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

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Plan of talk

- **What is Leptoquark (LQ)?**
- **Why $\tilde{R}_2$ is motivated?**
- **Constraints on LQ mass and coupling.**
- **Production Channels at *pp* and *ep* colliders.**
- **LHC vs LHeC/FCC-eh**
- **Analysis**
- **Results**
- **Summary**

What is Leptoquark (LQ)?

- Leptoquark(LQ) is a BSM particle. It couples to quark-lepton pair.
- Emerge naturally 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) ; $F = \pm 2$.

Why $\tilde{R}_2$ is motivated?

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

.

$$\mathcal{L} = -Y_{ij}\bar{d}^i_R e^j_L \tilde{R}_2^{2/3} + (YU_{\rm PMNS})_{ij}\bar{d}^i_R \nu^j_L \tilde{R}_2^{-1/3} + (V_{\rm CKM}Z)_{ij}\bar{u}^i_L N^j_R \tilde{R}_2^{2/3} + Z_{ij}\bar{d}^i_L N^j_R \tilde{R}_2^{-1/3} + h.c.,$$

[I. Doršner *et al.* Phys. Rept.(2016)]

- 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

  [Mohapatra and Senjanovic, PRL (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

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

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

LFV process

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

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

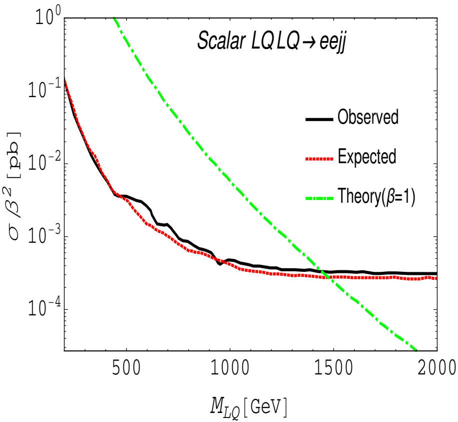
- Large couplings allowed for heavy LQ.

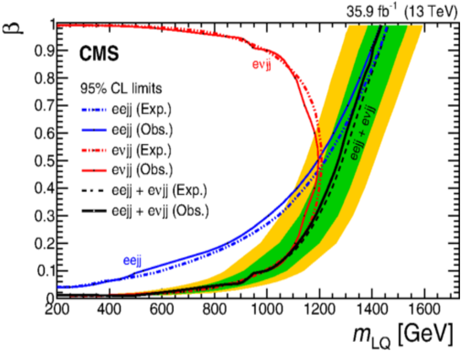
[I. Doršner *et al.*, JHEP (2014)]

Collider bounds on M_{LQ}

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

[A. M. Sirunyan *et al.*, PRD (2019)]





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

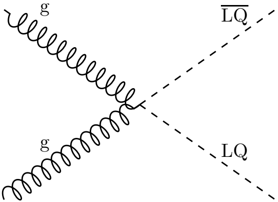
$M_{LQ}[GeV]$	Y_{11}	Z_{11}
687	0.233	1.29
860	0.29	1.27
1000	0.34	1.03
1110	0.377	0.84
1204	0.41	0.65

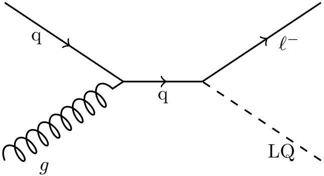
- $\beta(LQ \to e^- j) < 1 \Rightarrow$ relaxed bound .

