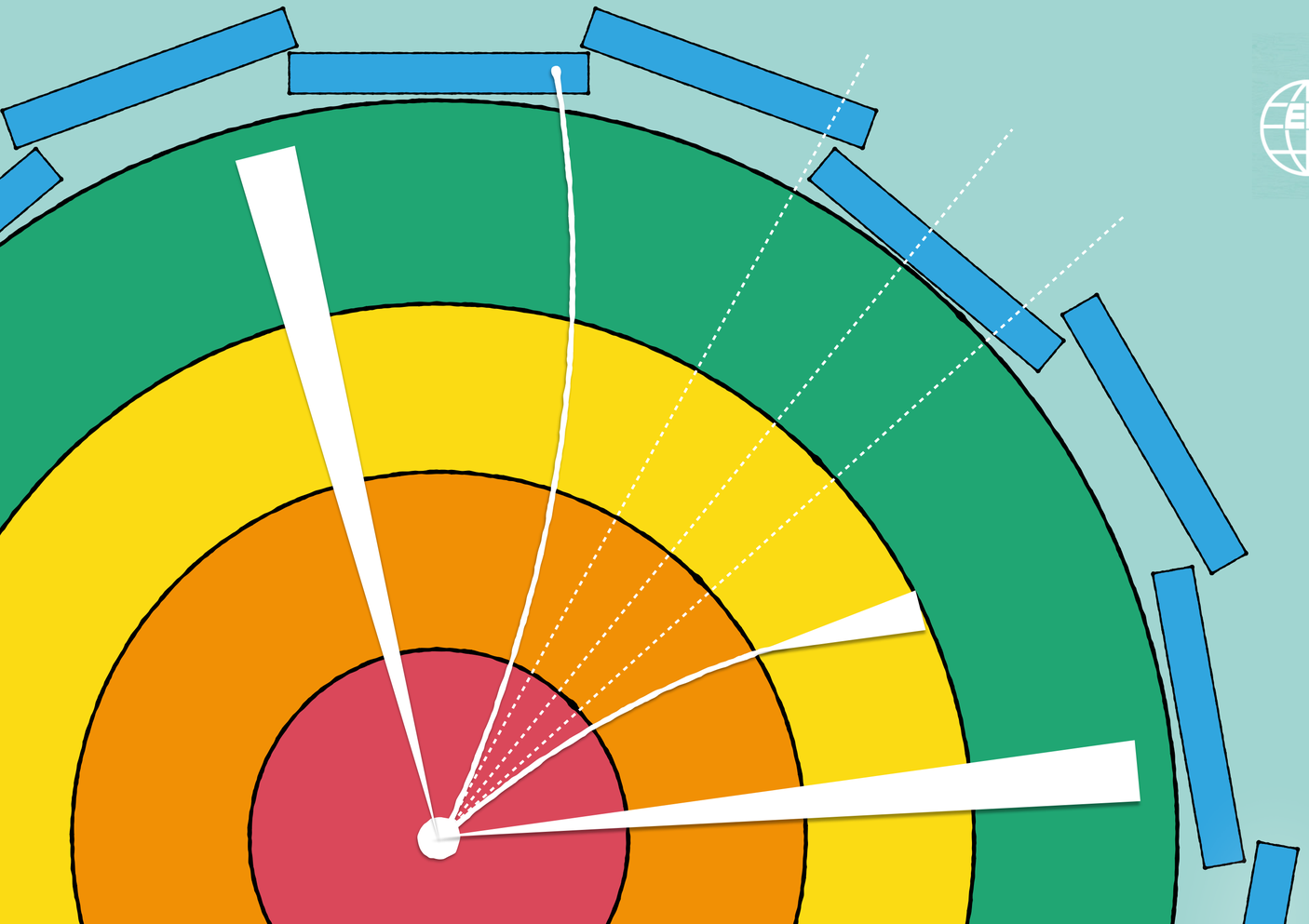
Searches for Leptoquarks with the ATLAS detector

Christian Appelt, *on behalf of the ATLAS collaboration*

22. Aug 2023

EPS HEP2023 HAMBURG



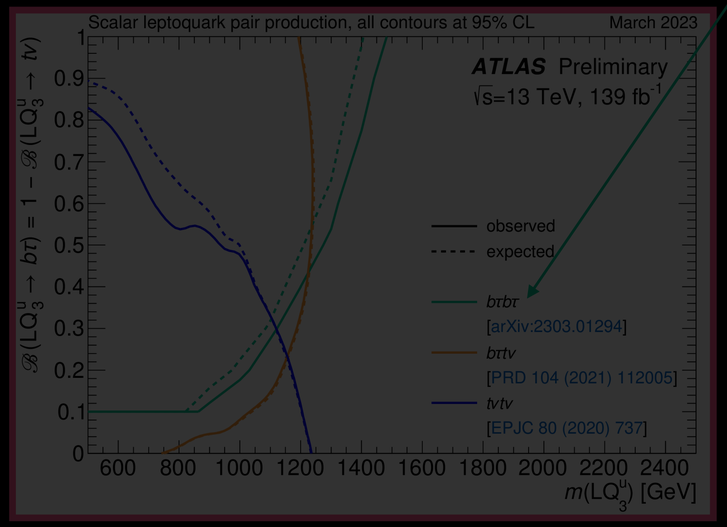
Why Leptoquarks?

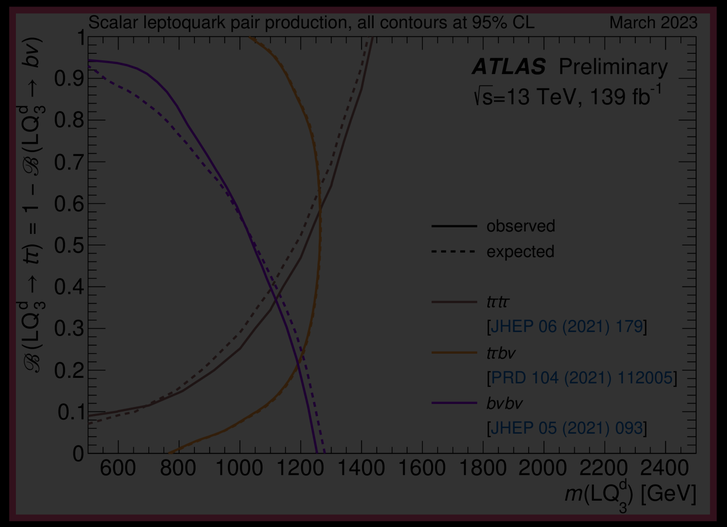
in a nutshell

- Many extensions to the SM predict particles known as Leptoquarks (LQ)*.
- LQs provide a connection between the lepton and quark sectors.
- LQs can be scalar (spin 0) or vector (spin 1) bosons.
- LQs carry colour and a fractional electric charge.
- LQs potentially explain hints of violations of lepton universality in flavour experiments (recent results from BaBar, Belle, and LHCb in B-meson decays).
- 4.2 σ deviation to the SM in the anomalous magnetic moment measurement could be caused by LQ contributions to the magnetic moment.

Scalar LQ_3 summary plots

Discussed in this talk + one more analysis!





[ATL-PHYS-PUB-2023-006]

* [Phys. Rev. D 10 (1 1974) 275, Phys. Rev. Lett. 32 (8 1974) 438, Nuclear Physics B 155 (1979) 237, Nuclear Physics B 168 (1980) 69, Physics Letters B 90 (1980) 125, Nuclear Physics B 292 (1987) 59, Physics Letters B 177 (1986) 377]

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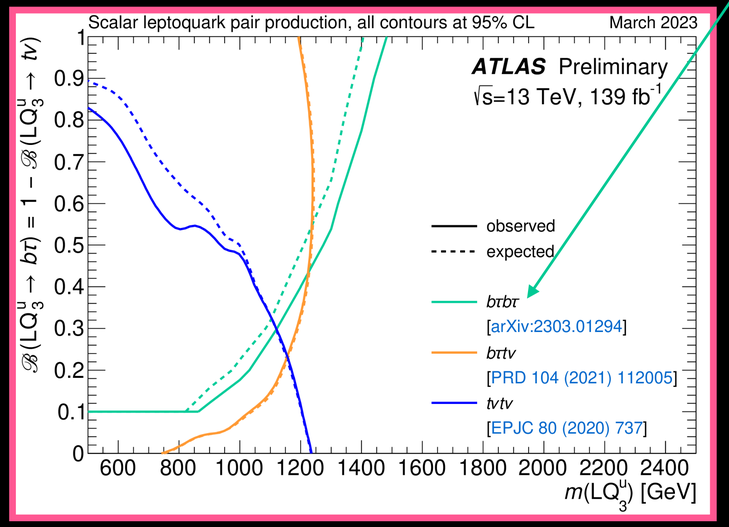

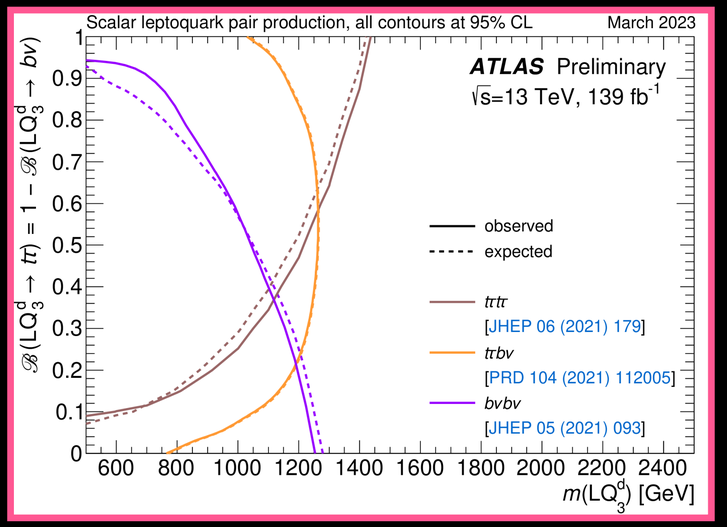

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Outline

Both in $\sqrt{s} = 13$ TeV pp collisions with $L = 139$ fb^{-1}

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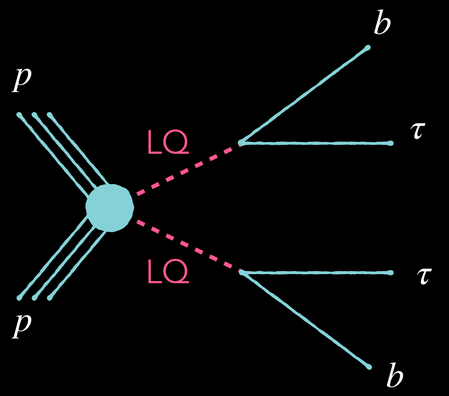
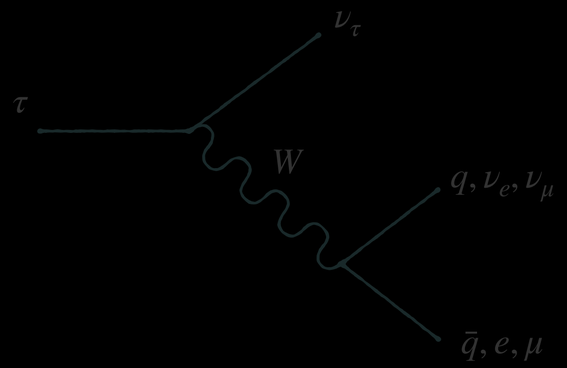


Search for pair production of third-generation leptoquarks decaying into a bottom quark and τ-lepton with the ATLAS detector.
[arXiv:2303.01294]
Submitted to: EPJC
March 2023

τ decays either hadronically or leptonically:



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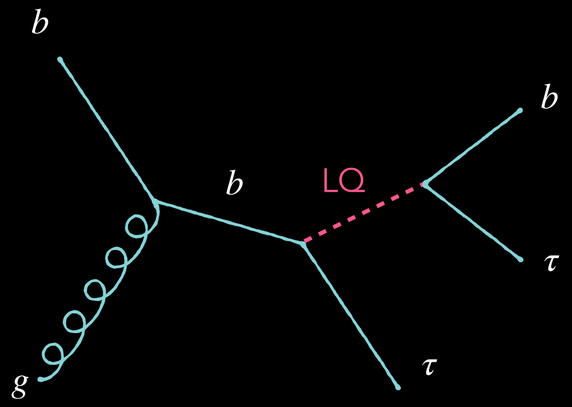

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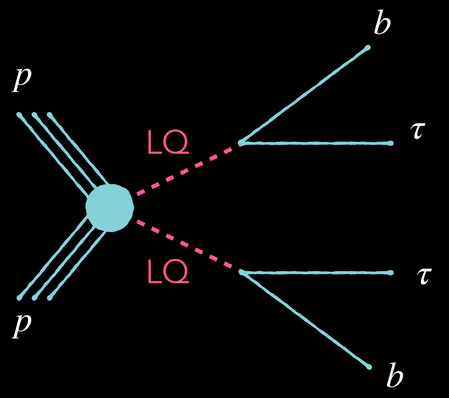

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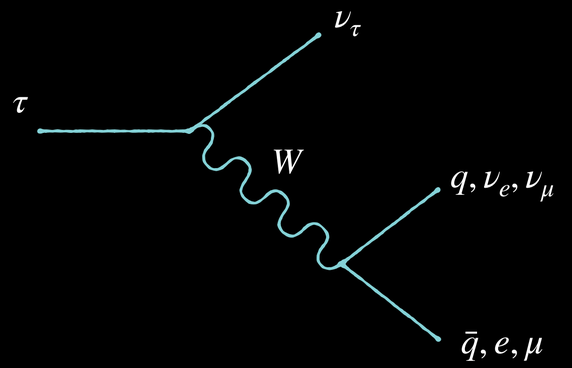

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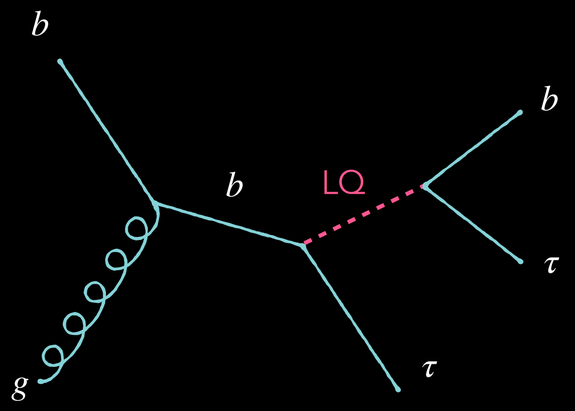

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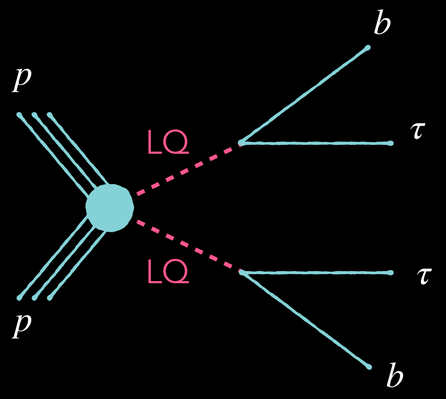
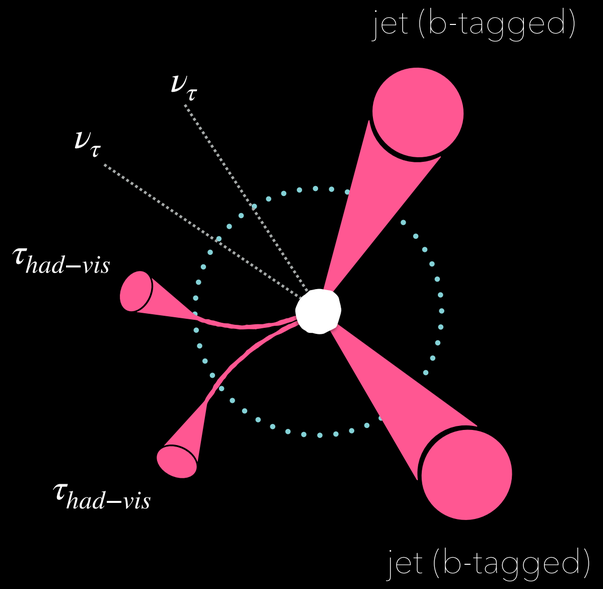


$\tau_{had}\tau_{had}$ channel



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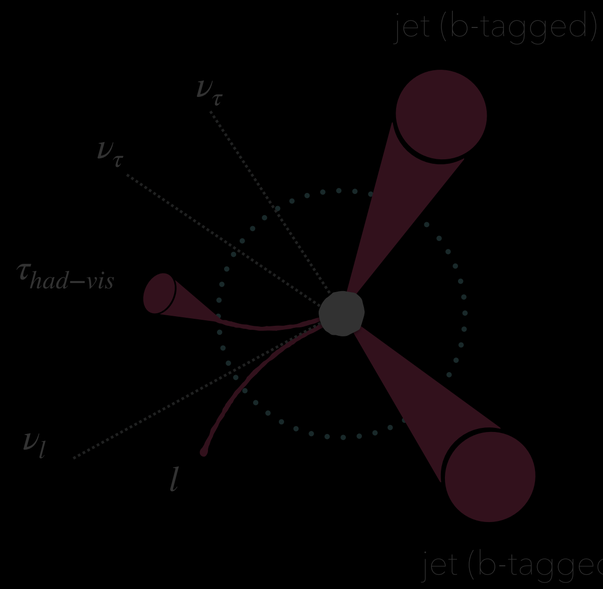

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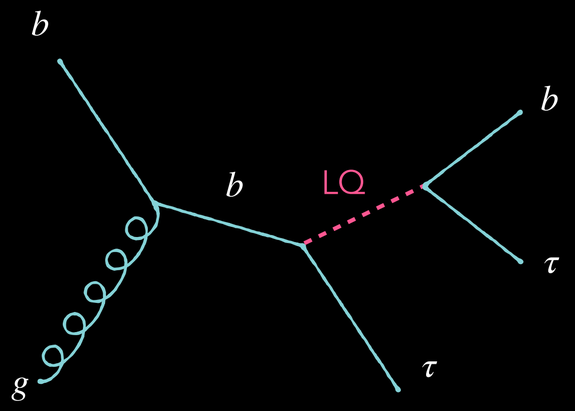

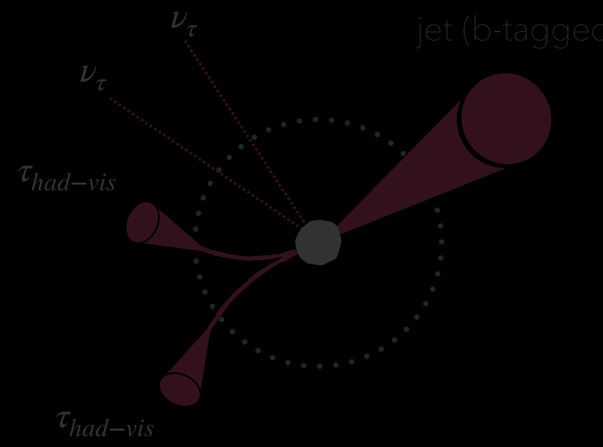

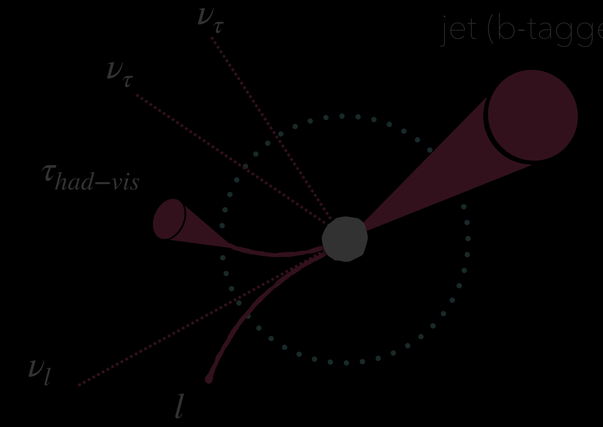

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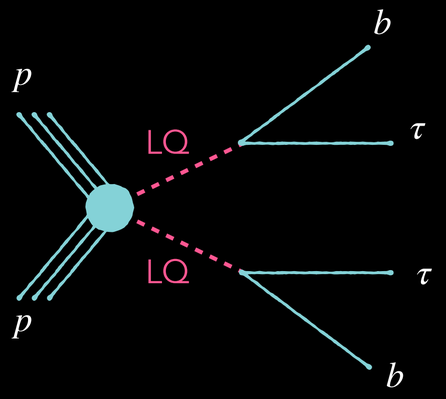

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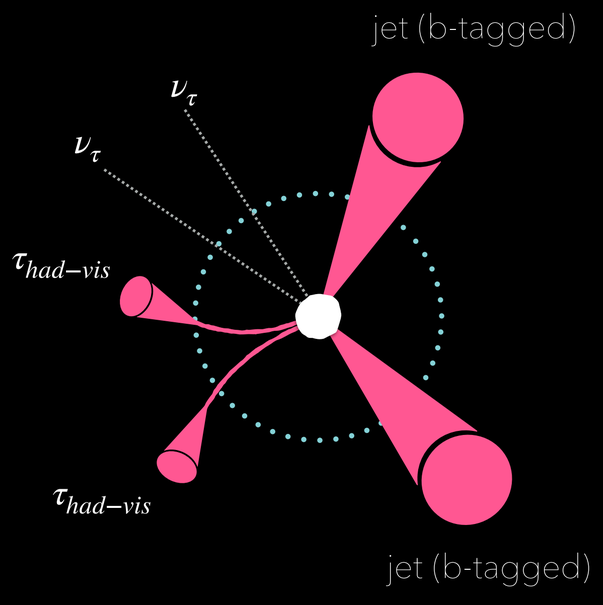

