The LHC as Lepton–Proton Collider:

Searches for Resonant Production of Leptoquarks

Daniel Buchin

Max Planck Institute for Physics

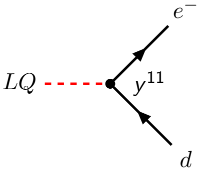
Monday 18th July, 2022

MAX-PLANCK-GESELLSCHAFT

Outline

- Leptoquarks
- Searches for Leptoquarks and what is special about this one
- Challenges in the signal generation
- First results on how our signal presents itself
- Strange quarks in protons

- Typically occur in Grand Unified Theories
- Can provide an appealing solution to observed flavour anomalies
- Couple simultaneously to leptons and quarks
  - $\rightarrow$ Carry both **colour** and **electric** charge
  - $\rightarrow$ **Baryon** and **lepton number** both non-zero
  - $\rightarrow$ Usually decay into a **lepton-quark pair**



A wide variety of candidates

- Scalar or vector boson
- Different electric charges possible
- Inter and intra-generation couplings y^{ij} allowed

LQ Models

- LQ models with fixed SM quantum numbers, e.g. scalar $\tilde{S}_1 = (\bar{\mathbf{3}}, \mathbf{1}, 4/3)$
- LQ model determines allowed decay modes
- Some searches do not specify LQ model $\rightarrow$ branching ratios (BRs) as search parameters

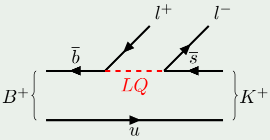
Leptoquarks in B-Physics

- LQs can resolve tensions in measurements of **lepton flavour universality**

R_K

$$R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)}$$

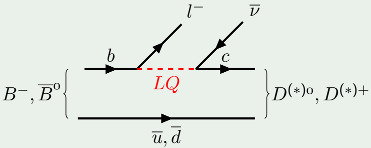
$> 3\ \sigma$ below SM prediction (arXiv:2103.11769)



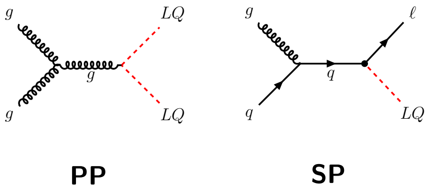
$\mathcal{R}(D)$

$$\mathcal{R}(D) = \frac{\mathcal{B}(B \to D \tau \nu_\tau)}{\mathcal{B}(B \to D l \nu_l)}$$

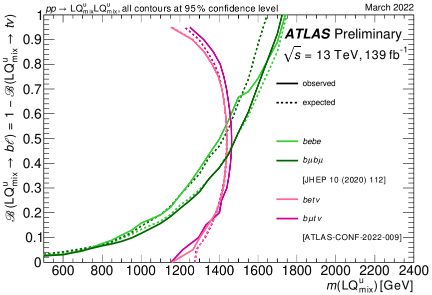
$> 3\ \sigma$ above SM prediction (arXiv:1711.02505)



- Main current search strategies consider **Pair Production (PP)** and **Single Production (SP)**
- PP independent of coupling strength y^{ij} (λ)
- Sensitive to LQ masses around 1-2 TeV

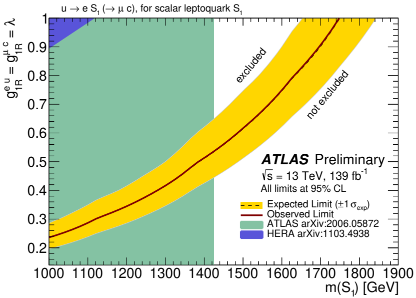


Generic up-type LQ for PP search



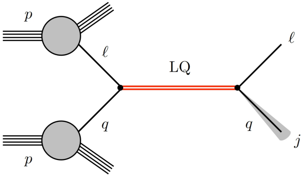
ATL-PHYS-PUB-2022-012

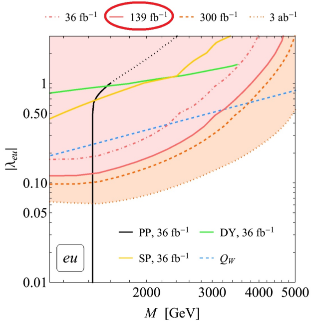
Specific LQ model for SP search



ATLAS-CONF-2021-045

- Production mode not yet probed at the LHC
- Novel approach: utilize lepton content of proton originating from quantum fluctuations
- **Lepton+Jet** final state not covered by existing ATLAS searches at Run 2





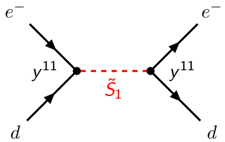
arXiv:2005.06475

- Production rate sensitive to both mass and coupling parameters

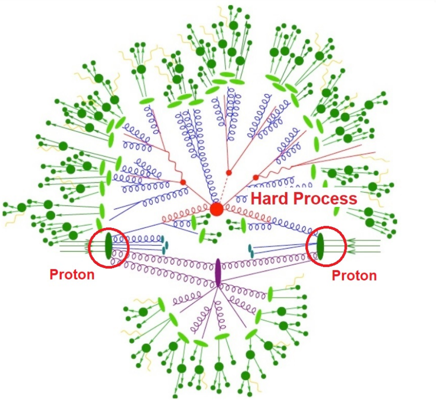
$\rightarrow$ Phenomenological studies suggest competitive sensitivity to existing PP and SP searches (arXiv:2005.06475, arXiv:2012.11474)

