First Results and Prospects for τ Lepton Physics at Belle II

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on behalf of the Belle II Collaboration

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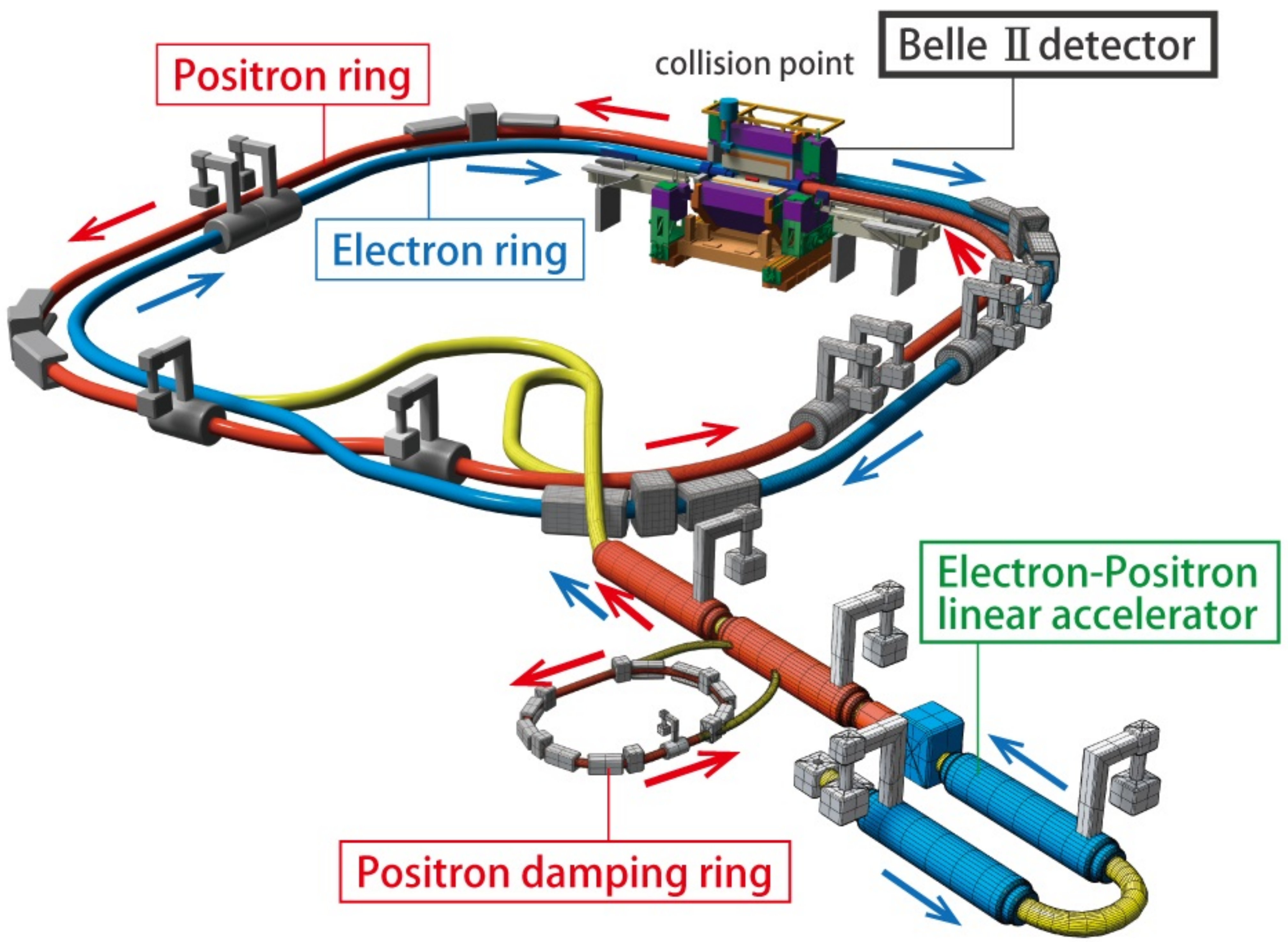
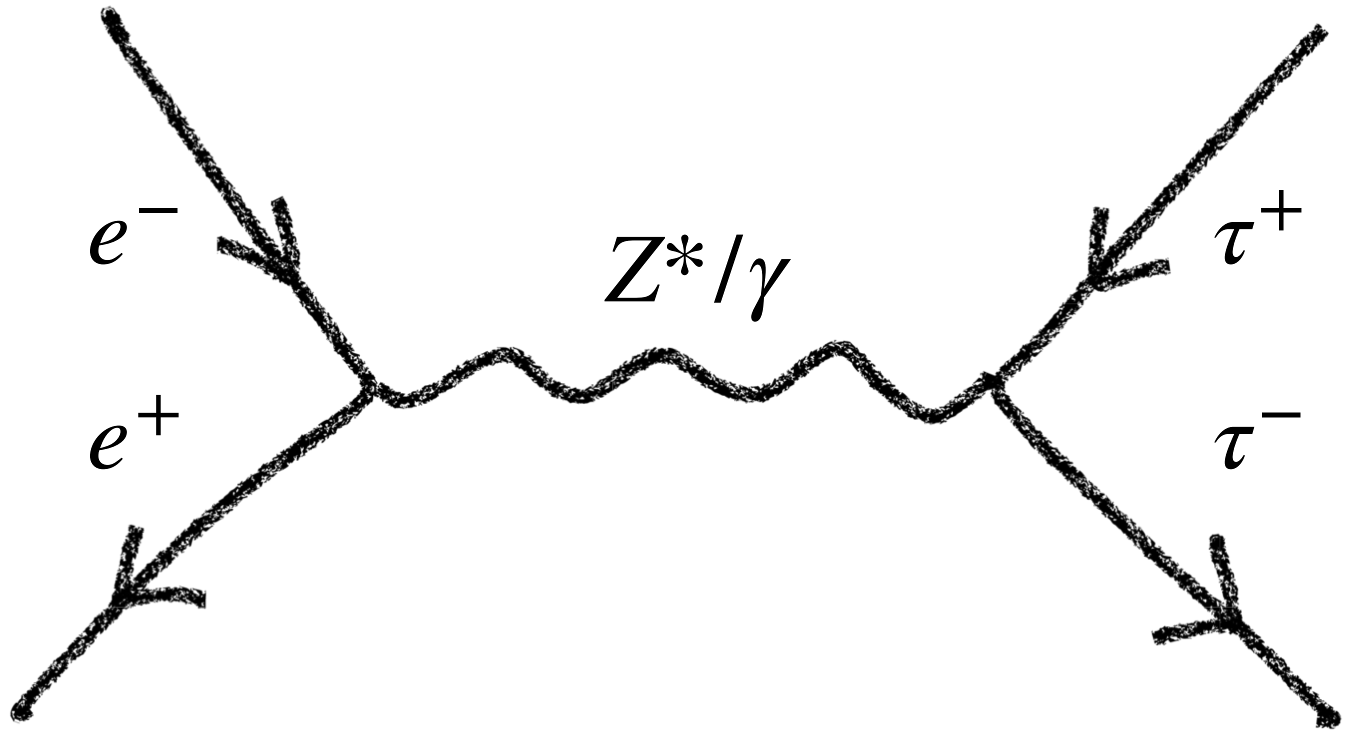
Belle II

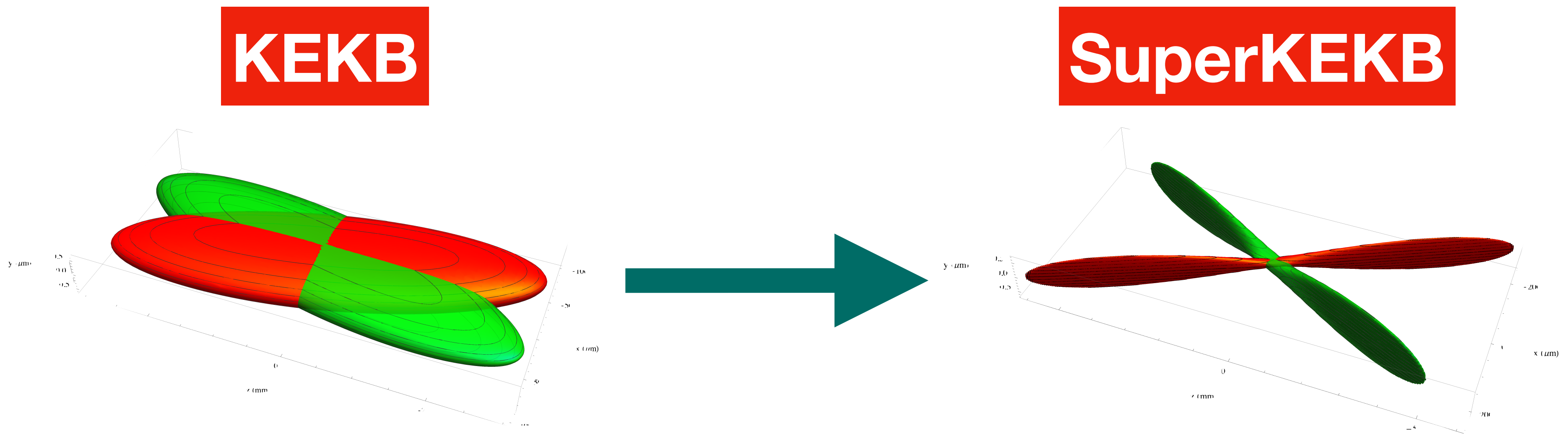
τ-Pair Production at Belle II

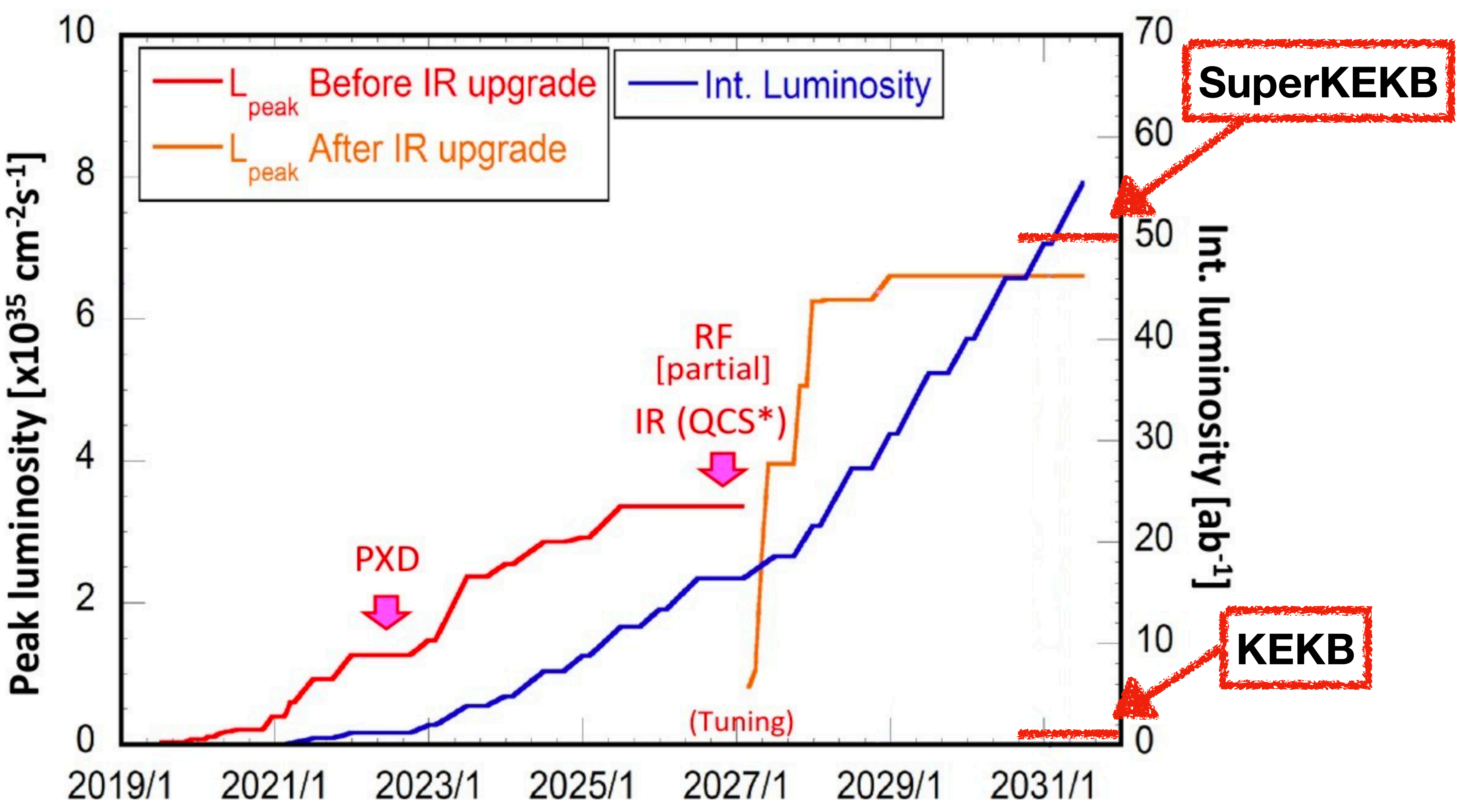


- At e^+e^- machines there is a low background and a well understood production mechanism for τ
- SuperKEKB is a τ-factory!
  - $\sigma(e^+e^- \to \tau^+\tau^-) = 0.92$ nb
    $\sigma(e^+e^- \to \Upsilon(4S)) \approx 1$ nb



