Searches for new resonances in final states comprising leptons using the ATLAS detector

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On behalf of ATLAS Collaboration

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Covered in this talk:

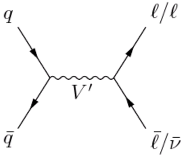
- Searches for TeV scale resonances in final states with at least one charged lepton using LHC Run-II *pp* collisions at $\sqrt{s} = 13$ TeV

Not covered:

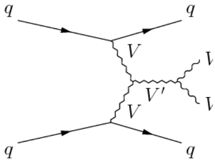
- SUSY-inspired searches
- $X \to \mathrm{invisible}$ recoiling against an SM state (covered in DM talks)
- Non-resonant signatures
- BSM decays of SM particles ($Z \to e\mu$, *etc.*)

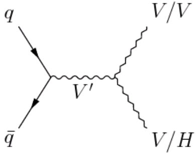
Motivation: new heavy resonances appear in a variety of SM extensions.

Resonance searches are not sensitive to *all* details of the particular model. An amplitude is dominated by a diagram with an $\sim$ on-shell resonance $\Rightarrow$ need to know only its quantum numbers $\Rightarrow$ Set limits in a parameter space of a simplified model $\Rightarrow$ facilitate **reinterpretations**

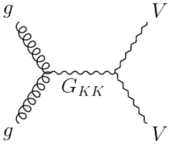


- Spin 0:
  - Extended Higgs sector: 2HDM
  - Warped extra dimensions (Randall–Sundrum model, RS)
  - superpartners of SM fermions





- Spin 1:
  - Extended gauge group $\Rightarrow$ HVT ...
  - DM mediators
  - superpartners of SM fermions
- Spin 2:
  - Randall–Sundrum G_{KK}



- Spin 1/2:
  - Vector-like fermions, Majorana neutrinos, excited fermions (technicolor models), superpartners of SM bosons

Resonant production:

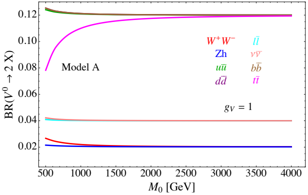
- *gg* fusion (ggF) • *VV* fusion (VBF) • $q\bar{q}$ • associated with 3rd generation fermions

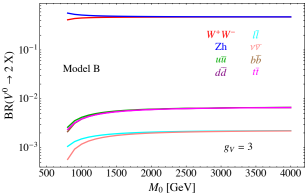
Benchmark models: heavy vector triplet arXiv:1402.4431

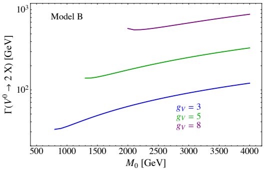
- V^a_μ: $I = 1,\ Y = 0$
  - Physical W, Z have an admixture of $V^{1,2}$, V^0
  - γ remains massless with SM couplings
- HVT realisations: ▸ $V' \to VV/VH, \ell\ell/\ell\nu$
  - (A) Weak coupling: $g_V^2 c_H \ll g^2 c_F$ $\Rightarrow W',\ Z'$
  - (B) Strong coupling: $g_V^2 c_H \gg g^2 c_F$ $\Rightarrow$ composite Higgs
  - Fermiophobic: $c_F = 0$ $\Rightarrow$ only VBF production
  - Parameter phase space beyond the above is also probed.

$$\begin{aligned}\mathcal{L}_{\mathrm{HVT}} = & -\frac{1}{4} D_{[\mu} V^a_{\nu]} D^{[\mu} V^{\nu]\,a} + \frac{m_V^2}{2} V^a_\mu V^{\mu\,a} \\ & + i\, g_V c_H V^a_\mu H^\dagger \tau^a \overleftrightarrow{D}^\mu H + \frac{g^2}{g_V} c_F V^a_\mu J_F^{\mu\,a} \\ & + \frac{g_V}{2} c_{VVV}\, \epsilon_{abc} V^a_\mu V^b_\nu D^{[\mu} V^{\nu]\,c} \\ & + g_V^2 c_{VVHH} V^a_\mu V^{\mu\,a} H^\dagger H \\ & - \frac{g}{2} c_{VVW} \epsilon_{abc} W^{\mu\nu\,a} V^b_\mu V^c_\nu ,\end{aligned}$$

where D_μ are $SU(2)_L$ covariant derivatives and $J_F^{\mu\,a} = \sum_f \bar{f}_L \gamma^\mu \tau^a f_L$ is the fermion current.







Benchmark models: Randall–Sundrum (RS1) warped extra dimensions

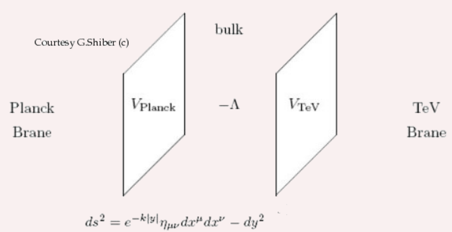
$$ds^2 = e^{-2kr_c\phi}\eta_{\mu\nu}dx^\mu dx^\nu - r_c^2 d\phi^2$$

$$0 \le \phi \le \pi,\ k \sim M_{Pl},\ kr_c \sim 10$$

Take with caution: oscillations with $\sim$ Planck frequency at the Planck brane are red-shifted down to the EW scale while going from Planck to the EW brane

A variant of the RS1 model as a benchmark [*Phys. Rev. D 76, 036006*]:

- Visible and hidden 3-branes at $\phi = 0$ and $\phi = \pi$
- The EW scale $\propto \bar{M}_{Pl} e^{-kr_c\pi} \Rightarrow$ no need for large r_c
- SM fields allowed to propagate in the bulk.
  Fermion localization explains flavours: light fermions are near the Planck brane, while 3rd generation and the Higgs are at the TeV brane.
- Zero mode bulk metric excitation $\Leftrightarrow m = 0$ graviton couples to $T^{\mu\nu} \propto 1/\bar{M}_{Pl}^2$
- Higher bulk metric excitations are $\sim O(\mathrm{TeV})$ and localized near the TeV brane.



- Bulk G_{KK} couples to SM gauge boson's and 3rd generation fermions' $T^{\mu\nu} \propto e^{2kr_c\pi}/\bar{M}_{Pl}^2 \sim 1/\mathrm{TeV}^2$
- G_{KK} couplings to 1,2-generation fermions are suppressed. [$G_{KK} \to VV$]

Final states and observables

- $X \to \ell\ell, \ell\nu, \nu\nu$
- $X \to tb \to \ell X$

  $\to$ light $q\bar{q}, gg$

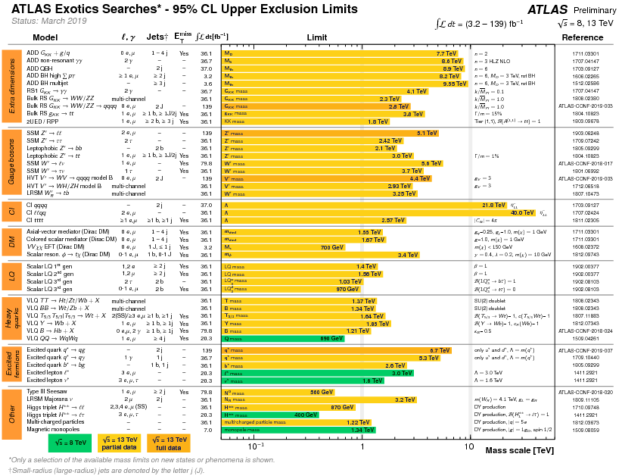
  $\to t\bar{t} \to \ell X$

  (see N.Nishu's talk)

- $X \to VV, VH, HH$

  $\to V\gamma, H\gamma$

  - $V \to \ell\ell'$
  - $H \to bb, \tau\tau, VV^*$



Observables:

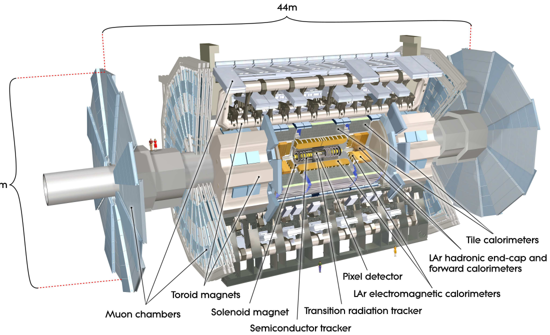
- $m(X)$
- m_T (if ν's)
- ...

