LFV and dark sector searches at Belle (II) experiment

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On behalf of the Belle and Belle II collaborations

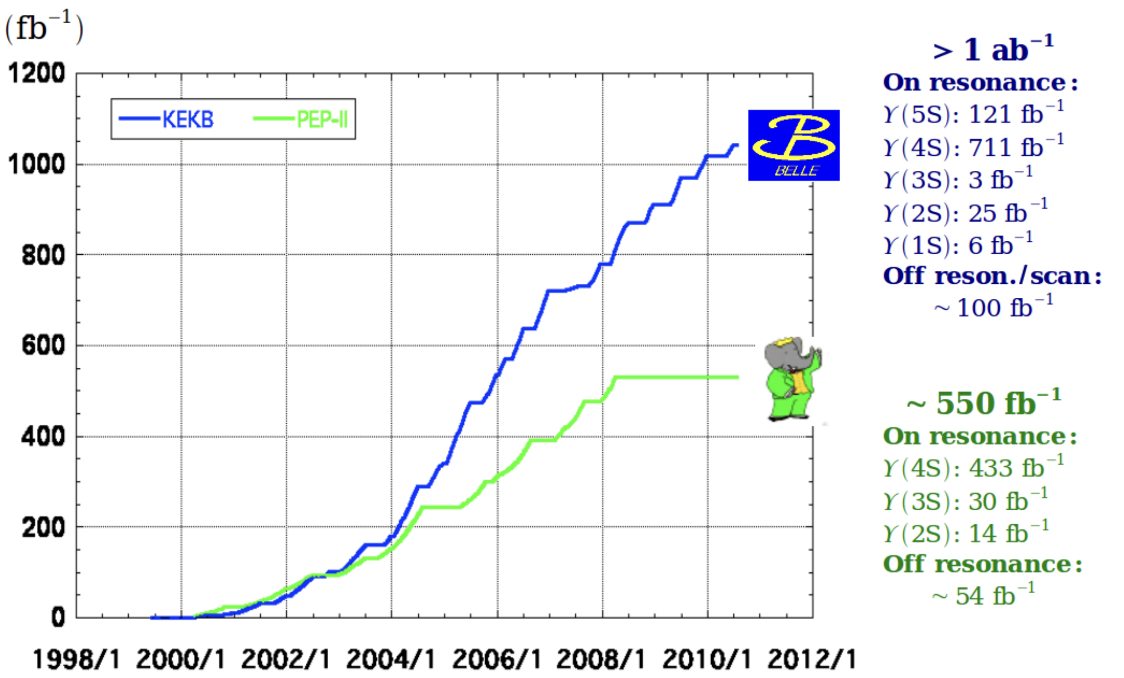
BELLE

Belle II

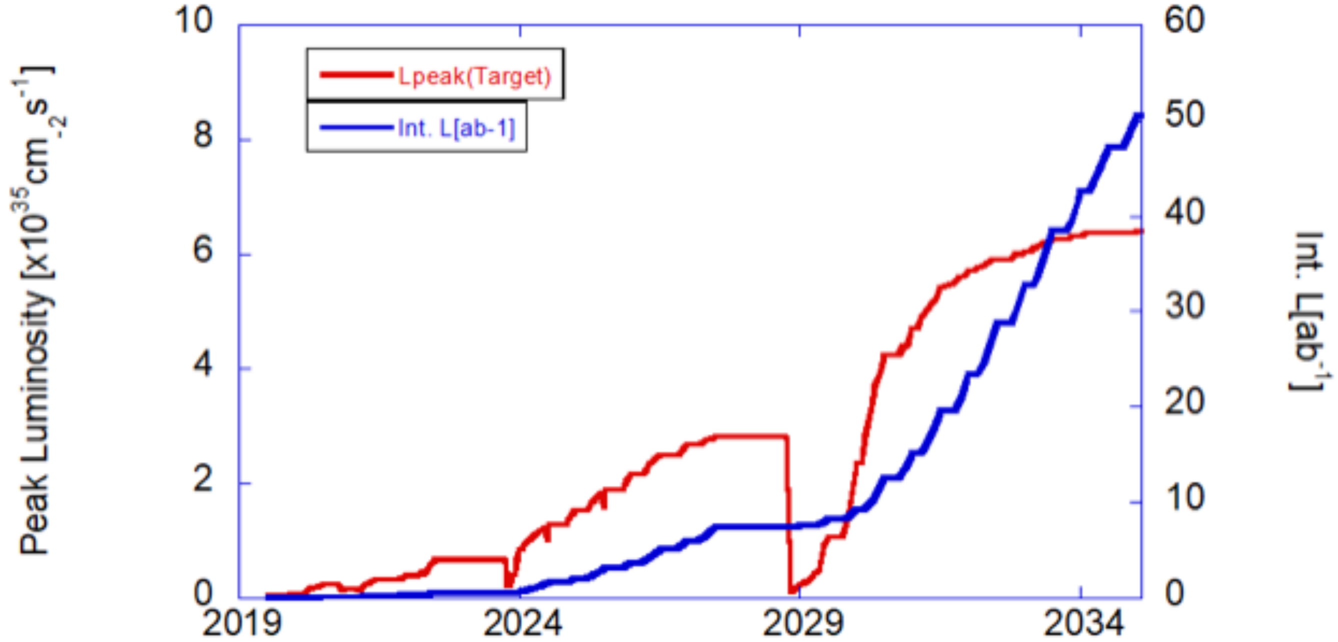
UJ Particle Physics Phenomenology and Experiments Seminar
Krakow
Sep 12, 2022

B factories are also τ factories

Integrated luminosity of B factories



Projected luminosity at SuperKEKB/Belle II



$$\sigma(e^+e^- \to b\bar{b}) = 1.05\ nb$$

$$\sigma(e^+e^- \to \tau^+\tau^-) = (0.919 \pm 0.003)\ nb$$

SwB, B. Pietrzyk, J.Roney, Z.Was
Phys.Rev.D 77 (2008) 054012

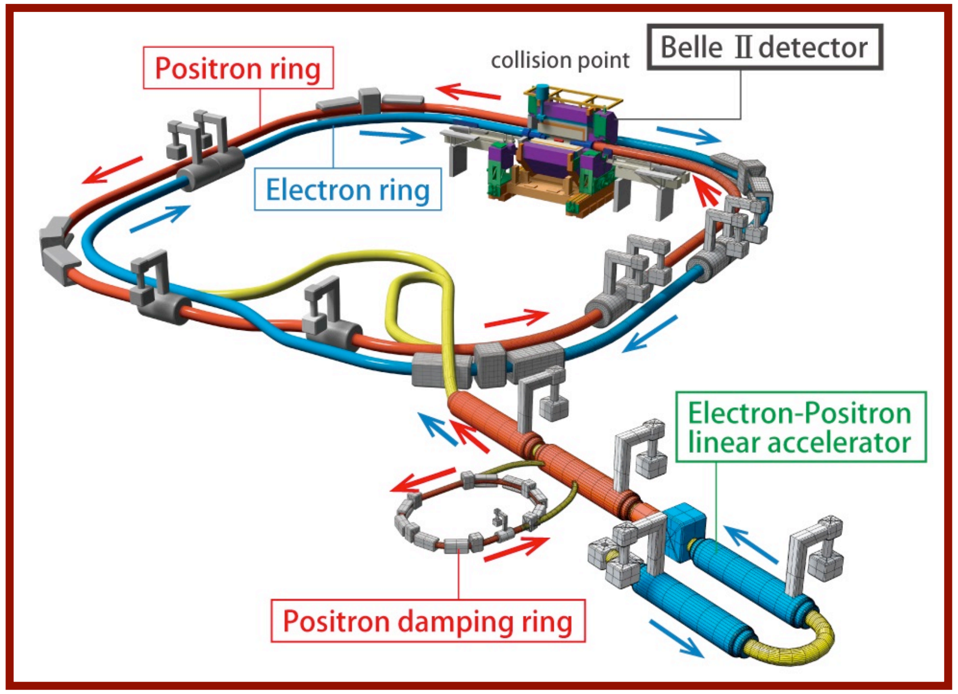
τ-pairs produced at Belle with $\simeq 1\ ab^{-1}$ of data $\simeq 10^9$

τ-pairs expected at Belle II with $\simeq 50\ ab^{-1}$ of data $\simeq 5 \times 10^{10}$

World's largest dataset of τ-leptons simulated with Monte Carlos:

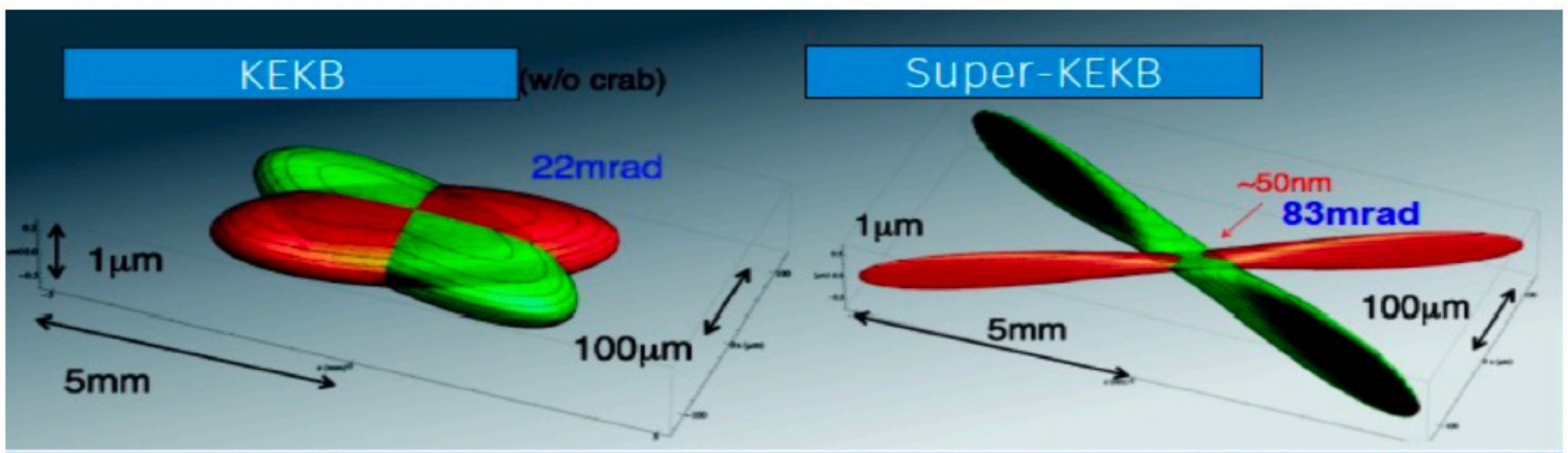
- KK2F [S.Jadach, B.F.L.Ward, Z.Was, Comput.Phys.Commun. 130 (2000) 260]
- TAUOLA [S.Jadach, Z.Was, R.Decker, J.H.Kuhn, Comput.Phys.Commun. 76 (1993) 361]
- PHOTOS [E.Barberio, Z.Was, Comput.Phys.Commun. 79 (1994) 291]

SuperKEKB/Belle II



Design instantaneous luminosity at SuperKEKB of 6.5 x 10^{35} cm^{-2} s^{-1}, e.g. factor of 30 more than KEKB:

- Nano-beam scheme
- Reducing e^- beam energy gives $(7/8)^4$ = 59% reduction in synchrotron radiation



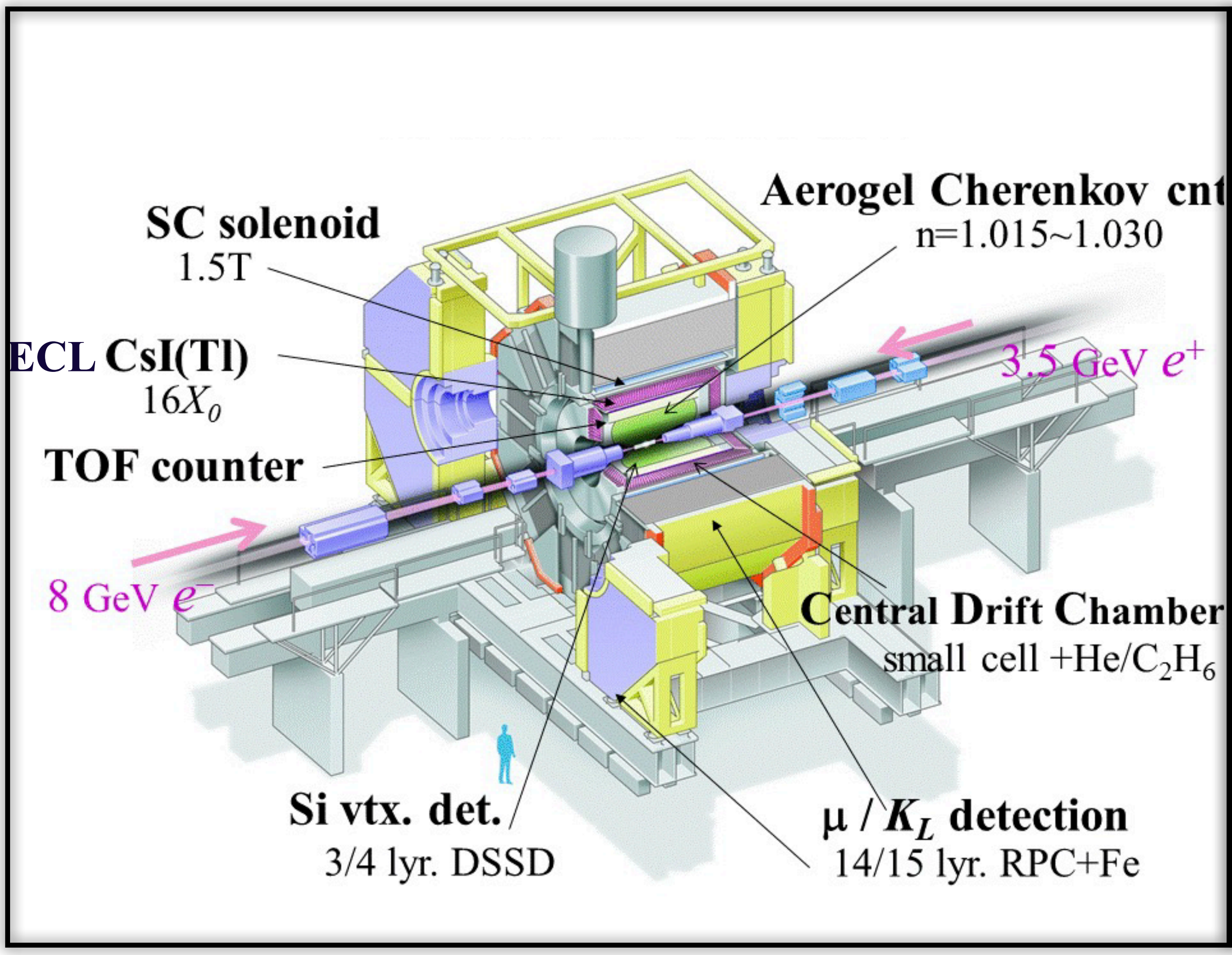
	Energy (GeV) LER/HER	β_y^* (mm) LER/HER	ε_x (nm) LER/HER	ξ_y LER/HER	φ (mrad)	I_{beam} (A) LER/HER	Luminosity ($cm^{-2}s^{-1}$) x 10^{34}
KEKB Achieved	3.5/8.0	5.9/5.9	18/24	0.13/0.09	11	1.6/1.2	2.11
SuperKEKB	4.0/7.0	0.27/0.3	3.2/2.4	0.09/0.09	41.5	2.8/2.0	65

factor 20 factor 1.5

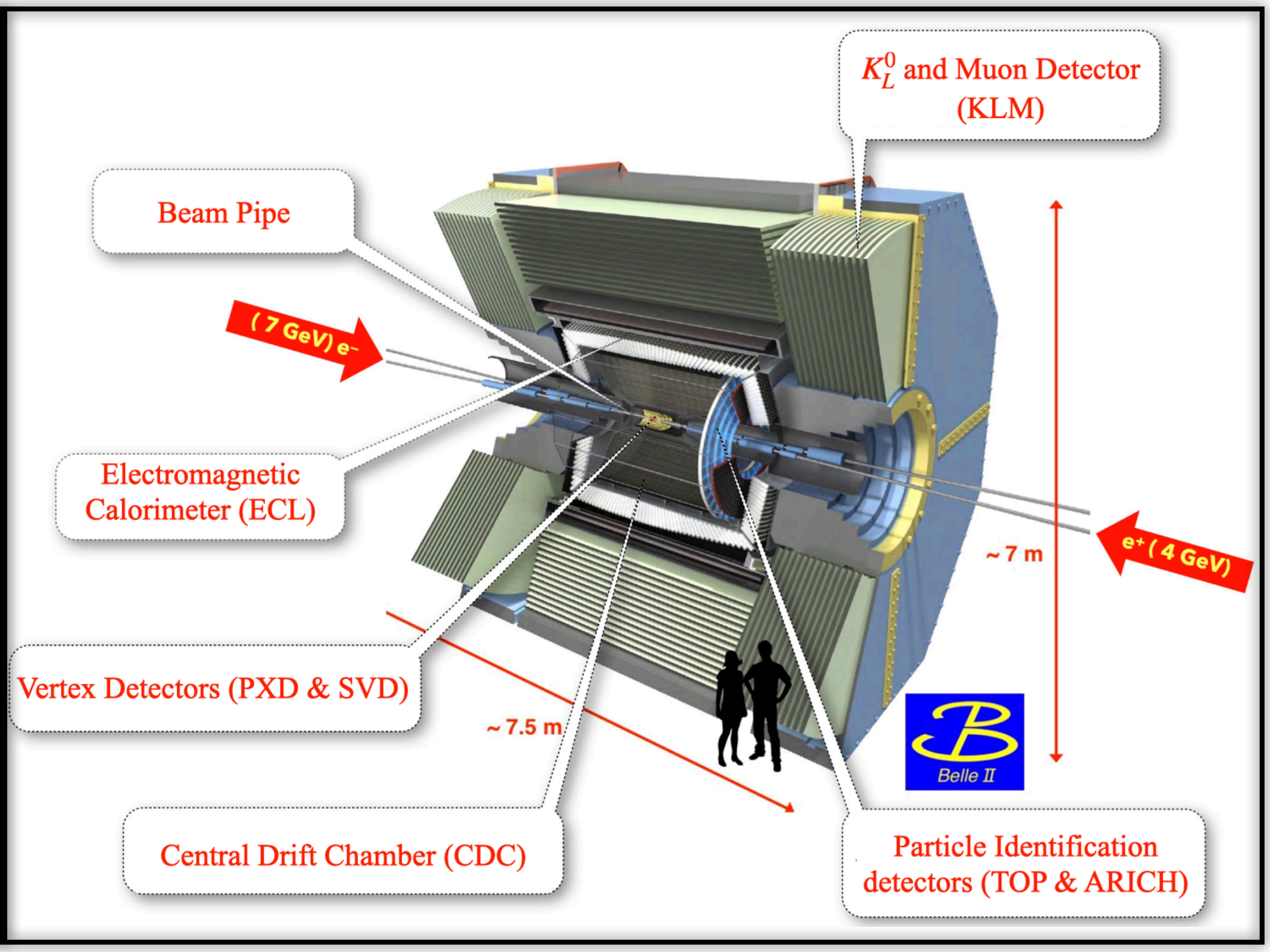
Factor of 30 increase in instantaneous luminosity

Belle and Belle II detectors

Belle Detector



Belle II Detector



Overview of this talk

- **Search for dark leptophilic scalar at Belle**
  - $e^+e^- \to \tau^+\tau^-\phi_L;\ \phi_L \to e^+e^-/\mu^+\mu^-$

New

BELLE-CONF-2201

arXiv:2207.07476 **[hep-ex]**

- **Search for lepton flavor violation at Belle**
  - $\tau^\pm \to e^\pm\gamma$
  - $\tau^\pm \to \mu^\pm\gamma$

JHEP 10 (2021) 19

arXiv:2103.12994 **[hep-ex]**

- **Search for lepton flavor violation at Belle II**
  - **τ → e/μ invisible**

New

Shown at ICHEP2022

- **Future prospects of LFV searches in τ sector**
  - **Belle II, LHC, STCF, EIC, FCC**

Snowmass Whitepaper

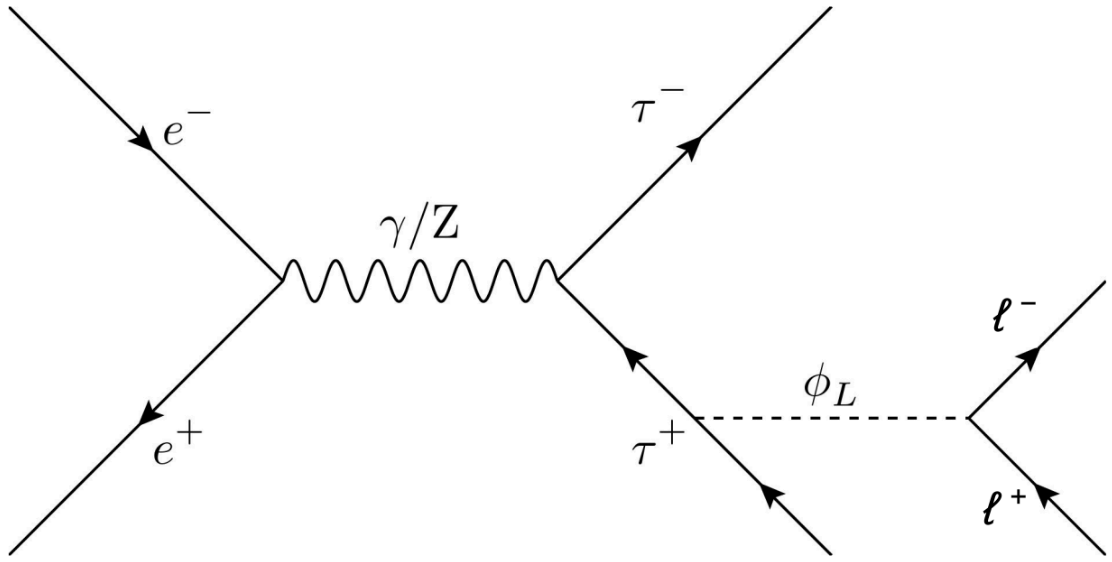
arXiv:2203.14919 **[hep-ph]**

Dark leptophilic scalar

Dark sector portal can explain $(g\text{-}2)_\mu$ excess and lepton flavor universality violation:

- Many of the beyond standard model (BSM) theories predict the existence of additional scalars other than the Higgs boson.
- The mixing between this dark scalar and the SM Higgs boson gives rise to couplings proportional to SM fermion masses.
- If this new scalar couples to both quarks and leptons, the existence of such particles is strongly constrained by the searches for rare flavor-changing neutral current decays of mesons, e.g. $B \to K\phi$ and $K \to \pi\phi$.

However, these bounds are evaded if the coupling of the scalar to quarks is suppressed and this scalar interacts preferentially with leptons.



$$\mathcal{L} = -\xi \sum_{\ell=e,\mu,\tau} \frac{m_\ell}{v} \bar{\ell}\, \phi_L \ell$$

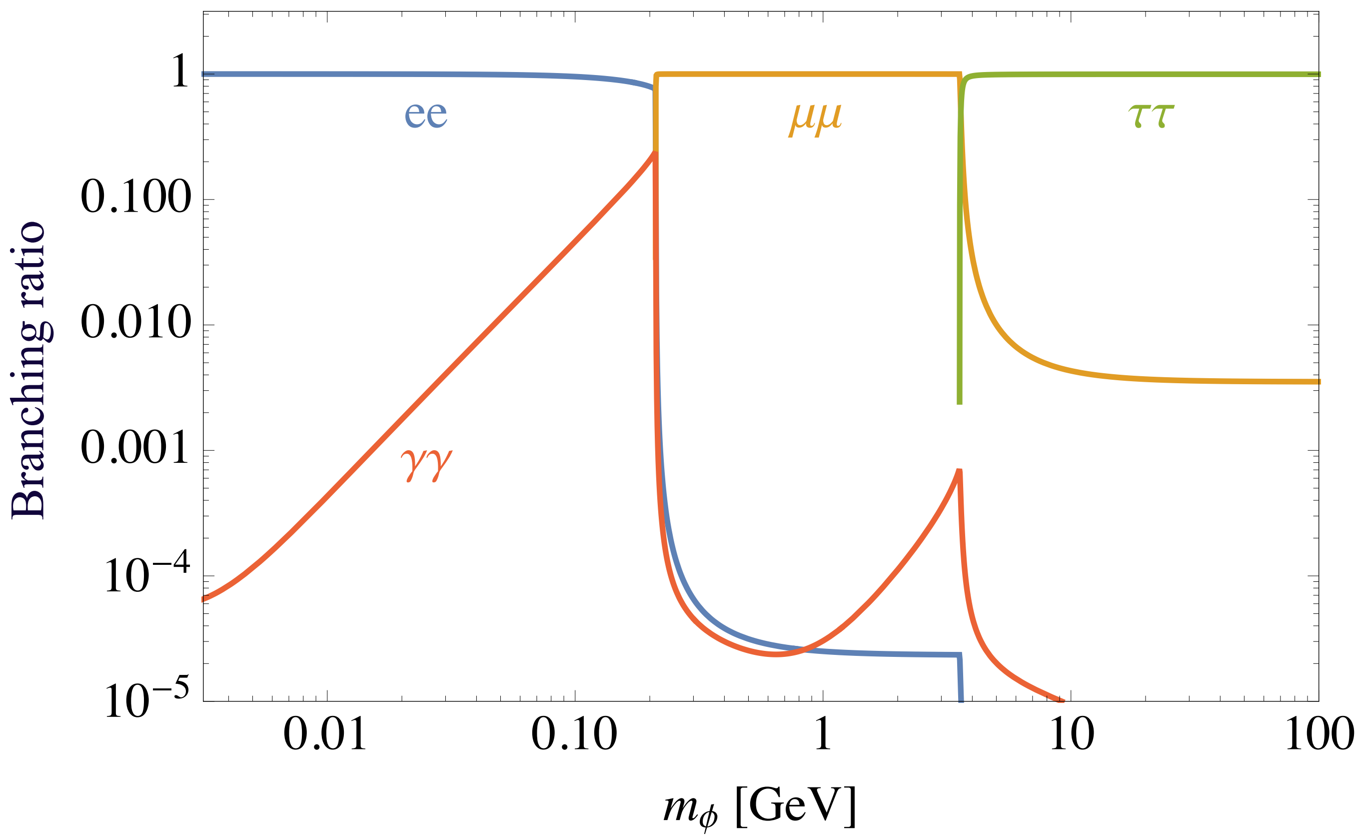
ξ is the lepton flavor independent coupling constant,
m_ℓ is mass of the lepton the dark scalar couples with,
v is the vacuum expectation value = 246 GeV

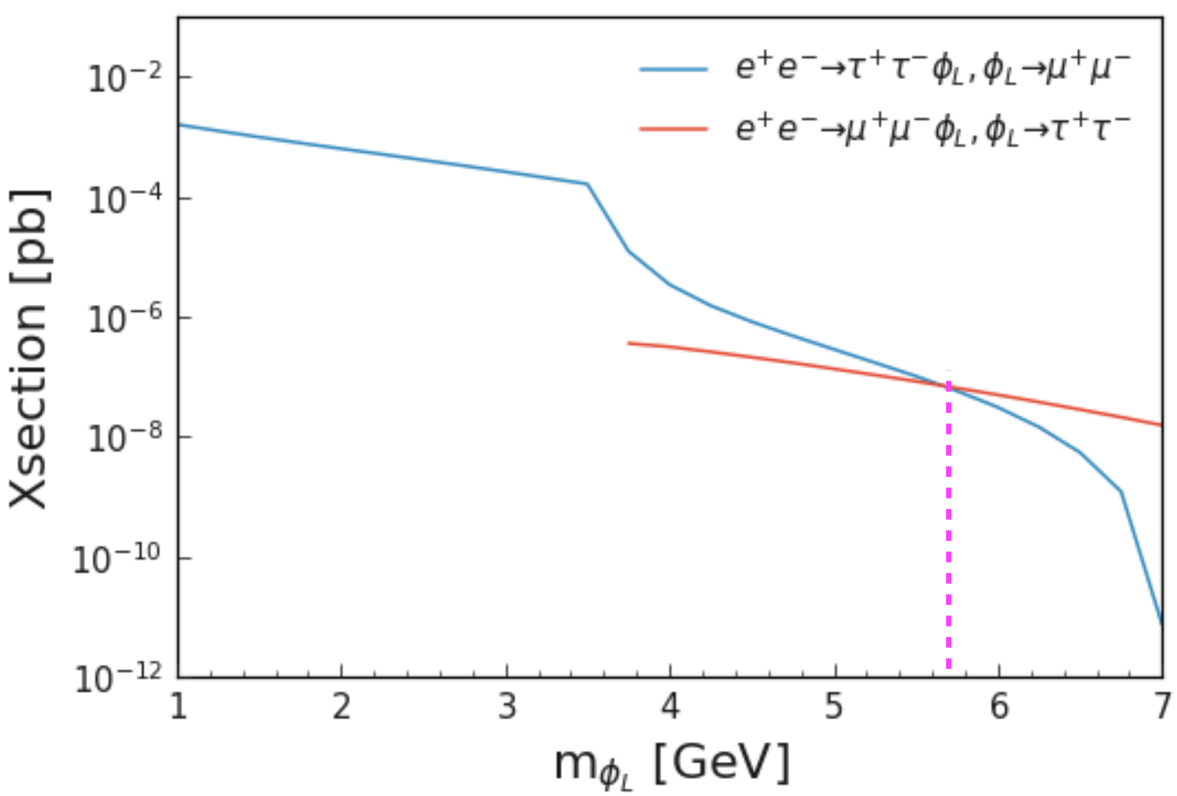
B. Batell, N. Lange, D. McKeen, M. Pospelov, and A. Ritz, "Muon anomalous magnetic moment through the leptonic higgs portal," Phys. Rev. D 95 (2017) 075003.

