Snowmass 2021 White Paper: Charged lepton flavor violation in the tau sector

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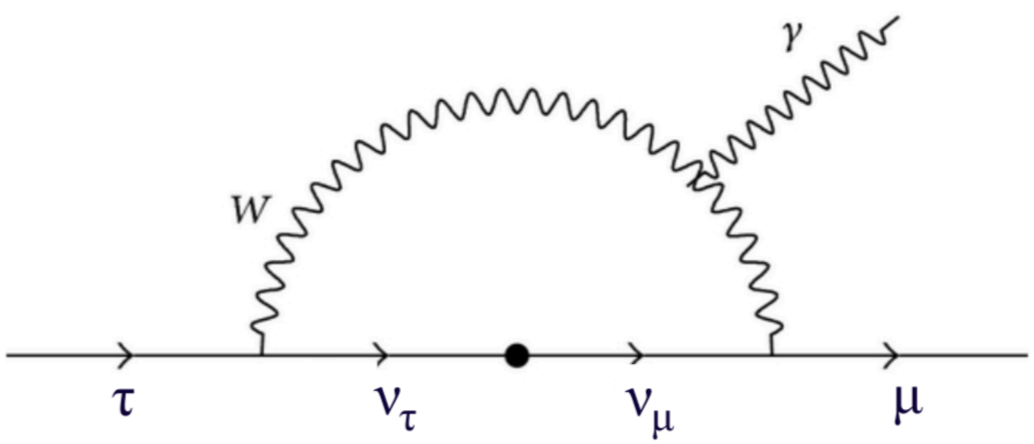
Snowmass 2021

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

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

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

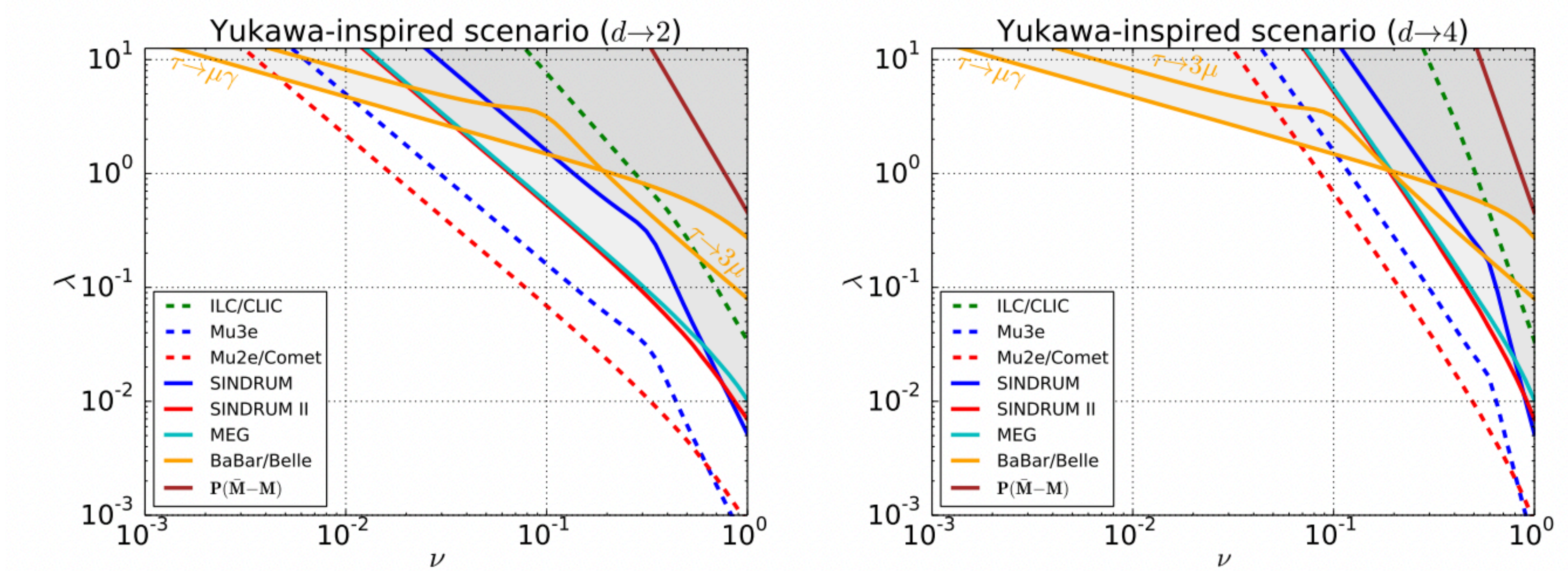
LFV in tau sector is complementary to muon sector in NP parameter space:
current limit on $\mathscr{B}(\mu \to e\gamma) \sim 10^{-13}$ does not forbid $\mathscr{B}(\tau \to \ell\gamma) \sim 10^{-8}$

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

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



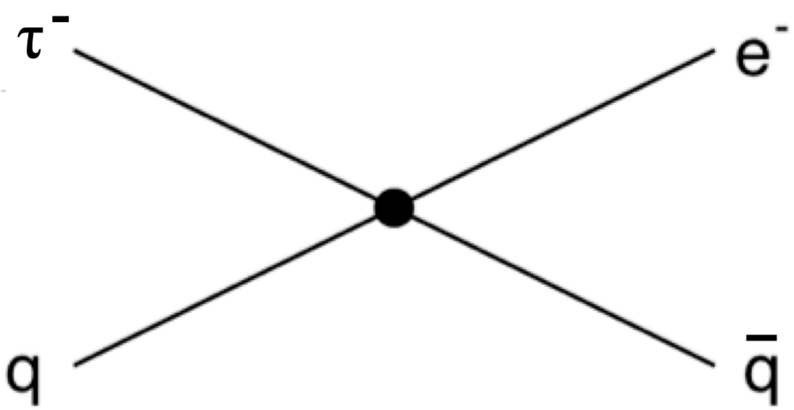
A. Crivellin et. al.
Phys. Rev. D 99, 035004 (2019)

- Some models predict LFV up to existing experimental bounds
- eg. SUSY models: non-diagonal slepton mass matrix $\Rightarrow$ LFV
- Normal (Inverted) hierarchy for slepton $\Rightarrow \tau \to \mu\gamma$ ($\tau \to e\gamma$)
- Neutrinoless 2 and 3 body τ decays have different sensitivity

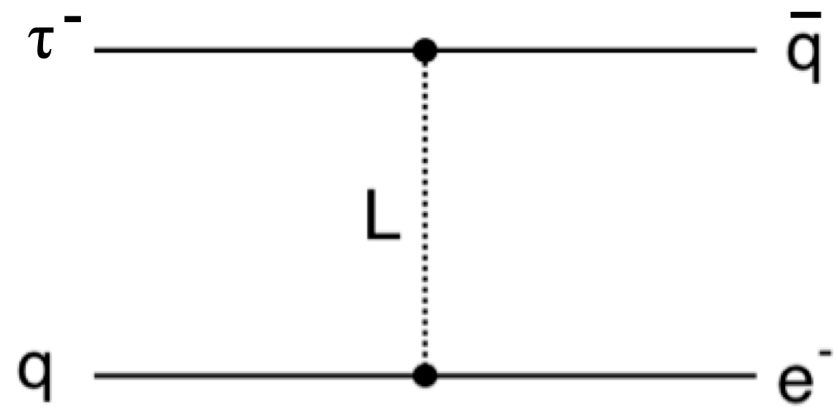
	$\mathcal{B}(\tau \to \ell\gamma)$	$\mathcal{B}(\tau \to \ell\ell\ell)$
mSUGRA+seesaw (EPJC14(2000)319, PRD66(2002)115013)	10^{-8}	10^{-9}
SUSY SO(10) (NPB649(2003)189, PRD68(2003)033012)	10^{-8}	10^{-10}
SUSY Higgs (PLB549(2002)159, PLB566(2003)217)	10^{-10}	10^{-8}
Non-Universal Z′ (PLB547(2002)252)	10^{-9}	10^{-8}
SM+Heavy Majorana ν_R (PRD66(2002)034008)	10^{-9}	10^{-10}

New Physics illustrations

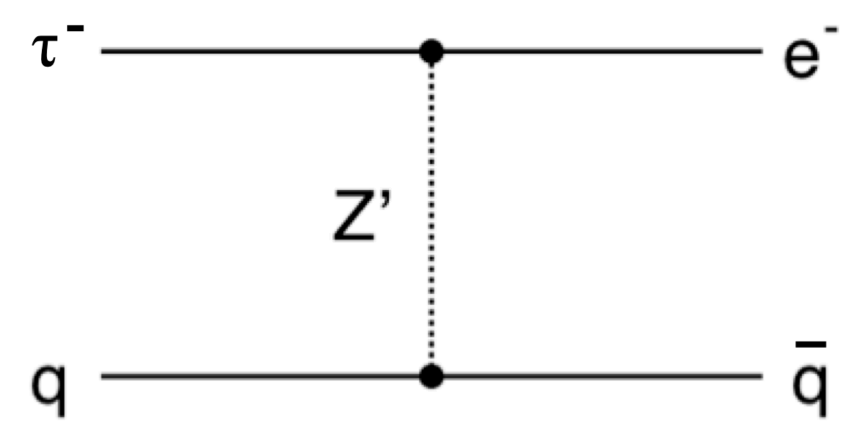
Tree level :



