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

Fei Huang

University of Jinan

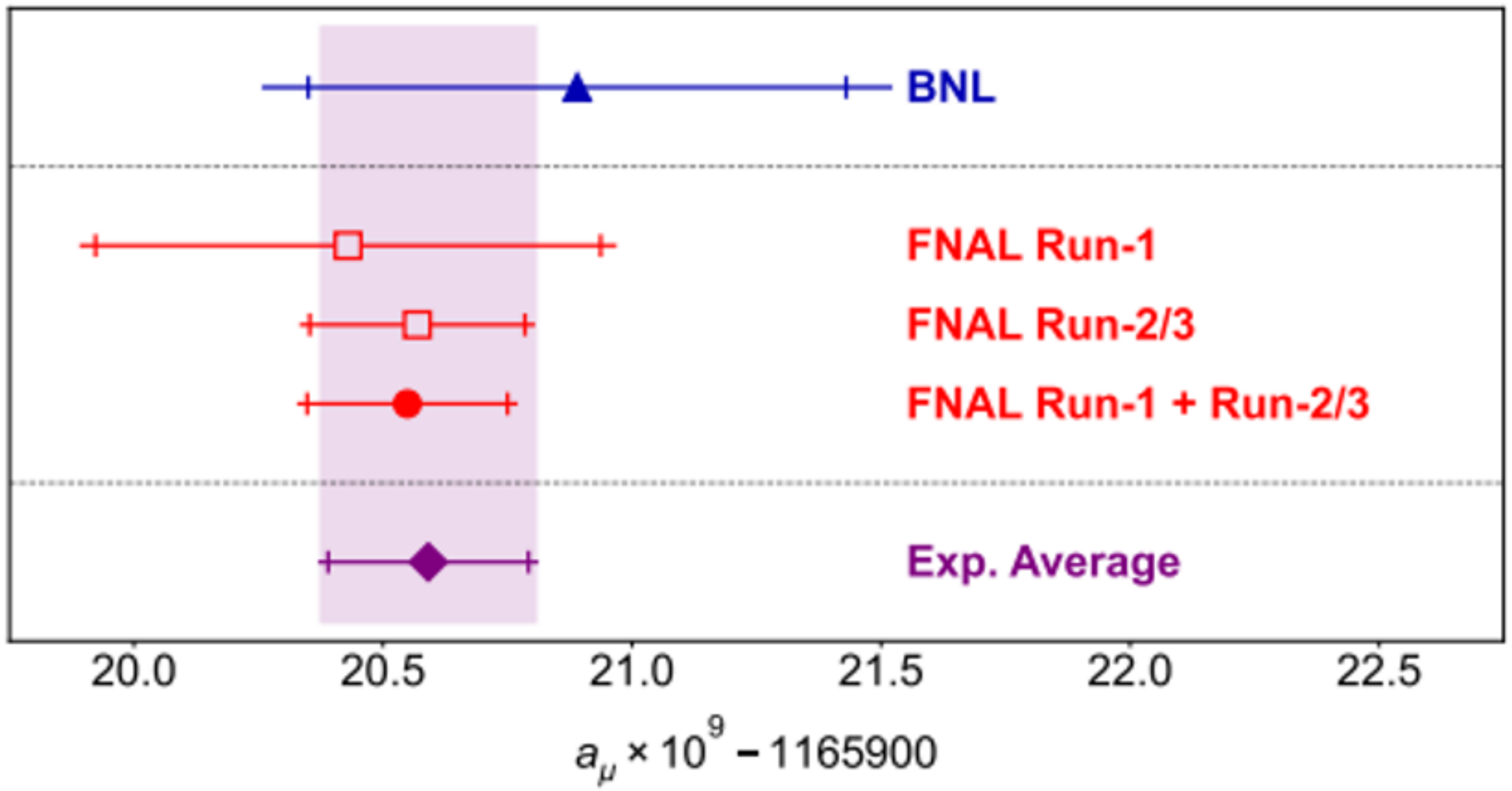
In collaboration with Xiao-Gang He and Jin Sun

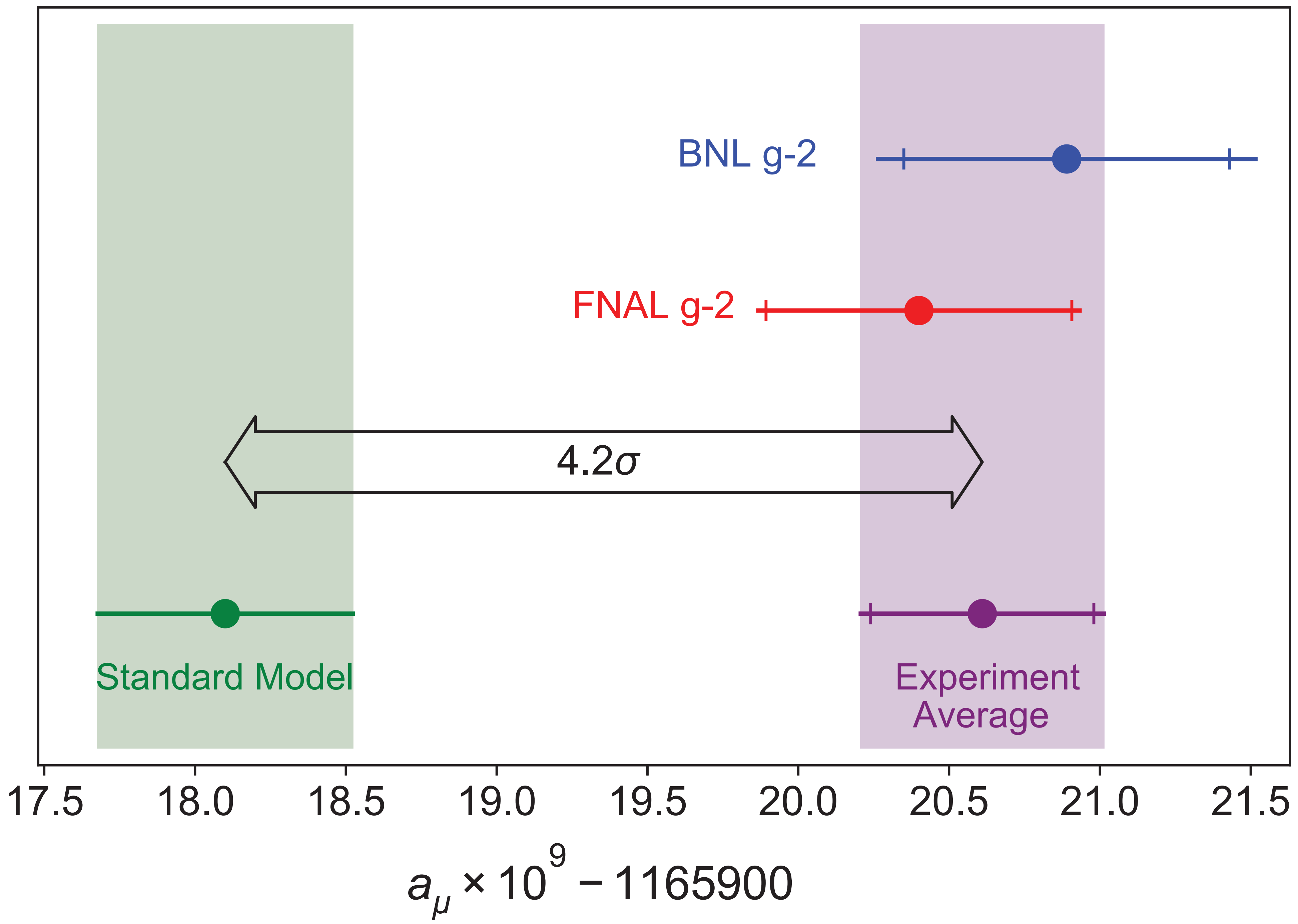
The 9th China LHC Physics Workshop (CLHCP2023)

Outline

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

Introduction





Phys. Rev. Lett. 131, 161802 (2023)

Phys. Rev. Lett. 126, 141801 (2021)

