Searches for Leptoquarks at the ATLAS Detector

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LHC Seminar

Max Planck Institute for Physics, Munich

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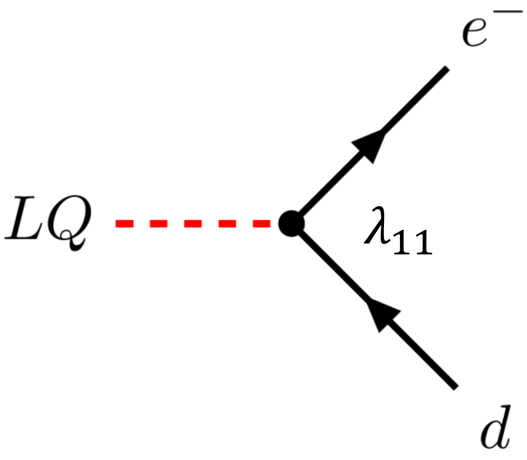
MAX PLANCK INSTITUTE
FOR PHYSICS

Leptoquark Introduction

- Theoretically motivated by e.g. Grand Unified Theories
- Appealing solutions to observed flavour anomalies in e.g. B-Factories
- Couple simultaneously to leptons and quarks:
  - → Carry both **colour** and **electric** charge
  - → **Baryon** and **lepton number** both non-zero
  - → Typically decay into **lepton-quark pair**



Wide variety of candidates!

- Scalar or vector boson
- Different electric charges possible → 1/3, 2/3, 4/3, 5/3
- Couplings λ_{ij} to any combination of fermion generations allowed

Scalar vs Vector Leptoquarks

Scalar Leptoquarks:

- Scalar leptoquarks and their interactions can be added to the Standard Model (SM)
- No larger theoretical framework needed (simple addition of Yukawa terms to the Lagrangian of the SM)

$$\boxed{\mathcal{L} \supset \lambda_{eu}\,\mathrm{LQ}_{eu}\,(E^c U^c)^* + \mathrm{h.c.}}$$

Vector Leptoquarks:

- Vector leptoquark models introduce new gauge interaction, always in need of UV completion
- These UV completing theories yield more heavy-mass particles even in the minimal scenario

  → E.g.: colouron g' and heavy "Z" Z'
- Coupling to other gauge bosons also depends on UV completion ("Yang-Mills" vs "Minimal Coupling")

$U(1)_Y$

$$SU(4) \times SU(3)' \times SU(2)_L \times U(1)' \xrightarrow{SSB} SU(3)_c \times SU(2)_L \times U(1)_Y$$

$+\boxed{U_1, g', Z' \quad \text{[2-4 TeV]}}$

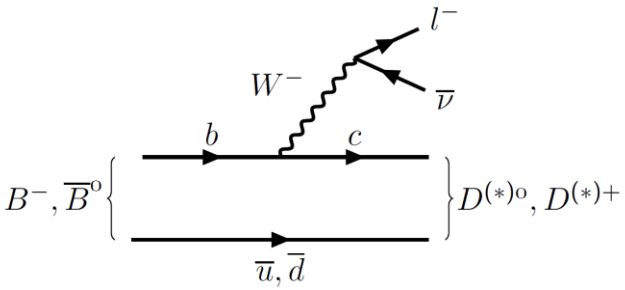
$SU(3)_c$

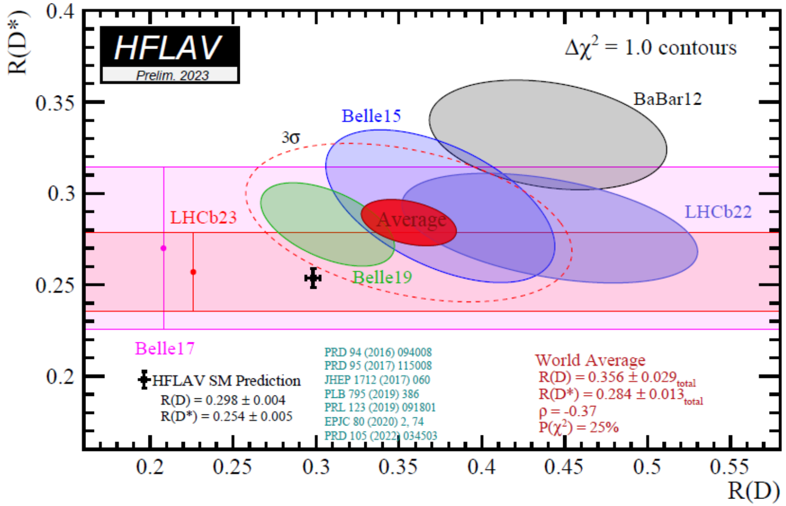
Leptoquarks in Lepton Flavour Violation

- Multiple experiments have shown tensions to the SM in measurements of the **Lepton Flavour Universality (LFU)**
- LHCb recently announced new results of the measurement of the $R\left(D^{(*)}\right)$:

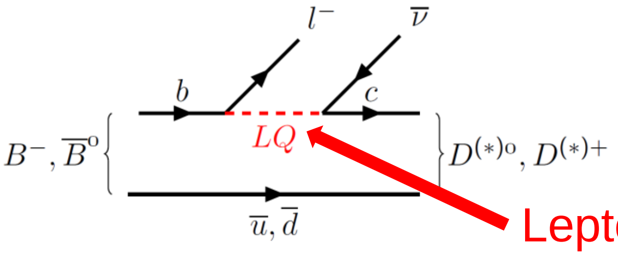
$$R\left(D^{(*)}\right) = \frac{\mathcal{B}(B \rightarrow D^{(*)}\tau\nu_{\tau})}{\mathcal{B}(B \rightarrow D^{(*)}l\nu_{l})}$$

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





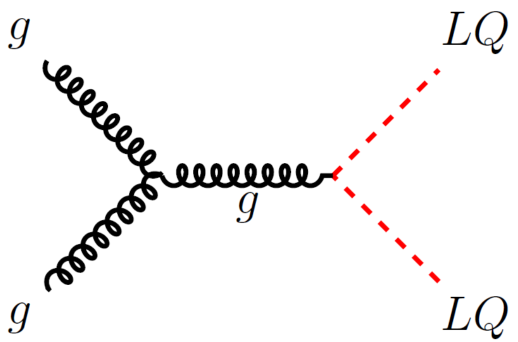
CERN Seminar



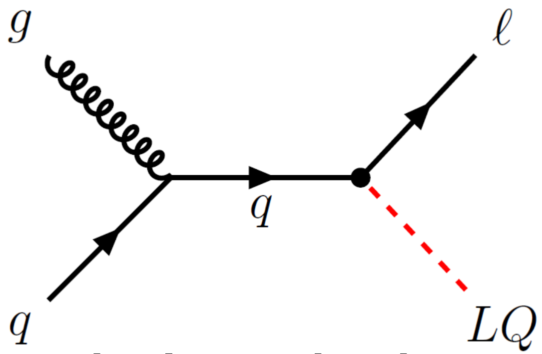
Leptoquark with stronger couplings to the τ

Leptoquark Production @ LHC

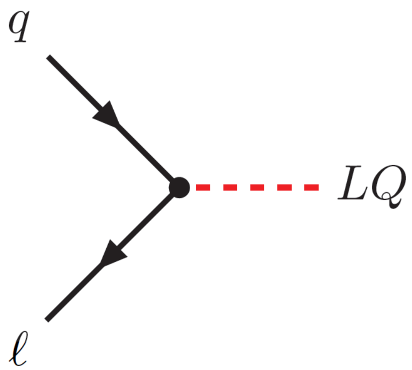
Four possible production modes for leptoquarks:



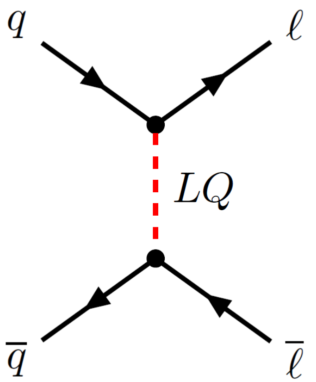
Pair Production



Single Production



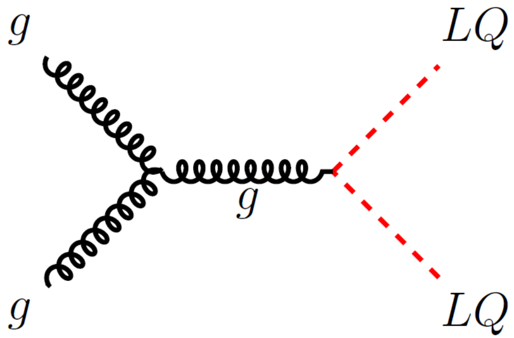
Resonant Production



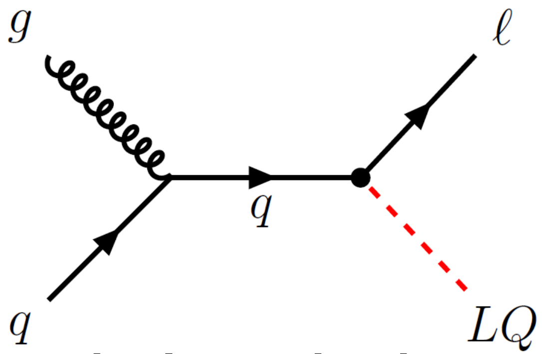
Drell-Yan Production

Leptoquark Production @ LHC

Four possible production modes for leptoquarks:

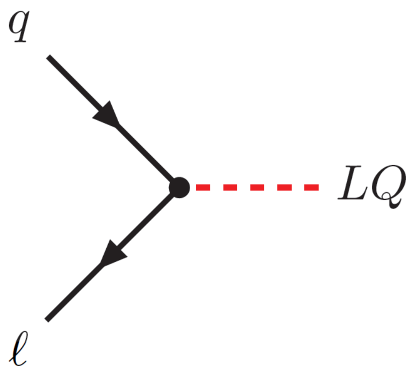


Pair Production



Single Production

ATLAS searches published + running



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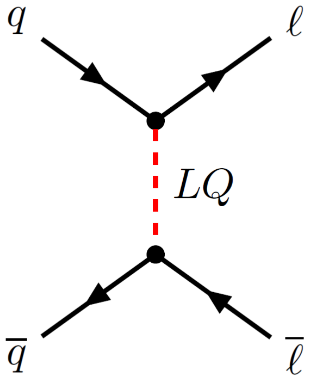