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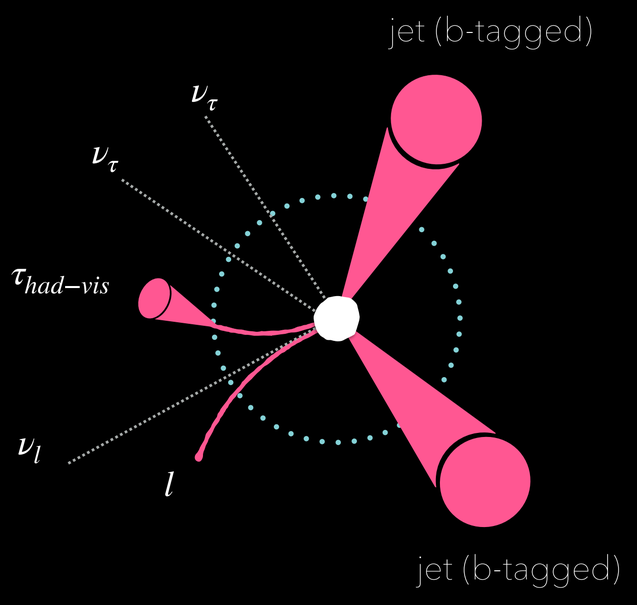

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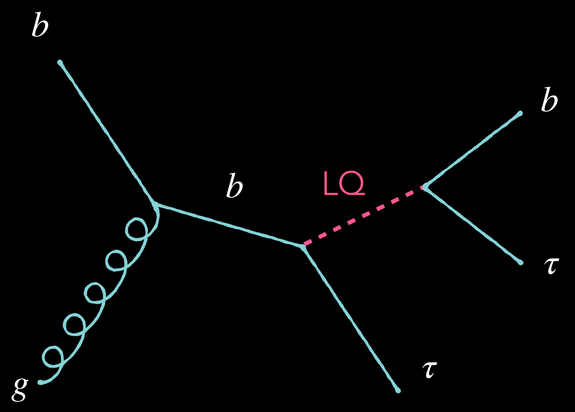

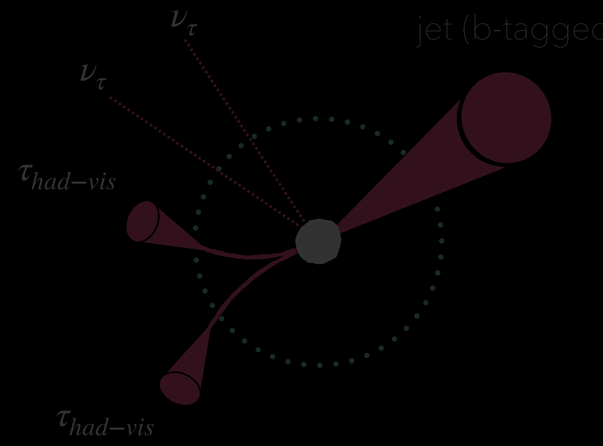

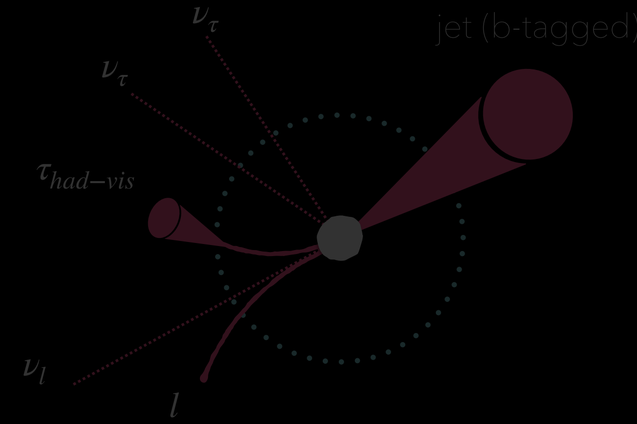

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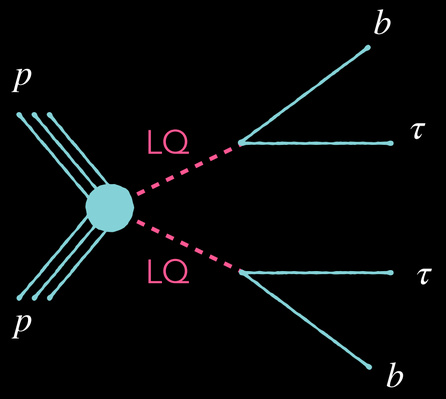

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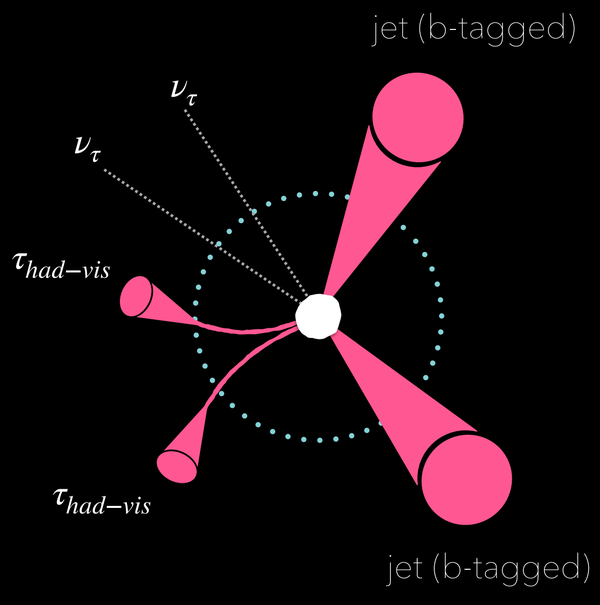

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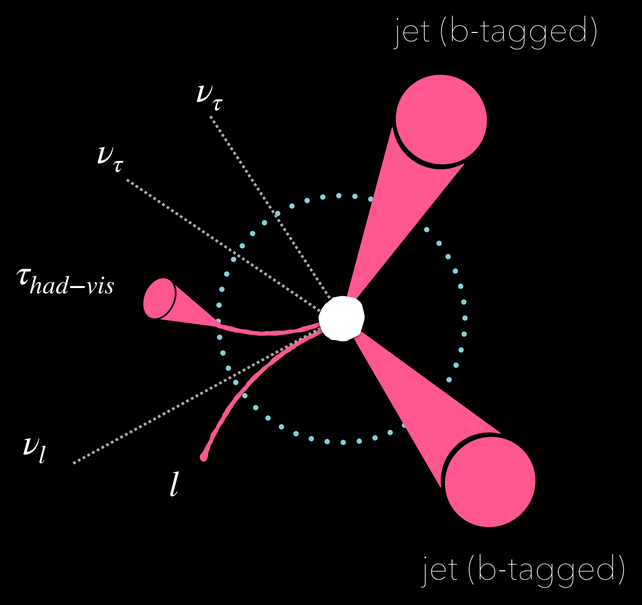

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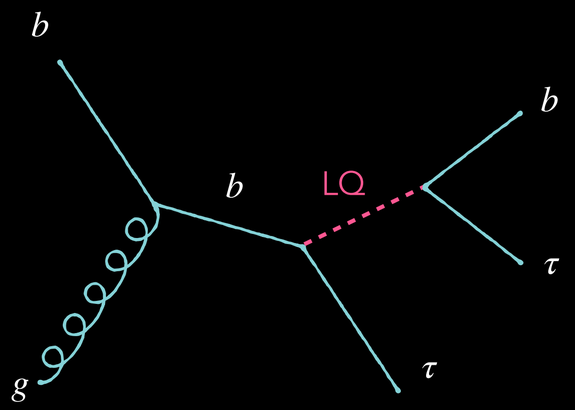

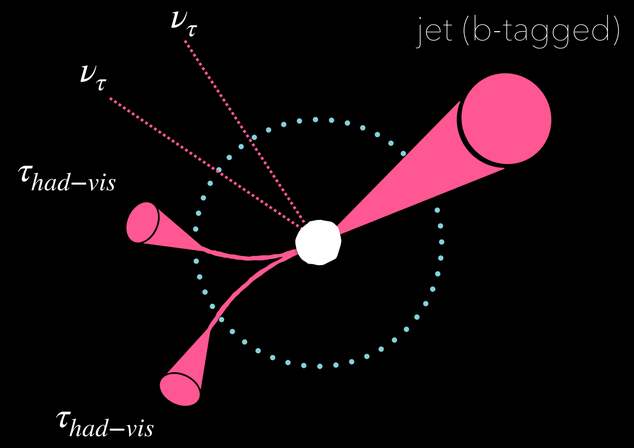

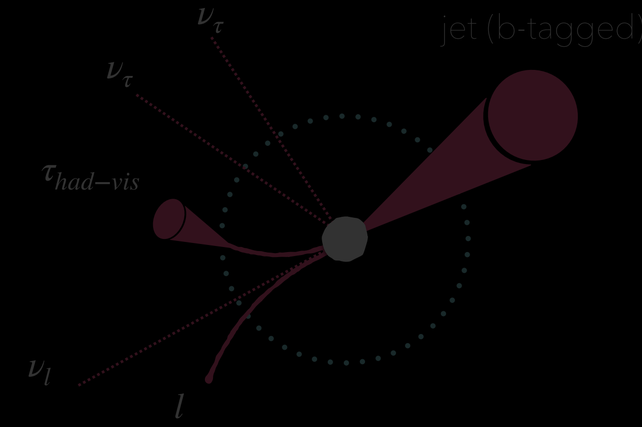

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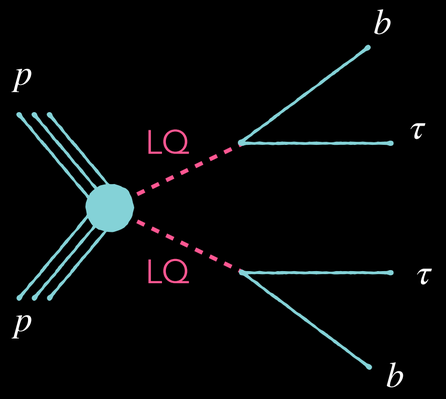

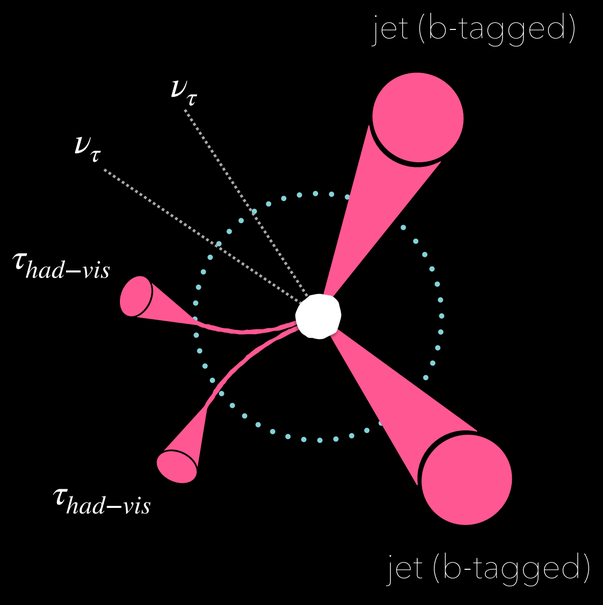

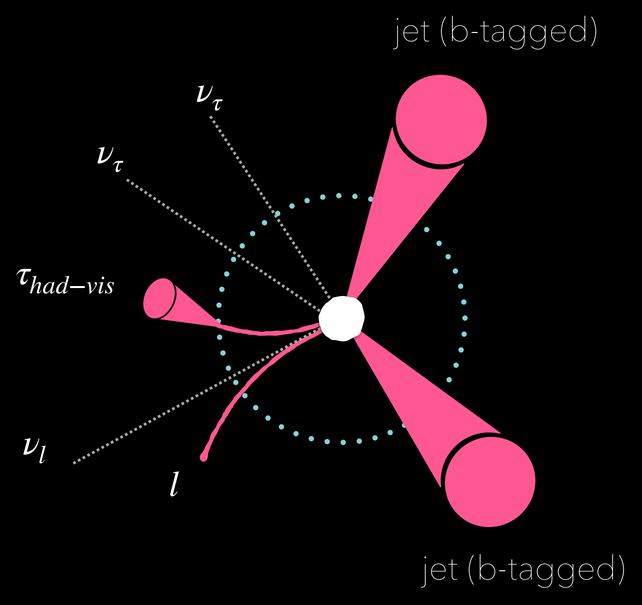

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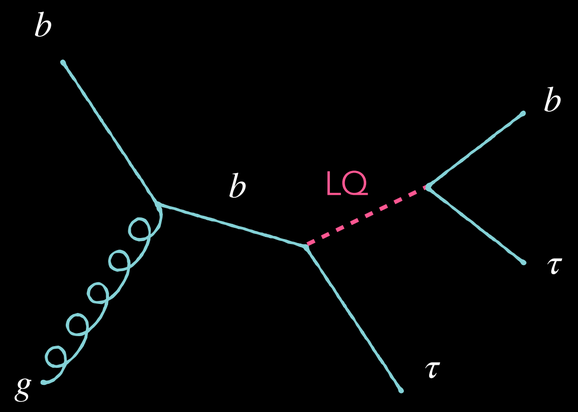

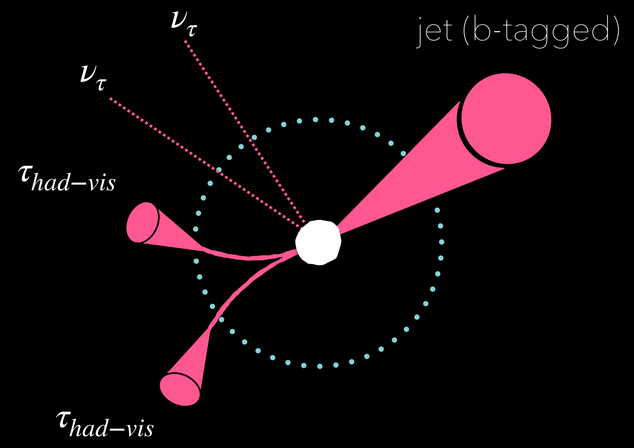

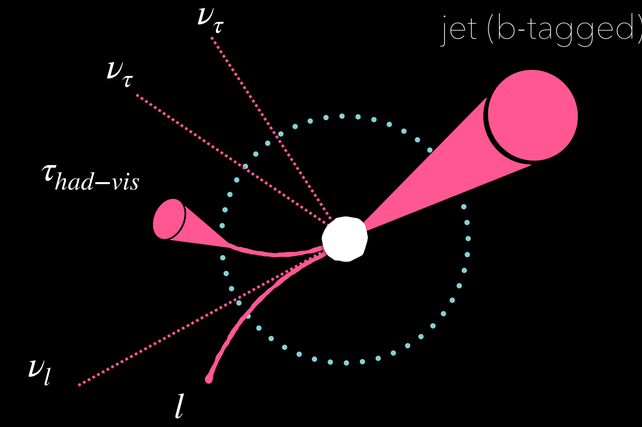

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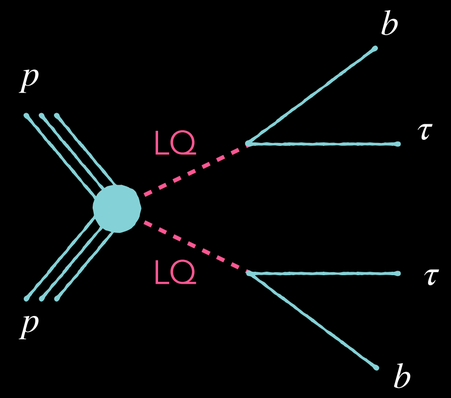
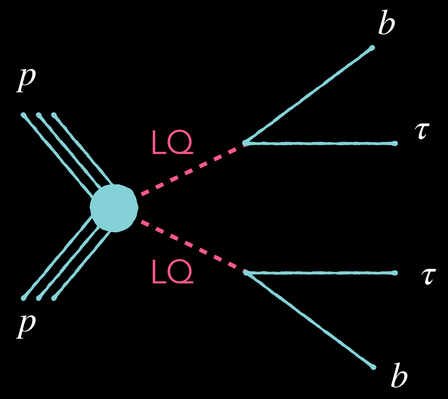


1) LQ pair production analysis details

[arXiv:2303.01294]



Selection

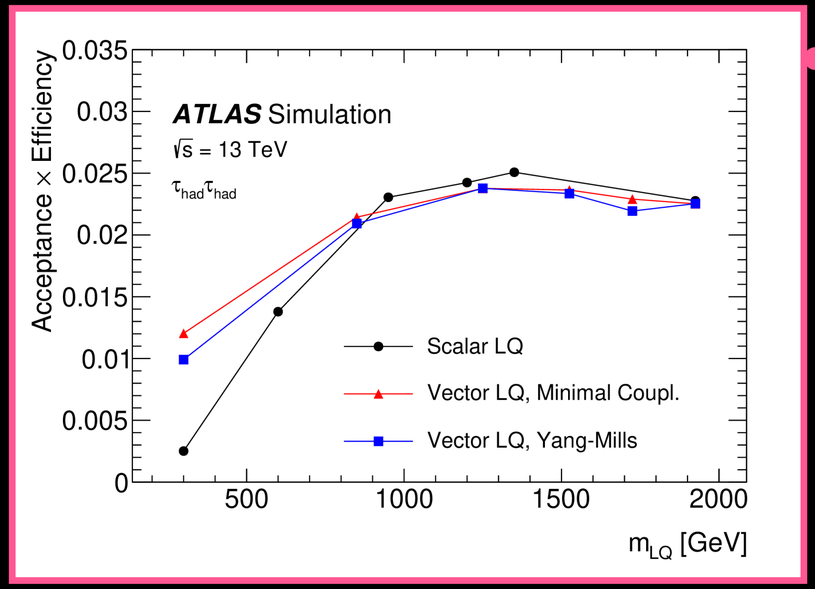
	$\tau_{\text{lep}}\tau_{\text{had}}$ channel	$\tau_{\text{had}}\tau_{\text{had}}$ channel
e/μ selection	= 1 'signal' e or μ $p_{\text{T}}^{e} > 25, 27$ GeV $p_{\text{T}}^{\mu} > 21, 27$ GeV	No 'veto' e or μ
$\tau_{\text{had-vis}}$ selection	= 1 $\tau_{\text{had-vis}}$ $p_{\text{T}}^{\tau} > 100$ GeV	= 2 $\tau_{\text{had-vis}}$ $p_{\text{T}}^{\tau} > 100, 140, 180$ (20) GeV
Jet selection	≥ 2 jets $p_{\text{T}}^{\text{jet}} > 45$ (20) GeV 1 or 2 b-jets	
Additional selection	Opposite charge $e, \mu, \tau_{\text{had}}$ and τ_{had} $m_{\tau\tau}^{\text{MMC}} \notin 40 - 150$ GeV $E_{\text{T}}^{\text{miss}} > 100$ GeV $s_{\text{T}} > 600$ GeV	

PNN input variables

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

PNN

parameterised neural network in terms of m_{LQ}



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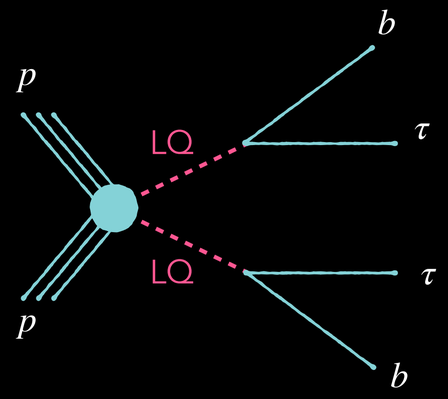

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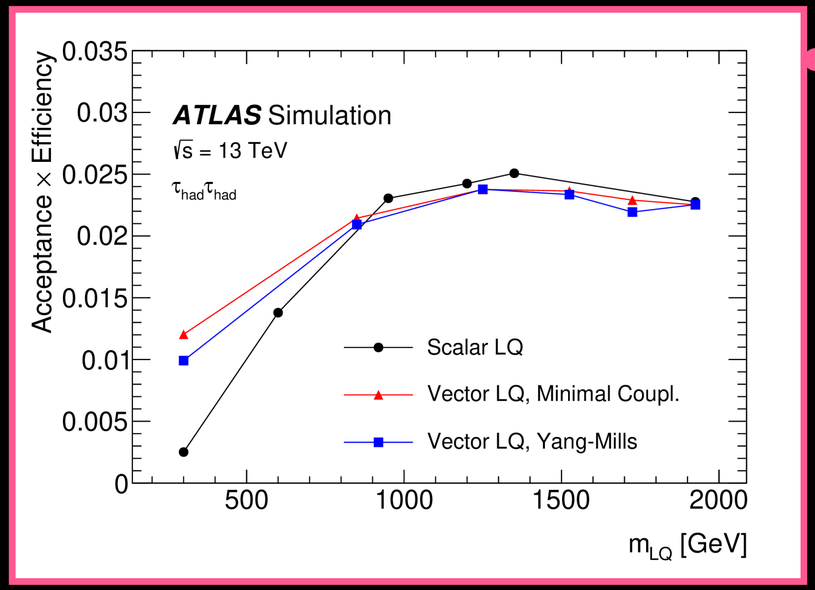

