بسم الله الرحمن الرحيم

Searching for lepton flavor violating interactions at future electron-positron colliders

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Outline

- Motivation & introduction
- Theoretical framework
- Data Simulation
- Analysis strategy
- Results & discussion
- Conclusion

Motivation & Introduction:

- In the SM: neutrinos are massless ⟶ LFV interactions are forbidden.
- Neutrino oscillations have been observed ⟶ neutrinos are massive.
- This leads to violation of lepton flavor conservation.
- LFV enters into the charged lepton sector from the neutrino sector via radiative corrections which are extremely suppressed because of the smallness of the ratio of neutrino mass to the W boson mass.
- The predicted branching fraction e.g. for $\tau \rightarrow 3\ell$ is $\lesssim 10^{-54}$, where $\ell = \mu, e$
- An increase of several orders of magnitude is predicted in some extensions of the SM.

Motivation & Introduction:

- any observation of LFV in the charged lepton sector:
  - an obvious hint to the BSM physics
  - An indirect way to search for beyond the SM scenarios.

- So far, no LFV interactions among the charged leptons have 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 future prospects at 90% CL with 50 ab^{-1} : $\mathrm{Br}(\tau \to e^- e^+ e^-) < 10^{-10}$

Motivation & Introduction:

- Future lepton colliders such as CLIC, ILC, CEPC and FCC-ee, are expected to provide an extraordinary place in flavor physics studies.

- The LFV through Z and Higgs have been studied.
- The Higgs and scalar LFV decays have been studied.

If the new degrees of freedom contributing to LFV are heavy comparing to the energy accessible at colliders then the LFV couplings could be reasonably parameterized via the effective contact interactions.

- Experiments can perfectly search for LFV in a model-independent approach, without any theoretical input.

- Effective field theories allow for a model-independent interpretation of the experimental results.

Motivation & Introduction:

- LFV $ee e\tau$ contact interactions have been already studied at future high energy lepton colliders:
  - the LFV contact operators probed:
    via $e^- e^+ \to e^\pm \tau^\mp$ process at $\sqrt{s}$ = 250, 500, 1000, 3000 GeV
    considering two main background sources, $\tau\tau$ and $e\tau\upsilon\upsilon$.
  - Similar study at $\sqrt{s}$= 250, 500, 1000 GeV:
    the effects of polarization beams
    detector response
    the main source of backgrounds of $e\tau\upsilon\upsilon$.
- In this study: Four FCC-ee benchmarks, ISR effect,
  other main backgrounds, statistical data combination.

Theoretical Framework

- considering four Fermi contact interactions provide the opportunity to characterize the new physics effects in a model-independent framework.

- Six chirality conserving four-Fermi operators $(\Delta L = 1)$: scalar and vector type

- In addition, there are LFV operators containing dipole structures which are tightly constrained by radiative LFV decays, therefore, they are not considered in this work.

Theoretical Framework

- The effective Lagrangian and the relevant set of operators:

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

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

- Λ : the energy scale of new physics
- $c_{i,j}$: Wilson couplings between leptons of flavor i and j
- $O_{i,j}$: four fermion leptonic operators, invariant under the SM gauge symmetry

Theoretical Framework

- LFV among 1st and 2nd generations is tightly constrained by experimental constraints arising from:
  - $\mu \to 3e$ at SINDRUM experiment,
  - the muon transition to $e\gamma$,
  - $e - \mu$ conversion.

- However, constraints on flavor violations between e and τ, and μ and τ are much looser.

