Search for new heavy resonances in leptonic or hadronic final states with the ATLAS detector

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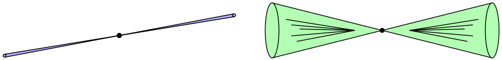
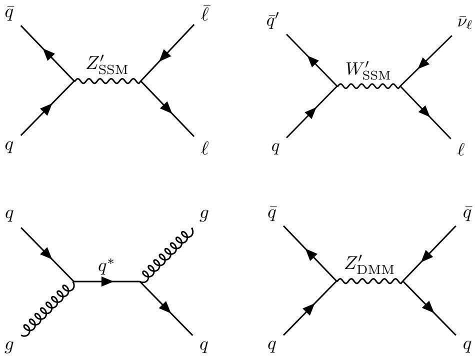
New physics through the lens of heavy resonances

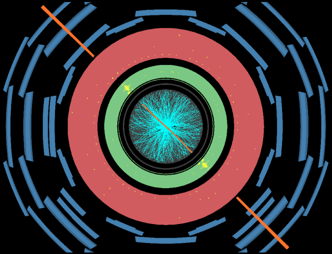
- Plethora of BSM models that predict new heavy resonances!
  - New scalars in MSSM
  - Sequential Standard Model (simplified models)
    - Heavy vector bosons Z'_{SSM}, W'_{SSM}
  - E_6-motivated Grand Unification Z'_{ψ}
  - Heavy Vector Triplet Z'_{HVT}
  - Compositness models with excited quarks q^*
  - Dark matter mediator Z'
- Excellent targets for searches using our trusted tools: leptons and jets



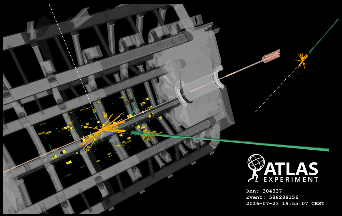
To sketch a few...



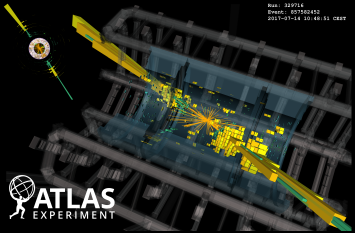
A talk in three searches



dilepton



lepton + E_T^{miss}



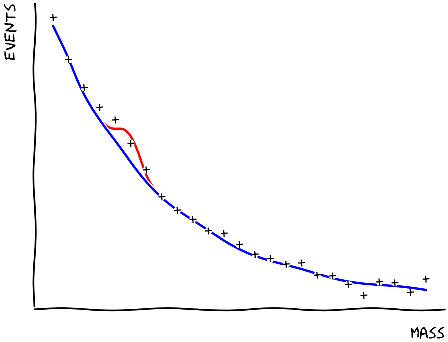
dijet

New! results from ATLAS using the full Run-2 data set (139 fb^{-1})

Search strategies

Resonant search strategy

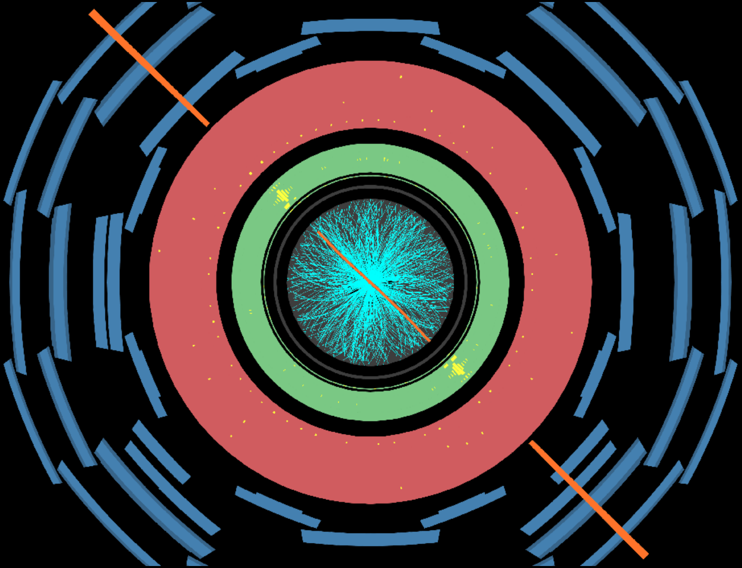
1. Reconstruct the 4-momentum of the final state particles
2. Combine to form the invariant mass spectrum
3. Fit the smoothly falling SM background to search for new resonances
4. If no significant deviations, set limits on the BSM process cross section



