ICHEP 2024

Search for LFV with the Z′ model in future lepton colliders

arXiv:2302.02203 JHEP 03,190 (2023)

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Outline

ICHEP 2024

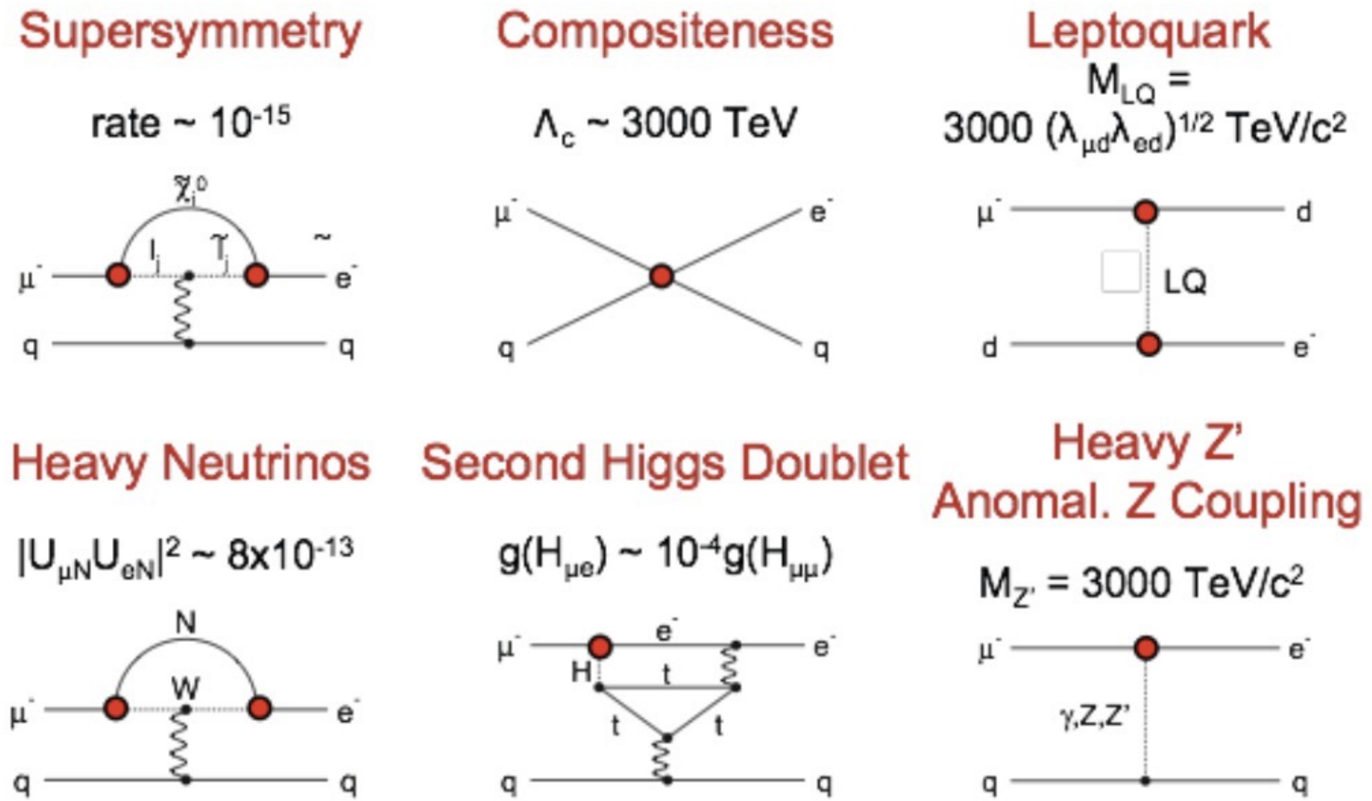
- Motivation
- Z′ model
- Future collider
- Event selection
- Analysis framework
- Upper limits and coupling
- Summary

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.

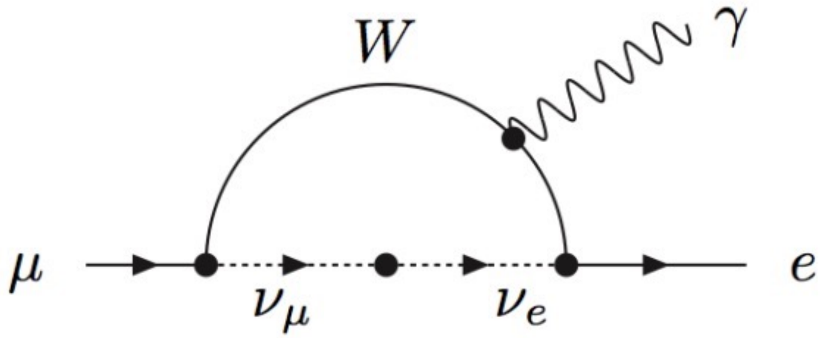
Eur. Phys. J. C57:13-182, 2008



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)

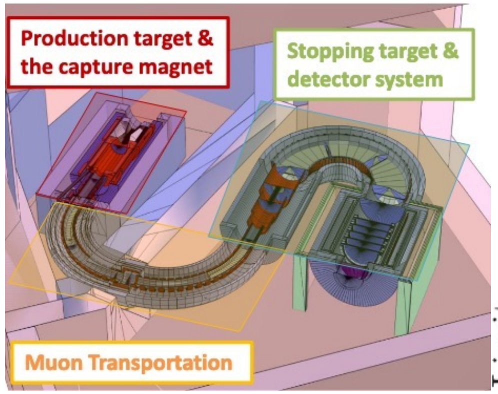
◆ Both experimental searches and upper-limit predictions, including μ, τ LFV decays, π, K LFV decays and $\phi, J/\psi$ two-body LFV decays, etc.

CLFV

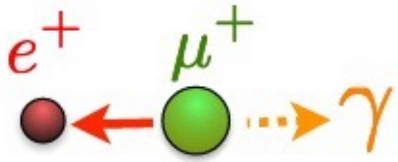
- $\mathcal{B}(\mu^+ \to e^+\gamma)<3.1\times10^{-13}$ @ 90% C.L. MEGII
- $\mathcal{B}(\tau^+ \to e^+\gamma)<3.3\times10^{-8}$ @ 90% C.L. BABAR
- $\mathcal{B}(\mu \to 3e)<1.0\times10^{-12}$ @ 90% C.L. SINDRUM
- $\mathcal{B}(Z \to e^\pm\mu^\mp)<7.5\times10^{-7}$ @ 95% C.L. ATLAS
- $\mathcal{B}(\phi \to e^\pm\mu^\mp)<2\times10^{-6}$ @ 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

Current best limit

Eur. Phys. J. C 84, 216 (2024)
Phys. Rev. Lett. 104, 021802 (2010)
Nucl. Phys. B 299, 1 (1988).
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)



