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

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Belle II

Motivation

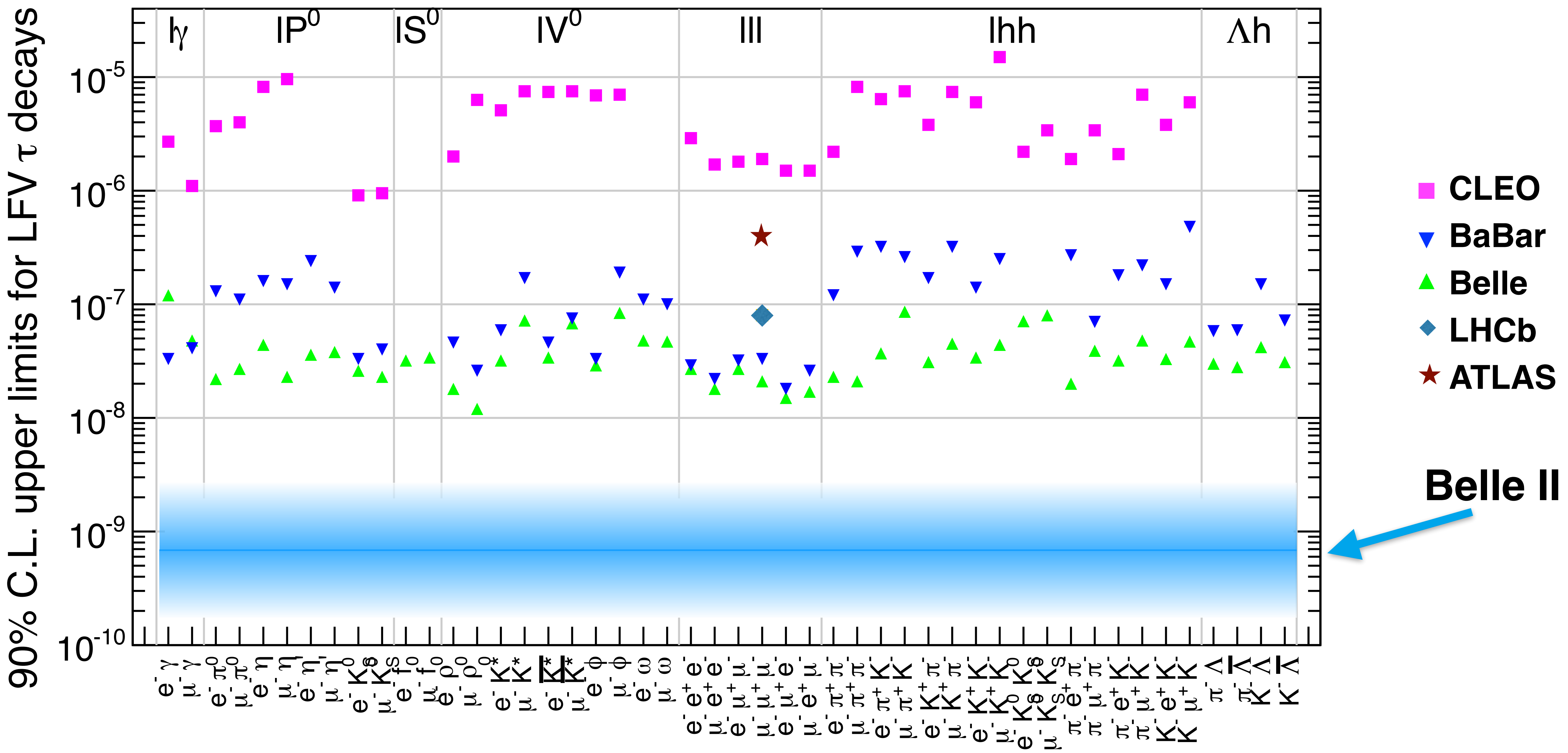
τ

- 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: $\tau \to l\alpha$

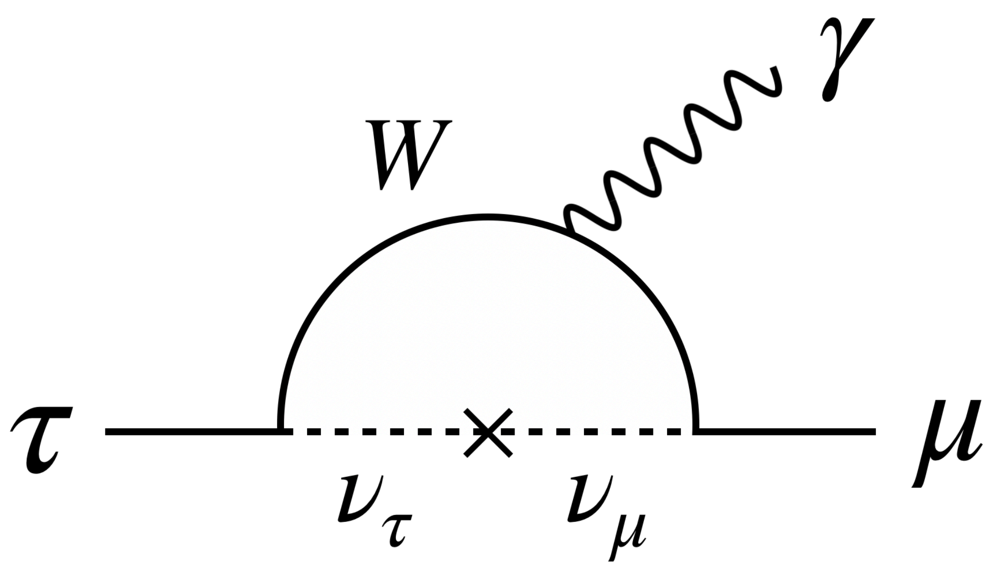
Lepton Flavour Violation

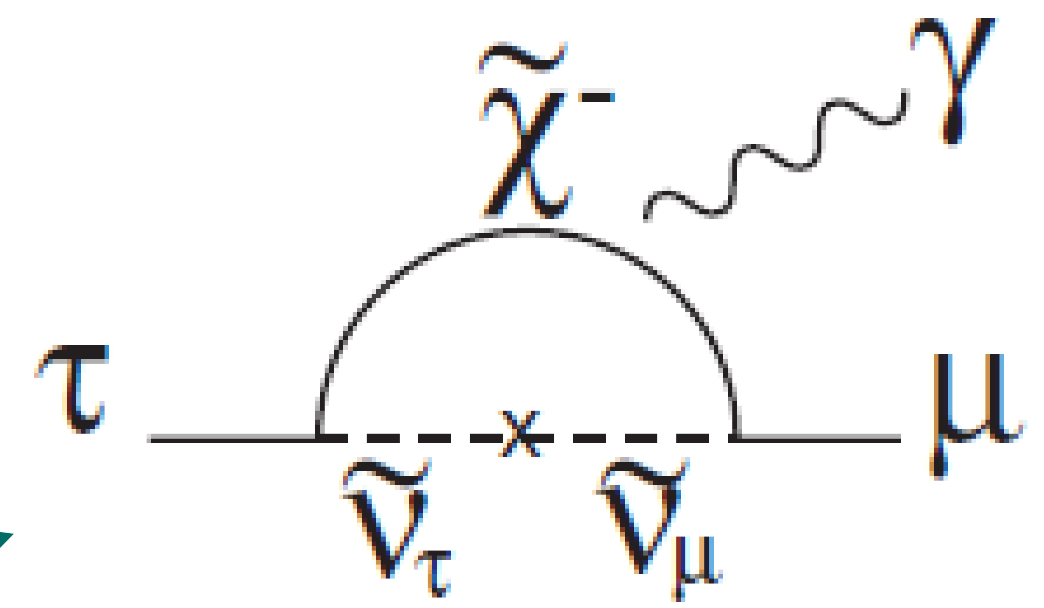


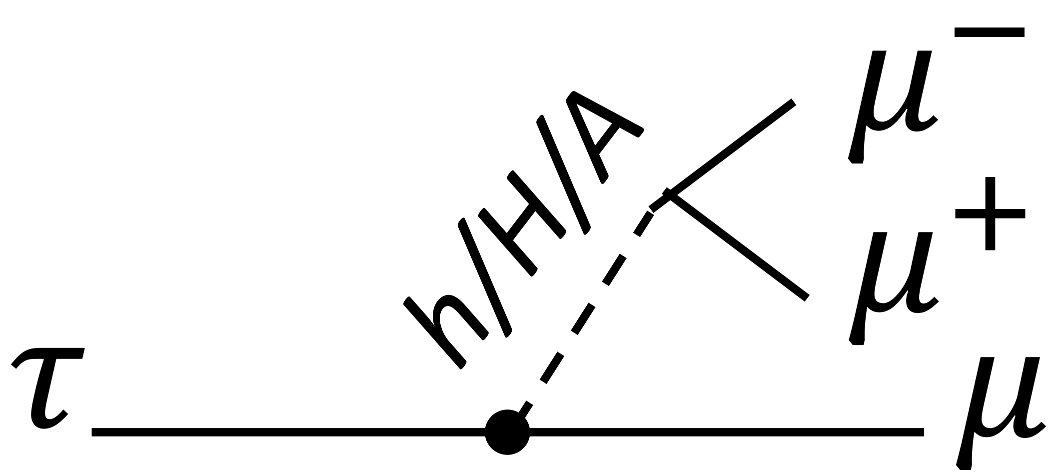
- Observation would be a direct sign of new Physics
- We expect LFV in many Beyond the Standard Model (BSM) models
- For Tau LFV decays are categorised as “golden modes” in Belle II

