Leptoquark and Z' / W' Searches @ ATLAS and CMS

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On behalf of the ATLAS and CMS Collaborations

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Physics Motivation

The Standard Model (SM) of particle physics has been extremely successful with the discovery of Higgs.

Some new physics are needed to address the phenomena like neutrino mass or dark matter.

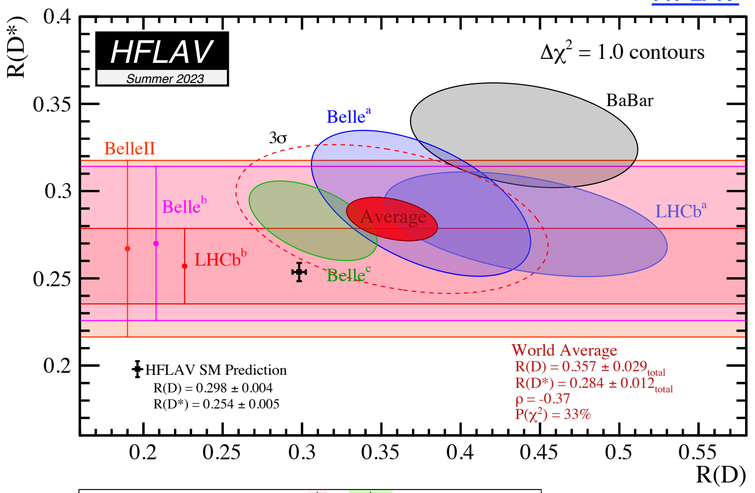
Hints for lepton flavor universality (LFU) violation have been observed in charged and neutral current processes in B-physics:

- R_D/R_{D*}: 3.3σ deviation in global average by BaBar
- R_K/R_{K*}: anomalies measured by LHCb in 2019, SM consistent in 2022
- Muon $g-2$ anomaly measured at Fermilab, …

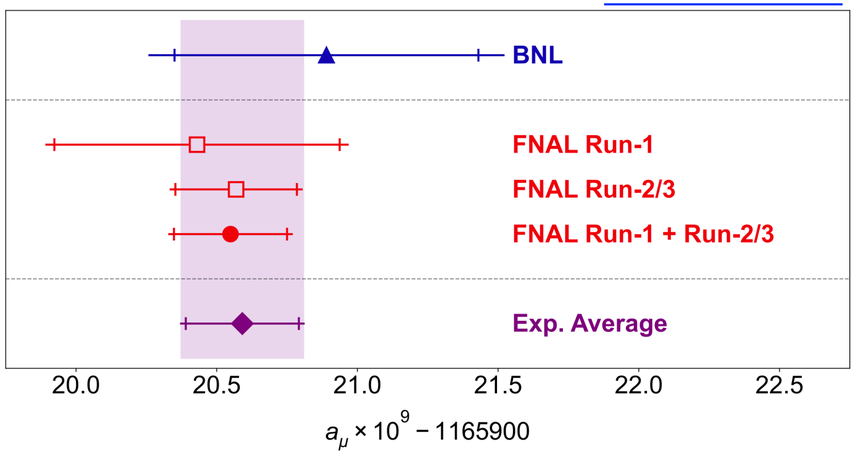
Possible new physics explanations:

- **Leptoquarks** ← ***This talk!***
- **Light and heavy vector bosons** ← ***This talk!***
- High-mass Drell-Yan tails and EFT interpretations
- Vector-like Fermions, …

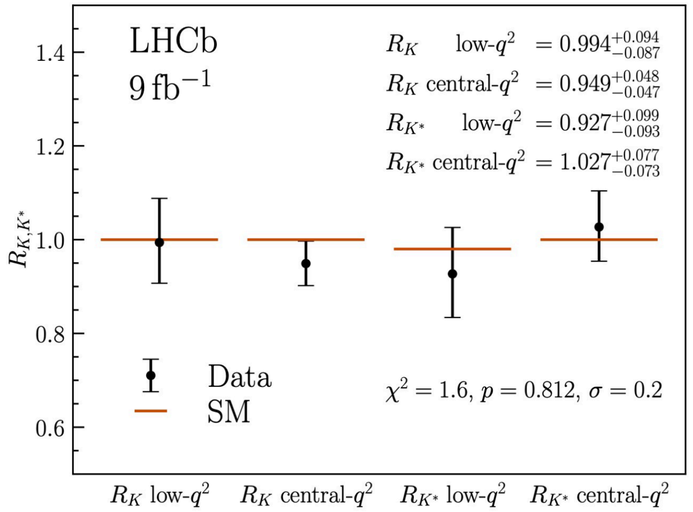
HFLAV

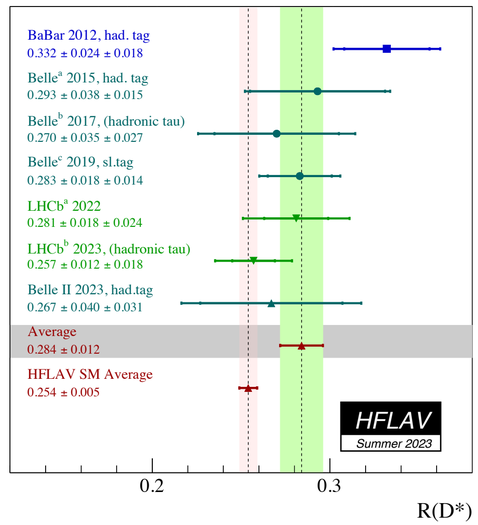


arXiv:2308.06230



arXiv:2212.09152





Analysis Results Covered Today

All Run-2 results at 13 TeV

	ATLAS	CMS
Searches for Leptoquarks	LQLQ → tete/tμtμ	
	LQLQ → bτbτ	
	LQ → bτ	
	3rd generation LQ combination	
	LQLQ → tνbl	LQLQ → bμbμ
		LQ → τq
Searches for Z'/W' in Leptonic Final States	Low mass Z' in the 4μ channel (CMS: 77.3/fb)	
	Low mass Z' in the 3μ channel	
	W' → τν	
	W' → tb 0/1-lepton	

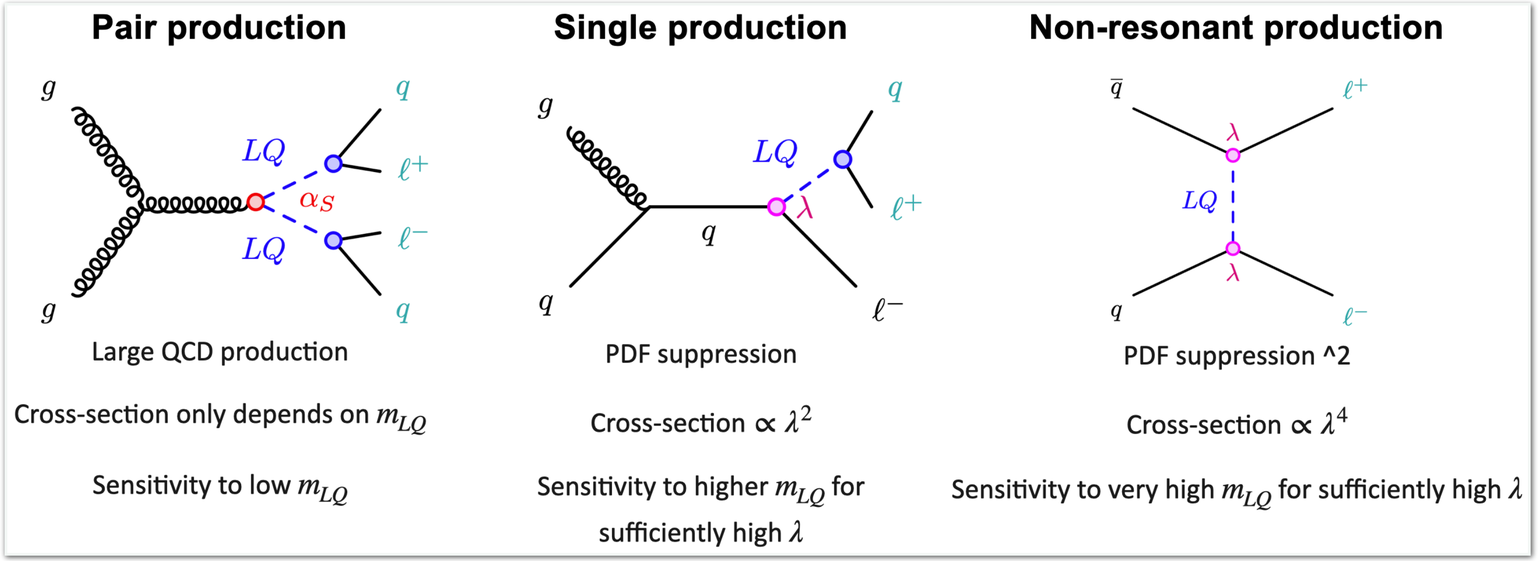
Leptoquarks Overview

Leptoquarks (LQs) are hypothetical particles predicted by many BSM theories

- Scalar or vector boson
- Carrying color charge and fractional electric charge
- Non-zero baryon number and lepton number
- Decaying into quark-lepton pair

Production modes:

- Pair-production is the **dominant** process



Production and decay determined by:

- LQ mass m_{LQ}
- Yukawa couplings λ to lepton and quark
- Branching fractions β to a given lepton and quark flavors, assuming $\beta(LQ \to q_i l) = 1 - \beta(LQ \to q_i' \nu)$
- Coupling parameter κ in case of vector LQs (coupling with the SM gauge fields)

LQ-t-l ($l = e, \mu$): Pair Production @ ATLAS

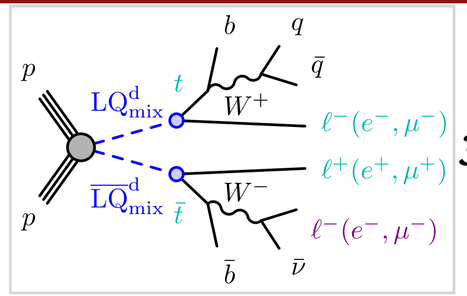
arXiv:2306.17642

Scalar (LQ^{d}_{mix}) and vector ($\tilde{U}_1^{min}$ & $\tilde{U}_1^{YM}$) LQ models considered

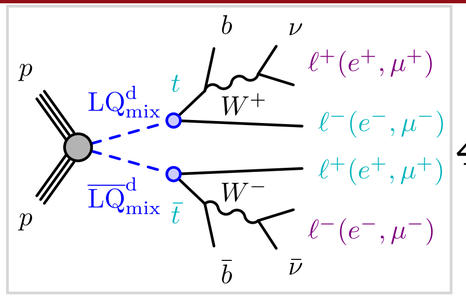
Event selections: 3 or 4 light leptons (e or μ), $\geq$ 2 jets, $\geq$ 1 b-jet

Signal regions: two channels ($3l$, $4l$) for $tete/t\mu t\mu$ are considered

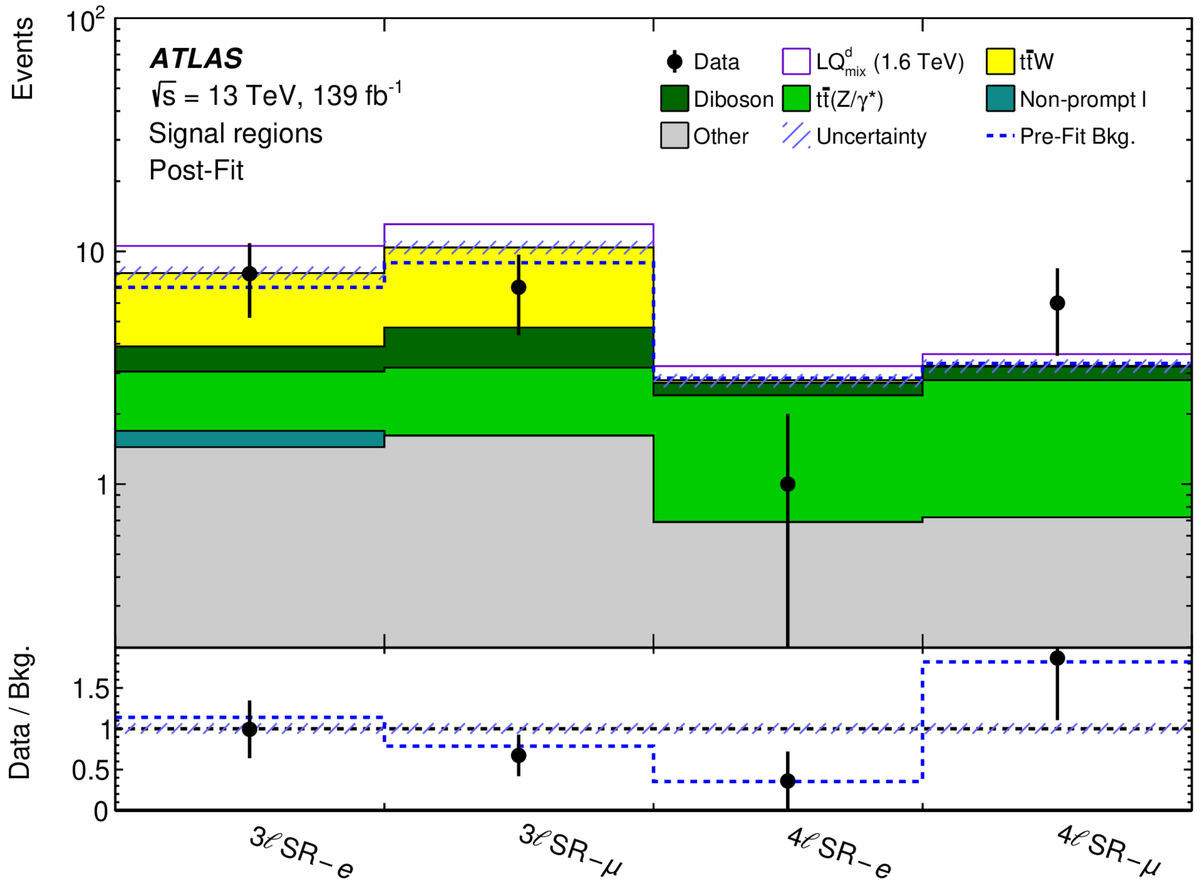
Final discriminant variable: effective mass $m_{eff} = \sum_{jet,e,\mu} p_T + MET$

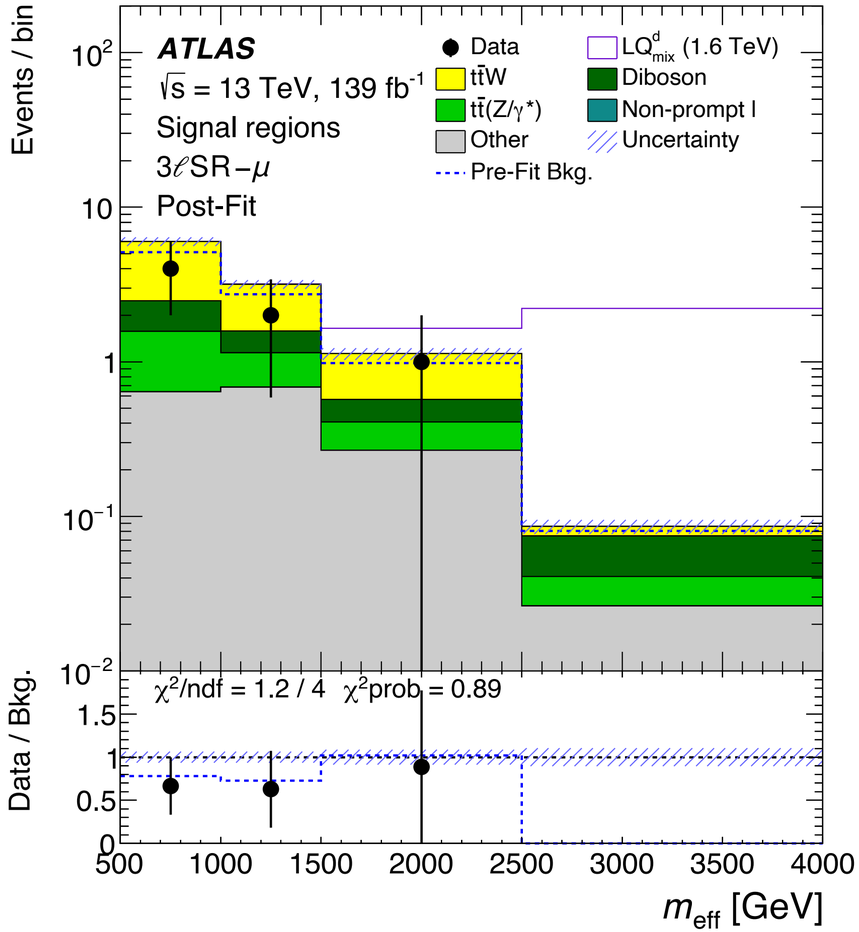


$3l$



$4l$





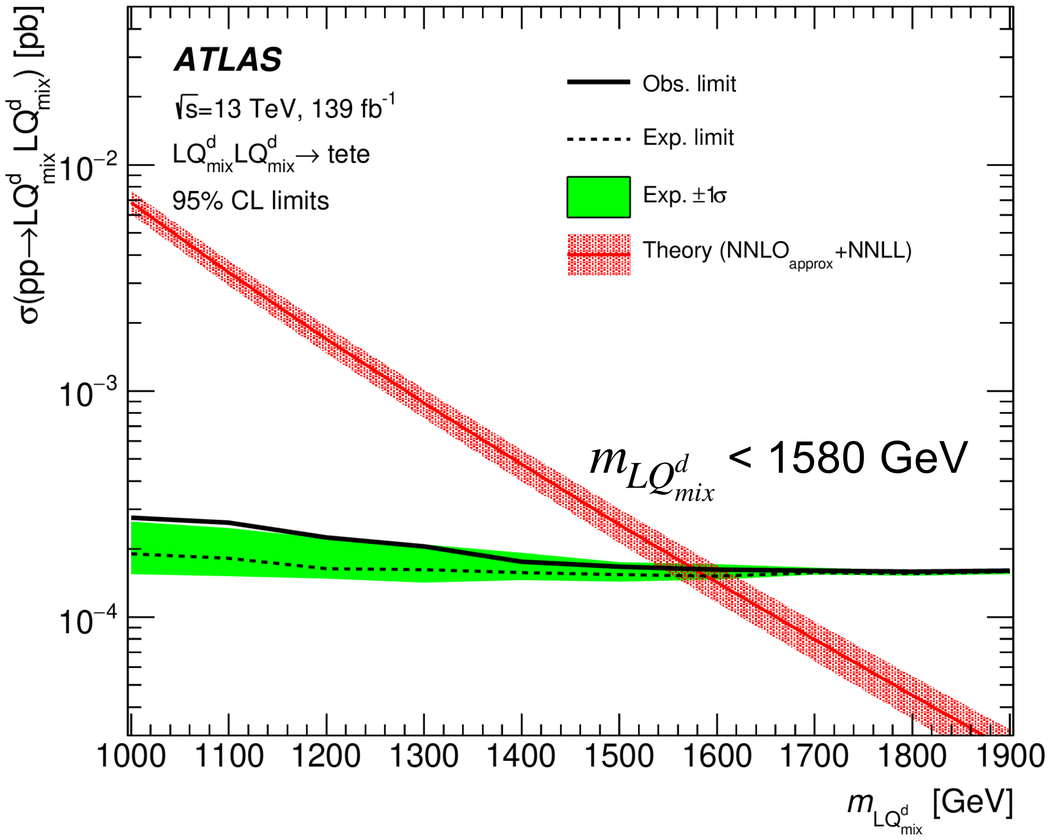
LQ-t-l ($l = e, \mu$): Pair Production @ ATLAS

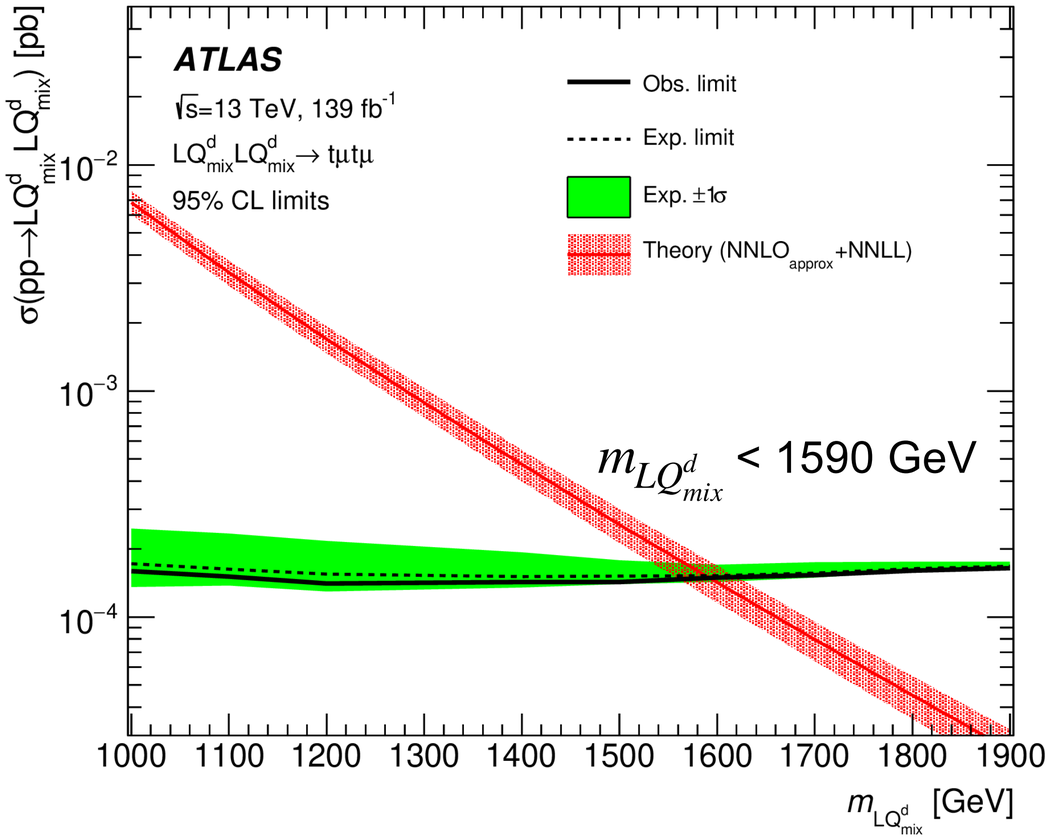
arXiv:2306.17642

No significant excess observed and 95% CL limits on the production cross-section times branching ratio are derived as a function of the LQ mass.

