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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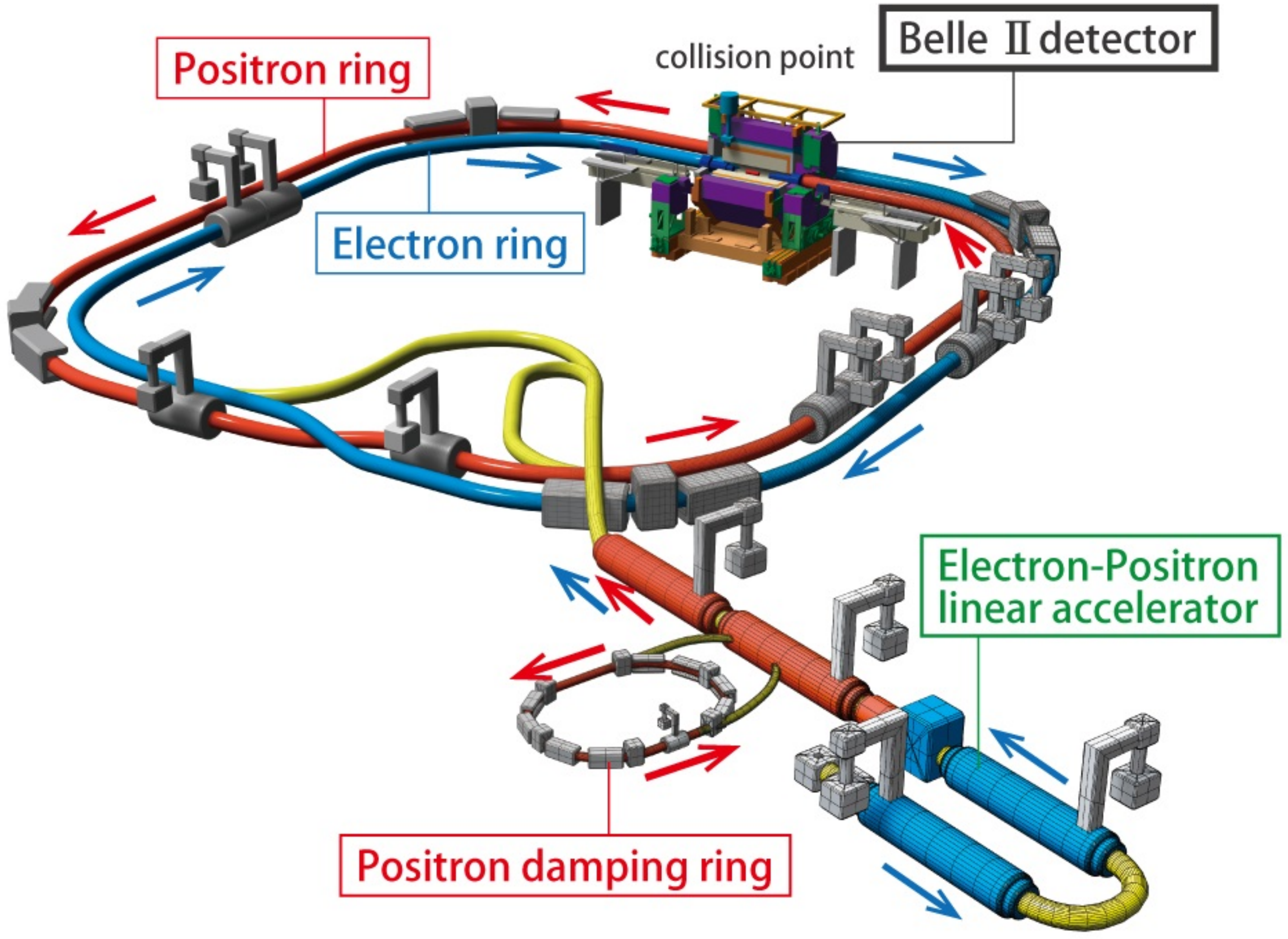
Motivation

- 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,…

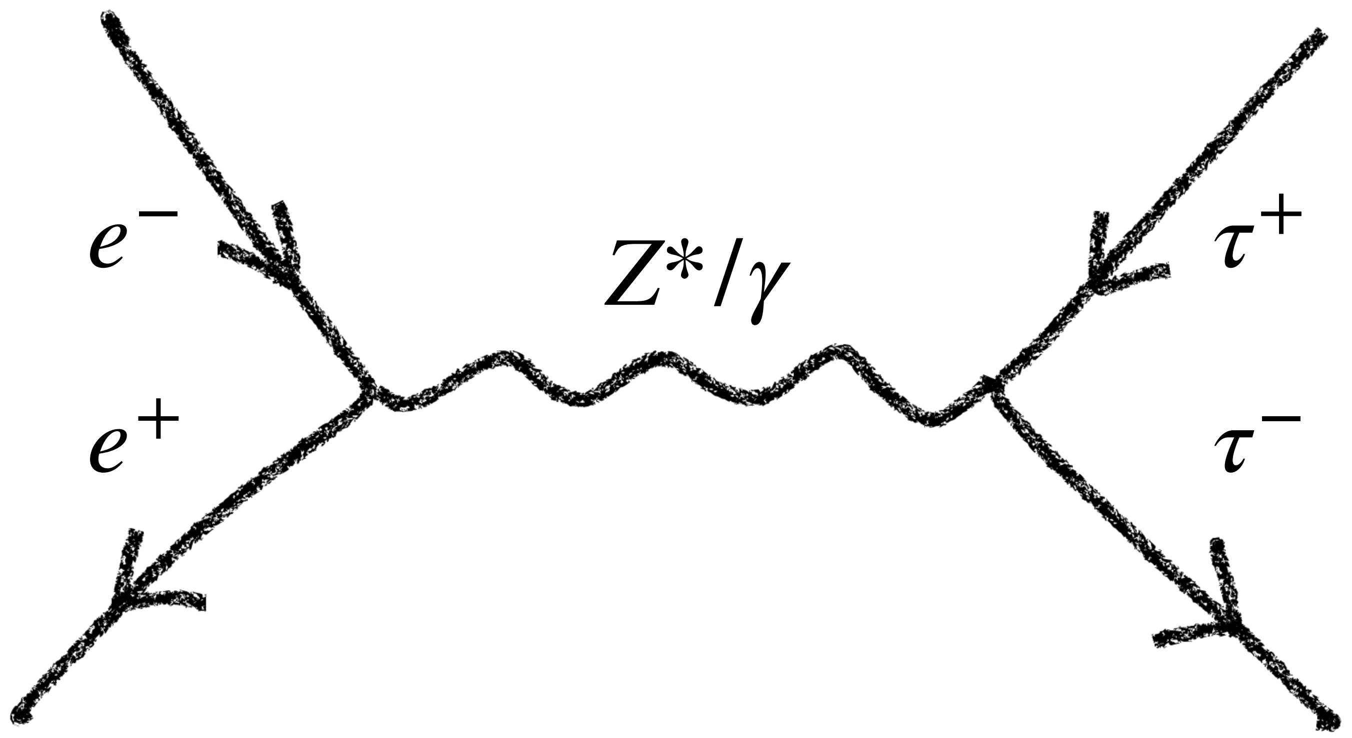
τ

- **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**
    - **…**

Where can one study the τ?



- At e^+e^- machines there is a low background and well understood production mechanism for τ
- SuperKEKB collider



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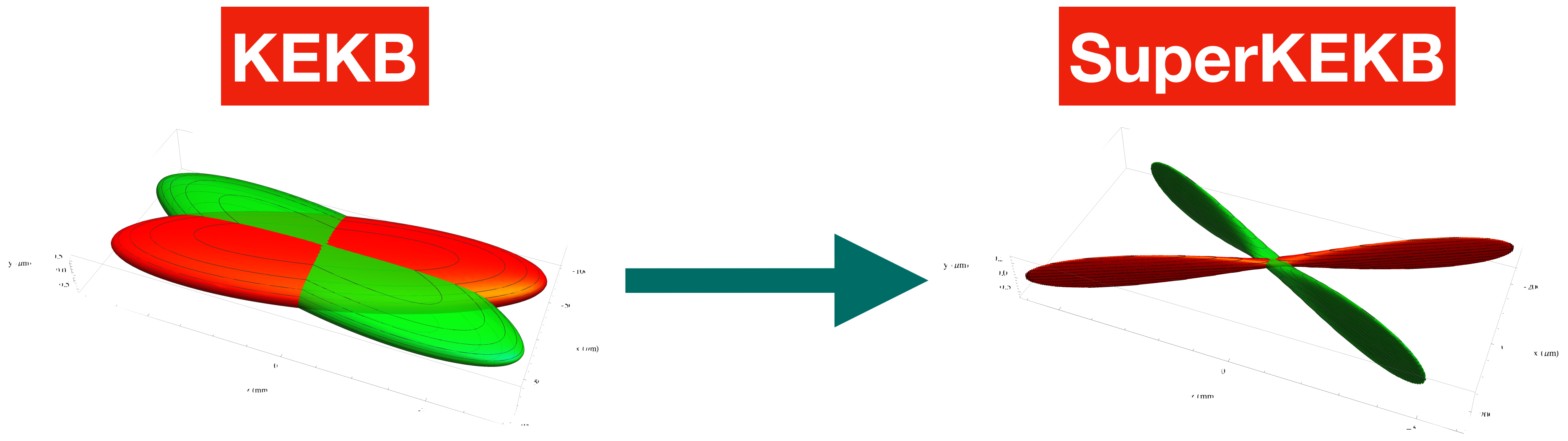
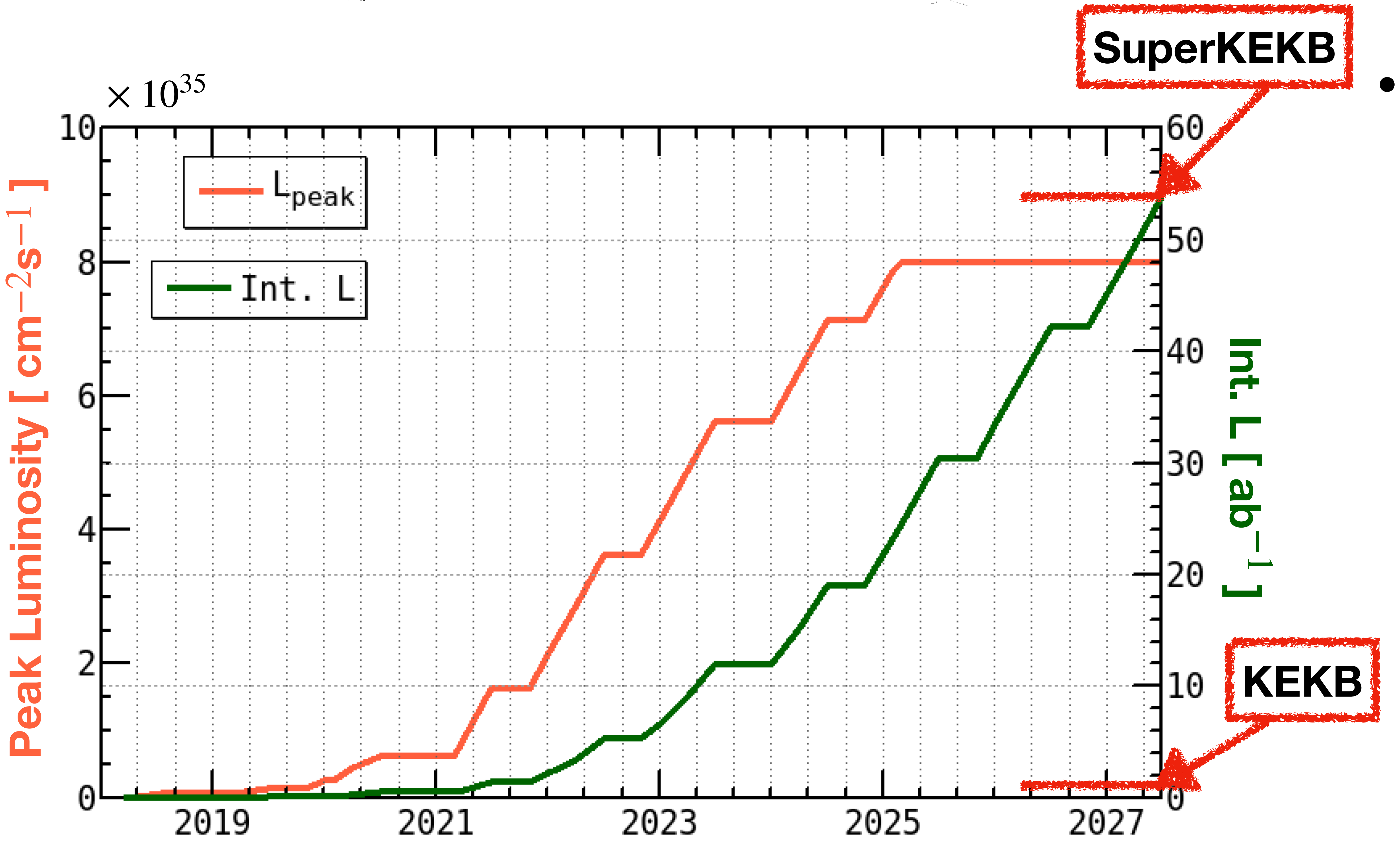