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

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

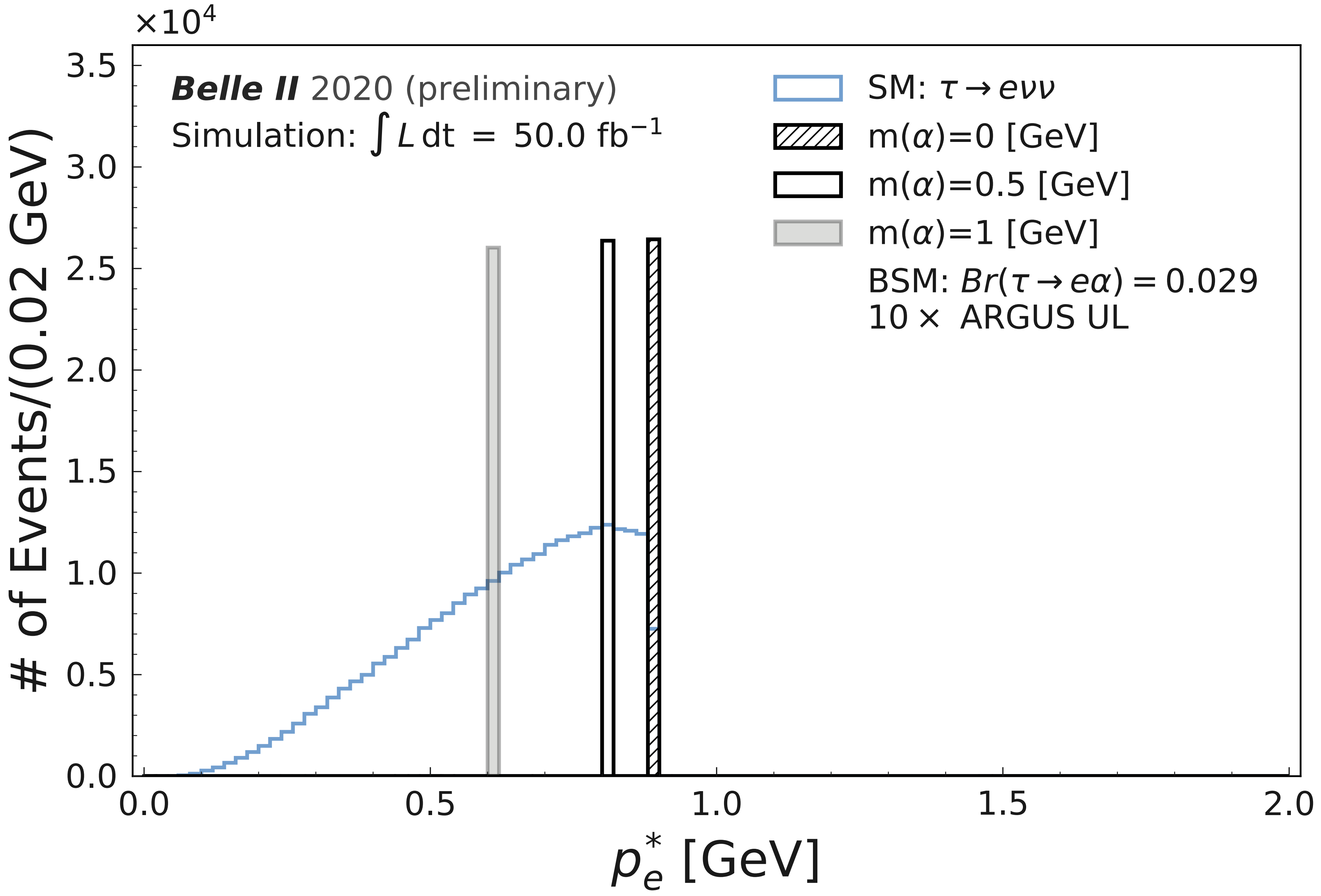






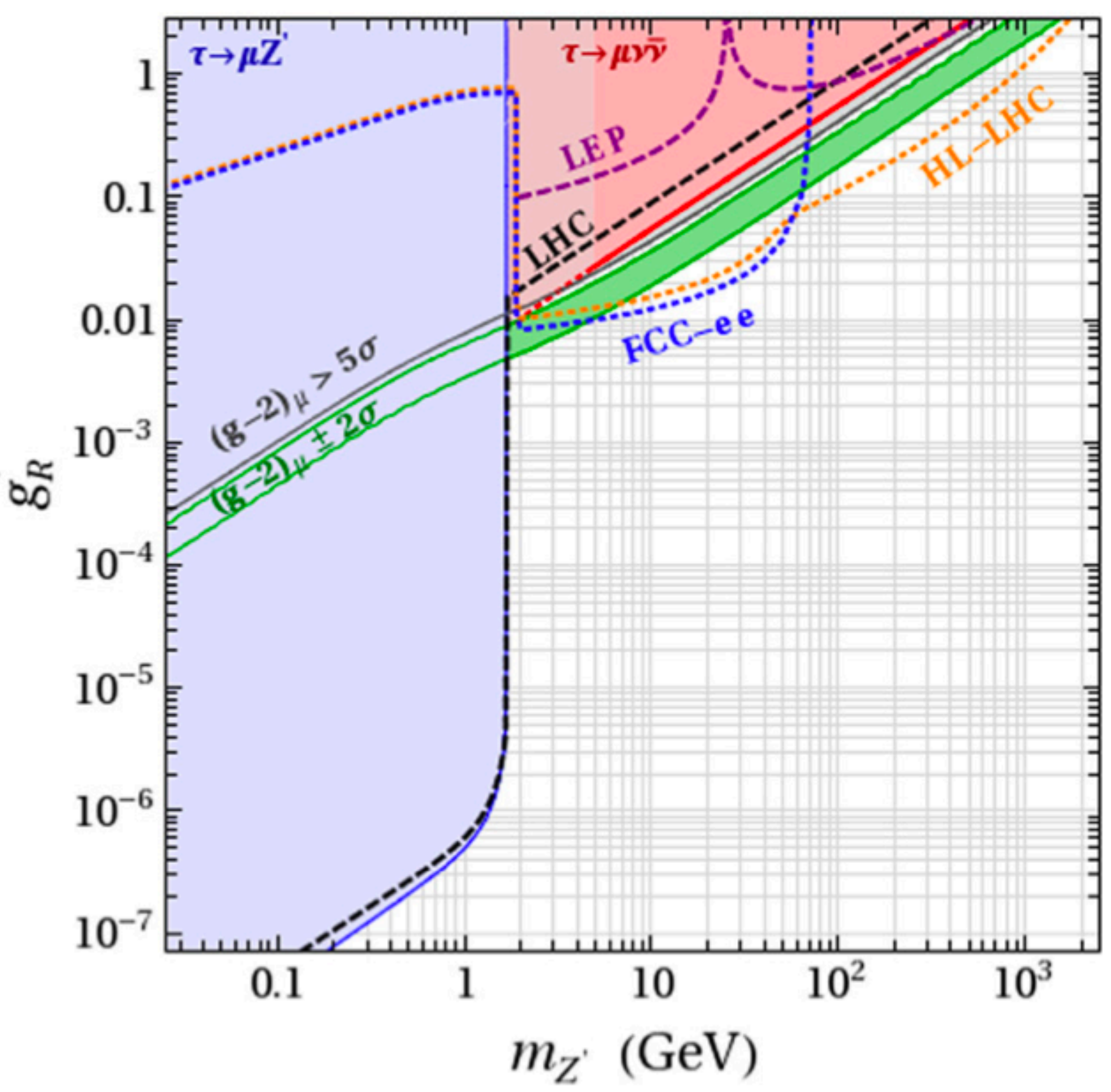
Introduction to: $\tau \rightarrow l + \alpha$ (invisible)

