The 16th International Workshop on Tau Lepton Physics (TAU2021)

Institute for Research in Fundamental Sciences

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

arXiv:2107.00545

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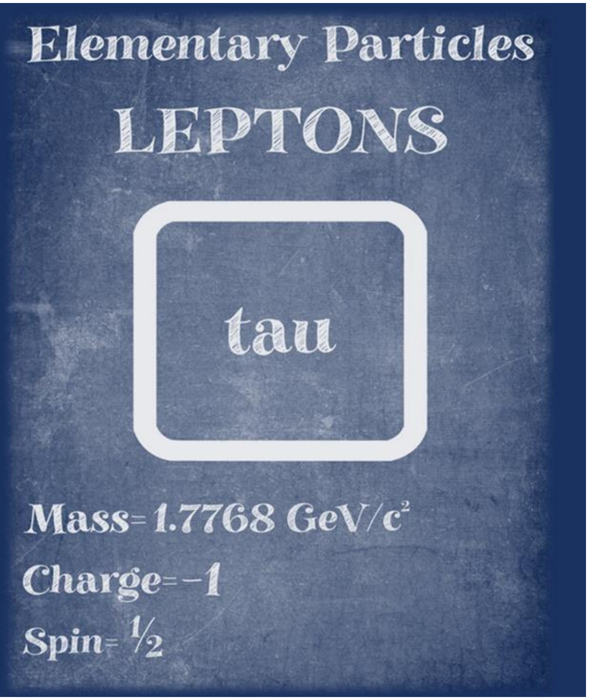
1 Oct. 2021



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MOTIVATION & INTRODUCTION

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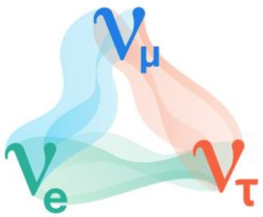
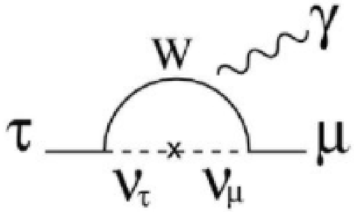
- In the SM neutrinos are massless → LFV interactions are forbidden.
- Neutrino oscillations have been observed Neutrinos are massive.
- This leads to LFV. But …





$$BR(\tau^- \to \ell^+\ell^-\ell'^-) \lesssim 10^{-54}$$

[arXiv:1912.09862]

- An increase of several orders of magnitude is predicted in some SM extensions. [arXiv:0406039]

Any detection of LFV signal → Clear evidence for BSM

- So far, no cLFV has been observed and there are several strong constraints from various experiments.

$$\mathcal{B}(\tau^- \to e^-e^+e^-) \leq 2.9 \times 10^{-8} \text{ (BaBar)}$$
$$\mathcal{B}(\tau^- \to e^-e^+e^-) \leq 2.7 \times 10^{-8} \text{ (Belle)}$$

- The Belle II prospect at 90% CL with 50 ab^{-1} :

$$\mathcal{B}(\tau^- \to e^-e^+e^-) \lesssim 10^{-10}$$

arXiv:1808.10567

THEORETICAL FRAMEWORK

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If the new degrees of freedom contributing to LFV are heavy enough, the LFV couplings could be reasonably parameterized via the effective contact interactions.

- **The effective Lagrangian and the relevant operators:** [arXiv:9909265]

