The LHC as Lepton–Proton Collider:

Searches for Resonant Production of Leptoquarks

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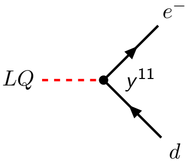
Leptoquarks

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

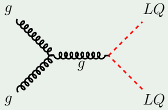


A wide variety of candidates

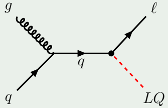
- Scalar or vector boson
- Different electric charges possible
- Inter and intra-generation couplings y^{ij} allowed

Existing Searches at the LHC

- Pair Production (PP)

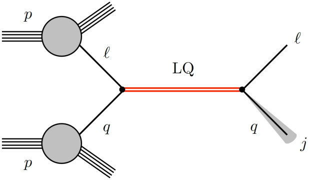


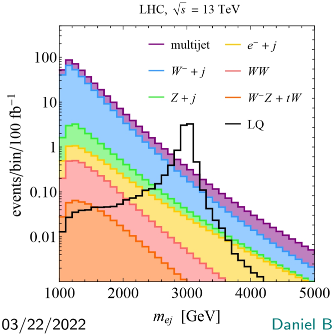
- Single Production (SP)



Resonant Leptoquark Production

- Production mode not yet probed at the LHC
- Novel approach: Utilize lepton content of proton originating from quantum fluctuations
- **Lepton+(small-R) Jet** final state not covered by existing ATLAS searches at run–2
- Production rate sensitive to both mass and coupling parameters



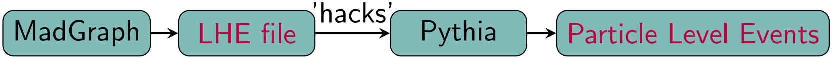


- **Invariant Mass** $m_{\ell j}$ of lepton-jet system as key observable

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

Signal Generation Studies

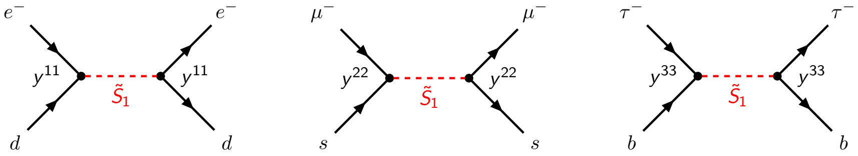
- Main challenge: limited support to lepton parton distribution functions in the common ATLAS event generation software
- **Private MadGraph + Pythia** configuration necessary:
  - Matrix Element generation with dedicated MadGraph version that gives access to leptons in the proton
  - Proton **PDF including 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
    - → Disable event check to circumvent charge conservation check



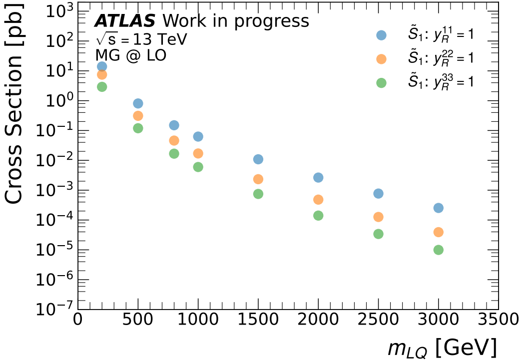
- To validate this generation setup, **key kinematic properties** of the LQ production are studied at the particle (truth) level

Particle-Level Studies

- 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**
- Assume only intra-generation couplings $\rightarrow$ three processes:



Cross section for the resonant production

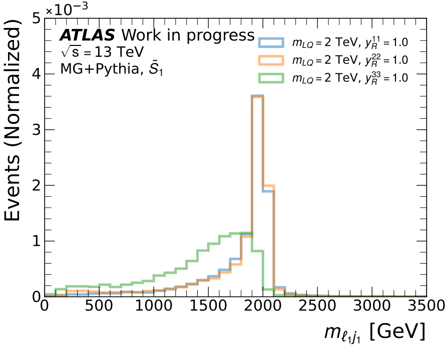


- LO cross sections calculated using MadGraph
- Verified that values are compatible with cross sections used by authors of phenomenological paper
- 2nd and 3rd generation suppressed due to suppressed s- and b-quark content of the proton

