Signatures of scalar Leptoquarks at the upcoming ep colliders

Talk is based on arXiv: 1912.07236

Sanjoy Mandal

Instituto de Física Corpuscular (**IFIC**), University of Valencia

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Introduction

LQs are hypothetical particles which can emerge from the unification of quarks and leptons

J.C Pati and A. Salam, Phys. Rev. D8 (1973) 1240-1251

LQs also exist in grand unified theories based on SU(5) and SO(10)

Under SM, there are in total 6 scalar and 6 vector type of LQ.

arXiv:1603.04993, I. Dorsner et al,

We considered a particular type of scalar LQ $\tilde{R}_2(3, 2, \frac{1}{6})$

$$\mathcal{L} = -Y_{ij}\bar{d}^i_R \tilde{R}^a_2 \epsilon^{ab} L^{j,b}_L + Z_{ij}\bar{Q}^{i,a}_L \tilde{R}^a_2 N^j_R + h.c.,$$
$$= -Y_{ij}\bar{d}^i_R e^j_L \tilde{R}^{2/3}_2 + (YU_{\rm PMNS})_{ij}\bar{d}^i_R \nu^j_L \tilde{R}^{-1/3}_2 + (V_{\rm CKM}Z)_{ij}\bar{u}^i_L N^j_R \tilde{R}^{2/3}_2 + Z_{ij}\bar{d}^i_L N^j_R \tilde{R}^{-1/3}_2 + h.c.,$$

Advantages:

(1). It allows for matter stability.

(2). It also couple to right handed neutrinos(RHNs).

(3). For this type of LQ model, RHNs production can be also independent of mixing angle.

For the case of seesaw models, the right handed neutrino production is proportional to light-heavy mixing angle, hence suppressed.

The prospect of discovering RHNs are significantly improved if they can be produced through other than the mixing angle.

For example if both the SM field and RHNs are charged under a new gauge group, then N pairs can be produced independent of mixing angle. B-L model is one such example.

(4). Advantage with the LQ model is that we don't need to even extend the SM gauge.

Phys.Rev. D97 (2018) no.1, 015024 , D.Das, K.Ghosh, M.Mitra, S.Mondal

Comparison: $\sigma(ep \to jN)_{\rm LQ} \sim \mathcal{O}(10^2\,{\rm fb})$ $\sigma(ep \to jN)_{\rm seesaw} \sim \mathcal{O}(10\,{\rm fb})$

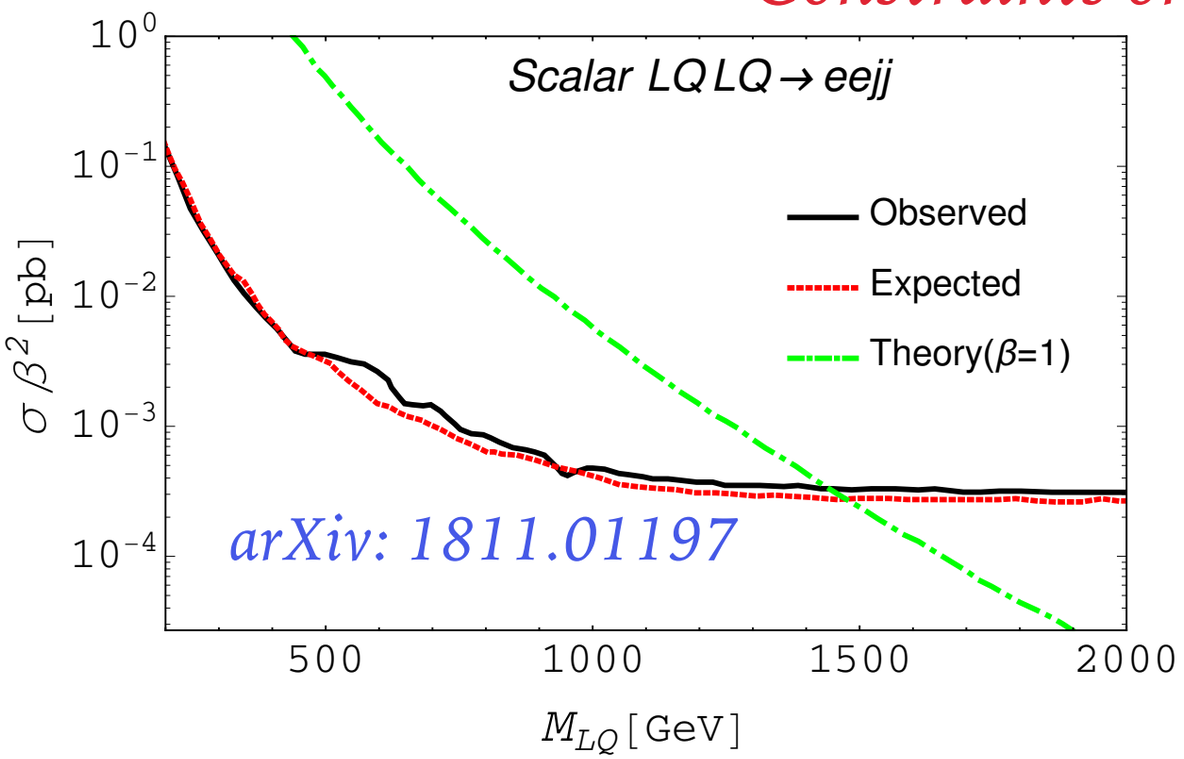
$$M_N = 100\,{\rm GeV},\ M_{\rm LQ} = 1\,{\rm TeV},\ |V_{eN}|^2 = 10^{-4}$$

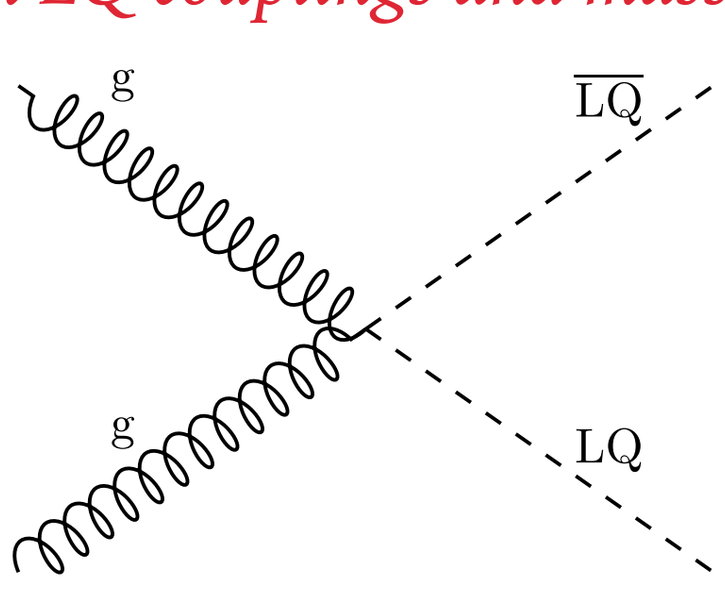
(5). Once produced, LQ can decay to no. of final states: ℓj , jN *and* tN

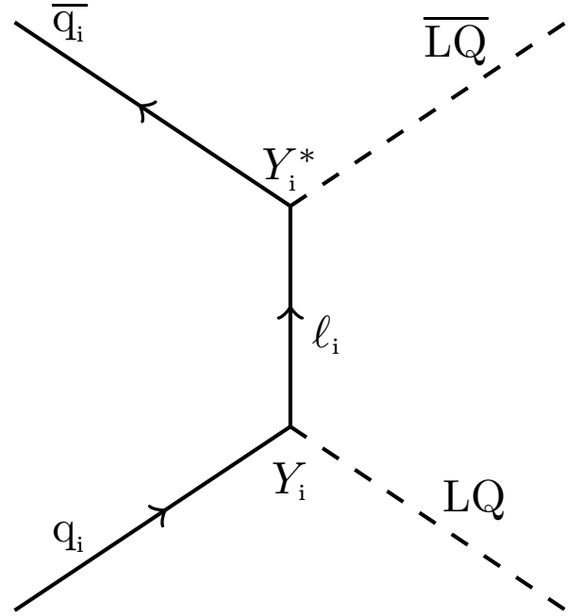
Here, we have focused on particular final state ℓj *, as it has the highest discovery potential for Leptoquarks at ep colliders such as LHeC and FCC-eh*

We have studied the final state $\ell^{\pm} j$ *at both the* $e^- p$ *and* $e^+ p$ *colliders*

Constraints on LQ couplings and mass







Assuming 100% branching ratio to ej final state (which implies Z=0), bound on LQ mass 1.435 TeV.

For the branching ratio β to ej is less than 100% (which is of course possible if LQ has additional interactions such as LQ-νj, LQ-jNi), the bound on LQ mass can be lowered.