$e^+e^- \to \tau^+\tau^-\phi_L;\ \phi_L \to e^+e^-/\mu^+\mu^-$

- ϕ_L decays to a lepton pair: search for narrow peak in lepton pair invariant mass distribution.
  - $\phi_L \to e^+e^-$ for $m_{\phi_L} < 2m_\mu$ and $\phi_L \to \mu^+\mu^-$ for $m_{\phi_L} > 2m_\mu$

- High production cross-section times branching ratio in the region 40 MeV $< m_{\phi_L} <$ 6.5 GeV.





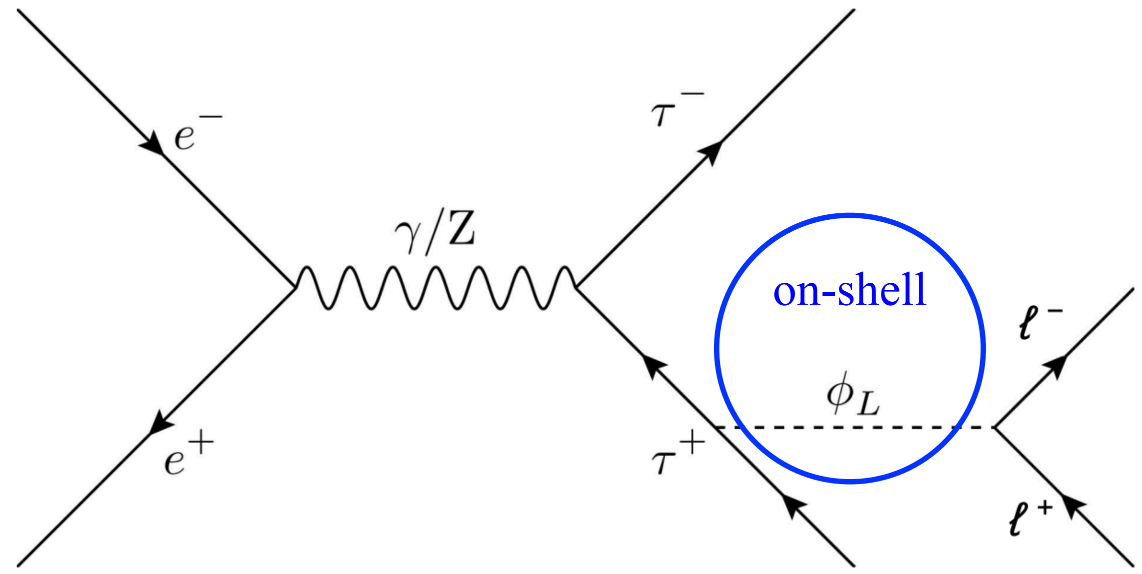
- Comparison between our signal process:
  - $e^+e^- \to \tau^+\tau^-\phi_L;\ \phi_L \to \mu^+\mu^-$

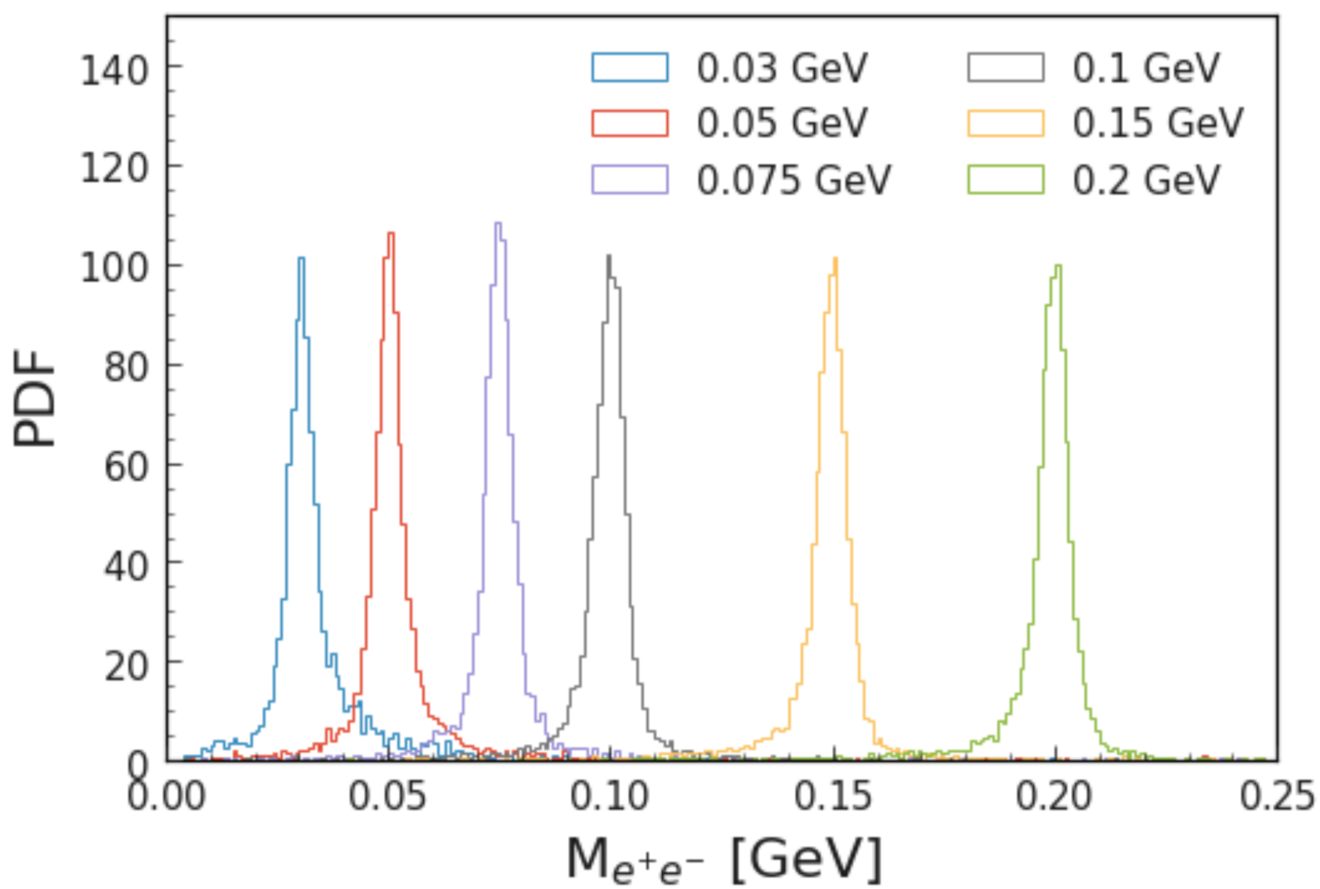
  and complementary process:
  - $e^+e^- \to \mu^+\mu^-\phi_L;\ \phi_L \to \tau^+\tau^-$

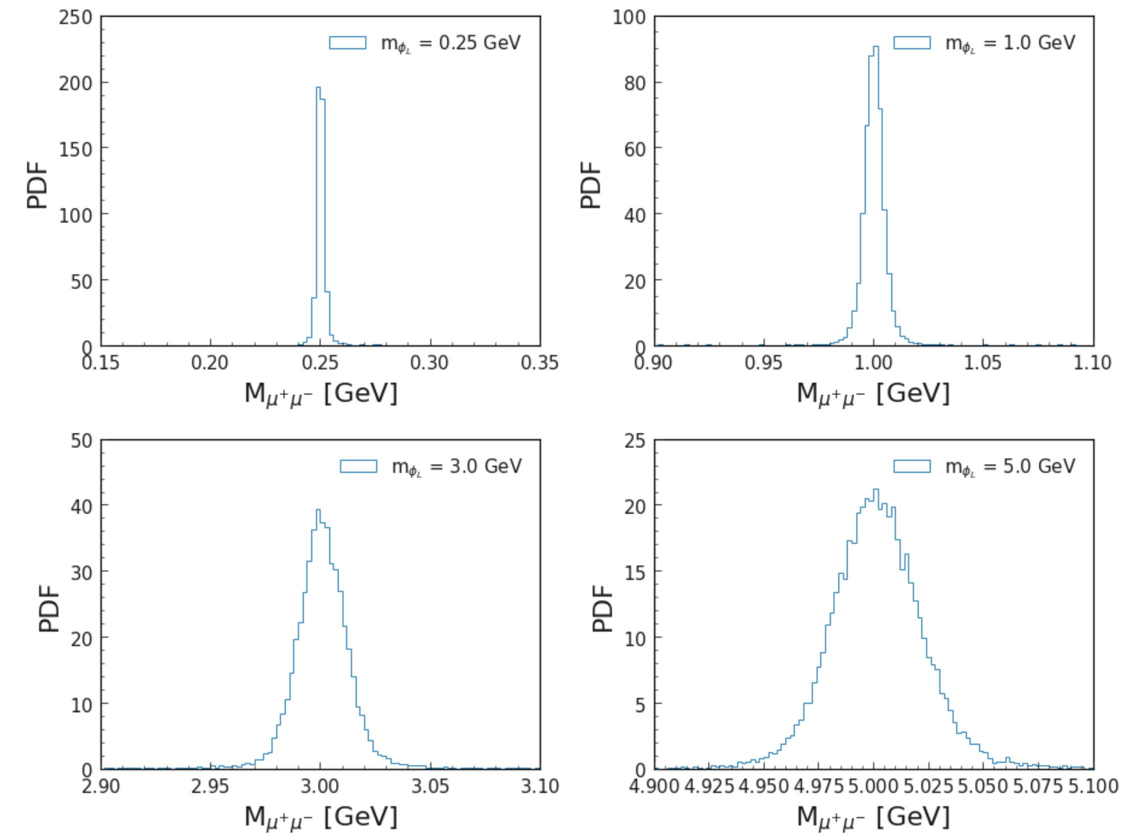
  shows signal process has higher rate till 5.7 GeV.

- Our search has sensitivity to place competitive limits on ξ till $m_{\phi_L} <$ 6.5 GeV.

Signal distribution of the discriminating variable



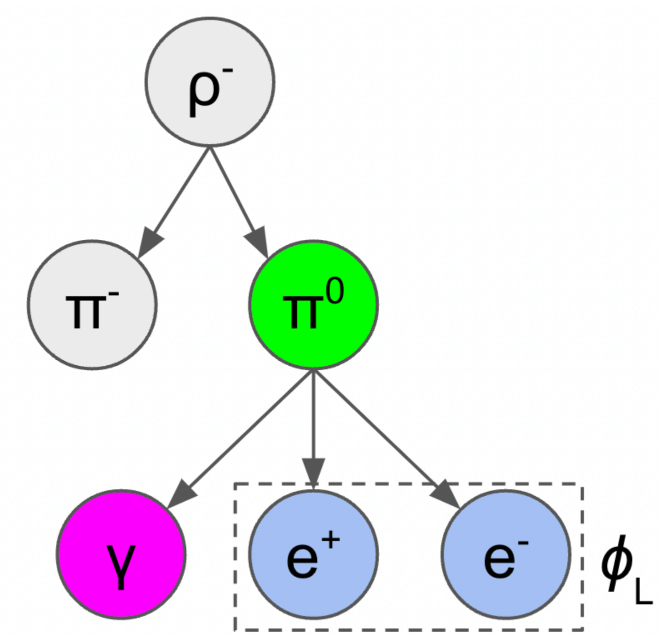


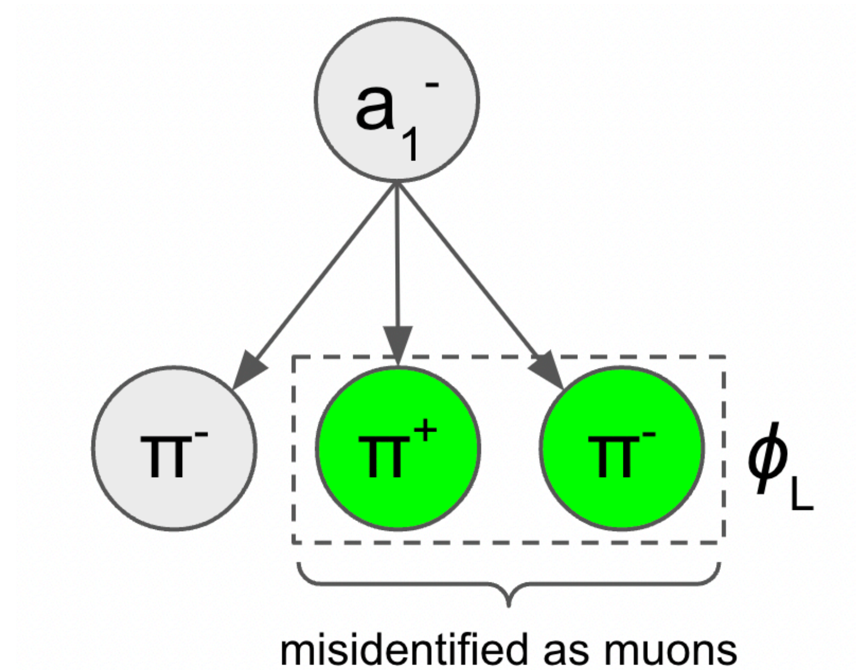


Resolution varies from 5 to 30 MeV, increasing at larger values of m_{ϕ_L}

Search strategy

- Event reconstruction:
  - Require 4 track events with net charge 0.
  - At least two tracks are identified as ℓ, for $\phi_L \rightarrow \ell^+\ell^-$ channel ($\ell = e$ or μ).
  - ℓ^+ and ℓ^- tracks are required to come from the same vertex.
- Backgrounds:
  - $\tau^- \rightarrow \rho^-\nu$, for $\phi_L \rightarrow e^+e^-$ channel. ρ^- decay produces e^+ and e^- as shown.
  - $\tau^- \rightarrow a_1^-\nu$, for $\phi_L \rightarrow \mu^+\mu^-$ channel. π^- from a_1^- decay is misidentified as μ^-.
  - Some $q\bar{q}$, $\ell^+\ell^-$, $\ell^+\ell^-\ell^+\ell^-$, $\ell^+\ell^-h^+h^-$ backgrounds in both of the channels.
- Backgrounds have been suppressed using Boosted Decision Tree (BDT).
- Signal extraction:
  - Fit to $\ell^+\ell^-$ invariant mass distribution.
  - Evaluate at each ϕ_L mass point.

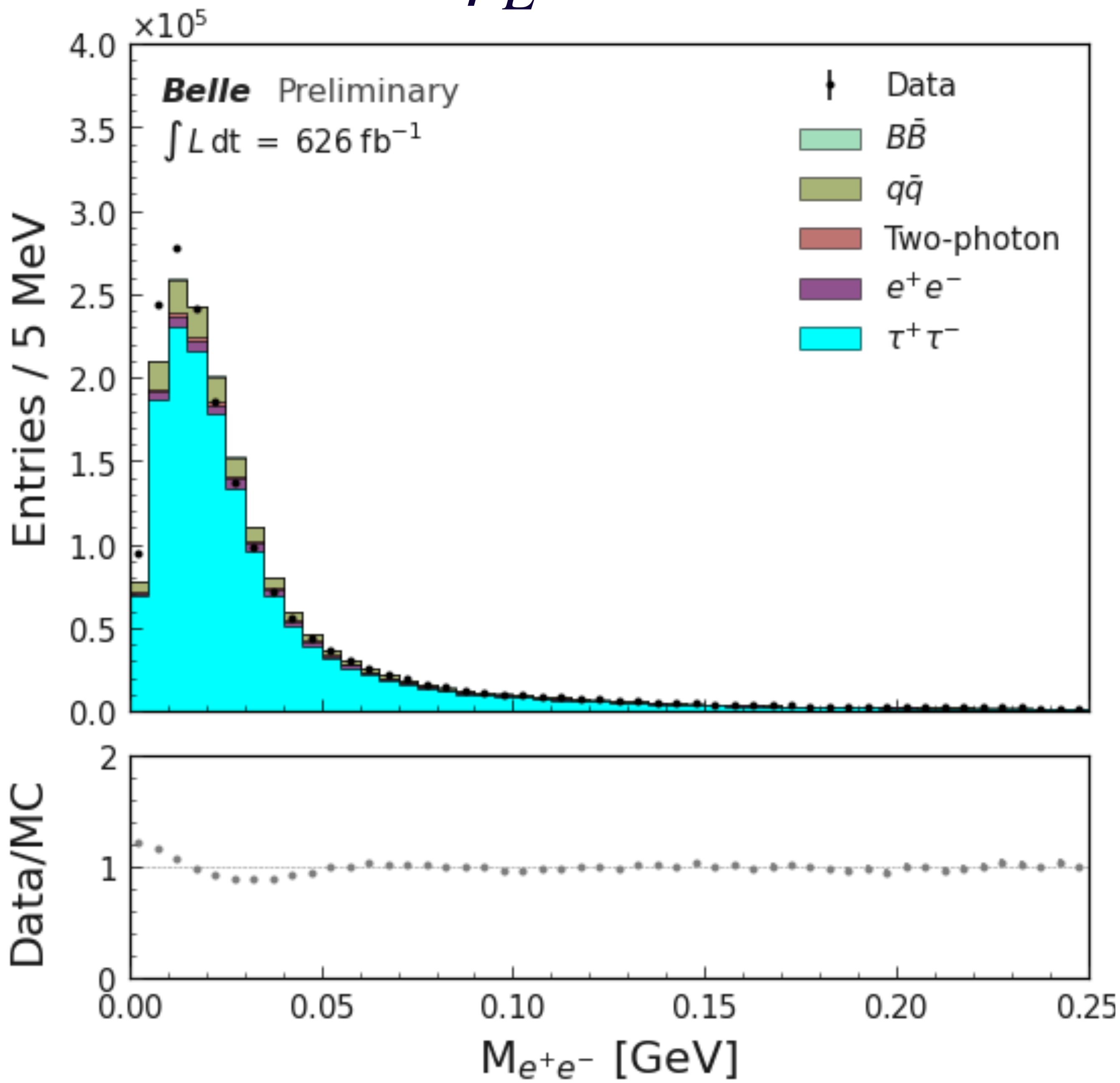




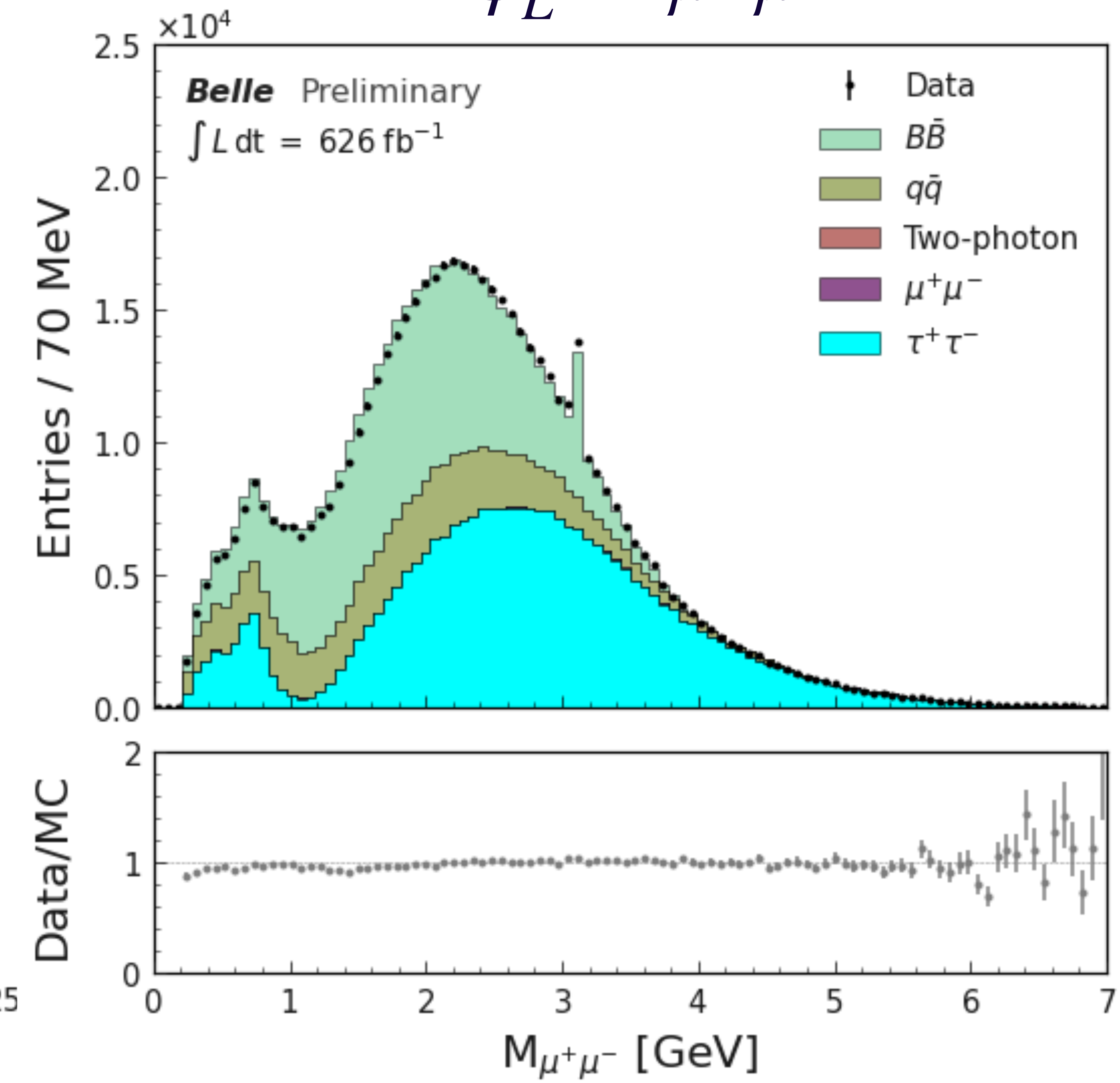
Search strategy

Good agreement seen in data vs. Monte Carlo comparison in control regions: BDT < 0.5