Drell-Yan Production

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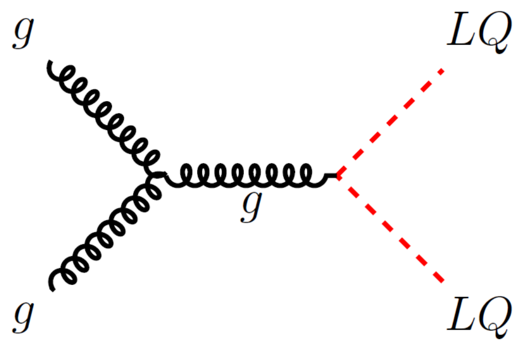
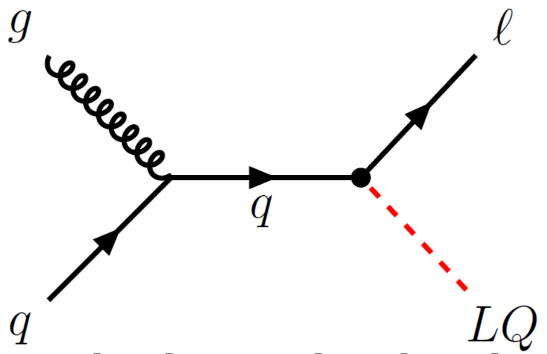
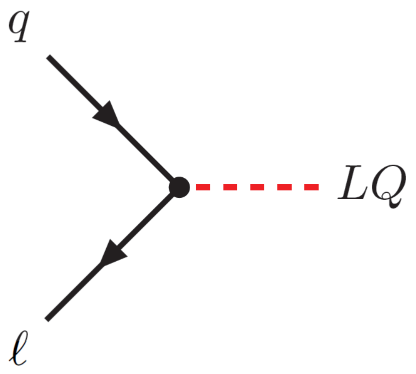


Pair Production (PP)

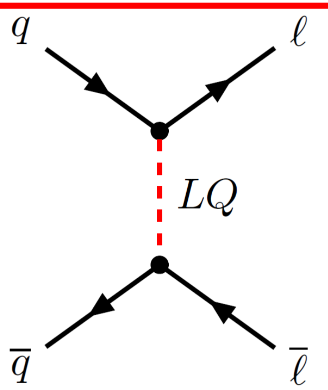


Single Production (SP)

ATLAS searches published + running



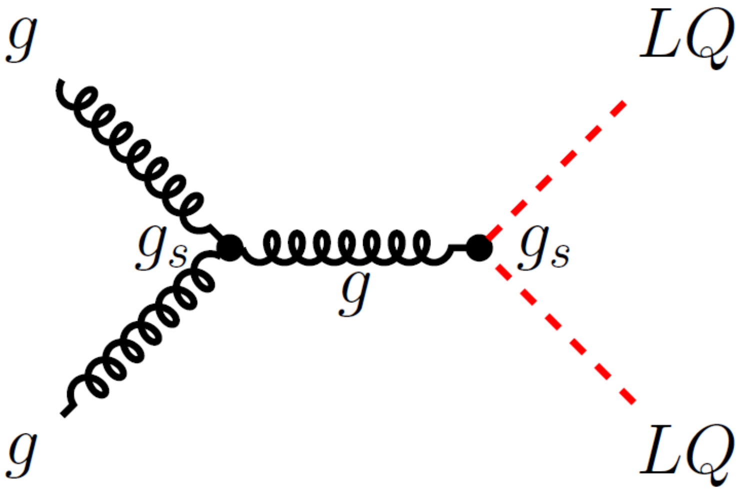
Resonant Production (RP)

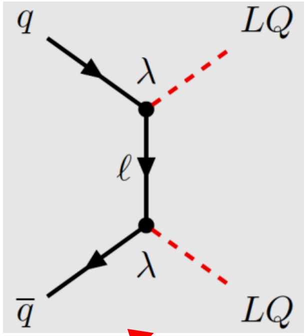


Drell-Yan Production (DY)

ATLAS searches running

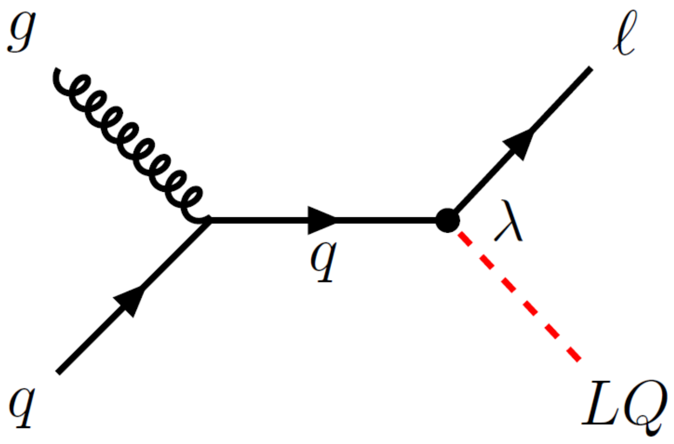
Pair Production

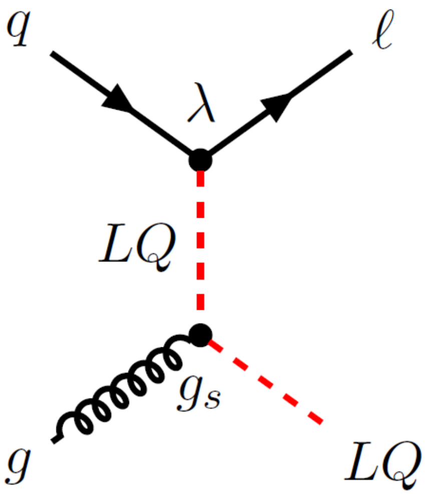




- PP independent of the LQ-to-fermion couplings λ (except for high couplings)
- Only dependent on **strong coupling** g_s (LQ has colour charge and hence couples to gluons) and **LQ mass**
- In terms of parameters beyond the SM, only the LQ mass is relevant!
- Final state consists of two lepton-quark (jet) pairs

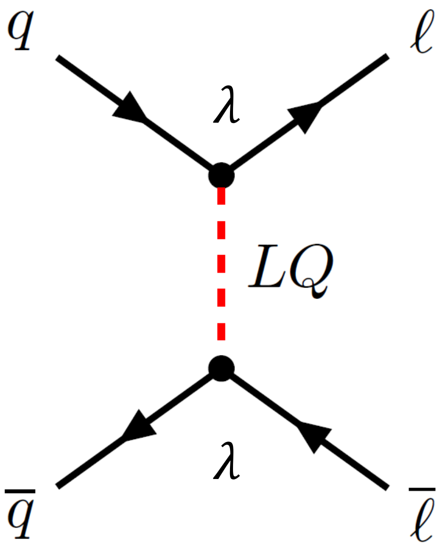
Single Production





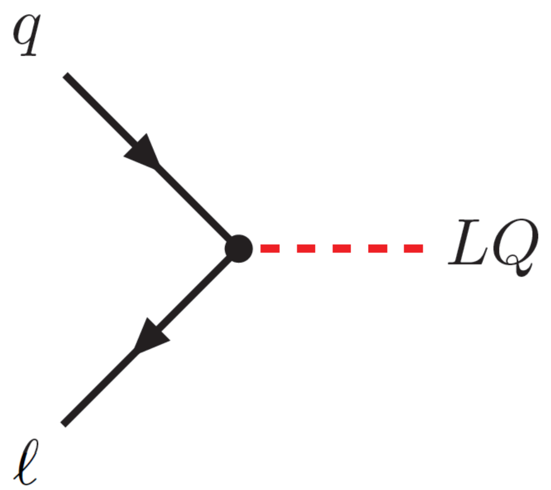
- SP involves one production vertex with LQ-to-fermion coupling λ
- Production rate dependent on **LQ mass and LQ-to-fermion coupling**
- Final state consists of one lepton-jet pair from the LQ decay and an additional lepton

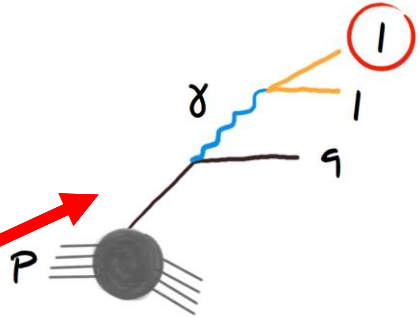
Drell-Yan Production



- DY involves two production vertices with LQ-to-fermion coupling λ, LQ in t-channel
- Production rate dependent on **LQ mass and LQ-to-fermion coupling** like SP, but stronger coupling dependency and **non-resonant**
- Interference with SM Z/γ t-channel

Resonant Production





- RP involves one production vertex with LQ-to-fermion coupling λ

  $\rightarrow$ Lepton from the proton needed, possible due to quantum fluctuations within the proton

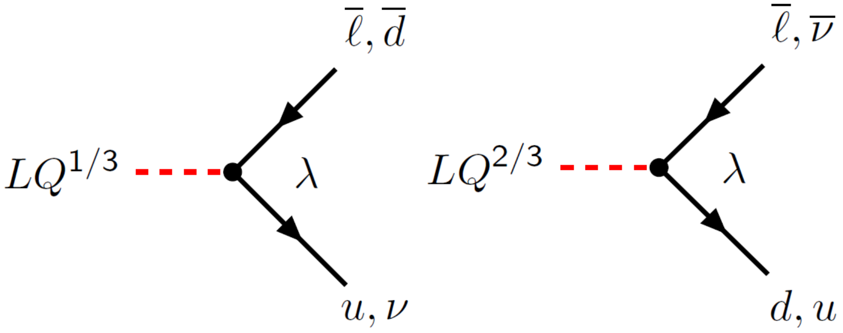
  $\rightarrow$ Lepton PDFs!
- Production rate dependent on **LQ mass and LQ-to-fermion coupling** like SP
- Final state only one lepton-jet pair from LQ decay

