$\tau \rightarrow l + \alpha(invisible)$

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on behalf of the Belle II Collaboration

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MAX PLANCK INSTITUTE
FOR PHYSICS

Motivation

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**
    - **…**

- The Standard Model is incomplete:
  - Small ν-masses?
  - Fermion/ν-hierarchy?
  - ν-mixing angles?
  - Weak strong CP phase?
  - Dark Matter

→ Motivation to look for a new Boson: $\tau \to l\alpha$

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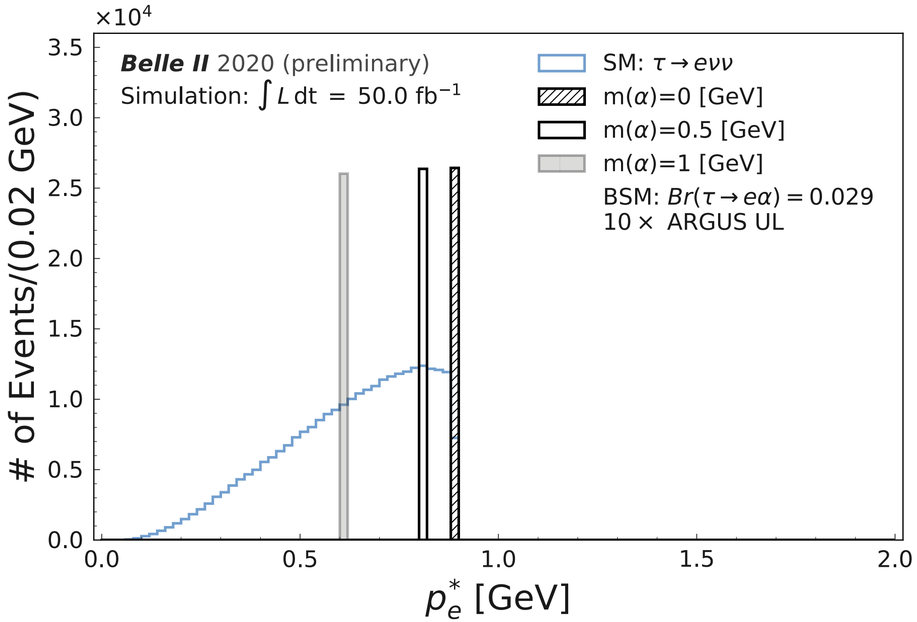
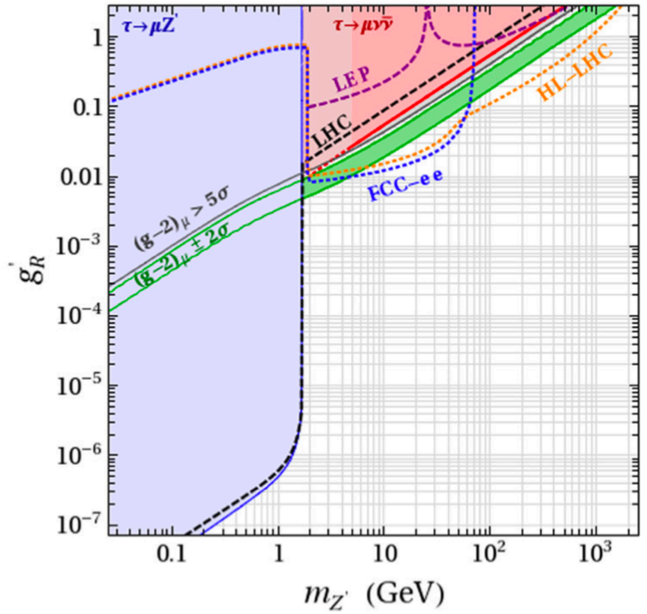
Introduction to: $\tau \to l + \alpha$ (invisible)

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

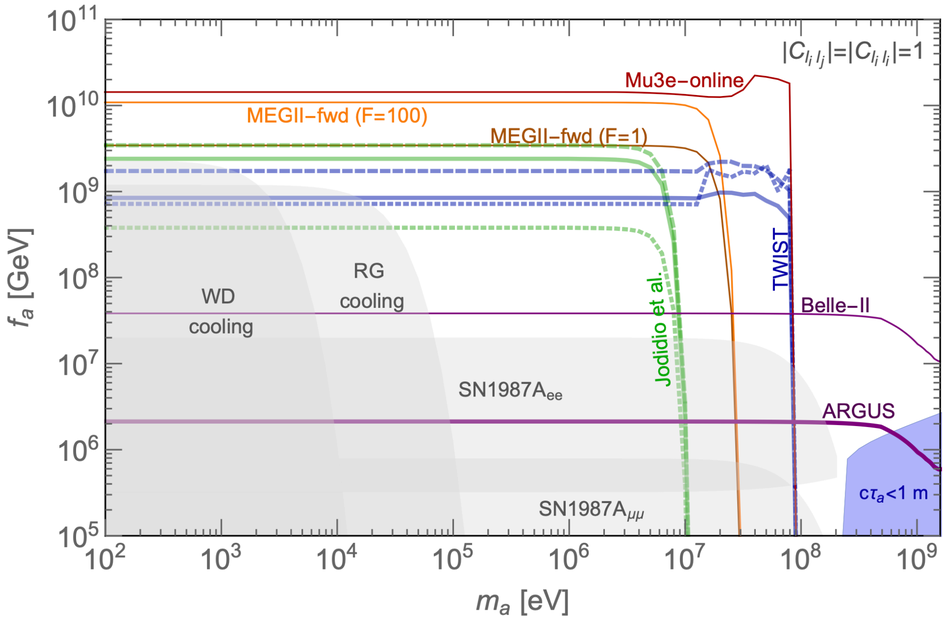


Various NP Scenarios:

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



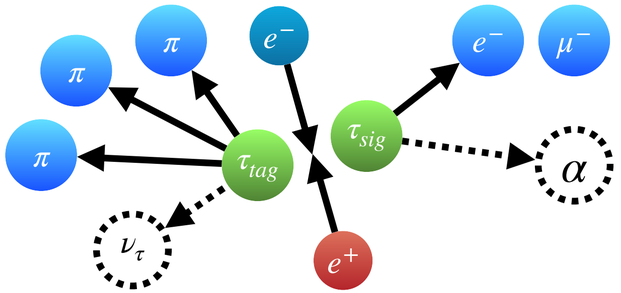
Wolfgang Altmannshofer, Chien-Yi Chen, P.S. Bhupal Dev, Amarjit Soni



