Tau physics program at Belle II

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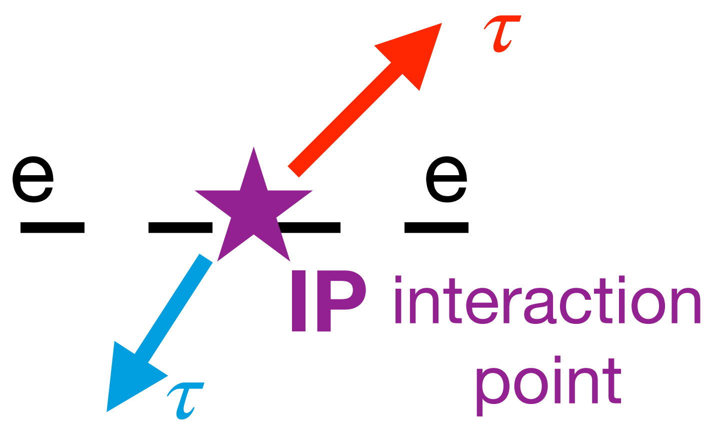
On behalf of the Belle II collaboration

IPA2022: Interplay between Particle and Astroparticle physics 2022, 5-9 Sep 2022, Wien

Introduction on τ physics at Belle II

Belle II: new generation of B-factory experiment
(talk given by Alan Schwarz on 6 Sep.)

Belle II will collect the world's largest sample of τ-pair events



Process	Cross section (nb)
$\Upsilon(4S)$	1.05
$\tau^+\tau^-$	0.919

B-factories are also τ-factories!

Advantages of studying τ physics at Belle II:

- τ produced in pairs
- Well defined initial state energy
- Clean environment wrt hadronic collider-based experiments
- High hermeticity of the detector

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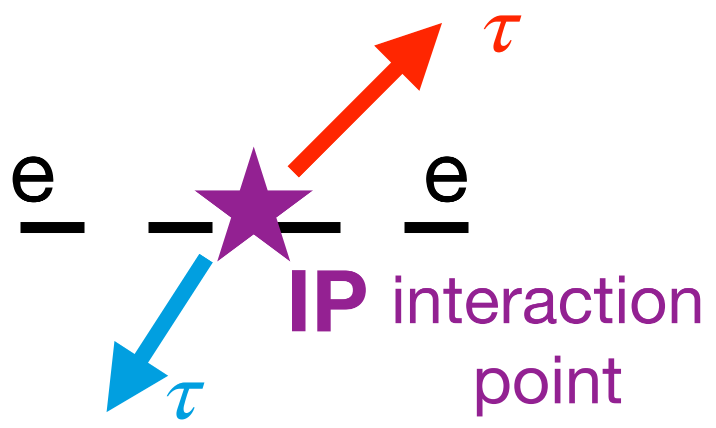

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Tau Physics program at Belle II is rich → high precision measurements (★→discussed in next slides)

- Lifetime ★
- Mass ★

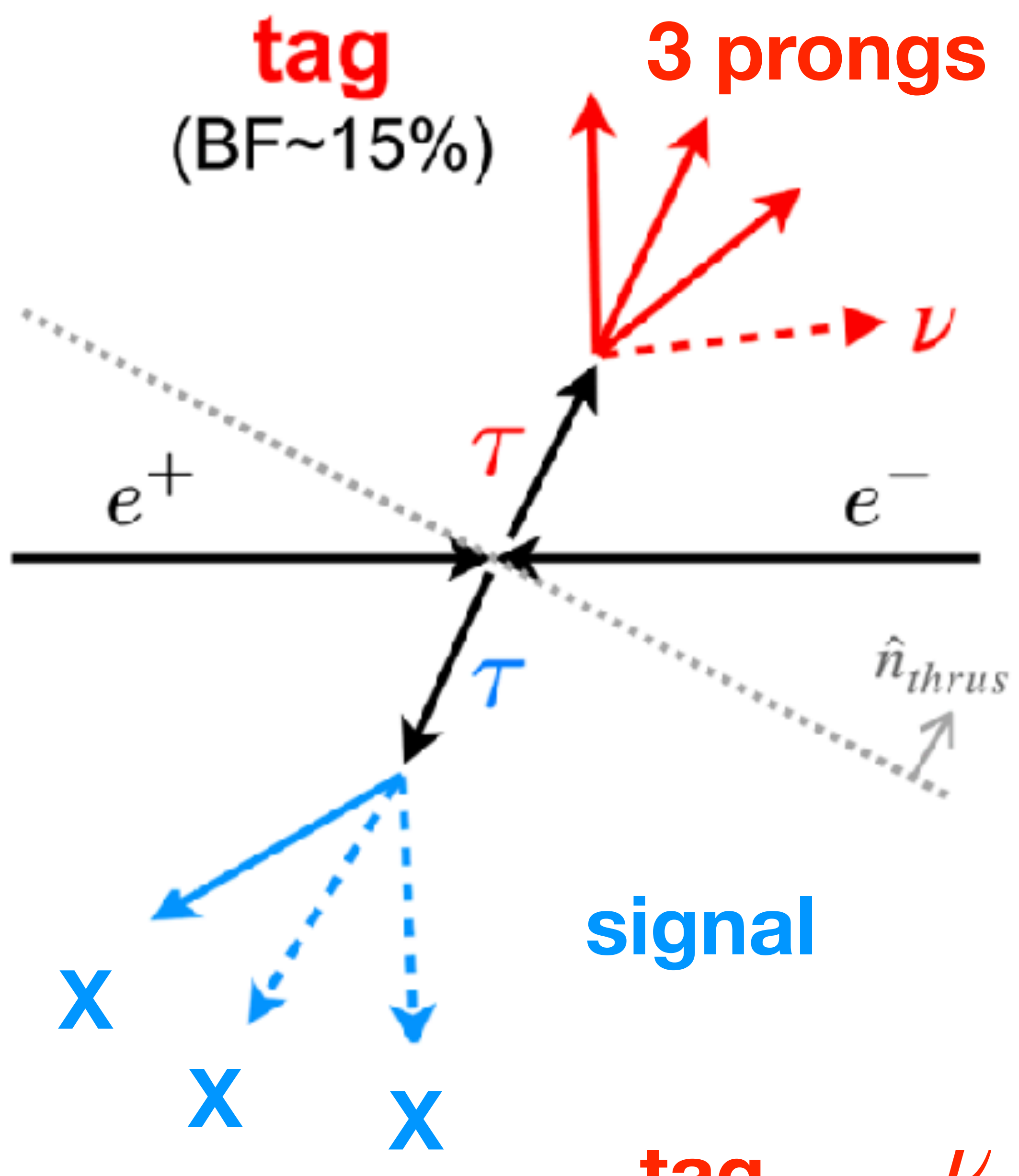
} Test of the SM

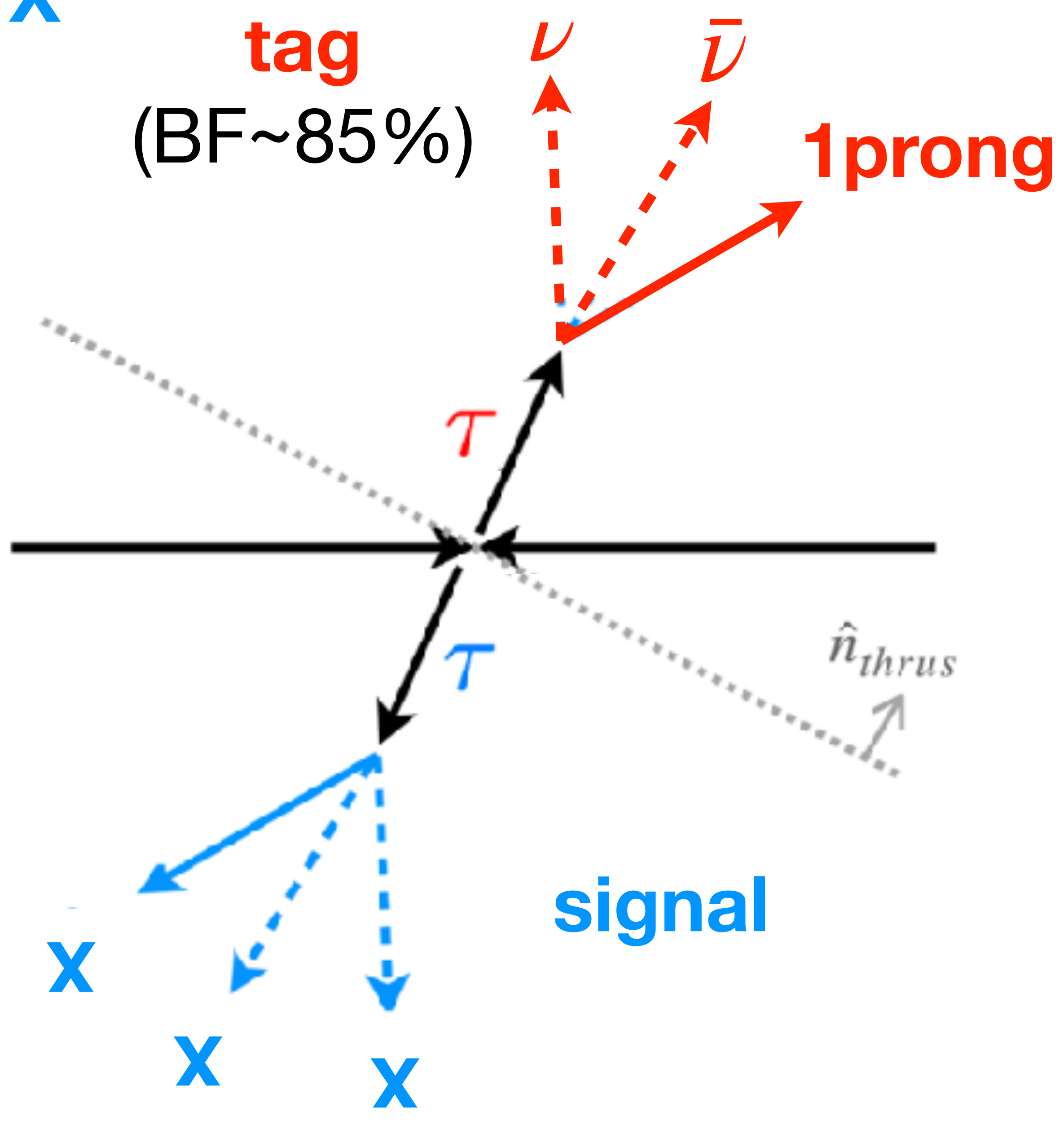
- $\tau \to l\, \alpha$ ★
- LFV channels ★
- LFUV channels ★
- Vus measurement
- EDM measurement
- CP channel: $\tau \to K_S \pi \nu$

} Direct New Physics (NP) searches

…

Main τ topologies @Belle II





BF of τ decays:

- 1-prong: 35.2% leptonic, 49.5% hadronic
- 3-prong: 15.2% hadronic

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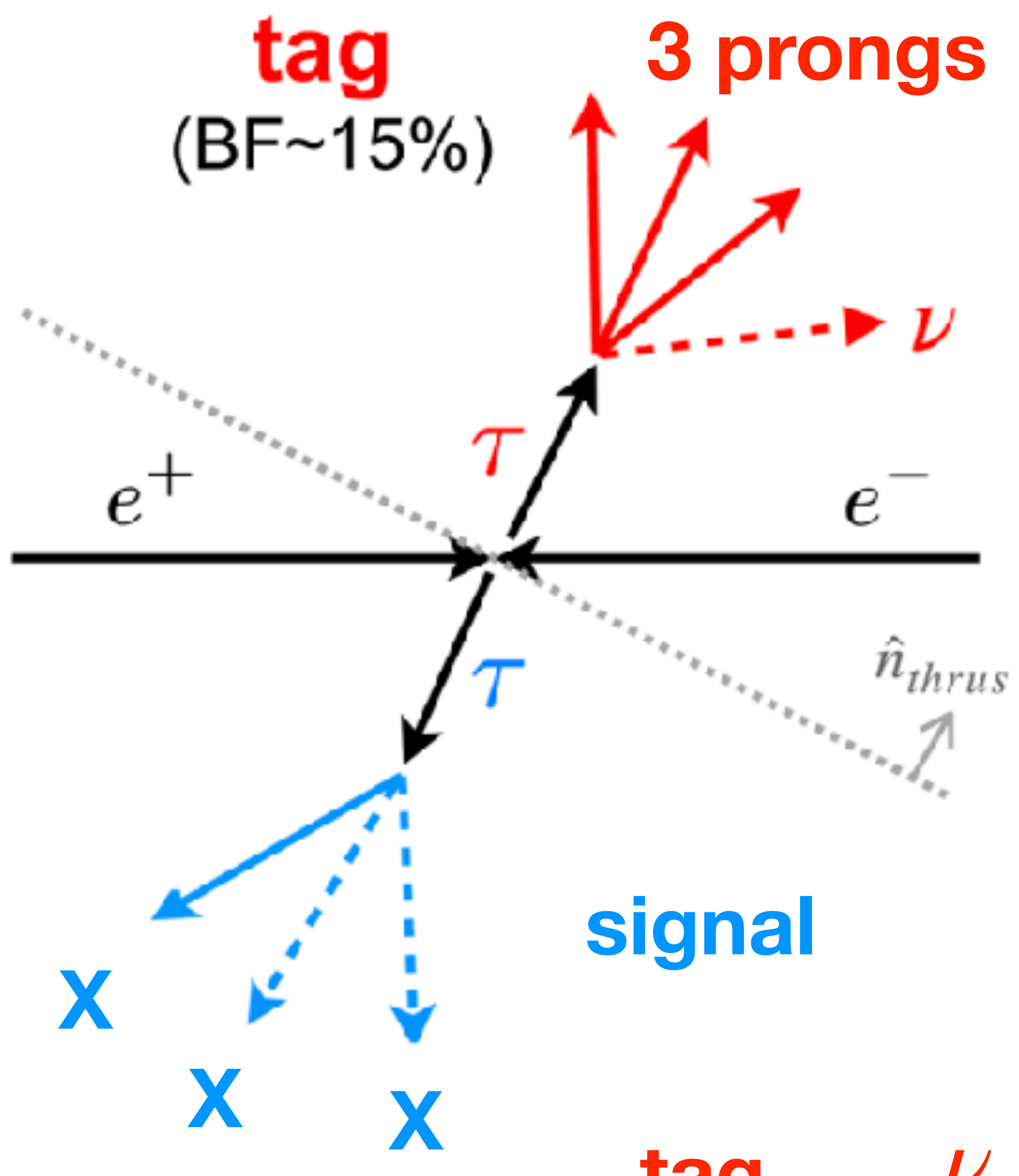

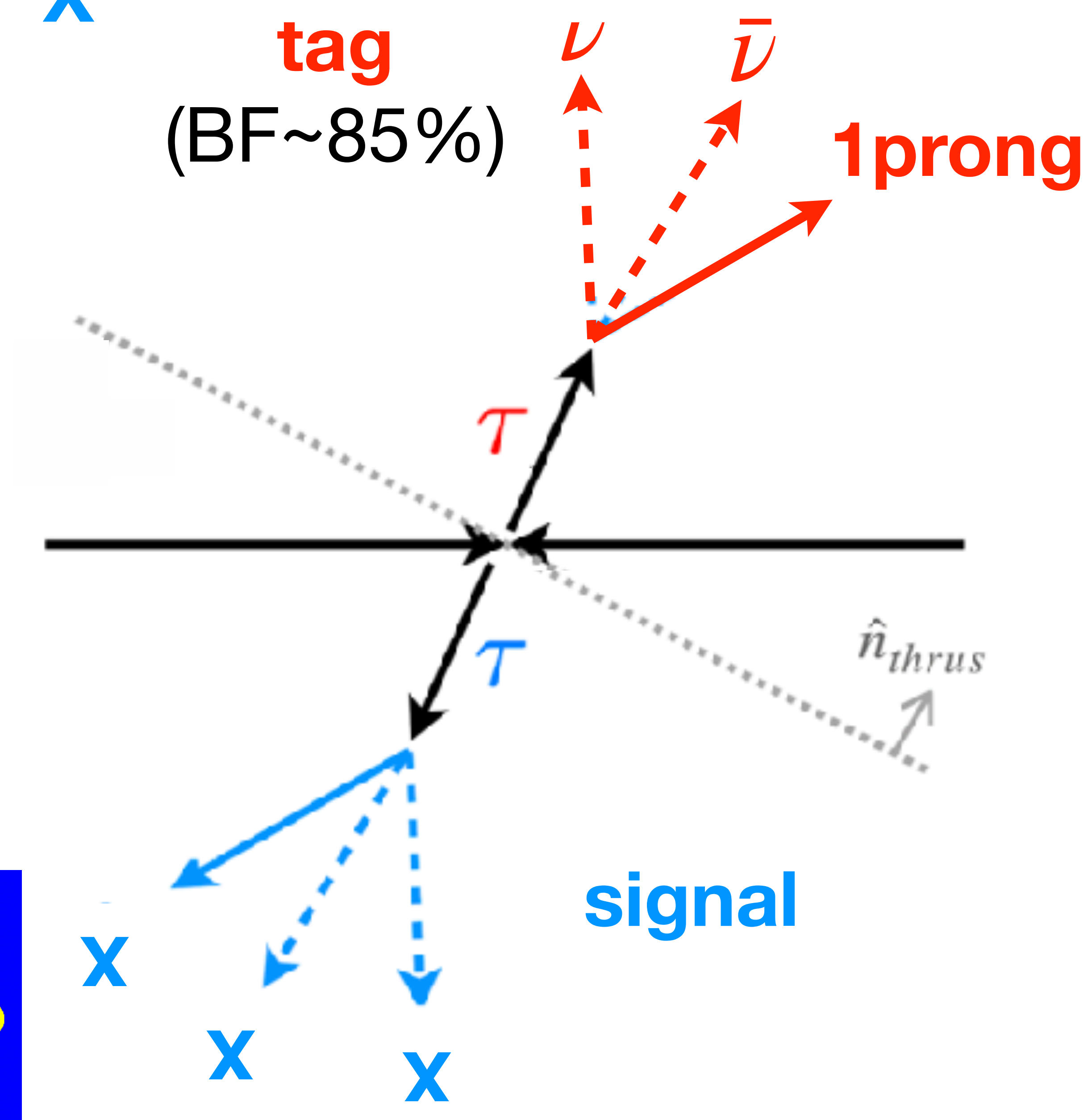

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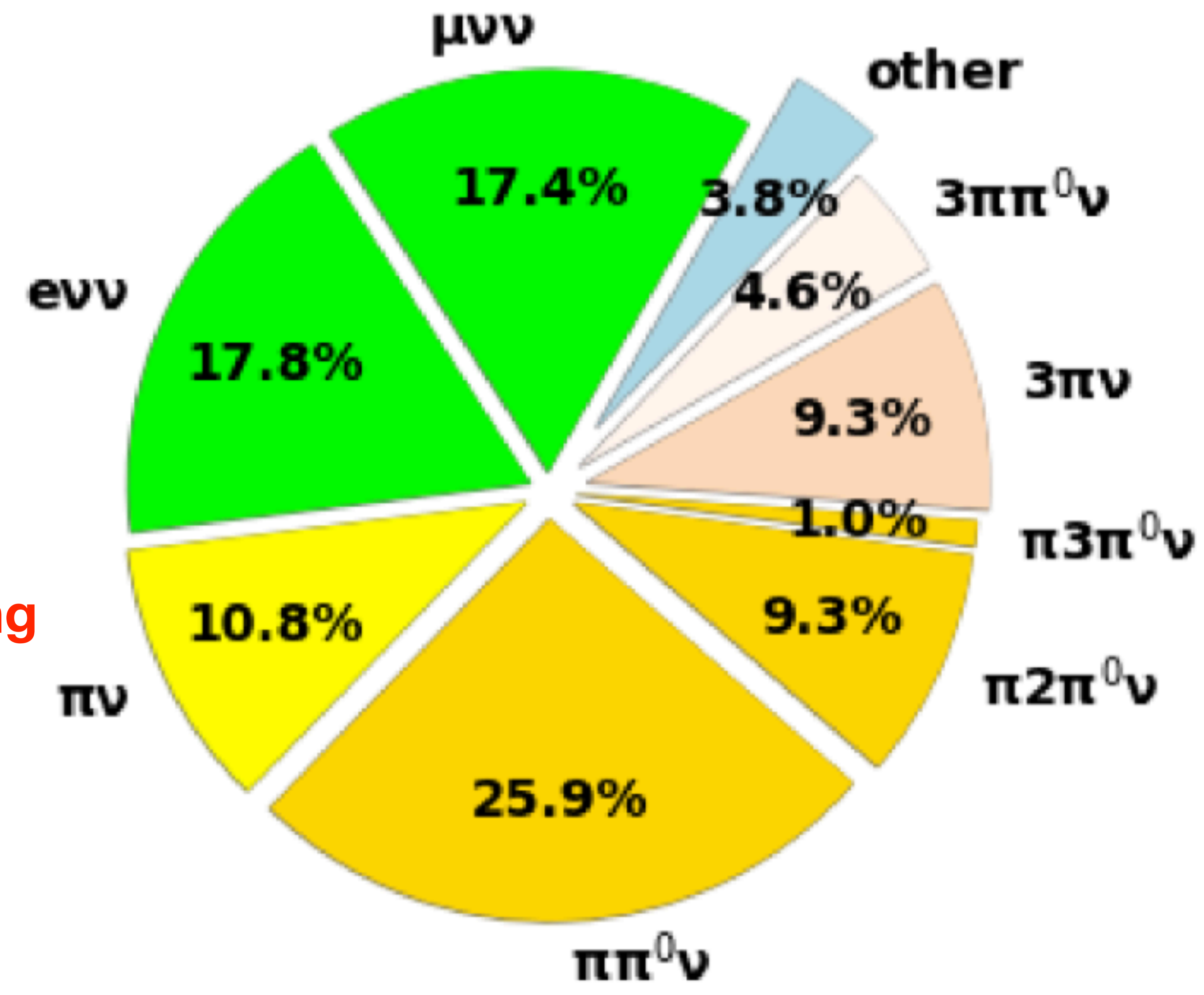

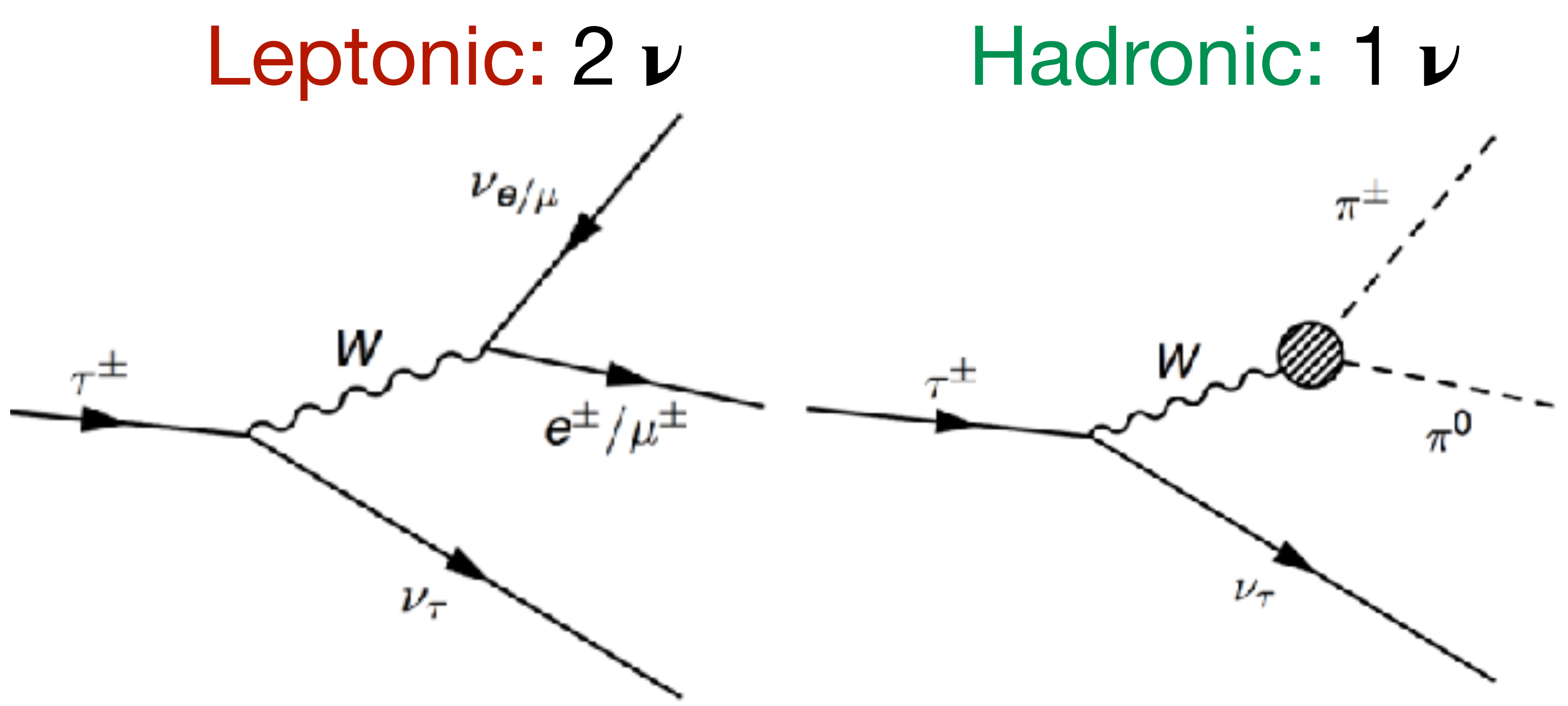

Each decay mode has its own experimental challenge:

- Large missing energy in leptonic modes
- Low multiplicity bkg for 1x1 topology
- π^0/γ in the final state → large $q\bar{q}$ bkg
- Highly efficient trigger system against low multiplicity channels (for example ee → ee, $\gamma\gamma$, eell)

Triggers for τ @Belle II

2 trigger categories:
EM calorimeter (ECL) and drift chamber triggers

→ **Belle II advantages wrt Belle and BaBar:** *several low multiplicity triggers* based on number of calorimetric clusters

