Searches for leptoquarks and heavy leptons with the ATLAS detector at the LHC

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Motivation

Vector-like leptons (VLL)

- explain mass hierarchy between lepton generations
- arise in composite Higgs and warped extra-dimensions

Type-III Seesaw leptons

- generate neutrino masses, couple to gauge bosons

Majorana neutrinos

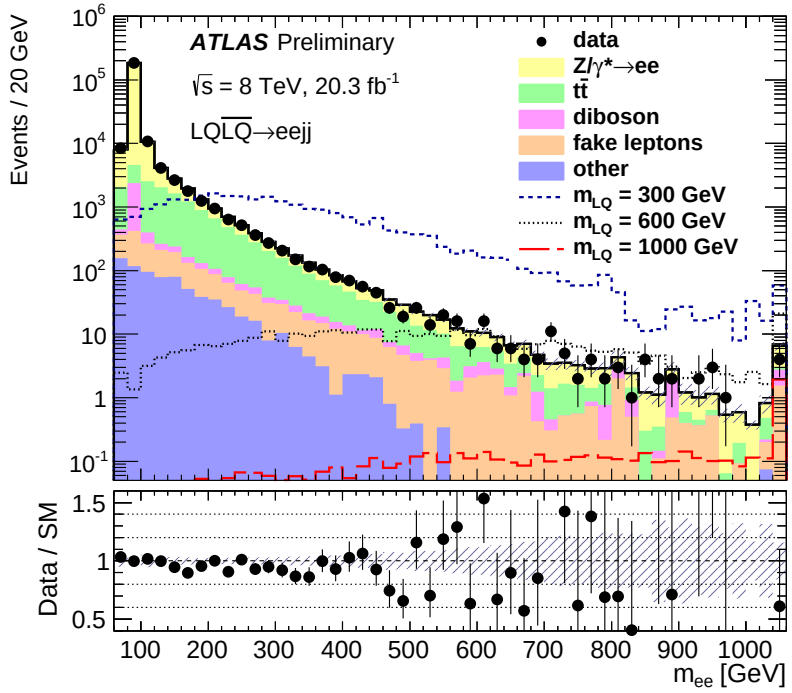
- explain neutrino mixing, allow for lepton number violation

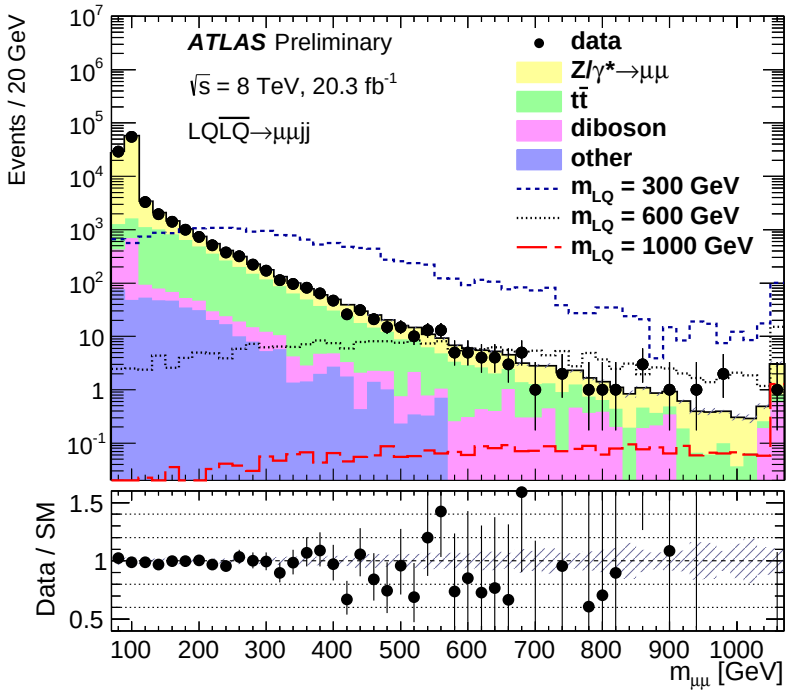
Scalar leptoquarks

- predicted by many extensions of SM
- explain similarities between quark and lepton sectors

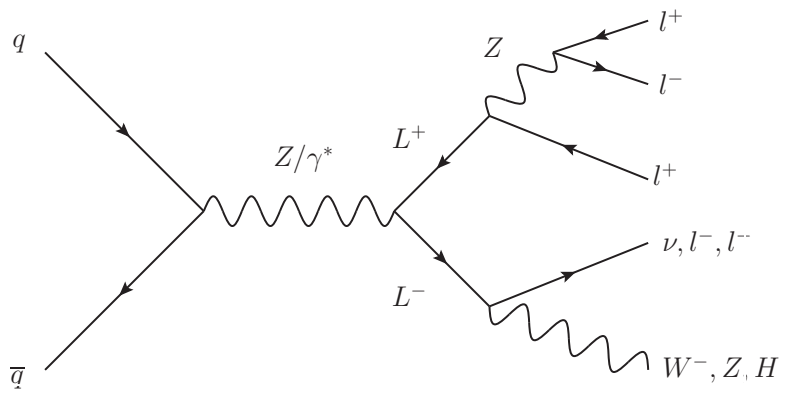
ATLAS Results from 8TeV dataset: 20.3 fb^{-1}

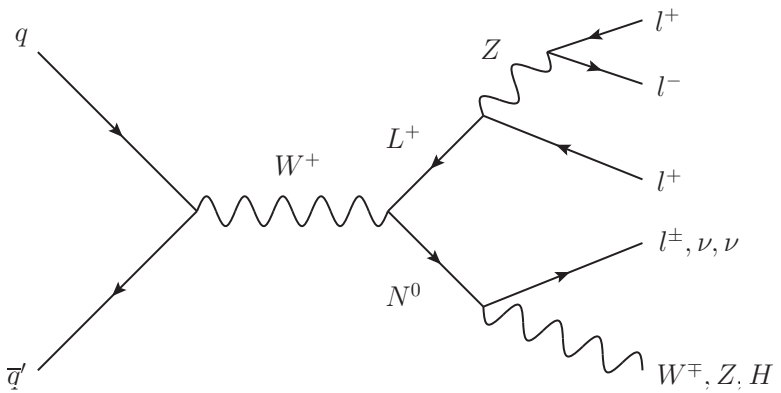
- No excess observed above the expected numbers of SM background events
- No evidence of new heavy particles observed
- Results are interpreted in the context of various models
- 95% CL exclusion limits are set for various masses and mixing parameters
- Systematic uncertainties are assumed to be uncorrelated, and included in the test statistic as nuisance parameters





Heavy leptons





Vector-like leptons (VLL)

- only charged, colourless, spin 1/2 fermions, same L/R chiral properties

Type-III Seesaw leptons

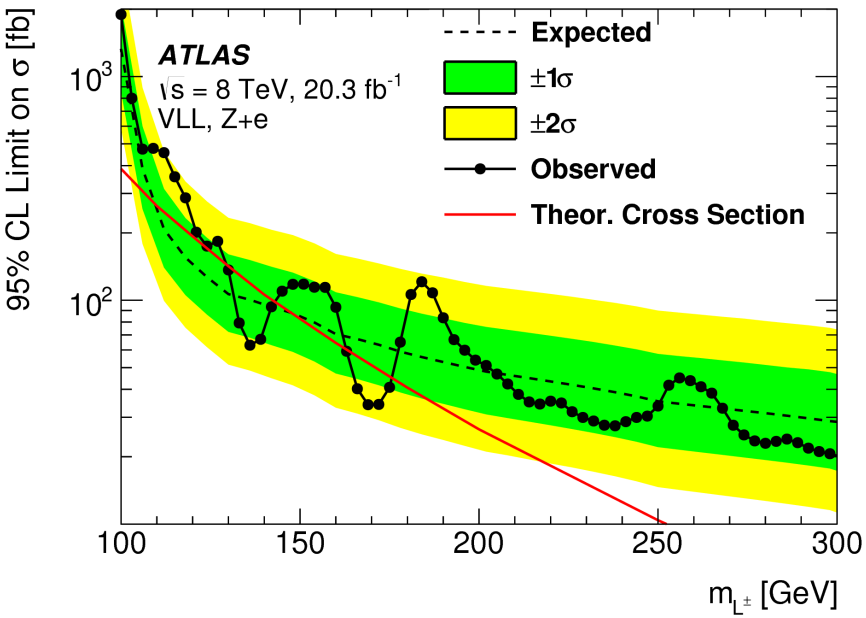
- charged and neutral, degenerate in mass
- heavy SU(2) triplets with zero hypercharge

