Institute for Research in Fundamental Sciences

XVth INTERNATIONAL CONFERENCE ON HEAVY QUARKS AND LEPTONS

HQL2021

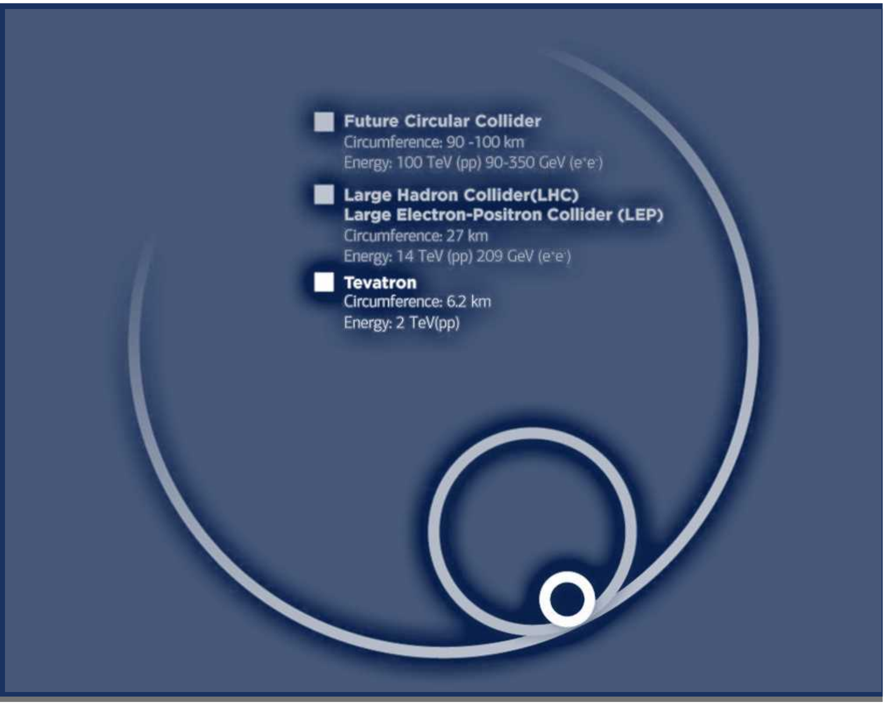
Searching For Lepton Flavor Violating Interactions At Future Electron-positron Colliders

arXiv:2107.00545

Presented by:
Seddigheh Tizchang

In Collaboration with:
S. M. Etesami, R. Jafari M. Mohammadi Najafabadi

School of Particles and Accelerators, IPM



*seddigheh.tizchang@cern.ch

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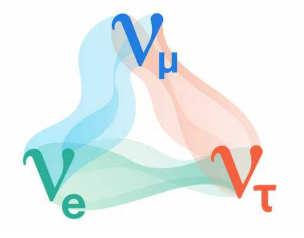
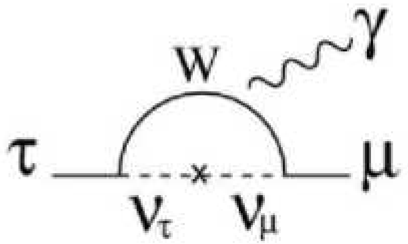
MOTIVATION

- **Lepton Flavor is an exact symmetry, as soon as neutrino are massless**



- **Neutrino oscillations have been observed → Neutrinos are massive.**
- **This leads to LFV.**

But ... $\mathrm{BR}(\mu \to e\gamma) \sim \left(\frac{\delta m_\nu^2}{m_W^2}\right)^2 < 10^{-54}$

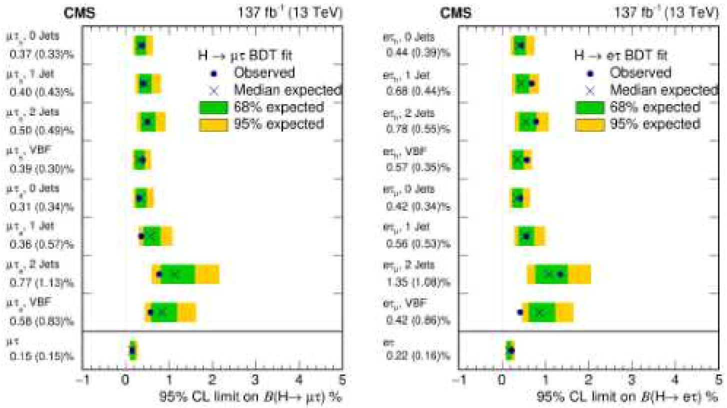


- **An increase of several orders of magnitude is predicted in some SM extensions.**