Six chirality conserving operators

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

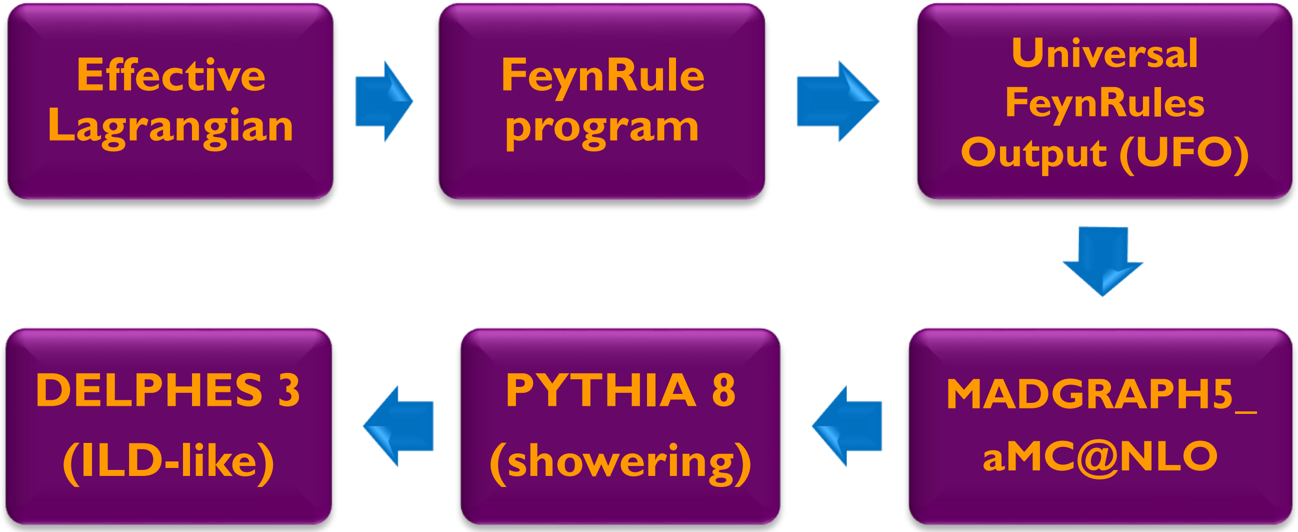
Four Fermi contact interactions (eeeτ)

$$\begin{aligned}
\mathcal{O}^{S,ij}_{RL} &= (\bar\ell_{jL}\ell_{iR})\,(\bar\ell_{jL}\ell_{jR})\,, & \mathcal{O}^{S,ij}_{LR} &= (\bar\ell_{iR}\ell_{jL})\,(\bar\ell_{jR}\ell_{jL})\,,\\
\mathcal{O}^{V,ij}_{RR} &= (\bar\ell_{iR}\gamma^\mu\ell_{jR})\,(\bar\ell_{jR}\gamma_\mu\ell_{jR})\,, & \mathcal{O}^{V,ij}_{LL} &= (\bar\ell_{iL}\gamma^\mu\ell_{jL})\,(\bar\ell_{V,jL}\gamma_\mu\ell_{jL})\,,\\
\mathcal{O}^{V,ij}_{LR} &= (\bar\ell_{iL}\gamma^\mu\ell_{jL})\,,(\bar\ell_{jR}\gamma_\mu\ell_{jR})\,, & \mathcal{O}^{V,ij}_{RL} &= (\bar\ell_{iR}\gamma^\mu\ell_{jR})\,(\bar\ell_{iL}\gamma_\mu\ell_{iL})\,,
\end{aligned}$$

Scalar type

Vector type

DATA SIMULATION



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

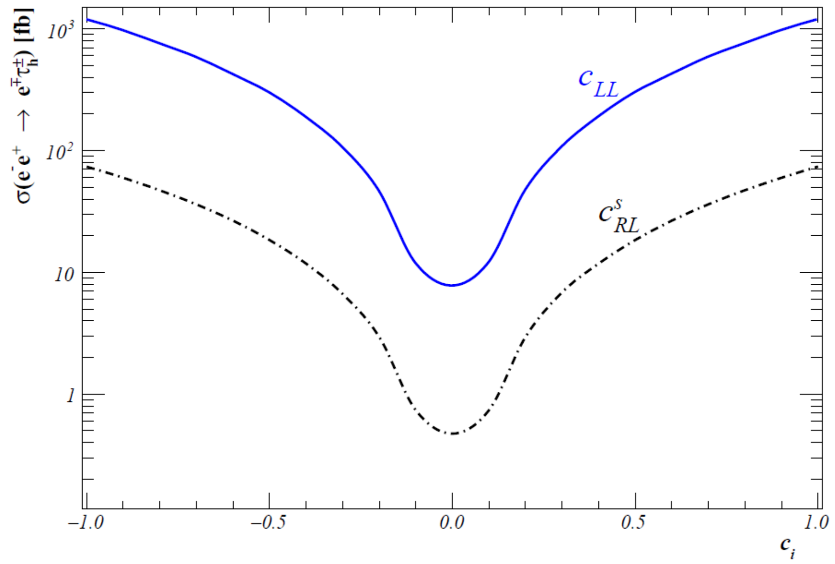
[arXiv: 0611222]

