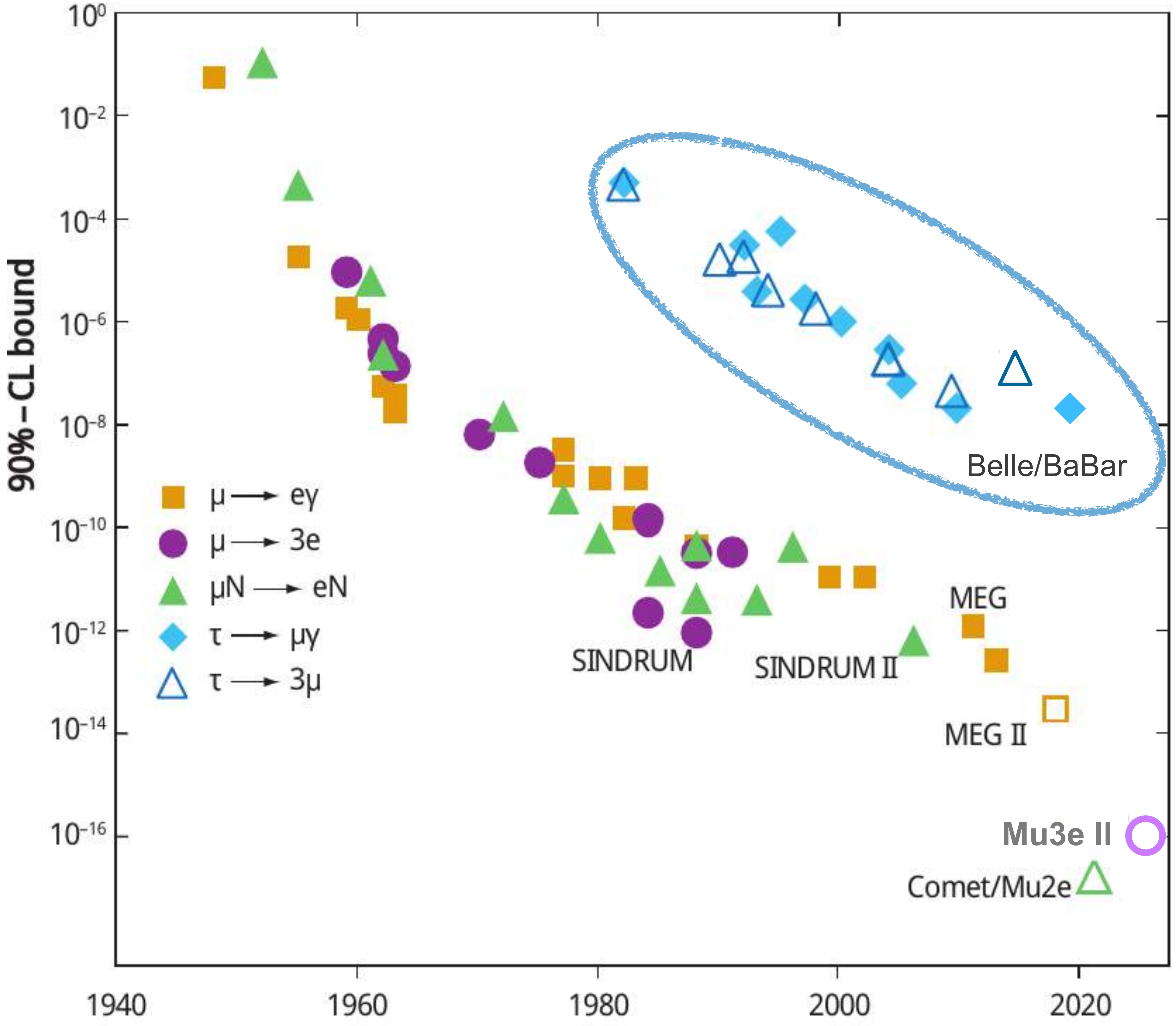
LFU and CLFV at Belle II

CLFV2023 Heidelberg, 21.06.2023

Francesco Tenchini
on behalf of the Belle II collaboration

Introduction

- CLFV is a powerful probe of NP → observation is unambiguous sign of BSM.



- Muon experiments have placed extremely tight constraints on CLFV over the years → no discovery yet...
- **Could CLFV be found in tau decays?**
- Also hinted by anomalies e.g. $R(D^{(*)})$
- Not as simple as muons - taus are short lived, you cannot form a tau beam.
- Historically done at e^+e^- colliders.

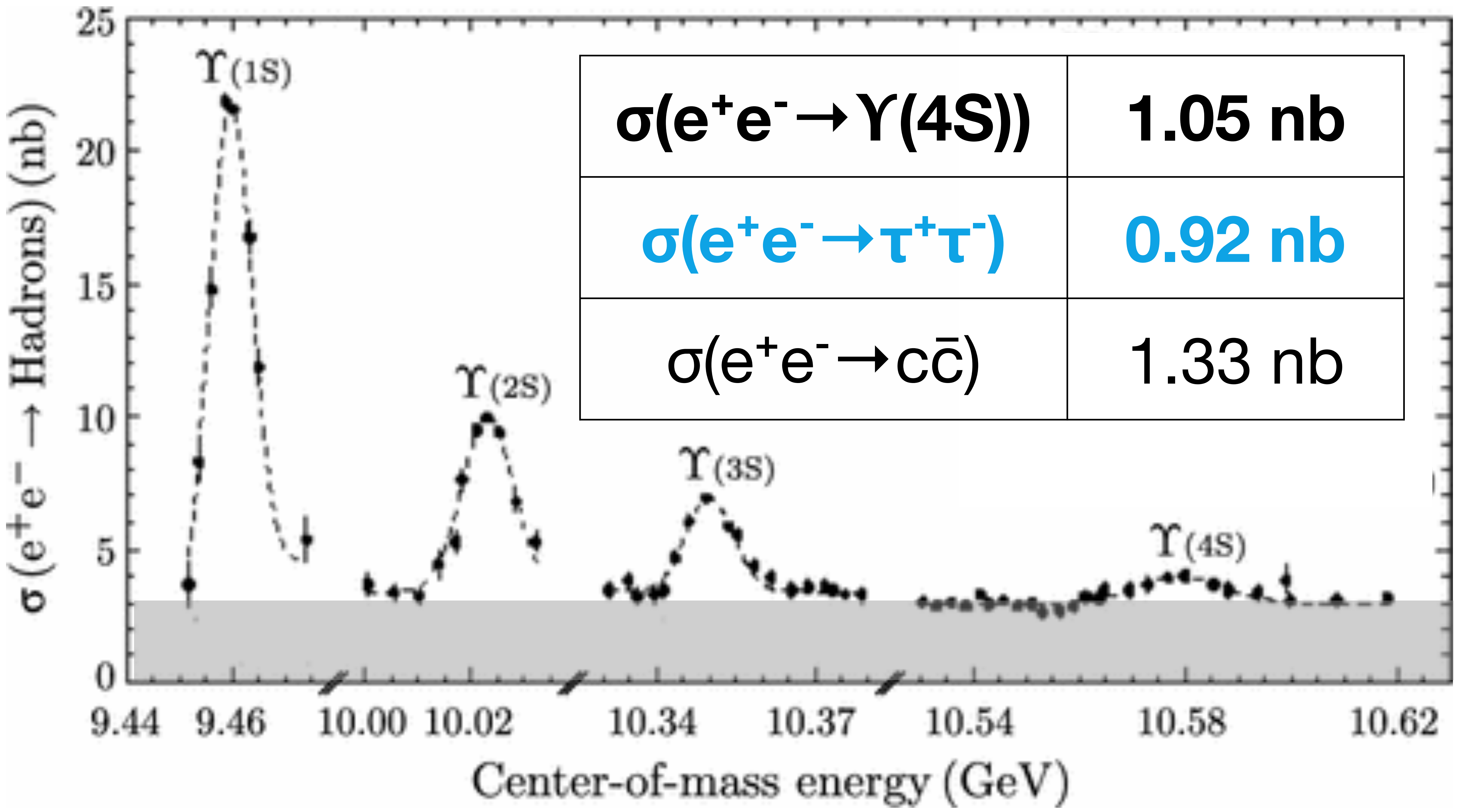
adapted from Ann.Rev.Nucl.Part.Sci. 58 (2008) 315-341

Talk outline

- SuperKEKB and Belle II
- CLFV and precision measurements with τ leptons
- LFU in charged currents ($B \to X\ell\nu$)
- LFU in neutral currents ($B \to K^{(*)}\ell\ell$)

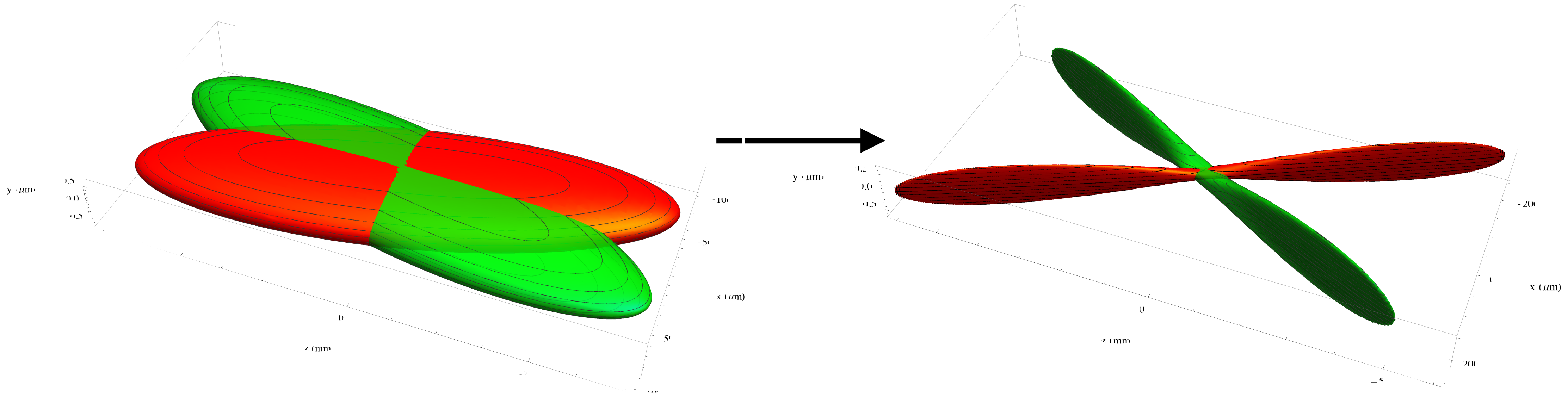
SuperKEKB at KEK, Tsukuba

- **B-Factory** colliding $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ at $\sqrt{s}$ = 10.58 GeV



$\sigma(e^+e^- \to \Upsilon(4S))$	**1.05 nb**
$\sigma(e^+e^- \to \tau^+\tau^-)$	**0.92 nb**
$\sigma(e^+e^- \to c\bar{c})$	1.33 nb

- Major upgrade to KEKB with unprecedented design luminosity (**6x10^{35} cm^{-2} s^{-1}**).
  - **x30** of KEKB with higher beam current and new nano-beam collision scheme (aiming for **~50 nm** beam spot).



- Provides large, relatively clean samples of **B-mesons**, **D-mesons** and **τ-leptons**.

Belle II TDR, arXiv:1011.0352

Belle II detector

- Successor of Belle with

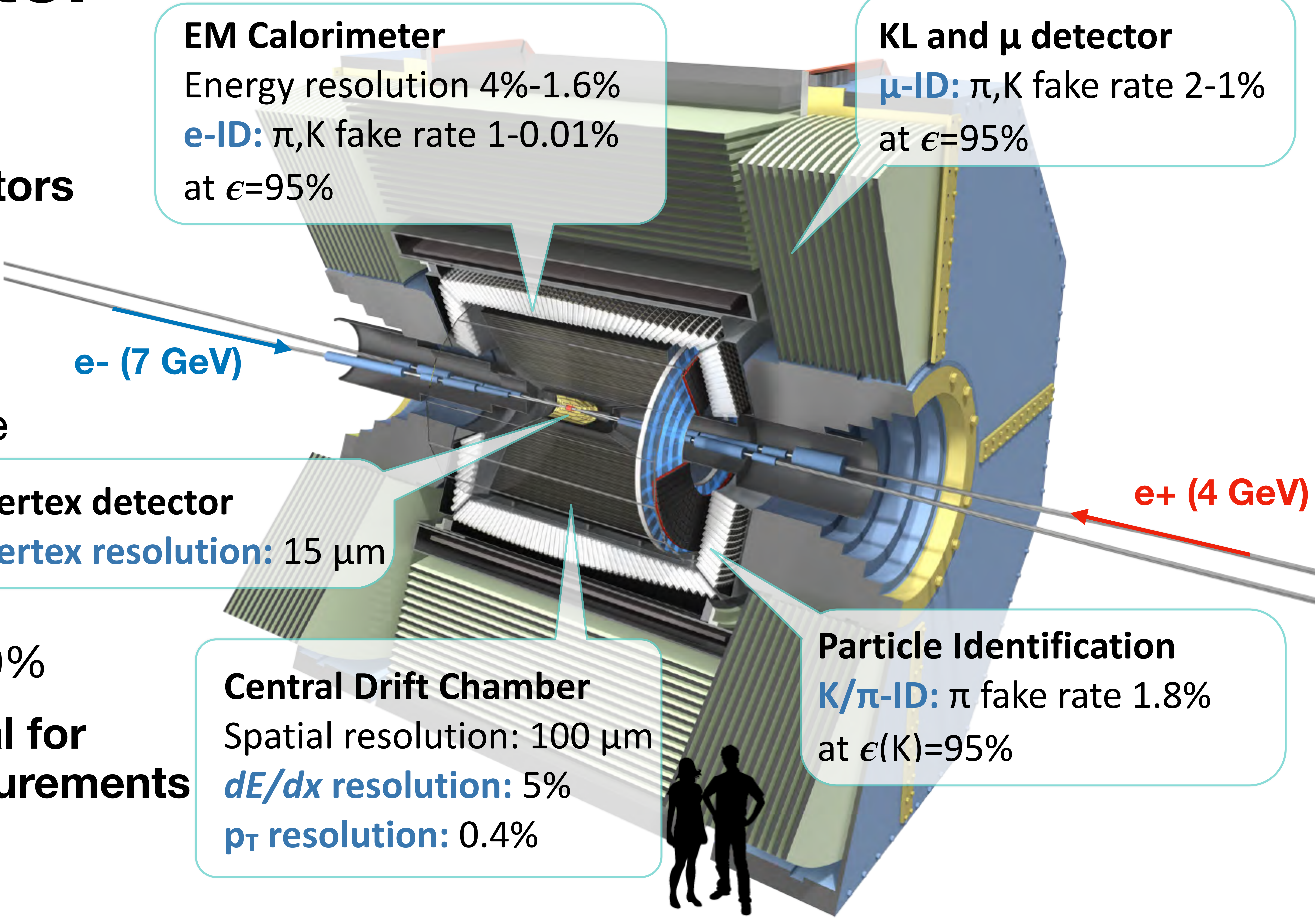
  → **Upgraded sub-detectors and trigger**

