Searching for Leptophilic *Z'* at Future Muon *Collider*

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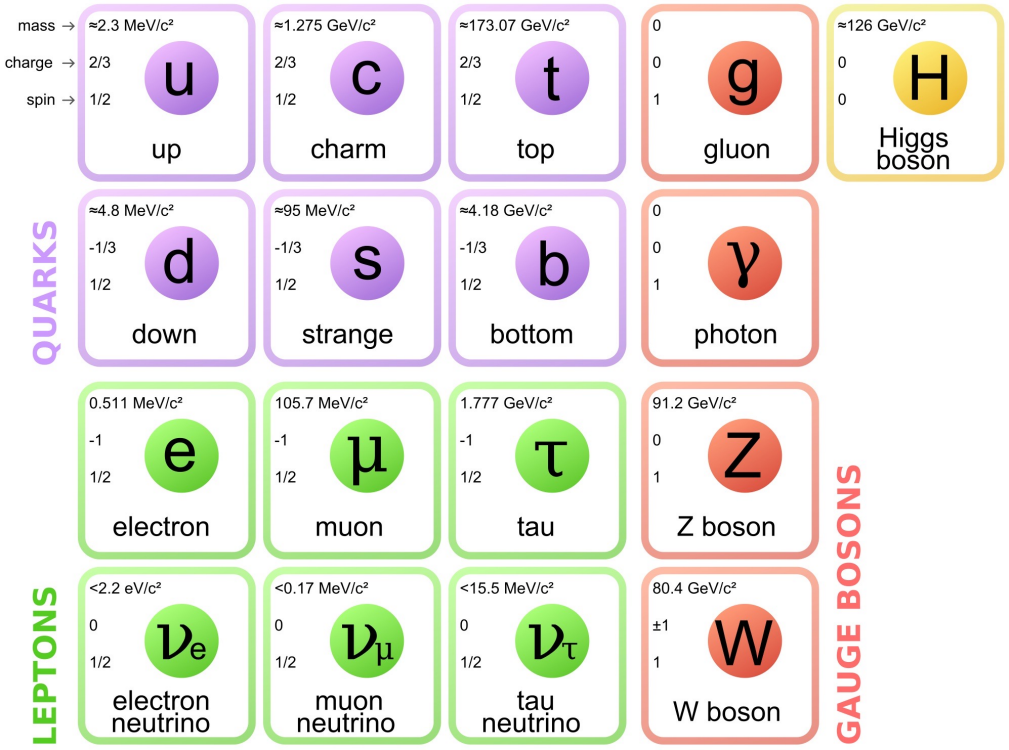
[arXiv:2308.12804]

(image credit: CERN)

Standard Model

- Standard Model Symmetries :
- $SU(3)_C \times SU(2)_L \times U(1)_Y$



(image credit: quantum diaries)

Is Standard Model the Final Theory?

Certainly not!

Dark Matter
Neutrino Masses
Matter-Antimatter Asymmetry
……

Beyond Standard Model

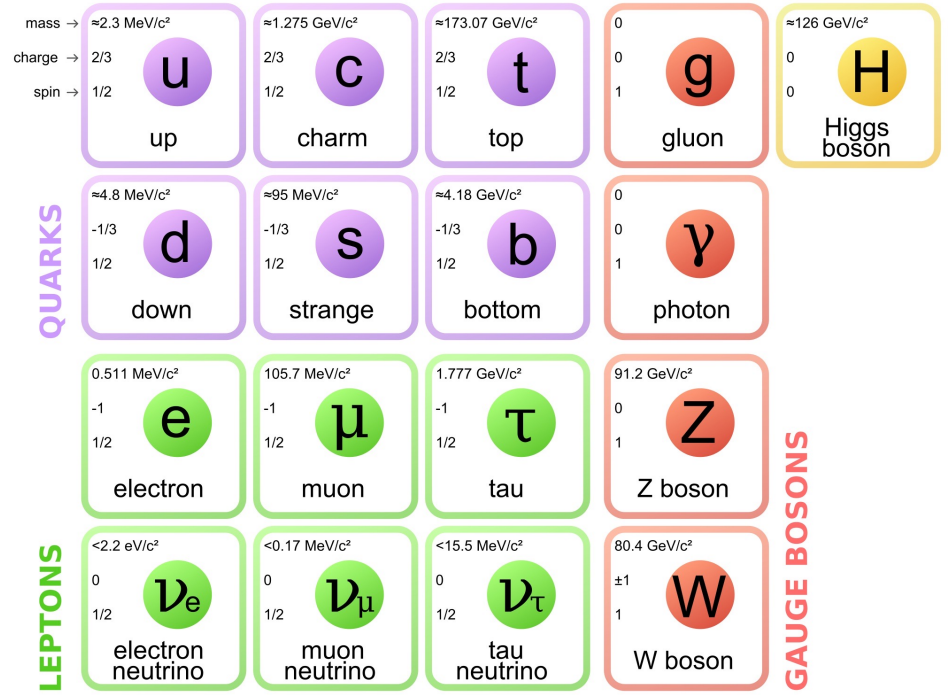
- Extra Symmetry

$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)'$

What does this new symmetry bring?

Z' Propagator of New force, Leptophilic

Φ only to produce the Z' mass



What are we studying?

Searching Z' signal at **future muon collider**

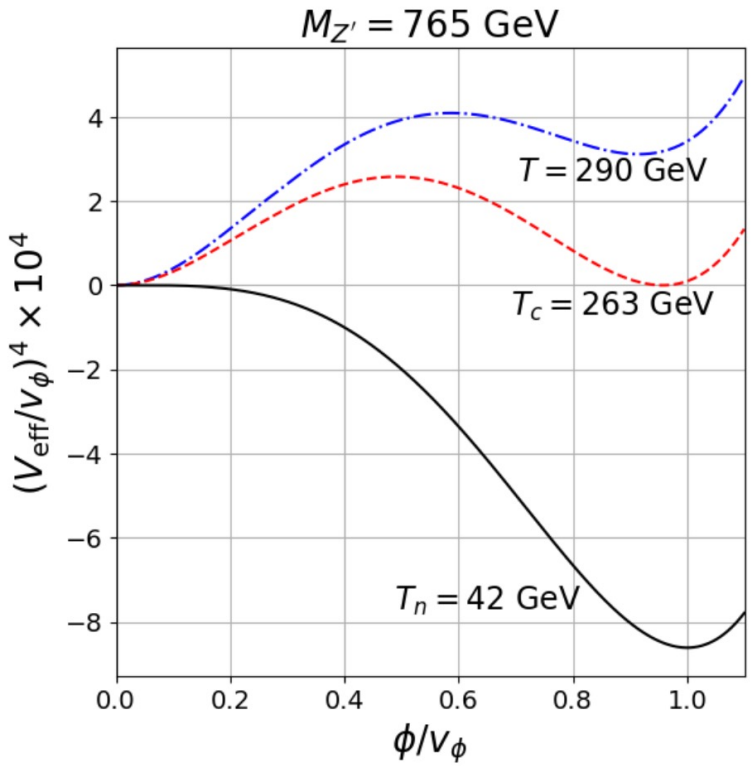
Why do we study this model ?

- Simplest Extension
- $(g-2)_\mu$ Anomalous Magnetic Dipole Moment

  [P. Fayet, arXiv:hep-ph/0702176]
- Gravitational Waves Generation

  [R. Jinno, M. Takimoto, arXiv: 1604.05035]
- Mediator to the Dark Sector

  [W. Altmannshofer, S. Gori, S. Profumo, F. S. Queiroz, arXiv: 1609.04026]



$L_\mu - L_\tau$ Model

B-L model Variant:

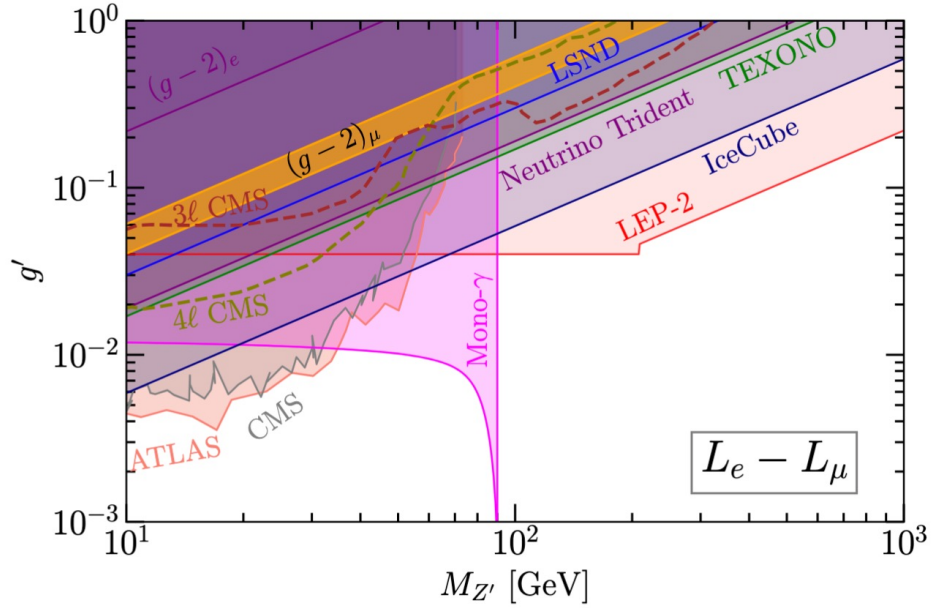
$L_e - L_\mu$, $L_e - L_\tau$, $L_\mu - L_\tau$ Models

