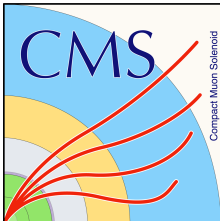


Search for new phenomena at the LHC

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Humboldt-Universität zu Berlin

on behalf of
ATLAS and CMS Collaborations
IPA2022 - Wien, Austria



FSP ATLAS
Erforschung von
Universum und Materie



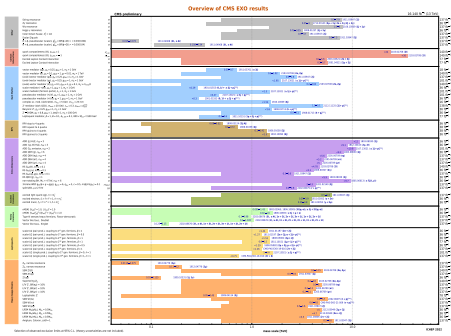
Beyond Standard Model (BSM) searches

- Unexplained phenomena → Standard Model (SM) is not complete: parameters fine tuning, matter/anti-matter asymmetry, dark-matter...
- Tension from SM predictions in B -physics measurements

ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits
 Status: July 2022
 $[C \cdot dt = (2.6 - 130) \text{ fb}^{-1}]$ ATLAS Preliminary
 $\sqrt{s} = 8, 13 \text{ TeV}$

Model	k, γ	Jets	$\sigma(\text{fb})^{\dagger}$	Limit	Reference
KK					
ADD (see e.g. [1])	8.4×10^{-3}	1-4	130	1.3 TeV	ATLAS 2015
ADD (see e.g. [1])	3.7	2	130	1.3 TeV	ATLAS 2015
ADD (see e.g. [1])	2.7	3	130	1.3 TeV	ATLAS 2015
ADD (see e.g. [1])	2.0	4	130	1.3 TeV	ATLAS 2015
ADD (see e.g. [1])	1.5	5	130	1.3 TeV	ATLAS 2015
ADD (see e.g. [1])	1.2	6	130	1.3 TeV	ATLAS 2015
ADD (see e.g. [1])	1.0	7	130	1.3 TeV	ATLAS 2015
ADD (see e.g. [1])	0.8	8	130	1.3 TeV	ATLAS 2015
ADD (see e.g. [1])	0.6	9	130	1.3 TeV	ATLAS 2015
ADD (see e.g. [1])	0.5	10	130	1.3 TeV	ATLAS 2015
ADD (see e.g. [1])	0.4	11	130	1.3 TeV	ATLAS 2015
ADD (see e.g. [1])	0.3	12	130	1.3 TeV	ATLAS 2015
ADD (see e.g. [1])	0.2	13	130	1.3 TeV	ATLAS 2015
ADD (see e.g. [1])	0.1	14	130	1.3 TeV	ATLAS 2015
ADD (see e.g. [1])	0.05	15	130	1.3 TeV	ATLAS 2015
ADD (see e.g. [1])	0.02	16	130	1.3 TeV	ATLAS 2015
ADD (see e.g. [1])	0.01	17	130	1.3 TeV	ATLAS 2015
ADD (see e.g. [1])	0.005	18	130	1.3 TeV	ATLAS 2015
ADD (see e.g. [1])	0.002	19	130	1.3 TeV	ATLAS 2015
ADD (see e.g. [1])	0.001	20	130	1.3 TeV	ATLAS 2015
ADD (see e.g. [1])	0.0005	21	130	1.3 TeV	ATLAS 2015
ADD (see e.g. [1])	0.0002	22	130	1.3 TeV	ATLAS 2015
ADD (see e.g. [1])	0.0001	23	130	1.3 TeV	ATLAS 2015
ADD (see e.g. [1])	0.00005	24	130	1.3 TeV	ATLAS 2015
ADD (see e.g. [1])	0.00002	25	130	1.3 TeV	ATLAS 2015
ADD (see e.g. [1])	0.00001	26	130	1.3 TeV	ATLAS 2015
ADD (see e.g. [1])	0.000005	27	130	1.3 TeV	ATLAS 2015
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ADD (see e.g. [1])	0.0000005	30	130	1.3 TeV	ATLAS 2015
ADD (see e.g. [1])	0.0000002	31	130	1.3 TeV	ATLAS 2015
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ADD (see e.g. [1])	0.00000002	34	130	1.3 TeV	ATLAS 2015
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ADD (see e.g. [1])	$0.000000000000000000000000000005$	99	130	1.3 TeV	ATLAS 2015
ADD (see e.g. [1])	$0.000000000000000000000000000002$	100	130	1.3 TeV	ATLAS 2015

*Only a selection of the available models is shown. For a full list of searches, please refer to the ATLAS website.
 †Small-radius (large-radius) jets are denoted by the letter (L) (S).

