Muon collider signatures for a Z' with a maximal $\mu - \tau$ coupling in $U(1)_{L_\mu - L_\tau}$

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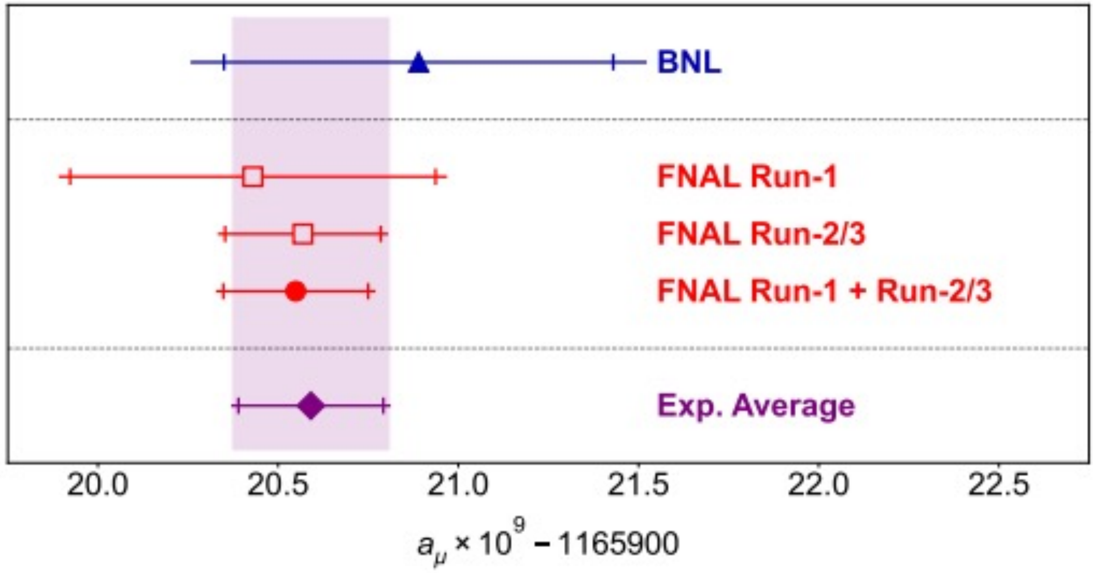
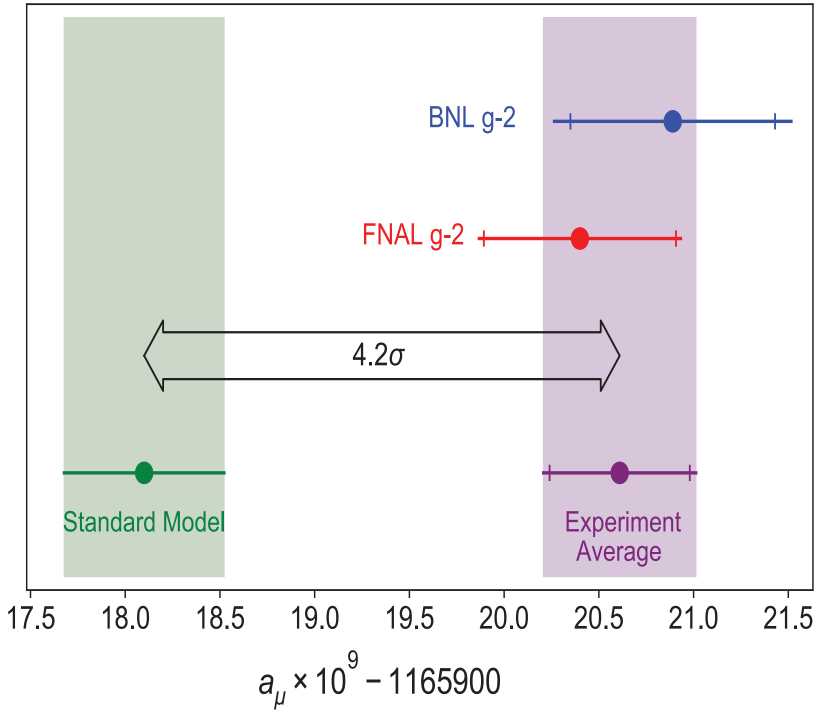
OutLine

- **Introduction**
- **U(1) model for maximal coupling**
- **Collider signatures**
- **Summary**

Introduction



Phys. Rev. L 131. 161802(2023)



Phys. Rev. L 126. 141801(2021)

Introduction

$$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = (251 \pm 59) \times 10^{-11} \qquad 4.2\sigma$$

Simplest $U(1)_{L_\mu - L_\tau}$ model :

- First, second and third generations $U(1)_{L_\mu - L_\tau}$ charge : 0,+1,-1

$$L_{\text{int}-Z'} = -\tilde{g}\left(\bar{\mu}\gamma^\mu\mu - \bar{\tau}\gamma^\mu\tau + \bar{\nu}_\mu\gamma^\mu L\nu_\mu - \bar{\nu}_\tau\gamma^\mu L\nu_\tau\right)Z'_\mu,$$

$$\Delta a_\mu^{Z'} = \frac{\tilde{g}^2}{8\pi^2}\frac{m_\mu^2}{m_{Z'}^2}\int_0^1 \frac{2x^2(1-x)dx}{1-x+(m_\mu^2/m_{Z'}^2)x^2}\,.$$

- In the limit $m_{Z'} >> m_\mu, \Delta a_\mu^{Z'} = (\tilde{g}^2/12\pi^2)(m_\mu^2/m_{Z'}^2)$.

$$\tilde{g}^2/m_{Z'}^2 = (2.66 \pm 0.63)\times 10^{-5}\text{GeV}^{-2}$$

- Will induce muon neutrino trident (MNT) process.

