清華大學
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FCPPL

Dark Z' & Doubly Charged Leptons

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Discovery of Higgs-like particle if it is proved really to be higgs completes SM

No hint of New Physics up to now from particle physics experiments

More than 40 years development of new physics models since founding of SM

Unfortunately Non of them show sign in the experiments !

This forces us to consider some exotic things

familiar matter is already well investigated

Two exotic thing will be discussed in this talk:

Dark Z'

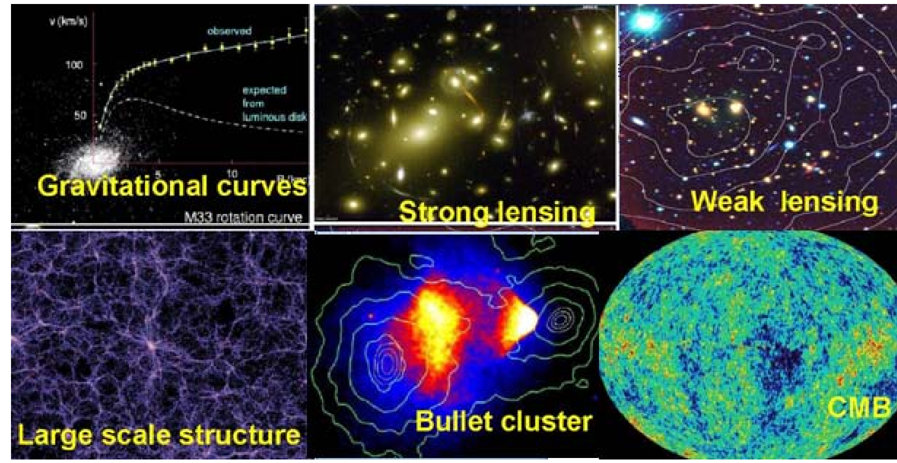
Doubly Charged Leptons

Dark Z'

Although No hint of New Physics from particle physics experiments

Cosmology tells us DM must exist

its particle characteristics ?



Search DM in particle physics !

Most discussed DM are spin $1/2$ fermions and spin 0 scalars

Spin 1 vectors are usually treated as messengers

connecting SM particles with dark world

We investigate possibility that Spin 1 vector is as DM candidate

simplest case is Z'

Stability of dark Z'

- Does not allow it directly couple to SM fermions
- Also prohibits Z' mixing with Z and γ mass, kinetic, Stueckelberg type mixings
- Further forbids $Z'VV$ and $Z'VVV$ operators $V = Z, W^{\pm}, \gamma$

Search for dark Z' model independently

- Start from a electroweak chiral Lagrangian for Z', Z, $W^{\pm}$ and γ
- Investigate the possibility satisfying above constraints
- Fortunately there exist such kind of a nontrivial chiral Lagrangian

EWCL for $W^\pm, Z, Z', \gamma$

$$T = \hat{U}\tau^3\hat{U}^\dagger \qquad \hat{V}_\mu = (D_\mu\hat{U})\hat{U}^\dagger \qquad D_\mu\hat{U} = \partial_\mu\hat{U} + i(gW_\mu - g''X_\mu)\hat{U} - i\hat{U}(\frac{\tau^3}{2}g' + \tilde{g}')B_\mu$$

$$\mathcal{L}_{\rm EWCL}^{\rm boson} = -\frac{f^2}{4}{\rm tr}(\hat{V}_\mu\hat{V}^\mu) + \frac{f^2}{4}\beta_1[{\rm tr}(T\hat{V}_\mu)]^2 + \frac{f^2}{4}\beta_2{\rm tr}(\hat{V}_\mu){\rm tr}(T\hat{V}_\mu) + \frac{f^2}{4}\beta_3[{\rm tr}(\hat{V}_\mu)]^2$$

$$-\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{2}{\rm tr}[W_{\mu\nu}W^{\mu\nu}] - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{1}{2}\alpha_1 gg'B_{\mu\nu}{\rm tr}[TW^{\mu\nu}] + \frac{i}{2}\alpha_2 g'B_{\mu\nu}{\rm tr}[T[\hat{V}^\mu,\hat{V}^\nu]] + i\alpha_3 g{\rm tr}[W^{\mu\nu}[\hat{V}^\mu,\hat{V}^\nu]]$$

$$+\alpha_4{\rm tr}[\hat{V}_\mu\hat{V}_\nu]{\rm tr}[\hat{V}^\mu\hat{V}^\nu] + \alpha_5{\rm tr}[\hat{V}_\mu\hat{V}^\mu]{\rm tr}[\hat{V}^\nu\hat{V}_\nu] + \alpha_6{\rm tr}[\hat{V}_\mu\hat{V}_\nu]{\rm tr}[T\hat{V}^\mu]{\rm tr}[T\hat{V}^\nu] + \alpha_7{\rm tr}[\hat{V}_\mu\hat{V}^\mu]{\rm tr}[T\hat{V}_\nu]{\rm tr}[T\hat{V}^\nu]$$

$$+\frac{1}{4}\alpha_8 g^2{\rm tr}[TW_{\mu\nu}]{\rm tr}[TW^{\mu\nu}] + \frac{i}{2}\alpha_9 g{\rm tr}[TW^{\mu\nu}]{\rm tr}[T[\hat{V}_\mu,\hat{V}_\nu]] + \frac{1}{2}\alpha_{10}{\rm tr}[T\hat{V}^\mu]{\rm tr}[T\hat{V}^\nu]{\rm tr}[T\hat{V}_\mu]{\rm tr}[T\hat{V}_\nu] + \alpha_{11}g\epsilon^{\mu\nu\rho\lambda}{\rm tr}[T\hat{V}_\mu]{\rm tr}[\hat{V}_\nu W_{\rho\lambda}]$$