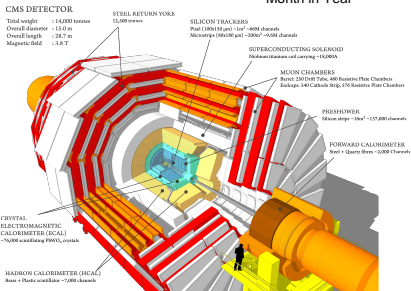
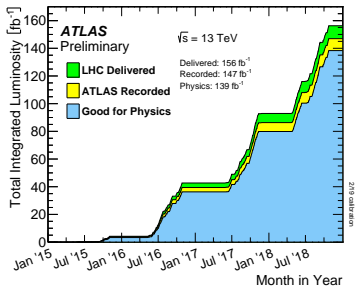
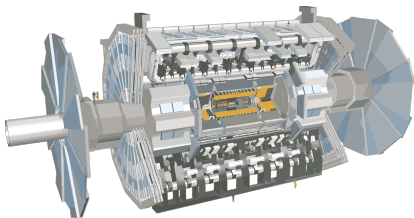


This review will focus on:

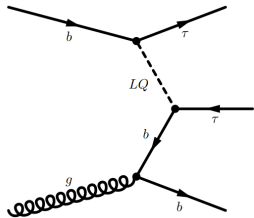
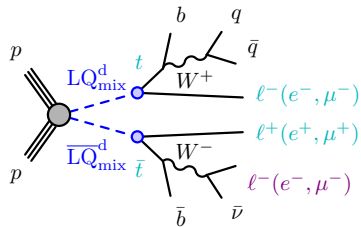
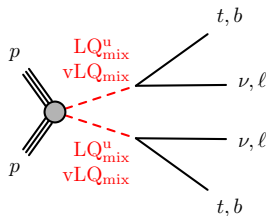
- Leptoquarks
- Vector-like particles
- Heavy resonances

Run 2 at LHC, ATLAS and CMS

- Run 2 (2015-2018)
 pp Dataset @ 13 TeV:
 ATLAS (CMS) 139(138) fb^{-1}



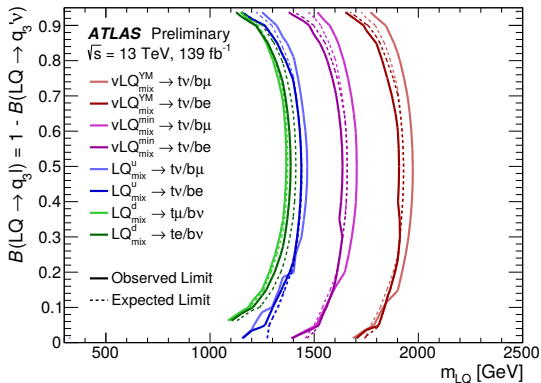
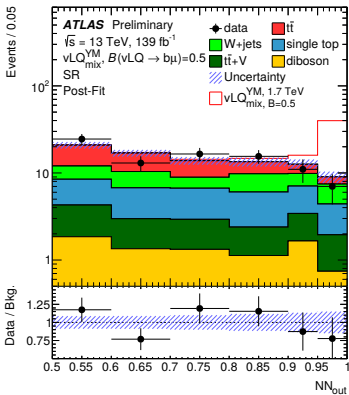
Leptoquarks (LQs)



- Introduced by several SM extensions: grand unification, technicolor, compositeness
- Hypothetical color-triplet, scalar or vector bosons
- Carry both baryon and lepton quantum numbers, fractional e charge
- Largest coupling expected to 3rd generation SM particles

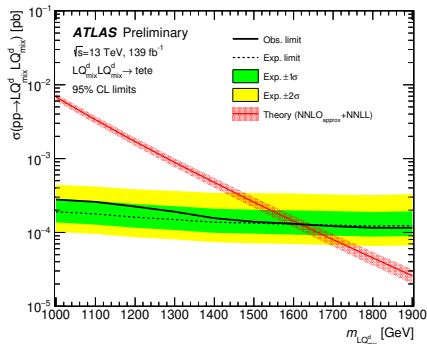
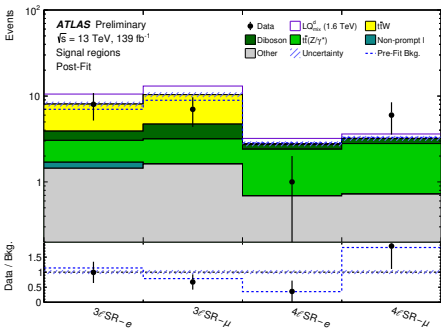
Leptoquarks pair $LQLQ \rightarrow tlb\nu/tvbl$ ATLAS-CONF-2022-009

- Search of scalar ($-1/3e, +2/3e$) and vector ($+2/3e$) leptoquarks coupling to t, b quarks and (e, μ, ν) leptons
- = 1 e or μ in final state. Aim to explain B -anomalies.
- No excess observed, lower limits on $m(LQ)$ for 8 models
- Exclude up to $m(LQ) < 1980$ GeV for a given coupling scenario



