The search for `mirror' quarks with distinguished signatures at the 13 TeV Large Hadron Collider

Shreyashi Chakdar[1], K. Ghosh[2], V. Hoang[1], P.Q Hung[1] and S. Nandi[2]

[1]Physics Department, University of Virginia, Charlottesville, VA 22904, USA

[2]Department of Physics and Oklahoma Center for High Energy Physics, Oklahoma State University, Stillwater, OK 74078, USA

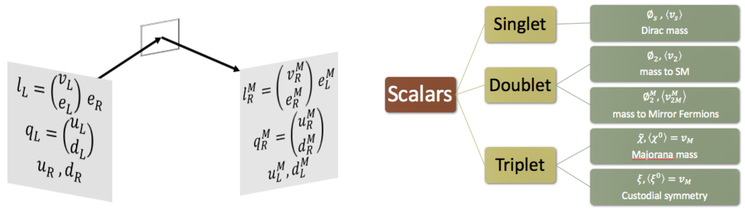
Contact: chakdar@virginia.edu

Abstract

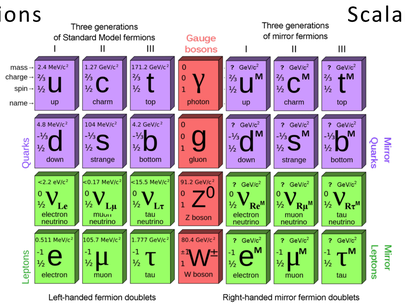
The model has been constructed to realize the seesaw mechanism with the **right-handed neutrinos at the electroweak scale**. The model has a mirror symmetry including both left and right-handed quark and lepton doublets and singlets with the **new mirror quarks having masses in the range ~150-800 GeV**. The mirror quarks/leptons decay to ordinary (SM) fermions + light neutral scalars (Miss E_T). We investigate distinguished final state signals arising from the pair production of these mirror quarks and their subsequent decays at the 13 TeV LHC. The **Jets + Miss E_t** final state signatures include **interesting large displaced vertices** at the LHC.

Model and Formalism

- Gauge group: $SU(3)_C$ X $SU(2)_W$ X $U(1)_y$
- SM fermions + Mirror fermions + extended scalar sector.



Mirror fermions Scalar sector



Particle content of the model

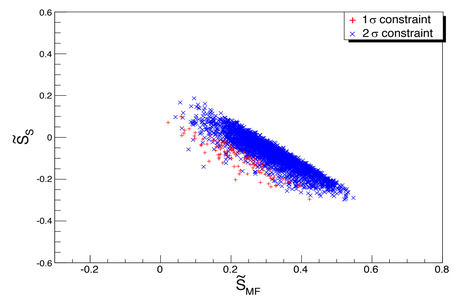
- Singlet scalar (v_s) couples to fermions: **Dirac mass**

$$L_S = g_{sl}\, \bar{l}_L\, \phi_S\, l_R^M + h.c.$$

- Triplet scalar (v_M) is responsible for **Majorana mass**

$$L_M = g_M\, l_R^{M,T} \sigma_2\, \tau_2\, \tilde{\chi}\, l_R^M$$

Electroweak Precision Constraints



Plot shows the – ve contributions to the S-parameter for the scalar sector (~ S_s) vs the relative cancellation from the +ve contributions of mirror fermion sector (~ S_{MF}). The total sum of the two contributions agrees with the current EW precision experimental constraints.

Phenomenology: New Physics signals at LHC

1. Mirror quark searches and exclusions at the LHC

- For large BR, mirror quark mass below ~600 GeV is excluded
- Mirror quark to light quark BR < 50 %, NO bound on mass
- Bounds applicable only on mirror quarks decays at hard scattering point
- **Final state signal**: 2 high transverse momentum jets (b quark jets or light jets) **+** large missing transverse energy

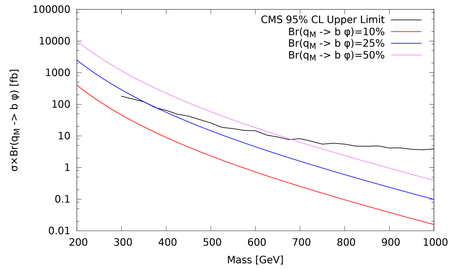


Figure:Plot corresponds to our model prediction for the production cross-section times branching ratio into b-jets + Miss p_t for different values of the branching ratio

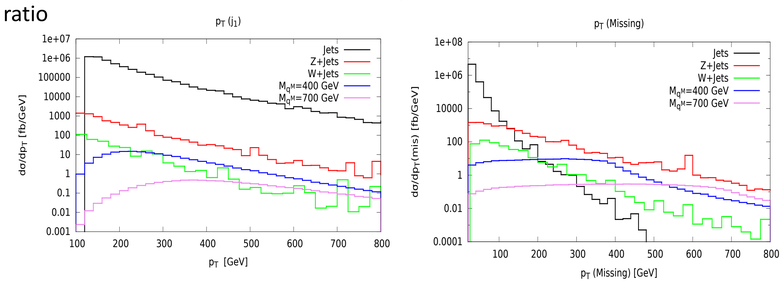


Figure: (Left Panel) :Transverse momentum distributions of jets (M = 400 and 700 GeV) for signal and background at 13 TeV LHC. (Right Panel): Missing transverse momentum distributions for signal and background at 13 TeV LHC.