Any detection of LFV signal Clear evidence for BSM

Experimental search for LFV

Phys. Rev. D 104 (2021) 032013



Map taken from Avelino Vicente slides

arXiv:2105.12491v1

Final state, polarization assumption	Observed (expected) upper limit on $\mathcal{B}(Z \to \ell\tau)$ [$\times 10^{-6}$] $e\tau$	$\mu\tau$
$\ell\tau_{had}$ Run 1 + Run 2, unpolarized τ	8.1 (8.1)	9.5 (6.1)
$\ell\tau_{had}$ Run 2, left-handed τ	8.2 (8.6)	9.5 (6.7)
$\ell\tau_{had}$ Run 2, right-handed τ	7.8 (7.6)	10 (5.8)
$\ell\tau_{\ell'}$ Run 2, unpolarized τ	7.0 (8.9)	7.2 (10)
$\ell\tau_{\ell'}$ Run 2, left-handed τ	5.9 (7.5)	5.7 (8.5)
$\ell\tau_{\ell'}$ Run 2, right-handed τ	8.4 (11)	9.2 (13)
Combined $\ell\tau$ Run 1 + Run 2, unpolarized τ	5.0 (6.0)	6.5 (5.3)
Combined $\ell\tau$ Run 2, left-handed τ	4.5 (5.7)	5.6 (5.3)
Combined $\ell\tau$ Run 2, right-handed τ	5.4 (6.2)	7.7 (5.3)

JHEP 01 (2021) 163

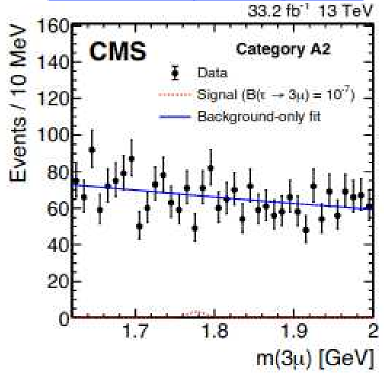
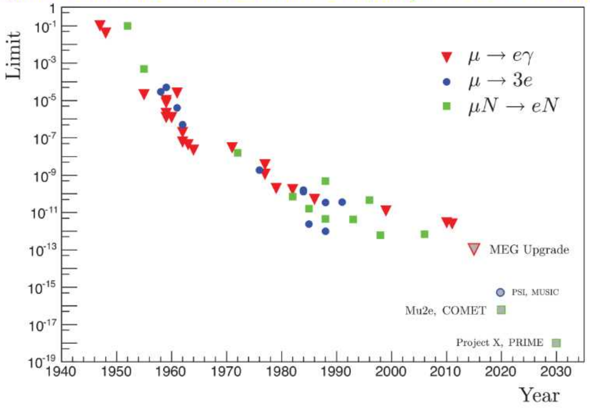
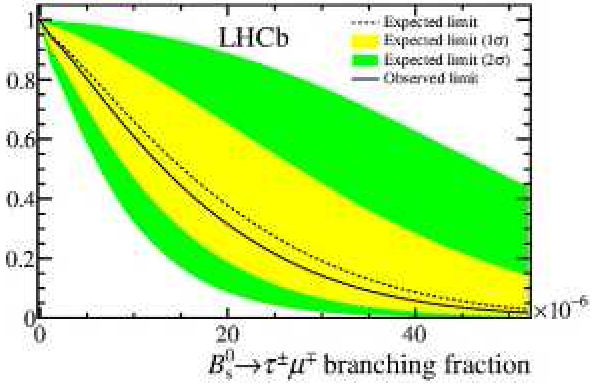


Figure taken from Bernstein & Cooper [arXiv:1307.5787]