$\phi_L \rightarrow e^+e^-$



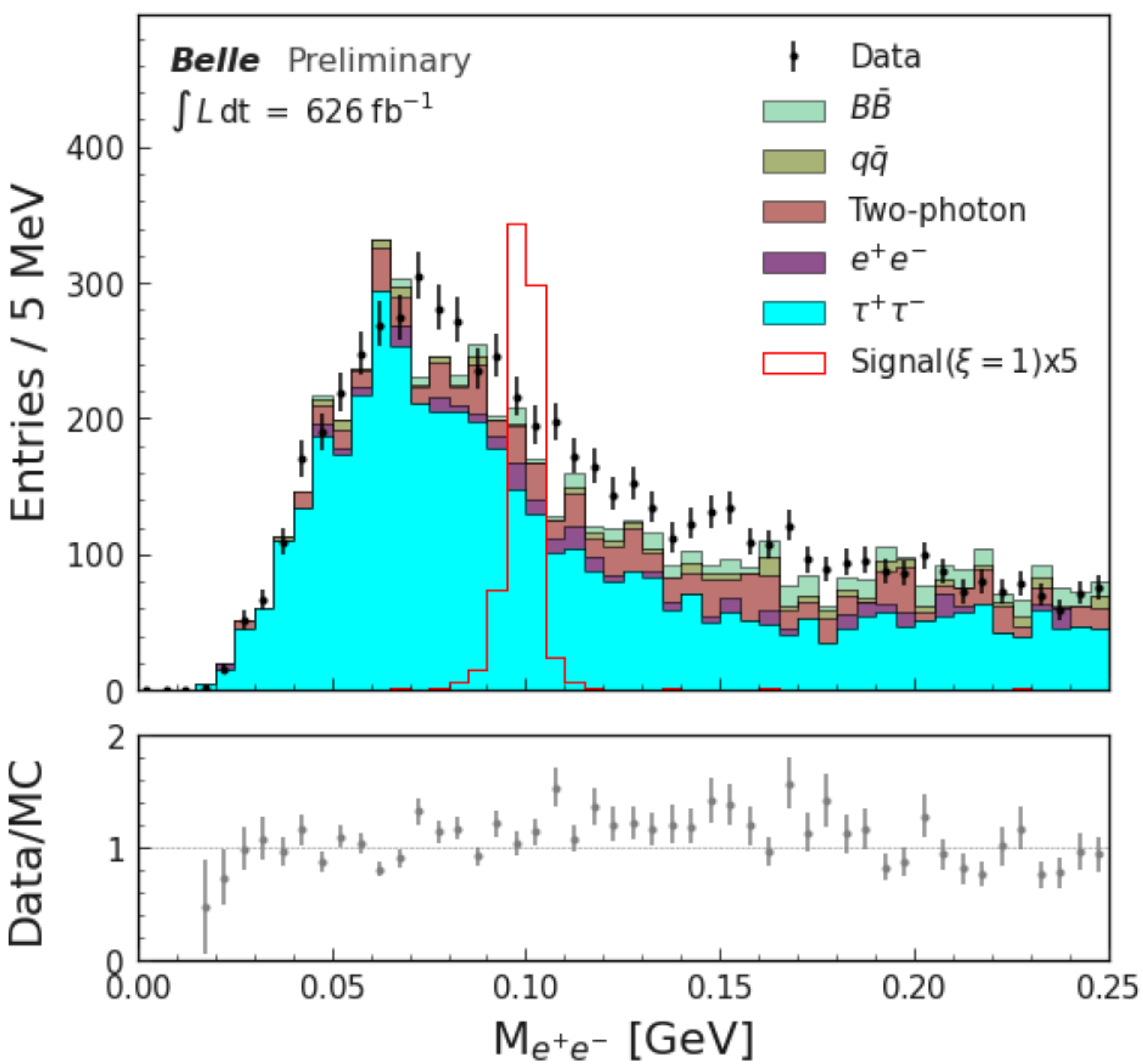
$\phi_L \rightarrow \mu^+\mu^-$



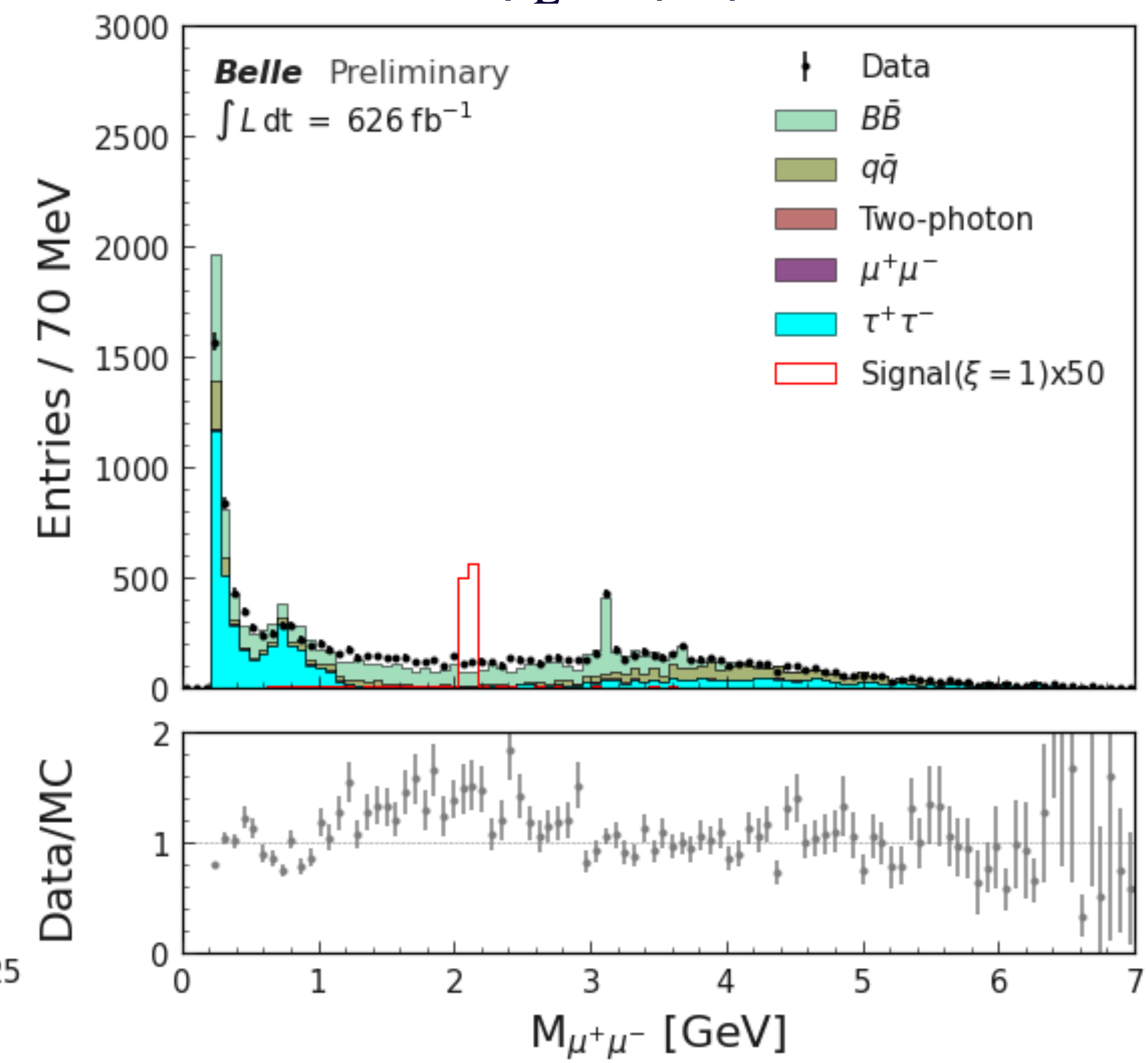
Search strategy

Data vs. Monte Carlo comparison in signal regions: BDT > 0.95 (0.65) for $\phi_L \to e^+e^-/\mu^+\mu^-$

$\phi_L \to e^+e^-$



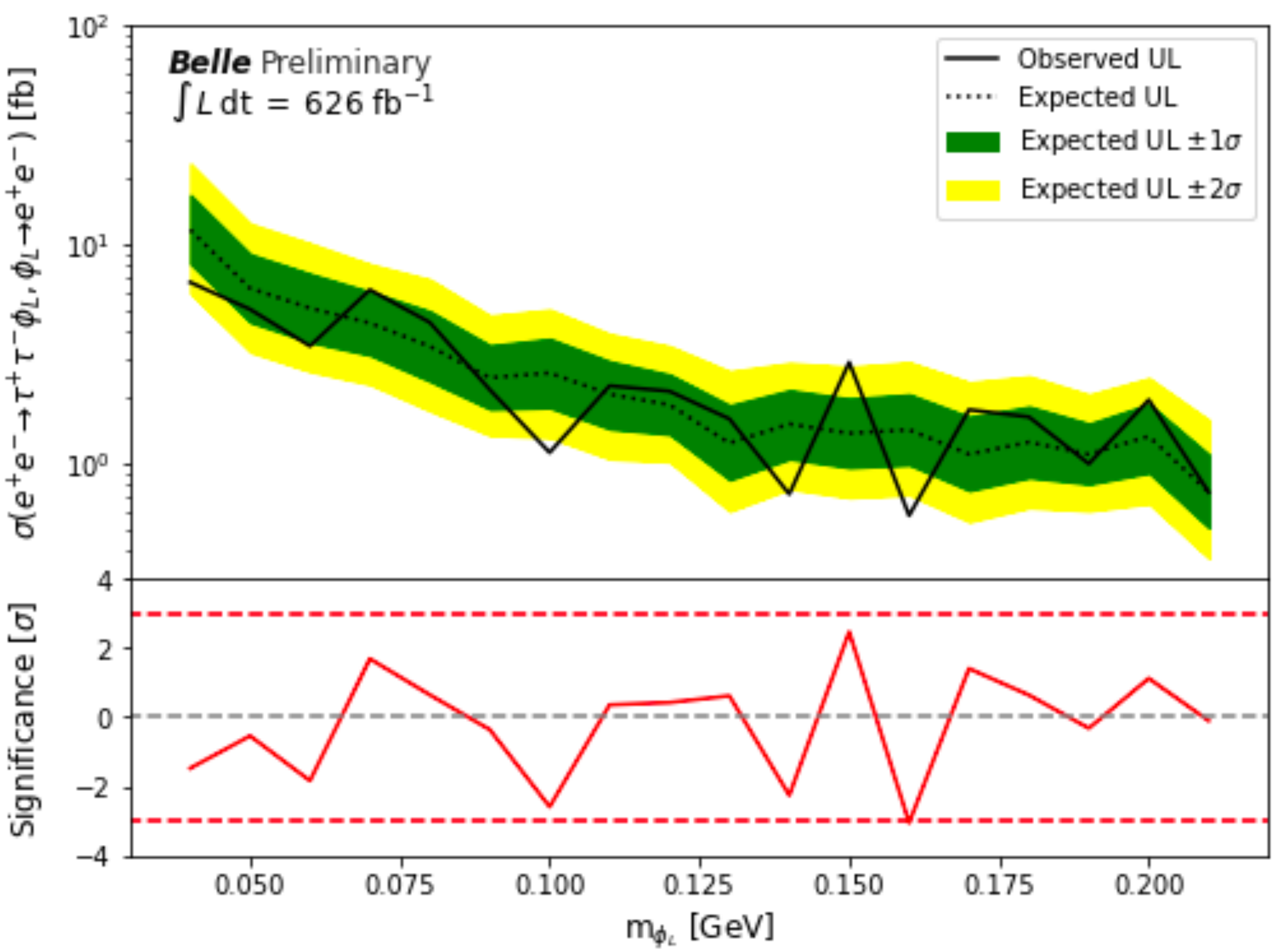
$\phi_L \to \mu^+\mu^-$



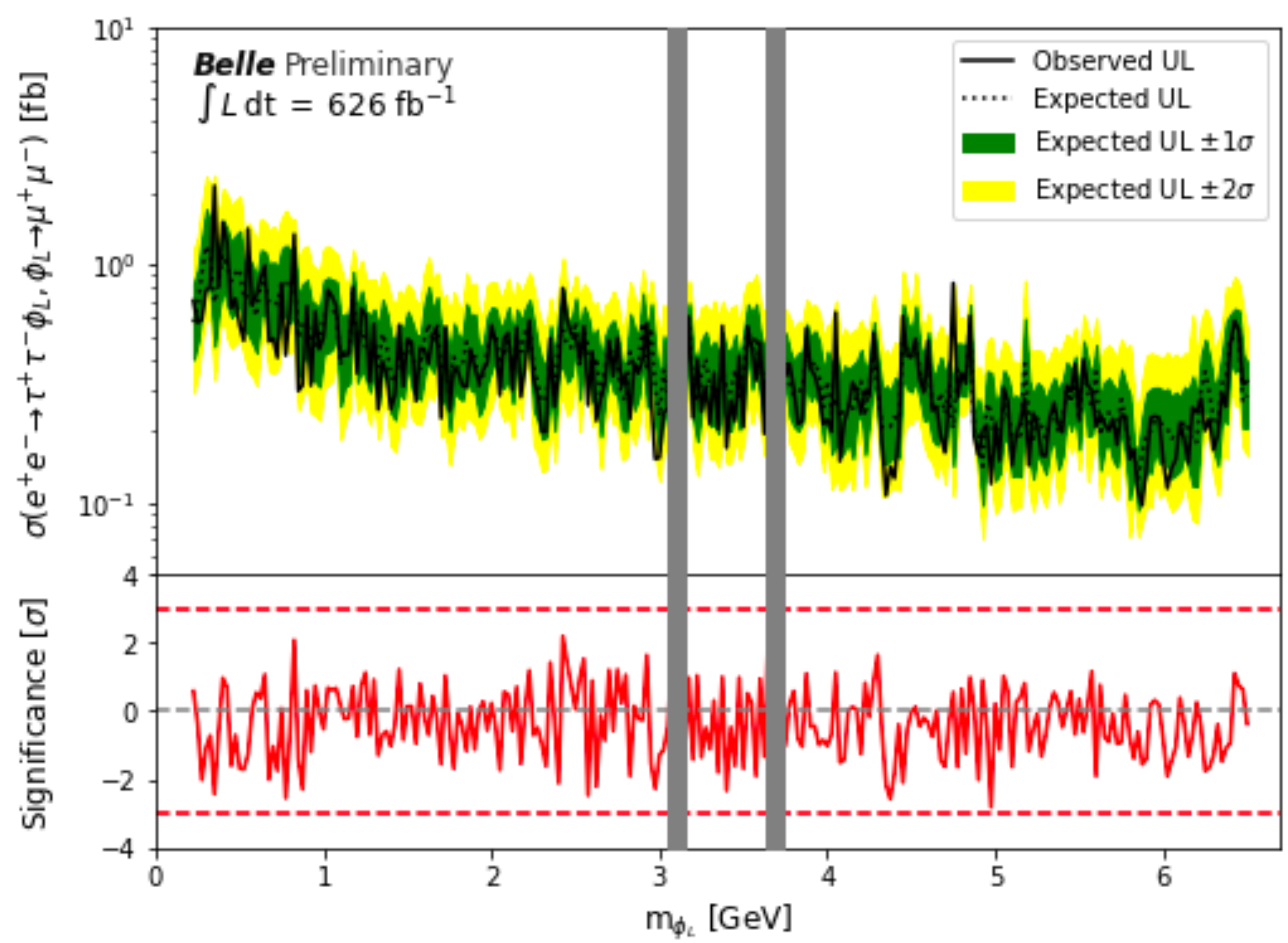
Results

90% confidence level upper limits on the signal cross-section

$\phi_L \to e^+e^-$



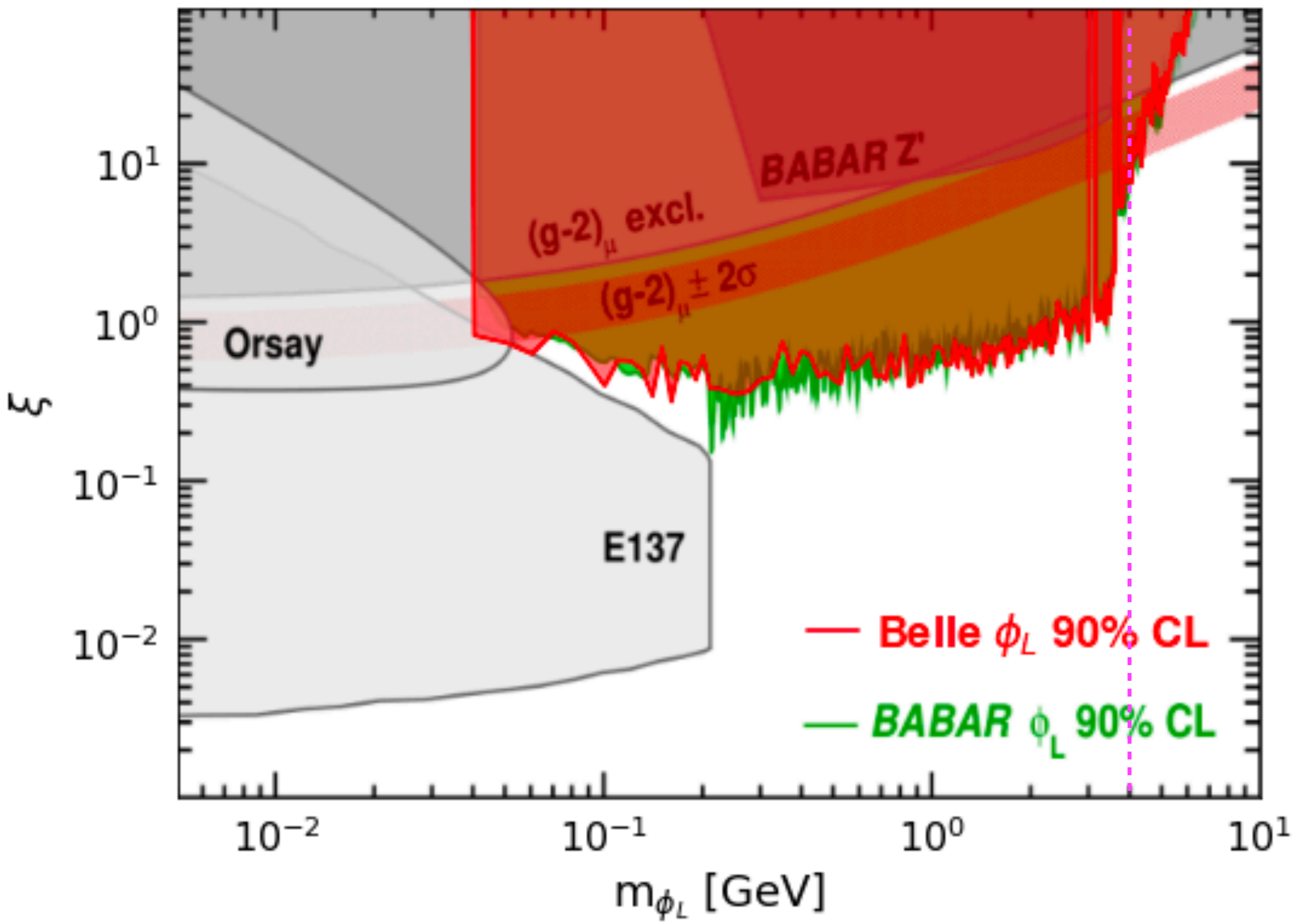
$\phi_L \to \mu^+\mu^-$



Significance < 3 standard deviations for all scan points

Results

90% confidence level upper limits on the coupling constant



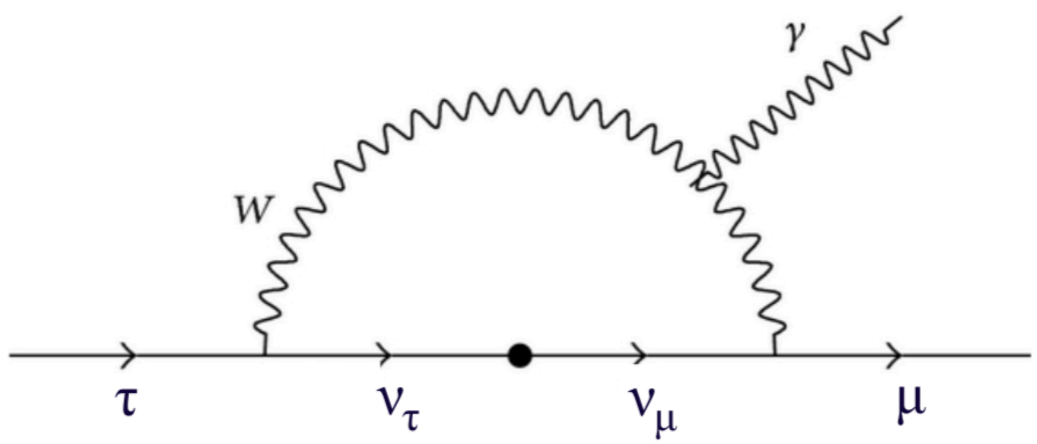
BELLE-CONF-2201

arXiv:2207.07476 **[hep-ex]**

No ϕ_L can explain observed excess in $(g\text{-}2)_\mu$ for $m_{\phi_L} < 4$ GeV

Charged Lepton flavor violation in τ decays

LFV is not forbidden by any continuous symmetry
$\Rightarrow$ most new physics (NP) models naturally includes LFV



$\mathcal{B}(\tau^\pm \to \mu^\pm\gamma)$ Lee & Shrock: Phys.Rev.D 16 (1977) 1444

$= \frac{3\alpha}{128\pi}\left(\frac{\Delta m_{23}^2}{M_W^2}\right)^2 \sin^2 2\theta_{\rm mix}\mathcal{B}(\tau \to \mu\bar{\nu}_\mu\nu_\tau)$

With $\Delta \sim 10^{-3}\,\mathrm{eV}^2$, $M_W \sim \mathcal{O}(10^{11})\,\mathrm{eV}$

$\approx \mathcal{O}(10^{-54})$ ($\theta_{\rm mix}$: max)

many orders below experimental sensitivity!

Any observation of LFV $\Rightarrow$ unambiguous signature of NP

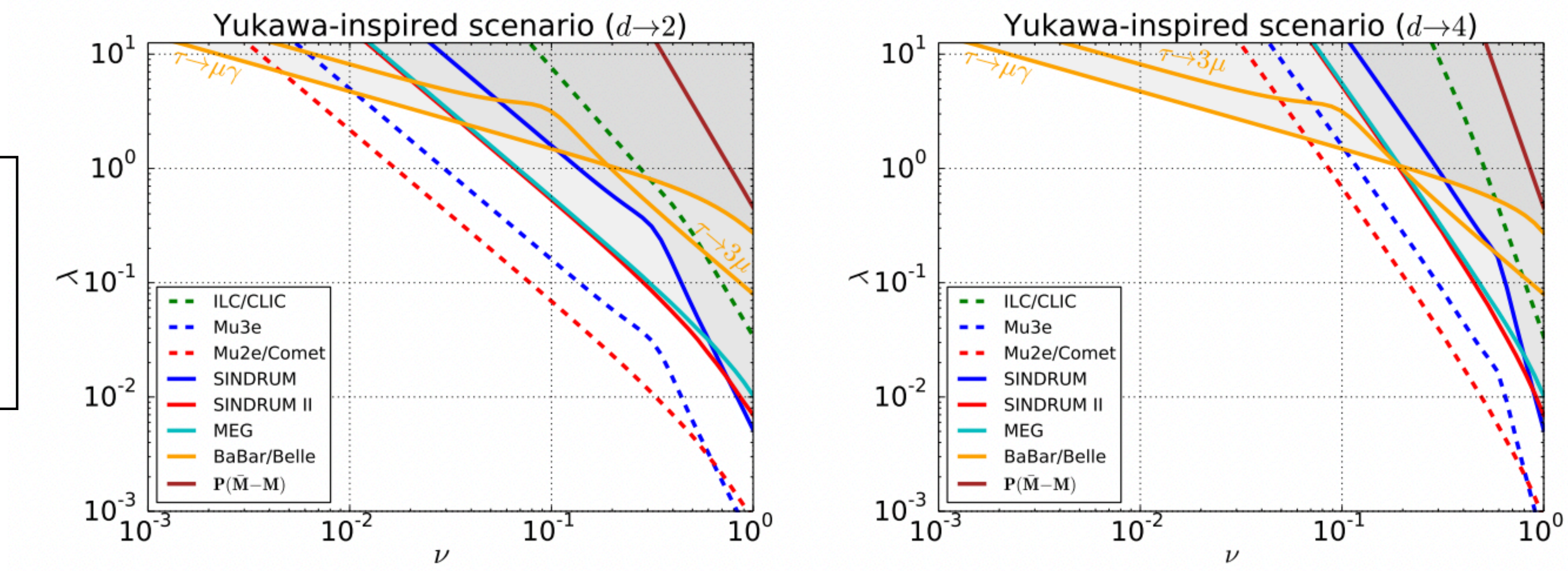
LFV in τ sector is complementary to μ sector in NP parameter space:
current limit on $\mathscr{B}(\mu \to e\gamma) \sim 10^{-13}$ does not forbid $\mathscr{B}(\tau \to \ell\gamma) \sim 10^{-8}$

Leptonic MFV:	$BR(\mu \to e\gamma) / BR(\tau \to \mu\gamma) \sim s_{13}^2 \sim 10^{-2}$
GUT models:	$BR(\mu \to e\gamma) / BR(\tau \to \mu\gamma) \sim \lvert V_{us}\rvert^6 \sim 10^{-4}$

Vincenzo Cirigliano, Benjamin Grinstein, Gino Isidori, Mark B. Wise: hep-ph/0507001 [hep-ph], hep-ph/0608123 [hep-ph]
R. Barbieri, L. Hall, A. Strumia: hep-ph/9501334 [hep-ph]

New Physics expectations

- Mass dependent couplings enhance tau LFV w.r.t. lighter leptons



Low– and high–energy phenomenology of a doubly charged scalar

A. Crivellin et. al.
Phys. Rev. D 99, 035004 (2019)

$$\lambda_{ab} \sim \left(y_a^l y_b^l\right)^{-1}$$

$$\lambda_{ab} = \lambda \begin{pmatrix} \pm1 & \nu^2 & \nu^3 \\ \nu^2 & \nu^4 & \nu^5 \\ \nu^3 & \nu^5 & \nu^6 \end{pmatrix}$$

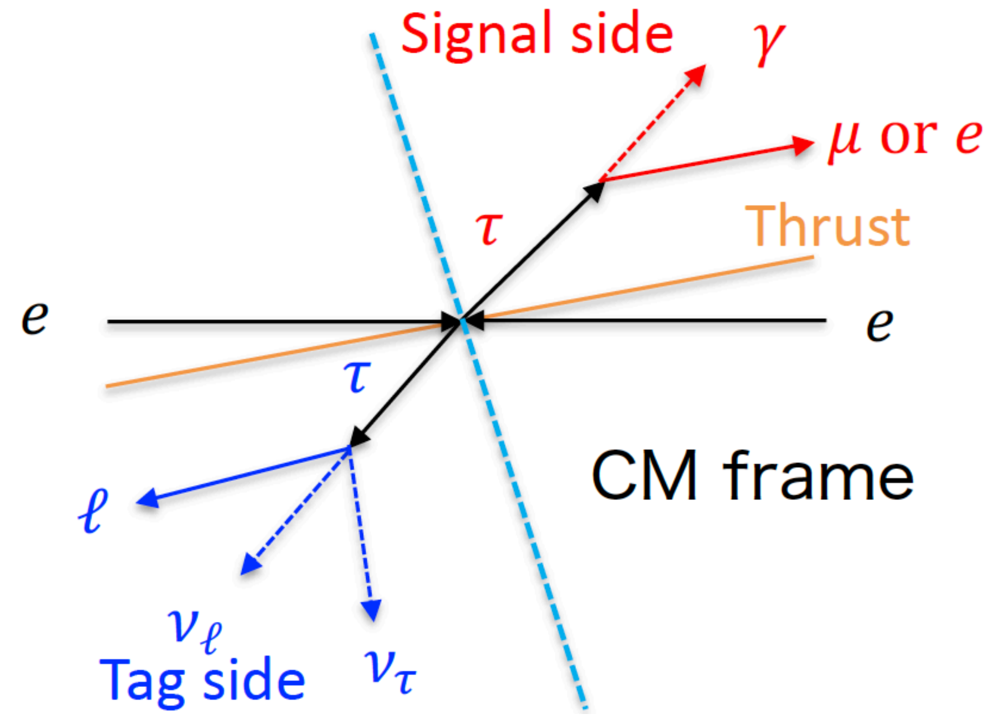
- Some models predict LFV up to existing experimental bounds

	$\mathcal{B}(\tau\to\ell\gamma)$
SUSY SO(10) (NPB649(2003)189, PRD68(2003)033012)	10^{-8}
SUSY Higgs (PLB549(2002)159, PLB566(2003)217)	10^{-10}
Non-Universal Z′ (PLB547(2002)252)	10^{-9}
SM+Heavy Majorana ν_R (PRD66(2002)034008)	10^{-9}

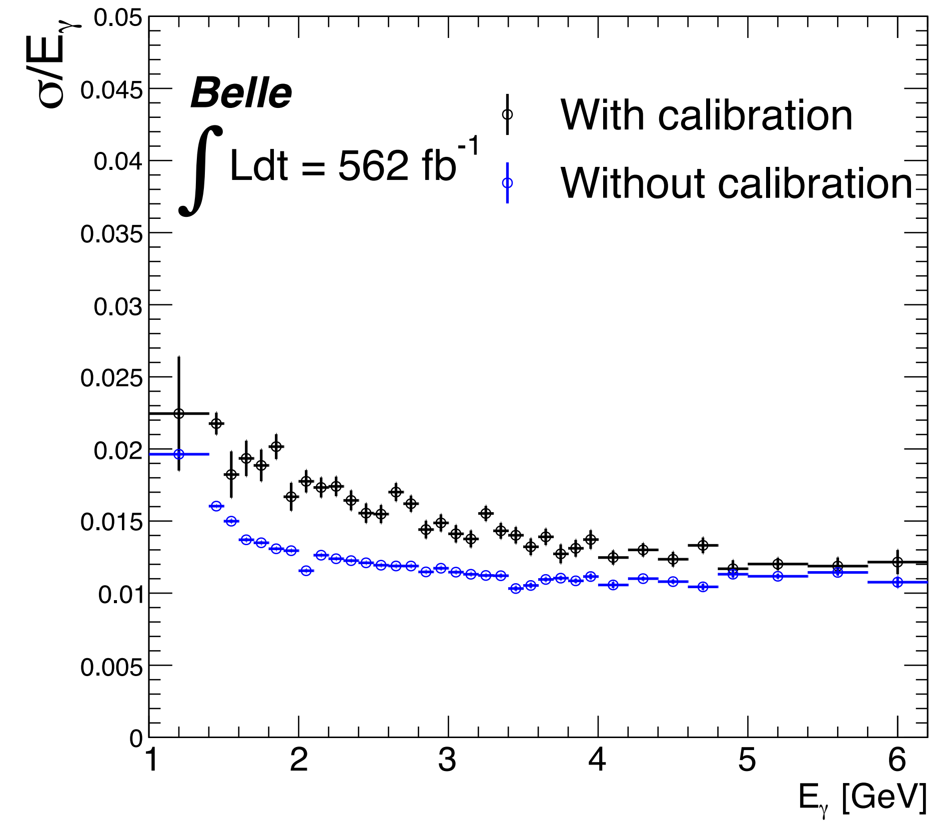
- Normal (Inverted) hierarchy for slepton $\Rightarrow \tau\to\mu\gamma$ ($\tau\to e\gamma$)
  eg. SUSY models: non-diagonal slepton mass matrix $\Rightarrow \mathrm{LFV}$