Introduction :Neutrino trident process

$\nu_\mu N \to \nu_i \mu \bar{\mu} N$: large $m_{Z'}$: Contribution Proportional to $\tilde{g}^2/m_{Z'}^2$

$$\left.\frac{\sigma_{Z'}}{\sigma_{SM}}\right|_{\text{trident}} = \frac{\left(1+4s_W^2+8\tilde{g}^2 m_W^2/g^2 m_{Z'}^2\right)^2+1}{1+(1+4s_W^2)^2},$$

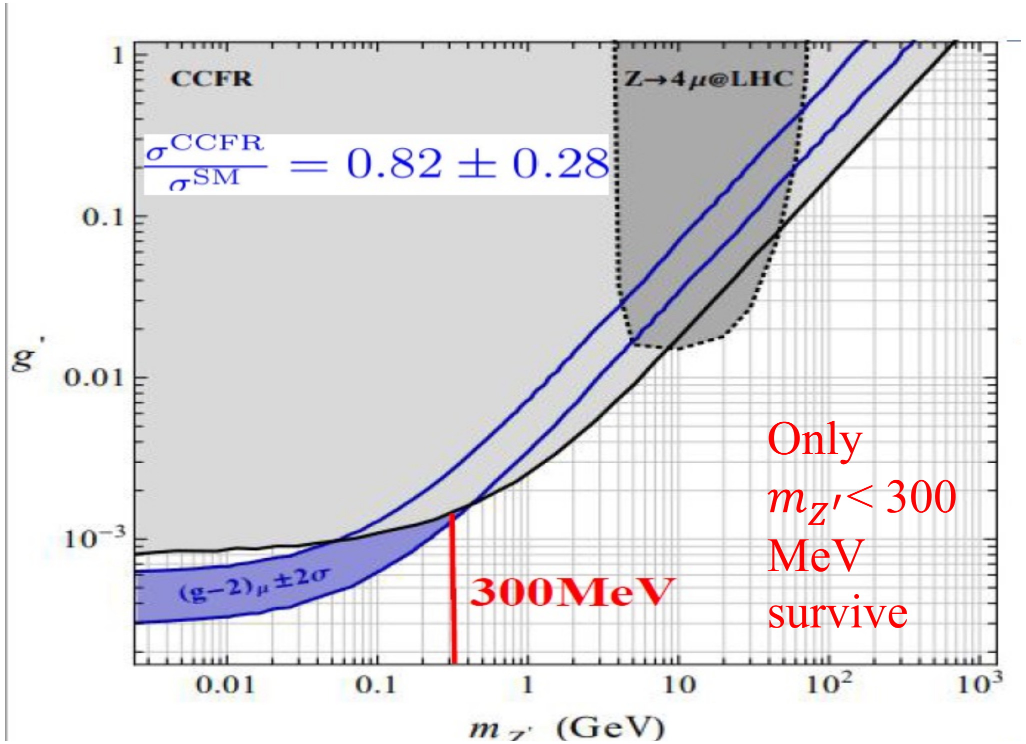
- $\sigma_{Z'}/\sigma_{SM} = 5.86$ for $\tilde{g}^2/m_{Z'}^2 = (2.66 \pm 0.63)\times 10^{-5}\mathrm{GeV}^{-2}$

Data:

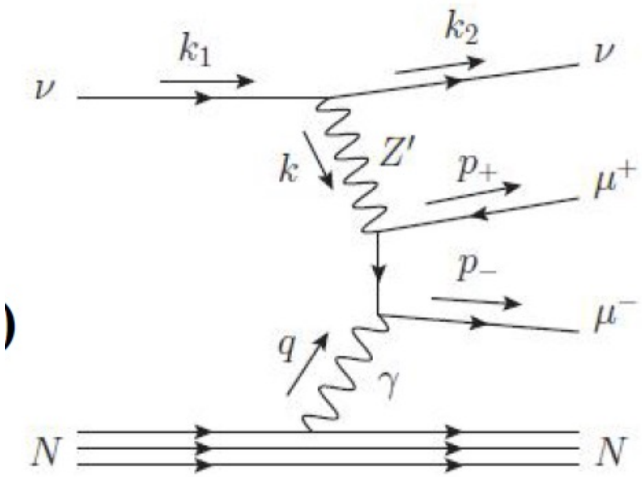
1.58 ± 0.57,CHARM –II

0.82 ± 0.28CCFR

$0.72^{+1.73}_{-0.72}$ NuTeV



Ruled out the model for GeV scale $m_{Z'}$



U(1) model for maximal coupling

$$Z' \to -Z',\ H_1 \leftrightarrow H_1,\ H_2 \leftrightarrow H_3$$

$$\begin{aligned} L_H = & -\tilde{g}(\bar{l}_2\gamma^\mu L l_2 - \bar{l}_3\gamma^\mu L l_3 + \bar{e}_2\gamma^\mu R e_2 - \bar{e}_3\gamma^\mu R e_3)Z'_\mu \\ & -[Y^l_{11}\bar{l}_1 R e_1 H_1 + Y^l_{22}(\bar{l}_2 R e_2 + \bar{l}_3 R e_3)H_1 + Y^l_{23}(\bar{l}_2 R e_3 H_2 + \bar{l}_3 R e_2 H_3)] + H.C. \end{aligned}$$

