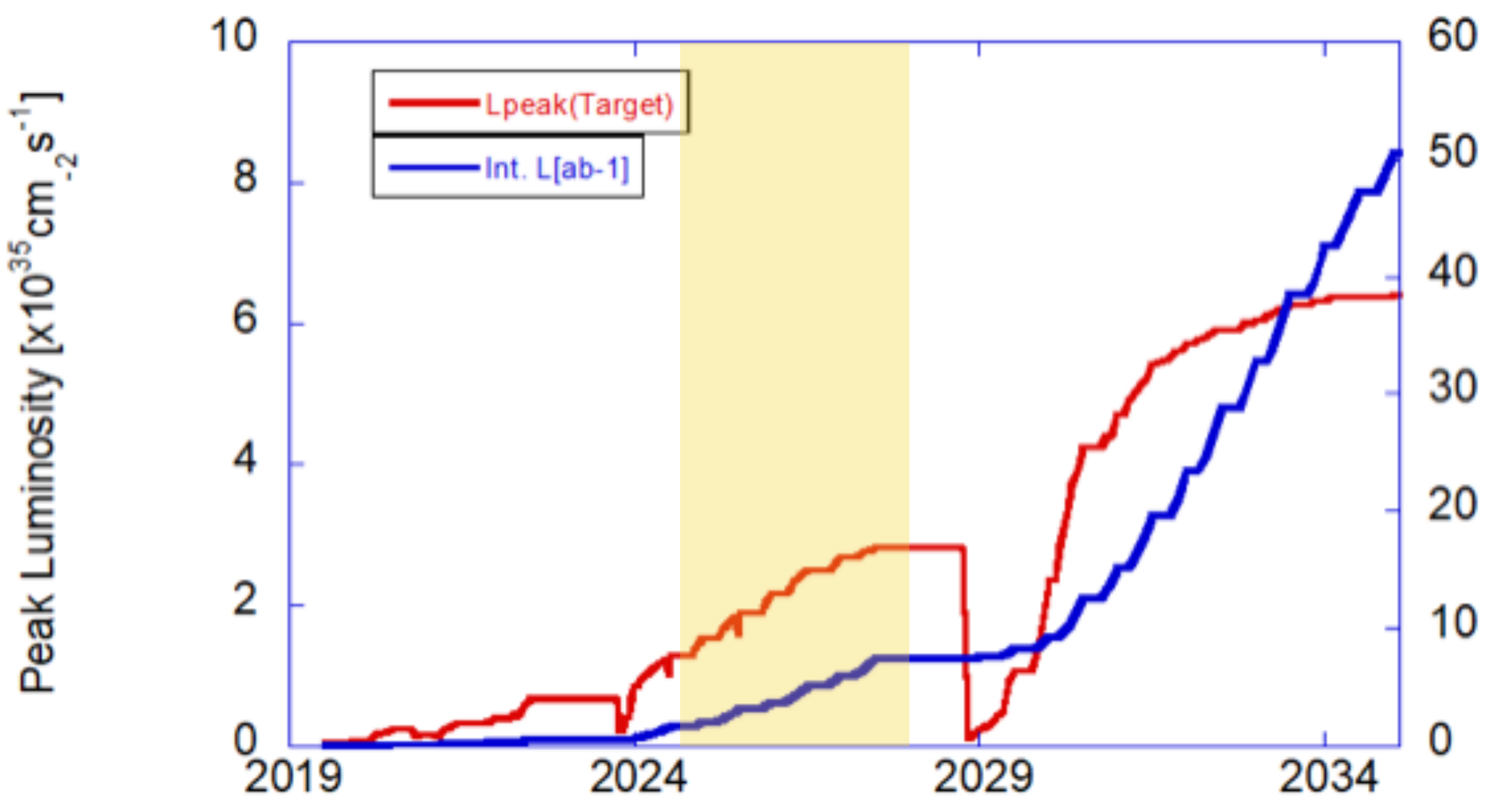
(Preparing for) Belle II tests of LFU: loop-induced $(b \to s\ell\ell)$

Prospects for Belle II

- Belle II LFU tests with rare electroweak penguins ($b \to s\ell\ell$) will be competitive w/ LHCb with a dataset of a few ab^{-1}

Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
R_K ([1.0, 6.0] GeV^2)	28%	11%	3.6%
R_K (> 14.4 GeV^2)	30%	12%	3.6%
R_{K^*} ([1.0, 6.0] GeV^2)	26%	10%	3.2%
R_{K^*} (> 14.4 GeV^2)	24%	9.2%	2.8%
R_{X_s} ([1.0, 6.0] GeV^2)	32%	12%	4.0%
R_{X_s} (> 14.4 GeV^2)	28%	11%	3.4%

The Belle II Physics Book, *PTEP* 2020 (2020) 2, 029201 (erratum)

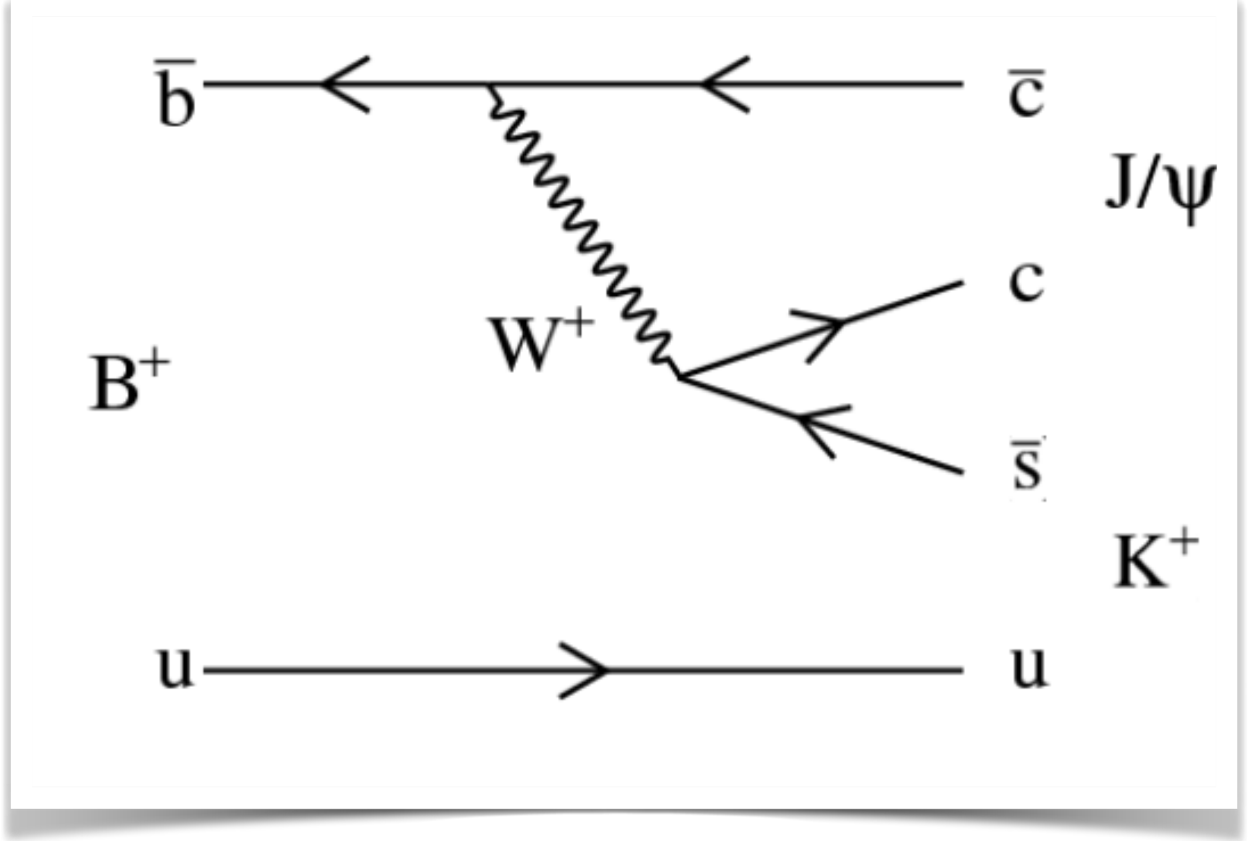


Preparing for $R(K)$: $r^K_{J/\psi}$ in $B \to J/\psi\, K$ decays

- Measure the $r^K_{J/\psi}$ ratio for decays $B^+(B^0) \to J/\psi(\ell^+\ell^-)K^+(K^0_S)$ [+ c.c.]

