Study of cLFV process on electron muon collider

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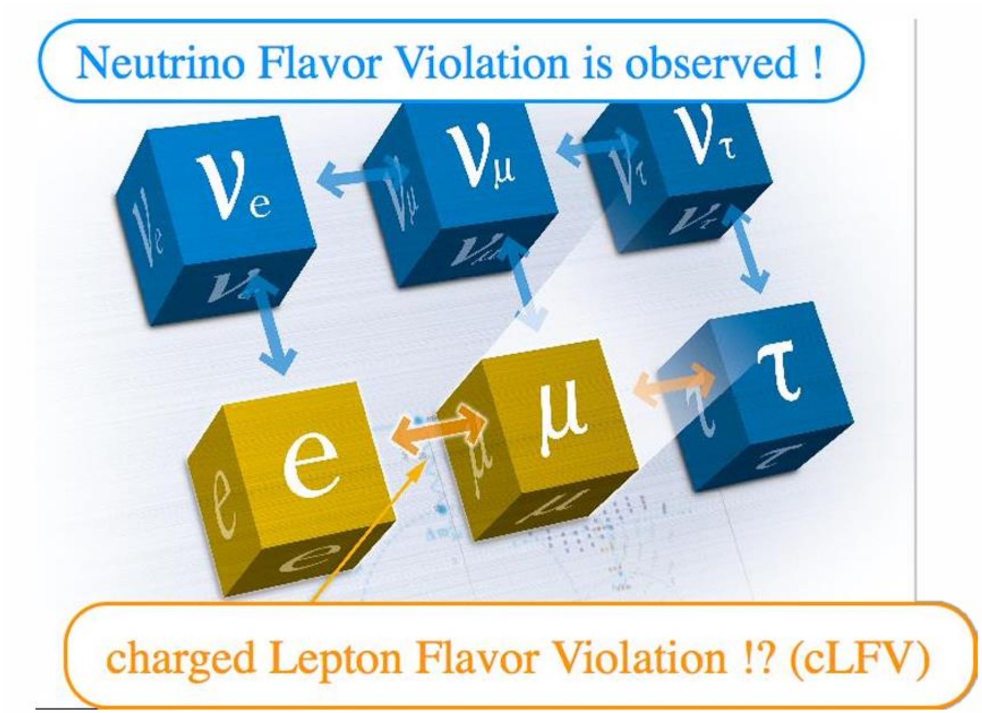
Outline

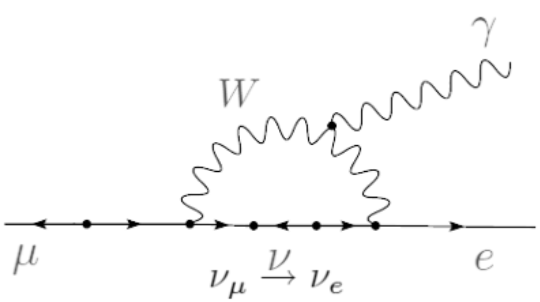
- Motivation
- Z’ model and cLFV process
- Electron muon collider
- Event simulation
- Background study
- Sensitivity result
- Summary

Motivation

◻ Charge lepton flavor violation

- Strongly suppress in SM
- Enhance by many BSM models:
  supersymmetry, leptoquark,
  Higgs-doublet, compositeness,
  heavy Z' ......
- A clear signal to new physics





$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i}U_{ei}\frac{\Delta m^2_{i1}}{M^2_W}\right|^2 \sim 10^{-54}$$

Z' model and cLFV process

- an extra U(1) gauge symmetry

$\rightarrow$ massive neutral gauge boson (Z')

predicted by many BSM models

- Generally, similar quark coupling and chiral structure as SM Z_0

- In leptonic decays, lepton flavor violation is allowed

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

$\Rightarrow$ gives the strength of the cLFV couplings relative to the SM couplings

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

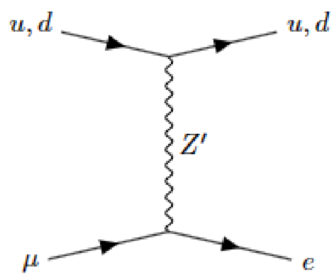
$M_{Z'}$: mass of Z'

