LFV τ searches at the Belle and Belle II experiments

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on behalf of the Belle II collaboration

Tau2023 conference - 5 December 2023

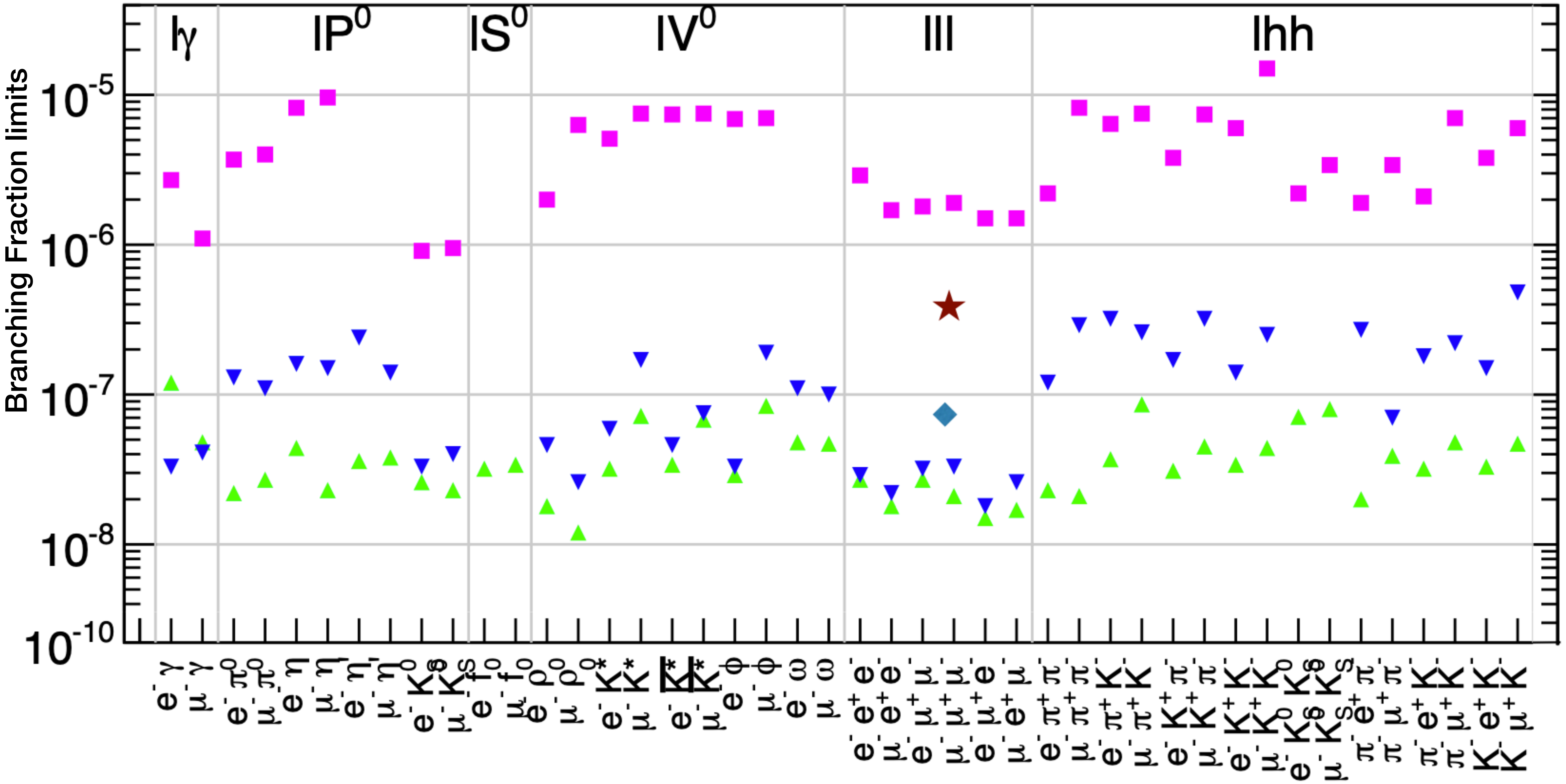
Status of the τ LFV searches at B-factories

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

Advantages of studying τ physics at B-factories:

- τ produced in pairs
- Well defined initial state energy
- Clean environment
- High hermeticity of the detector

See talks of XX and XX on respectively



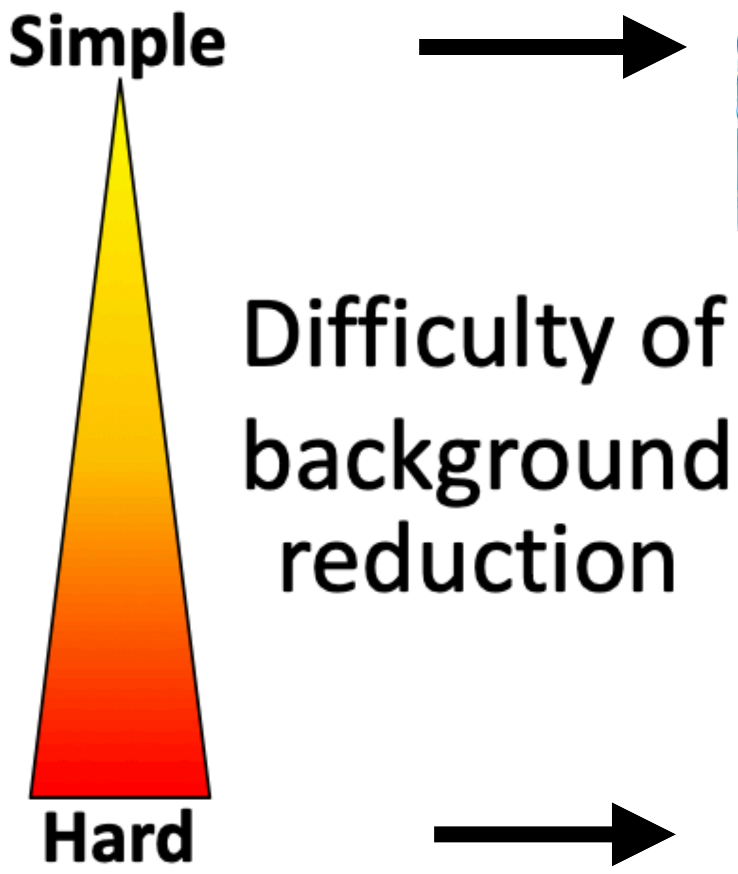
$\int Ldt$ used:

CLEO	~9fb^{-1}
BaBar	~500fb^{-1}
Belle	~800fb^{-1}
LHCb	~3fb^{-1}
ATLAS	~20fb^{-1}

τ LFV channels

Search various decay modes:

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



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

Irreducible physics backgrounds + bad τ mass and energy determination

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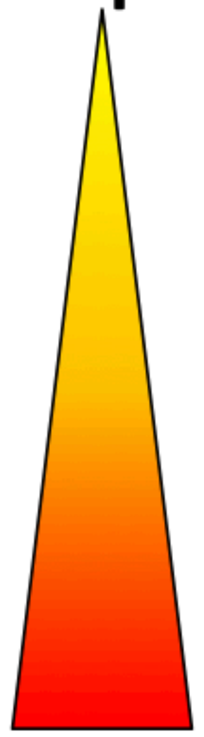
Simple

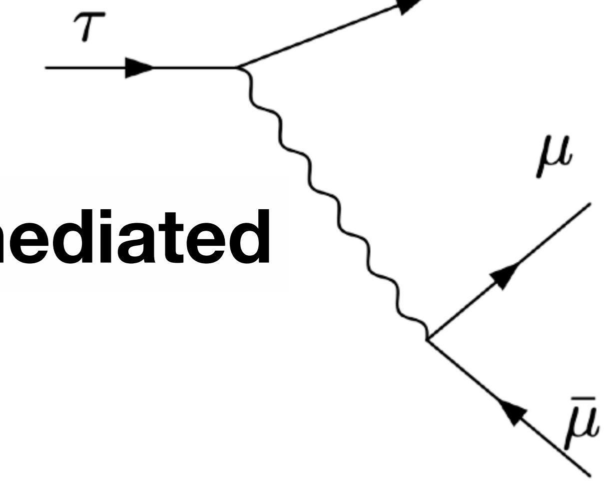


Hard

Difficulty of background reduction

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

Golden channel: $\tau \to \mu\mu\mu$ experimentally the most accessible

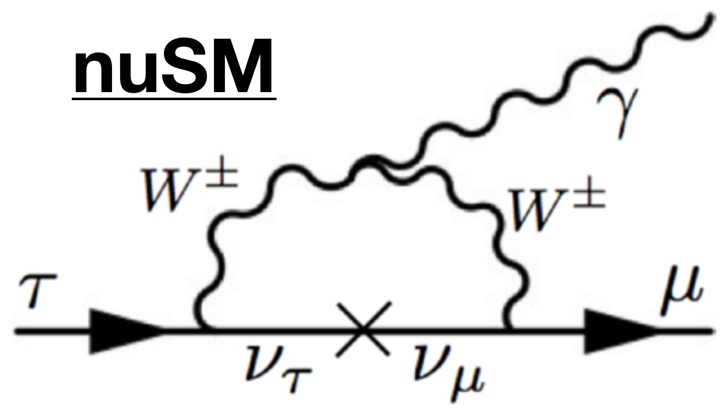


Z' mediated

Irreducible physics backgrounds + bad τ mass and energy determination

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

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	$10^{-49} \sim 10^{-52}$	$10^{-53} \sim 10^{-56}$ [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: https://arxiv.org/abs/hep-ph/0702136

An observation would be a clear signature of NP!

τ LFV channels

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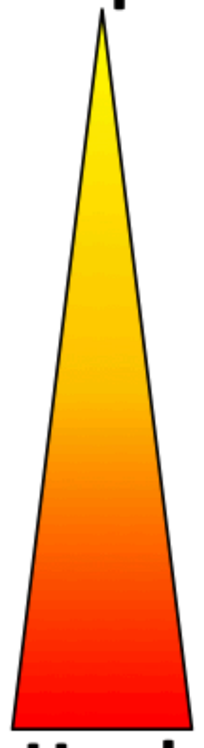

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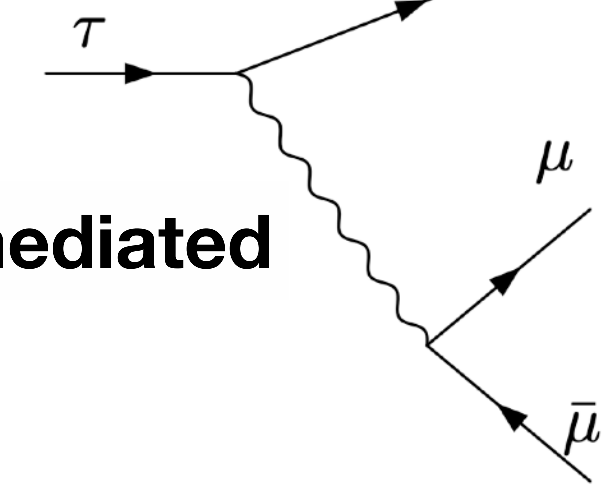

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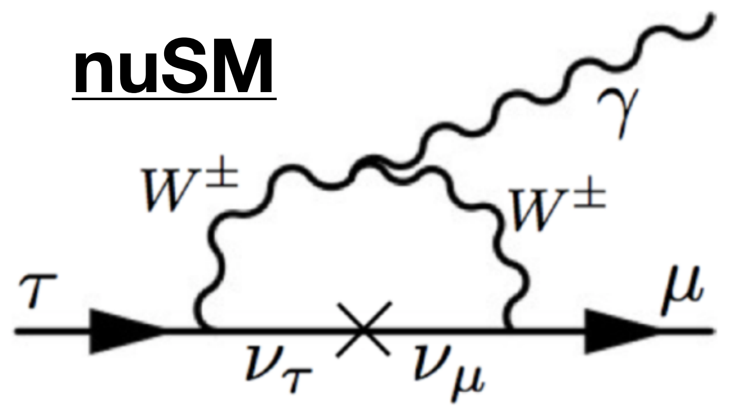

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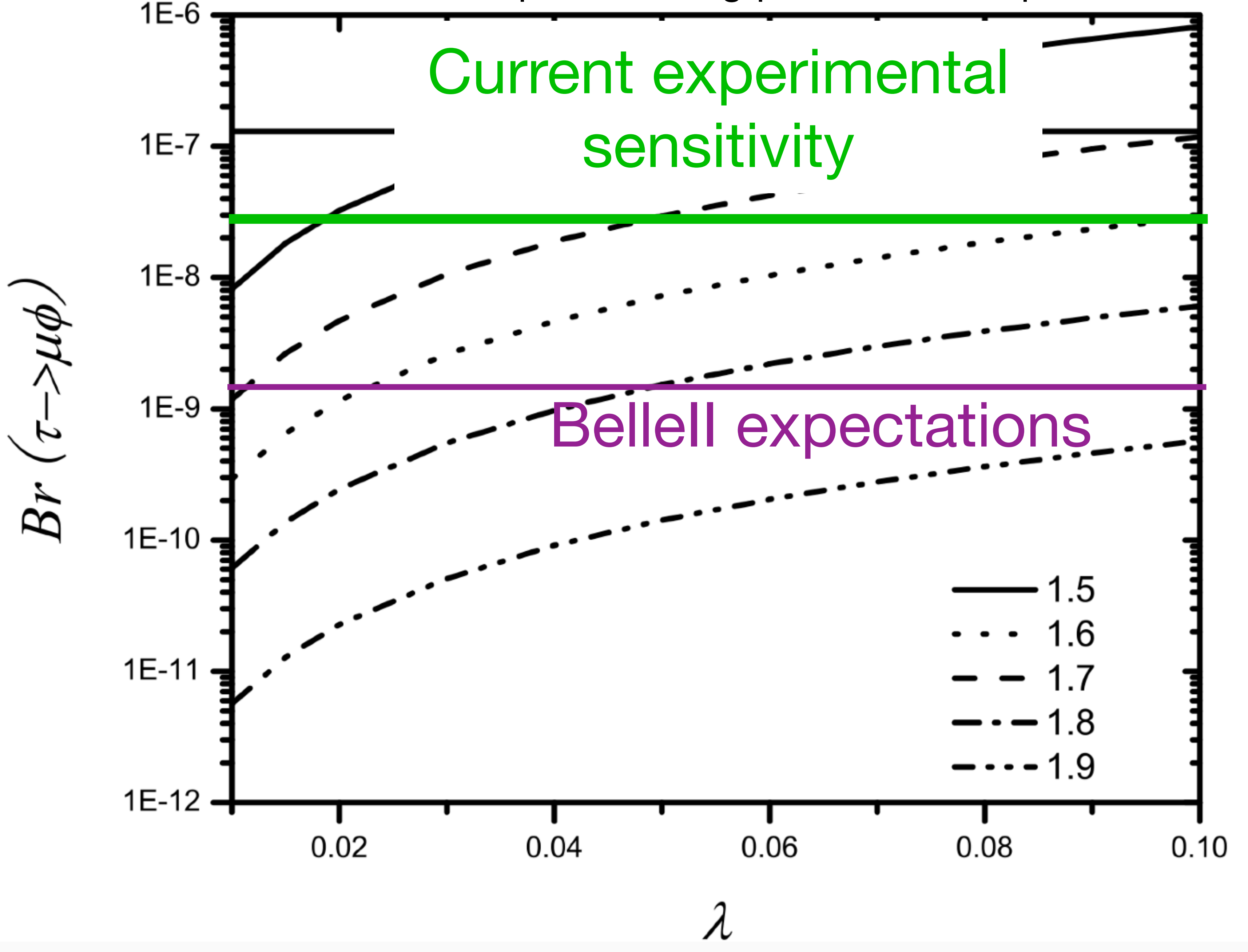
Analysis motivations: $\tau \to lV^0$

