The LHC as a Lepton-Proton Collider: Search for Resonant Production of Leptoquarks

Daniel Buchin supervised by Michael Holzbock

Max Planck Institute for Physics

DPG Spring Meeting 2023

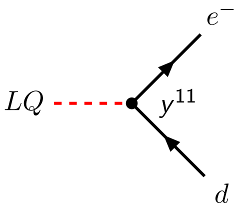
Tuesday 21st March, 2023

FSP ATLAS
Erforschung von Universum und Materie

MAX-PLANCK-GESELLSCHAFT

Leptoquarks

- Theoretically motivated by e.g. Grand Unified Theories
- Appealing solution to observed flavour anomalies in e.g. B-factories
- Couple simultaneously to a lepton and a quark
  - → Carry both **colour** and **electric** charge
  - → Typically decay into a **lepton-quark pair**

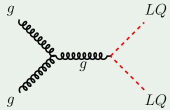


A wide variety of candidates

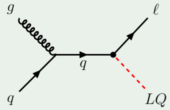
- Scalar or vector boson
- Different electric charges possible
- Couplings y^{ij} to any combination of fermion generations allowed

Existing Searches at the LHC

- Pair Production (PP)

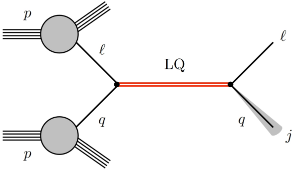


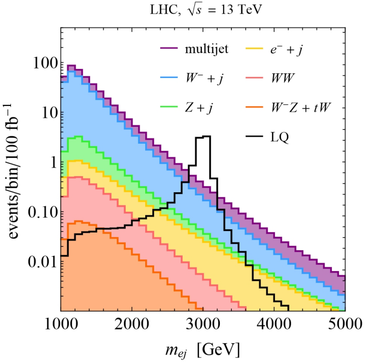
- Single Production (SP)



Resonant Leptoquark Production

- Production mode **not yet probed** at the LHC
- Novel approach: utilize lepton content of proton originating from quantum fluctuations
- Production rate sensitive to both mass and fermion coupling





[Buonocore, Haisch, Nason, Tramontano & Zanderighi, PRL 125 (2020) 23]

- **Lepton PDF** recently made available → possibility to study this production mode at the LHC

  [Buonocore, Nason, Tramontano & Zanderighi, JHEP 08 (2020) 019]

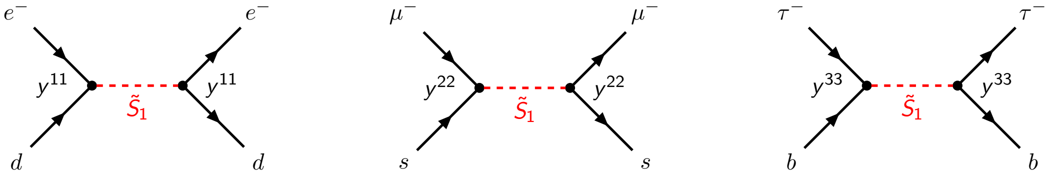
- Phenomenological studies motivate searching for this production mode

  [Buonocore, Haisch, Nason, Tramontano & Zanderighi, PRL 125 (2020) 23]
  [Haisch & Polesello, JHEP 05 (2021) 057]

  → **Competitive** to existing searches
  → Clear signature in **invariant mass of lepton+jet system**

Signal Model

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



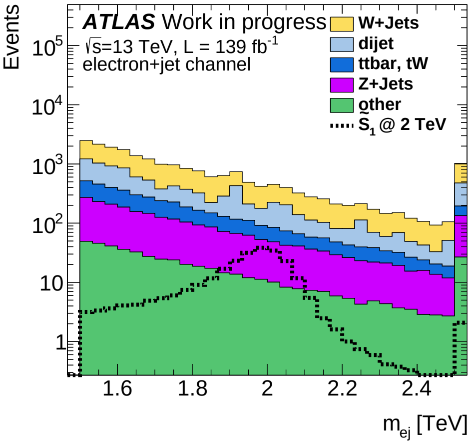
- Generation of resonantly produced LQs requires special setup and workflow (inspired by the phenomenological studies)
- Current LO setup produces **consistent results** as suggested by phenomenologists
  - → Migration to state-of-the-art NLO event generation in progress

[Buonocore, Greljo, Krack et al., JHEP 129 (2022)]

Event Selection

- Produced first set of samples with detailed ATLAS detector simulation of the mentioned signal model
- Main focus on 1st and 2nd generation at the moment → **electron/muon+light-jet** topology
- Preselection to focus on lepton + jet signature:
  - Exactly one electron/muon with $p_T > 25$ GeV
  - At least one jet with $p_T > 100$ GeV
- Calculate m_{lj} using the leading jet (i.e. jet with highest p_T)

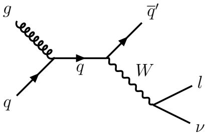
Electron+Jet channel



Dominating SM processes that might be reconstructed as a lepton + jet signature:

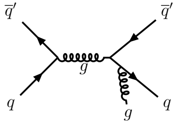
W + jet(s)

→ Same visible final state



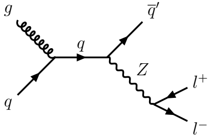
Multijet

→ One jet is misidentified as a lepton



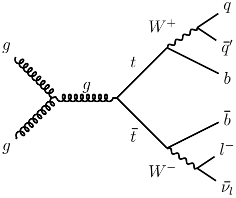
Z + jet(s)

→ Miss one lepton in the reconstruction



ttbar

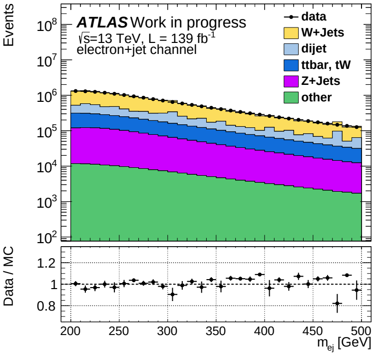
→ Veto of *b*-jets not fully efficient



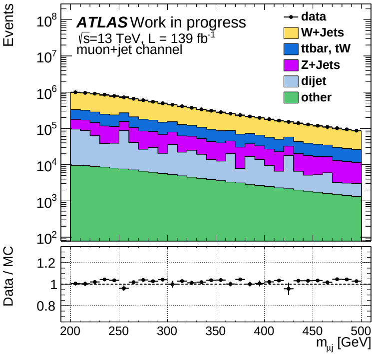
MC vs Data at Low Lepton-Jet Invariant Masses

- Validate modelling of MC-simulated backgrounds w.r.t. actual Run 2 data
- Look in a region expected to be devoid of any LQ signal
  - → Low $m_{\ell j}$ regime may serve to develop **background estimation** strategy
  - → Considered background MC in **good agreement** with data
  - → Sufficiently well modelled for preliminary optimisation of signal selection criteria

Electron+Jet channel



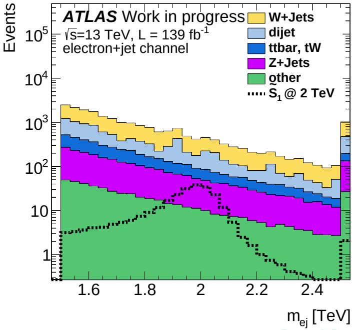
Muon+Jet channel



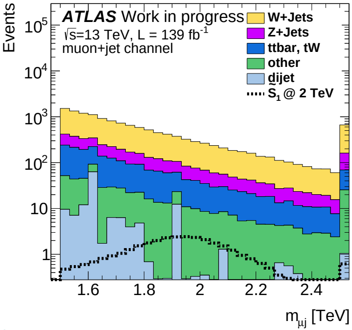
Signal and Background MC at High Masses

- Now looking into potentially signal-rich region $m_{\ell j} > 1.5$ TeV and comparing signal and background distribution
- Less signal sensitivity in the muon+jet channel:
  - → Smaller cross-section for 2nd generation couplings (2.6 fb vs. 0.48 fb)
  - → $m_{\ell j}$ distribution much **wider in the muon+jet channel** → low muon p_{T} resolution of ≈ 10 % at high-p_{T} caused by the limitations of the muon spectrometer

Electron+Jet channel

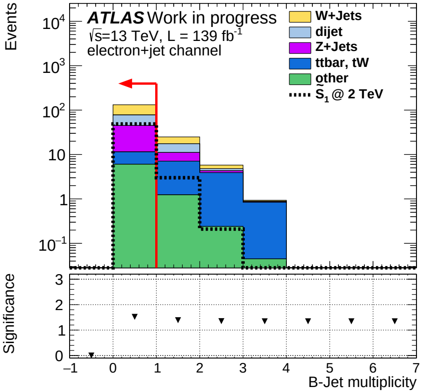


Muon+Jet channel

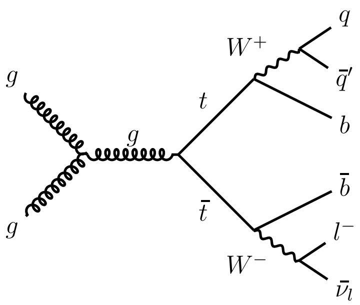


Signal Region Optimization

- First studies of a signal selection optimisation in the **electron+jet channel**
- Signal significance in bottom panel serves as a figure of merit
- One promising selection cut vetoes any jets that have been identified as originating from a *b*-quark, mainly affecting ttbar:

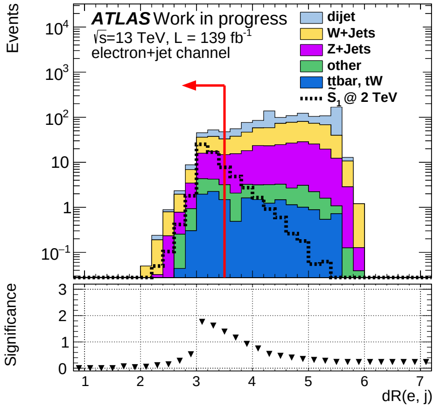


ttbar

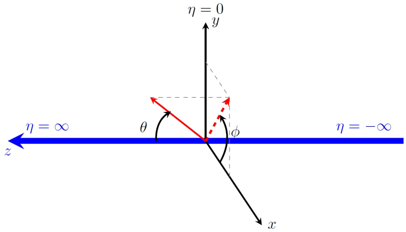


Signal Region Optimization

- Another cut exploits the shape difference in the distribution of **angular distance** between a lepton and a jet
- Lepton + jet in SM backgrounds rarely share parent particle → broader distribution of angular distance



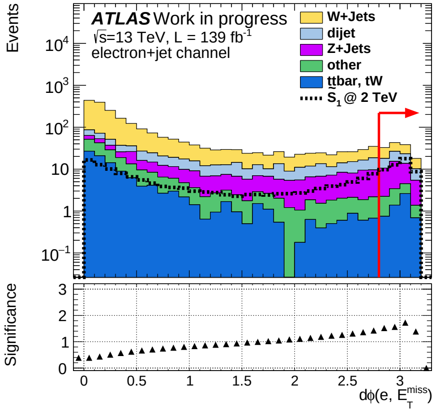
ATLAS coordinate system

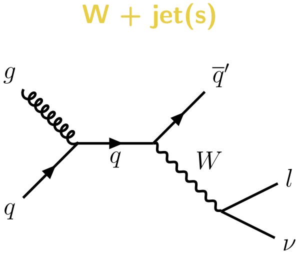


Angular distance

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

- Lower cut on $d\phi(\ell, E_T^{miss})$ to exploit alignment of lepton and neutrino (i.e. E_T^{miss}) in W+jets

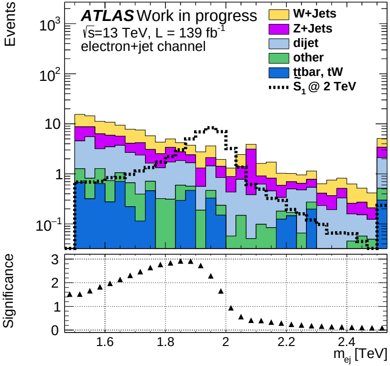




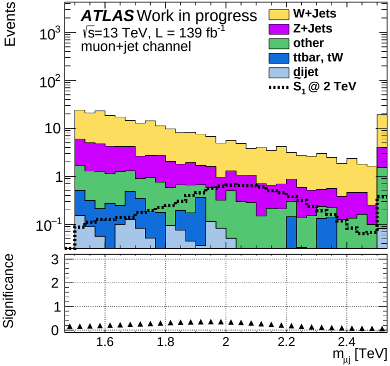
Preliminary Optimized Signal Region

- Invariant mass distribution after the three proposed cuts
- **High significances expected** in electron+jet channel
  - → Exclusion at 95 % CL can be reached for the used signal model with full Run 2 ATLAS data
- Still little sensitivity in muon+jet channel, dedicated optimisation in progress

Electron+Jet channel



Muon+Jet channel



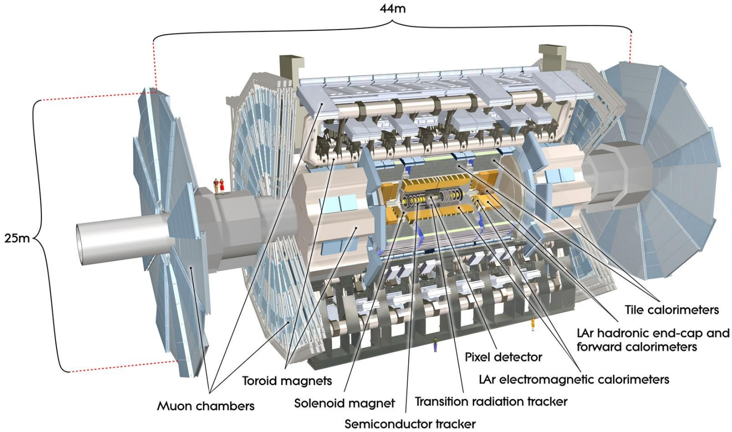
Summary & Future Plans

- First study of the Leptoquark resonant production at the LHC
- Will be using Run 2 as well as early Run 3 data (2022/23)
- Signal generation requires special setup including lepton PDFs
  - Ongoing efforts in collaboration with the theorists to refine this setup
- Promising sensitivity prospects after preliminary signal optimization in the electron channel
- Next step: develop analysis strategy sensitive to a larger range of LQ masses