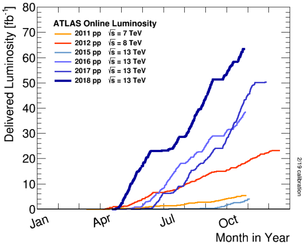
Combination of multiple channels in a context of a benchmark model to increase sensitivity: $\{\ VV,\ VH,\ \ell\ell'\ \} \to \{\ \{VV\ \&\ VH\}\ ,\ \ell\ell\ \} \to \{VV\ \&\ VH\ \&\ \ell\ell'\}$

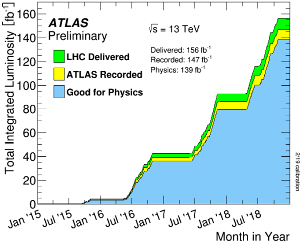
The ATLAS experiment

Reported results are based on $L_{int} = 36 - 139$ /fb

Searches with a partial dataset will be extended to the full LHC Run-II statistics (*stay tuned)*





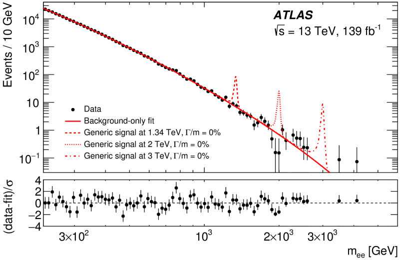


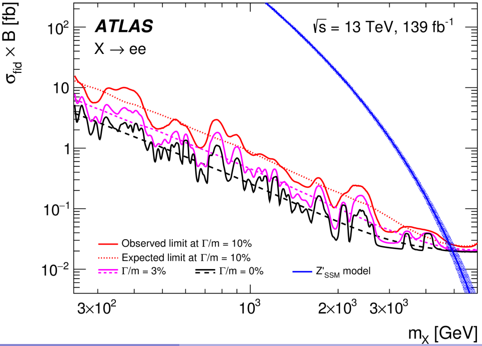
- Phase space coverage:
  - Tracking system: $|\eta| < 2.5$, $p_T > 0.1$ GeV
  - Calorimetry: $|\eta| < 3.2$ (EM), $|\eta| < 4.9$ (HAD), $\sigma_E^{\mathrm{jet}}/E^{\mathrm{jet}} \sim 2\%$ for $|\eta^{\mathrm{jet}}| < 0.8$ and $E_T \sim 1$ TeV
  - Muon system: $|\eta| < 2.7$, $\sigma(p_T^\mu) \sim 2$ GeV for $20 < p_T^\mu < 300$ GeV
- LHC *pp* runs at $\sqrt{s} = 13$ TeV:
  - 2015: $\mathcal{L}_{int} = 3.2$/fb with a fully operational detector
  - 2016: $\mathcal{L}_{int} = +33$/fb
  - 2017-2018: $\mathcal{L}_{int} \rightarrow 139$/fb

Search for high-mass $X \to ee/\mu\mu$

arXiv:1903.06248
CERN-EP-2019-030

- $\sqrt{s} = 13$ TeV, $L_{int} = 139$/fb
- Fitting the $M_{\ell\ell}$ distribution by a smooth background parameterisation and BW⊕(Gauss+CB) function for the signal with the given M_X, Γ_X
- **No significant deviation from the background-only hypothesis**, upper limits on $\sigma \times \mathcal{B}(X \to \ell\ell)$ are set at CL=95%
- The limits apply to X spin$= 0, 1, 2$
- Model-dependent $ee \oplus \mu\mu$ limits: $M_X > 4.5$ and 4.7 TeV for the E_6 $Z'_{\psi,\chi}$ bosons, $M_X > 5$ TeV for Z'_{SSM}





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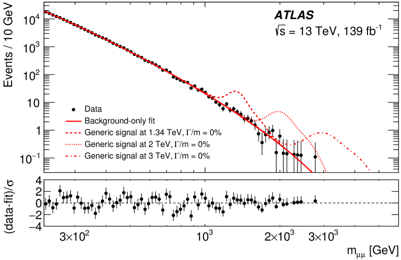
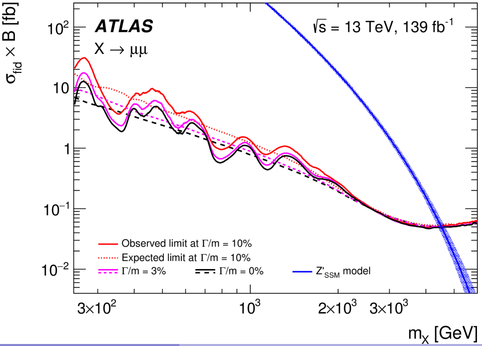




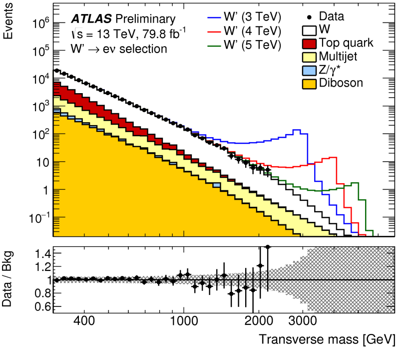
Search for $W' \to e\nu/\mu\nu$

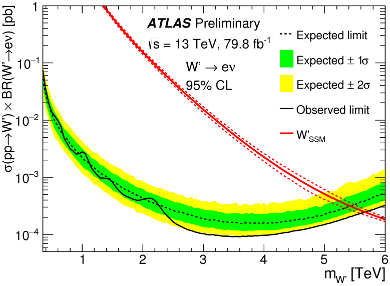
ATLAS-CONF-2018-017

- $\sqrt{s} = 13$ TeV,
  $L_{int} = 79.8/\text{fb}$
  partial LHC Run 2 data, to be extended to the full 2015–2018 dataset,
  $L_{int} = 140/fb$
- The discriminating variable:
  $$M_T(\ell\nu) = \sqrt{2p_T^{\ell}E_T^{\text{miss}}(1-\cos\phi_{\ell\nu})}$$
- **No significant excess above the SM background**, upper limits on $\sigma \times \mathcal{B}(W' \to \ell\nu)$ $\ell = e, \mu$ are set at CL=95%
- Assuming SM couplings for the W': $M_{W'} > 5.6$ TeV at CL=95%

More on lepton non-universality:

$M_{W'} > 3.7$ TeV in $W'(\tau\nu)$





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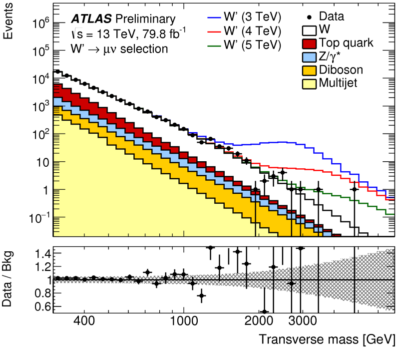
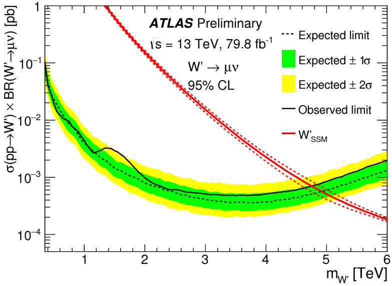
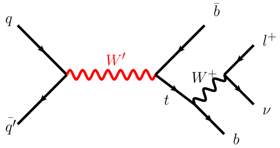




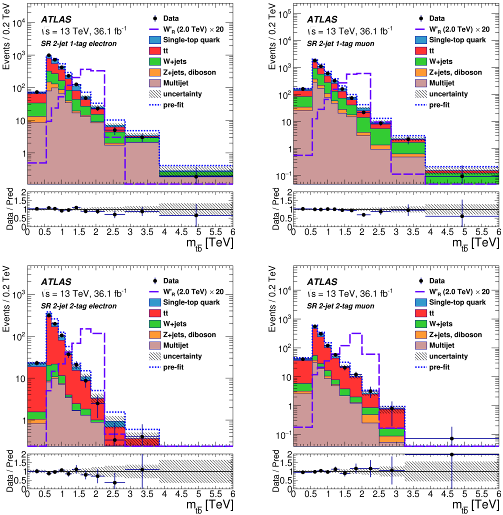
Search for $W' \to tb$ in $\ell^{\pm}$ + jets

Phys. Lett. B 788 (2019) 347



- $\sqrt{s} = 13$ TeV, $L_{int} = 36.1/\text{fb}$
- Motivation: $W' \to t\bar{b} \to W(\ell\nu)b\bar{b}$
- $\Rightarrow \ell^{\pm} + \geq 1b\text{-jet} + \geq 1 \text{ jets} + E_T^{miss}$, $\ell = e, \mu$
  - $\ell^{\pm}$, $\vec{E}_T^{miss}$, m_W mass constraint $\Rightarrow \vec{p}_\nu$
  - $\min|m(W,\text{jet}) - 172.5 \text{ GeV}| \Rightarrow m_{top}^{reco}$
- Signal regions are categorised by numbers of jets, b-tags and $\ell = e, \mu$:

m_{tb} in **2**-jet and 1,2b-tag SR →



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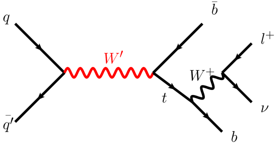
Phys. Lett. B 788 (2019) 347



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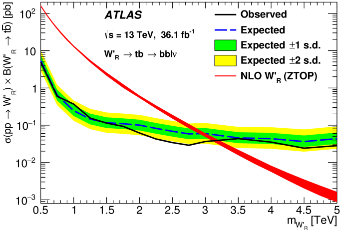
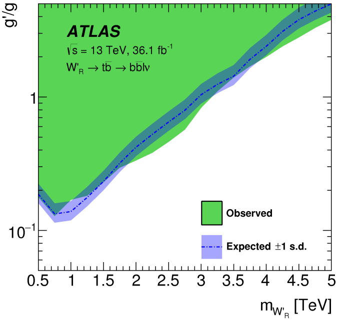
- Motivation: $W' \to t\bar{b} \to W(\ell\nu)b\bar{b}$
- $\Rightarrow \ell^\pm + \geq 1b$-jet $+ \geq 1$ jets $+ E_T^{miss}$, $\ell = e, \mu$
  - $\ell^\pm$, $\vec{E}_T^{miss}$, m_W mass constraint $\Rightarrow \vec{p}_\nu$
  - $\min |m(W, \text{jet}) - 172.5 \text{ GeV}| \Rightarrow m_{top}^{reco}$
- CL=95% limits on $\sigma(pp \to W'_R X) \times B(W'_R \to t\bar{b})$ for $g'/g = 1$ and on g'/g vs $m_{W'_R}$ →
- $g'/g > 0.13$ is excluded for $M_{W'_R} = 1$ TeV
- Combination with the $W'_R \to t\bar{b} \to b\bar{b}q\bar{q}'$ search [Phys. Lett. B 781 (2018) 327] improves the $\sigma \cdot B$ limit by 35% at $M_{W'_R} > 1$ TeV.