Here only shows the limits on the production cross-section on scalar LQ:

CMS arXiv:2202.08676 , see more details in Backup





Observed exclusion limits @ CMS:

$tete$: $m_{LQ^d_{mix}}$ < 1340 GeV

$t\mu t\mu$: $m_{LQ^d_{mix}}$ < 1420 GeV

LQ-b-τ: Pair Production @ ATLAS

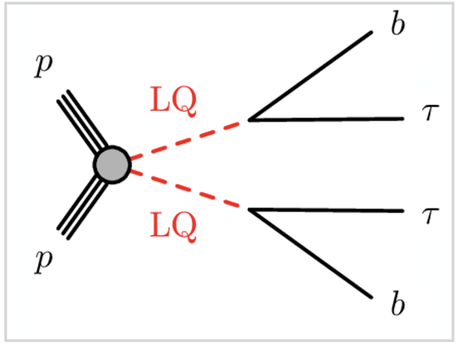
arXiv:2303.01294

Focuses on 3^{rd} generation LQ pair-production

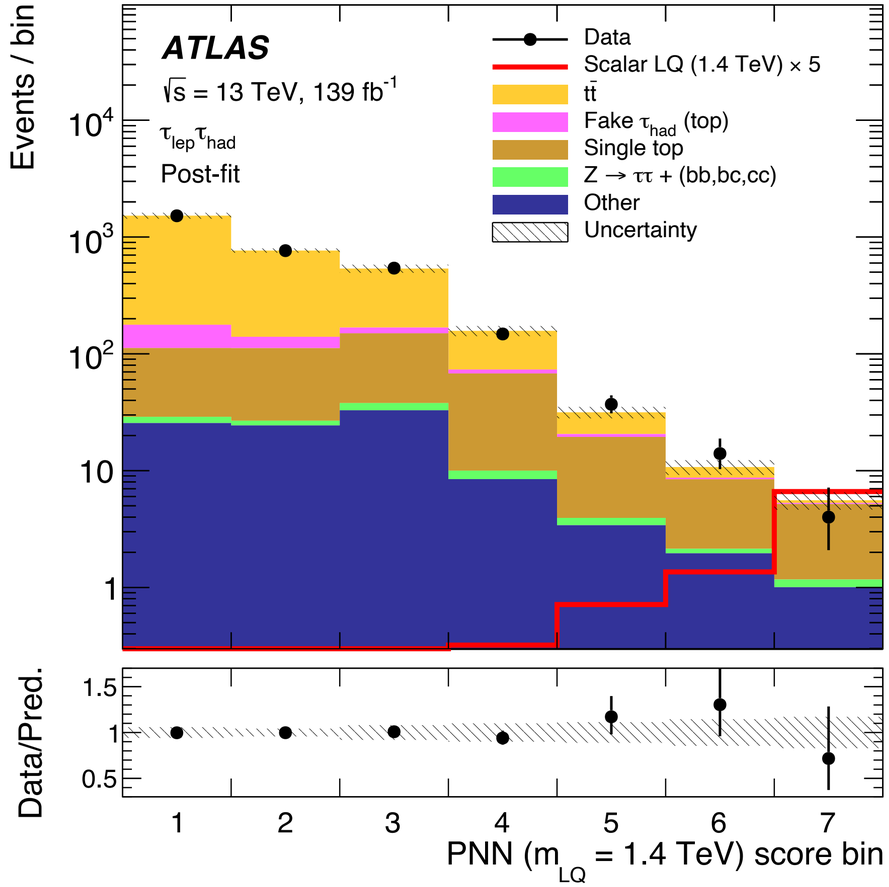
Event selections:

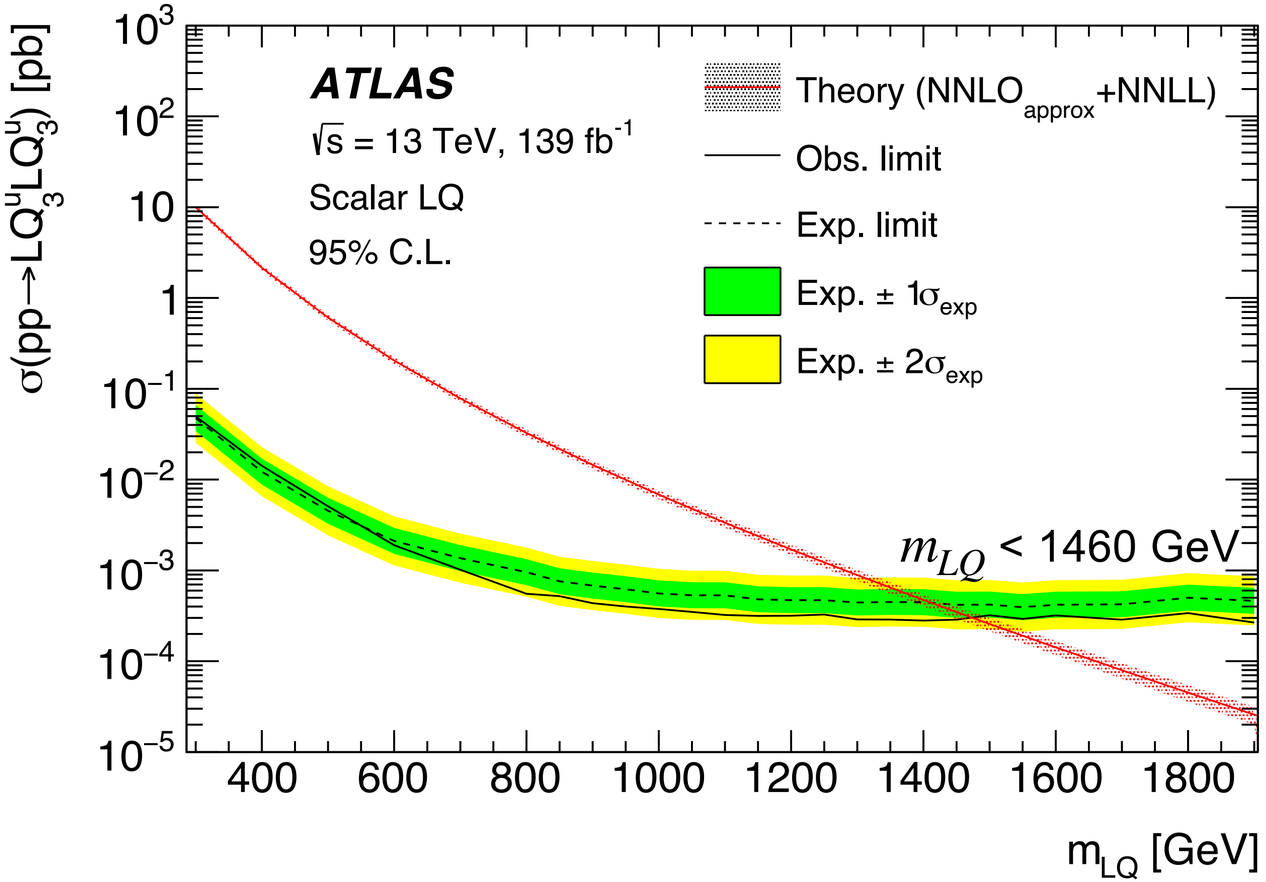
- $\geq$ 2 jets, $\geq$ 1 b-jet
- Two channels: $\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$ $(l = e, \mu)$

Final discriminant variable: Parametric Neural Network (PNN)



See more details in Federico's talk later in YSF session





LQ-b-μ: Pair Production @ CMS

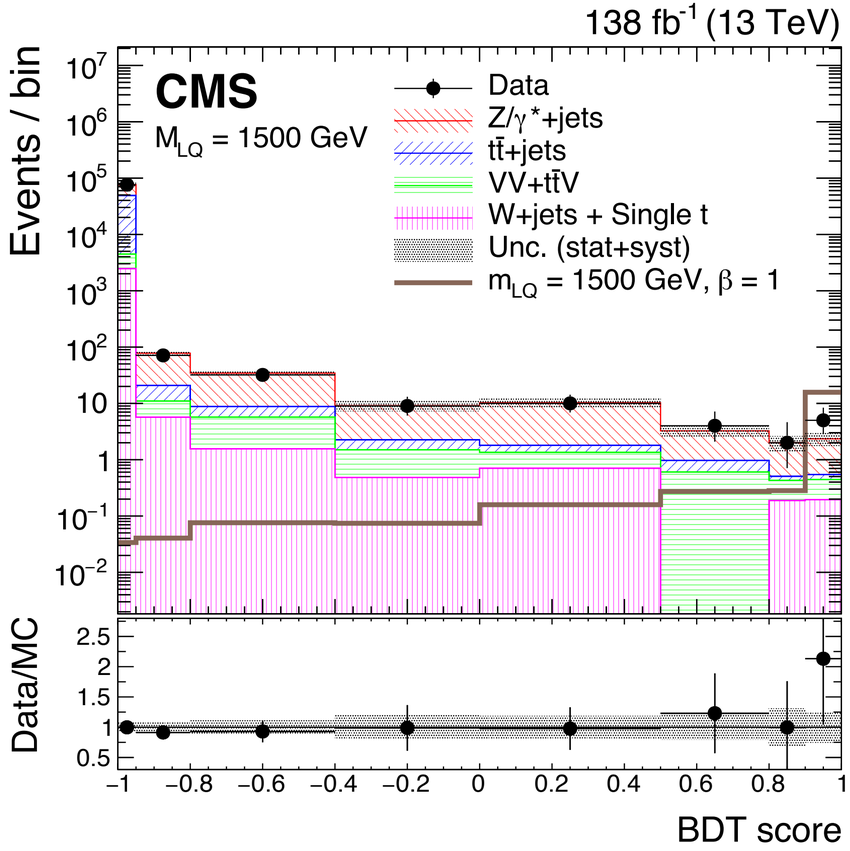
arXiv:2402.08668

Event selections:

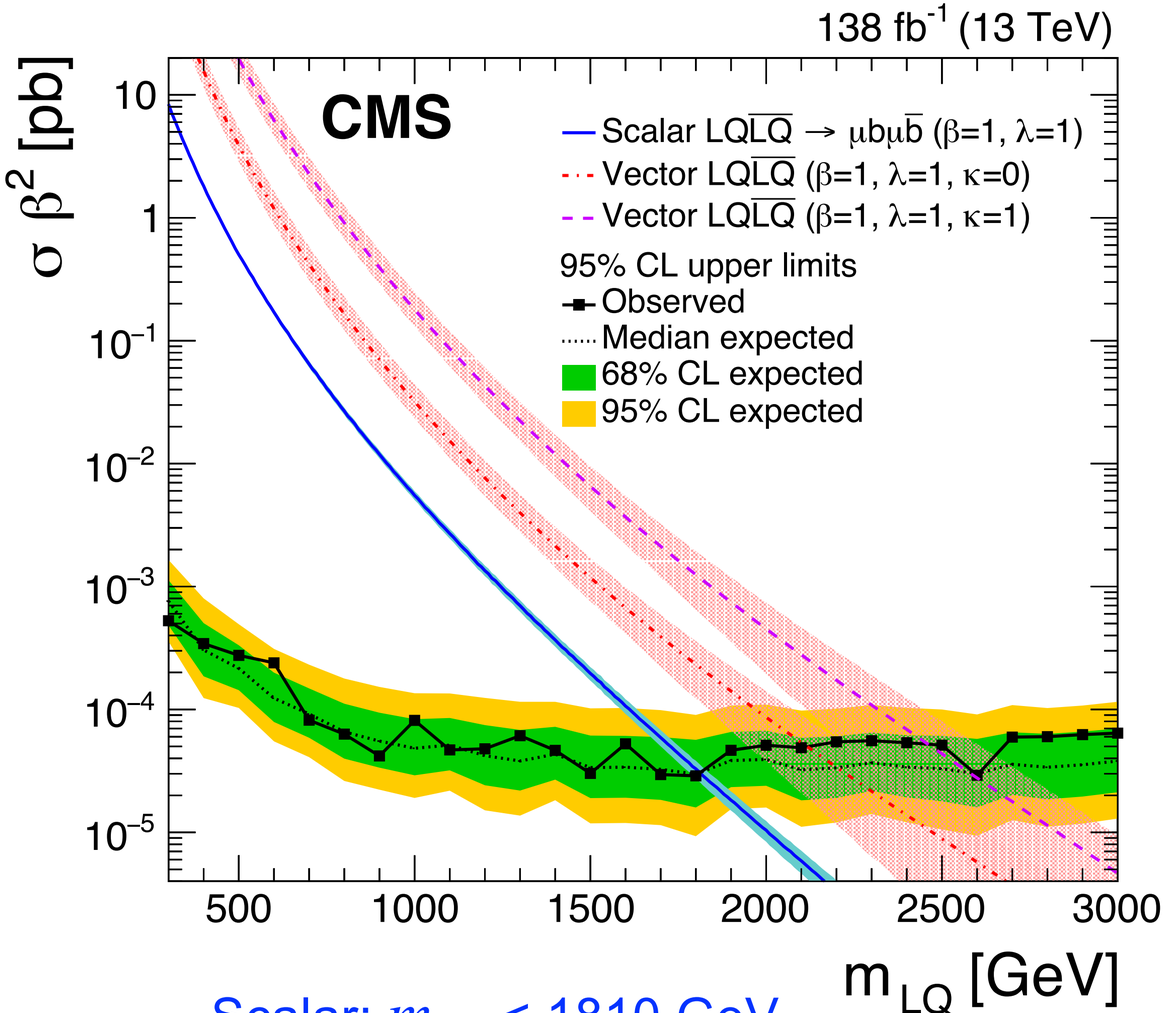
- 2 μ, $\geq$ 2 jets, $\geq$ 1 b-jet
- $S_T = p_T^{\mu_1} + p_T^{\mu_2} + p_T^{j_1} + + p_T^{j_2}$ > 300 GeV
- $m_{\mu\mu}$ > 250 GeV

Final discriminant variable: BDT (trained for each LQ mass)

No significant excess seen, **most stringent limits to date**!



ATLAS arXiv:2210.04517 , see more details in Backup



Scalar: m_{LQ} < 1810 GeV

ATLAS limits: m_{LQ} < 1460 GeV

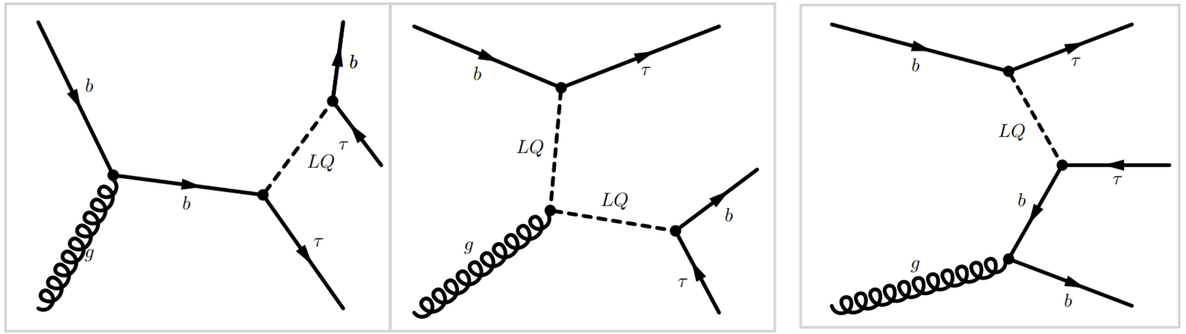
LQ-b-τ: All Production Modes @ ATLAS

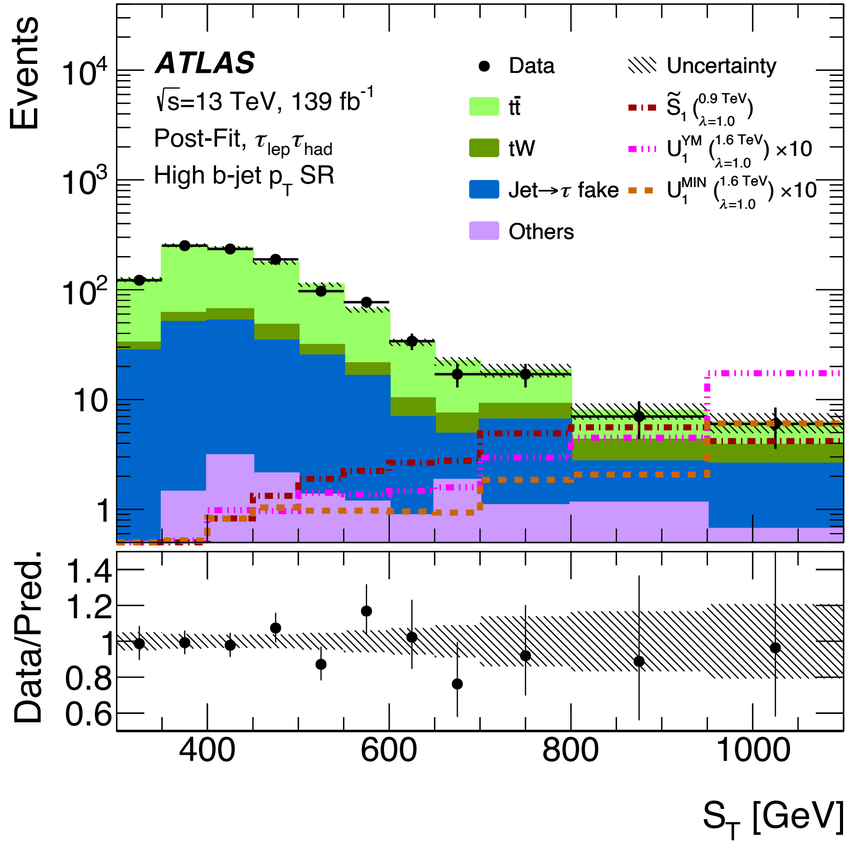
arXiv:2305.15962

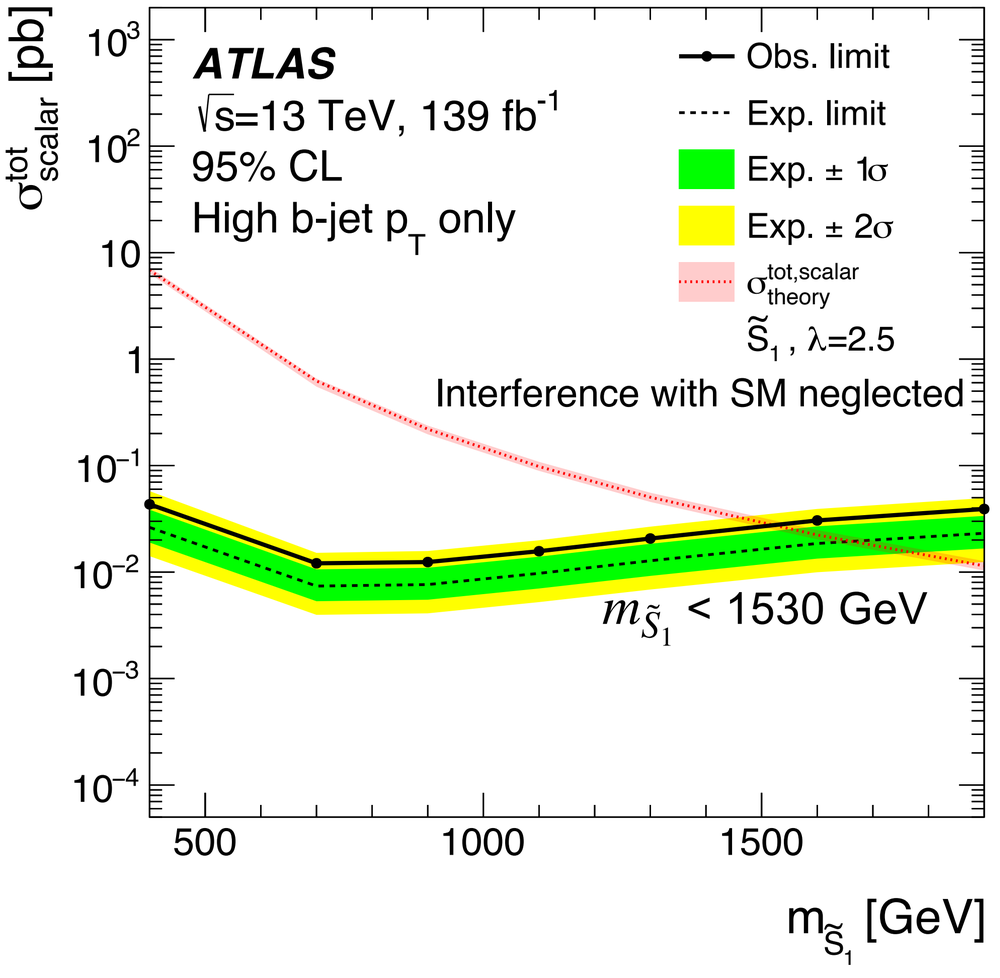
Single + Pair + Non-resonant production are considered
- Single: scalar ($\tilde{S}_1$) and vector (U_1^{Min} and U_1^{YM}) LQ models

Event selections:
- $\geq$ 1 jets, $\geq$ 1 b-jets (p_T > 25 GeV)
- Two channels: $\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$ ($l = e, \mu$)

Final discriminant variable: $S_T = p_T^{\tau_1} + p_T^{\tau_2} + p_T^{bjet}$







LQ-b-τ: All Production Modes @ CMS

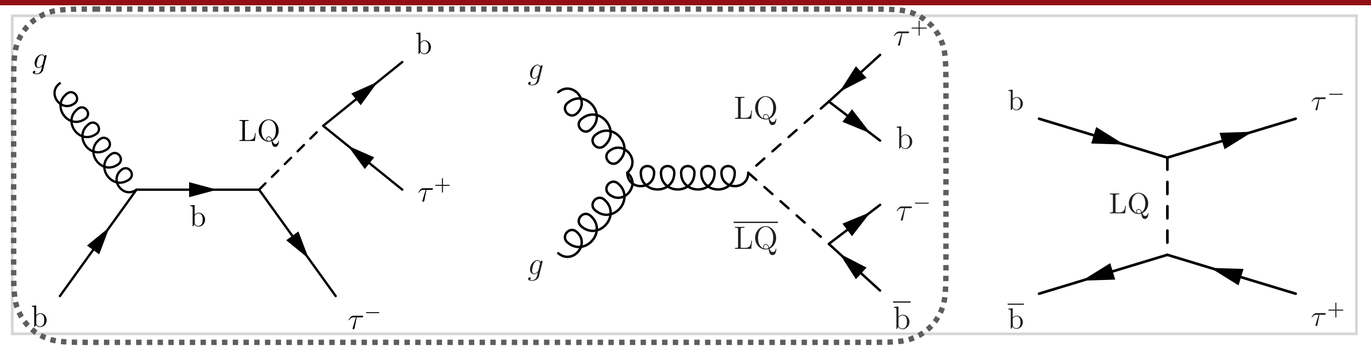
arXiv:2308.07826

Event categorization:

- Resonant: $\geq$ 1 jets (p_T > 50 GeV)
  - split in 2 categories: 0 and $\geq$ 1 b-jets (p_T > 50 GeV)
- Non-resonant: = 0 jets (p_T > 50 GeV)
  - split in 3 m_{vis} categories

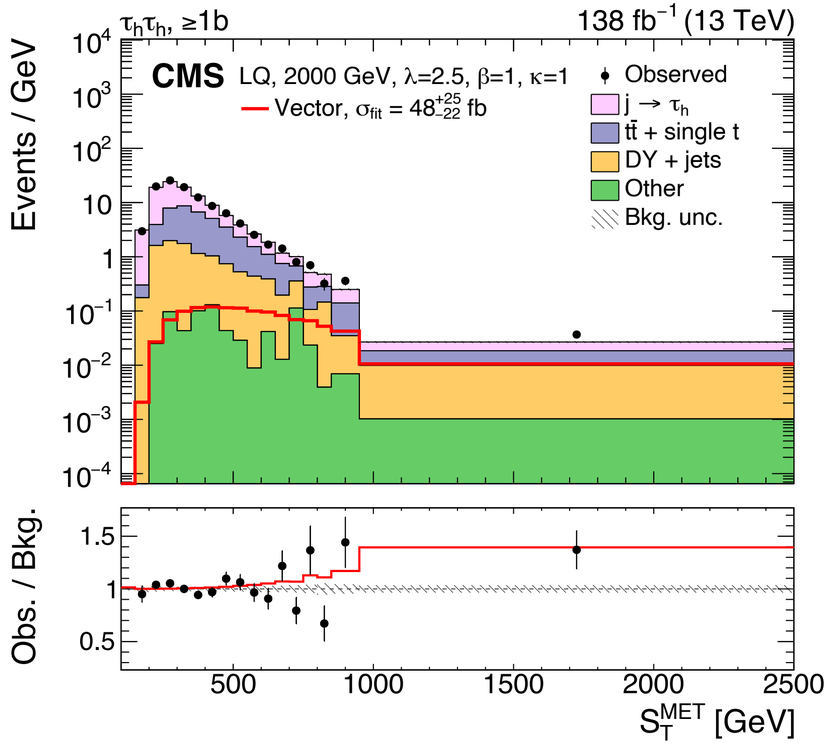
Final discriminating variable:

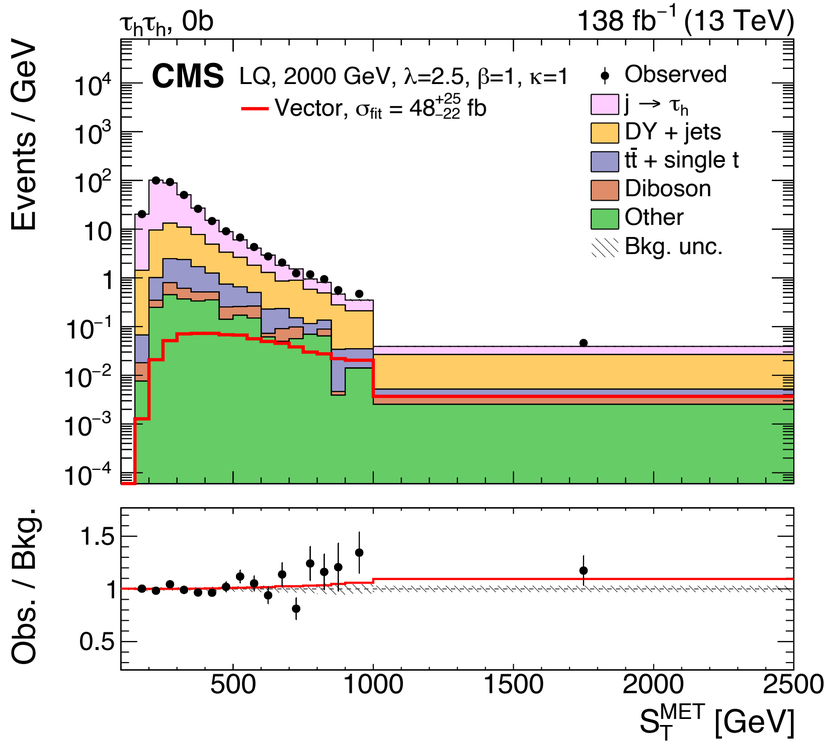
- Resonant: $S_T^{MET} = p_T(\tau_1) + p_T(\tau_2) + p_T(j_1) + p_T^{miss}$
- Non-resonant: $\chi = \exp(|\Delta\eta_{\tau\tau}|)$

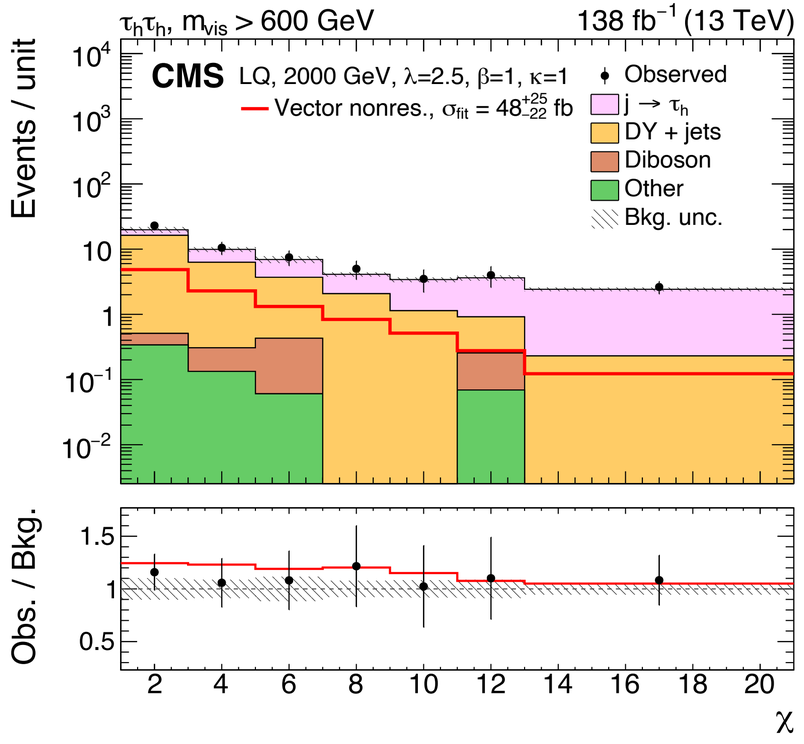


Resonant channels: S_T^{MET}

Non-resonant channels: χ







LQ-b-τ: All Production Modes @ CMS

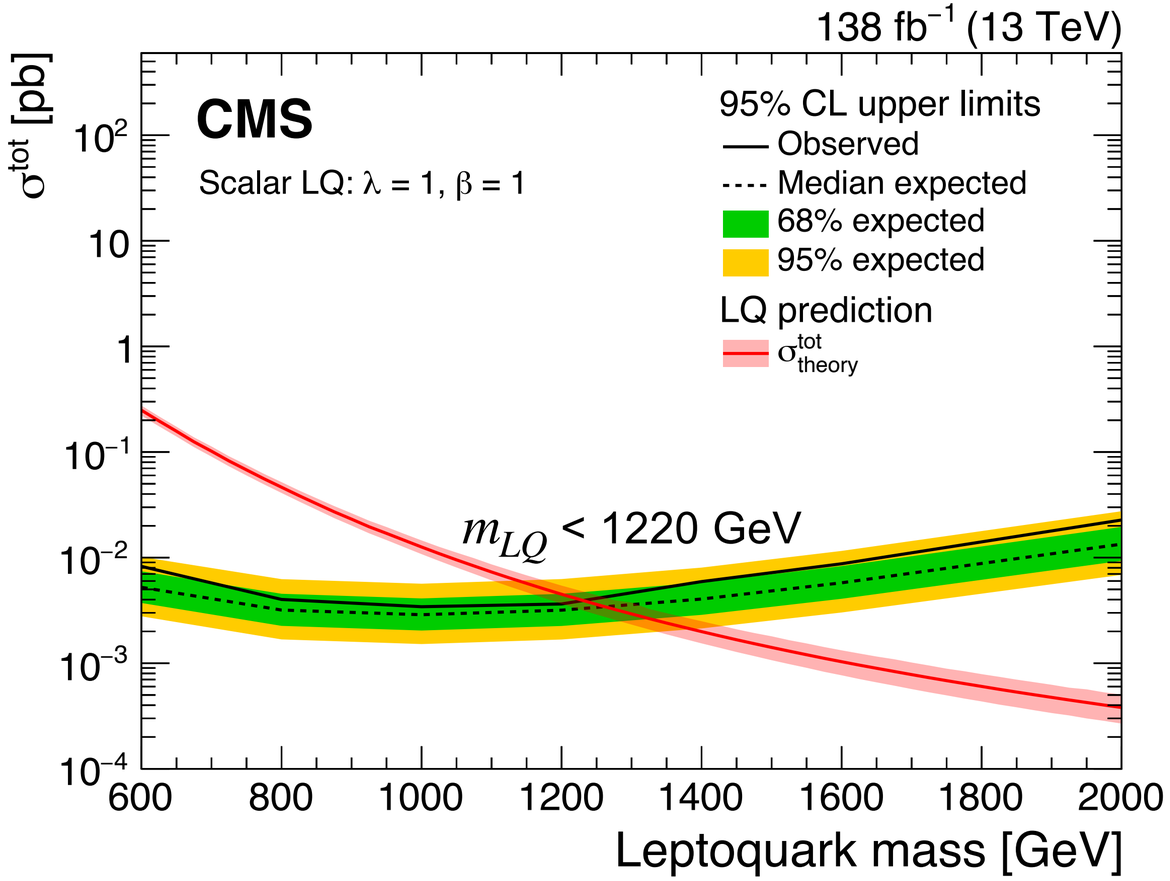
arXiv:2308.07826

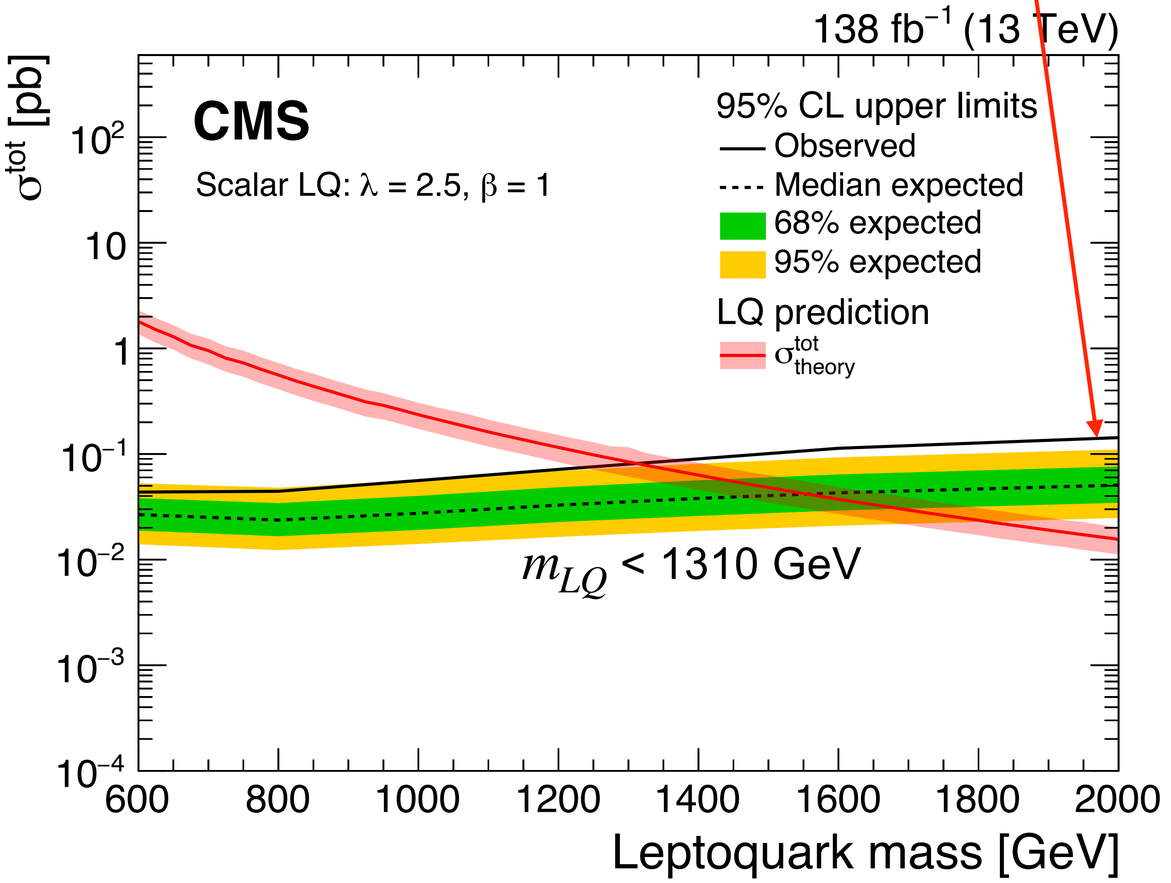
No significant excess observed below a coupling strength of λ = 1.5.

Highest local significance 2.8σ for scalar LQ with λ = 2.5 and m_{LQ} = 2 TeV

- The present excess is driven by events with at least one highly energetic jet but no b-tagged jets.

Observed upper limits are ~3 times larger than expected





$LQ\ 3^{rd}$ Generation Pair Production Combination @ ATLAS arXiv:2401.11928

Focus on decays into 3^{rd} generation quarks

Aim to improve sensitivity through statistical combination of analyses

Inputs from 9 analyses: 6 dedicated searches & 2 SUSY re-interpretations (★) & 1 SUSY re-optimization (★)

Signal regions designed to be orthogonal, overlapping events identified & removed

All final states from $l(e/\mu)$, τ_{had}, (b-)$jets$ and E_T^{miss}, with different selection criteria based on analysis

Interpretations:

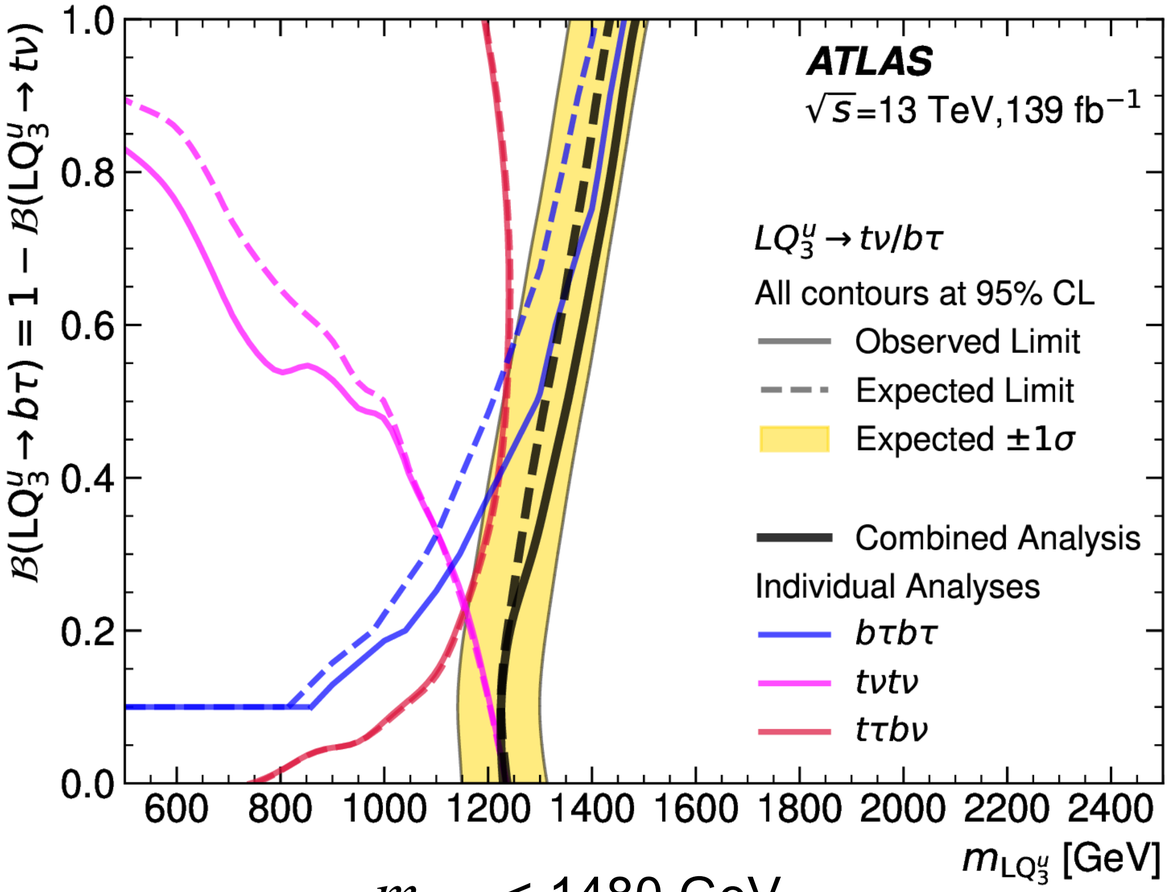
- 5 signal models covered by combining 3~4 analyses for each ($LQ_3^{u/d}$, $LQ_{mix}^{u/d}$, $U_1^{YM/MC}$)
- 1 additional re-interpretation of search in $t\tau t\tau$ final state ($\tilde{U}_1^{YM/MC}$)

Most stringent results to date for majority of the models.

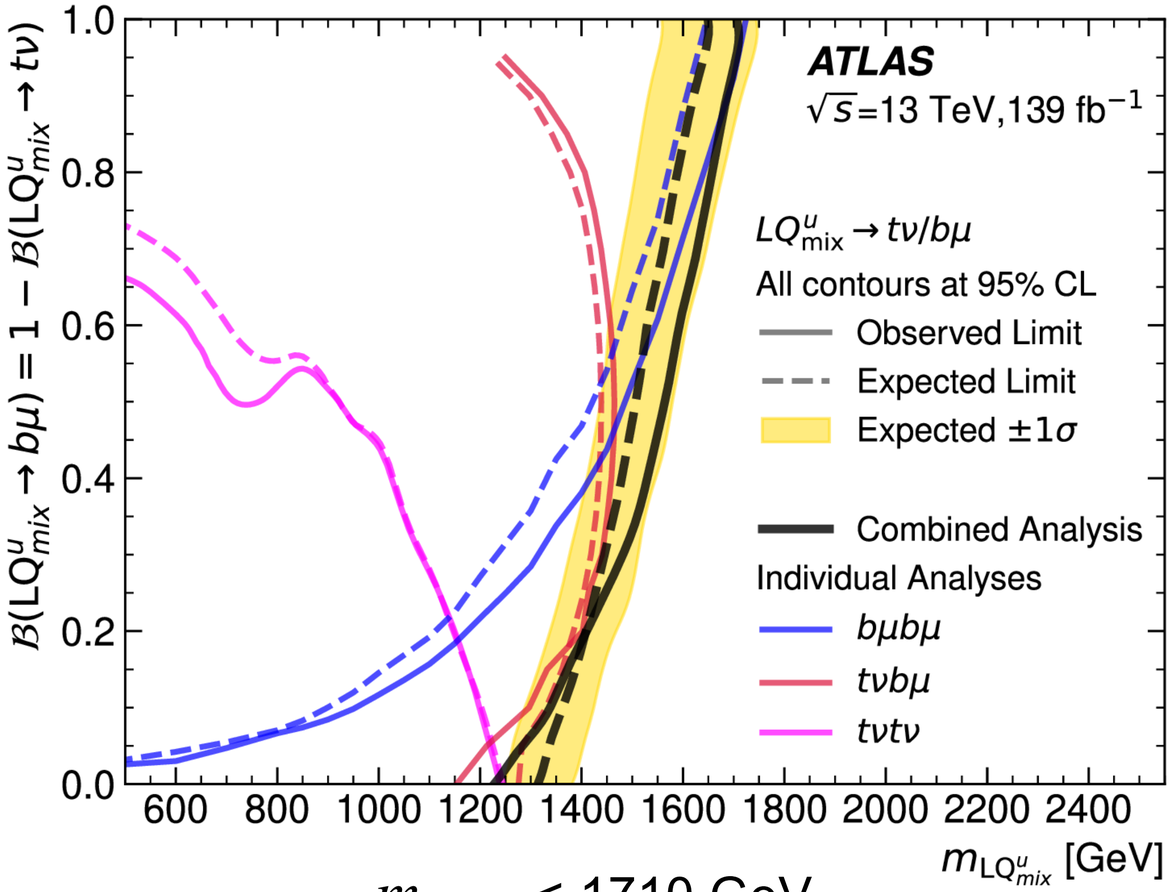
	Search		**Interpretation**						**Signal Region**		
			Scalar				**Vector**				
	Final State	Citation	LQ_3^u	LQ_3^d	LQ_{mix}^u	LQ_{mix}^d	$U_1^{YM/MC}$	$\tilde{U}_1^{YM/MC}$	N_ℓ	$N_{\tau_{had}}$	$N_{b\text{jets}}$
	$t\nu b\tau$		✓	✓	–	–	✓	–	0	1	≥ 2
	$b\tau b\tau$		✓	–	–	–	✓	–	$\{0,1\}$	$\{1,2\}$	$\{1,2\}$
★	$t\tau t\tau$		–	✓	–	–	–	✓	$\{1,2,3\}$	≥ 1	≥ 1
	$t\nu b\ell$		–	–	✓	✓	–	–	1	–	≥ 1
	$b\ell b\ell$		–	–	✓	–	–	–	2	–	$\{0,1,2\}$
	$t\ell t\ell$ (2ℓ))		–	–	–	✓	–	–	2	–	–
	$t\ell t\ell$ $(\geq 3\ell)$		–	–	–	✓	–	–	$\{3,4\}$	–	≥ 2
★	$t\nu t\nu$		✓	–	✓	–	✓	–	0	0	≥ 2
★	$b\nu b\nu$		–	✓	–	✓	–	–	0	–	≥ 2

