

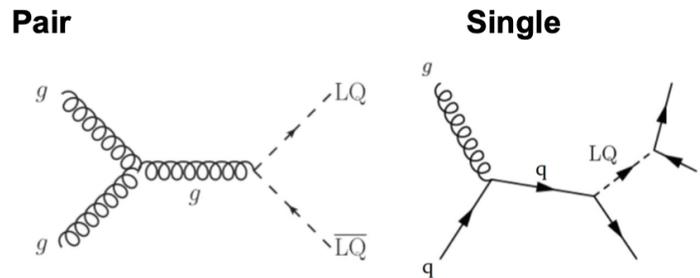
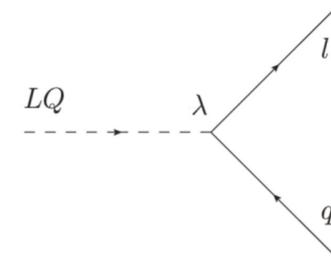
Search for leptoquarks at CMS

Muon Anomalies Workshop
(2021/May/21)

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Leptoquark(LQ) physics

- The leptoquark is a boson that couples to a lepton and a quark with coupling λ , and carries both lepton and baryon number.
- LQ Charge : $\pm\frac{5}{3}e$, $\pm\frac{4}{3}e$, $\pm\frac{2}{3}e$, $\pm\frac{1}{3}e$
- Types :
 - Scalar : LQ_S
 - Vector : LQ_V
- Couplings
 - λ : LQ and SM lepton/quark
 - k : dimensionless, relevant only for vector
 - $k=0$: minimal coupling , $k=1$: Yang-Mills
- Production



Motivation

From EXO-19-015 slide

Several BSM ideas foresee new bosons that carry both lepton and baryon number

Can $SU(3) \times SU(2) \times U(1)$ originate from a larger symmetry group?

→ [Grand Unified Theory](#)

→ Quarks and leptons unified in a fermionic multiplet with lepton-quark interaction mediated by new gauge bosons

Can fermions be made of more fundamental objects?

→ [Compositeness](#)

→ Bound states of fundamental constituents may decay to a quark and a lepton

Can a symmetry exist between fermions and bosons?

→ [Supersymmetry](#)

→ Possible decay of sparticles to a quark and a lepton (see e.g. R-parity violation scenario)

- Searches for LQ at the LHC are well-motivated.
- LQ is a possible candidate to explain some recent anomalies in B-physics and $g-2$ measurement.

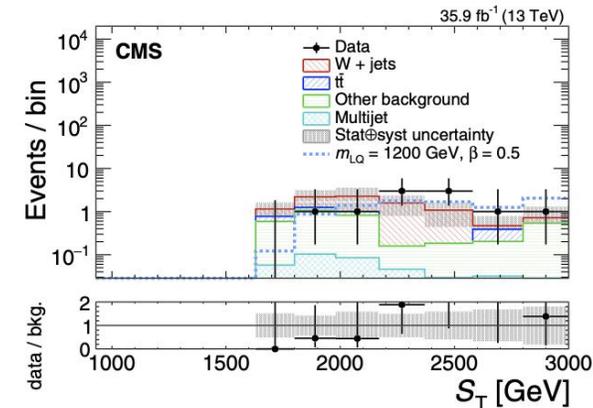
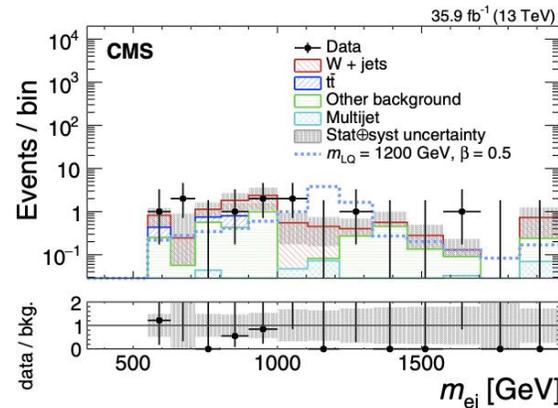
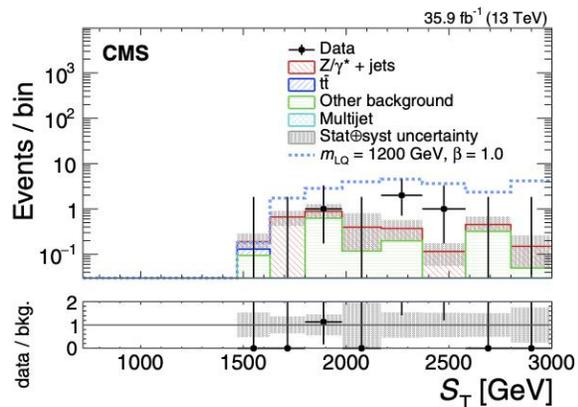
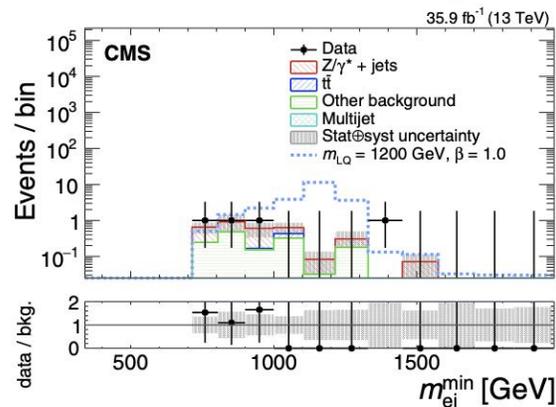
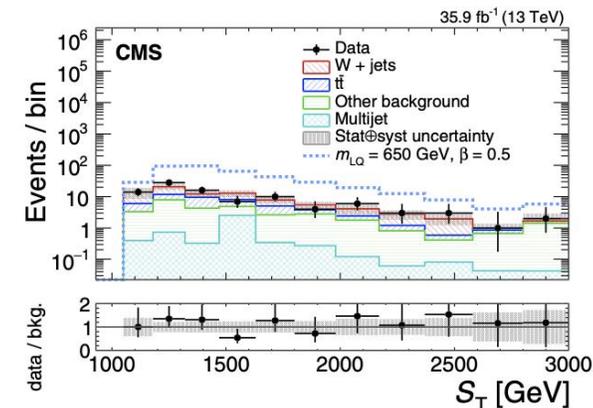
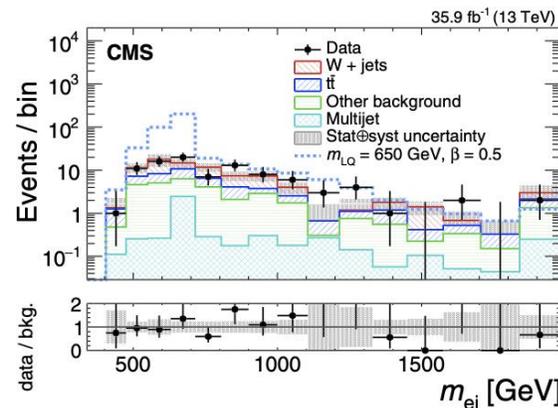
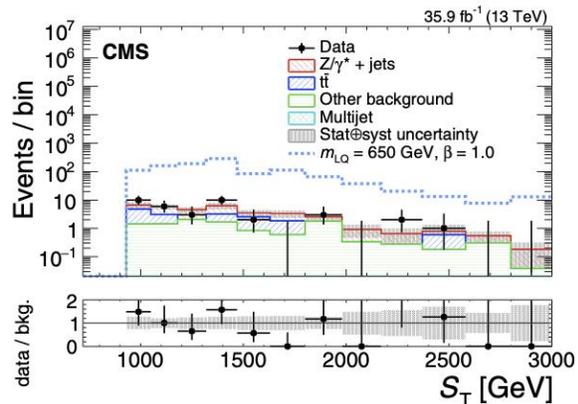
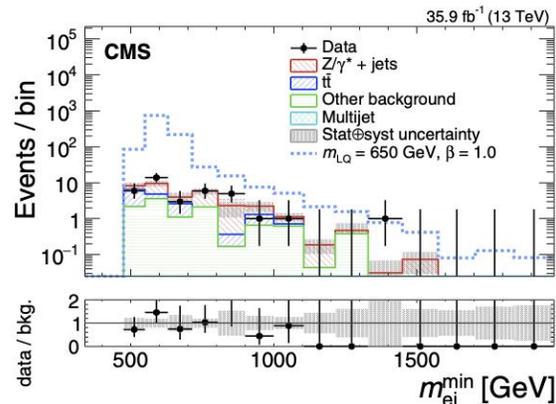
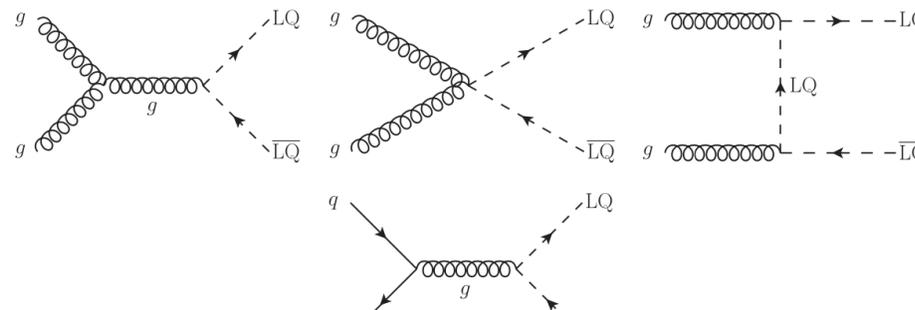
This talk is based on recent CMS public results

- 1st generation : $LQ > eq$
PRD.99.052002(2019), arXiv:1811.01197
PRD.93.032005(2016), arXiv:1509.03750
- 2nd generation : $LQ > \mu q$
PRD.99.032014(2019), arXiv:1808.05082
PRD.93.032005(2016), arXiv:1509.03750
PRL.121.241802(2018), arXiv:1809.05558
- 3rd generation : $LQ > \tau q$
JHEP03(2019)170, arXiv:1811.00806
JHEP07(2018)115, arXiv:1806.03472
EPJC(2018)78:707, arXiv:1803.02864
arXiv:2012.04178(submitted to PLB) (full run2 data , 137 fb⁻¹)
- Neutrino coupling : $LQ > \nu q$, ($q=u d c s t b$)
EPJC(2020)80:3, arXiv:1909.03460 (full run2 data , 137 fb⁻¹)

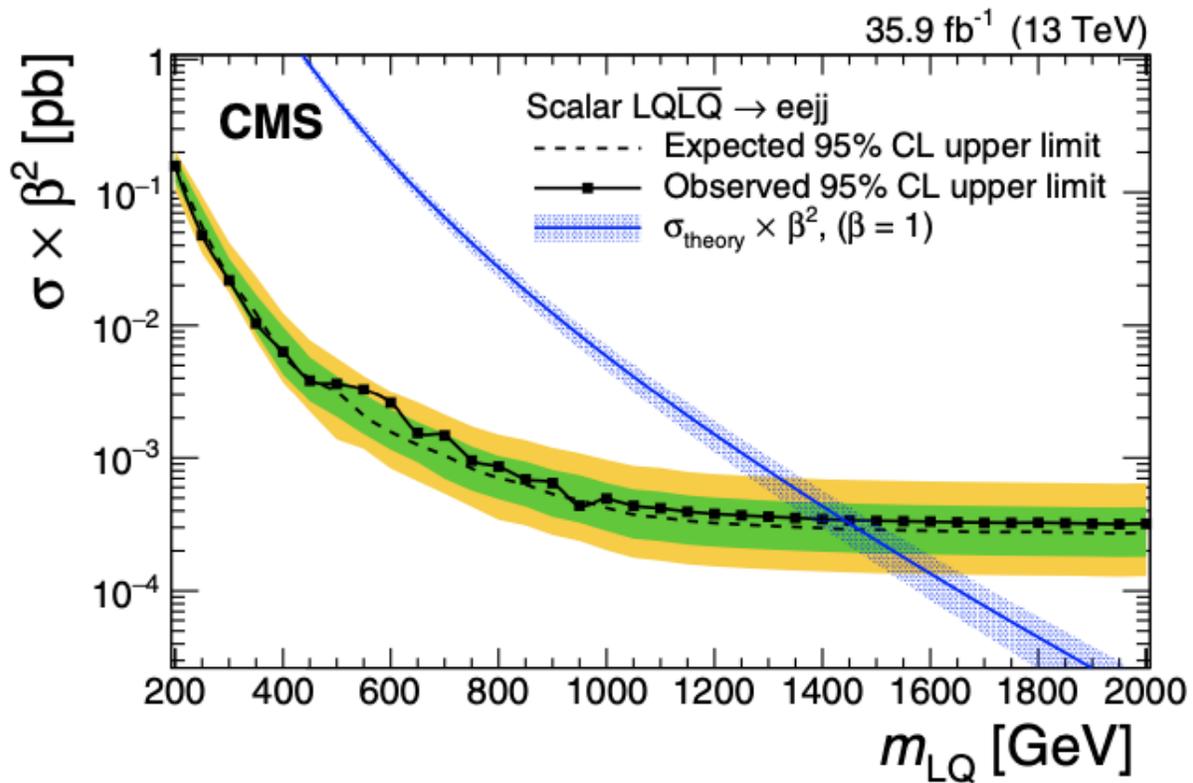
1st generation scalar LQ - pair production

PRD.99.052002(2019)
(arXiv:1811.01197)

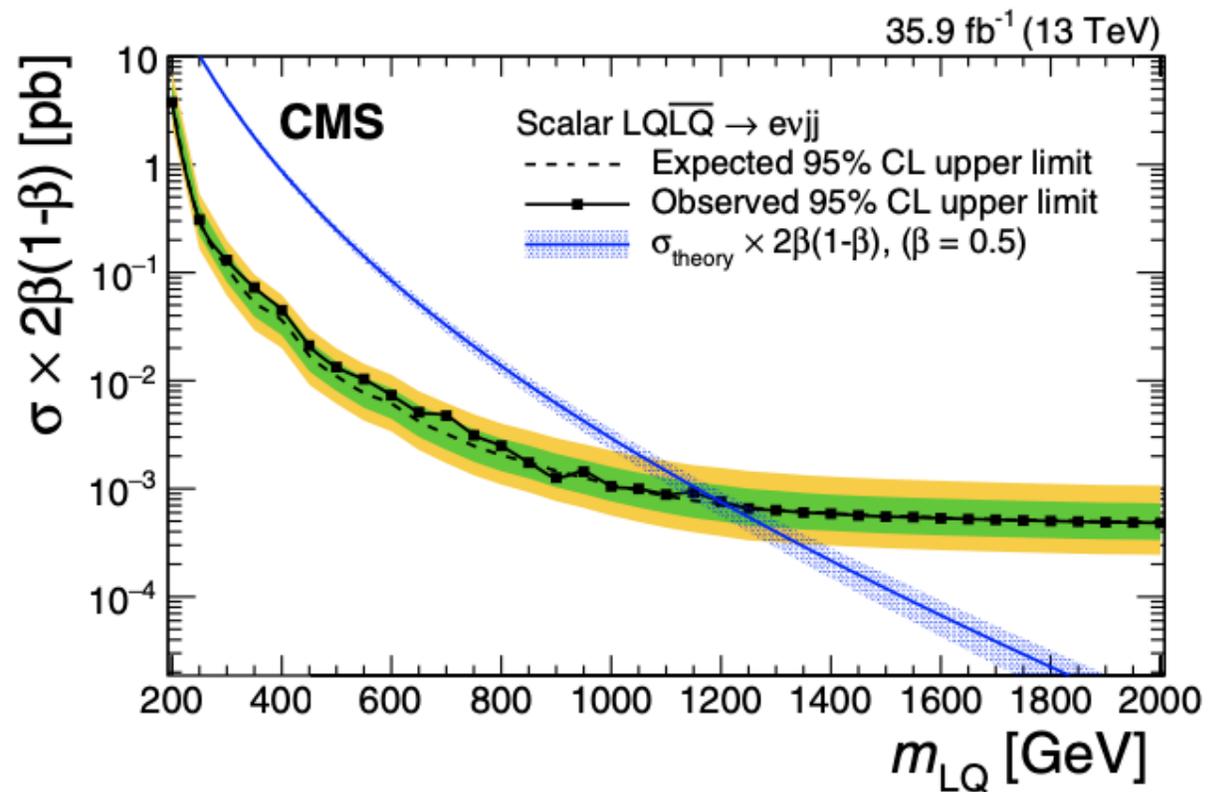
- $\mathcal{L} = 35.9 \text{ fb}^{-1}$, $\sqrt{s} = 13 \text{ TeV}$
- $LQ \rightarrow eu$, $LQ \rightarrow \nu_e d$
- Search channels
 - $eejj$
 - $evjj$



