TeV-Scale Alternative Left-Right Model

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- Understanding the origin of the parity violation in low energy weak interactions:
  The parity violation assumption is clear in the choice of the SM gauge group:

  $$G_{\text{SM}} = SU(3)_c \times SU(2)_L \times U(1)_Y.$$

  The Left-Right symmetric model (LRM) is based on the gauge group [1]:

  $$G_{\text{LRM}} = SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}.$$

- Physical meaning of the 'adhoc' hypercharge:

  $$\frac{Y}{2} = I_R^3 + \frac{B-L}{2}$$

- Massive neutrinos. Left-Right Models contains ν_R.

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- Tree level flavor changing neutral current.
- TeV Scale LR.

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- The LRM gauge group is:

$$G_{\text{LRM}} = SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

- The ALRM gives the following assignment to fermions [2]:

Fermions	$SU(3)_c$	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$	S
$Q_L \equiv \begin{pmatrix} u \\ d \end{pmatrix}_L$	3	2	1	$+\frac{1}{6}$	0
$Q_R \equiv \begin{pmatrix} u \\ d' \end{pmatrix}_R$	3	1	2	$+\frac{1}{6}$	$-\frac{1}{2}$
d'_L	3	1	1	$-\frac{1}{3}$	-1
d_R	3	1	1	$-\frac{1}{3}$	0
$\psi_L \equiv \begin{pmatrix} \nu \\ e \end{pmatrix}_L$	1	2	1	$-\frac{1}{2}$	0
$\psi_R \equiv \begin{pmatrix} n \\ e \end{pmatrix}_R$	1	1	2	$-\frac{1}{2}$	$+\frac{1}{2}$
n_L	1	1	1	0	$+1$
ν_R	1	1	1	0	0

Table: Fermion content and their quantum numbers in the ALRM.

- The SM electric charge formula in terms of physical quantum numbers

$$Q = I_{3_L} + \frac{Y}{2}.$$

- The LRM electric charge formula in terms of physical quantum numbers

$$Q = I_{3_L} + I_{3_R} + \frac{B-L}{2}.$$

- Here the hypercharge gains its physical meaning through the combination

$$\frac{Y}{2} = I_{3_R} + \frac{B-L}{2}.$$

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Scheme of electroweak symmetry breaking:

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$$\downarrow$$

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

$$\downarrow$$

$$U(1)_{em}$$

The minimal set of Higgs fields required to break the electroweak symmetry [2]:

Higgs	$SU(3)_c$	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$	S
$\Phi \equiv \begin{pmatrix} \phi_1^0 & \phi_1^+ \\ \phi_2^- & \phi_2^0 \end{pmatrix}$	1	2	2^*	0	$-\frac{1}{2}$
$\chi_L \equiv \begin{pmatrix} \chi_L^+ \\ \chi_L^0 \end{pmatrix}$	1	2	1	$+\frac{1}{2}$	0
$\chi_R \equiv \begin{pmatrix} \chi_R^+ \\ \chi_R^0 \end{pmatrix}$	1	1	2	$+\frac{1}{2}$	$+\frac{1}{2}$

Table: Scalar content and their quantum numbers in the ALRM.

The Higgs potential [3]:

$$\begin{aligned} V(\Phi,\chi_{L,R}) &= -\mu_1^2 Tr[\Phi^\dagger\Phi] + \lambda_1 (Tr[\Phi^\dagger\Phi])^2 + \lambda_2 Tr[\Phi^\dagger\widetilde{\Phi}]\ Tr[\widetilde{\Phi}^\dagger\Phi] \\ &-\mu_2^2(\chi_L^\dagger\chi_L + \chi_R^\dagger\chi_R) + \lambda_3[(\chi_L^\dagger\chi_L)^2 + (\chi_R^\dagger\chi_R)^2] \\ &+2\lambda_4(\chi_L^\dagger\chi_L)(\chi_R^\dagger\chi_R) + 2\alpha_1 Tr(\Phi^\dagger\Phi)(\chi_L^\dagger\chi_L + \chi_R^\dagger\chi_R) \\ &+2\alpha_2(\chi_L^\dagger\Phi\Phi^\dagger\chi_L + \chi_R^\dagger\Phi^\dagger\Phi\chi_R) \\ &+2\alpha_3(\chi_L^\dagger\widetilde{\Phi}\widetilde{\Phi}^\dagger\chi_L + \chi_R^\dagger\widetilde{\Phi}^\dagger\widetilde{\Phi}\chi_R) + \mu_3(\chi_L^\dagger\Phi\chi_R + \chi_R^\dagger\Phi^\dagger\chi_L). \end{aligned} \tag{1}$$

where $\widetilde{\Phi} = \tau_2\Phi^*\tau_2$.