Existing Searches and Models

Pair Production:

- Search for either $LQ^u = LQ^{2/3}$ or $LQ^d = LQ^{1/3}$
- These have two possible decay modes, involving either a charged lepton or a neutrino

→ Parameter space: **branching ratio** of these decay modes and **LQ mass**



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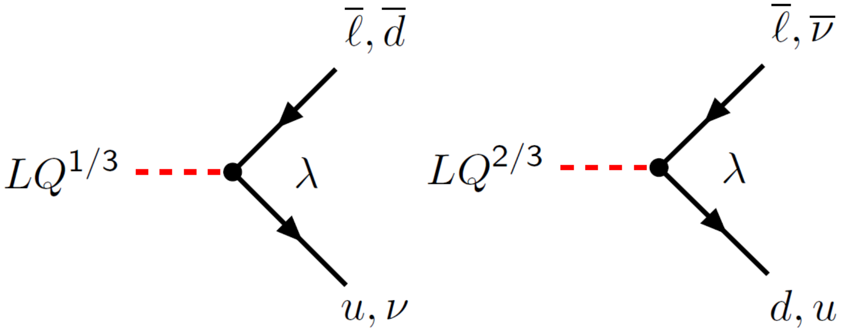
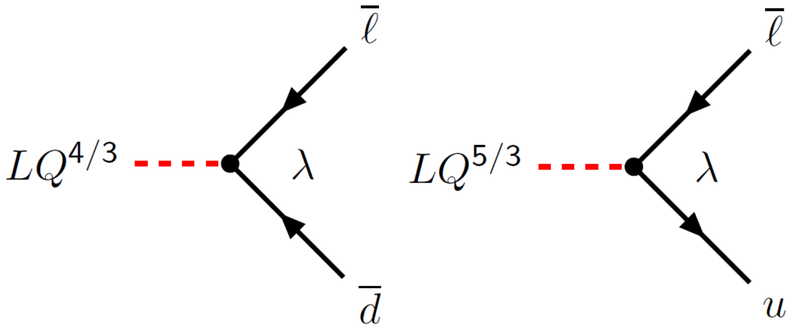


NB: Signatures with charged leptons can be interpreted as coming from $LQ^{4/3}$ or $LQ^{5/3}$, where the branching ratio can be set to 1



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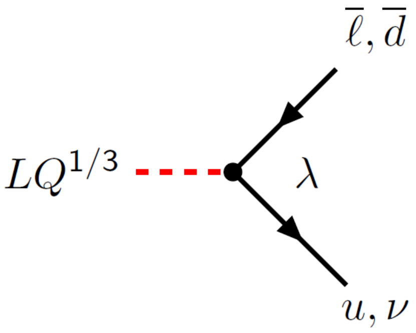
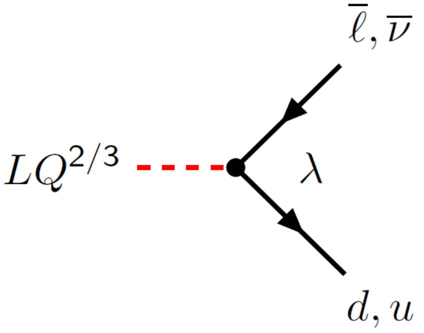
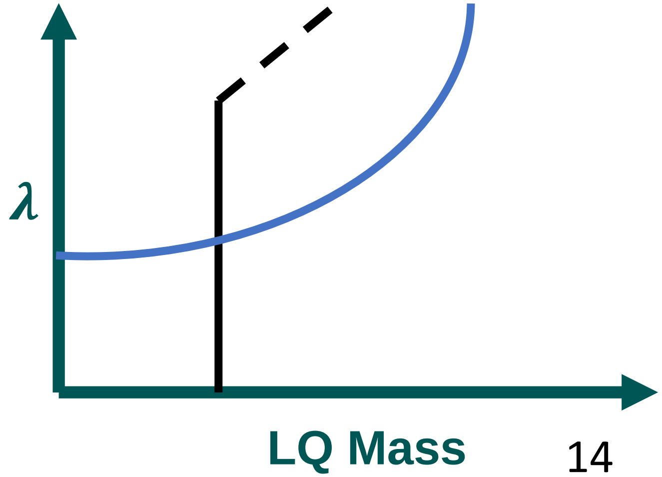




Single Production:

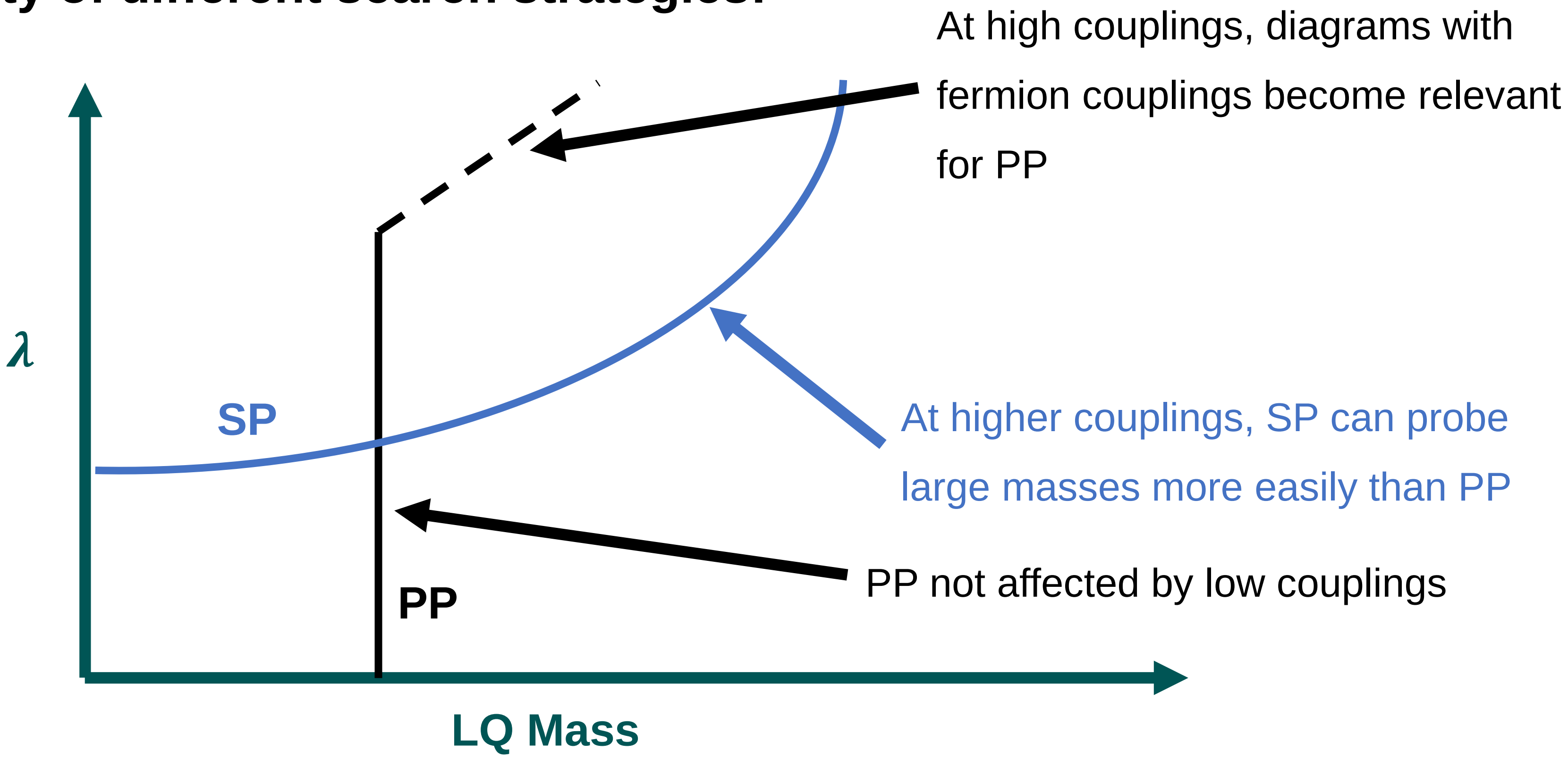
- Decide for model with **one** decay mode
- Parameter space: **LQ-to-fermion coupling** λ and **LQ mass**

Sensitivity Estimates



Sensitivity of different Strategies

Complementarity of different search strategies:



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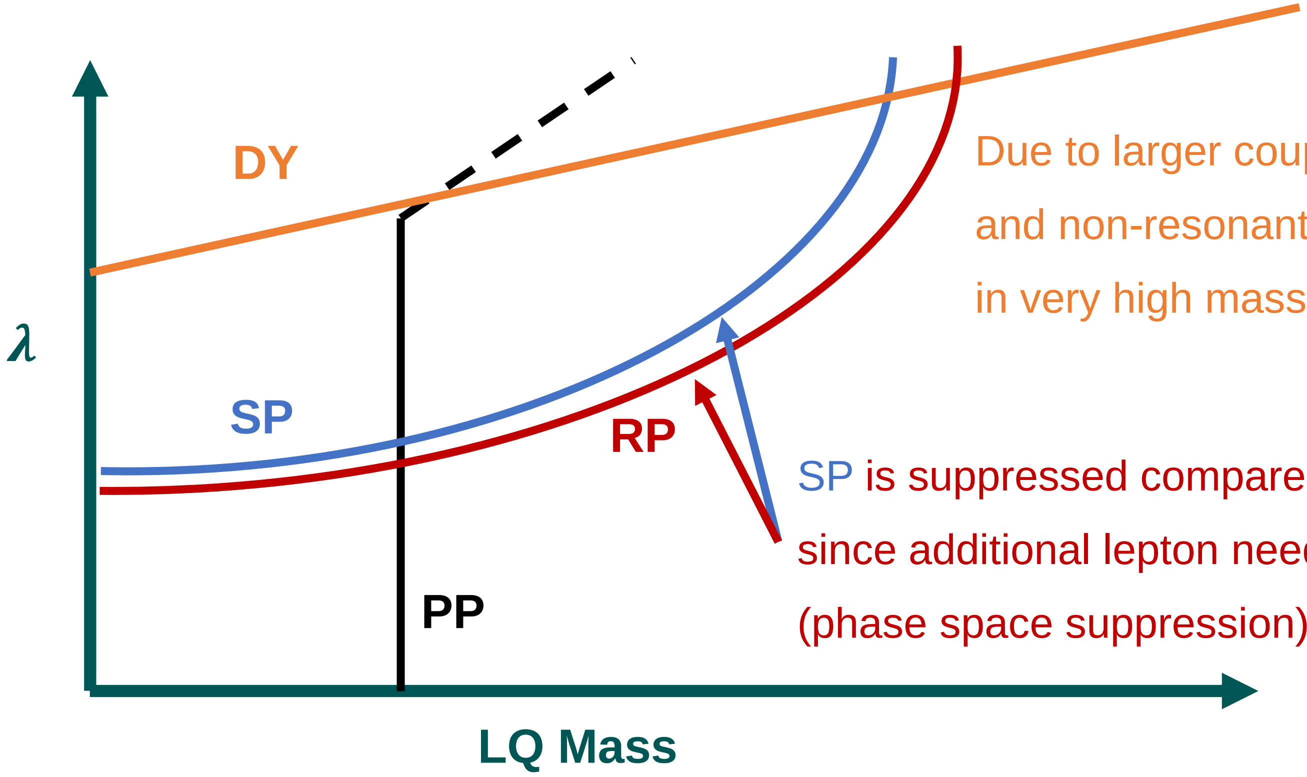


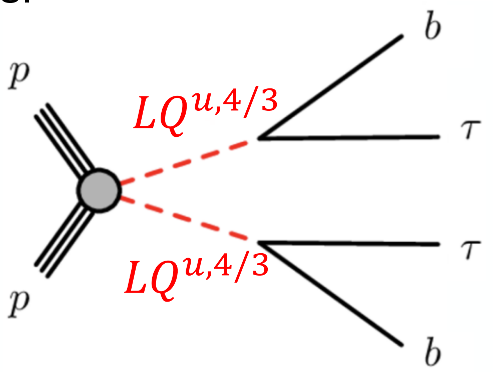
Due to larger coupling dependency and non-resonant LQ, DY dominates in very high mass + coupling regime

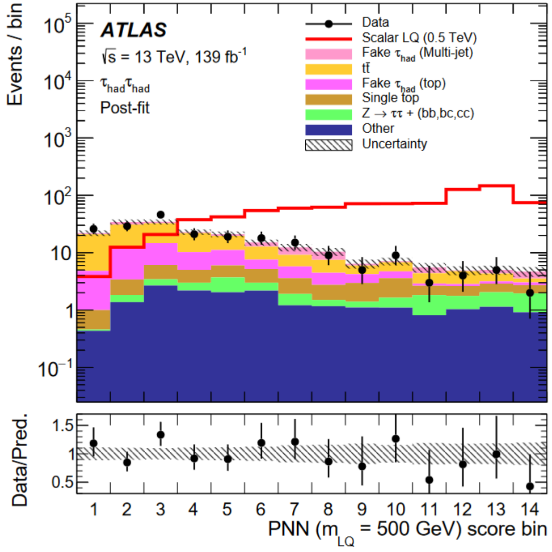
SP is suppressed compared to RP since additional lepton needed (phase space suppression)

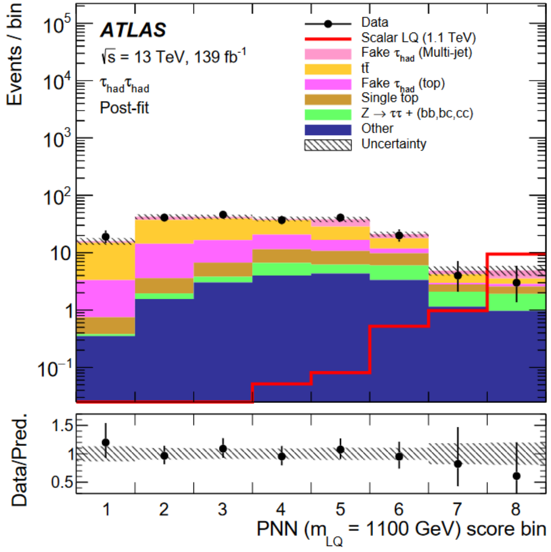
Existing ATLAS Searches

PP of 3rd Generation Leptoquarks

- LFV in the $R(D^{(*)})$ measurement causes large focus on 3rd generation couplings!
- As an example: CERN-EP-2022-267, submitted in March 2023
  - Look for **2 tau, 2 bottom** signature → two signal regions, targeting full hadronic $\tau_{had}\tau_{had}$ and semi-leptonic $\tau_{lep}\tau_{had}$ tau signatures
  - At least two jets required, of which one or two need to be b-tagged



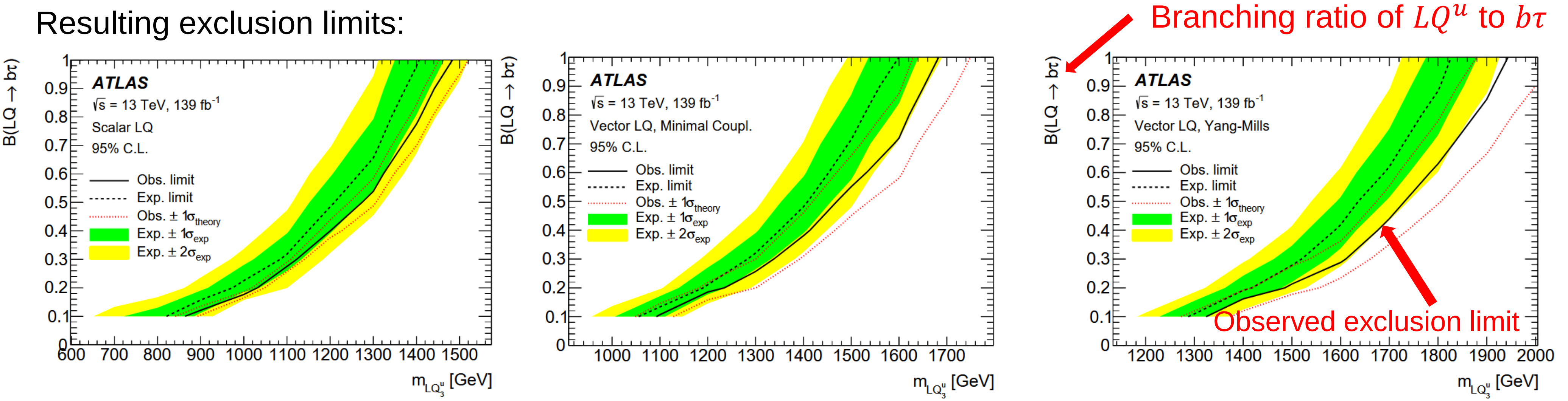




- **Parametrised Neural Network** (PNN):
  - LQ mass additional parameter!
  - Trained with kinematic/angular observables of above objects
  - E.g. sum of above object p_T's: $\boldsymbol{s_T}$
  - Discriminate against main top-quark background

PP of 3rd Generation Leptoquarks

- Background estimation using control regions (CRs):
  - Defined top CR to determine s_T-dependent reweighting factors to normalise MC to data (top backgrounds are over-estimated by MC at high top p_T)
  - CR to estimate rate of non-tau jets being misidentified as taus (fake factor) → multi-jet background
  - Z+jets CR to normalise MC to data
- Resulting exclusion limits:

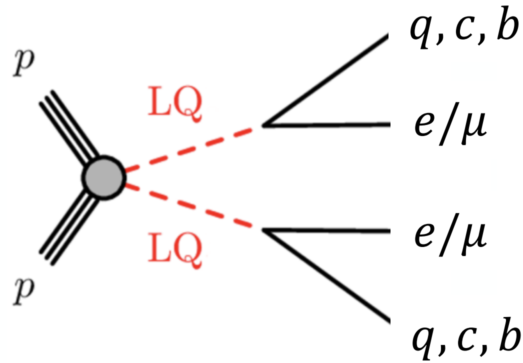


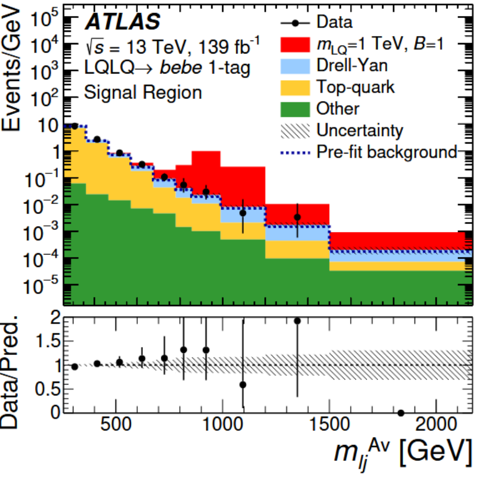
→ Excluded scalar LQs up to 1.49 TeV, vector LQs up to 1.69 (1.96) TeV for minimal (Yang-Mills) coupling