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

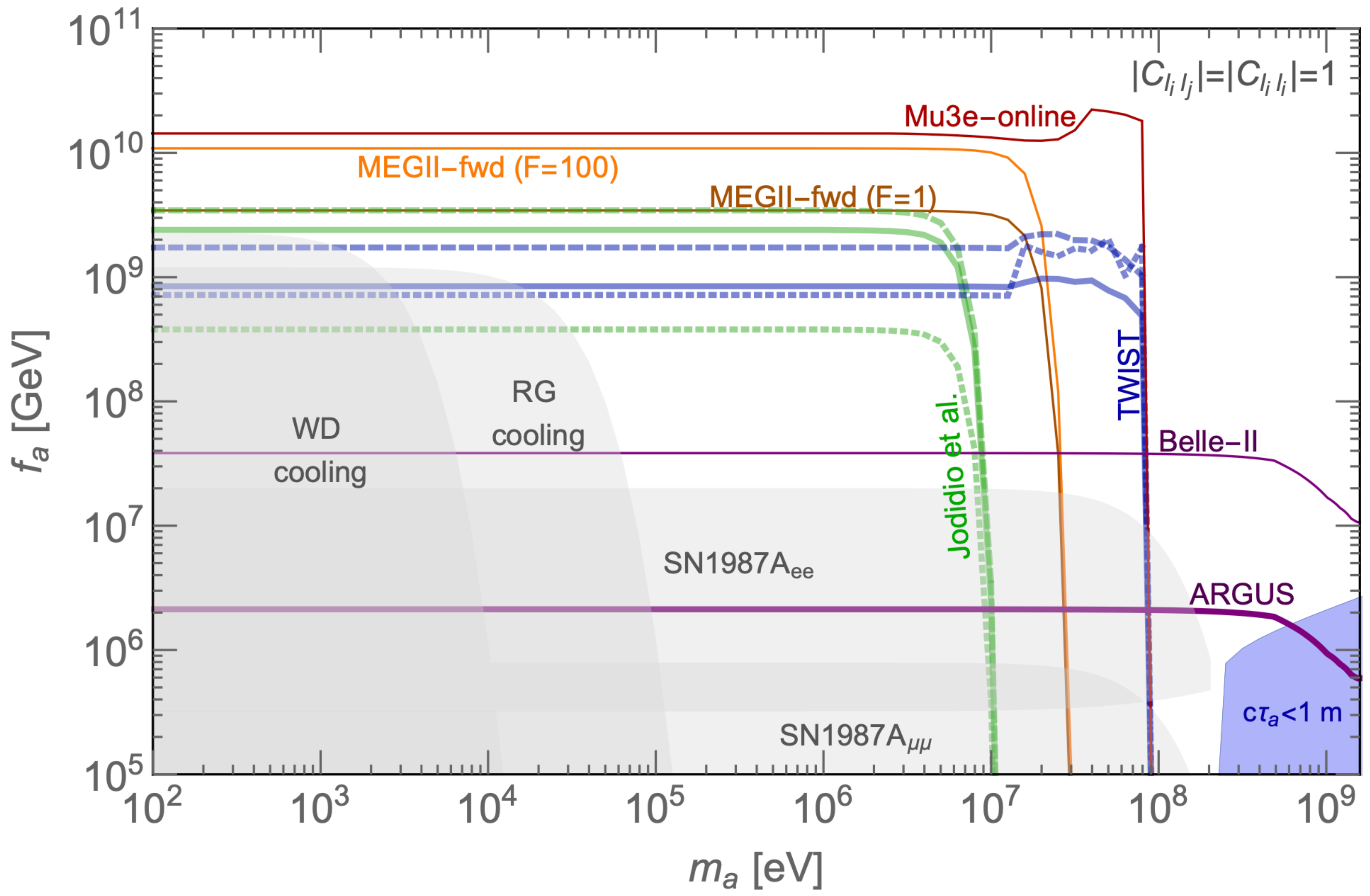


Various NP Scenarios:

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



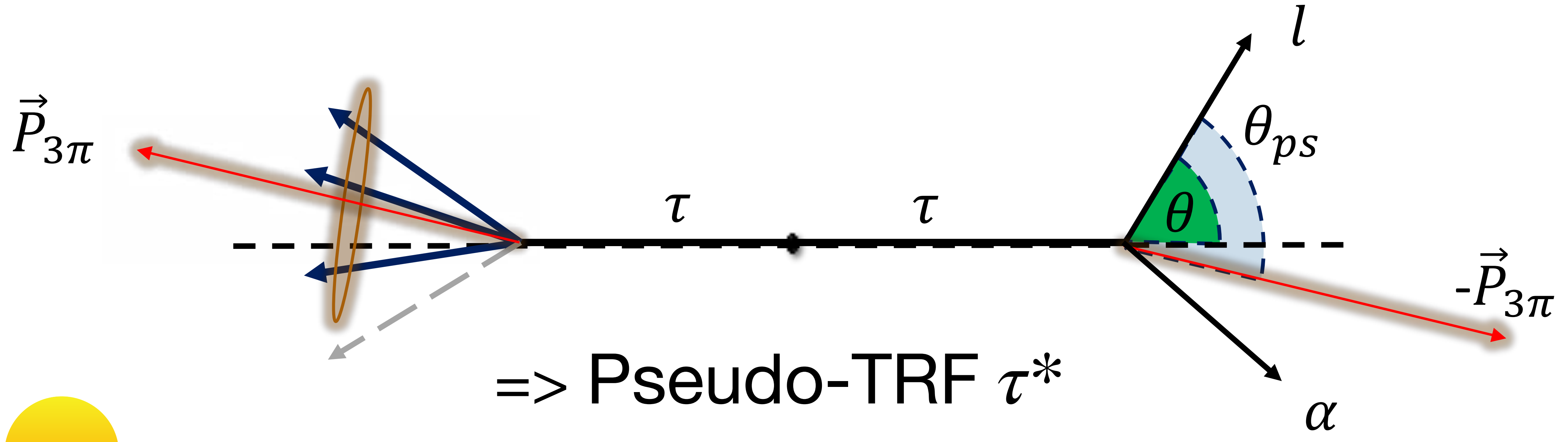
Wolfgang Altmannshofer, Chien-Yi Chen, P.S. Bhupal Dev, Amarjit Soni



