Searches for new resonances in lepton+jets, lepton+photon and jets+photon final states

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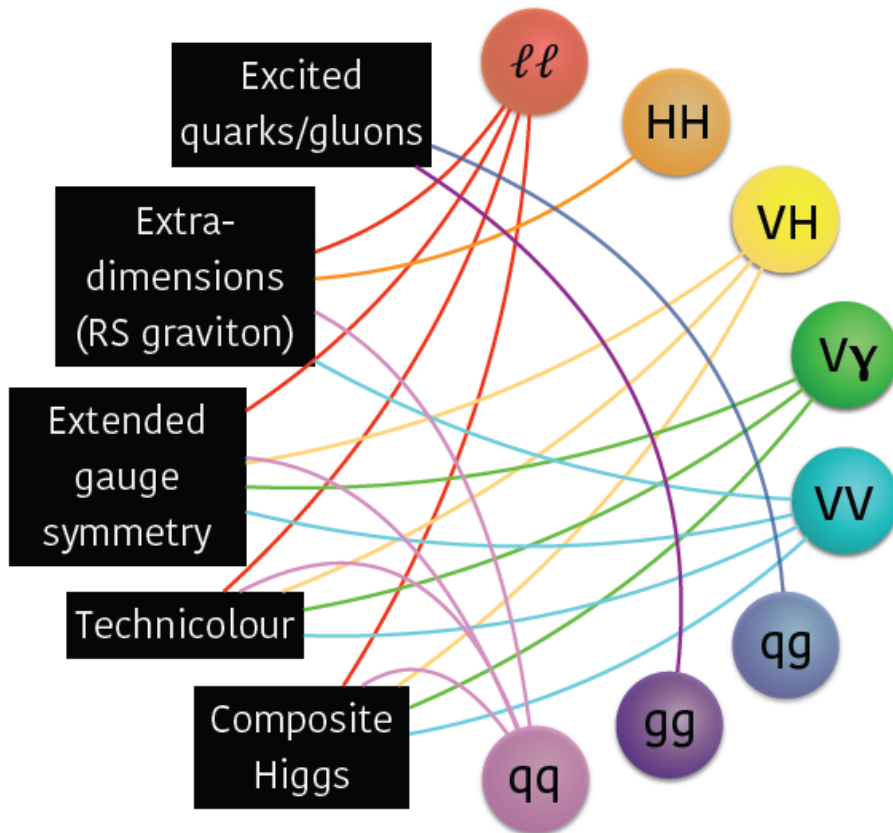*2015.09.02*

2010-2012: Successful Run1

ATLAS p-p run: April-December 2012

Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.9	99.1	99.8	99.1	99.6	99.6	99.8	100.	99.6	99.8	99.5

All good for physics: 95.5%

Luminosity weighted relative detector uptime and good quality data delivery during 2012 stable beams in pp collisions at √s=8 TeV between April 4th and December 6th (in %) – corresponding to 21.3 fb-1 of recorded data.

CMS Integrated Luminosity, pp

Data included from 2010-03-30 11:21 to 2012-12-16 20:49 UTC

- **2010, 7 TeV, 44.2 pb^{-1}**
- **2011, 7 TeV, 6.1 fb^{-1}**
- **2012, 8 TeV, 23.3 fb^{-1}**

July 2015

CMS Preliminary

- 7 TeV CMS measurement (L ≤ 5.0 fb^{-1})
- 8 TeV CMS measurement (L ≤ 19.6 fb^{-1})
- 7 TeV Theory prediction
- 8 TeV Theory prediction
- CMS 95%CL limit

All results at: http://cern.ch/go/pNj7

Glorious SM

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SciVerse ScienceDirect

http://www.elsevier.com/locate/physletb

The Nobel Prize in Physics 2013

Photo: A. Mahmoud
François Englert
Prize share: 1/2

Photo: A. Mahmoud
Peter W. Higgs
Prize share: 1/2

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

2

BSM Searches at the LHC

Resonance **Shape** **Rate**

Excited quarks/gluons

Extra-dimensions (RS graviton)

Extended gauge symmetry

Technicolour

Composite Higgs

ℓℓ HH VH Vγ VV qg gg qq

Katharine Leney

In this report, we focus on ATLAS and CMS resonance **searches for**

(1) Leptoquarks (or SUSY)
   Leptons+Jets

(2) Excited quark
   Jet+photon

(3) Excited lepton
   Lepton+photon

Leptoquarks

- GUT, Composite or Techicolor models
- With both baryon number (B) and lepton number (L).
- Fractional charge, scalar or vector: **Scalar in BRW as a benchmark**
- FCNC limit disfavor LQ couples to different generation leptons and quarks

- **Mass, Decay Branch Ratio β, Yukawa coupling** $\lambda_{LQ \to lq}$

Pair or **Single** production of LQs
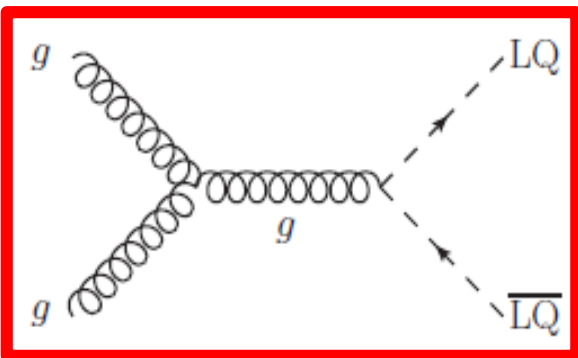
gg fusion and qqbar annihilation; Only depend on M_{LQ}
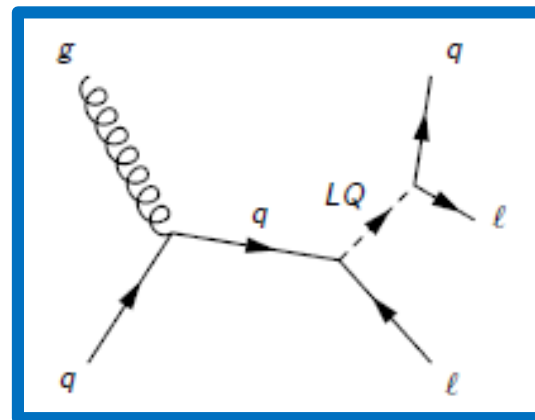
depend on both M_{LQ} and $\lambda_{LQ \to lq}$

LQs decays:
$$BR(LQ \to l + q) = \beta; \qquad BR(LQ \to v + q) = 1 - \beta$$
$$\Gamma = \frac{\lambda^2}{16\pi^2} \times M_{LQ}$$

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2014 Review of Particle Physics

$\beta=1$ $\beta=0.5$

ATLAS 7TeV;   CMS 7TeV

http://pdg.lbl.gov/2014/reviews/rpp2014-rev-leptoquark-quantum-numbers.pdf 5
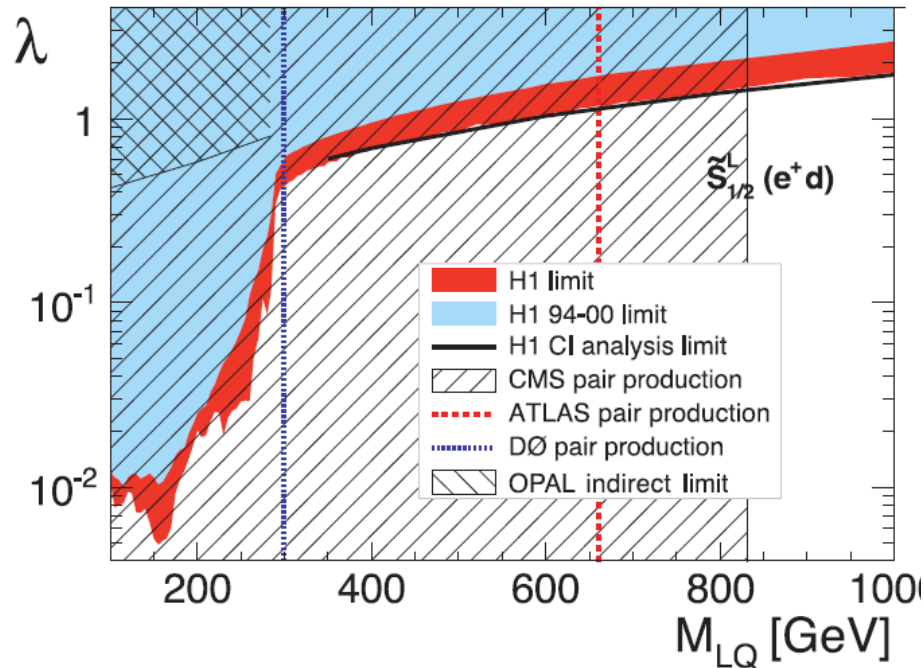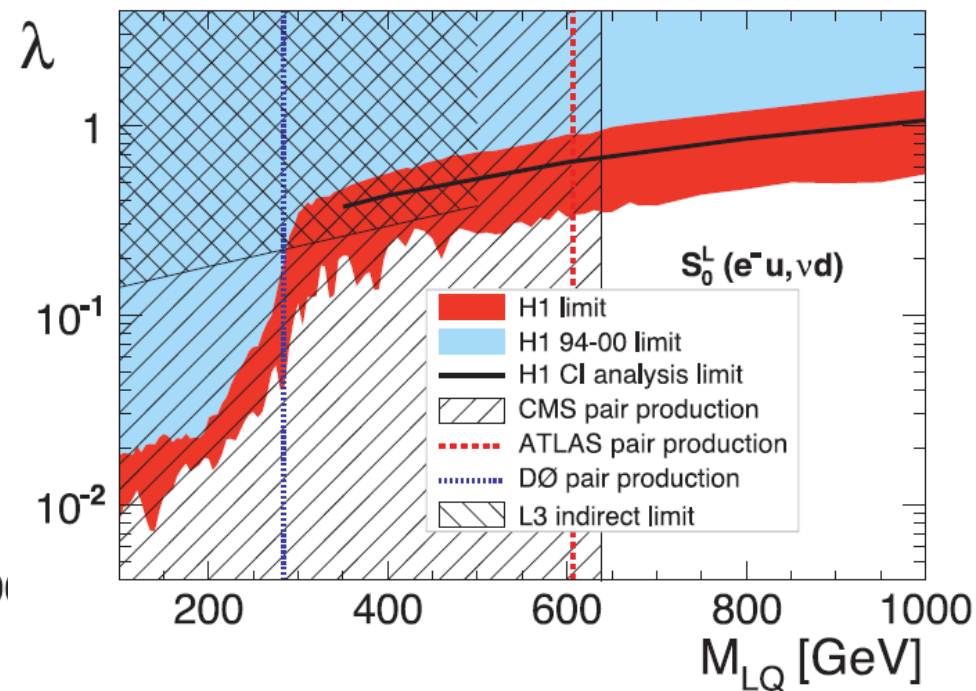
ATLAS 1st /2nd generation LQs   8TeV   arXiv:1508.04735

eejj pre-selections
Trigger: two ECAL clusters
2 and only 2 electrons: $|\eta| < 2.47$
    $pT1 > 40GeV, pT2 > 30GeV$
2 jets $|\eta| < 2.8, pT > 30GeV$

μμjj pre-selections
Trigger: SingleMuon ($pT > 36GeV$ **)**
2 and only 2 muons: $|\eta| < 2.4$
    $pT > 40GeV$ **and opposite charge**
2 jets $|\eta| < 2.8, pT > 30GeV$

Further optimize m_{ll}, S_T and m_{LQ}^{min}
(the choice of combination makes m_{LQ}^{min} and m_{LQ}^{max} $differ\ smaller$)

	LQ masses [GeV]	$m_{\ell\ell}$ [GeV]	S_T [GeV]	m_{LQ}^{min} [GeV]
SR1	300	130	460	210
SR2	350	160	550	250
SR3	400	160	590	280
SR4	450	160	670	370
SR5	500–550	180	760	410
SR6	600–650	180	850	490
SR7	700–750	180	950	580
SR8	800–1300	180	1190	610

ATLAS 1st /2nd generation LQs   8TeV   arXiv:1508.04735

Z+jets   from control region with $60 < m_{ee}$<120 or $70 < m_{\mu\mu}$<110
ttbar   from eμjj control region
SF obtained from combined fit with HISTFITTER

