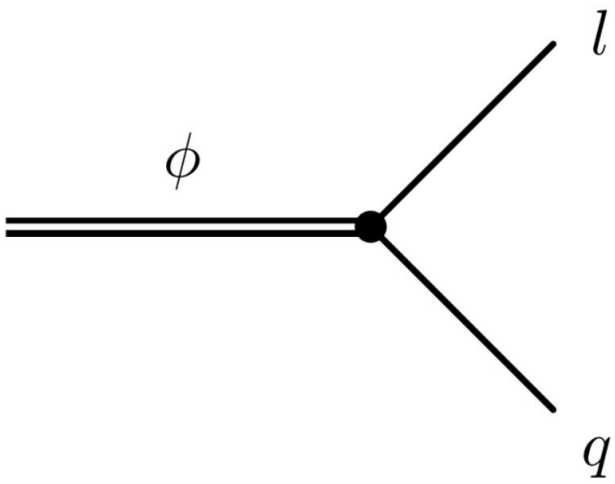
Leptoquark searches

Vojtech Pleskot, Charles University
On behalf of ATLAS and CMS

19. 9. 2023

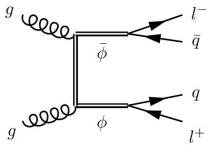
Leptoquarks



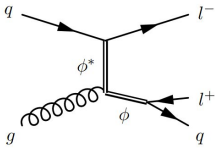
- Simultaneously couple to a lepton and a quark
- Have:
  - baryon and lepton quantum numbers
  - electric charge
  - **colour charge**
  - spin 0 or 1
- Could explain R_{D^*} or $(g-2)_\mu$ deviations

Search strategies

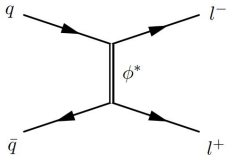
Pair production $\sigma \sim \lambda^0$



Single production $\sigma \sim \lambda^2$



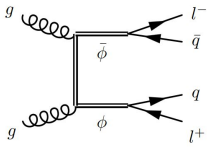
DY production $\sigma \sim \lambda^4$



*arXiv:1706.05033, arXiv:1810.10017

Search strategies

Pair production $\sigma \sim \lambda^0$



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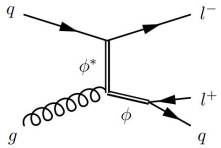

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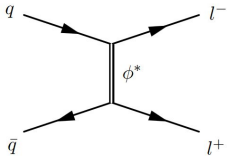

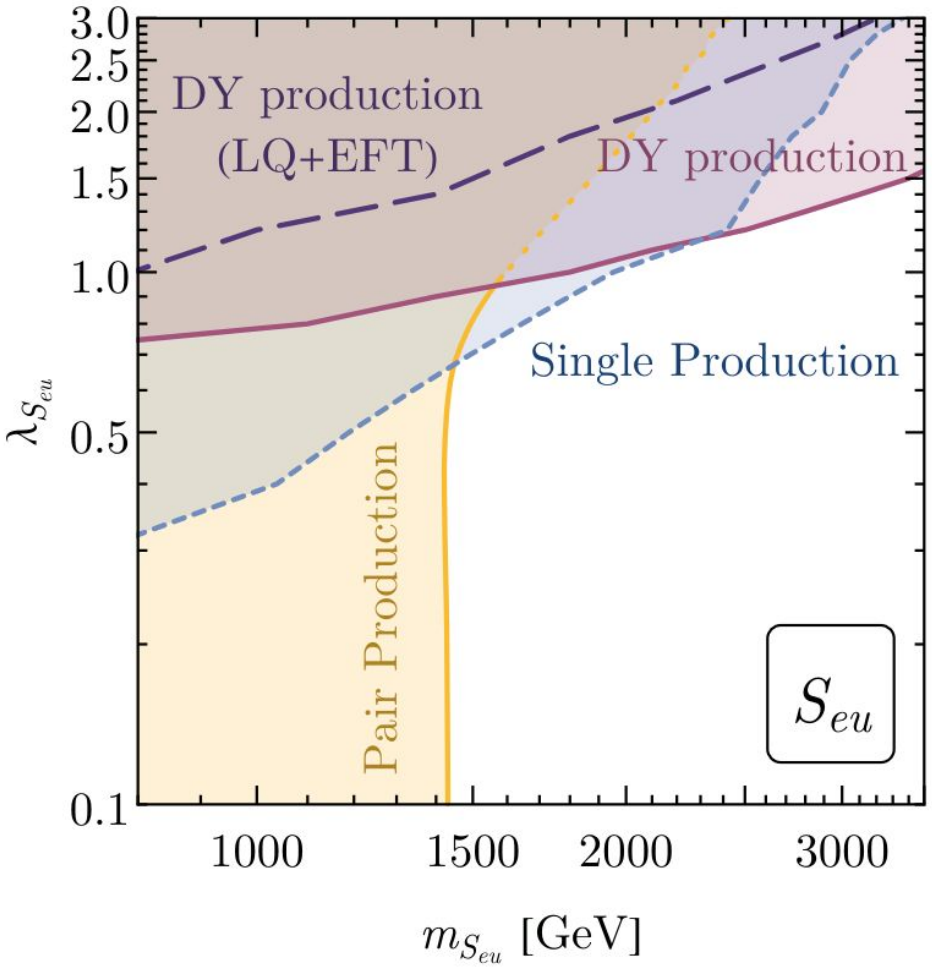

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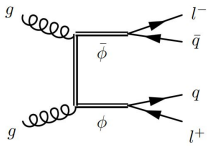
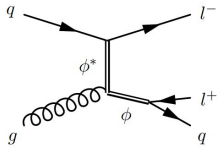
Search strategies

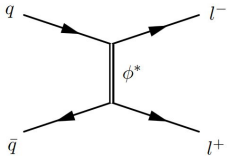
Pair production $\sigma \sim \lambda^0$



Single production $\sigma \sim \lambda^2$



DY production $\sigma \sim \lambda^4$

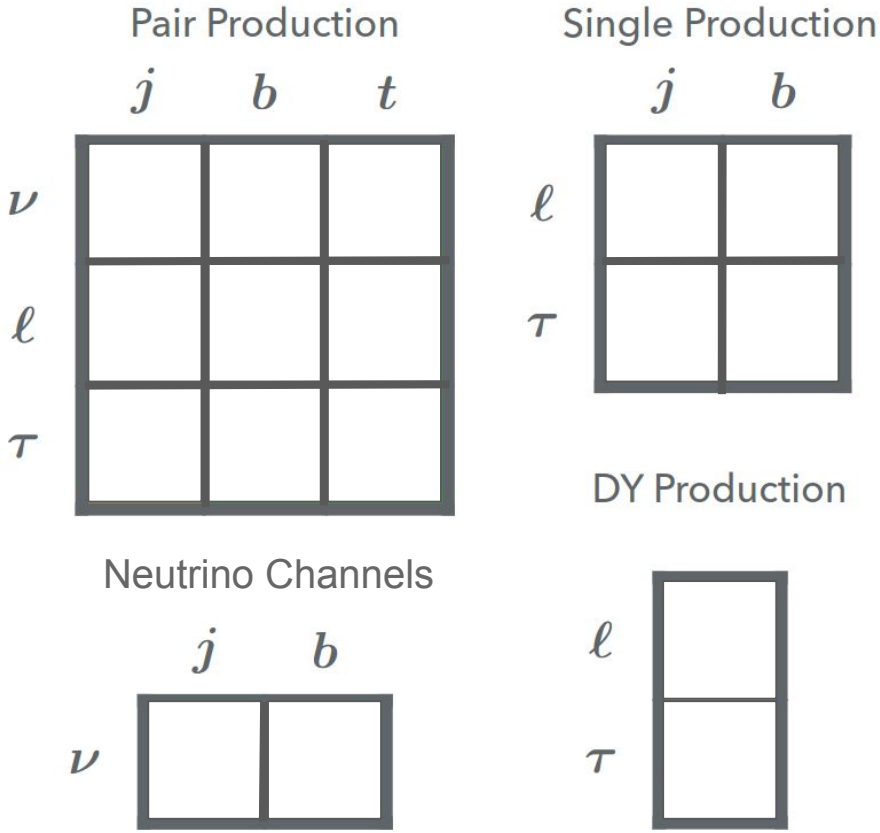


σ of all production modes depends on the LQ spin
- ATLAS/CMS acceptance x efficiency depends on the spin just mildly