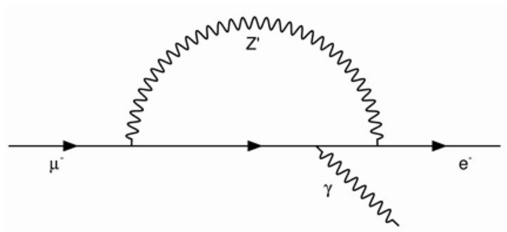
α: fine structure constant

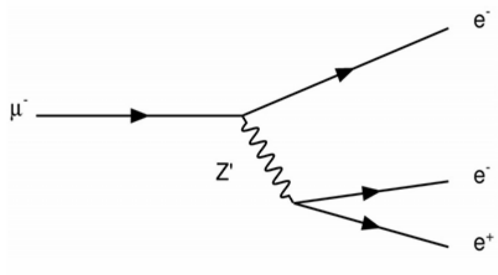
s_W: sine of the weak mixing angle

c_W: cosine of the weak mixing angle

Z' model and cLFV process







- **μ to e conversion** $$R = \lambda_{e\mu}^2 \frac{G_F^2 \alpha^3 m_\mu^5 Z_{eff}^4 |F(q)|^2}{2\pi^2 \Gamma_{\text{capture}} Z} \cdot \left(\frac{M_Z}{M_{Z'}}\right)^4 f(s_W, Z, N)$$
- $\boldsymbol{\mu^- \to e^- e^- e^+}$ $$Br(\mu \to eee) = 4\,\lambda_{e\mu}^2 \left(\frac{M_Z}{M_{Z'}}\right)^4 \left[s_W^4 + \left(s_W^2 - \frac{1}{2}\right)^2\right]^2$$
- $\boldsymbol{\mu^- \to e^- \gamma}$ $$Br(\mu \to e\gamma) = \lambda_{e\mu}^2 \frac{48\alpha s_W^4}{\pi}\left(s_W^2 - \frac{1}{2}\right)^2 \left(\frac{M_Z}{M_{Z'}}\right)^4$$

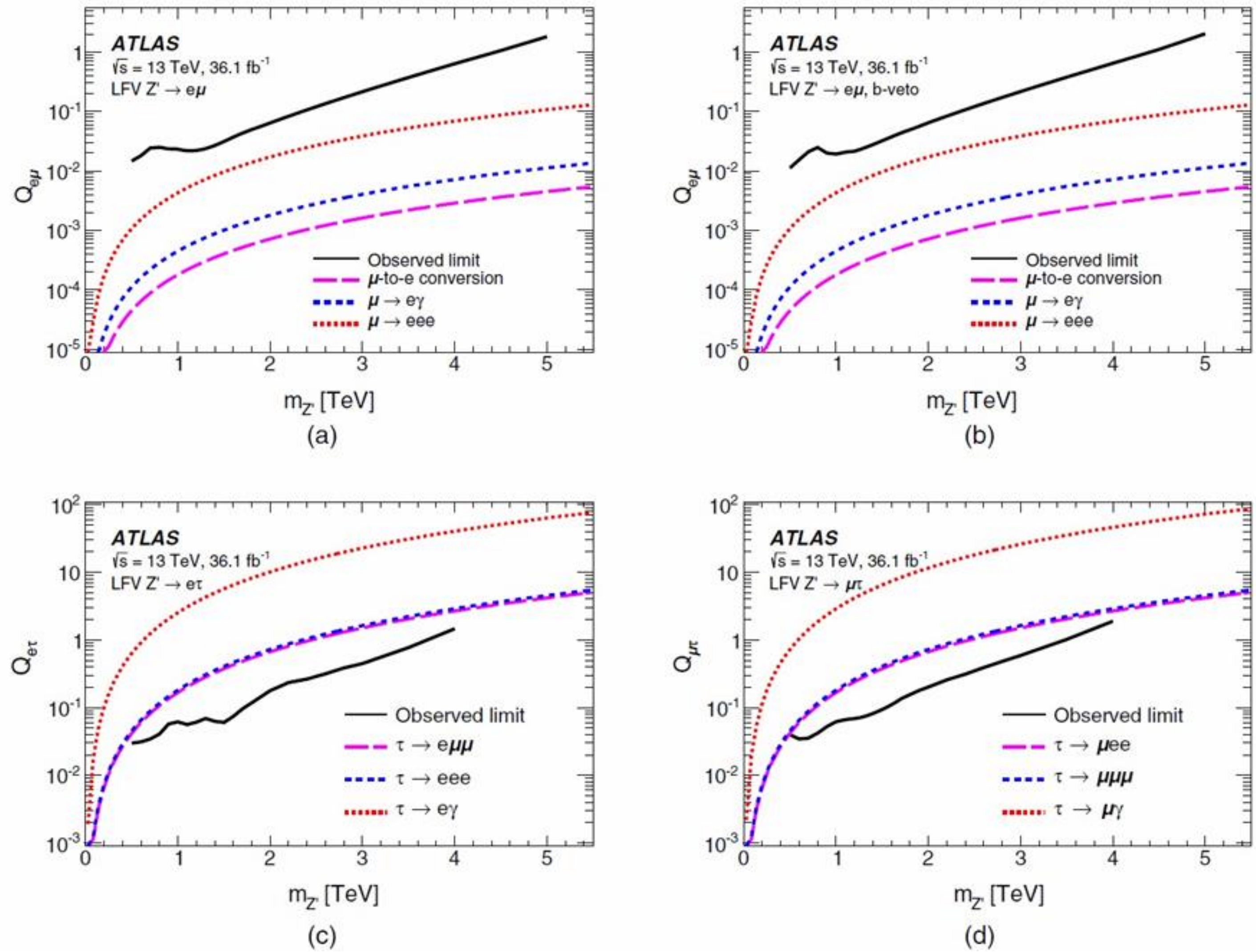
$\boldsymbol{M_Z, M_{Z'}}$: mass of Z and Z' $\boldsymbol{\alpha}$: fine structure constant $\boldsymbol{s_W}$: sine of weak mixing angle