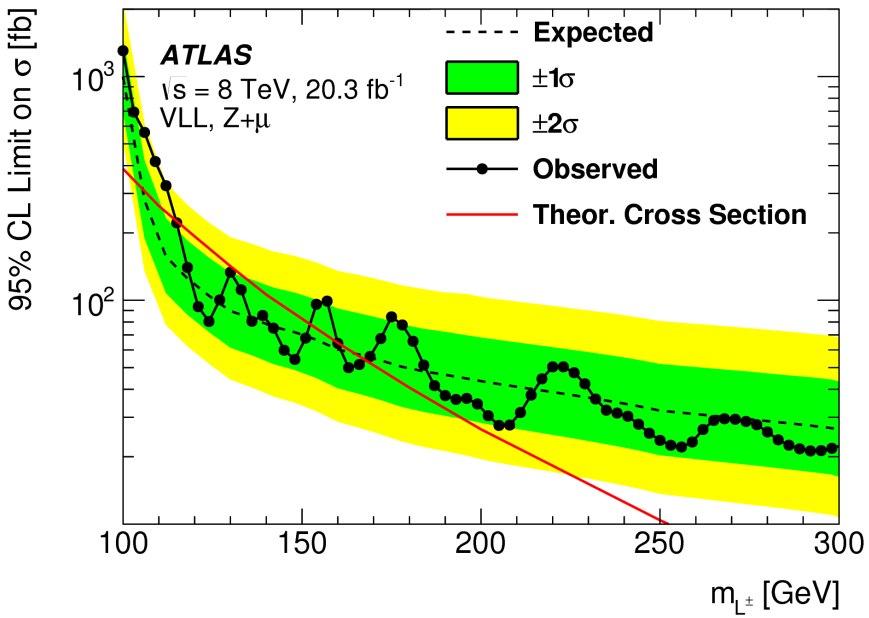
Previous searches

- L3: excl $m_{L^\pm} < 100$ GeV ($L^\pm \to W^\pm \nu$)
- CMS: excl $m_{L^\pm} < 180 - 210$ GeV (BR dep)

- Phys.Lett.B517 (2001) 75
- Phys.Lett.B718 (2012) 348

Results: vector like lepton – three leptons channel





VLL Limits ($Z + e$):

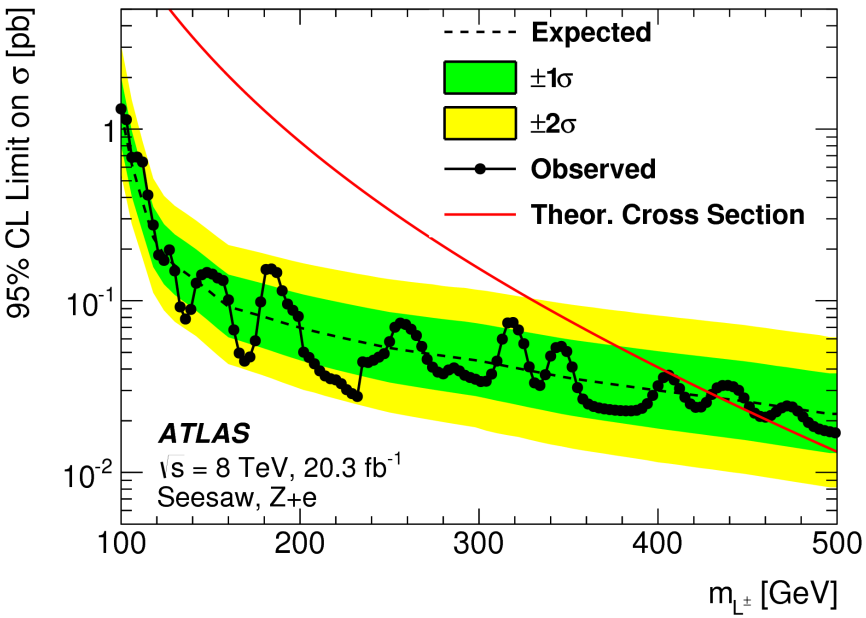
- Observed:
  $129 \leq m_{VLL} \leq 144$ GeV and
  $163 \leq m_{VLL} \leq 176$ GeV
- Expected:
  $109 \leq m_{VLL} \leq 152$ GeV

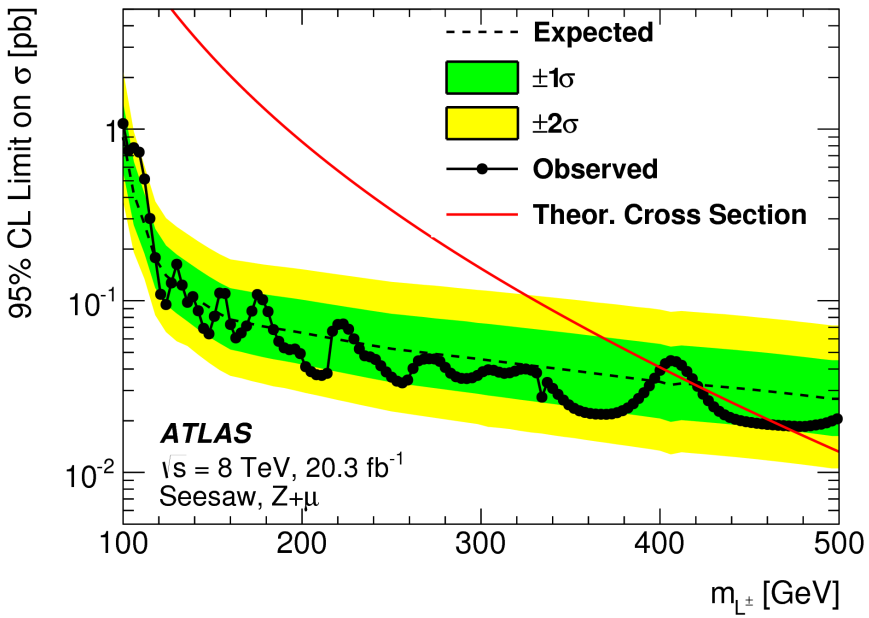
VLL Limits ($Z + \mu$):

- Observed:
  $114 \leq m_{VLL} \leq 153$ GeV and
  $160 \leq m_{VLL} \leq 168$ GeV
- Expected:
  $105 \leq m_{VLL} \leq 167$ GeV

arXiv:1506.01291 [hep-ex]

Results: type-III seesaw – three leptons channel





Type-III seesaw limits ($Z + e$):

- Observed:
  $100 \leq m_{L^\pm} \leq 430$ GeV
- Expected:
  $100 \leq m_{L^\pm} \leq 436$ GeV

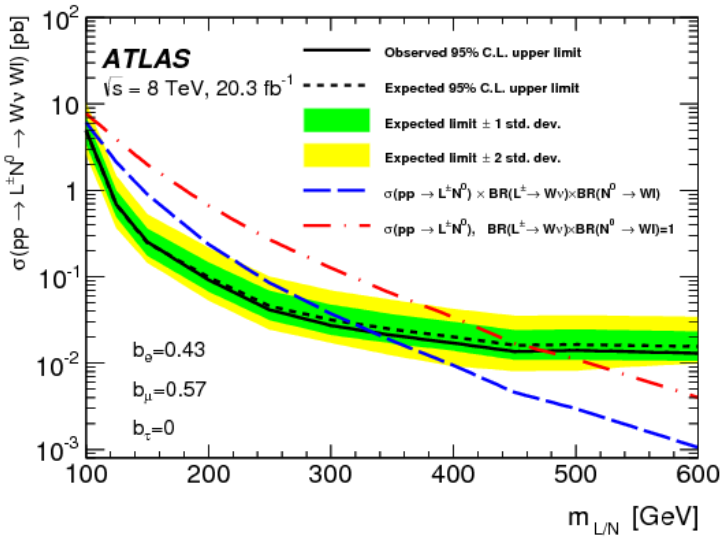
Type-III seesaw limits ($Z + \mu$):

- Observed:
  $100 \leq m_{L^\pm} \leq 401$ GeV and
  $419 \leq m_{L^\pm} \leq 468$ GeV
- Expected:
  $100 \leq m_{L^\pm} \leq 419$ GeV