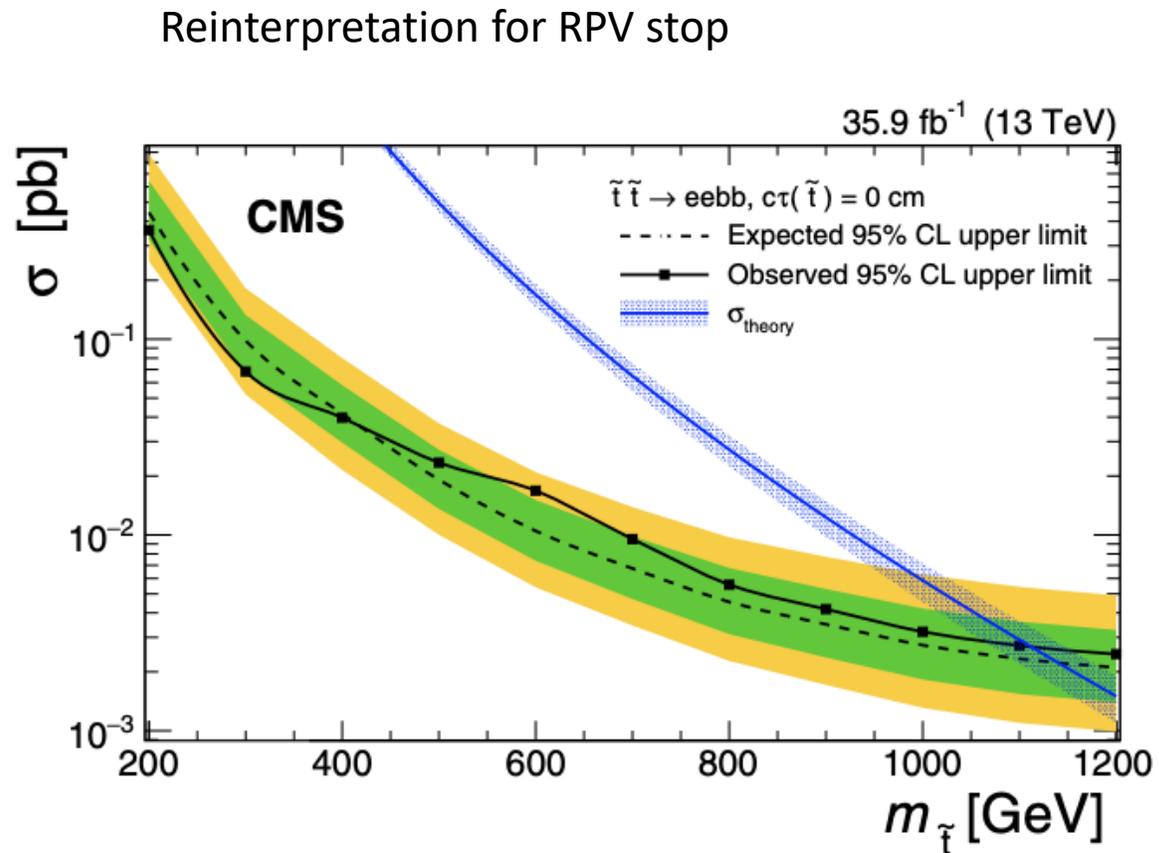
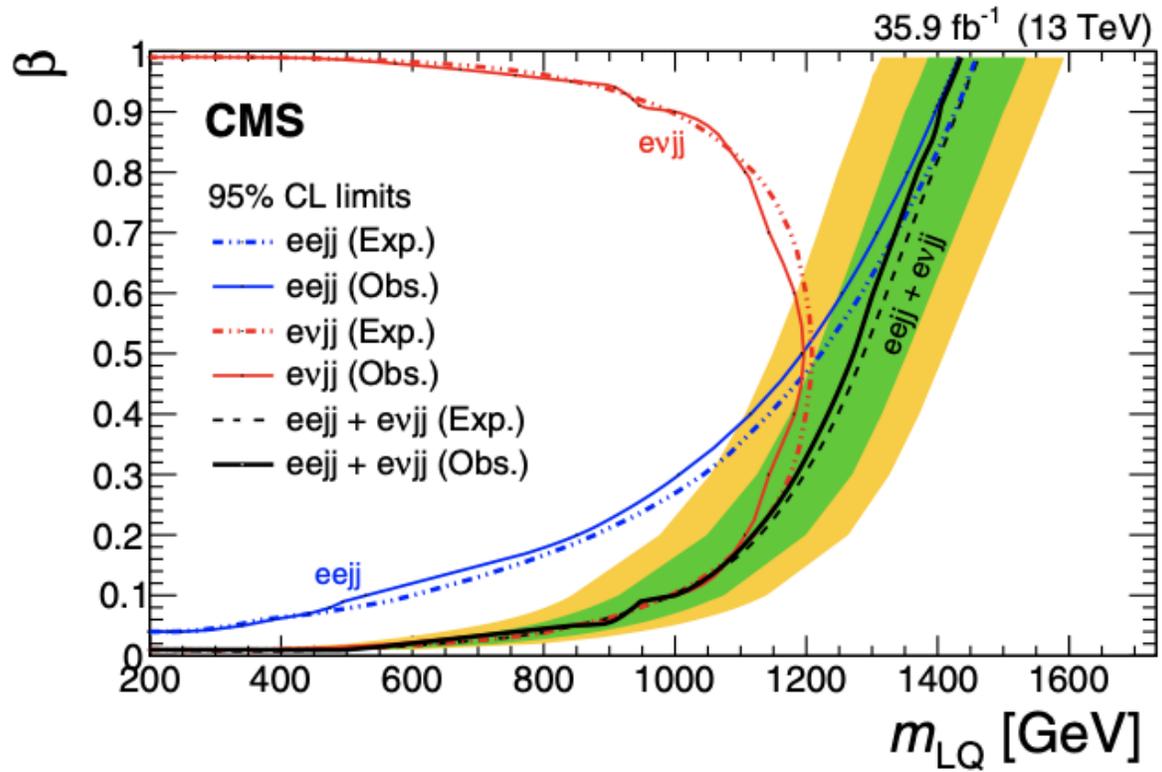
$$\beta = BR(LQ \rightarrow ej)$$



< 1.44 TeV

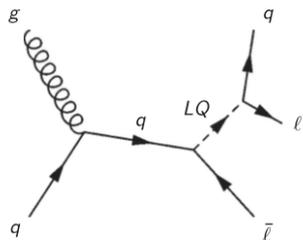


< 1.27 TeV

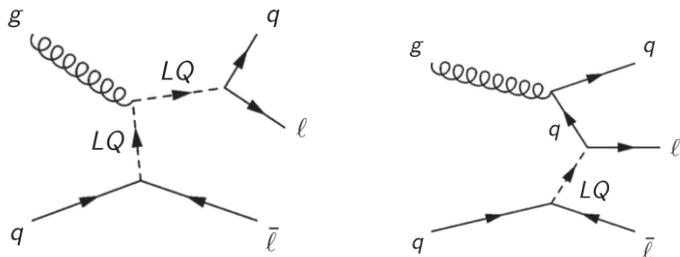


< 1.1 TeV

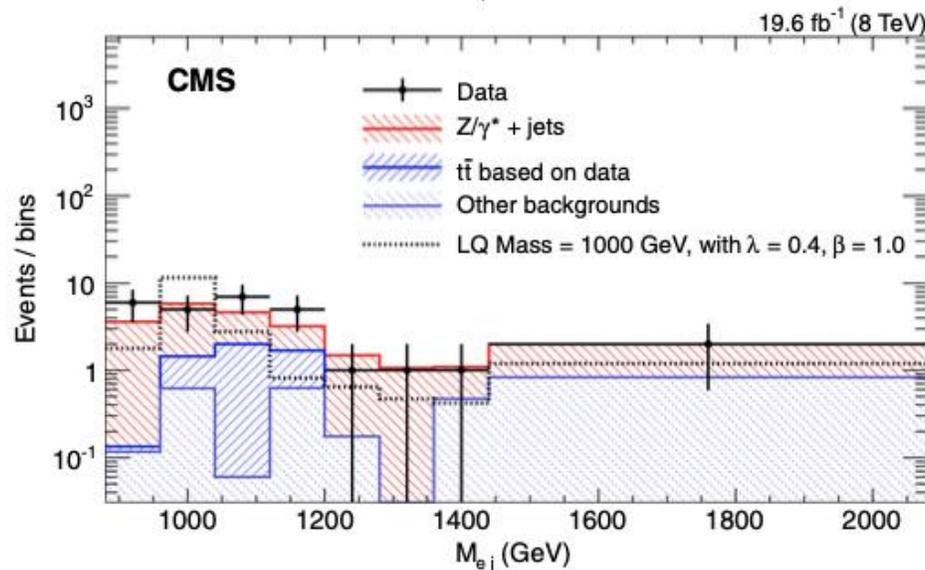
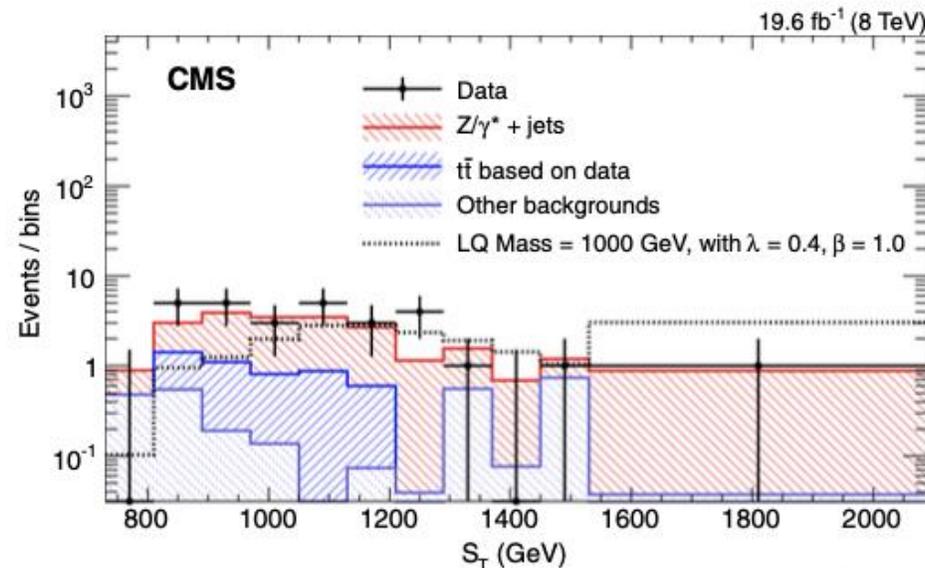
- $\mathcal{L} = 19.6 \text{ fb}^{-1}$, $\sqrt{s} = 8 \text{ TeV}$
- Only $LQ \rightarrow eu$ is considered
- Search channel
 - eej