  → **Improved vertex reconstruction**

- Comparable performance in **electron and muon reconstruction.**

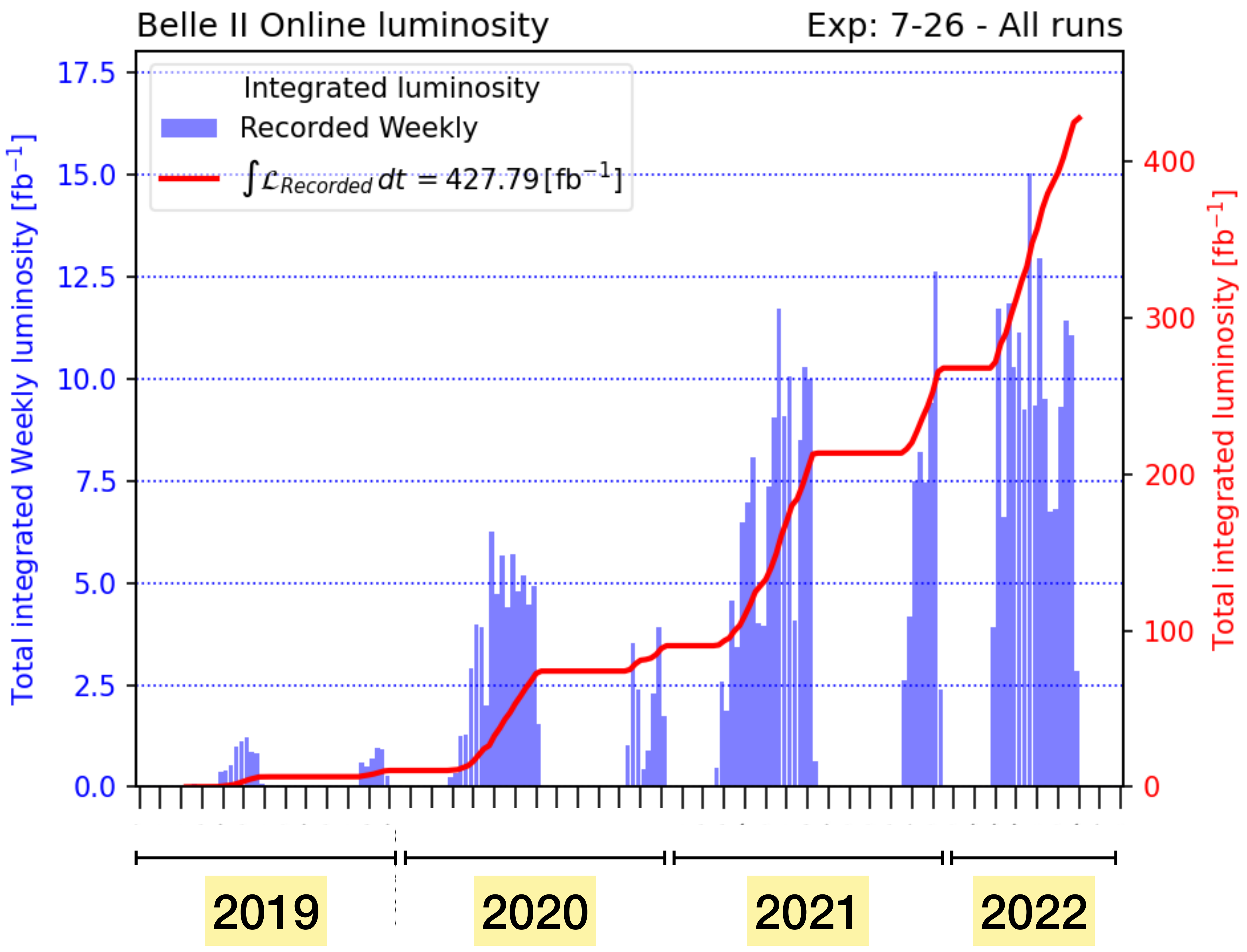
- Solid angle coverage >90%

  → **High hermeticity ideal for missing energy measurements**



Belle II timeline

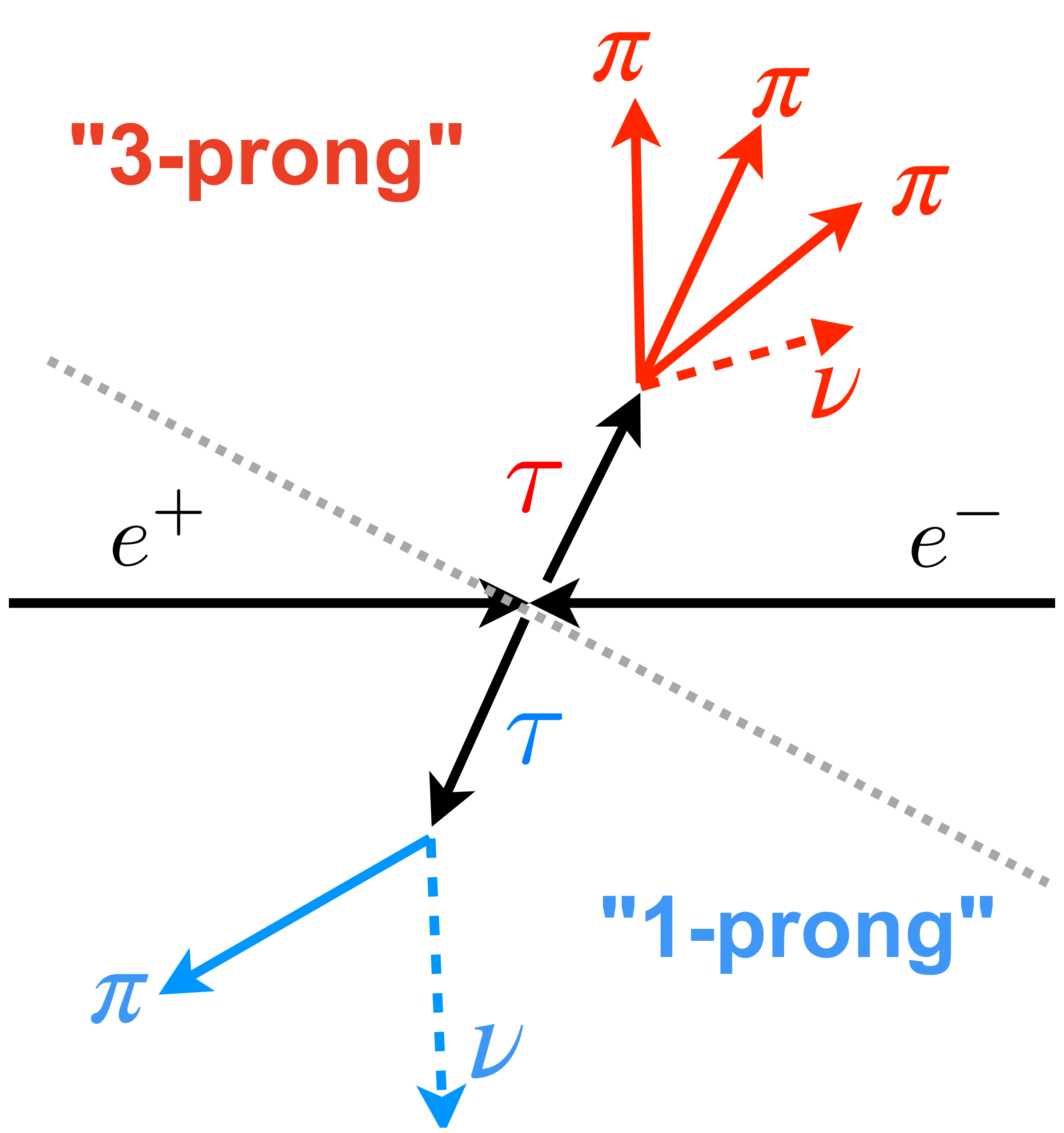
- **Full detector operation started in 2019.**
- Achieved **world record** luminosity of **$4.7\text{x}10^{34}$ cm^{-2} s^{-1}** (June 8th, 2022)
  - **x2** Belle instantaneous luminosity
  - **Aiming one order higher**



- Collected **424 fb^{-1}** before **summer 2022.**
  - **189 fb^{-1}** used for the analyses shown here.
- Long Shutdown 1 (LS1) to replace PXD + detector maintenance and improvement → aiming to restart in winter 2023.
- **LS1 dataset** already matches BaBar **(~500 fb^{-1})** and challenges Belle **(~1 ab^{-1})** thanks to improved reconstruction performance.

The potential of τ measurements

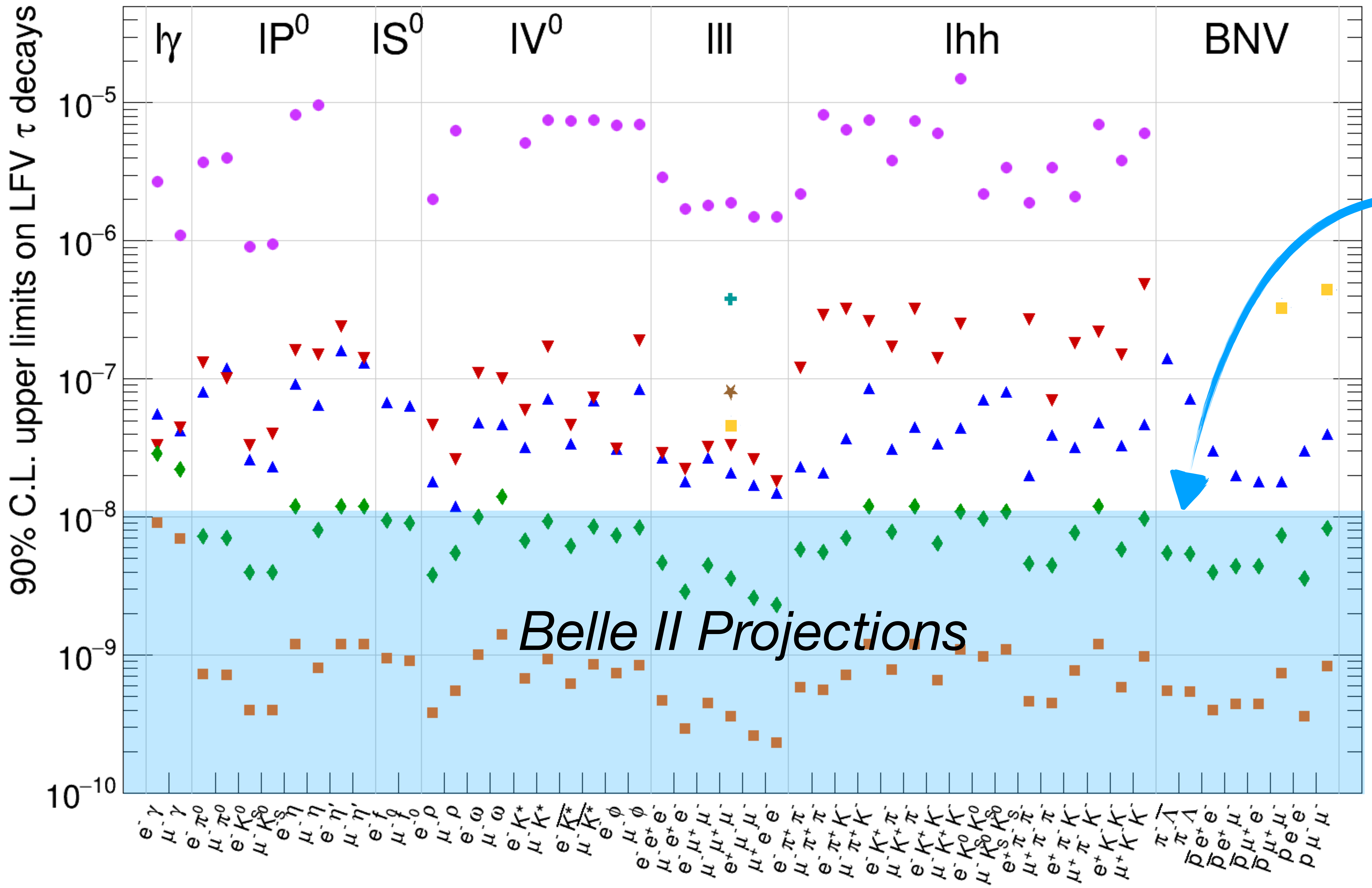
- B-factories are ideal for missing energy channels.
- Well known initial state: $E^*_\tau = E^*_{beam} = \sqrt{s}/2$
- Excellent control over invisible particles: **missing energy/mass can be precisely determined.**
- Decay products are well separated along the event thrust:



$$|\vec{T}| = max\left(\sum_i \frac{\vec{p_i}\cdot\hat{T}}{|p_i|}\right)$$

- Heaviest lepton and the only one that decays into hadrons.
- Numerous possible LFV and even LNV couplings:
  - $\tau \to \ell\gamma$ (radiative)
  - $\tau \to \ell\ell\ell$ (leptonic)
  - $\tau \to \ell h(\ldots)$ (semileptonic)
- **Many ways to test the SM.**

History of CLFV in the τ sector



- Progress in the CLFV search was mainly driven by Belle and BaBar.

Limits approach the region sensitive to NP.

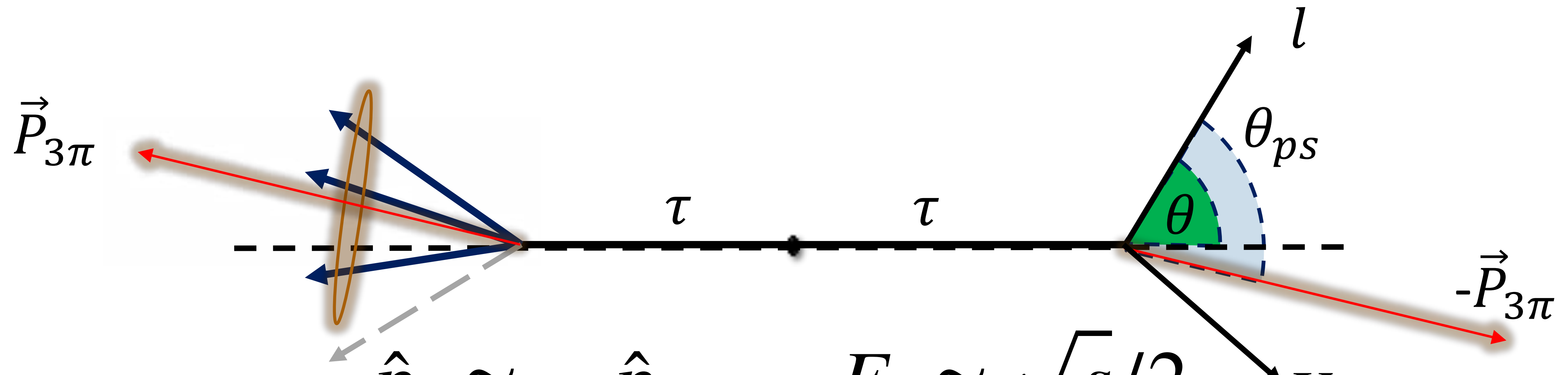
- Belle II can probe this region with **a few ab^{-1}** - what about now?

arXiv:2203.14919

PRL 130, 181803 (2023) | 63 fb⁻¹

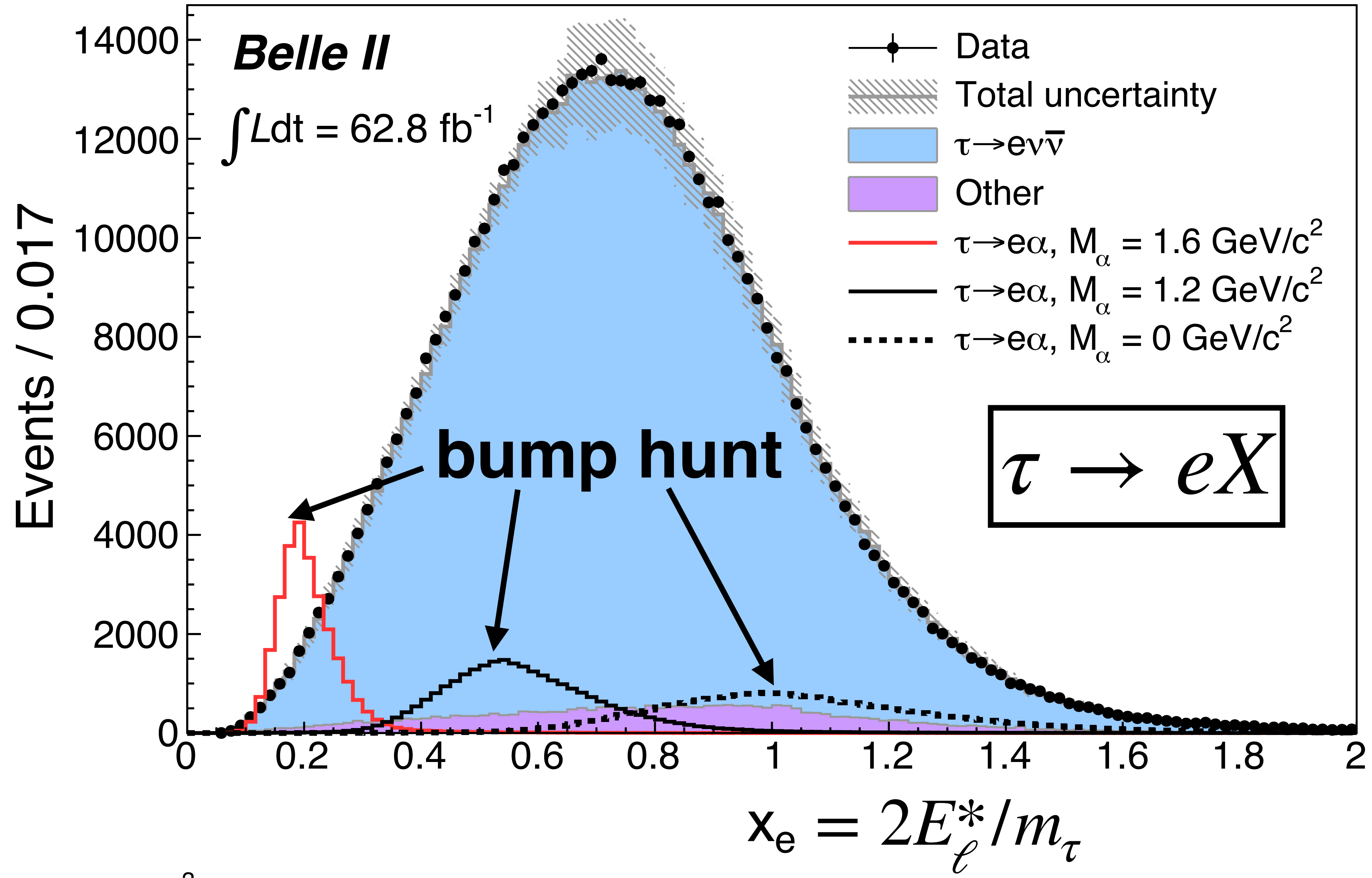
New searches: $\tau \to \ell X$

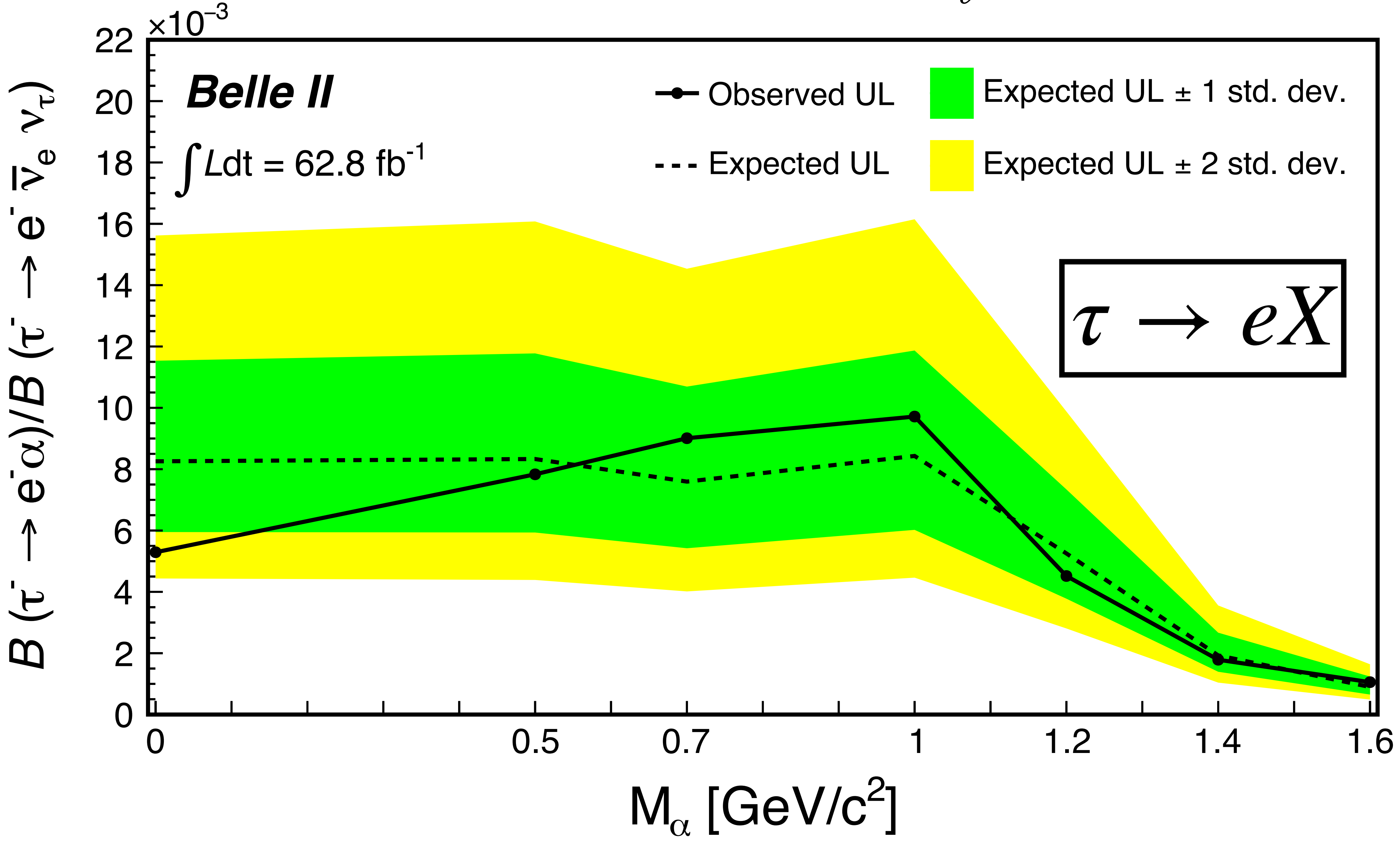
- Invisible LFV particles ("X" or "α") can emerge from NP models e.g. light ALP: JHEP 09 (2021) 173
- Approximate the τ rest frame using $\tau \to 3\pi\nu$:



$$\hat{p}_\tau \approx -\hat{p}_{3\pi}\,,\quad E_\tau \approx \sqrt{s}/2$$

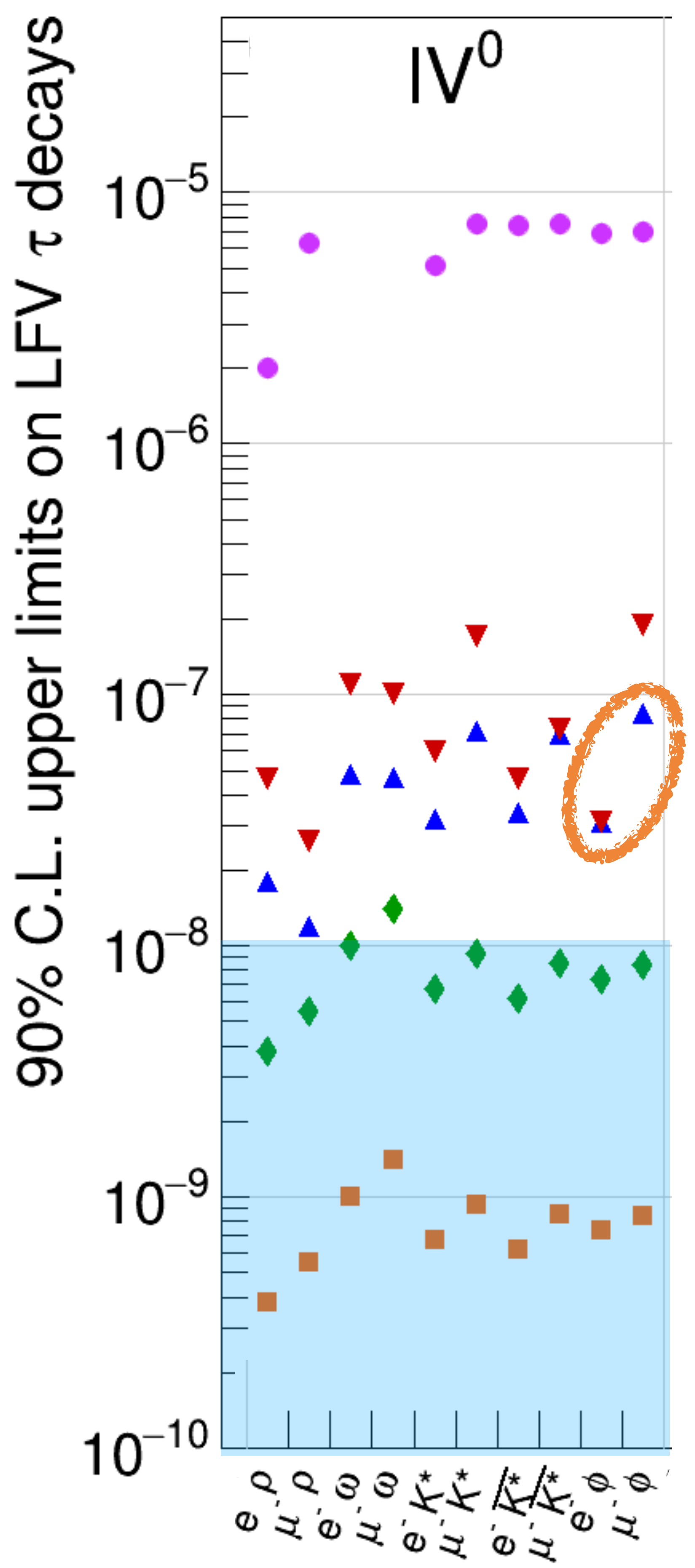
- Bump search over the $\tau \to \ell\bar{\nu}\nu$ spectrum.
- Ratio $\mathscr{B}(\tau \to \ell X)/\mathscr{B}(\tau \to \ell\bar{\nu}\nu)$ allows partial cancellation of systematics (mainly lepton ID).
- **Most stringent** limit, **2.2-14 better** than previous.



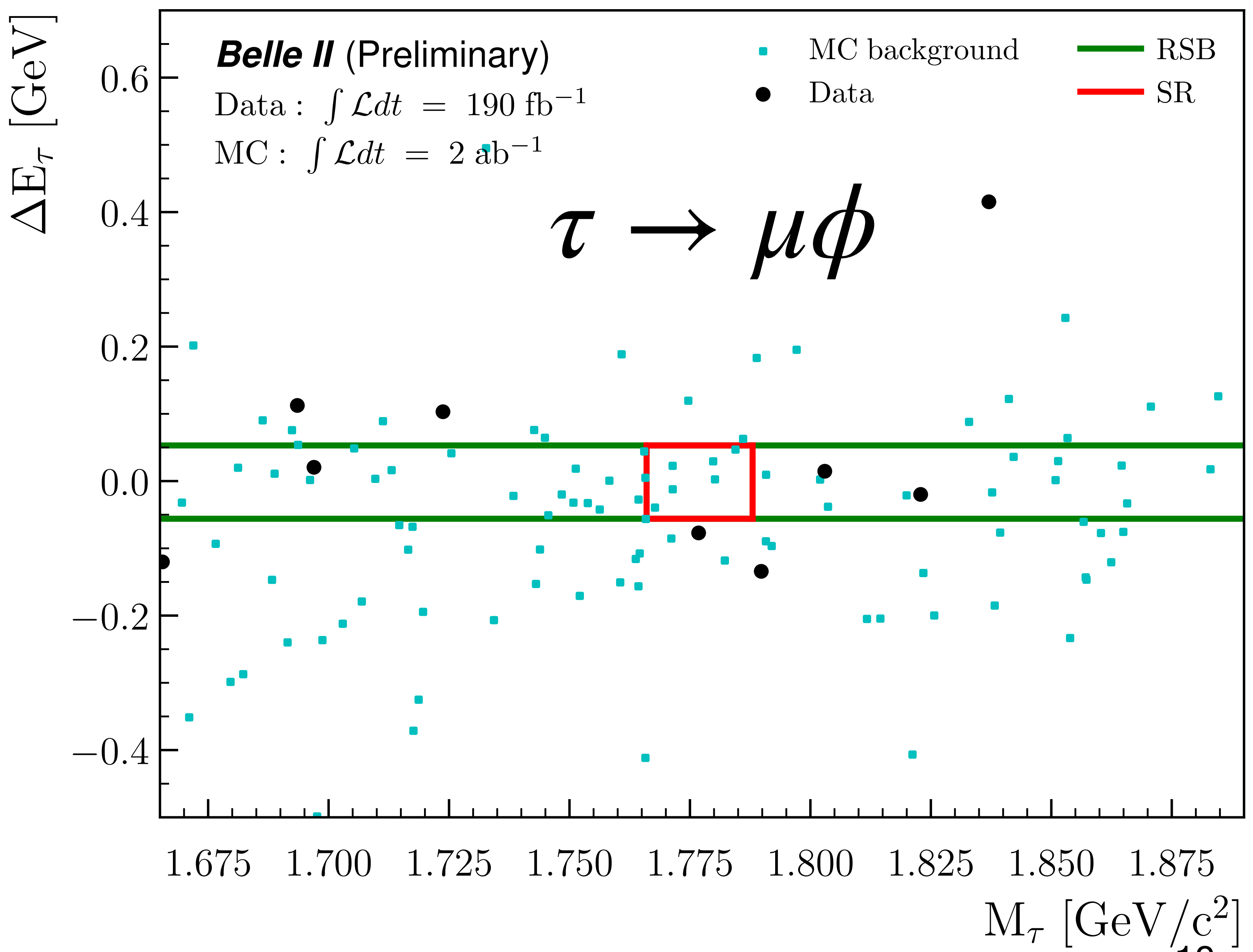


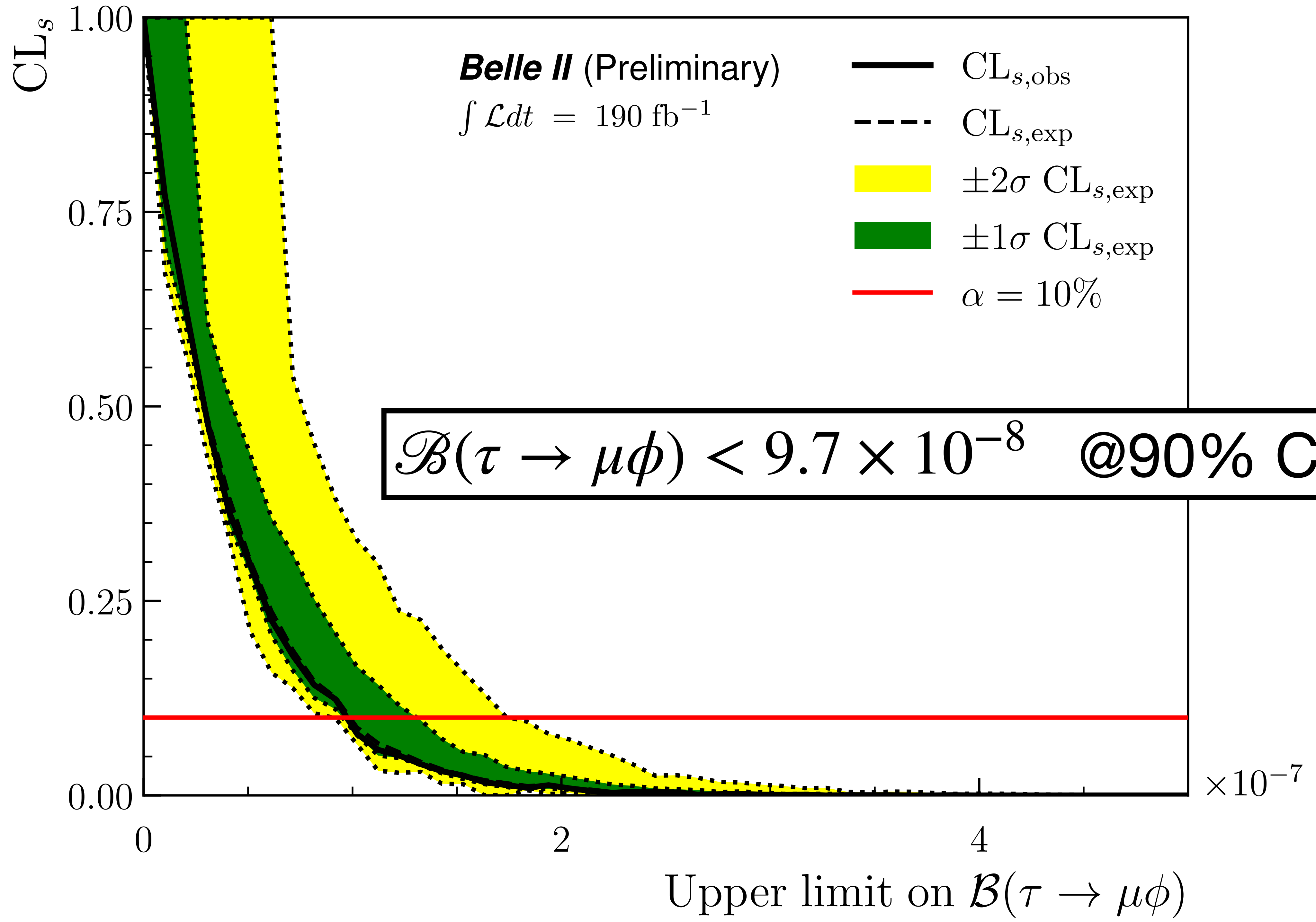
arXiv:2305.04759

Enhancing statistics: $\tau \to \ell\phi$



- Channel favored by models with e.g. vector leptoquarks.
- **Improve Belle efficiency x2** by not reconstructing the other τ: **ε=6.5%(μ)/6.1%(e)**
- Reconstruct $\tau \to \ell\phi(\to K^+K^-)$, suppress background with BDT instead.
- Poisson counting in **signal region (SR)**, expected background from **reduced sidebands (RSB)** in data, scaled with simulations.





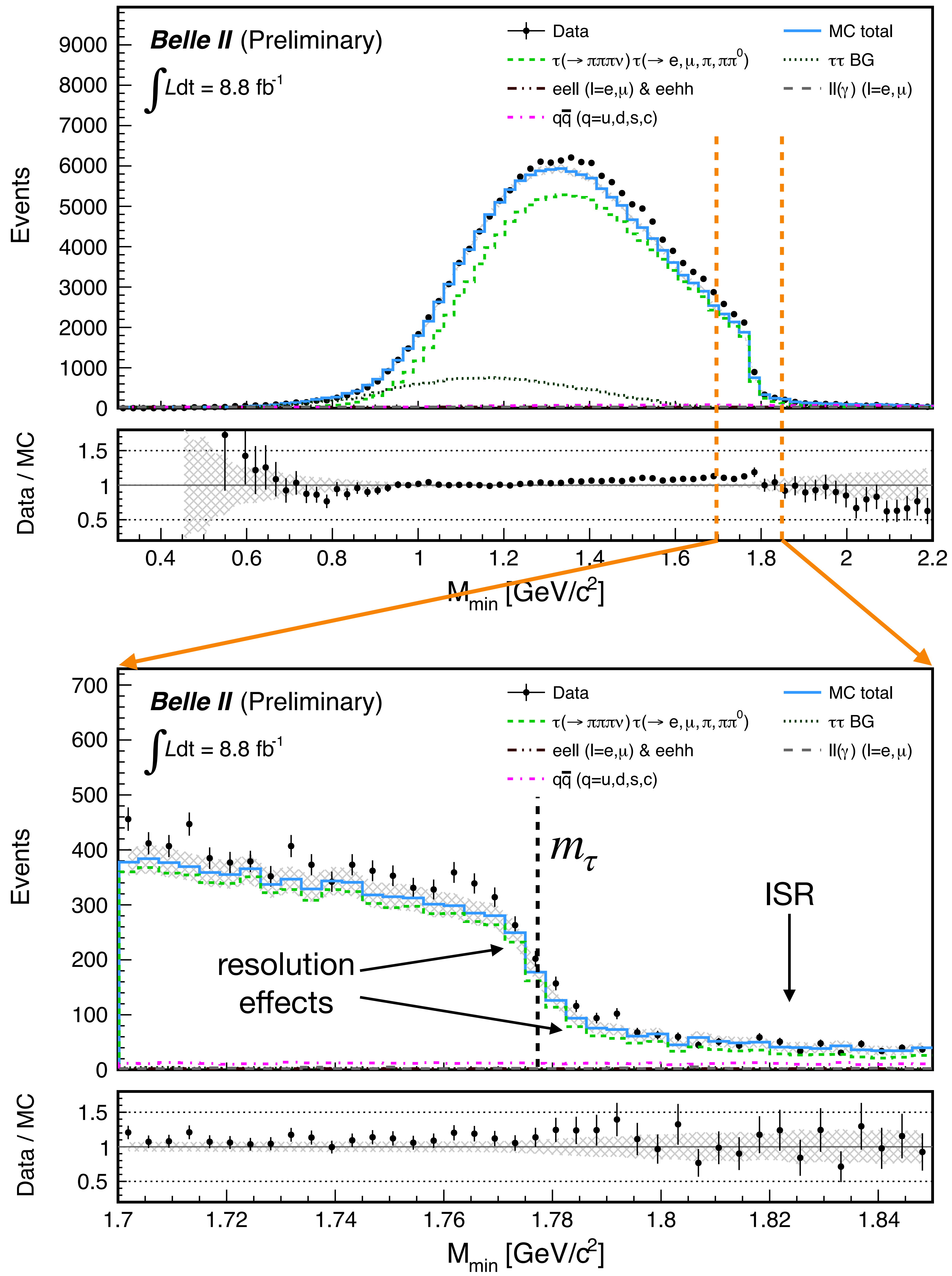
$\mathscr{B}(\tau \to \mu\phi) < 9.7 \times 10^{-8}$ @90% C.L.