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

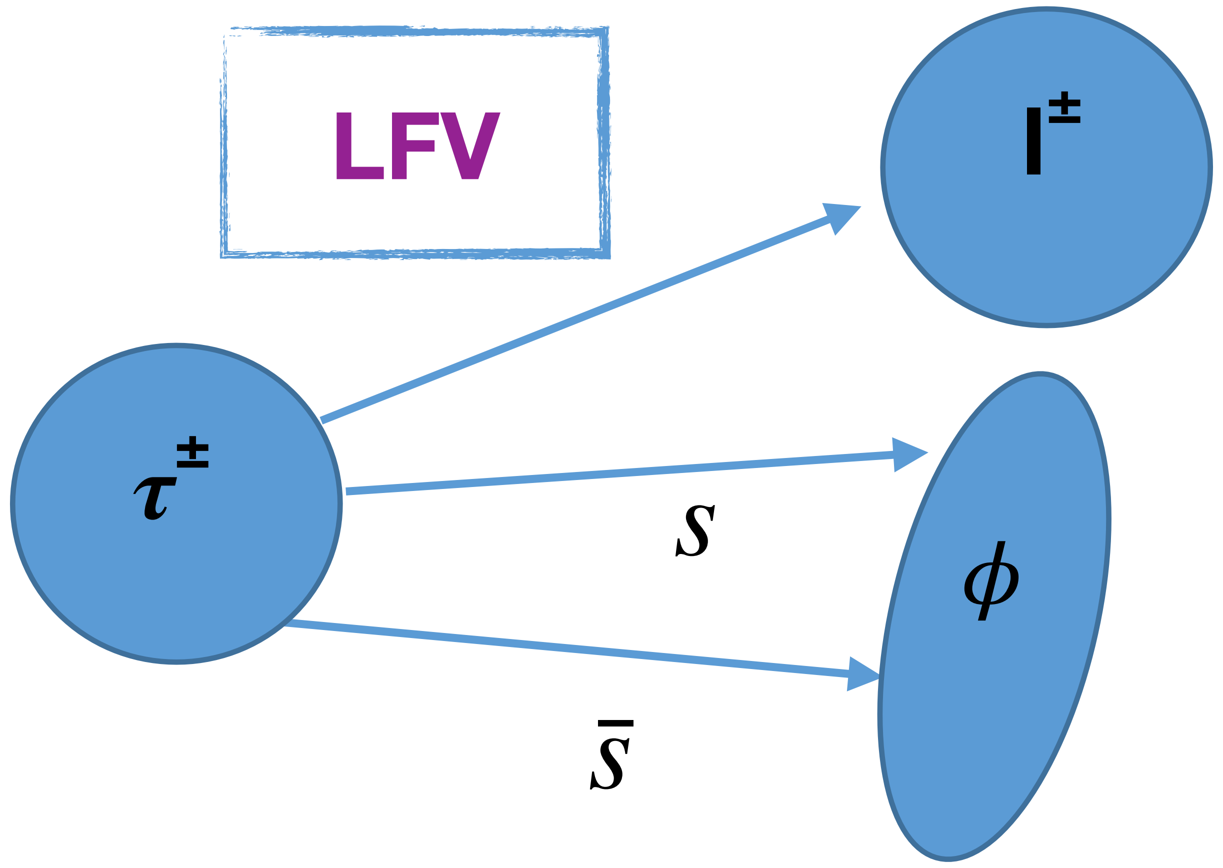
Unparticle model

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

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

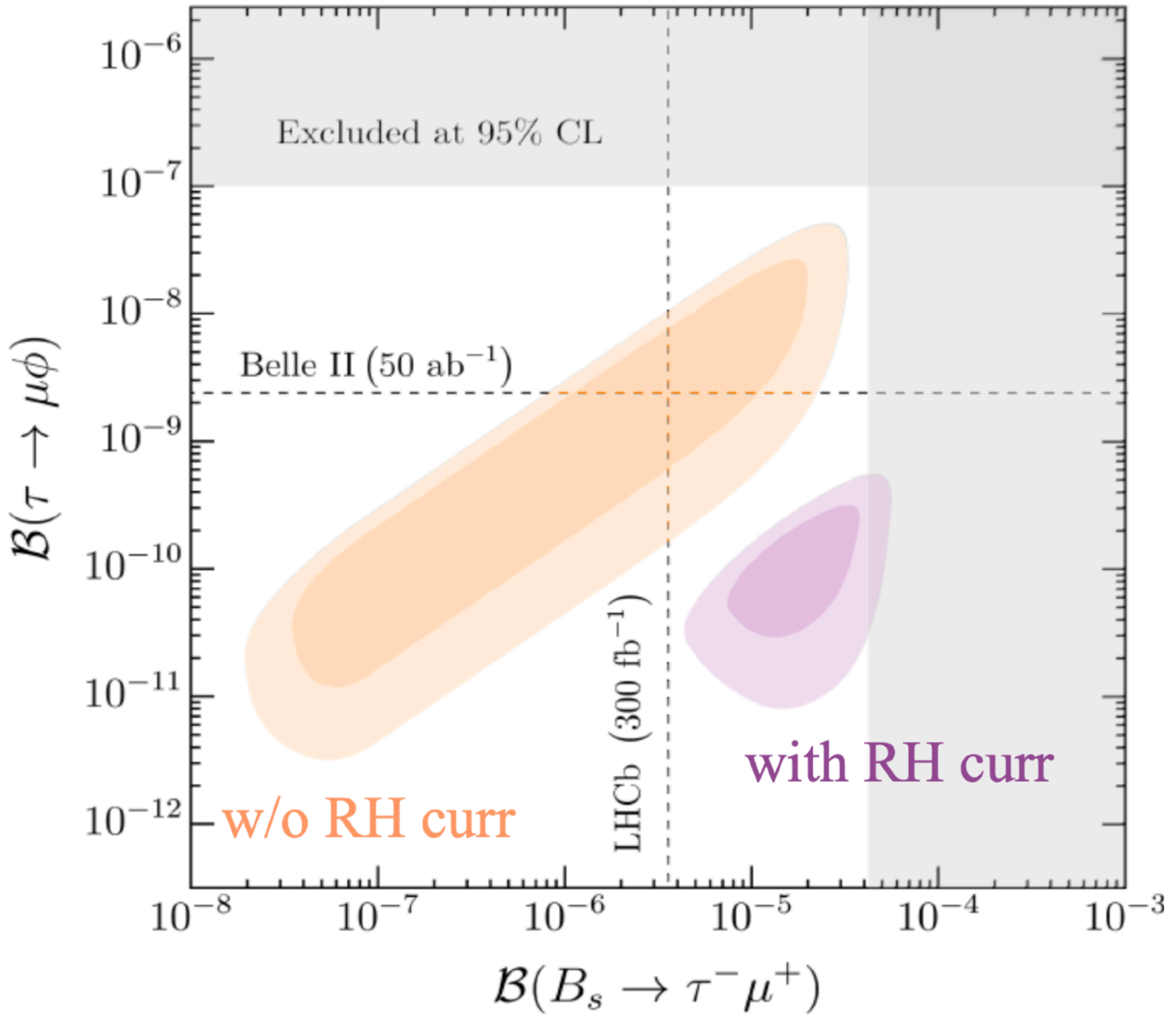


One of the golden channel for this model



Leptoquark model

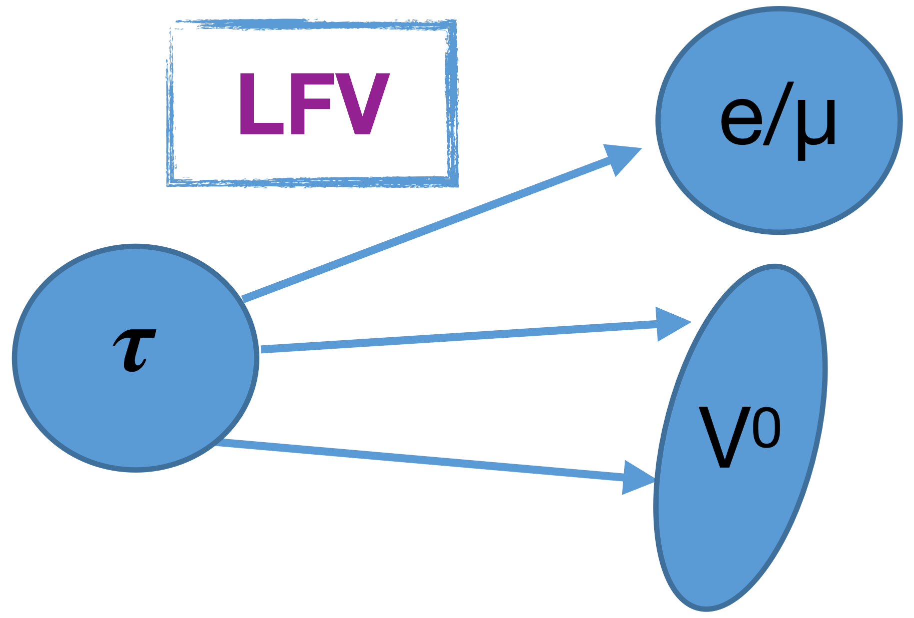
Ref: https://arxiv.org/pdf/2103.16558.pdf



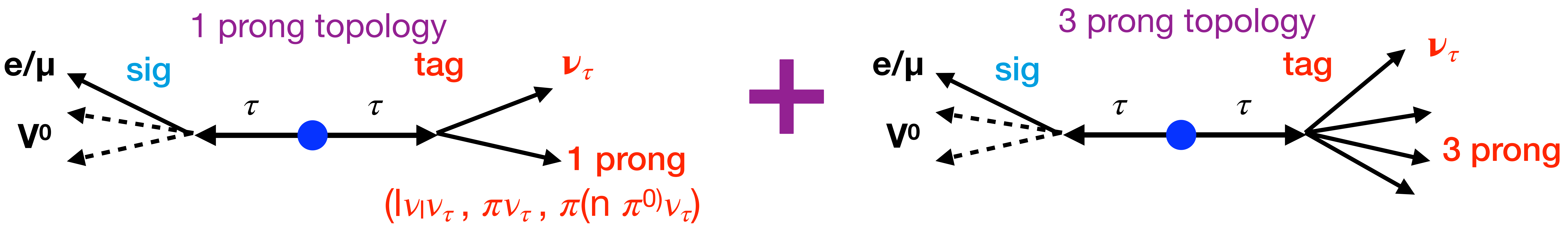
Nice interplay between B and τ physics!

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

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



Analysis update including 3-prong decay for τ_{tag} with ~980 fb^{-1}



Analysis steps:

- Event selection and background suppression done by BDT
- Prepare BDT classifier for each LFV mode
  - Training: 11 input variables for $l\omega$, 9 input variables for others

Dominant syst. from tracking efficiency and particle identification

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

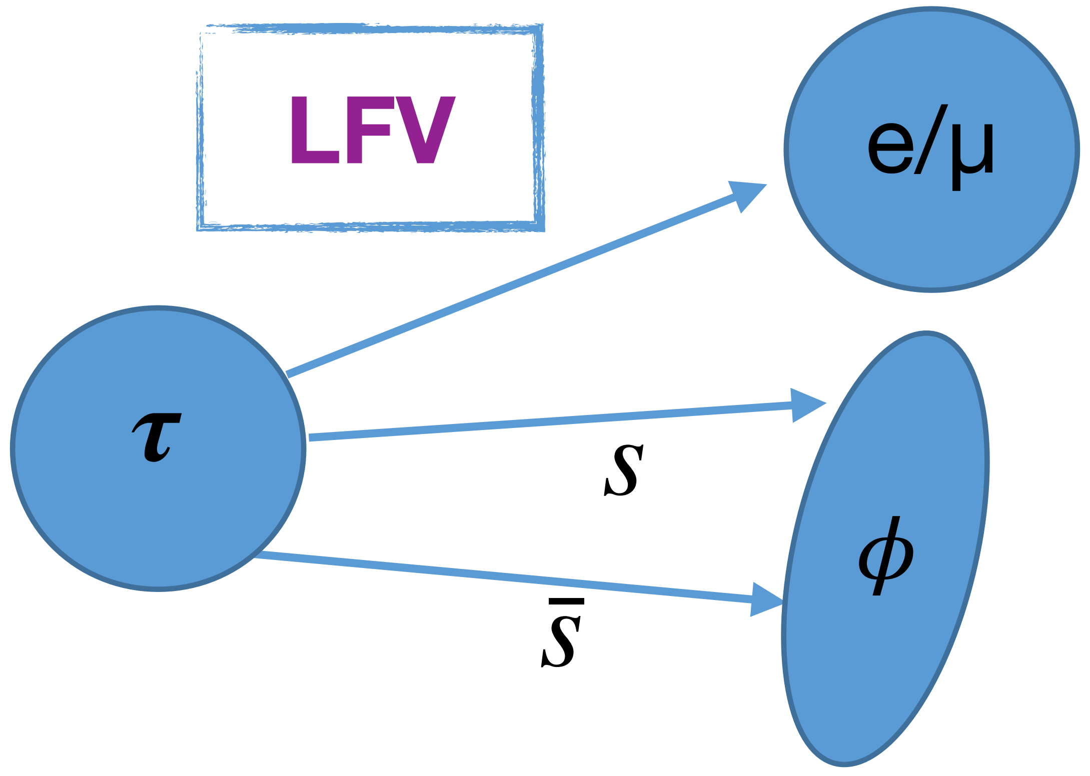
$$B(\tau \to eV^0) < (1.7 - 2.4) \times 10^{-8}$$
$$B(\tau \to \mu V^0) < (1.7 - 4.3) \times 10^{-8}$$

World best result!
~30% improvement wrt previous results!