- Final states with leptons have lower backgrounds that can be triggered on efficiently
- Resonances with hadronic decays can have larger branching ratios
- Modified couplings can result in preferential decays to heavy flavour

Dilepton (starting clean)

Highest invariant mass dielectron candidate 2015–2018 data with $m_{ee} = 4.06$ TeV [Phys. Lett. B 796 (2019) 68]



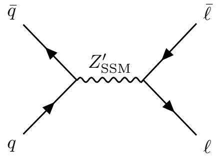
Dilepton: Search strategy

[Phys. Lett. B 796 (2019) 68]

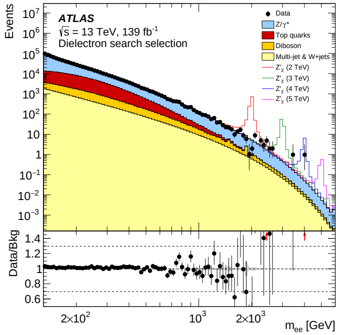
- Benefits from a factor of 4 increase in luminosity over previous search (36.1 fb^{-1}) [JHEP 10 (2017) 182]
- After event selection require $m_{\ell\ell} > 225$ GeV to be above the Z peak region
- Background fit made on data with a functional form chosen to minimize spurious signal

$$f_{\ell\ell}(m_{\ell\ell}) = f_{\mathrm{BW,Z}}(m_{\ell\ell}) \cdot (1 - x^c)^b \cdot x^{\sum_{i=0}^{3} p_i \log(x)^i}$$

  for $x = m_{\ell\ell}/\sqrt{s}$ and $f_{\mathrm{BW,Z}}(m_{\ell\ell})$ as non-relativistic Breit-Wigner
- Generic signal shape of non-relativistic Breit-Wigner (width varies) convolved with the detector resolution used to determine the significance of observed deviations



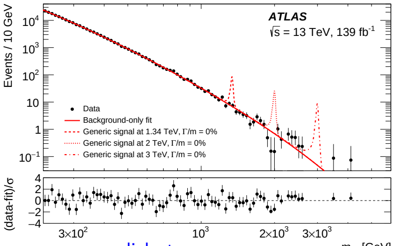
$\ell \in \{e, \mu\}$



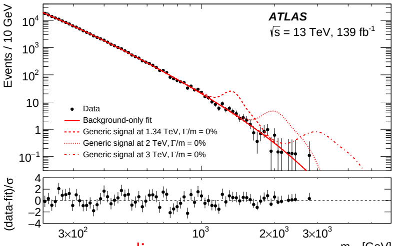
Dilepton: Results

- No significant excesses observed in the dielectron or the dimuon channels
- 95% CL upper limits set on the fiducial cross-section × branching ratio for generic resonances decaying to dileptons
- Lower limit on $m_{Z'}$
  - Z'_{SSM}: 5.1 TeV
  - Z'_{ψ}: 4.5 TeV
  - Z'_{χ}: 4.8 TeV
- Most stringent limits to date

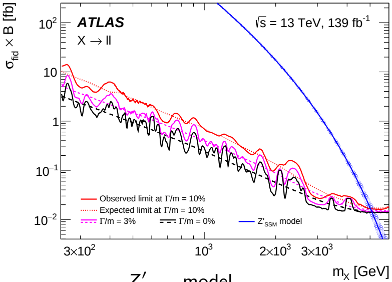
(HVT limits in backup)