$\boldsymbol{G_F}$: Fermi constant $\boldsymbol{\Gamma_{capture}}$: nuclear muon rate $\boldsymbol{m_\mu}$: mass of muon

$\boldsymbol{Z_{eff}, F(q), Z, N}$: nuclear parameters

Nucl. Phys. B 409 (1993), 69-86.

Search for Z' on collider

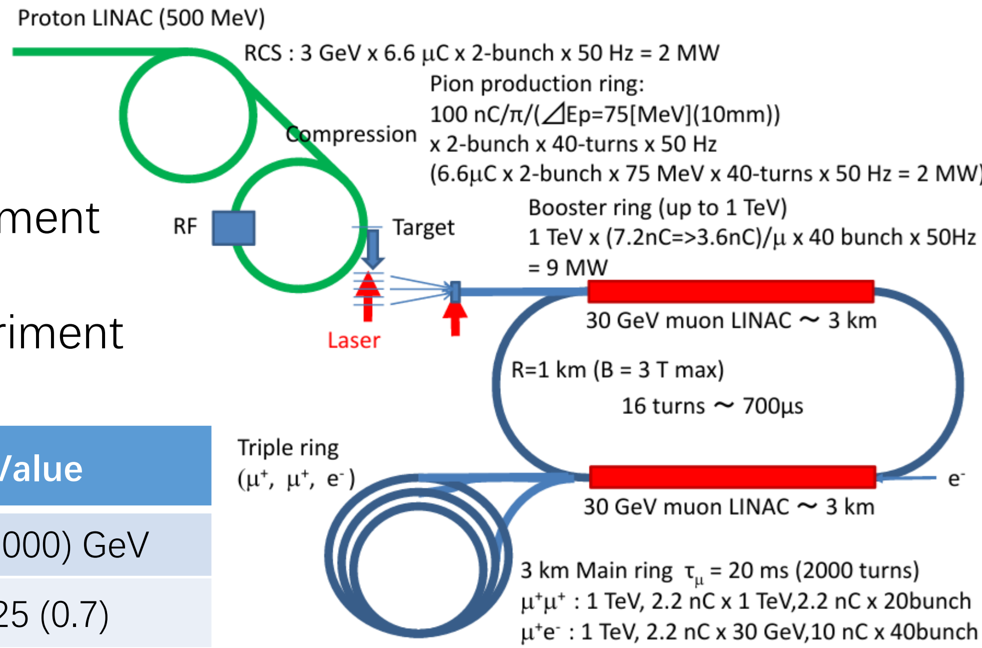


Phys.Rev.D 98 (2018) 9, 092008.

Electron muon collider

☐ μTRISTAN

- Muon beam from J-PARC g-2 experiment
- Electron beam from SuperKEKB experiment



Parameter	Value
Beam energy of electron (muon)	30 (1000) GeV
Polarization P_μ (P_e)	0.25 (0.7)
Luminosity	4.6×10^{33} cm^{-2}s^{-1}
Num of particle per bunch electron(muon)	6.2 (1.4) $\times 10^{10}$
Collision frequency	4×10^6 Hz

- Higgs production (WW/ZZ fusion)
- New physics signal
- Low background value (s-channel annihilation $W^+W^-/q\bar{q}$ absent)

☐ High energy electron muon collider

$$E_e = 200\ \text{GeV}, E_\mu = 3\ \text{TeV}\ (\sqrt{s} = 1.55\ \text{TeV})$$

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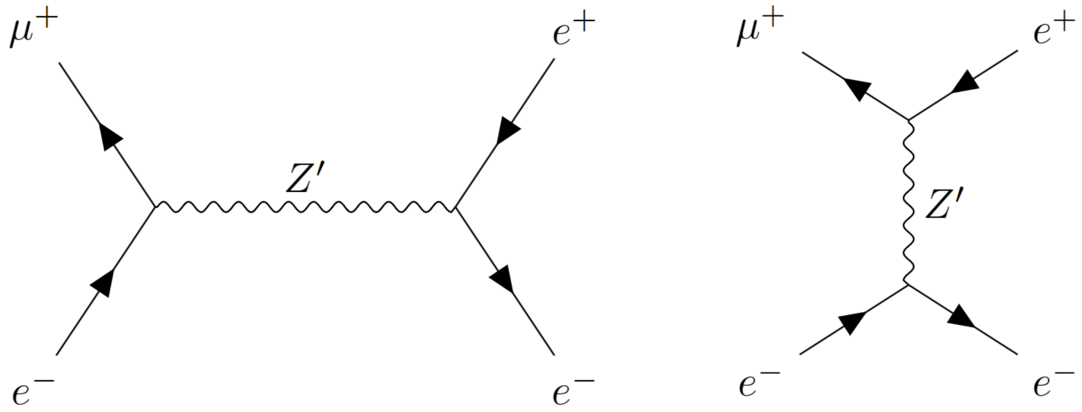
Event simulation