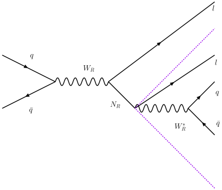
The $M_{W'_R}$ limit in the ZTOP model is improved from 3.15 to 3.25 TeV.

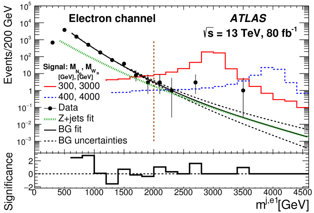


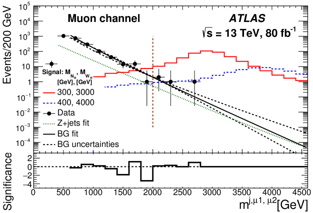


Search for W_R and a heavy neutrino

arXiv:1904.12679



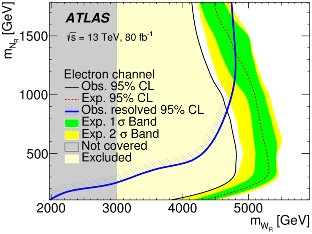


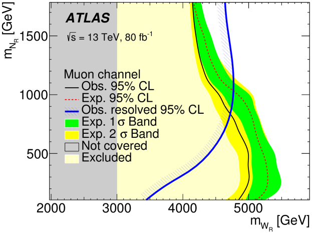


- $\sqrt{s} = 13$ TeV, $L_{int} = 80/\text{fb}$
- Left-Right Symmetric Model:
  - Restores P-symmetry at a high scale
  - SM-singlet heavy neutrinos N_R
  - Heavy gauge boson W_R coupled to right-handed fermion currents
- $m_{N_R}/m_{W_R} \lesssim 0.1$: $W_R \to N_R \ell^{\pm}$ ($\ell = e, \mu$),

  boosted $N_R \to \ell^{\pm} +$ large-R jet
  - Complementary to previous searches with $m_{N_R} > m_{W_R}$
  - Fully reconstructed N_R
- $m_{W_R} > 3.8 - 5$ TeV for $m_{N_R} = 0.1$–1.8 TeV at CL=95%

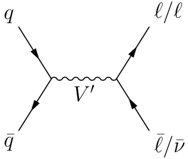
- ↑ Signal regions: $m_{W_R,reco} > 2$ TeV, same ℓ flavour
- Control regions: $m_{W_R,reco} < 2$ TeV, same ℓ flavour.
- Validation region: all $m_{W_R,reco}$, mixed flavour, leading μ

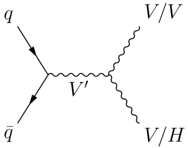


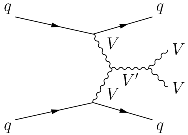


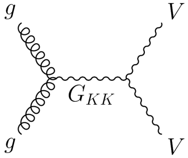
Combination of $X \to VV/VH$, $\ell\nu/\ell\ell$ searches   *Phys. Rev. D 98 (2018) 052008*

- $\sqrt{s} = 13$ TeV, $L_{int} = 36/\text{fb}$
- Benchmark models:
  - HVT: ◂ see the HVT introduction
    (A) Weakly coupled scenario:
    $g_H \equiv g_V c_H^{1/2} = -0.56$, $g_f = g_q = g_\ell = 0.55$
    (B) Strong $V'VH/V'HH$ coupling: $g_H = -2.9$, $g_f = 0.14$
    (C) Fermiophobic V': $g_f = 0$, $g_H = 1$
    $\Rightarrow$ VBF V' production only
  - Bulk RS1 with the heavy spin-2 $G_{KK} \to VV$ ◂ see the RS introduction
    - ★ Gravity and SM fields propagate in the bulk
    - ★ G_{KK} coupling to SM $T^{\mu\nu} \propto k/\bar{M}_{Pl}$, where k is the curvature of the extra dimension
    - ★ G_{KK} couplings to light fermions are suppressed, gg, WW/ZZ and $t\bar{t}$ preferred
  - Empirical: heavy scalar singlet $\to VV$
- Combination of channels:
  $WZ \to \ell\nu qq, \ell\nu\ell\ell, qqqq$, $WW \to \ell\nu\ell\nu, \ell\nu qq$, $qqqq$, $ZZ \to \ell\ell qq, \ell\ell\nu\nu, \ell\ell\ell\ell, qqqq, \nu\nu qq$
  $WH \to \ell\nu bb, qqbb$, $ZH \to \ell\ell bb, qqbb, \nu\nu bb$
  $V' \to \ell\nu, \ell\ell$
- The limits: ▸ backup
  - HVT: $m_{V'} > 5.5$ TeV (weakly coupled) and > 4.5 TeV (strongly coupled) at CL=95%
  - Bulk RS1 with $k/\bar{M}_{Pl} = 1$: $m_{G_{KK}} > 2.3$ TeV at CL=95% ▸ backup
  - Heavy scalar: cross section limits for $gg \to S$ and $VV \to S$ ▸ backup
  - Limits on V' couplings to fermions and gauge bosons, ▸ backup
    better than the limits from EW fits





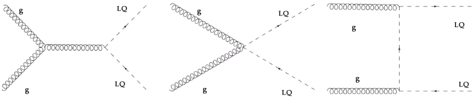


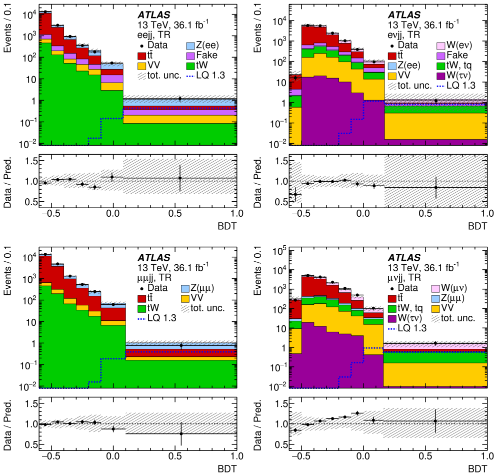


Pair production of 1st and 2nd generation scalar leptoquarks

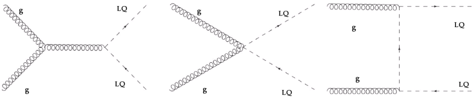
arXiv:1902.00377
CERN-EP-2018-262

- $\sqrt{s} = 13$ TeV, $L_{int} = 36/\text{fb}$
- The benchmark model: 3 generations of scalar LQs, only same-generation couplings, $LQ_1 \to eq/\nu_e q$, $LQ_2 \to \mu q/\nu_\mu q$
  - Parameters: M_{LQ}, $\beta = \mathrm{Br}(LQ \to \ell^{\pm} q)$
  - Production modes: $gg \to LQ\overline{LQ}$ at $M_{LQ} < 1$ TeV, $q\bar{q} \to LQ\overline{LQ}$ dominates at higher M_{LQ}
- Search channels covering all β values: $eejj$, $\mu\mu jj$, $e\nu jj$, $\mu\nu jj$
- Variables for the BDT ordered by the discriminating power (from high to low):
  $\underline{\ell\ell jj}$: $m_{LQ}^{\min} = \min\{m(\ell j)\}$, $m_{\ell\ell}$, subleading jet p_T, subleading lepton p_T, $m_{LQ}^{\max} = \max\{m(\ell j)\}$
  $\underline{\ell\nu jj}$: $m_{LQ} = m(\ell j)$ and $m_{LQ}^T = m^T(\vec{E}_T^{\text{miss}}, \vec{p}_T^{\,j})$ with ℓj paired to minimize $|m_{LQ} - m_{LQ}^T|$, $m_T(\ell, \vec{E}_T^{\text{miss}})$, E_T^{miss}, subleading jet p_T, p_T^{ℓ}
- V+jets and $t\bar{t}$ backgrounds constrained in the dedicated control regions; 2×29 $\ell\ell jj$ and $\ell\nu jj$ signal regions (SRs) for each $\ell = e, \mu$ and for each of 29 M_{LQ} mass hypotheses. An **SR is a highest BDT score bin** defined individually for each M_{LQ} value. The BDT is trained for each M_{LQ}.
  $\underline{\ell\ell jj}$: $m_{\ell\ell} > 130$ GeV, 1 BDT bin
  $\underline{\ell\nu jj}$: $m_T(\ell\nu) > 130$ GeV, $E_T^{\text{miss}} > 150$ GeV, $E_T^{\text{miss}}/\sqrt{p_T^{j1} + p_T^{j2} + p_T^{\ell}} > 3\ \text{GeV}^{1/2}$