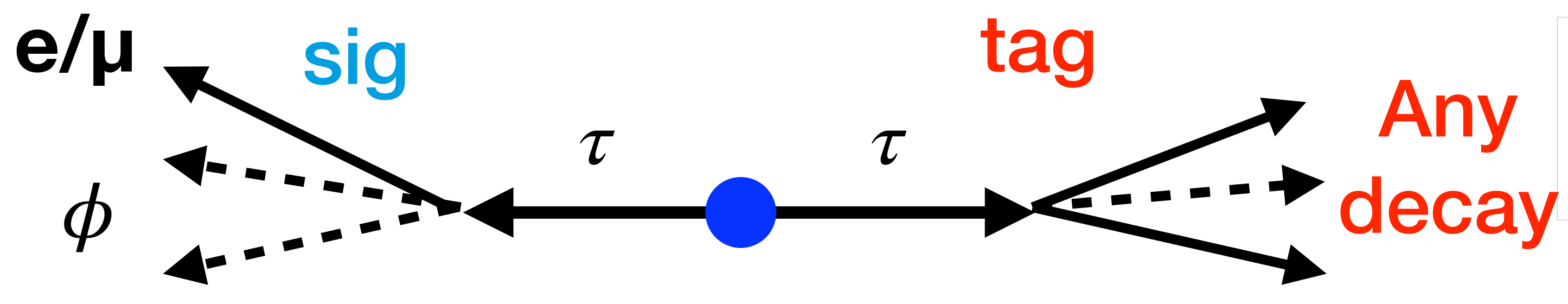
Analysis steps for $\tau \to l\phi$ @Belle II

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

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



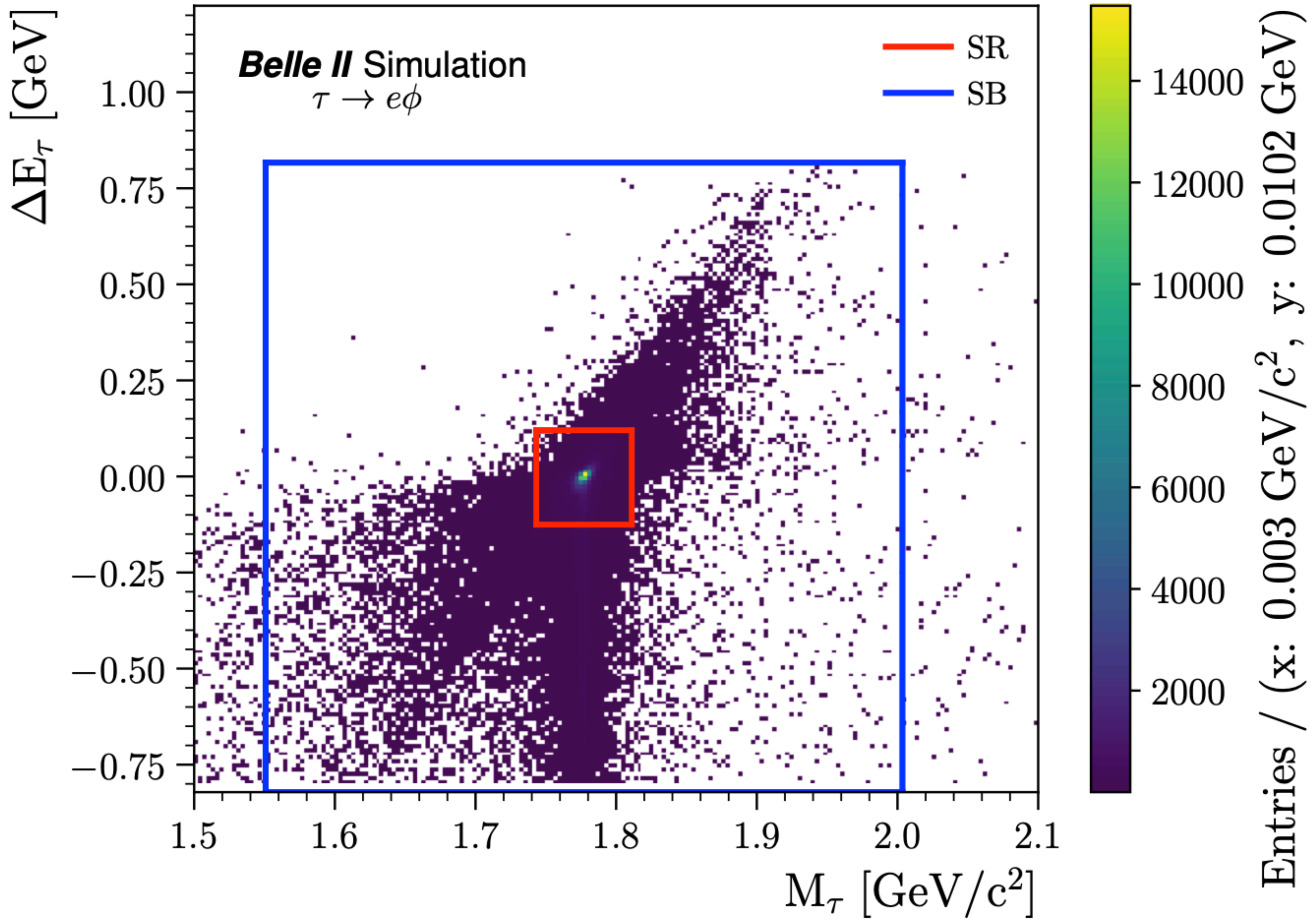
Untagged topology



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

Analysis steps

- Definition of a 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
- Background events are evaluated from data in the sideband
- Perform Poisson counting experiment approach in SR



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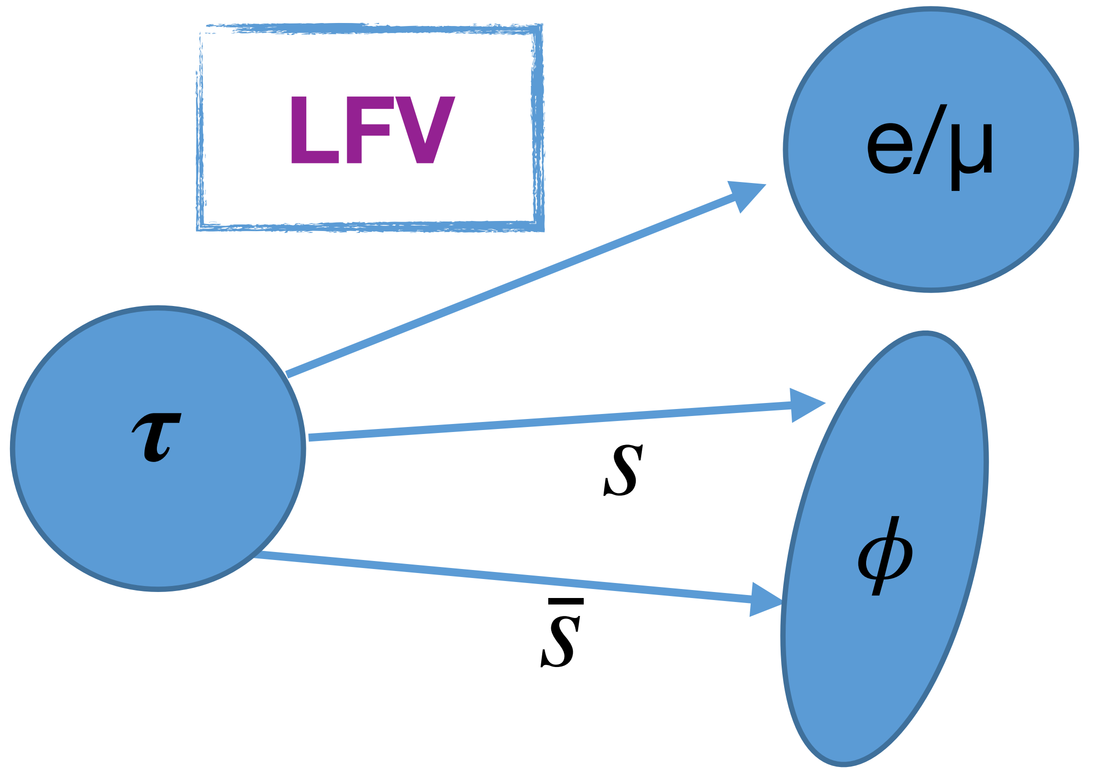

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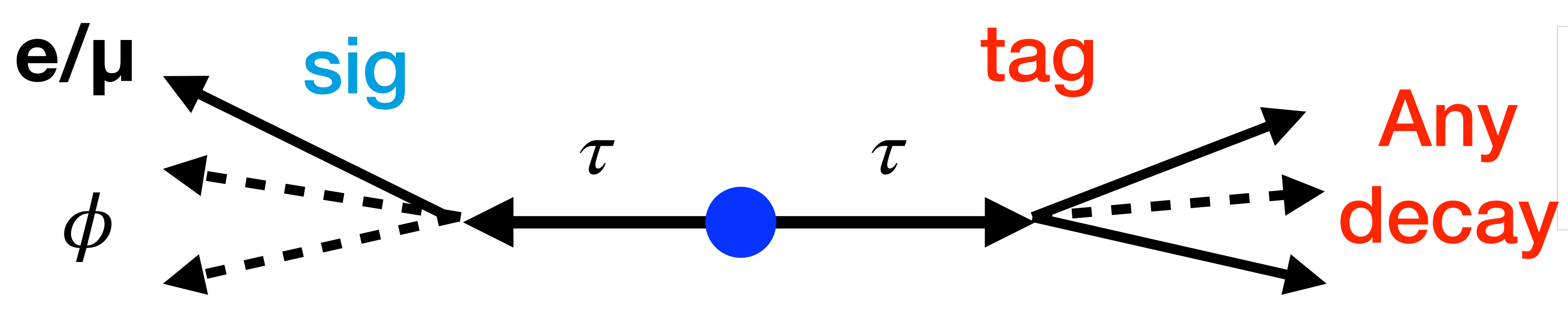

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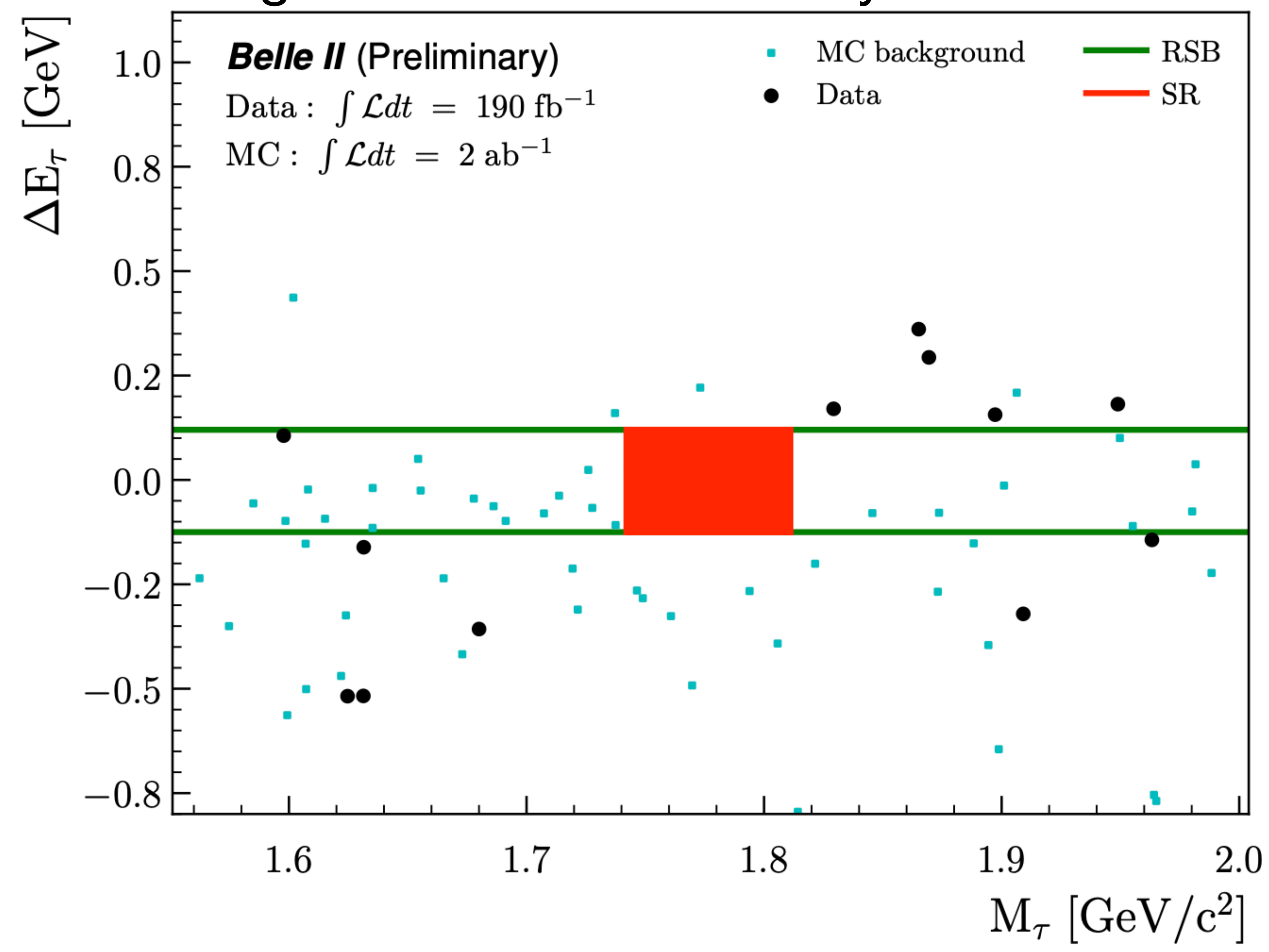
Signal detection efficiency ~ 2 × Belle



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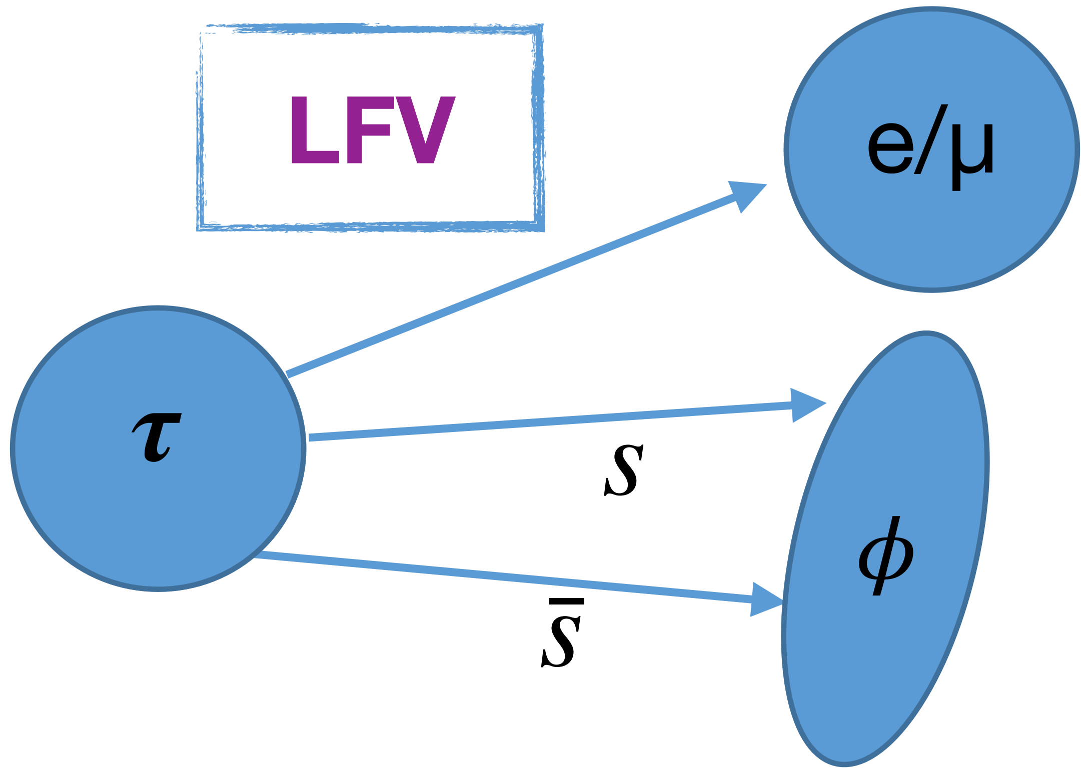

