Signatures of $\tilde{R}_2$ class of Leptoquarks and right handed neutrinos at the upcoming *ep* colliders

Based on work with S. Mandal, M. Mitra and N. Sinha
[Phys. Rev. D 101, 075037 (2020)]

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Plan of talk

- **Introduction to Leptoquark (LQ)**
- **Motivation for $\tilde{R}_2$ LQ**
- **Constraints on LQ mass and coupling.**
- **LHC vs LHeC/FCC-he**
- **Channel-1:** $e^{\pm}p \to l^{\pm}j$
- **Channel-2:** $e^{\pm}p \to jN$

Introduction

- Leptoquark(LQ): predicted in many BSM scenarios. Ex. unified models, technicolor model and models exhibiting quark and lepton substructures.

- 6 scalar LQ's and 6 vector LQ's. [Buchmuller, Ruckl and Wyler PLB(1987)]

- $SU(3)_C$: triplet; $SU(2)_L$: singlet, doublet, triplet

- Fermion number : F = 3B + L

  $F = 0$ (Genuine LQ) ; $F = \pm 2$.

Review on LQ: [I. Doršner *et al.*, 2016]

Motivation for $\tilde{R}_2$ LQ

$$\tilde{R}_2(3,2,1/6) = (\tilde{R}_2^{\frac{2}{3}}, \tilde{R}_2^{-\frac{1}{3}})^T; \quad N_R(1,1,0) \Rightarrow \text{ RH neutrino}$$

.

$$\boxed{\begin{aligned}\mathcal{L} = \quad & -Y_{ij}\bar{d}_R^i e_L^j \tilde{R}_2^{2/3} + (YU_{\text{PMNS}})_{ij}\bar{d}_R^i \nu_L^j \tilde{R}_2^{-1/3} + \\ & (V_{\text{CKM}}Z)_{ij}\bar{u}_L^i N_R^j \tilde{R}_2^{2/3} + Z_{ij}\bar{d}_L^i N_R^j \tilde{R}_2^{-1/3} + h.c.,\end{aligned}}$$

[I. Doršner *et al.* 2014; S. Mandal *et al.* 2018; M. Mitra *et al.*, 2018]

- Allows matter stability at tree level. Accessible at collider.
- Presence of $N_R \Rightarrow$ $m_\nu \sim \frac{y^2 v^2}{M_{N_R}}$ $\rightarrow$ Seesaw Mechanism ($\frac{LLHH}{M}$)

  [Weinberg, 1979; Minkowski, 1977; Yanagida, 1979; Mohapatra and Senjanovic, 1980]
- $LQ \rightarrow N_R\, j$ $\Rightarrow$ N_R production independent of the mixing between light and heavy neutrino ($\frac{vy}{M_{N_R}}$).

Constraints on LQ mass and coupling

Atomic Parity Violation

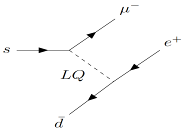
$\mathcal{L}_{APV} \sim \frac{G^F}{\sqrt{2}} C_{1q}(\bar{e}\gamma^\mu\gamma^5 e\bar{q}\gamma^\mu q)$

$$|Y_{de}| \leq 0.34 \; \frac{M_{\mathrm{LQ}}}{1\;\mathrm{TeV}}$$

$$|Y_{ue}| \leq 0.36 \; \frac{M_{LQ}}{1\mathrm{TeV}}$$

- Large couplings allowed for heavy LQ.

LFV process



- $K_L \to \mu^- e^+$

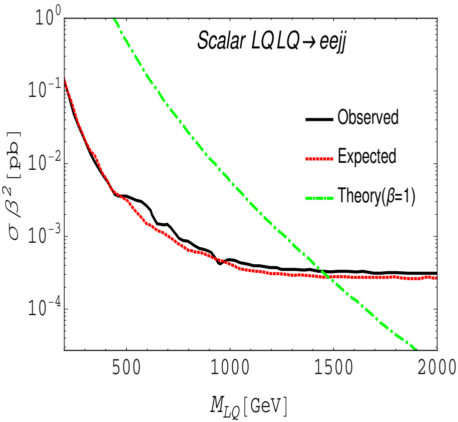
$$|Y_{s\mu} Y^*_{de}| \leq 2.1 \times 10^{-5} \left(\frac{M_{LQ}}{1\mathrm{TeV}}\right)^2$$