Atomic parity violation: $Y_{de} < 0.34\frac{M_{LQ}}{1\,\mathrm{TeV}}$ *and* $Y_{ue} < 0.36\frac{M_{LQ}}{1\,\mathrm{TeV}}$ arXiv:1406.4831

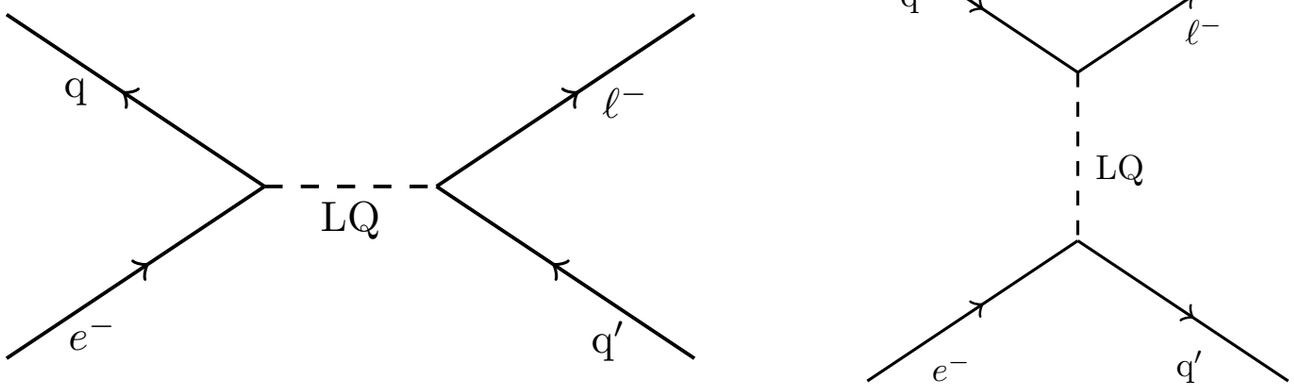
LFV decay modes: $K_L \to \mu^- e^+, \quad |Y_{s\mu}Y^*_{de}| < 2.1 \times 10^{-5}(\frac{M_{LQ}}{1\,TeV})^2$

Benchmarks	M_{LQ}	M_{N_1}	Y	Z
BP_1	1000	100	$(0.34, 0, 0)$	$(1.03, 0, 0)$

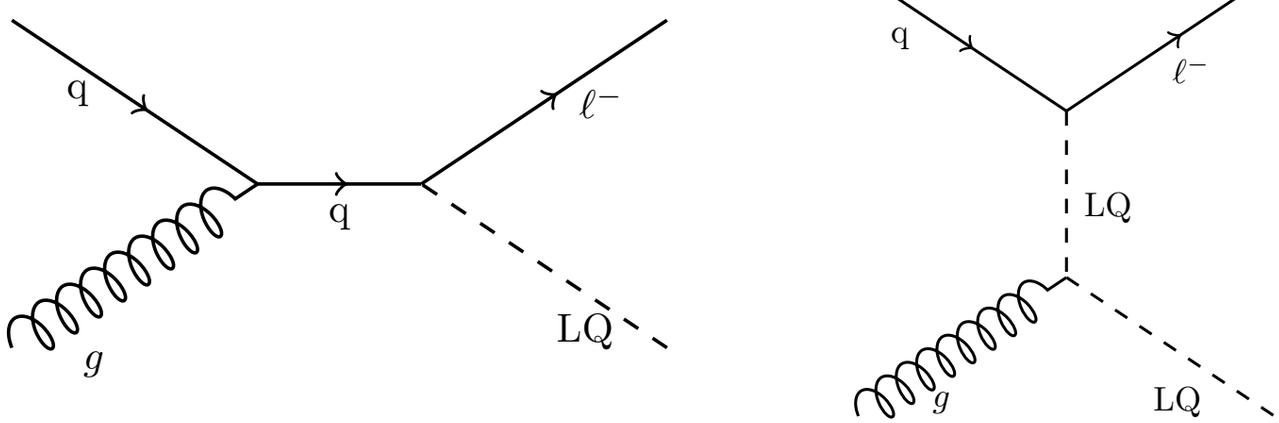
M_{LQ}	Y_{11}	Z_{11}
687	0.233	1.29
860	0.29	1.27
1000	0.34	1.02
1110	0.377	0.84
1204	0.41	0.65

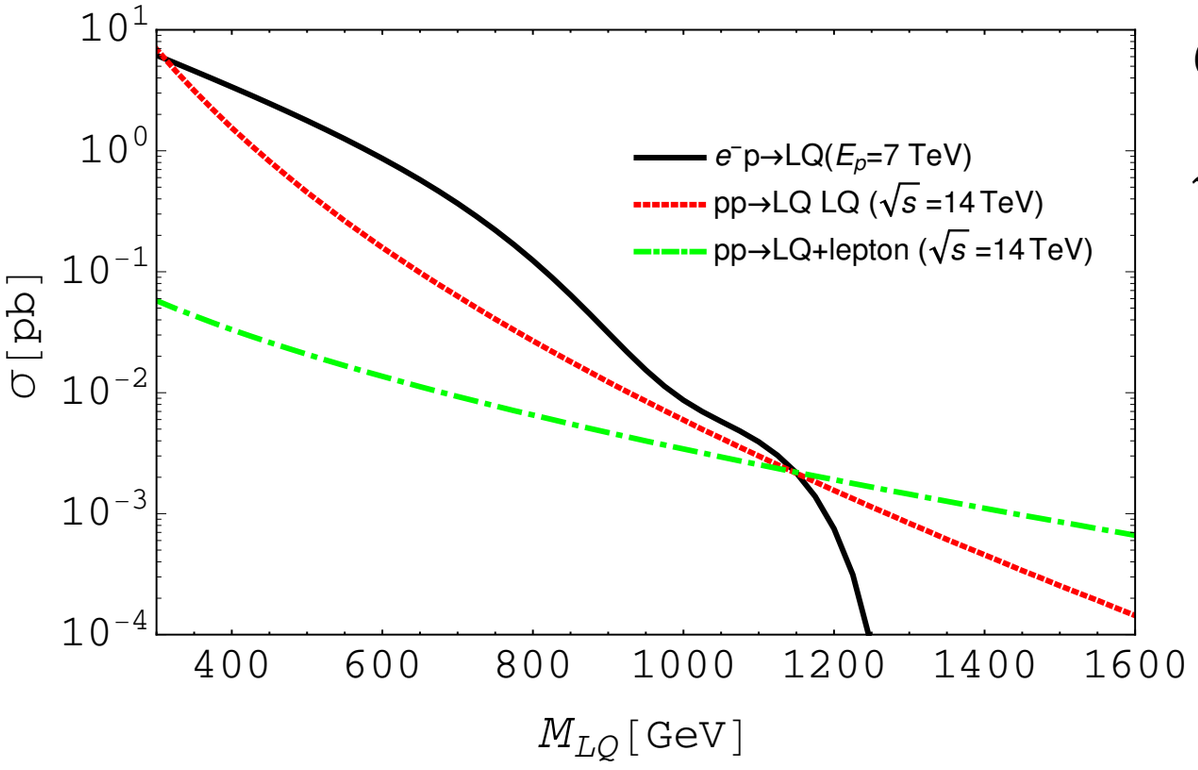
LQ productions at ep and pp collider

Single LQ production at ep collider:



Single LQ production at pp collider:

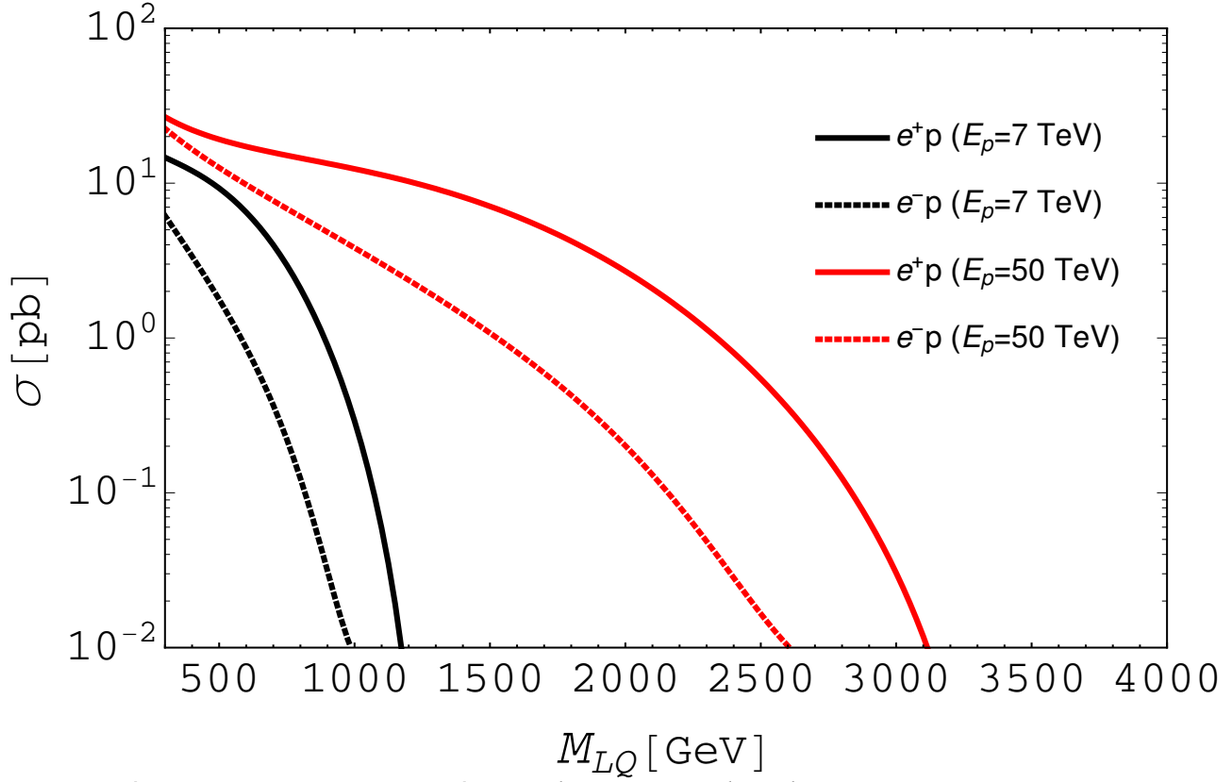




Comparison of single LQ production at LHeC with respect to single or pair production of LQ at LHC.

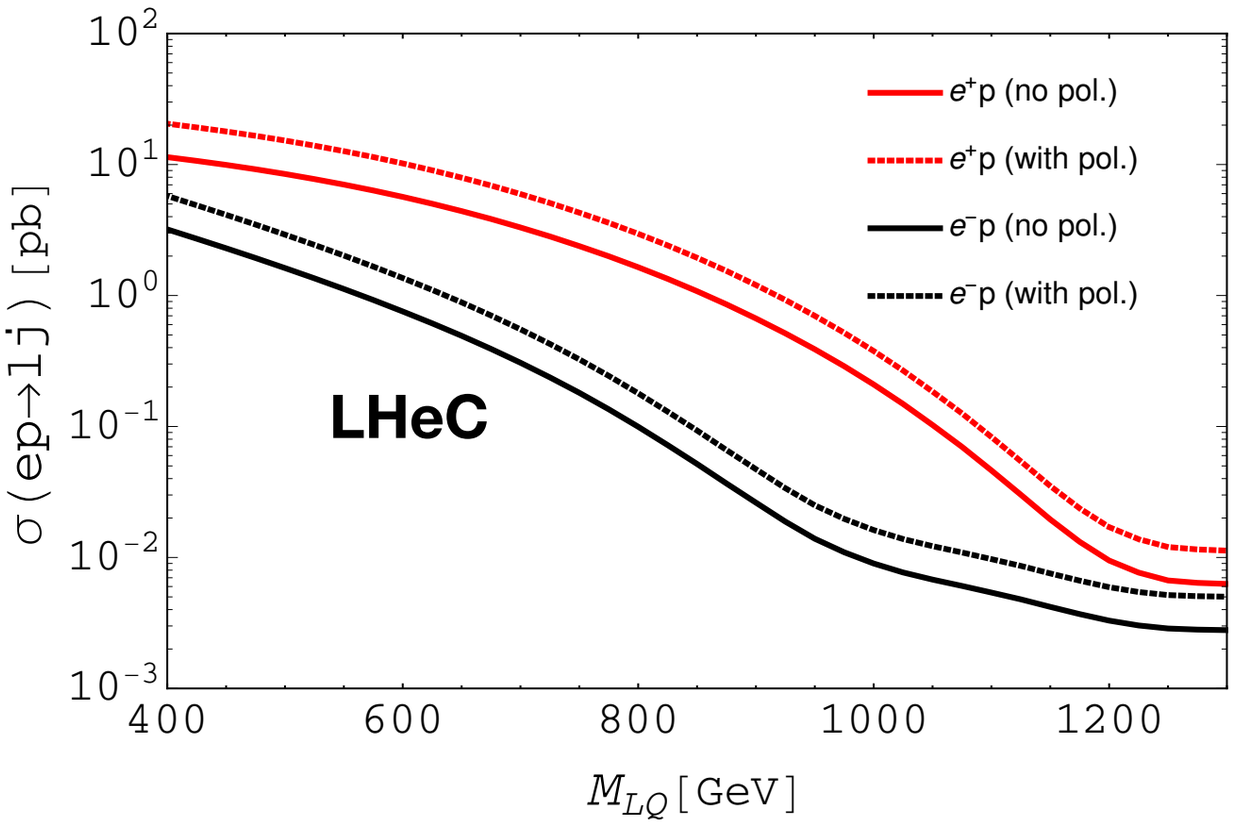
At $e^- p$ and $e^+ p$ colliders, LQ couples with $e^- - \bar{d}$ and $e^+ - d$, respectively.

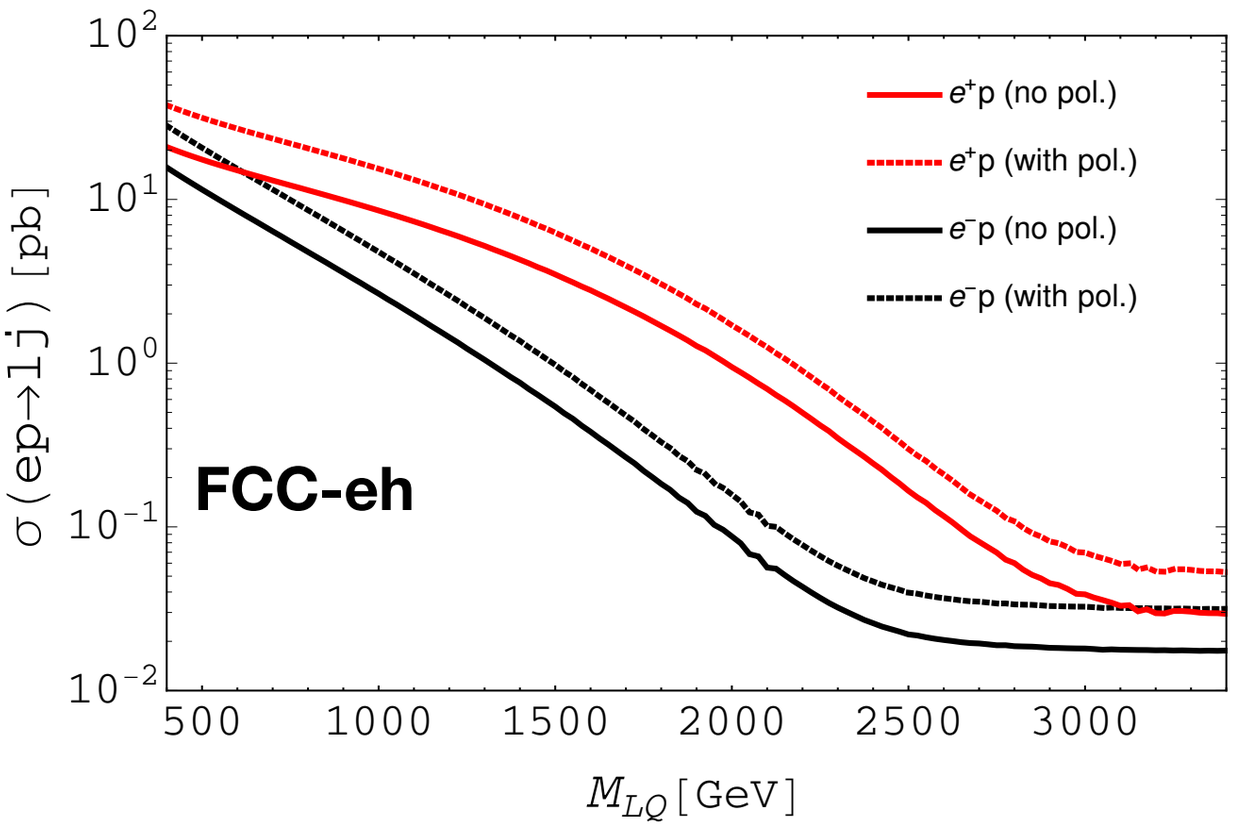
Note that, quark parton distribution function is larger than that for anti-quark.