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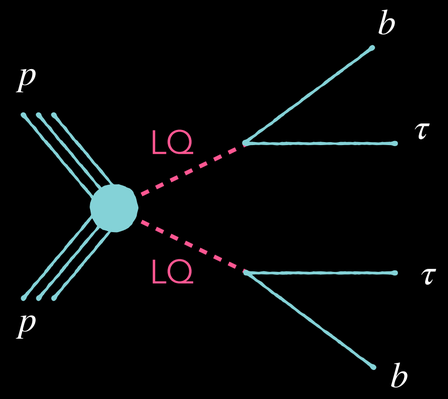

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$m(\ell, \text{jet})$, $m(\tau_{\text{had}}, \text{jet})$	✓	
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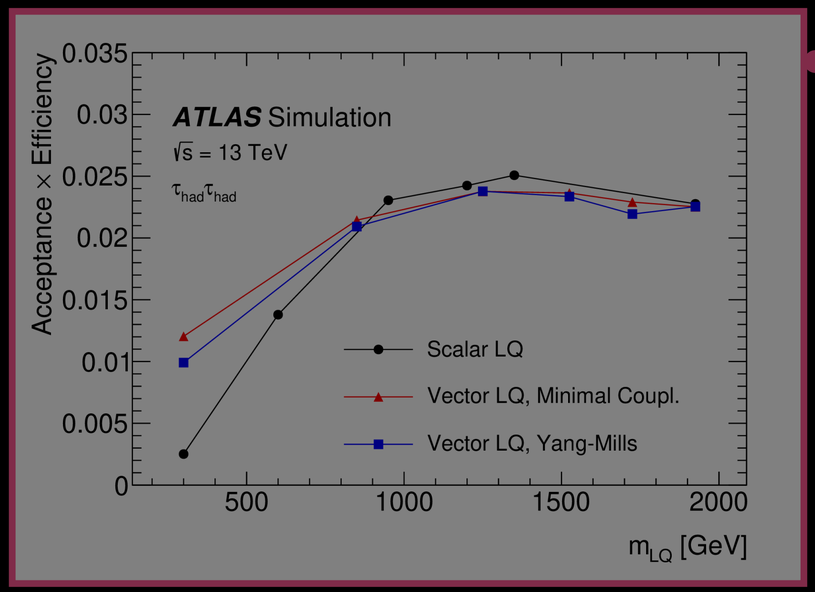
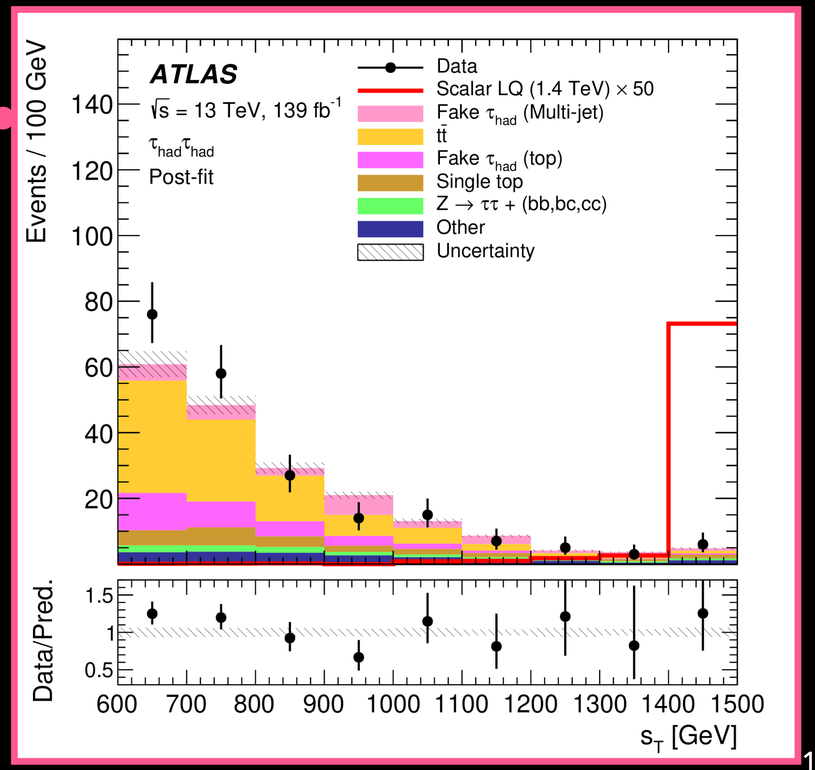


The search is optimised to probe high m_{LQ} values.

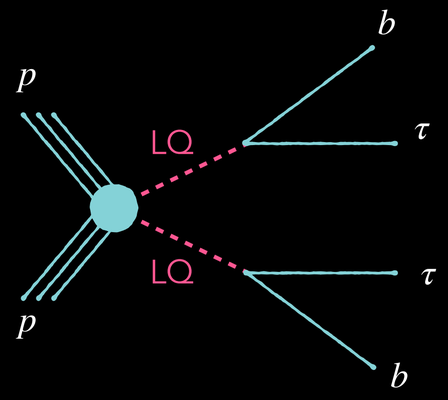
Here s_T is the scalar sum of transverse momenta ((light lepton) + $\tau_{had-vis}$ + two leading jets + E_T^{miss}).

s_T is a powerful discriminator and is used in both channels.



1) LQ pair production analysis details

[arXiv:2303.01294]



Selection

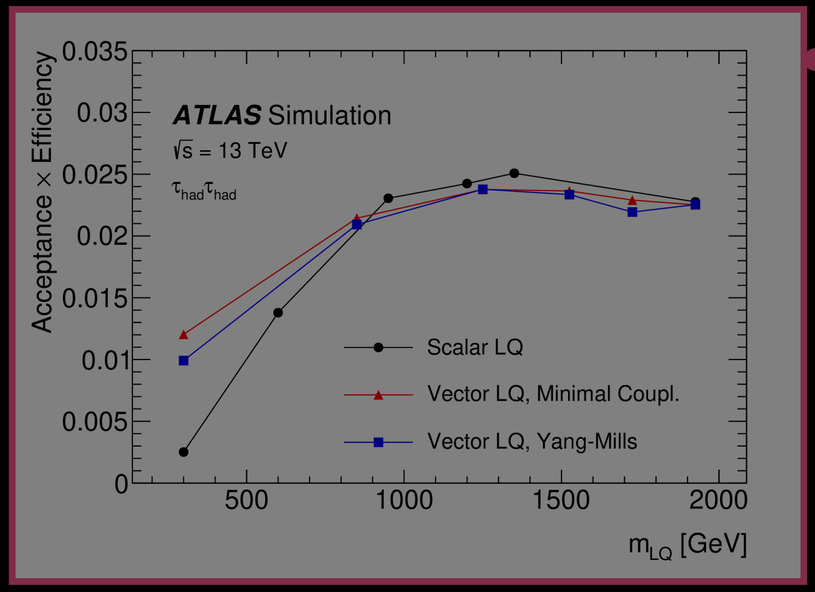
	$\tau_{\text{lep}}\tau_{\text{had}}$ channel	$\tau_{\text{had}}\tau_{\text{had}}$ channel
e/μ selection	= 1 'signal' e or μ $p_{\text{T}}^{e} > 25, 27$ GeV $p_{\text{T}}^{\mu} > 21, 27$ GeV	No 'veto' e or μ
$\tau_{\text{had-vis}}$ selection	= 1 $\tau_{\text{had-vis}}$ $p_{\text{T}}^{\tau} > 100$ GeV	= 2 $\tau_{\text{had-vis}}$ $p_{\text{T}}^{\tau} > 100, 140, 180$ (20) GeV
Jet selection	≥ 2 jets $p_{\text{T}}^{\text{jet}} > 45$ (20) GeV 1 or 2 b-jets	
Additional selection	Opposite charge $e, \mu, \tau_{\text{had}}$ and τ_{had} $m_{\tau\tau}^{\text{MMC}} \notin 40 - 150$ GeV $E_{\text{T}}^{\text{miss}} > 100$ GeV $s_{\text{T}} > 600$ GeV	

PNN input variables

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

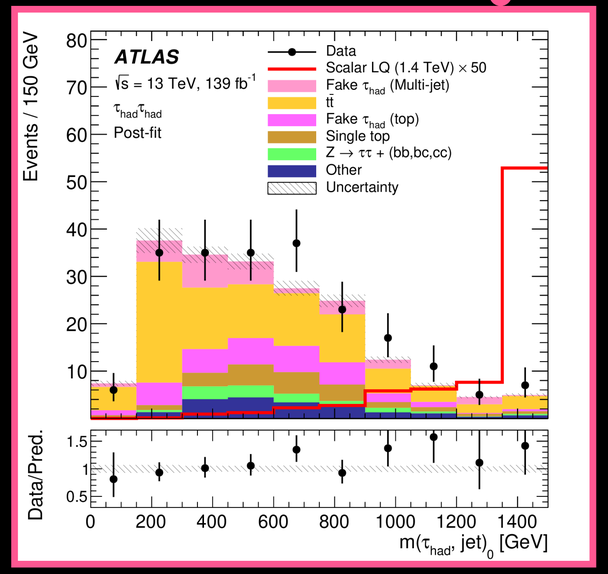
PNN

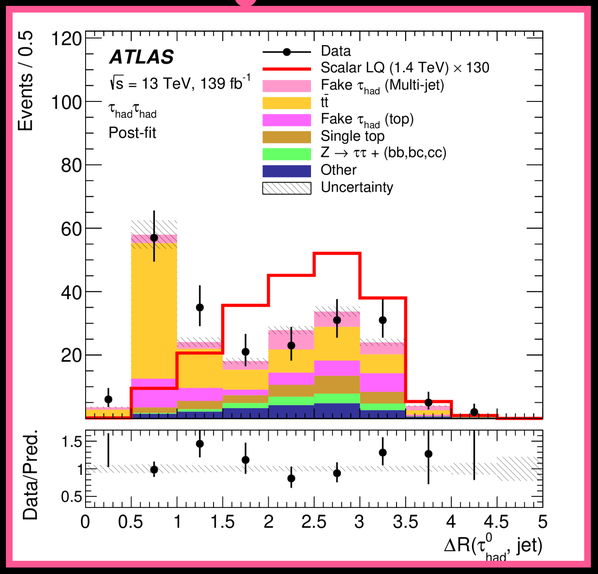
parameterised neural network in terms of m_{LQ}



The search is optimised to probe high m_{LQ} values.

Invariant mass of $\tau_{had-vis}$ and leading jet.





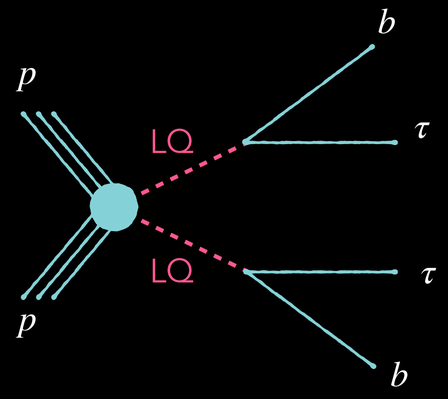
ΔR between leading $\tau_{had-vis}$ and mass paired jet.

1) Final PNN scores

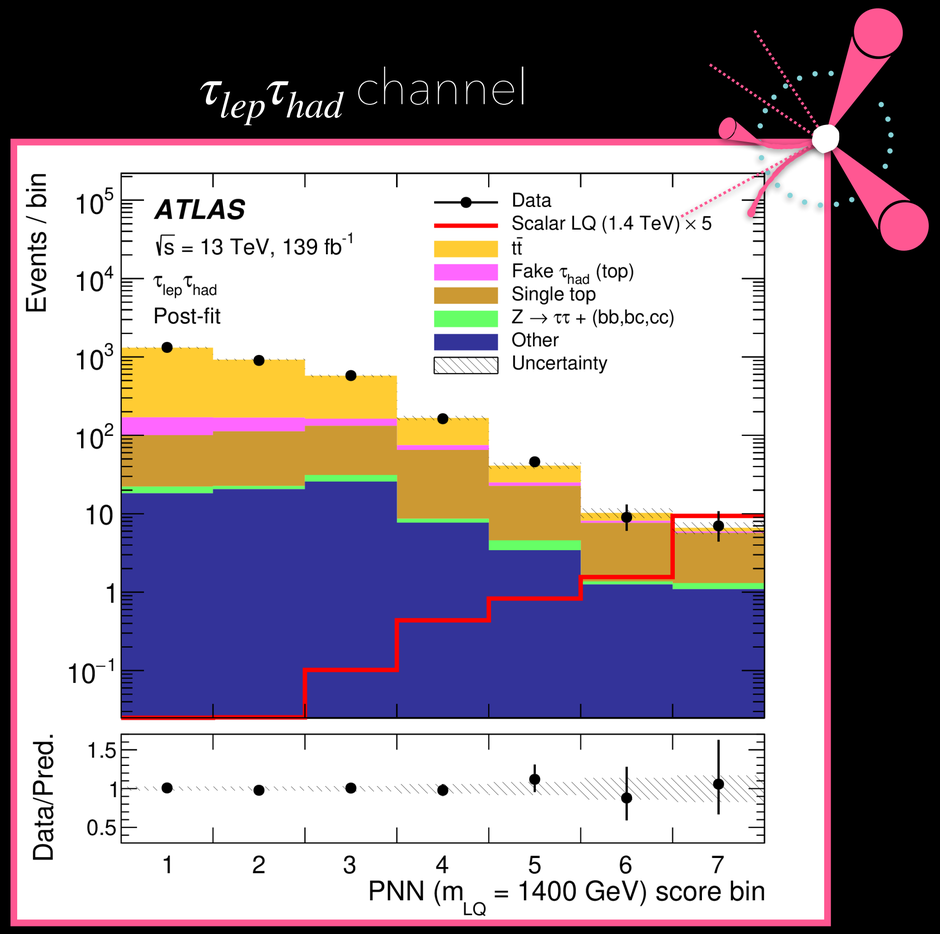
[arXiv:2303.01294]

-> PNN binning is optimised for each LQ mass point.

-> A simultaneous binned maximum-likelihood fit is performed on the PNN score distributions for each LQ hypothesis.

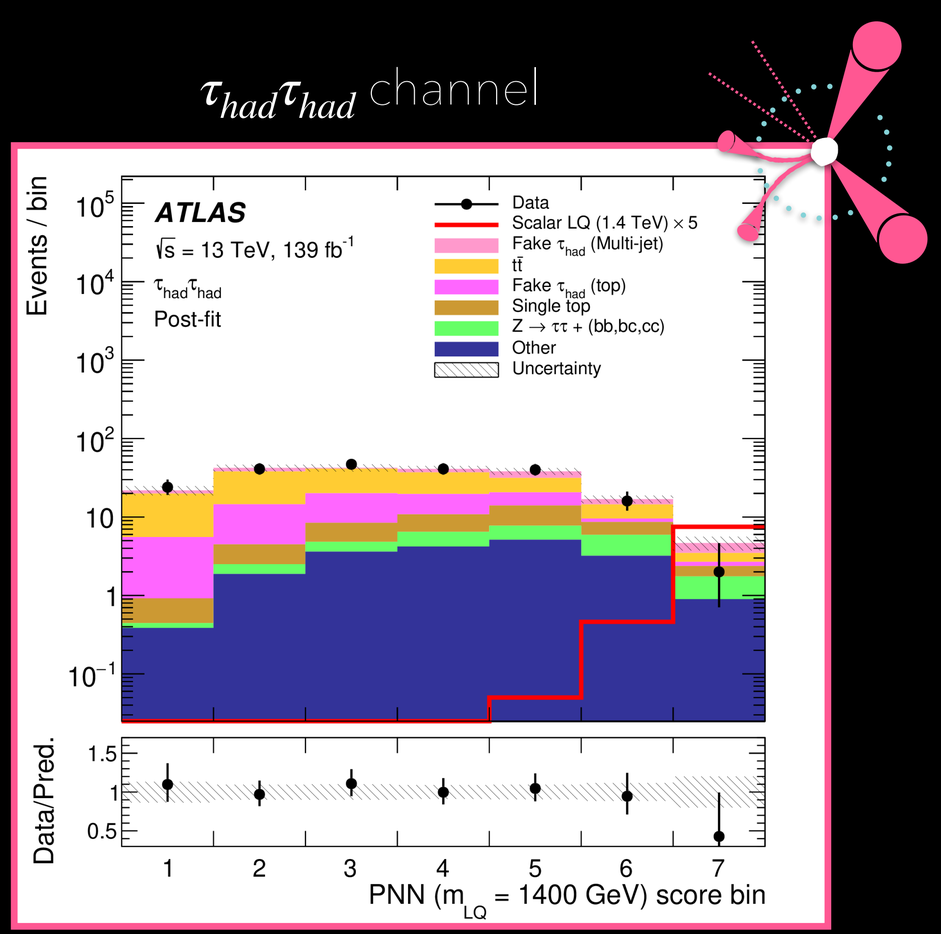


$\tau_{lep}\tau_{had}$ channel



At high values of the PNN score, top backgrounds dominate in the $\tau_{lep}\tau_{had}$ channel.

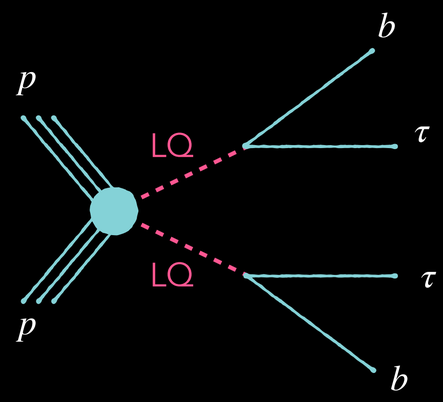
$\tau_{had}\tau_{had}$ channel



Slight deficit of data relative to the background prediction in the highest PNN score bin for the $\tau_{had}\tau_{had}$ channel.

1) Results

no significant excess above the SM prediction is observed

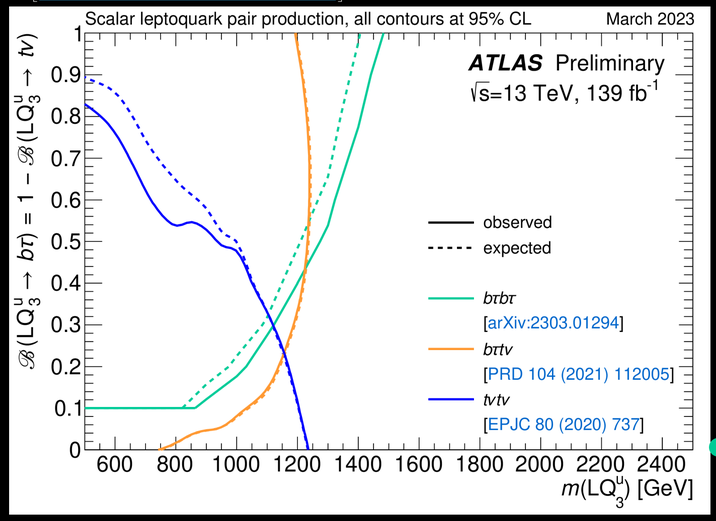


-> The improvement in the observed limit compared with the expectation is driven by the data deficit in the highest PNN bin for the $\tau_{had}\tau_{had}$ channel.

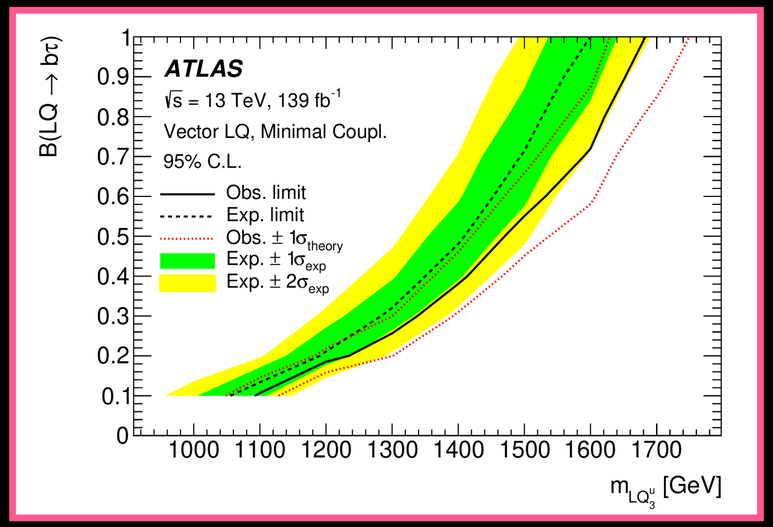
+ larger at high m_{LQ} because the signal becomes more localised at a high PNN score.