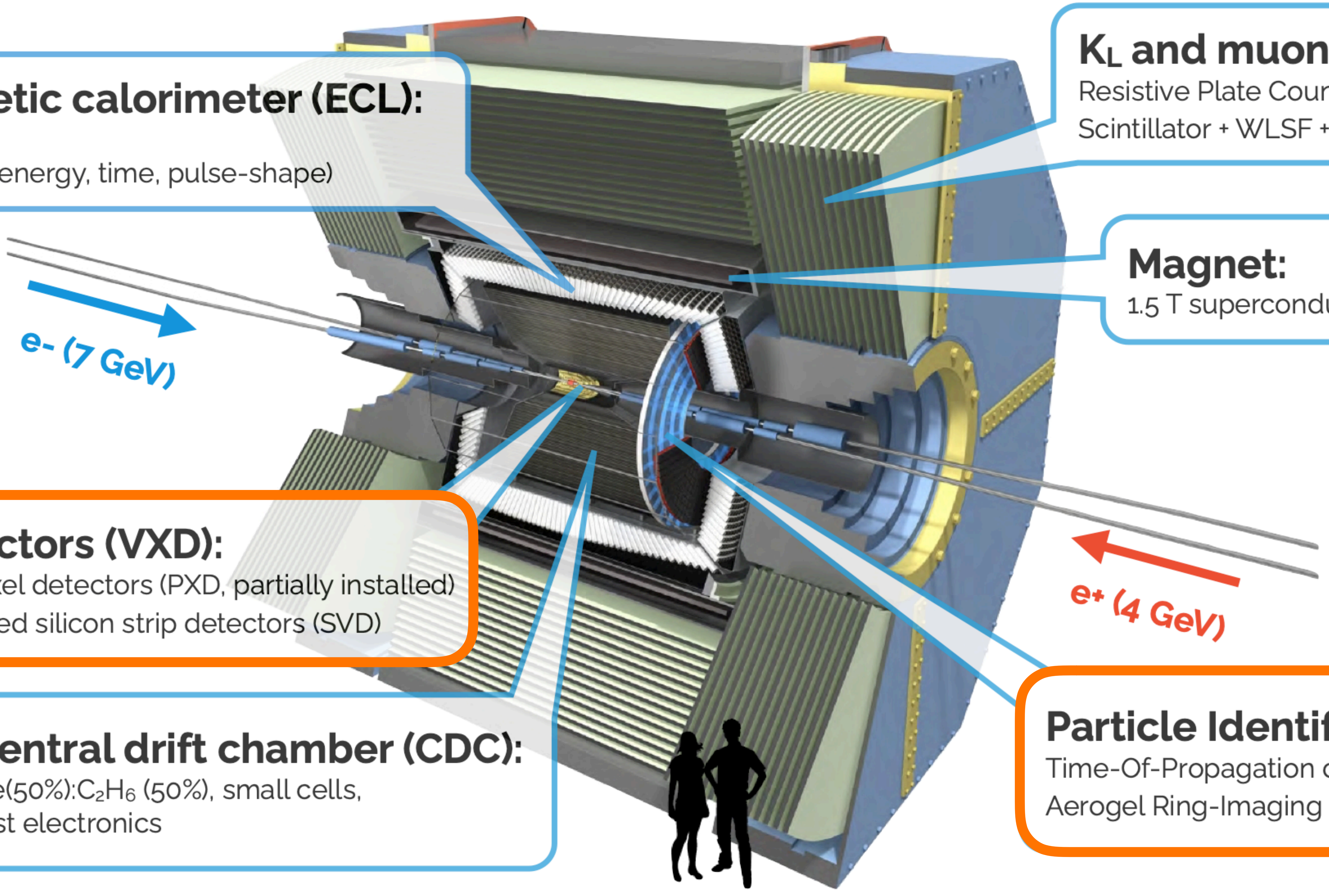
- At e^+e^- machines there is a low background and well understood production mechanism for τ
- SuperKEKB collider
  - Increased Integrated Luminosity: 1 ab^{-1}(KEKB) → 50 ab^{-1}(SuperKEKB)
  - SuperKEKB is a τ-factory!
    - $\sigma(e^+e^- \rightarrow \Upsilon(4s)) \approx \sigma(e^+e^- \rightarrow \tau^+\tau^-)$
    - ~ 45 billion tau pairs for full Belle II program

How to Study τ at Belle II?

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



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

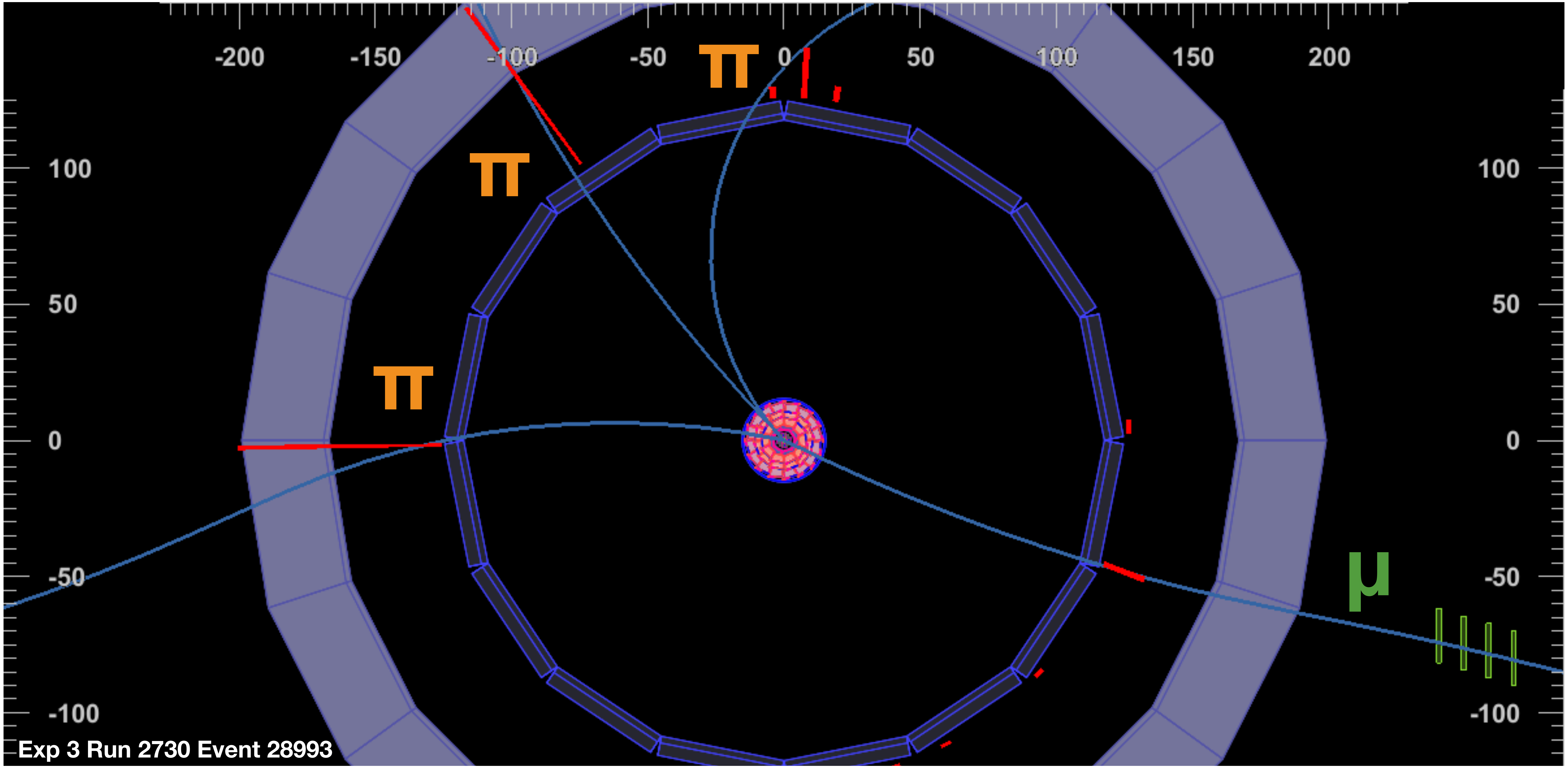
Vertex detectors (VXD):
2 layer DEPFET pixel detectors (PXD, partially installed)
4 layer double-sided silicon strip detectors (SVD)

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

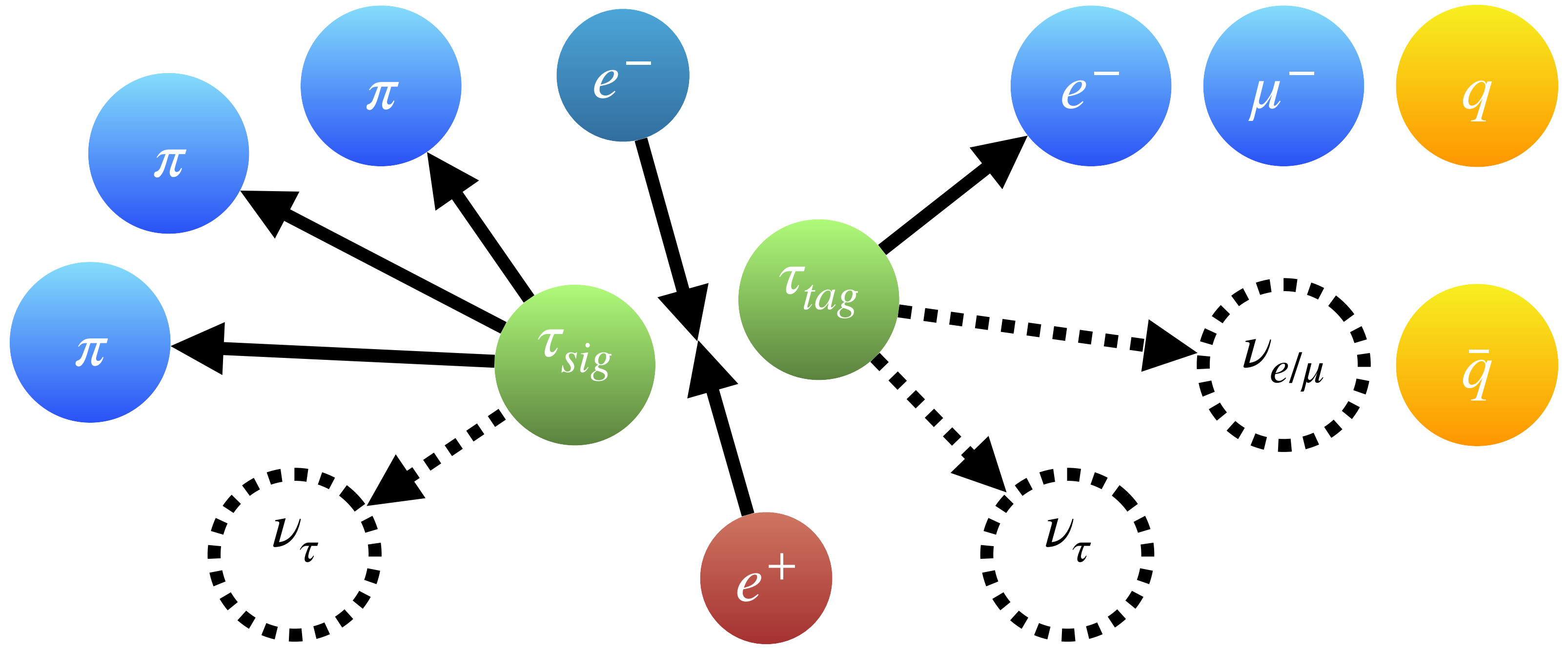
Particle Identification (PID):
Time-Of-Propagation counter (TOP) (barrel)
Aerogel Ring-Imaging Cherenkov Counter (ARICH) (FWD)

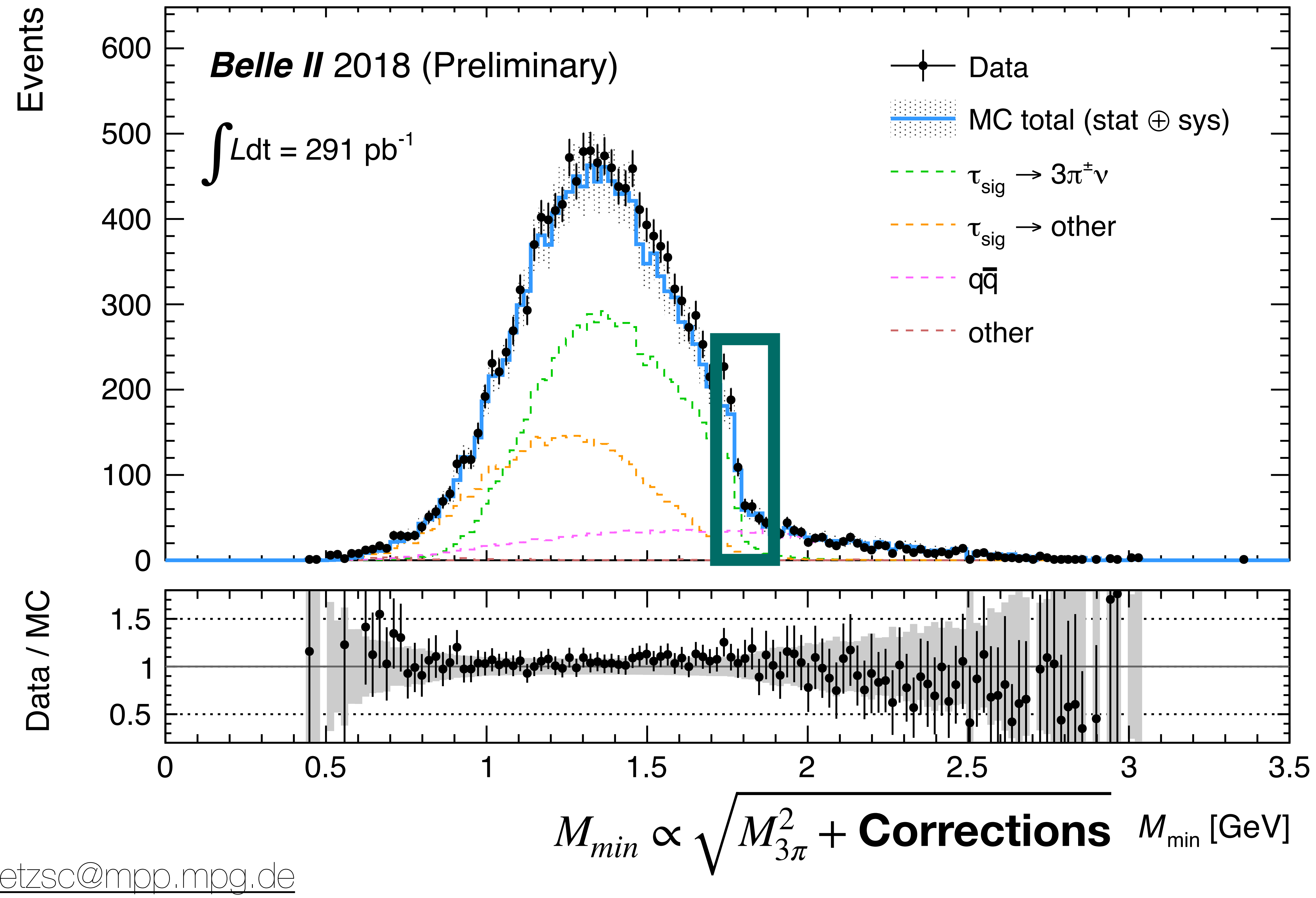
DEPFET: depleted p-channel field-effect transistor
WLSF: wavelength-shifting fiber
MPPC: multi-pixel photon counter

