# A Comparative Study of Searching for Charged Lepton Flavor Violation at future lepton colliders

JHEP 03,190 (2023). & Universe 10 (2024) 6, 243.

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# Outline

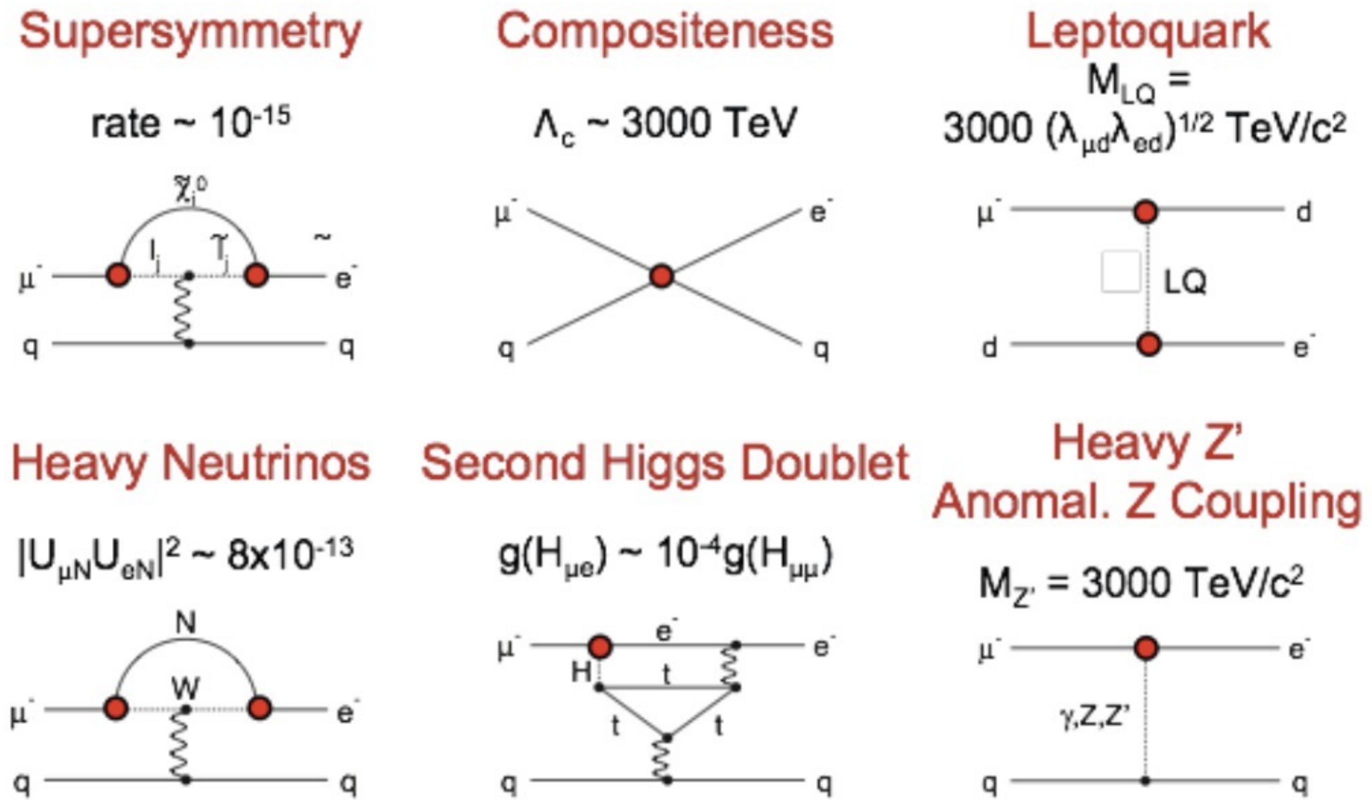
- Motivation
- Future colliders
- Search for CLFV with the Z’ model in future lepton colliders
- Search for R-parity Violation induced CLFV at future lepton colliders
- Summary

# Motivation


- Since LFV decay is forbidden in the SM, the observation of any LFV decay would be a signal of new physics beyond SM.
- In SM, Lepton Flavour is conserved for zero degenerate $\boldsymbol{\nu}$ masses and now we have clear indication that $\boldsymbol{\nu}$s have finite mass.

- Models may enhance LFV effects up to a detectable level, such as leptoquark, Compositeness, Supersymmetry, Heavy Z′ and Anomalous boson Coupling model.

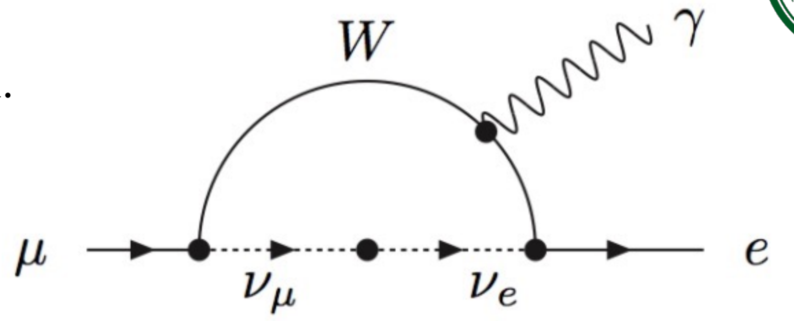
Eur. Phys. J. C57:13-182, 2008



# Motivation

In the charged lepton sector, LFV is heavily suppressed in the Standard Model.

$$BR(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i}U_{ei}\frac{\Delta m^2_{1i}}{M_W^2}\right|^2 < 10^{-54}$$

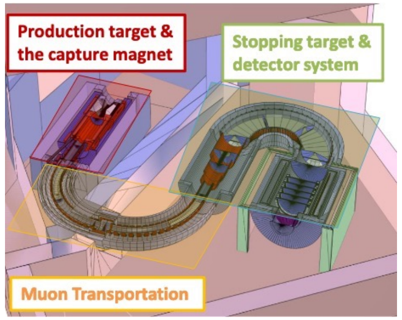



Neutrinoless muon decay

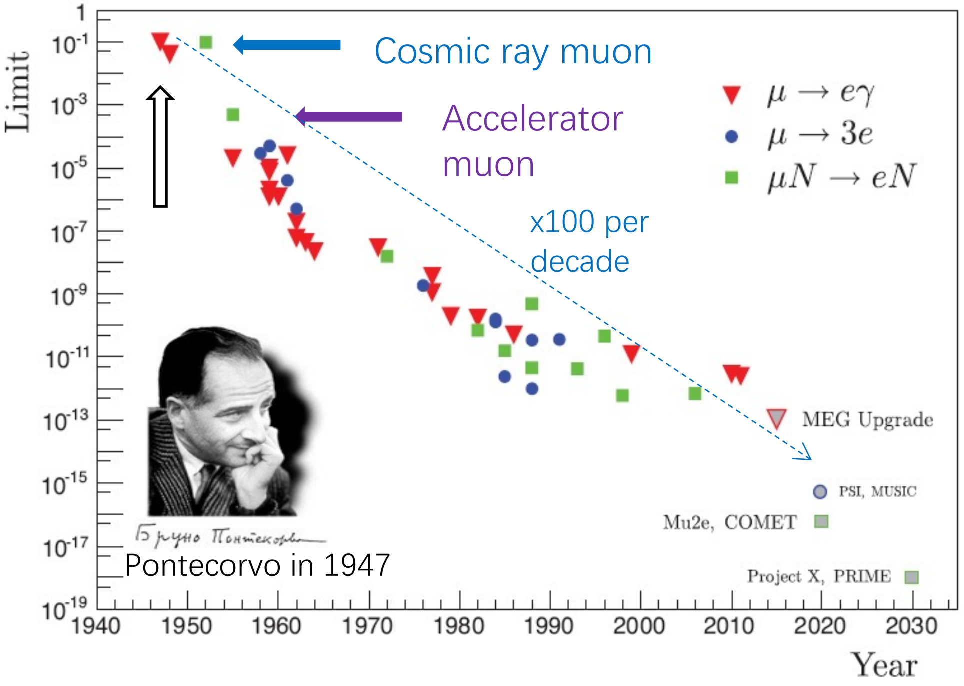
Nucl. Phys. 25, 340 (1977)
Phys. Rev. Lett. 104, 021802 (2010)
Nucl. Phys. B 299, 1 (1988).

- **Current limits:**
- $\mathcal{B}(\mu^+ \to e^+\gamma) < 3.1\times10^{-13}$ @ 90% C.L. MEGII ← Current best limit
- $\mathcal{B}(\tau^+ \to e^+\gamma) < 3.3\times10^{-8}$ @ 90% C.L. BABAR
- $\mathcal{B}(\mu \to 3e) < 1.0\times10^{-12}$ @ 90% C.L. SINDRUM
- $\mathcal{B}(Z \to e^\pm\mu^\mp) < 7.5\times10^{-7}$ @ 95% C.L. ATLAS
- $\mathcal{B}(\phi \to e^\pm\mu^\mp) < 2\times10^{-6}$ @ 90% C.L. SND
- $\mathcal{B}(J/\psi \to e^\pm\tau^\mp) < 7.1\times10^{-8}$ @ 90% C.L. BESIII
- $\mathcal{B}(J/\psi \to e^\pm\mu^\mp) < 4.5\times10^{-9}$ @ 90% C.L. BESIII

Eur. Phys. J. C 84, 216 (2024)
Phys. Rev. D 90, 072010 (2014)
Phys. Rev. D 81, 057102 (2010)
Phys. Lett. B 598, 172 (2004)
Phys. Rev. D 103, 112007 (2021)
Sci. Chin. Mech. Astron. 66 2 (2023)



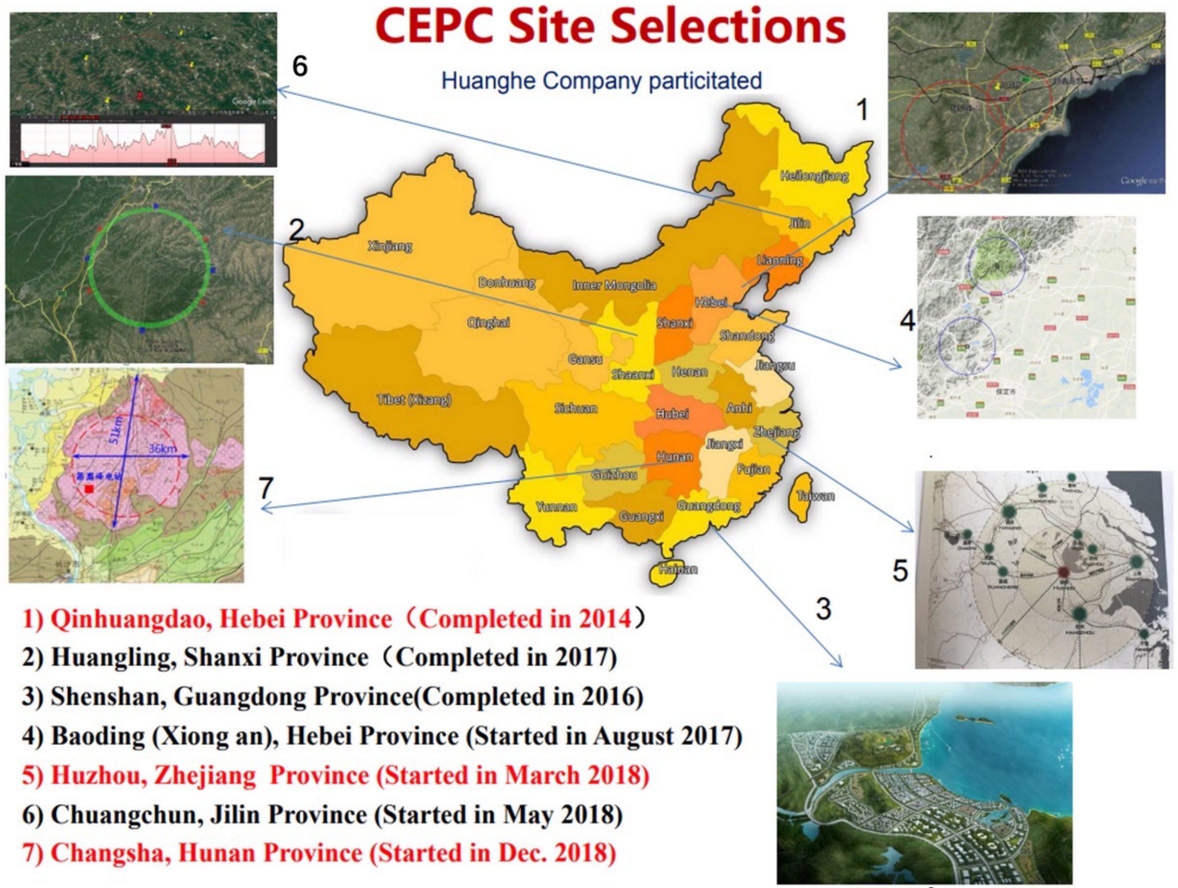

- Mu2e and COMET will search $\mu N \to eN$
  Improve the current limit by a factor of $10^4$
  Next goal $<6\times10^{-17}$ (90%C.L.)
- MEGII and Mu3e has similar beam requirements.
  Intensity $O(10^8$ muon/s), low momentum p = 28 MeV/c
  MEGII was started in 2021 and will continue to run until 2026 aiming at a sensitivity down to $6\times10^{-14}$ (90%C.L.)