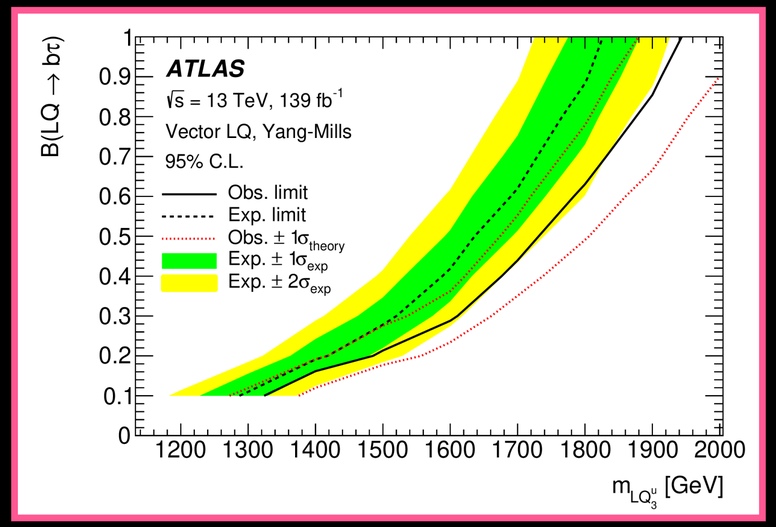
[arXiv:2303.01294]

[ATL-PHYS-PUB-2023-006]

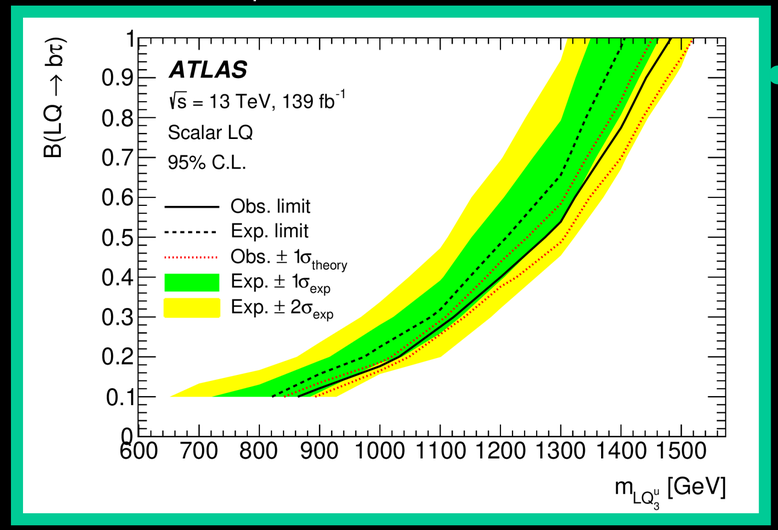


-> Extend the full Run 2 ATLAS reach for third-generation up-type LQs by around 200 GeV in all three models compared with the LQ LQ → $t\nu t\nu$ decay mode (see summary plot).

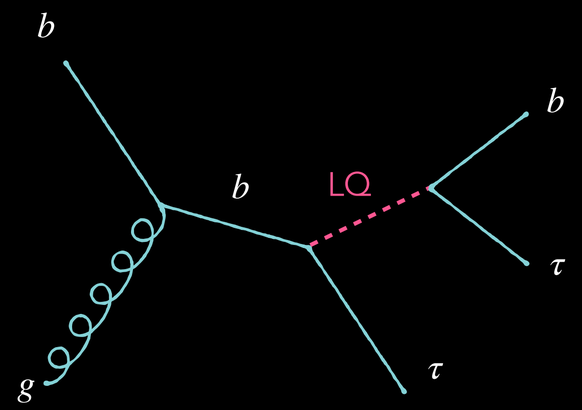




-> Improvement of 450 GeV compared to 36 fb^{-1} result.

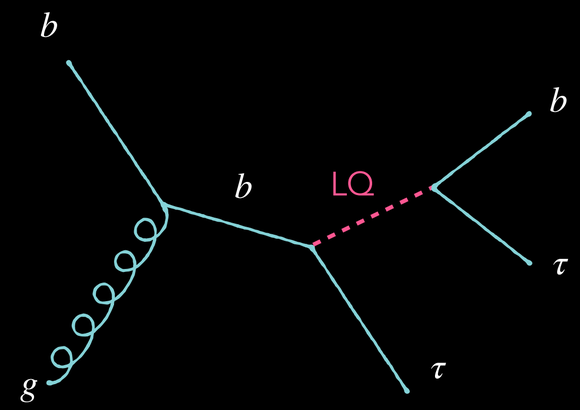


2



2) Singly produced LQs analysis details

[arXiv:2305.15962]



Selection

$\tau_{lep}\tau_{had}$

Signal Regions	Selection
Preselection	ℓ (trigger, isolated), $\tau_{\text{had-vis}}$ (medium τ_{had}-ID), $q(\ell) \times q(\tau_{\text{had-vis}}) < 0$, $\Delta\phi(\ell, E_{\text{T}}^{\text{miss}}) < 1.5$, $m_{\text{vis}}(\ell, \tau_{\text{had-vis}}) > 100$ GeV, $S_{\text{T}} > 300$ GeV, at least one b-jet
High b-jet p_{T} SR	Leading b-jet $p_{\text{T}} > 200$ GeV

$\tau_{had}\tau_{had}$

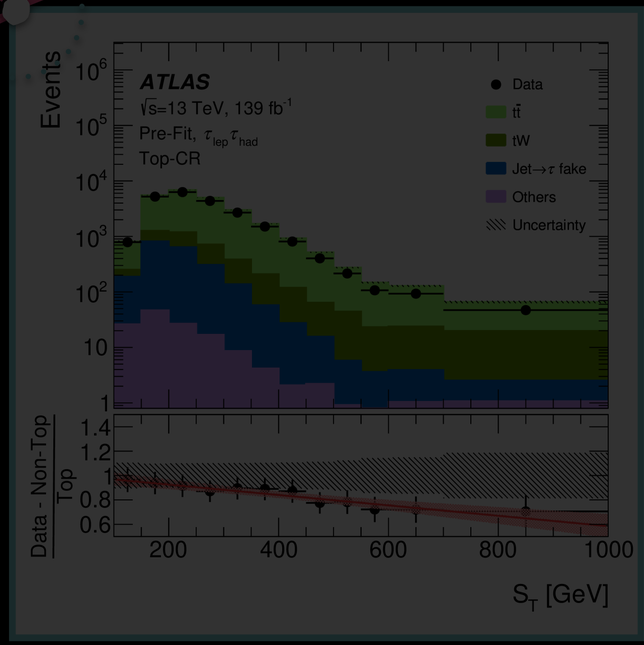
Signal Regions	Selection
Preselection	$\tau_{\text{had,1}}$ (trigger, medium τ_{had}-ID), τ_2 (loose τ_{had}-ID), $q(\tau_1) \times q(\tau_2) < 0$, $m_{\text{vis}}(\tau_1, \tau_2) > 100$ GeV, $S_{\text{T}} > 300$ GeV, at least one b-jet
High b-jet p_{T} SR	Leading b-jet $p_{\text{T}} > 200$ GeV

*tables shortened, full list of CR selections in [arXiv:2305.15962]

Top-CR

Satisfy SR except
- $\Delta\phi(l, E_T^{miss}) > 2.5$
- no S_T and leading b-jet p_T requirement

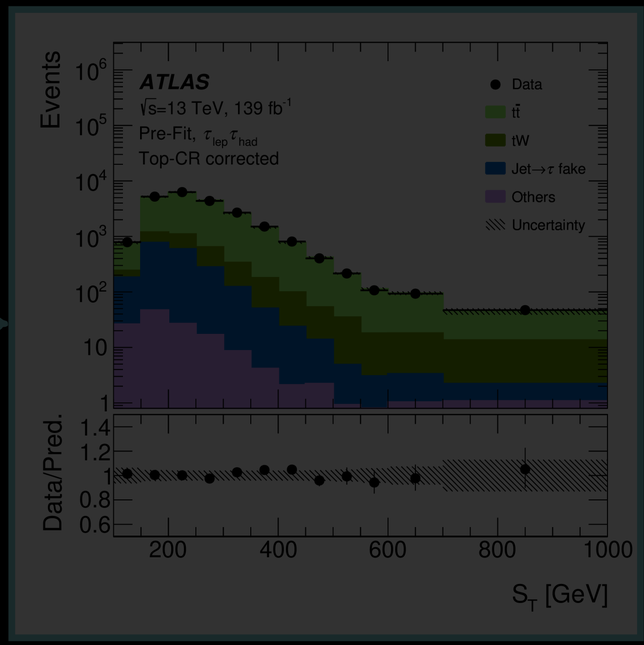
-> Ensure the background is accurately modelled



Current simulations of $t\bar{t}$ processes overestimate the upper tail of the top-quark p_T spectrum. [1908.0735]

apply correction

$$SF_{Top}(S_T) = \frac{(N_{data-} - N_{non-Top})(S_T)}{N_{Top}(S_T)}$$



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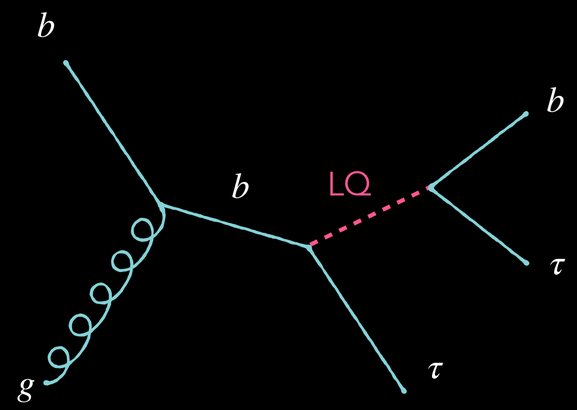

[arXiv:2305.15962]

Selection

$\tau_{lep}\tau_{had}$

Signal Regions	Selection
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High b-jet p_{T} SR	Leading b-jet $p_{\text{T}} > 200$ GeV

$\tau_{had}\tau_{had}$

Signal Regions	Selection
Preselection	$\tau_{\text{had,1}}$ (trigger, medium τ_{had}-ID), τ_2 (loose τ_{had}-ID), $q(\tau_1) \times q(\tau_2) < 0$, $m_{\text{vis}}(\tau_1, \tau_2) > 100$ GeV, $S_{\text{T}} > 300$ GeV, at least one b-jet
High b-jet p_{T} SR	Leading b-jet $p_{\text{T}} > 200$ GeV

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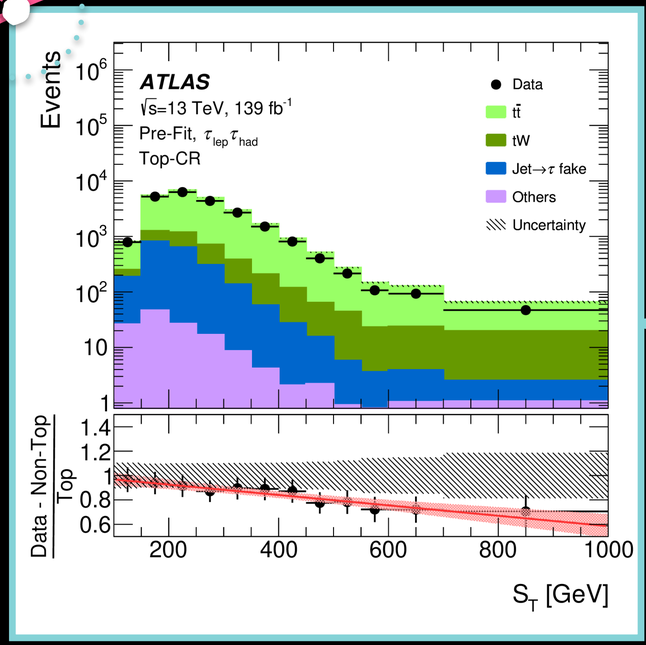
-> Ensure the background is accurately modelled



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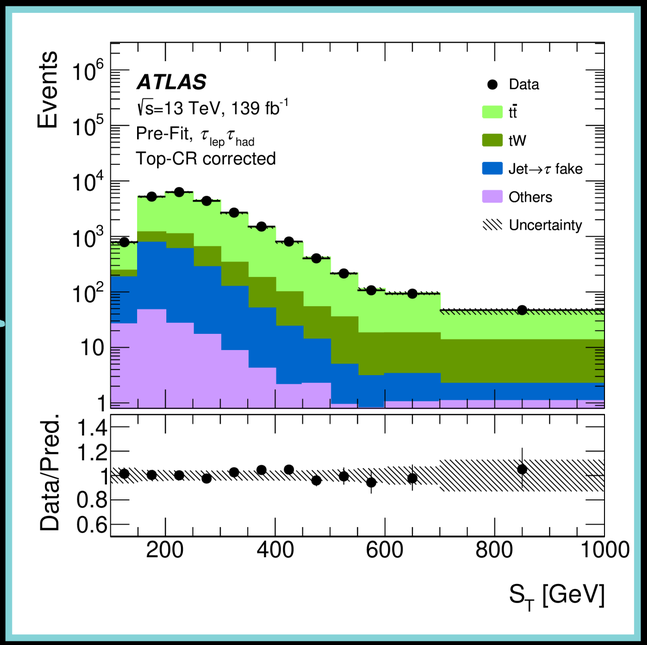
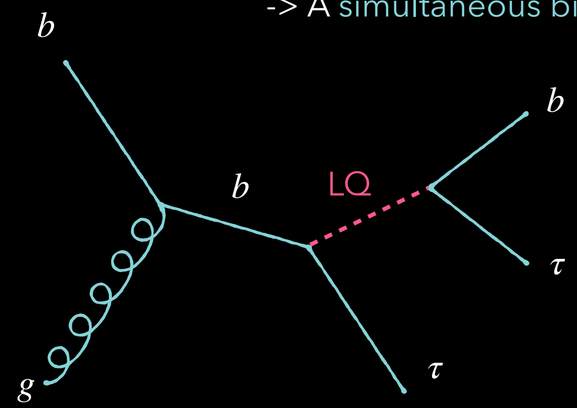


2) Discriminating variable

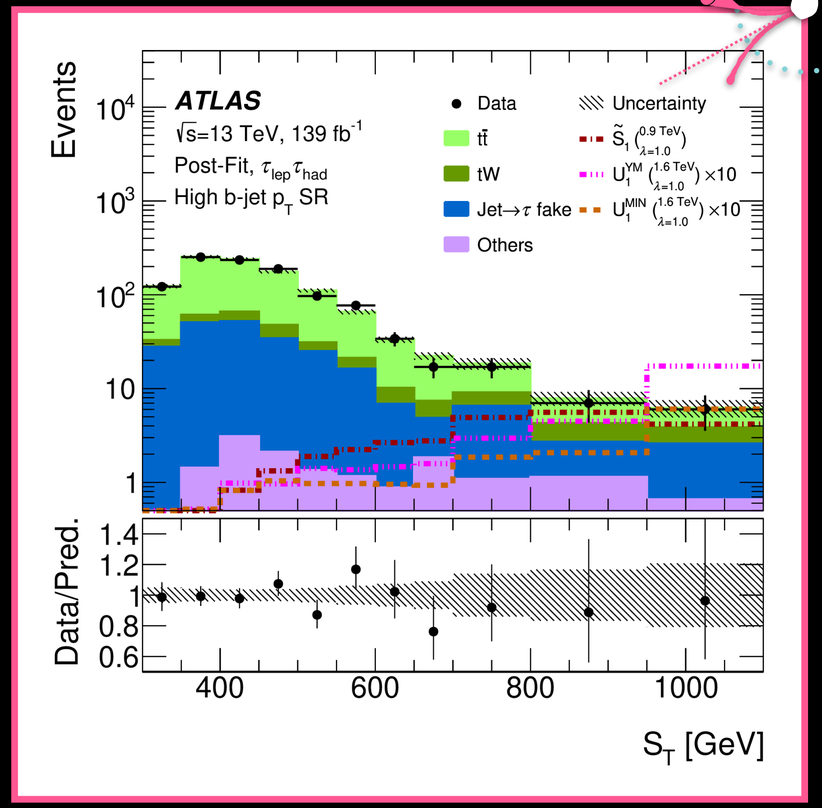
[arXiv:2305.15962]



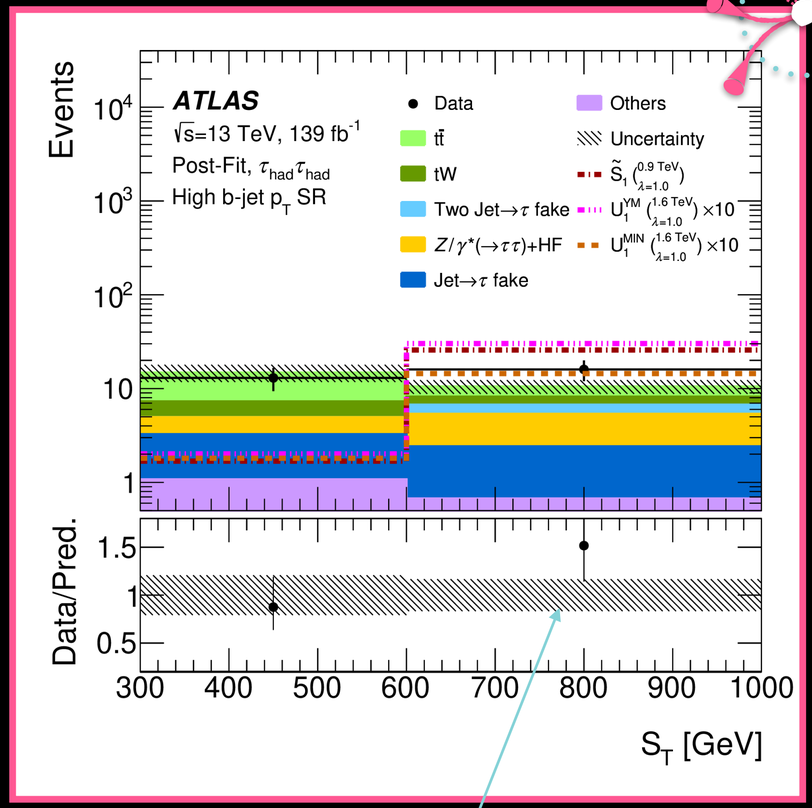
-> A simultaneous binned maximum-likelihood fit is performed on the S_T distributions for each LQ hypothesis.

-> more sensitive due to larger signal/ background ratio in the last S_T bin

$\tau_{lep}\tau_{had}$ channel



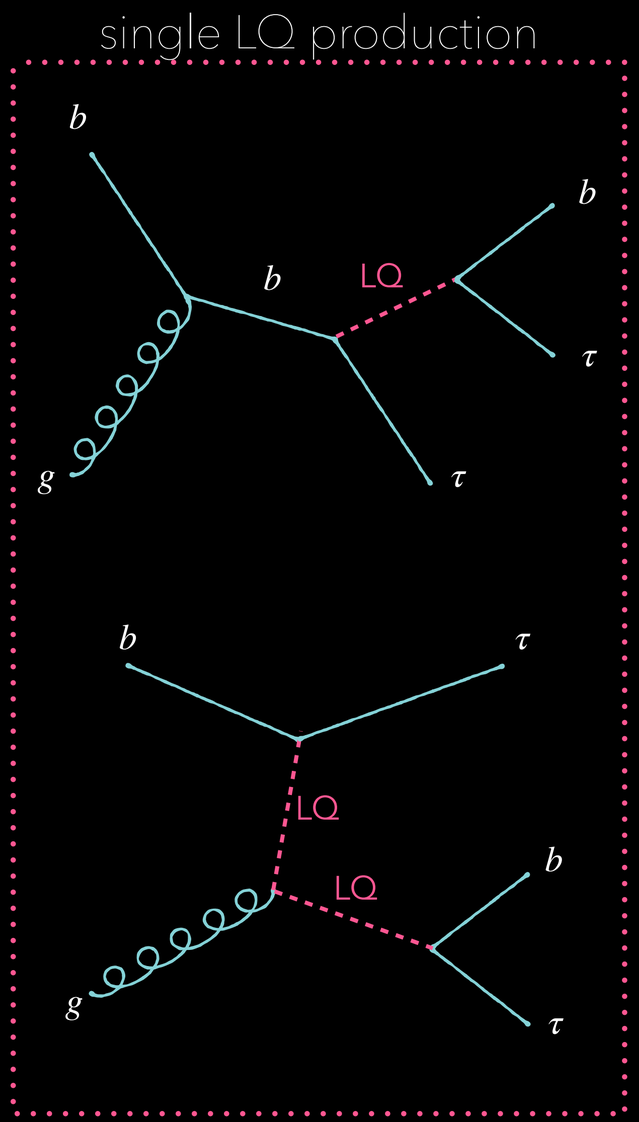
$\tau_{had}\tau_{had}$ channel

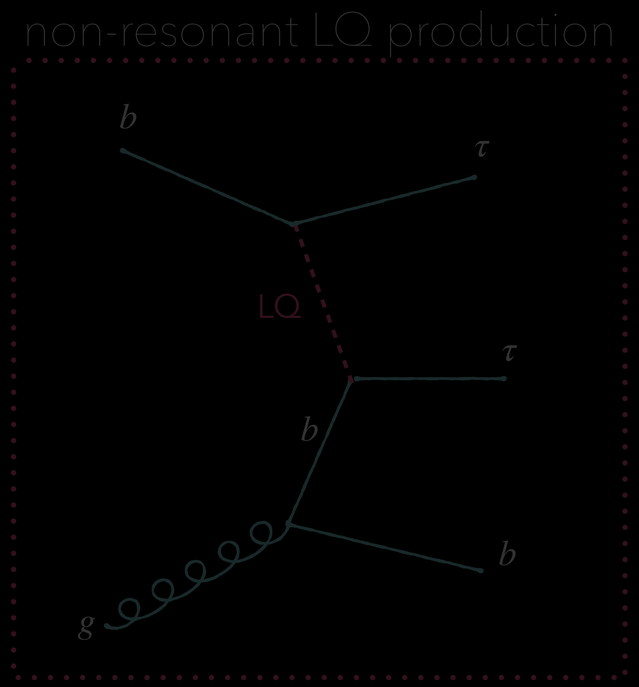


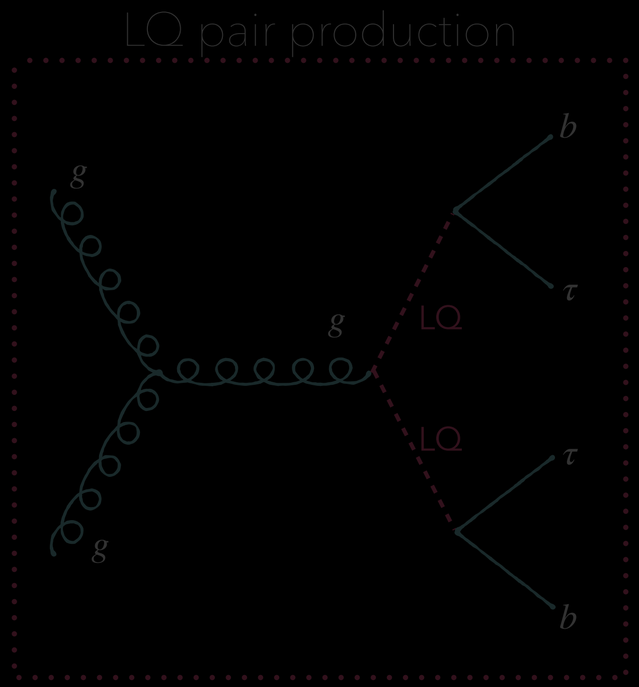
Keep this in mind for the next (next) slide.