Measuring the τ mass

- Precision test of SM properties, important input for LFU tests.
- Reconstruct events into four tracks with $\tau_{tag} \to \ell\nu\bar{\nu}, \pi(\pi^0)\nu$ and $\tau_{sig} \to 3\pi\nu$
- Access $\mathbf{m_\tau}$ with pseudo-mass technique:

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

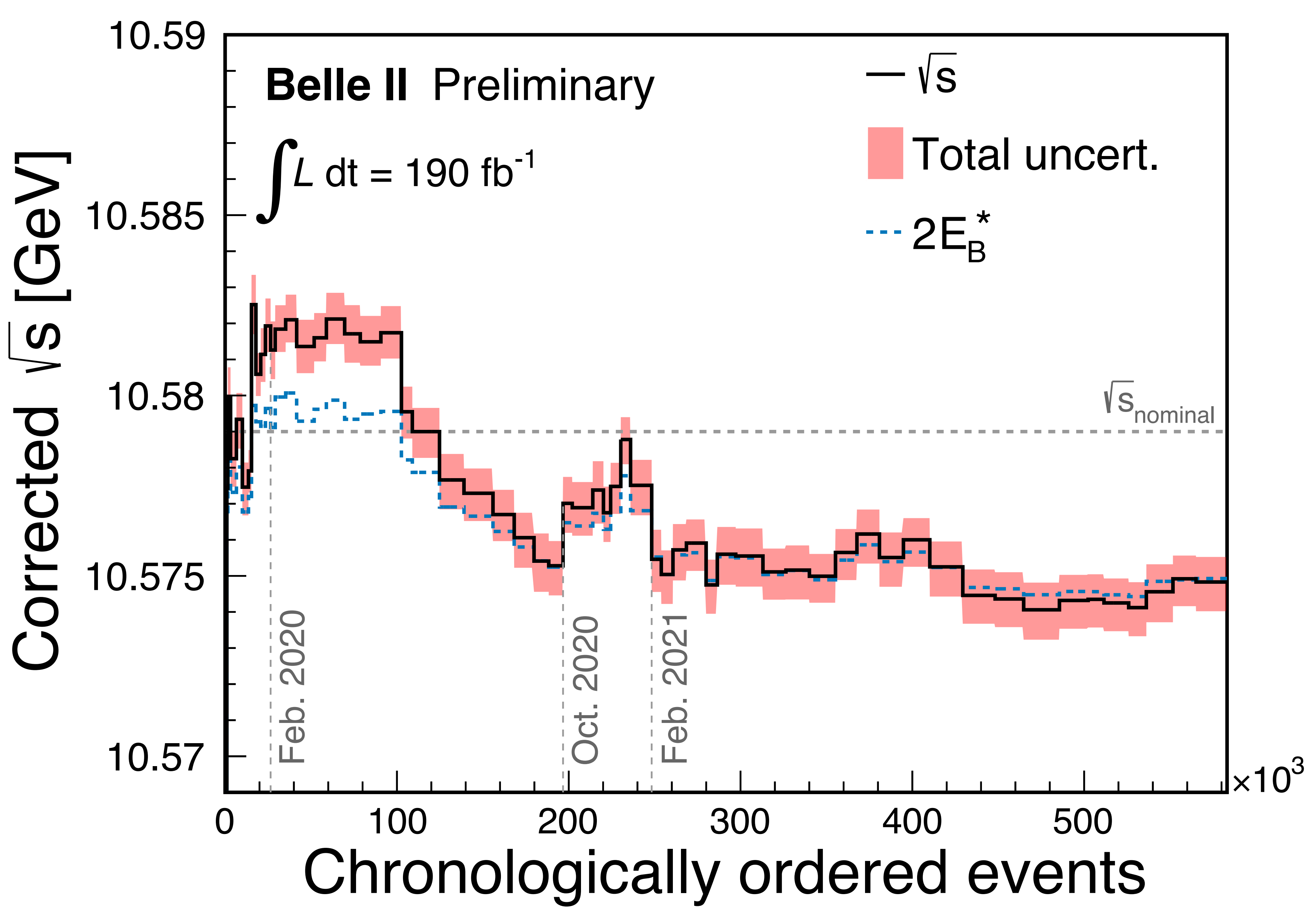
- Fit endpoint with empirical function incorporating smearing from ISR and detector resolution effects.

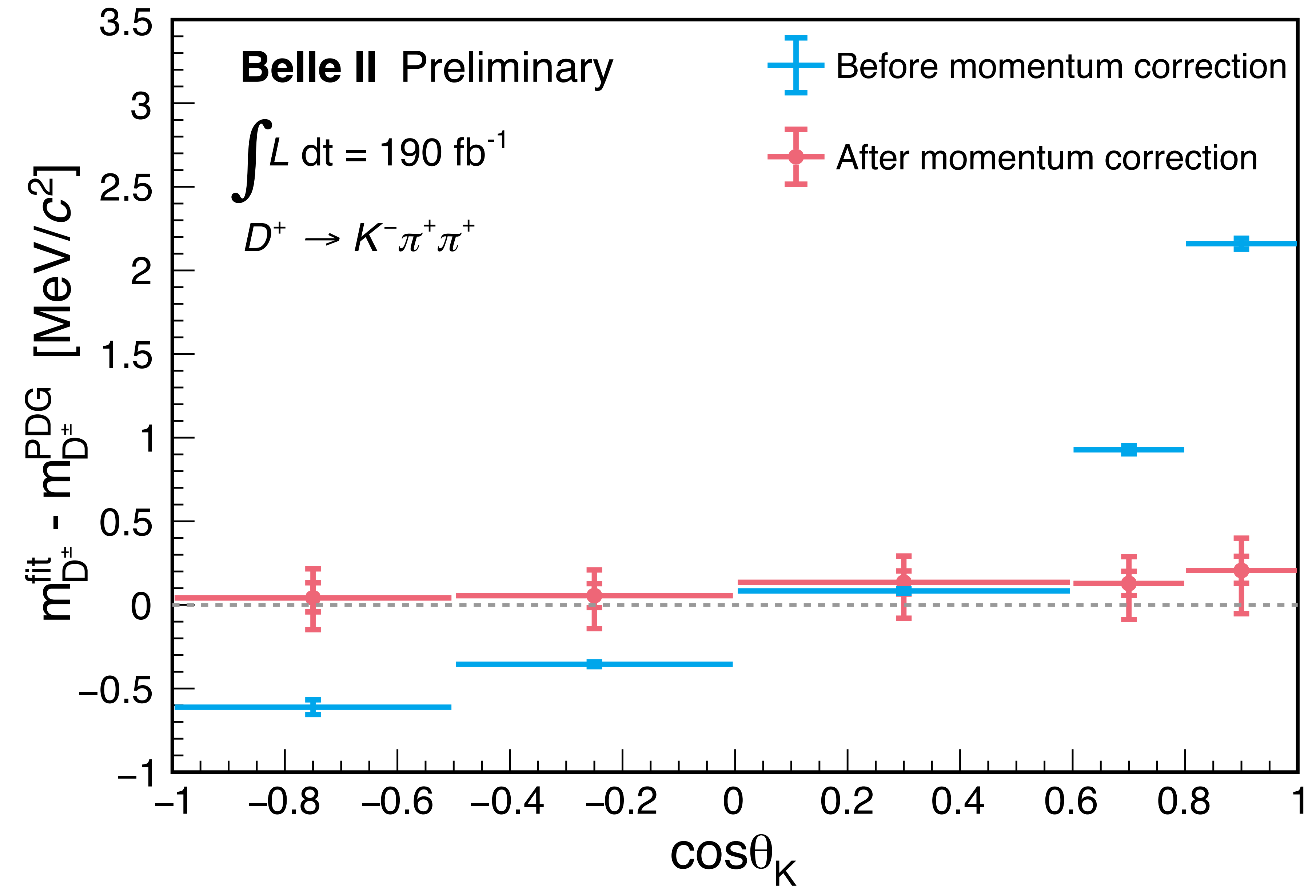


Understanding systematics

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

Source	Uncertainty [MeV/c^2]
Knowledge of the colliding beams:	
Beam-energy correction	0.07
Boost vector	< 0.01
Reconstruction of charged particles:	
Charged-particle momentum correction	0.06
Detector misalignment	0.03
Fit model:	
Estimator bias	0.03
Choice of the fit function	0.02
Mass dependence of the bias	< 0.01
Imperfections of the simulation:	
Detector material density	0.03
Modeling of ISR, FSR and τ decay	0.02
Neutral particle reconstruction efficiency	≤ 0.01
Momentum resolution	< 0.01
Tracking efficiency correction	< 0.01
Trigger efficiency	< 0.01
Background processes	< 0.01
Total	0.11

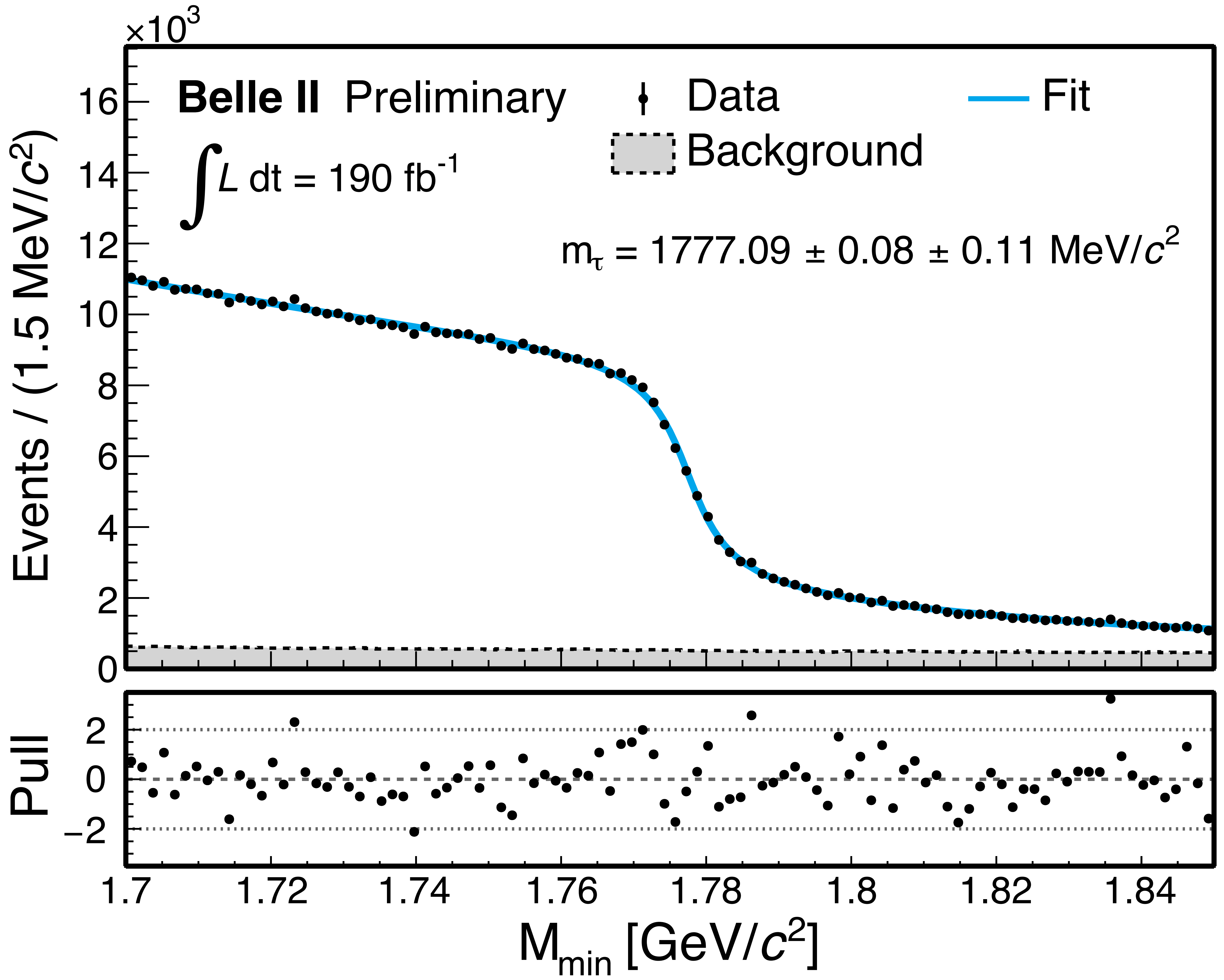


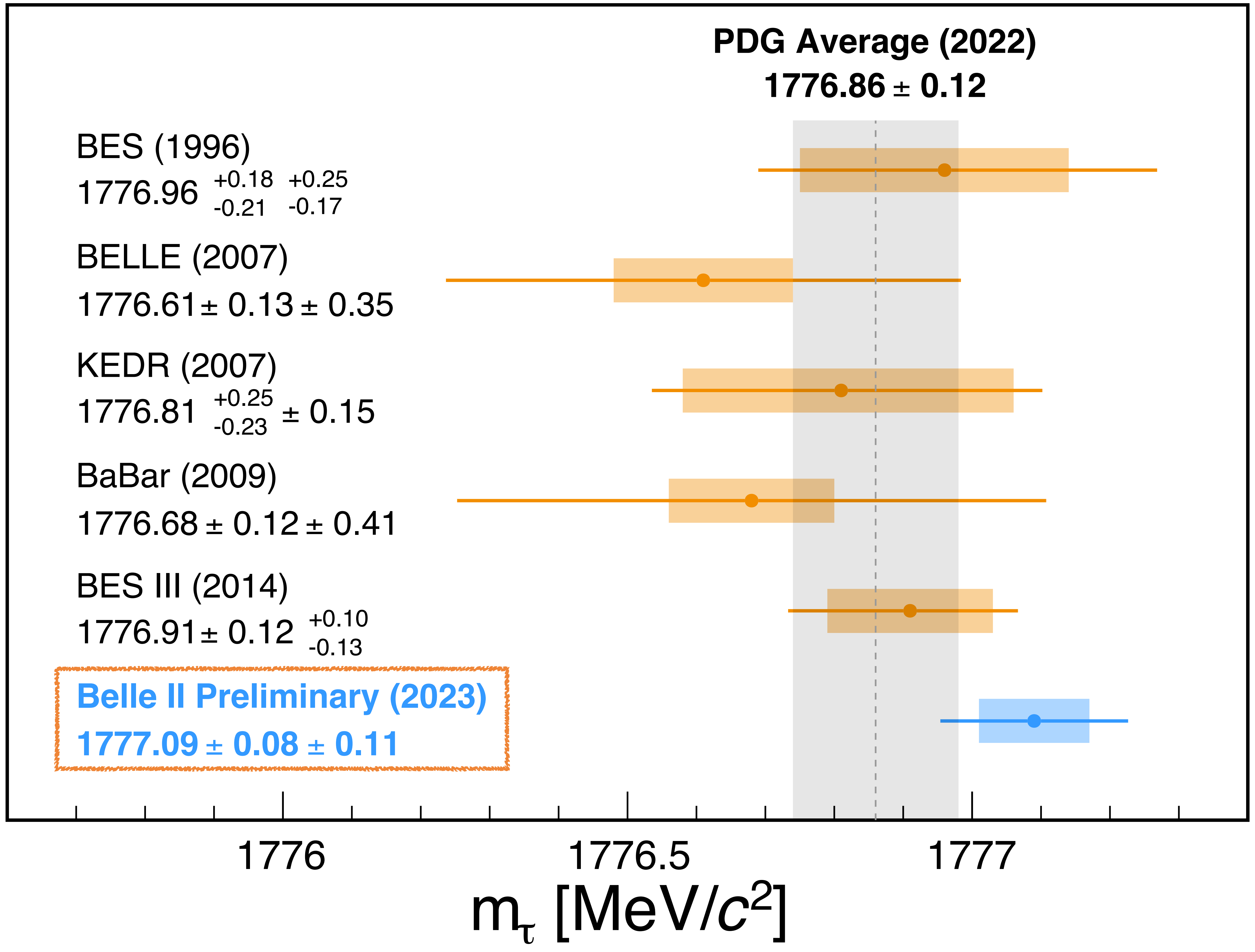


arXiv:2305.19116
Submitted to PRD

World's most precise measurement

- Proof of high-precision capabilities of Belle II.





LFU anomalies in B decays

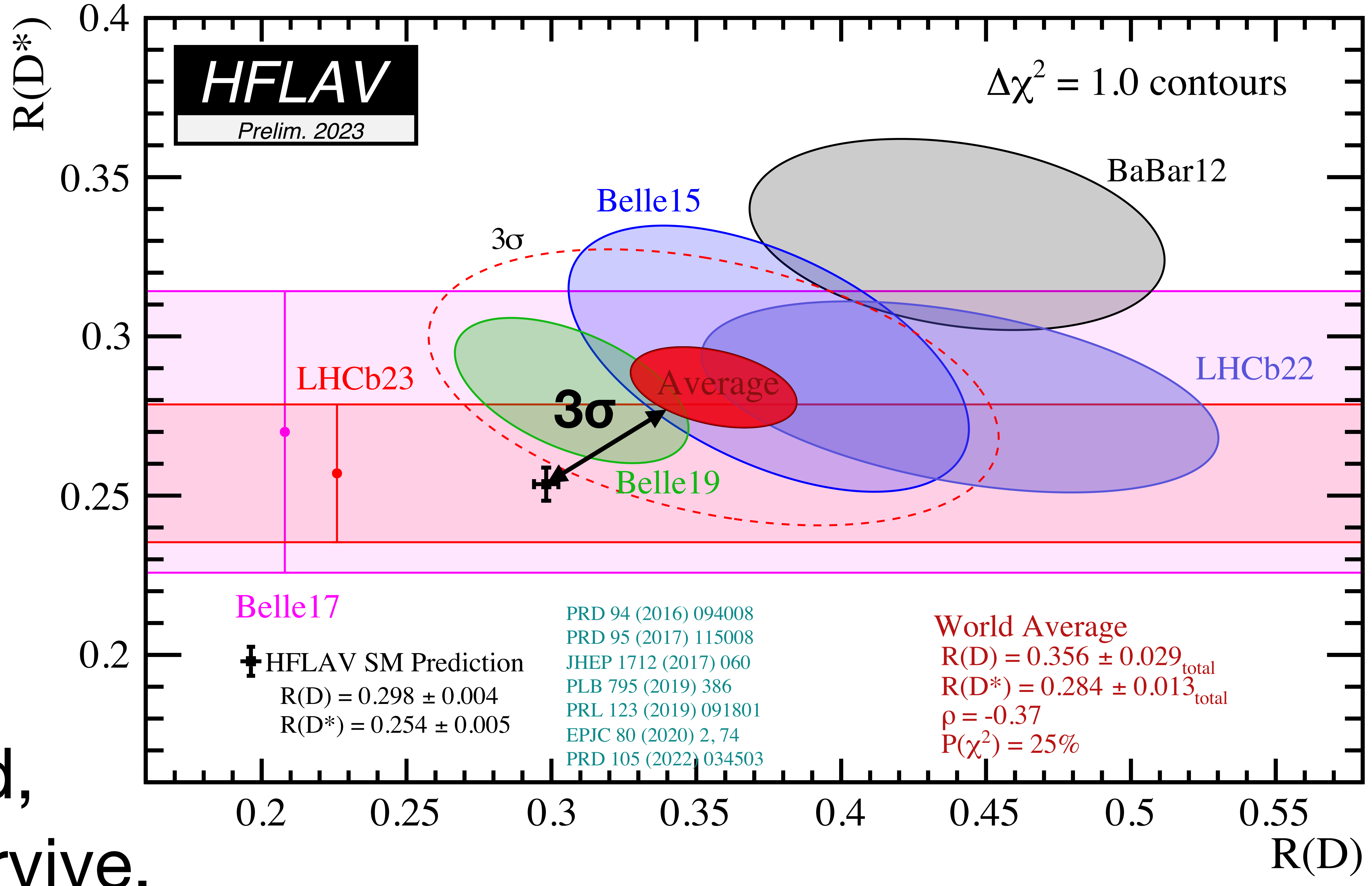
- SM expects lepton coupling to EW gauge bosons to be flavour-universal, but tensions exist:

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

- Until December 2022, also in:

$$R_{K^{(*)}} = \frac{BF(B \to K^{(*)}\mu^+\mu^-)}{BF(B \to K^{(*)}e^+e^-)}$$

- The latter now essentially disappeared, though other tensions in $b \to s\ell\ell$ survive.