Signal Generation Studies

- Main challenge: limited support to lepton parton distribution functions (PDFs) in the common ATLAS event generation software
- **Private Event Generation** configuration necessary
- First step: simulation of the **hard process**
- For the resonant LQ production, e.g.:



→ Done using special version of the **MadGraph** software that supports leptons in the proton

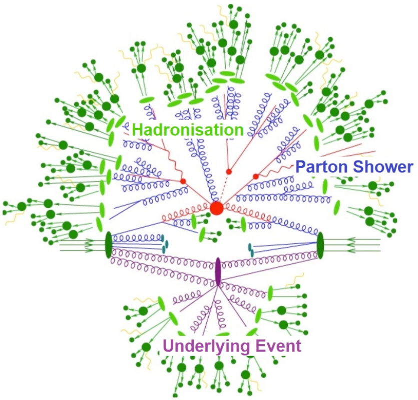


Sherpa Artist

Signal Generation Studies

- Next step: **parton showering**
- Includes hadronisation, simulation of the underlying event, ...

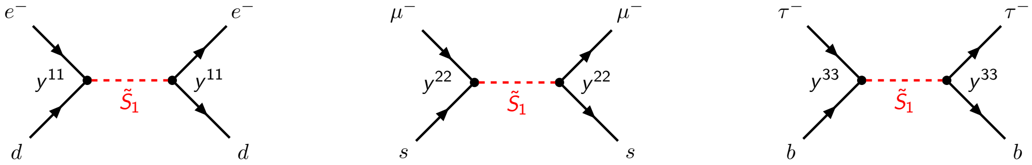
→ Done using official version of the **Pythia** software inside ATLAS framework
  - But: 'hack' needed, pretend that initial state leptons are photons
- Can be done alternatively using the **Herwig** software, no hack needed in newest versions!



Sherpa Artist

- To validate this generation setup, **key kinematic properties** of the LQ production are studied at the **particle level**
  - Simulated events in a state as 'right before entering the detector'

- Assume simple scalar LQ model: $\tilde{S}_1$ (charge -4/3, $SU(2)$ singlet)
  - One decay mode involving a **charged lepton** and a **down-type quark** (both right-handed)
- Assume only intra-generation couplings $\rightarrow$ three processes:



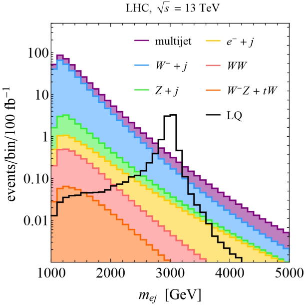
$\rightarrow$ Treat these three processes separately and optimize dedicated analyses

- **Invariant mass** of the lepton-jet system defined as:

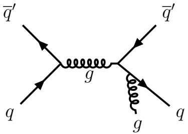
$$m_{\ell j}^2 = (E_\ell + E_j)^2 - \left(\overrightarrow{p_\ell} + \overrightarrow{p_j}\right)^2$$

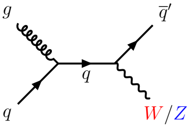
$\rightarrow$ Estimate of the LQ mass

- Sensitivity to LQ signal by performing **bump hunt** on $m_{\ell j}$ spectrum



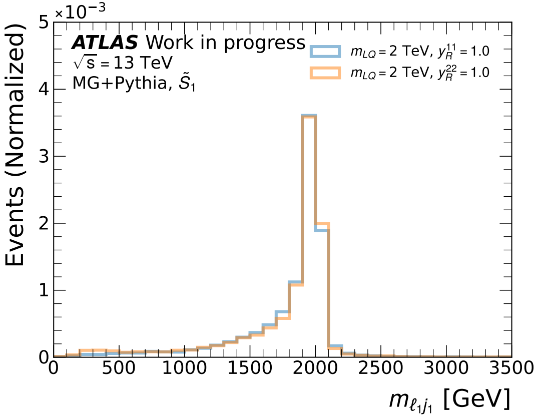
arXiv:2005.06475





- Dominant backgrounds:
  - Multijet
  - W + jet
  - Z + jet

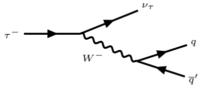
- Invariant Mass most important observable for this search
- Objects used for the definition in the 1st and 2nd generation:
  - **Leading (highest p_T) lepton** and **leading jet** of the event
  - → As expected: clear peak at the mass of the LQ resonance



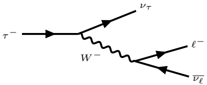
Invariant Mass of LQ Decay Products

- For couplings to 3rd generation:
  - **Leading hadronic tau** and **leading b-jet** of the event
  - → Peak is smeared as expected due to neutrino in the tau decay
- Possibility to use leading lepton instead of hadronic tau to get leptonic taus