Fake lepton also from data-driven as in Z' search (PRD90, 052005 (2014))
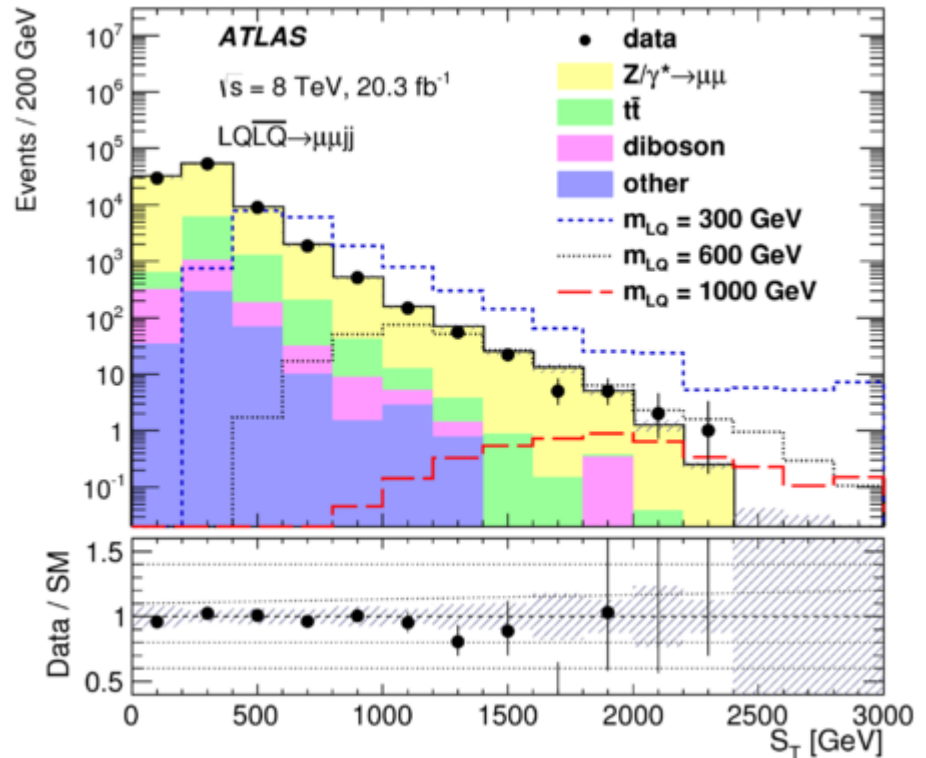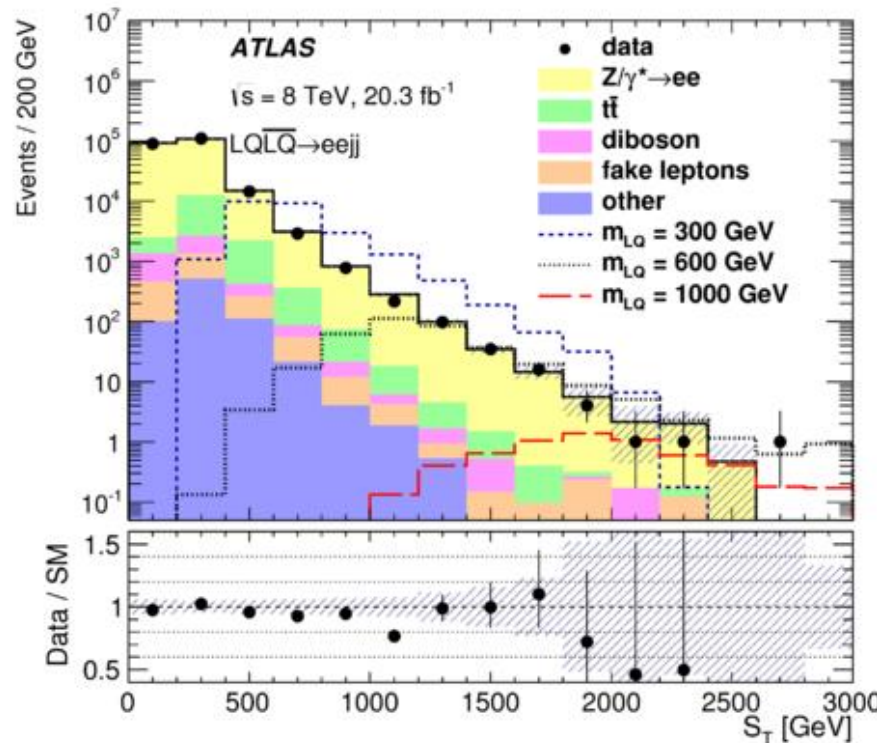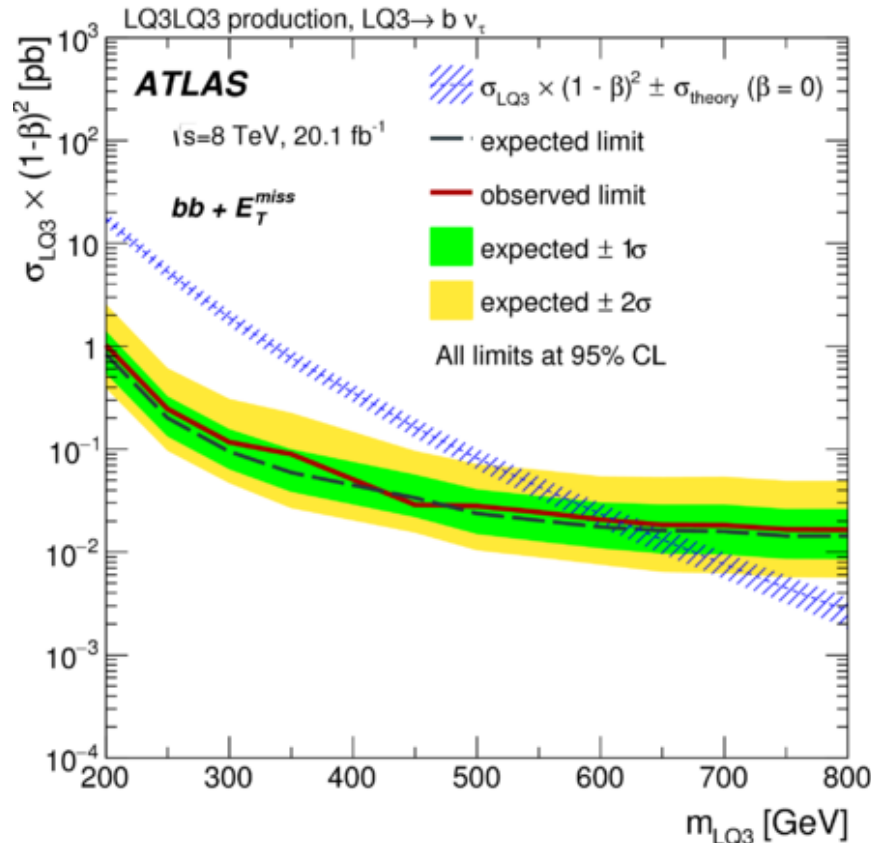

After preselection
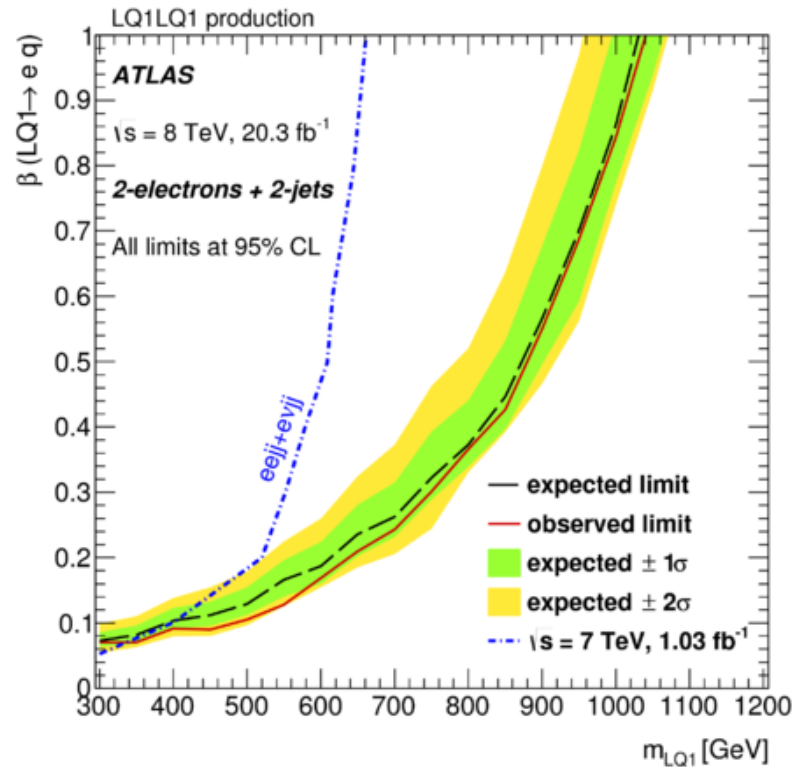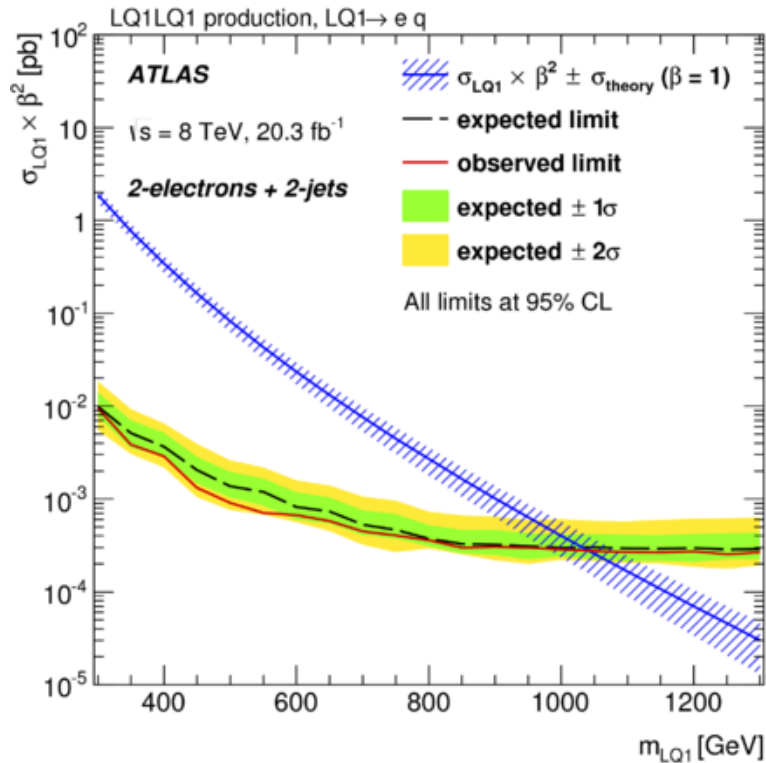
LQ1 with masses less than
1050 GeV are excluded for β = 1

ATLAS 2nd generation LQs   8TeV   arXiv:1508.04735
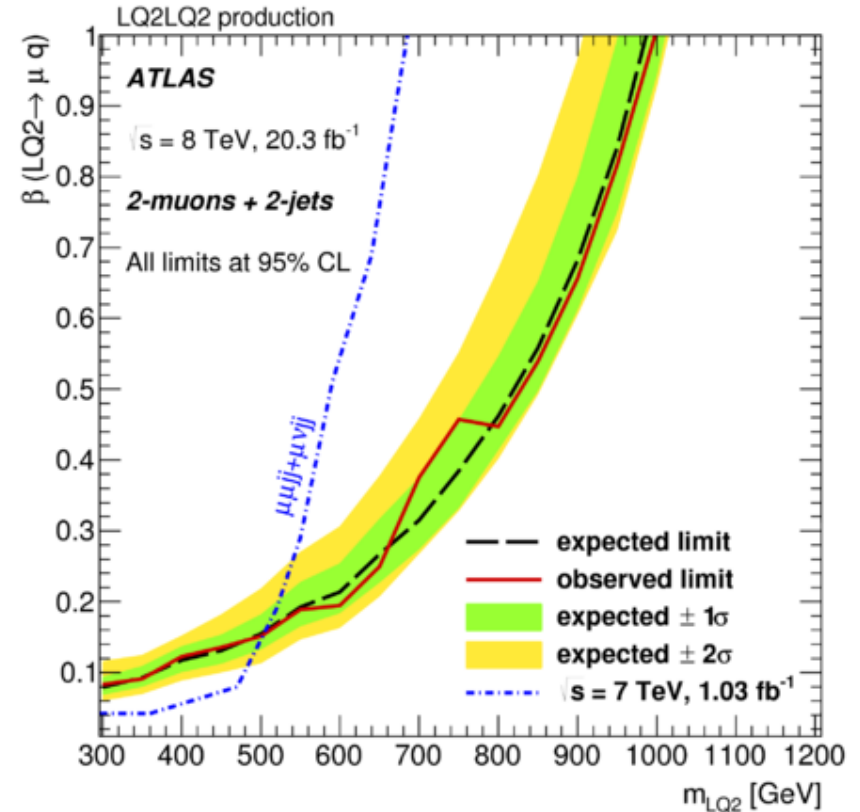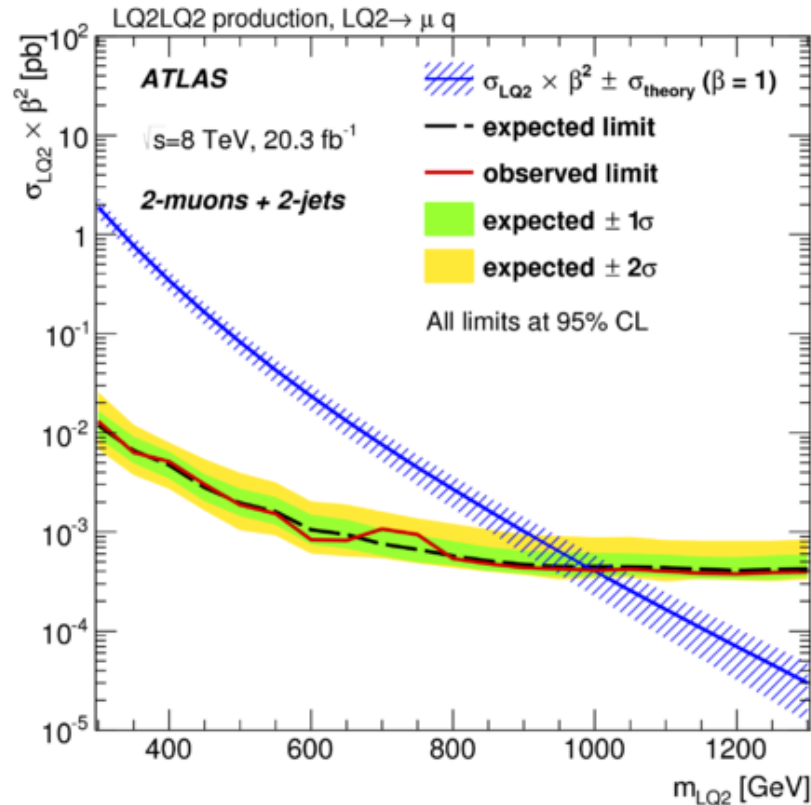
LQ2 with masses less than
1000 GeV are excluded for β = 1

ATLAS   3rd generation LQs   8TeV   arXiv:1508.04735

Reinterpreted from two analysis SUSY for $LQ3LQ3 \rightarrow t\nu t\nu$, and $b\nu b\nu$
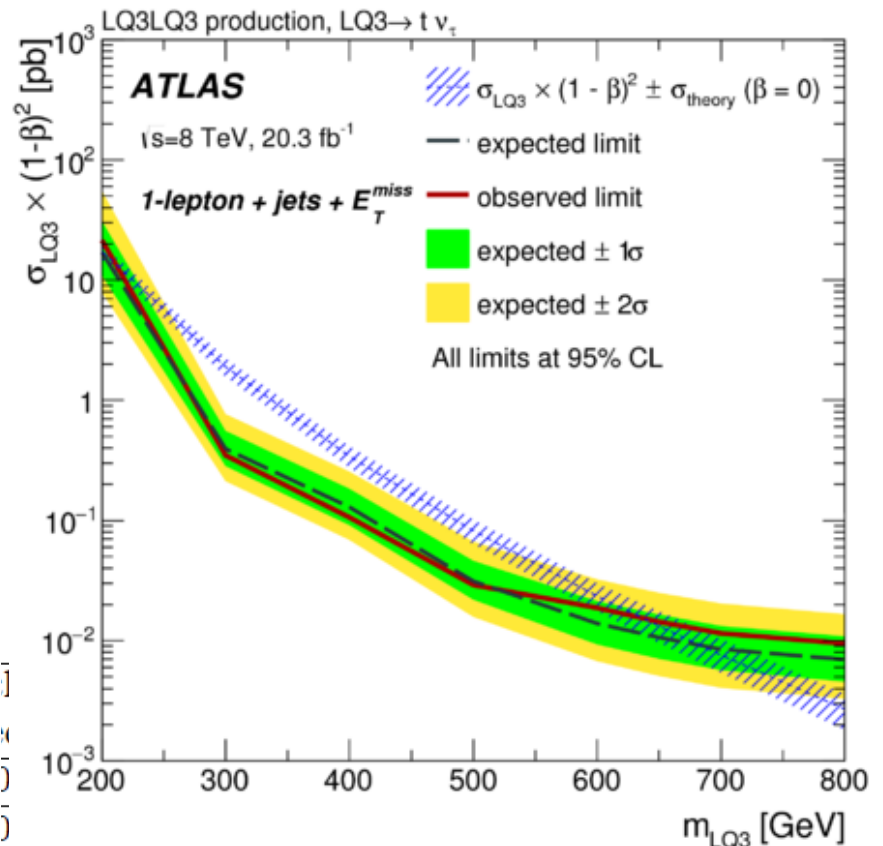
	$\sqrt{s}=8$ TeV analysis	$\sqrt{s}=8$ TeV analysis
$b\nu_\tau \overline{b\nu_\tau}(\beta = 0.0)$	$m_{\mathrm{LQ3}} < 640$ GeV	$m_{\mathrm{LQ3}} < 625$ GeV
$t\nu_\tau \overline{t\nu_\tau}(\beta = 0.0)$	$200 < m_{\mathrm{LQ3}} < 685$ GeV	$210 < m_{\mathrm{LQ3}} < 640$ GeV

Reminds: *Previously at 7TeV,*
pair productions with $LQ3 \rightarrow \tau b$ $\Rightarrow LQ3 < 534 GeV, for \beta = 1$