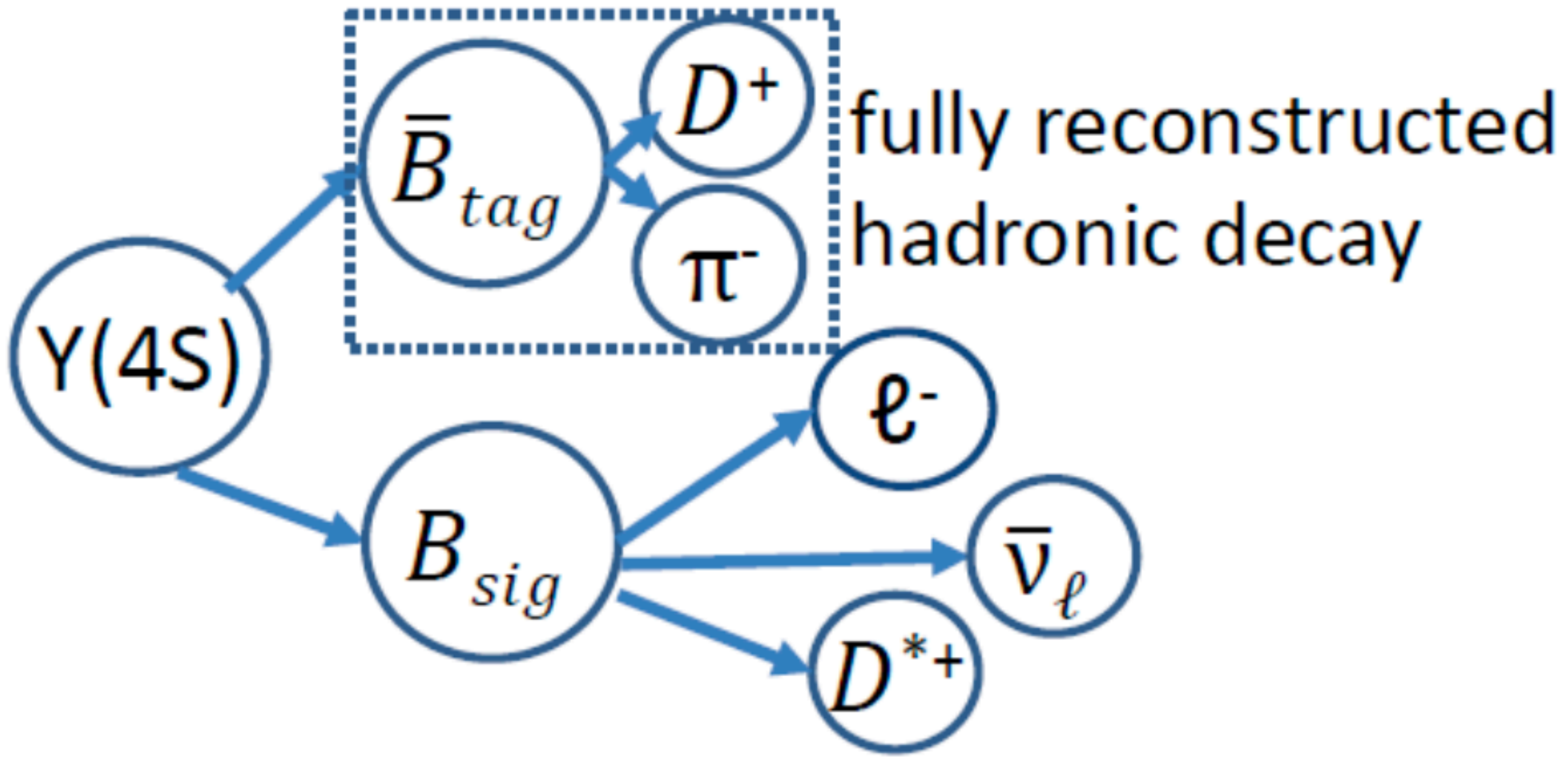


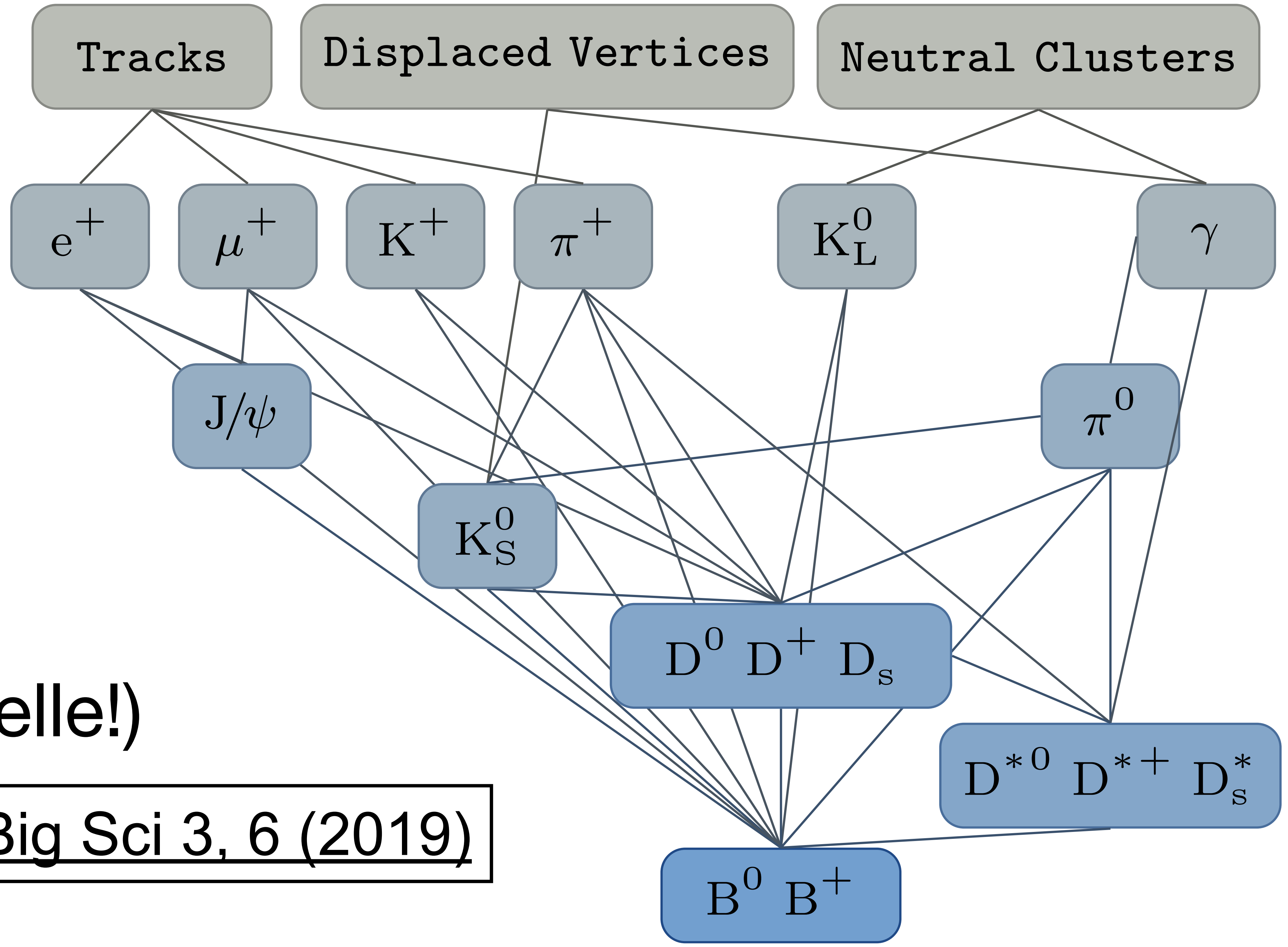
PRD 107, 052008 (2023)

B decay reconstruction: tagging

- The kinematics of a B decay with neutrinos can be precisely known through the use of ***tagging*** i.e. the complete reconstruction of the other B produced in the collision.

- Hadronic channels provide **exact** knowledge of kinematics - at the price of statistics.





- **Full Event Interpretation** using MVA:
$\varepsilon(B^+/B^0)=(0.5/0.3)\%$ for hadronic tags (x2 of Belle!)

Comput Softw Big Sci 3, 6 (2019)

NEW!

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

- Test light lepton LFU in five different angular observables:

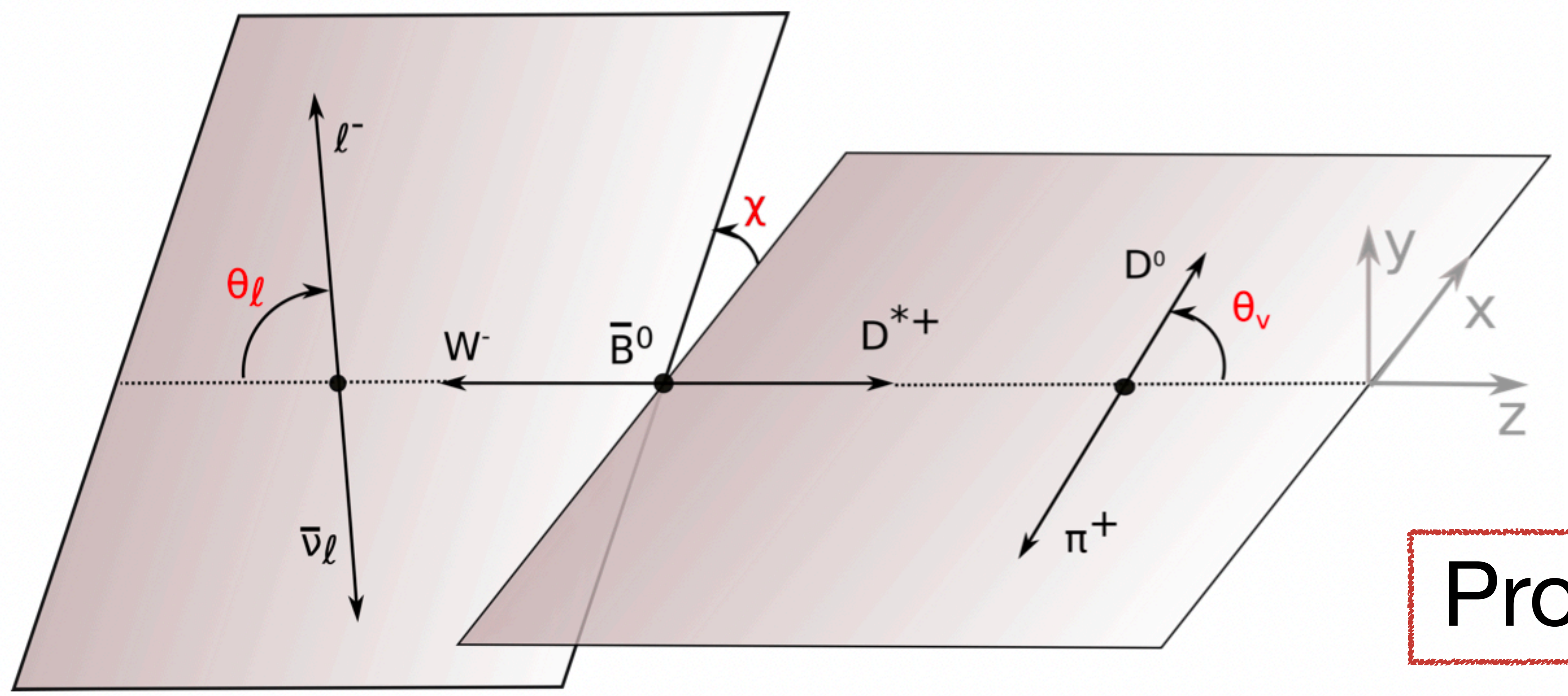
$$\mathscr{A}_x(w) = \left(\frac{d\Gamma}{dw}\right)^{-1}\left[\int_0^1 - \int_{-1}^0\right] dx \frac{d^2\Gamma}{dw dx}$$ where

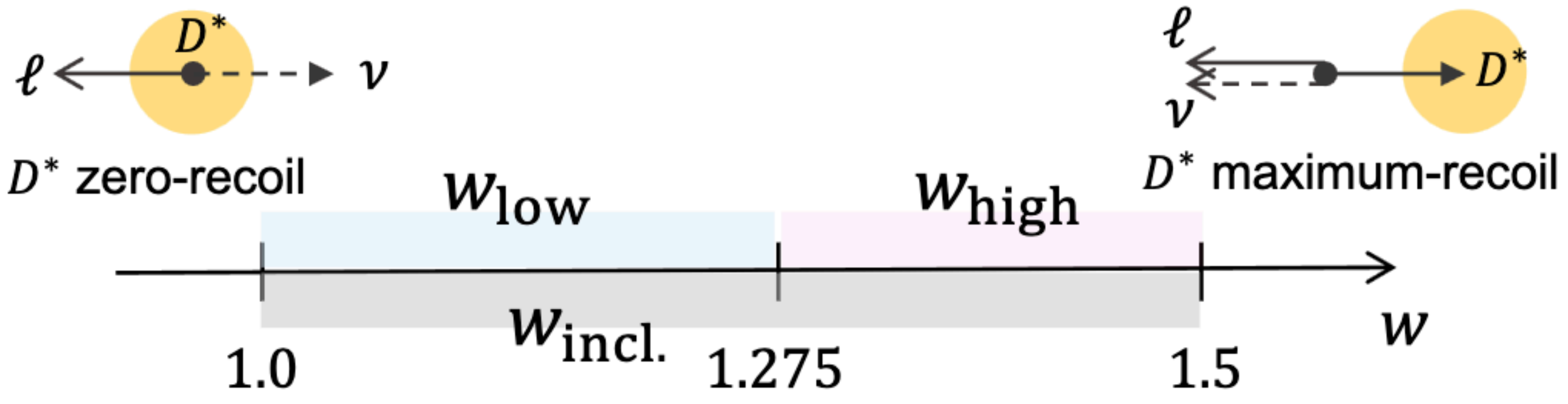
$A_{FB} : x = \cos\theta_\ell$
$S_3 : x = \cos 2\chi$
$S_5 : x = \cos\chi \cos\theta_\nu$
$\vdots$

recoil parameter

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

- **Most uncertainties cancel** in the difference $\Delta\mathscr{A}_x = \mathscr{A}_x^\mu - \mathscr{A}_x^e$