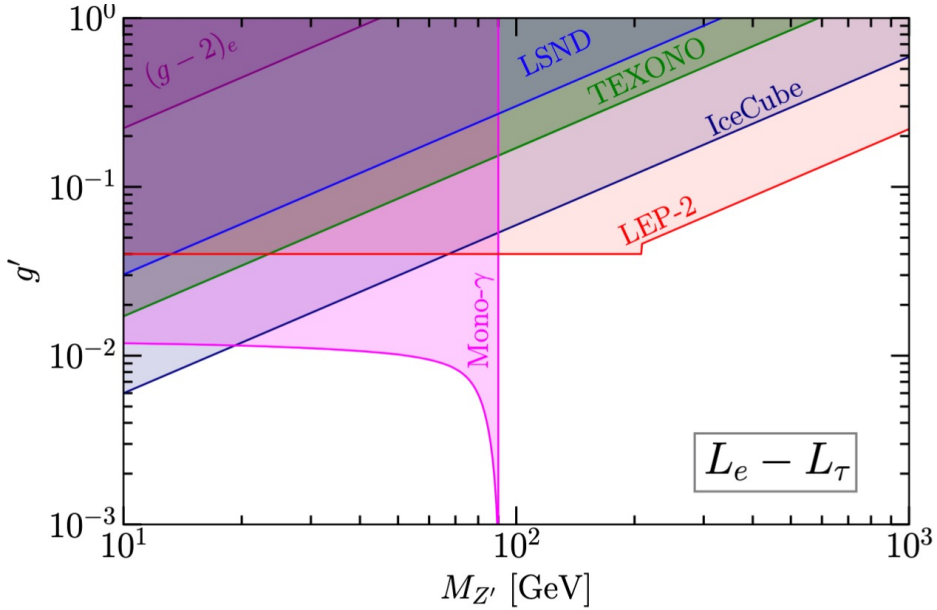
Gauge group	L_e	L_μ	L_τ	e_R	μ_R	τ_R	H	Φ
$SU(3)_c$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$SU(2)_L$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$
$U(1)_Y$	$-\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{2}$	-1	-1	-1	$\frac{1}{2}$	0
$U(1)_{L_\mu - L_\tau}$	0	1	-1	0	1	-1	0	2

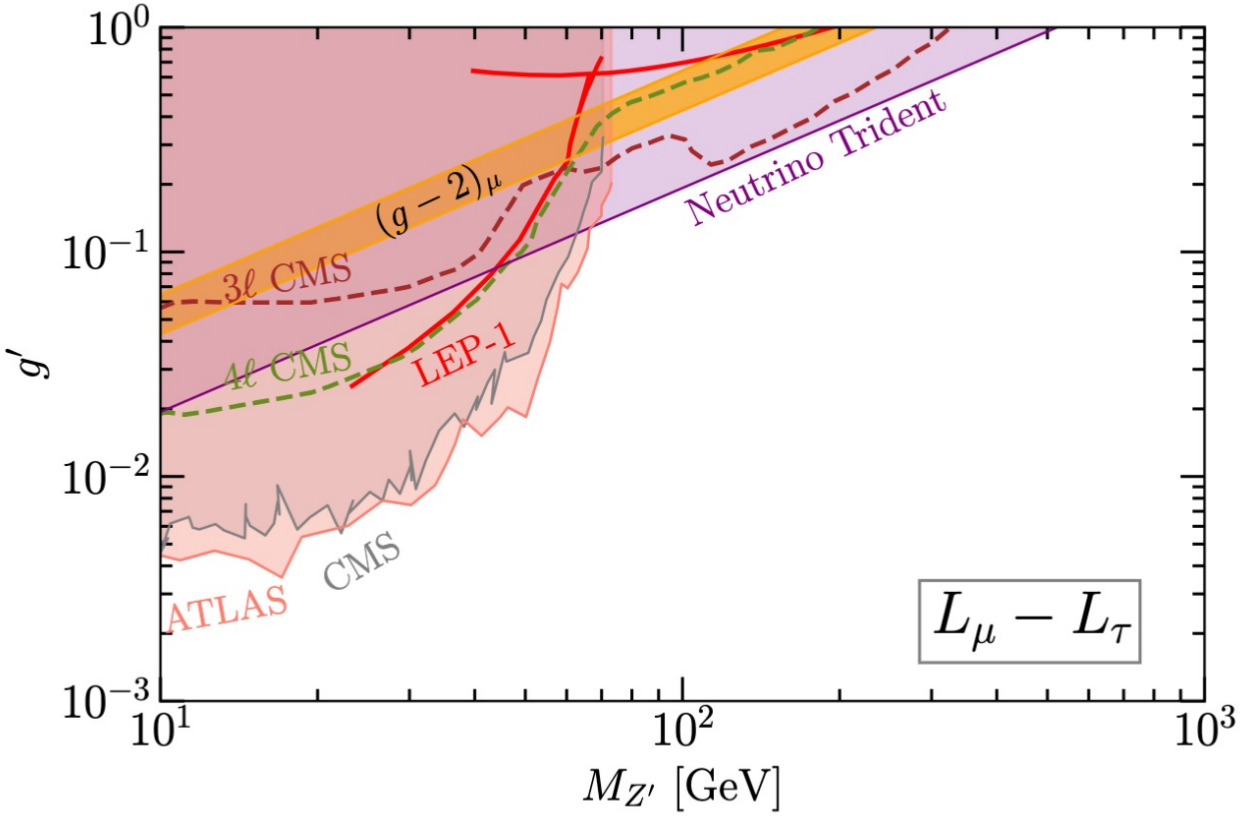
$$\mathcal{L}_{\mu-\tau} = g' Z'_\nu (\bar{L}_\mu \gamma^\nu L_\mu - \bar{L}_\tau \gamma^\nu L_\tau + \bar{\mu}_R \gamma^\nu \mu_R - \bar{\tau}_R \gamma^\nu \tau_R) + \frac{1}{2} M^2_{Z'} Z'_\mu Z'^\mu$$

$$M_{Z'} = 2 g' v_\Phi$$

Current Exclusion Bounds







Current:

LHC: ATLAS, CMS
Neutrino scattering: LSND, TEXONO
LEP, IceCube, $(g-2)_l$

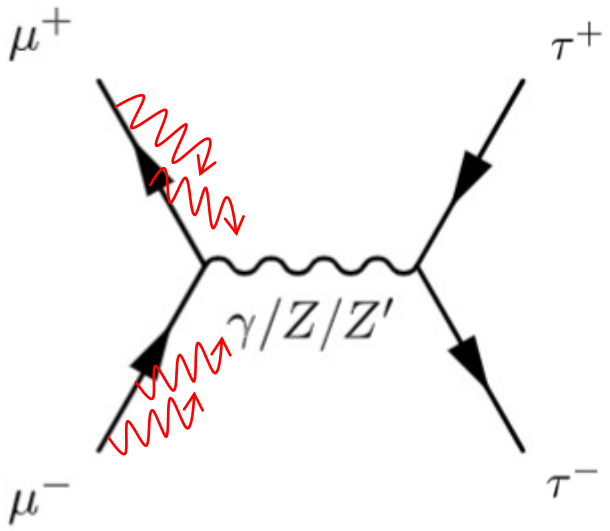
Future:

Muon Collider, CLIC, ILC,
CEPC, FCC,

Muon Collider Search Example

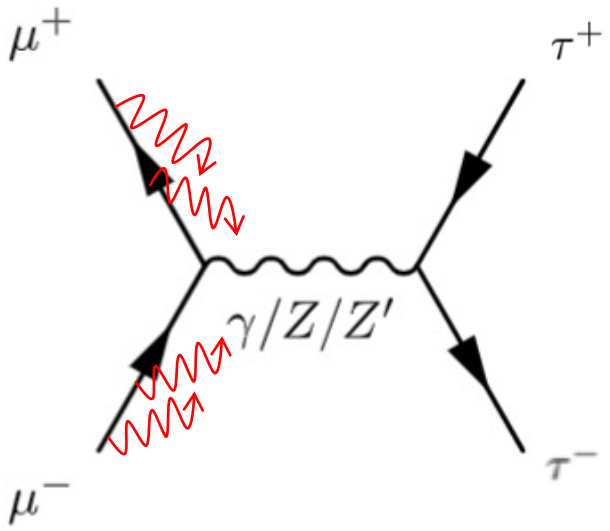
On-Shell Z' Particle Production

$\mu^+\mu^- \to \tau^+\tau^-$ With Initial State Radiation (ISR)