Phys.Rev.Lett. 123 (2019) 211801



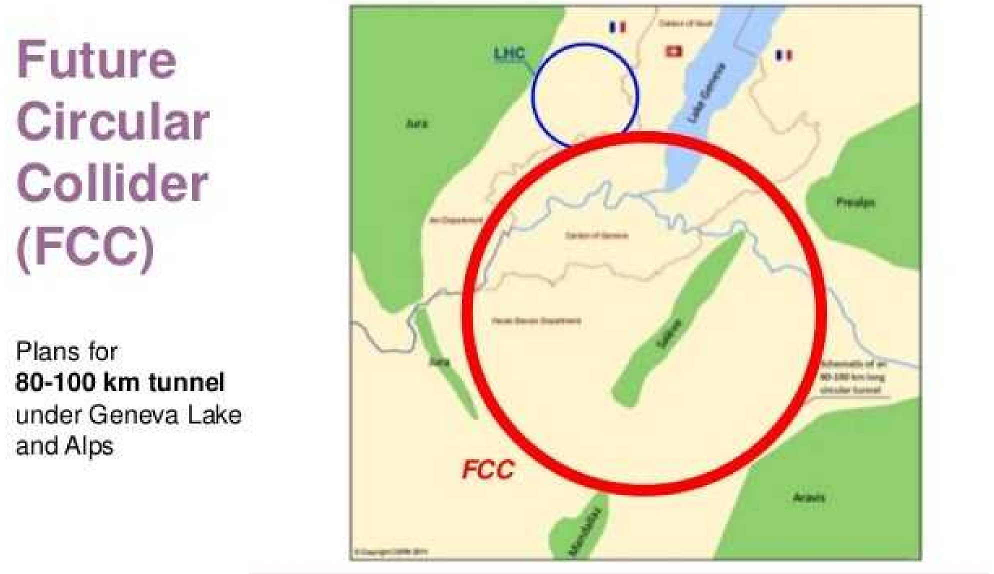
ArXiv:1808.10567

$$\mathcal{B}(\tau^- \to e^- e^+ e^-) \leq 2.9 \times 10^{-8} \text{ (BaBar)}$$

$$\mathcal{B}(\tau^- \to e^- e^+ e^-) \leq 2.7 \times 10^{-8} \text{ (Belle)}$$

Experiment	Observed (Expected) upper limit on B($\tau \to 3\mu$) (x 10^8 at 90% C.L.)
Belle	2.1 (-)
BaBar	3.3 (4.0)
LHCb (Run I data)	4.6 (5.0)
ATLAS (Run I data)	38 (39) Eur. Phys. J. C 76 (2016) 232
CMS	8.0(6.9)

FCC-ee collider



- FCC-ee is designed to provide e+e- collisions in the beam energy range of 45 to 185 GeV.
- Instantaneous luminosity expected at FCC-ee, in a configuration with four interaction points operating simultaneously, as a function of the center-of-mass energy.

C.M. Energy (GeV)	365	240	162.5	157.5
$IL\,ab^{-1}$	1.5	5	5	5

Future lepton colliders are expected to provide a new place in flavor physics.

THEORETICAL FRAMEWORK

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Historic example: 4-fermion vertex (dim-6), Weak Interactions

$\Lambda = M_W$

$\propto \frac{g^2}{8}\frac{1}{q^2 - M_W^2}$ $\xrightarrow{q^2 << M_W^2}$

$\propto \frac{g^2}{8}\frac{1}{M_W^2} = \frac{G_F}{\sqrt{2}}$

$$\mathcal{L}_{\rm eff} \supset \sum_{\alpha,\beta}\sum_{ij}\frac{c^{ij}_{\alpha\beta}}{\Lambda^2}\mathcal{O}^{ij}_{\alpha\beta},$$

$$\mathcal{O}^{S,ij}_{RL} = (\bar{\ell}_{jL}\ell_{iR})(\bar{\ell}_{jL}\ell_{jR}), \qquad \mathcal{O}^{S,ij}_{LR} = (\bar{\ell}_{iR}\ell_{jL})(\bar{\ell}_{jR}\ell_{jL}),$$

