LFV τ searches at the Belle and Belle II experiments

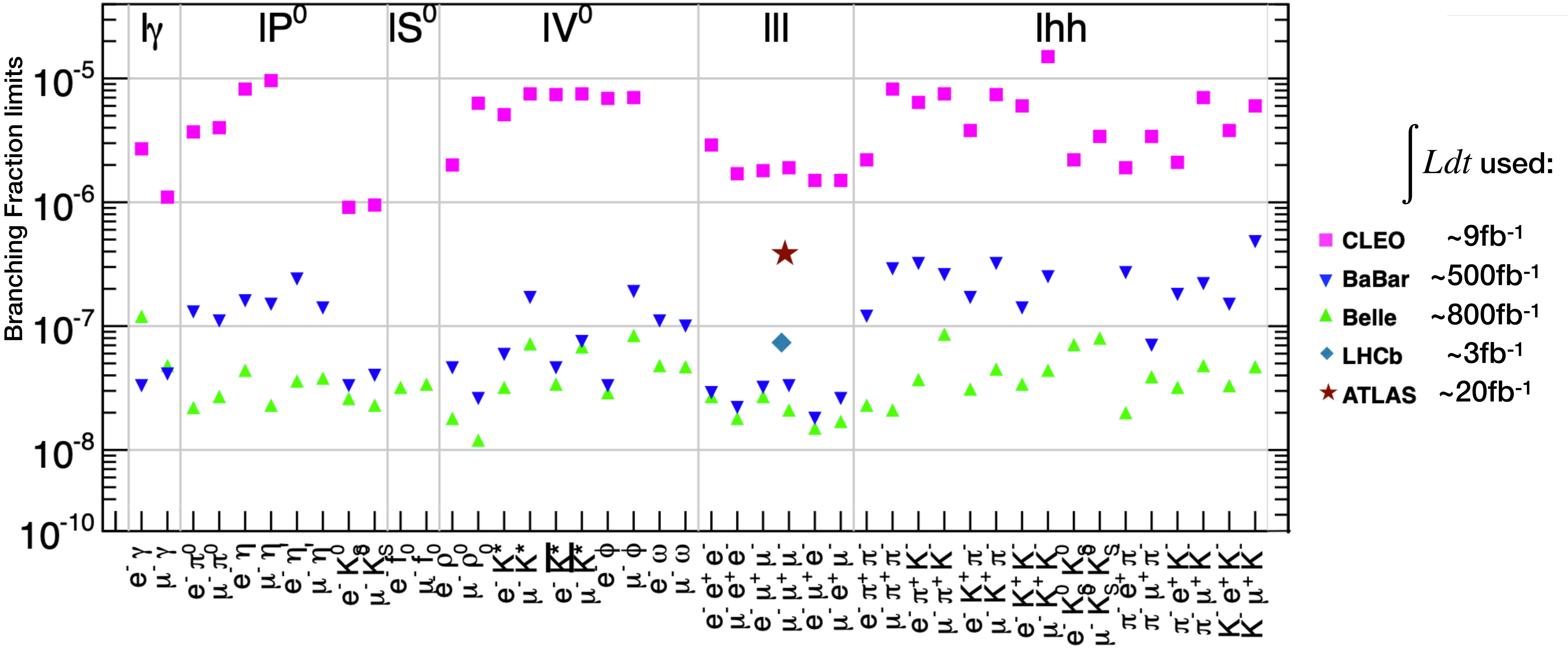
Alberto Martini - DESY (Deutsches Elektronen-Synchrotron)
on behalf of the Belle & Belle II collaborations

Tau2023 conference - 5 December 2023

τ LFV searches at B-factories

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

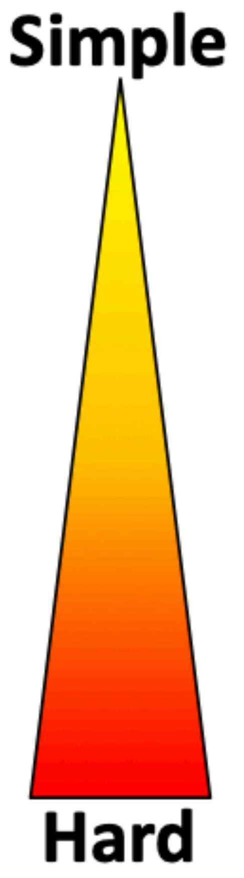
See talks by:
Kiyoshi Hayasaka
Pankaj Munbodh
Innes Bigaran



τ LFV channels

Search various decay modes:

- $\tau \to \ell\ell\ell$
- $\tau \to \ell K_s, \Lambda h$
- $\tau \to \ell V^0(\to hh')$
- $\tau \to \ell P^0\ (\to \gamma\gamma)$
- $\tau \to \ell hh'$
- $\tau \to \ell\gamma$



Difficulty of background reduction

Good determination of τ mass and energy + few SM background sources

Tough determination of τ mass and energy + irreducible SM backgrounds

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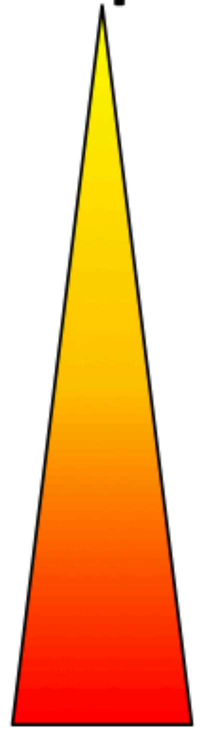
Simple



Hard

Difficulty of background reduction

Good determination of τ mass and energy + few SM background sources

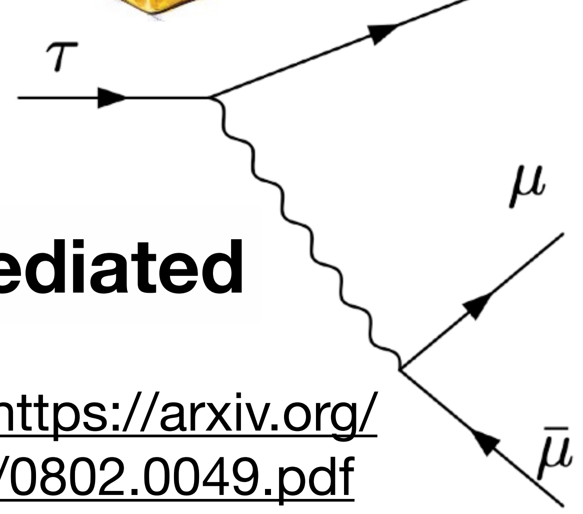
Tough determination of τ mass and energy + irreducible SM backgrounds

Golden channel: $\tau \to \mu\mu\mu$

experimentally the most accessible

ref: https://arxiv.org/pdf/1808.10567.pdf

Z' mediated

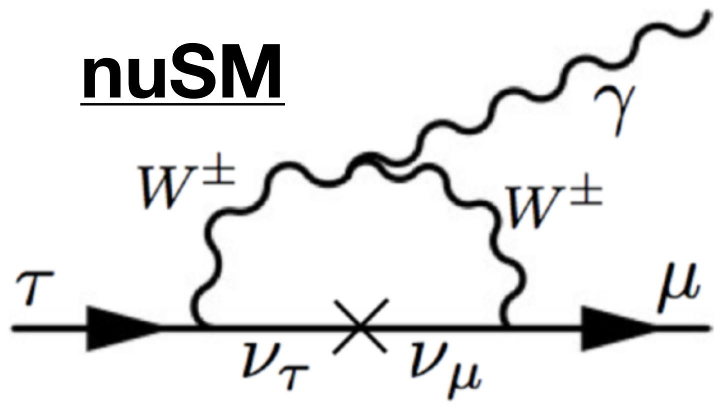


ref: https://arxiv.org/pdf/0802.0049.pdf

Golden channel: $\tau \to \mu\gamma$

Largest BF in models where a one-loop diagram is involved

nuSM



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

Physics models	$B(\tau \to \mu\gamma)$	$B(\tau \to \mu\mu\mu)$
SM + ν mixing	$10^{-49} \sim 10^{-52}$	$10^{-53} \sim 10^{-56}$
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: https://arxiv.org/abs/hep-ph/0702136

An observation would be a clear signature of NP!

τ LFV channels

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- $\tau \to \ell hh'$
- $\tau \to \ell\gamma$
- ★ $\tau \to$ l α

See talk from Sourav Dey later today

Simple

Difficulty of background reduction

Hard

Simple → Good determination of τ mass and energy + few SM background sources

Hard → Tough determination of τ mass and energy + irreducible SM backgrounds

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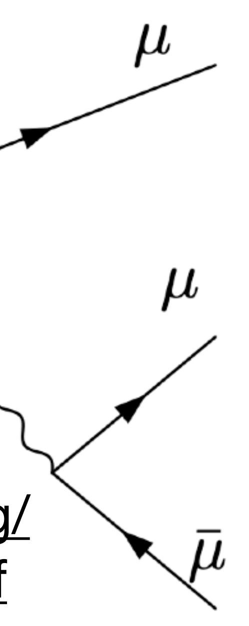

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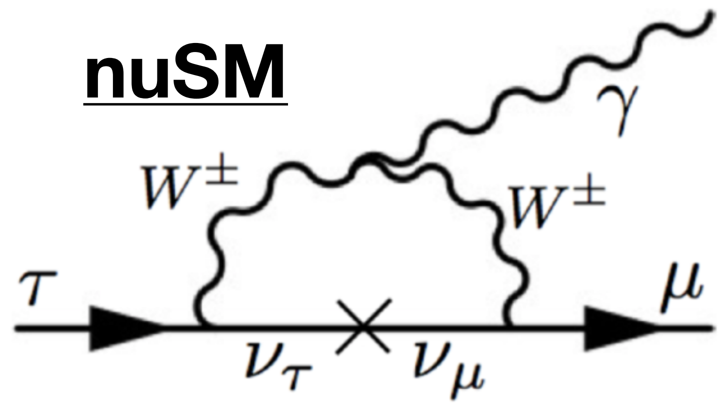

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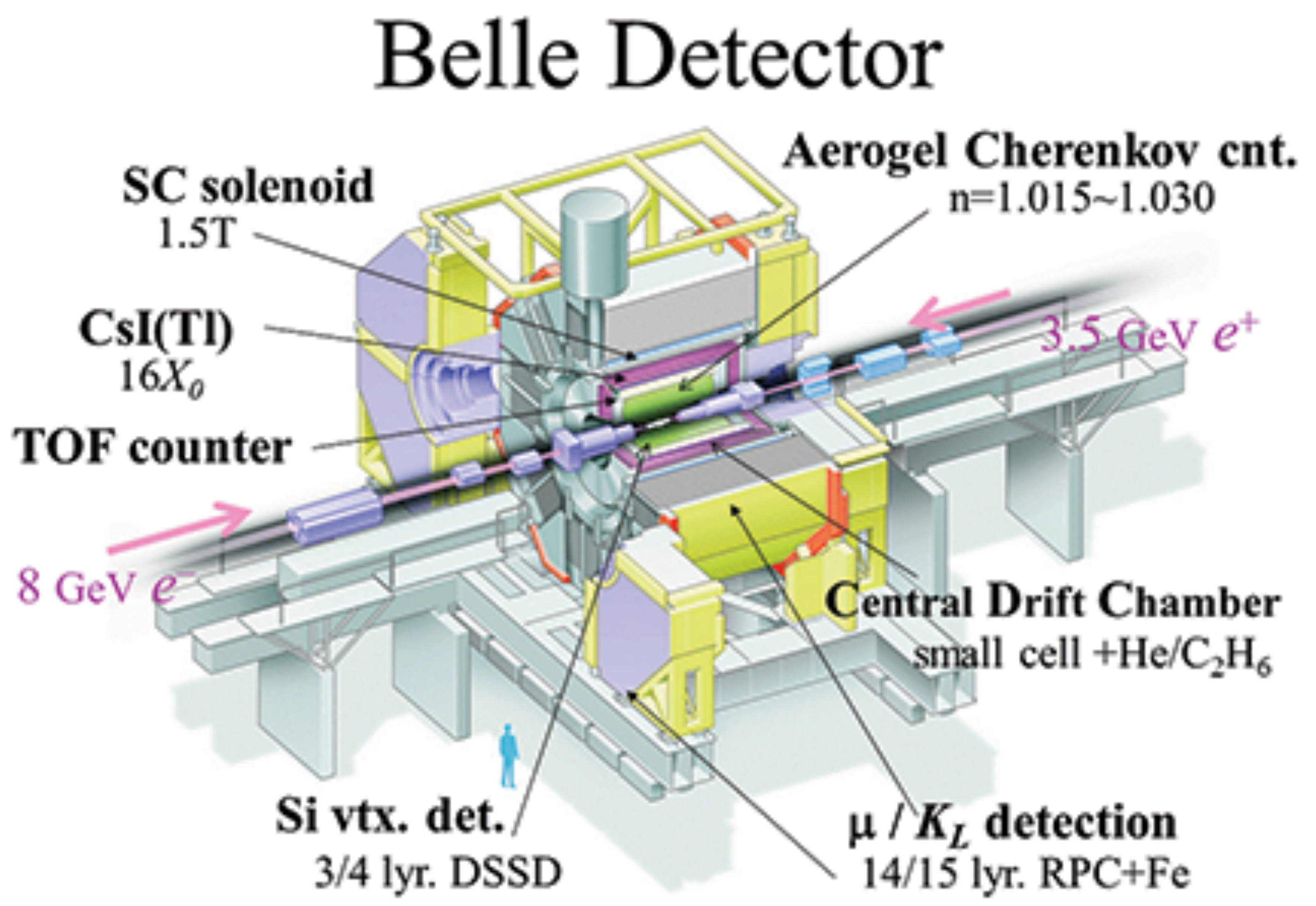
Introduction to the B-factories: Belle & Belle II

The **Belle experiment (1999 - 2010)** and the **Belle II experiment (2018 -)** operate at B-factories KEKB and SuperKEKB → collisions of $e^+ e^-$ at Υ(4S) resonance: 10.58 GeV

Belle recorded L_{int} ~1000 fb^{-1}

Belle II recorded L_{int}= 424 fb^{-1}

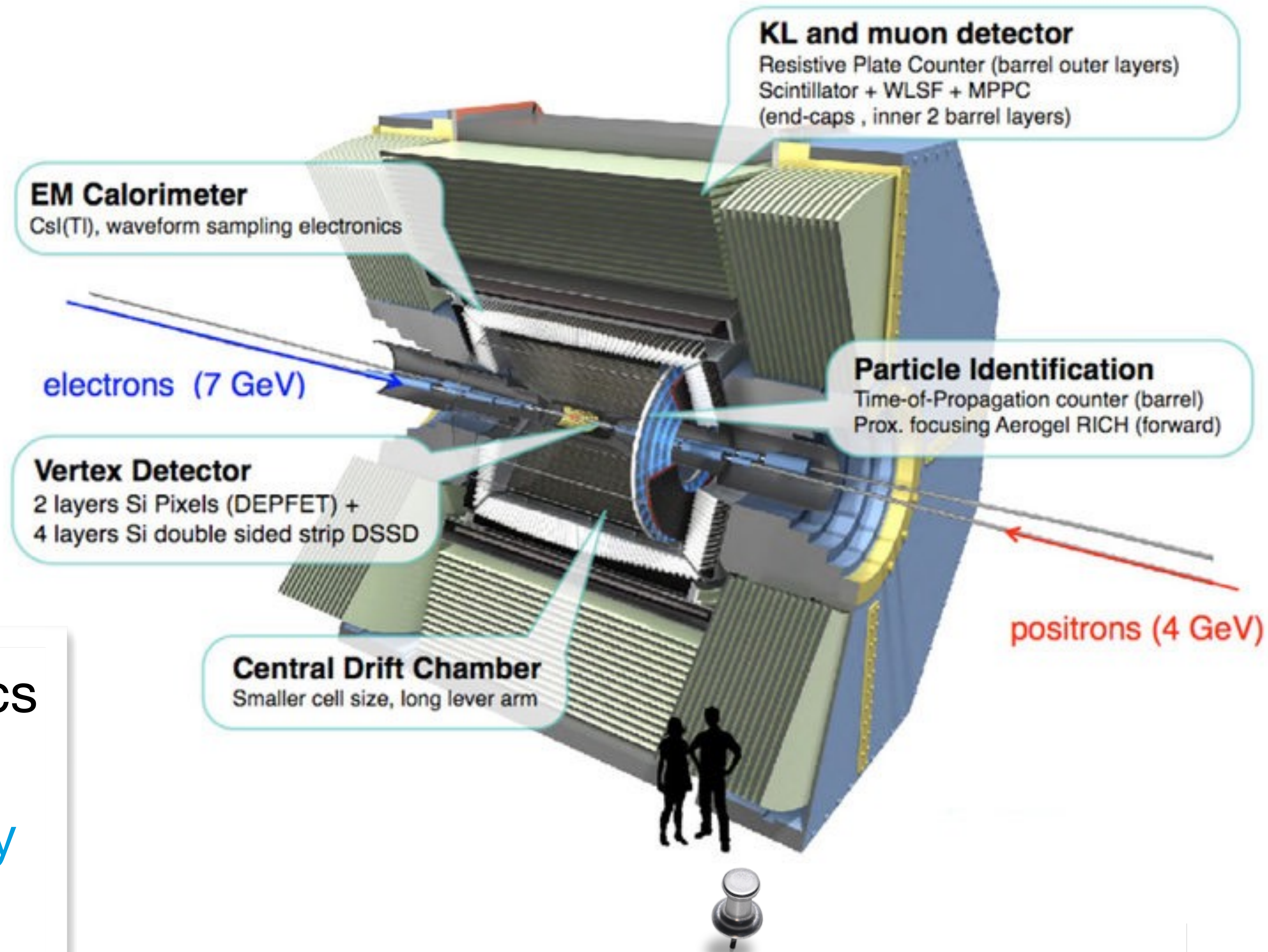


$$\sigma(ee \to bb) \simeq 1.1 \text{ nb}$$
$$\sigma(ee \to \tau\tau) \simeq 0.9 \text{ nb}$$

↓

$N_{\tau\tau}$ ~ 4x10^8 @Belle II

→ τ factory!