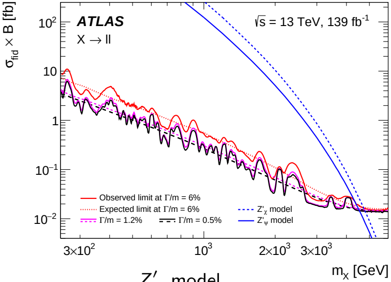
dielectron mass



dimuon mass



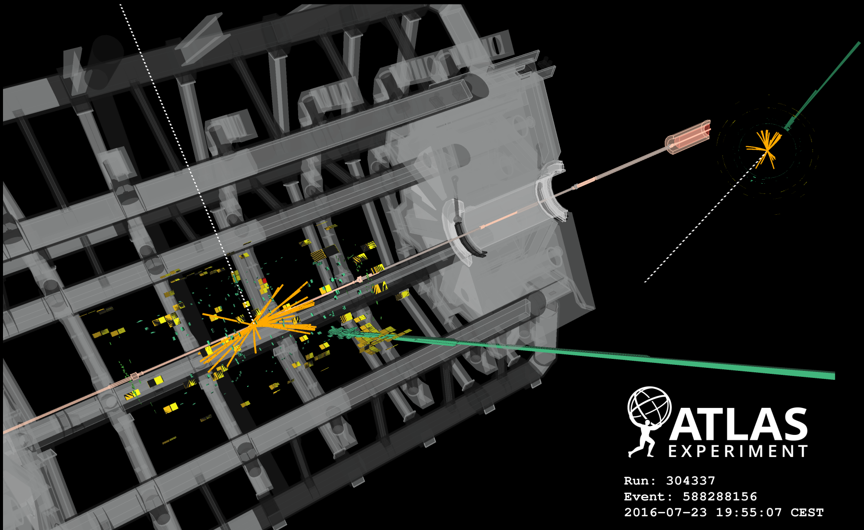
Z'_{SSM} model



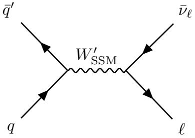
Z'_{ψ} model

lepton + missing transverse momentum (finding friends)

Event with highest m_T in electron + E_T^{miss} channel in 36.1 fb^{-1} data [Eur. Phys. J. C 78 (2018) 401]



- Uses full Run-2 (139 fb^{-1}) dataset for improvements over [Eur. Phys. J. C 78 (2018) 401] (36.1 fb^{-1})
- Uses high p_T single-electron or single-muon triggers to fight against Drell-Yan W background
  - Shown in muon p_T and E_T^{miss} (pre-fit) plots

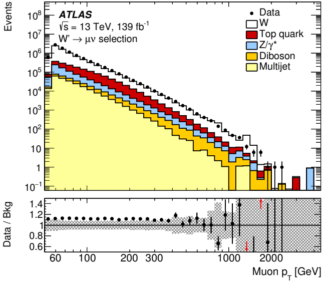


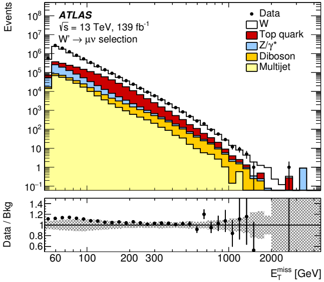
$\ell \in \{e, \mu\}$

- Signal and background discrimination relies on the transverse mass

$$m_T = \sqrt{2 p_T E_T^{\mathrm{miss}} \left(1 - \cos \phi_{\ell\nu}\right)}$$

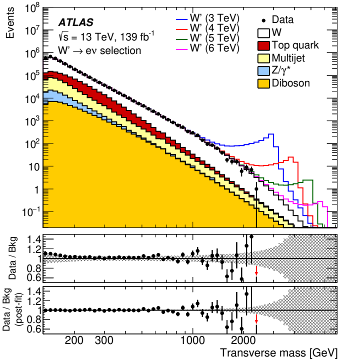
for $\phi_{\ell\nu}$ angle between the charged lepton and missing transverse momentum directions in the transverse plane