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

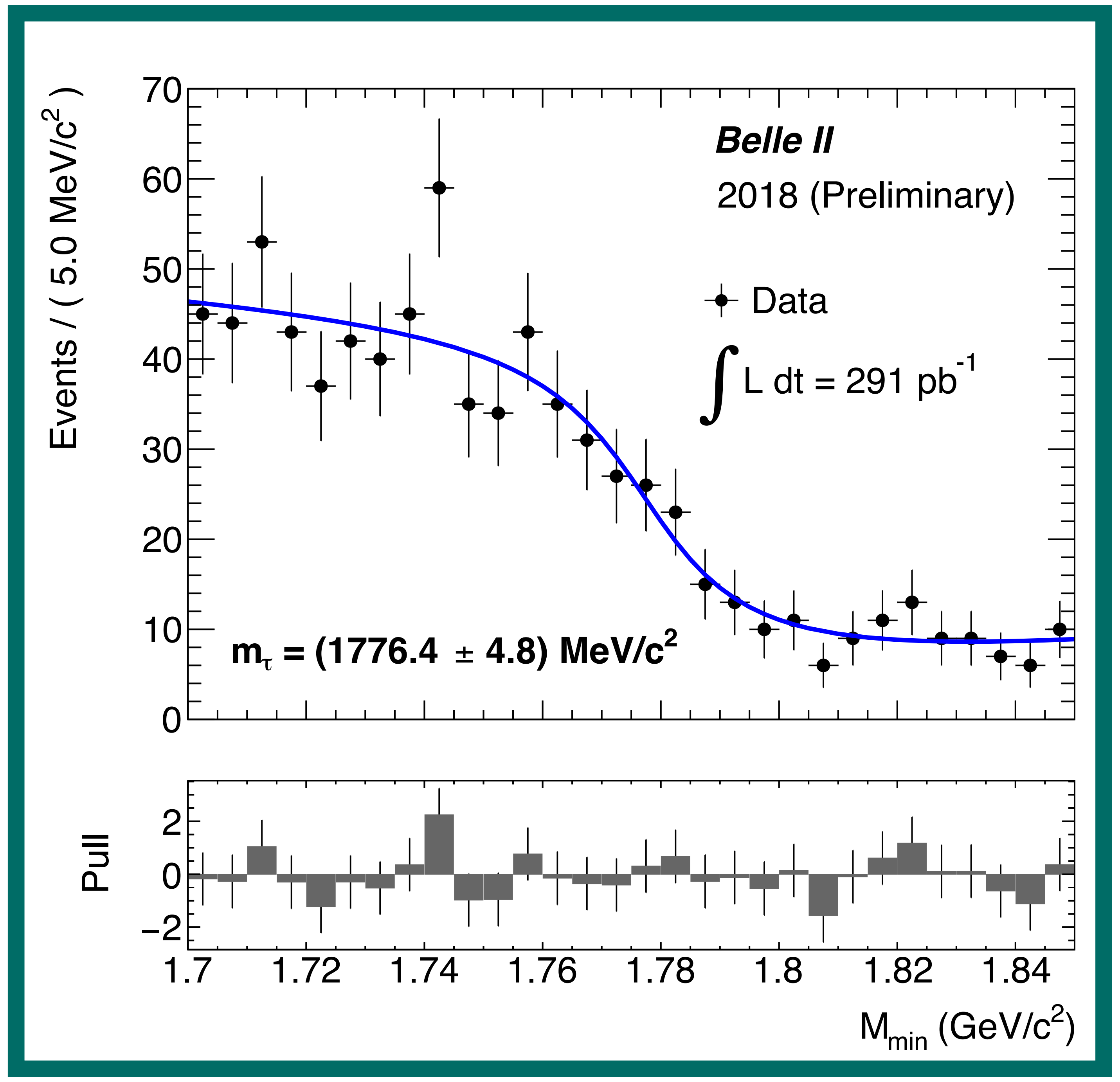


τ Mass Measurement (Preliminary)





- Tau mass measured using an analysis of a 3x1 prong decay.
  - Mass extraction from pion decay only
- Using a dataset of approximately 291 pb^{-1} of early data.



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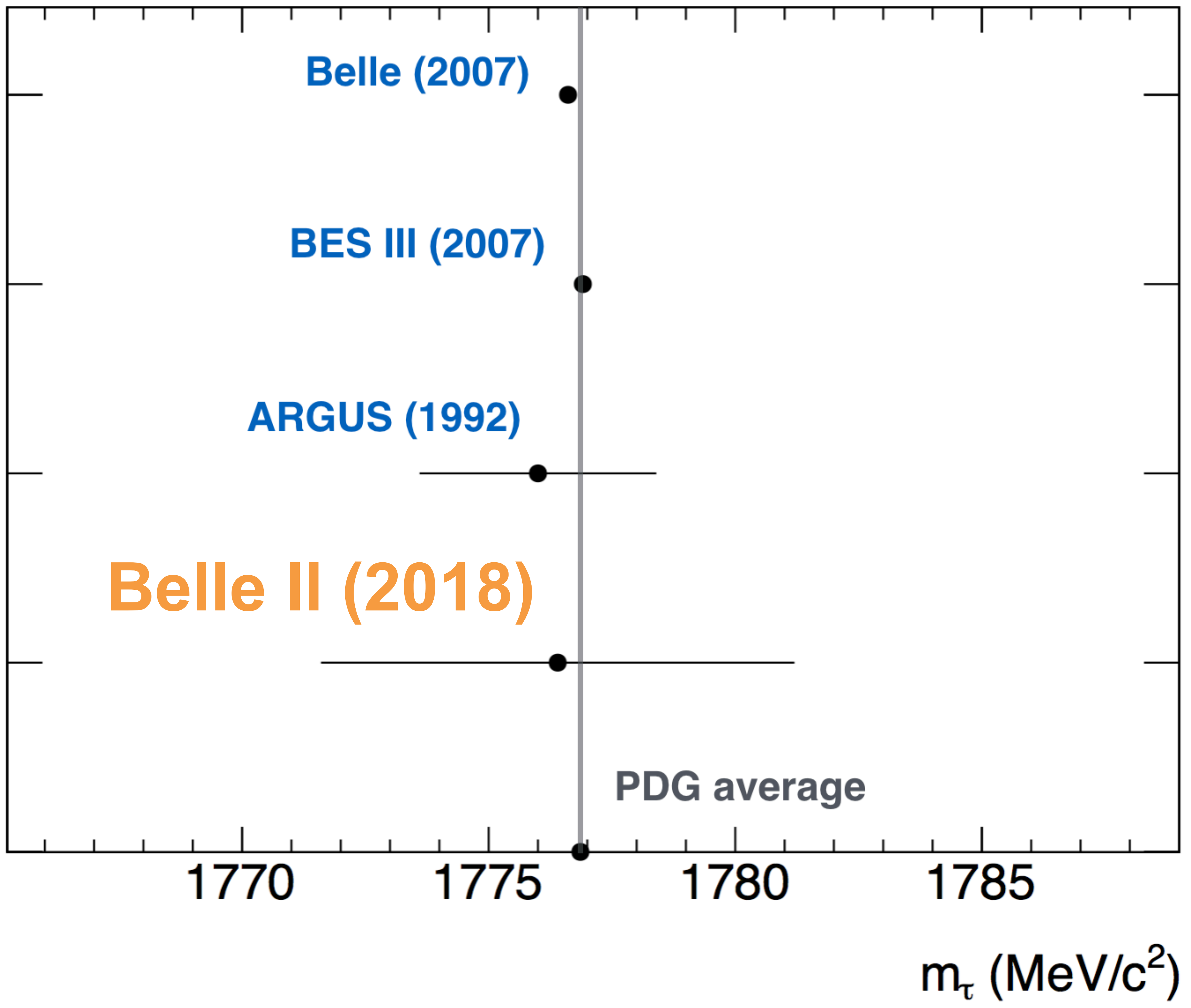
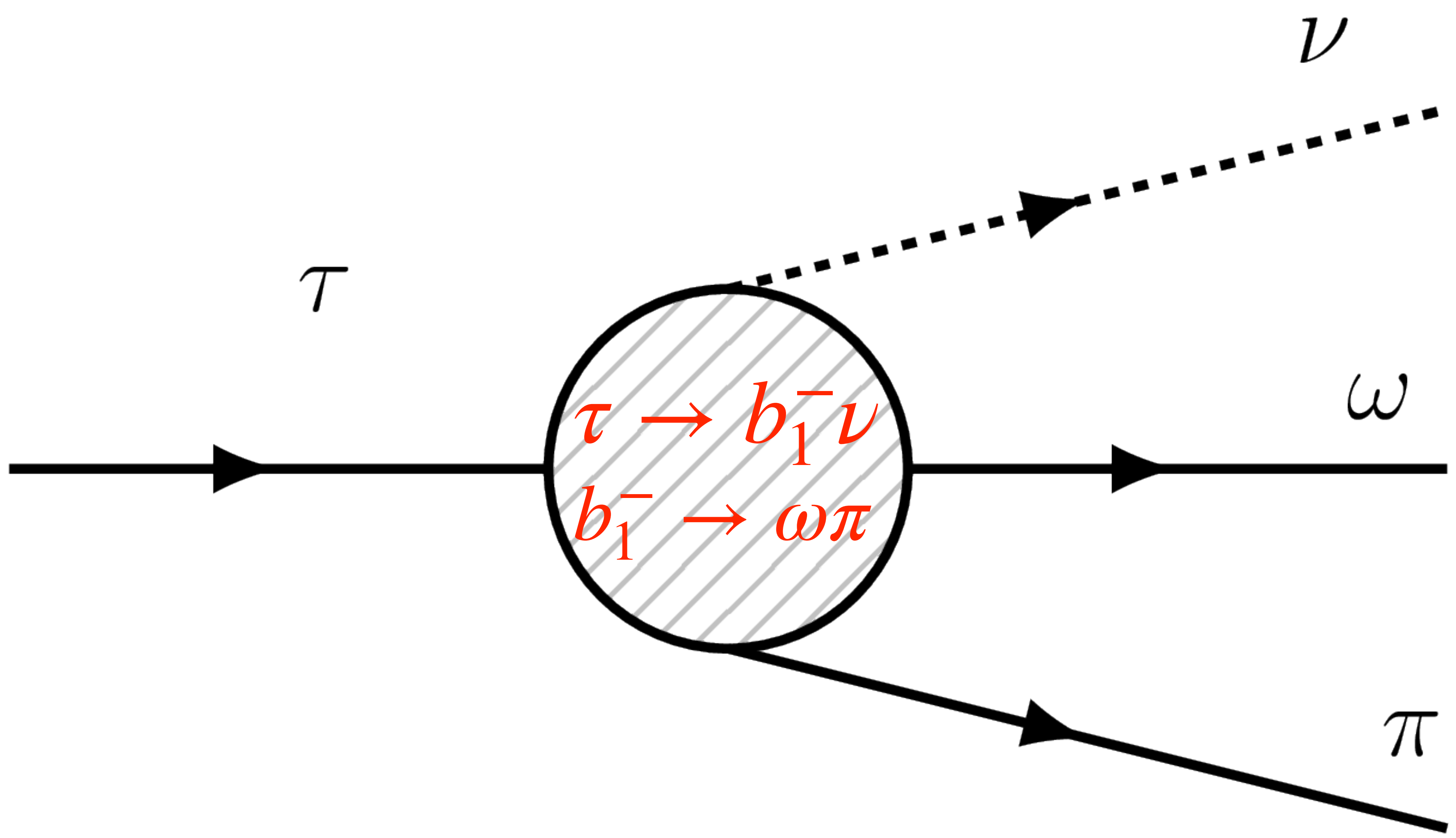


- Tau mass measured using an analysis of a 3x1 prong decay.
  - Mass extraction from pion decay only
- Using a dataset of approximately 291 pb^{-1} of early data.
- $m_\tau = (1776.4 \pm 4.8)\,\mathrm{MeV}$
- First τ physics results with early data: consistent with previous measurements!