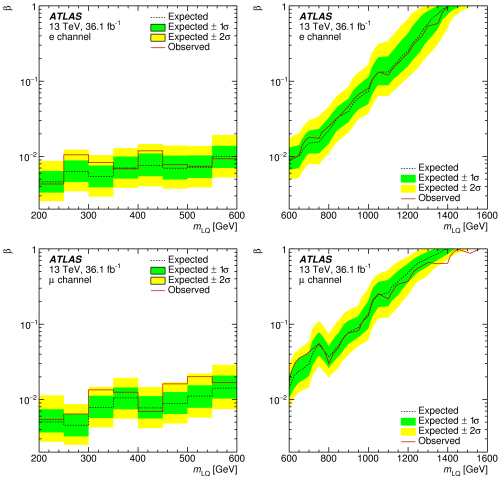




Pair production of 1st and 2nd generation scalar leptoquarks

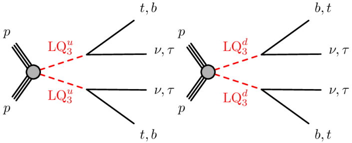


- $\sqrt{s} = 13$ TeV, $L_{int} = 36$/fb
- The benchmark model: 3 generations of scalar LQs, only same-generation couplings, $LQ_1 \to eq/\nu_e q$, $LQ_2 \to \mu q/\nu_\mu q$
  - Parameters: M_{LQ}, $\beta = \mathrm{Br}(LQ \to \ell^{\pm} q)$
  - Production modes: $gg \to LQ\overline{LQ}$ at $M_{LQ} < 1$ TeV, $q\bar{q} \to LQ\overline{LQ}$ dominates at higher M_{LQ}
- Search channels covering all β values: $eejj$, $\mu\mu jj$, $e\nu jj$, $\mu\nu jj$
- Limits on LQ_1 (upper) and LQ_2 (lower) in the $\{m_{LQ}, \beta\}$ plane →
- For $\beta = 0.5$ $m_{LQ_{1,2}} < 1.25$ TeV are excluded at CL=95%
- *The paper also includes particle-level differential cross section measurements in the phase space regions not covered by "standard" SM measurements*

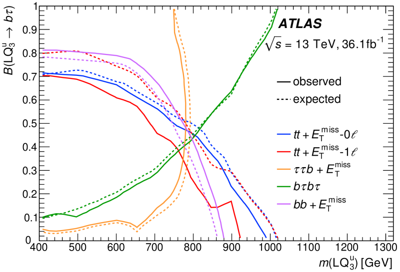


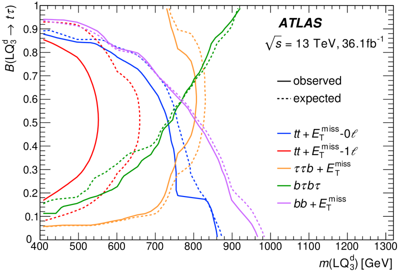
Pair production of 3rd generation scalar leptoquarks

arXiv:1902.08103
CERN-EP-2019-026



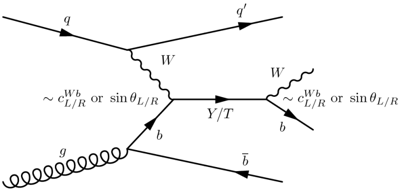
- $\sqrt{s} = 13$ TeV, $L_{int} = 36.1/\text{fb}$
- The LQ model is identical to the one in 1,2-generation LQ searches.
  Results presented in terms of m_{LQ} and $B(LQ \to \tau q)$.
- Multiple search channels:
  - $bb\tau\tau$ (based on $HH \to bb\tau\tau$ search)
  - $tt + E_T^{\text{miss}}$: $LQ\overline{LQ} \to t\nu\bar{t}\nu$, reinterpretation of $\tilde{t}\bar{\tilde{t}}$ search
  - $tt + E_T^{\text{miss}}$ in 0ℓ channel: $LQ\overline{LQ} \to t\nu\bar{t}\nu$, $LQ^d\overline{LQ^d} \to b\nu\, b\nu / t\tau$
  - $\tau\tau b + E_T^{\text{miss}}$, reinterpretation of $\tilde{t}\bar{\tilde{t}}$ search
  - $bb + E_T^{\text{miss}}$, reinterpretation of the $\tilde{b}\bar{\tilde{b}}$ search
    - ★ 0ℓ for $LQ\overline{LQ} \to b\nu b\nu$ ($B = 0$)
    - ★ 1ℓ for $LQ_3^{d,u}$ with $B \neq 0$
- **The main result:** exclusion plots in the $\left\{M(LQ_3^{u,d}), B(LQ_3^{u,d} \to \tau b, \tau t)\right\}$ plane →



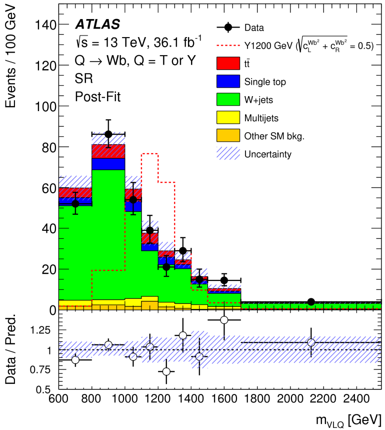


Details in backup

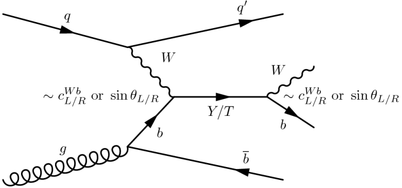
Search for VLQ $\to Wb$ *arXiv:1812.07343*



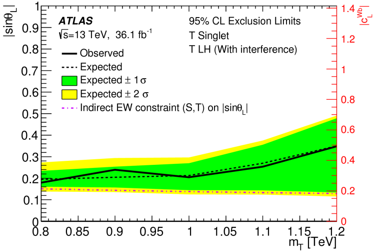
- $\sqrt{s} = 13$ TeV, $L_{int} = 36/\text{fb}$
- Motivation:
  - VLQs are safe for EW precision fits: L/R isospin singlets or mass degenerate doublet
  - small Yukawa couplings $\Rightarrow$ small contribution to $\sigma(gg \to H)$, safe for $V(H)$
  - VLQ appear in some models: extra dimensions, composite/little Higgs
- Benchmark models:
  - Renormalisable SM extension, fully parameterised by $\theta_{L,R}$ mixing angles and m_{VLQ}
  - Non-renormalisable: $c^{Wb}_{L,R}$ coulplings, $B(\text{VLQ} \to Wb, Zt, Ht)$ as free parameters
- $\text{VLQ} = T$ $(Q = +2/3$, any isospin) or Y $(Q = -4/3$, can't be an SU(2) singlet)
  - Non-negligible mixing with 3rd generation
- $\text{VLQ} \to Wb$, $W \to \ell\nu$
- Search optimised for high $m_{VLQ} \leftrightarrow$ back-to-back b-jet and $\ell^{\pm}$
- Control regions to constrain $t\bar{t}$ and W+jets
- $m_{VLQ} \leftarrow p_z(\nu)$ from $m_{\ell\nu} = m_W$ constraint
- Interference with SM backgrounds is crucial

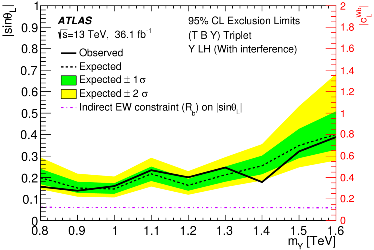


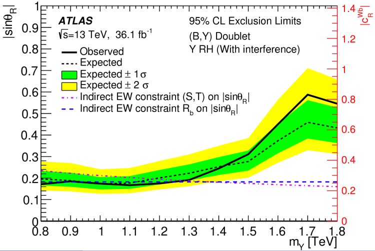
Search for VLQ $\rightarrow Wb$ *arXiv:1812.07343*



- $\sqrt{s} = 13$ TeV, $L_{int} = 36$/fb
- Benchmark models:
  - Renormalisable SM extension, fully parameterised by $\theta_{L,R}$ mixing angles and m_{VLQ}
  - Non-renormalisable: $c^{Wb}_{L,R}$ coulplings, $B(\mathrm{VLQ} \rightarrow Wb, Zt, Ht)$ as free parameters
- VLQ $= T$ ($Q = +2/3$, any isospin) or Y ($Q = -4/3$, can't be an SU(2) singlet)
  - Non-negligible mixing with 3rd generation
- Limits on VLQ–3rd gen. mixing parameters vs m_{VLQ} for T-singlet, (T, B, Y) triplet, and (B, Y) doublet models