# Future collider

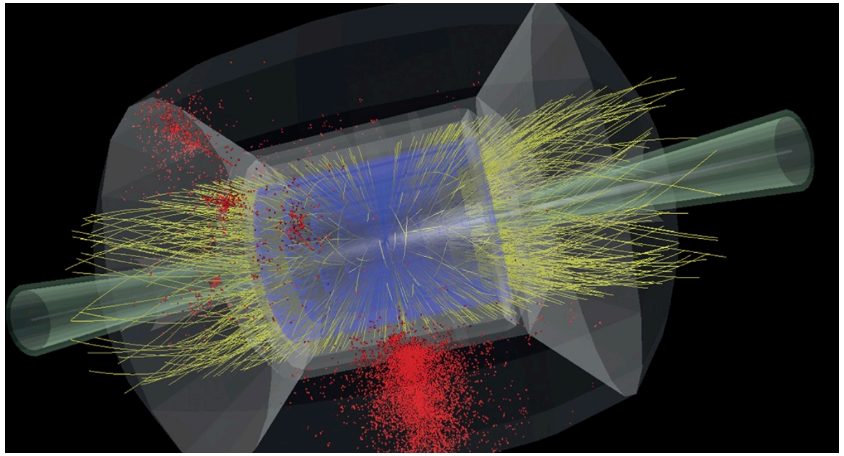
integrated luminosity $L \simeq 10\,\mathrm{ab}^{-1} \times \left(\sqrt{s}/10\,\mathrm{TeV}\right)^2$

## Circular Electron Positron Collider (CEPC)



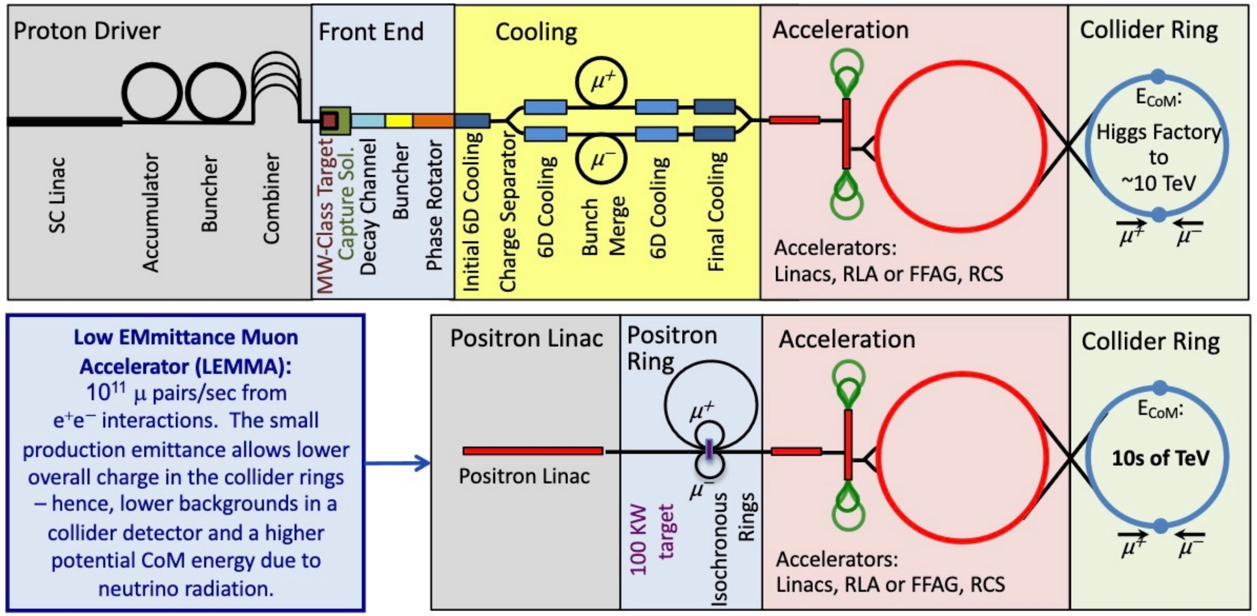

*large-scale high-energy physics experimental facility*
*perform high-precision detection of the Higgs boson*

JACoW IPAC2023 (2023) MOPL051
Radiat. Detect. Technol. Methods 8 (2024)



## Muon Collider

arXiv:1901.06150
JINST 19 (2024) 02, T02015
Eur.Phys.J.C 84 (2024) 1, 36



# Search for CLFV with the Z' model in future lepton colliders

# Z' model for CLFV

- A new *U*(1) gauge symmetry ➡ *Z'*
- *Z'* , a neutral vector boson with the same couplings to fermion-antifermion as the *Z*, but with a larger mass.
- May interact with different particles and produce different decay modes ➡ New physics
- May lead to the development of new technologies, such as higher-energy particle accelerators and more sensitive detectors.
- Searching for Z' ⬅ LHC, CERN, FNAL…

| $f$ | $\Gamma_{f\bar{f}}$ |
|---|---|
| $\ell$ | $\frac{\alpha M_{Z'}}{24 s_W^2 c_W^2}\left(1 - 4s_W^2 + 8s_W^4\right)$ |
| $\nu$ | $\frac{\alpha M_{Z'}}{24 s_W^2 c_W^2}$ |
| $u$ | $\frac{3\alpha M_{Z'}}{24 s_W^2 c_W^2}\left(1 - \frac{8}{3}s_W^2 + \frac{32}{9}s_W^4\right)$ |
| $d$ | $\frac{3\alpha M_{Z'}}{24 s_W^2 c_W^2}\left(1 - \frac{4}{3}s_W^2 + \frac{8}{9}s_W^4\right)$ |

$\alpha$: the fine structure constant

$M_{Z'}$: the mass of Z'

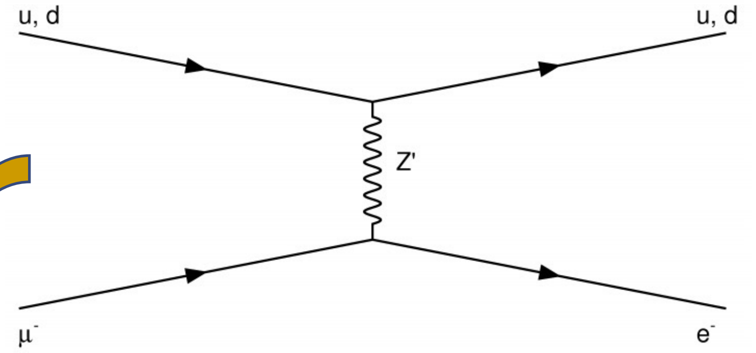
$c_W$ : the cosine of the weak mixing angle

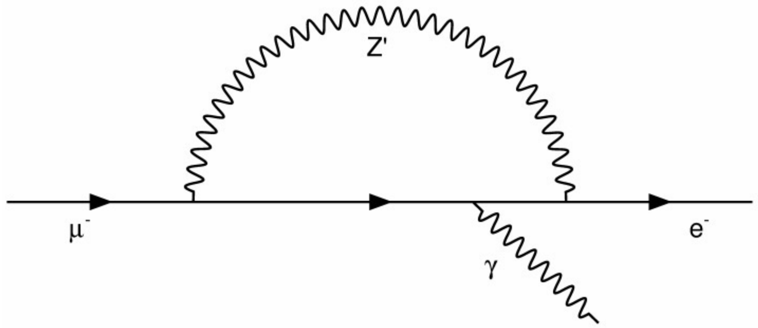
$s_W$ : the sine of the weak mixing angle

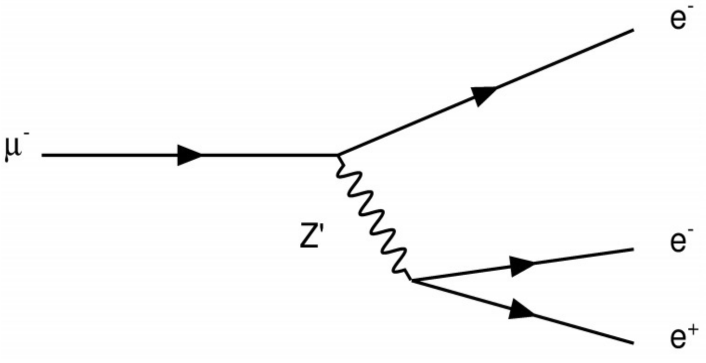
# Z′ model for CLFV

Phys. Rev. D 62, 013006 (2000)
Phys. Lett. B 723, 15, (2013)

- $\mu$ to $e$ conversion
- $\mu^- \to e^-\gamma$
- $\mu^- \to e^-e^- e^+$




$Z' - e - \mu$ coupling

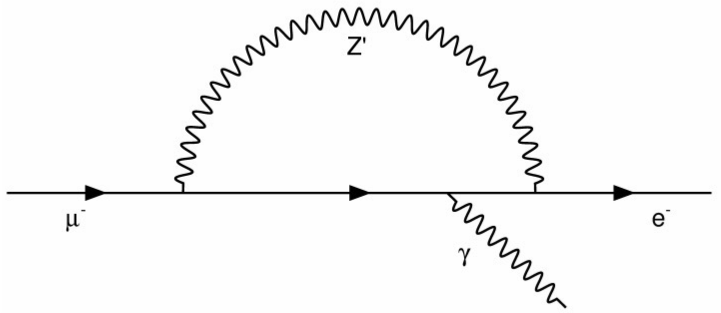
$$\lambda_{e\mu}^2 = \frac{2\pi^2 \Gamma_{capture} ZR}{G_F^2 \alpha^3 m_\mu^5 Z_{eff}^4 |F(q)|^2} \cdot \frac{M_{Z'}^4}{M_Z^4} \times \frac{1}{S_W^4 + \left(S_W^2 - \frac{1}{2}\right)^2} \times \frac{1}{\left[(2Z+N)\left(\frac{1}{2} - \frac{4}{3}S_W^2\right) + (Z+2N)\left(-\frac{1}{2} + \frac{2}{3}S_W^2\right)\right]^2}$$

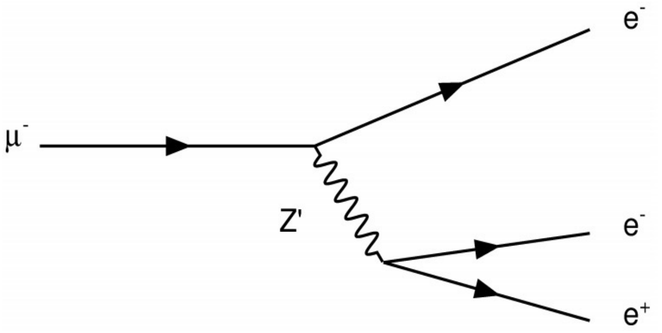
$G_F$: the Fermi constant, $\alpha$: the fine structure constant, $\Gamma_{capture}$ : nuclear muon capture rate,