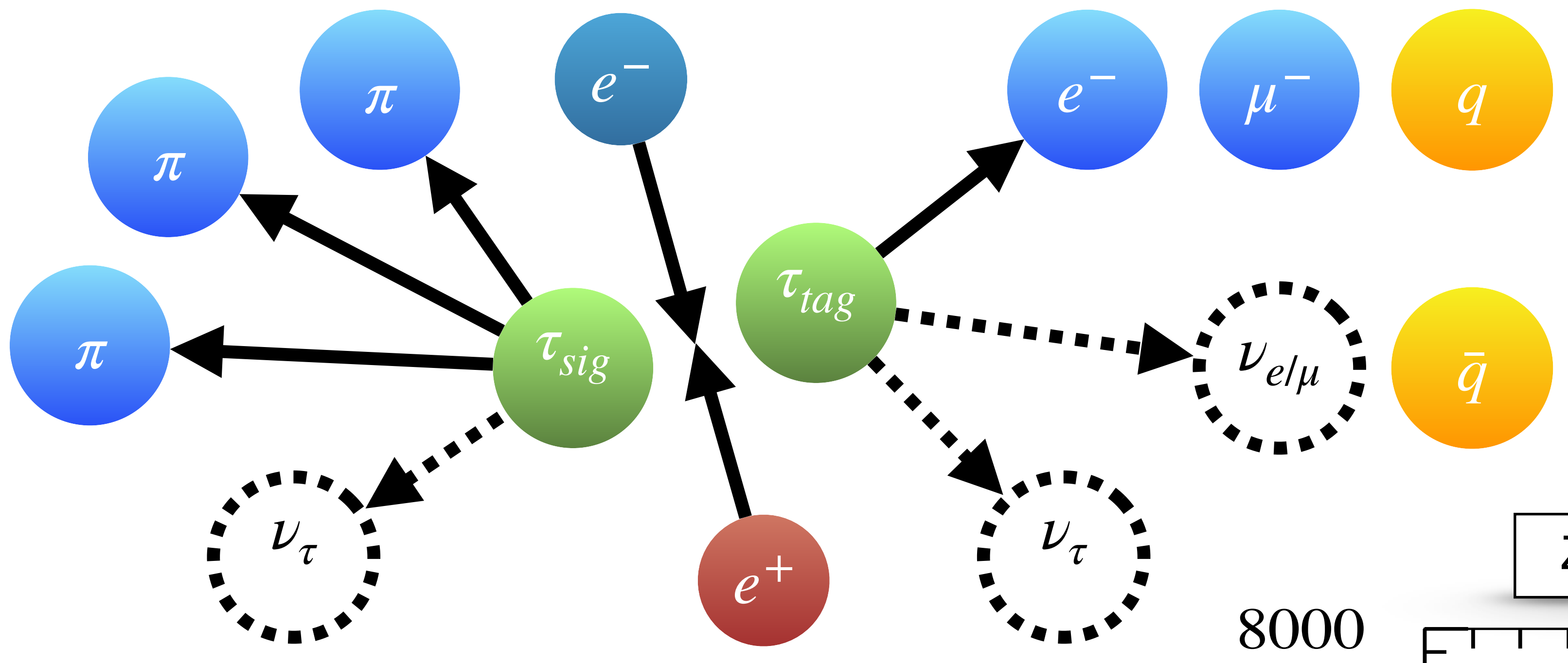
Lorenzo Calibbi, Diego Redigolo, Robert Ziegler, Jure Zupan,

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

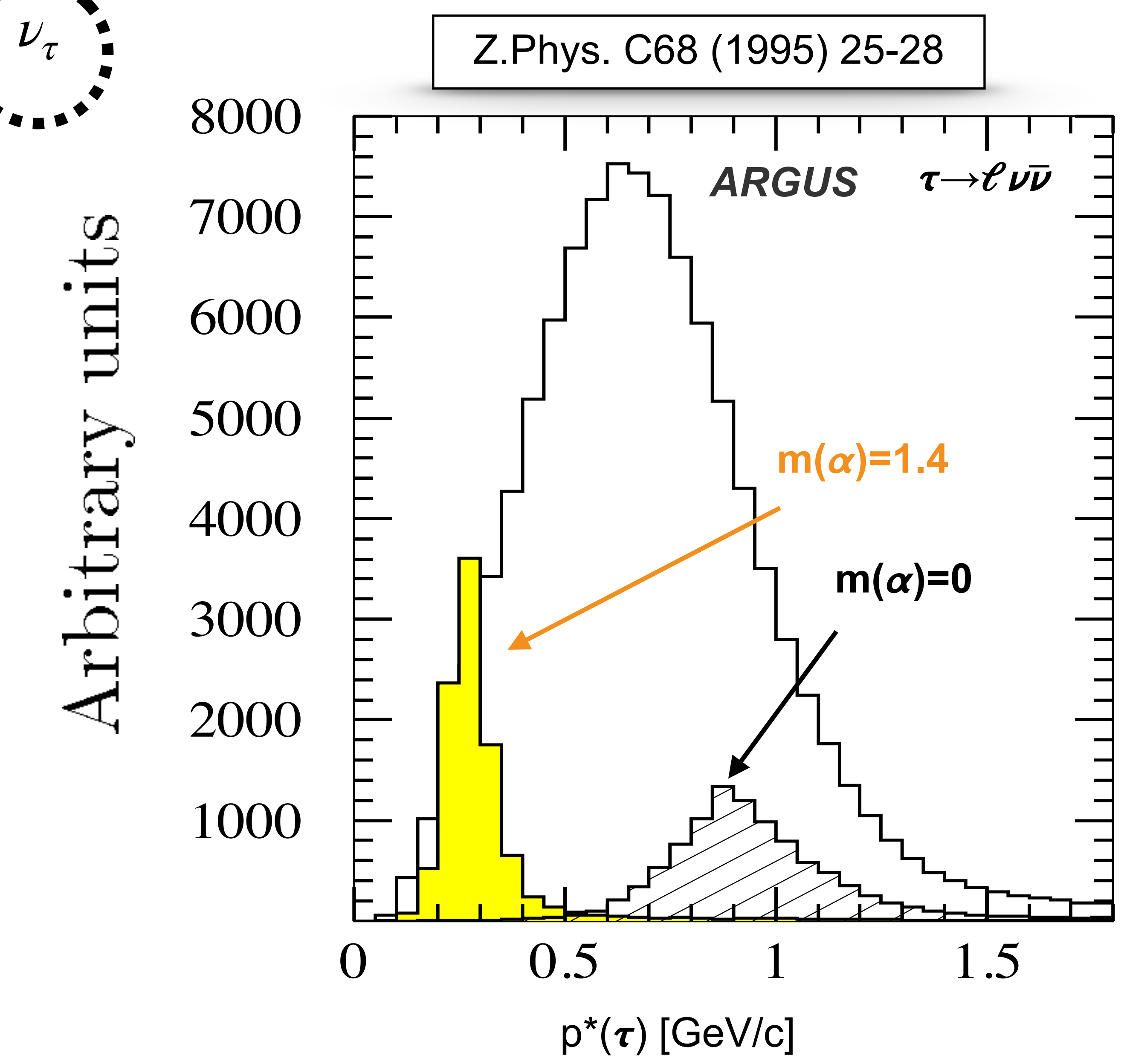
- Idea: search for a two body decay spectrum
  - Challenge: Estimate TRF with missing ν_τ momentum
  - Using $E_\tau \approx E_{CMS}/2$ $\quad \vec{p}_\tau \approx \vec{p}_{3\pi} = \sum_{i=1}^{3} \vec{p}_\pi^{\,i}$



=> Pseudo-TRF τ^*



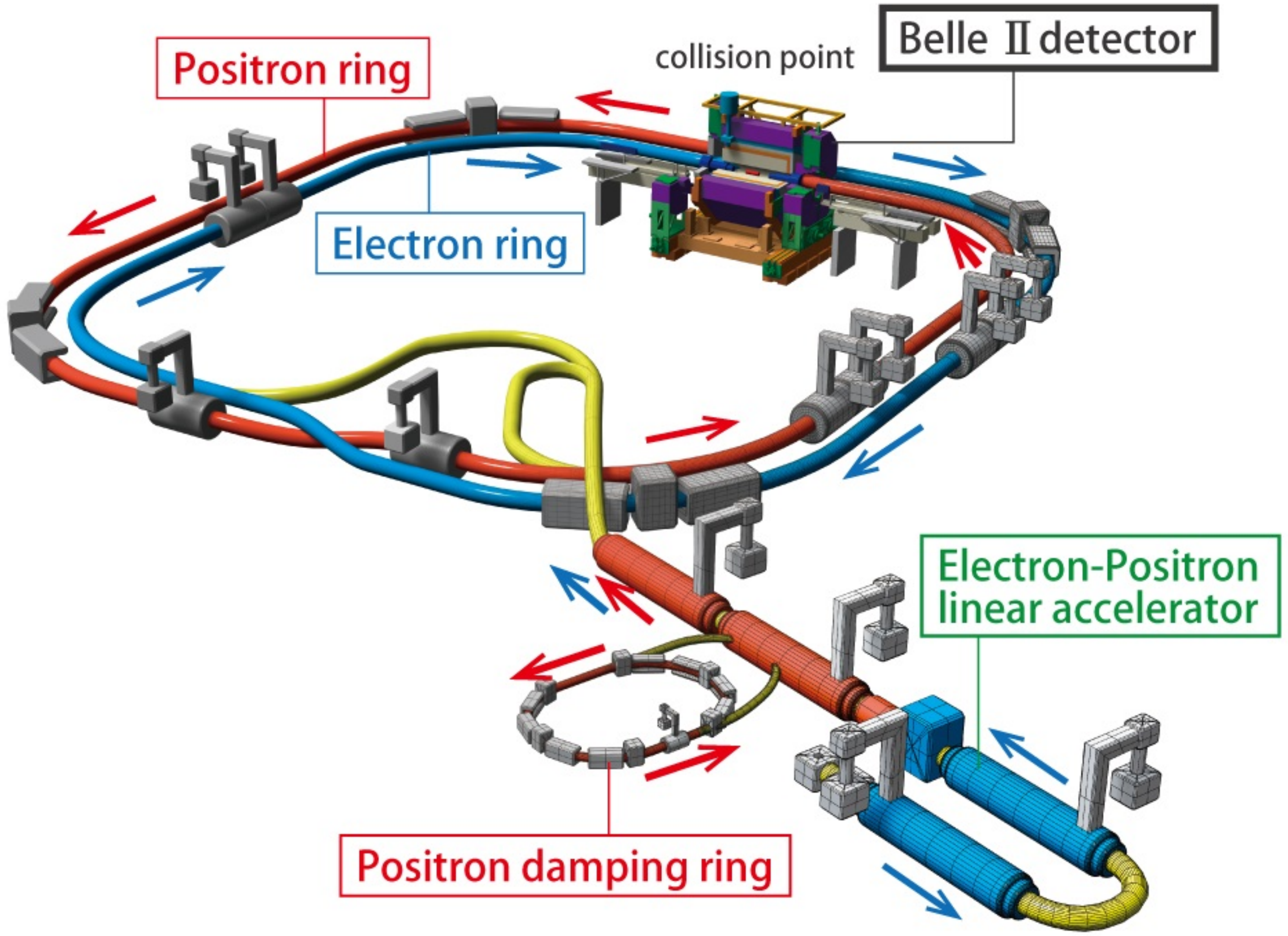
- No signal region → fit full spectrum with
  - SM expectation
  - SM + NP expectation
  - → compare likelihood of the two models



