Search for new phenomena at the LHC

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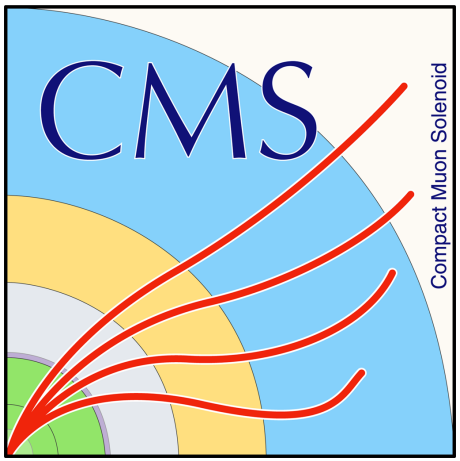
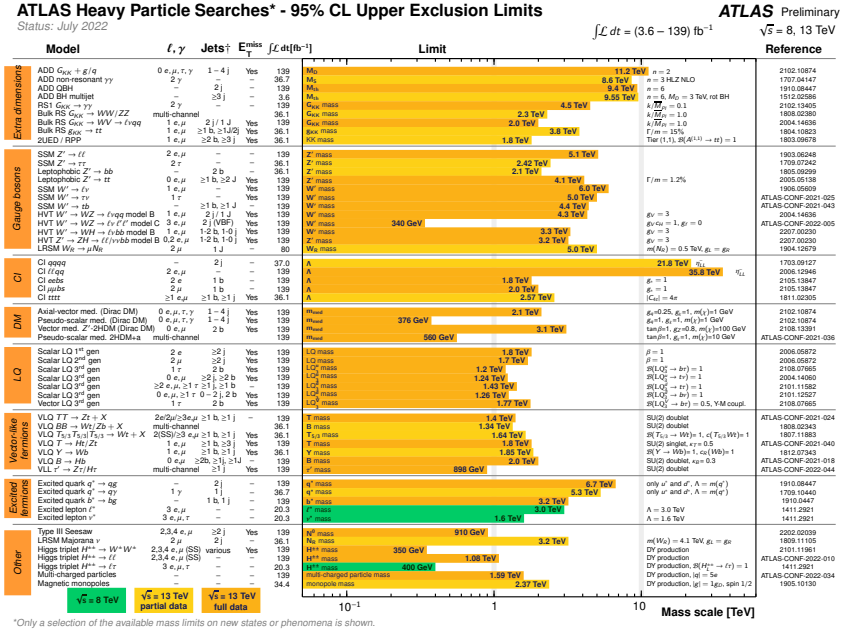
on behalf of
ATLAS and CMS Collaborations
IPA2022 - Wien, Austria

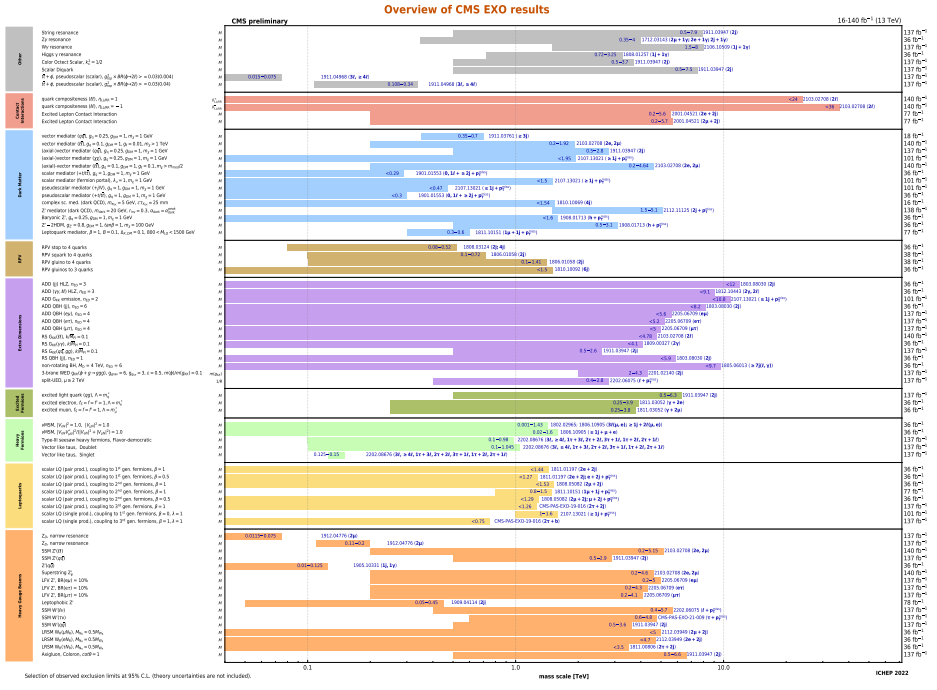


FSP ATLAS
Erforschung von
Universum und Materie

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



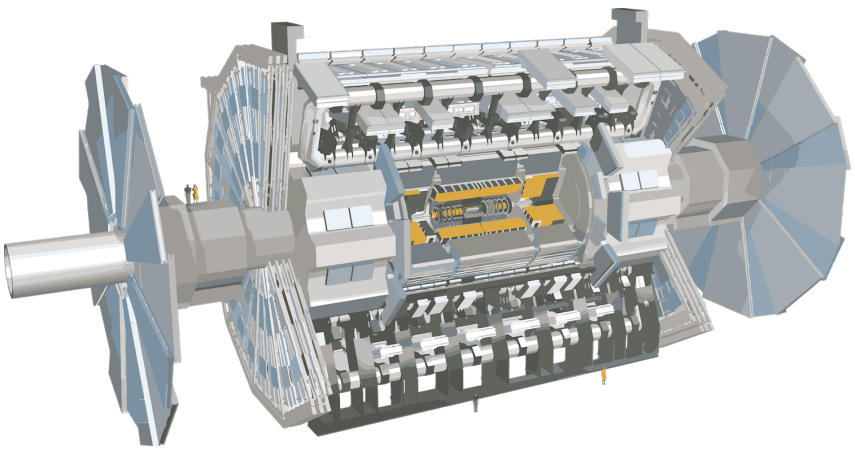


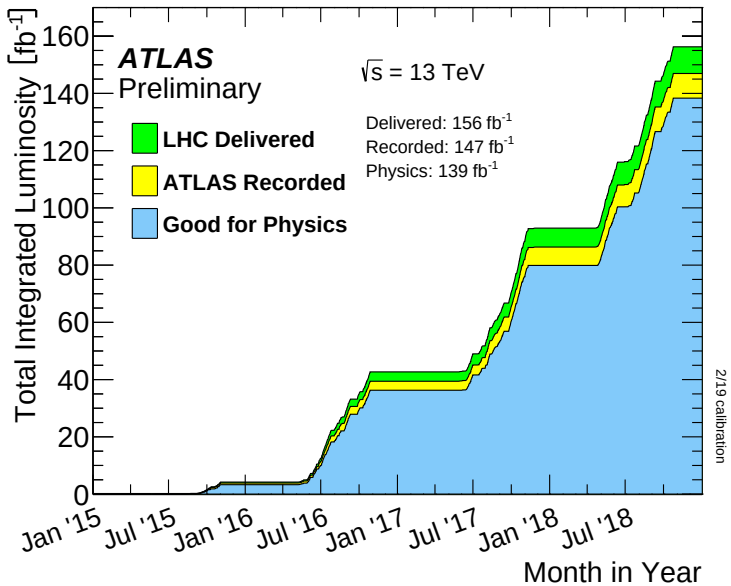
This review will focus on:

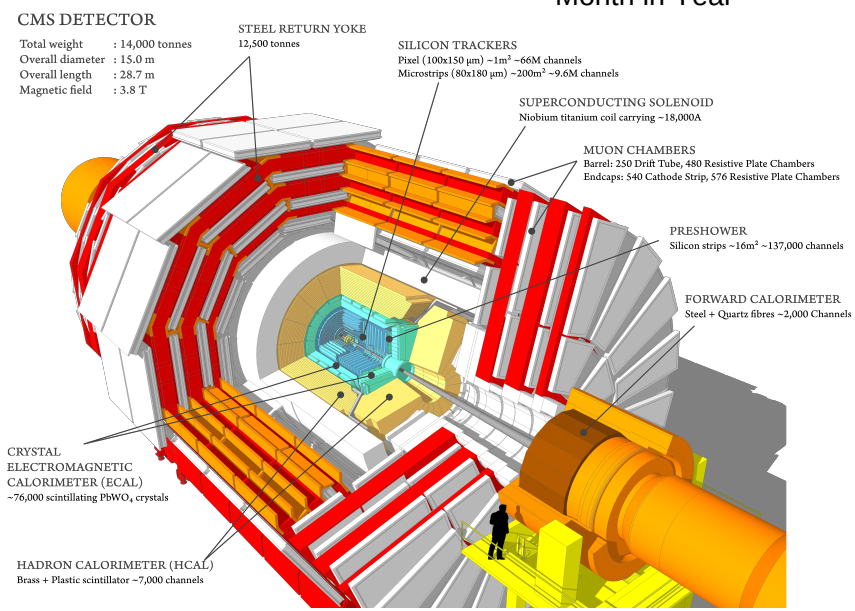
- Leptoquarks
- Vector-like particles
- Heavy resonances

Run 2 at LHC, ATLAS and CMS

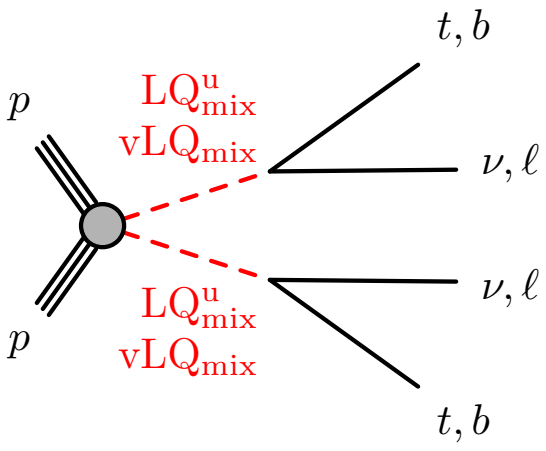
- Run 2 (2015-2018)
  pp Dataset @ 13 TeV:
  ATLAS (CMS) 139(138)fb^{-1}

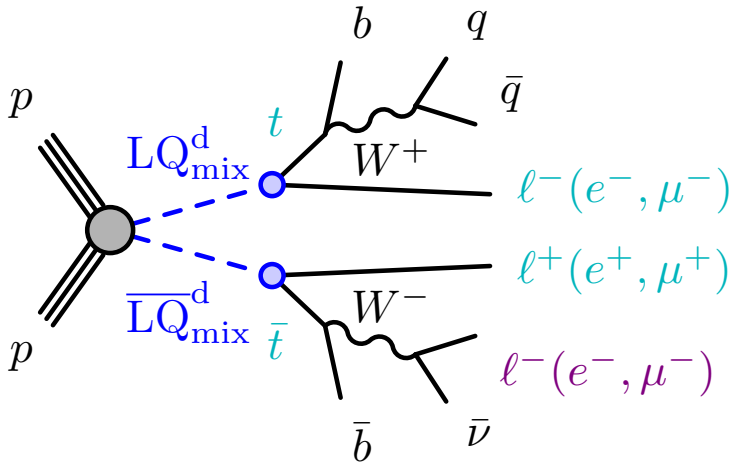


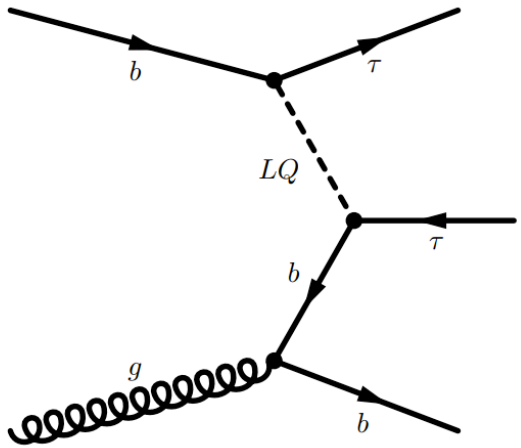




Leptoquarks (LQs)