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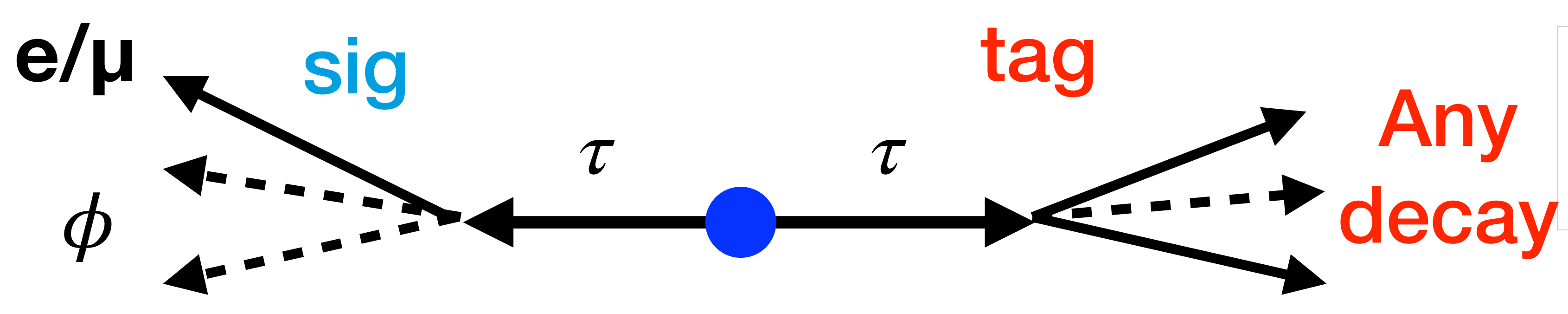

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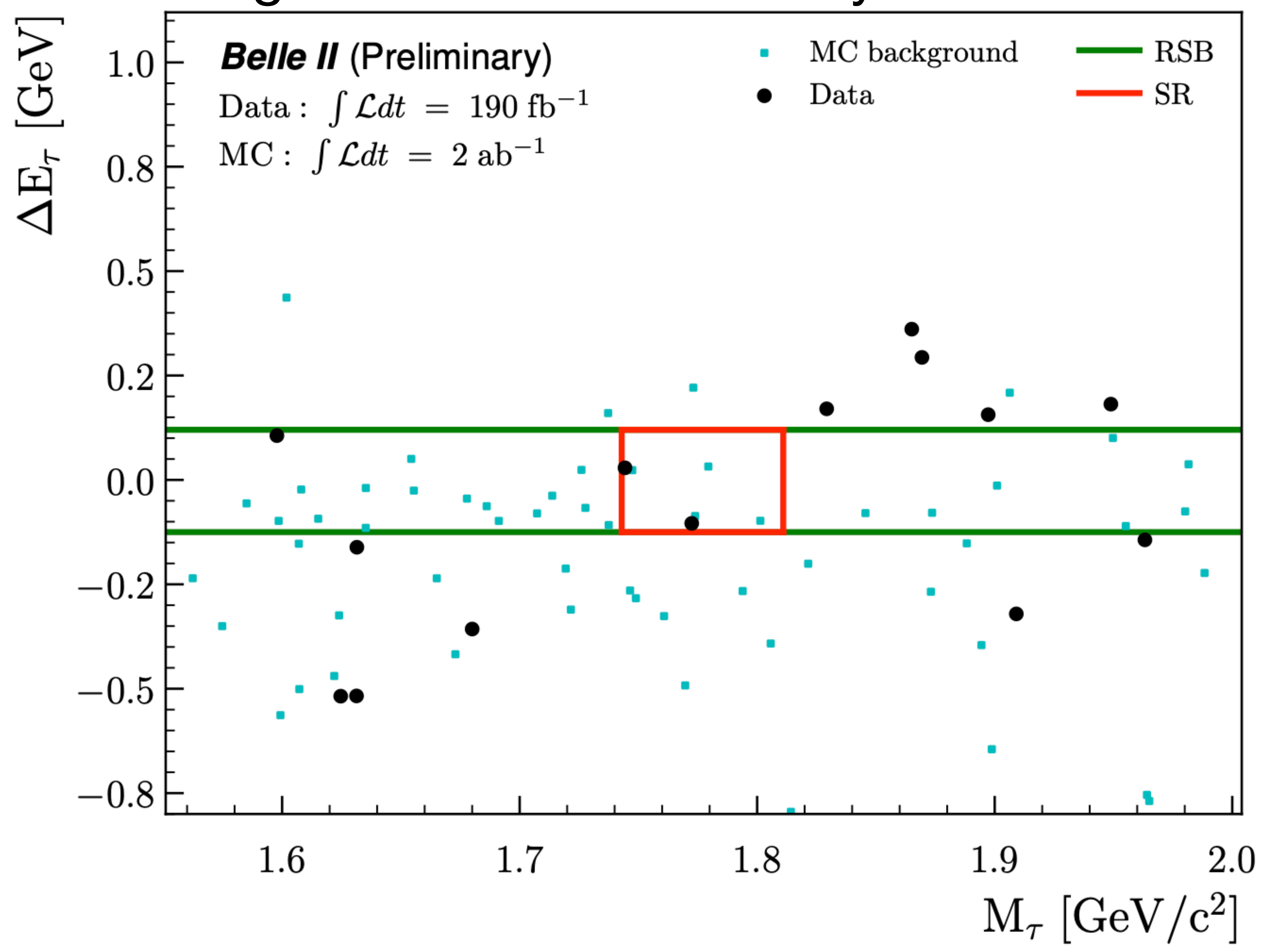


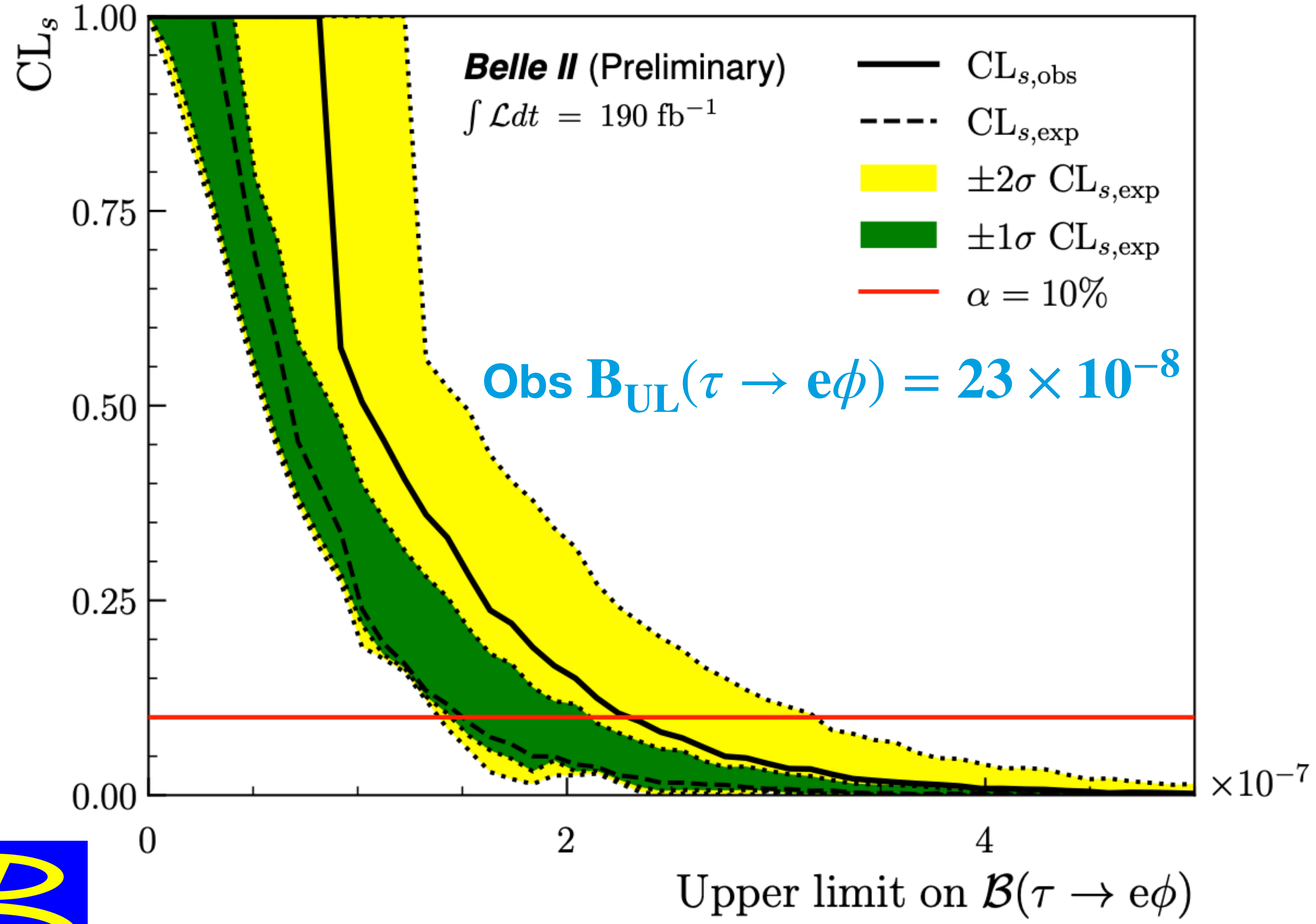
Results for $\tau \to l\phi$ @Belle II

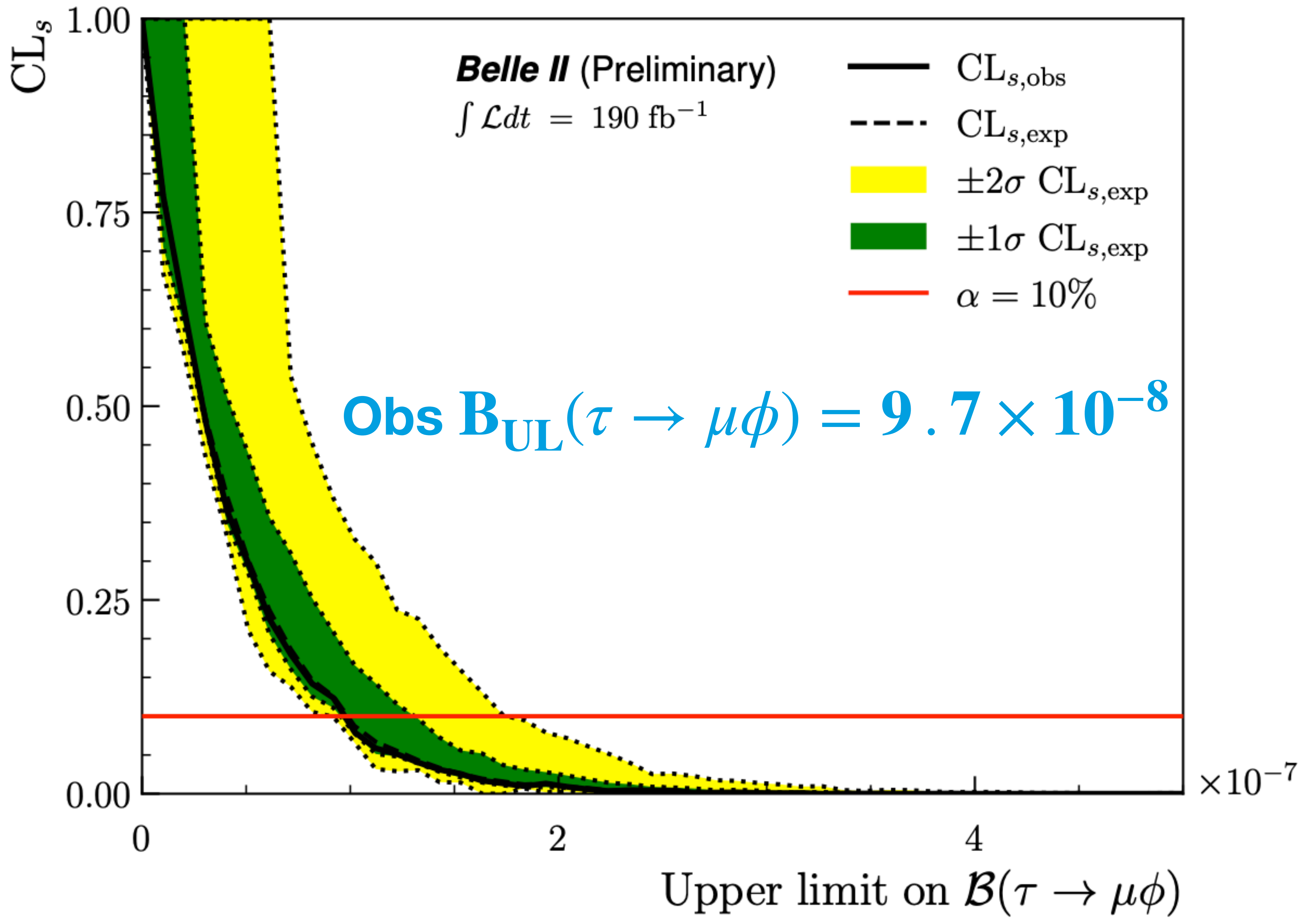
Belle II will be competitive with more data!