The VEV's are as follows:

$$\langle \chi_{L,R} \rangle = \begin{pmatrix} 0 \\ v_{L,R} \end{pmatrix}, \qquad \langle \phi \rangle = \begin{pmatrix} 0 & 0 \\ 0 & k \end{pmatrix}. \tag{2}$$

In addition, from the minimization conditions, one finds that the non-vanishing vevs are given by

$$\sqrt{2} v_L v_R = \frac{-\mu_3 k}{\lambda_4 - \lambda_3}, \tag{3}$$

$$v_L^2 + v_R^2 = \frac{\mu_2^2 - (\alpha_1 + \alpha_2) k^2}{\lambda_3}, \tag{4}$$

$$k^2 = \frac{2\left(\lambda_3 \mu_1^2 - (\alpha_1 + \alpha_2)\mu_2^2\right)(\lambda_4 - \lambda_3) + \lambda_3 \mu_3^2}{2\left(\lambda_1 \lambda_3 - (\alpha_1 + \alpha_2)^2\right)(\lambda_4 - \lambda_3)}. \tag{5}$$

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- The Yukawa Lagrangian is

$$
\begin{aligned}
\mathcal{L}_{\mathrm{Y}} &= \overline{Q}_L Y^q \widetilde{\Phi} Q_R + \overline{Q}_L Y^q_L \chi_L d_R + \overline{Q}_R Y^q_R \chi_R d'_L + \overline{\psi}_L Y^\ell \Phi \psi_R \\
&+ \overline{\psi}_L Y^\ell_L \widetilde{\chi}_L \nu_R + \overline{\psi}_R Y^\ell_R \widetilde{\chi}_R n_L + \overline{\nu}^c_R M_R \nu_R + \text{h.c.}\ ,
\end{aligned} \tag{6}
$$

- Fermion masses:

$$\begin{aligned} m_u &= \frac{1}{\sqrt{2}} Y^q v \sin\beta, \quad m_d = \frac{1}{\sqrt{2}} Y^q_L v \cos\beta, \quad m_{d'} = \frac{1}{\sqrt{2}} Y^q_R v_R, \\ m_\ell &= \frac{1}{\sqrt{2}} Y^\ell v \sin\beta, \quad m_n = \frac{1}{\sqrt{2}} Y^\ell_R v_R, \end{aligned} \tag{7}$$

where $\tan\beta = k/v_L$.

- Neutrino masses:

$$M_\nu = \left(\begin{array}{c|cc} & \nu_L^c & \nu_R \\ \hline \overline{\nu}_L & 0 & m_{\nu D} \\ \overline{\nu}_R^c & m_{\nu D}^T & M_R \end{array}\right), \tag{8}$$

where $m_{\nu D} = Y_L^\ell v_L/\sqrt{2}$. The mass M_R is not related to the $SU(2)_R$ symmetry breaking scale, so it can be quite large.
The well known seesaw mass eigenvalues of the light and heavy neutrinos are

$$m_{\nu_l} \simeq m_{\nu D} M_R^{-1} m_{\nu D}^T, \qquad m_{\nu_h} \simeq M_R. \tag{9}$$

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- The gauge bosons and scalars gains their masses from the scalar kinetic Lagrangian

$$\mathcal{L}_{\text{kin}}^{\text{scalar}} = Tr[(D_\mu \Phi)^\dagger (D_\mu \Phi)] + (D_\mu \chi_L)^\dagger (D_\mu \chi_L) + (D_\mu \chi_R)^\dagger (D_\mu \chi_R), \tag{10}$$