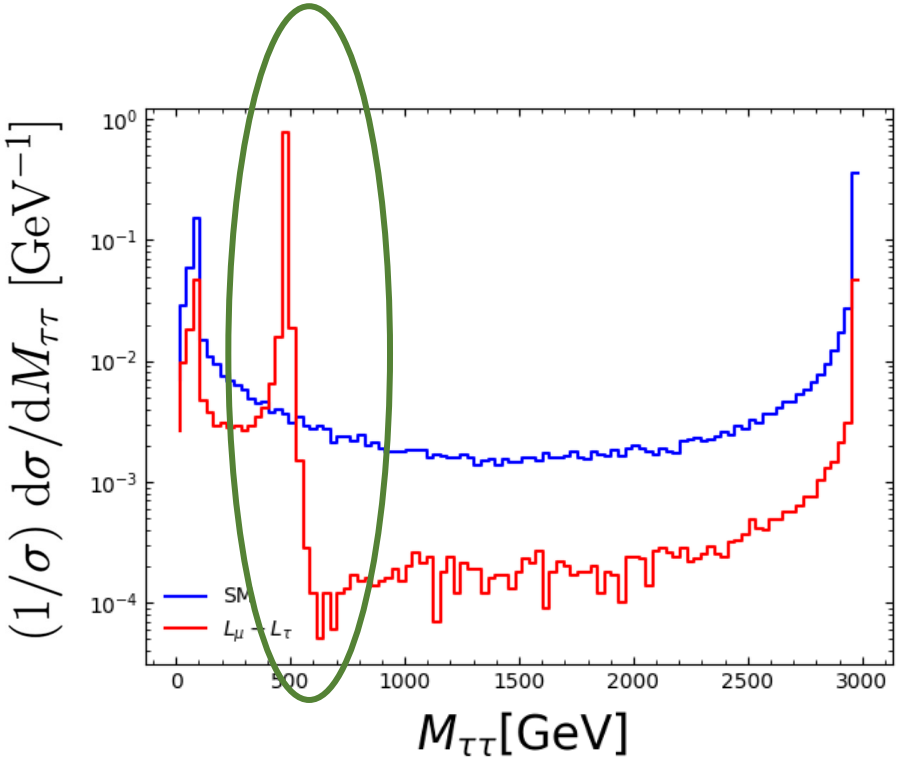


On-Shell Z' Particle Production Resonance

$\mu^+\mu^- \to \tau^+\tau^-$ With Initial State Radiation (ISR)



$\sqrt{s} = 3$ TeV
$M_{Z'} = 500$ GeV
g'=0.2

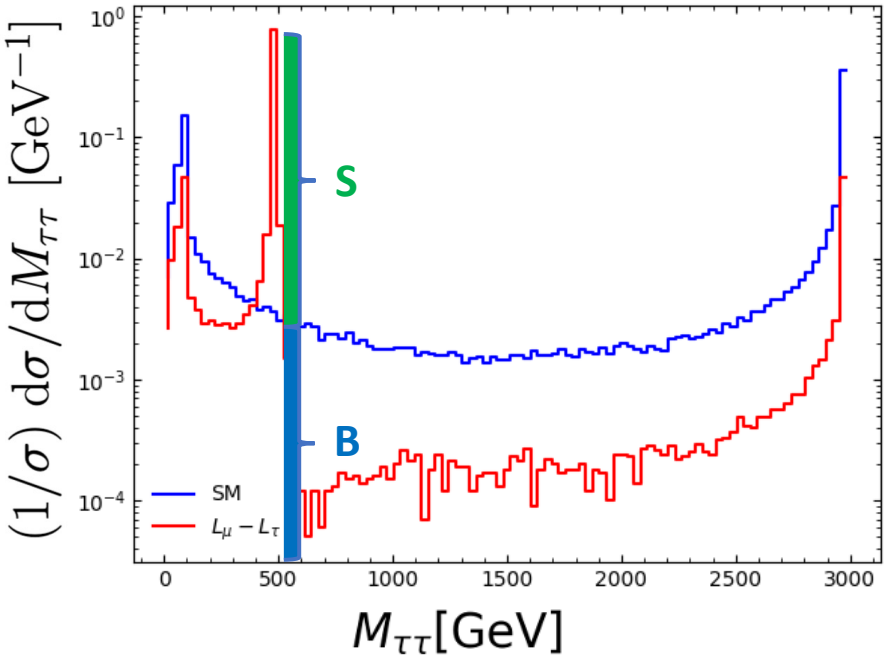


propagator:

$$\frac{1}{(s - M_{Z'}^2)^2 + M_{Z'}^2\Gamma^2} \longrightarrow \text{peak}$$

On-Shell Z' Particle Production Method

$\mu^+\mu^- \to \tau^+\tau^-$ With Initial State Radiation (ISR)



$\sqrt{s} = 3$ TeV
$M_{Z'} = 500$ GeV
g'=0.2

For $M_{Z'}$, from 100 GeV to 3TeV

Significance:

$$\mathcal{S} = \frac{S}{\sqrt{S + B + \delta^2 (S+B)^2}} = 2$$ (equivalent to 95% CL)

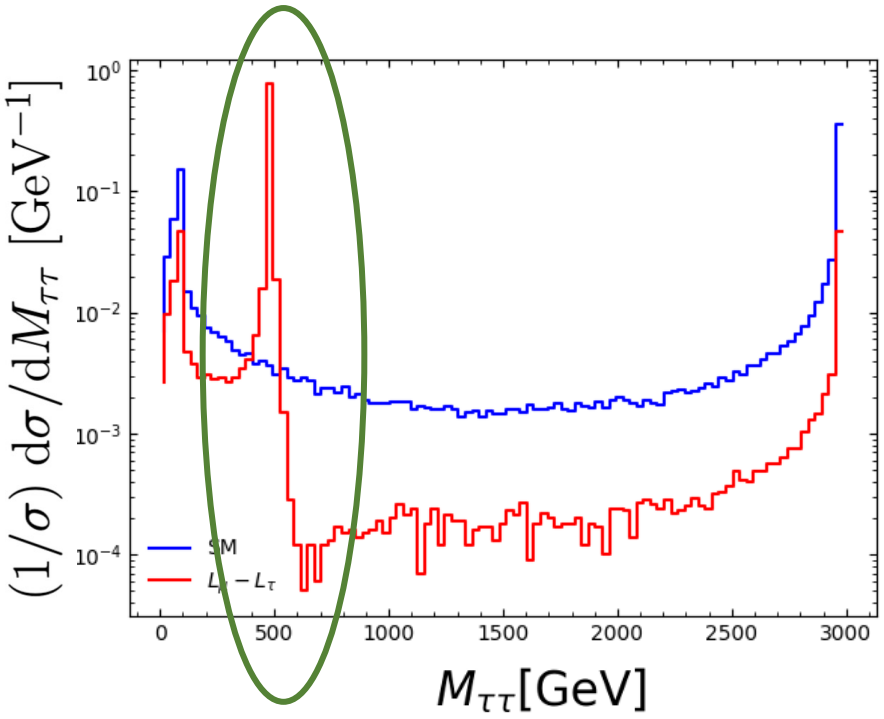
$$S = N^{SM+Z'} - N^{SM} = \epsilon\, \mathcal{L}\, (\sigma^{SM+Z'} - \sigma^{SM})$$

$$B = N^{SM} = \epsilon\, \mathcal{L}\, \sigma^{SM}$$

Whizard, Madgraph

On-Shell Z' Particle Production Selection Cuts

$\mu^+\mu^- \to \tau^+\tau^-$ With Initial State Radiation (ISR)



$\sqrt{s} = 3$ TeV
$M_{Z'} = 500$ GeV
g'=0.2

Pre-selection Cuts:

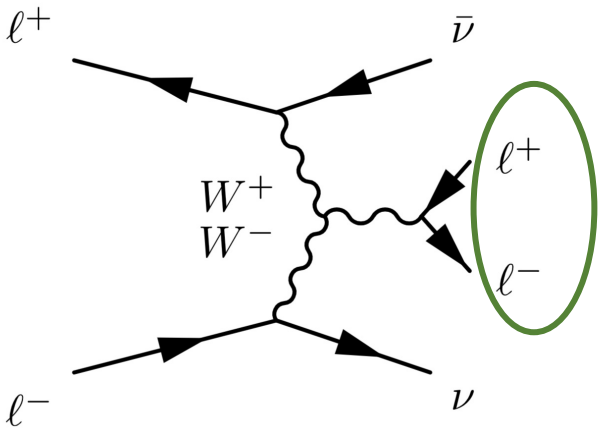
$$p_T^\ell > 30\ \mathrm{GeV},\ |\eta_\ell| < 2.44,\ \Delta R_{\ell\ell} > 0.3$$

Optimization Cuts:

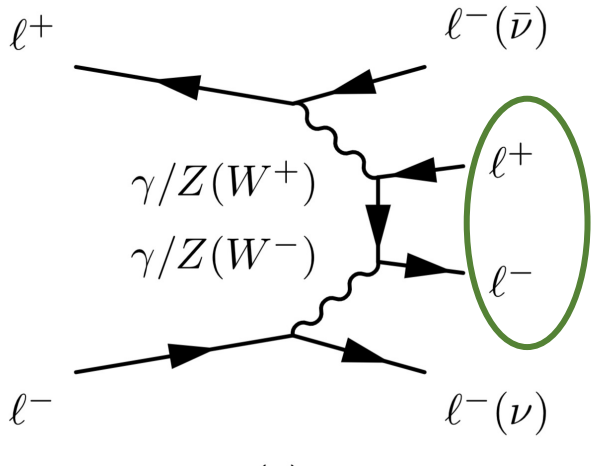
$$|M_{\ell\ell} - M_{Z'}| < 0.05 M_{Z'}\ (10\ \mathrm{GeV})$$