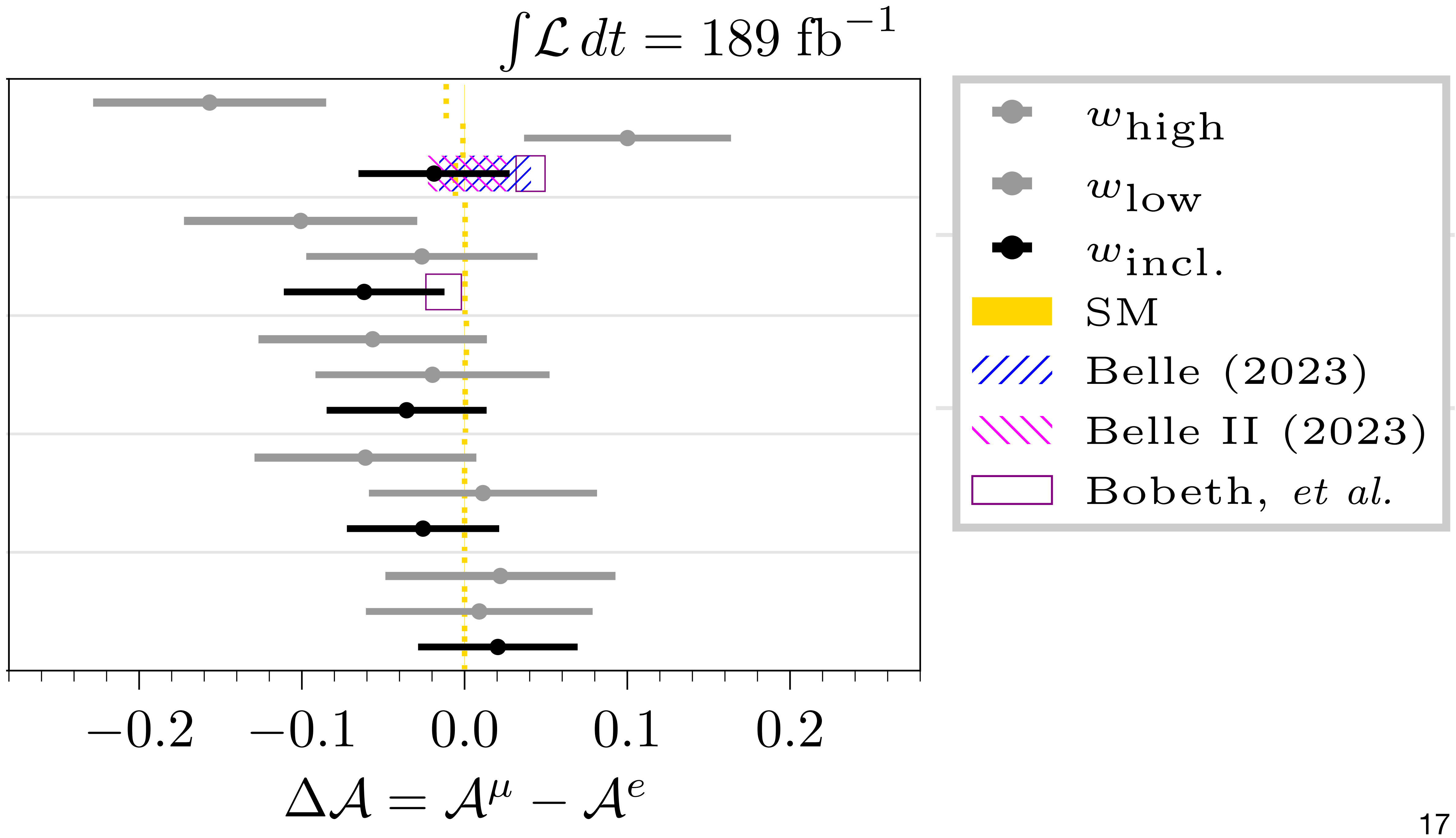


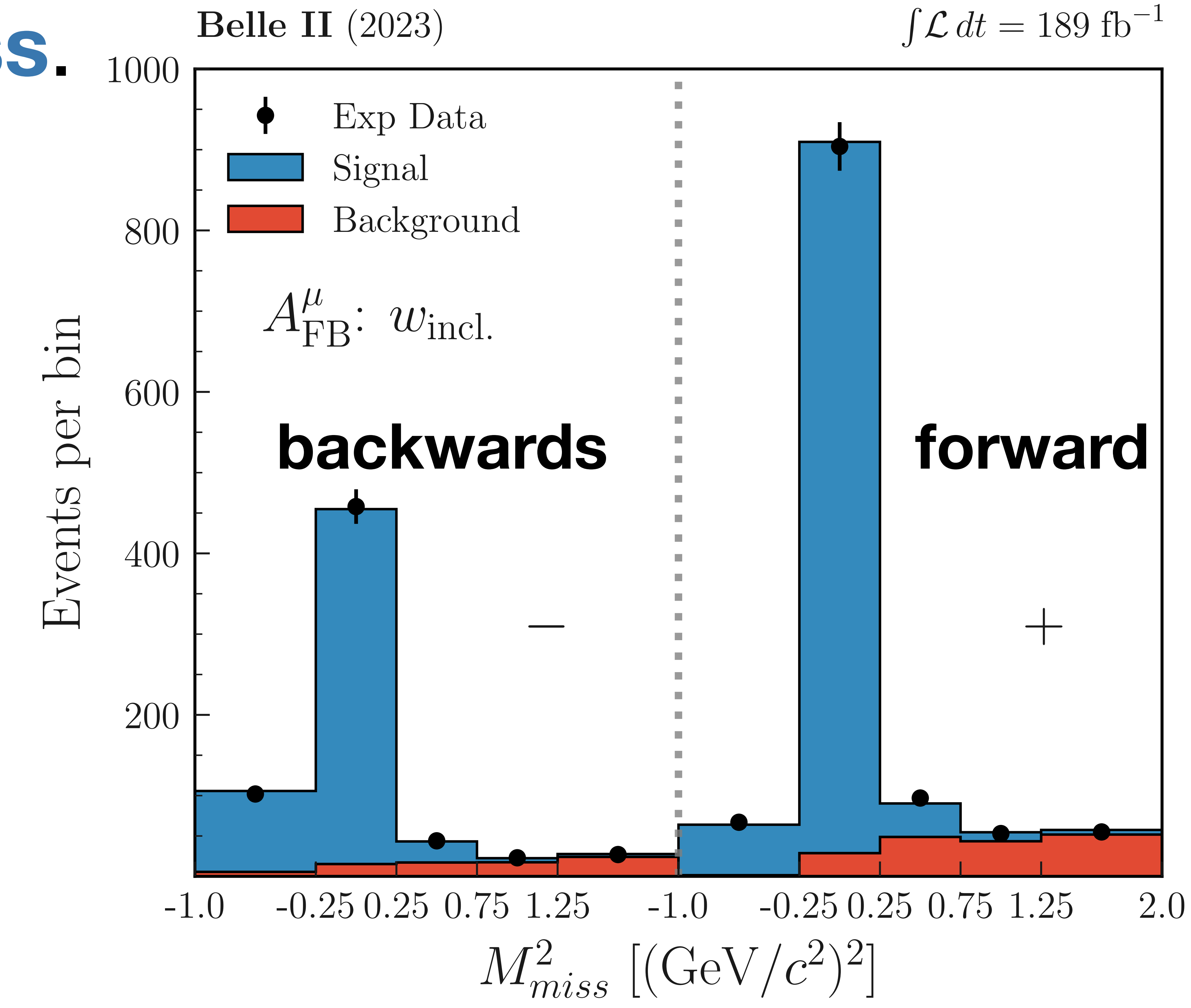
Probe LFU **independently** from anomalies.

NEW!

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

- Extract signal from fits to M^2_{miss} for each variable in 3 recoil ranges.
- **First dedicated test** of LFU using a full set of angular variables.
- Statistically limited: **full LS1 analysis in progress**.





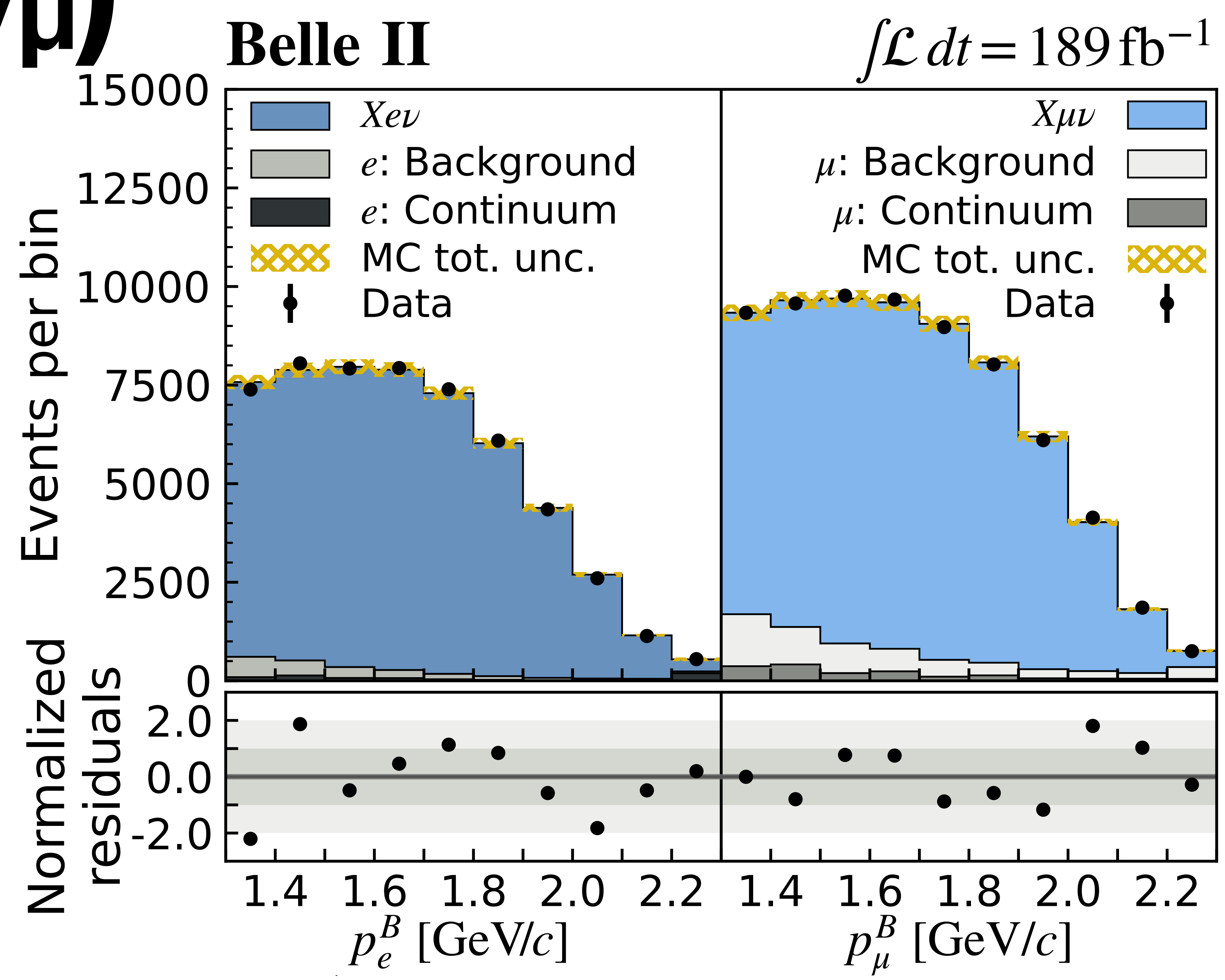
arXiv:2301.08266

Independent LFU test: R(X$_{e/\mu}$)

- $R(X_{e/\mu}) = \dfrac{\mathscr{B}(B \to Xe\nu)}{\mathscr{B}(B \to X\mu\nu)}$ with hadronic tag.
- Binned fit on lepton momentum in the B frame.
- Backgrounds fixed from off-resonance data and sidebands, while $X\ell\nu$ floats freely.
- **Most precise measurement**, in agreement w/SM:

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

- Systematically dominated by lepton ID
- Paves the way for $R(X_{\tau/\ell}) = \mathscr{B}(X\tau\nu)/\mathscr{B}(X\ell\nu)$
- $R(D^{(*)})$ cross-check, **only possible at Belle II**!



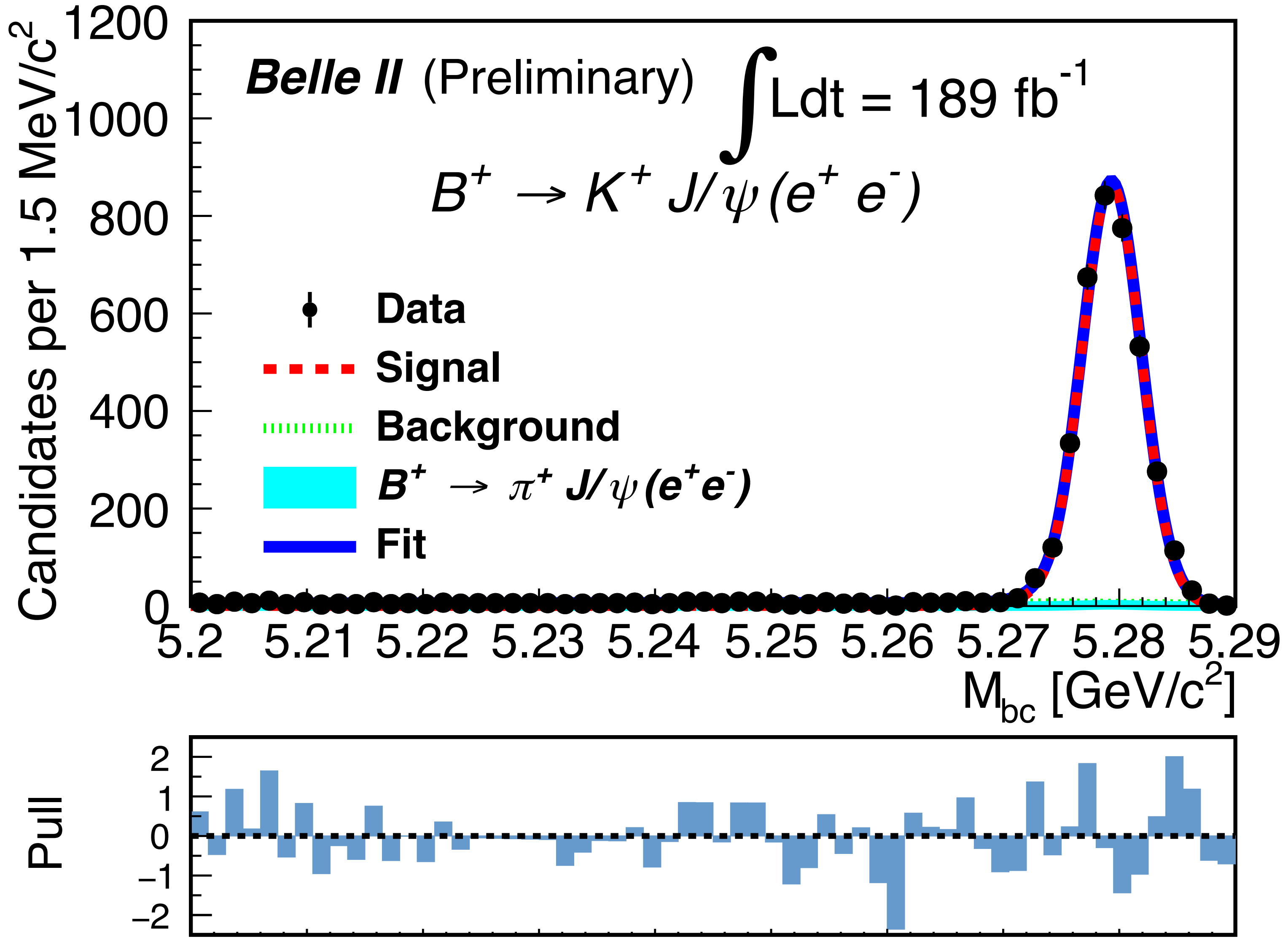
Source	Uncertainty [%]
Sample size	0.9
Lepton identification	1.9
$X\,\ell\,\nu$ branching fractions	0.2
$X_c\,\ell\,\nu$ form factors	0.1
Total	2.1

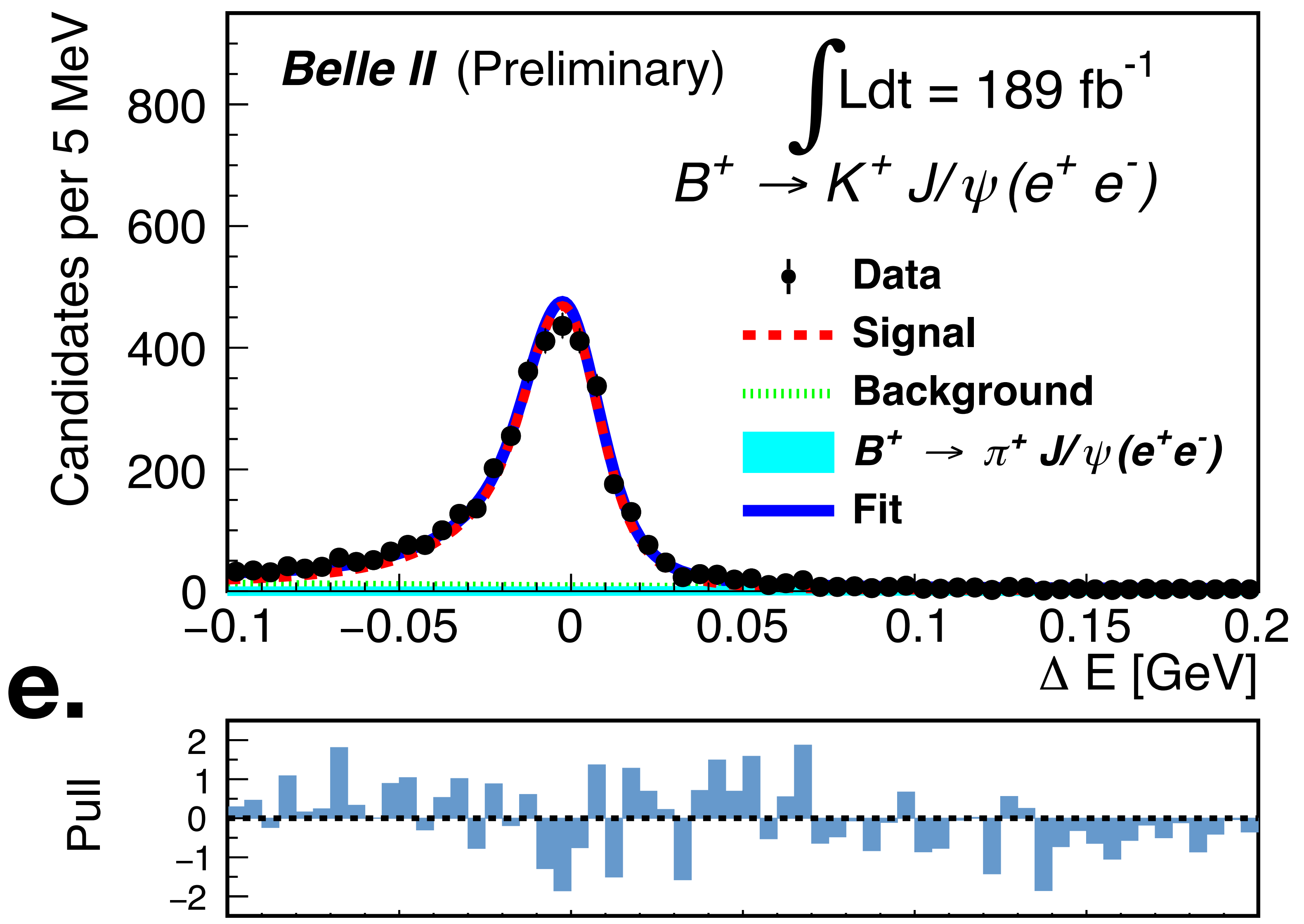
LFU in neutral currents: $B \to J/\psi(\to \ell\ell)K$

- **Tree level** transition. Control sample for $B \to K^{(*)}\ell\ell$.
- $R_K(J/\psi)^{SM} = \dfrac{\mathscr{B}(B \to J/\psi(\mu^+\mu^-)K)}{\mathscr{B}(B \to J/\psi(e^+e^-)K)} \simeq 1$
- Fit $\mathbf{M_{bc}} = \sqrt{E{*}^2_{beam} - \mathbf{p}{*}^2_B}$ and $\mathbf{\Delta E} = E{*}_{beam} - E{*}_B$

Observable	Belle II	Belle (2021)
$R_{K^+}(J/\psi)$	$1.009 \pm 0.022 \pm 0.008$	$0.994 \pm 0.011 \pm 0.010$
$R_{K^0_S}(J/\psi)$	$1.042 \pm 0.042 \pm 0.008$	$0.993 \pm 0.015 \pm 0.010$

- Agrees with unity, **still statistically limited**.
- Systematics dominated by lepton ID, **improved from Belle.**