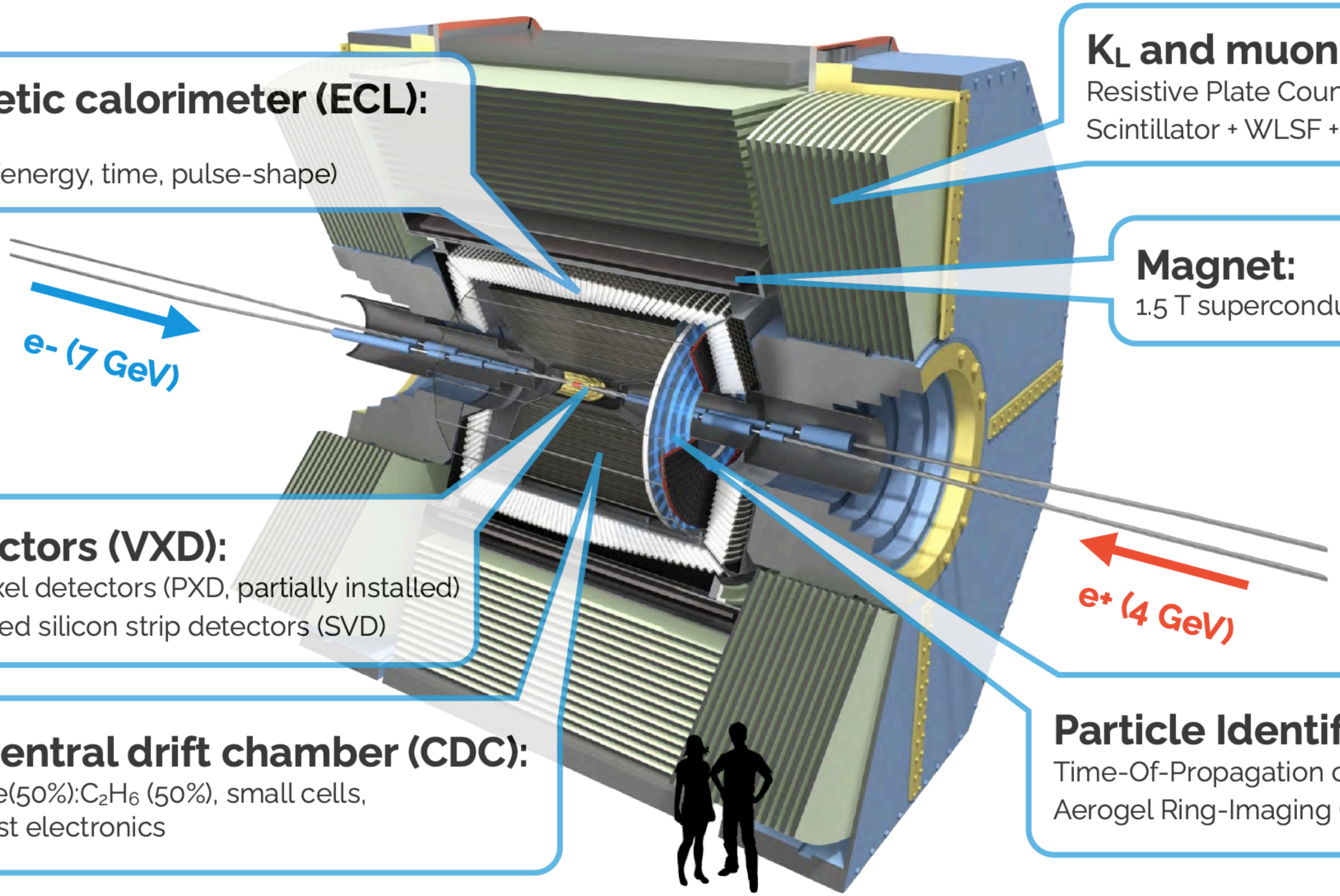
SuperKEKB a (Super-)τ-Factory





- At e^+e^- machines there is a low background and well understood production mechanism for τ
- Exploit τ-tag method
- SuperKEKB collider
  - Increased Integrated Luminosity: 1 ab^{-1}(KEKB) → 50 ab^{-1}(SuperKEKB)
  - ~ 45 billion tau pairs for full Belle II program
  - World Record Peak Luminosity so far: 3.1×10^{34} cm^{-2} s^{-1}

The Belle II Detector



Electromagnetic calorimeter (ECL):
CsI(Tl) crystals
waveform sampling (energy, time, pulse-shape)

K_L and muon detector (KLM):
Resistive Plate Counters (RPC) (outer barrel)
Scintillator + WLSF + MPPC (endcaps, inner barrel)

Magnet:
1.5 T superconducting

Vertex detectors (VXD):
2 layer DEPFET pixel detectors (PXD, partially installed)
4 layer double-sided silicon strip detectors (SVD)

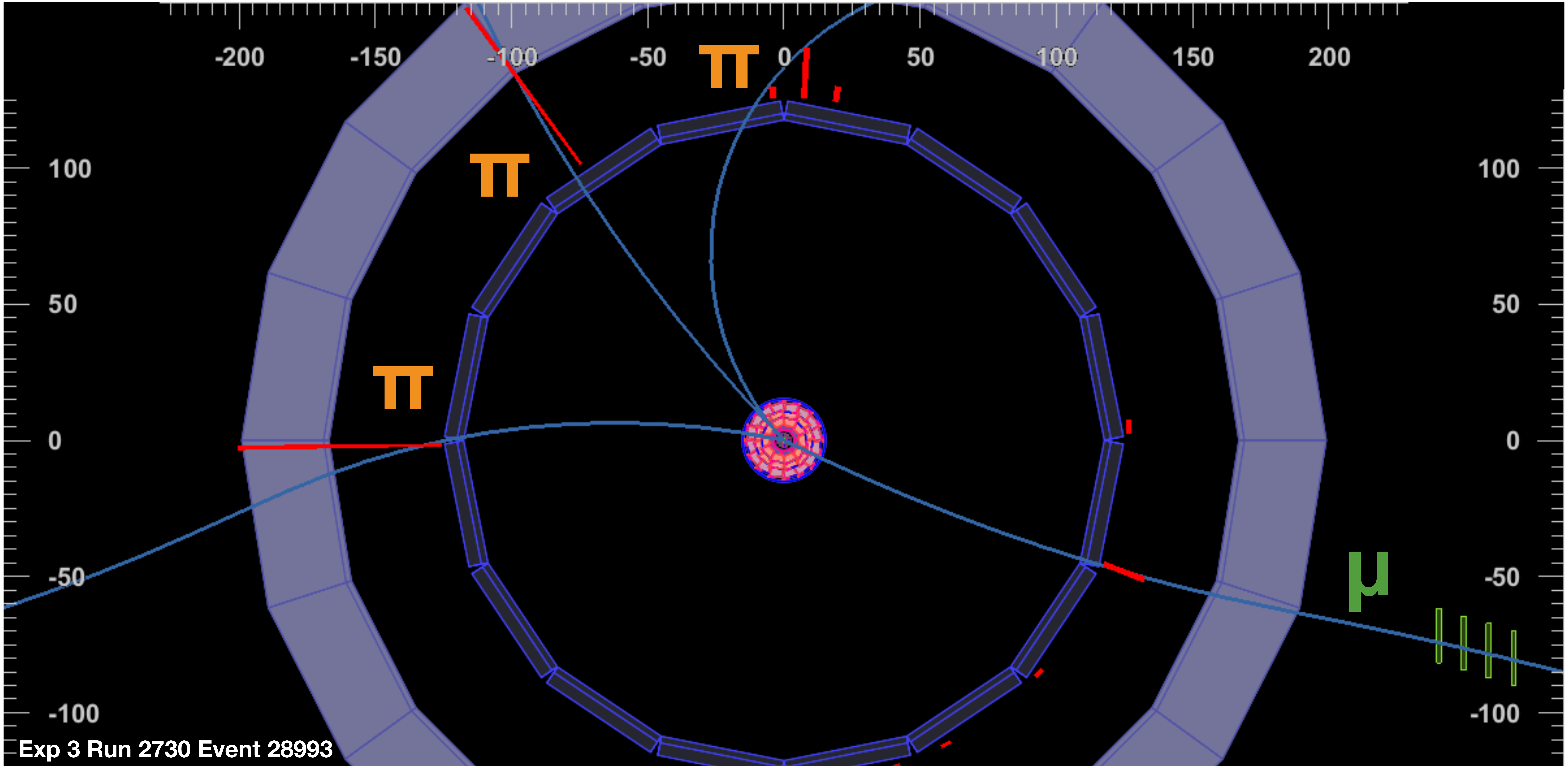
Trigger:
Hardware: < 30 kHz
Software: < 10 kHz

Central drift chamber (CDC):
He(50%):C_2H_6 (50%), small cells,
fast electronics

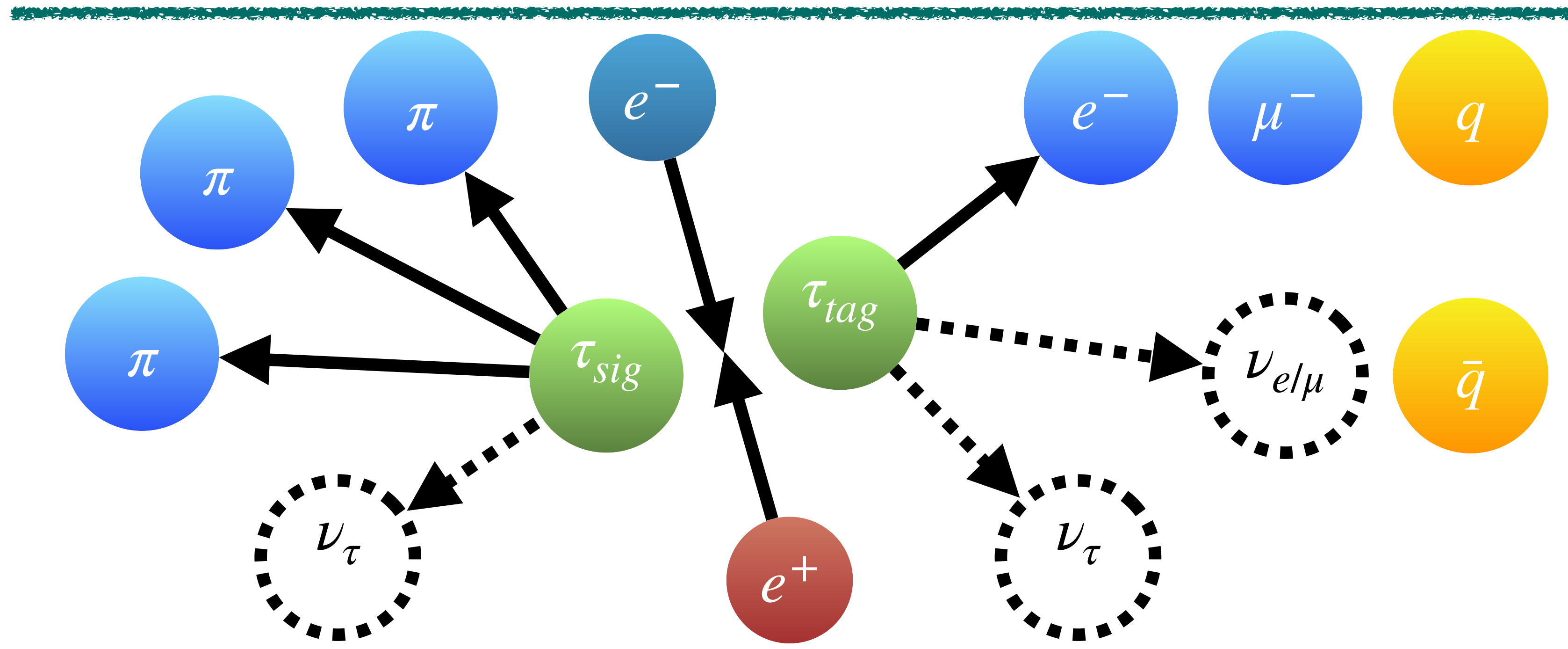
Particle Identification (PID):
Time-Of-Propagation counter (TOP) (barrel)
Aerogel Ring-Imaging Cherenkov Counter (ARICH) (FWD)

DEPFET: depleted p-channel field-effect transistor
WLSF: wavelength-shifting fiber
MPPC: multi-pixel photon counter

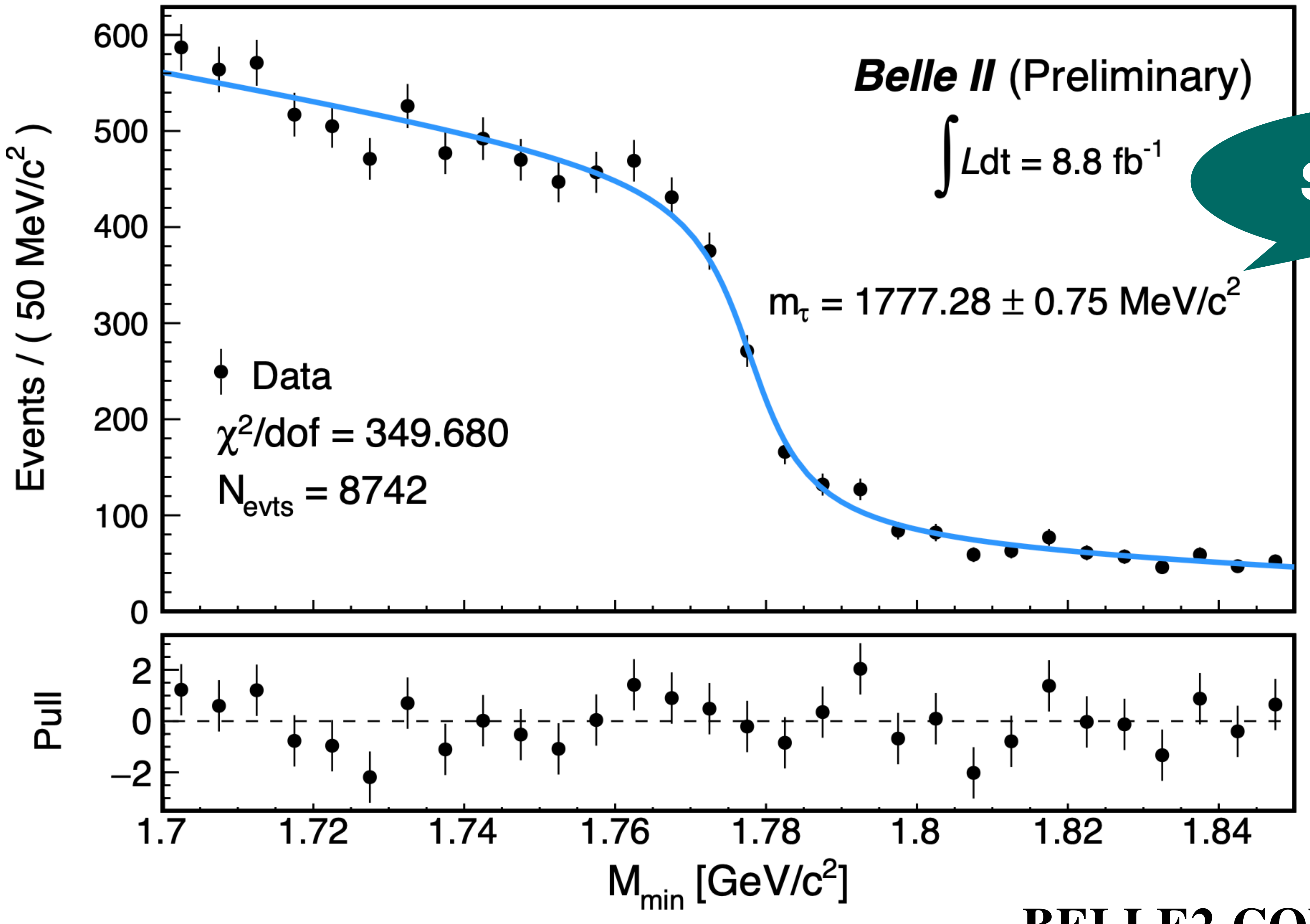
One of The First $\tau^+\tau^-$ Events



τ Mass Measurement (Preliminary)



$$M_{min} \leq m_\tau$$



Statistical

- τ mass measured using an analysis of 3x1 prong decays.
  - Mass extraction from 3-pion decay channel
- Using a dataset of approximately 8.8 fb^{-1} of data.
- Systematic uncertainty dominated by track momentum scale
  → going to improve!