$$\mathcal{O}^{V,ij}_{RR} = (\bar{\ell}_{iR}\gamma^\mu\ell_{jR})(\bar{\ell}_{jR}\gamma_\mu\ell_{jR}), \qquad \mathcal{O}^{V,ij}_{LL} = (\bar{\ell}_{iL}\gamma^\mu\ell_{jL})(\bar{\ell}_{V,jL}\gamma_\mu\ell_{jL}),$$

$$\mathcal{O}^{V,ij}_{LR} = (\bar{\ell}_{iL}\gamma^\mu\ell_{jL}),(\bar{\ell}_{jR}\gamma_\mu\ell_{jR}), \qquad \mathcal{O}^{V,ij}_{RL} = (\bar{\ell}_{iR}\gamma^\mu\ell_{jR})(\bar{\ell}_{iL}\gamma_\mu\ell_{iL}),$$

- **Λ : the energy scale of new physics**
- **Constraints on LFVs between e and τ, and μ and τ are much looser ⇒ eeeτ couplings**

THEORETICAL FRAMEWORK

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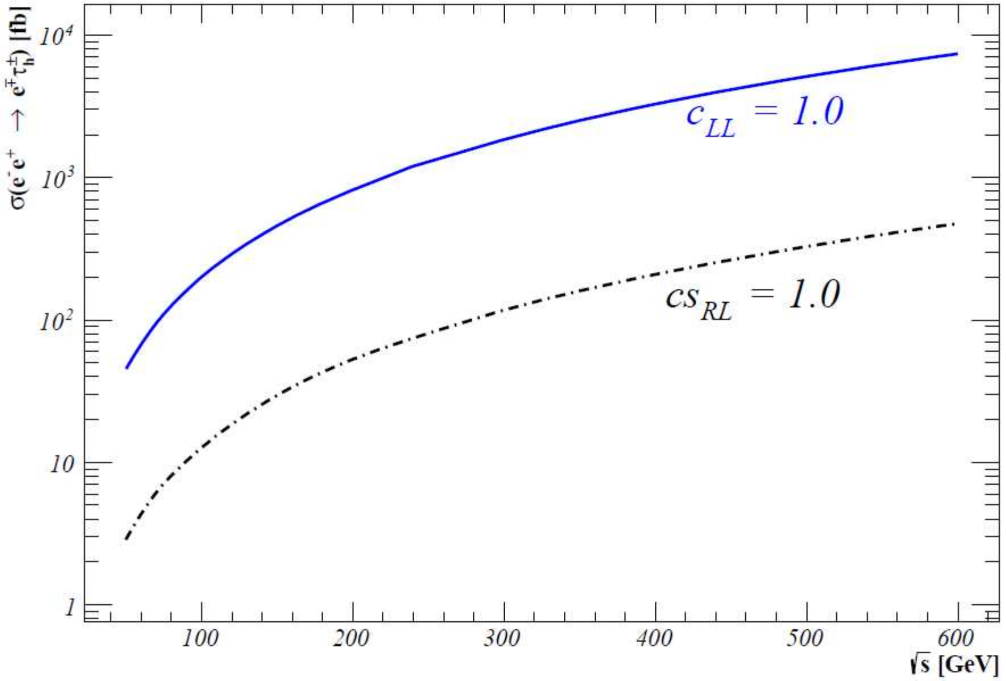
- **The theoretical cross section of $e^-e^+ \to e^\pm\tau^\mp$:**

[arXiv: 0611222]

$$\sigma(s) = \frac{s}{96\pi\Lambda^4}\left\{(|c^S_{LR}|^2 + |c^S_{RL}|^2) + 16(|c^V_{LL}|^2 + |c^V_{RR}|^2 + |c^V_{LR}|^2 + |c^V_{RL}|^2)\right\}$$

- $$\sigma(e^-e^+ \to e\tau) \propto s$$



- **Vector type operators are larger than the scalar type ones by a factor of 16 .**

DATA SIMULATION

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Effective Lagrangian → **FeynRule program** → **Universal FeynRules Output (UFO)** → **MADGRAPH5_aMC@NLO** → **PYTHIA 8 (showering)** → **DELPHES 3 (ILD-like)**

- **Six different signal samples Six operators**
- **Tau-lepton hadronic decay.**
- **Wilson coefficients $c_{i,j}$ =0.1, with i, j = L,R, and Λ = 1 TeV.**