Where the covariant derivatives of the scalars are

$$D_\mu \Phi = \partial_\mu \Phi - i\frac{g}{2}\left(\tau^a W^a_{L_\mu}\,\Phi - \Phi\,\tau^a W^a_{R_\mu}\right), \tag{11}$$

$$D_\mu \chi_{L,R} = \partial_\mu \chi_{L,R} - i\frac{g}{2}\tau^a W^a_{L,R_\mu}\chi_{L,R} - i\frac{g_{BL}}{2}B_\mu \chi_{L,R}. \tag{12}$$

- Due to the vanishing vev of $\phi_1^0 \in \Phi$, the mixing between $W_L^\pm$ and $W_R^\mp$ is identically zero. Thus the physical eigenstates are given by: SM gauge bosons $W^\pm = W_L^\pm$ and $W'^\pm = W_R^\pm$ with masses

$$M_W^2 = \frac{1}{4} g^2 \left(k^2 + v_L^2\right) = \frac{1}{4} g^2 v^2, \quad (13)$$

$$M_{W'}^2 = \frac{1}{4} g^2 \left(k^2 + v_R^2\right). \quad (14)$$

- The situation of the neutral gauge bosons: W_L^3, W_R^3, B is more involved. One can show that their mass matrix is given by

$$\left(\begin{array}{c|ccc} & W_L^3 & W_R^3 & B \\ \hline W_L^3 & \frac{1}{4}g^2\left(k^2+v_L^2\right) & -\frac{1}{4}g^2k^2 & -\frac{1}{4}gg_{BL}v_L^2 \\ W_R^3 & -\frac{1}{4}g^2k^2 & \frac{1}{4}g^2\left(k^2+v_R^2\right) & -\frac{1}{4}gg_{BL}v_R^2 \\ B & -\frac{1}{4}gg_{BL}v_L^2 & -\frac{1}{4}gg_{BL}v_R^2 & \frac{1}{4}{g_{BL}}^2\left(v_L^2+v_R^2\right) \end{array}\right). \quad (15)$$

- One can define $s_w \equiv \sin\theta_w = e/g$ and then $g_{BL} = e/\sqrt{c_w^2 - s_w^2}$. The diagonalization

$$\begin{pmatrix} A \\ Z_L \\ Z_R \end{pmatrix} = \begin{pmatrix} s_w & s_w & \sqrt{c_w^2 - s_w^2} \\ c_w & -s_w^2/c_w & -s_w\sqrt{c_w^2 - s_w^2}/c_w \\ 0 & \sqrt{c_w^2 - s_w^2}/c_w & -s_w/c_w \end{pmatrix} \begin{pmatrix} W_L^3 \\ W_R^3 \\ B \end{pmatrix}. \tag{16}$$

gives their masses

$$M_A^2 = 0, \tag{17}$$

$$M_Z^2 \simeq \frac{g^2 v^2}{4\cos^2\theta_w}, \tag{18}$$

$$M_{Z'}^2 \simeq \frac{g^2(2v^2\sin^4\theta_w + 2(k^2 + v_R^2)\cos^4\theta_w - k^2\sin^2 2\theta_w)}{8\cos^2\theta_w \cos 2\theta_w}. \tag{19}$$

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- The charged Higgs bosons mass matrix, in the basis $\begin{pmatrix} \phi_1^+ & \chi_L^+ & \phi_2^+ & \chi_R^+ \end{pmatrix}$, is block diagonal and the physical charged Higgs bosons $H_{1,2}^{\pm}$ are given by

$$\begin{pmatrix} \phi_1^+ \\ \chi_L^+ \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} H_1^+ \\ G_1^+ \end{pmatrix}, \tag{20}$$

$$\begin{pmatrix} \phi_2^+ \\ \chi_R^+ \end{pmatrix} = \begin{pmatrix} \cos\zeta & \sin\zeta \\ -\sin\zeta & \cos\zeta \end{pmatrix} \begin{pmatrix} H_2^+ \\ G_2^+ \end{pmatrix}. \tag{21}$$

where $\tan\zeta = k/v_R$, in analogy to $\tan\beta = k/v_L$ with left-right switch. The eigenstates $G_{1,2}^{\pm}$ are the charged Goldstone bosons eaten by the gauge bosons $W^{\pm}$ and $W'^{\pm}$ to acquire their masses.