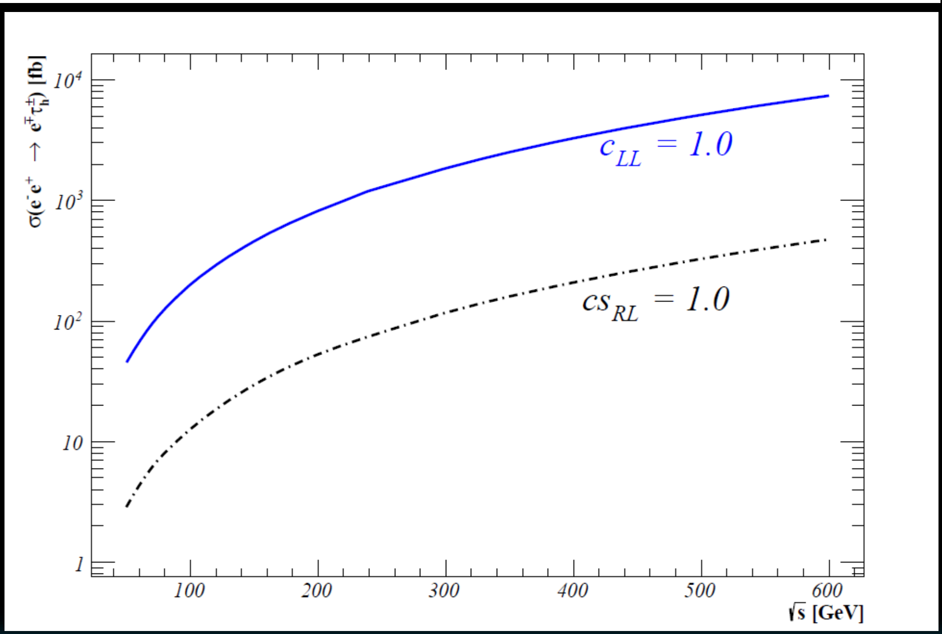
- In addition to the $eee\tau$ four-Fermi contact interactions, contact interactions among leptons and quarks (like $eeqq'$), and electrons and Higgs-Z ($eeHZ$) are of favourite topics which have been probed in several papers.

Theoretical Framework

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

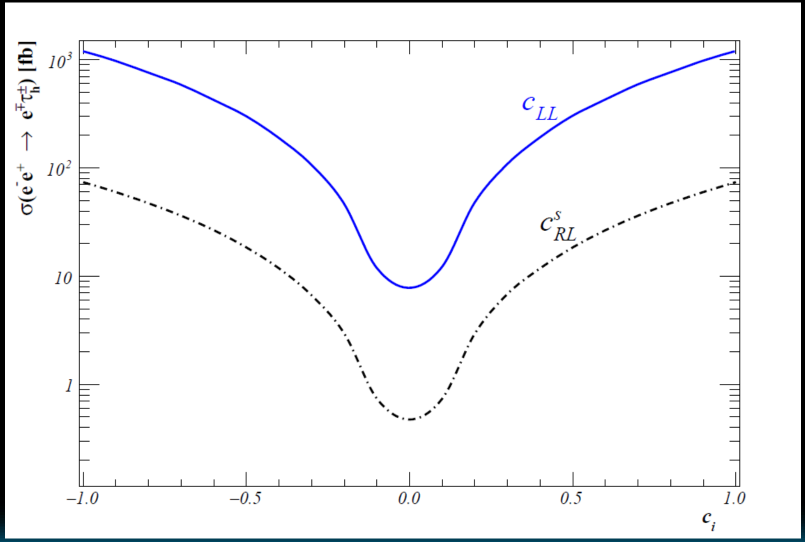
$$\sigma(s) = \frac{s}{96\pi\Lambda^4}\left\{(|c^S_{LR}|^2 + |c^S_{RL}|^2) + 16(|c^V_{LL}|^2 + |c^V_{RR}|^2 + |c^V_{LR}|^2 + |c^V_{RL}|^2)\right\}$$

- The lepton masses are set to zero
- Production rate of the 4-f interactions grows with the squared center-of-mass energy.
- Vector type operators are larger than the scalar type by a factor of 16 .



Data Simulation

- MADGRAPH5_aMC@NLO : Monte Carlo event generator
- The effective Lagrangian is implemented in the FeynRule program.
- the Universal FeynRules Output (UFO) model is inserted to the MadGraph.
- Six different signal samples corresponding to the six operators are generated.
- In order to generate signal events, we set related effective Wilson coefficient $c_{i,j}$=0.1, with i, j = L,R, and Λ = 1 TeV