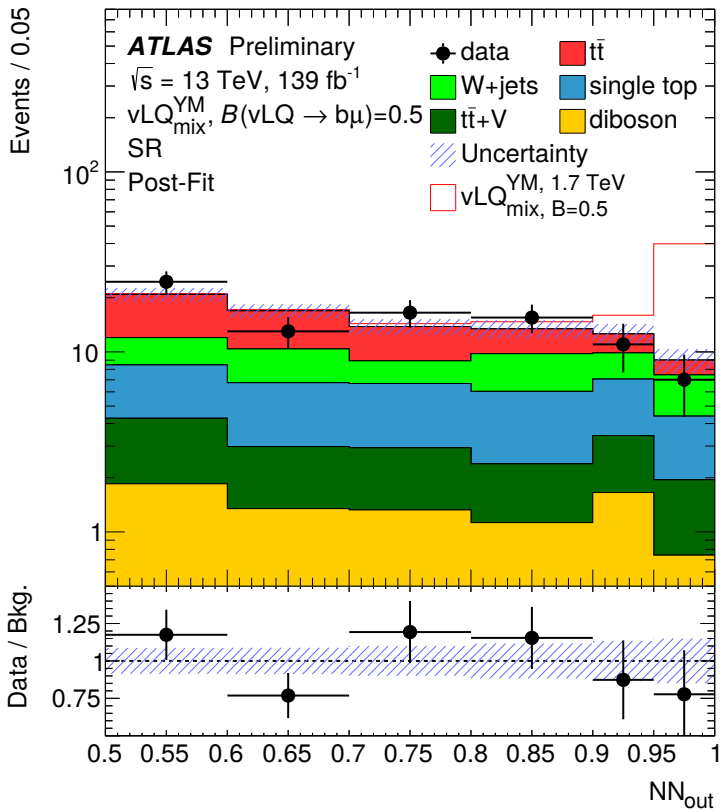


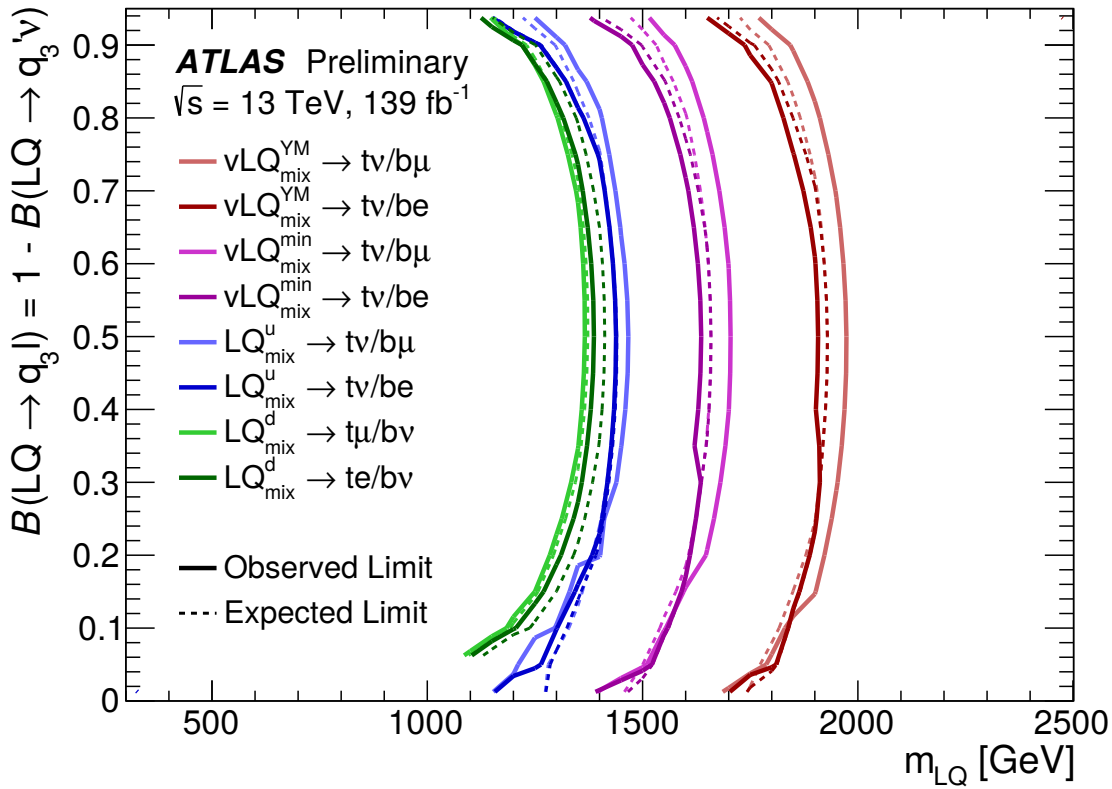


- Introduced by several SM extensions:
  grand unification, technicolor, compositeness
- Hypothetical color-triplet, scalar or vector bosons
- Carry both baryon and lepton quantum numbers, fractional e charge
- Largest coupling expected to 3^{rd} generation SM particles

Leptoquarks pair LQLQ$\rightarrow t\ell b\nu/t\nu b\ell$ ATLAS-CONF-2022-009

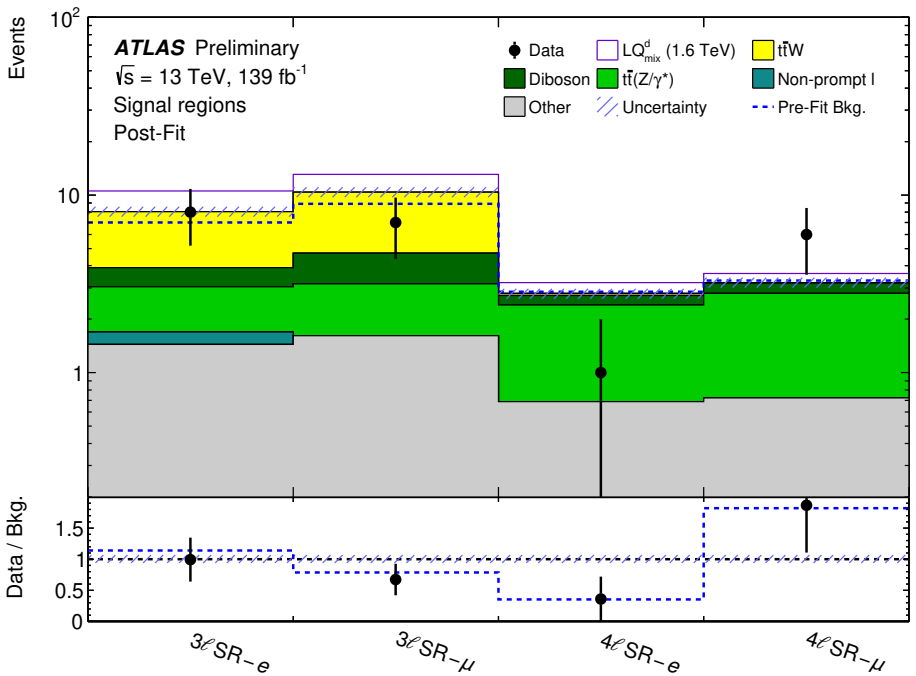
- Search of scalar $(-1/3e, +2/3e)$ and vector $(+2/3e)$ leptoquarks coupling to t, b quarks and (e, μ, ν) leptons
- $= 1$ e or μ in final state. Aim to explain B-anomalies.
- No excess observed, lower limits on m(LQ) for 8 models
- Exclude up to $m(LQ) < 1980$ GeV for a given coupling scenario

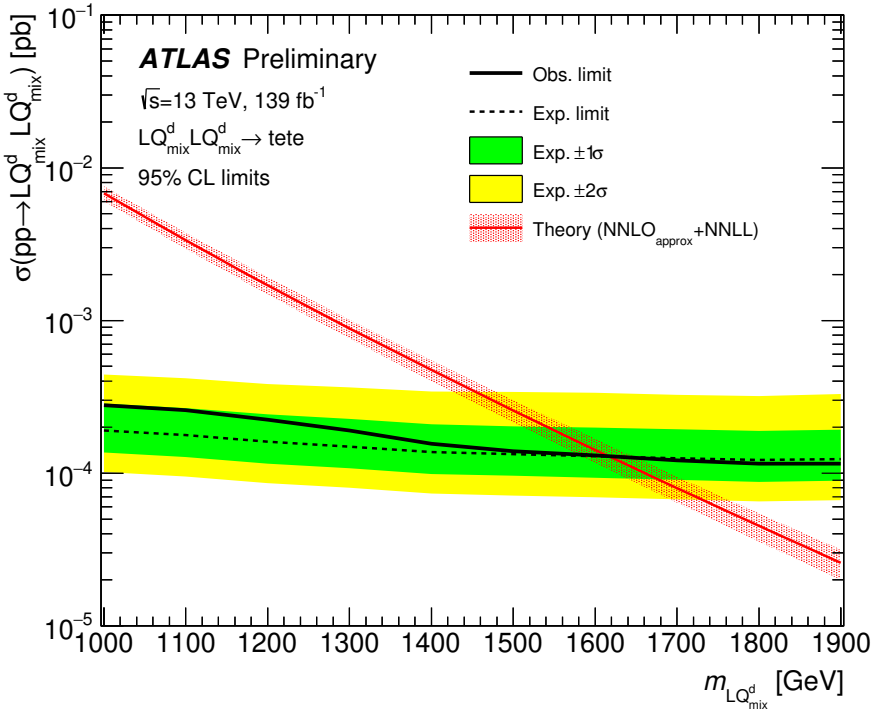




Leptoquarks pair LQLQ$\rightarrow t\ell^{-}\bar{t}\ell^{+}$ ATLAS-CONF-2022-052

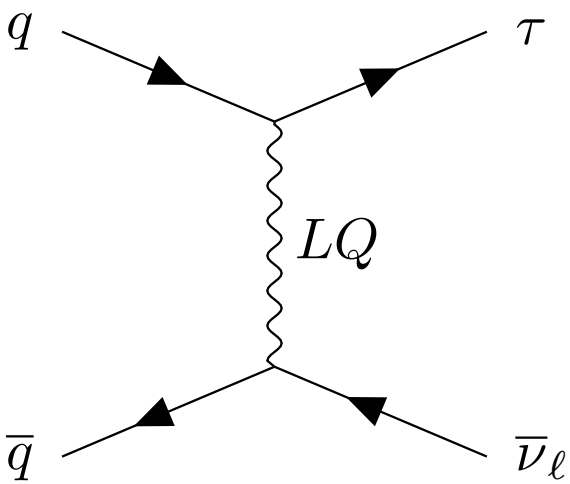
- Consider events w/ $\geq 2\ell$, ≥ 2 jets ($\geq 1b$-jet)
- SR: $= 3\ell$, $= 4\ell$ ($\ell = e$ or μ, also from τ decays)
- Lower limits under assumption of exclusive decays into te ($t\mu$):
  $m(LQ) < 1.61(1.64)$ TeV for scalar mixed-generation scenario
  $m(LQ) < 1.71(1.73)$ TeV for vector in minimal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

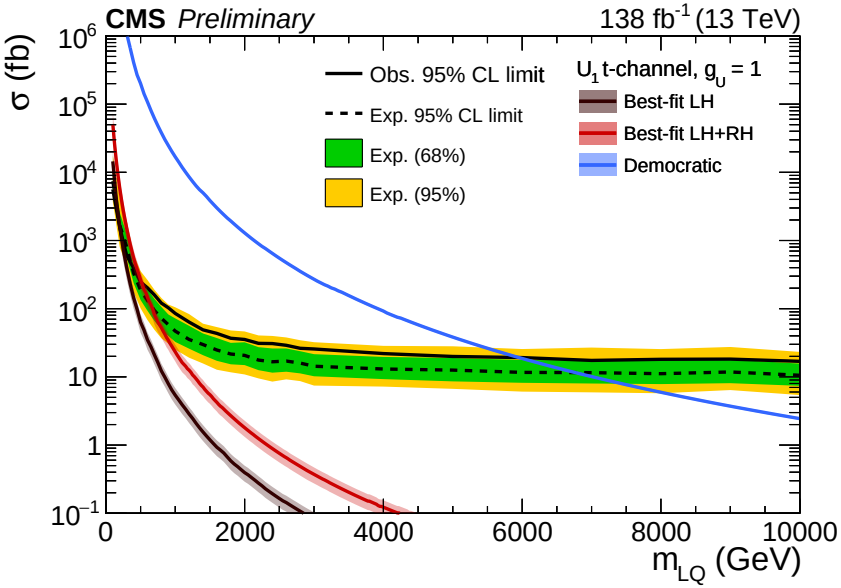




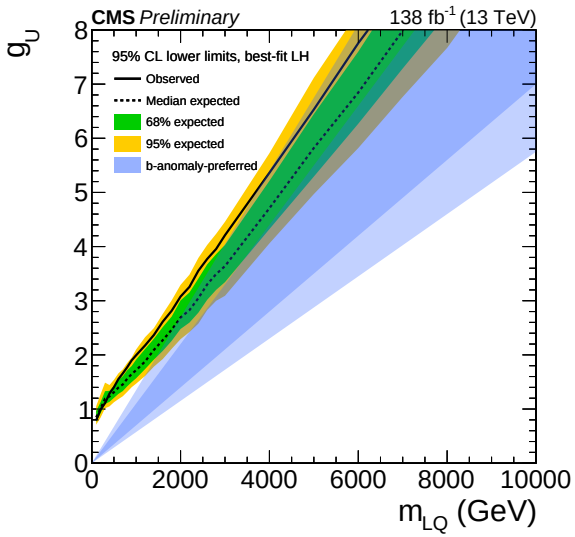
Leptoquark in t-channel CMS-PAS-EXO-21-009