- **cLFV signal : Z' model** $M_{Z'}$: floating from 0.2 TeV to 3 TeV

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

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

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

$$E_{\mathrm{Beam}} \begin{cases} E_e = 200\ \mathrm{GeV}, E_\mu = 3\ \mathrm{TeV}\ (\sqrt{s} = 1.55\ \mathrm{TeV}) \\ E_e = 30\ \mathrm{GeV},\ E_\mu = 1\ \mathrm{TeV}\ (\sqrt{s} = 346\ \mathrm{GeV}) \end{cases}$$

- **The coupling strength**

$$\lambda_{ij} = \begin{cases} 1\ \ (i = j) \\ 1\ \ (i \neq j, only\ one\ element) \\ 0\ \ (else\ i \neq j) \end{cases} \quad i, j = e, \mu, \tau$$

- **No s-channel in $e^+\mu^- \to \tau^+\mu^-$**

- **MadGraph5, Pythia8, Delphes**

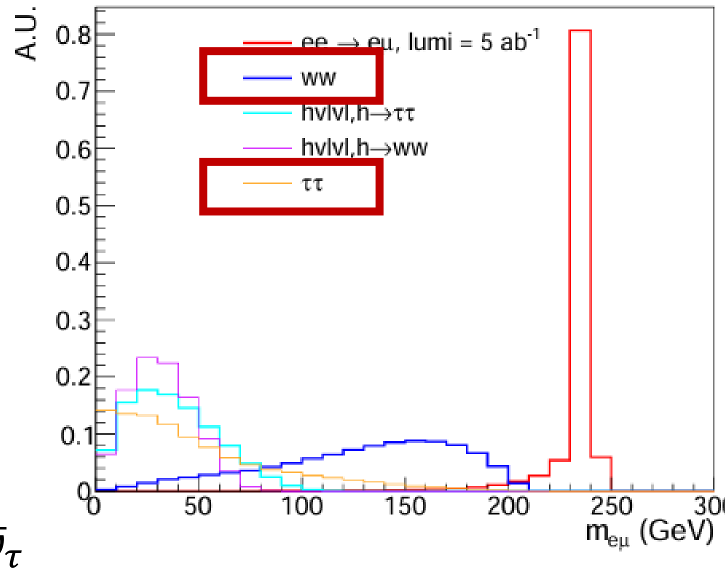
Background study

JHEP 03 (2023) 190

☐ SM background

Initial lepton flavor is non-zero: 2 → 2 background are forbidden

- Much cleaner than different-sign electron / muon collider

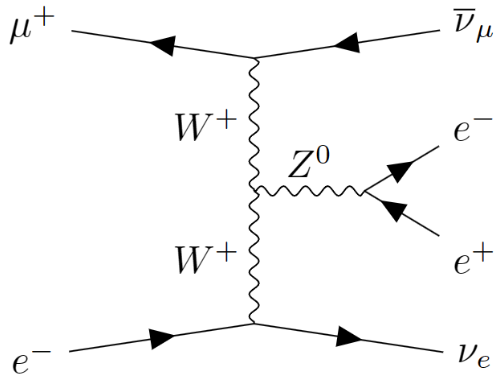


Main background (Eg. $\lambda_{e\mu}$ process)

in e^+e^- collision
$$\begin{cases} e^+e^- \to W^+W^- \to e^+\mu^-\upsilon_\mu\bar{\upsilon}_e \\ e^+e^- \to \tau^+\tau^- \to e^+\mu^-\upsilon_\mu\bar{\upsilon}_e\upsilon_\tau\bar{\upsilon}_\tau \end{cases}$$

- **large cross section && close to the signal at the kinematic level**

in μ^+e^- collision $\quad \mu^+e^- \to Z^0\upsilon_e\bar{\upsilon}_\mu \to e^+e^-\upsilon_e\bar{\upsilon}_\mu$



Background study

- **Accidental background:**

$e^-\mu^+ \to e^-\mu^+$ ($e\mu$ scattering)

