New limit on $\tau \rightarrow \ell$+invisible

Recent τ-lepton results at Belle II

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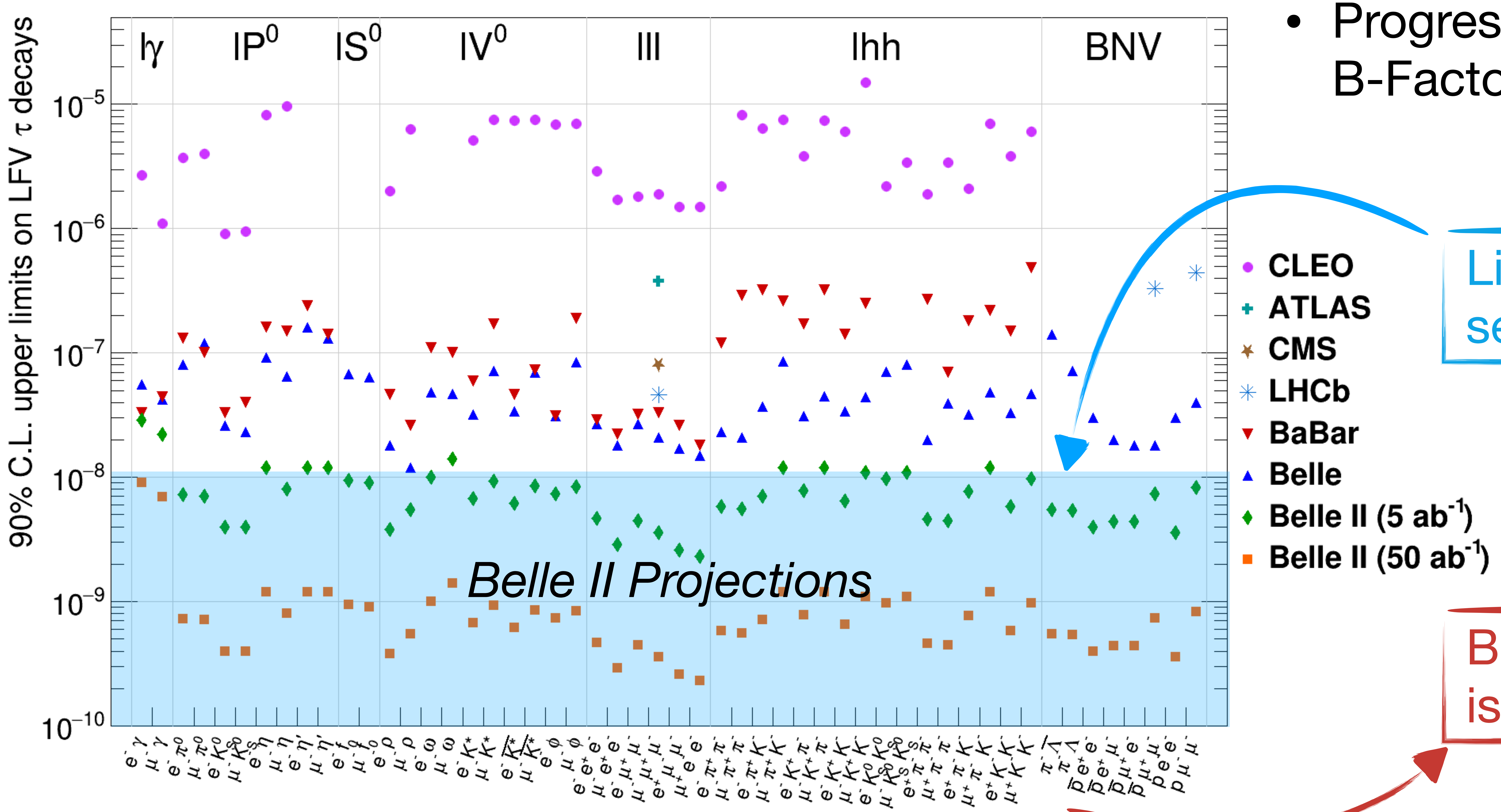
on behalf of the Belle II Collaboration

τ physics overview

- Heaviest known lepton → can decay into leptons but also hadrons.
- New physics (NP) may couple preferentially to the 3rd generation.
  - Precision measurement of tau properties → **indirect** hint of NP in SM deviations.
  - Forbidden decays violating lepton flavour conservation and/or universality (LFV/LFUV) → **direct observation** of would be **unambiguous** sign of NP!
- **Challenges:**
  - Presence of neutrinos requires good reconstruction of missing energy.
  - Low multiplicity requires appropriate triggers.
  - Excellent vertexing capabilities needed e.g. for lifetime measurements.

Perspectives in the search for charged LFV



- Progress mostly occurred at B-Factories over the last years.

Limits approach the region sensitive to NP.

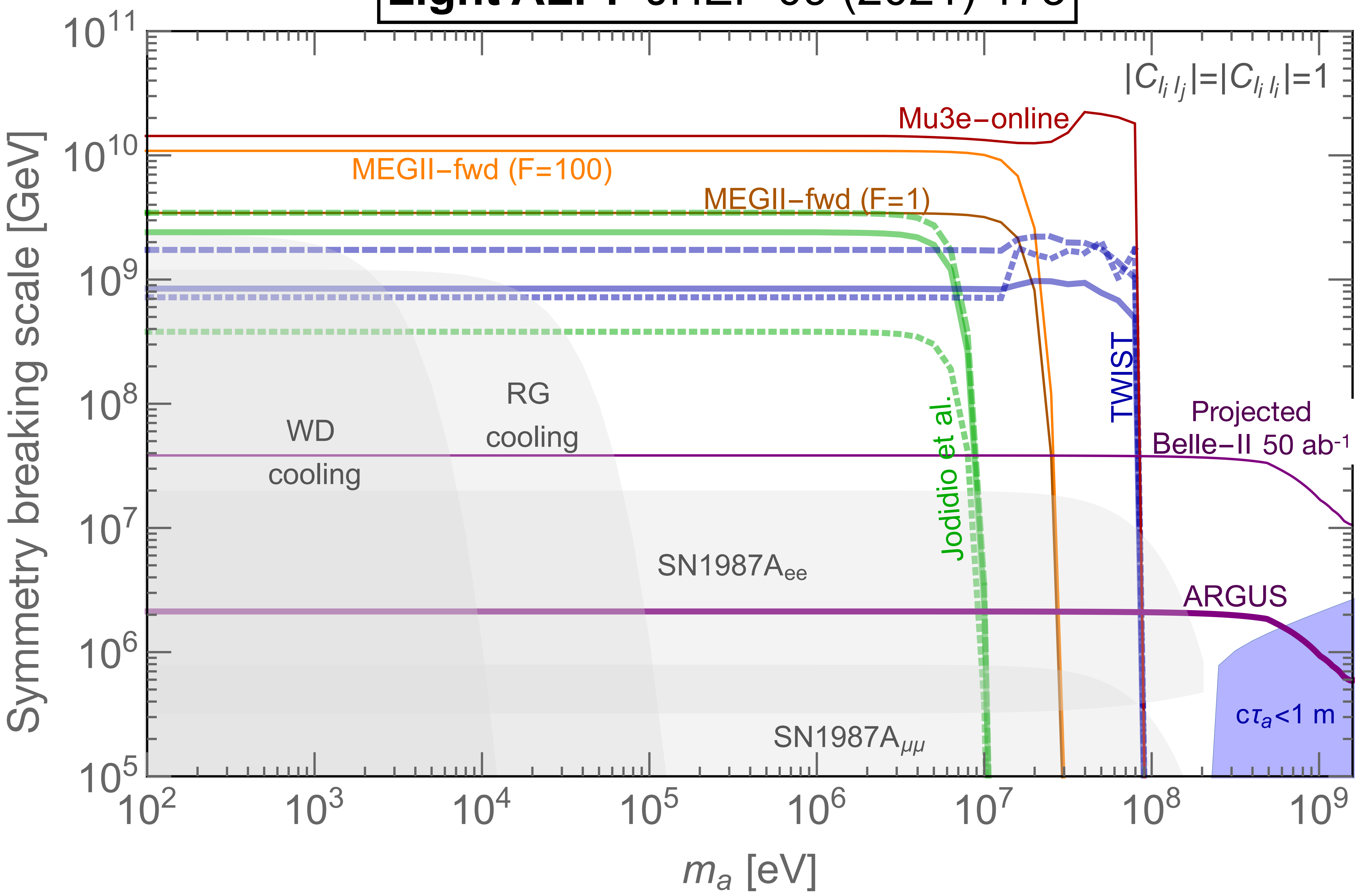
But this list of channels is not exhaustive...