BACKUP

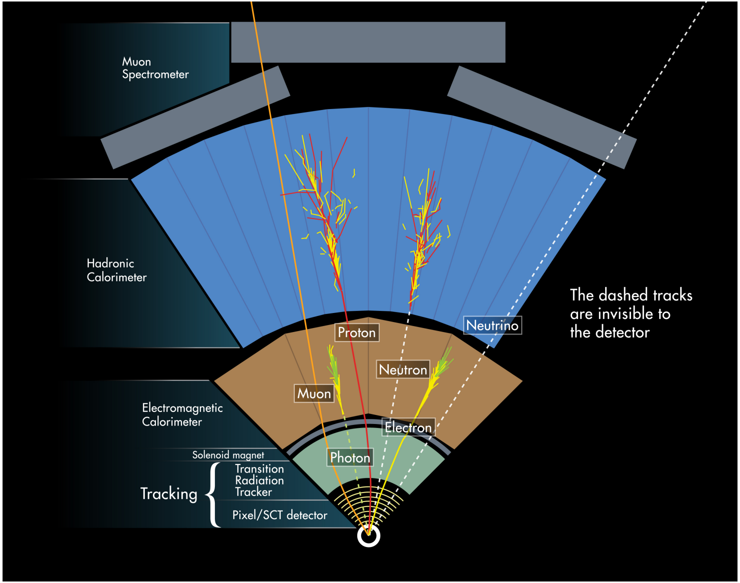
ATLAS detector

- General-purpose particle detector at the Large Hadron Collider (LHC)
- Records products of proton-proton collisions
- Standard Model (SM) precision measurements, searches for physics beyond the SM



CERN PhotoLab

ATLAS detector

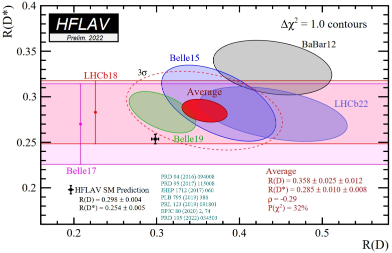


CERN PhotoLab

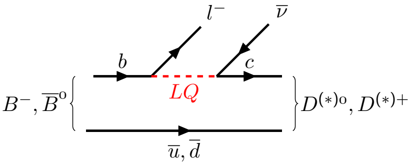
- Multiple experiments have shown tensions to the SM in measurements of **lepton flavour universality (LFU)**
- LHCb recently announced new results of the measurement of the $\mathcal{R}(D^{(*)})$ observable, probing LFU:

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

→ Current global average: 3.2 σ above SM prediction, clear hint towards lepton flavour violation in B decays

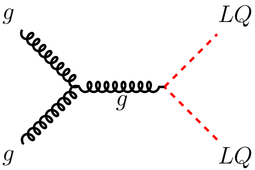


LHC Seminar

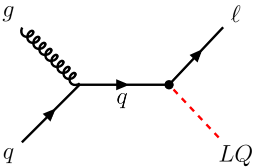


- Leptoquarks could explain such a violation through additional diagrams

- Main current search strategies consider **Pair Production (PP)** and **Single Production (SP)** of Leptoquarks
- PP only sensitive to LQ mass, SP also to coupling to fermions



PP



SP

Existing Leptoquark Searches at the LHC

ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: July 2022

ATLAS Preliminary

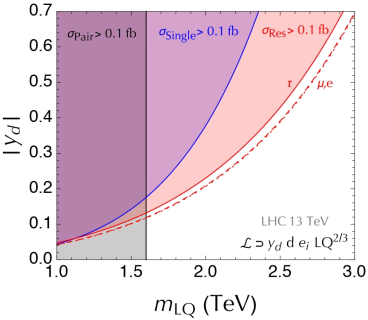
$\int \mathcal{L}\, dt = (3.6 - 139)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Limit			Reference
LQ	Scalar LQ 1st gen	$2\ e$	≥ 2 j	Yes	139	LQ mass	1.8 TeV	$\beta = 1$	2006.05872
	Scalar LQ 2nd gen	$2\ \mu$	≥ 2 j	Yes	139	LQ mass	1.7 TeV	$\beta = 1$	2006.05872
	Scalar LQ 3rd gen	$1\ \tau$	2 b	Yes	139	LQ_3^u mass	1.2 TeV	$\mathcal{B}(\mathrm{LQ}_3^u \to b\tau) = 1$	2108.07665
	Scalar LQ 3rd gen	$0\ e, \mu$	≥ 2 j, ≥ 2 b	Yes	139	LQ_3^u mass	1.24 TeV	$\mathcal{B}(\mathrm{LQ}_3^u \to t\nu) = 1$	2004.14060
	Scalar LQ 3rd gen	$\geq 2\ e, \mu, \geq 1\ \tau$	≥ 1 j, ≥ 1 b	–	139	LQ_3^d mass	1.43 TeV	$\mathcal{B}(\mathrm{LQ}_3^d \to t\tau) = 1$	2101.11582
	Scalar LQ 3rd gen	$0\ e, \mu, \geq 1\ \tau$	$0-2$ j, 2 b	Yes	139	LQ_3^d mass	1.26 TeV	$\mathcal{B}(\mathrm{LQ}_3^d \to b\nu) = 1$	2101.12527
	Vector LQ 3rd gen	$1\ \tau$	2 b	Yes	139	LQ_3^V mass	1.77 TeV	$\mathcal{B}(\mathrm{LQ}_3^V \to b\tau) = 0.5$, Y-M coupl.	2108.07665

