# Tau Physics at Belle II

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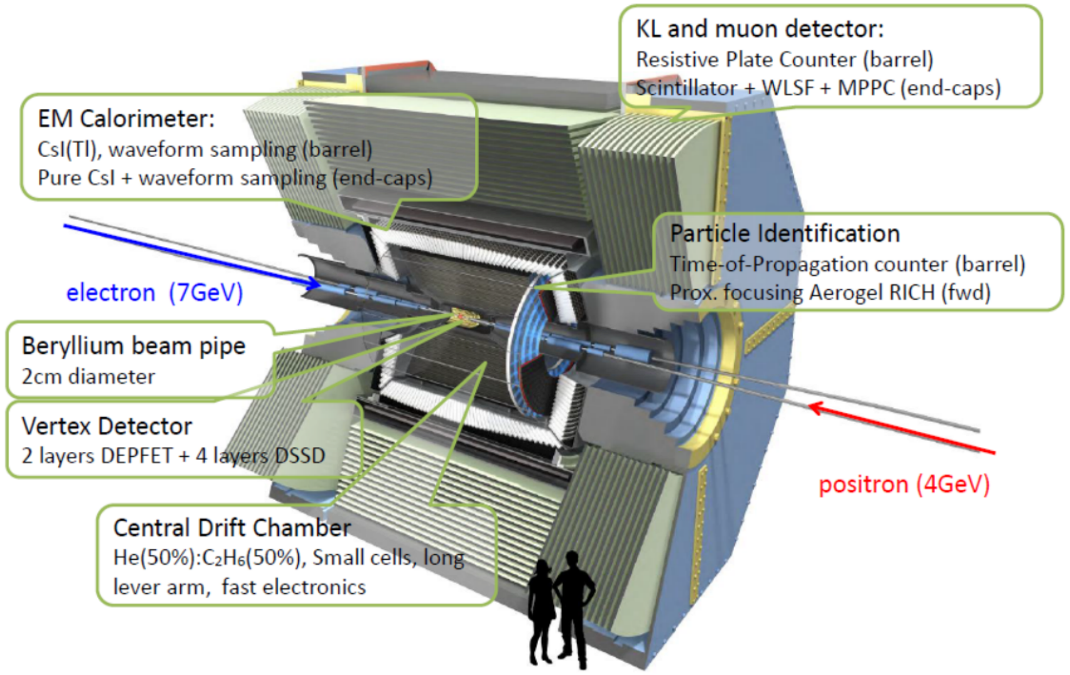
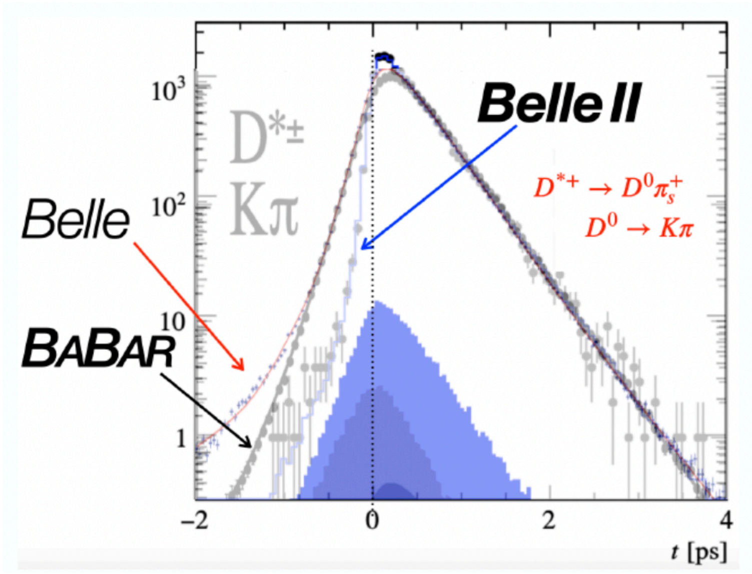
# Belle II Detection

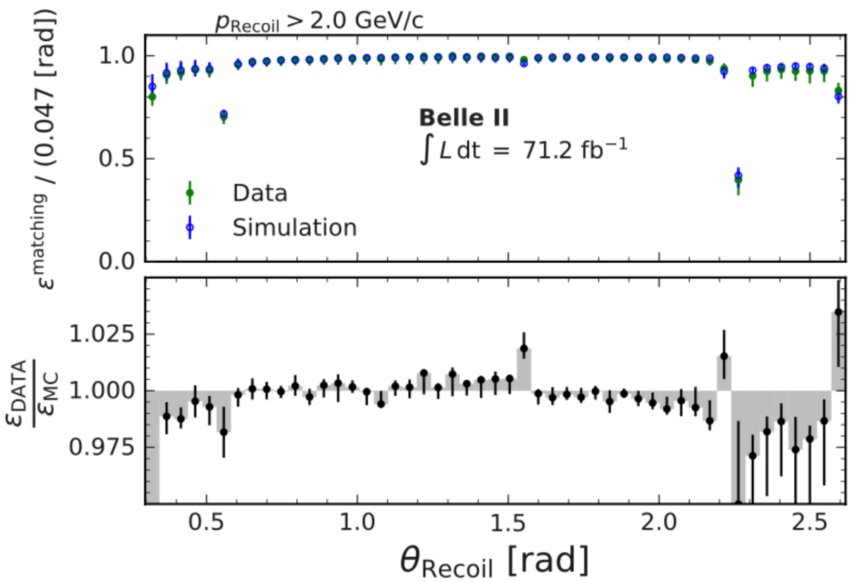
**Belle → Belle II detector**

- new 2-layer Pixel Detector with first layer at 1.4cm
- 4-layer Silicon Vertex Detector with larger acceptance
- Central Drift Chamber with larger outer radius
- improved particle ID (K/π separation)
- improved trigger, and faster electronics in general