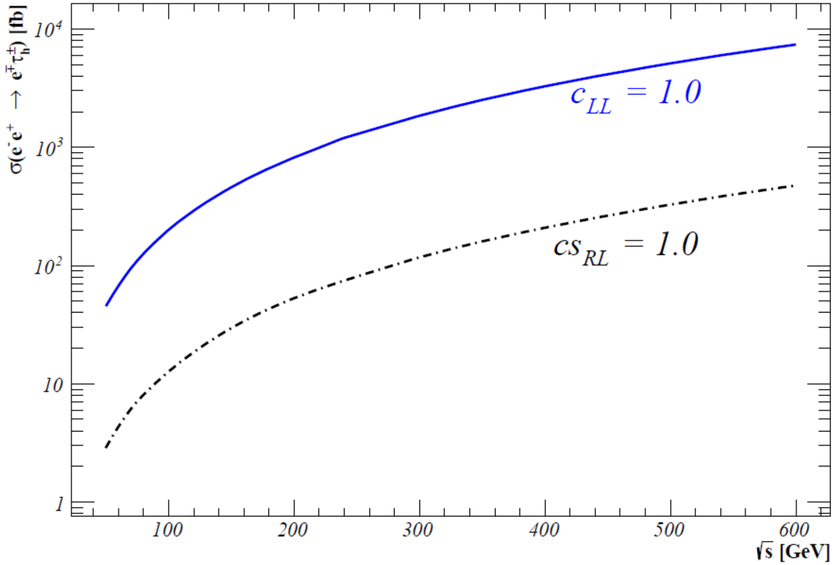
$$\sigma(s) = \frac{s}{96\pi\Lambda^4}\left\{(|c^S_{LR}|^2 + |c^S_{RL}|^2) + 16(|c^V_{LL}|^2 + |c^V_{RR}|^2 + |c^V_{LR}|^2 + |c^V_{RL}|^2)\right\}$$

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

- **ISR effects are considered using the MGISR plugin**

[arXiv:1705.04486]
[arXiv:1804.00125]





ANALYSIS STRATEGY

- Four FCC-ee benchmarks

C.M. Energy (GeV)	365	240	162.5	157.5
Integrated luminosity (ab^{-1})	1.5	5	5	5

Event selection:

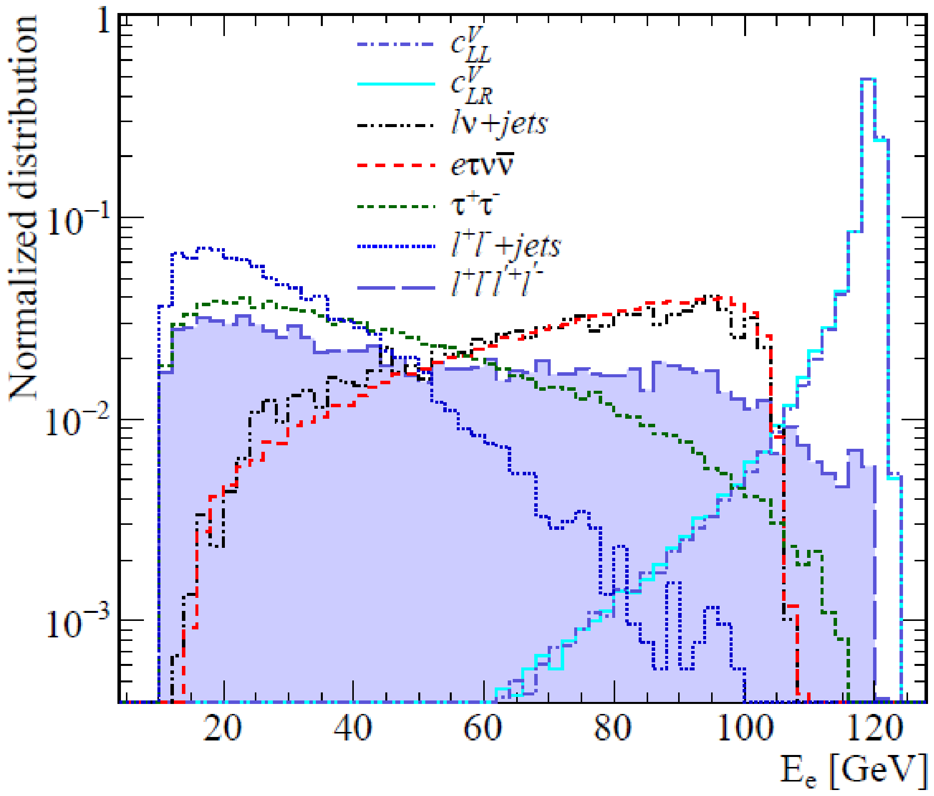
- Exactly 1 tau-tagged jet (Hadronic decay)
- Exactly 1 electron (positron)
- Opposite sign leptons