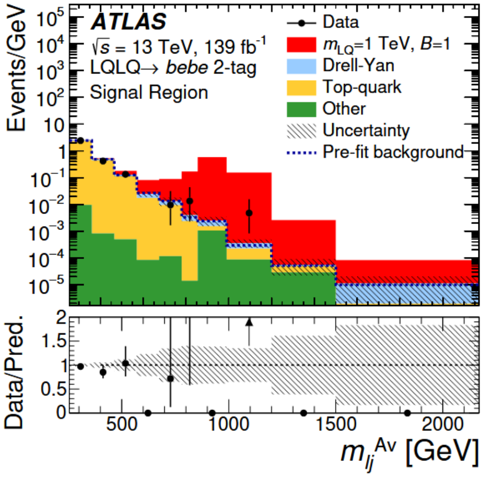
PP with other Generations

- Searches for LQs with couplings to 1st and 2nd generation fermions part of the ATLAS program, too
- Latest example: JHEP10 (2020) 112 looking into PP of scalar LQs with electrons or muons in the final state
  - Preselection requires $e^+e^-/\mu^+\mu^- + \geq$ **2 jets**
  - Find LQ candidates through two lepton-jet pairs closest in invariant mass
  - Main search variable is the average of the two invariant masses

$$\rightarrow m_{lj}^{Av} = (m_{lj}^{max} + m_{lj}^{min})/2$$



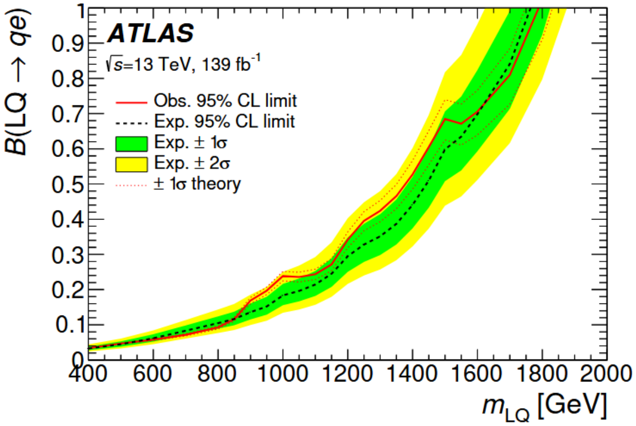


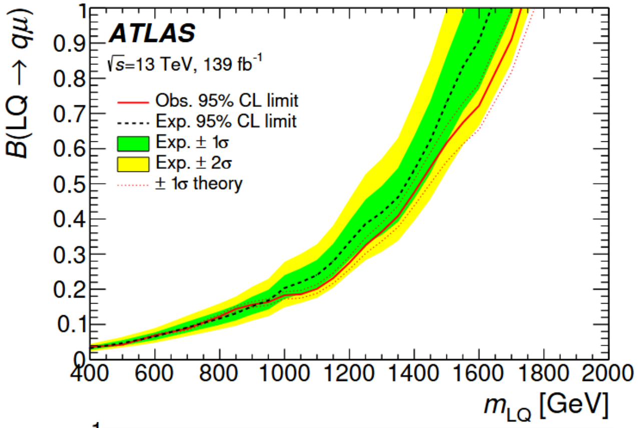


- Background estimation using **dedicated CRs** for top and DY backgrounds
- Search performed for LQ decays to light quarks q, charms c and bottoms b where in the latter two cases additional c/b-tag information on the jets is used

PP with other Generations

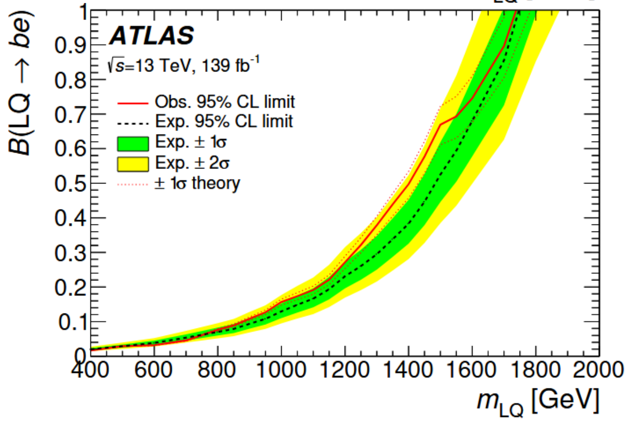
- Latest example: JHEP10 (2020) 112 looking into PP of scalar LQs with electrons or muons in the final state

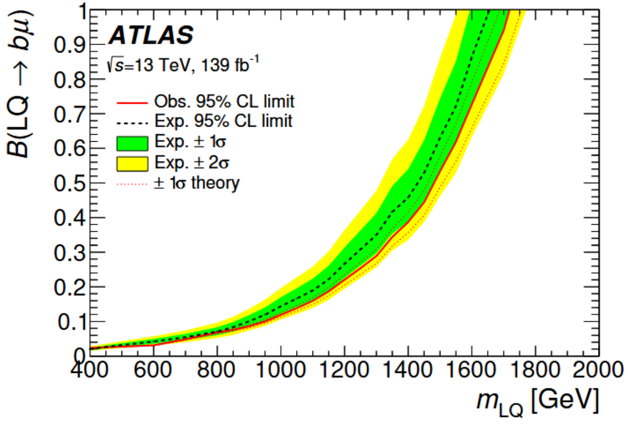




$$LQ \to e/\mu + q$$

$$LQ \to e/\mu + b$$

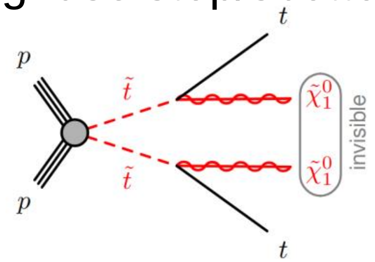


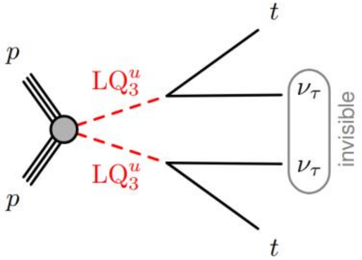


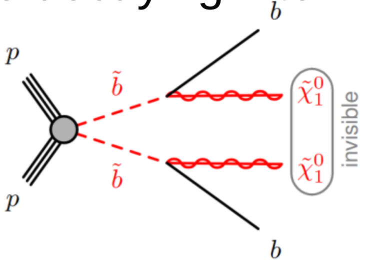
→ Limits for electron (muon) coupling at 1.8 (1.7) TeV, only slightly weaker for heavy quarks

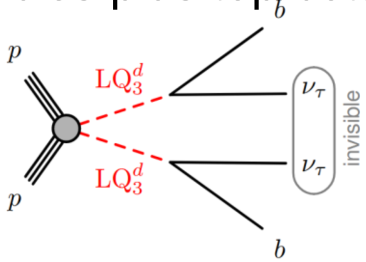
PP as SUSY Reinterpretation

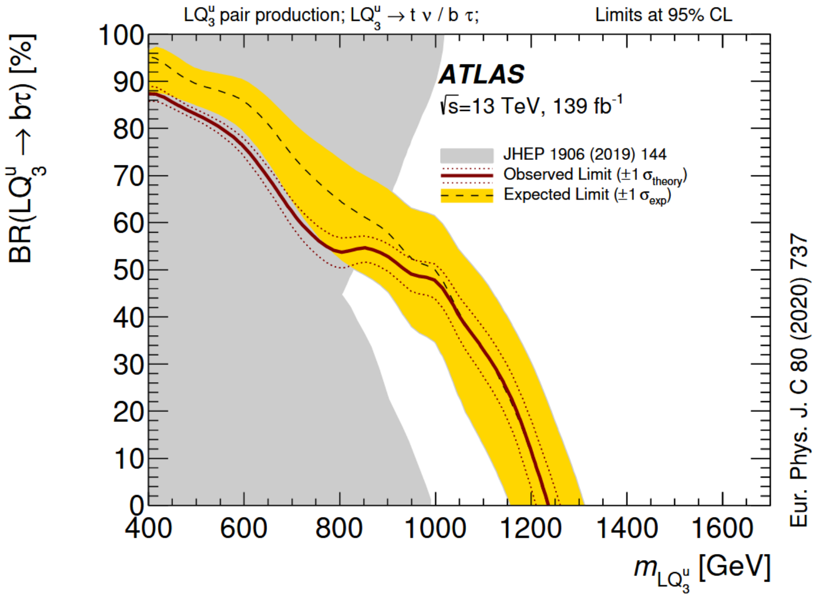
- Leptoquark searches can be combined with Supersymmetry (SUSY) searches!
- E.g. use stop/sbottom searches: scalar new particle decaying into invisibles plus top/bottom