Exotic Hadronic Currents

$J^{PG} = 0^{+-}$ (a_0)
$= 0^{-+}$ (η)
$= 1^{--}$ (ω)
$= 1^{++}$ (b_1)



- Hadronic Decays are classified by spin, parity and G-parity
- Old measurements:
  - CLEO: $B(\tau \to \omega h^- \nu) = (1.91 \pm 0.07 \pm 0.06) \times 10^{-2}$
  - ALEPH: $B(\tau \to \omega h^- \pi^0 \nu) = (4.3 \pm 0.6 \pm 0.5) \times 10^{-3}$
- Yet to be observed:
  - Belle: $B(\tau \to \eta\pi\nu) < 7.3 \cdot 10^{-5}$
  - BaBar: $B(\tau \to \eta\pi\nu) < 4.0 \cdot 10^{-6}$

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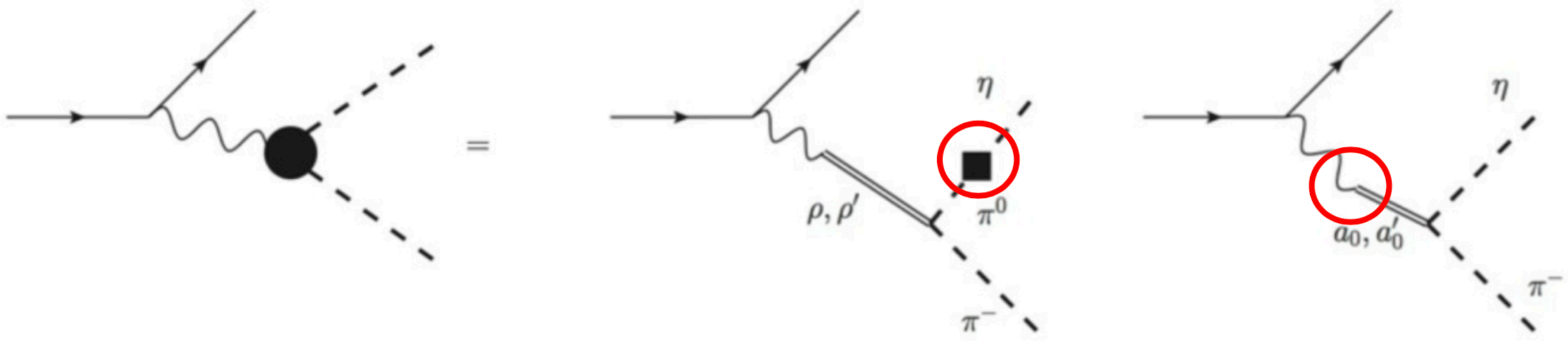

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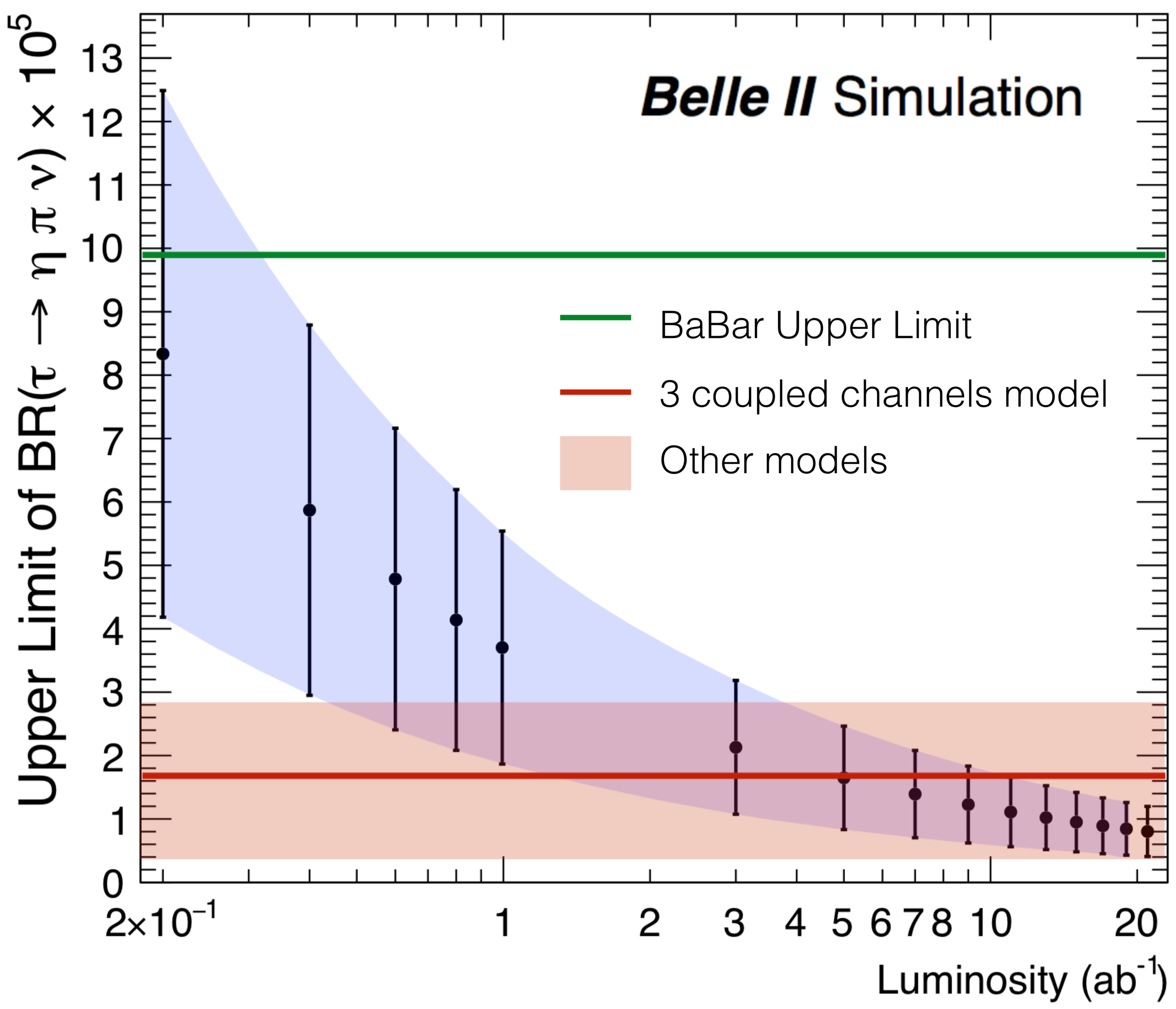

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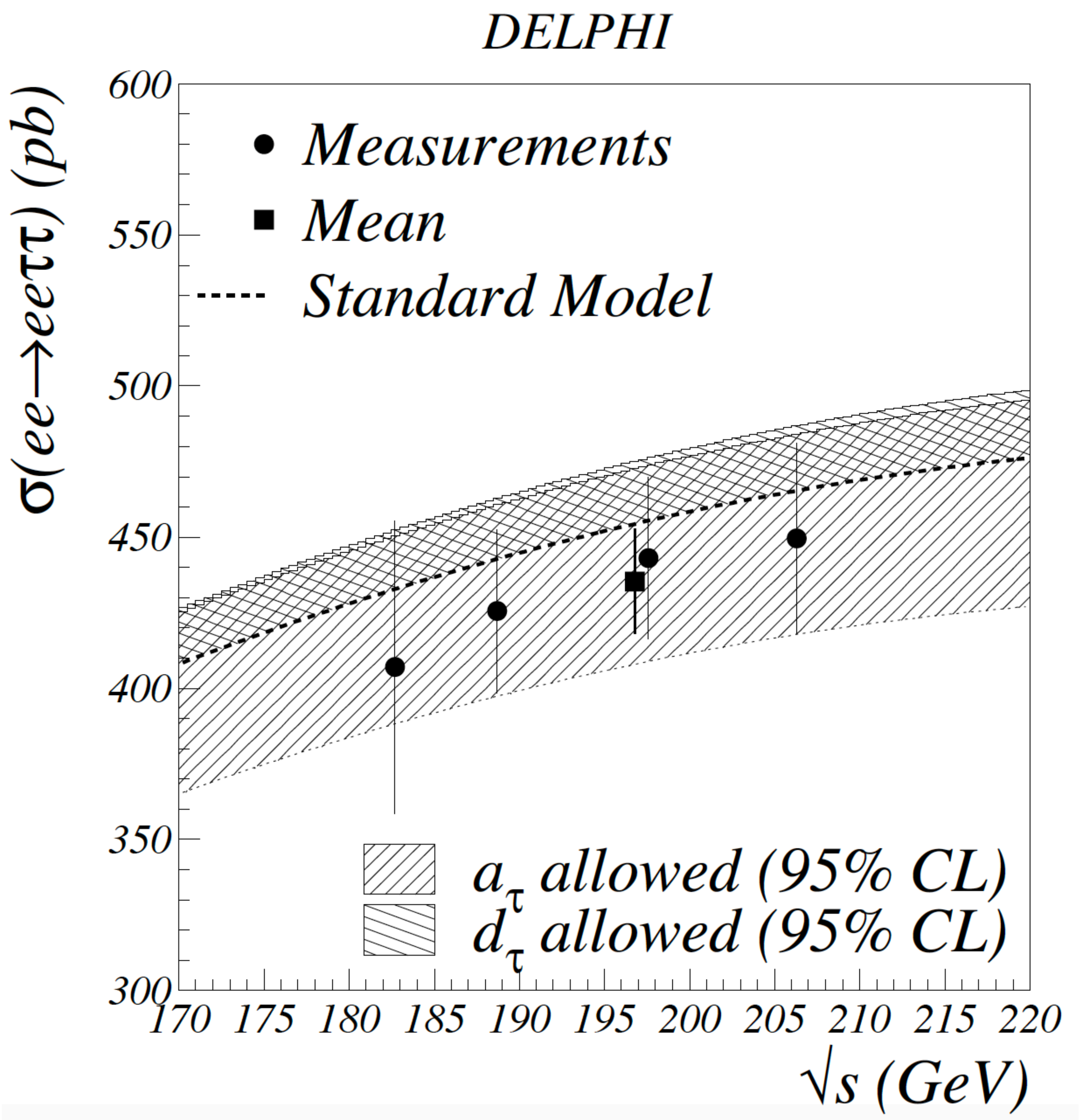
Further Standard Model Measurements

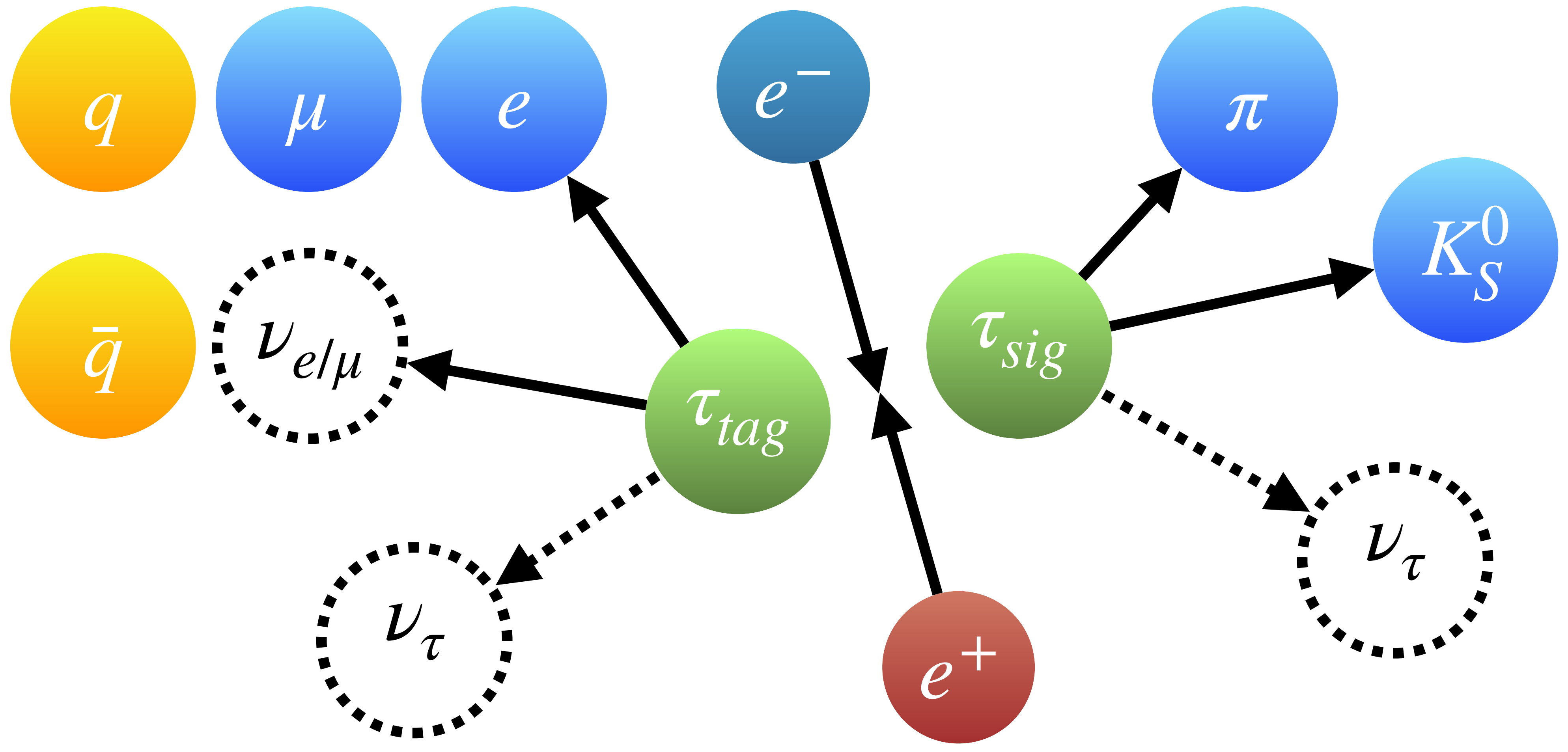


- Michel Parameters
- Tau $g-2$ and EDM
  - Belle (30 fb^{-1}): EDM < $\mathcal{O}(10^{-17})$
  - First ever test of SM $g-2$!