ATL-PHYS-PUB-2022-034

→ Existing searches currently sensitive to Leptoquark masses around 1-2 TeV

Resonant Production of Leptoquarks

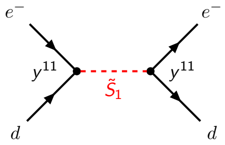


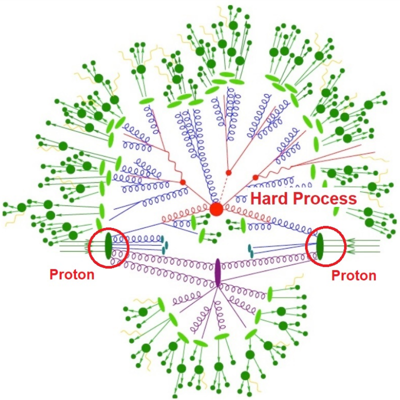
[Greljo & Selimovic, JHEP 03 (2021) 279]

- Even though lepton content in proton suppressed:
  - At high LQ masses, PP cross-sections more suppressed
  - Larger phase space leads to consistently larger cross-sections than for the SP mode

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.:





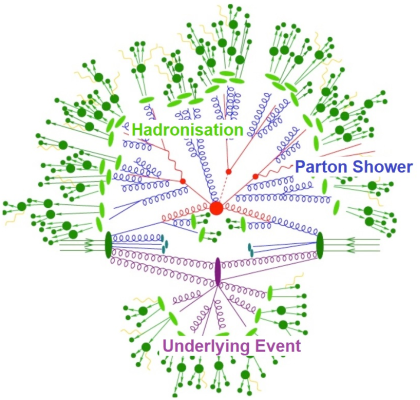
Sherpa Artist

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

- 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!

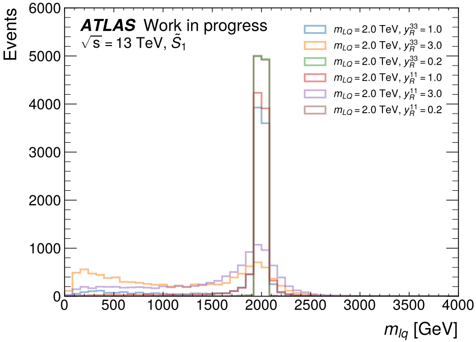


Sherpa Artist

- 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'

'Parton-Luminosity Tail'

- Invariant mass of multi-TeV LQs shows surprisingly long low-mass tail
- Mentioned as 'Parton-Luminosity Tail' in previous ATLAS searches for e.g. high-mass Z' or W' resonances
- Explanation: Interplay of low PDF values at the needed high bjorken x and high decay widths of the resonances
- More prominent in 3rd gen due to smaller b-quark PDFs at high bjorken x



LQ Decay Width

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

Technical Details

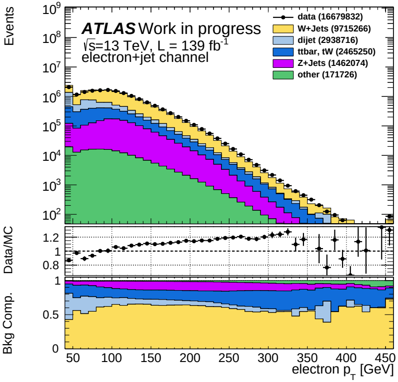
- Set up analysis framework based on xAODAnaHelpers
- Using PHYS derivations (p5001/p5002)
- Current object selection mostly defaults → to be optimized
- All studies currently based on R21 (moving to R22 now)
- Main focus at the moment: el/μ+light-jet topology
- Current skimming in framework:
  - Exactly one e/mu with $p_{\mathrm{T}} > 25$ GeV
  - At least one jet with $p_{\mathrm{T}} > 100$ GeV
  - Logical OR of lowest unprescaled single-lepton and single jet triggers

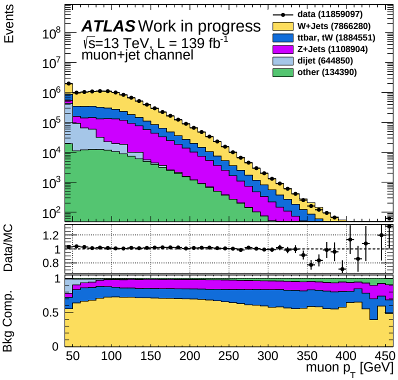
Object Definitions

Property	Requirement
Electrons	
Kinematic	$p_T > 25$ GeV, $\|\eta\| < 2.47$
Identification	TightLLH
Isolation	HighPtCaloOnly
Impact parameter	$\|d_0/\sigma(d_0)\| < 5$, $\|z_0 \sin\theta\| < 0.5$ mm
Muons	
Kinematic	$p_T > 25$ GeV, $\|\eta\| < 2.5$
Identification	HighPt
Isolation	HighPtTrackOnly
Impact parameter	$\|d_0/\sigma(d_0)\| < 3$ & $\|z_0 \sin\theta\| < 0.5$ mm
Jets (Anti-k_t $R = 0.4$ PFlow)	
Kinematic	$p_T > 20$ GeV, $\|\eta\| < 2.5$
Pileup mitigation	JVT Tight for $p_T < 60$ GeV, $\|\eta\| < 2.4$
b-Jets (Anti-k_t $R = 0.4$ PFlow)	
Kinematic	$p_T > 20$ GeV, $\|\eta\| < 2.5$
Pileup mitigation	JVT Tight for $p_T < 60$ GeV, $\|\eta\| < 2.4$
b-tagging	DL1r FixedCutBeff 77%

