



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

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

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Contents

- Dark matter anomalies by XENON1T
- Models with gravitational wave like signatures
- Experiment vs theory $g-2$ of electron and Muon
- New developments in Muon Physics
- Lattice results on semi-leptonic B decays
- Neutrop Physics

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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:** $e^\pm p \rightarrow l^\pm j$
- **Channel-2:** $e^\pm p \rightarrow jN$

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

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

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

[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 $N_R \Rightarrow m_\nu \sim \frac{y^2 v^2}{M_{N_R}}$ → 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

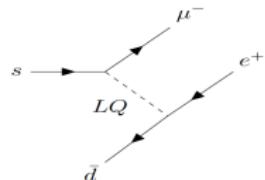
$$\mathcal{L}_{APV} \sim \frac{G_F}{\sqrt{2}} C_{1q} (\bar{e} \gamma^\mu \gamma^5 e \bar{q} \gamma^\mu q)$$

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

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

LFV process

$$\bullet K_L \rightarrow \mu^- e^+$$



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

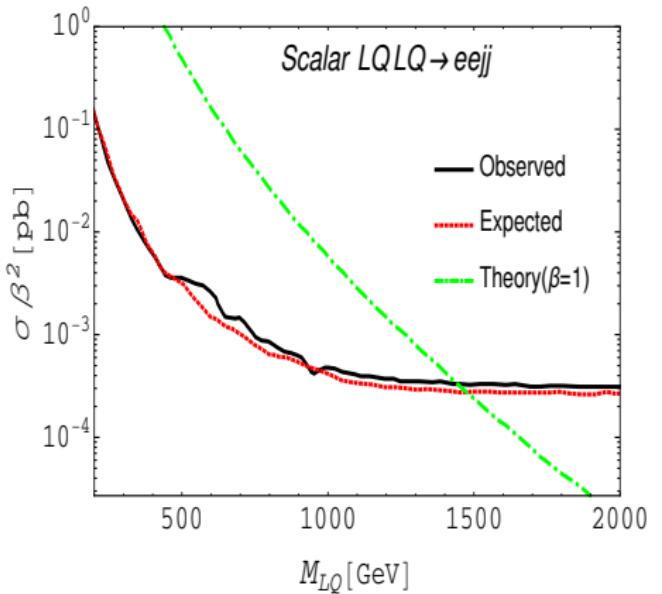
- Large couplings allowed for heavy LQ.

[I. Doršner *et al.*, 2014]

Collider bounds on M_{LQ}

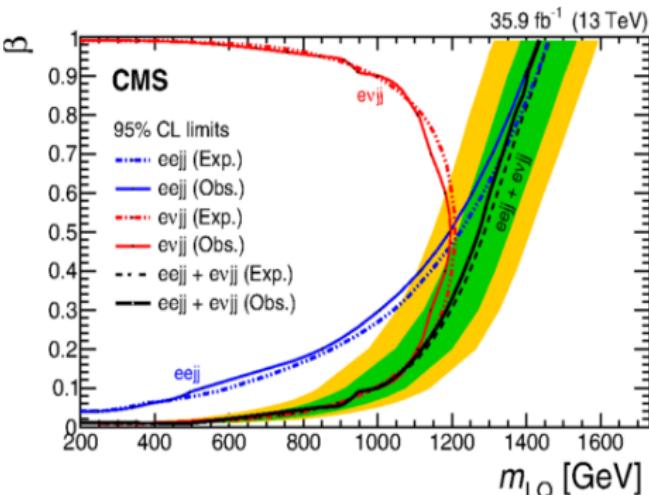
- $pp \rightarrow LQ LQ \rightarrow ej ej / e\nu jj$
- For 1st generation LQ, $M_{LQ} < 1.4 \text{ TeV}$ ruled out.

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



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

[CMS collaboration, 2019]