Compositeness

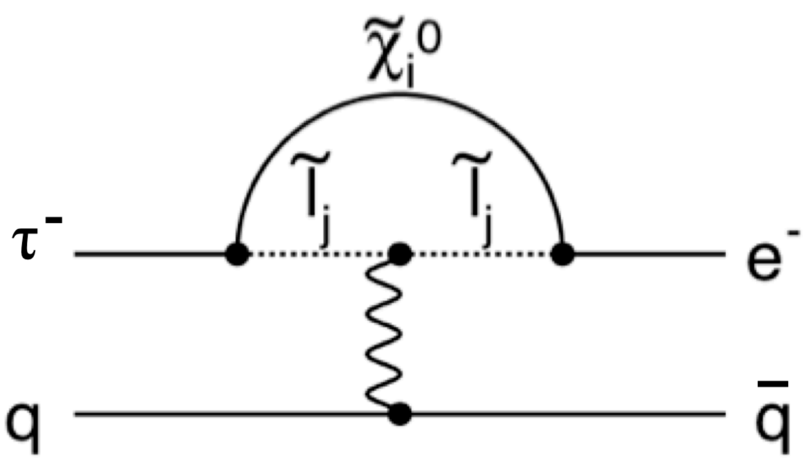


Leptoquarks

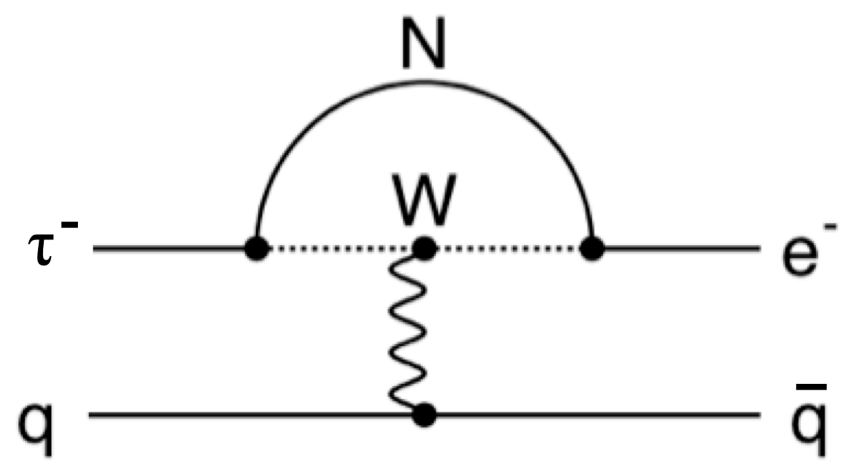


Heavy gauge bosons

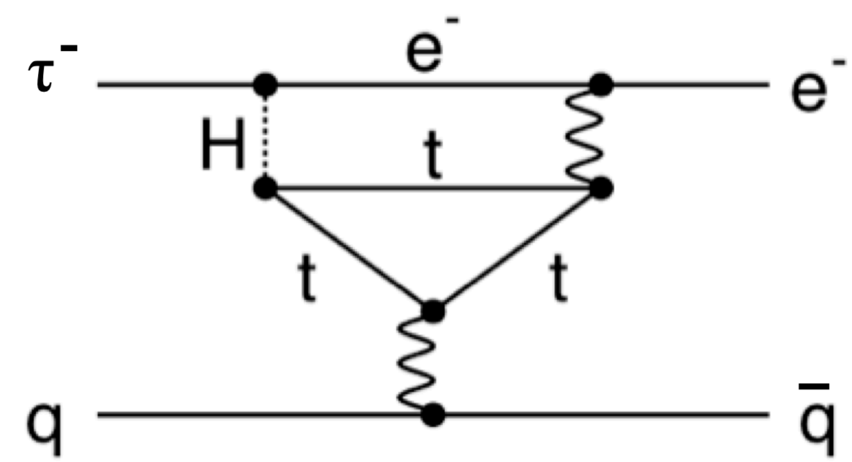
Loop induced :



Supersymmetry



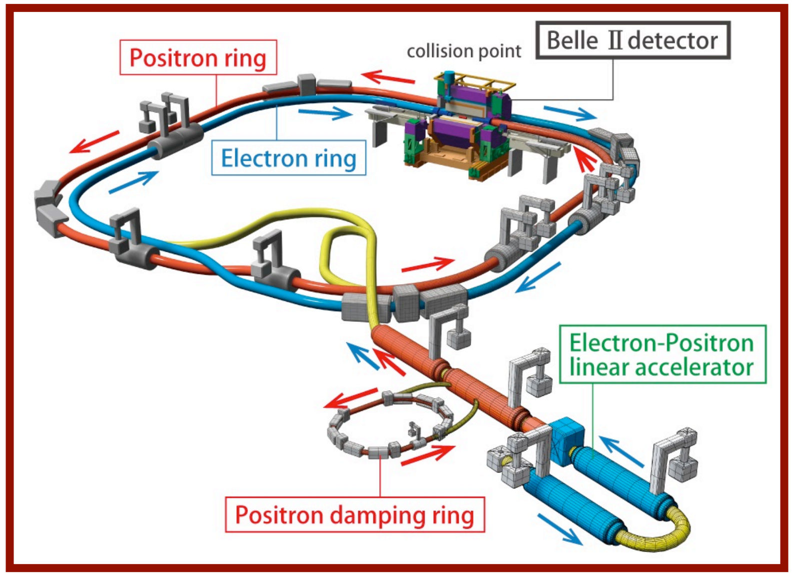
Heavy neutrinos



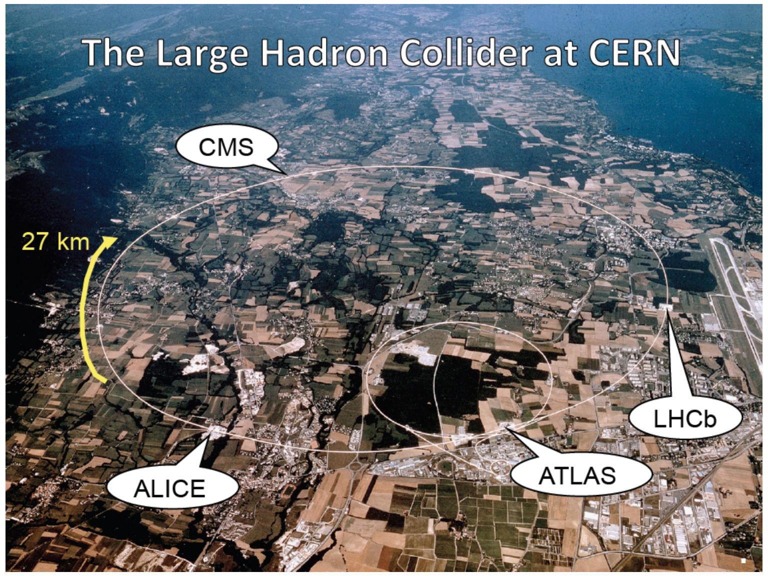
Extended Higgs models

Current and future experiments

Belle II at SuperKEKB

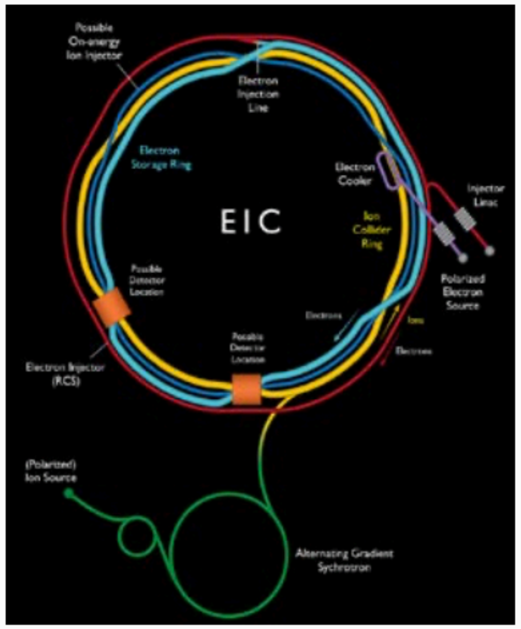


ATLAS, CMS, LHCb at LHC

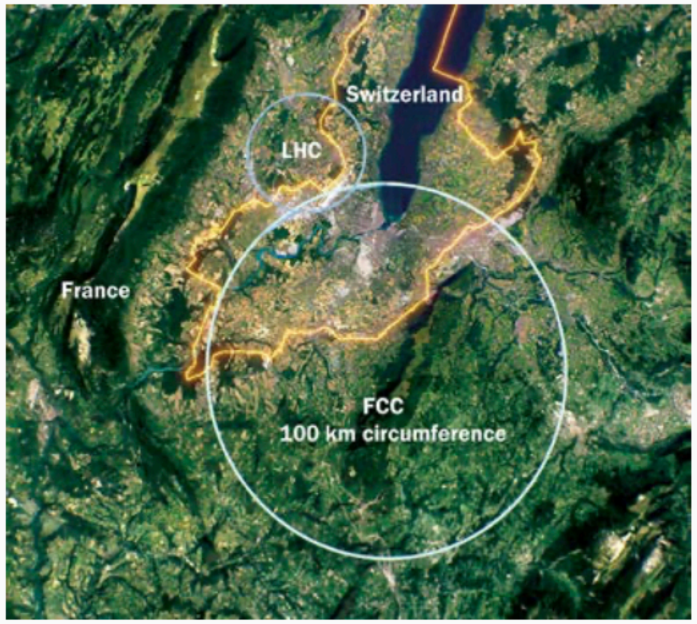


STCF proposal at China/Novosibirsk

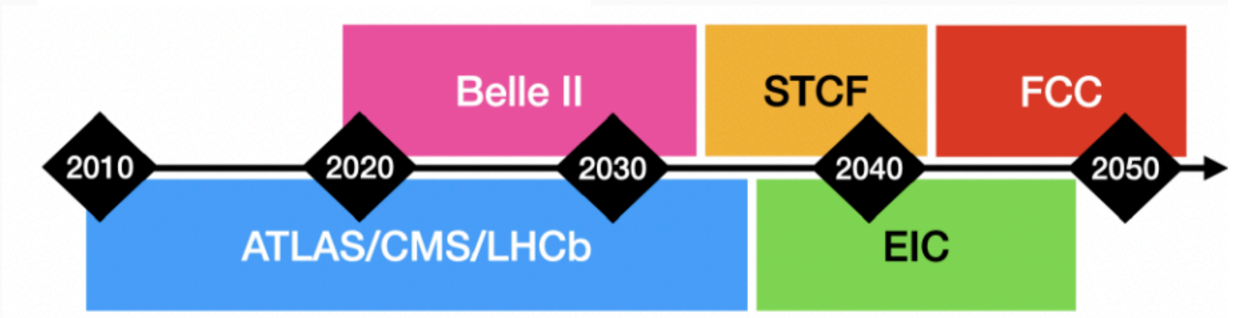
EIC at Brookhaven



FCC-ee proposal – CERN



Tentative timeline



About fifty τ decay modes & many transitions with τ in the final state

- **Lepton flavor violation (charge conjugate modes implied)**
  - $\tau \to e/\mu\ \gamma$ (Belle II, STCF, FCC-ee)
  - $\tau \to e/\mu$ (scalar/pseudoscalar/vector mesons) (Belle II)
  - $\tau \to e\ e\ e$ (Belle II)
  - $\tau \to \mu\ \mu\ \mu$ (Belle II, ATLAS, CMS, LHCb, STCF, FCC-ee)
  - $\tau \to e\ \mu\ \mu$, $\mu\ e\ e$ (Belle II)
  - $\tau \to e/\mu\ h\ h$ (non-resonant final states with $h=\pi/K$) (Belle II, STCF)
  - $H \to e\ \tau$, $\mu\ \tau$ (ATLAS, CMS)
  - $Z(Z') \to e\ \tau$, $\mu\ \tau$ (ATLAS, CMS)
  - $e \to \tau$ transitions (EIC)