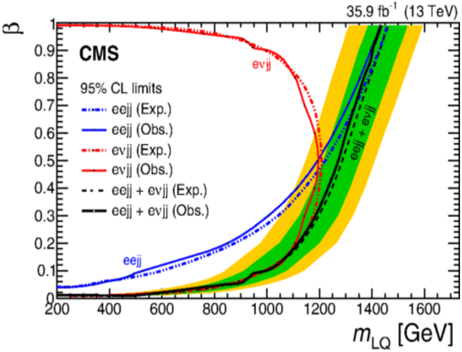
[I. Doršner *et al.*, 2014]

Collider bounds on M_{LQ}

- $pp \to \mathrm{LQ\,LQ} \to ejej/e\nu jj$
- For **1st generation LQ, $M_{LQ} < 1.4$ TeV ruled out.**

[CMS collaboration, A. M. Sirunyan *et al.*, 2019]





- $\beta(LQ \to e^- j) < 1 \Rightarrow$ relaxed bound
.

[CMS collaboration, 2019]

- Combined limits on $\beta(LQ \to e^- j)$.

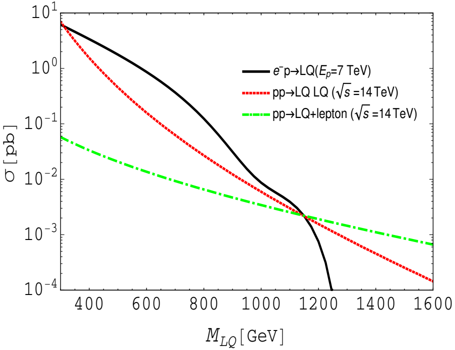
$M_{LQ}[GeV]$	Y_{11}	Z_{11}
687	0.233	1.29
860	0.29	1.27
1000	0.34	1.03
1110	0.377	0.84
1204	0.41	0.65

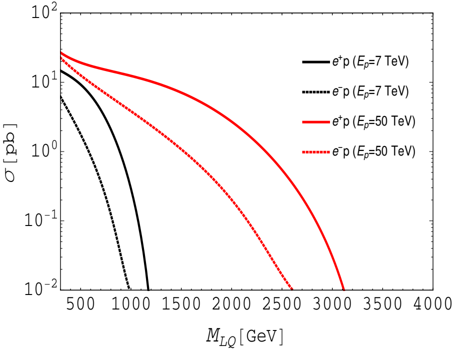
$$\mathcal{L} \supset (Y_{11} \bar{d}_R e_L + Z_{11} \bar{u}_L N_R)\, LQ$$

LHC vs LHeC/FCC-he

LHeC : e (60 GeV) & p (7 TeV), $\sqrt{s} = 1.3$ TeV, $\mathcal{L} = 1\text{ab}^{-1}$

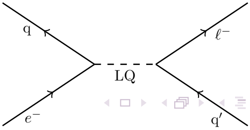
FCC-he : e (60 GeV) & p (50 TeV), $\sqrt{s} = 3.46$ TeV, $\mathcal{L} = 3\text{ab}^{-1}$

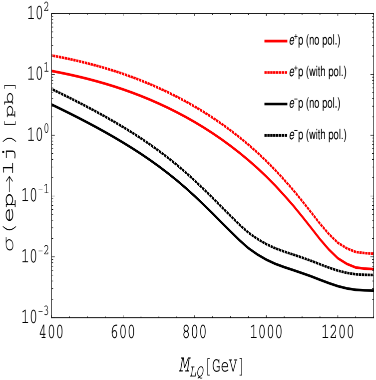


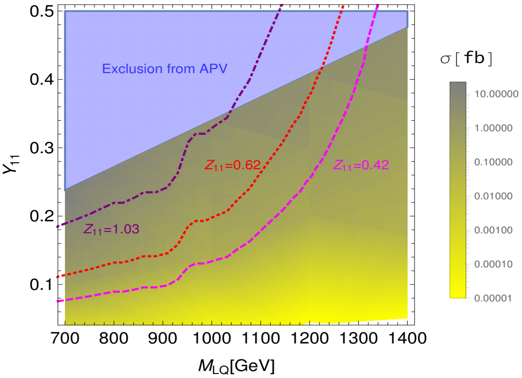


⇒ Asymmetry,

$$\mathcal{A}_{ep} = \frac{\sigma(e^+p) - \sigma(e^-p)}{\sigma(e^+p) + \sigma(e^-p)} > 0$$







- CMS limit translated to $M_{LQ} - Y_{11}$ plane.