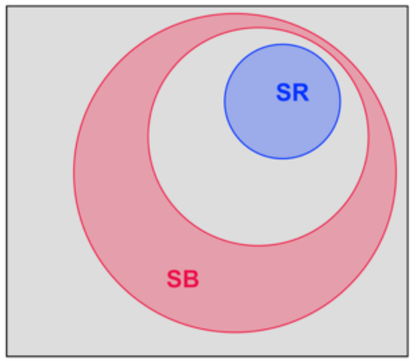
Lorenzo Calibbi, Diego Redigolo, Robert Ziegler, Jure Zupan,

Analysis Strategy: $\tau \rightarrow l + \alpha$ (invisible)

- No signal region → fit full-spectrum with
  - SM expectation
  - SM + NP expectation
    →compare the model likelihoods

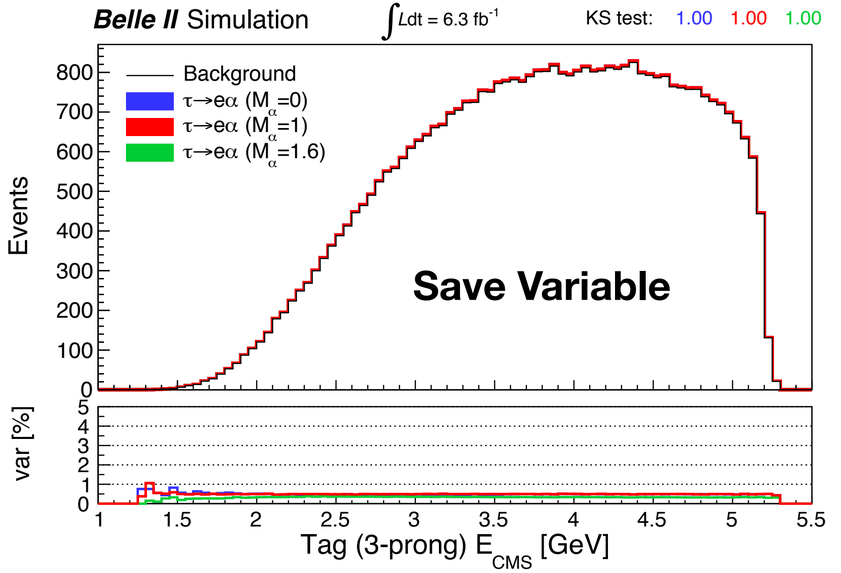


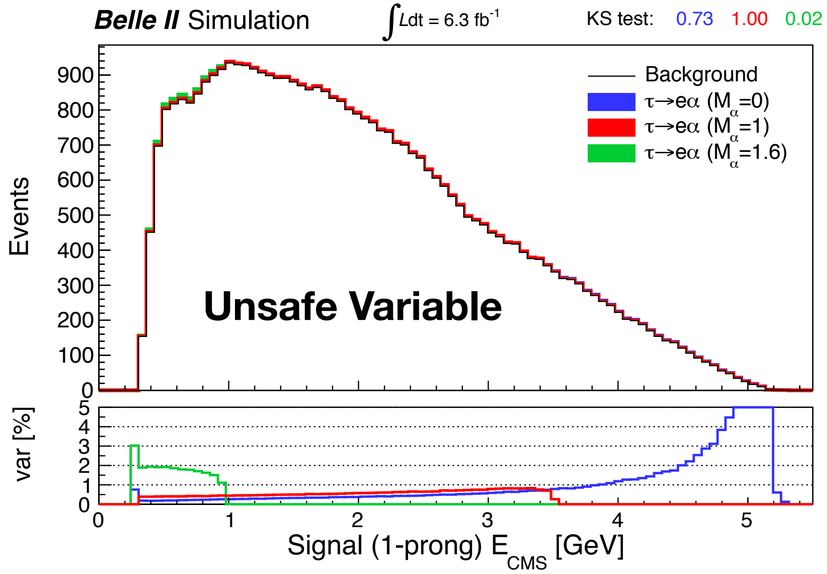
- Blinded Analysis
  - Event selection based on Simulations
  - Statistical Treatment devoted with Simulation Data



- Unblinding: Evaluate on 10% of Data
  - Save Variables ✓
  - Unsafe Variables ✓
  - Evaluate Statistical Treatment ✓

→ **Unblind** 🎉





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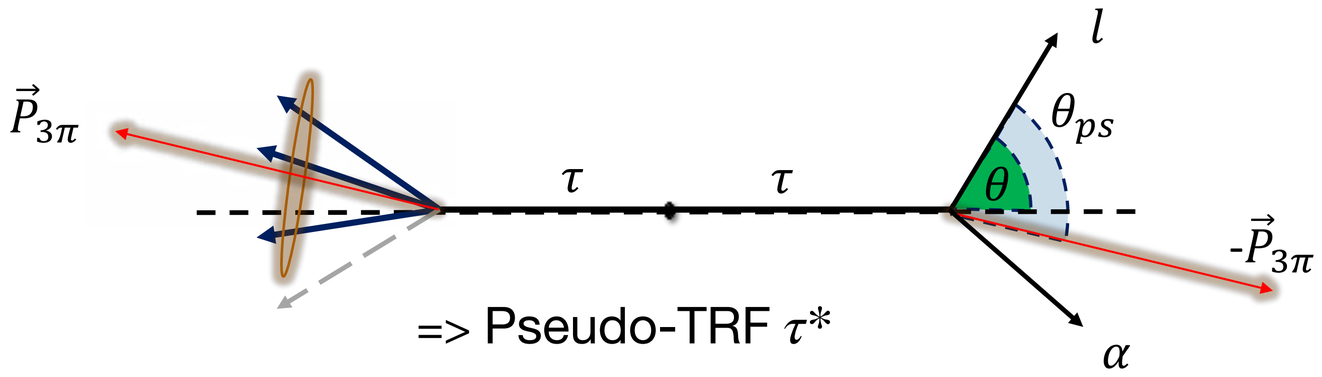
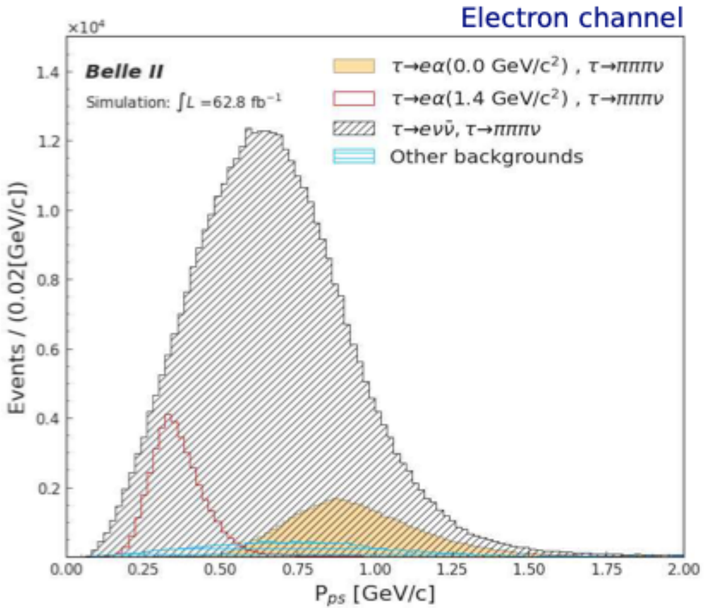
Current status: $\tau \rightarrow l + \alpha$ (invisible)

