Searches for leptoquarks and excited leptons with the ATLAS detector

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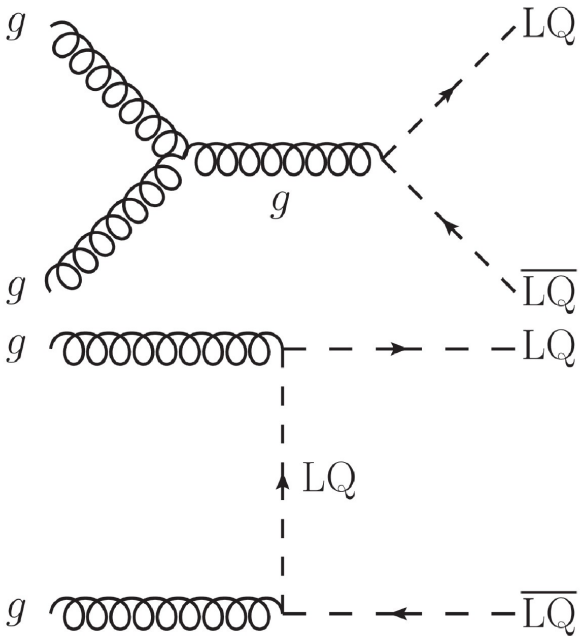
Introduction

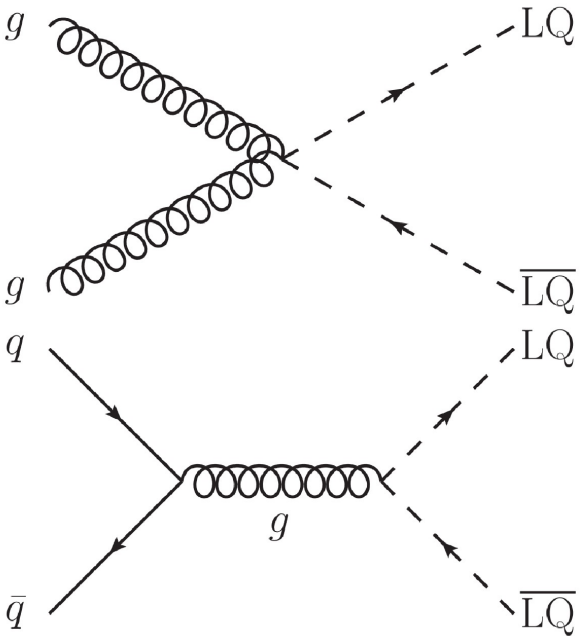
- The observed similarity of the quark and lepton sectors in the Standard Model seems to point at a connection between the two
- **Grand unified theories** and models with **quark and lepton substructure** are two possible ways to make this connection
  - Example: E_6 unification

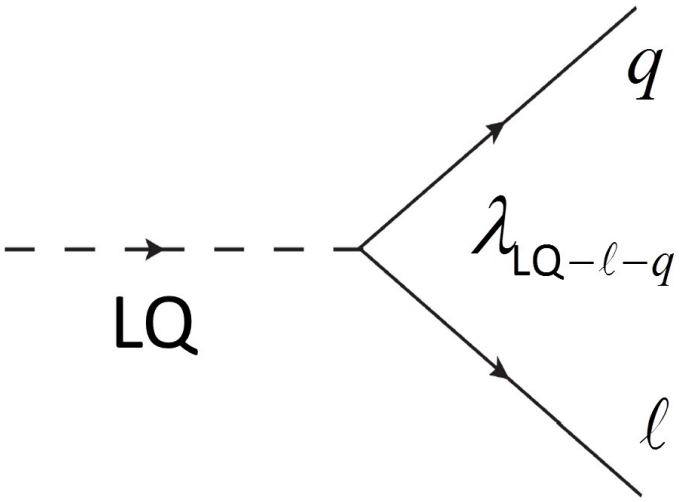
$E_6 \rightarrow SO(10) \times U(1)_\psi$
$\rightarrow$ **SU(5)** $\times U(1)_\chi \times U(1)_\psi$
$\rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_\theta$
$\rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y$
$\rightarrow SU(3)_C \times U(1)_Q$

$E_6 \rightarrow SO(10) \times U(1)_\psi$
$\rightarrow$ **$SU(4)_C$** $\times SU(2)_L \times SU(2)_R$
$\rightarrow SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
$\rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y$
$\rightarrow SU(3)_C \times U(1)_Q$

  - In general, leptoquarks predicted in these theories are ruled out at the TeV scale, as they would mediate processes such as proton decay, $K \rightarrow e\mu$, etc.
- Experimental **bounds can be evaded** with a number of model constraints
- Searches at the Large Hadron Collider are **uniquely sensitive** to classes of models predicting **leptoquarks** or **excited leptons**





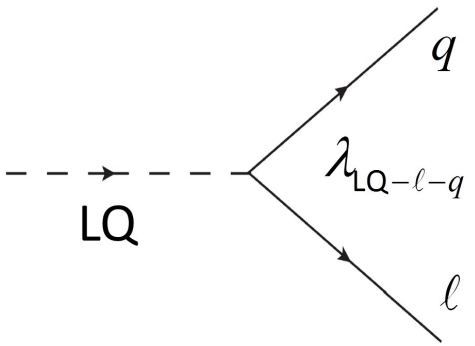


Search for scalar leptoquarks at $\sqrt{s}$ = 13 TeV

May 2016, arXiv: 1605.06035,
submitted to New Journal of Physics

Benchmark signal model

- **Benchmark** signal: minimal Buchmüller–Rückl–Wyler model
  - Scalar leptoquarks with fermion number = 0 or 2
  - Lepton number and baryon number **separately conserved**
  - Leptoquark couplings are purely chiral
  - **Three generations** of leptoquarks with **flavour-diagonal** couplings
    - LQ1 → **eu**, **ed**, vu, vd
    - LQ2 → **μc**, **μs**, vc, vs
    - LQ3 → τt, τb, vt, vb



Channels in bold: **this search**
LQ3 searches in bonus slides

- Nevertheless this search is designed to be as **model-independent** as possible
  - no requirement on lepton charge
  - no requirement on hadronic jet flavour
  - focus on final states with **two electrons or two muons**, and **at least two jets**
    - LQ1 LQ1 → **eejj**, LQ2 LQ2 → **μμjj**

Analysis strategy

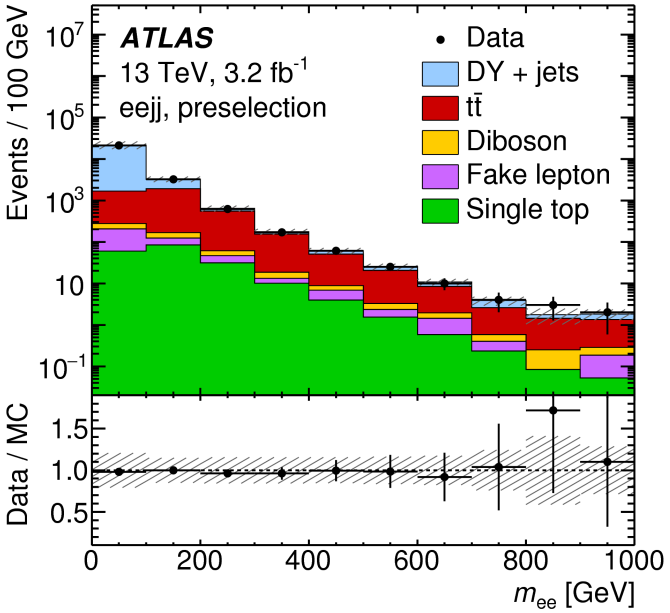
- Select **high-quality, high-momentum same-flavour leptons**
  - Electrons: reliable energy measurement in the EM calorimeter

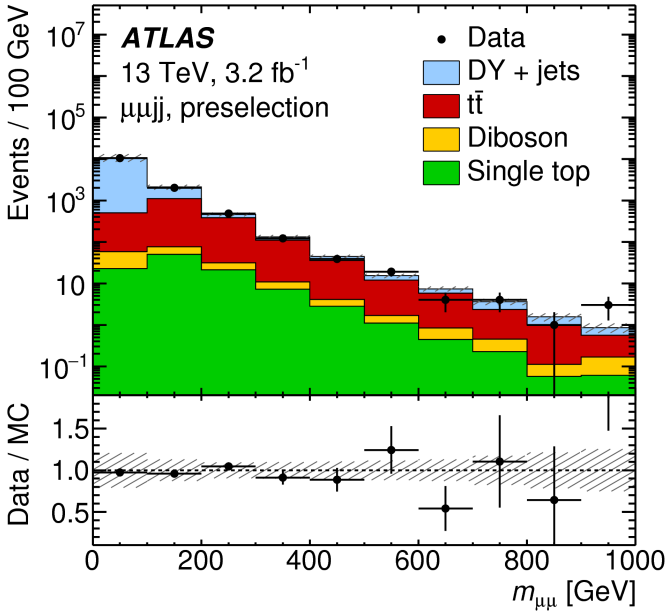
$$\frac{\sigma(E)}{E} = \frac{k_1}{\sqrt{E}} + k_2$$

    - Main challenge is **particle identification**: need to select against jets and converted photons
    - **Data-driven** strategies to estimate the remaining fake electrons after selection
  - Muons: Very high momentum → very straight tracks!