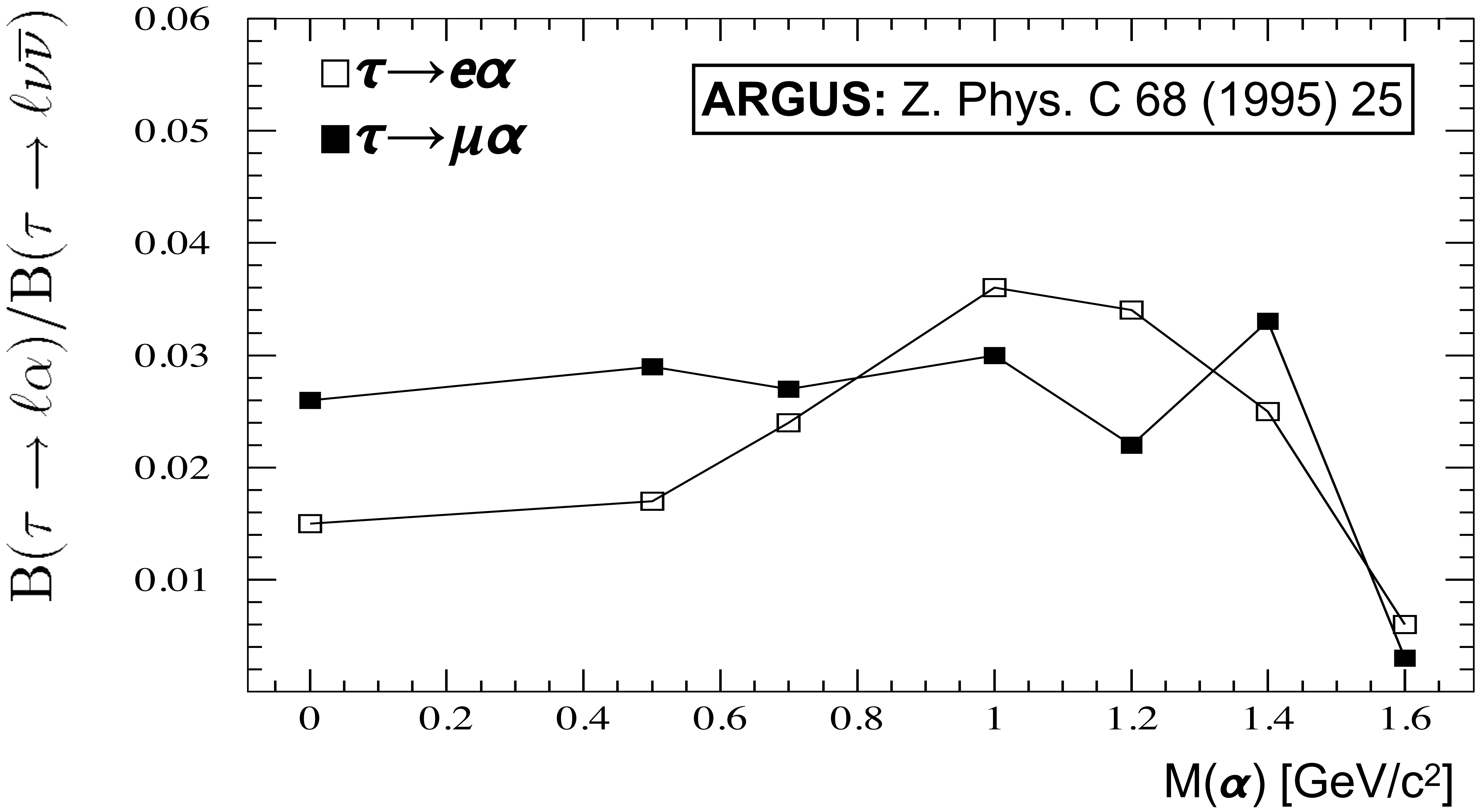
arXiv:2203.14919

$\tau \to \ell + \alpha$ (invisible)

- Can enter from NP models such as light ALP.
- Best upper limits on B($\tau \to \ell \alpha$)/B($\tau \to \ell \bar{\nu} \nu$) from **ARGUS** (1995, **476 pb^{-1}**)
- Phenomenology:
  consistency of BR($\tau \to \ell \bar{\nu} \nu$) W.A.
  with SM predictions: 0.8(e)-1.1(μ) x10^{-2}
  (*Phys. Rev. 104, 075032 (2021)*).
- **Belle II can already set more stringent limits with current data.**

Light ALP: JHEP 09 (2021) 173

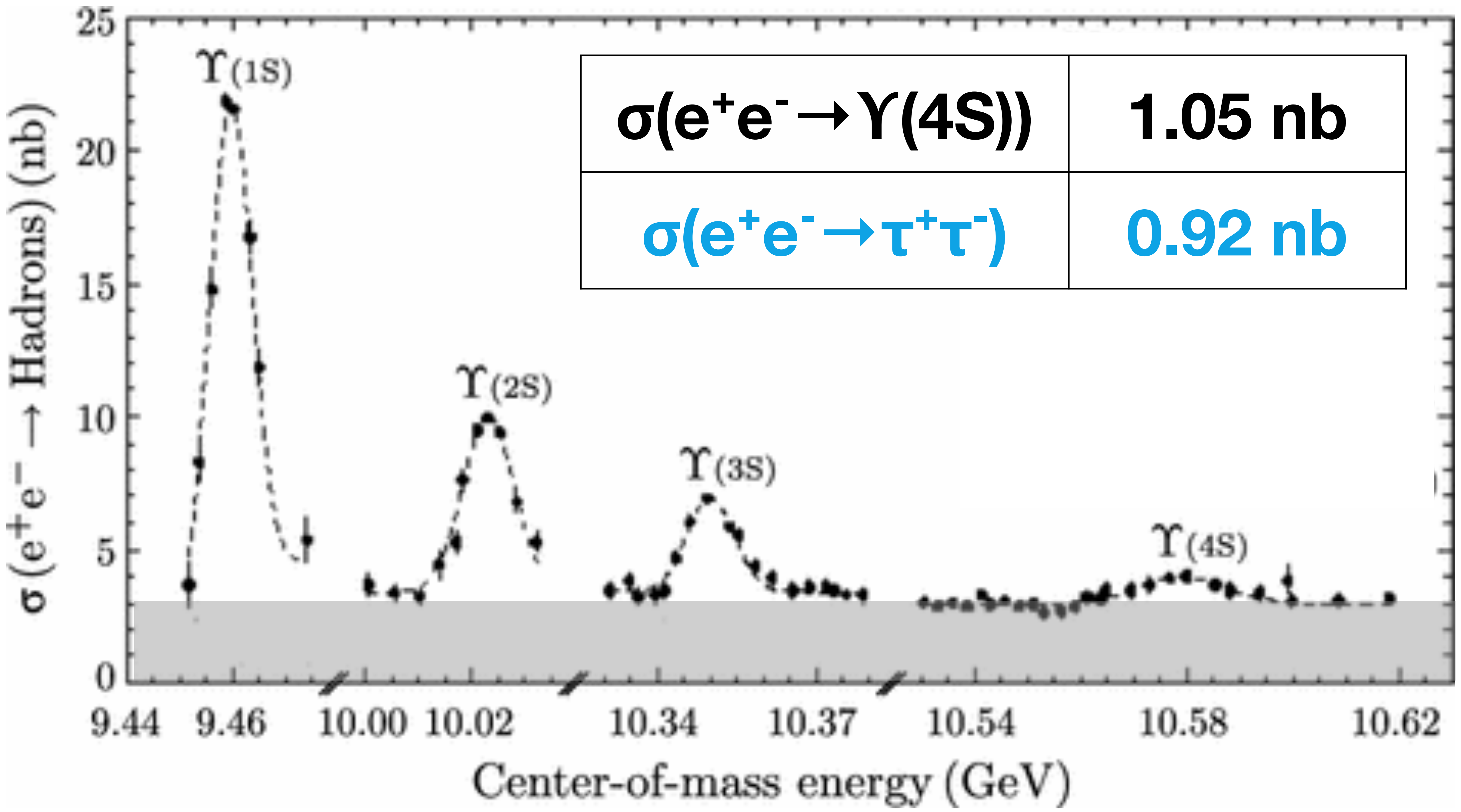




ARGUS: Z. Phys. C 68 (1995) 25

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

- 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).
- Achieved **world record instantaneous** luminosity of **4.7x10^{34} cm^{-2} s^{-1}**.
- Collected **424 fb^{-1}** before summer 2022.