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



=> Pseudo-TRF τ*

- No signal region → fit full spectrum with
  - SM expectation
  - SM + NP 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})

→ **Belle II is competitive with early data ~62.8 fb^{-1}**

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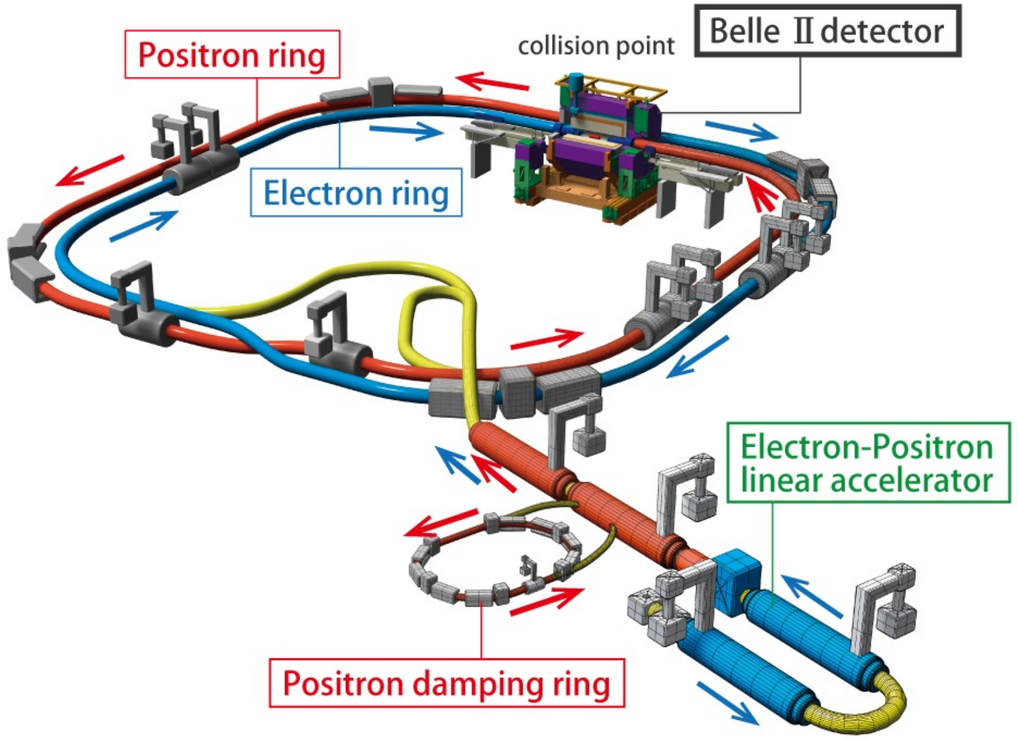
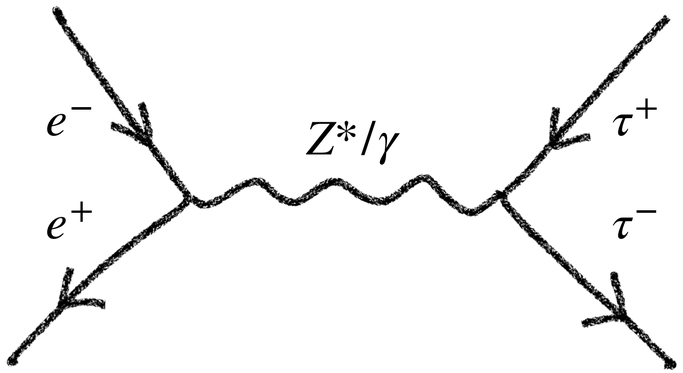
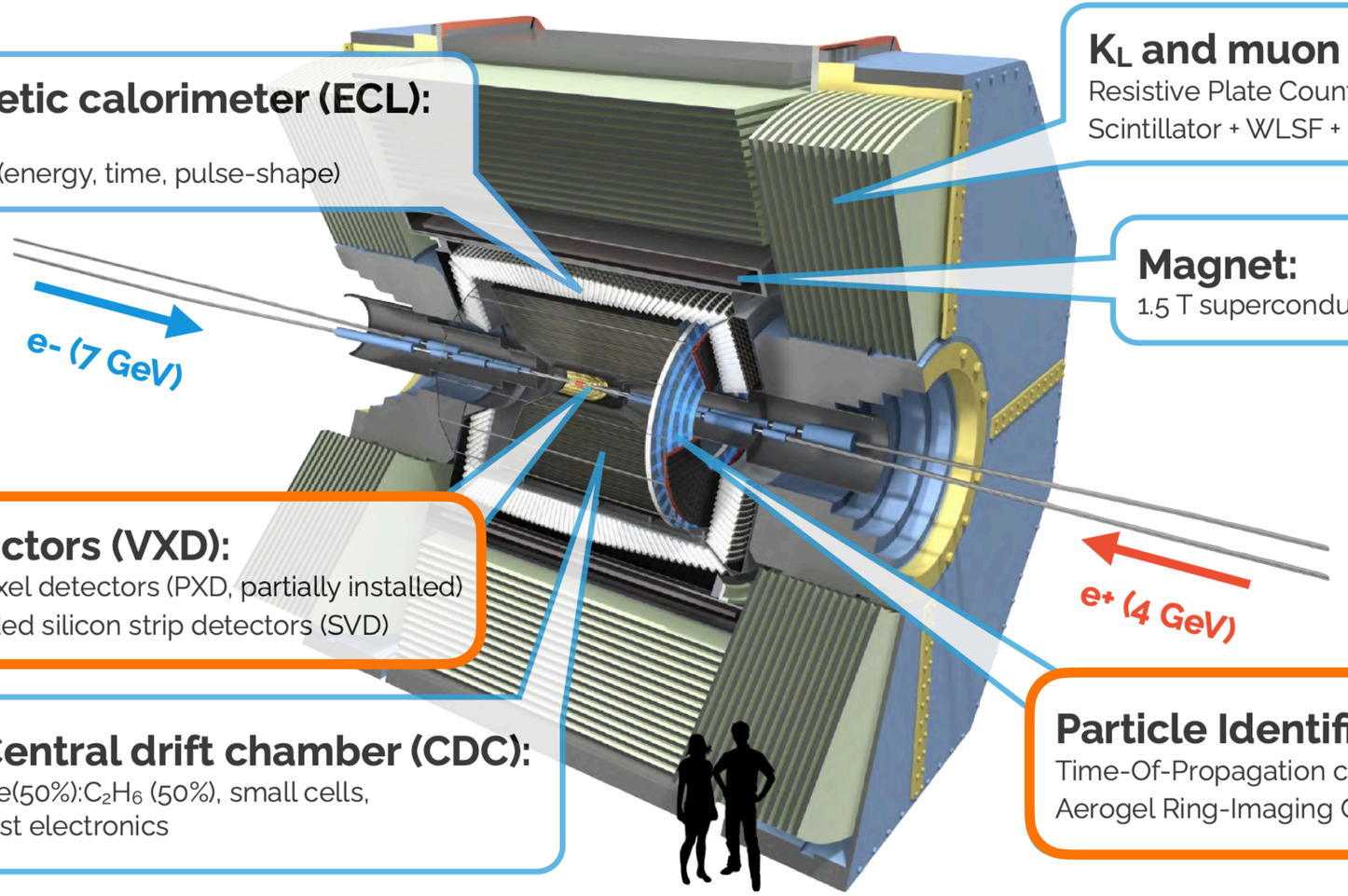
Where can one study the τ?



