Search for charged lepton flavor violation at lepton colliders

Tong Li (李佟)
Nankai University

Based on works in collaboration with Michael A. Schmidt
arXiv: 1809.07924, 1907.06963

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Outline

- Motivation
- Existing (low-energy) precision constraints
- Results at future lepton colliders
- Summary

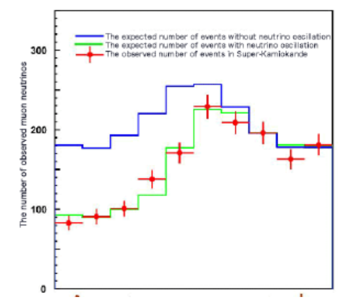
- The past and ongoing particle colliders (LEP, $\mathrm{Sp}\bar{p}$S, PETRA, SPEAR, SLC, Tevatron, and LHC) made important measurements for the SM particles.
- They have so far seen no conclusive evidence of beyond the SM phenomena, although strong arguments based on naturalness imply TeV scale BSM physics.

Where is the BSM?

BSM observation

- The only BSM physics observed so far in the lab is neutrino mass (from flavor change in oscillation, 1998)

$\nu_e \leftrightarrow \nu_\mu$ (SNO):
$$\begin{aligned} \nu_e + {}^2_1 D &\rightarrow p + p + e^- \\ \nu_\mu + {}^2_1 D &\rightarrow p + n + \nu_\mu \end{aligned}$$
$\nu_\mu \leftrightarrow \nu_\tau$ (Super-K):



- What we know about neutrino:

$$\begin{aligned}
6.8 \times 10^{-5}\,\mathrm{eV}^2 &< \Delta m^2_{21} < 8.02 \times 10^{-5}\,\mathrm{eV}^2, \\
2.399 \times 10^{-3}\,\mathrm{eV}^2 &< \Delta m^2_{31} < 2.593 \times 10^{-3}\,\mathrm{eV}^2, \\
(-2.562 \times 10^{-3}\,\mathrm{eV}^2 &< \Delta m^2_{32} < -2.369 \times 10^{-3}\,\mathrm{eV}^2), \\
0.272 &< \sin^2\theta_{12} < 0.346, \\
0.418\ (0.435) &< \sin^2\theta_{23} < 0.613\ (0.616), \\
0.01981\ (0.02006) &< \sin^2\theta_{13} < 0.02436\ (0.02452), \\
144^\circ\ (192^\circ) &< \delta_{\mathrm{CP}} < 374^\circ (354^\circ),
\end{aligned}$$

$\theta_{13} \approx 8.4^\circ$ (Daya Bay)

$\delta_{CP} \approx 3\pi/2$ (T2K, NOvA)

$\sum m_\nu < 0.23$ eV (Planck)

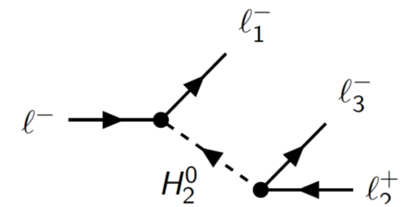
- See **Y. Cai, T. Han, TL, R. Ruiz, arXiv: 1711.02180** for the probes of neutrino mass generation at colliders

(charged) Lepton Flavor Violation

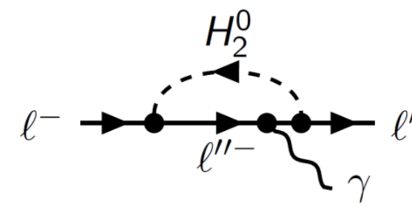
- neutrino oscillations -> LFV in neutrino sector
- can be completely unrelated to neutrino mass
- charged LFV in processes $l \to l' + X, X \neq \nu$
- cLFV suppressed by unitarity in SM+mν, $\mathcal{A} \sim G_F {m_\nu}^2 \sim 10^{-26}$ **T. P. Cheng and L.-F. Li, PRL 45, 1908 (1980)**
- the observation of any cLFV process implies the existence of new physics beyond the SM

Existing (low-energy) precision constraints

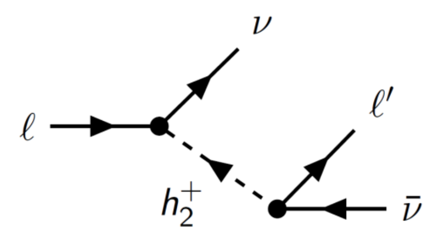
- LFV trilepton decays $\ell \to \ell_1 \overline{\ell}_2 \overline{\ell}_3$



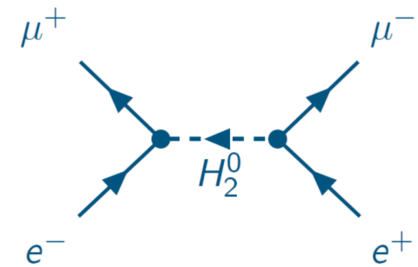
- LFV radiative lepton decays $\ell \to \ell' \gamma$



- anomalous magnetic dipole moments
- lepton flavor non-universality $\ell \to \ell' \nu \bar{\nu}$

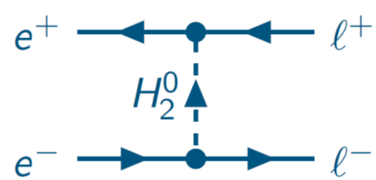


- electroweak precision observables
- muonium-antimuonium conversion



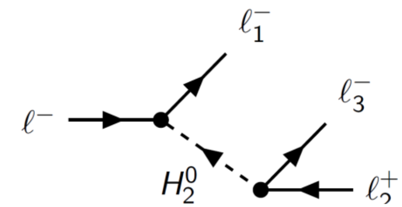
Future sensitivity improvements, e.g. Belle-II, Mu3E, J-PARC, …

- LEP/LHC searches
  Z/Higgs rare decays,
  top decay, Z' decay



CMS EXO-13-005, 1408.5774, 1804.09568, ATLAS-CONF-2019-013, 1712.07173, CMS-PAS-HIG-16-005, 1607.03561, 1711.07243, ATLAS-CONF-2018-044, 1807.06573

Existing (low-energy) precision constraints



- LFV trilepton decays $\ell \to \ell_1 \overline{\ell}_2 \overline{\ell}_3$
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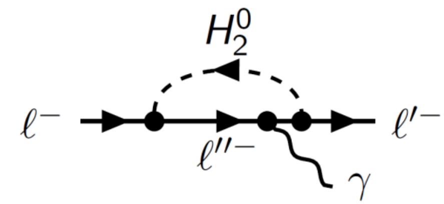

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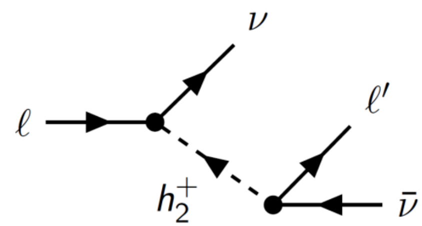

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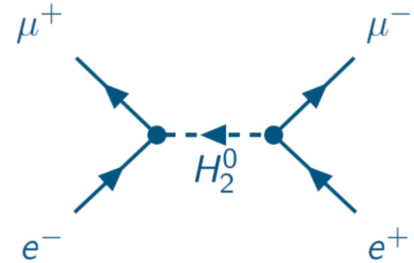