- Favorable $\boldsymbol{\tau}$ cross-sections → B-Factories are also **τ-Factories.**

Belle II detector

Belle II TDR, arXiv:1011.0352

- Increased beam background

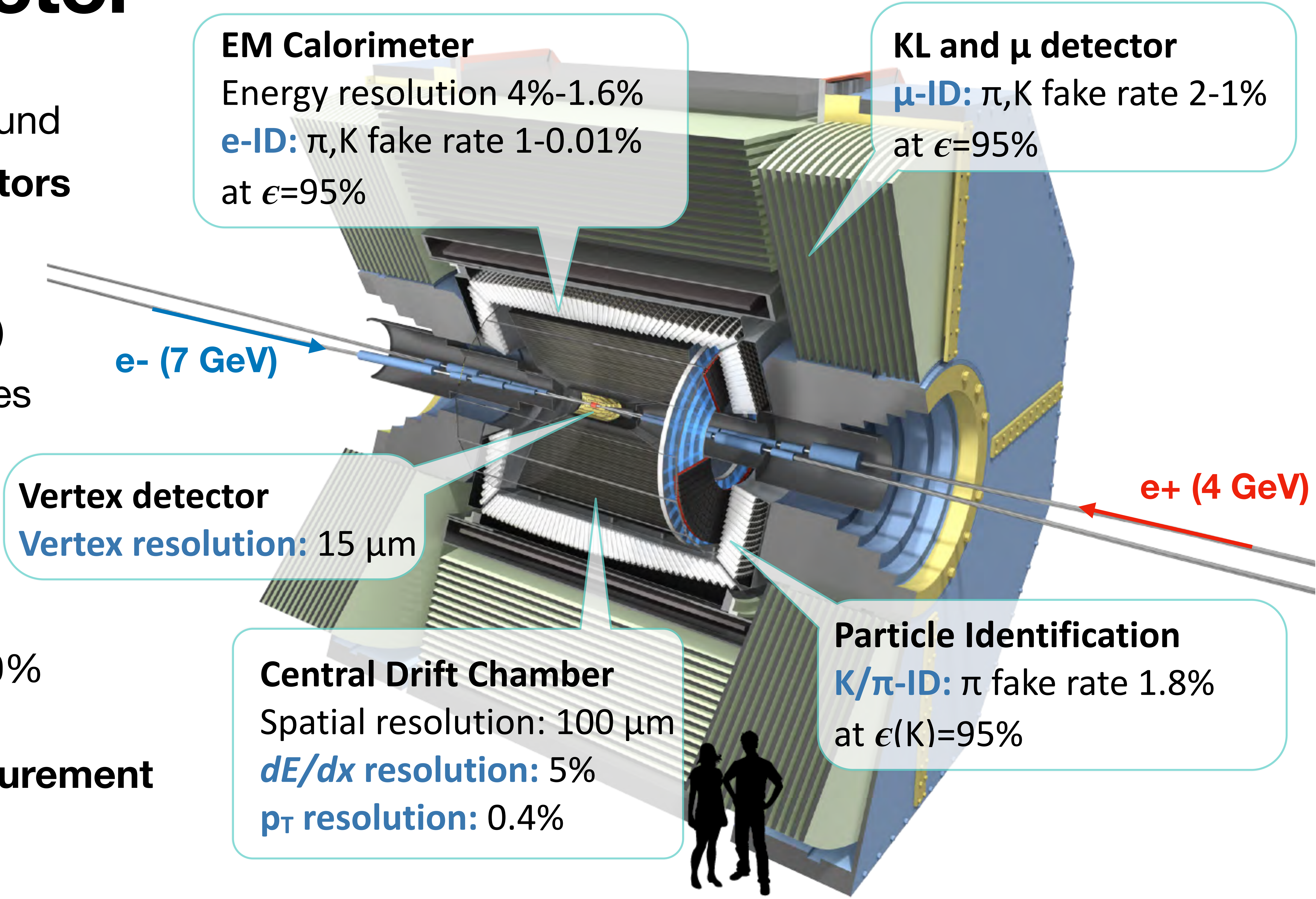
  → **Upgraded sub-detectors and trigger**

- **$\beta\gamma$**=0.28 (vs 0.42 @KEKB)

  → Reduced boost requires **improved vertex reconstruction:**

- Solid angle coverage >90%

  → **High hermeticity for missing energy measurement**



EM Calorimeter
Energy resolution 4%-1.6%
e-ID: π,K fake rate 1-0.01%
at ϵ=95%

KL and μ detector
μ-ID: π,K fake rate 2-1%
at ϵ=95%

Vertex detector
Vertex resolution: 15 µm

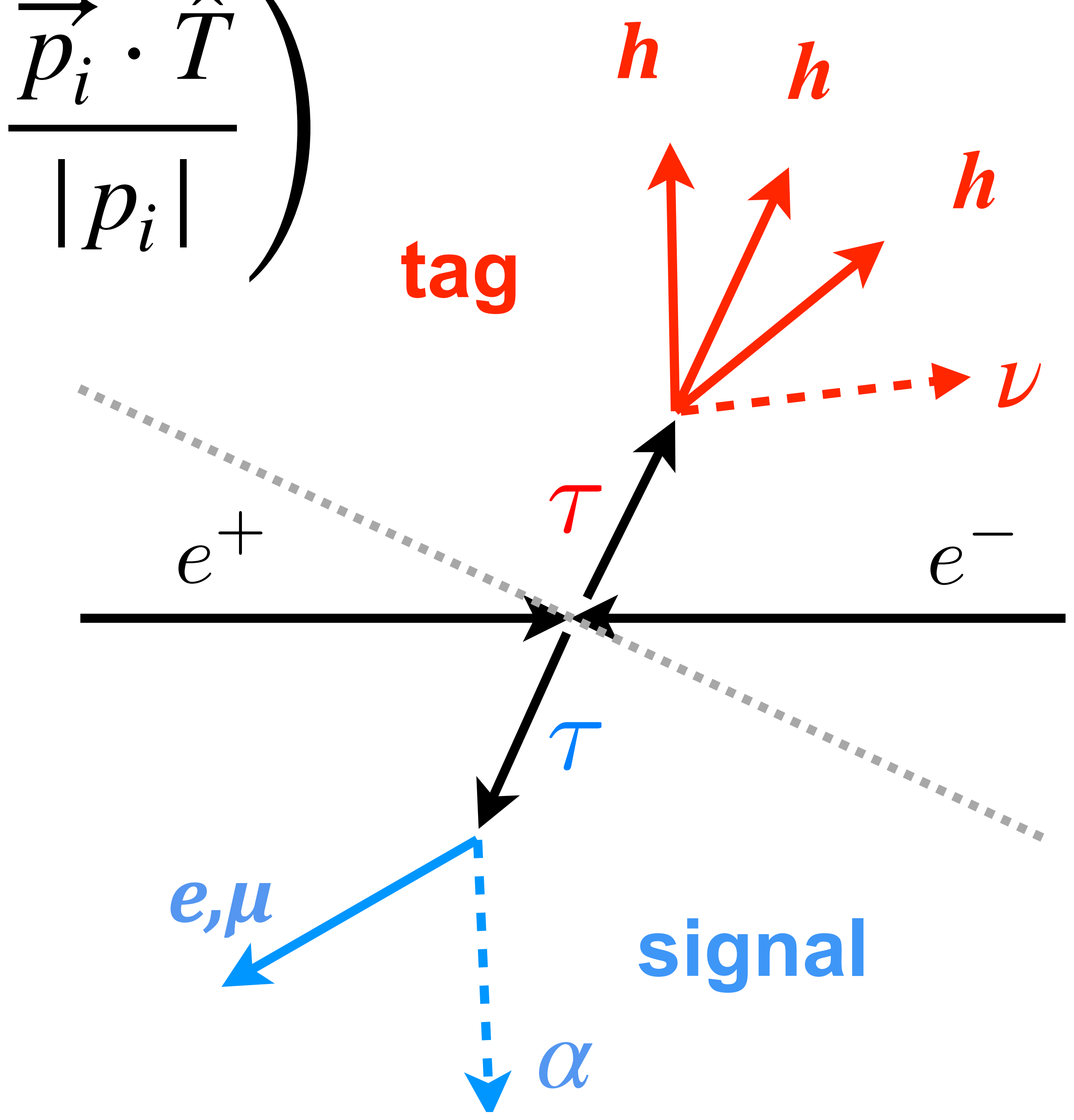
Central Drift Chamber
Spatial resolution: 100 µm
***dE/dx* resolution:** 5%
p_T resolution: 0.4%

Particle Identification
K/π-ID: π fake rate 1.8%
at ϵ(K)=95%

$\tau\to\ell\alpha$ reconstruction (in a nutshell)

Analyzed data:
62.8 fb^{-1}

- Split event in two hemispheres across thrust axis $\vec{T} = max\left(\sum_i \frac{\vec{p_i}\cdot\hat{T}}{|p_i|}\right)$
- Require exactly 4 tracks:
    - *signal* with **1 lepton** track.
    - *tag* with **3-pion** vertex identifying the $\boldsymbol{\tau\to 3\pi\nu}$ decay.
    - **veto** neutrals ($\boldsymbol{\pi^0}$,γ) to suppress hadronic background.