$\tau^{\pm} \to \ell^{\pm}\gamma$

- Event reconstruction:
  - Split event into hemispheres ⊥ to thrust axis ($\hat{n}_T$) which maximizes Thrust = $\max\left(\sum |\vec{p}_i| \cdot \hat{n}_T\right) / \left(\sum |\vec{p}_i|\right)$
  - Require exactly 2 tracks: 1 in signal-side, 1 in tag-side
  - Signal side: $E_\gamma \in [0.1, 6]$ GeV identified in ECL



- Major improvement w.r.t previous analysis performed by the Belle Collaboration [Phys. Lett. B 666, 16 (2008)]:
  - Photon energy calibration with $e^+e^- \to \mu^+\mu^-\gamma$ events
  - Calibrated energy cross-checked with test beam data
    H. Ikeda et al., Nucl.Instrum.Meth.A 441 (2000) 401



Signal characteristics

Beam constraint mass: $M_{\rm bc} = \sqrt{(E^{\rm CM}_{\rm beam})^2 - |\vec{p}^{\,\rm CM}_{\ell\gamma}|^2} \simeq m_\tau$

$$\Delta E/\sqrt{s} = (E^{\rm CM}_{\ell\gamma} - \sqrt{s}/2)/\sqrt{s} \simeq 0$$

Signal PDF fitted to asymmetric Gaussian function: JHEP 10 (2021) 019

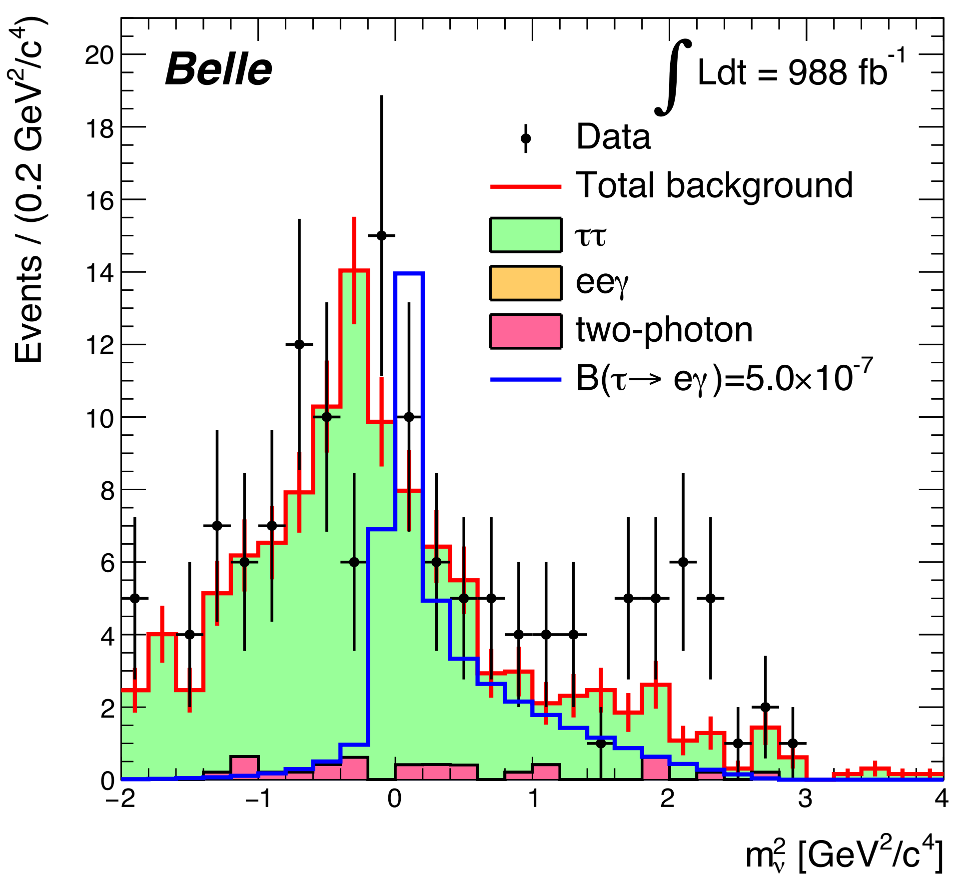
$\tau^\pm \to e^\pm\gamma$	Mean	Width (lower side)	Width (higher side)
M_{bc}	1.79 MeV/c^2	(10.59 ± 0.19) MeV/c^2	(11.55 ± 0.27) MeV/c^2
$\Delta E / \sqrt{s}$	-1.0 x 10^{-3}	(4.4 ± 0.3) x 10^{-3}	(6.1 ± 0.7) x 10^{-3}

$\tau^\pm \to \mu^\pm\gamma$	Mean	Width (lower side)	Width (higher side)
M_{bc}	1.78 MeV/c^2	(7.46 ± 0.23) MeV/c^2	(11.08 ± 0.08) MeV/c^2
$\Delta E / \sqrt{s}$	-0.6 x 10^{-3}	(4.2 ± 0.2) x 10^{-3}	(5.6 ± 0.4) x 10^{-3}

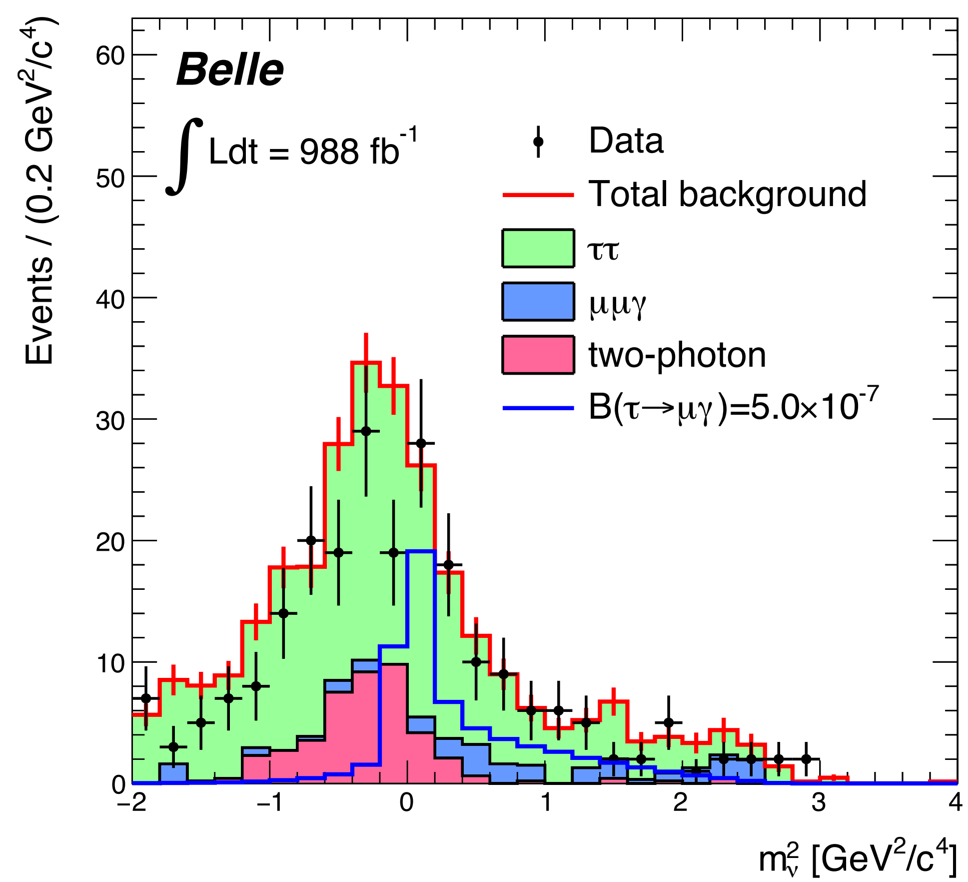
Beam constraint mass has about factor of two better resolution than invariant mass.

Background rejection

- Dominant backgrounds:
  - $\tau^{\pm} \longrightarrow \ell^{\pm}\nu\overline{\nu}$ + ISR γ or beam background
  - $e^{+} e^{-} \longrightarrow \ell^{+}\ell^{-}$ + ISR γ or beam background

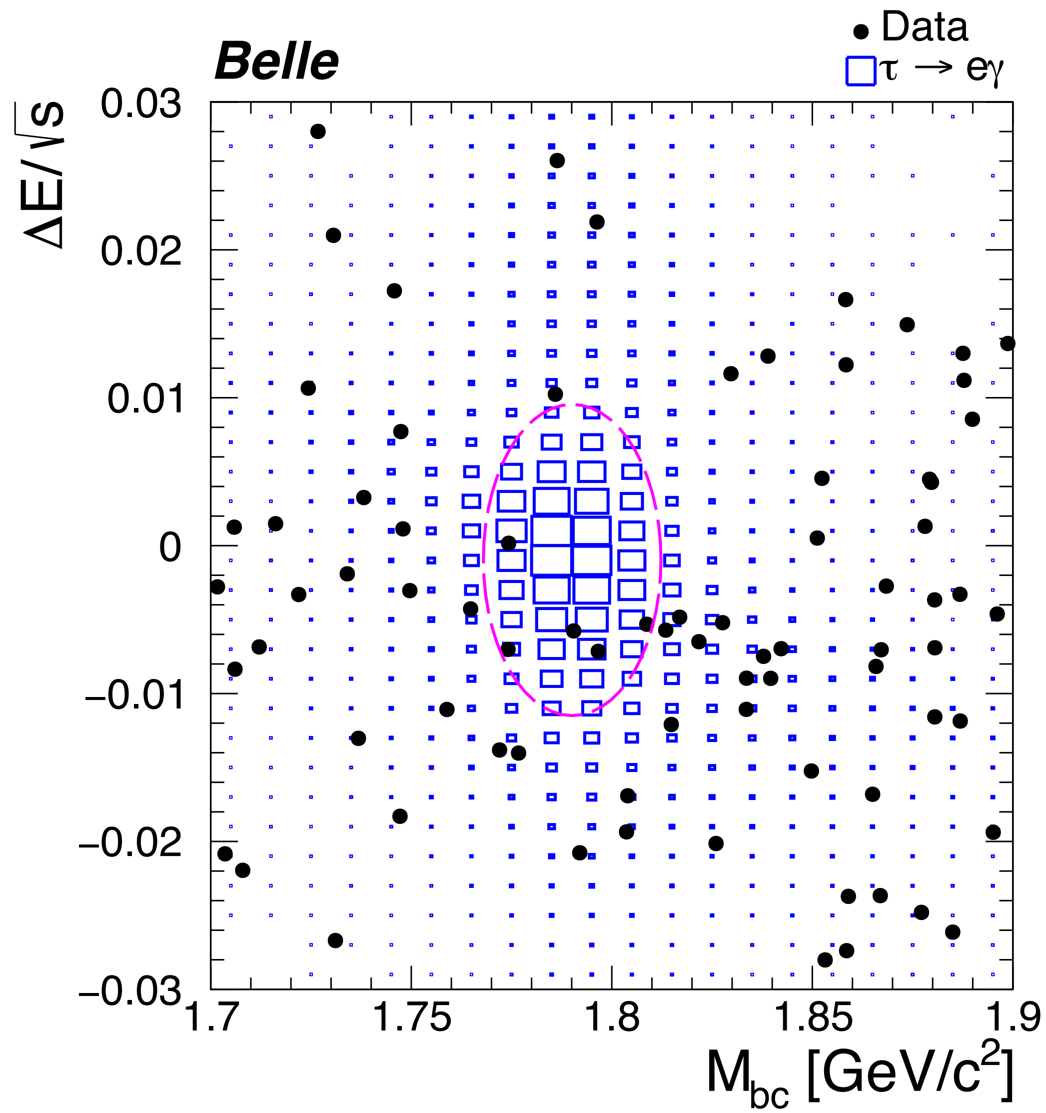


JHEP 10 (2021) 019

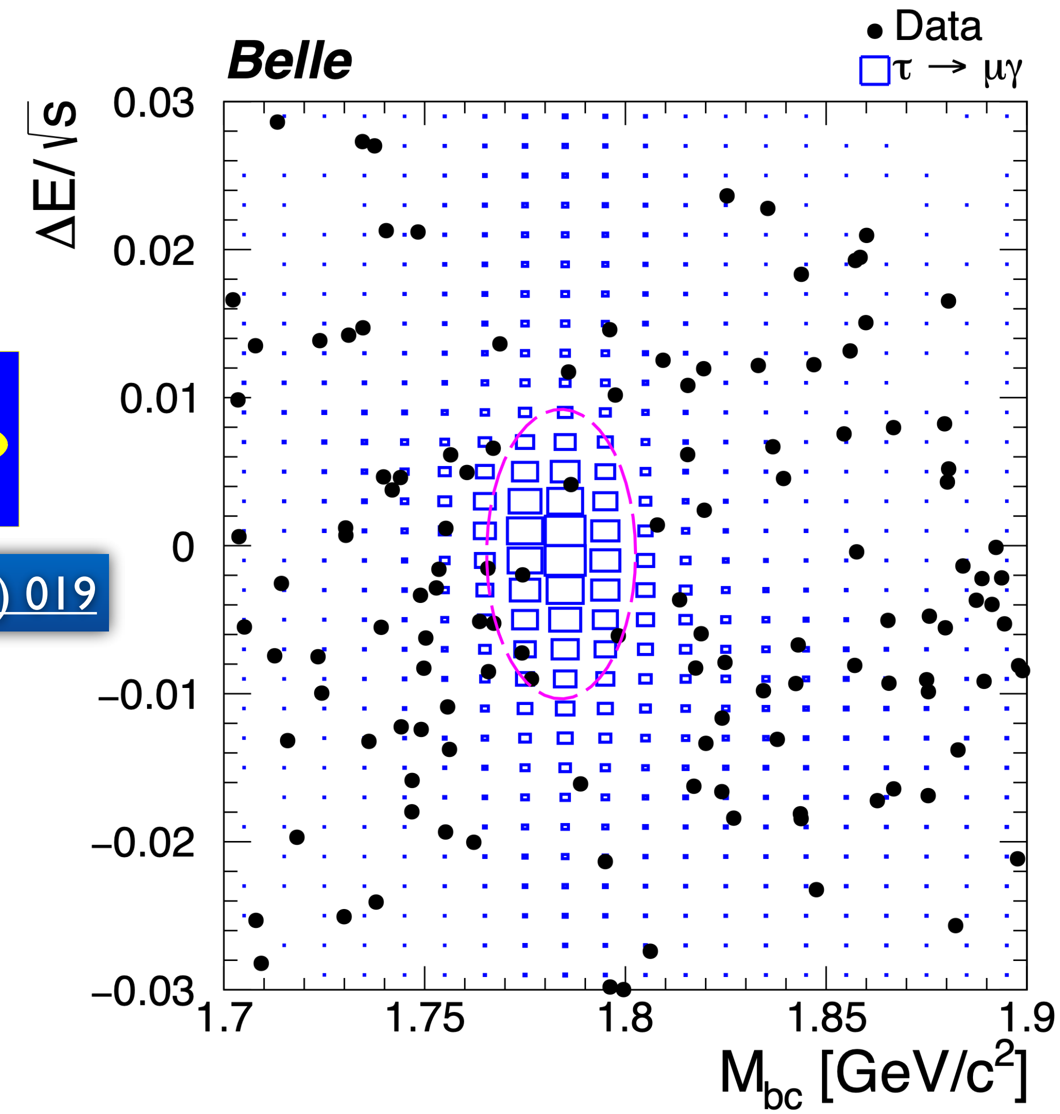


# of ν(s) in Signal-side	Signal: 0	$\tau^+\tau^-$: 1-2	Bhabha, di-muon, $q\overline{q}$: 0
# of ν(s) in Tag-side	Signal: 1-2	$\tau^+\tau^-$: 1-2	Bhabha, di-muon, $q\overline{q}$: 0

Results



JHEP 10 (2021) 019

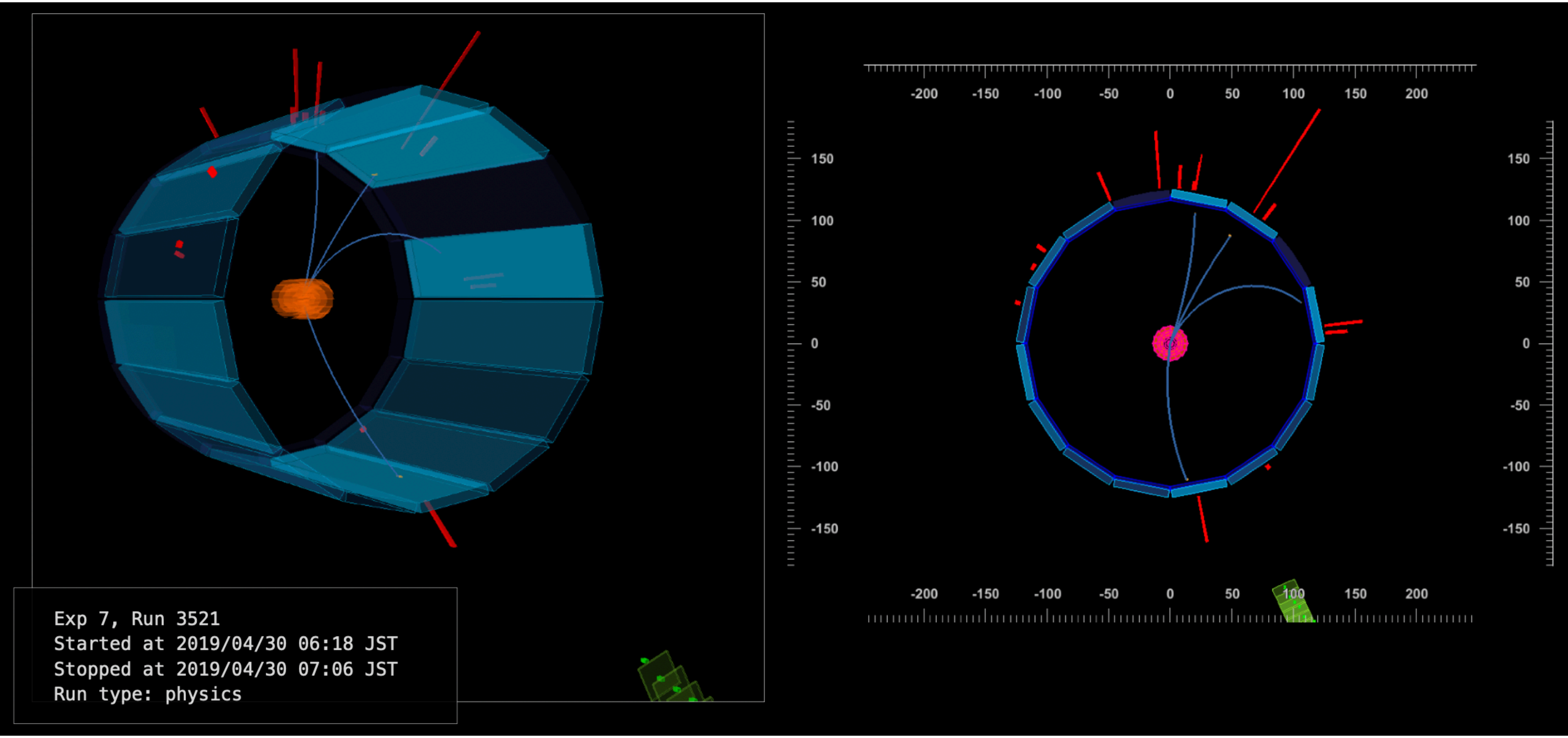


$B \times 10^{-8}$ at 90% CL	BaBar $N_{\tau\tau} = 477 \times 10^6$		Belle $N_{\tau\tau} = 480 \times 10^6$		Belle $N_{\tau\tau} = 912 \times 10^6$	
	Exp	Obs	Exp	Obs	Exp	Obs
$B(\tau^\pm \to \mu^\pm \gamma)$	8.2	4.4	8.0	4.5	4.9	4.2
$B(\tau^\pm \to e^\pm \gamma)$	9.8	3.3	12	12	6.5	5.6

PRL 104 (2010) 021802 | PLB 666 (2008) 16 | JHEP 10 (2021) 019

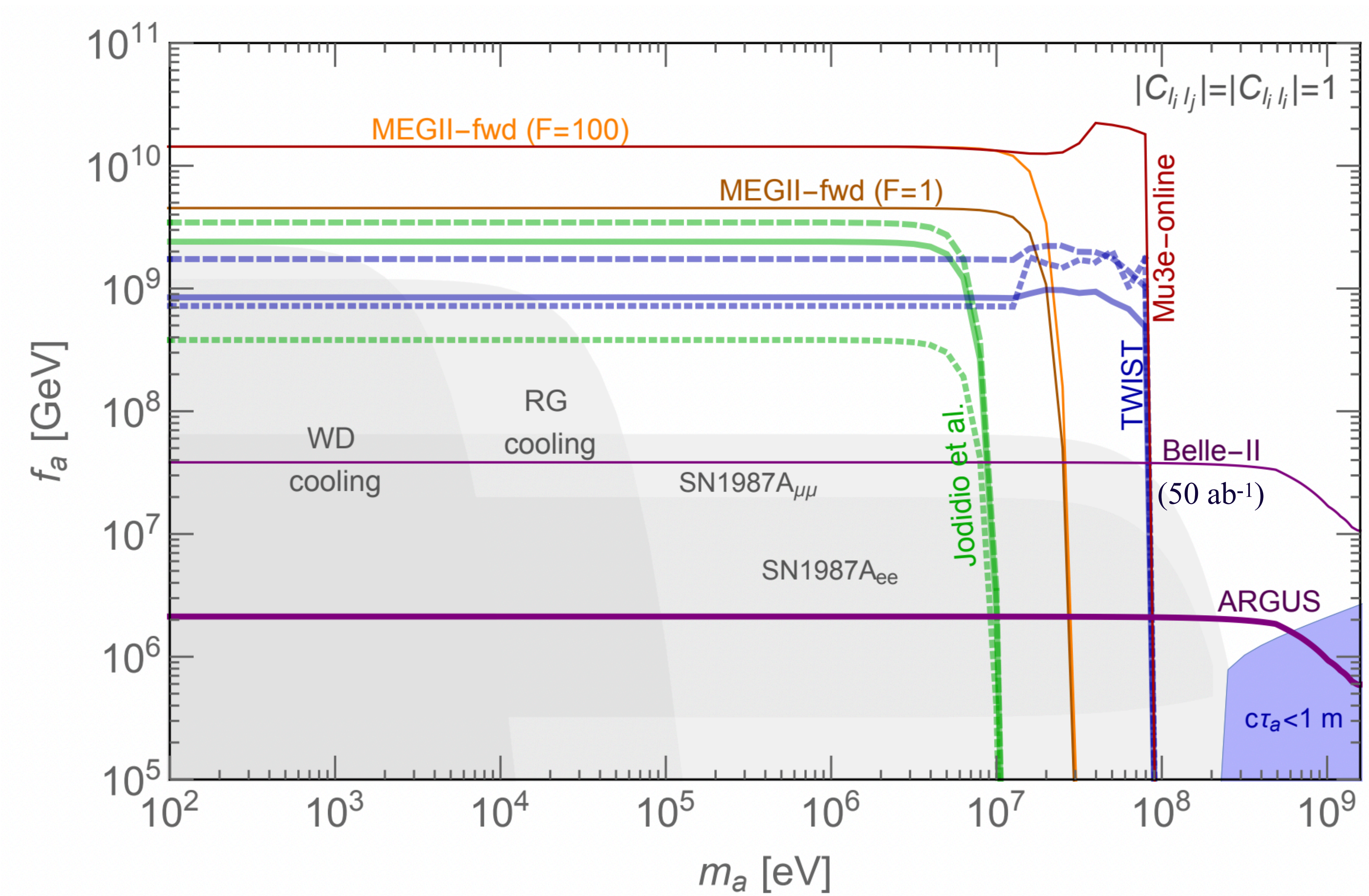
Tau-pair event at Belle II

1-vs-3 topology



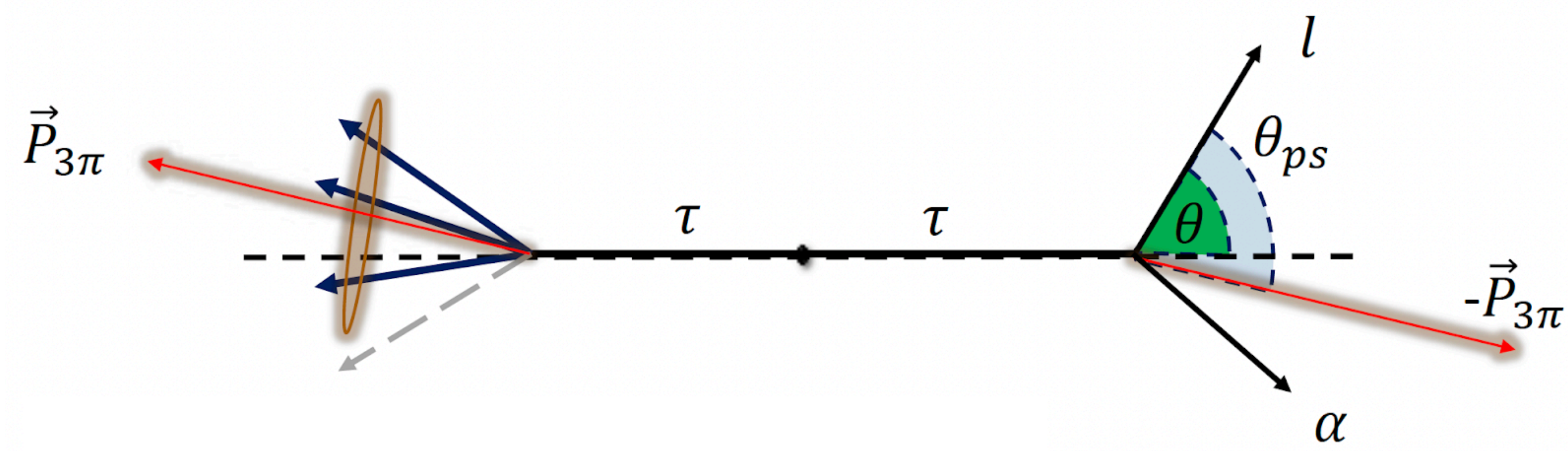
$\tau \to \ell\alpha$ at Belle II

- LFV decay: $\tau \to \ell\alpha$ (where ℓ = e or μ, and α is an invisible boson)
- α can enter from new physics models, eg. light axion like particles (ALP), Z', etc.