The production rates improve by almost a factor of 2 in case of polarised electron or positron beam. This enhancement is due to the couplings $e_L^- - \mathrm{LQ} - \bar{d}$ and $e_R^+ - \mathrm{LQ} - d$ at $e^- p$ and $e^+ p$ colliders.

80% polarised electron or positron beam





Analysis

We consider the process $e^{\pm}p \rightarrow l^{\pm}j$ as the signal.

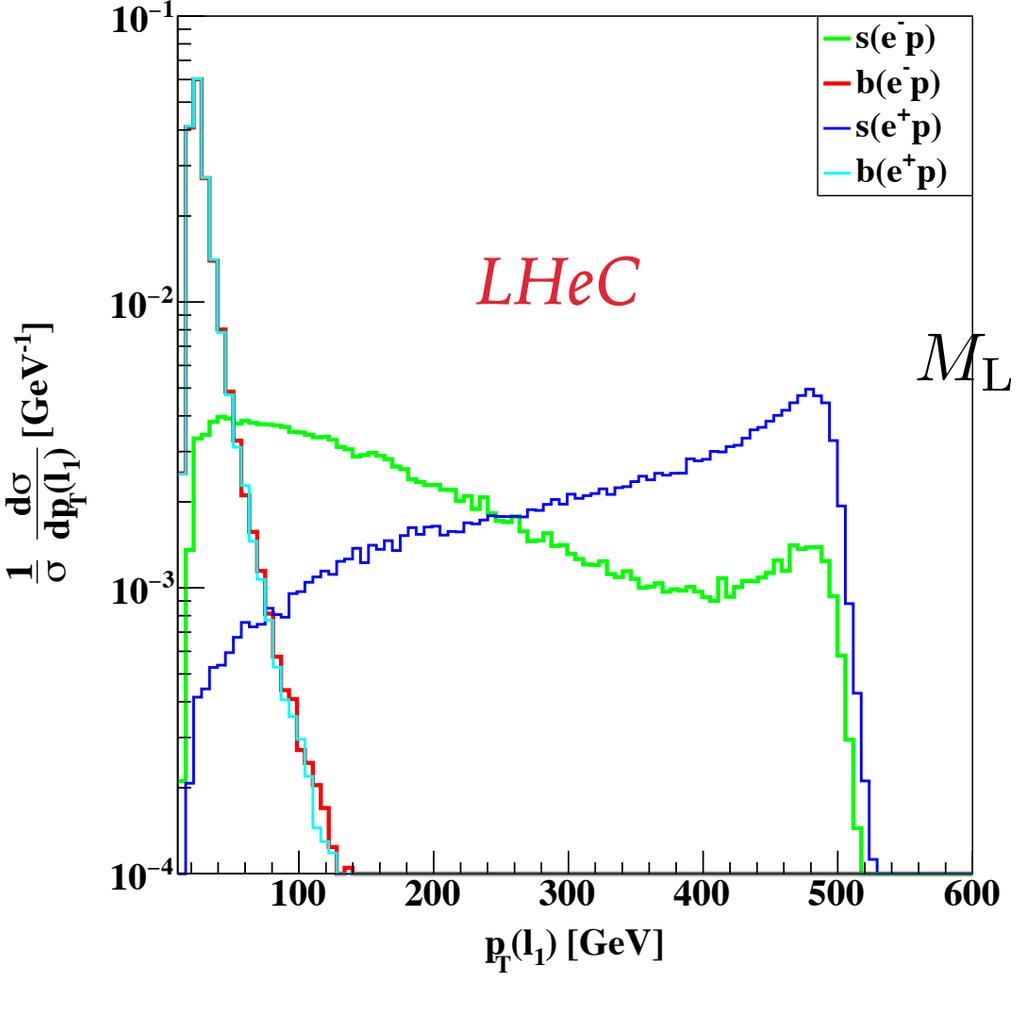
The dominant background for this process comes from the SM processes $e^{\pm}p \rightarrow l^{\pm}j$, $l^{\pm}jj$.

The analysis is carried out with 1.3 TeV LHeC and 3.46 TeV FCC-eh

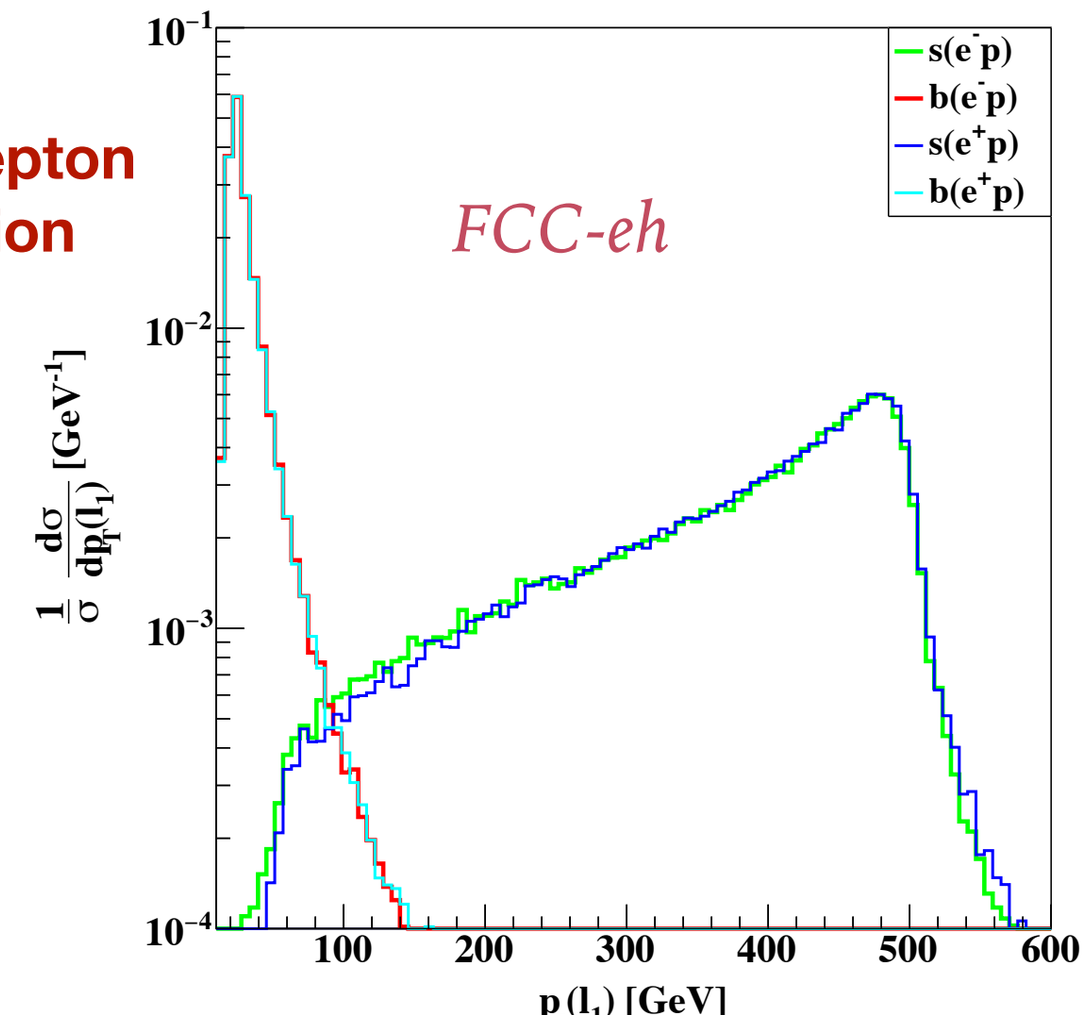
We apply the following basic cuts PT (l) > 10 GeV, PT(j) >20GeV, $|\eta(l)| < 5$, $|\eta(j)| < 5$, $\Delta Rll > 0.4$, $\Delta Rjj > 0.4$, $\Delta Rlj > 0.4$ for event generations.

Due to the initial and final state radiations, additional jets will be present in the final states considered. For signal selection we demand atleast one lepton and one jet in the final state.