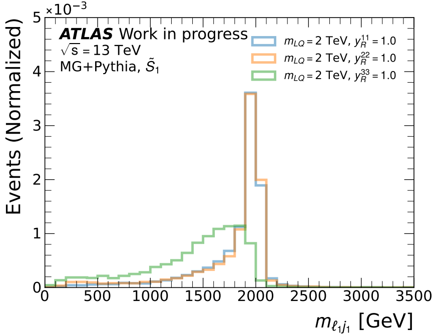
Hadronic Tau Decay



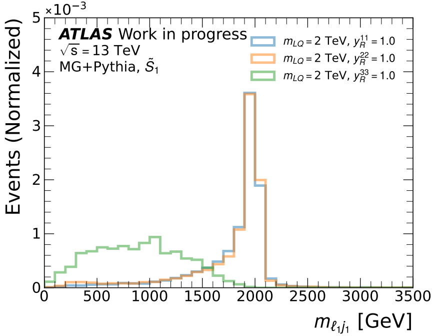
Leptonic Tau Decay



Hadronic Taus

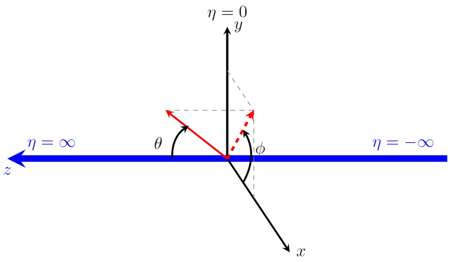


Leptonic Taus

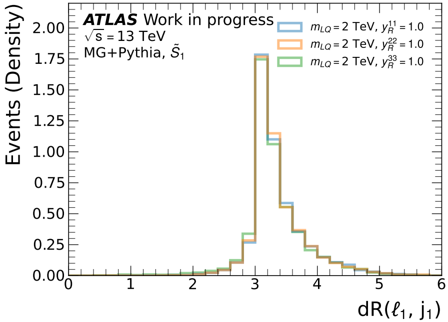


Angular Distance between Decay Products

ATLAS coordinate system



Different LQ generations



- Introducing the lorentz-invariant **pseudorapidity** $\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$
- Angular distance defined as:

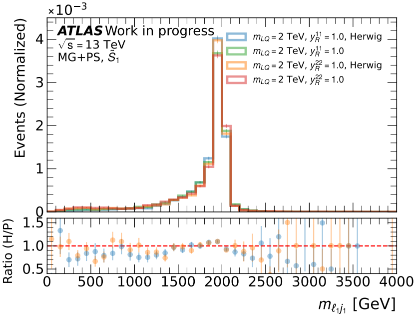
$$\mathrm{dR}(\ell_1, \mathrm{Jet}_1) = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

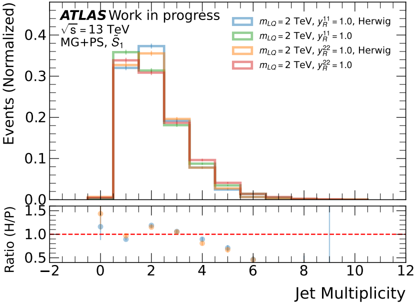
- Lepton and jet well separated, as expected

Herwig vs Pythia

- Observables behave as expected when Pythia used for parton showering, what about Herwig?

→ Open question in Herwig generation:
  - $\approx 30\ \%$ of events get discarded during simulation
  - 'Physical' consequences? → check observables!





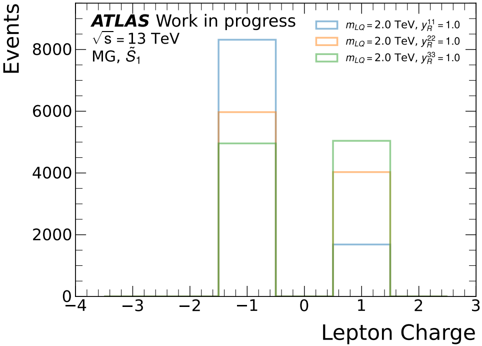
- Sharper peak in m_{lj} with Herwig, differences in jet multiplicity
  - Due to event loss in Herwig?

Charge Asymmetry

- One observable showed surprising behaviour though

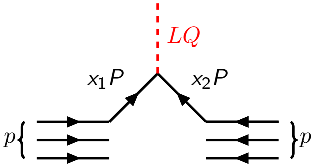
→ Lepton charge, i.e. occurrence of LQs vs Anti-LQs, is **asymmetric in 2nd generation**

- Asymmetry in 1st generation expected due to valence *d*-quark in initial state, no asymmetries expected in other generations due to sea-quarks in initial state

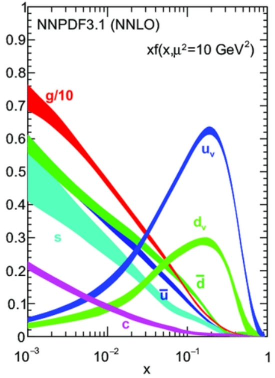


Intermezzo: PDFs

- Short reminder: PDFs describe the probability $f(x, Q^2)$ that a certain parton of the proton
  - carries a certain fraction x of the proton momentum
  - at a certain scale Q (e.g. the LQ mass in this case)