- **Lepton number violation**
  - $\tau^- \to e^+\ h^-\ h^-$ (non-resonant final states with $h=\pi/K$) (Belle II)
  - $\tau^- \to \mu^+\ h^-\ h^-$ (non-resonant final states with $h=\pi/K$) (Belle II)

- **Baryon number violation**
  - $\tau^- \to \Lambda\ \pi^-$, $\bar{\Lambda}\ \pi^-$ (Belle II)
  - $\tau^- \to \bar{p}\ \mu^+\ \mu^-$, $p\ \mu^-\ \mu^-$ (Belle II, LHCb)

Sensitivity estimates

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

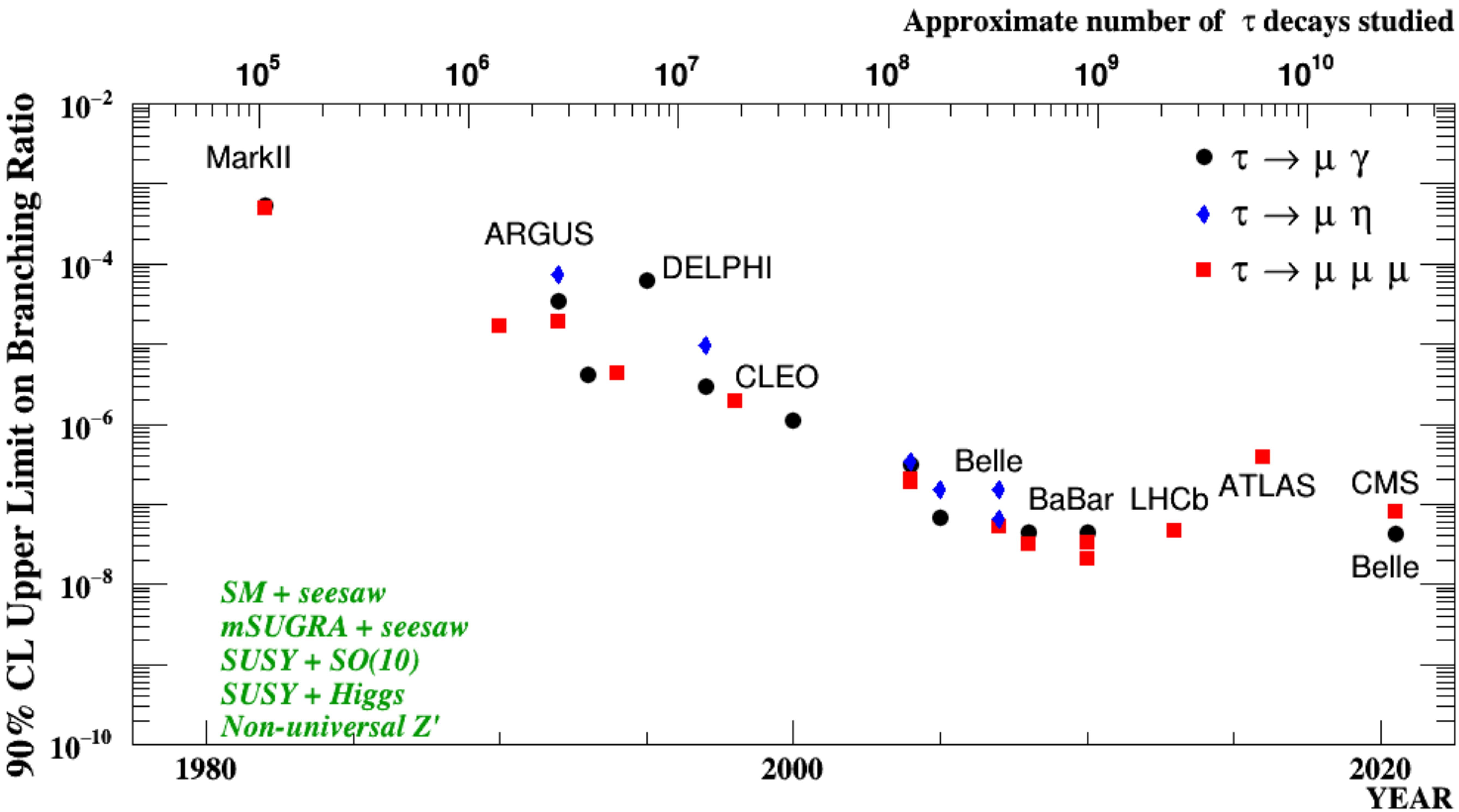
- ε: high statistics signal MC simulated for different Data-taking periods

ε = **Trigger . Reco . Topology . PID . Cuts . Signal–Box**

	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}



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

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

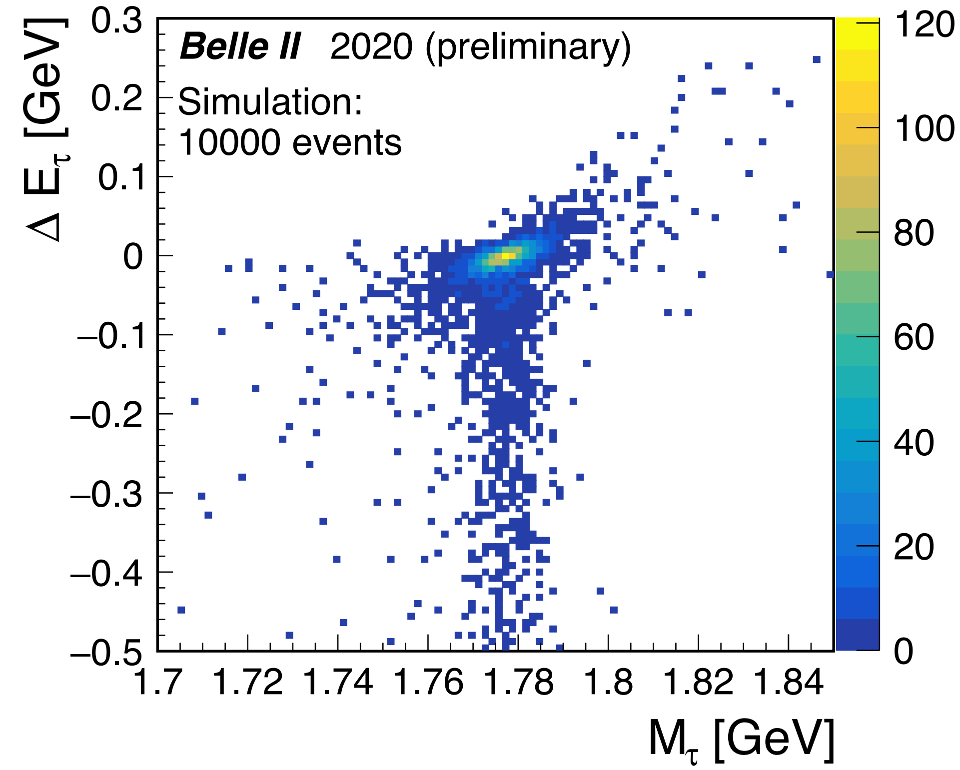
Two independent variables:

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

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

➡ ΔE close to 0 for signal

➡ Mass of tau daughters close to τ mass



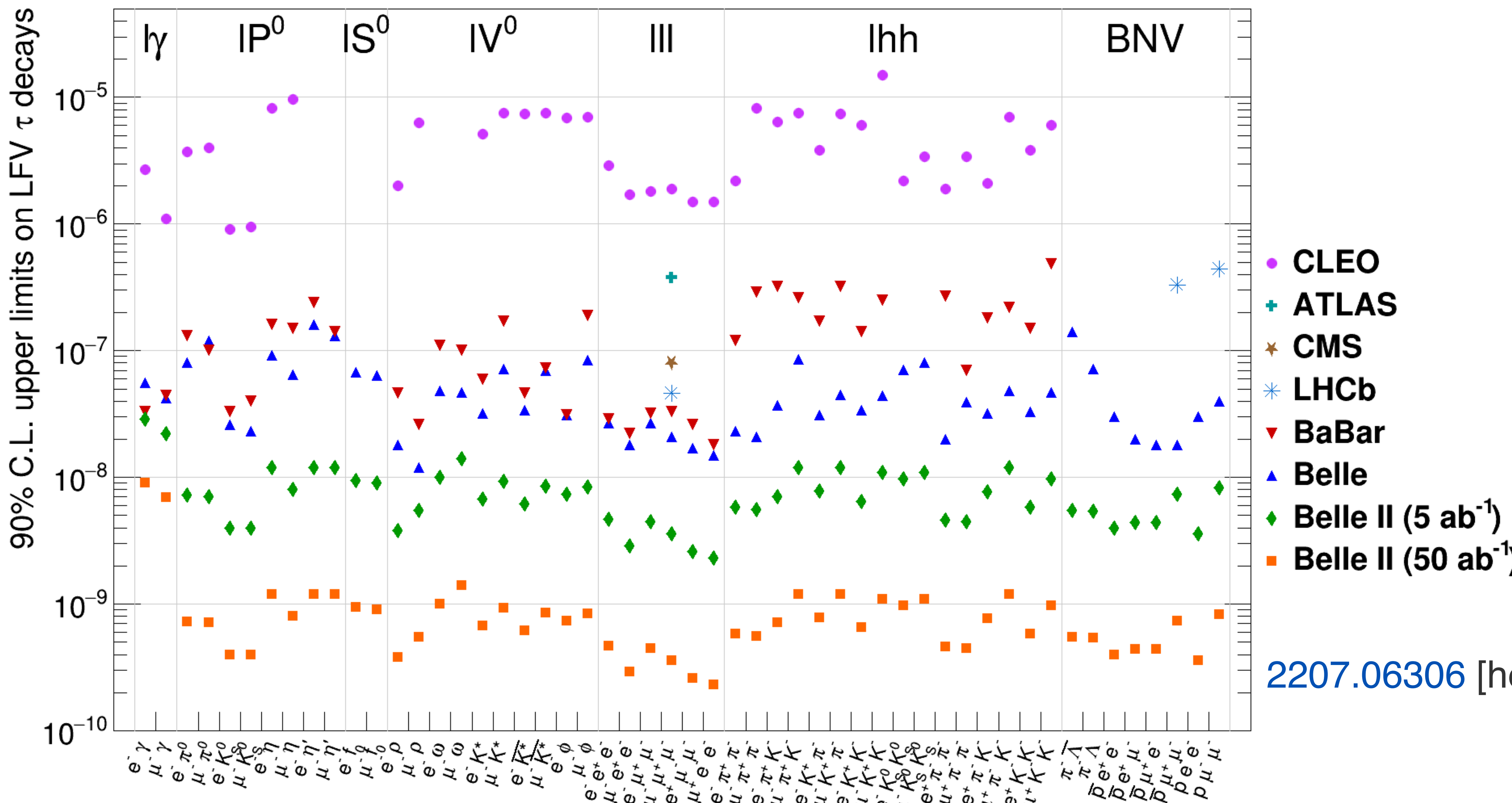
Higher signal efficiency is foreseen at Belle II than at Belle or BaBar