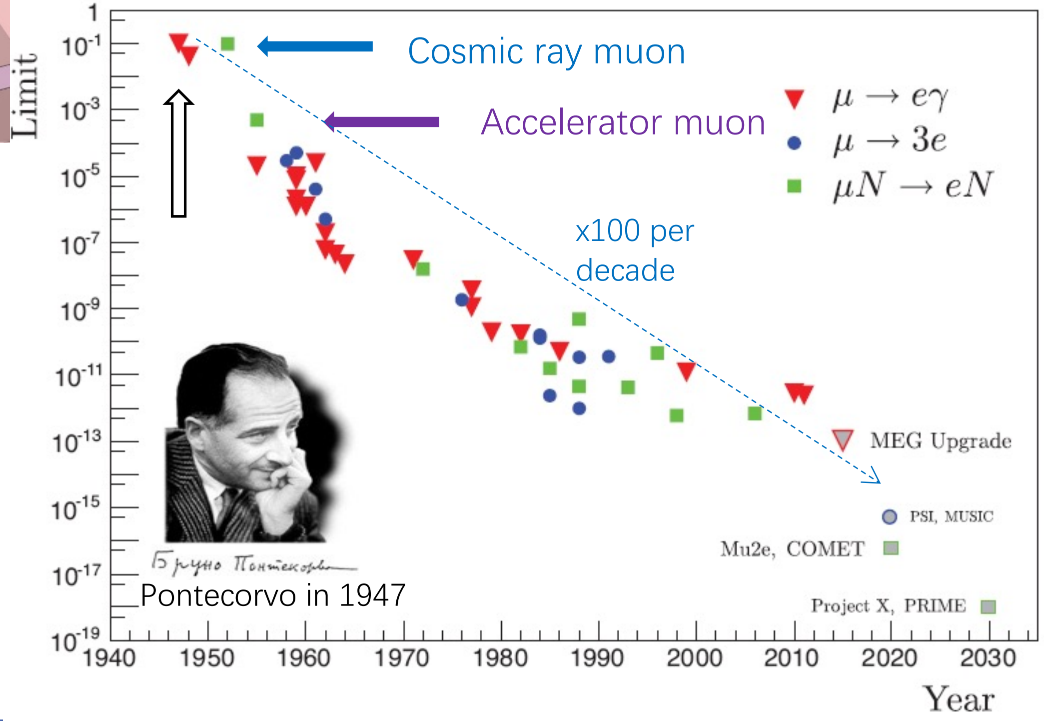
COMET



MEGII process

- Mu2e and COMET will search for CLFV with $\mu N \to eN$
  Improve the current limit by a factor of 10^4
  Next goal $<6\times10^{-17}$ (90%C.L.)
  Search for New Physics with energy scale up to 10^4 TeV

- 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 6×10^{-14} (90%C.L.)



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 benefit from the development of new technologies, such as higher-energy particle accelerators and more sensitive detectors.
- Searching for Z' ⟸ LHC, FNAL...

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

α: the fine structure constant

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

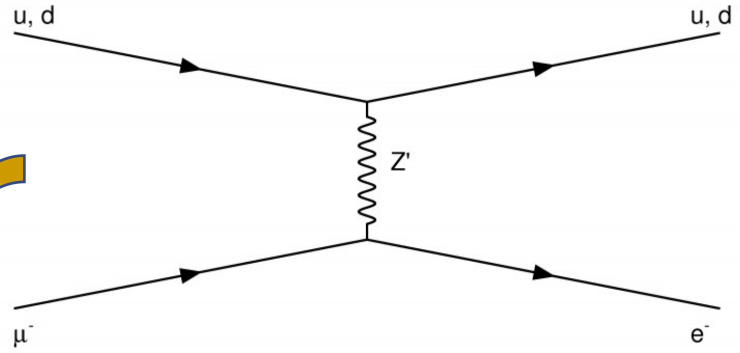
c_W : the cosine of the weak mixing angle

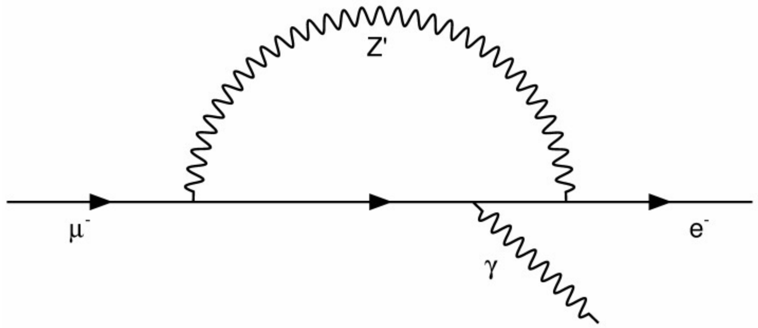
s_W : the sine of the weak mixing angle

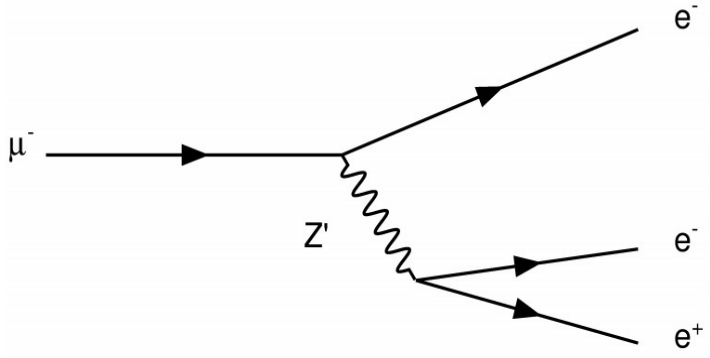
Z' model for CLFV

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

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







$Z' - e - \mu$ coupling

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

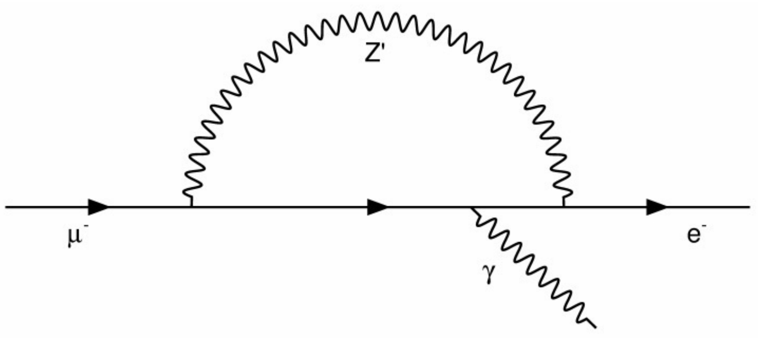
G_F: the Fermi constant, α: the fine structure constant, $\Gamma_{capture}$: nuclear muon capture rate,

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_μ: the muon mass

Z' model for CLFV

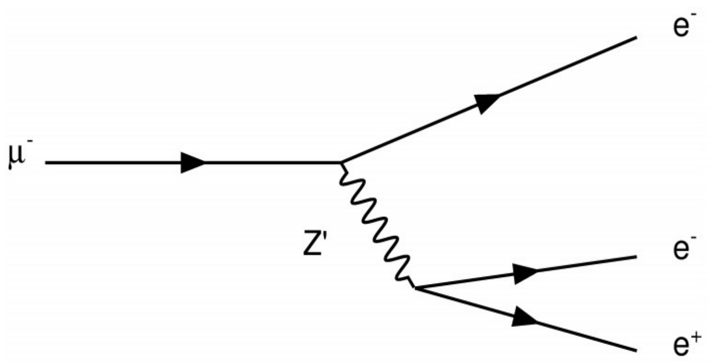
◆ $\mu^- \to e^-\gamma$



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

$Z' - e - \mu$ coupling

◆ $\mu^- \to e^-e^-e^+$



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

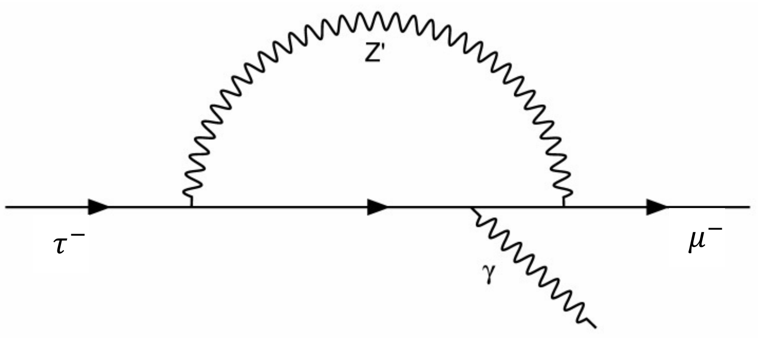
α: the fine structure constant, M_Z: the Z boson mass,

$M_{Z'}$: 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)