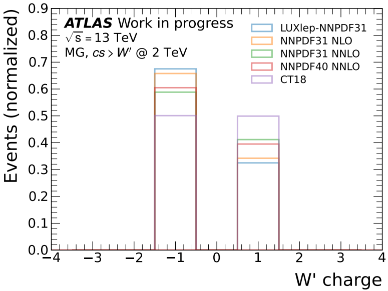
$\rightarrow$ **Parametrisation of the proton structure**

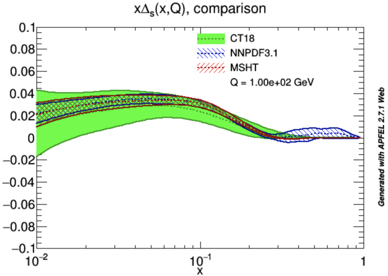


- Different, independent implementations of PDFs available to be used in simulations of *pp* collisions, e.g. by the NNPDF collaboration
- Special and at the moment unique implementation that includes lepton PDFs was used for this study (**LUXlep-NNPDF31-NLO**)

Strange Quarks in the Proton

- Change to the resonant production of W' which does not need initial state leptons $\rightarrow$ cross check with different PDF implementations
- Look at how often $\bar{c}s > W'^- > \bar{c}s$ occurs compared to $c\bar{s} > W'^+ > c\bar{s}$ with different PDF sets





- NNPDF sets predict significant strange/anti-strange asymmetry in proton for high x and Q

$\rightarrow$ Expected behaviour! (at least for LUXlep)

Conclusion

- First study of the Leptoquark resonant production at the LHC
- Event generation involving lepton PDFs requires a special setup
- Setup validation through the studies of kinematic properties at particle level
  - $\rightarrow$ Distributions of key observables behave as expected
- Next steps:
  - Develop and optimize analysis using signal samples with simulated detector response:
    - $\rightarrow$ Estimate sensitivity to these signals via a "bump-hunt" on the m_{lj} spectrum
  - Possible extension to more LQ models, e.g. vector LQs
    - $\rightarrow$ and final states, i.e. $e/\mu/\tau$ x light jet/c-jet/b-jet

BACKUP

All Leptoquarks

- Arrange different LQs w.r.t. their SM quantum numbers
- Six multiplets for scalar and vector LQs, respectively
- Chirality of interacting fermions depends on the spin and $SU(2)$ multiplet of the LQ

$(SU(3), SU(2), U(1))$	Spin	Symbol	Type	F
$(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	0	S_3	$LL\,(S_1^L)$	-2
$(\mathbf{3}, \mathbf{2}, 7/6)$	0	R_2	$RL\,(S_{1/2}^L)$, $LR\,(S_{1/2}^R)$	0
$(\mathbf{3}, \mathbf{2}, 1/6)$	0	$\tilde{R}_2$	$RL\,(\tilde{S}_{1/2}^L)$, $\overline{LR}\,(\tilde{S}_{1/2}^L)$	0
$(\bar{\mathbf{3}}, \mathbf{1}, 4/3)$	0	$\tilde{S}_1$	$RR\,(\tilde{S}_0^R)$	-2
$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	0	S_1	$LL\,(S_0^L)$, $RR\,(S_0^R)$, $\overline{RR}\,(S_0^{\overline{R}})$	-2
$(\bar{\mathbf{3}}, \mathbf{1}, -2/3)$	0	$\bar{S}_1$	$\overline{RR}\,(\bar{S}_0^R)$	-2
$(\mathbf{3}, \mathbf{3}, 2/3)$	1	U_3	$LL\,(V_1^L)$	0
$(\bar{\mathbf{3}}, \mathbf{2}, 5/6)$	1	V_2	$RL\,(V_{1/2}^L)$, $LR\,(V_{1/2}^R)$	-2
$(\bar{\mathbf{3}}, \mathbf{2}, -1/6)$	1	$\tilde{V}_2$	$RL\,(\tilde{V}_{1/2}^L)$, $\overline{LR}\,(\tilde{V}_{1/2}^R)$	-2
$(\mathbf{3}, \mathbf{1}, 5/3)$	1	$\tilde{U}_1$	$RR\,(\tilde{V}_0^R)$	0
$(\mathbf{3}, \mathbf{1}, 2/3)$	1	U_1	$LL\,(V_0^L)$, $RR\,(V_0^R)$, $\overline{RR}\,(V_0^{\overline{R}})$	0
$(\mathbf{3}, \mathbf{1}, -1/3)$	1	$\bar{U}_1$	$\overline{RR}\,(\bar{V}_0^R)$	0

arXiv:1603.04993

LQ Candidates in B–Physics

- Only certain LQs have the proper interaction terms to explain observed tensions in B meson decays

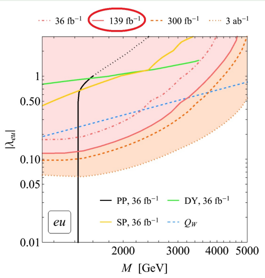
Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
S_1	✗*	✓	✗*
R_2	✗*	✓	✗
$\widetilde{R}_2$	✗	✗	✗
S_3	✓	✗	✗
U_1	✓	✓	✓
U_3	✓	✗	✗

arXiv:1808.08179

Phenomenological papers on resonant LQ production:

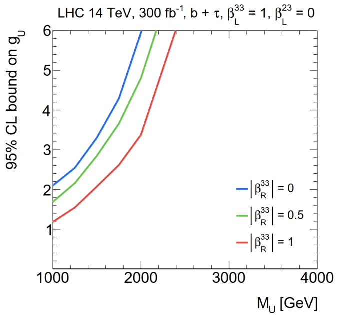
arXiv:2005.06475

- Targets scalar LQs with right-handed couplings
- Two different final states: *eu* and *ed* (1st/2nd generation)



arXiv:2012.11474

- Targets vector LQ model: $U_1 = (\mathbf{3}, \mathbf{1}, 2/3)$
- Mainly 3rd generation final states ($b_L\tau_L$, $b_R\tau_R$ and $\nu_{\tau L} t_L$)



Signal Generation Studies

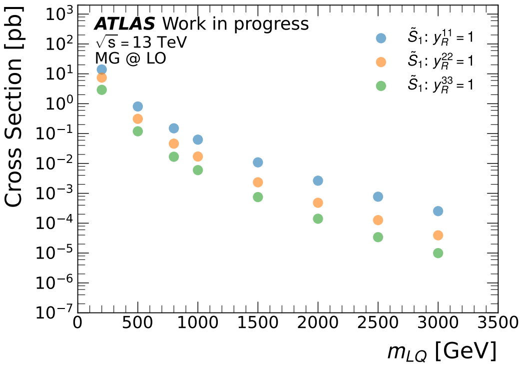
- **Private MadGraph + Pythia** configuration necessary:
  - Hard Process event generation with dedicated MadGraph version that gives access to leptons in the proton
  - Proton **PDF including leptons** needed
  - Parton showering done using official Pythia version, but:
    - Some "hacks" needed, i.e. **replace initial state leptons** with photons in the input LHE file

    $\rightarrow$ Disable event check to circumvent charge conservation check

MadGraph $\rightarrow$ LHE file $\xrightarrow{\text{'hacks'}}$ Pythia $\rightarrow$ Particle Level Events

- To validate this generation setup, **key kinematic properties** of the LQ production are studied at the particle (truth) level

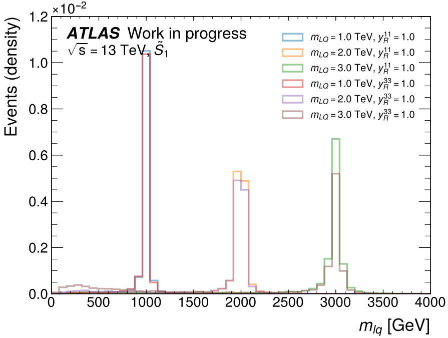
Cross Section for the Resonant Production



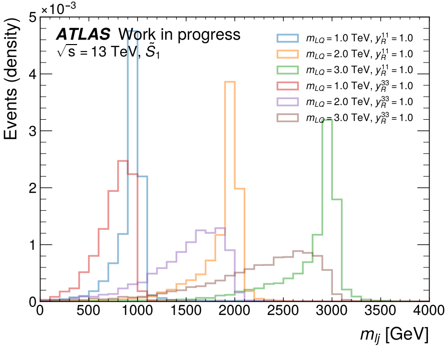
- Leading Order (LO) cross sections calculated using MadGraph
- Verified that values are compatible with cross sections used by authors of phenomenological paper
- 2nd and 3rd generation suppressed due to suppressed s- and b-quark content of the proton

Invariant Masses: LHE vs Particle level

- 1st generation: leading lepton and leading jet
- For 3rd generation: leading tau and leading b-jet



Before parton showering

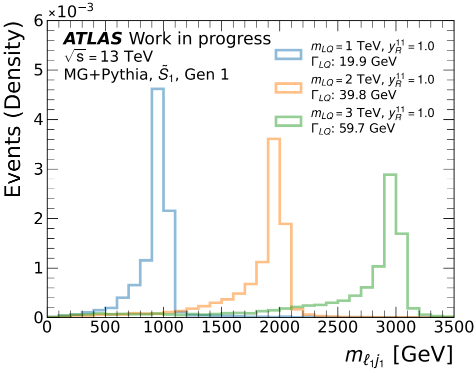


After parton showering

Invariant Mass of LQ Decay Products

- Distributions smeared at high masses due to LQ decay width Γ_{LQ}

Different LQ masses



Scalar LQ Decay Width

$$\Gamma_{\tilde{S}_1} \simeq \frac{1}{16\pi} \sum_{ij} |y^{ij}|^2 m_{\tilde{S}_1}$$

Effect of bwcutoff parameter in MadGraph

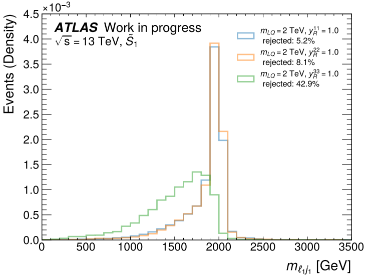
- MG's bwcutoff parameter (default: 15) steers if an intermediate particle counts as on-shell:

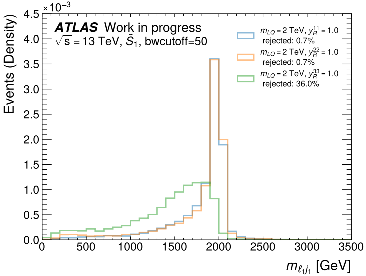
$$\mathrm{m}_{LQ} - \mathit{bwcutoff} \cdot \Gamma_{LQ} \leq \mathrm{m}_{\ell j} \leq \mathrm{m}_{LQ} + \mathit{bwcutoff} \cdot \Gamma_{LQ}$$

- Only on-shell particles appear in LHE file → important for truth studies (e.g. MCTruthClassifier doesn't label leptons from off-shell LQs as prompt)
- Noticed that fraction of events with no explicit LQ in LHE relatively large in 3rd gen (11 % at 2 TeV)
- Can mitigate this by increasing bwcutoff to 50 → didn't observe notable changes in distributions

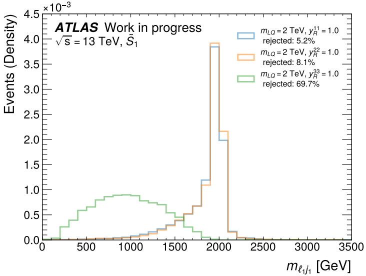
Effect of bwcutoff parameter in MadGraph

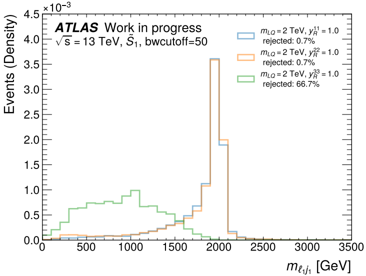
Invariant mass of leading tau and leading b-jet for 3rd gen.





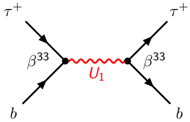
Invariant mass of leading lepton and leading jet for 3rd gen.

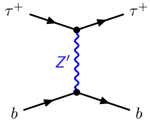




Outlook: Vector Leptoquarks

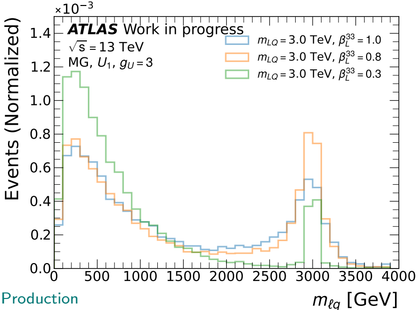
- Vector $U_1 = (\mathbf{3}, \mathbf{1}, 2/3)$ model able to **resolve tensions** in both R_K and $\mathcal{R}(D)$ measurements
- Complications:
  - More decay modes (up-type quark + neutrino, chirality sensitive $\rightarrow$ separate β_L, β_R)
  - Vector LQ models require additional vector bosons G' and Z'
  - $\rightarrow$ Additional t-channel diagram with Z'
  - Width-to-mass ratio > 10 % for larger couplings





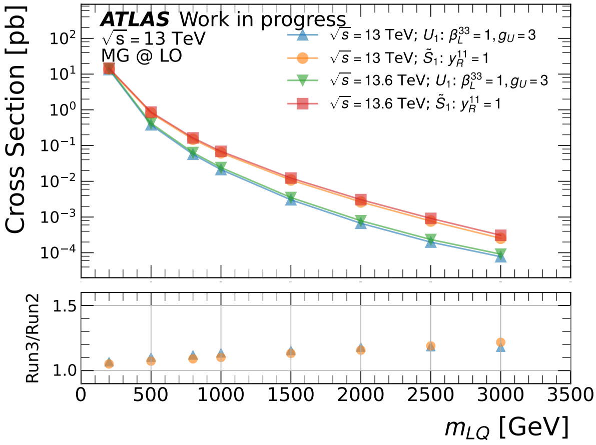
Vector LQ Decay Width

$$\Gamma(U_1 \rightarrow \tau^+ b) \simeq \frac{g_U^2}{48\pi} \sum_{ij} \left(|\beta_L^{ij}|^2 + |\beta_R^{ij}|^2 \right) m_{U_1}$$



Outlook: LHC Run 3

- LHC Run 3 with higher $\sqrt{s} = 13.6$ TeV (Run 2: $\sqrt{s} = 13$ TeV)
- 15-20% higher cross sections for LQ masses between 2-3 TeV
- Including early Run 3 data potentially interesting for this search