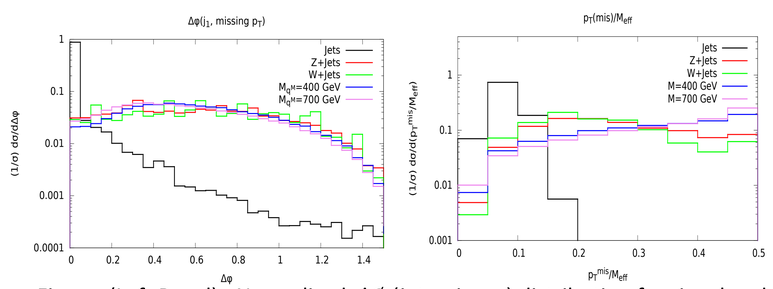
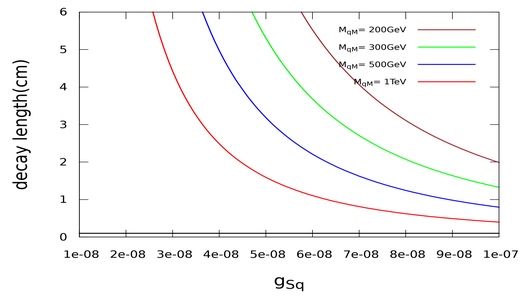


Figure: (Left Panel) : Normalized Δ∅ (jet; miss p_T) distribution for signal and background at 13 TeV LHC. (Right Panel): Normalized miss p_T/M_{eff} distribution for signal and background at 13 TeV LHC.

Yukawa Interactions of Mirror & SM quarks

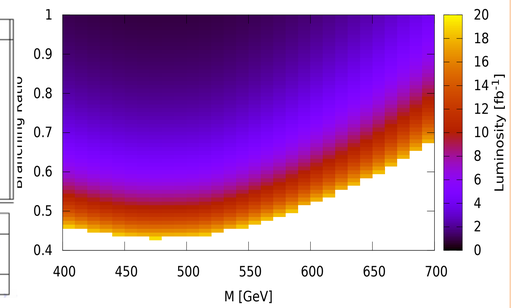


- The Yukawa sector incorporates the mixing between the mirror and ordinary (SM) fermions
- The coupling g_{sq} in the decay of mirror quarks can be very small leading to displaced vertices in few mm to cm range.

2. Selection Cuts and LHC Reach

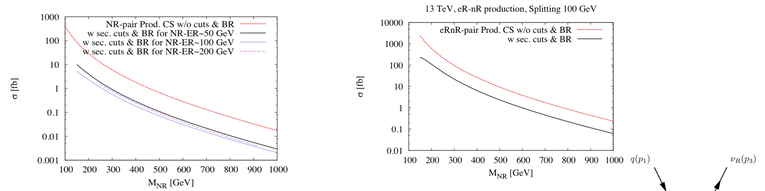
Variable	Lower bound	Upper bound
$\not{p}_T$	160 GeV	
$p_T(j_1)$	130 GeV	
$p_T(j_2)$	60 GeV	
η_j	-2.5	2.5
$DeltaR_{j_1j_2}$	0.7	
$\Delta\phi(j, \not{p}_T)$	0.4	
M_{eff}	1000 GeV	
$\not{p}_T/M_{eff}$	0.2	

Signal		Background		
M_{q^M} [GeV]		Jets	Z/W+jets	Total
400	700			
111.6	51.8	-	400	400



- Final selection cuts and cross sections for signal and background at 13 TeV LHC
- Required integrated luminosity (color gradient) for 5 sigma discovery at the 13 TeV LHC is presented as a function of mirror-quark mass (x-axis) and the branching ratio (y-axis).

3. Same Sign di-lepton signals at displaced vertices



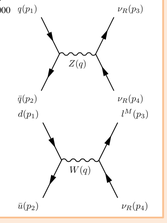
Pair production of υ_R : **Like-sign dileptons + 4 jets** signals :

$$u + \bar{u} \to Z \to \upsilon_R + \upsilon_R \to e_R^{-,M} + e_R^{-,M} + 2\,W \to 2\,e_L^- + 4\,jets + 2\,\phi_s$$

Production of υ_R and charged lepton: **Like-sign dileptons + 2 jets** signals:

$$d + \bar{u} \to W^- \to \upsilon_R + e_R^{-,M} \to e_R^{-,M} + e_R^{-,M} + W^+ \to 2\,e_L^- + 2\,jets + 2\,\phi_s$$

$\Longrightarrow$ Lepton-number violating signals



Conclusions

- The Electroweak scale Right handed neutrino model is well motivated, and is proposed to obtain tiny neutrino masses via the seesaw mechanism **with the RH neutrino at the EW scale.**
- In this model the RH quarks/lepton doublets, and the left handed singlets are called mirror quarks and leptons.
- Satisfies constraints providing a glimpse into BSM physics responsible for light neutrinos mass at the Run II of LHC
- Characteristic signals at LHC with "macroscopic" decay lengths of distinct jet + miss ET signals and like-sign di-lepton events
- 700 GeV q^M mass is projected with integrated luminosity $\sim 100\ fb^{-1}$ at 13 TeV LHC

References

1. P. Q. Hung, Phys. Lett. B 649, 275 (2007) [hep-ph/0612004].
2. V. Hoang, P. Q. Hung and A. S. Kamat, Nucl. Phys. B 896 (2015) 611-656, [arXiv:1412.0343 [hep-ph]].
3. P. Q. Hung, T. Le, V. Q. Tran and T. C. Yuan, JHEP 1512, 169 (2015), [arXiv:1508.07016 [hep-ph]].
4. S. Chakdar, K. Ghosh, V. Hoang, P. Q. Hung and S.Nandi, arXiv:1606.08502 [hep-ph].

Acknowledgements

Presenter SC is thankful to Pirrung Foundation, University of Virginia for support during completion of this work.