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CMS 1st generation LQs   8TeV   CMS PAS-EXO-12-041

eejj selections
ele+dijet HLT
2 and only 2 electrons:
$pT > 45GeV, \quad |\eta| < 2.5$
2 jets $|\eta| < 2.4$:
$pT1 > 125GeV, pT2 > 45GeV$
$m_{ee} > 40GeV, \qquad S_T > 300GeV$
Veto tight muon with $pT > 10GeV$

Further optimize m_{ee}, S_T and m_{ej}^{min}

evjj selections
ele+dijet HLT
1 and only 1 electron:
$pT > 45GeV, \quad |\eta| < 2.1$
2 jets $|\eta| < 2.4$:
$pT1 > 125GeV, pT2 > 45GeV$
$E_T^{miss} > 55GeV, \quad S_T > 300GeV$
$\Delta\varphi(E_T^{miss}, e) > 0.8, \Delta\varphi(E_T^{miss}, j1) > 0.5$
$\min\Delta R(e, jets) > 0.7$
Veto tight muon with $pT > 10GeV$
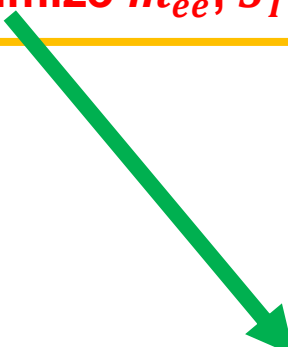
Further optimize $E_T^{miss}, S_T, m_{ej},$
and $m_{T,ev}$

	LQ mass ($eejj$)														
	300	350	400	450	500	550	600	650	700	750	800	850	900	950	≥ 1000
S_T [GeV]	435	485	535	595	650	715	780	850	920	1000	1075	1160	1245	1330	1425
m_{ee} [GeV]	110	110	115	125	130	140	145	155	160	170	175	180	190	195	205
$m_{ej}^{\min}$ [GeV]	50	105	160	205	250	290	325	360	390	415	435	450	465	470	475

CMS 1st generation LQs   8TeV   CMS PAS-EXO-12-041

eejj

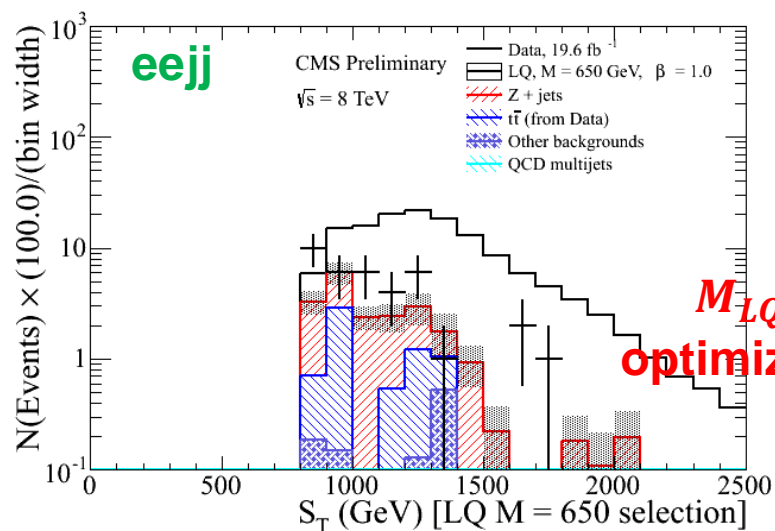|	
Z+jets	from control region with $70 < m_{ee} < 110$
ttbar	from eμjj control region, with single muon trigger
QCD multijet	from loose el sample with single photon trigger

evjj

W+jets and ttbar evaluated from
    (1) ttbar-enriched region: $70 < m_{T,ev} < 110$, $\geq 4 jets$
    (2) W+jets region: same as (1) but $< 4 jets$
QCD multijet: similar as eejj

preselections

eejj

evjj

CMS 1st generation LQs   8TeV   CMS PAS-EXO-12-041
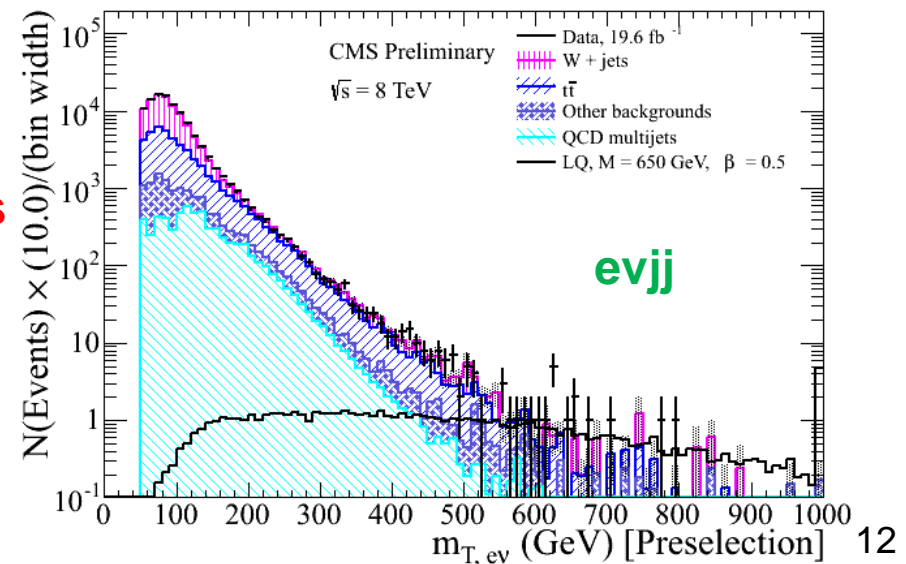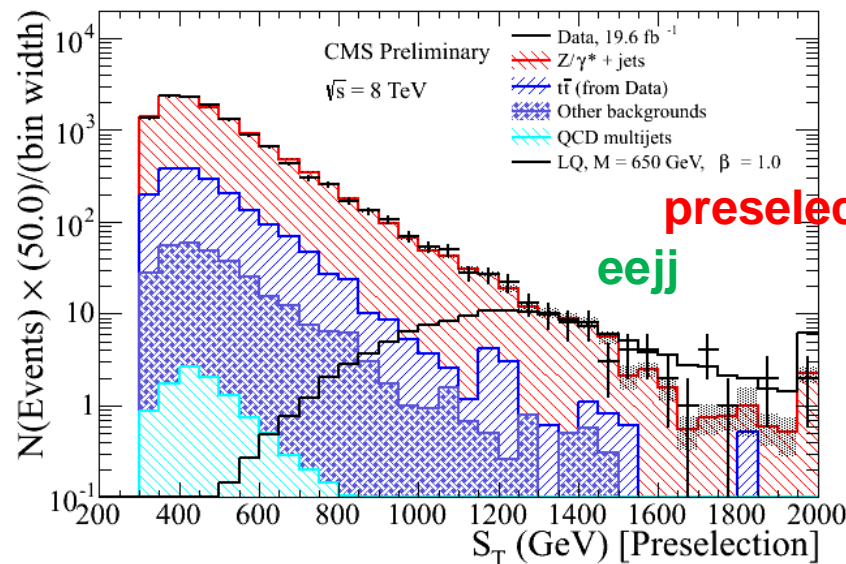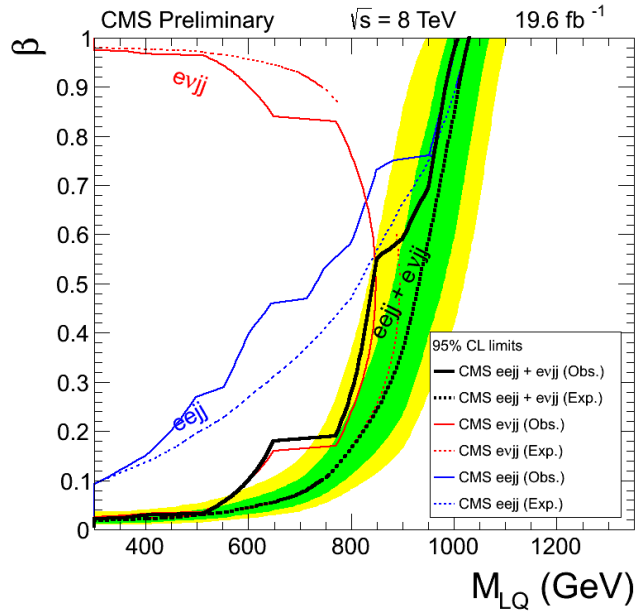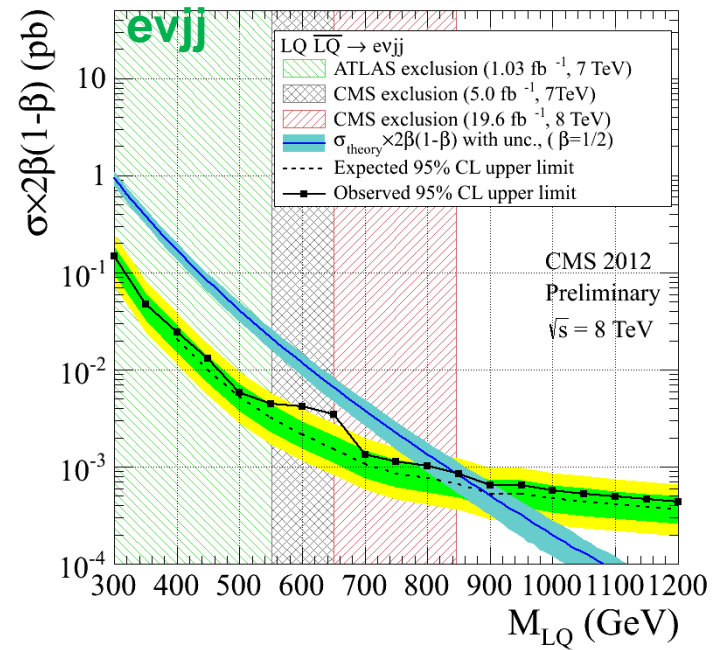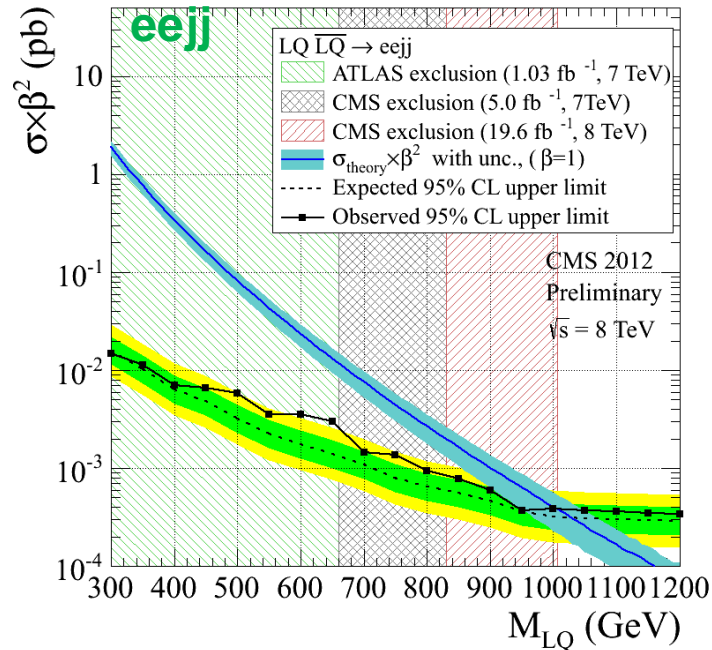
LQ1 with masses less than 1005 (845) GeV
are excluded for   β = 1(0.5)

CMS 1st generation LQs 8TeV CMS PAS-EXO-12-041

eejj

CMS Preliminary
$\sqrt{s} = 8$ TeV

Data, 19.6 fb^{-1}
LQ, M = 650 GeV, β = 1.0
Z + jets
$t\bar{t}$ (from Data)
Other backgrounds
QCD multijets

$M_{LQ} = 650 GeV$
optimized selections

M_{LQ}

evjj

CMS Preliminary
$\sqrt{s} = 8$ TeV

Data, 19.6 fb^{-1}
LQ, M = 650 GeV, β = 0.5
W + jets
$t\bar{t}$
Other backgrounds
QCD multijets
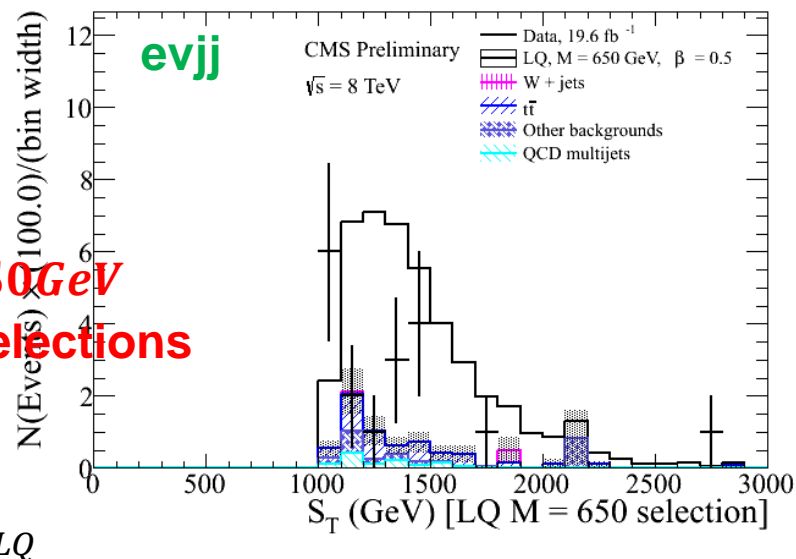
Expected:
  $20.49 \pm 2.14(stat) \pm 2.45(syst)$
Observed: 36
2.4σ