No signal evidence → set ULs at 90% CL

$$\mathcal{B}_{\mathrm{UL}}(\tau \to \ell\phi) = \frac{s}{L \times 2\sigma_{\tau\tau} \times \varepsilon_{\ell\phi}}$$

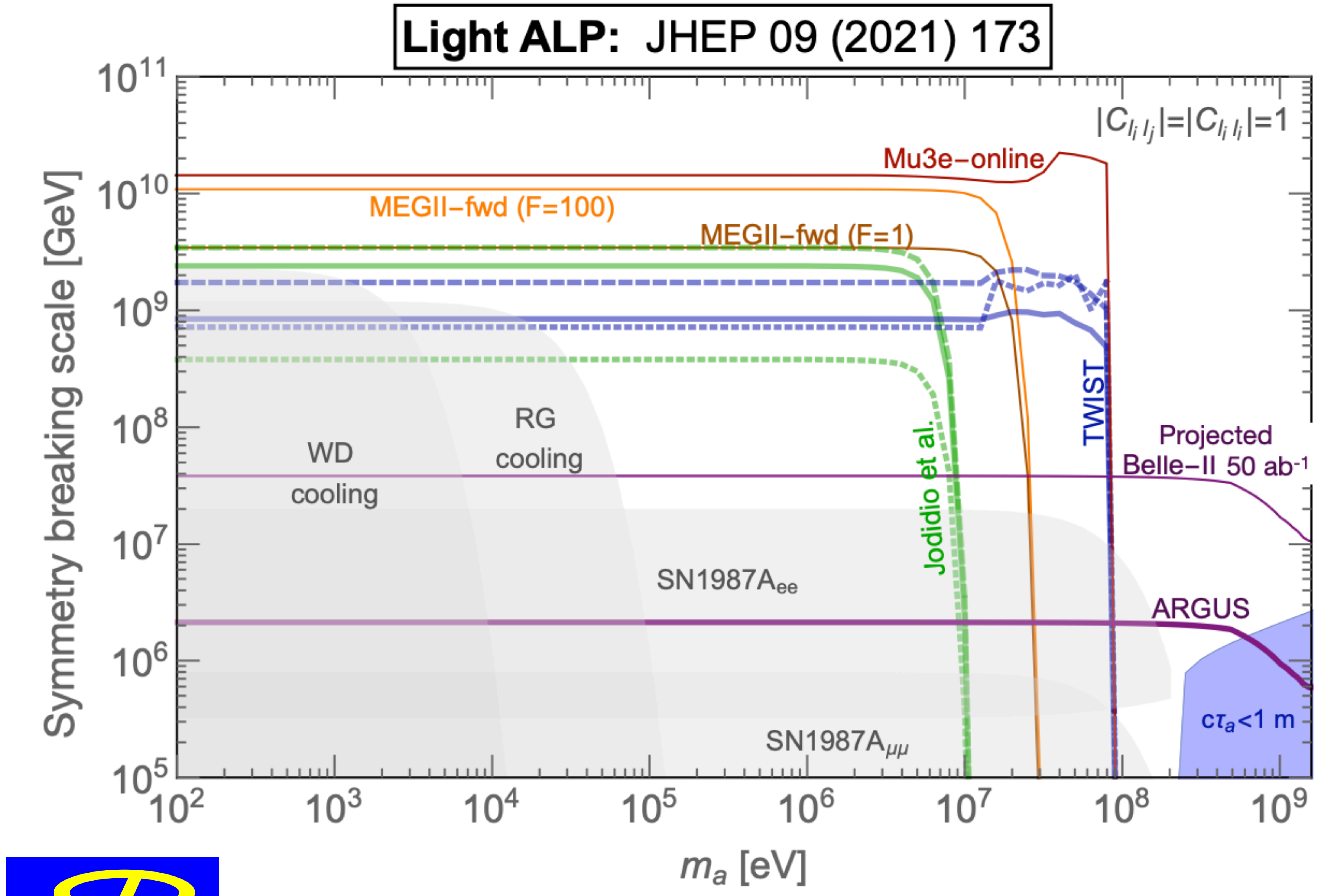
Dominant syst. from signal variable mismodeling



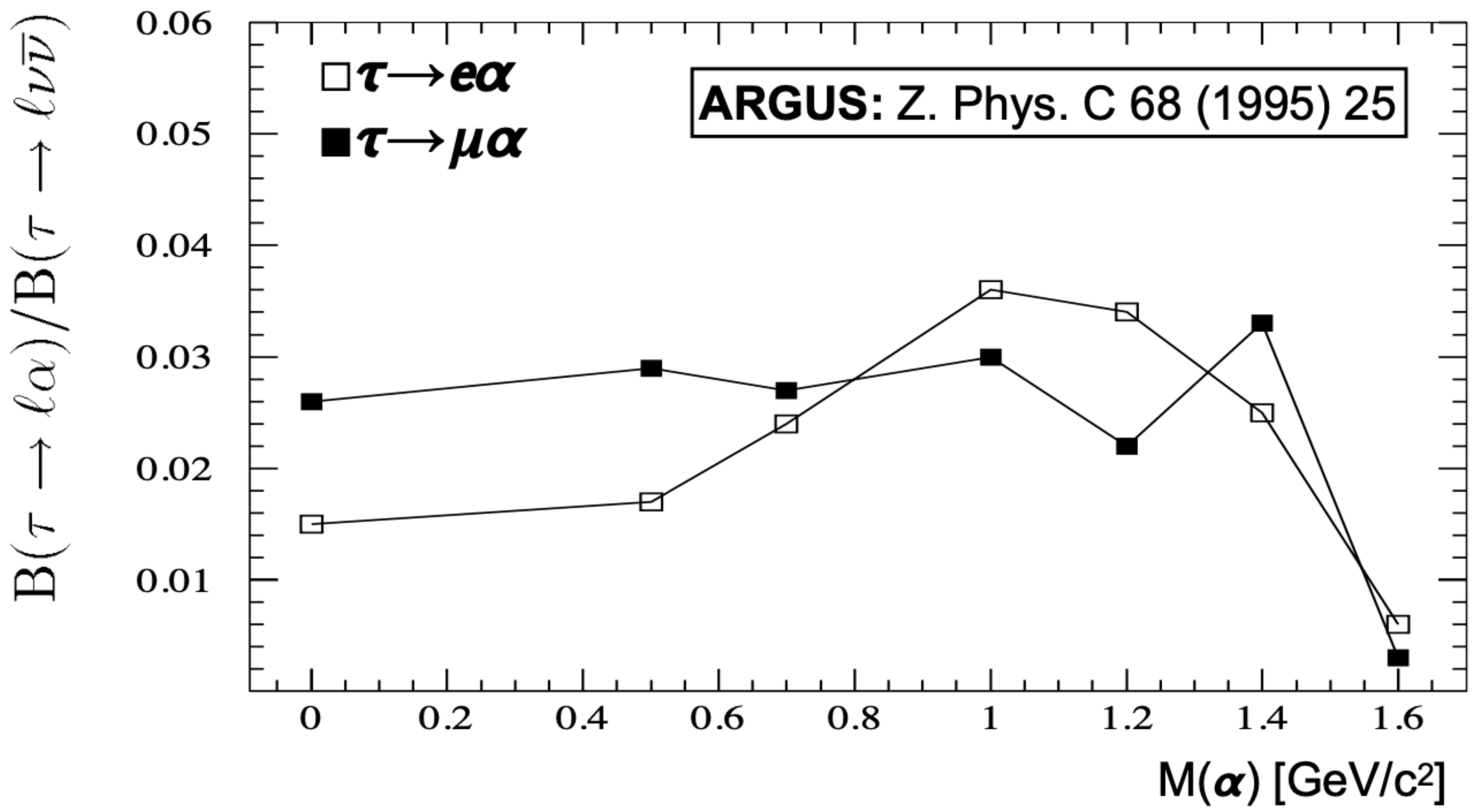


$\tau \to l\alpha$ motivation

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..



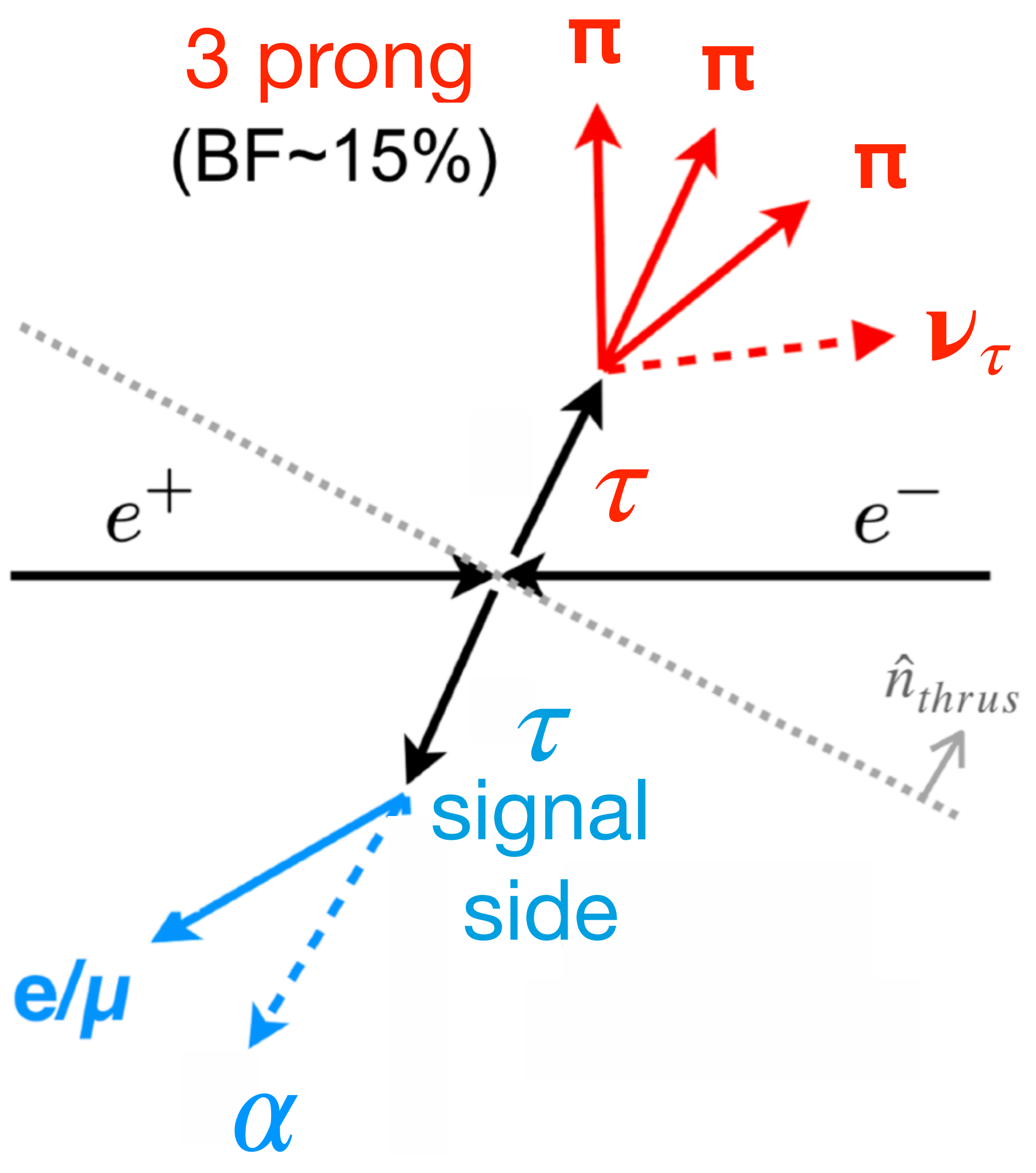
Best upper limits on $B(\tau \to l\alpha)/B(\tau \to l\nu\bar{\nu})$ from ARGUS (1995, 476 pb^{-1})



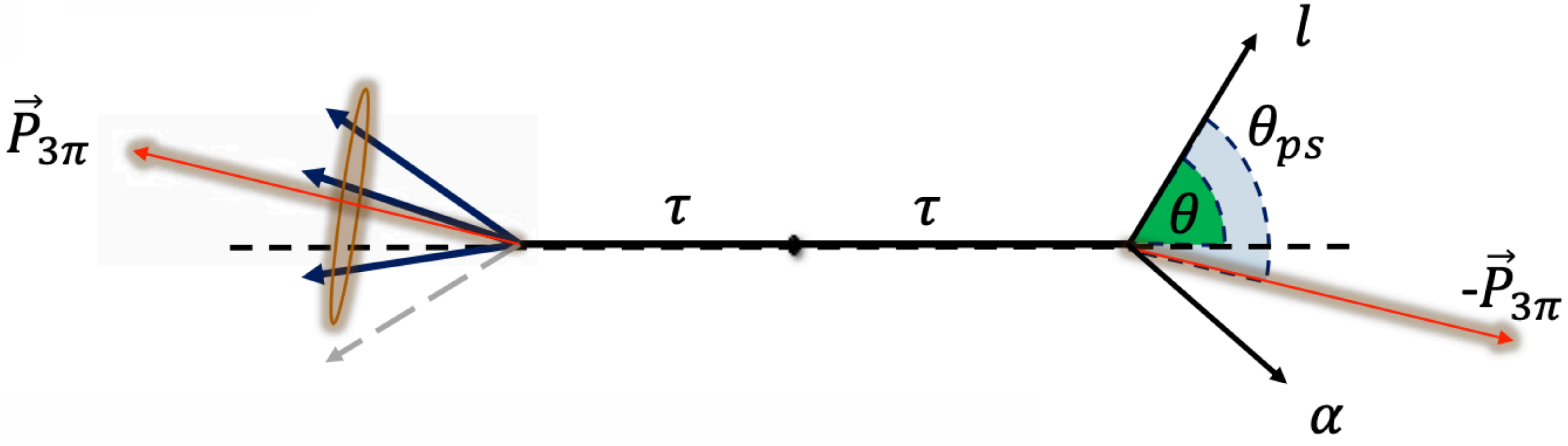
Can Belle II do better?

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

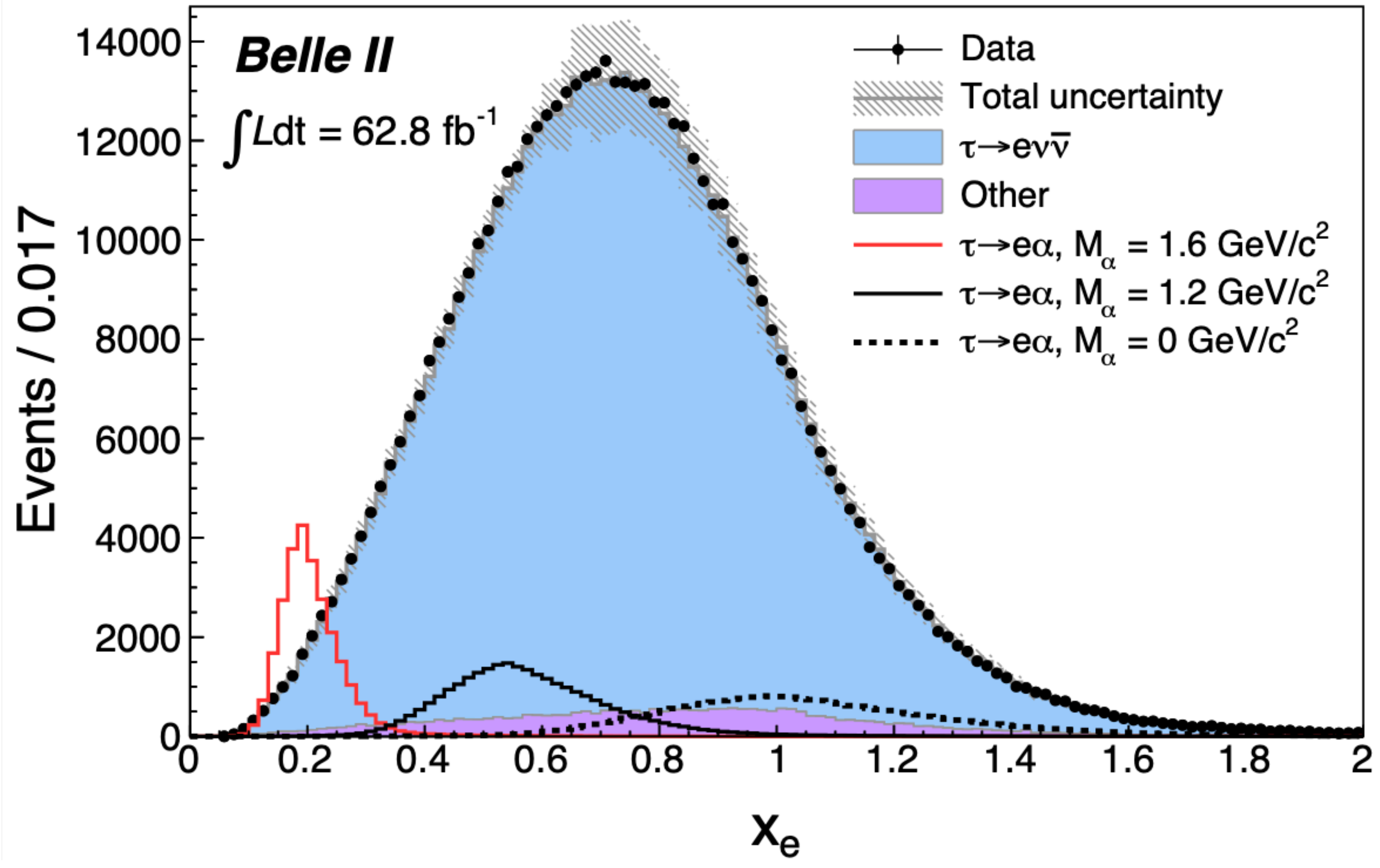
ARGUS analysis approach is adopted → definition of pseudo-rest (ps) frame