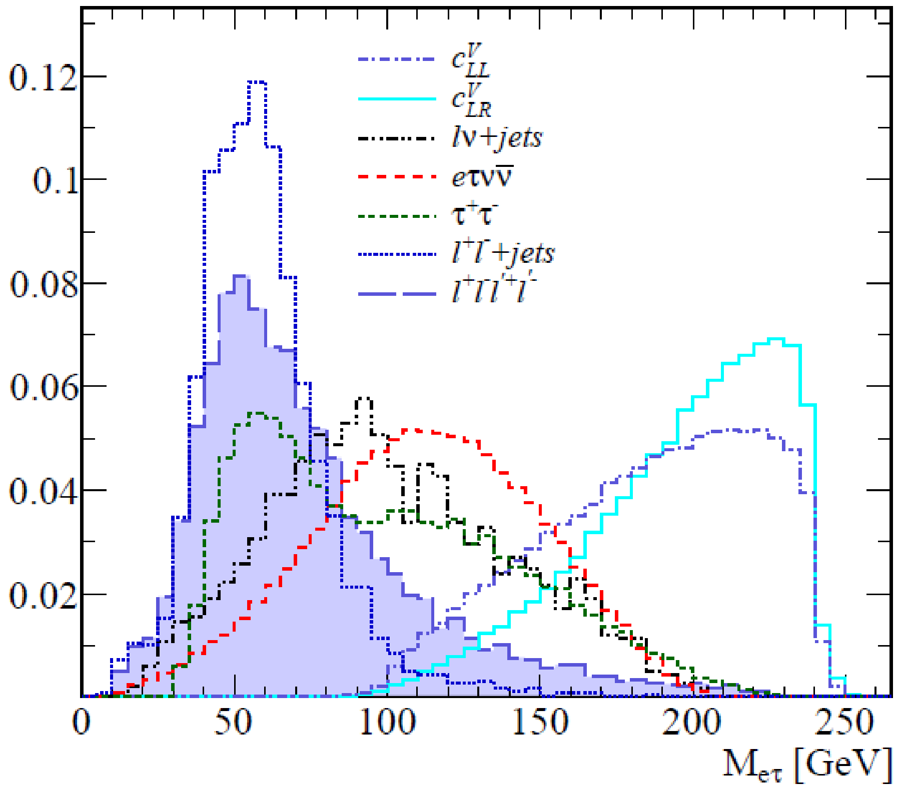
- $P_T > 20$ GeV for tau
- $P_T > 10$ GeV for electron (positron)
- $|\eta| \leq 2.5$ for all objects
- $\Delta R > 0.5$ GeV for all objects