$$\frac{\sigma(p)}{p} = \frac{S_0}{p_T} + S_1 + S_2 \cdot p_T$$

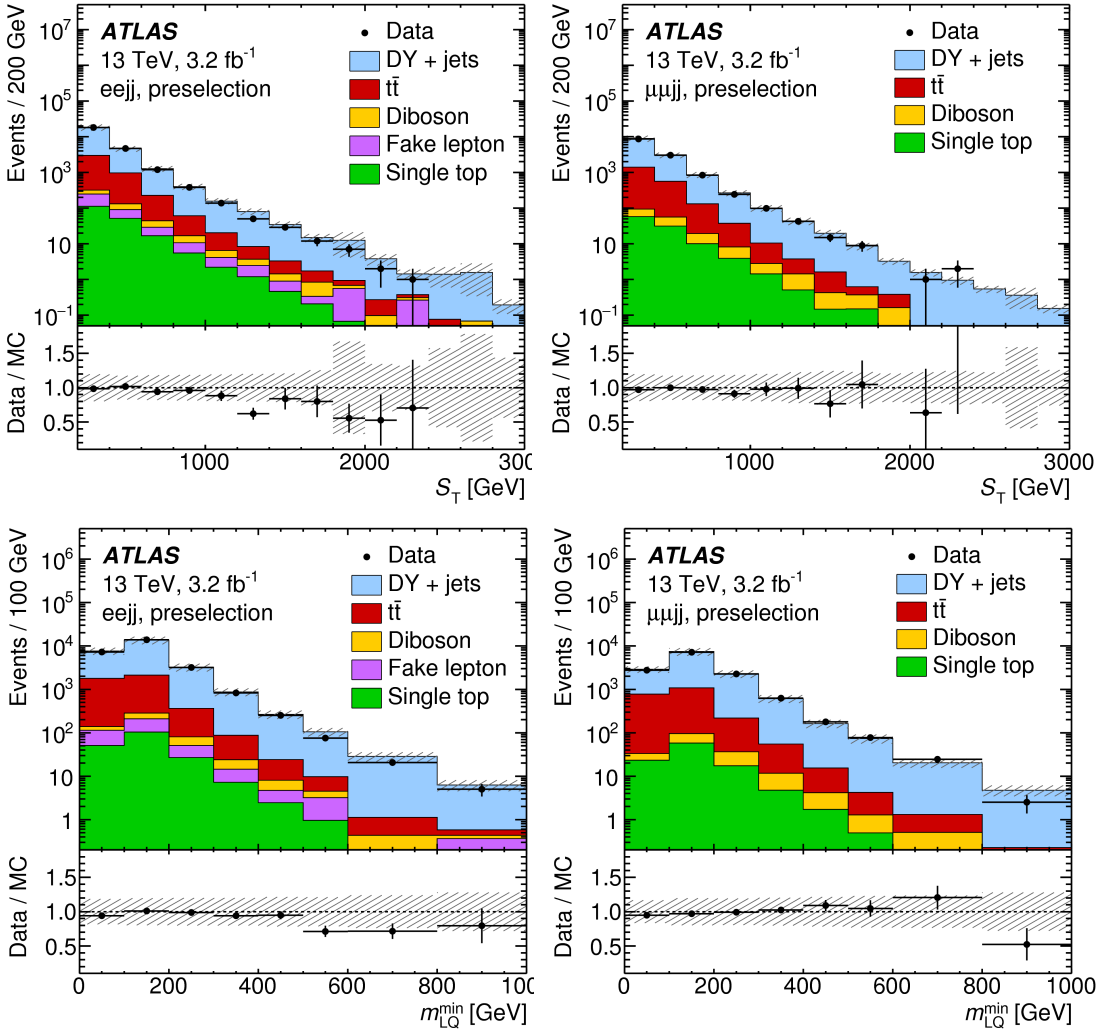
    - Use only the **best-aligned detector chambers**, with stringent hit requirements
- Require the presence of **at least two hadronic jets** with pT > 50 GeV



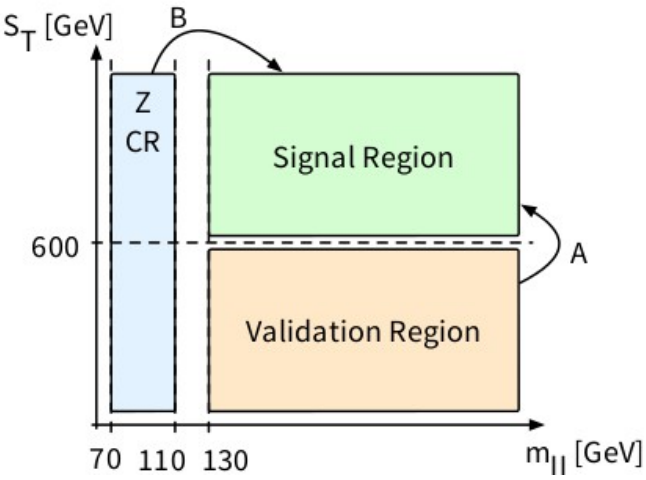


Analysis strategy

- Main discriminating variables in search for leptoquarks:
  - High lepton invariant mass: $\mathbf{m_{ll} > 130\ GeV}$
  - High scalar transverse momentum sum $\mathbf{S_T}$ of the two leptons and two leading jets



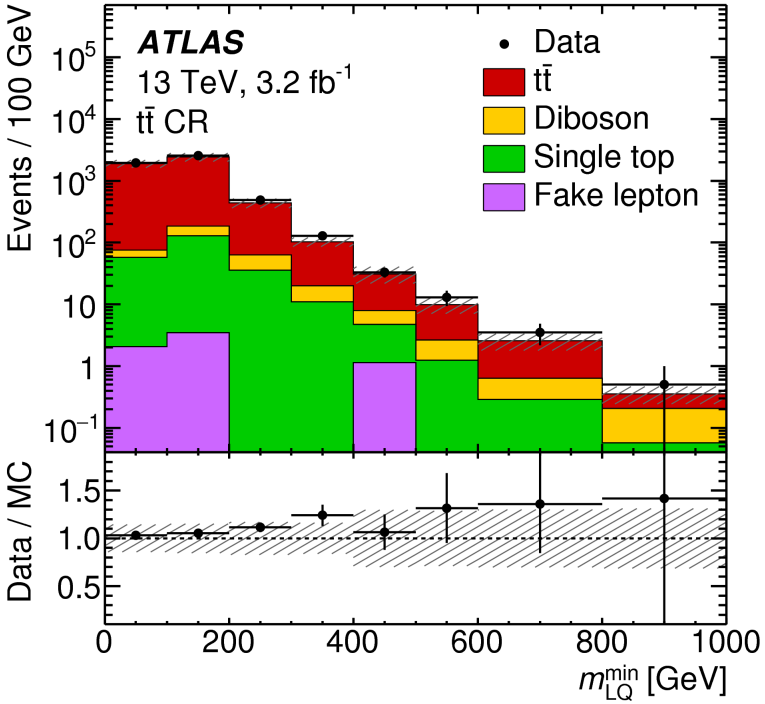
- High minimum invariant mass of lepton-jet pairs $\mathbf{m_{LQ}^{min}}$
  - Pairs are chosen such that the invariant mass difference $|m_{LQ}^{max} - m_{LQ}^{min}|$ is minimized
  - Thus for signal both m_{LQ} are high, but $\mathbf{m_{LQ}^{min}}$ **is low for backgrounds**

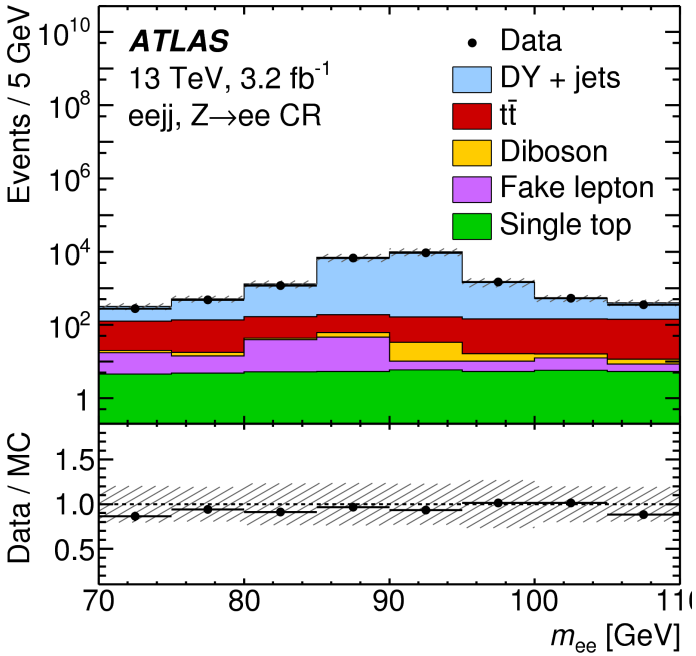


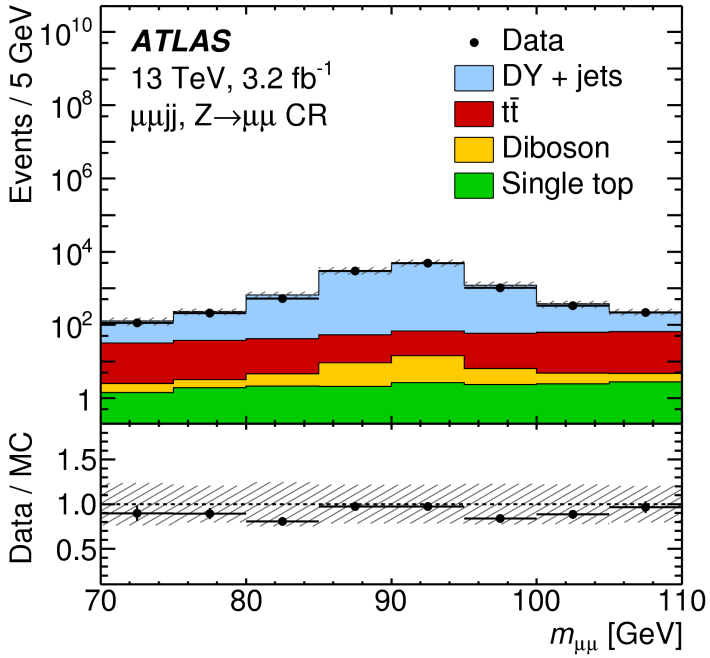
Control regions

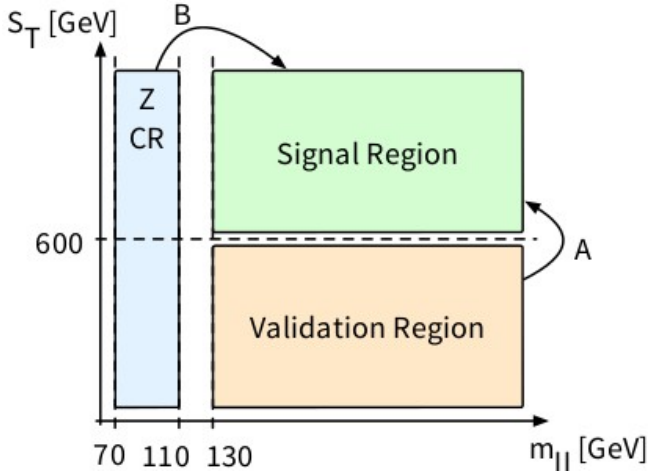
- Leading background normalizations are constrained in **control regions**
  - **Drell-Yan**: 70 GeV < m_{ll} < 110 GeV
  - **$t\bar{t}$**: require exactly one electron and one muon
- Resulting normalization factors consistent with unity

Channel	DY+jets	$t\bar{t}$
$eejj$	0.9 ± 0.1	1.0 ± 0.1
$\mu\mu jj$	0.9 ± 0.1	$1.0^{+0.2}_{-0.1}$