Introduction

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

- 1st, 2nd and 3rd generations $U(1)_{L_\mu - L_\tau}$ charge: 0, +1, −1

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

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

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

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

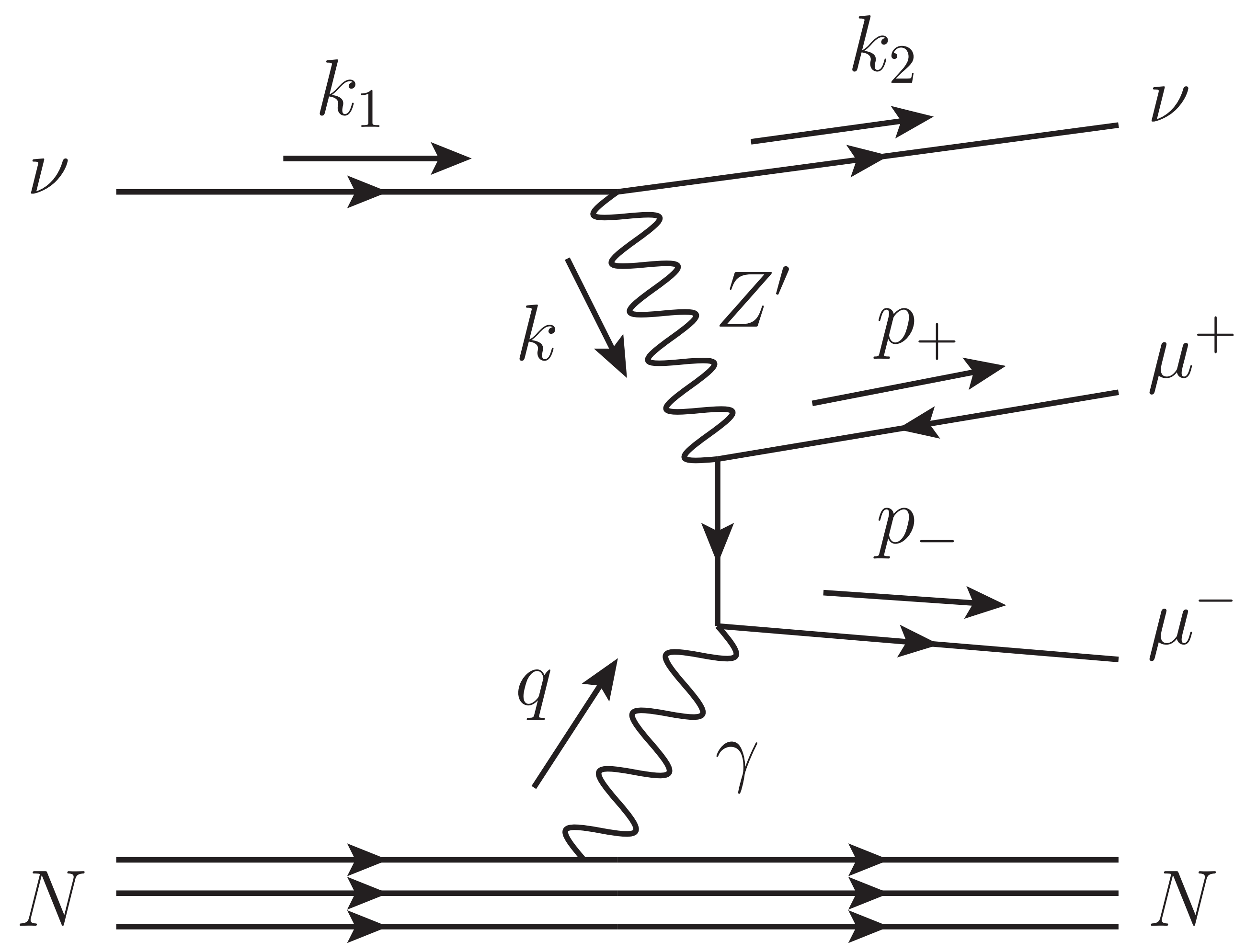
$$\Delta a_\mu = a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = (251 \pm 59) \times 10^{-11}$$

4.2σ

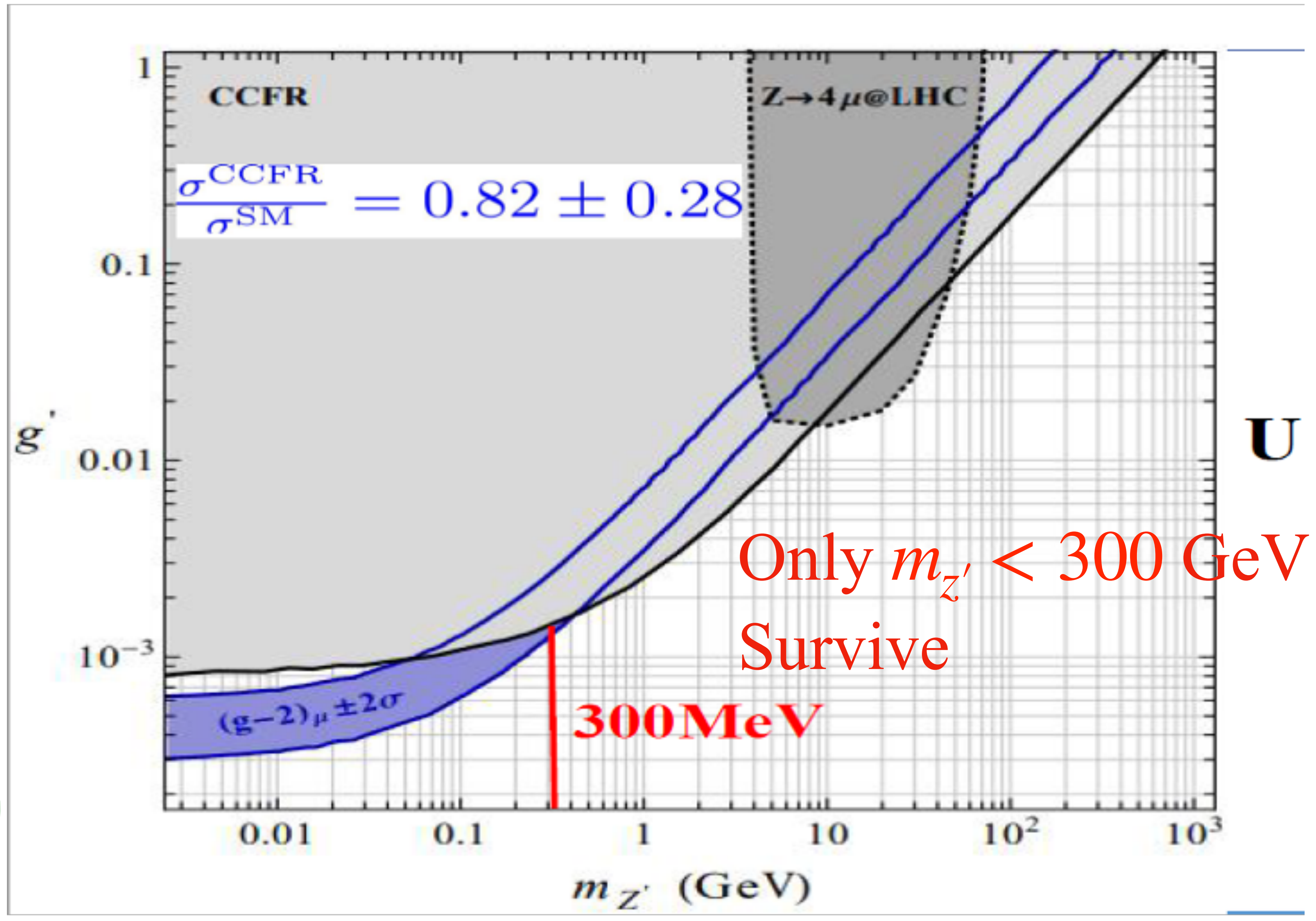
- Induce muon neutrino trident (MNT) process

Introduction

$\nu_\mu N \rightarrow \nu_i \mu \bar{\mu} N$



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



PRL, 113,091801(2014)