2) What I need to say before the next slide…

[arXiv:2305.15962]



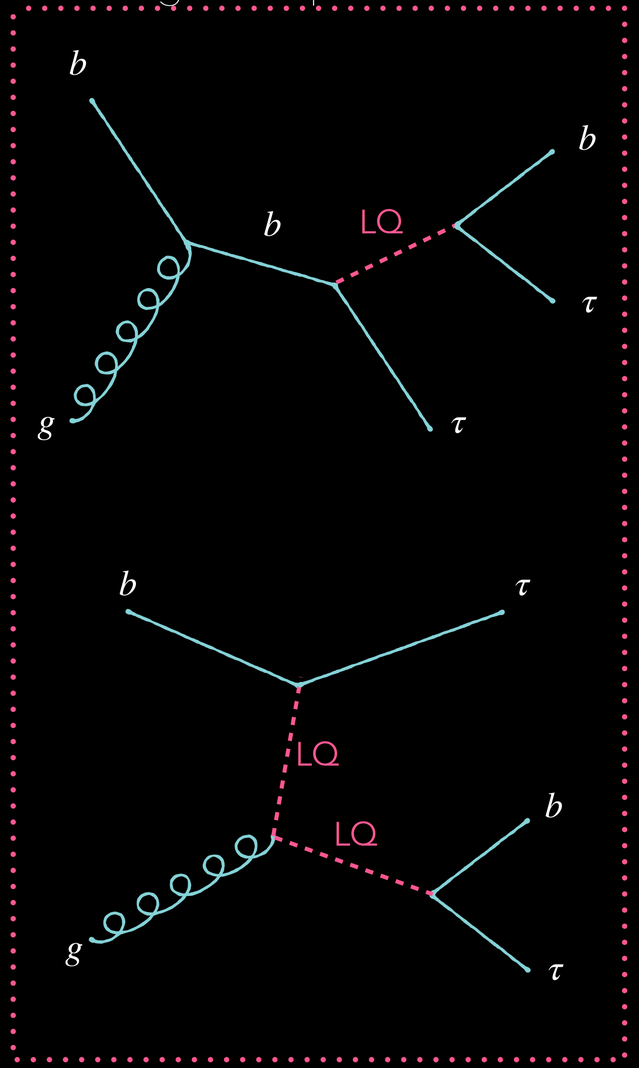




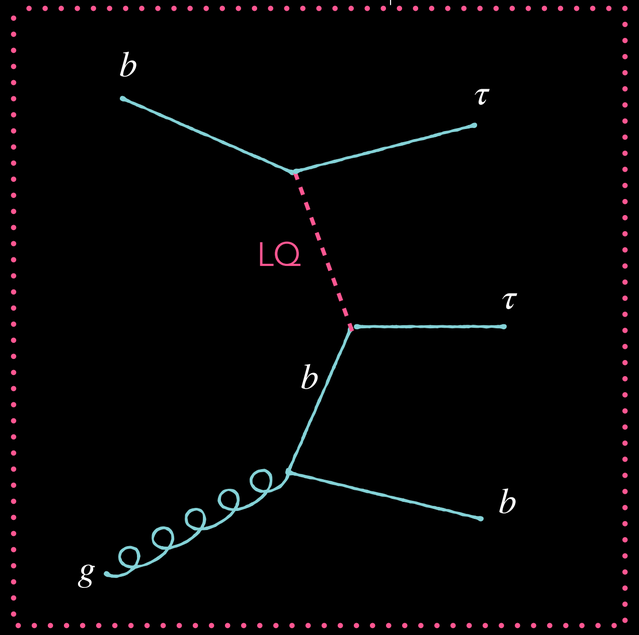
2) What I need to say before the next slide…

[arXiv:2305.15962]

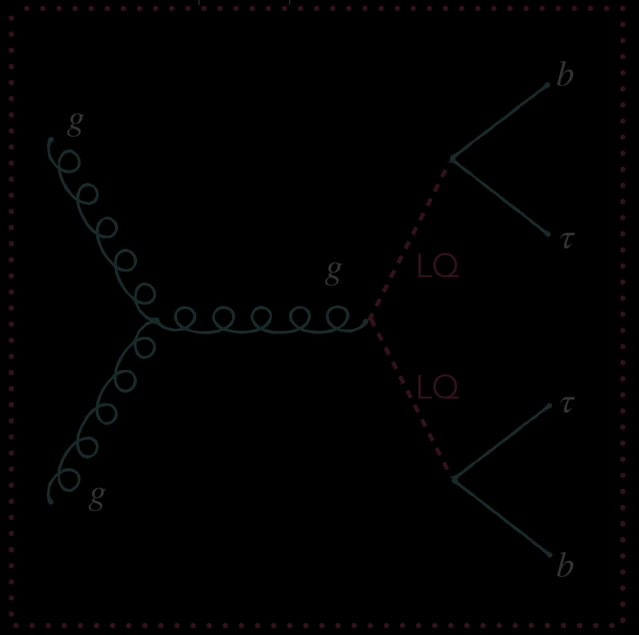
single LQ production



non-resonant LQ production



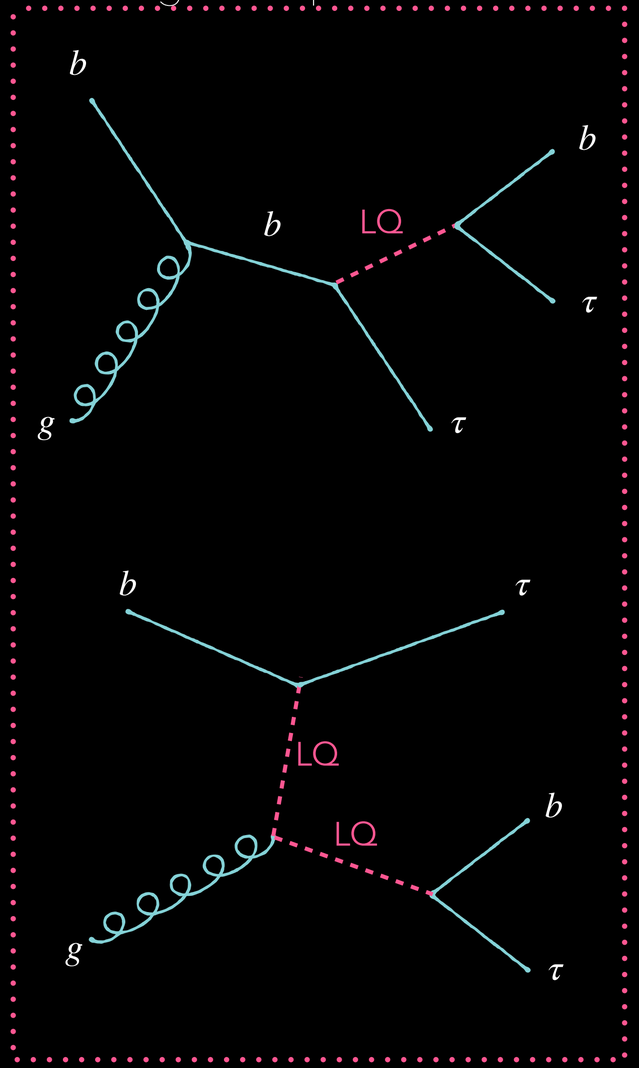
LQ pair production



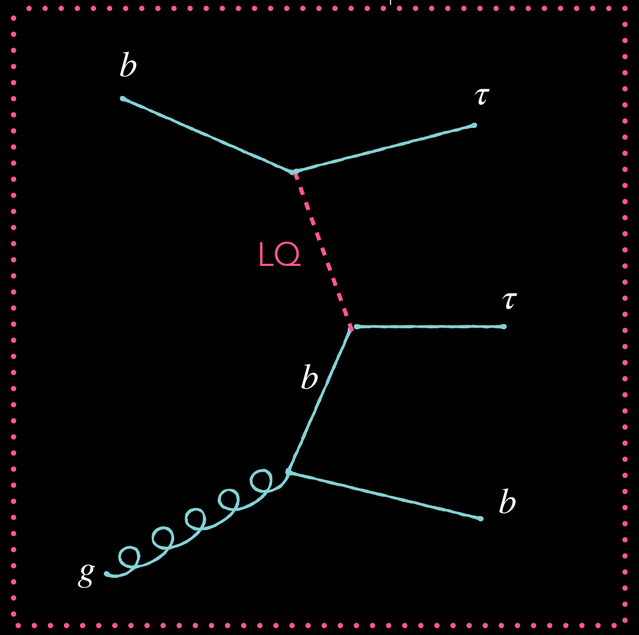
2) What I need to say before the next slide…

[arXiv:2305.15962]

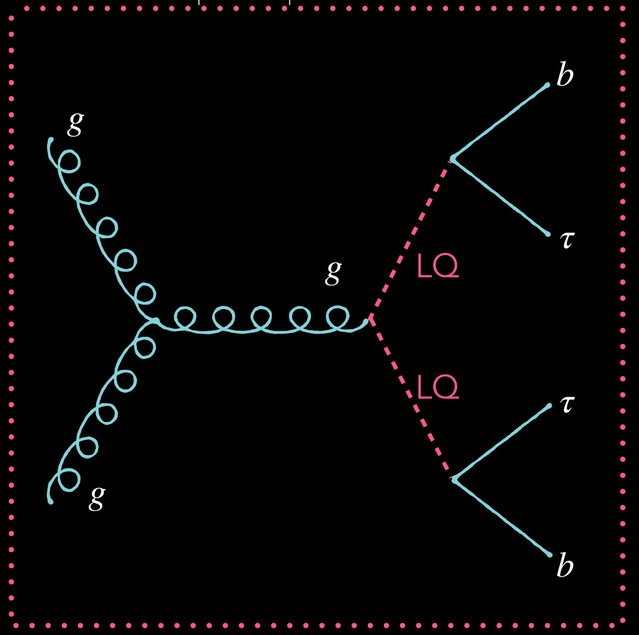
single LQ production



non-resonant LQ production

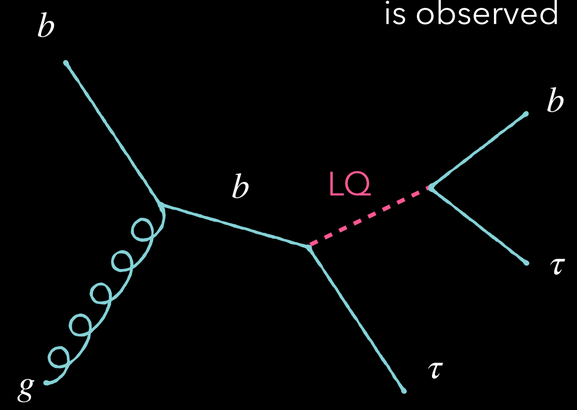


LQ pair production



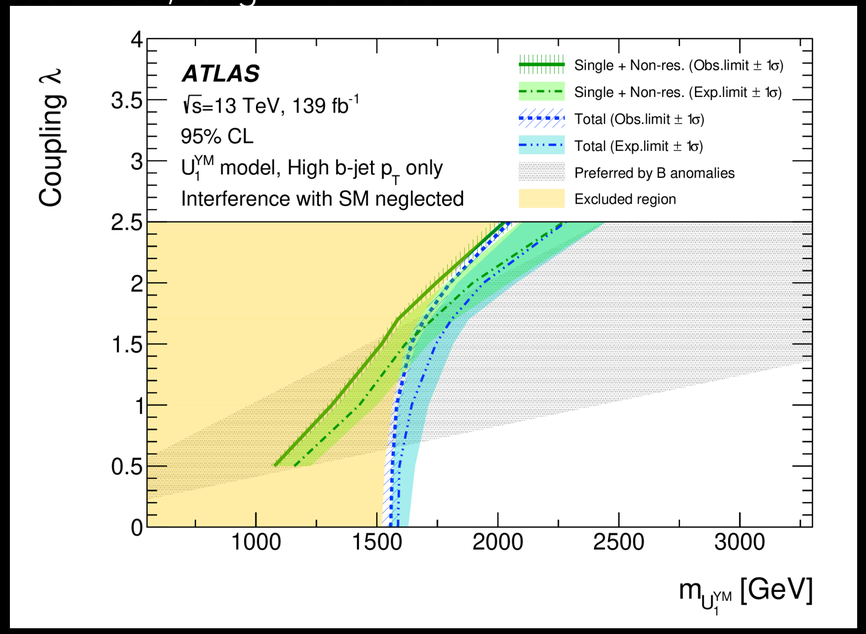
2) Results

no significant excess above the SM prediction is observed



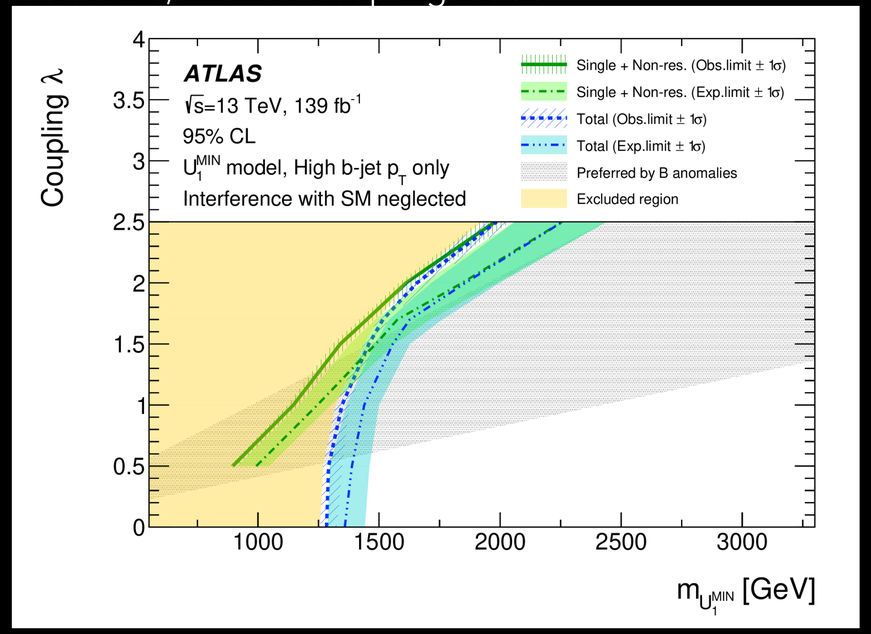
Measurement excludes part of the $\lambda(m_{U_1})$ space that is preferred by B anomalies!
[Eur. Phys. J. C 83 (2023) 153]

Vector LQs, Yang-Mills model

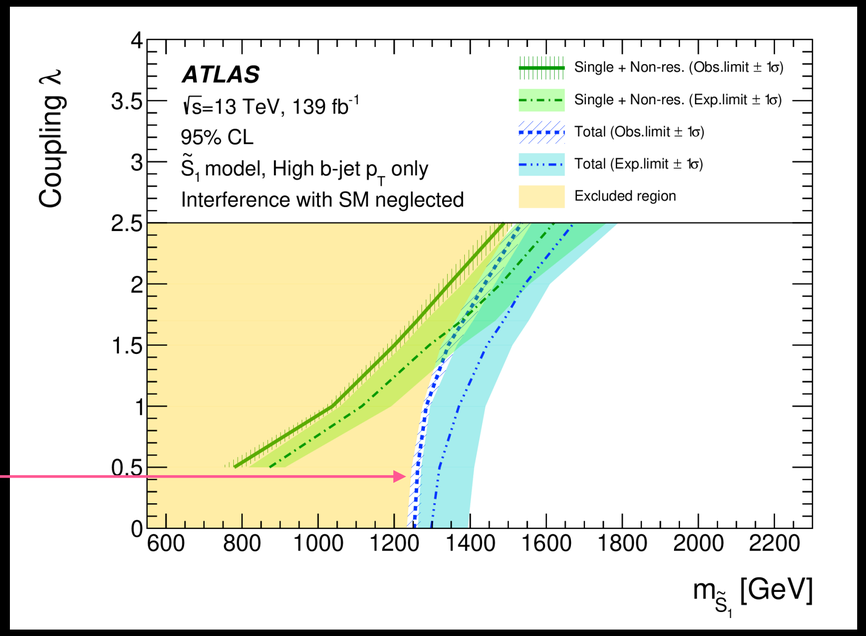


Vector LQs, Minimal coupling model

[arXiv:2305.15962]



Scalar LQs



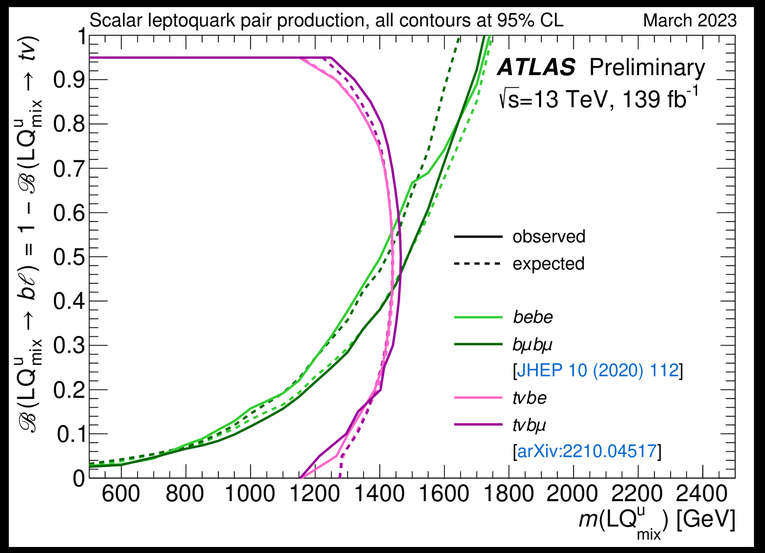
total := single + non-resonant + pair LQ

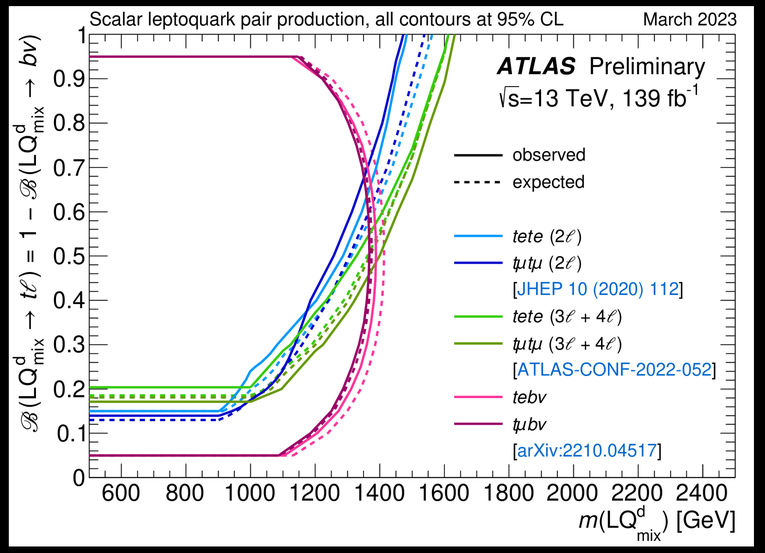
First ATLAS result for the search of singly produced LQs in the $b\tau\tau$ final state.