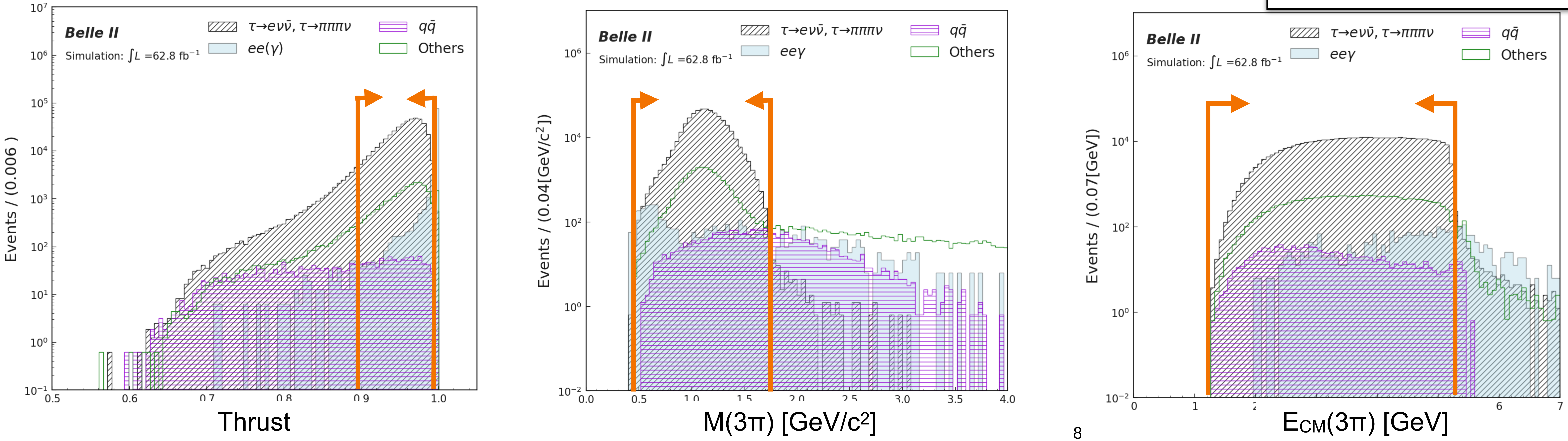
- Individual $\boldsymbol{\tau\to\ell\alpha}$ events are indistinguishable from $\boldsymbol{\tau\to\ell\bar{\nu}\nu}$ (irreducible background).
- Reducible background: **q$\bar{\text{q}}$**, $\ell^+\ell^-$, $\ell^+\ell^-\ell^+\ell^-$, $\ell^+\ell^-h^+h^-$, and correctly-tagged $\boldsymbol{\tau^+\tau^-}$ with misidentified signal (e.g. $\boldsymbol{\tau\to\pi\nu}$) → suppressed by selection cuts.

Background suppression

$$\text{FOM} = \frac{N_{SM}}{\sqrt{N_{SM} + B}}$$

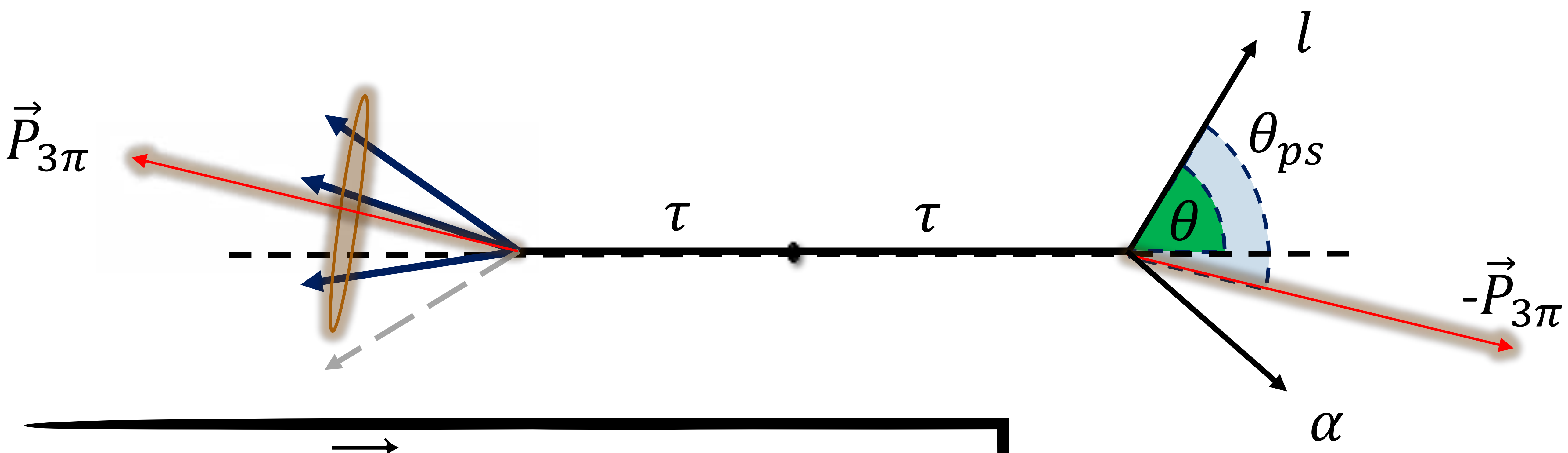
- We do not know the mass of the $\boldsymbol{\alpha}$ → Optimise selection using SM $\boldsymbol{\tau \rightarrow \ell \bar{\nu} \nu}$.
- Use "safe" variables which cannot distinguish between $\boldsymbol{\tau \rightarrow \ell \bar{\nu} \nu}$ and $\boldsymbol{\tau \rightarrow \ell \alpha}$.
- High purity: 96(e)-92(μ)% with ϵ=9-17% depending on $\boldsymbol{\alpha}$.

electron channel example

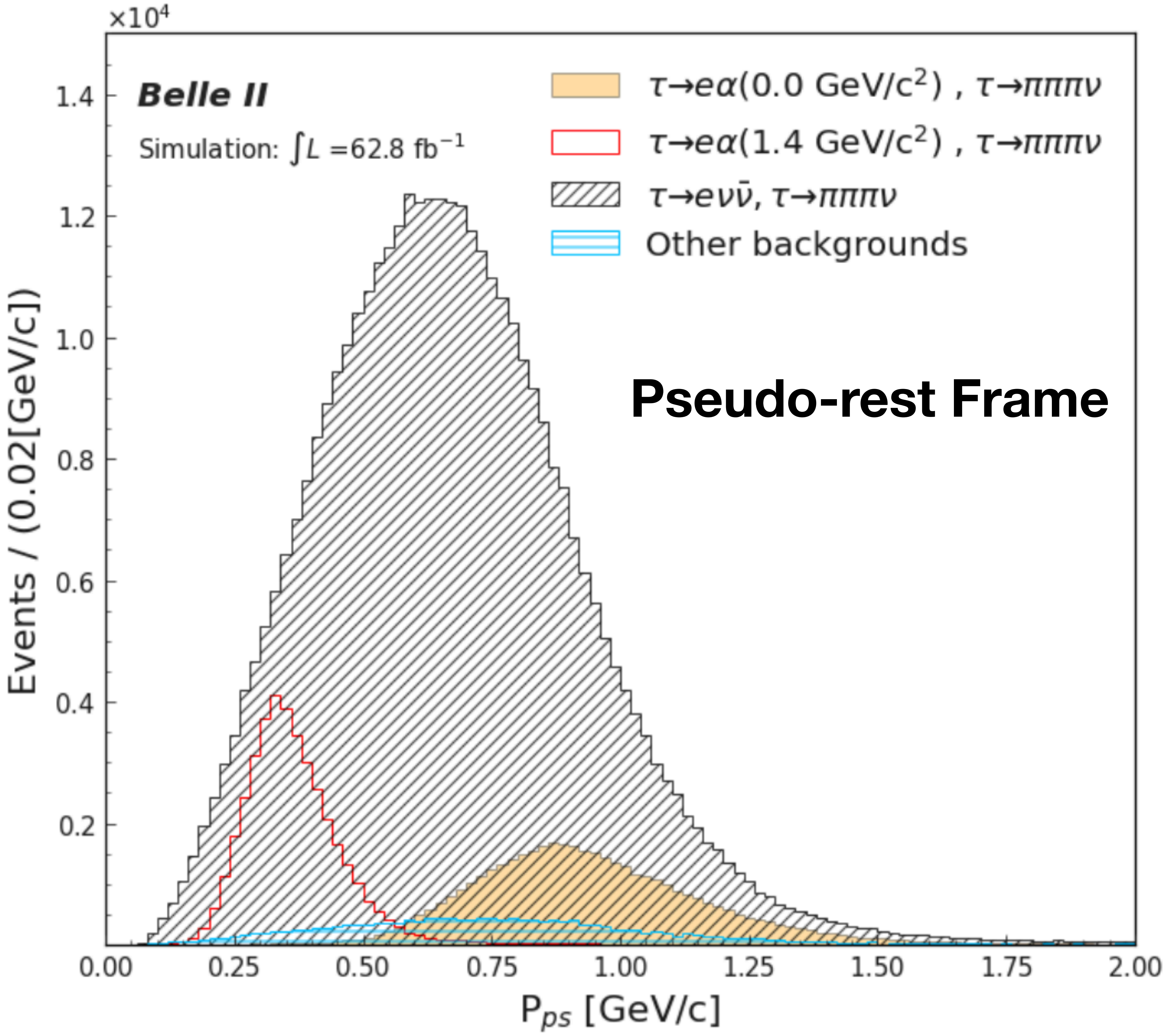


Event signature

- After background suppression, we search for an excess above the SM spectrum.
- The most prominent $\boldsymbol{\tau \to \ell \alpha}$ signal would be in the $\boldsymbol{\tau}$ rest frame (monochromatic peak)
- **Cannot** boost to it due to undetected $\boldsymbol{\nu}$ in both $\boldsymbol{\tau}$.
- We approximate using the *pseudo-rest frame:*



$$\hat{p}_\tau \approx -\frac{\overrightarrow{p}_{tag}}{|\overrightarrow{p}_{tag}|}, \quad E_\tau \approx \sqrt{s}/2$$