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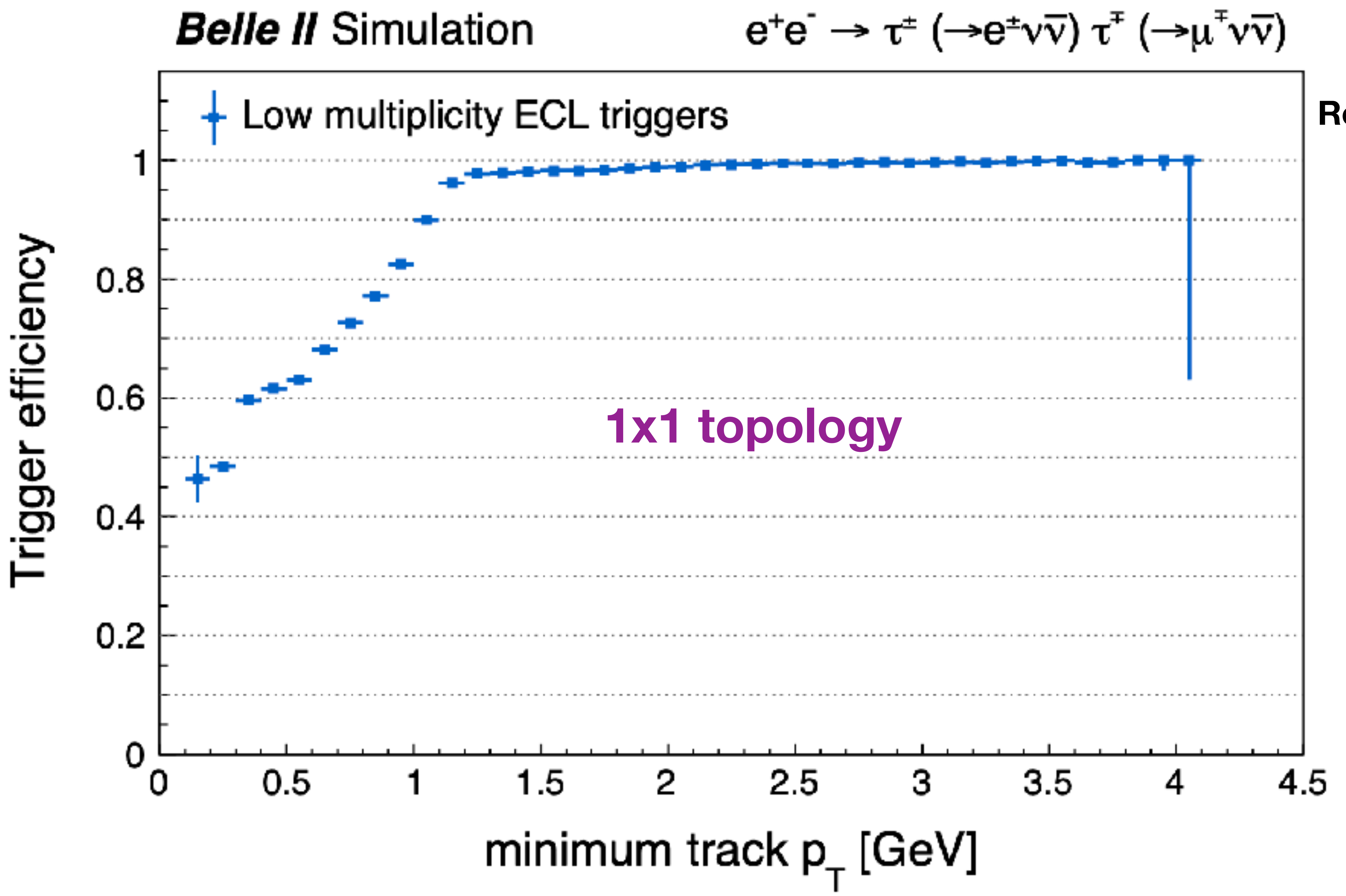
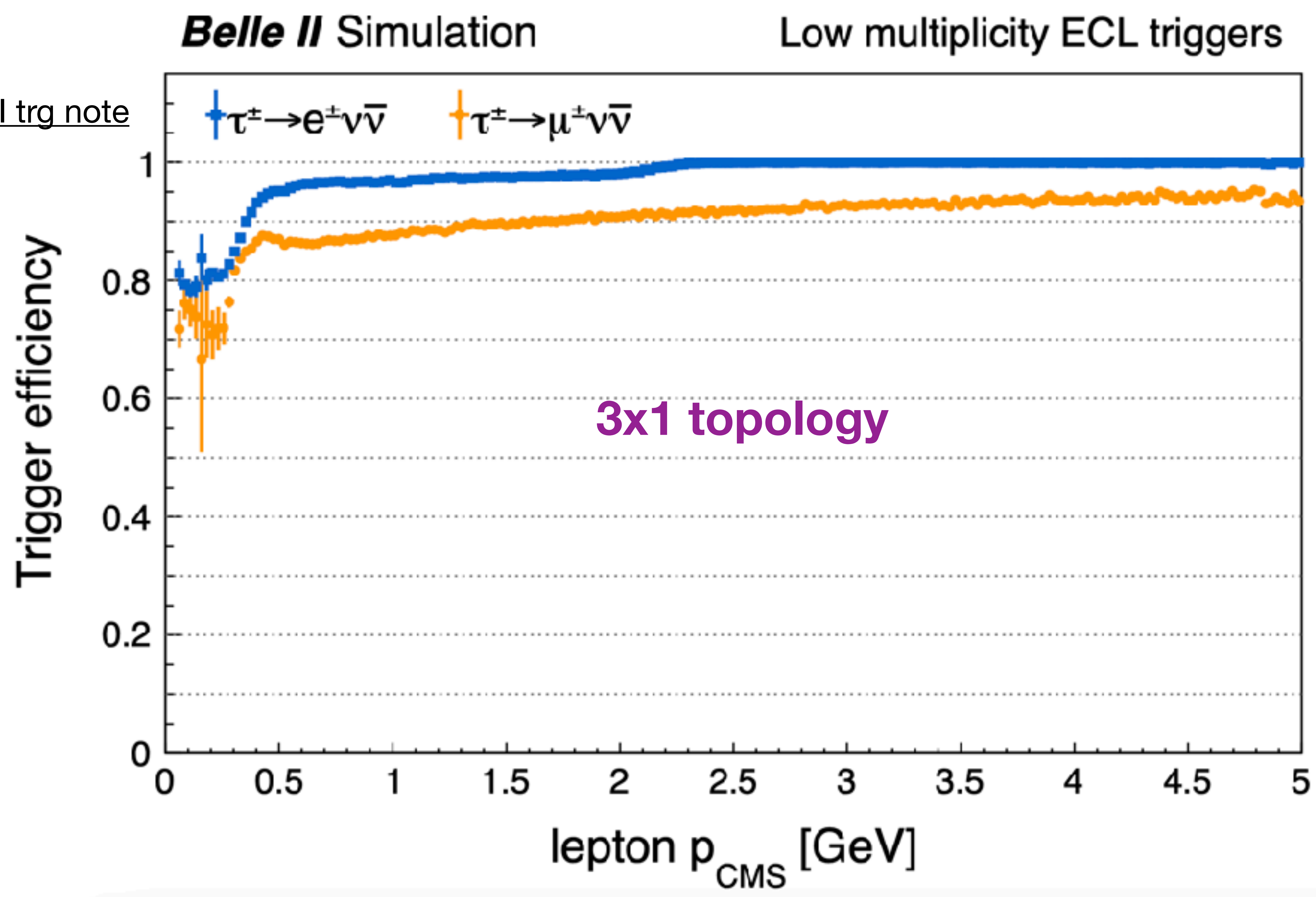


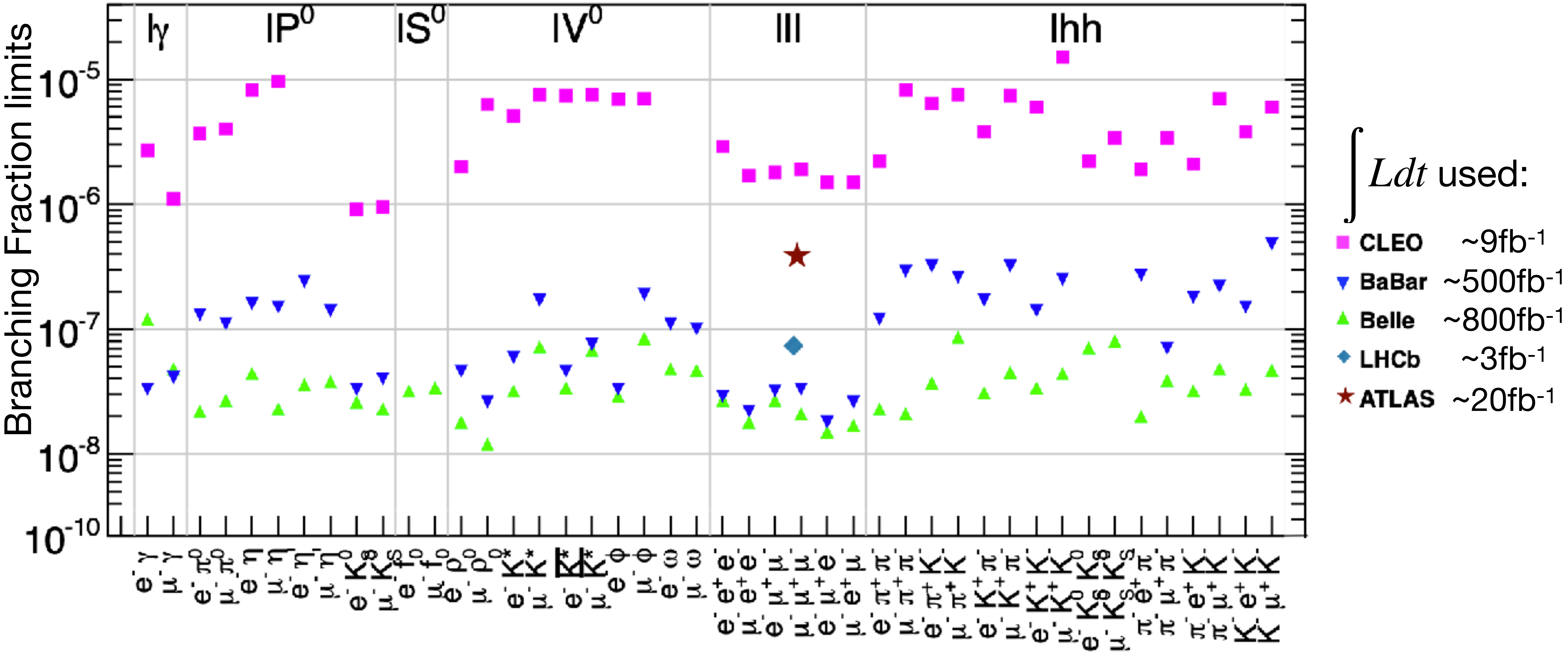
Ref: BelleII trg note



Logical OR of all available lml triggers → **High efficiency also for the 1x1 topology!**

Lepton Flavour Violation program

Lepton Flavor Violation (LFV) is allowed in various extensions of the SM but it has never been observed



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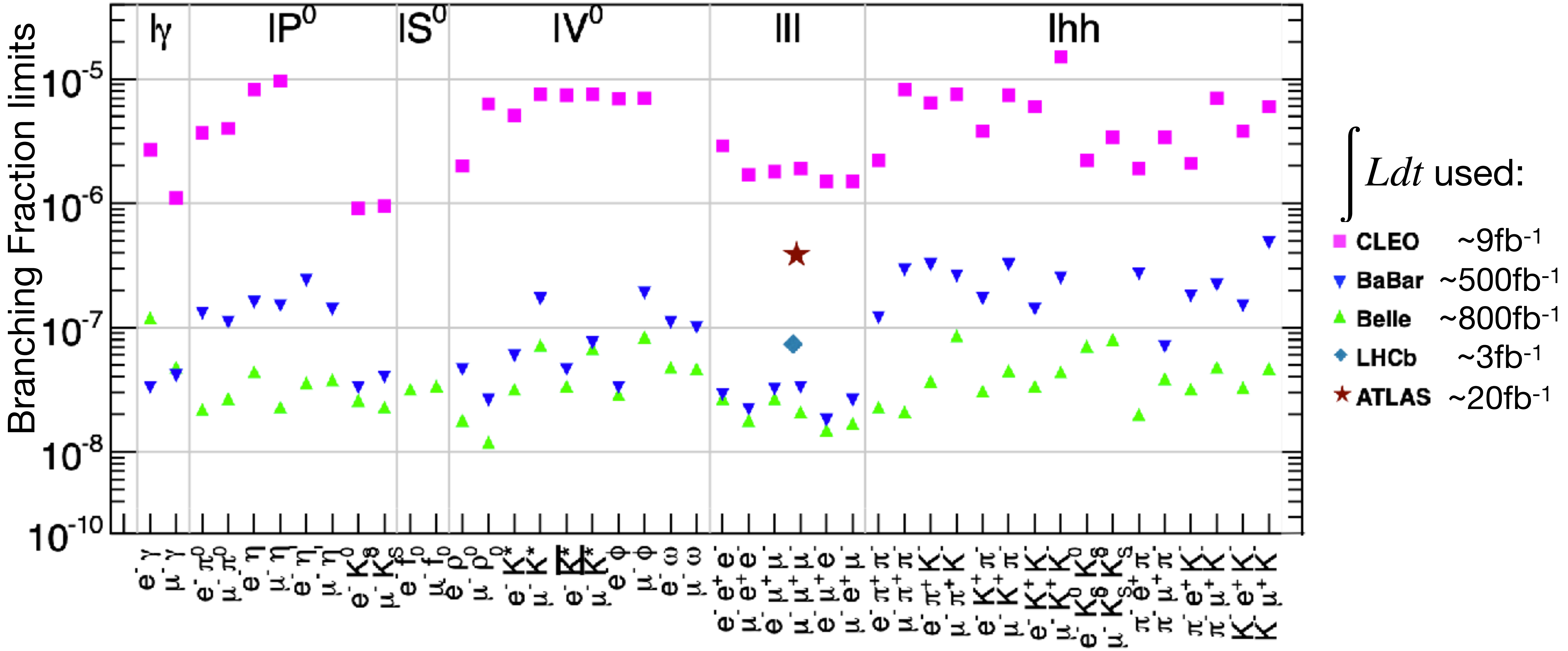
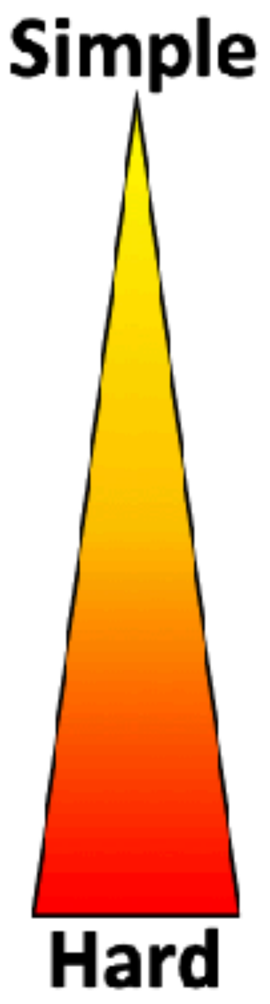


Analysis in terms of background reduction

- $\tau \to \ell\ell\ell$
- $\tau \to \ell K_S, \Lambda h$
- $\tau \to \ell V_0(\to hh')$
- $\tau \to \ell P^0\ (\to \gamma\gamma)$
- $\tau \to \ell hh'$
- $\tau \to \ell\gamma$
- ...



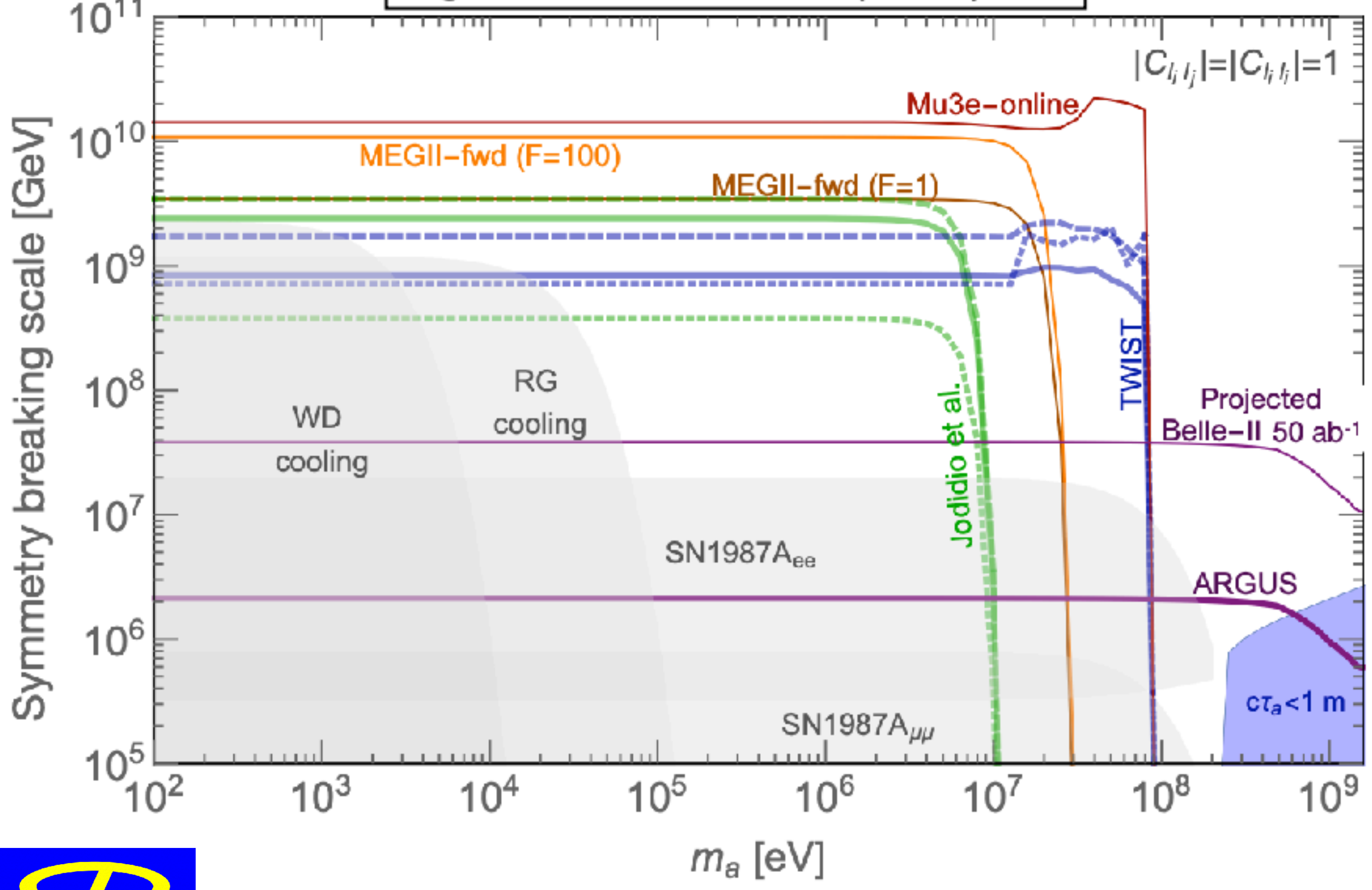
- $\tau \to l + \text{invisible}$

Large irreducible bkgs → next slides

$\tau \to l\alpha$ motivation

Search for LFV two-body decay $\tau \to l + \alpha$ (l = e, μ)
α is an invisible gauge boson that can be predicted by several NP models → LFV Z', **light ALP candidate**, more..

Light ALP: JHEP 09 (2021) 173



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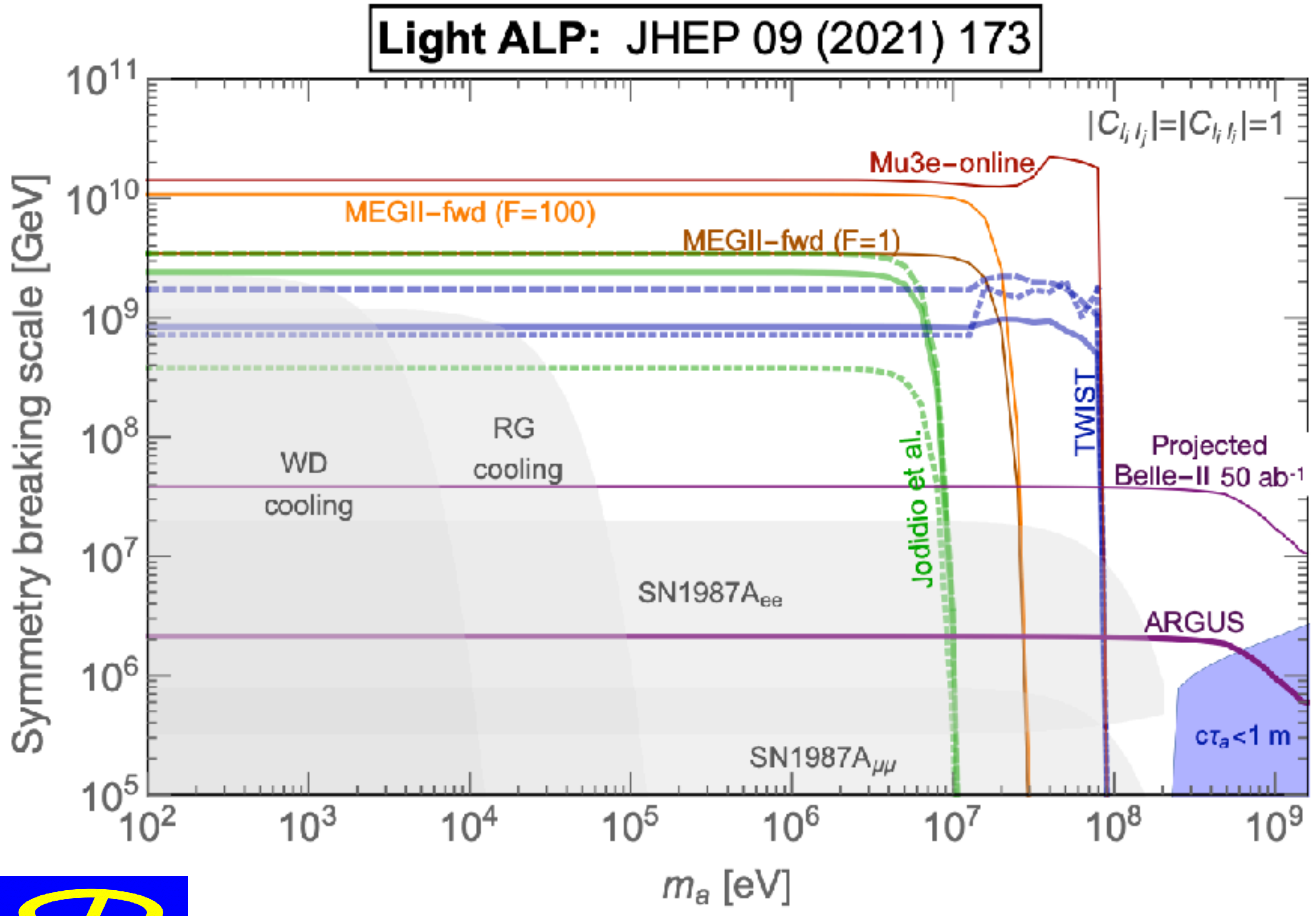
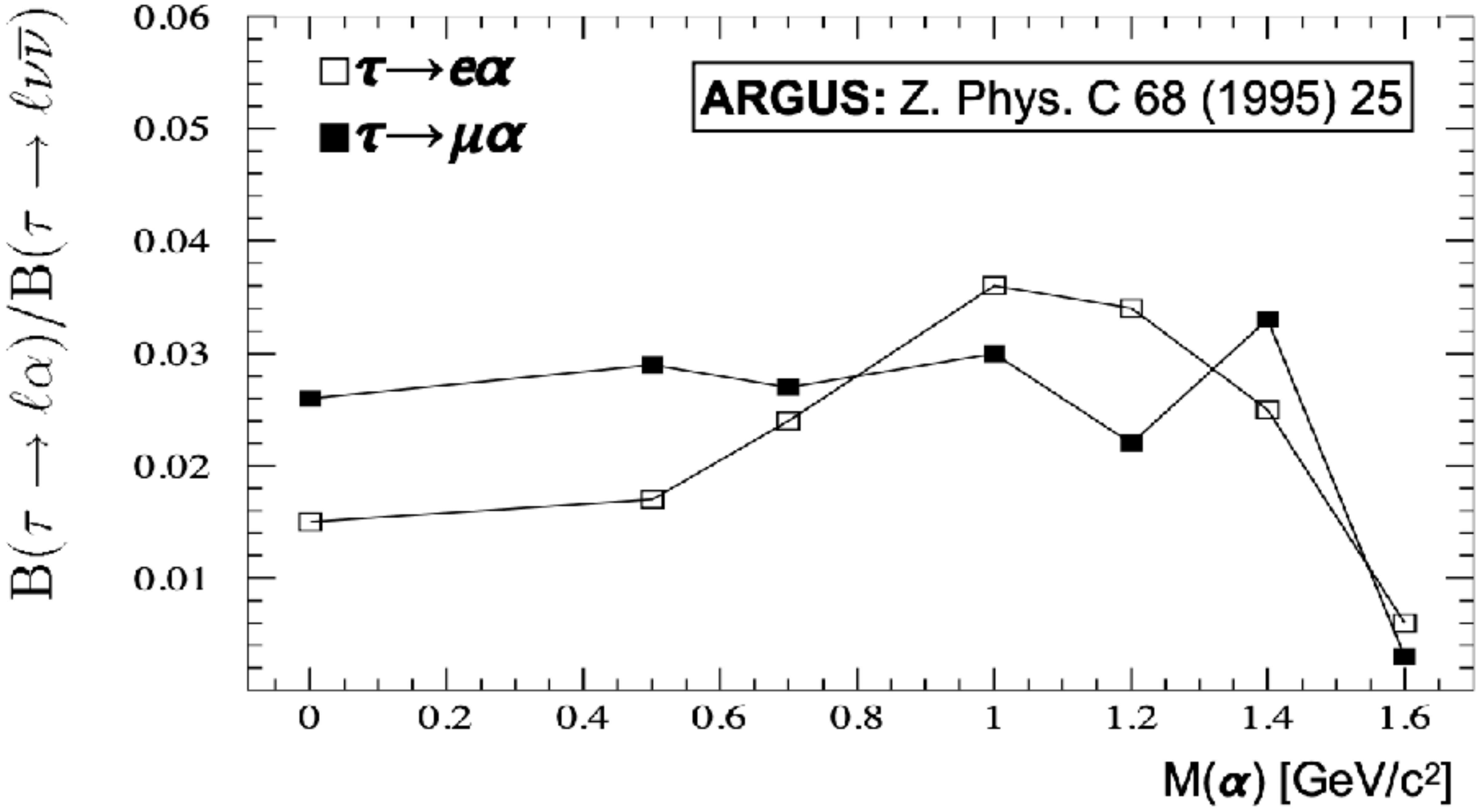