- **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 50ab^{-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}	$\propto 1/\sqrt{\mathcal{L}}$	$\propto 1/\mathcal{L}$

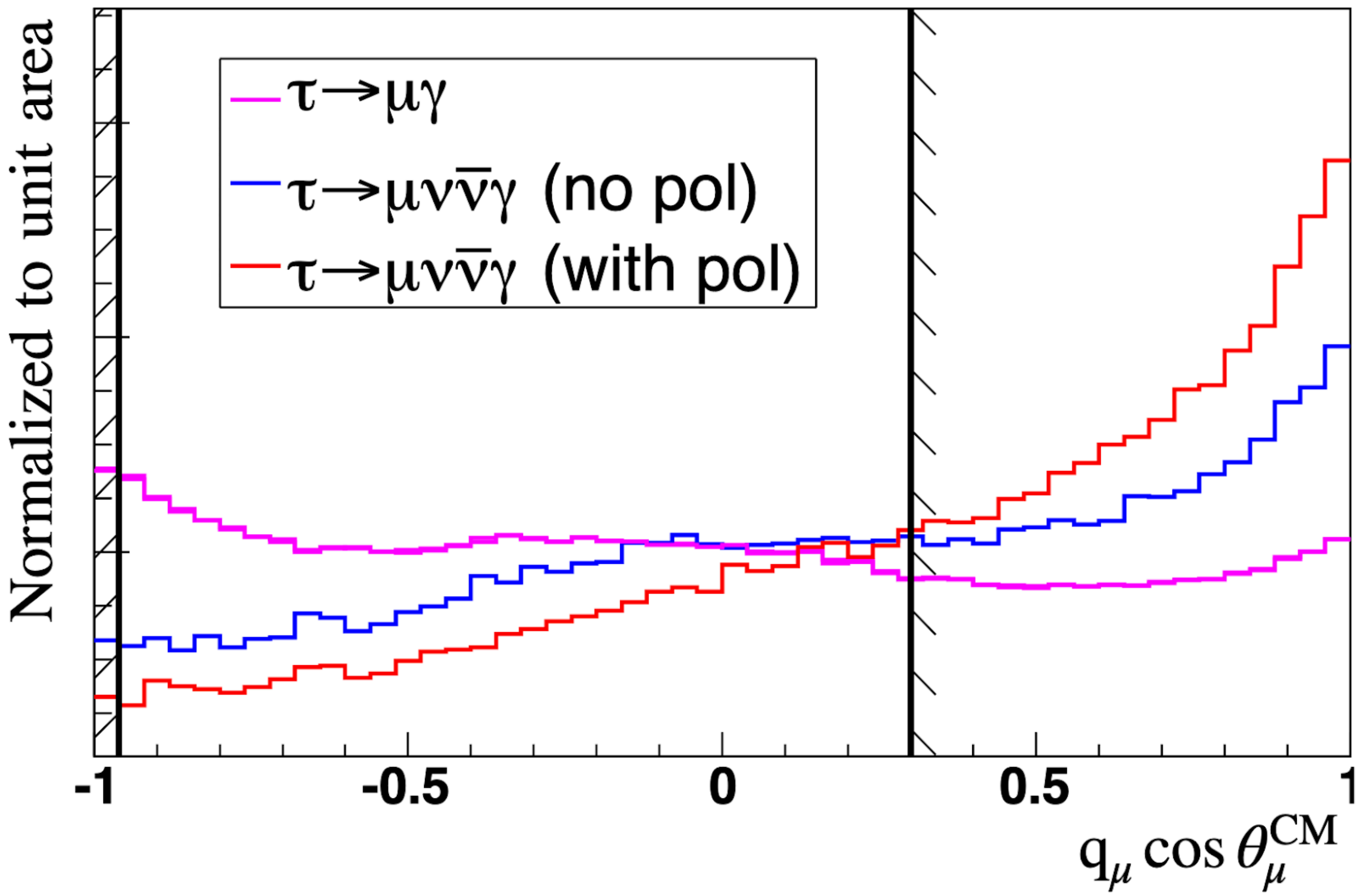


2207.06306 [hep-ex]

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

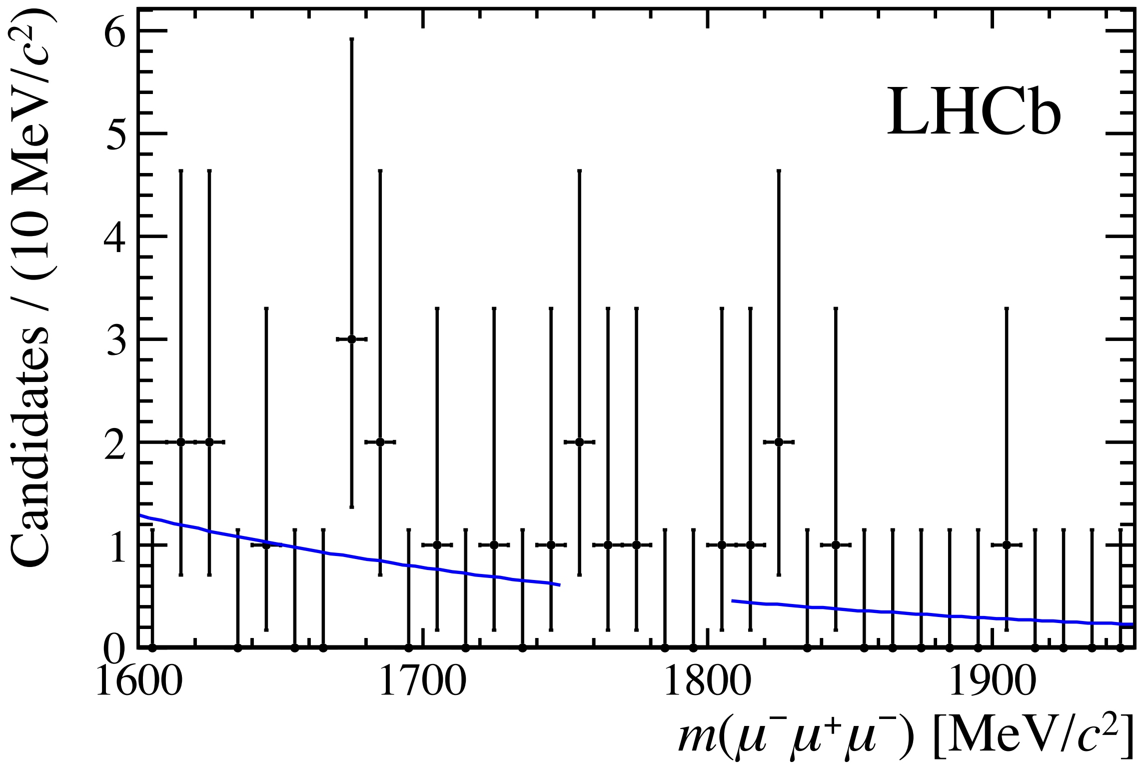
- Further improvements are expected with polarized beams
- With beam polarization, helicity distributions can suppress backgrounds
- Optimization study shows at least 10% improvement in $\tau\to\ell\gamma$ sensitivity



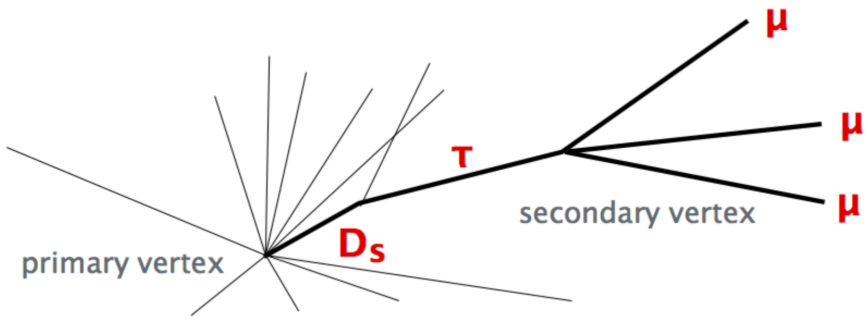
https://arxiv.org/pdf/0810.1312.pdf

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.

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



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



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

- 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.