Z' model for CLFV

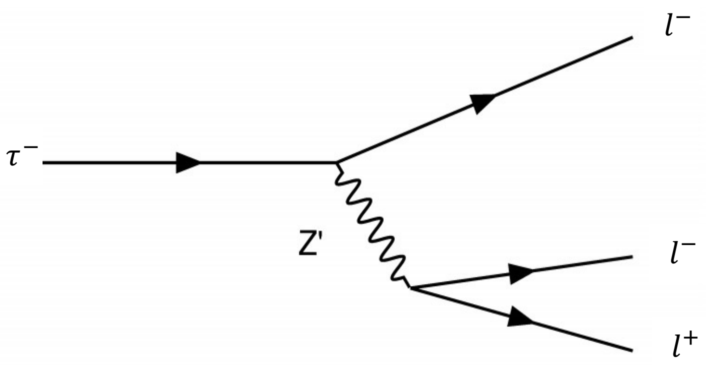
- $\tau^- \to \mu^-\gamma$



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

$Z' - \mu - \tau$ coupling

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



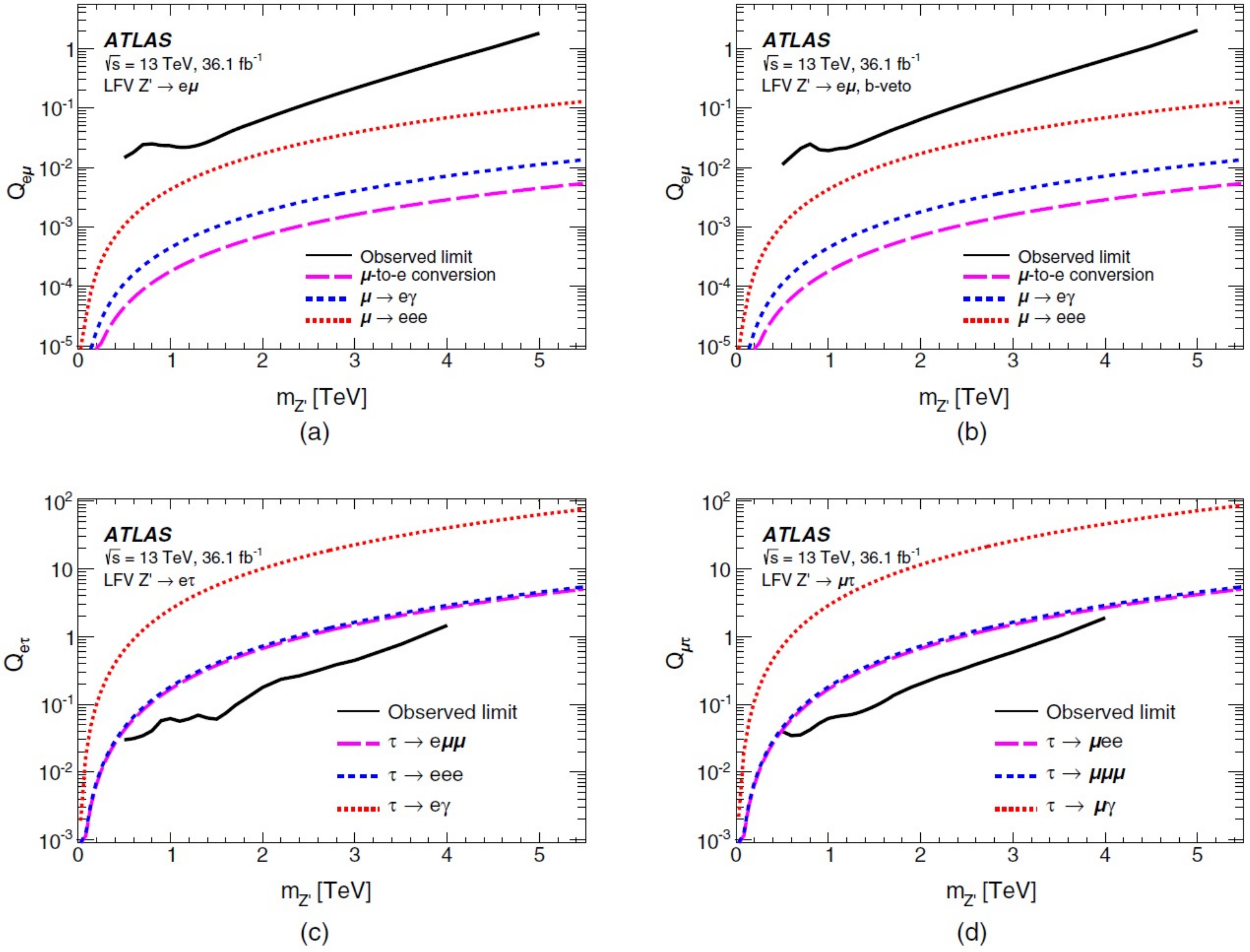
$$BR(\tau \to lll) = 4 \cdot \lambda_{\mu\tau}^2 \cdot \frac{M_{Z'}^4}{M_Z^4} \left[S_W^4 + \left(S_W^2 - \frac{1}{2}\right)^2\right]^2 BR(\tau \to \mu\nu\nu)$$

α: 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



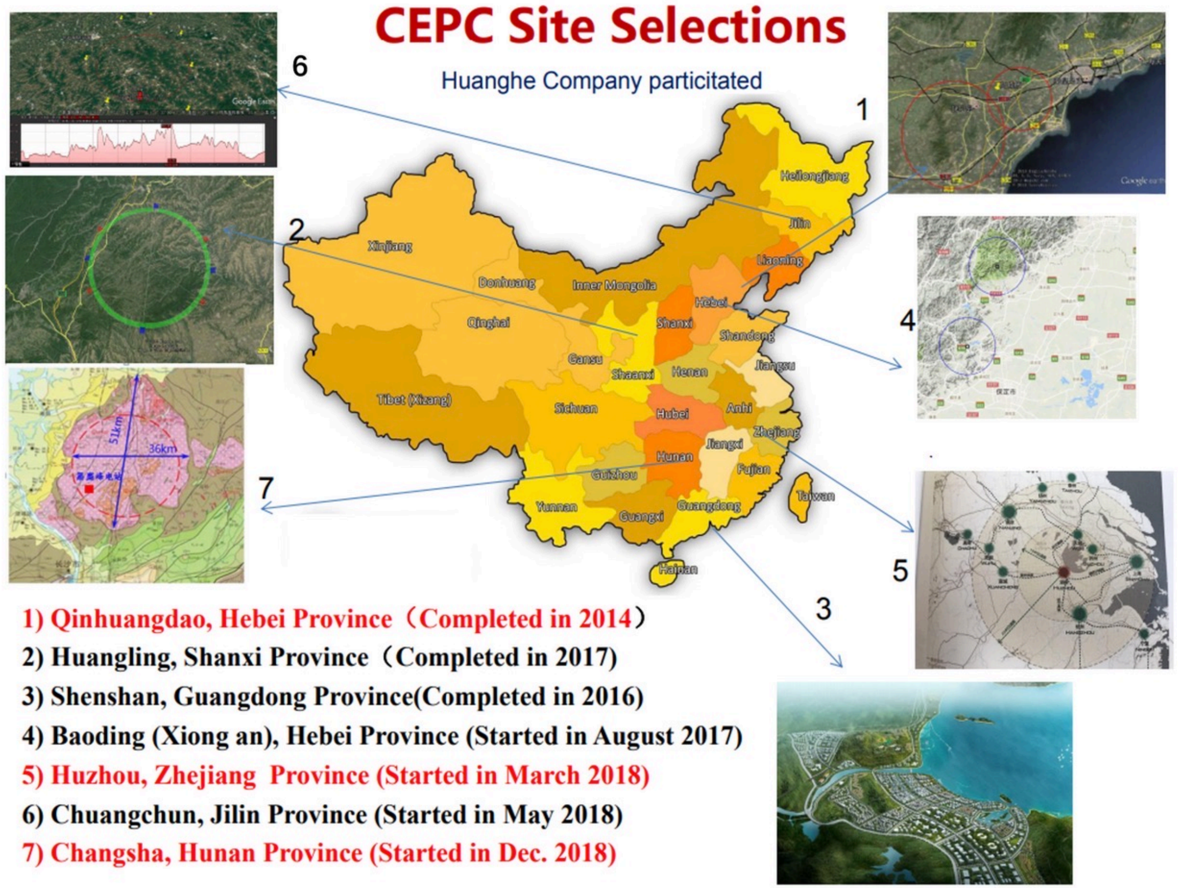
- The ATLAS cross-section times branching ratio limits (solid lines) compared with similar limits from low-energy experiments