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



How is the τ detected 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

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Reconstruction And Selection

Firm Requirements

- 3x1-prong topology:
  $\tau \to l\alpha$ (signal), $\tau \to 3\pi\nu$ (tag)
  - Requiring exactly four tracks
  - Hemisphere separation with thrust
    $$\vec{T} = max\left(\sum_i \frac{\vec{p}_i \cdot \vec{T}}{|\vec{p}_i|} \right)$$
  - No neutrals allowed
    $\to$ rejects $q\bar{q}$, beam background, and allows to define a sideband
- Vertex fit: reject displaced tag vertices
- Use SM $\tau \to \ell\nu\nu$ for selection optimisation

Current status: Cut Based Analysis

Tracks originate from:
$|dz| < 3$ **cm**
$dr < 1$ **cm**

Particle Identification (**PID**)
ℓ : ℓID> 0.9
π : E/p < 0.8

Neutrals:
Photons: $E(\gamma) > 200$ **MeV**
π_0: $E(\gamma) > 100$ **MeV** and $M(\gamma\gamma) \in (115,152)$ **MeV**

Ranked p_T cuts for Electrons (Muons)

1. leading $p_T > 0.69$ (0.47) **GeV/c**
2. Sub-leading $p_T > 0.29$ (0.17) **GeV/c**
3. Third $p_T > 0.08$ (0.04) **GeV/c**

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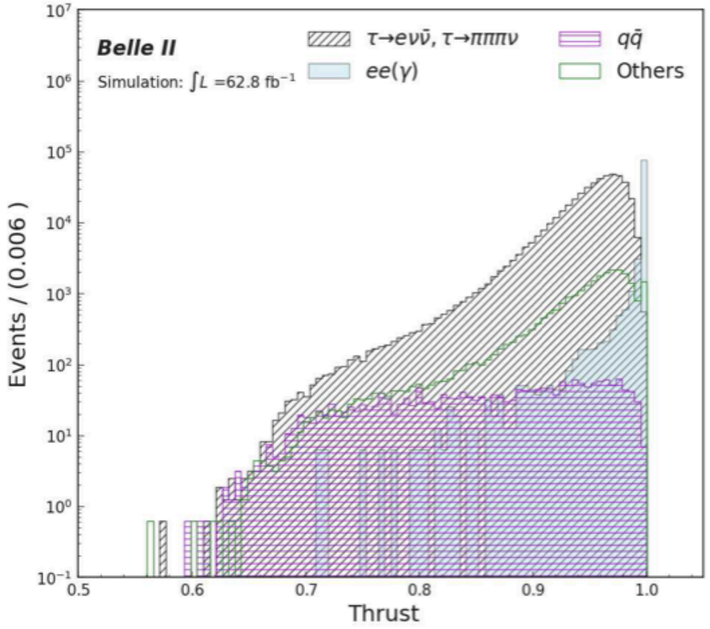
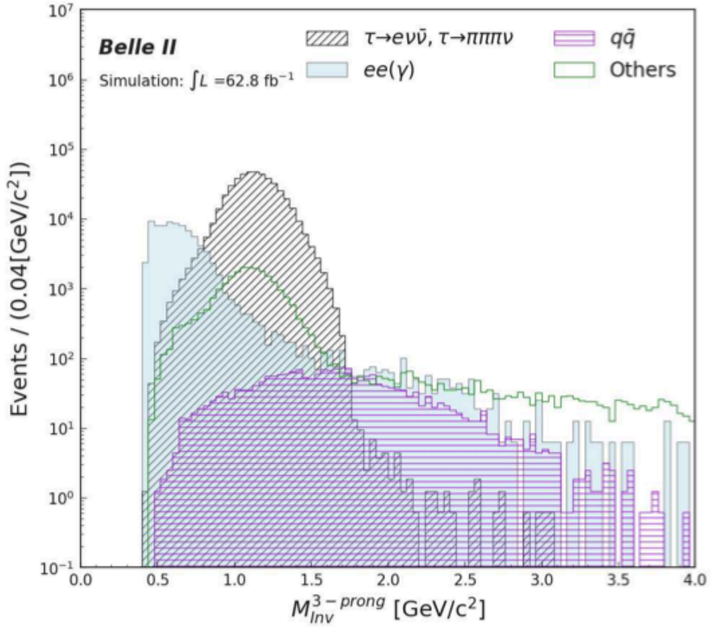
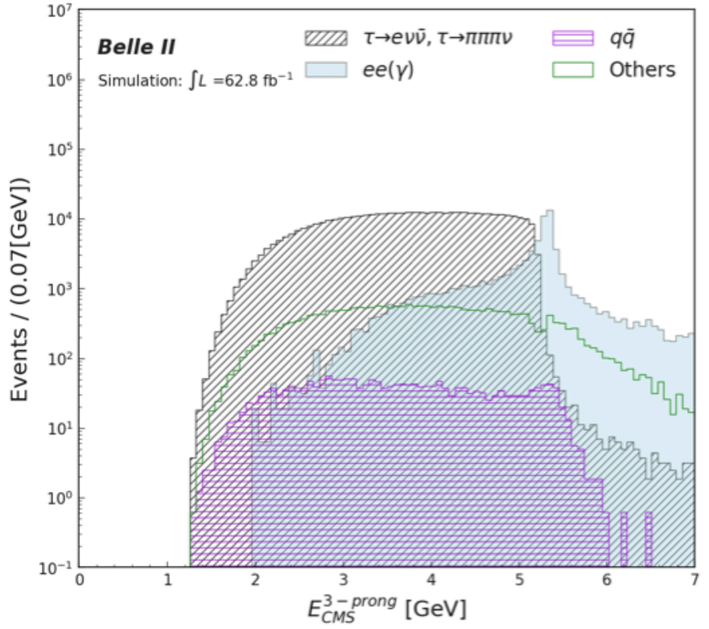
Background Suppression