L. Calibbi, D. Redigolo, R. Ziegler, J. Zupan,
JHEP 09 (2021) 173 arXiv:2006.04795 **[hep-ph]**

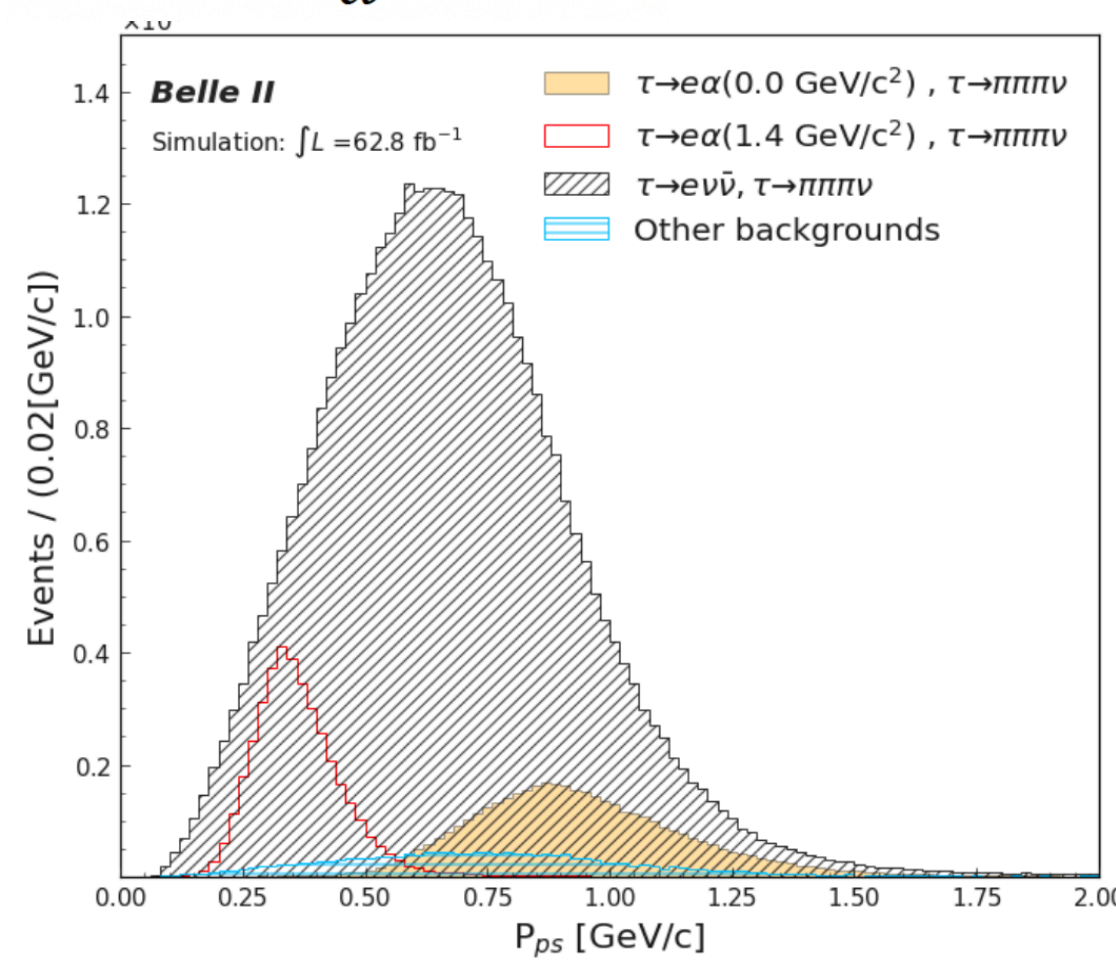
Signature of the signal process



τ pseudo-rest frame

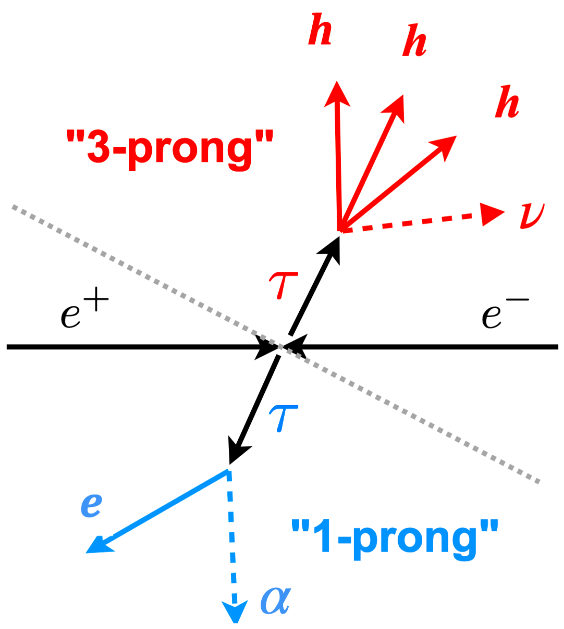
2-body $\tau \to \ell\alpha$ decay will appear as a bump against the SM 3-body $\tau \to \ell\nu\bar{\nu}$ background in the p_ℓ distribution in the τ pseudo-rest frame

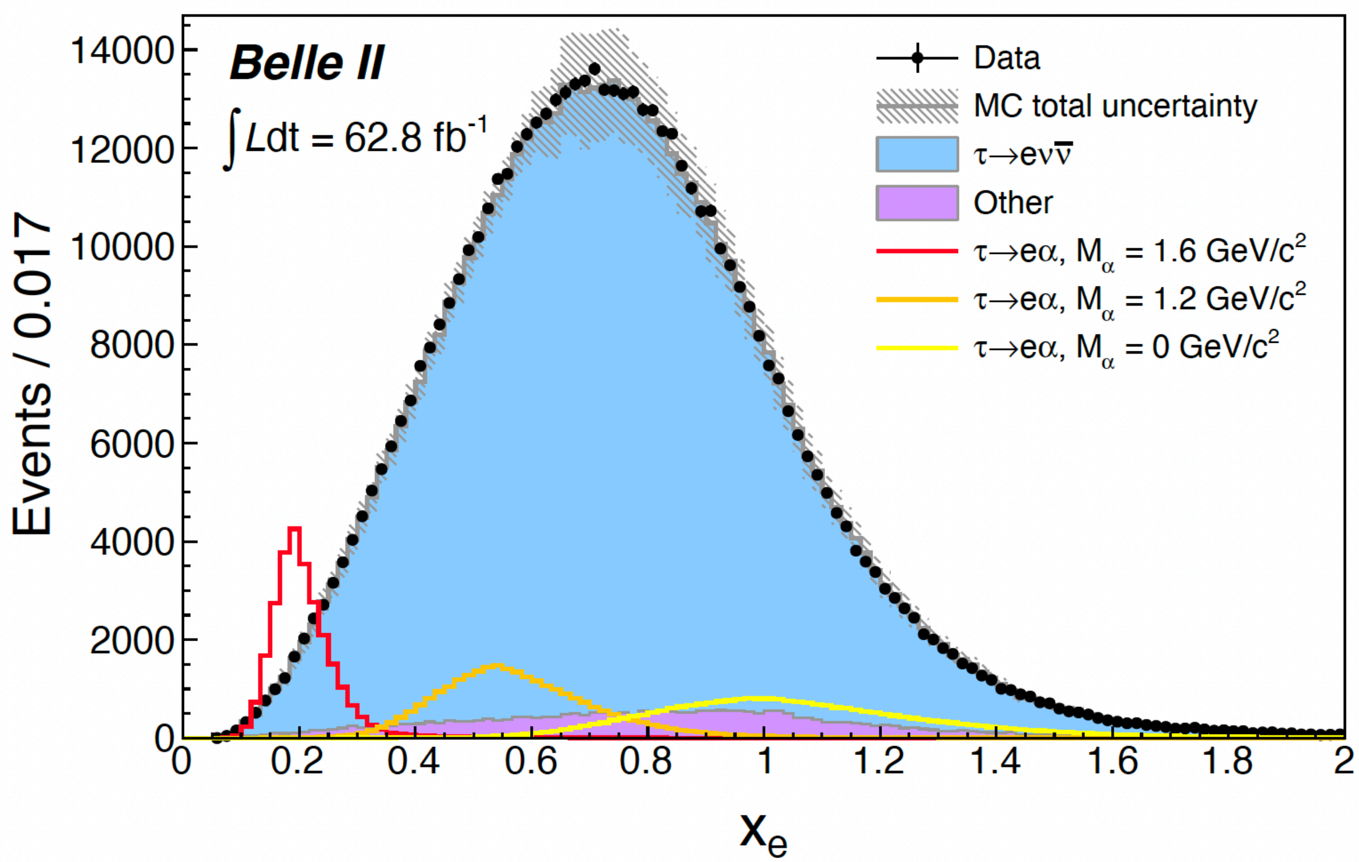
$$\hat{p}_\tau \approx -\frac{\overrightarrow{p}_{tag}}{|\overrightarrow{p}_{tag}|}, \quad E_\tau \approx \sqrt{s}/2$$

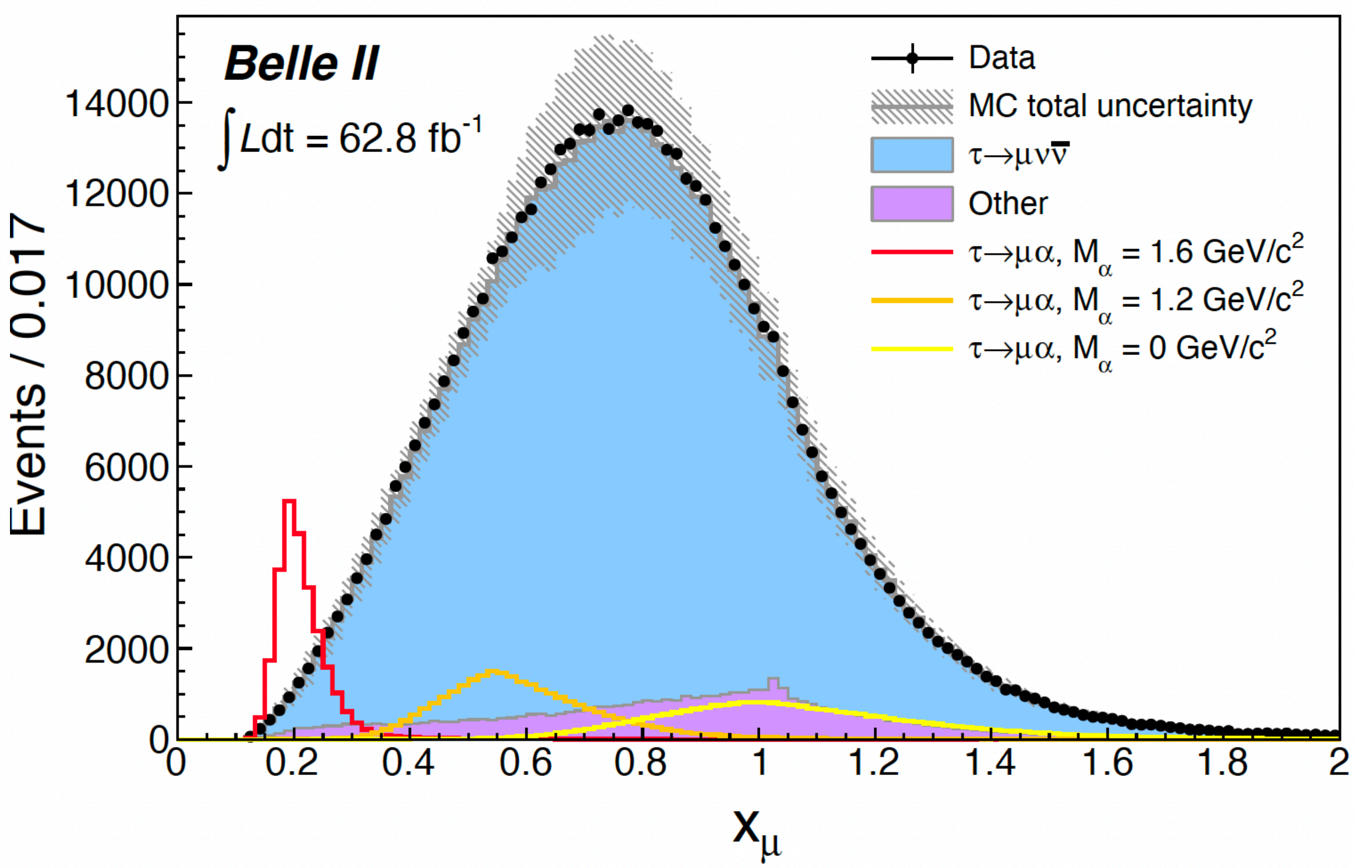


$\tau \to \ell\alpha$ at Belle II

- Event reconstruction:
  - Split event into hemispheres ⊥ to thrust axis ($\hat{n}_T$) which maximizes Thrust = $\max\left(\sum|\vec{p}_i|\cdot\hat{n}_T\right)/\left(\sum|\vec{p}_i|\right)$
  - Require exactly 4 tracks: 1 in signal-side, 3 in tag-side
  - Veto neutrals (π^0,γ) to suppress hadronic background.
- Backgrounds reduced by cuts:
  - $q\bar{q}$, $\ell^+\ell^-$, $\ell^+\ell^-\ell^+\ell^-$, $\ell^+\ell^-h^+h^-$ and $\tau^+\tau^-$ with misidentified signal (e.g. $\tau \to \pi\nu$)
- Data-MC agreement in the discriminating variable: $x_\ell = 2E_\ell^{ps}/m_\tau$

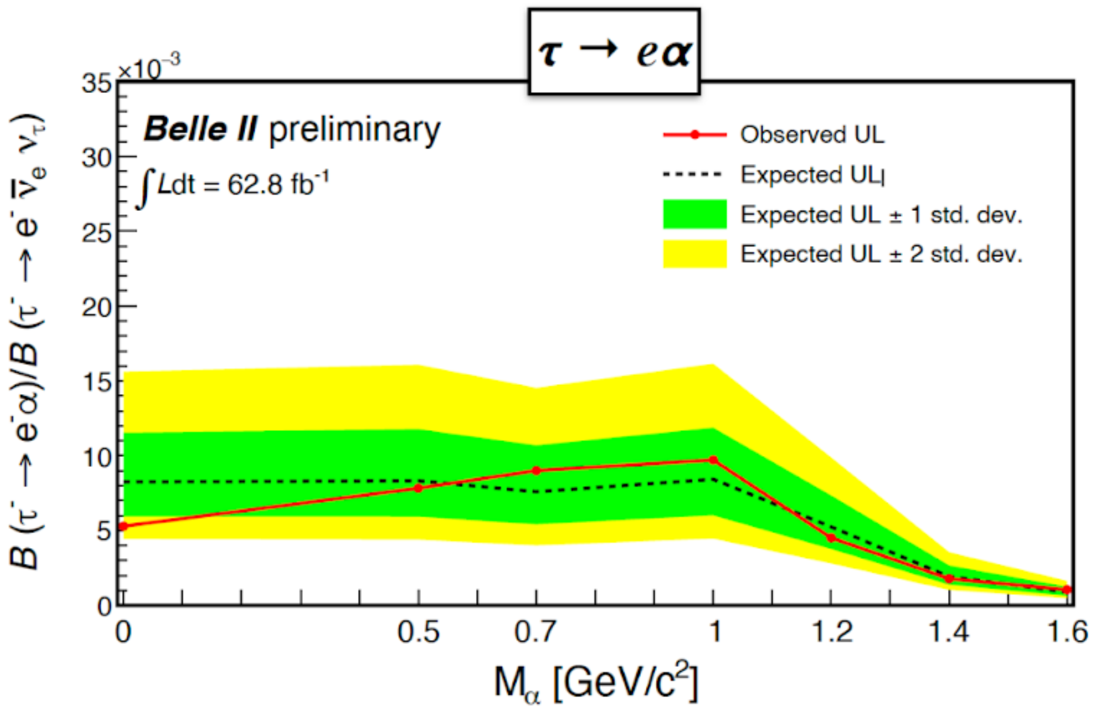


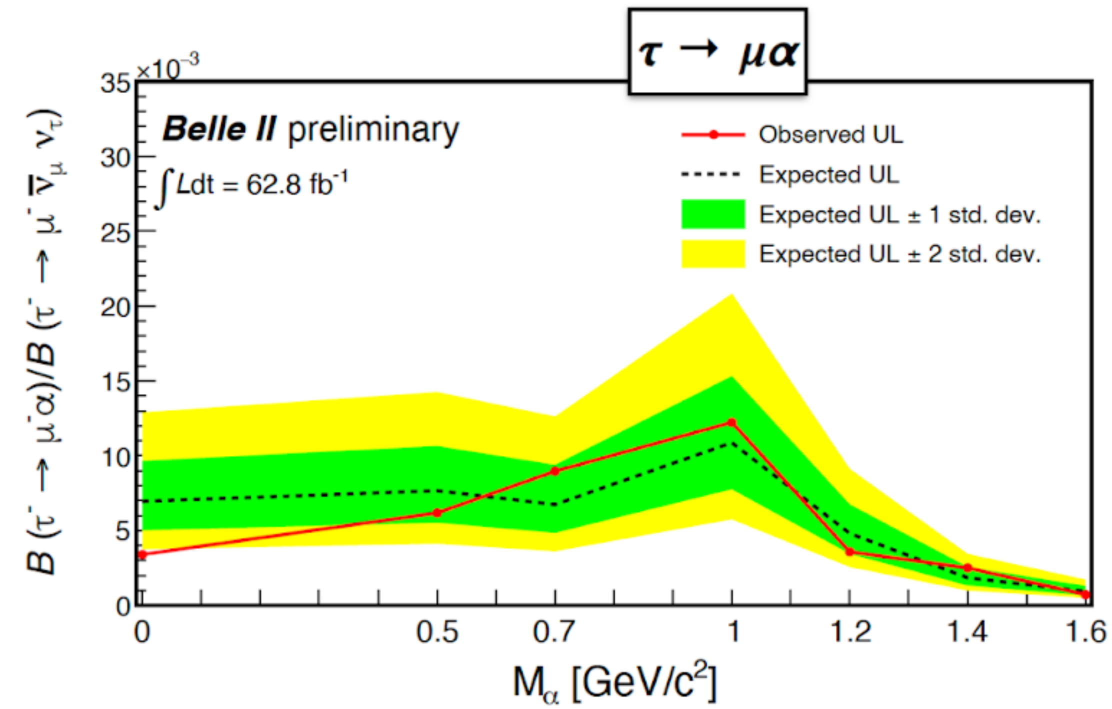




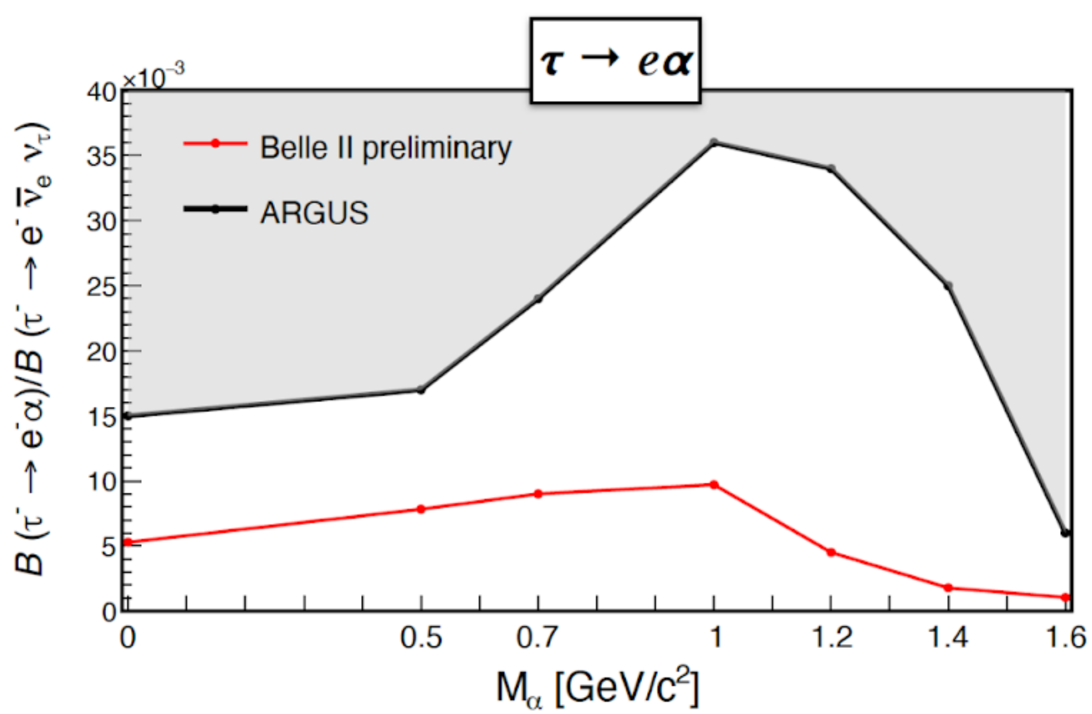
$\tau \to \ell\alpha$ at Belle II

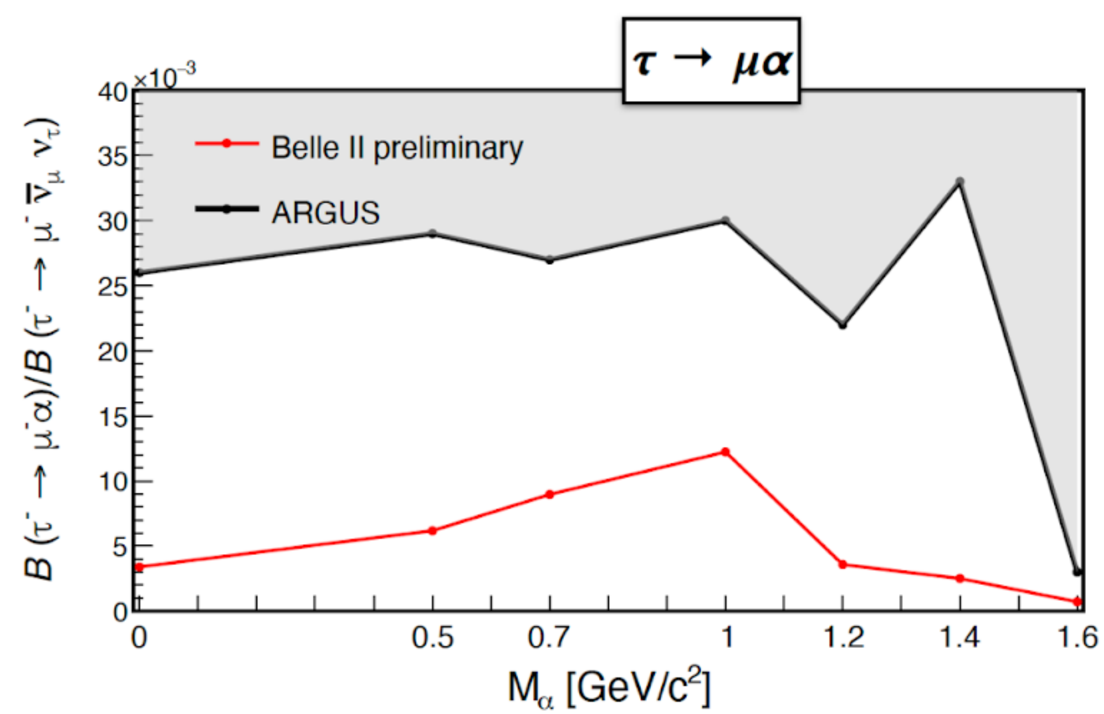
95% C.L. upper limits from Belle II (ICHEP'2022)





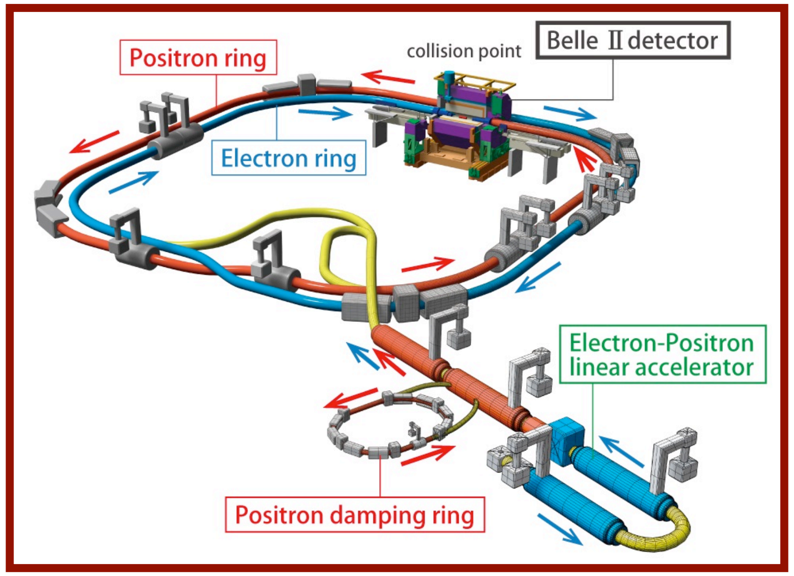
Comparison with previous limits from ARGUS (0.472 fb^{-1}) [Z. Phys. C68 (1995) 25]



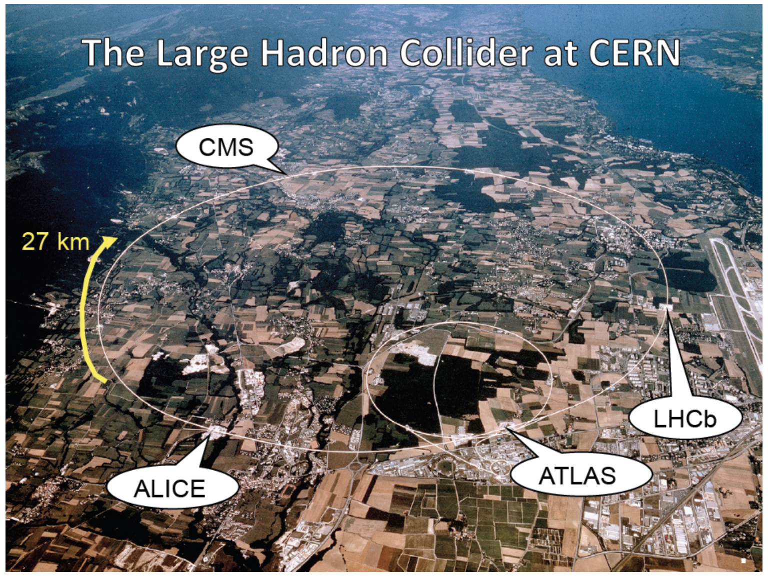


Current and future experiments

Belle II at SuperKEKB

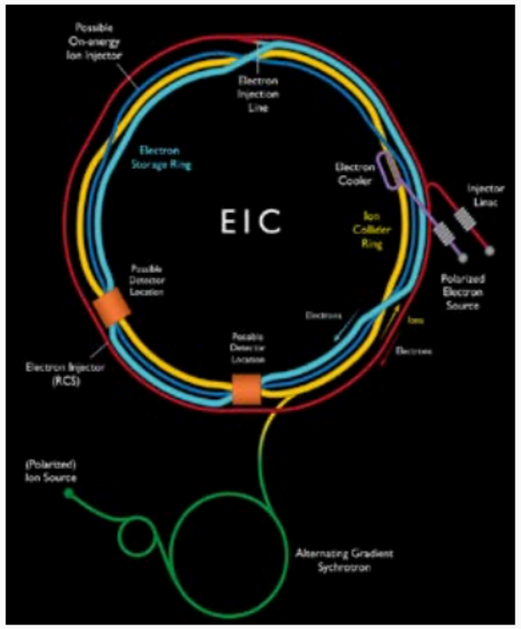


ATLAS, CMS, LHCb at LHC

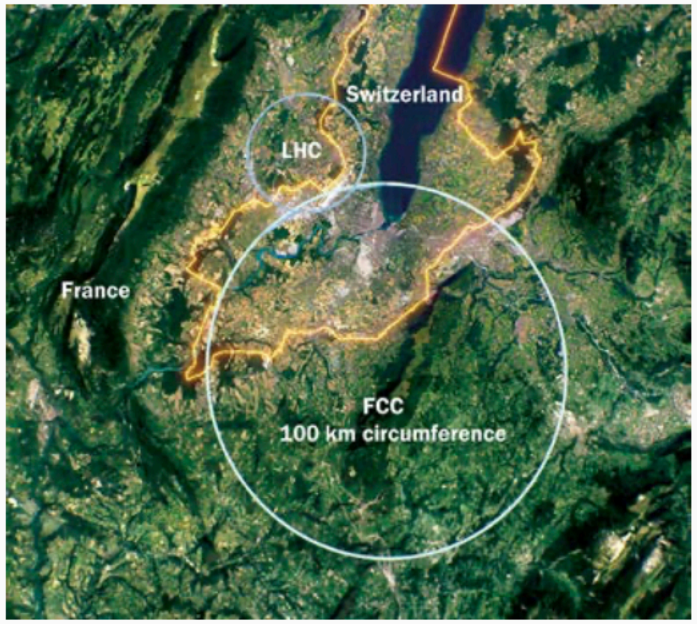


STCF proposal at China/Novosibirsk

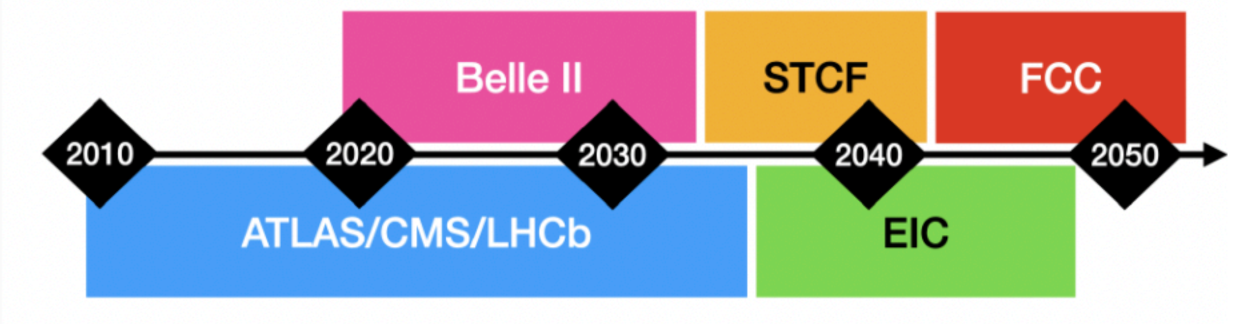
EIC at Brookhaven



FCC-ee proposal – CERN



Tentative timeline



e-Print: 2203.14919 [hep-ph]