$$+\alpha_{12}g{\rm tr}[T\hat{V}^\mu]{\rm tr}[\hat{V}^\nu W_{\mu\nu}] + \alpha_{13}gg'\epsilon^{\mu\nu\rho\lambda}B_{\mu\nu}{\rm tr}[TW_{\rho\lambda}] + \alpha_{14}g^2\epsilon^{\mu\nu\rho\lambda}{\rm tr}[TW_{\mu\nu}]{\rm tr}[TW_{\rho\lambda}] + \alpha_{15}{\rm tr}[\hat{V}_\mu]{\rm tr}[T\hat{V}^\mu]{\rm tr}[T\hat{V}_\nu]{\rm tr}[T\hat{V}^\nu]$$

$$+\alpha_{16}{\rm tr}[\hat{V}_\mu]{\rm tr}[T\hat{V}^\mu]{\rm tr}[\hat{V}_\nu\hat{V}^\nu] + \alpha_{17}{\rm tr}[\hat{V}_\mu]{\rm tr}[T\hat{V}_\nu]{\rm tr}[\hat{V}^\mu\hat{V}^\nu] + \alpha_{18}{\rm tr}[\hat{V}_\mu]{\rm tr}[\hat{V}_\nu]{\rm tr}[T\hat{V}^\mu]{\rm tr}[T\hat{V}^\nu] + \alpha_{19}{\rm tr}[\hat{V}_\mu]{\rm tr}[\hat{V}_\nu]{\rm tr}[\hat{V}^\mu\hat{V}^\nu]$$

$$+\alpha_{20}{\rm tr}[\hat{V}_\mu]{\rm tr}[\hat{V}^\mu]{\rm tr}[T\hat{V}_\nu]{\rm tr}[T\hat{V}^\nu] + \alpha_{21}{\rm tr}[\hat{V}_\mu]{\rm tr}[\hat{V}^\mu]{\rm tr}[\hat{V}_\nu\hat{V}^\nu] + \alpha_{22}{\rm tr}[\hat{V}_\mu]{\rm tr}[\hat{V}^\mu]{\rm tr}[\hat{V}_\nu]{\rm tr}[T\hat{V}^\nu] + \alpha_{23}{\rm tr}[\hat{V}_\mu]{\rm tr}[\hat{V}_\nu]{\rm tr}[\hat{V}^\mu]{\rm tr}[\hat{V}^\nu]$$

$$+gg''\alpha_{24}X_{\mu\nu}{\rm tr}[TW^{\mu\nu}] + g'g''\alpha_{25}B_{\mu\nu}X^{\mu\nu} + \alpha_{26}\epsilon^{\mu\nu\rho\lambda}{\rm tr}[\hat{V}_\mu]{\rm tr}[T\hat{V}_\nu]{\rm tr}[T[\hat{V}_\rho,\hat{V}_\lambda]] + ig'\alpha_{27}\epsilon^{\mu\nu\rho\lambda}{\rm tr}[\hat{V}_\mu]{\rm tr}[T\hat{V}_\nu]B_{\rho\lambda}$$

$$+ig\alpha_{28}\epsilon^{\mu\nu\rho\lambda}{\rm tr}[\hat{V}_\mu]{\rm tr}[T\hat{V}_\nu]{\rm tr}[TW_{\rho\lambda}] + g\alpha_{29}\epsilon^{\mu\nu\rho\lambda}{\rm tr}[\hat{V}_\mu]{\rm tr}[\hat{V}_\nu W_{\rho\lambda}] + ig''\alpha_{30}\epsilon^{\mu\nu\rho\lambda}X_{\mu\nu}{\rm tr}[T[\hat{V}_\rho,\hat{V}_\lambda]] + ig''\alpha_{31}X_{\mu\nu}{\rm tr}[T[\hat{V}^\mu,\hat{V}^\nu]]$$

$$+g''\alpha_{32}\epsilon^{\mu\nu\rho\lambda}{\rm tr}[\hat{V}_\mu]{\rm tr}[T\hat{V}_\nu]X_{\rho\lambda} + \alpha_{33}{\rm tr}[\hat{V}_\mu]{\rm tr}[T\hat{V}_\nu]{\rm tr}[T[\hat{V}^\mu,\hat{V}^\nu]] + g'g''\alpha_{34}\epsilon^{\mu\nu\rho\lambda}B_{\mu\nu}X_{\rho\lambda} + gg''\alpha_{35}\epsilon^{\mu\nu\rho\lambda}X_{\mu\nu}{\rm tr}[TW_{\rho\lambda}]$$

$$+ig'\alpha_{36}{\rm tr}[\hat{V}_\mu]{\rm tr}[T\hat{V}_\nu]B^{\mu\nu} + ig\alpha_{37}{\rm tr}[\hat{V}_\mu]{\rm tr}[T\hat{V}_\nu]{\rm tr}[TW^{\mu\nu}] + g\alpha_{38}{\rm tr}[\hat{V}^\mu]{\rm tr}[\hat{V}^\nu W_{\mu\nu}] + g''\alpha_{39}{\rm tr}[\hat{V}_\mu]{\rm tr}[T\hat{V}_\nu]X^{\mu\nu}$$