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- The mass matrix M of the CP-even Higgs bosons is given in the basis $\begin{pmatrix} \phi_2^{0R} & \chi_L^{0R} & \chi_R^{0R} \end{pmatrix}$. It can diagonalized by a unitary transformation:

$$T^\dagger M T = \mathrm{diag}\left(M_{H_2}^2, M_{H_3}^2, M_H^2\right). \tag{22}$$

The lightest eigenstate H is the SM-like Higgs, which we will fix its mass to be 125 GeV. In general, from the numerical checks, we found that three CP-even Higgs bosons (H and $H_{1,3}$) are light (of $\mathcal{O}(100)$ GeV) and the other one H_2 is heavy (of $\mathcal{O}(1)$ TeV).

- From the Yukawa Lagrangian (6), one finds that the SM-like Higgs couplings with fermions in the ALRM are given by

$$
\begin{aligned}
Y_{H\bar{u}u} &= \frac{m_u}{v}\frac{T_\Phi}{\sin\beta}, \qquad Y_{H\bar{d}d} = \frac{m_d}{v}\frac{T_L}{\cos\beta}, \qquad Y_{H\bar{d}'d'} = \frac{m_{d'}}{v_R}T_R, \\
Y_{H\bar{e}e} &= \frac{m_e}{v}\frac{T_\Phi}{\sin\beta}, \qquad Y_{H\bar{n}n} = \frac{m_n}{v_R}T_R,
\end{aligned}
\tag{23}
$$

where the elements T_Φ, T_L and T_R are the mixing couplings of the gauge eigenstates ϕ_2^{0R}, χ_L^{0R} and χ_R^{0R}, respectively, with the lightest Higgs H.

- From the kinetic Lagrangian of the scalars, one can derive the following SM-like Higgs couplings with the electroweak charged gauge bosons:

$$g_{HWW} = gM_W \left(T_\Phi \sin\beta + T_L \cos\beta \right), \quad (24)$$

$$g_{HW'W'} = gM_W \left(T_\Phi \sin\beta + T_R \frac{v_R}{v} \right), \quad (25)$$

and the following SM-like Higgs couplings with the charged Higgs bosons:

$$\lambda_{HH_1^\pm H_1^\mp} = M_{1\Phi} T_\Phi + M_{1L} T_L + M_{1R} T_R, \quad (26)$$

$$\lambda_{HH_2^\pm H_2^\mp} = M_{2\Phi} T_\Phi + M_{2L} T_L + M_{2R} T_R, \quad (27)$$

where $M_{xy}(x = 1, 2,\ y = \Phi, L, R.)$ are functions of the vevs and potential parameters.

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- CMS [4] and ATLAS [5] collaborations observed a SM-like Higgs boson with mass around 125 GeV and signal decay strengths as given in the following:
  CMS:

$$\begin{aligned}
\mu_{\gamma\gamma} = \mu(H \to \gamma\gamma) &= 1.14^{+0.26}_{-0.23}, & (28)\\
\mu_{ZZ} = \mu(H \to ZZ) &= 0.91^{+0.3}_{-0.24}, & (29)\\
\mu_{WW} = \mu(H \to WW) &= 0.76 \pm 0.21, & (30)
\end{aligned}$$

  ATLAS:

$$\begin{aligned}
\mu_{\gamma\gamma} = \mu(H \to \gamma\gamma) &= 1.17 \pm 0.27, & (31)\\
\mu_{ZZ} = \mu(H \to ZZ) &= 1.7 \pm 0.5, & (32)\\
\mu_{WW} = \mu(H \to WW) &= 1.01 \pm 0.31. & (33)
\end{aligned}$$

  These results are almost the SM values.