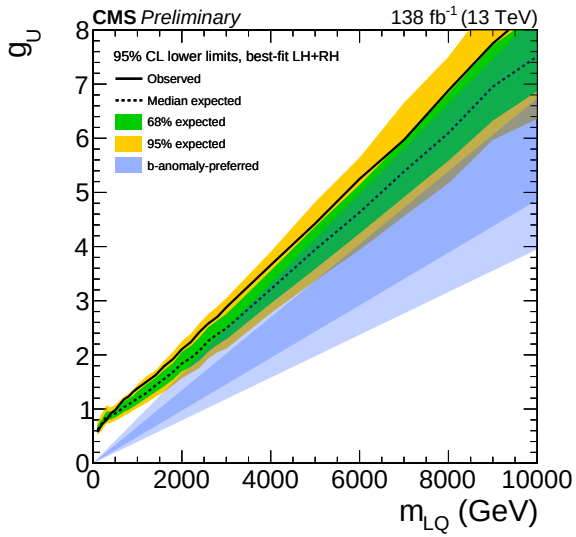
- Final state with a hadronically decaying τ lepton and neutrino

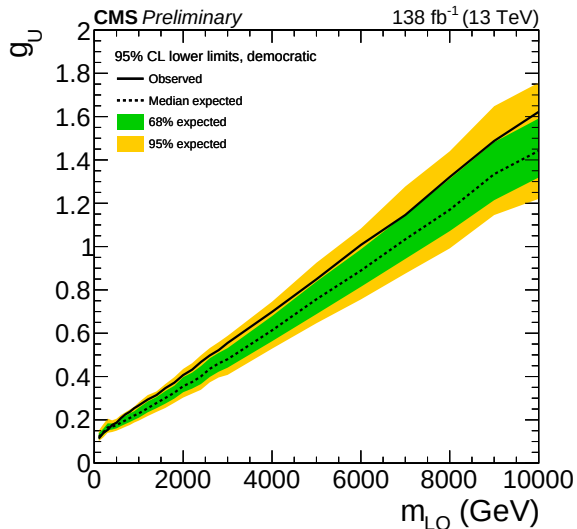




- Upper limits on the cross section of t-channel leptoquark exchange

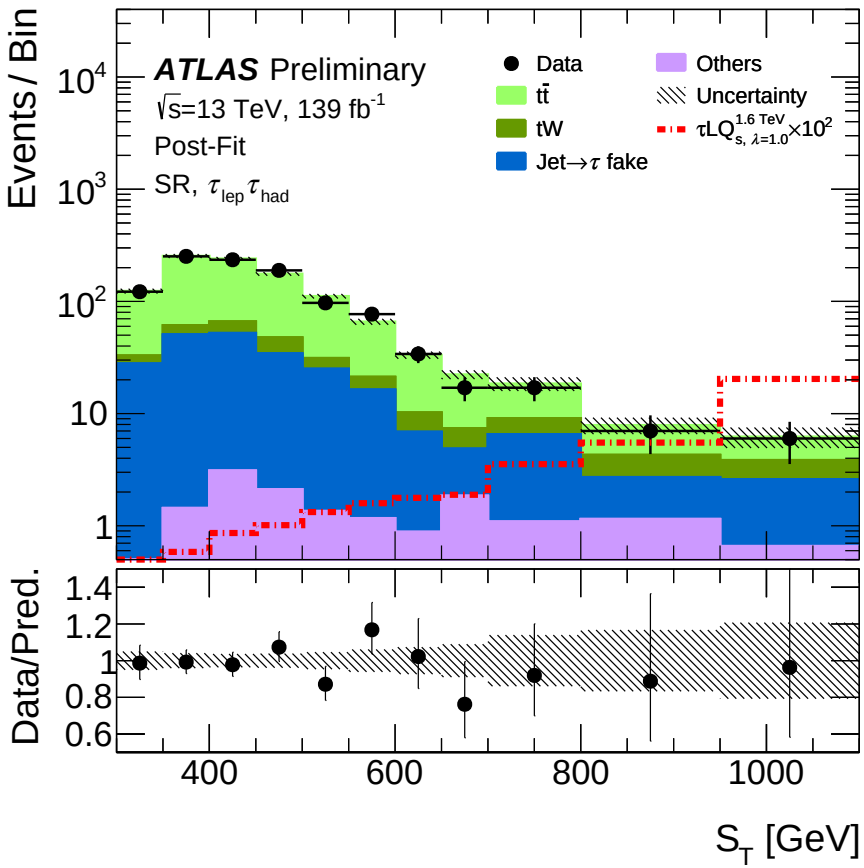


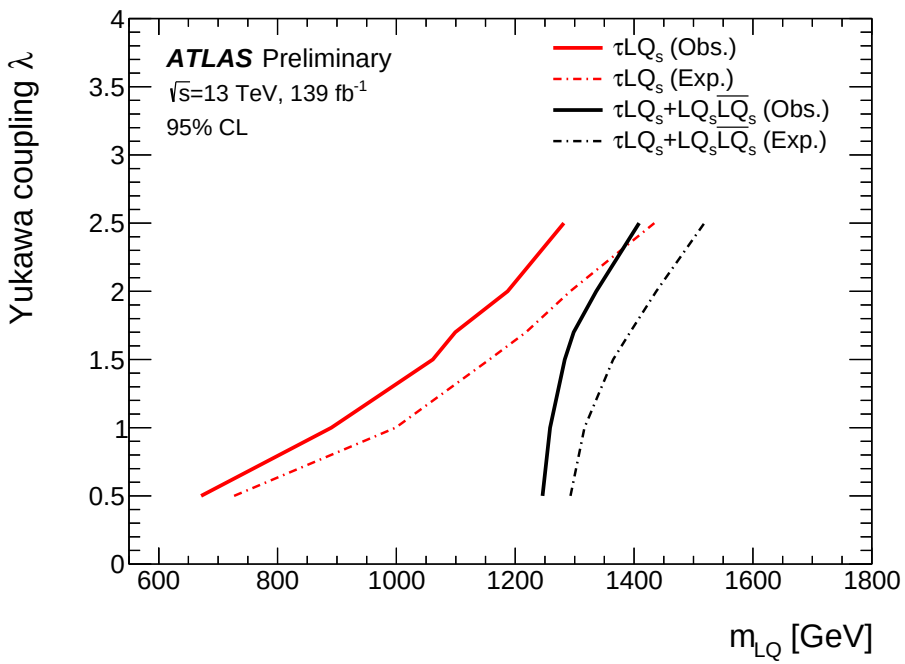




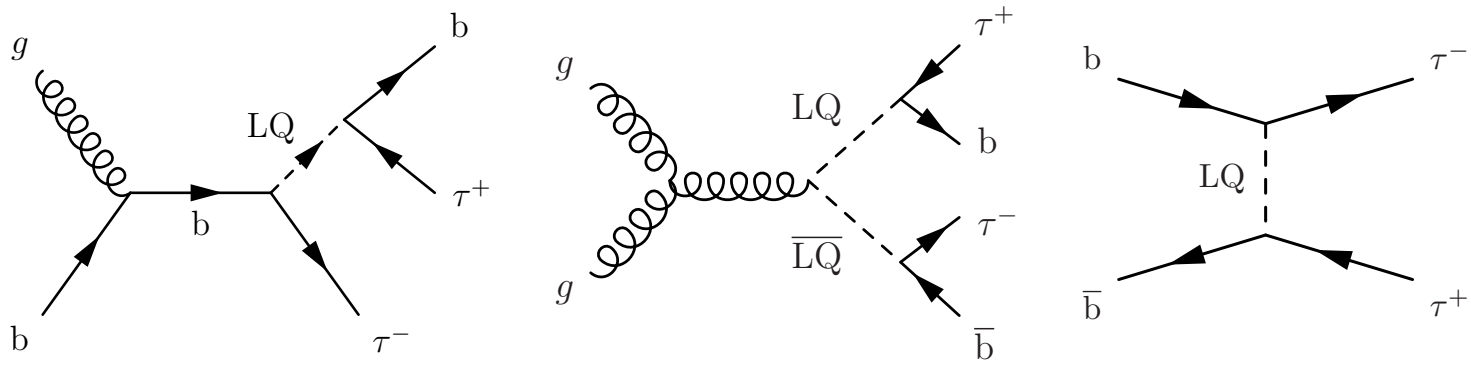
Single Leptoquark in $b\tau\tau$ channel ATLAS-CONF-2022-037

- 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

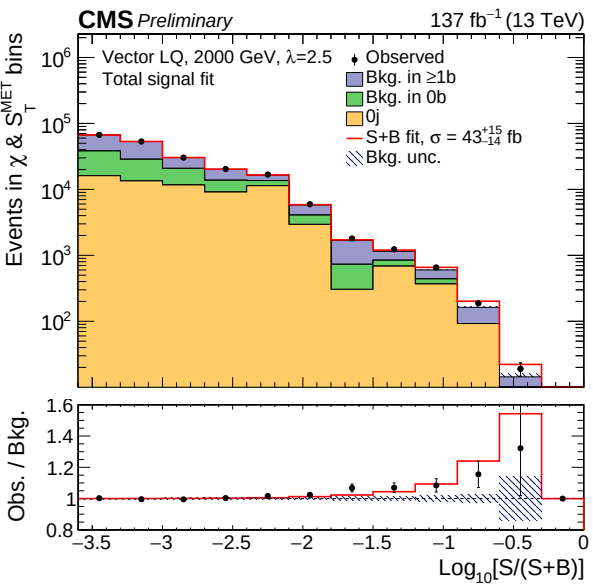


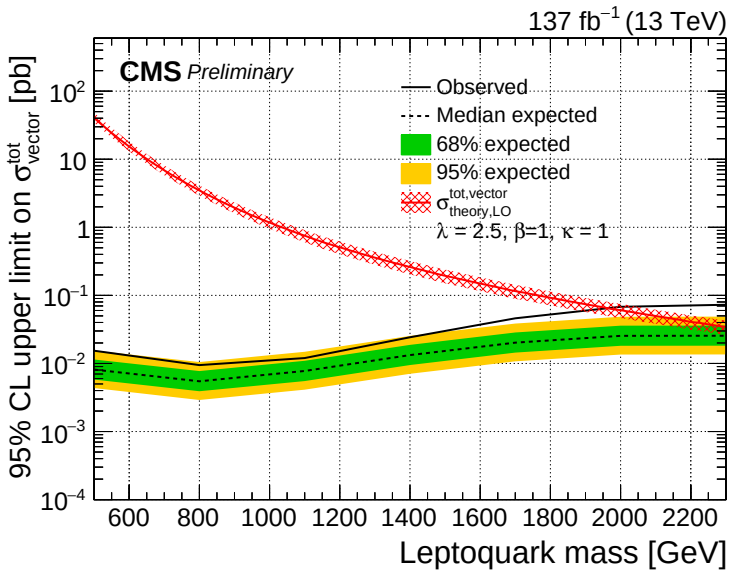


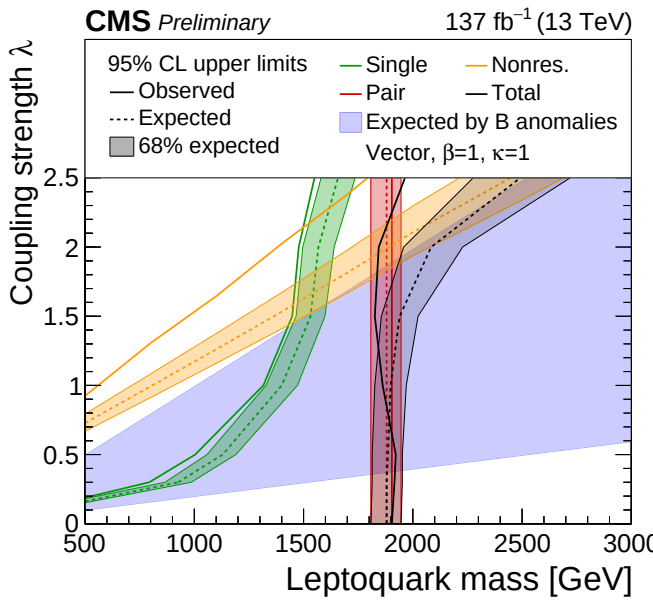
Leptoquark in $b\tau$ in $s-$ and $t-$channels CMS-PAS-EXO-19-016