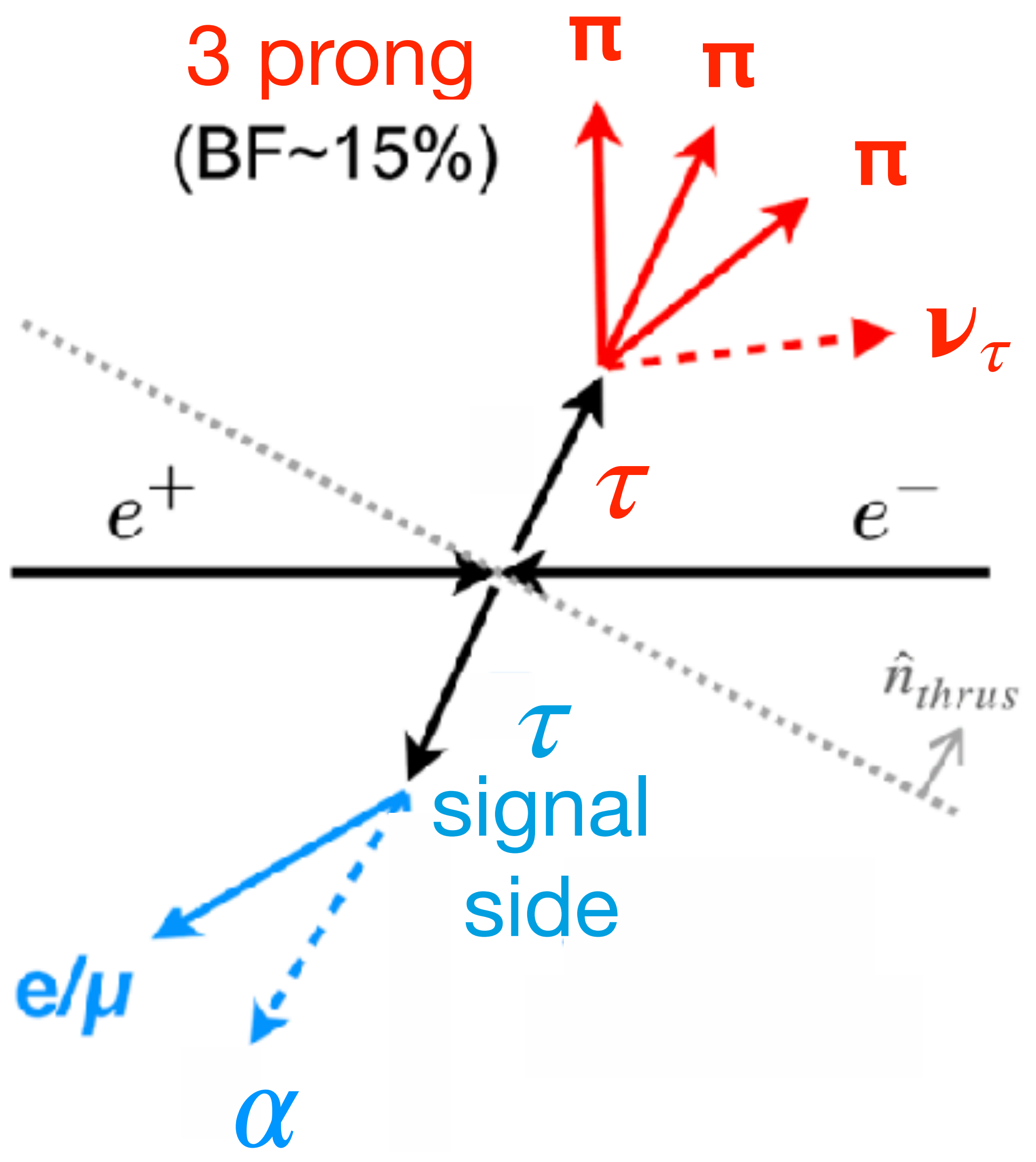
Best upper limits on $B(\tau \to l\alpha)/B(\tau \to l\nu\bar{\nu})$ from ARGUS (1995, 476 pb^{-1})



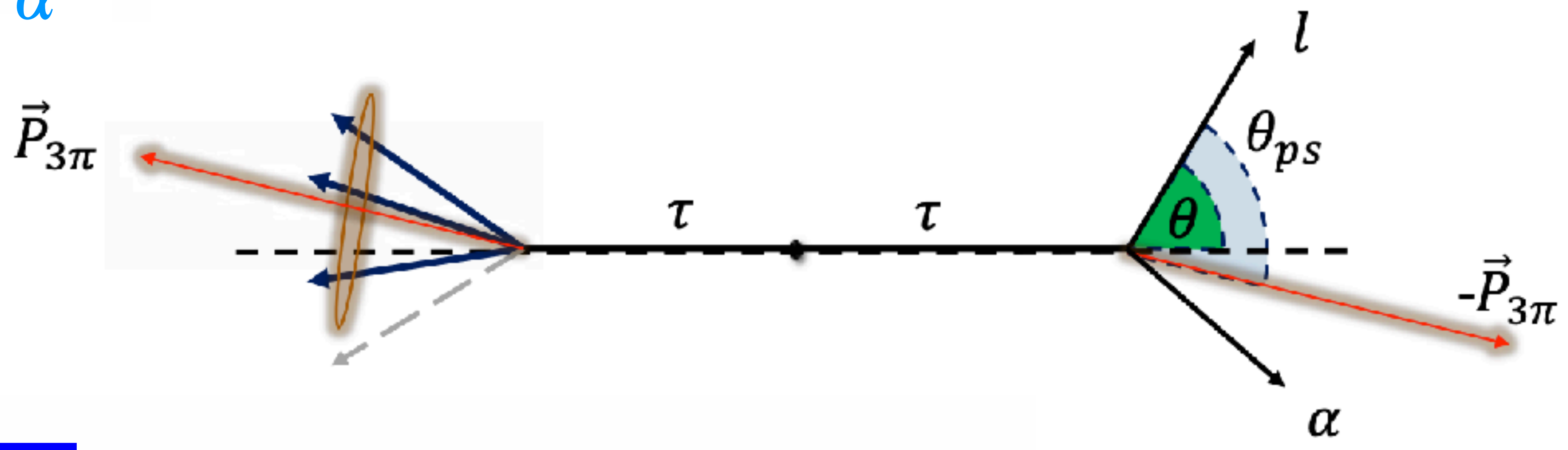
Can Belle II do better?

$\tau \to l\alpha$ analysis status

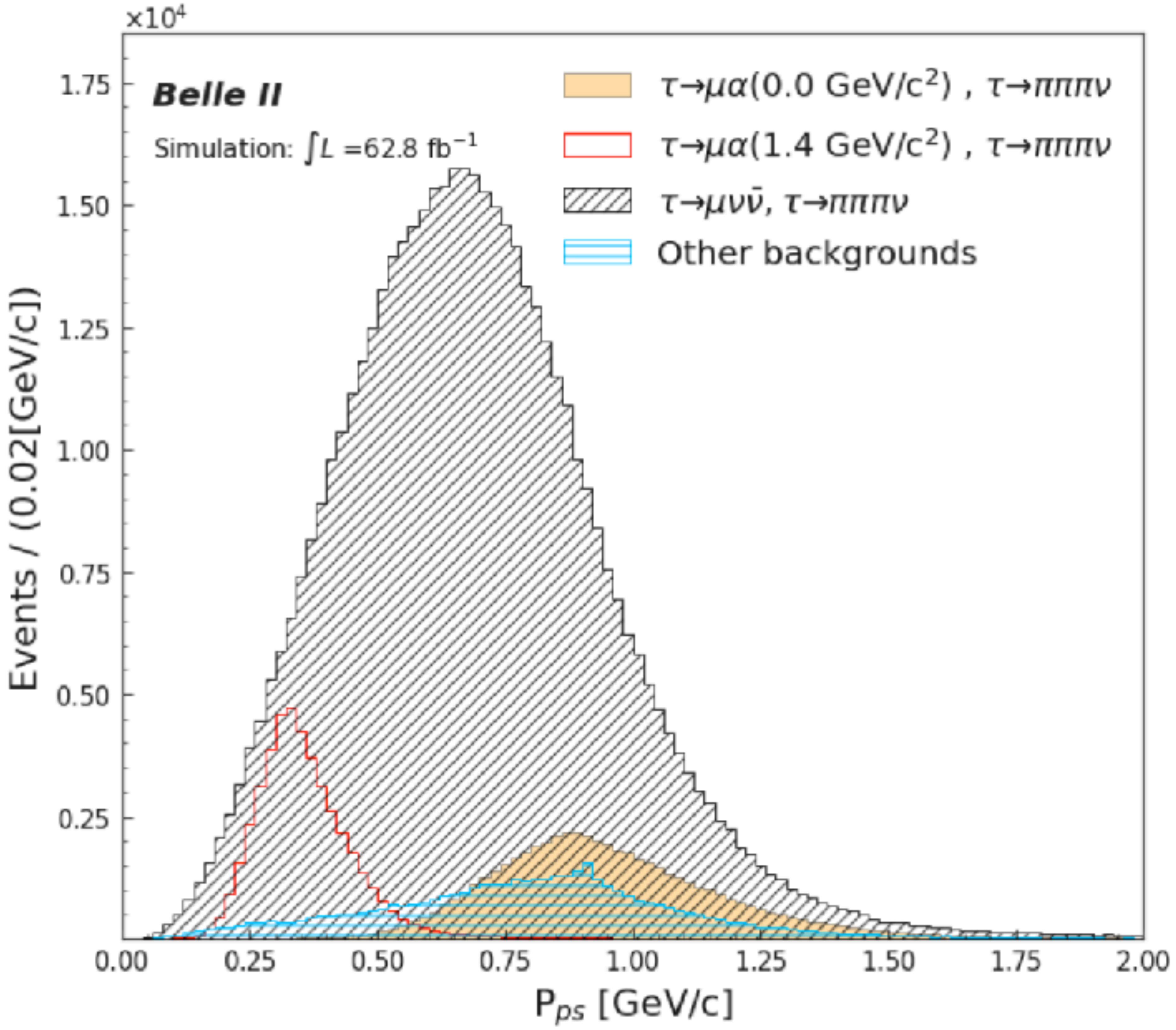
ARGUS analysis approach is adopted → definition of pseudo-rest (ps) frame



- Tag side: $\tau \to 3\pi\nu_\tau$
- Pseudo-rest frame implies:
  - $\overrightarrow{p_\tau} \sim -\overrightarrow{p}_{3\pi}$
  - $E_\tau \sim \sqrt{s}/2$
- Veto neutrals: π^0, γ
- Selection optimised on $\tau \to l\nu\bar{\nu}_\tau$ as irreducible background



Signal signature:
bump in the lepton p_{ps} distribution



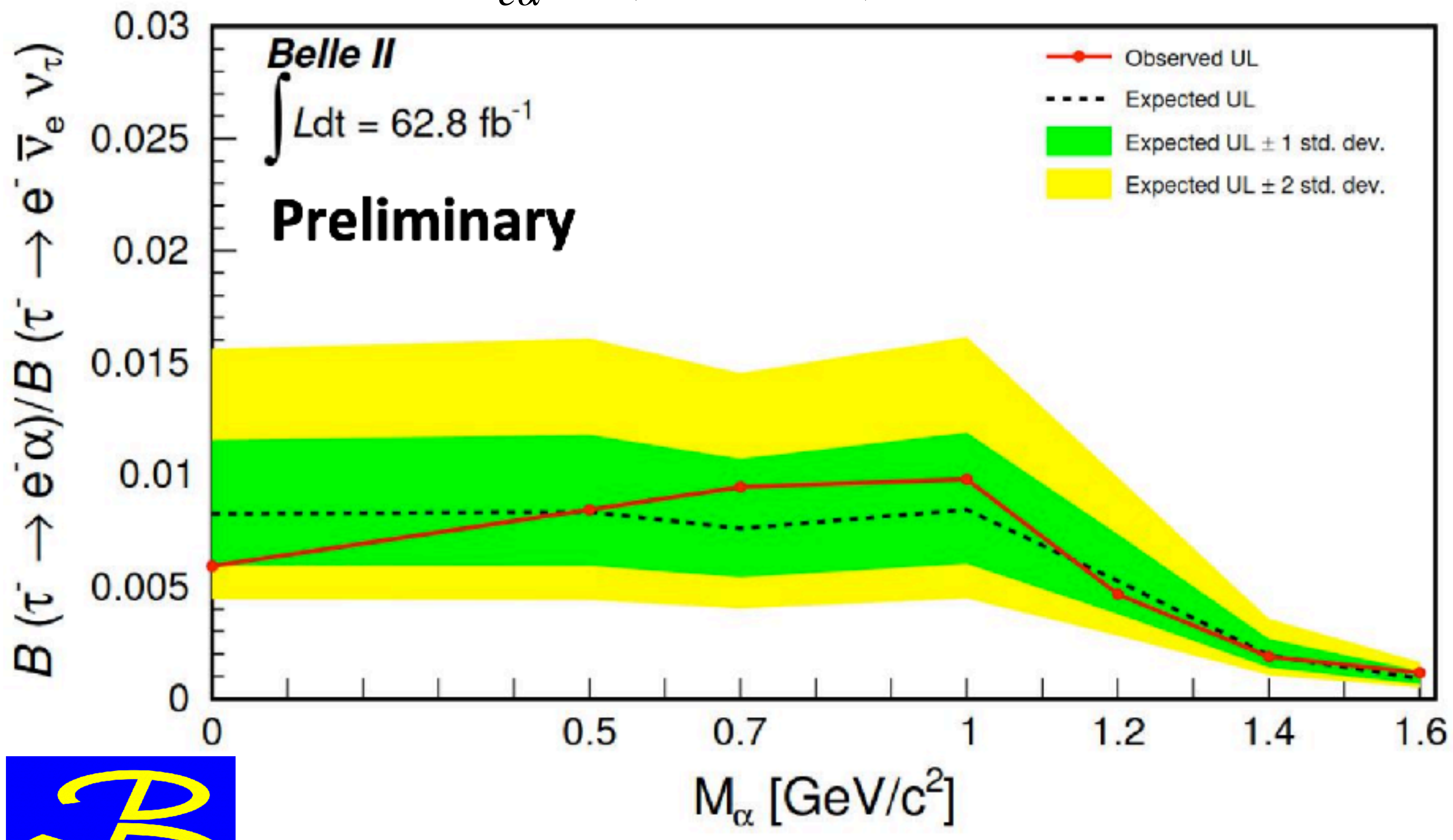
$\tau \to l\alpha$ results

95% C.L. upper limits using the CLs method → **no significant excess in 62.8 fb⁻¹ of data (2019-20)** **Ref:** ICHEP talk

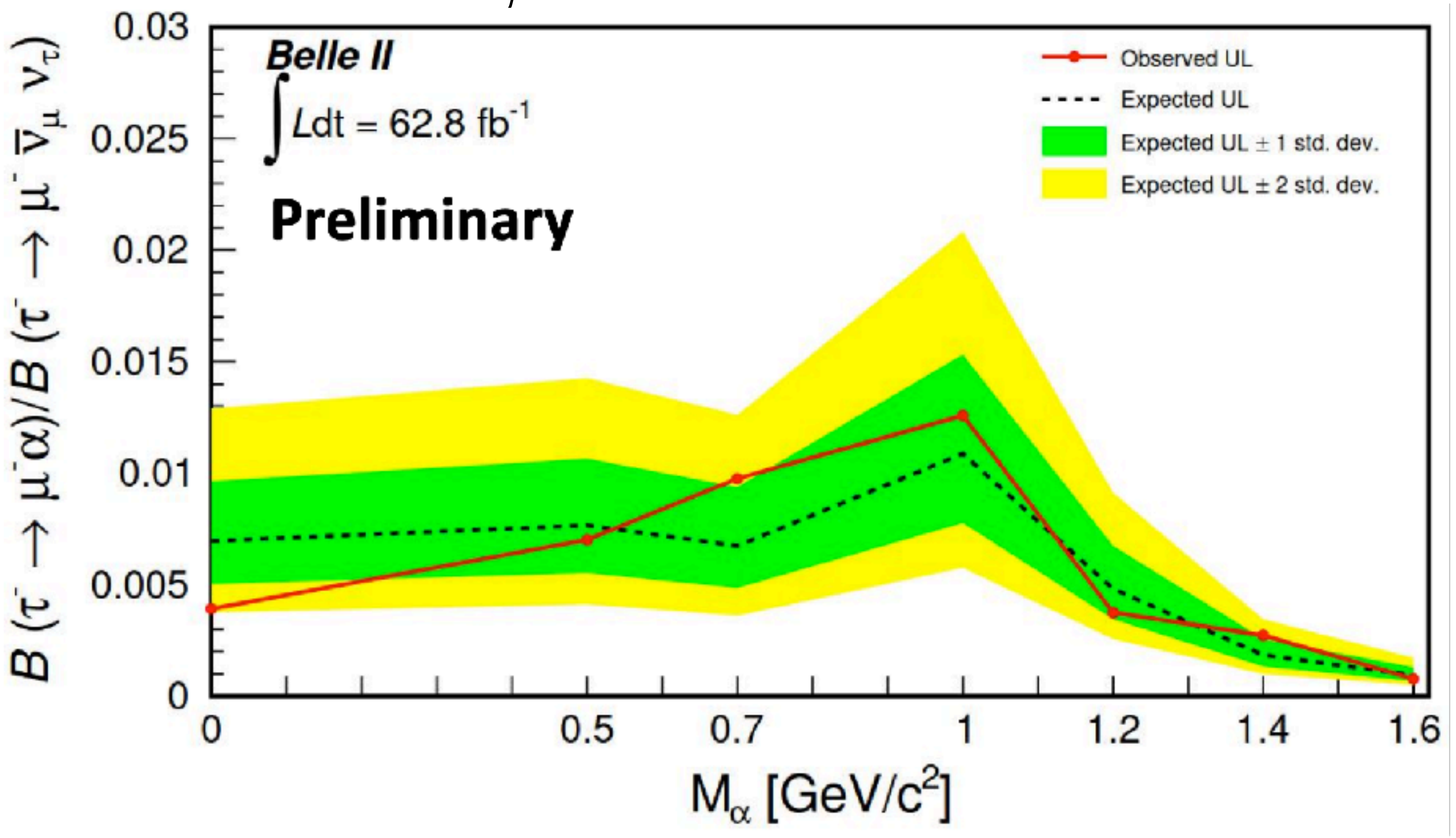
Publication?

Best measurement today

$R_{e\alpha} < (1.2 - 9.8) \times 10^{-3}$



$R_{\mu\alpha} < (0.8 - 12.6) \times 10^{-3}$

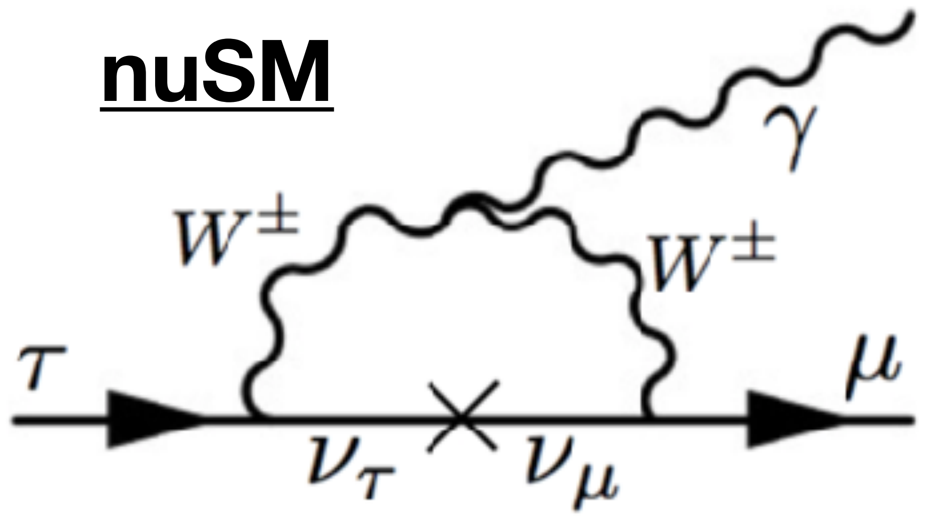


Belle II

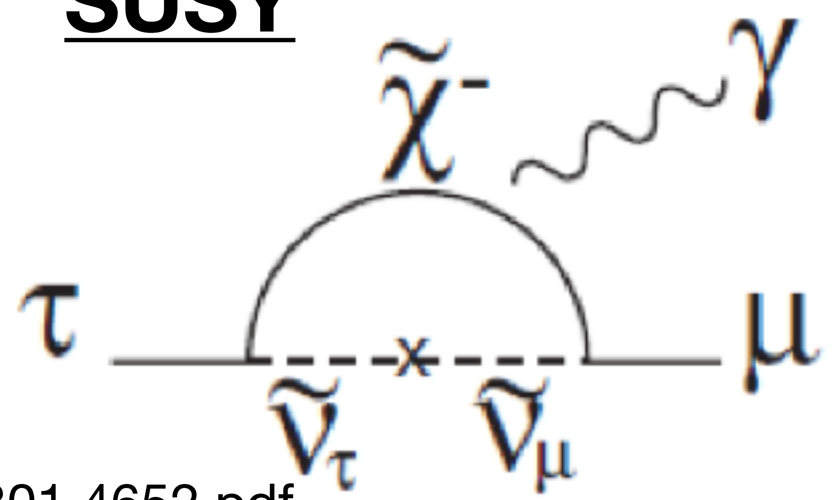
Lepton Flavour Violation: golden channels

First golden channel: $\tau \to \mu\gamma$
as the Highest non-SM BF contribution

nuSM

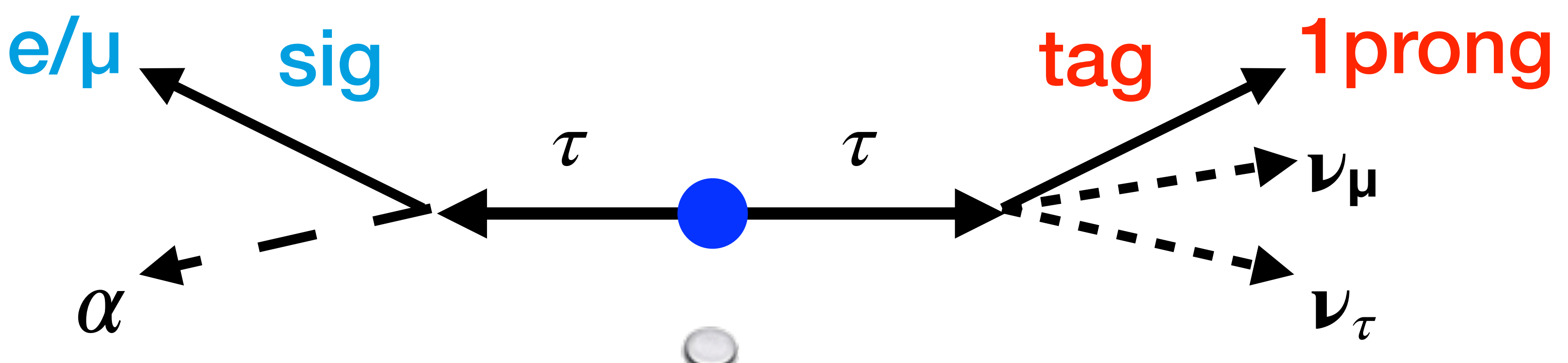


SUSY



Ref: https://arxiv.org/pdf/1301.4652.pdf

Decay scheme



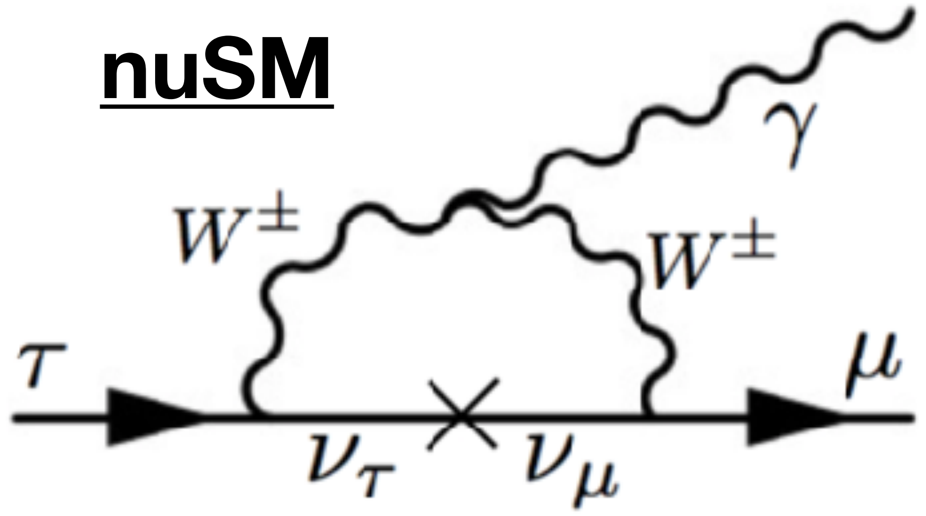
Experimentally tough: Irreducible physics backgrounds + large uncertainty in mass and energy determination

Lepton Flavour Violation: golden channels

First golden channel: $\tau \rightarrow \mu\gamma$
as the Highest non-SM BF contribution

Second golden channel: $\tau \rightarrow \mu\mu\mu$
experimentally the most accessible

nuSM



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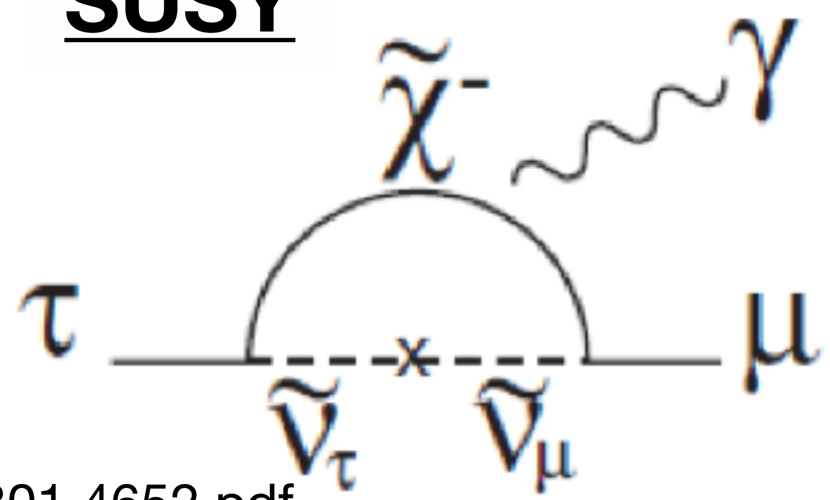