Estimates of experimental sensitivity in LFV searches

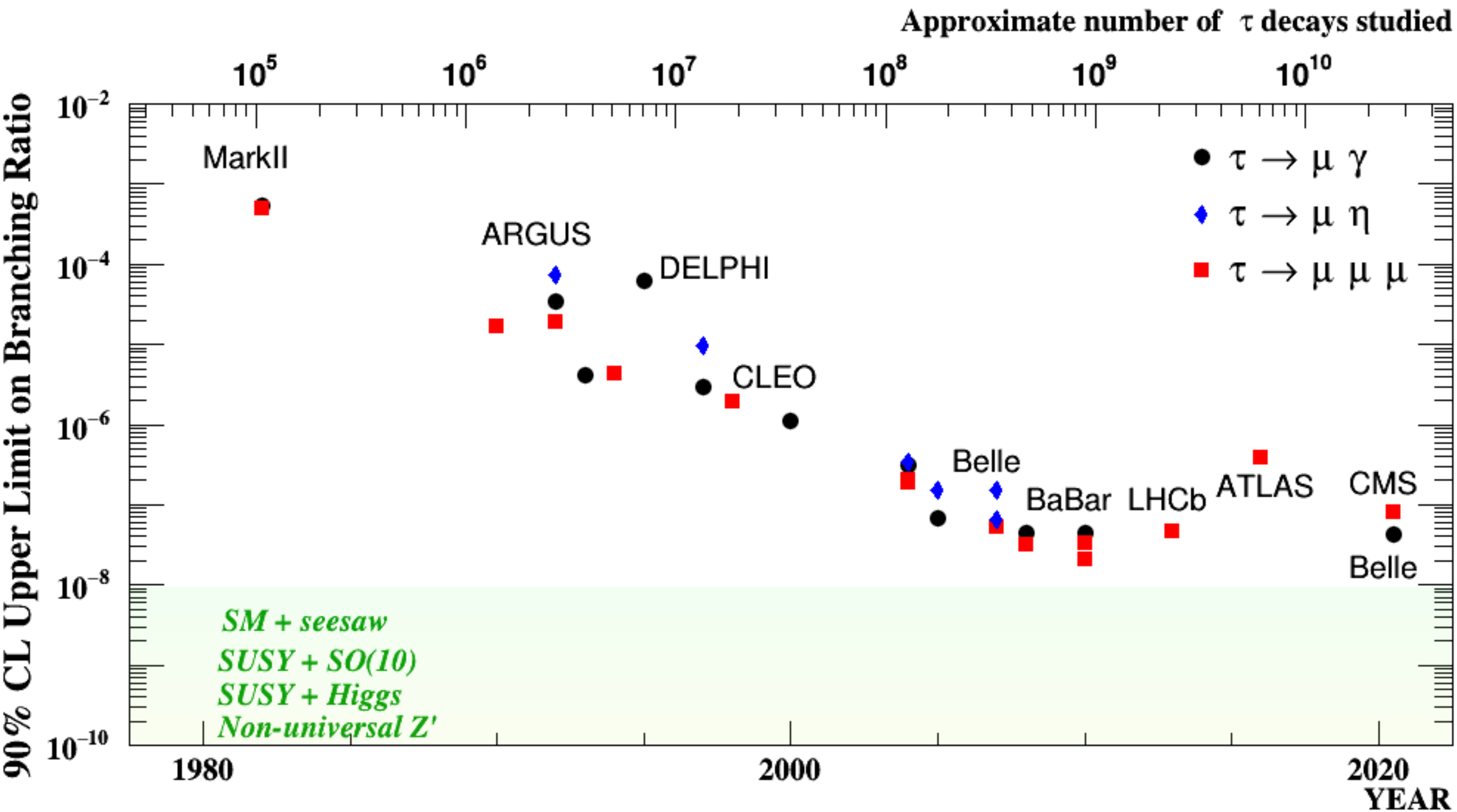
$$B_{\mathrm{UL}}^{90} = N_{\mathrm{UL}}^{90}/(N_\tau \times \varepsilon)$$

- ε: *high statistics signal MC simulated for different Data-taking periods*

$\varepsilon =$	Trigger .	Reco .	Topology .	PID .	Cuts .	Signal–Box
	90%	**70%**	**70%**	**50%**	**50%**	**50%**
Cumulative:	**90%**	**63%**	**44%**	**22%**	**11%**	**~5%**

	$\sqrt{s}$	Luminosity (L)	$N_\tau = 2L\sigma$	
Belle II	10.58 GeV	50 ab^{-1}	9.2 $\times 10^{10}$	
HL-LHC	14 TeV	3 ab^{-1}	$\mathcal{O}(10^{15})$	(Efficiency much lower)
STCF	2-7 GeV	1 ab^{-1}	7.0 $\times 10^{9}$	
FCC-ee	91.2 GeV	150 ab^{-1}	3.4 $\times 10^{11}$	

Current status of LFV τ decays ~ 10^{-7}



$\tau \to \mu\mu\mu$ at Belle II

- Known initial conditions (beam energy constraint)
- Clean environment (fewer backgrounds)

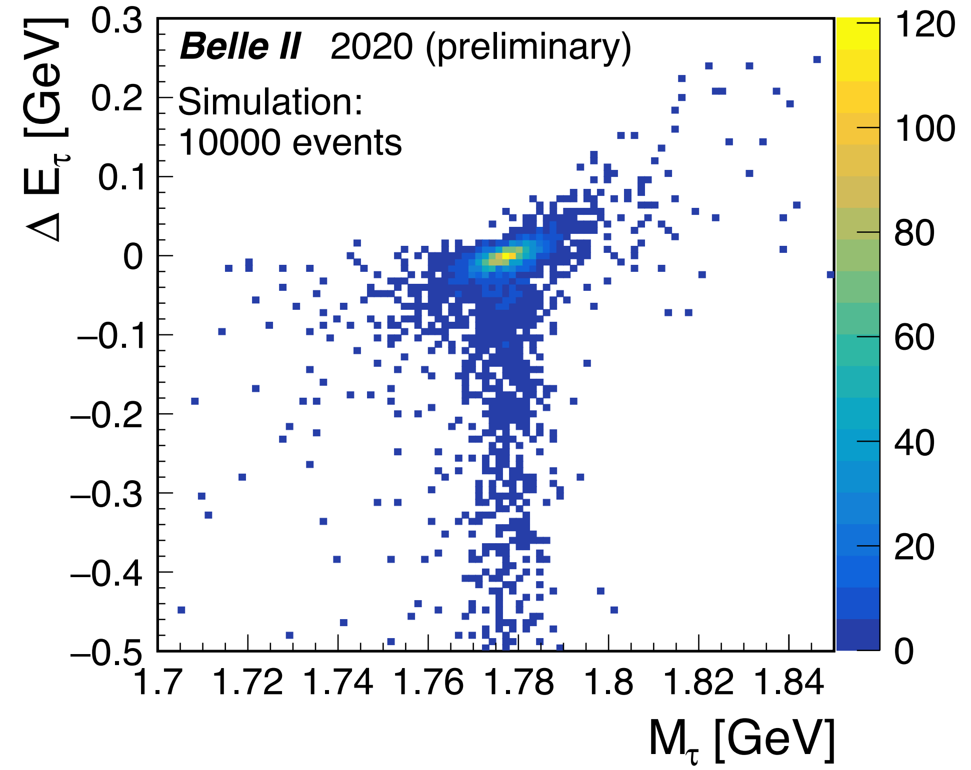
Two independent variables:

$$M_\tau = \sqrt{E^2_{\mu\mu\mu} - P^2_{\mu\mu\mu}}$$

$$\Delta E = E^{CMS}_{\mu\mu\mu} - E^{CMS}_{\text{beam}}$$

➡ ΔE close to 0 for signal

➡ Mass of tau daughters close to τ mass



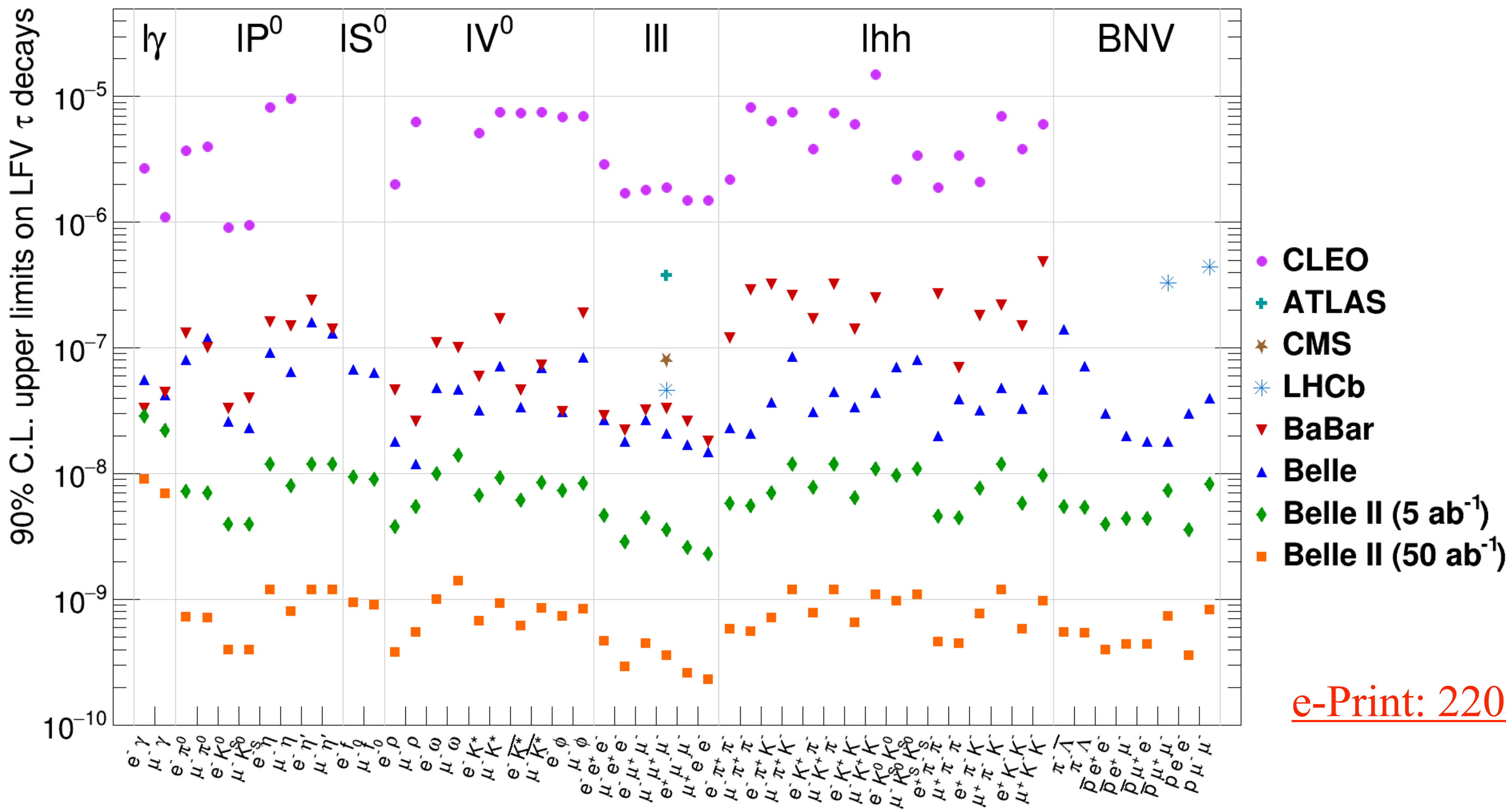
Higher signal efficiency is foreseen at Belle II than at Belle or BaBar

- **higher trigger efficiencies**
- **improved vertexing detectors**
- **upgraded tracking /calorimetry**
- **momentum dependent particle identification optimizations**

Expected Belle II sensitivity: $\mathscr{B}(\tau \to \mu\mu\mu) < 3.6 \times 10^{-10}$ with 50 ab^{-1}

Projected limits at Belle II

	Background limited search	*Background free search*
N_{UL}^{90}	$\sqrt{\mathcal{L}}$	2.44 [Feldman – Cousins for $N_{obs} = 0$]
B_{UL}^{90}	$\propto 1/\sqrt{\mathcal{L}}$	$\propto 1/\mathcal{L}$



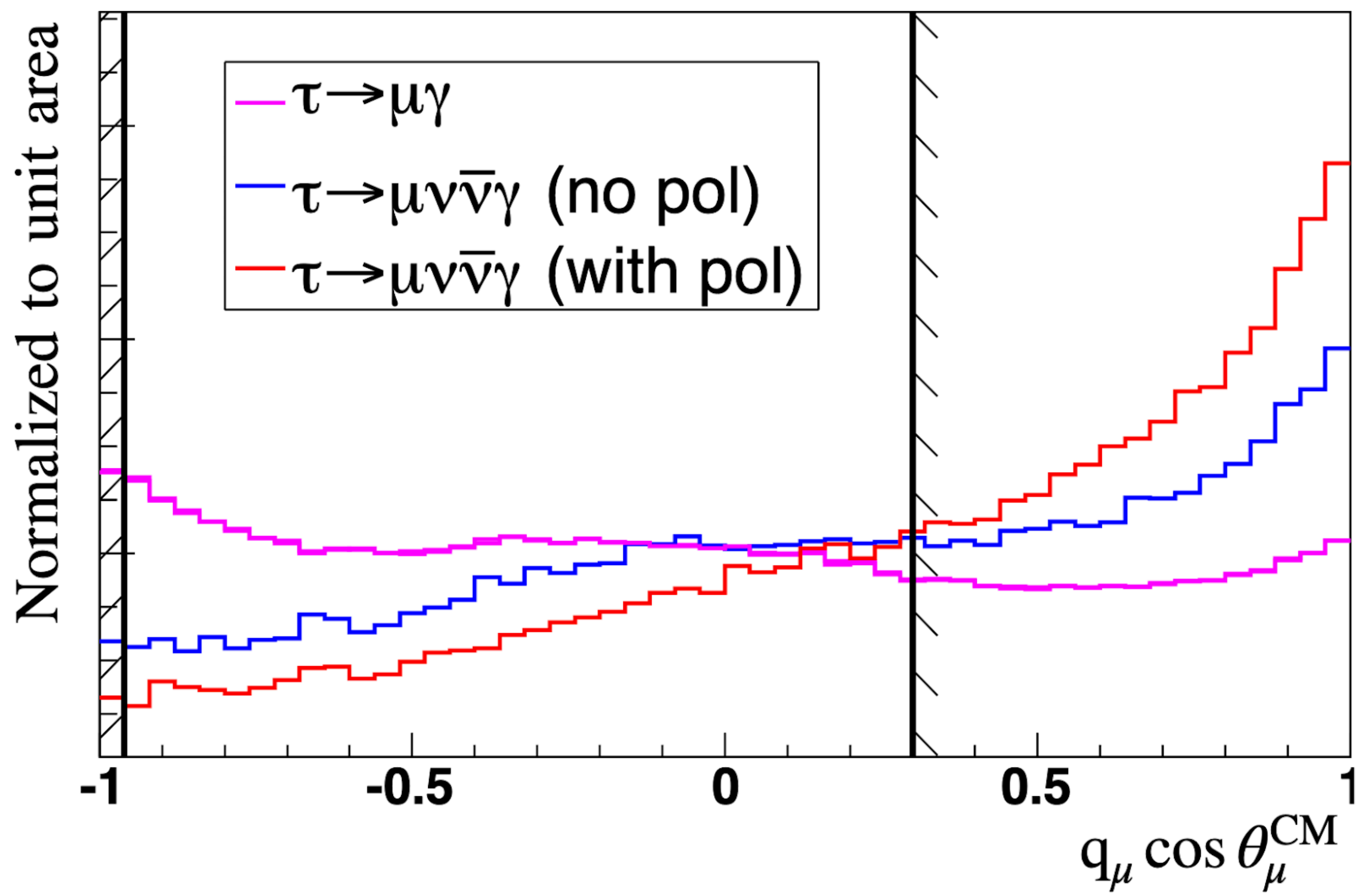
Projections

e-Print: 2207.06307 [hep-ex]

Belle II to probe LFV in several channels ≃ $\mathcal{O}(10^{-10})$ to $\mathcal{O}(10^{-9})$ with 50 ab^{-1}

Beam polarization upgrade at SuperKEKB/Belle II

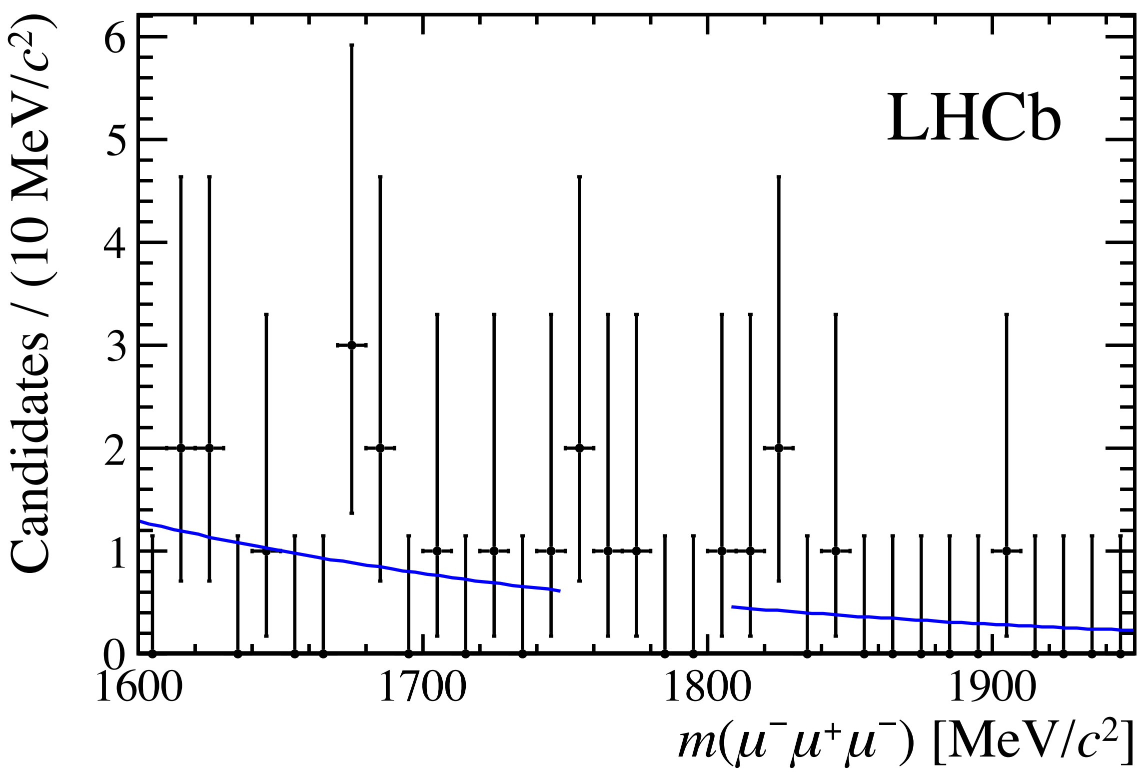
- Further improvements are expected with polarized beams
- With beam polarization, helicity distributions can suppress backgrounds
- Optimization study shows at least 10% improvement in $\tau \to \ell\gamma$ sensitivity



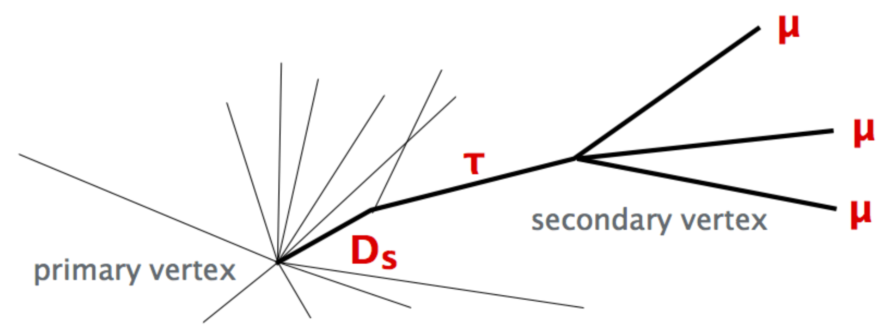
https://arxiv.org/pdf/0810.1312.pdf

Intriguing aspect of having the polarization is the possibility to determine the helicity structure of the LFV coupling in $\tau \to \mu\mu\mu$ from Dalitz plots.

$\tau \to \mu\mu\mu$ at LHCb



Using D decays (3fb^{-1} at 7/8 TeV)



$$\mathcal{B}\left(\tau^- \to \mu^-\mu^+\mu^-\right) = \frac{\mathcal{B}\left(D_s^- \to \phi\left(\mu^+\mu^-\right)\pi^-\right)}{\mathcal{B}\left(D_s^- \to \tau^-\bar{\nu}_\tau\right)} \times f_\tau^{D_s} \times \frac{\epsilon^{\rm R}_{\rm cal}}{\epsilon^{\rm R}_{\rm sig}} \times \frac{\epsilon^{\rm T}_{\rm cal}}{\epsilon^{\rm T}_{\rm sig}} \times \frac{N_{\rm sig}}{N_{\rm cal}} \equiv \alpha N_{\rm sig}$$

- LHCb limit on the $\tau^- \to \mu^-\mu^+\mu^-$ branching ratio

$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) < 4.6 \times 10^{-8} \quad @\ 90\%\ \text{C.L.}$$

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LHCb-PUB-2018-009

The cross-section is five orders of magnitude larger than at Belle II. This compensates for the higher background levels and lower integrated luminosity. As pointed out in [76], during the HL-LHC era, the LHCb Upgrade II detector will allow to collect 300 fb^{-1}. With this large data sample, LHCb will be able to probe the branching ratio down to $O(10^{-9})$, and either independently confirm any Belle II discovery or significantly improve the limit.

$\tau \to \mu\mu\mu$ at ATLAS & CMS

- ATLAS limit on the $\tau^- \to \mu^-\mu^+\mu^-$ branching ratio

$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) < 3.76 \times 10^{-7} \quad @\, 90\%\text{ C.L.}$$

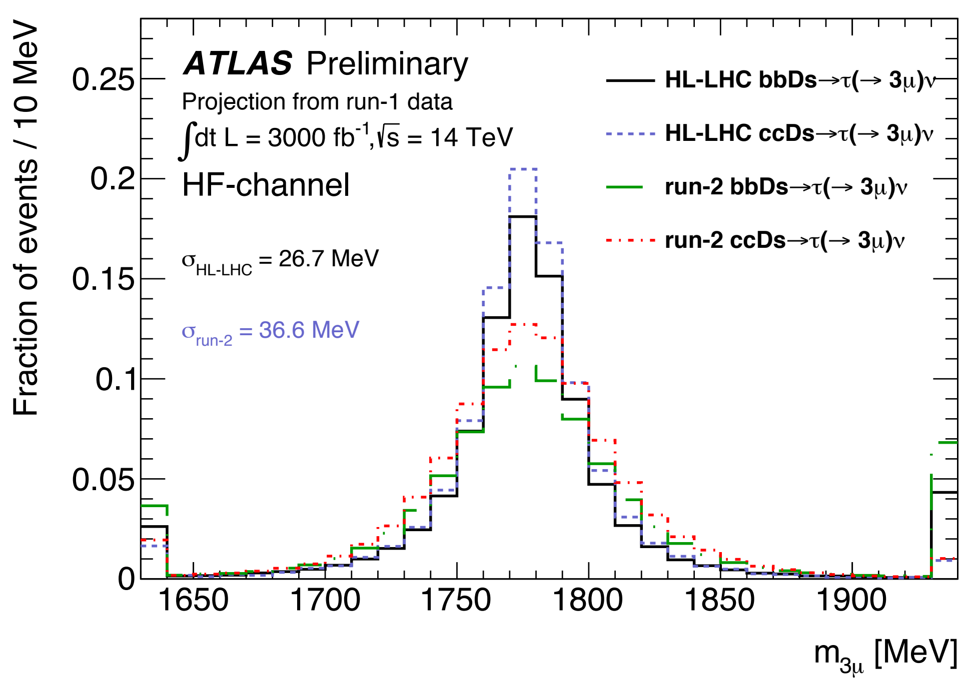
(20 fb^{-1} at 8 TeV)
Eur. Phys. J. C (2016) 76:232

- CMS limit on the $\tau^- \to \mu^-\mu^+\mu^-$ branching ratio

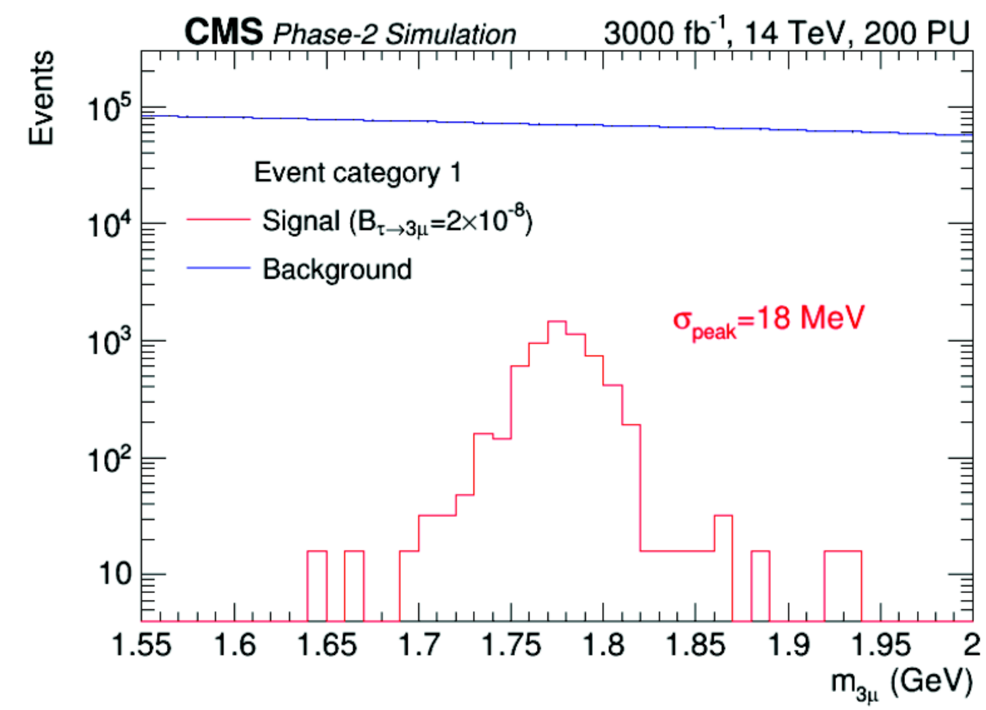
$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) < 8.0 \times 10^{-8} \quad @\, 90\%\text{ C.L.}$$