σ depends on:
- quark flavour due to PDF
- chirality of the fermions

*arXiv:1706.05033, arXiv:1810.10017

Leptoquark search landscape



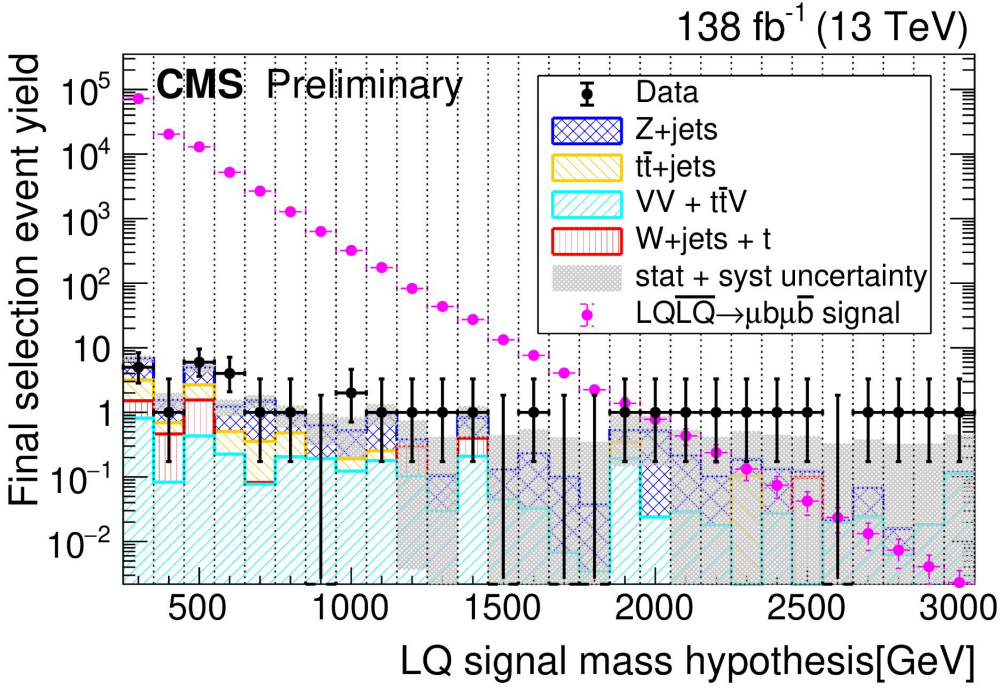
- Classification by the final state objects
- This is a very minimal set of possible searches
  - Each time, focusing just on one LQ-l-q coupling and ignoring the rest
- ATLAS and CMS do more
  - exploit “mixed” final states to maximize sensitivity
    - e.g. combination of ejej and vjej final states

*arXiv:1810.10017

LQLQ → μbμb CMS

CMS-PAS-EXO-21-019

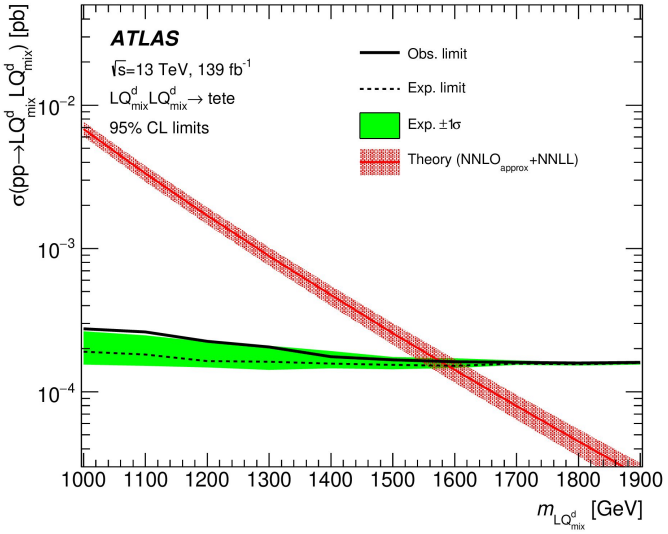
- Event selection:
  - 2μ, ≥2 jets, at least 1 b-tagged
  - $S_T = p_{T,\mu 0} + p_{T,\mu 1} + p_{T,j0} + p_{T,j1}$ > 300 GeV
  - $m_{\mu\mu}$ > 250 GeV
- BDT trained for each LQ mass
- Excluded: m_{LQ} < 1810 GeV
  - ATLAS limit: 1.7 TeV
    - ATLAS arXiv:2006.05872

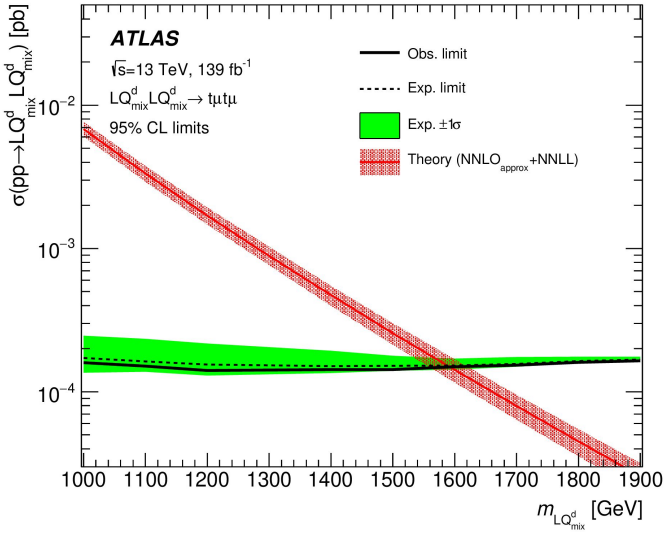


LQLQ → tete or tμtμ ATLAS

arXiv:2306.17642

- Events with 3 or 4 leptons
- $S_T = \Sigma\, p_T^{\text{lep, jet}} + \text{MET}$
- Scalar LQ limits shown here





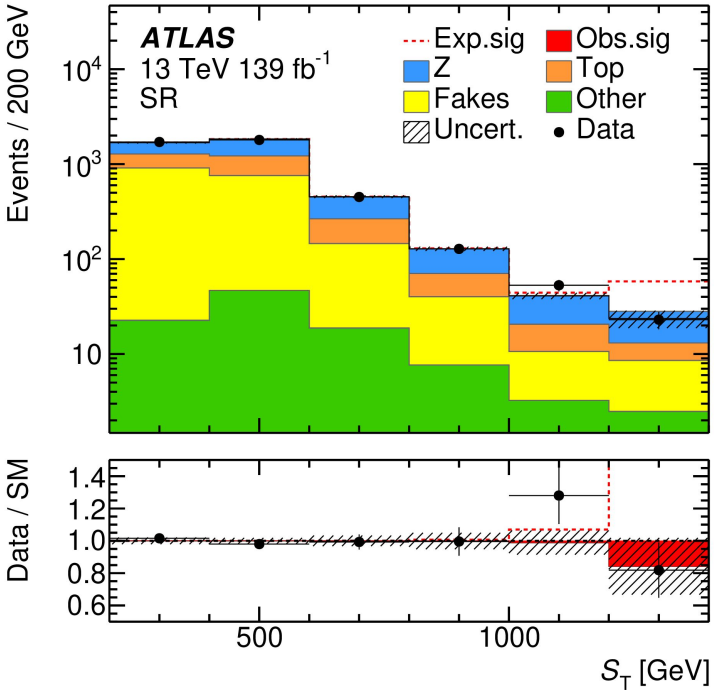
CMS (arXiv:2202.08676) 2t2e: $m_{LQ} < 1340$ GeV

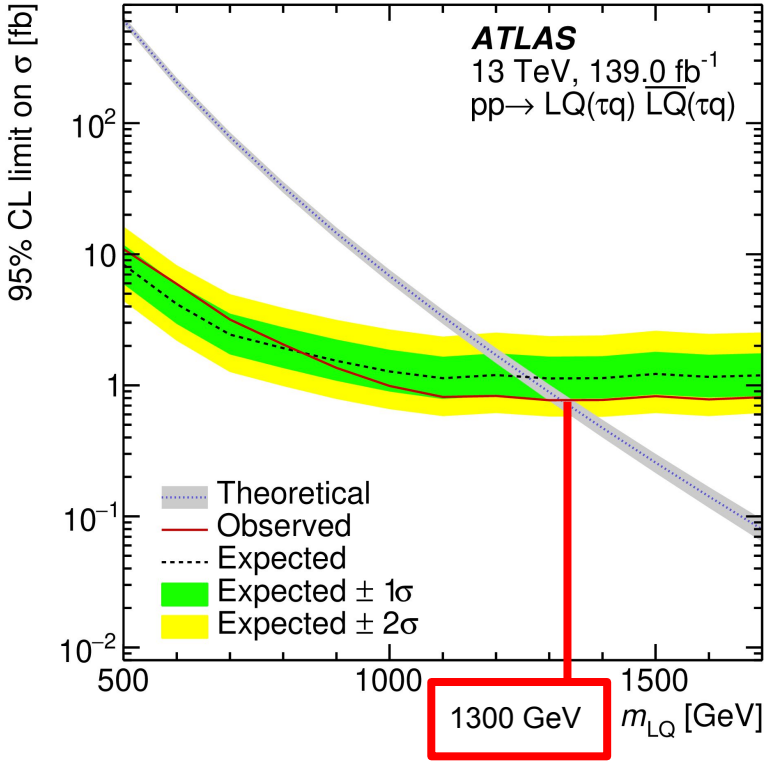
CMS 2t2μ, $m_{LQ} < 1420$ GeV

LQLQ → τqτq ATLAS

arXiv:2303.09444

- 2 τ_{had} + 2 jets final state; no jet flavour tagging!