$\Downarrow$ $e-\mu$ misidentify ~10^{-6}

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

Signal Process	SM and accidental background
$\mu^+e^- \to e^+e^-$	$\mu^+e^- \to e^+e^-\nu_e\bar{\nu}_\mu$ $\mu^+e^- \to e^+e^-\nu_e\bar{\nu}_\mu\nu\bar{\nu}$ $\mu^+e^- \to \mu^+e^-$
$\mu^+e^- \to \mu^+\mu^-$	$\mu^+e^- \to \mu^+\mu^-\nu_e\bar{\nu}_\mu$ $\mu^+e^- \to \mu^+\mu^-\nu_e\bar{\nu}_\mu\nu\bar{\nu}$ $\mu^+e^- \to \mu^+e^-$
$\mu^+e^- \to \mu^+\tau^-$	$\mu^+e^- \to \mu^+\tau^-\nu_e\bar{\nu}_\mu$ $\mu^+e^- \to \mu^+\tau^-\nu_e\bar{\nu}_\mu\nu\bar{\nu}$

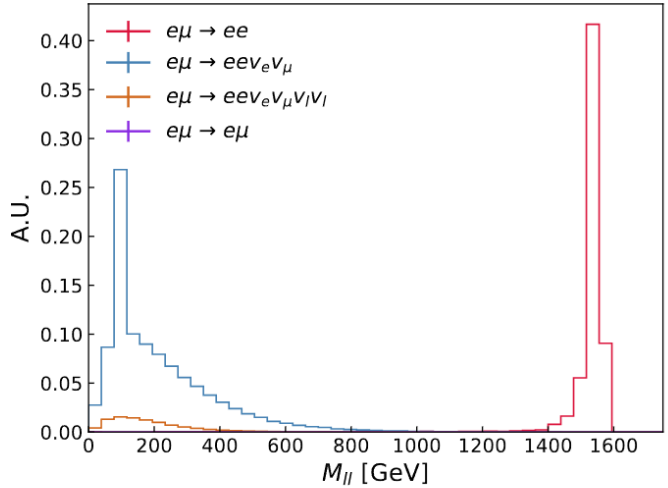
- Signal candidate should have correct final state leptons
- Leptons $p_T, |\eta|, \phi$: obtained by Delphes output
- Invariant mass of final state dileptons (M_{ll}) is utilized to remove background

$\boldsymbol{p_T}$: the transverse momentum

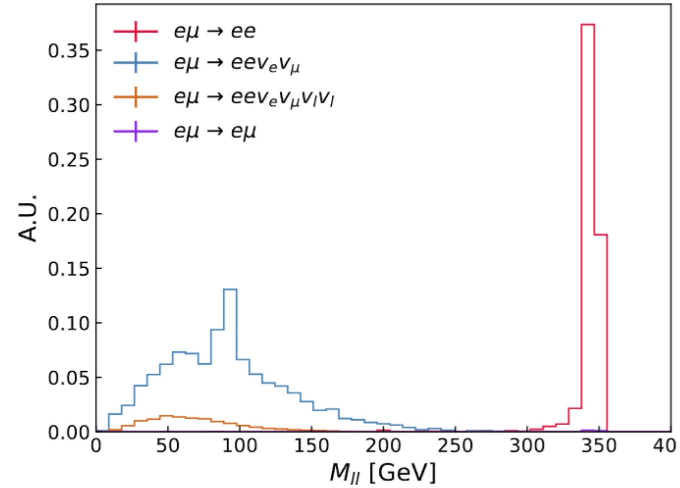
$|\boldsymbol{\eta}|$: the pseudo-rapidity