Advantages of studying τ physics at B-factories:

- Well defined initial state energy
- Clean environment
- High hermeticity of the detector

Luminosity world record @SuperKEKB: $4.7 \times 10^{34} cm^{-2} s^{-1}$

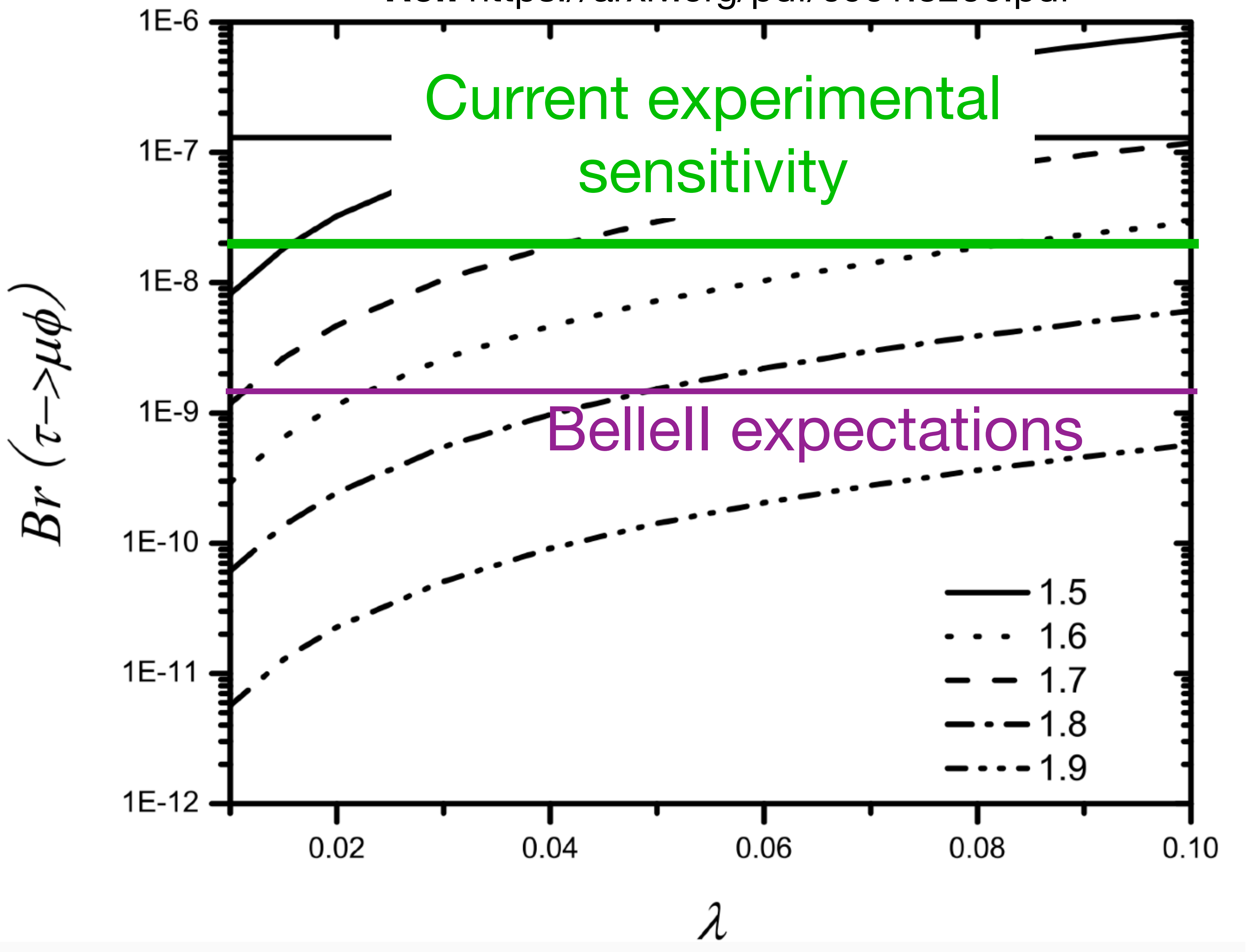
Analysis motivations: $\tau \to lV^0$

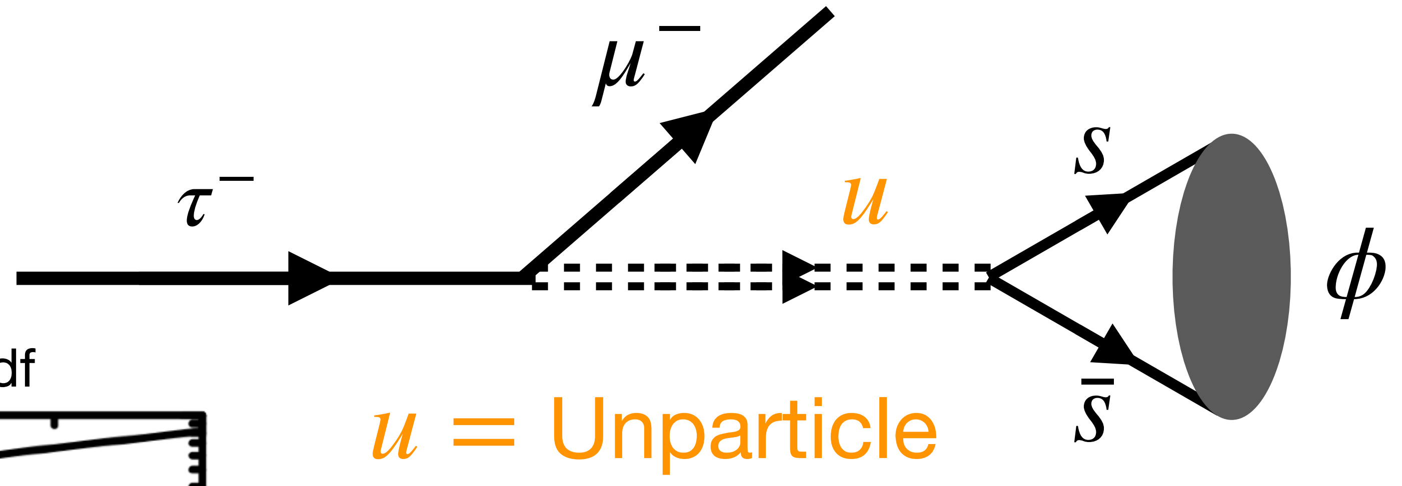
Decay channel forbidden in the SM but allowed in several new physics scenarios

Unparticle model

Ref: https://arxiv.org/pdf/hep-ph/0703260.pdf

Ref: https://arxiv.org/pdf/0901.3266.pdf

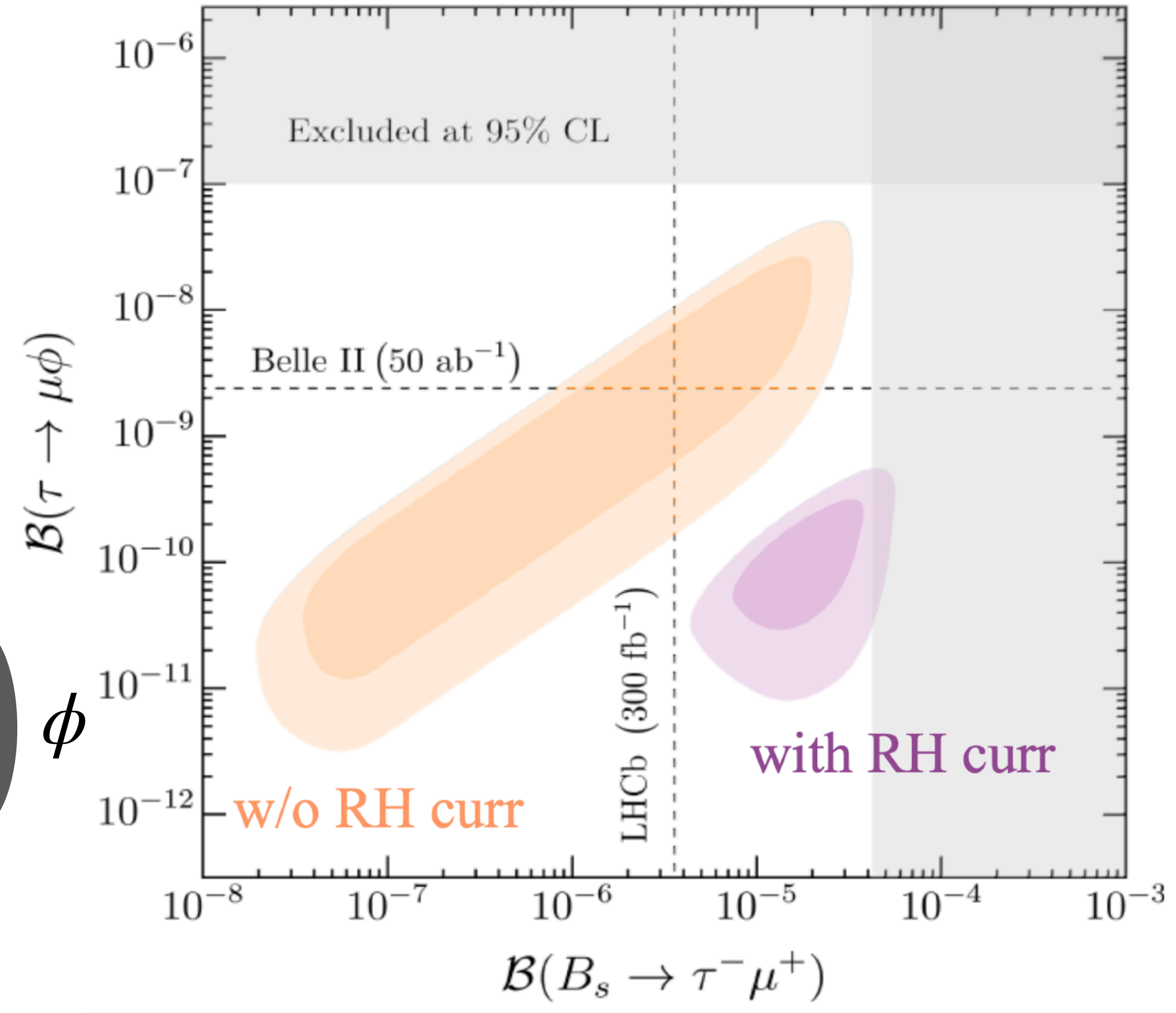


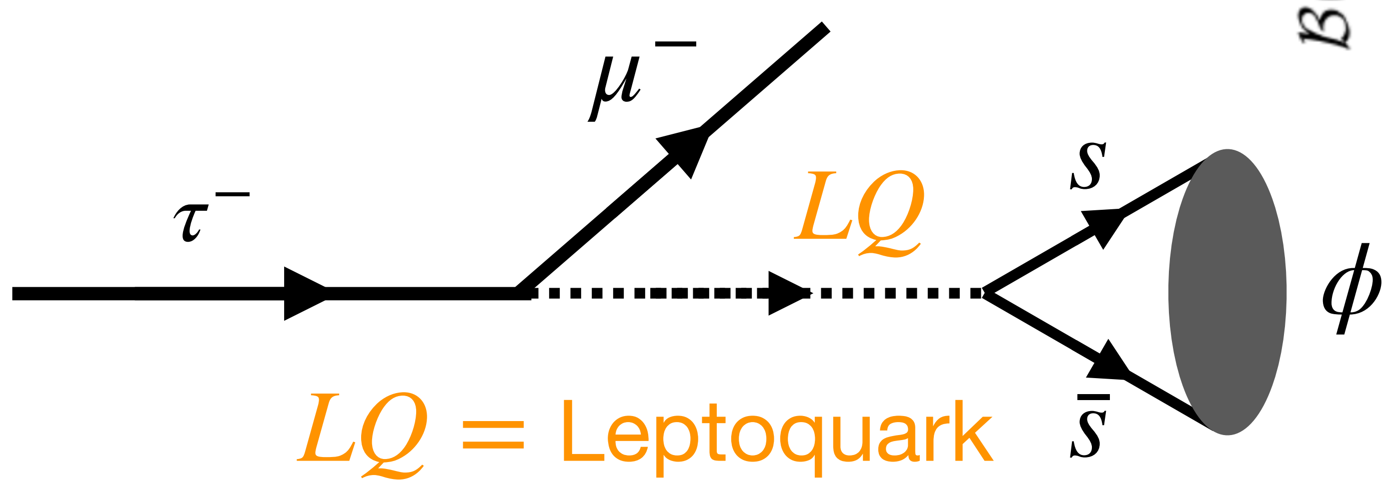


One of the golden channels for this model

Leptoquark model

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



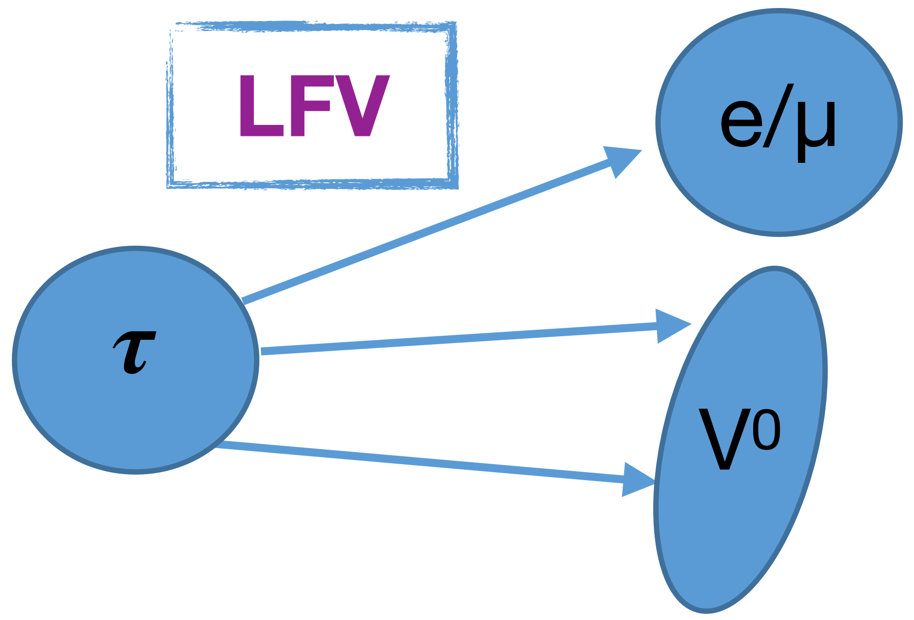


Nice interplay between B and τ physics!

