

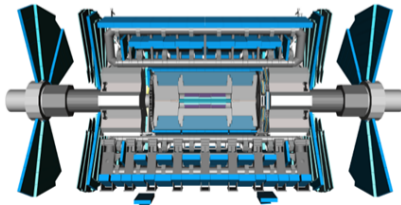
# Leptoquarks and $\tau$ -ID with the ATLAS Detector

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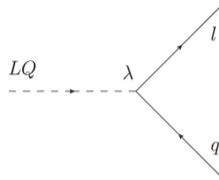
22-May-2026 - Liverpool PP Annual Meeting

Supervisors: Prof Andrew Mehta (P), Prof Monica D'Onofrio (S), Dr Jordy Degens



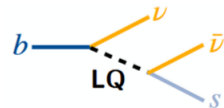
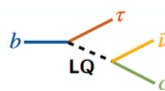
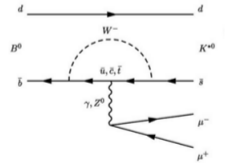
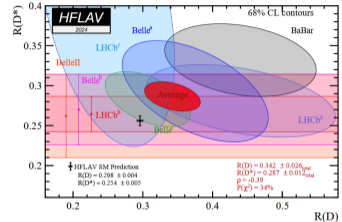
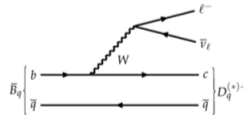
# Leptoquarks: What are they? Why are they interesting?

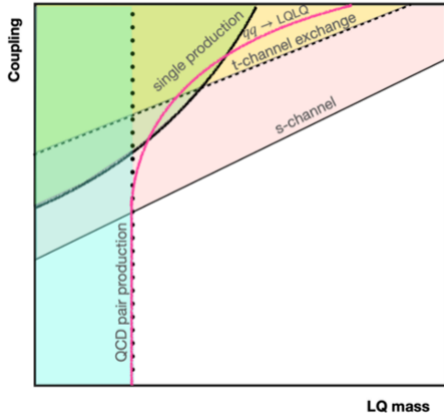
- ▶ Hypothetical particles with both baryon and lepton quantum numbers
- ▶ Provide a link between similar structure of lepton and quark families



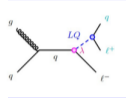
## Motivations:

- ▶ General class of BSM models predict states with LQ properties: GUT, Pati-Salam, Technicolour
- ▶ B-Anomalies measured at LHC-b, BaBar & Belle
  - ▶ SM prediction of FCNC is a loop diagram
  - ▶ LQ mediator would be Tree level process



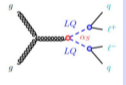


## Single Production



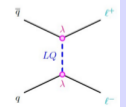
- ▶  $\sigma$  is dependent on mass and coupling ( $\lambda$ ) coupling
- ▶ Drives sensitivity to higher LQ mass

## Pair-Production



- ▶  $\sigma$  is dependent on mass only

## Non-resonant

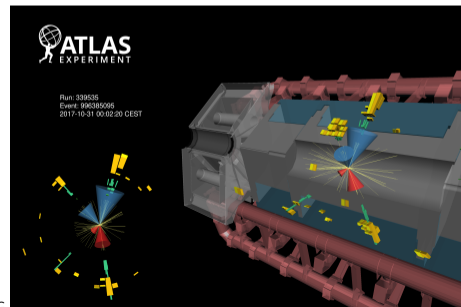
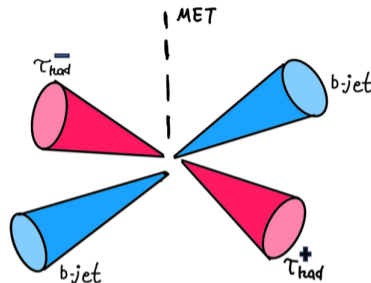


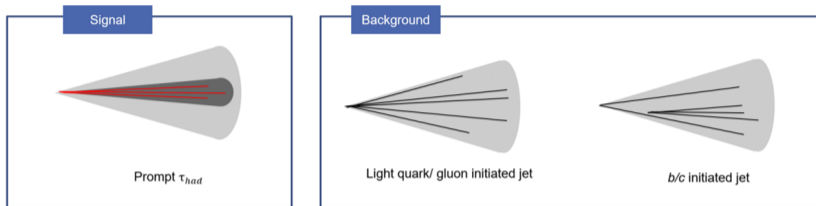
- ▶  $\sigma$  is  $\propto \lambda^4$
- ▶ Depends on quark-PDF squared