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

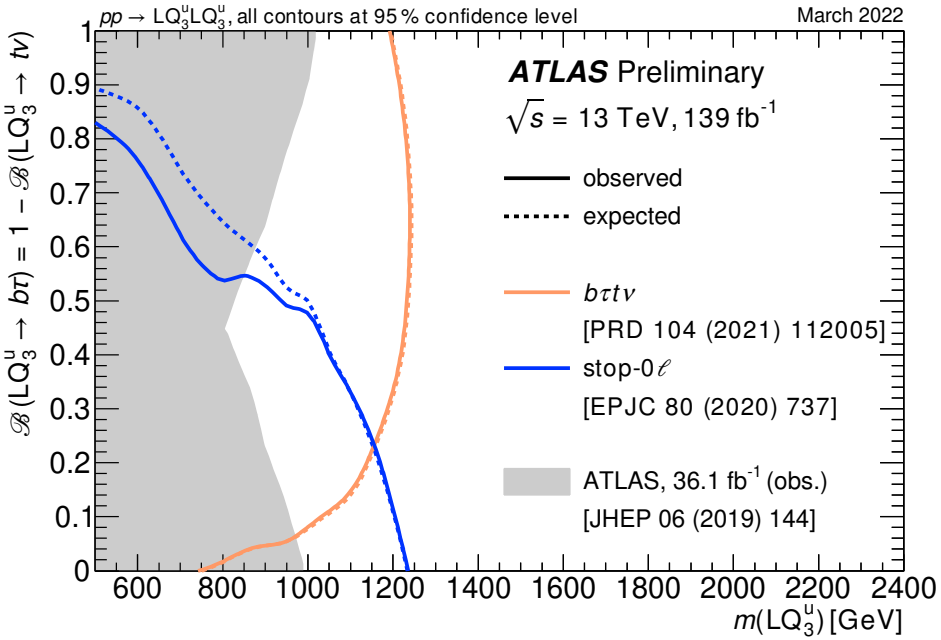


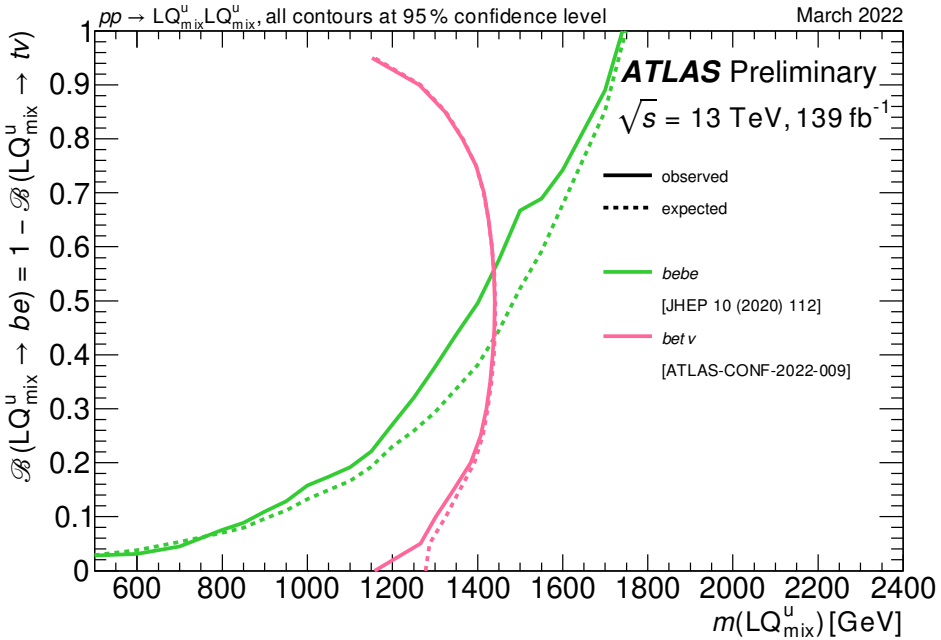


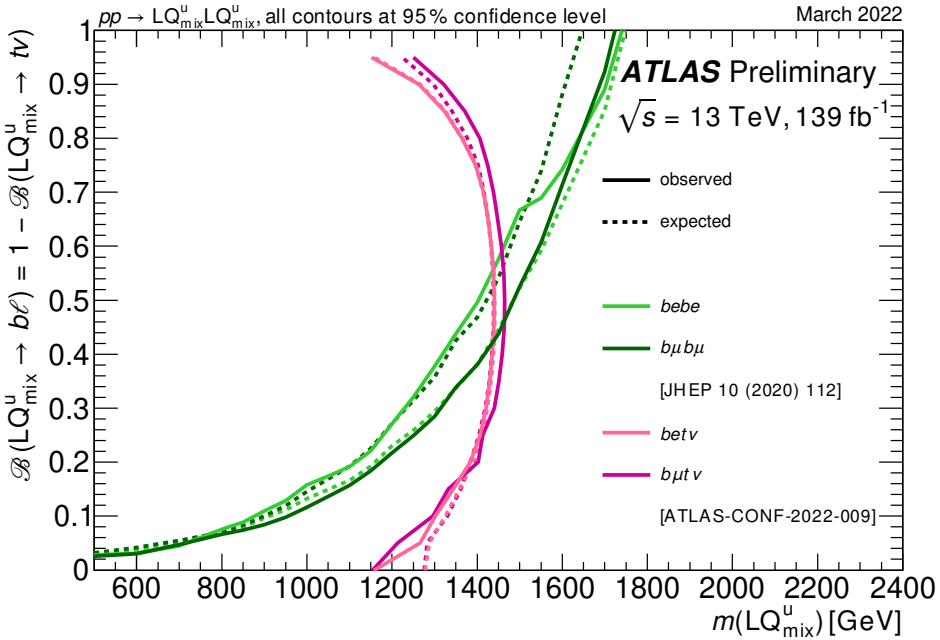


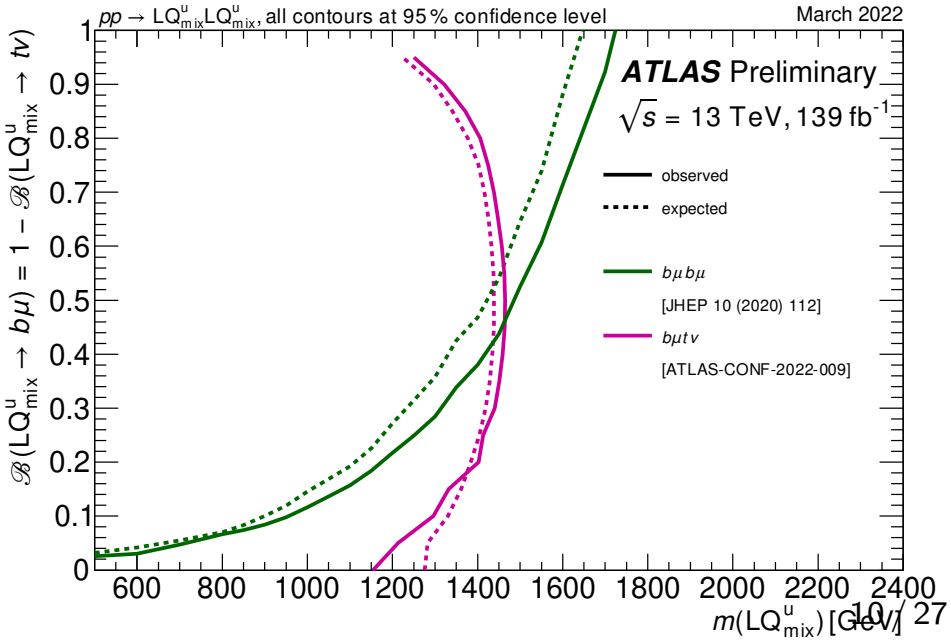
- Significant 3.4σ excess for a LQ mass of 2 TeV and $\lambda = 2.5$