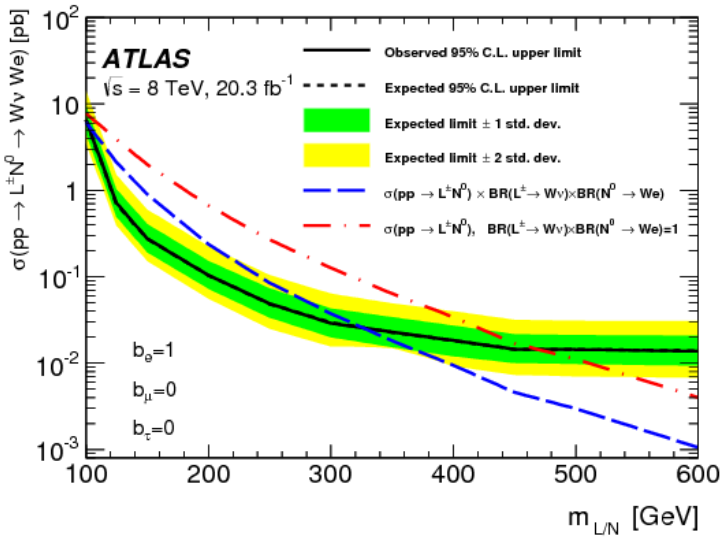
arXiv:1506.01291 [hep-ex]

Results: type-III seesaw – dilepton + dijet + E_T^{miss} channel

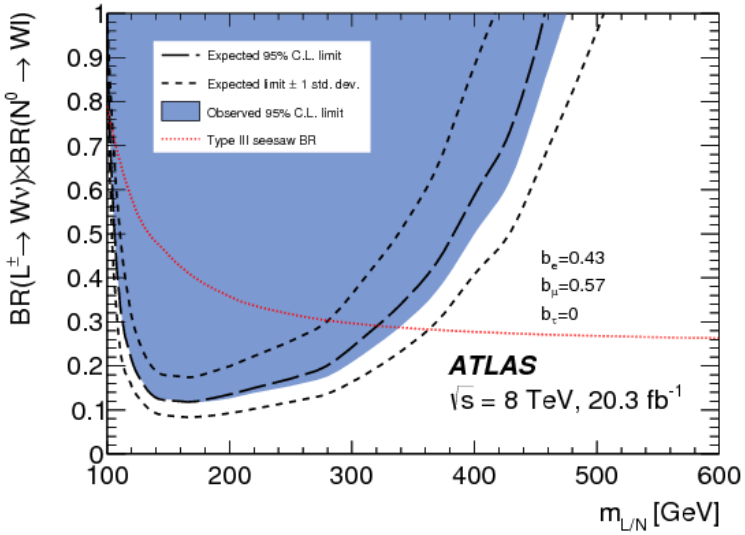
arXiv:1506.01839 [hep-ex]



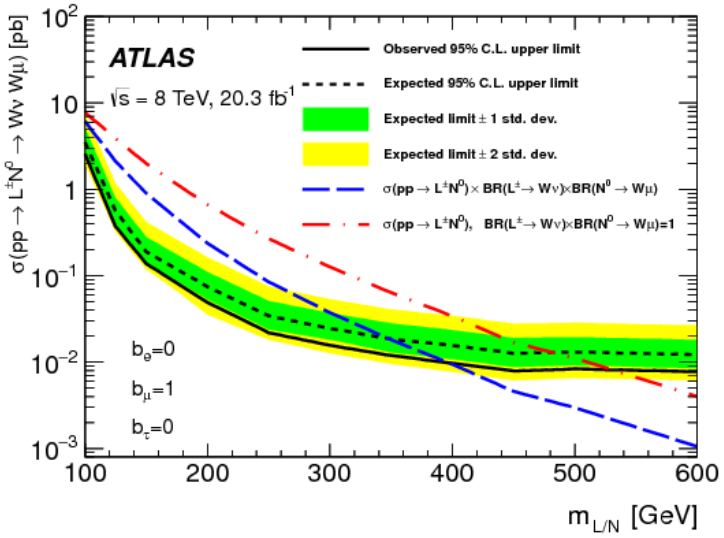
Obs lim (b_τ=0): $m_{L/N} \leq 335$ GeV



Obs lim (e): $m_{L/N} \leq 325$ GeV

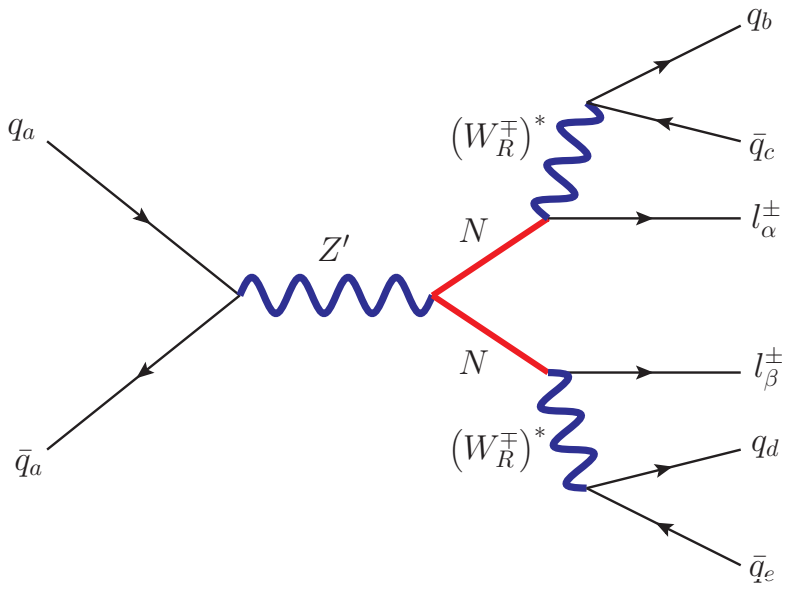


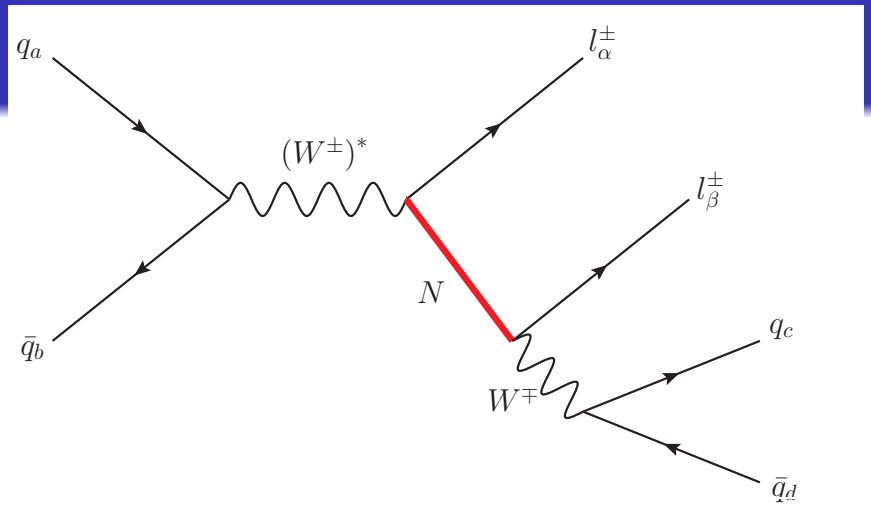
Obs lim ($N, L \to W\nu, \ell$): $m_{L/N} \leq 475$ GeV



Obs lim (μ): $m_{L/N} \leq 400$ GeV

Majorana neutrinos





Left-right symmetric model – LRSM

- predict heavy gauge bosons $V_R = W_R, Z'$

- ATLAS: $m_{W_R} < 2.3$ TeV, ($m_{W_R} - m_N > 0.3$ TeV) Eur.Phys.J.C72 (2012) 2056
- CMS: $m_{W_R} < 3.0$ TeV, ($m_{W_R} - m_N > 0.05$ TeV) Eur.Phys.J.C74 (2014) 3149

Type-I seesaw – mTISM

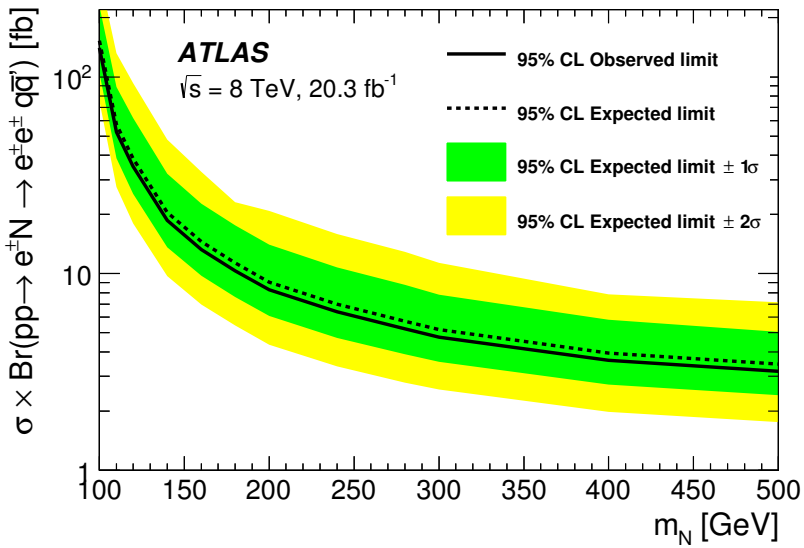
- include right-handed neutrinos, type-I seesaw ν mass generation
- produced via off-shell W boson, decays on-shell to $W\ell$