$$\sigma_{CHARM-II}/\sigma_{SM} = 1.58 \pm 0.57$$

$$\sigma_{CCFR}/\sigma_{SM} = 0.82 \pm 0.28$$

$$\sigma_{NuTeV}/\sigma_{SM} = 0.72^{+1.73}_{-0.72}$$

Z' contribution

$$\frac{\sigma_{Z'}}{\sigma_{SM}} = 5.86$$

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

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

Introduction

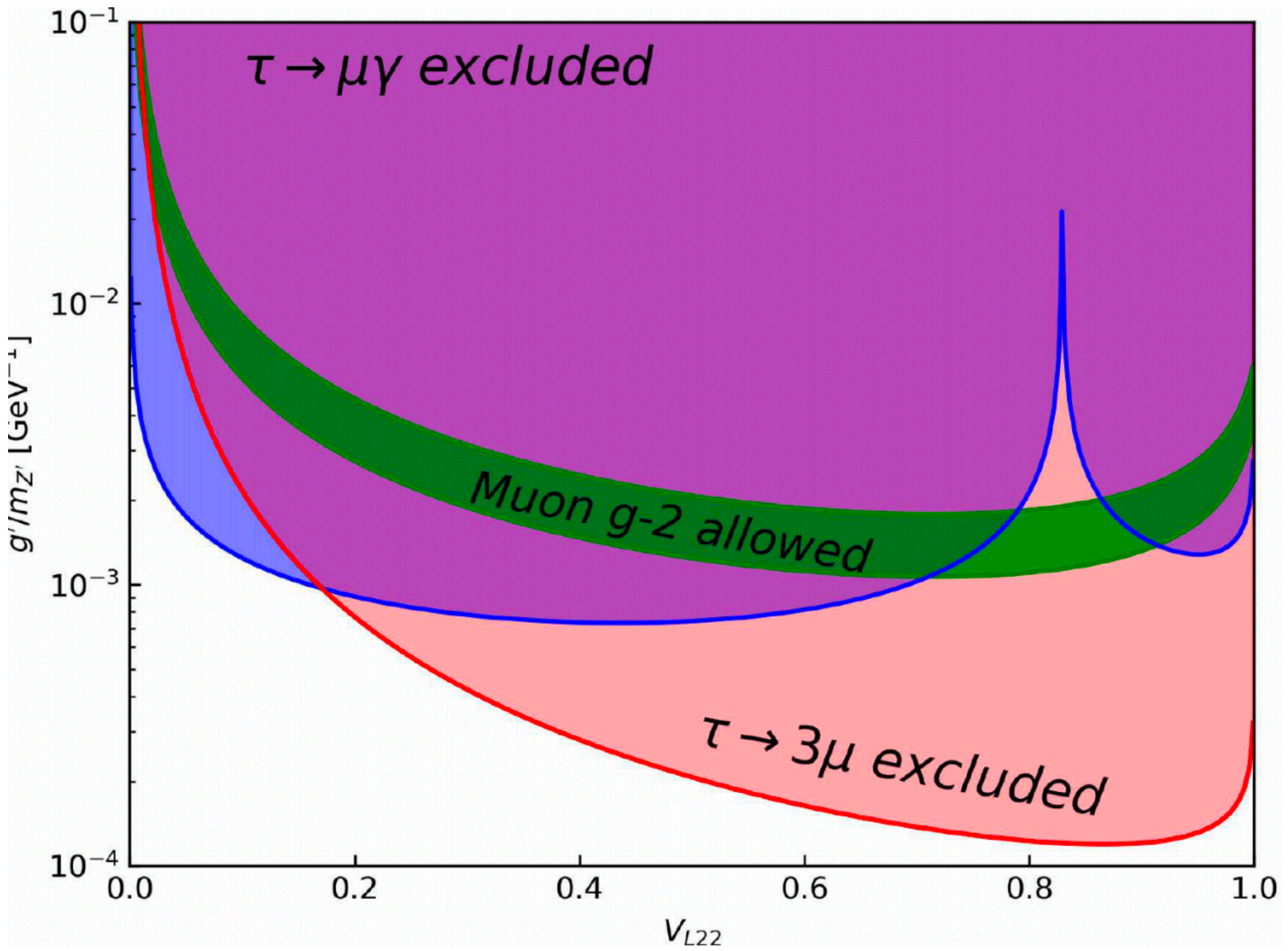
- $\mu - \tau$ mixing

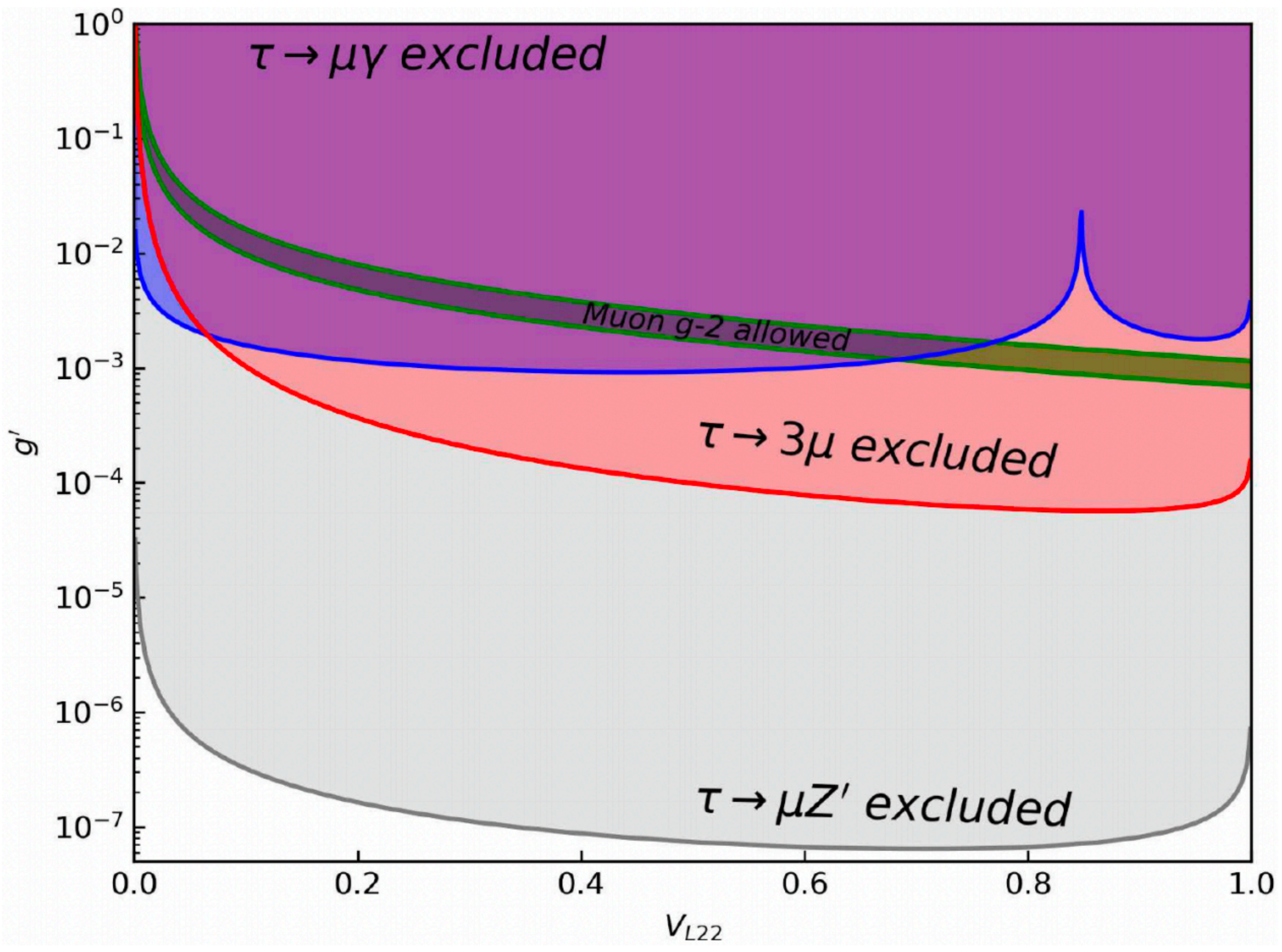
  The MNT process will be suppressed by mixing angle θ^2

  $$\tilde{g}^2/m_{Z'}^2 \sim \theta^2 \frac{m_\tau}{m_\mu}$$

- Flavor diagonal and off-diagonal Z' coupling to μ and τ

  So far so good, but induce $\tau \to \mu\bar{\mu}\mu, \mu\gamma$ processes





$U(1)_{L_\mu - L_\tau}$ model for maximal coupling

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

$$\mathcal{L}_{Z'} = -\tilde{g}(\bar{\mu}\gamma^\mu \tau + \bar{\tau}\gamma^\mu \mu + \bar{\nu}_\mu \gamma^\mu L \nu_\tau + \bar{\nu}_\tau \gamma^\mu L \nu_\mu) Z'_\mu$$

☑ MNT process
☑ $\tau \to 3\mu, \tau \to \mu\gamma$

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

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

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

Ruled out the model more than 5σ

$U(1)_{L_\mu - L_\tau}$ model for maximal coupling

Introduction scalar triplet: $\Delta_i(1,3,1)$

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

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

The transformation between the lepton mass eigenstate and weak eigenstate basis

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

$U(1)_{L_\mu - L_\tau}$ model for maximal coupling

Yukawa terms in the mass eigenstate 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 the model

☑ $Y_{11}, Y_{23} << Y_{22}, m_{\Delta 2} = m_{\Delta 3}$

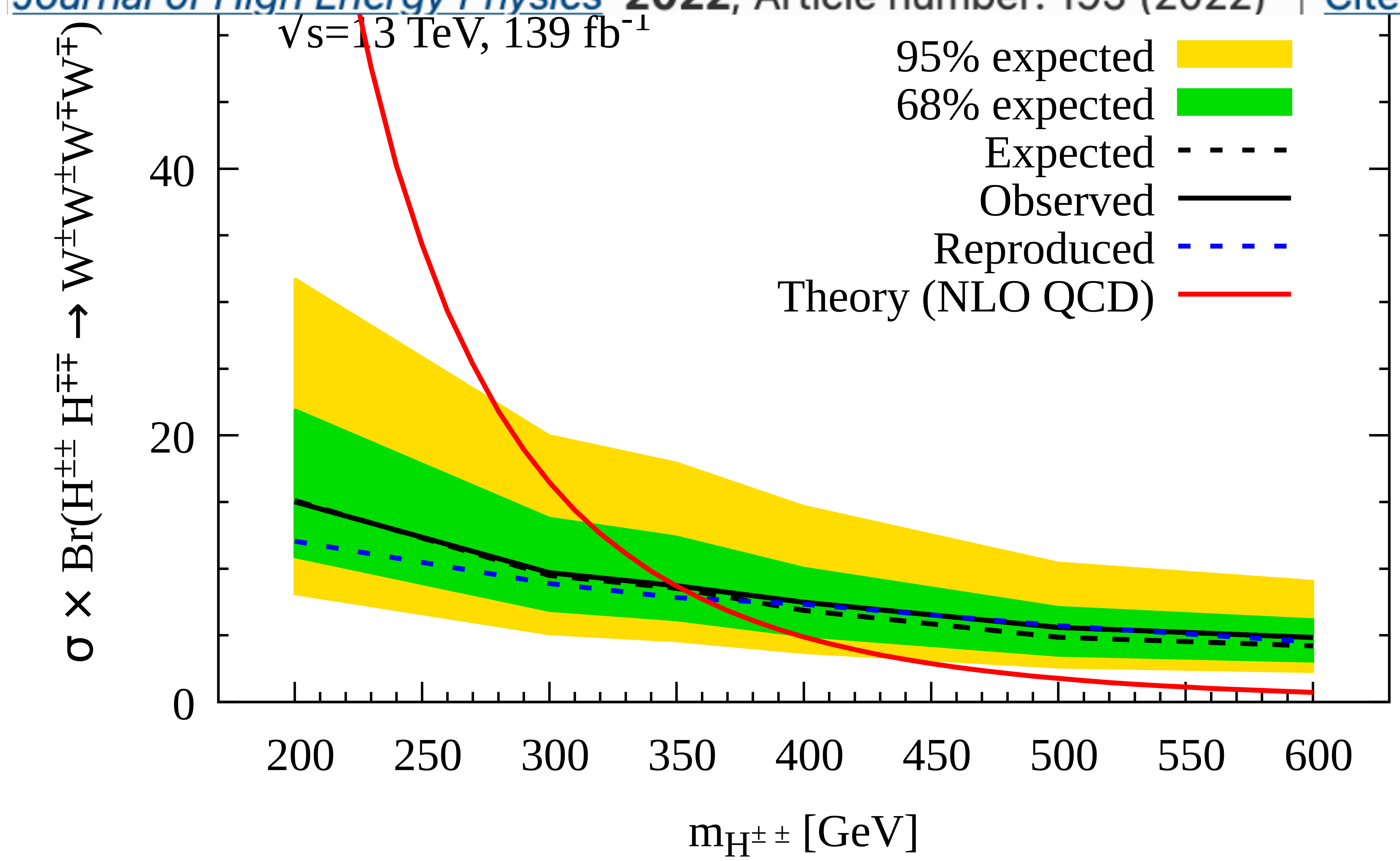
☑ $m_{\Delta^{++}} = m_{\Delta^+} = m_\Delta$