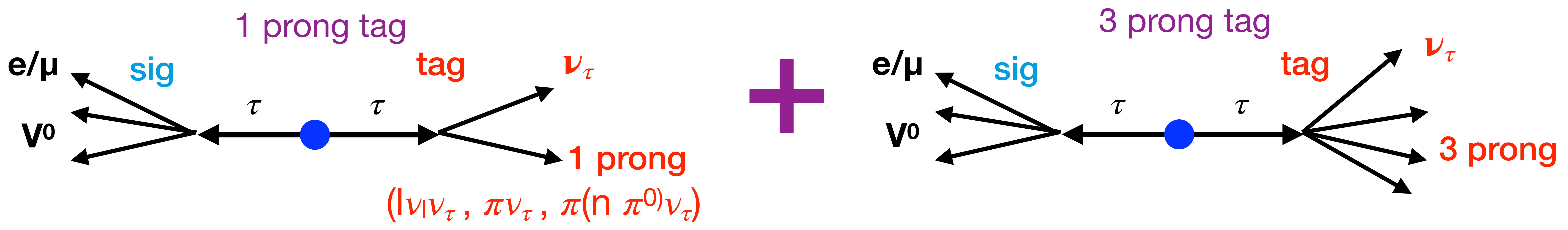
Analysis steps for $\tau \to lV^0$ @Belle

Belle analysis on $V^0 = (\rho^0, \phi, \omega, K^*)$

ref: https://arxiv.org/pdf/2301.03768.pdf



Analysis including 3-prong decay for τ_{tag} with ~850 fb^{-1}



Analysis steps:

- Event selection and background suppression via **BDT**
- Prepare BDT classifier **for each LFV mode**
  - For all modes: V^0 mass; event tag side & decay modes; event shape and kinematics
    - Additional for the lω modes: momentum of π^0 from ω and lower energy of the two photons from π^0

Dominant syst. from tracking efficiency and particle identification
Negligible impact on the limit

Analysis results for $\tau \to lV^0$ @Belle

No significant excess found → set ULs at 90% CL by counting approach

Mode	ε (%)	N_{BG}	σ_{syst} (%)	N_{obs}	$\mathcal{B}_{obs}$ ($\times 10^{-8}$)	
$\tau^\pm \to \mu^\pm \rho^0$	7.78	0.95±0.20(stat.) ±0.15(syst.)	4.6	0	< 1.7	
$\tau^\pm \to e^\pm \rho^0$	8.49	0.80±0.27(stat.) ±0.04(syst.)	4.4	1	< 2.2	
$\tau^\pm \to \mu^\pm \phi$	5.59	0.47±0.15(stat.) ±0.05(syst.)	4.8	0	< 2.3	•
$\tau^\pm \to e^\pm \phi$	6.45	0.38±0.21(stat.) ±0.00(syst.)	4.5	0	< 2.0	•
$\tau^\pm \to \mu^\pm \omega$	3.27	0.32±0.23(stat.) ±0.19(syst.)	4.8	0	< 3.9	•
$\tau^\pm \to e^\pm \omega$	5.41	0.74±0.43(stat.) ±0.06(syst.)	4.5	0	< 2.4	•
$\tau^\pm \to \mu^\pm K^{*0}$	4.52	0.84±0.25(stat.) ±0.31(syst.)	4.3	0	< 2.9	•
$\tau^\pm \to e^\pm K^{*0}$	6.94	0.54±0.21(stat.) ±0.16(syst.)	4.1	0	< 1.9	•
$\tau^\pm \to \mu^\pm \overline{K}^{*0}$	4.58	0.58±0.17(stat.) ±0.12(syst.)	4.3	1	< 4.3	•
$\tau^\pm \to e^\pm \overline{K}^{*0}$	7.45	0.25±0.11(stat.) ±0.02(syst.)	4.1	0	< 1.7	•

$$\mathbf{B}(\tau \to e V^0) < (1.7 - 2.4) \times 10^{-8}$$
$$\mathbf{B}(\tau \to \mu V^0) < (1.7 - 4.3) \times 10^{-8}$$

World best results!
~30% improvement wrt previous results done @Belle with 543 fb^{-1}!

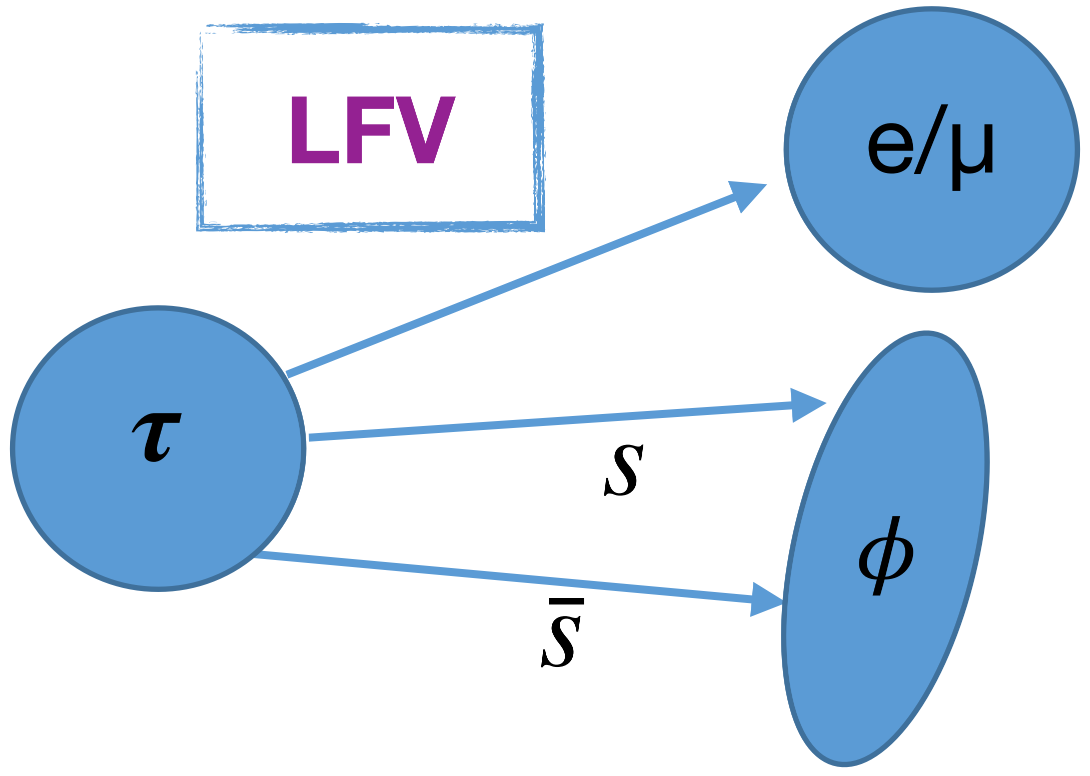
ref: https://arxiv.org/pdf/0801.2475.pdf

Analysis steps for $\tau \to l\phi$ @Belle II

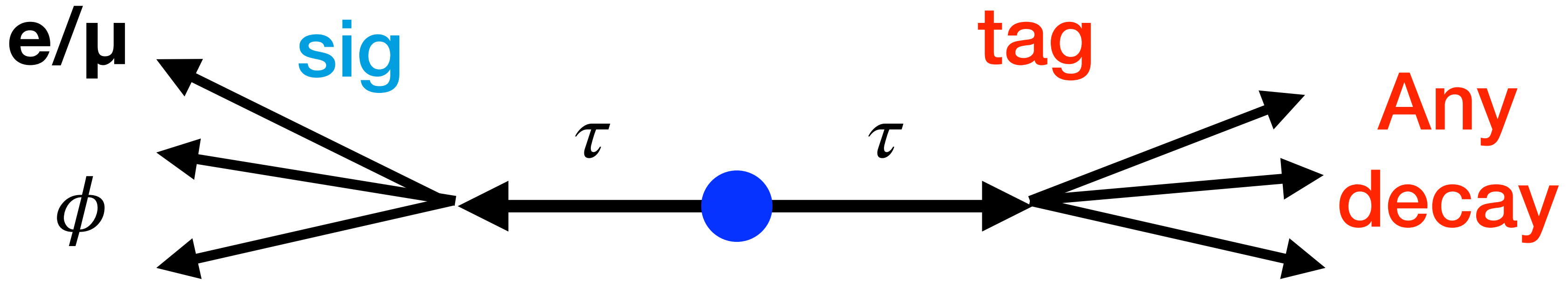
Belle II analysis where $V^0 = \phi$

ref: https://arxiv.org/pdf/2305.04759.pdf

First application of untagged approach with 190 fb^{-1}



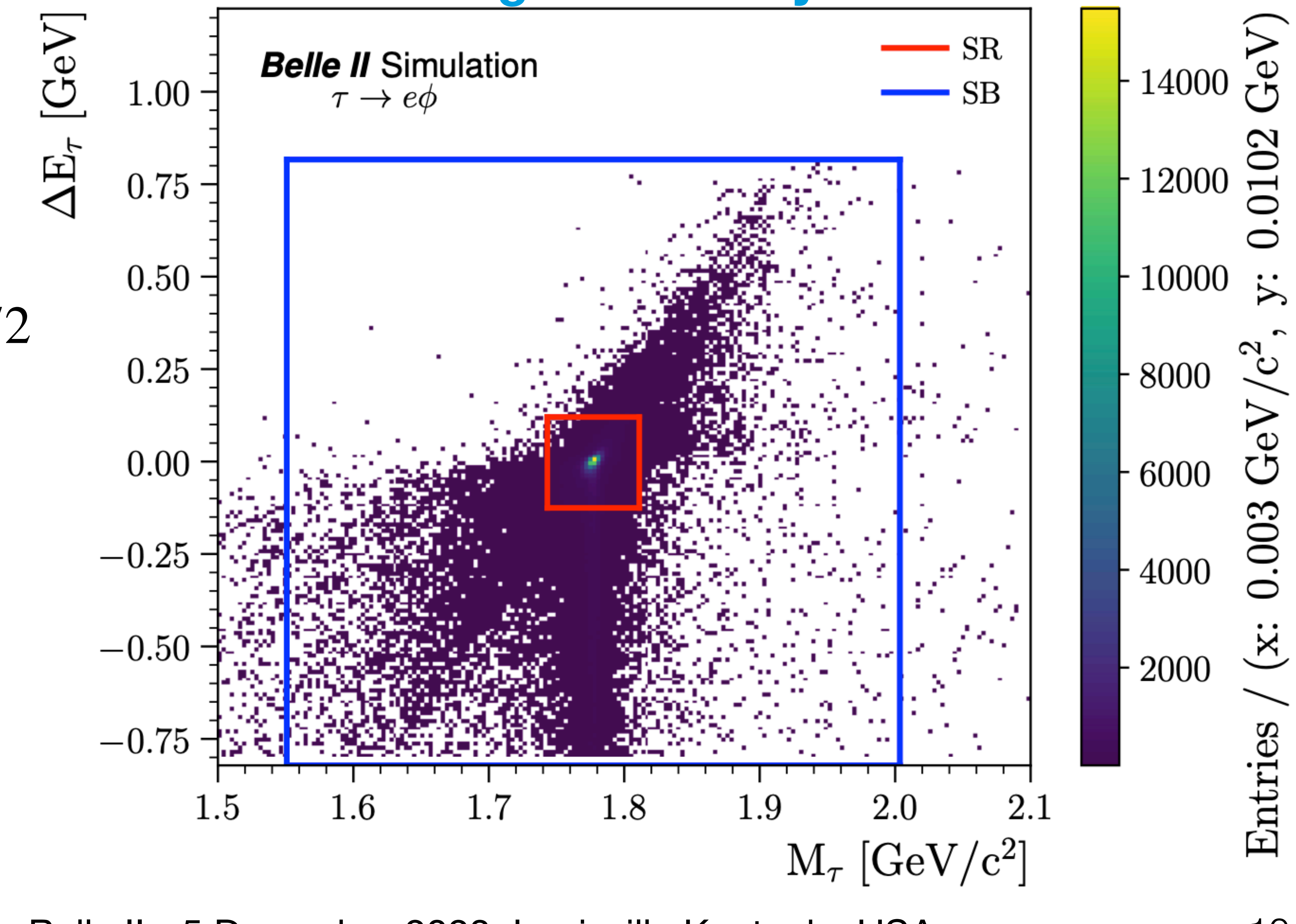
Untagged reconstruction approach



Analysis steps

- Definition of a Signal Region (SR) via the $M_{l\phi}$ and $\Delta E_{l\phi} = E^*_{l\phi} - \sqrt{s}/2$
- Event selection and background rejection using via BDT

Signal MC only



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ref: https://arxiv.org/pdf/2305.04759.pdf

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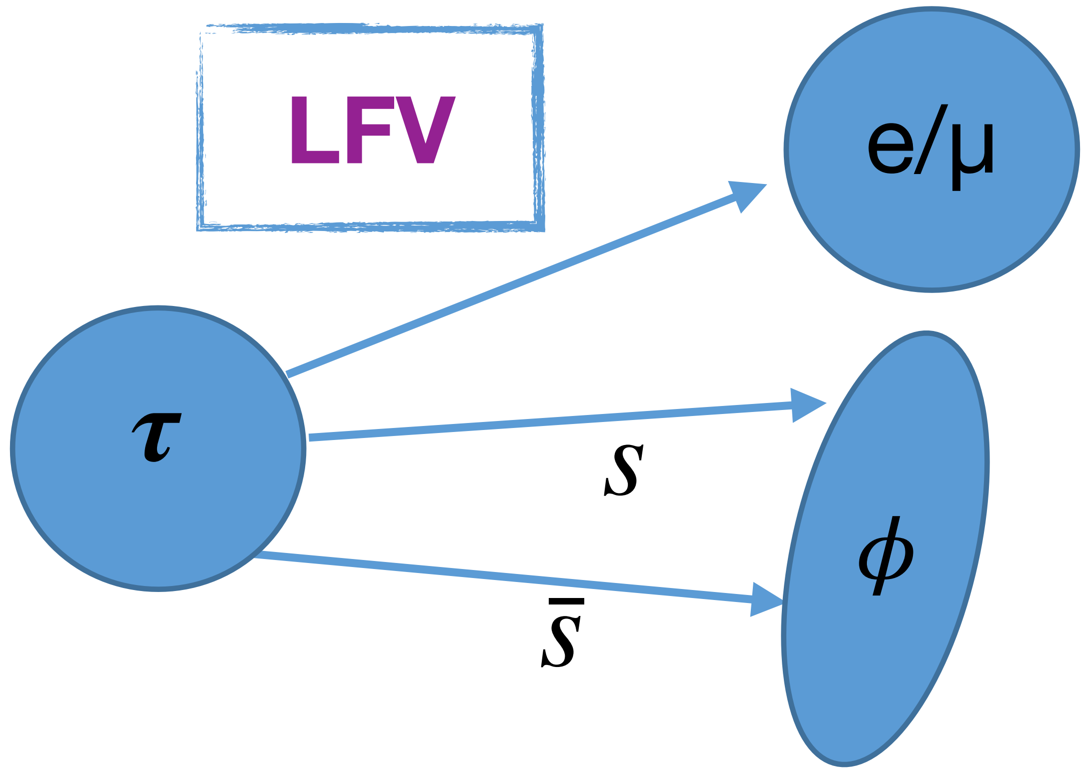

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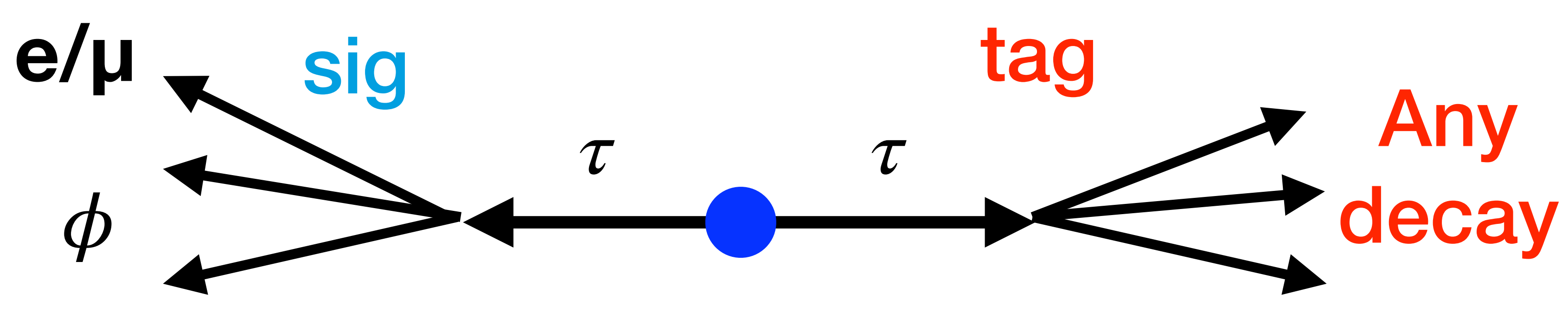