Expected:
   $7.54 \pm 1.20(stat) \pm 1.07(syst)$
Observed: 18
2.6σ

Broad excess, no peak structure
More bkg like

CMS 2nd generation LQs   8TeV   CMS PAS-EXO-12-042

µµjj and µνjj **channnles,   details similar as for LQ1**
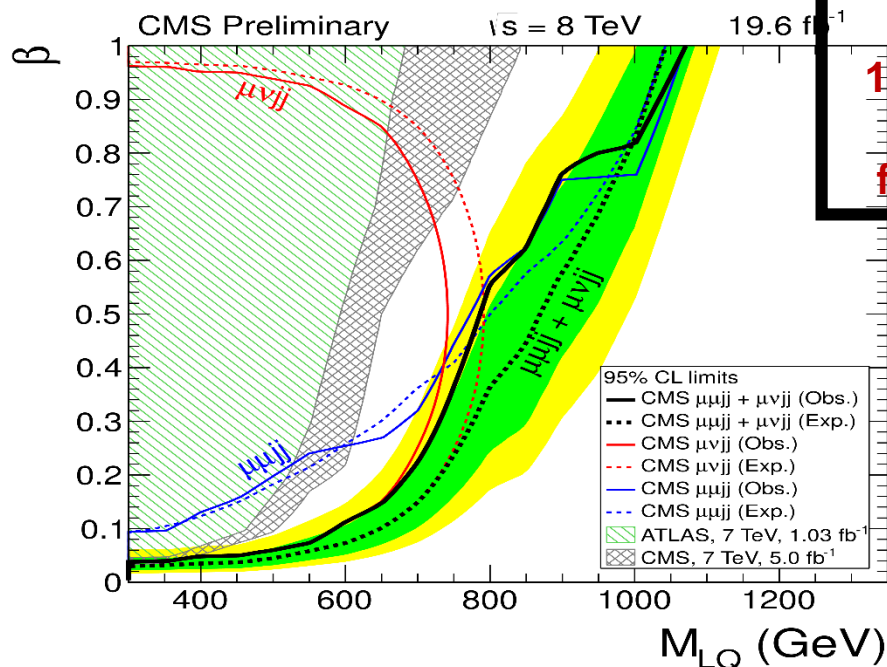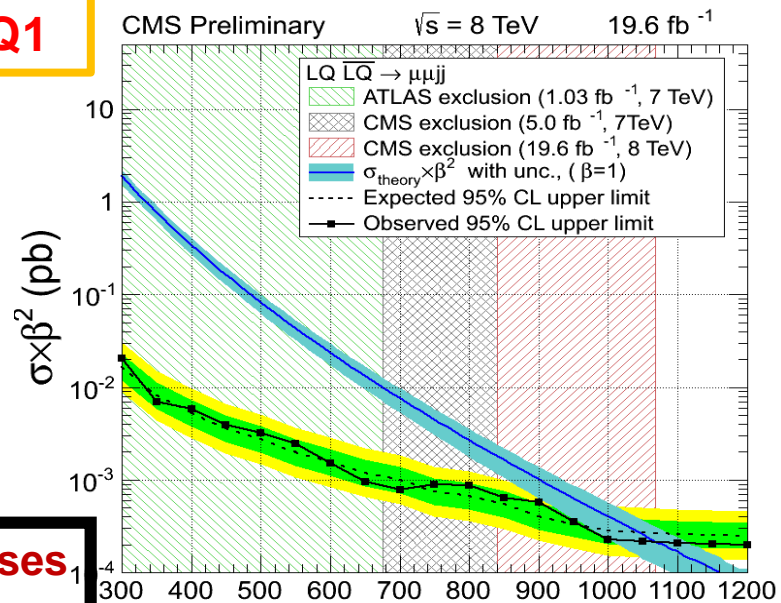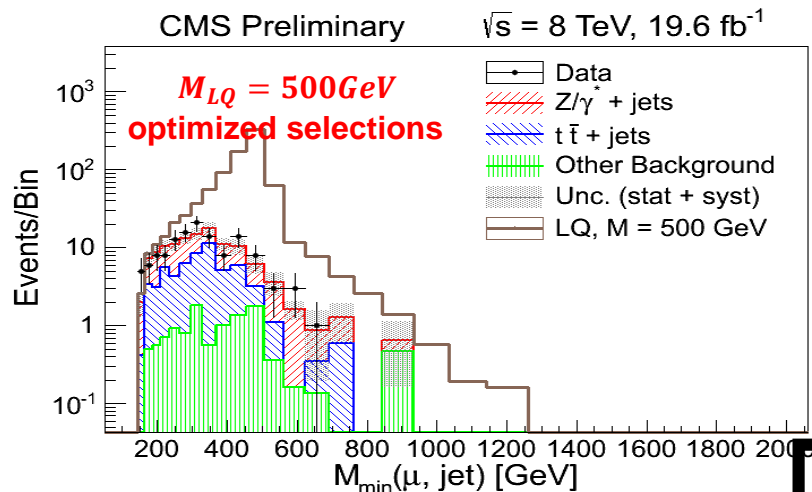
LQ2 with masses less than 1070 (785) GeV are excluded for   β = 1(0.5)

Focusing on β = 1
eej for LQ1
μμj for LQ2
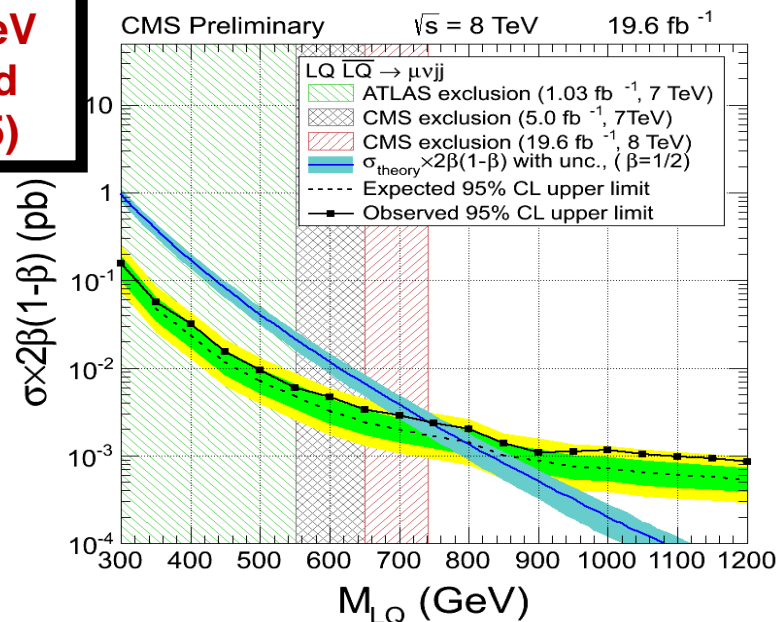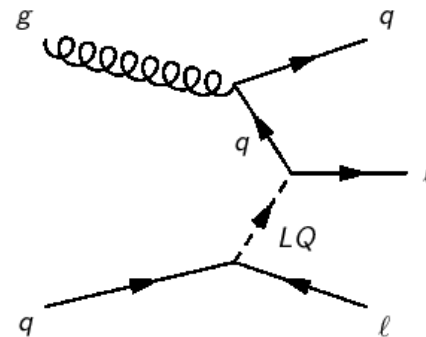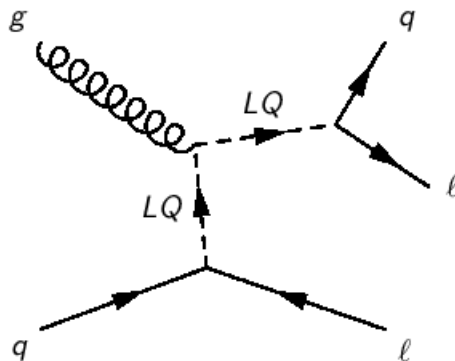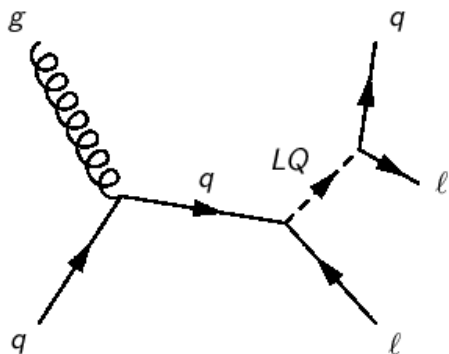
Fiducial xsec for different $\lambda_{LQ \to lq}$

Two generator cuts:
$m_{ll} > 110 GeV$ to remove Z interference
$M_{ej} > 0.65 M_{LQ}$ or $M_{\mu j} > 0.75 M_{LQ}$ **to remove low mass tail from t-channel diagrams**
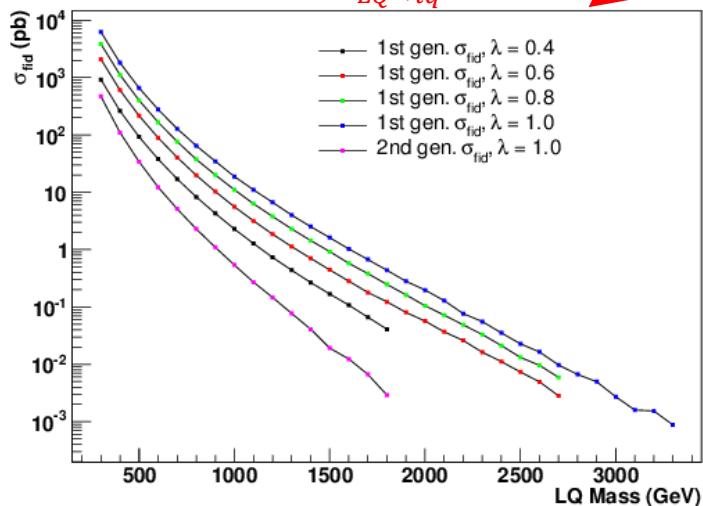
selections
2 leptons: $pT > 45 GeV, \quad |\eta| < 2.1$
1 jet $|\eta| < 2.4, \ pT > 125 GeV$
$\Delta R(l, jet) > 0.3$
Further optimize M_{lj} **and** S_T **for each mass**

CMS   Single produced LQ1/2   8TeV   CMS PAS-EXO-12-043

Z/γ^*+jets, ttbar, QCD multijet from Data-Driven
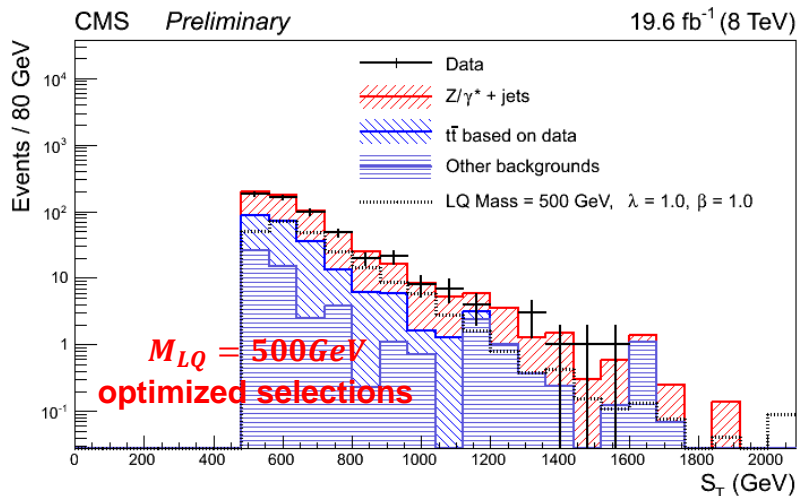
LQ generation, coupling	Excluded mass (GeV)
1st gen., $\lambda = 0.4$	895
1st gen., $\lambda = 0.6$	1260
1st gen., $\lambda = 0.8$	1380
1st gen., $\lambda = 1.0$	1730
2nd gen., $\lambda = 1.0$	530

Stronger than limit
from pair production

$M_{LQ} = 500 GeV$
optimized selections
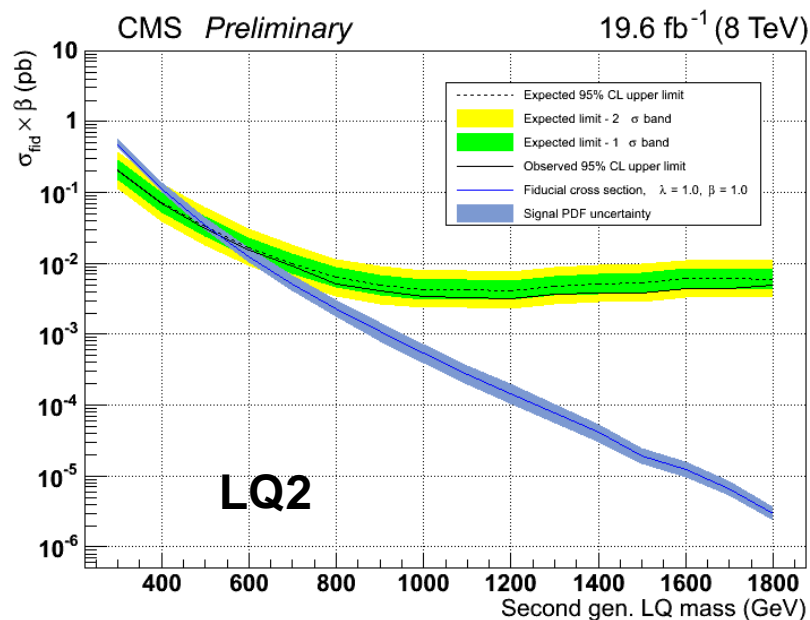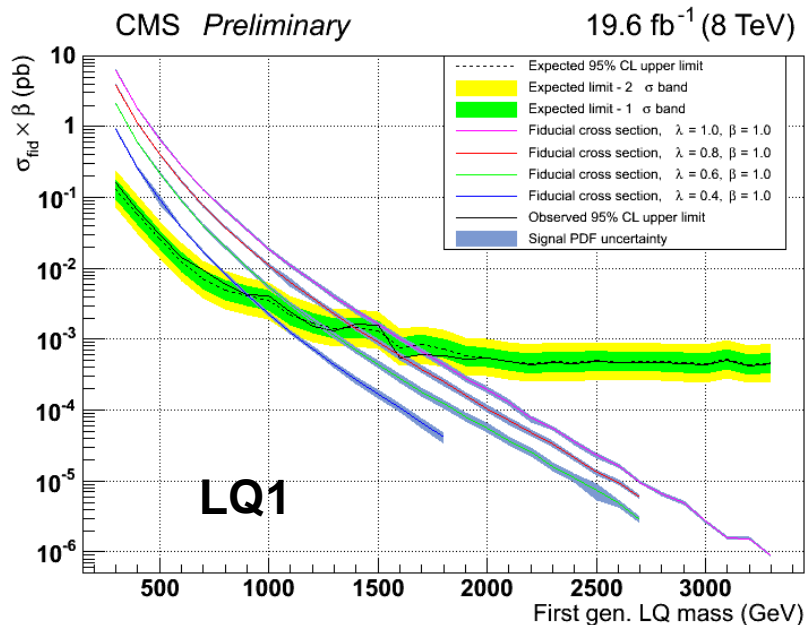
pair productions with LQ3 → τb
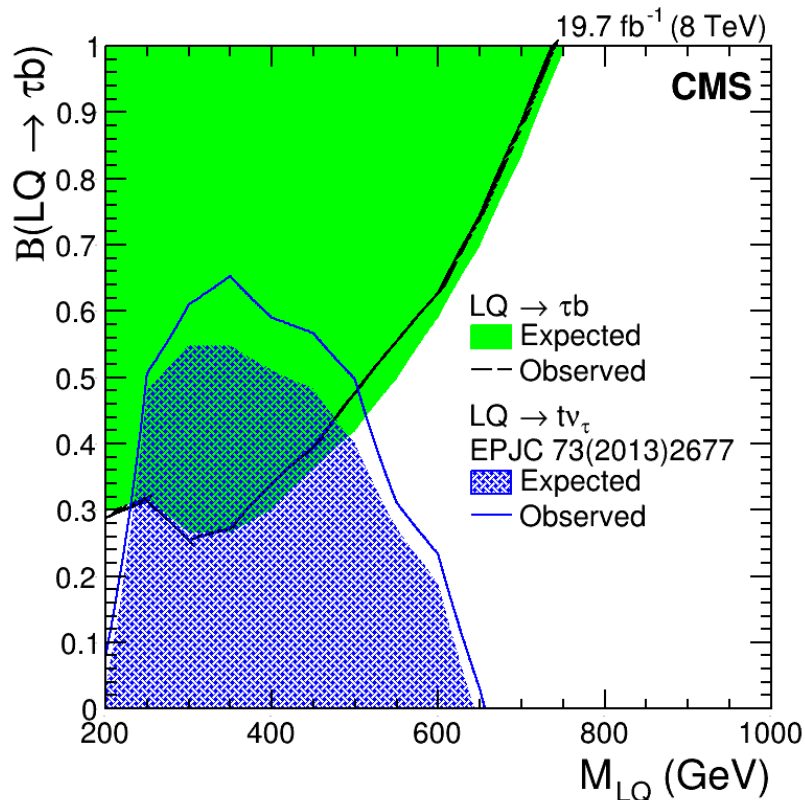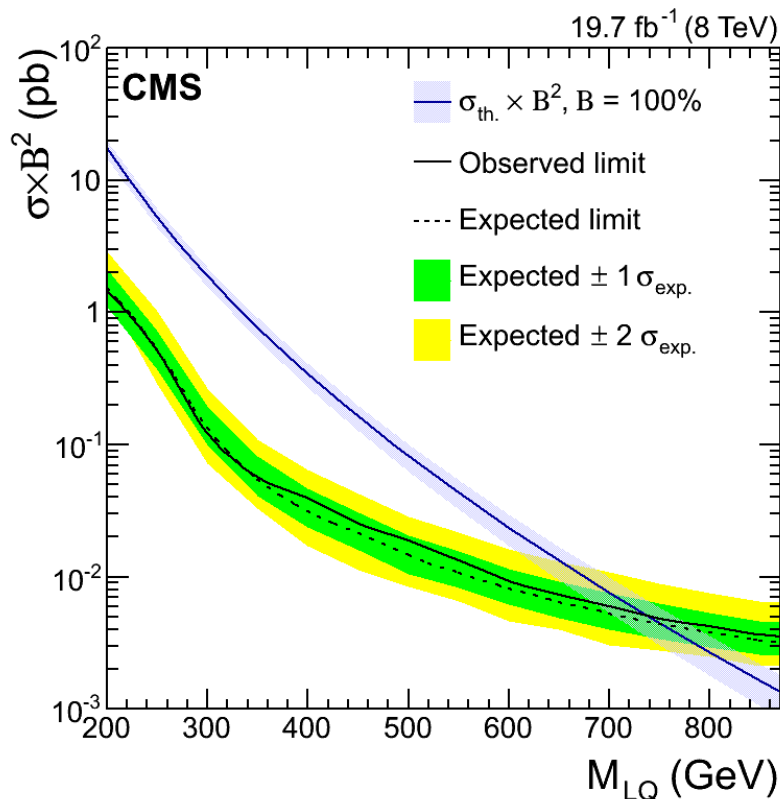
Also reinterpreted for RPV SUSY