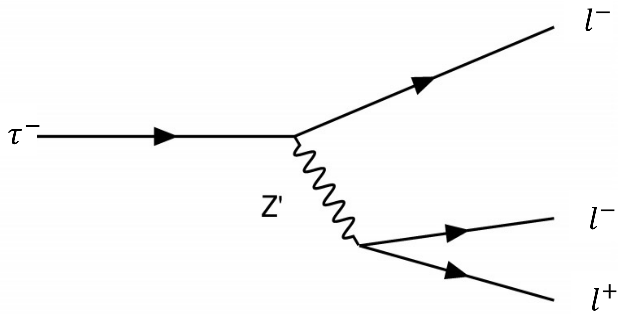
$Z_{eff}, F_p$: nuclear parameters, $Z$: the atomic number, $N$: the number of neutrons in the nucleus,

$S_w$ : the sine of the weak mixing angle, $M_{Z'}$: the mass of Z', $m_\mu$: the muon mass

# $Z'$ model for CLFV




- $\mu^- \to e^-\gamma$

$$BR(\mu \to e\gamma) = \frac{\Gamma_{\mu\to e\gamma}}{\Gamma_{\mu\to e\nu\nu}} = \frac{48\alpha}{\pi} S_W^4 \left(S_W^2 - \frac{1}{2}\right)^2 \lambda_{e\mu}^2 \cdot \frac{M_Z^4}{M_{Z'}^4}$$

- $\mu^- \to e^-e^-e^+$

$Z' - e - \mu$ coupling

$$BR(\mu \to eee) = \frac{\Gamma_{\mu\to eee}}{\Gamma_{\mu\to e\nu\nu}} = 4 \cdot \lambda_{e\mu}^2 \cdot \frac{M_Z^4}{M_{Z'}^4}\left[S_W^4 + \left(S_W^2 - \frac{1}{2}\right)^2\right]^2$$

- $\tau^- \to \mu^-\gamma$

$$BR(\tau \to \mu\gamma) = \frac{48\alpha}{\pi} S_W^4 \left(S_W^2 - \frac{1}{2}\right)^2 \lambda_{\mu\tau}^2 \cdot \frac{M_Z^4}{M_{Z'}^4} BR(\tau \to \mu\nu\nu)$$

- $\tau^- \to l^-l^-l^+$

$Z' - \mu - \tau$ coupling

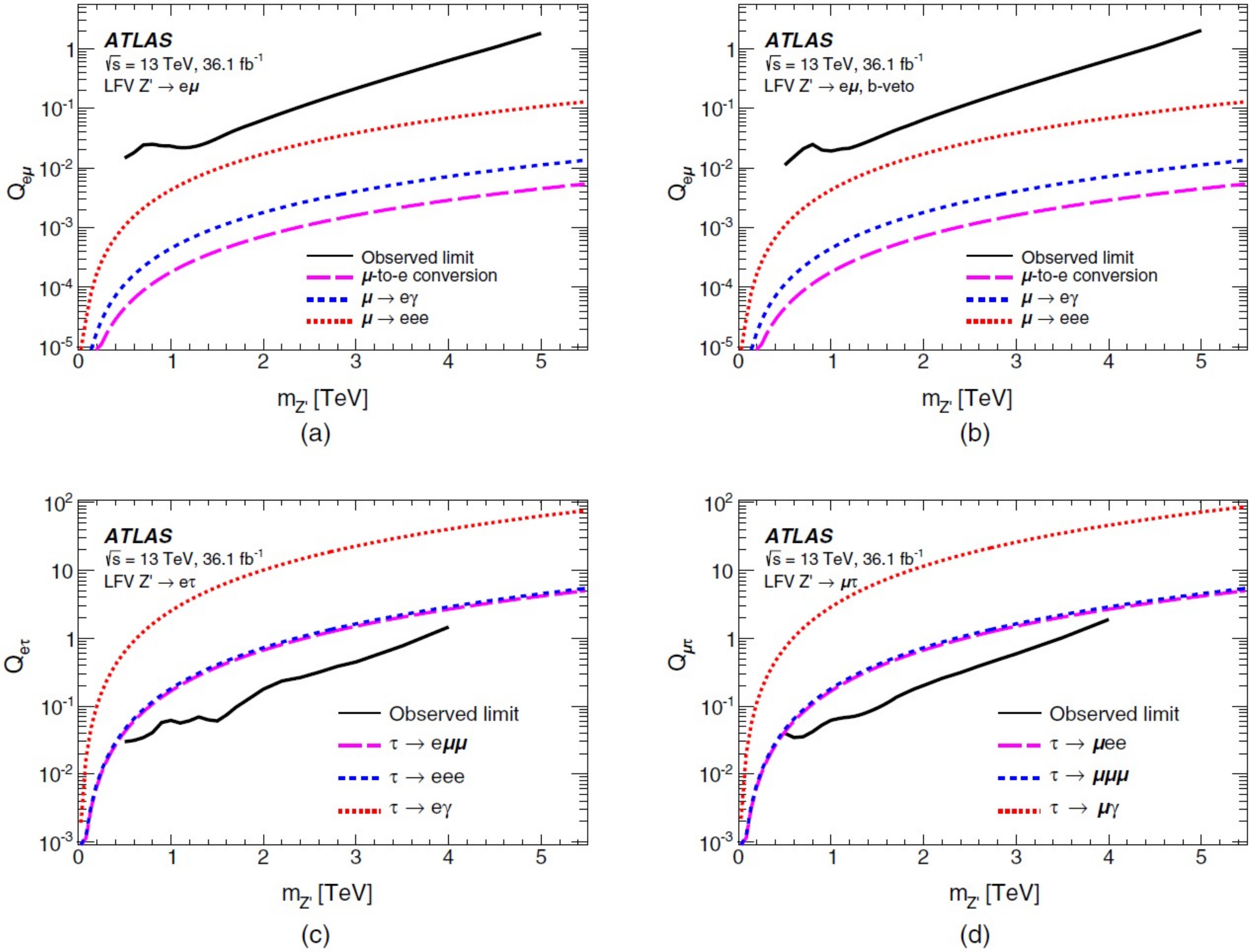
$$BR(\tau \to lll) = 4 \cdot \lambda_{\mu\tau}^2 \cdot \frac{M_{Z'}^4}{M_Z^4}\left[S_W^4 + \left(S_W^2 - \frac{1}{2}\right)^2\right]^2 BR(\tau \to \mu\nu\nu)$$

$\alpha$: the fine structure constant, $M_Z$: the Z boson mass,

$M_{Z'}$: the mass of Z', $S_w$ : the sine of the weak mixing angle


Phys. Rev. D 62, 013006 (2000)
Phys. Lett. B 723, 15, (2013)

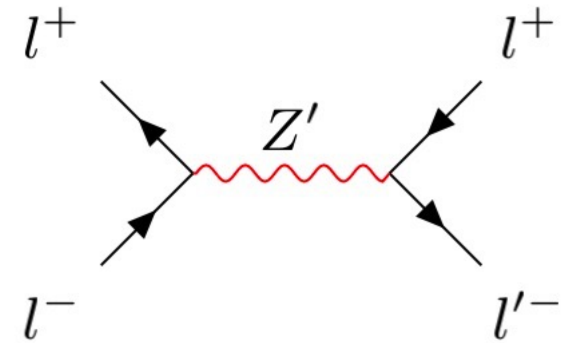
# ATLAS CLFV Z′ decay result

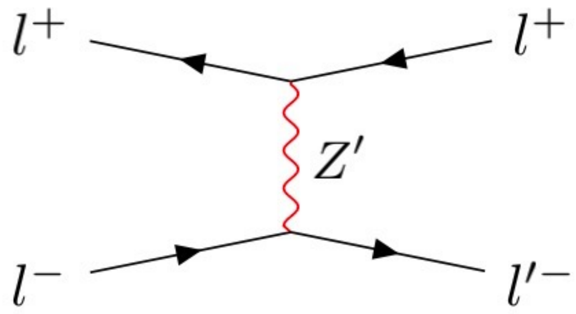



- The ATLAS cross-section times branching ratio limits (solid lines) compared with similar limits from low-energy experiments

Phys. Rev. D 98, 092008 (2018)

# Signal process



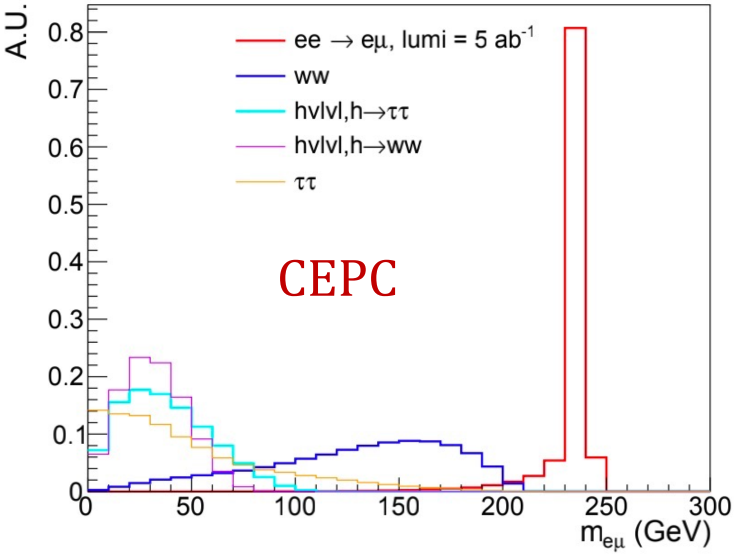



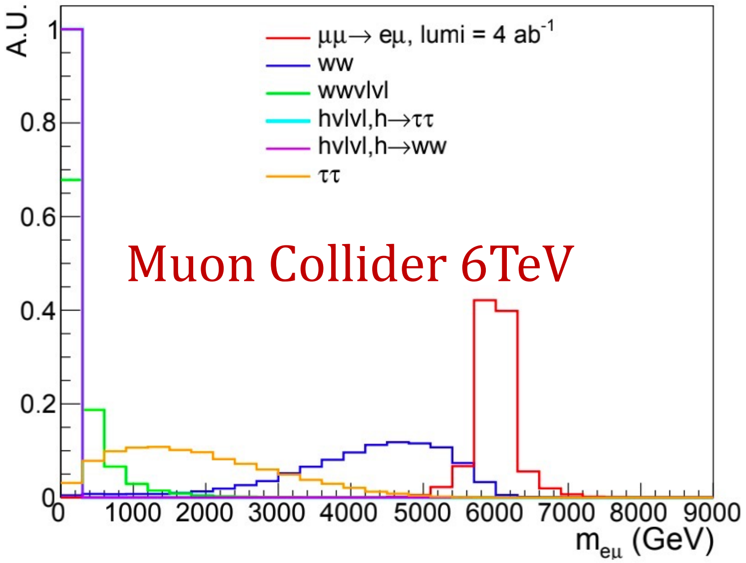

$$\lambda_{ij} = \begin{pmatrix} \lambda_{ee} & \lambda_{e\mu} & \lambda_{e\tau} \\ \lambda_{\mu e} & \lambda_{\mu\mu} & \lambda_{\mu\tau} \\ \lambda_{\tau e} & \lambda_{\tau\mu} & \lambda_{\tau\tau} \end{pmatrix}$$

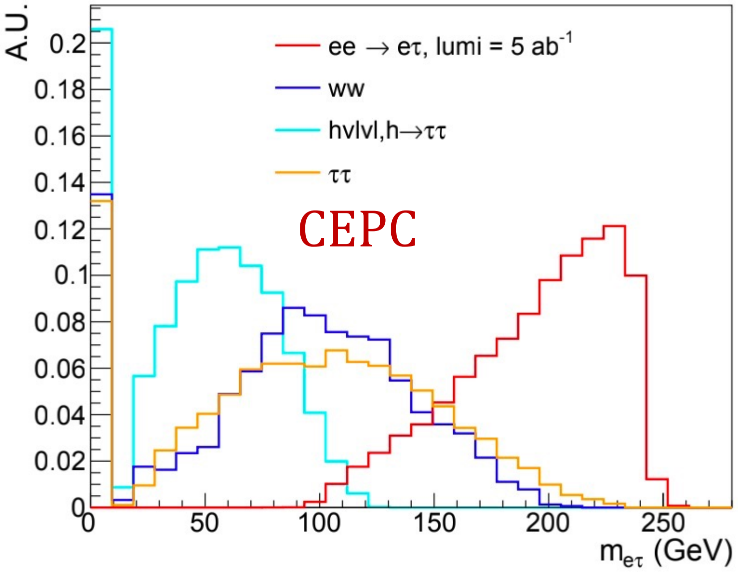
- CEPC: $ee \to e\mu, ee \to e\tau$
- Muon collider: $\mu\mu \to e\mu, \mu\mu \to \mu\tau$
- Only one CLFV coupling $\lambda_{ij}(i \neq j)$ is assumed to be non-zero while the diagonal couplings $\lambda_{ij}(i = j)$ are always set as 1.
- Using @Madgraph, @Pythia8 and @Delphes to generate.
- Table shows an example of the background corresponding to the signal process.