Signal extraction fit

- Construct **template pdfs** $f(x_\ell)$ using MC where $x_\ell \equiv E_\ell/(m_\tau/2)$
- Data modeled as:

$$\frac{dN}{dx_\ell} = \overbrace{N_{\ell\bar{\nu}\nu}\,\frac{\epsilon_{\ell\alpha}}{\epsilon_{\ell\nu\nu}}\,\underbrace{\frac{\mathrm{B}(\tau\to\ell\alpha)}{\mathrm{B}(\tau\to\ell\bar{\nu}\nu)}}_{R}}^{N_{\tau\alpha}} f_{\ell\alpha}(x_\ell)+N_{\ell\bar{\nu}\nu}f_{\ell\bar{\nu}\nu}(x_\ell)+N_{\mathrm{b}}f_{\mathrm{b}}(x_\ell)$$

and N, R are free parameters.

- Signal and SM systematics will partially cancel out in the ratio R.
- Template fit, followed by hypothesis test scan to extract relative BR UL (asymptotic CLs method - profile likelihood ratio test statistic)

Corrections and systematic uncertainties

- Correct template PDFs for
  - **Lepton ID efficiency and fake rate**
  - Low multiplicity **trigger efficiency.**
  - (Vetoed) **π^0 reconstruction efficiency**

→

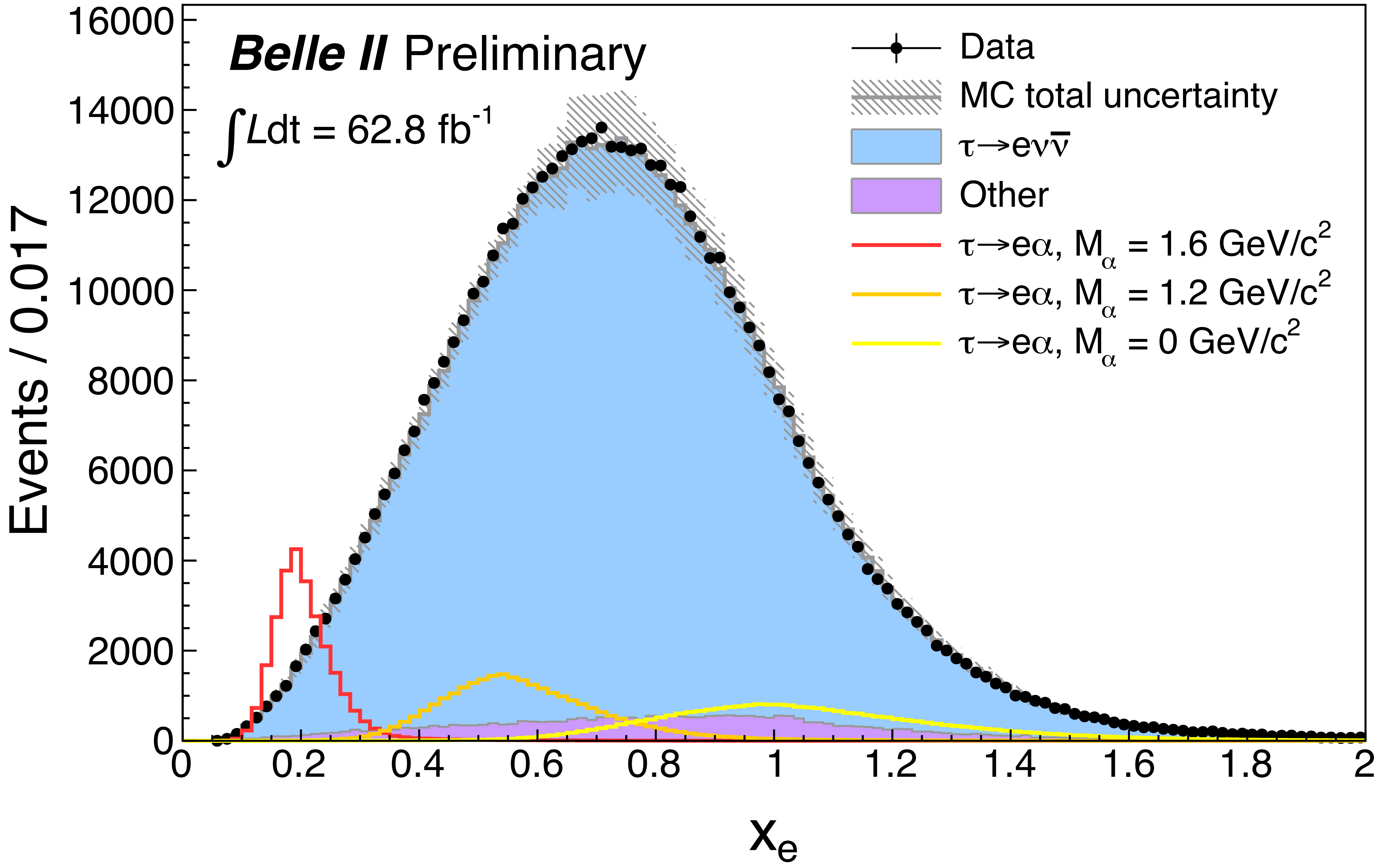
Differing $\tau\to\ell\bar{\nu}\nu$ and $\tau\to\ell\alpha$ kinematic regimes lead only to partial cancellation.

→ systematics still matter!

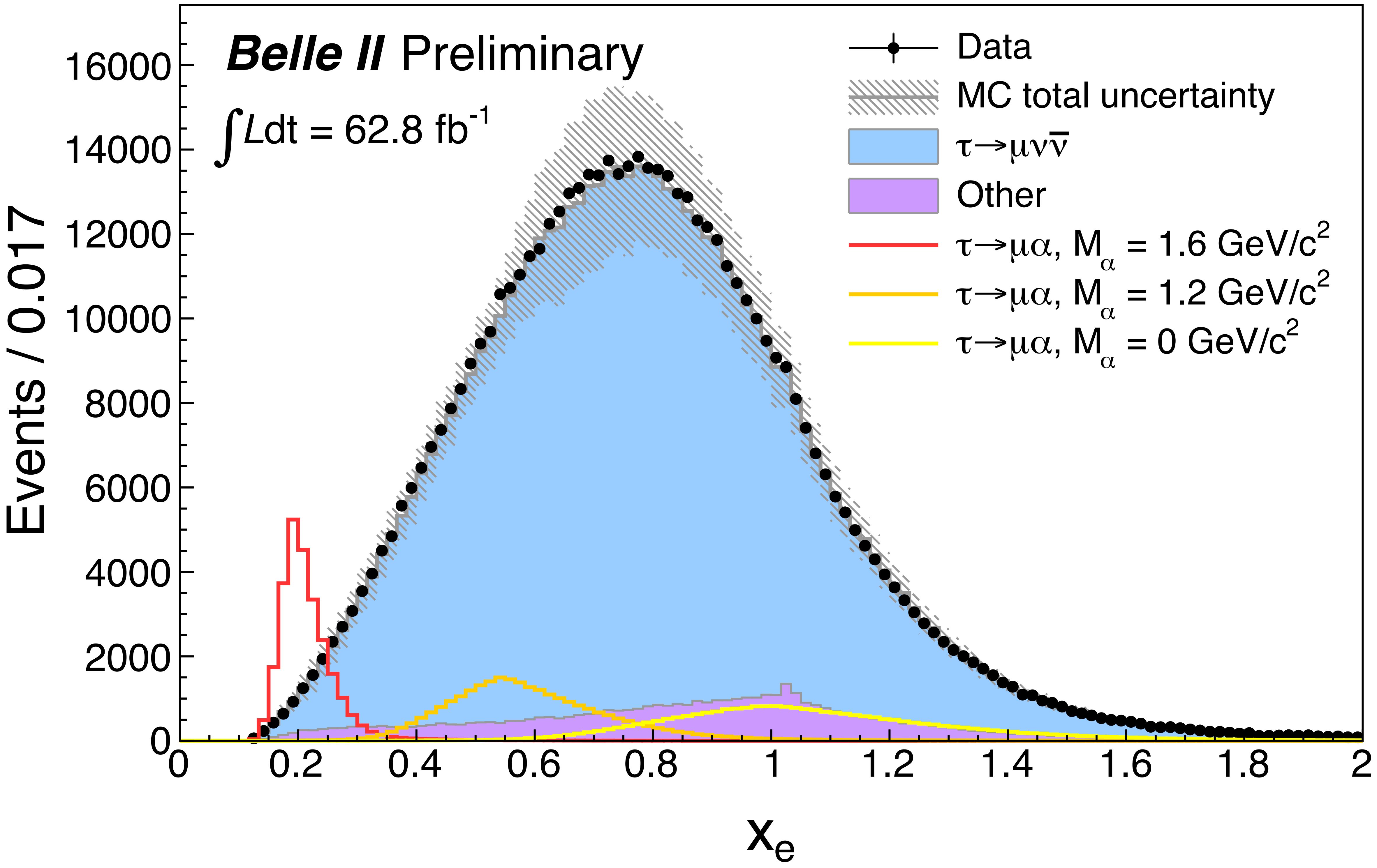
- Associated systematic uncertainties each implemented as a shape-correlated nuisance parameter (Gaussian, with $\pm\sigma$ corresponding to the per-bin variation).
- Overall effect degrades sensitivity by **~30%** (dominated by **lepton ID**).
  - Improvements in particle ID would directly impact future sensitivity.