Background processes:

$$
\begin{array}{ll}
\text{(I)} & e^-e^+ \to e^\pm\tau^\mp\nu\bar{\nu}, \\
\text{(II)} & e^-e^+ \to \tau^+\tau^-, \\
\text{(III)} & e^-e^+ \to \ell^\pm\ell^\mp\ell'^\pm\ell'^\mp \; (\ell,\ell' = e,\mu,\tau), \\
\text{(IV)} & e^-e^+ \to \ell^\pm\ell^\mp jj \; (\ell = e,\mu,\tau), \\
\text{(V)} & e^-e^+ \to \ell^\pm\nu jj(\ell = e,\mu,\tau), \\
\text{(VI)} & e^-e^+ \to jj.
\end{array}
$$

ANALYSIS STRATEGY

Event selection:

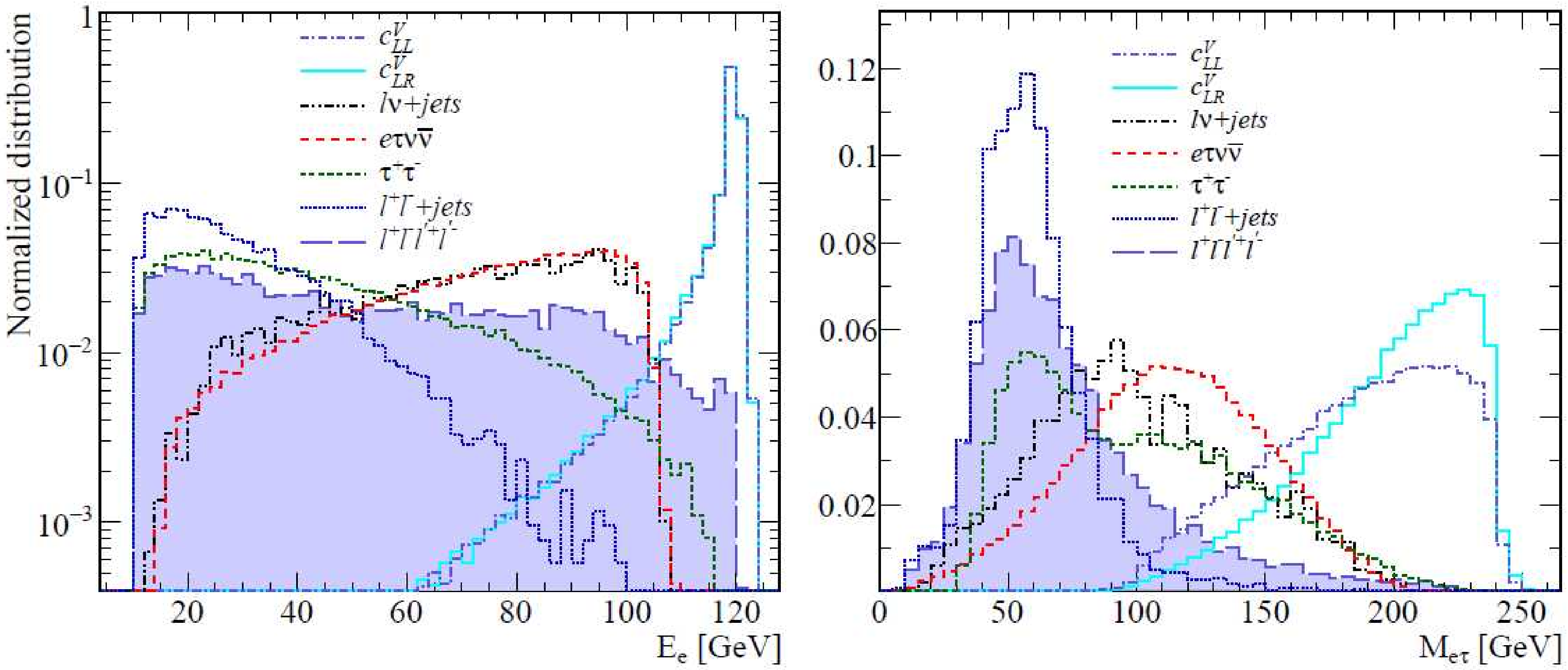
- Exactly 1 tau-tagged jet (Hadronic decay)
- Exactly 1 electron (positron)
- Opposite sign leptons

- $P_T > 20$ GeV for tau
- $P_T > 10$ GeV for electron (positron)
- $|\eta| \leq 2.5$ for all objects
- $\Delta R > 0.5$ GeV for all objects

- RelIso < 0.15; The ratio of the sum of P_T of charged particle tracks inside a cone of size 0.5 around the electron track to P_T of the electron.

