

Search for leptoquarks produced in the t-channel at the FCC-hh

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1 Introduction

The possibility of new particles carrying both lepton and quark quantum numbers, known as leptoquarks (LQs), has long attracted attention as a compelling extension of the standard model of particle physics (SM). LQs arise naturally in several theoretical frameworks, including grand unified theories, composite models, and scenarios addressing the observed flavor anomalies in semileptonic B-meson decays. Their unique couplings to quark-lepton pairs offer a direct window onto the interplay between the flavor and electroweak sectors, while simultaneously providing possible explanations for the apparent non-universality among lepton generations.

Although much of the experimental effort so far has focused on the pair production of LQs through QCD interactions, the t-channel exchange of virtual LQs can also give rise to characteristic deviations in dilepton final states. These effects are particularly relevant at high energies, where the momentum transfer enhances the sensitivity to heavy states far beyond the direct production threshold. Probing such t-channel processes therefore provides complementary information on the LQ parameter space, especially in the multi-TeV mass regime where direct searches lose sensitivity.

The HL-LHC will extend direct LQ searches up to masses of order 2–3 TeV. However, its limited center-of-mass energy constrains the reach for heavier states, especially in the indirect channel. The FCC-ee will probe LQ effects indirectly through precision electroweak and flavor measurements, which are sensitive to loop-level or off-shell effects, but cannot fully map out the high-energy dynamics of t-channel exchange.

The FCC-hh, with a proton-proton center-of-mass energy of 84 TeV and a planned integrated luminosity of 30 ab⁻¹, uniquely combines the necessary energy and statistics

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to explore this physics case. Its kinematic reach allows the study of dilepton spectra and angular distributions at invariant masses above several TeV, where deviations from the SM induced by t-channel LQ exchange could become significant. In this regime, the FCC-hh has the potential to probe LQ masses up to tens of TeV, surpassing the reach of the HL-LHC, while also disentangling flavor structures and chiral couplings in a way not possible at FCC-ee alone. Strong indirect projections in the mass-coupling plane can be obtained from indirect measurements at the FCC-ee at the Z pole and during the flavor program.

In this work we investigate the sensitivity of the FCC-hh to leptoquark exchange in the t-channel, and interpret the results in the mass-coupling plane. We probe two types of LQs:

1. a vector U_1 LQ with couplings to left-handed third-generation quarks and leptons ("tauonic LQ");
2. a vector U_1 LQ with couplings to left-handed third-generation quarks and second-generation leptons ("muonic LQ").

The tauonic LQ is searched for in the final state with an electron and a muon, both coming from leptonic τ decays, whereas the muonic LQ is searched for in the final state with 2 muons.

2 Event generation and simulation

For the signal, we generate separately the t-channel productions of a vector U_1 LQ with couplings to left-handed third-generation quarks and leptons ("tauonic LQ"), and of a vector U_1 LQ with couplings to left-handed third-generation quarks and second-generation leptons ("muonic LQ"). The tauonic LQ signal corresponds to the following Lagrangian [1]:

$$\mathcal{L}_{U_1} \supset \frac{g_U}{\sqrt{2}} \beta_{i\tau} \bar{Q}_L^i \gamma_\alpha L_L^3 U_1^\alpha + h.c., \quad (1)$$

with $\beta_{b\tau} = 1$ and $\beta_{s\tau} = 0.1$, and g_U is the coupling. The muonic LQ signal corresponds to the following Lagrangian:

$$\mathcal{L}_{U_1} \supset \frac{g_U}{\sqrt{2}} \beta_{i\mu} \bar{Q}_L^i \gamma_\alpha L_L^2 U_1^\alpha + h.c., \quad (2)$$

with $\beta_{b\mu} = 1$ and $\beta_{s\mu} = 0.1$. The muonic LQ samples include $b\bar{b}$, $b\bar{s} + s\bar{b}$, and $s\bar{s}$ initial states. The latter two give much smaller contributions compared to the $b\bar{b}$ case, since $\beta_{s\mu} = 0.1 \times \beta_{b\mu}$. The samples are generated for $g_U = 1$, and other coupling values are obtained by rescaling the LQ cross section with g_U^4 . Distinct samples were generated for different dilepton mass ranges, and stitched together to form the LQ signal prediction.