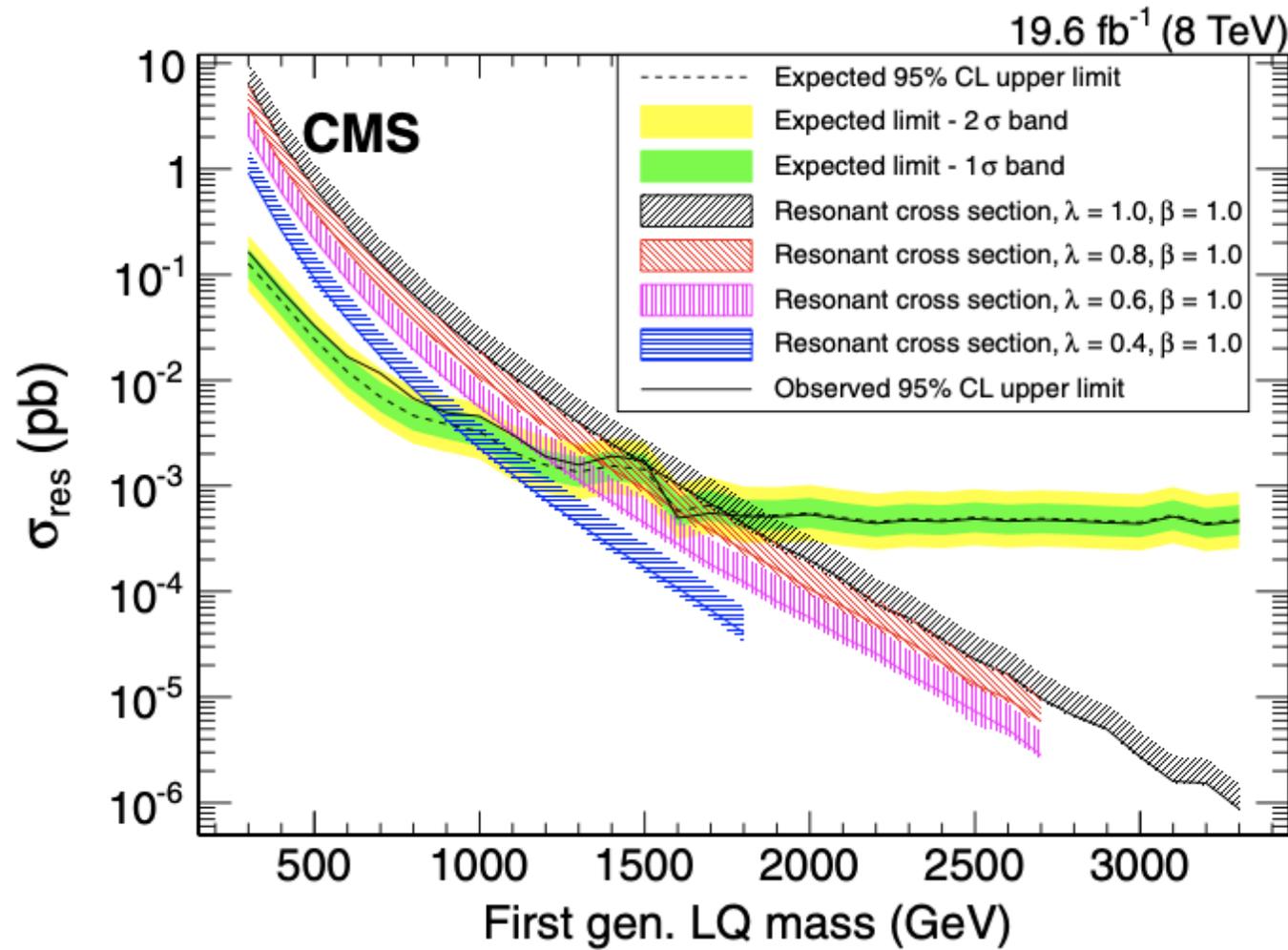


The s-channel LQ production



The t-channel LQ production



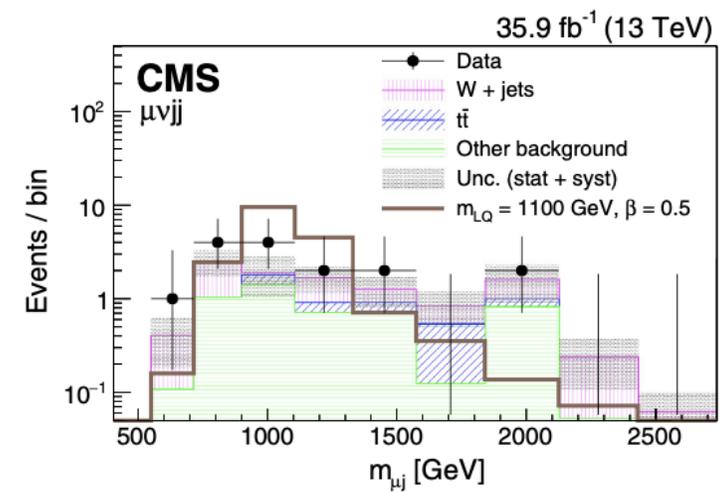
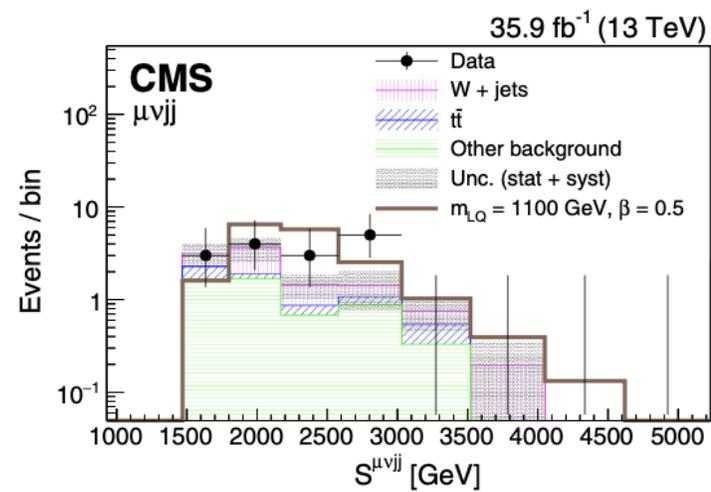
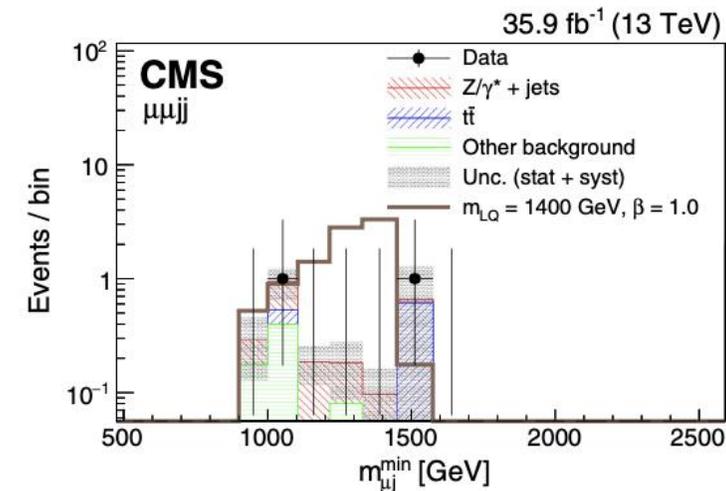
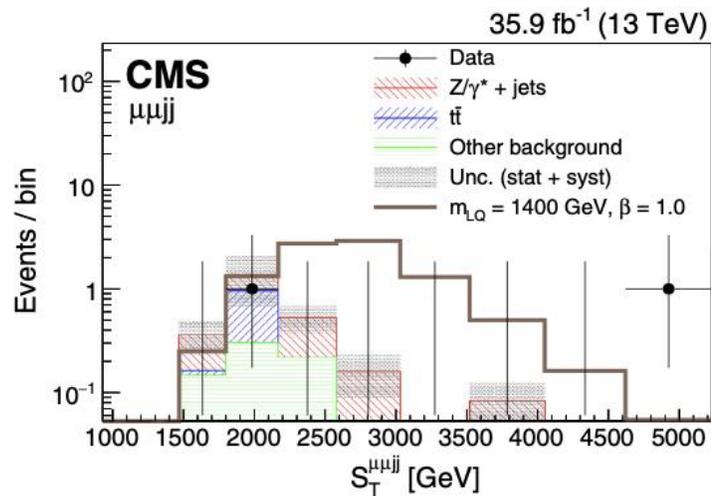
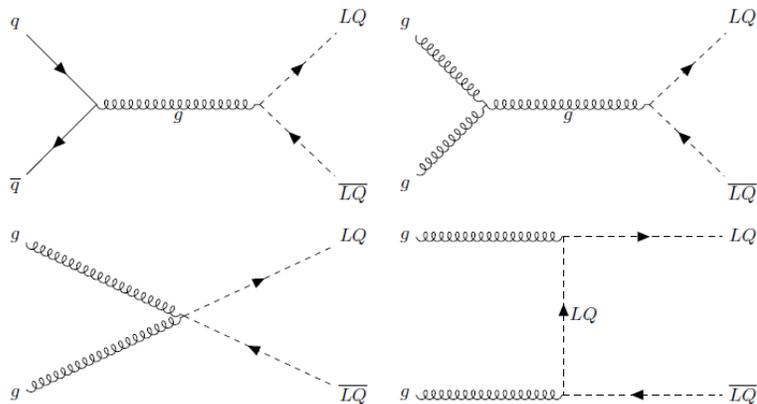


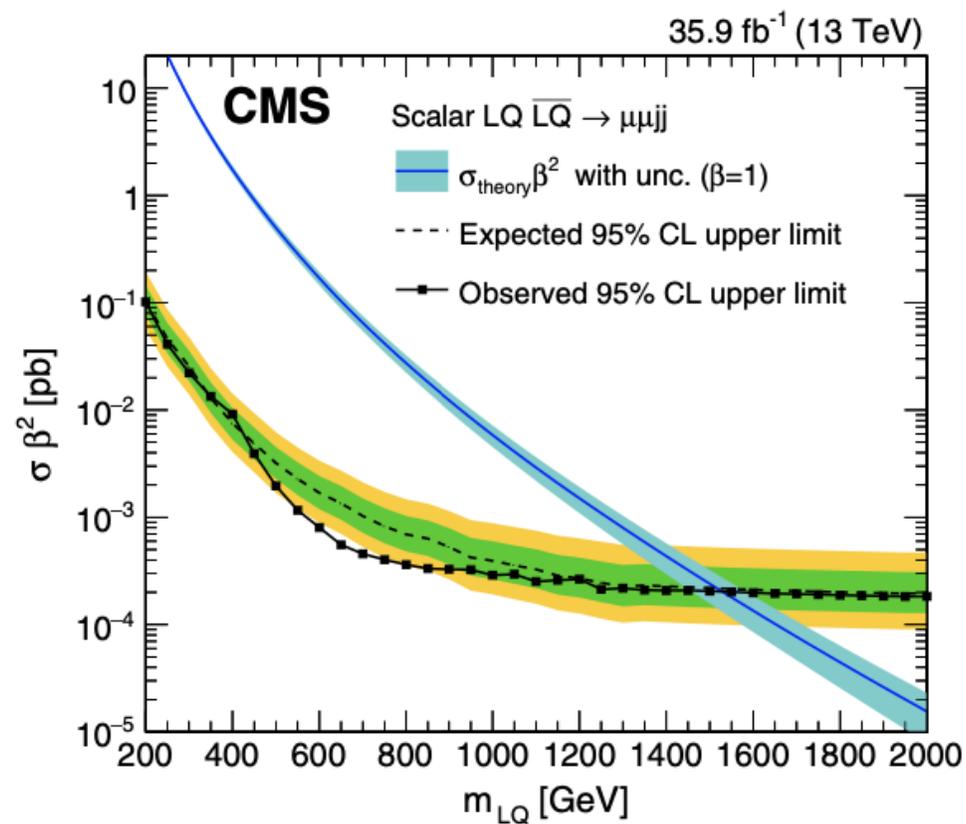
$< 1.76 \text{ } (\lambda = 1)$

2nd generation scalar LQ - pair production

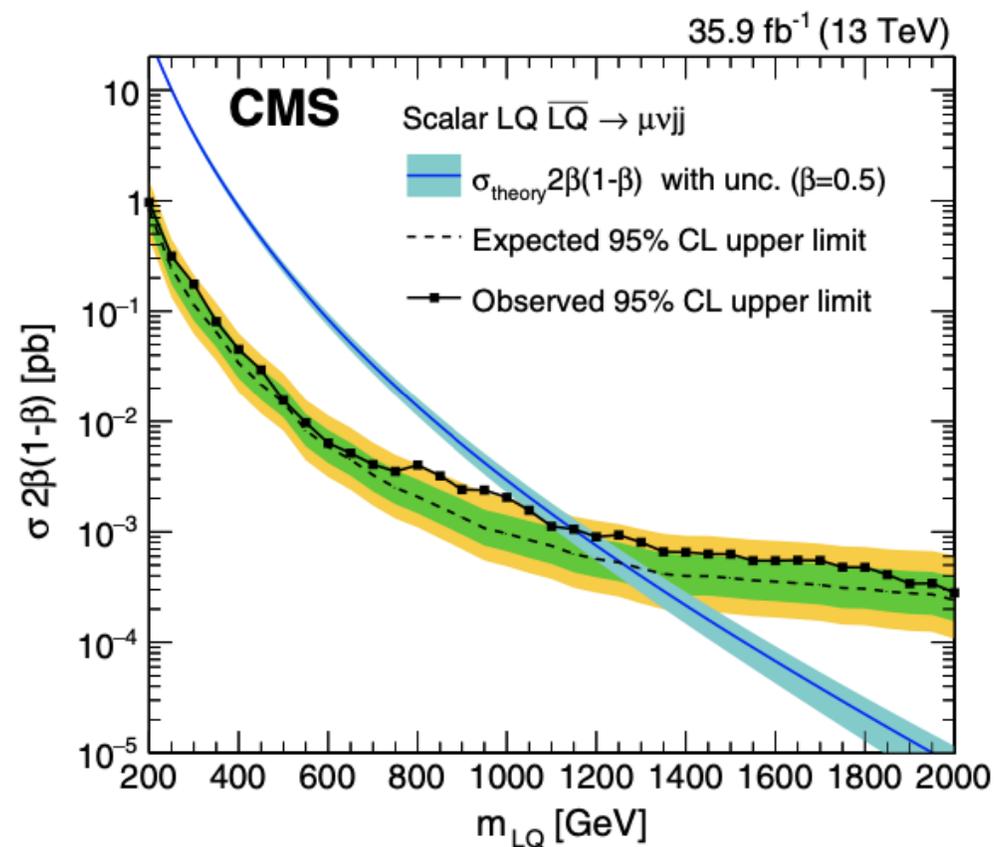
PRD.99.0322014(2019)
(arXiv:1808.05082)

- 2016 data
 - $\mathcal{L} = 35.9 \text{ fb}^{-1}$, $\sqrt{s} = 13 \text{ TeV}$
- $LQ \rightarrow \mu u$, $LQ \rightarrow \nu_\mu d$
- Search channels
 - $\mu\mu jj$
 - $\mu\nu jj$



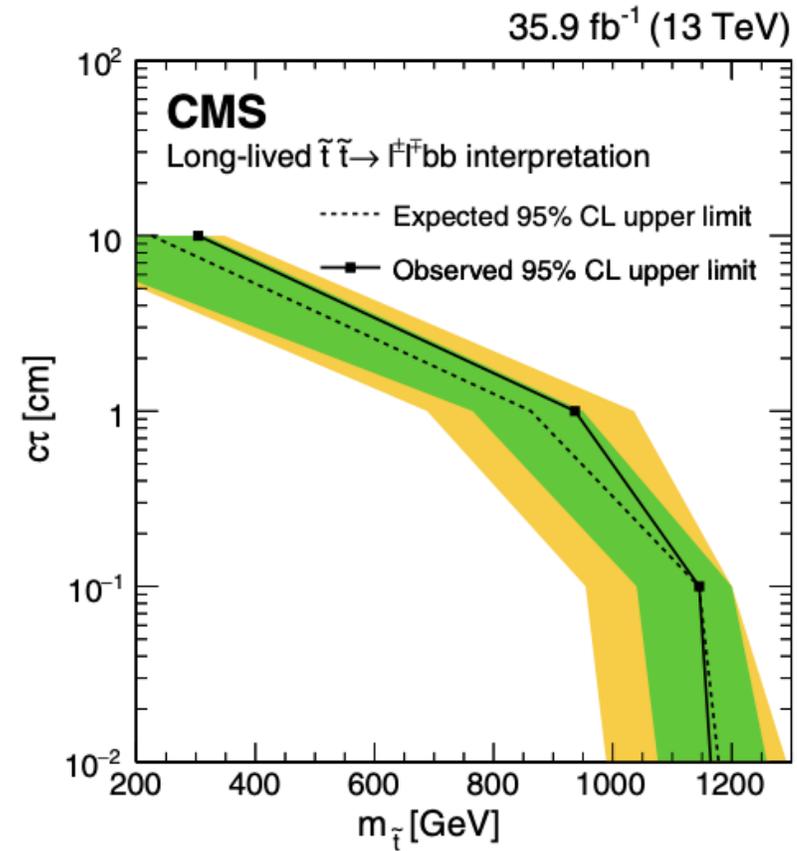
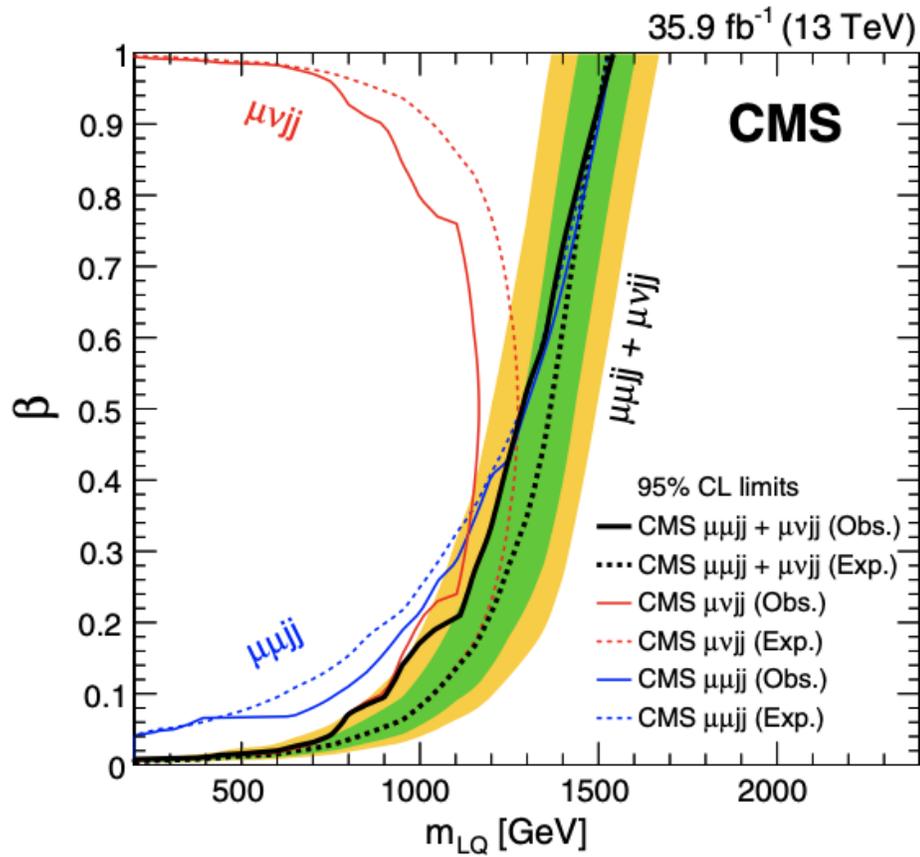


< 1.53 TeV

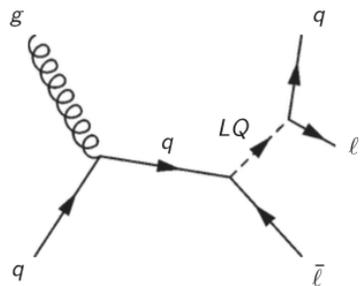


< 1.23 TeV

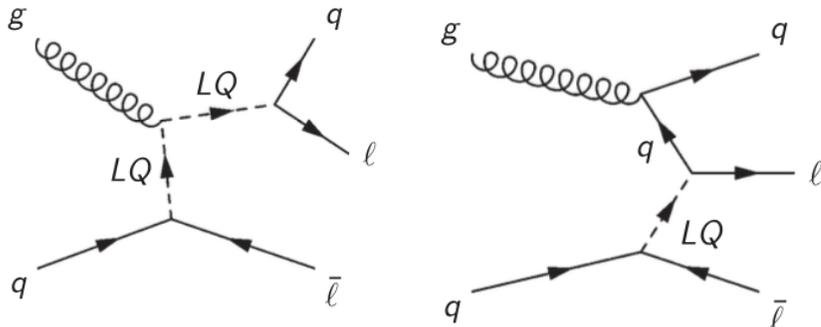
Reinterpretation for long-lived RPV stop