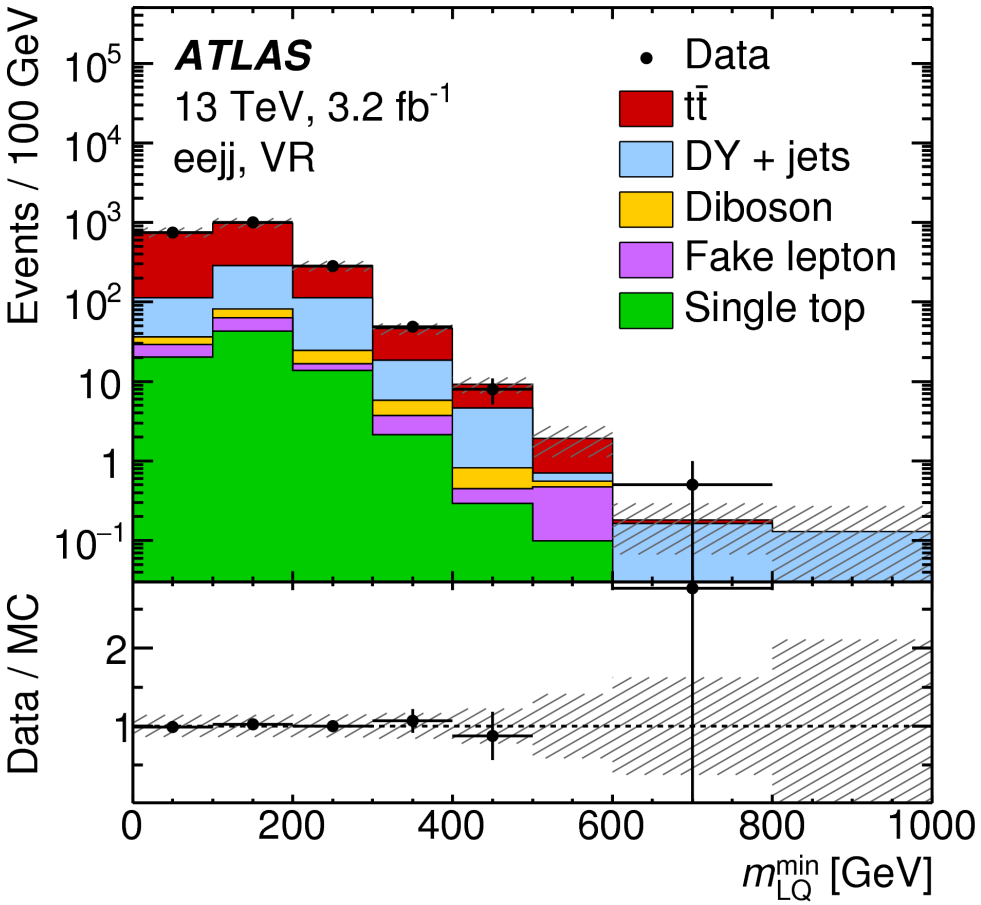


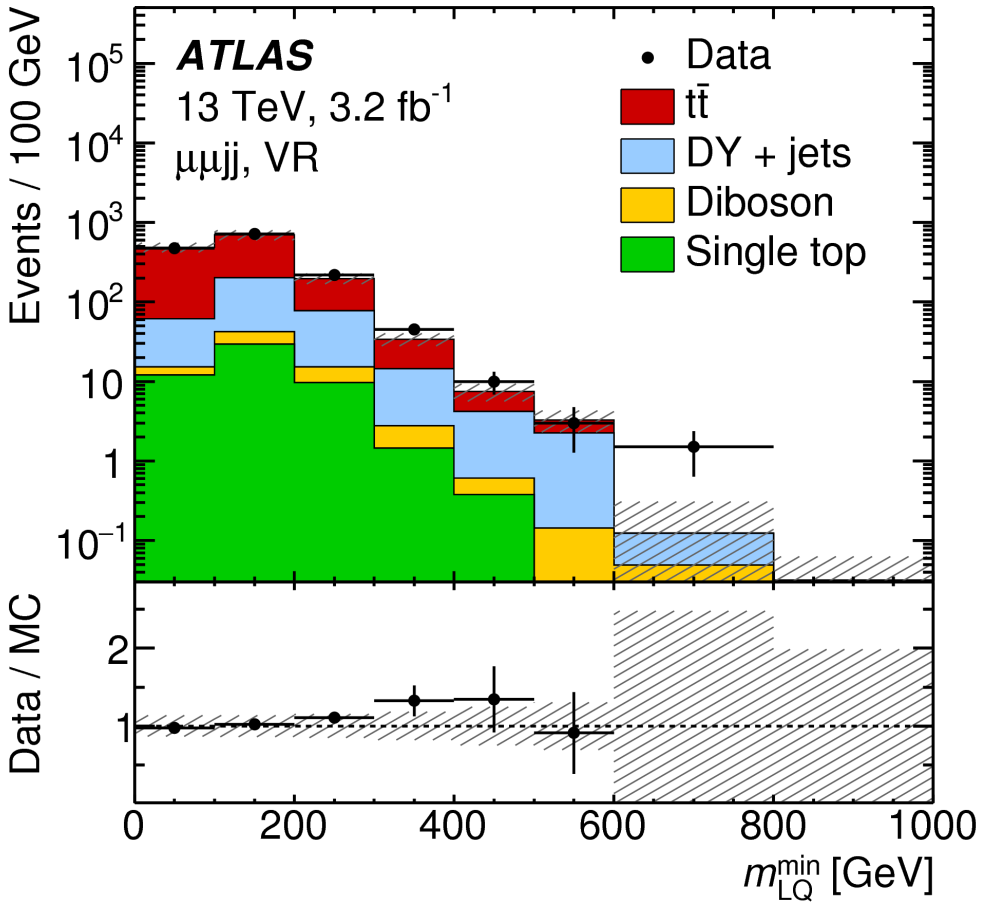






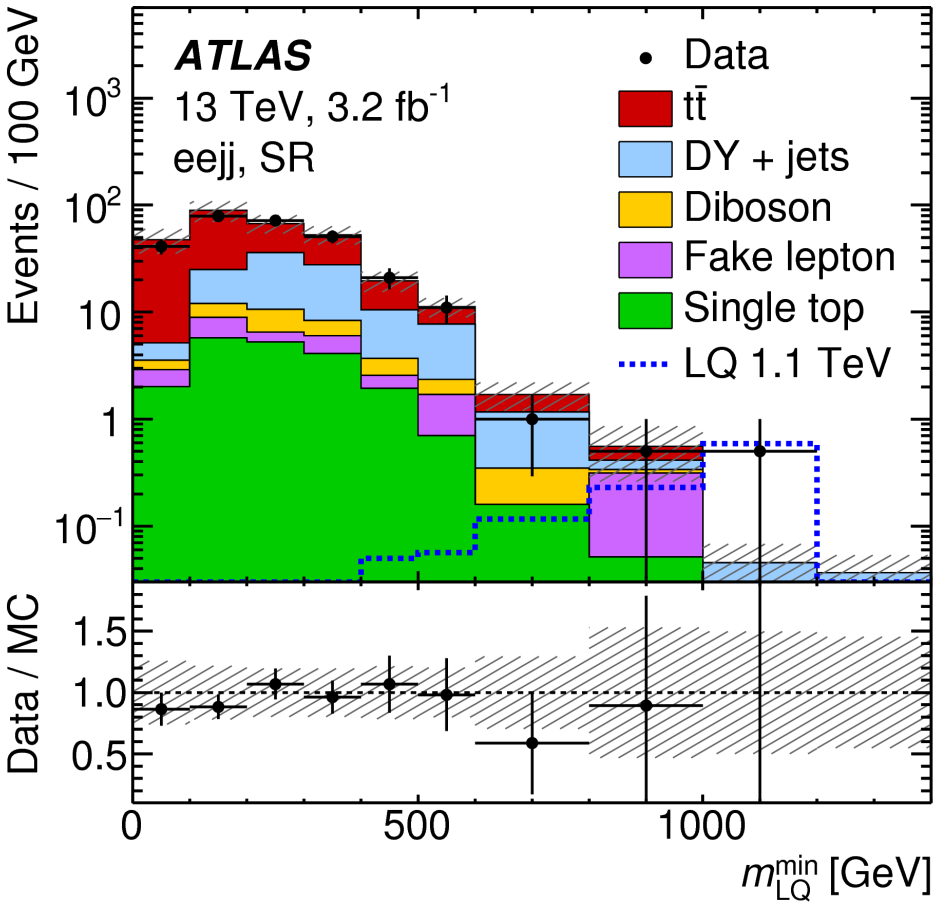
Validation regions

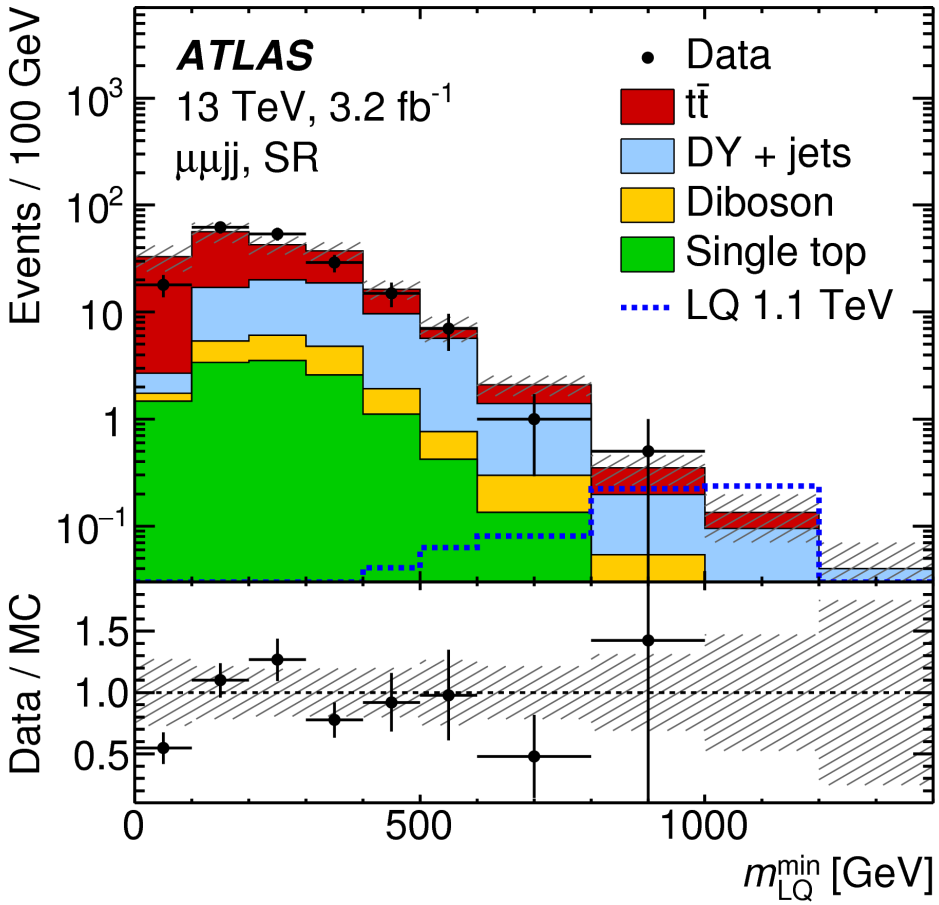




- No signal expected here, and **good agreement** with background predictions
  - m_{ll} > 130 GeV but inverted requirement on S_T < 600 GeV
- Main systematic uncertainties from theoretical background predictions
  - Experimental uncertainties mainly from jet calibration and lepton identification