- The Higgs signal strength of decay channel, $H \to \gamma\gamma$, relative to the SM expectation is defined as

$$\mu_{\gamma\gamma} = \frac{\sigma(pp \to H \to \gamma\gamma)}{\sigma(pp \to H \to \gamma\gamma)^{\mathrm{SM}}} = \frac{\sigma(pp \to H)}{\sigma(pp \to H)^{\mathrm{SM}}} \frac{\mathrm{BR}(H \to \gamma\gamma)}{\mathrm{BR}(H \to \gamma\gamma)^{\mathrm{SM}}}$$
$$= \frac{\Gamma(H \to gg)}{\Gamma(H \to gg)^{\mathrm{SM}}} \frac{\Gamma_{\mathrm{tot}}^{\mathrm{SM}}}{\Gamma_{\mathrm{tot}}} \frac{\Gamma(H \to AA)}{\Gamma(H \to \gamma\gamma)^{\mathrm{SM}}} = \kappa_{gg} \cdot \kappa_{\mathrm{tot}}^{-1} \cdot \kappa_{\gamma\gamma}, \quad (34)$$

where $\sigma(pp \to H)$ is the total Higgs production cross section and $\mathrm{BR}(H \to \gamma\gamma)$ is the branching ratio of the corresponding channel.

- the one-loop partial decay width of the H decay into two photons is given by [6]

$$\Gamma(H \to \gamma\gamma) = \frac{\alpha^2 m_H^3}{1024\pi^3} \left| \frac{g_{HWW}}{M_W^2} Q_W^2 F_1(x_W) + N_{c,t} Q_t^2 \frac{2Y_{H\bar{t}t}}{m_t} F_{1/2}(x_t) + \sum_{i=1}^{2} Q_{H_i^\pm}^2 \frac{\lambda_{HH_i^\pm H_i^\mp}}{M_{H_i^\pm}^2} F_0(x_{H_i^\pm}) \right|^2, \tag{35}$$

where $x_t = M_H^2/4m_t^2$, $x_k = M_H^2/4M_k^2$, $k = W, H_{1,2}^\pm$. The color factor and electric charges are given by: $N_{c,t} = 3$, $Q_W = Q_{H_i^+} = 1$, and $Q_t = 2/3$. The loop functions values for W, t, $H^\pm$ (with $M_{H^\pm} = 200$ GeV) are given by [6]

$$F_1(x_W) = -8.3442, \tag{36}$$
$$F_{1/2}(x_t) = 1.37574, \tag{37}$$
$$F_0(x_{H^\pm}) = 0.351866. \tag{38}$$

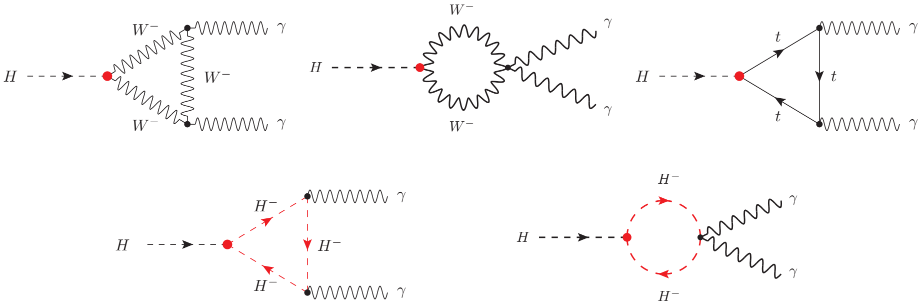

Figure: Feynman diagrams for the Higgs decay $H \to \gamma\gamma$ mediated by gauge bosons $W^{\pm}$, top quark and charged scalars $H^{\pm}$.

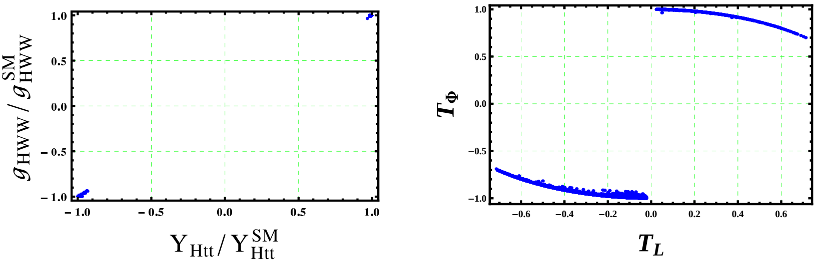

Figure: (Left panel) The relation between the coupling ratios g_{HWW}/g_{HWW}^{SM} and $Y_{H\bar{t}t}/Y_{H\bar{t}t}^{SM}$. (Right panel) The relation between the mixing parameters T_Φ and T_L.