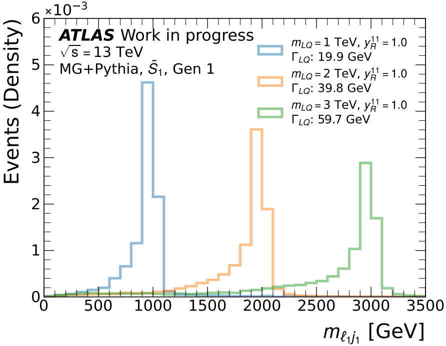
Invariant Mass of LQ decay products

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

Different LQ generations

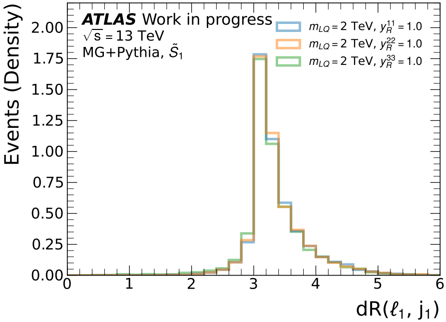


Different LQ masses

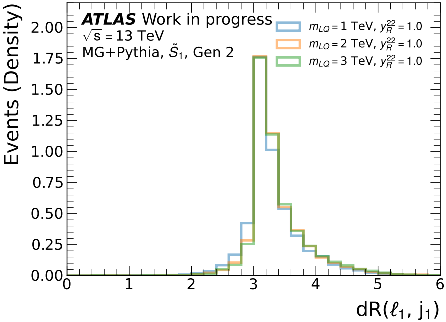


Angular distance between decay products

Different LQ generations



Different LQ masses

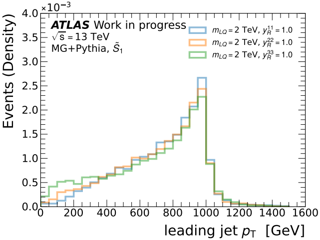


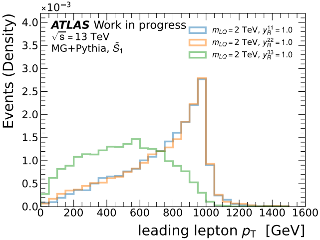
- Angular distance defined as:

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

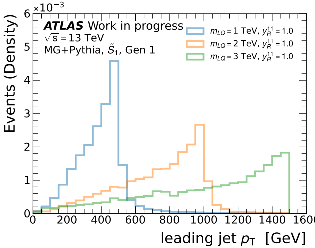
- Lepton and Jet well separated, as expected

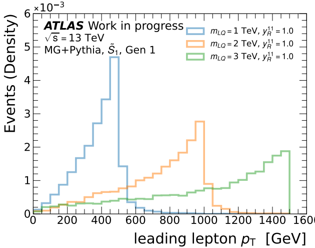
Different LQ generations





Different LQ masses





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

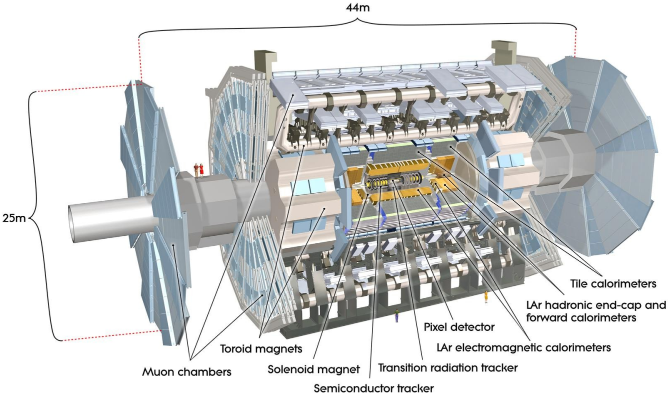
Conclusion & Outlook

- 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
  → Distributions of key observables behave as expected
- Next steps:
  - Pass LQ signals through ATLAS simulation chain to allow analysis optimization at reconstruction level
  - Estimate sensitivity to these signals via a "bump-hunt" on the m_{lj} spectrum
  - Possible extension to more LQ models and final states, i.e. $e/\mu/\tau$ x light jet/c-jet/b-jet