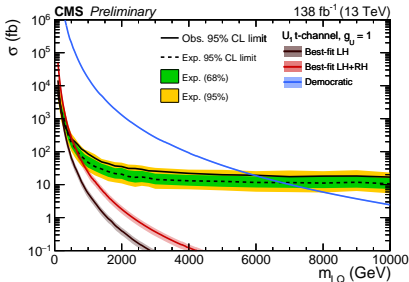
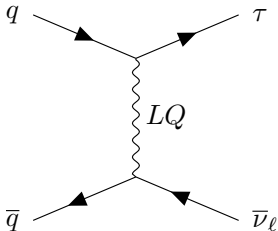
Leptoquarks pair $LQLQ \rightarrow t\bar{t}l\bar{l}$ ATLAS-CONF-2022-052

- Consider events w/ $\geq 2\ell$, ≥ 2 jets ($\geq 1b$ -jet)
- SR: $= 3\ell$, $= 4\ell$ ($\ell = e$ or μ , also from τ decays)
- Lower limits under assumption of exclusive decays into te ($t\mu$):
 $m(LQ) < 1.61(1.64)$ TeV for scalar mixed-generation scenario
 $m(LQ) < 1.71(1.73)$ TeV for vector in minimal coupling scenario
 $m(LQ) < 2.0(2.0)$ TeV for Yang-Mills scenario

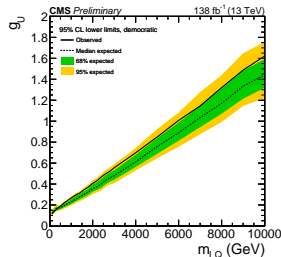
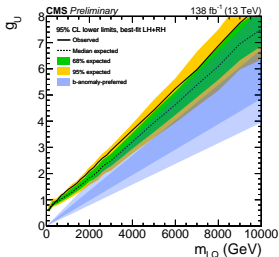
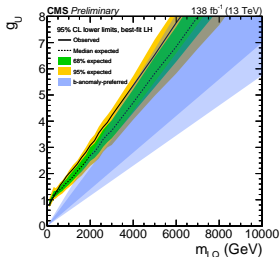


Leptoquark in t -channel CMS-PAS-EXO-21-009

- Final state with a hadronically decaying τ lepton and neutrino

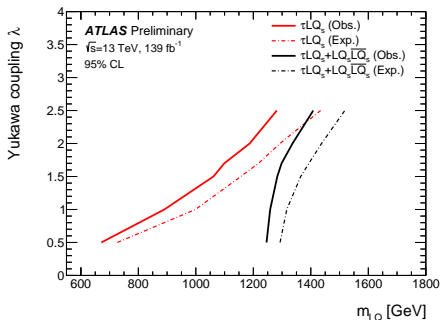
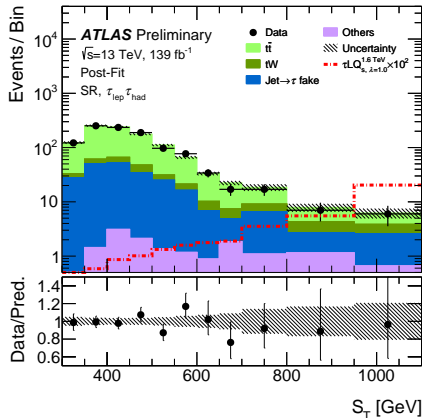


- Upper limits on the cross section of t -channel leptoquark exchange

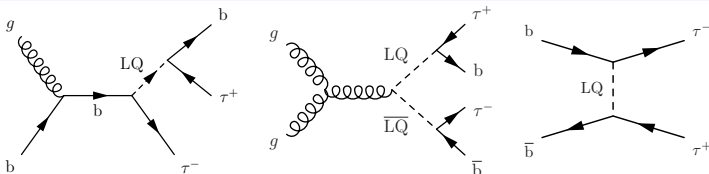


Single Leptoquark in $b\tau\tau$ channel ATLAS-CONF-2022-037

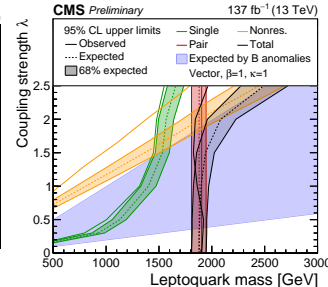
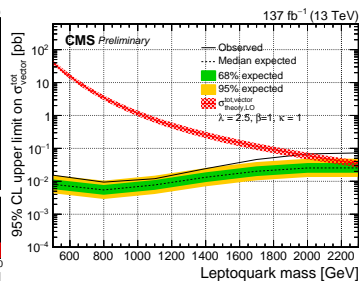
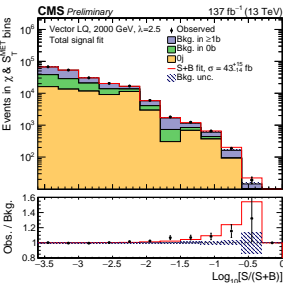
- Search for single scalar leptoquark ($+4/3e, 3B + L = -2$) production decaying into $b\tau$
- No excess: $m(LQ) < 1.26$ TeV, 1.30 TeV and 1.41 TeV are excluded for Yukawa coupling to $b\tau$ of 1.0, 1.7 and 2.5, respectively