$LQ\ 3^{rd}$ Generation Pair Production Combination @ ATLAS arXiv:2401.11928

Combination of searches for **scalar** up-type and down-type LQs decaying into 3^{rd} or $1^{st}/2^{nd}$ generation leptons
Exclusion limits improved by up to **100 GeV** w.r.t individual analyses



$m_{LQ_3^u} < 1480$ GeV

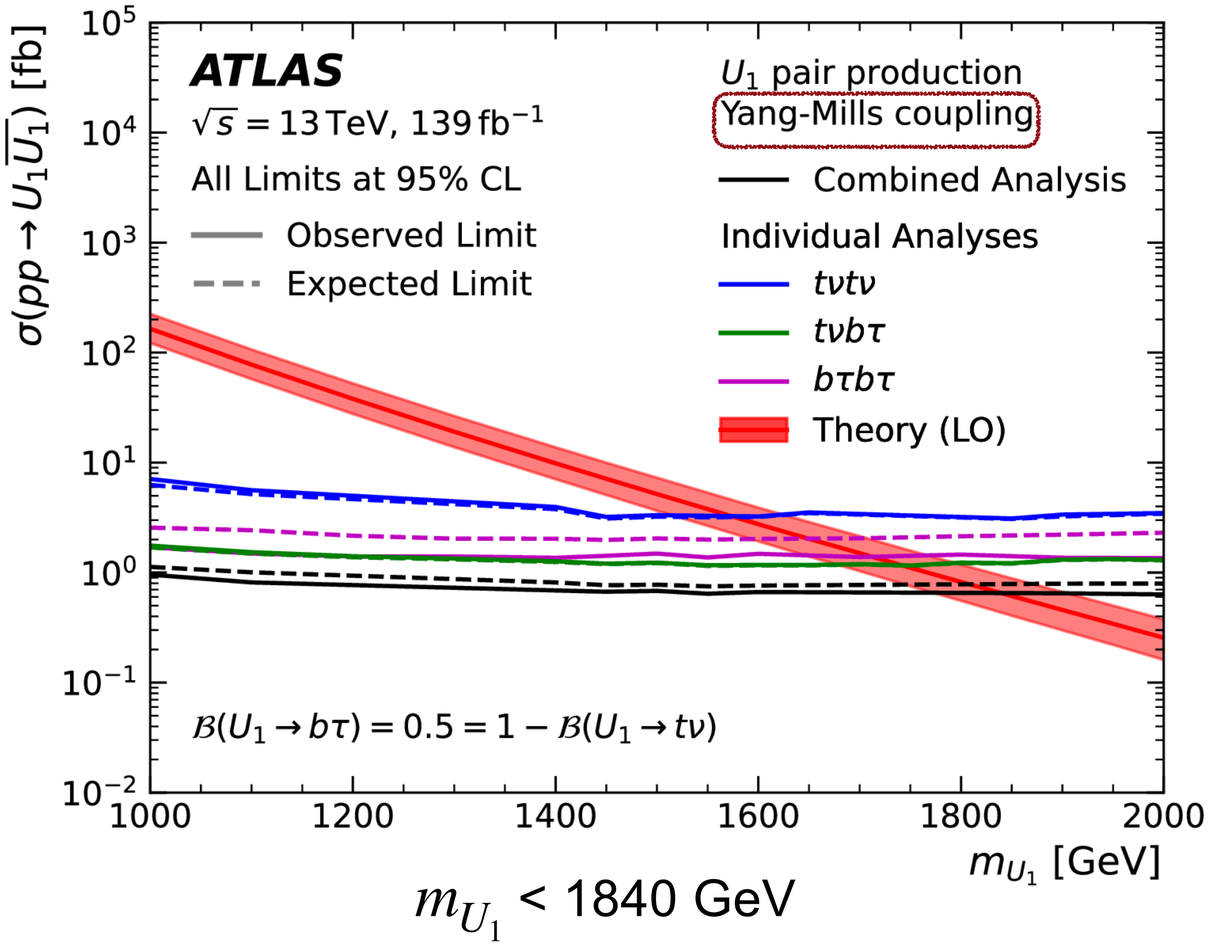


$m_{LQ_{mix}^u} < 1710$ GeV

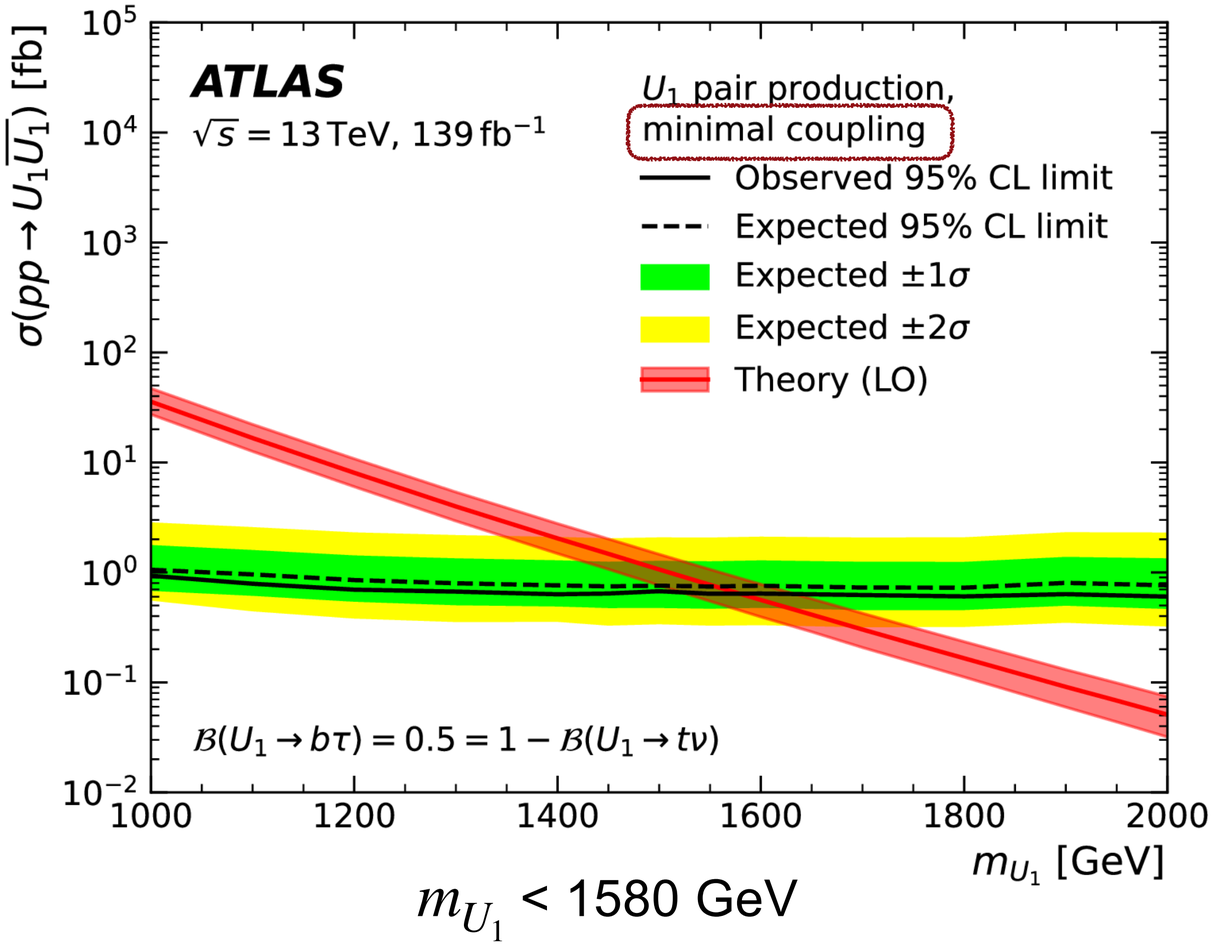
$LQ\ 3^{rd}$ Generation Pair Production Combination @ ATLAS arXiv:2401.11928

Combination of searches for U_1 **vector** LQs decaying into $t\nu/b\tau$

Limit on production cross-section improves upon individual results by **70 GeV** (U_1^{YM}) and **80 GeV** (U_1^{MC}), assuming β=0.5



m_{U_1} < 1840 GeV

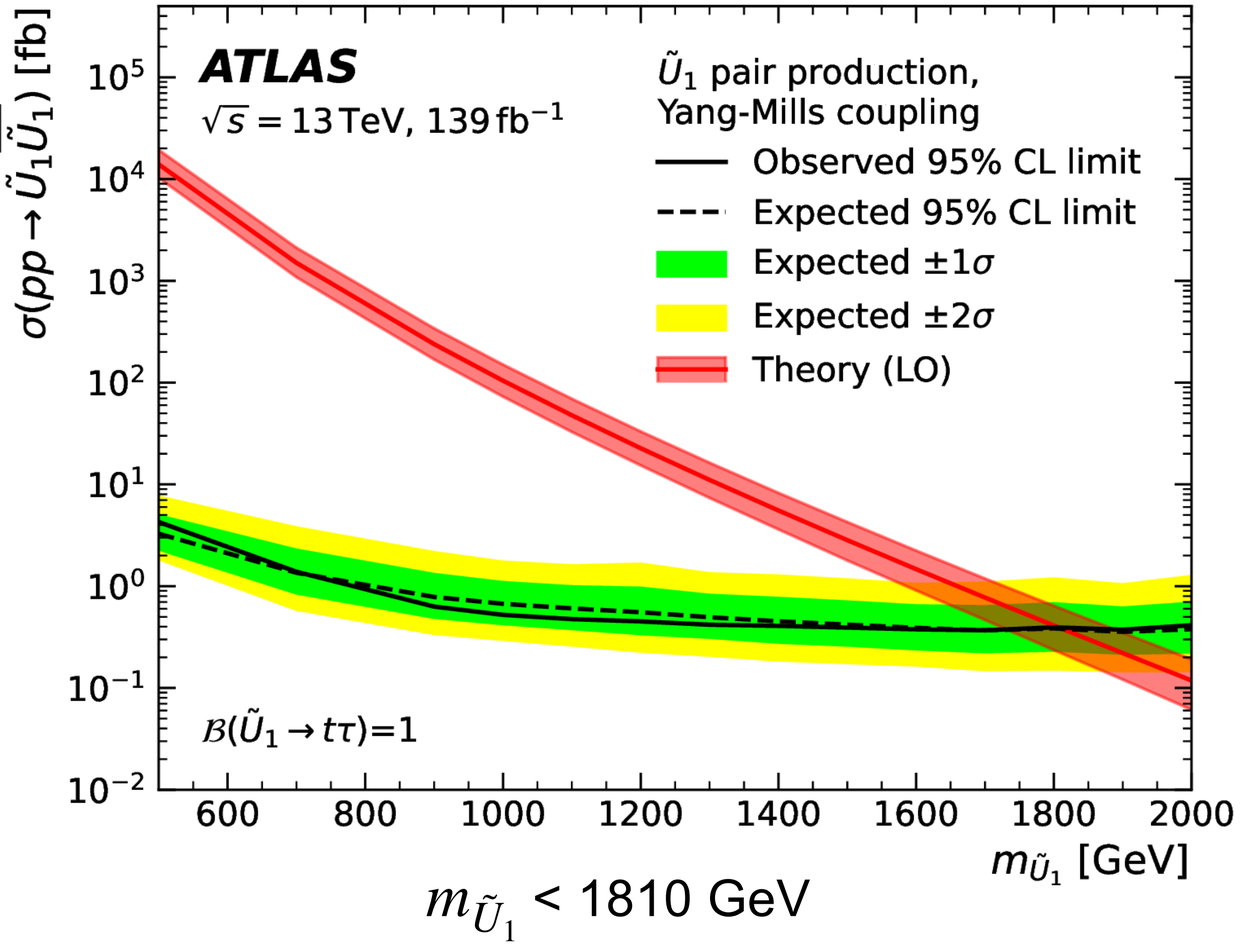


m_{U_1} < 1580 GeV

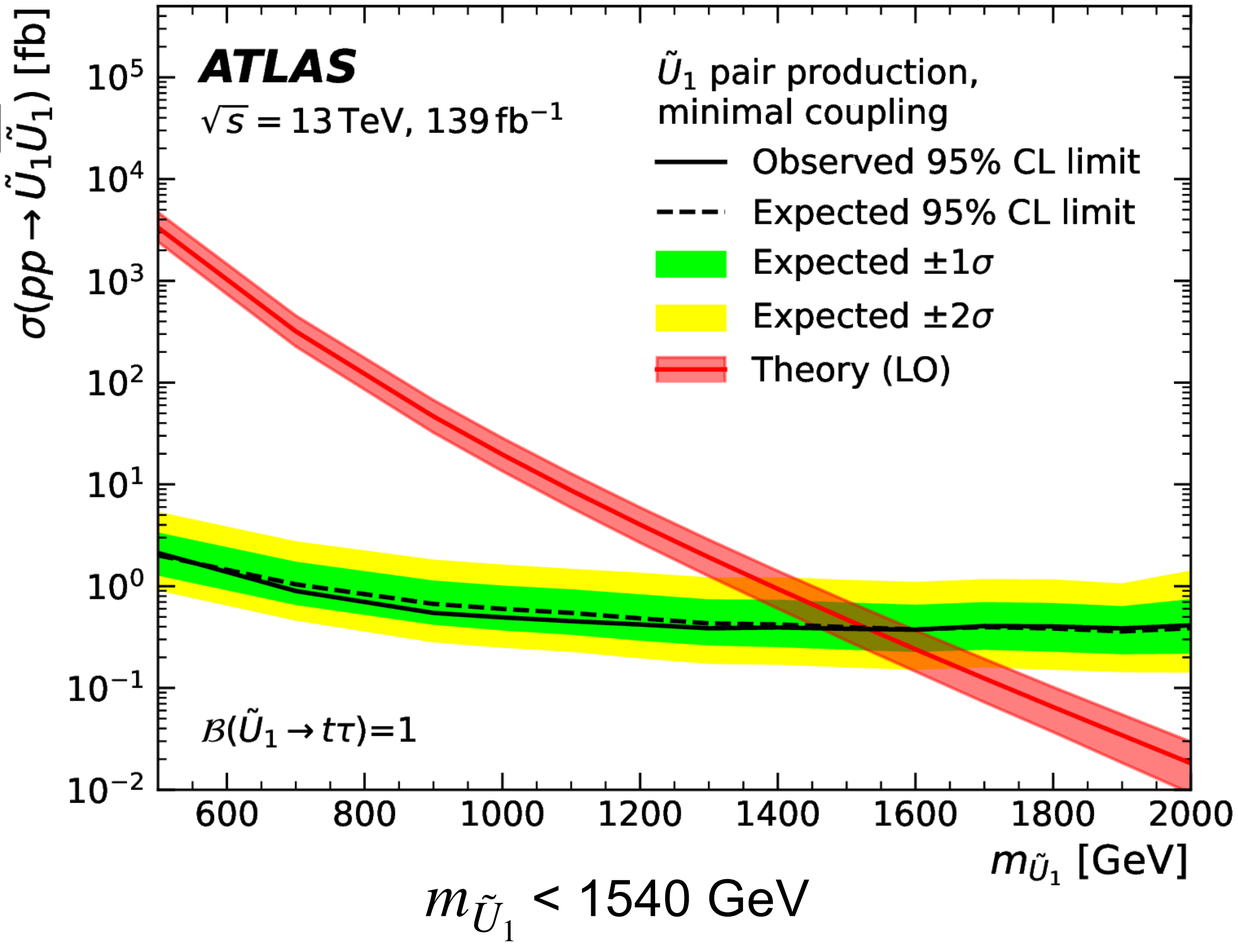
$LQ\ 3^{rd}$ Generation Pair Production Combination @ ATLAS arXiv:2401.11928

No combination possible in case of $\tilde{U}_1$

Set lower limit on mass of 1810 GeV for $\tilde{U}_1^{YM}$ and 1540 GeV for $\tilde{U}_1^{MC}$



$m_{\tilde{U}_1}$ < 1810 GeV



$m_{\tilde{U}_1}$ < 1540 GeV

LQ-τ-b / LQ-τ-q @ CMS

arXiv:2308.06143

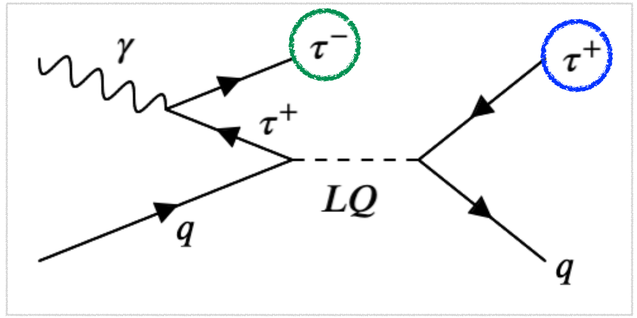
First search for scalar LQs produced via **lepton-quark scattering**
- Possible due to recent advances in precision of lepton PDFs

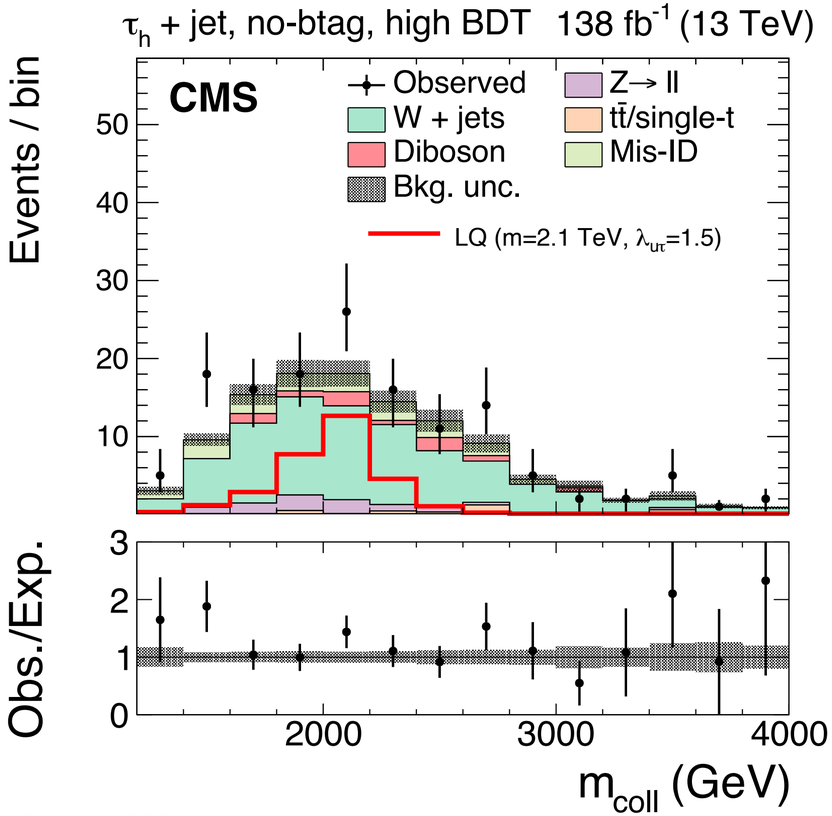
Event selections:
- Single lepton (e, μ, τ_h) + high p_T jet: both τ_{had} and τ_{lep} decays exploited
- Veto events with additional leptons:complementary to single/pair production

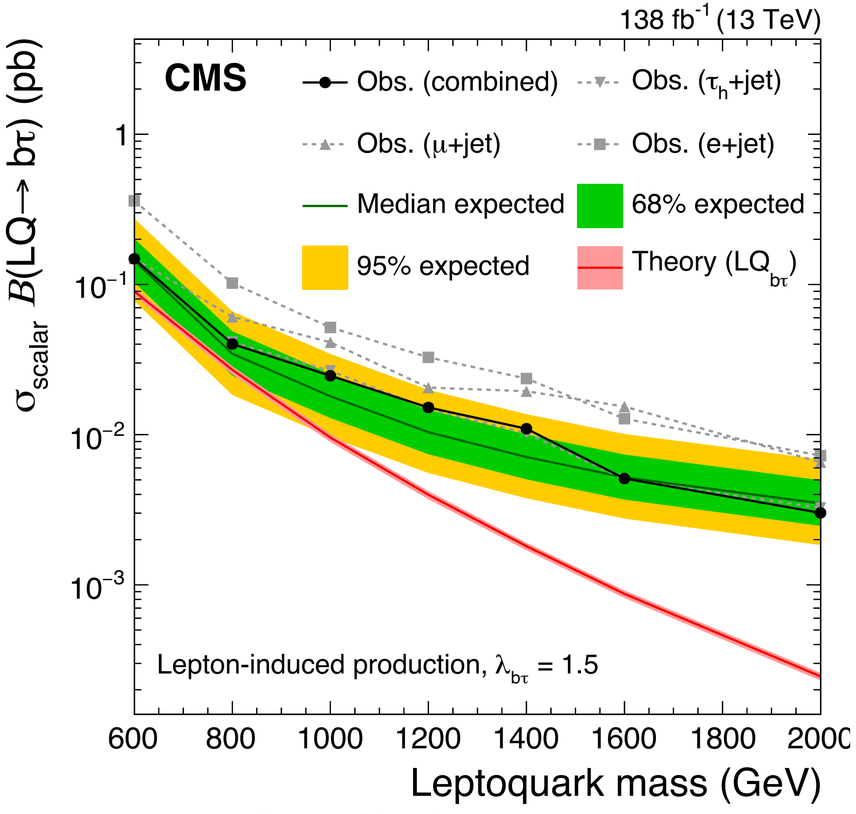
Two categories based on "b-tag" of leading jet: probes both $\lambda_{\tau b}$ and $\lambda_{\tau q}$