$LQ3 → t + v$
limit obtained from SUSY stop pair search
Eur. Phys. J. C 73 (2013) 2677

1 lep + 1 τ_h + $\geq$ 2jets
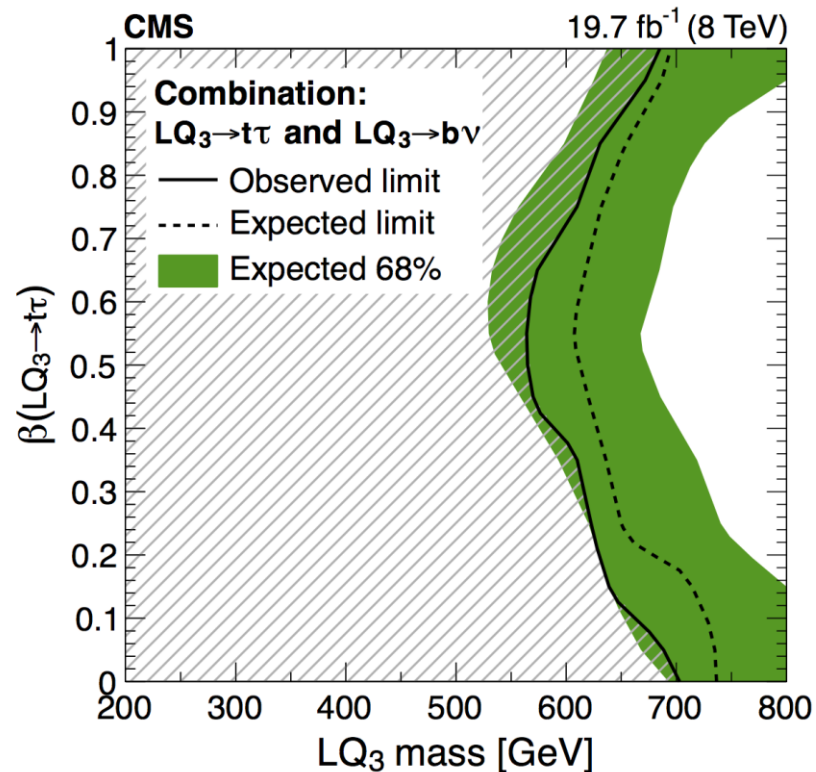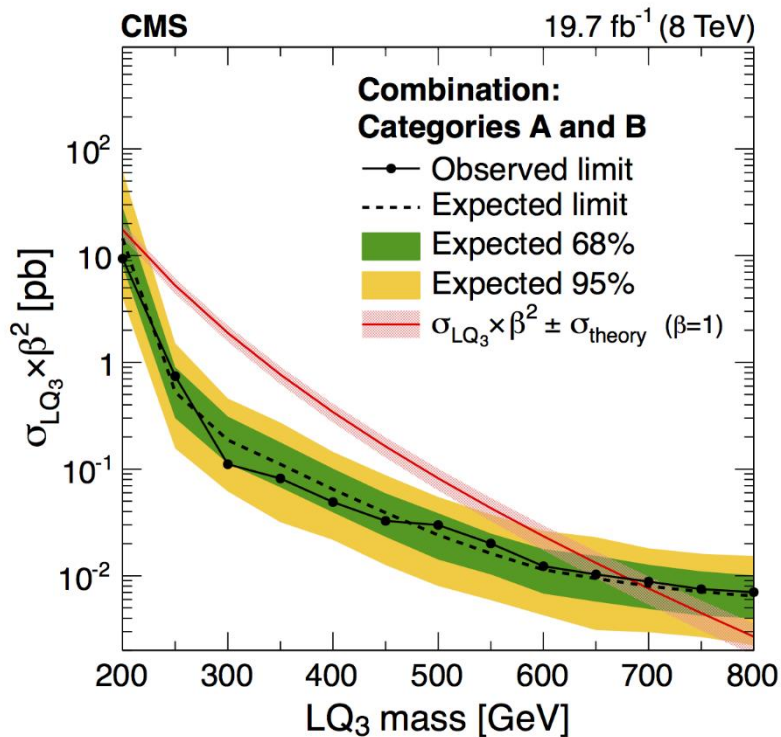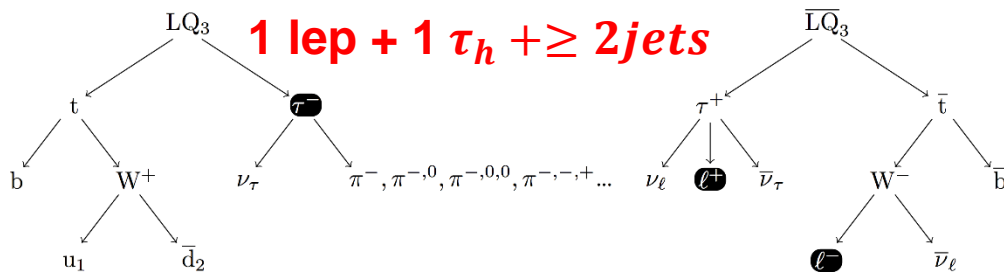
$LQ3 \rightarrow bv$
limit obtained from SUSY sbottom pair search
with $\widetilde{b} \rightarrow b\widetilde{x_0}$
JHEP 06 (2015) 116

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Excited quark

$$\mathcal{L}_{\text{int}} = \frac{1}{2\Lambda} \bar{q}_R^* \, \sigma^{\mu\nu} \left[g_s f_s \frac{\lambda_a}{2} G_{\mu\nu}^a \; + \; g f \frac{\tau}{2} W_{\mu\nu} \; + \; g' f' \frac{Y}{2} B_{\mu\nu} \right] q_L + \text{h.c.},$$
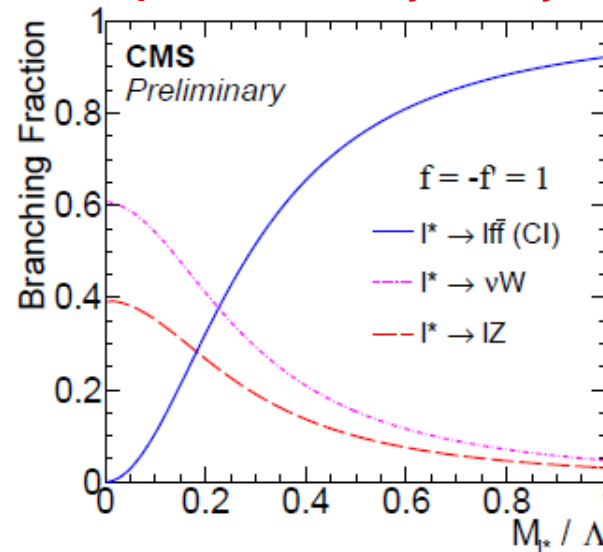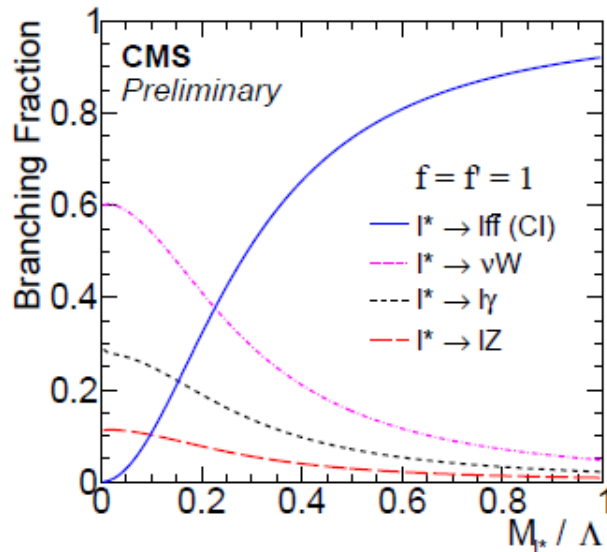
- **Assuming** $f = f_s = f'$
- **Focusing on** $\Lambda = M_{q^*}$
- **Variation of f and** M_{q^*}/Λ **has same effect in xsec**
- $\Gamma \sim 0.04 f^2 M_{q^*}$

Dijet resonance set limit on excited quark: M<3.5-4TeV

Excited lepton

$$\mathcal{L}_{\text{CI}} = \frac{g_*^2}{2\Lambda^2} j^\mu j_\mu \qquad \mathcal{L}_{\text{GM}} = \frac{1}{2\Lambda} \bar{f}_R^* \sigma^{\mu\nu} \left(g f \frac{\tau}{2} W_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu} \right) f_L + \text{h.c.}$$
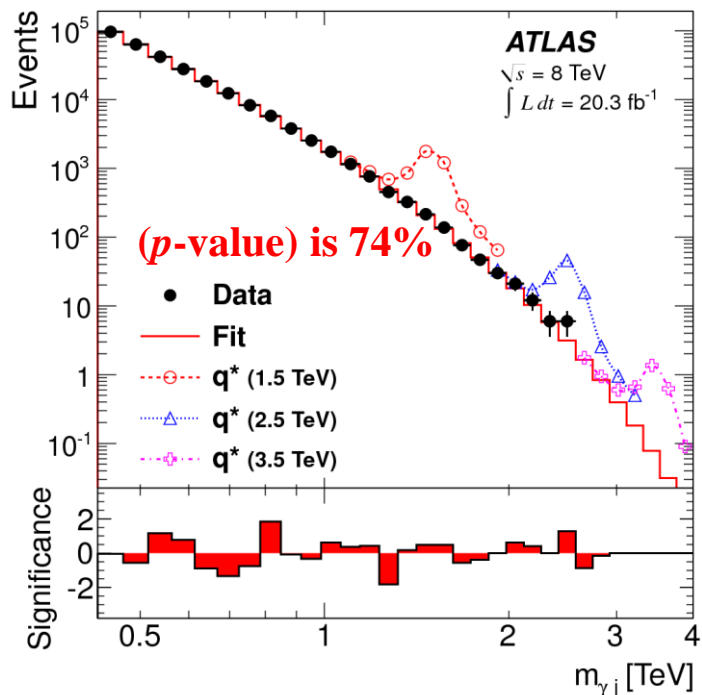
$l^* \rightarrow l + \gamma \quad closed \quad for \quad f = -f'$

GM preferred over CI for large Λ

ATLAS   Excited quark: q+γ

$$f(x \equiv m_{\gamma j}/\sqrt{s}) = p_1(1-x)^{p_2} x^{-(p_3 + p_4 \ln x)}$$

Bayes' theorem is used to set limits on Gaussian shaped signals

Tested with Pythia and Sherpa $\gamma + jets$ and JETPHOX NLO predictions; and also validated in 2 control samples by reverting Photon ID variables
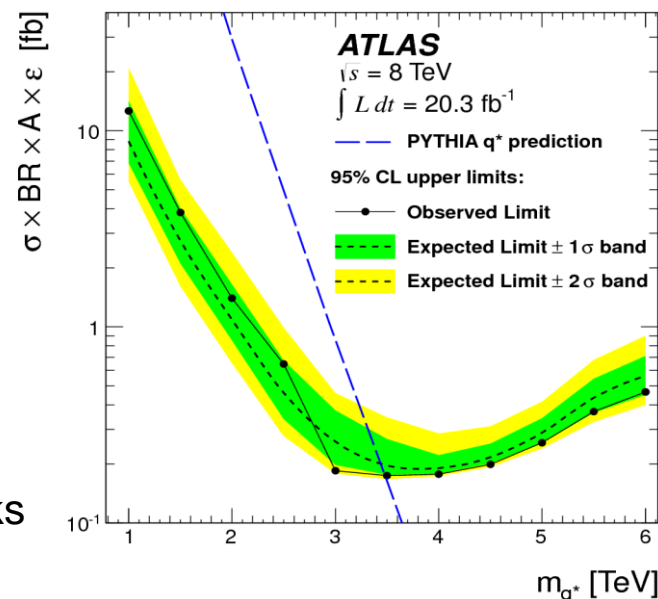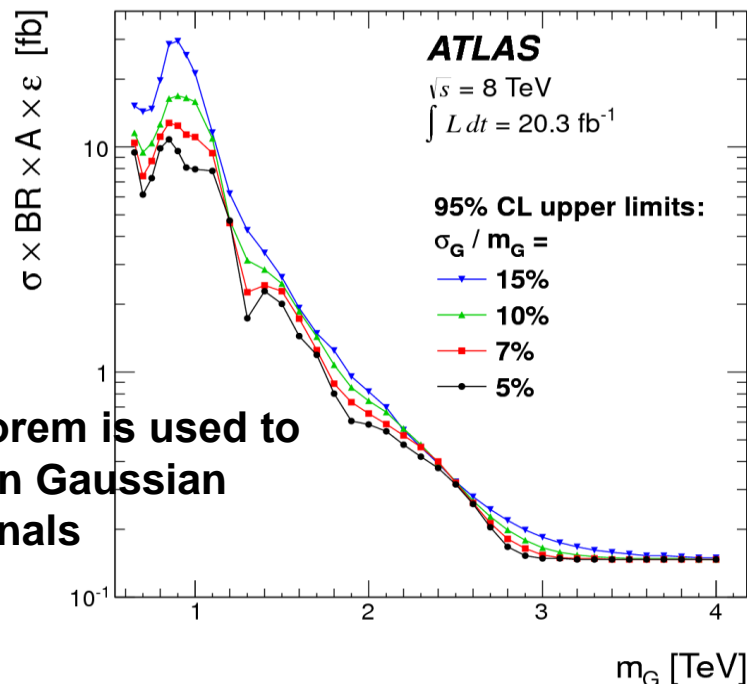
Limits on excited quarks and also QBHs