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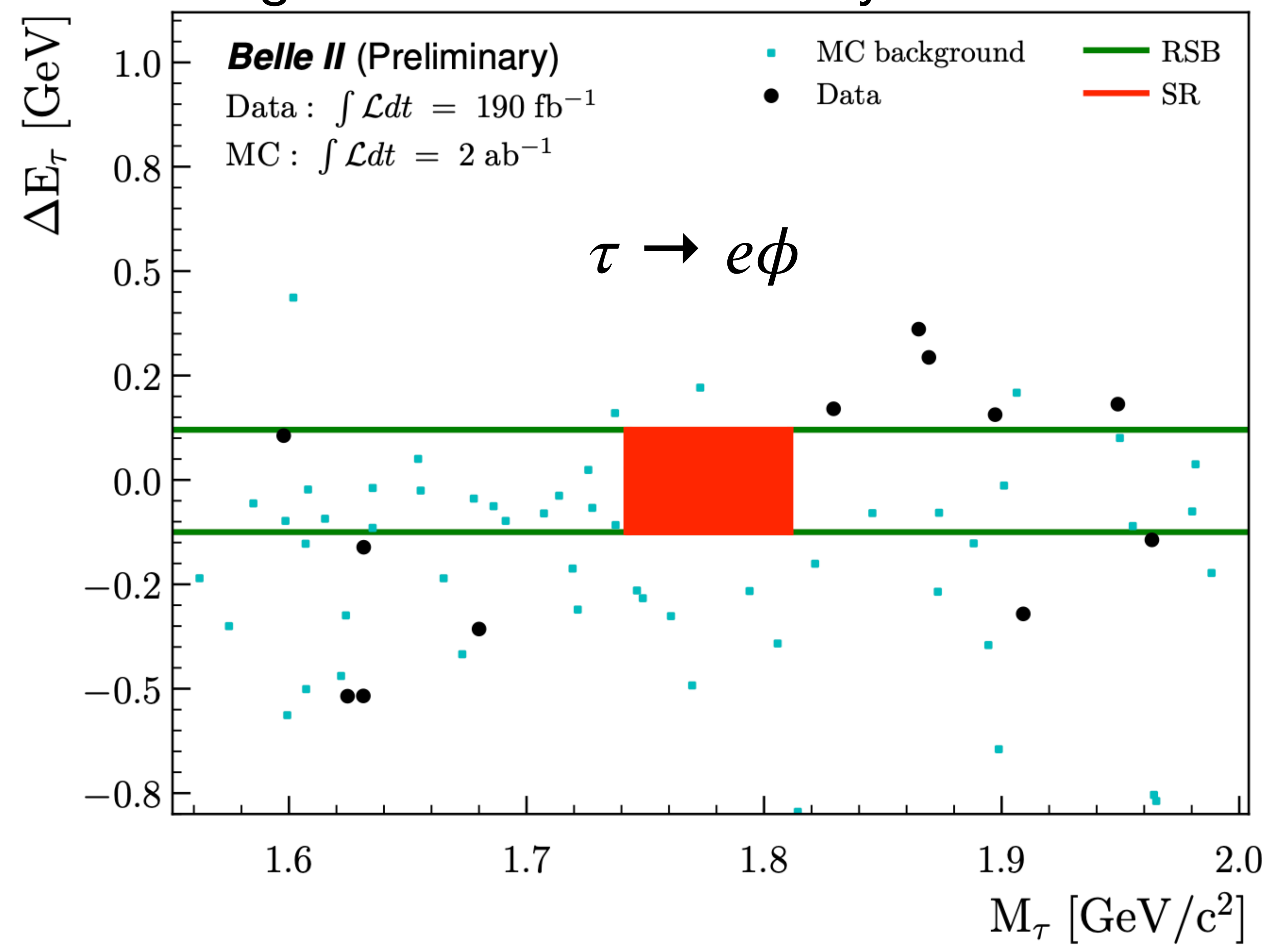
- Event selection and background rejection using via BDT
- Background events evaluated from data in the sideband

Signal detection efficiency ~ 2 × Belle



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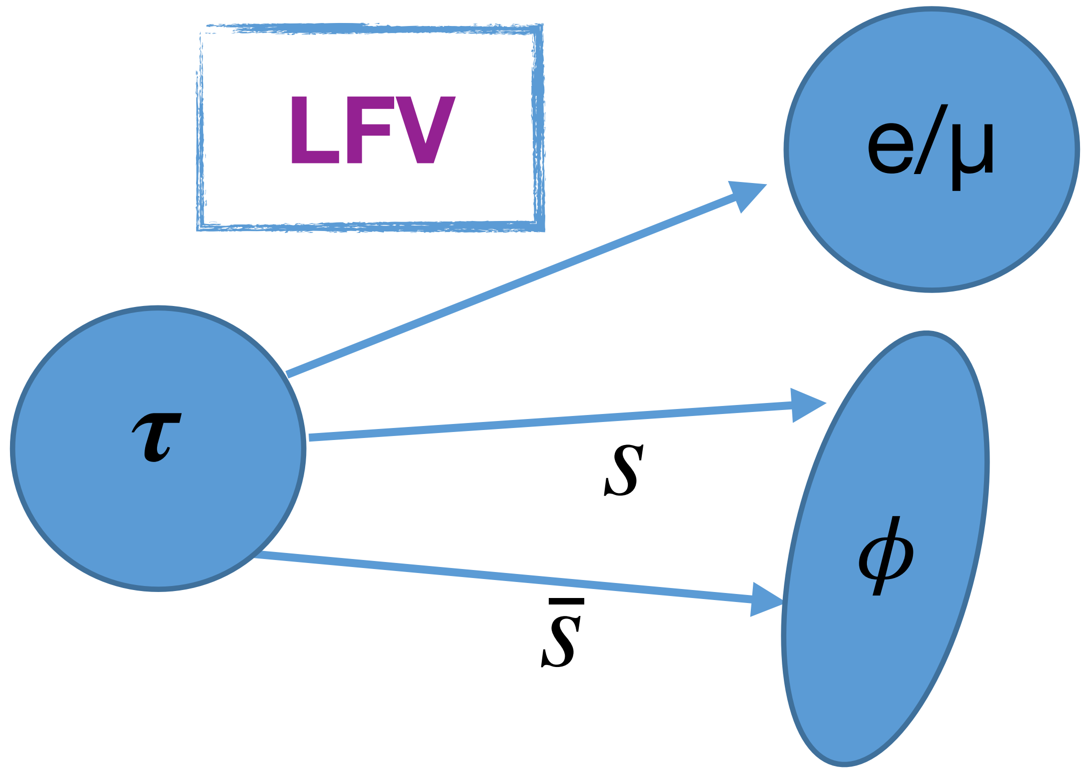

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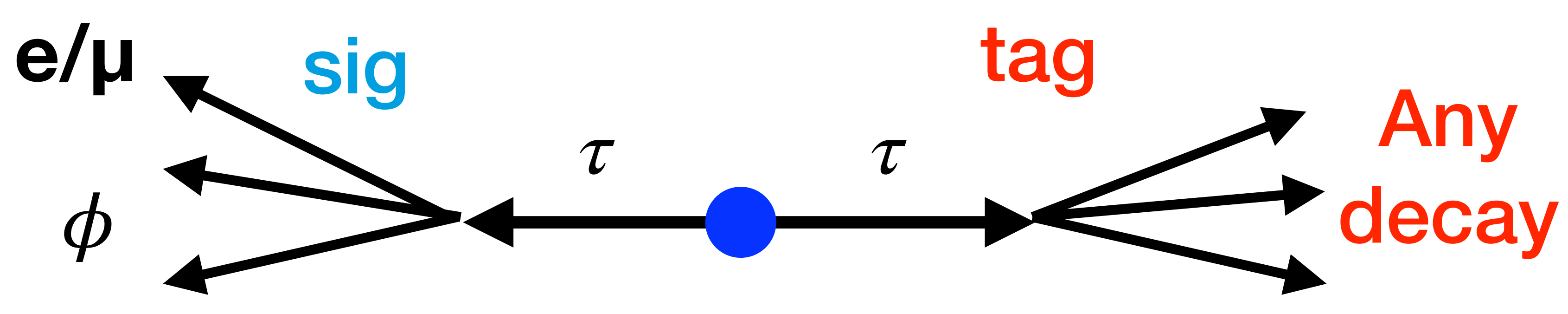

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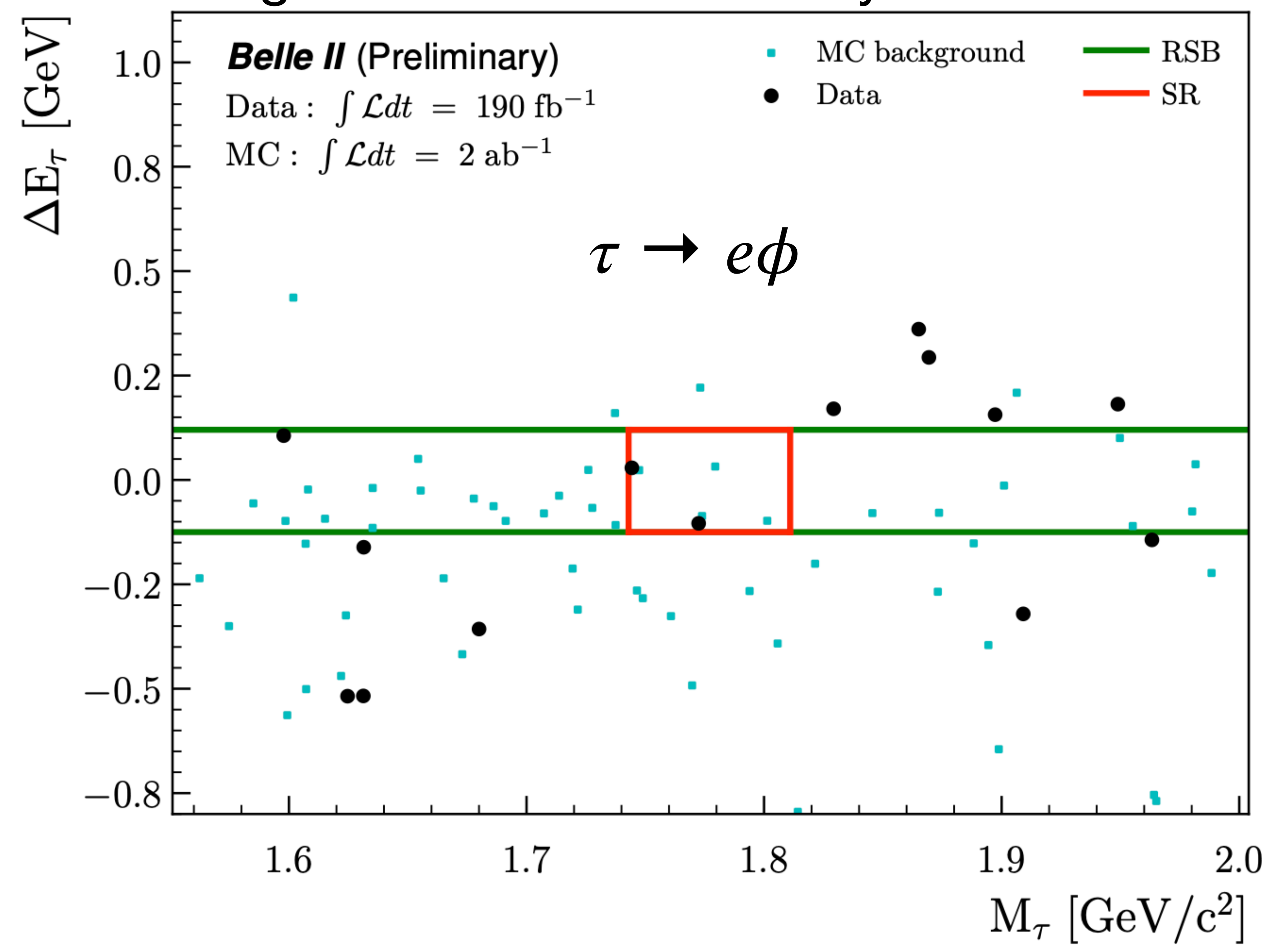

Analysis steps

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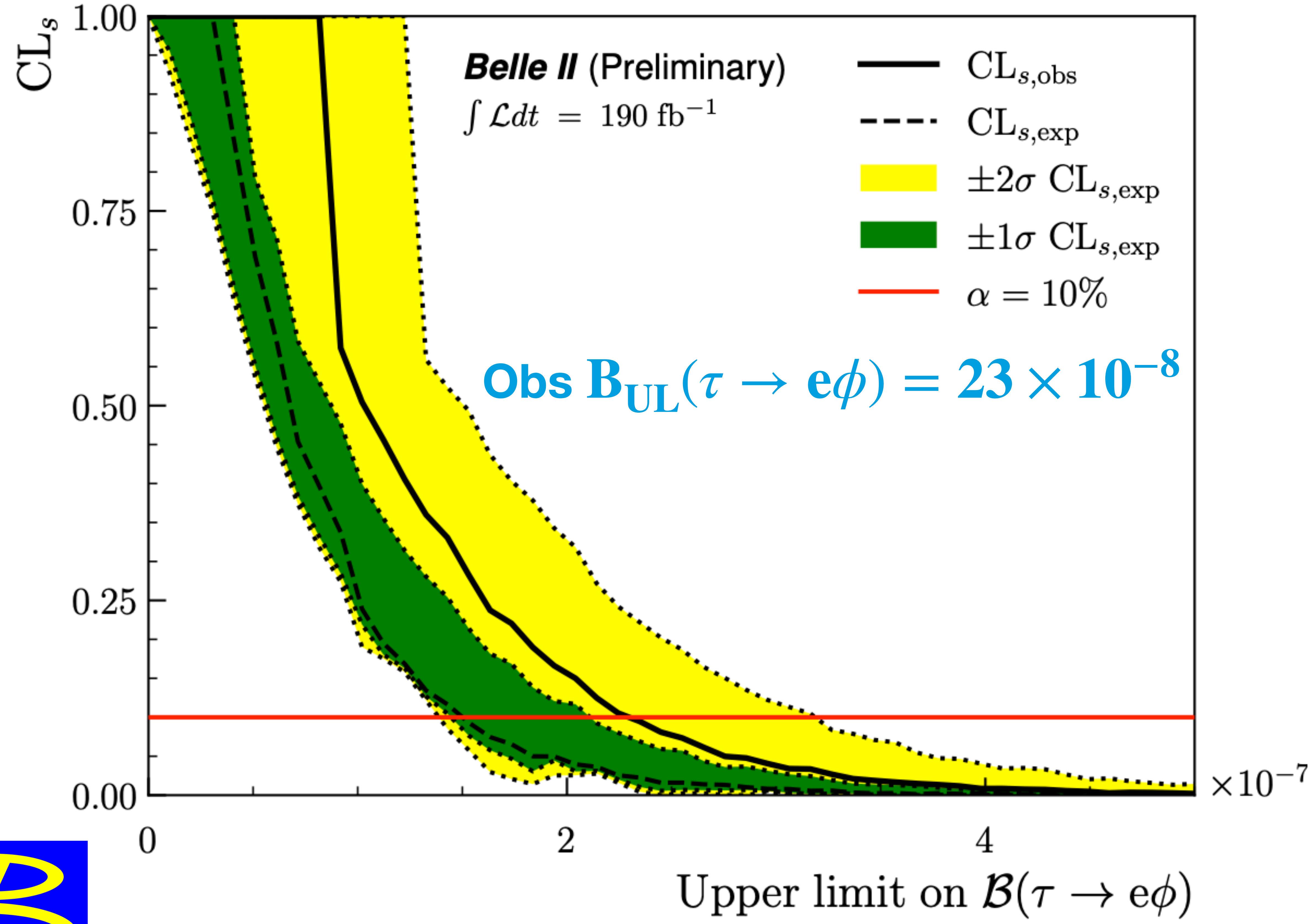
- Background events evaluated from data in the sideband
- Poisson counting experiment approach in SR