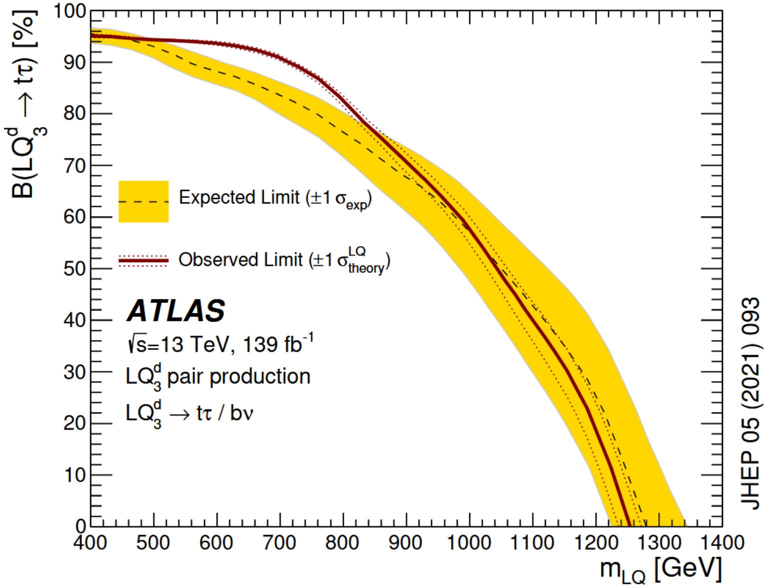






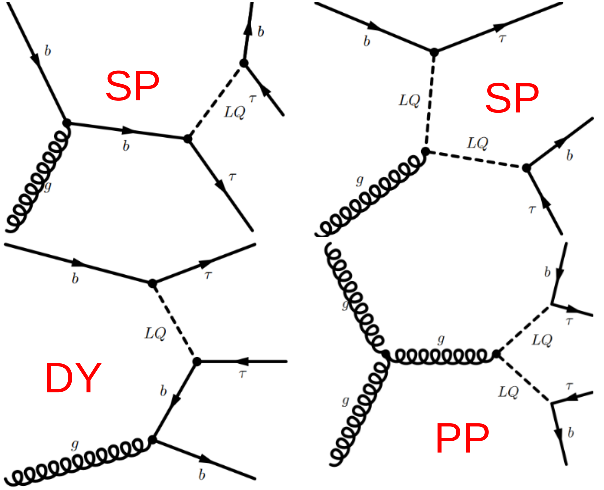


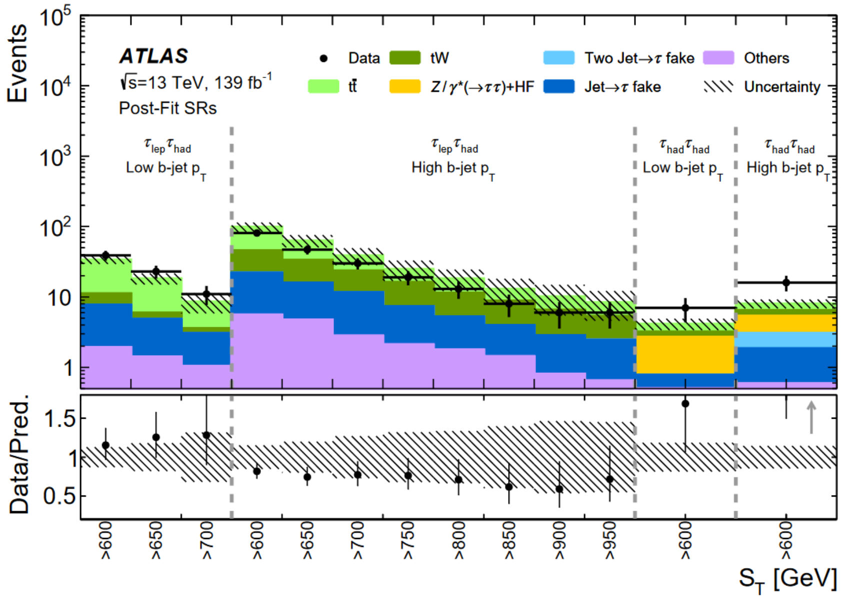




PP + SP + DY Search

- Very recent search covers both PP and SP (and DY + jet) diagrams (submitted as arXiv:2305.15962)
- Look for **2 tau, ≥ 1 bottom** signature → as in previous analysis separate $\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$ SRs
- Split each SR in high/low-p_T b-jet region targeting non-resonant/resonant LQs
- Previously defined p_T-sum variable s_T as main observable

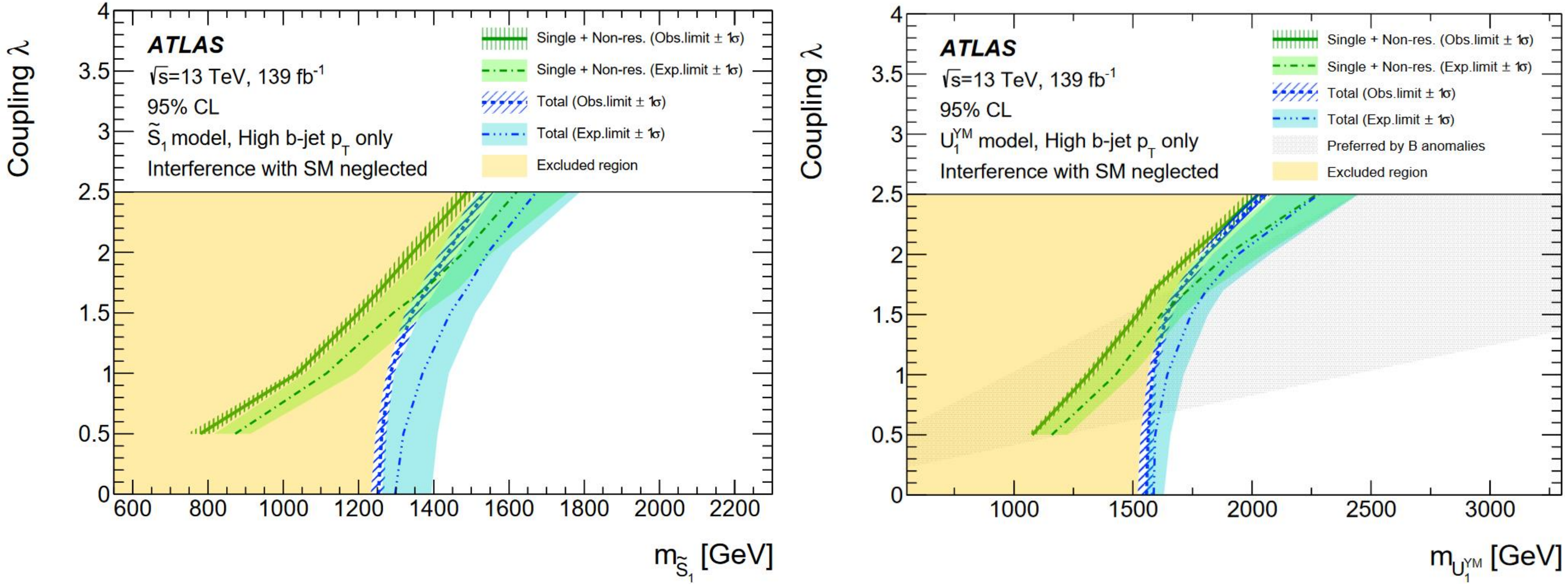




- Background estimation using dedicated CRs for top backgrounds and Z + heavy flavor (HF), fake factor method used for multi-jet background

PP + SP + DY Search

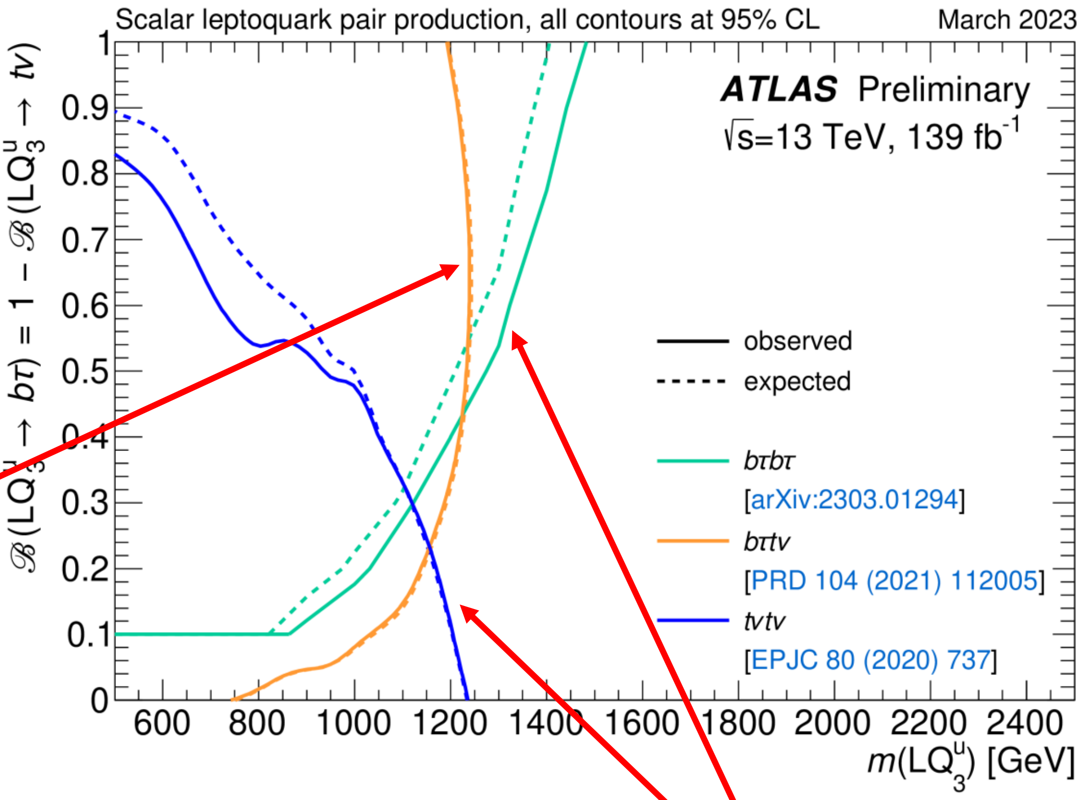
- Very recent search covers both PP and SP (and DY + jet) diagrams (submitted as arXiv:2305.15962)
- Derived exclusion limits illustrative example of interplay of different production modes



→ Limits for scalar $LQ^{4/3}$ model and vector $LQ^{2/3}$ model (only Yang-Mills scenario shown above)