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

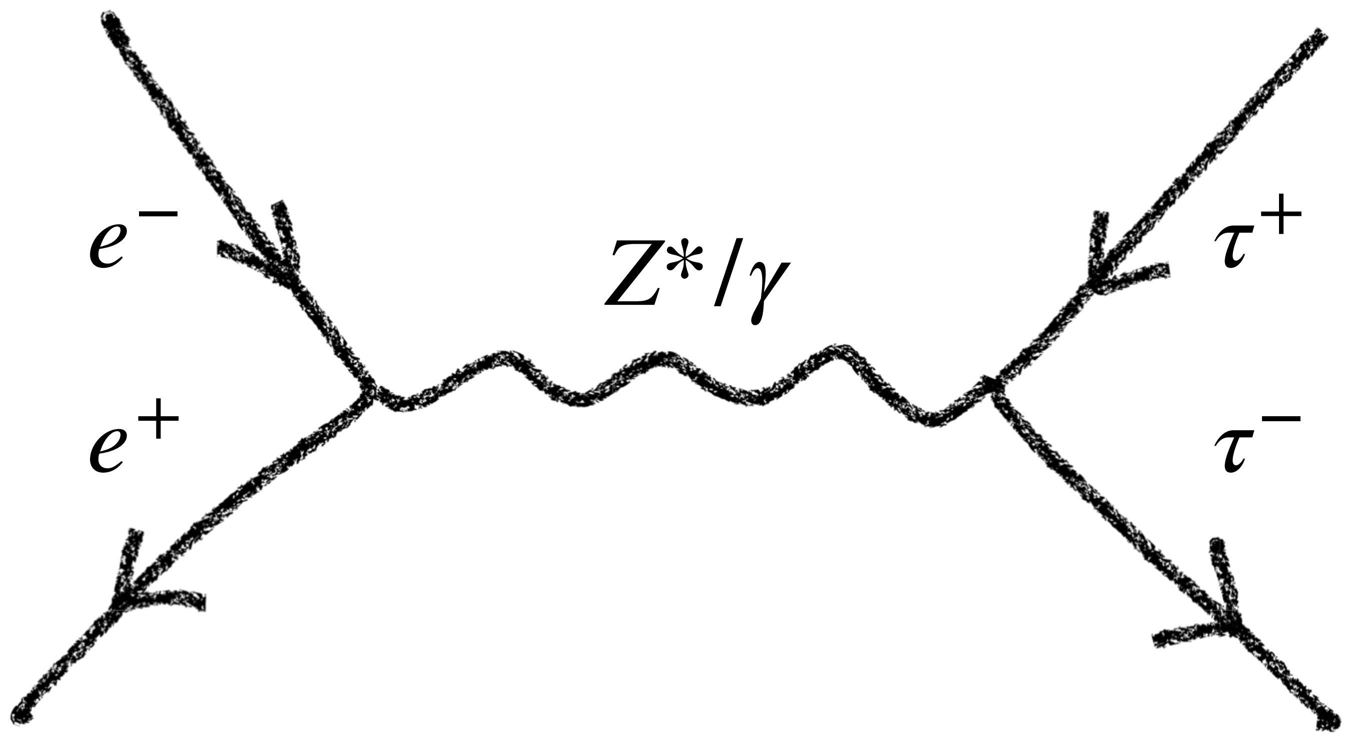
→ **Belle II is competitive with early data ~70 fb^{-1}**

Where can one study the τ?