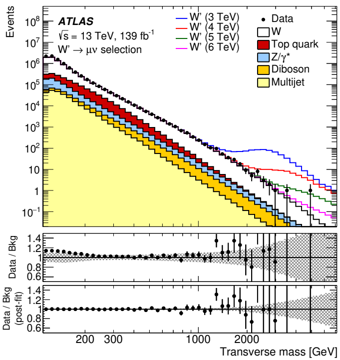


Lepton + MET: Results

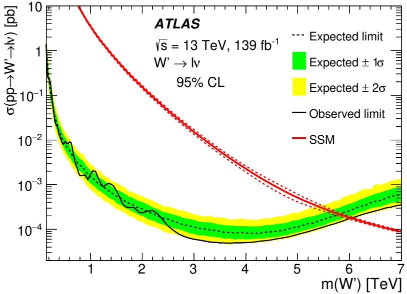
[Phys. Rev. D 100 (2019) 052013]



electron channel transverse mass



muon channel transverse mass



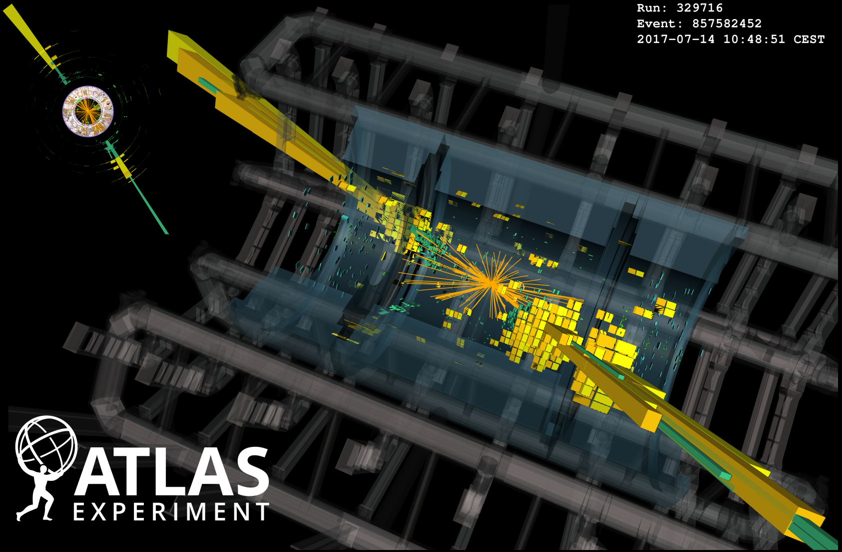
Combined upper limits on SSM W' model

- No significant excesses observed in the electron or the muon channels
- 95% CL upper limits set on the cross-section for SSM W' decaying to leptons of a single generation

- Observed lower limit on $m_{W'}$
  - $W'_{\mathrm{SSM}} \to e\nu$: 6.0 TeV
  - $W'_{\mathrm{SSM}} \to \mu\nu$: 5.1 TeV
  - $W'_{\mathrm{SSM}} \to \ell\nu$: 6.0 TeV

Dijet (ending with multitudes)

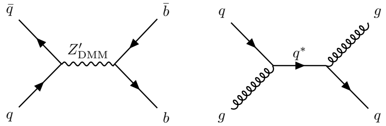
Dijet event 2017 data with $m_{jj} = 9.5$ TeV [arXiv:1910.08447]

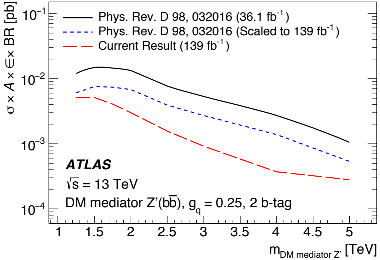


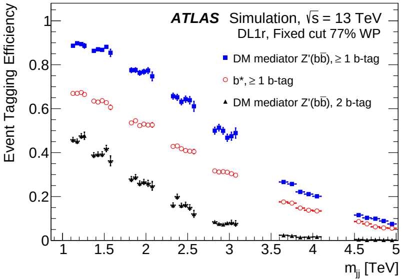
Dijet: Search strategy

[arXiv:1910.08447]

- Events selected using single-jet trigger with $p_T > 420$ GeV (lowest p_T un-prescaled)
- Uses variable binning given varying resolution
- b-jet identification done using deep neural network ($\mathrm{DL1r}$) for first time at ATLAS!
- Improvements in jet flavour identification at high p_T increase sensitivity over previous analysis [Phys. Rev. D 98 (2018) 032016] more than expected from increased luminosity ($36\ \mathrm{fb}^{-1} \rightarrow 139\ \mathrm{fb}^{-1}$)