Systematic uncertainty	MeV/c^2
Momentum shift due to the B-field map	0.29
Estimator bias	0.12
Choice of p.d.f.	0.08
Fit window	0.04
Beam energy shifts	0.03
Mass dependence of bias	0.02
Trigger efficiency	$\leq$ 0.01
Initial parameters	$\leq$ 0.01
Background processes	$\leq$ 0.01
Tracking efficiency	$\leq$ 0.01

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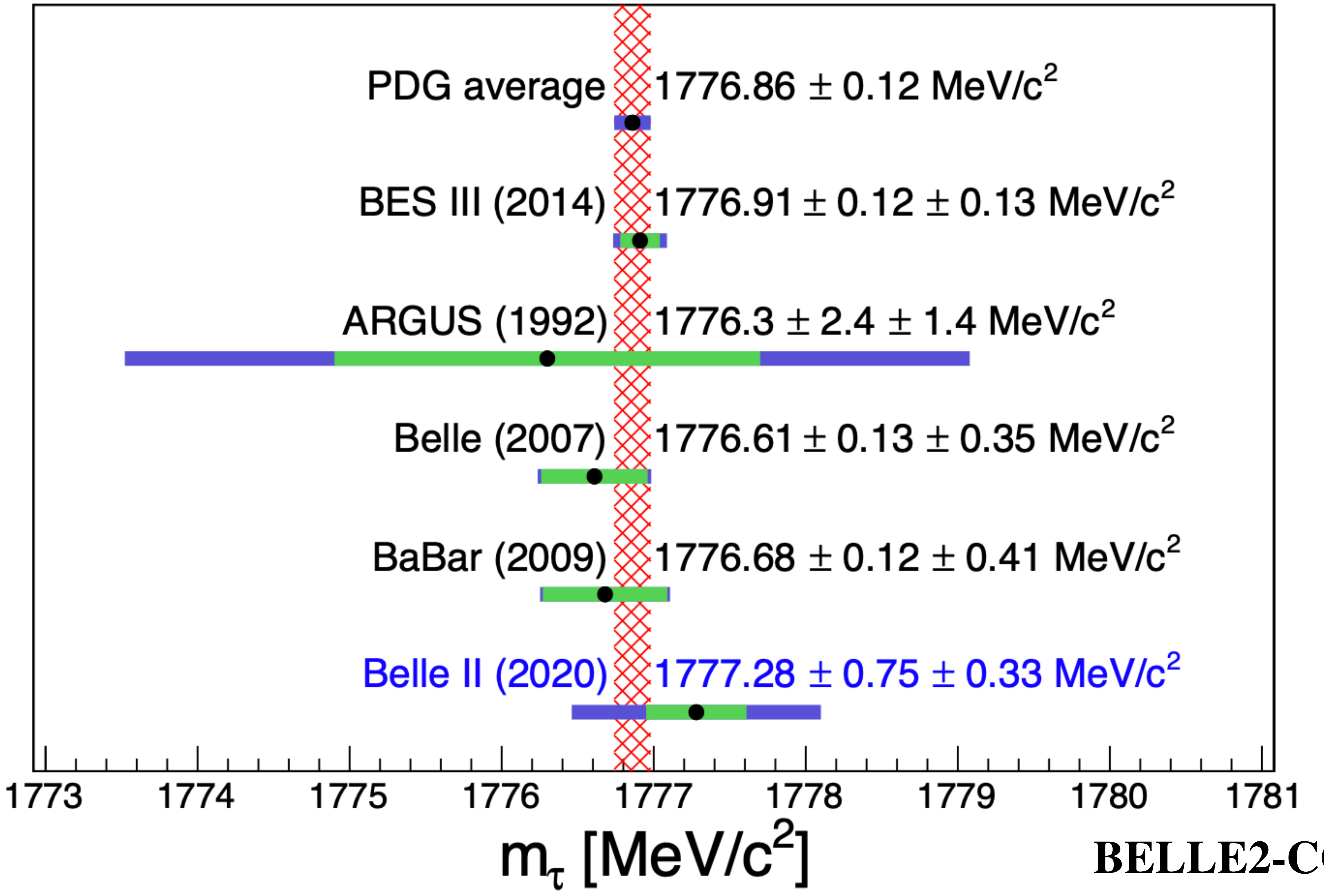
τ Mass Measurement (Preliminary)

- $m_\tau = (1777.28 \pm 0.75 \pm 0.33)\,\mathrm{MeV/c^2}$
- First τ physics results with early data: consistent with previous measurements!
- Future improvements of statistical precision and systematic uncertainties



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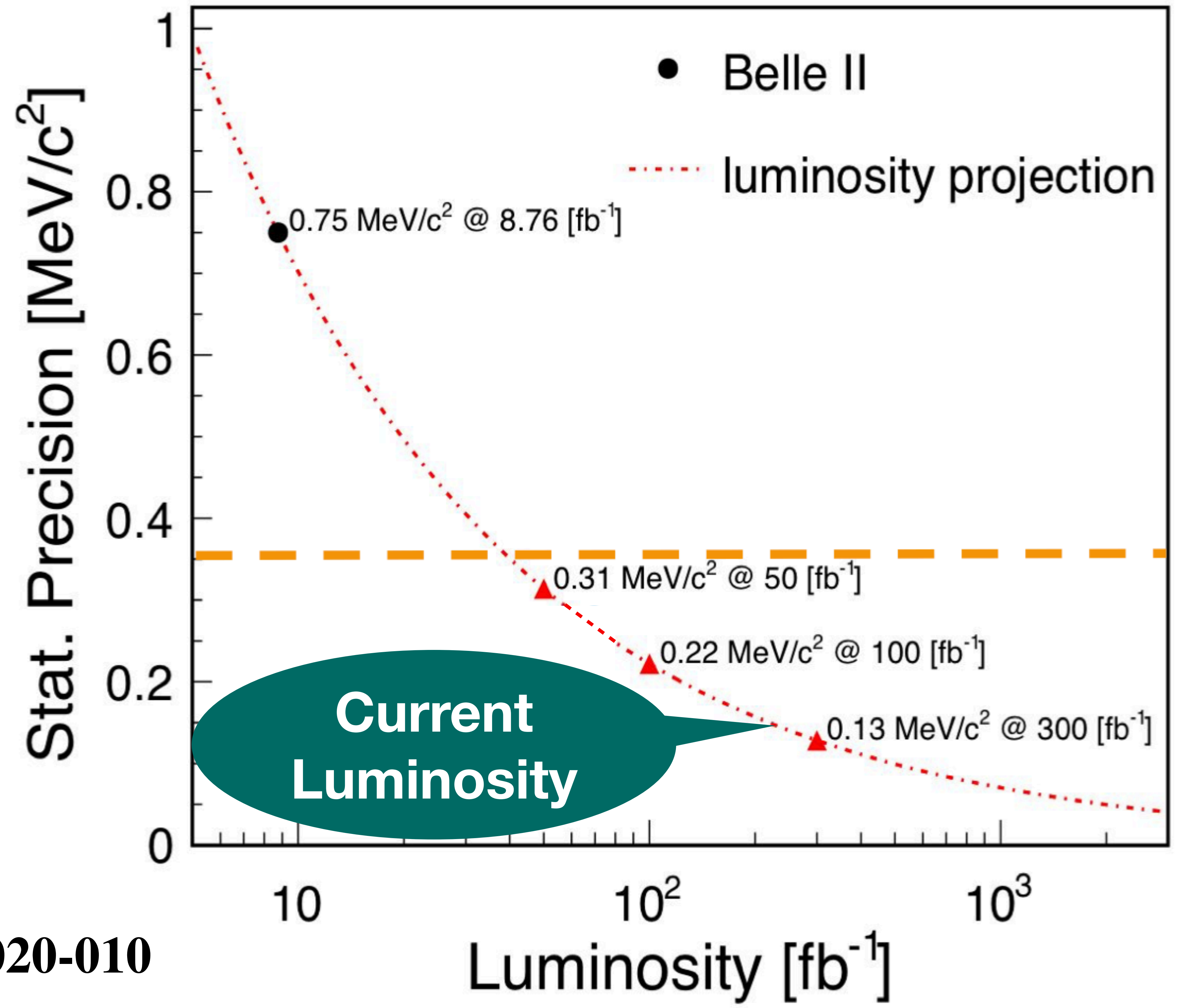
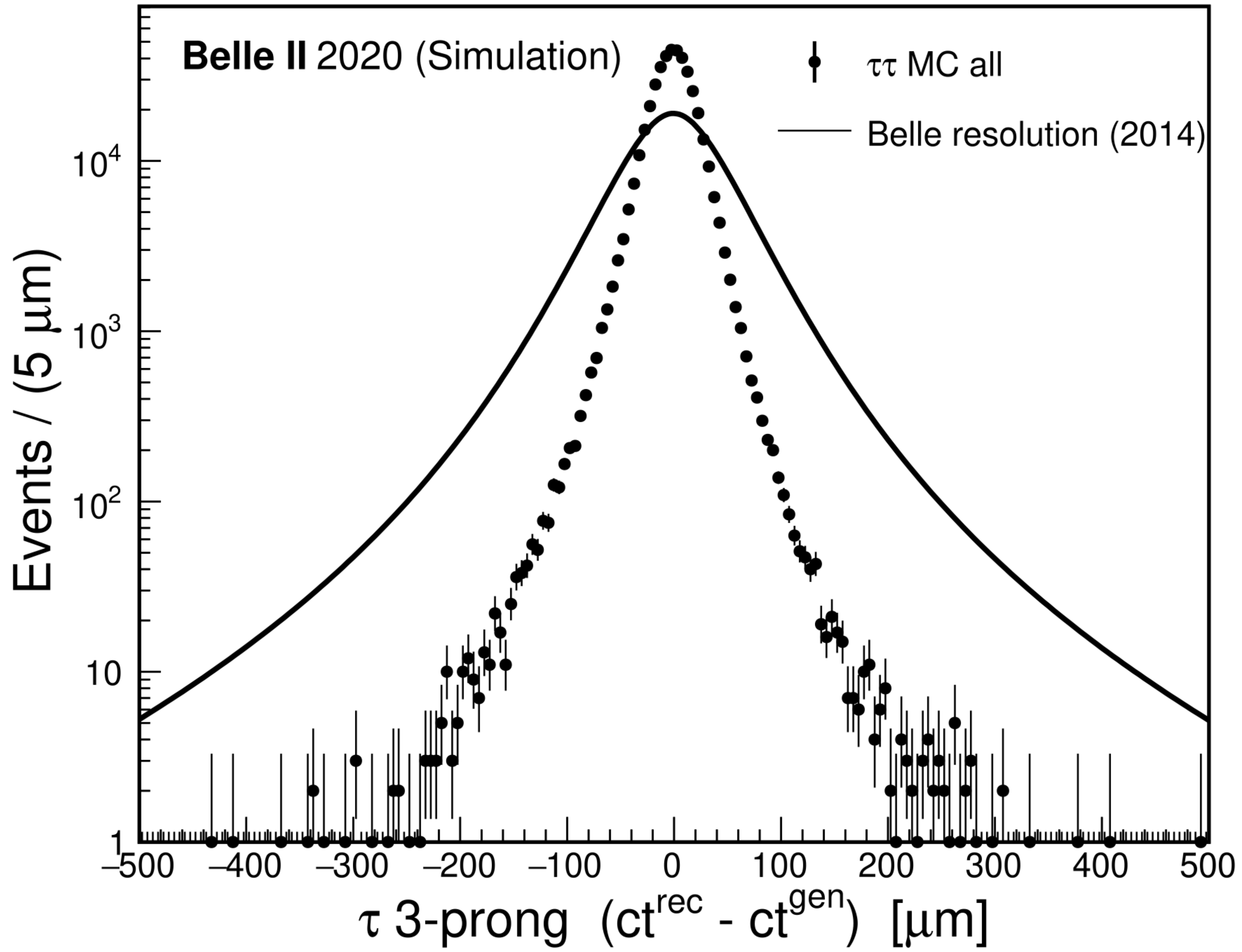
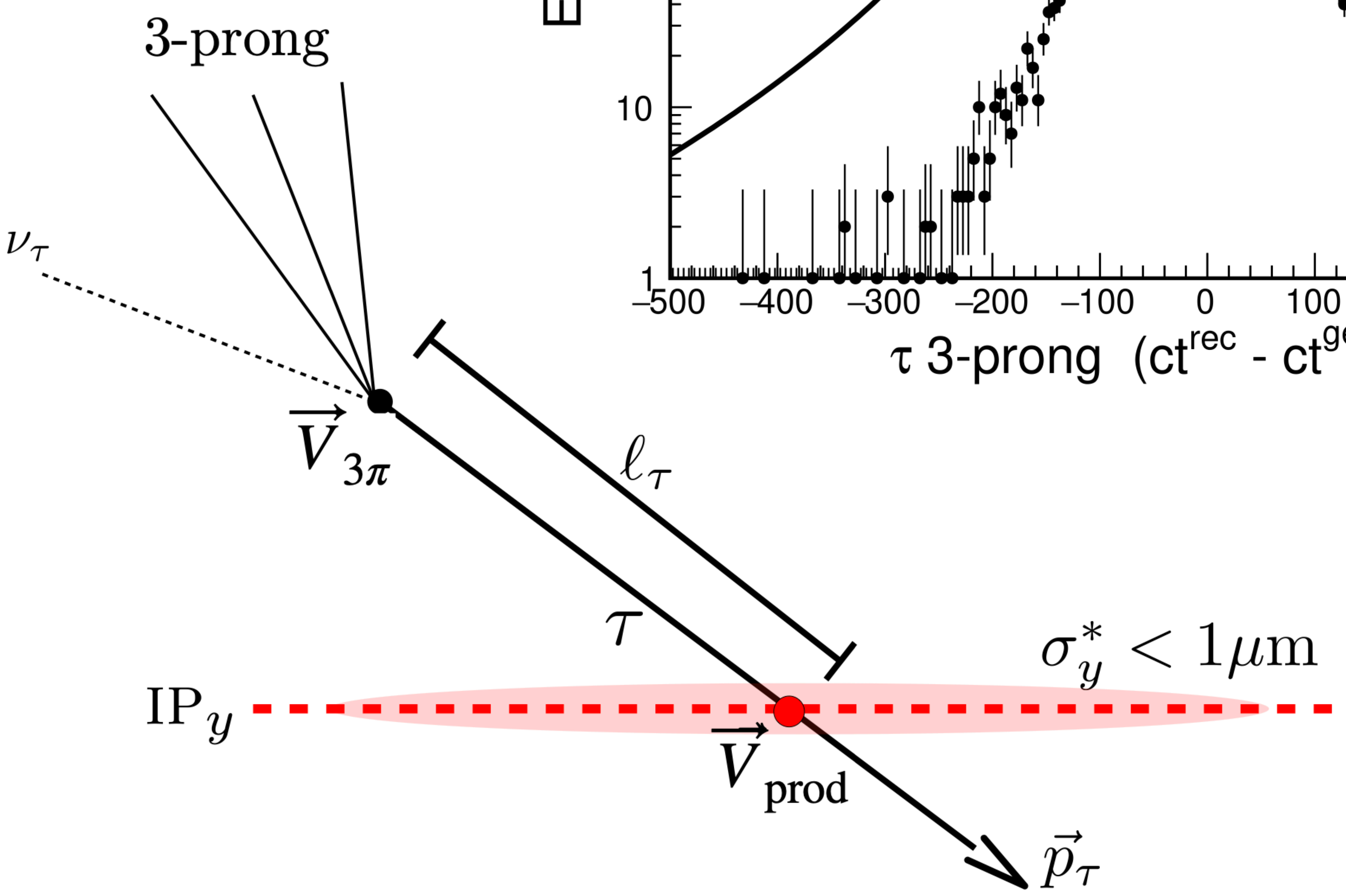