- The transformation between the lepton mass eigen- state and weak eigen-state basis

$$\begin{pmatrix} \mu \\ \tau \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & -1 \\ 1 & 1 \end{pmatrix}\begin{pmatrix} e_2 \\ e_3 \end{pmatrix}, \quad \begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & -1 \\ 1 & 1 \end{pmatrix}\begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix}.$$

U(1) model for maximal coupling

The conflict can also be avoided if Z' only has $\bar{\mu}\gamma^{\mu}\tau Z'_{\mu}$ type of interaction.

$$L_{\text{int}-Z'} = -\tilde{g}(\bar{\mu}\gamma^{\mu}\tau + \bar{\tau}\gamma^{\mu}\mu + \bar{\nu}_{\mu}\gamma^{\mu}L\nu_{\tau} + \bar{\nu}_{\tau}\gamma^{\mu}L\nu_{\mu})Z'_{\mu} \; .$$

- Give addition contribution to $\tau \to \mu\nu\bar{\nu}$ decay which is highly constrained the model.

$$L_{Z'+W} = -\frac{g^2}{2m_W^2}\bar{\nu}_{\tau}\gamma^{\mu}L\nu_{\mu}\bar{\mu}\gamma_{\mu}L\tau - \frac{\tilde{g}^2}{m_{Z'}^2}(\bar{\nu}_{\tau}\gamma^{\mu}L\nu_{\mu} + \bar{\nu}_{\mu}\gamma^{\mu}L\nu_{\tau})\bar{\mu}\gamma_{\mu}\tau \; .$$

$$R_{\tau\mu} = \Gamma(\tau \to \mu\nu\bar{\nu})/\Gamma_{SM}(\tau \to \mu\nu\bar{\nu}) = 1.0066 \pm 0.0041$$

Ruled out the model more than 5σ

U(1) model for maximal coupling

- Introduce scalar triplet: Δ_i: (1,3, 1)

$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$

Yukawa terms in the mass-eigen basis

$$L_\Delta = -(\bar{\nu}_e^c, \bar{\nu}_\mu^c, \bar{\nu}_\tau^c) M(\Delta^0) L \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} + \sqrt{2}(\bar{\nu}_e^c, \bar{\nu}_\mu^c, \bar{\nu}_\tau^c) M(\Delta^+) L \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix} + (\bar{e}^c, \bar{\mu}^c, \bar{\tau}^c) M(\Delta^{++}) L \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix}$$

$$M(\Delta) = \begin{pmatrix} Y_{11}^\nu \Delta_1 & 0 & 0 \\ 0 & (Y_{22}^\nu(\Delta_2 + \Delta_3) - 2Y_{23}^\nu \Delta_1)/2 & Y_{22}^\nu(\Delta_2 - \Delta_3)/2 \\ 0 & Y_{22}^\nu(\Delta_2 - \Delta_3)/2 & (Y_{22}^\nu(\Delta_2 + \Delta_3) + 2Y_{23}^\nu \Delta_1)/2 \end{pmatrix}$$

Simplification

1. $Y_{11,23} << Y_{22}$, $m_{\Delta 2} = m_{\Delta 3}$ 2. $m_{\Delta^{++}} = m_{\Delta^+} = m_\Delta > 420\text{GeV}$

3. Other heavier new degrees of freedom

U(1) model for maximal coupling

Model parameters

Four parameters $U(1)_{L_\mu - L_\tau}$: $\tilde{g}, m_{Z'}$ + $Y=1$ *triplet* : Y_{22}, m_Δ

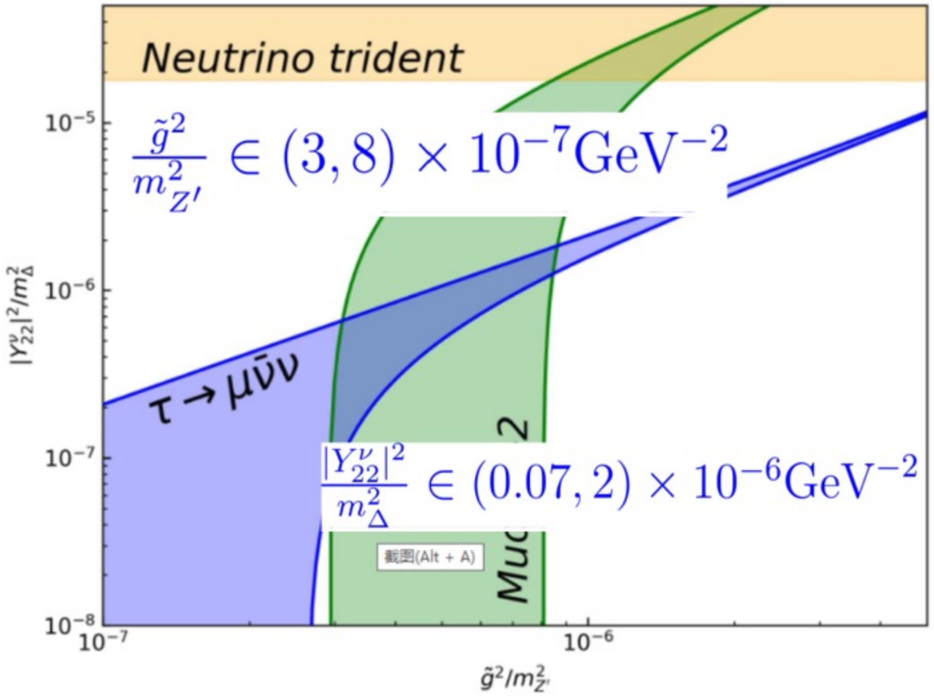
Revisiting type-II see-saw: present limits and future prospects at LHC