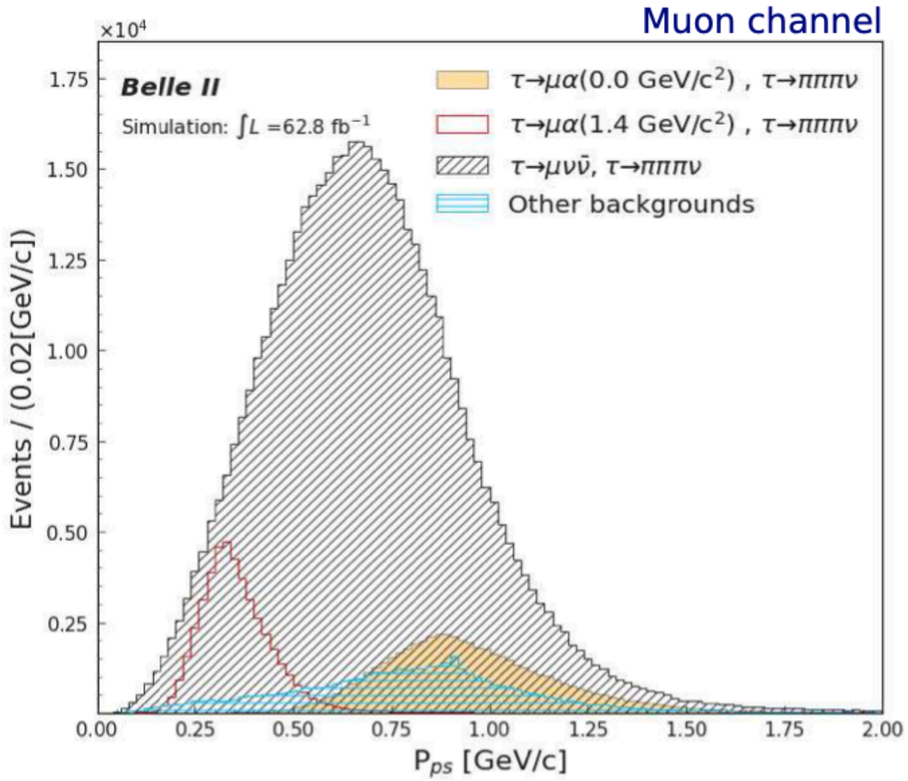




Background Suppression Electron	**Background Suppression Muon**
1. 0.9 < thrust < 0.99	1. 0.9 < thrust < 1
2. 1.2 < E_{CMS} of 3-prong τ < 5.3 [**GeV**]	2. 1.1 < E_{CMS} of 3-prong τ < 5.3 [**GeV**]
3. 0.5 < Invariant Mass of tag side < 1.7 [**GeV/c²**]	3. 0.4 < Invariant Mass of tag side < 1.7 [**GeV/c²**]

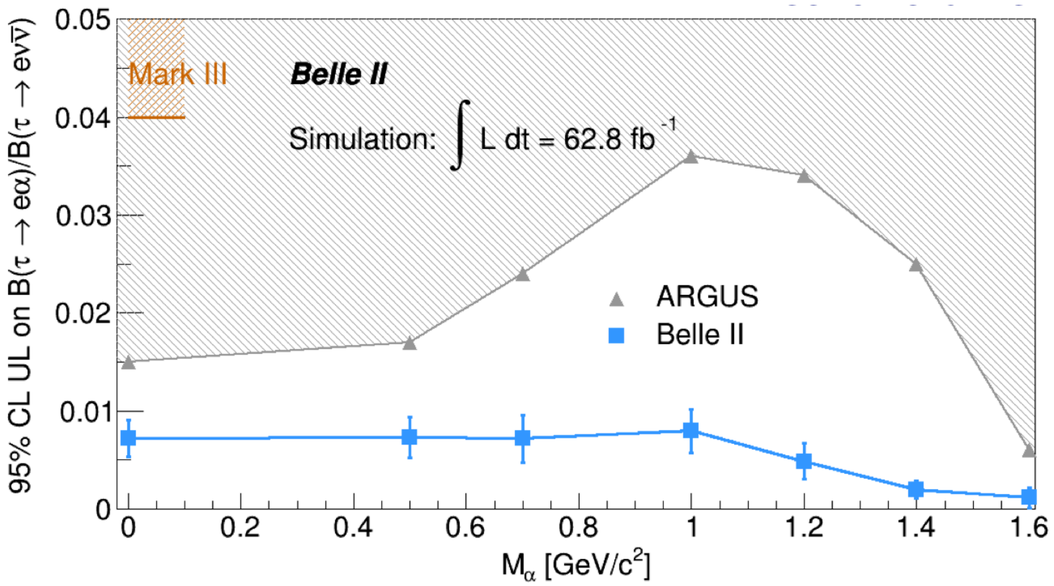
Statistical Treatment

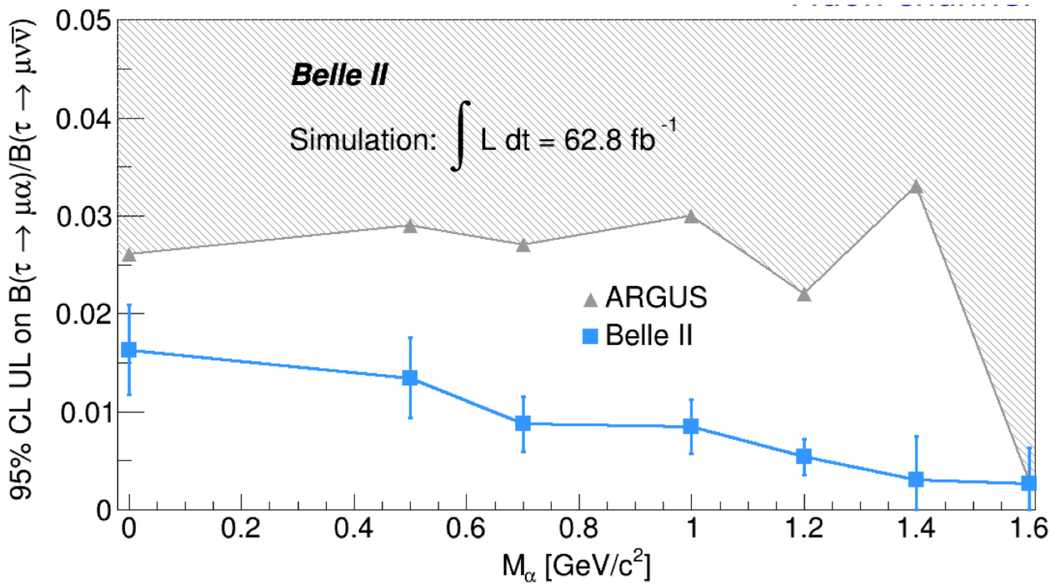
- Currently, we are using a template-based approach for the search
- The data can be modelled as:
  $f(x) = N_{sig} \cdot f_{\ell\alpha}(x) + N_{\ell\nu\nu} \cdot f_{\ell\nu\nu}(x) + N_{BG} \cdot f_{BG}(x)$
  - With x being the momentum in the tau rest-frame
- Upper Limit estimated with a Frequentist profile-likelihood method:
  $CL_{sig} = \frac{CL_{sig+bg}}{CL_{bg}}$
- The signal hypothesis is excluded at a 95% Confidence Level if
  $1 - CL_{sig} \leq 0.95$
- To double-check the results, **alternative** tests using **BAT** (Bayesian) and **pyHF** (Frequentist) are used