- CMS limit on LQ coupling to b+τ but exploiting the same events: 1.0 TeV
  - CMS arXiv:1811:00806

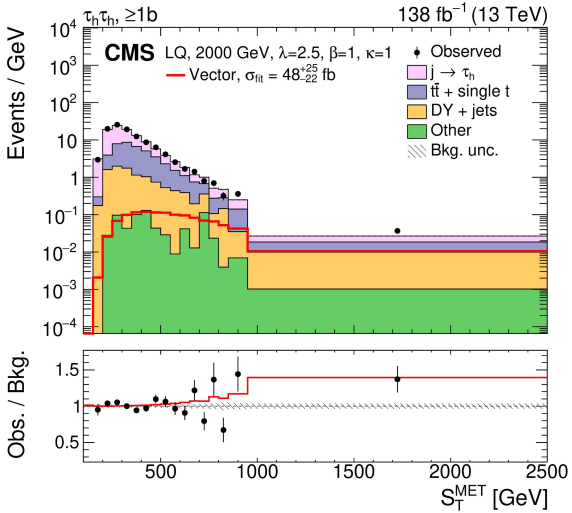
LQ→bτ CMS search

arXiv:2308.07826

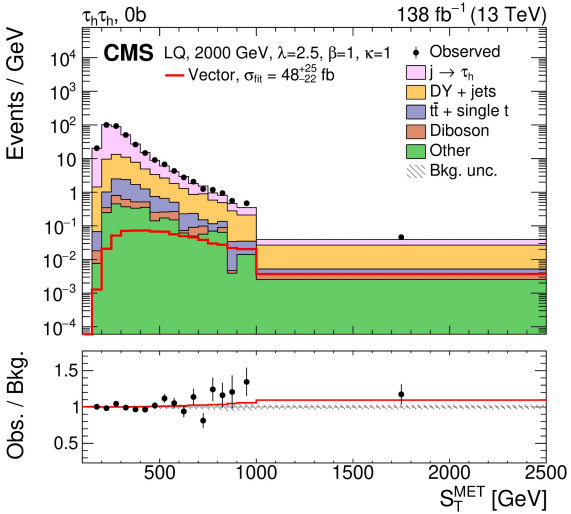
- Signal: Pair + Single + DY production - $p_T^{e,\mu,\tau,j} > 50$ GeV, $m_{TT}^{vis} > 100$ GeV

$\tau_{had}\tau_{had}$ decay channel

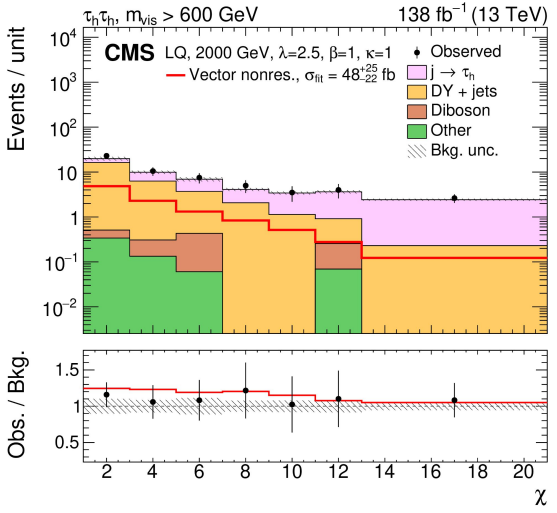
≥ 1 b-jet



≥ 1 jet, 0 b-jets



0 jets



$S_T^{MET} = \Sigma\, p_T^{e,\mu,\tau,j} + MET$

$\chi = \exp(|\Delta\eta_{TT}|)$

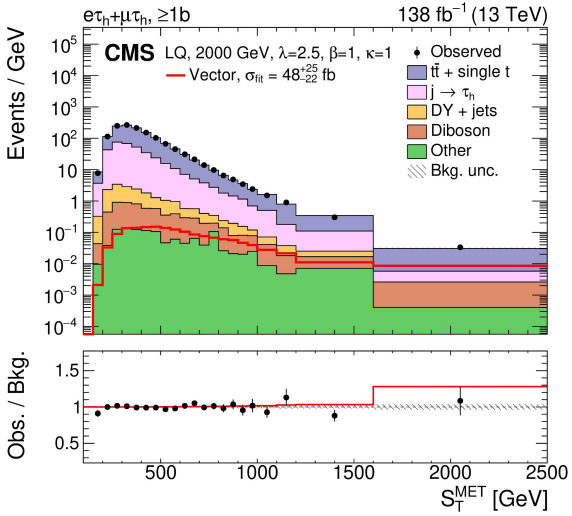
LQ→bτ CMS search

arXiv:2308.07826

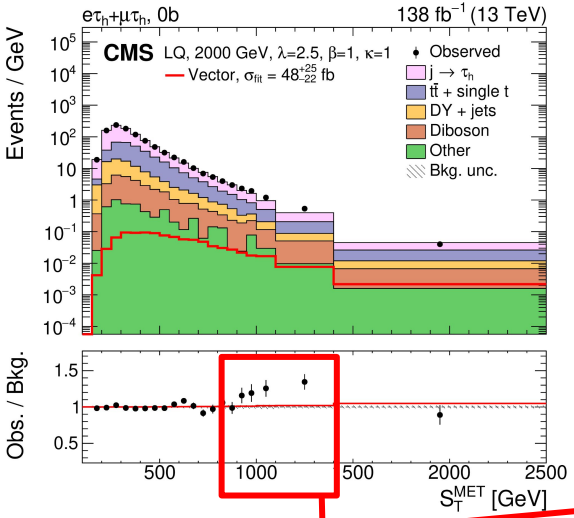
- Signal: Pair + Single + DY production
- $p_T^{e,\mu,\tau,j} > 50$ GeV, $m_{TT}^{vis} > 100$ GeV

$\tau_{lep}\tau_{had}$ decay channel

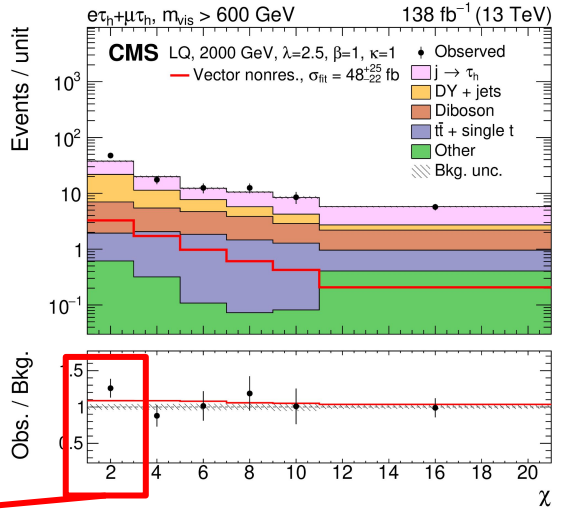
≥ 1 b-jet



≥ 1 jet, 0 b-jets



0 jets

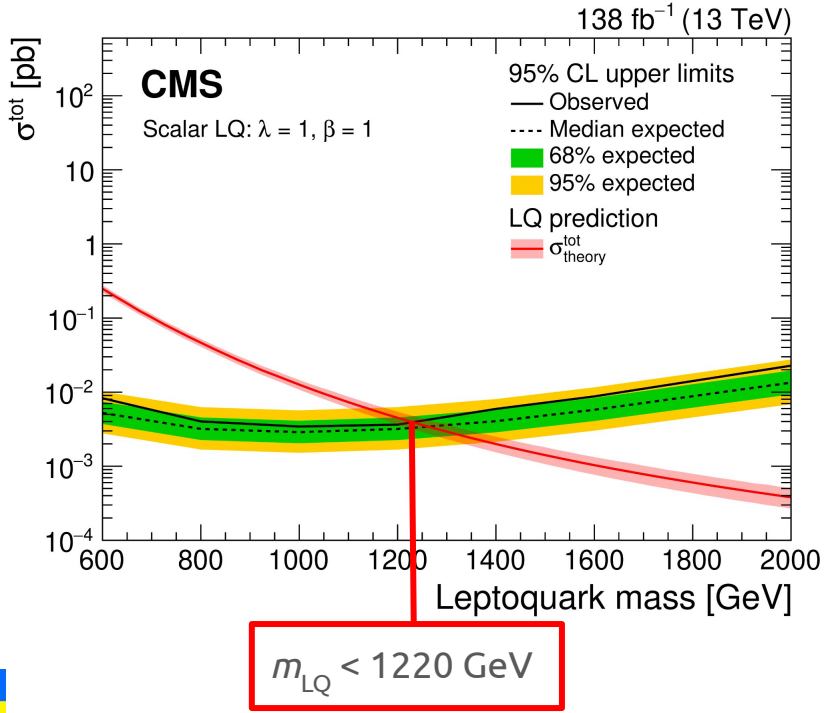


This largest excess is not really expected by the model with just the LQ-b-τ coupling!