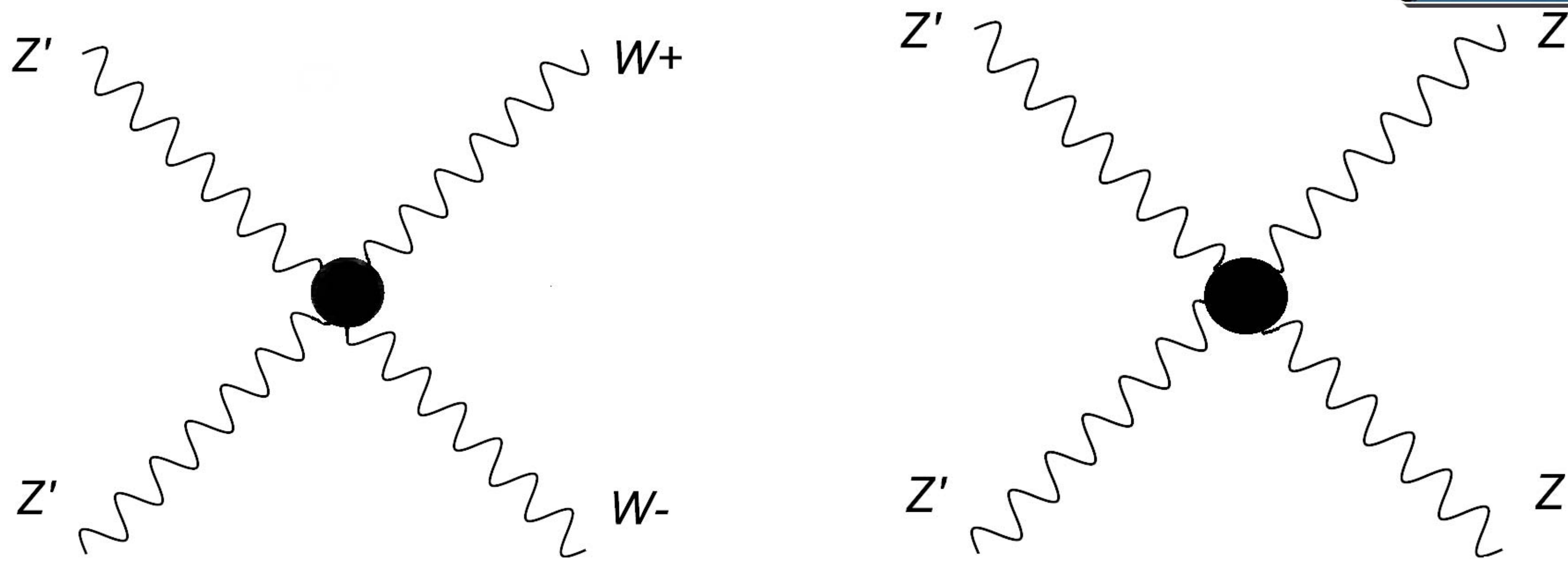
$$+ig\alpha_{40}{\rm tr}[\hat{V}^\mu]{\rm tr}[T\hat{V}^\nu W_{\mu\nu}] + O(p^6)$$

Y.Zhang, S.Z.Wang and Q.Wang JHEP03(2008)047

No mixings $\Rightarrow \quad \beta_1 = \beta_2 = \beta_3 = \alpha_1 = \alpha_8 = \alpha_{24} = \alpha_{25} = \tilde{g}' = 0$

No $Z'VV$, $Z'VVV$ vertices $\Rightarrow \quad \alpha_{15} = \alpha_{16} = \alpha_{17} = \alpha_{22} = \alpha_{31} = 0$

Relic Density



$$D_{+-Z'Z'}W^+_\mu W^{-\mu}Z'_\nu Z'^\nu + D_{+Z'-Z'}W^+_\mu Z'^\mu W^-_\nu Z'^\nu \qquad D_{V_1V_2V_3V_4}V_{1\mu}V_2^\mu V_{3\nu}V_4^\nu$$

$$D_{+-Z'Z'} = \underline{\mathbf{g_1}} = 4g^2g''^2(\alpha_5+\alpha_{21}) \qquad D_{Z'Z'ZZ} = \underline{\mathbf{g_3}} = g_Z^2g''^2(\alpha_5+2\alpha_7+4\alpha_{20}+2\alpha_{21})$$

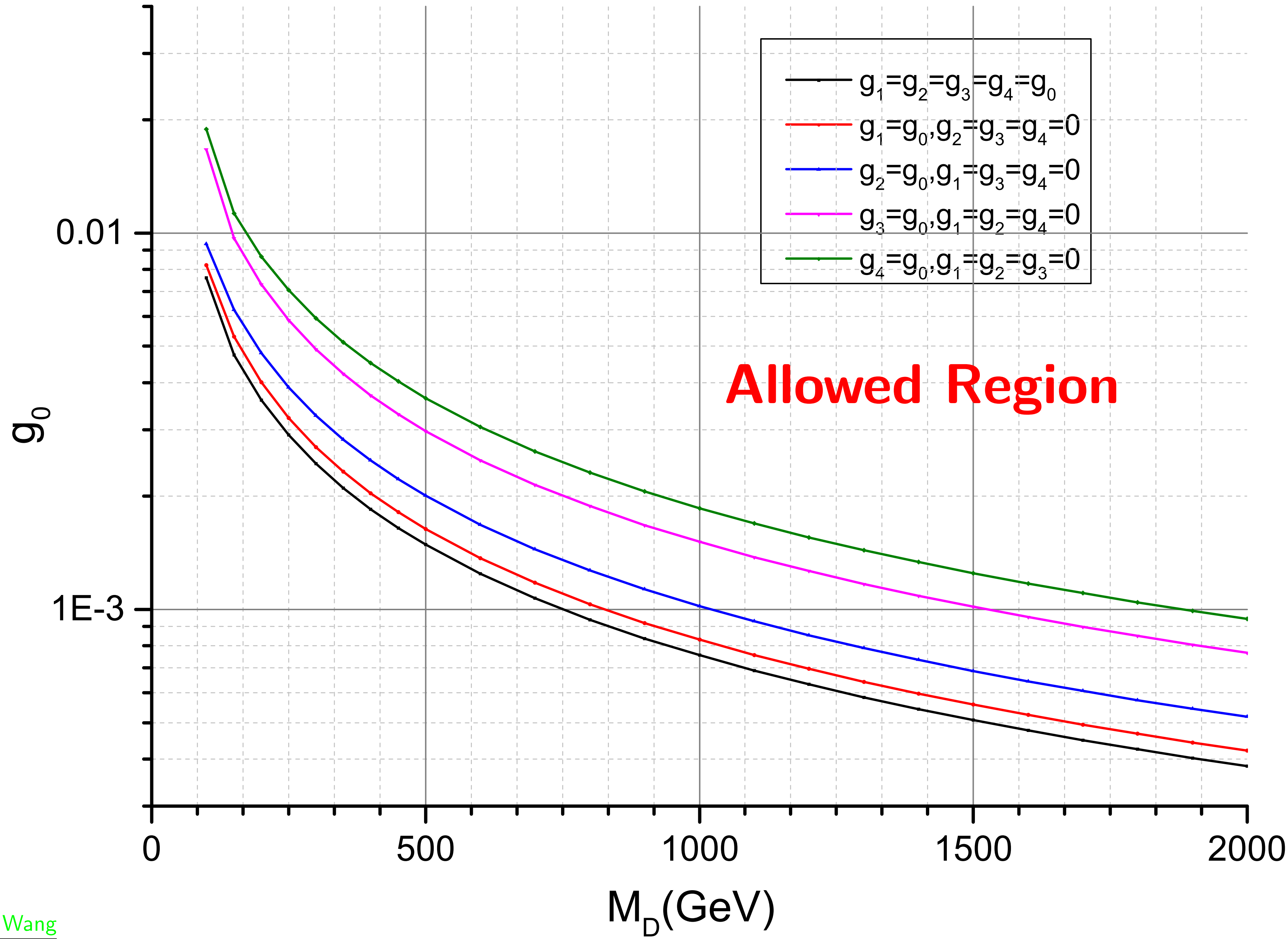
$$D_{+Z'-Z'} = \underline{\mathbf{g_2}} = 4g^2g''^2(\alpha_4+\alpha_{19}) \qquad D_{Z'ZZ'Z} = \underline{\mathbf{g_4}} = 4g_Z^2g''^2(\alpha_4+\alpha_6+2\alpha_{18}+\alpha_{19})$$