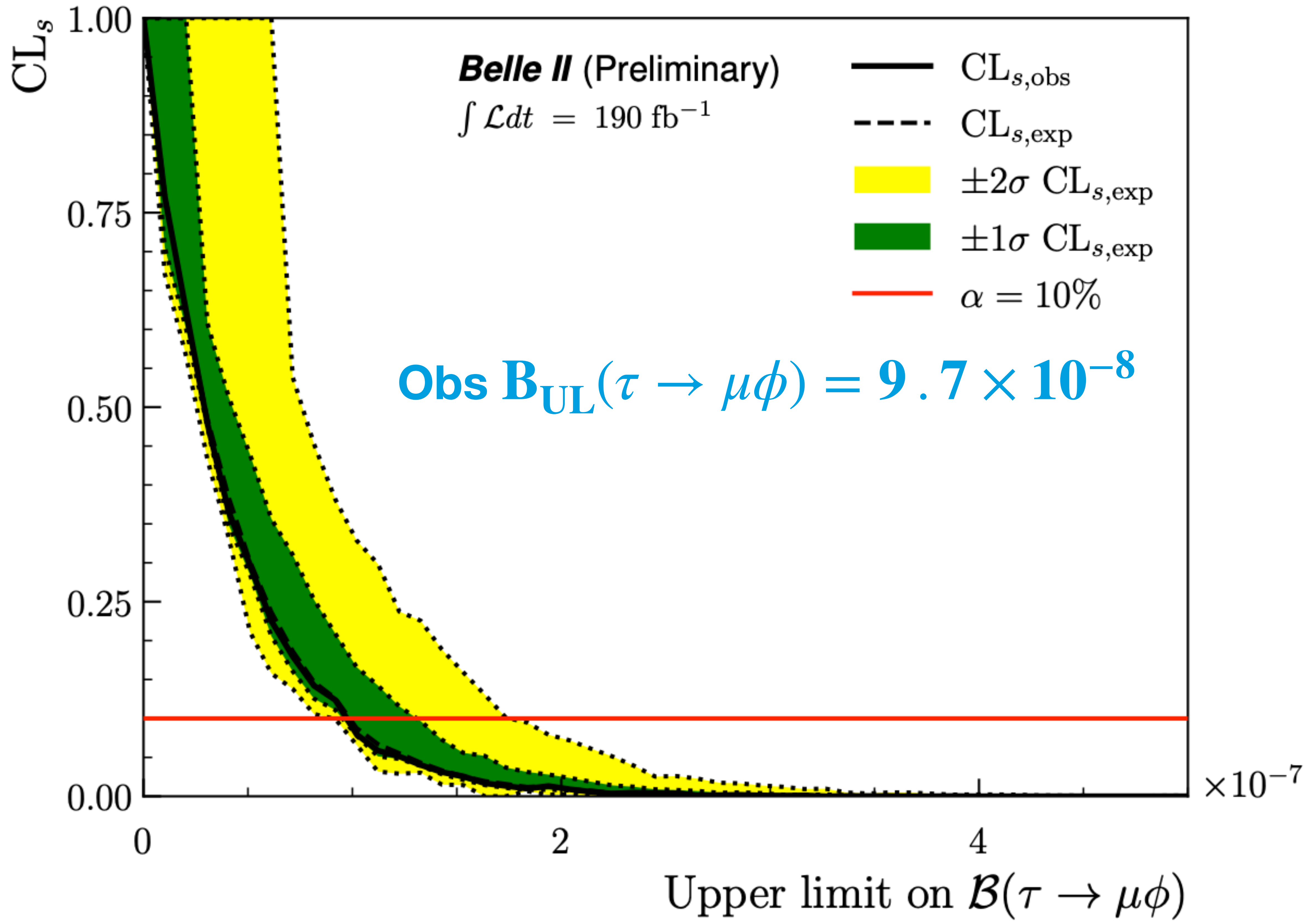
Results for $\tau \to l\phi$ @Belle II

No signal evidence → set ULs at 90% CL

Quantity	Region	Mode $e\phi$	Mode $\mu\phi$
$N_{\rm exp}$	SR	$0.23^{+0.55}_{-0.21}$ (stat)	$0.36^{+0.39}_{-0.23}$ (stat)
$N_{\rm obs}$	SR	$2.0^{+2.6}_{-1.3}$ (stat)	$0.0^{+1.8}_{-0.0}$ (stat)

Dominant syst. from signal variable mismodeling
Negligible impact on the limit



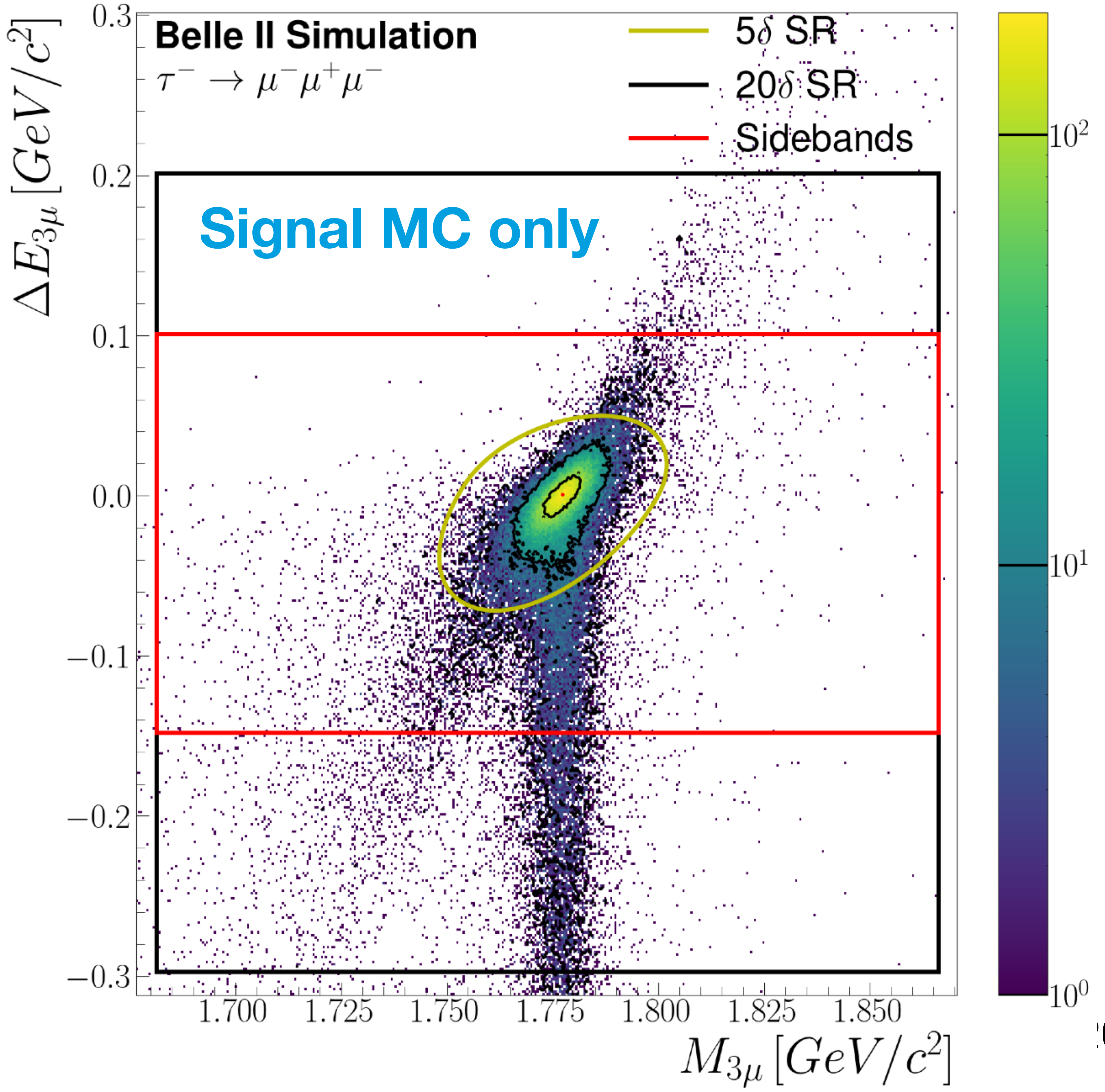


Analysis of $\tau \to 3\mu$ @Belle II

Best upper limits on $\tau \to 3\mu$ from Belle: **2.1 x 10^{-8}** @90% CL with 782 fb^{-1} but Belle II is already competitive with 424 fb^{-1}

Fully reconstucted decay of the signal tau

- No backgrounds from SM processes
- Tight signal region → large background reduction using $\mathbf{\Delta E_{3\mu} \equiv E_{\tau sig} - E_{beam}}$ and $M_{3\mu}$



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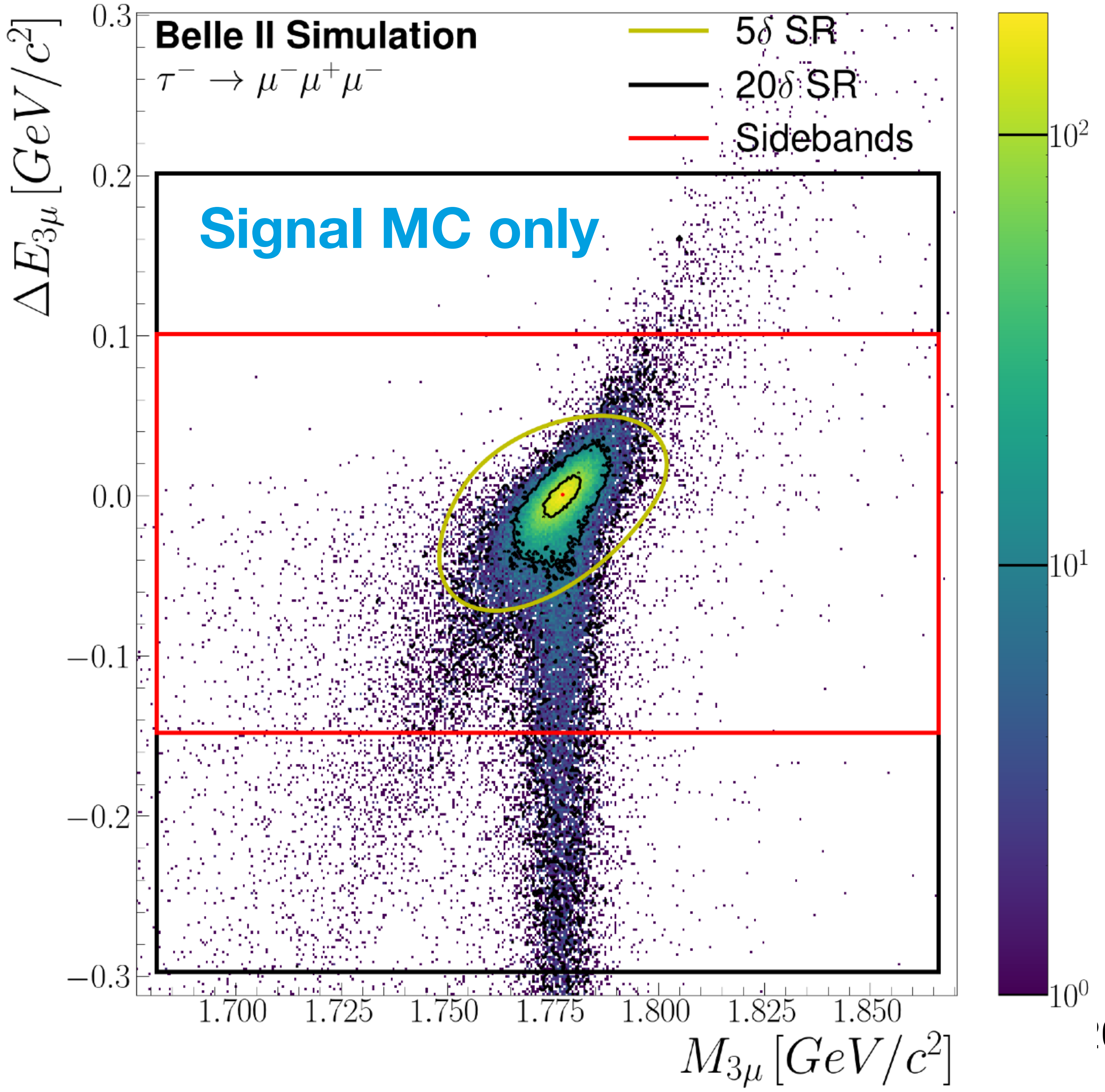
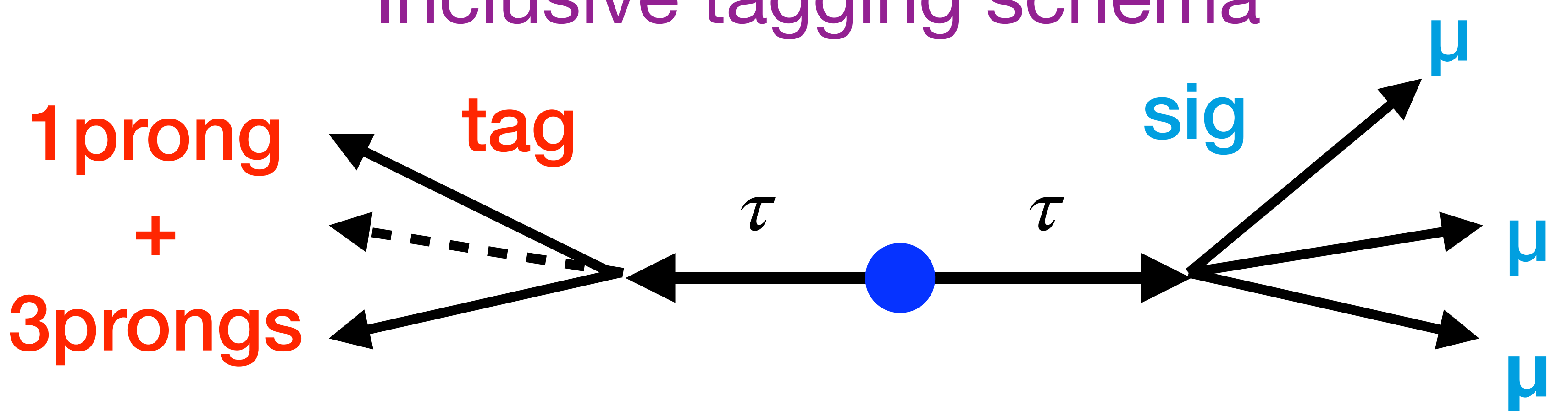


Main analysis approach:

- Inclusive approach:
  - Selection and background rejection based on BDT
  - Inclusion of 3x1 and 1x1 topologies

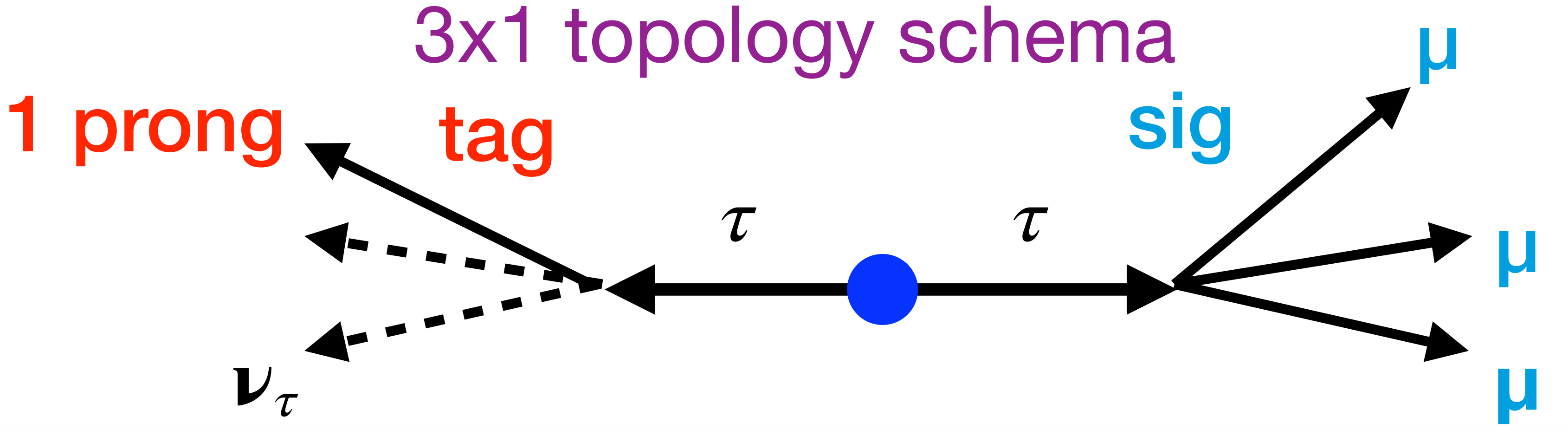
Inclusive tagging schema



Conventional 3x1 tagging approach:

- muon identification cuts optimised as a function of the track momentum

3x1 topology schema



Results for $\tau \to 3\mu$ @Belle II: inclusive approach

Analysis selection and results: inclusive approach

GBoost BDT trained on 32 variables:

- Inputs from: signal τ; event tag side; event shape and kinematics

ε_{sig}= **20.42** ± 0.06% ~3x larger than Belle & Expected BKG: $0.5^{+1.4}_{-0.5}$ events