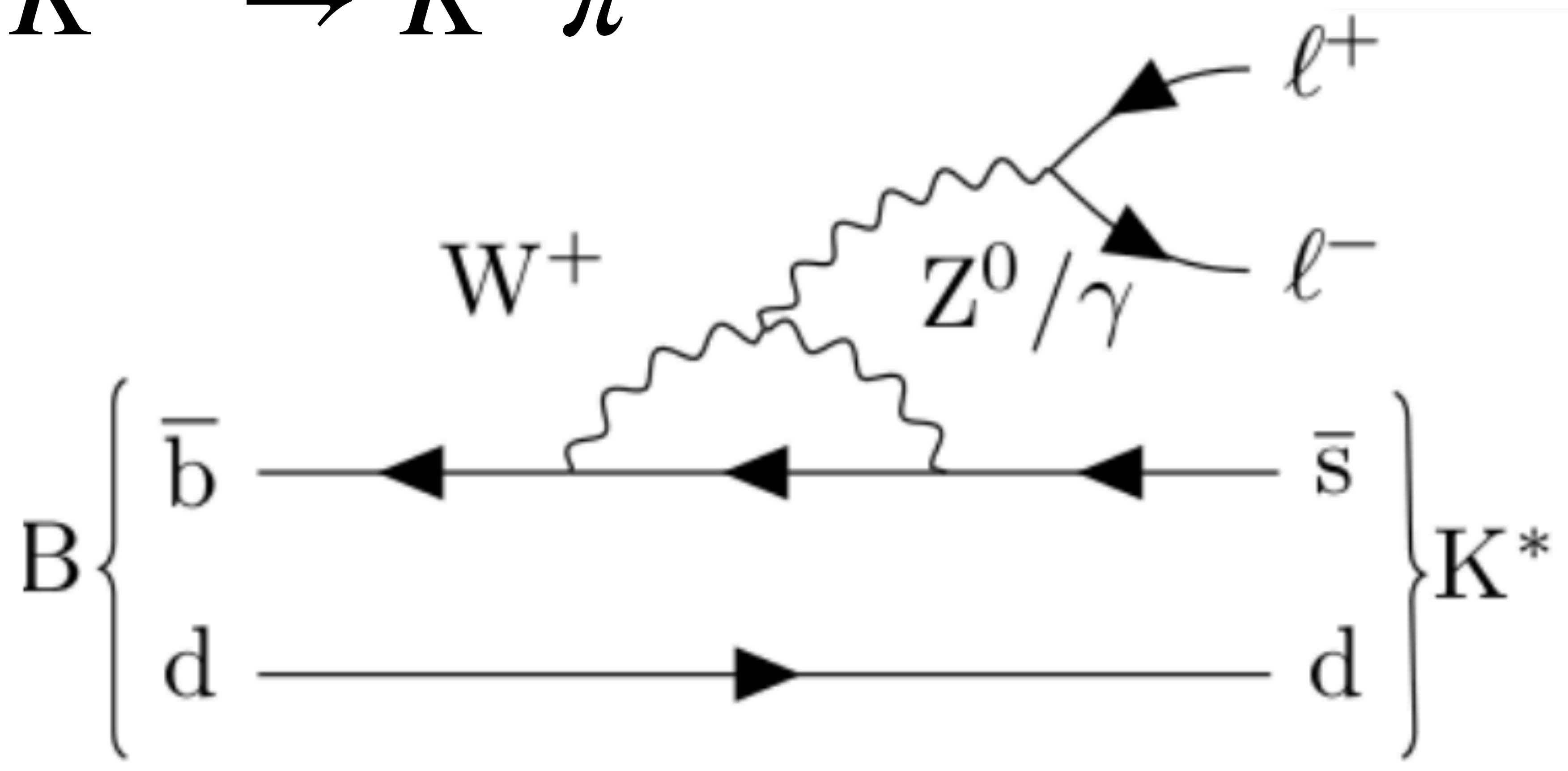




arXiv:2206.05946

LFU in neutral currents: $B \to K^*(892)\ell\ell$

- Measure BF reconstructing $K^{*+}(\to K_S^0\pi^+, K^+\pi^0)$ or $K^{*0} \to K^+\pi^-$
  - Mass veto on $J/\psi, \psi(2S) \to \ell^+\ell^-, \gamma \to e^+e^-$
  - Remaining background suppressed with BDT
- Fit on $\mathbf{M_{bc}}$, $\mathbf{\Delta E}$ with PDFs from $B \to J/\psi(\ell\ell)K$

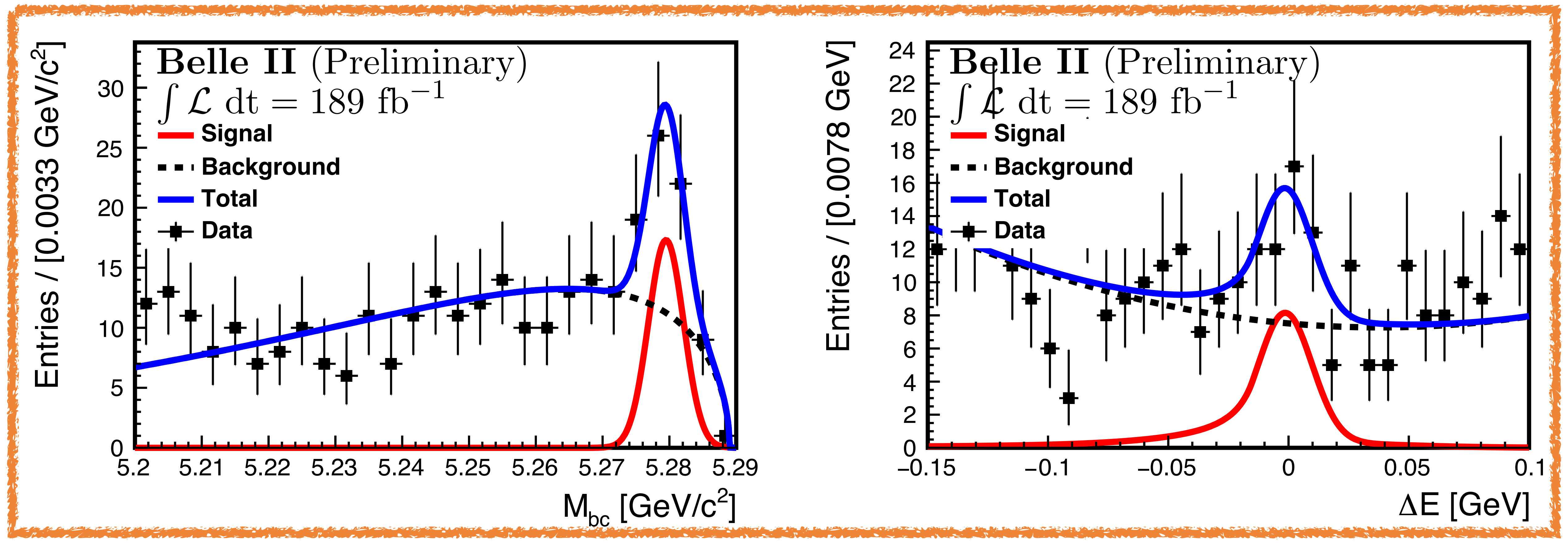


arXiv:2206.05946

Preparing for LFU: $B \to K^*(892)\ell\ell$

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

$\mathbf{K^*\ell\ell}$



- Compatible with world averages.
- **Comparable performance between e^+e^- and $\mu^+\mu^-$**
- Statistically limited, with subleading systematics driven by particle ID.
- Branching fraction measurement of $B \to K\ell\ell$ is also ongoing.
- Ready to provide an independent $R_{K^{(*)}}$ measurement with 5~10 ab^{-1}.

Perspectives for $b \to s\tau\tau$

PRL 120 (2018), 181802

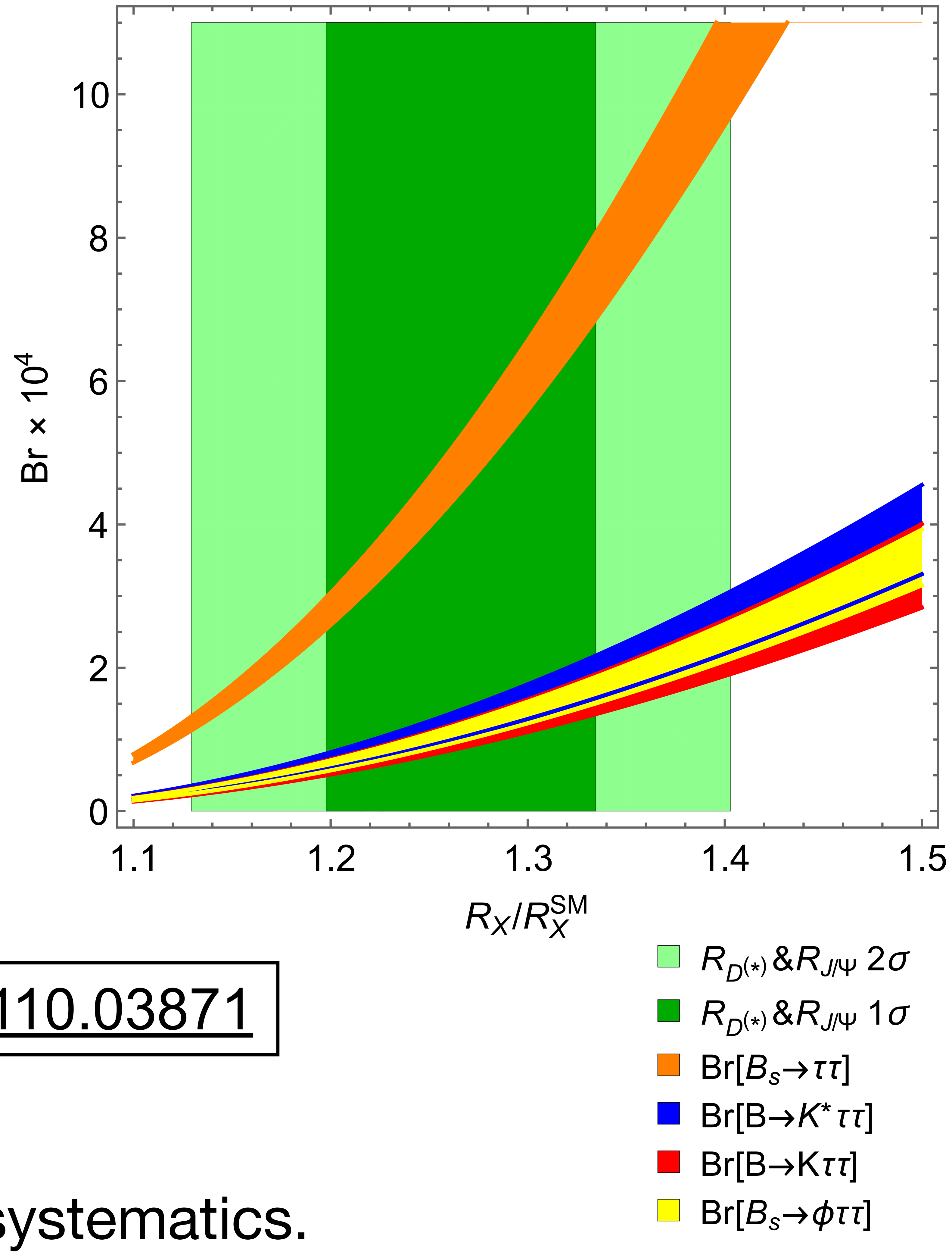
- SM suppressed: $\mathscr{B}_{SM}(B \to K^*\tau\tau) \sim \mathcal{O}(10^{-7})$, **very sensitive to NP:** → up to $\times\, 10^3$ enhancement with LFUV in 3rd generation

- Experimental limits much weaker, $\mathcal{O}(10^{-3})$ at 90% C.L.

	$\mathcal{B}(B^0 \to K^{*0}\tau\tau)$ (had tag)	
ab^{-1}	"Baseline" scenario	"Improved" scenario
1	$< 3.2 \times 10^{-3}$	$< 1.2 \times 10^{-3}$
5	$< 2.0 \times 10^{-3}$	$< 6.8 \times 10^{-4}$
10	$< 1.8 \times 10^{-3}$	$< 6.5 \times 10^{-4}$
50	$< 1.6 \times 10^{-3}$	$< 5.3 \times 10^{-4}$

→ **Unique Belle II reach!**

arXiv:2207.06307



- "*Baseline*" follows Belle's analysis (hadronic tag, $\tau \to \ell\nu\bar{\nu}$) arXiv:2110.03871
- "*Improved*" incorporates $\tau \to \pi\nu$.
- Can be improved even further by including $B \to K^{*+}\tau\tau$ and better systematics.

- Similar considerations apply to CLFV searches e.g. $B \to X\tau e$ and $B \to X\tau\mu$

Summary

- Belle II offers a unique and fertile environment for LFU and CLFV tests.
- Analyses using **189 fb^{-1}** can already provide world-leading results and access unique observables.
- **424 fb^{-1}** recorded on tape: new analyses with larger statistics incoming!
- Data-taking soon to restart in winter 2023.

BACKUP

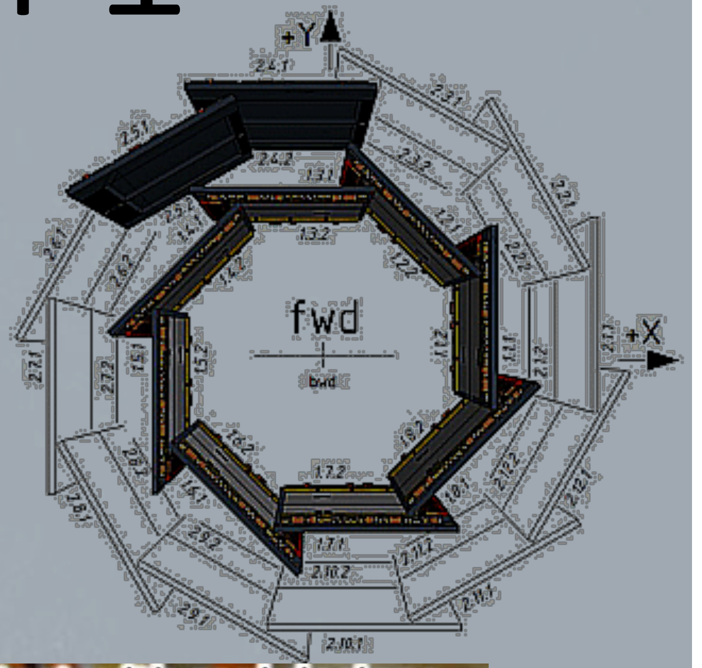
Kodai Matsuoka

(from July 2022 until October 2023)

Major upgrade in Long Shutdown 1

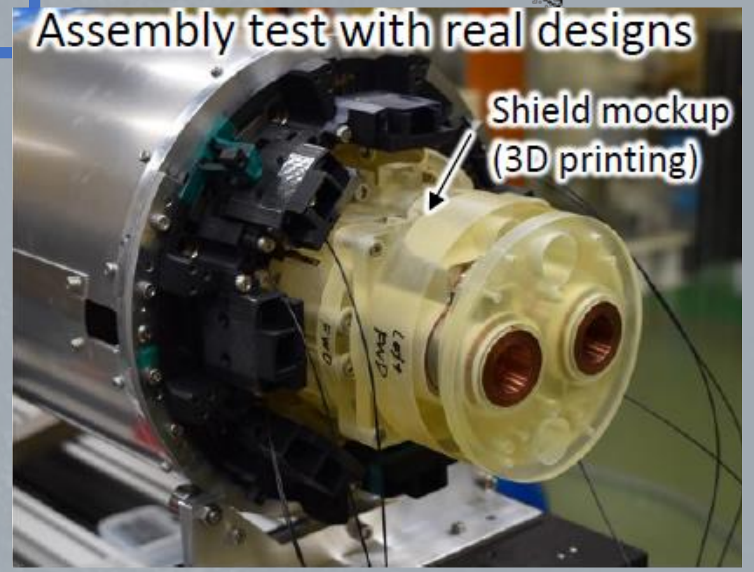
Belle II detector upgrade

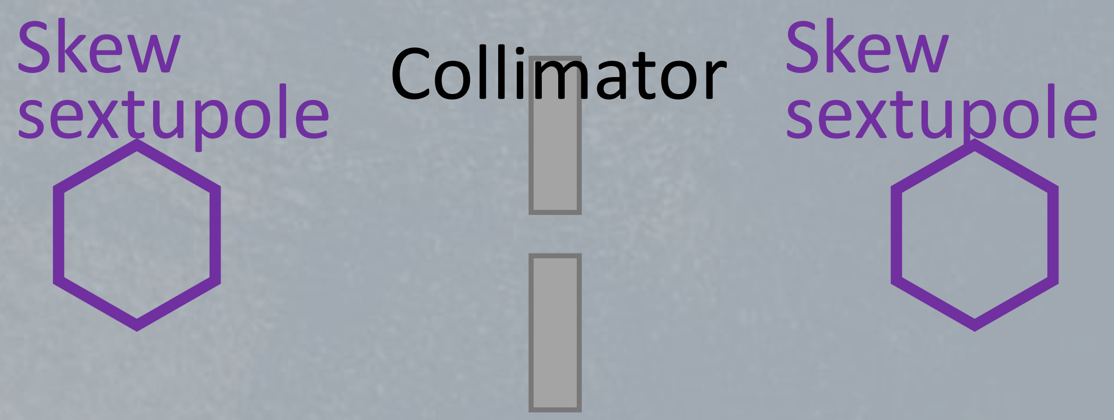
- Exchange of PXD (pixel detector) with the full 2nd layer
- TOP conventional MCP-PMT replacement (TBD)
- Migration to new back-end readout (COPPER → PCIe40)



Beam background mitigation

- Additional shield on the QCS(*) bellows
- Additional shield for neutron background
- Installation of a non-linear collimator





Beam kick by skew sextupole:

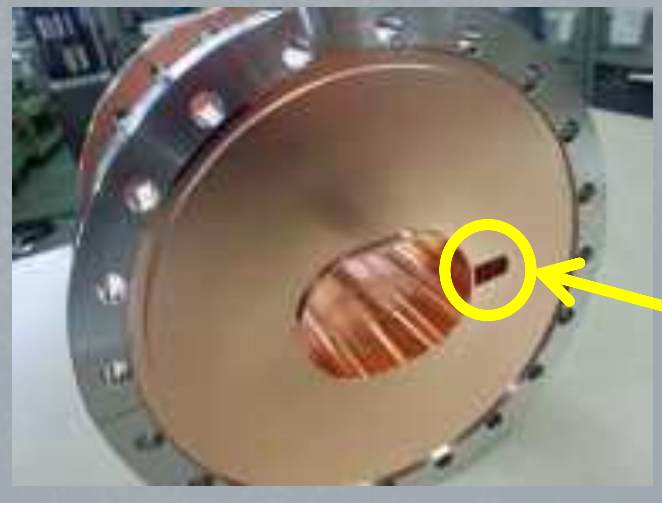
$$\Delta p_y = \frac{SK_2}{2}(y^2 - x^2),\ \Delta p_x = SK_2 xy$$