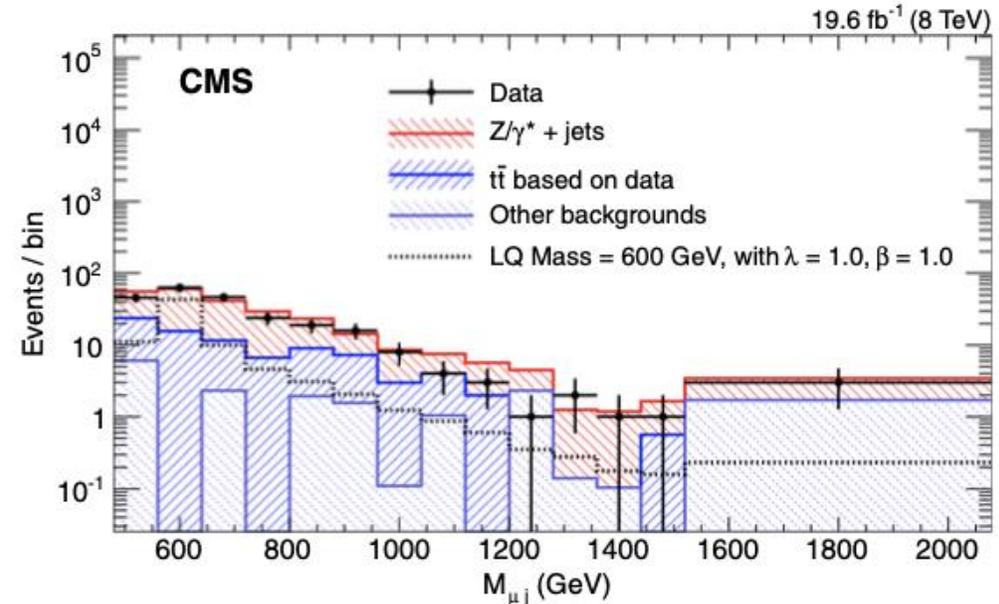
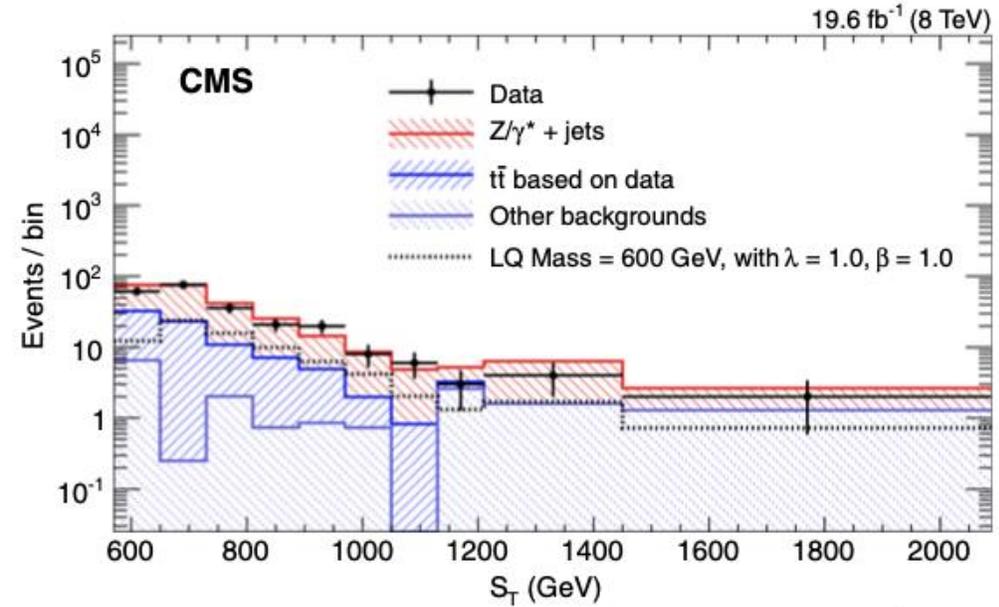
- $\mathcal{L} = 19.6 \text{ fb}^{-1}$, $\sqrt{s} = 8 \text{ TeV}$
- Only $LQ \rightarrow \mu\mu$ is considered
- Search channels
 - $\mu\mu j$

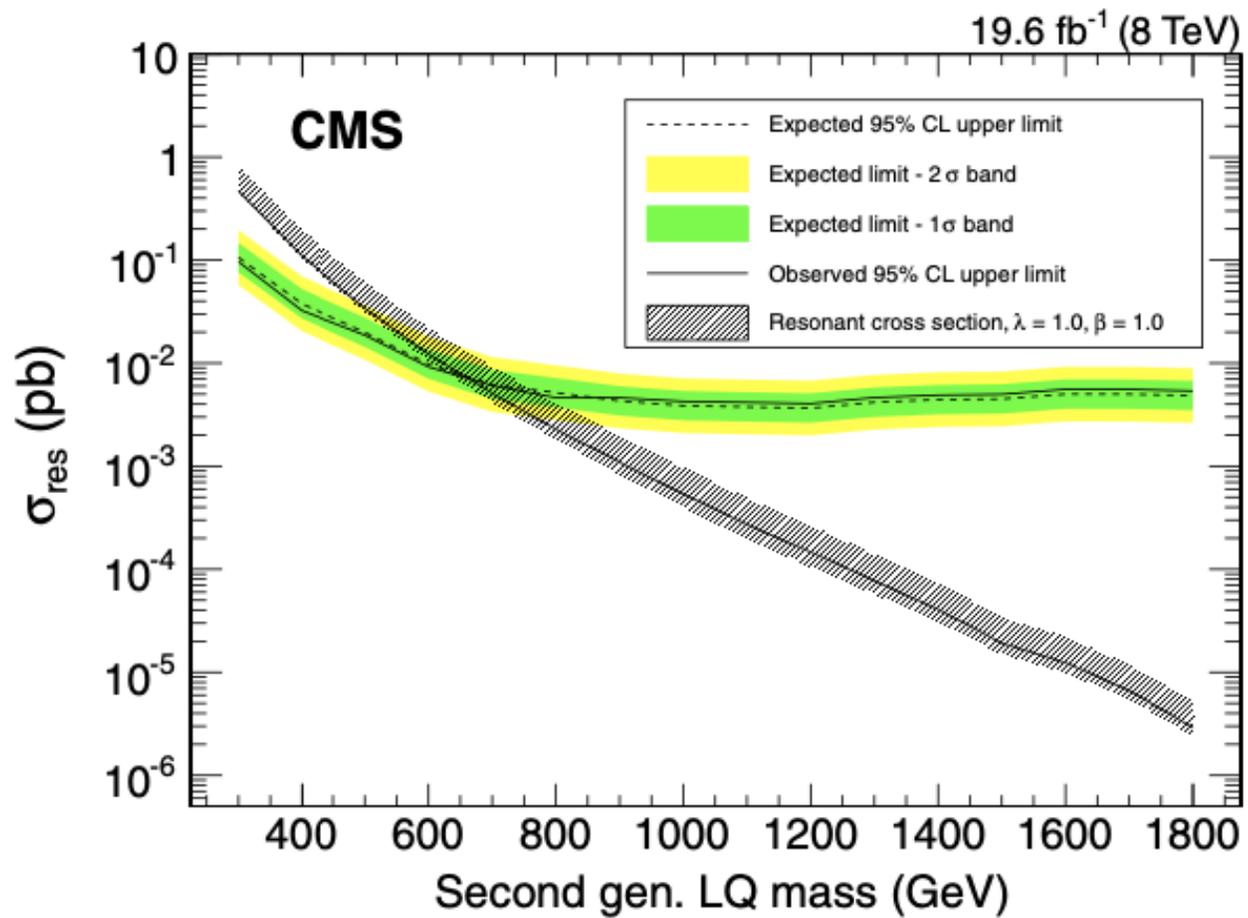


The s-channel LQ production



The t-channel LQ production



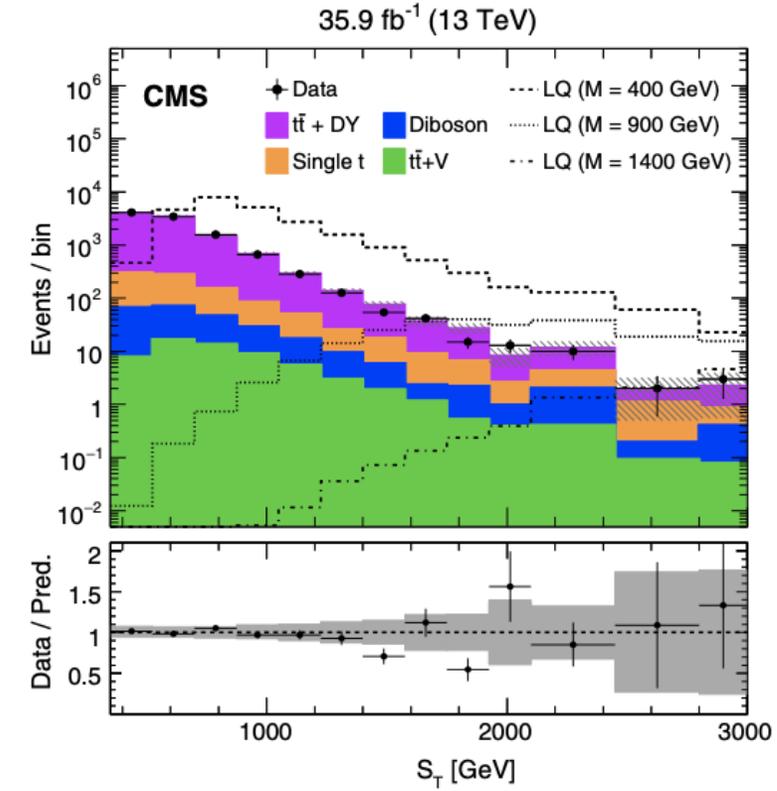
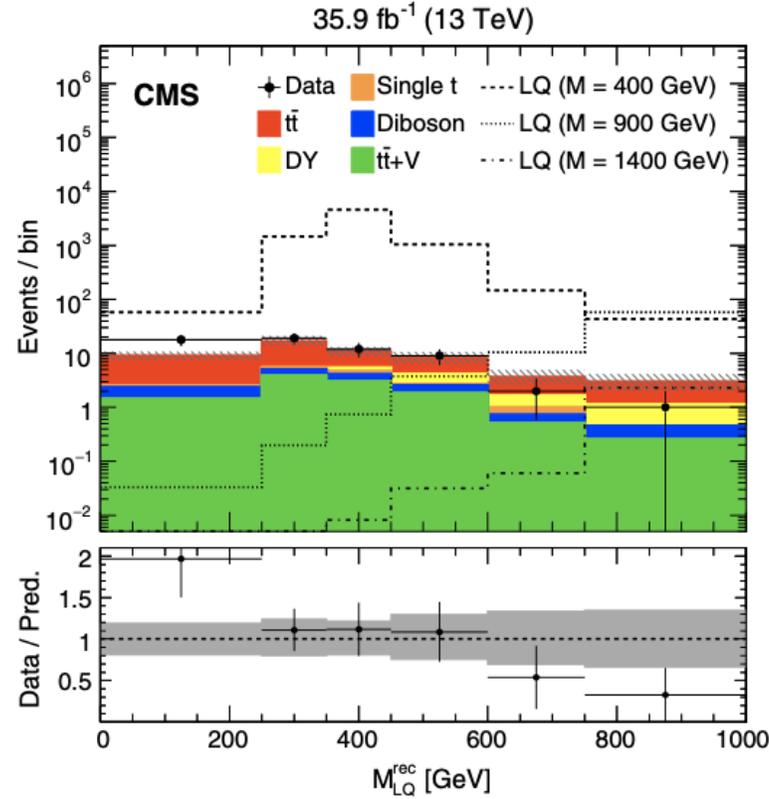
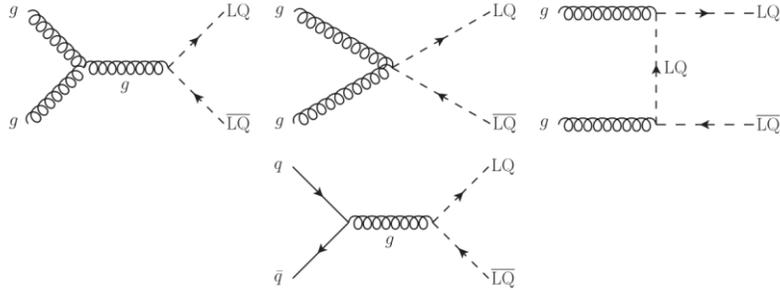


< 660 GeV

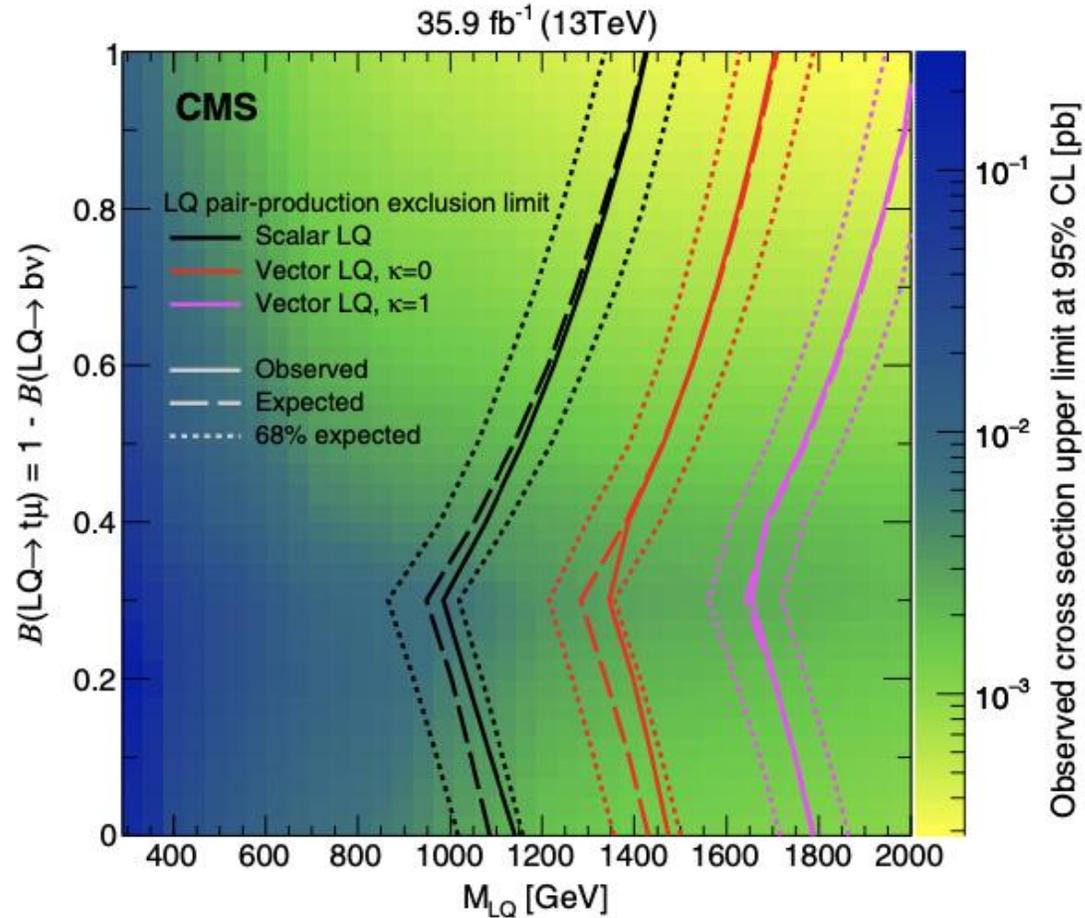
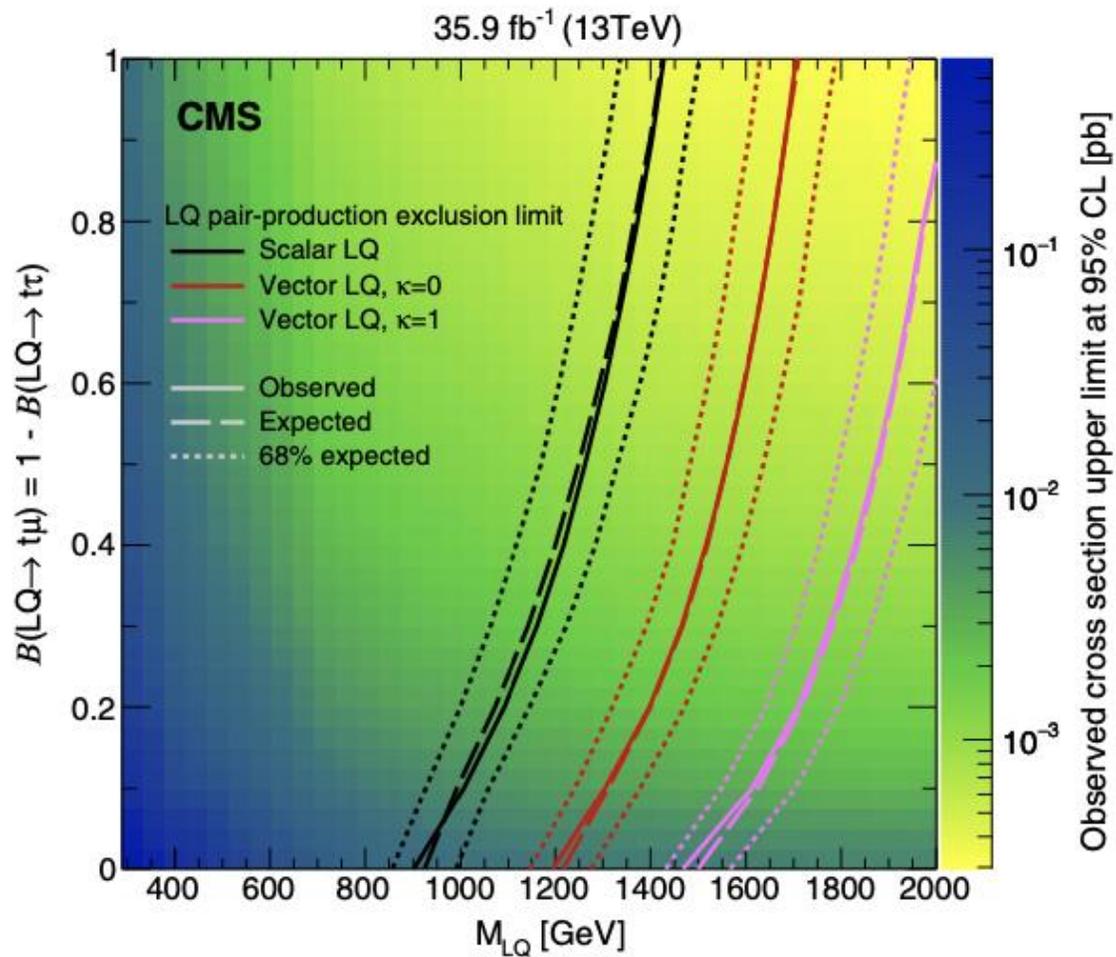
Search for LQ coupled to muon and 3rd quarks – pair production