ANALYSIS STRATEGY

- **To enhance the sensitivity, we apply additional cuts on (for $\sqrt{s}$ =240 GeV):**



EFFICIENCY

$\sqrt{s} = 157.5$ GeV	Signal $c_{LR}^V = 0.1$	Signal $c_{LR}^S = 0.1$	SM Backgrounds $e\tau\nu\bar{\nu}$	$\tau\bar{\tau}$	$\ell\ell\ell'\ell'$	$\ell\ell jj$	$\ell\nu jj$
(I): Pre-selection cuts	0.1746	0.1698	0.099	0.045	4.9×10^{-3}	1.4×10^{-3}	3.3×10^{-4}
(II): $M_{e\tau} > 65$ GeV	0.1741	0.1697	0.038	0.019	2.2×10^{-3}	1.8×10^{-4}	7.5×10^{-5}
(III): $E_e > 78.6$ GeV	0.0984	0.0831	2.8×10^{-8}	1.5×10^{-7}	6.02×10^{-6}	1.7×10^{-7}	0.0
$\sqrt{s} = 162.5$ GeV	$c_{LR}^V = 0.1$	$c_{LR}^S = 0.1$	$e\tau\nu\bar{\nu}$	$\tau\bar{\tau}$	$\ell\ell\ell'\ell'$	$\ell\ell jj$	$\ell\nu jj$
(I): Pre-selection cuts	0.1727	0.1711	0.106	0.048	4.9×10^{-3}	1.6×10^{-3}	4.5×10^{-4}
(II): $M_{e\tau} > 65$ GeV	0.1727	0.1710	0.041	0.025	2.4×10^{-3}	2.1×10^{-4}	1.0×10^{-4}
(III): $E_e > 81$ GeV	0.1122	0.0949	6×10^{-8}	2.0×10^{-7}	3.61×10^{-6}	2.1×10^{-7}	0.0
$\sqrt{s} = 240$ GeV	$c_{LR}^V = 0.1$	$c_{LR}^S = 0.1$	$e\tau\nu\bar{\nu}$	$\tau\bar{\tau}$	$\ell\ell\ell'\ell'$	$\ell\ell jj$	$\ell\nu jj$
(I): Pre-selection cuts	0.2156	0.2137	0.131	0.037	8.8×10^{-3}	6.2×10^{-3}	4.9×10^{-4}
(II): $M_{e\tau} > 100$ GeV	0.2150	0.2134	0.084	0.017	1.6×10^{-3}	2.4×10^{-4}	2.0×10^{-4}
(III): $E_e > 119.7$ GeV	0.1072	0.0989	2.1×10^{-8}	1.5×10^{-7}	1.2×10^{-5}	2.4×10^{-7}	0.0
$\sqrt{s} = 365$ GeV	$c_{LR}^V = 0.1$	$c_{LR}^S = 0.1$	$e\tau\nu\bar{\nu}$	$\tau\bar{\tau}$	$\ell\ell\ell'\ell'$	$\ell\ell jj$	$\ell\nu jj$
(I): Pre-selection cuts	0.2093	0.2097	0.133	0.066	0.012	6.0×10^{-3}	5.0×10^{-4}
(II): $M_{e\tau} > 150$ GeV	0.2053	0.2051	0.093	0.041	2.0×10^{-3}	1.5×10^{-4}	2.4×10^{-4}
(III): $E_e > 182$ GeV	0.0993	0.0986	2.6×10^{-8}	3.2×10^{-7}	2.6×10^{-5}	1.4×10^{-7}	0.0

RESULTS & DISCUSSION

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- **In order to achieve better sensitivity, the results from four energy benchmarks are combined.**
- **Comparison to the Belle-II experiment with 50 ab^{-1} data** [arXiv:1803.10475]
- **Comparison to a study at TeV with beam polarization:**