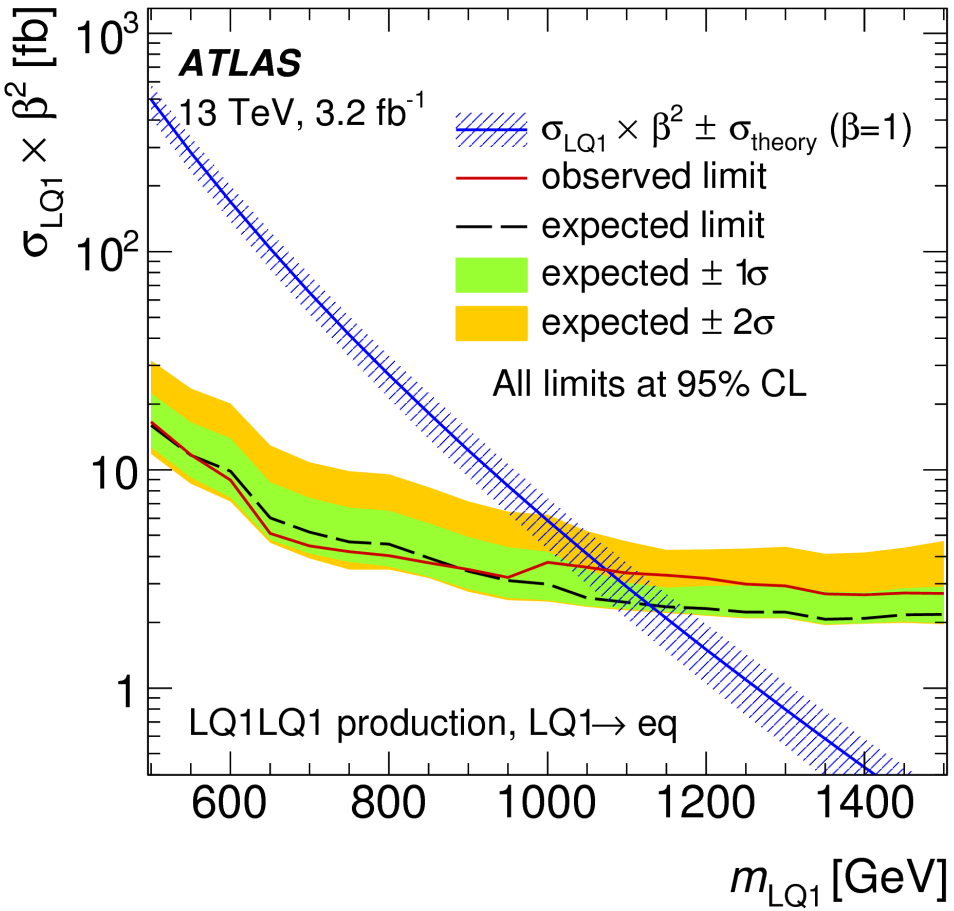
Signal regions

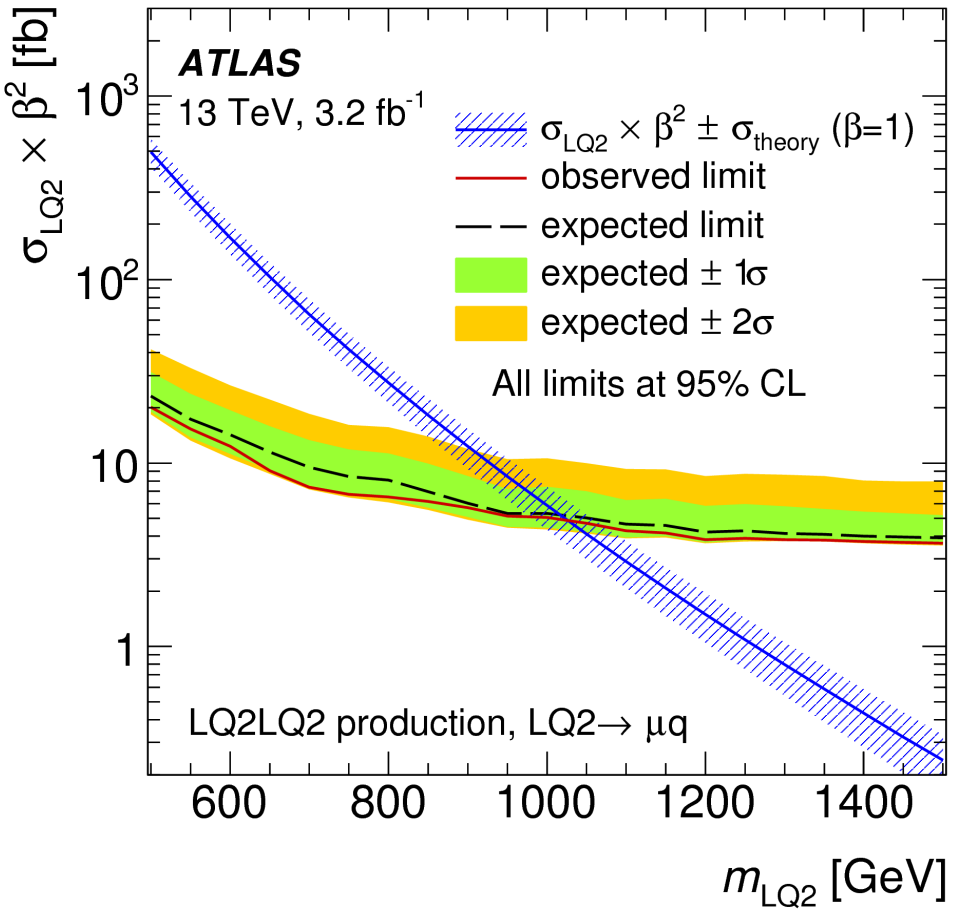




- **No significant excess** above Standard Model predictions
- Limits are set on the LQ signal strength