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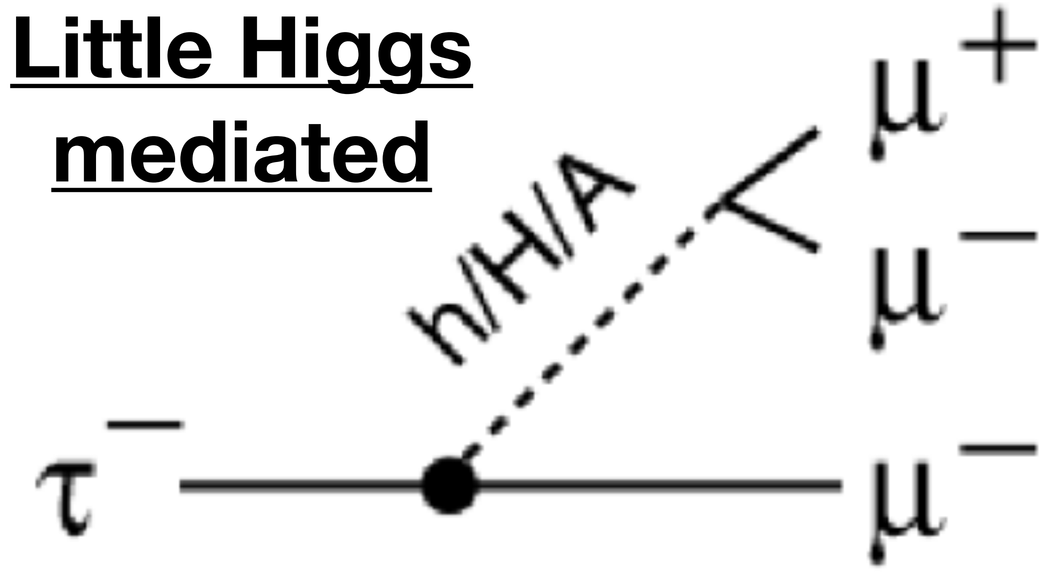
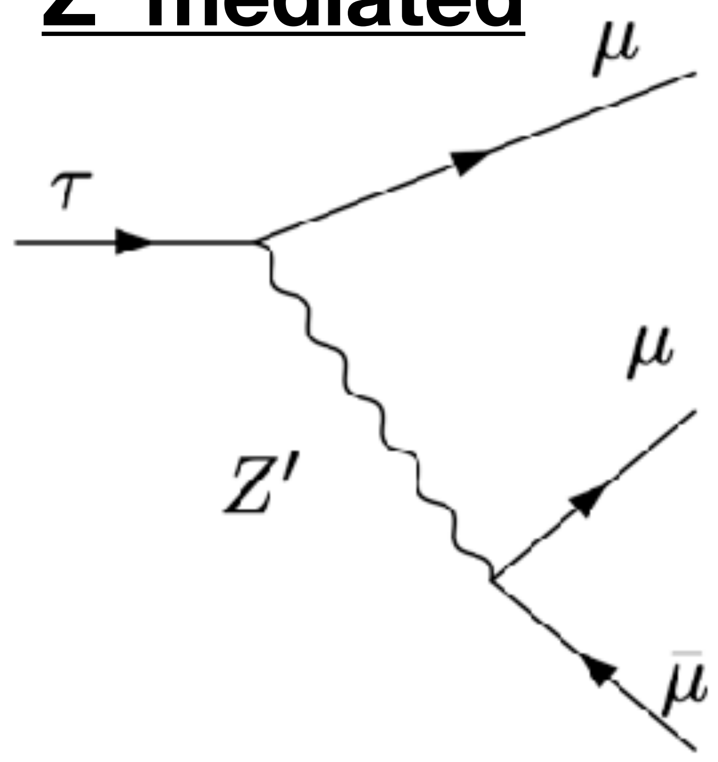
Little Higgs mediated



Z' mediated



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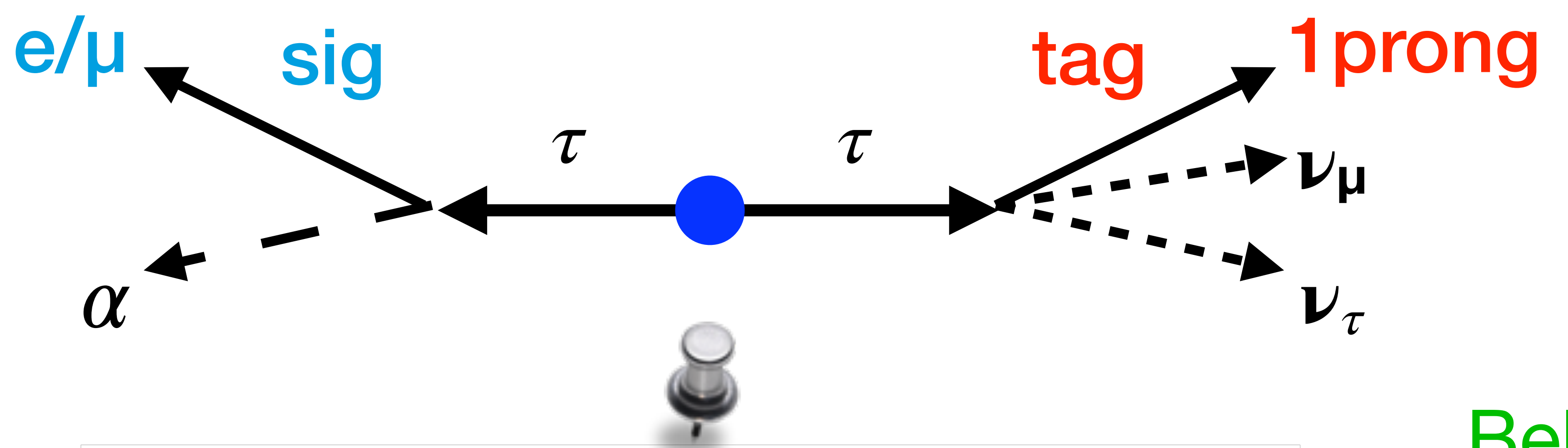


Experimentally tough: Irreducible physics backgrounds + large uncertainty in mass and energy determination

Belle II can probe these NP models using 50 ab^{-1}

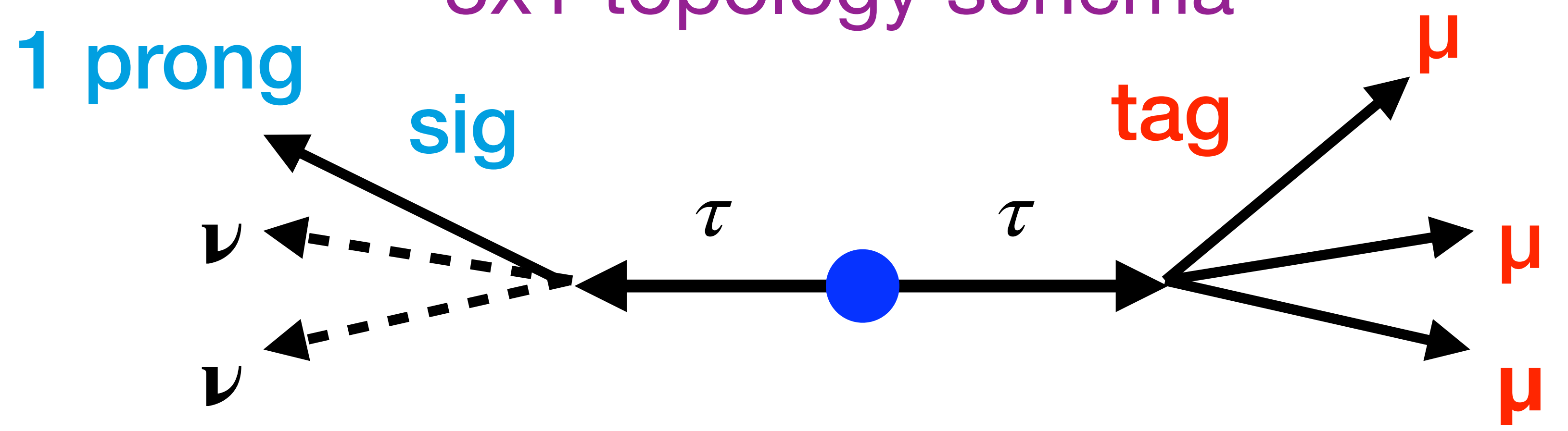
Physics models	$B(\tau \rightarrow \mu\gamma)$	$B(\tau \rightarrow \mu\mu\mu)$
SM + ν mixing	$10^{-49} \sim 10^{-52}$	$10^{-53} \sim 10^{-56}$ [1]
SM+heavy Majorana ν_R	10^{-9}	10^{-10}
Non-universal Z'	10^{-9}	10^{-8}
SUSY SO(10)	10^{-8}	10^{-10}
mSUGRA + seesaw	10^{-7}	10^{-9}
SUSY Higgs	10^{-10}	10^{-7}

Ref: M. Blanke, et al., Charged Lepton Flavour Violation and (g – 2)μ in the Littlest Higgs Model with T-Parity: a clear Distinction from Supersymmetry, JHEP 0705, 013 (2007).

Belle II

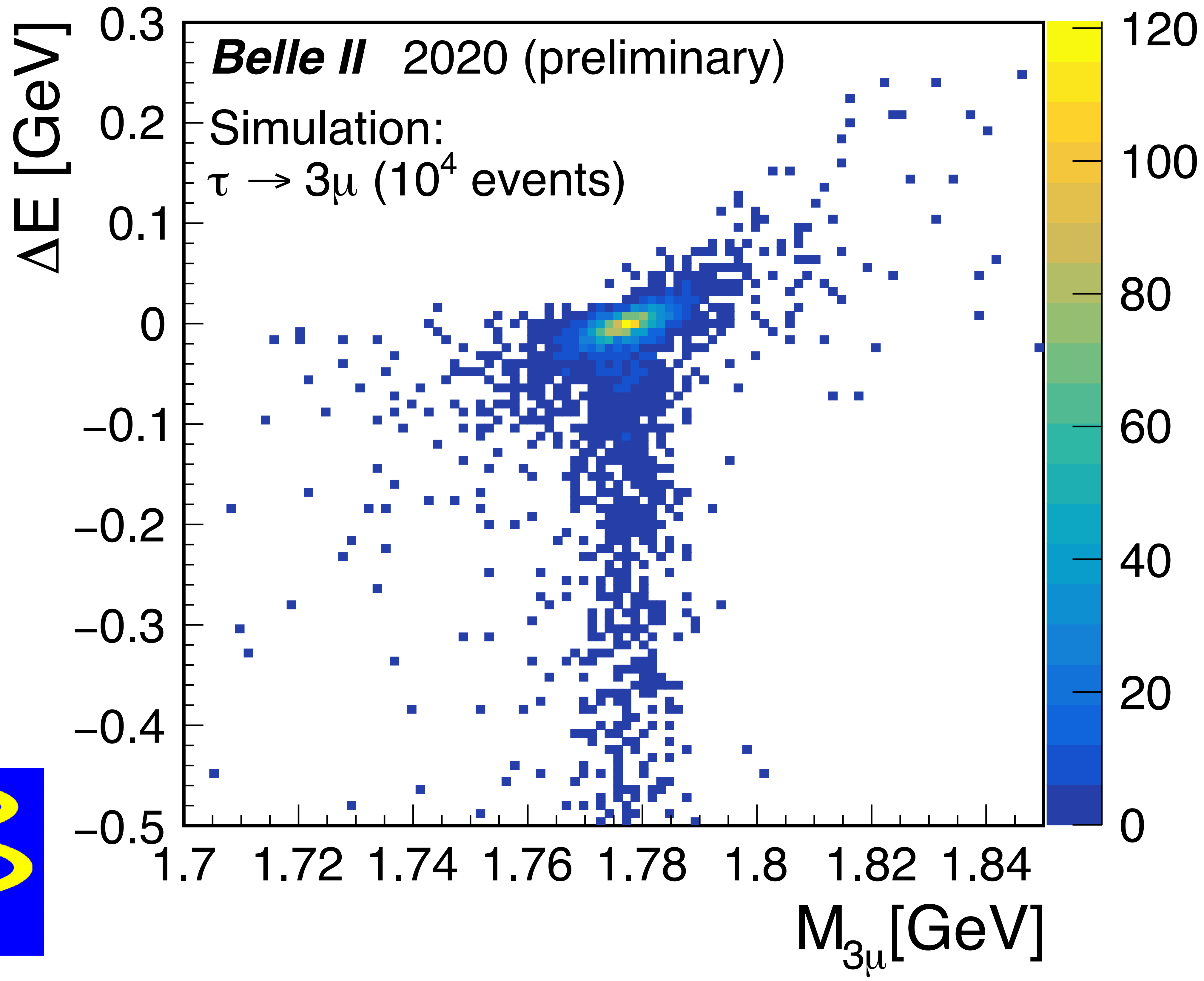
$\tau\to 3\mu$ Lepton Flavour Violation

Best upper limits on $\tau\to 3\mu$ from Belle: **2.1 x 10^{-8}** @90% CL: $\int L dt = 782 fb^{-1}$



Closed signal side kinematics

- No physical backgrounds
- Tight signal region → large background reduction using $\mathbf{\Delta E_{3\mu} \equiv E_{\tau sig} - E_{beam}}$ and $\tau_{3\mu}$ mass



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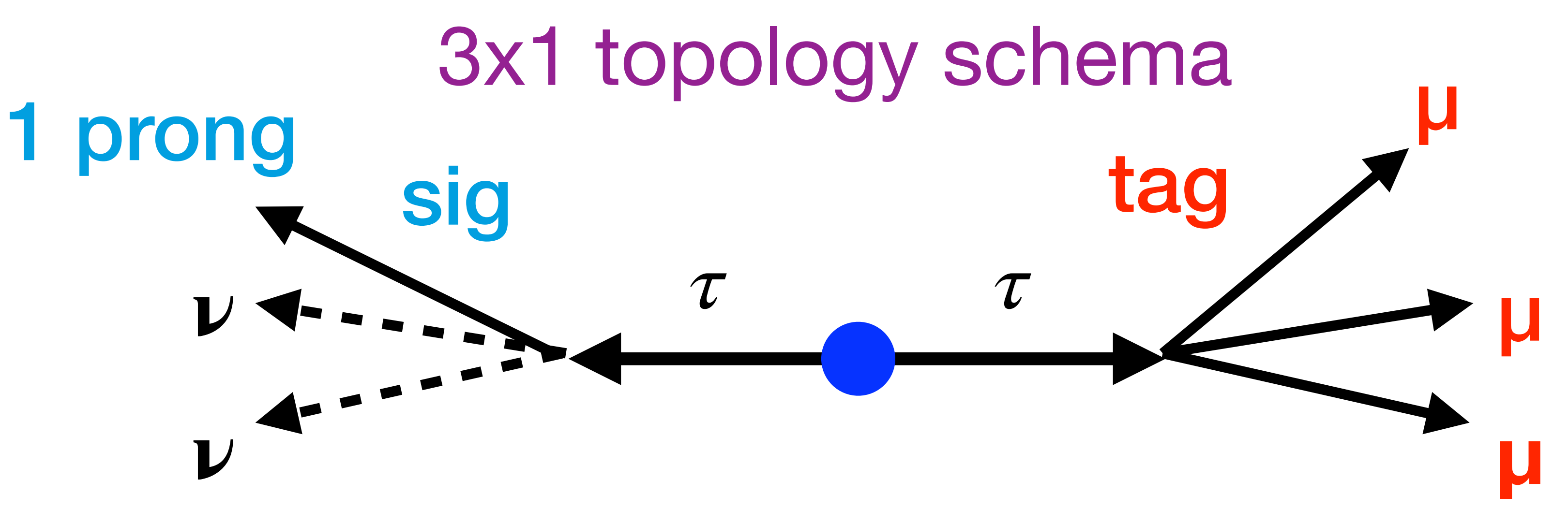

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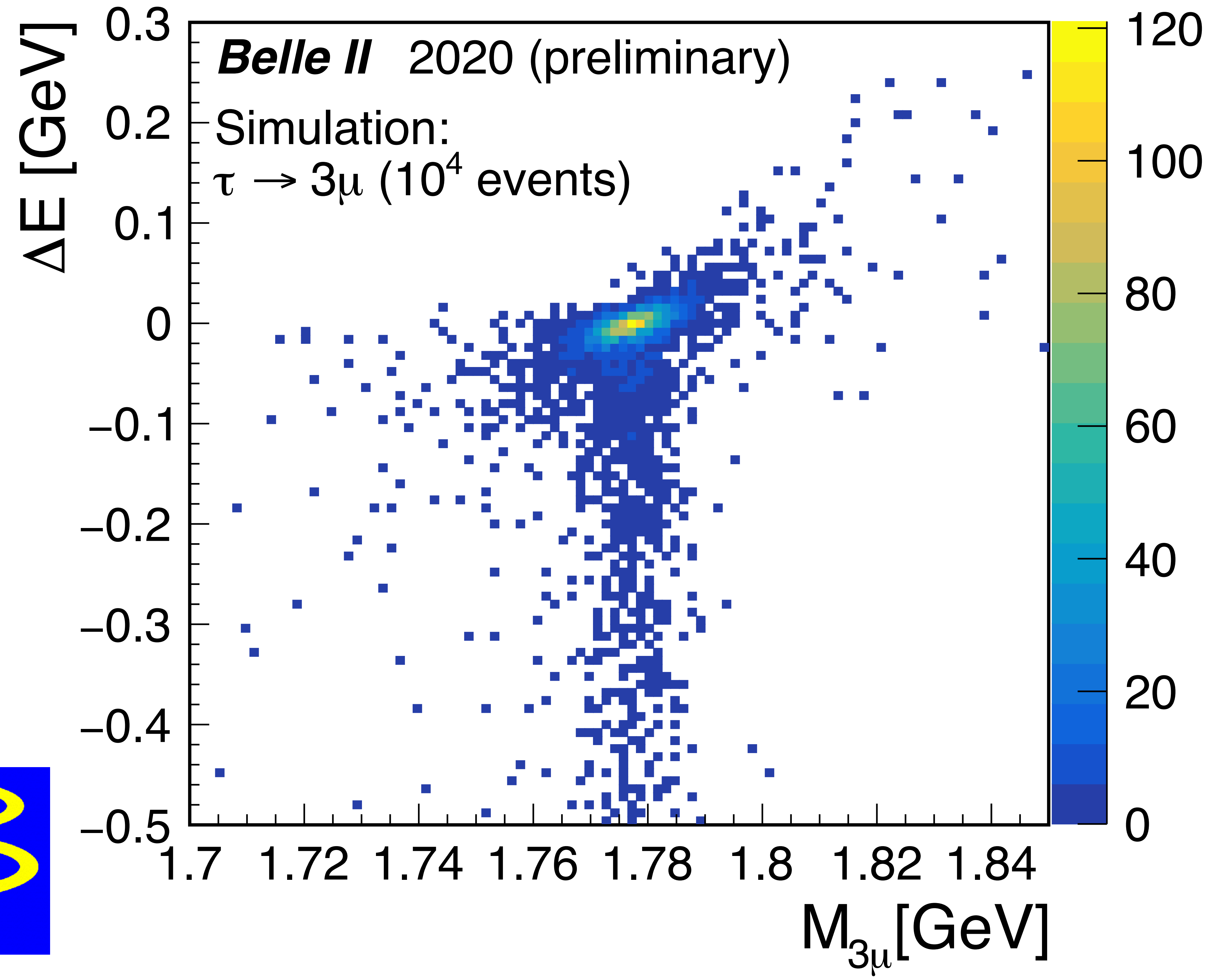


Proposed analysis improvement:

3 muons in the event → muon identification (muonID) optimised as a function of the track momentum

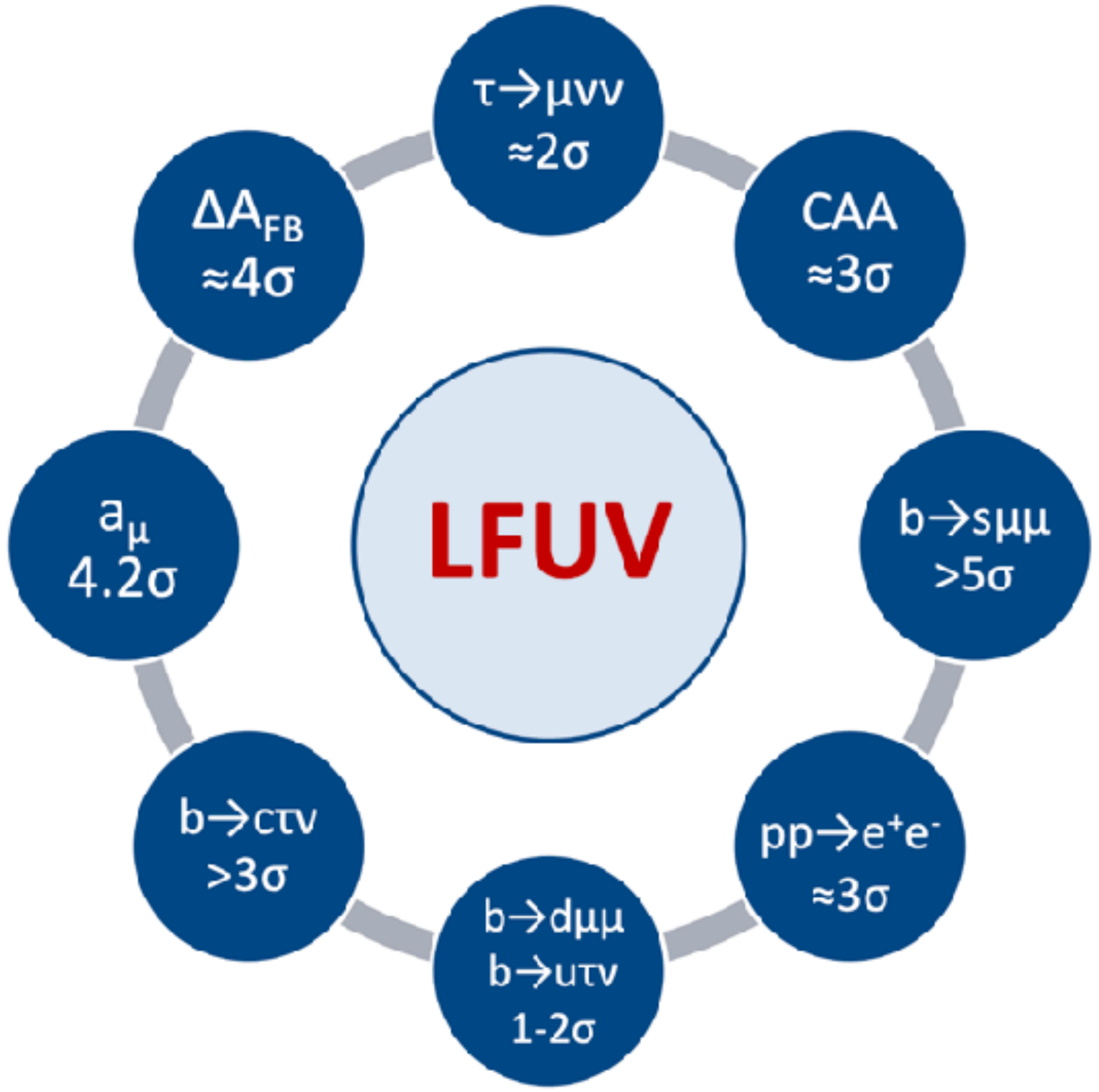
Analysis first hints **(based on MC only)**:

- 0 events surviving the selection
- x2 efficiency gain wrt Babar

The Belle II experiment will be already competitive with the current dataset of ~ 400 fb^{-1} → analysis is ongoing!