Future sensitivity improvements, e.g. Belle-II, Mu3E, J-PARC, …

Prospect of cLFV search at future e+e- colliders

top decay, Z decay

1607.03561, 1711.07243,
ATLAS-CONF-2018-044, 1807.06573

Seven bilepton models

$\Delta L = 0$

complex scalar $H_2 \sim (2, \frac{1}{2})$

$$\mathcal{L} = y_2^{ij} H_2 \bar{L}_i P_R \ell_j + h.c.$$

LH singlet vector $H_1 \sim (1, 0)$

$$\mathcal{L} = y_1^{ij} H_{1\mu} \bar{L}_i \gamma^\mu P_L L_j$$

LH triplet vector $H_3 \sim (3, 0)$

$$\mathcal{L} = y_3^{ij} \bar{L}_i \gamma^\mu \vec{\sigma} \cdot H_{3\mu} P_L L_j$$

right-handed vector $H_1' \sim (1, 0)$

$$\mathcal{L} = y_1'^{ij} H_{1\mu}' \bar{\ell}_i \gamma^\mu P_R \ell_j$$

$\Delta L = 2$

right-handed scalar $\Delta_1 \sim (1, 2)$

$$\mathcal{L} = \lambda_1^{ij} \Delta_1 \ell_i^T C P_R \ell_j + h.c.$$

left-handed scalar $\Delta_3 \sim (3, 1)$

$$\mathcal{L} = -\frac{\lambda_3^{ij}}{\sqrt{2}} L_i^T C i \sigma_2 \vec{\sigma} \cdot \vec{\Delta}_3 P_L L_j + h.c.$$

vector $\Delta_2 \sim (2, \frac{3}{2})$

$$\mathcal{L} = \lambda_2^{ij} \Delta_{2\mu\alpha} L_{i\beta}^T \gamma^\mu P_R \ell_j \epsilon_{\alpha\beta} + h.c.$$

assumption: real and symmetric Yukawa coupling matrices

See also arXiv: 1711.08430, 1712.03642, 1803.11167

Low-energy precision constraints

- Anomalous magnetic moments

$$\Delta a_\mu \equiv a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (2.74 \pm 0.73) \times 10^{-9}$$

$$\Delta a_e \equiv a_e^{\text{exp}} - a_e^{\text{SM}} = (-0.88 \pm 0.36) \times 10^{-12}$$

- do not attempt to explain the deviations from the SM but rather derive a constraint on the cLFV couplings

$$\Delta a_\ell(H_1^{(\prime)0}) = \frac{(y_1^{(\prime)\dagger} y_1^{(\prime)})^{\ell\ell}}{12\pi^2} \frac{m_\ell^2}{m^2_{H_1^{(\prime)0}}} \geq 0 \,,$$

$$\Delta a_\ell(H_3) = \frac{(y_3^\dagger y_3)^{\ell\ell}}{12\pi^2} \frac{m_\ell^2}{m^2_{H_3^0}} - \frac{5(y_3^\dagger y_3)^{\ell\ell}}{24\pi^2} \frac{m_\ell^2}{m^2_{H_3^+}} \,,$$

$$\Delta a_\ell(\Delta_2) = -\frac{7(\lambda_2^\dagger \lambda_2)^{\ell\ell}}{24\pi^2} \frac{m_\ell^2}{m^2_{\Delta_2^{++}}} - \frac{5(\lambda_2^\dagger \lambda_2)^{\ell\ell}}{48\pi^2} \frac{m_\ell^2}{m^2_{\Delta_2^+}} \leq 0$$

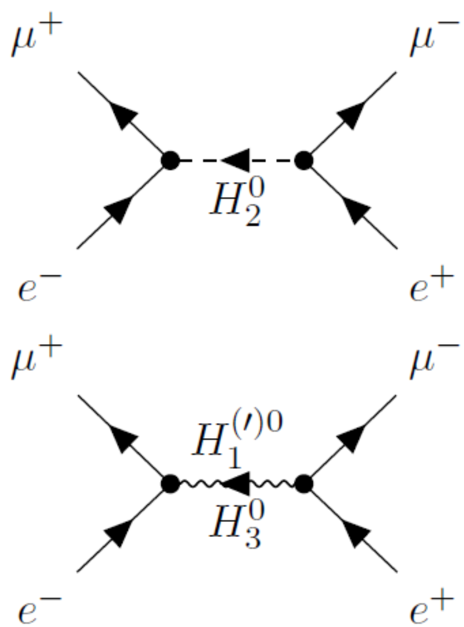
$$\Delta a_\ell(\Delta_1) = \frac{(\lambda_1^\dagger \lambda_1)^{\ell\ell}}{6\pi^2} \frac{m_\ell^2}{m^2_{\Delta_1^{++}}} \geq 0 \,,$$

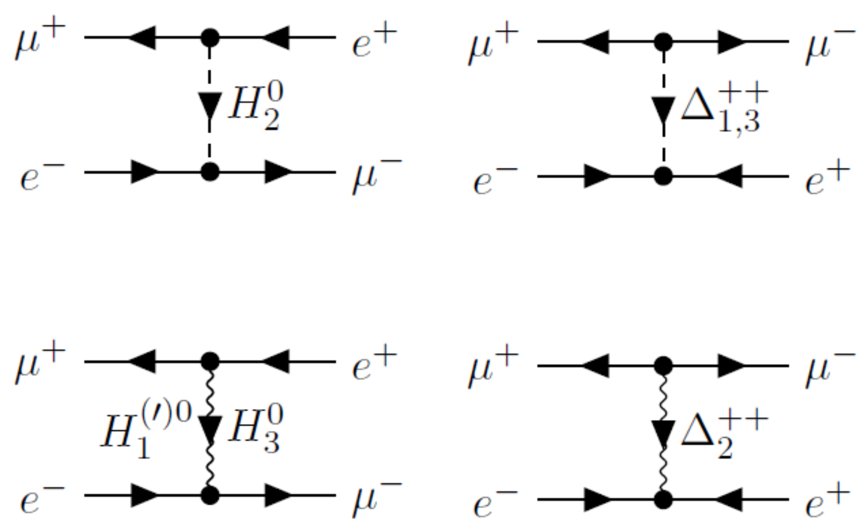
$$\Delta a_\ell(\Delta_3) = \frac{(\lambda_3^\dagger \lambda_3)^{\ell\ell}}{6\pi^2} \left(\frac{m_\ell^2}{m^2_{\Delta_3^{++}}} + \frac{m_\ell^2}{8 m^2_{\Delta_3^+}} \right) \geq 0 \,,$$

$$\Delta a_\ell(H_2) = -\frac{(y_2^\dagger y_2 + y_2 y_2^\dagger)^{\ell\ell}}{96\pi^2} \left(\frac{m_\ell^2}{m^2_{h_2}} + \frac{m_\ell^2}{m^2_{a_2}} \right) + \frac{(y_2^\dagger y_2)^{\ell\ell}}{96\pi^2} \frac{m_\ell^2}{m^2_{H_2^+}}$$
$$+ \sum_k \text{Re}[y_2^{k\ell} y_2^{\ell k}] \frac{m_k m_\ell}{16\pi^2} \left(\frac{\ln\left(\frac{m_k^2}{m_{h_2}^2}\right) + \frac{3}{2}}{m^2_{h_2}} - \frac{\ln\left(\frac{m_k^2}{m_{a_2}^2}\right) + \frac{3}{2}}{m^2_{a_2}} \right)$$

- If there is a mixing of muonium ($\mu^+ e^-$) and antimuonium ($\mu^- e^+$), the lepton flavor conservation must be violated
- The probability of muonium-antimuonium conversion, P(B=0.1 T)<8.3x10^-11

Phys. Rev. Lett. 82, 49 (1999)





- New contributions to effective operators with two leptons and two neutrinos constrained by lepton flavor universality

$$-2\sqrt{2}G_F[\bar{\nu}_i\gamma_\mu P_L\nu_j][\bar{\ell}_k\gamma^\mu\left(g_{LL}^{ijkl}P_L+g_{LR}^{ijkl}P_R\right)\ell_l]$$

$$R_{\mu e}=\frac{\Gamma(\tau\to\nu_\tau\mu\bar{\nu}_\mu)}{\Gamma(\tau\to\nu_\tau e\bar{\nu}_e)}\simeq R_{\mu e}^{\rm SM}\left(1+2{\rm Re}(g_{LL,NP}^{\tau\mu\mu\tau}-g_{LL,NP}^{\tau ee\tau})\right)$$

$$R_{\tau\mu}=\frac{\Gamma(\tau\to\nu_\tau e\bar{\nu}_e)}{\Gamma(\mu\to\nu_\mu e\bar{\nu}_e)}\simeq R_{\tau\mu}^{\rm SM}\left(1+2{\rm Re}(g_{LL,NP}^{\tau ee\tau}-g_{LL,NP}^{\mu ee\mu})\right)$$

$$\frac{R_{\mu e}^{\rm exp}}{R_{\mu e}^{\rm SM}}=1.0034\pm0.0032 \qquad \text{and} \qquad \frac{R_{\tau\mu}^{\rm exp}}{R_{\tau\mu}^{\rm SM}}=1.0022\pm0.0028$$