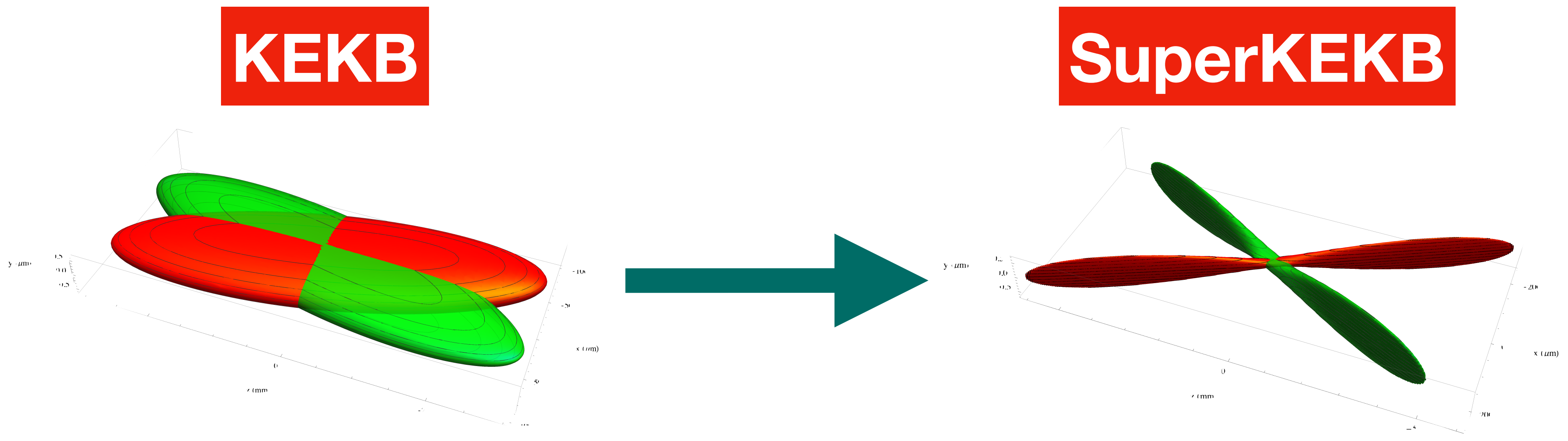


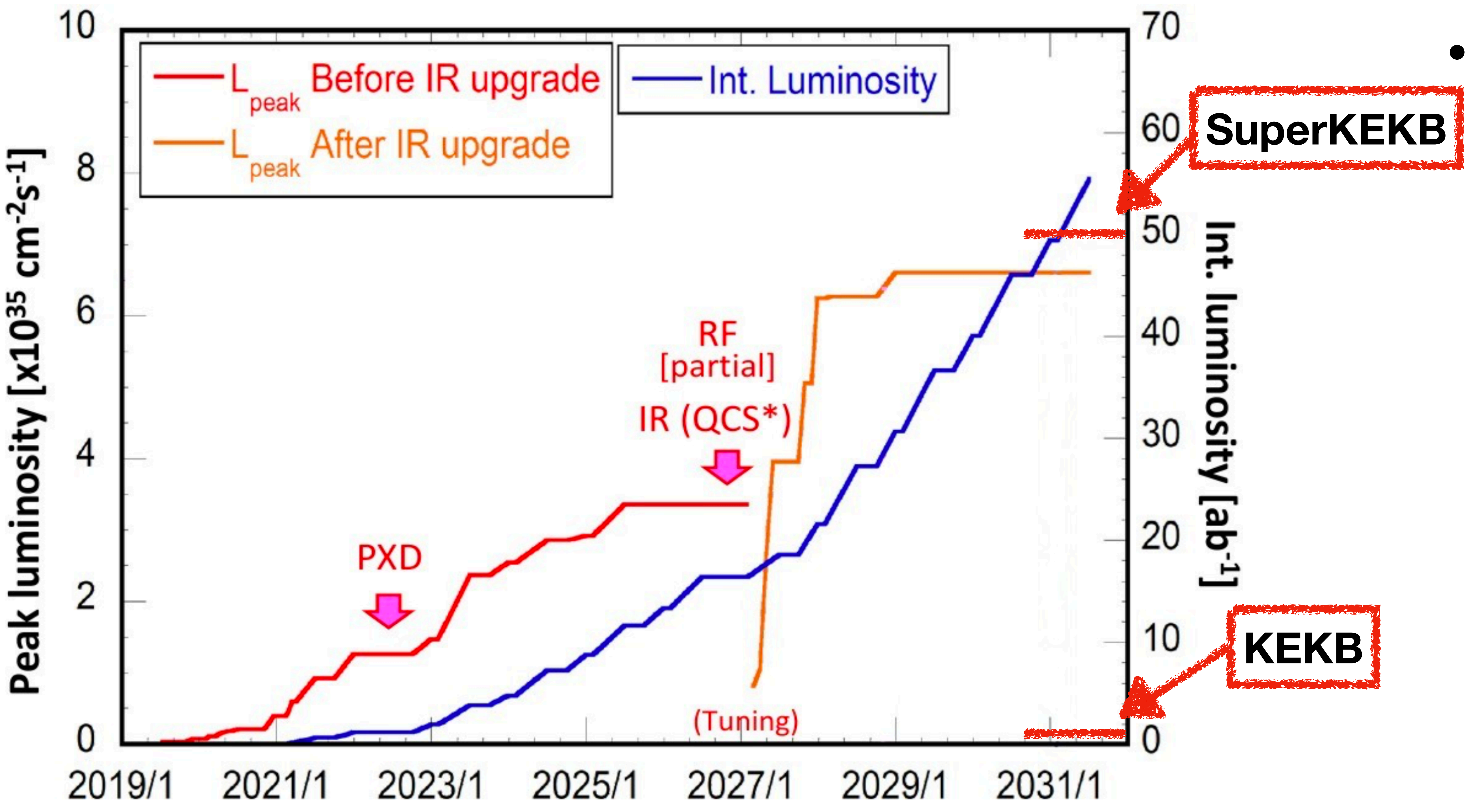
- At e^+e^- machines there is a low background and well understood production mechanism for τ

- SuperKEKB collider



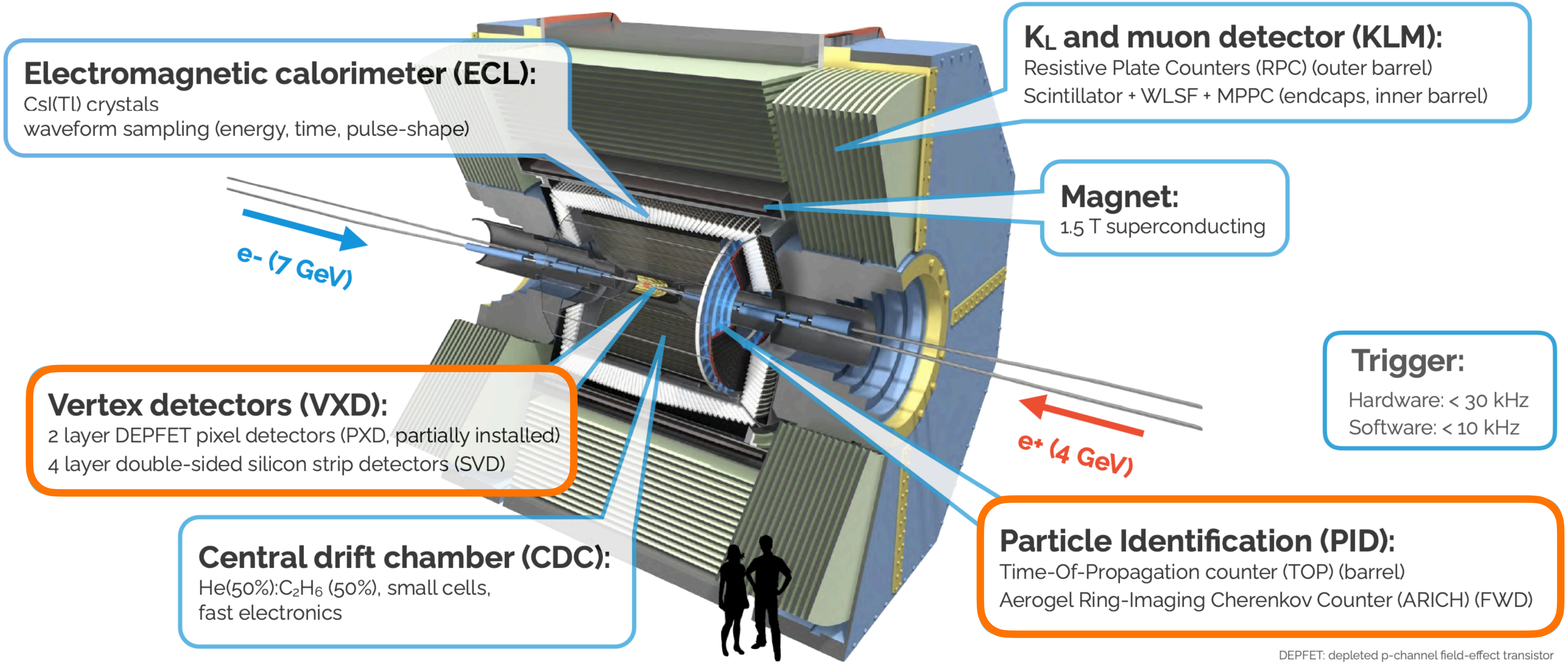
Why study the τ at SuperKEKB?





- 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

How is the τ detected at Belle II?



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

Reconstruction And Selection

Firm Requirements

- 3x1-prong topology:
  $\tau \rightarrow l\alpha$ (signal), $\tau \rightarrow 3\pi\nu$ (tag)
  - Requiring exactly 4 tracks
  - Hemisphere separation with thrust
    $$\vec{T} = max\left(\sum_i \frac{\vec{p}_i \cdot \hat{T}}{|\vec{p}_i|}\right)$$
  - No neutrals allowed
    $\rightarrow$ reject $q\bar{q}$ and beam background
- Vertex fit: reject displaced tag vertices
- Use SM $\tau \rightarrow e\nu\nu$ for selection optimisation

Current status: Cut Based Analysis

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

Particle Identification (**PID**)
e : E/p > 0.8
π : 0 < E/p < 0.8

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

Background Suppression - Used for Plots Presented

1. 0.67 < thrust < 0.99
2. 2.0 < invisible Energi in CMS < 9.9
3. 0.48 < Invariant Mass of tag side < 1.66

Revising The Reconstruction

Goal: Achieve highest possible Purity and Efficiency at the same time!