Saiyad Ashanujjaman & Kirtiman Ghosh

Journal of High Energy Physics **2022**, Article number: 195 (2022) | Cite this articl

$$\Delta m = 0 \ with \ v_\Delta \sim O(\mathrm{GeV})$$

$$m_\Delta > 420\mathrm{GeV}$$



Highlight Z' effects and suppress the triplet contribution

$$m_\Delta = 450\mathrm{GeV}, \, |Y_{22}| = 0.117$$

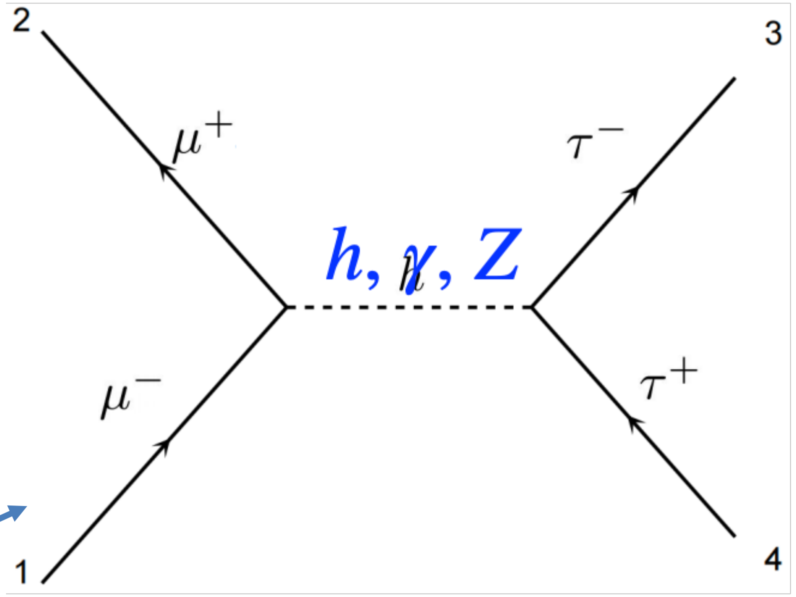
Collider signatures

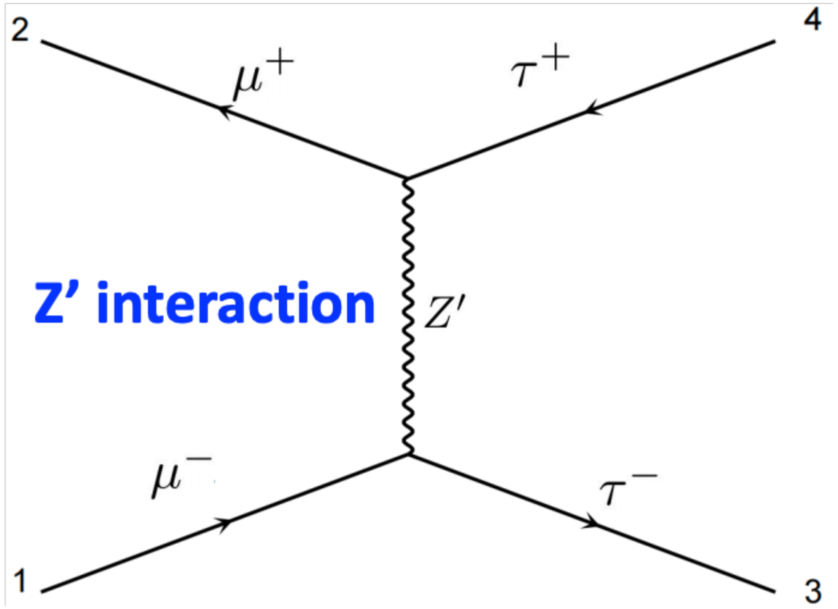
Muon collider

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

$$\mu^+\mu^- \to \tau^+\tau^- (t-channel)$$

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



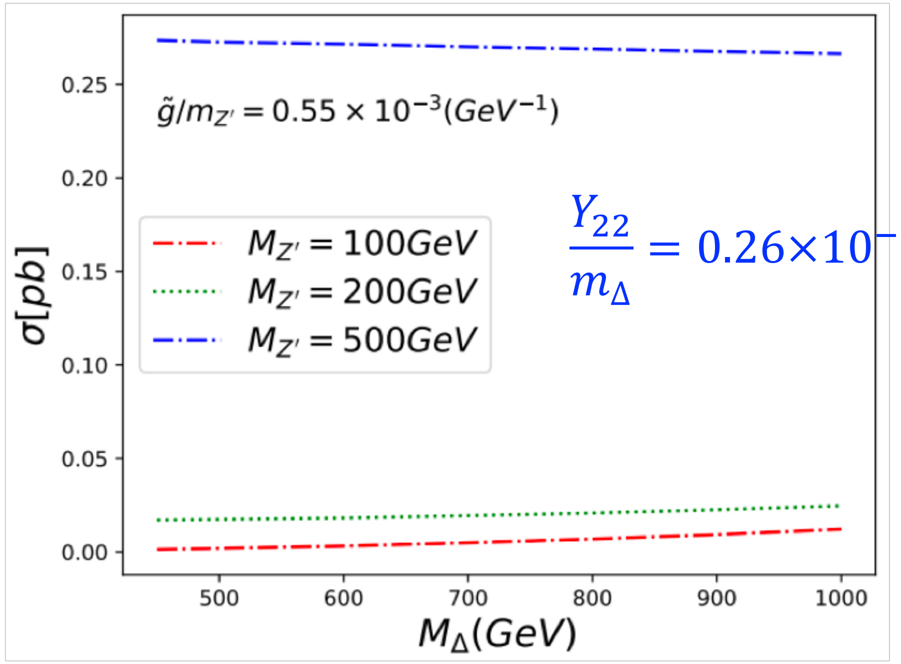


The cross section of SM background $\tau^\pm\tau^\mp$ at $\sqrt{s}=3$ TeV.