Analysis will focus on 3<sup>rd</sup> gen coupling ( $\Gamma$  (decay rate) is  $\propto$  CKM matrix elements)

Event Topology:

- ▶ 2- $b$  jets
  - ▶ 2- $\tau_{\text{had}}$ -tagged jets (Opposite-sign)
  - ▶  $E_T^{\text{miss}}$
- 
- ▶ Exploit the better  $\tau/b$ -jet tagging algorithms
  - ▶ Higher CoM energies
  - ▶ More data (Run 2  $\sim 140\text{fb}^{-1}$ , Run 3 (2022-24)  $\sim 165\text{fb}^{-1}$ )
  - ▶ Targeted analysis for the high- $p_T$  phase-space





## Properties:

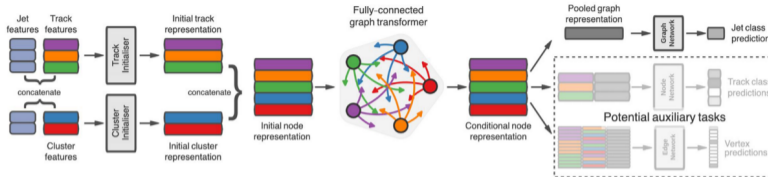
- ▶ Mass: 1.8 GeV ( $\sim 3500 m_e$ )
- ▶ Lifetime:  $2.9 \times 10^{-13} s$
- ▶ Branching fraction:  
Hadronic  $\sim 66\%$  & leptonic  $\sim 34\%$
- ▶ Categorized into 1-3 prong  
 $\rightarrow n_{\text{charged-tracks}}$

## Signatures:

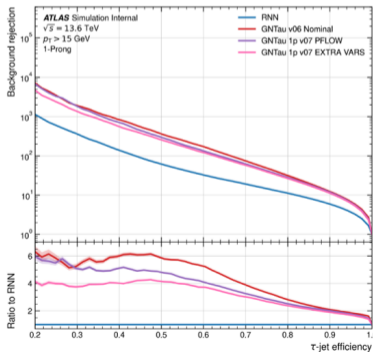
- ▶ Secondary vertex
- ▶ Jet shape  $\rightarrow$   
narrower/collimated
- ▶ 1/3- reconstructed charge  
tracks in the "core"-region  
( $\Delta R \leq 0.25$ ) of the jet

## Method:

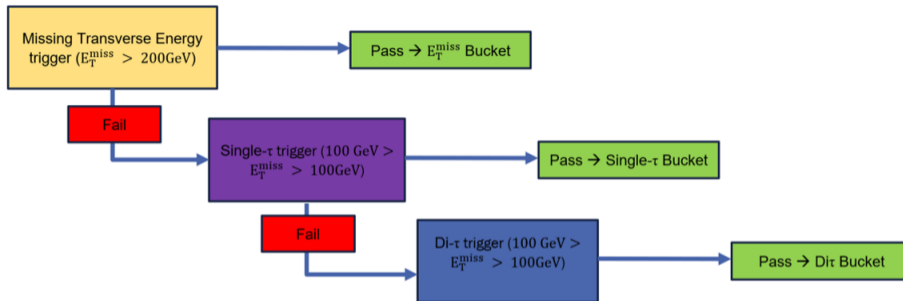
- ▶ Neural network for binary  
classification task
- ▶ Input features: high-level jet  
variables, track-level features  
& clusters



- ▶ Transitioning from Recurrent Neural network to graph/transformer architecture
- ▶ Allows more natural representation between all objects within the  $\tau_{\text{cand-jet}}$
- ▶ Attention layers learn long term dependencies
- ▶ Parallelizable  $\rightarrow$  scales with data



- ▶ GNN/transformer architecture outperforms RNN (compare to blue curve)
- ▶ Performed studies across different configurations/inputs/architectures
- ▶ Plot is showing results with a model with additional input features related to information about neutral hadronic objects within the  $\tau_{\text{cand-jet}}$  (purple curve)