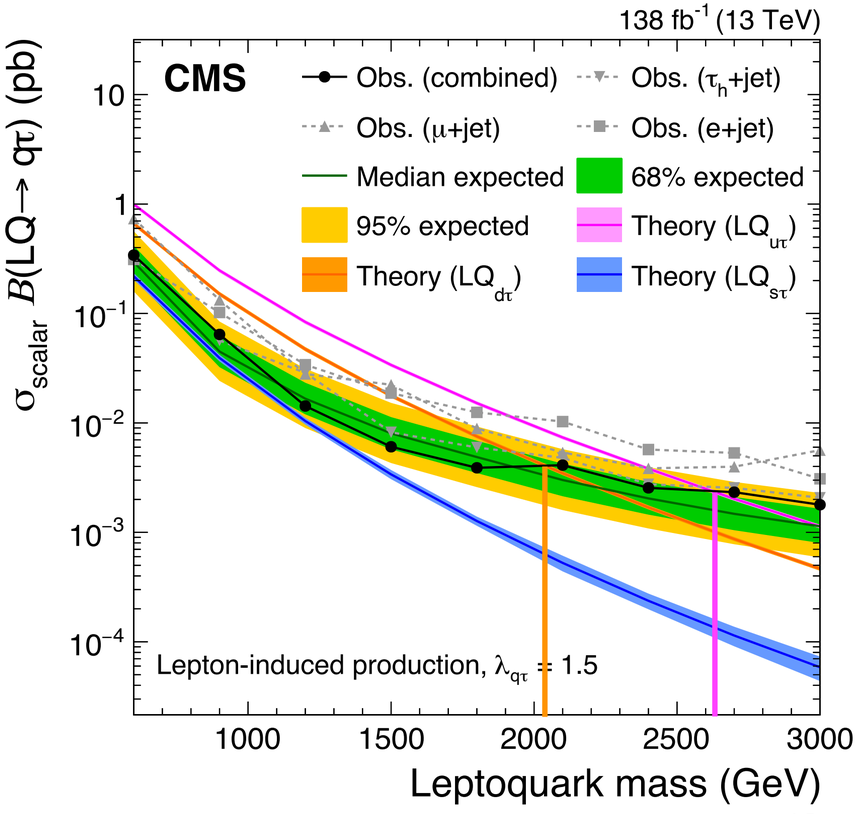
Final discriminant variable: collinear mass m_{coll} of τ candidate and jet

Forward and soft **Central and high p_T**









New Z' Vector Boson in 4μ Events @ ATLAS

arXiv:2301.09342

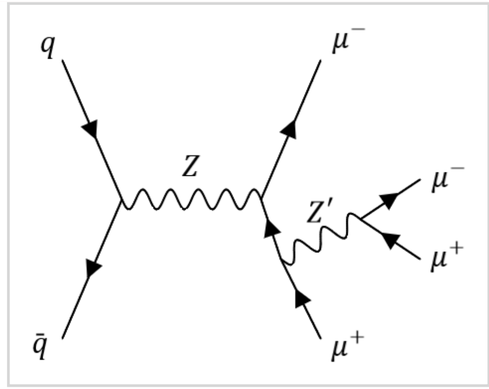
Experimental signature: 4μ opposite-charge pair events around Z pole

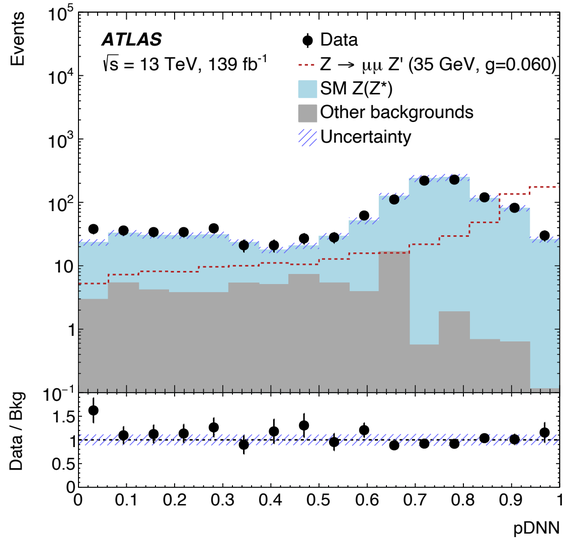
Basic selections to select 4μ events in the mass region of [80, 180] GeV, excluding Higgs region [110, 130] GeV

Events further split into low mass ($m_{Z'}$ < 42 GeV) and high mass ($m_{Z'}$ > 42 GeV) region

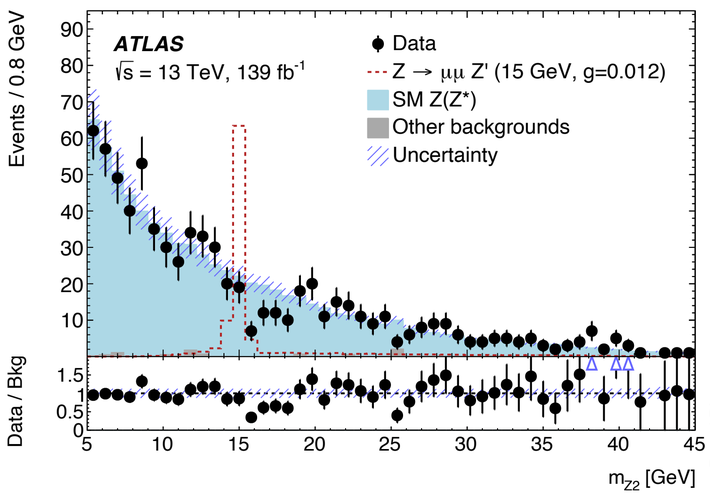
Parameterized deep neural network (pDNN) score to categorize 4μ events as signal or background at different Z' hypothesis masses

Final discriminant variable: m_{Z1} or m_{Z2} after pDNN cut

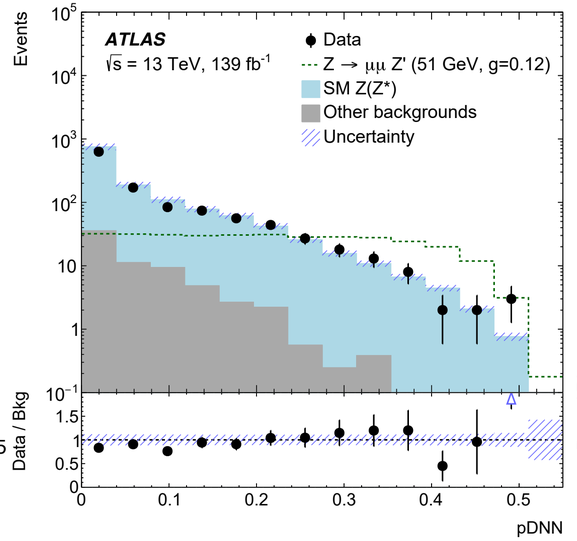




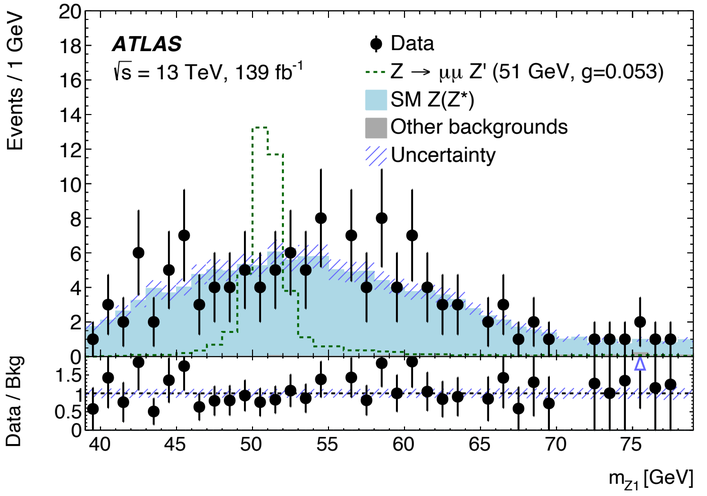
$m_{Z'}$ < 42 GeV



Z_2 for Z



$m_{Z'}$ > 42 GeV



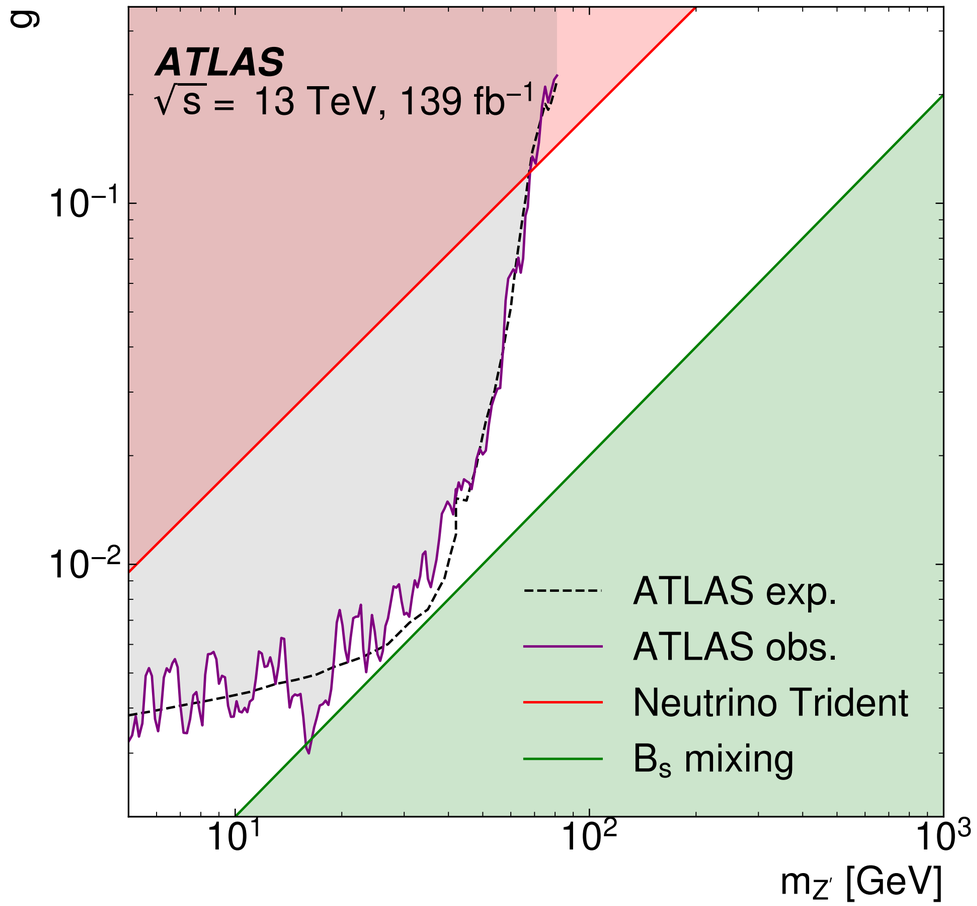
Z_1 for Z

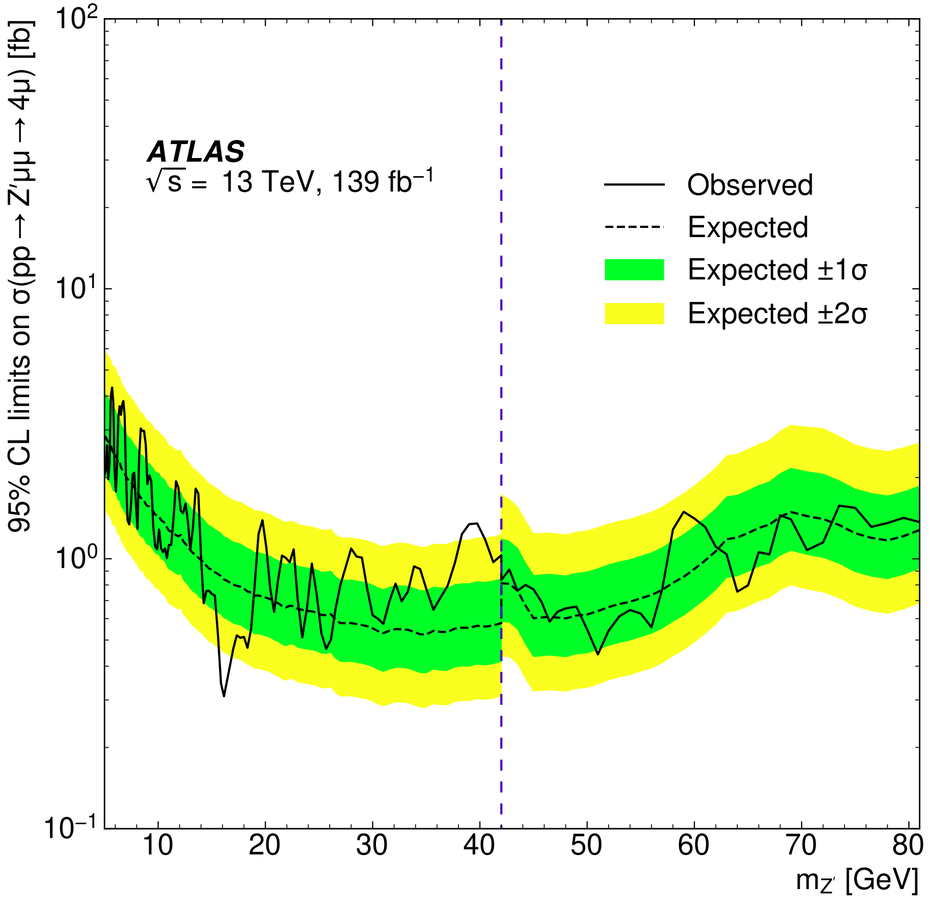
New Z' Vector Boson in 4μ Events @ ATLAS

arXiv:2301.09342

Exclusion limits on coupling strength $g_{Z'}$ vary from 0.003 to 0.2

CMS arXiv:1808.03684 ,
see more details in Backup





Observed exclusion limits @ CMS: $0.004 < g_{Z'} < 0.3$, using 2016+2017 dataset 77.3 fb^{-1}

New Z' Vector Boson in 3μ Events @ ATLAS

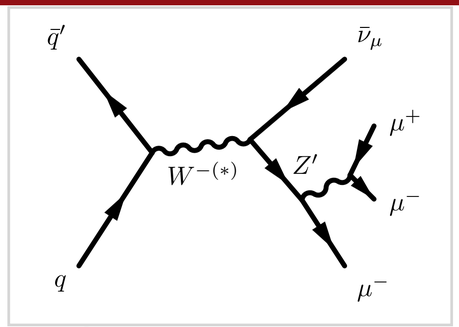
arXiv:2402.15212

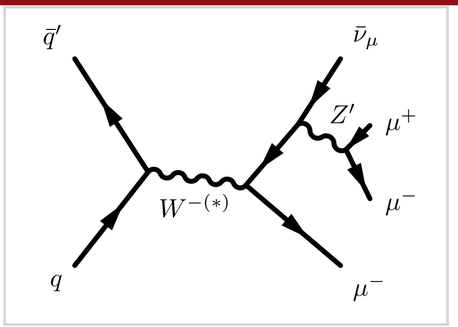
First time to use the 3μ final state to search the new Z' gauge boson
- Model contains two additional parameters $\{g_{Z'}, M_{Z'}\}$

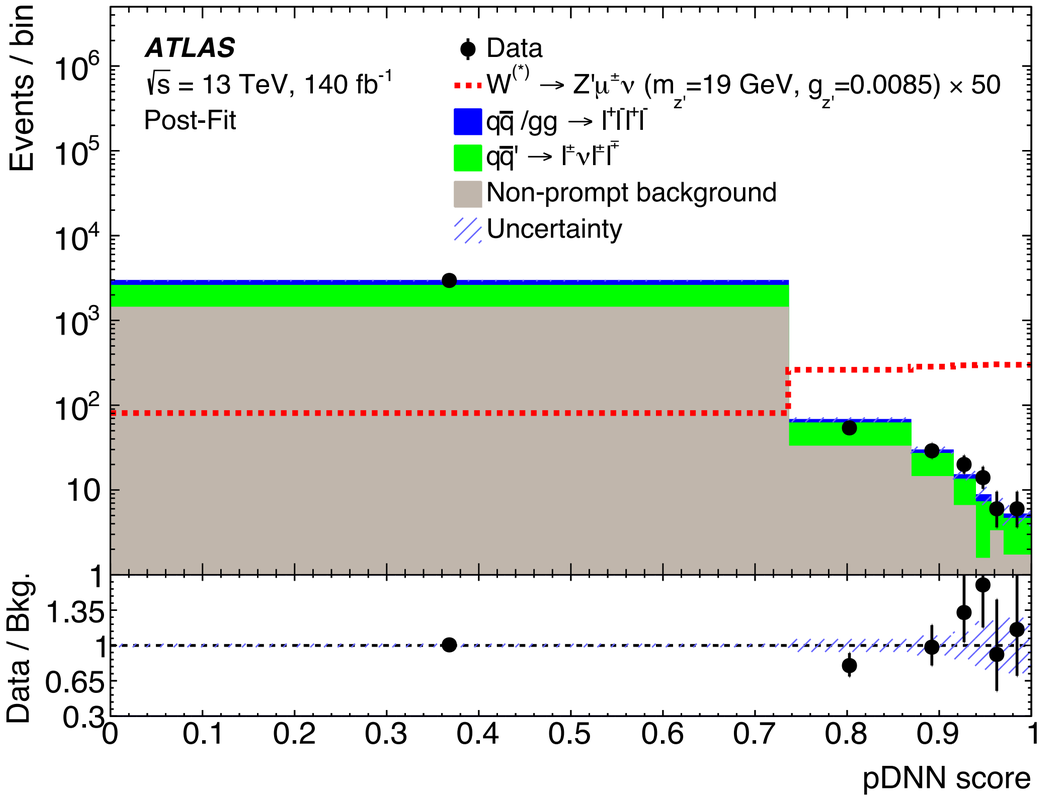
Search for Z' in mass region from 5 to 81 GeV

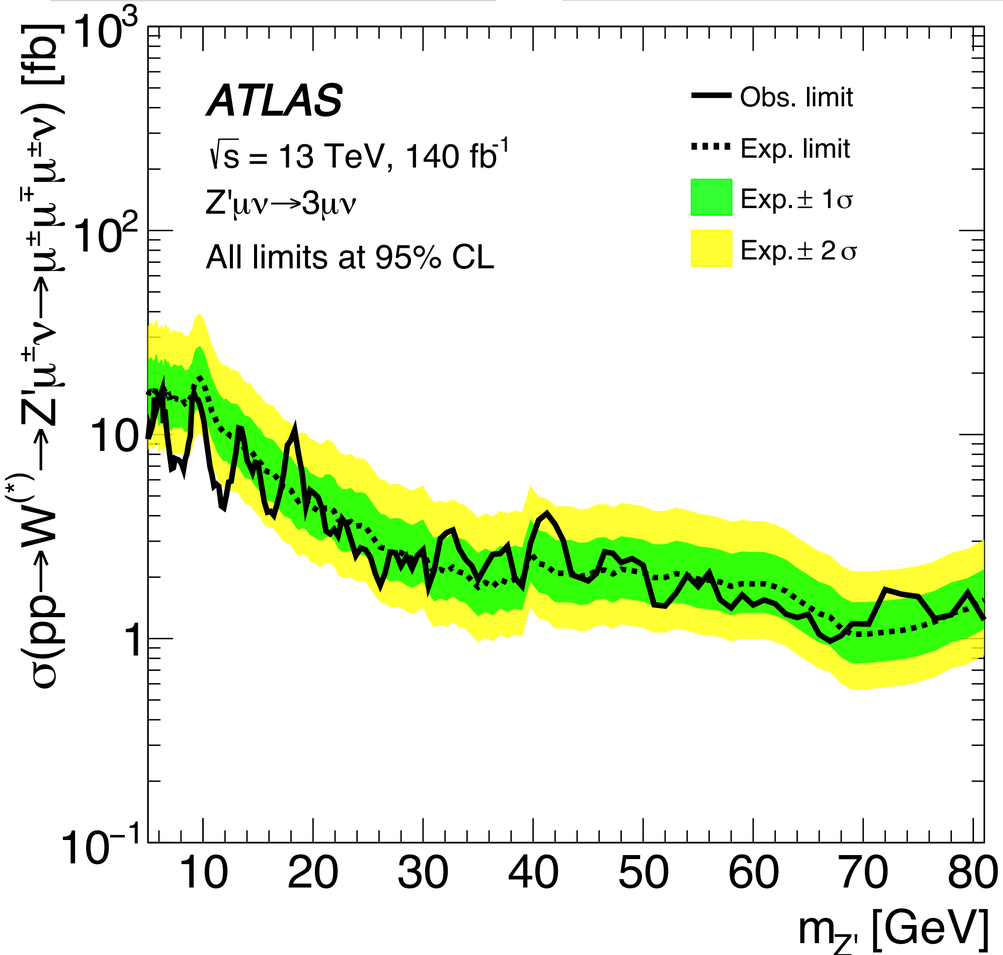
Candidate events in the signal region:
- Exactly 3 isolated muons
- Large missing transverse momentum

Final discriminant variable: Parameterized deep neural network (pDNN)









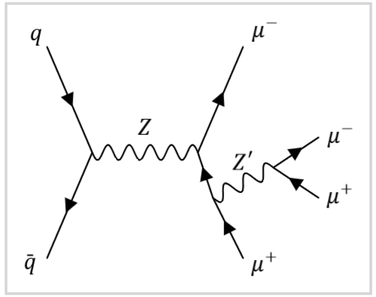
New Z' Vector Boson in 3μ Events @ ATLAS

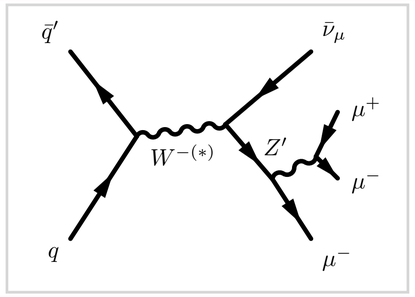
arXiv:2402.15212

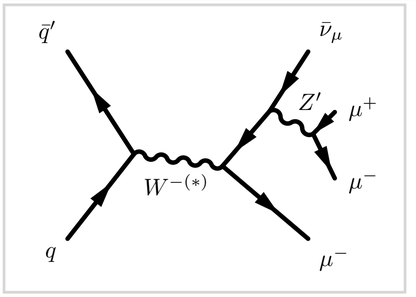
Combination

Statistical combination with previous search using neutral-current Drell-Yan process (4μ final state)