$$\sigma_W v = \frac{\sqrt{1-\frac{1}{r_W^2}}}{9\times 64\pi m_{Z'}}\left[(224r_W^4+112r_W^2+136)g_1^2-(160r_W^4+80r_W^2+176)g_1g_2+(152r_W^4+128r_W^2+96)g_2^2\right]$$

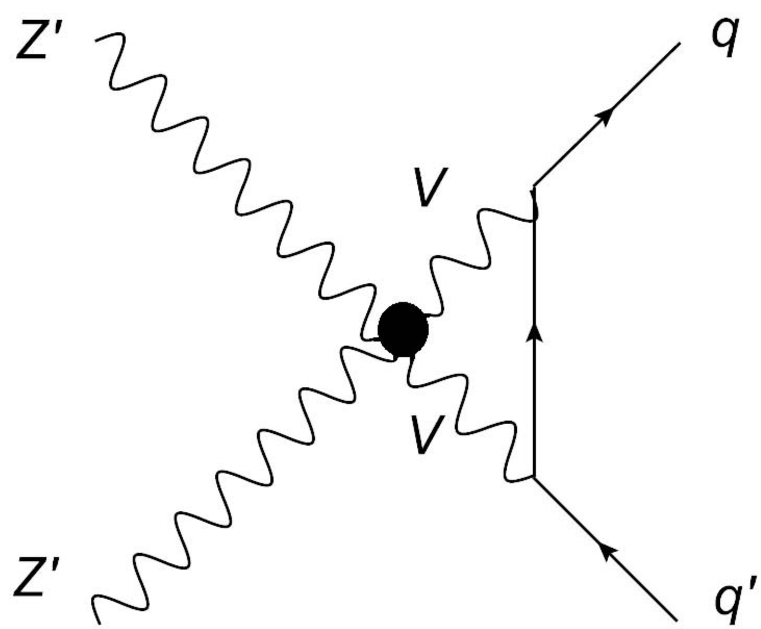
$$\sigma_Z v = \frac{\sqrt{1-\frac{1}{r_Z^2}}}{18\times 64\pi m_{Z'}}\left[(224r_Z^4+112r_Z^2+136)g_1^2-(160r_Z^4+80r_Z^2+176)g_1g_2+(152r_Z^4+128r_Z^2+96)g_2^2\right]$$