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

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

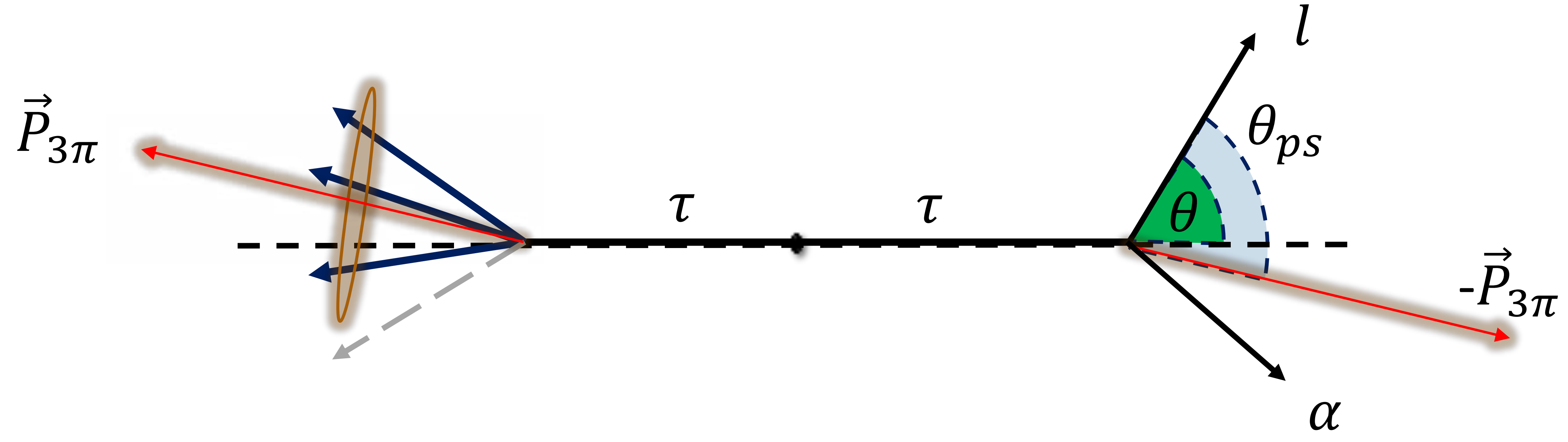
CP Violation

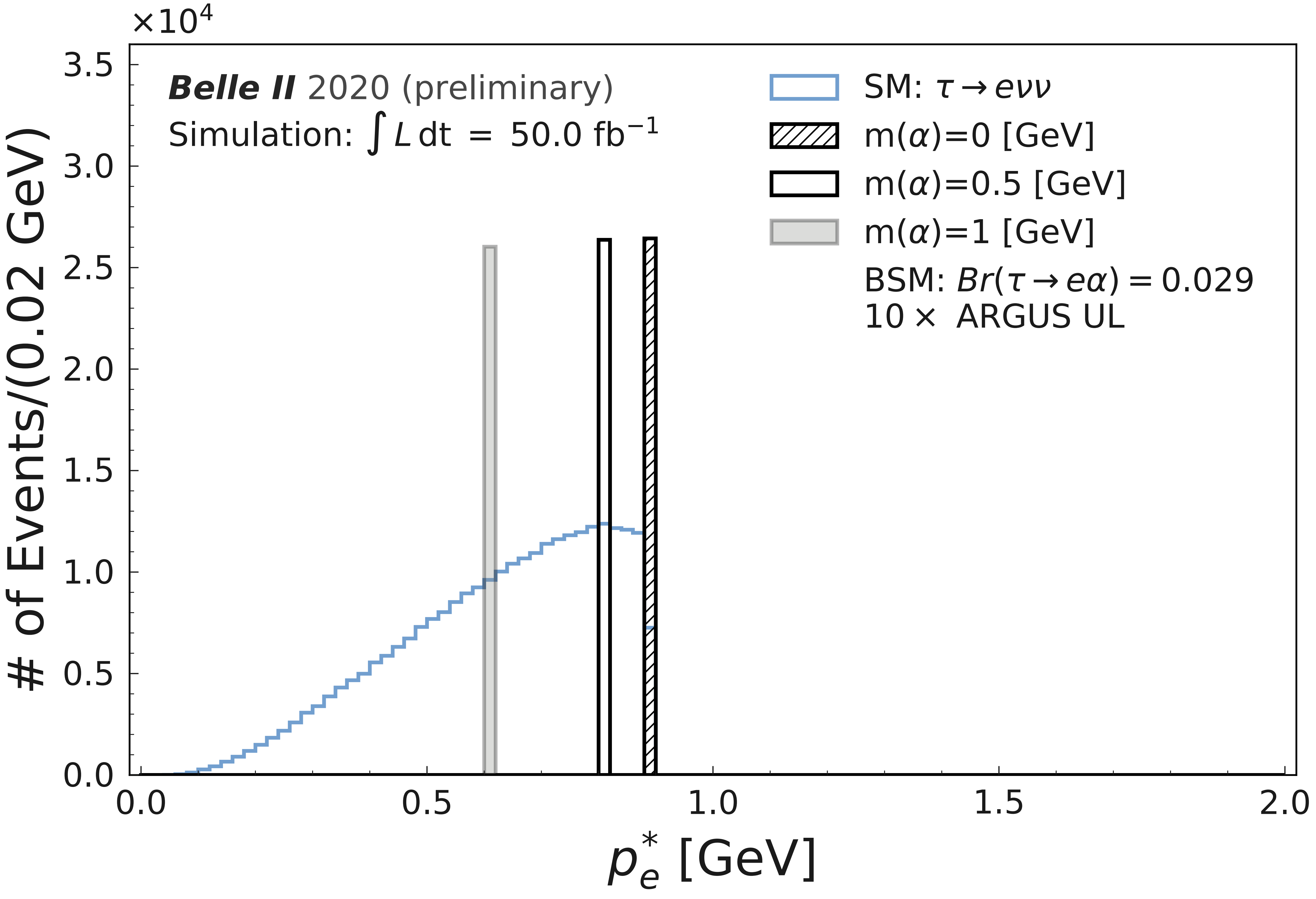


$$A_Q = \frac{\Gamma(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau) - \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)}{\Gamma(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau) + \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)}$$

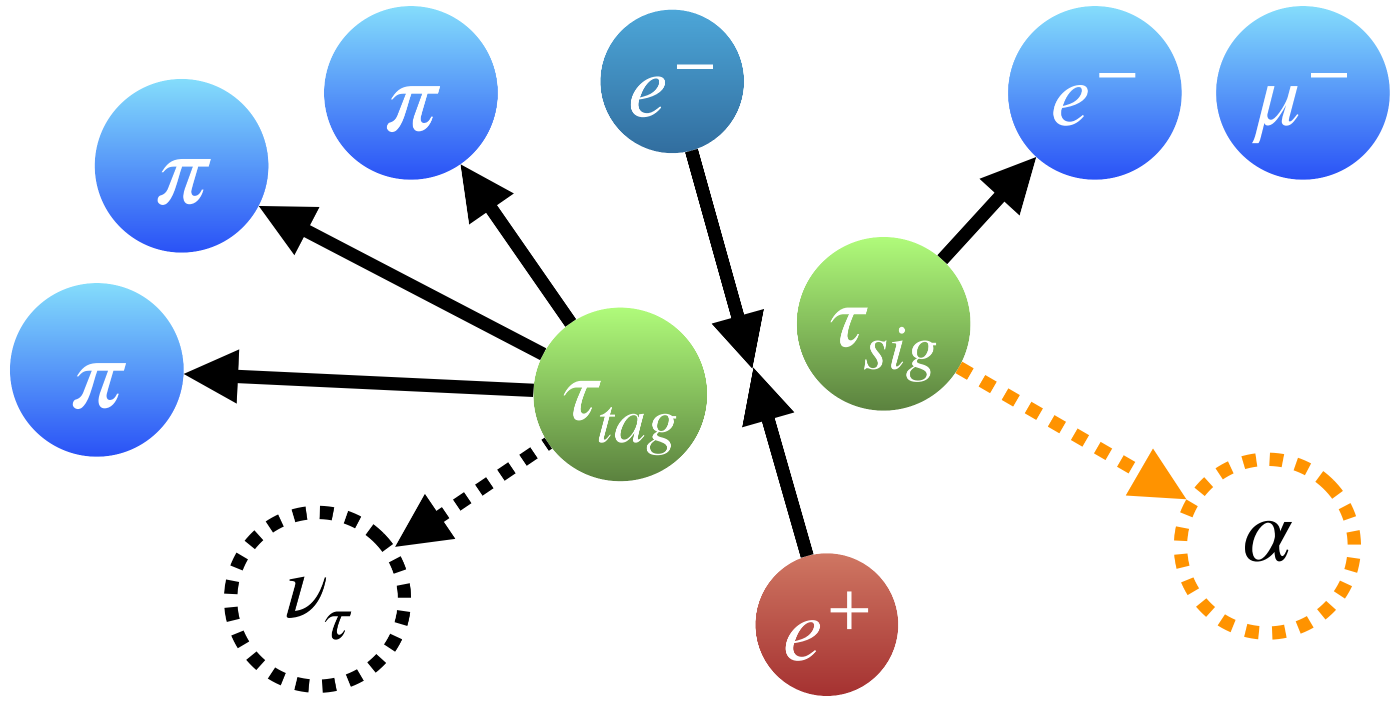
- SM prediction by Bigi and Sanda for CP-violating decay-rate asymmetry
  - $A_Q^{SM} = (0.36 \pm 0.01)\,\%$
- Measurement by BaBar:
  - $A_Q^{Exp} = (-0.36 \pm 0.23 \pm 0.11)\,\%$
  - 2.8 σ from SM prediction → verification needed!
  - Sensitivity increase by a factor of 8 for 50 ab^{-1}

LFV Search: $\tau \rightarrow l + \alpha$ (invisible)





- Motivation to look for a new Boson:
  - fermion/ν-hierarchy, ν-mixing, ν-masses
  - Light dark matter
- Idea: Search for a two body decay spectrum
- Signal will manifest as a peak in the tau rest frame (TRF)
  - Challenge: Estimate TRF with missing ν_τ momentum
  - Using
    $E_\tau \approx E_{CMS}/2$
    $\vec{p}_\tau \approx \vec{p}_{3\pi} = \sum_{i=1}^{3} \vec{p}_\pi^{\,i}$
    => Pseudo-TRF τ^*



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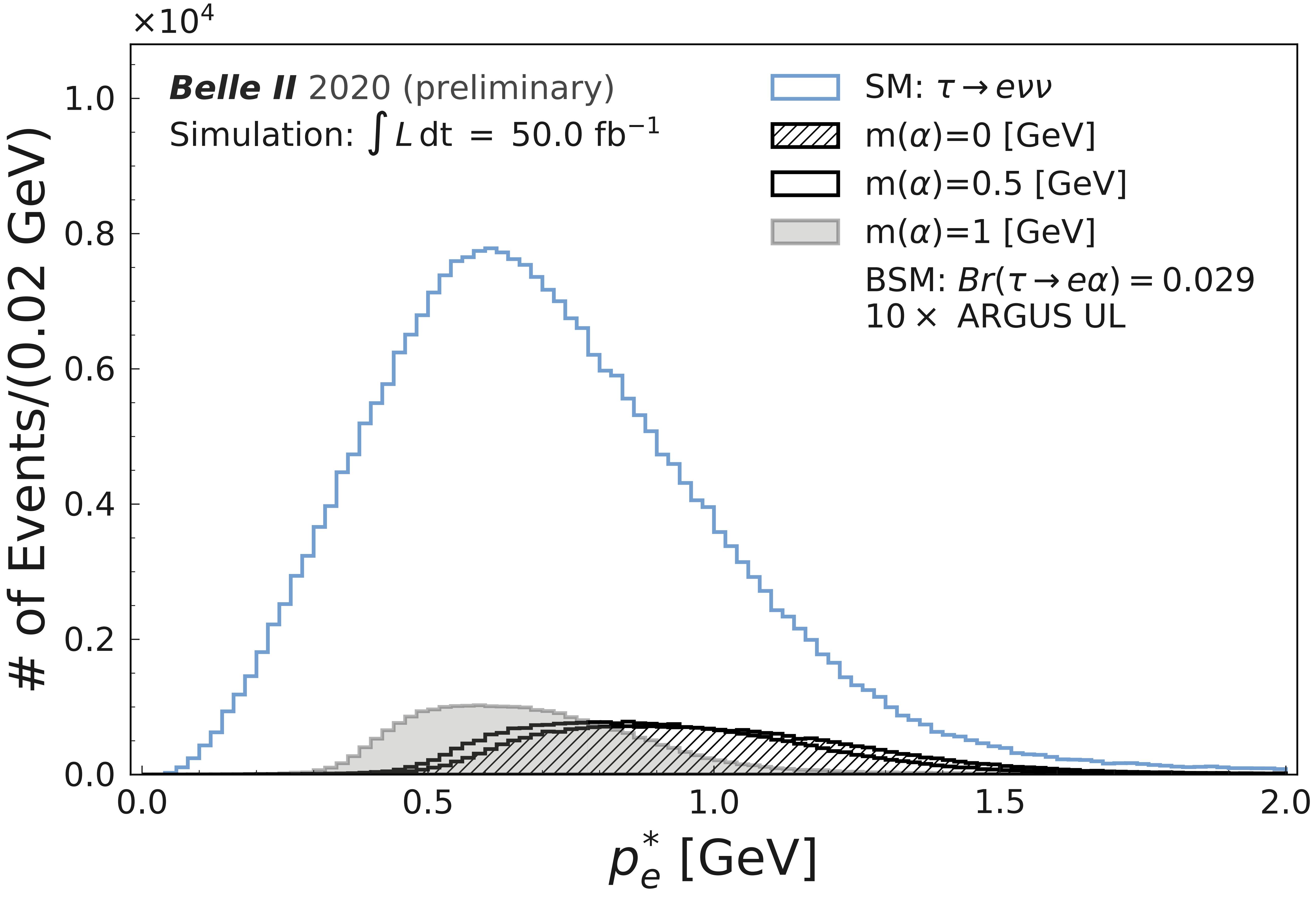