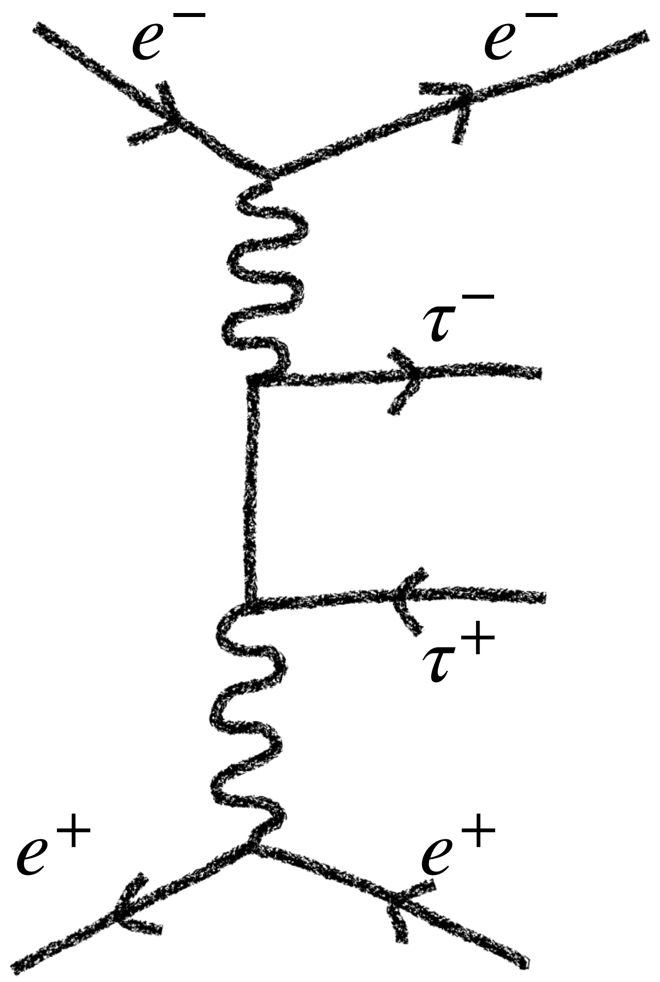
τ lifetime measurement



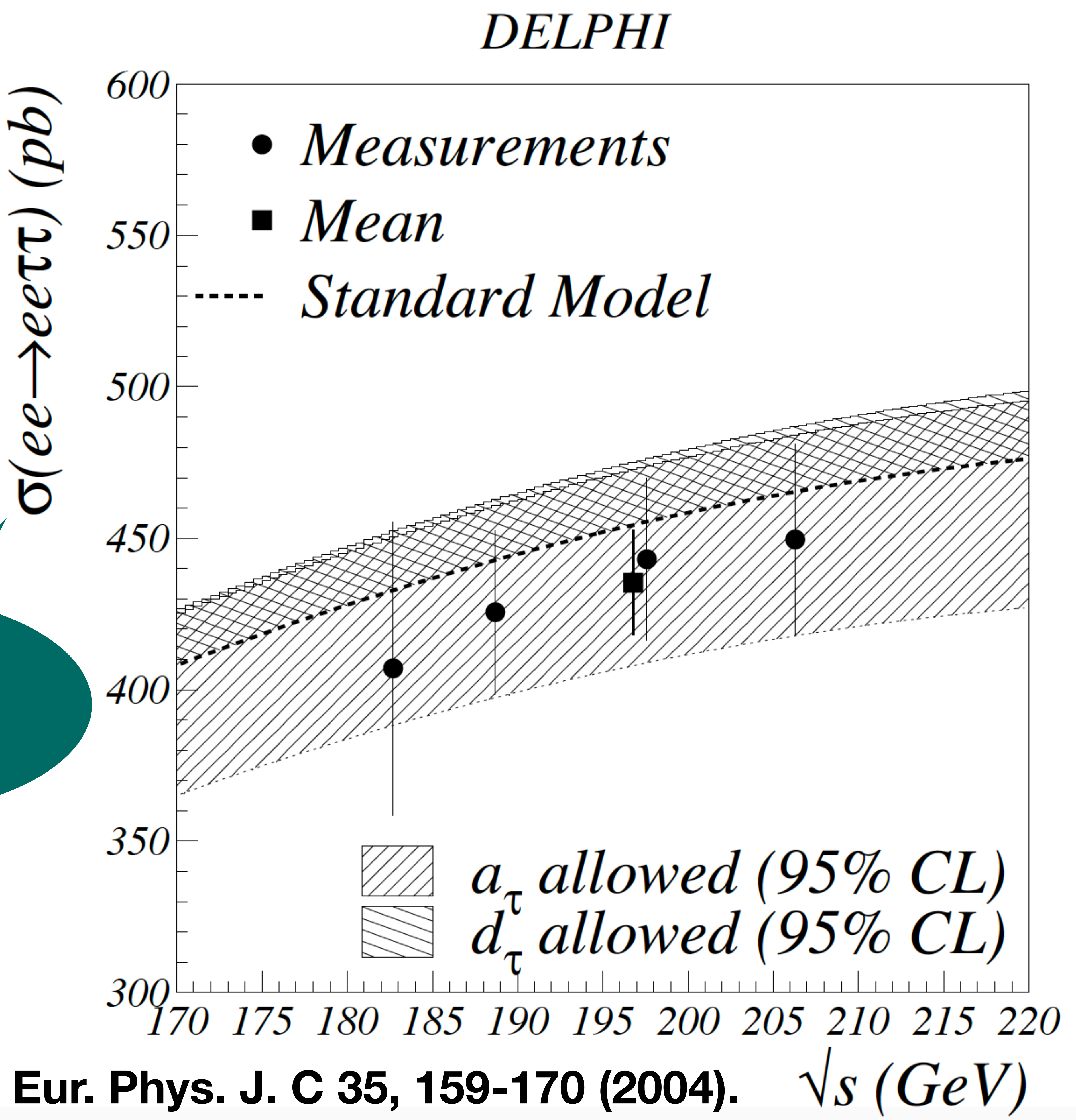


- Decay time given by $t_\tau = m_\tau \frac{l_\tau}{p_\tau}$
- Belle: $\tau_\tau = 290.17 \pm 0.53 \pm 0.33$ fs with 711 fb^{-1} of data
  DOI: 10.1103/PhysRevLett.112.031801
- Exploits Belle II unique
  - Small beam spot size
  - High resolution of the vertex detector
    → Almost twice as good resolution as Belle.
    arXive:2108.03216
- Competitive results may be feasible with current dataset > 200 fb^{-1}

Further Standard Model Measurements



g-2 influences correction

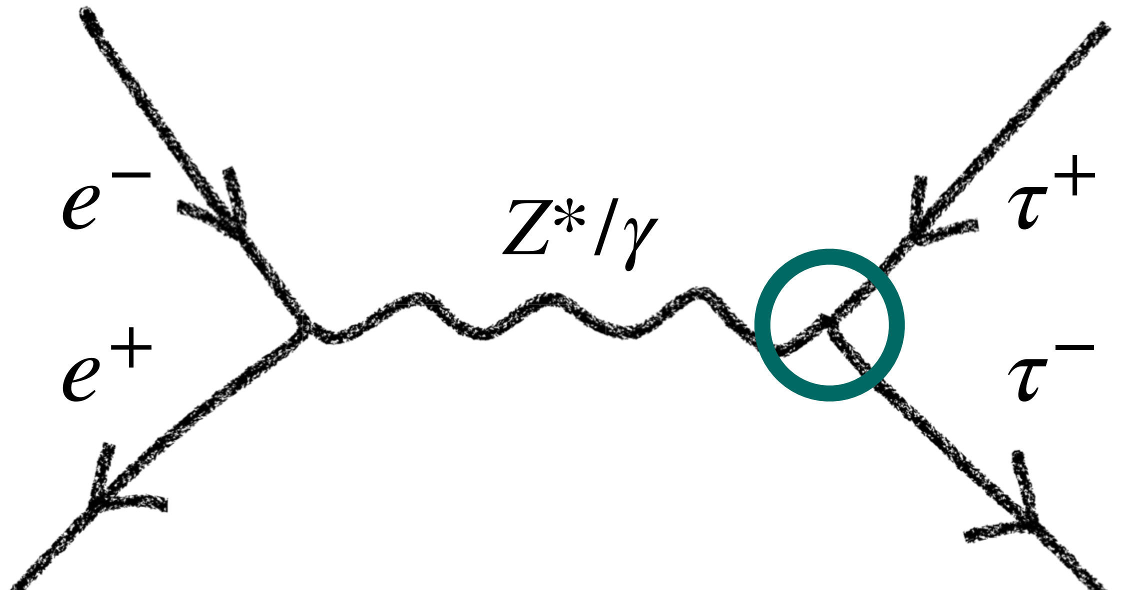


Eur. Phys. J. C 35, 159-170 (2004).
DOI: 10.1140/epjc/s2004-01852-y

- τ $g-2$ and EDM
  - Belle (30 fb^{-1}): EDM < $\mathcal{O}(10^{-17})$
    DOI: 10.1016/S0370-2693(02)02984-2
    - To be updated: **arxiv:2108.11543**
  - Prospect for first significant measurement of non-zero SM $g-2$, with full Belle II luminosity!

$$\frac{g-2}{2} \equiv a_\tau^{SM} = (1{,}17721 \pm 0.00005)\cdot 10^{-3}$$

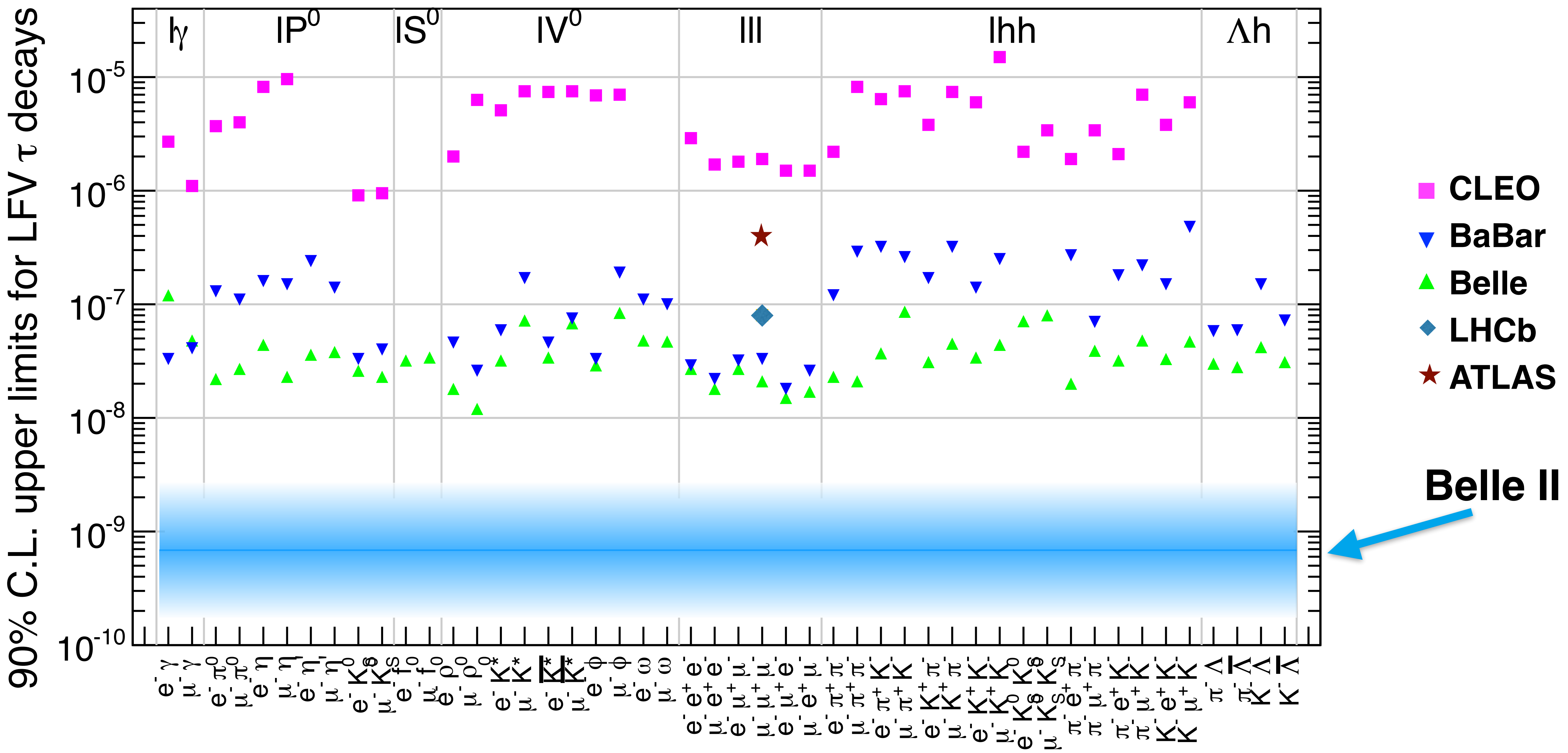
$$a_\tau^{Exp} = 0.018 \pm 0.017$$



Belle/Belle II Measurement

Lepton Flavour Violation Motivation

The Belle II Physics Book, E. Kou et al., PTEP Vol. 2019 Issue 12
https://doi.org/10.1093/ptep/ptz106