$U(1)_{L_\mu - L_\tau}$ model for maximal coupling

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

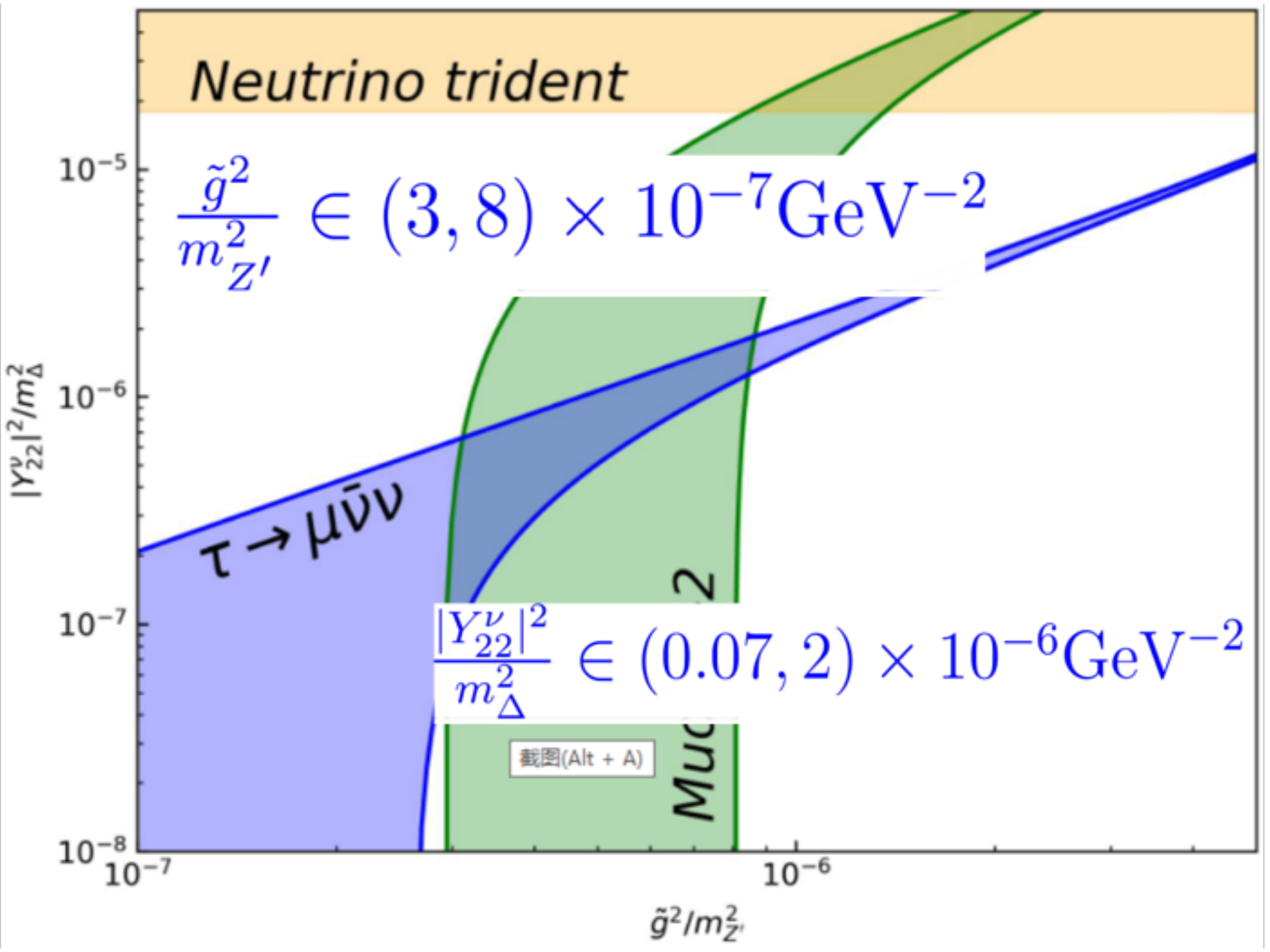
Saiyad Ashanujjaman & Kirtiman Ghosh

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



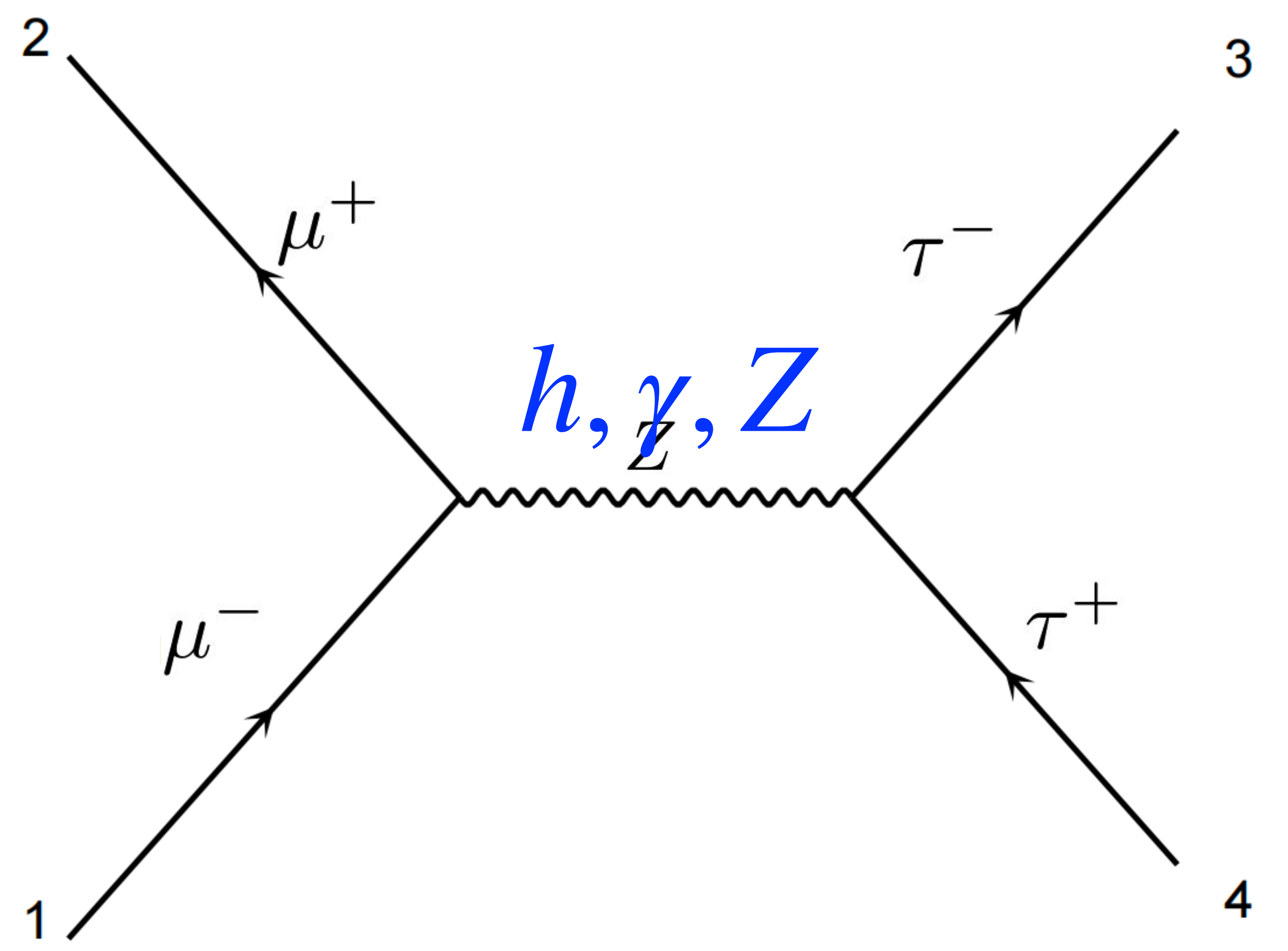
$$\Delta m = 0 \text{ with } v_\Delta \sim \mathcal{O}(GeV)$$