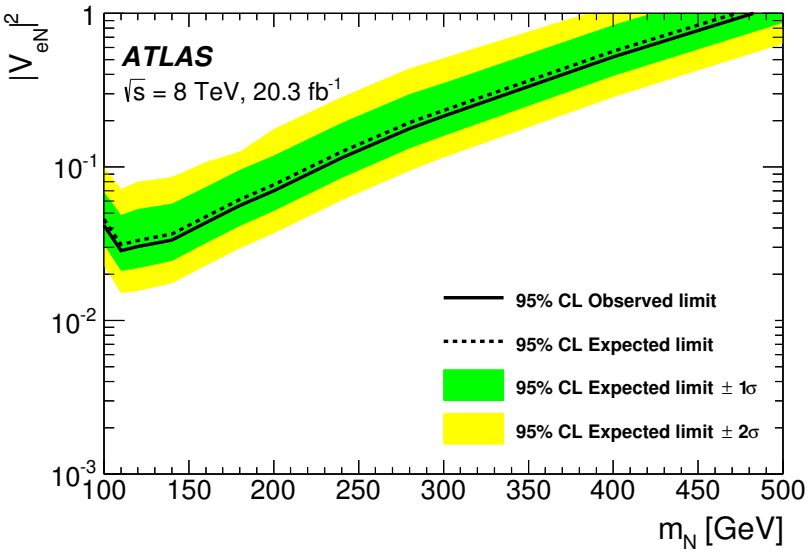
Previous searches

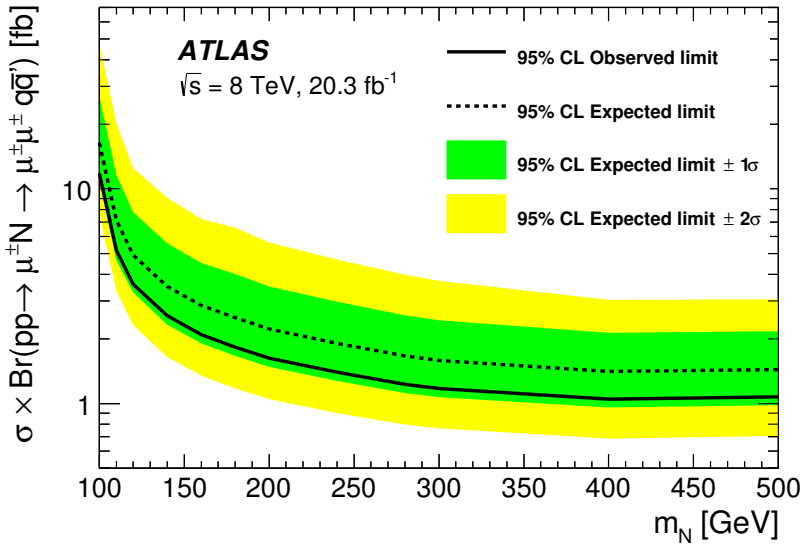
- LEP: excl $m_N < m_Z$ Z.Phys.C75 (1997) 580, Phys.Lett.B295 (1992) 371
- CMS: excl $90 < m_N < 200$ GeV (ee), $40 < m_N < 500$ GeV ($\mu\mu$) Phys.Lett.B717 (2012) 109, arXiv:1501.05566 [hep-ex]

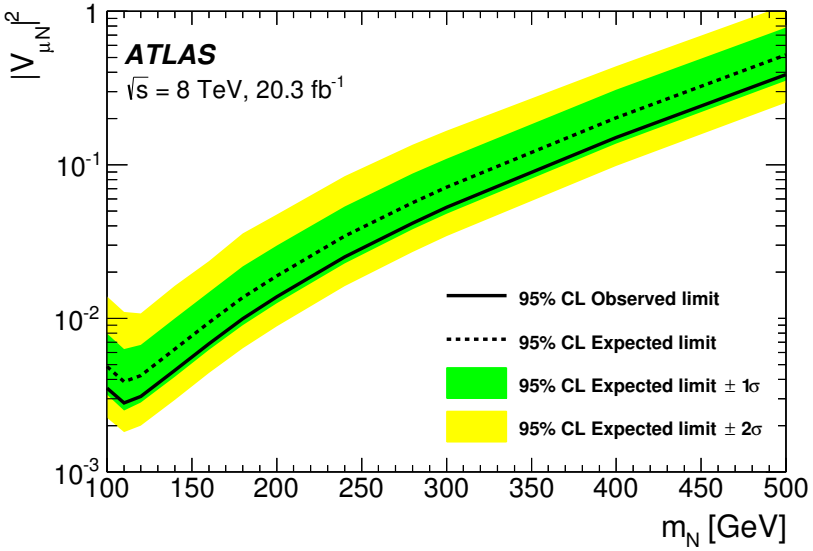
Results: Majorana ν (mTISM), ==2 leptons + jet(s)

arXiv:1506.06020 [hep-ex]







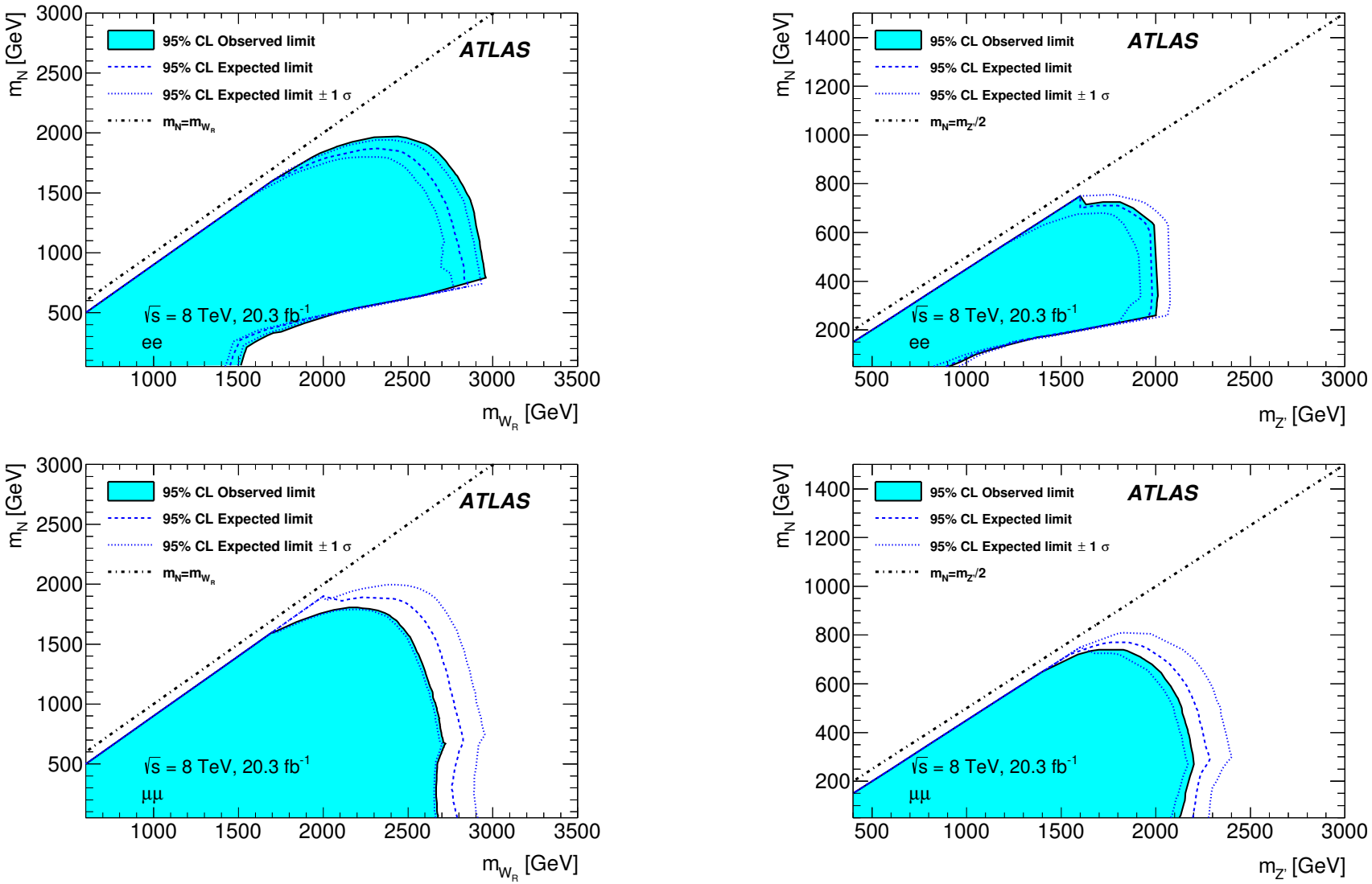


$\sigma \times$BR production limits

Mixing parameter $|V_{\ell N}|^2$ limits

Results: Majorana ν (LRSM), ==2 leptons + jet(s)

arXiv:1506.06020 [hep-ex]