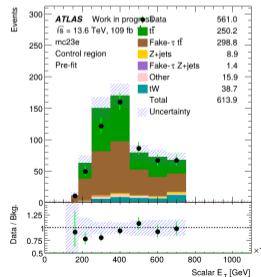
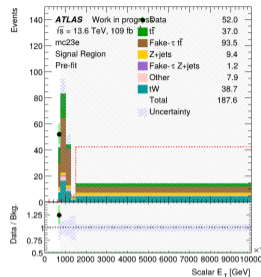
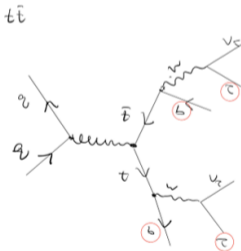


- ▶ ATLAS has two-level trigger system for recording events to disk
  - ▶ L1: Hardware based trigger
  - ▶ HLT: High-level trigger - Software based
- ▶ Various different triggers for different physics signatures

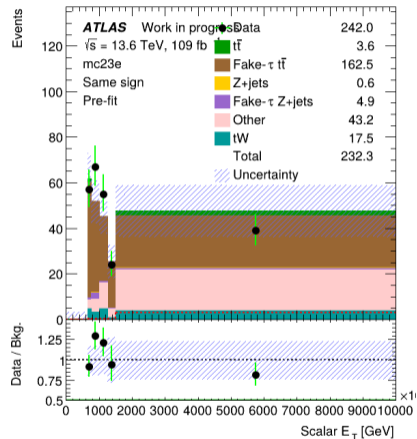
Trigger	Overall Efficiency
MET	95%
STT	75%
DTT	45%
Single Jet	72%
Multi Jet	57%

- ▶ Conducted studies to determine the most efficient triggers
- ▶ Trigger strategy is using "buckets"

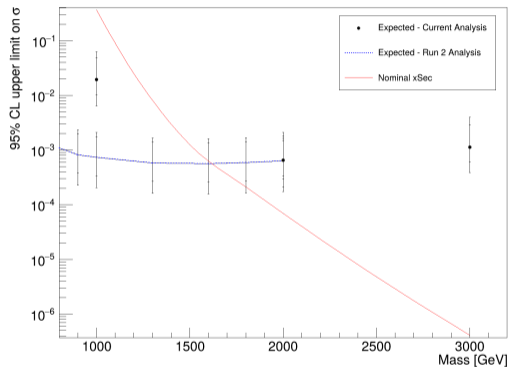
- ▶ Dominant backgrounds are:  $t\bar{t}$  (same final state - e.g see diagram),  $Z + \text{jets}$
- ▶  $t\bar{t}$  normalizations are derived from an  $e\mu$  Opposite Sign (OS) region
- ▶  $Z + \text{jets}$  normalizations are derived from a  $ee/\mu\mu$  OS region
- ▶ Normalizations are applied as function jet multiplicity



- ▶ Analyses with  $\tau_{\text{had}}$  must deal with QCD-jets that fake  $\tau$ 's (i.e pass the NN)
- ▶ Look at the Same-sign region to estimate the size of this contribution
- ▶ Plots show data and MC agree reasonably well  $\rightarrow$  indicates the contribution of QCD fake- $\tau$  is small
- ▶ Overall will use the data-driven method to derive scale factor



- ▶ Plot showing the upper-limit of  $\sigma$  at the 95% CL
- ▶ We do not currently have the full signal MC grid (I worked on the validation and this is production in currently)
- ▶ Currently sensitivity is worse at lower LQ mass
  - ▶ Work in progress
  - ▶ Analysis has focused on high  $p_T$  phase space where statistics are worse and therefore binning is less granular



## Leptoquarks:

- ▶ Optimize the sensitivities
- ▶ Study on the full MC signal grid
- ▶ Systematics

## $\tau$ -tagging:

- ▶ Continue studies on alternative tagger (TauJetGraphs)
- ▶ Talk at ATLAS week 2026

## Other:

- ▶ Completed LTA at CERN
- ▶ ATLAS Control Room shifts: Muon, Calorimeter and Run-control/Trigger desk ( $\sim 30$  total shifts)
- ▶ CERN tour guide
- ▶ Industrial placement

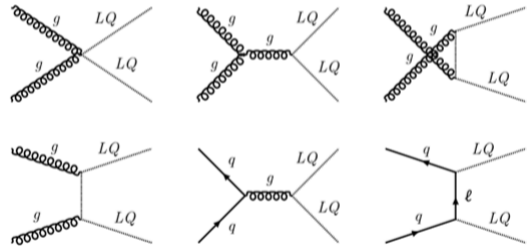


Figure: With the ATLAS detector

Thanks for listening, any questions?