Belle II arXiv: 2207.11275, **189 fb^{-1}**

$$r^K_{J/\psi} = \frac{\mathscr{B}(B^+ \to J/\psi(\to \mu\mu)K)}{\mathscr{B}(B^+ \to J/\psi(\to ee)K)} = \frac{N_{J/\psi(\mu\mu)K}}{N_{J/\psi(ee)K}} \cdot \frac{\epsilon_{J/\psi(ee)K}}{\epsilon_{J/\psi(\mu\mu)K}}$$

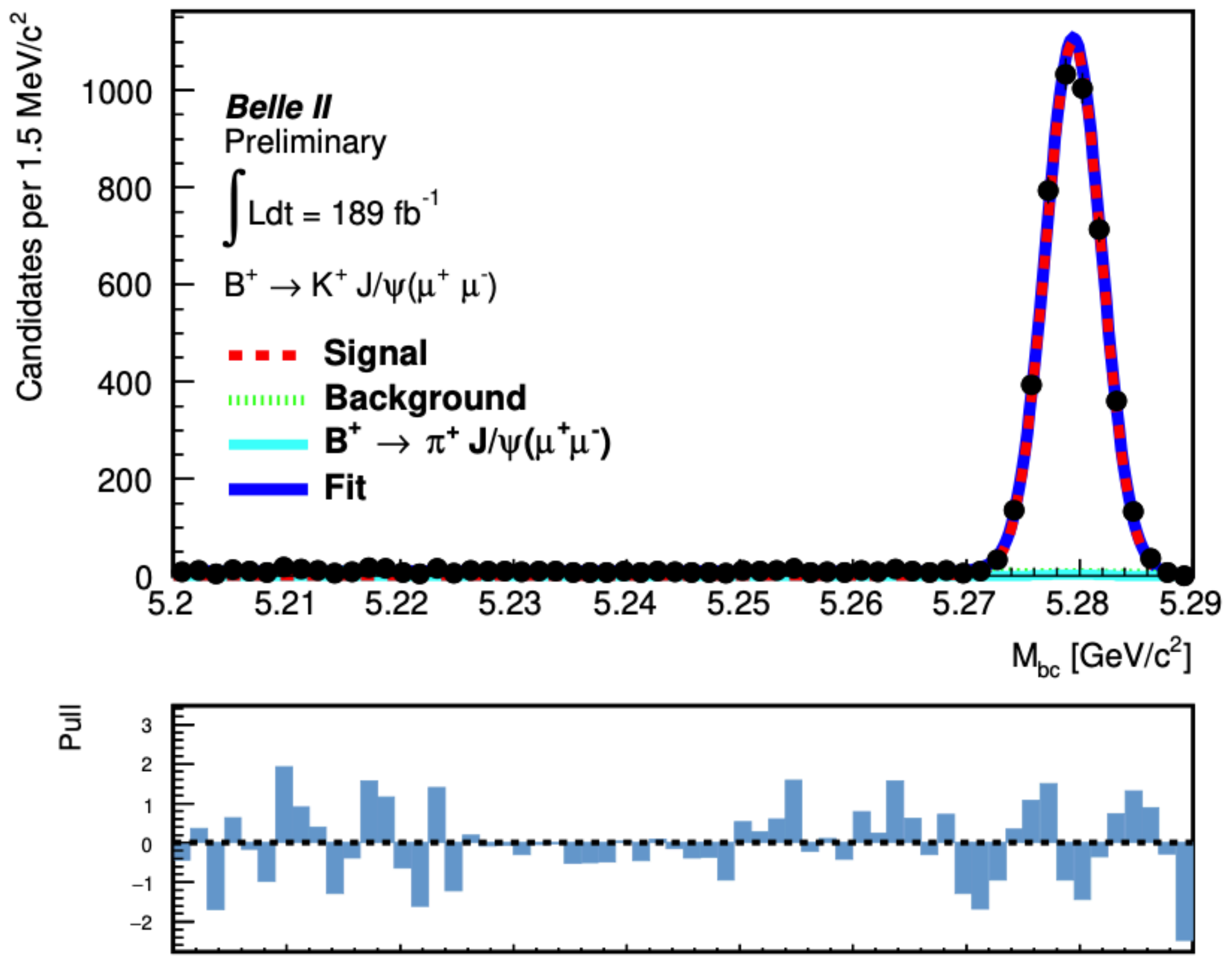


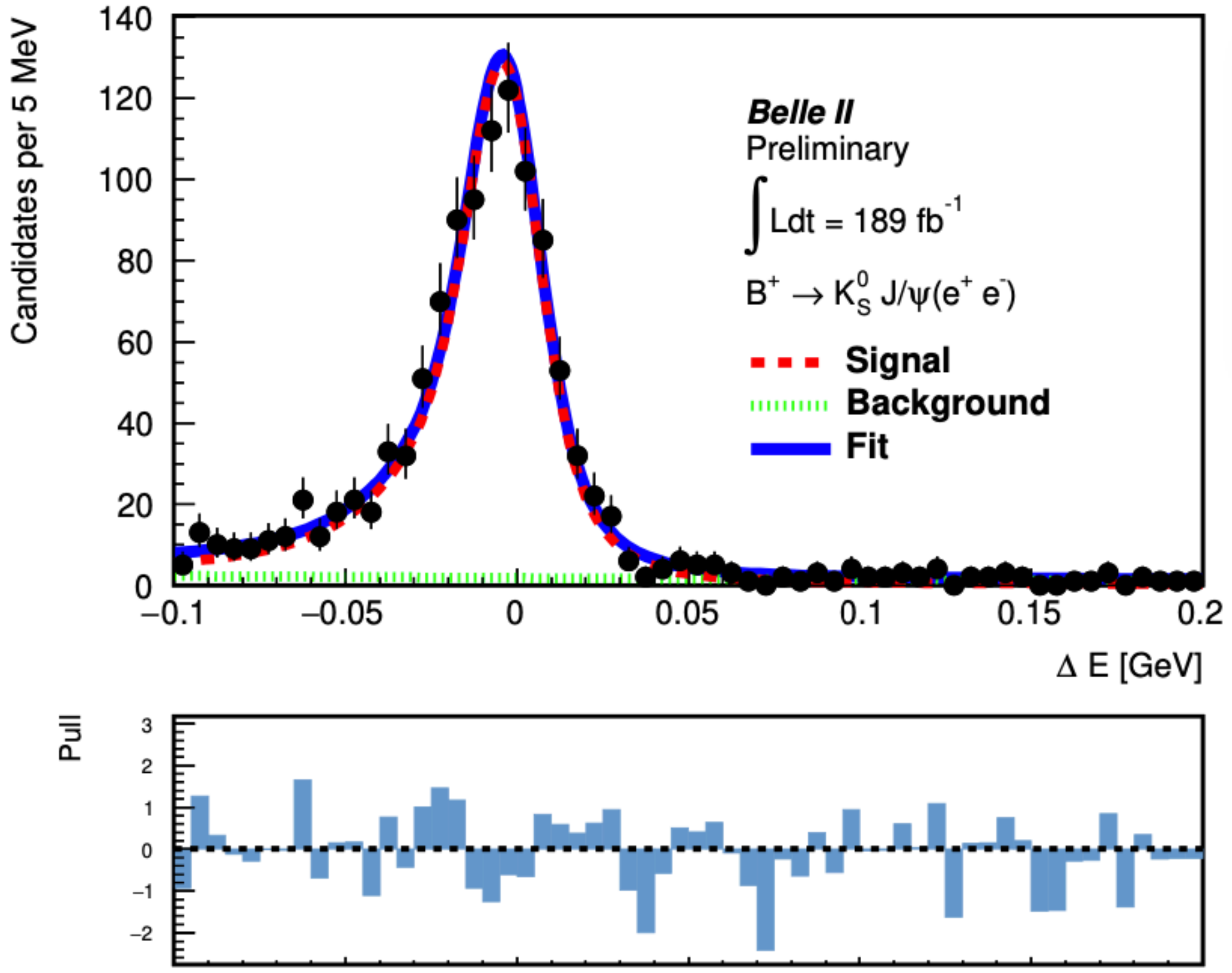
- Fully resolved final state(s), very pure selection (90-95%) via mass cuts on intermediate resonances ($J/\psi, K^0_S$) and PID criteria on leptons and charged kaons.