The analysis relies on Monte Carlo generated events for both the signal and the background processes considered. In general, all samples are generated at leading-order (LO) precision using MadGraph5 aMC@NLO [2], with additional jets and higher corrections, and with NNPDF3.0NLO [3]. Up to two additional jets are included in the $t\bar{t}$ events. Pythia8 [4] is used for the parton showering and hadronization effects.

Process	Cross section (pb)
$pp \rightarrow \mu\mu$	
$0.2 < Q < 1 \text{ TeV}$	20.5
$1 < Q < 3 \text{ TeV}$	1.19×10^{-1}
$3 < Q < 10 \text{ TeV}$	2.39×10^{-3}
$10 < Q < 30 \text{ TeV}$	1.15×10^{-5}
$30 < Q < 84 \text{ TeV}$	3.88×10^{-9}
$pp \rightarrow \tau_\ell \tau_\ell$	
$0.2 < Q < 1 \text{ TeV}$	1.02
$1 < Q < 3 \text{ TeV}$	8.16×10^{-3}
$3 < Q < 10 \text{ TeV}$	2.25×10^{-4}
$10 < Q < 30 \text{ TeV}$	1.31×10^{-6}
$30 < Q < 84 \text{ TeV}$	4.64×10^{-10}
$pp \rightarrow \ell\nu\ell\nu$	
$0.2 < Q < 1 \text{ TeV}$	40.6
$1 < Q < 3 \text{ TeV}$	0.742
$3 < Q < 10 \text{ TeV}$	2.65×10^{-2}
$10 < Q < 30 \text{ TeV}$	2.43×10^{-4}
$30 < Q < 84 \text{ TeV}$	1.84×10^{-7}
$t\bar{t}$	
$0.2 < Q < 1 \text{ TeV}$	1.73×10^4
$1 < Q < 3 \text{ TeV}$	1.21×10^3
$3 < Q < 10 \text{ TeV}$	18.7
$10 < Q < 30 \text{ TeV}$	4.72×10^{-2}
$30 < Q < 84 \text{ TeV}$	6.33×10^{-6}

Table 1: Overview of the background samples. The symbol τ_ℓ refers to τ leptons decaying leptonically

Table 1 gives an overview of the simulated backgrounds. Background contributions from misidentified objects ("fakes") are not considered in the analysis.

A reference detector for the FCC-hh has been designed and described in the conceptual design report [5]. It follows the same principles as current LHC general purpose experiments ATLAS and CMS by combining different detector component layers for different purposes and with different technologies, and it is split into a central region (covering the range $|\eta| < 2.5$), and two forward endcaps (expanding the coverage up to $|\eta| < 6.0$), which are placed at a distance of 10 m from the interaction point. High precision silicon tracking detectors constitute the tracking systems in both central region and endcaps, requiring solenoid magnetic fields of 4T, and Liquid Argon technology is relied on for the electromagnetic calorimeter in both regions as well as the hadronic calorimeter in the forward endcaps. In the central region the hadronic calorimeter uses scintillating tiles with steel and lead absorbers. A muon system employing drift tube technology forms the outermost layer in each region. This reference detector design is implemented into the DELPHES tool [6], which describes the response of the detector components using parameterizations of the resolution and efficiency functions, and used as the baseline for the studies presented here.

3 Event selection

3.1 Tauonic LQ

The final state of an electron and a muon is used to search for the tauonic LQ. This final state covers only 6% of the di- τ final states but presents several advantages: the final states with hadronic τ decays suffer from a large background from misidentified jets, which are currently difficult to model precisely at the FCC-hh because of their high p_T , whereas the final states with same-flavor leptons (ee or $\mu\mu$) suffer from large backgrounds from the Drell-Yan dilepton production.