Full results for all mass points are in HepData

Leptoquarks

LQ1, LQ2, LQ3

- each coupling with corresponding SM families
- colour triplet bosons, fractional electric charge
- carry both baryon and lepton numbers
- can be scalar or vector, decay directly into ℓq pair
- coupling strength $\lambda_{LQ\to\ell q}$ affecting lifetime and width

Previous searches

- ATLAS: excl $m_{LQ_1} < 660(607)\ \mathrm{GeV}$, $\beta = 1(0.5)$
- ATLAS: excl $m_{LQ_2} < 685(594)\ \mathrm{GeV}$, $\beta = 1(0.5)$
- ATLAS: excl $m_{LQ_3} < 534\ \mathrm{GeV}$, $LQ_3 \to b\tau$
- CMS: excl $m_{LQ_1} < 830(640)\ \mathrm{GeV}$, $\beta = 1(0.5)$
- CMS: excl $m_{LQ_2} < 840(650)\ \mathrm{GeV}$, $\beta = 1(0.5)$
- CMS: excl $m_{LQ_3} < 440\ \mathrm{GeV}$, $LQ_3 \to b\nu_\tau$
- CMS: excl $m_{LQ_3} < 740\ \mathrm{GeV}$, $LQ_3 \to b\tau$
- CMS: excl $m_{LQ_3} < 685\ \mathrm{GeV}$, $LQ_3 \to t\tau$

- Phys.Lett.B709 (2012) 158
- Eur.Phys.J.C72 (2012) 2151
- JHEP 06 (2013) 033
- Phys.Rev.D86 (2012) 052013
  - CMS update (8TeV) LQ1: CMS-PAS-EXO-12-041
- JHEP 12 (2012) 055
- Phys.Lett.B739 (2014) 229
- arXiv:1503.09049 [hep-ex]

Analysis method

- Selection
- Background estimate
- Systematic uncertainties

Will focus on most recent leptoquark (LQ_1, LQ_2) searches

Event selection – Leptoquarks

Preliminary

Good detector components working condition

LQ1

- not isolated dielectron trigger
  - allow for data-driven background estimate
  - thresholds: 35GeV, 25GeV
- ==2 e, no charge request
  - $p_T^{e_1} > 40$ GeV, $p_T^{e_2} > 30$ GeV
- ≥ 2 jets, $p_T > 30$ GeV

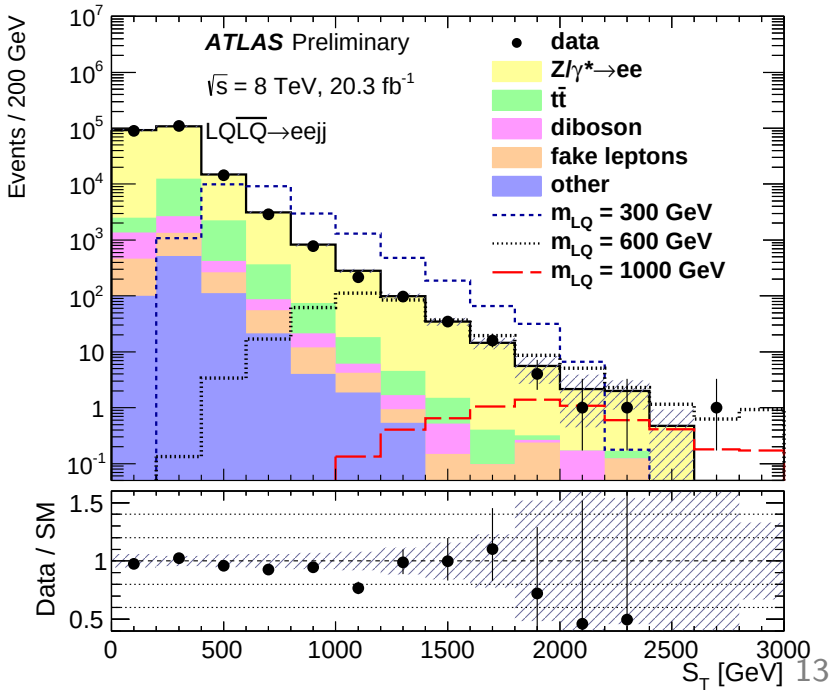
LQ2

- single muon trigger $p_T > 36$ GeV
- ==2 μ, $p_T > 40$ GeV, OS
- ≥ 2 jets, $p_T > 30$ GeV

Acceptance: $eejj$ 65-80%, $\mu\mu jj$ 50%

Various signal regions, based on $m_{\ell\ell}$, m_{LQ}^{min}, S_T

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



Background estimates

MC

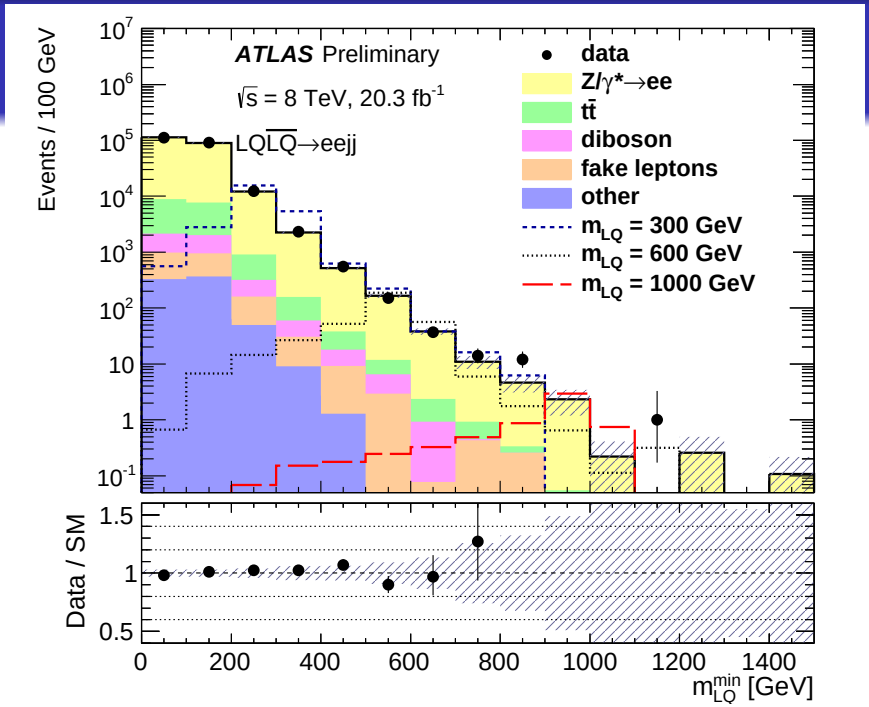
- normalisation factors applied to MC predictions
- derivation from background enriched control regions
- Z/γ+jets: $ee jj$ 1.1 ± 0.2; $\mu\mu jj$ 0.97 ± 0.15
- $t\bar{t}$: $ee jj$ 1.10 ± 0.05; $\mu\mu jj$ 1.01 ± 0.05

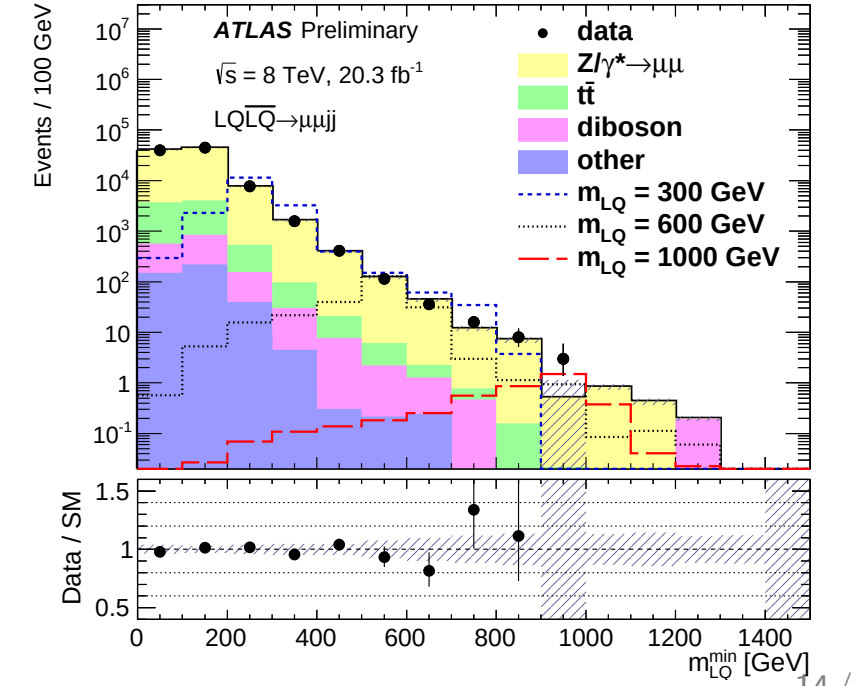
Data-driven

- mis-identified or non-prompt lepton contribution:
- multi-jets, W+jets, hadronic $t\bar{t}$, single t
- estimated with matrix method using a loose lepton selection
- E_T, η dependent fake rate ($\sim 10\%$) measured in background enriched samples