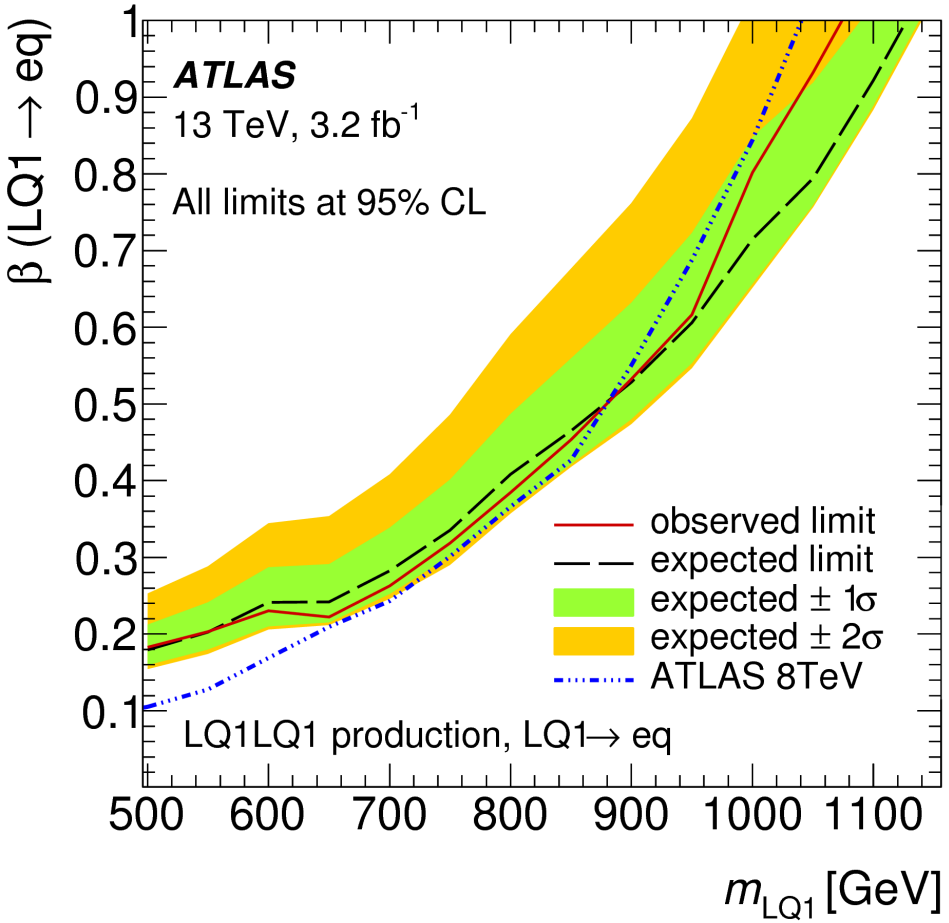
Results

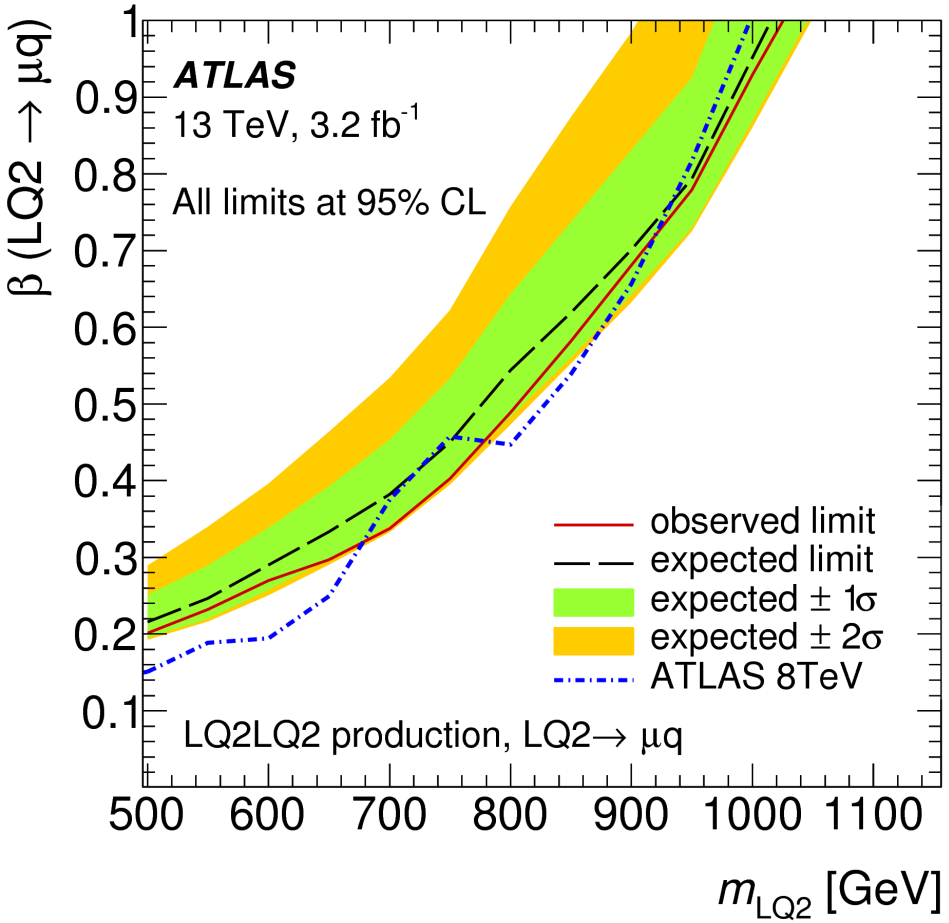




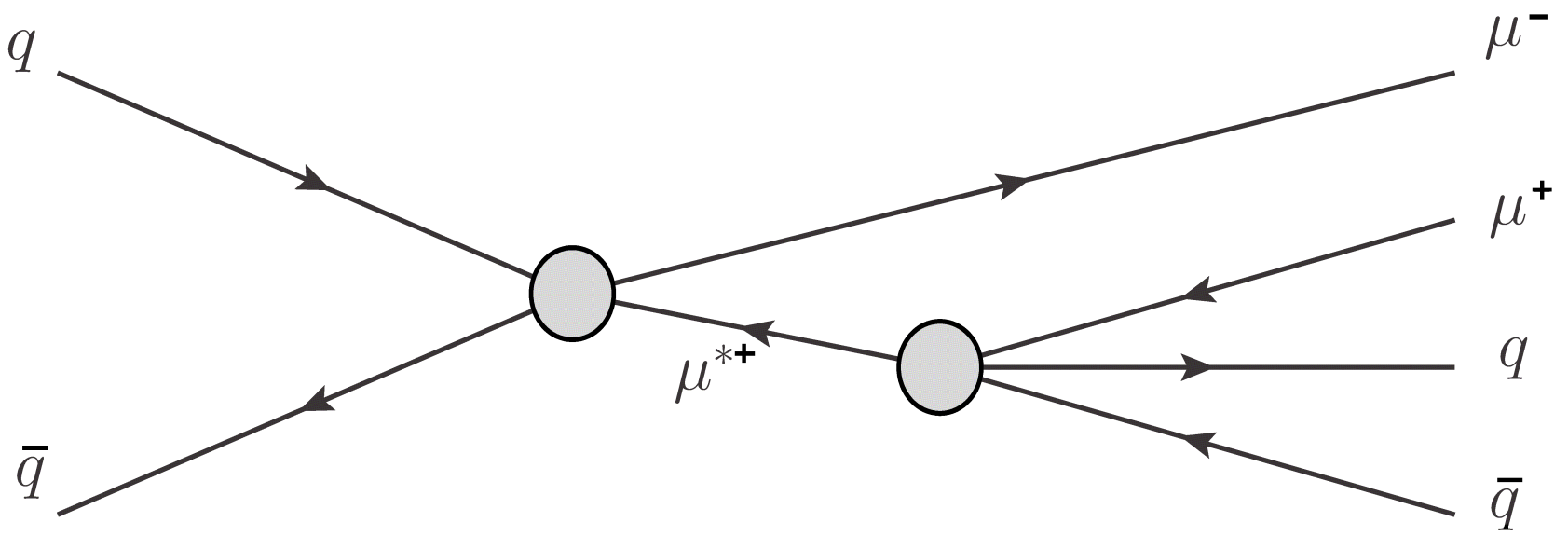
- Limits are set on the signal cross-section times LQ branching ratio to quark and charged lepton squared (β^2) at 95% CL, for leptoquark masses m_{LQ1} and m_{LQ2}
- Benchmark LQ mass limits with $\beta = 1$ are **m_{LQ1} > 1100 GeV, m_{LQ2} > 1050 GeV**

Results





- Also interpreted as limits on the branching ratio β as a function of m_{LQ}
- Sensitivity is the same as with 20.3 fb^{-1} of 2012 data at $\sqrt{s}$ = 8 TeV
  - **Much more data to come in Run 2** → entering unexplored territory!

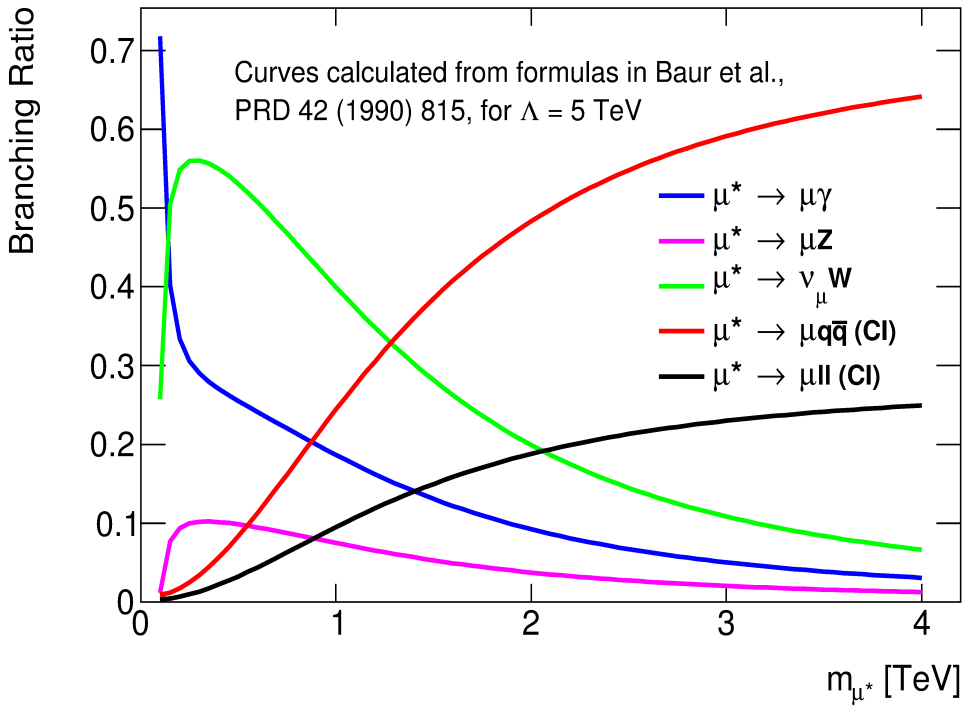


Search for excited muons at $\sqrt{s}$ = 8 TeV

January 2016, arXiv: 1601.05627,
submitted to New Journal of Physics

Analysis strategy

- Signal model: excited **composite muon** decaying via **μμjj contact interaction**
  - **Largest branching ratio** for $m_{\mu^*} > 0.25\ \Lambda$, where Λ is the compositeness scale
    - Figure shown for $\Lambda = 5$ TeV approximately scales as m_{μ^*} / Λ
- Selection of **high-momentum muons** and at least **two hadronic jets**
  - More sensitive to excited leptons at high m_{μ^*} / Λ than the traditional search $\mu^* \rightarrow \mu\gamma$



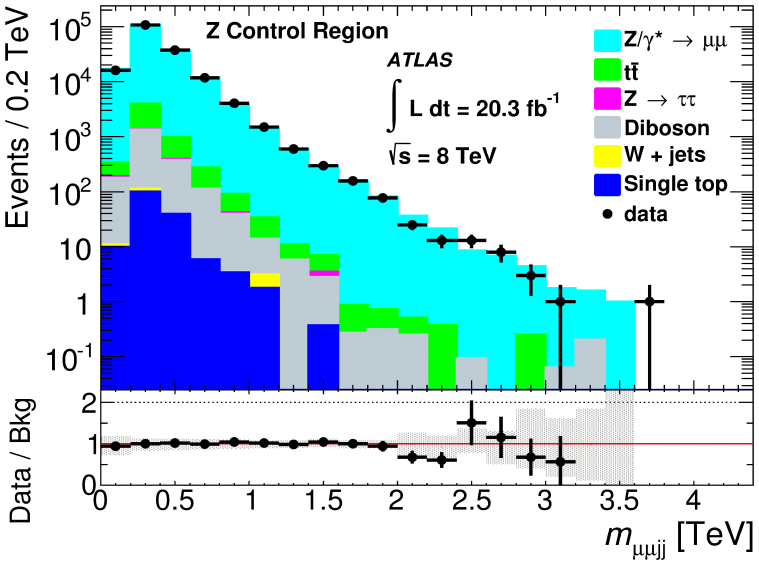
Main discriminating variables:

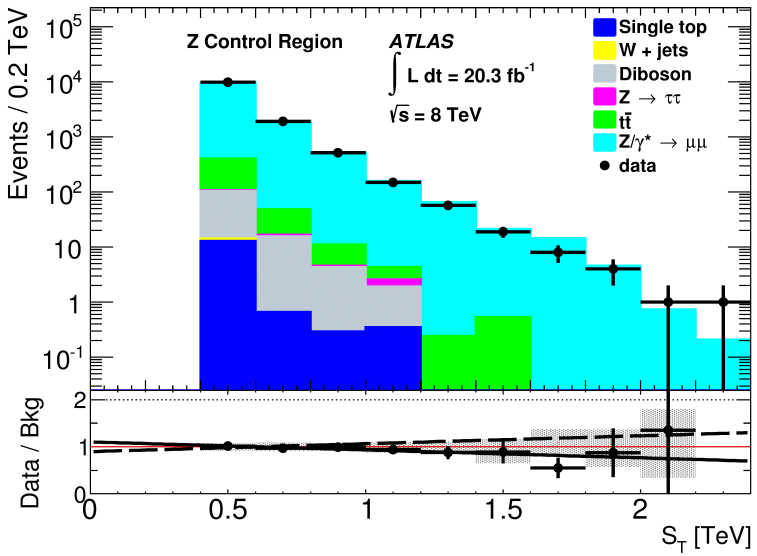
- High lepton invariant mass: $\mathbf{m_{\mu\mu}}$
- High scalar transverse momentum sum $\mathbf{S_T}$ of the two leptons and two leading jets
- High four-object invariant mass $\mathbf{m_{\mu\mu jj}}$
- Three-object invariant mass combinations were found to bring no further improvement to the search sensitivity

Control regions

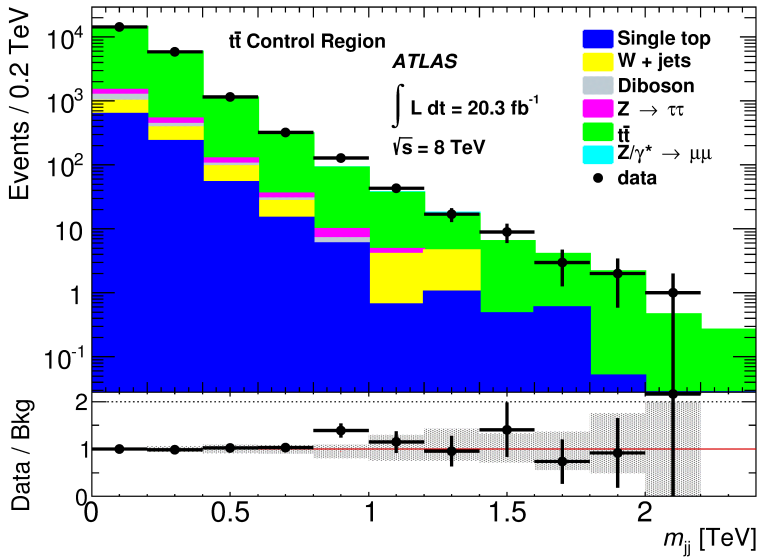
- Drell-Yan and $t\bar{t}$ background normalization constrained in control regions