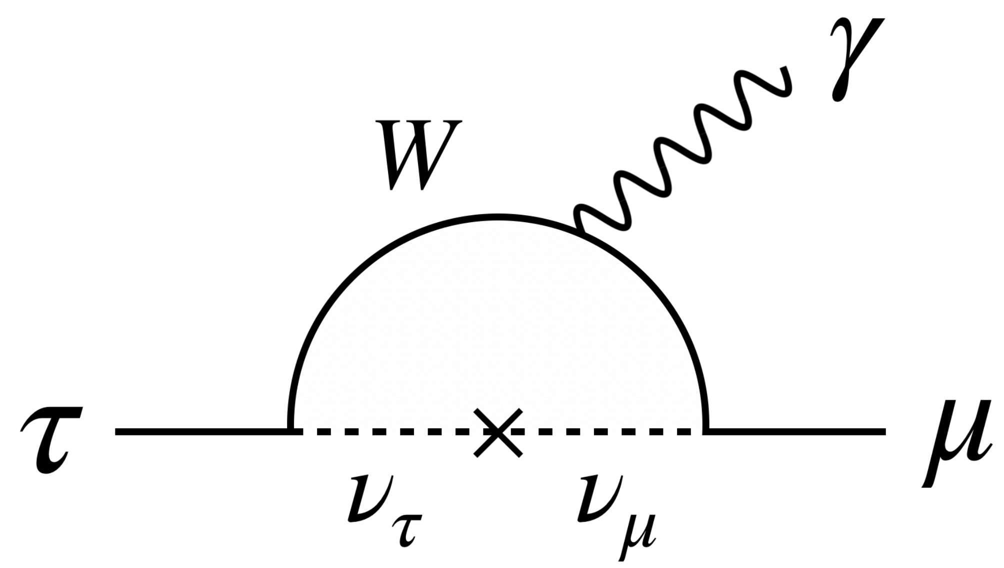


- We expect LFV in many Beyond the Standard Models (BSM)
- For τ at Belle II the "golden modes" are:

  $\tau \to \mu\gamma$

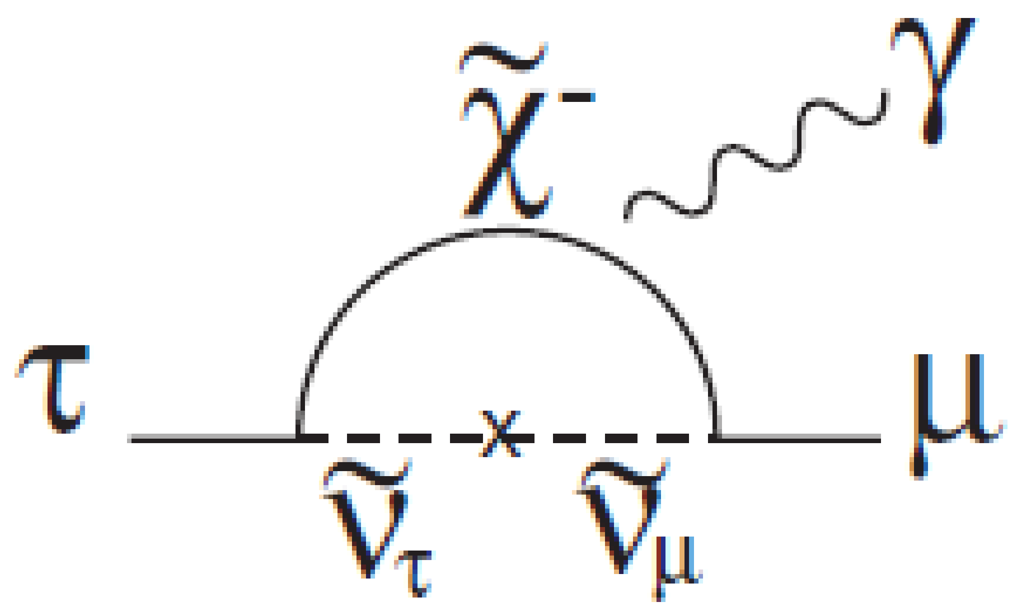
  $\tau \to lll$

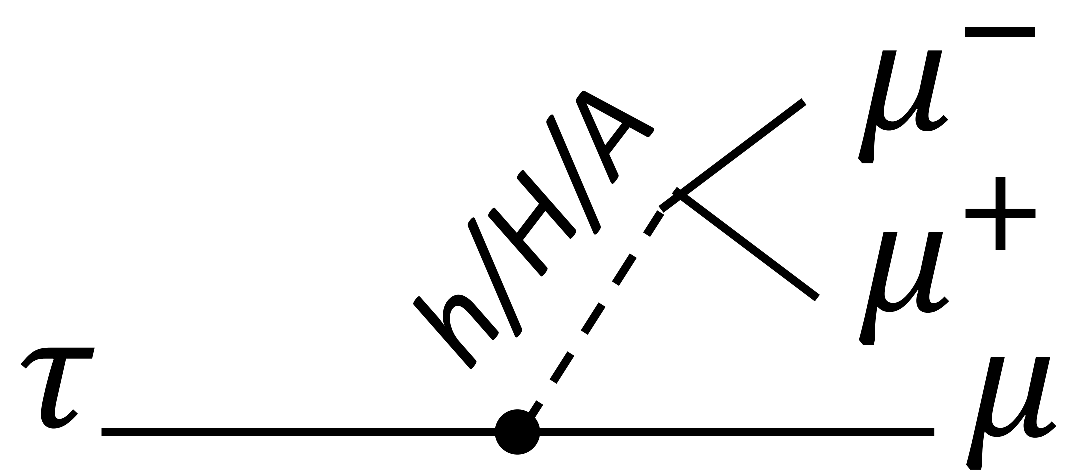
- $\tau \to 3\mu$ one of the priorities



New SM: $\mathcal{O}(10^{-54})$-$\mathcal{O}(10^{-49})$

NP: $\mathcal{O}(10^{-10})$-$\mathcal{O}(10^{-7})$





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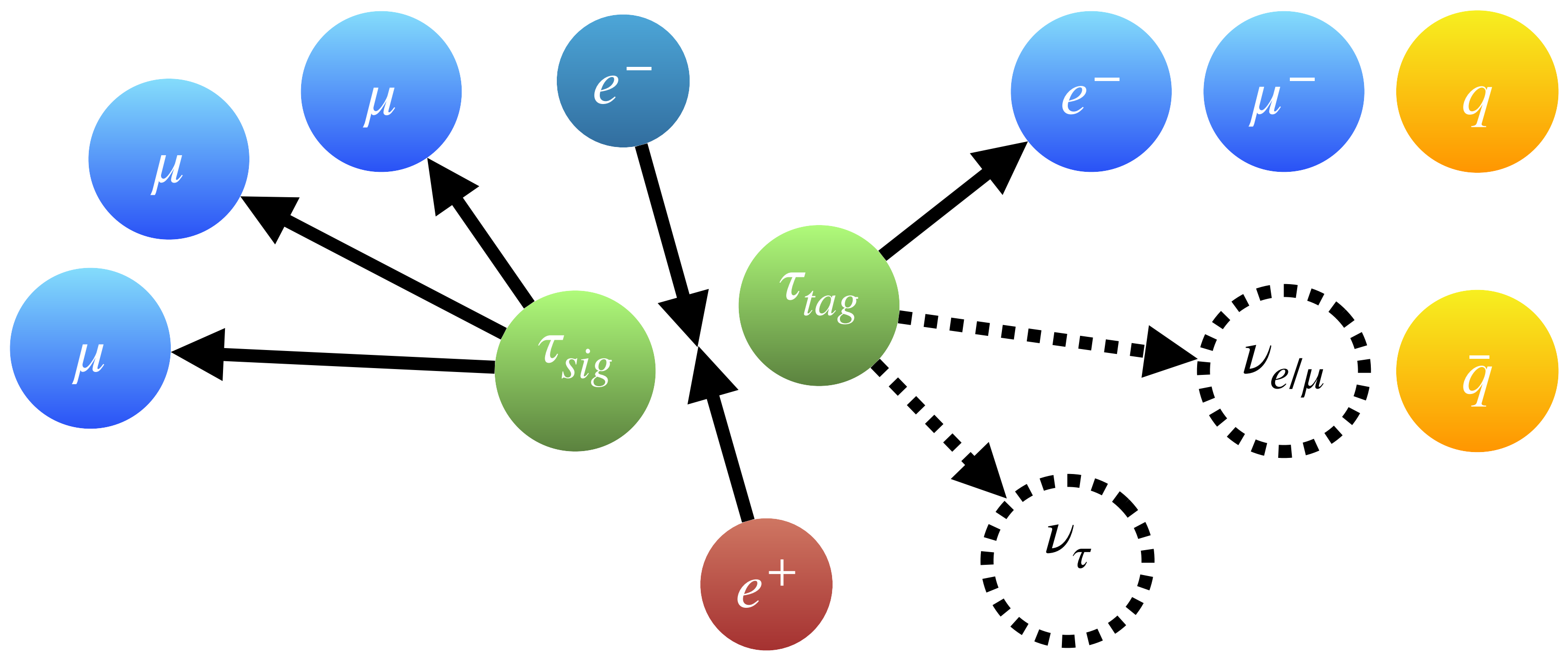
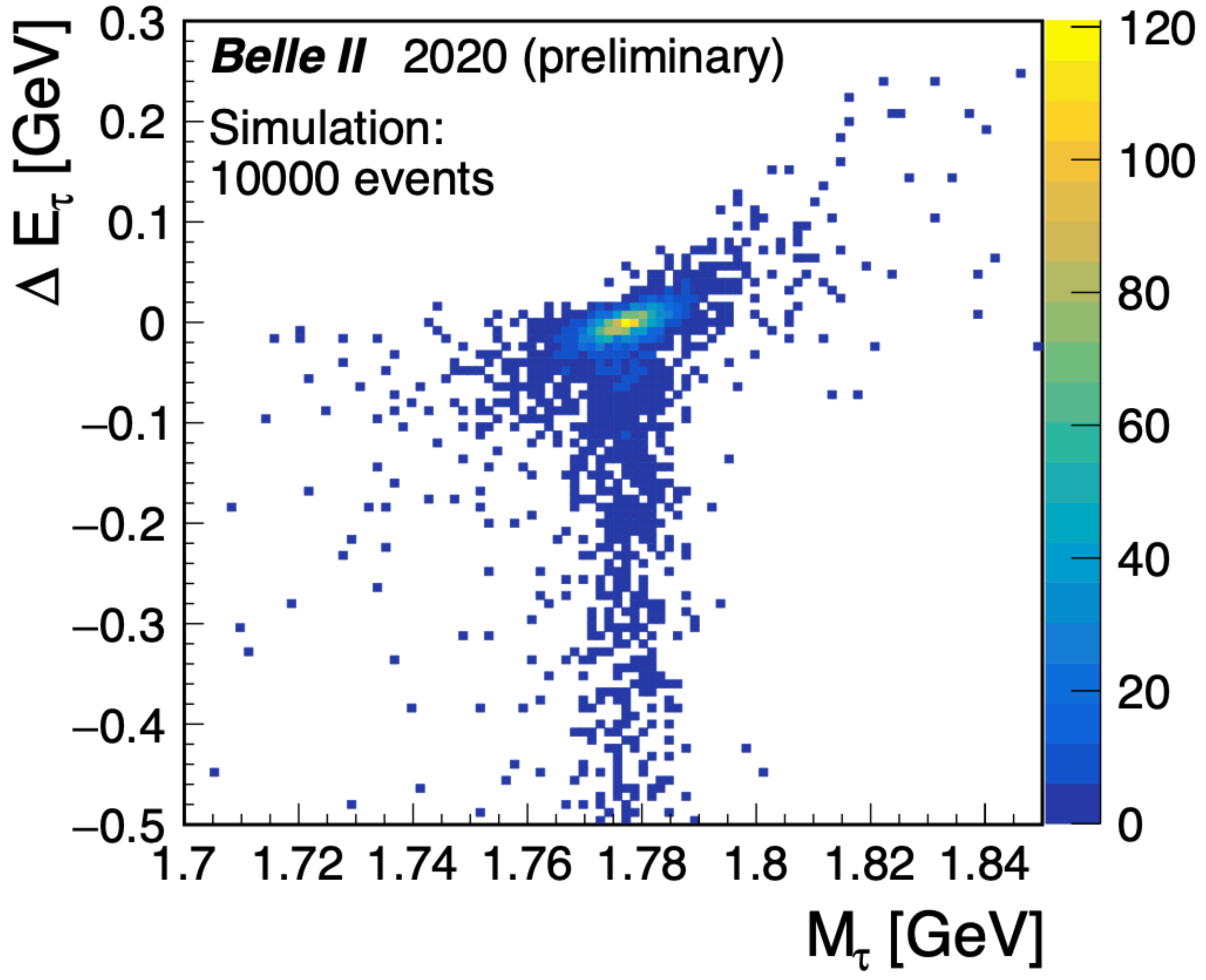
Looking Forward To $\tau \to \mu\mu\mu$

- Highly suppressed backgrounds.
- Current limits are $B(\tau \to \mu\mu\mu) = 2.1 \times 10^{-8}$.
- Prospects for 50 ab^{-1}: $\mathcal{O}(10^{-10})$
- Uncertainties scale with sample size!
  - Improvements through:
    - increase in luminosity
    - increase in signal detection efficiency
      $\rightarrow$ Motivation to improve efficiency





- Belle II could improve the efficiency by
  - Introducing momentum dependent muID optimisation
  - Increasing muon momentum range
  - Allowing a muon tag