Main systematic uncertainties

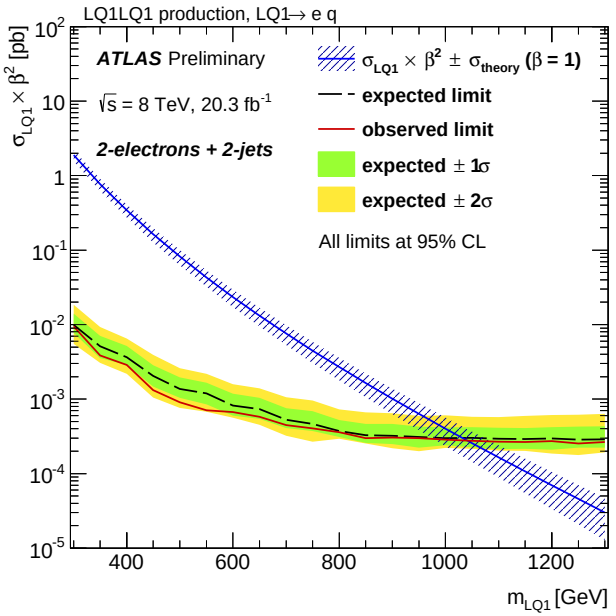
MC modelling, PDF, QCD, JES, ...

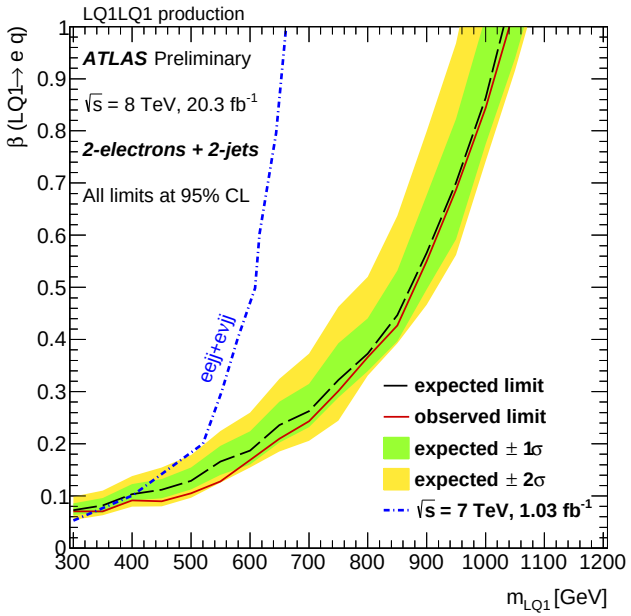


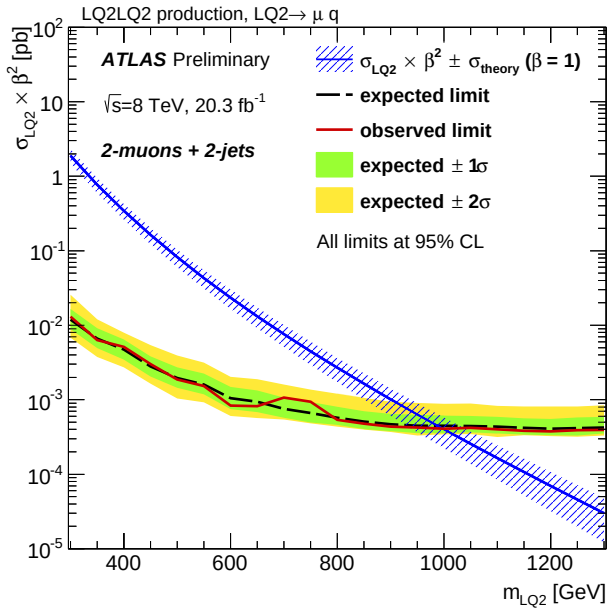


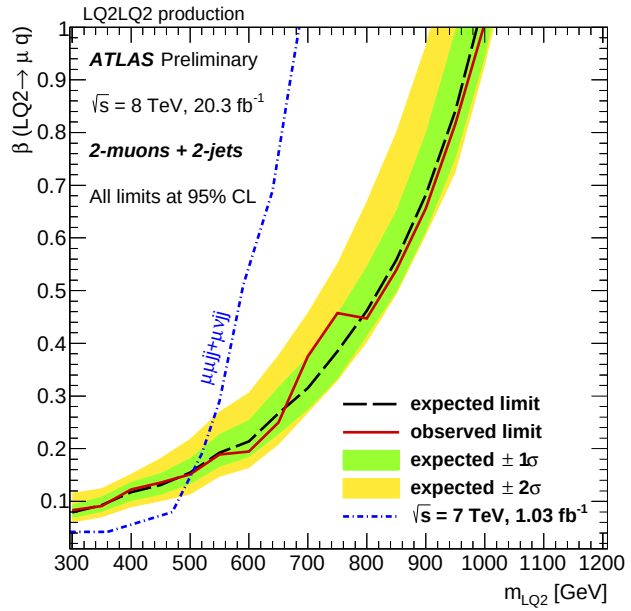
Results: Leptoquarks, 2 leptons + $\geq$ 2 jets

Preliminary









Observed limits

$\beta = 1.0$

- $m_{LQ1} < 1050$ GeV
- $m_{LQ2} < 1000$ GeV

$\beta = 0.5$

- $m_{LQ1} < 900$ GeV
- $m_{LQ2} < 850$ GeV

$\beta = 0.2$

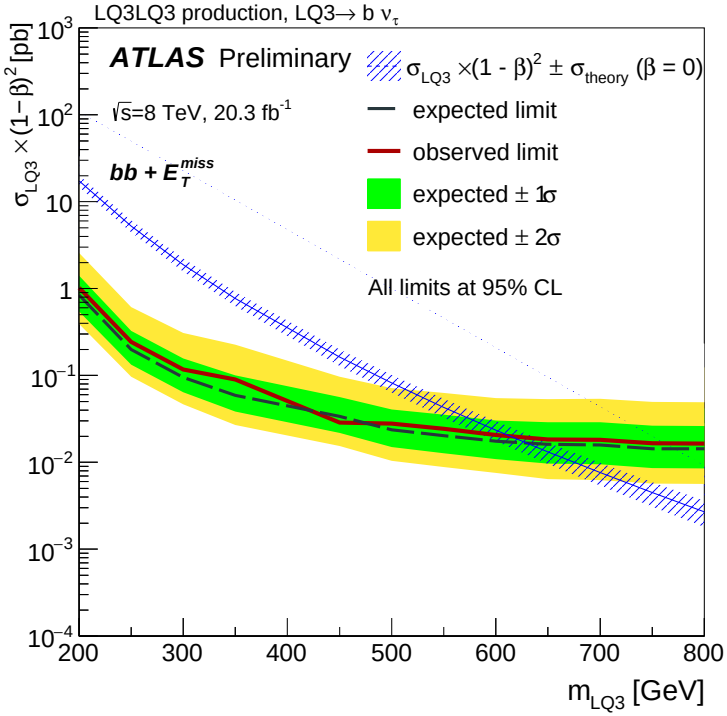
- $m_{LQ1} < 650$ GeV
- $m_{LQ2} < 650$ GeV