The following preselection is applied to select events in this final state:

- exactly 1 electron with $p_T > 30$ GeV and $|\eta| < 4$;
- exactly 1 muon with $p_T > 30$ GeV and $|\eta| < 4$, and with opposite-sign electric charge to the electron.

We examine the distributions of several variables after the preselection to determine an optimized selection. The distributions of H_T , the missing transverse momentum MET, the azimuthal angle differences between the leptons $\Delta\phi(e, \mu)$ and between the dilepton system and the MET $\Delta\phi(e\mu, \text{MET})$, the dilepton invariant mass $m(e, \mu)$, and the pseudo-rapidity difference between the leptons $|\Delta\eta(e, \mu)|$, are shown in Fig. 1 at the preselection level for events with no b-tagged jet with $p_T > 30$ GeV.

Based on the signal-background separation, the following selection criteria are added to form the optimized selection:

- $|\Delta\eta(e, \mu)| < 4.0$;
- $|\Delta\phi(e\mu, \text{MET})| > 2.0$;
- $|\Delta\phi(e, \mu)| < 2.0$.

While the p_T , $m(e\mu)$, and H_T distributions also exhibit a good separation between the signal and the background, they are strongly correlated with the MET, which is chosen as the observable, and are therefore not included in the optimized selection criteria. The results are extracted by performing a maximum likelihood of the MET distributions after the optimized selection, in 2 orthogonal categories: without b-tagged jet, or with at least 1 b-tagged jet. The signal-to-background ratio increases with the b jet multiplicity as the dominant $\ell\nu\ell\nu$ background mostly contributes to the category without any b-tagged jet.

3.2 Muonic LQ

The final state of two muons is used to search for the muonic LQ. The following preselection is applied to select events in this final state:

- exactly muons with $p_T > 30$ GeV and $|\eta| < 4$;
- the two muons have opposite-sign electric charge.

We examine the distributions of several variables after the preselection to determine an optimized selection. The distributions of H_T , MET, $\Delta\phi(\mu, \mu)$, $|\Delta\eta(\mu, \mu)|$, $m(\mu, \mu)$, and $\Delta R(\mu, \mu)$, are shown in Fig. 2 at the preselection level for events with no b-tagged jet with $p_T > 30$ GeV.

Based on the signal-background separation, the following selection criteria are added to form the optimized selection:

- $|\Delta\eta(e, \mu)| < 4.0$;
- $\Delta R(\mu, \mu) > 2.0$;
- $H_T > 2000$ GeV.

The results are extracted by performing a maximum likelihood of the dimuon mass distributions after the optimized selection, in 3 orthogonal categories: without b-tagged jet, with exactly 1 b-tagged jet, and with at least 2 b-tagged jets. The signal-to-background ratio increases with the b jet multiplicity as the dominant $pp \rightarrow \mu\mu$ background mostly contributes to the category without any b-tagged jet.

4 Systematic uncertainties

Several systematics are included in the maximum likelihood fit used to extract the results. The background and signal processes each have a 1% normalization uncertainty. For the backgrounds, we assume we will be able to derive high-precision control regions enriched in the different processes, which will allow us to reach that level in precision. Each object (electron, muon, b-tagged jet) also has a 1% uncertainty assigned to its identification efficiency. For light jets tagged as b jets, the uncertainty is increased to 2%. Finally, an uncertainty of 1% in the integrated luminosity is considered.

5 Results

5.1 Tauonic LQ

The MET distributions in the three categories after the optimized selection are shown in Fig. 3. Interference effects are neglected. They are used to extract upper limits at 95% confidence level on the signal strength with the asymptotic calculation, using the CMS statistical analysis tool COMBINE, as shown in Fig. 4 (left) for $g_U = 1$. These results are interpreted as limits in the coupling-mass plane for a tauonic LQ, assuming the LQ cross section scales with g_U^4 , as shown in Fig. 4 (right).