Data Simulation

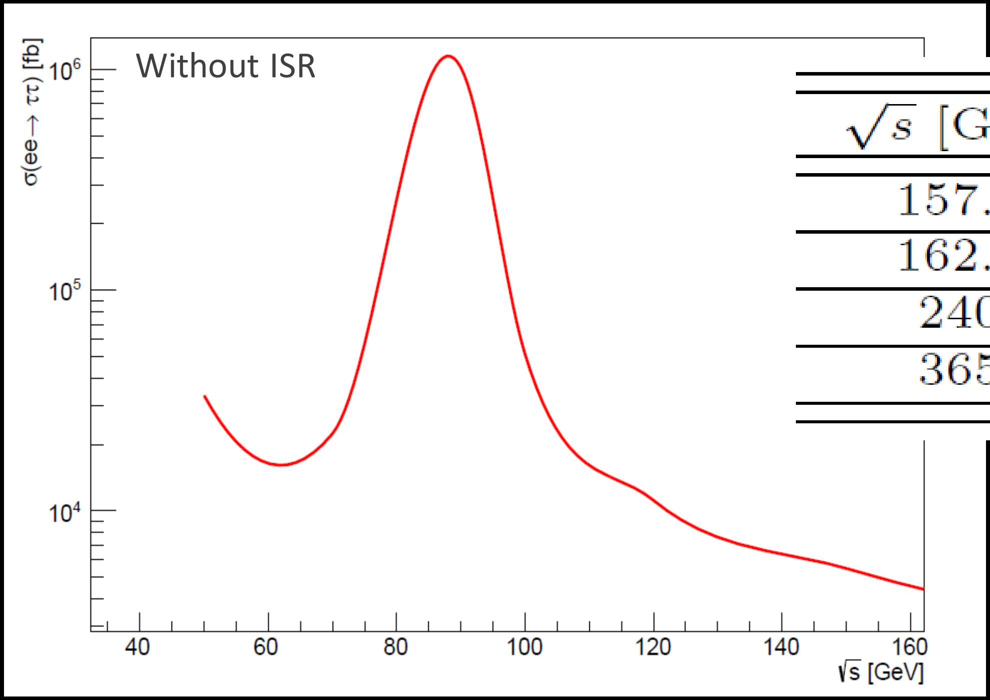
- Four benchmarks of the FCC-ee: 365, 240, 162.5, 157.5 GeV
  with their integrated luminosities : 1.5, 5, 5, 5 ab^{-1}

- Background processes:

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

Data Simulation

- ISR effects are confsidered using the MGISR plugin (MadGraph5 version: 2.6.6)



$\sqrt{s}$ [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

$\tau\tau$ cross section [fb]

Data Simulation

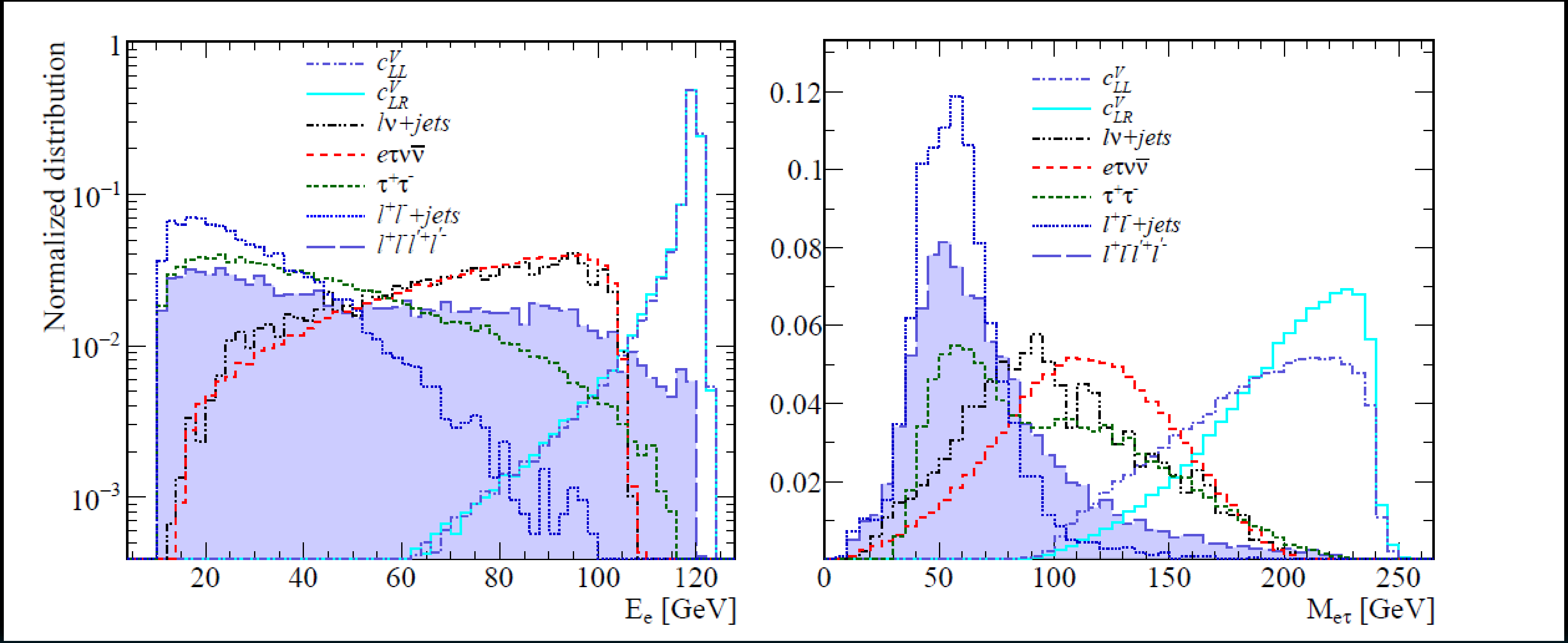
- The generated samples are passed through the PYTHIA8 for parton shower, hadronization, and decay of unstable particles.
- Simulation of detector: DELPHES3.4.2 using a ILD-like detector,
- For electrons with $P_T > 10$ GeV and $|\eta| \leq 2.5$, the identification efficiency in the ILD card is 95%.
- Tau-lepton hadronic decay mode which produces a jet containing a few neutral and charged hadrons is considered.
- The Tau-tagging efficiency in the ILD simulation card is 40% and the tau misidentification rate is assumed to be equal 0.1%