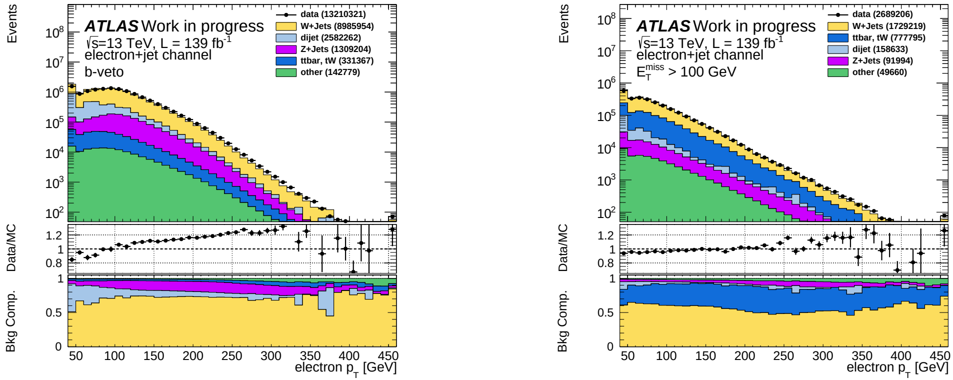
MC vs Data at low Masses

- However, slope in Data/MC ratio observed in lepton p_T in the electron channel
- Looking at the Bkg composition, ttbar or dijet could be the cause



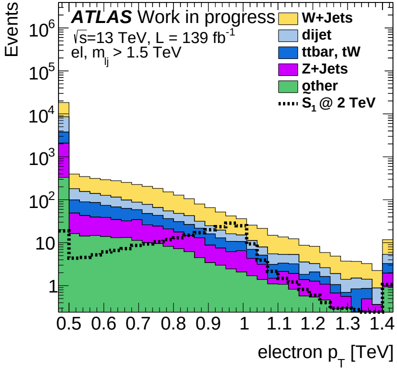


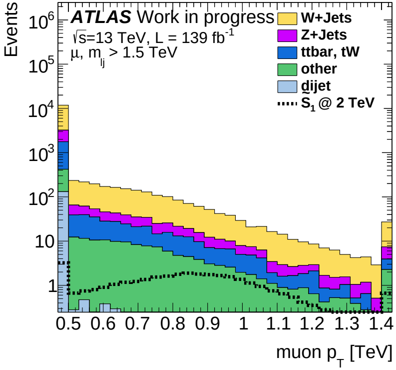
- Use b-veto/E_T^{miss}-cut to reduce ttbar/dijet background



→ dijet seems to cause the slope in Data/MC ratio (probably due to fake electron mismodeling)

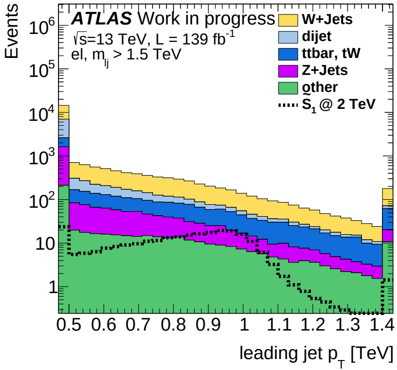
- Lepton p_T spectra actually look similarly promising as $m_{\ell j}$ $\rightarrow$ might exploit the lepton p_T spectra in bump-hunt

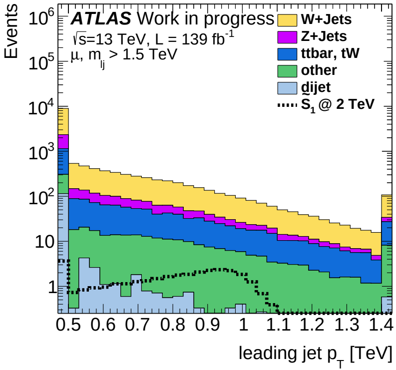




Signal vs Background - Jet p_T

- Leading jet p_T not as pronounced as lepton p_T
- Both should be highly correlated