5.2 Muonic LQ

The dimuon mass distributions in the three categories after the optimized selection are shown in Fig. 5. Interference effects are neglected. They are used to extract upper limits at 95% confidence level on the signal strength, as shown in Fig. 6 (left) for $g_U = 1$. These results are interpreted as limits in the coupling-mass plane for a muonic LQ, assuming the LQ cross section scales with g_U^4 , as shown in Fig. 6 (right).

6 Conclusion

An analysis of the prospects of searching for leptoquarks produced in the t-channel at the FCC-hh is presented. The electron-muon and dimuon final states are used to probe leptoquarks coupling to second- or third-generation leptons, respectively. Expected upper limits are set on the mass-coupling plane, surpassing searches for other LQ production modes at high mass, and competitive with indirect bounds planned to be set during the flavor program of the FCC-ee.

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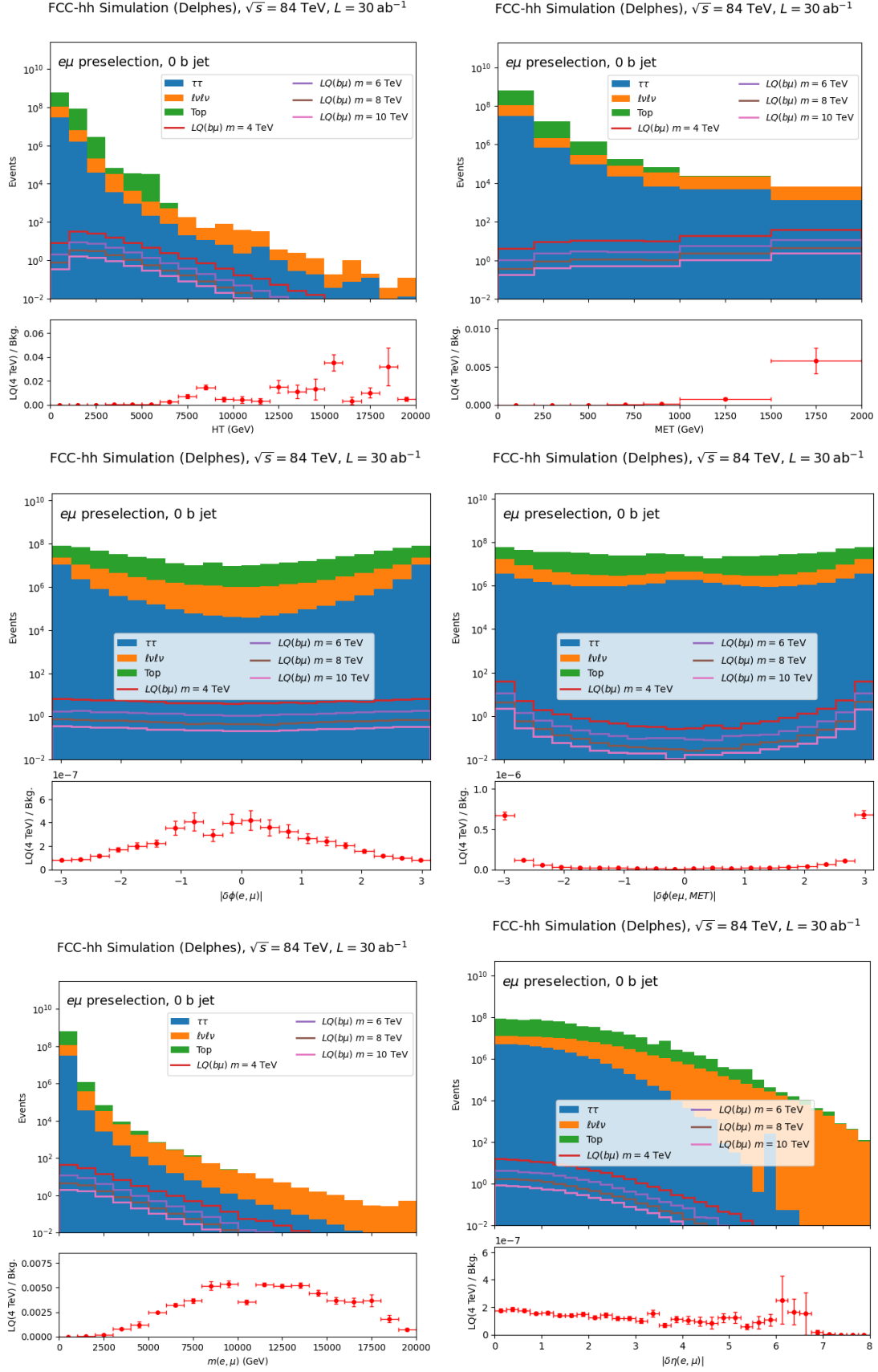