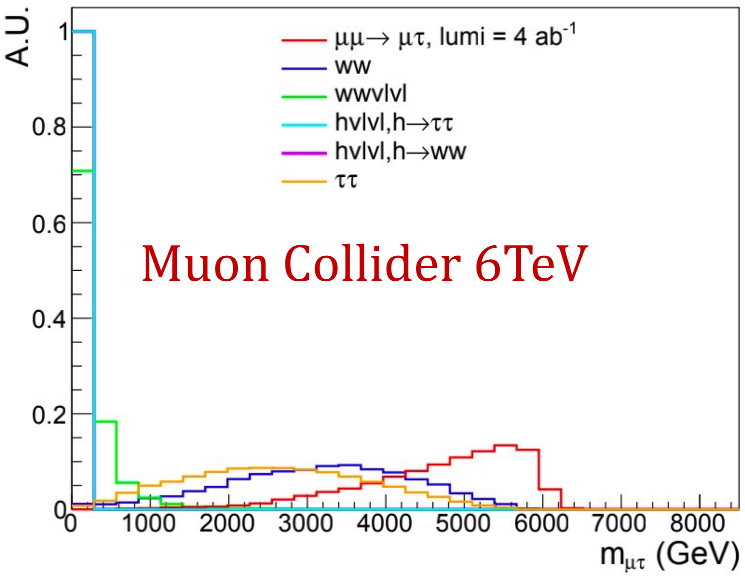
| process | Cross section(pb) |
|---|---|
| $ee \to e\mu$ | $4.04*10^{-5}$ |
| $ee \to \mathrm{ww}, \mathrm{w} \to e\nu, \mathrm{w} \to \mu\nu$ | 0.395 |
| $ee \to \tau\tau, \tau \to e\nu\nu, \tau \to \mu\nu\nu$ | 0.241 |
| $ee \to h\nu\nu, h \to \tau\tau, \tau \to e\nu\nu/\mu\nu\nu$ | $1.13*10^{-4}$ |
| $ee \to h\nu\nu, h \to \mathrm{ww}, \mathrm{w} \to e\nu/\mu\nu$ | $3.93*10^{-6}$ |

# Further cuts




- Using $e\mu, e\tau, \mu\tau$ invariant mass to separate the signal and the backgrounds.

| Collider | Cuts |
|---|---|
| CEPC | $m_{e\mu} > 220$ GeV |
| | $m_{e\tau} > 160$ GeV |
| 6TeV Muon Collider | $m_{e\mu} > 5.2$ TeV |
| | $m_{\mu\tau} > 4$ TeV |
| 14TeV Muon Collider | $m_{e\mu} > 10$TeV |
| | $m_{\mu\tau} > 9.5$ TeV |

Optimized by maximizing the FOM $\left(\frac{s}{\sqrt{s+b}}\right)$

# Analysis framework

- After all selections, get binned histograms on the final state lepton $p_T$ distributions
- Per-event weight to account for the cross-section difference: $n_{L_X} = \sigma_X L / N_X$
- Defined the negative log likelihood test statistics Z:

$\sigma_X$: cross section

$L$ : luminosity

$N_X$ : events generated

$$Z = \sum_{i=1}^{bins} Z_i$$

$$Z_i \coloneqq 2[n_i - b_i + b_i \ln(b_i/n_i)]$$ 95% C.L. Exclusion

$i$: the bin number, $s$: the beyond SM signal, $b$: the SM background

$n = s + b$ : the total yields containing both signal and background

- The Z statistic subjects to a $\chi^2$ distribution with 1 degree of freedom.

# Current and prospect limits

*Using the Z' model formula, these upper limits can be converted into coupling upper limits*

- $\mathcal{B}(\mu^- \to e^-\gamma) < 3.1\times10^{-13}$ @ 90% C.L. MEGII
- $\mathcal{B}(\mu^- N \to e^- N) < 7.0\times10^{-13}$ @ 90% C.L. Mu2e
- $\mathcal{B}(\mu^- \to e^-e^+e^-) < 1.0\times10^{-12}$ @ 90% C.L. Mu3e
- $\mathcal{B}(\tau^- \to e^-\gamma) < 3.3\times10^{-8}$ @ 90% C.L. BABAR
- $\mathcal{B}(\tau^- \to \mu^-\gamma) < 4.2\times10^{-8}$ @ 90% C.L. Belle
- $\mathcal{B}(\tau^- \to e^-e^+e^-) < 2.7\times10^{-8}$ @ 90% C.L. Belle
- $\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) < 2.1\times10^{-8}$ @ 90% C.L. Belle
- $\mathcal{B}(\tau^- \to \mu^-e^+e^-) < 1.8\times10^{-8}$ @ 90% C.L. Belle
- $\mathcal{B}(\tau^- \to e^-\mu^+\mu^-) < 2.7\times10^{-8}$ @ 90% C.L. Belle

Eur. Phys. J. C 84, 216 (2024)
Eur. Phys.J. C 47, 337 (2006)
Nucl. Phys. B 299, 1 (1988).
Phys. Rev. Lett. 104, 021802 (2010)
High Energ. Phys. 2021, 19 (2021)
Phys.Lett.B 687, 139 (2010)
Symmetry 13 no.9, 1591 (2021)
PTEP 3, 033C01 (2020)
arXiv:1501.05241
Nucl.Instrum.Meth.A 1014, 165679 (2021)

Current

- $\mathcal{B}(\mu^- \to e^-\gamma) < 6.0\times10^{-14}$ @ 90% C.L. MEGII
- $\mathcal{B}(\mu^- N \to e^- N) < 3.0\times10^{-17}$ @ 90% C.L. COMET
- $\mathcal{B}(\mu^- N \to e^- N) < 8.0\times10^{-17}$ @ 90% C.L. Mu2e
- $\mathcal{B}(\mu^- \to e^-e^+e^-) < 1.0\times10^{-16}$ @ 90% C.L. Mu3e
- $\mathcal{B}(\tau^- \to e^-\gamma) < 9.0\times10^{-9}$, $\mathcal{B}(\tau^- \to \mu^-\gamma) < 6.9\times10^{-9}$

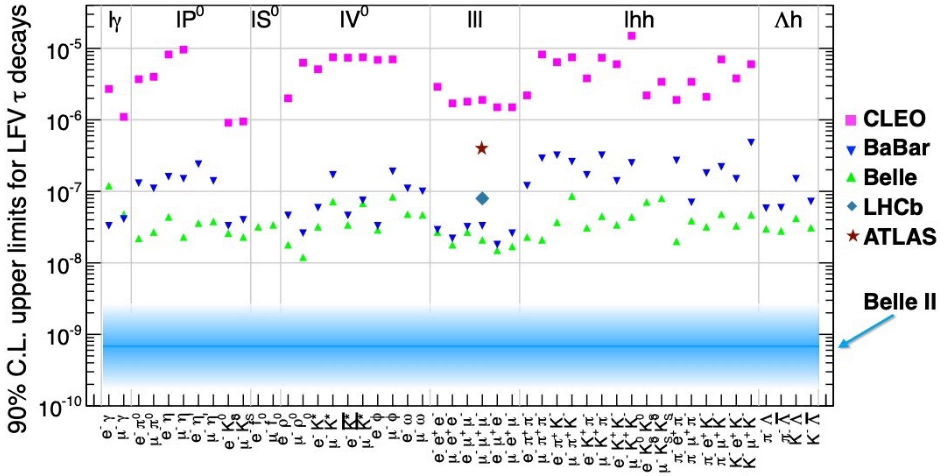
  $\mathcal{B}(\tau^- \to e^-e^+e^-) < 4.7\times10^{-10}$, $\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) < 3.6\times10^{-10}$

  $\mathcal{B}(\tau^- \to \mu^-e^+e^-) < 2.9\times10^{-10}$, $\mathcal{B}(\tau^- \to e^-\mu^+\mu^-) < 4.5\times10^{-10}$