- Weak mixing angle

$$\frac{\delta s_W^2}{s_W^2} = \frac{s_{W,exp}^2 - s_W^2}{s_W^2} = \frac{c_W^2}{s_W^2 - c_W^2}\delta G_F$$

$$s_{W,exp}^2 = 0.22343 \pm 0.00007 \text{ in PDG}$$

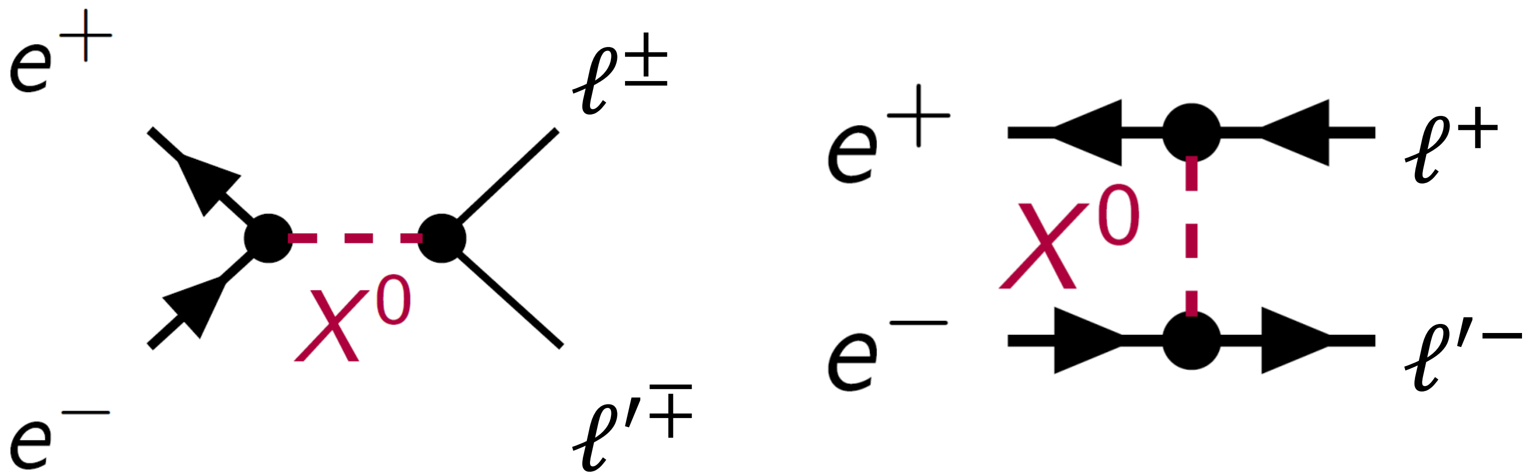
- W boson mass

$$\frac{\delta m_W^2}{m_W^2} \equiv \frac{m_{W,exp}^2}{m_W^2} - 1 = -\left(\delta G_F + \frac{\delta s_W^2}{s_W^2}\right) = \frac{s_W^2}{c_W^2 - s_W^2}\delta G_F$$

$$\frac{m_{W,\mathrm{exp}}^2}{m_{W,\mathrm{SM}}^2} = 1.00040 \pm 0.00058$$

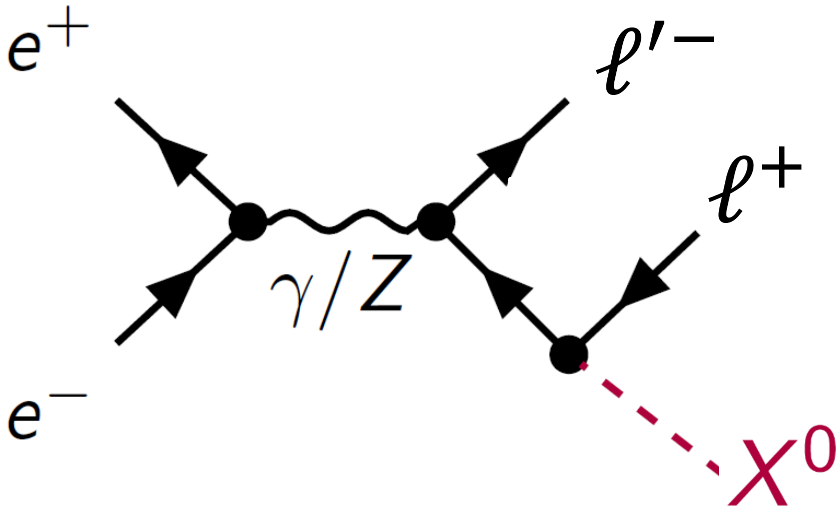
LFV at future lepton colliders

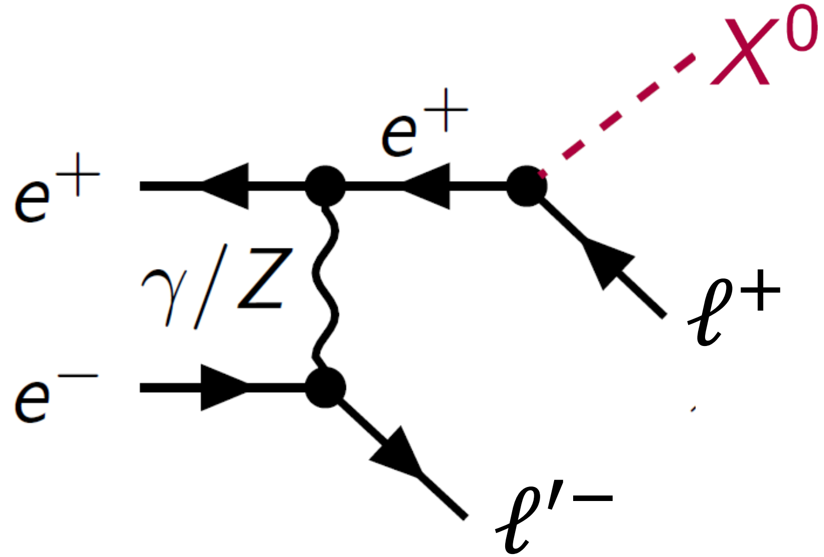
- Off-shell production



CLFV channel	flavor $ij, i'j'$	$\Delta L = 0$	$\Delta L = 2$
$e^+e^- \to e^\pm\mu^\mp$	$ee, e\mu$	s+t	t
$e^+e^- \to e^\pm\tau^\mp$	$ee, e\tau$	s+t	t
$e^+e^- \to \mu^\pm\tau^\mp$	$ee, \mu\tau$	s	-
$e^+e^- \to \mu^\pm\tau^\mp$	$e\mu, e\tau$	t	t

- On-shell production





flavor ij	$\Delta L = 0$ CLFV channel	$\Delta L = 2$ CLFV channel
$e\mu$	$e^+e^- \to e^\pm\mu^\mp H^0$ (s+t)	$e^+e^- \to e^\pm\mu^\pm\Delta^{\mp\mp}$ (s+t)
$e\tau$	$e^+e^- \to e^\pm\tau^\mp H^0$ (s+t)	$e^+e^- \to e^\pm\tau^\pm\Delta^{\mp\mp}$ (s+t)
$\mu\tau$	$e^+e^- \to \mu^\pm\tau^\mp H^0$ (s)	$e^+e^- \to \mu^\pm\tau^\pm\Delta^{\mp\mp}$ (s)

- Five collider configurations:

CEPC: 5 ab^-1, 240 GeV

FCC-ee: 16 ab^-1, 240 GeV

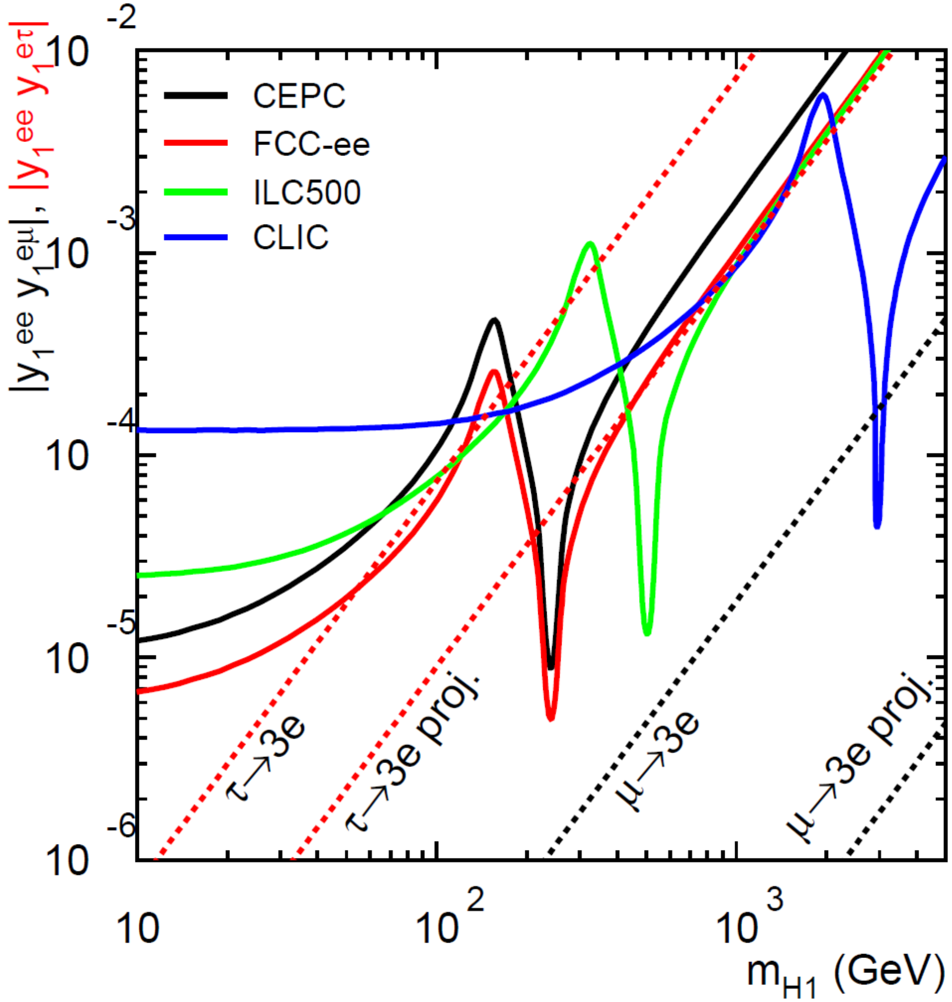
ILC (500 GeV): 4 ab^-1, 500 GeV

ILC (1 TeV): 1 ab^-1, 1 TeV

CLIC: 5 ab^-1, 3 TeV

- Basic cuts: pT>10 GeV and $|\eta|$<2.5
- Small SM backgrounds from WW, Zh
- Assume 10% efficiency for the reconstruction of the new particles in on-shell scenario
- Tau-tagging efficiency 60%
- Assume $\frac{S}{\sqrt{S+B}} = 3$ significance for observation

$H_{1\mu}, H'_{1\mu}: e^+e^- \to e^\pm\mu^\mp, e^\pm\tau^\mp$



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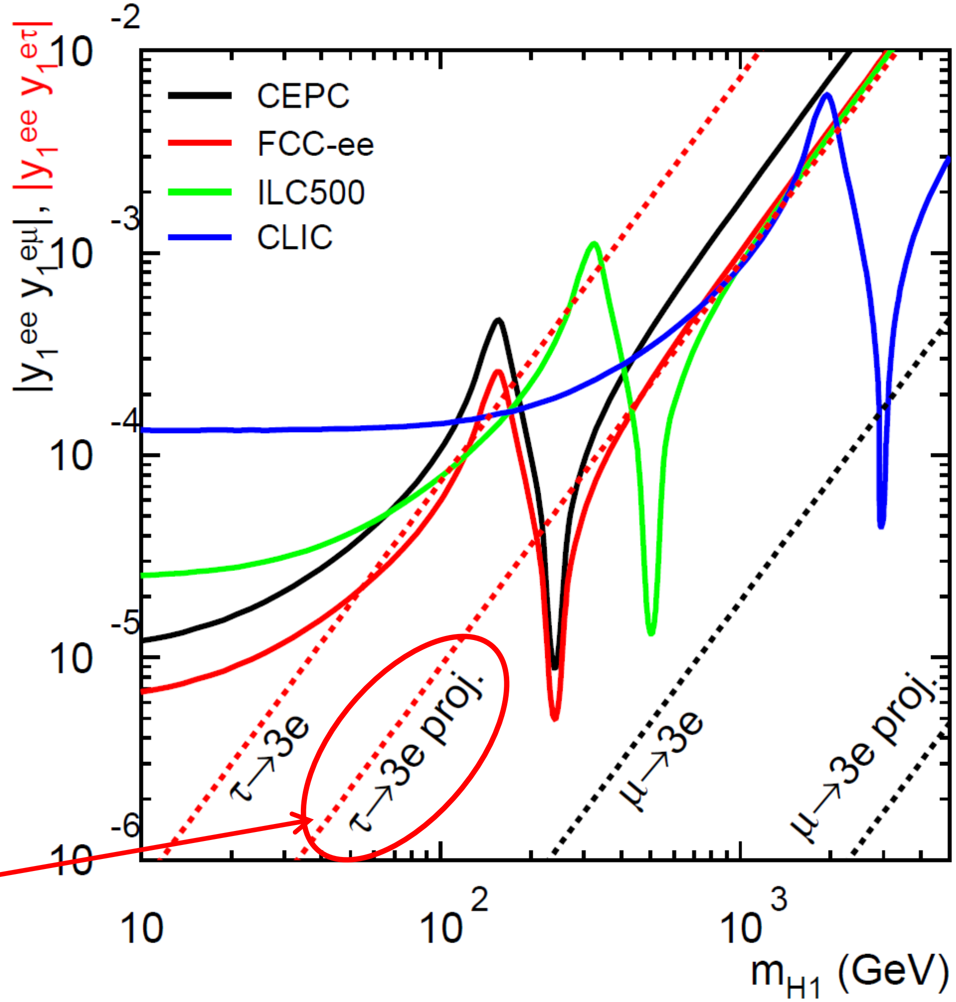
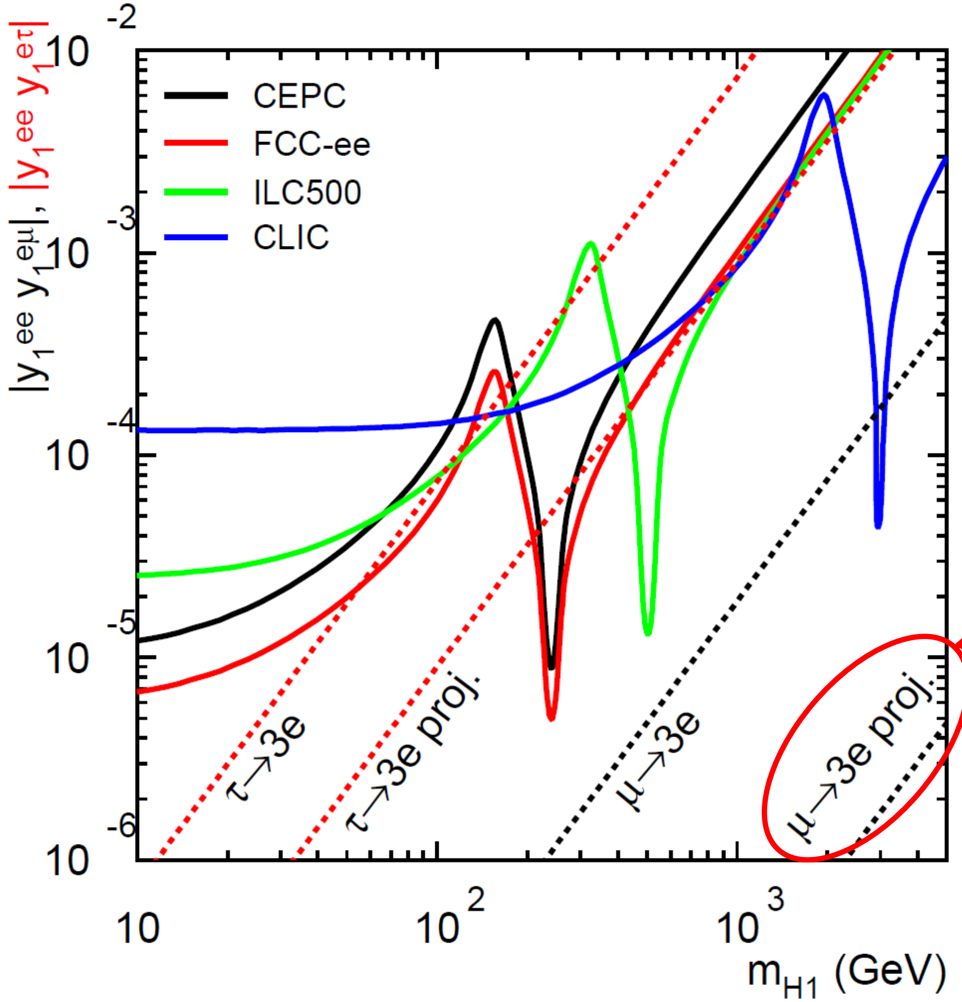