The observed limits obtained are less stringent than the expected limits, which is mainly driven by the higher data yields relative to the predicted yields in the highest S_T bin in the $\tau_{had}\tau_{had}$ channel.

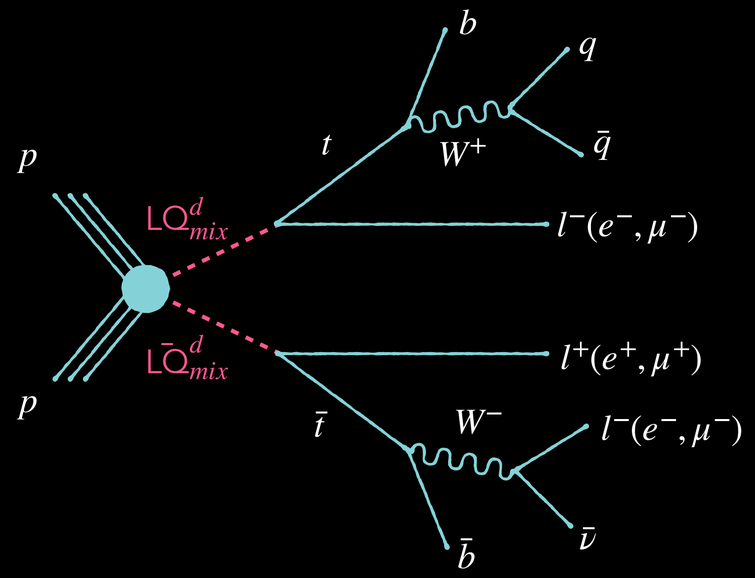
Final slide - Other results - Leaving the world of third-gen-only coupling

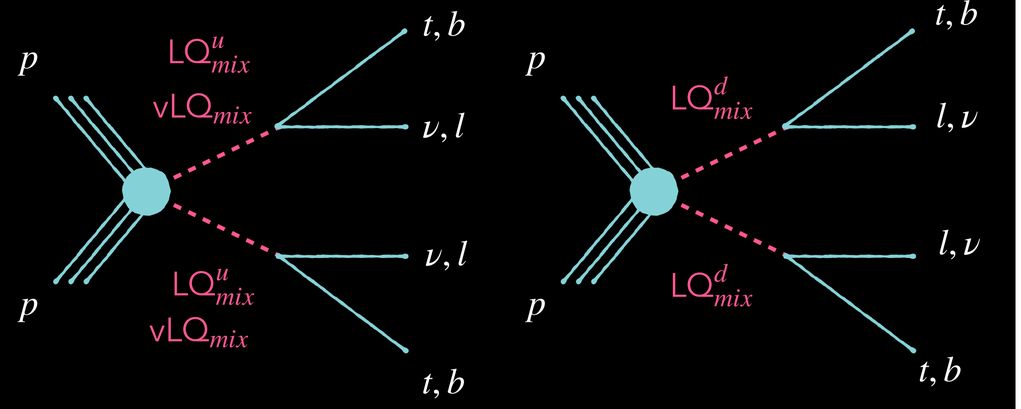
LQ_{mix} summary plots



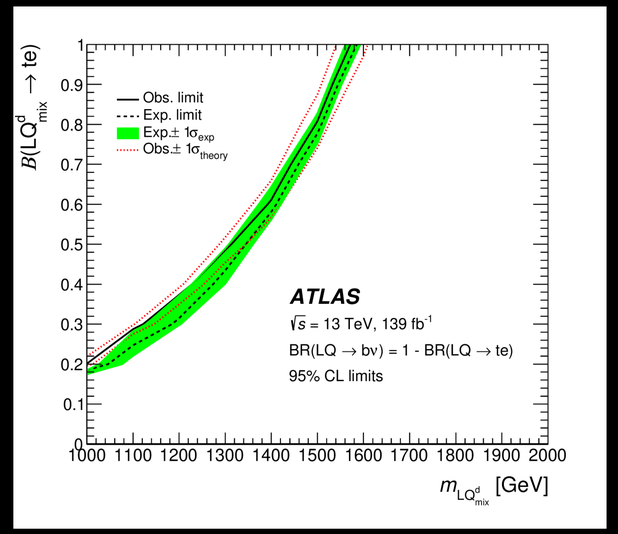


[ATL-PHYS-PUB-2023-006]



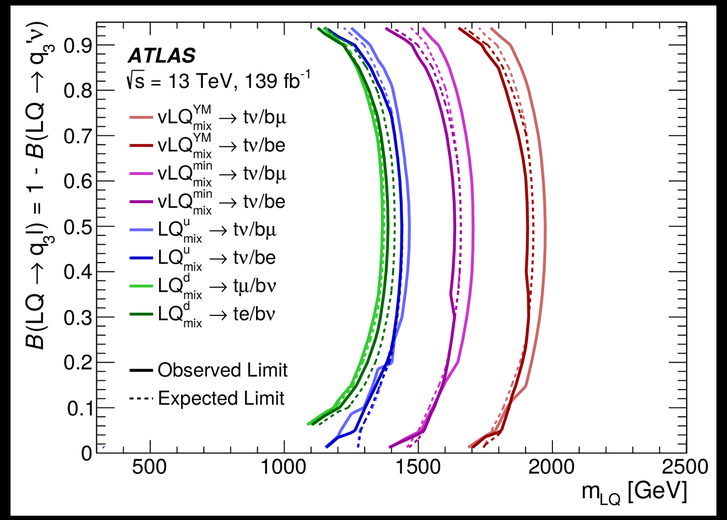


vLQ := vector LQ



June 2023 arXiv:2306.17642

+event display on the next slide

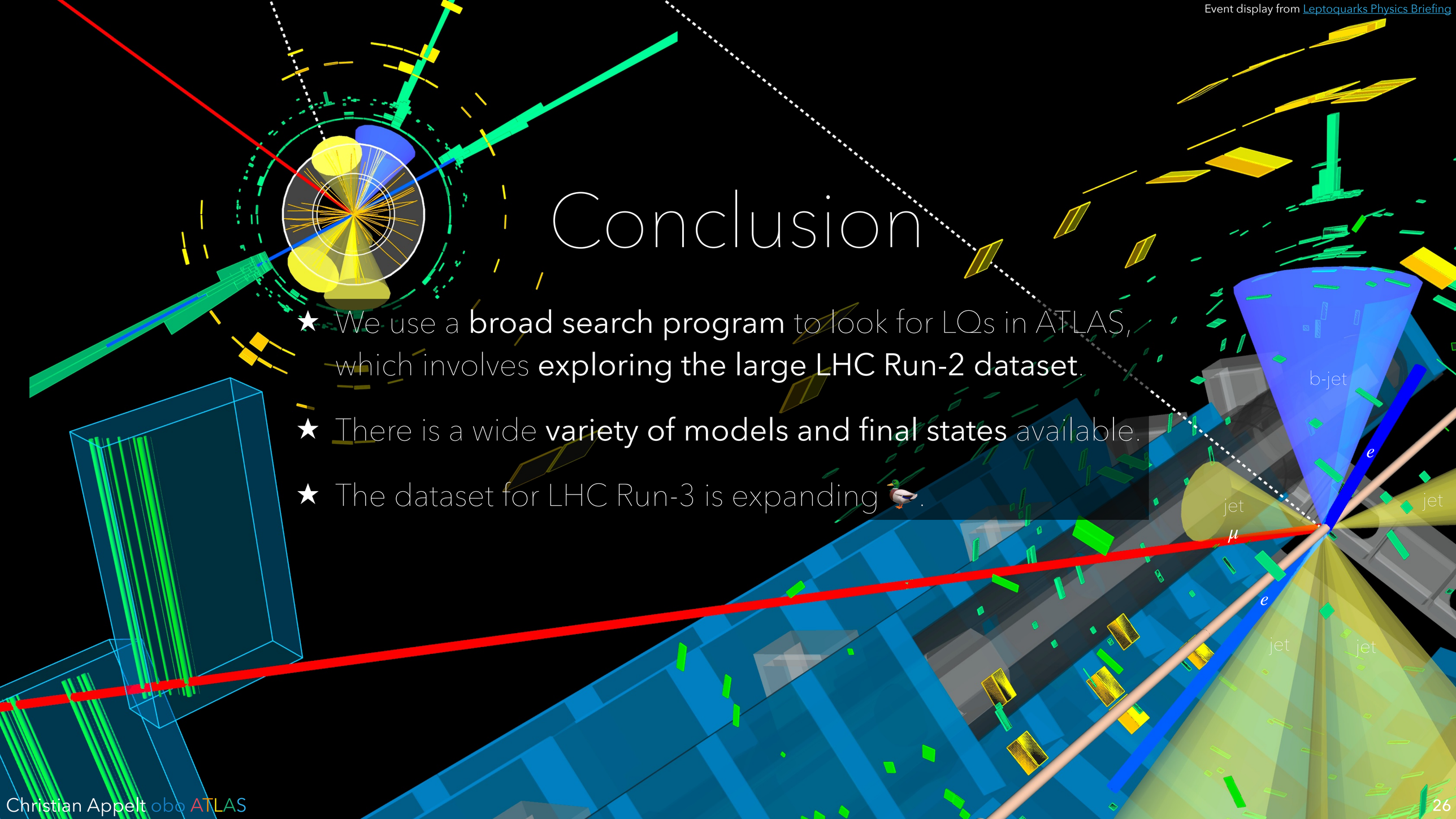


October 2022 arXiv:2210.04517

Event display from Leptoquarks Physics Briefing

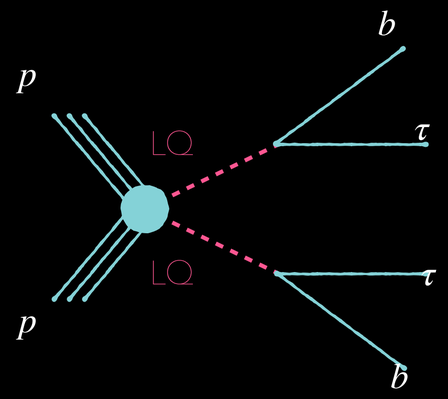
Conclusion

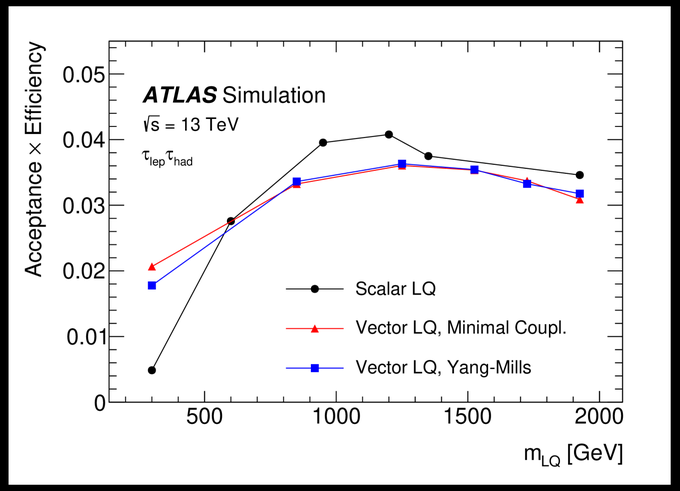
- ★ We use a **broad search program** to look for LQs in ATLAS, which involves **exploring the large LHC Run-2 dataset**.
- ★ There is a wide **variety of models and final states** available.
- ★ The dataset for LHC Run-3 is expanding 🦆.



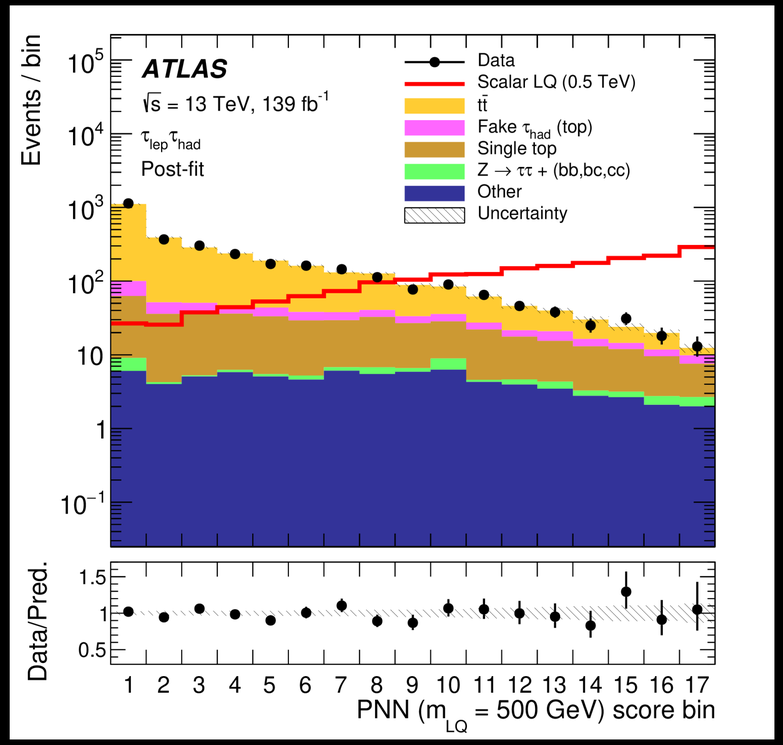
Backup

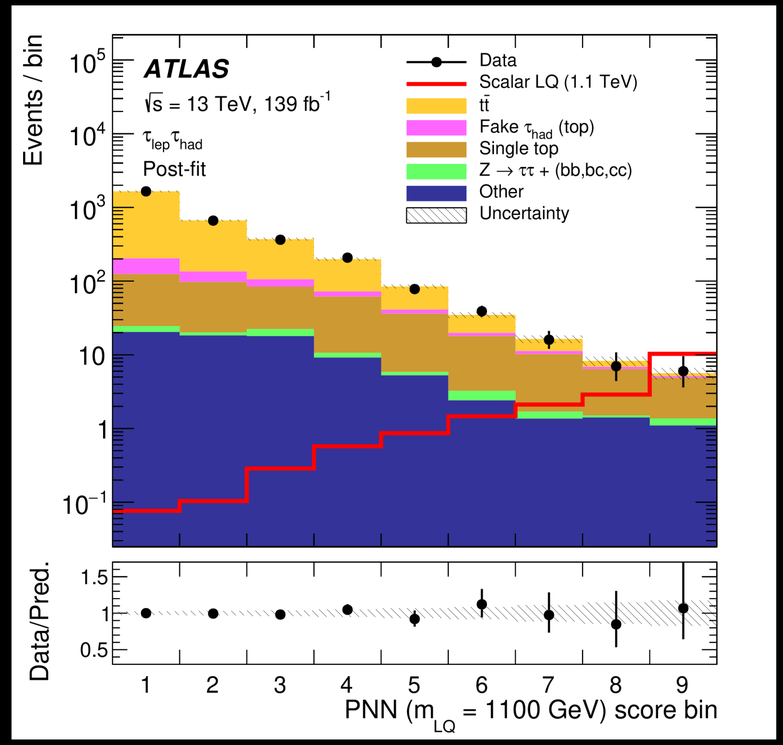
BACKUP

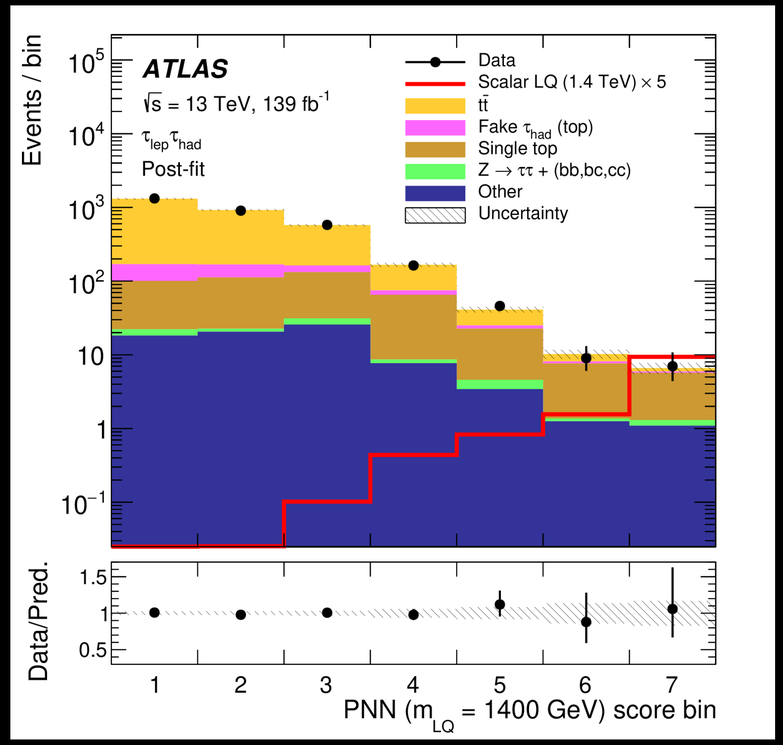




	$\tau_{\text{lep}}\tau_{\text{had}}$ channel	$\tau_{\text{had}}\tau_{\text{had}}$ channel
$t\bar{t}$	2420 ± 90	93 ± 9
single-top	355 ± 27	20 ± 4
Fake τ_{had} (top)	170 ± 90	43 ± 18
$Z\rightarrow \tau\tau$ + (bb, bc, cc)	13.9 ± 2.4	10.3 ± 1.4
Multi-jet	–	22 ± 11
Other	78 ± 7	19 ± 5
Total Background	3040 ± 60	207 ± 13
Data	3031	211







More info on this analysis: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2021-15/

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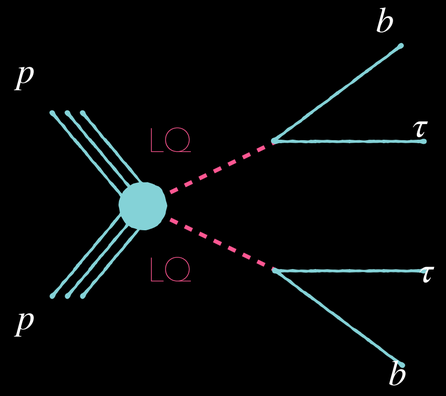

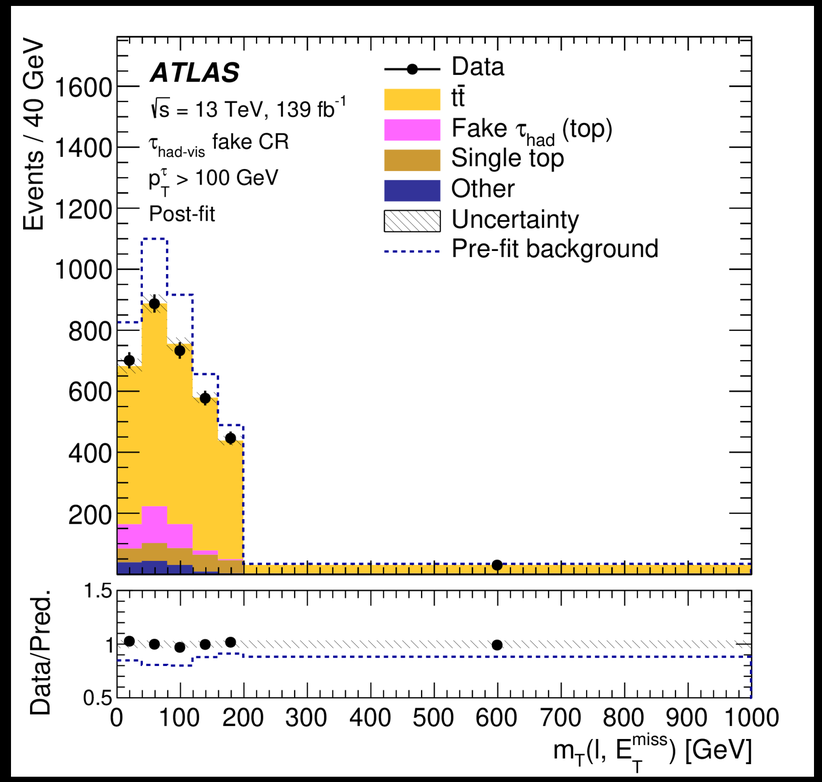

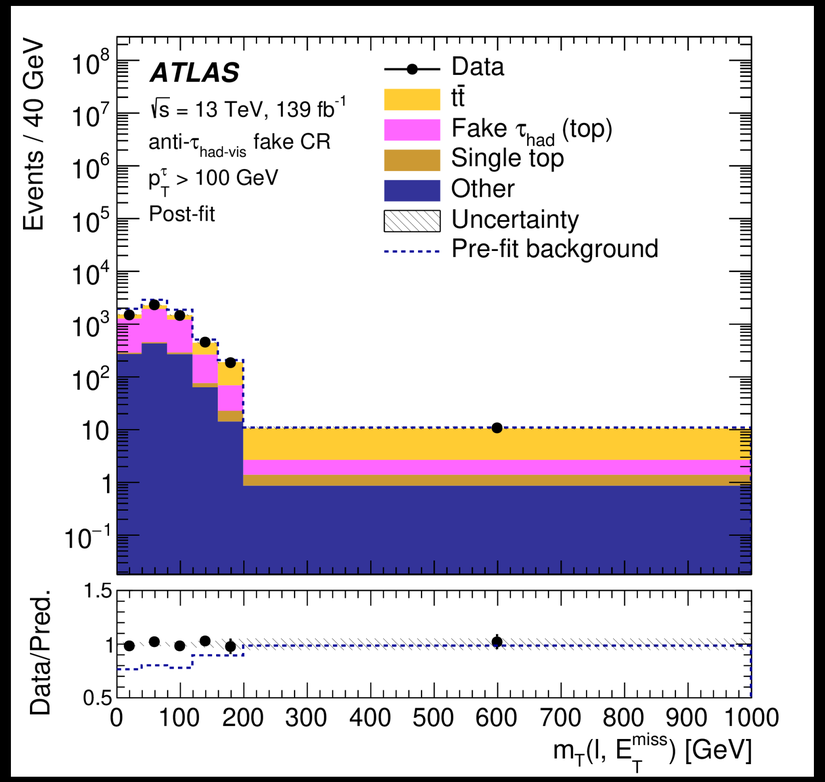

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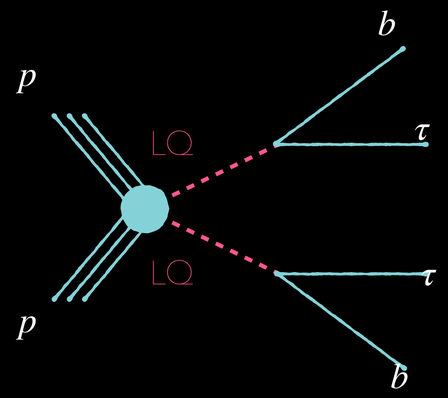