$$r_W = m_{Z'}/m_W \qquad r_Z = m_{Z'}/m_Z$$

Relic Density Constraint



Direct Detection



$$c_u = \frac{ig}{4\cos\theta_W}(1 - \frac{8}{3}\sin^2\theta_W)$$

$$c_d = \frac{ig}{4\cos\theta_W}(-1 + \frac{4}{3}\sin^2\theta_W)$$

$$c'_u = \frac{ig}{4\cos\theta_W}$$

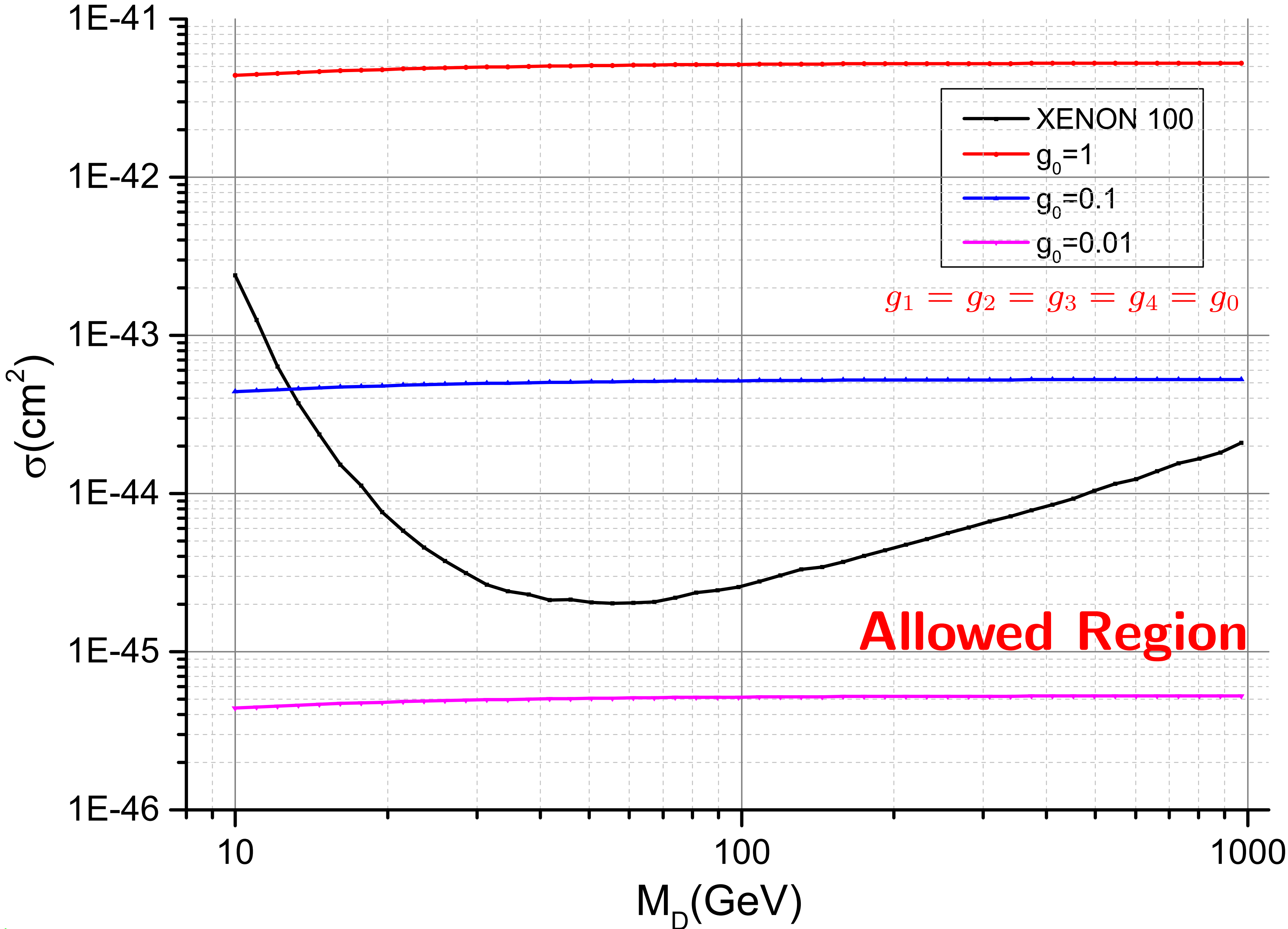
$$c'_d = -\frac{ig}{4\cos\theta_W}$$

$$\mathcal{L}_{eff} = \sum_q \frac{K_{V,q}}{\sqrt{2}}(Z'_\nu i \overleftrightarrow{\partial}_\mu Z'^\nu)\bar{q}\gamma^\mu q + \underbrace{\sum_q \frac{K_{A,q}}{\sqrt{2}}(Z'_\nu i \overleftrightarrow{\partial}_\mu Z'^\nu)\bar{q}\gamma^\mu\gamma_5 q}_{\text{No contribution to spin independent DD}}$$

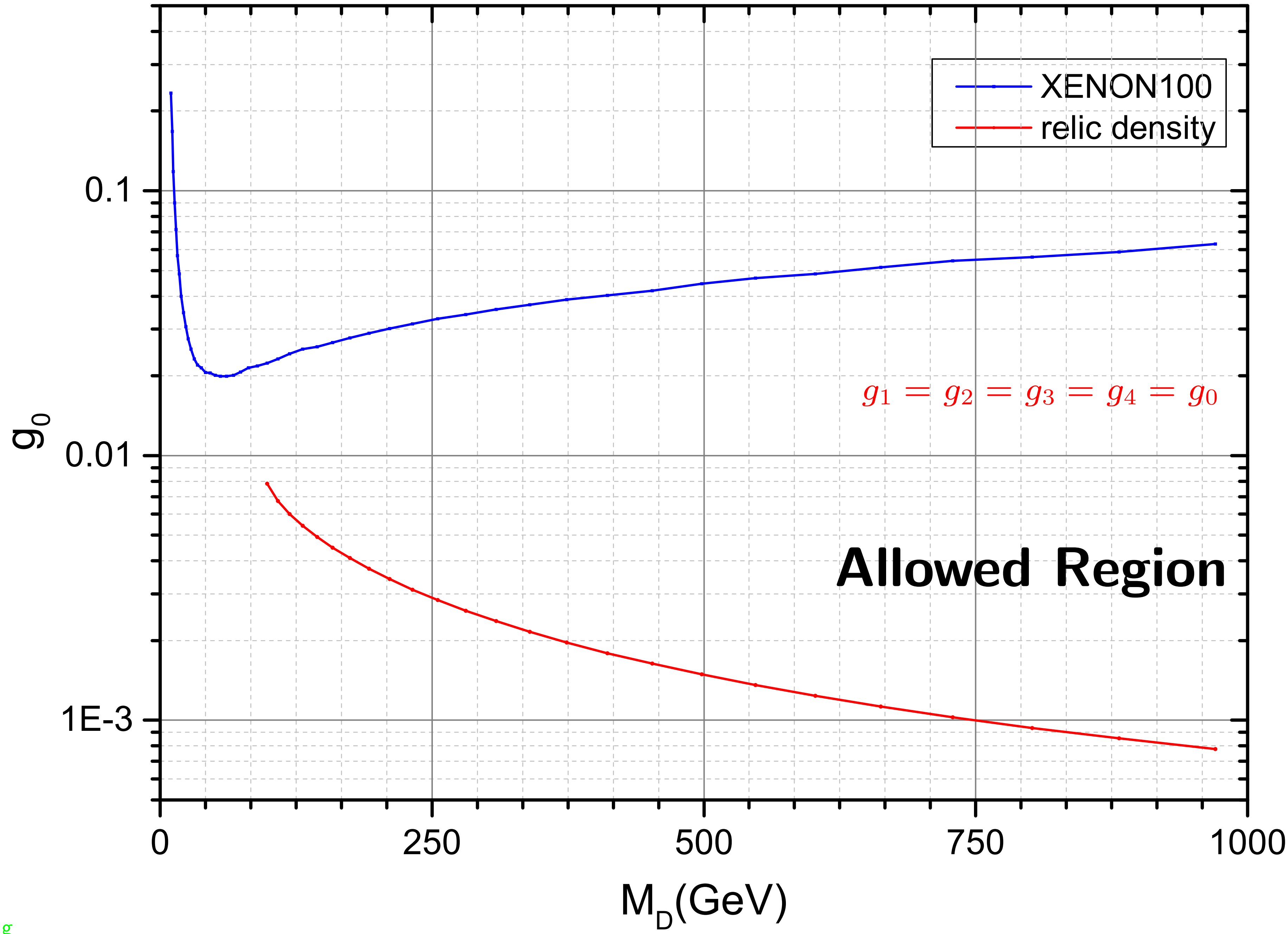
$$\sigma_{V,Z'N} = \frac{m_N^2 m_{Z'}^2}{\pi(m_{Z'} + m_N)^2}(\frac{K_{V,N}}{\sqrt{2}})^2 \qquad K_{V,p} = 2K_{V,u} + K_{V,d}, \quad K_{V,n} = K_{V,u} + 2K_{V,d}$$

$$\frac{K_{V,q}}{\sqrt{2}} = \frac{(g_1 + g_2)(c_q^2 + c_q'^2)}{32\pi^2 m_W^2} + \frac{(g_3 + g_4)(c_q^2 + c_q'^2)}{32\pi^2 m_Z^2}$$