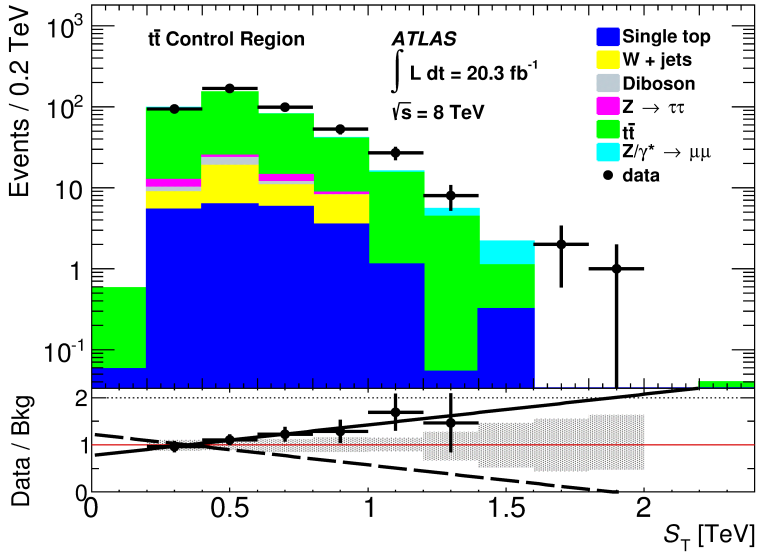
Drell-Yan: 70 GeV < m_{ll} < 110 GeV





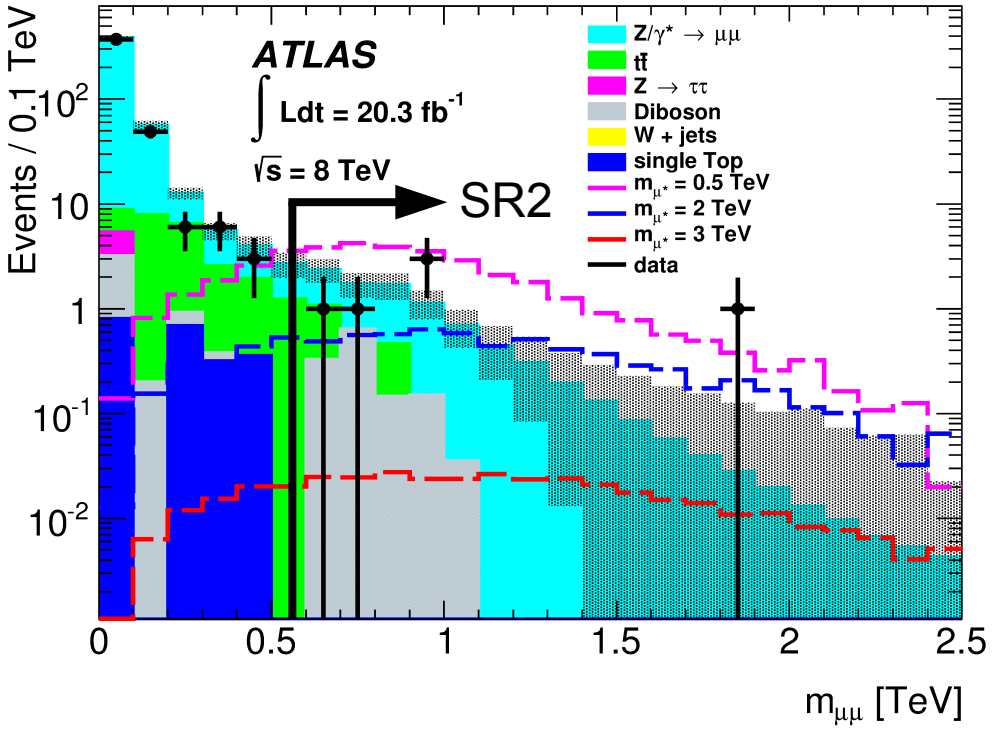
$t\bar{t}$: exactly one electron and one muon

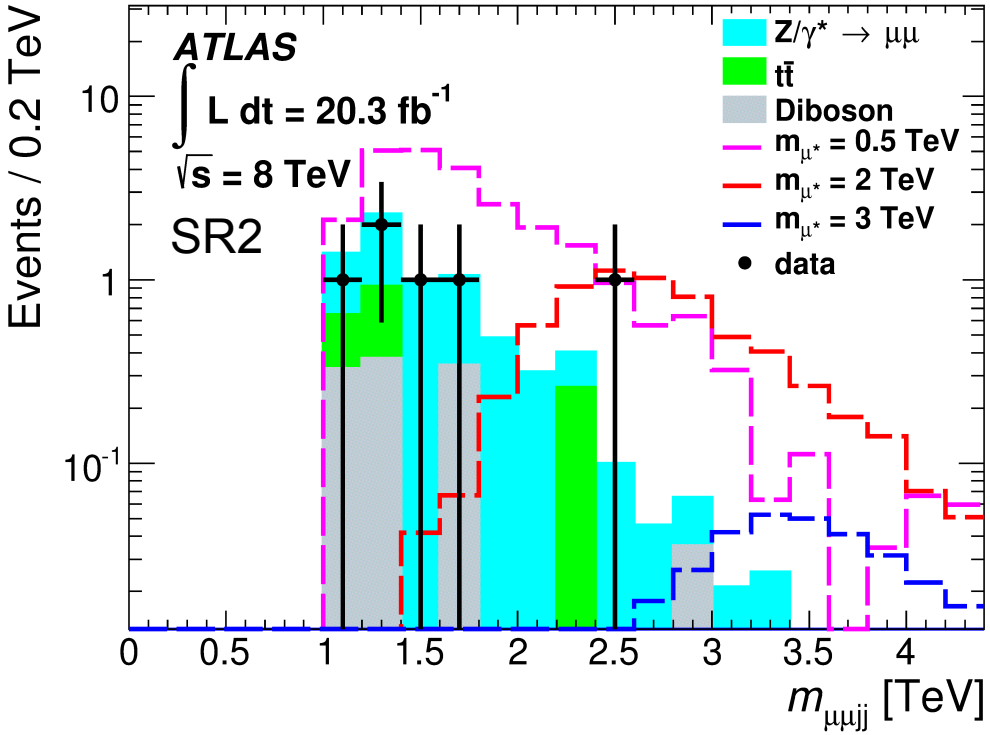




Results

- No significant excess above Standard Model predictions in any signal region
  - Optimized a different **signal region for each m_{μ^*} point** considered
  - For example, shown here is signal region #2, optimized for m_{μ^*} = 300 – 500 GeV
    - Requirements $m_{\mu\mu}$ > 550 GeV, S_T > 900 GeV, $m_{\mu\mu jj}$ > 1 TeV



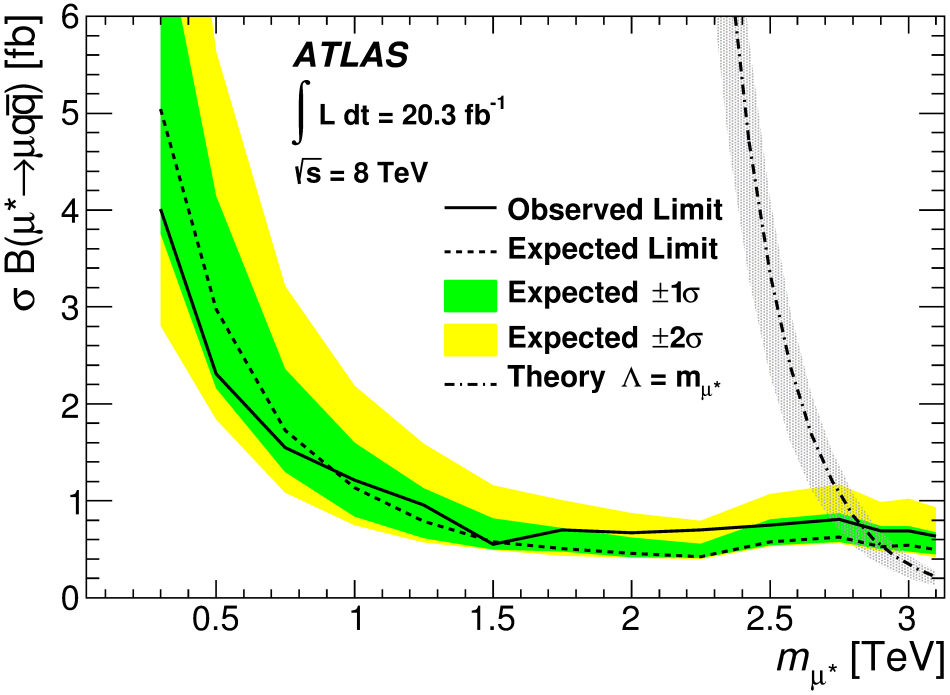


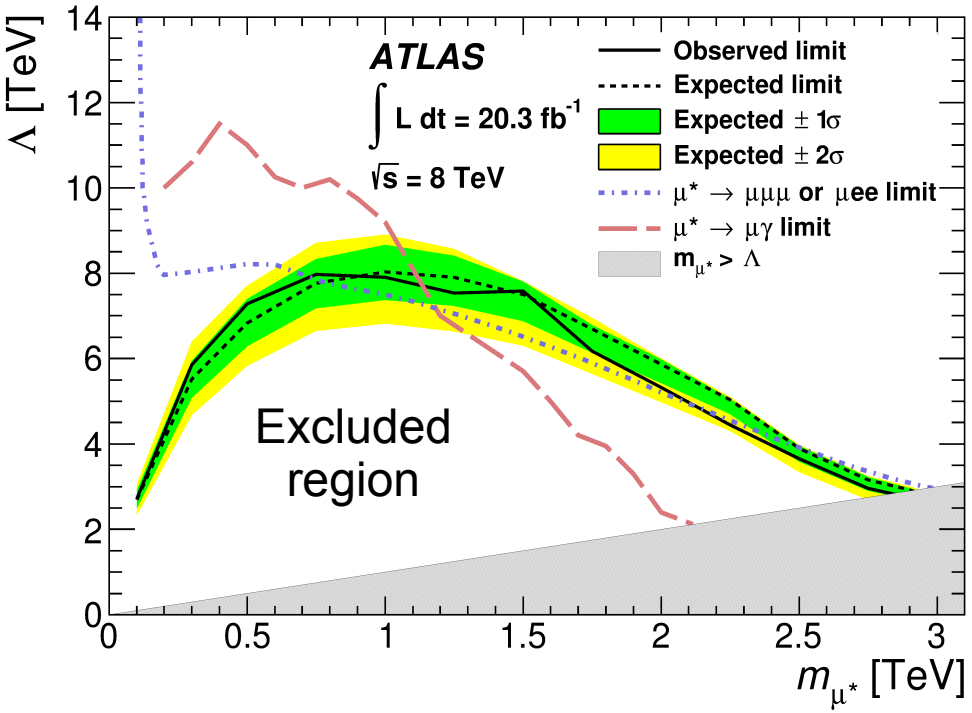
Results

- No significant excess above Standard Model predictions in any signal region
  - Optimized different, non-orthogonal signal regions for m_{μ^*} points considered

m_{μ^*} [GeV]	Signal Region	$m_{\mu\mu}$ [GeV]	S_T [GeV]	$m_{\mu\mu jj}$ [GeV]	Acc × Eff	Expected Signal	Expected BG	Observed Events
100	1	500	450	0	0.041	3.0±0.3	71.7±8.6	71
300	2	550	900	1000	0.088	12.5±0.9	7.8±2.2	6
500	2	550	900	1000	0.15	29.4±1.6	7.8±2.2	6
750	3	450	900	1300	0.23	43.7±2.2	5.8±1.9	5
1000	4	450	1050	1300	0.31	44.1±1.8	4.6±1.9	5
1250	5	450	1200	1500	0.38	29.8±1.3	2.1±1.0	3
1500	6	400	1200	1700	0.38	19.8±0.8	1.3±0.6	1
1750	7	300	1350	1900	0.41	11.8±0.5	0.9±0.5	2
2000	8	300	1350	2000	0.40	6.6±0.2	0.7±0.4	2
2250	9	300	1500	2100	0.37	3.4±0.1	0.4±0.3	2
2500	10	110	1650	2300	0.39	1.65±0.07	$0.2^{+1.0}_{-0.2}$	2
2750	10	110	1650	2300	0.45	0.72±0.02	$0.2^{+1.0}_{-0.2}$	2
2900	10	110	1650	2300	0.45	0.52±0.02	$0.2^{+1.0}_{-0.2}$	2
3000	10	110	1650	2300	0.46	0.38±0.02	$0.2^{+1.0}_{-0.2}$	2
3100	10	110	1650	2300	0.45	0.30±0.02	$0.2^{+1.0}_{-0.2}$	2