Leptoquark in $b\tau$ in s - and t -channels CMS-PAS-EXO-19-016



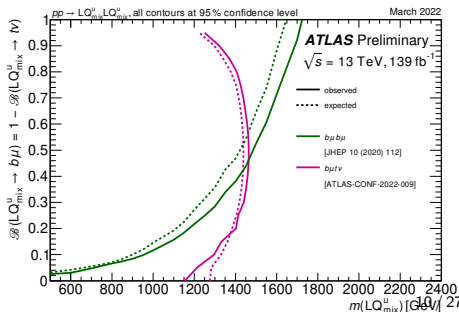
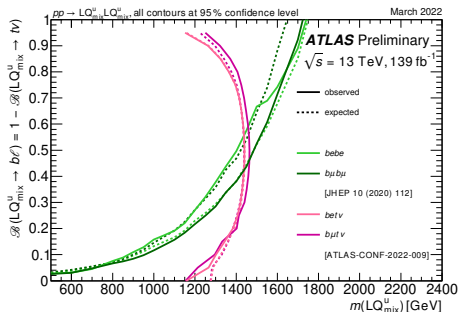
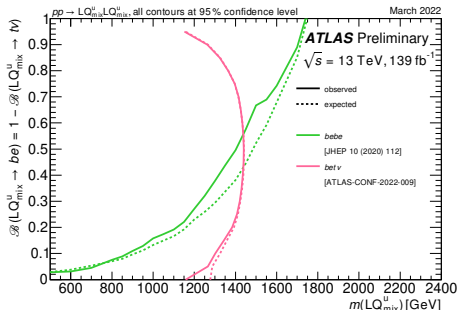
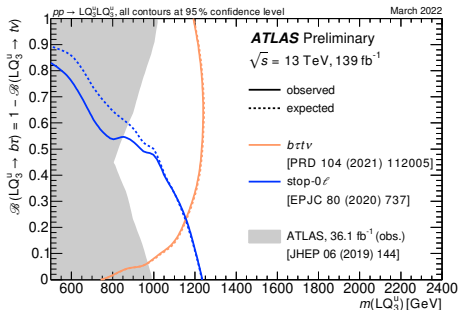
- $LQ \rightarrow b\tau$ in events w/ τ and ≥ 1 b-jets
- Range of coupling strengths and masses tested



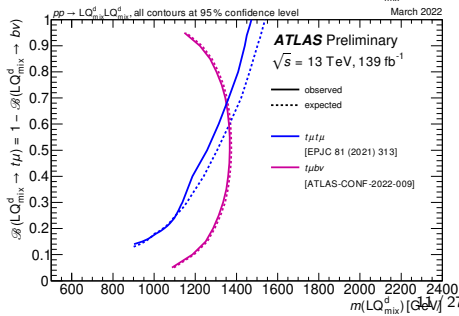
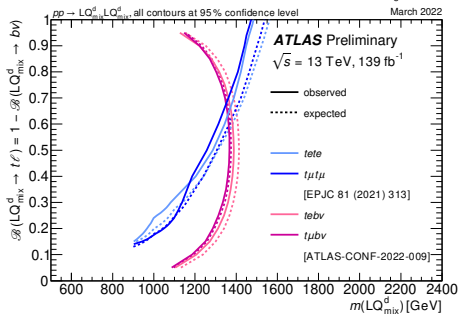
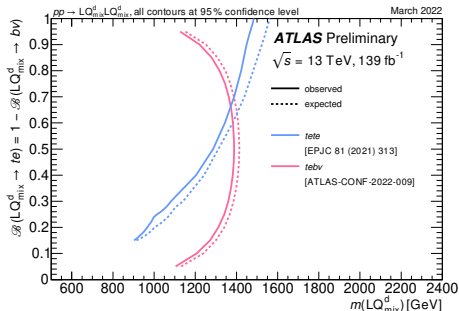
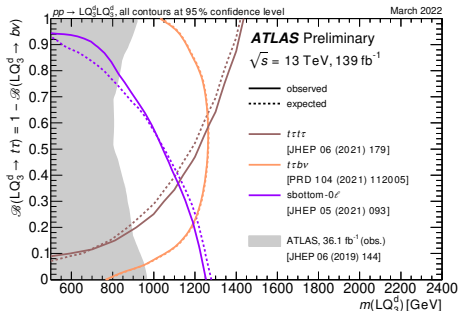
- Significant 3.4σ excess for a LQ mass of 2 TeV and $\lambda = 2.5$

Up-type Scalar Leptoquarks Pair

ATL-PHYS-PUB-2022-012

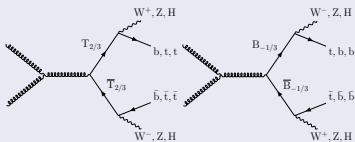


Down-type Scalar Leptoquarks Pair ATL-PHYS-PUB-2022-012



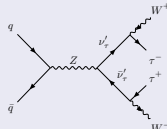
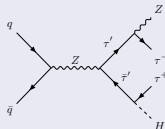
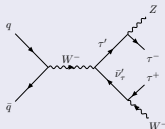
Vector-like particles: quarks (VLQ), leptons (VLL)