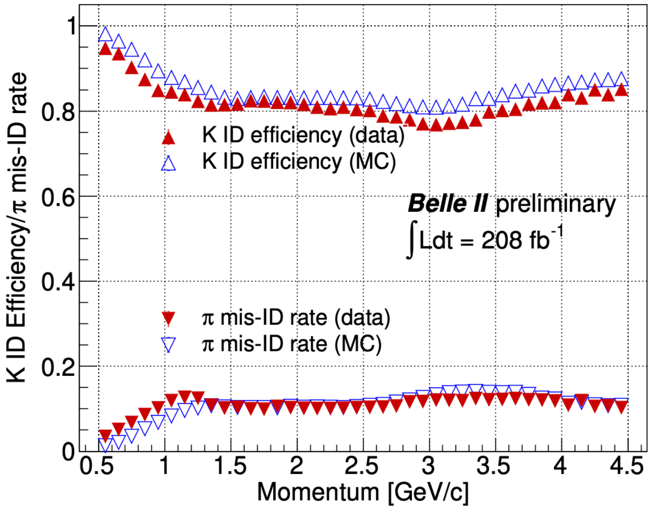



Great improved time resolution

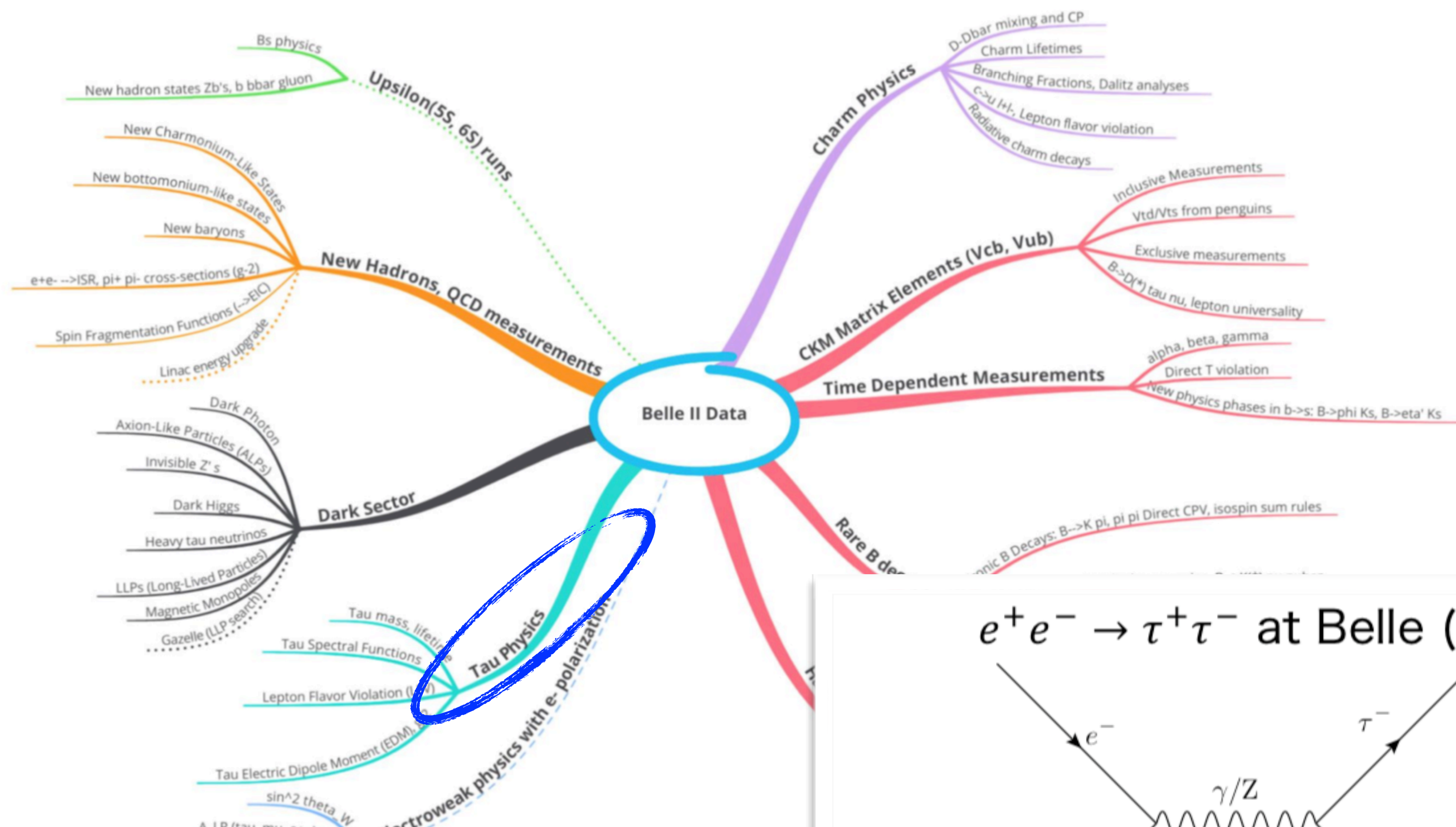


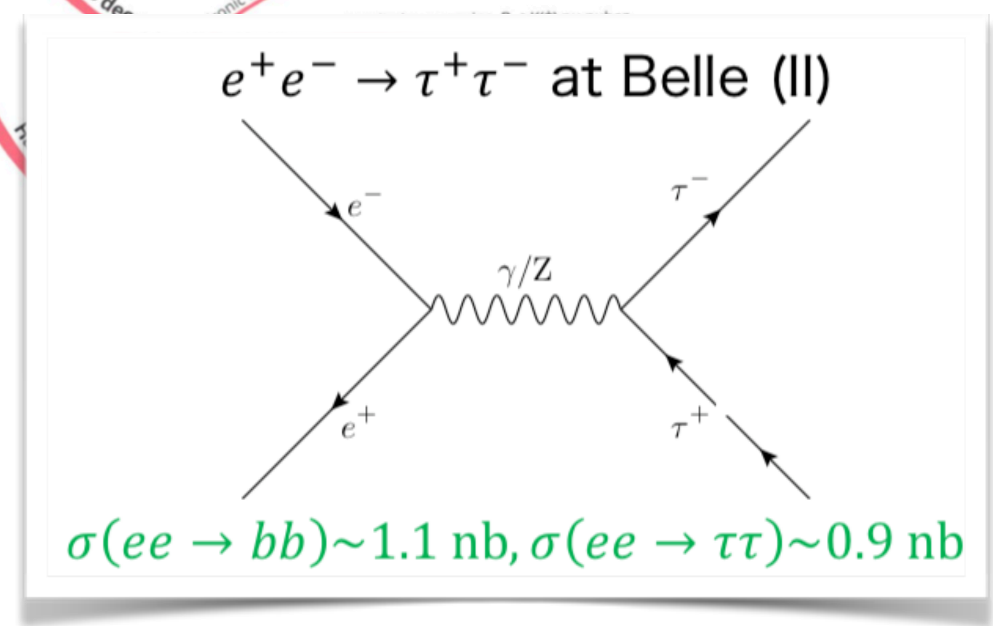

High photon efficiency




Good Kaon identification

# Belle II Physics




τ physics at B-factories

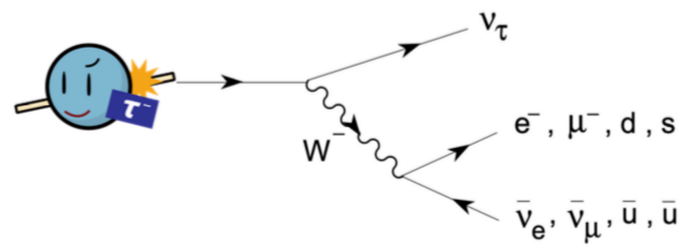
- Produced in pairs
- Precise initial energy
- Clear environment
- High hermeticity of the detector

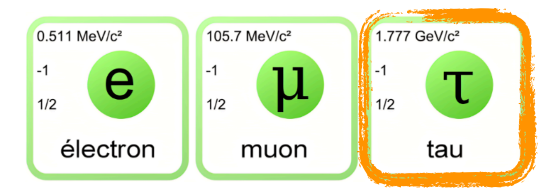
Belle II: 424 fb$^{-1}$ → ~390 million tau pairs

# Tau physics

τ lepton

- heaviest lepton in SM
- Sensitive to new physics




- Lepton Flavor Violation

Observation → Clear signs of new physics

$\tau \to \ell\ell\ell$

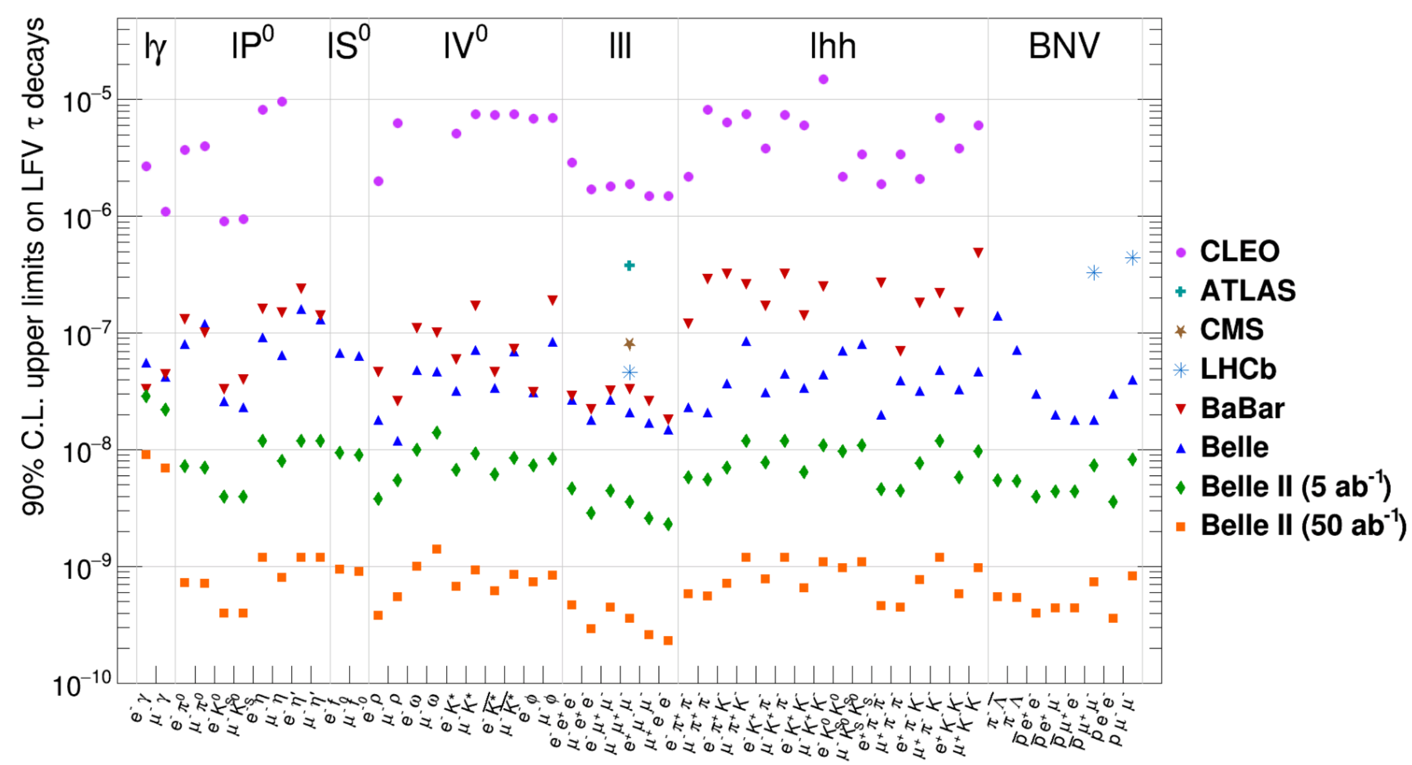
$\tau \to \ell K_s, \Lambda h$

$\tau \to \ell V_0 (\to hh')$

$\tau \to \ell P^0\ (\to \gamma\gamma)$

$\tau \to \ell hh'$

$\tau \to \ell\gamma$




*Belle II Snowmass White Paper*
*arXiv: 2203.14919*

- Lepton Flavor Universality

Deviation from the SM → Indirect signs of new physics

# Tau physics at Belle II

**LFV**

**$\tau \to l\phi$**
**$\tau \to l\alpha$**
**$\tau \to \mu\mu\mu$**

**LFU**

$$R_\mu = \frac{\mathcal{B}(\tau^- \to \nu_\tau \mu^- \overline{\nu}_\mu(\gamma))}{\mathcal{B}(\tau^- \to \nu_\tau e^- \overline{\nu}_e(\gamma))}$$

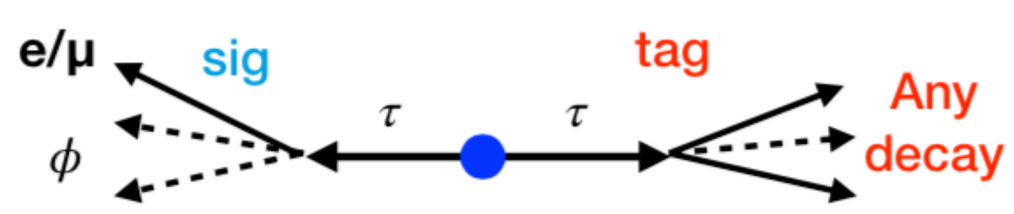
**$\tau$ mass measurement**

# τ→e/μ φ

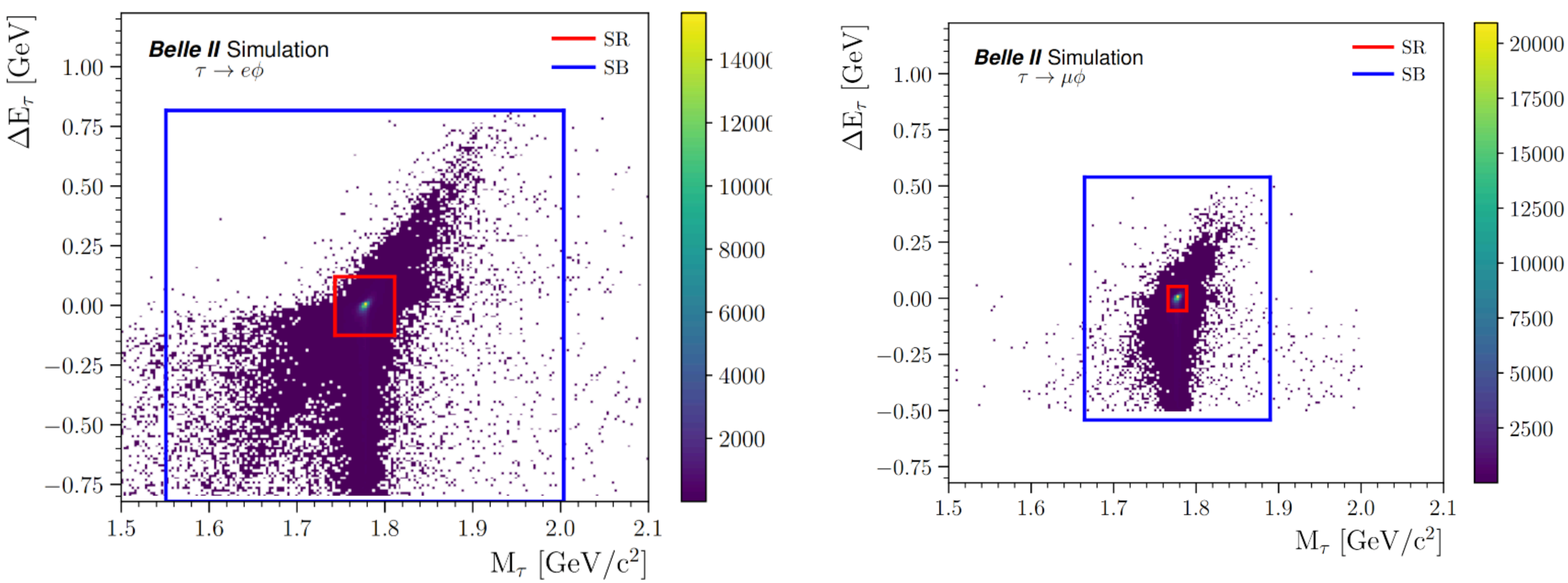
*arXiv: 2305.04759*

$L$=190 fb$^{-1}$

untagged approach




- Definition of a SR via the $M_{l\phi}$ and $\Delta E_{l\phi} = E^*_{l\phi} - \sqrt{s}/2$
- Event selection and background rejection using via BDT