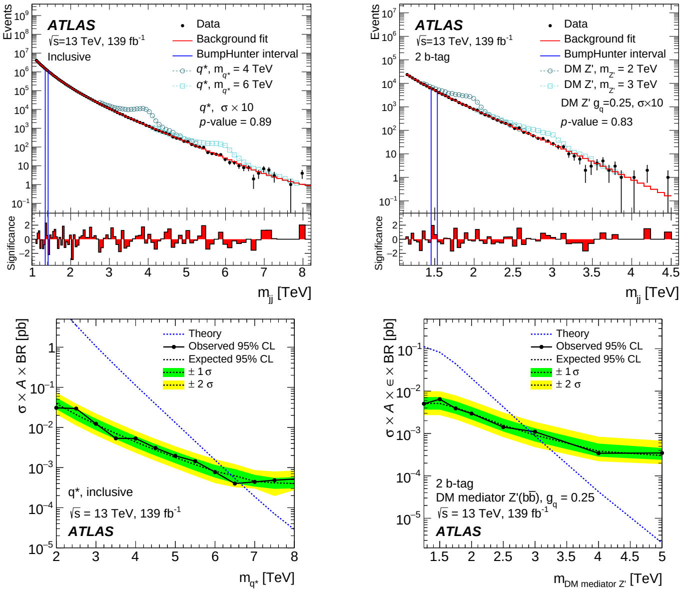


77% efficient b-tagging $\mathrm{DL1r}$ working point gives maximal signal sensitivity for b-tagged categories

Dijet: Results (subset)

[arXiv:1910.08447]

- No significant excesses observed
- 95% CL upper limits set on
  - signal cross-section × acceptance × branching ratio
  - signal cross-section × acceptance × branching ratio × b-tagging selection efficiency (for 1b and 2b)
- Observed lower limits on mass
  - Excited quark q^*: 6.7 TeV
  - $Z'_{\mathrm{DMM}} \to b\bar{b}$ for $g_q = 0.25$: 2.9 TeV
- (Quantum black hole, Z', W', W^*, and KK graviton results in backup)



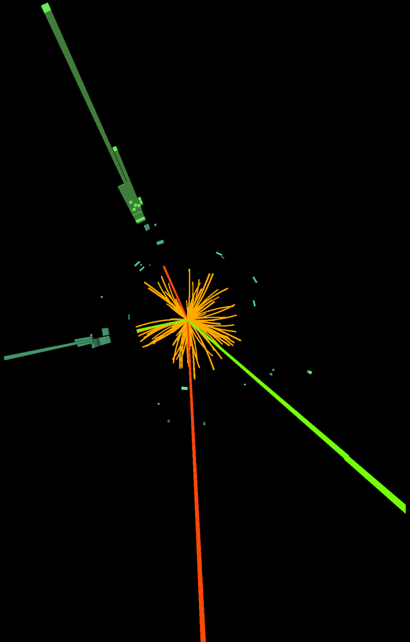
Search prospects at the HL-LHC

- At high mass and high-p_T resonant signatures are relatively clean and so great for HL-LHC environment
- The increased luminosity of 3–4 ab^{-1} (factor of 20–25 from Run-2 delivered) gives a nice boost
- Important for:
  - models ATLAS is just on the edge of being sensitive to
  - tail effects of new physics