- New heavy fermions, introduced by many models (Little/Composite Higgs, string theory, large extra-dimensions...)
- Left-/right-handed components transform identically
- Mass term included in \mathcal{L} , independent of Yukawa couplings to H
- Assuming to mix only to 3rd generation quarks

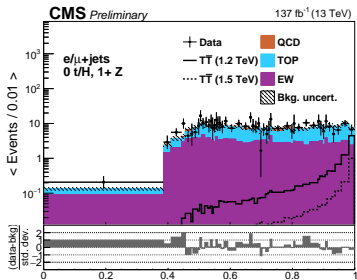


- $T(+2/3e)$, $B(-1/3e)$ in singlet, doublet or triplet w/ further VLQs
- VLQ Decay modes: $T \rightarrow tH, tZ, bW$,
 $B \rightarrow bH, bZ, tW$

- VLL: $(\nu'_\tau \tau')$ doublet
- $\nu'_\tau \rightarrow W^+ \tau^-$
 $\tau'^- \rightarrow Z \tau^-, \tau'^- \rightarrow H \tau^-$

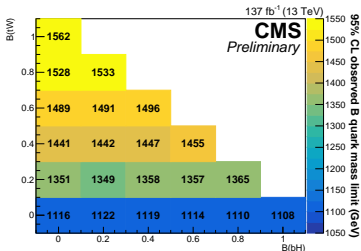
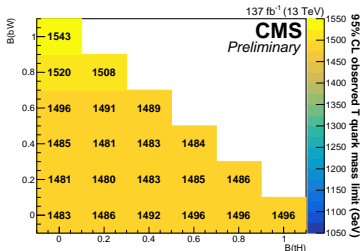


Vector-like quark pairs in leptons CMS-PAS-B2G-20-011



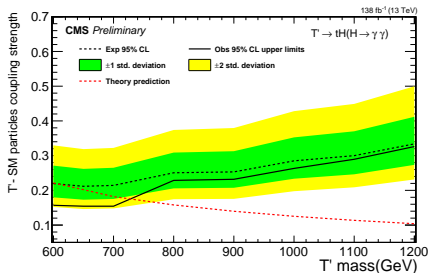
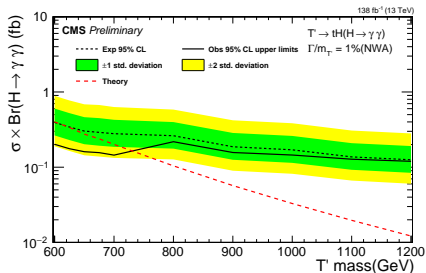
Search of vector-like $T\bar{T}$ and $B\bar{B}$ pairs

- = 1e or μ , \cancel{E}_T , ≥ 3 large-radius jets in single-lepton channel
- = 2e or μ w/ same charge, in the same-sign dilepton channel
- ≥ 3 e or μ in multilepton channel



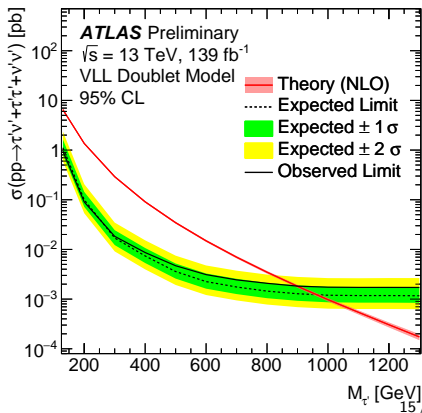
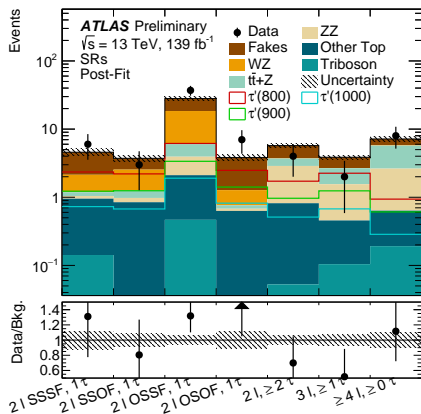
- Exclude pair production for $m(T) < 1.54$ TeV, $m(B) < 1.56$ TeV
- Strongest limits to date for $T \rightarrow tH/bW$ and $B \rightarrow tW$

- First search profiting of the 1-2% resolution in $H \rightarrow \gamma\gamma$ invariant mass reconstruction. Exploits Boosted Decision Trees
- Both $t \rightarrow bq\bar{q}$ and $t \rightarrow bl\nu$ channels considered

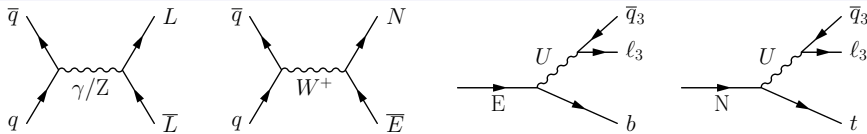


- $m(T') < 730$ GeV excluded
- ATLAS: using mono-top channel, most restrictive limits on single production of a T singlet JHEP05 (2019) 41