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

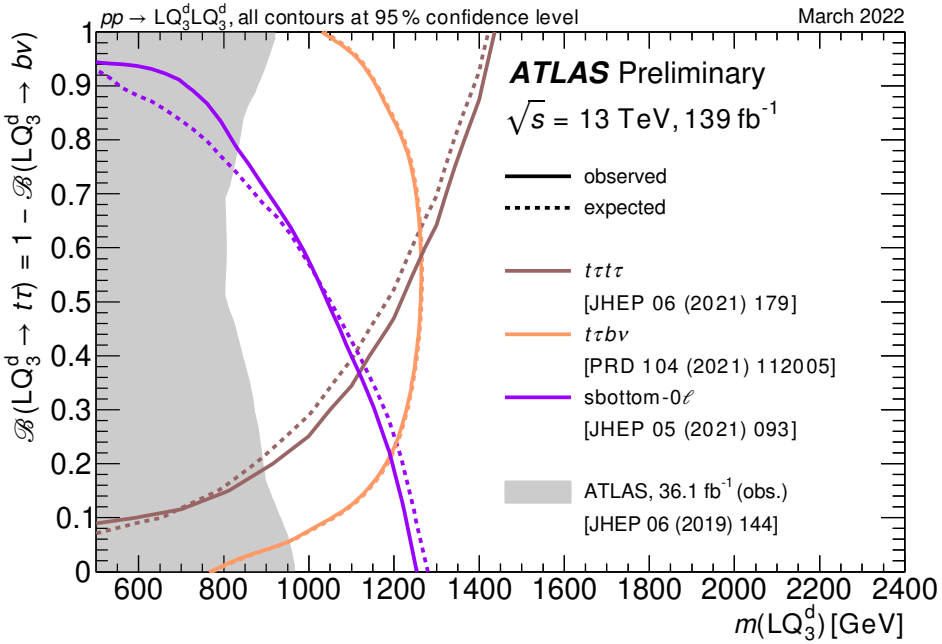


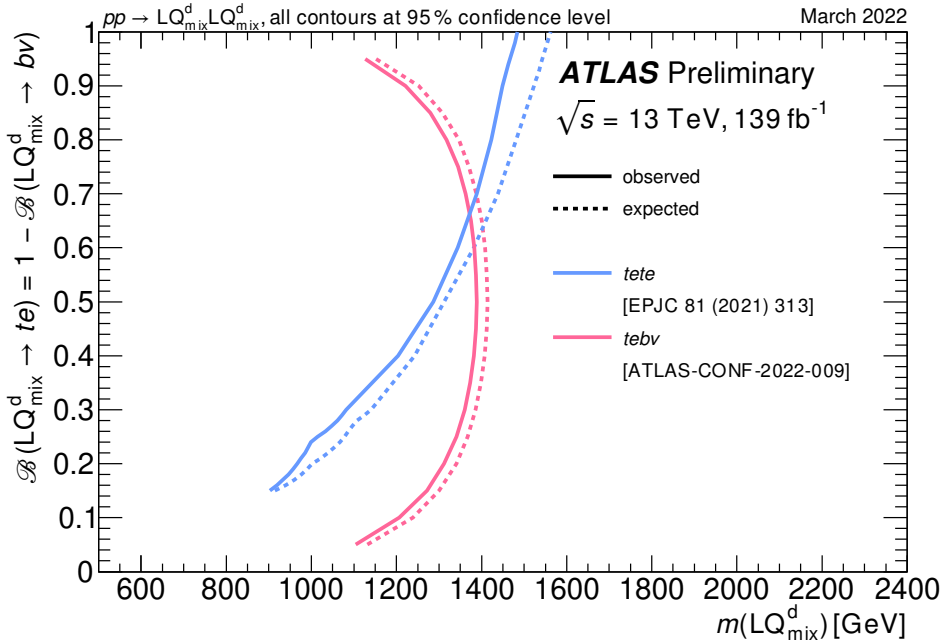


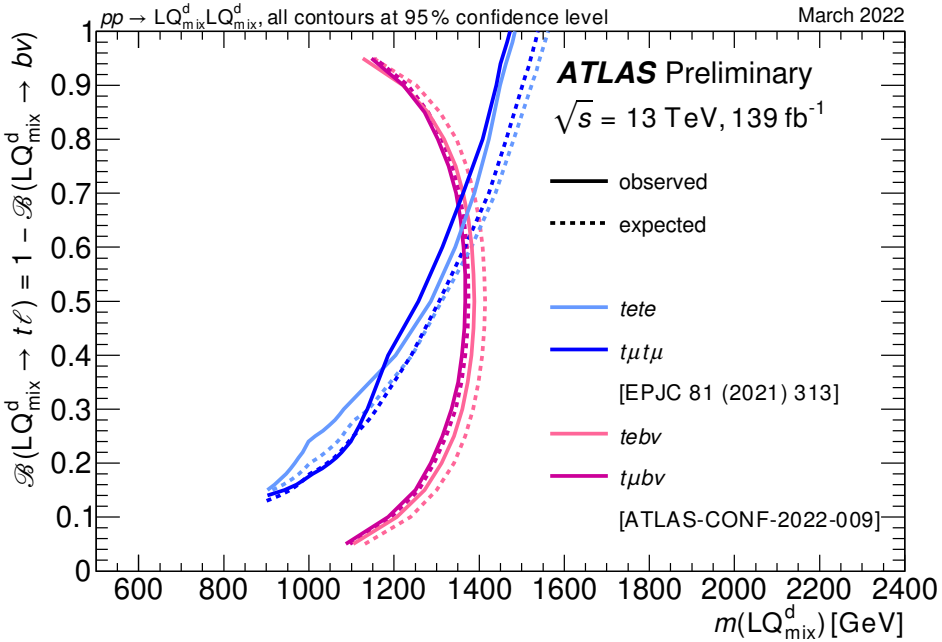


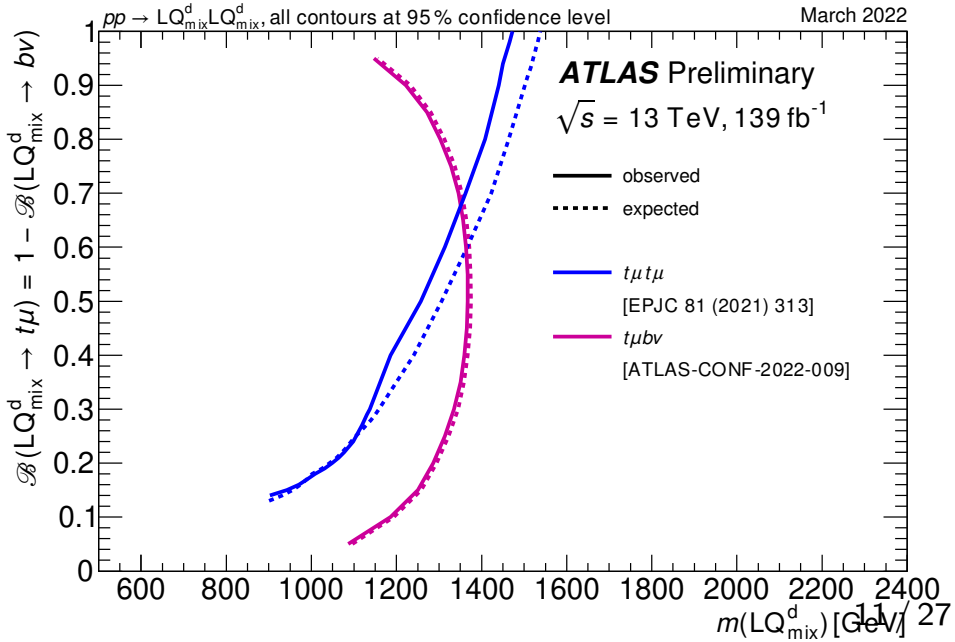


Down-type Scalar Leptoquarks Pair ATL-PHYS-PUB-2022-012



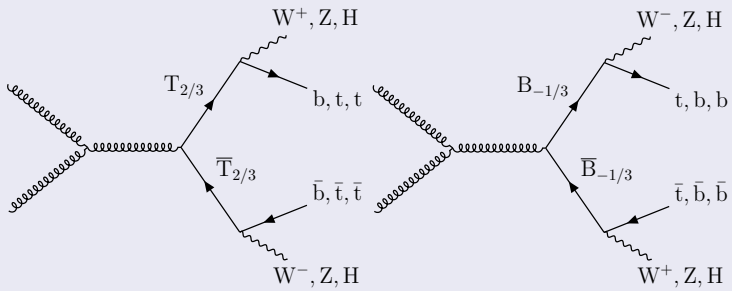






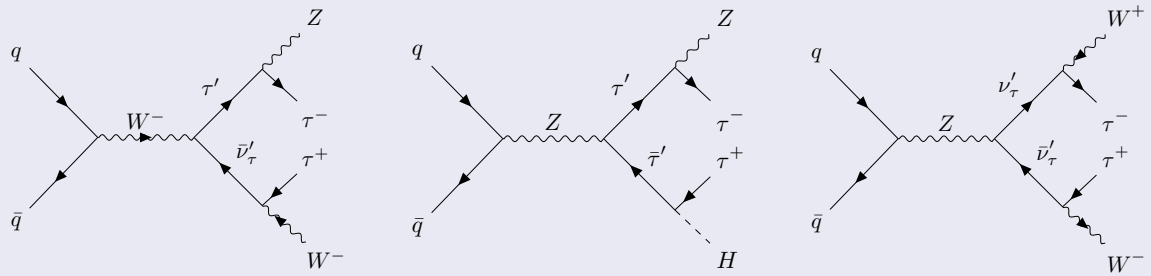
Vector-like particles: quarks (VLQ), leptons (VLL)

- 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 $\mathscr{L}$, independent of Yukawa couplings to H
- Assuming to mix only to 3^{rd} generation quarks

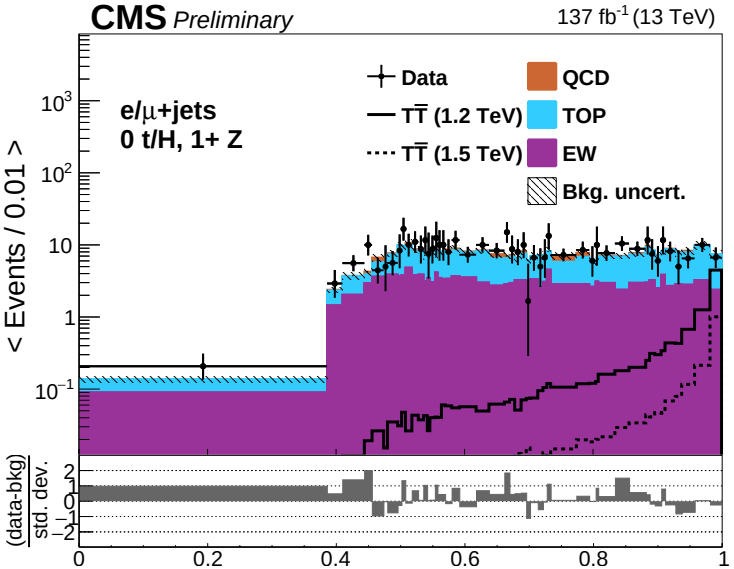


- $T(+2/3e)$, $B(-1/3e)$ in singlet, doublet or triplet w/ further VLQs
- VLQ Decay modes: $T \to tH$, tZ, bW, $B \to bH$, bZ, tW

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

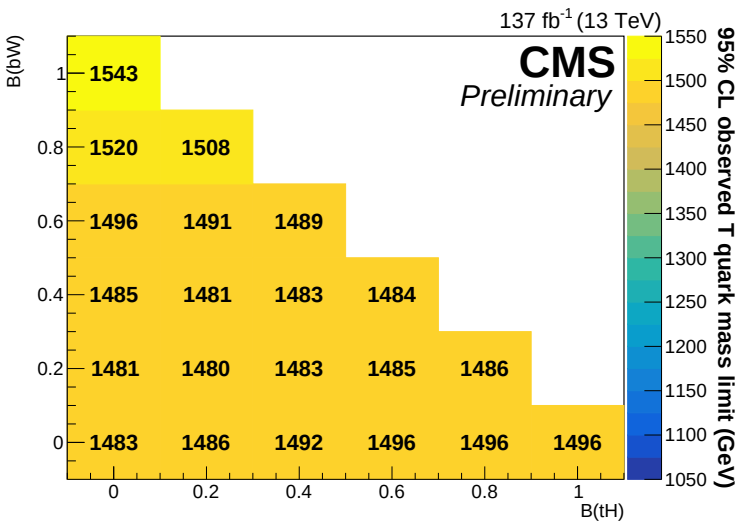


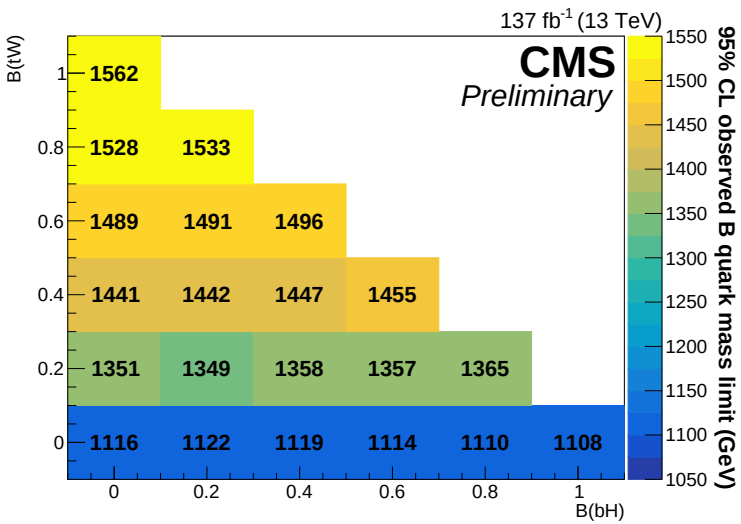
Vector-like quark pairs in leptons CMS-PAS-B2G-20-011



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

- $= 1e$ or μ, $\not{E}_T$, ≥ 3 large-radius jets in single-lepton channel
- $= 2e$ or μ w/ same charge, in the same-sign dilepton channel
- $\geq 3e$ or μ in multilepton channel

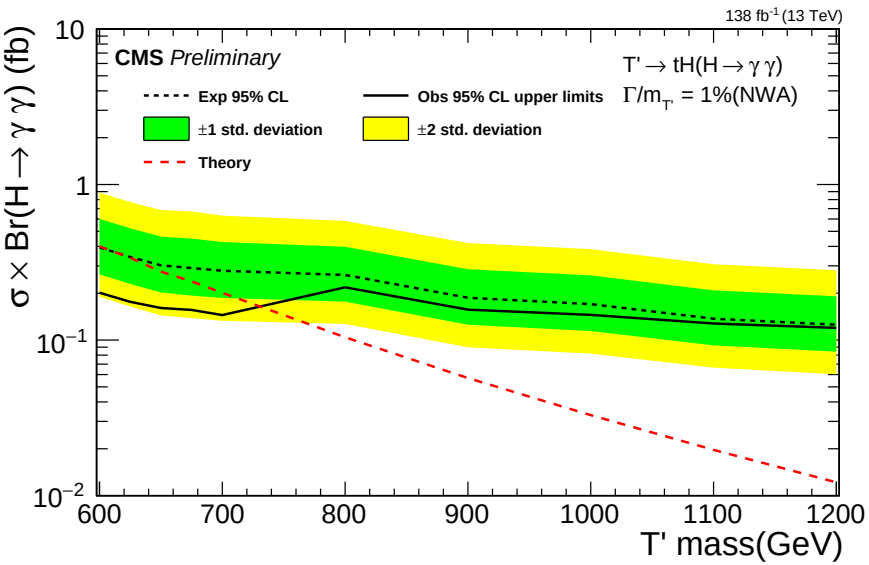


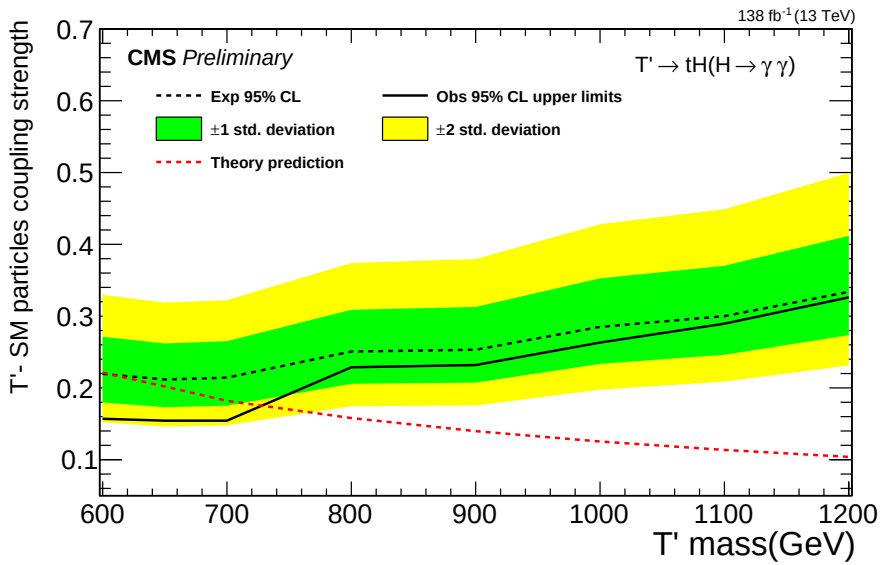


- Exclude pair production for $m(T) < 1.54$ TeV, $m(B) < 1.56$ TeV
- Strongest limits to date for $T \to tH/bW$ and $B \to tW$