Phys. Rev. D 98, 092008 (2018)

Future collider

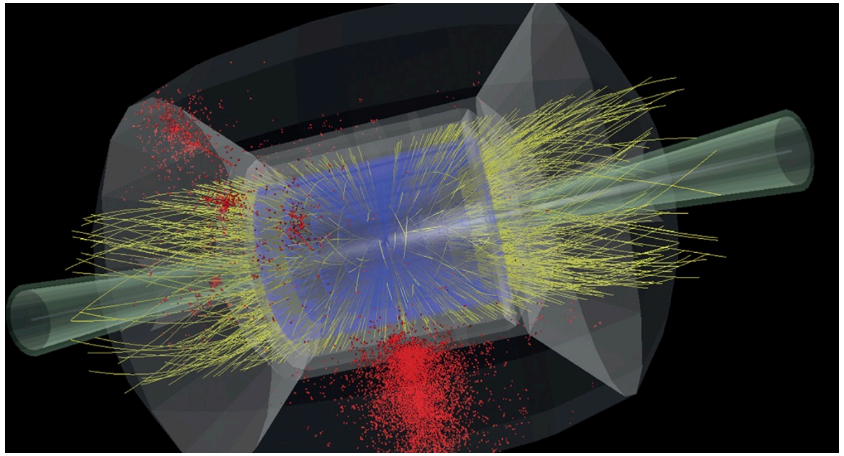
integrated luminosity $L \simeq 10\,\mathrm{ab}^{-1} \times \left(\sqrt{s}/10\,\mathrm{TeV}\right)^2$

Circular Electron Positron Collider (CEPC)



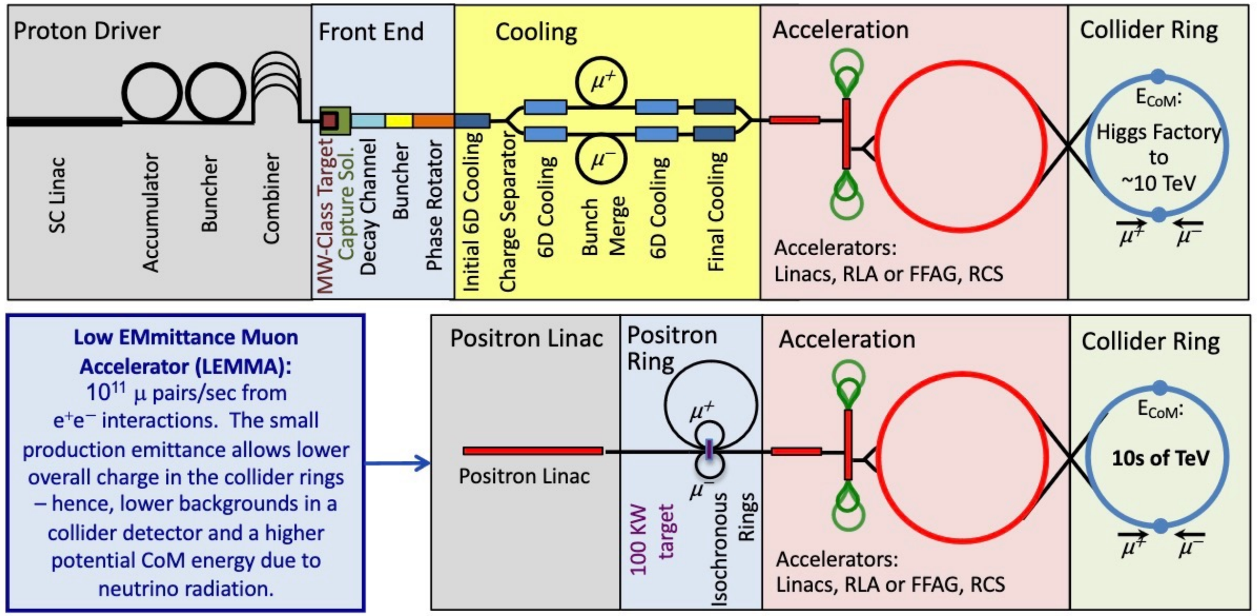
large-scale high-energy physics experimental facility
perform high-precision detection of the Higgs boson

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

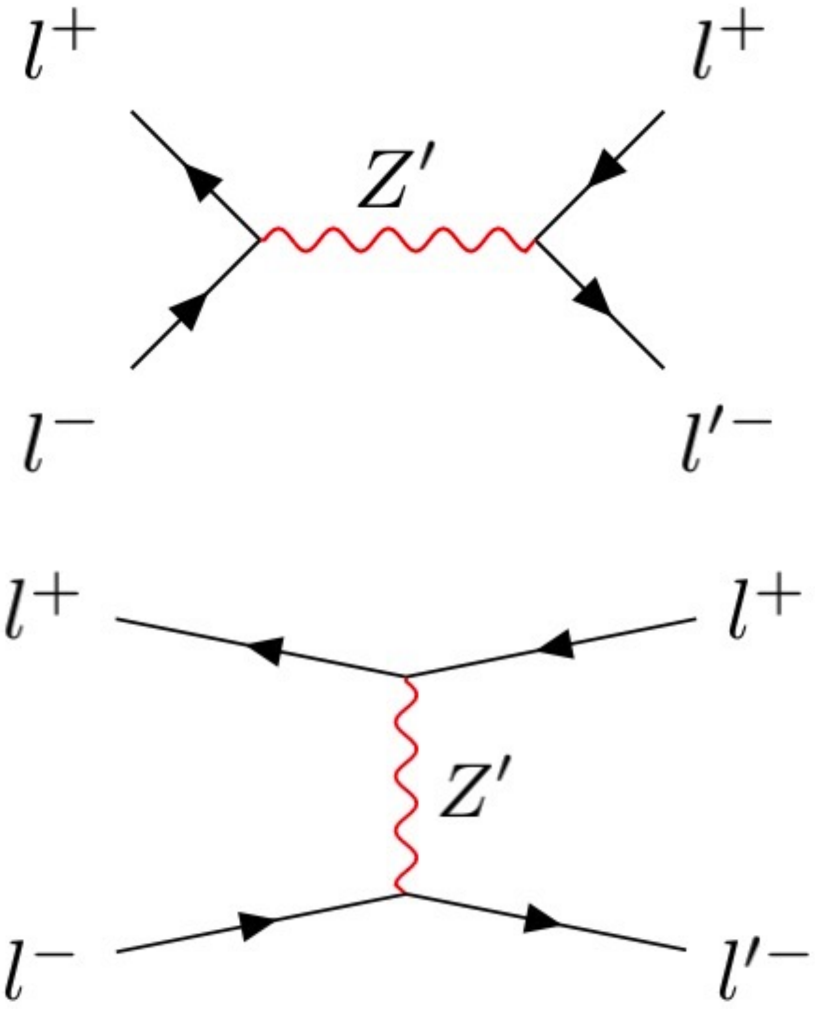


Muon Collider

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



Signal process



- 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.