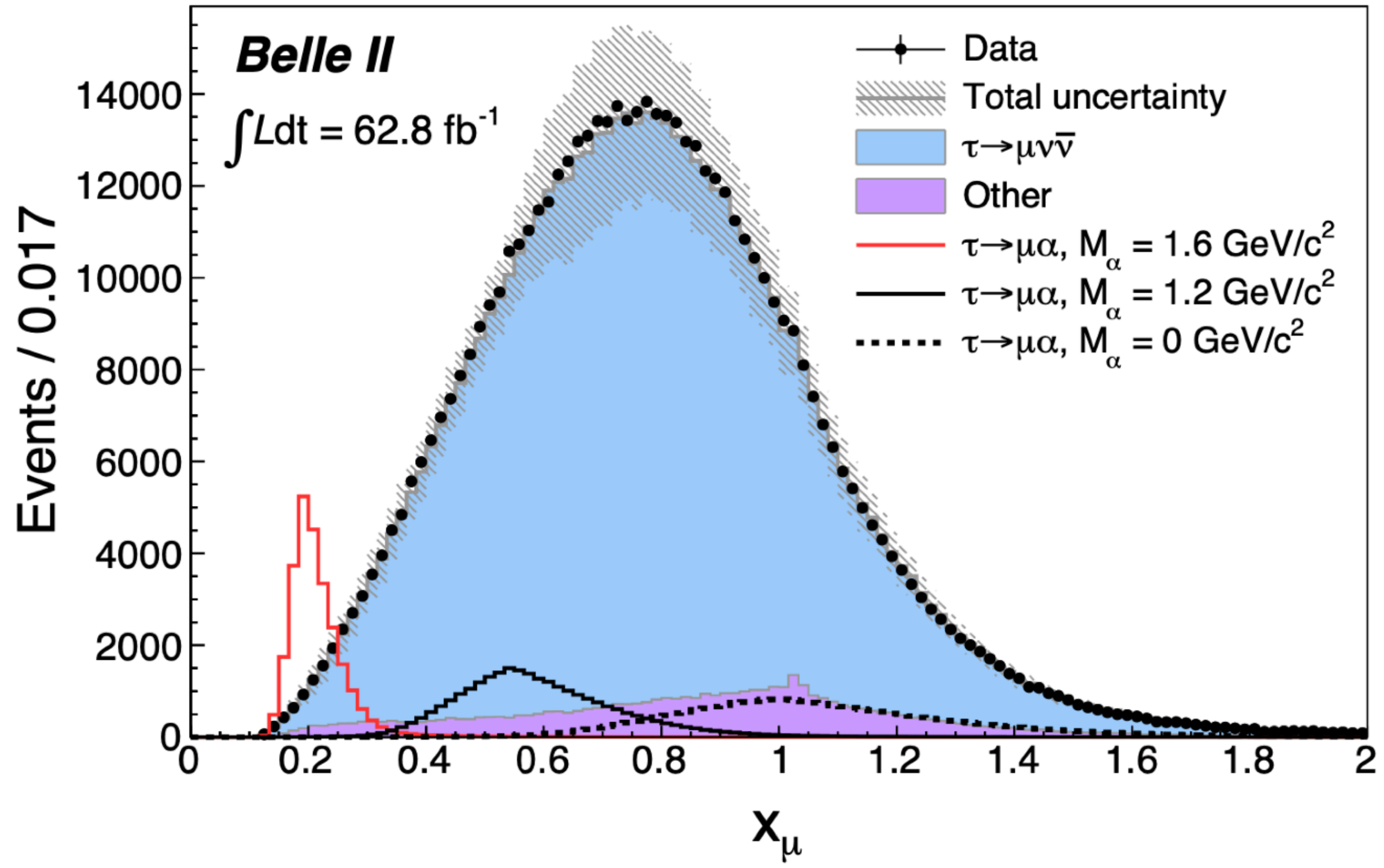


- Tag side: $\tau \to 3\pi\nu_\tau$
- Pseudo-rest frame implies:
  - $\overrightarrow{p_\tau} \sim -\vec{p}_{3\pi}$
  - $E_\tau \sim \sqrt{s}/2$
- Veto neutrals: π^0, γ
- Selection optimised on $\tau \to l\nu\bar{\nu}_\tau$ as irreducible background



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

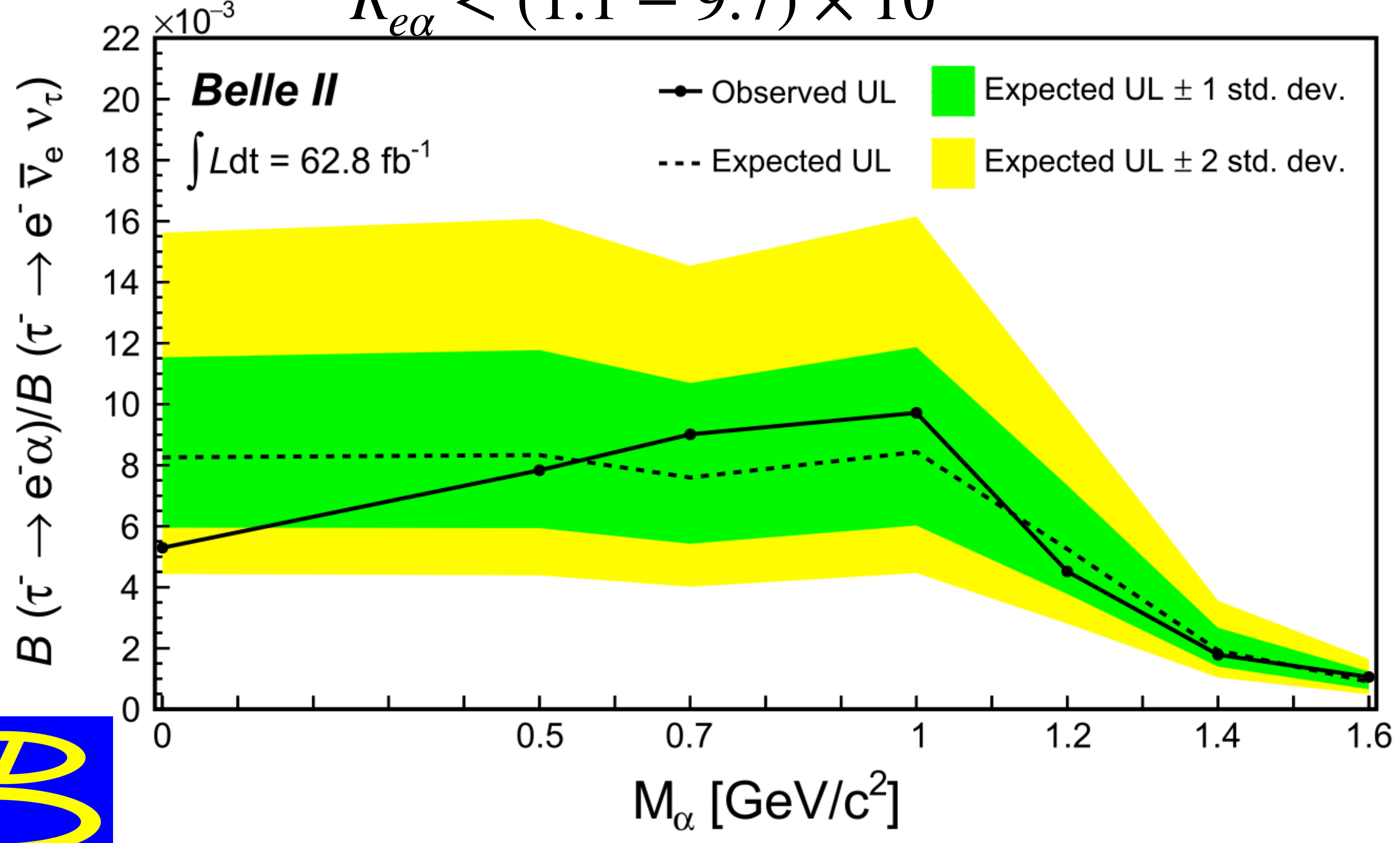
Ref: https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.130.181803

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

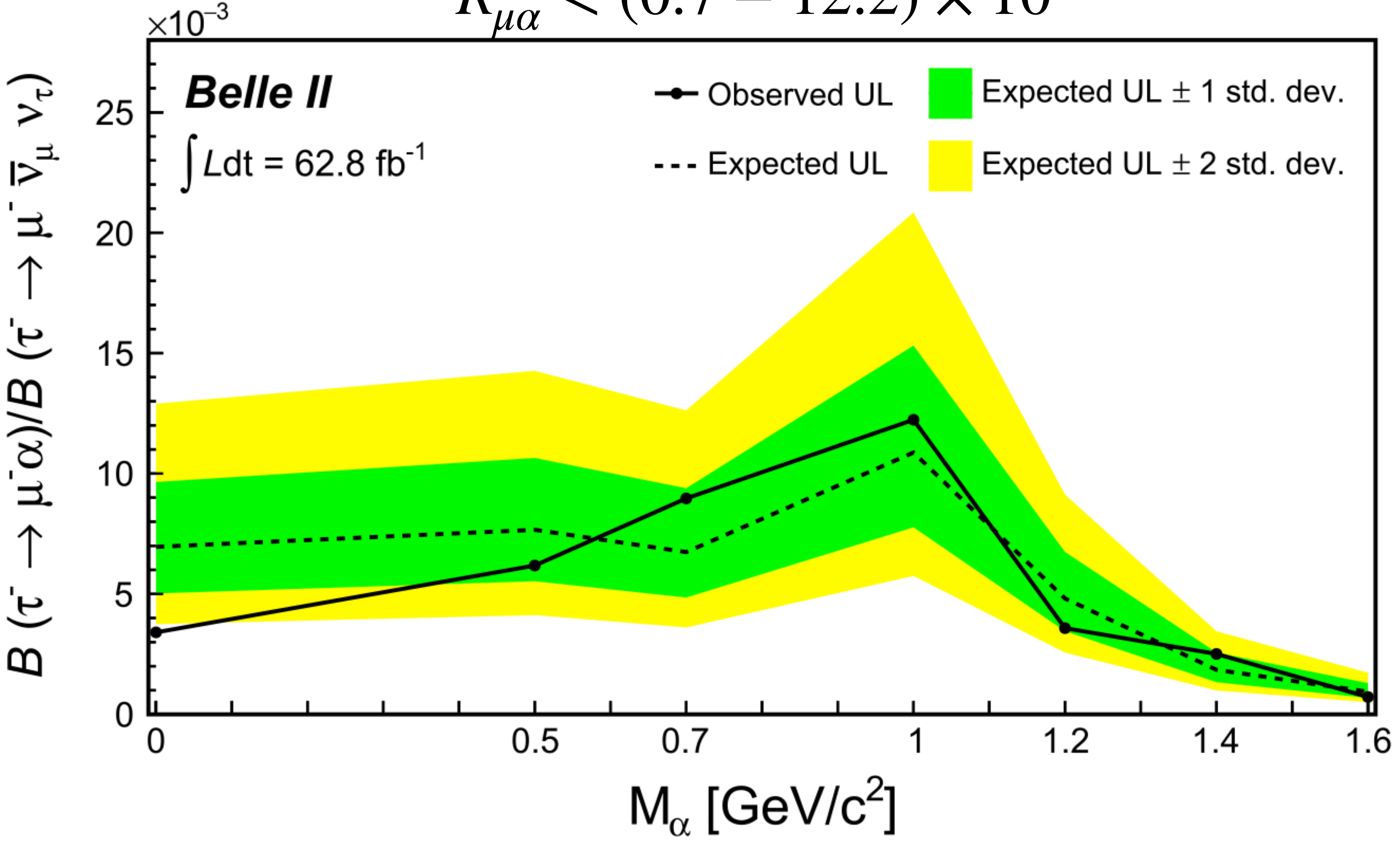
Best measurement today: 2.2–14 times more stringent than Belle depending on the value of the α mass