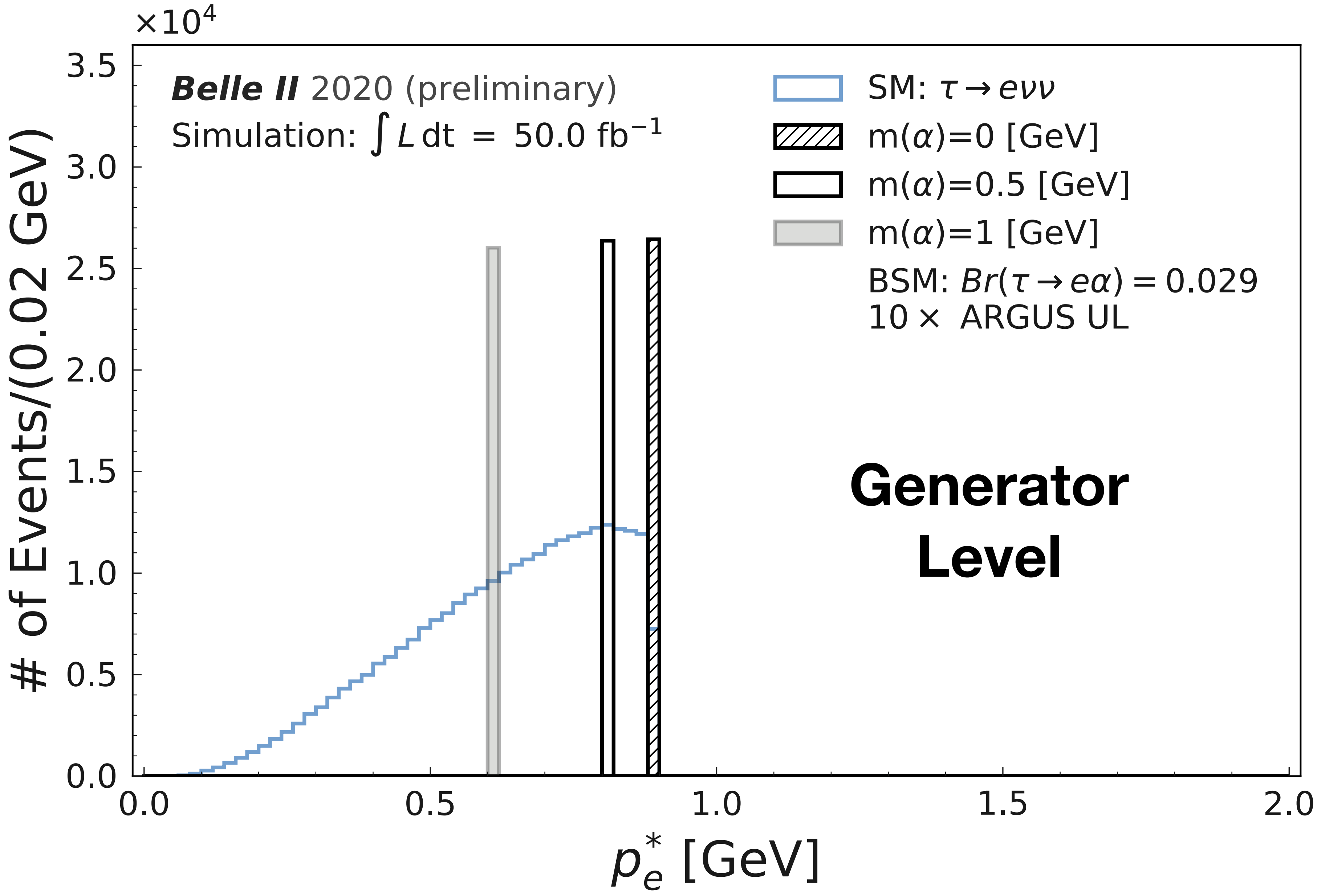
Two Independent Variables

1. $M_\tau = \sqrt{E_{\mu\mu\mu}^2 - P_{\mu\mu\mu}^2}$
2. $\Delta E_\tau = E_{\mu\mu\mu}^{CMS} - E_{beam}^{CMS}$

$\Rightarrow$ For Signal:
$\rightarrow$ ΔE_τ close to 0
$\rightarrow$ M_τ close to m_τ

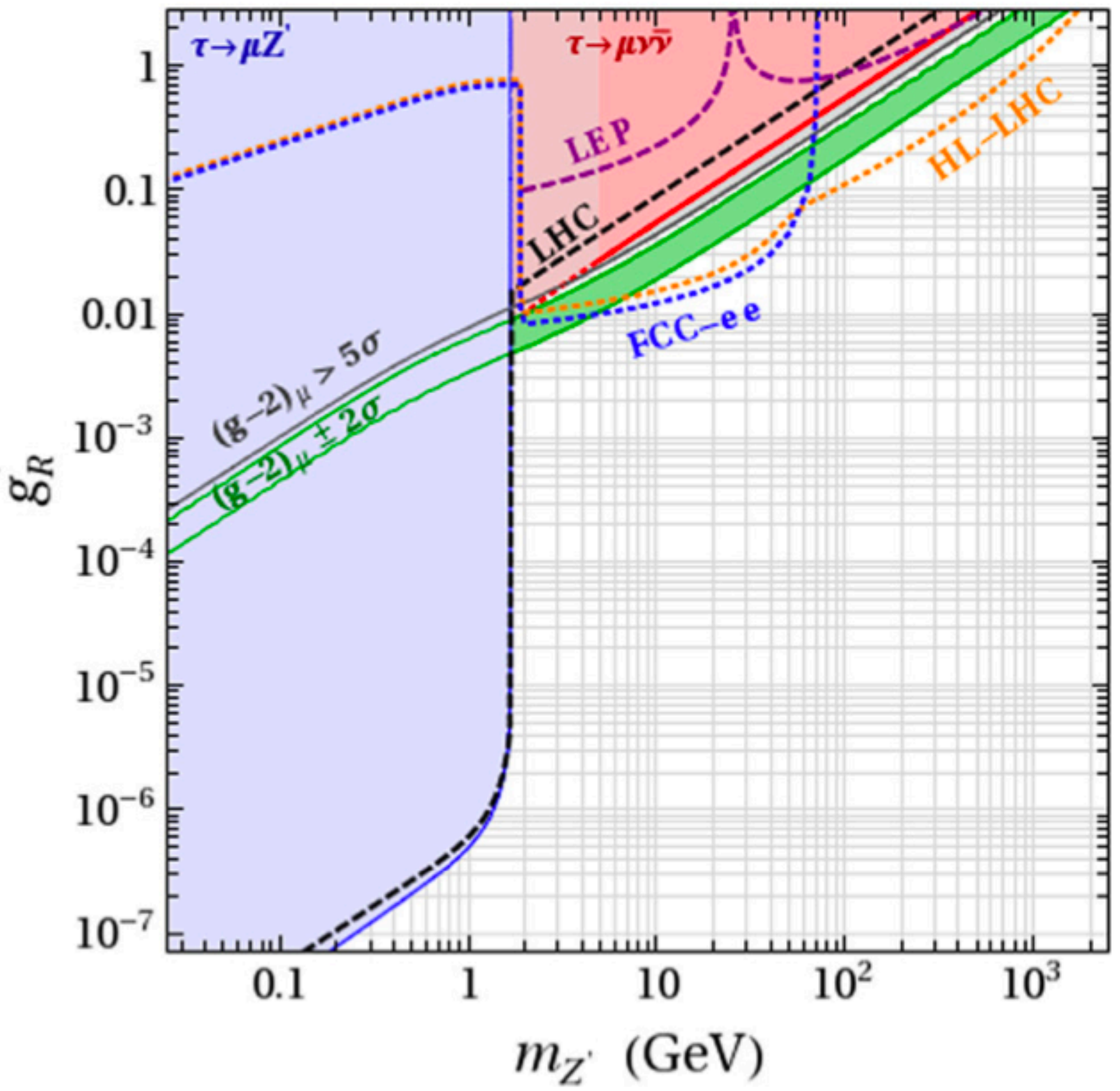
Looking Forward To $\tau \rightarrow l + \alpha$ (invisible)

- Search for a two body decay spectrum
- Signal will manifest as a peak in the τ-rest-frame (TRF)

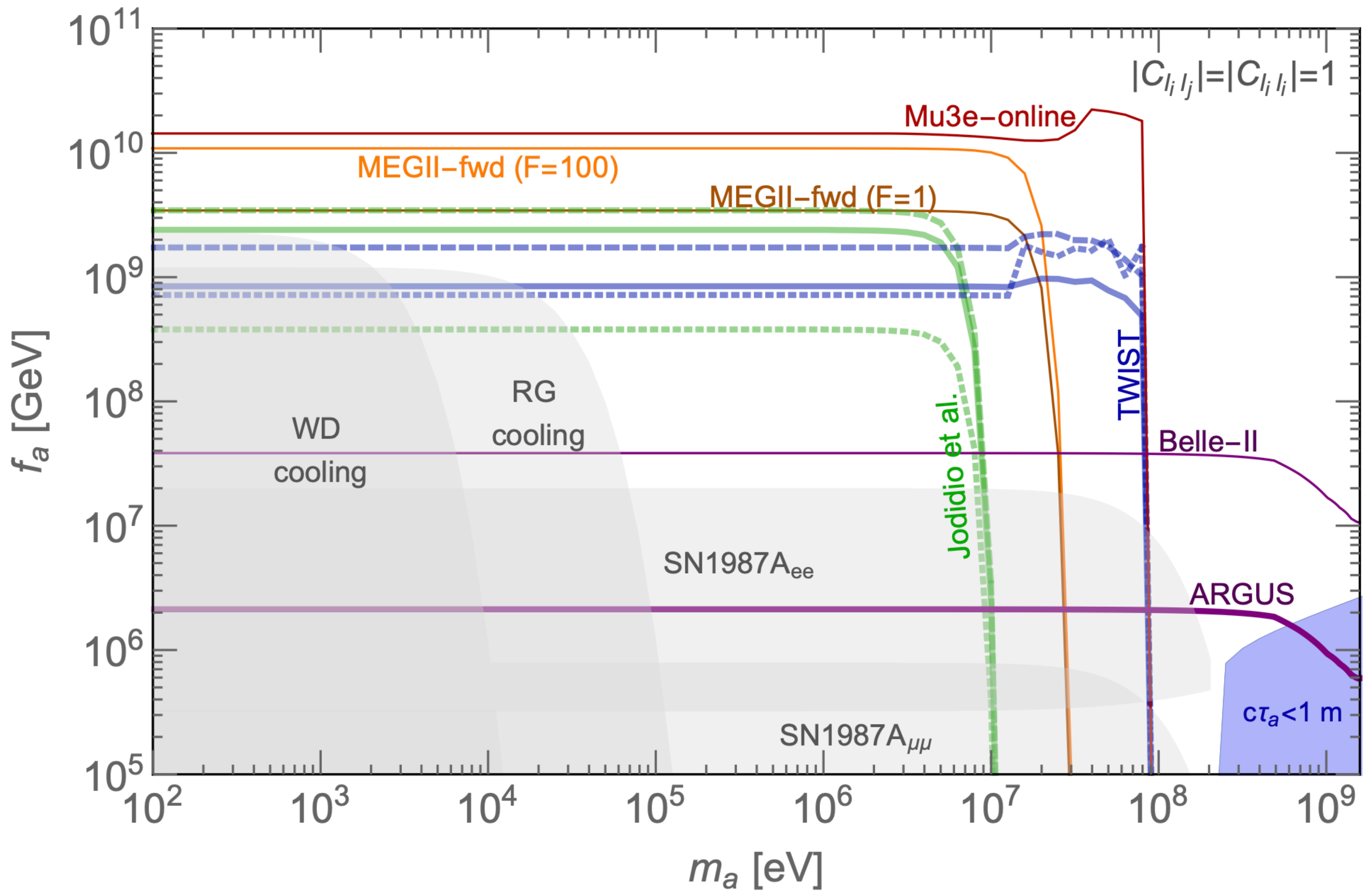


Various NP Scenarios:

- **LFV Z':** strong bound from ARGUS
- **Light ALP a:** unique parameter space accessible



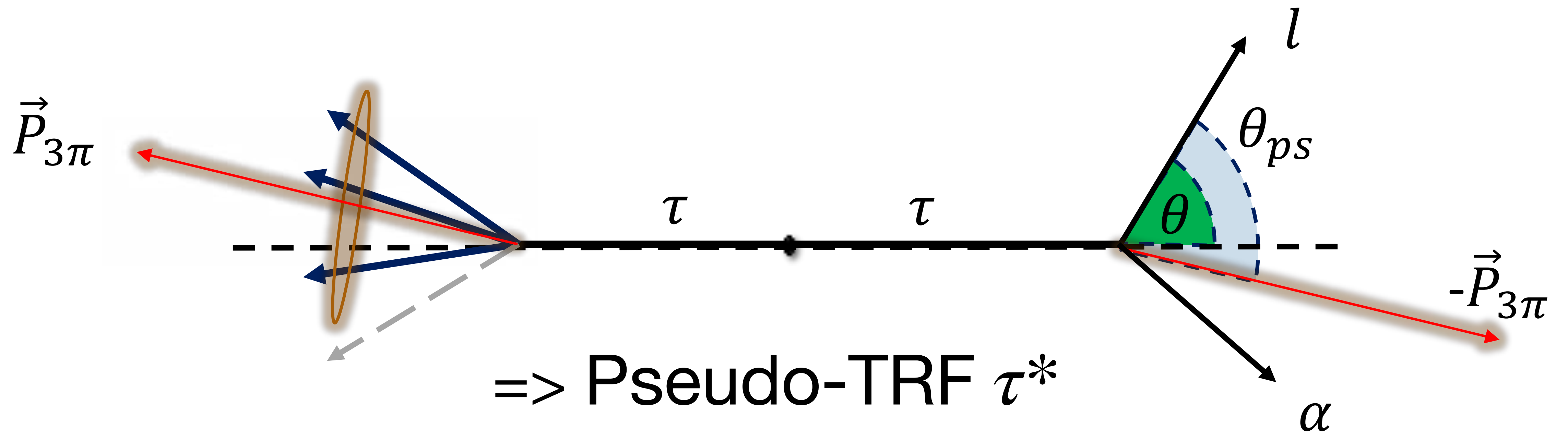
Wolfgang Altmannshofer, Chien-Yi Chen, P.S. Bhupal Dev, Amarjit Soni