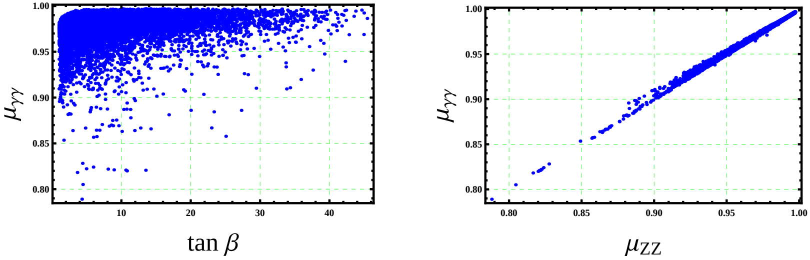

Figure: (Left panel) The signal strength $\mu_{\gamma\gamma}$ as a function of $\tan\beta$ and the parameters $\lambda_3,\ \alpha_1,\ \alpha_2$ and $M_{H^{\pm}_{1,2}}$. (Right panel) Correlation between $\mu_{\gamma\gamma}$ and μ_{ZZ} in the ALRM.

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In this section we study the interesting signatures of the exotic quark d' associated with our ALRM at the LHC. In particular, we will analyze and compute the cross section for the production of this heavy quark and its subsequent decays into jets, leptons and missing energy.

- The kinetic Lagrangian of d' leads to the following strong interactions

$$\mathcal{L}^{d'}_{\text{gauge}} = -\frac{ig_s}{2}\overline{d}'\gamma^{\mu}\lambda \cdot G_{\mu}d'. \tag{39}$$

The interactions with the other gauge bosons W', Z, Z, γ are more weaker than this which with glouns because of the sizable strong coupling g_s.

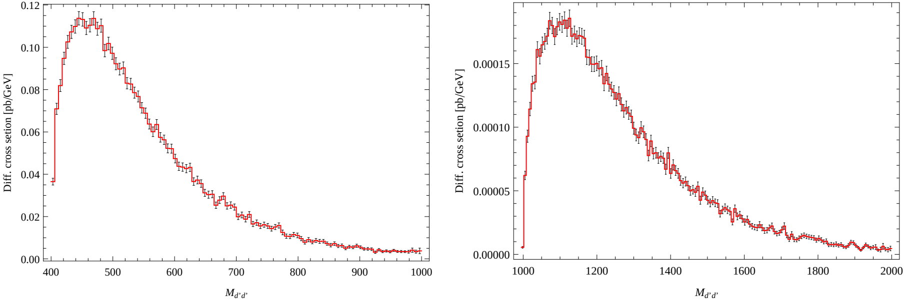

Figure: Differential production cross section of exotic quark d' as a function of the invariant mass $M_{d'd'}$. In left pane $m_{d'} = 300$ GeV and in right pane $m_{d'} = 500$ GeV.

- The Lagrangian of d' interactions with the SM quarks can be derived from Eq. (6) as

$$\mathcal{L}_{\rm Y}^{d'} = -\overline{u}\ \left(\cos\zeta Y^q P_R + \sin\zeta Y_R^q P_L\right)\ H_2^+ V'_{\rm CKM}\ d' + {\rm h.c.}, \quad (40)$$

- The charged Higgs boson H_2^+ decays into lepton and scotino through the interactions

$$\mathcal{L}_{\rm Y}^{H_2^+} = \overline{n}\ H_2^+\ U'_{\rm MNS}\left(\cos\zeta Y^\ell P_L + \sin\zeta Y_R^\ell P_R\right)\ e + {\rm h.c.} \quad (41)$$

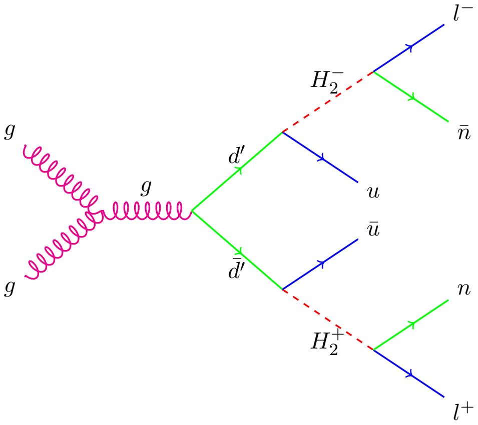

Figure: The exotic quark, d', creation and decay.