- Branching fractions and $r^K_{J/\psi}$ extracted from 2D unbinned ML fit to $\Delta E, M_{bc}$ distributions.

$$M_{bc} = \sqrt{\left(\sqrt{s}/2\right)^2 - |\vec{p}_{B^*}|^2}$$

$$\Delta E = E_{B^*} - \sqrt{s}/2$$





[*] Belle, JHEP 03 (2021) 105, **711 fb^{-1}**

	Belle II (2022)	Belle (2021)
$r^{K^+}_{J/\psi}$	1.009 ± 0.022 (stat.)± 0.008 (sys.)	0.994 ± 0.011 (stat.)± 0.010 (sys.)
$r^{K^0_S}_{J/\psi}$	1.042 ± 0.042 (stat.)± 0.008 (sys.)	0.993 ± 0.015 (stat.)± 0.010 (sys.)

- In agreement w/ Belle [*] and w/ the SM.

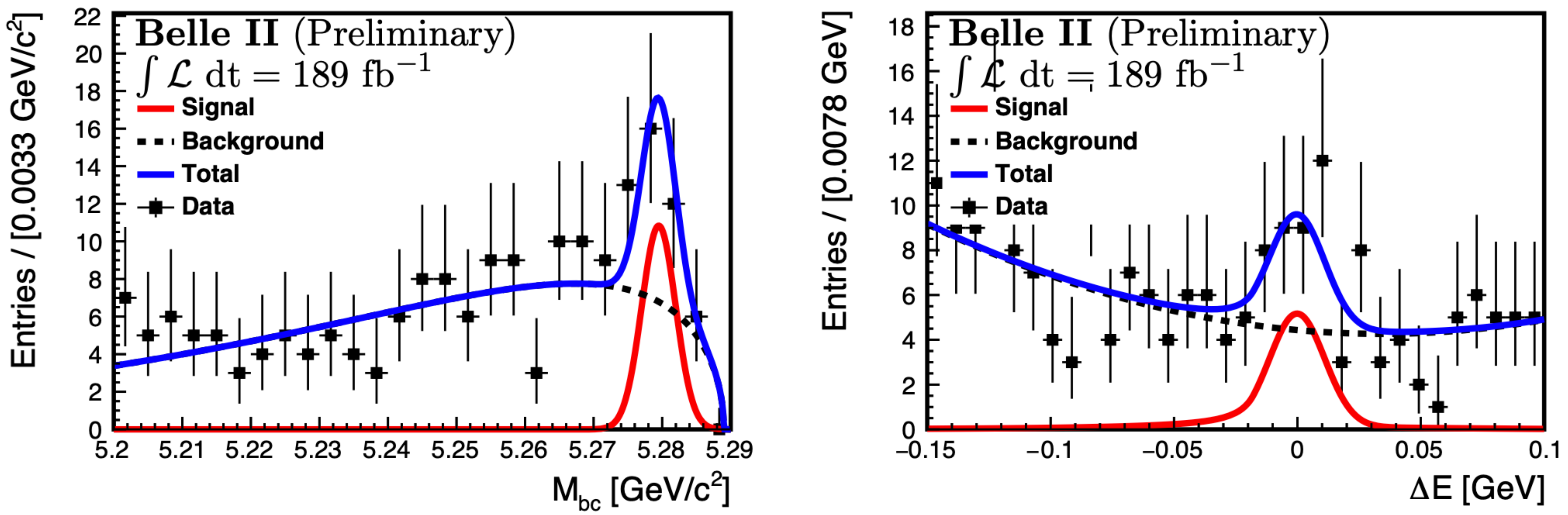
- Uncertainties due to lepton ID reduced wrt. Belle by a factor ~2.