$$m_\Delta > 420 GeV$$

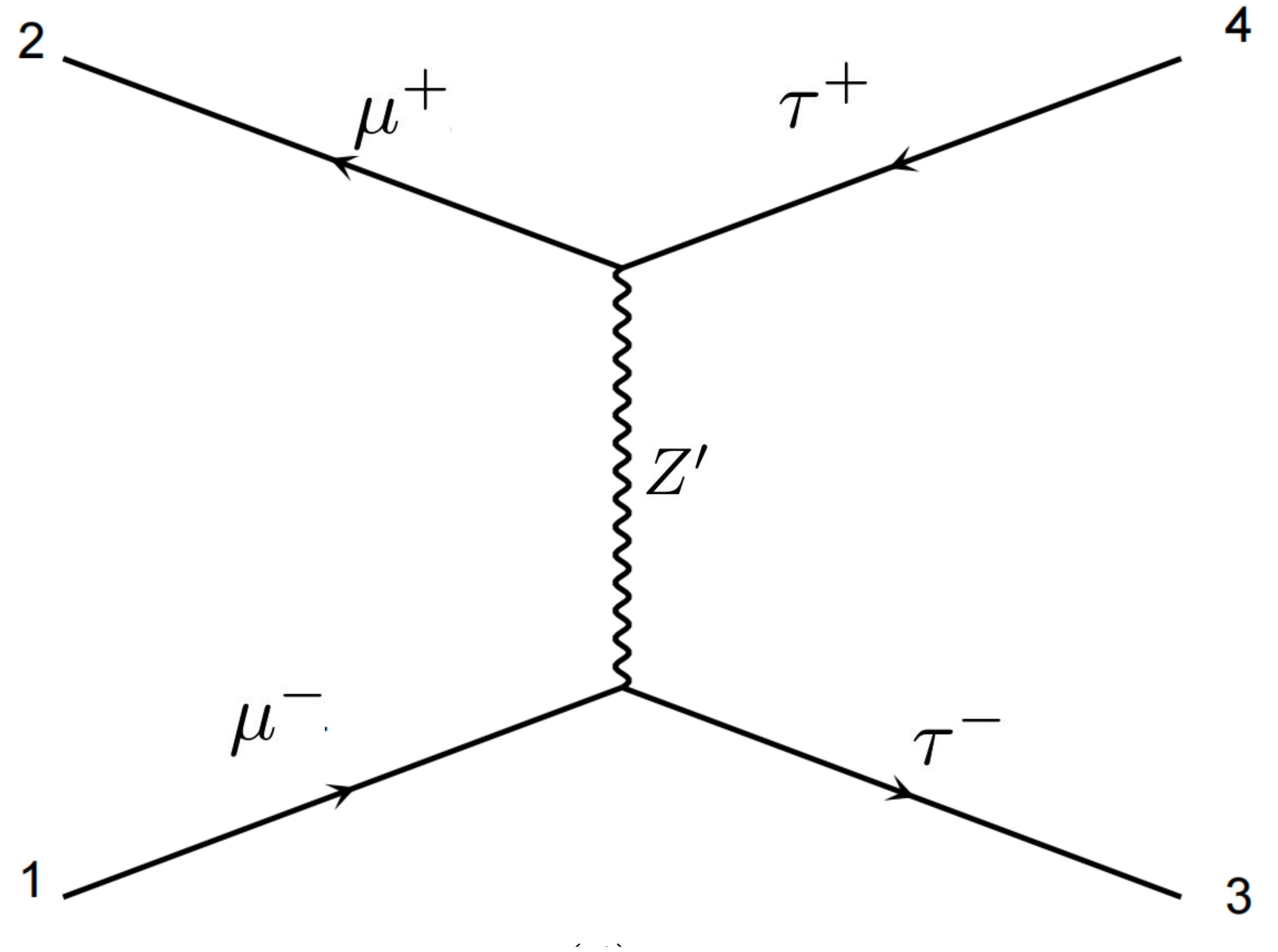


Muon collider signatures

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



SM background



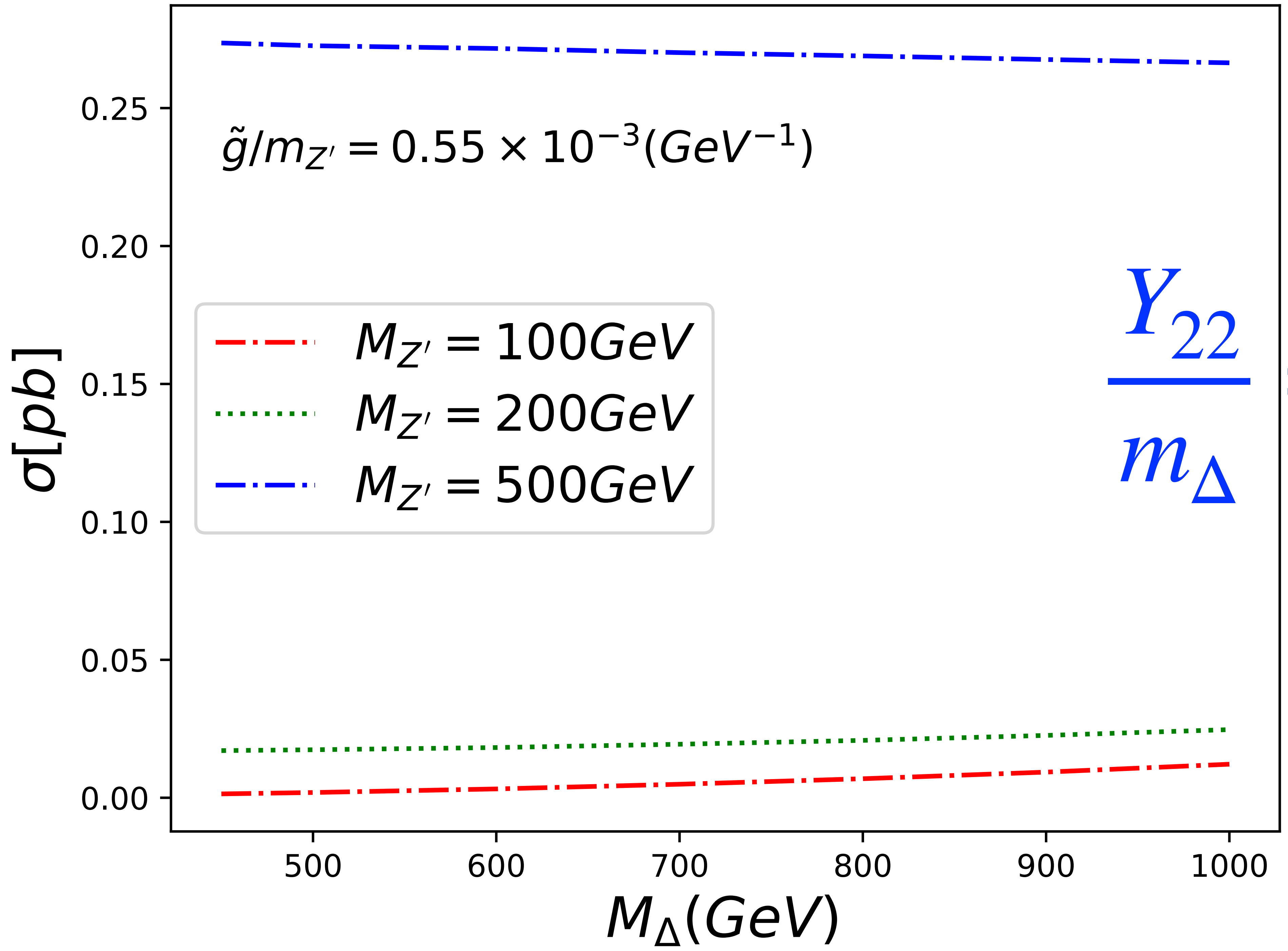
t-channel signal

σ(pb)	$\tau^+\tau^-$	$\tau^+\tau^-\gamma$	$\gamma(\to \tau^+\tau^-)\nu\bar{\nu}$	$Z(\to \tau^+\tau^-)\nu\bar{\nu}$	$h(\to \tau^+\tau^-)\nu\bar{\nu}$	$W^+(\to \tau^+\nu_\tau)W^-(\to \tau^-\bar{\nu}_\tau)$	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

The cross section of SM at $\sqrt{S} = 3\ TeV$

Muon collider signatures

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



$$\frac{Y_{22}}{m_\Delta} = 0.26 \times 10^{-3}$$

Increasing Delta mass m_Δ ↑

↓

Cross section varies slightly

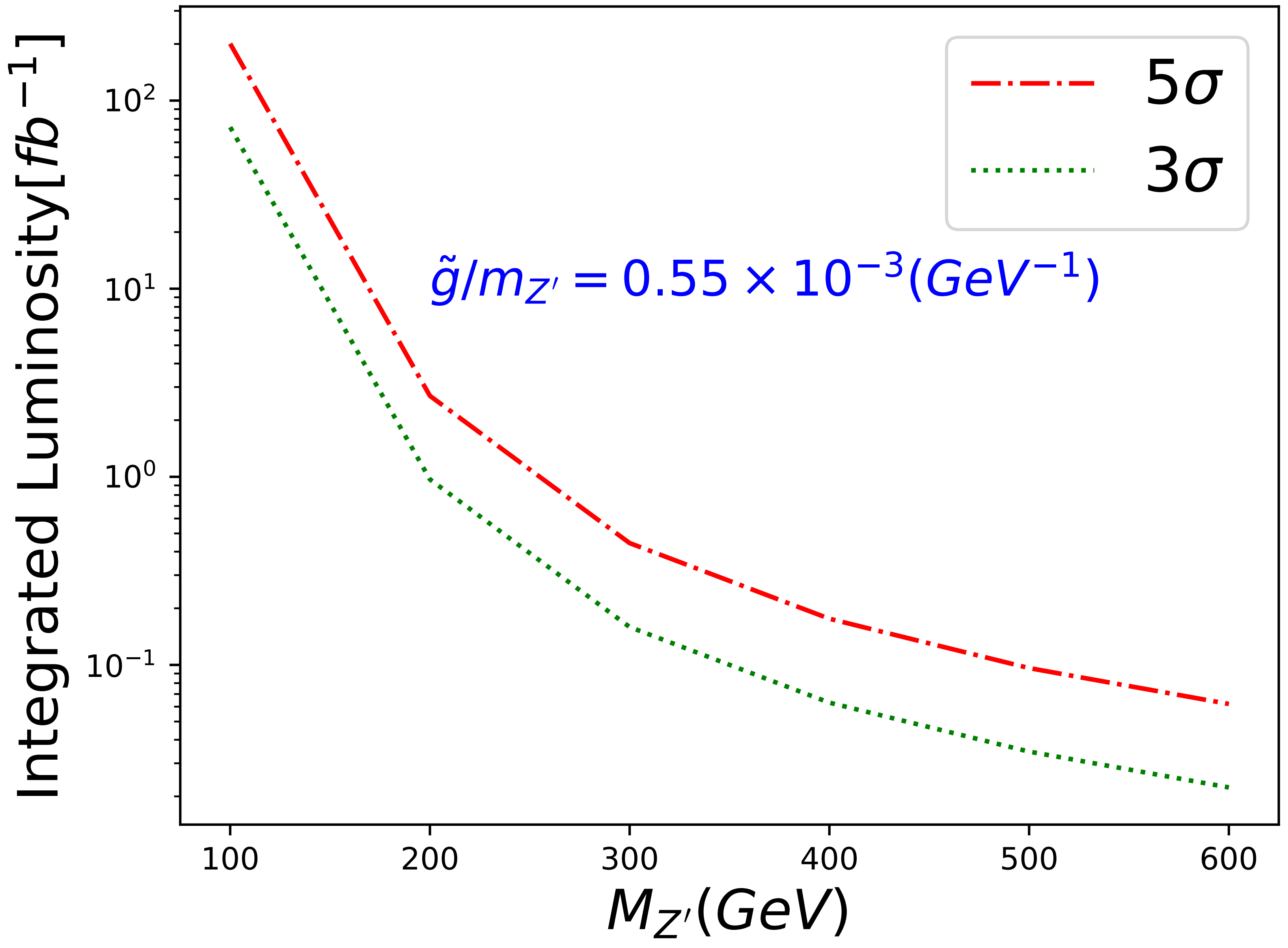
$m_\Delta = 450\text{GeV}, |Y_{22}| = 0.117$

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_Δ = 450 GeV and Y_{22} = 0.117.