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

- Using @Madgraph, @Pythia8 and @Delphes to generate the processes

Background process

CEPC

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
$ee \to h\nu\nu, h \to \tau\tau, \tau \to e\nu\nu/\mu\nu\nu$	$1.13*10^{-4}$
$ee \to h\nu\nu, h \to \mathrm{ww}, \mathrm{w} \to e\nu/\mu\nu$	$3.93*10^{-6}$
$ee \to e\tau$	$6.94*10^{-5}$
$ee \to \mathrm{ww}, \mathrm{w} \to e\nu, \mathrm{w} \to \tau\nu$	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 τ decay to μ in MG5, and control another τ to hadrons in Pythia8.
- For the τ final state, only the hadronized τ is considered, the cross section needs to $\times$ 60%.

Muon Collider

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

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 μ^-.
- $e\mu$ final states:

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

- Final state containing τ:

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

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

- μ tracking efficiency

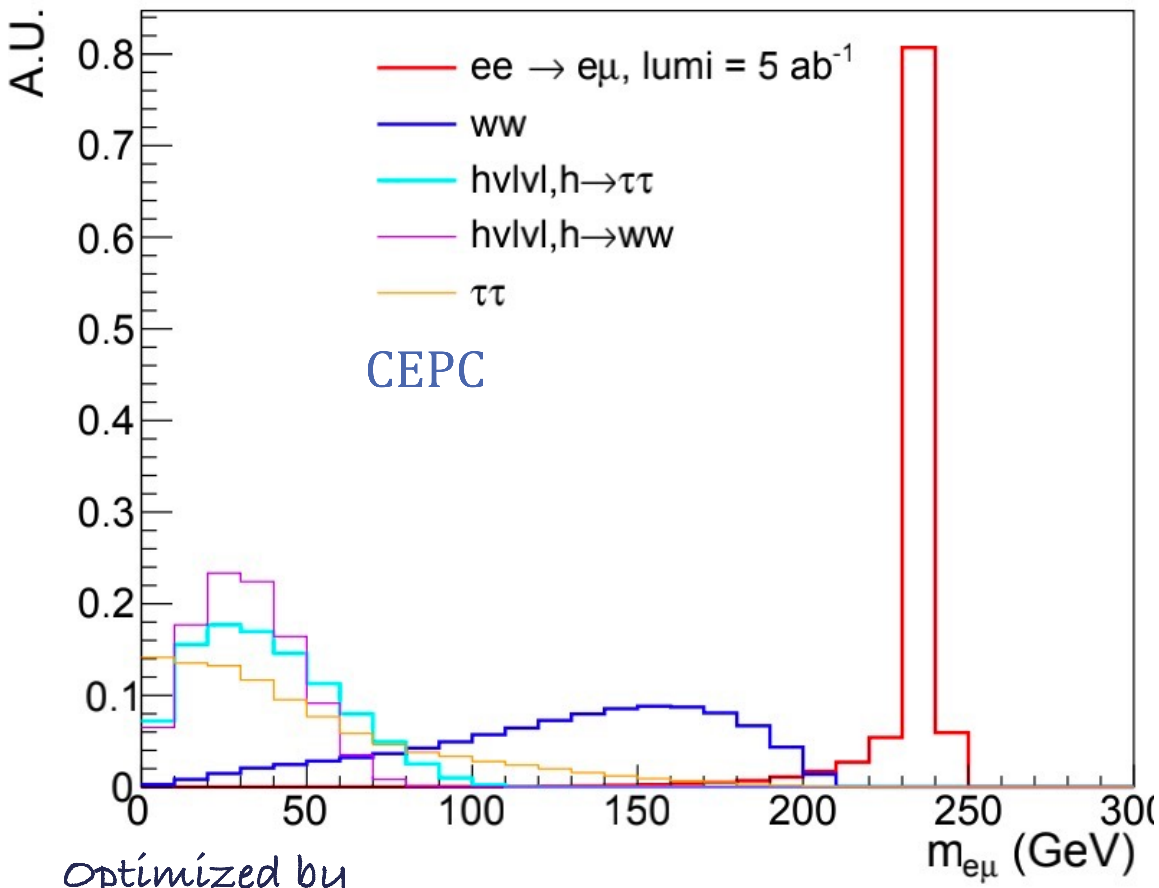
Collider	Conditions	Efficiency
CEPC	$0.1 < \|\eta\| \leq 3$	100%
	$\|\eta\| > 3$	0%
Muon Collider	$\|\eta\| < 2.0,\ 0.5 < p_T < 1$ GeV	95%
	$\|\eta\| \leq 2.0,\ p_T > 1$ GeV	99%
	$2.0 < \|\eta\| < 2.5,\ 0.5 < p_T \leq 1$ GeV	90%
	$2.0 < \|\eta\| < 2.5,\ p_T > 1$ GeV	95%
	$\|\eta\| > 2.5$	0%

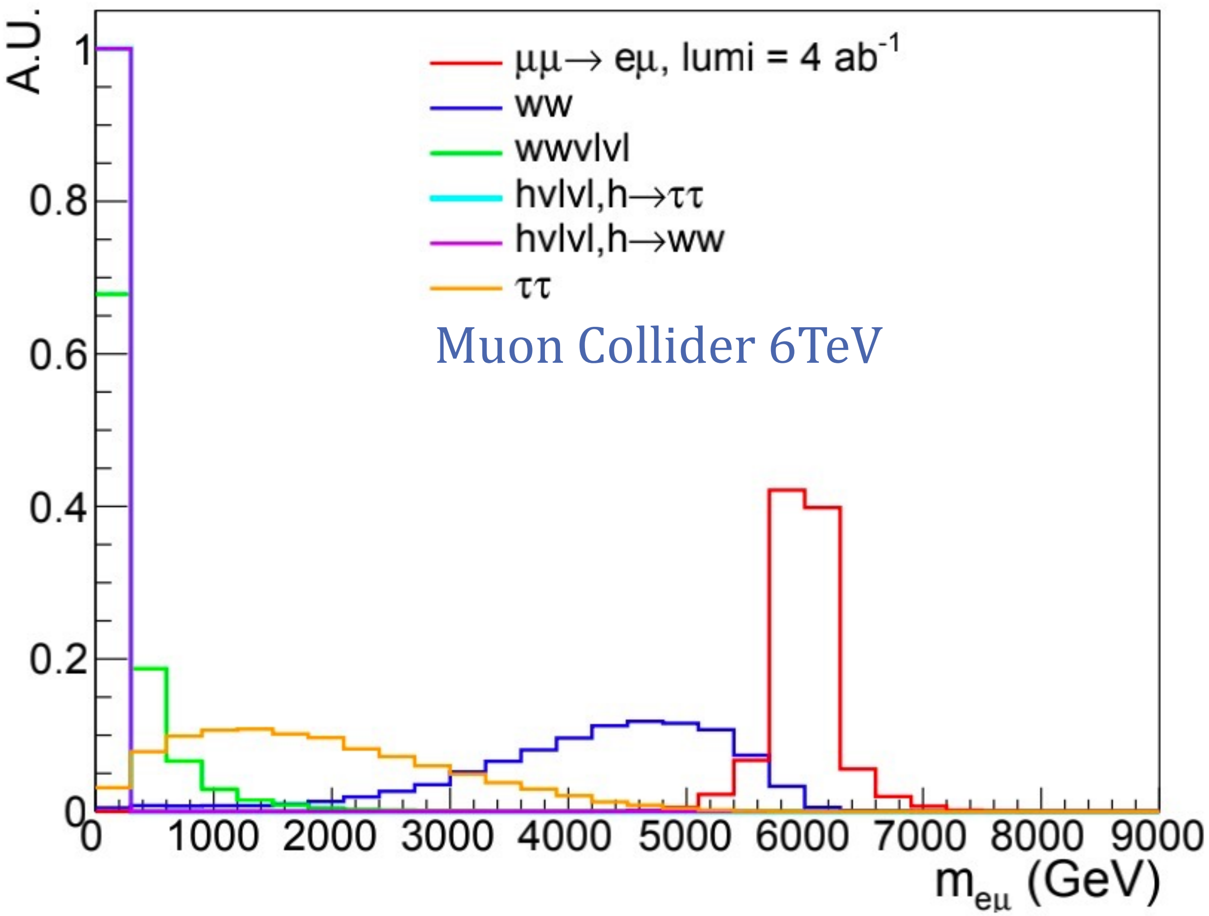
- τ tagging efficiency

Collider	Efficiency
CEPC	40%
Muon Collider	80%

Further cuts

◆ Using $e\mu$ invariant mass to separate the signal and the backgrounds.