PRL.121.241802(2018)
(arXiv:1809.05558)

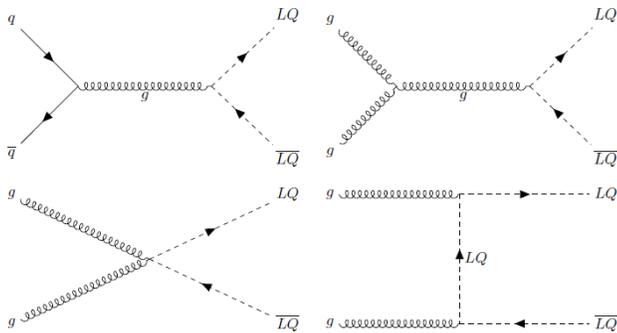
- $\mathcal{L} = 35.9 \text{ fb}^{-1}$, $\sqrt{s} = 13 \text{ TeV}$
- $LQ \rightarrow \mu t$ (LQ couplings to 2nd and 3rd SM fermions)
- $LQ \rightarrow \tau t$, $LQ \rightarrow b\nu$
- Search channels
 - $\mu\tau tt$
 - $\mu\nu tb$



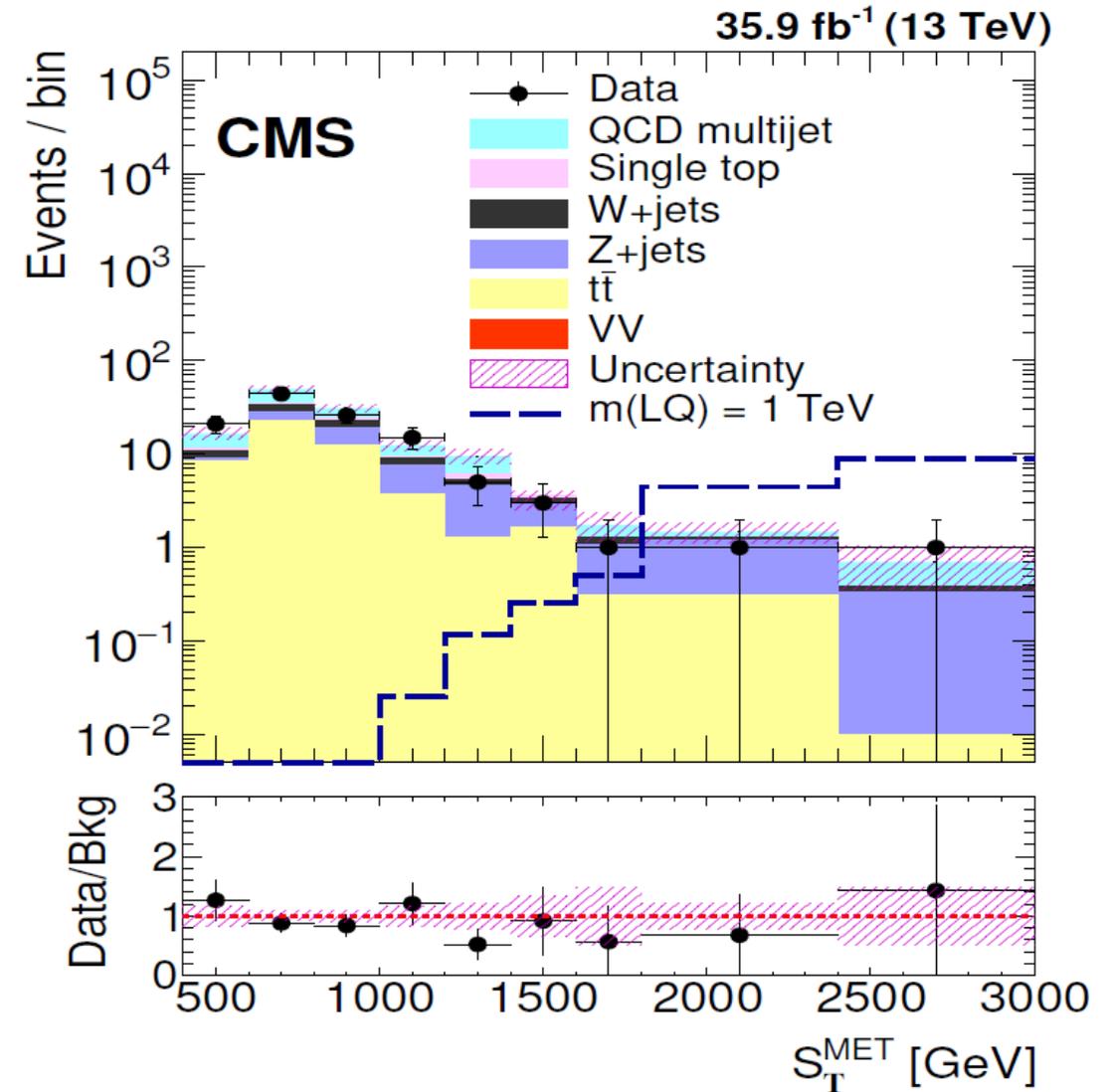
@ $BR(LQ \rightarrow t\mu) = 1$
 < 1.42 TeV : Scalar LQ
 < 1.70 TeV : Vector LQ, $\kappa=0$
 < 2.05 TeV : Vector LQ, $\kappa=1$



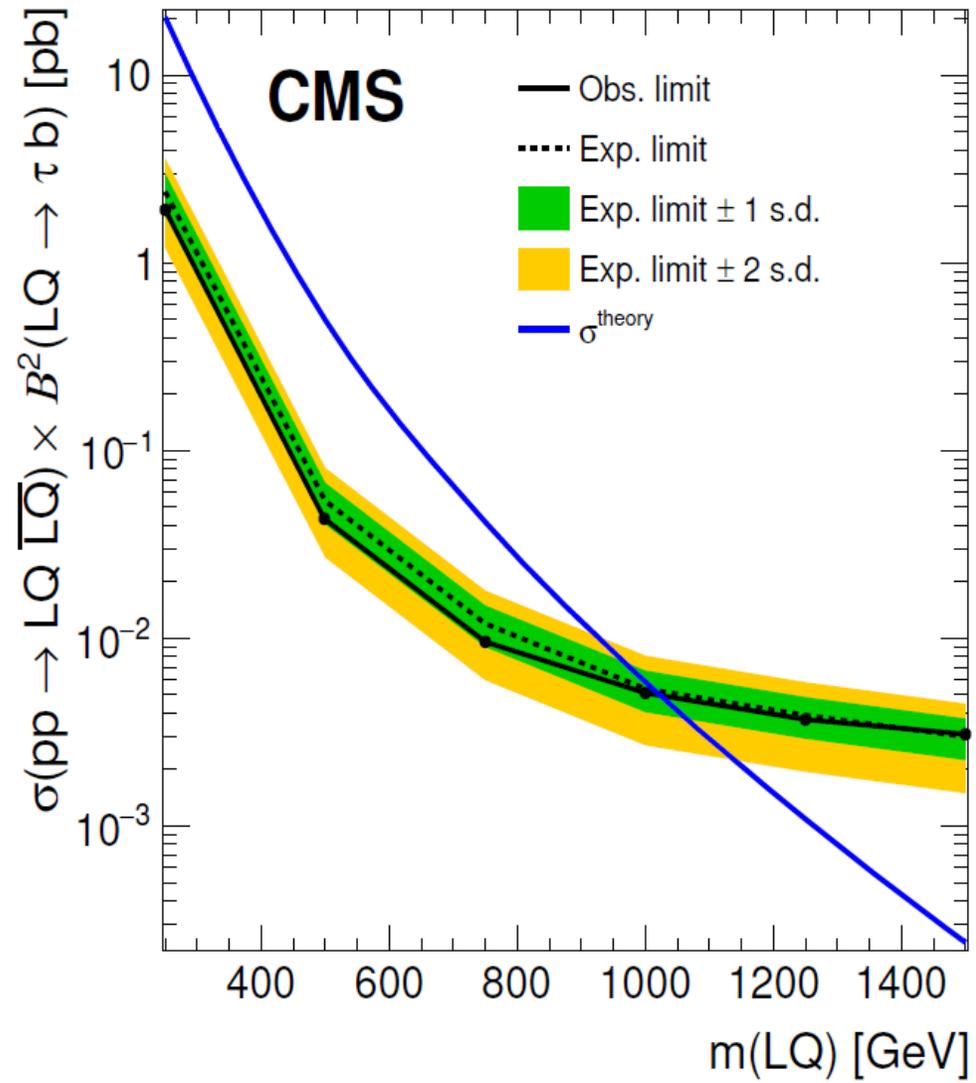
- $\mathcal{L} = 35.9 \text{ fb}^{-1}$, $\sqrt{s} = 13 \text{ TeV}$
- $LQ \rightarrow \tau b$
- Search channels
 - $\tau_h \tau_h b b$
 - τ_h : hadronic tau channel



Process	Yield
$t\bar{t}$	49.8 ± 11.8
QCD	33.8 ± 9.3
Z+jets	23.4 ± 6.5
W+jets	13.4 ± 6.2
Single top	4.6 ± 2.2
VV	2.0 ± 1.5
Total	127.0 ± 17.7
Observed	117
$m(LQ) = 1.0 \text{ TeV}$	14.2 ± 2.1



35.9 fb⁻¹ (13 TeV)

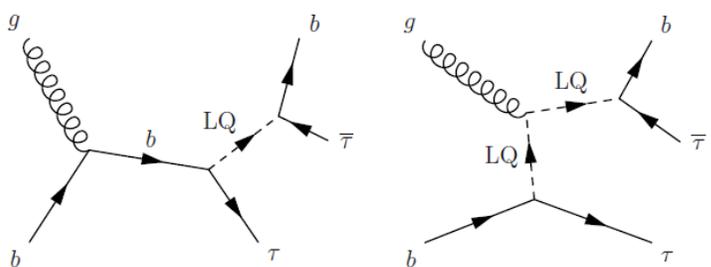


< 1.02 TeV

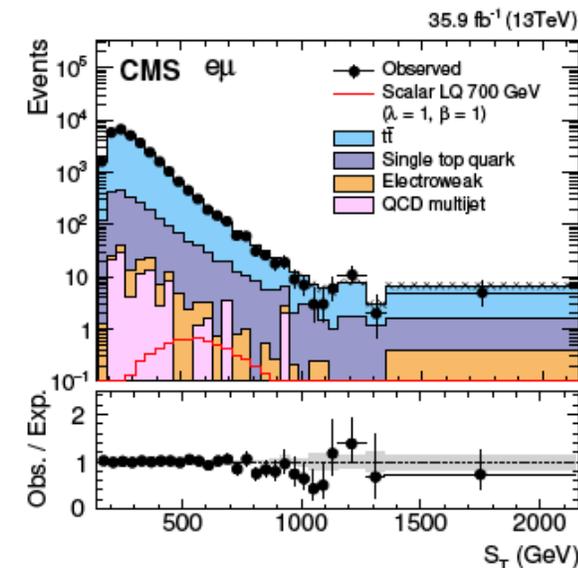
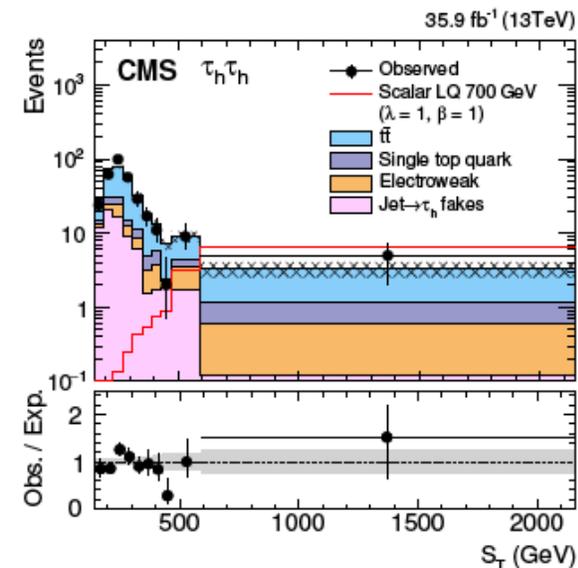
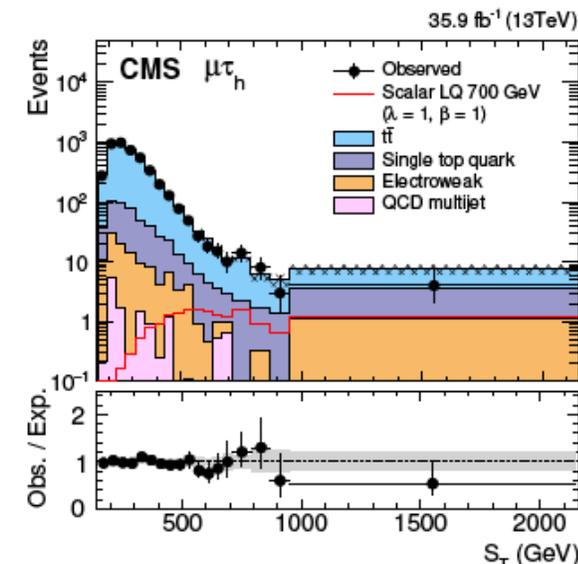
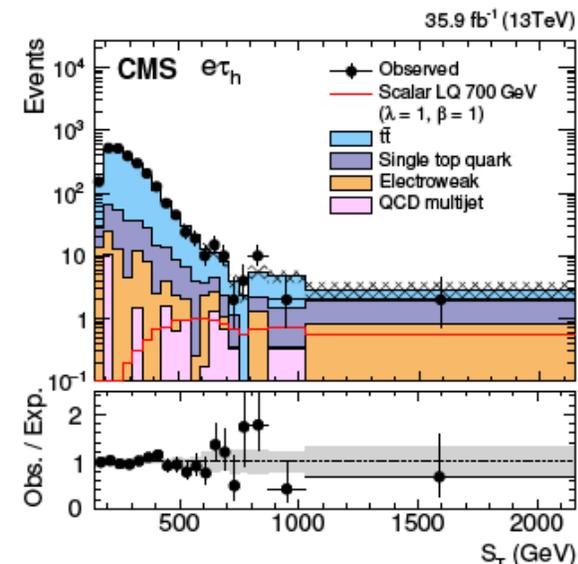
3rd generation scalar LQ - single production