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

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

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

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

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

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

(33 fb^{-1} at 13 TeV)
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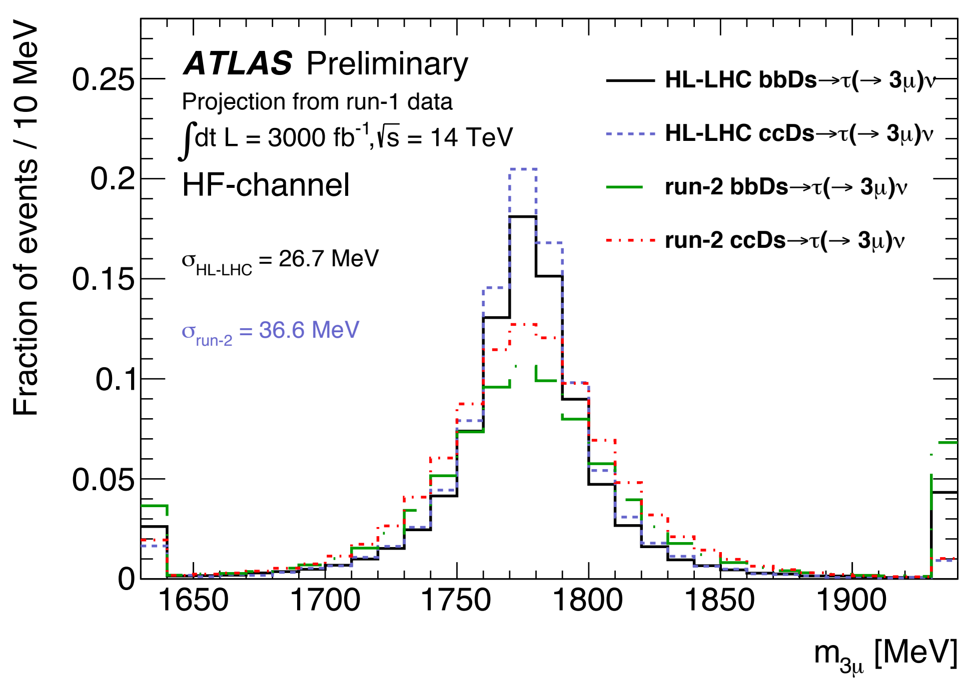
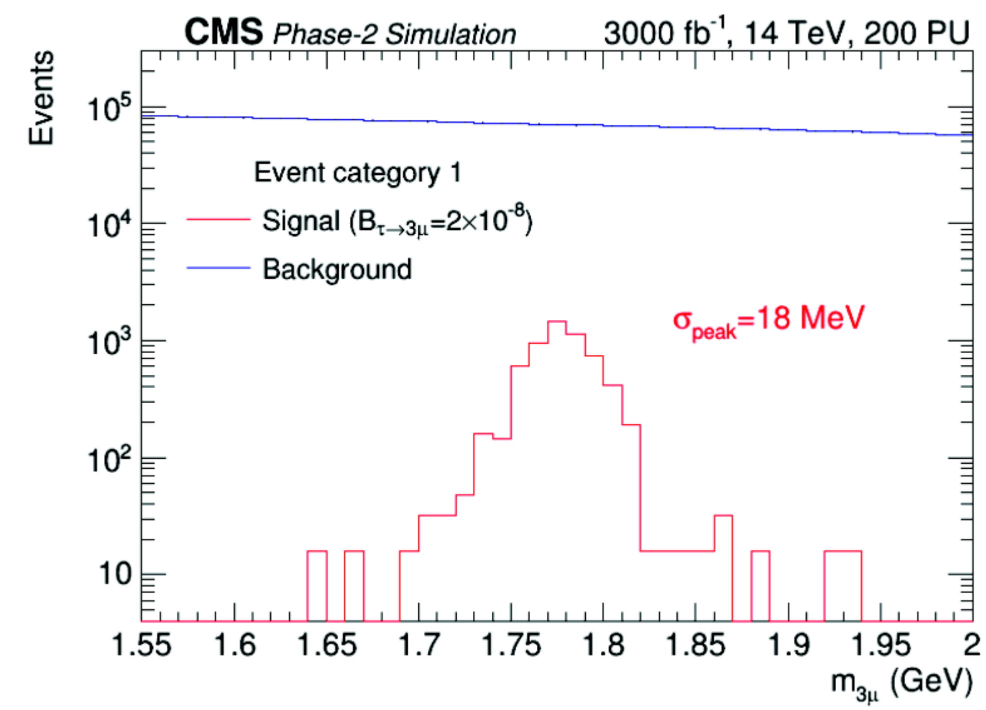
Future prospects using D & B decays (3 ab^{-1} at 14 TeV) :



ATL-PHYS-PUB-2018-032

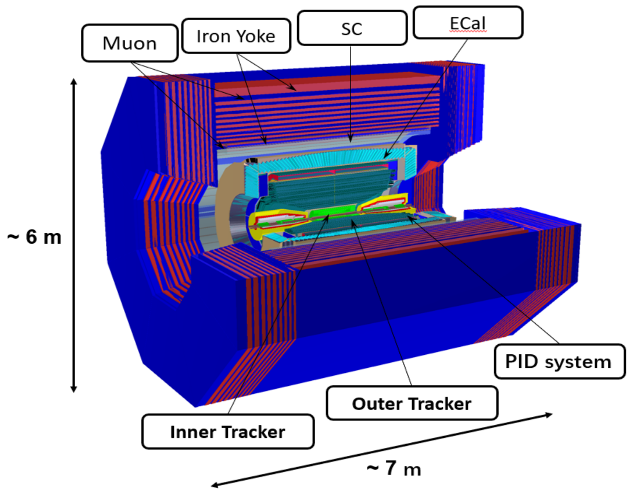


CMS-TDR-016

Scenario	$\mathcal{A} \times \epsilon$ [%]	$N_{\text{bkg}}^{\text{exp}}$	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}	

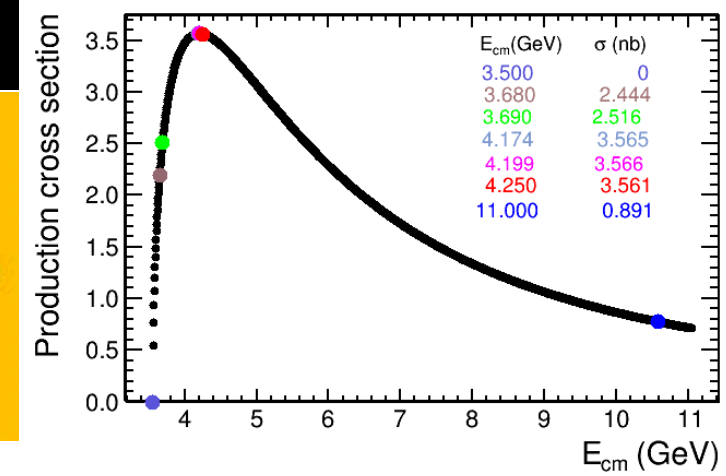
Super Tau-Charm Facility



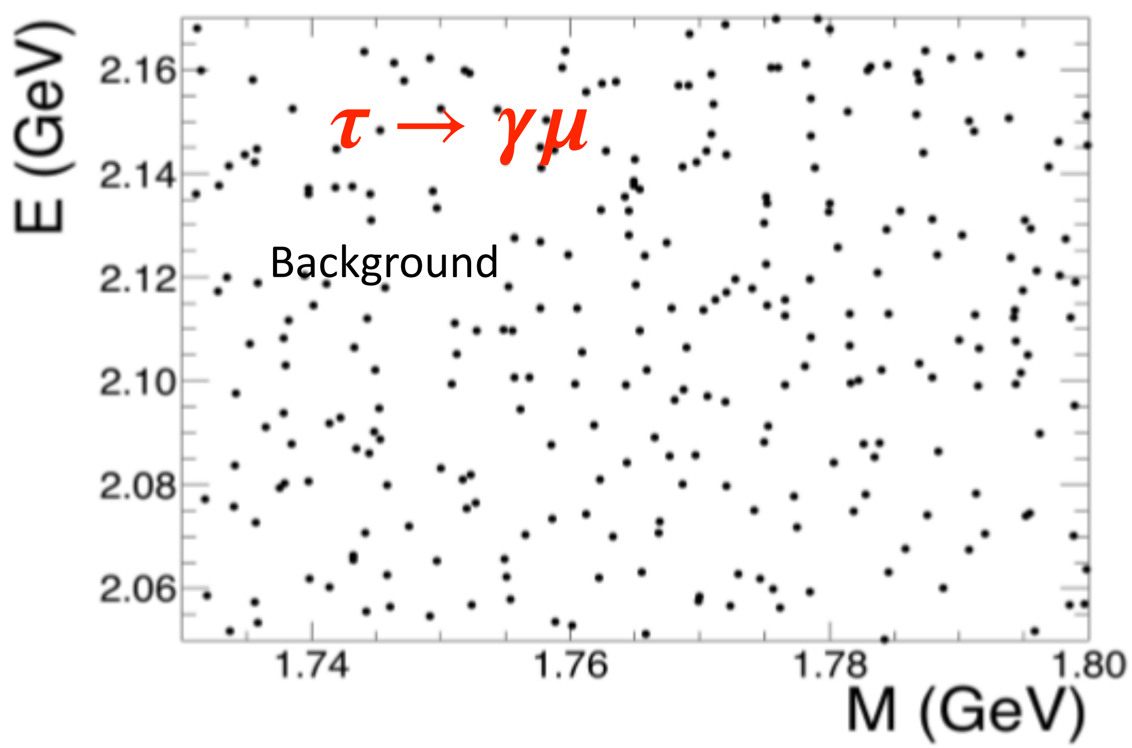
"Physics Potential of a Super tau-Charm Facility" (RF/SNOWMASS21-RF7_RF1_STCF-013.pdf)