σ (pb)	$\boxed{\tau^+\tau^-}$	$\tau^+\tau^-\gamma$	$\gamma(\to\tau^+\tau^-)\nu\bar{\nu}$	$Z(\to\tau^+\tau^-)\nu\bar{\nu}$	$h(\to\tau^+\tau^-)\nu\bar{\nu}$	$W^+(\to\tau^+\nu_\tau)W^-(\to\tau^-\bar{\nu}_\tau)$	Total
1. Basic Cut	0.008	0.00162304	0.016896	0.043552	0.0126848	0.0035424	0.086304
2. $P_T > 250$ GeV	0.007808	0.00032	0.003584	0.00192	0.000064	0.000704	0.0144

Collider signatures

Triplet effect for $\mu^+\mu^- \to \tau^+\tau^-$



$$\frac{Y_{22}}{m_\Delta} = 0.26\times10^{-3}$$

increasing Delta mass

Cross section varies slightly

$$m_\Delta = 450GeV, |Y_{22}| = 0.117$$

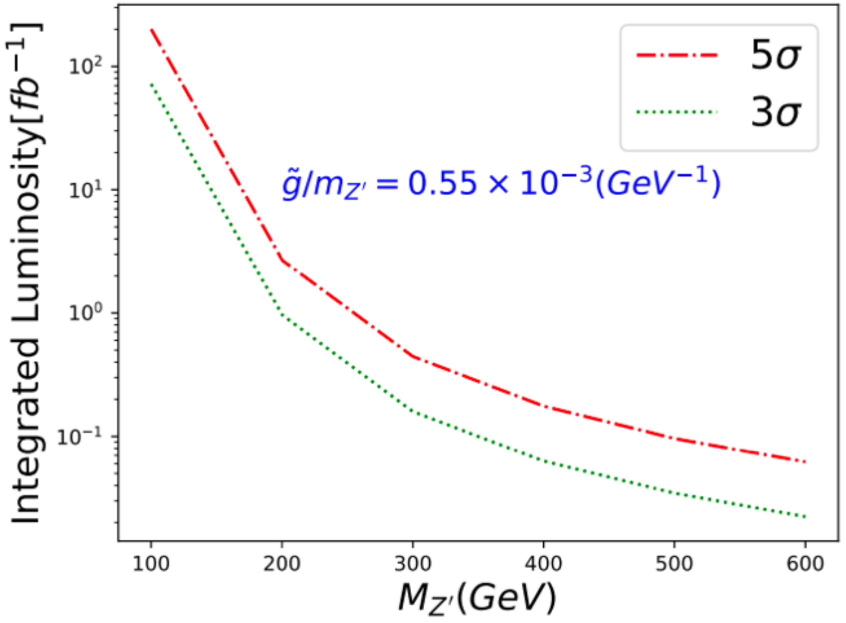
TABLE III: The cross section $\tau^\pm\tau^\mp$ for $U(1)_{L_\mu - L_\tau}$ model with $Y = 1$ triplet at $\sqrt{s} = 3$ TeV for fixing $m_{Z'} = 100$ GeV and $\tilde{g} = 0.055$.

$U(1)_{L_\mu-L_\tau}$ with triplet model	$m_\Delta = 800$ GeV		$m_\Delta = 500$ GeV		$m_\Delta = 450$ GeV	
	$Y_{22} = 0.208$	$Y_{22} = 1.136$	$Y_{22} = 0.13$	$Y_{22} = 0.71$	$Y_{22} = 0.117$	$Y_{22} = 0.639$
cross section (pb)	0.0069	2.6156	0.0019	0.5180	0.0014	0.3569
luminosity (fb^{-1}) with 3σ	4.00	0.0035	39.287	0.018	72.2335	0.026
Events ($\mathcal{L} = 1ab^{-1}$)	6900	2615600	1900	518000	1400	356900