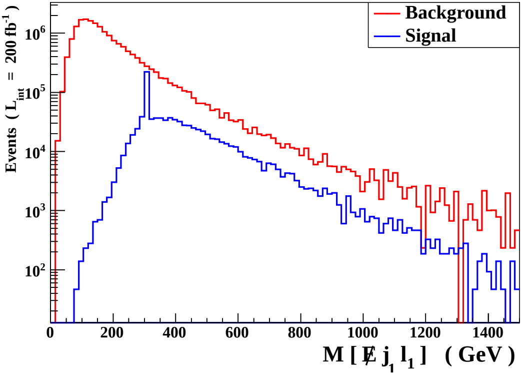

Figure: The reconstructed invariant mass of extra quark, d', which decays to $l + jet + \mathrm{missing\ energy}$ and its background for $m_{d'} = 300$ GeV. No cut has been imposed yet.

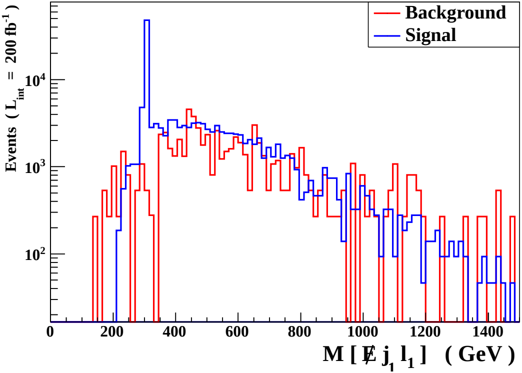

Figure: The reconstructed invariant mass of extra quark, d', which decays to $l + jet + \text{missing energy}$ for $m_{d'} = 300$ GeV, with $\not{E}_T > 200$ GeV.

Where $\not{E}_T = \left|\left|\sum_{\text{visible particles}} \vec{p}_T\right|\right|$.

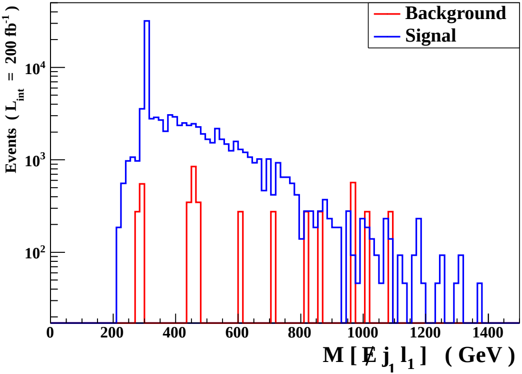

Figure: The reconstructed invariant mass of extra quark, d', which decays to $l + jet + \text{missing energy}$ for $m_{d'} = 300$ GeV, with $H_T < 200$ GeV cut.

Where $H_T = \sum_{\text{hadronic particles}} ||\vec{p}_T||$.

Cuts [GeV]	Signal (S)	Background (B)	S vs B
Initial (no cut)	463999	9309732 ± 21646	0.049840 ± 0.0001
Cut 1 ($\not{E}_T > 200$)	72291 ± 247	33523 ± 198	2.1564 ± 0.0148
Cut 2 ($H_T < 200$)	47977 ± 207	1942.7 ± 44.3	24.696 ± 0.573

Table: Signal versus background for the process $pp \to d'd' \to (l^- l^+) + (u\bar{u}) + (nn)$ with/without cuts.

References

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- M. Ashry and S. Khalil, *Phenomenological aspects of a TeV-scale alternative left-right model*, *Phys. Rev.* **D91** (2015), no. 1 015009, [arXiv:1310.3315].

Publications

- This work has been published in the following paper [7]:
  M. Ashry and S. Khalil, *"Phenomenological aspects of a TeV-scale alternative left-right model"*, Phys.Rev. D91 (2015) 015009 (arXiv:1310.3315 [hep-ph]).
- The ALRM has been implemented by *M. Ashry* into FeynRules/CalcHEP:
  https://feynrules.irmp.ucl.ac.be/wiki/ALRM.

Thank you