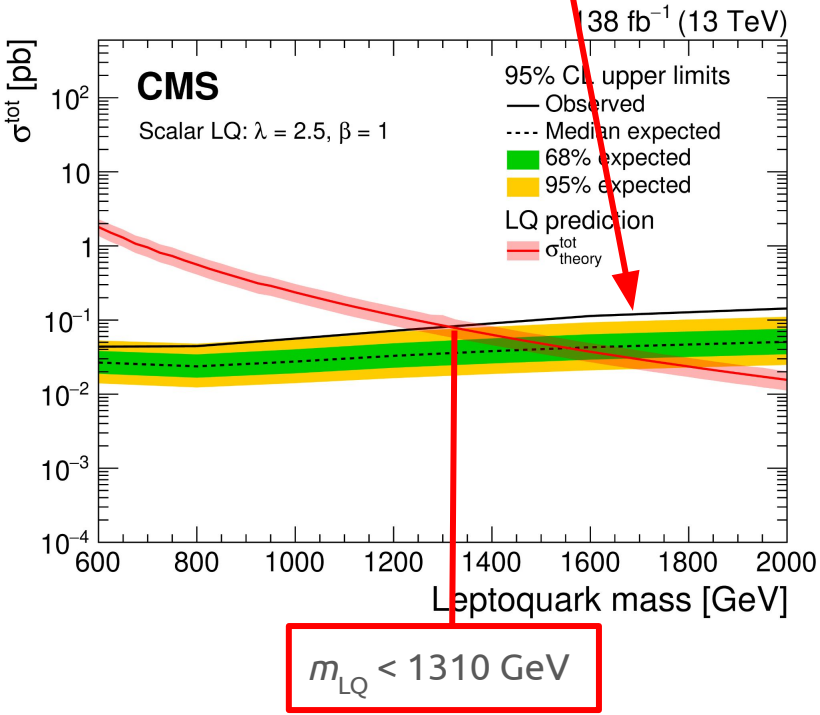
LQ→bτ CMS search

arXiv:2308.07826

- Highest significance of 2.8σ for scalar LQ with λ = 2.5 and m_{LQ} ~ 2 TeV



Due to the excess of events in several regions

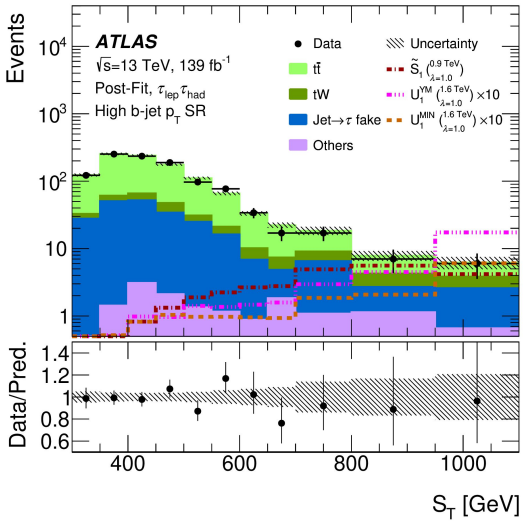


LQ→bτ ATLAS search

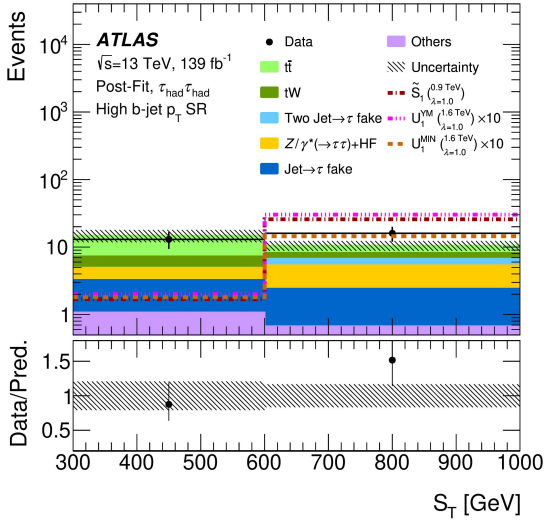
arXiv:2305.15962

- Pair + Single + DY production
- 2τ + b-jet events
- Limit: m_{LQ} < 1.8 TeV (2.8 TeV) for λ = 2.5 scalar (vector) LQ model

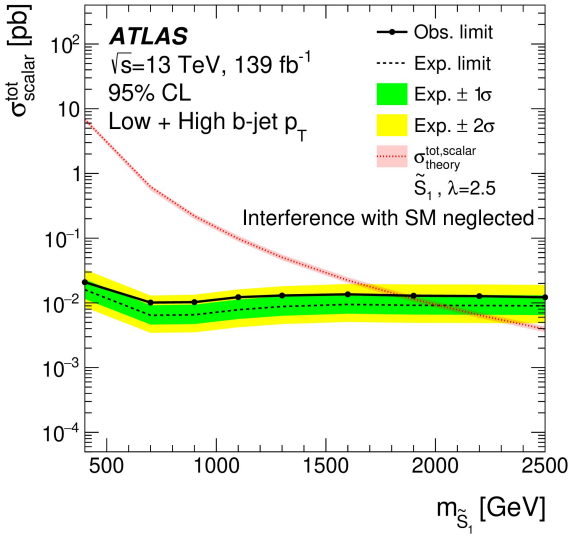
$T_{lep}T_{had}$



$T_{had}T_{had}$

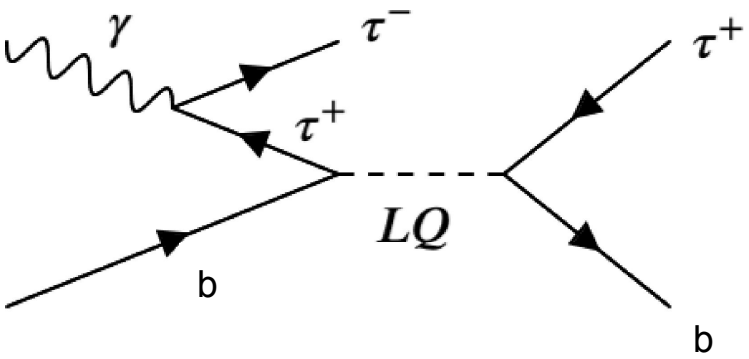


Scalar LQ σ limit



LQ → τb, produced in τ-b scattering! CMS [arXiv:2308.06143]

- Possible thanks to the lepton PDF LUXLEP!
- Complementary to the single LQ searches using 2τ + b-jet events!



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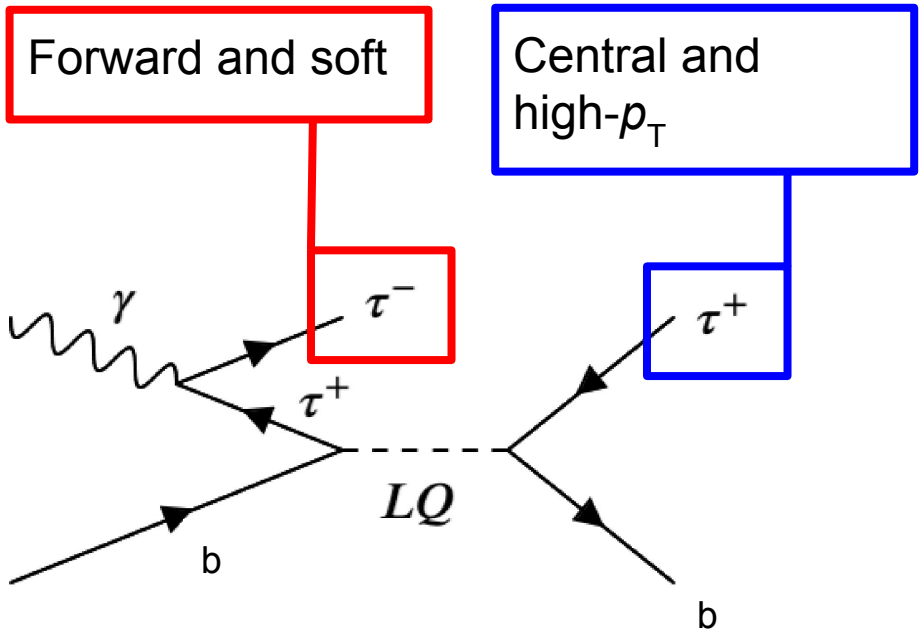
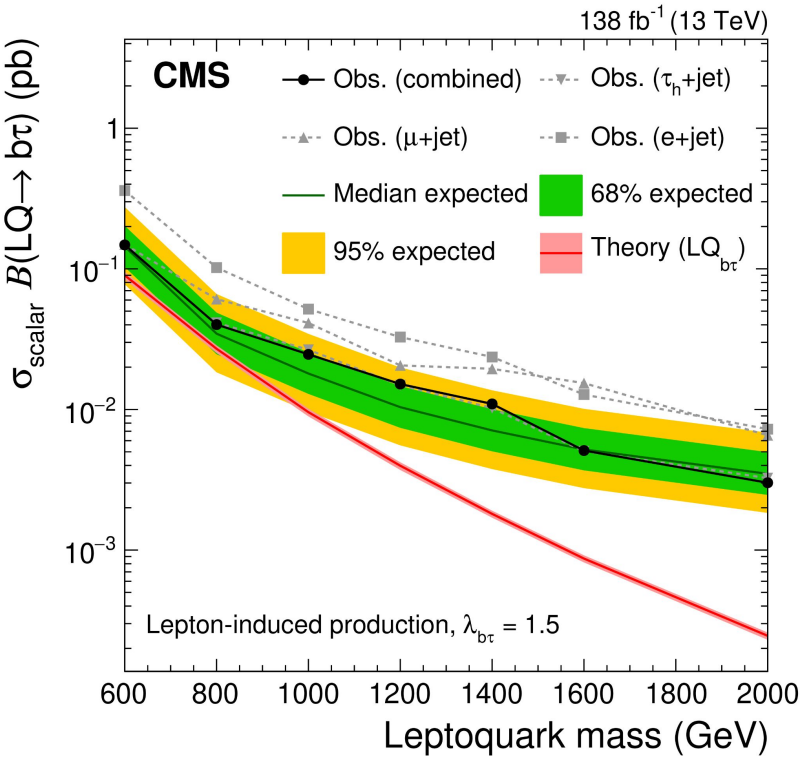
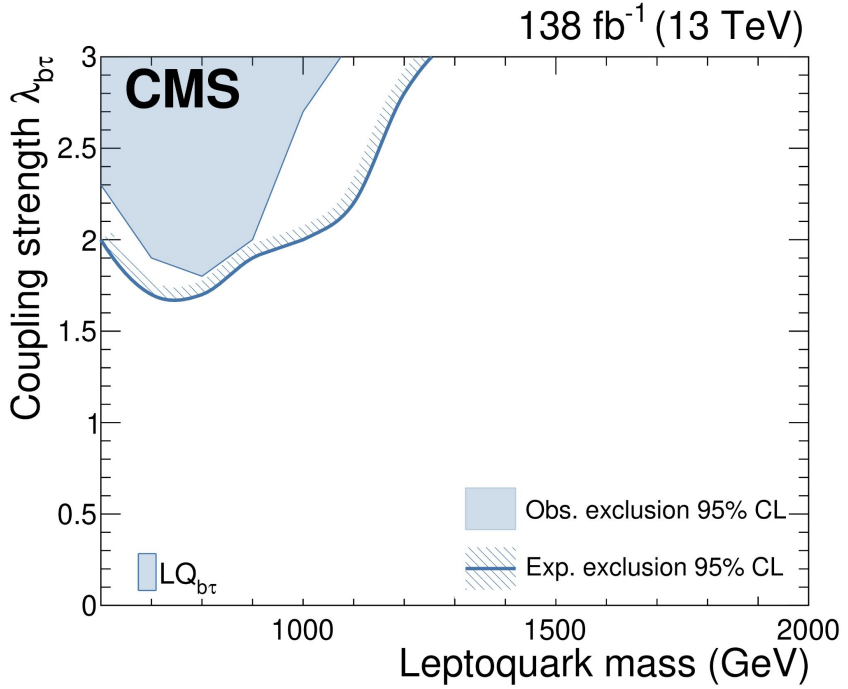