τ e, μ

Vector Boson Fusion (VBF) Background

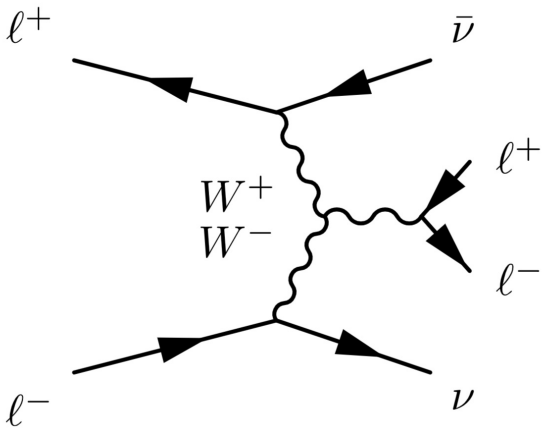


Charge Current (CC) VBF

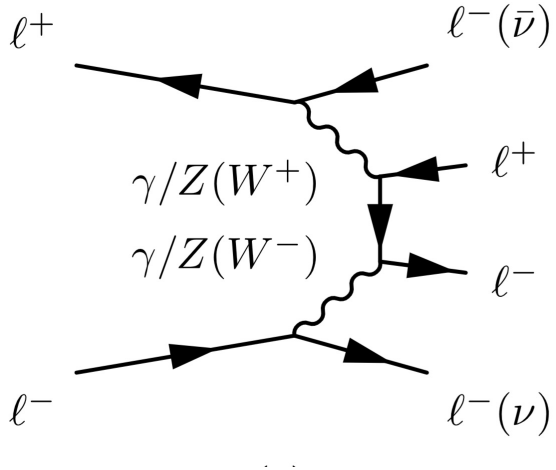


Neutral Current (NC) VBF

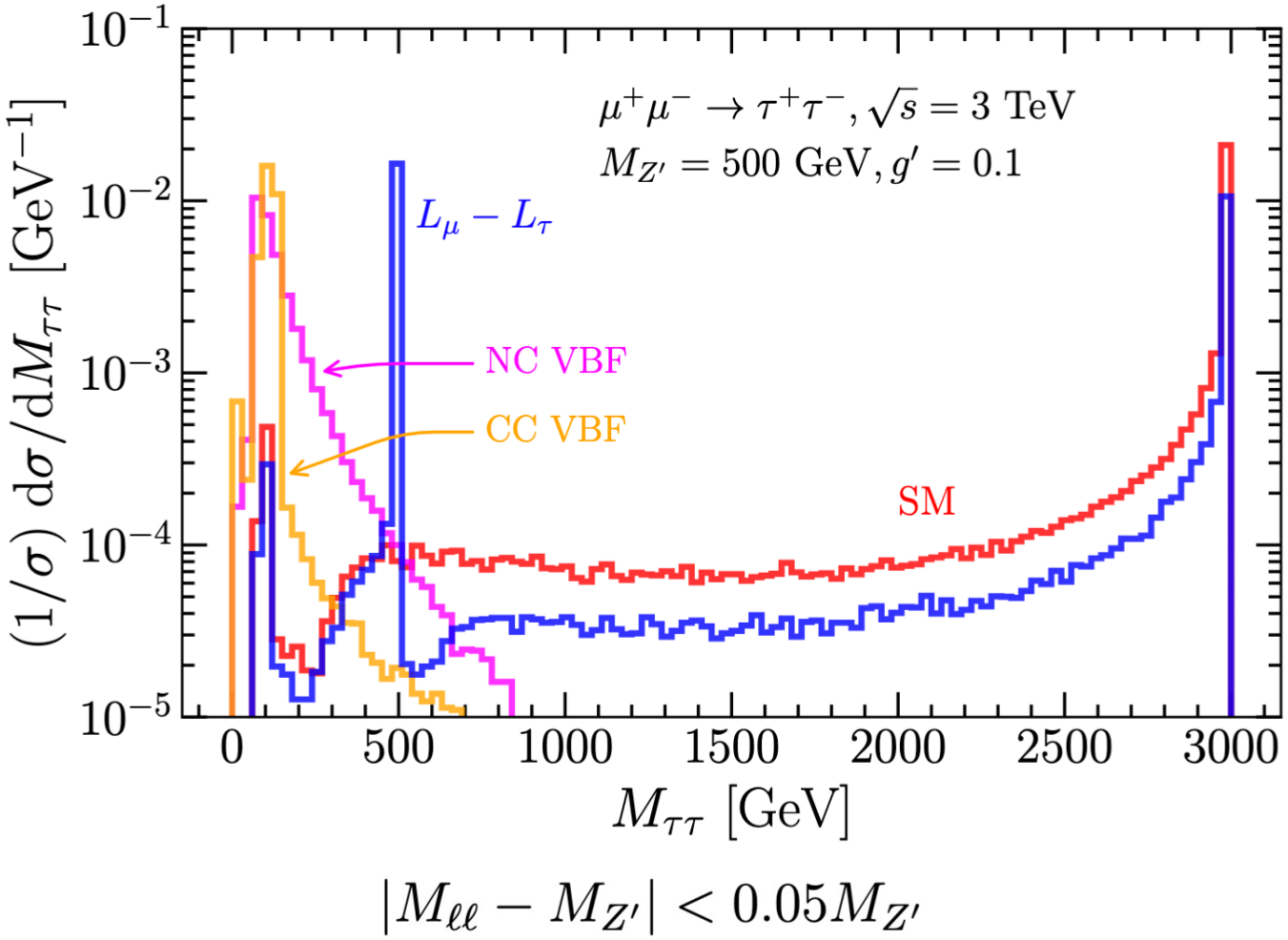
Vector Boson Fusion (VBF) Background



(CC)

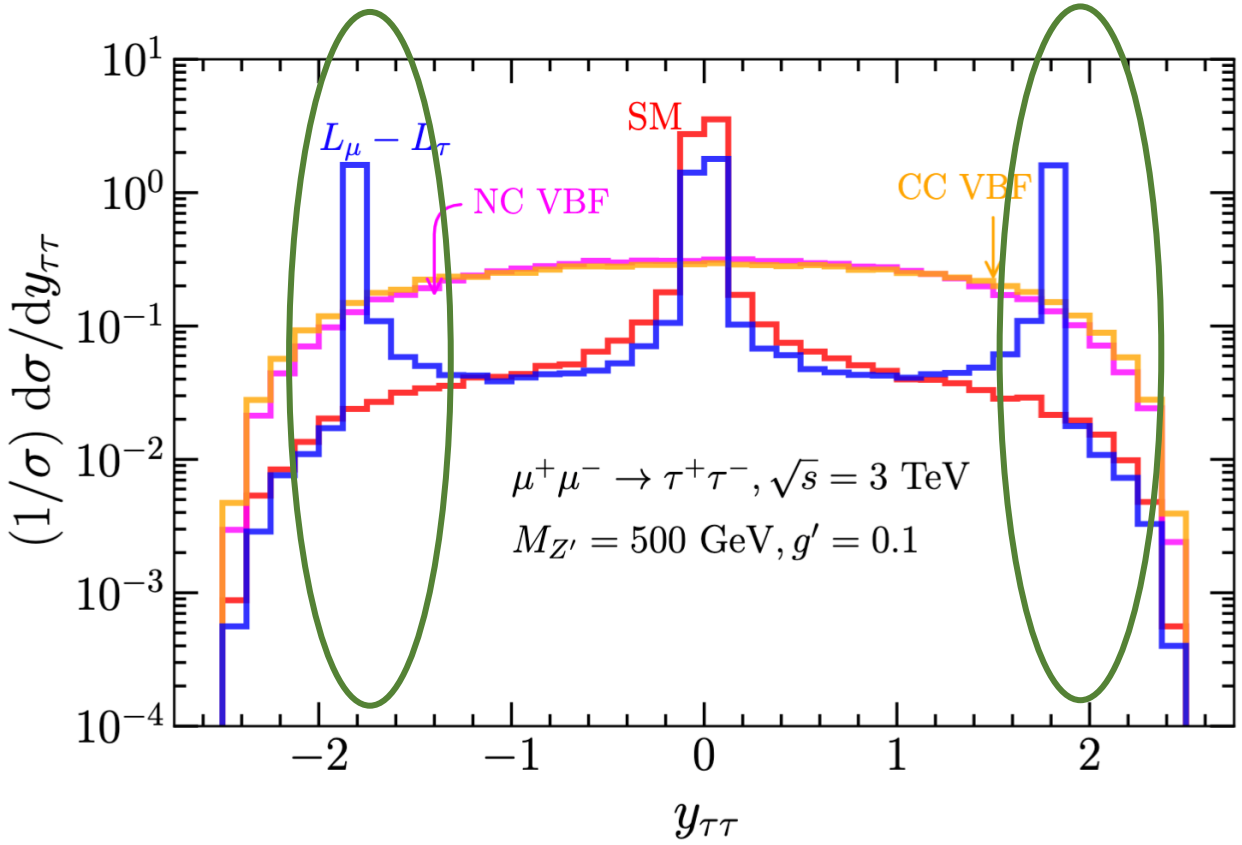


(NC)