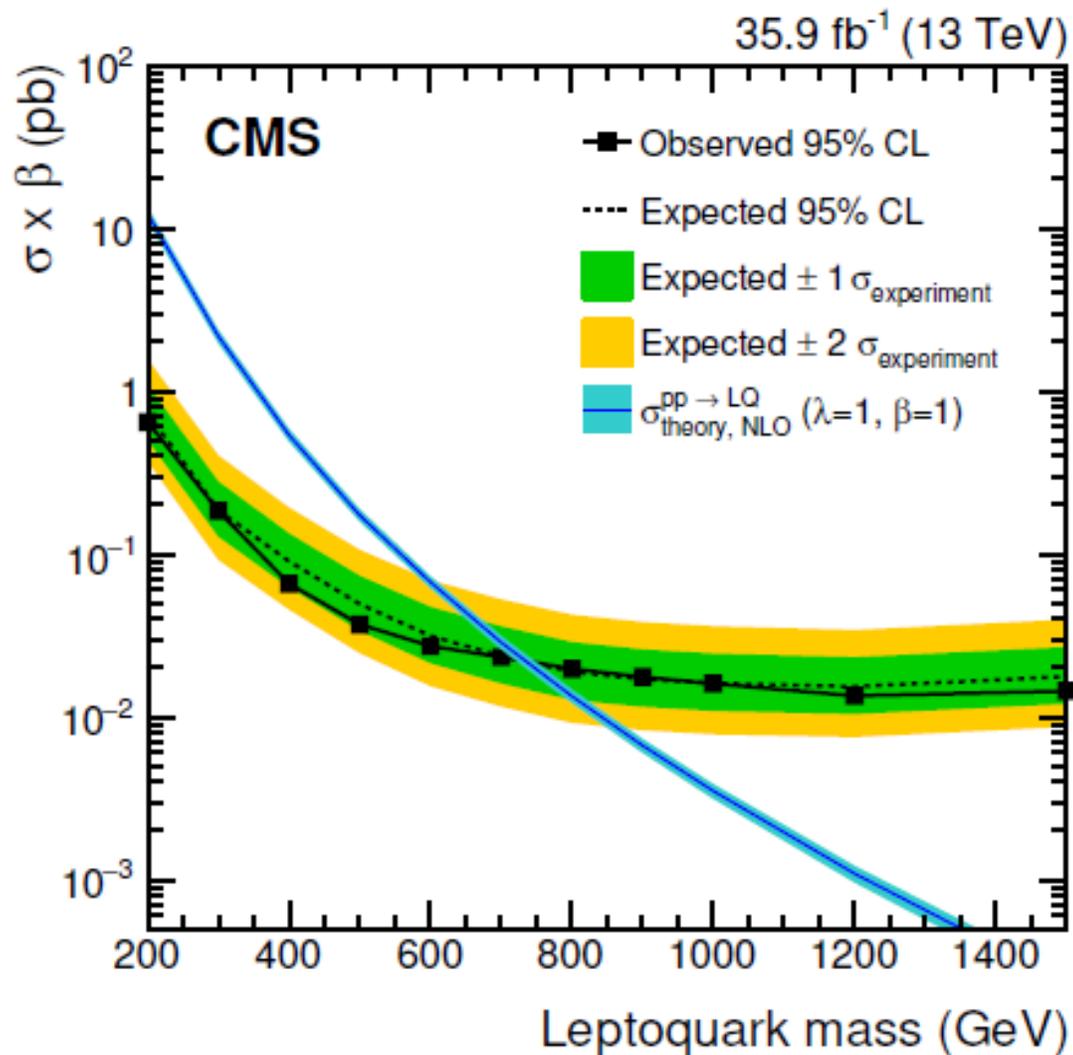
JHEP07(2018)115
(arXiv:1806.03472)

- $\mathcal{L} = 35.9 \text{ fb}^{-1}$, $\sqrt{s} = 13 \text{ TeV}$
- $\text{LQ} \rightarrow \tau b$
- Search channels
 - $\tau\tau b$: Leptonic and hadronic τ decays considered.
 - $e\tau_h b$, $\mu\tau_h b$, $\tau_h\tau_h b$, $e\mu b$

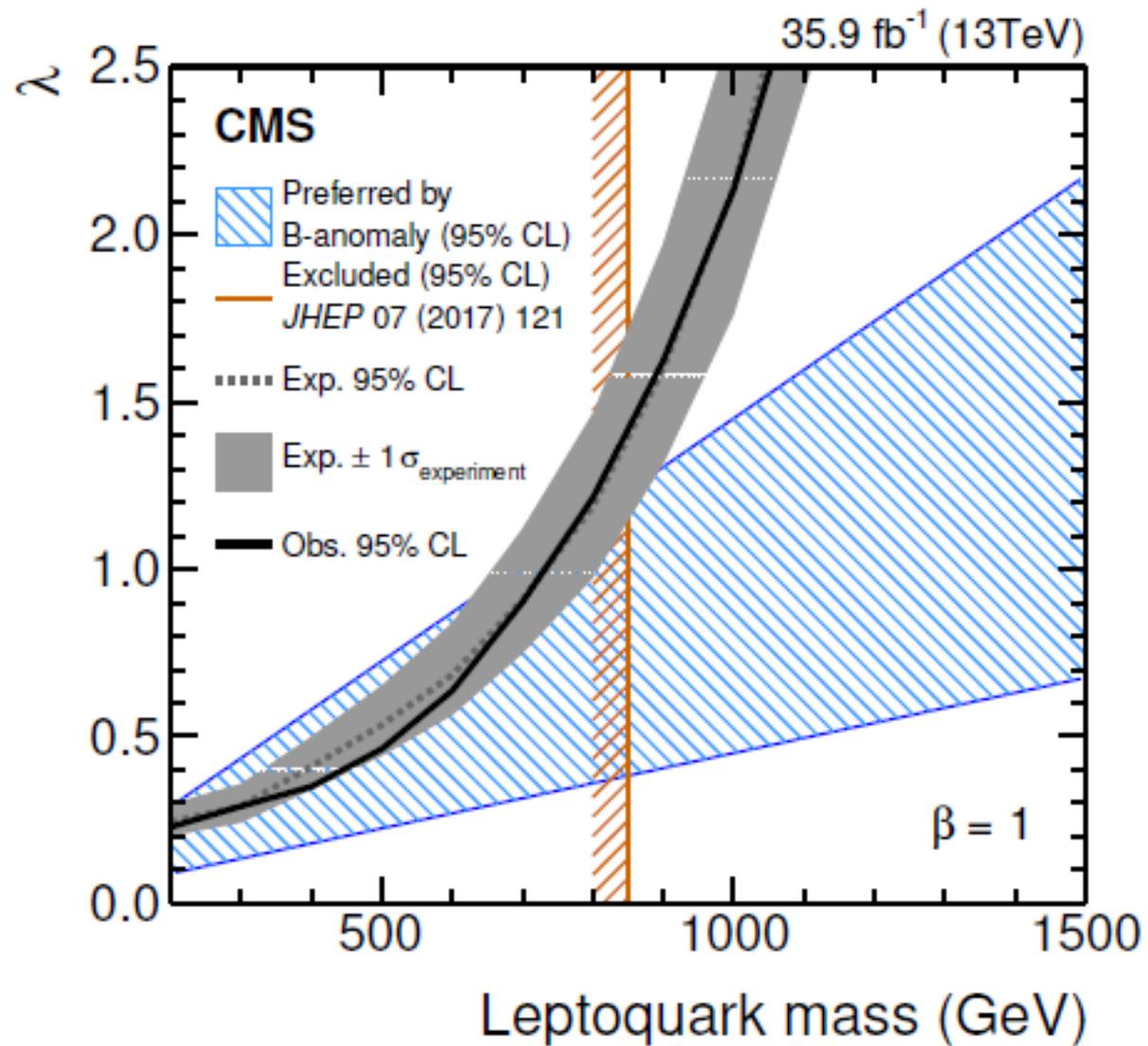


Process	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$	$e\mu$
$t\bar{t}$	114.8 ± 2.9	194.6 ± 4.4	6.7 ± 1.0	1895.2 ± 14.4
Single top quark	23.2 ± 2.2	36.6 ± 2.6	1.5 ± 0.5	263.4 ± 6.8
Electroweak	9.1 ± 2.3	10.9 ± 3.1	2.2 ± 1.0	16.0 ± 2.4
QCD multijet	4.5 ± 4.6	1.5 ± 5.3	1.9 ± 0.6	8.3 ± 5.6
Total expected background	151.6 ± 6.3	243.6 ± 8.0	12.3 ± 1.7	2182.9 ± 17.0
LQ signal ($m_{\text{LQ}} = 700 \text{ GeV}$, $\lambda = 1$, $\beta = 1$)	8.8 ± 0.3	12.9 ± 0.4	9.5 ± 1.2	4.9 ± 0.2
Observed data	143	225	14	2147



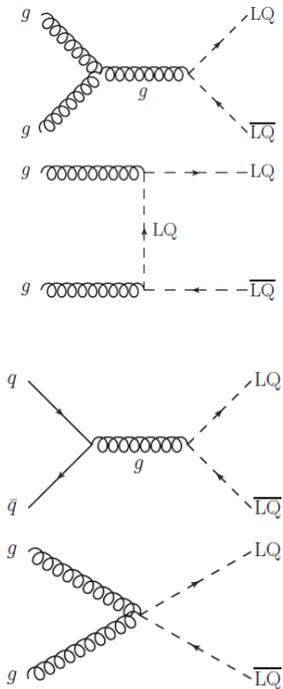


< 0.74 TeV

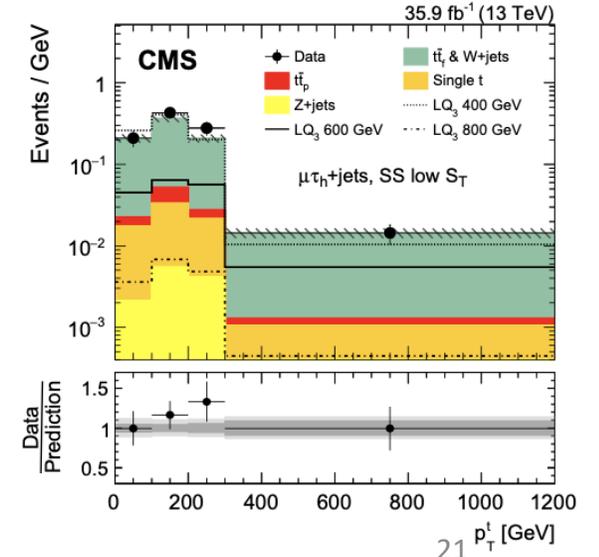
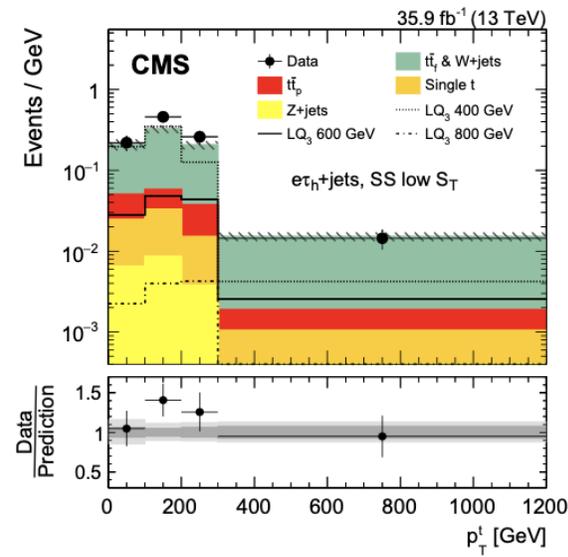
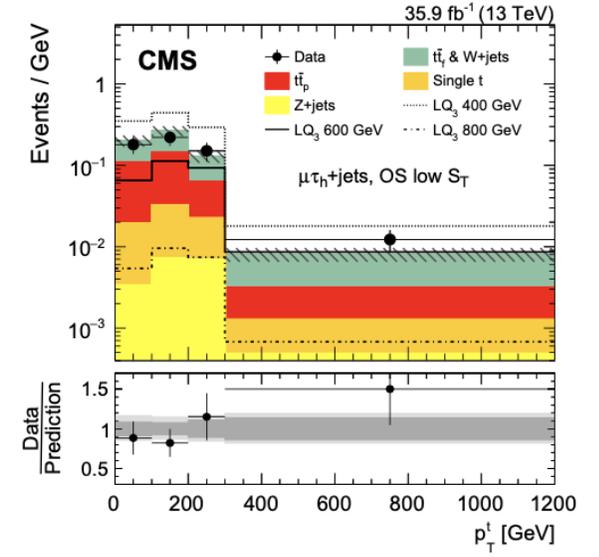
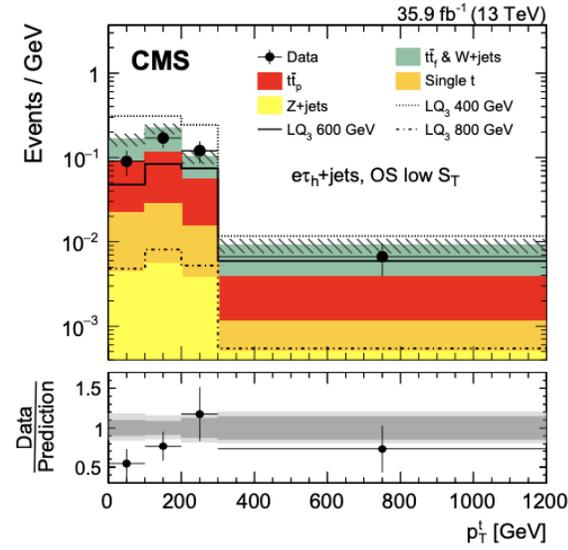