$\boldsymbol{\phi}$: the azimuthal angle

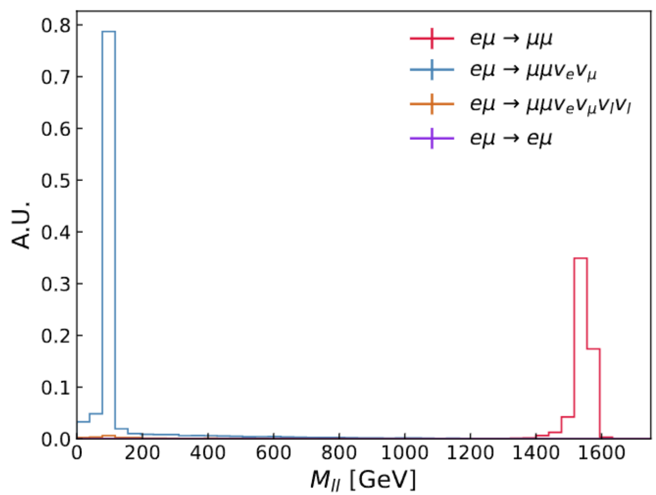
Background study



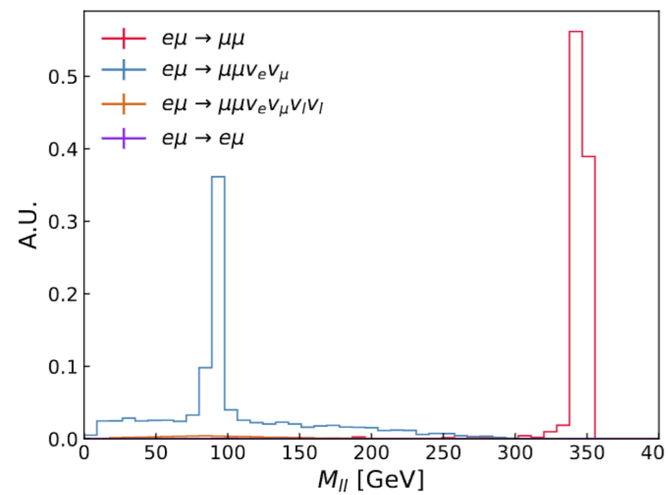
(a) $\sqrt{s} = 1.55$ TeV



(b) $\sqrt{s} = 346$ GeV

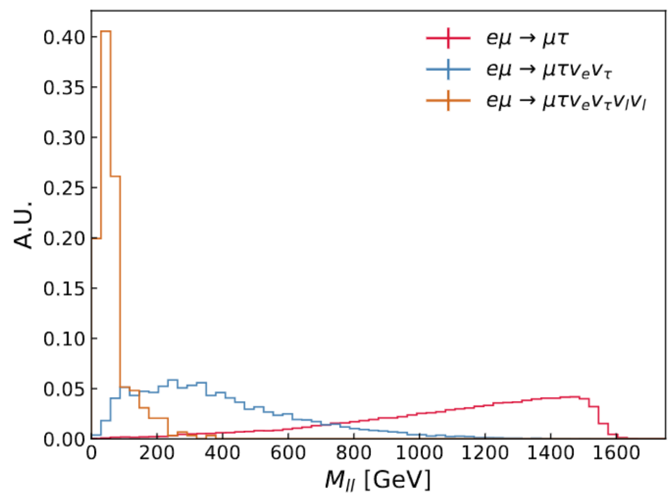


(c) $\sqrt{s} = 1.55$ TeV

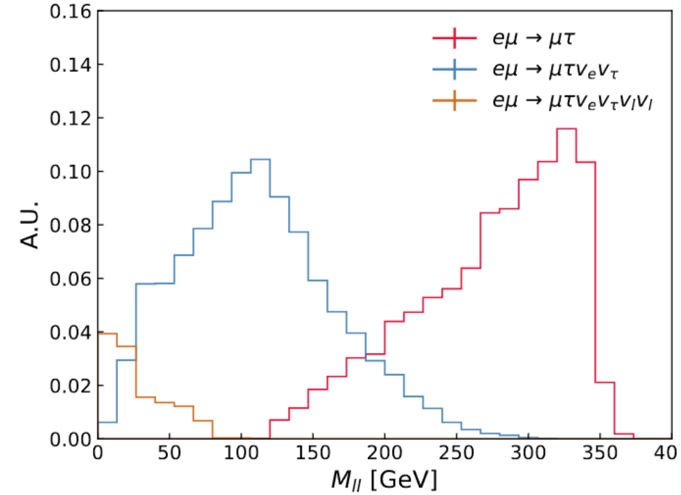


(d) $\sqrt{s} = 346$ GeV

Background study



(e) $\sqrt{s} = 1.55$ TeV



(f) $\sqrt{s} = 346$ GeV

- Integral area (BKG) determined by the cross section, specially for $e\mu$ scattering also includes the probability of misidentification (~10^{-6})

- In simulation τ should decay to hadron ~ 60%

- Optimized by maximizing the FOM

Analysis framework

- Get the binned histogram of final leptons p_T
- Per-event weight of each signal / background: $n_x = \sigma_x L/N$
- Define the test statistic Z as:

$\boldsymbol{\sigma_x}$**: cross section**

$\boldsymbol{L}$**: luminosity**

$\boldsymbol{N}$**: generate number**

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

$$Z_i \coloneqq 2[n_i - b_i + b_i \ln(b_i/n_i)]$$

- Subject to a χ^2 distribution, iterate to get the σ_{sig} of 90% exclusion and corresponding λ_{ll}

Current and prospect limit

☐ BF limits @ 90% C. L.