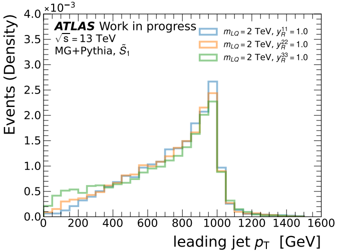


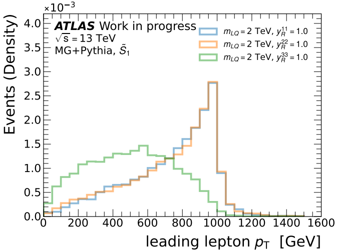
Requirements in SimpleAnalysis

- Parton showered events are analysed using SimpleAnalysis software framework
- Applied kinematic requirements on truth objects to mimic acceptance at reconstruction-level:
  - Jets: $p_{\mathrm{T}} > 20$ GeV, $\eta < 2.8$
  - Electrons: $p_{\mathrm{T}} > 10$ GeV, $\eta < 2.47$
  - Muons: $p_{\mathrm{T}} > 10$ GeV, $\eta < 2.7$
  - Taus: $p_{\mathrm{T}} > 20$ GeV, $\eta < 2.5$
  - OR of jets within $\Delta R < 0.4$ of a lepton and electrons within $\Delta R < 0.01$ of a muon

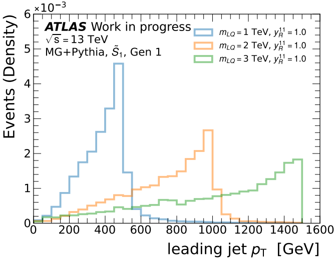
Kinematic Distributions

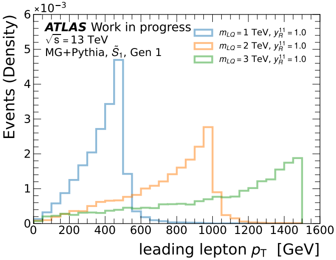
Different LQ generations



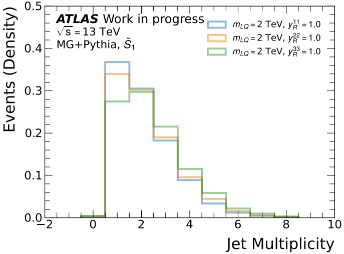


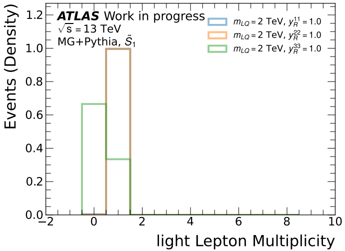
Different LQ masses

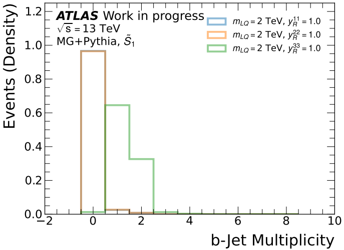


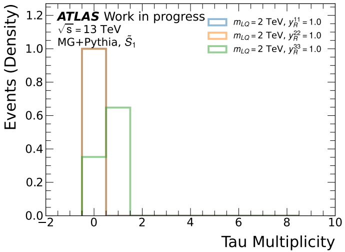


- **As expected**, p_T peak and cutoff at $m_{LQ}/2$
- Tau p_T smeared due to neutrino from the decay



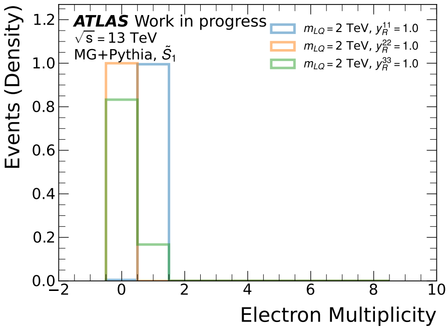


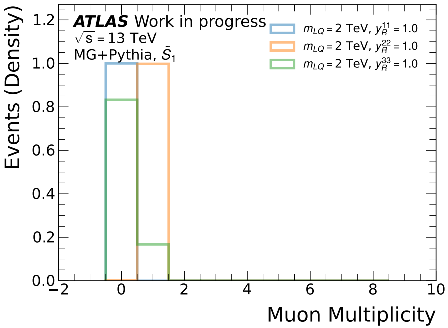


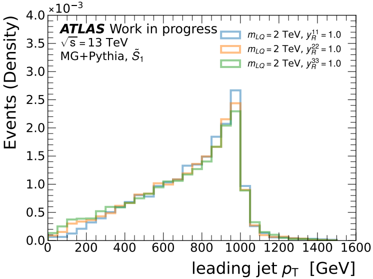


- Multiplicities behave as expected; high occurrence of 2nd b-jets in 3rd generation case still being studied

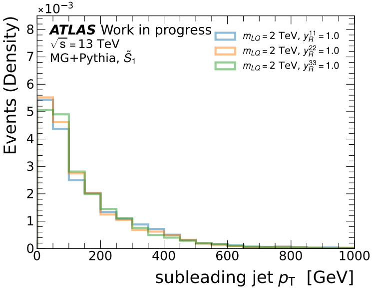
Lepton Multiplicities



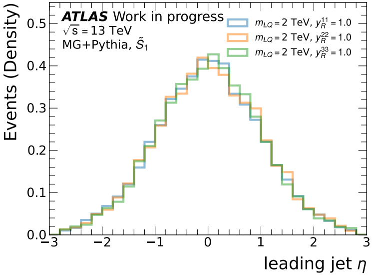




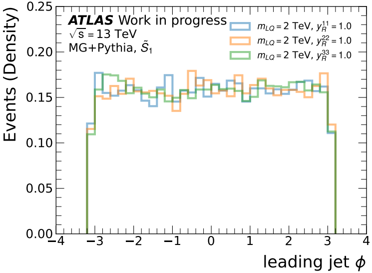
×10⁻³
ATLAS Work in progress
√s = 13 TeV
MG+Pythia, S̃₁
m_LQ = 2 TeV, y_R^11 = 1.0
m_LQ = 2 TeV, y_R^22 = 1.0
m_LQ = 2 TeV, y_R^33 = 1.0
Events (Density)
leading jet p_T [GeV]