TAU 2021 MC-study: Upper Limit Estimate

- UL estimate for the ratio $Br(\tau \to \ell\alpha)/Br(\tau \to \ell\nu\nu)$
- The main systematics were taken into account
  - Trigger and Particle Identification





Conclusion and Outlook

- The analysis is in full swing towards publication.
- We are working in parallel to make this search ready.
- We received permission to unblind recently and are currently finishing the last studies - stay tuned!

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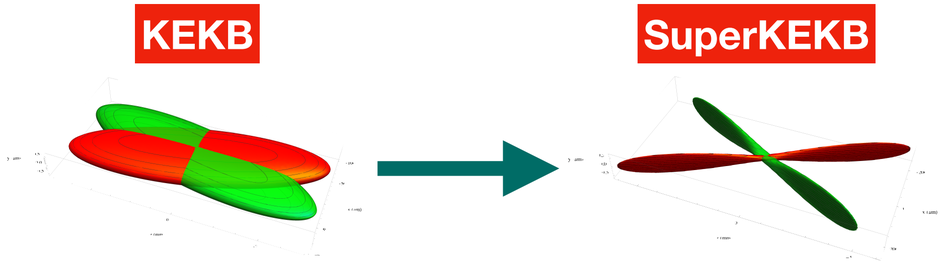
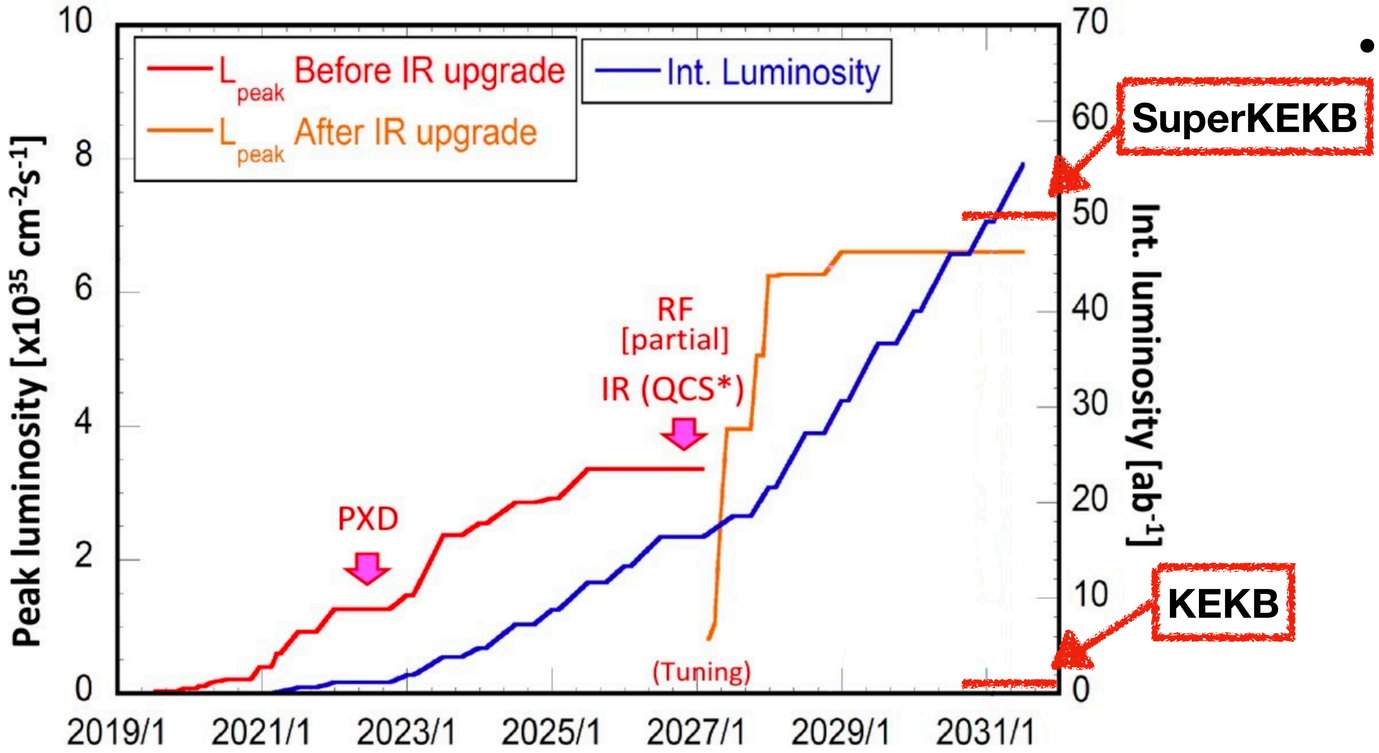
Why study the τ at SuperKEKB?