Results





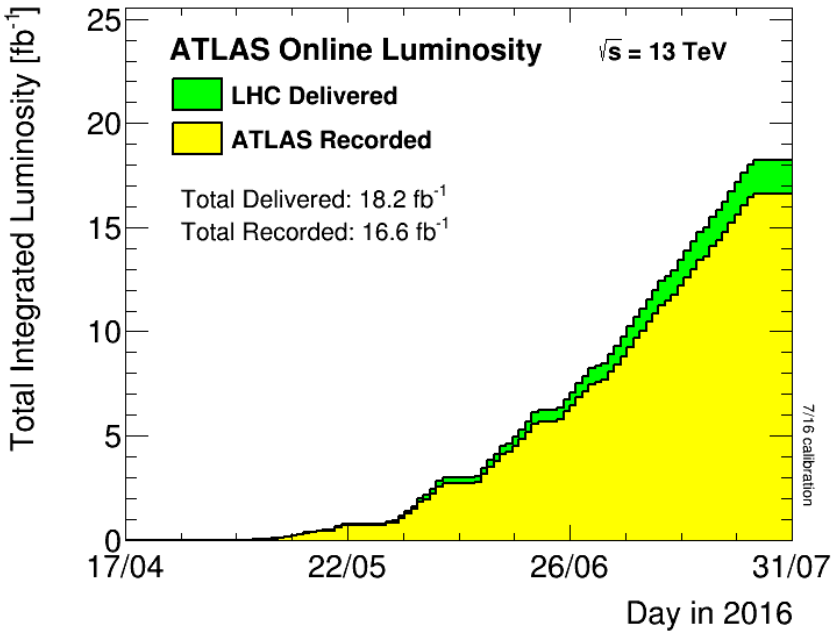
- Limits are set on the signal cross-section times branching ratio, as a function of m_{μ^*}
- For $\Lambda = m_{\mu^*}$ the limit at 95% CL is **$m_{\mu^*} > 2.8$ TeV**
- Also interpreted as limits on Λ as a function of m_{μ^*}
  - Previous ATLAS searches in the $\mu^* \rightarrow \mu\gamma$ and $\mu^* \rightarrow \mu\ell\ell$ channels are also presented
  - Observed limits on Λ in the $\mu\mu jj$ channel are the best for 1.1 TeV < m_{μ^*} < 2.1 TeV

Conclusion

- Searches for **leptoquarks** and **excited muons** in final states with two leptons and two jets are performed with the ATLAS experiment
- No significant excess is found above Standard Model predictions
- Limits are set on benchmark models:

β	95% CL limit on m_{LQ1} [GeV]		95% CL limit on m_{LQ2} [GeV]	
	Expected	Observed	Expected	Observed
1.00	1160	1100	1040	1050
0.75	1050	1000	950	960
0.50	900	900	800	830
0.25	680	700	580	600

$m_{\mu^*} > 2.8$ TeV at 95% CL ($\Lambda = m_{\mu^*}$)



- **Much more data** at $\sqrt{s}$ = 13 TeV are now available: analysis in progress!

BONUS SLIDES

Leptoquark search: Systematic uncertainties

Main systematic uncertainties in the first-generation search

Systematic uncertainties	Signal Region		CR DY+jets	CR $t\bar{t}$
	Signal	Background	Background	Background
Trigger S.F.	10%	up to 1.5%	3%-4%	3%-4%
Electron Identification S.F.	8%	up to 2%	up to 1.5%	up to 1%
Electron Isolation S.F.	2%-7%	2%-3%	less than 1%	up to 2%
JES_{NP1}	less than 1%	3%-4%	6%-8%	2%-5%
JES_{NP2}	less than 1%	up to 2%	2%-3%	up to 2%
JES_{NP3}	less than 1%	up to 2%	2%-3%	up to 1.5%

Main systematic uncertainties in the second-generation search

Systematic uncertainties	Signal Region		CR DY+jets	CR $t\bar{t}$
	Signal	Background	Background	Background
Trigger S.F.	up to 2%	up to 2%	3%-4%	up to 1%
Muon Efficiency S.F.	4%-8%	2%-4%	up to 1.5%	less than 1%
Muon Isolation S.F.	2%-7%	up to 1%	less than 1%	less than 1%
JES_{NP1}	less than 1%	2%-5%	6%-7%	2%-5%
JES_{NP2}	less than 1%	up to 2%	2%-3%	2%-3%
JES_{NP3}	less than 1%	up to 2%	up to 4%	1.5%-2%

Excited muon search: Systematic uncertainties

m_{μ^*} [GeV]	100	300	500	750	1000	1250	1500	1750
Luminosity	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8
Jet energy scale	7.4	3.8	2.7	2.6	1.8	1.6	1.5	1.6
Hadronization and factorization scales	3.9	3.4	2.0	1.3	0.8	0.5	0.5	0.3
Muon efficiency	0.6	0.7	0.7	0.8	0.7	0.8	0.8	0.8
Jet energy resolution	2.2	0.9	0.9	0.4	0.5	<0.1	0.2	0.1
Muon spectrometer resolution	0.8	0.1	0.3	<0.1	0.1	0.2	<0.1	0.4
PDF	4.7	4.2	3.0	3.1	2.0	2.8	2.5	1.7
Total	9.5	6.4	5.1	5.0	4.0	4.3	4.1	3.8

m_{μ^*} [GeV]	2000	2250	2500	2750	2900	3000	3100	3250
Luminosity	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8
Jet energy scale	1.1	1.1	1.1	0.7	0.7	0.5	0.4	0.5
Hadronization and factorization scales	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Muon efficiency	0.8	0.9	0.9	0.9	0.9	0.9	1.5	0.9
Jet energy resolution	0.2	0.3	0.5	<0.1	0.2	0.2	0.2	0.3
Muon spectrometer resolution	<0.1	0.3	0.2	0.1	0.3	<0.1	0.1	0.1
PDF	1.3	1.0	2.7	0.9	1.1	1.1	1.0	2.6
Total	3.4	3.3	4.2	3.1	3.2	3.2	3.4	4.0

Main systematic uncertainties in the signal yield [%]

Signal region	1	2	3	4	5	6	7	8	9	10
Z/γ^*+ jets generation	12	25	30	34	41	47	51	52	60	65
Jet energy scale	7.5	19	21	15	7.1	9.0	12	15	8.7	6.2
$t\bar{t}$ generation	18	12	7.4	4.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Muon spectrometer resolution	0.3	6.2	1.1	1.9	0.2	0.6	1.1	0.2	2.8	63
PDFs	3.2	4.2	5.9	6.9	7.0	8.8	10	9.7	10	17
Jet energy resolution	2.9	3.2	0.1	6.2	1.7	1.7	9.3	13	0.5	0.6
Muon efficiency	0.6	0.7	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.9
Luminosity	0.2	0.4	0.3	0.3	0.3	0.1	0.1	0.2	<0.1	<0.1
Z/γ^*+ jets extrapolation	–	–	–	–	–	–	2.9	2.9	17	480
Total	23	35	38	38	42	49	54	56	64	490

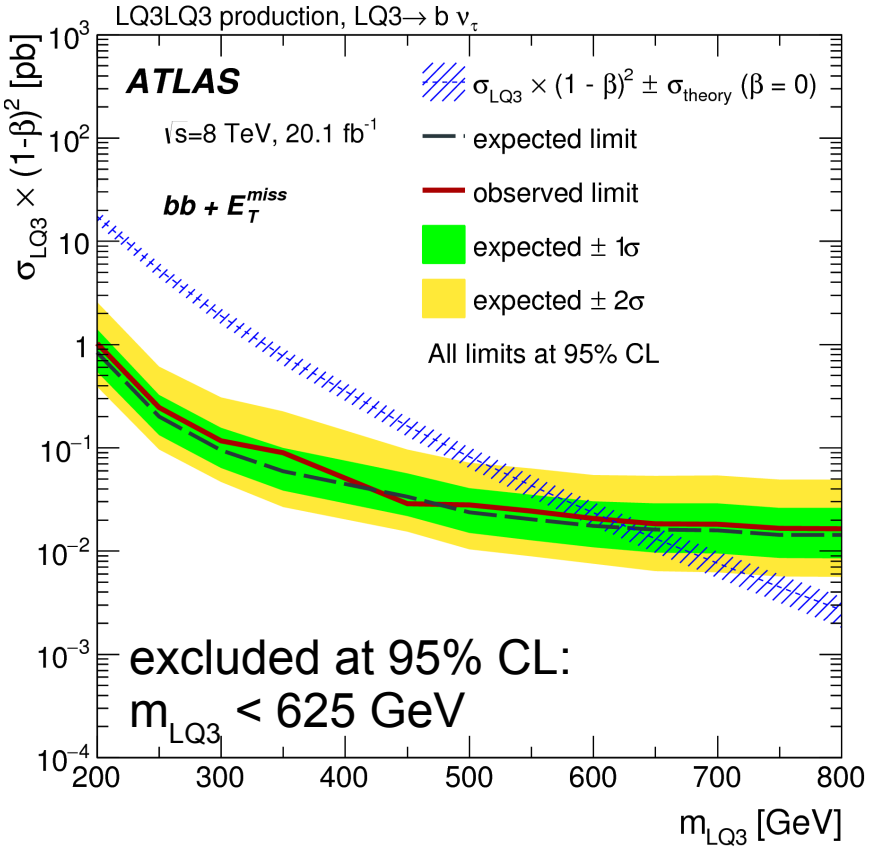
Main systematic uncertainties in the background yield [%]