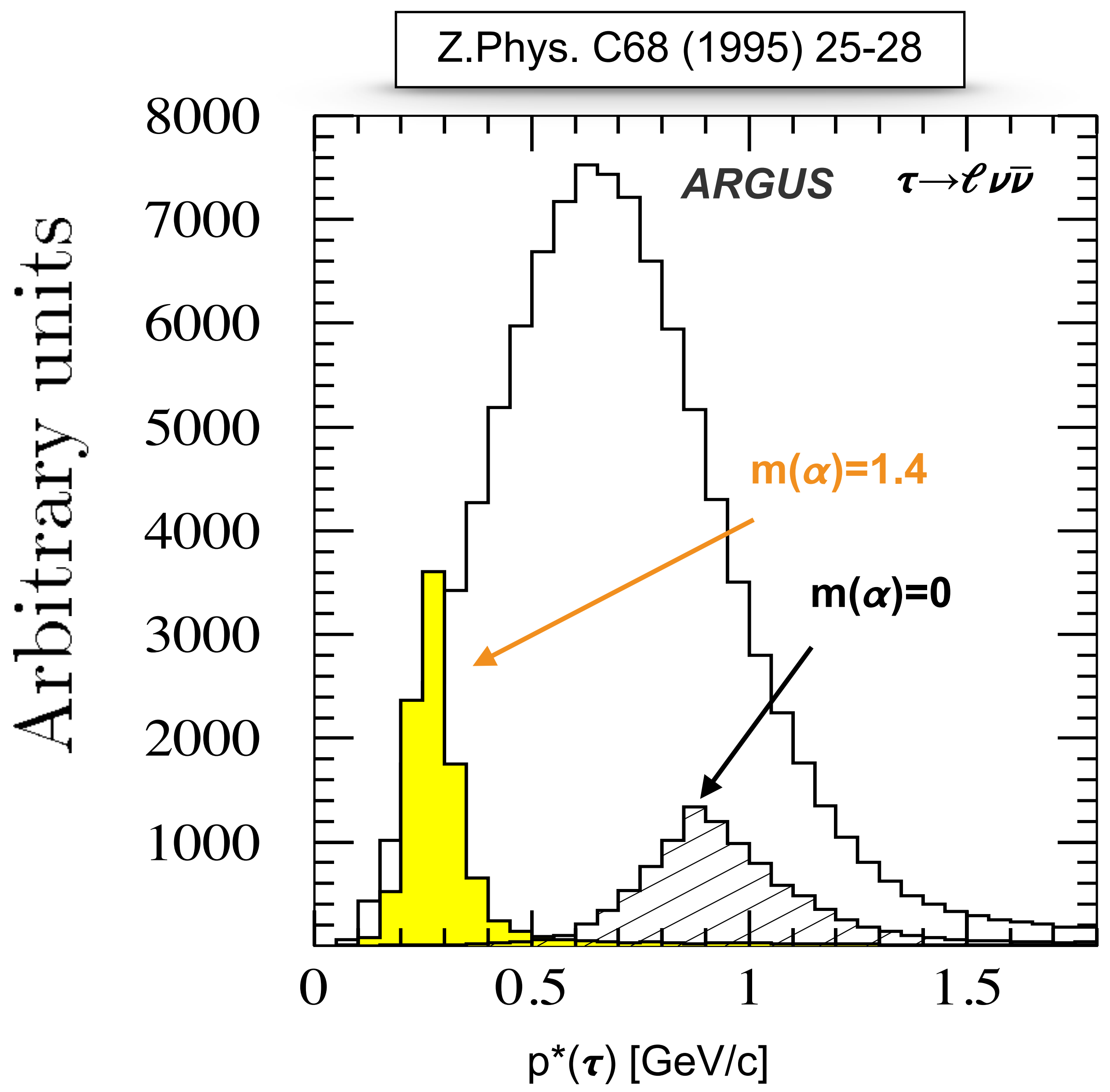
Lorenzo Calibbi, Diego Redigolo, Robert Ziegler, Jure Zupan,

Current status: $\tau \to l + \alpha$ (invisible)

- Idea: search for a two body decay spectrum
  - Challenge: Estimate TRF with missing ν_τ momentum
  - Using
    $E_\tau \approx E_{CMS}/2$
    $\vec{p}_\tau \approx \vec{p}_{3\pi} = \sum_{i=1}^{3} \vec{p}^{\,i}_\pi$



- No signal region → fit full spectrum with
  - SM expectation
  - SM + BSM expectation
  - → compare likelihood of the two models



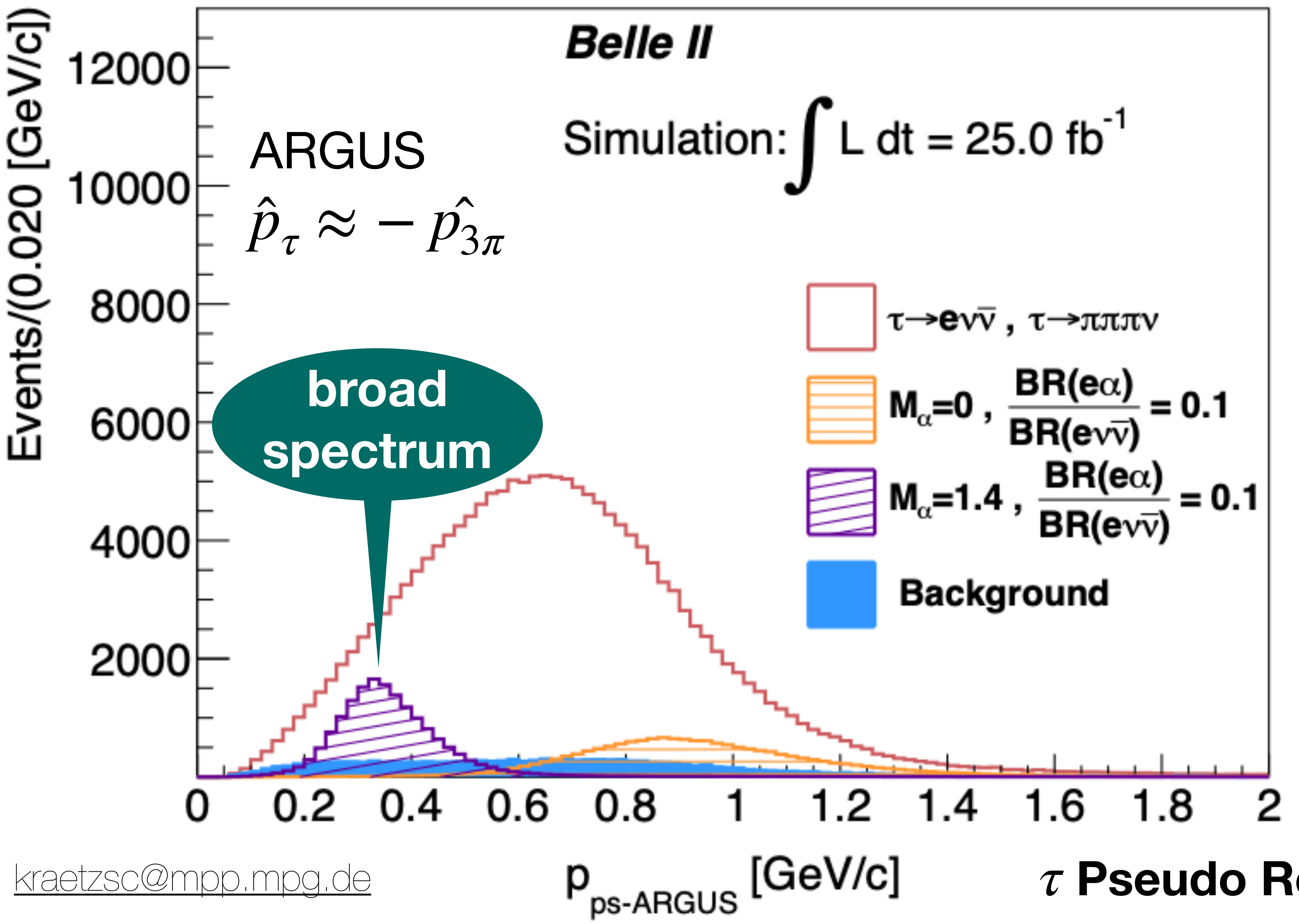
- Sensitivity depends on m_α
  - Last results from
    - ARGUS (472 pb^{-1})
    - MARK III (9.4 pb^{-1})

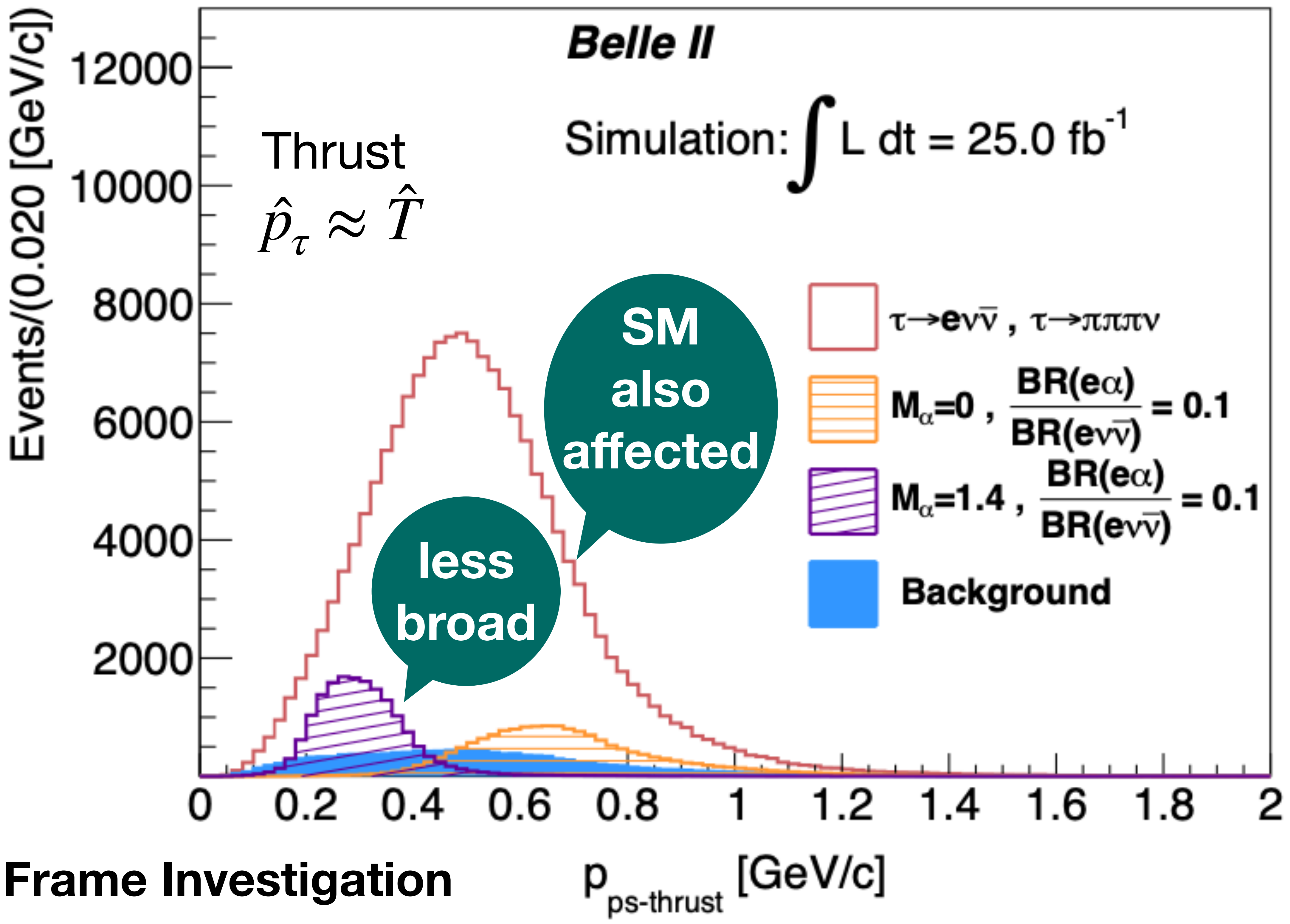
  → **we aim to update with ~60 fb^{-1} of Belle II data**

Analysis Strategy

- Using a cut-based Selection
- Statistical treatment with a template Fit
- The data can be modelled as: $f(x) = N_{sig} \cdot f_{e\alpha}(x) + N_{e\nu\ nu} \cdot f_{e\nu\nu}(x) + N_{BG} \cdot f_{BG}(x)$
    - With x being the momentum in the tau rest-frame
- Upper Limit estimated with a Frequentist profile-like-hood method:

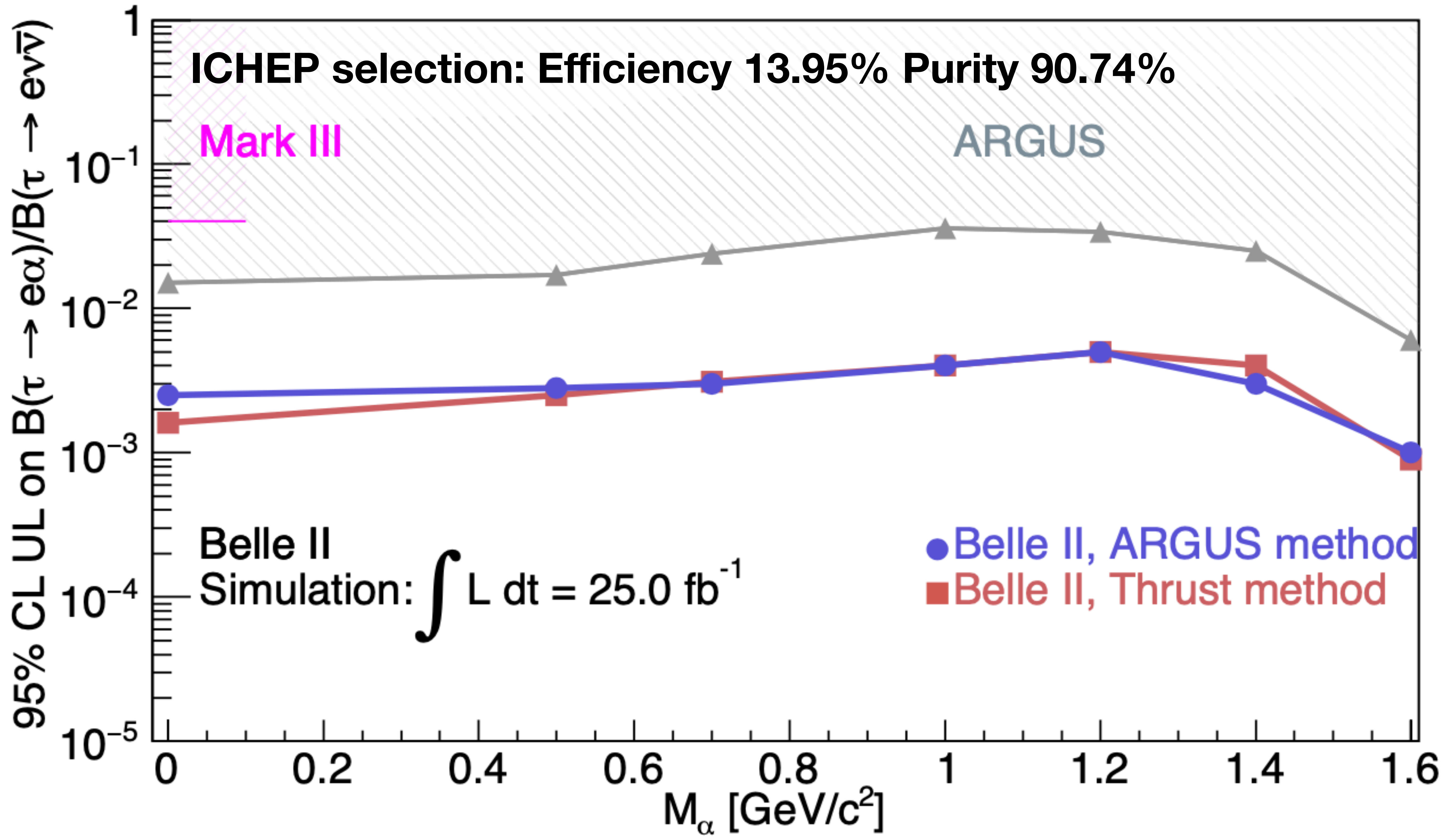
$$CL_{sig} = \frac{CL_{sig+bg}}{CL_{bg}}$$





ICHEP MC-study: Upper Limit Estimate

- UL estimate for ratio $Br(\tau \to e\alpha)/Br(\tau \to e\nu\nu)$
- No systematics were taken into account
  $\to$ work in progress



	UL(95% c.l.)		
$M(\alpha)$ [GeV/c^2]	ARGUS (1995)	Argus method	Thrust method
0	0.015	0.0025	0.0016
0.5	0.017	0.0028	0.0025
0.7	0.024	0.003	0.0031
1.0	0.036	0.004	0.004
1.2	0.034	0.005	0.005
1.4	0.025	0.003	0.004
1.6	0.006	0.001	0.0009

→ Performance of ARGUS and Thrust method is similar

Conclusion And Outlook

- The τ has various interesting physics prospects at Belle II:
  - Improvements of SM Parameters
    - τ-mass
    - τ-lifetime
  - Potential measurements/verifications of SM parameters: $g-2$ or EDM
  - Potential observation of LFV
    - $\tau \rightarrow l + \alpha$
    - $\tau \rightarrow \mu\mu\mu$
    - $\tau \rightarrow l\gamma$, ...