- 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!
    - $\sigma(e^+e^- \to \Upsilon(4s)) \approx \sigma(e^+e^- \to \tau^+\tau^-)$
    - ~ 45 billion tau pairs
      for full Belle II program

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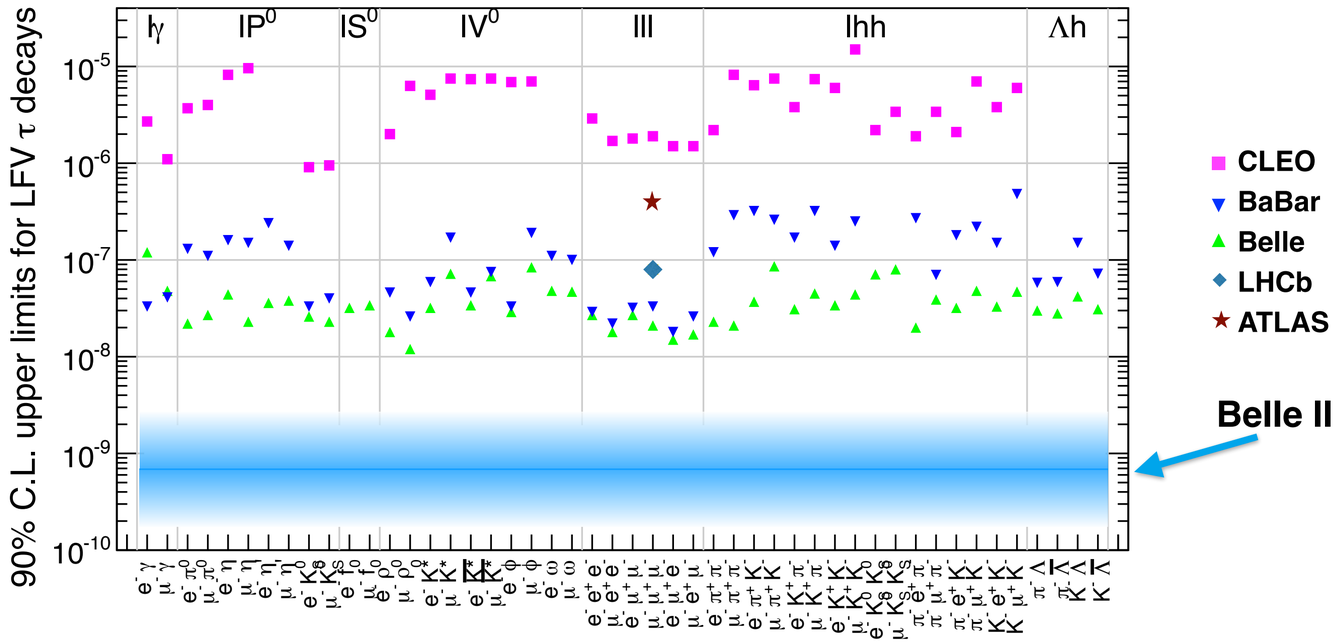
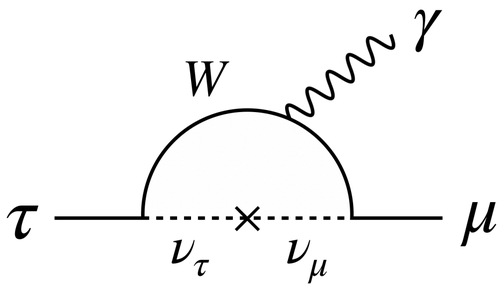
Lepton Flavour Violation

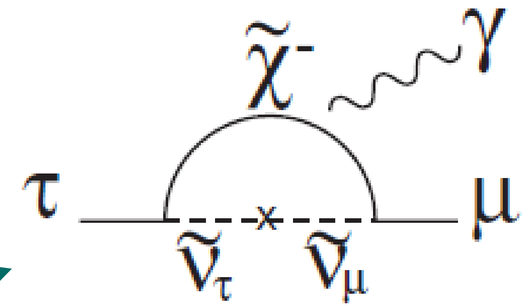


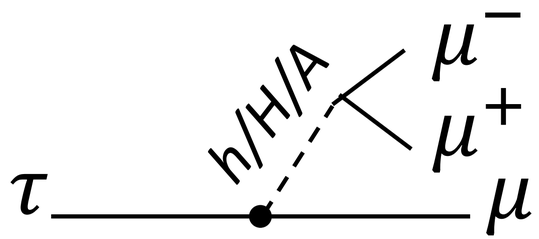
- Observation would be a direct sign of new Physics
- We expect LFV in many Beyond the Standard Model (BSM) models
- For Tau LFV decays are categorised as “golden modes” in Belle II



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

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





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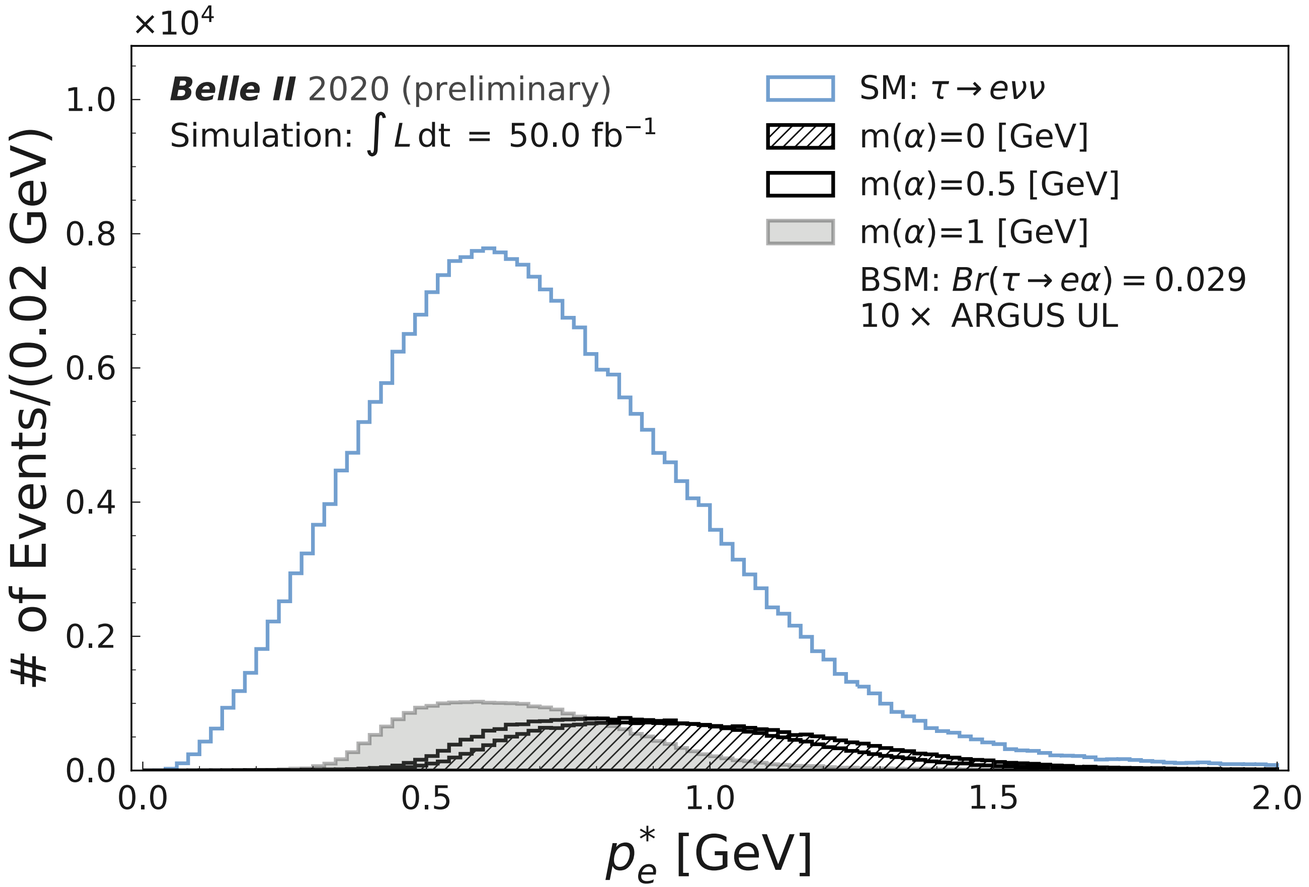
LFV Search: $\tau \to l + \alpha$ (invisible)