Protection of machine and Belle II

- Collimator heads of more robust material
- Faster beam abort system

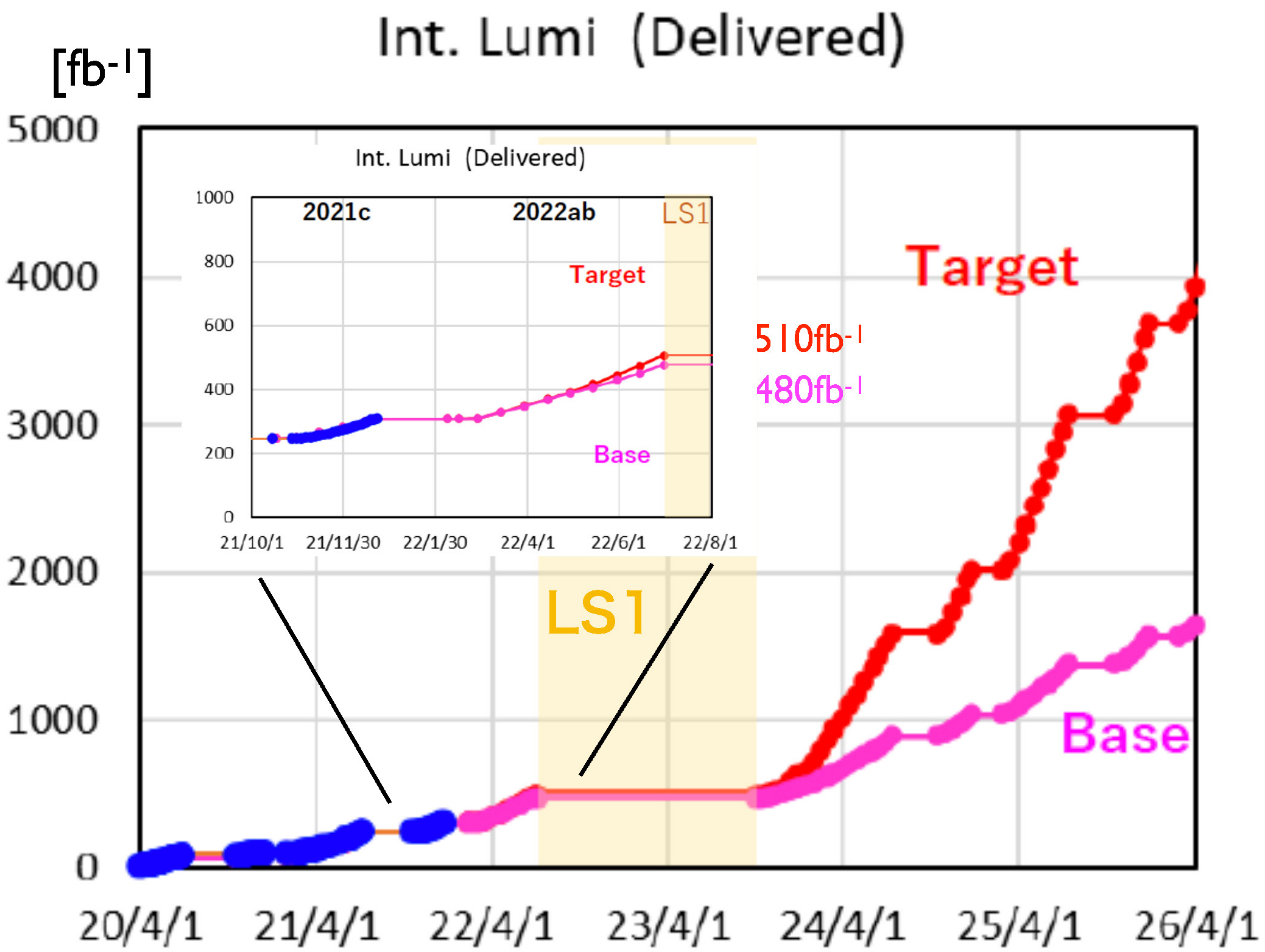
Improvement of beam injection

- Enlarged beam pipe at the HER injection
- Pulse-by-pulse beam control for Linac



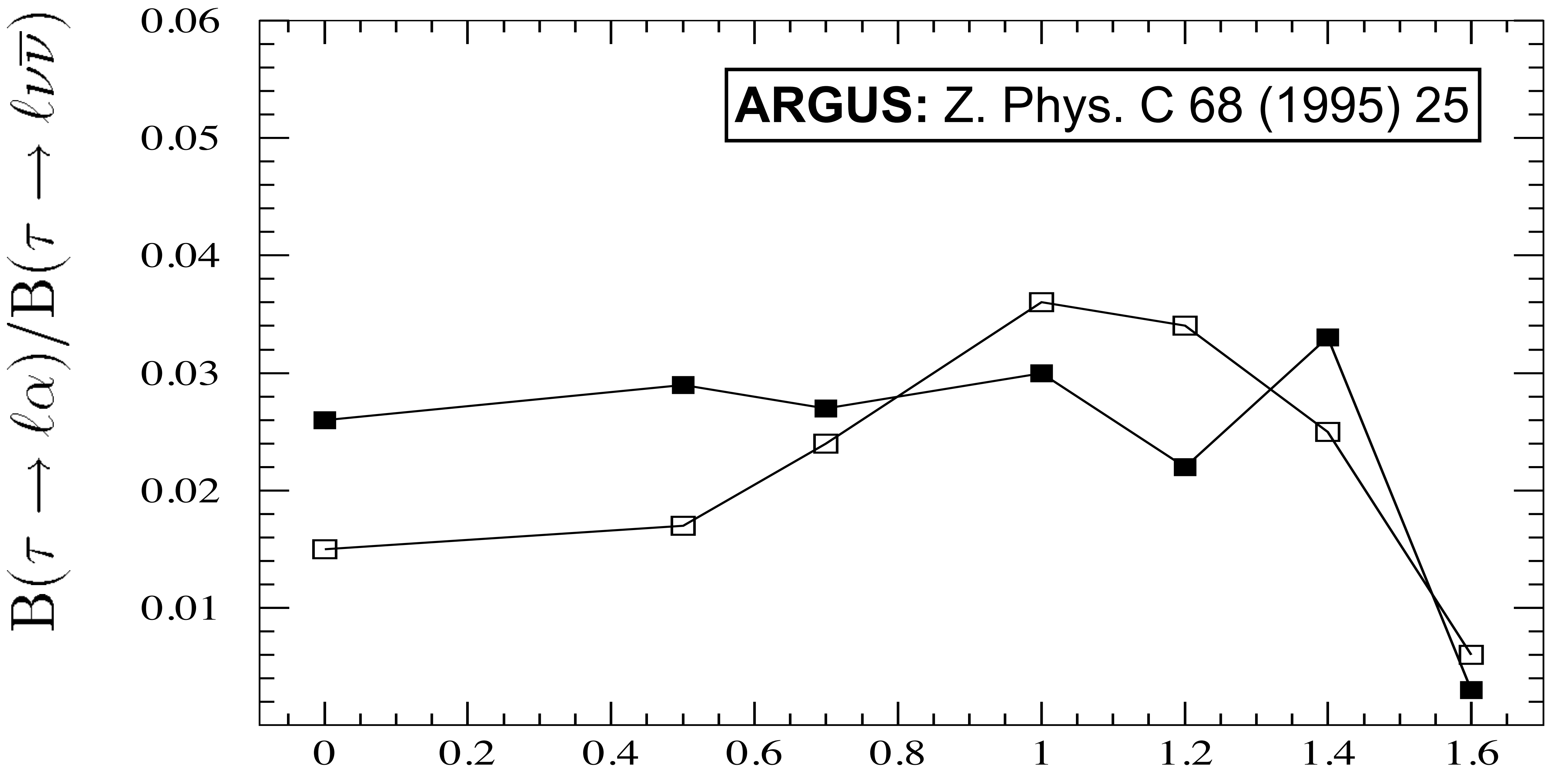
Beam channel for injection

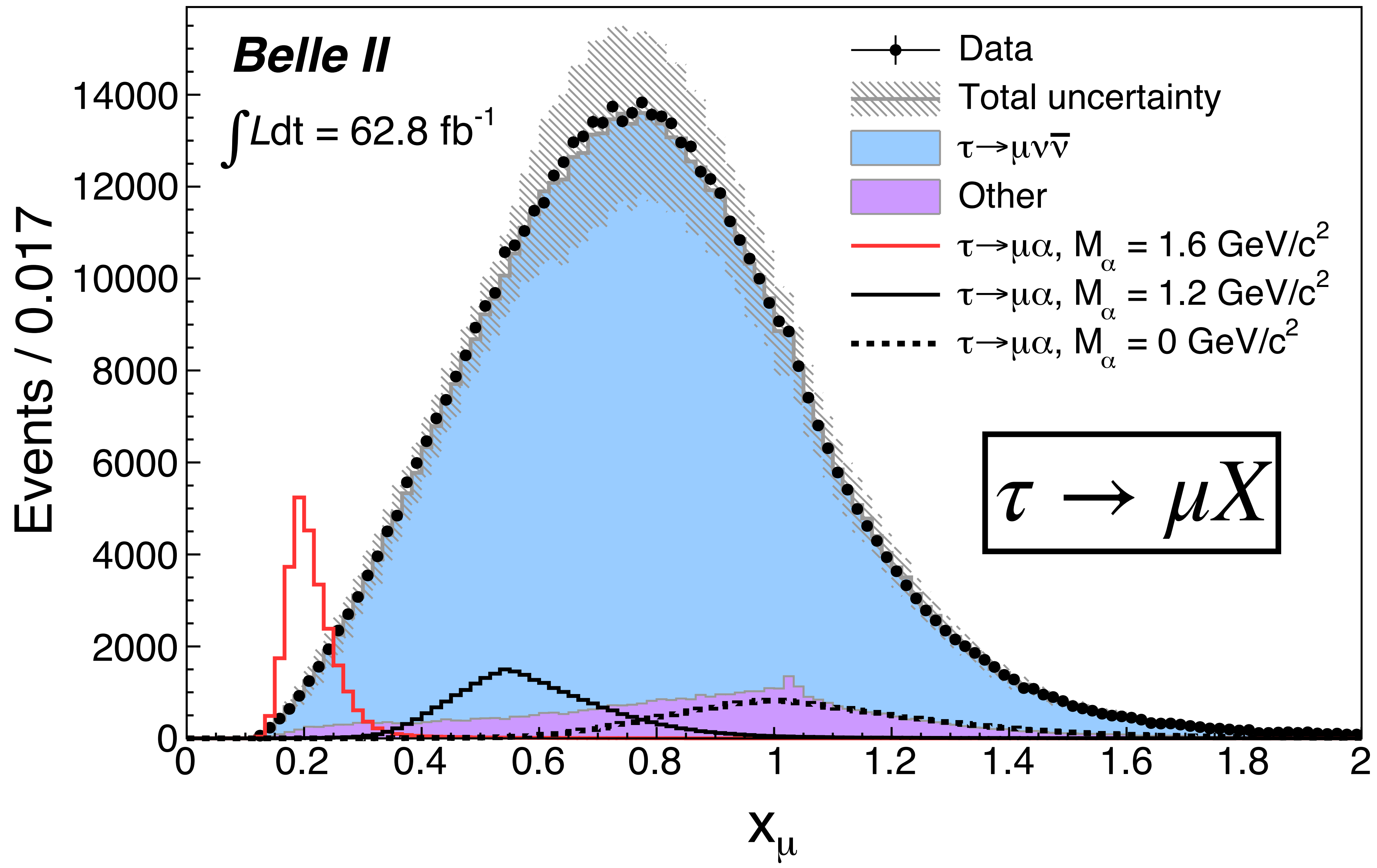
QCS: Final focusing system

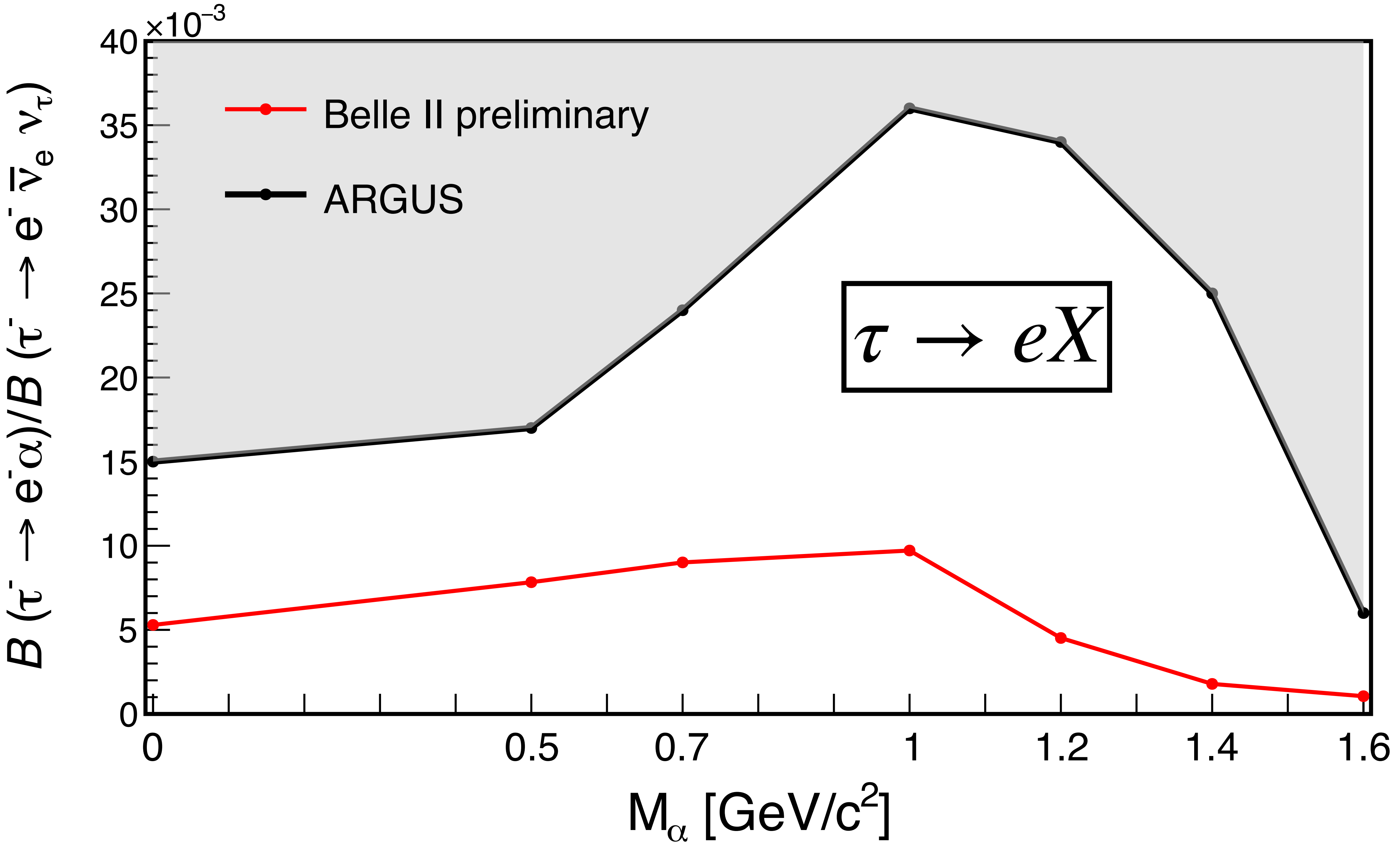


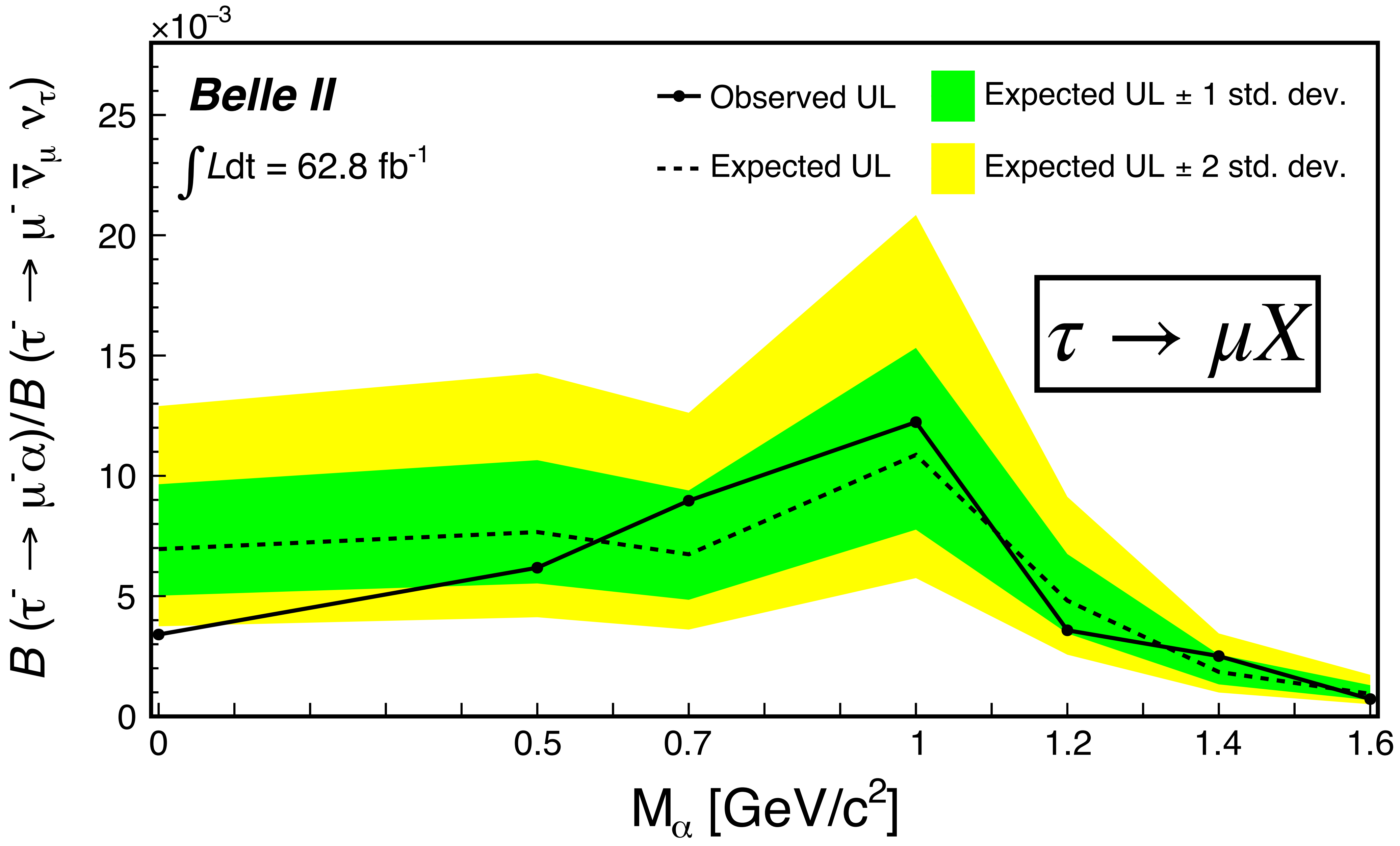
Base: Conservative extrapolation from 2021 run parameters

Target: Extrapolation from 2021 with expected improvements


ARGUS: Z. Phys. C 68 (1995) 25
B(τ → ℓα)/B(τ → ℓνν̄)


Belle II
∫Ldt = 62.8 fb-1
Data
Total uncertainty
τ→μνν̄
Other
τ→μα, Mα = 1.6 GeV/c2
τ→μα, Mα = 1.2 GeV/c2
τ→μα, Mα = 0 GeV/c2
τ → μX
Events / 0.017
xμ


Belle II preliminary
ARGUS
τ → eX
B (τ- → e-α)/B (τ- → e- ν̄e ντ)
Mα [GeV/c2]


Belle II
∫Ldt = 62.8 fb-1
Observed UL
Expected UL
Expected UL ± 1 std. dev.
Expected UL ± 2 std. dev.
τ → μX
B (τ- → μ-α)/B (τ- → μ- ν̄μ ντ)
Mα [GeV/c2]

NEW!

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