Analysis strategy

- Event selection:
  - Exactly 1 tau-tagged jet (Hadronic tau 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
  - $\text{RelIso} < 0.15$; 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

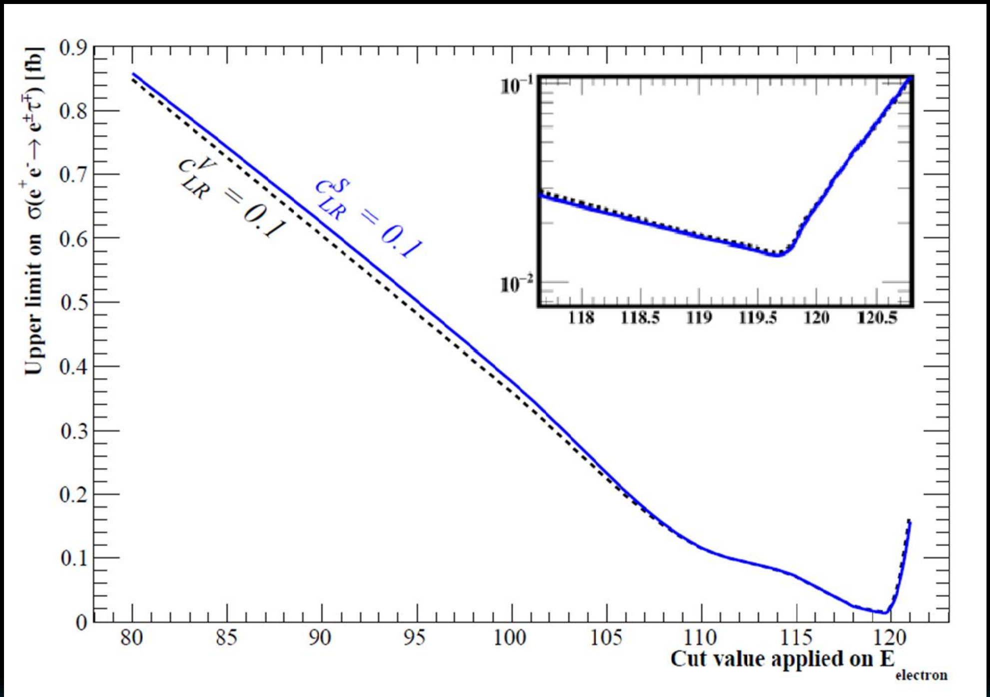
Analysis strategy

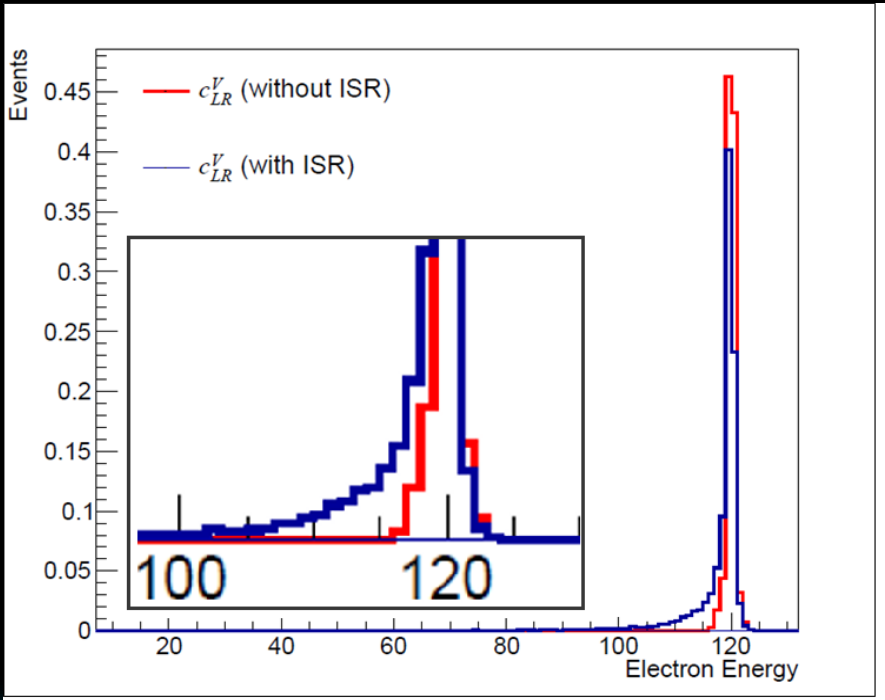
- To enhance the sensitivity, we apply additional cuts on:



Analysis strategy

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.





Analysis strategy

- About the $ee \rightarrow jj$ background:
  - jets could be misidentified as and electron. Therefore, processes with jets in the final state contribute to the background.
  - The jet fake probability is expected to be 0.1%. The rate of background is assessed to be less than 5% of the total background contributions after event selection criteria.
  - The contribution of the $ee \rightarrow jj$ background decreases to a negligible level after all cuts, and we do not mention it in the efficiency table (next slide).

LFV at Lepton Colliders