- Idea: Search for a two body decay spectrum
- Signal will manifest as a peak in the tau momentum rest frame (TRF)
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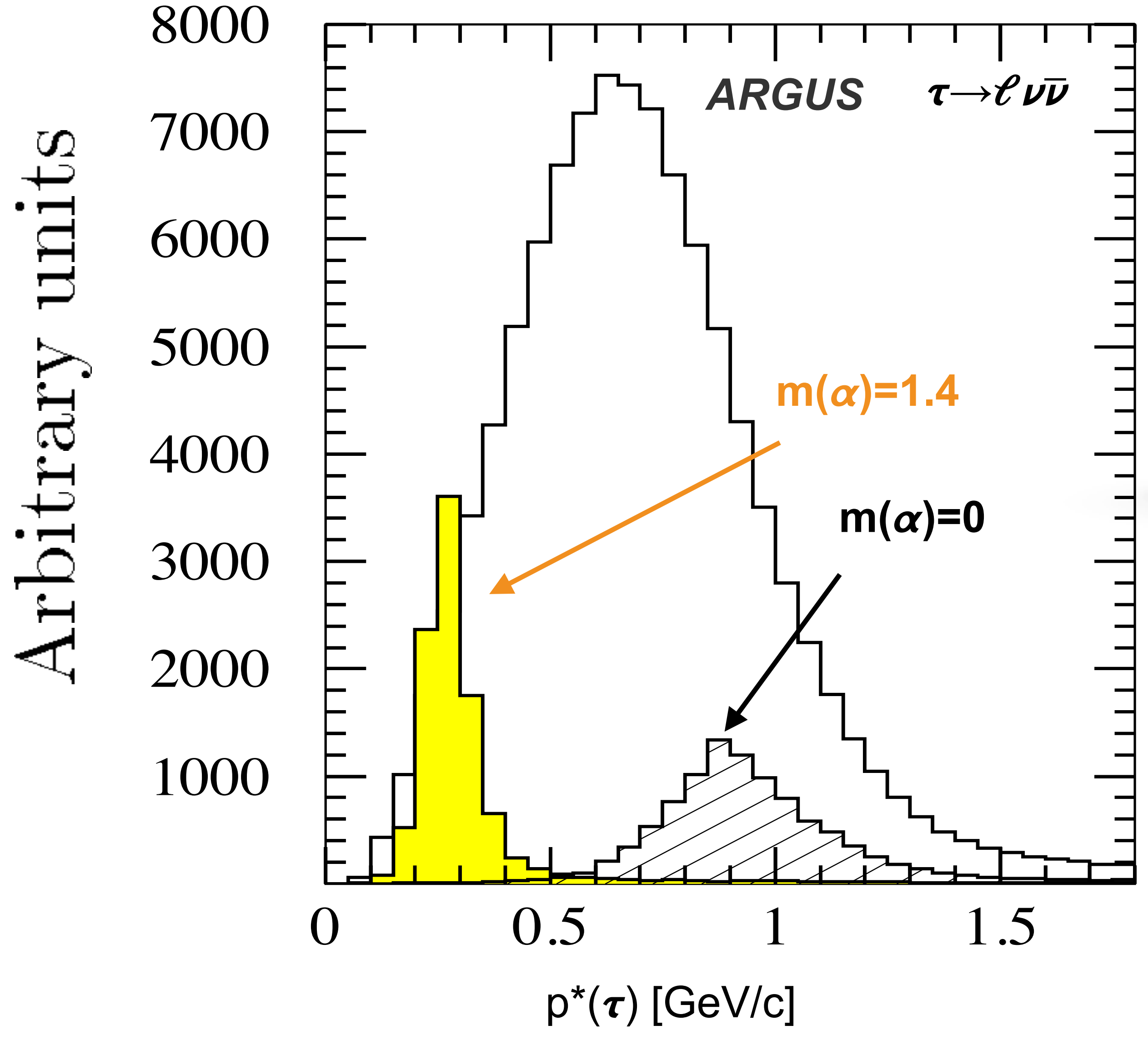
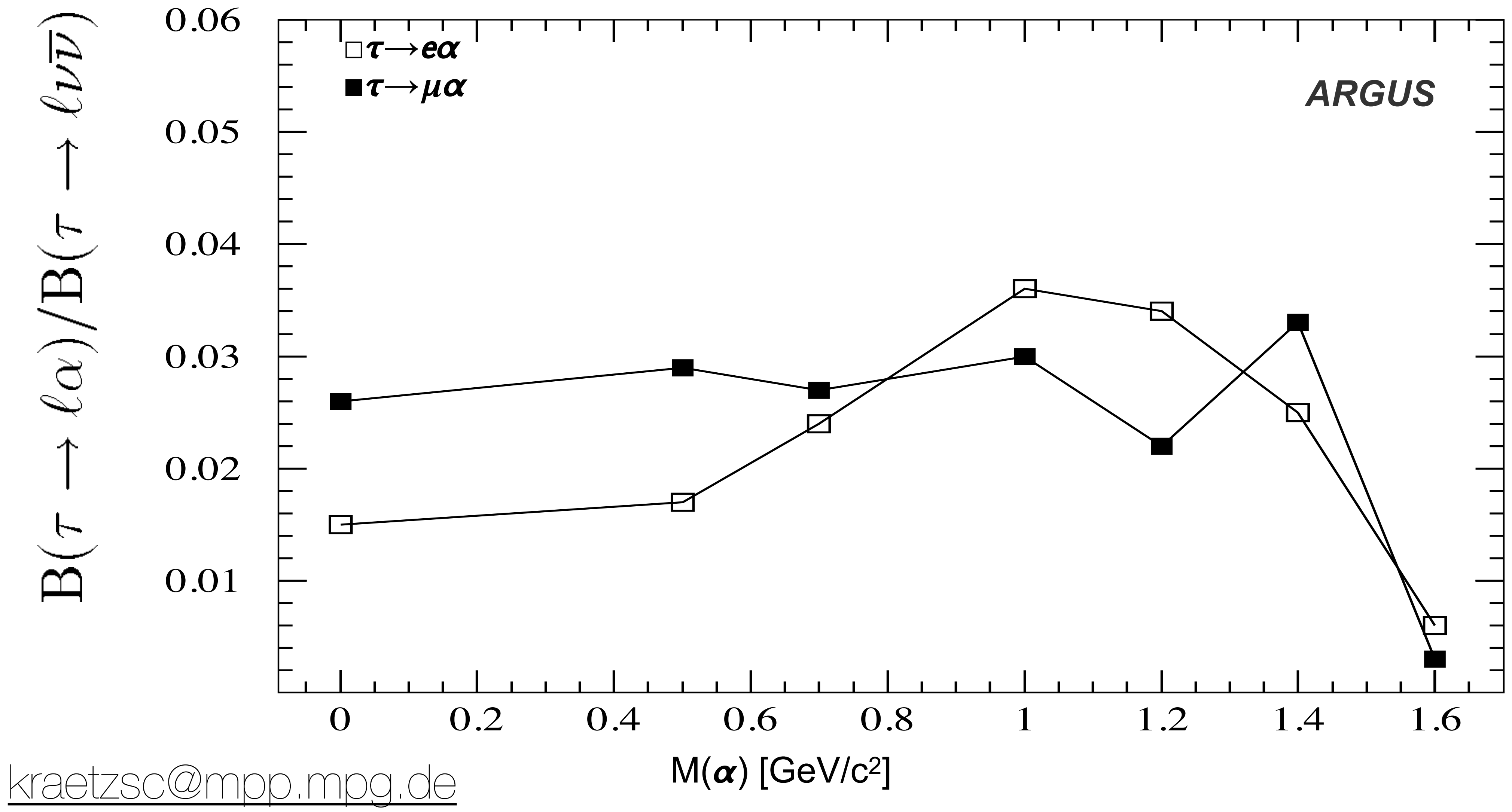
    => Pseudo-TRF τ^*
- No signal region → fit full spectrum with
  - SM expectation
  - SM + NP expectation
    → compare likelihood of the two models

LFV Search: $\tau \rightarrow l + \alpha$ (invisible)

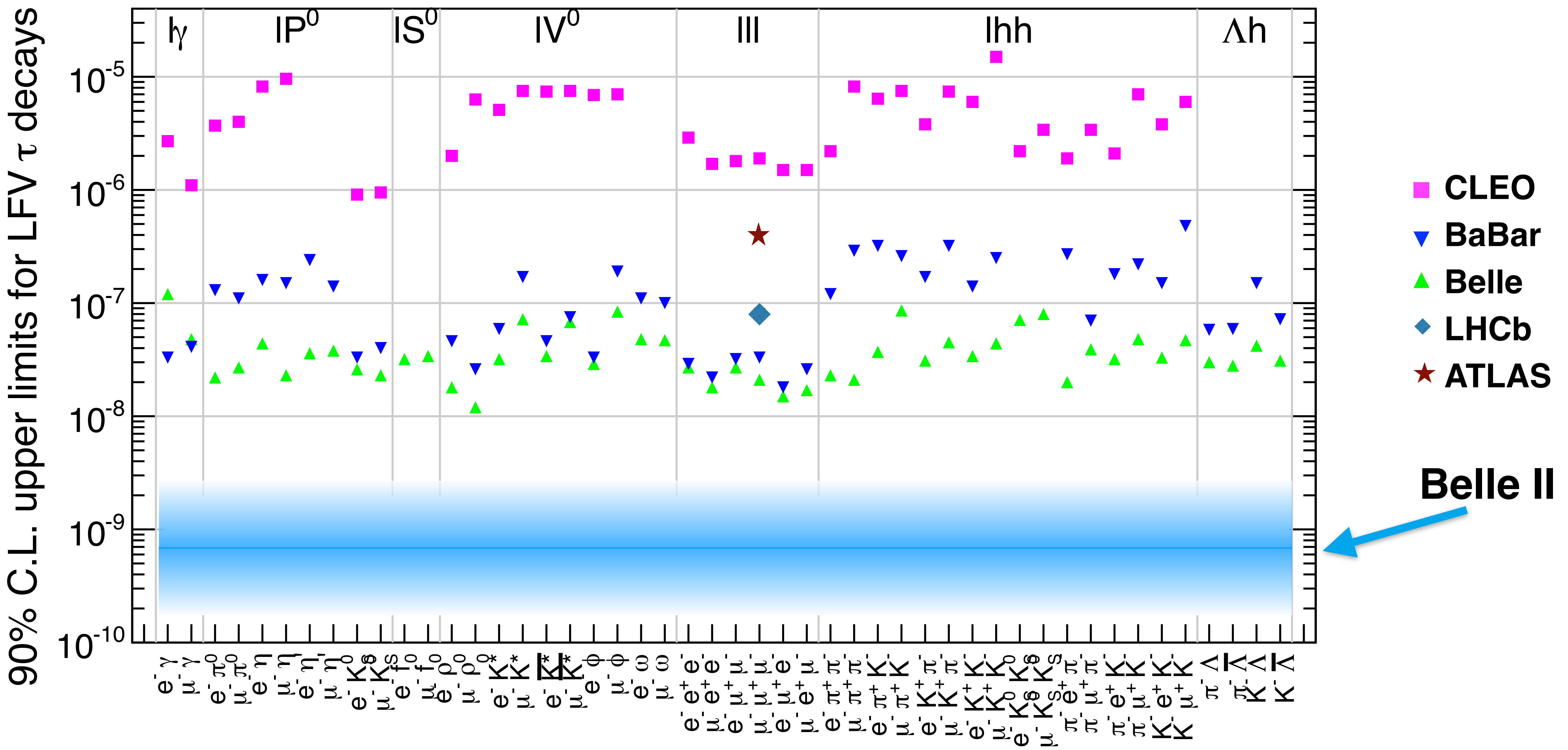


Z.Phys. C68 (1995) 25-28



- Idea: search for a two body decay spectrum
- No signal region → fit full spectrum with
  - SM expectation
  - SM + NP expectation
  - → compare likelihood of the two models
- Sensitivity dependent on m_α
  - Last results from
    - ARGUS (472 pb^{-1}) → **Belle II is competitive with early data ~10 fb^{-1}**
    - MARK III (9.4 pb^{-1})