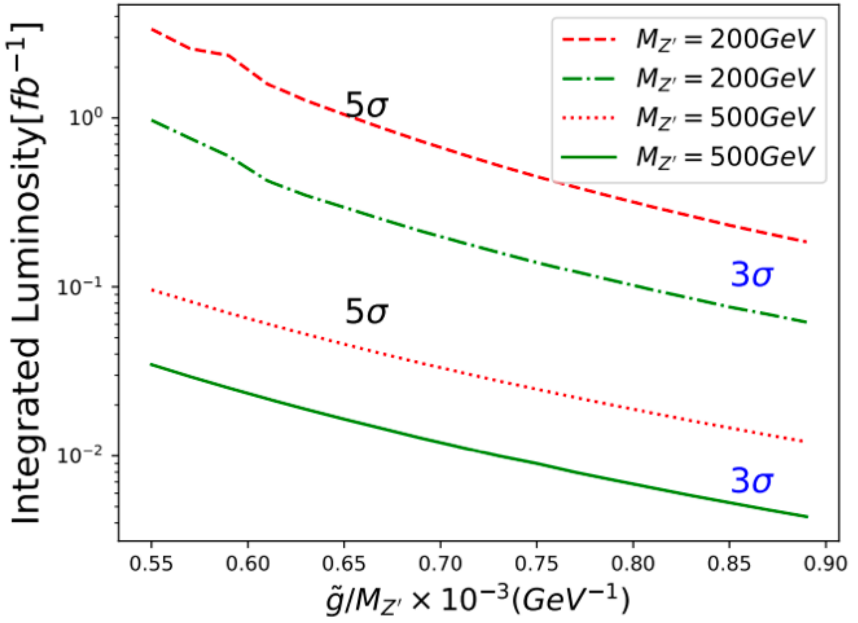
Collider signatures

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

$$S/\sqrt{S+S_0} = \mathscr{L} \times (\sigma - \sigma_{SM})/\sqrt{\mathscr{L} \times \sigma} > 3 \text{ or } 5$$



(a). The required luminosity for 3σ and 5σ discovery with $\tilde{g}/M_{Z'} = 0.55 \times 10^{-3}\mathrm{GeV}^{-1}$.



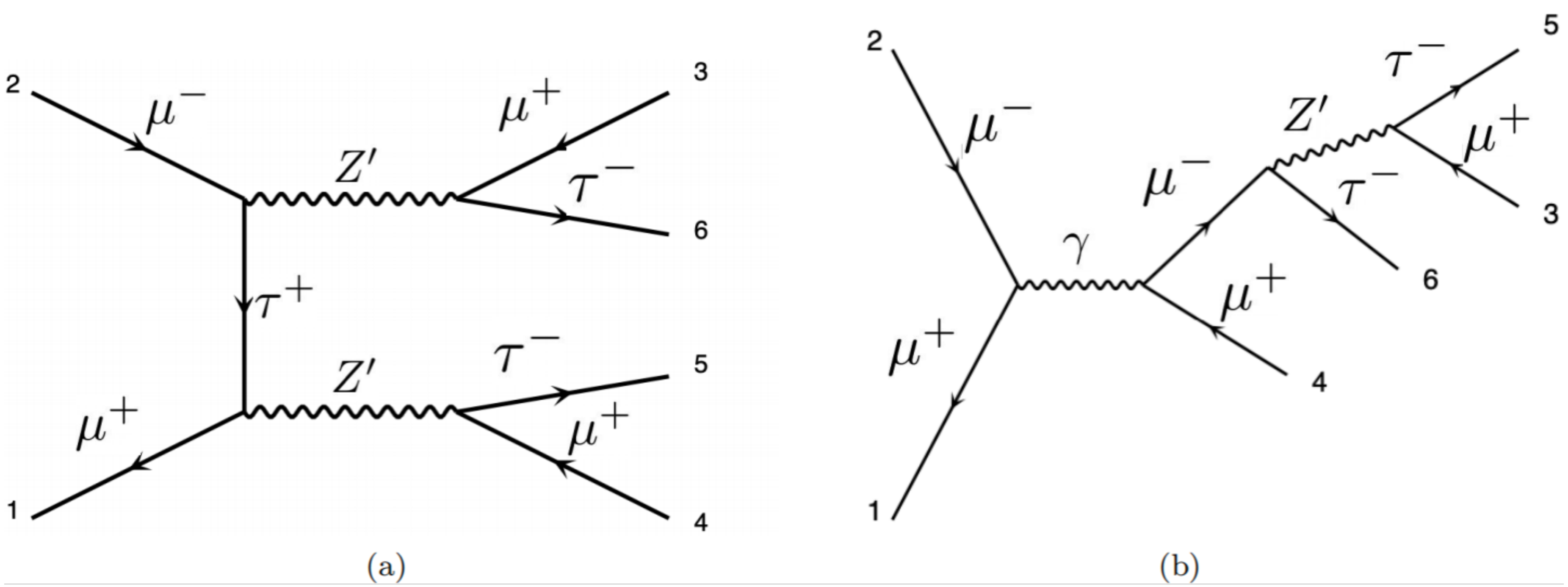
(b). The required luminosity for 3σ and 5σ discovery with different Z' mass.

t-channel pair production can easily be distinguished at more than 5\sigma level from the s-channel production in SM

Collider signatures

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

This signal is very clean and effectively background-free.