$\sqrt{s} = 157.5$ GeV	Signal		SM Backgrounds				
	$c^V_{LR} = 0.1$	$c^S_{LR} = 0.1$	$e\tau\nu\bar{\nu}$	$\tau\bar{\tau}$	$\ell\bar{\ell}\ell'\bar{\ell}'$	$\ell\bar{\ell}jj$	$\ell\nu jj$
(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}	6.58×10^{-11}
$\sqrt{s} = 162.5$ GeV	Signal		SM Backgrounds				
	$c^V_{LR} = 0.1$	$c^S_{LR} = 0.1$	$e\tau\nu\bar{\nu}$	$\tau\bar{\tau}$	$\ell\bar{\ell}\ell'\bar{\ell}'$	$\ell\bar{\ell}jj$	$\ell\nu jj$
(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}	1.65×10^{-11}
$\sqrt{s} = 240$ GeV	Signal		SM Backgrounds				
	$c^V_{LR} = 0.1$	$c^S_{LR} = 0.1$	$e\tau\nu\bar{\nu}$	$\tau\bar{\tau}$	$\ell\bar{\ell}\ell'\bar{\ell}'$	$\ell\bar{\ell}jj$	$\ell\nu jj$
(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}	5.59×10^{-12}
$\sqrt{s} = 365$ GeV	Signal		SM Backgrounds				
	$c^V_{LR} = 0.1$	$c^S_{LR} = 0.1$	$e\tau\nu\bar{\nu}$	$\tau\bar{\tau}$	$\ell\bar{\ell}\ell'\bar{\ell}'$	$\ell\bar{\ell}jj$	$\ell\nu jj$
(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}	3.24×10^{-11}