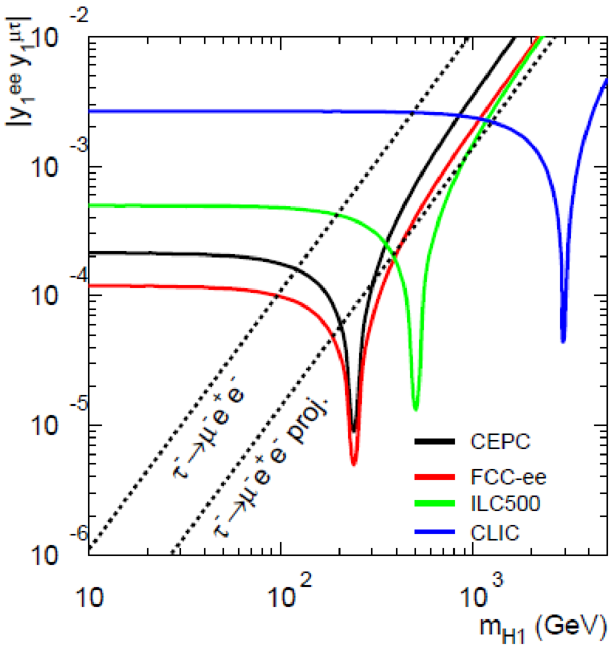
$|y^{ee}y^{e\tau}|$

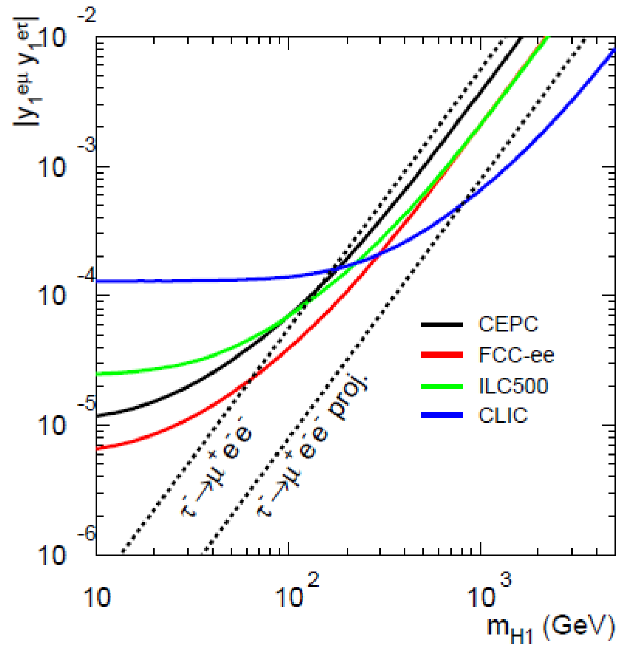
$H_{1\mu}, H'_{1\mu}: e^+e^- \to e^\pm\mu^\mp, e^\pm\tau^\mp$



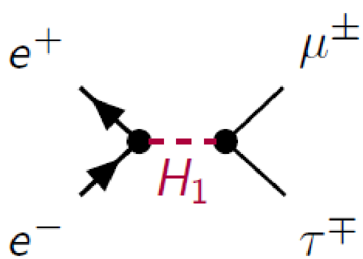
$|y^{ee}y^{e\mu}|$

$H_{1\mu}, H'_{1\mu}: e^+e^- \to \mu^\pm\tau^\mp$

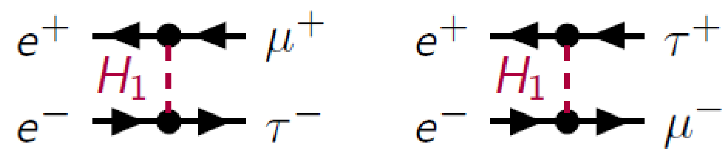




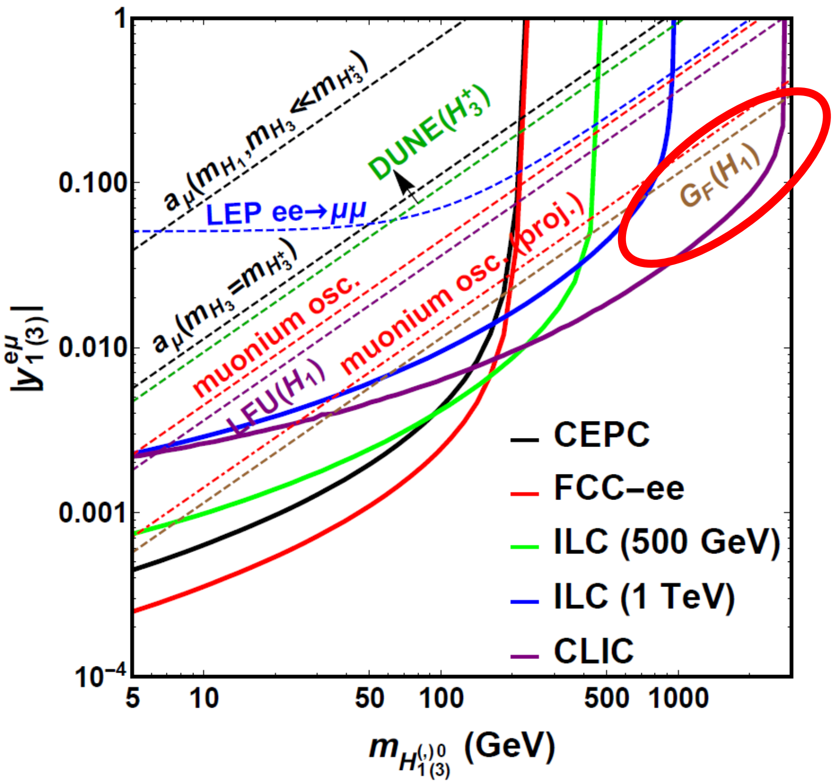
rel. couplings $|y_1^{ee} y_1^{\mu\tau}|$