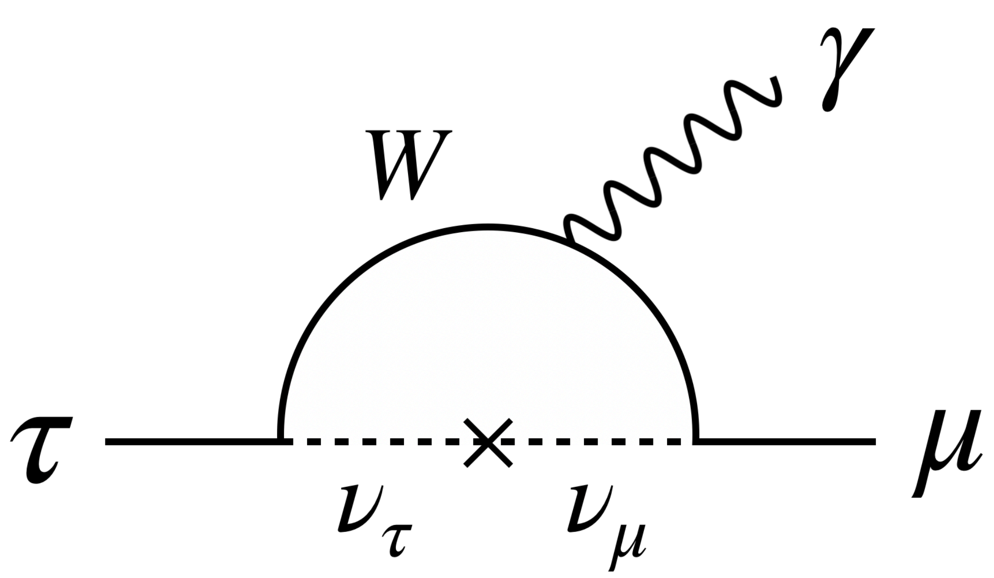
Lepton Flavour Violation Motivation

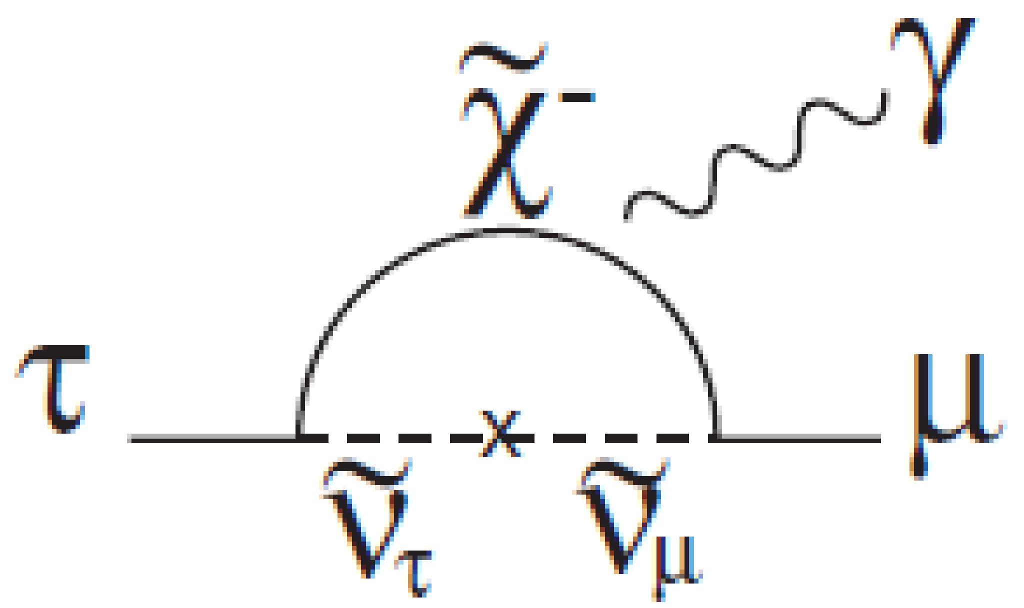


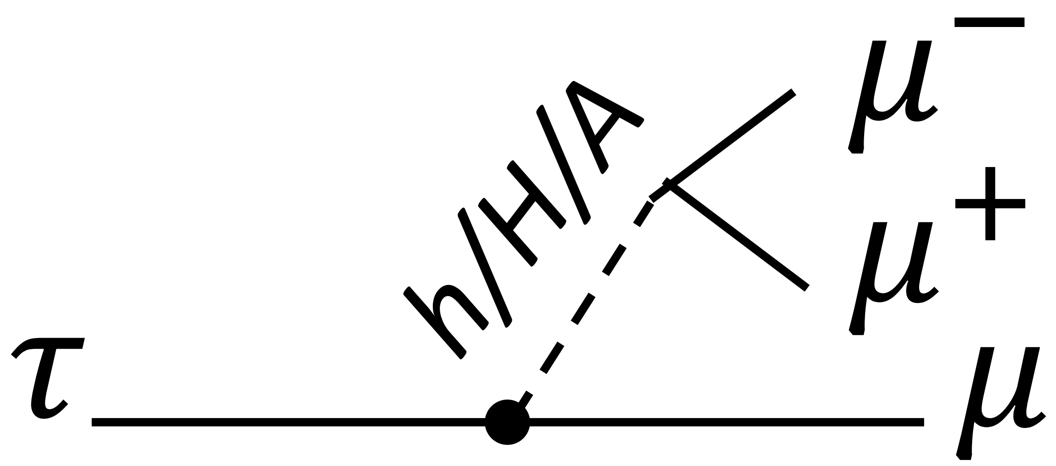
- We expect LFV in many Beyond the Standard Model (BSM) models
- For Tau at Belle II the "golden modes" are: $\tau \rightarrow \mu\gamma$
  $\tau \rightarrow lll$
- See talk from Alberto Martini

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

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



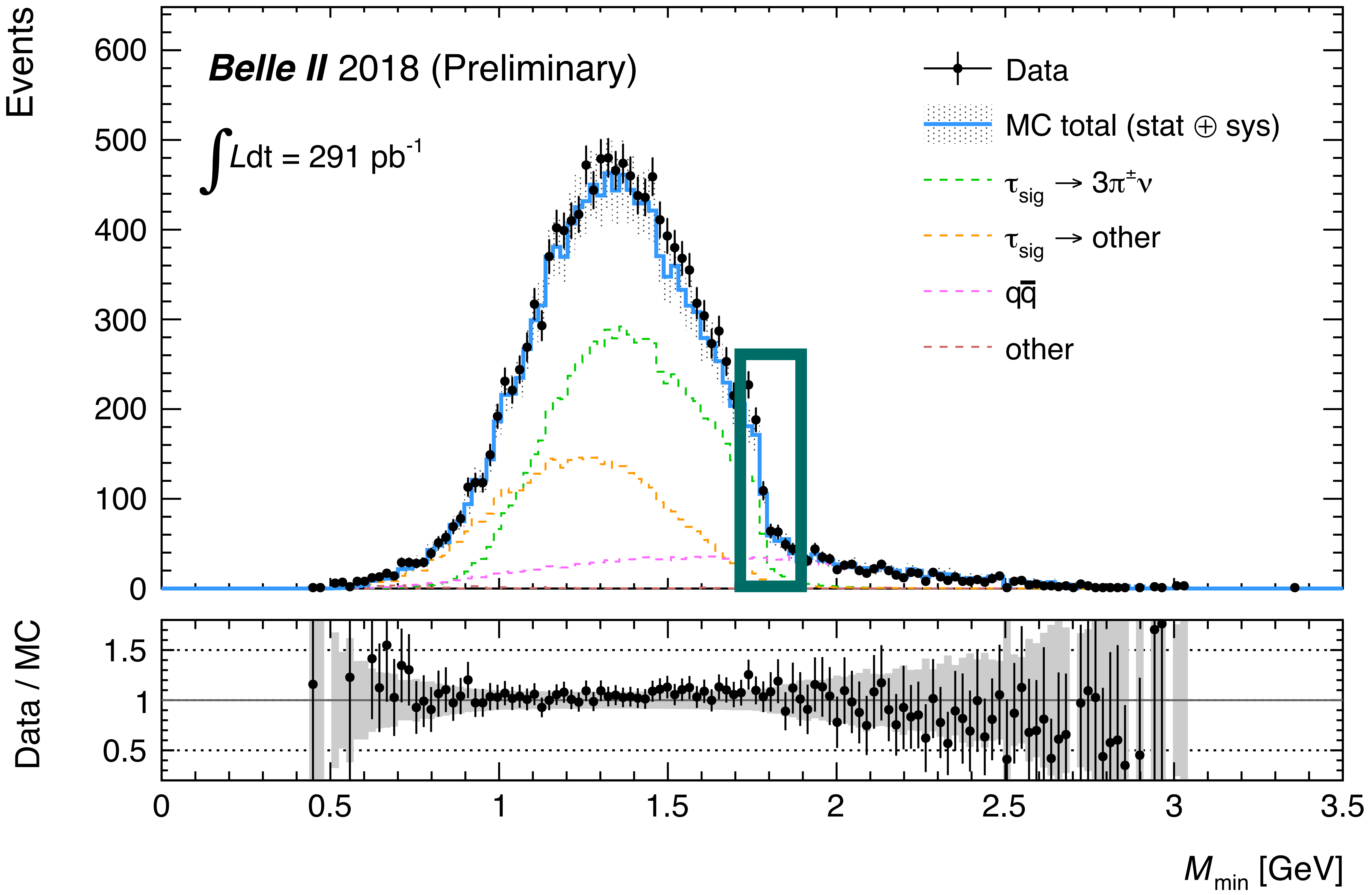




Conclusion

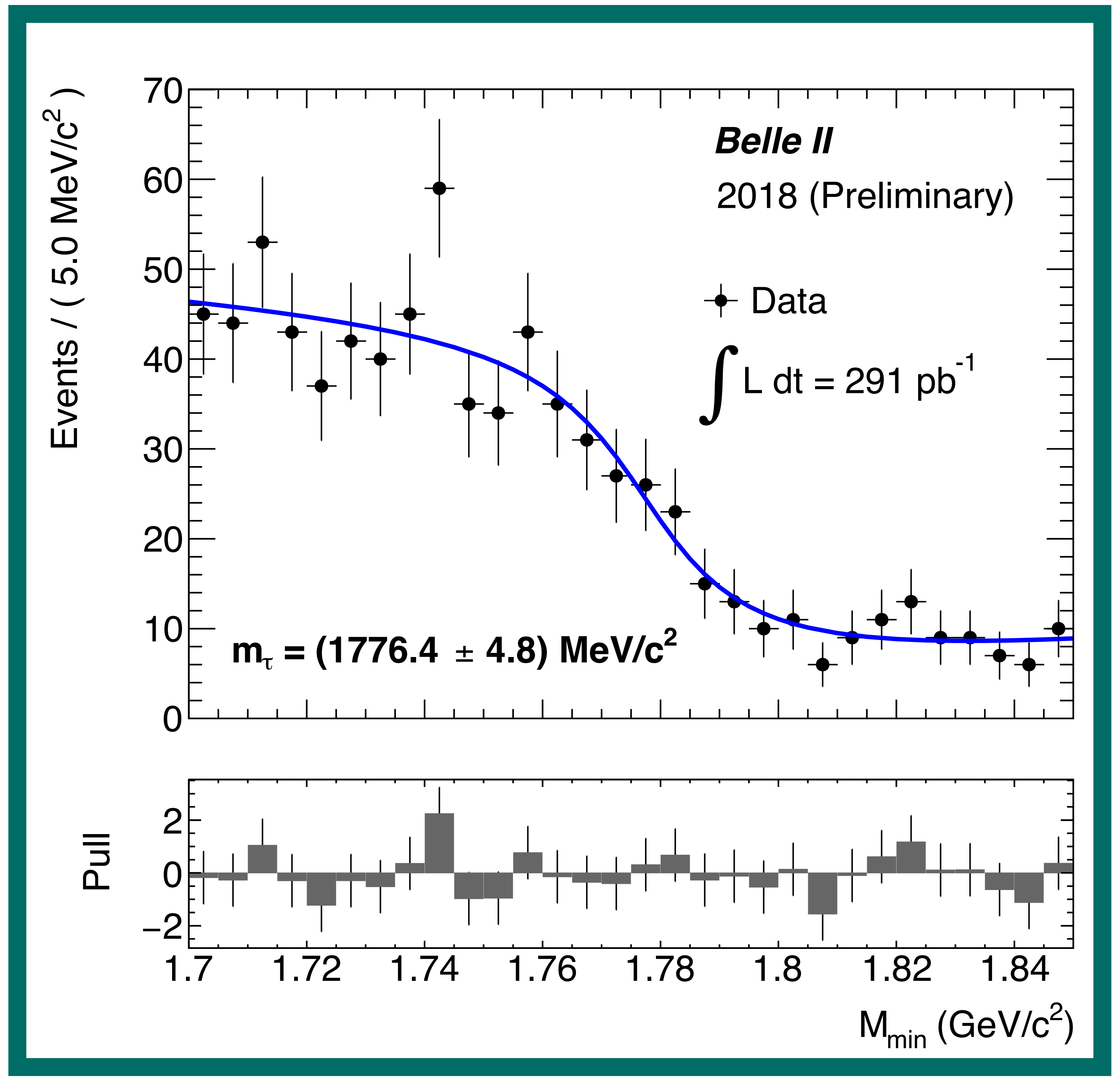
- The Tau has various interesting physics opportunities at Belle II:
  - Interesting results with early data possible
    - Potential observation of LFV in $\tau \rightarrow e + \alpha$
    - Exotic hadronic currents
  - With larger data set rich physics program with various interesting results
    - Improvements of SM Parameters
    - Potential measurements/verifications of SM parameters: $g - 2$
    - Potential verification of non SM CP violation
    - Potential observation of LFV in $\tau \rightarrow l\gamma, \tau \rightarrow lll, \ldots$

τ Mass Measurement (Preliminary)

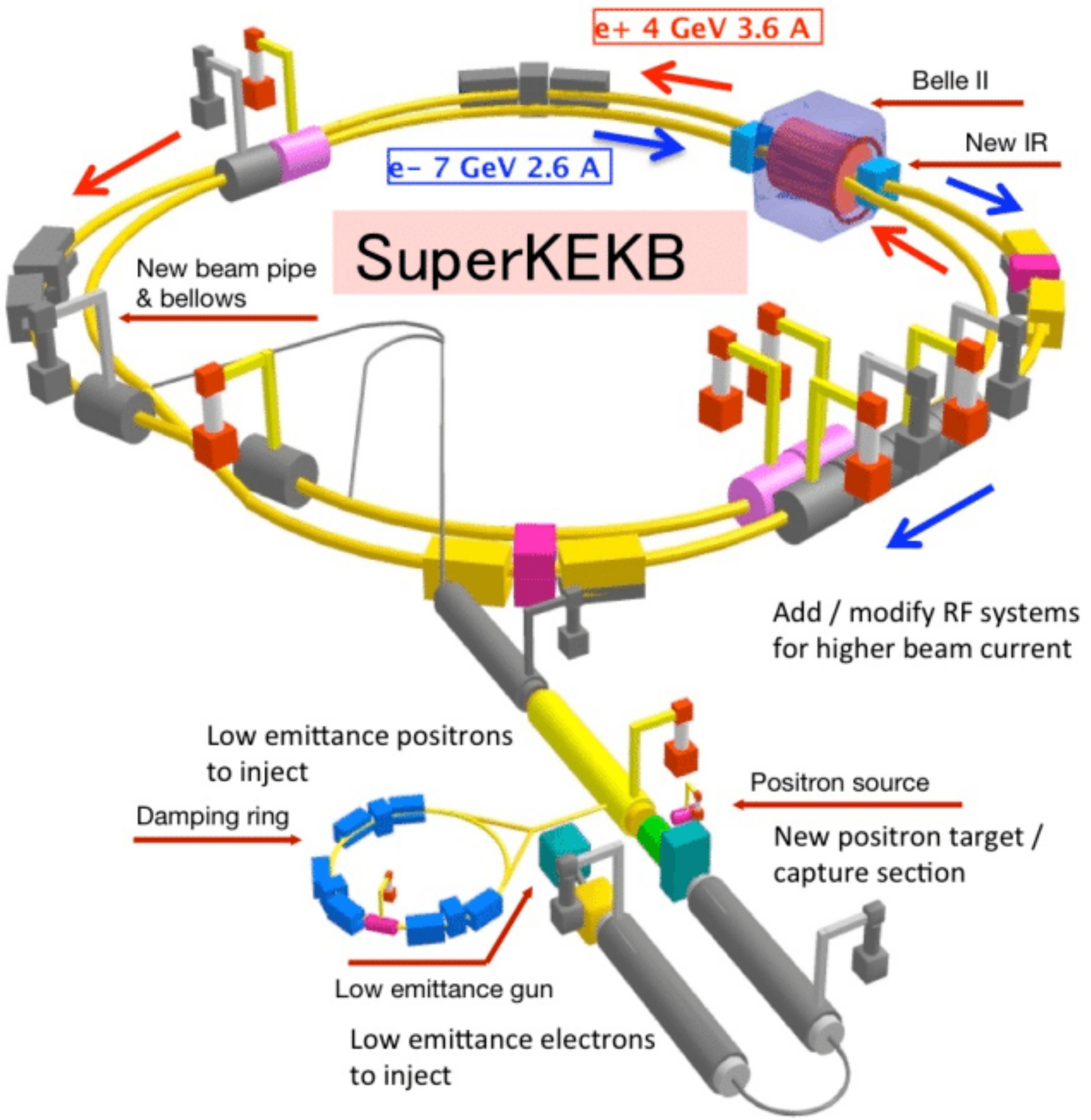


$$M_{min} = \sqrt{M_{3\pi}^2 + \frac{2(E_{beam} - E_{3\pi})}{E_{3\pi} - P_{3\pi}}}$$

- Tau mass measured using an analysis of a 3x1 prong pion decay.
- Using a dataset of approximately 291 pb^{-1} of early data.
- $m_\tau = (1776.4 \pm 4.8)\,\mathrm{MeV}$



Why Study the τ at Belle II?