Preparing for $R(K^*)$: rediscovery of $B \to K^*(892)\ell^+\ell^-$

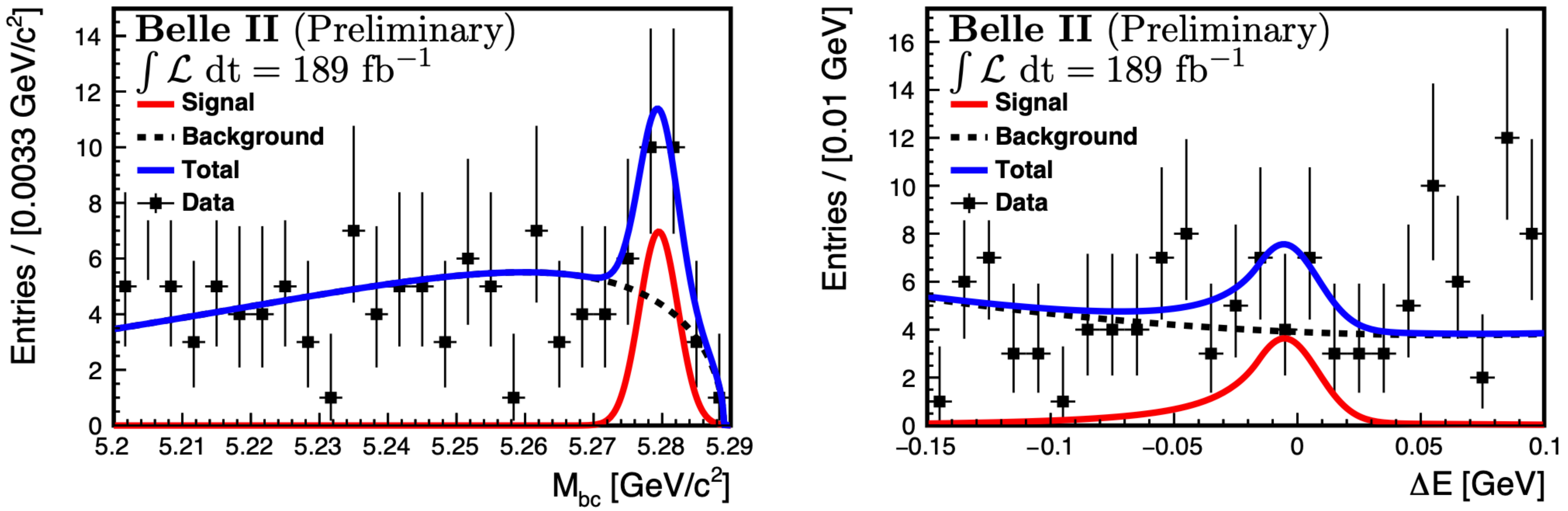
- Measure the branching fraction of $B \to K^*(892)\ell^+\ell^-$ in three K^* decay modes: 1) $K^{*0} \to K^+\pi^-$, 2) $K^{*+} \to K^0_S\pi^+$, 3) $K^{*+} \to K^+\pi^0$ [+ c.c.]

Belle II arXiv: 2206.05946, **189 fb^{-1}**

$B \to K^*\mu^+\mu^-$



$B \to K^*e^+e^-$



- Dilepton mass (q^2) window vetoes to reject $J/\psi, \psi(2S)$ charmonium resonances and γ conversions.
- Use BDT based on event shape, kinematics and vertexing to reject continuum and $B\bar{B}$ backgrounds $\to$ 98% bkg. rej. @ 65-70% sig. eff.
- 2D unbinned ML fit to $\Delta E, M_{bc}$ distributions.
- Results compatible w/ world averages (PDG):