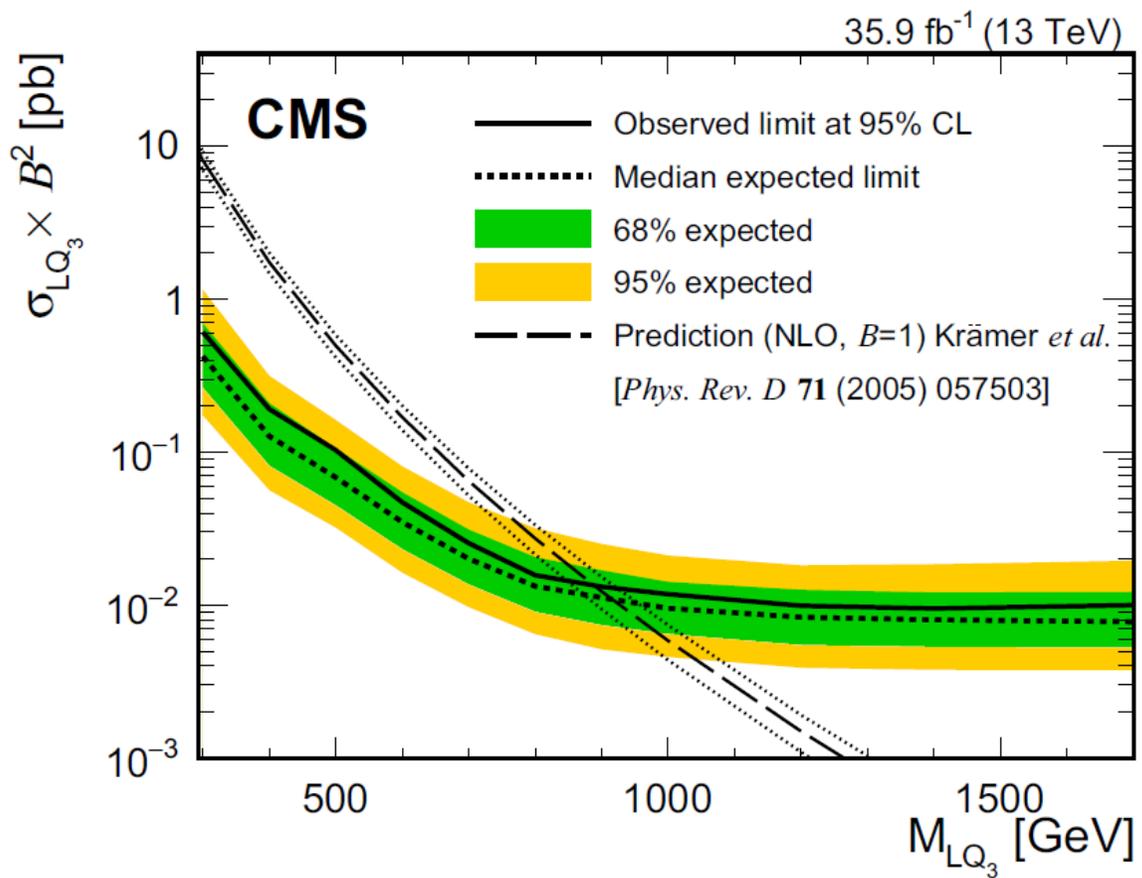
3rd generation scalar LQ decaying to top and tau - pair production

- $\mathcal{L} = 35.9 \text{ fb}^{-1}$, $\sqrt{s} = 13 \text{ TeV}$
- $LQ \rightarrow \tau\tau$
- Search channels
 - $e\tau_h + \text{jets}$, $\mu\tau_h + \text{jets}$, $e\tau_h\tau_h + \text{jets}$, $\mu\tau_h\tau_h + \text{jets}$
 - e, μ and τ_h are coming from τ or top

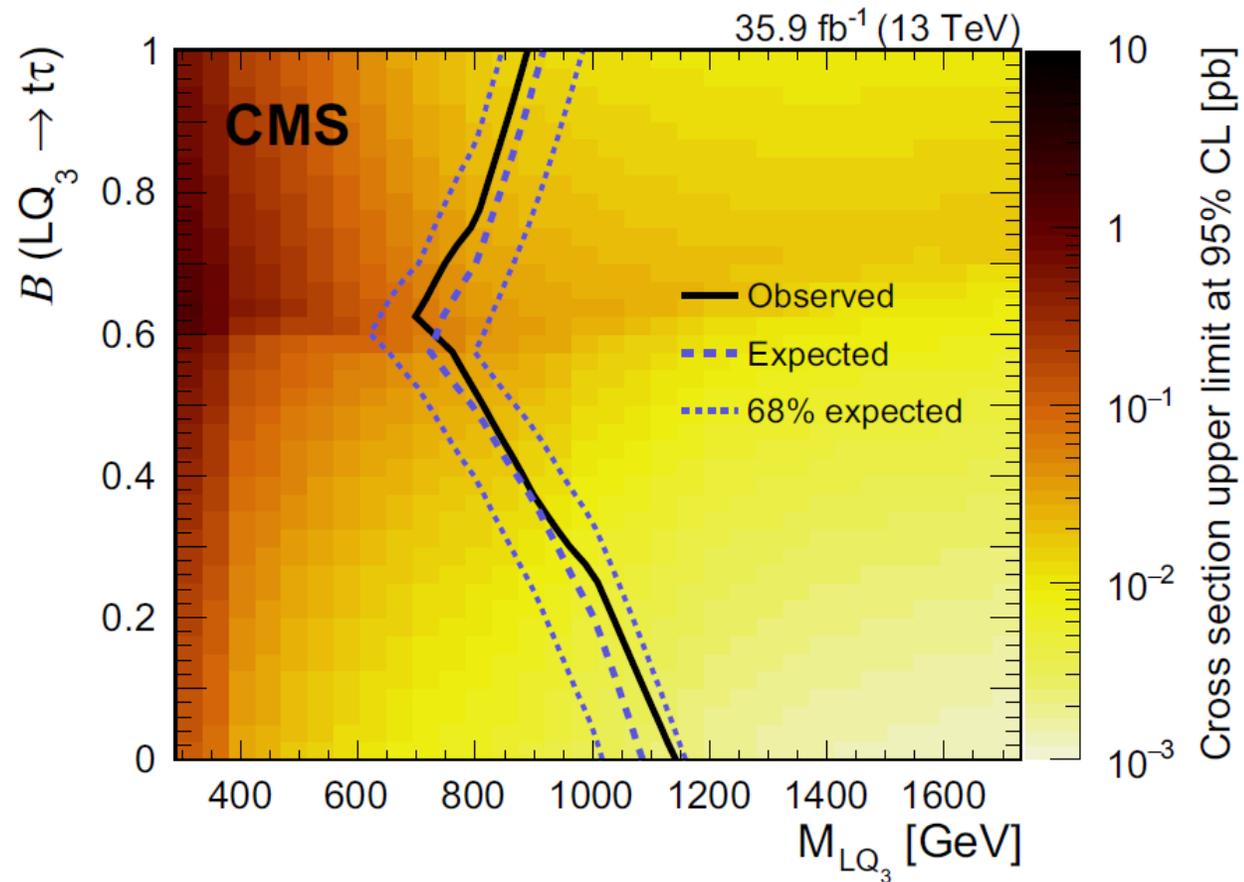


Process	$e\tau_h\tau_h + \text{jets}$	$\mu\tau_h\tau_h + \text{jets}$
LQ ₃ (300 GeV)	97 ⁺²⁵ ₋₂₄	167 ⁺³⁶ ₋₃₇
LQ ₃ (400 GeV)	73 ⁺¹⁴ ₋₁₃	98 ⁺¹⁹ ₋₁₇
LQ ₃ (500 GeV)	34.1 ^{+6.6} _{-6.2}	44.9 ^{+8.5} _{-7.9}
LQ ₃ (600 GeV)	14.1 ^{+2.8} _{-2.7}	21.1 ^{+4.1} _{-3.8}
LQ ₃ (700 GeV)	7.3 ^{+1.5} _{-1.4}	7.1 ^{+1.5} _{-1.4}
LQ ₃ (800 GeV)	3.2 ^{+0.7} _{-0.7}	4.4 ^{+1.0} _{-0.9}
LQ ₃ (900 GeV)	1.5 ^{+0.4} _{-0.3}	1.9 ^{+0.4} _{-0.4}
LQ ₃ (1000 GeV)	0.8 ^{+0.2} _{-0.2}	0.9 ^{+0.2} _{-0.2}
$t\bar{t}$	2.5 ^{+0.8} _{-1.2}	3.2 ^{+1.5} _{-1.2}
$t\bar{t}_{p+f}$	1.5 ^{+0.8} _{-0.8}	2.0 ^{+0.8} _{-0.9}
Single t	0.3 ^{+0.3} _{-0.3}	0.0 ^{+0.2} _{-0.0}
W+jets	0.5 ^{+1.2} _{-0.5}	0.4 ^{+0.7} _{-0.4}
Z+jets	1.4 ^{+0.5} _{-0.5}	1.0 ^{+0.4} _{-0.4}
Diboson	1.6 ^{+1.7} _{-1.6}	1.7 ^{+1.8} _{-1.7}
Total background	7.9 ^{+2.4} _{-2.5}	8.4 ^{+2.6} _{-2.3}
Data	9	11





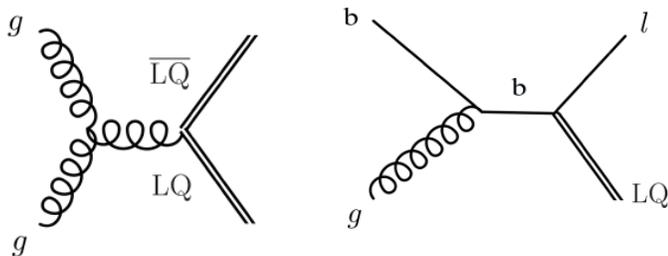
< 0.9 TeV



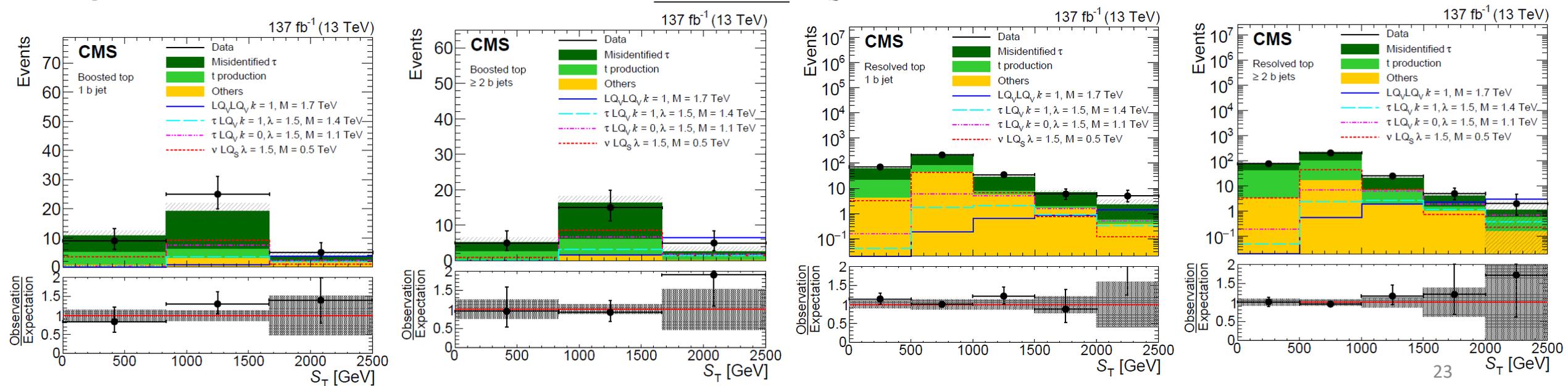
3rd generation scalar/vector LQ decaying to 3rd fermions – pair/single production

Submitted to PLB
(arXiv:2012.04178)

- $\mathcal{L} = 137 \text{ fb}^{-1}$, $\sqrt{s} = 13 \text{ TeV}$
- Scalar LQ $\rightarrow \tau\tau$ or νb , vector LQ $\rightarrow \nu t$ or τb
- Search channels
 - Scalar : $LQLQ \rightarrow \tau\tau \nu b$, $\nu LQ \rightarrow \nu \tau t$
 - Vector : $LQLQ \rightarrow \tau b \nu t$, $\tau LQ \rightarrow \tau \nu t$
 - $\tau t \nu(b)$: top and tau hadronic decay



Category	Boosted		Resolved	
	$N_{b\text{-jet}}=1$	$N_{b\text{-jet}} \geq 2$	$N_{b\text{-jet}}=1$	$N_{b\text{-jet}} \geq 2$
Misidentified τ	20.5 ± 2.1	14.4 ± 1.8	199 ± 13	170 ± 12
t production	7.8 ± 2.1	8.2 ± 1.9	58.8 ± 5.1	126.6 ± 9.5
Others	5.3 ± 2.0	1.64 ± 0.83	56 ± 25	23 ± 11
Total background	33.5 ± 3.6	24.2 ± 2.7	314 ± 29	320 ± 19
Data	39	25	332	316
$LQ_V \bar{LQ}_V k=1, m_{LQ} = 1.7 \text{ TeV}$	4.58 ± 0.72	8.0 ± 1.2	3.09 ± 0.34	7.71 ± 0.69
$\tau LQ_V k=1, \lambda=1.5, m_{LQ} = 1.4 \text{ TeV}$	5.51 ± 0.38	4.77 ± 0.35	5.02 ± 0.22	6.62 ± 0.31
$\tau LQ_V k=0, \lambda=1.5, m_{LQ} = 1.1 \text{ TeV}$	10.05 ± 0.71	8.64 ± 0.65	13.36 ± 0.58	16.38 ± 0.76
$\nu LQ_S \lambda=1.5, m_{LQ} = 0.5 \text{ TeV}$	13.54 ± 0.78	11.98 ± 0.77	52.7 ± 2.7	57.5 ± 2.9

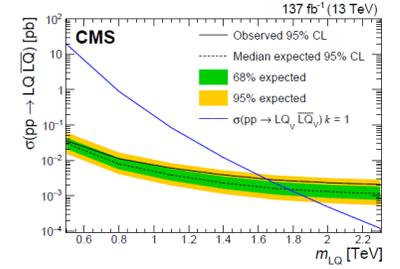
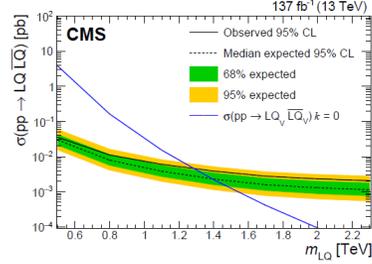
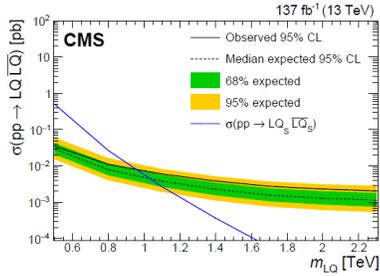


Scalar

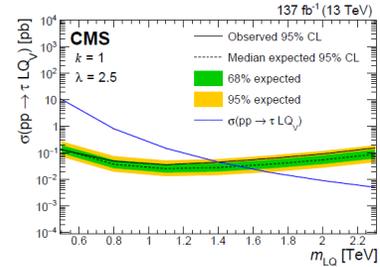
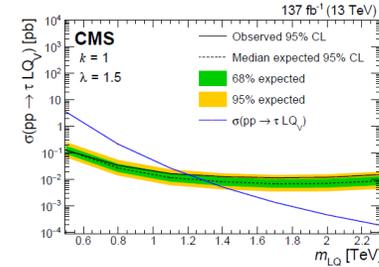
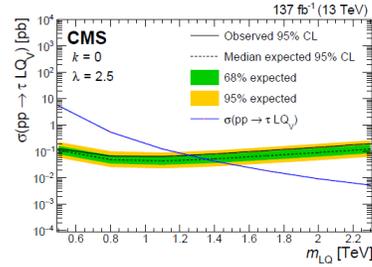
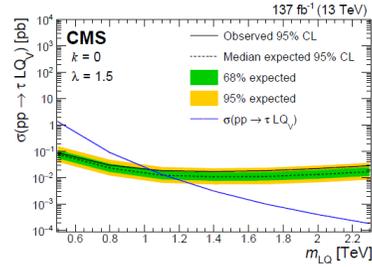
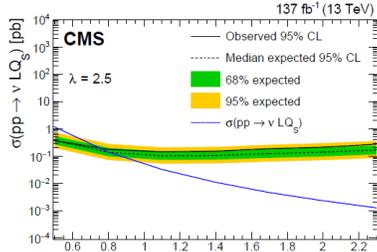
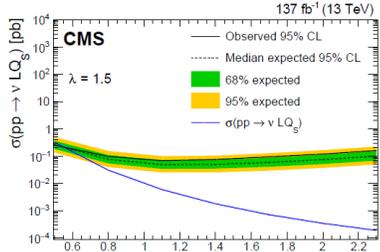
Vector(k=0)

Vector(k=1)