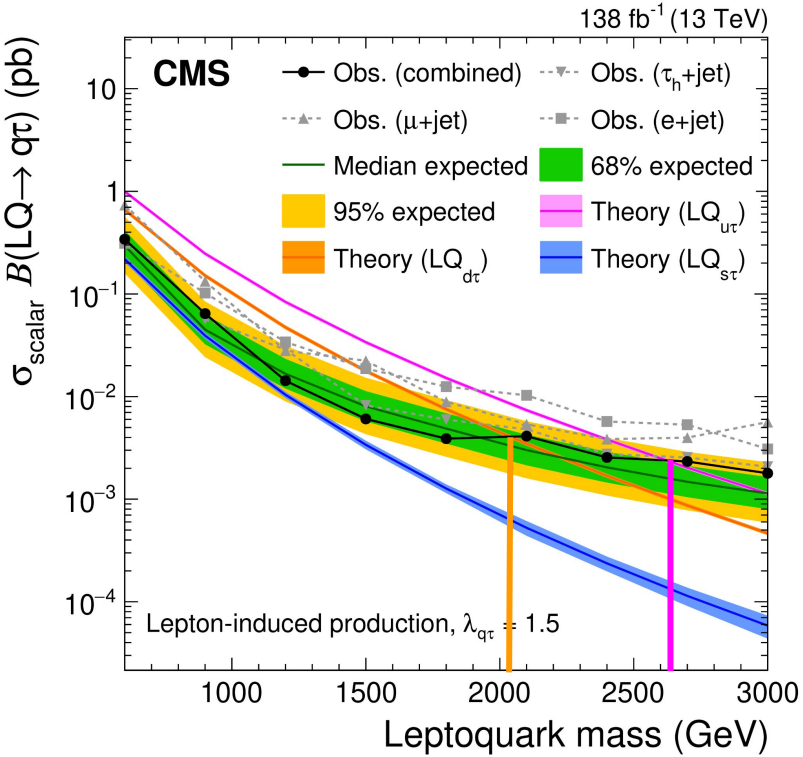
- Possible thanks to the lepton PDF LUXLEP!
- Complementary to the single LQ searches using 2τ + b-jet events!
- τ + b-jet in the final state
  - Both τ_{had} and τ_{lep} decays exploited
  - Veto events with a second e, μ or τ
- $p_T(\tau) > 200$ GeV, $p_T(e, \mu) > 100$ GeV
- Using BDT and m_{coll}

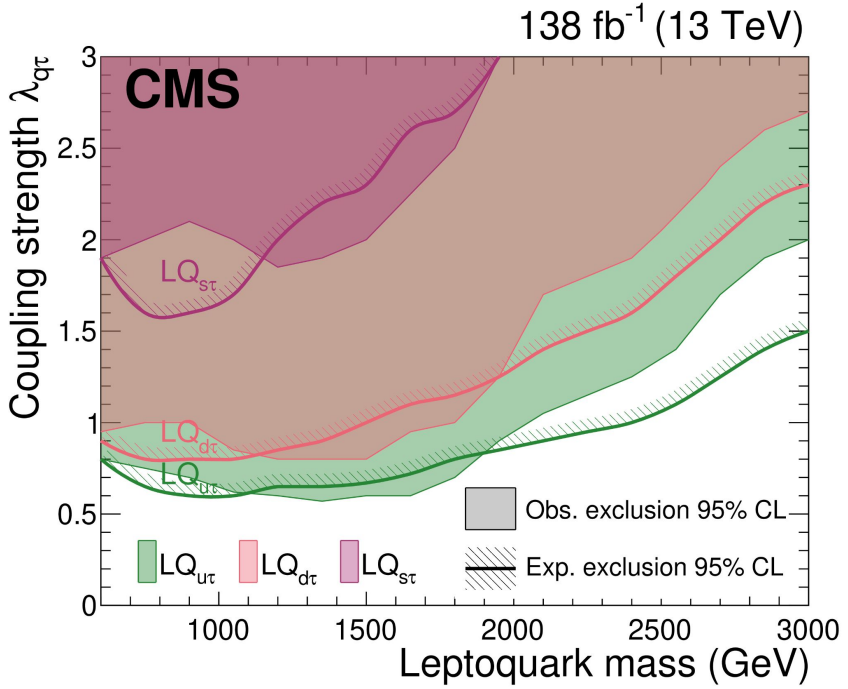
LQ → τb, produced in τ-b scattering! CMS arXiv:2308.06143