Signal	Current	Prospect
$\mu^- \to e^-\gamma$	4.2×10^{-13} MEG (PSI)	6.0×10^{-14} MEGII
$\mu^- N \to e^- N$	7.0×10^{-13} SINDRUM II (Au)	3.0×10^{-17} COMET
$\mu^- \to e^- e^- e^+$	1.0×10^{-13} SINDRUM	1.0×10^{-16} Mu3e
$\tau^- \to e^-\gamma$	3.3×10^{-8} Belle	9.0×10^{-9} Belle II
$\tau^- \to e^- e^- e^+$	2.7×10^{-8} Belle	4.7×10^{-10} Belle II
$\tau^- \to e^- \mu^- \mu^+$	2.7×10^{-8} Belle	4.5×10^{-10} Belle II

Eur. Phys. J. C 76 (2016) no.8, 434
Nucl. Phys. B 299 (1988) 1
Eur. Phys. J. C 47 (2006) 337.
Phys. Rev. Lett. 104 (2010) 021802
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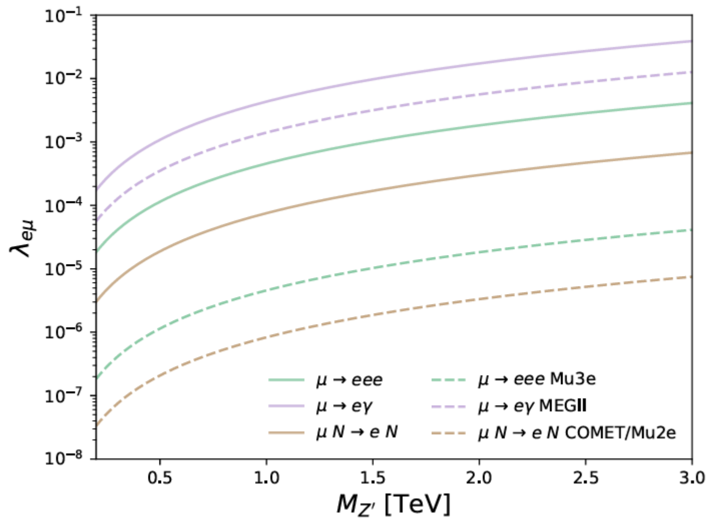
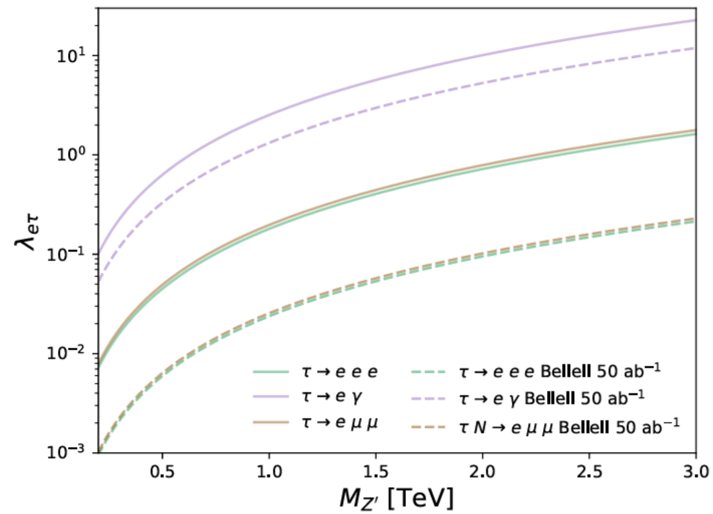
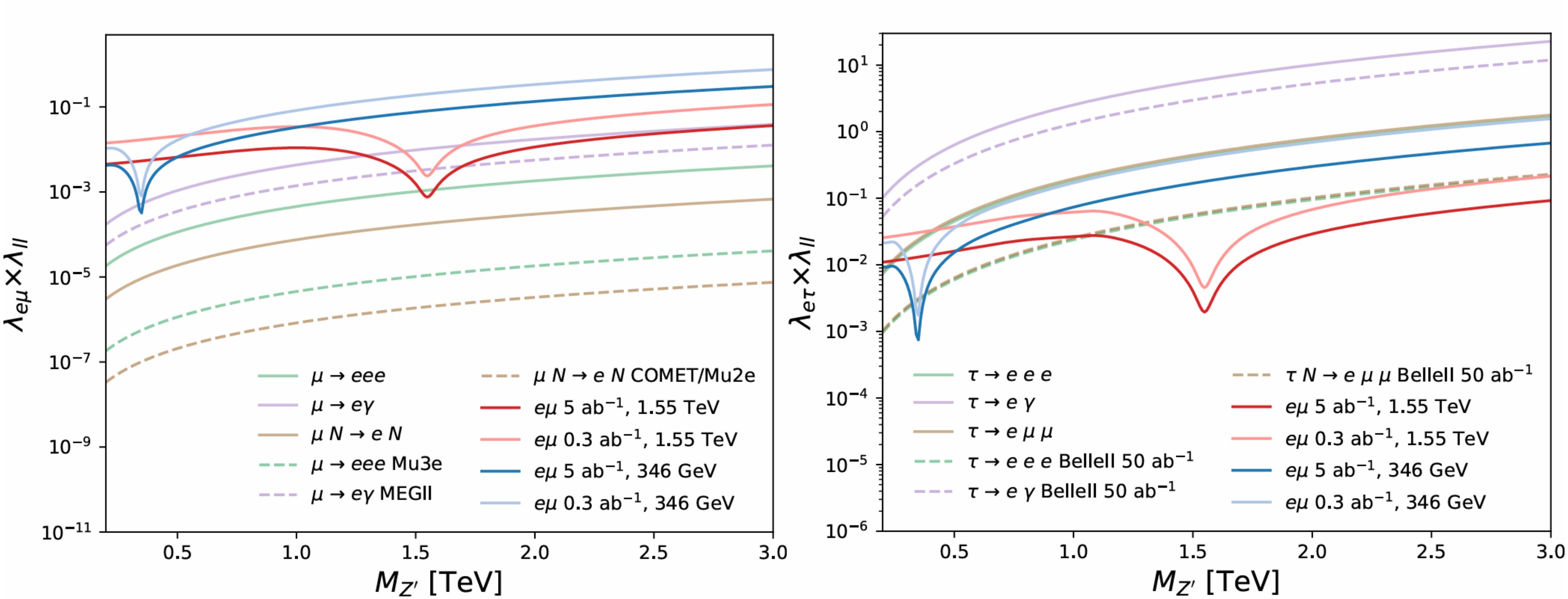
☐ Sensitivity of the λ_{ij}