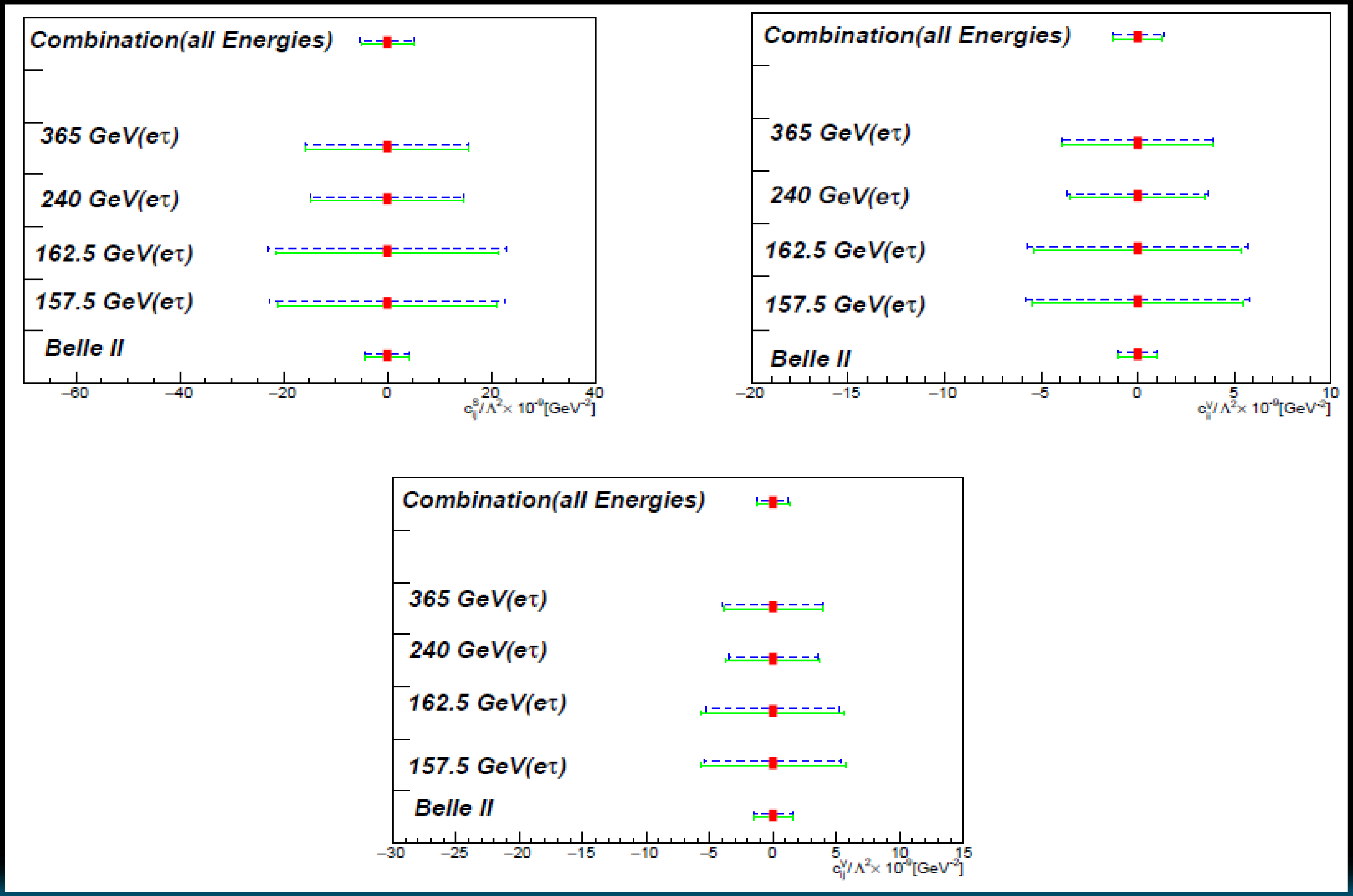
Results & Discussion

- In order to achieve better sensitivity, the results from four energy benchmarks are combined.

  - Comparison to the Belle-ll experiment with 50 ab^{-1} data
  - Comparison to a study at $\sqrt{s} = 1$ TeV with beam polarization: $P(e^-) = 0.8$, $P(e^+) = -0.3$

$\sqrt{s}$ (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



Results & Discussion

- Impact of systematic uncertainties on the results

- Based on a search for LFV at LEP2 with the OPAL detector:
  - the systematic uncertainty on the signal efficiency is 3.5%
  - on the number of expected background events is 5%.