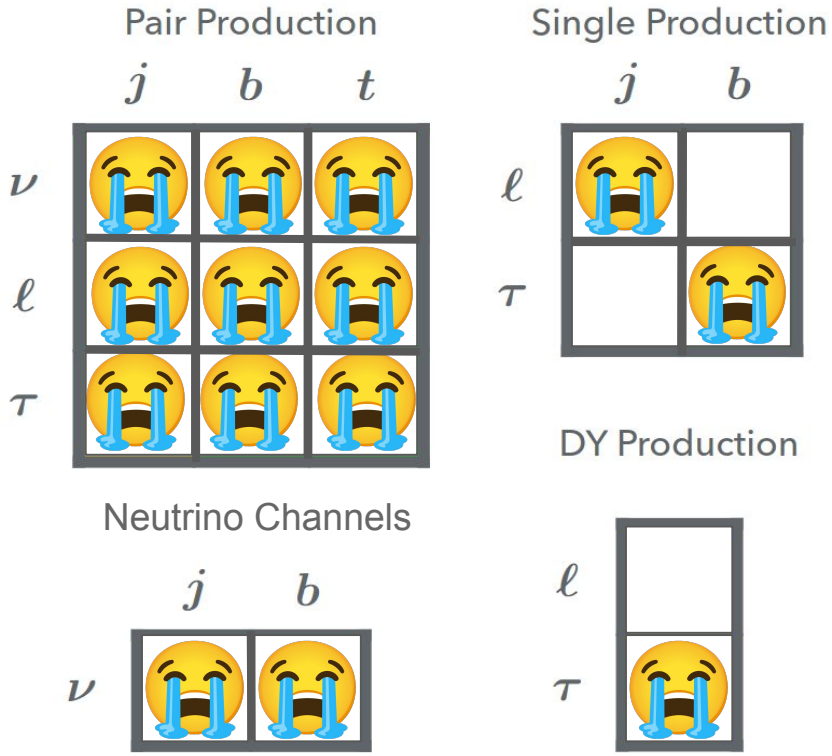


LQ → τq, produced in τ-q scattering! CMS arXiv:2308.06143





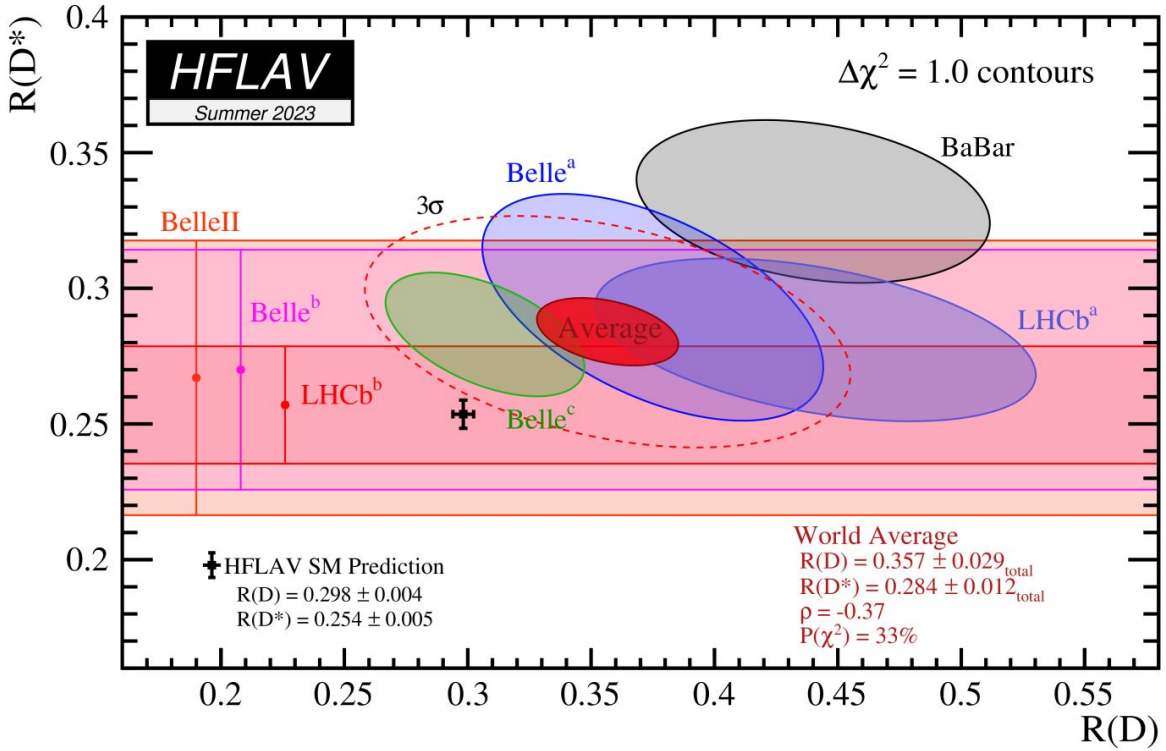
Conclusion

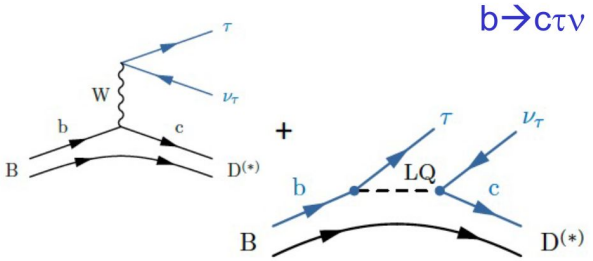


😭 = excluded by LHC searches within a certain (m, λ) range
Limits are mostly at masses of 1 - 1.5 TeV for scalar and 1.5 - 2 TeV for vector LQs

Backup

Interesting motivation for leptoquarks





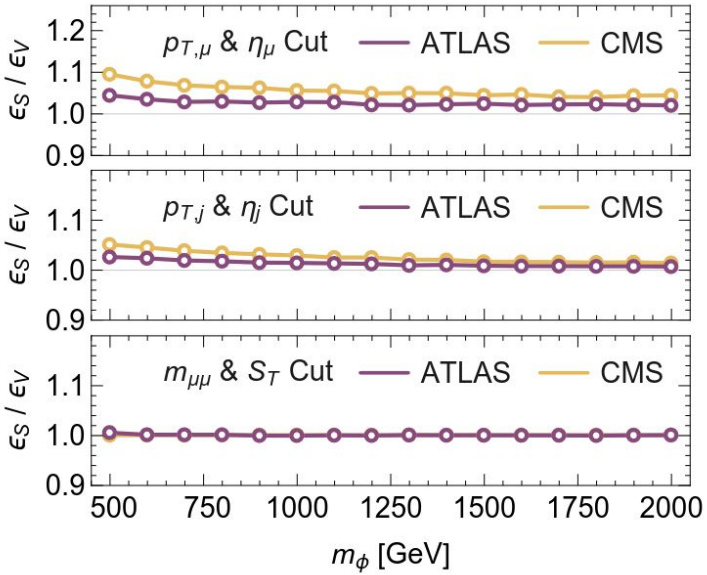
Important LQ couplings:

- LQ-b-τ
- LQ-c-ν_τ

Scalar vs. vector LQ searches

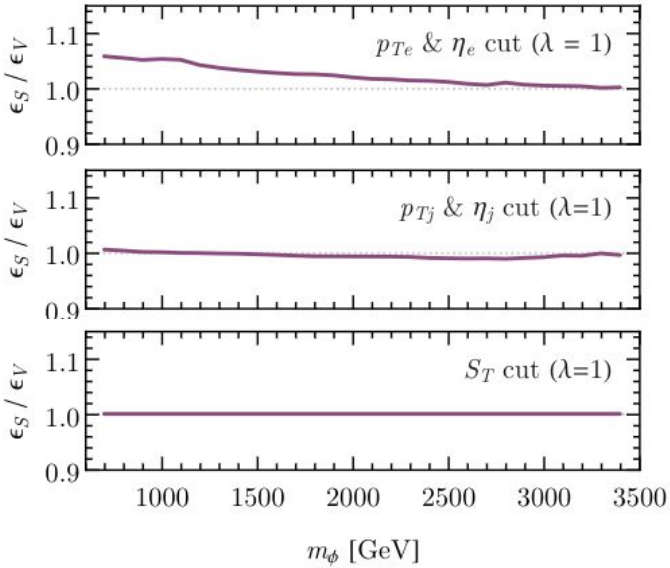
- Efficiency differences small, cross-section for vector LQs larger

Pair production



LQ Hunter's Guide: arXiv:1706.05033,
2μ2j ATLAS: arXiv:1605.06035,
2μ2j CMS: CMS-PAS-EXO-16-007

Single production



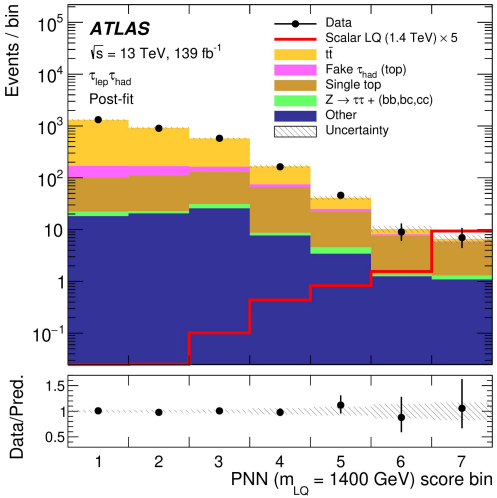
LQ Hunter's Guide: arXiv:1810.10017,
2e1j CMS: arXiv:1509.03750

LQLQ → 2τ 2b ATLAS search

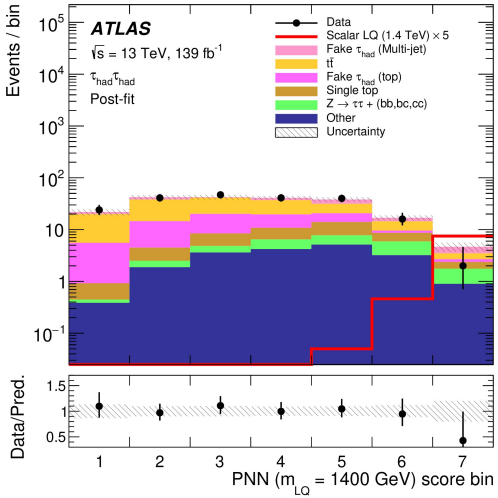
arXiv:2303.01294

- High p_T e, μ, τ, jets, high MET
- Perfect agreement of the data with the background
- Limit: m_{LQ} < 1490 GeV …still lower than the 2 TeV preferred by CMS…