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

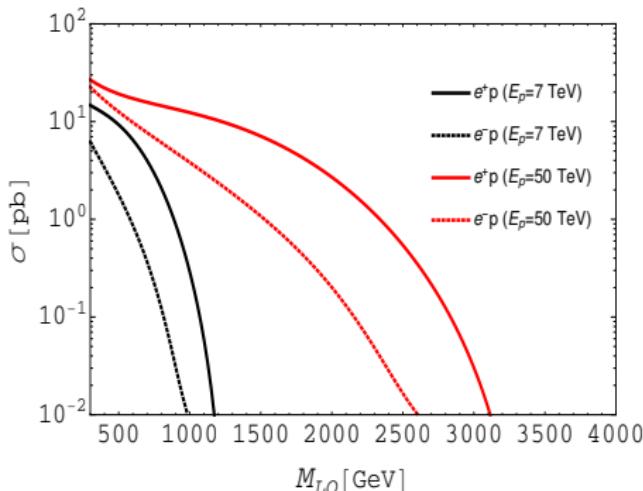
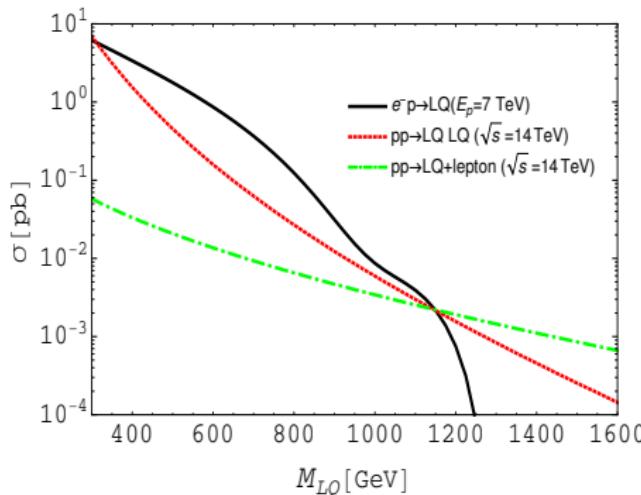
$M_{LQ} [\text{GeV}]$	Y_{11}	Z_{11}
687	0.233	1.29
860	0.29	1.27
1000	0.34	1.03
1110	0.377	0.84
1204	0.41	0.65

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

LHC vs LHeC/FCC-he

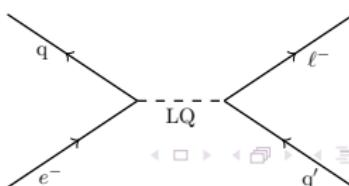
LHeC : e (60 GeV) & p (7 TeV), $\sqrt{s} = 1.3$ TeV, $\mathcal{L} = 1\text{ab}^{-1}$

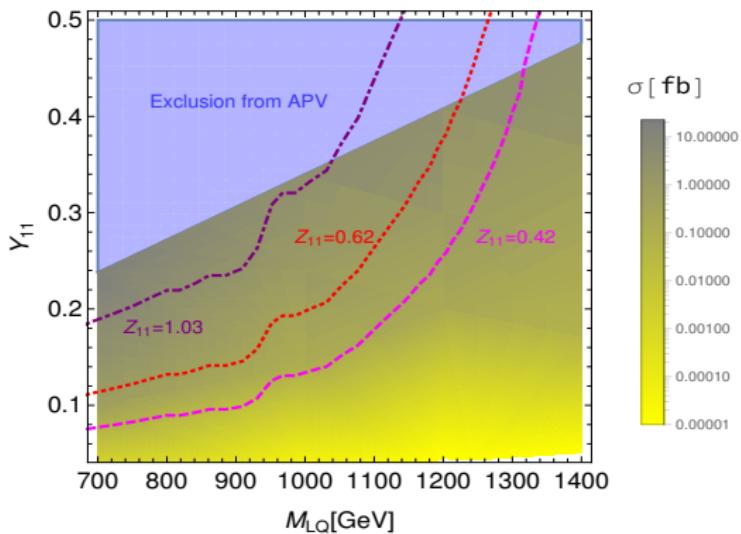
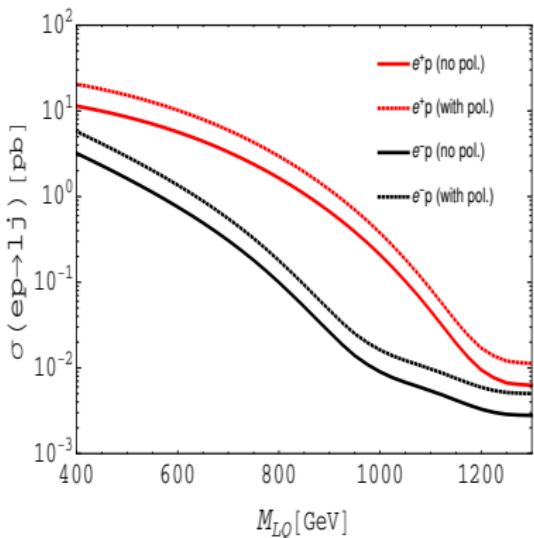
FCC-he : e (60 GeV) & p (50 TeV), $\sqrt{s} = 3.46$ TeV, $\mathcal{L} = 3\text{ab}^{-1}$



⇒ 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 \Rightarrow Factor of 2 enhancement in σ