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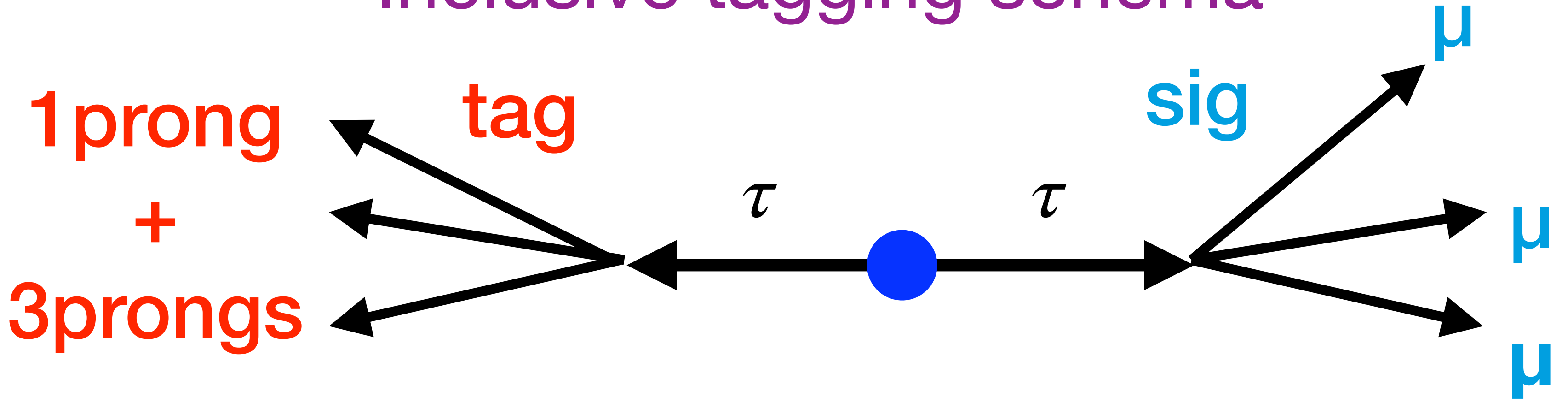

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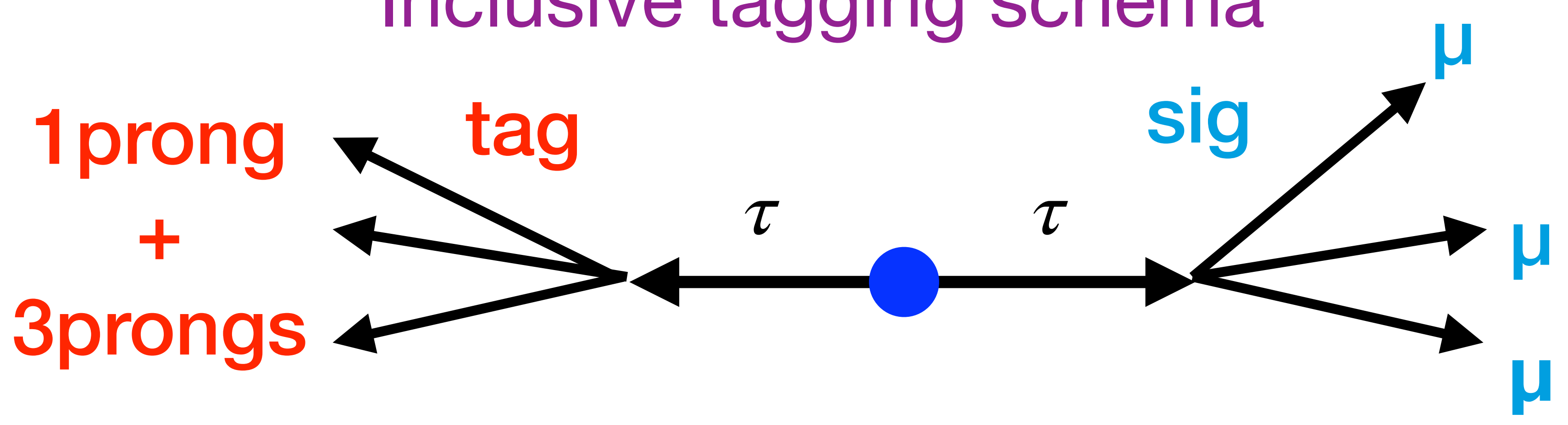
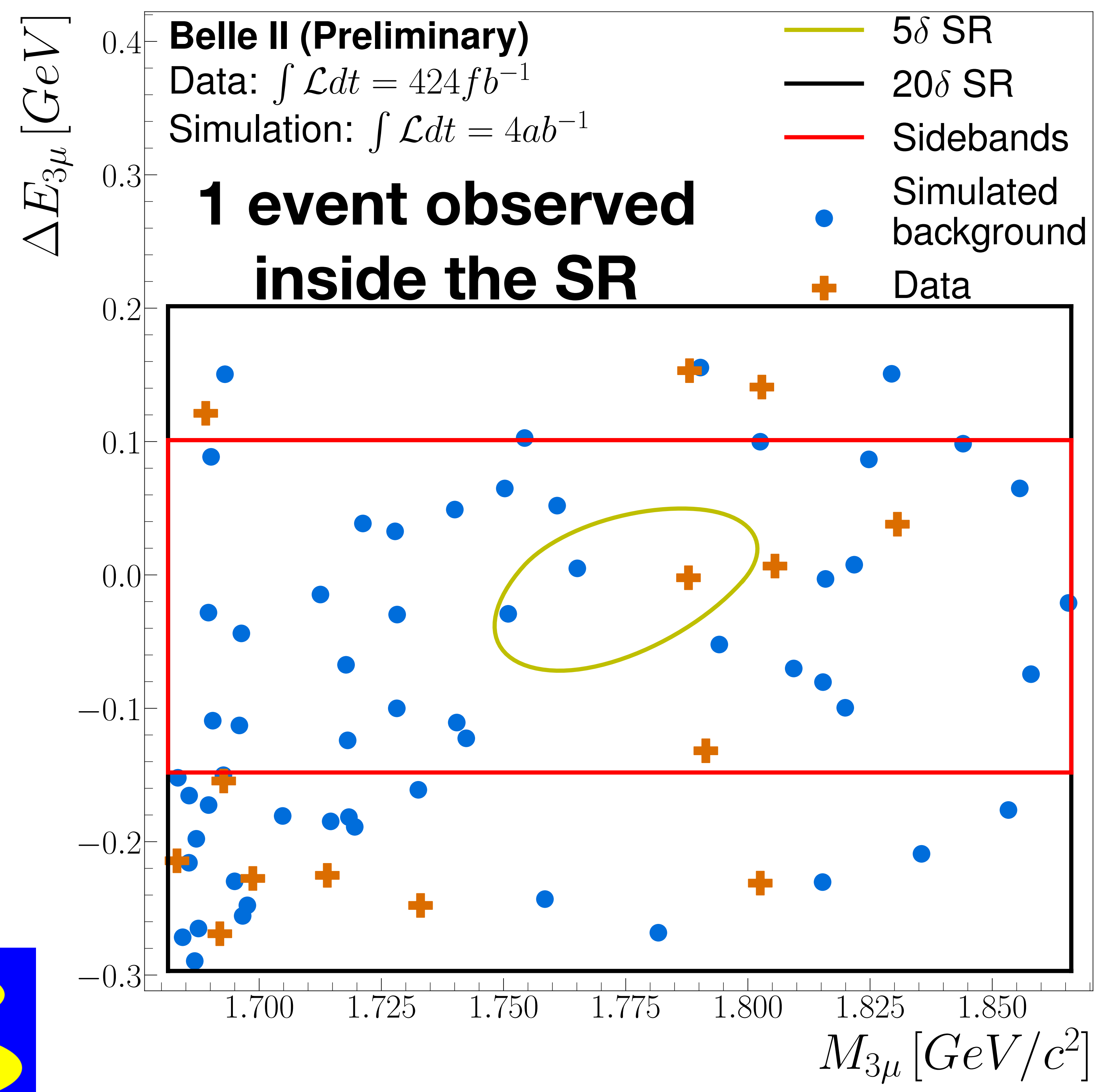
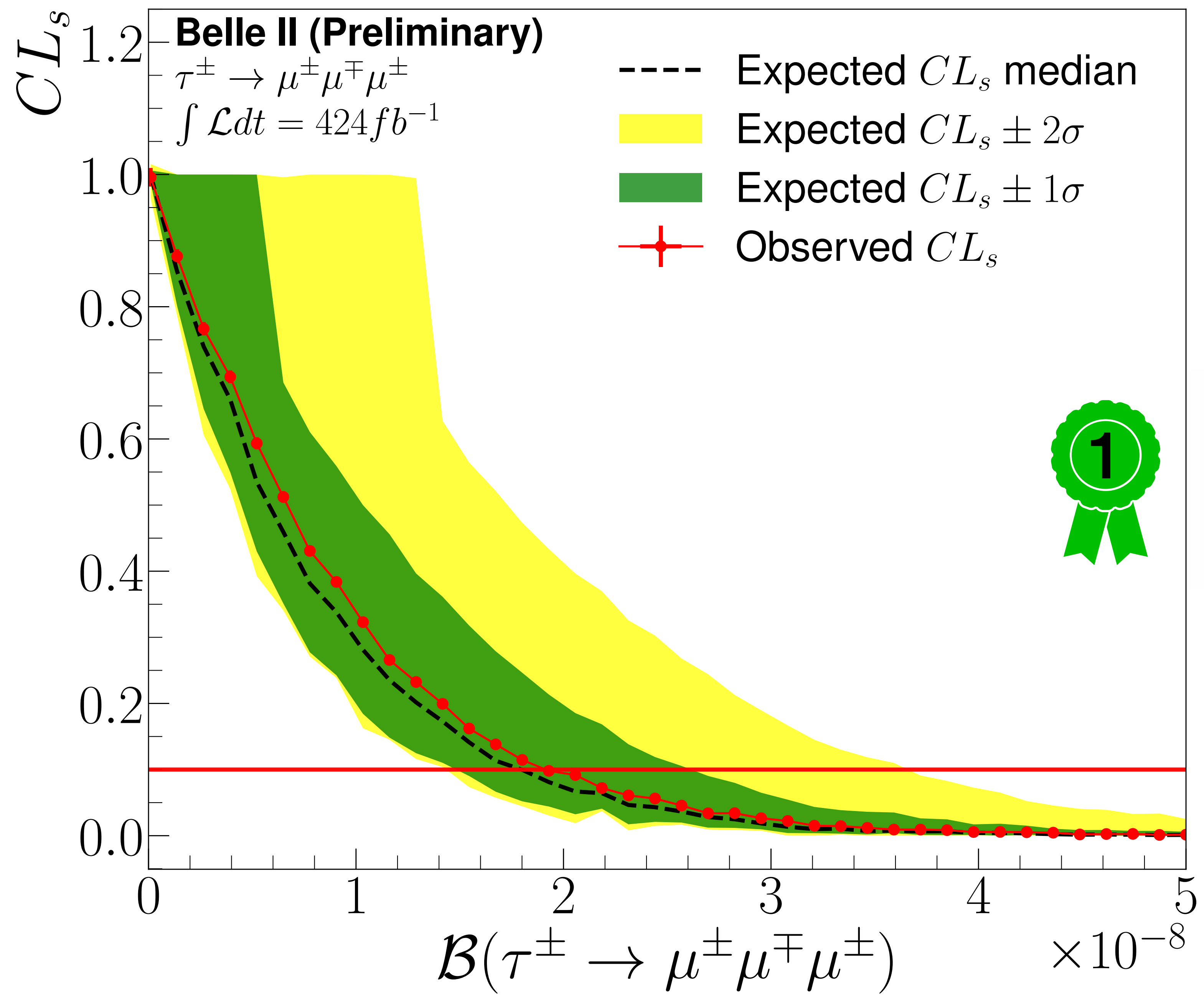




No significant excess in 424 fb^{-1} of data → 90% C.L. upper limits using the CLs method



Dominant syst. from lepton ID efficiency Negligible impact on the limit

Obtained most stringent limit

1.9×10^{-8}

Summary

- B-factories are a perfect environment for LFV searches on τ sector
  - Belle and Belle II are also a τ-factories!

★ World best result!

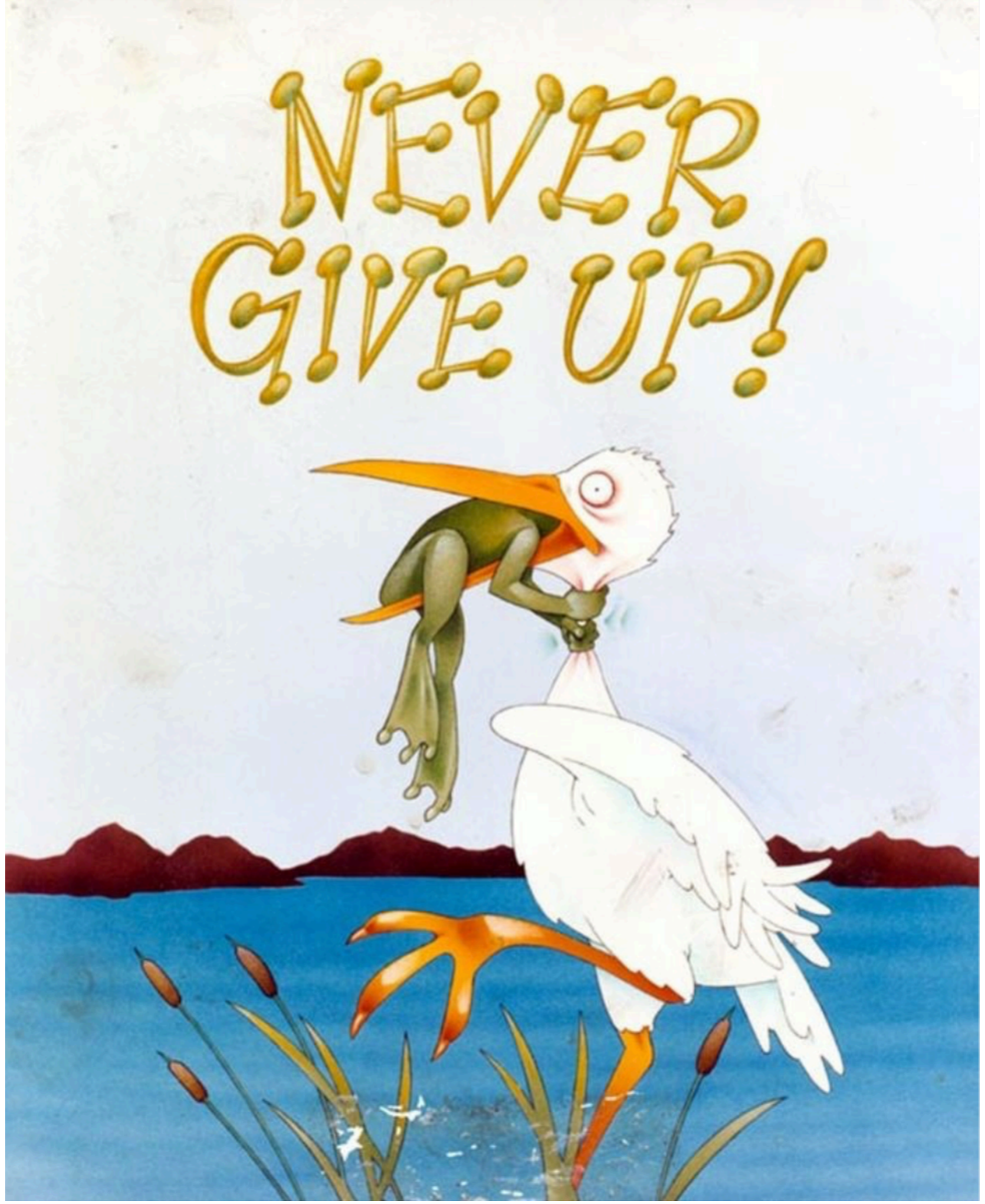
- New high profile searches:
  - $\tau \to lV^0$ @Belle & Belle II and $\tau \to 3\mu$ @Belle II