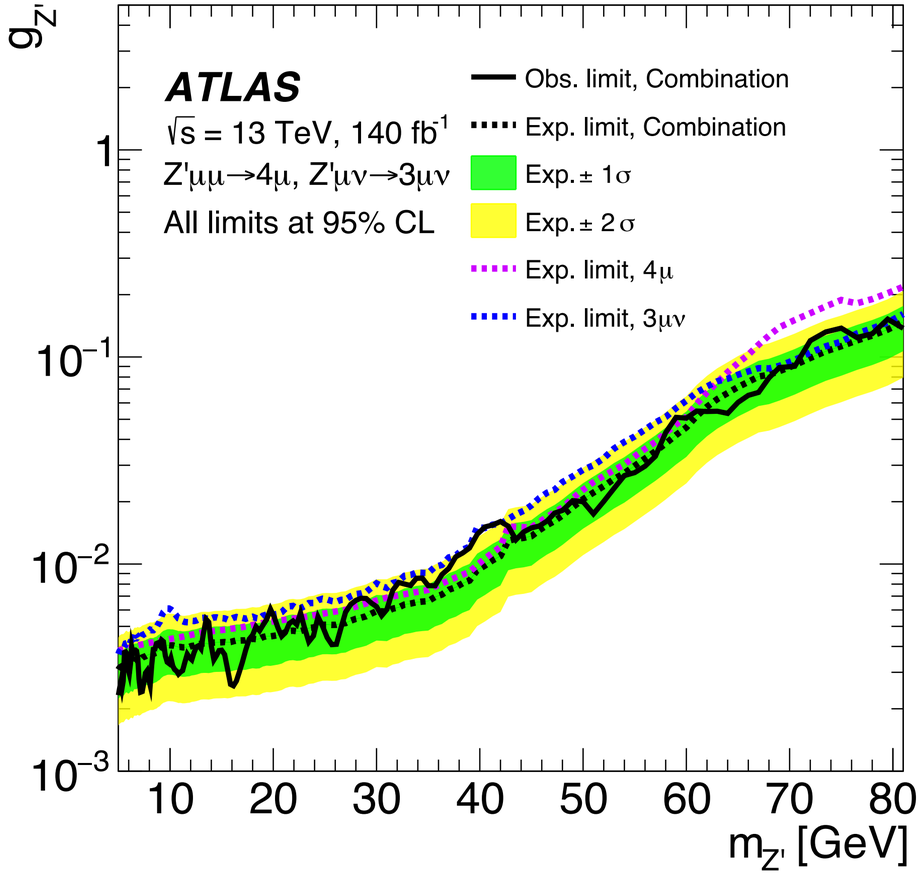
Common parameter of interest: coupling parameter $g_{Z'}$

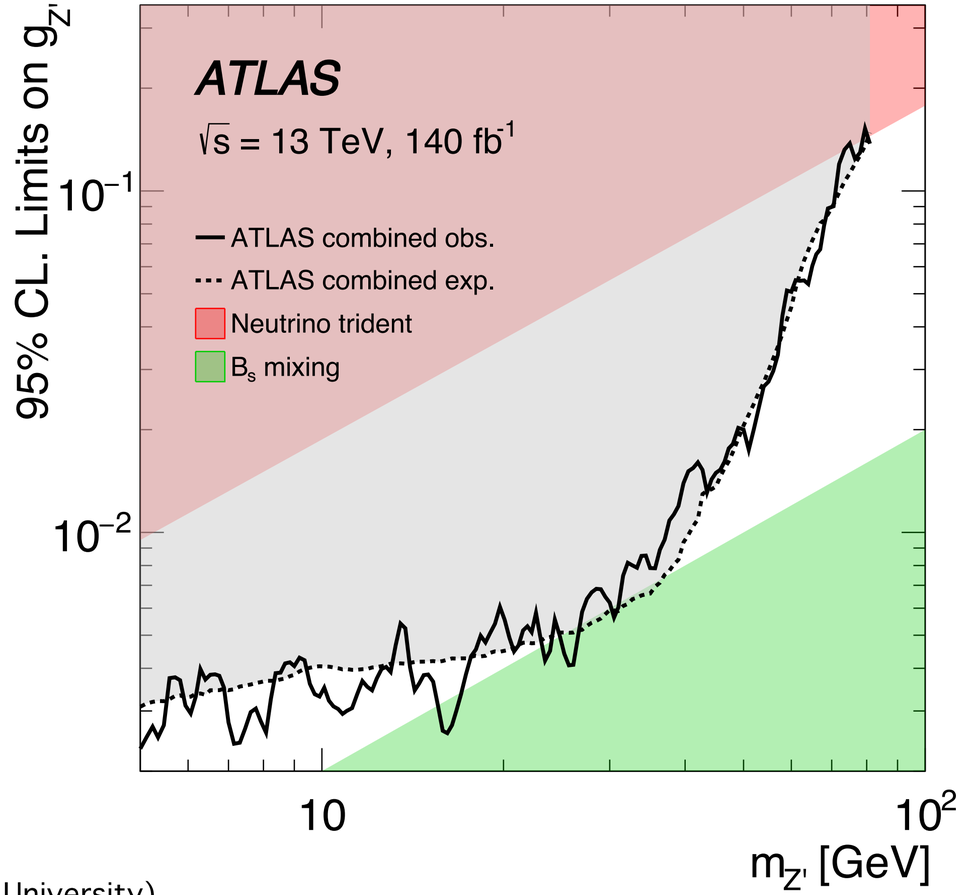






Significant improvement relative to the previous search, **up to 40%** in the high mass region ($m_{Z'}$ > 65 GeV)





τ-lepton + Missing Transverse Momentum @ ATLAS

arXiv:2402.16576

Target high mass resonances $W' \to \tau\nu \to \tau_{had-vis}\nu\nu$

- B($\tau \to \tau_{had}$) = 65%

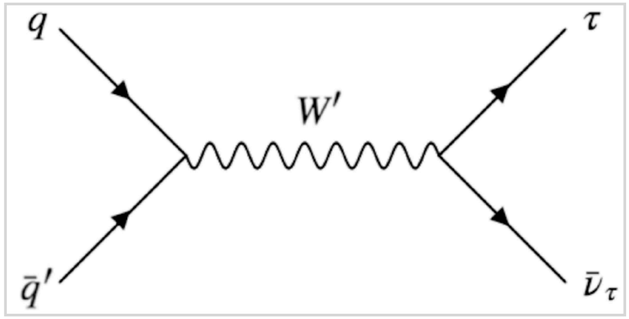
Profit from improved τ-ID w.r.t Run1, complement light lepton W' searches for flavor-universal model (**SSM**)

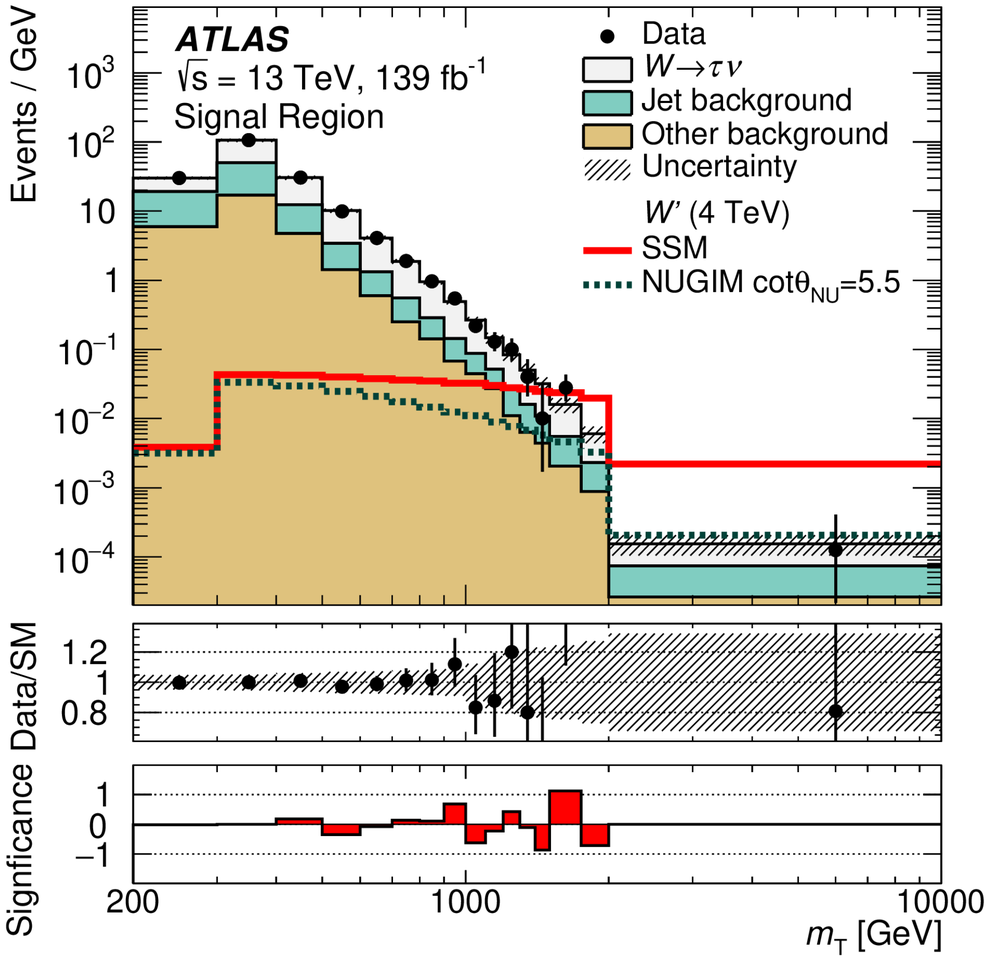
Also motivated by models which favor $\tau\nu$:

- Non-Universal Gauge Interaction Models (**NUGIM**)
  - Non-universality of couplings to SM fermions parameterized as θ_{NU}

Final discriminant variable:

- transverse mass $m_T = \sqrt{2E_T^{miss} p_T (1 - cos\Delta\phi)}$

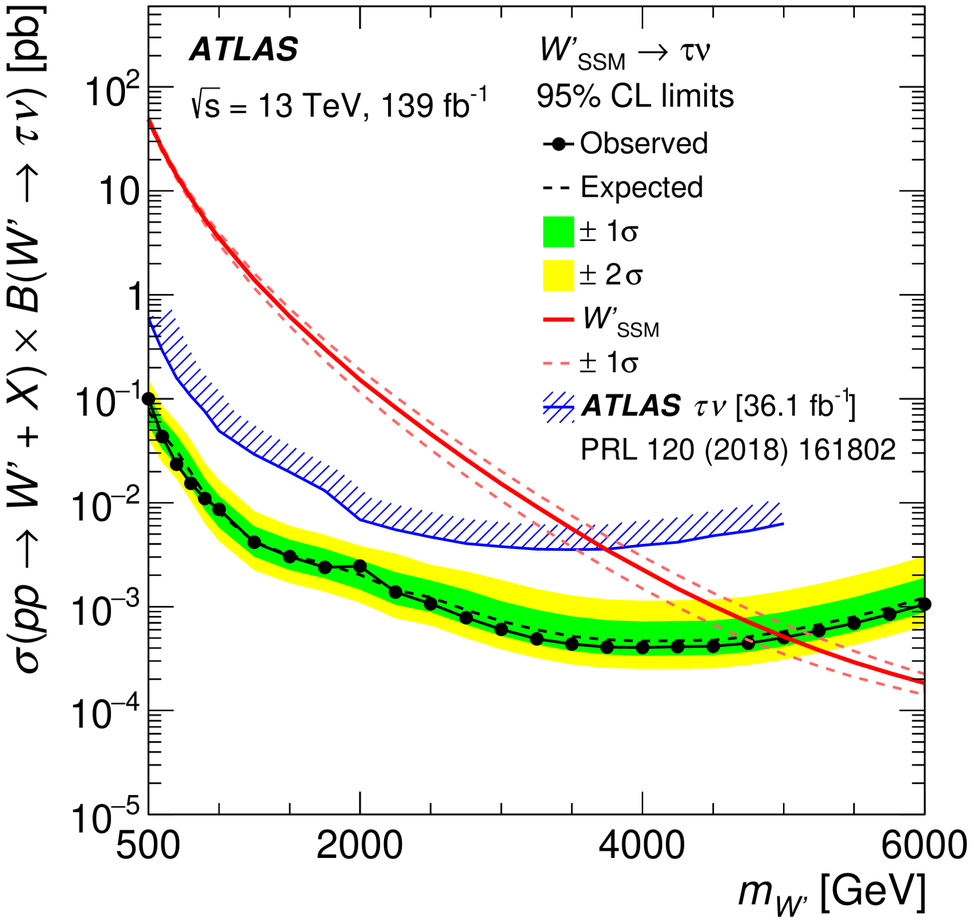




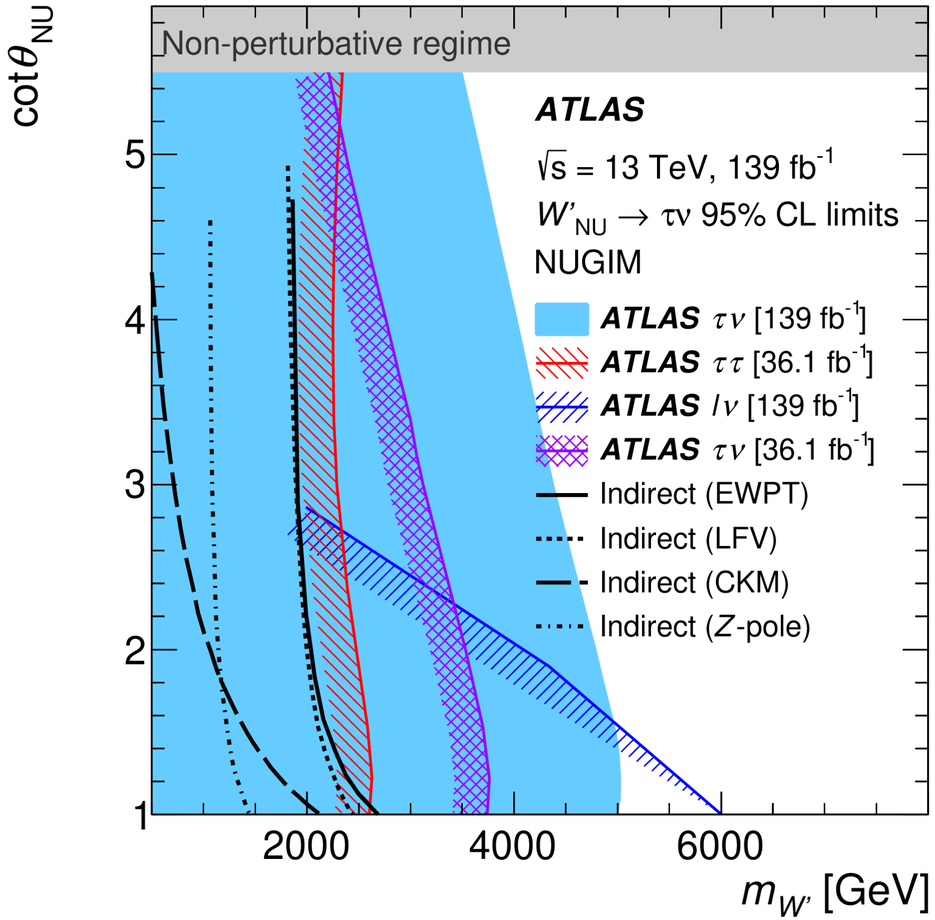
τ-lepton + Missing Transverse Momentum @ ATLAS

arXiv:2402.16576

SSM → Excluded W' mass **up to 5 TeV**



NUGIM → Excluded W' mass vary from **3.5 to 5.0 TeV**



Observed exclusion limits @ CMS:

SSM: $m_{W'} < 4.8$ TeV

NUGIM: $2.2 < m_{W'} < 4.8$ TeV

CMS arXiv:2212.12604 ,
see more details in Backup

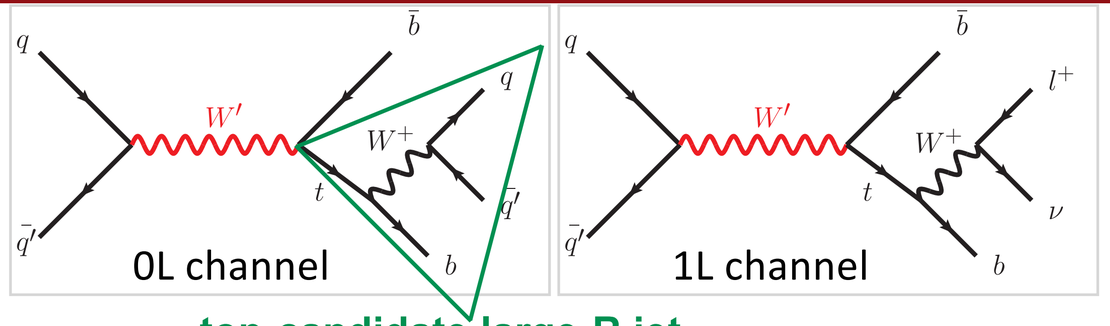
$W' \to tb$ in 0/1-lepton Final States @ ATLAS

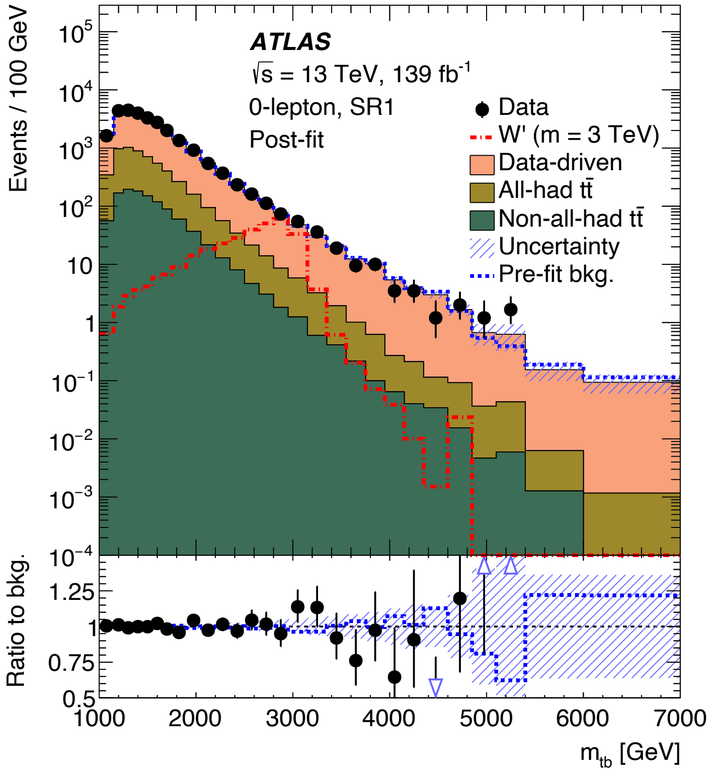
arXiv:2308.08521

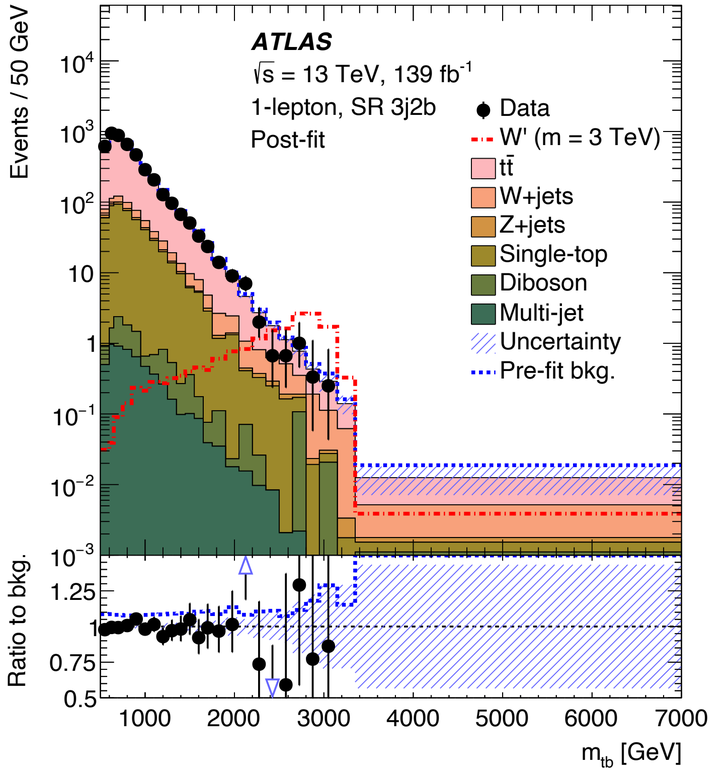
Fully reconstruct tb system:

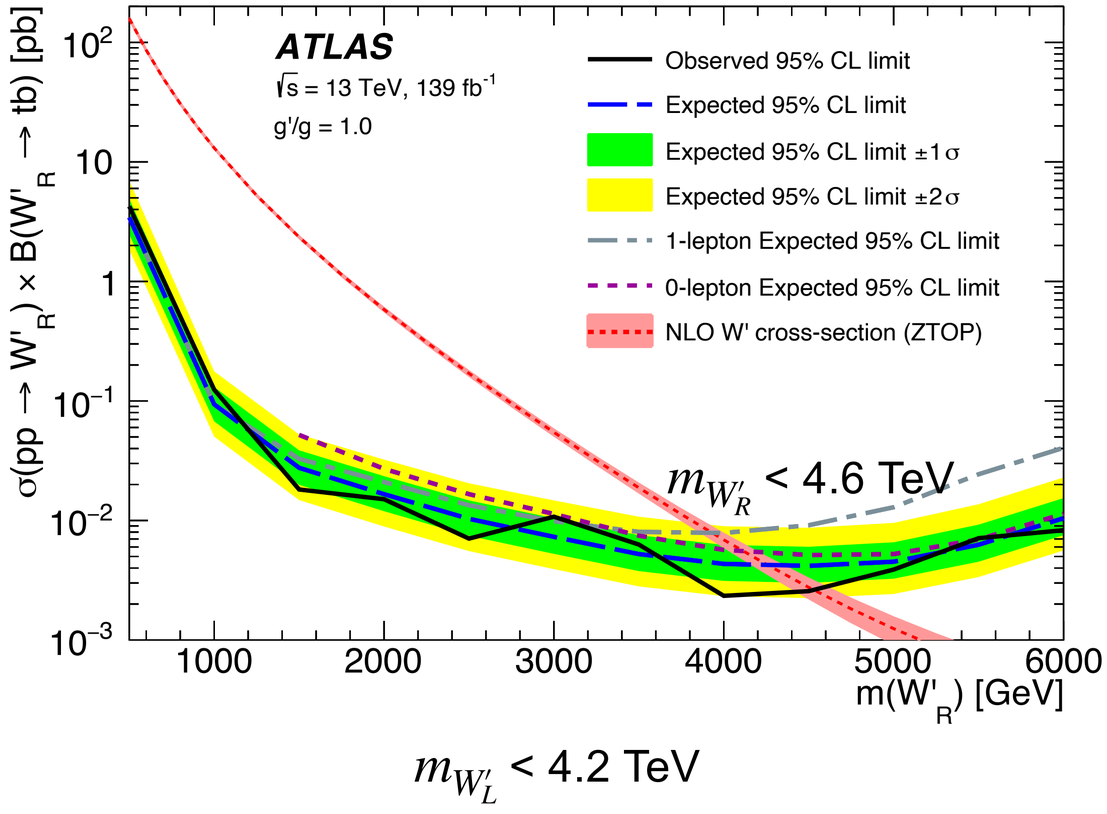
- 0-lepton channel: large-R jet + small-R jet
- 1-lepton channel: 1 lepton + neutrino (MET) + 2 small-R jet

Final discriminant variable: m_{tb}









$m_{W'_L} < 4.2$ TeV

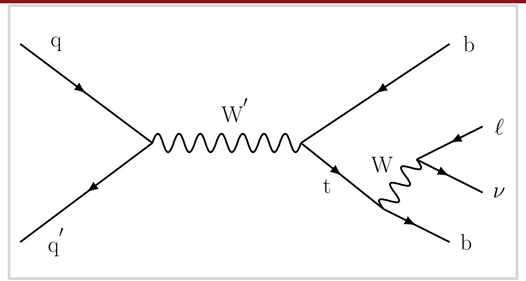
$W' \to tb$ in Leptonic Final States @ CMS

arXiv:2310.19893

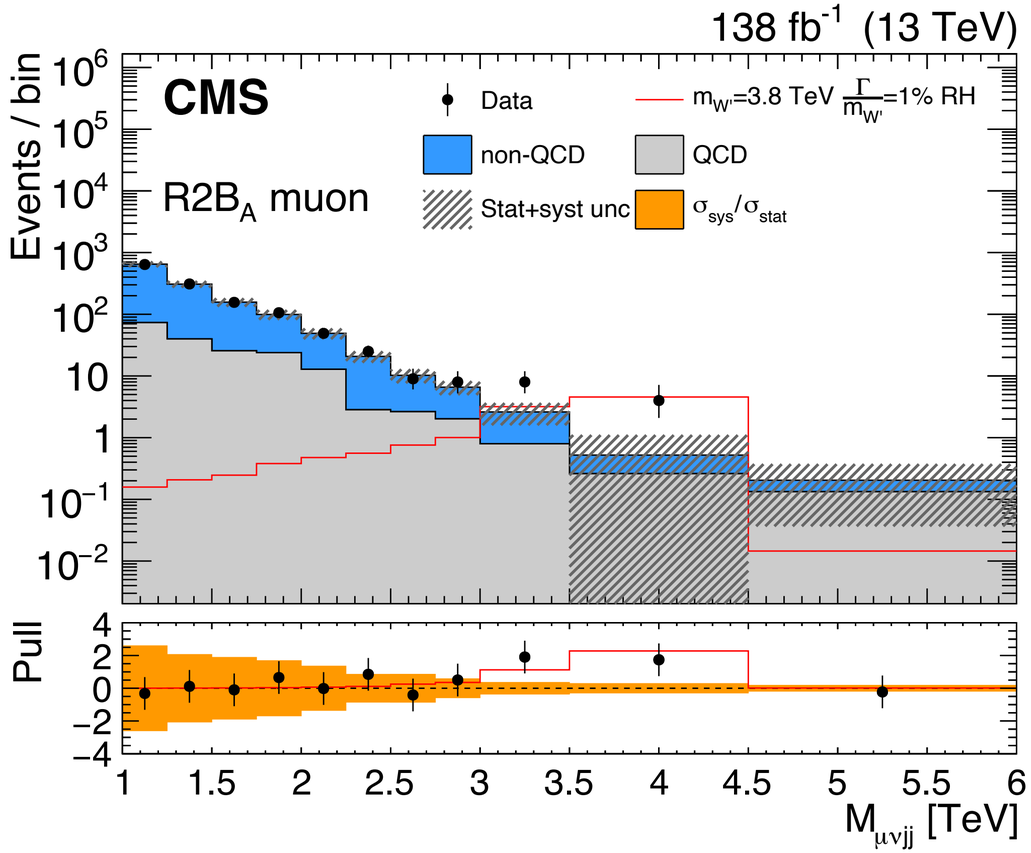
One muon or electron, at least two AK4 jets, and one neutrino
- AK4 jets: jets clustered with a radius parameter of R = 0.4

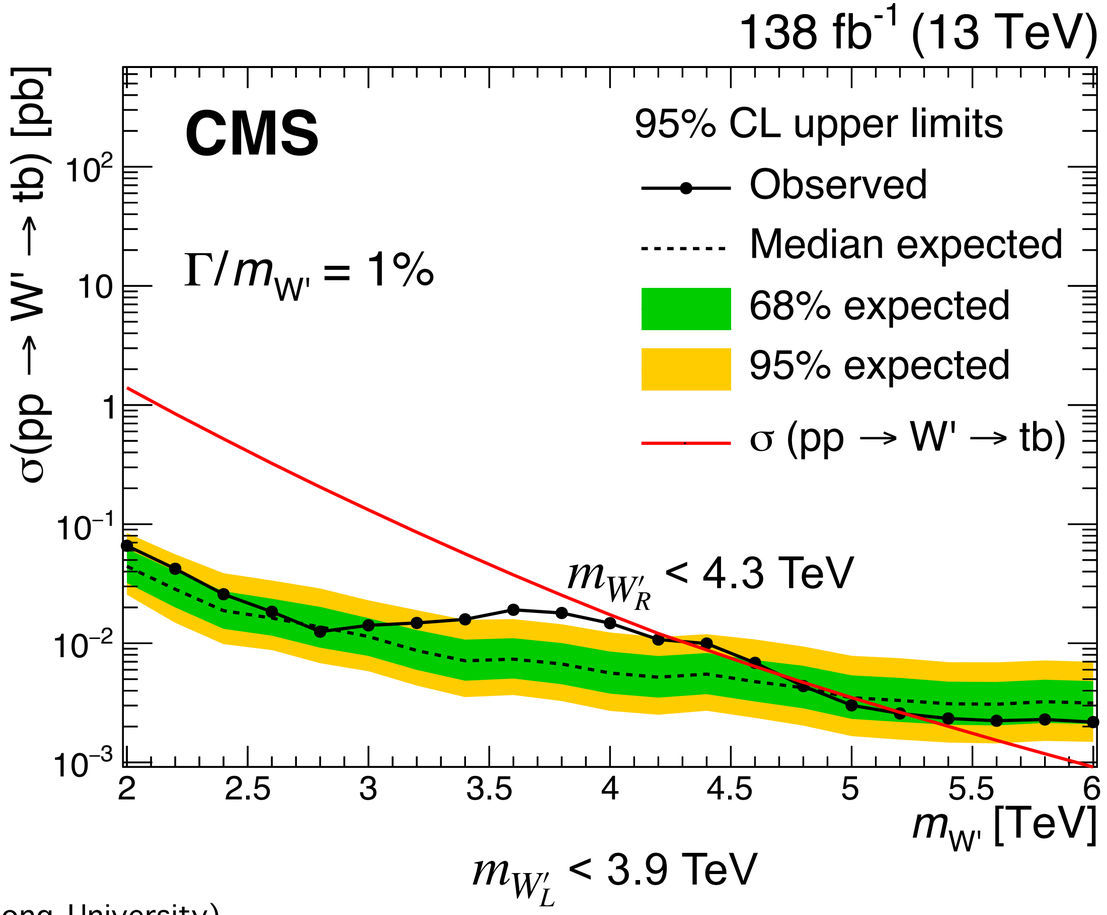
Categorization based on b-tagging condition of top jet and W' jet

Final discriminant variable: $M_{l\nu jj}$



The largest local (global) significance 2.6σ (2.0σ) for $m_{W'}$ at **3.8 TeV** with a relative decay width of 1%





Conclusions and Outlook

ATLAS and CMS performed extensive search programme for BSM during Run-2

- Only a handful of the latest results presented here
- See the list of all public results on the AtlasPublic twiki and CMS Publications

No clear **new physics** evidence in the full LHC Run-2 dataset in searches for:

- Leptoquarks: limits are mostly at masses of 1 - 1.5 TeV for scalar and 1.5 - 2 TeV for vector LQs
- Exotic vector bosons Z' and W'

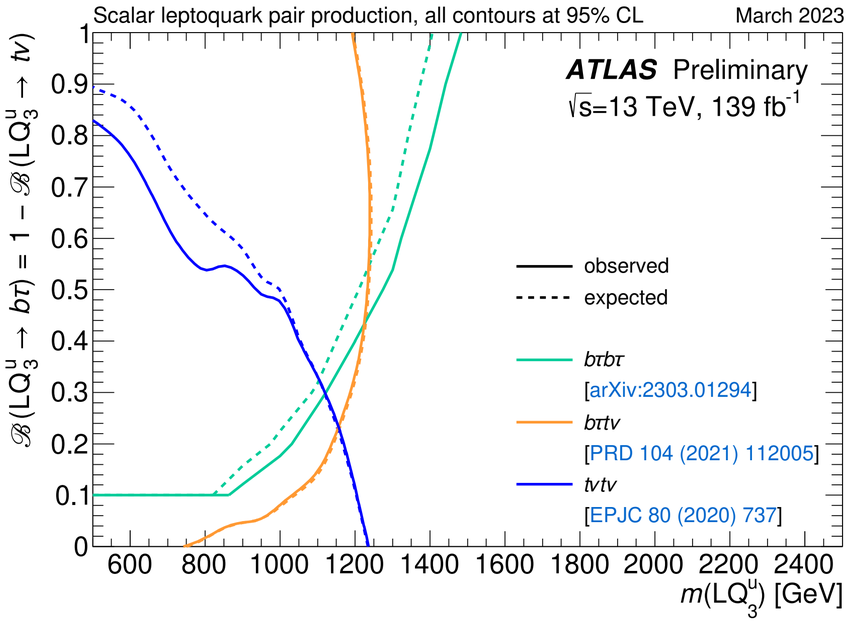
Run-3 of the LHC is ongoing, with 13.6 TeV collision energy and the inclusion of multiple upgrades

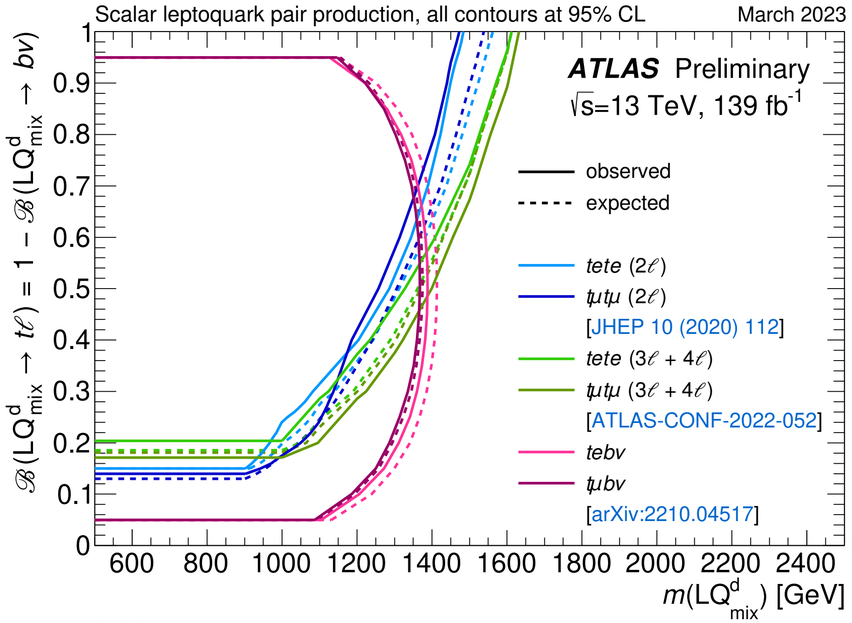
✦Looking forward to further sensitivity improvements with this dataset

Thanks for your attention!

Backup

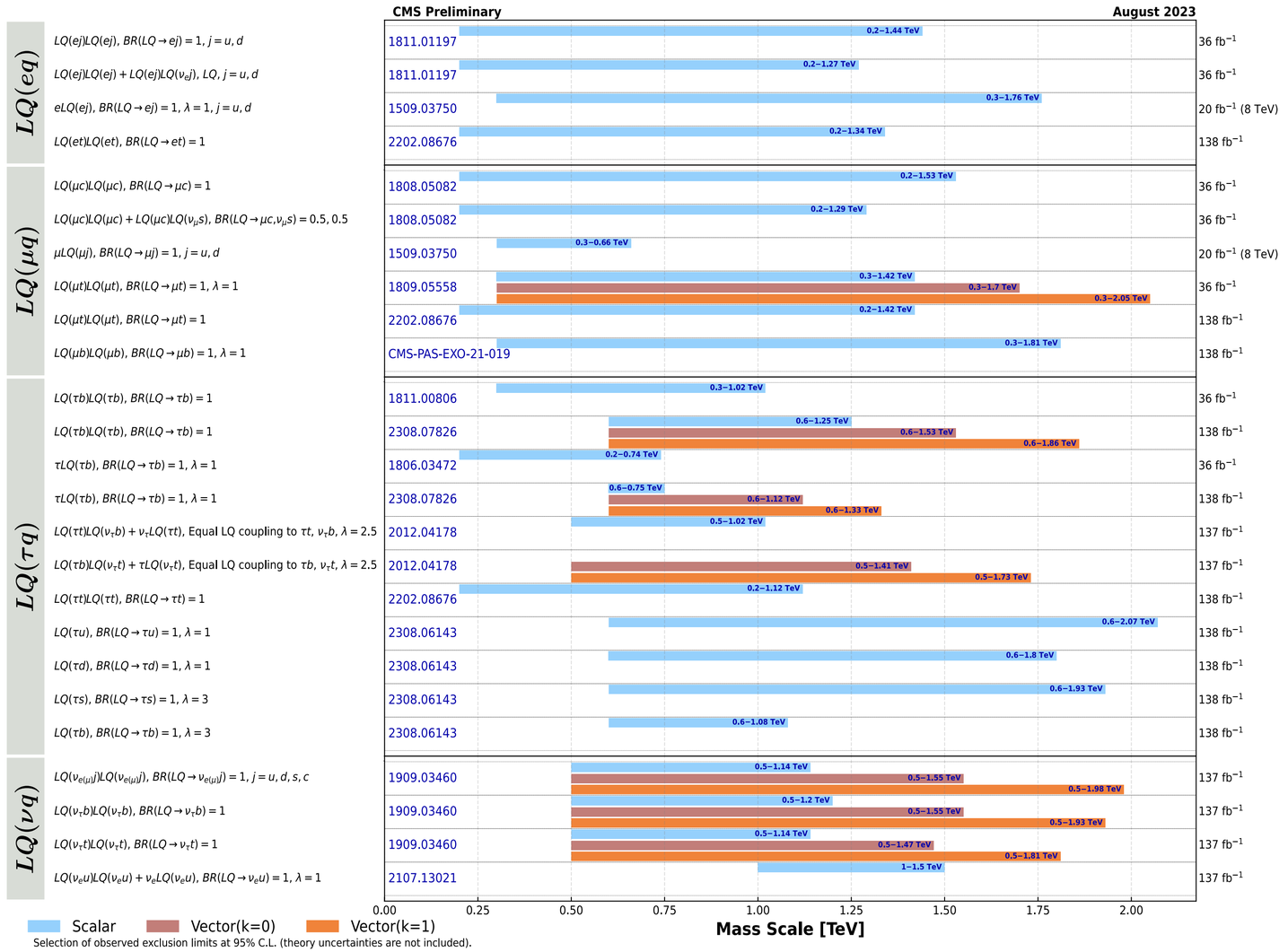
Leptoquarks: State of the art





ATL-PHYS-PUB-2023-006

Overview of CMS leptoquark searches



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

LQ summary

$LQLQ \to tbl\nu$ ($l = e, \mu$): Pair Production @ ATLAS

arXiv:2210.04517

Target pair-produced up- and down-type LQs with $\beta(LQ \to q_3 l)$ = 0.5

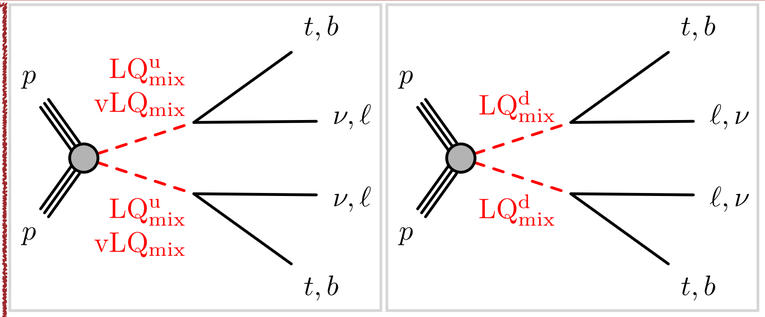
- LQs couple simultaneously to a top quark and a light lepton (e or μ)
- Following the notation LQ^d_{mix} (scalar) and $\tilde{U}_1$ (vector)

Event selections: 1 light lepton, $\geq$ 2 jets, $\geq$ 1 b-jet, $p_T^{miss} \geq 250$ GeV

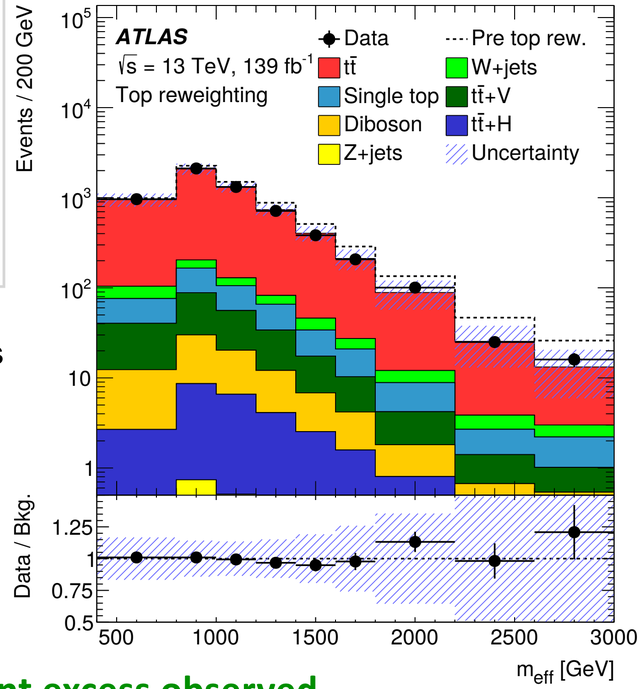
Main backgrounds $t\bar{t}$, single top, W+jets

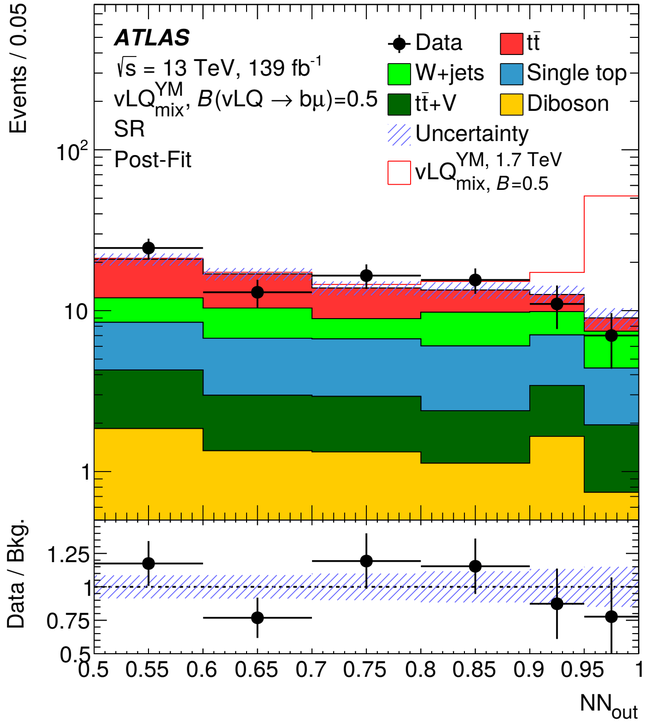
Train neural networks (NNs) for several signals (scalar/vector, up/down, $\beta(LQ^u_{mix} \to bl)$) in inclusive "training" region

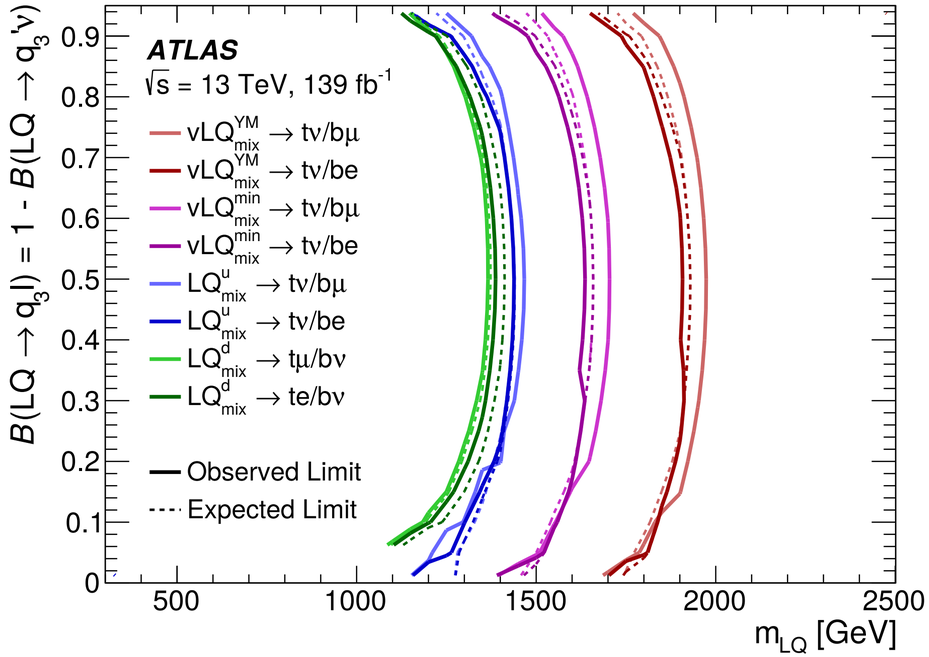
Final discriminating variable: NN score



Mis-modeling of high-p_T top quarks → data-driven correction of $t\bar{t}$ and single top backgrounds







No significant excess observed.