$$\mathcal{L}_{U_1} = -\frac{1}{2} U_{1\mu\nu}^\dagger U_1^{\mu\nu} + M_U^2 U_{1\mu}^\dagger U_1^\mu - ig_s (1 - \kappa_U) U_{1\mu}^\dagger T^a U_{1\nu} G^{a\mu\nu} - ig_Y \frac{2}{3} (1 - \tilde{\kappa}_U) U_{1\mu}^\dagger U_{1\nu} B^{\mu\nu} + \frac{g_U}{\sqrt{2}} [U_1^\mu (\beta_L^{ij} \bar{q}_L^i \gamma_\mu \ell_L^j + \beta_R^{ij} \bar{d}_R^i \gamma_\mu e_R^j) + \text{h.c.}],$$

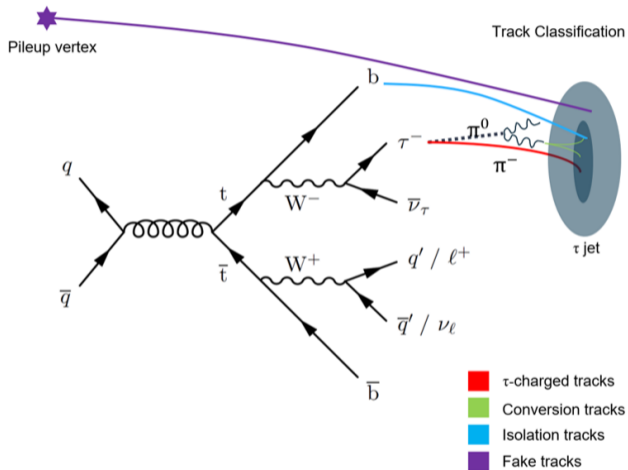
- ▶ Effective phenomenological lagrangian for Vector LQ (U1) model
- ▶  $\beta_{L/R}$  : Coupling controlling branching fraction to charged/neutral lepton & to LH/RH fermions
- ▶  $\kappa_U$  &  $\tilde{\kappa}_U$  : Coupling to YM/Minimal model  $\rightarrow$  overall just enhancement in cross-section