$|M_{\ell\ell} - M_{Z'}| < 0.05 M_{Z'}$

On-Shell Z' Particle Production — System Rapidity Cut

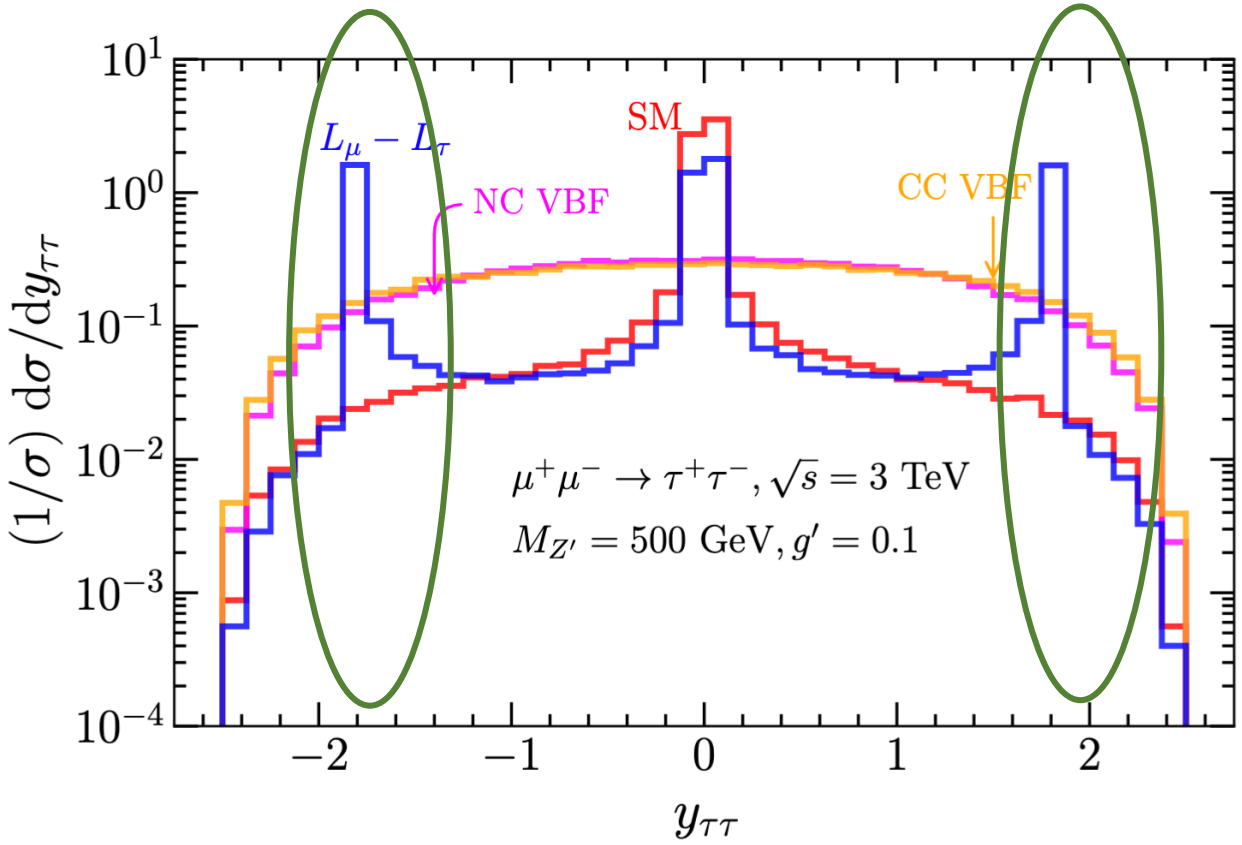


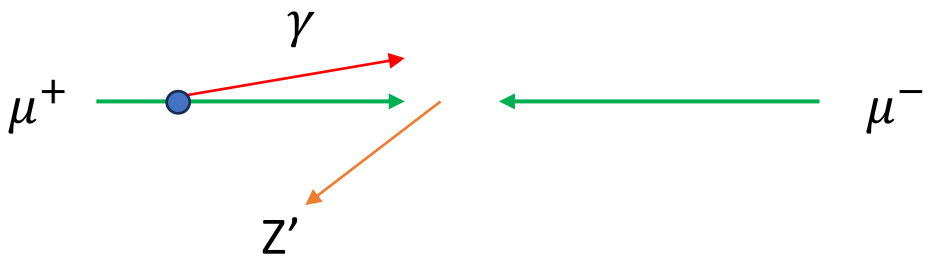
Additional Optimization Cuts:

$$|y_{\tau\tau} \pm y_{Z'}| < 0.2$$

On-Shell Z' Particle Production

System Rapidity Cut





Additional Optimization Cuts:

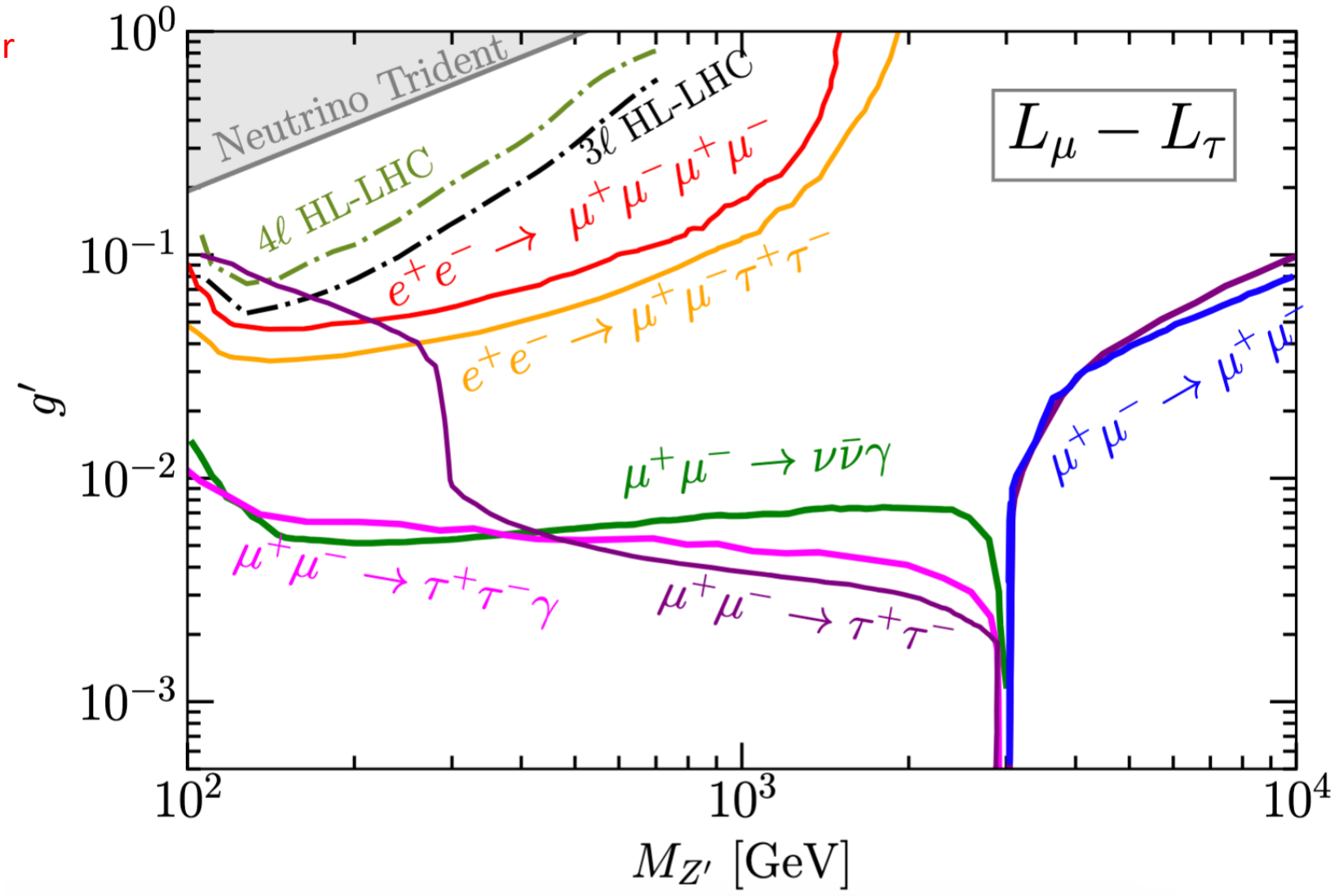
$$|y_{\tau\tau} \pm y_{Z'}| < 0.2$$

Final Significance Plots

Significance Plot

Muon Collider

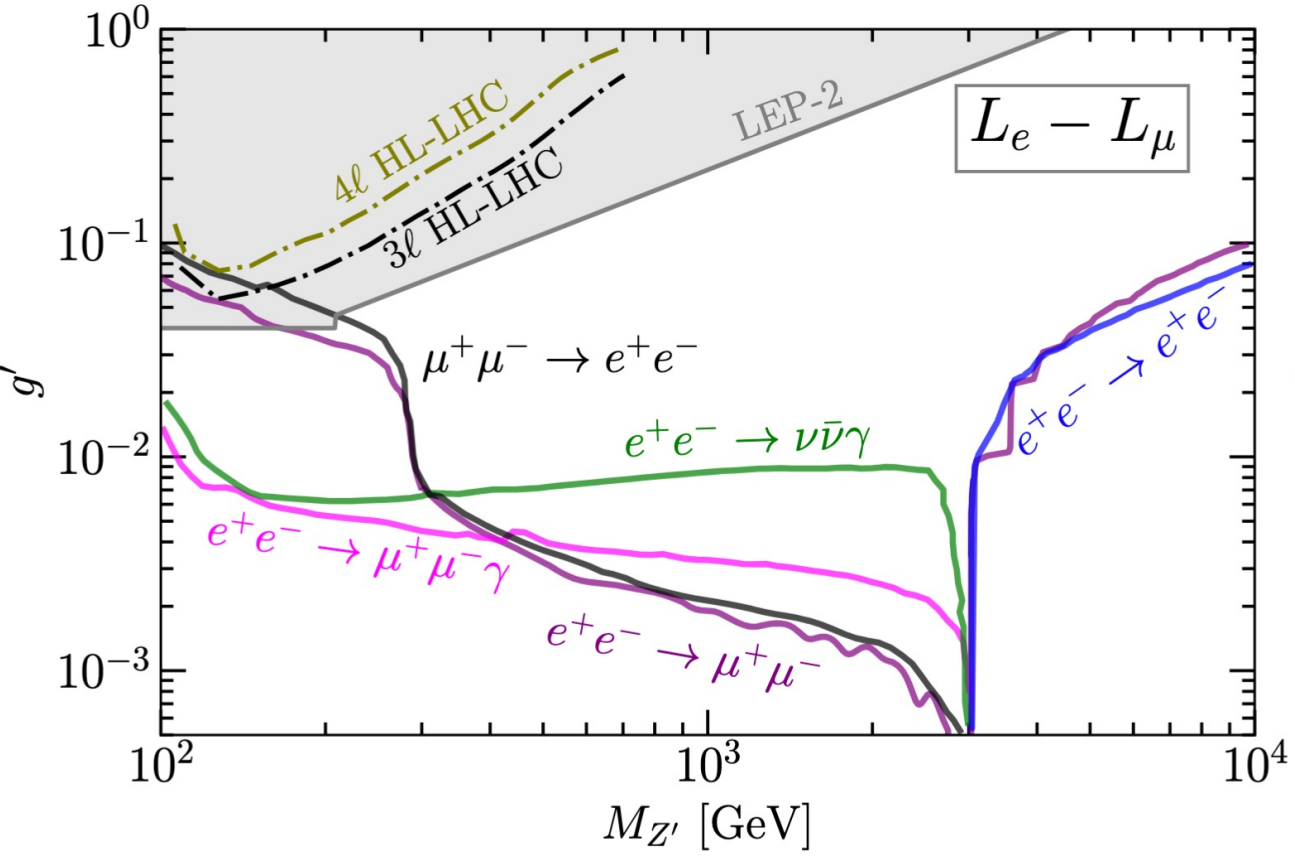
$\sqrt{s} = 3$ TeV
$\mathcal{L} = 1\ ab^{-1}$

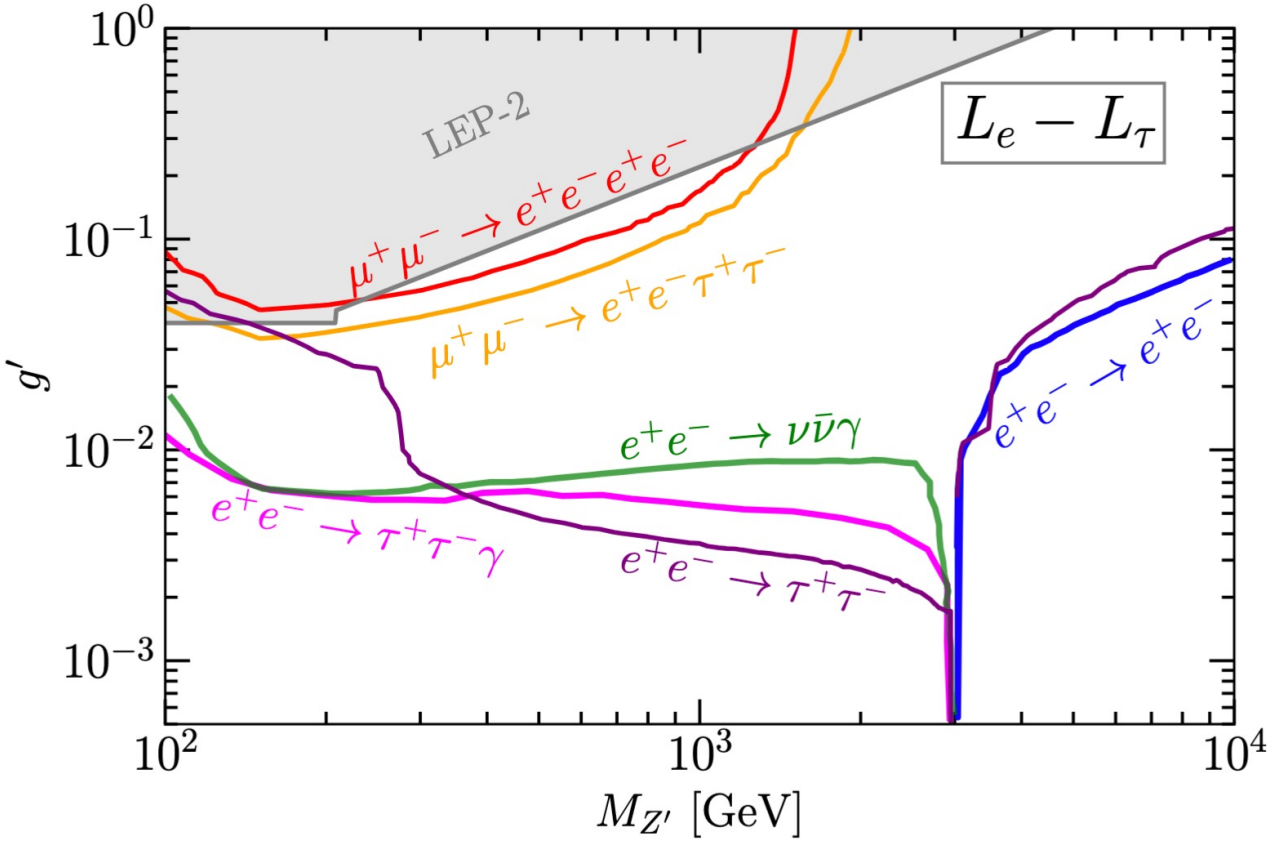


Final Constraints

Electron Collider

$\sqrt{s} = 3$ TeV
$\mathcal{L} = 1\ ab^{-1}$





Summary

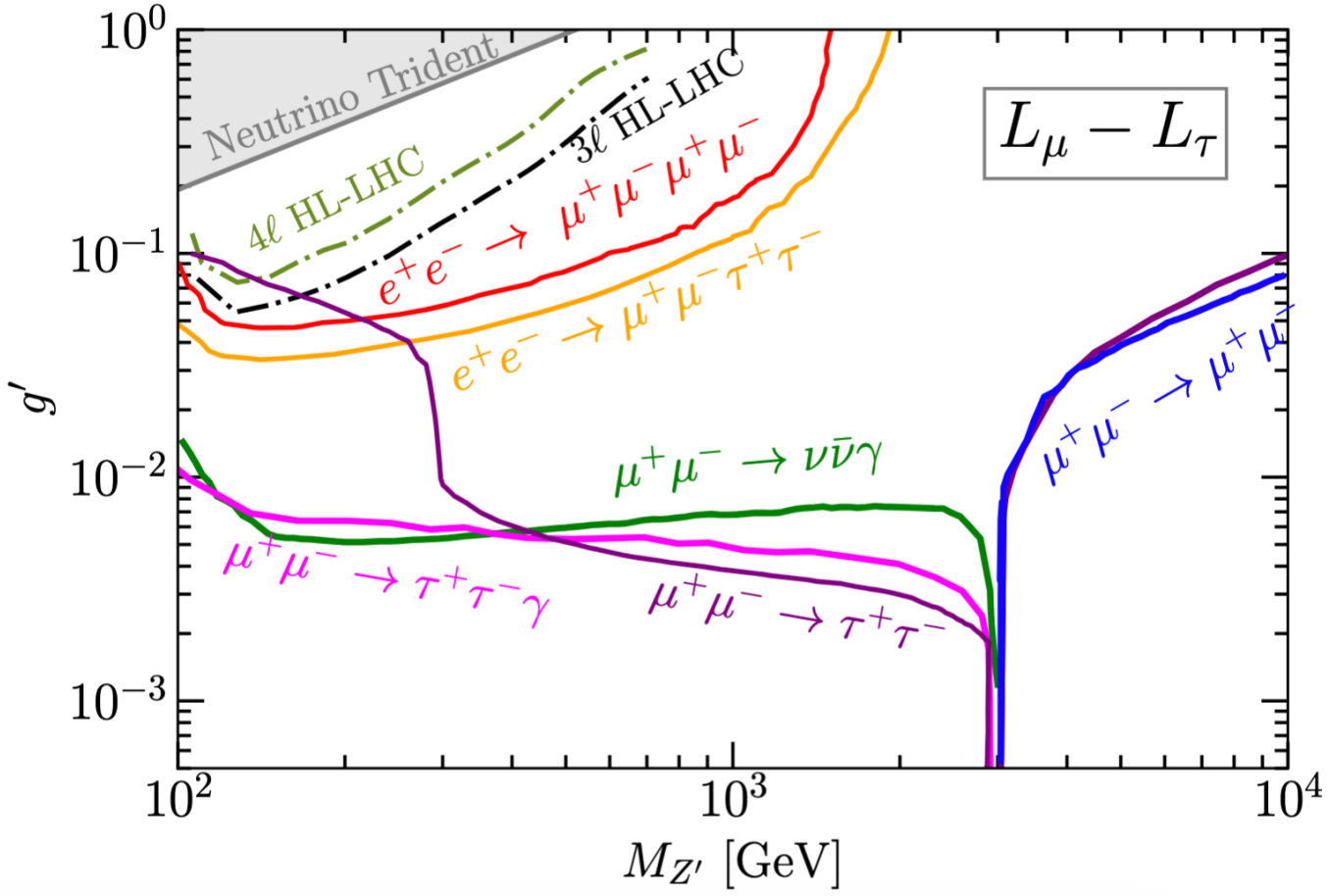
1. $SU(2)_L \times U(1)_Y \times$U(1)'