CMS   Excited quark: q+γ
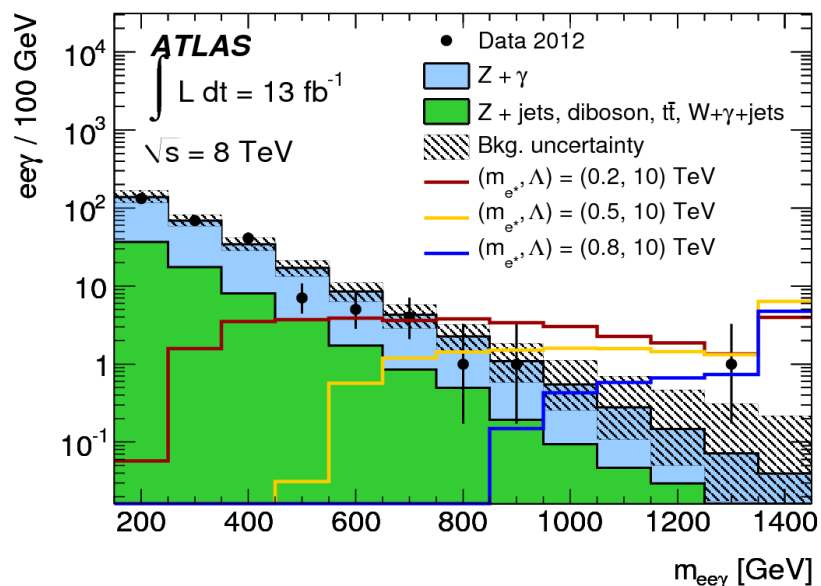
$$\mathcal{L}_{\text{int}} = \frac{1}{2\Lambda} \bar{q}_R^* \, \sigma^{\mu\nu} \left[g_s f_s \frac{\lambda_a}{2} G_{\mu\nu}^a + g f \frac{\tau}{2} W_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu} \right] q_L + \text{h.c.}$$

Focus on $\Lambda = M_{q^*}$ And $f_s = f = f'$
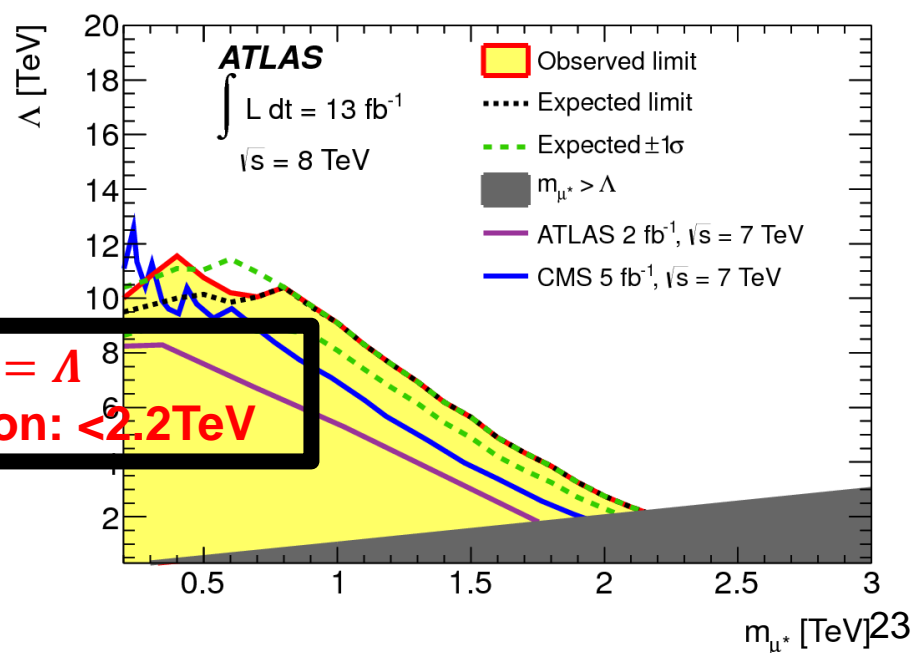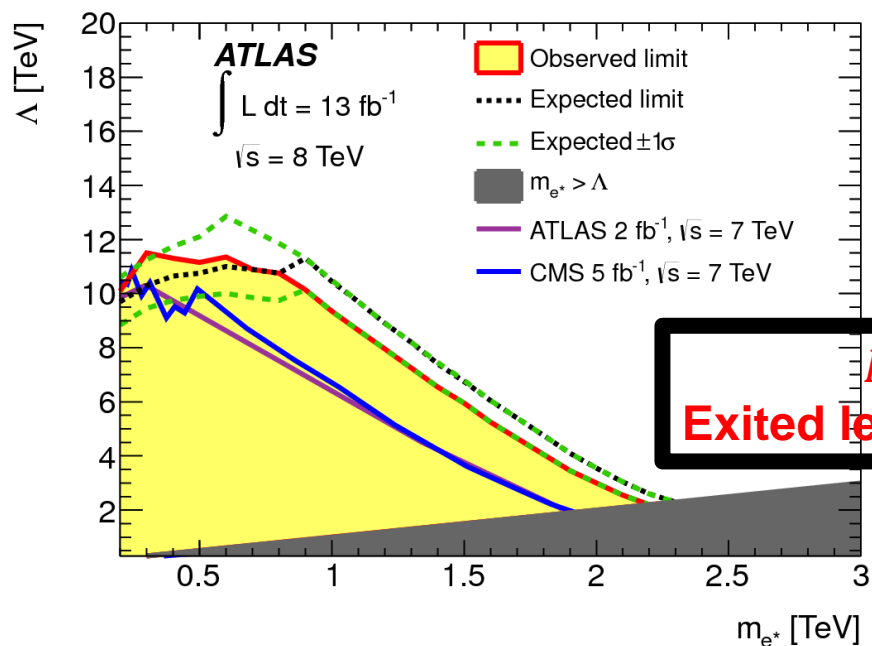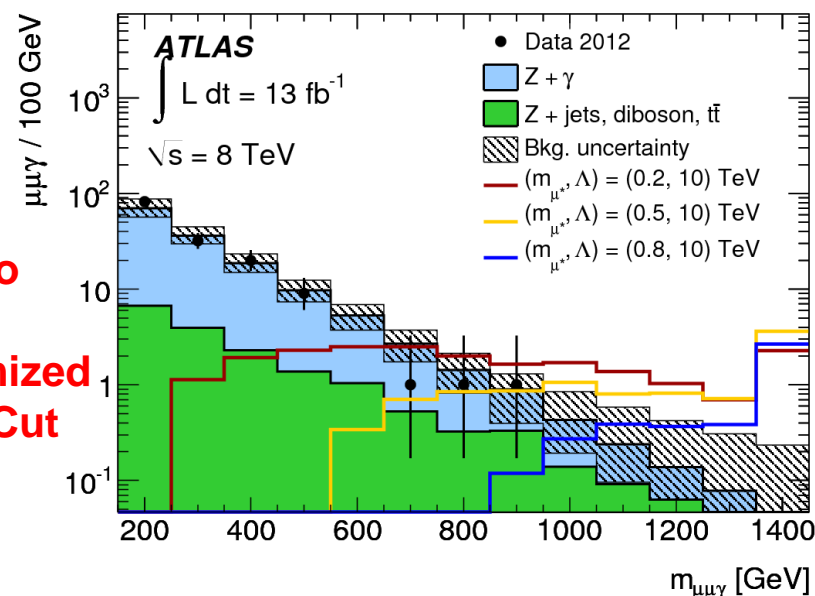

$$\chi^2 = 20.57/34$$
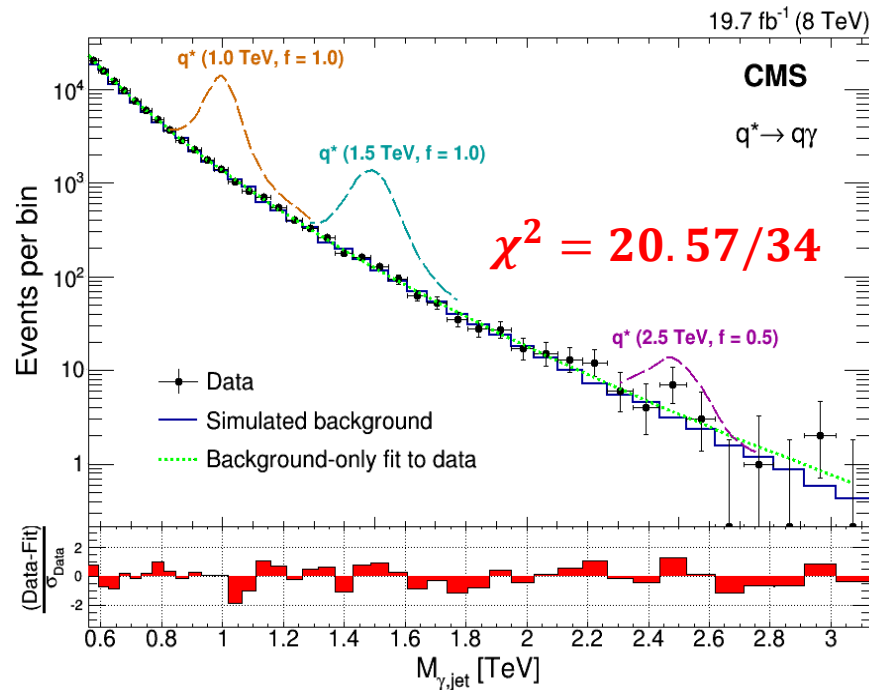
$$\frac{d\sigma}{dm} = \frac{P_0(1 - m/\sqrt{s})^{P_1}}{(m/\sqrt{s})^{P_2 + P_3 \ln(m/\sqrt{s})}}$$

Bkg modelling:
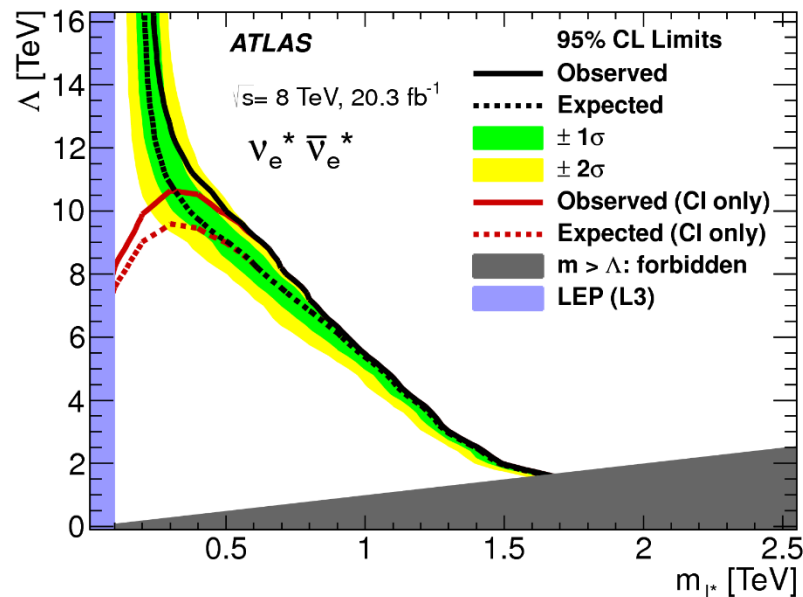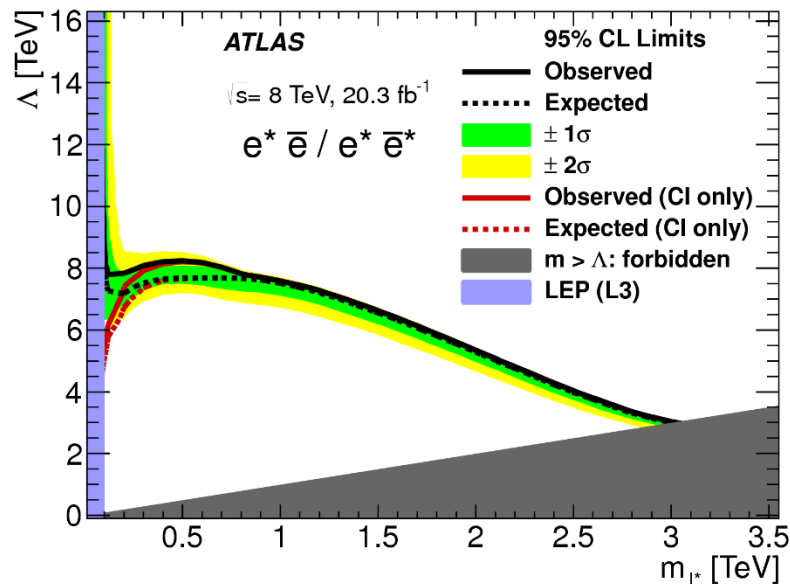**Numerator-> Parton distributions**
Denominator-> QCD ME

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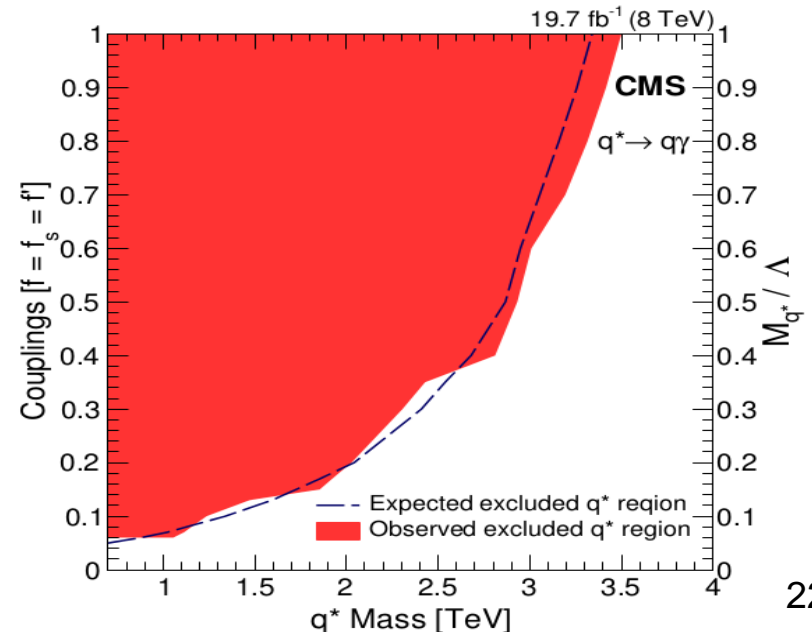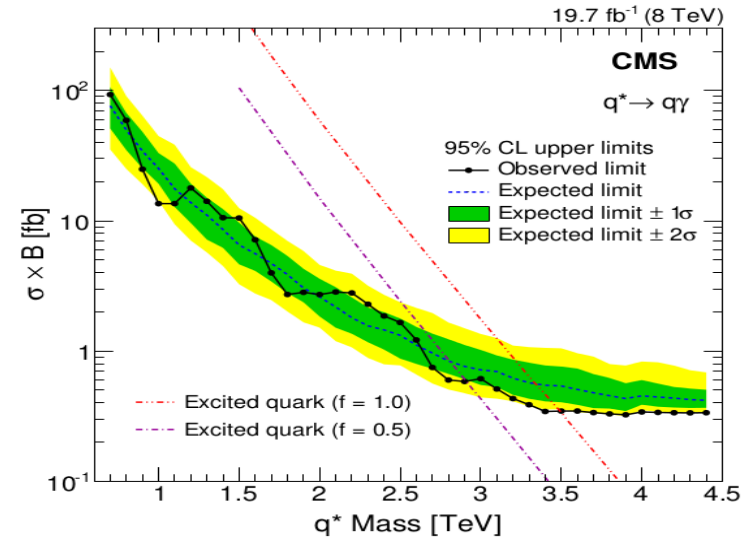
Z-veto
and
optimized
$m_{ll\gamma}$ Cut

$M_{l^*} = \Lambda$
Exited lepton: <2.2TeV

Plot (top): ATLAS, $\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}, $e^* \bar{e} / e^* \bar{e}^*$. Axes: Λ [TeV] vs m_{l^*} [TeV]. 95% CL Limits: Observed, Expected, $\pm 1\sigma$, $\pm 2\sigma$, Observed (CI only), Expected (CI only), m > Λ: forbidden, LEP (L3).