Leading Lepton distribution



$$M_{\mathrm{LQ}} = 1\,\mathrm{TeV}$$



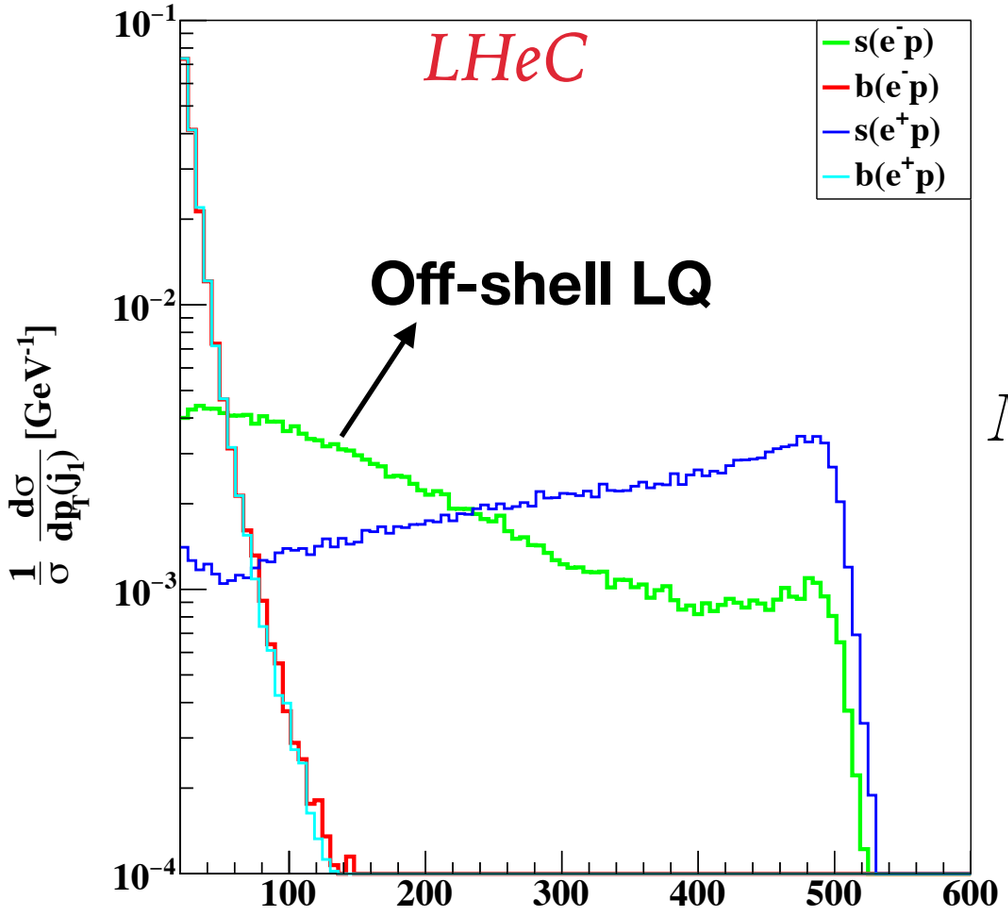
For LHeC and FCC- eh, the distributions of background sample are similar for both the e^- and e^+ case.

At LHeC, for e^- beam there are two peaks: lower pT region (off-shell LQ production) and higher pT region.

For e^+ beam there is no second peak → *less off-shell LQ production*

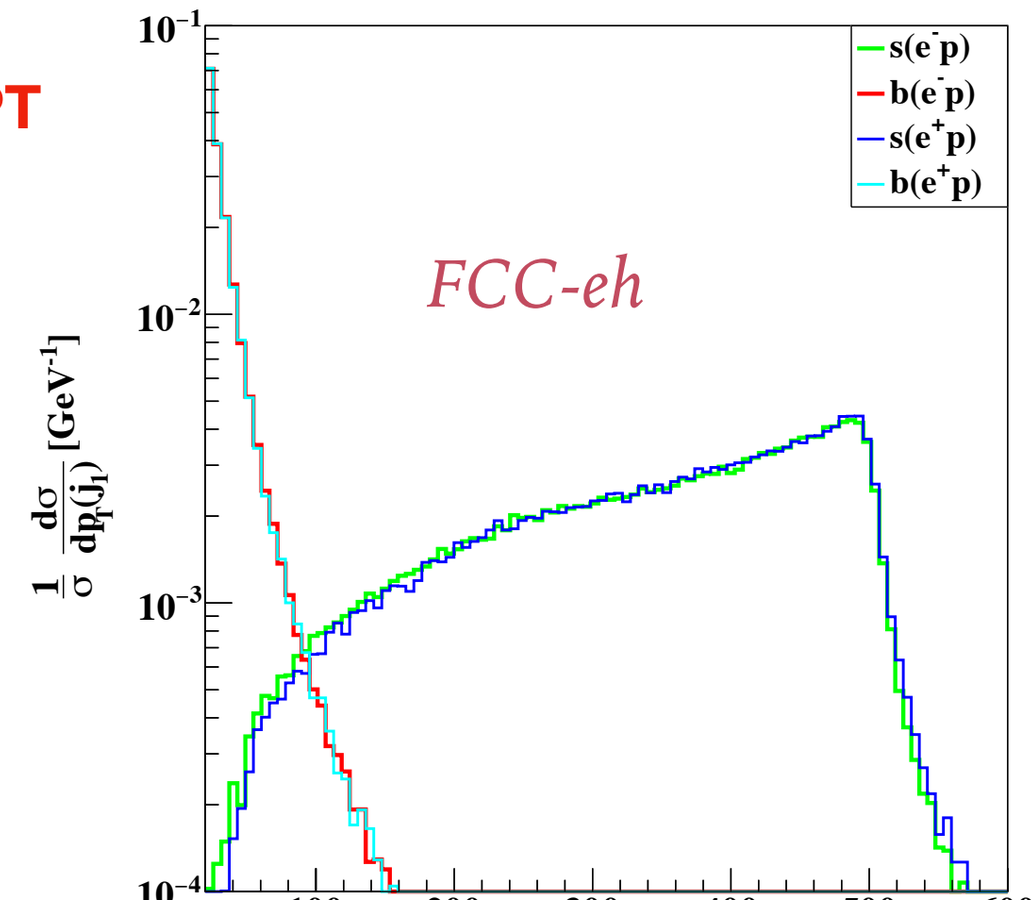
This occurs since for e^-p (e^+p) collider, LQ couples to $e^- - \bar{d}$ ($e^+ - d$). The d quark carries greater fraction of proton momentum.

For FCC-eh, there are no such differences between the use of e^- and e^+ beams due to availability of enough c.m. energy for LQ mass 1 TeV.