Background Suppression - Used for Plots Presented

1. 0.67 < thrust < 0.99
2. 2.0 < invisible Energi in CMS < 9.9
3. 0.48 < Invariant Mass of tag side < 1.66

Background Suppression

1. 0.67 < thrust < 0.99
2. 1.2 < E_{CMS} of 3-prong τ < 5.3
3. 0.6 < Invariant Mass of tag side < 1.7

- Introduce smarter PID
  - Global electron ID
  - π : 0 < E/p → asymmetric ranked p_t cuts

→ Gain in Statistics by a factor of ~ 25%

Selection Evolution	Efficiency	Purity
ICHEP	13.95%	90.74%
PID Improvements	17.28%	90.09%

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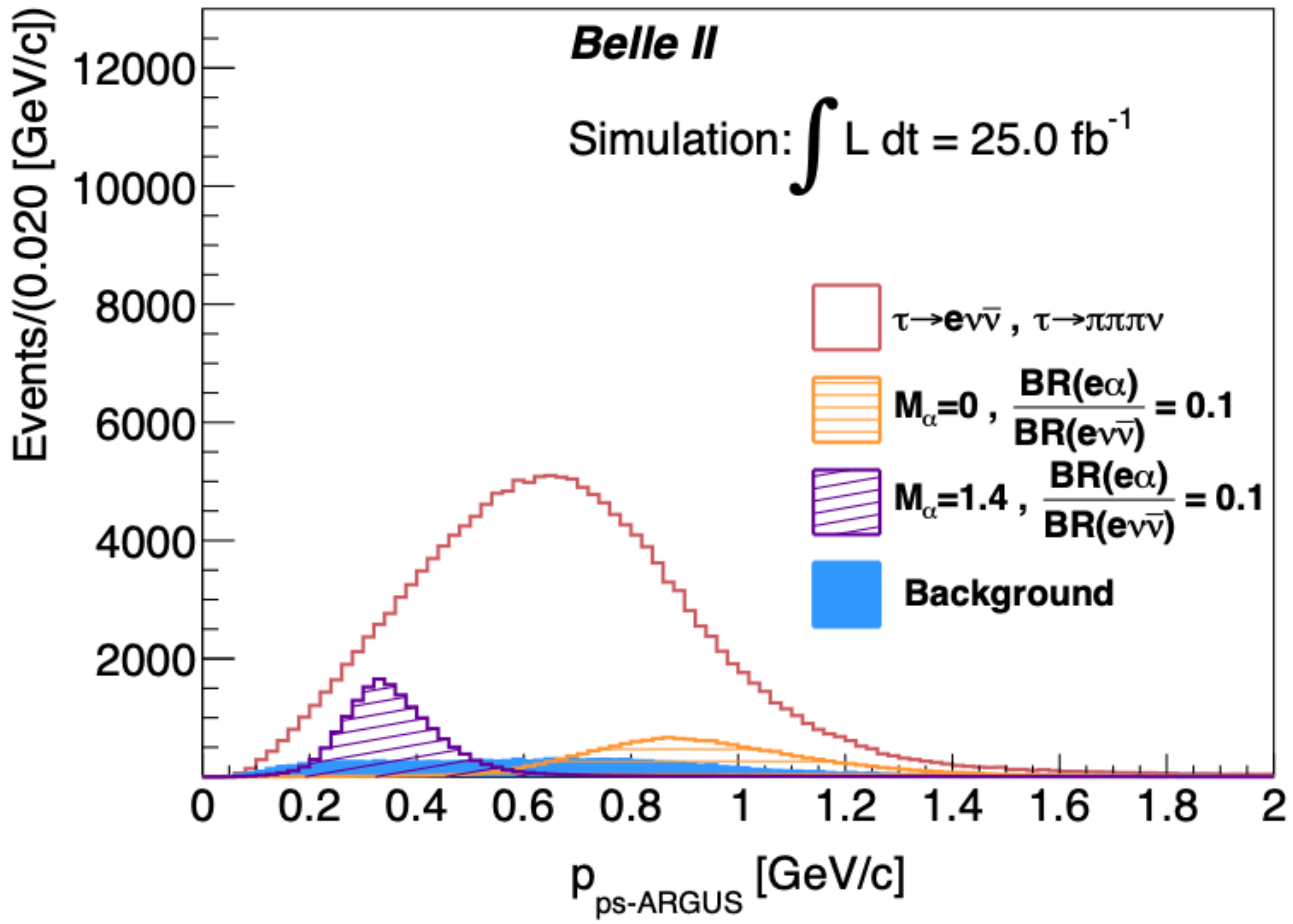
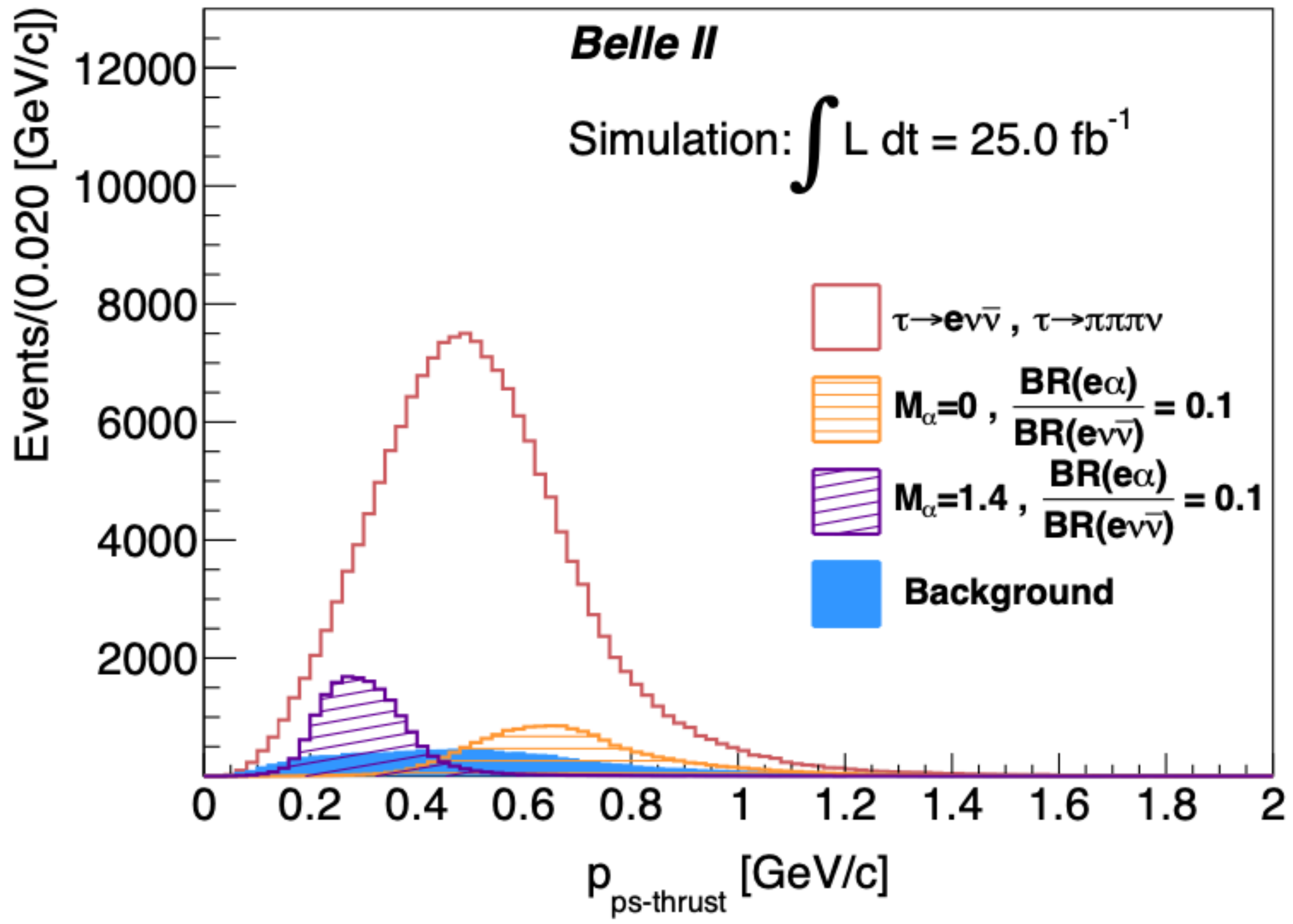
Challenge: The Pseudo-Rest Frame





- 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

Statistical Treatment

- Currently we are using a template-based approach for the search

- The data can be modelled as:
$f(x) = N_{sig} \cdot f_{e\alpha}(x) + N_{e\nu\ nu} \cdot f_{e\nu\nu}(x) + N_{BG} \cdot f_{BG}(x)$