Lepton Flavour Universality violation

Lepton Flavour Universality (LFU) requires that the coupling between the three charged leptons and W boson is the same



ref: https://indico.belle2.org/event/4615/contributions/22866/attachments/12010/18311/Mini-Workshop.pdf

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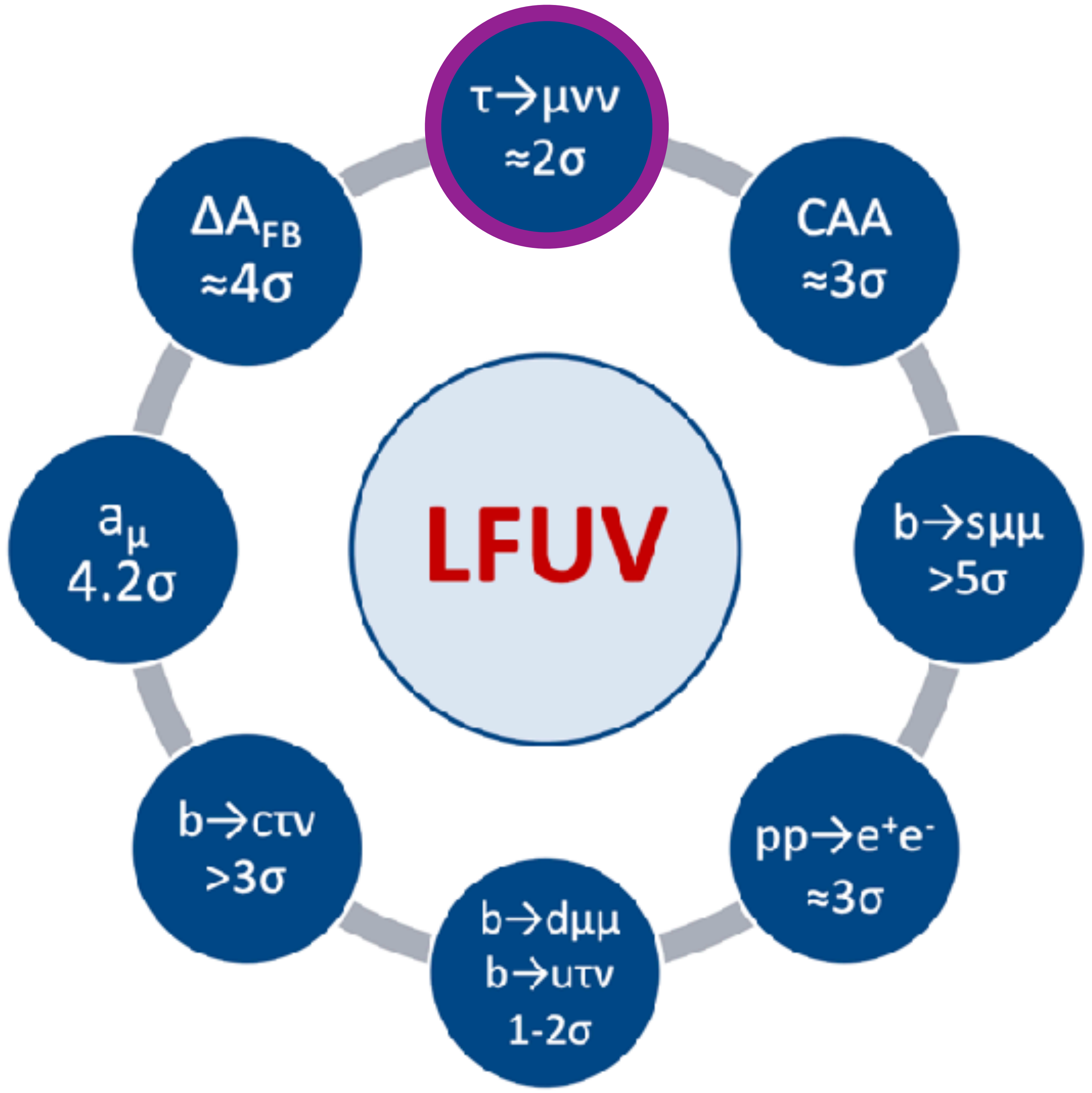

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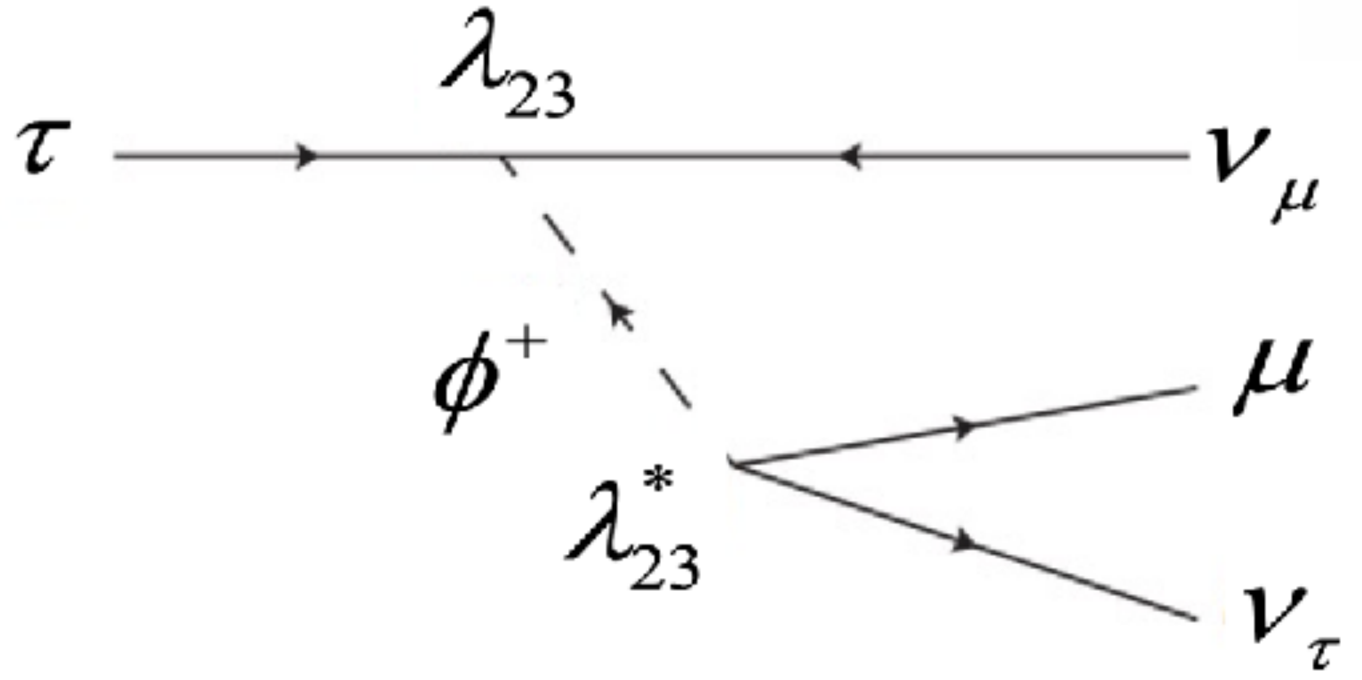
Several NP models can explain the anomaly:
W', Modified *Wlν* couplings
Z', **Singly-Charged Scalar** …

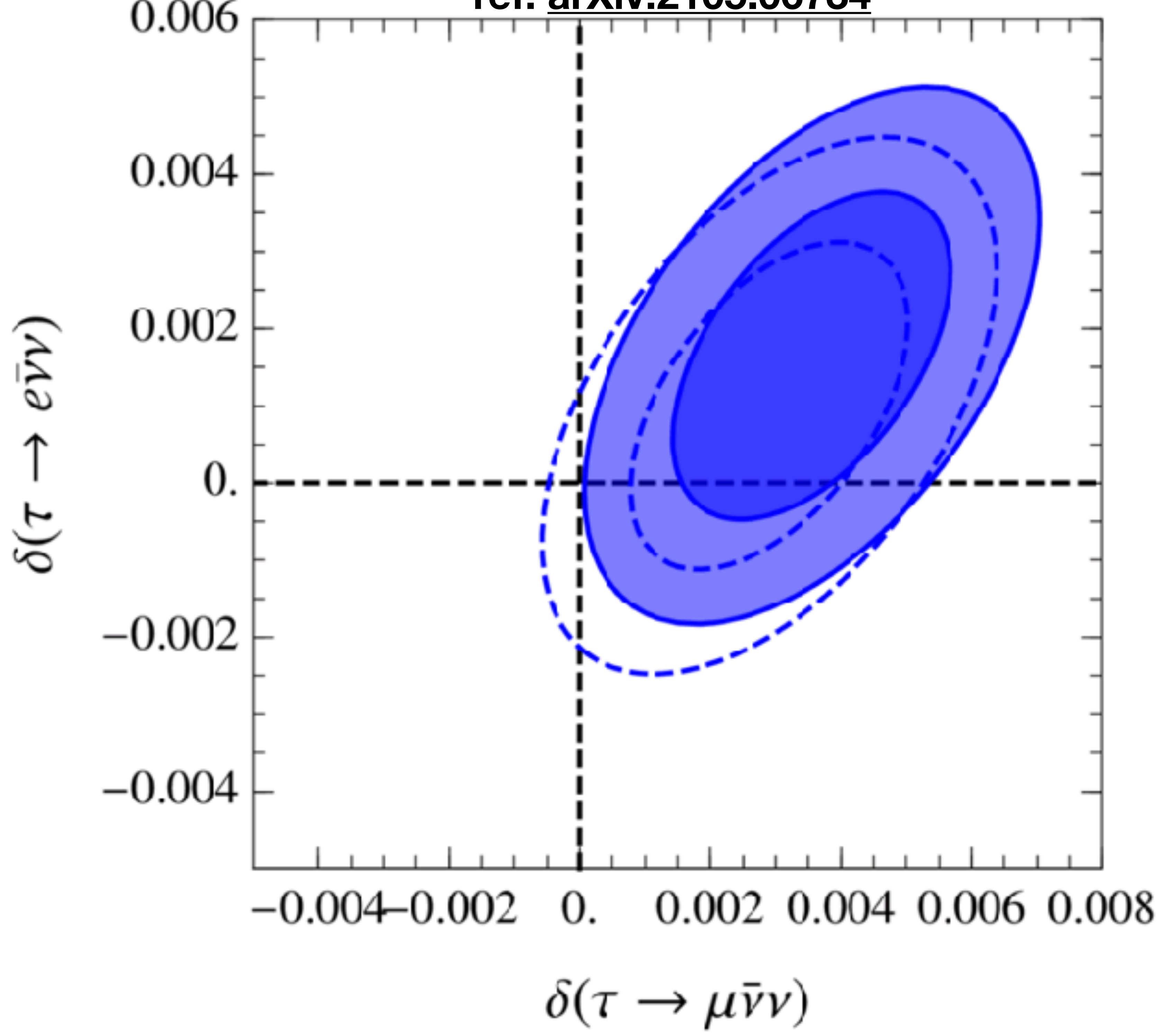


$$\frac{\mathcal{A}_{\rm EXP}(\tau\to\mu\nu\bar{\nu})}{\mathcal{A}_{\rm SM}(\mu\to e\nu\bar{\nu})}=1.0029\pm0.0014$$

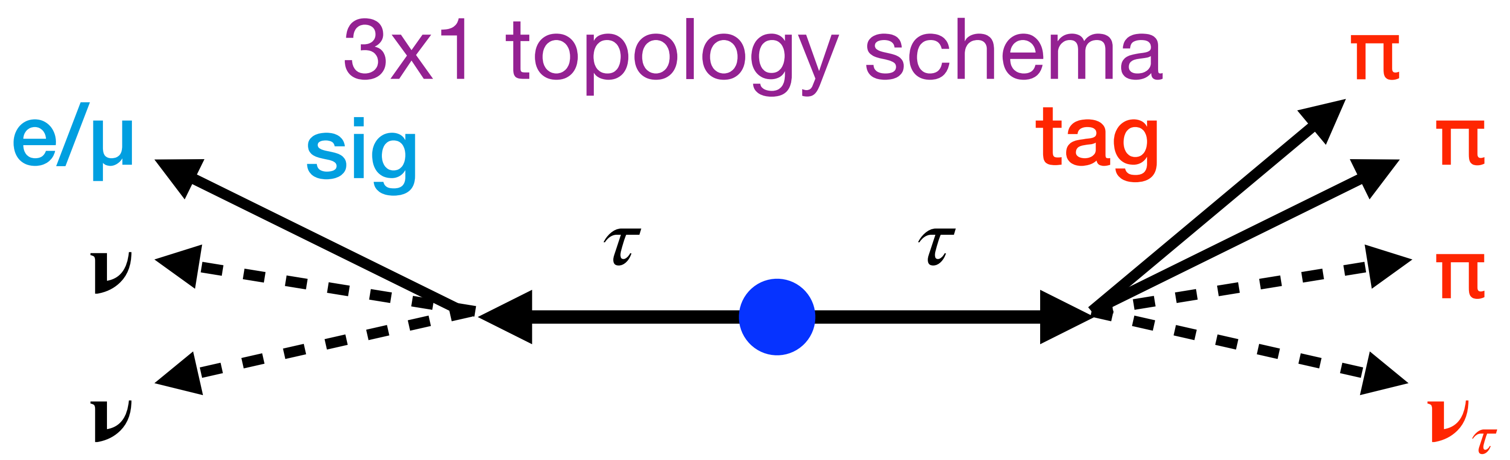
$$\frac{\mathcal{A}_{\rm EXP}(\tau\to\mu\nu\bar{\nu})}{\mathcal{A}_{\rm SM}(\tau\to e\nu\bar{\nu})}=1.0018\pm0.0014$$

$$\frac{\mathcal{A}_{\rm EXP}(\tau\to e\nu\bar{\nu})}{\mathcal{A}_{\rm SM}(\mu\to e\nu\bar{\nu})}=1.0010\pm0.0014$$

ref: arXiv:2105.06734



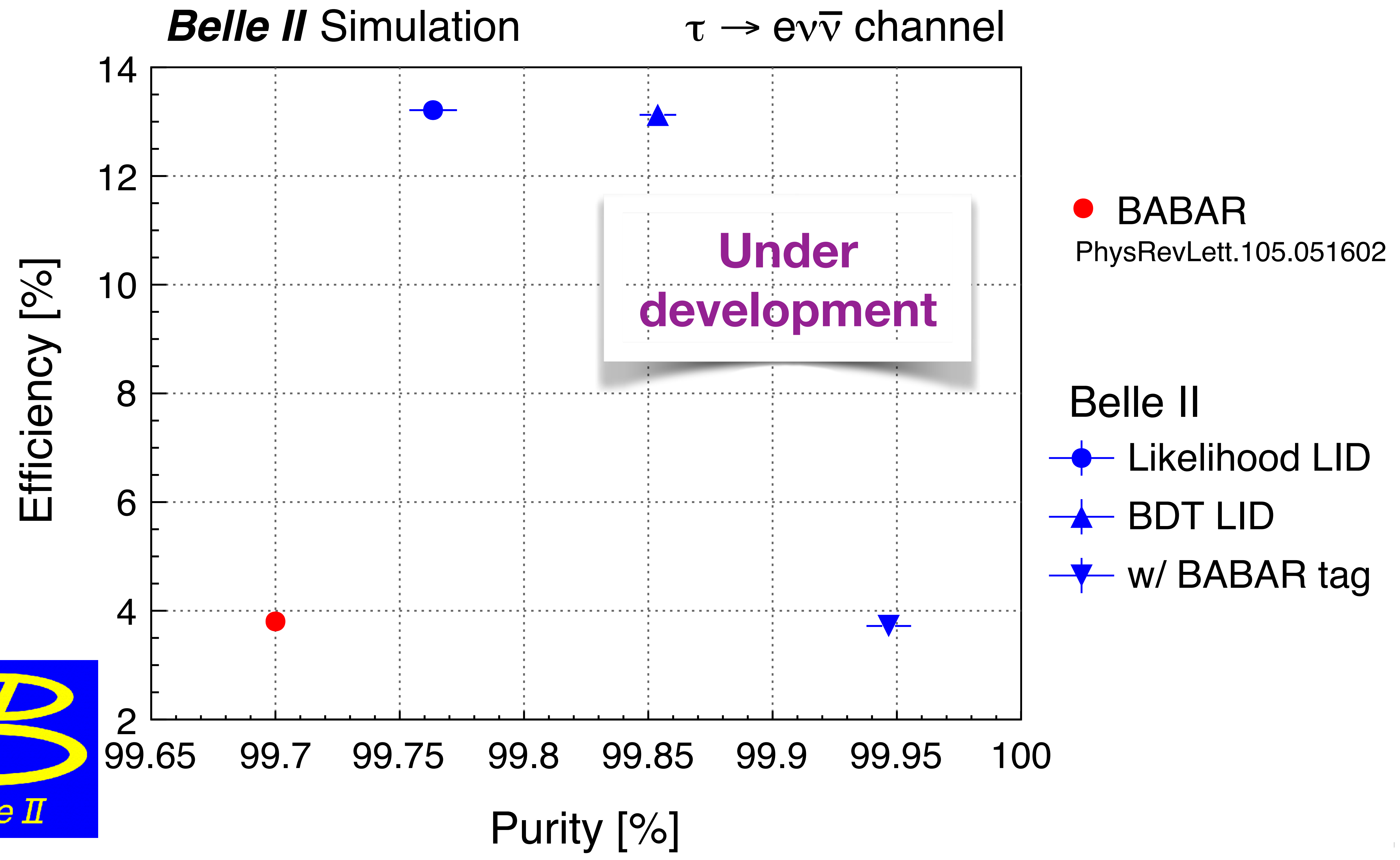
The $\tau \to l\nu\nu$ LFU at Belle II



Best result from Babar (467 fb^{-1}):

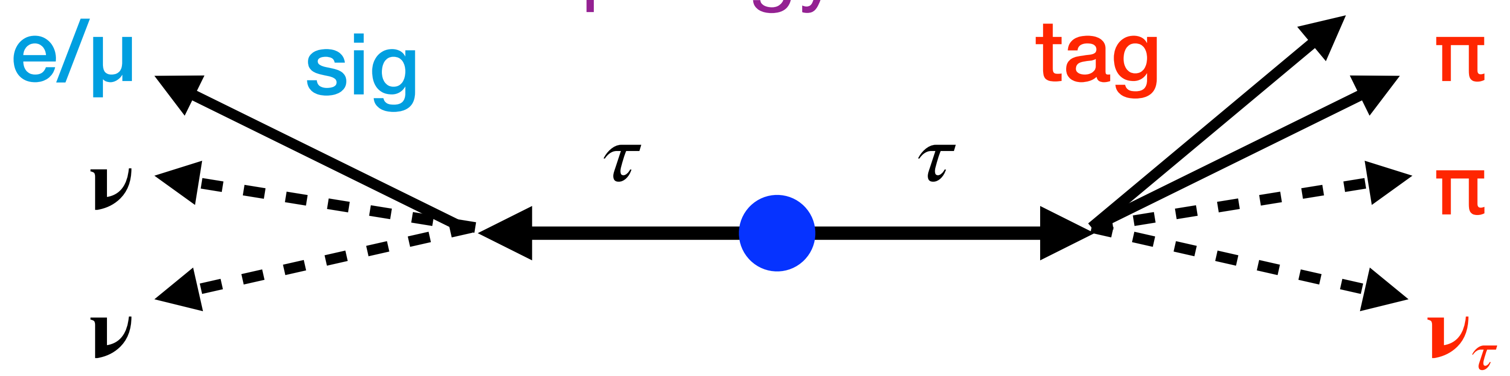
$R_\mu = 0.9796 \pm 0.0016$ (stat) ± 0.0036 (sys)

Cut based analysis @Belle II → efficiency ~4x larger than Babar with better purities!



The $\tau \to l\nu\nu$ LFU at Belle II

3x1 topology schema



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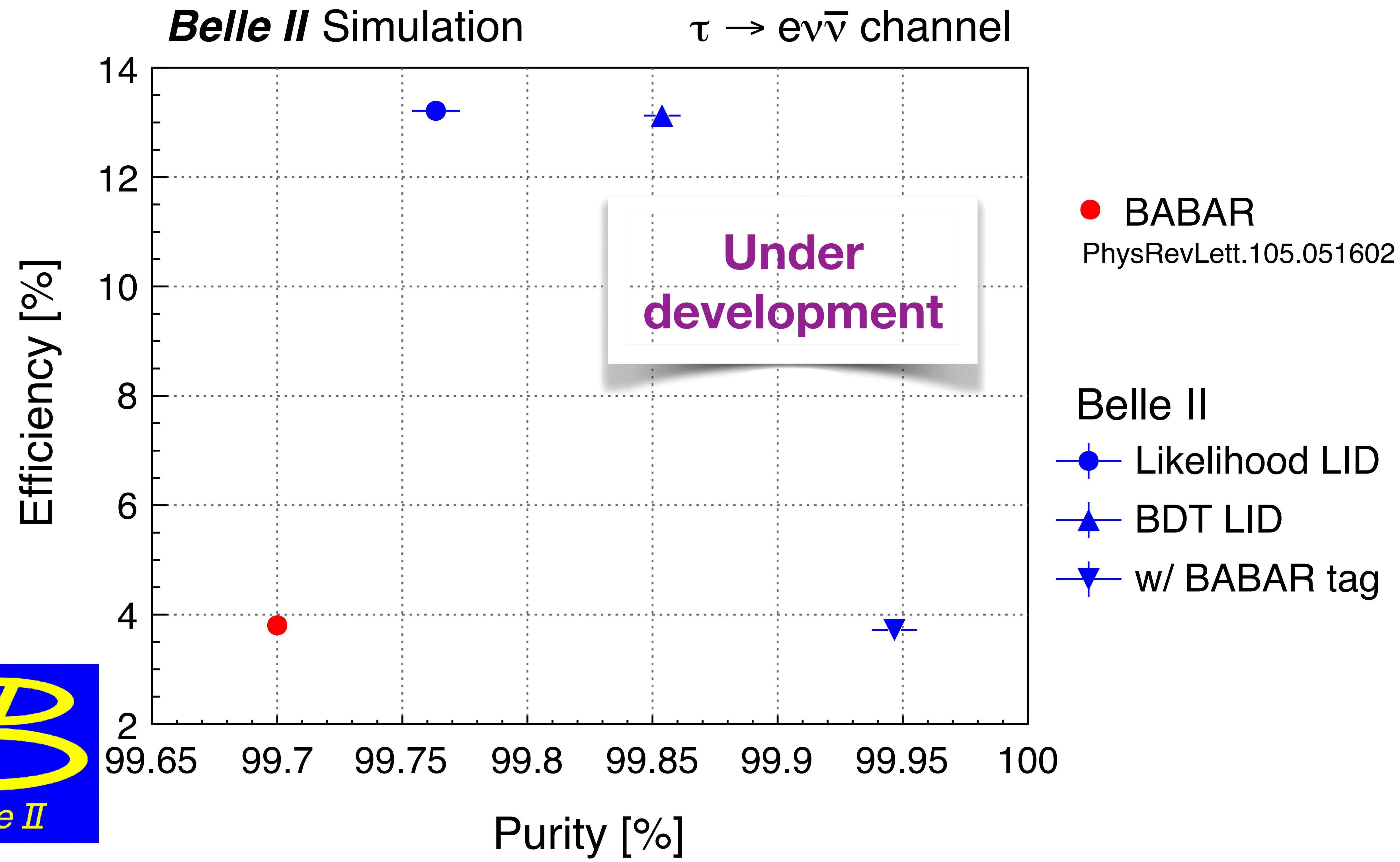
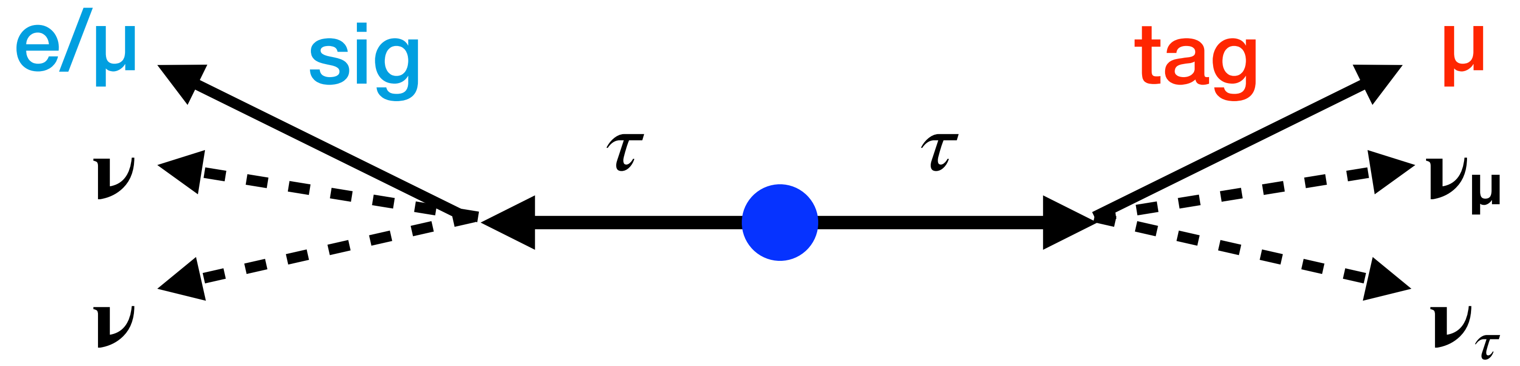


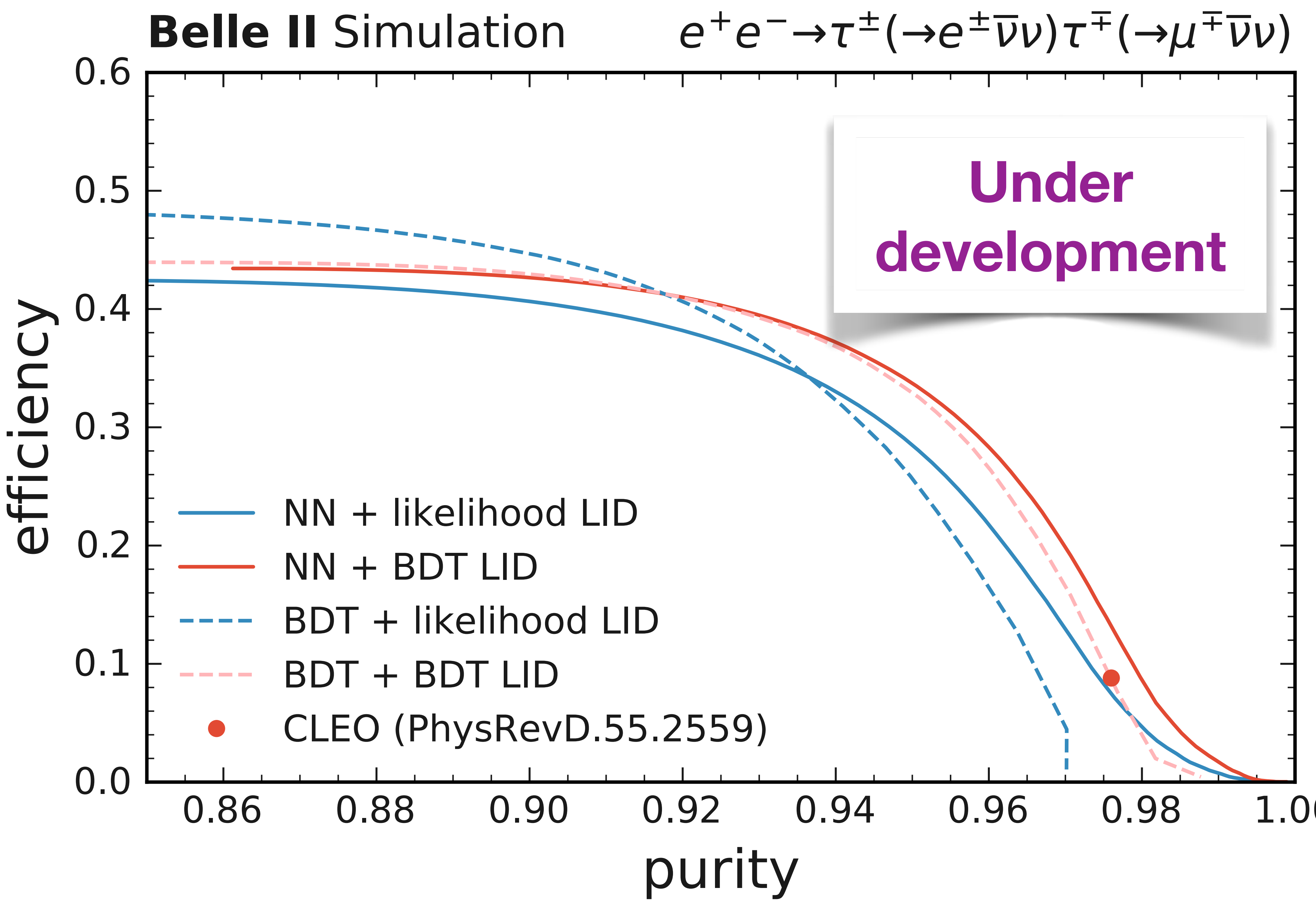
1x1 topology schema



Never studied by Belle/Babar due to trigger unavailability → best results from CLEO using 3.56 fb^{-1}

ref: <u>inspirehep</u>

Belle II relies on BDT and NN approaches → already shows compatible statistical precision wrt CLEO