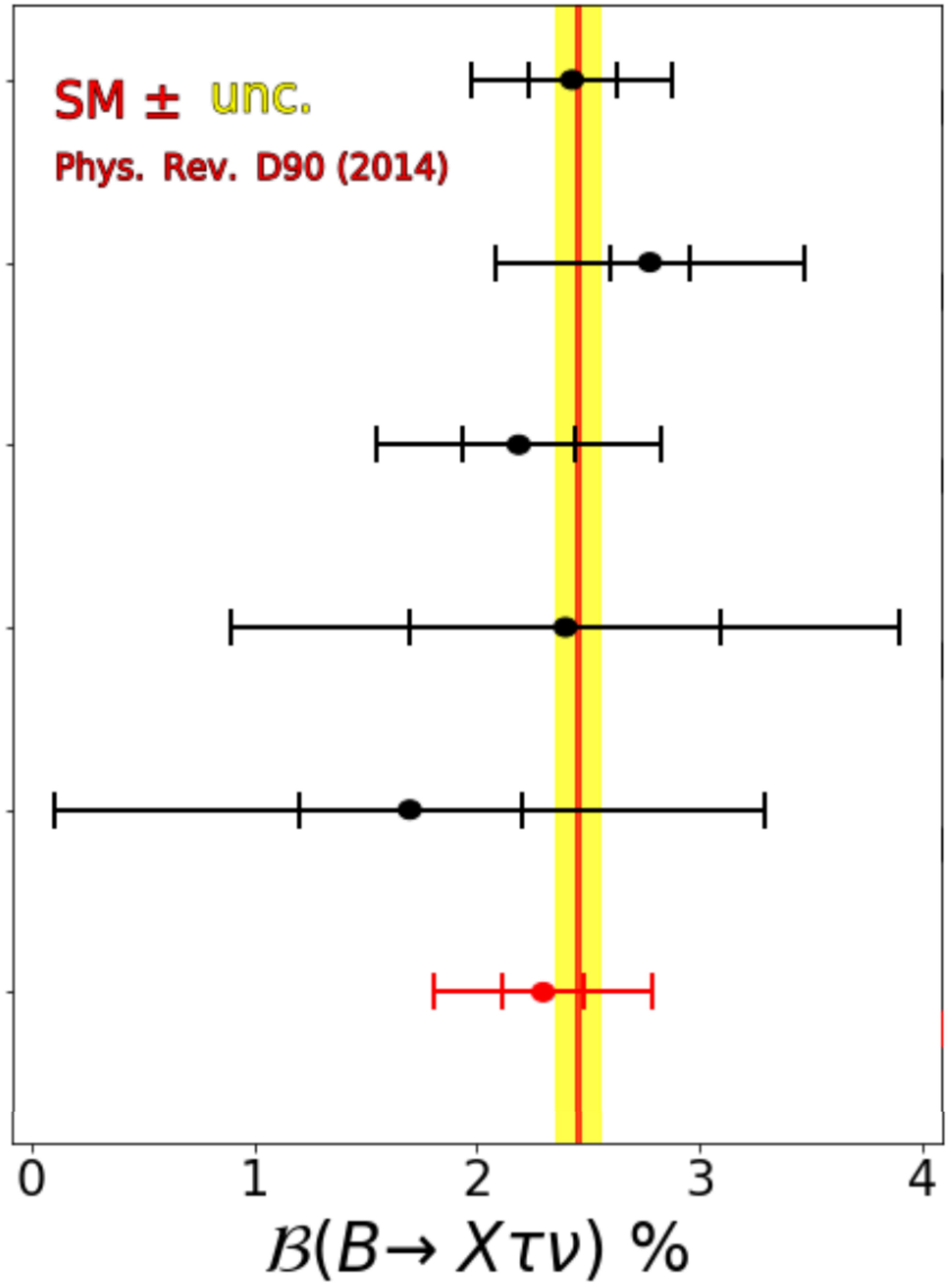
$$\mathcal{B}(B \to K^*\mu^+\mu^-) = (1.19 \pm 0.31^{+0.08}_{-0.07}) \times 10^{-6},$$
$$\mathcal{B}(B \to K^*e^+e^-) = (1.42 \pm 0.48 \pm 0.09) \times 10^{-6},$$
$$\mathcal{B}(B \to K^*\ell^+\ell^-) = (1.25 \pm 0.30^{+0.08}_{-0.07}) \times 10^{-6}.$$

Summary and conclusions

- Recent, world-leading results of Belle II were showcased:
  - Most precise LFU test with inclusive semileptonic B decays ($R(X_{e/\mu})$).
  - Most stringent upper limits on invisible scalar boson production in LFV $\tau \to \ell\alpha$ decays.
- Exciting new results for LF(U)V ahead for Belle II, with both:
  - Increased dataset size (critical for $b \to s\ell\ell$).
  - Ongoing improvements in experimental techniques for lepton identification to reduce systematic uncertainties.

Backup material

$R(X)$ at LEP and theoretical expectations



ALEPH
R. Eur. Phys. J. C (2001)

OPAL
Phys. Lett. B500 (2001)

DELPHI
Phys. Lett. B496 (2000)

L3
Phys. Lett. B332 (1994)

L3
Z. Phys. C71 (1996)

Average
Phys. Rev. D 98, 030001 (2018)

$\mathscr{B}(B \to X_c \tau\nu)_{SM} = (2.45 \pm 0.10)\ \%$
Phys. Rev. D 90(3), 034021 (2014)