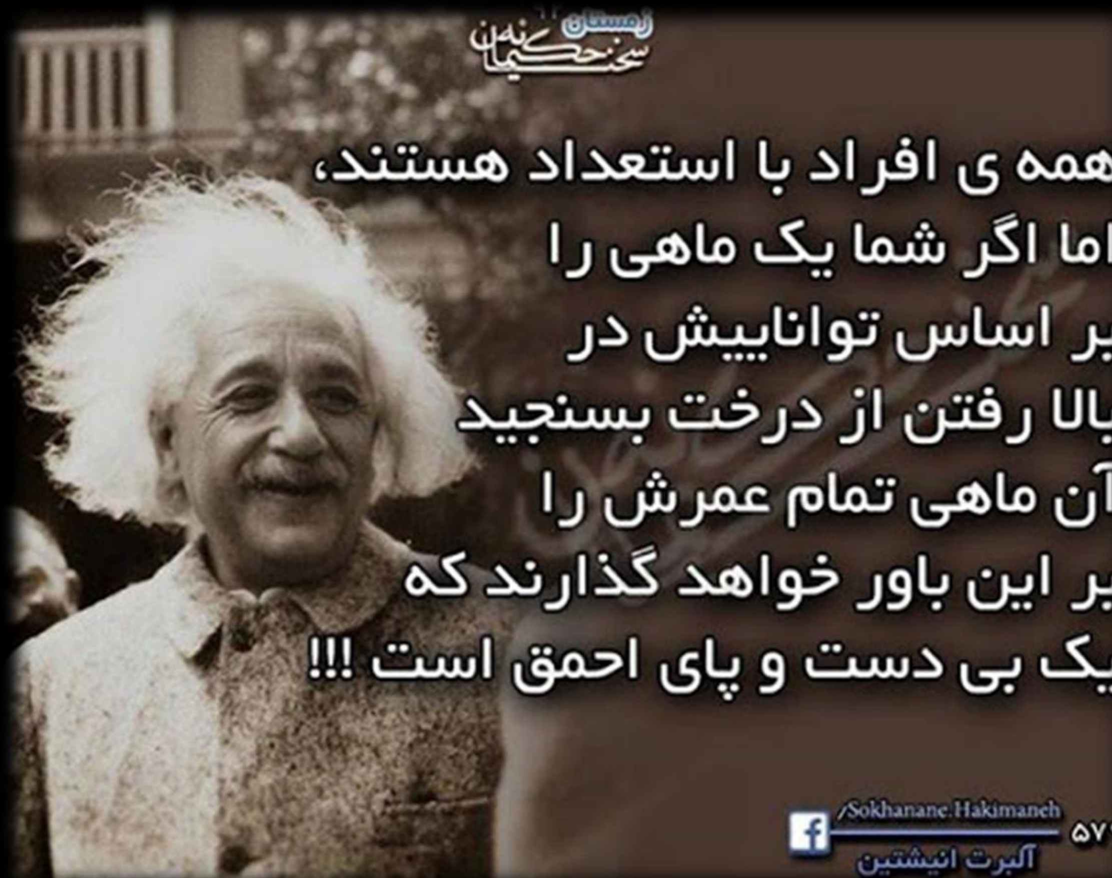
- While the future experiments are expected to be more accurate, we consider 5% uncertainty on both signal selection efficiency and on background expectation at 365 GeV. The limits with this uncertainty are [$\times 10^{-9}$ (GeV^{-2})]:

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

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 for 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 have been obtained for the four center-of-mass energies. 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!



Backup

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:

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

- The signal cross section is constrained using

$$\mathrm{CL_s} = \mathrm{P_{Signal+Bkg}}(\mathrm{Q} > \mathrm{Q_0})/(1 - \mathrm{P_{Bkg}}(\mathrm{Q} < \mathrm{Q_0})) \leq 0.05$$

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

Combination method Based on 1606.02266 [hep-ex]:

The signal yield in a category k, $n_{\text{signal}}(k)$, can be expressed as a sum over all possible Higgs boson production processes i, with cross section σ_i, and decay modes f, with branching fraction B^f:

$$n_{\text{signal}}(k) = \mathcal{L}(k) \cdot \sum_i \sum_f \left\{\sigma_i \cdot A_i^{f,SM}(k) \cdot \varepsilon_i^f(k) \cdot \text{B}^f\right\}$$
$$= \mathcal{L}(k) \cdot \sum_i \sum_f \mu_i \mu^f \left\{\sigma_i^{\text{SM}} \cdot A_i^{f,SM}(k) \cdot \varepsilon_i^f(k) \cdot \text{B}^f_{\text{SM}}\right\},$$

where $\mathcal{L}(k)$ represents the integrated luminosity, $A_i^{f,SM}(k)$ the detector acceptance assuming SM Higgs boson production and decay, and $\varepsilon_i^f(k)$ the overall selection efficiency for the signal category k. The symbols μ_i and μ^f are the production and decay signal strengths, respectively, defined in Section 2.3. As Eq. (7) shows, the measurements considered in this paper are only sensitive to the products of the cross sections and branching fractions, $\sigma_i \cdot \text{B}^f$.