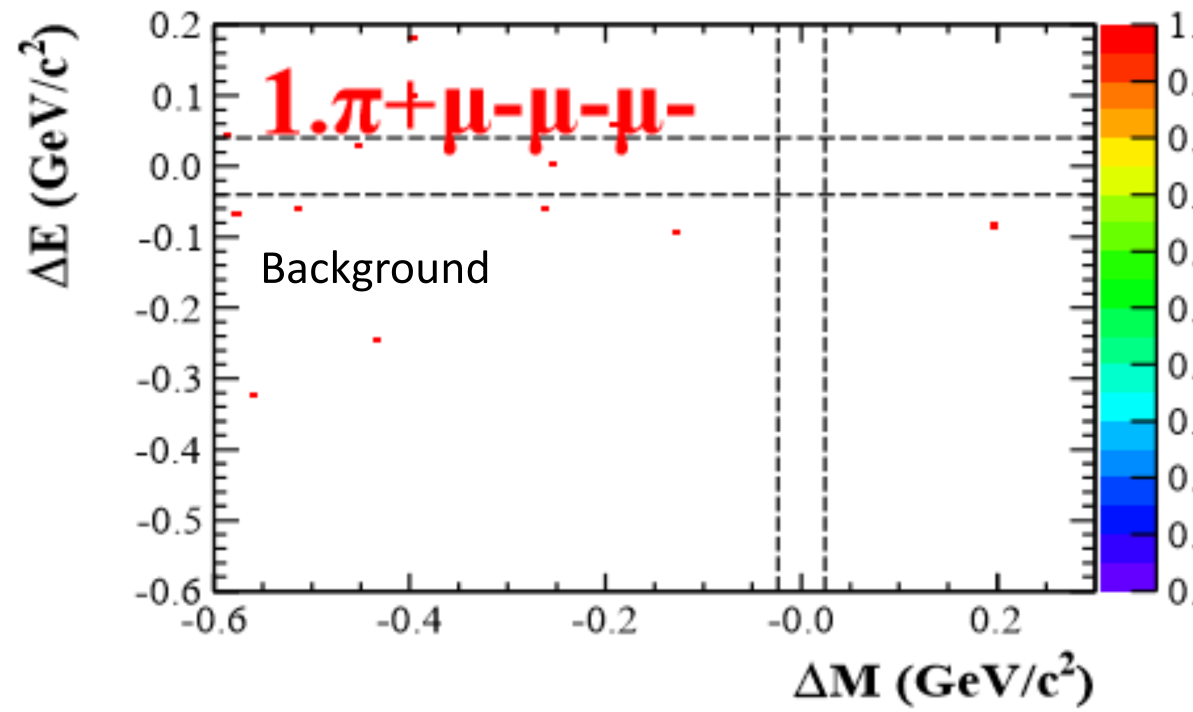
- Peaking luminosity $>0.5\times10^{35}$ cm^{-2}s^{-1} at 4 GeV
- Energy range E_{cm} = 2-7 GeV
- Potential to increase luminosity and realize beam polarization
- A nature extension and a viable option for China accelerator project in the post BEPCII/BESIII era

X. Zhou



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}





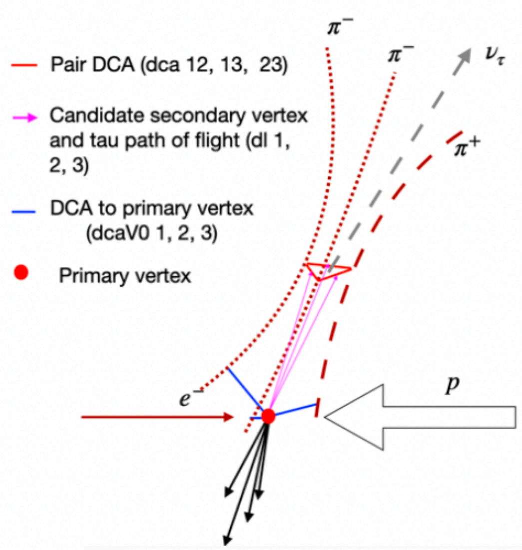
➢ STCF with 1ab^{-1}:

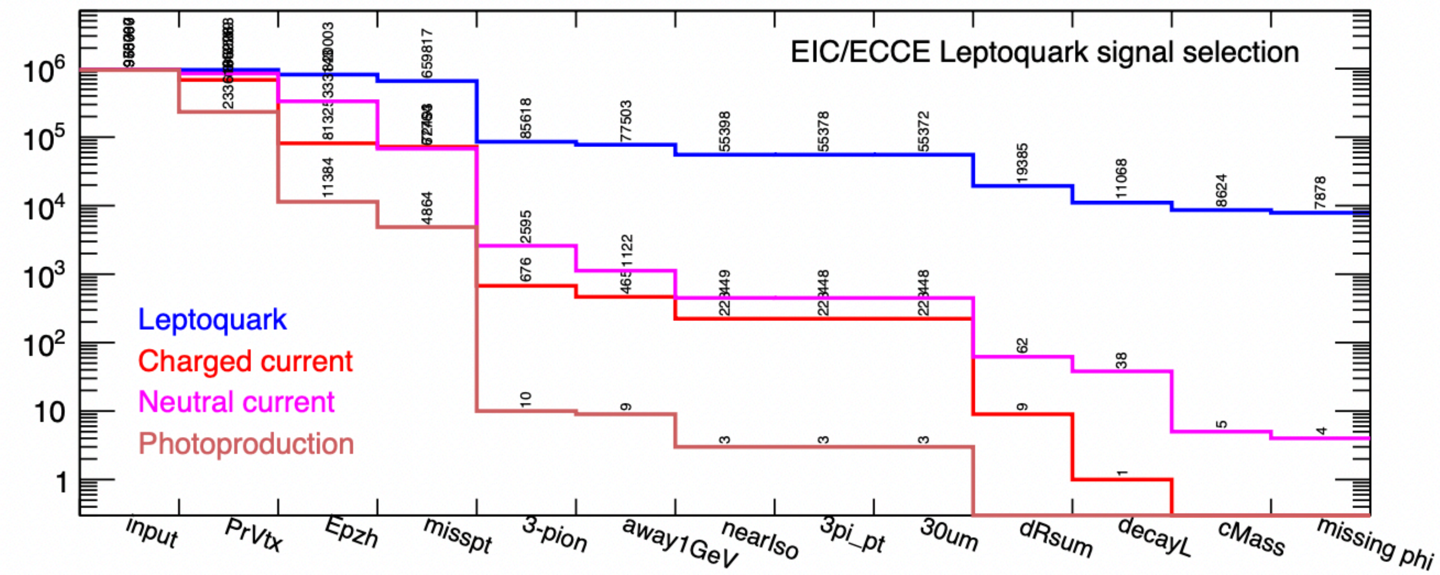
$$\mathscr{B}^{90}_{UL}(\tau\to\gamma\mu) < \frac{N^{90}_{UL}}{2\varepsilon N_{\tau\tau}} \sim 1.2\times10^{-8}$$

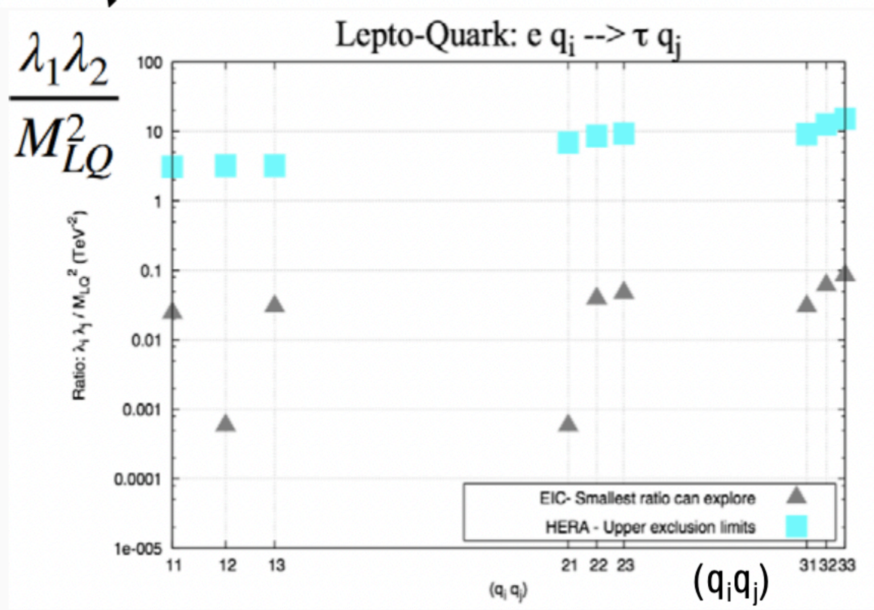
➢ STCF with 1ab^{-1}:

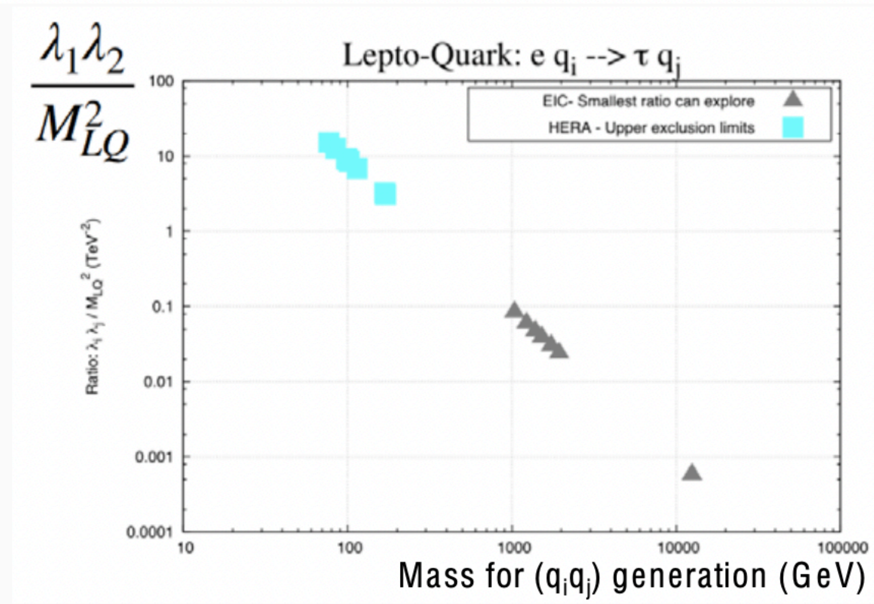
$$\mathscr{B}^{90}_{UL}(\tau\to\mu\mu\mu) < \frac{N^{90}_{UL}}{2\varepsilon N_{\tau\tau}} \sim 1.4\times10^{-9}$$

$\sqrt{s}$ between 20 GeV (5 GeV electron on 41 GeV protons) and 140 GeV (18 GeV electron on 275 GeV protons)