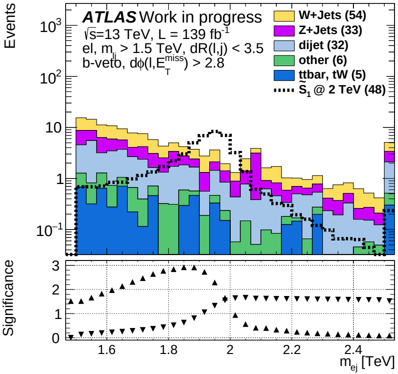


Significance Calculation

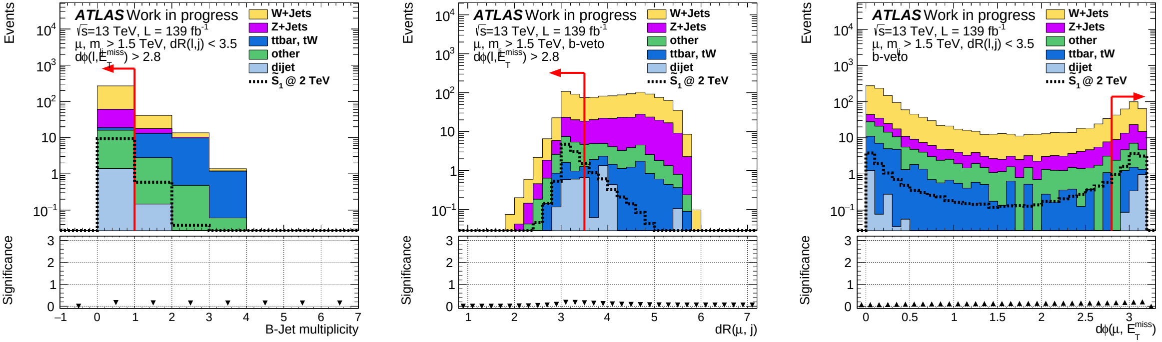
- Significance calculated as recommended in this PUB note
- Uncertainty $\sigma = \sqrt{\sigma^2_{\text{stat}} + \sigma^2_{\text{syst}}}$ with a preliminary systematic uncertainty of 20 %

$$Z = \begin{cases} +\sqrt{2\left(n\ln\left[\frac{n(b+\sigma^2)}{b^2+n\sigma^2}\right] - \frac{b^2}{\sigma^2}\ln\left[1+\frac{\sigma^2(n-b)}{b(b+\sigma^2)}\right]\right)} & \text{if } n \geqslant b \\ -\sqrt{2\left(n\ln\left[\frac{n(b+\sigma^2)}{b^2+n\sigma^2}\right] - \frac{b^2}{\sigma^2}\ln\left[1+\frac{\sigma^2(n-b)}{b(b+\sigma^2)}\right]\right)} & \text{if } n < b. \end{cases}$$

Electron channel



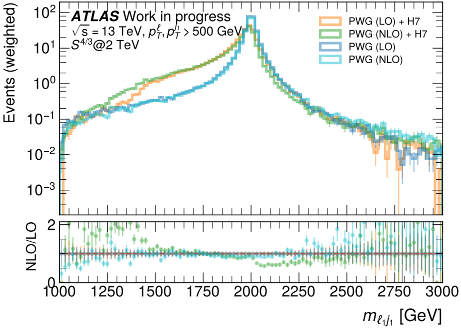
- $N-1$ plots in the muon channel:



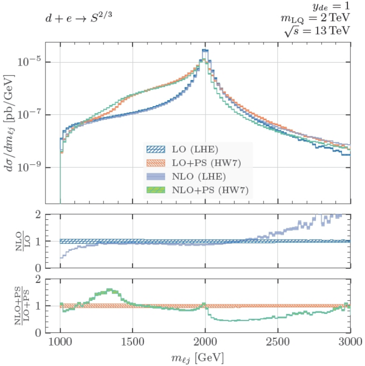
Migration to NLO Signal Generation

- Fairly new Powheg implementation of the LQ resonant production makes signal generation at NLO precision possible (arXiv:2209.02599)
- Currently, working local setup consistent with phenomenological results
- Effort to implement this setup in the ATLAS software framework *Athena*

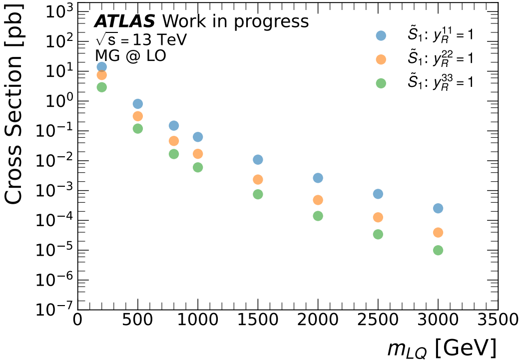
Local Powheg setup + Athena parton showering



arXiv:2209.02599 results



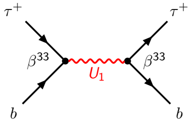
Cross Section for the Resonant Production

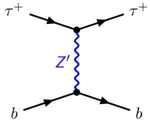


- Leading Order (LO) cross sections calculated using MadGraph
- Verified that values are compatible with cross sections used by authors of phenomenological paper
- 2nd and 3rd generation suppressed due to suppressed s- and b-quark content of the proton