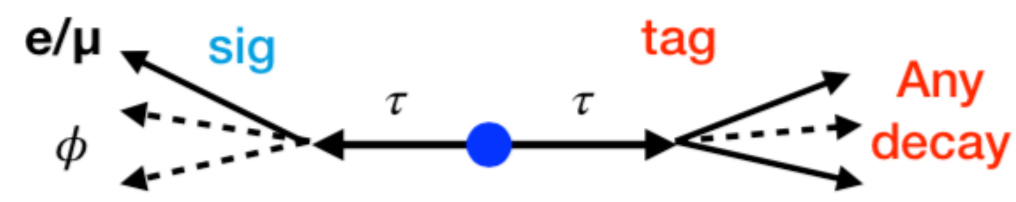


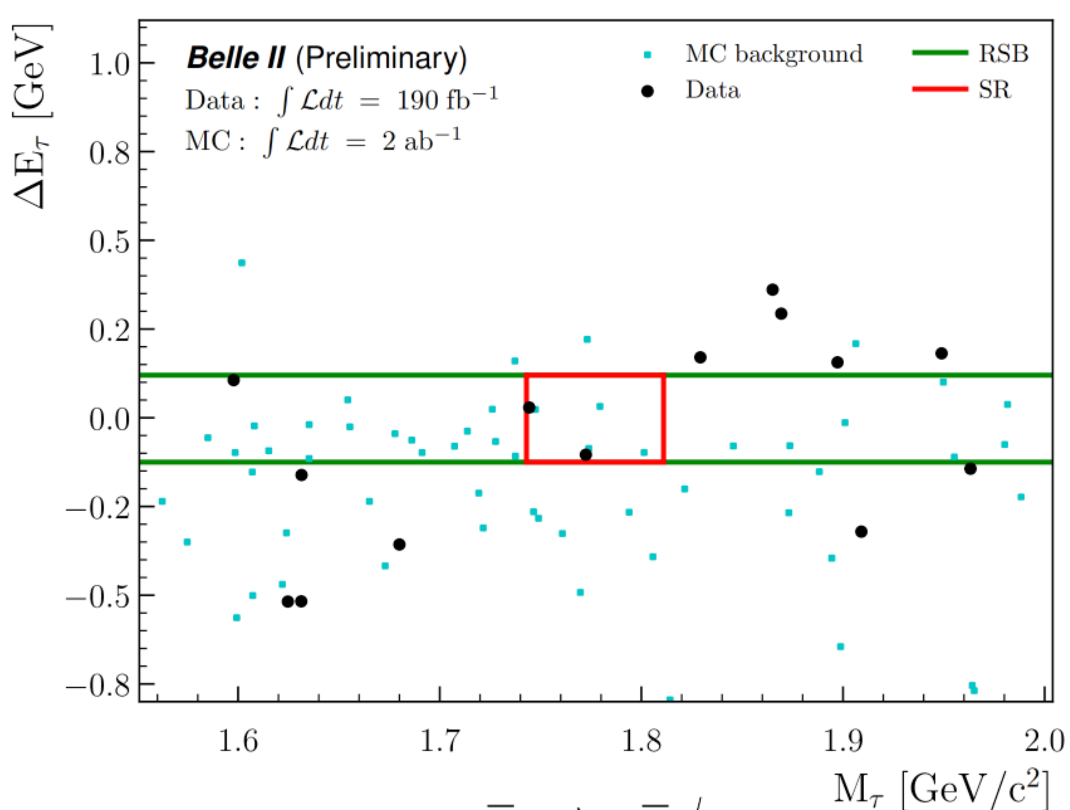
# $\tau \to e/\mu\ \phi$

arXiv: 2305.04759

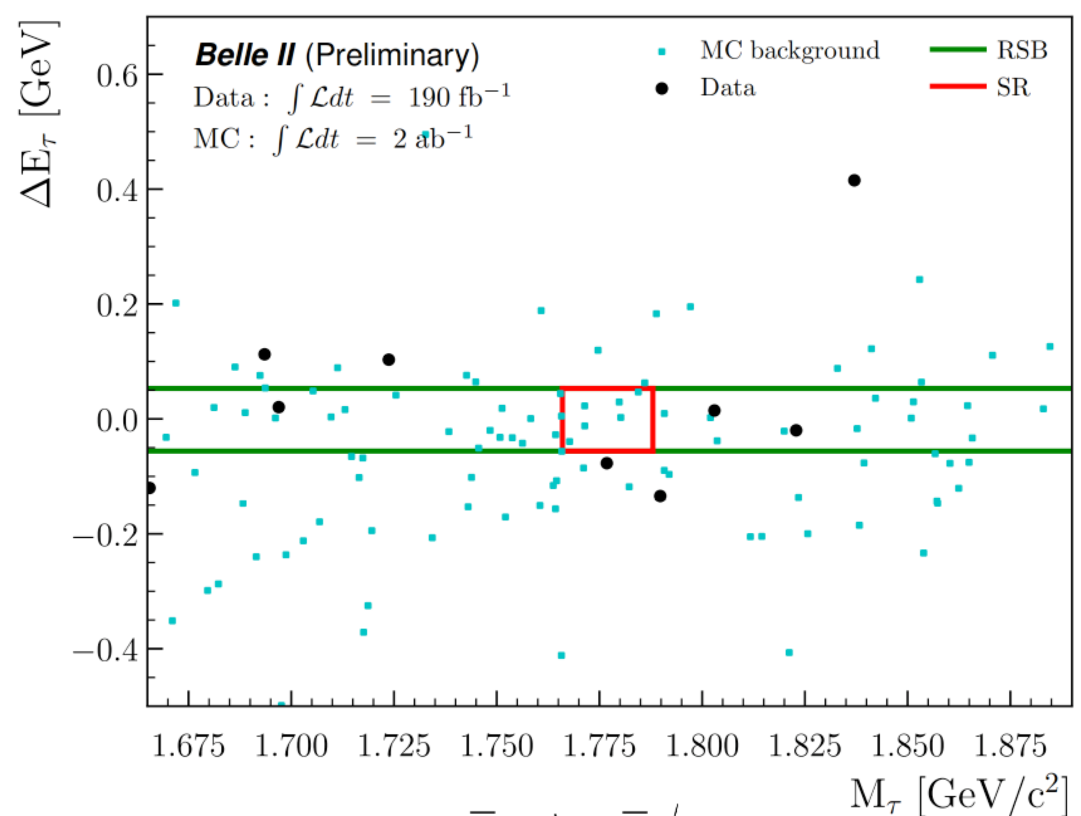
untagged approach

- Background events are evaluated from data in the sideband
- Perform Poisson counting experiment approach in SR




$\tau^- \to e^- \phi$



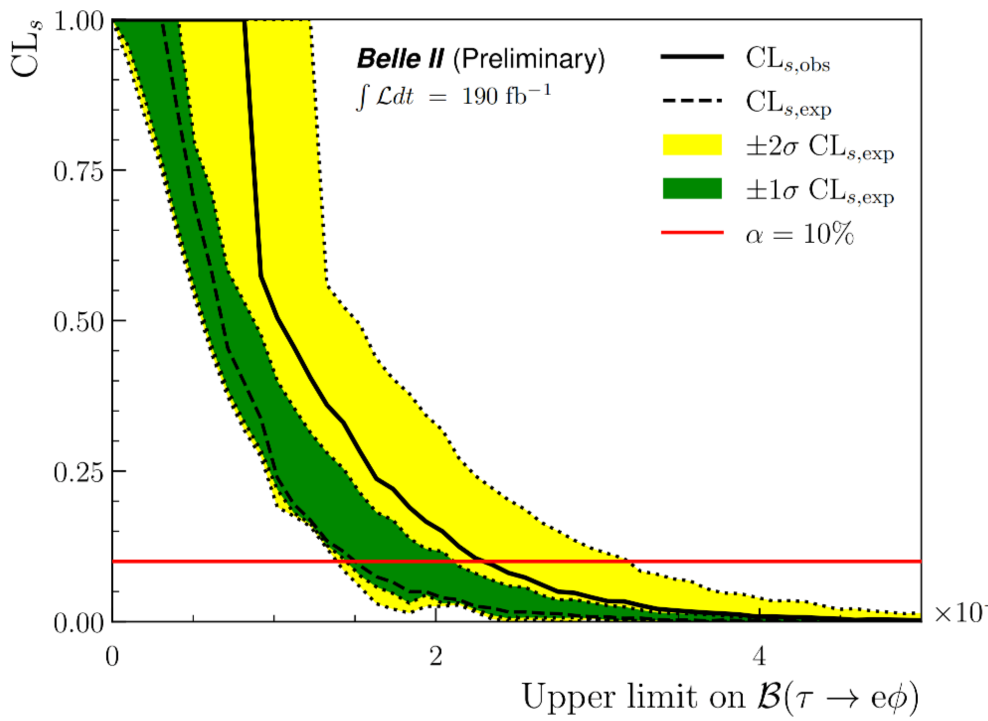

$\tau^- \to \mu^- \phi$

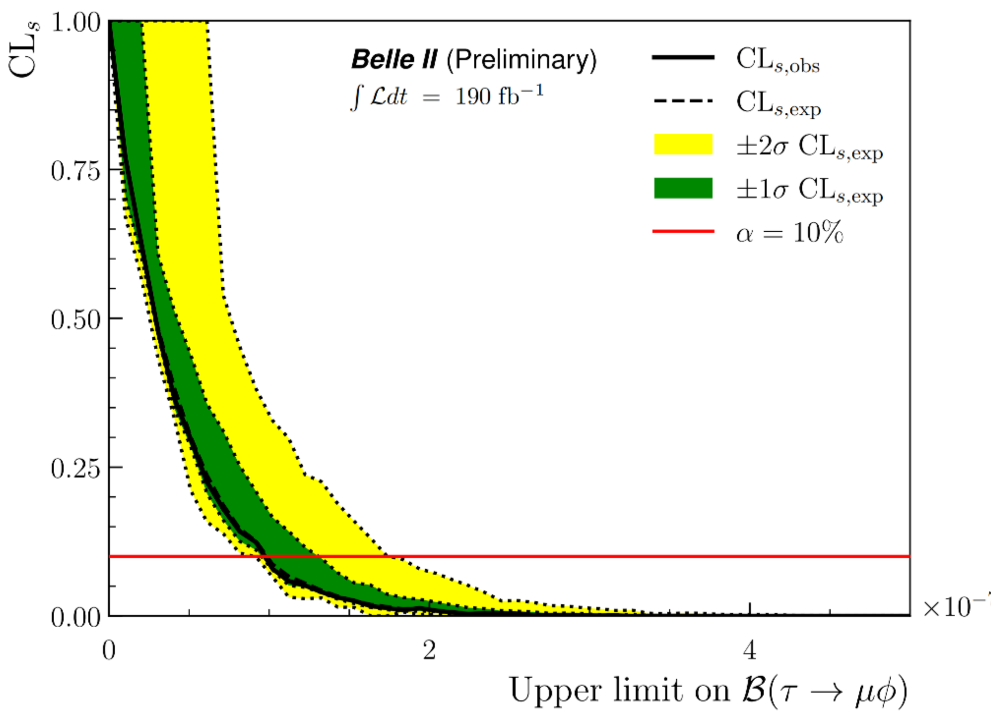
# $\tau \to e/\mu\ \phi$

arXiv: 2305.04759

No evidence→set ULs at 90% C.L.

$$\mathcal{B}_{\text{UL}}(\tau \to \ell\phi) = \frac{s}{L \times 2\sigma_{\tau\tau} \times \varepsilon_{\ell\phi}}$$




Obs. $B_{\text{UL}}(\tau \to e\phi) = 23 \times 10^{-8}$
Exp. $B_{\text{UL}}(\tau \to e\phi) = 15 \times 10^{-8}$

$B_{\text{UL}}(\tau \to e\phi) = 2.0 \times 10^{-8}$ at Belle

Obs. $B_{\text{UL}}(\tau \to \mu\phi) = 9.7 \times 10^{-8}$
Exp. $B_{\text{UL}}(\tau \to \mu\phi) = 9.9 \times 10^{-8}$