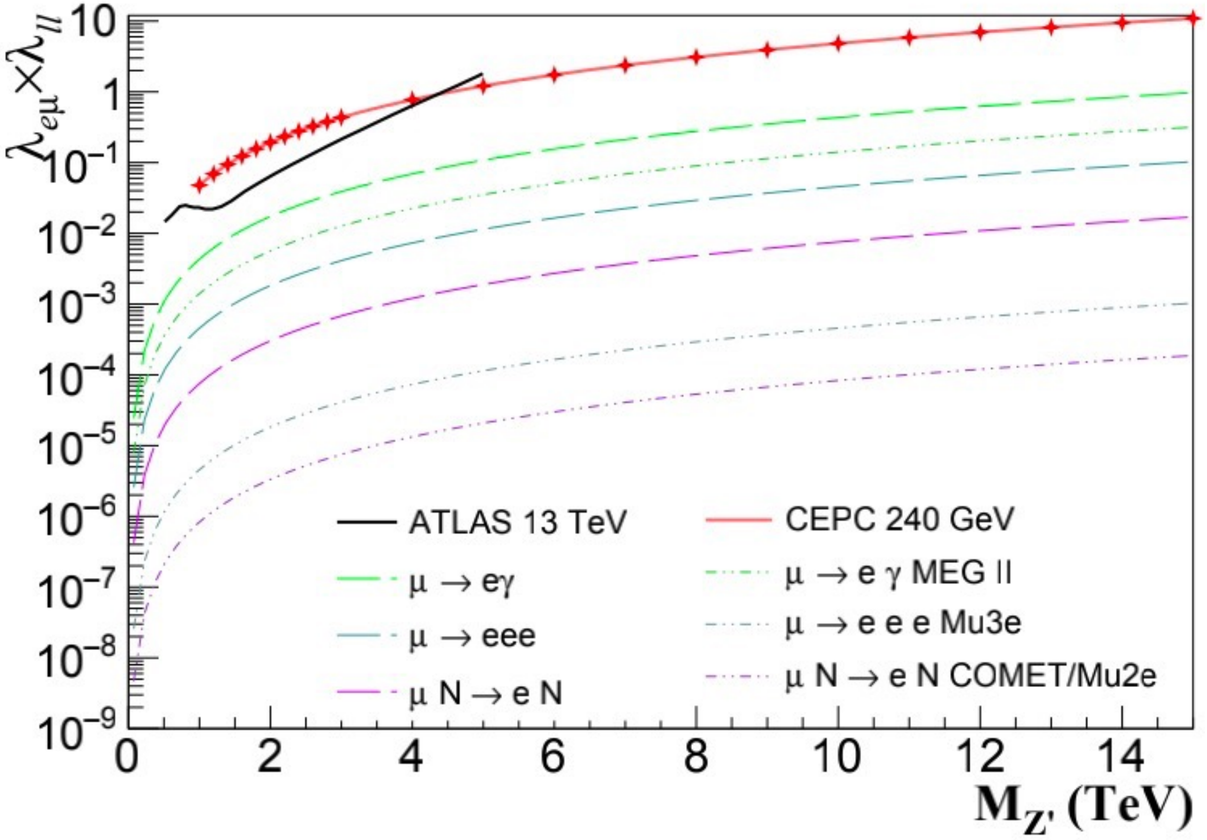
  @ 90% C.L. Belle II

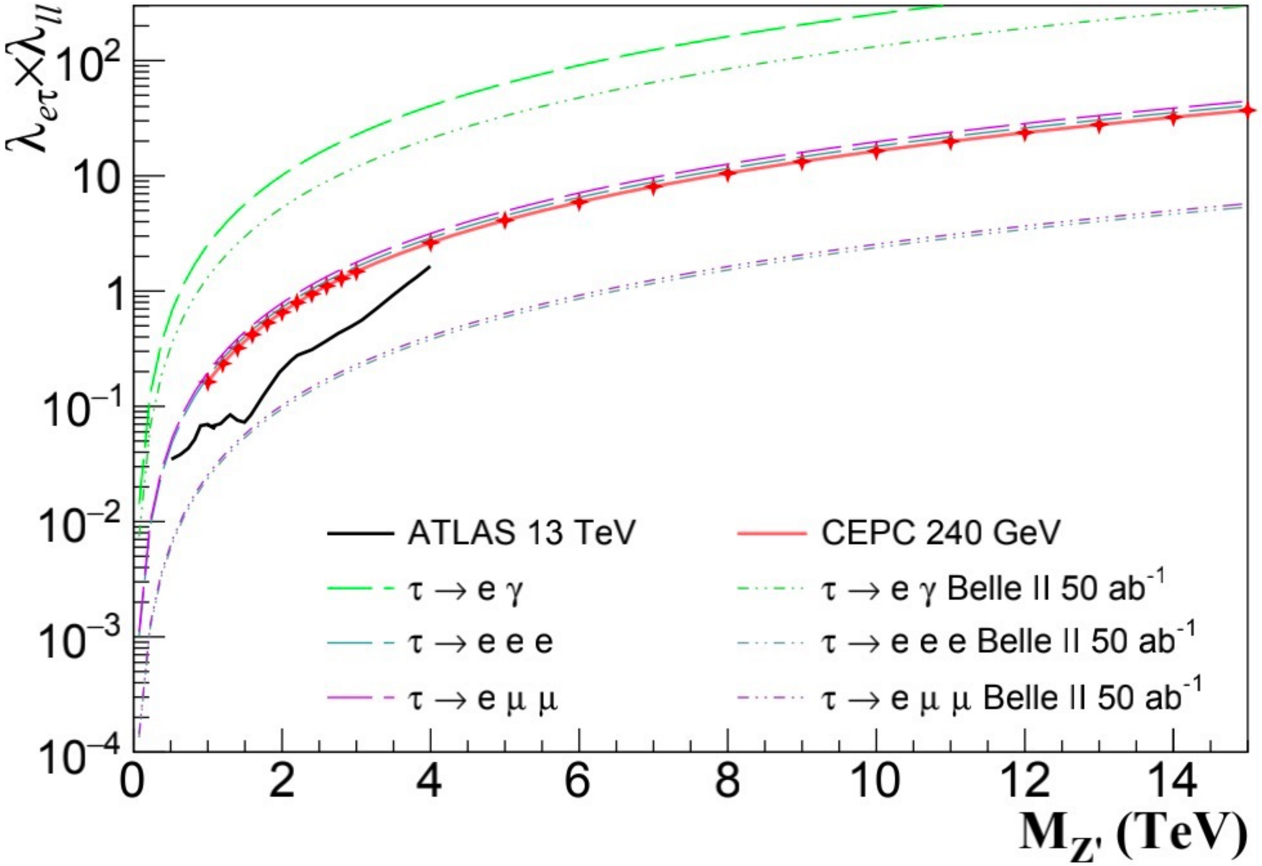
Universe 8 no.9, 480 (2022)

prospect



- The curves are plotted as functions of $M_{Z'}$ from the cross-section times branching ratio limits.

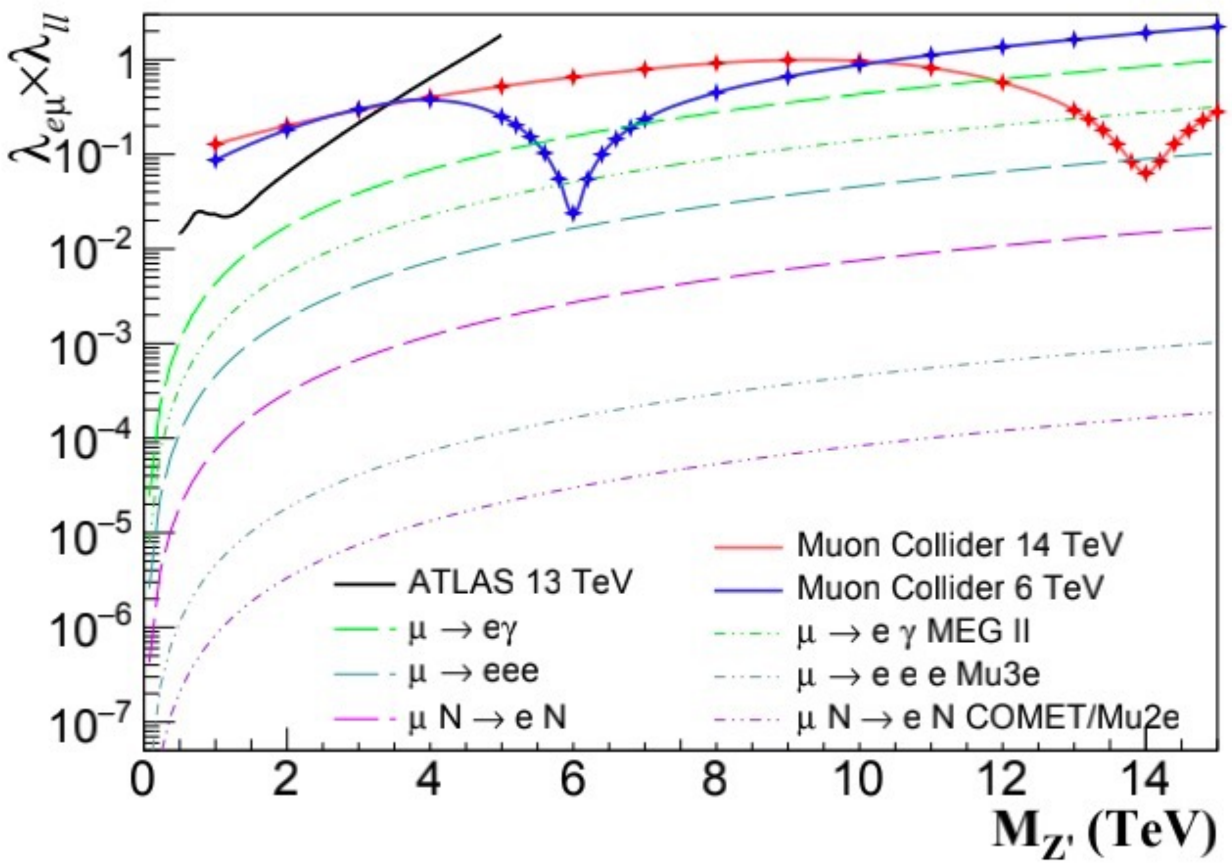


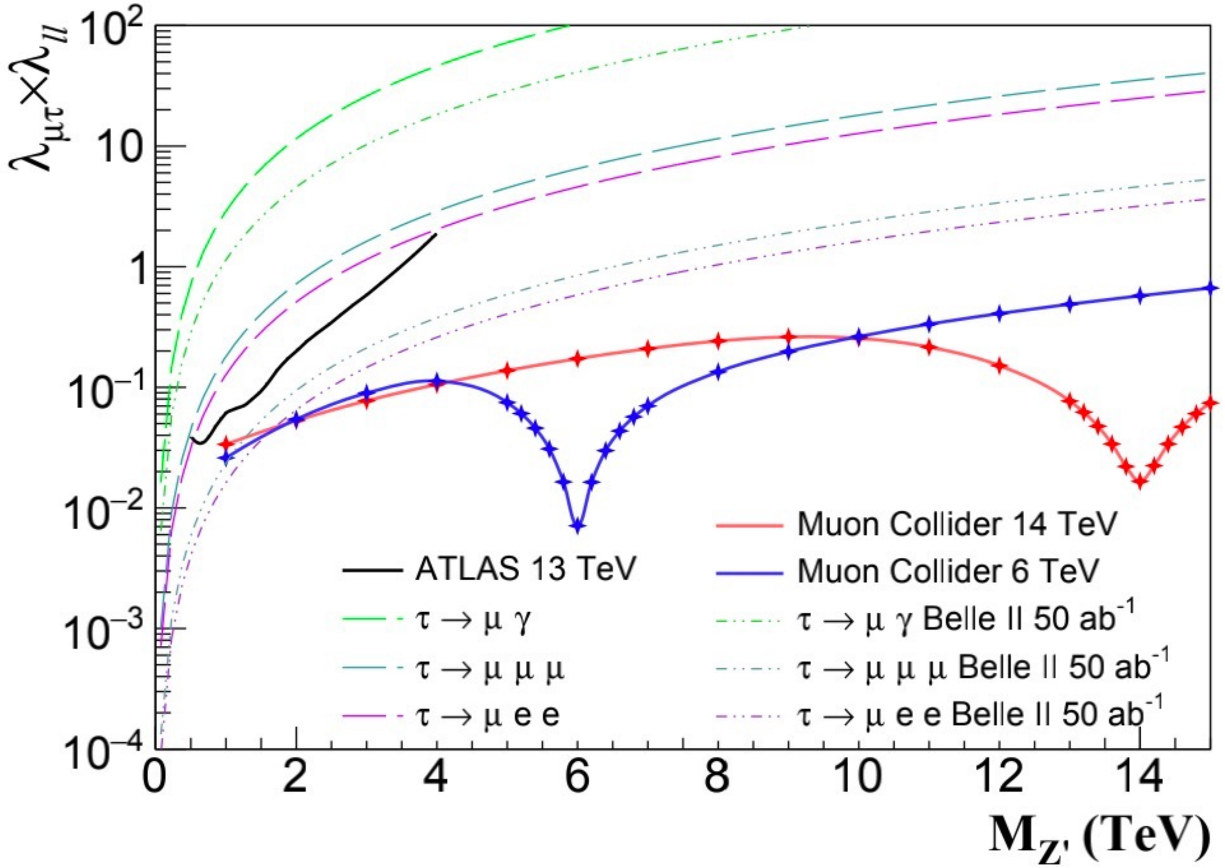




- Compared with the ATLAS experiment, current low-energy experiments (dashed lines) and future experiments (dash-dotted lines) .

# Upper limit on MuonC

- The curves are plotted as functions of $M_{Z'}$ from the cross-section times branching ratio limits.




- For $\mu\tau$ channel, the two coupling limits in this work are the most stringent when the mass of Z′ is greater than 1.5 TeV.