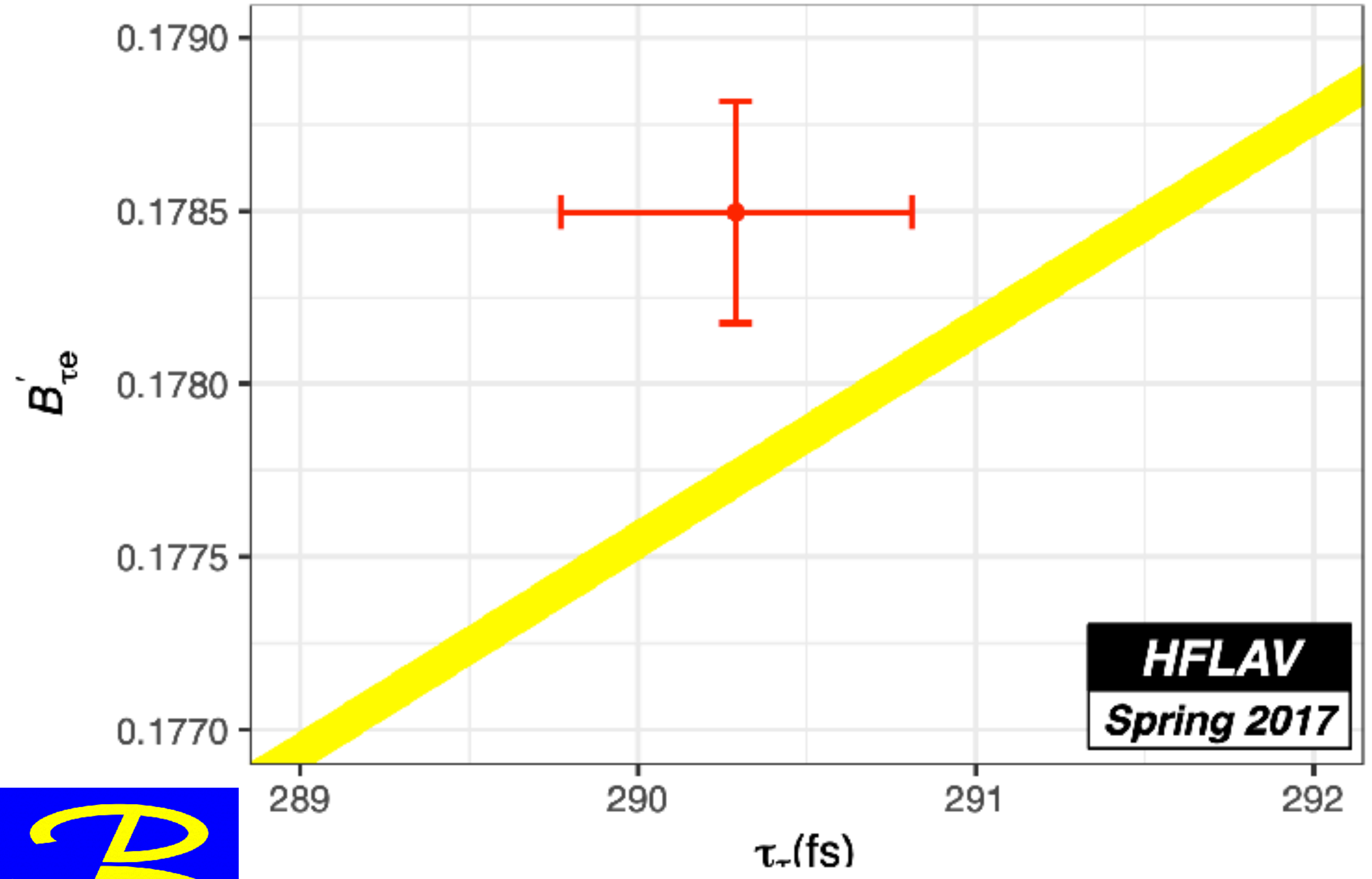


Direct standard model probes

τ **mass and lifetime** are crucial measurements for lepton flavour universality (LFU) tests of the SM:

$$B_{\tau\ell}^{SM} = B_{\mu e} \frac{\tau_\tau}{\tau_\mu} \frac{m_\tau^5}{m_\mu^5} \frac{f_{\tau\ell}}{f_{\mu e}} \frac{r_W^\tau r_\gamma^\tau}{r_W^\mu r_\gamma^\mu}$$

arXiv:1804.08436



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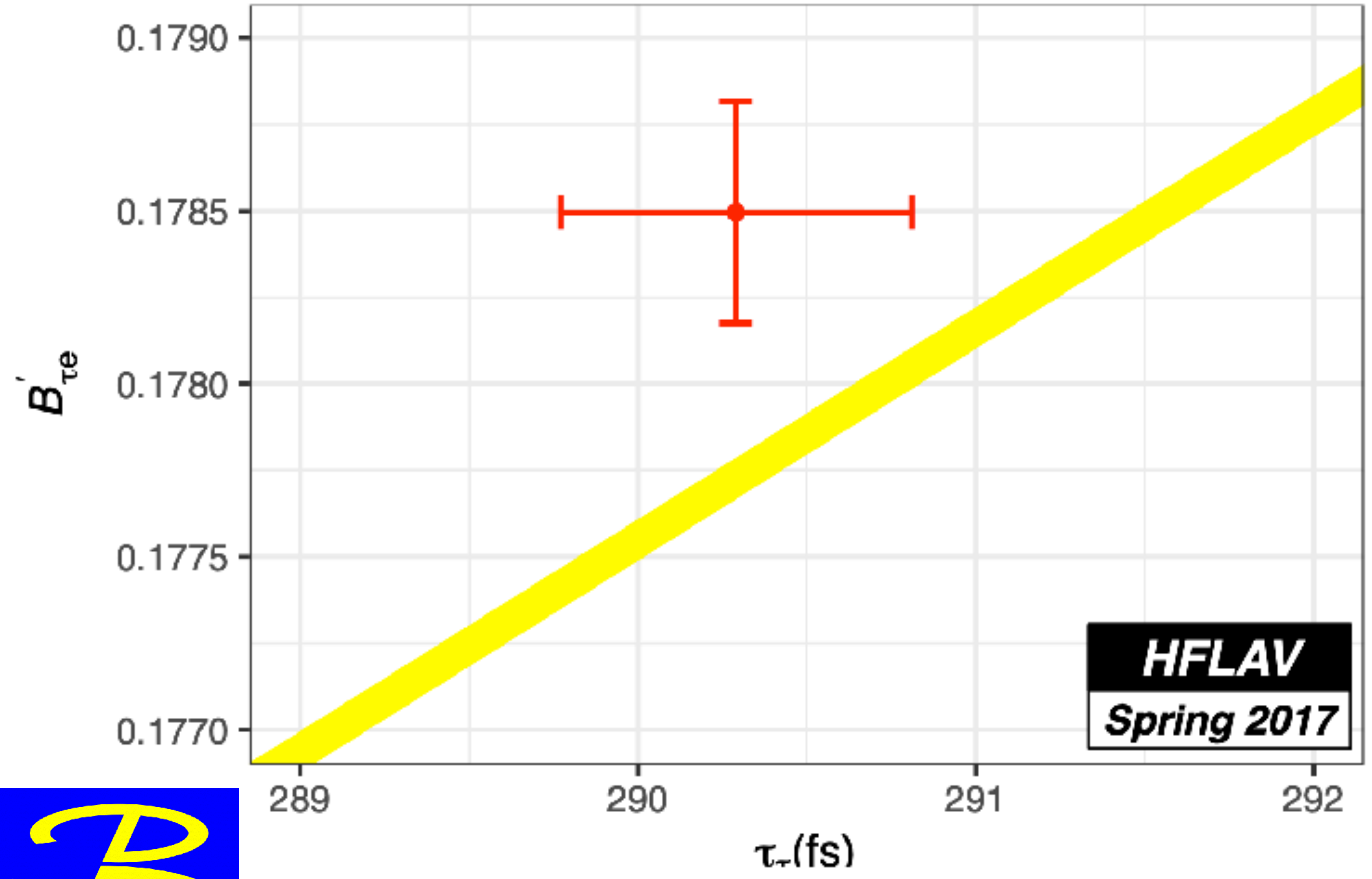
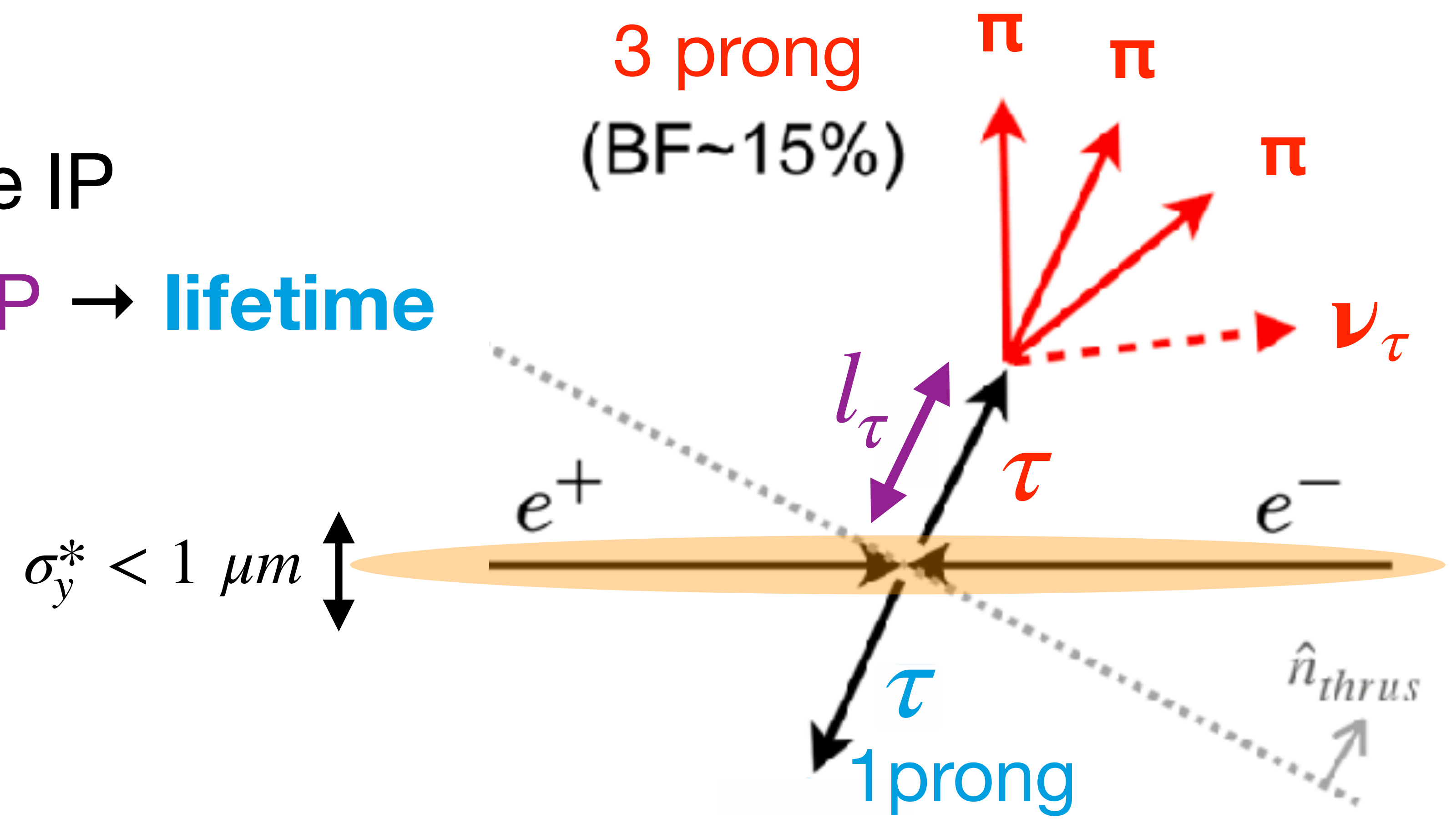
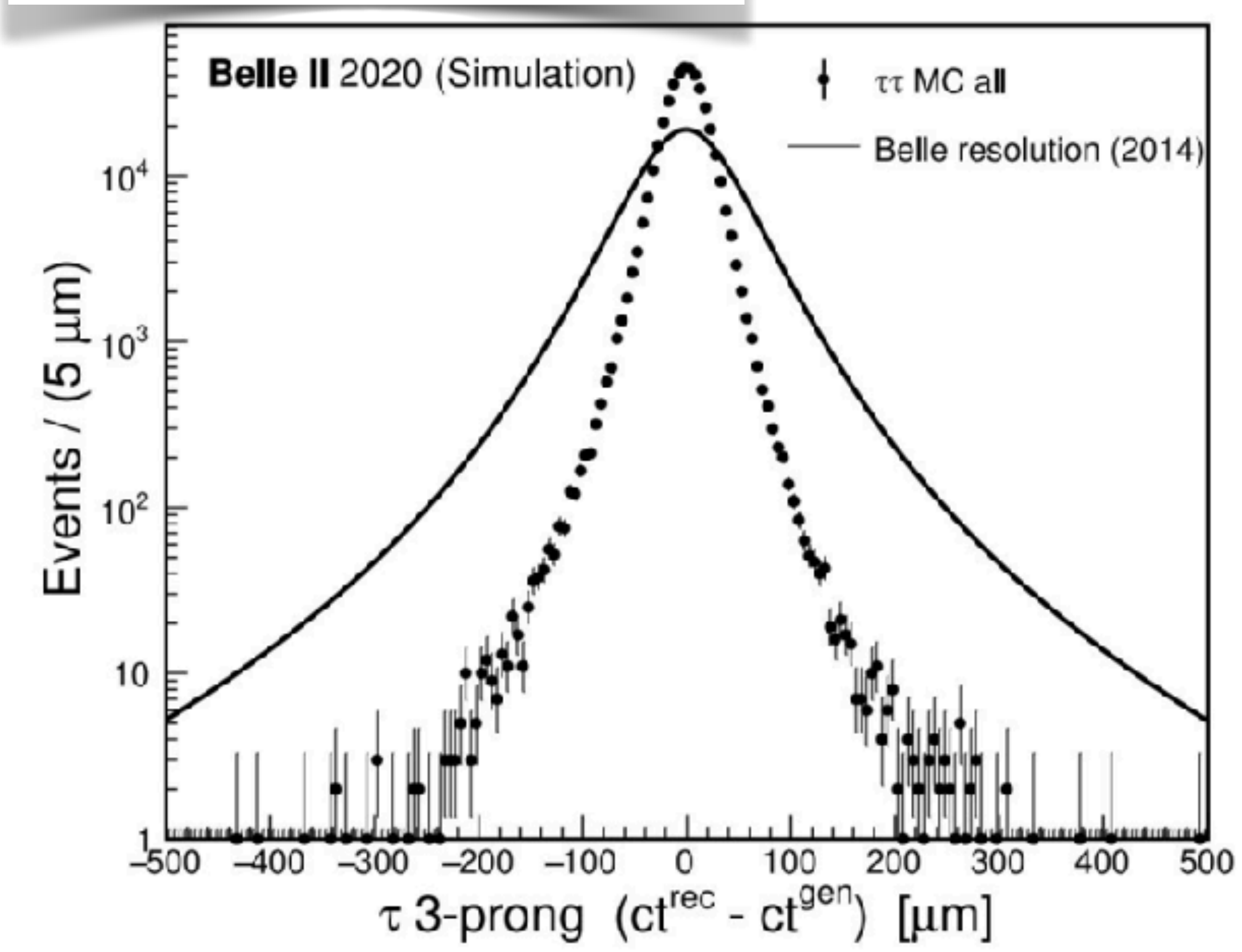


Tau lifetime analysis strategy at Belle II:

- Reconstruct 3x1 topology
- τ vertex constrained to the IP
- τ travelled distance from IP → **lifetime**

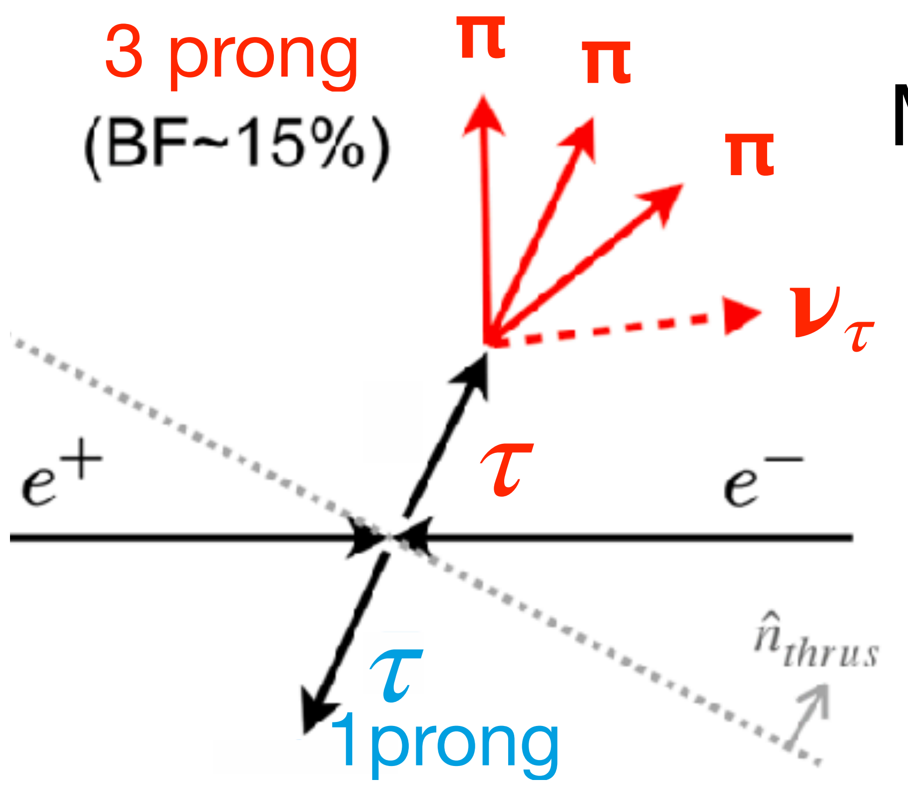


Early stage analysis



Decay-time resolution is 2x better than Belle

τ mass analysis status



Measure m_τ using 3-prong decay → pseudo mass method developed by ARGUS

Ref: https://doi.org/10.1016/0370-2693(92)90634-G

↓

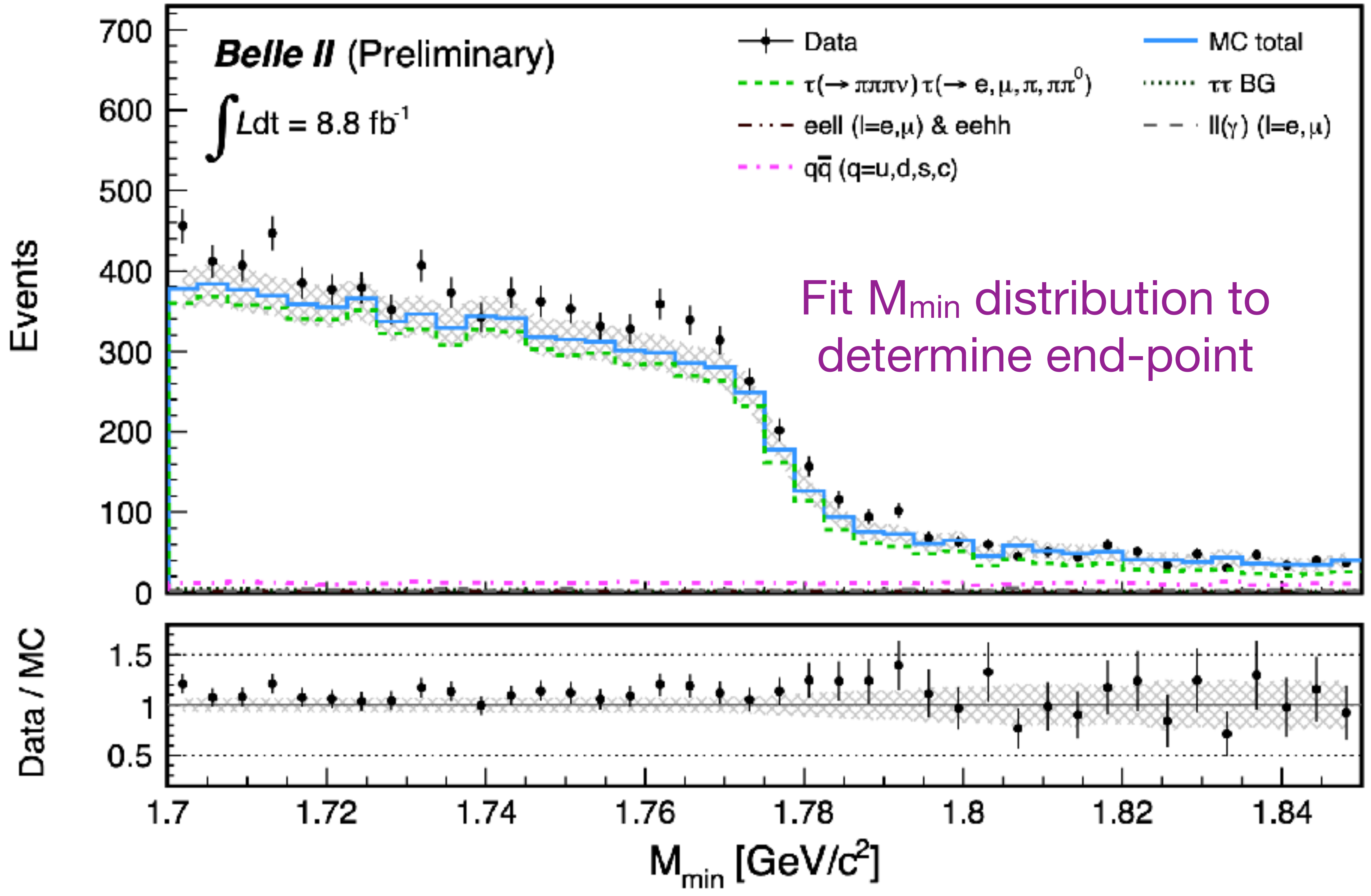
$$M_{\min} \equiv \sqrt{m_{3\pi}^2 + 2(E_{\text{beam}} - E_{3\pi})(E_{3\pi} - |p_{3\pi}|)} \leq m_\tau$$

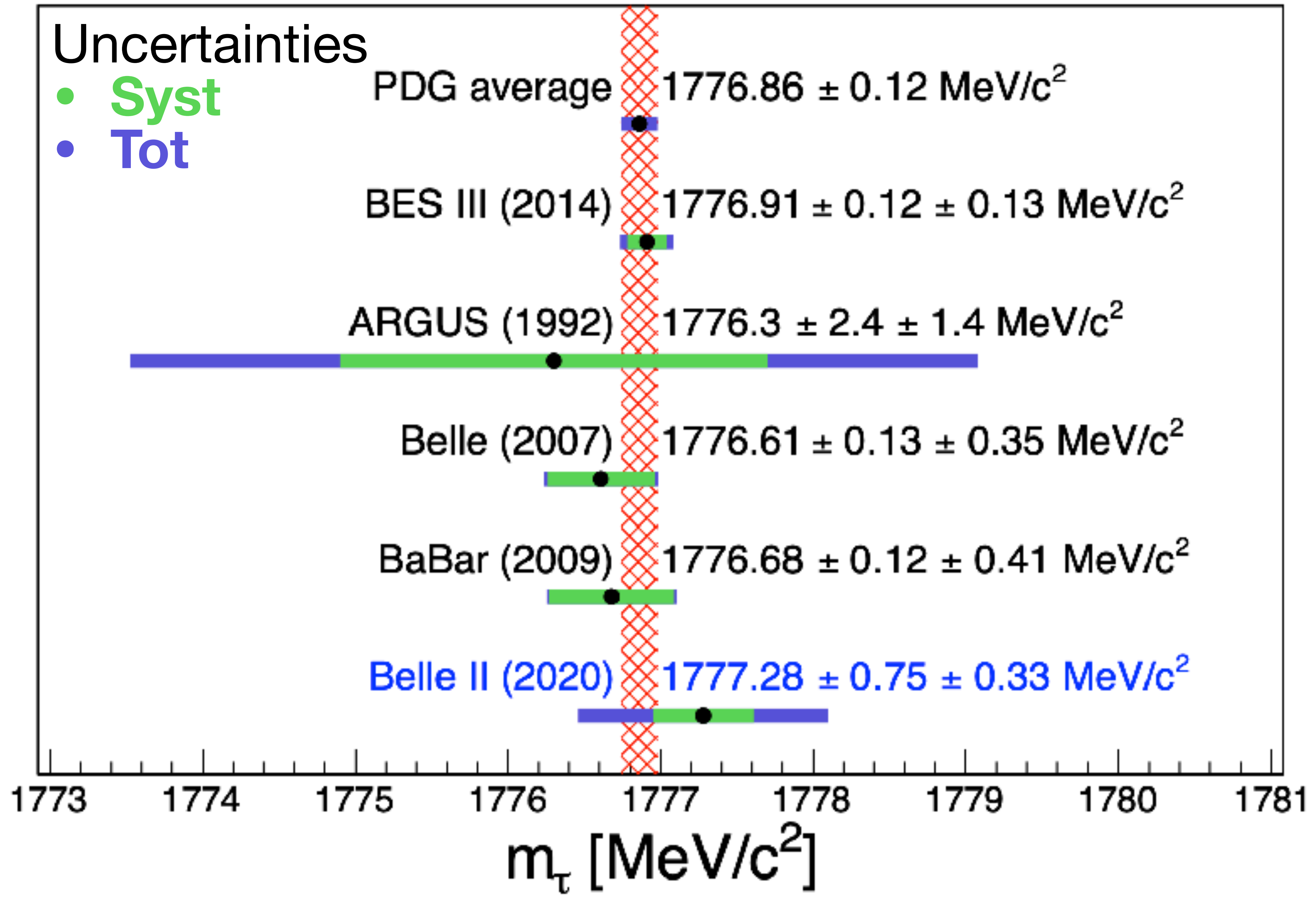
Systematics

- Leading: momentum shift due to B field map $0.29\ \text{MeV/c}^2$
- Sub-leading: end-point to mass method $0.12\ \text{MeV/c}^2$

$$m_\tau = 1777.28 \pm 0.75(\text{stat.}) \pm 0.33(\text{syst.})\text{MeV/c}^2$$

Ref: arXiv:2008.04665

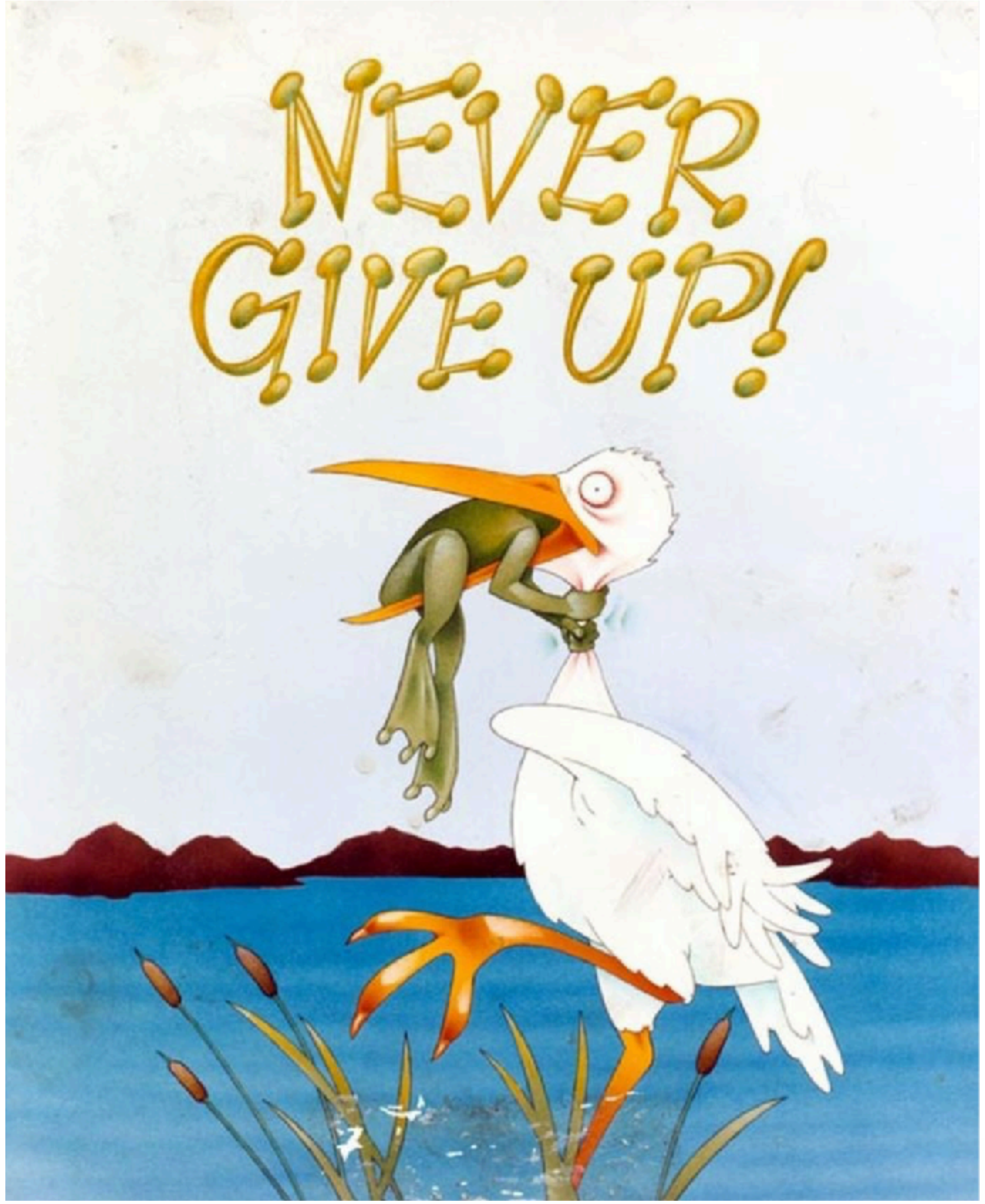




Conclusions

- Various τ-based searches are ongoing at Belle II
- Highly efficient trigger system allows to produce competitive analysis in an early stage
- Overview of some of the analyses is presented:
  - Search for $\tau \rightarrow l\ \alpha$ offers wold-best constraint!
    - Results no significant deviation/excess wrt the SM
  - Measurement of tau mass likely to be already competitive with current Belle II data set
  - LFUV, LFV and τ lifetime analysis are underway with very promising perspectives
- **With the current collected data sample Belle II is able to provide world leading results**