$B_{\text{UL}}(\tau \to \mu\phi) = 2.3 \times 10^{-8}$ at Belle

# $\tau \rightarrow e/\mu\ \alpha$

*PRL 130,181803 (2023)*

*L*=62.8 $fb^{-1}$

α: invisible spin-0 boson, e.g. Axion-like particle

Upper limit from ARGUS in 1995 [ZPC 68,25,1(995)]

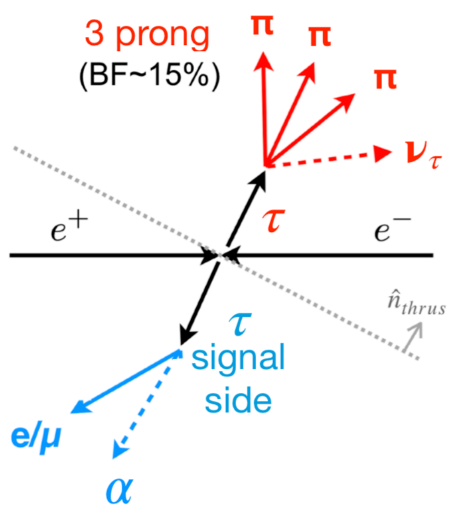
$$\mathcal{B}(\tau^{\pm} \to e^{\pm}\alpha)/\mathcal{B}(\tau^{\pm} \to e^{\pm}\nu\bar{\nu}) \quad < \quad (0.6 - 3.4) \times 10^{-2},$$
$$\mathcal{B}(\tau^{\pm} \to \mu^{\pm}\alpha)/\mathcal{B}(\tau^{\pm} \to \mu^{\pm}\nu\bar{\nu}) \quad < \quad (0.3 - 3.6) \times 10^{-2},$$

$$0.0 < m_{\alpha} < 1.6 \text{ GeV}$$

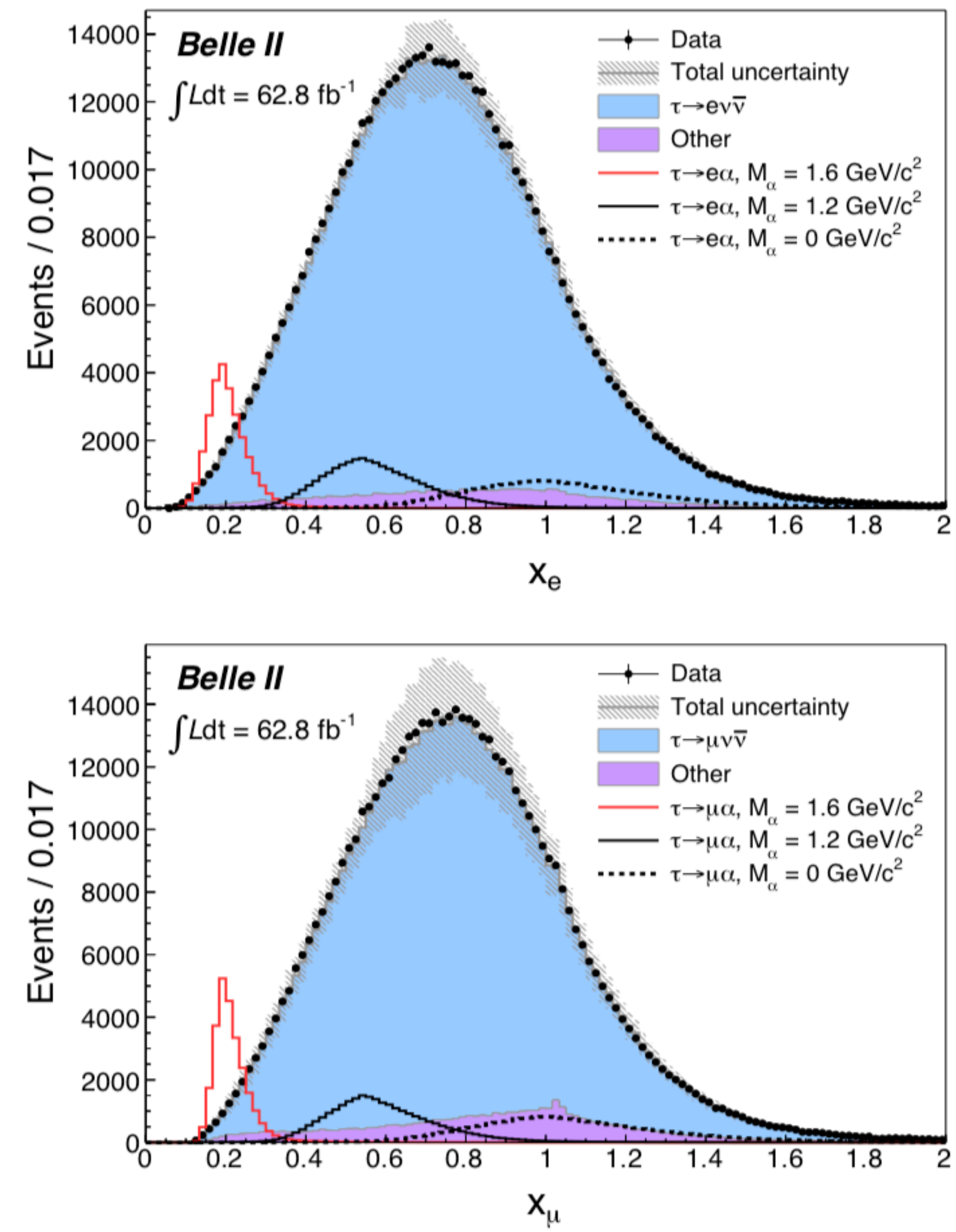
# $\tau \to e/\mu\ \alpha$

PRL 130,181803 (2023)

$L$=62.8 fb$^{-1}$




- Tag side: $\tau \to 3\pi\nu_\tau$
- Pseudo-rest frame implies:
  - $\overrightarrow{p_\tau} \sim -\vec{p}_{3\pi}$
  - $E_\tau \sim \sqrt{s}/2$
- Veto neutrals: $\pi^0, \gamma$




Discriminating variable

$$x_\ell \equiv \frac{E^*_\ell}{m_\tau c^2/2}$$

$E^*$: lepton energy in the τ rest frame

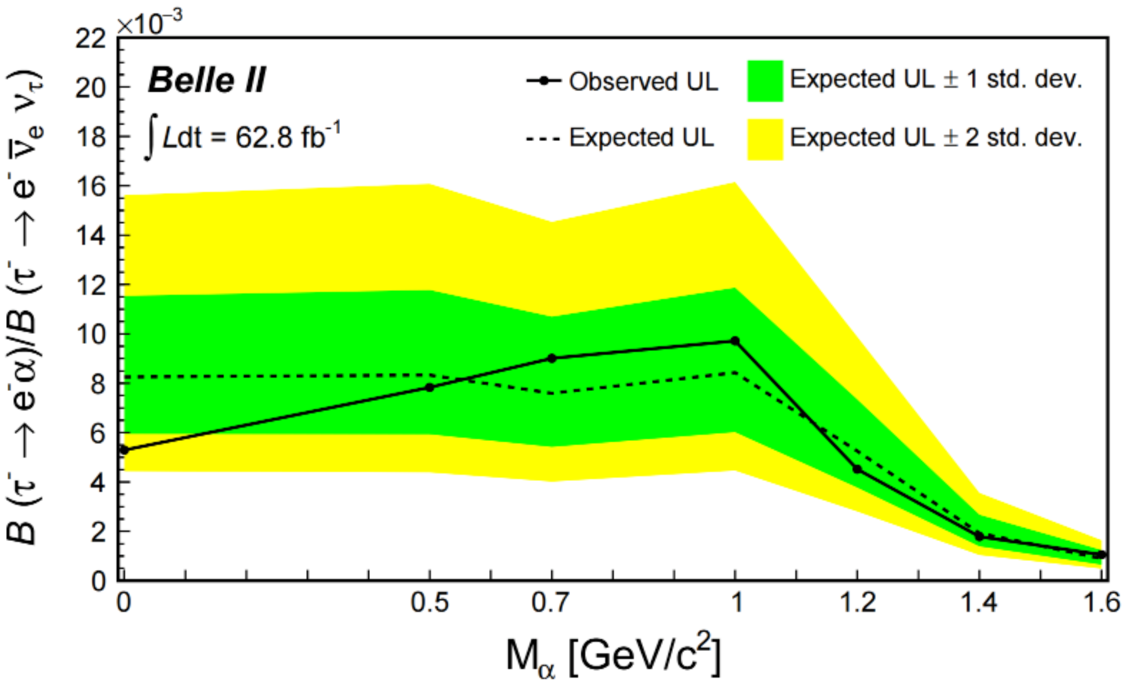
Signal signature: bump in the $x_l$ distribution

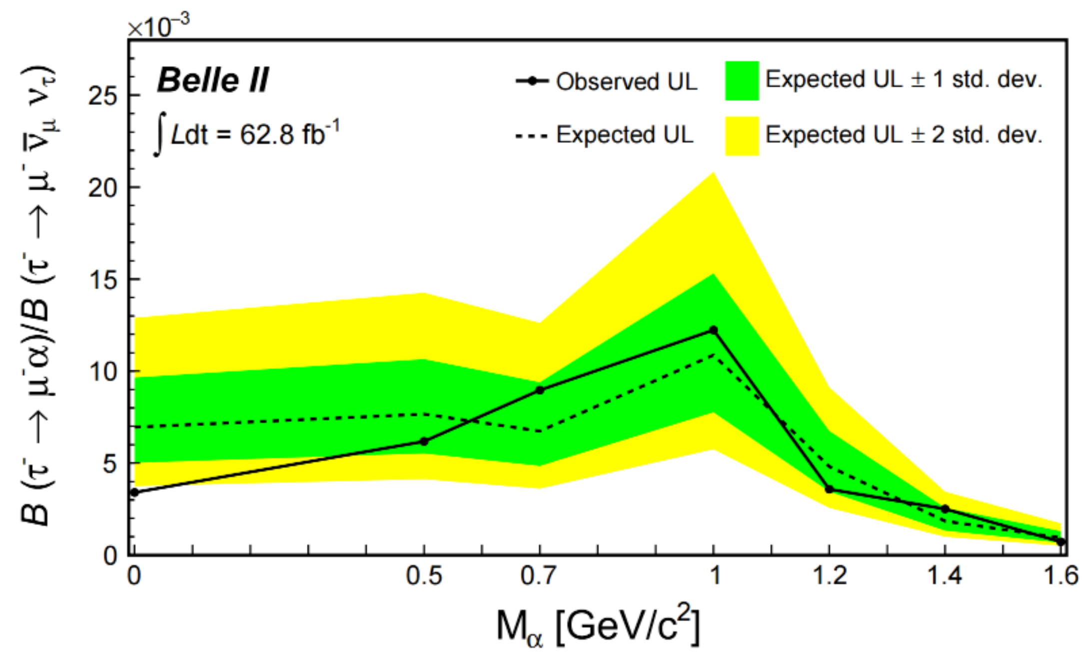
# τ→e/μ α

PRL 130,181803 (2023)

Signal yield extraction:
- Maximum likelihood fit to $x_l$ distributions
- Signal/background PDF → MC simulation

Set 95% CL upper limits on branching fractions




Most stringent bounds on α production from τ decays!