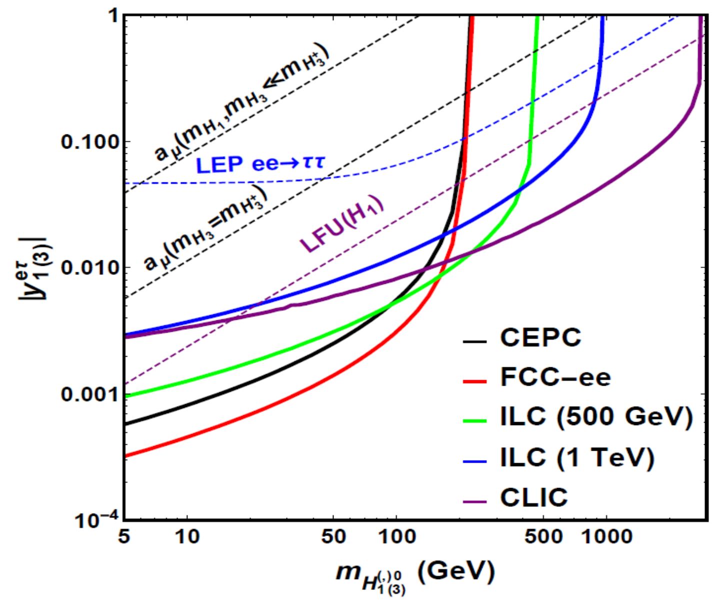


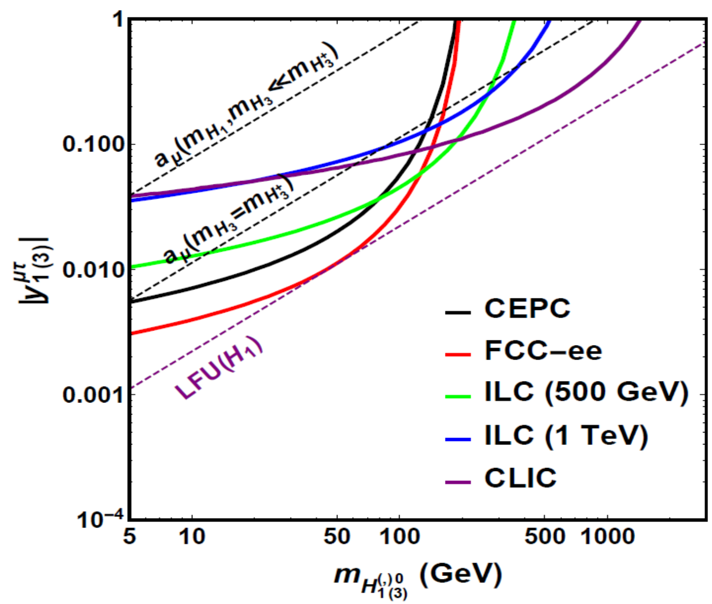
rel. couplings $|y^{e\mu} y^{e\tau}|$

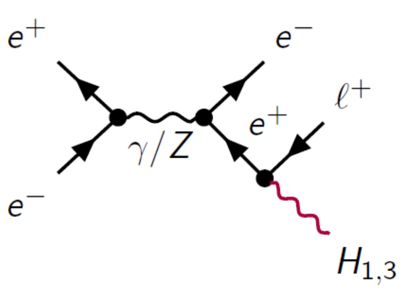


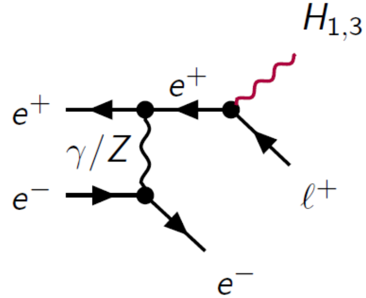
$H_{1\mu}$, $H'_{1\mu}$: on-shell production