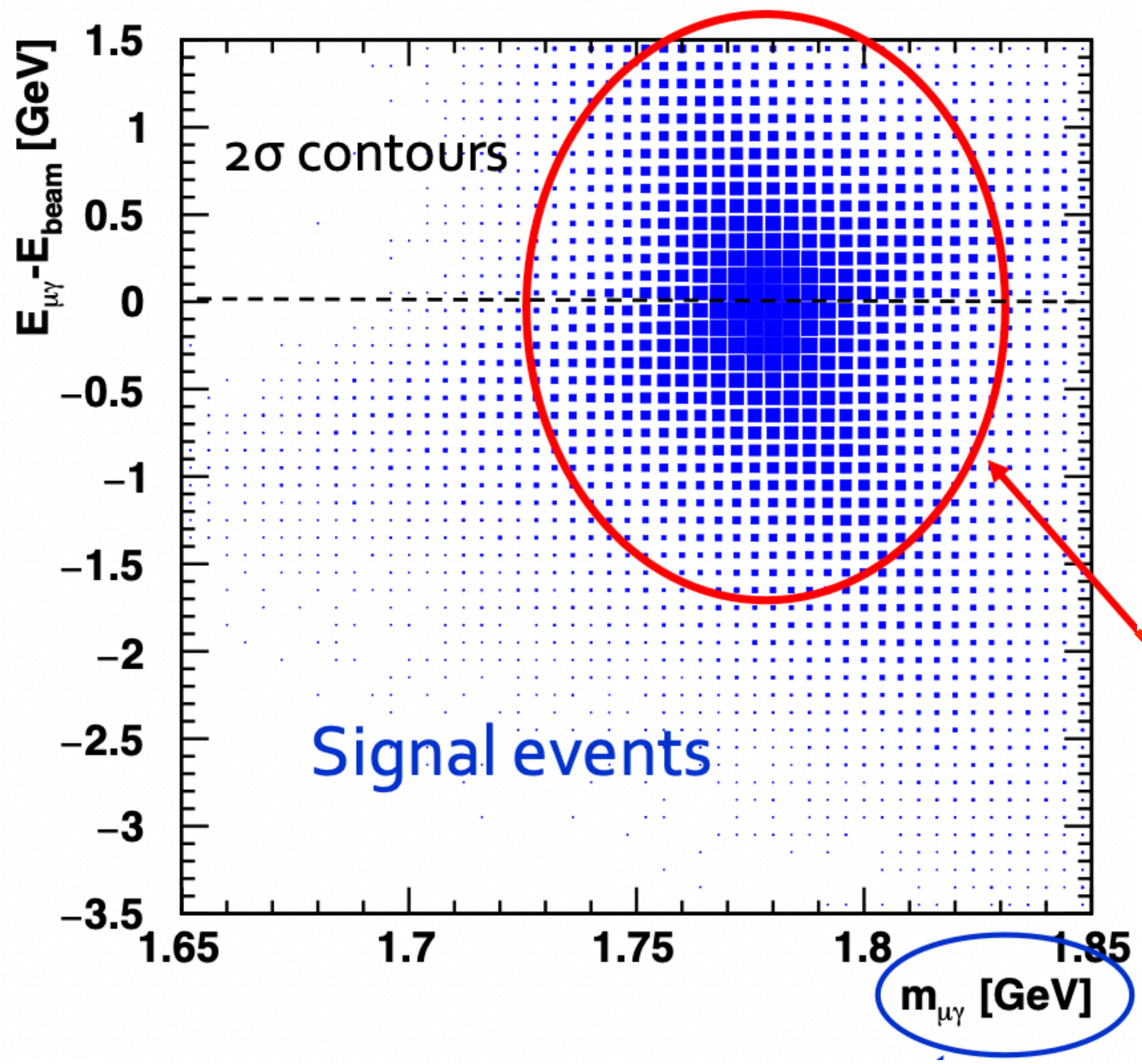
Deshpande, Huang, Kumar Zhang, Zhao

Potential to improve current sensitivity by two orders of magnitude

FCC-ee

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

M. Dams



- **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]
  $\sigma(p_T)/p_T = 2\text{x}10^{-5} \text{x}\ p_T \oplus 1\text{x}10^{-3}$
- 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

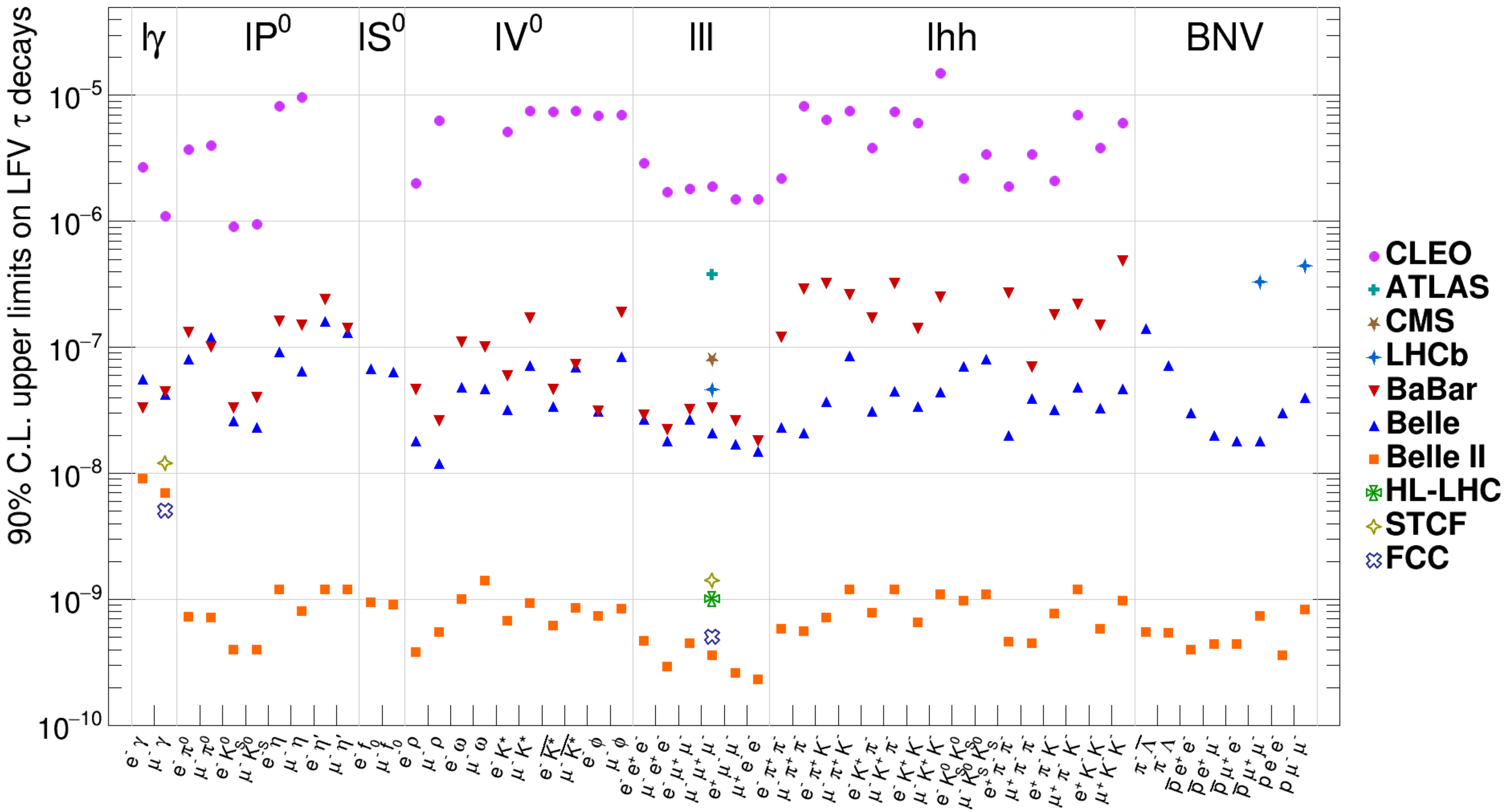
$\sigma(m_{\gamma\mu})$ = 26 MeV; $\sigma(E_{\gamma\mu})$ = 850 MeV

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

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

- 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



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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.

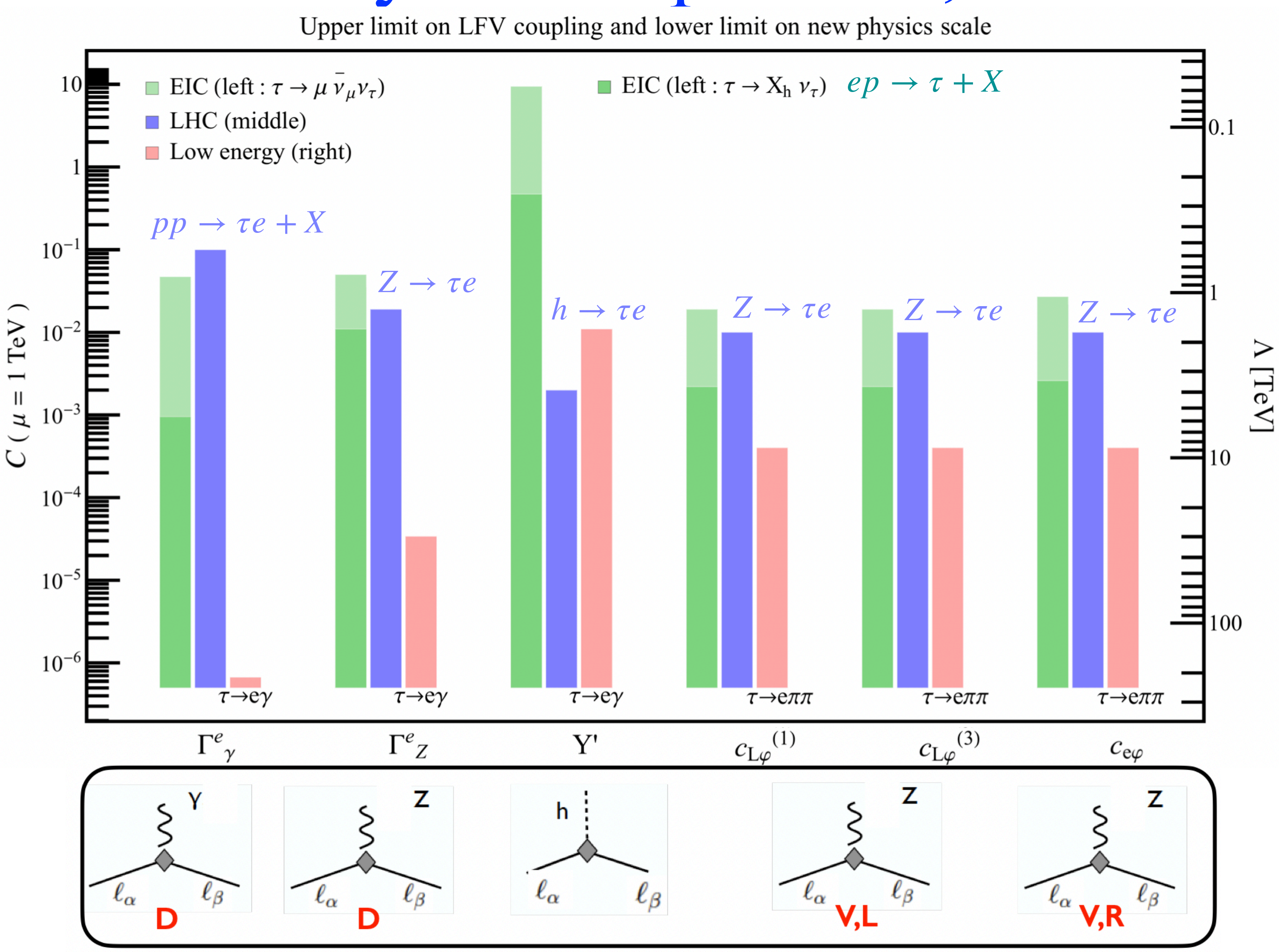
2203.14919 [hep-ph]

Global fit: $\tau \rightarrow e$ 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.