Direct Detection Constraint



Combination Constraints



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Doubly Charged Leptons

Two possibilities to embed the doubly charged lepton in a representation of SU(2):

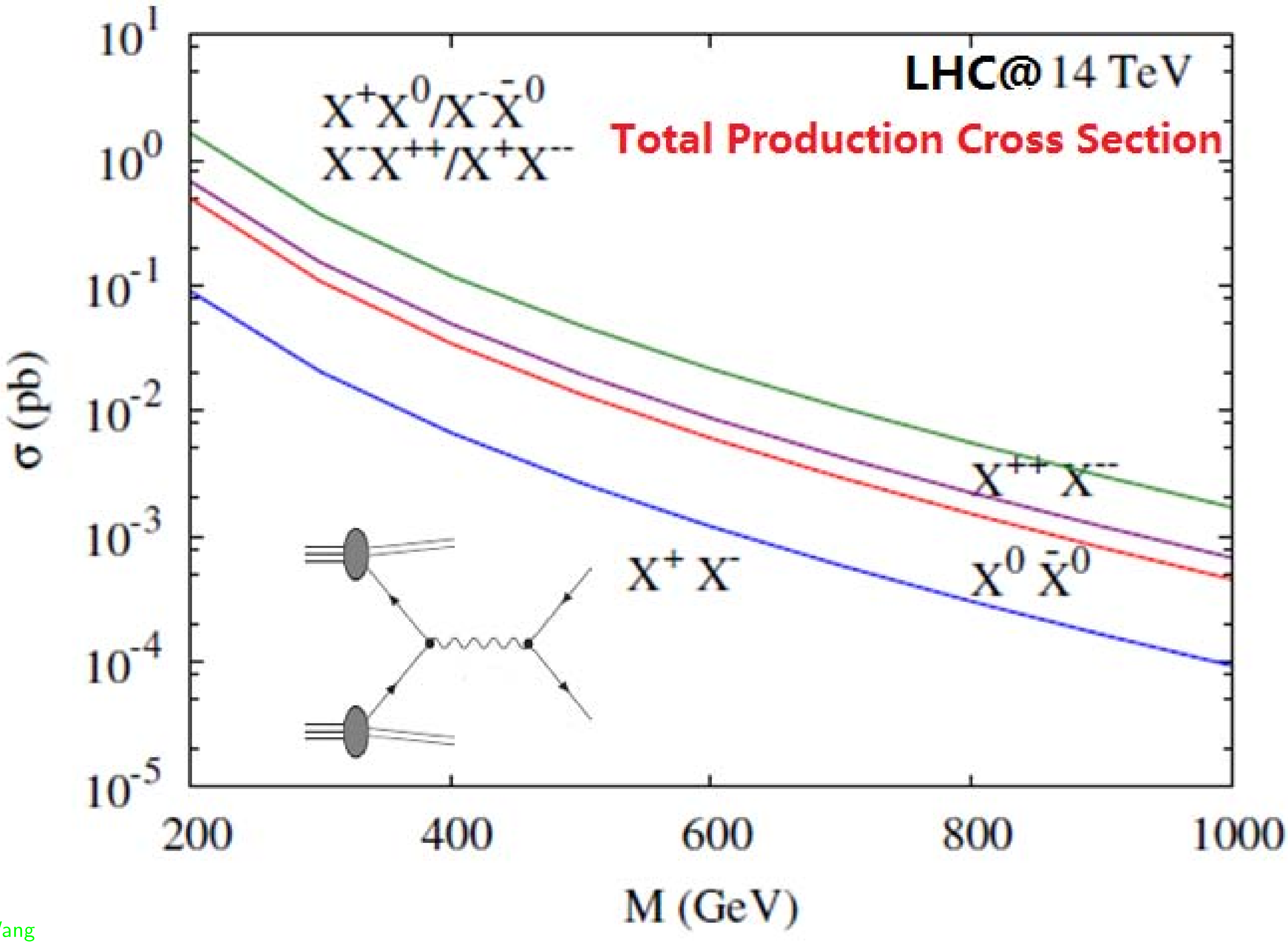
- **Doublet:** $\psi_D = (2, 2/3) = (x_d, \tau_d)$
- **Triplet:** $\psi_T = (3, -1) = (\nu_t, \tau_t, x_t)$

- The masses of the two new states and are very close.
- New state can not decay to the other, only to light leptons.
- Single production of the heavy leptons is negligible.
- off-diagonal couplings small, can work in same mass approx

$$\mathcal{L}_{\text{Yukawa}} = \begin{cases} -y_i \overline{L}^i \phi_H e_R^i - \underbrace{\lambda_j \overline{\psi}_{DL} \phi_H^c e_R^j}_{\text{couple to } e_R} - M\overline{\psi}_{DL}\psi_{DR} + h.c. & \text{doublet} \\ -y_i \overline{L}^i \phi_H e_R^i - \underbrace{\lambda_j \overline{L}^j \phi_H \psi_{TR}}_{\text{couple to } e_L} - M\overline{\psi}_{TL}\psi_{TR} + h.c. & \text{triplet} \end{cases}$$