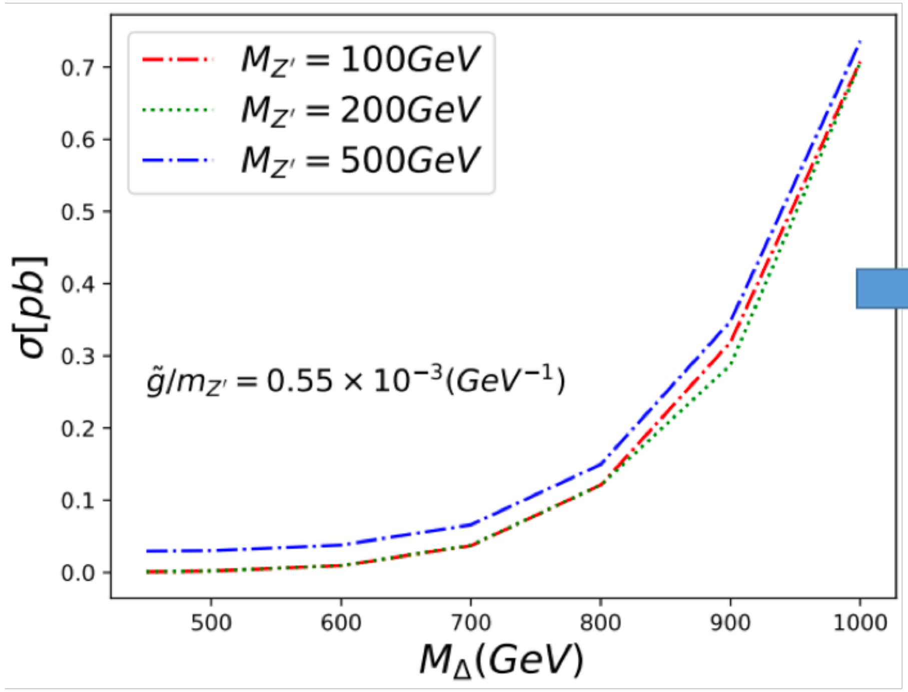
Two different source

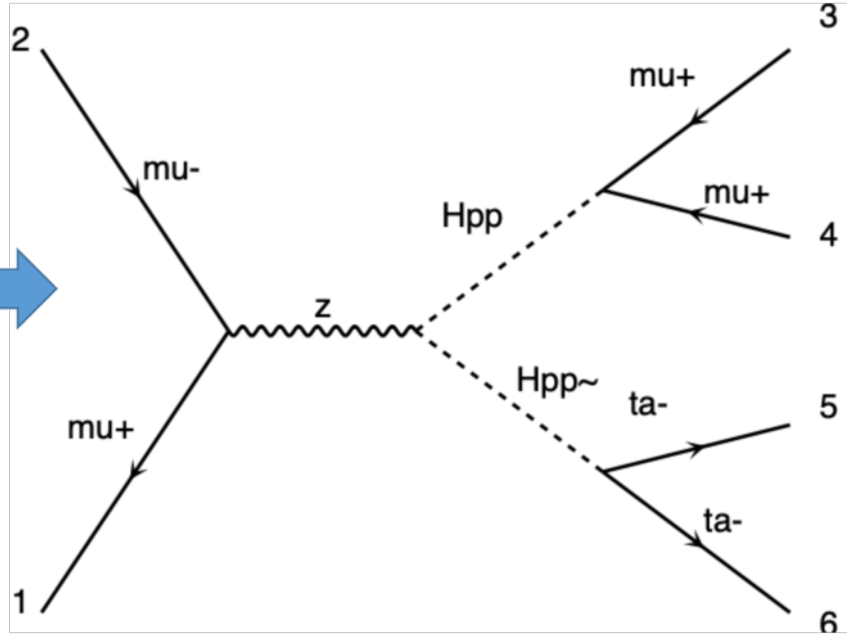
$$\mu^+\mu^- \to h^*/\gamma^*/Z^* \to \mu^\pm\tau^\mp + (Z' \to \mu^\pm\tau^\mp)$$

$$\mu^+\mu^- \to \Delta^{++}\Delta^{--} \to \mu^\pm\mu^\pm\tau^\mp\tau^\mp$$

Collider signatures

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





increasing Delta mass

Triplet effects rise

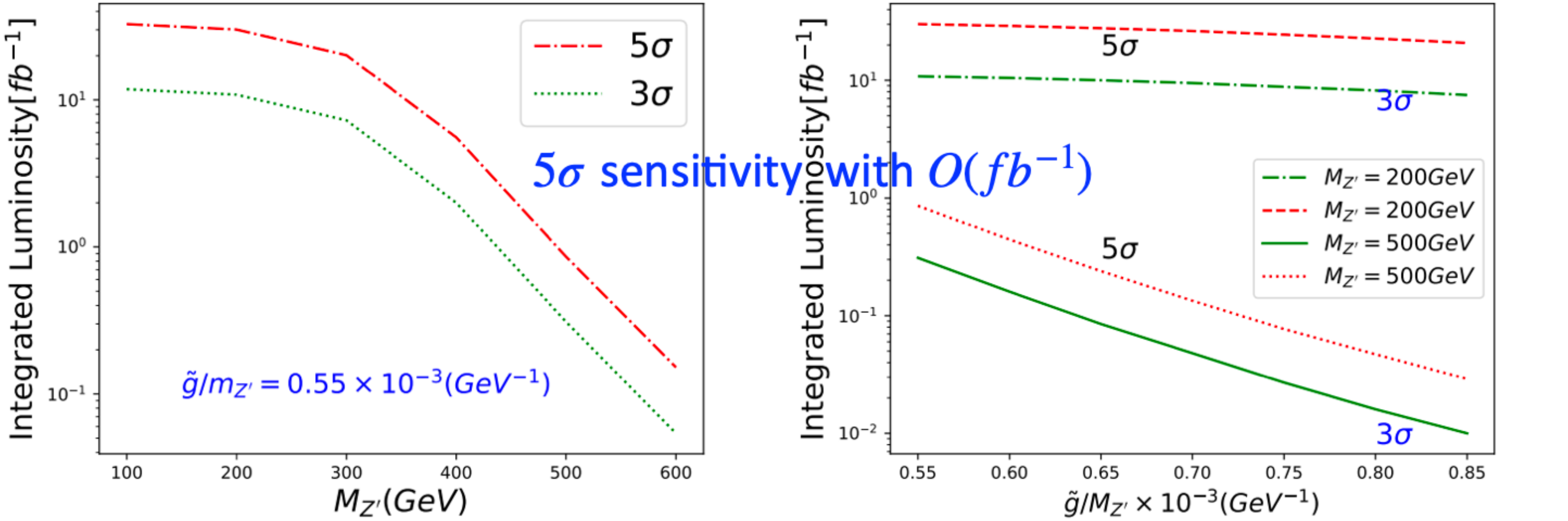
$$|Y_{22}|^2/\boxed{(s_1 - m_\Delta^2)(s_2 - m_\Delta^2)}$$

Bigger

Smaller

Collider signatures

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



(a). The required luminosity for 3σ and 5σ discovery with $\tilde{g}/M_{Z'} = 0.55 \times 10^{-3}\text{GeV}^{-1}$.