# Search for R-parity Violation induced CLFV at future lepton colliders

# R-parity

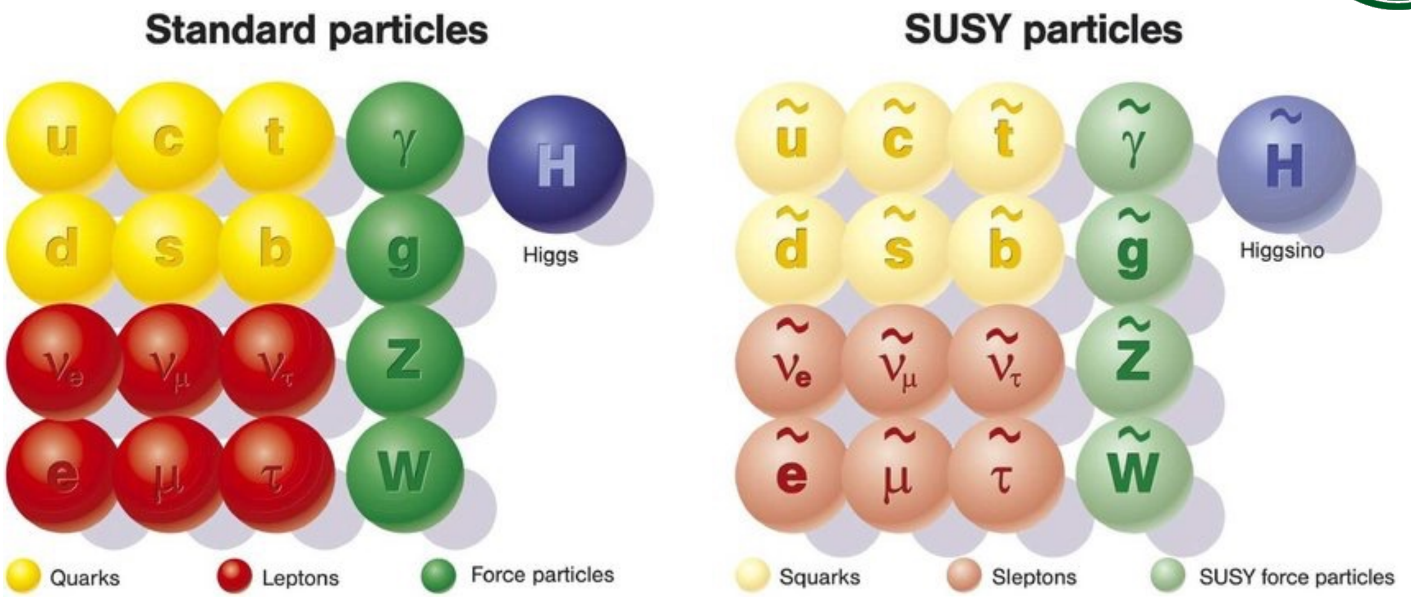
$$R\text{-parity} = (-1)^{2S}(-1)^{3B+L}$$

S自旋，B重子数，L轻子数

存在可重整耦合使得B和L守恒被破坏

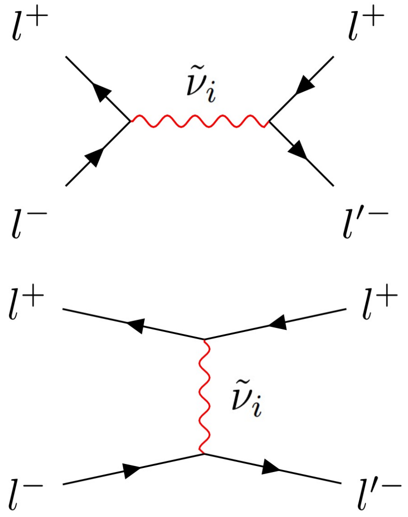
Phys. Rept., 420 (2005)

最小超对称标准模型 (MSSM)




◆ RPV CLFV 拉氏量

$$\mathcal{L}_I = -\frac{1}{2}\lambda_{ijk}\left(\tilde{\nu}_{iL}\bar{l}_{kR}l_{jL} + \tilde{l}_{jL}\bar{l}_{kR}\nu_{iL} + \tilde{l}^*_{kR}\bar{\nu}^c_{iR}l_{jL} - (i\leftrightarrow j)\right) - \lambda'_{ijk}\left(\tilde{\nu}_{iL}\bar{d}_{kR}d_{jL} + \tilde{d}_{jL}\bar{d}_{kR}\nu_{iL} + \tilde{d}^*_{kR}\bar{\nu}^c_{iR}d_{jL} - \tilde{l}_{iL}\bar{d}_{kR}u_{jL} - \tilde{u}_{jL}\bar{d}_{kR}l_{iL} - \tilde{d}^*_{kR}\bar{l}^c_{iR}u_{jL}\right) + \text{h.c.}$$

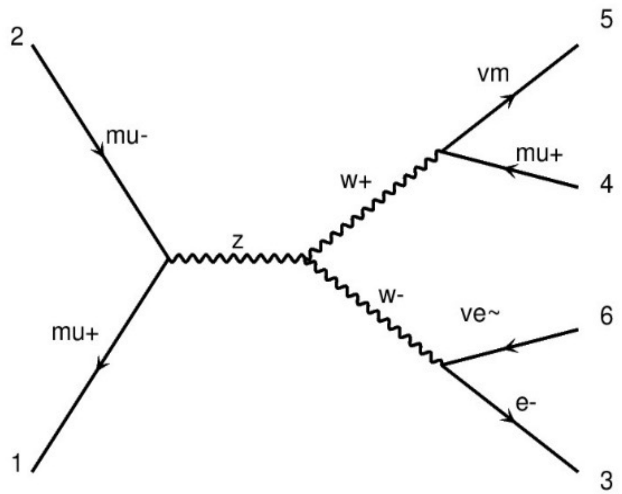


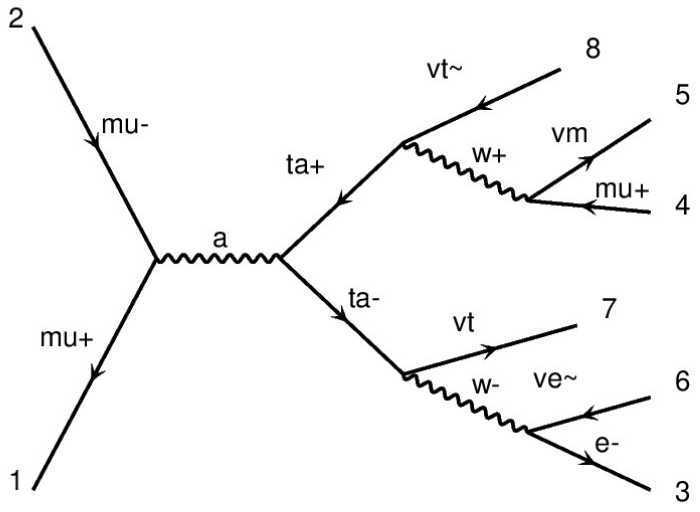

$v$: 中微子，$l$:带电轻子, u, $d$:上下夸克, 波浪号代表超对称伴子场

# Signal and Background process

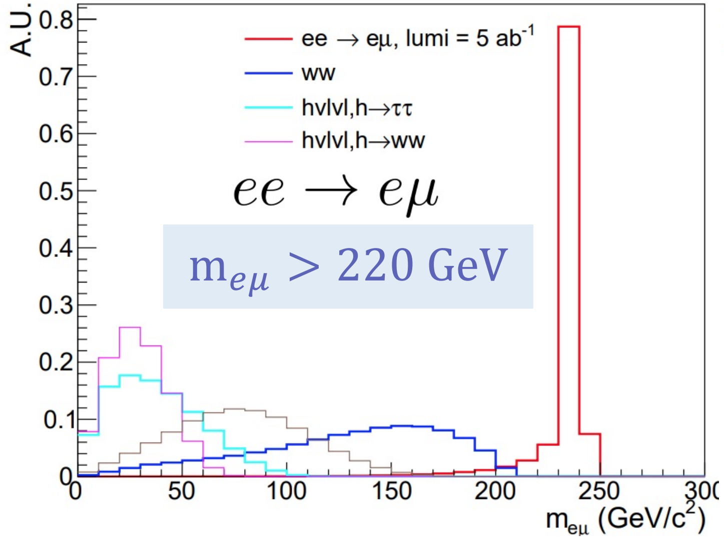
| Signal process | background process |
|---|---|
| $ee \to e\mu$ | $\mathrm{WW}, \mathrm{H}\nu\bar{\nu}(\mathrm{H} \to \tau\tau), \mathrm{H}\nu\bar{\nu}(\mathrm{H} \to \mathrm{WW}), \tau\tau$ |
| $ee \to e\tau$ | $\mathrm{WW}, \mathrm{H}\nu\bar{\nu}(\mathrm{H} \to \tau\tau), \tau\tau$ |
| $ee \to \mu\tau$ | $\mathrm{WW}, \mathrm{H}\nu\bar{\nu}(\mathrm{H} \to \tau\tau), \tau\tau$ |
| $\mu\mu \to e\mu$ | $\mathrm{WW}, \mathrm{WW}\nu\bar{\nu}, \mathrm{H}\nu\bar{\nu}(\mathrm{H} \to \tau\tau), \mathrm{H}\nu\bar{\nu}(\mathrm{H} \to \mathrm{WW}), \tau\tau$ |
| $\mu\mu \to e\tau$ | $\mathrm{WW}, \mathrm{WW}\nu\bar{\nu}, \mathrm{H}\nu\bar{\nu}(\mathrm{H} \to \tau\tau), \mathrm{H}\nu\bar{\nu}(\mathrm{H} \to \mathrm{WW}), \tau\tau$ |
| $\mu\mu \to \mu\tau$ | $\mathrm{WW}, \mathrm{WW}\nu\bar{\nu}, \mathrm{H}\nu\bar{\nu}(\mathrm{H} \to \tau\tau), \mathrm{H}\nu\bar{\nu}(\mathrm{H} \to \mathrm{WW}), \tau\tau$ |

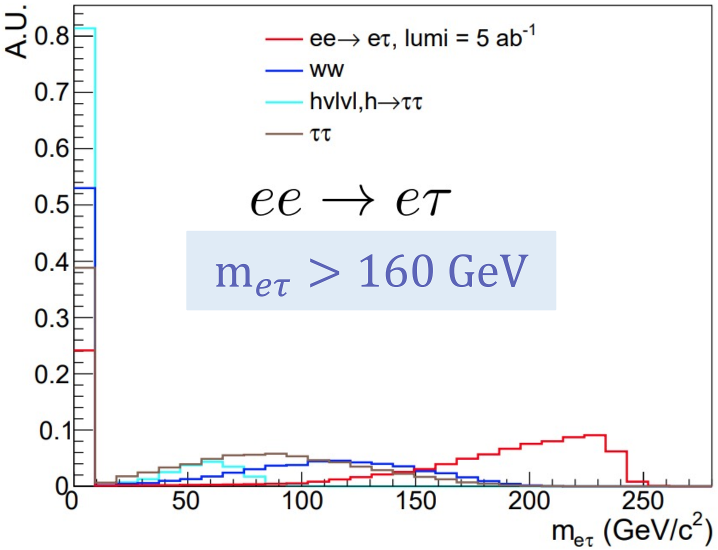
- For $\mu\mu \to e\mu$, shows the WW background and $\tau\tau$ background.
- Using @Madgraph, @Pythia8 and @Delphes to generate the processes