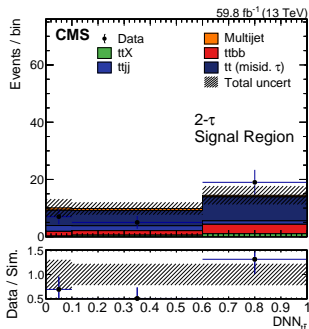
- Search of vectorlike leptons coupling to 3rd generation SM leptons in 2, 3, ≥ 4 leptons in final state (no hadronic τ decays)
- Using machine learning classifier, no excess beyond SM expectations
- Doublet vectorlike lepton model to exclude $130 < m < 900$ GeV @ 95% CL (970 GeV expected)



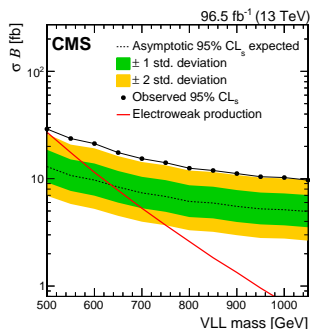
Vector-like lepton pair production CMS-B2G-21-004



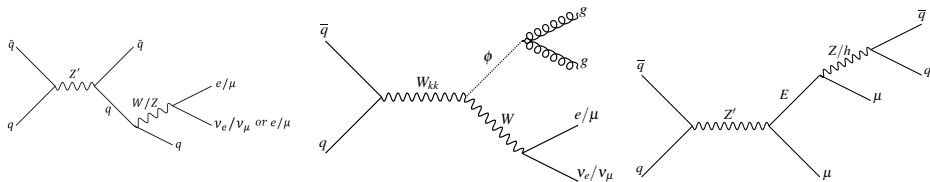
- Aim to explain B -physics SM tension w/ in “4321” model context
- Doublet $E \rightarrow b\bar{q}_3\ell_3$, $N \rightarrow t\bar{q}_3\ell_3$, decay via U LQ
- Final states with third-gen leptons ($\tau\tau$, $\tau\nu_\tau$, or $\nu_\tau\nu_\tau$), and $\geq 3b$ -jets



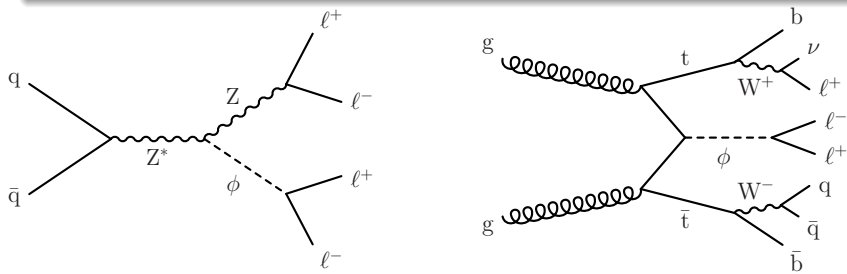
- Slight excess in last bins in 1-, 2- τ_h SR
- 2.8 σ deviation for a representative $m(VLL) = 600$ GeV
- Observed limits $\sim 2\times$ expected limits
- Data: 2017 and 2018



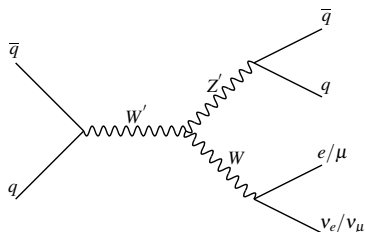
Heavy resonances



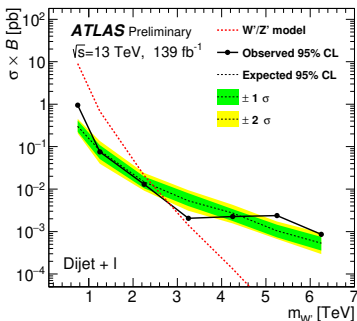
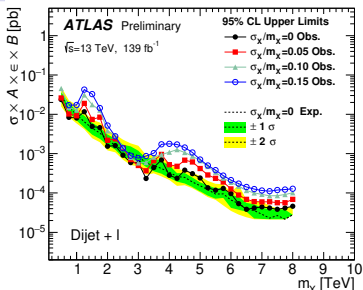
- Several SM extensions predict the existence of heavy particles
- Searches for new gauge bosons (W' , Z'), and dilepton resonances
- Multiple final states explored



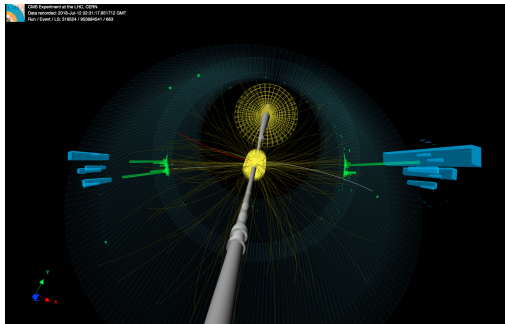
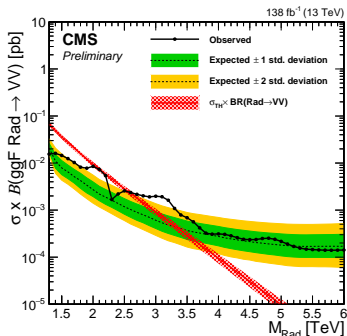
3-/4-body invariant masses ATLAS-CONF-2022-048