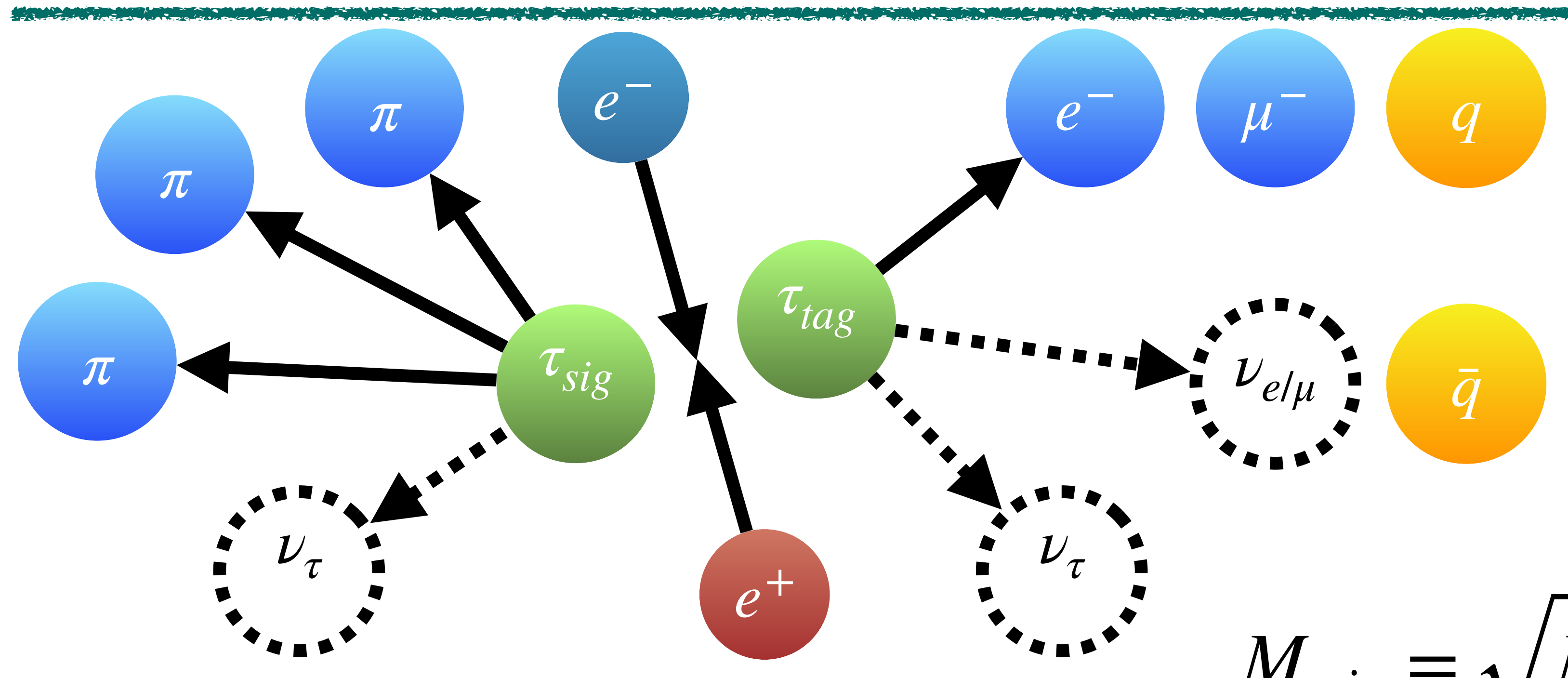
Motivation

- The Standard Model (SM) is in trouble, as it can not answer questions to:
  - Dark Matter, CP problem, …
- Precision measurements of Leptons to test the SM and new physics models
  - Well understood QED
  - Parameters measured are
    - Free parameters: mass, lifetime,…
    - Predicted observable: g-2, EDM,…

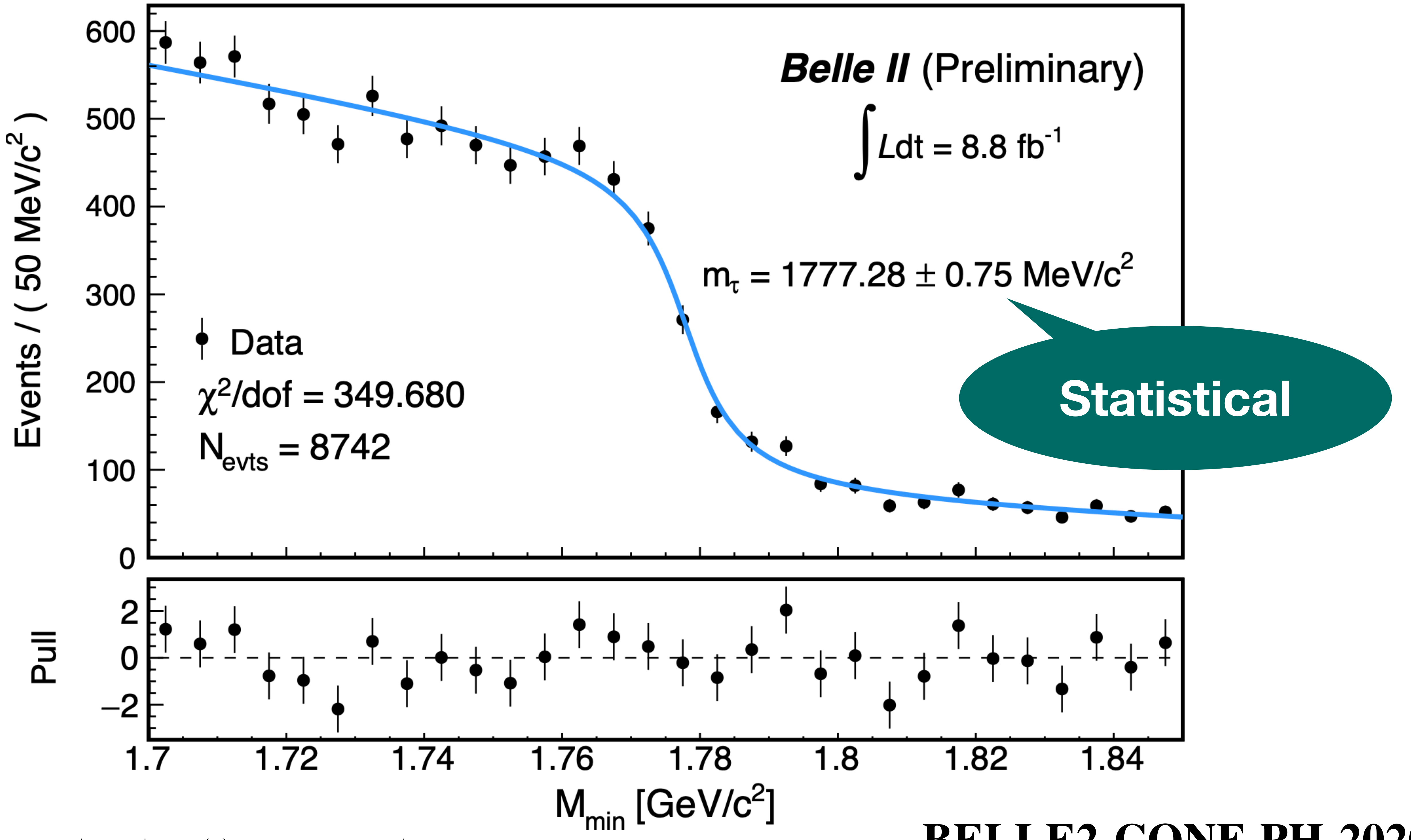
τ

- **3rd Generation Lepton**
  - **Mass:** $1776 \pm 0.12\,\mathrm{MeV}$
  - **Lifetime:** $290.3 \pm 0.5\,\mathrm{fs}$
- **Properties**
  - **Hadronic Decays**
    - **Probe QCD**
    - **CP violation**
  - **Bigger coupling to New Physics?**
    - **Lepton Flavour Violation**
    - **4th Generation Neutrino**
    - **…**

τ Mass Measurement (Preliminary)



$$M_{min} = \sqrt{M_{3\pi}^2 + 2(E_{beam} - E_{3\pi})(E_{3\pi} - P_{3\pi})}$$



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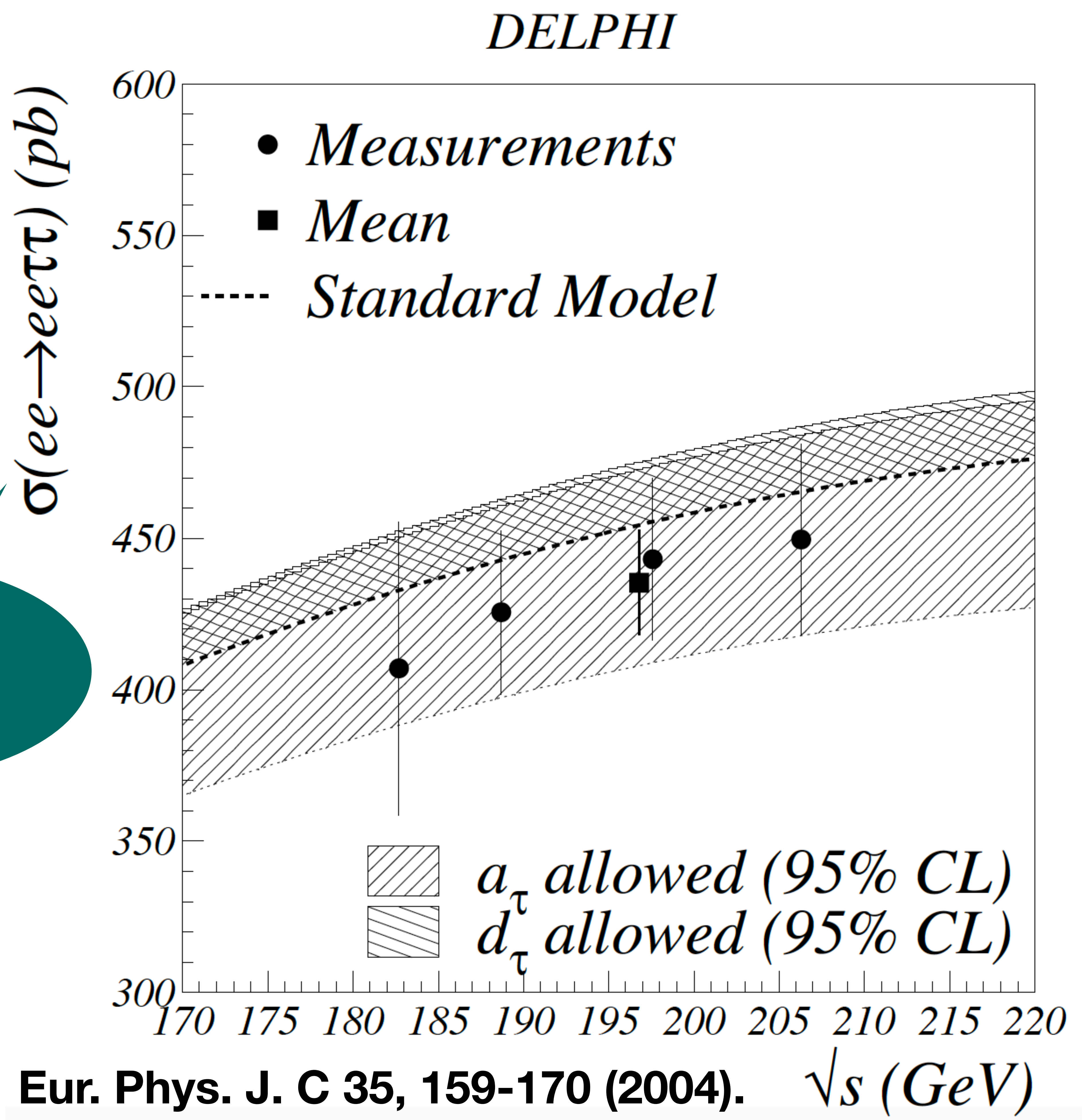
g-2 and EDM Measurements

g-2 influences correction



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  - Prospect for first significant measurement of non-zero SM $g-2$, with full Belle II luminosity!

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$$a_\tau^{Exp} = 0.018 \pm 0.017$$

- Interaction vertex for off-shell γ and on-shell $\tau\tau$:

$$\Gamma^\mu(q^2 \to 0) \propto i a_\tau - \frac{2m_\tau d_\tau}{e}$$

  - e: positron charge
  - m_τ: τ-mass
  - d_τ : electric dipole moment