★ $\tau \to l\alpha$ search @Belle II in Sourav Dey's talk

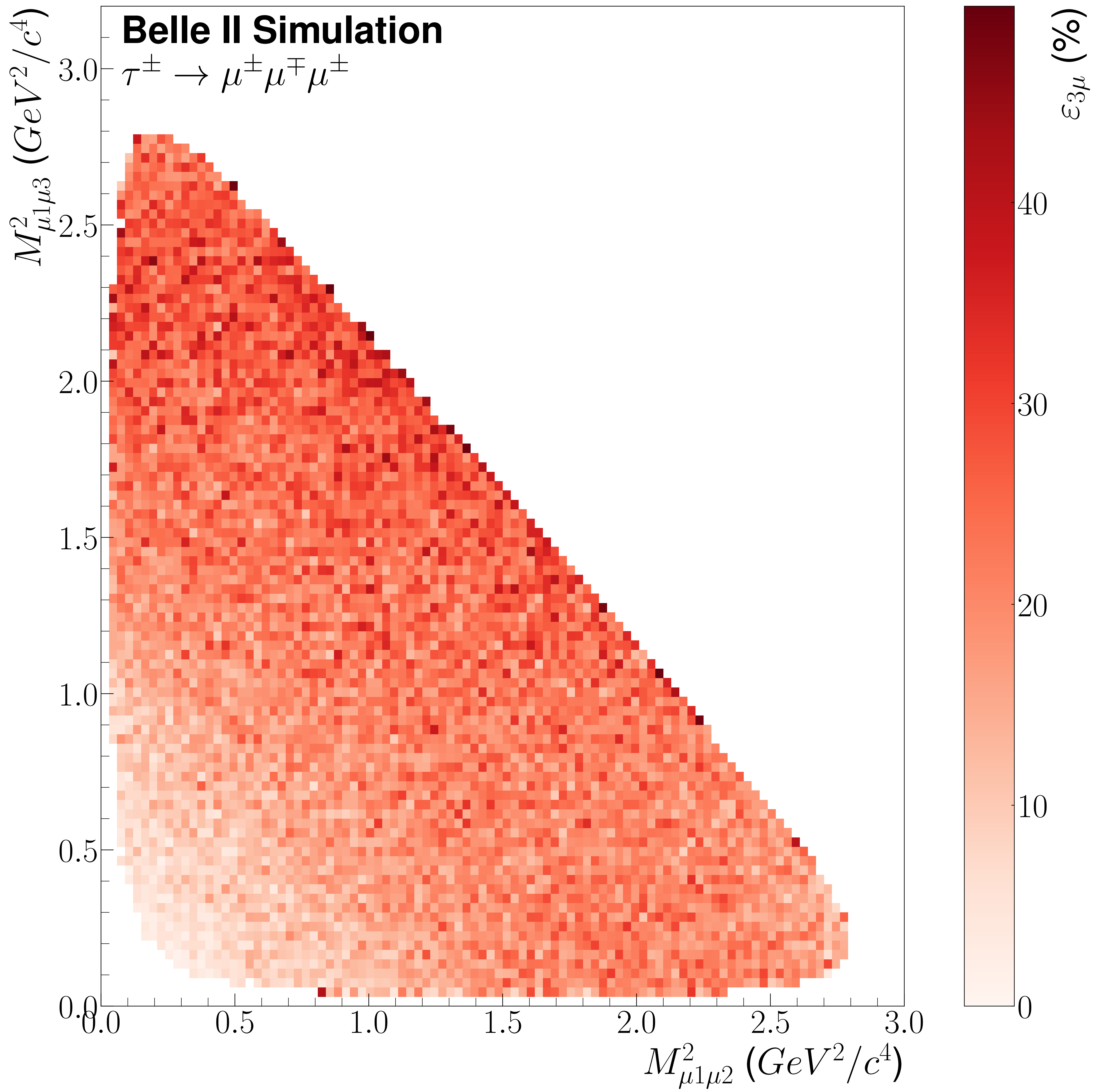
- Belle II worked hard to overcome the larger samples from Belle/BABAR to produce competitive limits

- More results to come with a larger dataset so stay tuned!

Emergency slides!!



Phase space for the $\tau \to 3\mu$ search

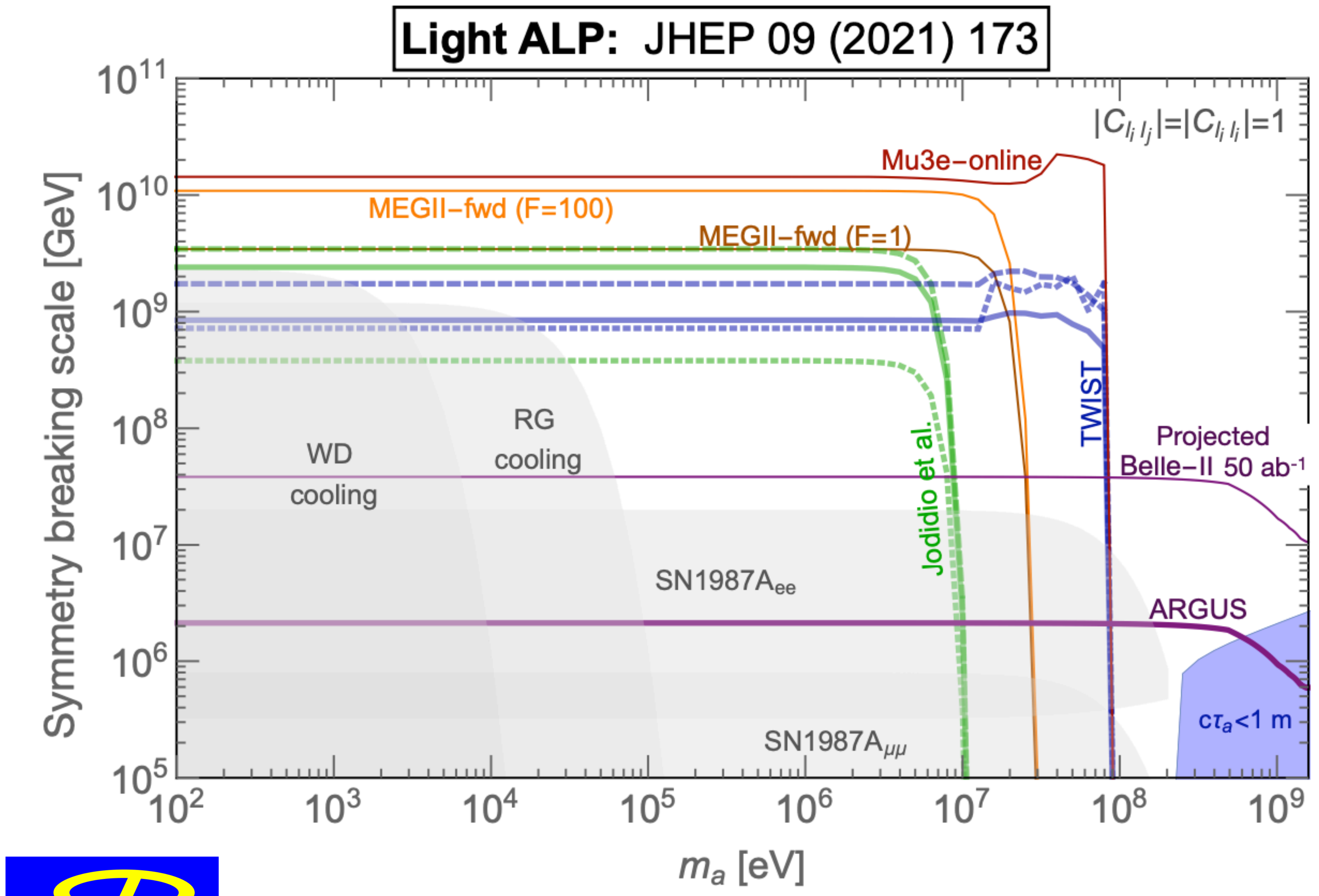


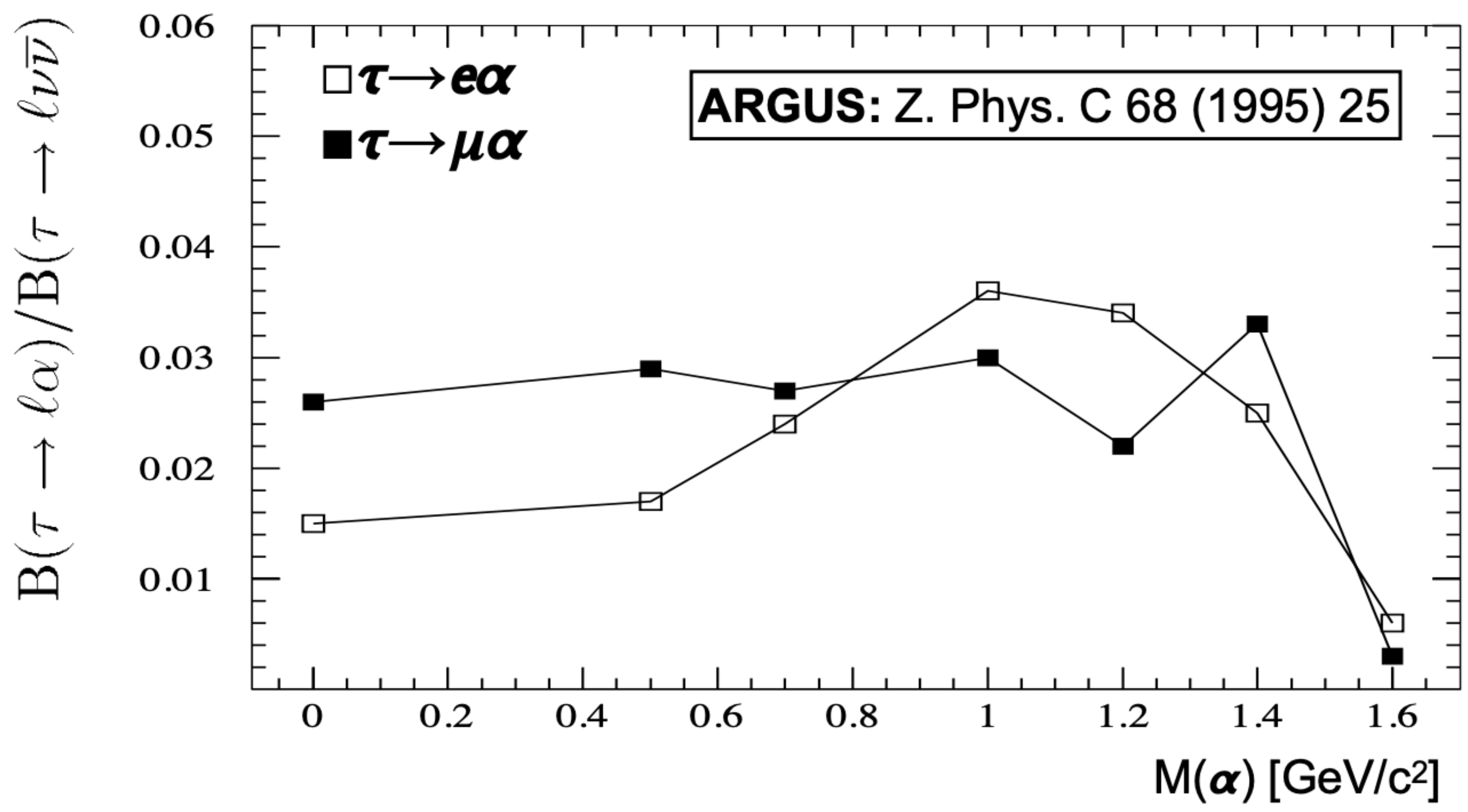
Quite uniform distribution, a part for low masses

$\tau \to l\alpha$ 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..

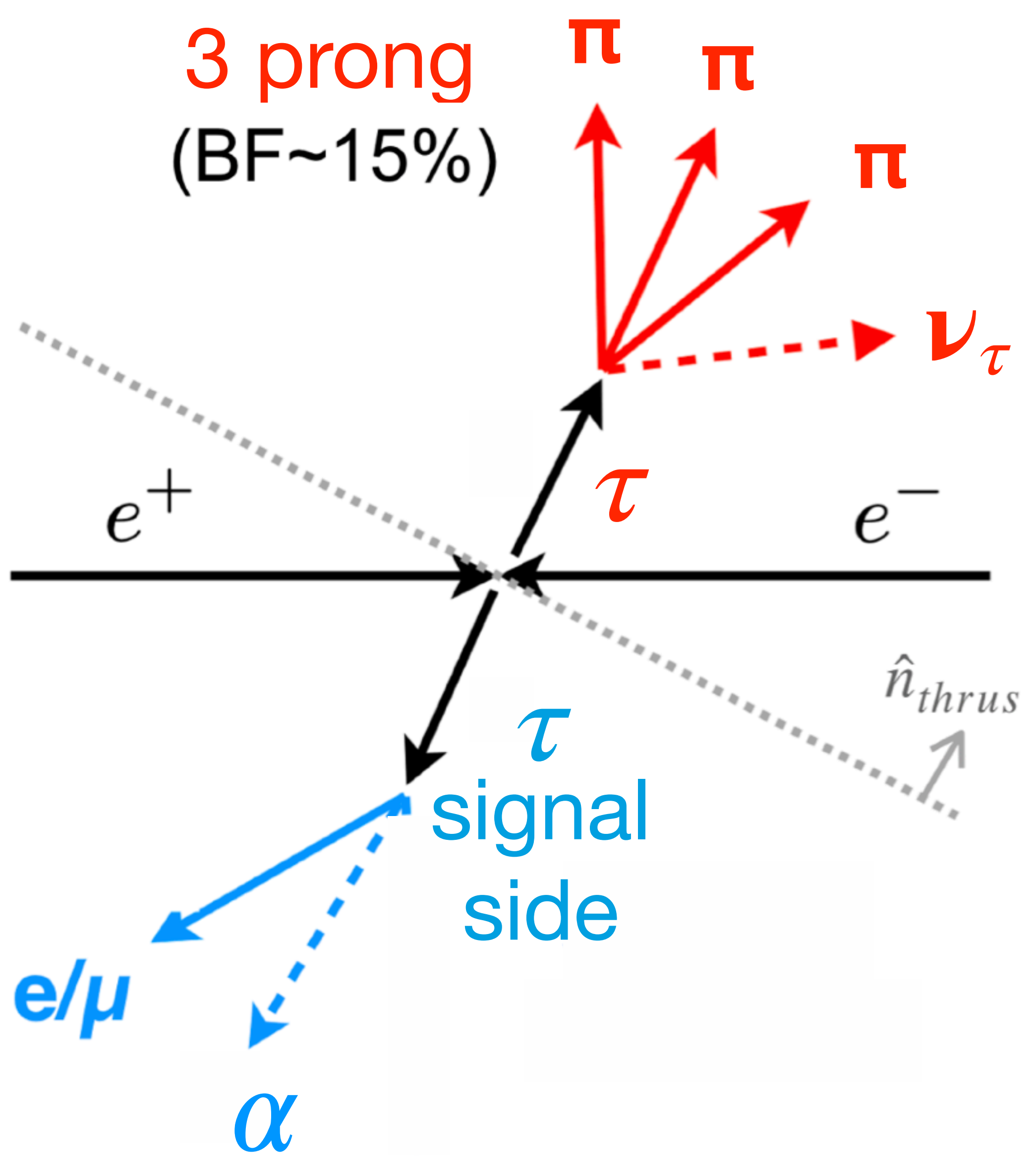
Best upper limits on B($\tau \to l\alpha$)/B($\tau \to l\nu\bar{\nu}$) from ARGUS (1995, 476 pb^{-1})