Data and MC spectra

Electrons



Muons

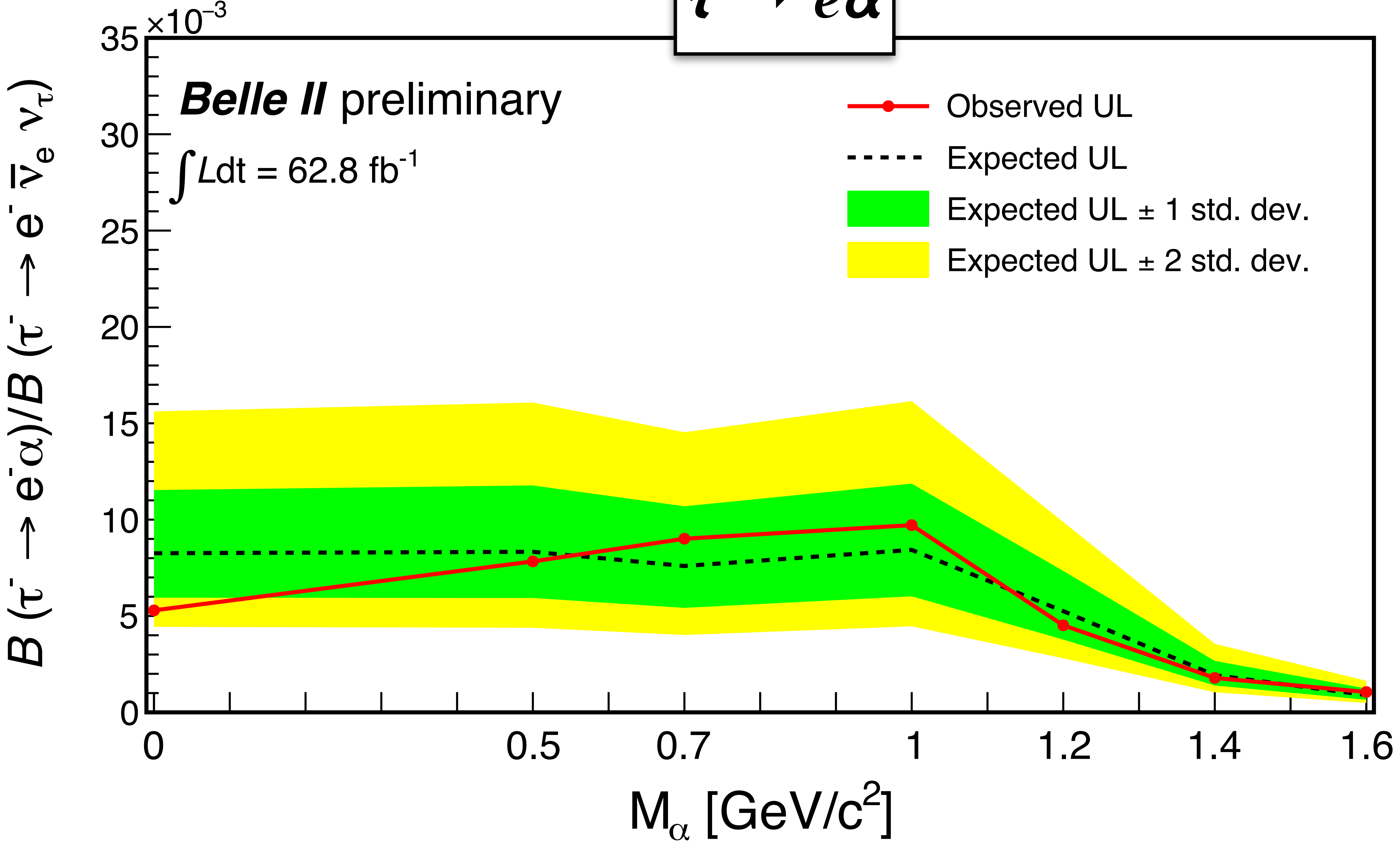


- $\boldsymbol{\tau \rightarrow \ell \alpha}$ channels shown normalised to a BF of 5%.

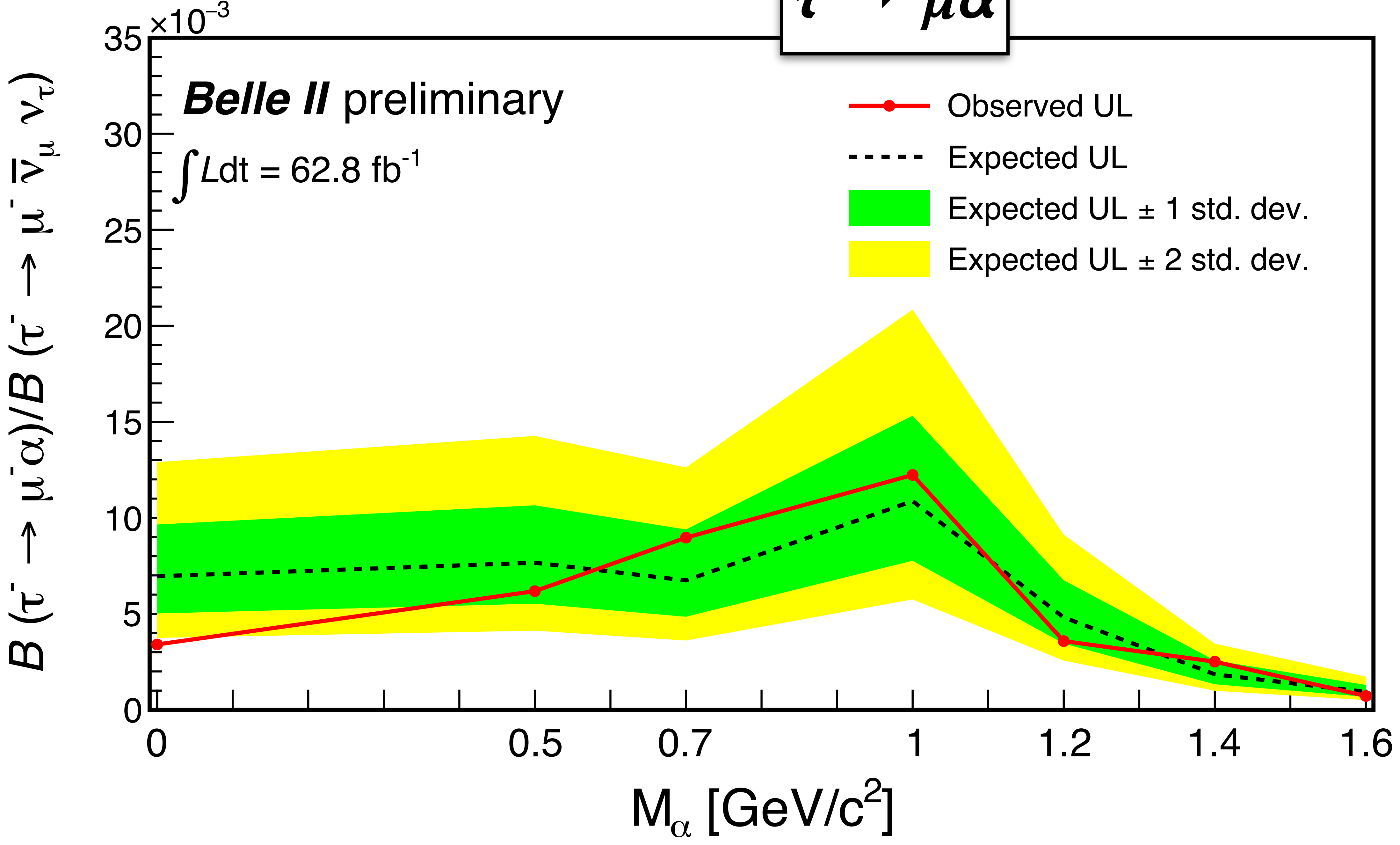
Analysis results

- We observe no signal and set 95% confidence level upper limits on B($\boldsymbol{\tau \to \ell \alpha}$) / B($\boldsymbol{\tau \to \ell \bar{\nu} \nu}$).
- Most stringent measurements in these channels to date.