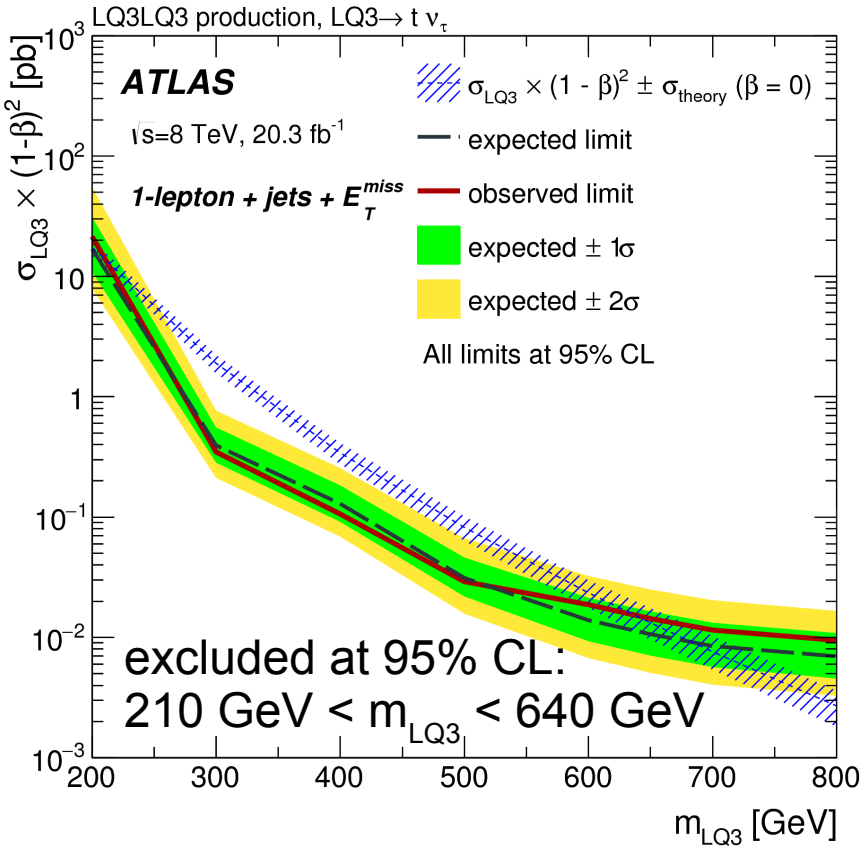
Search for scalar leptoquarks at $\sqrt{s}$ = 8 TeV

August 2015, Eur. Phys. J. C (2016) 76:5

Search for third-generation scalar leptoquarks at $\sqrt{s}$ = 8 TeV

- Latest limits on LQ3 → bν, LQ3 → tν (search for LQ3 → bτ at $\sqrt{s}$ = 7 TeV in next slides)
- Re-interpretation of SUSY searches for bottom squarks and top squarks
  - JHEP 1310, 189 (2013); JHEP 1411, 118 (2014)
  - same final states of **2 bottom or 2 top quarks** plus **missing transverse momentum** in the limit of neutralino mass comparable to neutrino mass



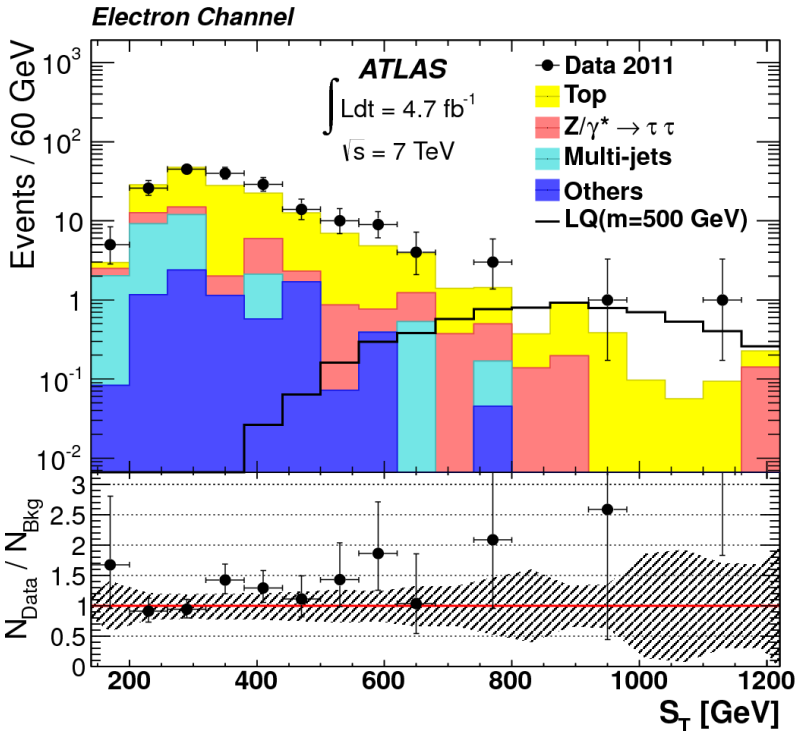


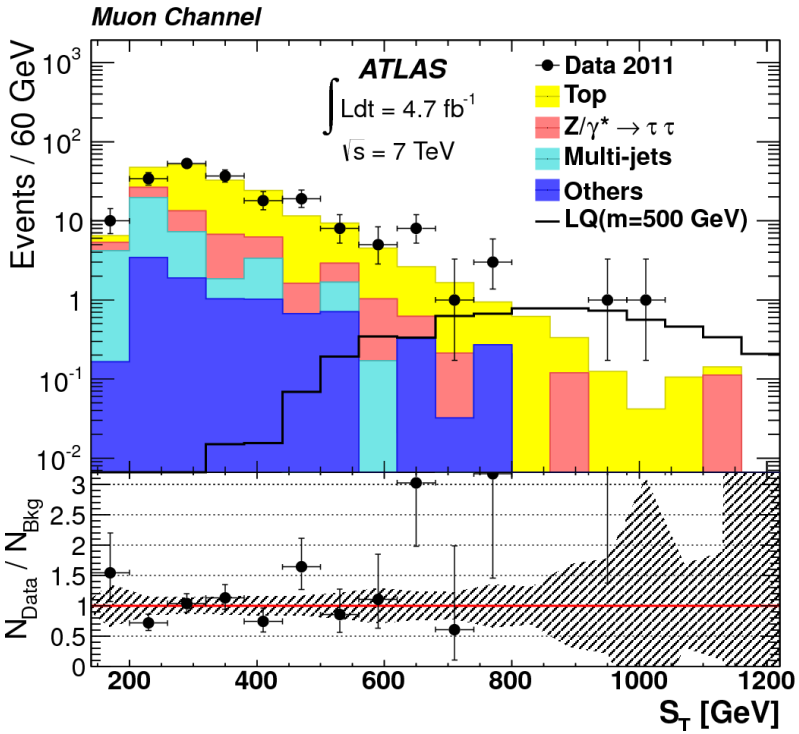
Search for 3rd generation scalar leptoquarks at $\sqrt{s}$ = 7 TeV

March 2013, JHEP 06 (2013) 033

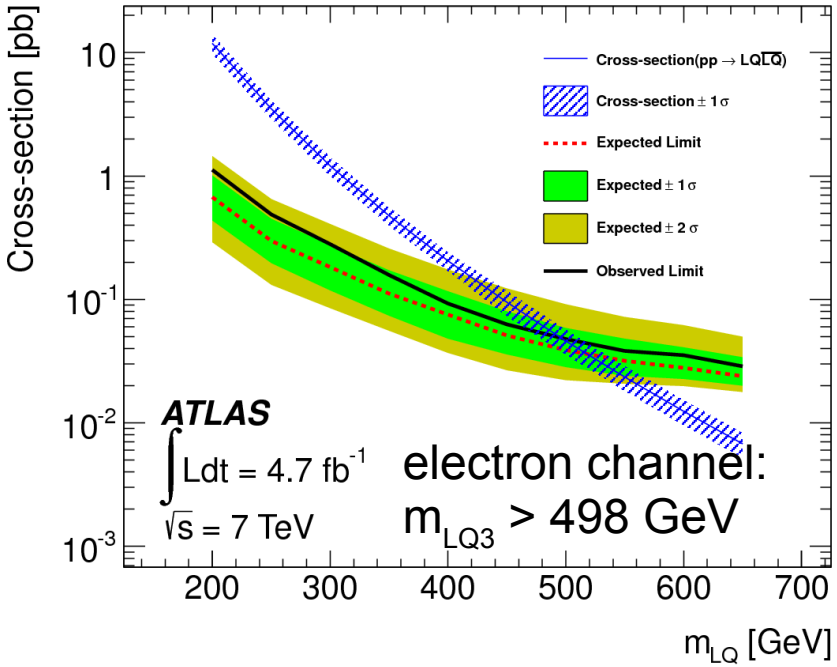
Search for third-generation scalar leptoquarks at $\sqrt{s}$ = 7 TeV

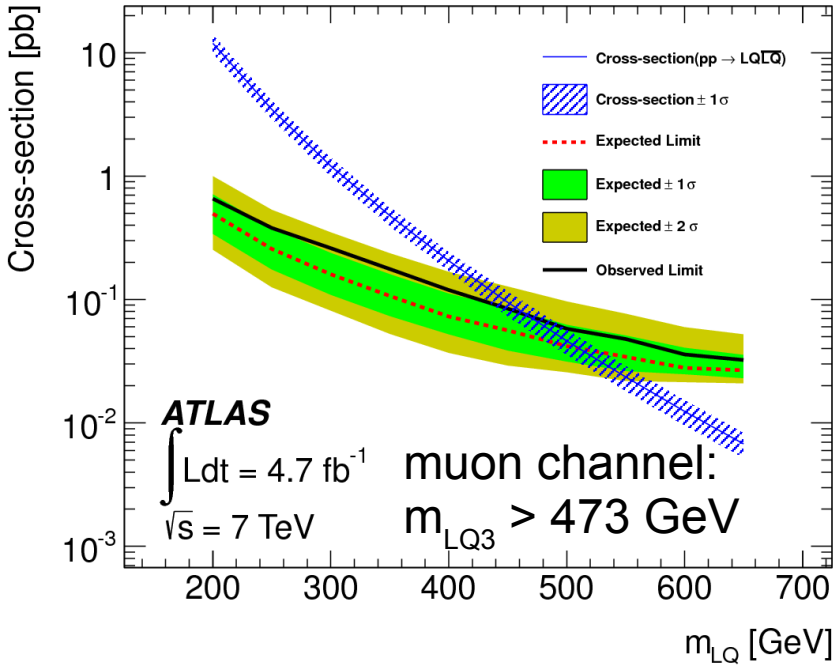
- Latest ATLAS search for pair-produced LQ3 → bτ
- Final states with one leptonic tau and one hadronic tau
  - Select events with exactly one **electron or muon**, exactly one **hadronic tau**, large **missing transverse momentum** and at least two jets, at least one of which is **b-tagged**
- Signal regions after event selection; binned log-likelihood ratio test vs. S_T
  - Background normalizations obtained in control regions





Search for third-generation scalar leptoquarks at $\sqrt{s}$ = 7 TeV





- No significant excess observed above background predictions
- Limits at 95% CL are set on the LQ3 cross-section, assuming 100% branching fraction of LQ3 → bτ