$$\mathcal{L}_{mass} = \begin{cases} -(\overline{e}_L^1, \overline{e}_L^2, \overline{e}_L^3, \overline{\tau}_{dL}) \cdot \begin{pmatrix} \tilde{m}_e & 0 & 0 & 0 \\ 0 & \tilde{m}_\mu & 0 & 0 \\ 0 & 0 & \tilde{m}_\tau & 0 \\ x_1 & x_2 & x_3 & M \end{pmatrix} \cdot \begin{pmatrix} \overline{e}_R^1 \\ \overline{e}_R^2 \\ \overline{e}_R^3 \\ \overline{\tau}_{dR} \end{pmatrix} - M\overline{x}_d x_d + h.c. & \text{doublet} \\ \text{mixing in } e_L \text{ and } \tau_{dL} \text{ sector are suppressed by } \tilde{m}_{e,\mu,\tau}/M; \text{ mixing in } e_R \text{ and } \tau_{dR} \text{ sector} \propto x_i/M \\ m_{e,\mu,\tau} \text{ are proportional to SM Yukawa couplings } \tilde{m}_{e,\mu,\tau} \\ \text{mixing in } e_R \text{ and } \tau_{tR} \text{ sector are suppressed by } \tilde{m}_{e,\mu,\tau}/M; \text{ mixing in } e_L \text{ and } \tau_{tL} \text{ sector} \propto x_i/M \\ -(\overline{e}_L^1, \overline{e}_L^2, \overline{e}_L^3, \overline{\tau}_{tL}) \cdot \begin{pmatrix} \tilde{m}_e & 0 & 0 & x_1 \\ 0 & \tilde{m}_\mu & 0 & x_2 \\ 0 & 0 & \tilde{m}_\tau & x_3 \\ 0 & 0 & 0 & M \end{pmatrix} \cdot \begin{pmatrix} \overline{e}_R^1 \\ \overline{e}_R^2 \\ \overline{e}_R^3 \\ \overline{\tau}_{tR} \end{pmatrix} - M\overline{x}_t x_t + h.c. & \text{triplet} \end{cases}$$

LHC phenomenology



Pair production process at LHC and decay modes

- $\mathbf{pp \rightarrow X^{--}X^{++} \rightarrow l^{-}W^{-}l^{+}W^{+}}$ **One of the W' s in the final state is required to decay leptonically for the charge identification and the other W to decay hadronically for the mass reconstruction. The production cross section at the 14TeV LHC is 13fb , for M=200GeV and the background is 5.5fb with kinematical acceptance on the transverse momentum, rapidity, missing transverse energy, and the particle separation as:**

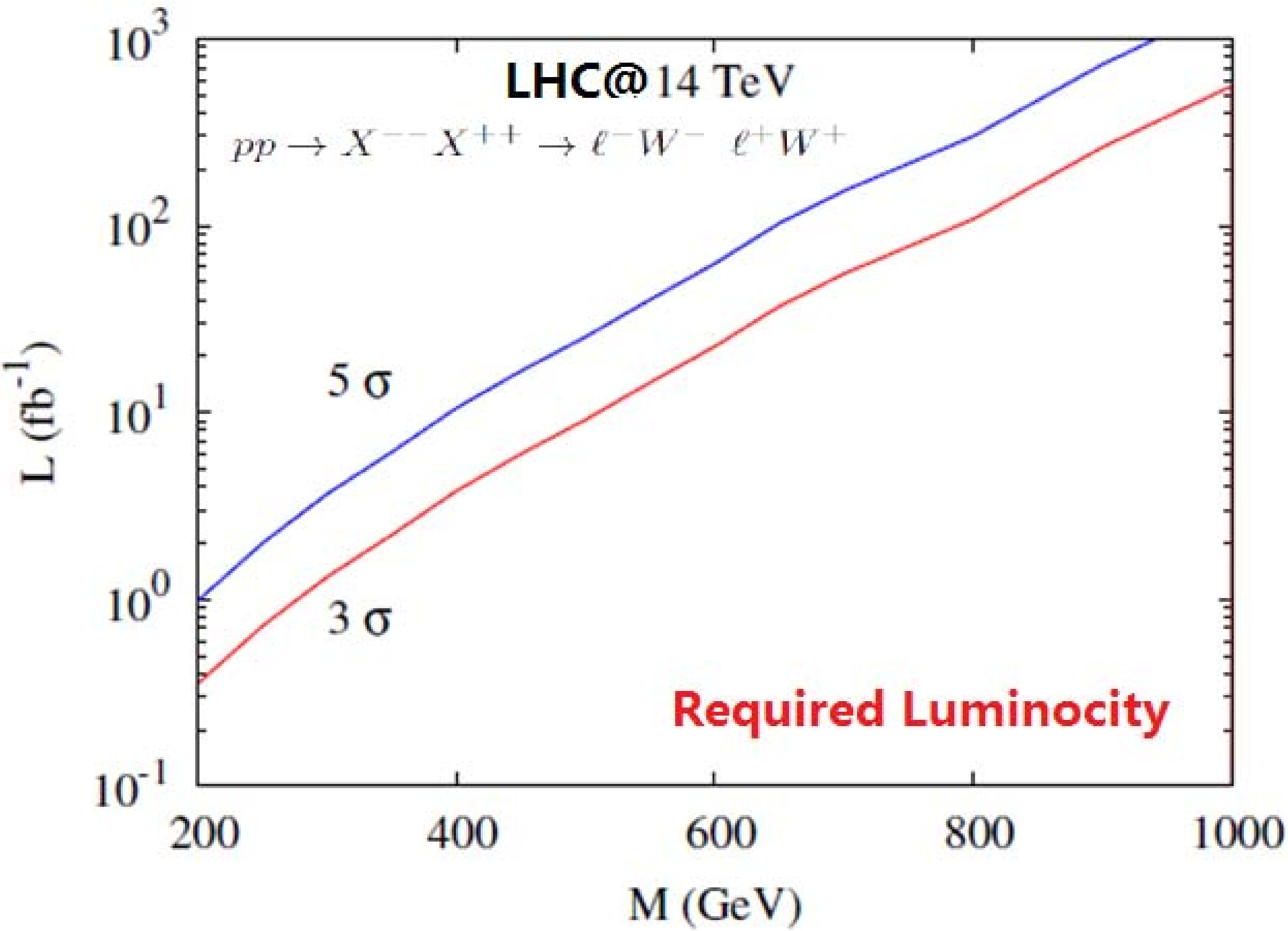
  $p_T(l) > 15$**GeV,**$|\eta_l| < 2.5$**,**$\not{E}_T > 25$**GeV;** $p_T(j) > 15$**GeV,**$|\eta_j| < 2.5$**;** $\Delta R(jj) > 0.4$**,** $\Delta R(jl) > 0.4$**,** $\Delta R(ll) > 0.3$**.**