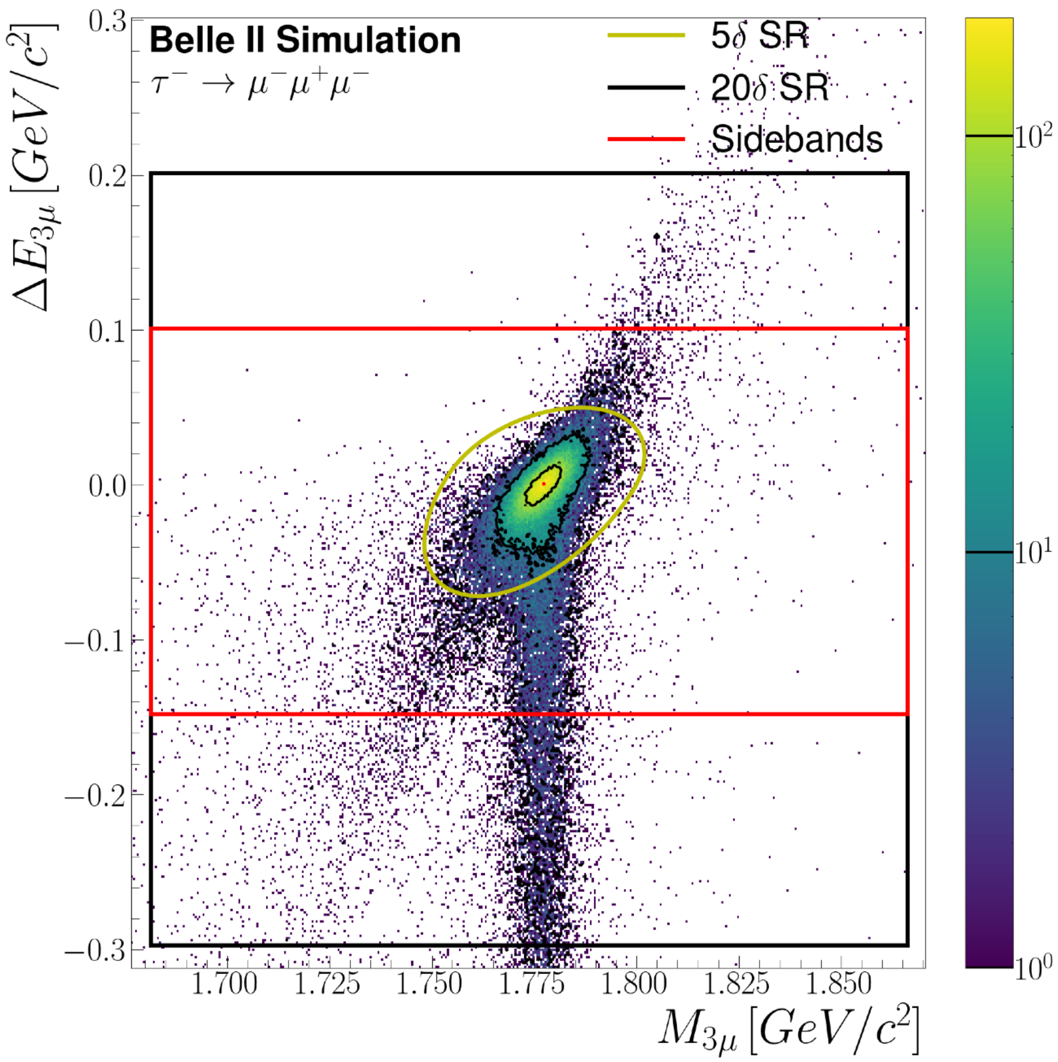
# τ→3μ

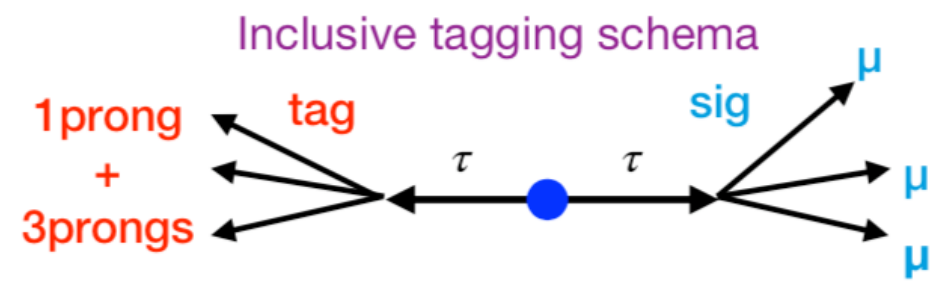
*Preliminary*

$L$=424 fb$^{-1}$

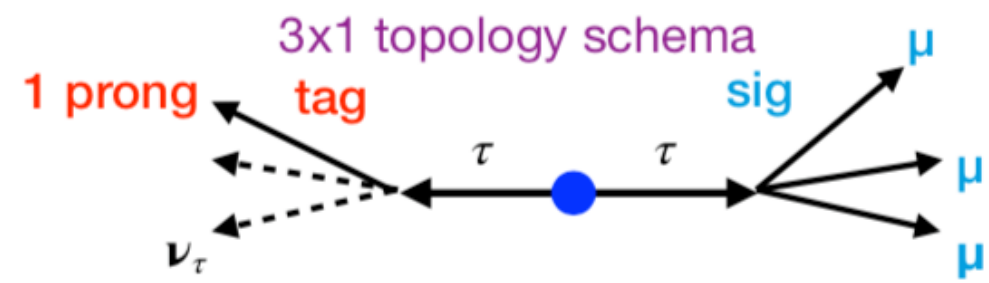
Signal extraction:

**$M_{3\mu}$ vs. $\Delta E \equiv E_{3\mu} - E_{beam}$**




- Untagged reconstruction
  - BDT based selection
  - 32 variables



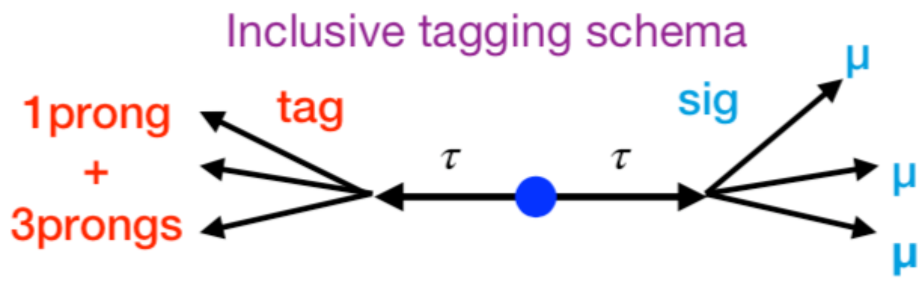

- Cut based selection with One prong tag

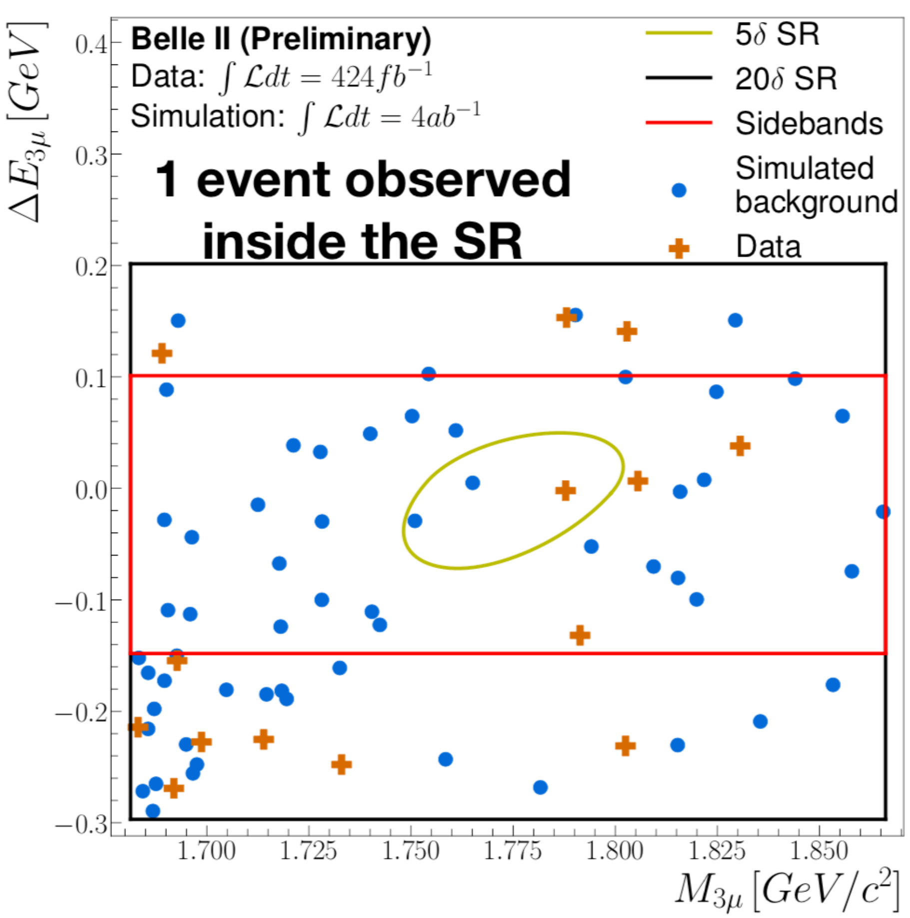
# τ→3μ

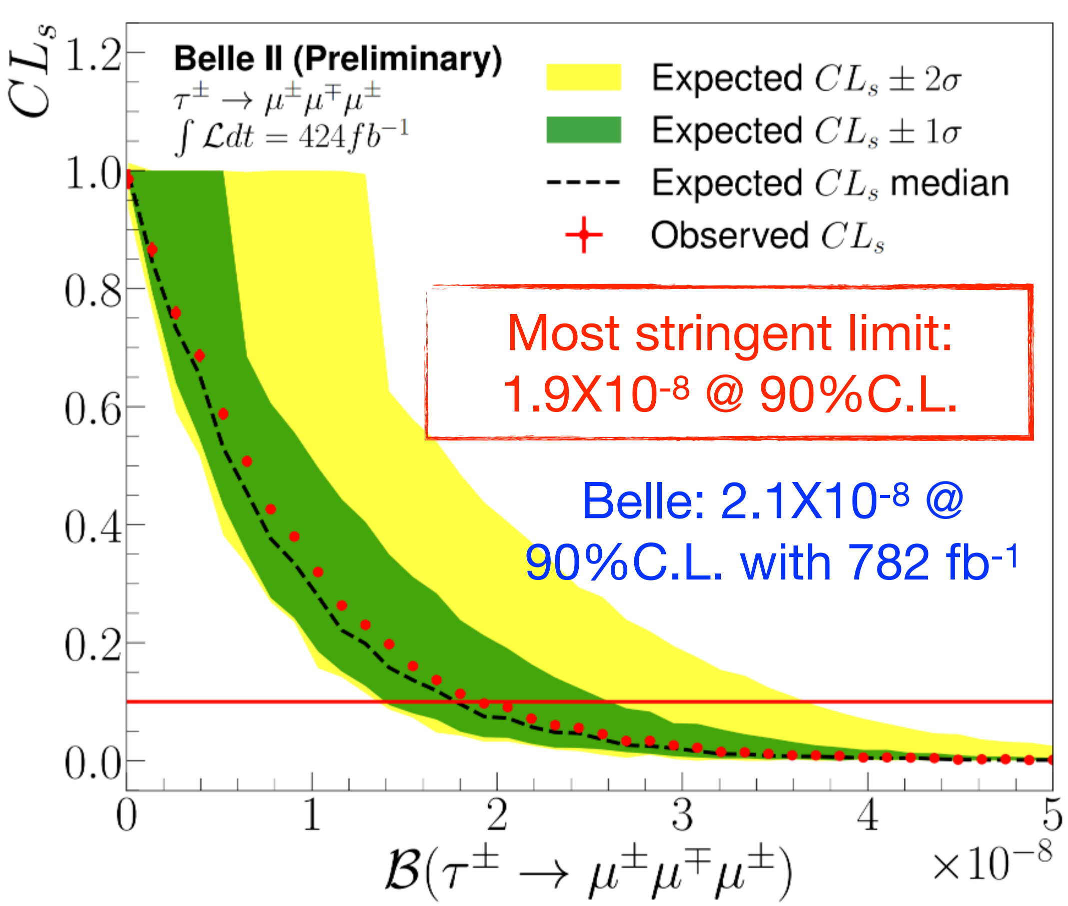
*Preliminary*

Signal yields:

- ε=20.42±0.06%, 3xε$_{Belle}$
- One event in SR
- Expected BKG: $0.5^{+1.4}_{-0.5}$ events



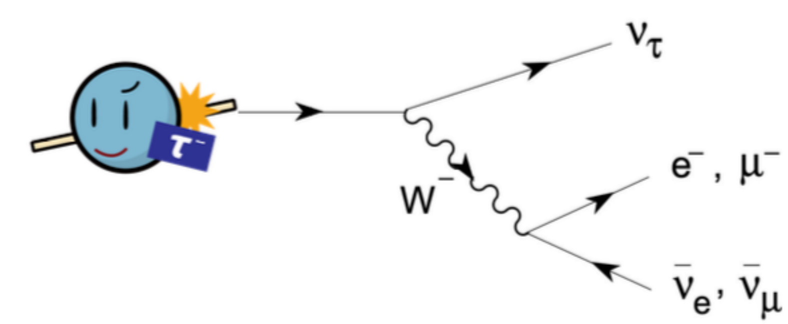



# LFU:$R_\mu$

*Preliminary*

$$R_\mu \equiv \frac{\mathcal{B}\left(\tau^- \to \nu_\tau \mu^- \overline{\nu}_\mu(\gamma)\right)}{\mathcal{B}\left(\tau^- \to \nu_\tau e^- \overline{\nu}_e(\gamma)\right)} \overset{\mathrm{SM}}{=} 0.9726$$

$$\left(\frac{g_\mu}{g_e}\right)_\tau = \sqrt{R_\mu \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}}$$

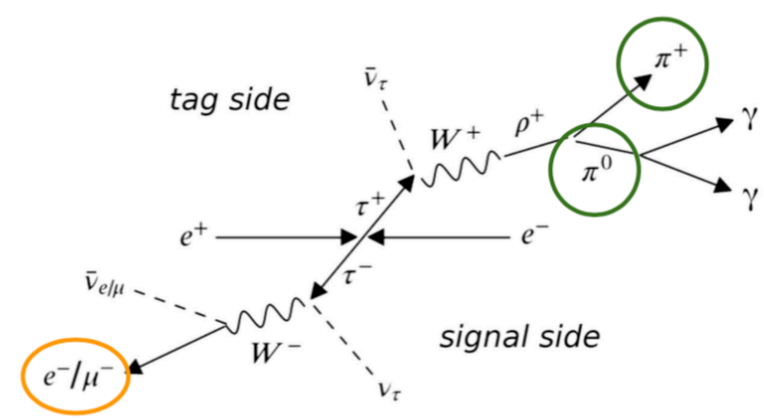



Same coupling to all generations of leptons in SM

Event reconstruction

- Tag side
    - 1-prong decays with one charged hadron and at least one $\pi^0$ on the tag side.
- Signal side
    - One $\mu$/e (Particle ID)

$L$=362 fb$^{-1}$



# LFU: $R_\mu$

*Preliminary*

Neural network is applied to suppress backgrounds

- thrust value
- thrust axis θ
- total visible energy (CMS)
- missing momentum: $p_T$, θ (CMS)
- tag side: p, θ, M (CMS)

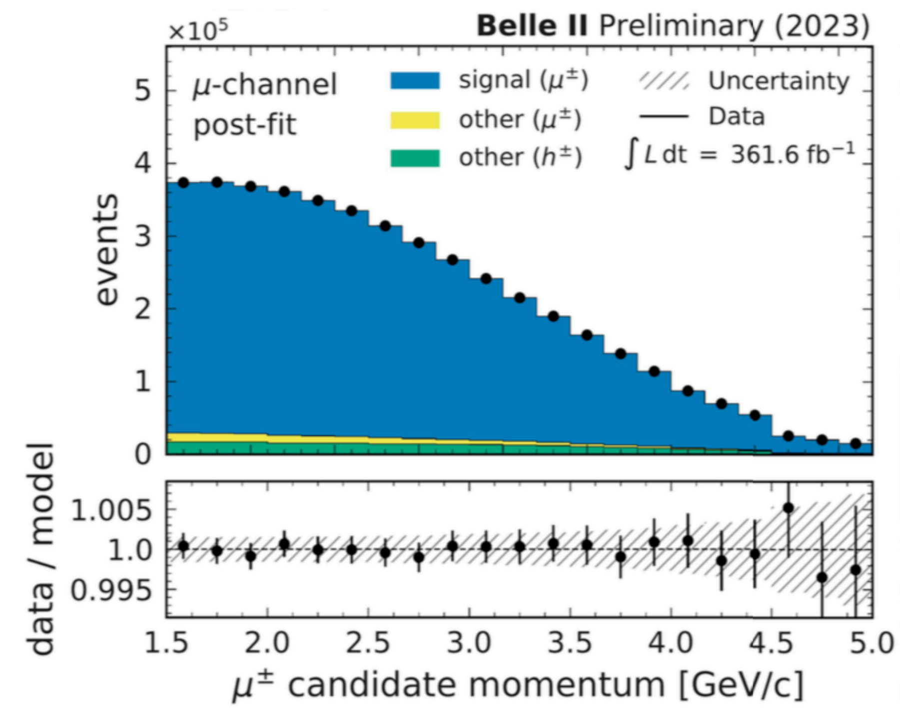
Main backgrounds

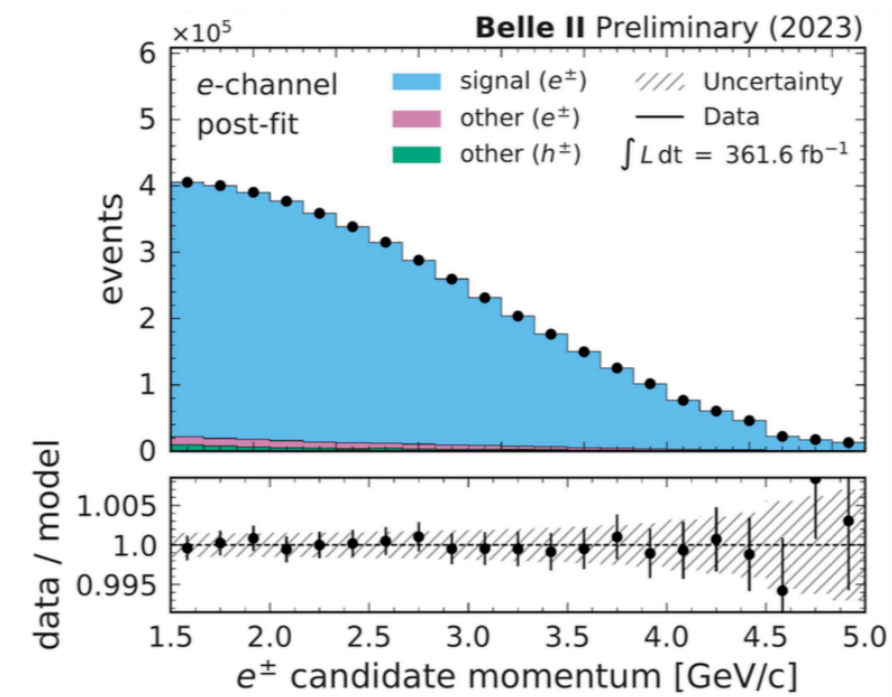
- $e^+e^- \to \tau^+\tau^-$ ($\pi^\pm$ faking $\mu^\pm/e^\pm$): ~3.3%
- $e^+e^- \to \tau^+\tau^-$ (wrong tag): ~2.3%
- $e^+e^- \to e^+e^-\tau^+\tau^-$: 0.2%

• 9.6% signal efficiency, 94% purity

Dominant systematic uncertainty

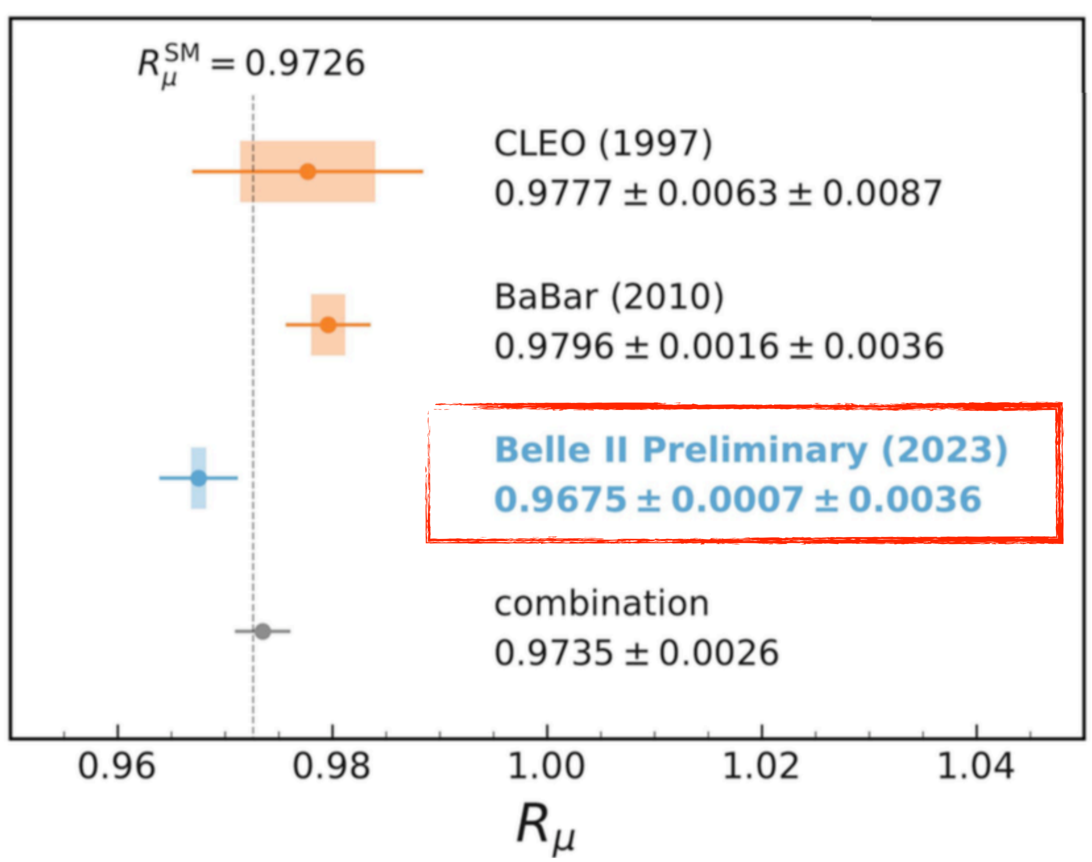
- Particle ID (0.32%)
- Trigger (0.10%)