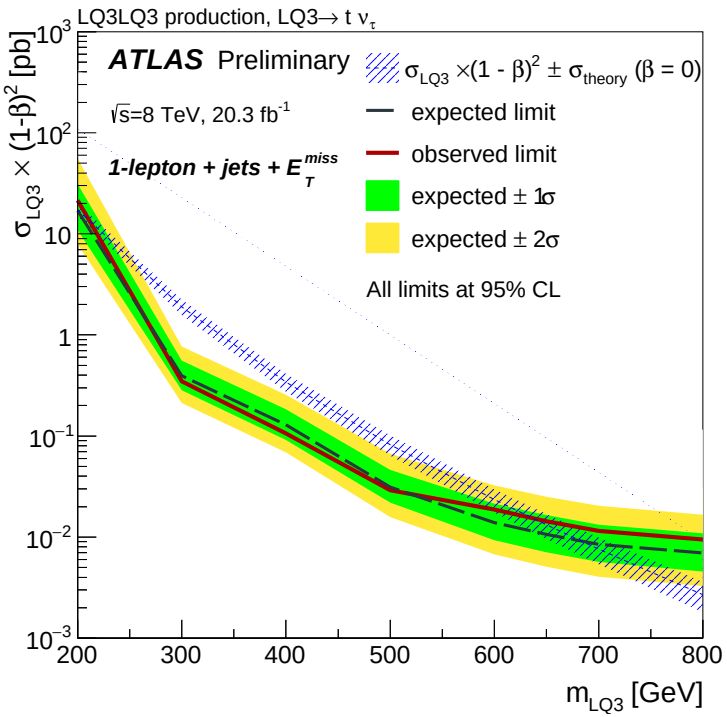
Results: Leptoquarks, reinterpreting SUSY searches

Preliminary

Search for SUSY $\tilde{b} \to b\tilde{\chi}^0$ and $\tilde{t} \to t\tilde{\chi}^0$ are reinterpreted in LQ model.

JHEP 10 (2013) 189 JHEP 11 (2014) 118





LQ3 pair production limits ($b\nu_\tau \bar{b}\bar{\nu}_\tau$):

- Observed: $m_{LQ3} < 625$ GeV
- Expected: $m_{LQ3} < 640$ GeV

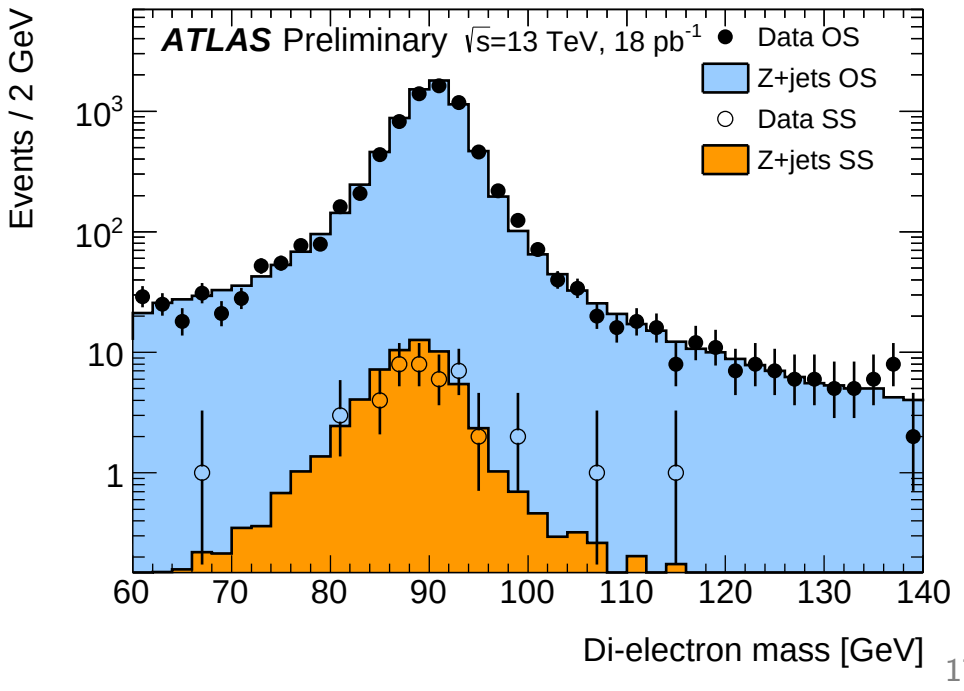
LQ3 pair production limits ($t\nu_\tau \bar{t}\bar{\nu}_\tau$):

- Obs: $210 < m_{LQ3} < 640$ GeV
- Exp: $200 < m_{LQ3} < 685$ GeV

Summary

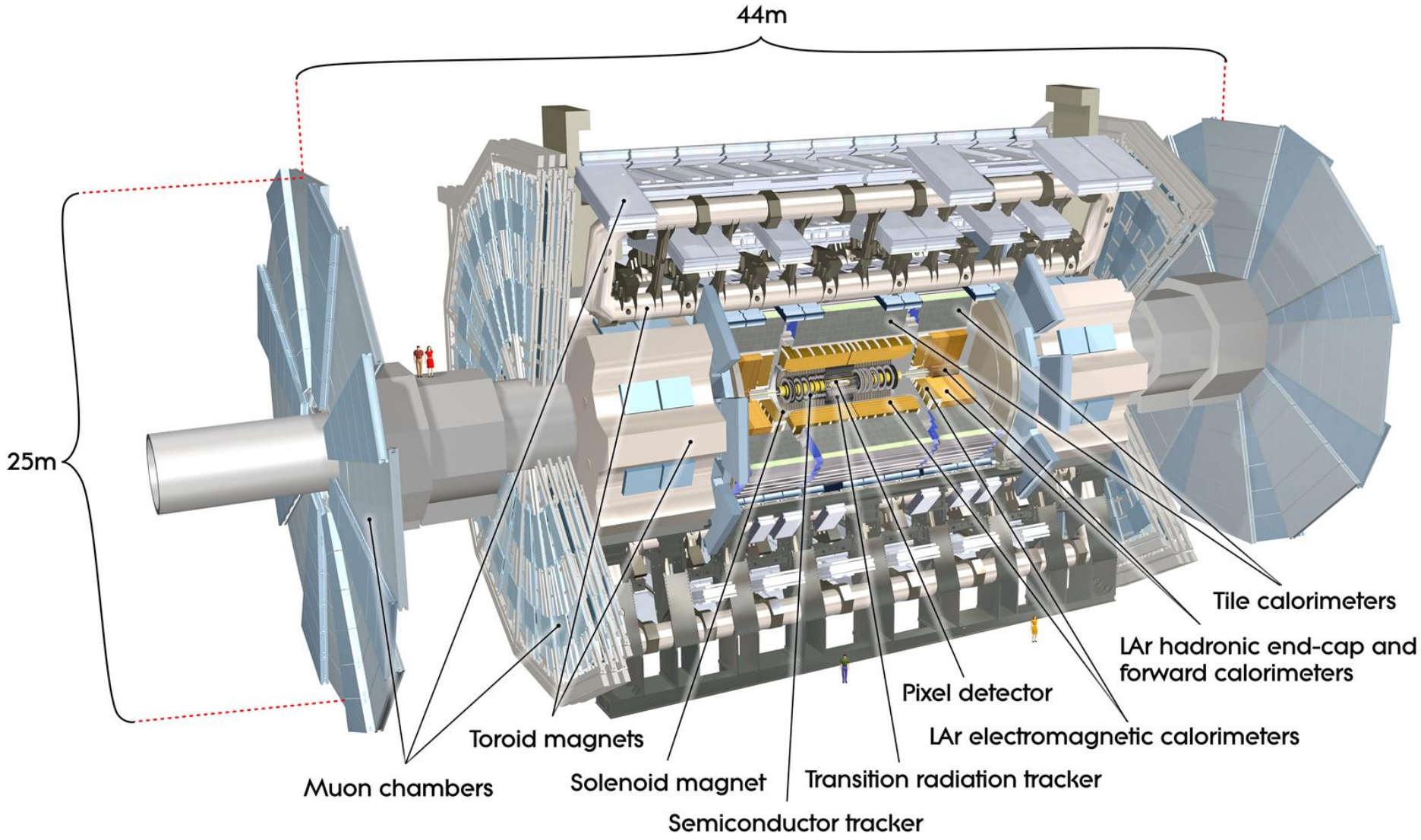
- Models predicting new heavy particles were tested
  - Vector-like leptons, type-III seesaw heavy leptons
  - Majorana neutrinos, leptoquarks
- No excess observed, using various final states
  - number of high momentum leptons, jets, *b*-tagged jets
  - highly specific signal and control region defined
  - good background understanding and prediction
- Potential of 8 TeV data exploited
- Looking forward for next updates at 13 TeV!