   New particles:
   gauge boson Z' and singlet scalar ϕ

2. ISR has worse sensitivity
   adding VBF background

   adding system rapidity cut
   enhanced the sensitivity

$L_e - L_\mu$, $L_e - L_\tau$, $L_\mu - L_\tau$



Back Up

- B-L

$$\mathscr{L} = \mathscr{L}_{YM} + \mathscr{L}_s + \mathscr{L}_f + \mathscr{L}_Y \,.$$

$$\mathscr{L}_{YM}^{\text{Abel}} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} - \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} \,,$$

$$\begin{aligned} F_{\mu\nu} &= \partial_\mu B_\nu - \partial_\nu B_\mu \,, \\ F'_{\mu\nu} &= \partial_\mu B'_\nu - \partial_\nu B'_\mu \,. \end{aligned}$$

$$D_\mu \equiv \partial_\mu + i g_S T^\alpha G_\mu^{\ \alpha} + i g T^a W_\mu^{\ a} + i g_1 Y B_\mu + i g_1' Y_{B-L} B'_\mu \,.$$

$$\begin{aligned} \mathscr{L}_f \;=\; & \sum_{k=1}^{3} \Big(i\overline{q_{kL}} \gamma_\mu D^\mu q_{kL} + i\overline{u_{kR}} \gamma_\mu D^\mu u_{kR} + i\overline{d_{kR}} \gamma_\mu D^\mu d_{kR} + \\ & + i\overline{l_{kL}} \gamma_\mu D^\mu l_{kL} + i\overline{e_{kR}} \gamma_\mu D^\mu e_{kR} + i\overline{\nu_{kR}} \gamma_\mu D^\mu \nu_{kR} \Big) \,, \end{aligned}$$

$$\mathscr{L}_s = (D^\mu H)^\dagger \, D_\mu H + (D^\mu \chi)^\dagger \, D_\mu \chi - V(H, \chi) \,,$$

$$V(H,\chi) = m^2 H^\dagger H + \mu^2 \mid \chi \mid^2 + \lambda_1 (H^\dagger H)^2 + \lambda_2 \mid \chi \mid^4 + \lambda_3 H^\dagger H \mid \chi \mid^2 \,,$$

$$\begin{aligned} \mathscr{L}_Y \;=\; & -y^d_{jk} \overline{q_{jL}} d_{kR} H - y^u_{jk} \overline{q_{jL}} u_{kR} \widetilde{H} - y^e_{jk} \overline{l_{jL}} e_{kR} H \\ & - y^\nu_{jk} \overline{l_{jL}} \nu_{kR} \widetilde{H} - y^M_{jk} \overline{(\nu_R)^c_j} \nu_{kR} \chi + \text{h.c.} \,, \end{aligned}$$

Z’ Particle Width

Propagator of New force, Neutral, No RH LH difference

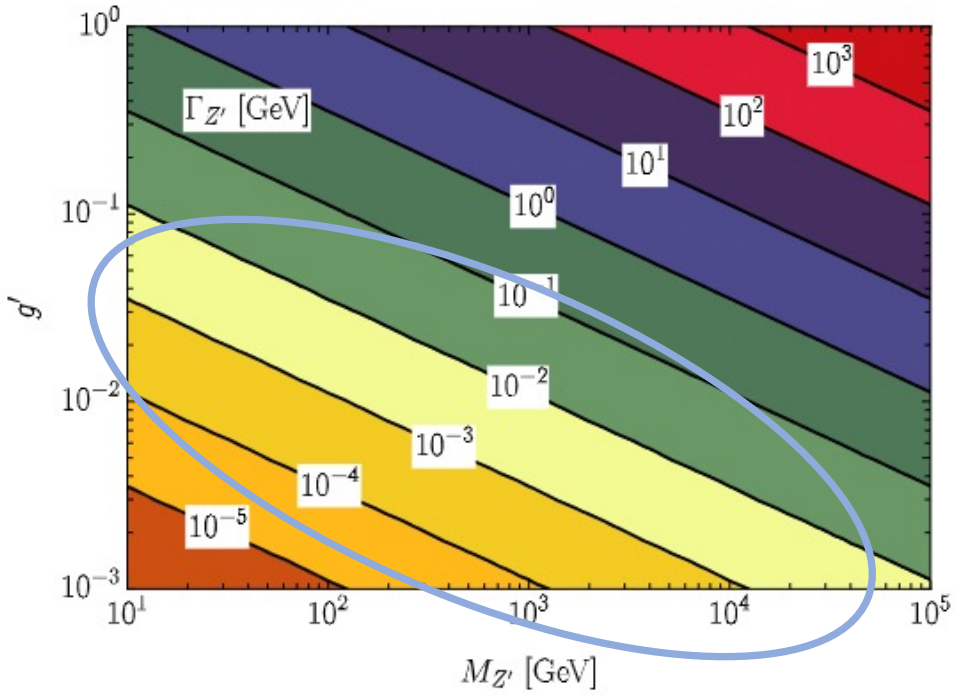
Width:

$$\mathcal{M} = -g'\epsilon^{\mu}\bar{u}(p_1)\gamma_{\mu}v(p_2)$$

$$\Gamma = \frac{g'^2 M_{Z'}}{12\pi}$$

$$\Gamma(Z' \to l\bar{l}) = 2\Gamma(Z' \to \nu\bar{\nu})$$

$$\Gamma_{tot} = \frac{(2N_l + N_\nu)g'^2}{24\pi} M_{Z'} = \frac{6g'^2}{24\pi} M_{Z'}$$



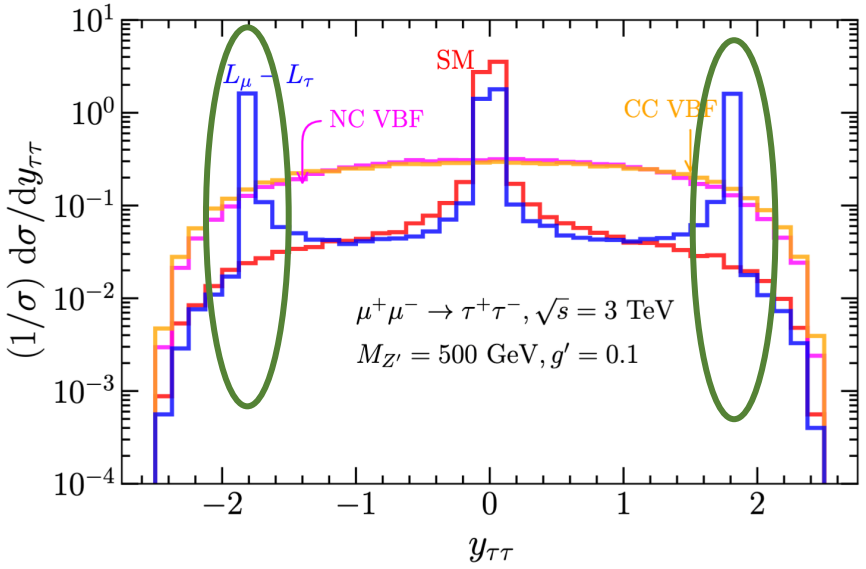
Ignore lepton masses

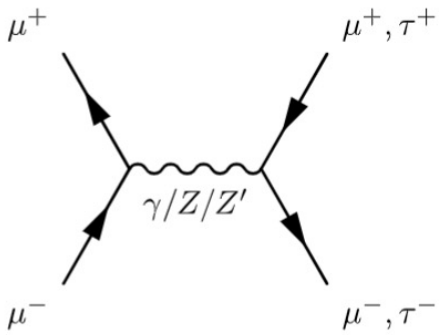
$$c\tau = \frac{c}{\Gamma(Z')} = 2.48 \times 10^{-4}\ \mu m \left(\frac{10^{-3}}{g'}\right)^2 \left(\frac{10\ \text{GeV}}{M_{Z'}}\right)$$

Prompt decay

On-Shell Z' Particle Production

System Rapidity Cut





(momentum conservation)

$$P_{Z'} = P_{\mu^+} + P_{\mu^-} = \left(\frac{1}{2}\sqrt{s} - E_\gamma, \frac{1}{2}\sqrt{s} - E_\gamma\right) + \left(\frac{1}{2}\sqrt{s}, -\frac{1}{2}\sqrt{s}\right) = (\sqrt{s} - E_\gamma, -E_\gamma)$$

$$M_{Z'}^2 = P_{Z'}^2 = (\sqrt{s} - E_\gamma)^2 - E_\gamma^2 = s - 2\sqrt{s}E_\gamma$$

(the energy-momentum relation)

$$E_\gamma = (s - M_{Z'}^2)/2\sqrt{s}$$

$$y_{Z'} = \frac{1}{2}\ln\frac{E + p_z}{E - p_z} = \frac{1}{2}\ln\frac{\sqrt{s} - 2E_\gamma}{\sqrt{s}} = \frac{1}{2}\ln\frac{M_{Z'}^2}{s}$$