$\boldsymbol{\tau \to e\alpha}$

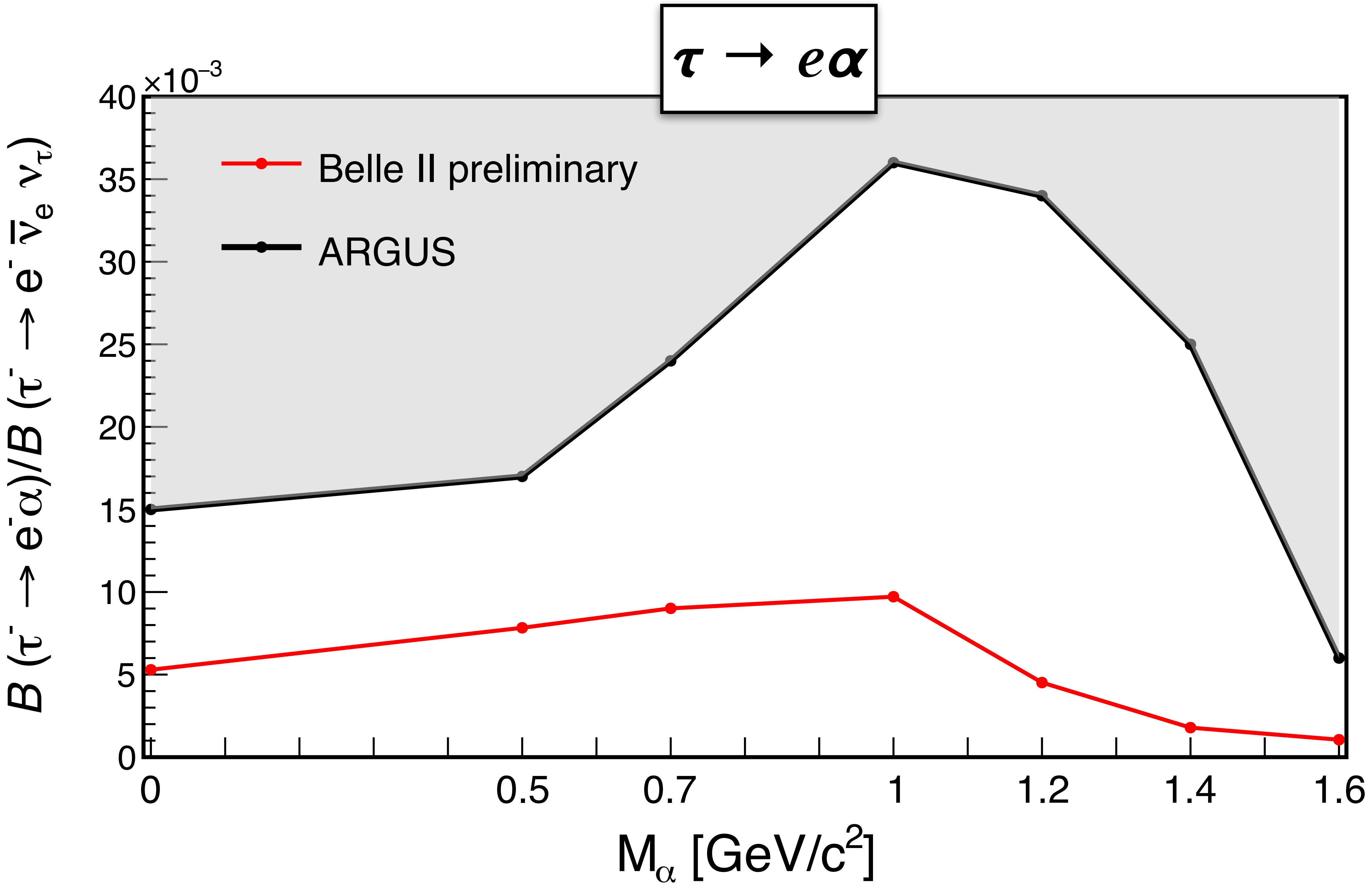


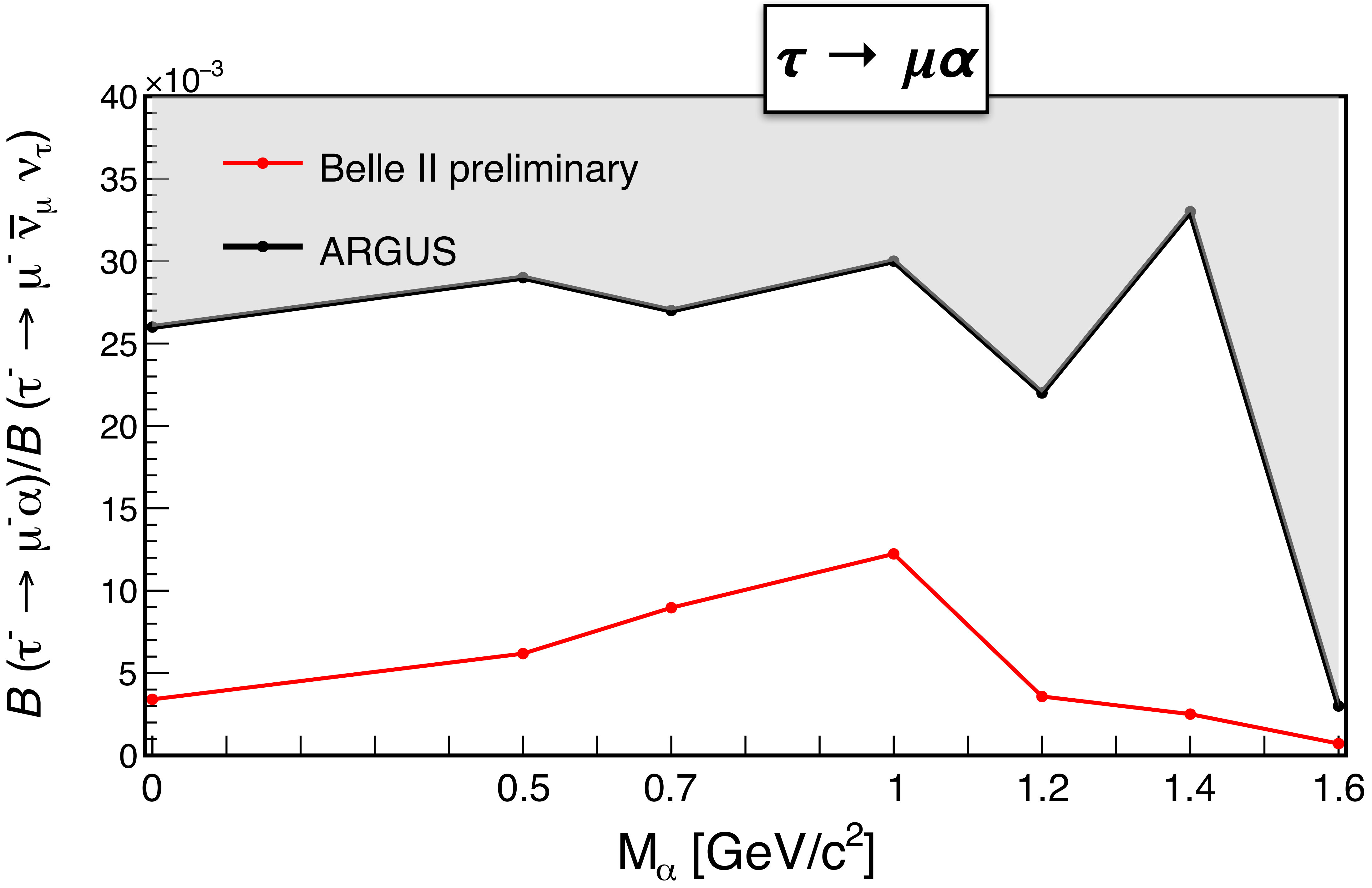
$\boldsymbol{\tau \to \mu\alpha}$



Analysis results (comparison to past limit)

- We observe no signal and set 95% confidence level upper limits on B($\boldsymbol{\tau} \rightarrow \boldsymbol{\ell\alpha}$) / B($\boldsymbol{\tau} \rightarrow \boldsymbol{\ell\bar{\nu}\nu}$).
- Most stringent measurements in these channels to date.