BACKUP

ATLAS detector

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



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
$(\mathbf{\bar{3}}, \mathbf{3}, 1/3)$	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	$\tilde{R}_2$	$RL\,(\tilde{S}_{1/2}^L)$, $\overline{LR}\,(\tilde{S}_{1/2}^{\overline{L}})$	0
$(\mathbf{\bar{3}}, \mathbf{1}, 4/3)$	0	$\tilde{S}_1$	$RR\,(\tilde{S}_0^R)$	-2
$(\mathbf{\bar{3}}, \mathbf{1}, 1/3)$	0	S_1	$LL\,(S_0^L)$, $RR\,(S_0^R)$, $\overline{RR}\,(S_0^{\overline{R}})$	-2
$(\mathbf{\bar{3}}, \mathbf{1}, -2/3)$	0	$\bar{S}_1$	$\overline{RR}\,(\bar{S}_0^{\overline{R}})$	-2
$(\mathbf{3}, \mathbf{3}, 2/3)$	1	U_3	$LL\,(V_1^L)$	0
$(\mathbf{\bar{3}}, \mathbf{2}, 5/6)$	1	V_2	$RL\,(V_{1/2}^L)$, $LR\,(V_{1/2}^R)$	-2
$(\mathbf{\bar{3}}, \mathbf{2}, -1/6)$	1	$\tilde{V}_2$	$RL\,(\tilde{V}_{1/2}^L)$, $\overline{LR}\,(\tilde{V}_{1/2}^{\overline{R}})$	-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	$\bar{U}_1$	$\overline{RR}\,(\bar{V}_0^{\overline{R}})$	0

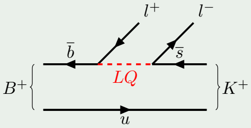
arXiv:1603.04993

- Resolve tensions in measurements of lepton flavour universality

R_K

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

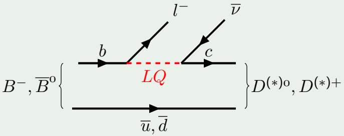
3.1 σ below SM prediction (arXiv:2103.11769)



$\mathcal{R}(D)$

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

4.1 σ above SM prediction (arXiv:1708.08856)



LQ Candidates in B–Physics

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

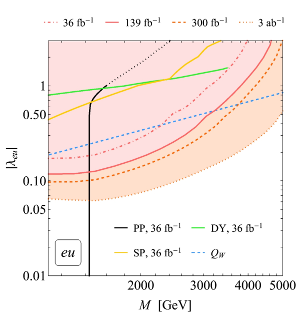
Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
S_1	✗*	✓	✗*
R_2	✗*	✓	✗
$\widetilde{R}_2$	✗	✗	✗
S_3	✓	✗	✗
U_1	✓	✓	✓
U_3	✓	✗	✗

arXiv:1808.08179

Phenomenological papers on resonant LQ production:

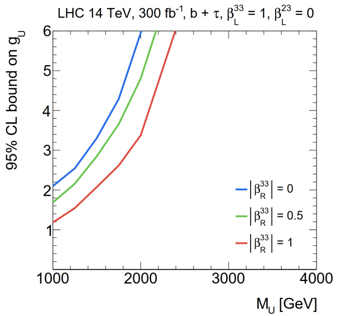
arXiv:2005.06475

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



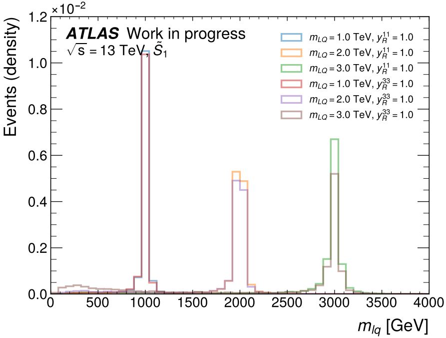
arXiv:2012.11474

- 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 $\nu_{\tau L} t_L$)

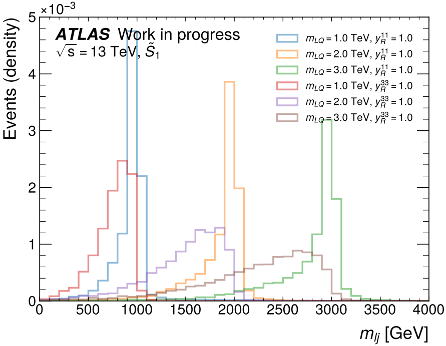


Invariant Masses: LHE vs Particle level

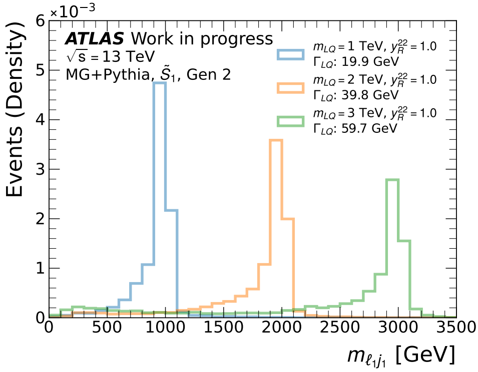
- 1st generation: leading lepton and leading jet
- For 3rd generation: leading tau and leading b-jet