- At e^+e^- machines there is a well understood production mechanism for τ
- SuperKEKB collider
  - Electron - Positron Asymmetric Accelerator
  - Runs at $\Upsilon(4S)$ resonance
  - Increased Integrated Luminosity: 1 ab^{-1}(KEKB) -> 50 ab^{-1}

What is the Tau particle?

- 3rd generation Lepton
  - Point like, fundamental
- $M_\tau = 1776 \pm 0.12$ **MeV**
  - Can decay hadronically
- $\tau_\tau = 290.3 \pm 0.5$ **fs**

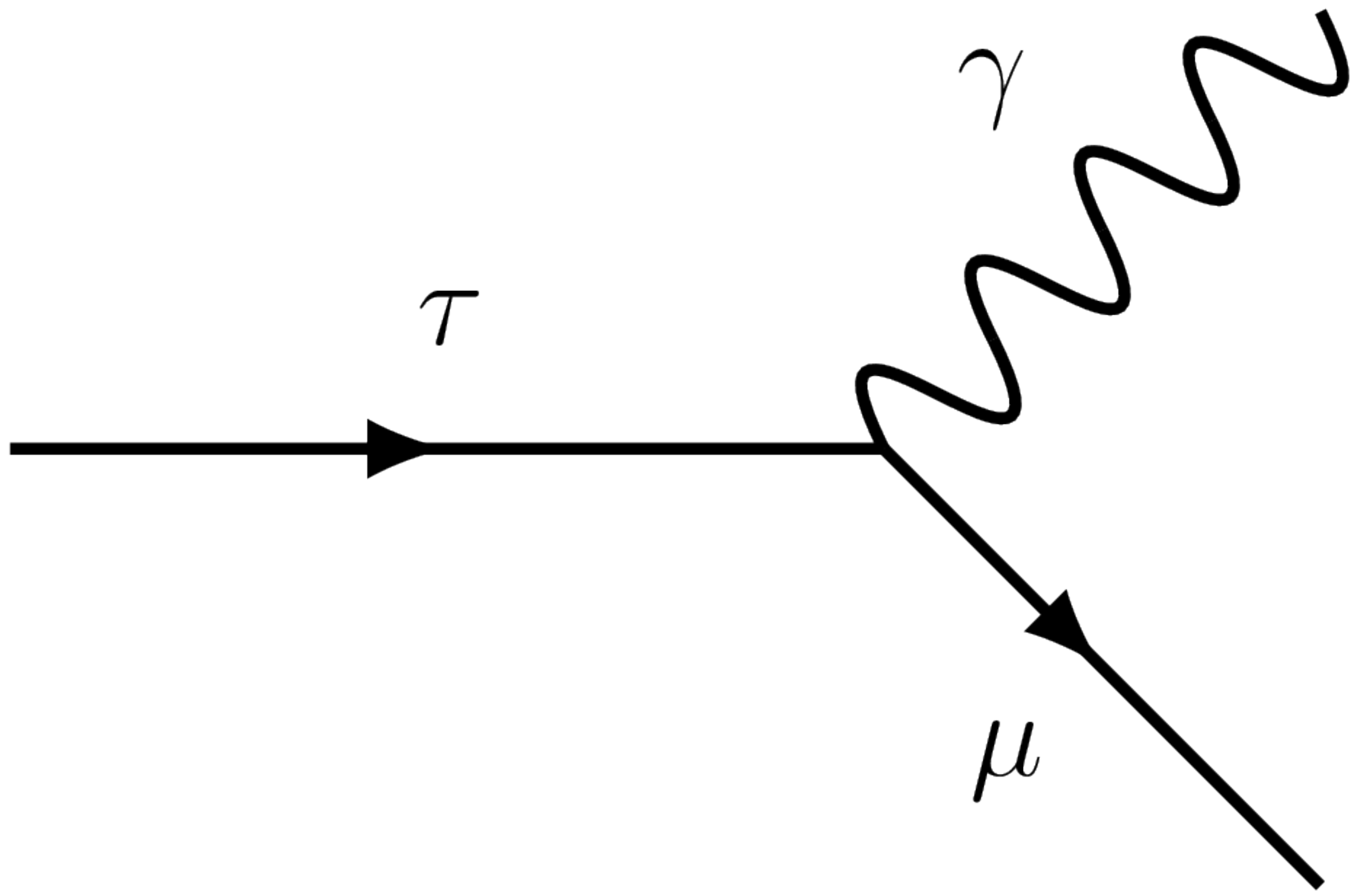
τ Physics Prospects at Belle II

- The most anticipated results can be grouped in three sectors:
  - Lepton Flavour Violation (LFV)
  - Charged Parity (CP) violation
  - Standard Model (SM) measurements

LFV in τ Decays

- Decay with highest predicted branching ratio:

  $\tau \to \mu\gamma$



- Neutrino induced LFV in τ is expected at a level of:

  $B(\tau \to \mu\gamma) \sim 10^{-45}$

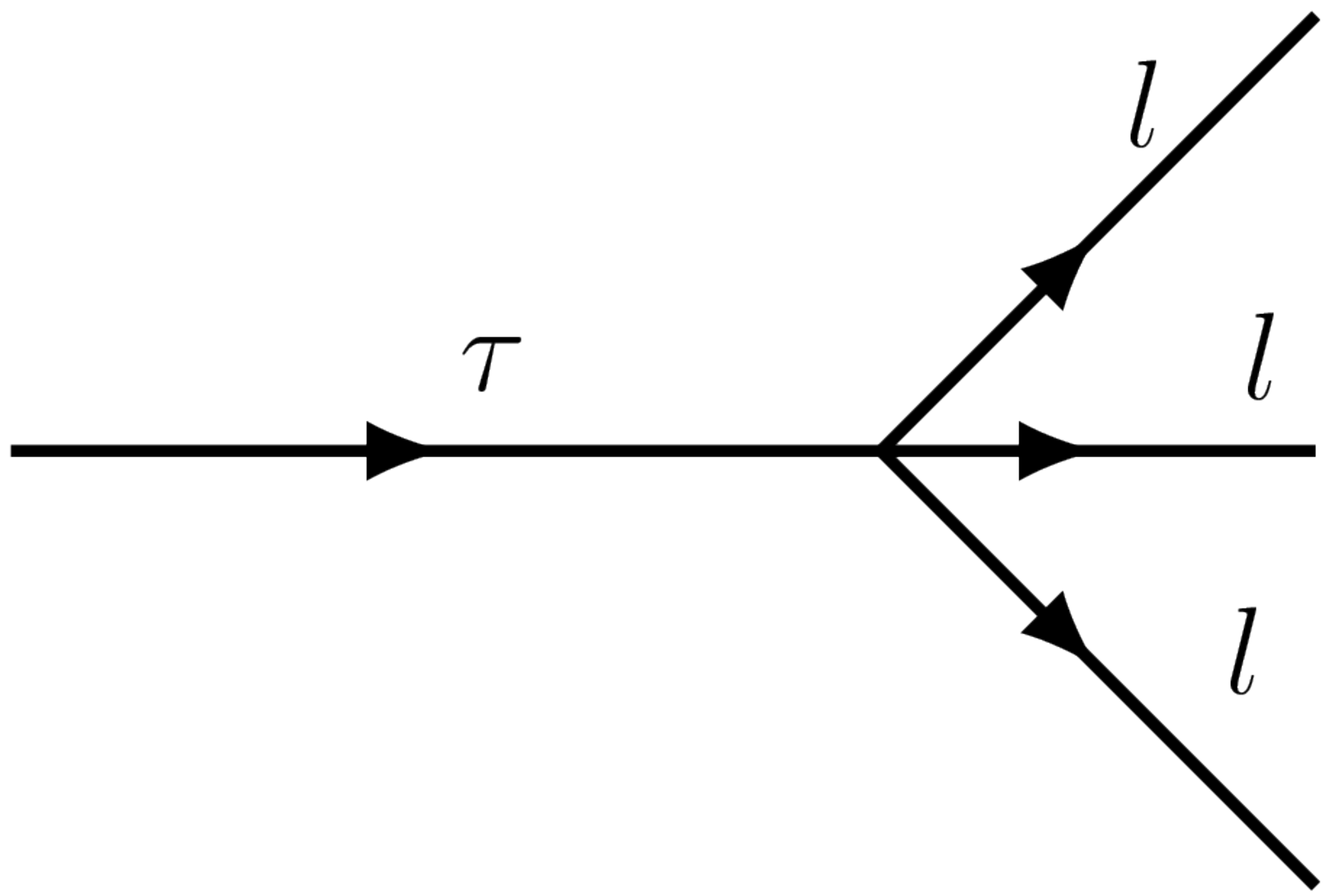
  - Current Limit: $B(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$
  - For 50 ab^{-1} the sensitivity is expected to improve by a factor of 2
  - Serious background (BG) from SM process: $\tau \to \mu\nu\nu$

LFV in τ Decays

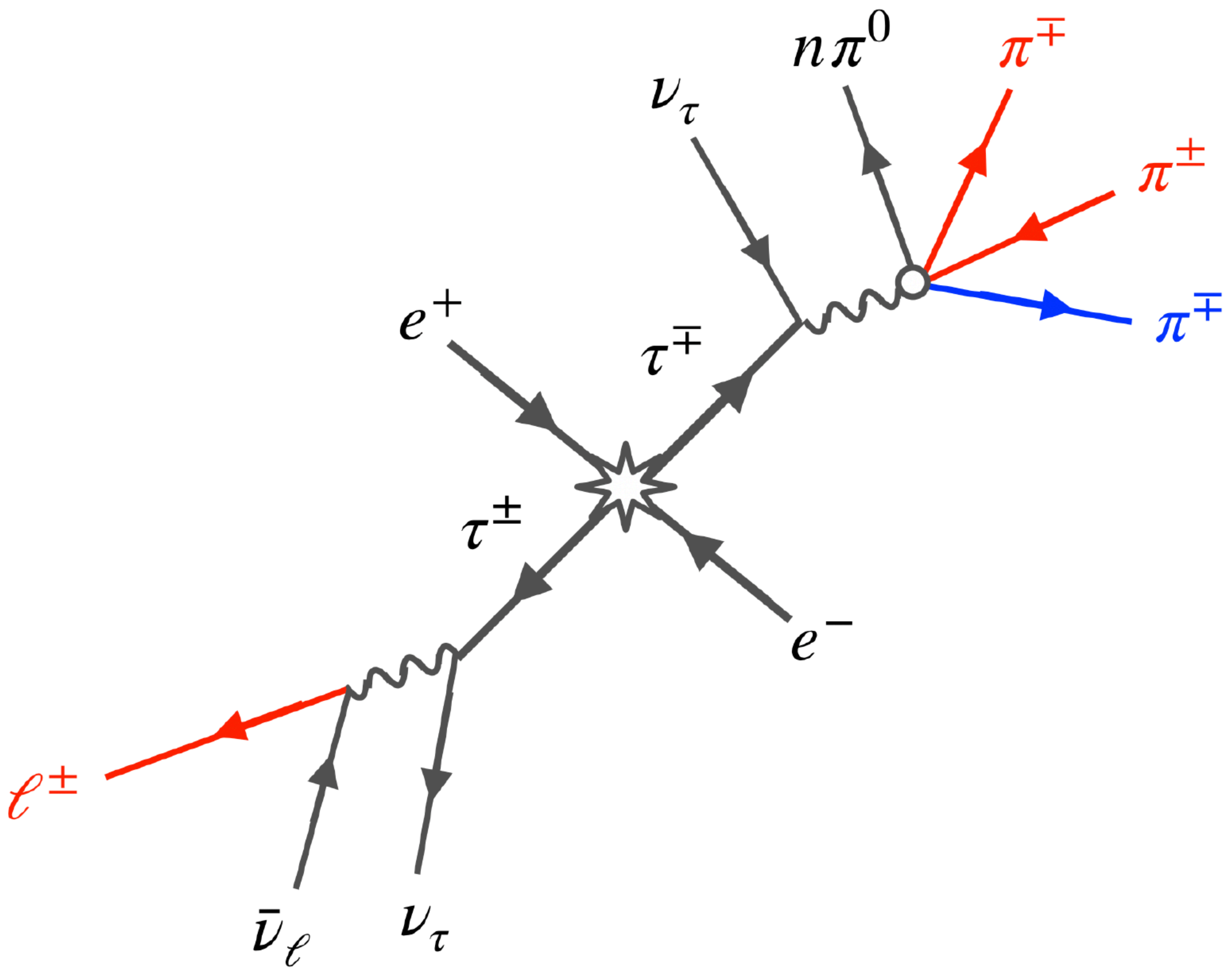
- Interesting alternative:

$$\tau \rightarrow lll$$

  - Highly suppressed backgrounds.
  - Uncertainties scale with sample size.
- Current limits are $B(\tau \rightarrow \mu\mu\mu) = 2.1 \times 10^{-8}$
- Prospects for 50 ab^{-1}: $\mathcal{O}(10^{-10})$



Physics in the Early Phases of Belle II



- Performance studies
  - 1 prong decays
    - $\tau \to \pi\nu$ for probing Lepton Universality
    - $\tau \to \pi\pi^0\nu$ for beam background studies
  - 3 prong decays
    - $\tau \to \pi\pi\pi\nu$ for measurements of the mass, lifetime, …