Analysis Results

Observed (expected) 95% CL limits at $\beta(LQ \to q_3 l) = 0.5$:

	$\beta(LQ \to q_3 e) = 1.0$	$\beta(LQ \to q_3 \mu) = 1.0$
LQ^u_{mix}	**1.44 (1.44) TeV**	**1.46 (1.44) TeV**
LQ^d_{mix}	**1.39 (1.41) TeV**	**1.37 (1.38) TeV**
U_1^{min}	**1.62 (1.65) TeV**	**1.71 (1.66) TeV**
U_1^{YM}	**1.90 (1.93) TeV**	**1.98 (1.93) TeV**

LQ-t-l ($l = e, \mu, \tau$): Pair Production @ CMS

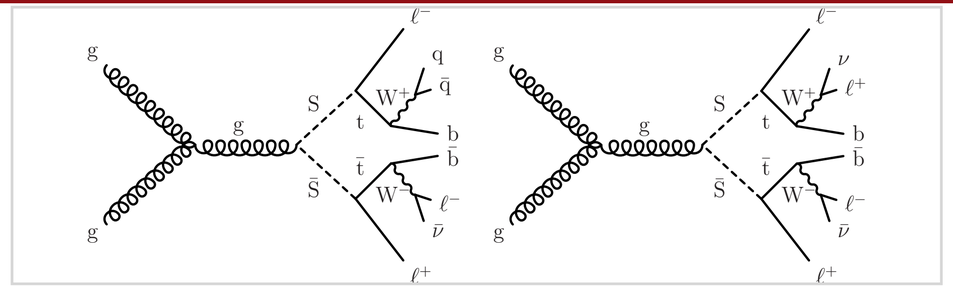
arXiv:2202.08676

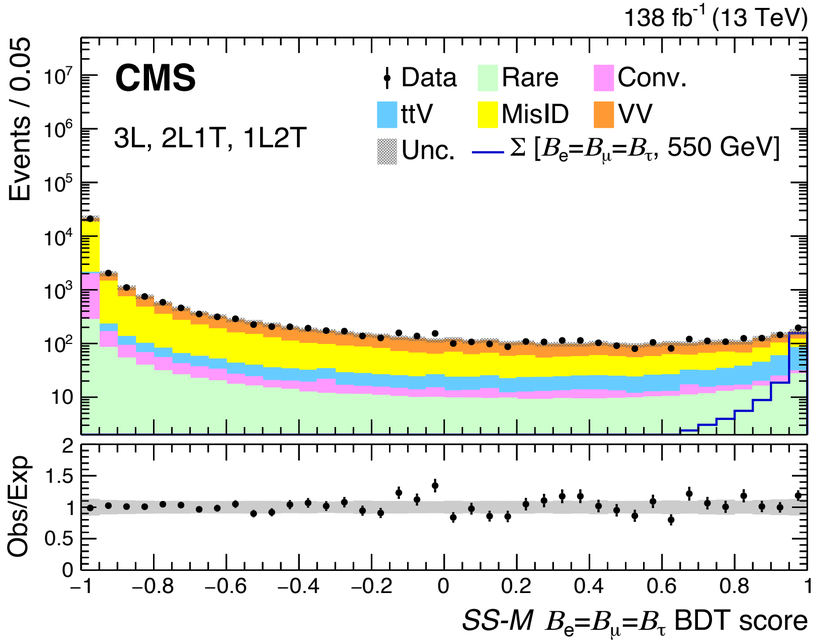
A broad BSM search targeting multi-lepton events
- Type-III seesaw heavy fermions
- Vector-like leptons
- Leptoquarks

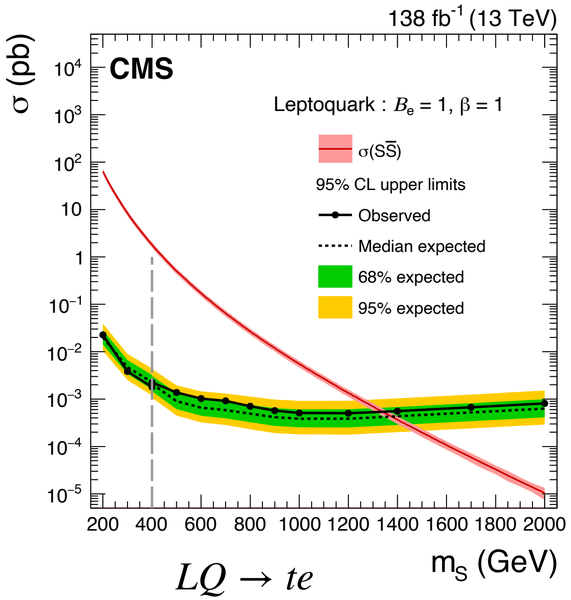
Event selections:
- 3 or 4 lepton signatures (e, μ, τ_{had}) with minimum p_T of 10-20 GeV
- Events are categorized based on lepton charge, mass, and flavor characteristics

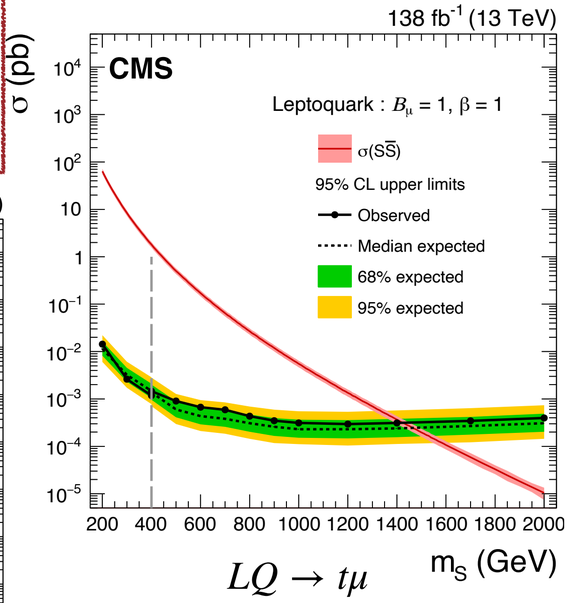
Main background: $ttW, ttZ/\gamma^*$, diboson, non-prompt/fake leptons

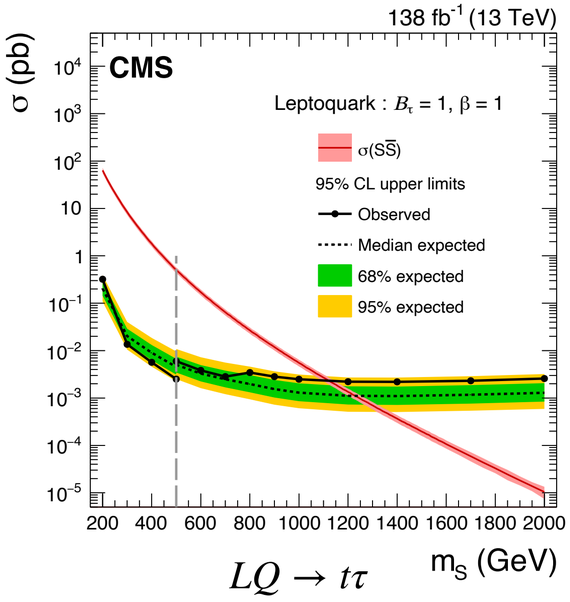
Final discriminating variable:
- BDT (for model-dependent interpretations)











No significant excess observed.

Observed (expected) upper limit at 95% CL (for BR=1):

Scalar $LQ(\rightarrow te)$: m_{LQ} < 1.34 (1.37) TeV

Scalar $LQ(\rightarrow t\mu)$: m_{LQ} < 1.42 (1.46) TeV

Scalar $LQ(\rightarrow t\tau)$: m_{LQ} < 1.12 (1.235) TeV

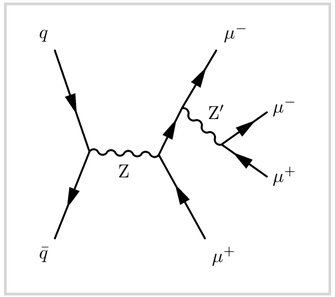
New Z' Vector Boson in 4μ Events @ CMS

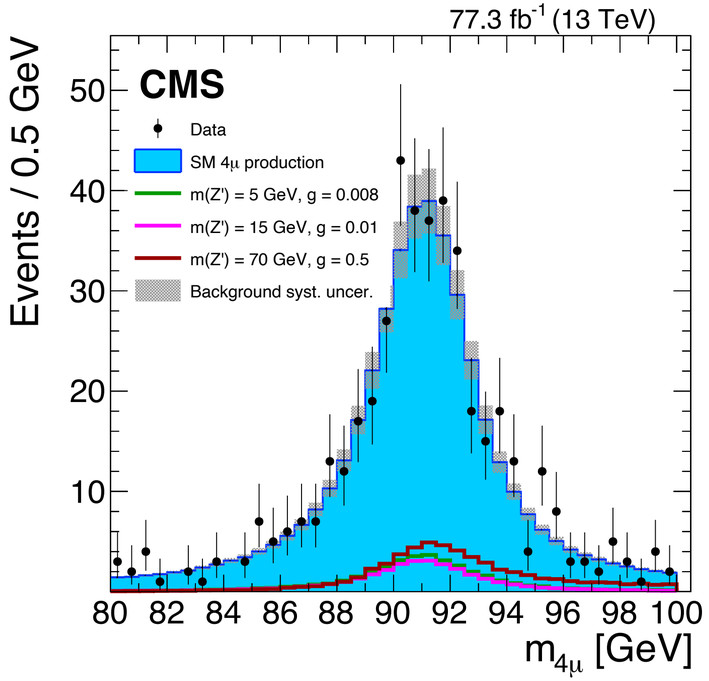
arXiv:1808.03684

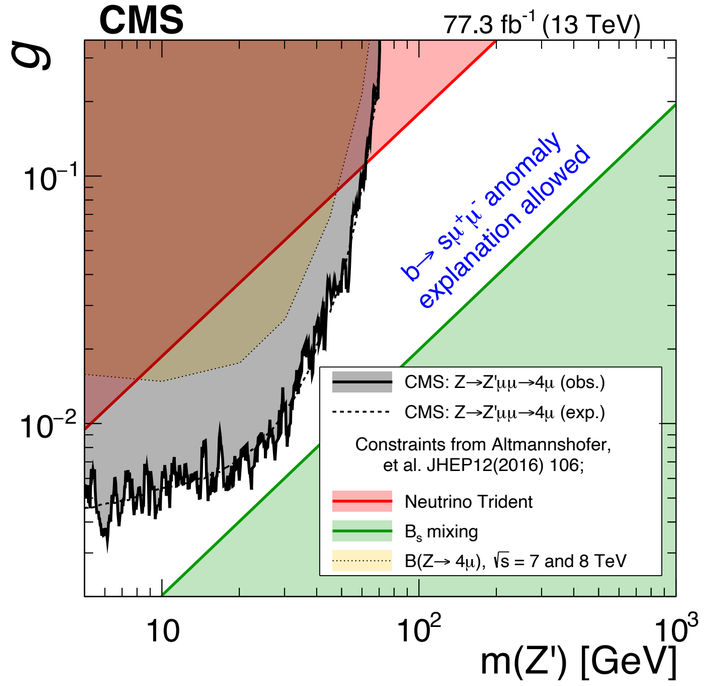
Search for a narrow light Z' with preferential coupling to second generation particles, suggested as possible explanation of $b \to s\mu\mu$ flavor anomalies

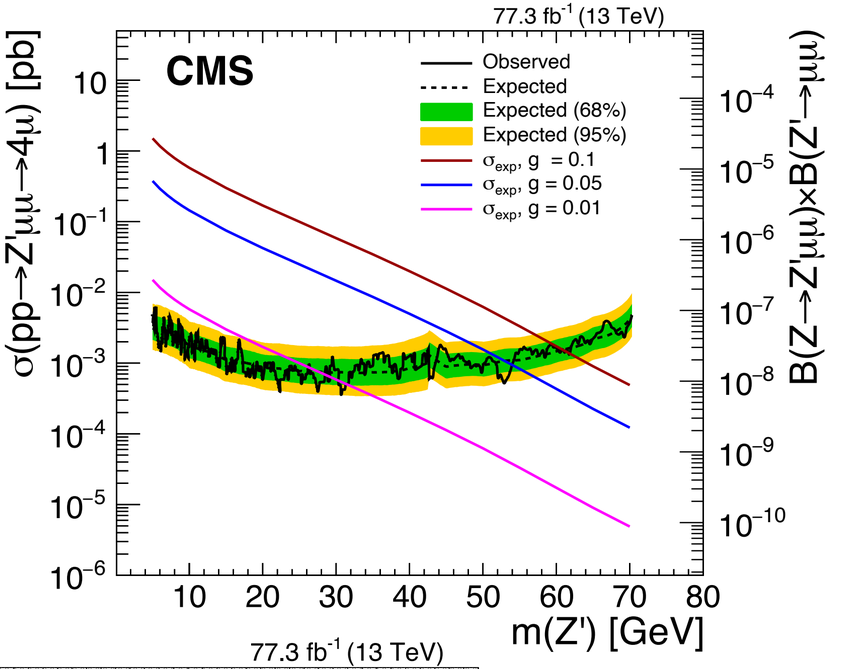
Based on $H(ZZ) \to 4\mu$ analysis, using **2016+2017** dataset ($77.3\, fb^{-1}$)

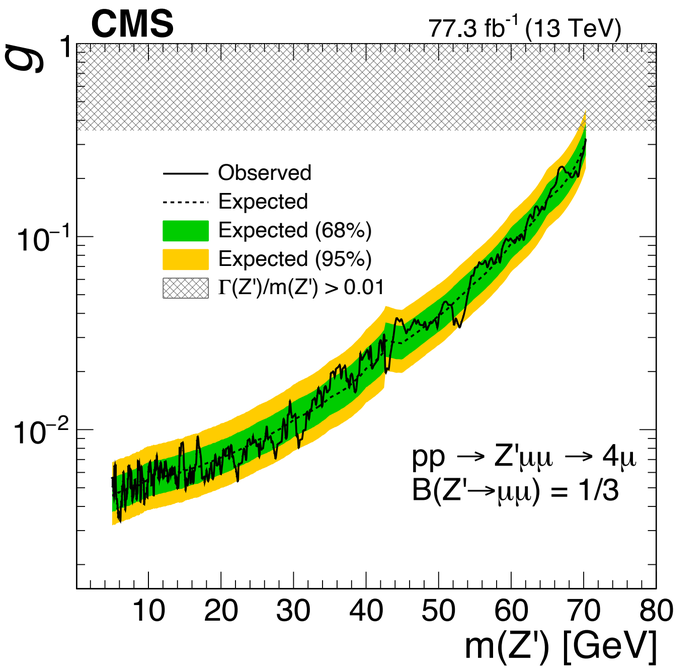
Closed significant fraction of the allowed parameter space in the $L_\mu - L_\tau$ model











Exclusion limit:

$0.004 < g < 0.3$

τ-lepton + Missing Transverse Momentum @ CMS

arXiv:2212.12604

Search for events with a hadronically decaying τ lepton (τ_{had}) and high missing transverse momentum (p_T^{miss})

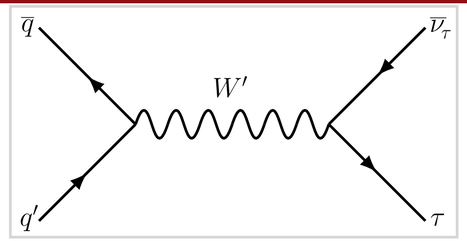
Signature:

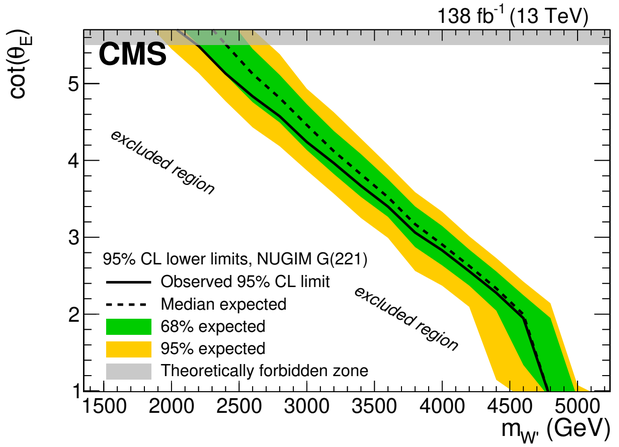
- Final state: at least one τ_{had} and high p_T^{miss} (p_T^{miss} > 200 GeV)
- Expect back-to-back kinematics and balanced in p_T

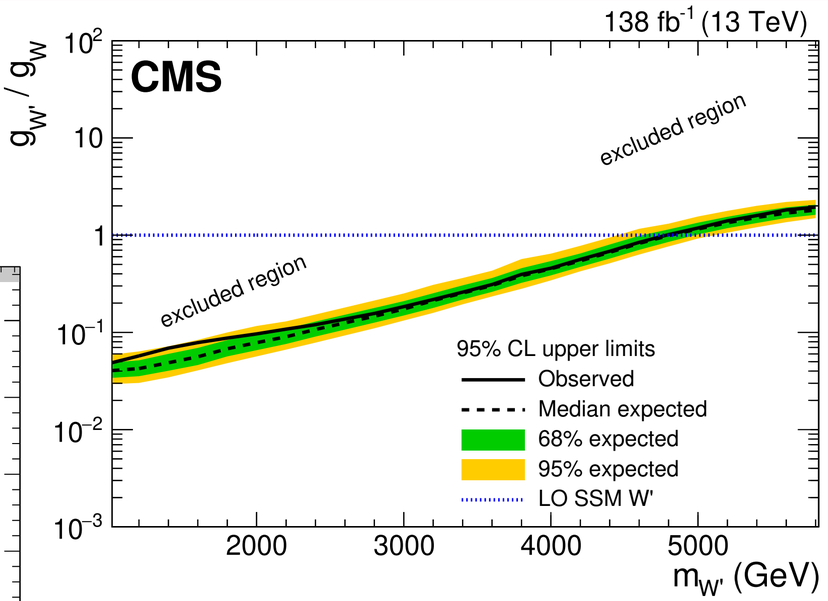
Main backgrounds:

- W+jets: dominant irreducible, same signature as signal
- $t\bar{t}$ production, single Top
- Z(ll)+jets
- Diboson (WW, WZ, ZZ)
- QCD multijet

Transverse mass (m_T) used as discriminating variable

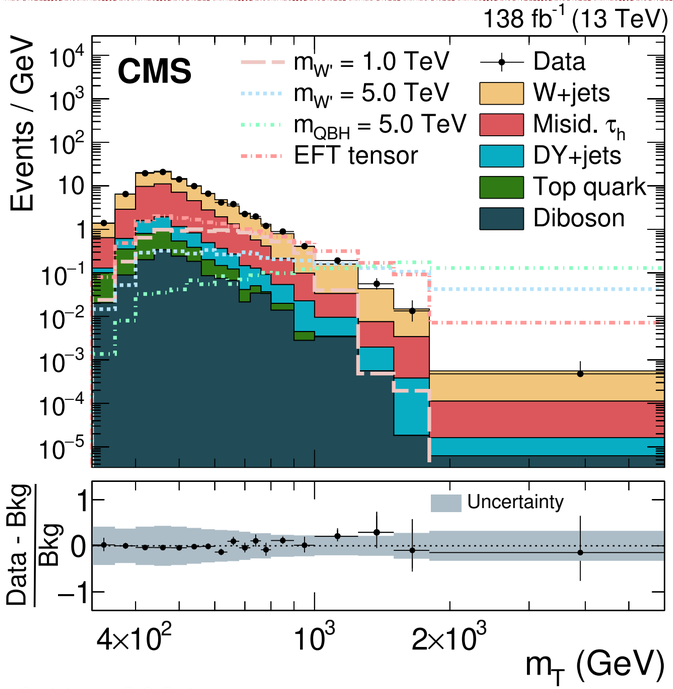


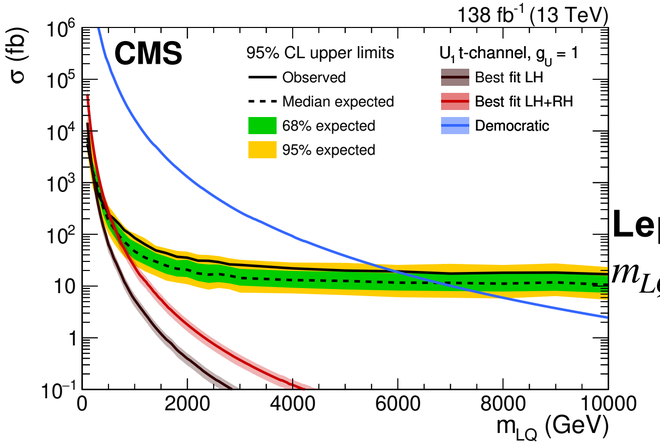




W' **up to 4.8 TeV** excluded in sequential SM (SSM) ($g_{W'} = g_W$)

Non-universal gauge interaction model G(221): $m_{W'}$ < 2.2 TeV for all values of θ_E





Leptoquarks:

m_{LQ} < 5.9 TeV (democratic)

< 205 GeV (best-fit LH)

< 515 GeV (best-fit LH+RH)

Quantum black holes:

m_{QBH} < 6.6 TeV