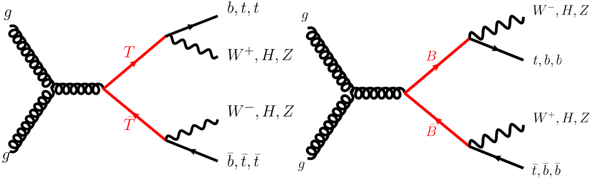




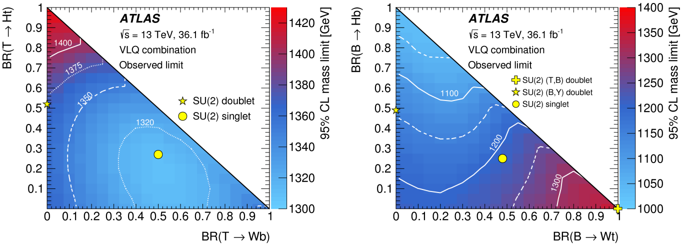


Combination of searches for vector-like $T\bar{T}$, $B\bar{B}$ *Phys. Rev. Lett. 121 (2018) 211801*

- $\sqrt{s} = 13$ TeV, $L_{int} = 36$/fb
- Combination of $T\bar{T}$ and $B\bar{B}$ searches with $T \to Zt/Wb/Ht$, $B \to Zb/Wt/Hb$
- Multiple channels:
  - leptonic: $H(bb)t + X$ $W(\ell\nu)b + X$, $W(\ell\nu)t + X$ $Z(\ell\ell)t/b + X$, $Z(\nu\nu)t + X$ $\ell^{\pm}\ell^{\pm} + \ell^{\mp} + X$
  - fully hadronic
- Combination significantly increases sensitivity.
- Singlet T and B are excluded for $m_{T,B} < 1.31$ and 1.22 TeV. For the (T, B) doublet, $m_{T,B} < 1.37$ TeV are excluded.



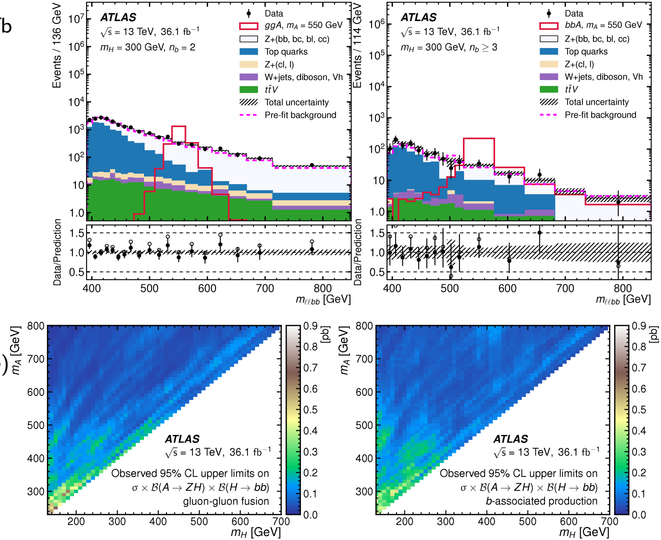
Analysis	$T\bar{T}$ decay	$B\bar{B}$ decay
$H(bb)t + X$ [16]	$HtH\bar{t}$	-
$W(\ell\nu)b + X$ [30]	$WbW\bar{b}$	-
$W(\ell\nu)t + X$ [32]	-	$WtW\bar{t}$
$Z(\nu\nu)t + X$ [33]	$ZtZ\bar{t}$	-
$Z(\ell\ell)t/b + X$ [35]	$ZtZ\bar{t}$	$ZbZ\bar{b}$
Tril./s.s. dilepton [36]	$HtH\bar{t}$	$WtW\bar{t}$
Fully hadronic [37]	$HtH\bar{t}$	$HbH\bar{b}$



Search for $A \to ZH \to \ell\ell bb$

Phys. Lett. B 783 (2018) 392

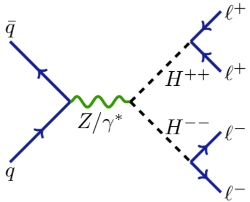
- $\sqrt{s} = 13$ TeV, $L_{int} = 36.1/\text{fb}$
- Motivation: 2HDM with $m_A > m_H > m_h$, $A \to ZH \to \ell^+\ell^- b\bar{b}$,
- Signature: $\ell^+\ell^-$ $(\ell = e, \mu)$ + $\geq 2b$-jets
  - $2b$-jets for $gg \to A$ production
  - $\geq 3b$-jets for $gg \to b\bar{b}A$ production
- Scan $m_{\ell\ell bb}$ distributions for different m_{bb} windows
- CL=95% upper limits on $\sigma(pp \to AX)\times$ $\times B(A \to ZH) \times B(H \to b\bar{b})$ for ggF and b-associated A production as functions of (m_A, m_H) →
- (m_A, m_H) exclusion regions vs $\tan\beta$ for Type I,II, lepton specific and flipped 2HDM ▸ see backup

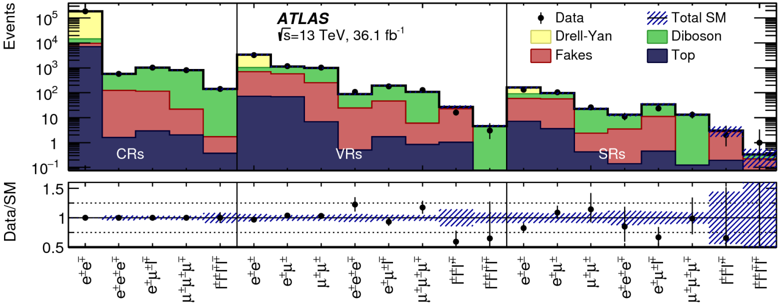


Search for $H^{++}H^{--}$ with same-charge leptons

Eur. Phys. J. C 78 (2018) 199

- $\sqrt{s} = 13$ TeV, $L_{int} = 36.1/\text{fb}$
- Motivation: left-right symmetric models, Higgs triplet models, little Higgs, ...
- Signature: $\ell^\pm\ell^\pm\ell'^\mp\ell'^\mp$, $\ell,\ell' = e,\mu$, b-jet veto, $Z(\ell^+\ell^-)$ veto
- SM backgrounds constrained in control regions
- Analysis regions are categorised by lepton multiplicity:
  - 2 or 3 leptons: one same-charge lepton pair
  - 4 leptons: two same charge lepton pairs, $\sum Q_\ell = 0$

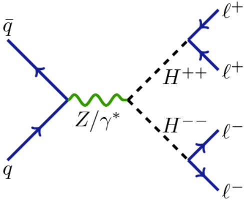


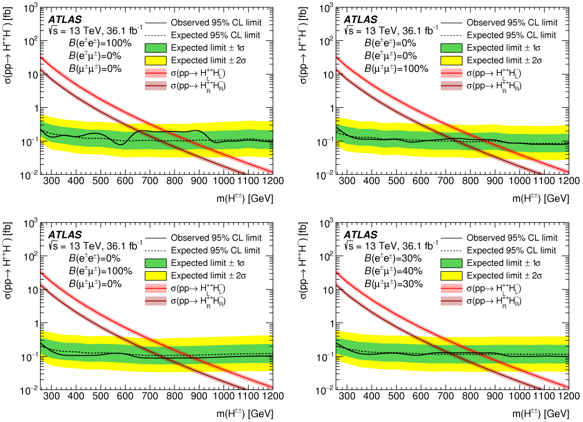


▸ see backup for region definitions and $m(\ell\ell')$ spectra

Search for $H^{++}H^{--}$ with same-charge leptons *Eur. Phys. J. C 78 (2018) 199*

- $\sqrt{s} = 13$ TeV, $L_{int} = 36.1/\text{fb}$
- Motivation: left-right symmetric models, Higgs triplet models, little Higgs, ...
- Signature: $\ell^{\pm}\ell^{\pm}\ell'^{\mp}\ell'^{\mp}$, $\ell, \ell' = e, \mu$, b-jet veto, $Z(\ell^+\ell^-)$ veto
- CL=95% upper limits on $\sigma(pp \to H^{++}H^{--})$ for several $B(ee)/B(e\mu)/B(\mu\mu)$ ratio values





$m(H_L^{\pm\pm}) > 0.77$ TeV and > 0.47 TeV
$m(H_R^{\pm\pm}) > 0.66$ TeV and > 0.32 TeV,
for $B(H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}) = 1$ and ≥ 0.1, resp.