Data-MC comparison for $Z \to ee$



events

Backup


44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker

Object selection

Primary vertex and Tracks

- ≥ 3 tracks with $p_T > 0.4$ GeV
- Largest $|p_T|^2$ sum associated
- Compatible tracks impact parameters: $|d_0|$, $|z_0|$

Electrons

- Track and calorimeter quality and match criteria
- Cluster energy deposit shape
- $|\eta| < 2.47$, exclude $1.37 < |\eta| < 1.52$
- Jet overlap removal
- Track and energy isolation

Muons

- Consistent MS and ID good quality track match
- $|\eta| < 2.5$
- Separated from jets
- Track isolation

Jets

- anti-k$_t$ clustering algorithm with 0.4 radius
- Calibrated (p_{T},η), in-situ correction
- Reject beam-halo, noise, overlap
- JVF > 0.5

E_T^{miss}

- Vector sum of transverse momenta of all calibratd leptons and jets, and unassociated clusters with $|\eta| < 4.9$

Event selection – VLL, Type-III

Single e or μ trigger (iso or not) Lepton matching trigger

- at least three leptons (e or μ)
- $p_T^{\ell_1} > 26\ \mathrm{GeV}$, $p_T^{\ell_{2,3}} > 15\ \mathrm{GeV}$
- $|m_{\ell\ell} - m_Z| < 10\ \mathrm{GeV}$
- $\Delta R(\ell, m_{\ell\ell}) \leq 3.0$
- if $\geq 4\ell$, no ZZ events

Event selection – Type-III

- ==2 leptons (e or μ)
- OS: $p_T^\ell > 100\ \mathrm{GeV}$, $p_T^\ell > 25\ \mathrm{GeV}$, $m_{\ell\ell} > 130\ \mathrm{GeV}$
- SS: $p_T^\ell > 70\ \mathrm{GeV}$, $p_T^\ell > 40\ \mathrm{GeV}$, $m_{\ell\ell} > 90\ \mathrm{GeV}$
- ≥ 2 jets, no b-tagged jets
- OS: $p_T^{j_1} > 60\ \mathrm{GeV}$, $p_T^{j_2} > 30\ \mathrm{GeV}$
- SS: $p_T^{j_1} > 40\ \mathrm{GeV}$, $p_T^{j_2} > 25\ \mathrm{GeV}$
- $60 < m_{j_1 j_2} < 100\ \mathrm{GeV}$ (W boson hadronic decay)
- OS: $\not{E}_T > 110\ \mathrm{GeV}$, $\Delta R_{jj} < 2$
- SS: $\not{E}_T > 100\ \mathrm{GeV}$

Event selection – Majorana

Common to Majorana analysis

- suite of single lepton (threshold $24\mathrm{GeV}$) and dimuon trigger (thresholds: $20\mathrm{GeV}$, $8\mathrm{GeV}$)
- ==2 same-sign leptons (e or μ), veto any more loose lepton
- $p_T^{\ell_1} > 25\ \mathrm{GeV}$, $p_T^{\ell} > 20\ \mathrm{GeV}$

mTISM

- ≥ 2 jets, $60 < m_{j_1 j_2} < 100\ \mathrm{GeV}$ (W boson hadronic decay)
- $m_{\ell\ell} > 40\ \mathrm{GeV}$, $|m_{\ell\ell} - m_Z| > 20\ \mathrm{GeV}$
- $\not{E}_T < 40\ \mathrm{GeV}$
- Total eff.: 0.5-24% (ee), 3-30% ($\mu^+\mu^-$)

LRSM

- ≥ 1 jet
- $m_{\ell\ell} > 110\ \mathrm{GeV}$
- W_R searches: $m_{\ell\ell j(j)} > 400\ \mathrm{GeV}$
- Z' searches: $m_{\ell\ell jj(jj)} > 200\ \mathrm{GeV}$
- Total eff.: 0.5-25% (ee), 1.5-30% ($\mu^+\mu^-$), 15% ($m_{V_R} >> m_N$)

Event selection – Leptoquarks

LQ3 ($b\nu_\tau \bar{b}\bar{\nu}_\tau$)

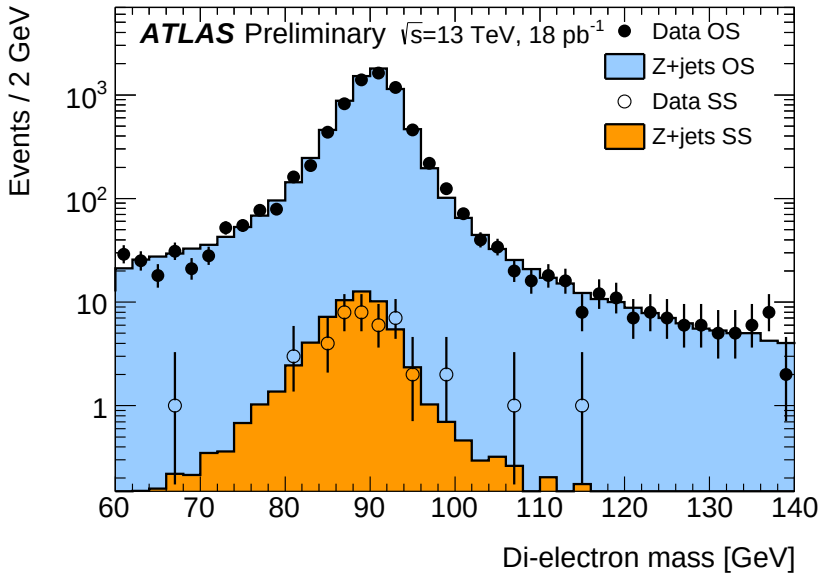
- E_T^{miss} trigger
- ==2 b-tagged jets, $p_T > 20\ \mathrm{GeV}$, $|\eta| < 2.5$
- other jets if $p_T > 20\ \mathrm{GeV}$, $|\eta| < 4.9$
- no e (μ) with $p_T > 7$ (6) GeV
- $E_T^{\mathrm{miss}} > 150\ \mathrm{GeV}$, various signal regions

LQ3 ($t\nu_\tau \bar{t}\bar{\nu}_\tau$)

- ==1 ℓ, $p_T > 25\ \mathrm{GeV}$, $|\eta| < 2.47$ (2.4) for e (μ)
- veto on additional loose leptons with $p_T > 10\ \mathrm{GeV}$
- ≥ 4 jets, $p_T > 20\ \mathrm{GeV}$, $|\eta| < 2.5$
- ≥ 1 b-tagged jet
- $E_T^{\mathrm{miss}} > 100\ \mathrm{GeV}$, various signal regions

Control regions

Tight e with $E_T > 20$ GeV



Z+jets control region

- $60 < m_{ee} < 120$ GeV
- $70 < m_{\mu\mu} < 110$ GeV

$t\bar{t}$

- ==1 lepton, $p_T > 40$ GeV
- single electron trigger

- Validate MC modeling accuracy
- Derive normalization scale factors

- Z/γ+jets:
  - $ee jj$ 1.1 ± 0.2
  - $\mu\mu jj$ 0.97 ± 0.15
- $t\bar{t}$:
  - $ee jj$ 1.10 ± 0.05
  - $\mu\mu jj$ 1.01 ± 0.05

Systematic uncertainties

- MC modelling as a function of S_T
  - Z+jets: $eejj$ 8-25%, $\mu\mu jj$ 10-30%
  - $t\bar{t}$: $eejj$ 6-24%, $\mu\mu jj$ 10-40%
- NLO cross-section of diboson, single t, W+jets, $Z \to \tau\tau$
- PDF set: 4-17% (low to high m_{LQ})
- Final PDF on signal: 1-4%
- QCD renormalisation and factorisation scales: 14%
- JES: 8-26% (SR1-SR8), JER: 1%
- e, μ scale, resolution: $\sim 1\%$

MC Signal samples

Heavy lepton resonances:

- production MadGraph 4.52 (VLL), 5.2.2.1 (type-III)
- CTEQ6L1 PDF, AU2 tune, Pythia8 showering
- Decay: Bridge (VLL) and MadGraph (type-III)

Type-III seesaw heavy leptons:

- MadGraph5 (matrix elements), MadEvent (MSTW2008 PDF)

Majorana (mTISM):

- Alpgen 2.14 (LO in QCD) with CTEQ6L1 PDF set
- Neutrino masses: 100-500GeV

MC Signal samples

Majorana (LRSM):

- Pythia 8.170 (LO in QCD)
- Same coupling for heavy gauge bosons and neutrino than for SM
- W_R masses between 0.6 and 4.5 TeV
- Z' masses between 0.4 and 3.6 TeV
- Majorana neutrino 50-100 GeV below the heavy gauge boson mass
- No heavy neutrino mixing, same-flavor final state leptons

Leptoquarks:

- Pythia 8.160 event generator, with CTEQ6L1 PDF
- $\lambda_{LQ\to\ell q} = \sqrt{0.01 \times 4\pi\alpha}$
- $200 \leq m_{LQ} \leq 1300$ GeV in 50 GeV steps
- Normalised to NLO cross-section for scalar LQ pair prod

Detector response modelled using GEANT4, or fast detector simulation where calorimeter is parametrised