- 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

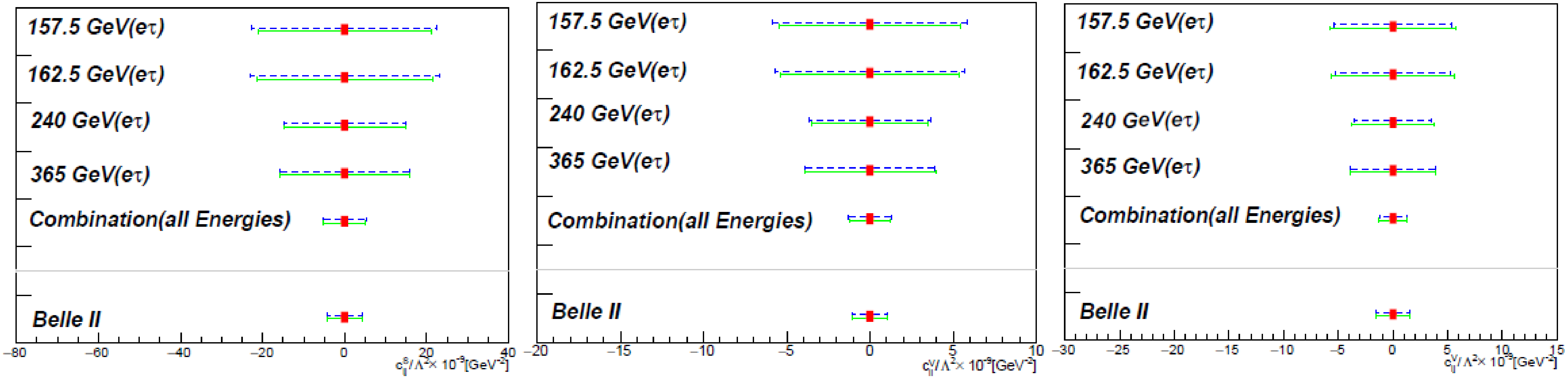
- **To enhance the sensitivity, we apply additional cuts on (for $\sqrt{s}$ =240 GeV):**





RESULTS & DISCUSSION

- 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:1808.10567]



- 5% uncertainty on both signal efficiency and on background expectation at 365 GeV:

c^V_{LL}/Λ^2	c^V_{RR}/Λ^2	c^V_{RL}/Λ^2	c^V_{LR}/Λ^2	c^S_{RL}/Λ^2	c^S_{LR}/Λ^2
4.14	4.15	4.12	4.13	16.57	16.65

$[\times 10^{-9}\ (\mathrm{GeV}^{-2})\ ]$

THANKS FOR YOUR ATTENTION!

BACKUP

- LFV among 1st and 2nd generations: tightly constrained by experimental constraints arising from:

Nucl. Phys. B 299 (1988) — $\mu \to 3e$ at SINDRUM experiment

arXiv:1605.05081 — Muon transition to $e\gamma$

Eur. Phys. J. C 47, 337-346 (2006) — $e-\mu$ conversion

However,

- Constraints on LFVs between e and τ, and μ and τ are much looser $\Rightarrow$ eeeτ couplings
- In addition to the $eee\tau$ four-Fermi contact interactions

Other favorite interactions

- Leptons and quarks $eeqq'$
- Electrons and Higgs-Z $eeHZ$

arXiv: 1602.01698 , 2101.05286 , …

BACKUP

- **Background processes:**

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

BACKUP

TABLE I. The cross sections of signal $e^-e^+ \to e^\pm\tau^\mp$ and main background processes with their corresponding uncertainties are presented. The cross section of two signal scenarios are given assuming $c^V_{LR} = 0.1$, $c^S_{LR} = 0.1$, and $\Lambda = 1$ TeV. The cross sections are in the unit of fb and include the ISR effects.

$\sqrt{s}$ [GeV]	$c^V_{LR} = 0.1$	$c^S_{LR} = 0.1$	$e\tau\nu\bar{\nu}$	$\tau\bar{\tau}$	$\ell\bar{\ell}\ell'\bar{\ell}'$	$\ell\bar{\ell}jj$	$\ell\nu jj$	jj
157.5	4.72 ± 0.007	0.29 ± 0.0004	22.33 ± 0.07	11076.5 ± 3.4	39.86 ± 0.08	80.95 ± 0.2	272.9 ± 0.4	32032 ± 8.1
162.5	5.02 ± 0.007	0.31 ± 0.0004	102.12 ± 0.3	10275.8 ± 2.9	42.23 ± 0.08	83.06 ± 0.3	1198.05 ± 0.8	29133 ± 6.2
240	10.98 ± 0.04	0.69 ± 0.0008	415.63 ± 0.6	4196.8 ± 1.2	86.24 ± 0.2	217.8 ± 0.5	4552.7 ± 1.3	10481 ± 3.5
365	25.26 ± 0.07	1.57 ± 0.002	327.59 ± 0.5	1803.6 ± 0.6	85.05 ± 0.1	195.13 ± 0.3	3247.02 ± 1.1	4306 ± 1.2