Process	ME generator	ME QCD order	ME PDF	PS and hadronisation	UE tune	Cross-section order
Top-quark						
$t\bar{t}^{(\S)}$	POWHEG-BOX v2	NLO	NNPDF3.0NLO	PYTHIA 8.230	A14	NNLO+NNLL
t-channel	POWHEG-BOX v2	NLO	NNPDF3.0NLO	PYTHIA 8.230	A14	NLO
s-channel	POWHEG-BOX v2	NLO	NNPDF3.0NLO	PYTHIA 8.230	A14	NLO
$Wt^{(\S)}$	POWHEG-BOX v2	NLO	NNPDF3.0NLO	PYTHIA 8.230	A14	NLO
Top-quark + W/Z						
$t\bar{t}Z$	SHERPA 2.2.1	NLO	NNPDF3.0NNLO	SHERPA 2.2.1	Default	NLO$^{(\dagger)}$
$t\bar{t}W$	SHERPA 2.2.8	NLO	NNPDF3.0NNLO	SHERPA 2.2.8	Default	NLO$^{(\dagger)}$
Vector boson + jets						
W/Z+jets	SHERPA 2.2.1	NLO ($\leq$ 2 jets) LO (3,4 jets)	NNPDF3.0NNLO	SHERPA 2.2.1	Default	NNLO
Diboson						
WW, WZ, ZZ	SHERPA 2.2.1	NLO ($\leq$ 1 jet) LO (2,3 jets)	NNPDF3.0NNLO	SHERPA 2.2.1	Default	NLO$^{(\dagger)}$
Higgs boson						
ggF	POWHEG-BOX v2	NNLO	NNPDF3.0NLO	PYTHIA 8.212	AZNLO	N3LO(QCD)+NLO(EW)
VBF	POWHEG-BOX v2	NLO	NNPDF3.0NLO	PYTHIA 8.212	AZNLO	NNLO(QCD)+NLO(EW)
$qq \rightarrow WH$	POWHEG-BOX v2	NLO	NNPDF3.0NLO	PYTHIA 8.212	AZNLO	NNLO(QCD)+NLO(EW)
$qq \rightarrow ZH$	POWHEG-BOX v2	NLO	NNPDF3.0NLO	PYTHIA 8.212	AZNLO	NNLO(QCD)+NLO(EW)$^{(\ddagger)}$
$gg \rightarrow ZH$	POWHEG-BOX v2	NLO	NNPDF3.0NLO	PYTHIA 8.212	AZNLO	NLO+NLL
$t\bar{t}H$	POWHEG-BOX v2	NLO	NNPDF3.0NLO	PYTHIA 8.230	A14	NLO

More info on this analysis: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2021-15/

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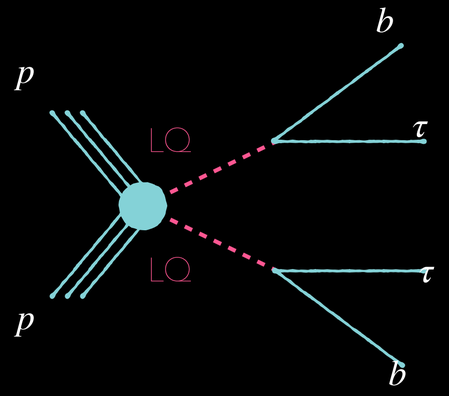

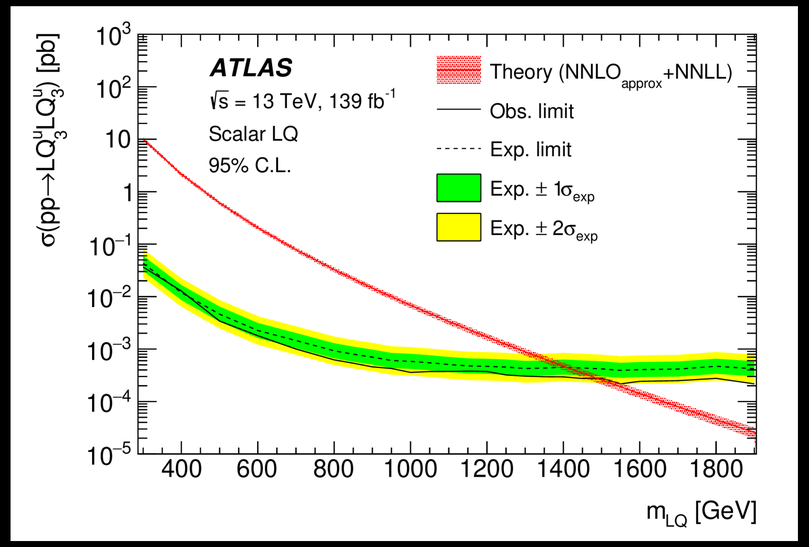

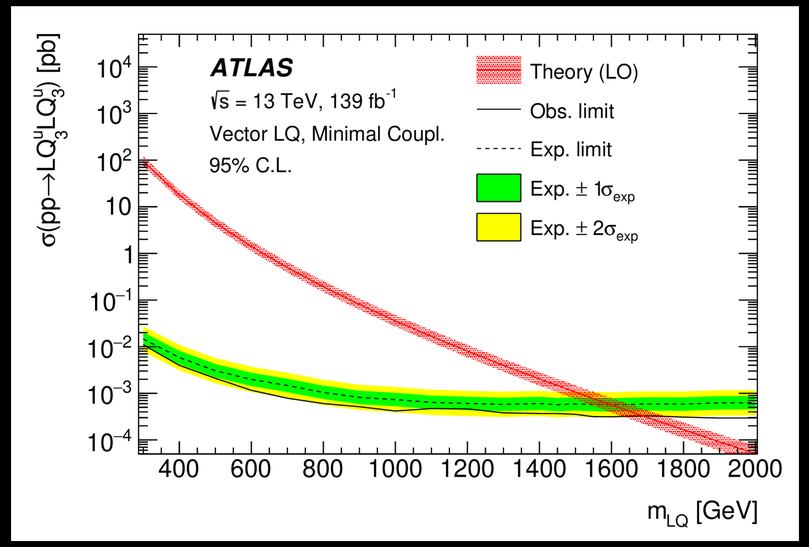

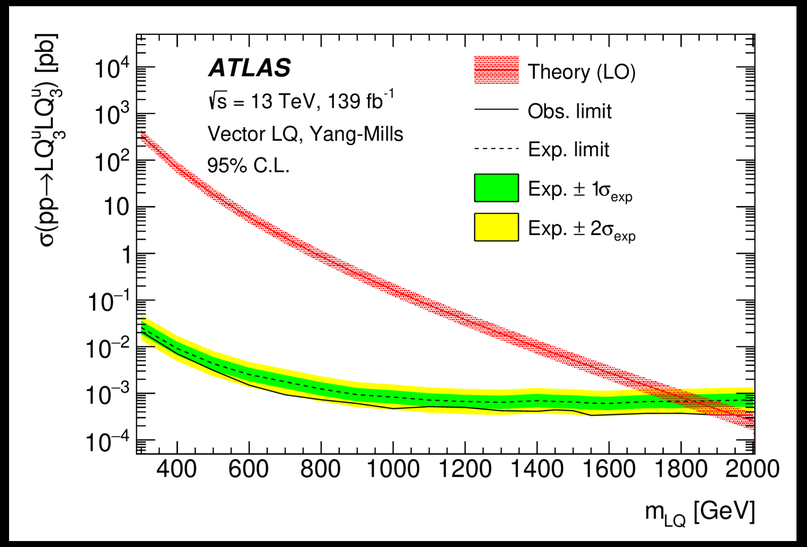

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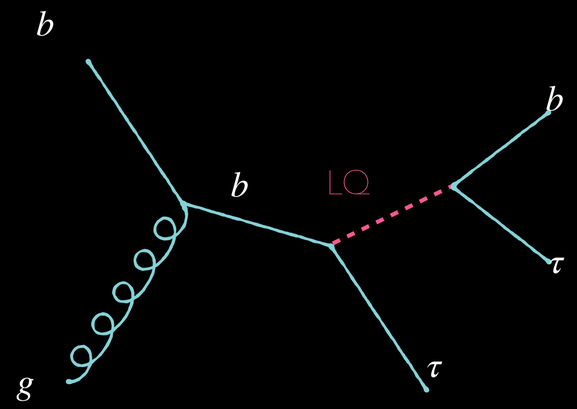
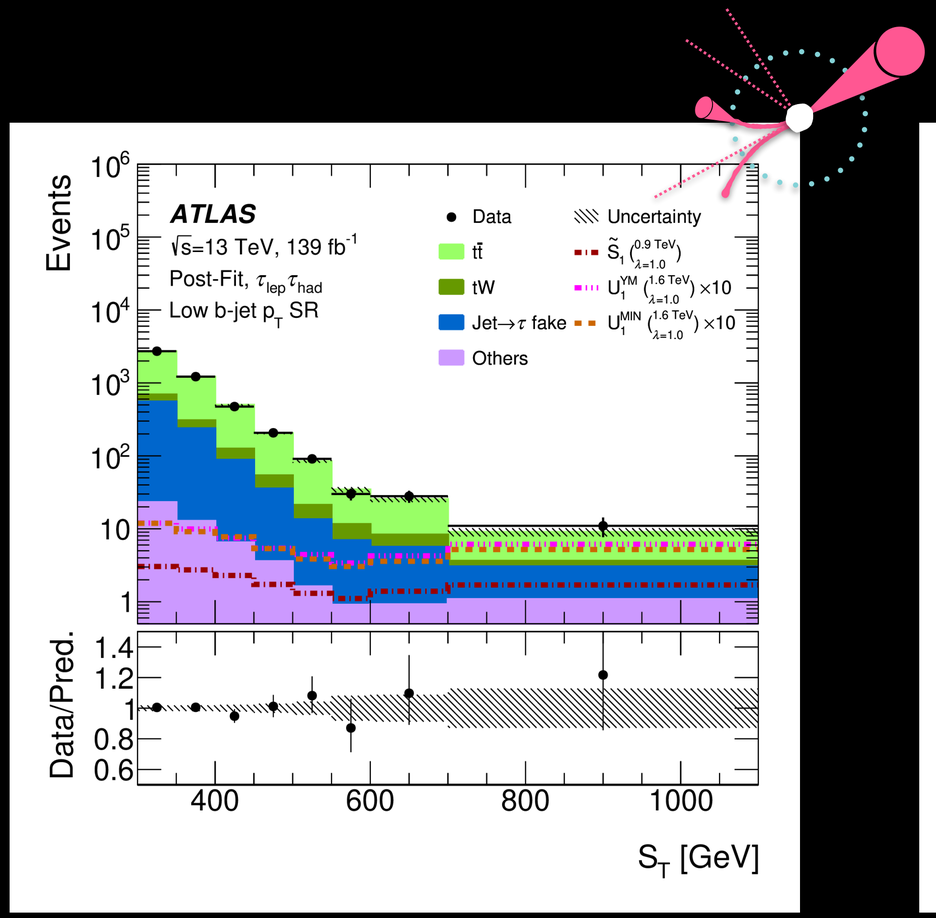
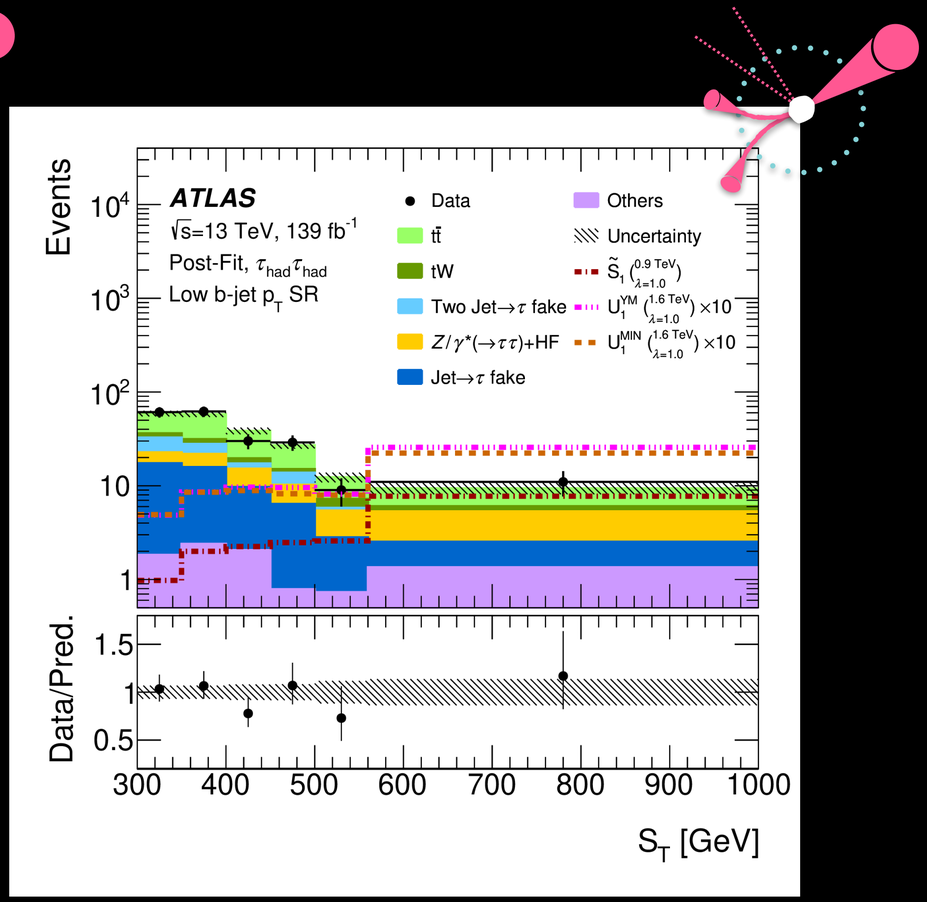


not considered in results





More info on this analysis: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2022-39/

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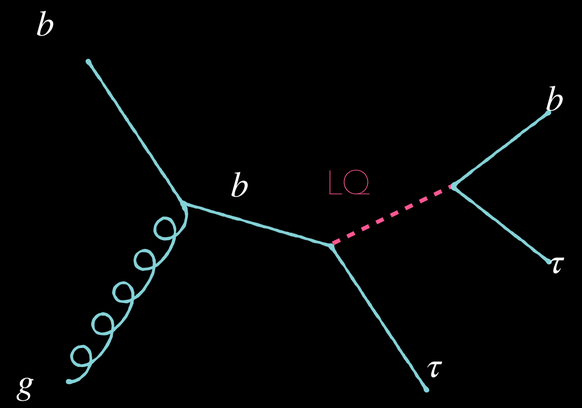

Process	$\tau_{\text{lep}}\tau_{\text{had}}$	$\tau_{\text{had}}\tau_{\text{had}}$
$t\bar{t}$	764 ± 82	9.9 ± 2.6
Single top	65 ± 35	3.9 ± 1.0
Jet→ τ *fake*	215 ± 79	3.9 ± 1.0
Two jet→ τ *fake*	–	1.34 ± 0.27
$Z(\rightarrow \tau\tau)$+HF jets	5.5 ± 0.4	4.6 ± 1.1
Others	9.7 ± 1.0	1.75 ± 0.30
Total	1059 ± 51	25.4 ± 4.9
Data	1053	29

$\tau_{lep}\tau_{had}$

Signal Regions	Selection	
Preselection	ℓ (trigger, isolated), $\tau_{\text{had-vis}}$ (medium τ_{had}-ID), $q(\ell) \times q(\tau_{\text{had-vis}}) < 0$, $\Delta\phi(\ell, E_{\text{T}}^{\text{miss}}) < 1.5$, $m_{\text{vis}}(\ell, \tau_{\text{had-vis}}) > 100$ GeV, $S_{\text{T}} > 300$ GeV, at least one b-jet	
High b-jet p_{T} SR	Leading b-jet $p_{\text{T}} > 200$ GeV	
Low b-jet p_{T} SR	Leading b-jet $p_{\text{T}} < 200$ GeV	
Control/Validation Regions	Selection	Purpose
Multijet-CR	ℓ (trigger, pass/fail offline isolation), $m_{\text{T}}(\ell, E_{\text{T}}^{\text{miss}}) < 30$ GeV, one b-jet, τ_{had}-ID score < 0.01, $E_{\text{T}}^{\text{miss}} < 50$ GeV	Measure lepton fake-factor
Top-CR	Satisfy SR except: $\Delta\phi(\ell, E_{\text{T}}^{\text{miss}}) > 2.5$, no S_{T} and lead. b-jet p_{T} req.	Derive top correction
SS-CR	Satisfy SR except: $q(\ell) \times q(\tau_{\text{had-vis}}) > 0$, no $\Delta\phi(\ell, E_{\text{T}}^{\text{miss}})$, and S_{T} req.	Measure jet→ τ background scale factor
High b-jet p_{T} VR	Satisfy high b-jet p_{T} SR except: $1.5 < \Delta\phi(\ell, E_{\text{T}}^{\text{miss}}) < 2.5$, 300 GeV < S_{T} < 600 GeV	Background modelling validation
Low b-jet p_{T} VR	Satisfy low b-jet p_{T} SR except: $1.5 < \Delta\phi(\ell, E_{\text{T}}^{\text{miss}}) < 2.5$, 300 GeV < S_{T} < 600 GeV	Background modelling validation
b-tag Z-CR	Satisfy SR except: 45 GeV < $m_{\text{vis}}(\ell, \tau_{\text{had-vis}}) < 80$ GeV, $p_{\text{T}}(\ell)/p_{\text{T}}(b\text{-jet}) > 0.8$, $\lvert\Delta\phi(\ell, \tau_{\text{had-vis}})\rvert > 2.4$, no S_{T} req.	Z+ heavy-flavour jets normalisation factor

$\tau_{had}\tau_{had}$

Signal Regions	Selection	
Preselection	$\tau_{\text{had},1}$ (trigger, medium τ_{had}-ID), τ_2 (loose τ_{had}-ID), $q(\tau_1) \times q(\tau_2) < 0$, $m_{\text{vis}}(\tau_1, \tau_2) > 100$ GeV, $S_{\text{T}} > 300$ GeV, at least one b-jet	
High b-jet p_{T} SR	Leading b-jet $p_{\text{T}} > 200$ GeV	
Low b-jet p_{T} SR	Leading b-jet $p_{\text{T}} < 200$ GeV	
Control/Validation Regions	Selection	Purpose
DJ-CR	τ_1 and τ_2 satisfy very loose τ_{had}-ID, $q(\tau_1) \times q(\tau_2) < 0$	Measure $\tau_{\text{had-vis}}$ fake-factor
CR-1	Satisfy SR except: τ_2 fail loose τ_{had}-ID	Apply $\tau_{\text{had-vis}}$ fake-factor
SS-VR	Satisfy SR except: $q(\tau_1) \times q(\tau_2) > 0$	Multijet modelling check
Z+light flavour jets VR	Satisfy SR except: 0 b-jets, $\Delta\phi(\tau_1, \tau_2) > 0.25$, $m_{\text{vis}}(\tau_1, \tau_2) < 100$ GeV, $E_{\text{T}}^{\text{miss}} > 60$ GeV	Z+light jets modelling

More info on this analysis: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2022-39/

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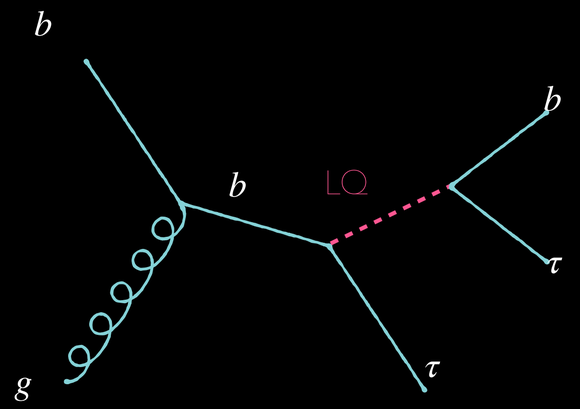