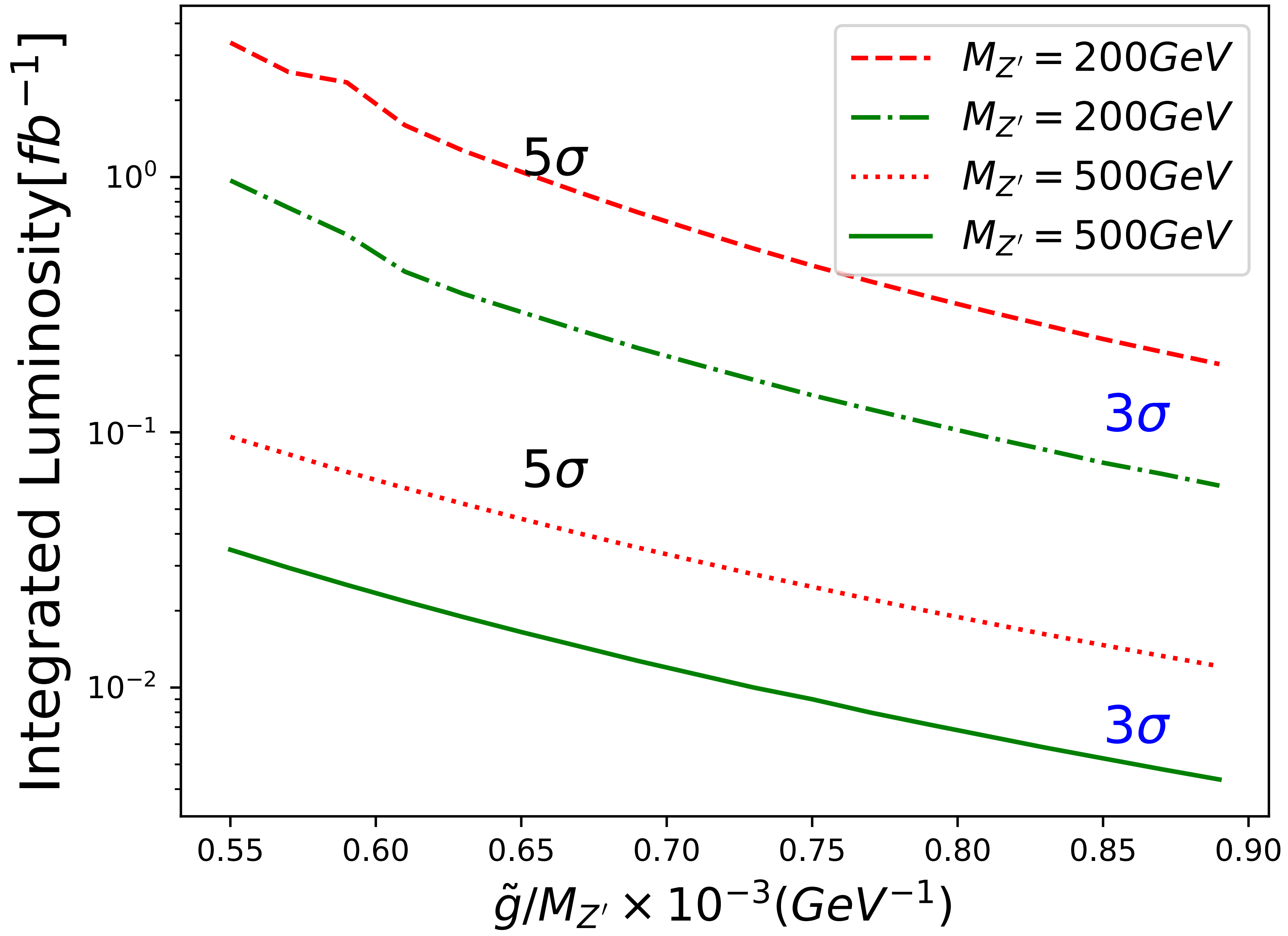
$U(1)_{L_\mu - L_\tau}$ with triplet model	$m_\Delta = 800$ GeV		$m_\Delta = 500$ GeV		$m_\Delta = 450$ GeV	
	$Y_{22} = 0.208$	$Y_{22} = 1.136$	$Y_{22} = 0.13$	$Y_{22} = 0.71$	$Y_{22} = 0.117$	$Y_{22} = 0.639$
cross section (pb)	0.0069	2.6156	0.0019	0.5180	0.0014	0.3569
luminosity (fb^{-1}) with 3σ	4.00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

Muon collider signatures

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



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

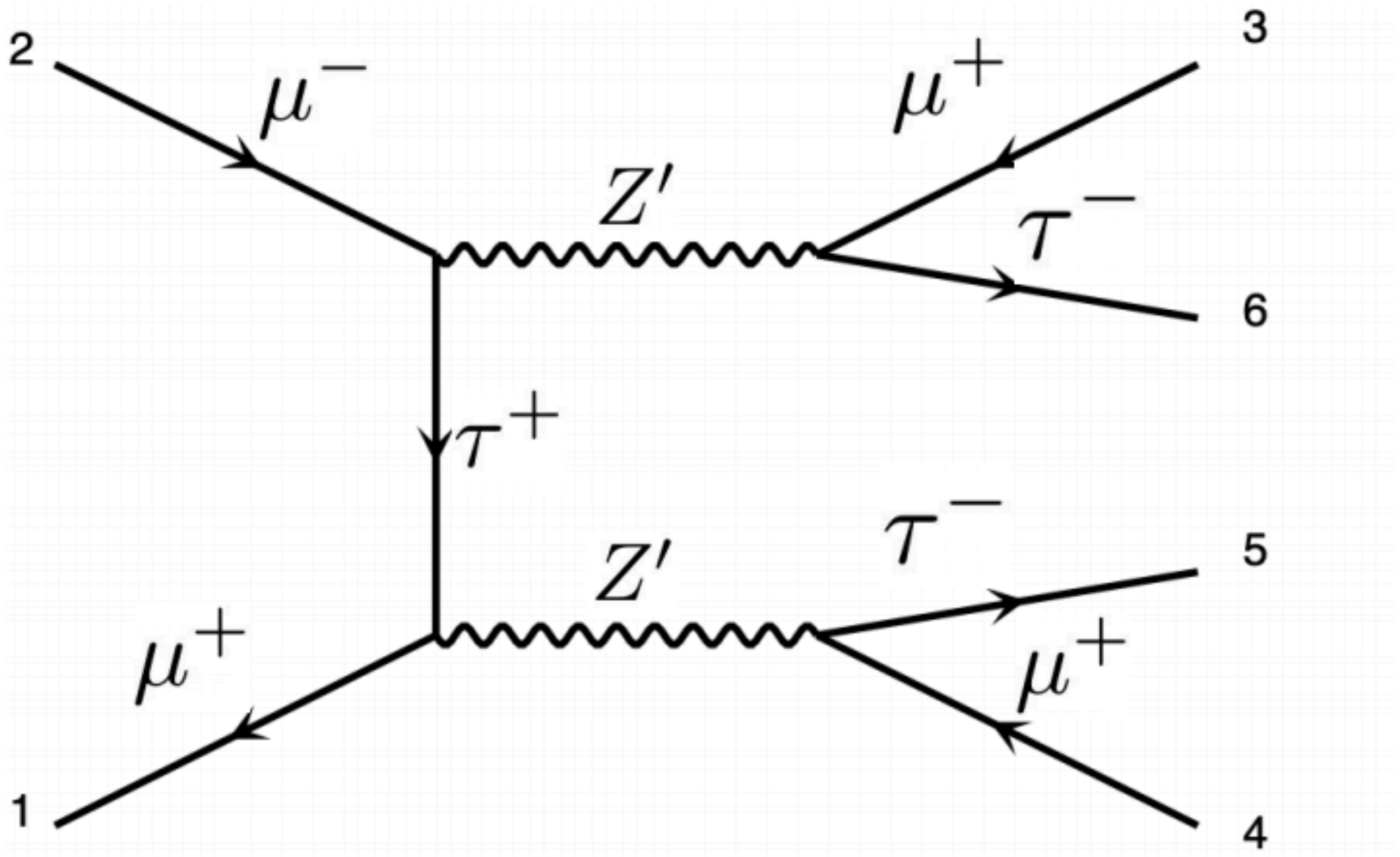


(b). The required luminosity for 3σ and 5σ discovery with different Z' mass.