- Use events w/ $\geq 1l$ (e or μ) to set model-independent limits
- Consider invariant masses ljj , $lljj$ (including b -jets)
- Assuming $m(W') - m(Z') = 250$ GeV exclude $W' \rightarrow WZ'$ for $m(W') < 2.5$ TeV



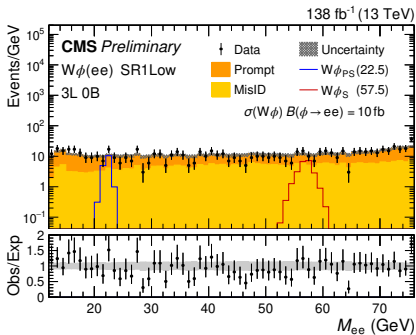
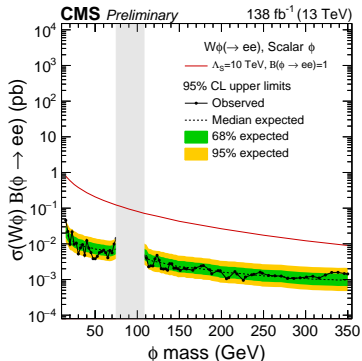
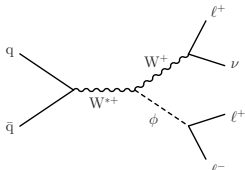
- All-jets final state. Highly Lorentz-boosted bosons ($V = W, Z$)
- Machine learning techniques employed to distinguish single large-radius jet from $W, Z,$ and H decays, from other jets
- Events categorized on kinematic properties of two additional jets



- Mild (2.3σ) excess at $m = 2.1$ and 2.9 TeV
- Excluded: spin-1 Z' and W' for $m < 4.8$ TeV
spin-2 gravitons (spin-0 radions) w/ $m < 1.4$ TeV (2.7 TeV)

Dilepton resonances w/ W , Z , or $t\bar{t}$ CMS-PAS-EXO-21-018

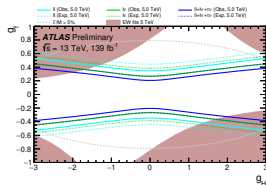
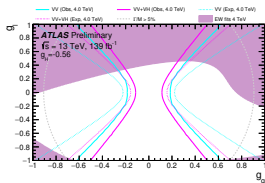
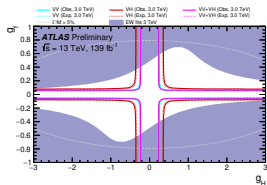
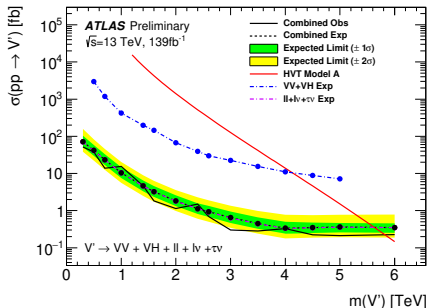
- Search for scalar and pseudoscalar bosons into ll ($l = e, \mu, \text{ or } \tau$)
- Consider events with 3 or 4 l , include hadronic τ decays



- No statistically significant excess observed over SM expectations
- Most stringent direct limits on production for masses in 15 – 350 GeV range for such particles and decay modes

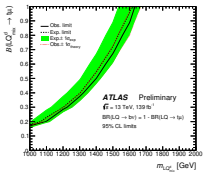
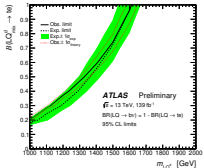
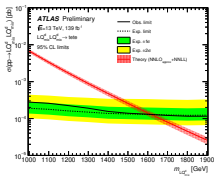
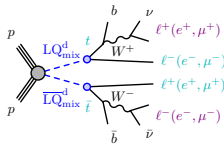
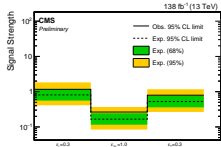
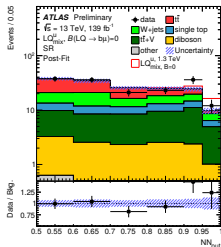
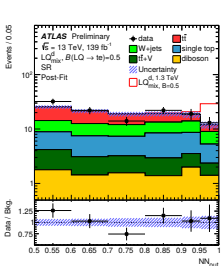
Heavy resonances combination ATLAS-CONF-2022-028

- Search for narrow resonance combining final states VV :
 $qqqq, \nu\nu qq, l\nu qq, llqq, l\nu ll$
 VH : $qqbb, \nu\nu bb, l\nu bb, llbb$
- Right: Cross section vs mass (at given couplings)
- Below: 2D limits on couplings (at a given signal mass pole)



- Exclude heavy vector-boson triplet w/ $m < 5.8$ TeV (4.5 TeV) in a weakly (strongly) coupled scenario

Conclusions



- Only a fraction of the work done covered in this talk
- Run 3 already started and LHC is quickly ramping up
- Several results will gain in sensitivity w/ improved statistic
- Stay tuned for further studies!