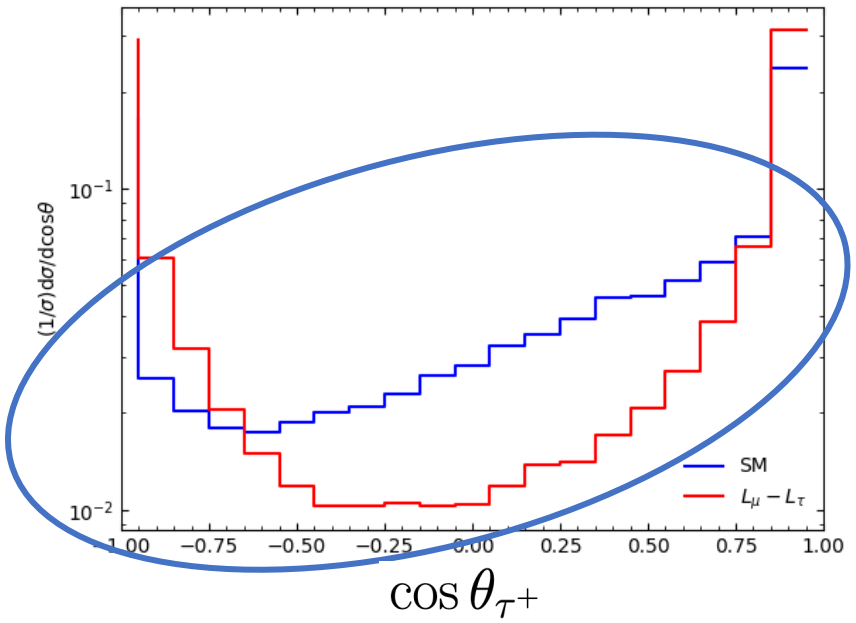
$$y_{Z'} \approx \log\cot(\theta/2) \longrightarrow \tan(\theta/2) \approx M_{Z'}/\sqrt{s}$$

$$|\eta_\ell| < 2.44$$

$$M < 0.088\sqrt{s}$$

Off-Shell Z' Particle Production Method

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



For $M_{Z'}$, from 3 TeV to 10 TeV

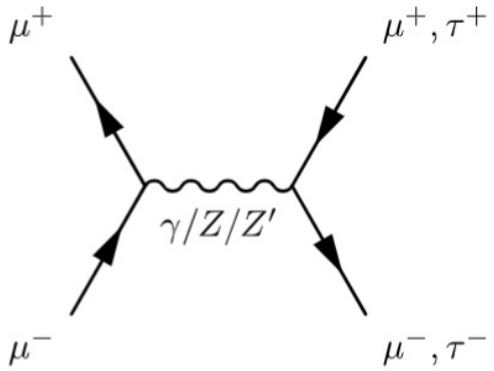
Chi square:

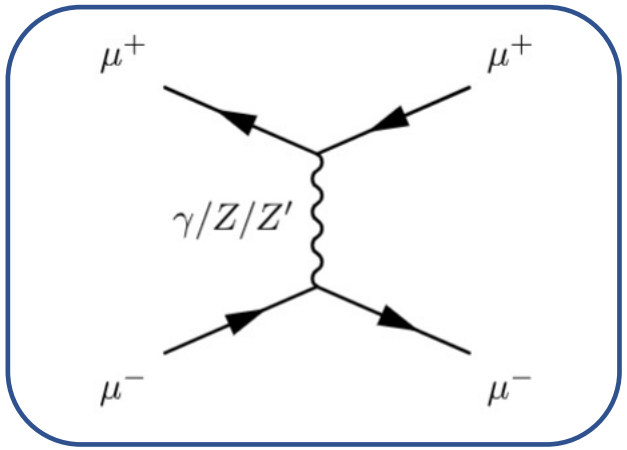
$$\chi^2 = \sum_i \frac{S_i^2}{S_i + B_i + \delta^2(S_i + B_i)^2} = 4$$

$\sqrt{s} = 3$ TeV
$M_{Z'} = 500$ GeV
g'=0.2

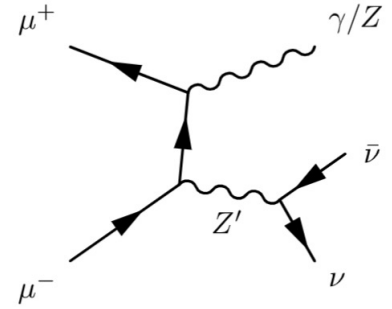
Directly Coupled to Z’ Particle

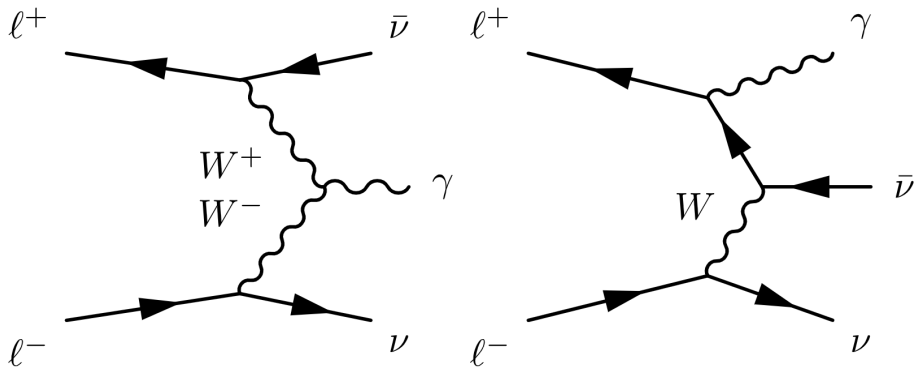
$\mu^+\mu^- \rightarrow \mu^+\mu^-$



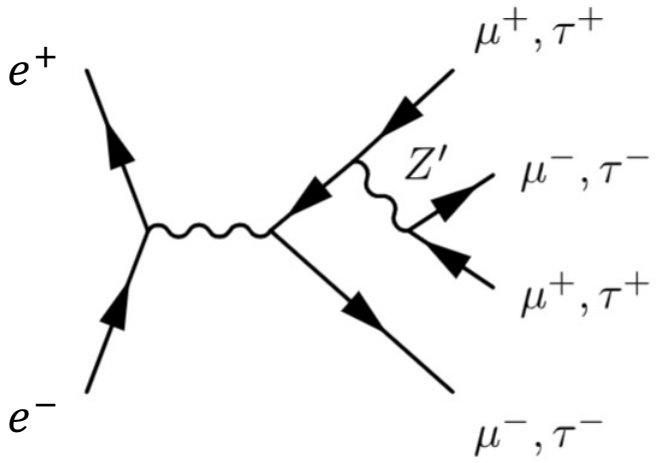


$\mu^+\mu^- \rightarrow \tau^+\tau^-\gamma$ (Mono Photon)





Not Directly Coupled to Z’ Particle



electron beams

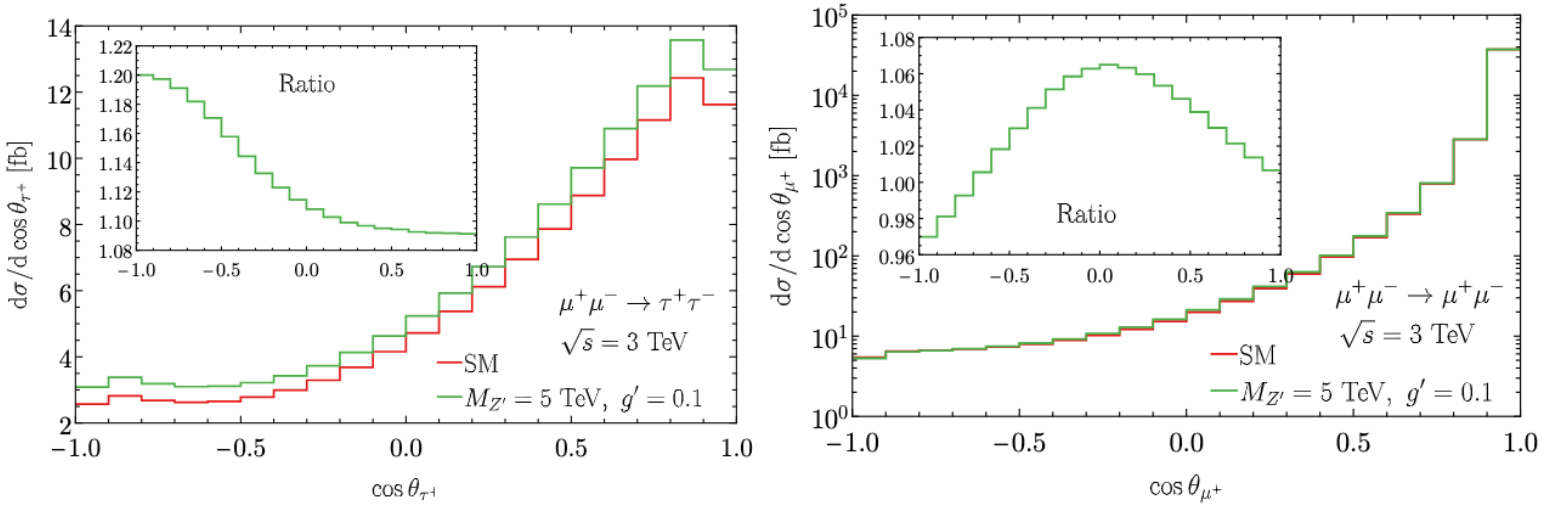


FIG. 7. The cosine angle distribution for the final-state leptons in the off-shell s-channel $\mu^+\mu^- \to \gamma/Z/Z' \to \tau^+\tau^-$ (left) and s/t-channel $\mu^+\mu^- \xrightarrow{\gamma/Z/Z'} \mu^+\mu^-$ (right) scatterings. The Z' signal comes from the difference between the SM and the Z' model, with the relative size of $(S+B)/B$ shown in the corresponding inset.