Summary Plots

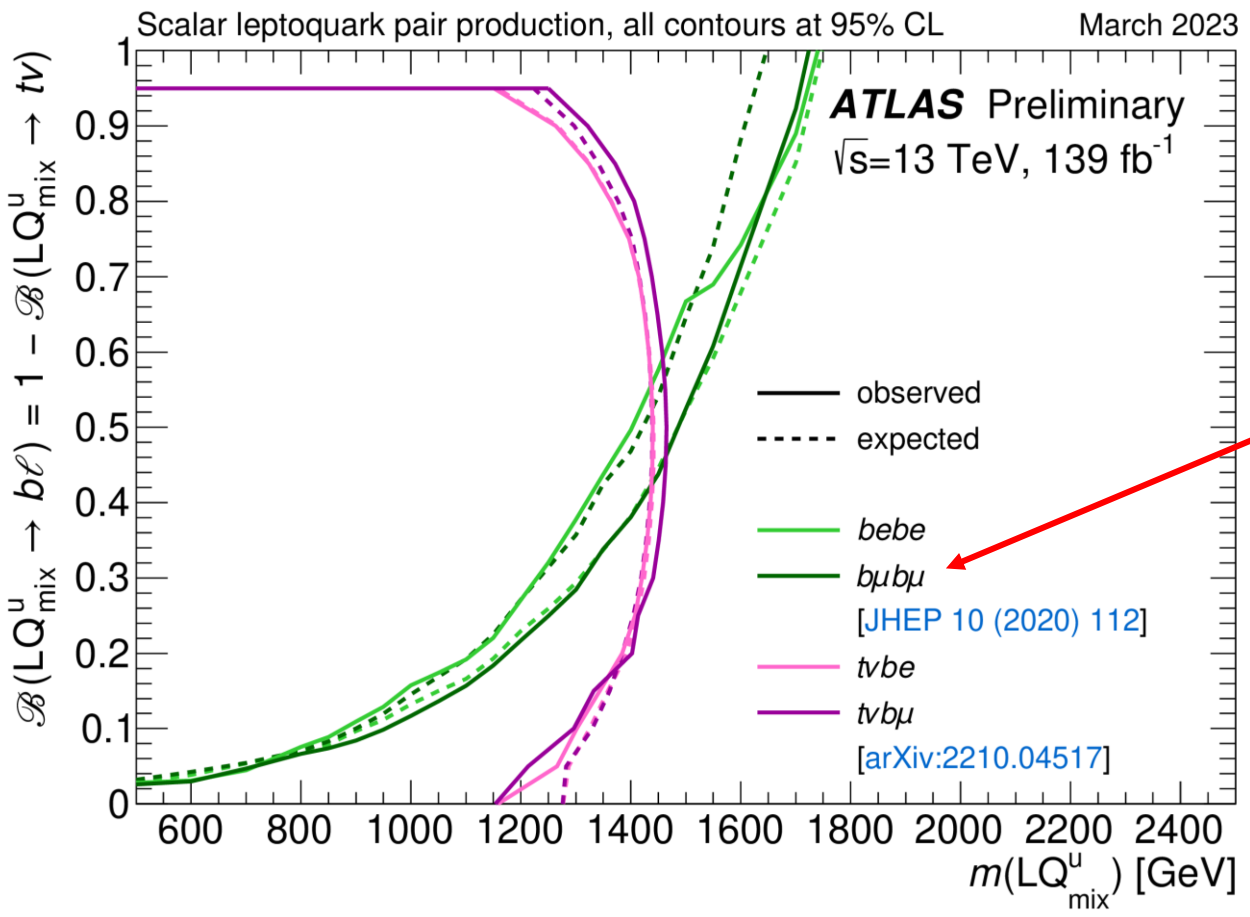
PP Summary 3rd Generation Scalars



Final state with both decay modes → strong exclusion at intermediate branching ratios

Focus on one decay mode → strong exclusion at small/high branching ratios

PP Summary Mixed Decays Scalars

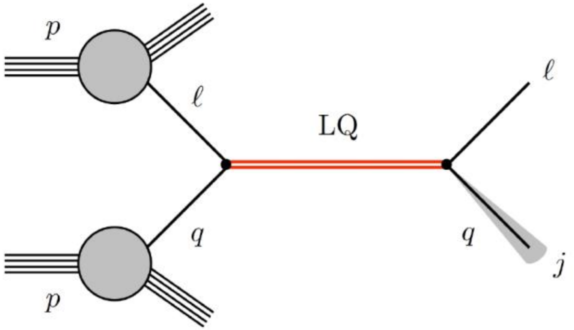


Mixture of 3rd generation quarks and 1st/2nd generation leptons

Outlook: Resonant Production

Resonant Production Search

- First ATLAS search for the resonant production currently ongoing
- Possibility to conduct this search since publication of lepton PDFs in 2020 [(JHEP 08 (2020) 019)]



JHEP 03 (2021) 279

PRL 125 (2020) 23

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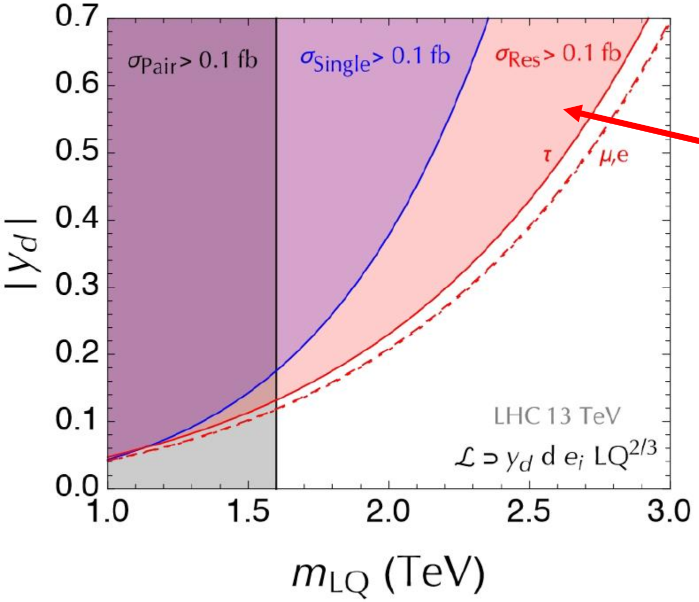
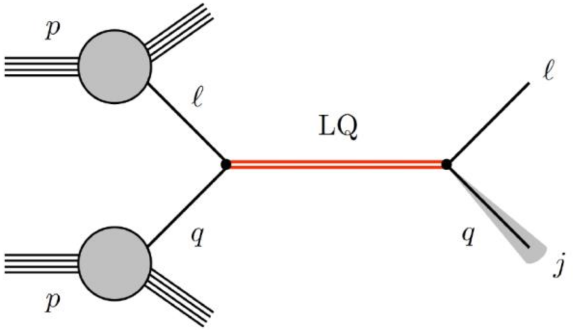


JHEP 03 (2021) 279

Competitive to SP searches due to higher cross sections



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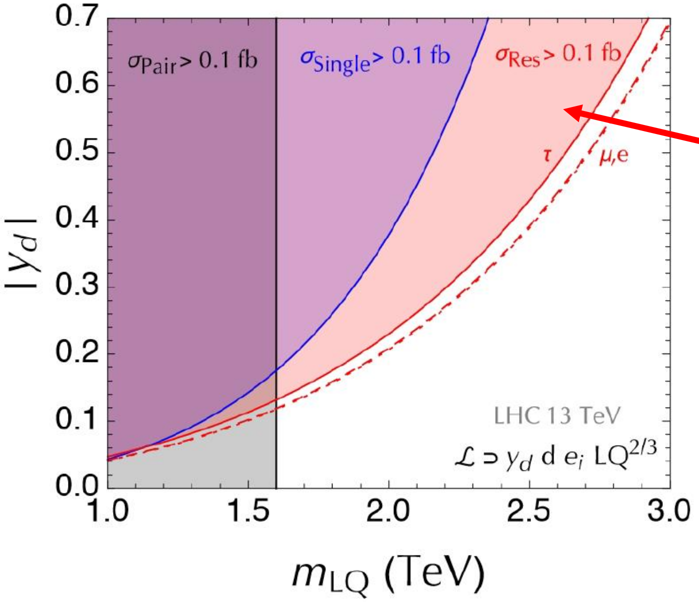
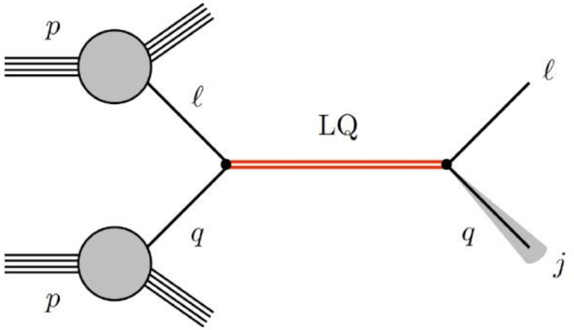
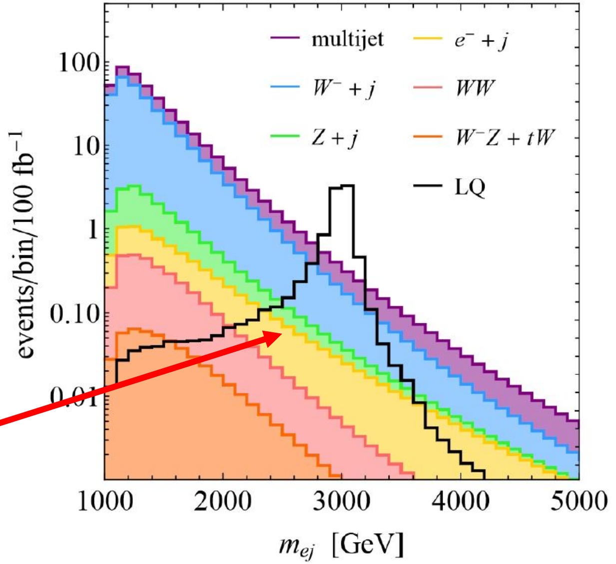


JHEP 03 (2021) 279

Competitive to SP searches due to higher cross sections

Invariant mass of the lepton-jet final state as an estimate of the LQ mass





PRL 125 (2020) 23

Resonant Production Search Strategy

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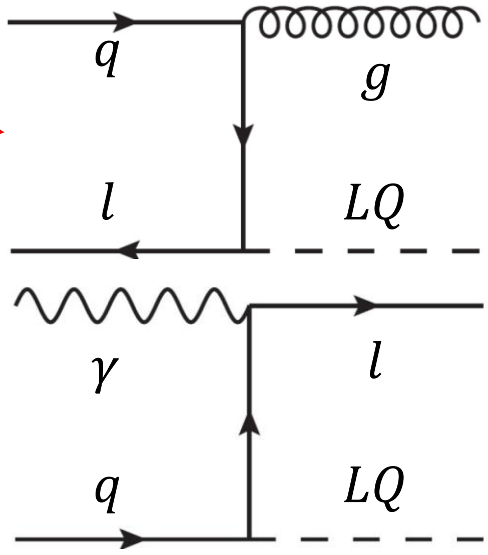