Plot (bottom): ATLAS, $\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}, $\nu_e^* \bar{\nu}_e^*$. Axes: Λ [TeV] vs m_{l^*} [TeV]. 95% CL Limits: Observed, Expected, $\pm 1\sigma$, $\pm 2\sigma$, Observed (CI only), Expected (CI only), m > Λ: forbidden, LEP (L3).

Extensive studies for single or pair productions of Exited leptons in $\geq$ 3leptons final states
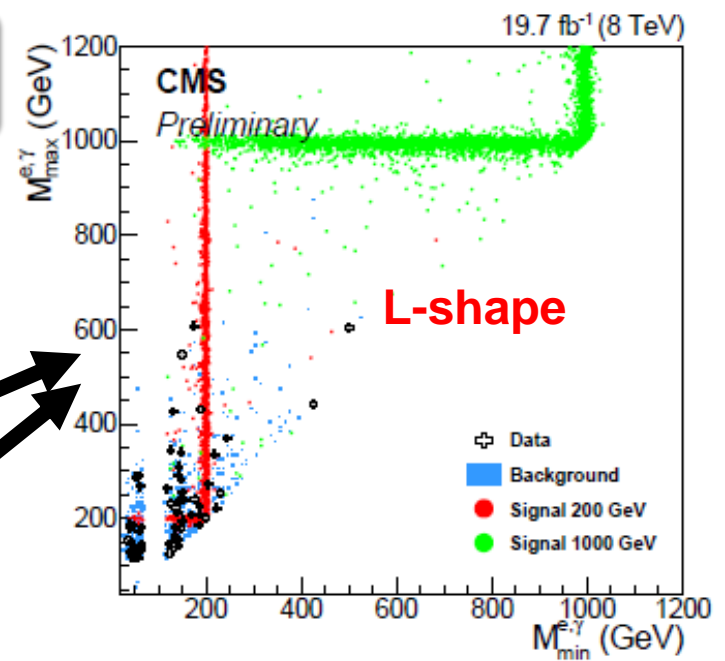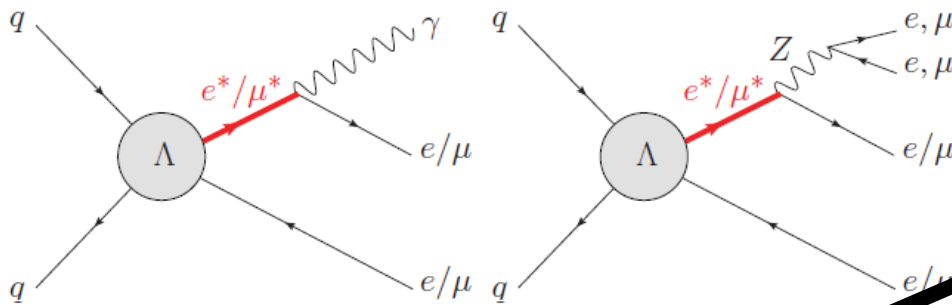
extend sensitivity to both high M_{l^*} and Λ (for nu*).

for $M_{l^*} = \Lambda$

Excited ele/mu: <3.0TeV
Excited tau: <2.5TeV
Excited neutrino: <1.6TeV

24

Excited lepton: l+γ

CMS PAS EXO-14-015
Phys. Lett. B 720 (2013) 309

L-shape

$19.7\ \text{fb}^{-1}$ (8 TeV)

Pruned Mass, tau21

CMS
Preliminary

$f = f' = 1$ $f = -f' = 1$

$19.7\ \text{fb}^{-1}$ (8 TeV)

- $ee^* \to ee\gamma$
- $ee^* \to eeZ \to eejj$
- $ee^* \to eeZ \to eeee$
- $ee^* \to eeZ \to ee\mu\mu$
- $ee^* \to eeZ \to eell$
- $\mu\mu^* \to \mu\mu\gamma$
- $\mu\mu^* \to \mu\mu Z \to \mu\mu jj$
- $\mu\mu^* \to \mu\mu Z \to \mu\mu\mu\mu$
- $\mu\mu^* \to \mu\mu Z \to \mu\mu ee$
- $\mu\mu^* \to \mu\mu Z \to \mu\mu ll$

Excluded mass for $\Lambda = M_{l*}$ (TeV)
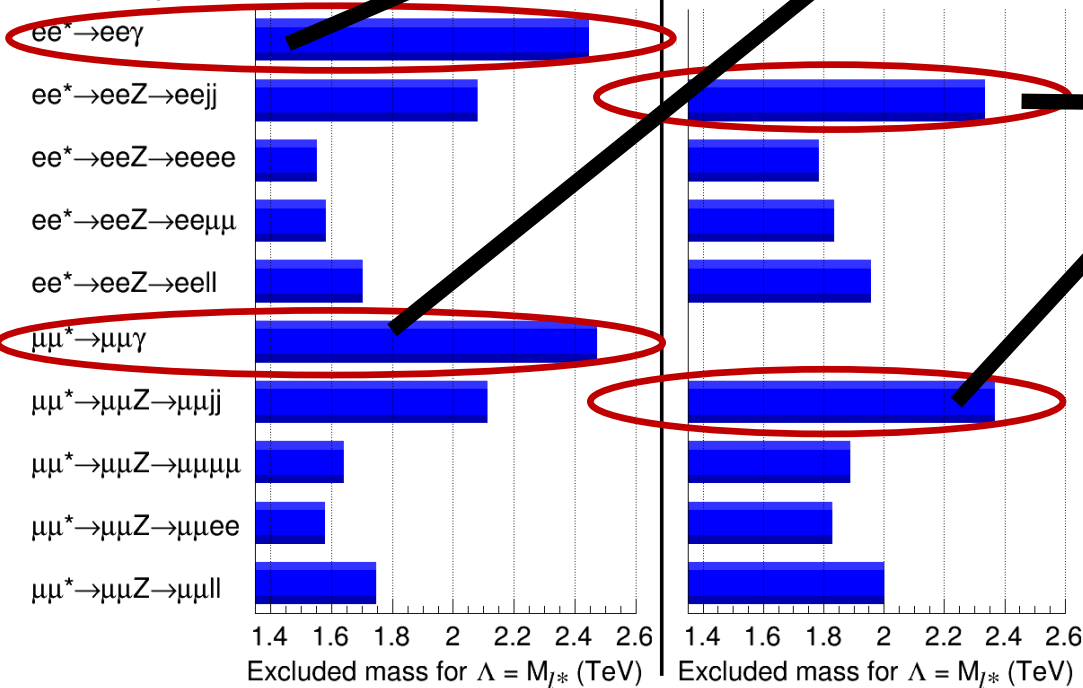
For f=f'=1 and $M_{l^*} = \Lambda$
Exited electron: <2.45TeV
Exited Muon: <2.48TeV

25

ATLAS overview

LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	20.3	LQ mass 1.05 TeV
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	20.3	LQ mass 1.0 TeV
	Scalar LQ 3rd gen	1 e, μ	≥1 b, ≥3 j	Yes	20.3	LQ mass 640 GeV

$\beta = 1$ Preliminary
$\beta = 1$ Preliminary
$\beta = 0$ Preliminary

Excited fermions	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	20.3	q* mass 3.5 TeV
	Excited quark $q^* \to qg$	–	2 j	–	20.3	q* mass 4.09 TeV
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2 j or 1 j	Yes	4.7	b* mass 870 GeV
	Excited lepton $\ell^* \to \ell\gamma$	2 e, μ, 1 γ	–	–	13.0	ℓ* mass 2.2 TeV
	Excited lepton $\nu^* \to \ell W, \nu Z$	3 e, μ, τ	–	–	20.3	ν* mass 1.6 TeV

only u^* and d^*, $\Lambda = m(q^*)$ 1309.3230
only u^* and d^*, $\Lambda = m(q^*)$ 1407.1376
left-handed coupling   1301.1583
$\Lambda = 2.2$ TeV   1308.1364
$\Lambda = 1.6$ TeV   1411.2921

CMS overview

Run2 and future

| | Shutdown/Technical stop |
| Protons physics |
| Commissioning |
| Ions |
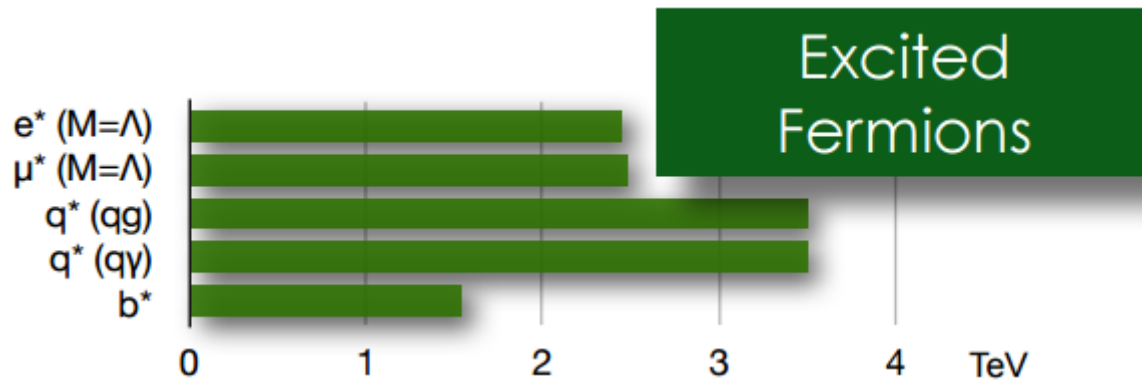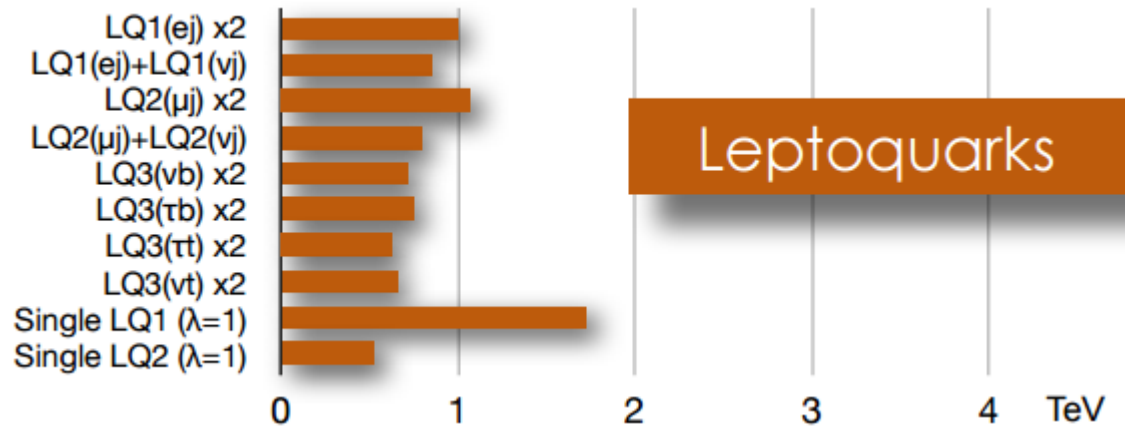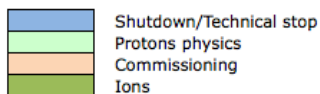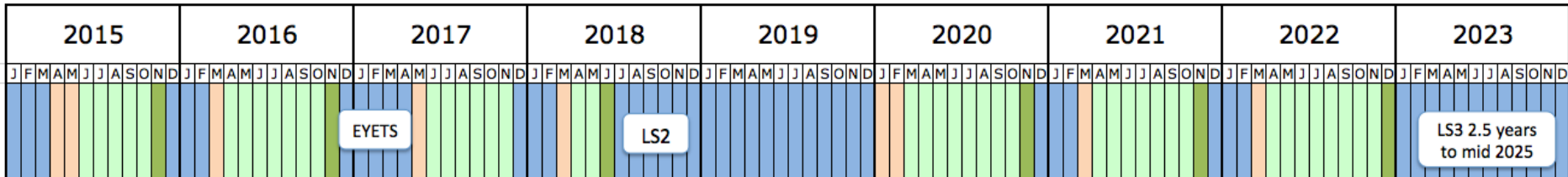
Phase	Days	Physics efficiency	Integrated luminosity
Initial low luminosity run	7	20%	few pb-1
50 ns intensity ramp-up	14 from 21	20%	0.1 fb-1
25 ns phase beta*=80 cm	65	30%	4 fb-1

Run2 Start on June/03, 2015, with stable beams at energy 6.5TeV
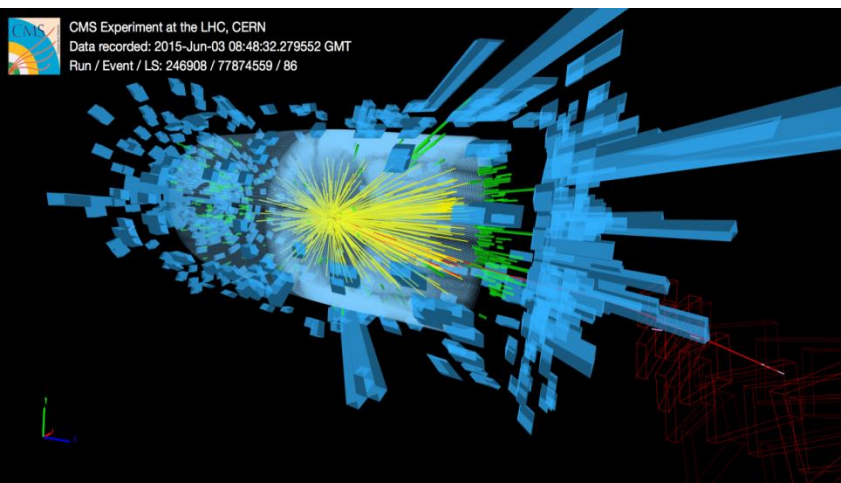
CMS Experiment at the LHC, CERN
Data recorded: 2015-Jun-03 08:48:32.279552 GMT
Run / Event / LS: 246908 / 77874559 / 86

Collider Reach

http://collider-reach.web.cern.ch
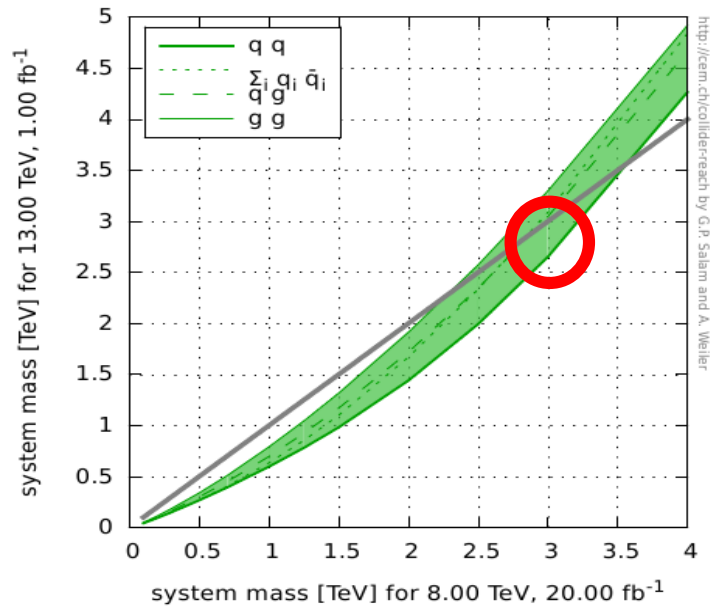
Run2 1fb-1, already surpass Run1 at ~3TeV
10fb-1 start overtake Run1
100fb-1 3TeV→5-6TeV