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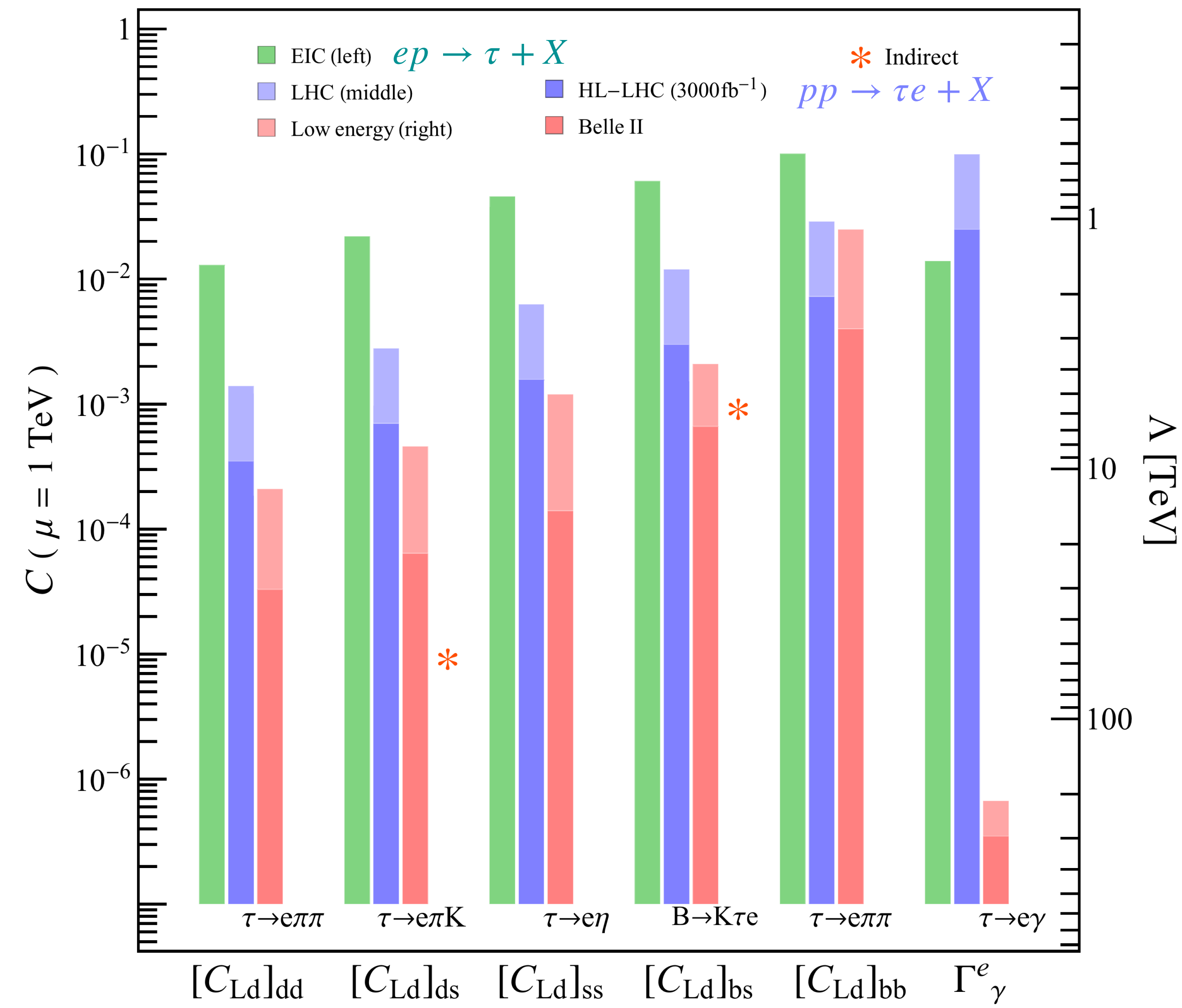

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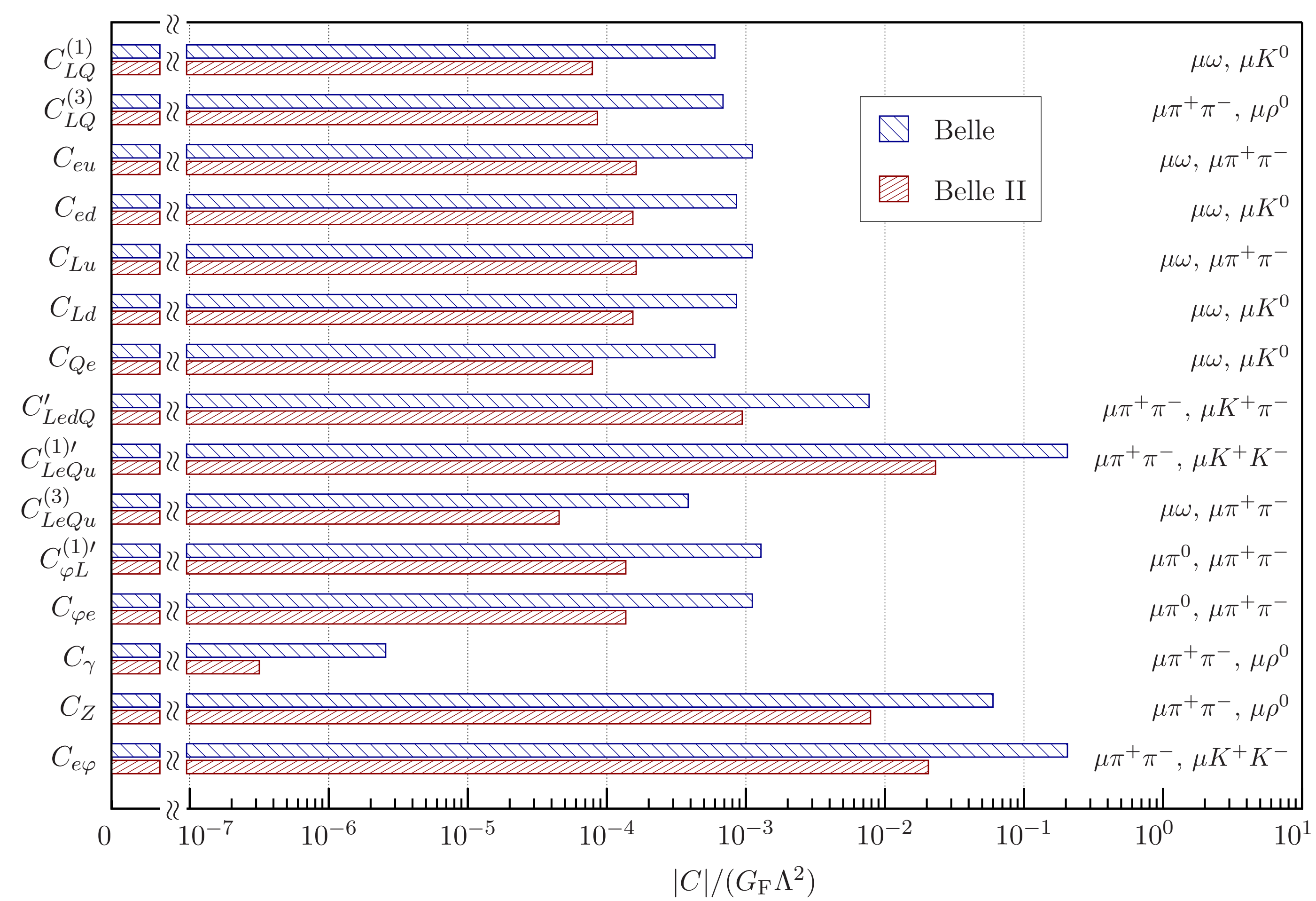
Global fit: $\tau \to \mu$ decays and transitions with τ in the final state

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
$C_{LQ}^{(1)}$	$(\bar{L}_p\gamma_\mu L_r)(\bar{Q}_s\gamma^\mu Q_t)$	$C_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{L}_p e_r\varphi)$
$C_{LQ}^{(3)}$	$(\bar{L}_p\gamma_\mu\sigma^I L_r)(\bar{Q}_s\gamma^\mu\sigma^I Q_t)$	$C_{\varphi e}$	$\left(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi\right)(e_p\gamma^\mu e_r)$
C_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	$C_{\varphi L}^{(1)}$	$\left(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi\right)(\bar{L}_p\gamma^\mu L_r)$
C_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$C_{\varphi L}^{(3)}$	$\left(\varphi^\dagger i\overleftrightarrow{D}_{I\mu}\varphi\right)(\bar{L}_p\sigma_I\gamma^\mu L_r)$
C_{Lu}	$(\bar{L}_p\gamma_\mu L_r)(\bar{u}_s\gamma^\mu u_t)$	C_{eW}	$(\bar{L}_p\sigma^{\mu\nu}e_r)\,\sigma_I\varphi W_{\mu\nu}^I$
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}	$(\bar{L}_p^j e_r)(\bar{d}_s Q_t^j)$		
$C_{LeQu}^{(1)}$	$(\bar{L}_p^j e_r)\,\varepsilon_{jk}\,(\bar{Q}_s^k u_t)$		
$C_{LeQu}^{(3)}$	$(\bar{L}_p^j\sigma_{\mu\nu}e_r)\,\varepsilon_{jk}\,(\bar{Q}_s^k\sigma^{\mu\nu}u_t)$		



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Summary and outlook

	Observed Limits			Expected Limits		
$\tau^- \to$	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.**