Vector Leptoquarks

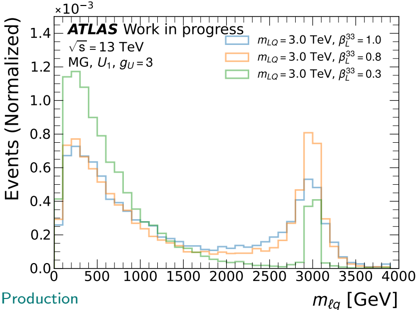
- Vector $U_1 = (\mathbf{3}, \mathbf{1}, 2/3)$ model able to **resolve tensions** in both R_K and $\mathcal{R}(D)$ measurements
- Complications:
  - More decay modes (up-type quark + neutrino, chirality sensitive $\rightarrow$ separate β_L, β_R)
  - Vector LQ models require additional vector bosons G'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





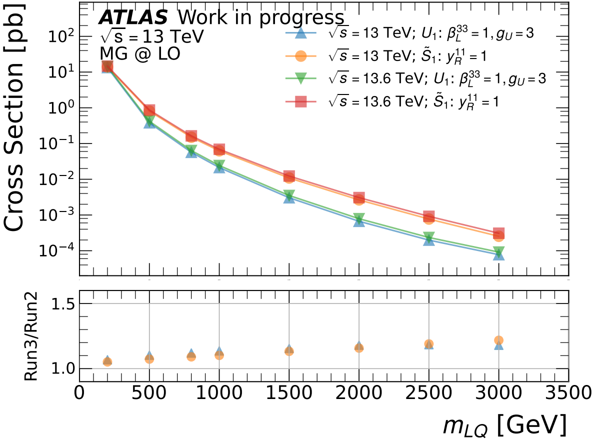
Vector LQ Decay Width

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



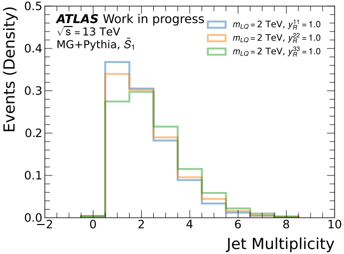
Outlook: LHC Run 3

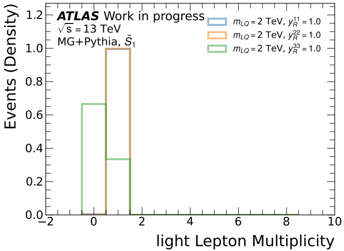
- LHC Run 3 with higher $\sqrt{s} = 13.6$ TeV (Run 2: $\sqrt{s} = 13$ TeV)
- 15-20% higher cross sections for LQ masses between 2-3 TeV
- Including Run 3 data from 2022/2023 beneficial to this search

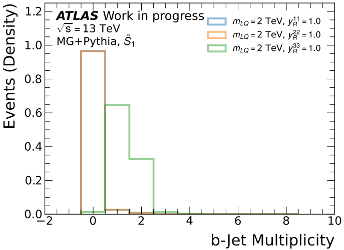


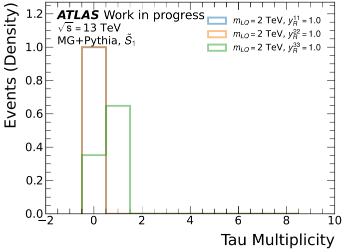
Requirements in SimpleAnalysis

- 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



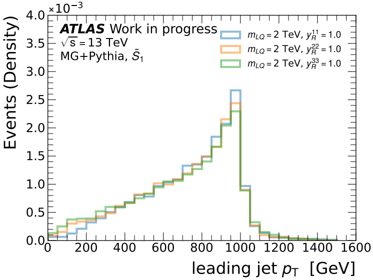


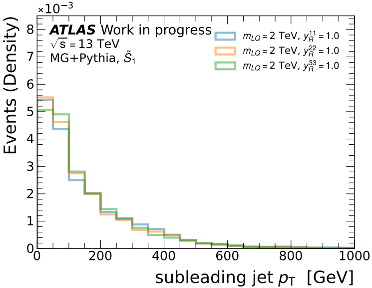


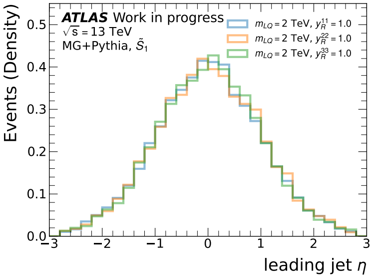


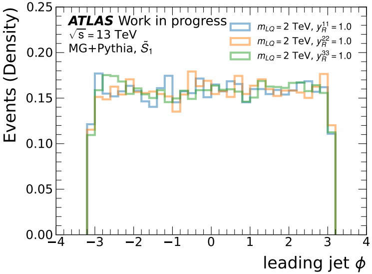
- Multiplicities behave as expected; high occurrence of 2nd b-jets in 3rd generation from gluon splitting?

Kinematic Distributions









Kinematic Distributions