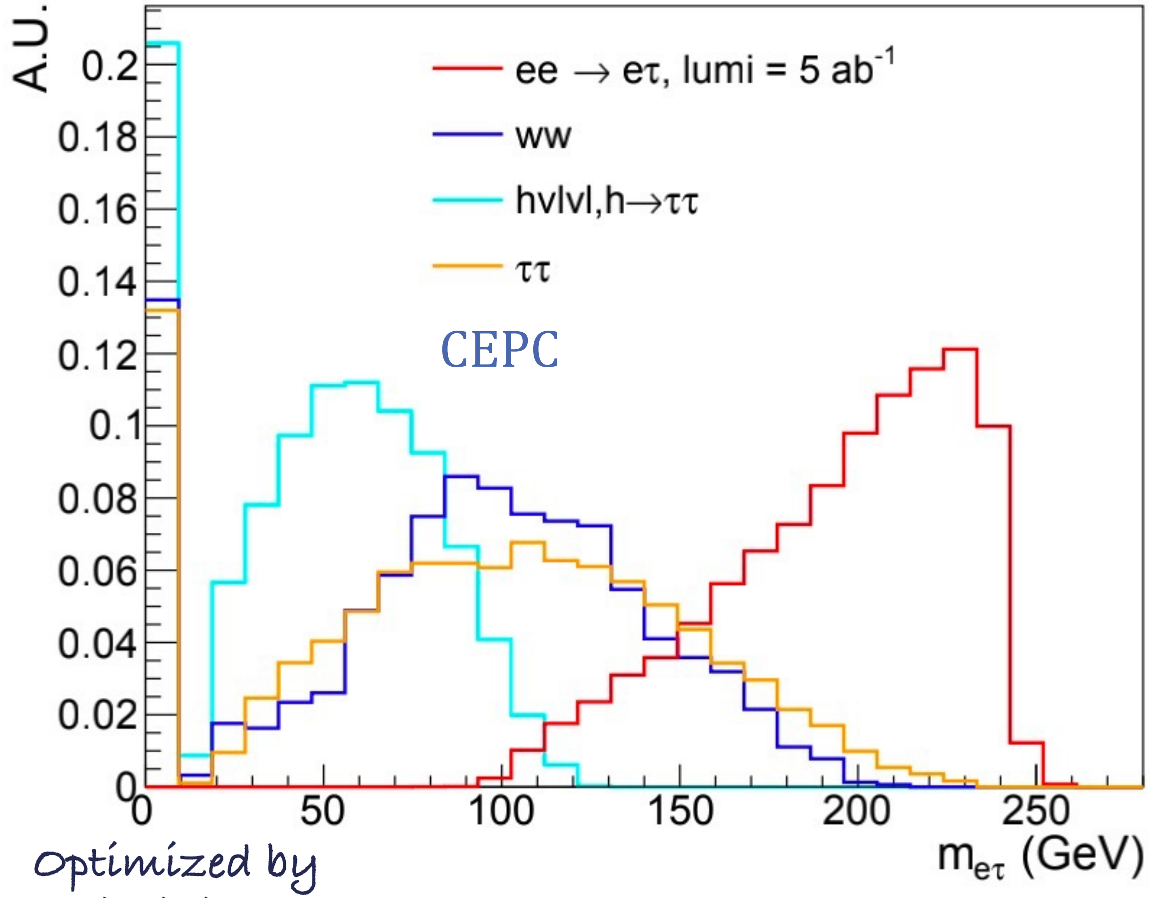
Optimized by maximizing the FOM $\left(\frac{s}{\sqrt{s+b}}\right)$

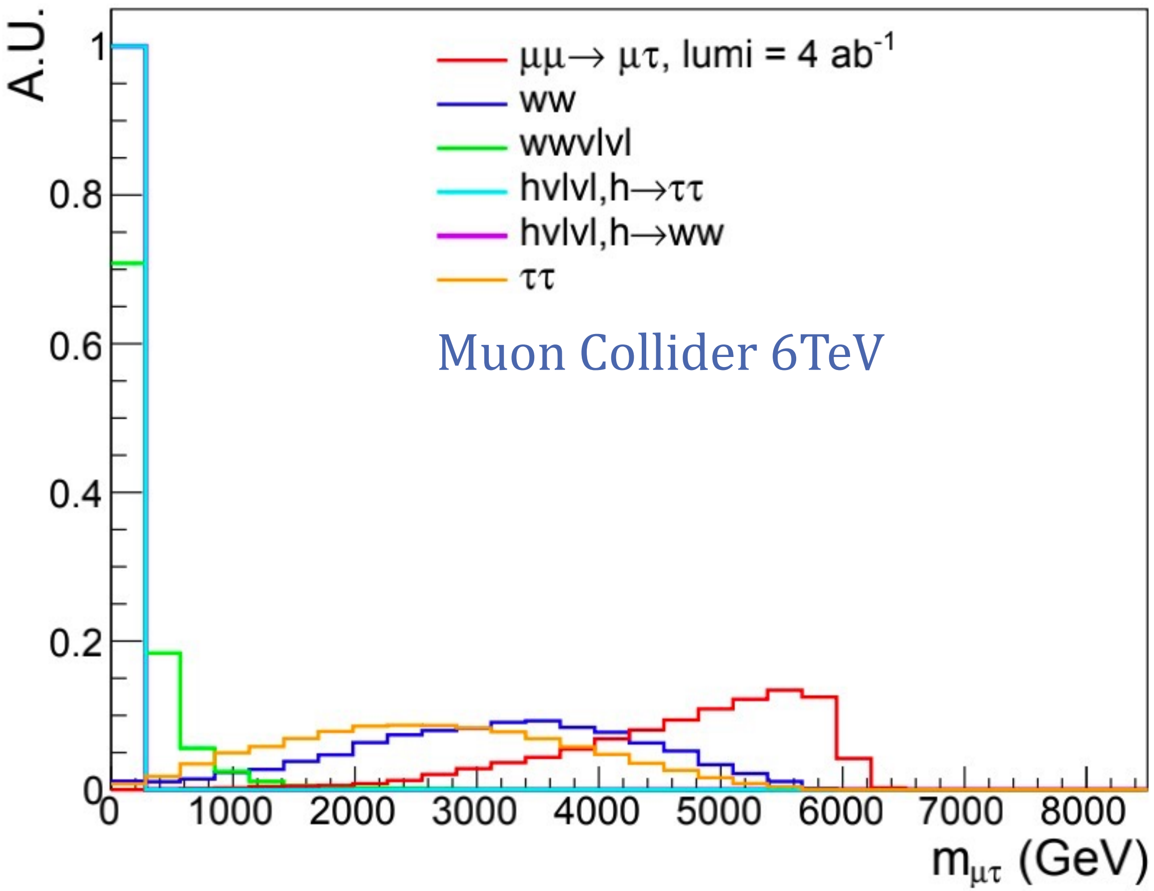
$m_{e\mu} > 220$ GeV

$m_{e\mu} > 5.2$ TeV ($m_{e\mu} > 10$TeV for 14TeV Muon collider)

Further cuts

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





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

$m_{e\tau} > 160$ GeV

$m_{\mu\tau} > 4$ TeV ($m_{\mu\tau} > 9.5$ TeV for 14TeV Muon collider)

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 : $n_{L_X} = \sigma_X L / N_X$

σ_X: cross section

L : luminosity

N_X : events generated

- Defined the negative log likelihood test statistics Z:

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

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

Eur. Phys. J. C 73, 2501 (2013)

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 χ^2 distribution with degree of freedom equals to 1.