Vector-Like Quark $T' \to tH(H \to \gamma\gamma)$ CMS-PAS-B2G-21-007

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

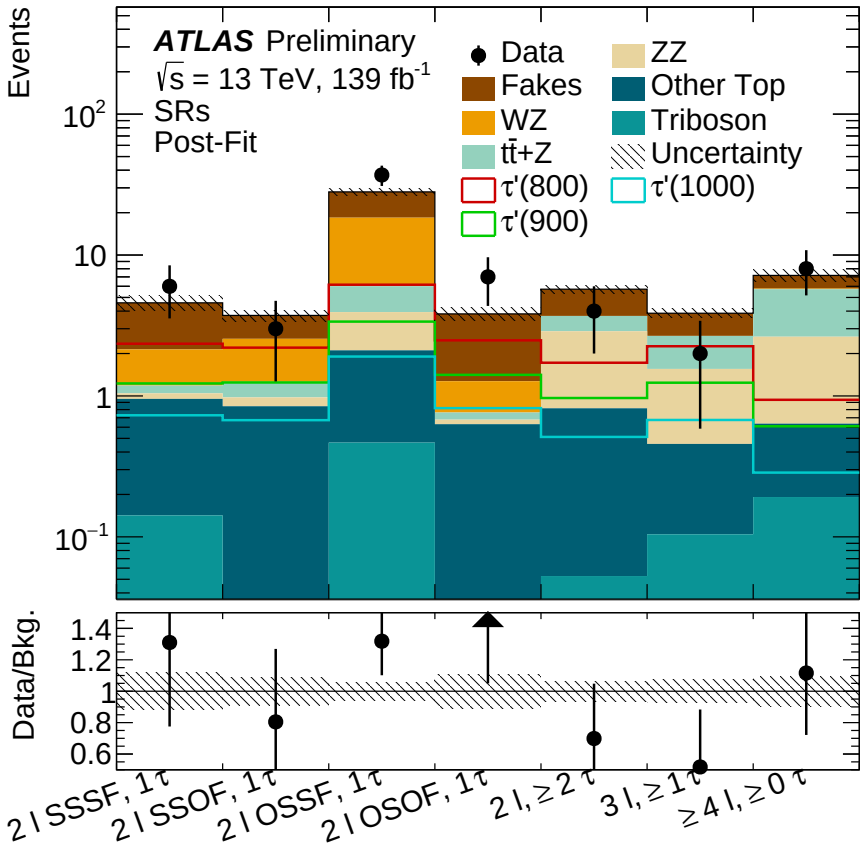


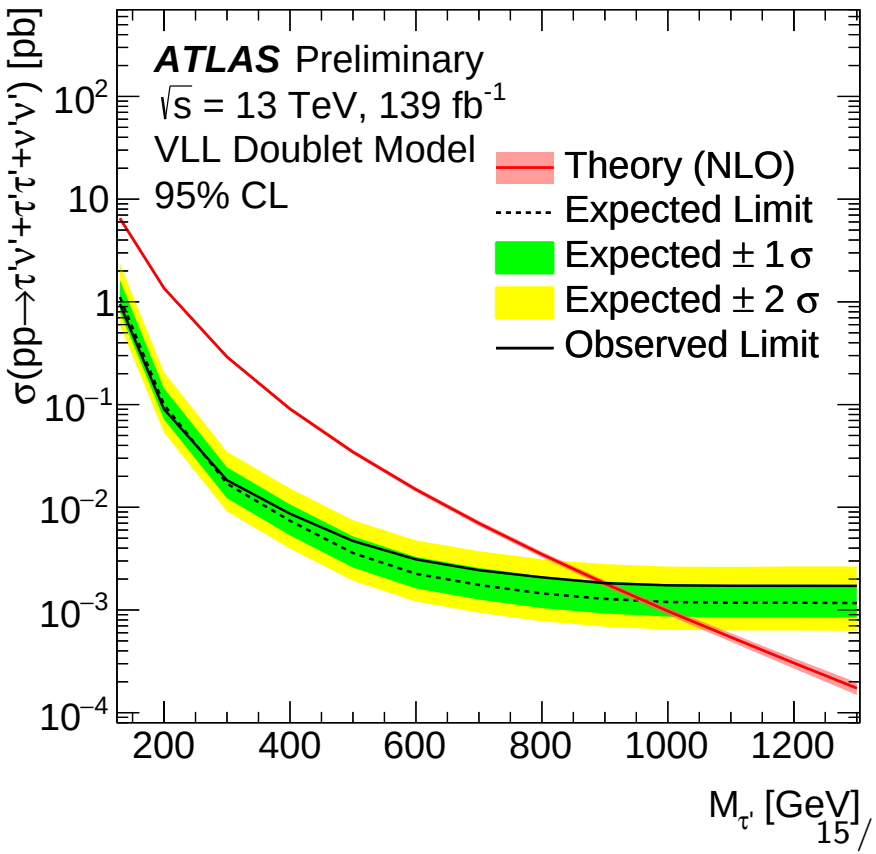


- $m(T') < 730$ GeV excluded
- ATLAS: using mono-top channel, most restrictive limits on single production of a T singlet JHEP05 (2019) 41

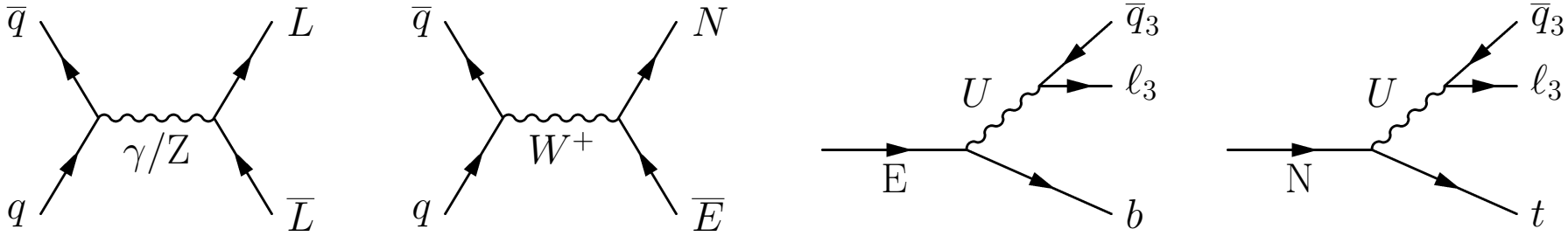
Vectorlike τ ATLAS-CONF-2022-044

- Search of vectorlike leptons coupling to 3^{rd} generation SM leptons in 2, 3, $\geq$ 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)

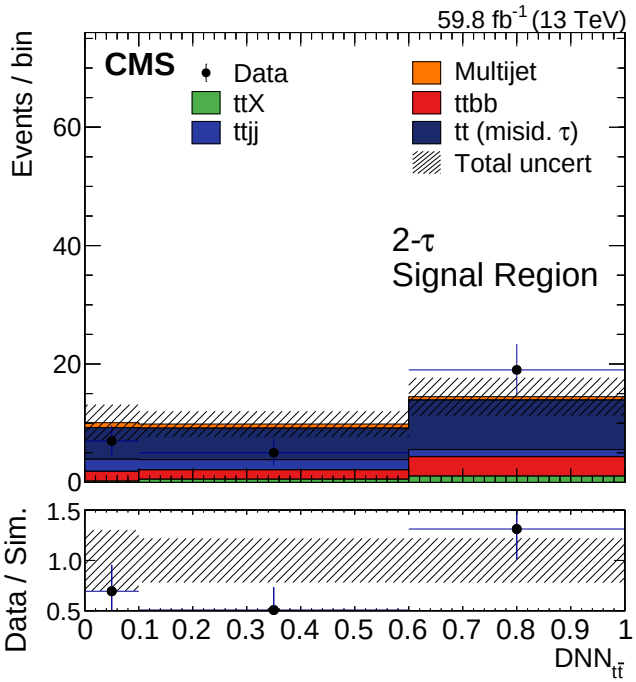




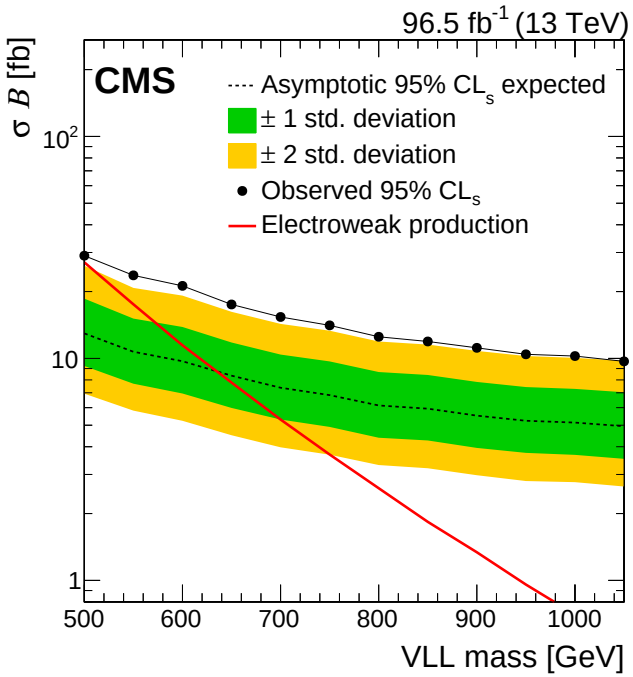
Vector-like lepton pair production CMS-B2G-21-004



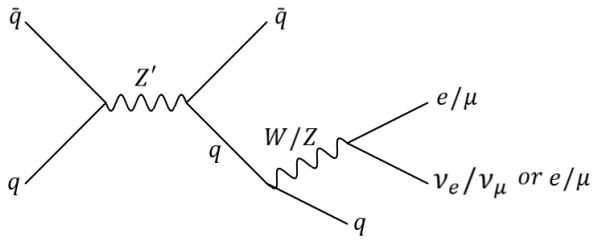
- Aim to explain B-physics SM tension w/ in "4321" model context
- Doublet $E \to b\bar{q}_3\ell_3$, $N \to t\bar{q}_3\ell_3$, decay via U LQ
- Final states with third-gen leptons ($\tau\tau$, $\tau\nu_\tau$, or $\nu_\tau\nu_\tau$), and $\geq 3b$-jets

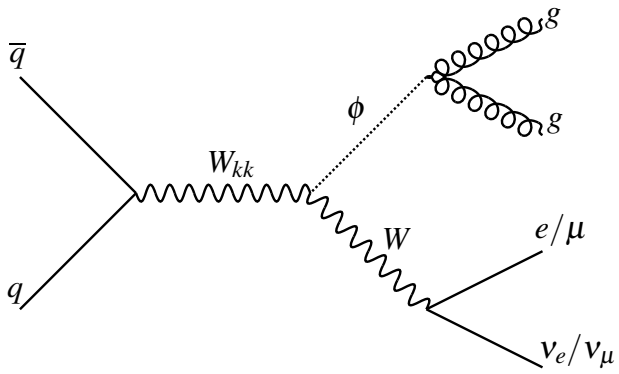


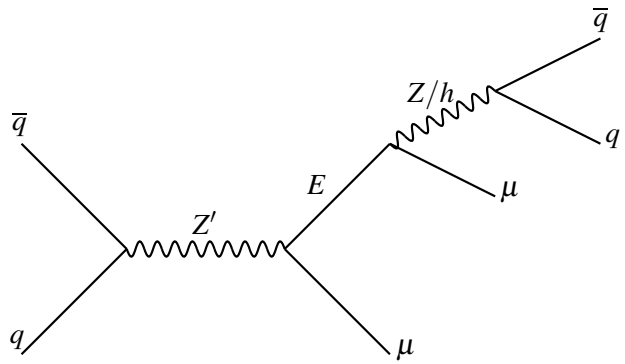
- Slight excess in last bins in 1-, 2-τ_h SR
- 2.8σ deviation for a representative $m(VLL) = 600$ GeV
- Observed limits $\sim 2\times$ expected limits
- Data: 2017 and 2018