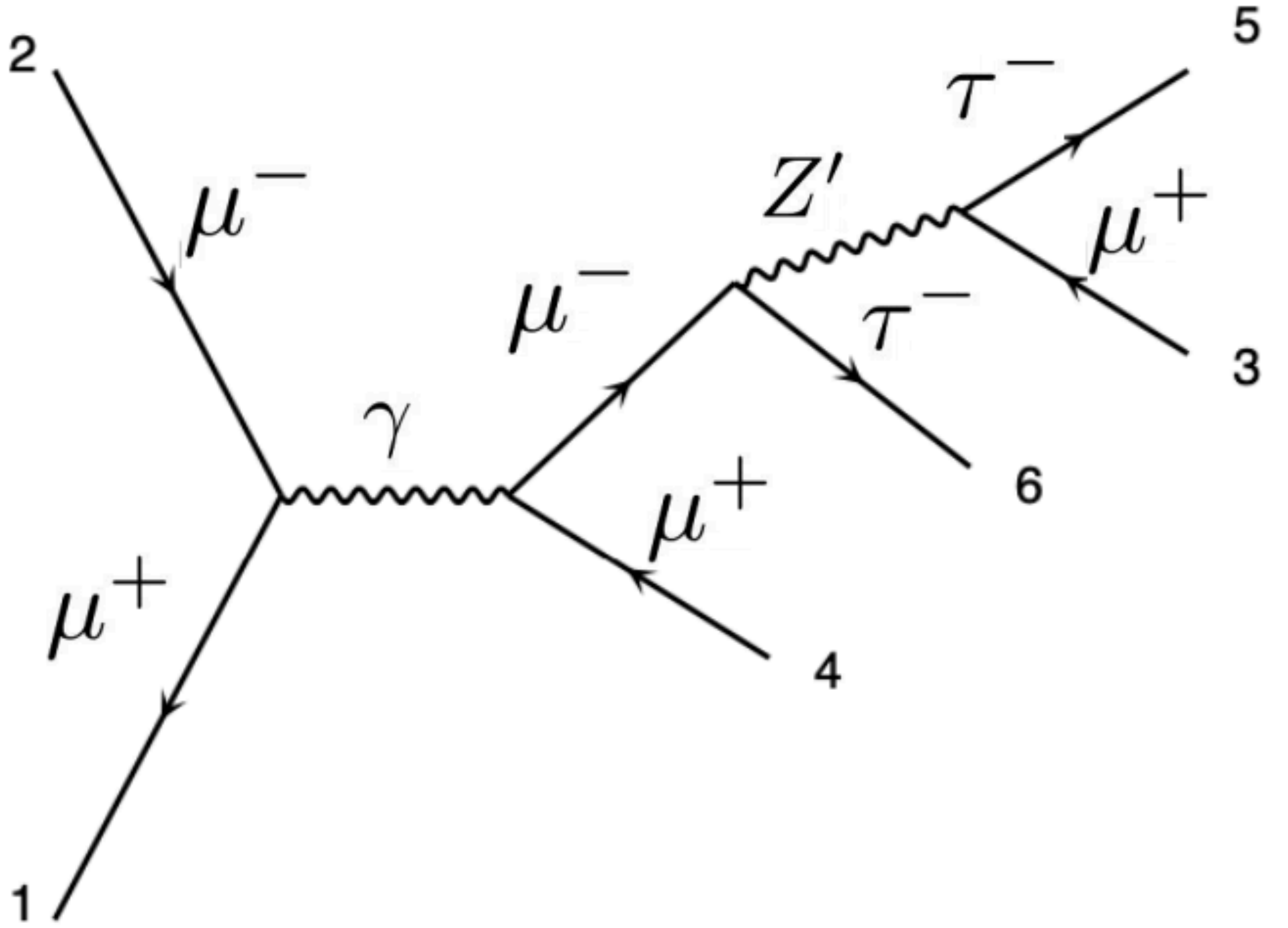
t-channel pair production can easily be distinguished at more than 5σ level from the s-channel production in SM

Muon collider signatures

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



(a)



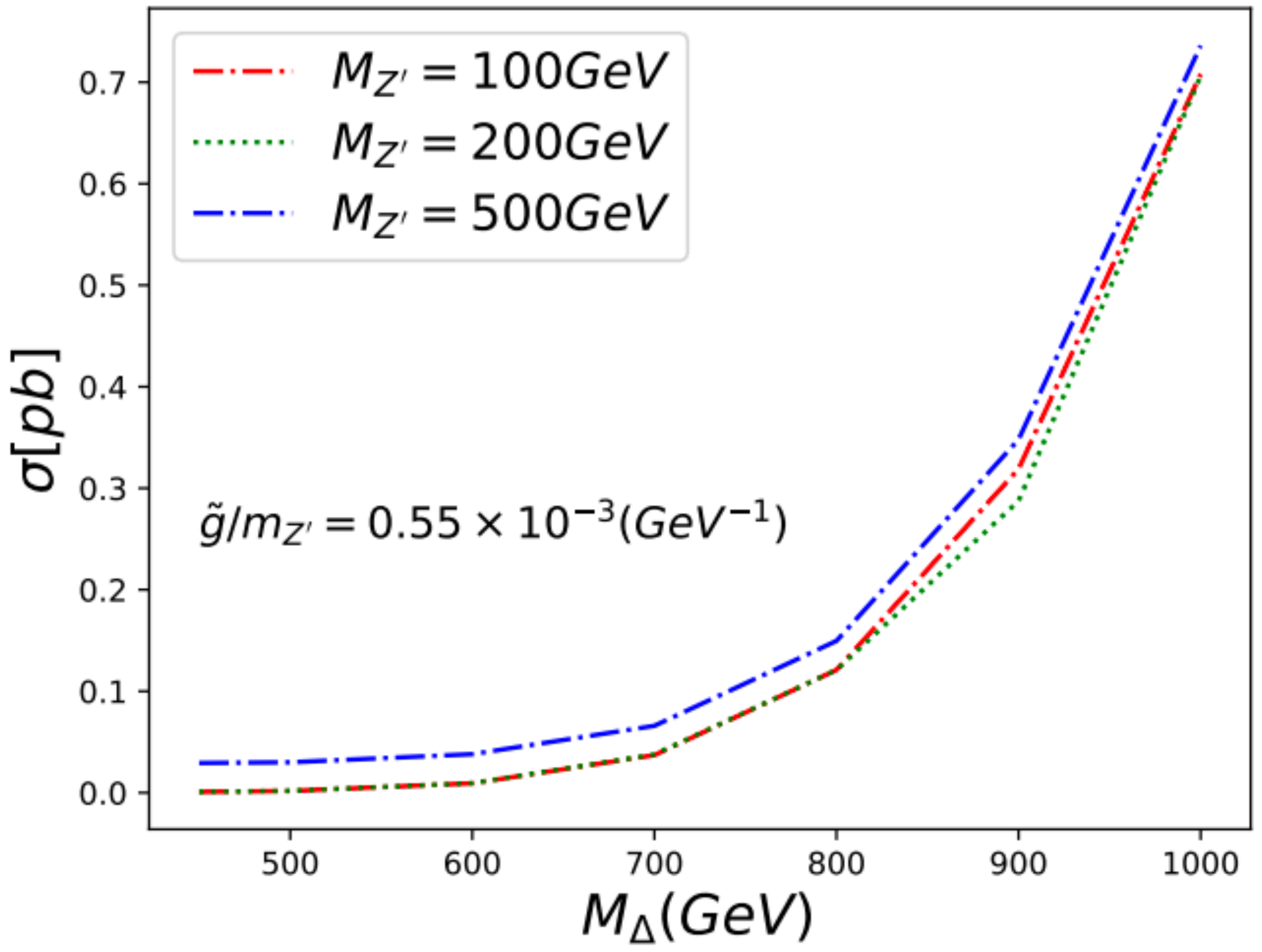
(b)

Two different source

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

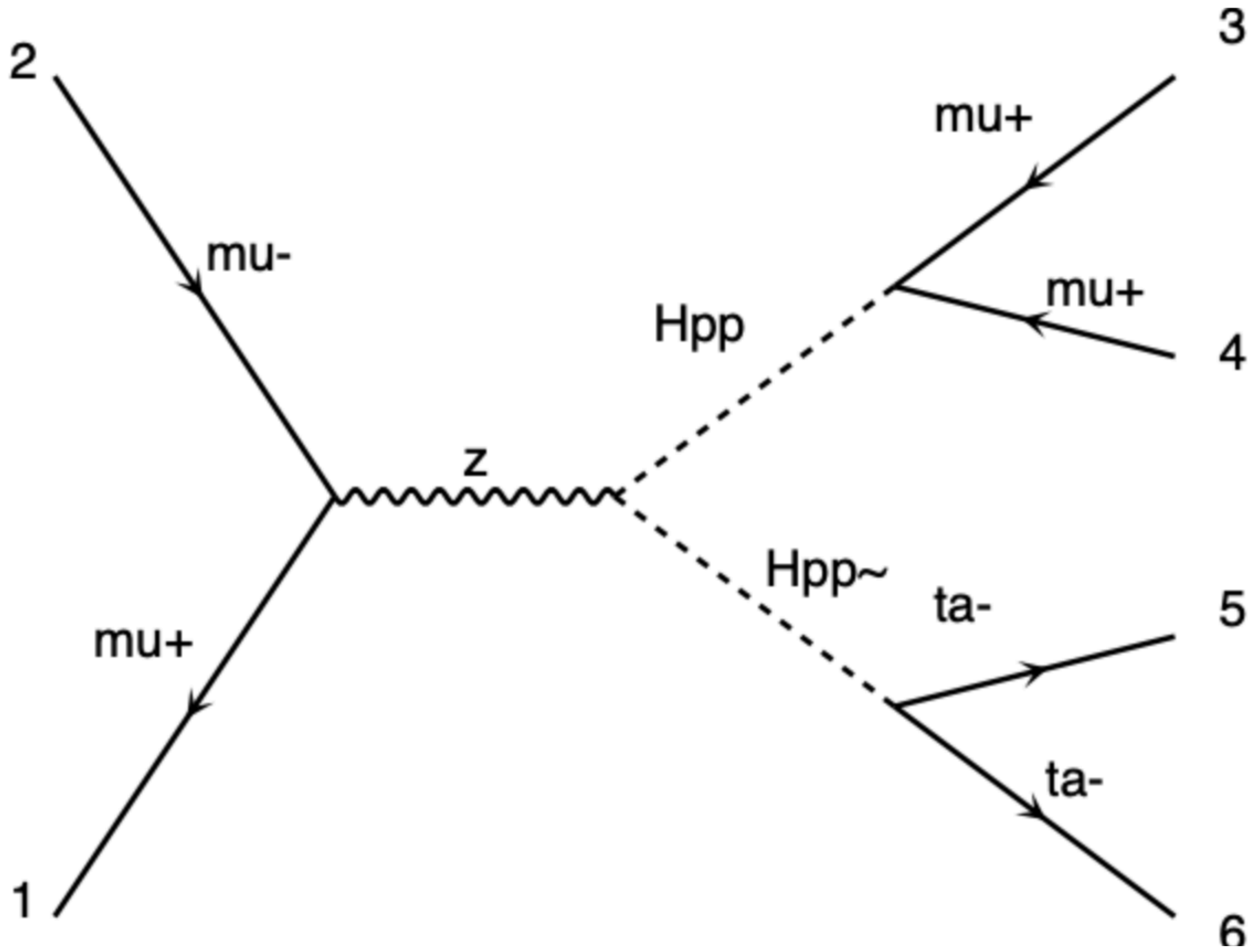
$$\mu^+\mu^- \to \Delta^{++}\Delta^{--} \to \mu^\pm\mu^\pm\tau^\mp\tau^\mp$$