×10⁻³
ATLAS Work in progress
√s = 13 TeV
MG+Pythia, S̃₁
m_LQ = 2 TeV, y_R^11 = 1.0
m_LQ = 2 TeV, y_R^22 = 1.0
m_LQ = 2 TeV, y_R^33 = 1.0
Events (Density)
subleading jet p_T [GeV]

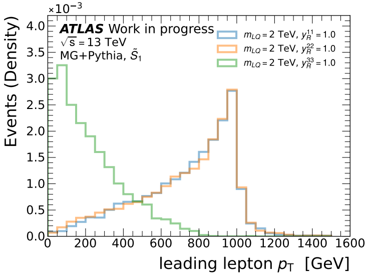


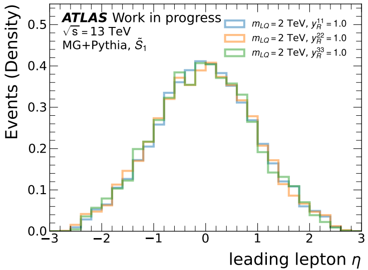
ATLAS Work in progress
√s = 13 TeV
MG+Pythia, S̃₁
m_LQ = 2 TeV, y_R^11 = 1.0
m_LQ = 2 TeV, y_R^22 = 1.0
m_LQ = 2 TeV, y_R^33 = 1.0
Events (Density)
leading jet η

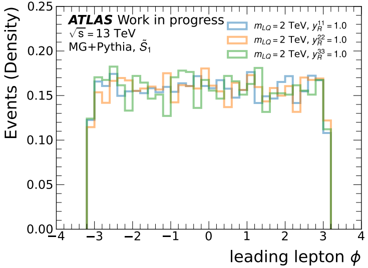


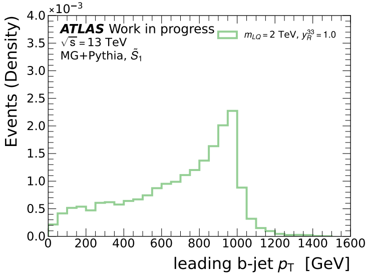
ATLAS Work in progress
√s = 13 TeV
MG+Pythia, S̃₁
m_LQ = 2 TeV, y_R^11 = 1.0
m_LQ = 2 TeV, y_R^22 = 1.0
m_LQ = 2 TeV, y_R^33 = 1.0
Events (Density)
leading jet ϕ

Kinematic Distributions

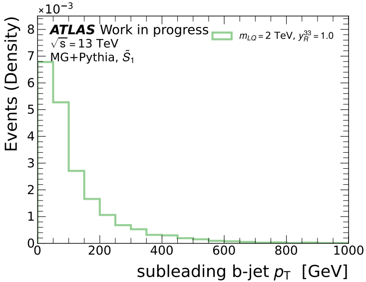




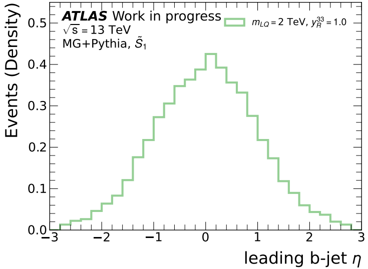




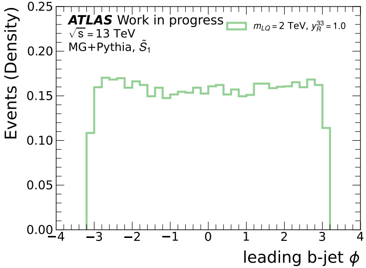
ATLAS Work in progress
$\sqrt{s} = 13$ TeV
MG+Pythia, $\tilde{S}_1$
$m_{LQ} = 2$ TeV, $y_R^{33} = 1.0$
Events (Density)
$\times 10^{-3}$
leading b-jet p_T [GeV]



ATLAS Work in progress
$\sqrt{s} = 13$ TeV
MG+Pythia, $\tilde{S}_1$
$m_{LQ} = 2$ TeV, $y_R^{33} = 1.0$
Events (Density)
$\times 10^{-3}$
subleading b-jet p_T [GeV]



ATLAS Work in progress
$\sqrt{s} = 13$ TeV
MG+Pythia, $\tilde{S}_1$
$m_{LQ} = 2$ TeV, $y_R^{33} = 1.0$
Events (Density)
leading b-jet η



ATLAS Work in progress
$\sqrt{s} = 13$ TeV
MG+Pythia, $\tilde{S}_1$
$m_{LQ} = 2$ TeV, $y_R^{33} = 1.0$
Events (Density)
leading b-jet ϕ

Kinematic Distributions