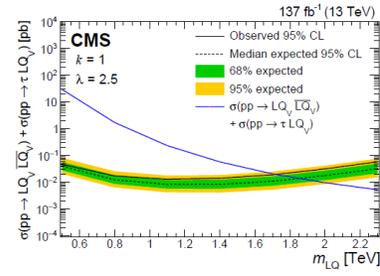
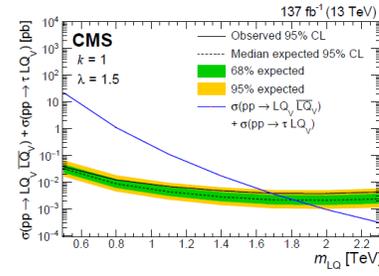
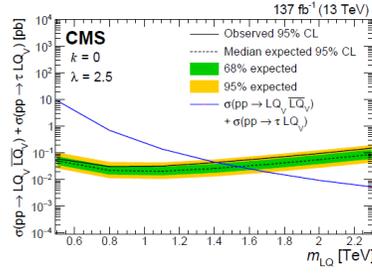
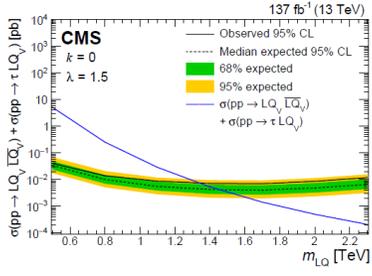
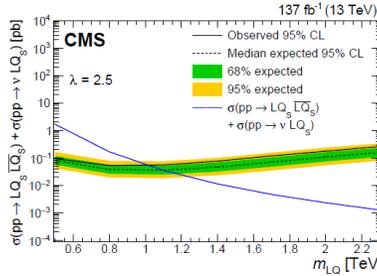
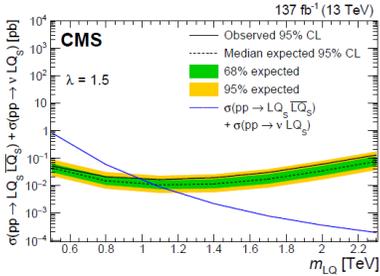
pair



single

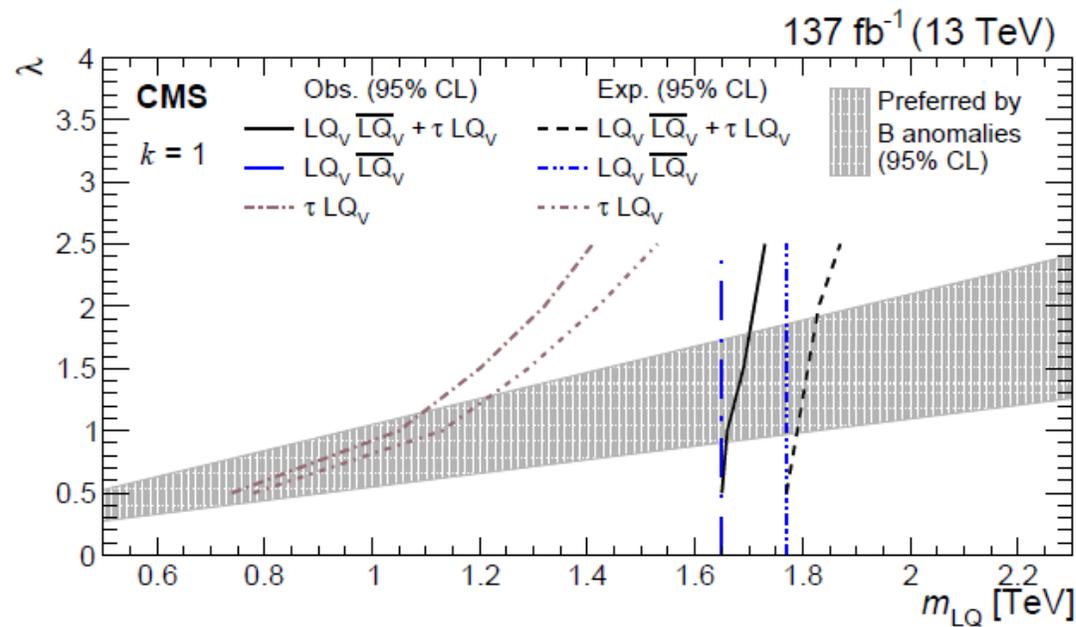
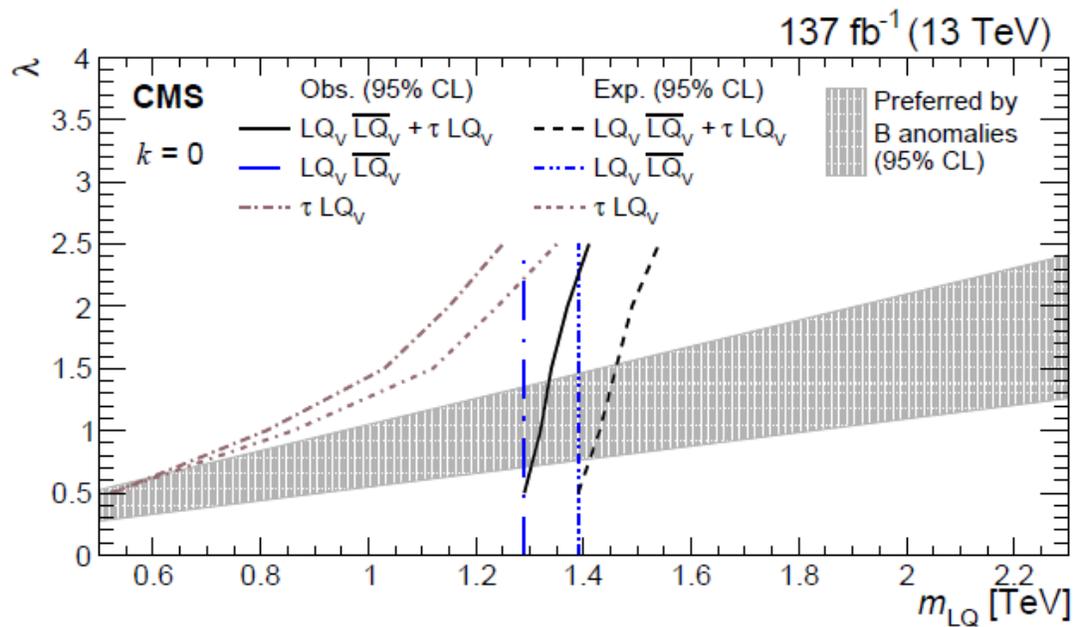
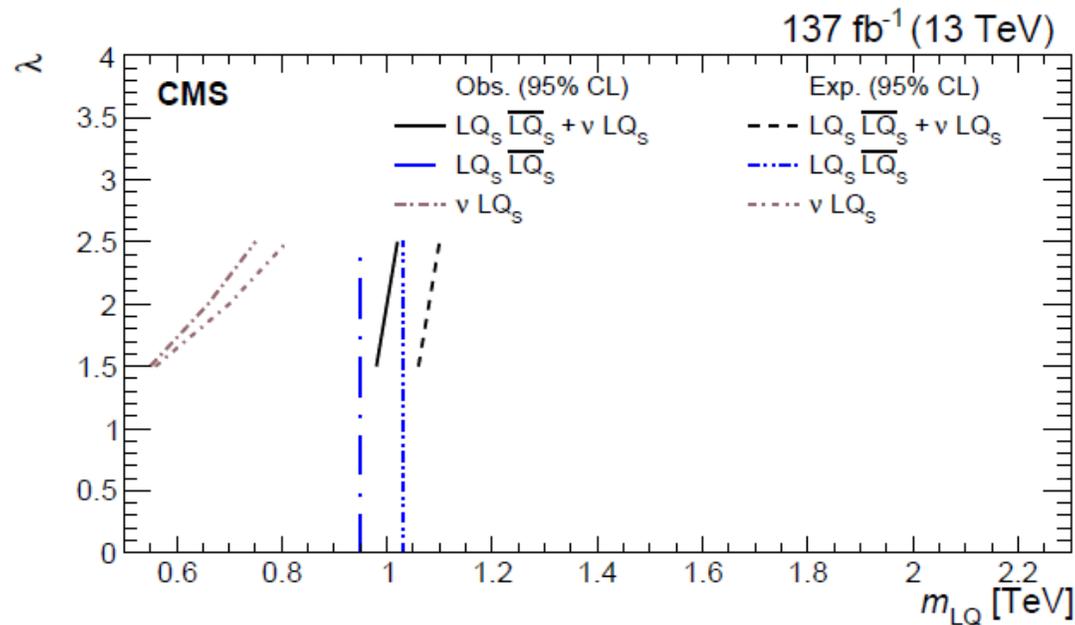


Pair + single



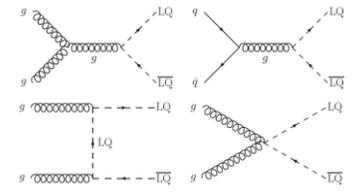
Summary of Obs(Exp) limits

	LQ _S (TeV)		LQ _V k = 0 (TeV)		LQ _V k = 1 (TeV)	
Pair	0.95 (1.03)		1.29 (1.39)		1.65 (1.77)	
	λ = 1.5	2.5	1.5	2.5	1.5	2.5
Single	0.55 (0.56)	0.75 (0.81)	1.03 (1.12)	1.25 (1.35)	1.20 (1.29)	1.41 (1.53)
Pair+Single	0.98 (1.06)	1.02 (1.10)	1.34 (1.46)	1.41 (1.54)	1.69 (1.81)	1.73 (1.87)

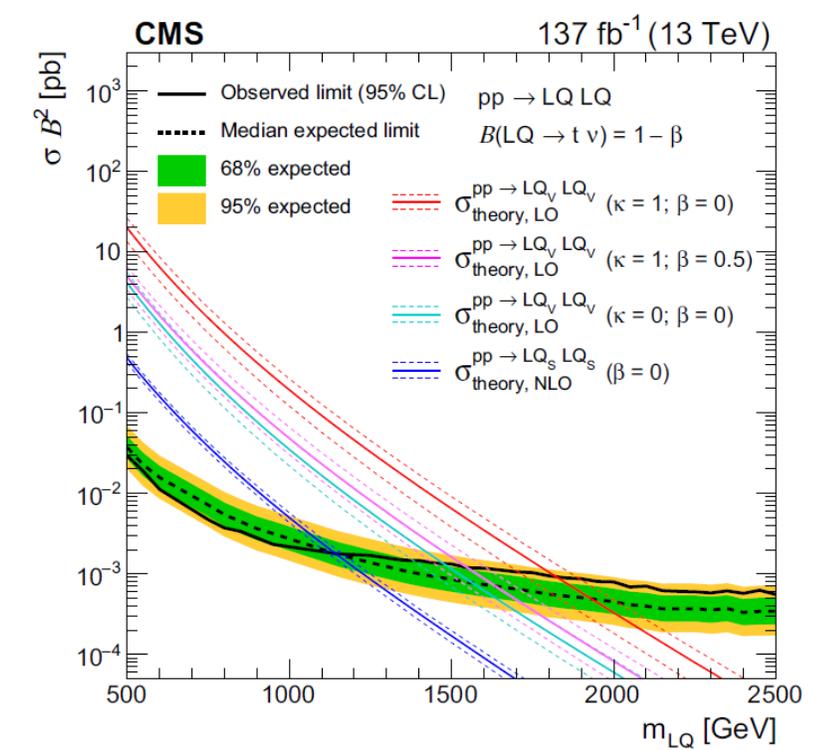
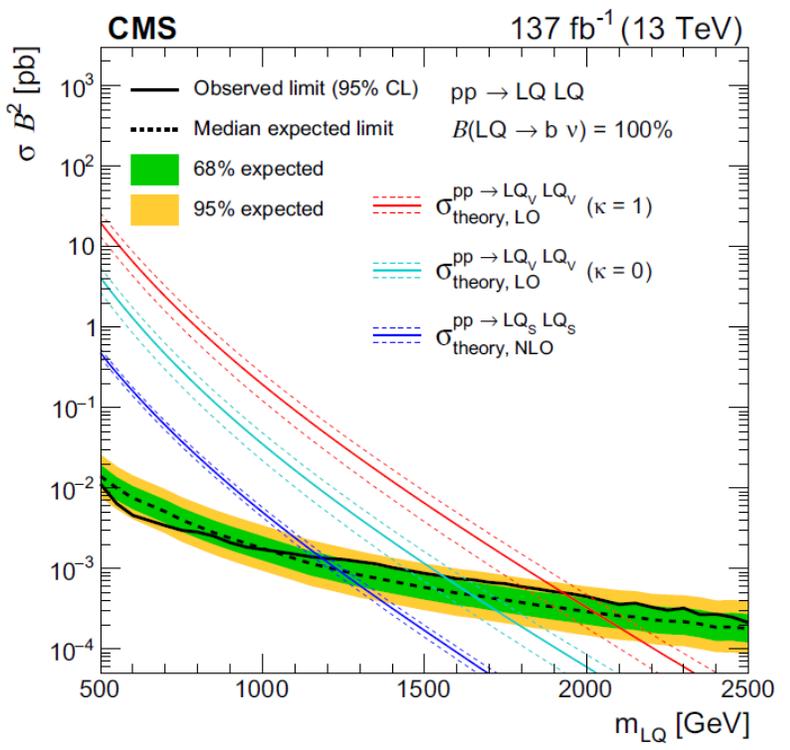
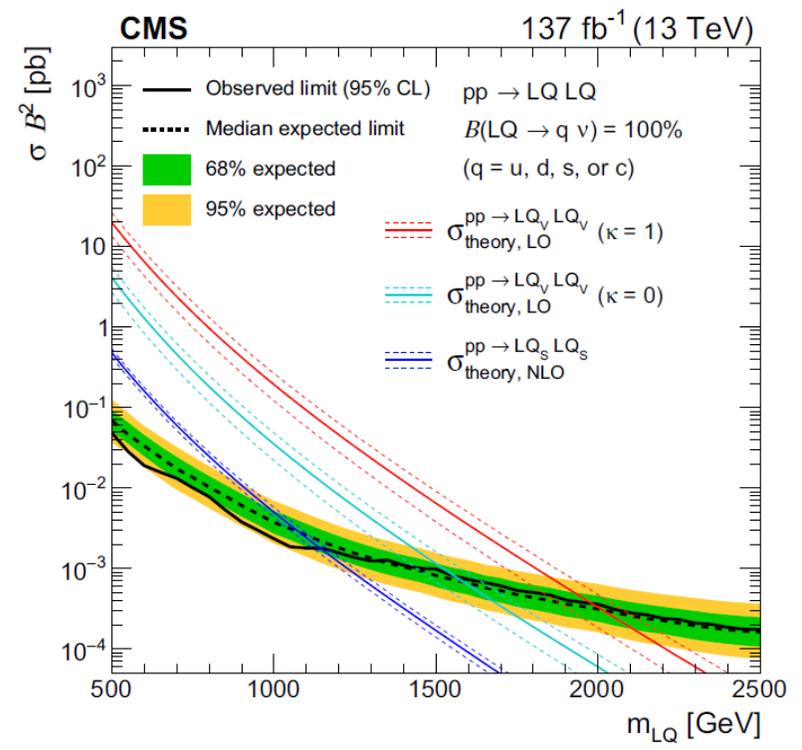


Scalar/vector LQ decaying to neutrino and quark – pair production

- $\mathcal{L} = 137 \text{ fb}^{-1}$, $\sqrt{s} = 13 \text{ TeV}$
- $LQ \rightarrow \nu q$, $q = u, d, c, s, b, t$
- Search channels
 - $\nu\nu qq$: MET + multijets
 - MT2



	LQ _S Mass (GeV)	LQ _V , $\kappa = 1$ Mass (GeV)	LQ _V , $\kappa = 0$ Mass (GeV)
$LQ \rightarrow q\nu$ ($q = u, d, s, \text{ or } c$)	1140	1980	1560
$LQ \rightarrow b\nu$	1185	1925	1560
$LQ \rightarrow t\nu$	1140	1825	1475
$LQ \rightarrow \begin{cases} t\nu & (\mathcal{B} = 50\%) \\ b\tau & (\mathcal{B} = 50\%) \end{cases}$	–	1550	1225



Summary

- CMS have performed the searches for LQ since LHC started
- The LQ searches have covered all of
 - generations of LQ – 1st, 2nd, 3rd
 - types – scalar, vector(k=0, k=1)
 - parameters – couplings, BR, mass
 - processes – pair, single production.
- The searches have not found any LQ-like signal yet, and set 95 % limits on LQ parameters
➔ Next page !
- However, we have more fascinating chances at RUN 3 and HL-LHC. Let's stay tuned.

■ Scalar ■ Vector (k=0) ■ Vector (k=1)