Before parton showering



After parton showering



LQ Decay Width

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

Effect of bwcutoff parameter in MadGraph

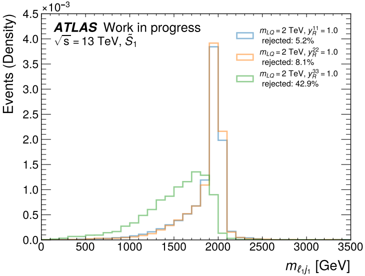
- MG's bwcutoff parameter (default: 15) steers if an intermediate particle counts as on-shell:

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

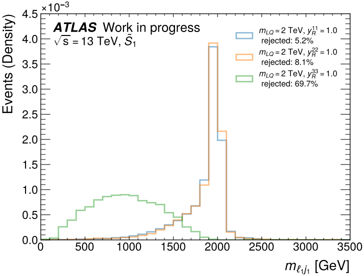
- Only on-shell particles appear in LHE file → important for truth studies (e.g. MCTruthClassifier doesn't label leptons from off-shell LQs as prompt)
- Noticed that fraction of events with no explicit LQ in LHE relatively large in 3rd gen (11 % at 2 TeV)
- Can mitigate this by increasing bwcutoff to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

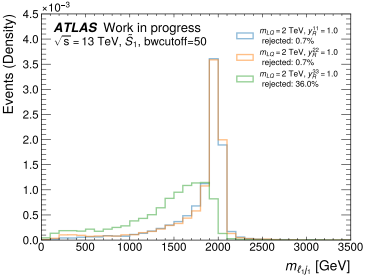
Effect of bwcutoff parameter in MadGraph

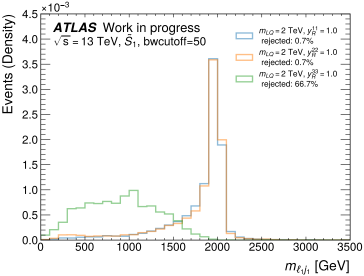
Invariant mass of leading tau and leading b-jet for 3rd gen.