Figure 1: Distributions of various variables in the $e\mu$ final state at the preselection level with no b-tagged jet. The tauonic LQ signal is shown for several mass hypotheses, using $g_U = 1$. The last bin includes the overflow.

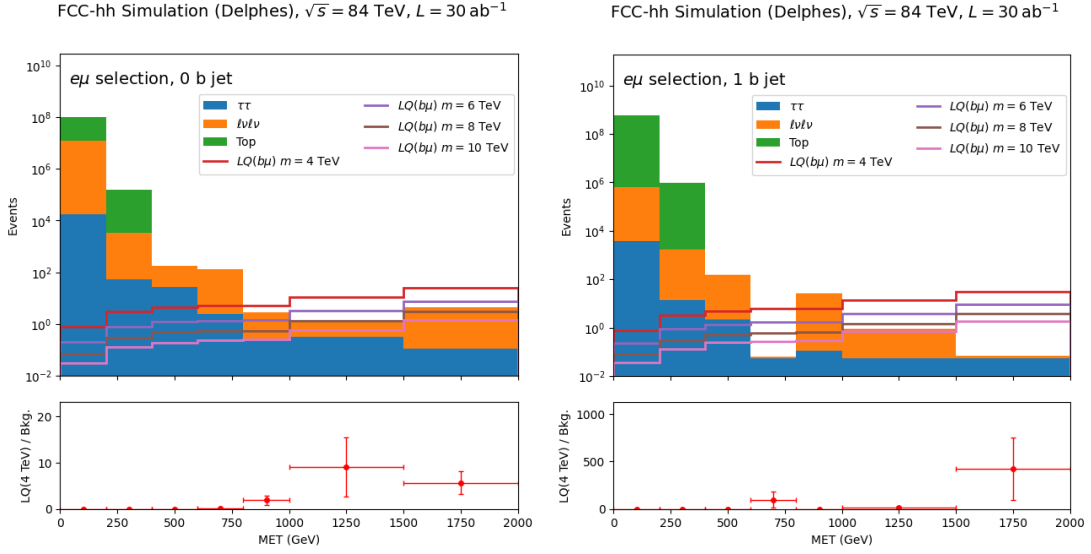


Figure 3: Distributions of the MET in the $e\mu$ final state at the optimized selection level, with 0 (upper left) or at least 1 (upper right) b-tagged jet. The tauonic LQ signal is shown for several mass hypotheses, using $g_U = 1$. The last bin includes the overflow.