Current limits

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

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)

- $\mathcal{B}(\mu^- \to e^-\gamma)<3.1\times10^{-13}$ @ 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

Prospect limits

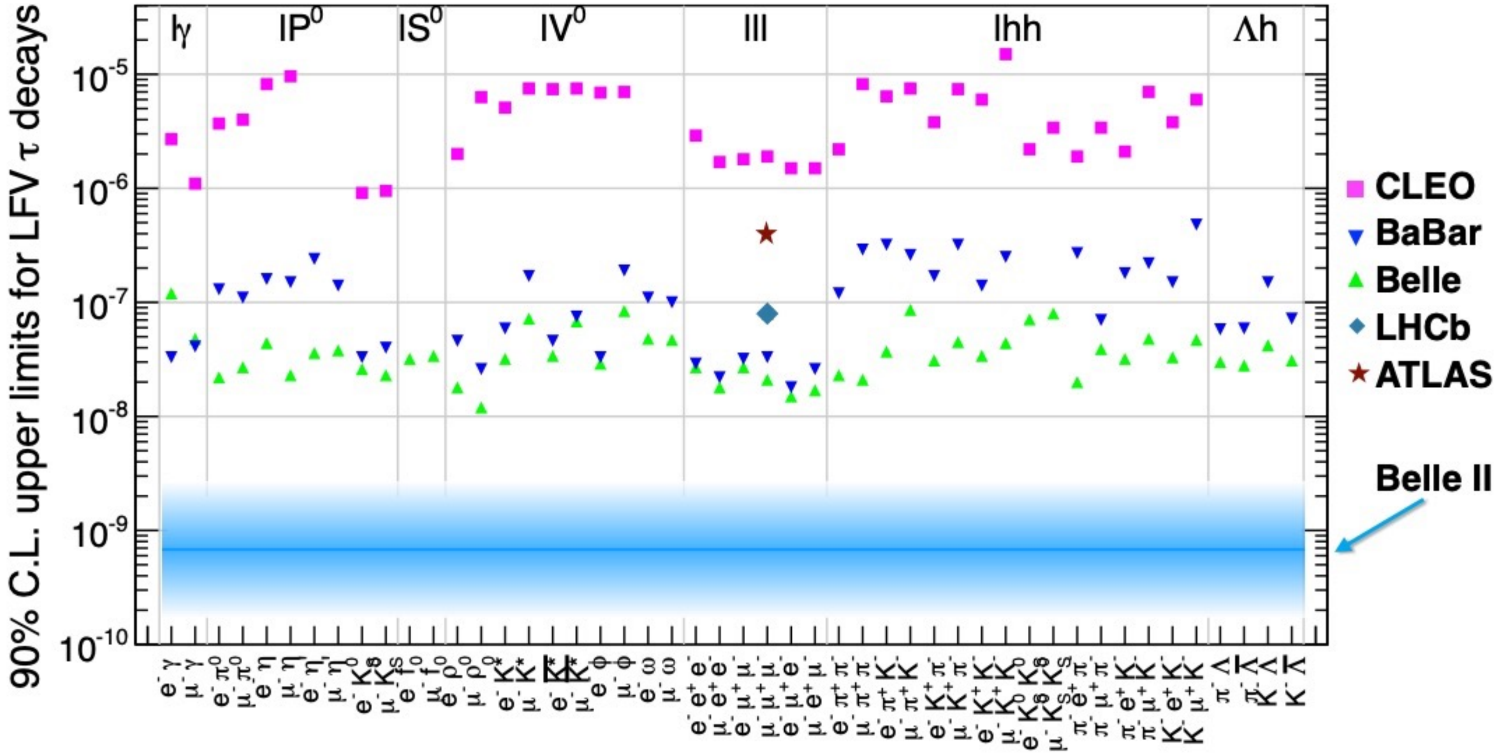
- $\mathcal{B}(\mu^- \to e^-\gamma) < 6.0\times10^{-14}$ @ 90% C.L. MEGII
- $\mathcal{B}(\mu^- N \to e^- N) < 3.0\times10^{-17}$ @ 90% C.L. COMET
- $\mathcal{B}(\mu^- N \to e^- N) < 8.0\times10^{-17}$ @ 90% C.L. Mu2e
- $\mathcal{B}(\mu^- \to e^- e^+ e^-) < 1.0\times10^{-16}$ @ 90% C.L. Mu3e

Symmetry 13 no.9, 1591 (2021)
PTEP 3, 033C01 (2020)
arXiv:1501.05241
Nucl.Instrum.Meth.A 1014, 165679 (2021)

- $\mathcal{B}(\tau^- \to e^-\gamma) < 9.0\times10^{-9}$
- $\mathcal{B}(\tau^- \to \mu^-\gamma) < 6.9\times10^{-9}$
- $\mathcal{B}(\tau^- \to e^- e^+ e^-) < 4.7\times10^{-10}$
- $\mathcal{B}(\tau^- \to \mu^- \mu^+ \mu^-) < 3.6\times10^{-10}$
- $\mathcal{B}(\tau^- \to \mu^- e^+ e^-) < 2.9\times10^{-10}$
- $\mathcal{B}(\tau^- \to e^- \mu^+ \mu^-) < 4.5\times10^{-10}$

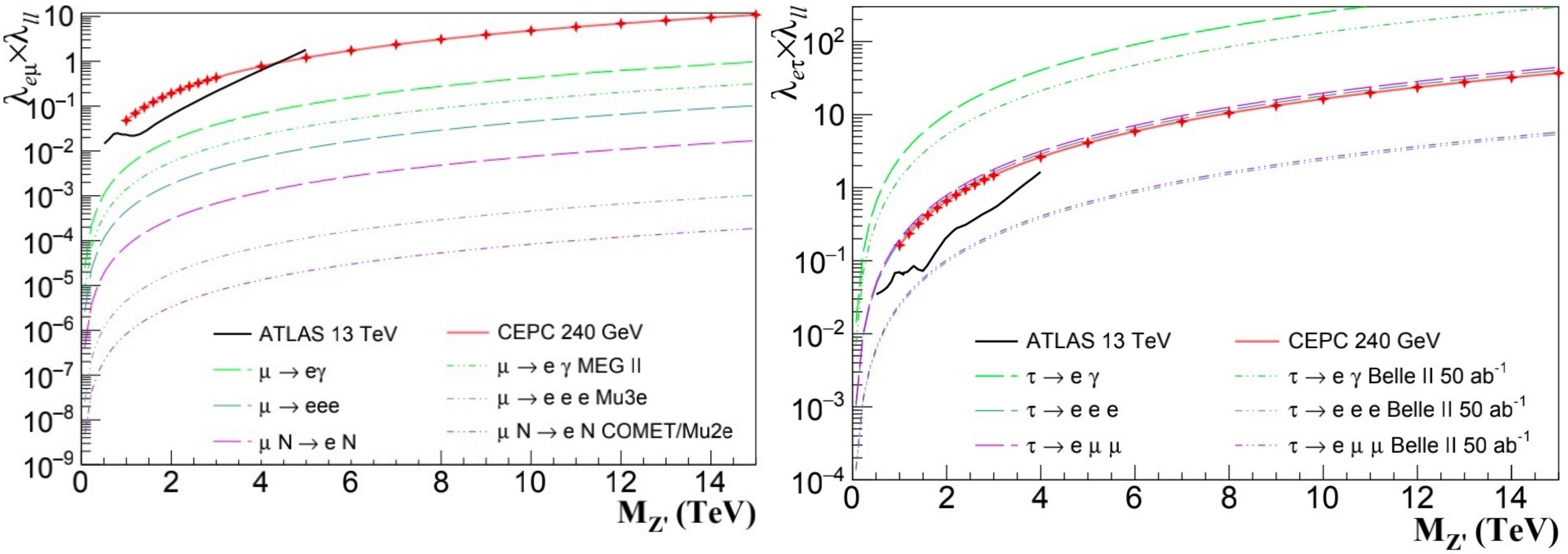
@ 90% C.L. Belle II

Universe 8 no.9, 480 (2022)