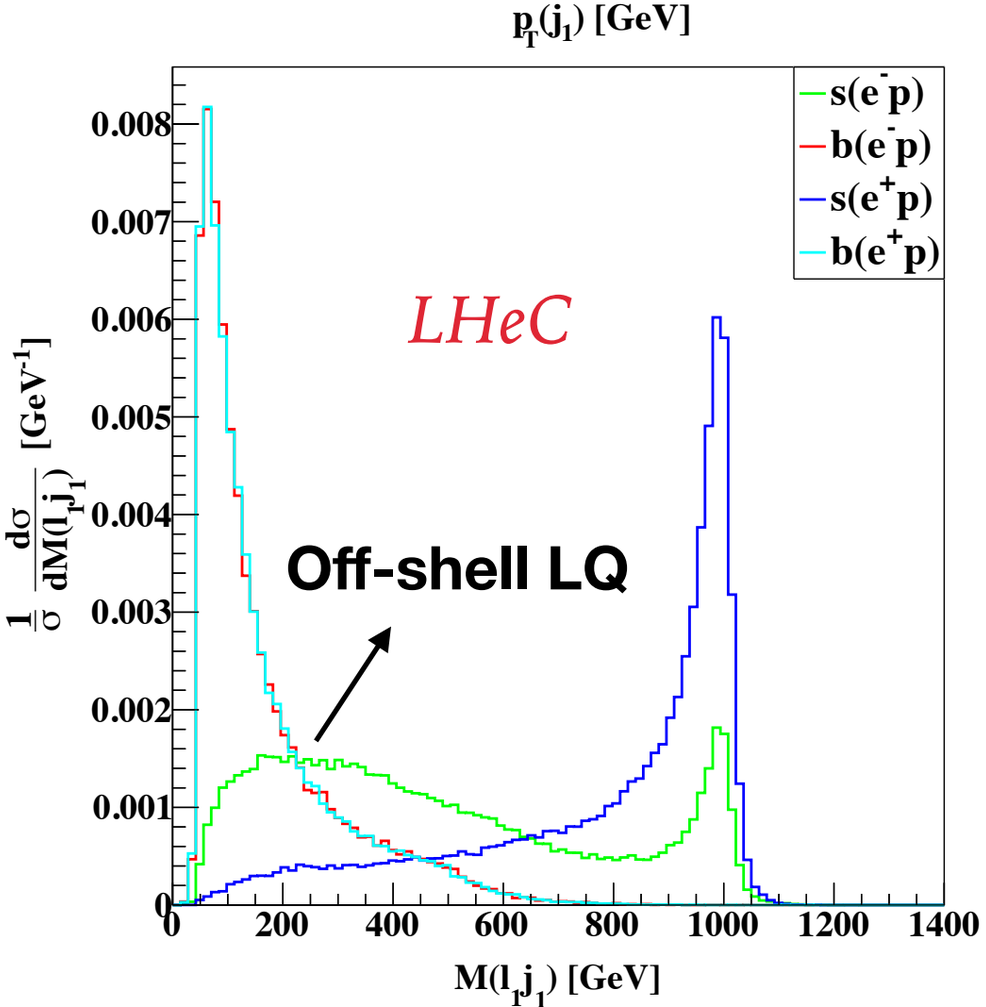


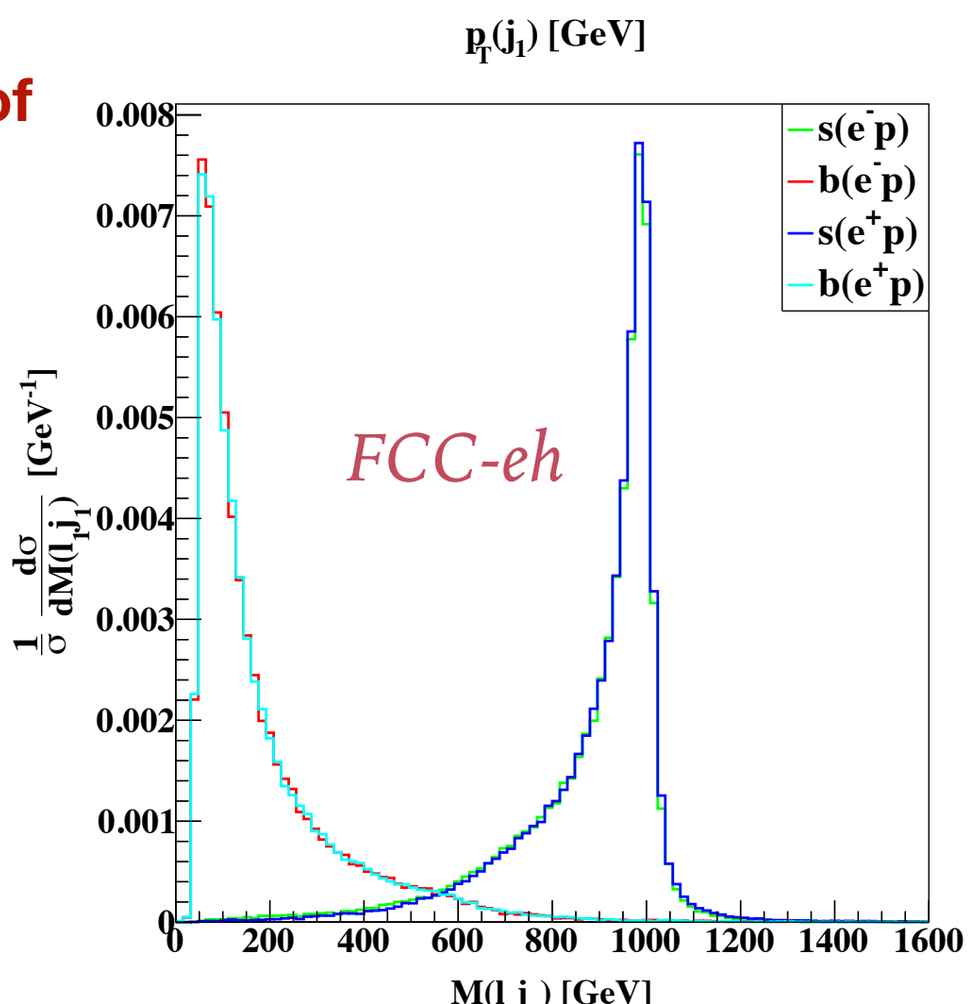
Leading jet PT distribution

$M_{\mathrm{LQ}} = 1\,\mathrm{TeV}$



Invariant mass of leading lepton and jet





Cut Flow.....

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]
before cut	4.016	2180		39.23	1440
$c_1 : N_j \geq 1 \ + N_\ell \geq 1$	3.01	1644		29.85	1079
$c_2 : c_1 + p_T(\ell_1) \geq 400$	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	

For $M_{LQ} \geq 1\,\text{TeV}$, *we use the same selection cuts.*

For $M_{LQ} < 1\,\text{TeV}$, *we replaced* c_2 *and* c_3

as $c_2 : c_1 + p_T(\ell_1) \geq 300$, $c_3 : c_2 + p_T(j_1) \geq 300$

$M_{LQ} = 1\,\text{TeV}$ $M_{LQ} = 2\,\text{TeV}$

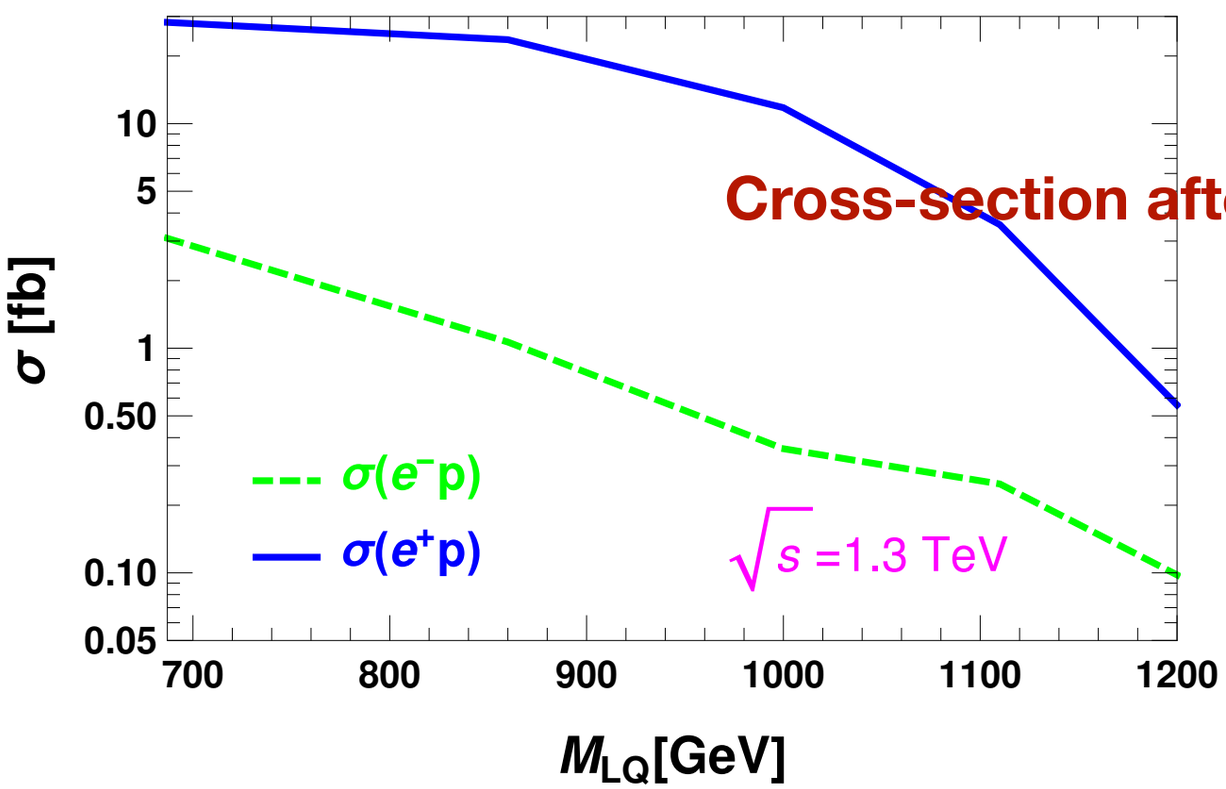
For $M_{LQ} \leq 2\,\text{TeV}$, *we use the same selection cuts.*