Use of polarized e-beam ⇒ Factor of 2 enhancement in σ

Channel-1: $e^{\pm}p \to l^{\pm}j$

- Signal: $e^{\pm}p \to l^{\pm}j$
- SM BKG: $e^{\pm}p \to l^{\pm}j,\ l^{\pm}jj$
- Table: 1 (LHeC)

	$e^{-}p \to l^{-}j$			$e^{+}p \to l^{+}j$	
	$\sigma^{\rm sig}$ [fb]	$\sigma^{\rm bkg}$ [fb]		$\sigma^{\rm sig}$ [fb]	$\sigma^{\rm bkg}$ [fb]
No cut	4.016	2180		39.23	1440
$c_1 : N_j \geq 1 + N_l \geq 1$	3.01	**1644**		29.85	**1079**
$c_2 : c_1 + p_T(l_1) \geq 400$	0.365	**13.98**		11.77	**6.54**
$c_3 : c_2 + p_T(j_1) \geq 400$	0.275	**9.51**		8.92	**4.48**
$c_4 : c_4 + \lvert M_{LQ} - M_{lj}\rvert \leq 100$	0.25	5.13		8.3	2.534
Significance for $\mathcal{L} = 1$ fb^{-1}	**0.107**			**2.5**	

- Table: 2 (FCC-he)

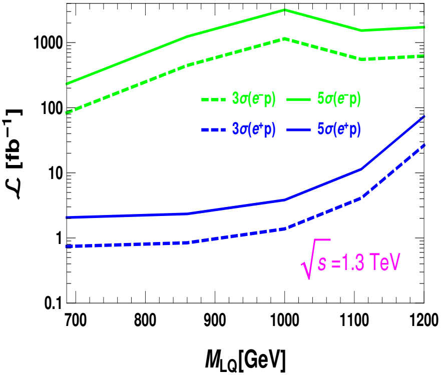
	$e^{-}p \to l^{-}j$			$e^{+}p \to l^{+}j$	
	$\sigma^{\rm sig}$ [fb]	$\sigma^{\rm bkg}$ [fb]		$\sigma^{\rm sig}$ [fb]	$\sigma^{\rm bkg}$ [fb]
No cut	**395.08**	10900		**1246.4**	9597
$c_1 : N_j \geq 1 + N_l \geq 1$	354.41	9836.93		1119.03	8652.58
$c_2 : c_1 + p_T(l_1) \geq 400$	180	839.141		578.13	611.459
$c_3 : c_2 + p_T(j_1) \geq 400$	129.97	618.963		417.26	441.812
$c_4 : c_3 + \lvert M_{LQ} - M_{lj}\rvert \leq 100$	**119.9**	141.112		**383.59**	90.279
Significance for $\mathcal{L} = 1$ fb^{-1}	**7.42**			**17.6**	

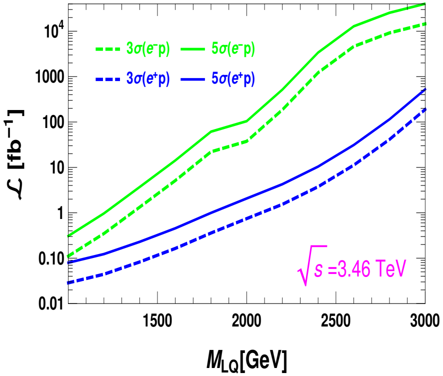
- Table-3

Benchmarks	M_{LQ}	M_{N_1}	Y	Z
	1 TeV	100 GeV	$(0.34, 0, 0)$	$(1.03, 0, 0)$

- signal selection criteria: High p_T jet and lepton, cut on $l - j$ invariant mass.
- Significant reduction in $\sigma^{\rm bkg}$.