  - With x being the momentum in the tau rest-frame

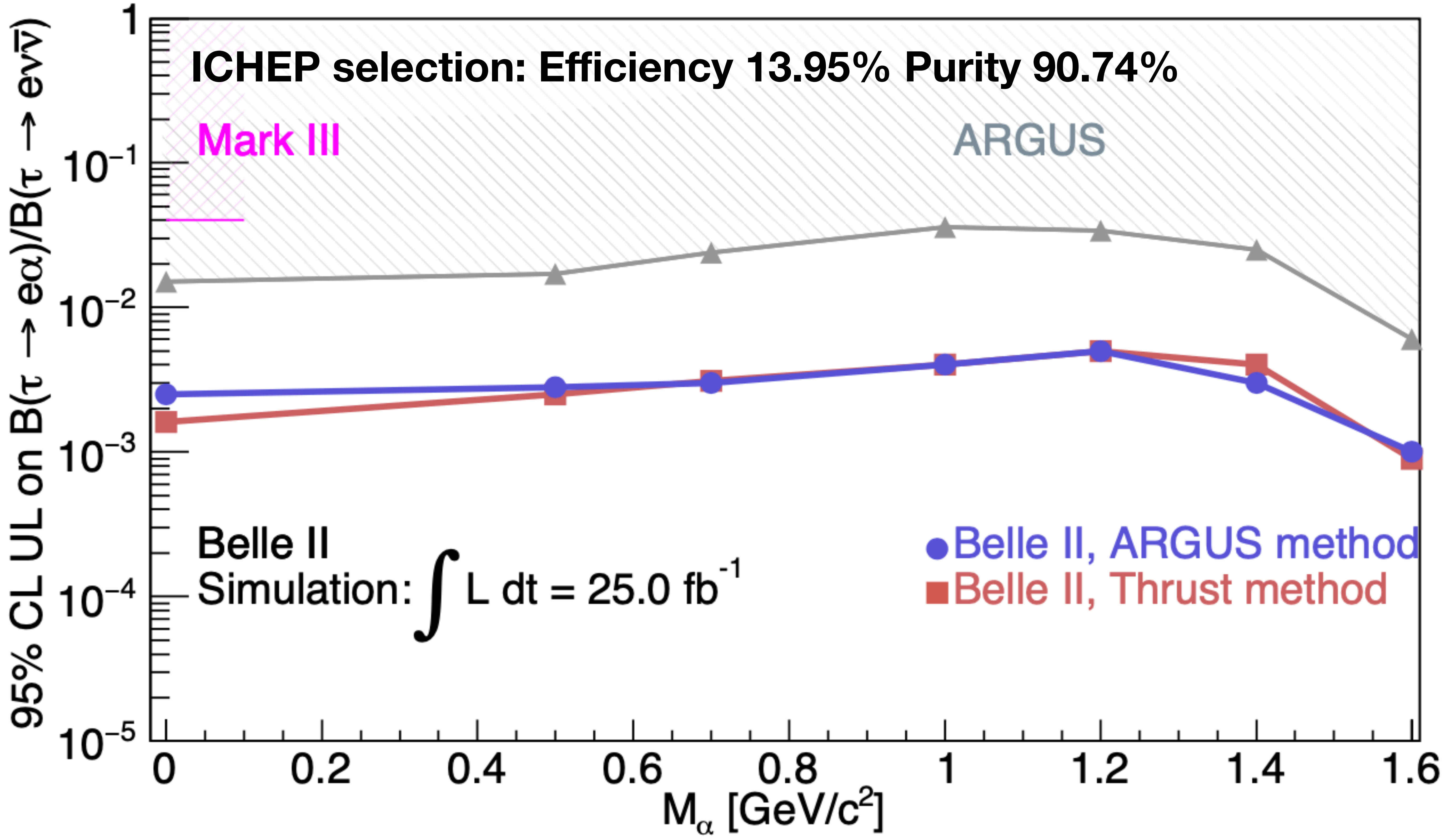
- Upper Limit estimated with a Frequentist profile-likehood method:
$$CL_{sig} = \frac{CL_{sig+bg}}{CL_{bg}}$$

- The signal hypothesis is excluded at 95% Confidence Level if $1 - CL_{sig} \leq 0.95$

- In order to double check the results **alternative** tests using
BAT (Bayesian) and **pyHF** (Frequentist) are used

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
  → in progress



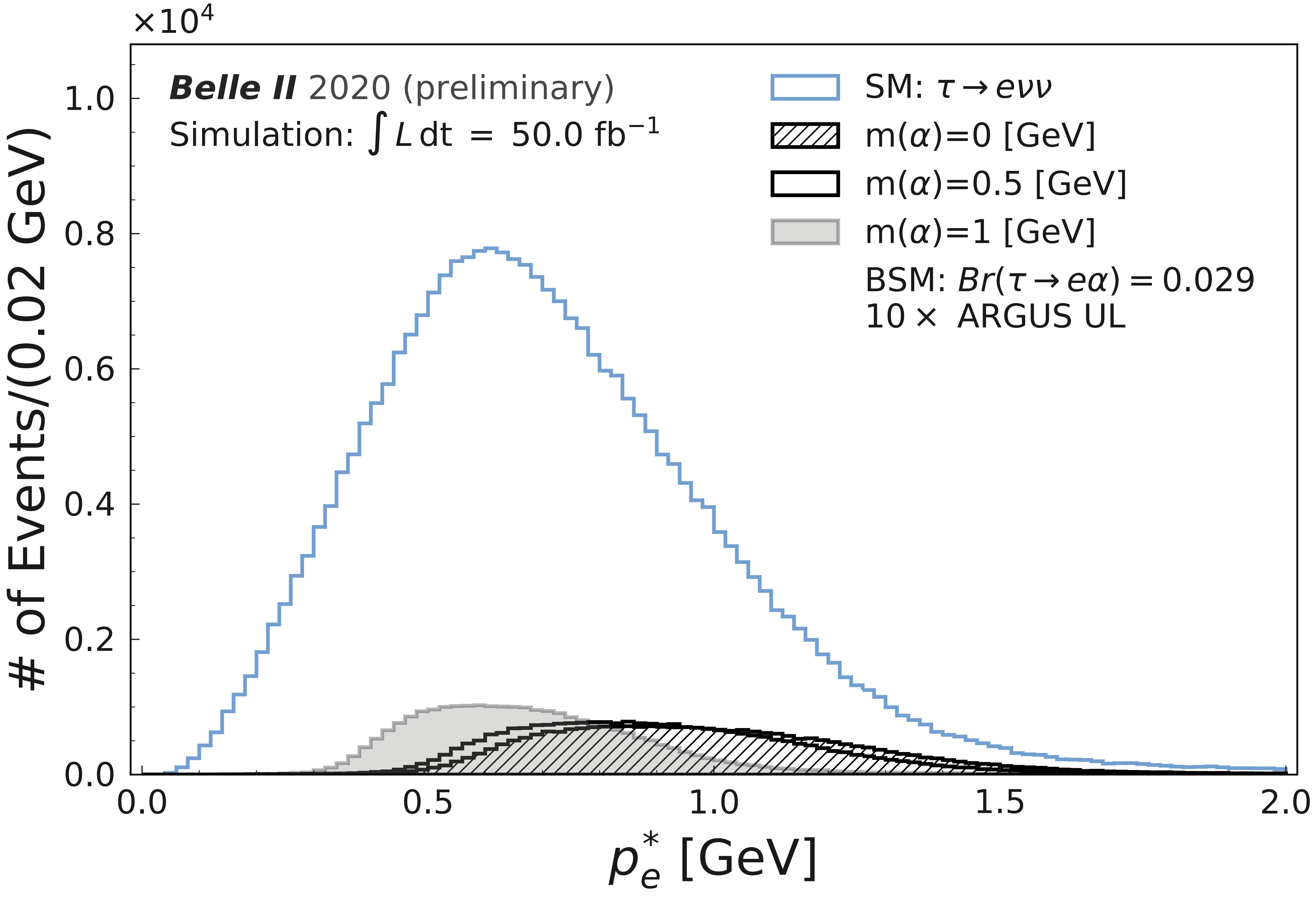
	UL(95% c.l.)		
$M(\alpha)$ [GeV/c^2]	ARGUS (1995)	Argus method	Thrust method
0	0.015	0.0025	0.0016
0.5	0.017	0.0028	0.0025
0.7	0.024	0.003	0.0031
1.0	0.036	0.004	0.004
1.2	0.034	0.005	0.005
1.4	0.025	0.003	0.004
1.6	0.006	0.001	0.0009

→ Performance of ARGUS and Thrust method is similar

Conclusion and Outlook

- Analysis is in full swing towards publication
- We are working in parallel to make this search ready
- Currently Systematics are evaluated.

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



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    => Pseudo-TRF τ^*

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