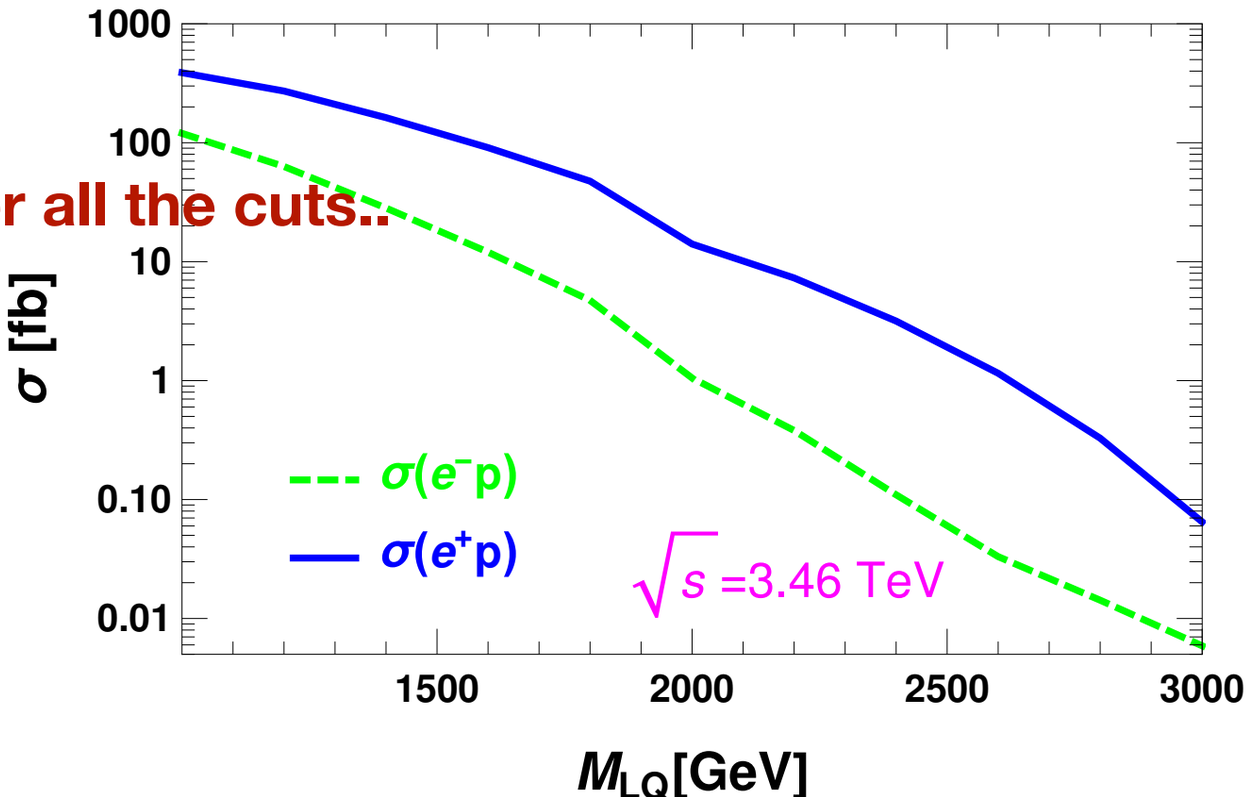
For $M_{LQ} > 2\,\text{TeV}$, *we replaced* c_2 *and* c_3

as $c_2 : c_1 + p_T(\ell_1) \geq 800$, $c_3 : c_2 + p_T(j_1) \geq 800$

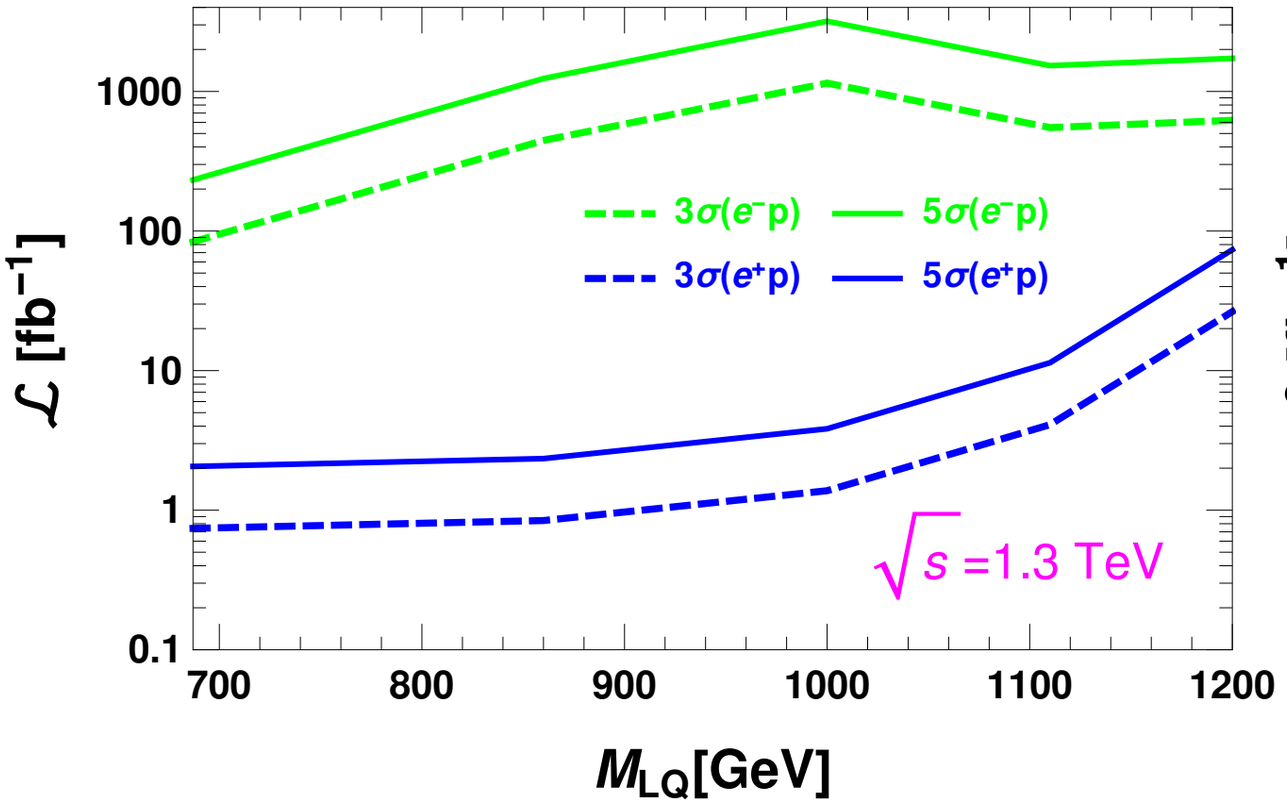
FCC-eh	$e^- p \to l^- j$			$e^+ p \to l^+ j$	
	$\sigma^{\rm sig}$ [fb]	$\sigma^{\rm bkg}$ [fb]		$\sigma^{\rm sig}$ [fb]	$\sigma^{\rm bkg}$ [fb]
before cut	395.08	10900		1246.4	9597
$c_1 : N_j \geq 1 \ + N_\ell \geq 1$	354.41	9836.93		1119.03	8652.58
$c_2 : c_1 + p_T(\ell_1) \geq 400$	180	839.141		578.13	611.459
$c_3 : c_2 + p_T(j_1) \geq 400$	129.97	618.963		417.26	441.812
$c_4 : c_3 + \lvert M_{LQ} - M_{\ell j}\rvert \leq 100$	119.9	141.112		383.59	90.279
Significance for $\mathcal{L} = 1$ fb^{-1}	7.42			17.6	

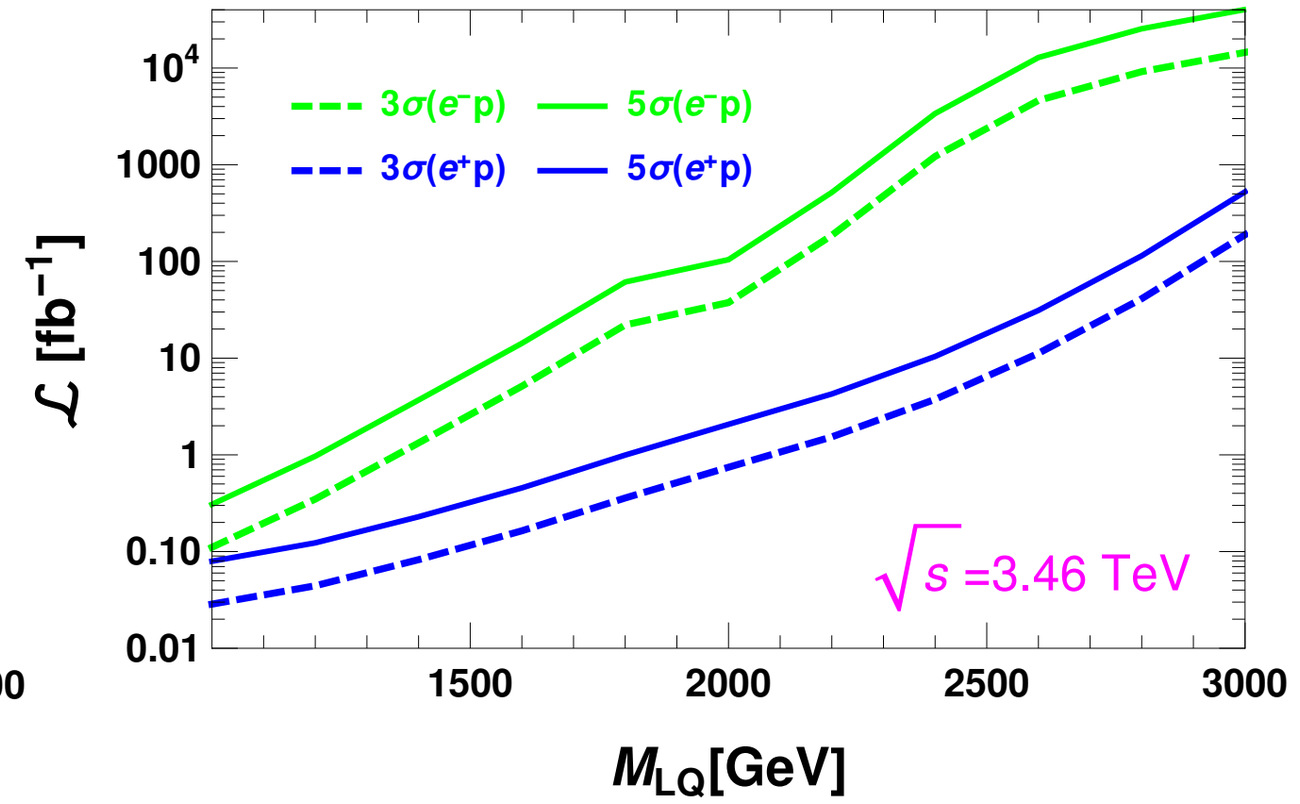
Cross-section after all the cuts..