# Backup: $\tau$ - ID input features

I don't know	Jet	Track	Clusters	Shell PFD	Neutral PFD	Truth	Scores
d0_oid	TAU_centFrac	d0inthetaSigTVA	TAU_ch_e	pfo_shots_pt1	pfo_neutral_cellBased_FIRST_ITA	beamSpotWeight	TAU_RNNNetScore
qOverP	TAU_sumMCcellEtoOverLeadTrkP	d0inthetaTVA	TAU_ch_et	pfo_shots_pt0	pfo_neutral_cellBased_SECOND_R	TruthType	TAU_RNNNetScoreSigTrans
theta	TAU_d0vtx	d0SigTVA	TAU_ch_dPhi	pfo_shots_pt0	pfo_neutral_cellBased_SECOND_LAMBDA	NewTruthType	TAU_GNTauScore
eProbabilityHT	TAU_trFlightPathSig	d0TVA	TAU_ch_dEta	pfo_shots_nPhotons	pfo_neutral_cellBased_DELTA_PHI	truthIntType	TAU_GNTauProbTau
eProbabilityMNonHT	TAU_enOverPLeadTrk	jdTVA	TAU_ch_SECOND_R		pfo_neutral_cellBased_DELTA_THETA	GNTau_TrackClass	TAU_GNTauProbTau
eProbabilityHT_eRll	TAU_ptRatioFlowApprox	ed0_TV_PVD	TAU_ch_SECOND_LAMBDA		pfo_neutral_cellBased_CENTER_LAMBDA	tauTruthCharge	
eProbabilityM_eRll	TAU_mFlowApprox	log_sumpt_TV	TAU_ch_FIRST_ENG_DENS		pfo_neutral_cellBased_LATERAL	tauTruthOrig	
eProbabilityMNonHT_eRll	TAU_msumTrkSys	log_sumpt2_TV	TAU_ch_EM_PROBABILITY		pfo_neutral_cellBased_LONGITUDINAL	tauTruthDecayMode	
	TAU_SumPTrkFrac	log_sumpt_PVD	TAU_ch_CENTER_MAG		pfo_neutral_cellBased_ENG_FRAC_EM	truthParticleOrigin	
	TAU_EMPOverTrkSysP	log_sumpt2_PVD	TAU_ch_CENTER_LAMBDA		pfo_neutral_cellBased_ENG_FRAC_MAX	truthParticleType	
	TAU_nuIFrac	ICorr			pfo_neutral_cellBased_ENG_FRAC_CORE		
	ip3dSeedTrk	C=med			pfo_neutral_cellBased_SECOND_ENG_DENS		
	isLRT	charge			pfo_neutral_cellBased_EM1CoreFrac		
	jetSeedPt	trackPt			pfo_neutral_cellBased_MHbinEM1		
	jetSeedEta	trackEta			pfo_neutral_cellBased_NPosCells_P5		
	jetSeedPhi	trackPhi			pfo_neutral_cellBased_NPosCells_EM1		
	tauPt	truthPt			pfo_neutral_cellBased_NPosCells_EM2		
	tauEta	numberOfInnermostPixelLayerHits			pfo_neutral_cellBased_firstEWRTClusterPosition_EM1		
	tauPhi	numberOfPixelHits			pfo_neutral_cellBased_firstEWRTClusterPosition_EM2		
	d0LeadSeedAis	numberOfPixelSharedHits			pfo_neutral_cellBased_secondEWRTClusterPosition_EM1		
	dPhiLeadSeedAis	numberOfPixelSharedDimensions			pfo_neutral_cellBased_secondEWRTClusterPosition_EM2		
	dEtaLeadSeedAis	numberOfSCTHits			pfo_neutral_cellBased_energy_EM1		
	dPhiIntrmediateAis	numberOfSCTSharedHits			pfo_neutral_cellBased_energy_EM2		
	dEtaIntrmediateAis	numberOfSCTSharedDimensions			pfo_neutral_ptSubRatio		
	tauPtDetectorAis	numberOFTRHighThresholdHits			pfo_neutral_pt		
	dPhiDetectorAis	numberOFTRHits			pfo_neutral_eta		
		nPixelHits			pfo_neutral_phi		
		nSCTHits			pfo_neutral_e		
		nSplits					
		nSplitsAndExp					
		expectInnermostPixelLayerHit					
		expectNextToInnermostPixelLayerHit					
		numberOFContribPixelLayers					
		numberOFPixelHoles					
		numberOFSCTHoles					
		rnn_chargeScore					
		rnn_isolationScore					
		rnn_conversionScore					
		rnn_fakeScore					
Taulets.nTracks	TauTracks.pt	TauClusters.e				Taulets.mcEventNumber	Taulets.RNNNetScore
Taulets.pt	TauTracks.eta	TauClusters.et				Taulets.mcEventWeight	Taulets.RNNNetScoreSigTrans
Taulets.eta	TauTracks.phi	TauClusters.eta				Taulets.beamSpotWeight	
Taulets.phi	TauTracks.dEta	TauClusters.phi				Taulets.PairTau_DecayMode	
Taulets.ptJetSeed	TauTracks.dPhi	TauClusters.dEta				Taulets.truthOrig	
Taulets.etaJetSeed	TauTracks.nInnermostPixelHits	TauClusters.dPhi				Taulets.truthEtaVs	
Taulets.phiJetSeed	TauTracks.nPixelHits	TauClusters.SECOND_R				Taulets.truthPVVs	
Taulets.rnn	TauTracks.nSCTHits	TauClusters.SECOND_LAMBDA				Taulets.isTruthMatched	
Taulets.rnnPFD	TauTracks.d0inthetaTVA	TauClusters.CENTER_LAMBDA				Taulets.truthDecayMode	
Taulets.centFrac	TauTracks.d0inthetaSigTVA					Taulets.truthParticleType	
Taulets.EMPOverTrkSysP	TauTracks.d0TVA						
Taulets.InnerTrkAvgDist	TauTracks.d0SigTVA						
Taulets.ptRatioFlowApprox	TauTracks.chargeScoreRNN						
Taulets.d0max	TauTracks.isolationScoreRNN						
Taulets.trFlightPathSig	TauTracks.conversionScoreRNN						
Taulets.mFlowApprox	TauTracks.fakeScoreRNN						
Taulets.SumPTrkFrac							
Taulets.absp3dSeedTrk							
Taulets.enOverPLeadTrk							
Taulets.ptIntrmediateAis							

# Backup: $\tau$ -track classifications



- ▶ Cross-section is independent of yukawa coupling to fermions
- ▶ Cross-section drops of very quickly as function of mass