Channel-1: $e^\pm p \rightarrow l^\pm j$

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

	$e^- p \rightarrow l^- j$		$e^+ p \rightarrow l^+ j$	
	σ^{sig} [fb]	σ^{bkg} [fb]	σ^{sig} [fb]	σ^{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
$c_4 : c_4 + M_{LQ} - M_{lj} \leq 100$	0.25	5.13	8.3	2.534
Significance for $\mathcal{L} = 1 \text{ fb}^{-1}$	0.107		2.5	

- Table: 2 (FCC-he)

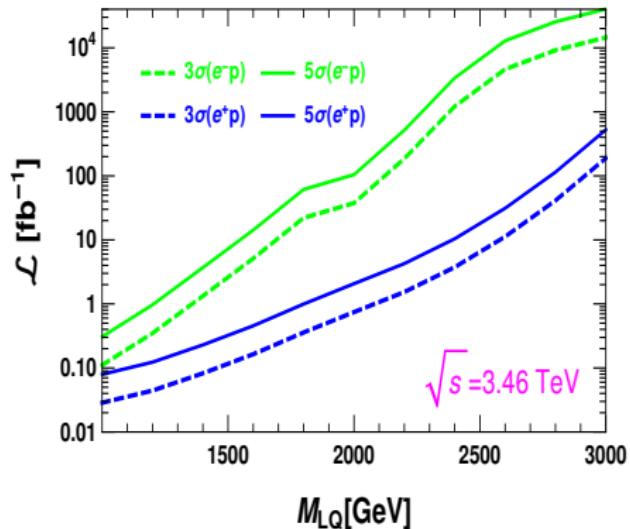
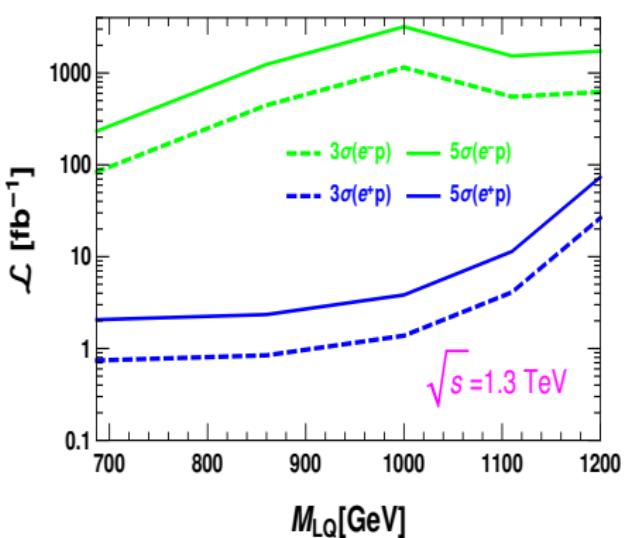
	$e^- p \rightarrow l^- j$		$e^+ p \rightarrow l^+ j$	
	σ^{sig} [fb]	σ^{bkg} [fb]	σ^{sig} [fb]	σ^{bkg} [fb]
No cut	395.08	10900	1246.4	9597
$c_1 : N_j \geq 1 + N_l \geq 1$	354.41	9836.93	1119.03	8652.58
$c_2 : c_1 + p_T(l_1) \geq 400$	180	839.141	578.13	611.459
$c_3 : c_2 + p_T(j_1) \geq 400$	129.97	618.963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

- Table-3

Benchmarks	M_{LQ}	M_{N_i}	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
 σ^{bkg} .

Results

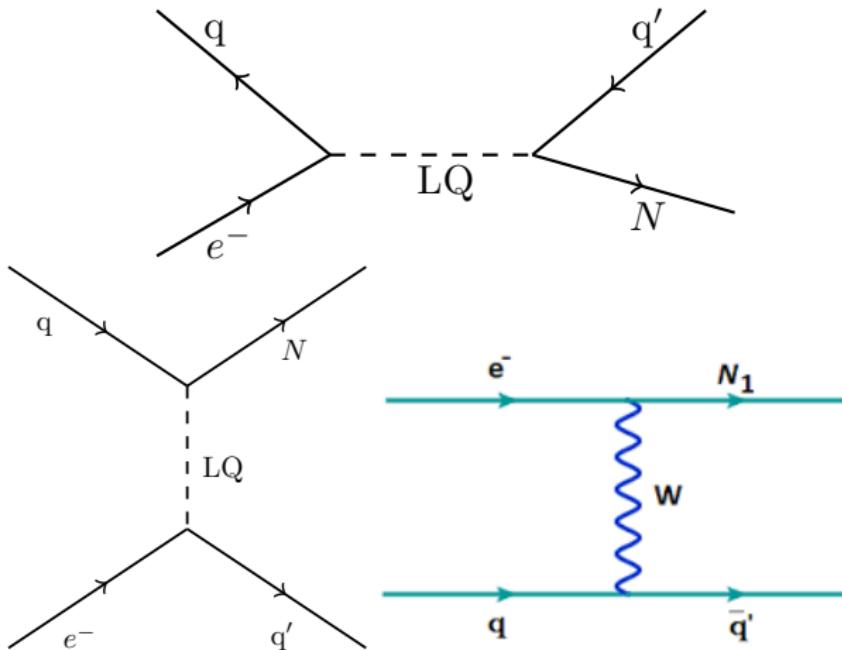


- At LHeC, with e^- beam \Rightarrow Less sensitive.
- e^+ beam $\Rightarrow M_{LQ}$ upto 1.2 TeV can be accessible with $\mathcal{L} < 100 \text{ fb}^{-1}$.