In the ideal case, each category would only contain signal events from a given production process and decay mode. Most decay modes approach this ideal case, but, in the case of the production processes, the categories are much less pure and there is significant cross-contamination in most channels.

Combination method Based on 1606.02266 [hep-ex]:

The overall statistical methodology used in the combination to extract the parameters of interest in various parameterisations is the same as that used for the individual ATLAS and CMS combinations, as published in Refs. [17, 18]. It was developed by the ATLAS and CMS Collaborations and is described in Ref. [115]. Some details of this procedure are important for this combination and are briefly reviewed here.

The statistical treatment of the data is based on the standard LHC data modelling and handling toolkits: RooFit [116], RooStats [117], and HistFactory [118]. The parameters of interest, $\vec{\alpha}$, e.g. signal strengths (μ), coupling modifiers (κ), production cross sections, branching fractions, or ratios of the above quantities, are estimated, together with their corresponding confidence intervals, via the profile likelihood ratio test statistic $\Lambda(\vec{\alpha})$ [119]. The latter depends on one or more parameters of interest, as well as on the nuisance parameters, $\vec{\theta}$, which reflect various experimental or theoretical uncertainties:

$$\Lambda(\vec{\alpha}) = \frac{L(\vec{\alpha}\,,\,\hat{\hat{\vec{\theta}}}(\vec{\alpha}))}{L(\hat{\vec{\alpha}},\hat{\vec{\theta}})}.$$

Combination method Based on 1606.02266 [hep-ex]:

The likelihood functions in the numerator and denominator of this equation are constructed using products of signal and background probability density functions (pdfs) of the discriminating variables. The pdfs are obtained from simulation for the signal and from both data and simulation for the background, as described in Refs. [17, 18]. The vectors $\hat{\vec{\alpha}}$ and $\hat{\vec{\theta}}$ represent the unconditional maximum likelihood estimates of the parameter values, while $\hat{\hat{\vec{\theta}}}$ denotes the conditional maximum likelihood estimate for given values of the parameters of interest $\vec{\alpha}$. Systematic uncertainties and their correlations are a subset of the nuisance parameters $\vec{\theta}$, described by likelihood functions associated with the estimate of the corresponding parameter.

As an example of a specific choice of parameters of interest, the parameterisation considered in Section 6.4 assumes that all fermion couplings are scaled by κ_F and all weak vector boson couplings by κ_V. The likelihood ratio is therefore a function of the two parameters of interest, κ_F and κ_V, and the profile likelihood ratio is expressed as:

$$\Lambda(\kappa_F, \kappa_V) = \frac{L(\kappa_F, \kappa_V, \hat{\hat{\vec{\theta}}}(\kappa_F, \kappa_V))}{L(\hat{\kappa}_F, \hat{\kappa}_V, \hat{\vec{\theta}})} .$$

Combination method

- Based on : https://inspirehep.net/files/aebd6033563c291bd897112e20e23437

Model details

For this exercise, the measurements in both experiments were treated as multichannel counting experiments. The likelihood function is therefore written as the product of Poisson terms for each channel times the product of all the constraint terms for the nuisance parameters θ associated to the systematic uncertainties.

$$\mathcal{L} = \prod_{i \in \text{obs.}} \text{Poisson}\left(n_i \,|\, \nu_i(\mu, \theta)\right) \cdot \prod_{j \in \text{nui.s}} \text{Constraint}(\theta_j, \tilde{\theta}_j)$$

Combination method

- Based on : https://inspirehep.net/files/aebd6033563c291bd897112e20e23437

For convenience, the θ_i are normalised so that the constraint is always a normal distribution with zero mean and unit variance, and all non-universal terms enter only in the relationship between parameters and expected yield in the signal regions $\nu_i(\mu,\theta)$. For uncertainties related to the statistical uncertainty in the control regions or in the simulation, the associated nuisance parameter is the expected yield in that region, and the constraint term is a Poisson likelihood for $\tilde{\theta}_j$ observed events and θ_j expected ones; this is mathematically equivalent to a Gamma distribution over θ_j with most probable value $\tilde{\theta}_j$.