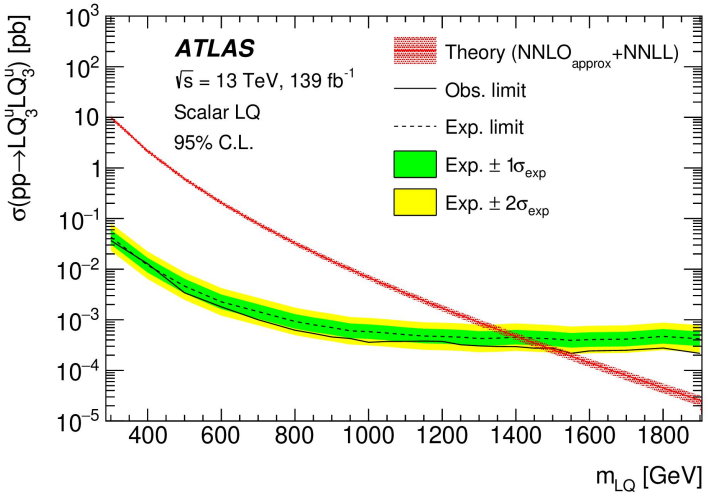
$T_{lep}T_{had}$



$T_{had}T_{had}$

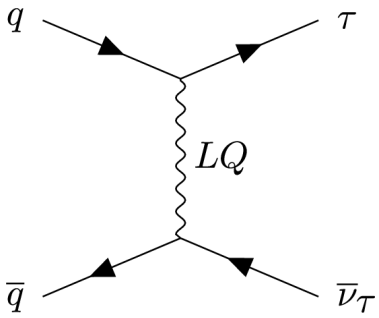


Scalar LQ σ limit

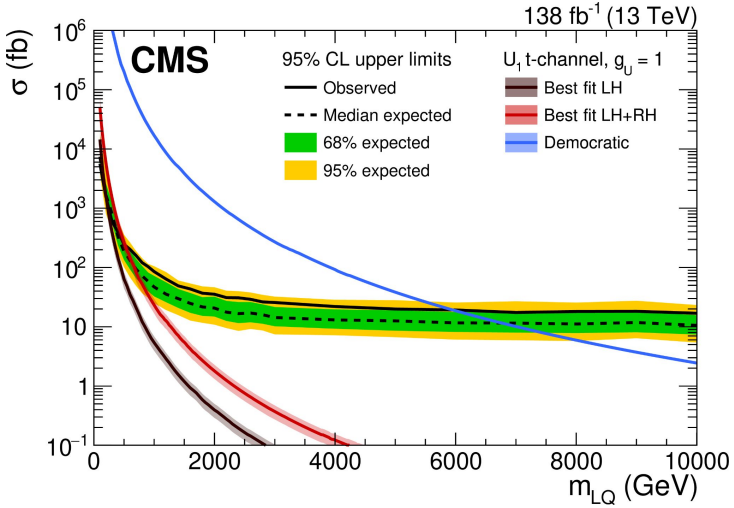


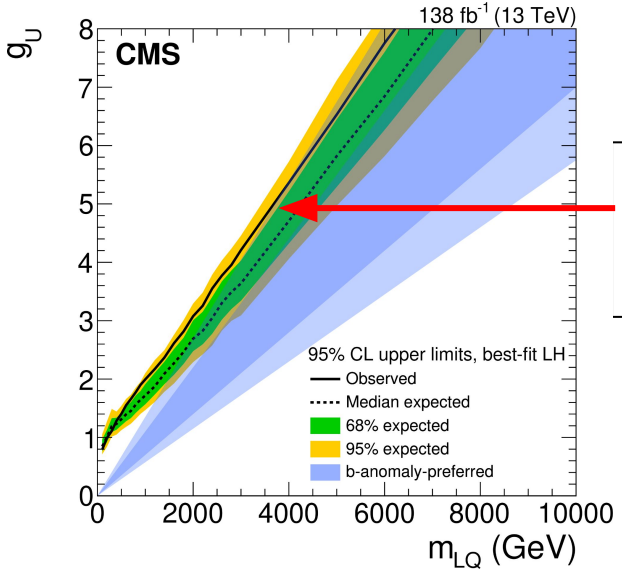
Novel: CMS non-resonant LQ search!

arXiv:2212.12604

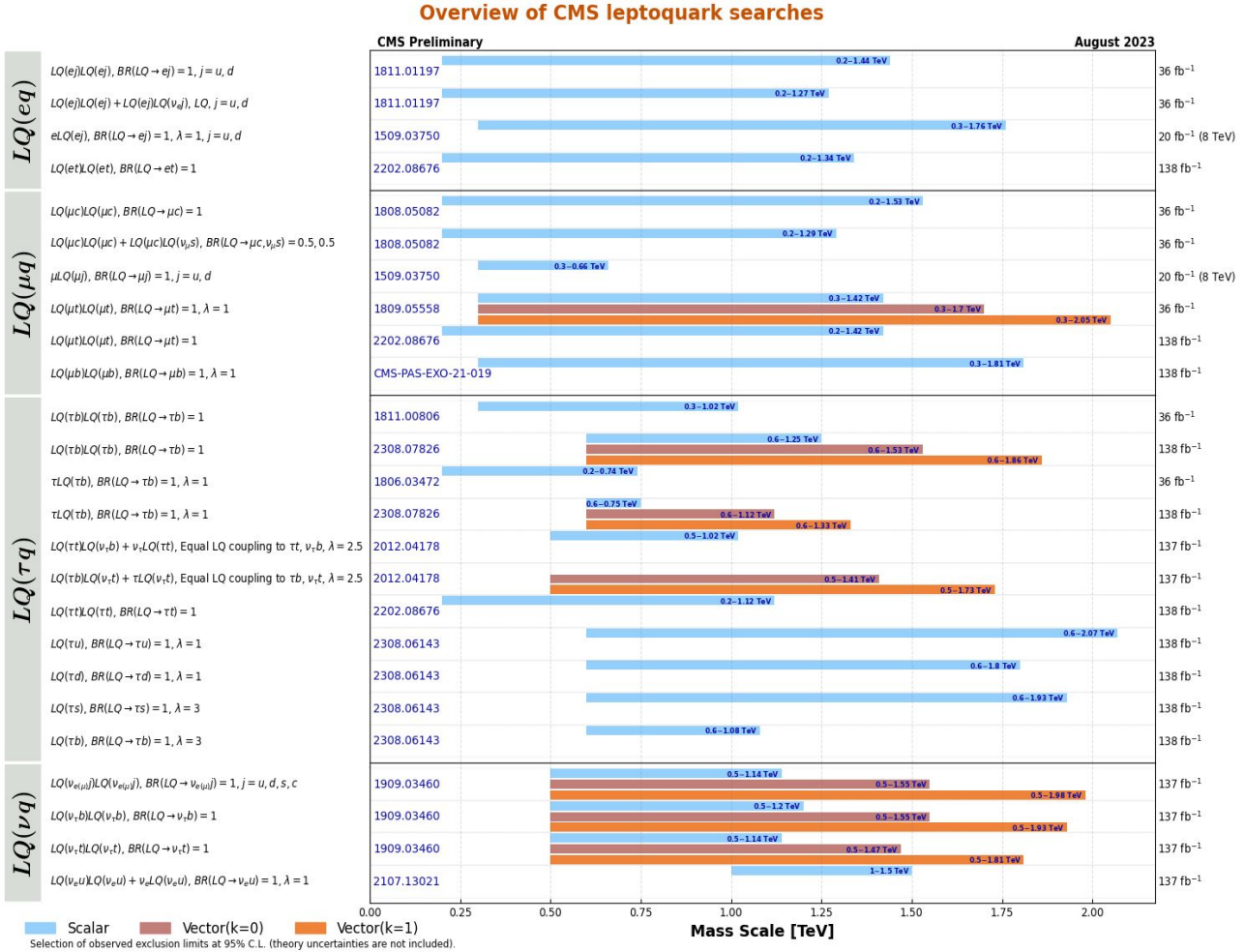


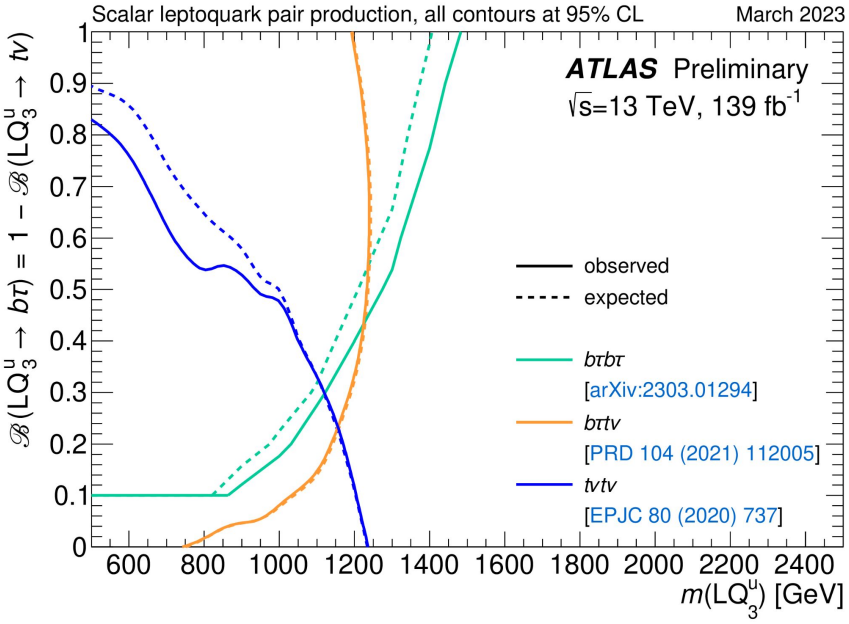
- U(1) vector LQ describing R(K*) and R(D*) data searched for
  - three different scenarios of LQ coupling to SM fermions
- Mass reach increases rapidly with g_U!
  - touching the region preferred by the R(K*) and R(D*) data!