BACKUP

- **LFV $eee\tau$ contact interactions previous studies:**

The LFV contact operators probed: [arXiv1410.1485]

- Via $e^-e^+ \rightarrow e^{\pm}\tau^{\mp}$ process at $\sqrt{s}$ = 250, 500, 1000, 3000 GeV.
- Considering two main background sources, $\tau\tau$ and $e\tau\nu\nu$.

Similar study at $\sqrt{s}$ = 250, 500, 1000 GeV: [arXiv1803.10475]

- The effects of polarization beams.
- Detector response
- The main source of backgrounds of $e\tau\nu\nu$.

- **In this study:**

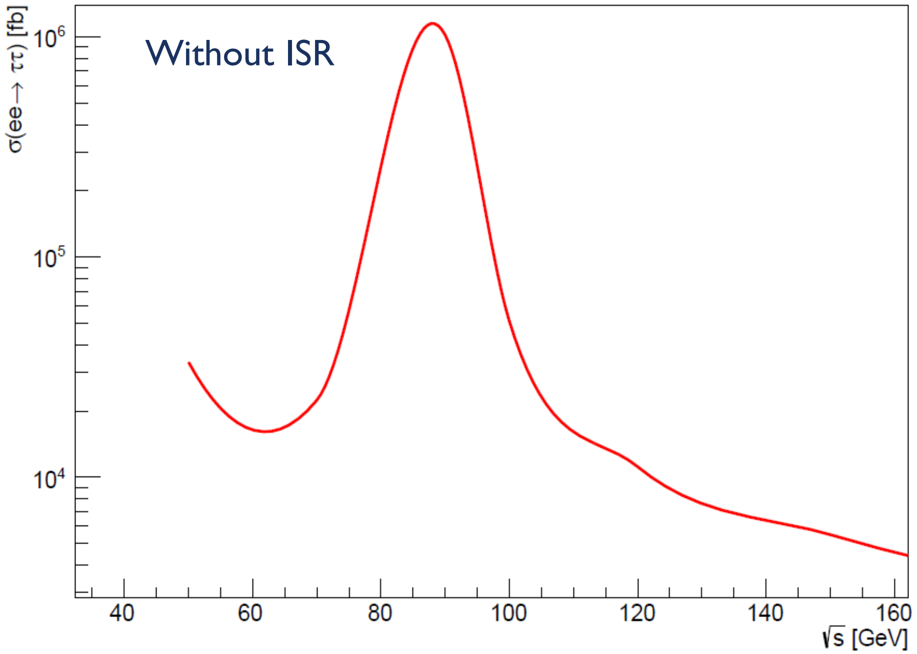
Four FCC-ee benchmarks	ISR effect
other main backgrounds	statistical data combination

BACKUP

- **ISR effects** are considered using the MGISR plugin (MadGraph5 version: 2.6.6) [arXiv:1705.04486] [arXiv:1804.00125]

$\sqrt{s}$ [GeV]	$\tau\bar{\tau}$(without ISR)	$\tau\bar{\tau}$(with ISR)
157.5	4869.4	11076.5
162.5	4514.9	10275.8
240	1910.5	4196.8
365	804.15	1803.6

ee → $\tau\tau$ cross section [fb]



BACKUP

SM relevant input values:

$$M_Z = 91.188 \text{ GeV}$$
$$m_\tau = 1.777 \text{ GeV}$$
$$G_F = 1.166 \times 10^{-5} \text{ GeV}^{-2}$$
$$\alpha_e = 1/127.9$$
$$\alpha_s = 0.118$$