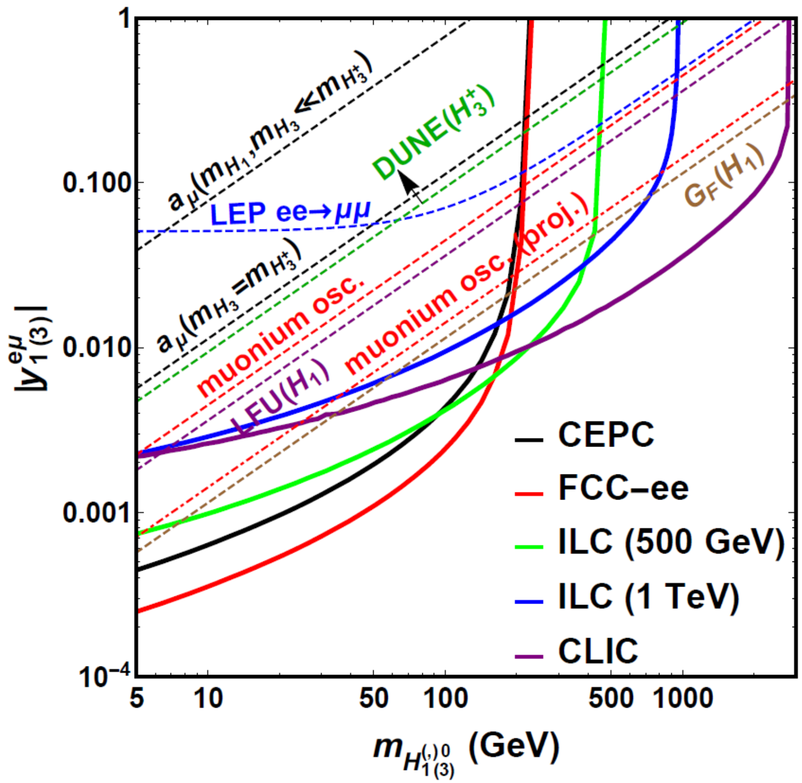


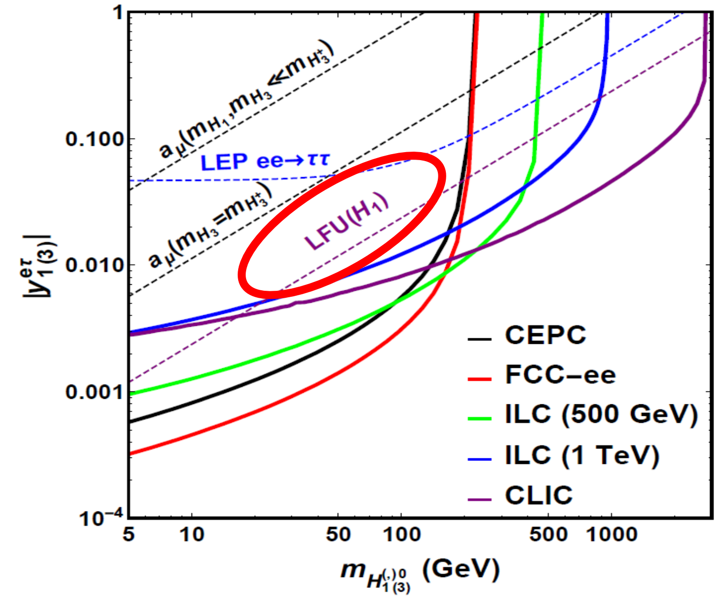


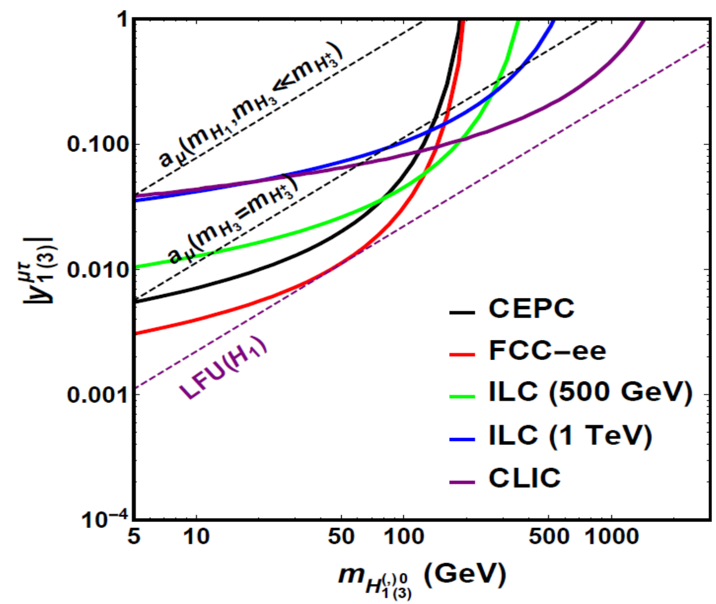


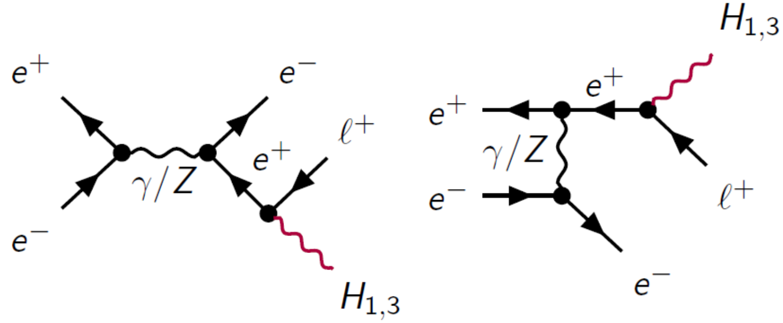


$H_{1\mu}$, $H'_{1\mu}$: on-shell production

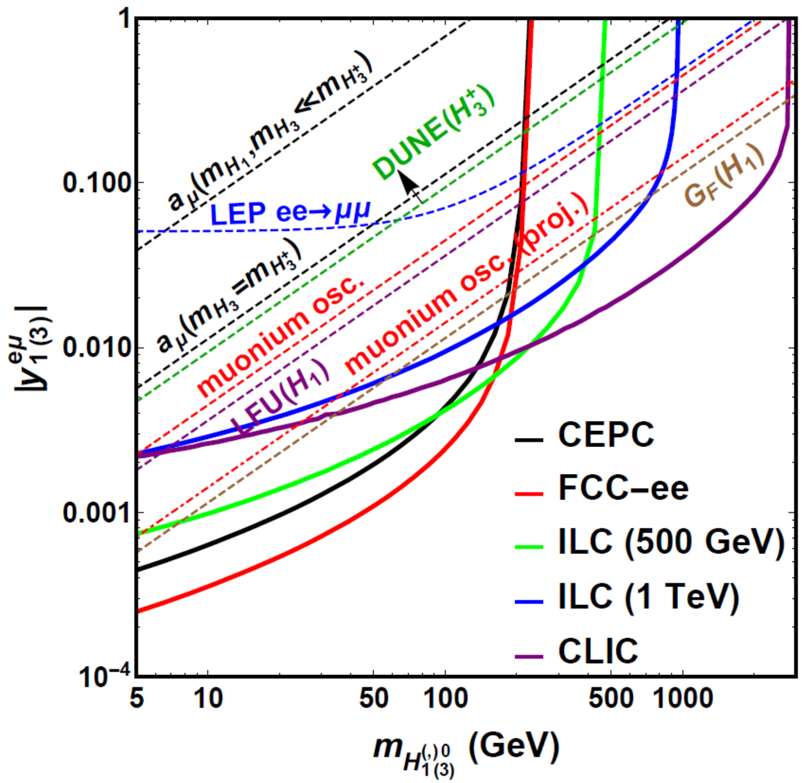


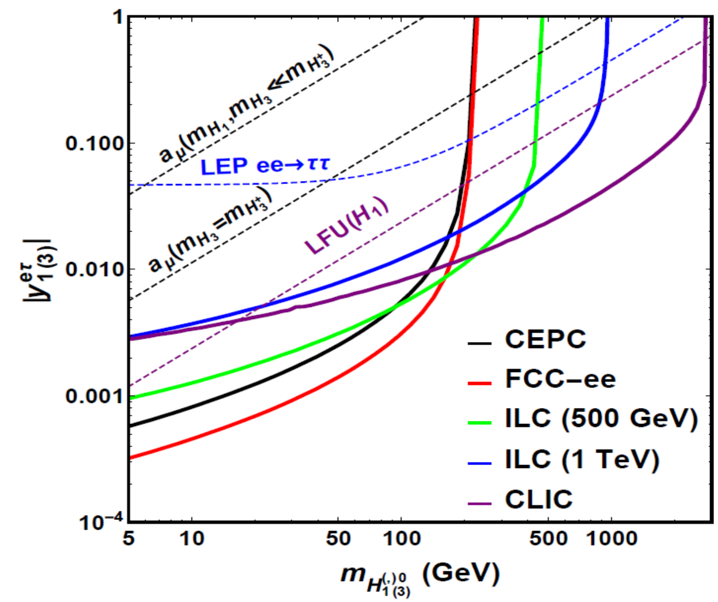


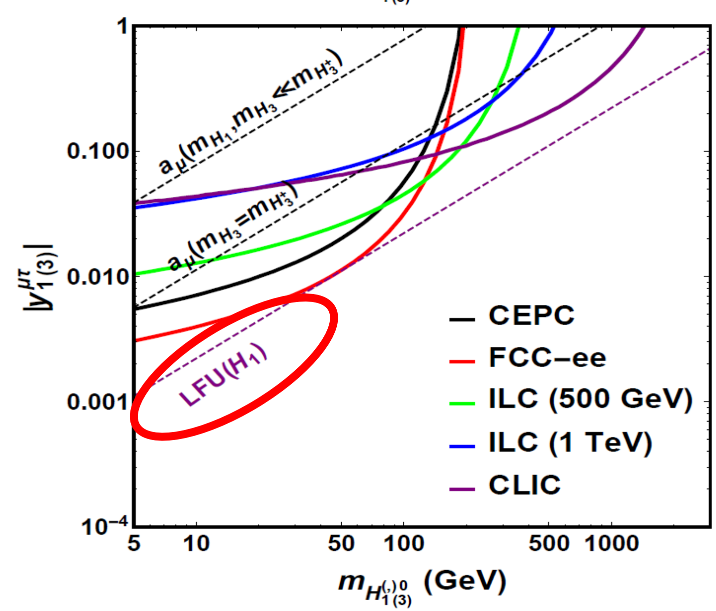


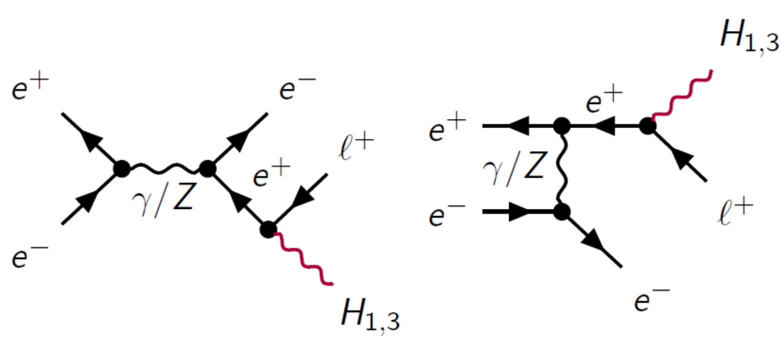


$H_{1\mu}$, $H'_{1\mu}$: on-shell production

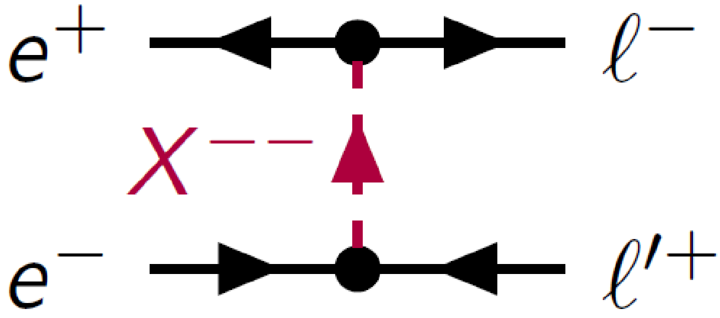




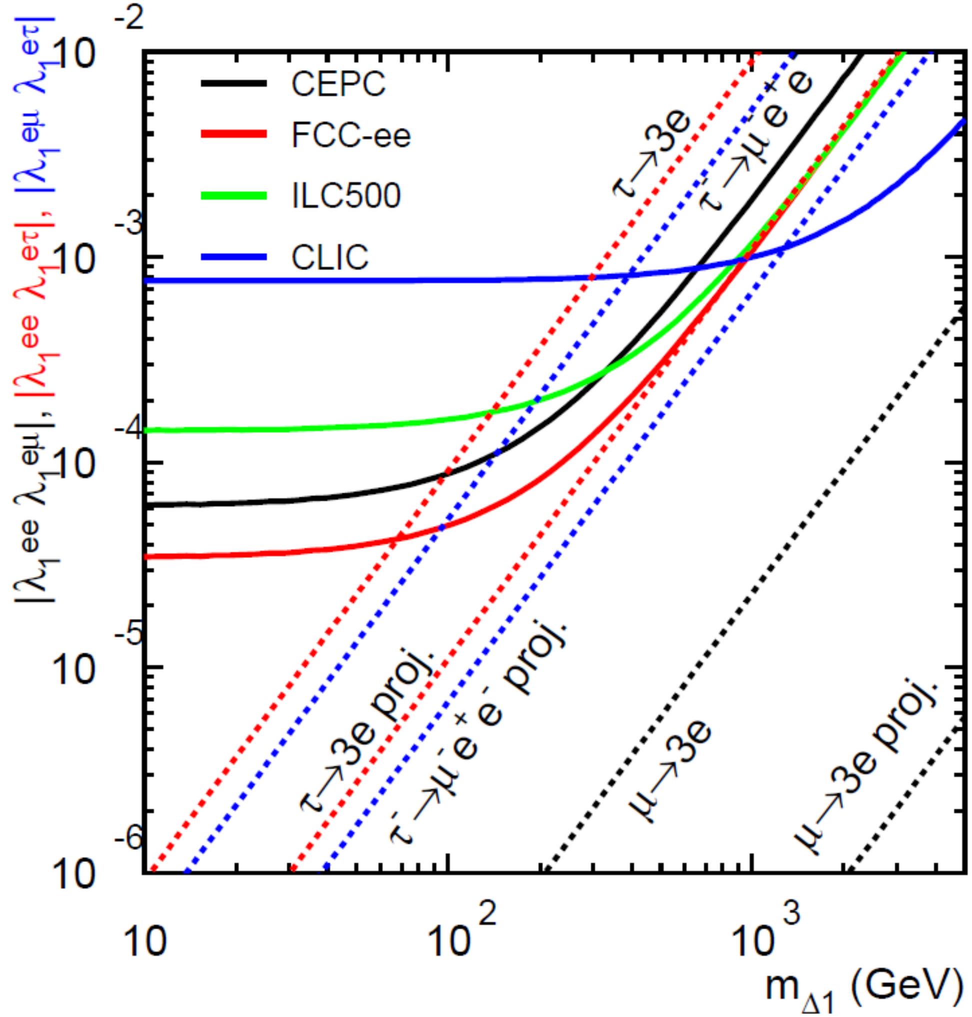




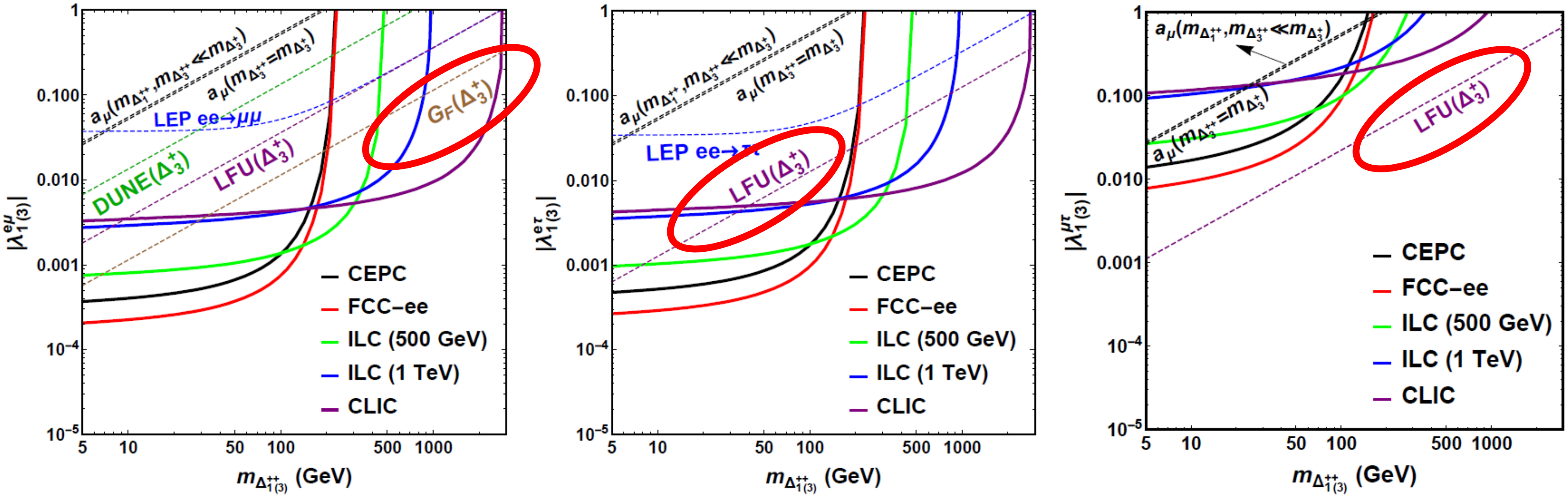