(b). The required luminosity for 3σ and 5σ discovery with different Z' mass.

Summary

- **We study in detail the maximal off-diagonal Z' interaction in $\mathrm{U}(\mathbf{1})_{L_\mu - L_\tau}$ at a muon collider**

- **A Z' with off-diagonal mixing leads to very distinctive signatures, such as t-channel $\mu^+\mu^- \to \tau^+\tau^-$ and $\mu^+\mu^- \to \mu^+\mu^+\tau^-\tau^-$ smoking gun**

- **With a 3TeV muon collider with O(fb^{-1}) luminosity, the above two processes can be distinguished at 5σ level.**

Thanks！

Backup

Cross section of $\mu^+\mu^- \to \tau^+\tau^-$

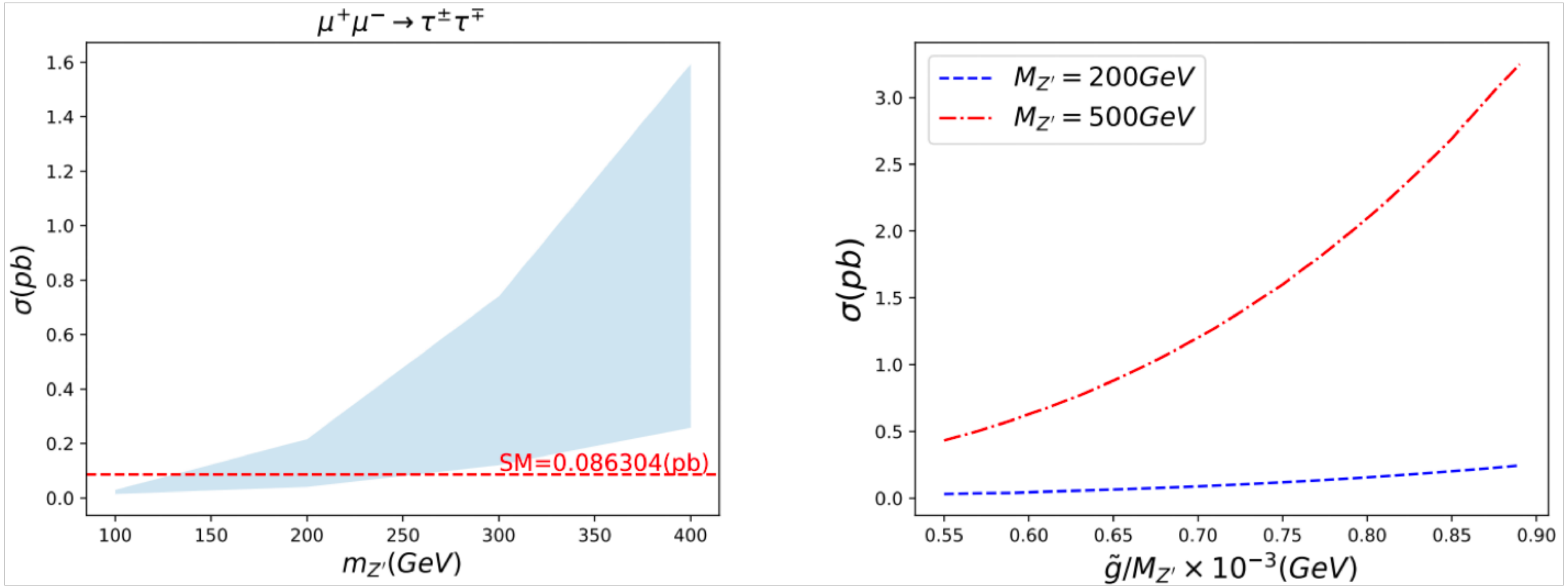


TABLE II: The cross section $\tau^\pm\tau^\mp$ for $U(1)_{L_\mu - L_\tau}$ model with $Y = 1$ triplet at $\sqrt{s} = 3$ TeV for fixing $m_\Delta = 450$ GeV and $Y_{22} = 0.117$.

$U(1)_{L_\mu - L_\tau}$ with triplet model	$m_{Z'} = 500$ GeV		$m_{Z'} = 200$ GeV		$m_{Z'} = 100$ GeV	
	$\tilde{g} = 0.275$	$\tilde{g} = 0.445$	$\tilde{g} = 0.11$	$\tilde{g} = 0.178$	$\tilde{g} = 0.055$	$\tilde{g} = 0.089$
cross section (pb)	0.274	2.08	0.017	0.154	0.0014	0.01
luminosity (fb^{-1}) with 3σ	0.034	0.004	0.97	0.063	72.2335	2.189
Events ($\mathcal{L} = 1ab^{-1}$)	274000	2080000	17000	154000	1400	10000