BACKUP

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```
#############
# tau-tagging
#############


module TauTagging TauTagging {
  set ParticleInputArray Delphes/allParticles
  set PartonInputArray Delphes/partons
  set JetInputArray JetEnergyScale/jets

  set DeltaR 0.5

  set TauPTMin 1.0

  set TauEtaMax 4.0

  # add EfficiencyFormula {abs(PDG code)} {efficiency formula as a function of eta and pt}

  # default efficiency formula (misidentification rate)
  add EfficiencyFormula {0} {0.001}
  # efficiency formula for tau-jets
  add EfficiencyFormula {15} {0.4}
}
```

BACKUP

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```
#######################
# Electron efficiency
#######################

module Efficiency ElectronEfficiency {
  set InputArray ElectronFilter/electrons
  set OutputArray electrons

  # set EfficiencyFormula {efficiency formula as a function of eta and pt}

  # efficiency formula for electrons
  set EfficiencyFormula {                                      (pt <= 10.0) * (0.00) +
                                         (abs(eta) <= 1.5) * (pt > 10.0)  * (0.95) +
                         (abs(eta) > 1.5 && abs(eta) <= 2.5) * (pt > 10.0)  * (0.95) +
                         (abs(eta) > 2.5)                                    * (0.00)}
}
```

```
####################
# Electron isolation
####################

module Isolation ElectronIsolation {
  set CandidateInputArray ElectronEfficiency/electrons
  set IsolationInputArray EFlowFilter/eflow

  set OutputArray electrons

  set DeltaRMax 0.5

  set PTMin 0.5

  set PTRatioMax 0.12
}
```

BACKUP

- **For electrons with $P_T > 10$ GeV and $|\eta| \leq 2.5$, the identification efficiency in the ILD card is 95%.**

- **The efficiency in the ILD simulation card is 40% and the tau misidentification rate is assumed to be equal 0.1%.**
- **considering the τ tagging efficiency, a jet is considered potentially as a τ candidate if a generated τ exists within a bellow distance from the jet axis.**

$$\Delta R = \sqrt{(\eta_{\text{jet}} - \eta_\tau)^2 + (\phi_{\text{jet}} - \phi_\tau)^2} = 0.3$$

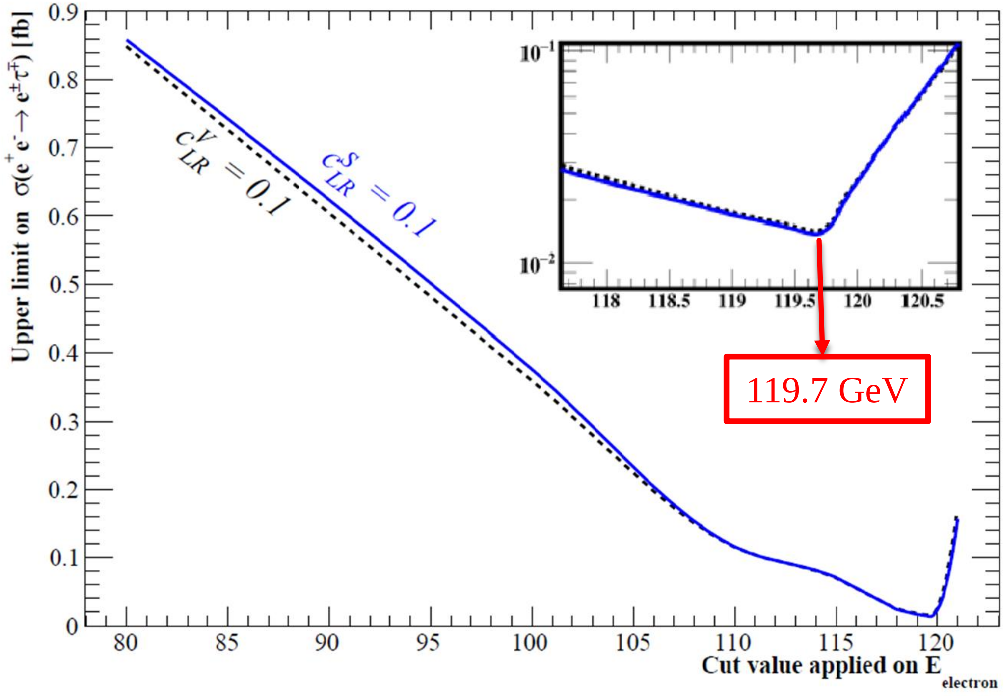
BACKUP

- **It is notable that the Meτ distribution has different behaviours for cV LL and cV LR which arises from the fact that for LL coupling** $d\sigma/d\cos\theta \propto (1+\cos\theta)^2$