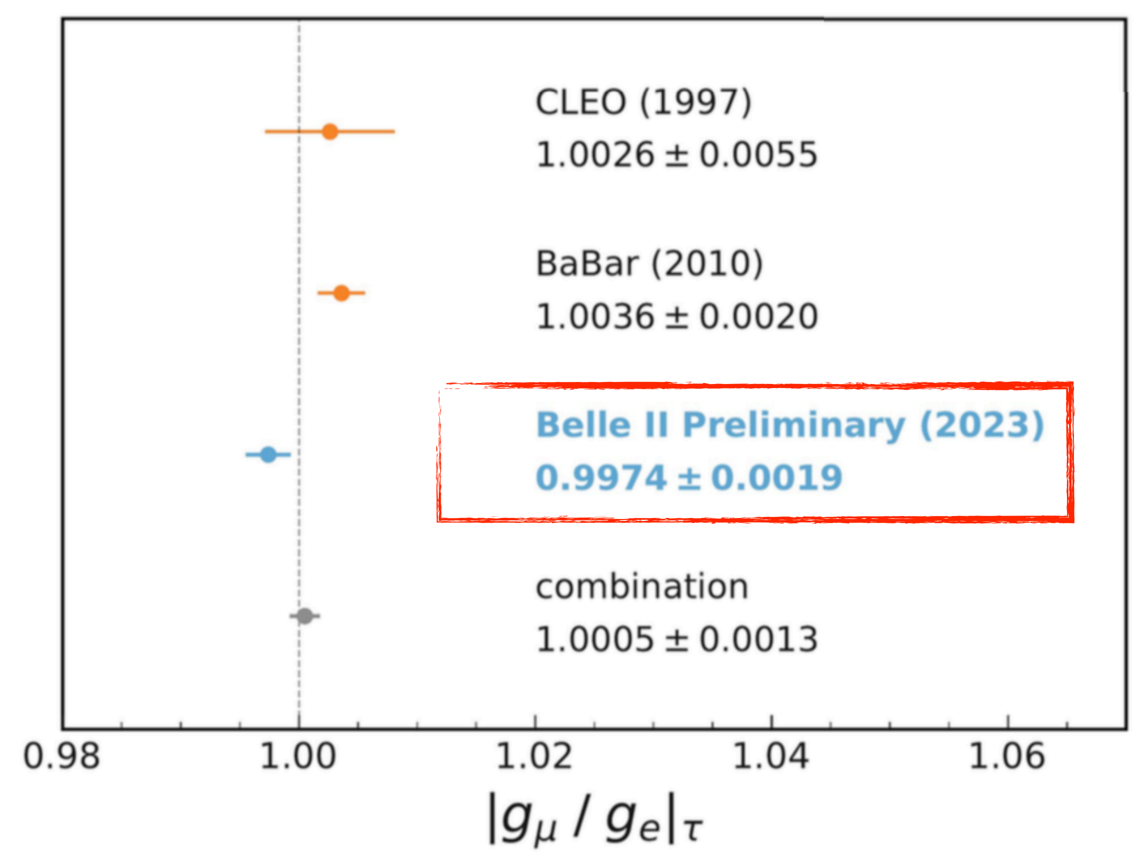


# LFU:$R_\mu$

*Preliminary*




$$R_\mu = \frac{\mathcal{B}\left(\tau^- \to \nu_\tau \mu^- \overline{\nu}_\mu(\gamma)\right)}{\mathcal{B}\left(\tau^- \to \nu_\tau e^- \overline{\nu}_e(\gamma)\right)}$$

$$\left(\frac{g_\mu}{g_e}\right)_\tau = \sqrt{R_\mu \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}}$$

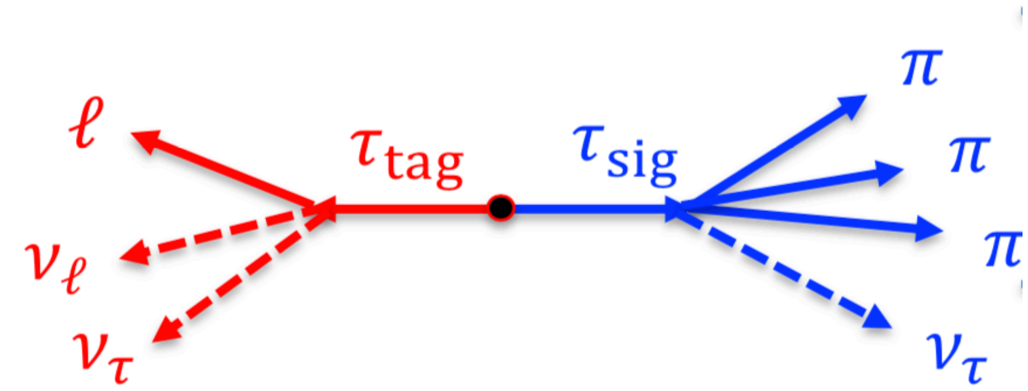
Most precise test of μ-e universality in τ decays

# τ mass measurement

*PRD 108, 032006 (2023)*

$m_\tau$: fundamental parameter of the standard model
Important input to lepton flavor universality tests

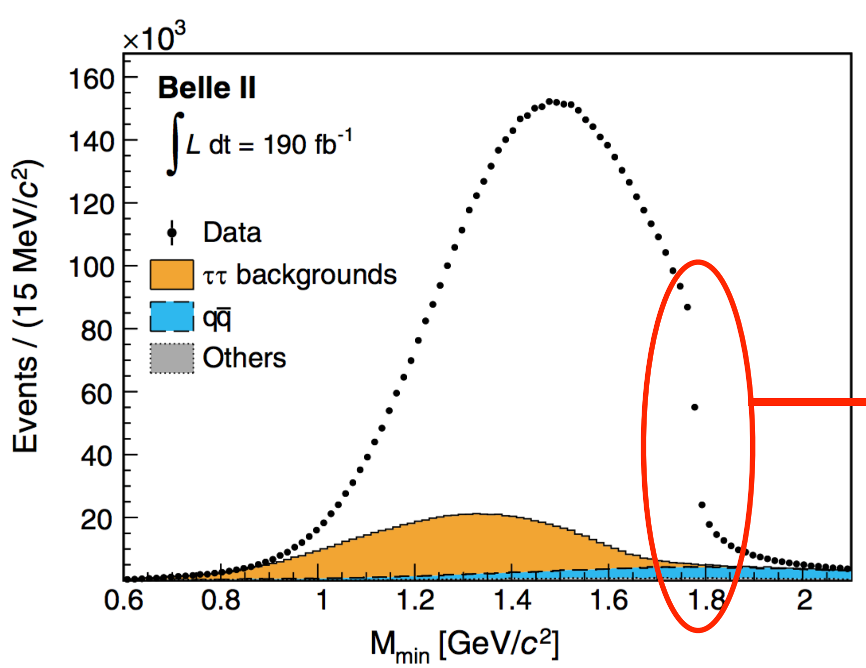
*How to measure τ mass at Belle II?*

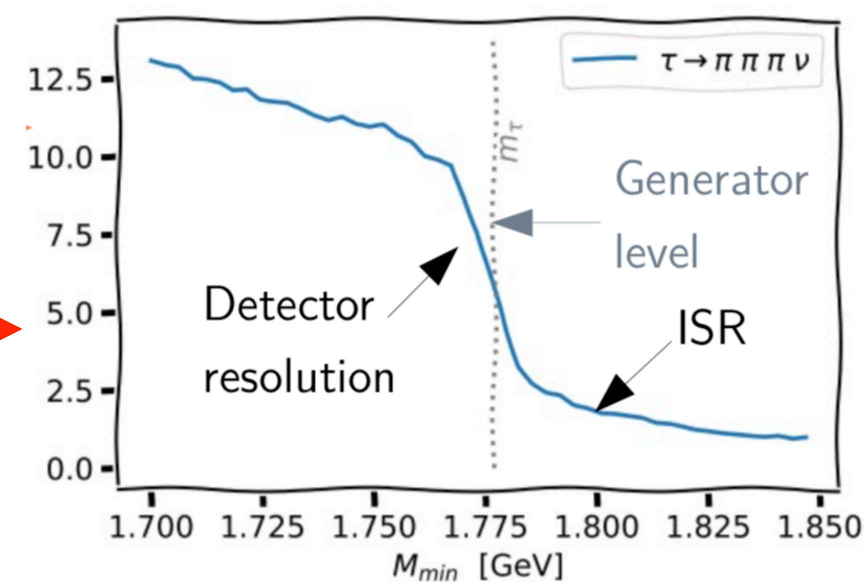



$$m_\tau = \sqrt{M_{3\pi}^2 + 2(E_\tau^* - E_{3\pi}^*)(E_{3\pi}^* - p_{3\pi}^* \cos\alpha^*)}$$