- Idea: Search for a two body decay spectrum
- Signal will manifest as a peak in the tau momentum rest frame (TRF)
  - Challenge: Estimate TRF with missing ν_τ momentum
  - Using
    $E_\tau \approx E_{CMS}/2$
    $\vec{p}_\tau \approx \vec{p}_{3\pi} = \sum_{i=1}^{3} \vec{p}^{\,i}_{\pi}$
    => Pseudo-TRF τ^*
- No signal region → fit full spectrum with
  - SM expectation
  - SM + NP expectation
    → compare likelihood of the two models

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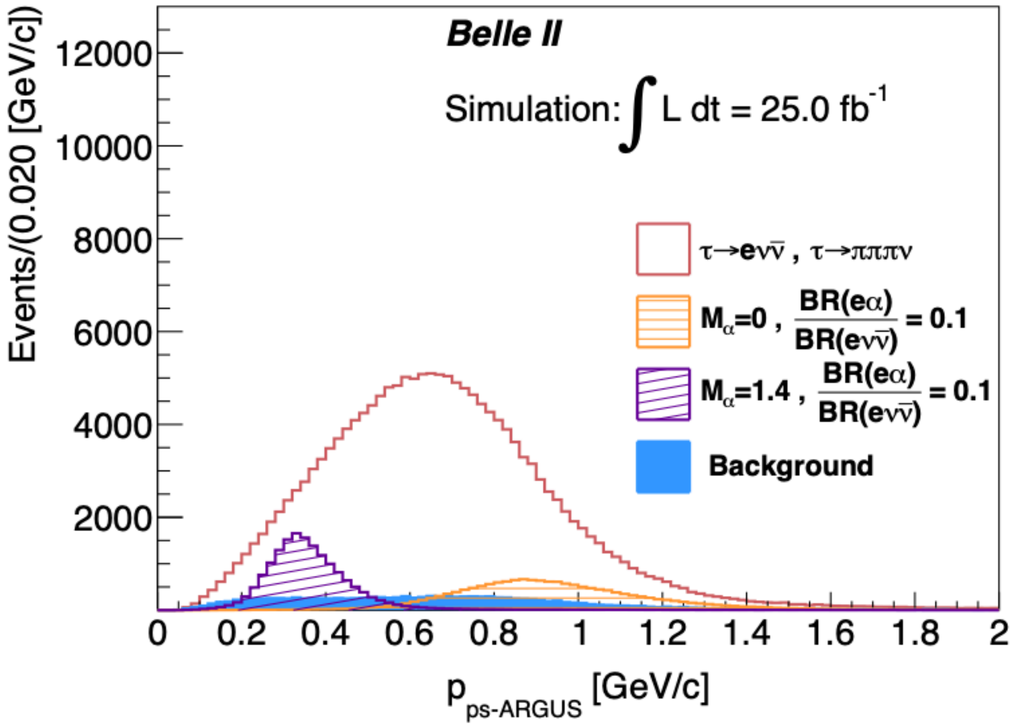
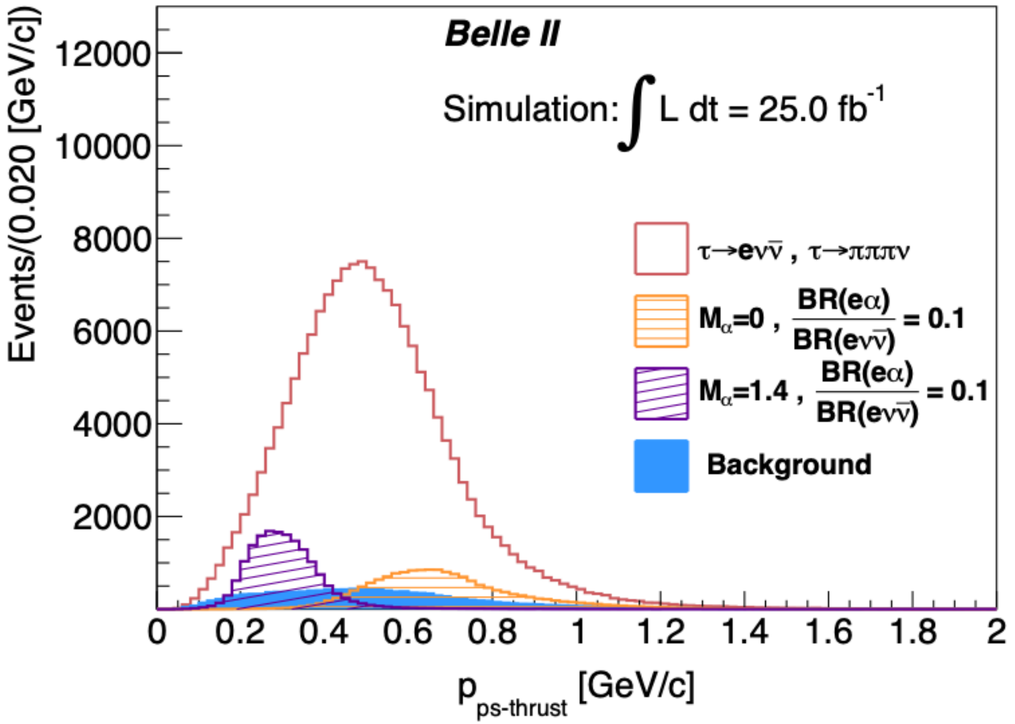
Challenge: The Pseudo-Rest Frame



- ARGUS method: $\hat{p}_\tau \approx -\hat{p_{3\pi}}$
  - Problem: broad $\tau \to l\alpha$ spectrum



- Thrust method: $\hat{p}_\tau \approx \hat{T}$
  - Spectrum is more peaking
  - Problem: SM and BSM are still similar