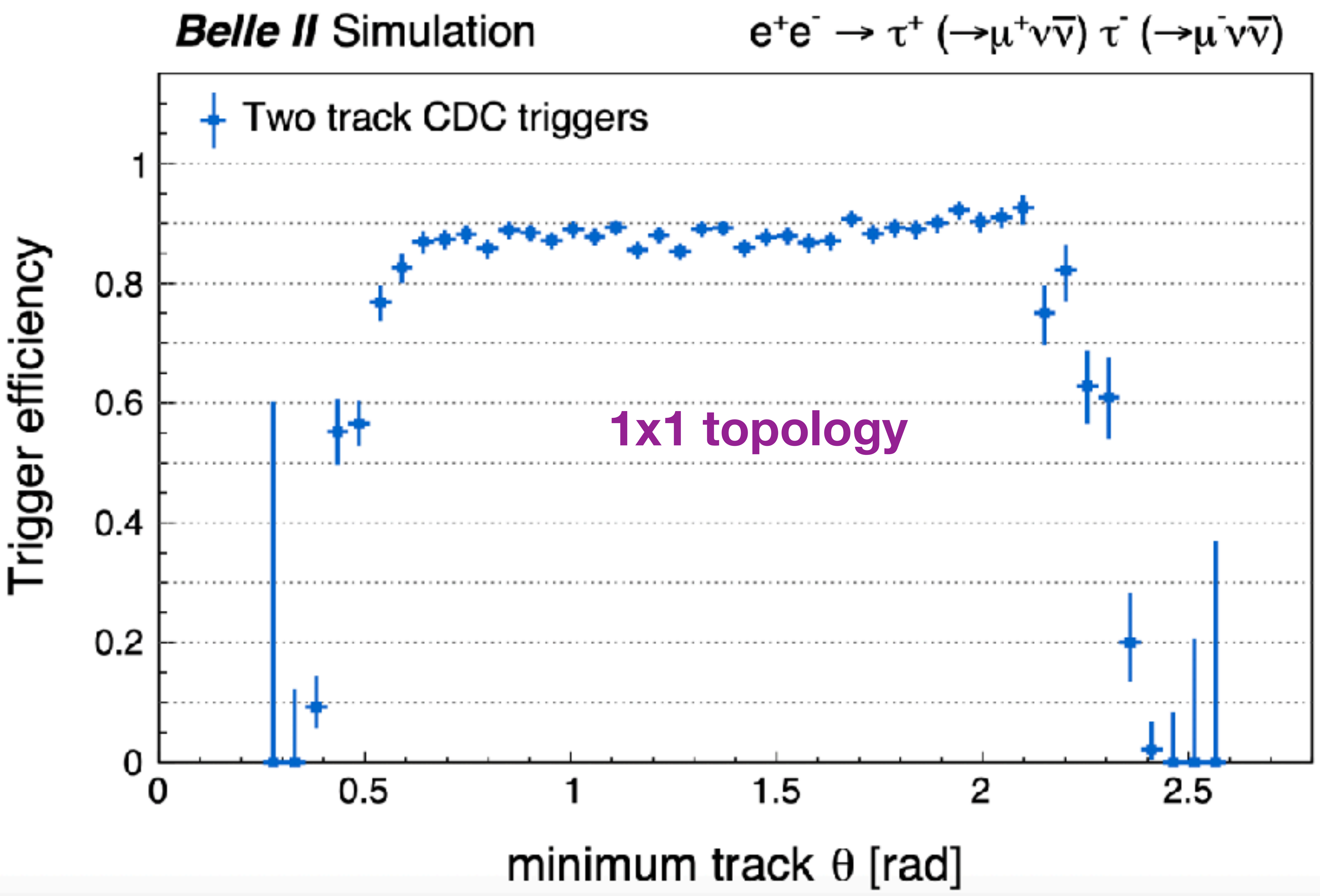
Emergency slides!!



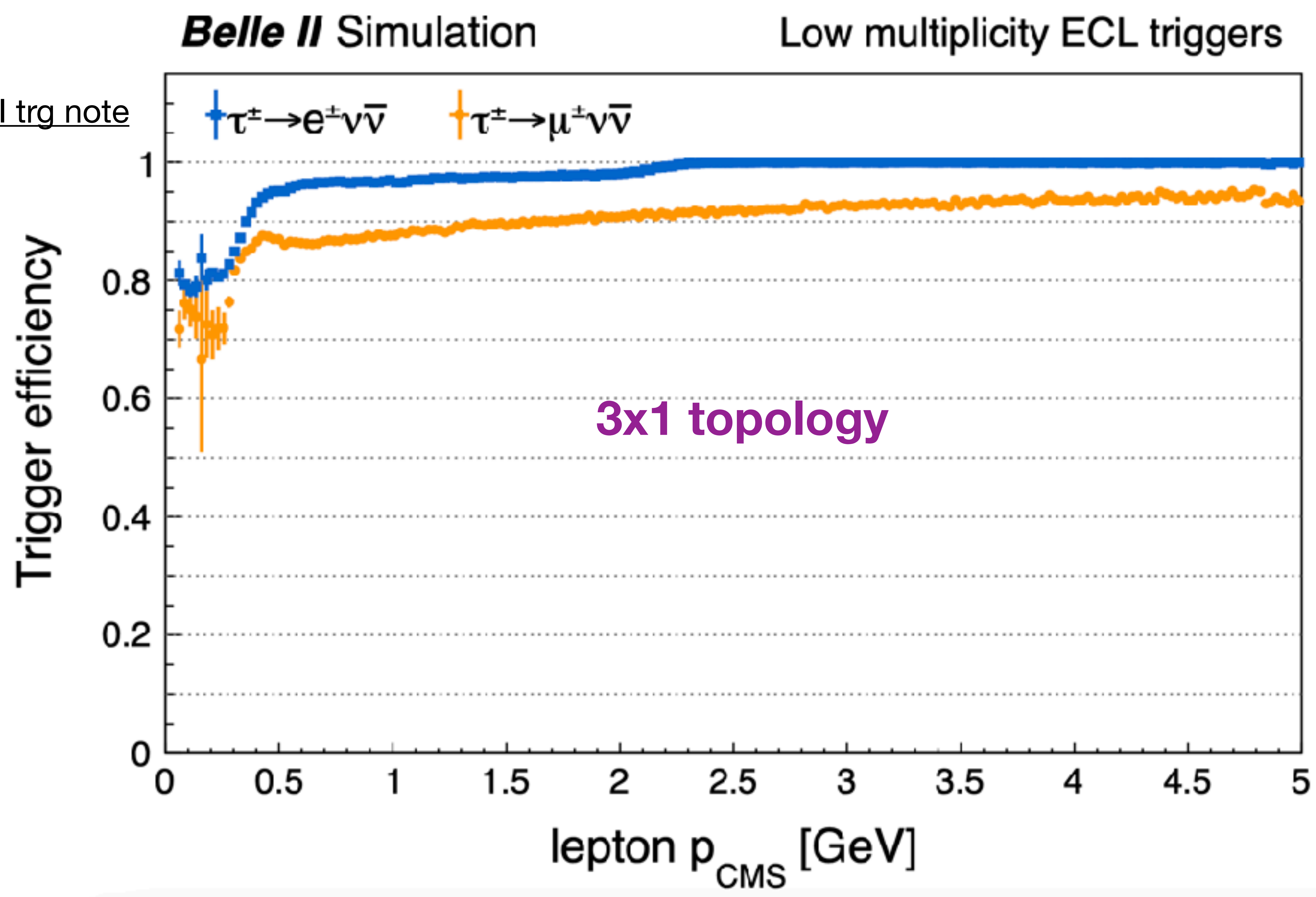
Triggers for τ @Belle II

2 trigger categories:
EM calorimeter (ECL) and drift chamber triggers

→ **Advantages at Belle II:** *several low multiplicity triggers* based on number of calorimetric clusters



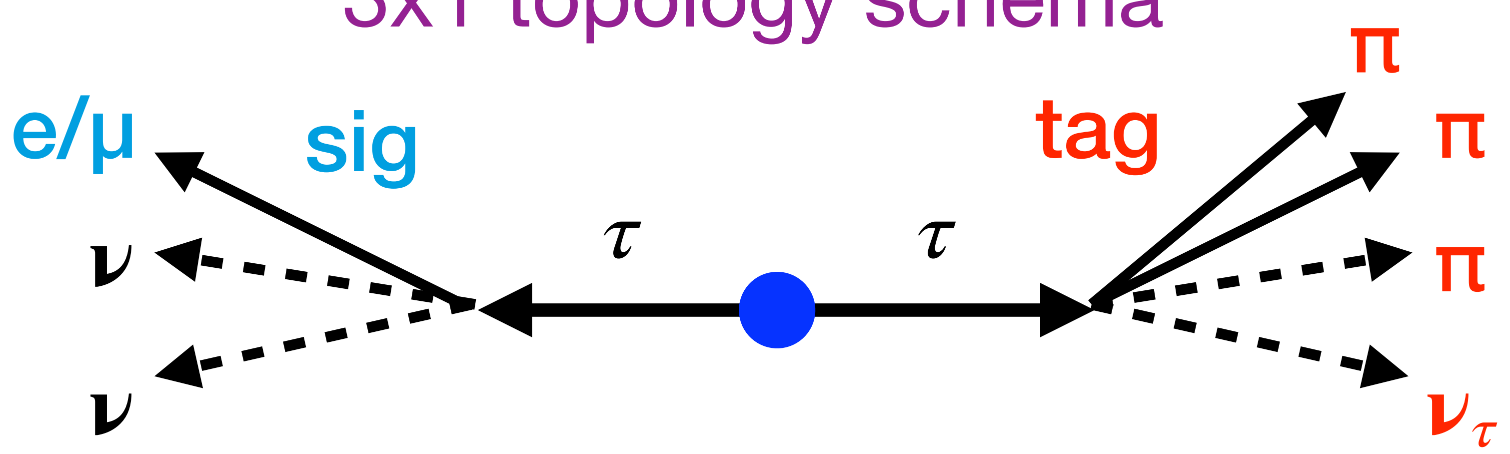
Ref: BelleII trg note



Logical OR of all available lml triggers → **High efficiency also for the 1x1 topology!**

The $\tau \to l\nu\nu$ LFU at Belle II: 3x1 topology

3x1 topology schema



Best result from Babar (467 fb^{-1}):

$R_\mu = 0.9796 \pm 0.0016$ (stat) ± 0.0036 (sys)

Main systematics:

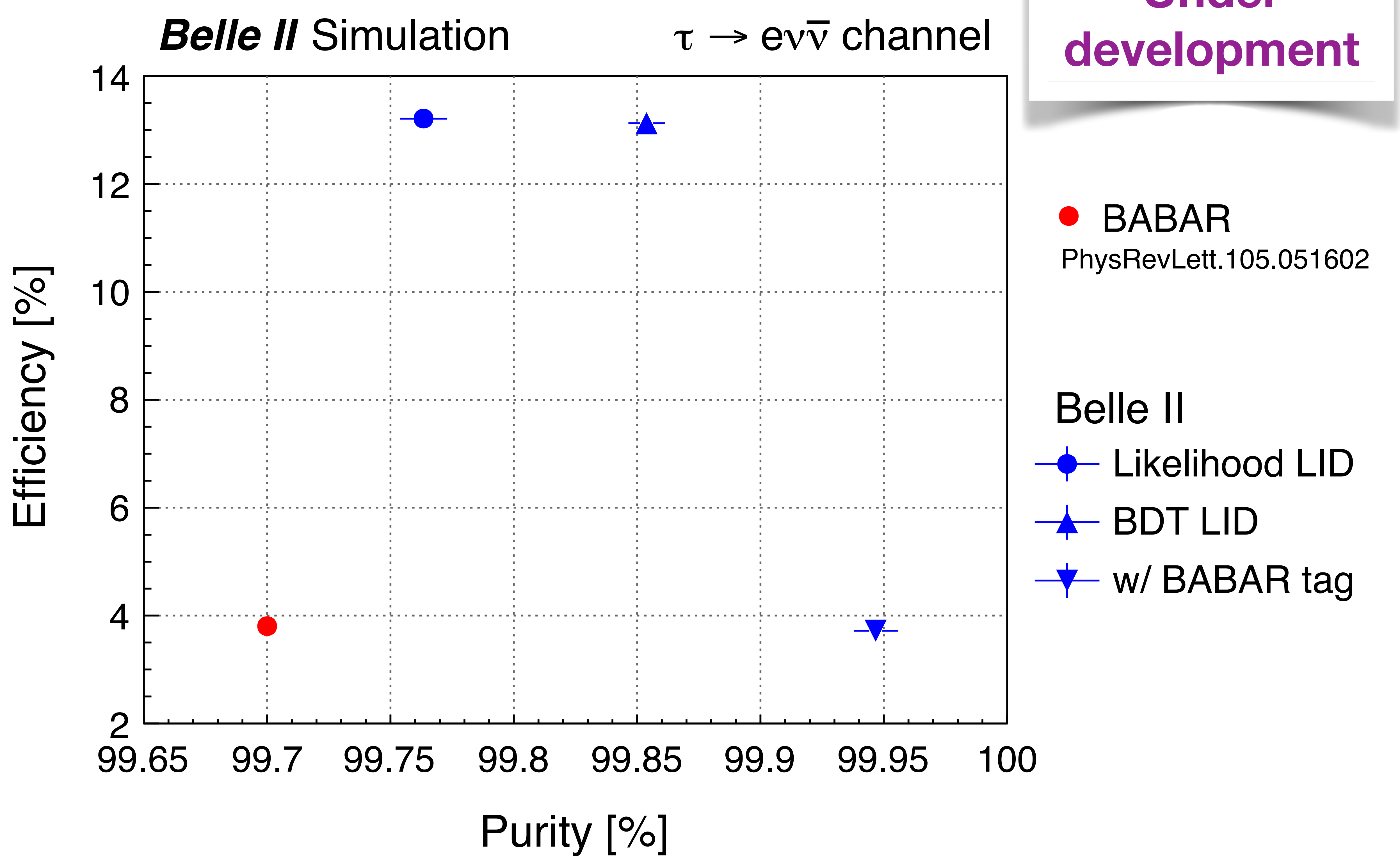
Systematic uncertainties:	
Particle ID	0.32
Detector response	0.08
Backgrounds	0.08
Trigger	0.10
$\pi^-\pi^-\pi^+$ modelling	0.01
Radiation	0.04
$\mathcal{B}(\tau^- \to \pi^-\pi^-\pi^+\nu_\tau)$	0.05
$\mathcal{L}\sigma_{e^+e^- \to \tau^+\tau^-}$	0.02
Total [%]	0.36

Cut based analysis @Belle II → efficiency ~4x larger than Babar with better purities!

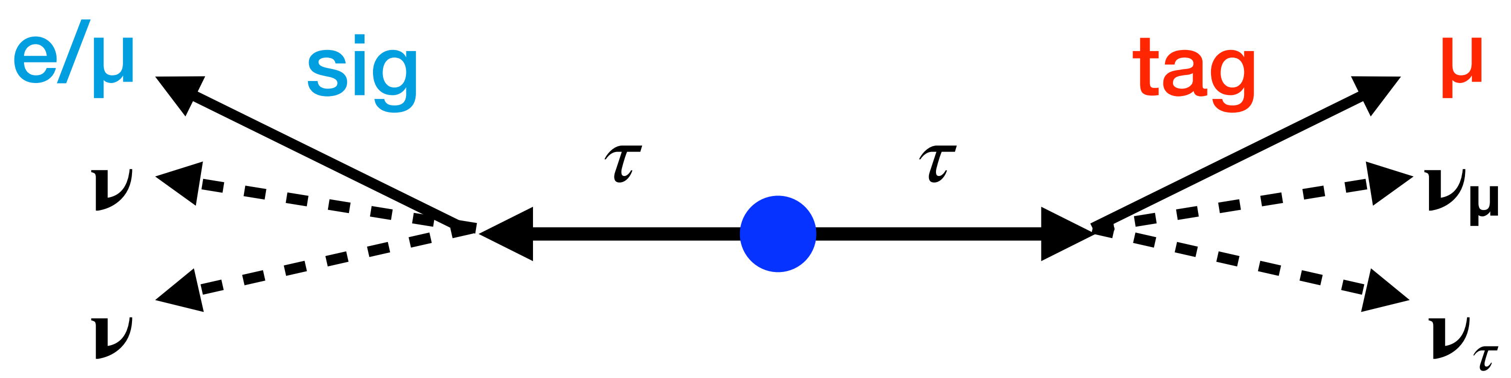
Improvements @Belle II:

- Trigger performances: data-MC model at few% level (preliminary studies)
- Better Lepton ID (LID) data-MC model: usage of likelihood and BDT based algorithms

Under development



The $\tau \rightarrow l\nu\nu$ LFU at Belle II: 1x1 topology



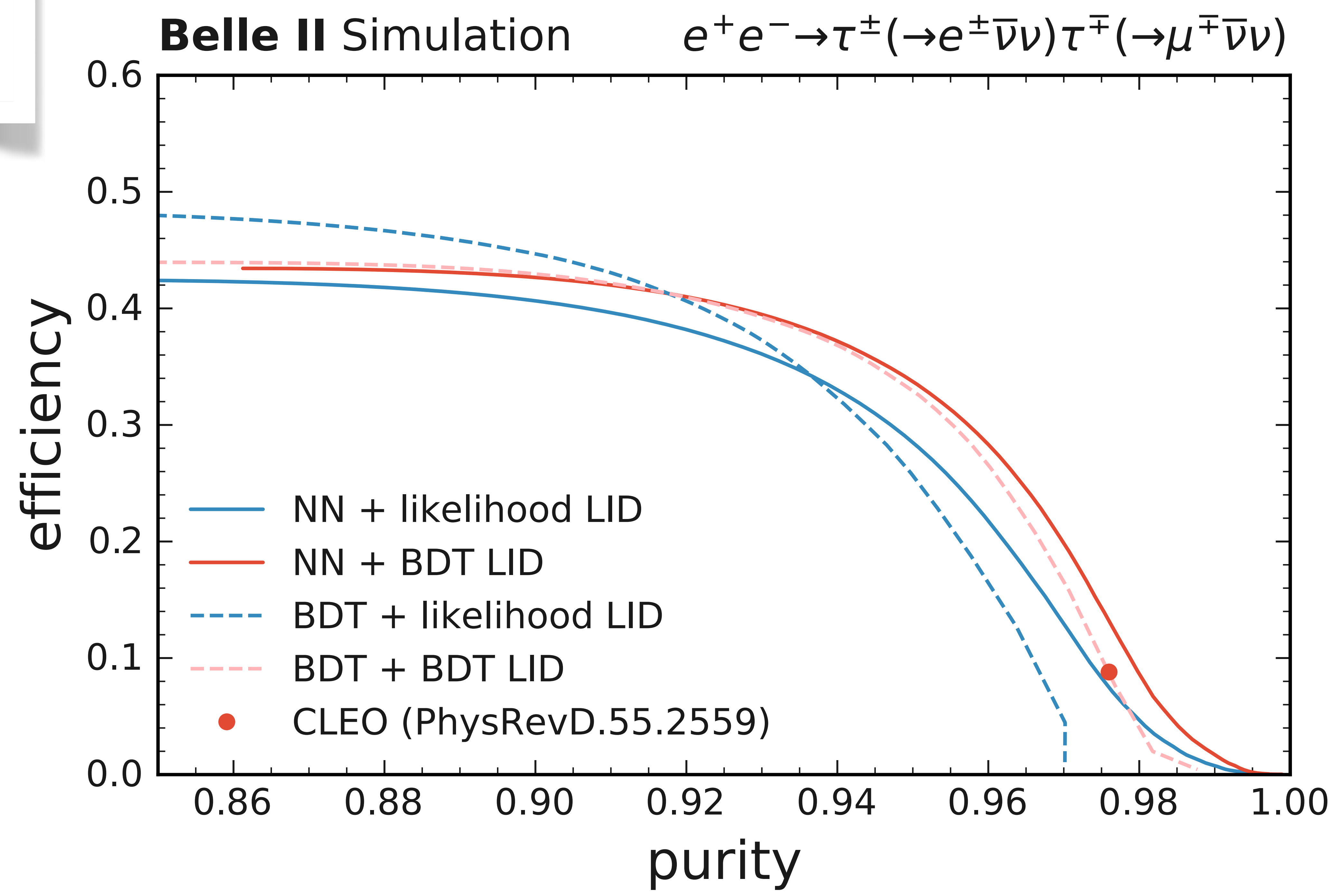
Best results from CLEO using 3.56 fb-1
ref: inspirehep

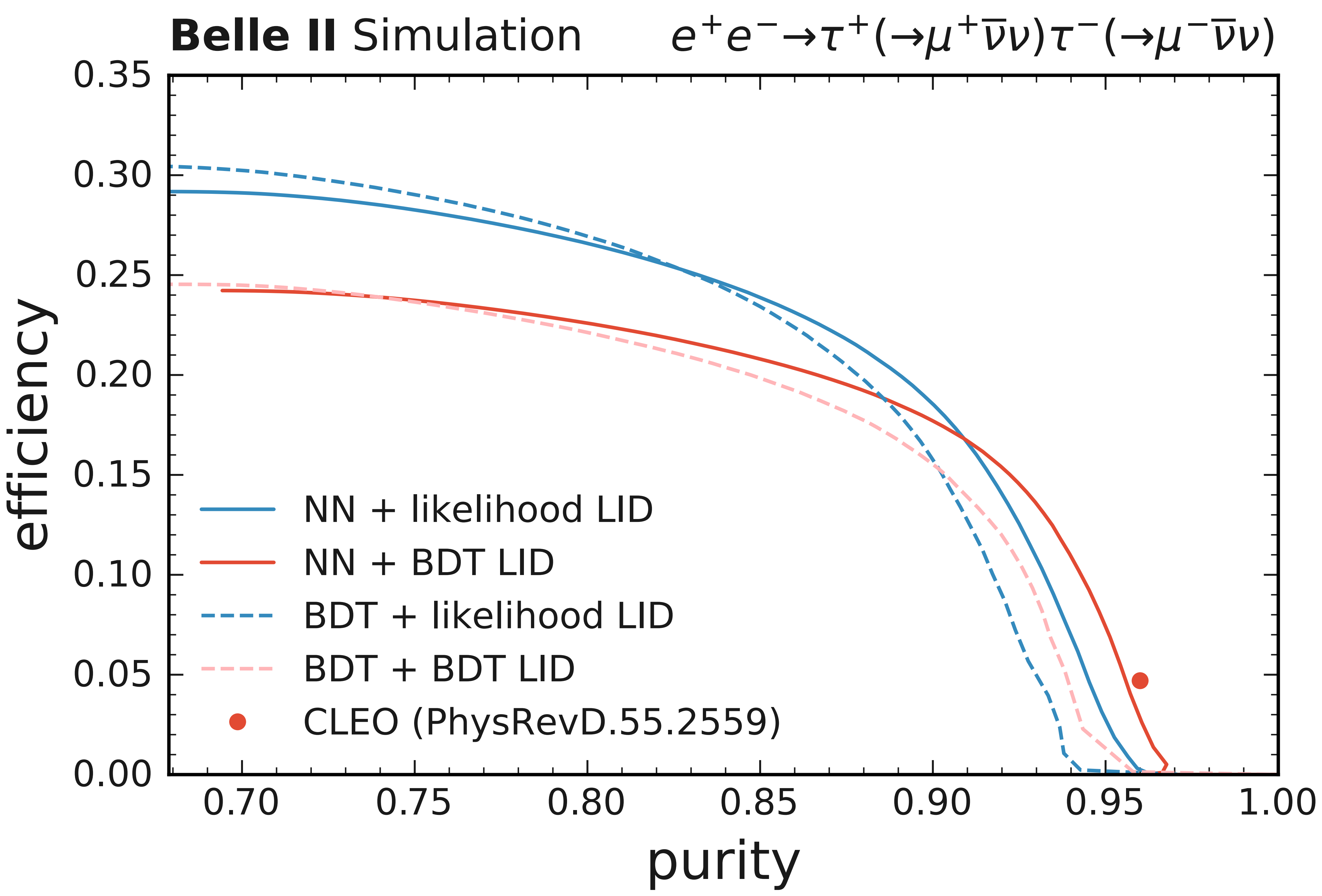
Never studied by Belle/Babar due to trigger unavailability

@Belle II for the moment only μ are considered in the tag side of the events → **e/μ or μ/μ events**

Belle II relies on BDT and NN approaches → already shows compatible statistical precision wrt CLEO