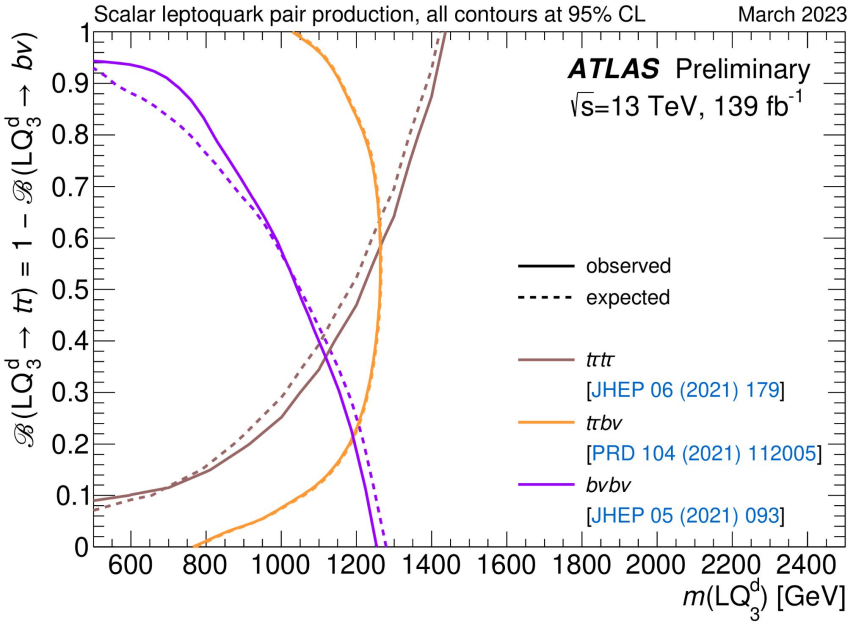


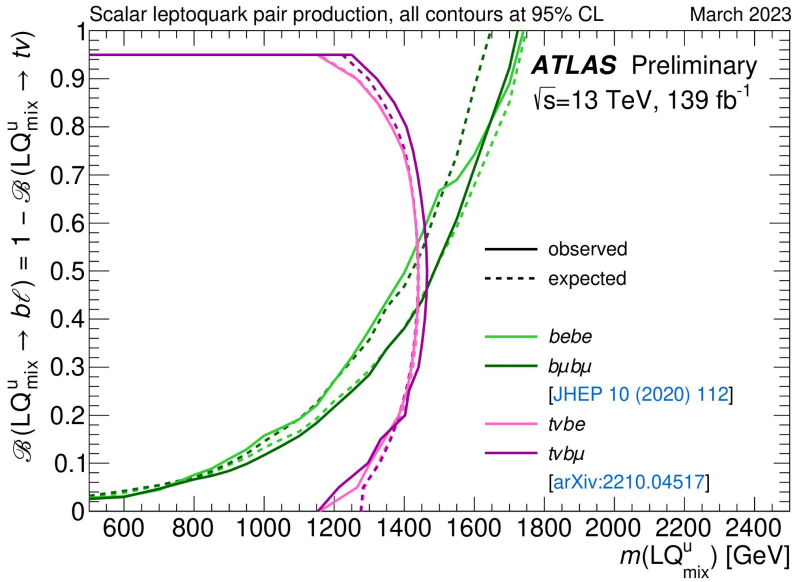


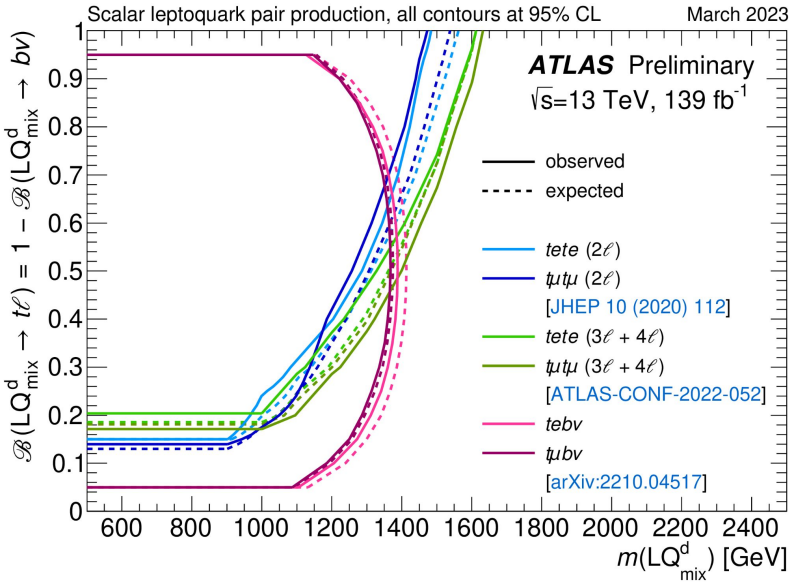
Just couplings to left-handed SM fermions considered here.


Overview of CMS leptoquark searches
CMS Preliminary
August 2023
LQ(eq)
LQ(ej)LQ(ej), BR(LQ → ej) = 1, j = u, d
1811.01197
0.2–1.44 TeV
36 fb−1
LQ(ej)LQ(ej) + LQ(ej)LQ(νej), LQ, j = u, d
1811.01197
0.2–1.27 TeV
36 fb−1
eLQ(ej), BR(LQ → ej) = 1, λ = 1, j = u, d
1509.03750
0.3–1.76 TeV
20 fb−1 (8 TeV)
LQ(et)LQ(et), BR(LQ → et) = 1
2202.08676
0.2–1.34 TeV
138 fb−1
LQ(μq)
LQ(μc)LQ(μc), BR(LQ → μc) = 1
1808.05082
0.2–1.53 TeV
36 fb−1
LQ(μc)LQ(μc) + LQ(μc)LQ(νμs), BR(LQ → μc, νμs) = 0.5, 0.5
1808.05082
0.2–1.29 TeV
36 fb−1
μLQ(μj), BR(LQ → μj) = 1, j = u, d
1509.03750
0.3–0.66 TeV
20 fb−1 (8 TeV)
LQ(μt)LQ(μt), BR(LQ → μt) = 1, λ = 1
1809.05558
0.3–1.42 TeV
0.3–1.7 TeV
0.3–2.05 TeV
36 fb−1
LQ(μt)LQ(μt), BR(LQ → μt) = 1
2202.08676
0.2–1.42 TeV
138 fb−1
LQ(μb)LQ(μb), BR(LQ → μb) = 1, λ = 1
CMS-PAS-EXO-21-019
0.3–1.81 TeV
138 fb−1
LQ(τq)
LQ(τb)LQ(τb), BR(LQ → τb) = 1
1811.00806
0.3–1.02 TeV
36 fb−1
LQ(τb)LQ(τb), BR(LQ → τb) = 1
2308.07826
0.6–1.25 TeV
0.6–1.53 TeV
0.6–1.86 TeV
138 fb−1
τLQ(τb), BR(LQ → τb) = 1, λ = 1
1806.03472
0.2–0.74 TeV
36 fb−1
τLQ(τb), BR(LQ → τb) = 1, λ = 1
2308.07826
0.6–0.75 TeV
0.6–1.12 TeV
0.6–1.33 TeV
138 fb−1
LQ(ττ)LQ(νtb) + νtLQ(tt), Equal LQ coupling to ττ, νtb, λ = 2.5
2012.04178
0.5–1.02 TeV
137 fb−1
LQ(τb)LQ(νtt) + τLQ(νtt), Equal LQ coupling to τb, νtt, λ = 2.5
2012.04178
0.5–1.41 TeV
0.5–1.73 TeV
137 fb−1
LQ(τt)LQ(τt), BR(LQ → τt) = 1
2202.08676
0.2–1.12 TeV
138 fb−1
LQ(τu), BR(LQ → τu) = 1, λ = 1
2308.06143
0.6–2.07 TeV
138 fb−1
LQ(τd), BR(LQ → τd) = 1, λ = 1
2308.06143
0.6–1.8 TeV
138 fb−1
LQ(τs), BR(LQ → τs) = 1, λ = 3
2308.06143
0.6–1.93 TeV
138 fb−1
LQ(τb), BR(LQ → τb) = 1, λ = 3
2308.06143
0.6–1.08 TeV
138 fb−1
LQ(νq)
LQ(νe(μ)j)LQ(νe(μ)j), BR(LQ → νe(μ)j) = 1, j = u, d, s, c
1909.03460
0.5–1.14 TeV
0.5–1.55 TeV
0.5–1.98 TeV
137 fb−1
LQ(νtb)LQ(νtb), BR(LQ → νtb) = 1
1909.03460
0.5–1.2 TeV
0.5–1.55 TeV
0.5–1.93 TeV
137 fb−1
LQ(νtt)LQ(νtt), BR(LQ → νtt) = 1
1909.03460
0.5–1.14 TeV
0.5–1.47 TeV
0.5–1.81 TeV
137 fb−1
LQ(νeu)LQ(νeu) + νeLQ(νeu), BR(LQ → νeu) = 1, λ = 1
2107.13021
1–1.5 TeV
137 fb−1
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
Mass Scale [TeV]
Scalar
Vector(k=0)
Vector(k=1)
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).


Scalar leptoquark pair production, all contours at 95% CL
March 2023
ATLAS Preliminary
√s=13 TeV, 139 fb-1
observed
expected
bτbτ
[arXiv:2303.01294]
bτtν
[PRD 104 (2021) 112005]
tνtν
[EPJC 80 (2020) 737]
B(LQ3u → bτ) = 1 − B(LQ3u → tν)
m(LQ3u) [GeV]


Scalar leptoquark pair production, all contours at 95% CL
March 2023
ATLAS Preliminary
√s=13 TeV, 139 fb-1
observed
expected
ττtt
[JHEP 06 (2021) 179]
ttbν
[PRD 104 (2021) 112005]
bνbν
[JHEP 05 (2021) 093]
B(LQ3d → tτ) = 1 − B(LQ3d → bν)
m(LQ3d) [GeV]


Scalar leptoquark pair production, all contours at 95% CL
March 2023
ATLAS Preliminary
√s=13 TeV, 139 fb-1
observed
expected
bebe
bμbμ
[JHEP 10 (2020) 112]
tνbe
tνbμ
[arXiv:2210.04517]
B(LQ^u_mix → bℓ) = 1 − B(LQ^u_mix → tν)
m(LQ^u_mix) [GeV]


Scalar leptoquark pair production, all contours at 95% CL
March 2023
ATLAS Preliminary
√s=13 TeV, 139 fb-1
observed
expected
tete (2ℓ)
tμtμ (2ℓ)
[JHEP 10 (2020) 112]
tete (3ℓ + 4ℓ)
tμtμ (3ℓ + 4ℓ)
[ATLAS-CONF-2022-052]
tebν
tμbν
[arXiv:2210.04517]
B(LQ^d_mix → tℓ) = 1 − B(LQ^d_mix → bν)
m(LQ^d_mix) [GeV]