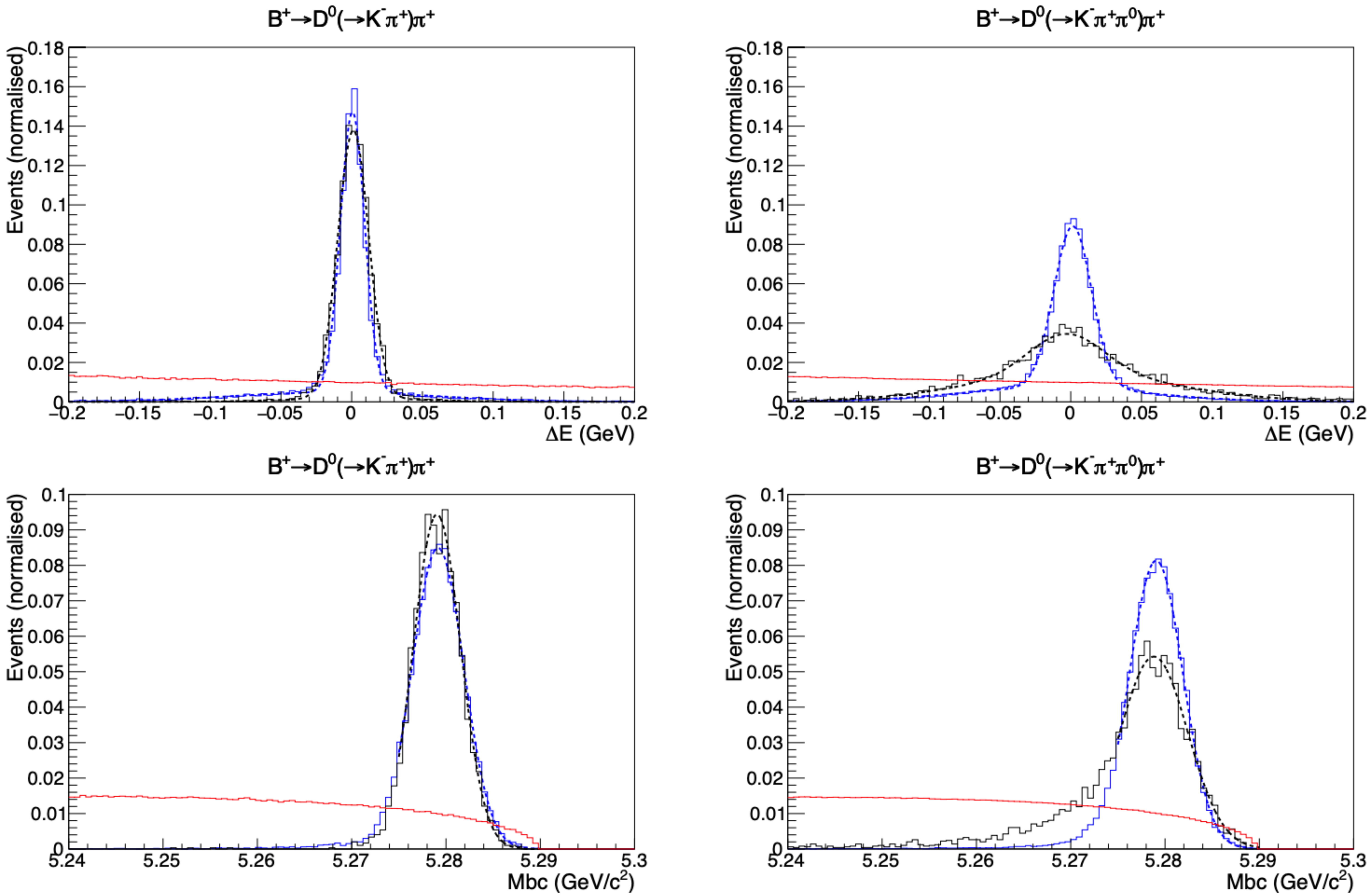
$R(X_c)_{SM} = 0.223 \pm 0.004$
Phys. Rev. D 92, 054018 (2015)

$\langle \mathscr{B} \rangle = (2.41 \pm 0.23)\,\%$, quoted as the average rate of an admixture of b-flavoured hadrons to decay semileptonically to $X\tau$

Beam-energy constrained variables @ B-factories

The Belle II Physics Book, *PTEP* 2020 (2020) 2, 029201 (erratum)

$$M_{bc} = \sqrt{\left(\sqrt{s}/2\right)^2 - |\vec{p}_{B*}|^2}$$



$$\Delta E = E_{B*} - \sqrt{s}/2$$

Fig. 42: ΔE and $M_{\rm bc}$ distributions for $B^+ \to [D^0 \to K^-\pi^+(\pi^0)]\pi^+$ simulated events in Belle II (*blue*) and comparison with Belle (*black*). The red curve shows the distribution for continuum background. Beam background is included in the simulation.