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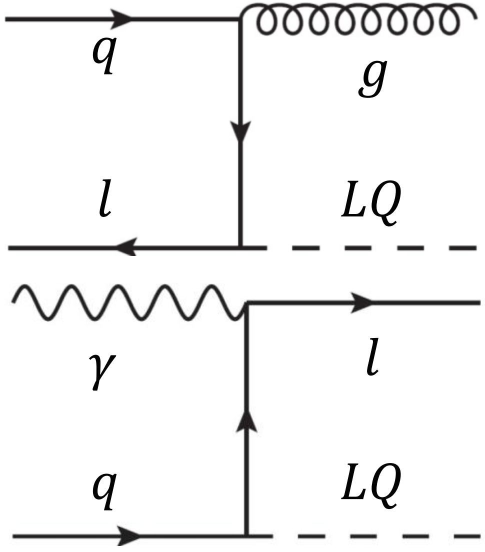
$$\begin{pmatrix} \lambda_{ue} & \lambda_{u\mu} & \lambda_{u\tau} \\ \lambda_{ce} & \lambda_{c\mu} & \lambda_{c\tau} \\ \lambda_{te} & \lambda_{t\mu} & \lambda_{t\tau} \end{pmatrix} \qquad \begin{pmatrix} \lambda_{de} & \lambda_{d\mu} & \lambda_{d\tau} \\ \lambda_{se} & \lambda_{s\mu} & \lambda_{s\tau} \\ \lambda_{be} & \lambda_{b\mu} & \lambda_{b\tau} \end{pmatrix}$$



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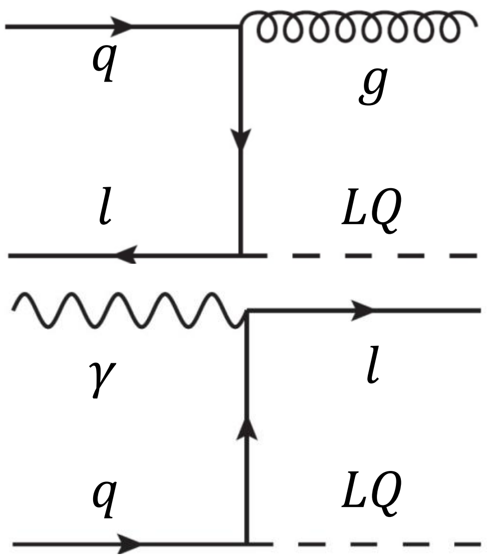

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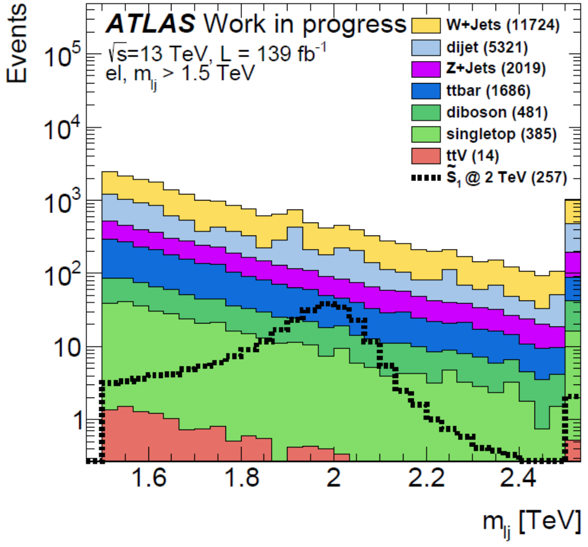
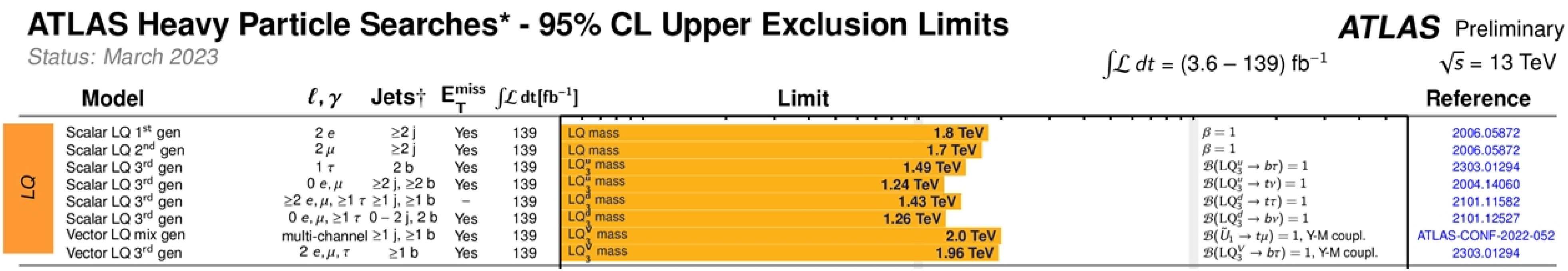


- Main variable is the invariant mass of the highest p_T lepton and jet
- Next steps:
  - Produce NLO MC samples with ATLAS simulation
  - Background estimation (CRs or fit the background using a smoothly falling distribution?)

Conclusion

- Leptoquarks are an important part of unifying the interactions of the SM
- Flavour anomalies in B-meson physics possibly hints towards Leptoquarks
- ATLAS has a very diverse and extensive search programme when it comes to Leptoquarks
  - Main focus until now on pair and single production → exclusion of Leptoquark masses between 1 TeV and 2 TeV
  - Drell-Yan and resonant production will be considered in coming searches



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

Status: March 2023

ATLAS Preliminary

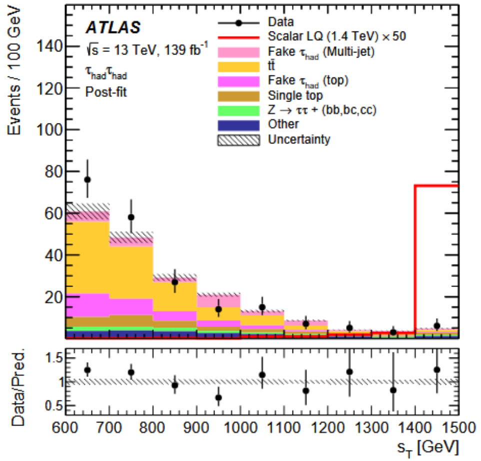
$\int \mathcal{L}\,dt = (3.6 - 139)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 13$ TeV

	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	1.49 TeV	$\mathcal{B}(\mathrm{LQ}_3^u \to b\tau) = 1$	2303.01294
	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 mix gen	multi-channel	≥ 1 j, ≥ 1 b	Yes	139	LQ_3^V mass	2.0 TeV	$\mathcal{B}(\tilde{U}_1 \to t\mu) = 1$, Y-M coupl.	ATLAS-CONF-2022-052
	Vector LQ 3rd gen	$2\ e, \mu, \tau$	≥ 1 b	Yes	139	LQ_3^V mass	1.96 TeV	$\mathcal{B}(\mathrm{LQ}_3^V \to b\tau) = 1$, Y-M coupl.	2303.01294

BACKUP

PP of 3rd Generation Leptoquarks

- As an example: CERN-EP-2022-267, submitted in March 2023
  - Look for **2 tau, 2 bottom** signature → two signal regions, targeting full hadronic $\tau_{had}\tau_{had}$ and semi-leptonic $\tau_{lep}\tau_{had}$ tau signatures
  - Training of PNN (arXiv:1601.07913) to discriminate against main top backgrounds



Preselection

	$\tau_{lep}\tau_{had}$ channel	$\tau_{had}\tau_{had}$ channel
e/μ selection	= 1 'signal' e or μ $p_T^e > 25, 27$ GeV $p_T^\mu > 21, 27$ GeV	No 'veto' e or μ
$\tau_{had\text{-}vis}$ selection	= 1 $\tau_{had\text{-}vis}$ $p_T^\tau > 100$ GeV	= 2 $\tau_{had\text{-}vis}$ $p_T^\tau > 100, 140, 180\ (20)$ GeV
Jet selection	≥ 2 jets $p_T^{jet} > 45\ (20)$ GeV 1 or 2 b-jets	
Additional selection	Opposite charge e, μ, τ_{had} and τ_{had} $m_{\tau\tau}^{MMC} \notin 40 - 150$ GeV $E_T^{miss} > 100$ GeV $s_T > 600$ GeV	

PNN Inputs

Variable	$\tau_{lep}\tau_{had}$ channel	$\tau_{had}\tau_{had}$ channel
$\tau_{had\text{-}vis}\ p_T^0$	✓	✓
s_T	✓	✓
N_{b-jets}	✓	✓
$m(\tau, \text{jet})_{0,1}$		✓
$m(\ell, \text{jet}),\ m(\tau_{had}, \text{jet})$	✓	
$\Delta R(\tau, \text{jet})$	✓	✓
$\Delta\phi(\ell, E_T^{miss})$	✓	
$E_T^{miss}\ \phi$ centrality	✓	✓

PP with other Generations

- Latest example: JHEP10 (2020) 112 looking into PP of scalar LQs with electrons or muons in the final state
  - Preselection requires $\boldsymbol{e^+e^-/\mu^+\mu^- + \geq 2}$ **jets**

Preselection

Preselection		
2 oppositely charged leptons (e, μ) 2 or more jets $p_{\mathrm{T}}^{e} > 27$ GeV, $\lvert\eta_e\rvert < 2.47$; $p_{\mathrm{T}}^{\mu} > 27$ GeV, $\lvert\eta_\mu\rvert < 2.7$ $p_{\mathrm{T}}^{j} > 45$ GeV, $\lvert\eta_j\rvert < 2.5$ $p_{\mathrm{T}}^{\ell\ell} > 75$ GeV $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}} < 3.5\ \mathrm{GeV}^{1/2}$ $m_{\ell\ell} > 130$ GeV		
SB	SR	Top CR
ee or $\mu\mu$		$e\mu$
$0.2 < m^{\mathrm{asym}} < 0.4$	$m^{\mathrm{asym}} < 0.2$	

Side-Band Region and Top CR