ATLAS results summary

- Exclude vector-like τ for $130 < m < 900$ GeV

CMS results summary

- Exclude vector-like quarks TT/BB pair production for $m(T) < 1.54$ TeV, $m(B) < 1.56$ TeV
- Exclude $m(T') < 730$ GeV
- Deviation (2.8σ) for a vector-like lepton w/ mass around ~ 600 GeV, coupling to 3rd-gen leptons,

Leptoquarks

ATLAS results exclusion summary

- LQ pair production up to $m(LQ) < 1980$ GeV, for couplings to 3^{rd} -gen quark and $1^{st}/2^{nd}$ -gen leptons
- LQ pair production up to $m(LQ) < 2.0$ TeV for coupling to $te/t\mu$ in various scenarios
- Single LQ in $b\tau\tau$ channel up to $m(LQ) < 1.41$ TeV for $\lambda = 2.5$
- Summary plots:
 - Four different pair-production scenarios of scalar leptoquarks
 - Decay include neutral/charged SM leptons from all three generations, quarks only from third generation

CMS results summary

- t -channel leptoquark: sensitivity reaching parameter space to explore B -meson decay anomalies
- Significant (3.4σ) excess for LQ $\rightarrow b\tau$ ($m(LQ) \sim 2$ TeV, $\lambda = 2.5$) in s/t -channels

ATLAS summary

- Exclude $W' \rightarrow WZ'$ contributions for $m(W') < 2.5$ TeV
- Exclude heavy vector-boson triplet w/
 $m < 5.8$ TeV (4.5 TeV) in a weakly (strongly) coupled scenario

CMS summary

- Mild (2.3σ) VV excess at $m = 2.1$, and 2.9 TeV
- Most stringent limits in 15 – 350 GeV range for $\ell\ell$ production

References (I)

ATLAS

- “Search for pair-produced scalar and vector leptoquarks decaying into third-generation quarks and first- or second-generation leptons in pp collisions with the ATLAS detector”, [ATLAS-CONF-2022-009](#)
- “Search for leptoquark pair production decaying to $t\ell^-\bar{\ell}^+$ in multilepton final states in pp collisions at 13 TeV with the ATLAS detector”, [ATLAS-CONF-2022-052](#)
- “Search for scalar leptoquarks in the $b\tau\tau$ final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, [ATLAS-CONF-2022-037](#)
- “Summary Plots from ATLAS Searches for Pair-Produced Leptoquarks”, [ATL-PHYS-PUB-2022-012](#)
- “Search for invisible particles produced in association with single top quarks in protonproton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, [ATLAS-CONF-2022-036](#)
- “Search for Third-Generation Vectorlike Leptons in pp Collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, [ATLAS-CONF-2022-044](#)
- “Search for new phenomena in multi-body invariant masses in events with at least one isolated lepton using $\sqrt{s} = 13$ TeV proton-proton collision data collected by the ATLAS detector”, [ATLAS-CONF-2022-048](#)
- “Combination of searches for heavy resonances using 139 fb^{-1} of protonproton collision data at $\sqrt{s} = 13$ TeV with the ATLAS detector”, [ATLAS-CONF-2022-028](#)

References (II)

CMS

- “Search of a Vector-Like Quark $T' \rightarrow tH$ in the di-photon final state”,
[CMS-PAS-B2G-21-007](#)
- “Search for pair production of vector-like quarks in leptonic final states at $\sqrt{s} = 13$ TeV”,
[CMS-PAS-B2G-20-011](#)
- “Search for pair-produced vector-like leptons in final states with third-generation leptons and at least three b quark jets in proton-proton collisions at $\sqrt{s} = 13$ TeV”,
[CMS-B2G-21-004](#)
- “Search for new heavy resonances decaying to WW, WZ, ZZ, WH, or ZH boson pairs in the all-jets final state in proton-proton collisions at $\sqrt{s} = 13$ TeV”, [CMS-PAS-B2G-20-009](#)
- “Search for new physics in the tau plus missing transverse momentum final state in proton-proton collisions at $\sqrt{s} = 13$ TeV”, [CMS-PAS-EXO-21-009](#)
- “The search for a third-generation leptoquark coupling to a τ lepton and a b quark through single, pair and nonresonant production at $\sqrt{s} = 13$ TeV”,
[CMS-PAS-EXO-19-016](#)
- Search for dilepton resonances from decays of (pseudo)scalar bosons produced in association with a massive vector boson or top quark anti-top quark pair at $\sqrt{s} = 13$ TeV
[CMS-PAS-EXO-21-018](#)