- $\mathbf{pp \rightarrow X^{++}X^{-} \rightarrow l^{+}W^{+}l^{-}Z \rightarrow l^{+}l^{+}\nu l^{-}jj}$ **The Drell-Yan production process can contribute the same signal as pair prodution And the final cross section for mass 200GeV is 13fb.**

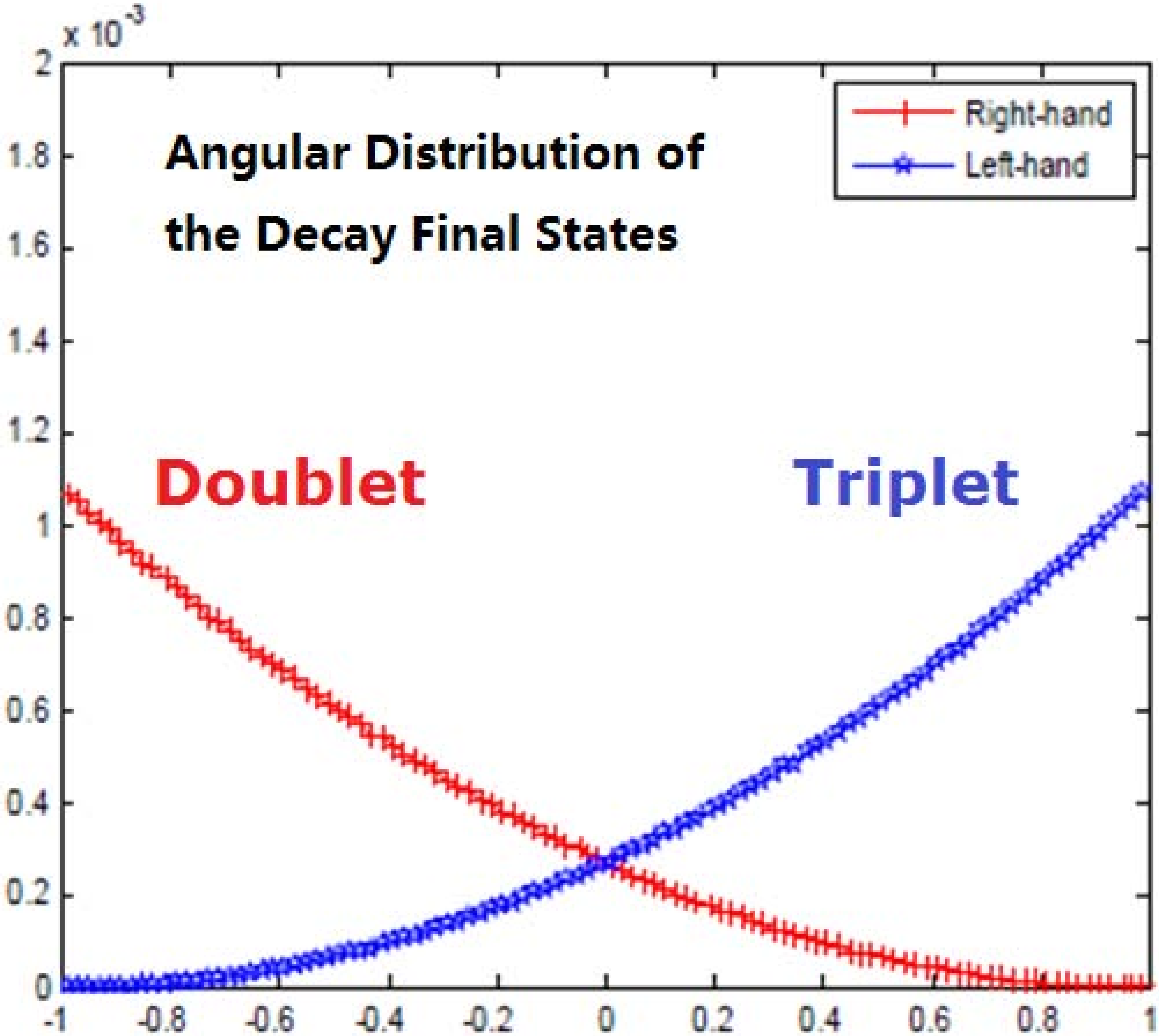
- $\mathbf{pp \rightarrow X^{++}X^{-} \rightarrow l^{+}W^{+}(jj)l^{-}Z(l^{+}l^{-})}$ **The final cross section for mass 200GeV is 3.9 fb and the background is 1.2fb.**

- $\mathbf{pp \rightarrow X^{++}X^{-} \rightarrow l^{+}W^{+}(jj)l^{-}Z(bb)}$ **The b-jet decay modes, the final cross section for mass 200GeV is 6 fb after consider the B-tagging efficiency as 70%. And the background is 0.2fb.**

- $\mathbf{pp \rightarrow X^{++}X^{-} \rightarrow l^{+}W^{+}(jj)l^{-}H(b\bar{b})}$ **The Drell-Yan production process X- also can decay to Higgs boson, , the final cross section for mass 200GeV is 15 fb when consider the Higgs mass is 126GeV , and the background is 0.3fb.**


LHC@14 TeV
$pp \to X^{--}X^{++} \to \ell^- W^- \ \ell^+ W^+$
5 σ
3 σ
Required Luminocity
L (fb^{-1})
M (GeV)
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
200
400
600
800
1000

Distinguish Doublet or Triplet



Summary

- Z' is possible to be as a dark matter candidate

- Relic density and DD give constraints on the couplings

- Further constraints from ID and collider exp are under investigation

- Doubly charged leptons only alow electroweak doublet and triplet

- Their very small mixing with light leptons lead rich phenomenology

Thanks!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