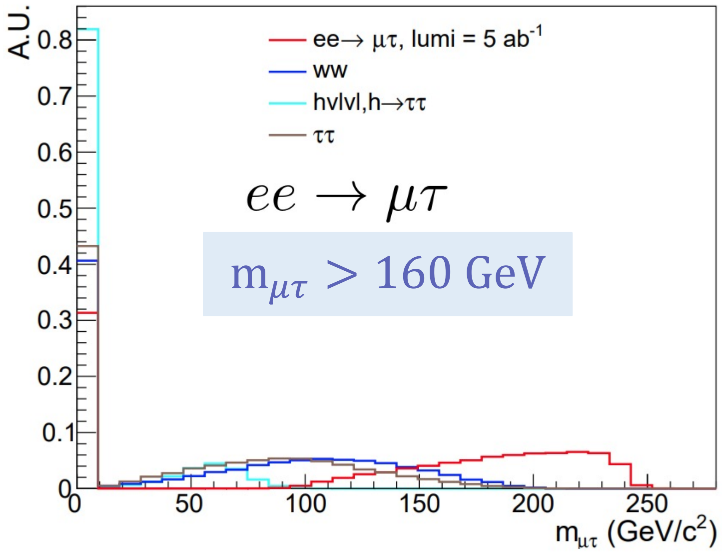


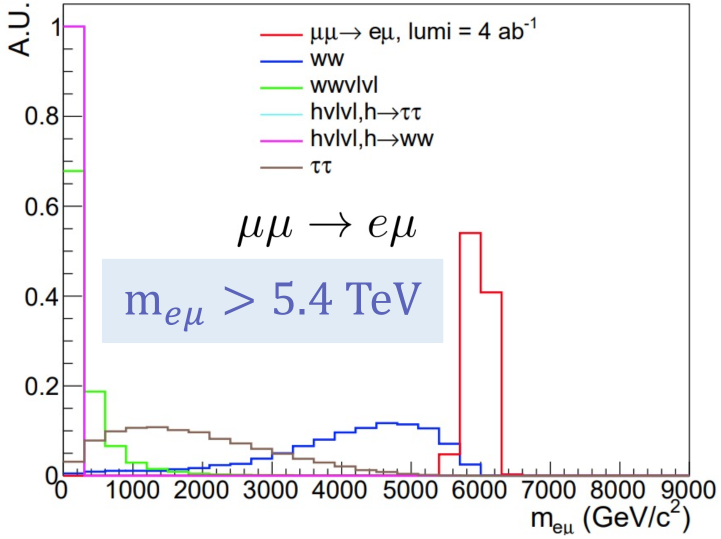
# Further cuts

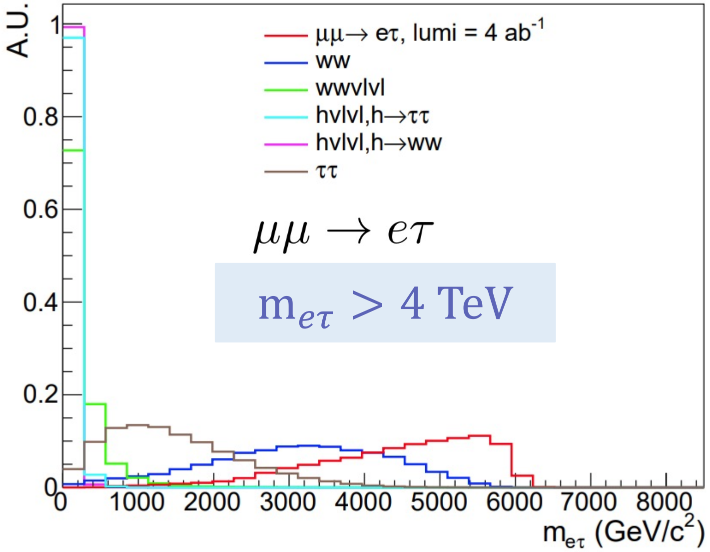


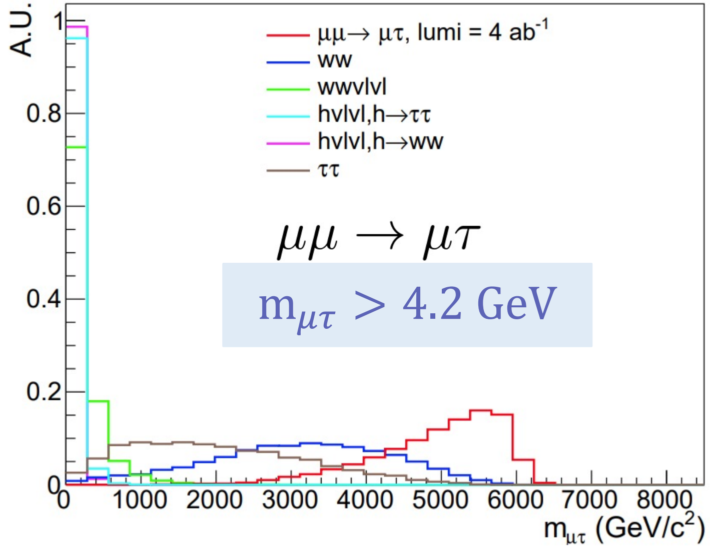




240GeV CEPC



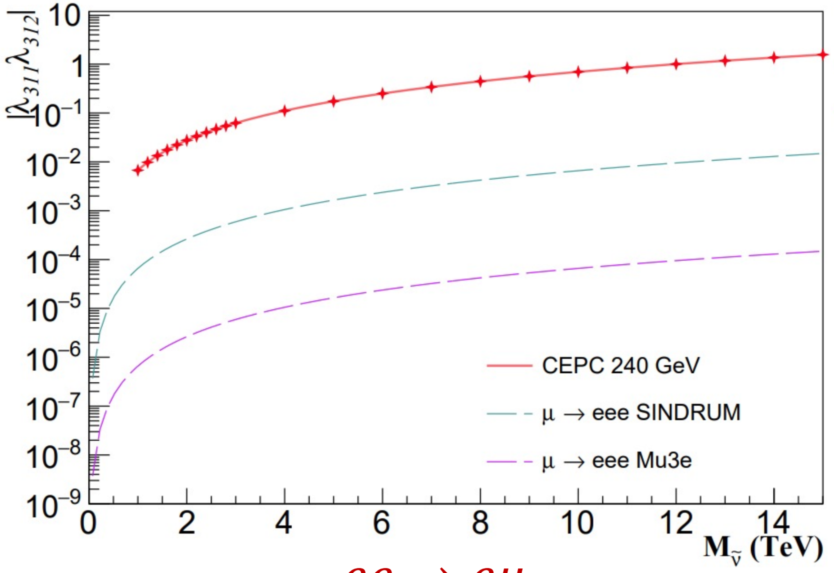




6TeV Muon Collider

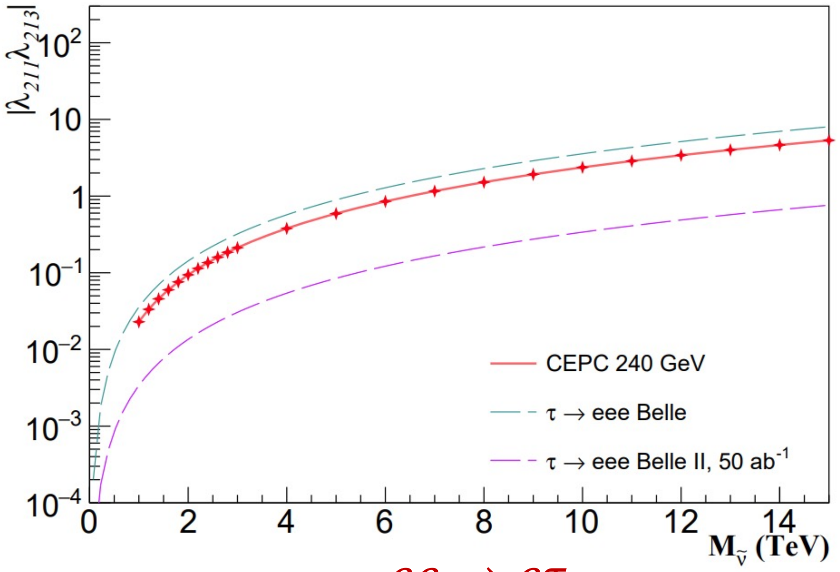
# Upper limit on CEPC

- The curves are plotted as functions of $M_{\tilde{\nu}}$ from the cross-section times branching ratio limits.



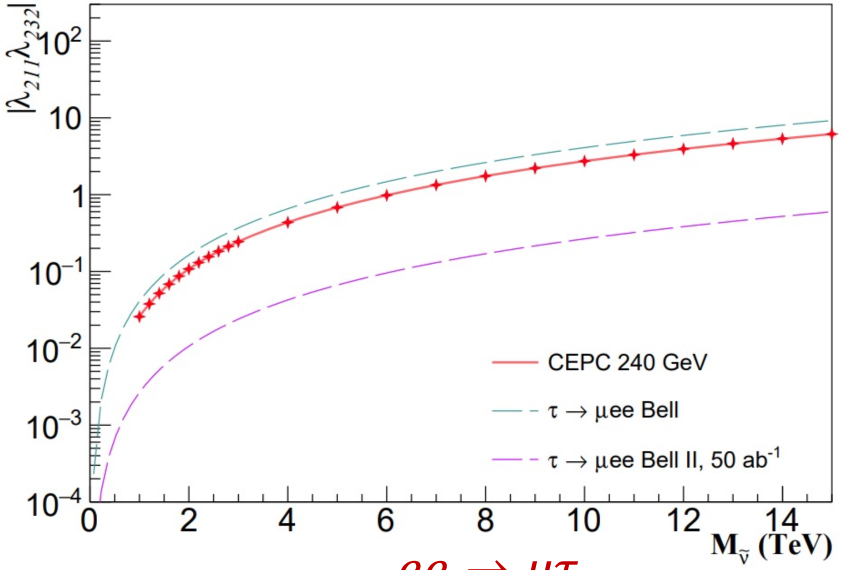

$ee \rightarrow e\mu$

$|\lambda_{311}\lambda_{312}|,\ |\lambda_{311}\lambda_{321}|,\ |\lambda_{211}\lambda_{212}|$




$ee \rightarrow e\tau$

$|\lambda_{211}\lambda_{213}|,\ |\lambda_{211}\lambda_{231}|,\ |\lambda_{311}\lambda_{313}|$



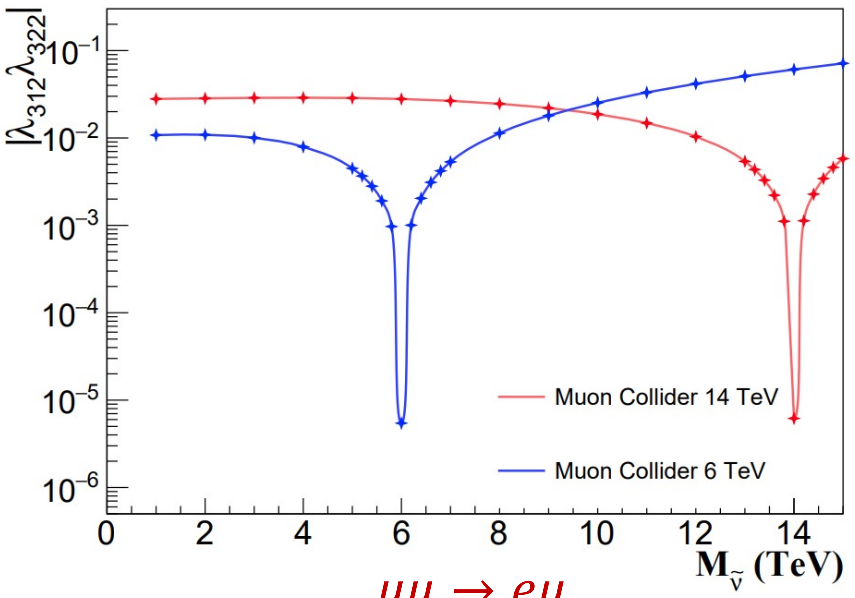

$ee \rightarrow \mu\tau$

$|\lambda_{211}\lambda_{232}|,\ |\lambda_{311}\lambda_{323}|$

- Compared with the SINDRUM, Mu3e, Belle and Belle2 experiment .

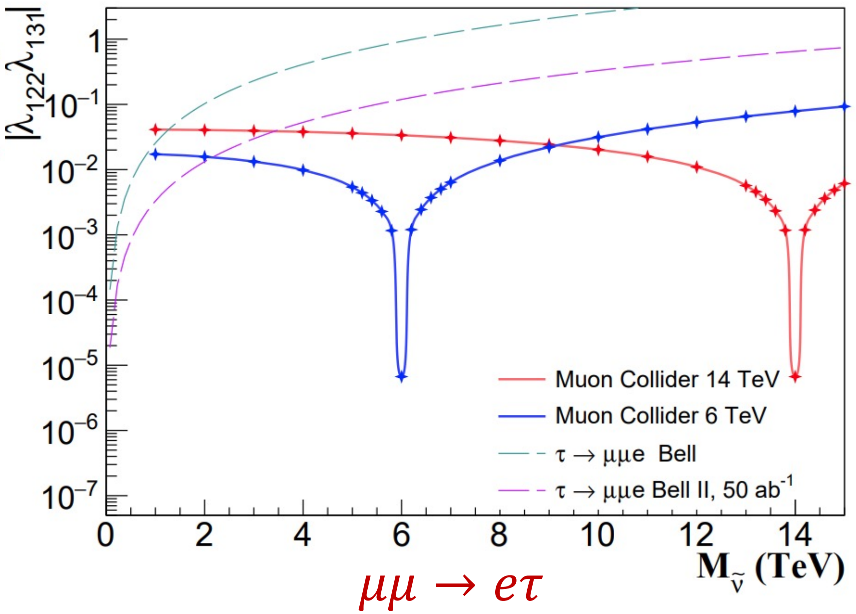
# Upper limit on MounC

- The curves are plotted as functions of $M_{\tilde{\nu}}$ from the cross-section times branching ratio limits.