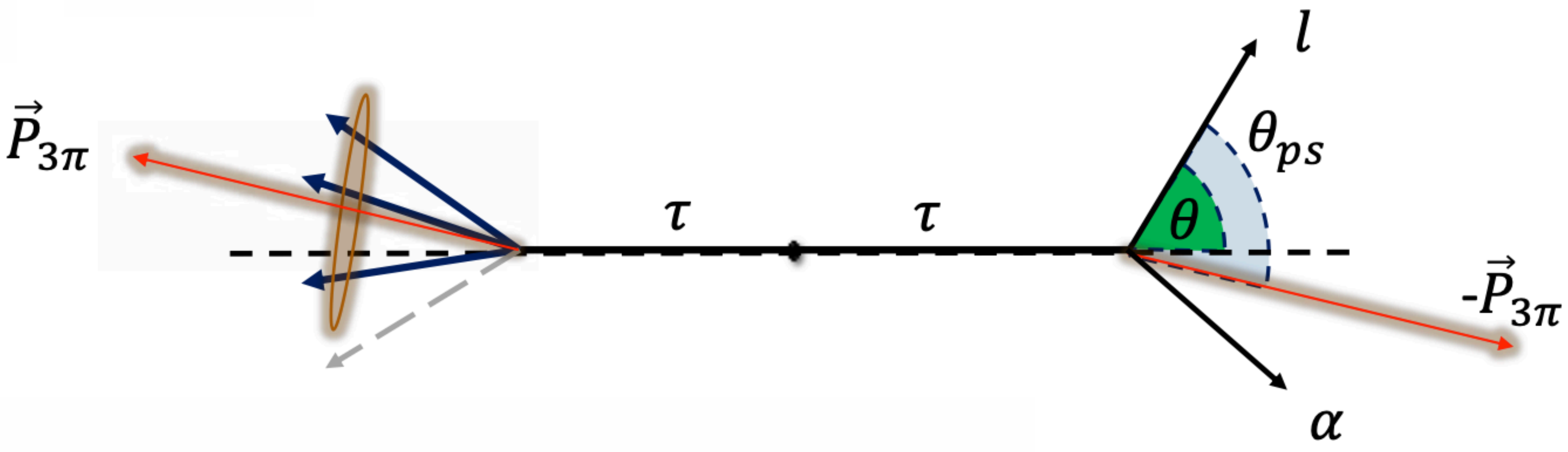


$\tau \to l\alpha$ analysis @Belle II

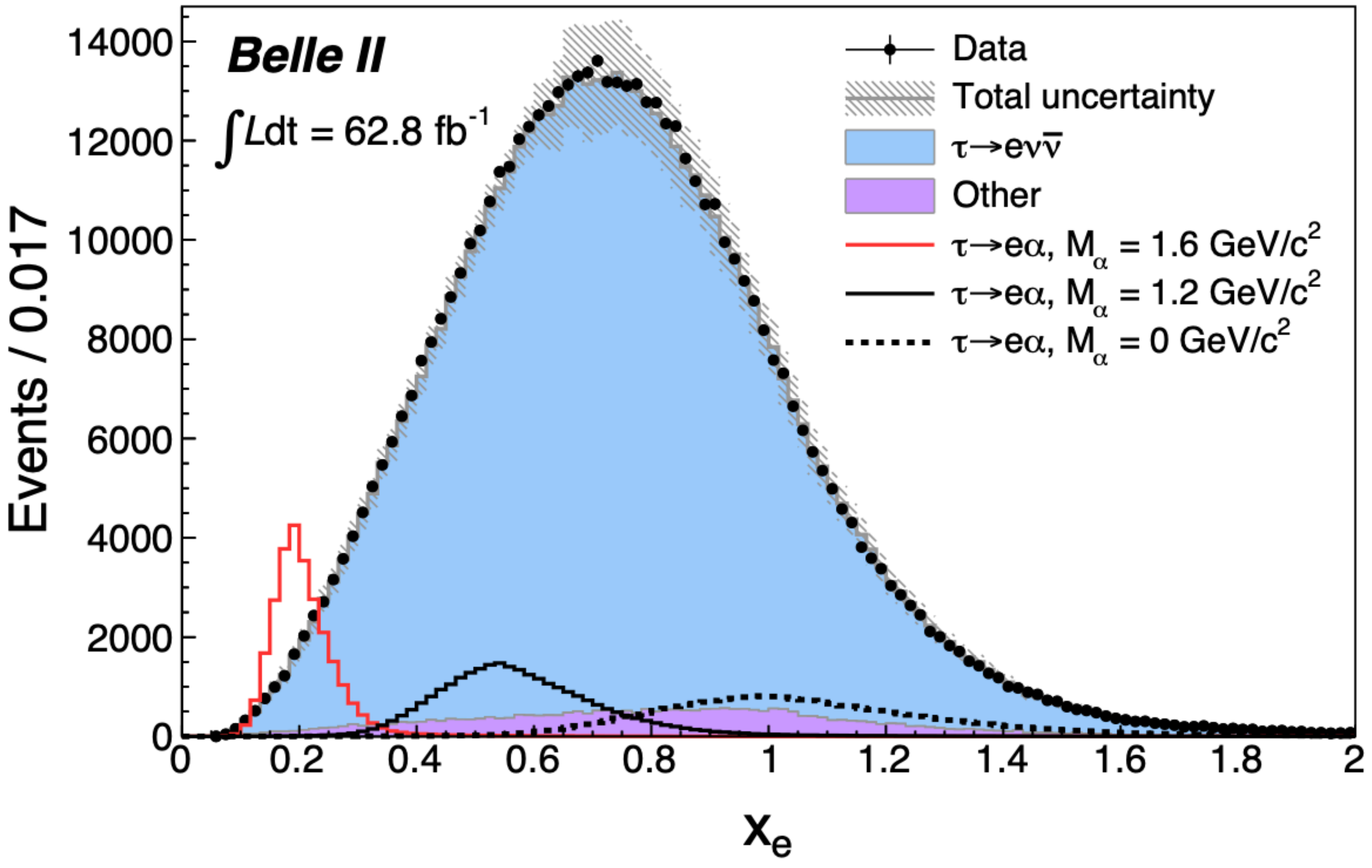
ARGUS analysis approach is adopted → definition of pseudo-rest (ps) frame

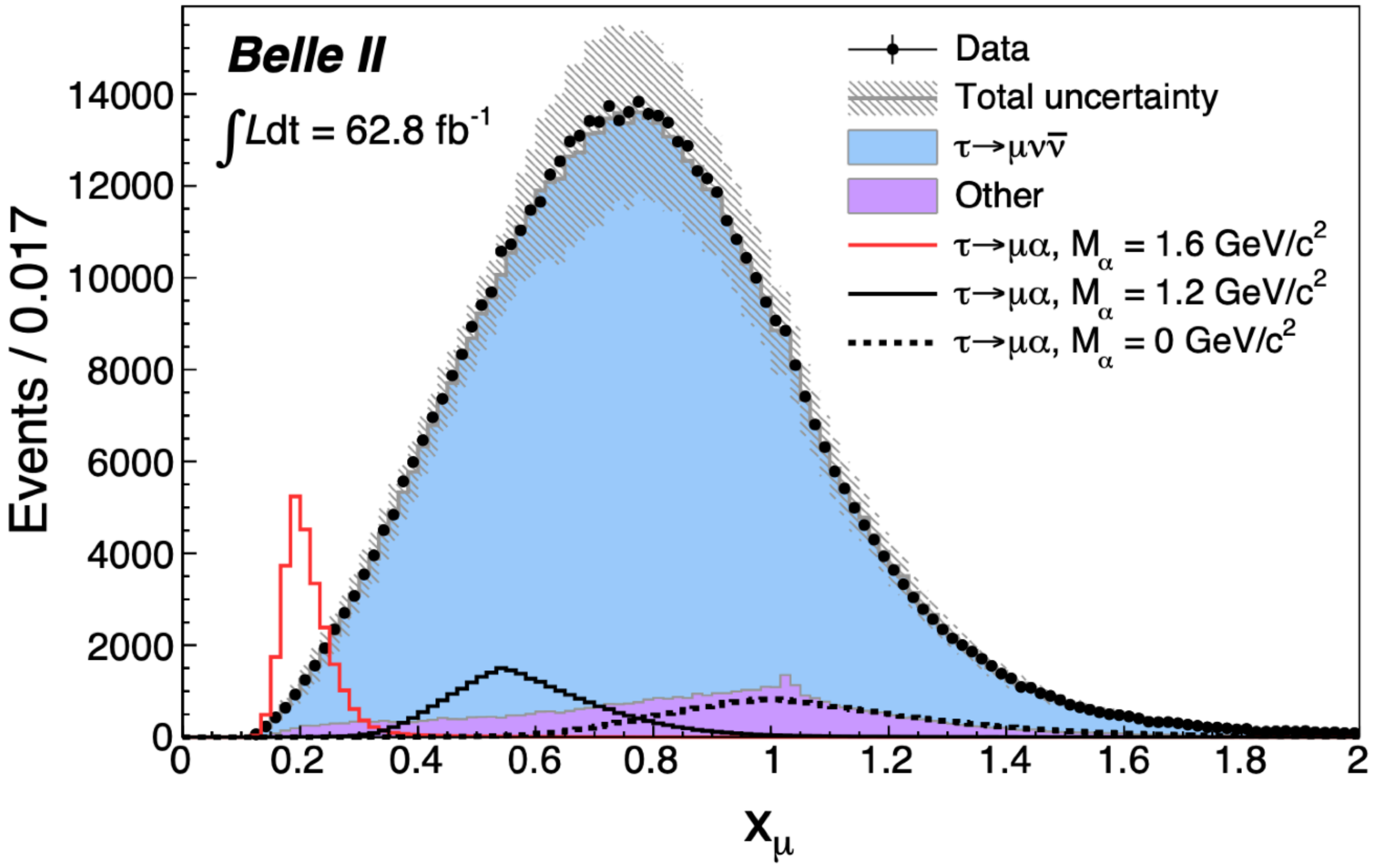


- Tag side: $\tau \to 3\pi\nu_\tau$
- Pseudo-rest frame implies:
  - $\overrightarrow{p_\tau} \sim -\vec{p}_{3\pi}$
  - $E_\tau \sim \sqrt{s}/2$
- Veto neutrals: π^0, γ
- Selection optimised on $\tau \to l\nu\bar{\nu}_\tau$ as irreducible background



Signal signature: bump in the $x_l \equiv \frac{E_l^*}{m_\tau c^2/2}$ distribution





Results for $\tau \to l\alpha$ @ Belle II

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

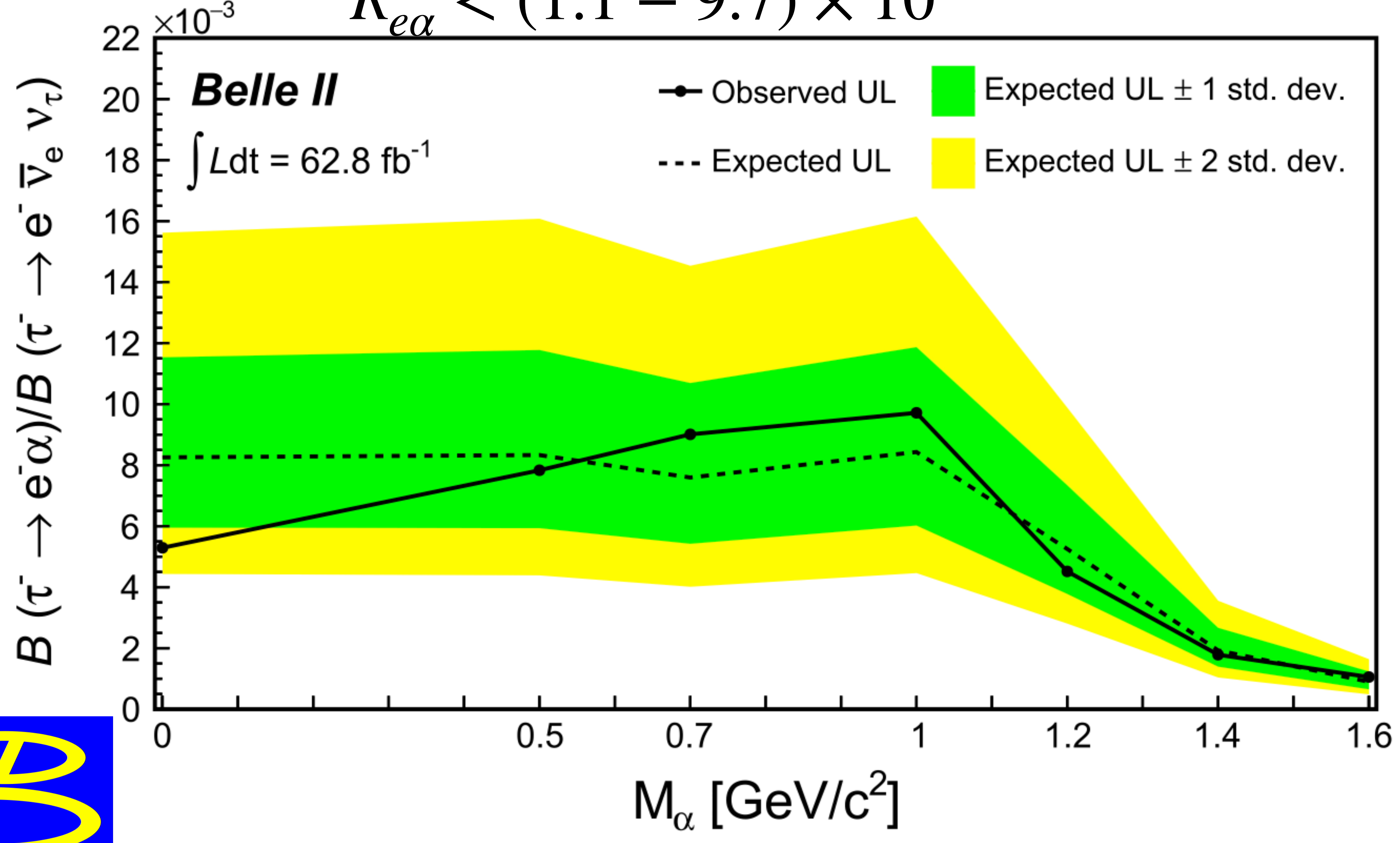
Ref: https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.130.181803

Maximum likelihood fit on x_l distributions → UL on the branching fractions

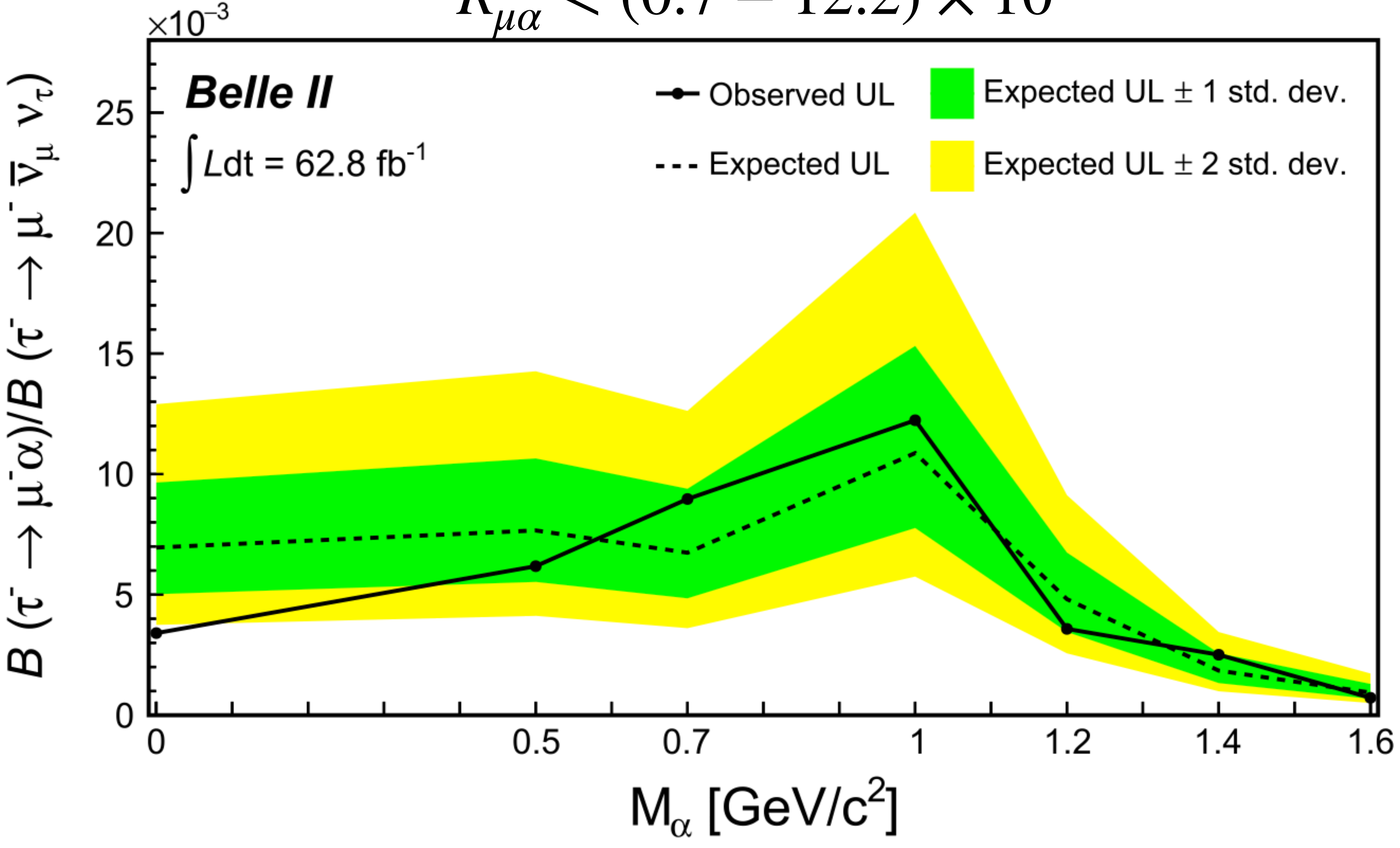
Best measurement today: 2.2–14 times more stringent than previous best limits depending on the value of the α mass

Dominant syst. from lepton ID efficiency
Negligible impact on the limit

$R_{e\alpha} < (1.1 - 9.7) \times 10^{-3}$



$R_{\mu\alpha} < (0.7 - 12.2) \times 10^{-3}$



Physics: τ analyses