2014 Review of Particle Physics

The search for LQ will be continued with more LHC data. Early feasability studies by the LHC experiments ATLAS [38] and CMS [39] indicate that clear signals can be established for masses up to about M(LQ) 1.3 to 1.4 TeV for first- and second-generation scalar LQ, with a likely final reach 1.5 TeV, for collisions at 14 TeV in the center of mass.
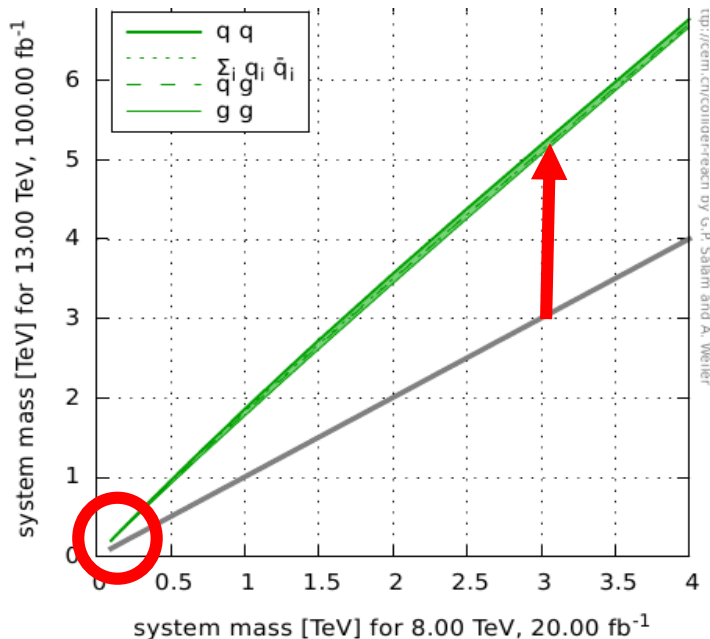
LEPTOQUARKS

Updated August 2013 by S. Rolli (US Department of Energy) and M. Tanabashi (Nagoya U.)
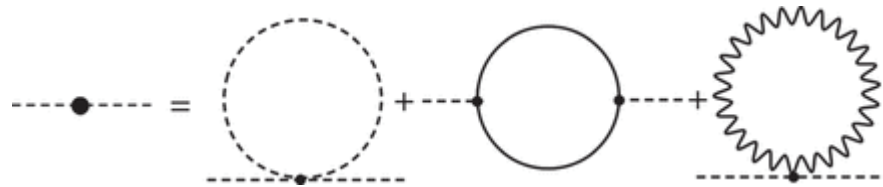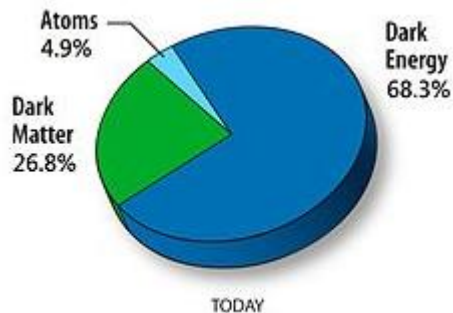
Summary

- **Extensive studies from Run1 ATLAS and CMS**
- **Most stringent limits on Leptoquarks, Exited Fermions, at TeV scale**

- **Run2 will definitely tell us more**

Thank you!

- **Fine Tuning**
- **Dark matter**
- **Gauge Unification**
- **Flavor structure**
- **Baryon Asymmetry**

$$\delta M_h^2 = \left(\frac{1}{4}(9g^2 + 3g'^2) - 6y_t^2 + 6\lambda \right) \frac{\Lambda^2}{32\pi^2}.$$

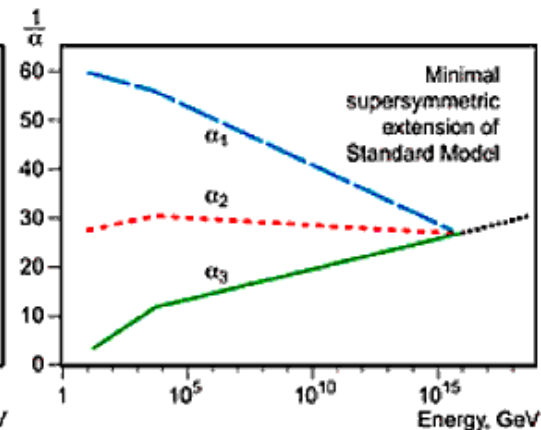- **SUSY**
- **Extra Dimensions**
- **Extra Gauge Symmetry: W', Z'**
- **Exotic heavy Quarks, Leptons, Leptoquarks …**
- **Compositeness: contact interaction …**
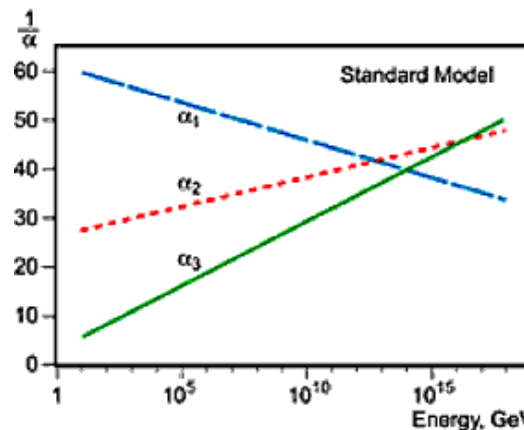
FIG. 8: Unification of interactions helped by SUSY

Di-jet resonance Phys. Rev. D 91, 052009 (2015)

$$\frac{d\sigma}{dm_{jj}} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\ln(x)}}$$
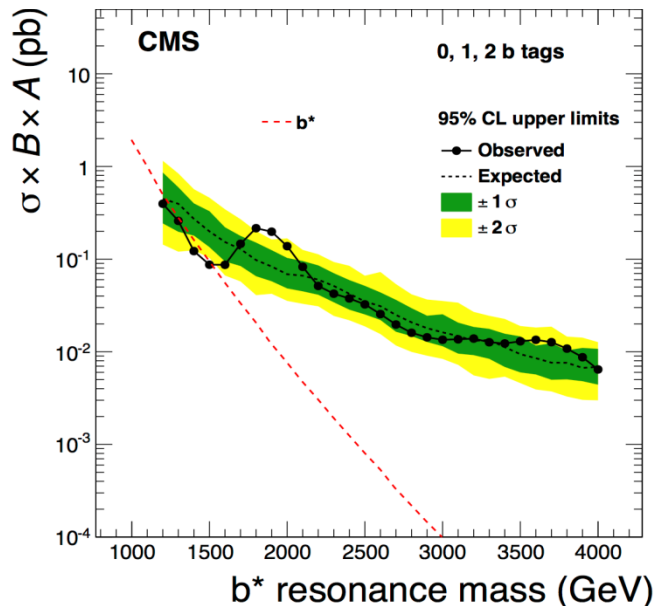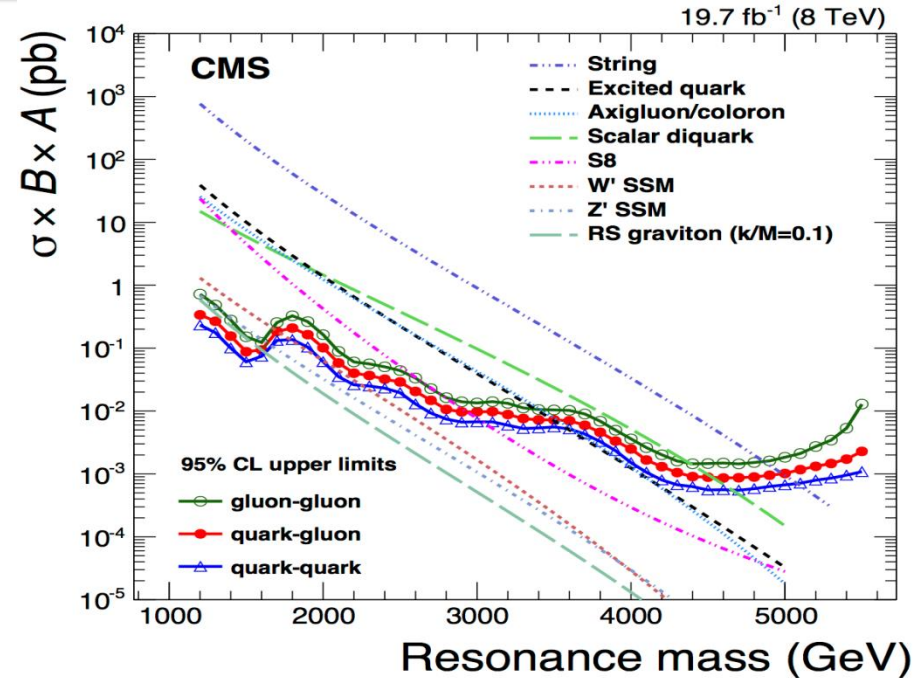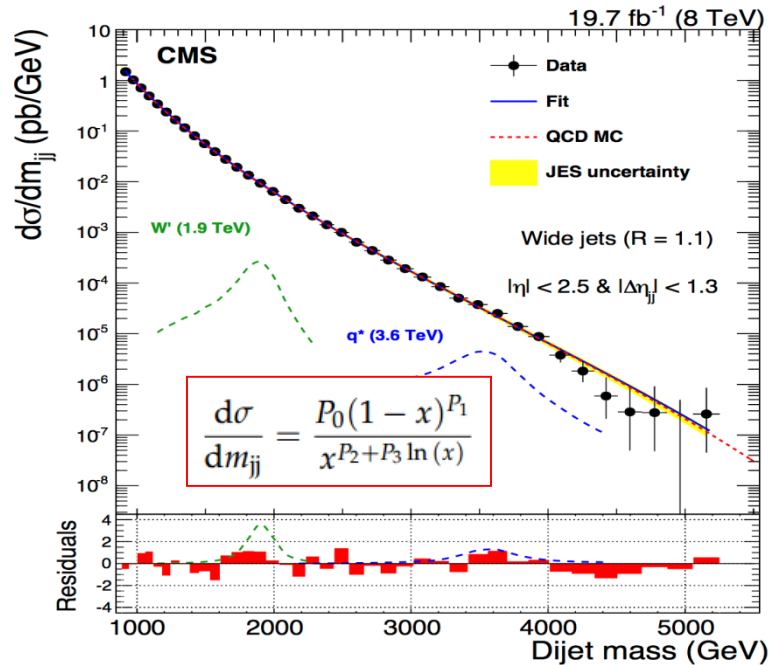
gg, qq, gq resonance: narrow or wide
Also for final states including b

Leading 2 jets as seeds ->   2 wide jets (DR<1.1)

SSM W', Z' < 2TeV
RS G <1.6TeV
Excited b* <1.2-1.6TeV

W. Buchmuller, R. Ruckl, D. Wyler, Phys. Lett. B 191 (1987) 442;
W. Buchmuller, R. Ruckl, D. Wyler, Phys. Lett. B 448 (1999) 320
(Erratum).

Table 1: Possible leptoquarks and their quantum numbers.

Leptoquarks	Spin	$3B+L$	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	Allowed coupling
$S_0^\dagger$	0	-2	$\bar{3}$	1	$1/3$	$\bar{q}_L^c \ell_L$ or $\bar{u}_R^c e_R$
$\tilde{S}_0^\dagger$	0	-2	$\bar{3}$	1	$4/3$	$\bar{d}_R^c e_R$
$S_1^\dagger$	0	-2	$\bar{3}$	3	$1/3$	$\bar{q}_L^c \ell_L$
$V_{1/2}^\dagger$	1	-2	$\bar{3}$	2	$5/6$	$\bar{q}_L^c \gamma^\mu e_R$ or $\bar{d}_R^c \gamma^\mu \ell_L$
$\tilde{V}_{1/2}^\dagger$	1	-2	$\bar{3}$	2	$-1/6$	$\bar{u}_R^c \gamma^\mu \ell_L$
$S_{1/2}^\dagger$	0	0	3	2	$7/6$	$\bar{q}_L e_R$ or $\bar{u}_R \ell_L$
$\tilde{S}_{1/2}^\dagger$	0	0	3	2	$1/6$	$\bar{d}_R \ell_L$
$V_0^\dagger$	1	0	3	1	$2/3$	$\bar{q}_L \gamma^\mu \ell_L$ or $\bar{d}_R \gamma^\mu e_R$
$\tilde{V}_0^\dagger$	1	0	3	1	$5/3$	$\bar{u}_R \gamma^\mu e_R$
$V_1^\dagger$	1	0	3	3	$2/3$	$\bar{q}_L \gamma^\mu \ell_L$

The results for each LQ3 channel cannot be combined since the parent leptoquarks have different electric charges in the two cases ($\frac{1}{3}e$ for the LQ3 $\overline{\text{LQ3}} \rightarrow b\nu_\tau \bar{b}\bar{\nu}_\tau$ channel and $\frac{2}{3}e$ for the LQ3 $\overline{\text{LQ3}} \rightarrow t\nu_\tau \bar{t}\bar{\nu}_\tau$ channel, where e is the elementary electric charge). The branching fractions of LQ3 decays to $b\nu_\tau$ and $t\nu_\tau$ are assumed to be equal to 100% in each case. Although complementary decays of a charge $\frac{1}{3}e$ ($\frac{2}{3}e$) LQ into a $t\tau^- \bar{t}\tau^+$ ($b\tau^+ \bar{b}\tau^-$) final state are also allowed, kinematic suppression factors which favour LQ decays to b-quarks over t-quarks and the relative strengths of the Yukawa couplings would have to be considered. Since these suppression factors are model dependent, limits are not provided as a function of β for the LQ3 channels, contrary to the LQ1 and LQ2 analyses.

Finally, two additional requirements are applied to drastically reduce the background level. The first one, referred to as the "Z veto" in the following, requires the dilepton mass to satisfy $m_{\ell\ell} > 110$ GeV. The second is a variable lower bound on the dilepton-photon mass that defines the signal search region. As a result of optimization studies, the signal region for $m_{\ell^*} < 900$ GeV is $m_{\ell\ell\gamma} > m_{\ell^*} + 150$ GeV. For $m_{\ell^*} \geq 900$ GeV, it is fixed to $m_{\ell\ell\gamma} > 1050$ GeV. The signal efficiency for these two requirements is above 98% for $m_{\ell^*} \geq 200$ GeV.

ATLAS   Excited lepton   arXiv:1411.2921

For low Λ-values, a broad range of masses up to 2 TeV can be excluded, while for higher Λ-values, only low masses are excluded. In the low-mass region, $\nu_\ell^* \to \ell + W$ is the main decay mode for excited neutrinos, while $\ell^* \to \ell + \gamma$ is the main decay mode for charged leptons. Therefore, pair-produced ν_e^* and ν_μ^* have the highest acceptance due to their final states with at least three leptons, and thus they have the most stringent limits.