$\sqrt{s}$ (GeV) , $\mathcal{L}$ (ab^{-1})	$\frac{c^V_{LL}}{\Lambda^2}[\times 10^{-9}]$(GeV^{-2})	$\frac{c^V_{RR}}{\Lambda^2}[\times 10^{-9}]$(GeV^{-2})	$\frac{c^V_{RL}}{\Lambda^2}[\times 10^{-9}]$(GeV^{-2})	$\frac{c^V_{LR}}{\Lambda^2}[\times 10^{-9}]$(GeV^{-2})	$\frac{c^S_{RL}}{\Lambda^2}[\times 10^{-9}]$(GeV^{-2})	$\frac{c^S_{LR}}{\Lambda^2}[\times 10^{-9}]$(GeV^{-2})
157.5 , 5	5.82	5.46	5.74	5.36	21.18	22.61
162.5 , 5	5.71	5.36	5.62	5.29	21.42	23.12
240 , 5	3.69	3.50	3.73	3.53	14.81	14.74
365 , 1.5	3.93	3.94	3.92	3.93	15.80	15.80
Combination	1.32	1.25	1.32	1.25	5.1	5.3
Belle II	1.06	1.06	1.55	1.55	4.29	4.29
$\sqrt{s} = 1$ TeV, pol. beam	4.3	1.1	1.6	1.8	13	5.9

RESULTS & DISCUSSION

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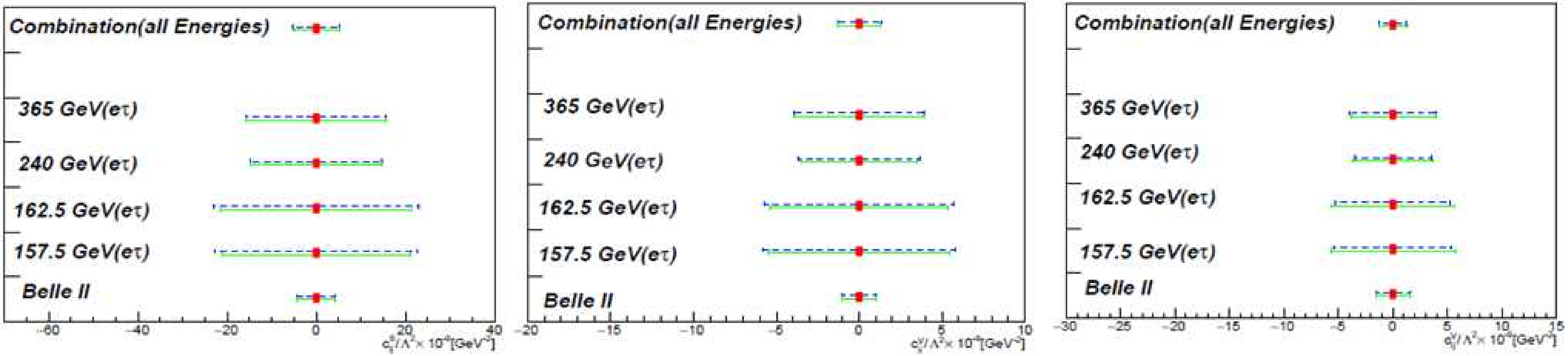
RESULTS & DISCUSSION



CONCLUSION

- LFV processes are absent in the SM but appear in some extensions of the SM.
- The sensitivity of the FCC-ee, to the LFV couplings is examined using $e\tau$ production.
- Effective Lagrangian: four Fermi contact interactions with vector and scalar types
- The events are generated using MadGraph5 considering ISR effect and passed through PYTHIA8 and Delphes using the ILD detector card.
- The hadronic tau decay channel and the main sources of background are considered.
- Cuts on E_e and $M_{e\tau}$ are applied to suppress the background contributions.
- Limits at 95% CL on the LFV couplings have been obtained for the four center-of-mass energies of the FCC-ee. Finally, a statistical combination of results is performed.
- We show that the statistical combination increases the sensitivity to the LFV couplings significantly with respect to the individual energies.

THANKS FOR YOUR ATTENTION!