α*=0

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



# τ mass measurement

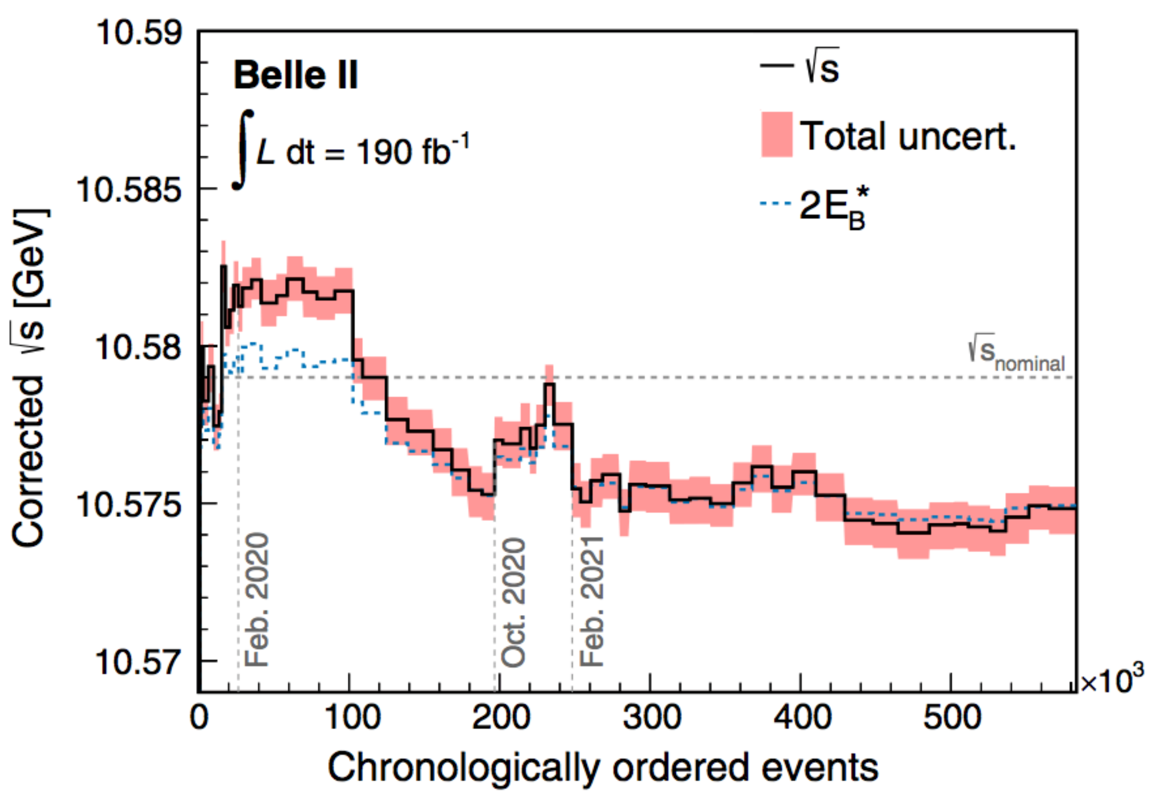
*PRD 108, 032006 (2023)*

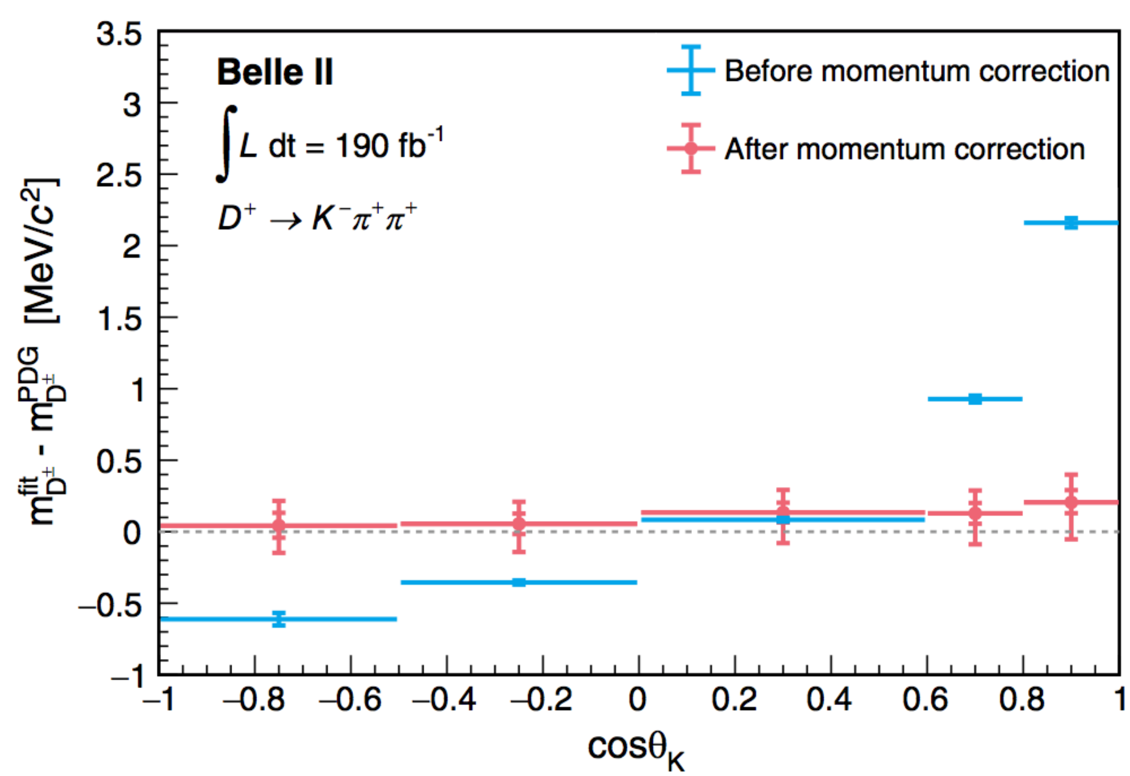
$$M_{\min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - p_{3\pi}^*)} \leq m_\tau$$

Beam energy and momentum corrections are crucial!

Beam energy is corrected using B-meson hadronic decays

Momentum correction: $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$

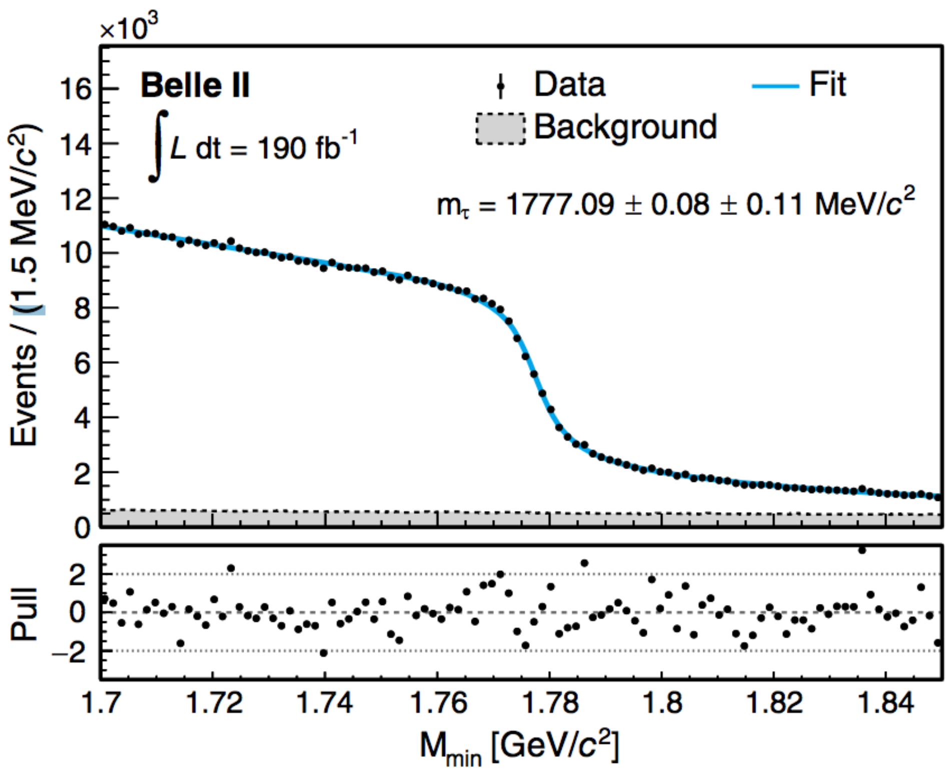


# τ mass measurement

PRD 108, 032006 (2023)

$$m_\tau = 1777.09 \pm 0.08 \pm 0.11 \ \mathrm{MeV}/c^2$$




*Systematic Uncertainty*

| 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 $\tau$ decay | 0.02 |
| Neutral particle reconstruction efficiency | $\leq 0.01$ |
| Momentum resolution | $< 0.01$ |
| Tracking efficiency correction | $< 0.01$ |
| Trigger efficiency | $< 0.01$ |
| Background processes | $< 0.01$ |
| Total | 0.11 |

# τ mass measurement

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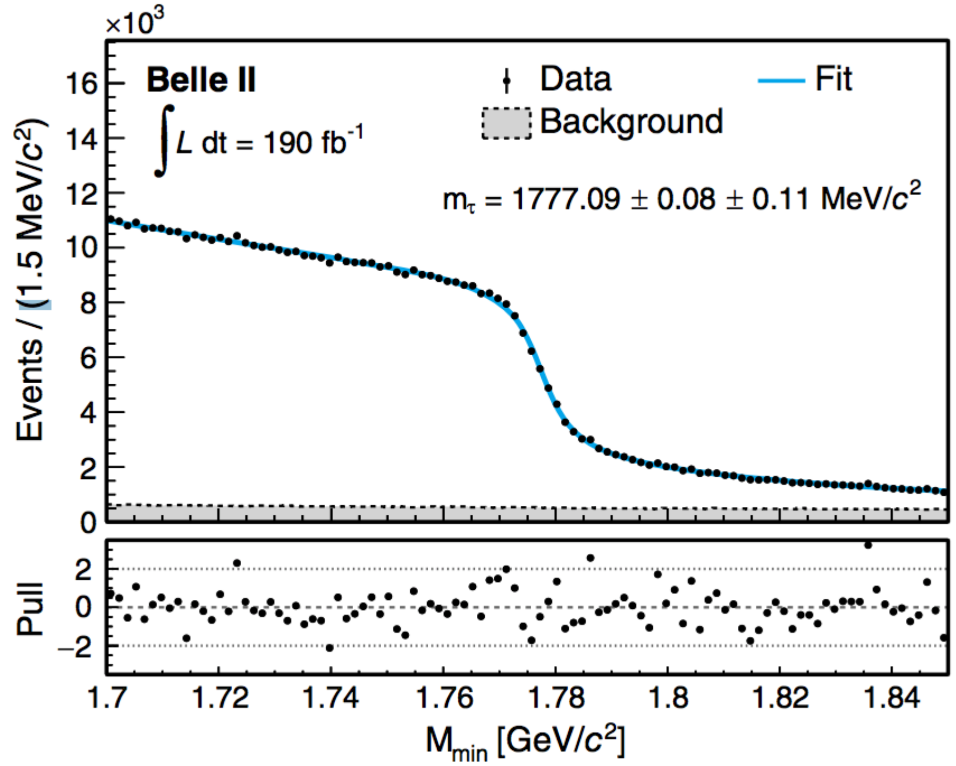


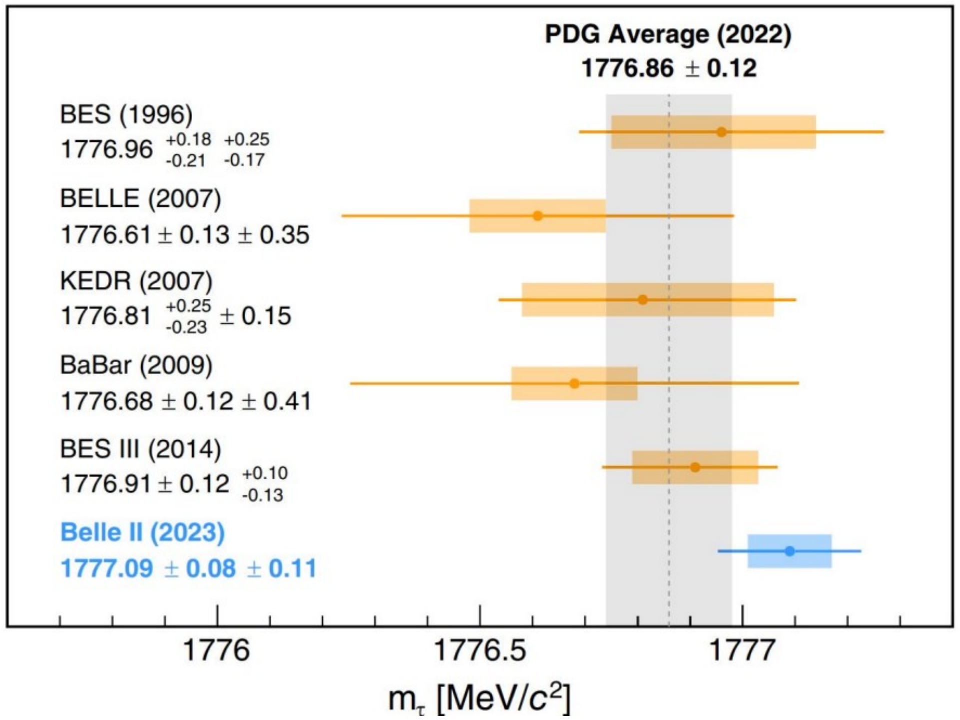


World's most precise measurement to date!

# Conclusion

- Belle II has an excellent sensitivity for τ physics
  - τ mass
  - LFV
  - LFU
- Long shutdown since summer 2022
  - Accelerator upgrades to mitigate background and increase luminosity
  - Detector upgrades
- Restart of Super KEKB in January 2024
- Path to 2 x $10^{35}$ $cm^{-2}s^{-1}$