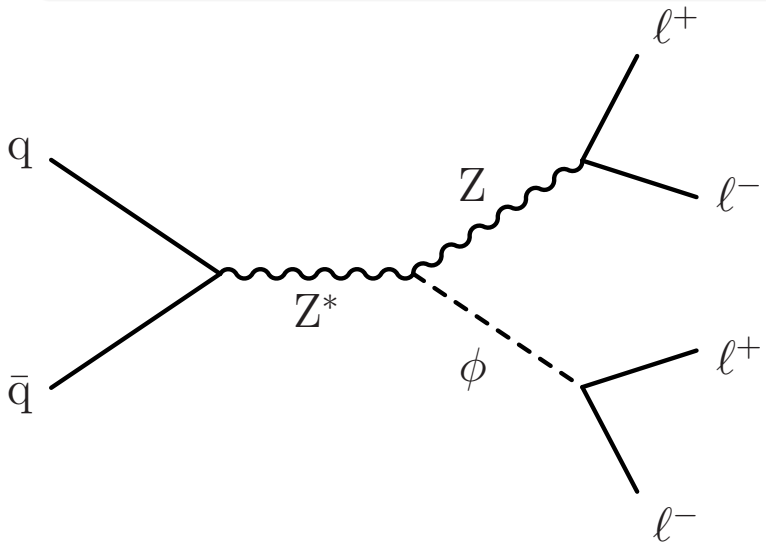
Heavy resonances

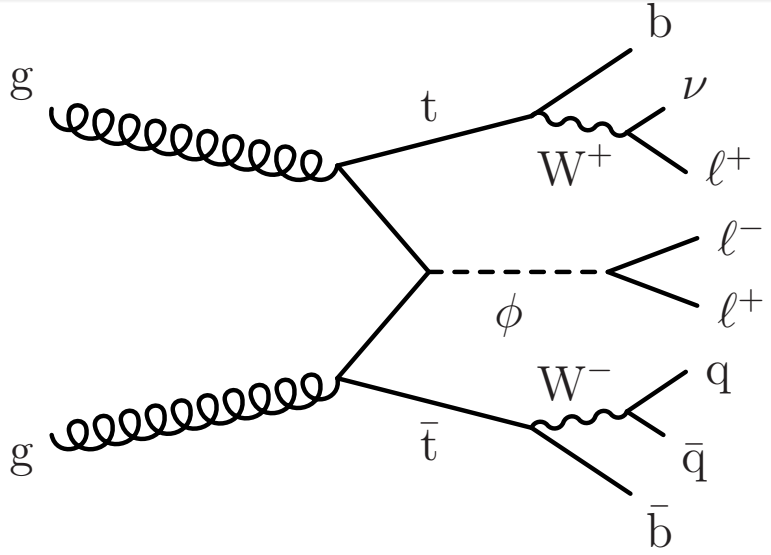




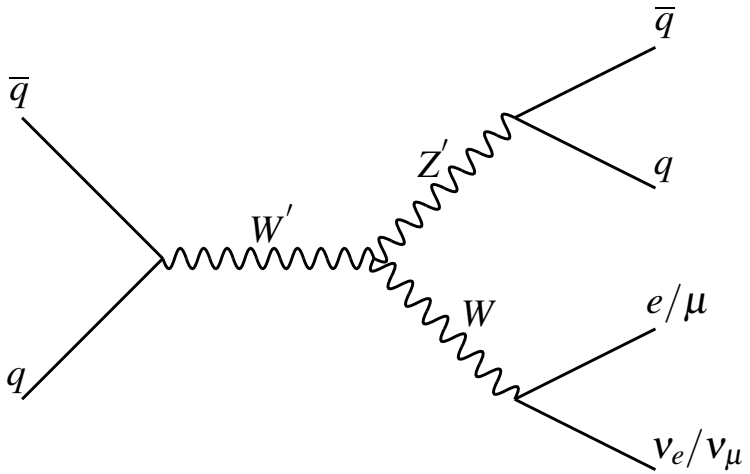


- Several SM extensions predict the existance of heavy particles
- Searches for new gauge bosons (W', Z'), and dilepton resonances
- Multiple final states explored

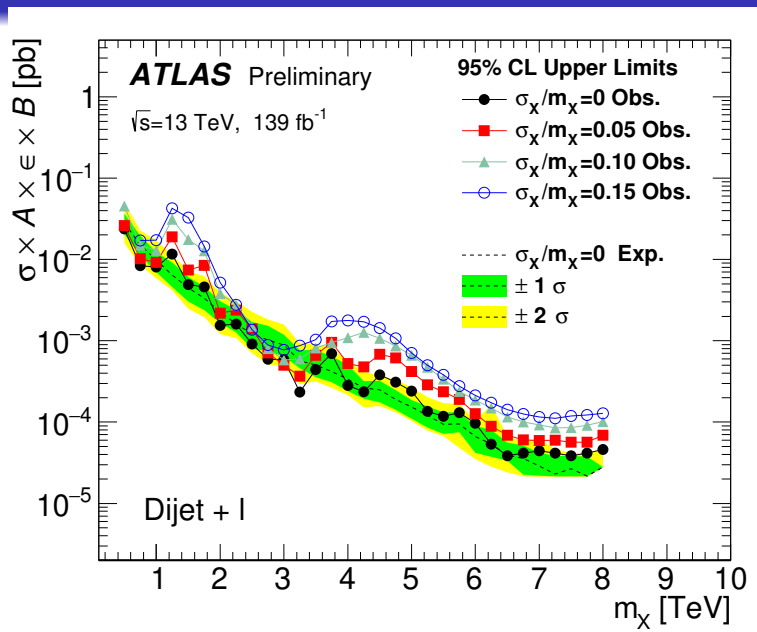


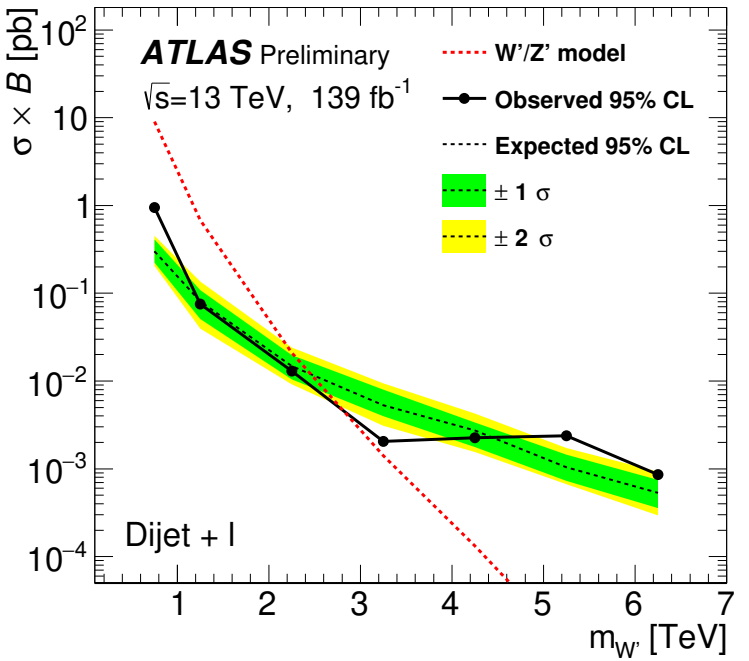


3-/4-body invariant masses ATLAS-CONF-2022-048



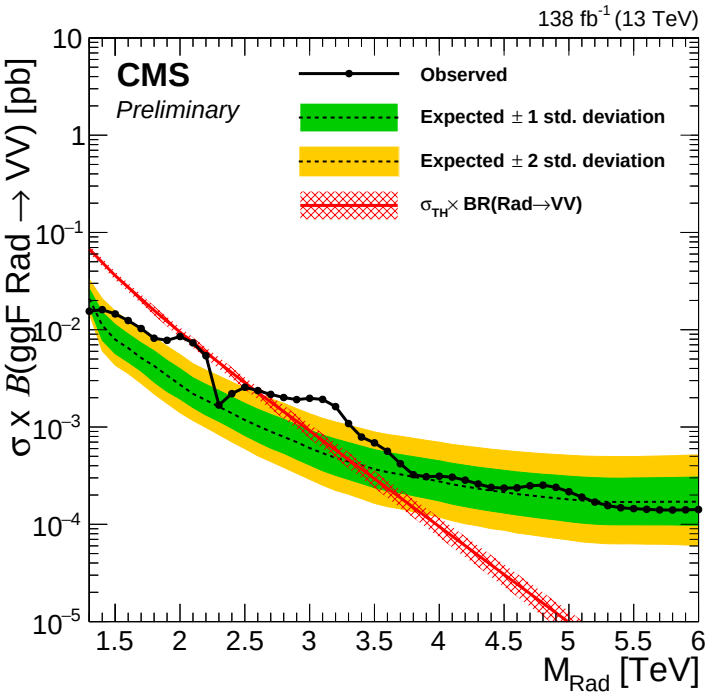
- Use events w/ $\geq 1\ell$ (e or μ) to set model-independent limits
- Consider invariant masses ℓjj, $\ell\ell jj$ (including b-jets)
- Assuming $m(W') - m(Z') = 250\ \mathrm{GeV}$ exclude $W' \to WZ'$ for $m(W') < 2.5\ \mathrm{TeV}$