Upper limit on CEPC

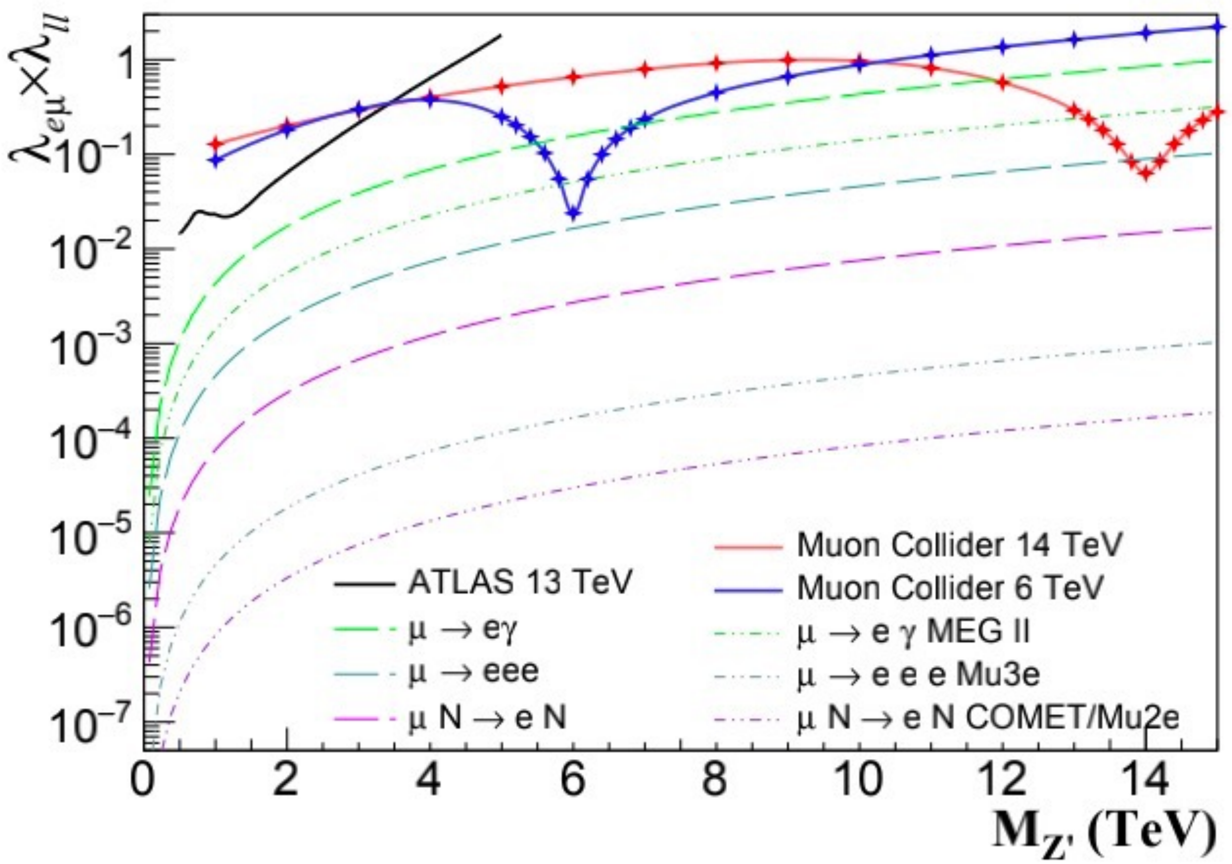
- The curves are plotted as functions of $M_{Z'}$ from the cross-section times branching ratio limits.

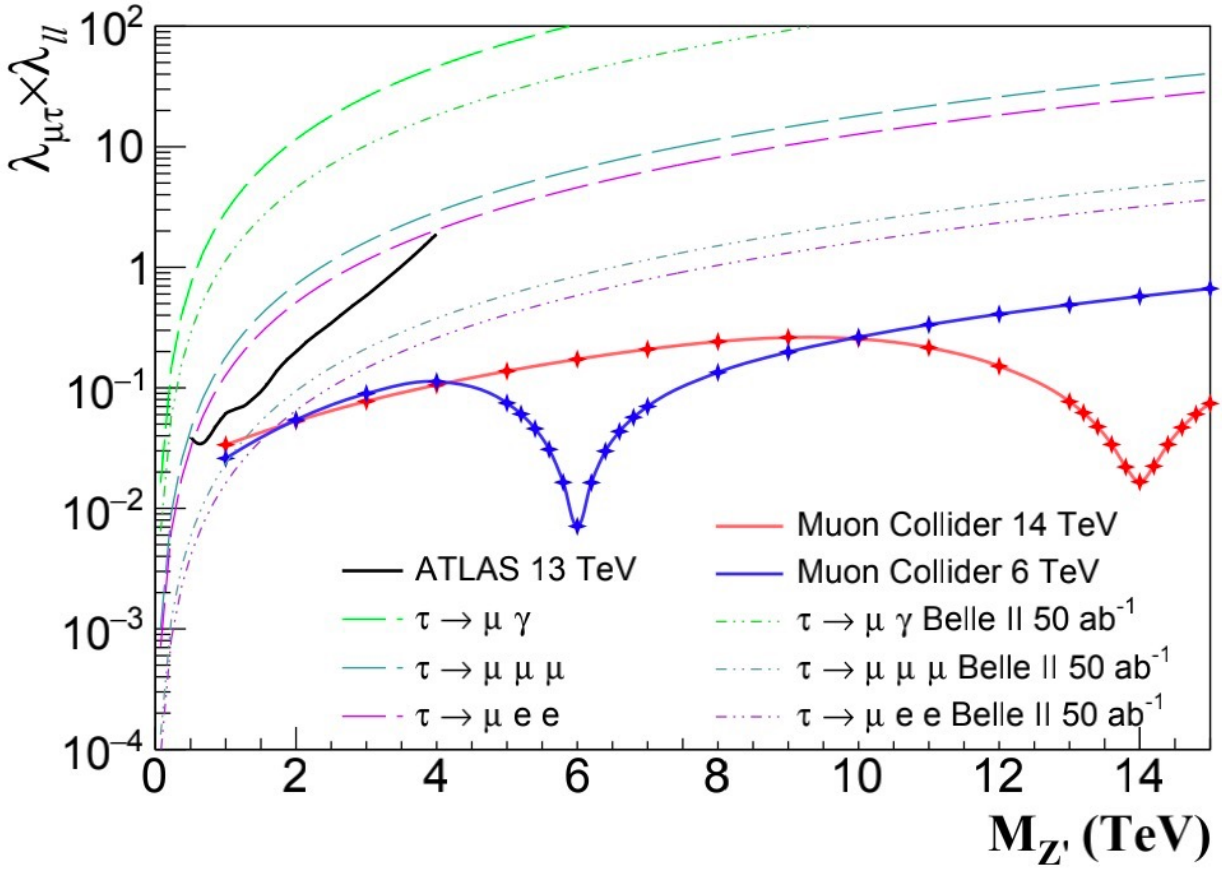


- Compared with the ATLAS experiment, current low-energy experiments (dashed lines) and future experiments (dash-dotted lines) .

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.

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 strongest constraint: $\mu\tau$ coupling at the 6Tev Muon collider, reaching 10^{-3} when Z' mass equals to 6 TeV, which is stronger than the current best limits on CLFV.
- The τ related CLFV coupling strength will be significantly improved.

Thank you!

Back up

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

$\mu - decay$ $\gamma - vertex$ $\vartheta - oscillation$

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

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