Results



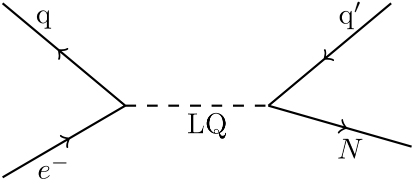


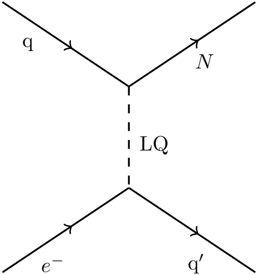
- At LHeC, with e^- beam $\Rightarrow$ Less sensitive.
- e^+ beam $\Rightarrow$ M_{LQ} upto 1.2 TeV can be acessible with $\mathcal{L} < 100$ fb^{-1}.

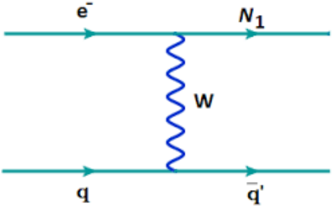
- At FCC-he, with e^- beam M_{LQ} upto 2.3 TeV can be probed with $\mathcal{L} < 1000$ fb^{-1}
- e^+ beam $\Rightarrow$ M_{LQ} upto 3 TeV can be probed with $\mathcal{L} < 500$ fb^{-1}.

Channel-2: $ep \to jN$

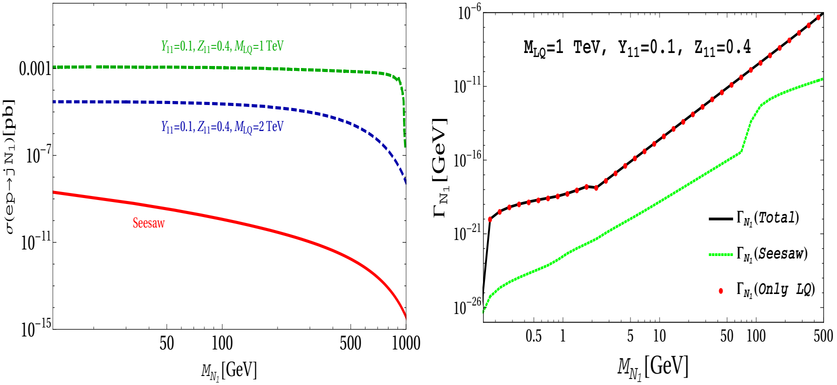
$$\mathcal{L} = -Y_{ij}\bar{d}^i_R e^j_L \tilde{R}_2^{2/3} + (V_{\rm CKM}Z)_{ij}\bar{u}^i_L N^j_R \tilde{R}_2^{2/3}$$







Comparison of $\tilde{R}_2$ model with seesaw scenario



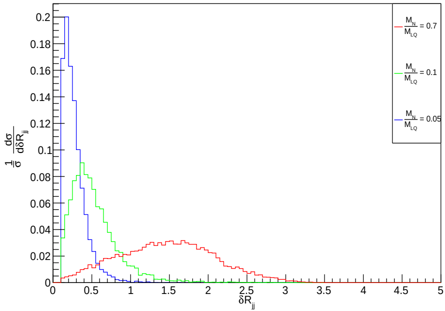
- Seesaw: $N_1 \to \ell W / \nu Z / \nu h$, LQ: $N_1 \to LQ^{\star}(\to lj) + j$

$ep \to jN, \;\; N \to ljj$

Different signatures:

- Prompt decay of RHN $\Rightarrow$ one prompt lepton + multi jet
- Boosted RHN $\Rightarrow j + j_N$ (Fat jet)

  $M_N \ll M_{LQ} \Rightarrow$ collimated decay product.



- Boosted + Displaced RHN $\Rightarrow j + j_N^d$ (Displaced Fat jet)

  $M_N \ll M_{LQ}$ and $c\tau_N \geq 1$ mm

- jet + MET $\Rightarrow c\tau_N >$ detector size

Summary

- There are bounds on mass and coupling of LQ. Tightest bound is from CMS experiment.

- LHeC and FCC-he provide larger cross section than LHC upto a certain M_{LQ}.

- $\sigma(e^{\pm} p \to l^{\pm}\, j)$ depend on Yukawa coupling. Results presented here are specific to chosen value of coupling.
- cross section for the channel, $ep \to jN$ is larger than usual seesaw scenario.
- A single channel, $ep \to jN,\ N \to ljj$ leads to various signatures.

Thank you for your attention!