(33 fb^{-1} at 13 TeV)
JHEP 01 (2021) 163

Future prospects using D & B decays (3 ab^{-1} at 14 TeV) :



ATL-PHYS-PUB-2018-032

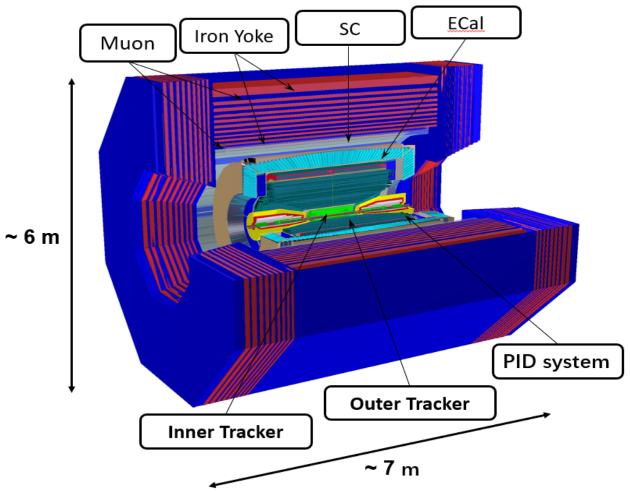


CMS-TDR-016

Scenario	$\mathcal{A} \times \epsilon$ [%]	N^{exp}_{bkg}	90% CL UL on BR($\tau \to 3\mu$) [10^{-9}]
High background	0.88	507.05	6.40
Medium background	0.88	152.12	2.31
Low background	0.88	50.71	1.03

	Category 1	Category 2
Number of background events	2.4×10^6	2.6×10^6
Number of signal events	4 580	3 640
Trimuon mass resolution	18 MeV	31 MeV
$B(\tau \to 3\mu)$ limit per event category	4.3×10^{-9}	7.0×10^{-9}
$B(\tau \to 3\mu)$ 90%C.L. limit	3.7×10^{-9}	

Super Tau-Charm Facility

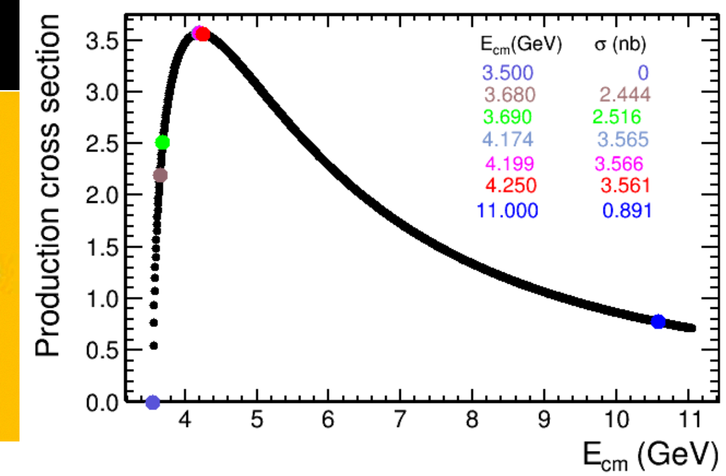


"Physics Potential of a Super tau-Charm Facility" (RF/SNOWMASS21-RF7_RF1_STCF-013.pdf)

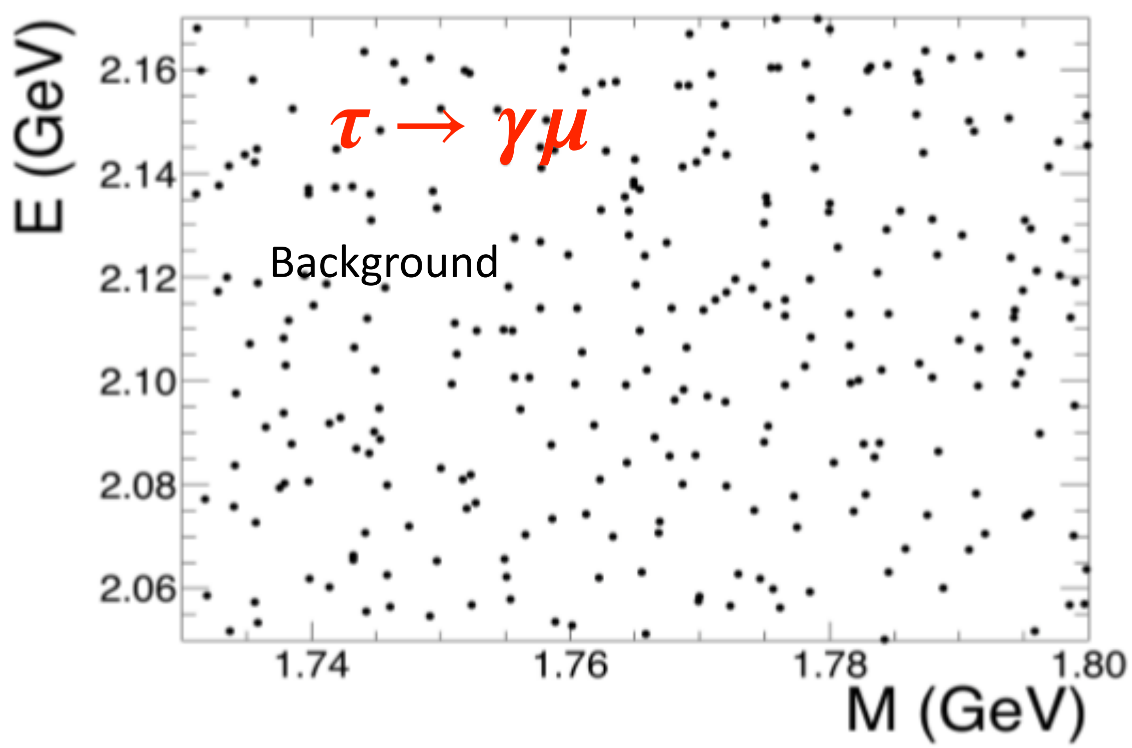
- Peaking luminosity $>0.5\times10^{35}\ \mathrm{cm^{-2}s^{-1}}$ at 4 GeV
- Energy range E_{cm} = 2-7 GeV
- Potential to increase luminosity and realize beam polarization
- A nature extension and a viable option for China accelerator project in the post BEPCII/BESIII era

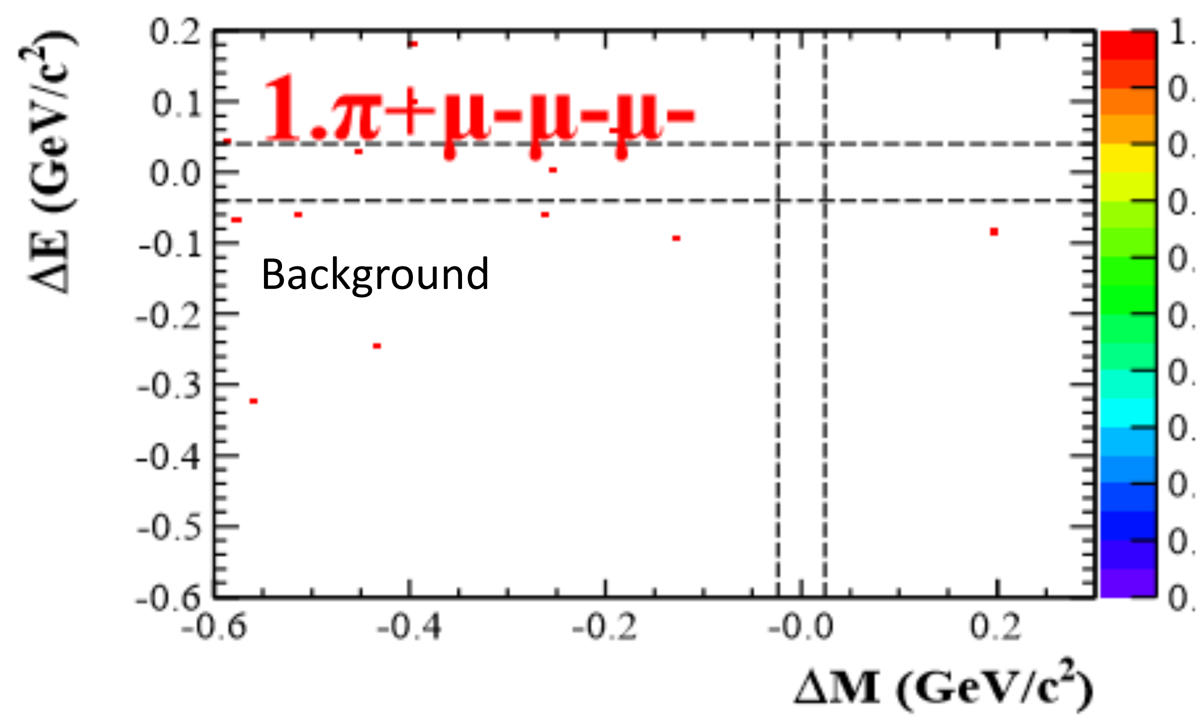
PoS CHARM2020 (2021), 007

Physics 49 (2020) 8, 513-524



At 4.26 GeV, number of tau pairs per year: $N_{\tau\tau}\sim$ **1.0 ab^{-1} ×3.5 nb = 3.5×10^{9}**





➢ **STCF with 1ab^{-1}:**

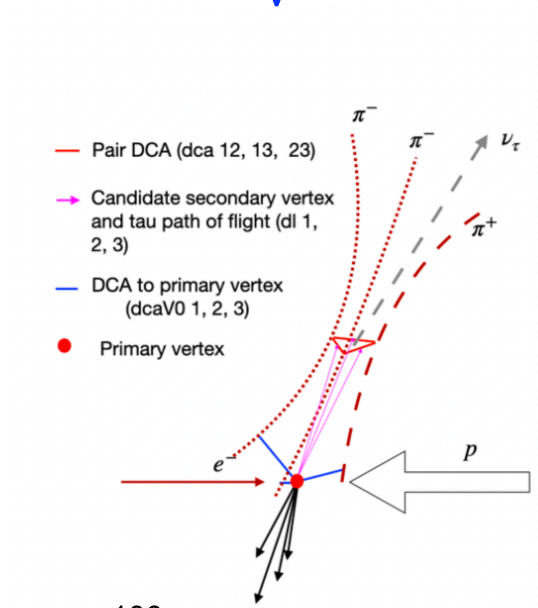
$$\mathcal{B}^{90}_{UL}(\tau\to\gamma\mu) < \frac{N^{90}_{UL}}{2\varepsilon N_{\tau\tau}} \sim 1.2\times10^{-8}$$

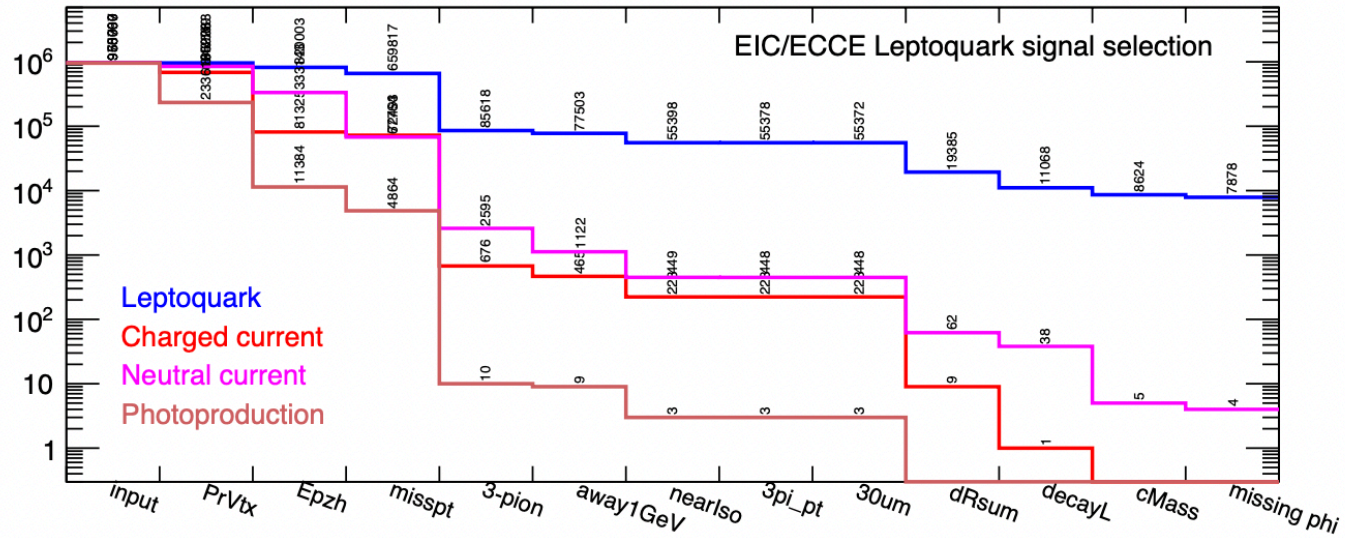
➢ **STCF with 1ab^{-1}:**

$$\mathcal{B}^{90}_{UL}(\tau\to\mu\mu\mu) < \frac{N^{90}_{UL}}{2\varepsilon N_{\tau\tau}} \sim 1.4\times10^{-9}$$

$e \to \tau$ transitions at EIC

Sensitivity study with 100 fb^{-1} of data to be collected at $\sqrt{s}$ =140 GeV (18 GeV electron on 275 GeV protons)

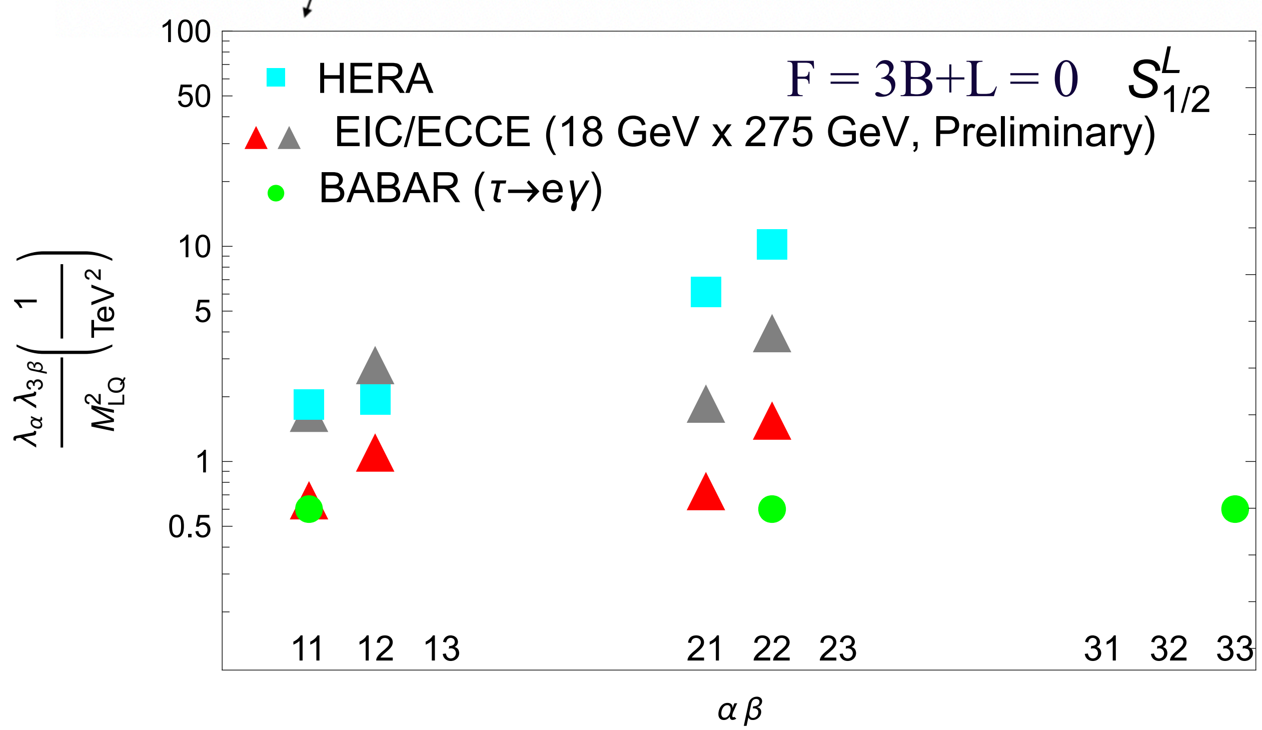


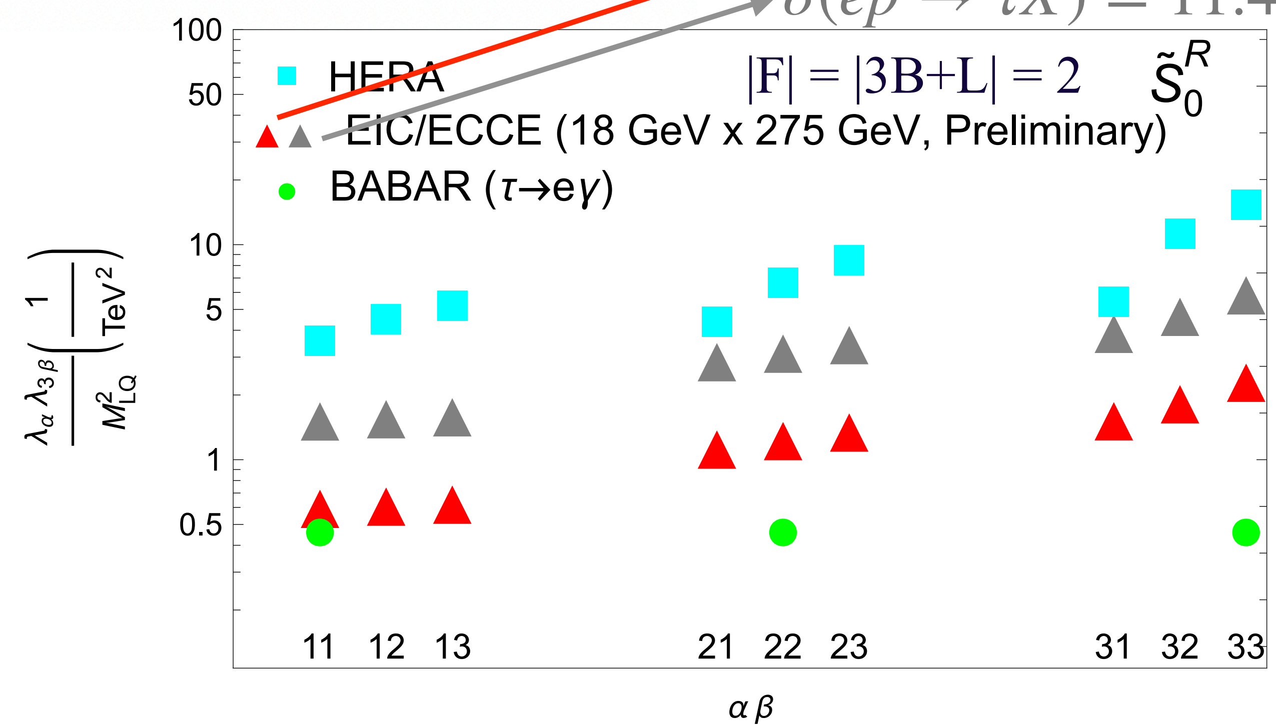


e-Print: 2207.10261 [hep-ph]

$\sigma(ep \to \tau X) = 1.7\ fb$

$\sigma(ep \to \tau X) = 11.4\ fb$



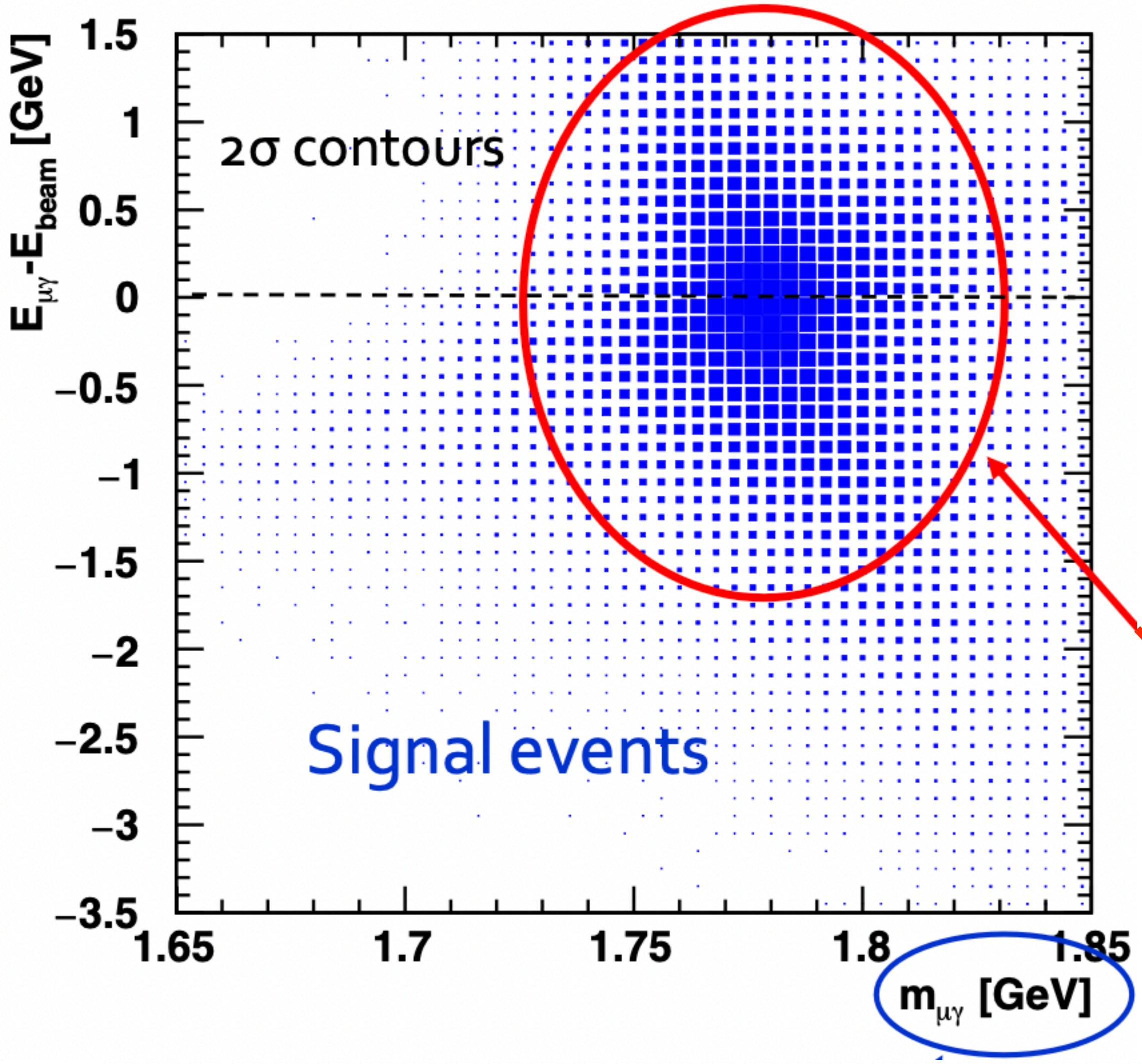


Expect to improve current sensitivity by an order of magnitude

FCC-ee

$\mathcal{B}(\tau \to \mu\gamma)$

e-Print: 1811.09408 [hep-ex]



- **Main background:** Radiative events (IRS+FSR), $e^+e^- \to \tau^+\tau^-\gamma$
  - $\tau \to \mu\gamma$ decay faked by combination of γ from ISR/FSR and μ from $\tau \to \mu\nu\bar{\nu}$

Smear with assumed FCC-ee detector resolutions (ILC-like detector):

- Muon momentum [GeV]
  $\sigma(p_T)/p_T = 2\times10^{-5} \times p_T \oplus 1\times10^{-3}$
- Photon ECAL energy [GeV]
  $\sigma(E)/E = 0.165/\sqrt{E} \oplus 0.010/E \oplus 0.011$
- Photon ECAL spatial [mm]
  $\sigma(x) = \sigma(y) = (6/E \oplus 2)$ mm

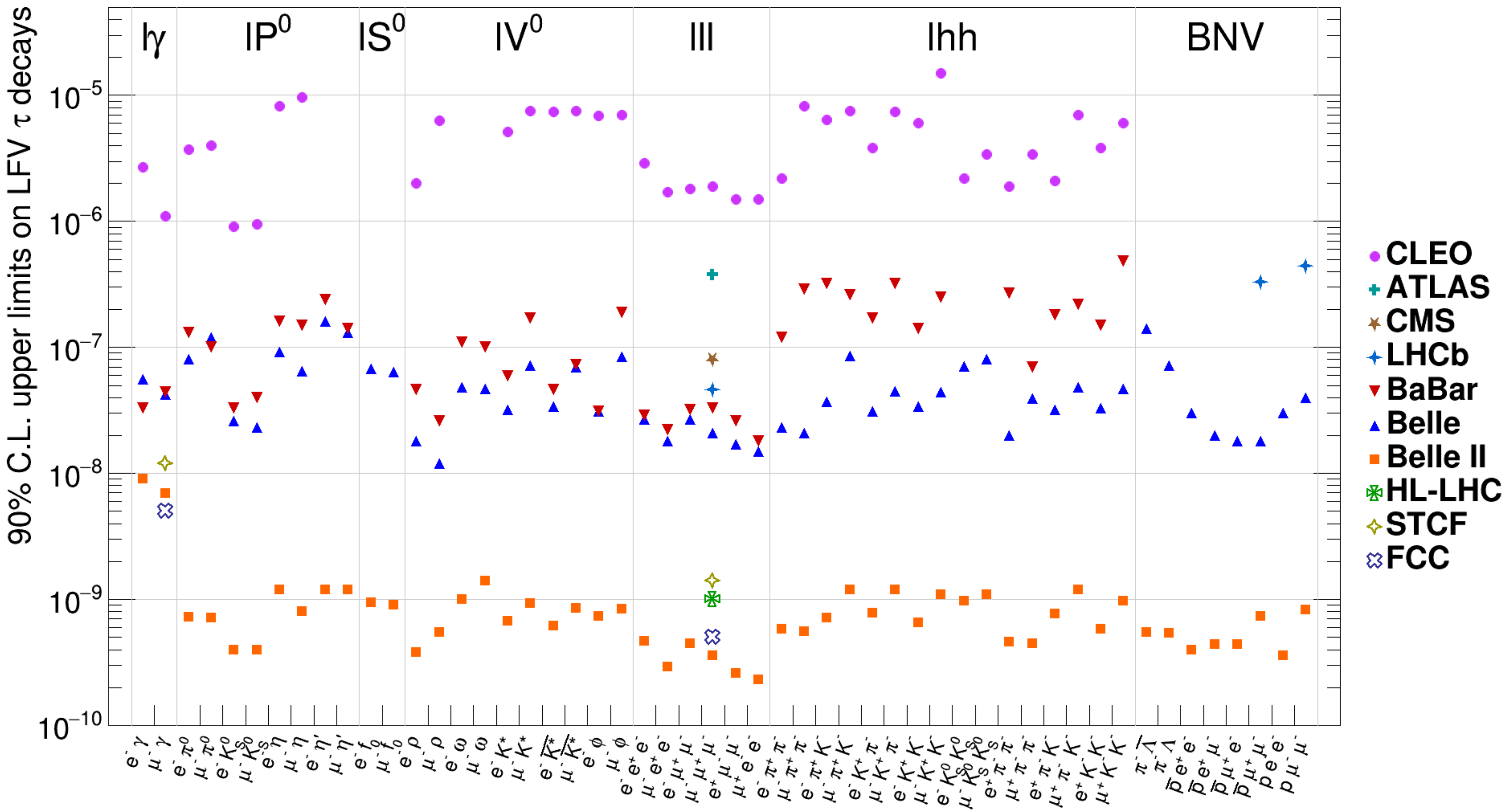
$\sigma(m_{\gamma\mu})$ = 26 MeV; $\sigma(E_{\gamma\mu})$ = 850 MeV