Under development

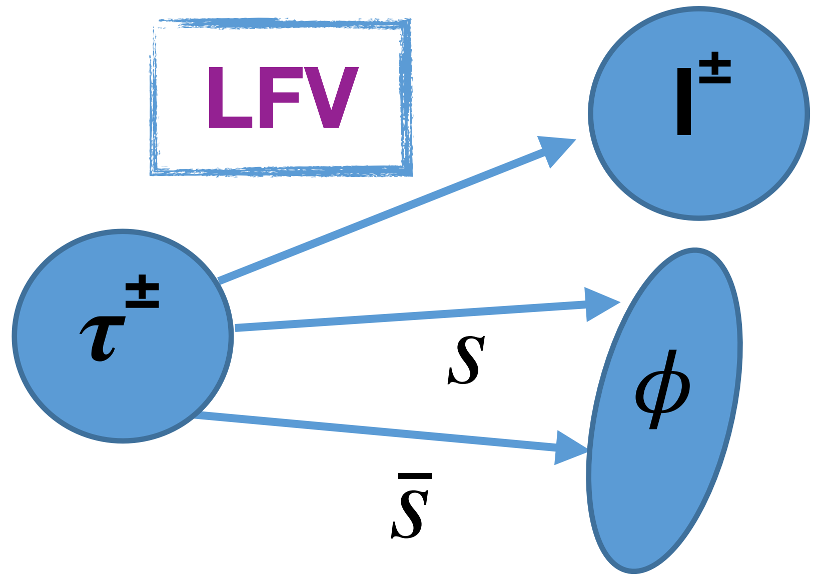




Expectations: $\tau \to lV^0(\phi \to h^+h^-)$

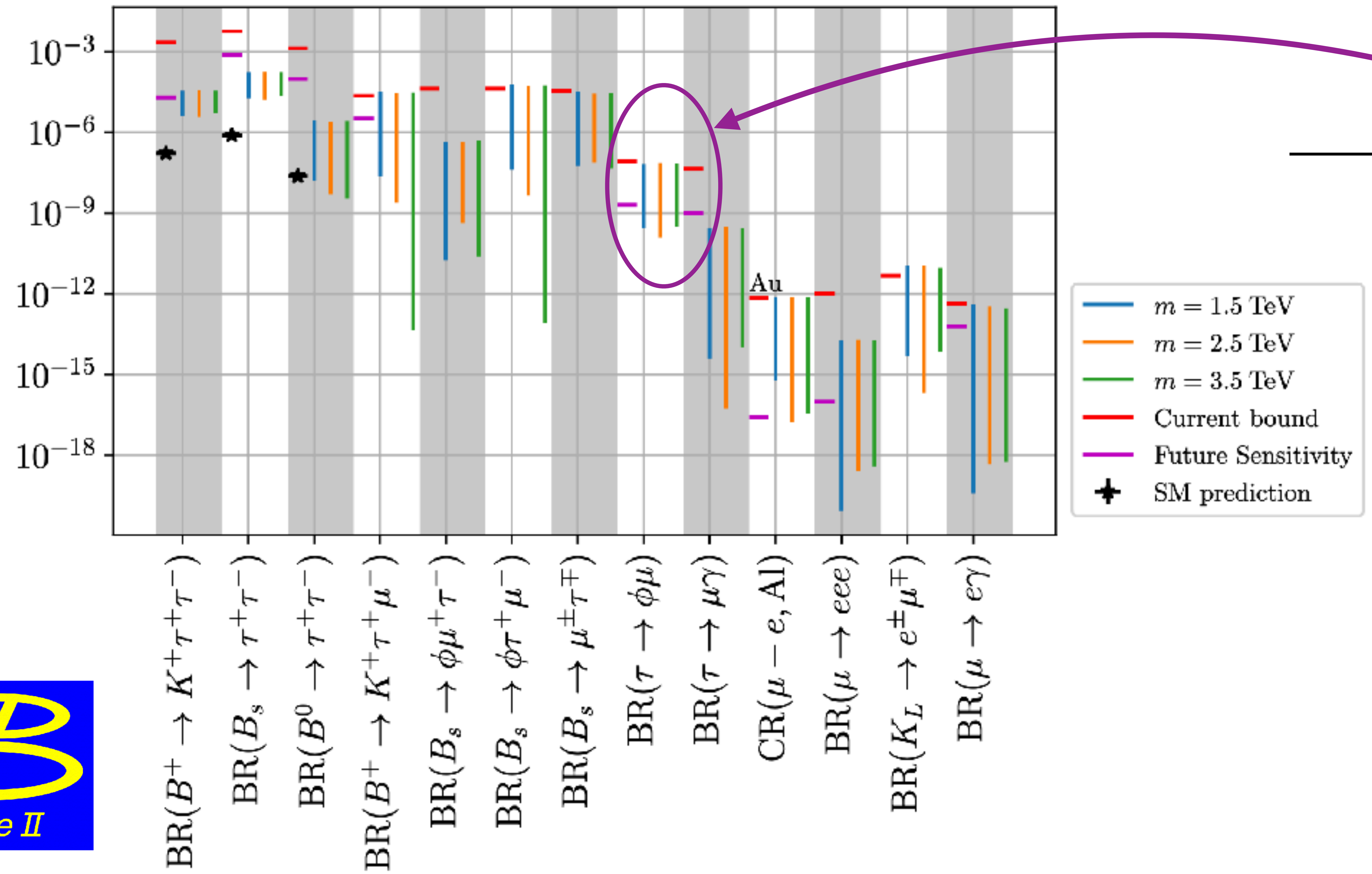
Experimental upper limits from **Belle** and **BaBar** for $\tau \to e/\mu\phi$:

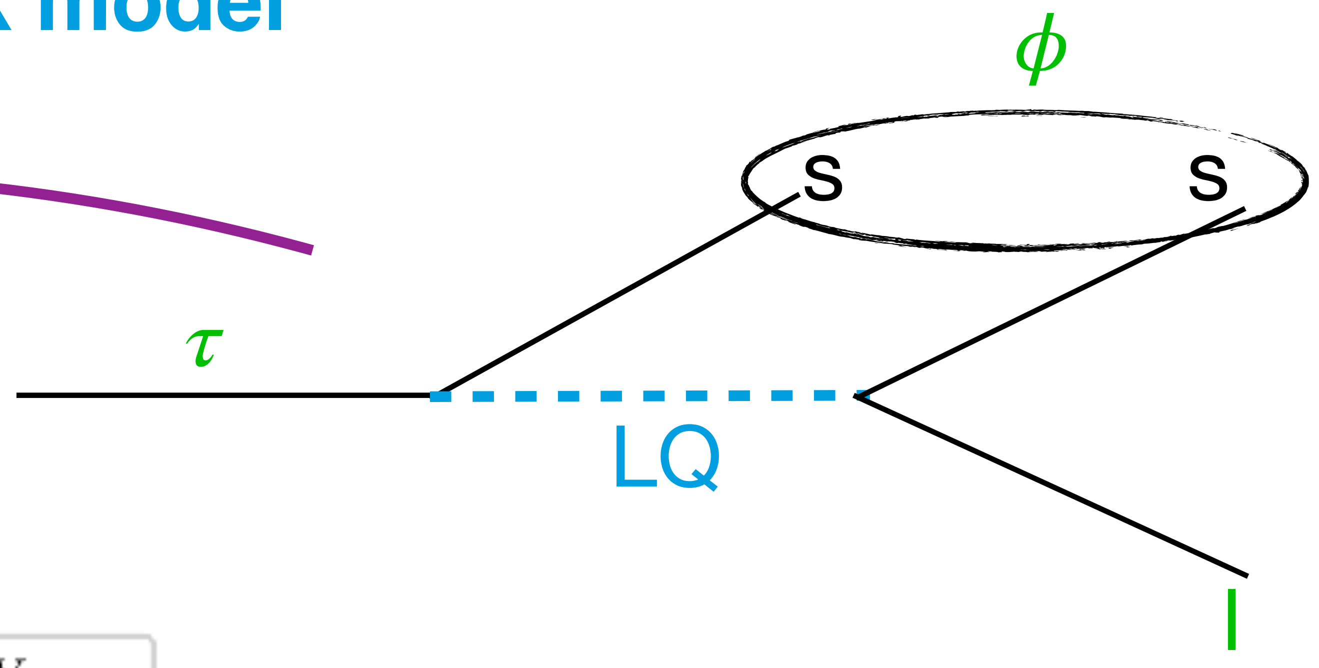
- Belle: **$3.1/8.4 \times 10^{-8}$** @90% confidence level using $\int Ldt = 845 fb^{-1}$
  https://arxiv.org/pdf/1101.0755.pdf
- BaBar: **$3.1/19 \times 10^{-8}$** @90% confidence level using $\int Ldt = 451 fb^{-1}$
  https://arxiv.org/pdf/0904.0339.pdf

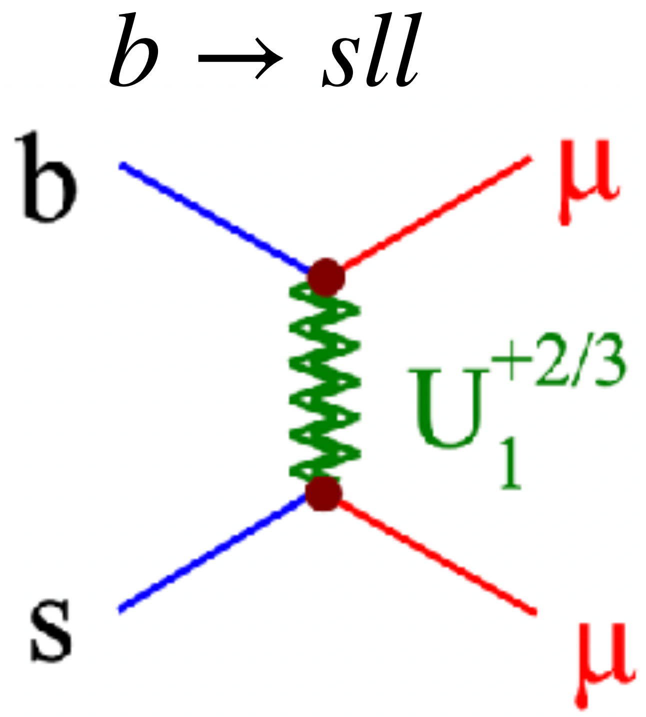


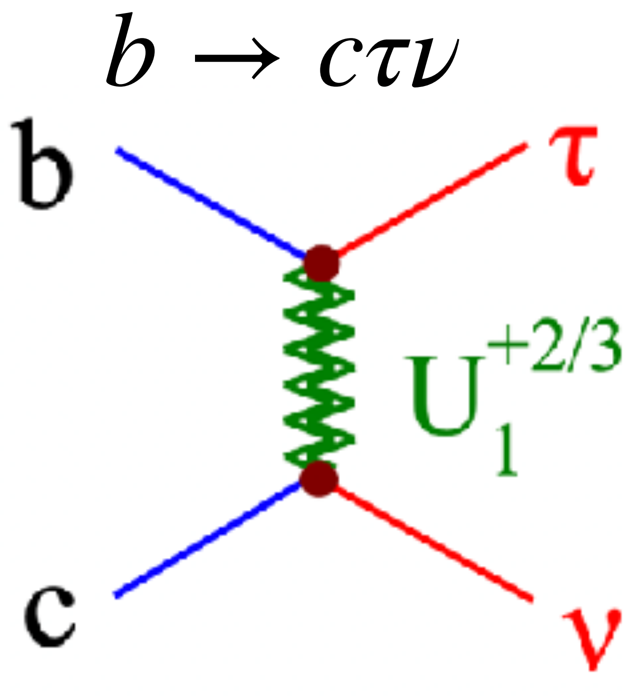
Leptoquark model

Ref: https://arxiv.org/pdf/2104.00015.pdf







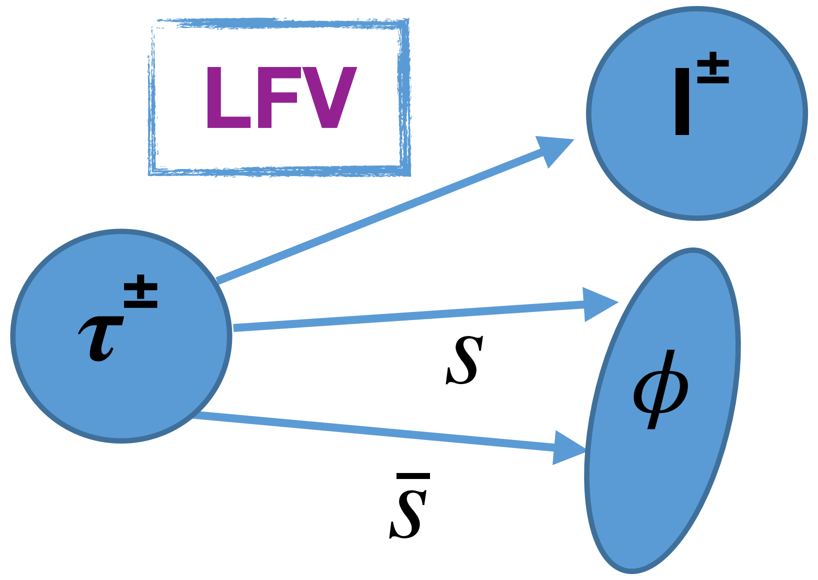


Belle II

Analysis motivations: $\tau \rightarrow lV^0(\phi \rightarrow h^+h^-)$

Experimental upper limits from **Belle** and **BaBar** for $\tau \rightarrow e/\mu\phi$:

- Belle: **3.1/8.4 x 10^{-8}** @90% confidence level using $\int Ldt = 845 fb^{-1}$
  https://arxiv.org/pdf/1101.0755.pdf
- BaBar: **3.1/19 x 10^{-8}** @90% confidence level using $\int Ldt = 451 fb^{-1}$
  https://arxiv.org/pdf/0904.0339.pdf



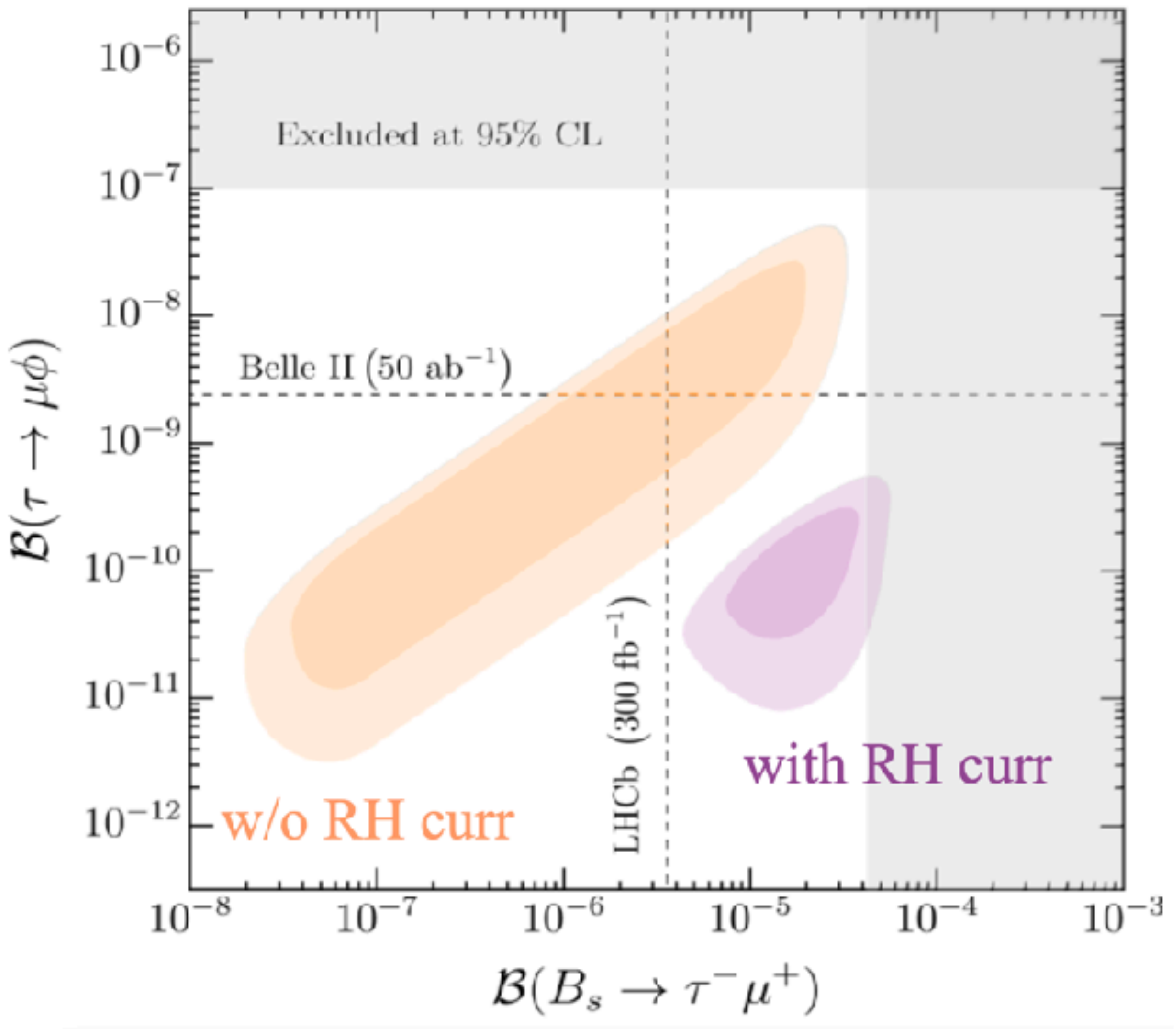
Leptoquark model

Ref: https://arxiv.org/pdf/2104.00015.pdf

	Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
Scalars	$S_1 = (\mathbf{3}, \mathbf{1})_{-1/3}$	✗	✓	✗
	$R_2 = (\mathbf{3}, \mathbf{2})_{7/6}$	✗	✓	✗
	$\widetilde{R}_2 = (\mathbf{3}, \mathbf{2})_{1/6}$	✗	✗	✗
	$S_3 = (\mathbf{3}, \mathbf{3})_{-1/3}$	✓	✗	✗
Vector	$U_1 = (\mathbf{3}, \mathbf{1})_{2/3}$	✓	✓	✓
	$U_3 = (\mathbf{3}, \mathbf{3})_{2/3}$	✓	✗	✗

Angelescu, Becirevic, DAF, Sumensari [1808.08179]

Ref: https://arxiv.org/pdf/2103.16558.pdf



Nice interplay between B and τ physics!

$\tau\to3\mu$ analysis key points

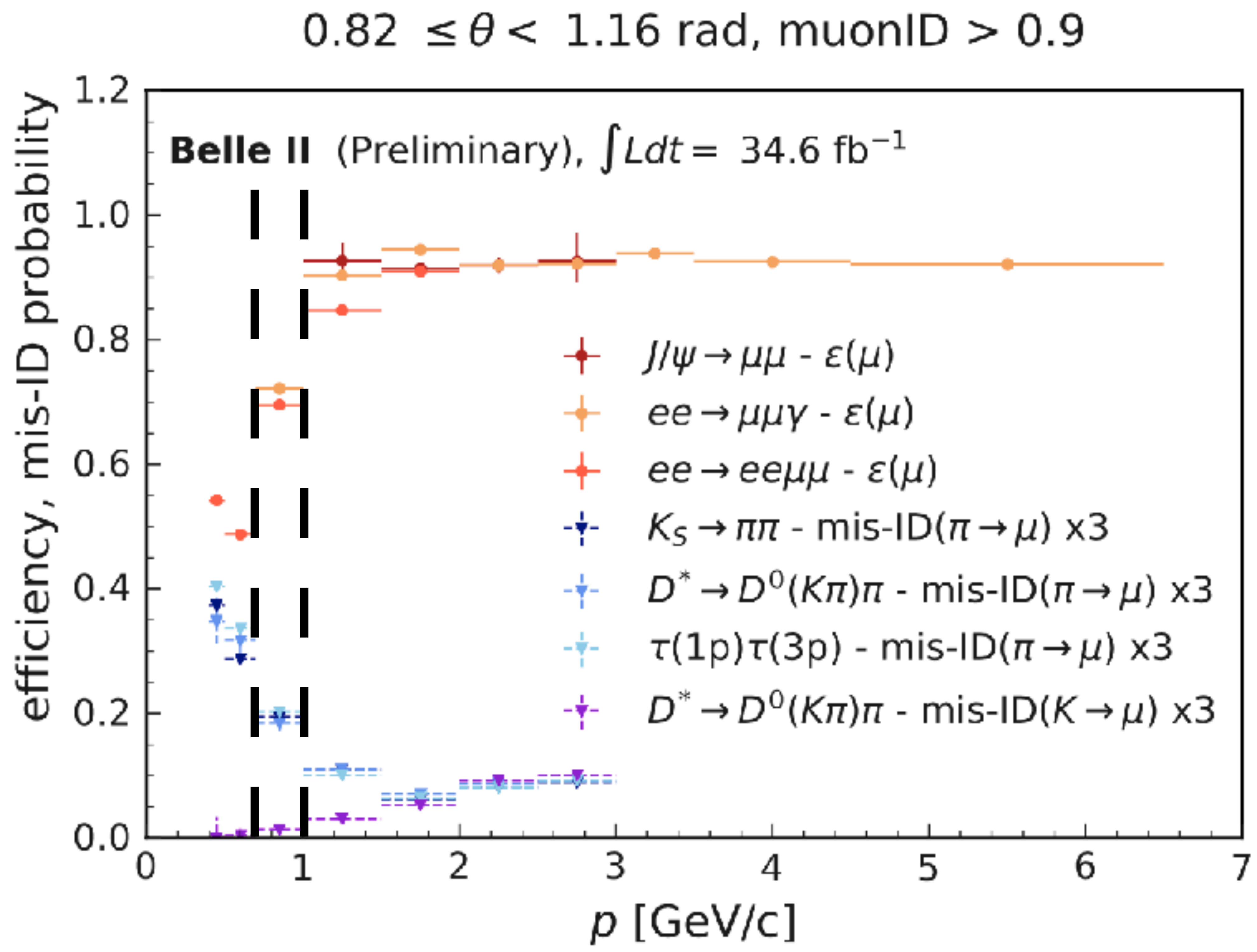
Best upper limits on $\tau\to3\mu$:

- Belle: **2.1 x 10^{-8}** @90% CL: $\int Ldt = 782 fb^{-1}$
- BaBar: **3.3 x 10^{-8}** @90% CL: $\int Ldt = 468 fb^{-1}$

Proposed improvement:
3 muons in the event → muon identification (muonID) performance plays a crucial role

Cut based approach based on μ momentum ranges:

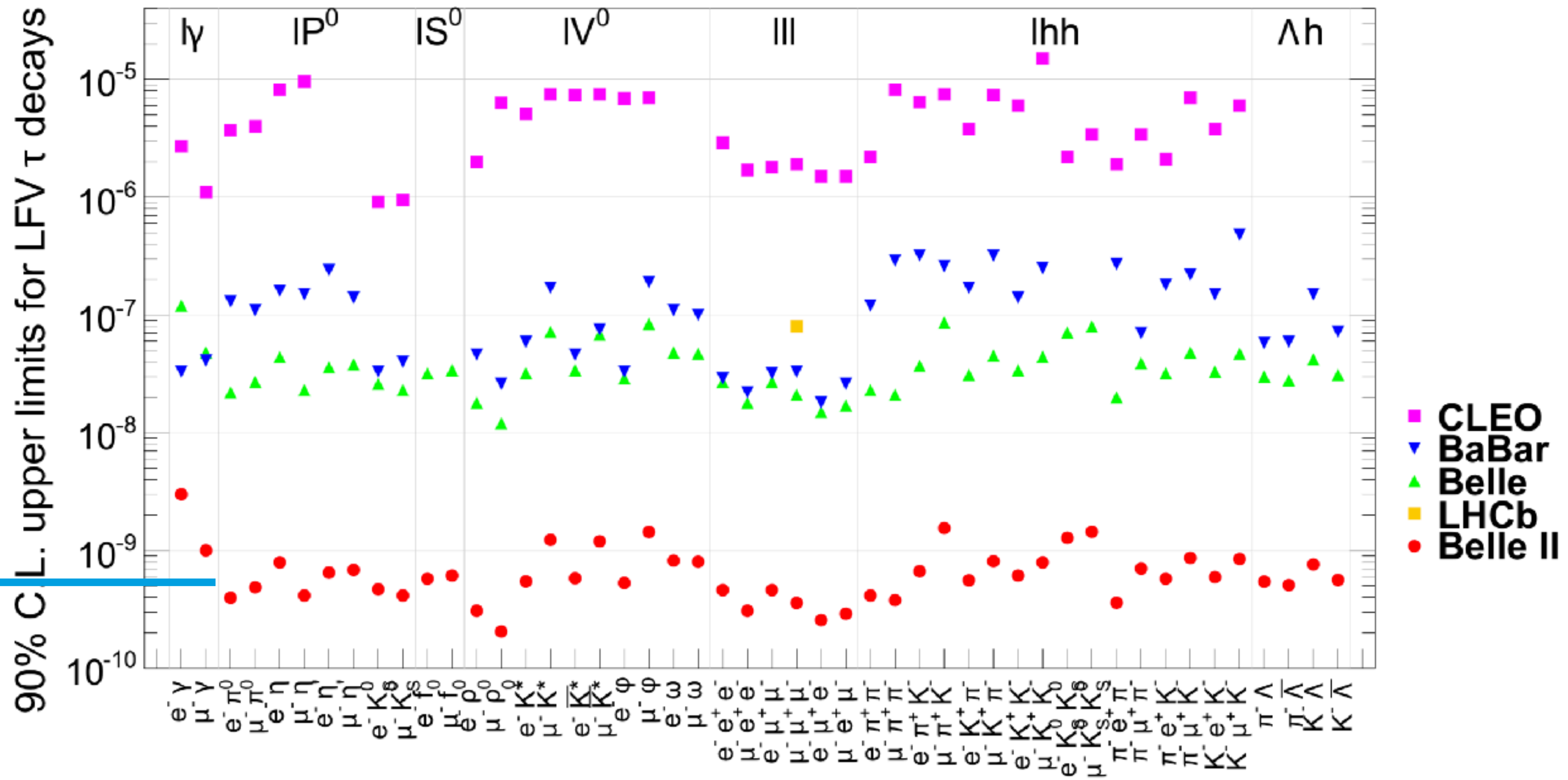
- **p_μ<0.7 GeV/c**: μ do not reach the μ detector (KLM)
- **0.7<p_μ<1 GeV/c**: μ barely reach KLM
- **p_μ>1 GeV/c**: μ properly reach KLM



Ref: https://docs.belle2.org/record/2062/files/BELLE2-NOTE-PL-2020-027.pdf

Belle II expected limits results on LFV channels

Expected limits with full statistics: 50 ab-1



Belle II is expected to improve the results of previous B-factory by a factor ~100 but…

With better analysis strategies results can be even better… and they are coming soon!