Process	Generator		PDF set		Tune	Normalisation
	ME	PS	ME	PS		
LQ→ $b\tau$	MadGraph5_aMC@NLO	Pythia 8.244	NNPDF3.0nnlo	NNPDF2.3lo	A14	LO
Scalar LQLQ→ $b\tau b\tau$	MadGraph5_aMC@NLO	Pythia 8.230	NNPDF3.0nnlo	NNPDF2.3lo	A14	NNLO + NNLL
Vector LQLQ→ $b\tau b\tau$	MadGraph5_aMC@NLO	Pythia 8.244	NNPDF3.0nnlo	NNPDF2.3lo	A14	LO
$t\bar{t}$	Powheg Box v2	Pythia 8.230	NNPDF3.0nnlo	NNPDF2.3lo	A14	NNLO + NNLL
Single top	Powheg Box v2	Pythia 8.230	NNPDF3.0nnlo	NNPDF2.3lo	A14	NLO
Z/γ^*	Powheg Box v1	Pythia 8.186	CT10nlo	CTEQ6L1	AZNLO	NLO
W+jets	Sherpa 2.2.1		NNPDF3.0nnlo		Sherpa	NNLO
Diboson	Sherpa 2.2.1/Sherpa 2.2.2		NNPDF3.0nnlo		Sherpa	NLO

More info on this analysis: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2022-39/

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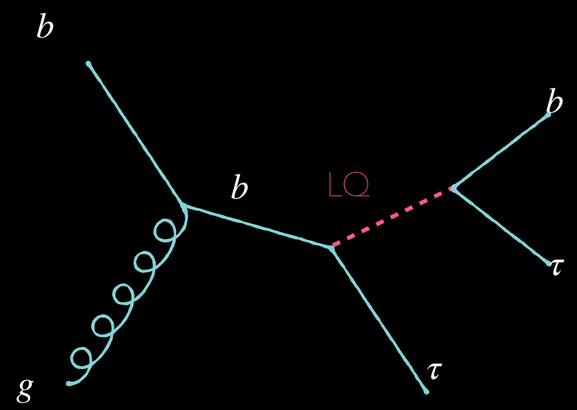

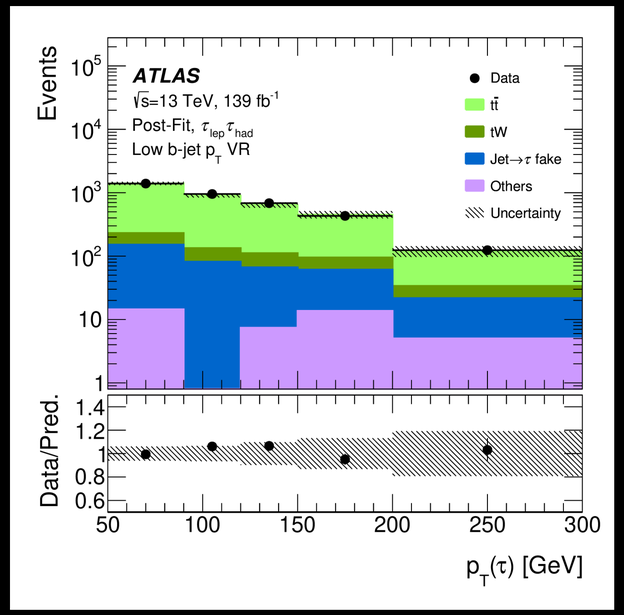

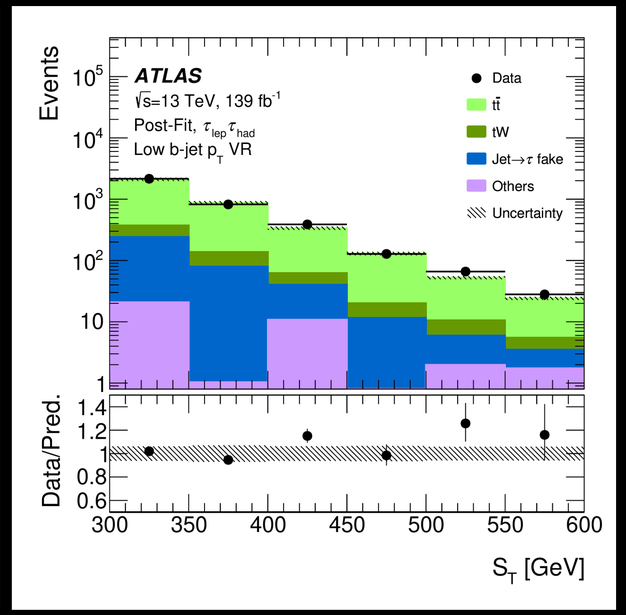

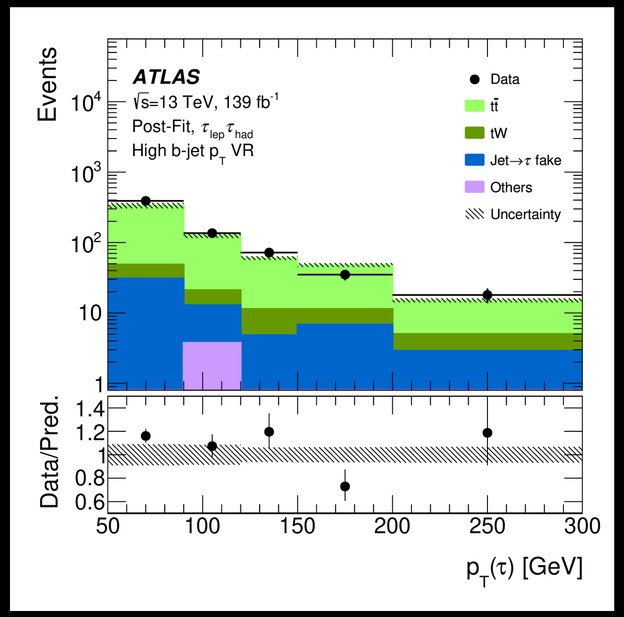

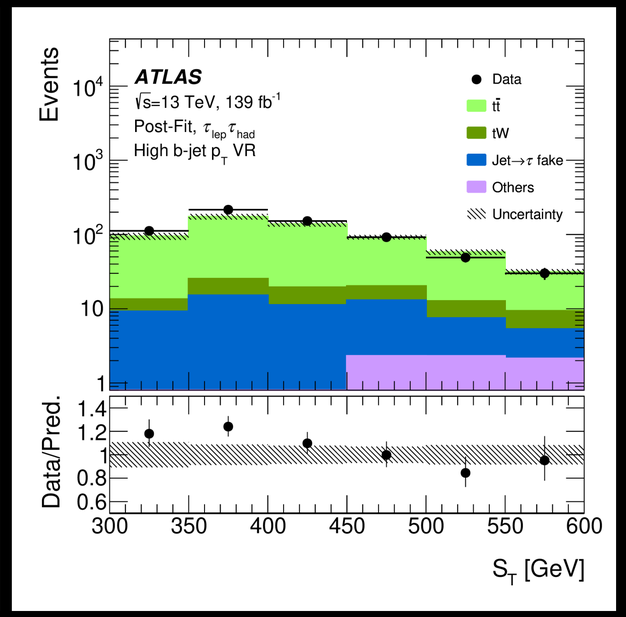

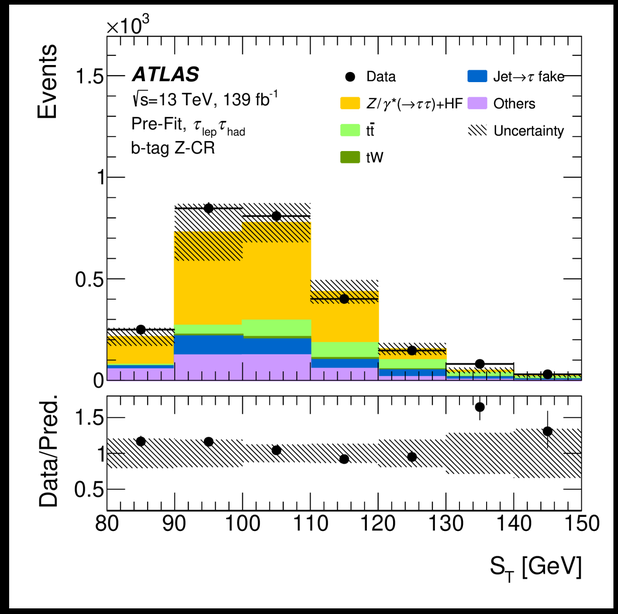

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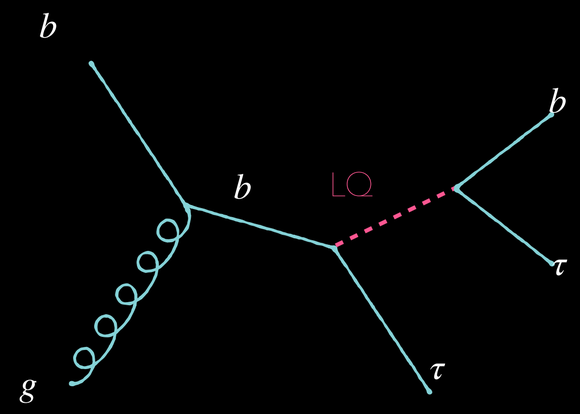

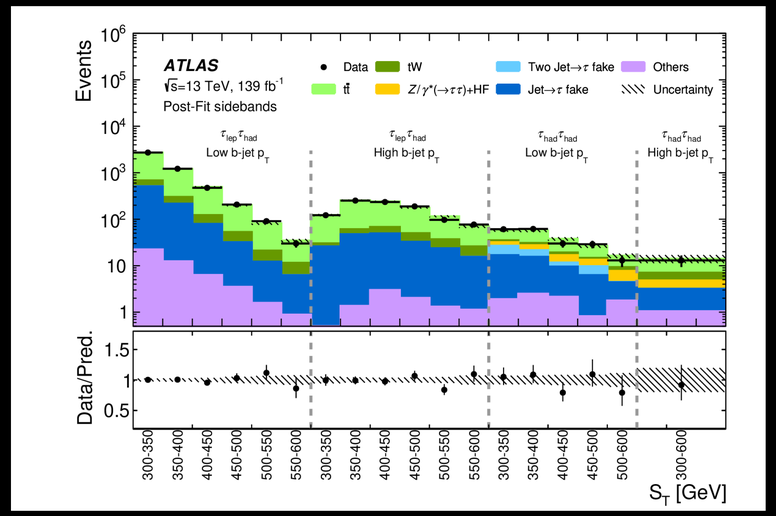

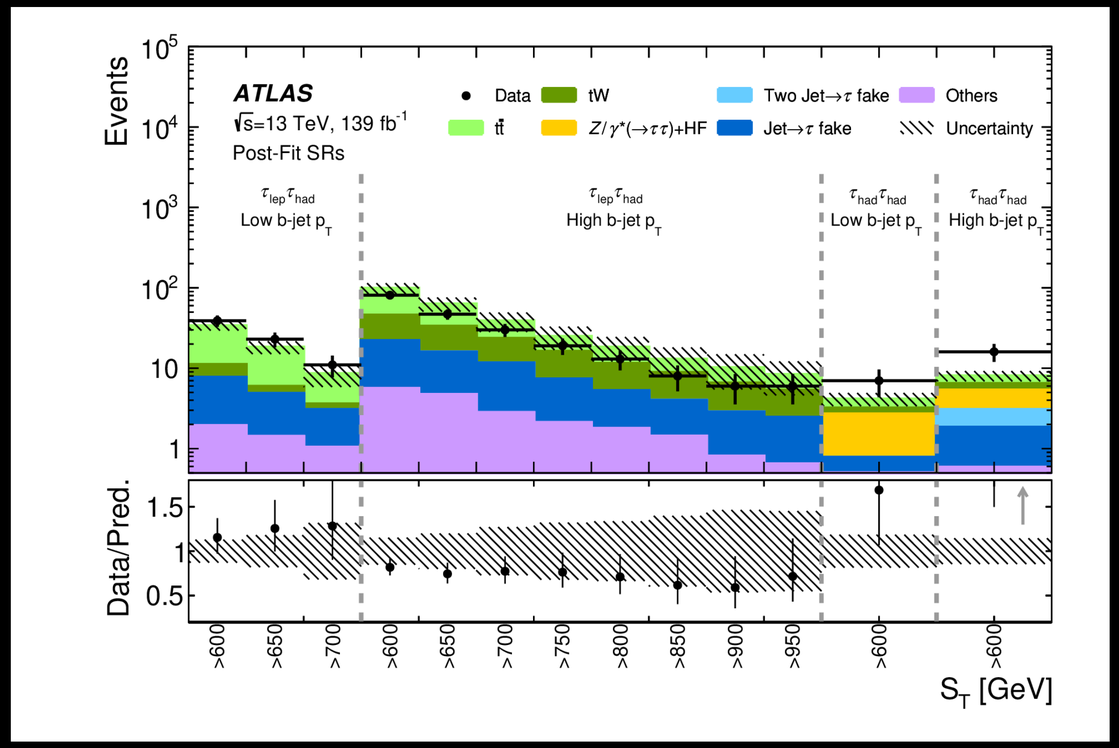

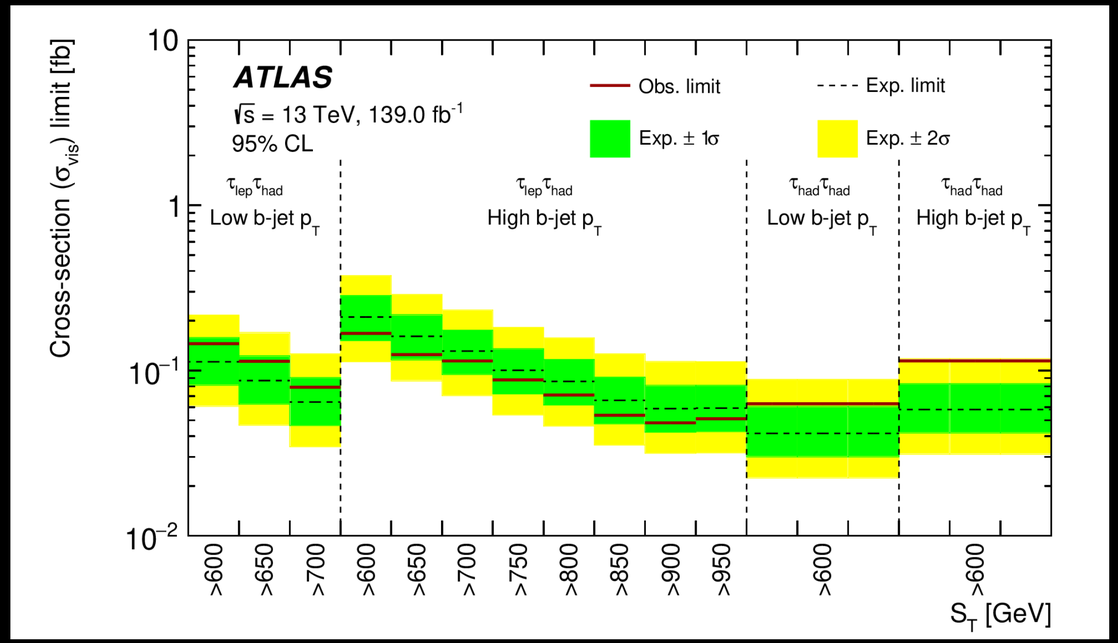

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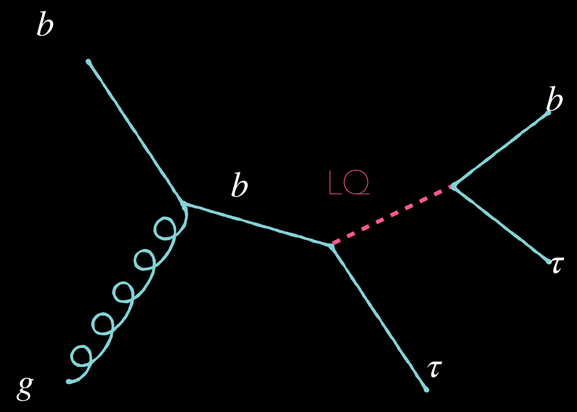
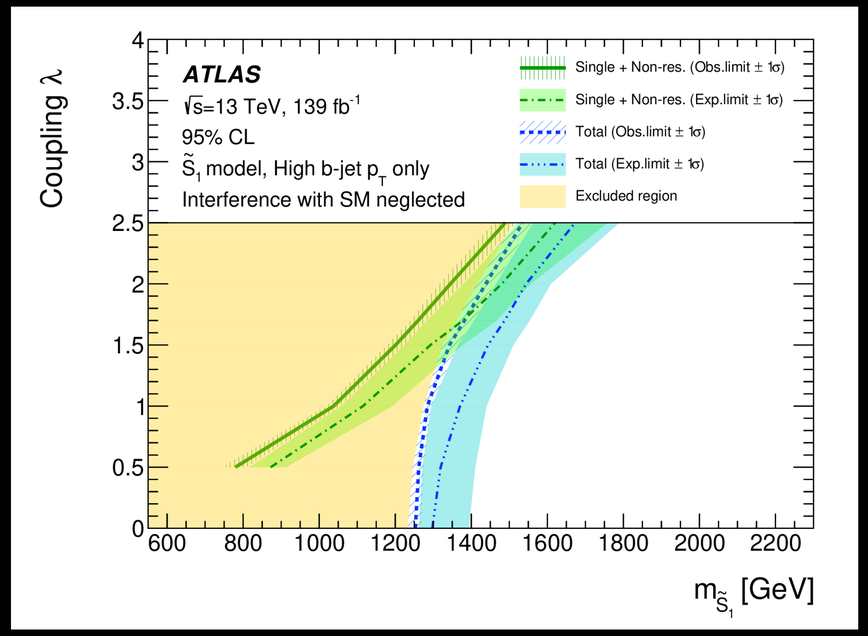
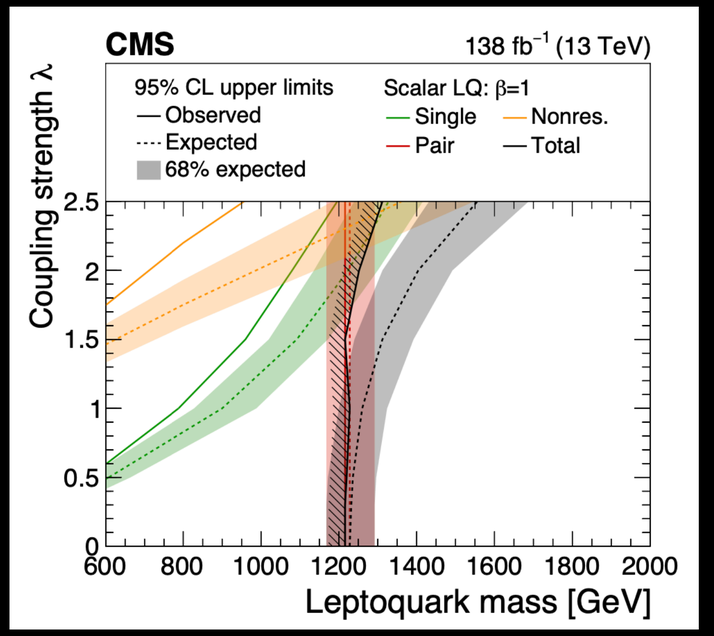
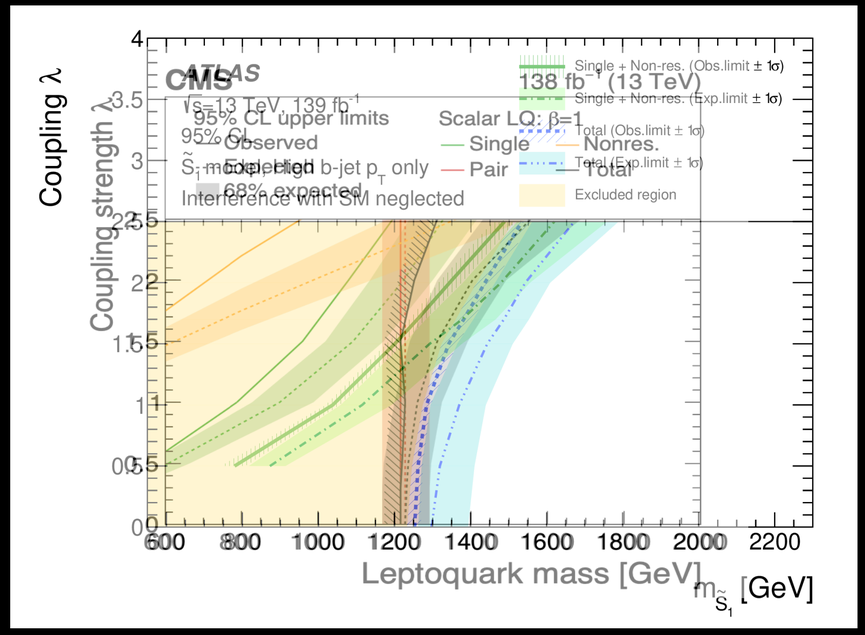






CMS results (submitted to JHEP)
https://cms-results.web.cern.ch/cms-results/public-results/publications/EXO-19-016/



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