- From study (assuming 25% signal & background efficiency), projected BR sensitivity **2×10^{-9}**

$\mathcal{B}(\tau \to \mu\mu\mu)$

- Expect this search to have *very low* background, even with FCC-ee like statistics
- Should be able to have sensitivity down to BRs of **$\lesssim 10^{-10}$**

Summary of experimental prospects of τ decays



e-Print: 2203.14919 [hep-ph]

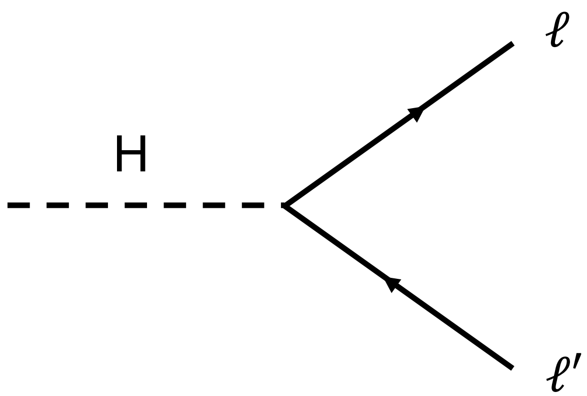
Summary of transitions with τ in the final state

Channel	Upper limit	Experiment [Ref.]
$J/\psi \to e^\pm \tau^\mp$	7.5×10^{-8}	BES III [108]
$J/\psi \to \mu^\pm \tau^\mp$	2.0×10^{-6}	BES [109]
$B^0 \to e^\pm \tau^\mp$	2.8×10^{-5}	BaBar [110]
$B^0 \to \mu^\pm \tau^\mp$	2.2×10^{-5}	BaBar [110]
	1.2×10^{-5}	LHCb [62]
$B^+ \to \pi^+ e^\pm \tau^\mp$	7.5×10^{-5}	BaBar [111]
$B^+ \to \pi^+ \mu^\pm \tau^\mp$	7.2×10^{-5}	BaBar [111]
$B^+ \to K^+ e^\pm \tau^\mp$	3.0×10^{-5}	BaBar [111]
$B^+ \to K^+ \mu^\pm \tau^\mp$	4.8×10^{-5}	BaBar [111]
$B^+ \to K^+ \mu^- \tau^+$	3.9×10^{-5}	LHCb [63]
$B_s^0 \to \mu^\pm \tau^\mp$	3.4×10^{-5}	LHCb [62]
$\Upsilon(1S) \to e^\pm \tau^\mp$	2.7×10^{-6}	Belle [112]
$\Upsilon(1S) \to \mu^\pm \tau^\mp$	2.7×10^{-6}	Belle [112]
$\Upsilon(2S) \to e^\pm \tau^\mp$	3.2×10^{-6}	BaBar [113]
$\Upsilon(2S) \to \mu^\pm \tau^\mp$	3.3×10^{-6}	BaBar [113]
$\Upsilon(3S) \to e^\pm \tau^\mp$	4.2×10^{-6}	BaBar [113]
$\Upsilon(3S) \to \mu^\pm \tau^\mp$	3.1×10^{-6}	BaBar [113]
$Z \to e^\pm \tau^\mp$	5.0×10^{-6} (*)	ATLAS [69]
$Z \to \mu^\pm \tau^\mp$	6.5×10^{-6} (*)	ATLAS [69]
$H \to e^\pm \tau^\mp$	0.47% (*)	ATLAS [65]
	0.22% (*)	CMS [66]
$H \to \mu^\pm \tau^\mp$	0.28% (*)	ATLAS [65]
	0.15% (*)	CMS [66]
	26% (*)	LHCb [64]

Table 2: Bounds on selected LFV decays with τ in the final state are shown at 90% CL, except for limits on those decays marked with a $(*)$, which are quoted at 95% CL.

e-Print: 2203.14919 [hep-ph]

LFV decays of Higgs Boson



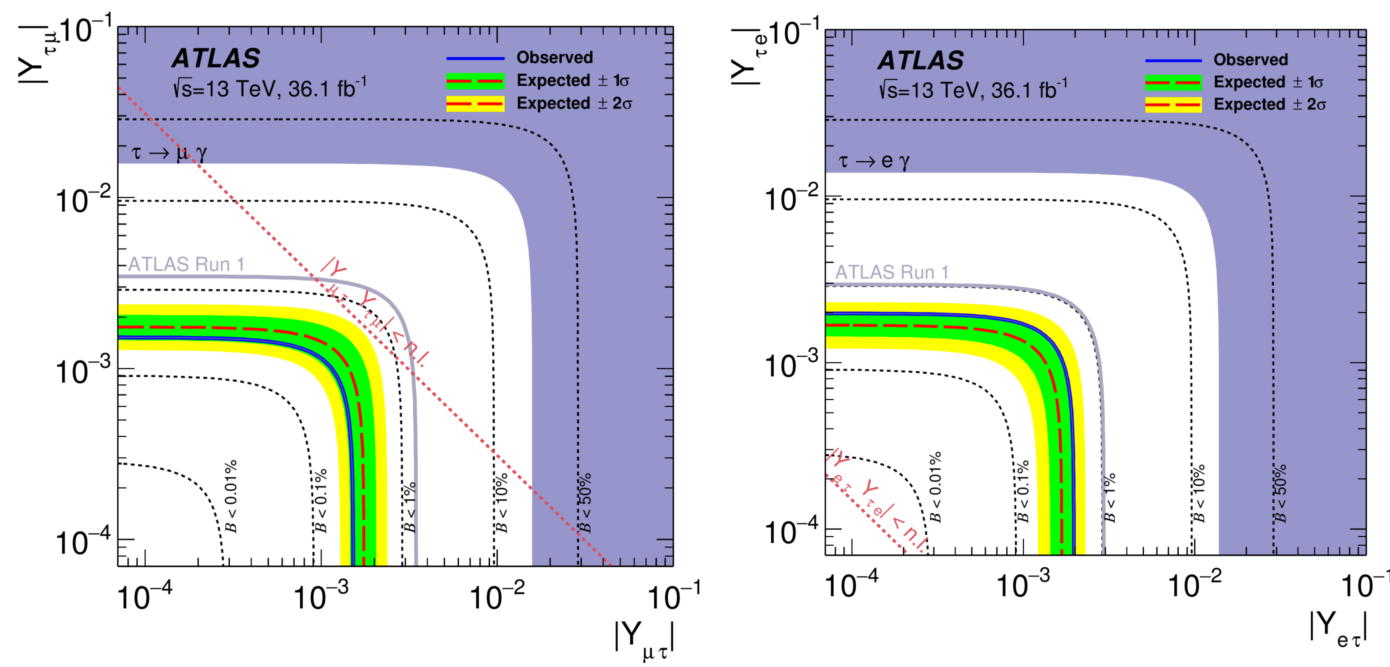
Yukawa off-diagonal terms

$$\mathcal{L}_Y = -m_i \bar{f}^i_L f^i_R - Y_{ij}(\bar{f}^i_L f^j_R)h + h.c. + \cdots ,$$

In the SM: $Y_{ij} = (m_i/v)\delta_{ij}$

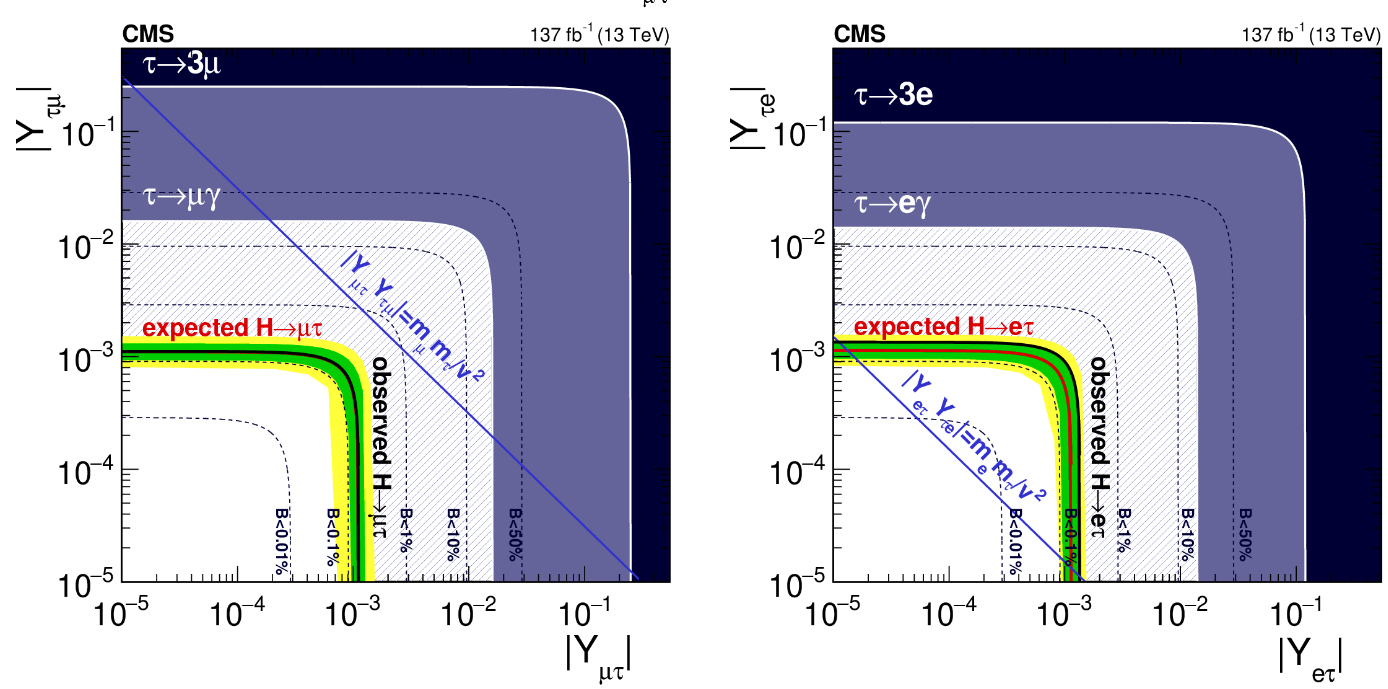
ATLAS

[Phys. Lett. B 800 (2020) 135069]()



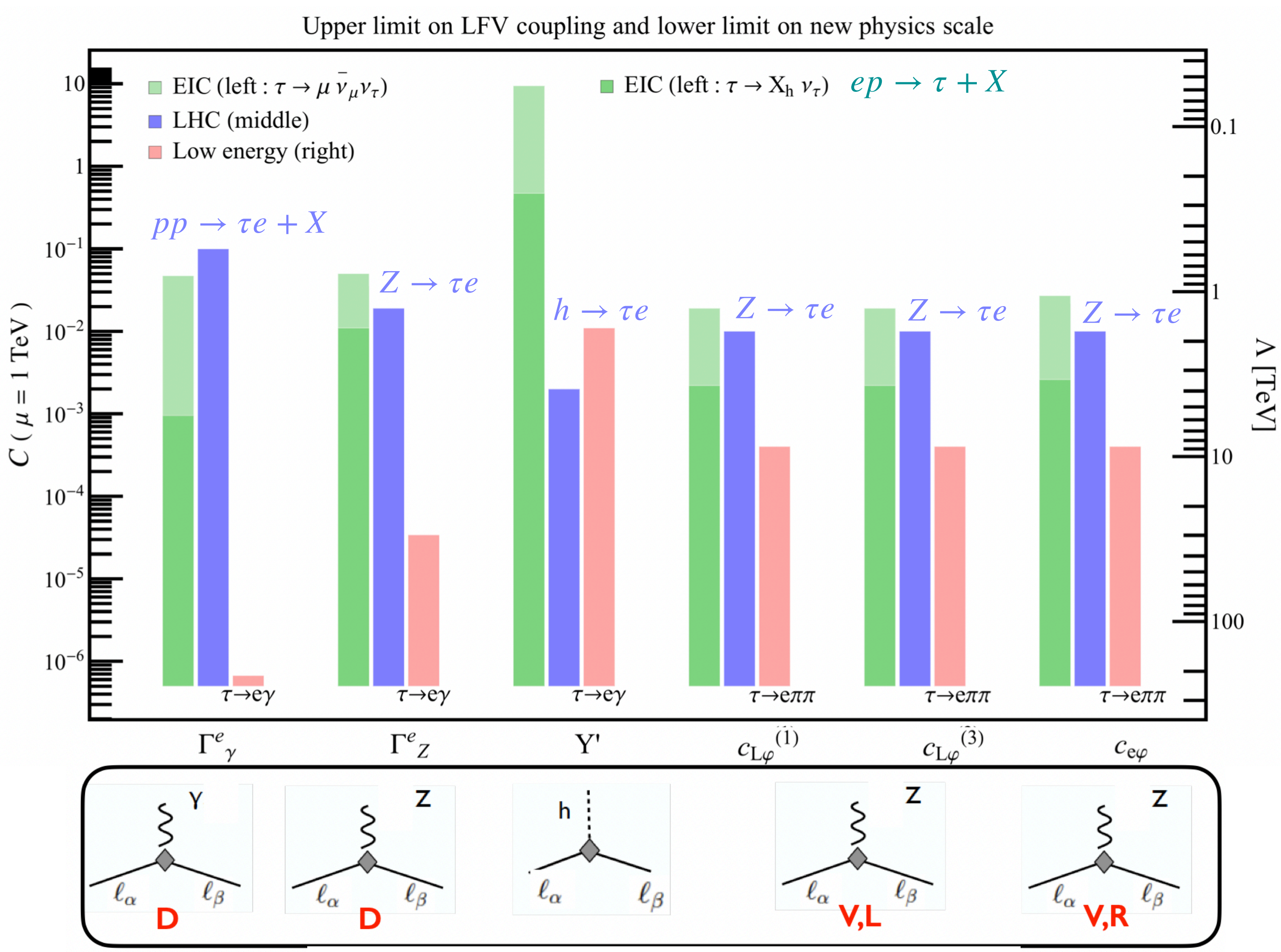
CMS

[Phys. Rev. D 104 (2021) 032013]()

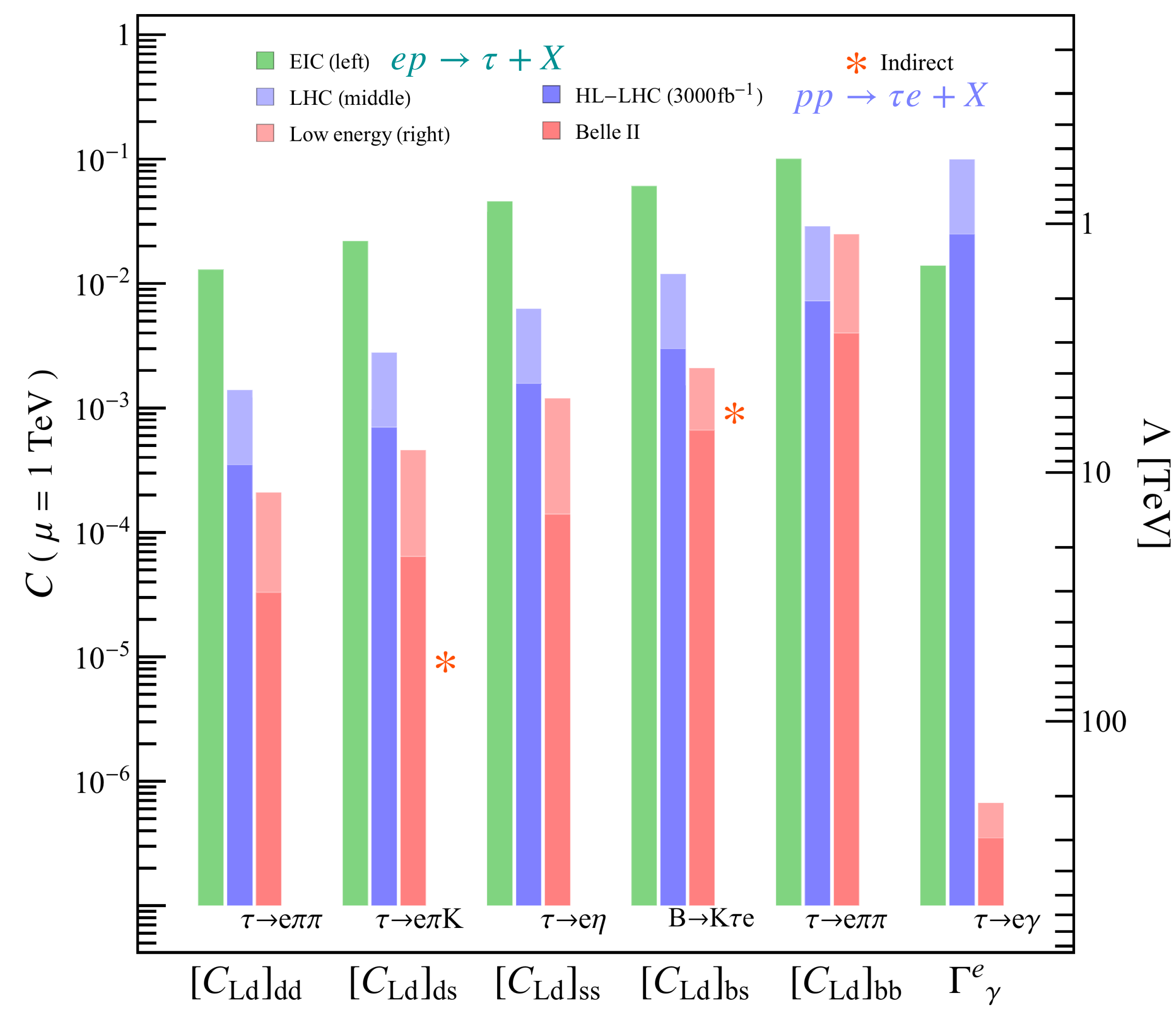


Global fit: $\tau \to e$ decays and transitions with τ in the final state

Model-independent probes of new physics at scale (Λ) encoded as Wilson coefficients (C_n) via EFT approach.
For certain operators, Higgs decay and LFV Drell-Yan compete, which are assumed to scale by factor of 4 at HL-LHC.
For many other operators, bounds dominated by τ and B-decays.



e-Print: 2102.06176 [hep-ph]

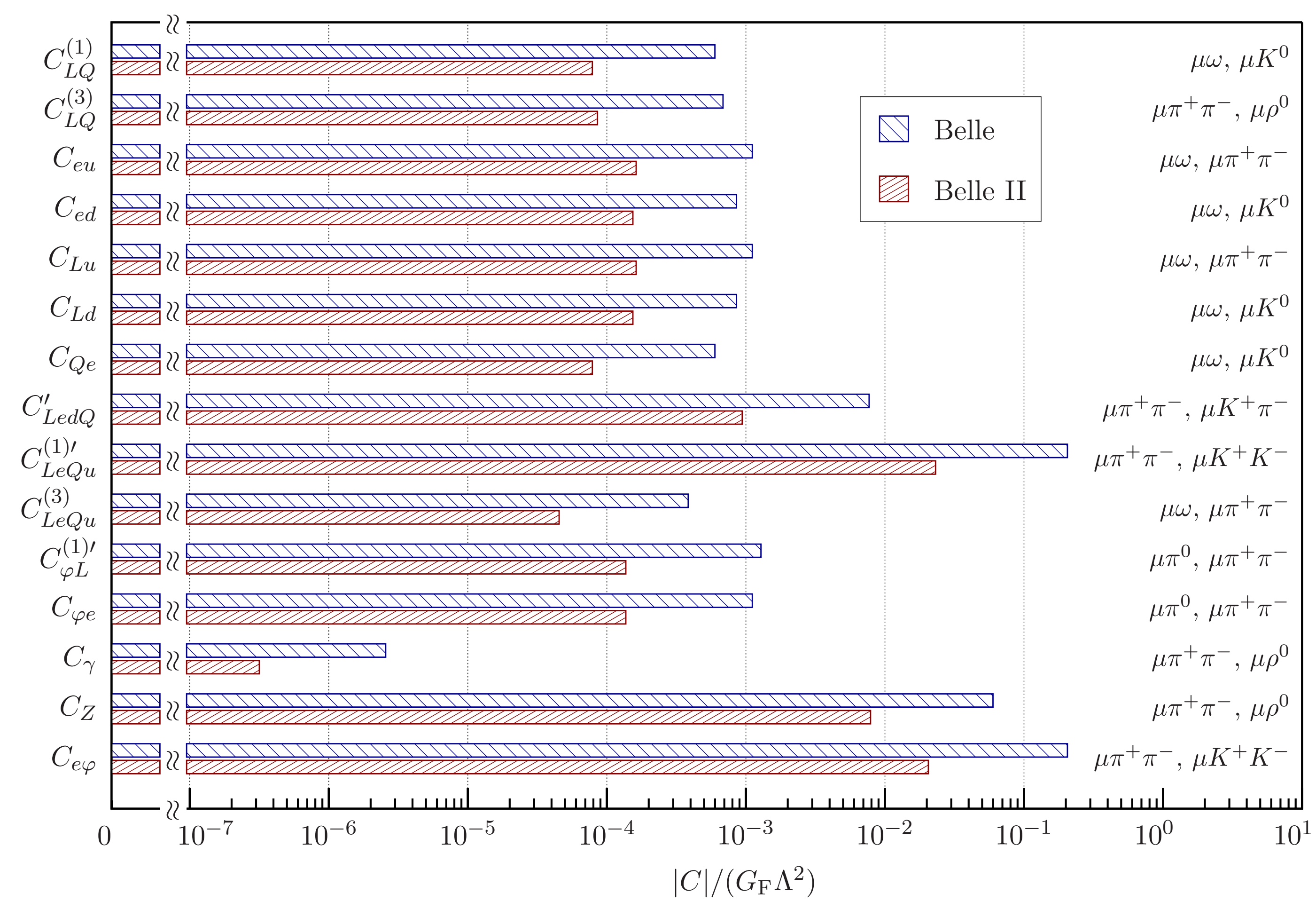


e-Print: 2203.14919 [hep-ph]

Global fit: $\tau \to \mu$ decays and transitions with τ in the final state

Model-independent probes of new physics at scale (Λ)
encoded as Wilson coefficients (C_n) via EFT approach.
For certain operators, Higgs decay and LFV Drell-Yan compete,
which are assumed to scale by factor of 4 at HL-LHC.
For many other operators, bounds dominated by τ and B-decays.

WC	Operator	WC	Operator
$C_{LQ}^{(1)}$	$(\bar L_p\gamma_\mu L_r)(\bar Q_s\gamma^\mu Q_t)$	$C_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar L_p e_r\varphi)$
$C_{LQ}^{(3)}$	$(\bar L_p\gamma_\mu\sigma^I L_r)(\bar Q_s\gamma^\mu\sigma^I Q_t)$	$C_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(e_p\gamma^\mu e_r)$
C_{eu}	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	$C_{\varphi L}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar L_p\gamma^\mu L_r)$
C_{ed}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$C_{\varphi L}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_{I\mu}\varphi)(\bar L_p\sigma_I\gamma^\mu L_r)$
C_{Lu}	$(\bar L_p\gamma_\mu L_r)(\bar u_s\gamma^\mu u_t)$	C_{eW}	$(\bar L_p\sigma^{\mu\nu}e_r)\,\sigma_I\varphi W^I_{\mu\nu}$
C_{Ld}	$(\bar L_p\gamma_\mu L_r)(\bar d_s\gamma^\mu d_t)$	C_{eB}	$(\bar L_p\sigma^{\mu\nu}e_r)\,\varphi B_{\mu\nu}$
C_{Qe}	$(\bar Q_p\gamma_\mu Q_r)(\bar e_s\gamma^\mu e_t)$		
C_{LedQ}	$(\bar L_p^j e_r)(\bar d_s Q_t^j)$		
$C_{LeQu}^{(1)}$	$(\bar L_p^j e_r)\,\varepsilon_{jk}\,(\bar Q_s^k u_t)$		
$C_{LeQu}^{(3)}$	$(\bar L_p^j\sigma_{\mu\nu}e_r)\,\varepsilon_{jk}\,(\bar Q_s^k\sigma^{\mu\nu}u_t)$		



e-Print: 2203.14919 [hep-ph]

Summary

- Search for dark leptophilic scalar in $e^+e^- \to \tau^+\tau^-\phi_L$; $\phi_L \to e^+e^-/\mu^+\mu^-$
  - Performed using 626 fb^{-1} of Belle data.
  - The analysis has been performed in a data-blinded manner: good understanding of the backgrounds.
  - Completely excludes the region favored by the $(g\text{-}2)_\mu$ anomaly, till ϕ_L mass of 4 GeV.

New **ICHEP2022** BELLE-CONF-2201 arXiv:2207.07476 **[hep-ex]**

- Search for LFV in $\tau^\pm \to \ell^\pm\gamma$ decays
  - Performed using 988 fb^{-1} of Belle data and improved analysis technique.
  - Most stringent limits for $\tau \to \mu\gamma$ at 90% CL.

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- Search for LFV in $\tau^\pm \to \ell^\pm\alpha$ decays
  - Performed using 62.8 fb^{-1} of Belle II data.
  - Belle II can already set most stringent limits in the world.

New **ICHEP2022**

Outlook

$\tau^- \to$	Observed Limits			Expected Limits		
	Experiment	Luminosity	UL (obs)	Experiment	Luminosity	UL (exp)
$\mu^-\gamma$	Belle [93]	988 fb^{-1}	4.2×10^{-8}	Belle II [54]	50 ab^{-1}	6.9×10^{-9}
	BaBar [83]	516 fb^{-1}	4.4×10^{-8}			
				STCF [74]	1 ab^{-1}	1.8×10^{-8}
				FCC-ee [87, 91]	150 ab^{-1}	$\mathcal{O}(10^{-9})$
$\mu^-\mu^+\mu^-$	Belle [102]	782 fb^{-1}	2.1×10^{-8}	Belle II [54]	50 ab^{-1}	3.6×10^{-10}
	BaBar [103]	468 fb^{-1}	3.3×10^{-8}			
	LHCb [61]	3 fb^{-1}	4.6×10^{-8}	LHCb [76]	300 fb^{-1}	$\mathcal{O}(10^{-9})$
	CMS [67]	33 fb^{-1}	8.0×10^{-8}	CMS [77]	3 ab^{-1}	3.7×10^{-9}
	ATLAS [68]	20 fb^{-1}	3.8×10^{-7}	ATLAS [78]	3 ab^{-1}	1.0×10^{-9}
				STCF [74]	1 ab^{-1}	1.4×10^{-9}
				FCC-ee [87, 91]	150 ab^{-1}	$\mathcal{O}(10^{-10})$

- **Observation of LFV in the charged lepton sector would completely change our understanding of physics and herald a new period of discoveries in particle physics. Synergies between different experiments compliment discovery potential/confirmation.**

- **Now is a very interesting era in the searches for LFV in decays of the τ lepton, as the current limits will improve by an order of magnitude down to a few parts in 10^{-10} to 10^{-9} at the Belle II experiment. Polarized beams can further improve the sensitivity.**

- **Similar sensitivities will be probed at ATLAS, CMS & LHCb with high luminosity upgrade.**

- **Proposed experiments at STCF, EIC & FCC-ee will continue searches for LFV in the tau sector, also with the possibility of beam polarization.**