Muon collider signatures



Increasing m_Δ

Triplet effects rise

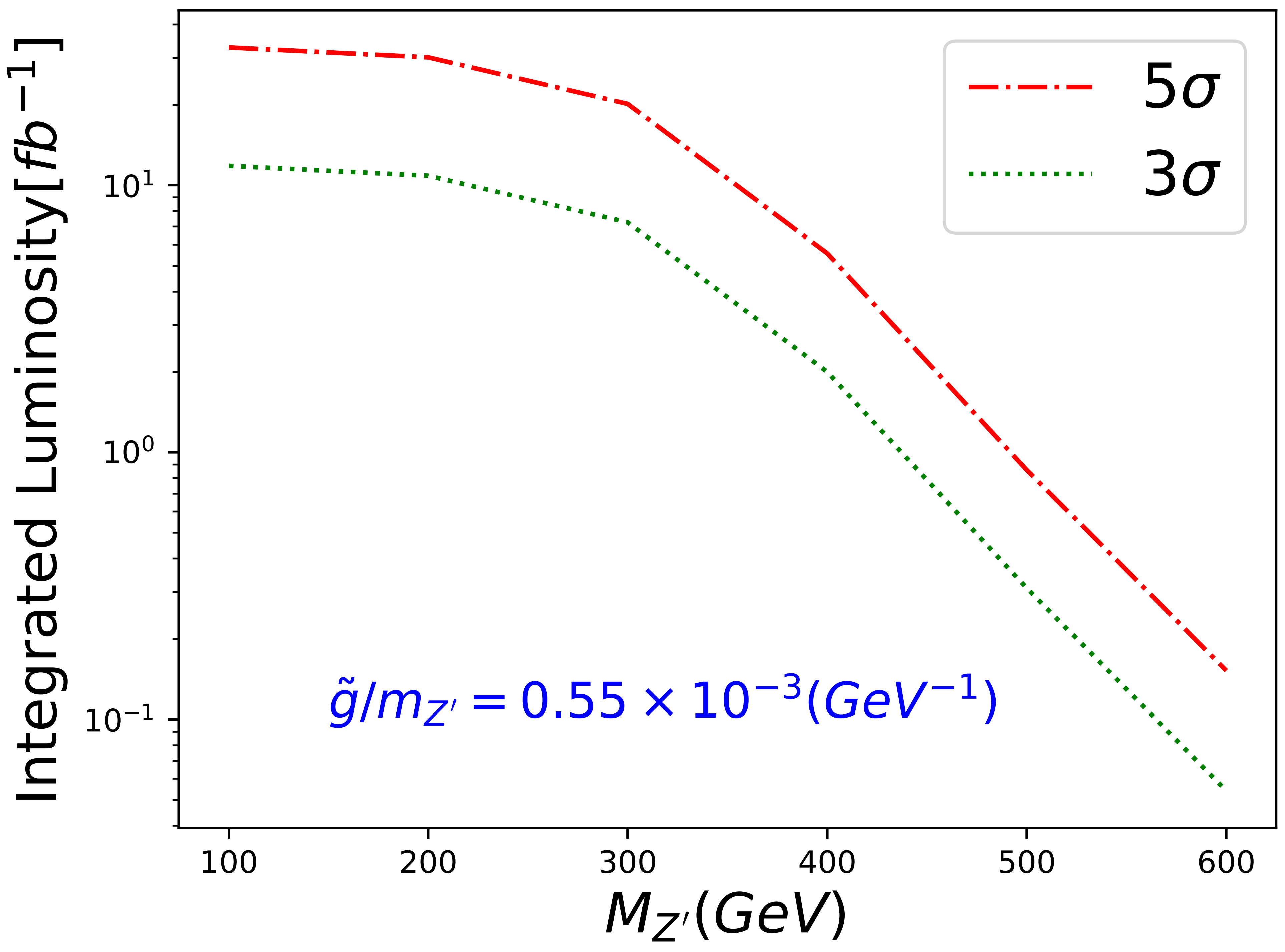


$$|Y_{22}|^2/(s_1 - m_\Delta^2)(s_2 - m_\Delta^2)$$

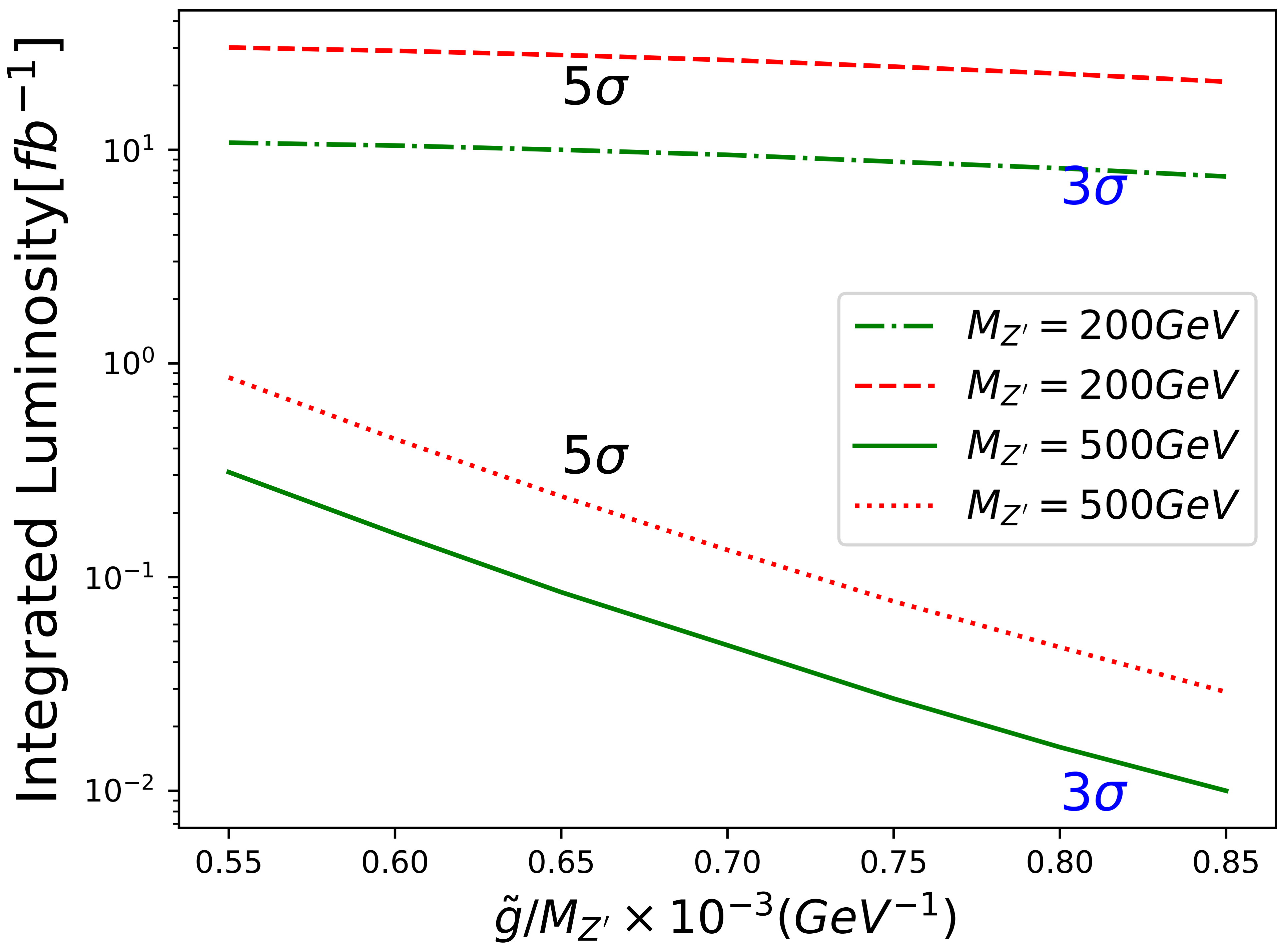
Bigger Smaller

Muon 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

- ☑ **The maximal off-diagonal Z' interaction in $U(1)_{L_\mu - L_\tau}$ at a muon collider**

- ☑ **A Z' with off-diagonal mixing leads to very distinctive signatures t-channel $\mu^+\mu^- \to \tau^+\tau^-$** and **four body smoking gun processes**

- ☑ **With a 3TeV muon collider with $\mathcal{O}(fb^{-1})$ luminosity, the signal processes can be distinguished at 5σ level**

Thanks!