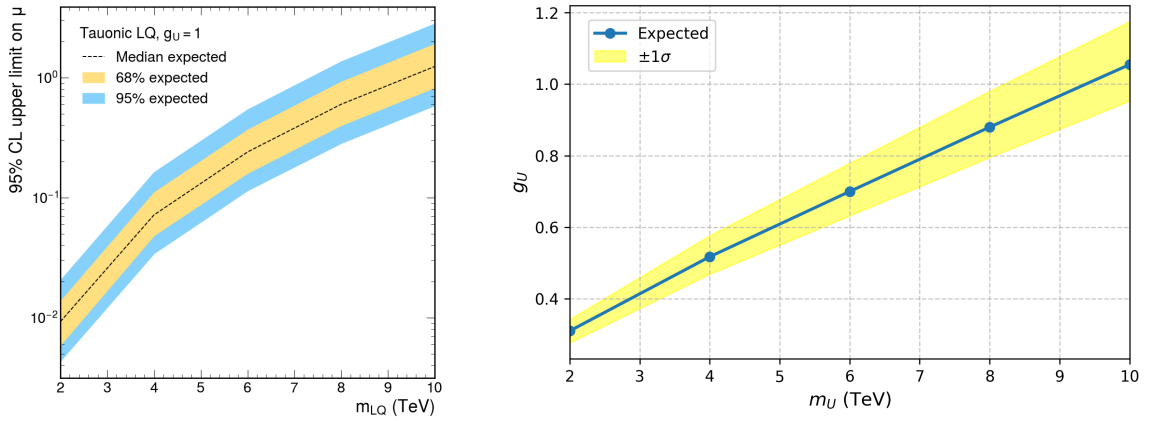


Figure 4: Left: Expected 65% confidence level upper limits on the signal strength of a tauonic LQ with $g_U = 1$. Right: Expected 95% confidence level upper limit on the coupling g_U for a tauonic LQ.