Dominant syst. from lepton ID efficiency

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



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

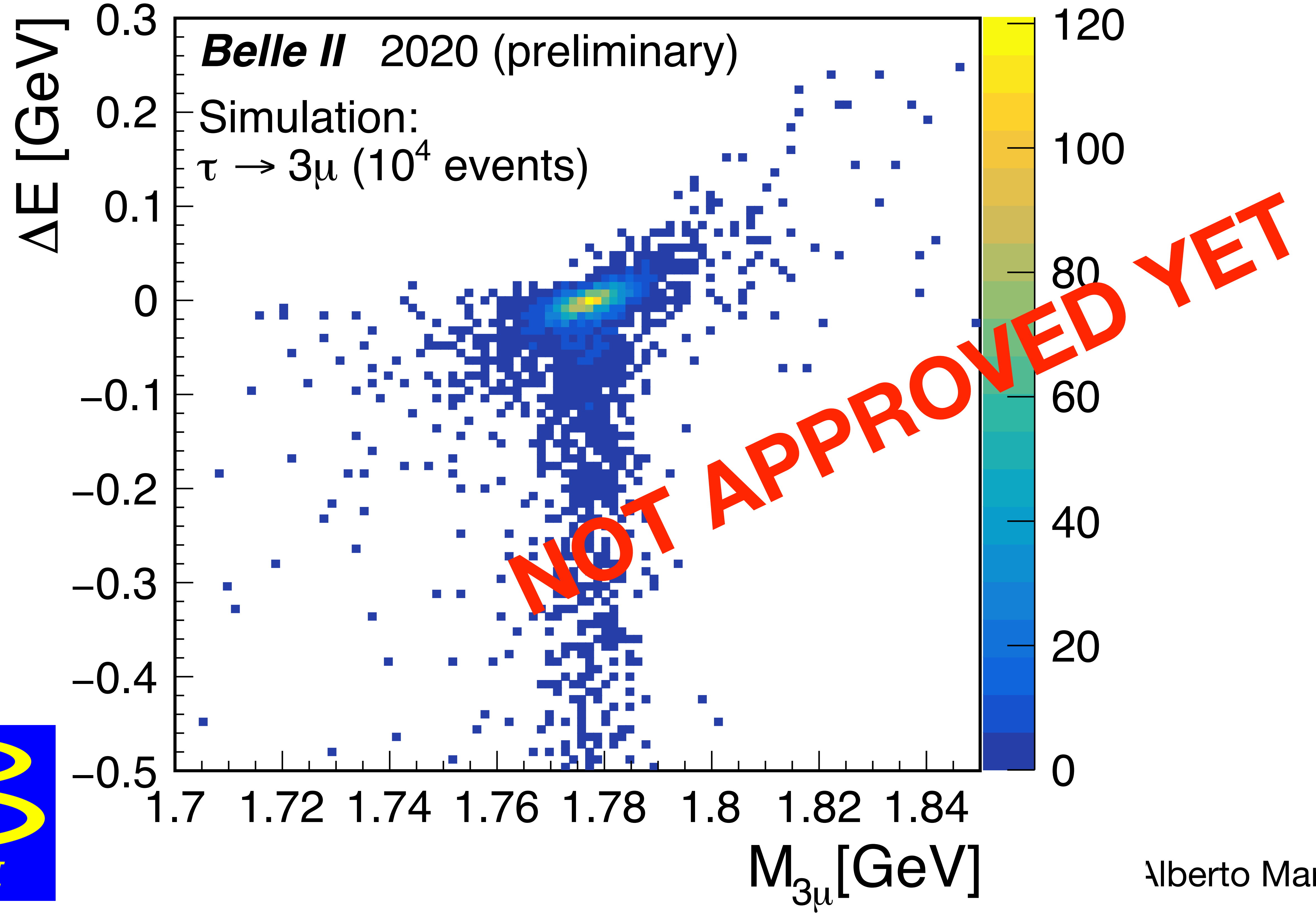


Analysis of $\tau \to 3\mu$ @Belle II

Best upper limits on $\tau \to 3\mu$ from Belle: **2.1 x 10^{-8}** @90% CL with 782 fb^{-1} → Belle II is already competitive with 434 fb^{-1}

Closed signal side kinematics

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



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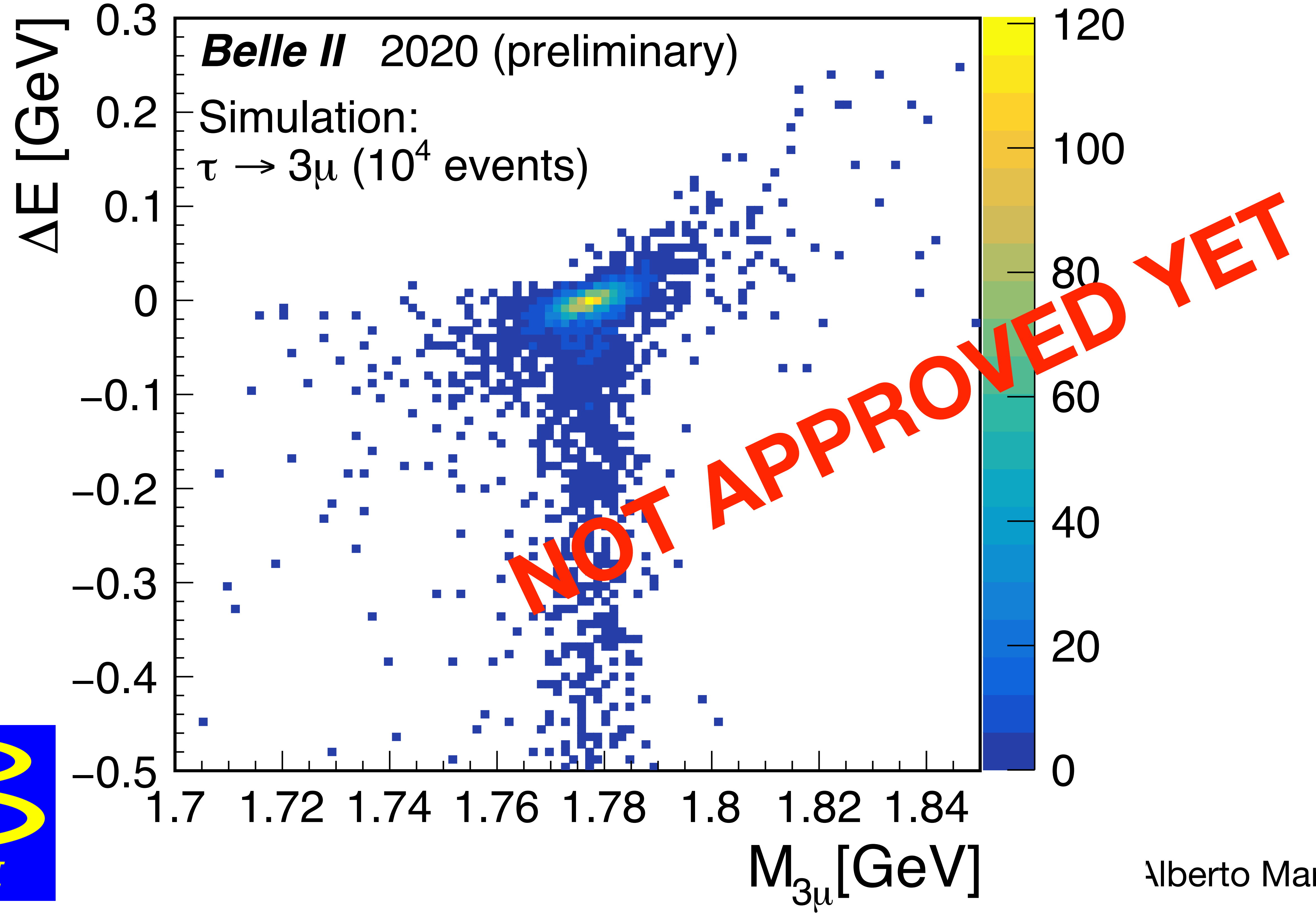
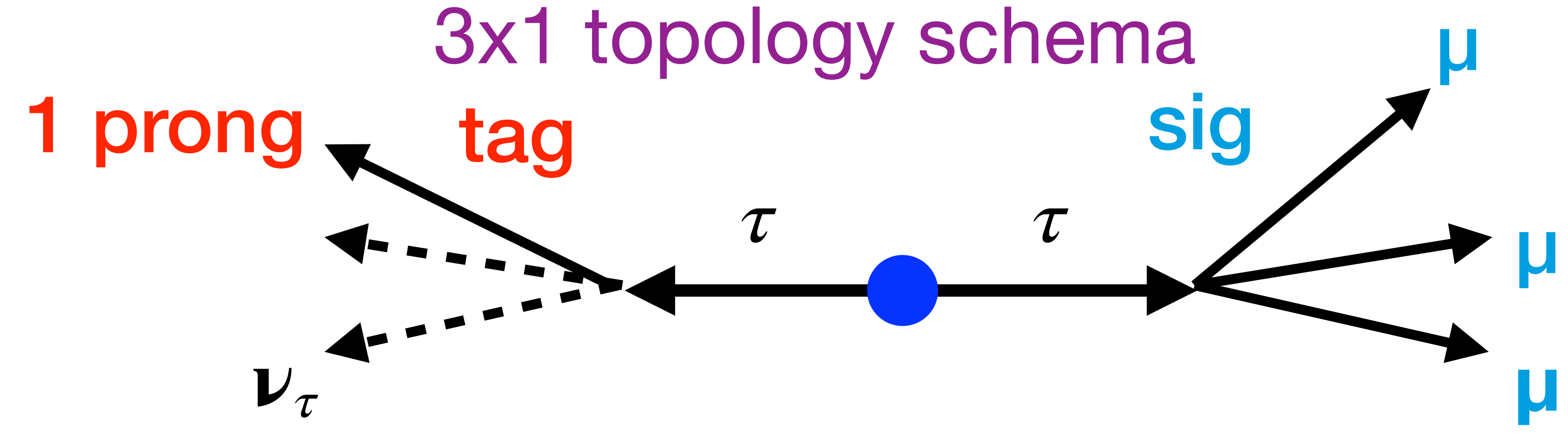
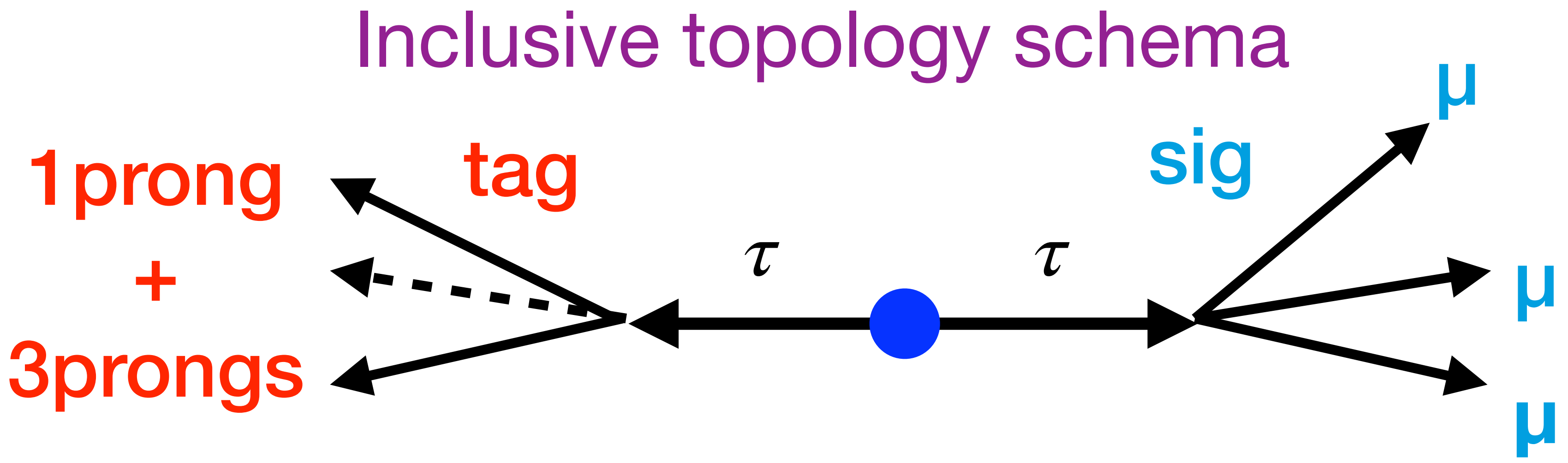


Two analysis approaches:

- Cut based with 3x1 topology:
  - muon identification cuts optimised as a function of the track momentum



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



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

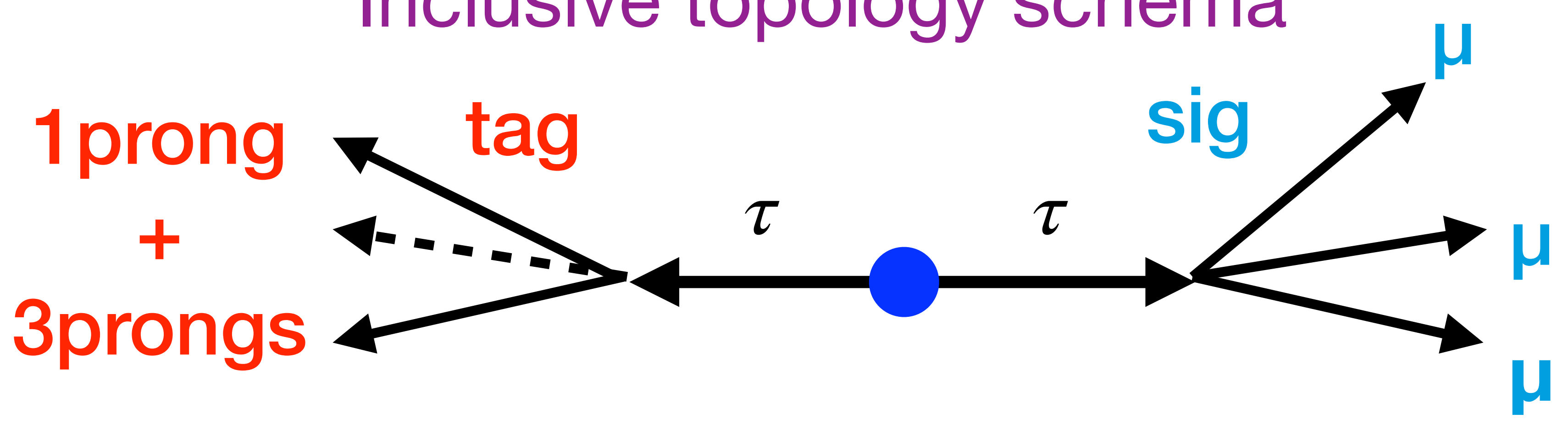
Analysis selection and results: inclusive approach

GBoost BDT trained on a statistics of 4 ab^{-1} using 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

Inclusive topology schema



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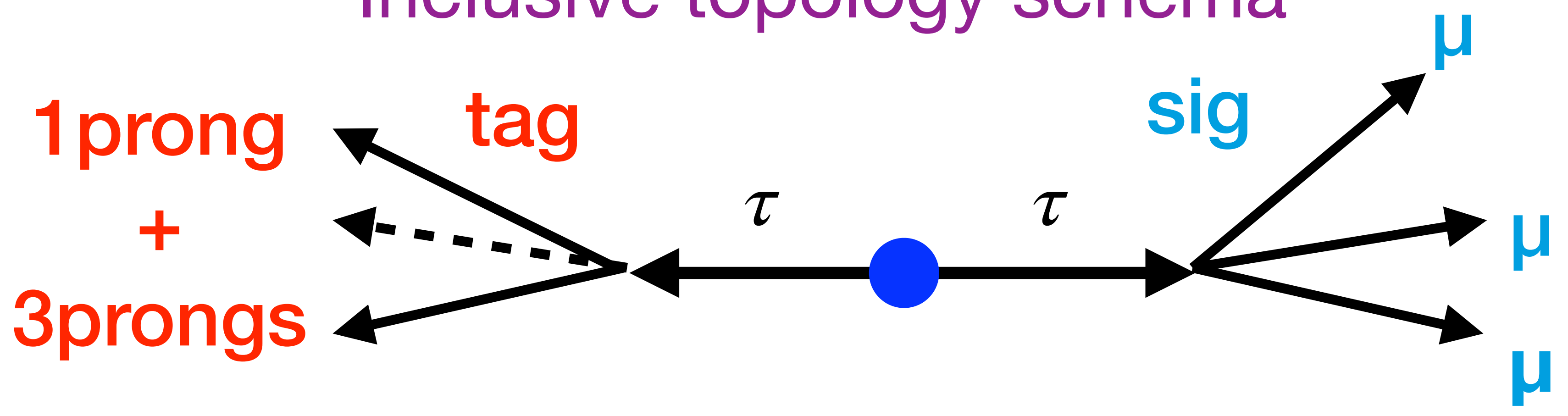