Discovery Potential at LHeC and FCC-eh.....





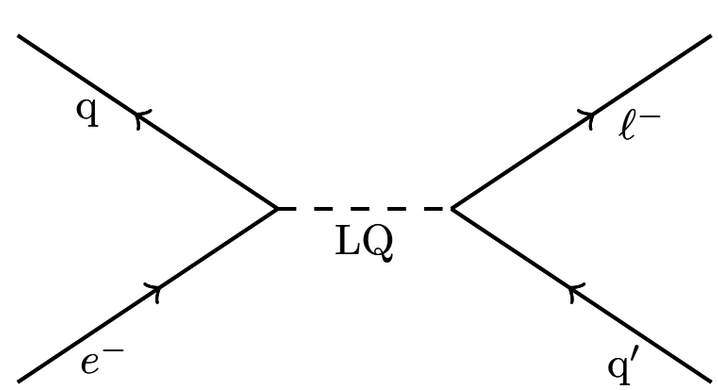
For LHeC with e^- beam, its difficult to probe LQ as the required luminosity is very high.

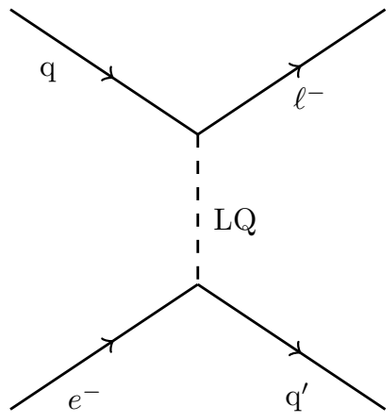
But at LHeC with e^+ beam, due to larger signal cross-sections, it is possible to probe the LQ mass upto 1.2 TeV.

For FCC-eh, even with e^- beam, we can probe LQ mass upto 2.3 TeV, but required luminosity quickly increases with higher masses.

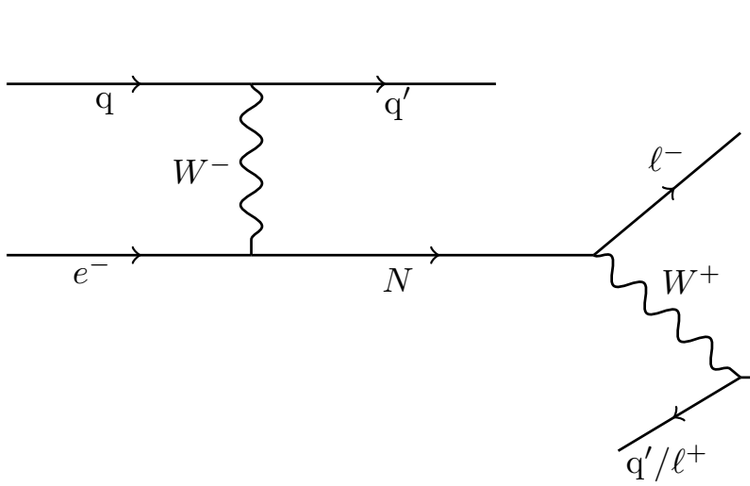
For the case of e^+ beam, due to enhanced cross-section we can probe the LQ mass upto 3 TeV.

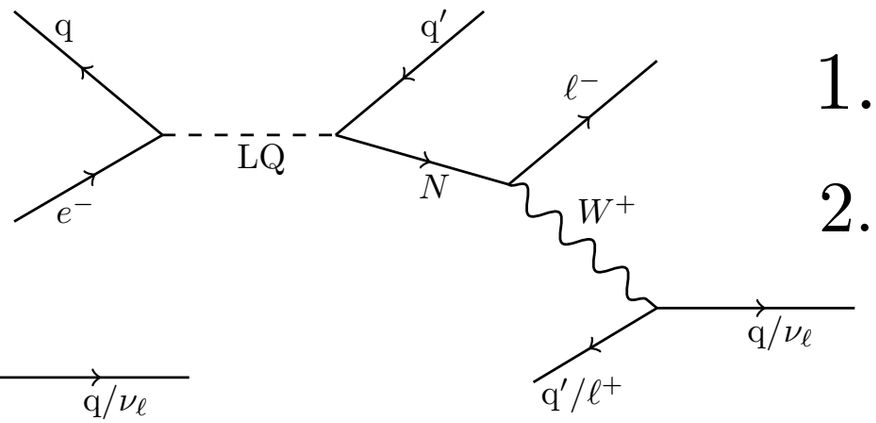
Possible final states to study……





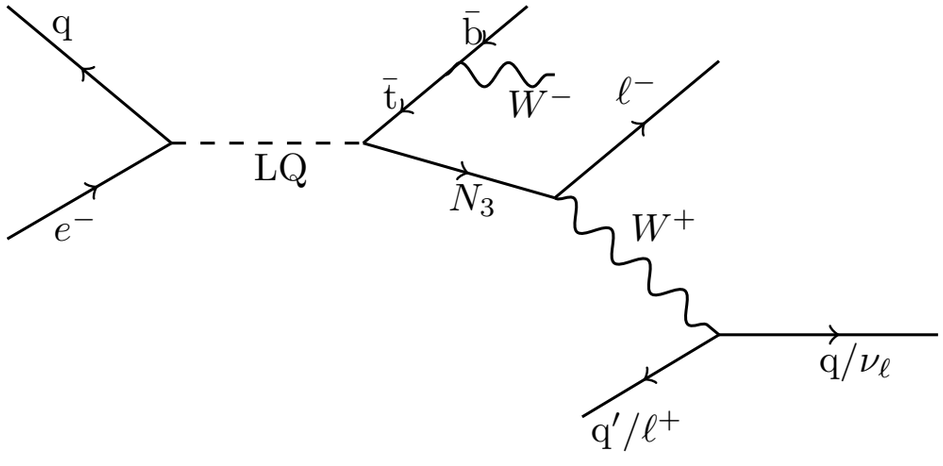
$$\ell^- + \text{n-jets}(1 \leq \text{n} \leq 2)$$





1. $\ell^- + \text{n-jets}(\text{n} \geq 3)$
2. $\ell^- + \ell^+ + \text{n-jets}(\text{n} \geq 1) + \not{E}_T$

arXiv:1807.06455, SM, M. Mitra and Nita Sinha



(1) $\bar{b}\ell^-\tau^-\ell^+ + \not{E}_T$

(2) $\bar{b}\ell^-\tau^- + \text{n-jets}\,(\text{n} = 2) + \not{E}_T$

(3) $\bar{b}\tau^-\ell^+ + \text{n-jets}\,(\text{n} = 2) + \not{E}_T$

Summary

We discuss the discovery prospects of LQ at LHeC and FCC-eh in the mass range 700 GeV-1200 GeV and 1 TeV-3 TeV, respectively.

We specifically focus on LQ production and its decay to a lepton and a jet.

LQ production at e^+p collider is larger than that at the e^-p collider. This occurs as the quark parton distribution function is larger than that for anti-quark.

We find that, we can probe the LQ mass up to 1.2 TeV at more than 5σ significance with e^+ beam at LHeC. For FCC-eh, we can easily probe LQ mass up to 2.2 TeV (3 TeV) with e^- (e^+) beams.

For this final state, we expect higher statistical significance at an ep collider compared to pp collider due to higher production cross-section as well as lower SM backgrounds.

Note that at an ep collider, polarization of the electron or positron beams can result in a substantial increase in the LQ production.

Thank You