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

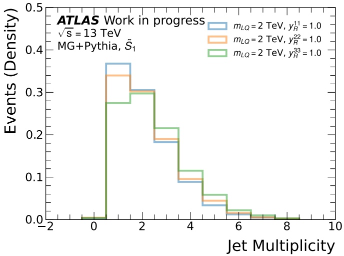


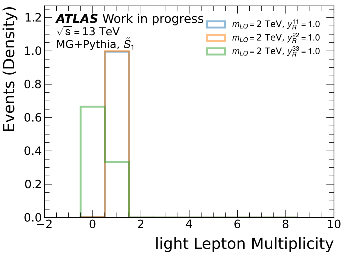


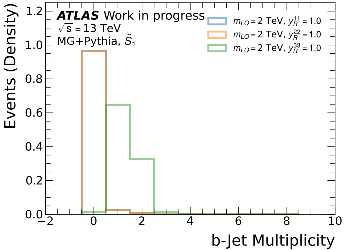


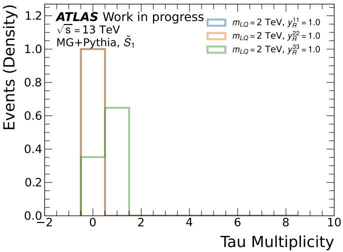
Requirements in SimpleAnalysis

- 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



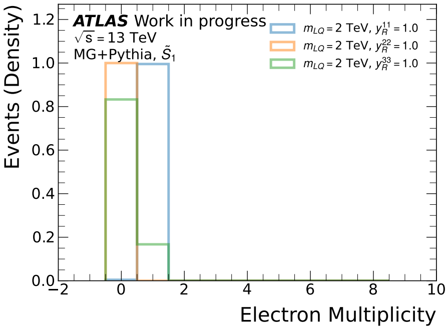


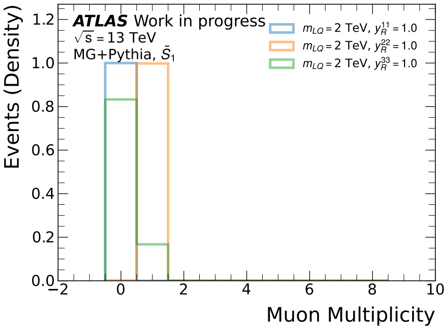




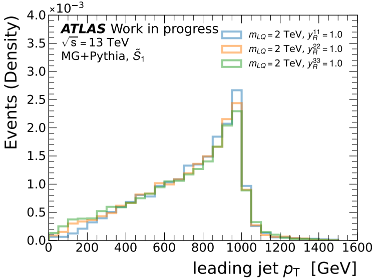
- Multiplicities behave as expected; high occurrence of 2nd b-jets in 3rd generation case still being studied

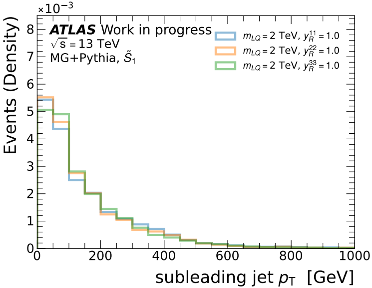
Lepton Multiplicities

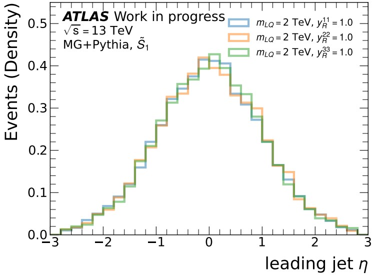


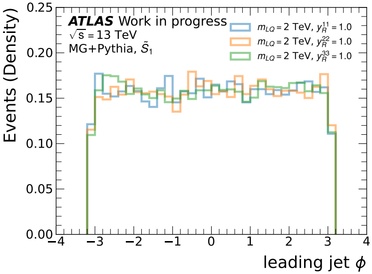


Kinematic Distributions









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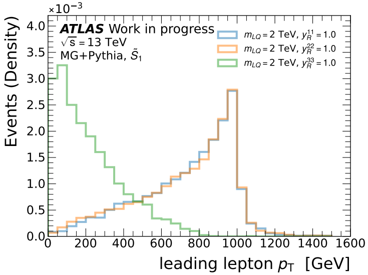

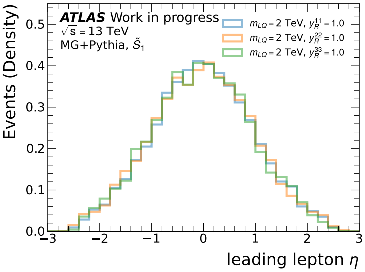

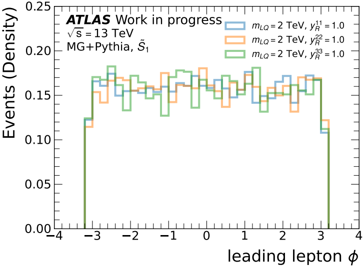

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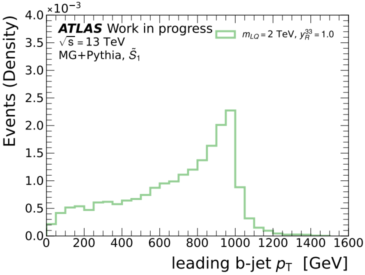

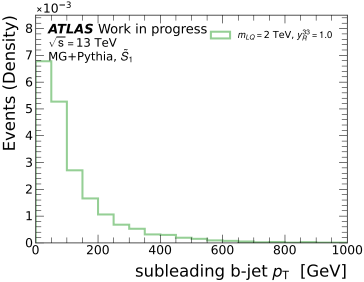

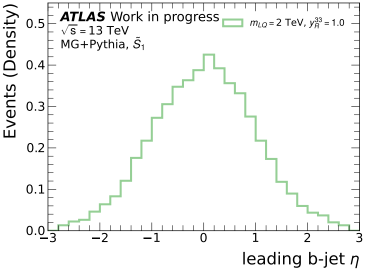

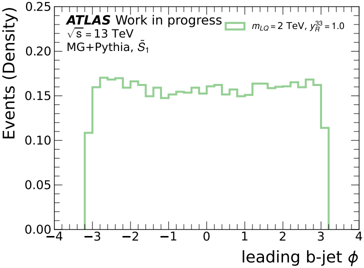

Kinematic Distributions