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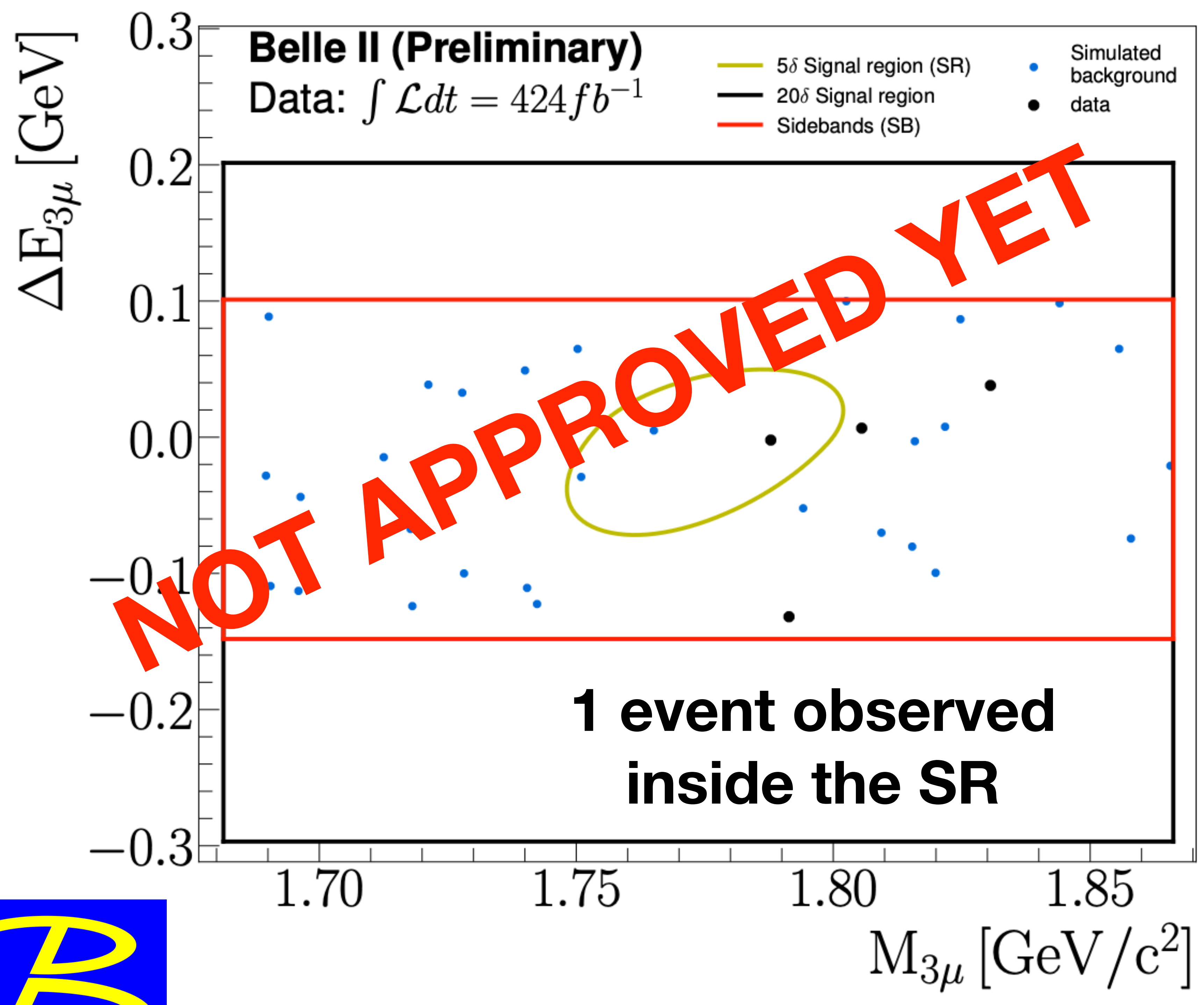
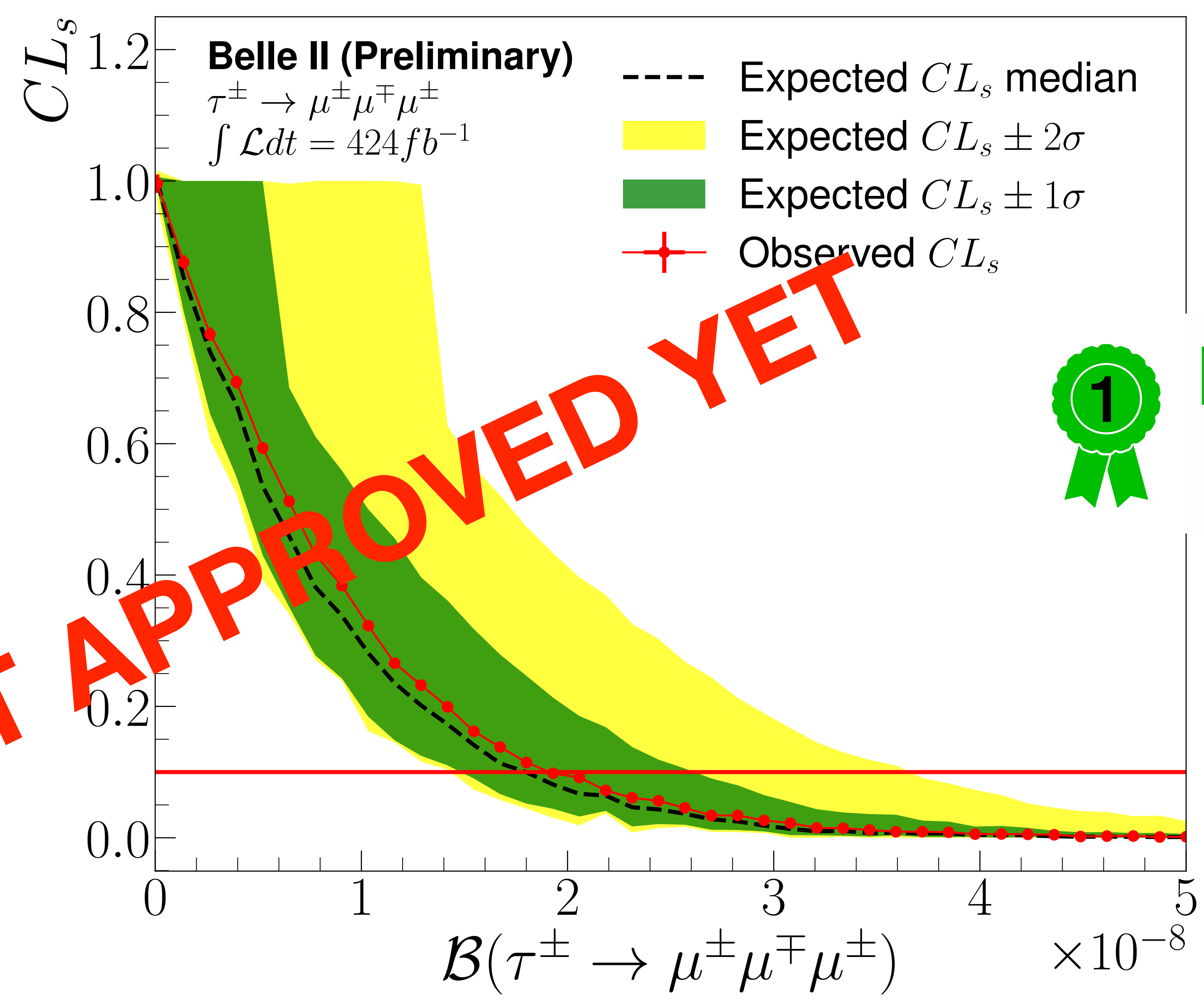




Expected most stringent limit

1.9×10^{-8}

Summary

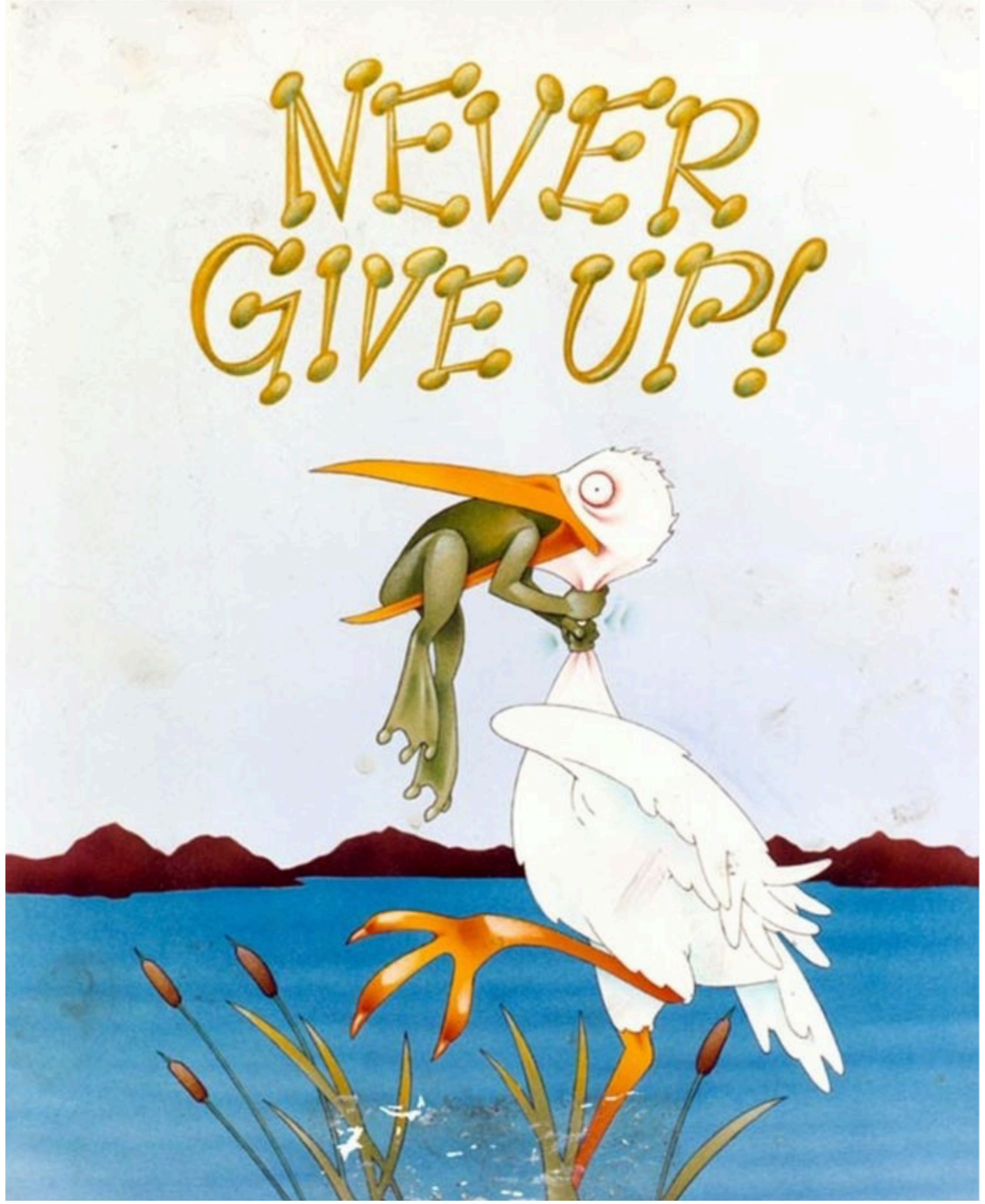
- B-factories are a perfect environment for LFV searches on τ sector
  - Belle and Belle II are also a τ-factories!

★ World best result!

- Several new high profile measurements:
  - $\tau \to lV^0$ @Belle & Belle II, $\tau \to l\alpha$ and $\tau \to 3\mu$ @Belle II
    ★ ★ ★

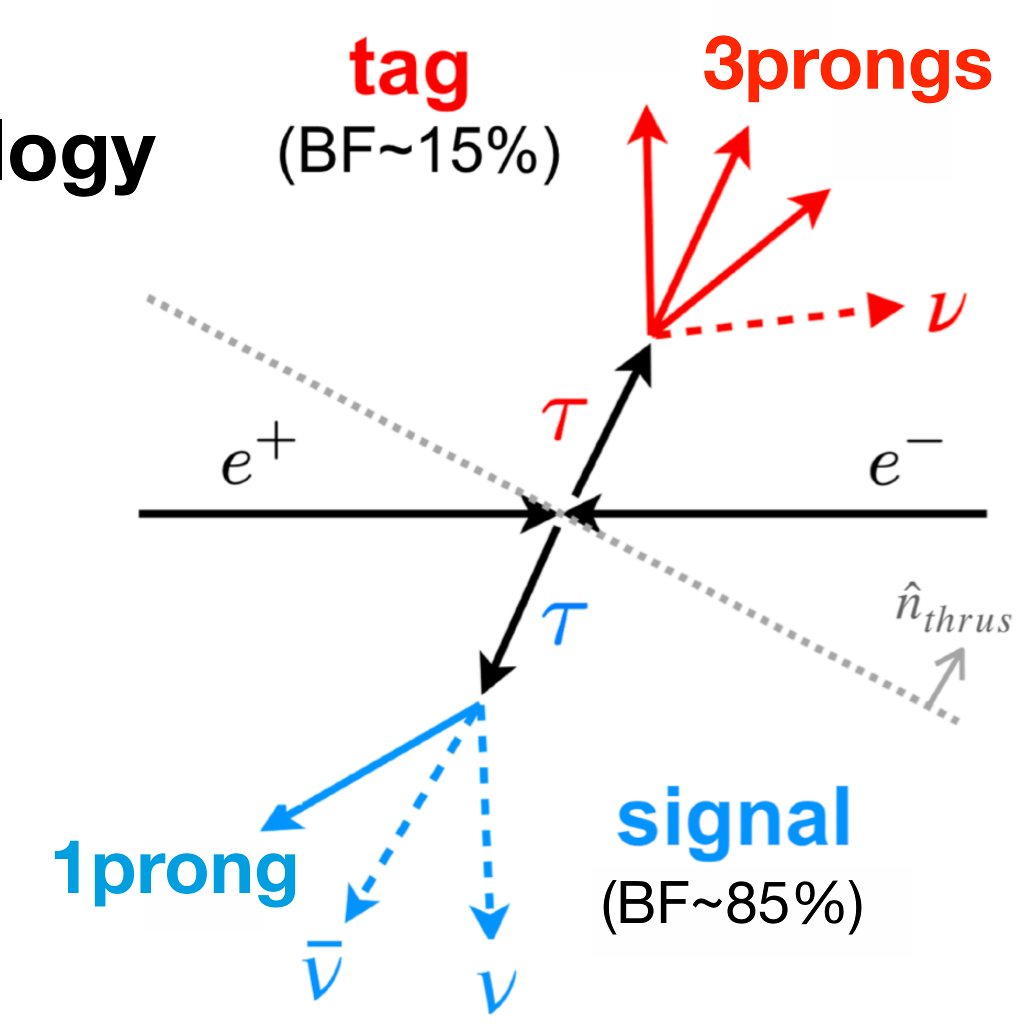
- More results to come so stay tuned!

Emergency slides!!



Physics: τ analyses

3x1 topology



1x1 topology