Sensitivity result

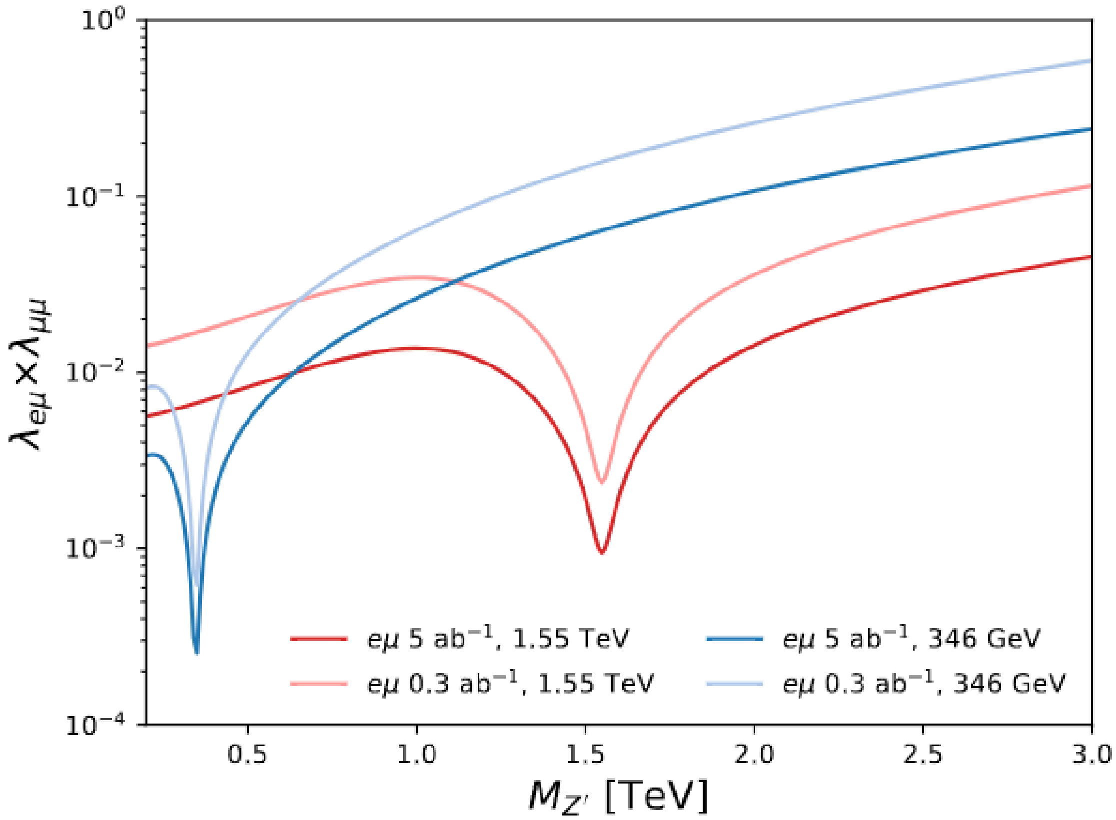


- Results among different signal channels on collider are on the same order of magnitude.

~ cross section, efficiency, background value……

- τ channel have a certain advantage among the current limits

Sensitivity result



(c) $\mu^+ e^- \to \mu^+ \mu^-$

- A special signal on collider that cannot search in low energy experiment: $\lambda_{e\mu} \times \lambda_{\mu\mu}$

Summary

- The observation of any cLFV process would be a clear signal of new physics beyond the SM
- Introduce a massive neutral boson Z'
- Perform a Monte Carlo study on cLFV searches at μTRISTAN (346 GeV) and a 1.5 TeV electron muon collider
- High luminosity electron muon collider have a certain advantage on cLFV searching especially in τ channel.

Thank you!