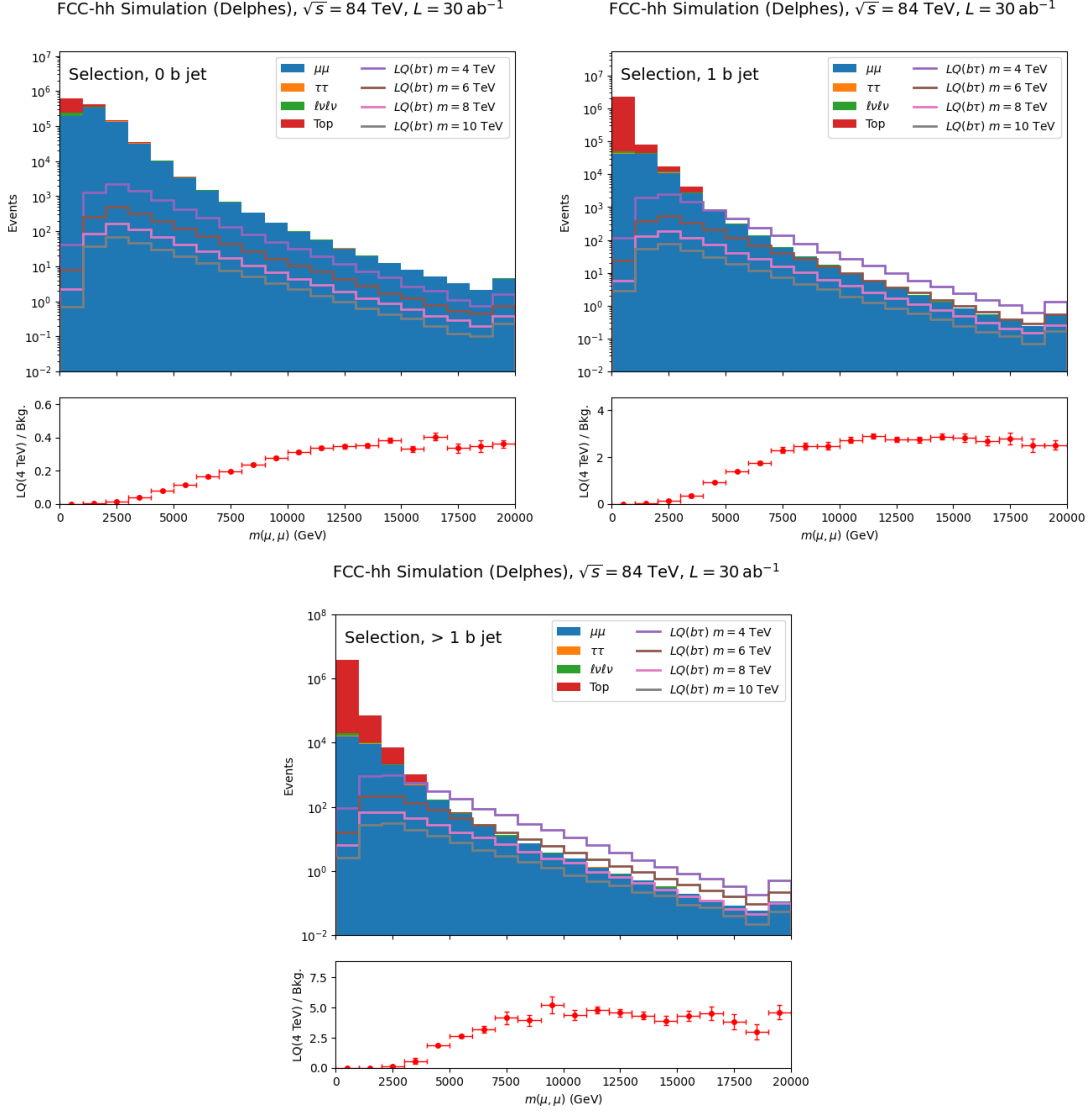


Figure 5: Distributions of the dimuon invariant mass in the $\mu\mu$ final state at the optimized selection level, with 0 (upper left), 1 (upper right), or at least 2 (lower) b-tagged jets. The muonic LQ signal is shown for several mass hypotheses, using $g_U = 1$. The last bin includes the overflow.

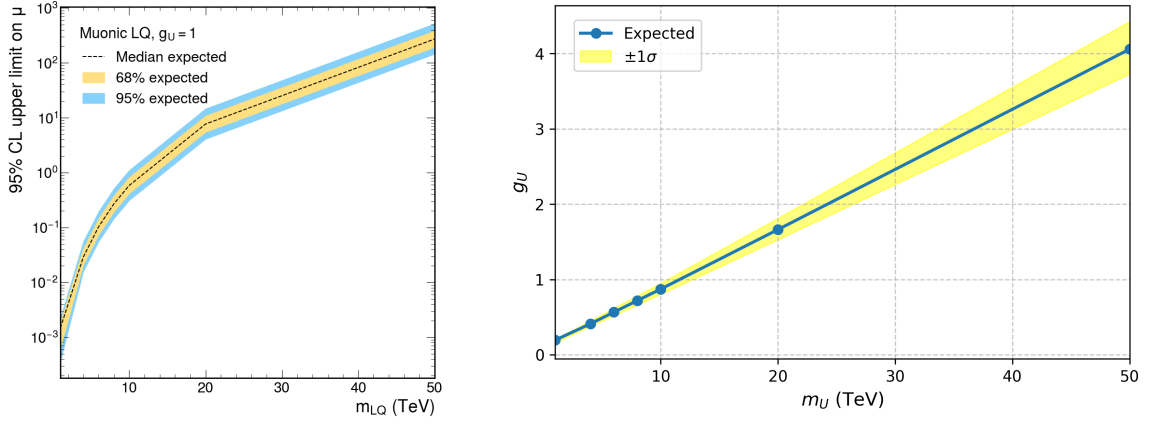


Figure 6: Left: Expected 65% confidence level upper limits on the signal strength of a muonic LQ with $g_U = 1$. Right: Expected 95% confidence level upper limit on the coupling g_U for a muonic LQ.