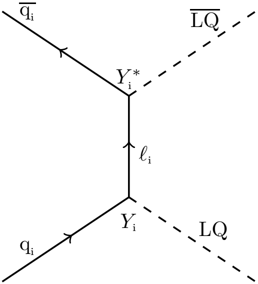
[A. M. Sirunyan *et al.*, PRD (2019)]

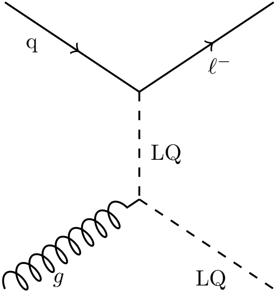
$$\mathcal{L} \supset (Y_{11} \bar{d}_R e_L + Z_{11} \bar{u}_L N_R)\, LQ$$

Production channels at *pp* colliders



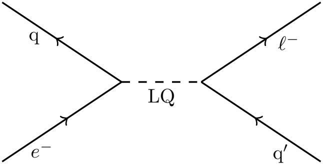


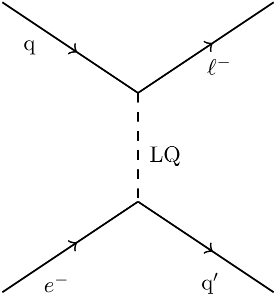




Production channels at *ep* colliders

- Production depend on Yukawa coupling.
- Can be produced as a s-channel resonance.

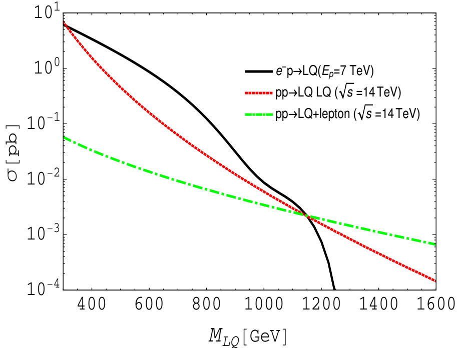


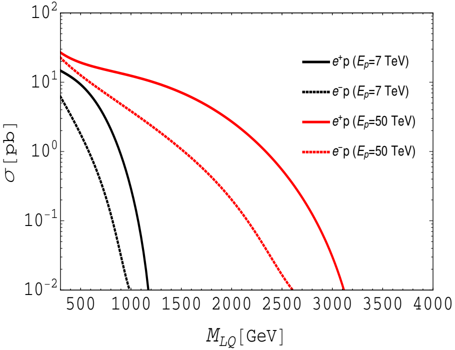


LHC vs LHeC/FCC-eh

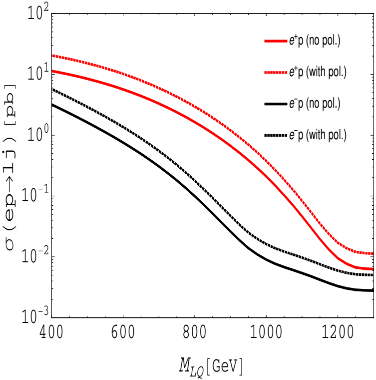
LHeC : e (60 GeV) & p (7 TeV), $\sqrt{s} = 1.3$ TeV

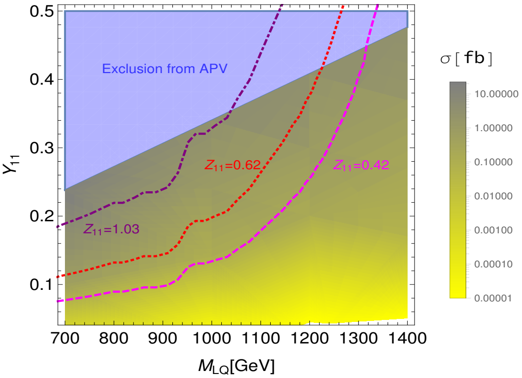
FCC-eh : e (60 GeV) & p (50 TeV), $\sqrt{s} = 3.46$ TeV





$\Rightarrow$ Asymmetry, $\mathcal{A}_{ep} = \dfrac{\sigma(e^+p) - \sigma(e^-p)}{\sigma(e^+p) + \sigma(e^-p)} > 0$