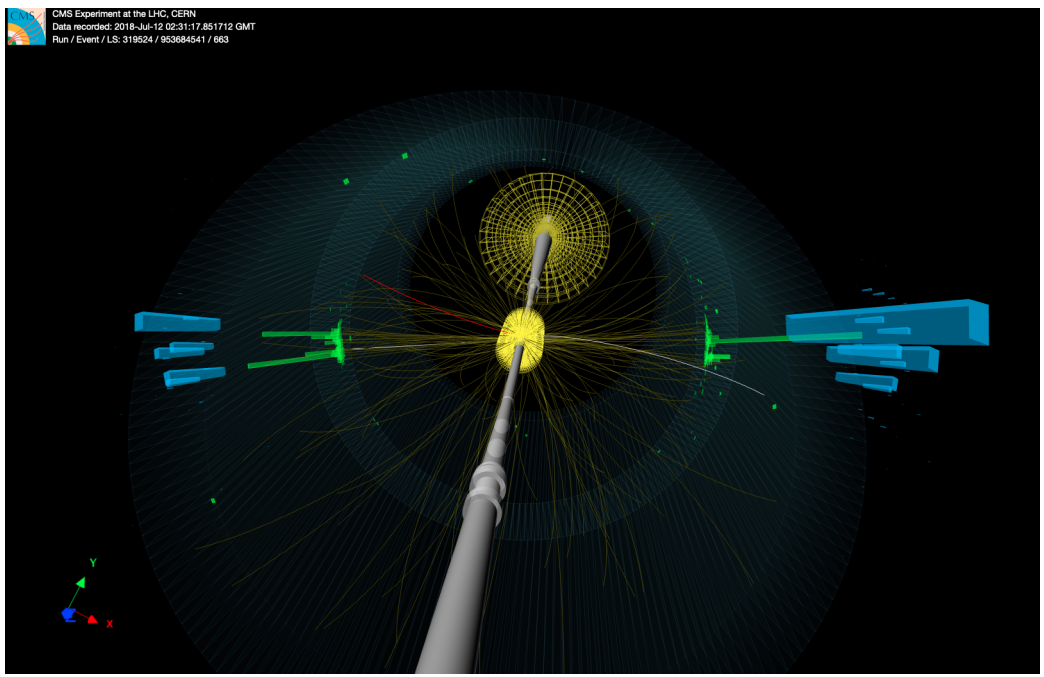




Heavy resonances into VV/VH CMS-PAS-B2G-20-009

- 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

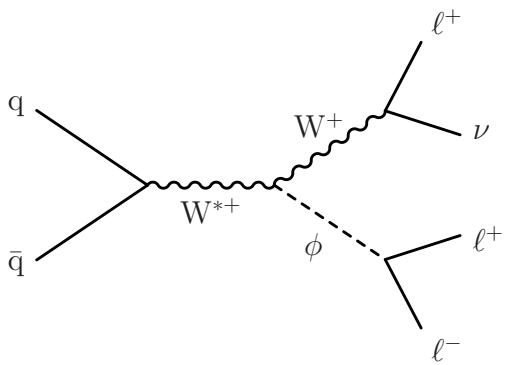


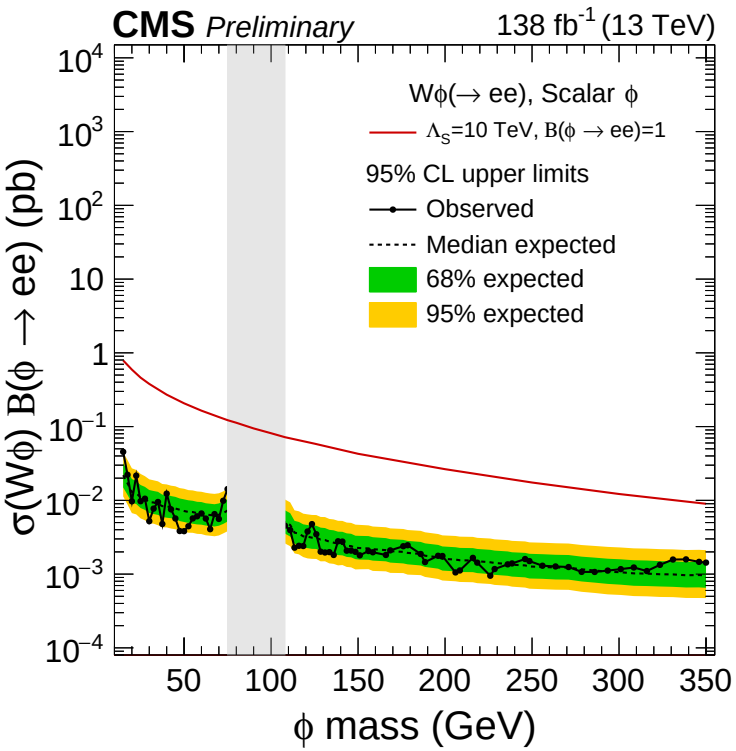


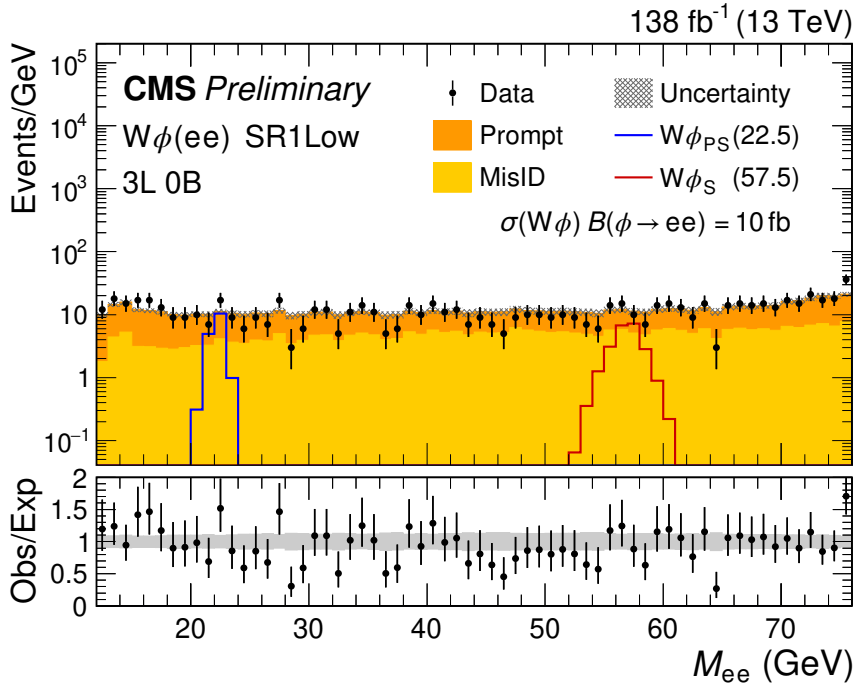
- Mild (2.3σ) excess at $m = 2.1$ and 2.9 TeV
- Excluded: spin-1 Z' and W' for $m < 4.8$ TeV
  spin-2 gravitons (spin-0 radions) w/ $m < 1.4$ TeV (2.7 TeV)

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

- Search for scalar and pseudoscalar bosons into $\ell\ell$ ($\ell = e$, μ, or τ)
- Consider events with 3 or 4 ℓ, include hadronic τ decays



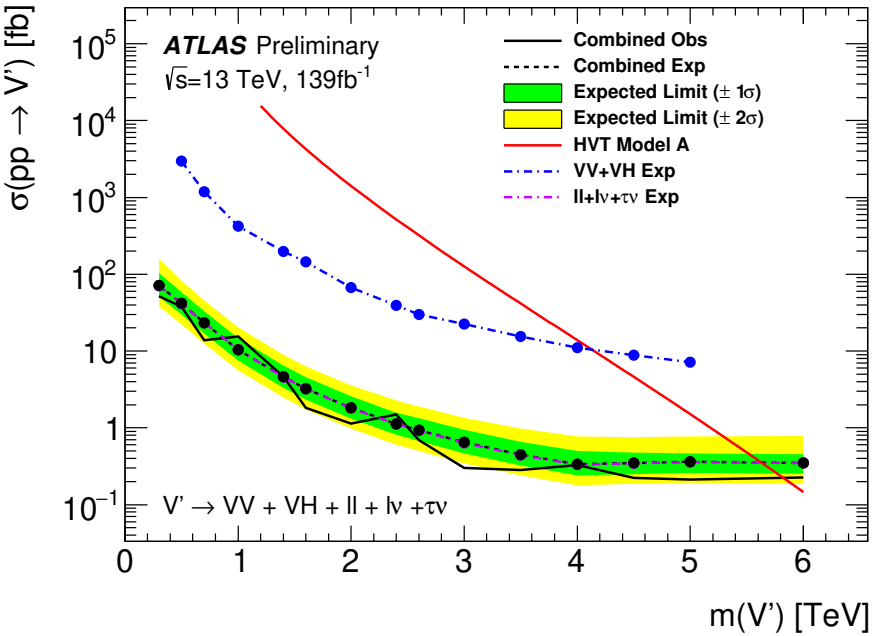


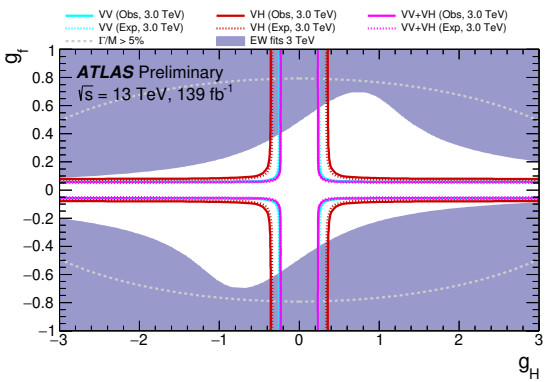


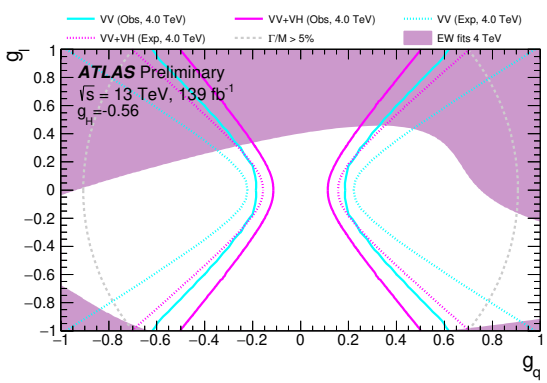
- No statistically significant excess observed over SM expectations
- Most stringent direct limits on production for masses in $15 - 350$ GeV range for such particles and decay modes

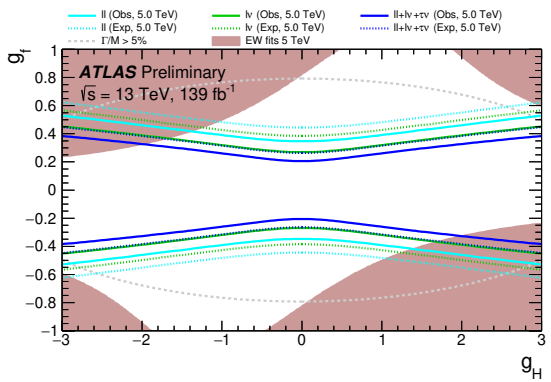
Heavy resonances combination ATLAS-CONF-2022-028

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



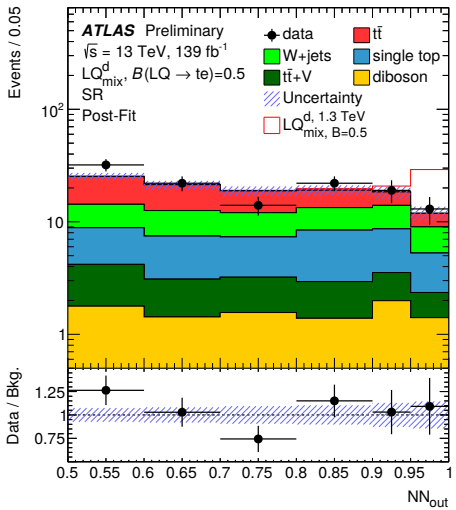


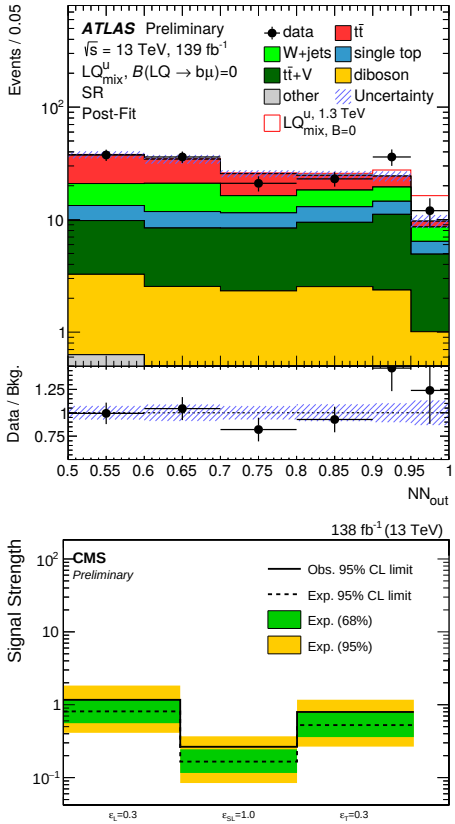


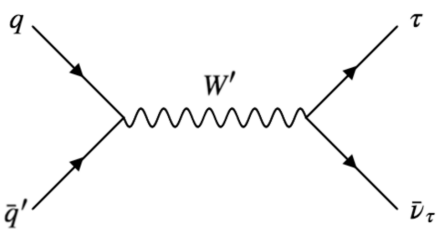


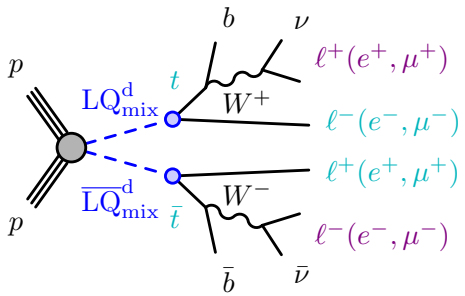
- Exclude heavy vector-boson triplet w/ $m < 5.8\ \mathrm{TeV}$ ($4.5\ \mathrm{TeV}$) in a weakly (strongly) coupled scenario

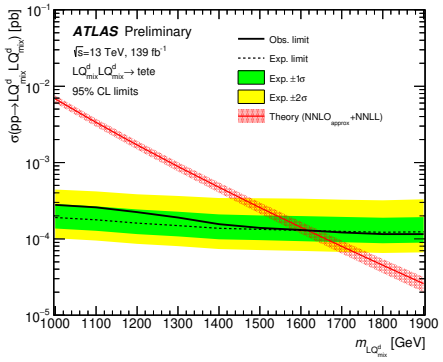
Conclusions

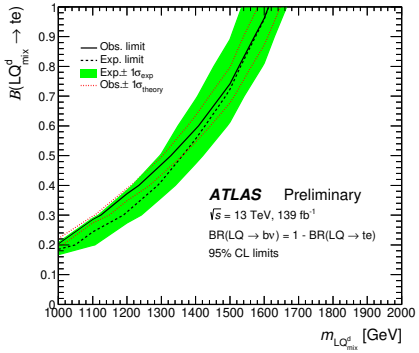


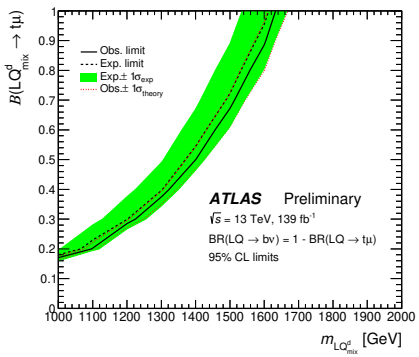












- Only a fraction of the work done covered in this talk
- Run 3 already started and LHC is quickly ramping up
- Several results will gain in sensitivity w/ improved statistic
- Stay tuned for further studies!

Vectorlike particles

ATLAS results summary

- Exclude vector-like τ for $130 < m < 900\ \mathrm{GeV}$

CMS results summary

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

Leptoquarks

ATLAS results exclusion summary

- LQ pair production up to $m(LQ) < 1980\ \mathrm{GeV}$, for couplings to 3^{rd}-gen quark and $1^{st}/2^{nd}$-gen leptons
- LQ pair production up to $m(LQ) < 2.0\ \mathrm{TeV}$ for coupling to $te/t\mu$ in various scenarios
- Single LQ in $b\tau\tau$ channel up to $m(LQ) < 1.41\ \mathrm{TeV}$ 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 $\rightarrow b\tau$ ($m(LQ) \sim 2\ \mathrm{TeV}$, $\lambda = 2.5$) in s/t-channels

Heavy resonances

ATLAS summary

- Exclude $W' \to WZ'$ contributions for $m(W') < 2.5\ \mathrm{TeV}$
- Exclude heavy vector-boson triplet w/
  $m < 5.8\ \mathrm{TeV}$ (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 $15 - 350\ \mathrm{GeV}$ 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 $t\ell^{-}\bar{t}\ell^{+}$ 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 $T' \to tH$ 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