Summary

- ATLAS searches for BSM resonances in final states with a charged lepton utilised 36 – 139/fb of LHC Run-II *pp* data at $\sqrt{s} = 13$ TeV
- **No significant deviations from the SM background hypothesis so far**
- Limits in terms of benchmark BSM models:
  - Heavy vector triplet: $M_{V'} \gtrsim 4.5$ TeV
  - Randall–Sundrum extra dimensions: $m_{G_{KK}} \gtrsim 2.3$ TeV
  - Vector-like quarks: $m_{\mathrm{VLQ}} \gtrsim 1$ TeV
  - Leptoquarks:
    - 1st, 2nd generation: $m_{\mathrm{LQ}1,2} > 1.25$ GeV for $\mathcal{B}(\ell^{\pm} q) = 0.5$
    - 3rd generation: $m_{\mathrm{LQ}3} \gtrsim 0.8$ TeV for $\mathcal{B}(\ell^{\pm} q) = 0.5$
- Combined limits on several benchmark models using multiple final states:
  - HVT and RS1: $\{ VV, VH, \ell\ell' \} \rightarrow \{VV \ \&\ VH\} \rightarrow \{VV \ \&\ VH \ \&\ \ell\ell'\}$
  - Vector-like quarks: $H(bb)t + X$ & $W(\ell\nu)b + X$, $W(\ell\nu)t + X$ & $Z(\ell\ell)t/b + X$, $Z(\nu\nu)t + X$ & $\ell^{\pm}\ell^{\pm} + \ell^{\mp} + X$
- Processing of the full LHC Run-II 139/fb dataset is in progress

Backup

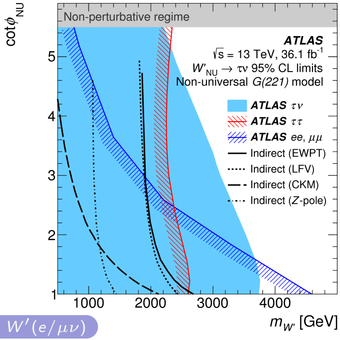
Search for $W' \to \tau\nu$ *PRL 120 (2018) 161802*

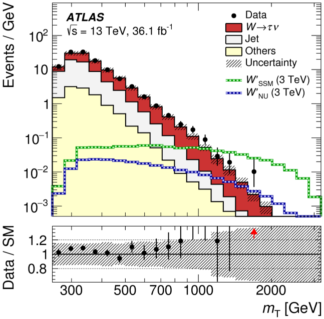
- $\sqrt{s} = 13$ TeV, $L_{int} = 36.1$/fb
- The discriminating variable:

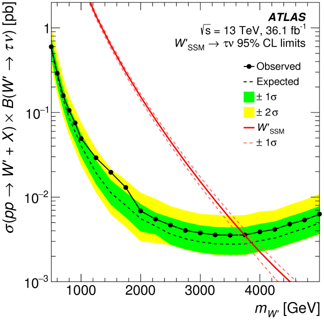
$$M_T(\tau_{had-vis}\nu) = \sqrt{2p_T^{\tau_{had-vis}} E_T^{\text{miss}}(1 - \cos\phi_{\tau\nu})}$$

- Assuming SM couplings for the W'_{SSM}: $M_{W'_{SSM}} > 3.7$ TeV at CL=95% ↘
- ↓ Excluded region for $G(221)$ W'_{NU} non-universally coupled to 1st/2nd and 3rd generation fermions.

$G(221)$ model: $SU(2)_1 \times SU(2)_2 \times U(1)_Y$ gauge group, *'1'* couples to 1st and 2nd gen. fermions $\propto g_1$, *'2'* to 3rd gen. $\propto g_2$, $\tan\phi_{NU} = g_2/g_1$. Upon breaking to $SU(2)_L \times U(1)_Y$ W' couples to 3rd gen. with $g\cot\phi_{NU}$ and to 1st and 2nd gen. with $g\tan\phi_{NU}$





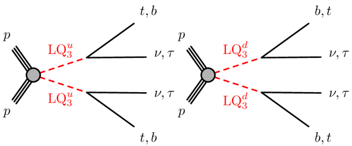


◂ $W'(e/\mu\nu)$

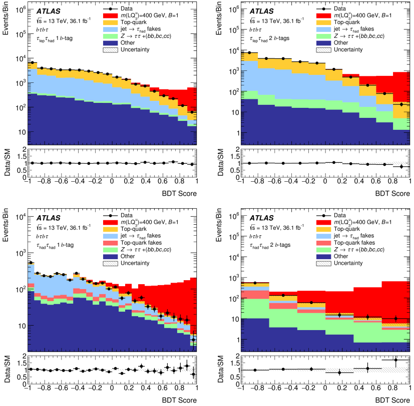
Related topic: search for LFV $Z \to \tau e/\tau\mu$ Phys. Rev. D 98 (2018) 092010

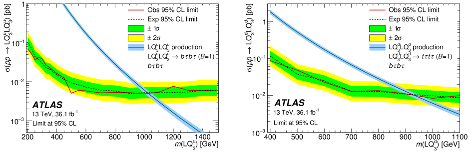
Pair production of 3rd generation scalar leptoquarks

arXiv:1902.08103
CERN-EP-2019-026



- $\sqrt{s} = 13$ TeV, $L_{int} = 36.1$/fb
- The LQ model is identical to the one in 1,2-generation LQ searches. Results presented in terms of m_{LQ} and $B(LQ \to \tau q)$.
- Multiple search channels:
- $bb\tau\tau$ channel based on $HH \to bb\tau_{\mathrm{lep/had}}\tau_{\mathrm{had}}$ search:
  - Event subsamples with 1 and 2 b-tagged jets
  - no additional jet veto $\Rightarrow$ sensitive to both $LQ^u\bar{LQ}^u \to b\tau b\tau$ and $LQ^d\bar{LQ}^d \to t\tau t\tau \to W(\to \mathrm{jets})b\tau W(\to \mathrm{jets})b\tau$
  - Variables: S_T, $m_{\tau(\ell),\mathrm{jet}}$, $\Delta R_{\tau(\ell),\mathrm{jet}}$, $\Delta\phi(E_T^{\mathrm{miss}}, \tau)$, p_T^{τ} $\Rightarrow$ BDT score





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Pair production of 3rd generation scalar leptoquarks

arXiv:1902.08103
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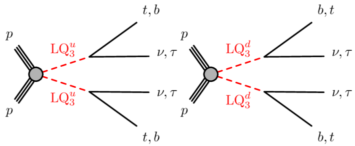
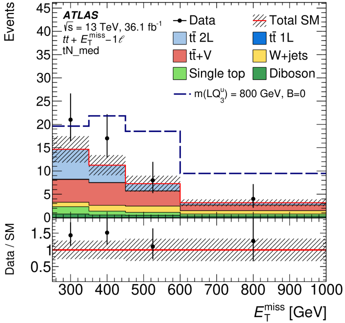
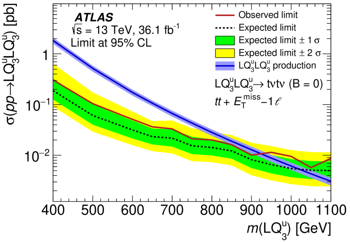




- $\sqrt{s} = 13$ TeV, $L_{int} = 36.1$/fb
- The LQ model is identical to the one in 1,2-generation LQ searches.
  Results presented in terms of m_{LQ} and $B(LQ \to \tau q)$.
- Multiple search channels:
- $tt + E_T^{\text{miss}}$ channel $LQ\overline{LQ} \to t\nu\bar{t}\nu$
  - reinterpretation of $\tilde{t}\bar{\tilde{t}}$ search
  - $t(\ell\nu b)t(\text{all hadronic}) \to e/\mu +$ $+ \geq 1$ b-jet $+ \geq 3$jets $+ E_T^{\text{miss}}$
  - two SRs targeting $m_{LQ} \sim 600$ GeV (SR binned in E_T^{miss}) and $m_{LQ} \sim 1$ TeV (single bin)



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Pair production of 3rd generation scalar leptoquarks

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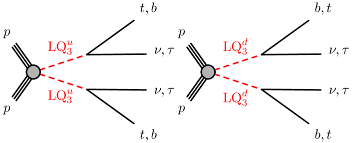
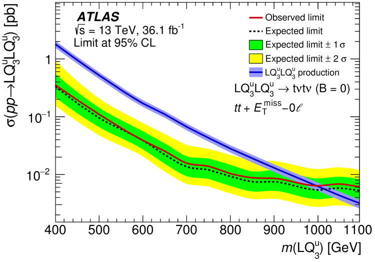
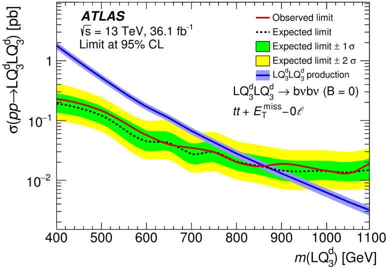


- $\sqrt{s} = 13$ TeV, $L_{int} = 36.1/\text{fb}$
- The LQ model is identical to the one in 1,2-generation LQ searches. Results presented in terms of m_{LQ} and $B(LQ \to \tau q)$.
- Multiple search channels:
- $tt + E_T^{\text{miss}} + 0\ell$ channel $LQ\overline{LQ} \to t\nu\bar{t}\nu$, $LQ^d\overline{LQ^d} \to b\nu\, b\nu/t\tau$
  - reinterpretation of $\tilde{t}\bar{\tilde{t}}$ search
  - $t(\text{all had.})\bar{t}(\text{all had.}) \to$ $\to \geq$ 1b-jet + $\geq$ 3jets + E_T^{miss}
  - Variables: E_T^{miss}, $\Delta R(b, b)$, $m_T(b, E_T^{\text{miss}})$ for b-jet with min/max $\Delta\phi(b, E_T^{\text{miss}})$
  - Three SRs:

  $m_{LQ} \sim 1$ TeV: high E_T^{miss}, boosted t's $\to$ 2 R=1.2 jets;
  $m_{LQ} \sim 0.5$ TeV: lower E_T^{miss}, lower boost of t's $\to$ 2 R=1.2 jets;
  for $LQ^d \to b\nu$: $\geq$ 5jets including 2 high-p_T b-jets + high E_T^{miss}

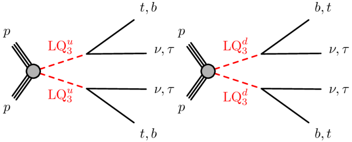


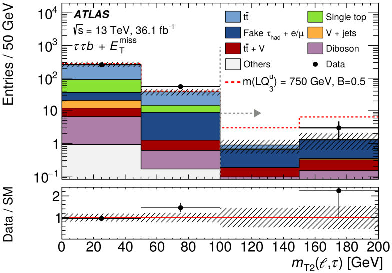


To main slide

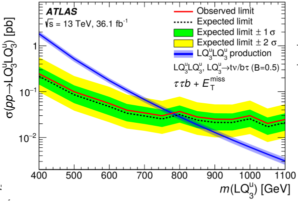
Pair production of 3rd generation scalar leptoquarks

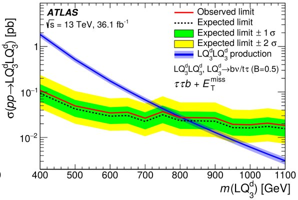
arXiv:1902.08103
CERN-EP-2019-026





- $\sqrt{s} = 13$ TeV, $L_{int} = 36.1$/fb
- The LQ model is identical to the one in 1,2-generation LQ searches.
  Results presented in terms of m_{LQ} and $B(LQ \to \tau q)$.
- Multiple search channels:
- $\tau\tau b + E_T^{\mathrm{miss}}$ channel
  - reinterpretation of $\tilde{t}\bar{\tilde{t}}$ search
  - $\tau^{\pm}_{\mathrm{lep/had}}\tau^{\mp}_{\mathrm{had}}$ + + $\geq$ 1b-jet + $\geq$ 1jets + E_T^{miss}
  - Variables: E_T^{miss}, $m_{T2}(\tau\tau, E_T^{mis}$

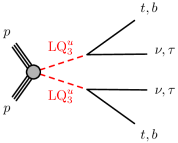


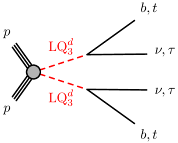


To main slide

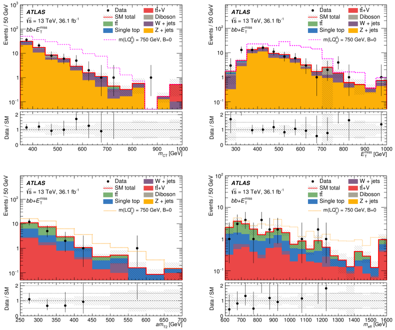
Pair production of 3rd generation scalar leptoquarks

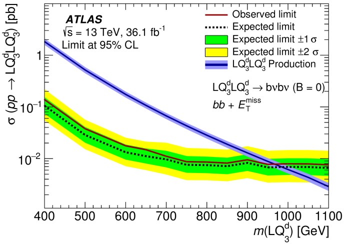
arXiv:1902.08103
CERN-EP-2019-026





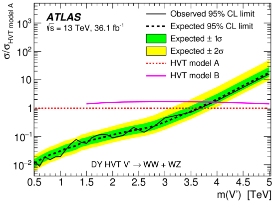
- $\sqrt{s} = 13$ TeV, $L_{int} = 36.1/$fb
- The LQ model is identical to the one in 1,2-generation LQ searches.
  Results presented in terms of m_{LQ} and $B(LQ \to \tau q)$.
- Multiple search channels:
- $bb + E_T^{\mathrm{miss}}$ channel
  - reinterpretation of the $\tilde{b}\bar{\tilde{b}}$ search
  - $2b$-jets + $0/1\ell$ + E_T^{miss},
    0ℓ for $LQ\overline{LQ} \to b\nu b\nu$ $(B = 0)$,
    1ℓ for $LQ_3^{d,u}$ with $B \neq 0$
  - Main discriminating variables:
    cotransverse mass m_{CT} (0ℓ), E_T^{miss} (1ℓ)

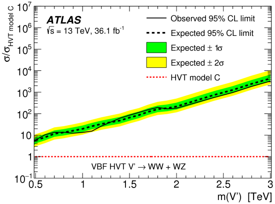


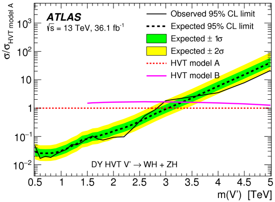


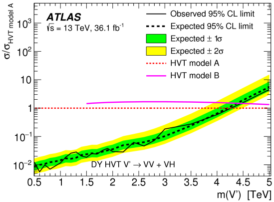
To main slide

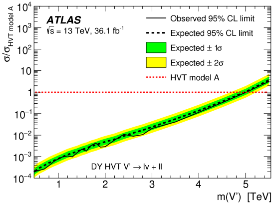
Combination of $X \to VV/VH$, $\ell\nu/\ell\ell$ searches: HVT *Phys. Rev. D 98 (2018) 052008*











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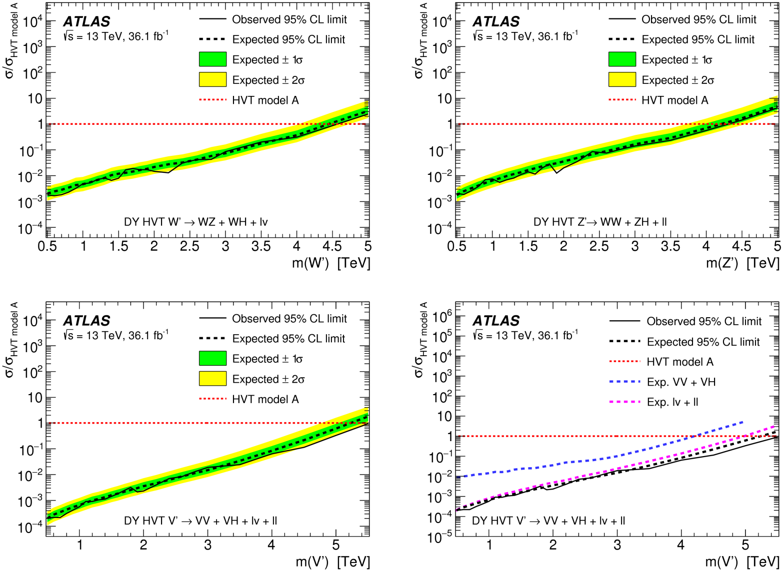
Combination of $X \to VV/VH$, $\ell\nu/\ell\ell$ searches: HVT *Phys. Rev. D 98 (2018) 052008*



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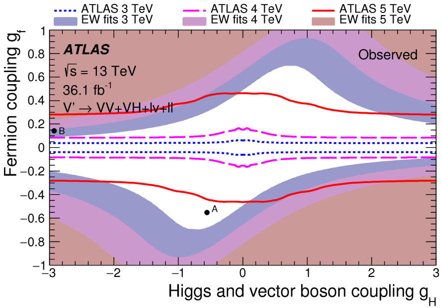
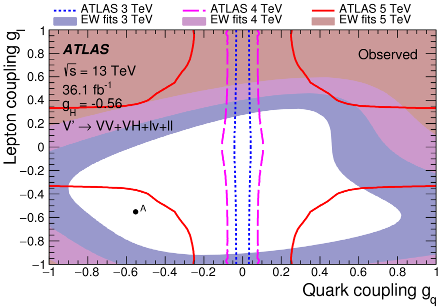
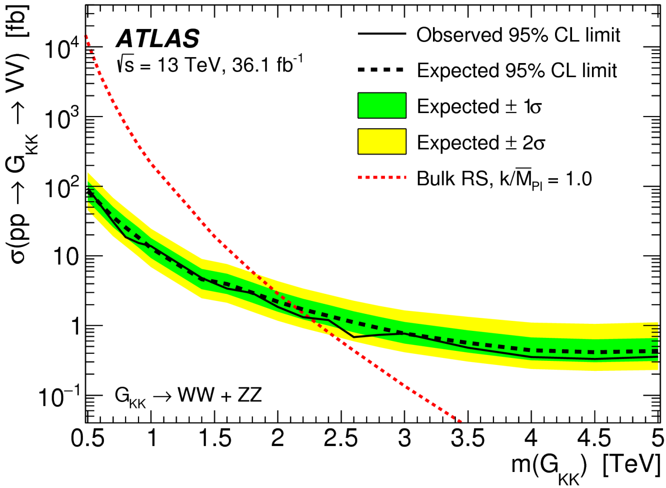
Combination of $X \to VV/VH$, $\ell\nu/\ell\ell$ searches: HVT couplings *Phys. Rev. D 98 (2018) 052008*





to main slide

Combination of $X \to VV/VH$, $\ell\nu/\ell\ell$ searches: RS1 G_{KK} *Phys. Rev. D 98 (2018) 052008*