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

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

Analysis

- 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**	

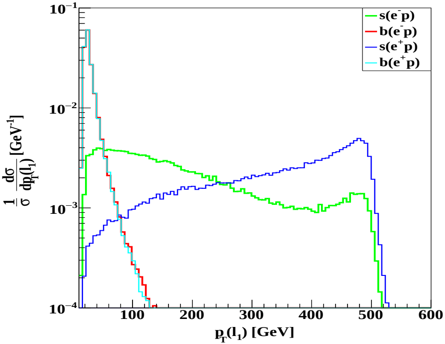
- Table: 2 (FCC-eh)

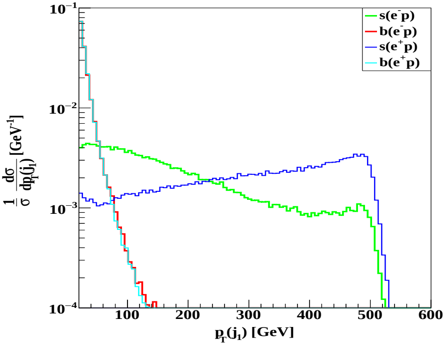
	$e^{-}p \to l^{-}j$		$e^{+}p \to l^{+}j$	
	$\sigma^{\rm sig}$ [fb]	$\sigma^{\rm bkg}$ [fb]	$\sigma^{\rm sig}$ [fb]	$\sigma^{\rm bkg}$ [fb]
No cut	**395.08**	10900	**1246.4**	9597
$c_1 : N_j \geq 1\ + N_l \geq 1$	354.41	9836.93	1119.03	8652.58
$c_2 : c_1 + p_T(l_1) \geq 400$	180	839.141	578.13	611.459
$c_3 : c_2 + p_T(j_1) \geq 400$	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**	

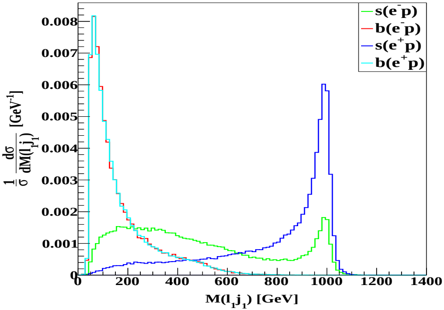
- Table-3

Benchmarks	$M_{\rm LQ}$	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 $\sigma^{\rm bkg}$.

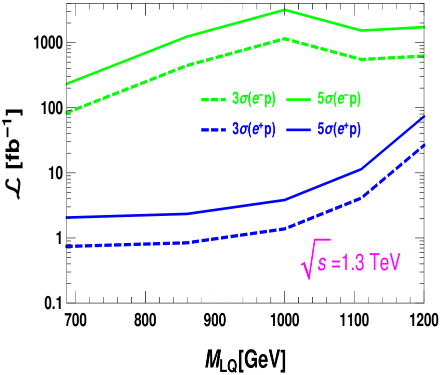


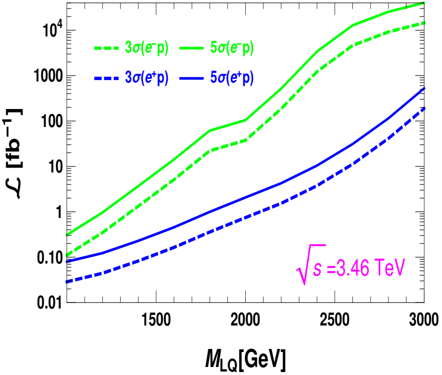




⇒ Distribution of $p_T(l_1)$, $p_T(j_1)$, $M(l_1 j_1)$ for both signal(s) and background (b) for LHeC.

Results





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

- At FCC-eh, 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}.

Summary

- **There are bounds on mass and coupling of LQ. Tightest bound is from CMS experiment.**
- **A comparison of cross-section indicates that LHeC and FCC-eh provide better cross section than LHC.**
- **An ep collider could be an ideal machine to search for LQ.**
- $\sigma(e^{\pm}p \to l^{\pm}\, j)$ **depend on Yukawa coupling. Results presented here are specific to chosen value of coupling.**
- **There are many interesting channels involving N_R to be explored.**

Thank you for your attention!