$\Delta_1^{++}, \Delta_3^{++}: e^+e^- \to e^\pm\mu^\mp, e^\pm\tau^\mp, \mu^\pm\tau^\mp$

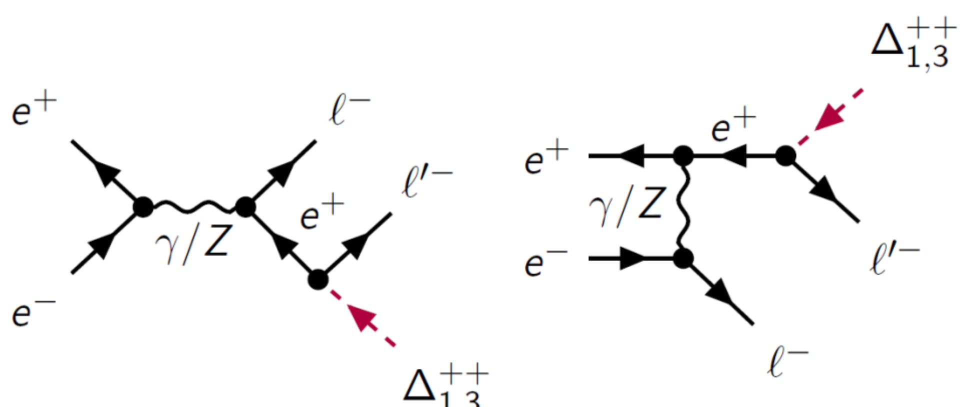


relevant couplings
$|\lambda^{ee}\lambda^{e\ell}|$ and $|\lambda^{e\mu}\lambda^{e\tau}|$



$\Delta_1^{++}, \Delta_3^{++}: e^+e^- \to l^\pm l'^\pm + \Delta_{1,3}^{\mp\mp}$





Summary

- The observation of cLFV process implies the existence of new physics beyond the SM
- Lepton colliders are ideal facilities to probe cLFV
- They can provide a complementary probe of cLFV couplings to low-energy precision experiments

Thank you!