  for RL coupling $d\sigma/d\cos\theta \propto (1-\cos\theta)^2$

BACKUP

- **The optimized lower cuts on the energy of electron are obtained to be 78.6, 81.0, 119.7 and 182.0 GeV for center-of-mass energy of 157.5, 162.5, 240 and 365 GeV, respectively.**



BACKUP

About the $ee \to jj$ background:

- **This process contributes to the backgrounds. But …**
- **The jet fake probability is expected to be 0.1%.**
- **The rate of this background is assessed to be less than 5% of the total background contributions after event selection criteria.**

BACKUP

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$\sqrt{s} = 157.5$ GeV	Signal		SM Backgrounds				
	$c^V_{LR} = 0.1$	$c^S_{LR} = 0.1$	$e\tau\nu\bar{\nu}$	$\tau\bar{\tau}$	$\ell\ell\ell'\ell'$	$\ell\ell jj$	$\ell\nu jj$
(I): Pre-selection cuts	0.1746	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	Signal		SM Backgrounds				
	$c^V_{LR} = 0.1$	$c^S_{LR} = 0.1$	$e\tau\nu\bar{\nu}$	$\tau\bar{\tau}$	$\ell\ell\ell'\ell'$	$\ell\ell jj$	$\ell\nu jj$
(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	Signal		SM Backgrounds				
	$c^V_{LR} = 0.1$	$c^S_{LR} = 0.1$	$e\tau\nu\bar{\nu}$	$\tau\bar{\tau}$	$\ell\ell\ell'\ell'$	$\ell\ell jj$	$\ell\nu jj$
(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	Signal		SM Backgrounds				
	$c^V_{LR} = 0.1$	$c^S_{LR} = 0.1$	$e\tau\nu\bar{\nu}$	$\tau\bar{\tau}$	$\ell\ell\ell'\ell'$	$\ell\ell jj$	$\ell\nu jj$
(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

BACKUP

- 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:1808.10567]
- Comparison to a study at $\sqrt{s} = 1$ TeV with beam polarization: $P(e^-) = 0.8, P(e^+) = -0.3$ [arXiv:1803.10475]

$\sqrt{s}$ (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

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Limit setting method

- The CLs technique is exploited to find upper limits on the signal cross section
- The RooStats package is used to perform the numerical evaluation of the CLs.
- CLs technique: we define log-likelihood functions L_{Bkg} and $L_{Signal+Bkg}$ for the background hypothesis, and for the signal+background hypothesis as the multiplication of Poissonian likelihood functions.
- The p-value for hypothesis of signal+background and for the background hypothesis are determined using the log-likelihood ratio:

$$\mathrm{Q} = -2\ln(\mathrm{L}_{\mathrm{Signal+Bkg}}/\mathrm{L}_{\mathrm{Bkg}})$$

- The signal cross section is constrained using

$$\mathrm{CL_s} = \mathrm{P}_{\mathrm{Signal+Bkg}}(\mathrm{Q} > \mathrm{Q}_0)/(1 - \mathrm{P}_{\mathrm{Bkg}}(\mathrm{Q} < \mathrm{Q}_0)) \leq 0.05$$

which is corresponding to 95% CL and Q_0 is the expected value of test statistics Q.

BACKUP

- **Other info:**
- There are a variety of theories that give rise to LFV. For instance, additional fermions present in the type III seesaw model or in the low-scale seesaw models give rise to large LFV effects
- production rate of the four-fermion interactions grows linearly with the squared center-of-mass energy s, and diverge when $s \to \infty$. However, one should note that we are working in a non-renormalizable formalism and these operators provide an acceptable description of physics at high energy up to an energy scale Λ.