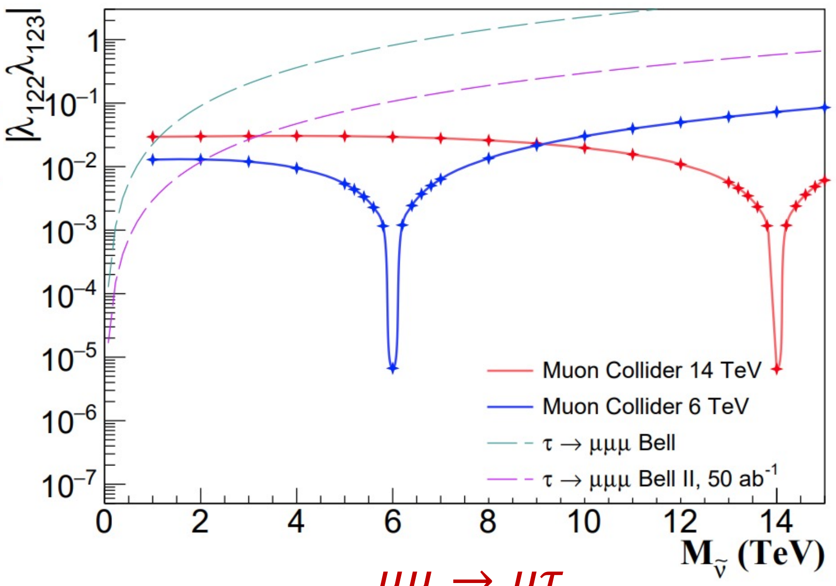

$\mu\mu \to e\mu$

$|\lambda_{312}\lambda_{322}|$, $|\lambda_{321}\lambda_{322}|$, $|\lambda_{121}\lambda_{122}|$




$\mu\mu \to e\tau$

$|\lambda_{122}\lambda_{131}|$, $|\lambda_{322}\lambda_{313}|$




$\mu\mu \to \mu\tau$

$|\lambda_{122}\lambda_{123}|$, $|\lambda_{122}\lambda_{132}|$, $|\lambda_{322}\lambda_{323}|$

- Compared with the Belle and Belle2 experiment .

# Summary

- The observation of any CLFV process would be a clear signal of new physics beyond the SM.
- Perform a detailed comparative study on CLFV searches at a 6 (14) TeV scale muon collider and a 240 GeV electron-positron collider.
- The $\tau$ related CLFV coupling strength will be significantly improved.

# Thank you!

中国物理学会高能物理分会
HIGH ENERGY PHYSICS BRANCH OF CPS

山东大学
SHANDONG UNIVERSITY

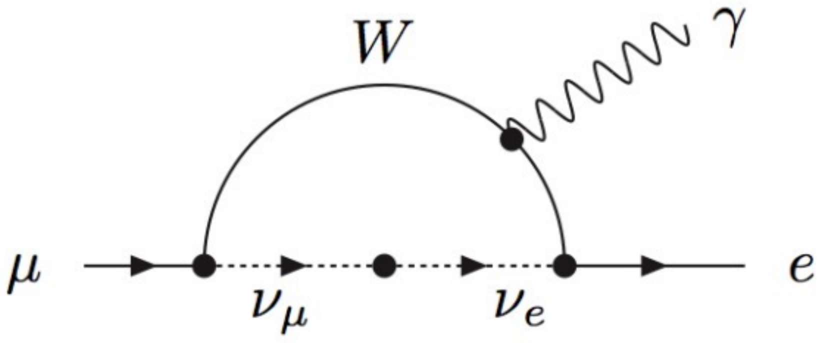
中山大学
SUN YAT-SEN UNIVERSITY

# Back up

$$\Gamma(\mu \to e\gamma) \approx \underbrace{\frac{G_F^2 m_\mu^5}{192\pi^3}}_{\mu-decay} \underbrace{\left(\frac{\alpha}{2\pi}\right)}_{\gamma-vertex} \underbrace{sin^2 2\theta sin^2\left(\frac{1.27\Delta m^2}{M_W^2}\right)}_{\vartheta-oscillation}$$

$$\approx \frac{G_F^2 m_\mu^5}{192\pi^3} \left(\frac{3\alpha}{32\pi}\right) \left(\frac{\Delta m_{23}^2 s_{13} c_{13} s_{23}}{M_W^2}\right)^2$$

with $\Delta \sim 10^{-3} eV^2, M_W \sim O(10^{11}) eV \approx \boldsymbol{O(10^{-54})}$



# Preliminary selection and efficiency

- The events are required to satisfy the requirements of lepton flavor and charge conservation, i.e., $e^+e^- \to e^+\mu^-$, all signal and background events are required to have one $e^+$ and one $\mu^-$.
- $e\mu$ final states:

$$p_T > 10\ \text{GeV}, |\eta| < 2.5$$

- Final state containing $\tau$:

$$p_T > 20\ \text{GeV}, |\eta| < 5$$

$p_T$ : the transverse momentum, $|\eta|$ : the pseudo-rapidity

- $\mu$ tracking efficiency

| Collider | Conditions | Efficiency |
|---|---|---|
| CEPC | $0.1 < \|\eta\| \leq 3$ | 100% |
| | $\|\eta\| > 3$ | 0% |
| Muon Collider | $\|\eta\| < 2.0,\ 0.5 < p_T < 1$ GeV | 95% |
| | $\|\eta\| \leq 2.0,\ p_T > 1$ GeV | 99% |
| | $2.0 < \|\eta\| < 2.5,\ 0.5 < p_T \leq 1$ GeV | 90% |
| | $2.0 < \|\eta\| < 2.5,\ p_T > 1$ GeV | 95% |
| | $\|\eta\| > 2.5$ | 0% |

- $\tau$ tagging efficiency

| Collider | Efficiency |
|---|---|
| CEPC | 40% |
| Muon Collider | 80% |

# Background process

## CEPC

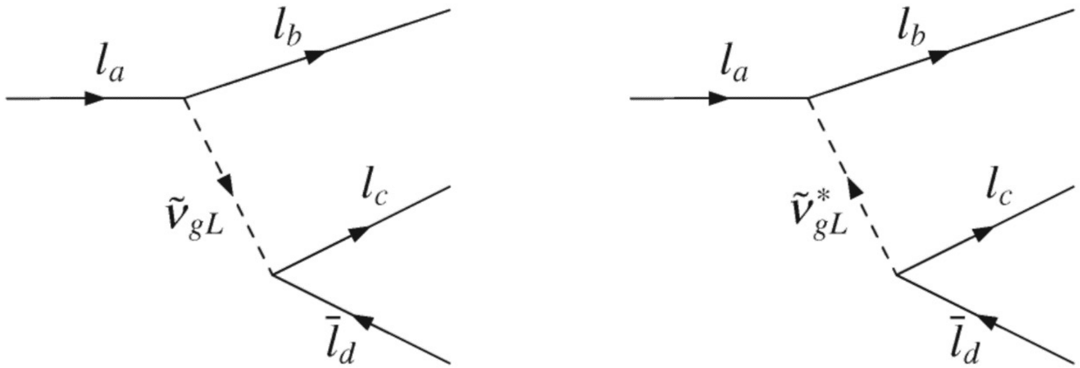
| process | Cross section(pb) |
|---|---|
| $ee \to e\mu$ | 4.04*10$^{-5}$ |
| $ee \to ww, w \to e\nu, w \to \mu\nu$ | 0.395 |
| $ee \to \tau\tau, \tau \to e\nu\nu, \tau \to \mu\nu\nu$ | 0.241 |
| $ee \to h\nu\nu, h \to \tau\tau, \tau \to e\nu\nu/\mu\nu\nu$ | 1.13*10$^{-4}$ |
| $ee \to h\nu\nu, h \to ww, w \to e\nu/\mu\nu$ | 3.93*10$^{-6}$ |
| $ee \to e\tau$ | 6.94*10$^{-5}$ |
| $ee \to ww, w \to e\nu, w \to \tau\nu$ | 3.733 |
| $ee \to \tau\tau, \tau \to \mu\nu\nu$ | 0.658 |
| $ee \to h\nu\nu, h \to \tau\tau, \tau \to \mu\nu\nu$ | 4.28*10$^{-3}$ |

- Control $\tau$ decay to $\mu$ in MG5, and control another $\tau$ to hadrons in Pythia8.
- For the $\tau$ final state, only the hadronized $\tau$ is considered, the cross section needs to × 60%.

## Muon Collider

| process | Cross section(pb) |
|---|---|
| $\mu\mu \to e\mu$ (14TeV collider) | 3.38*10$^{-4}$ |
| $\mu\mu \to ww\nu\nu, w \to e\nu, w \to \mu\nu$ | 0.013 |
| $\mu\mu \to ww, w \to e\nu, w \to \mu\nu$ | 7.71*10$^{-4}$ |
| $\mu\mu \to \tau\tau, \tau \to e\nu\nu, \tau \to \mu\nu\nu$ | 3.20*10$^{-5}$ |
| $\mu\mu \to h\nu\nu, h \to \tau\tau, \tau \to e\nu\nu/\mu\nu\nu$ | 2.22*10$^{-3}$ |
| $\mu\mu \to h\nu\nu, h \to ww, w \to e\nu/\mu\nu$ | 7.68*10$^{-5}$ |
| $\mu\mu \to \mu\tau$ (6TeV collider) | 0.042 |
| $\mu\mu \to ww\nu\nu, w \to \tau\nu, w \to \mu\nu$ | 6.47*10$^{-3}$ |
| $\mu\mu \to ww, w \to \tau\nu, w \to \mu\nu$ | 3.40*10$^{-3}$ |
| $\mu\mu \to \tau\tau, \tau \to \mu\nu\nu$ | 9.81*10$^{-4}$ |
| $\mu\mu \to h\nu\nu, h \to \tau\tau, \tau \to \mu\nu\nu$ | 2.28*10$^{-3}$ |
| $\mu\mu \to h\nu\nu, h \to ww, w \to \tau\nu/\mu\nu$ | 2.92*10$^{-5}$ |

a, b, c, d: 带电轻子, g: 代表超中微子的世代， a → $bcd$的衰变宽度为




$$\begin{cases} \Gamma_{a\to bc\bar{d}} = \dfrac{m_{la}^5}{6144\pi^3 m_{\tilde{\nu}g}^4}\left(\lambda_{gdc}^2\lambda_{gba}^2 + \lambda_{gcd}^2\lambda_{gab}^2 + \lambda_{gdb}^2\lambda_{gca}^2 + \lambda_{gbd}^2\lambda_{gac}^2\right) & b \neq c \\ \Gamma_{a\to bb\bar{d}} = \dfrac{m_{l_a}^5}{6144\pi^3 m_{\tilde{\nu}_{gL}}^4}\left(\lambda_{gdb}^2\lambda_{gba}^2 + \lambda_{gbd}^2\lambda_{gab}^2\right). & b = c \end{cases}$$

可以把实验得到的分支比上界转换到耦合常数的上界[11]，
从而使得模拟结果可以与实验结果对比

[11] Dreiner et al., Bounds on R-parity violating supersymmetric couplings from leptonic and semi-leptonic meson decays arXiv: hep-ph/0612278