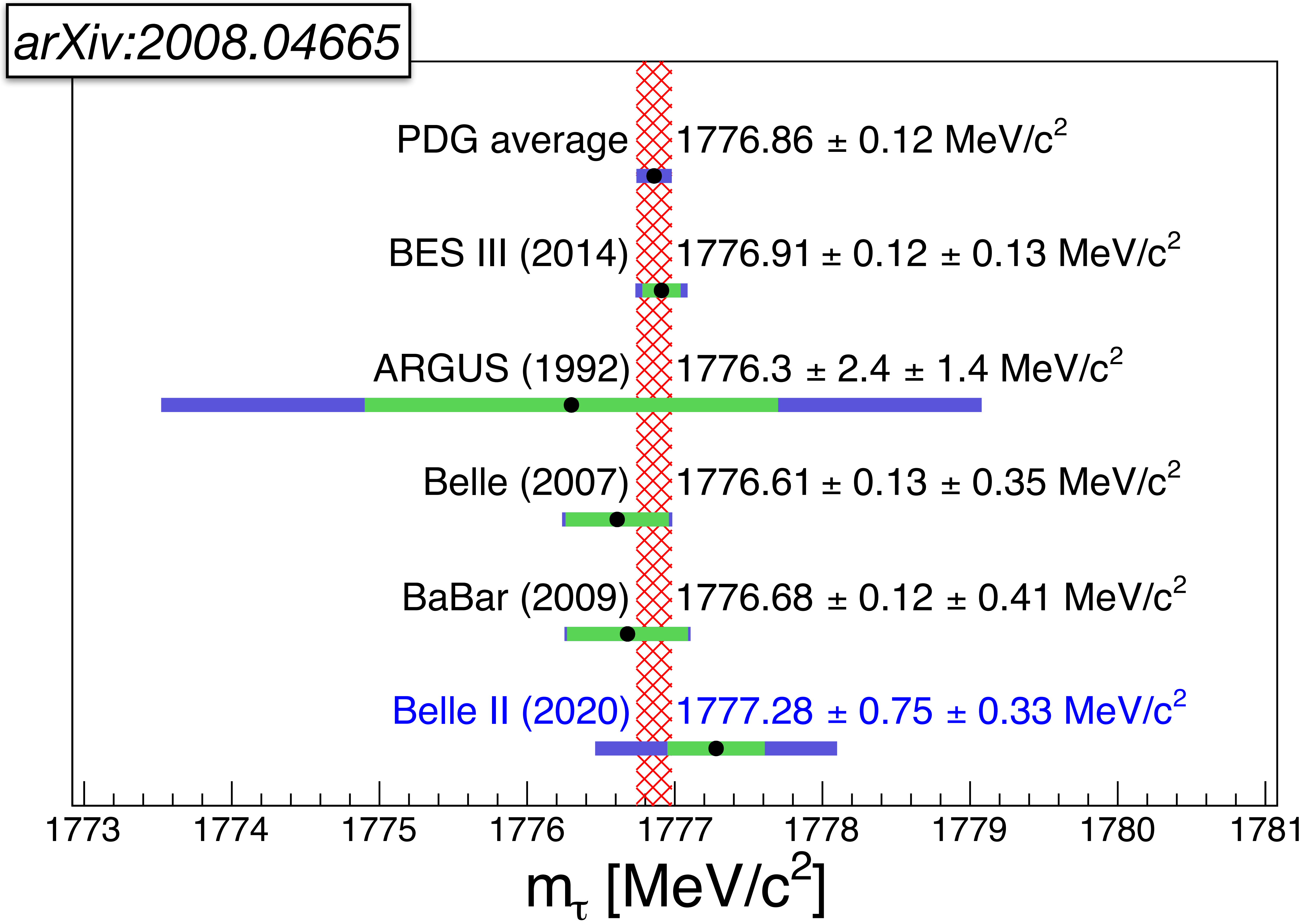




Other τ perspectives at Belle II

- **τ mass and lifetime** → crucial inputs for lepton flavour universality tests.

arXiv:2008.04665



- **Mass** systematics already comparable to Belle/BaBar in preliminary studies.

  → Improve statistics with 2022 luminosity.

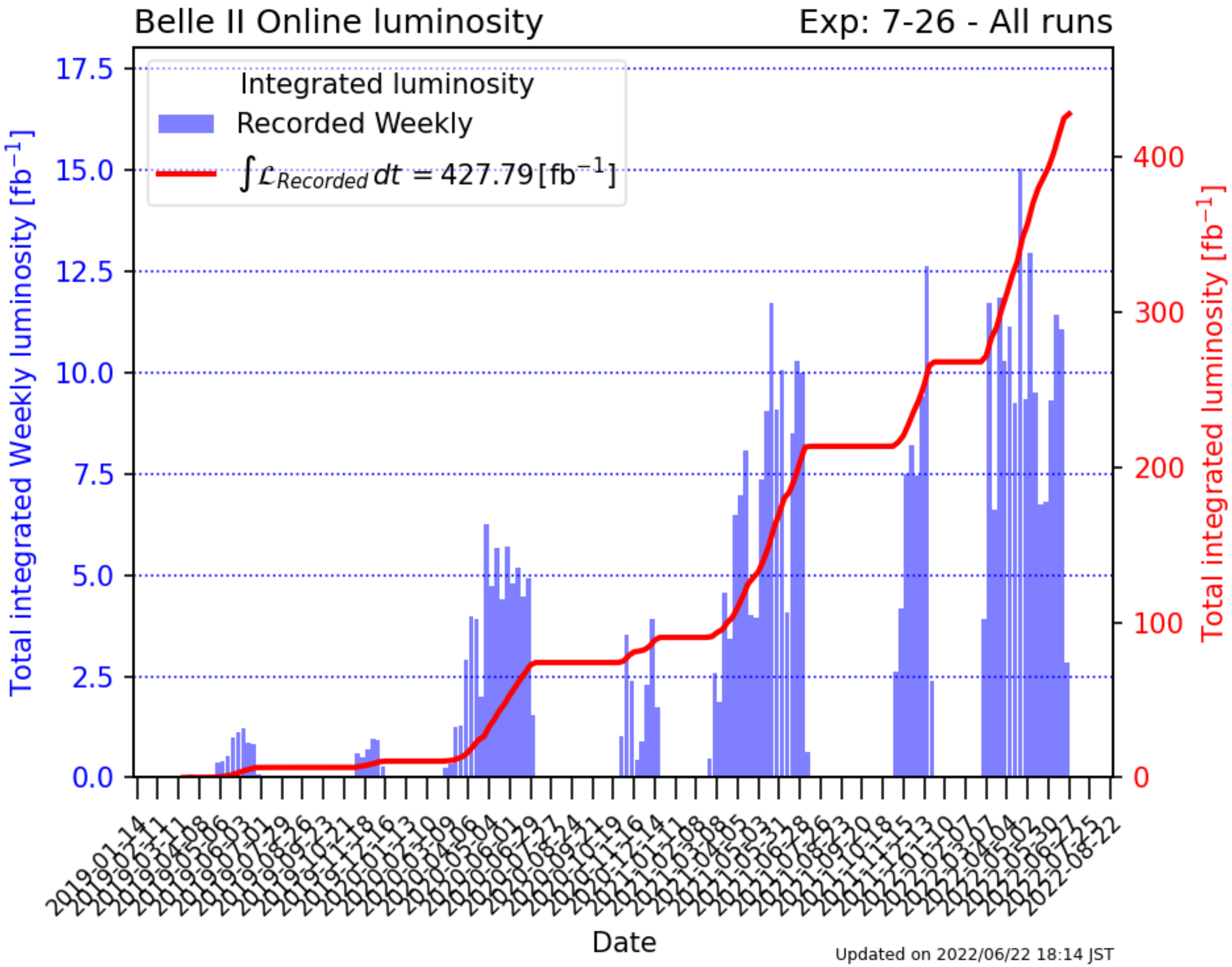
- Improved vertex reconstruction (**x2** of Belle) allows precise **lifetime** measurements and study of **CP violation** in $\tau \rightarrow K_S \pi \nu$.
- Wide range of other observables e.g. lepton universality, V_{us} from hadronic decays, anomalous moments, etc.

Summary

- Belle II provides a fertile environment for precision tau physics.
- We performed an analysis of $\boldsymbol{\tau \rightarrow \ell + \alpha}$ (invisible) using 62.8 fb^{-1} of Belle II data.
  - 3x1 decay topology ($\boldsymbol{\tau \rightarrow 3\pi\nu}$ tag).
  - 95% CL ULs extracted with template fit of normalized energy spectrum.
- The resulting limit is the **most stringent** yet on this process.
- Belle II will be the leading tau factory in the coming years, providing direct and/or indirect insights into new physics.

BACKUP

Belle II 2022 luminosity



Background suppression (Pt)

electron channel