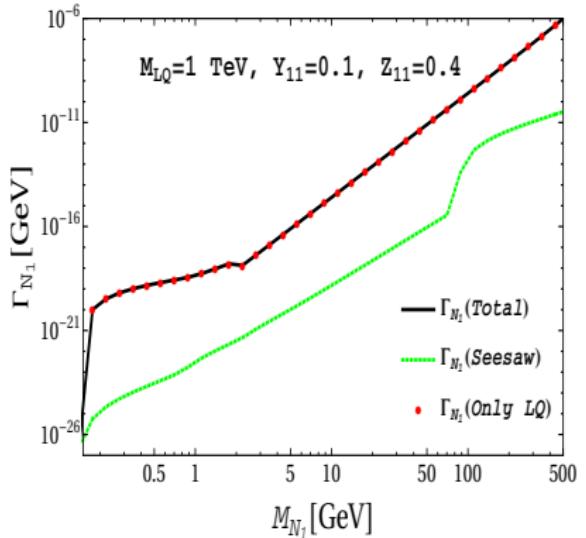
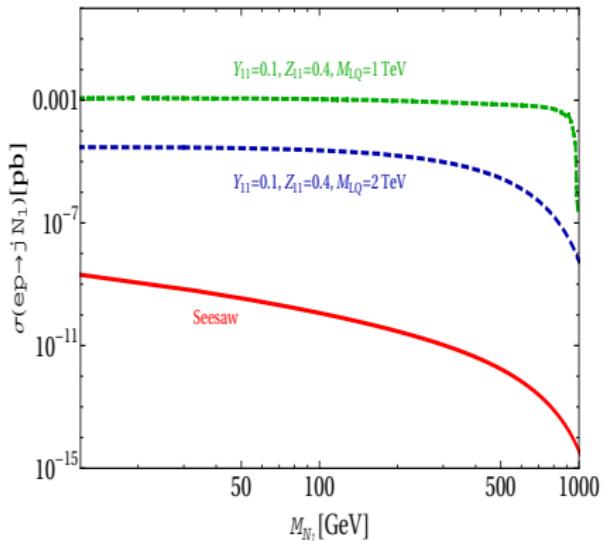
- At FCC-he, with e^- beam M_{LQ} upto 2.3 TeV can be probed with $\mathcal{L} < 1000 \text{ fb}^{-1}$
- e^+ beam $\Rightarrow M_{LQ}$ upto 3 TeV can be probed with $\mathcal{L} < 500 \text{ fb}^{-1}$

Channel-2: $ep \rightarrow jN$

$$\mathcal{L} = -Y_{ij}\bar{d}_R^i e_L^j \tilde{R}_2^{2/3} + (V_{\text{CKM}} Z)_{ij} \bar{u}_L^i N_R^j \tilde{R}_2^{2/3}$$



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



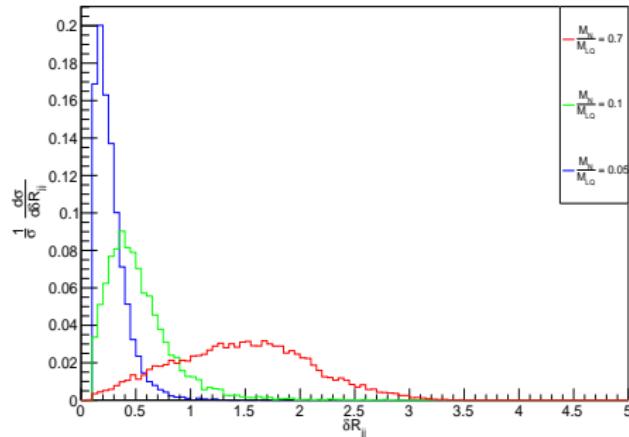
- Seesaw: $N_1 \rightarrow \ell W / \nu Z / \nu h$, LQ: $N_1 \rightarrow LQ^*(\rightarrow jj) + j$

$$ep \rightarrow jN, \ N \rightarrow jj$$

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

Thank you for your attention!