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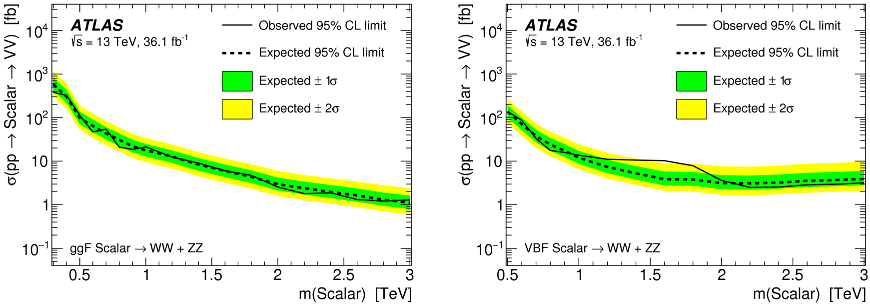
Combination of $X \to VV/VH$, $\ell\nu/\ell\ell$ searches: scalar *Phys. Rev. D 98 (2018) 052008*



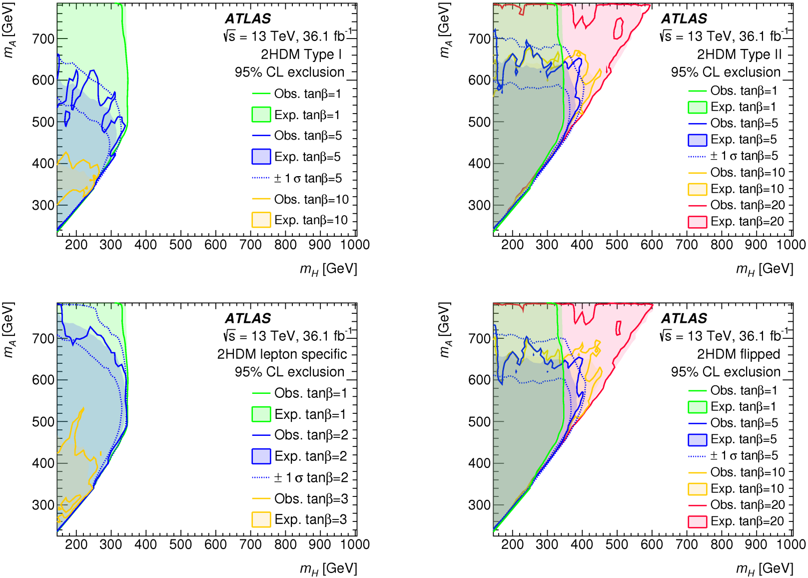
◂ to main slide

Search for $A \to ZH \to \ell\ell bb$

Phys. Lett. B 783 (2018) 392

◂ to main slide

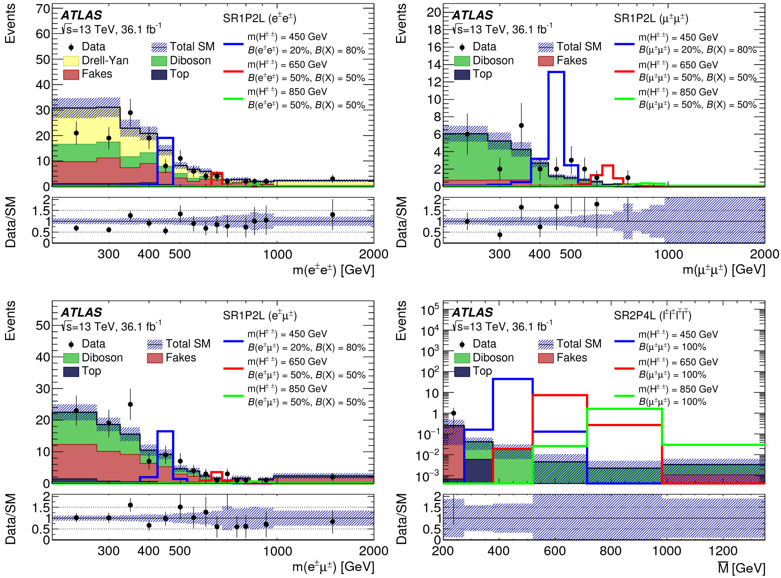
(m_A, m_H) exclusion regions vs $\tan\beta$ for Type I,II, lepton specific and flipped 2HDM



Region / Channel	Control Regions			Validation Regions			Signal Regions		
	OCCR	DBCR	4LCR	SCVR	3LVR	4LVR	1P2L	1P3L	2P4L
Electron channel	$e^\pm e^\mp$	$e^\pm e^\pm e^\mp$		$e^\pm e^\pm$	$e^\pm e^\pm e^\mp$		$e^\pm e^\pm$	$e^\pm e^\pm e^\mp$	
Mixed channel	-	$e^\pm \mu^\pm \ell^\mp$	$\ell^\pm \ell^\pm$ $\ell^\mp \ell^\mp$	$e^\pm \mu^\pm$	$e^\pm \mu^\pm \ell^\mp$ $\ell^\pm \ell^\pm \ell'^\mp$	$\ell^\pm \ell^\pm$ $\ell^\mp \ell^\mp$	$e^\pm \mu^\pm$	$e^\pm \mu^\pm \ell^\mp$ $\ell^\pm \ell^\pm \ell'^\mp$	$\ell^\pm \ell^\pm$ $\ell^\mp \ell^\mp$
Muon channel	-	$\mu^\pm \mu^\pm \mu^\mp$		$\mu^\pm \mu^\pm$	$\mu^\pm \mu^\pm \mu^\mp$		$\mu^\pm \mu^\pm$	$\mu^\pm \mu^\pm \mu^\mp$	
$m(e^\pm e^\pm)$ [GeV]	$[130, 2000]$	$[90, 200)$		$[130, 200)$	$[90, 200)$		$[200, \infty)$	$[200, \infty)$	
$m(\ell^\pm \ell^\pm)$ [GeV]	-	$[90, 200)$	$[60, 150)$	$[130, 200)$	$[90, 200)$	$[150, 200)$	$[200, \infty)$	$[200, \infty)$	$[200, \infty)$
$m(\mu^\pm \mu^\pm)$ [GeV]	-	$[60, 200)$		$[60, 200)$	$[60, 200)$		$[200, \infty)$	$[200, \infty)$	
b-jet veto	✓	✓	✓	✓	✓	✓	✓	✓	✓
Z veto	-	inverted	-	-	✓	-	-	✓	✓
$\Delta R(\ell^\pm, \ell^\pm) < 3.5$	-	-	-	-	-	-	✓	✓	-
$p_T(\ell^\pm \ell^\pm) > 100$ GeV	-	-	-	-	-	-	✓	✓	-
$\sum \lvert p_T(\ell) \rvert > 300$ GeV	-	-	-	-	-	-	✓	✓	-
$\Delta M / \bar{M}$ requirement	-	-	-	-	-	-	-	-	✓

◂ to main slide

Search for $H^{++}H^{--}$ with same-charge leptons *Eur. Phys. J. C 78 (2018) 199*



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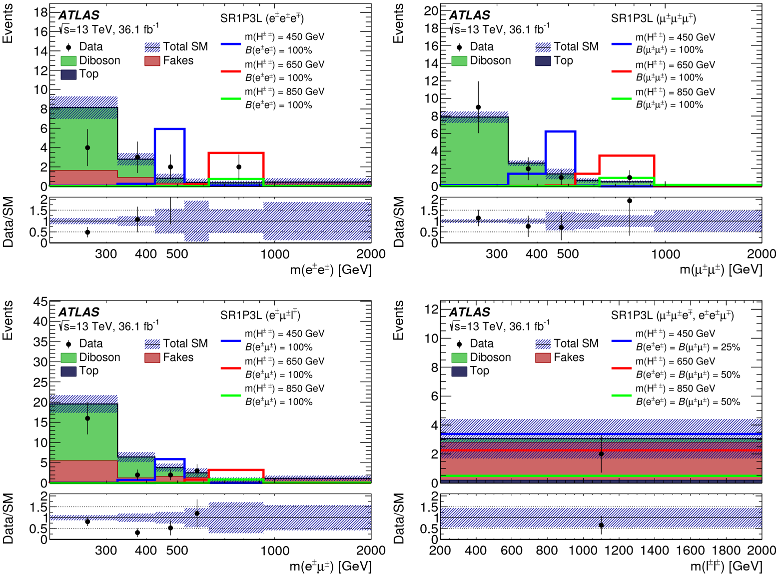
Search for $H^{++}H^{--}$ with same-charge leptons *Eur. Phys. J. C 78 (2018) 199*



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