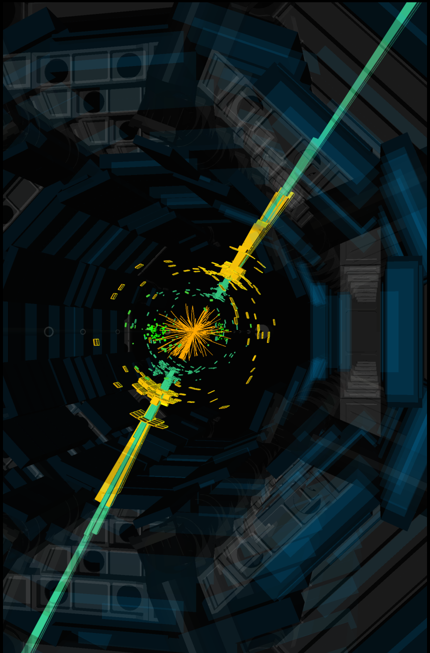
Conclusions

Model	Final State	Lower Limit	arXiv
$Z'_\psi \to \ell\ell$	$2e, \mu$	$m_{Z'_\psi} > 4.5$ TeV	1903.06248
$Z'_\chi \to \ell\ell$	$2e, \mu$	$m_{Z'_\chi} > 4.8$ TeV	1903.06248
$Z'_{\mathrm{SSM}} \to \ell\ell$	$2e, \mu$	$m_{Z'_{\mathrm{SSM}}} > 5.1$ TeV	1903.06248
$W'_{\mathrm{SSM}} \to e\nu$	$1e + E_T^{\mathrm{miss}}$	$m_{W'_{\mathrm{SSM}}} > 6.0$ TeV	1706.04786
$W'_{\mathrm{SSM}} \to \mu\nu$	$1\mu + E_T^{\mathrm{miss}}$	$m_{W'_{\mathrm{SSM}}} > 5.1$ TeV	1706.04786
$W'_{\mathrm{SSM}} \to \ell\nu$	$1e, \mu + E_T^{\mathrm{miss}}$	$m_{W'_{\mathrm{SSM}}} > 6.0$ TeV	1706.04786
$q^* \to qg$	$2j$	$m_{q^*} > 6.7$ TeV	1910.08447
$QBH \to jj$	$2j$	$m_{QBH} > 9.4$ TeV	1910.08447
$W' \to q\bar{q}'$	$2j$	$m_{W'} > 4.0$ TeV	1910.08447
$W^* \to q\bar{q}'$	$2j$	$m_{W^*} > 3.9$ TeV	1910.08447
$Z'_{\mathrm{DMM}} \to q\bar{q}, g_q = 0.20$	$2j$	$m_{Z'_{\mathrm{DMM}}} > 3.8$ TeV	1910.08447
$Z'_{\mathrm{DMM}} \to q\bar{q}, g_q = 0.25$	$2j$	$m_{Z'_{\mathrm{DMM}}} > 4.6$ TeV	1910.08447
$b^* \to bg$	$1b, 1j$	$m_{b^*} > 3.2$ TeV	1910.08447
$Z'_{\mathrm{DMM}} \to b\bar{b}, g_q = 0.20$	$2b$	$m_{Z'_{\mathrm{DMM}}} > 2.8$ TeV	1910.08447
$Z'_{\mathrm{DMM}} \to b\bar{b}, g_q = 0.25$	$2b$	$m_{Z'_{\mathrm{DMM}}} > 2.9$ TeV	1910.08447
$Z'_{\mathrm{SSM}} \to b\bar{b}$	$2b$	$m_{Z'_{\mathrm{SSM}}} > 2.7$ TeV	1910.08447
$G_{KK} \to b\bar{b}, k/\bar{M}_{\mathrm{PL}} = 0.2$	$2b$	$m_{G_{KK}} > 2.8$ TeV	1910.08447

- No evidence of new physics. However,...
- Numerous BSM models tested with the full Run-2 139 fb^{-1} dataset using dilepton, lepton + E_T^{miss}, and dijet searches
- Between the three analyses 17 new limits set!
- Further searches in Run-3 and beyond at the HL-LHC will increase range of sensitivity



Backup



Z' in BSM Models

- Sequential Standard Model:
  - Z'_{SSM} couplings to SM fermions is the same as the SM Z
  - Z'_{SSM} width increases proportional to its mass
  - Couplings to SM vector bosons suppressed (or 0)
- E_6-motivated Grand Unification
  - $\mathrm{SU}(5)$ with two additional $\mathrm{U}(1)$, resulting in two new gauge fields: ψ and χ
  - Particle associated with the fields can mix to form Z' candidates

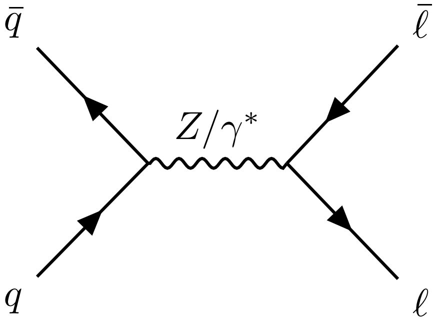
$$Z' = Z'_\psi \cos\theta_{\mathrm{E}_6} + Z'_\chi \sin\theta_{\mathrm{E}_6}$$

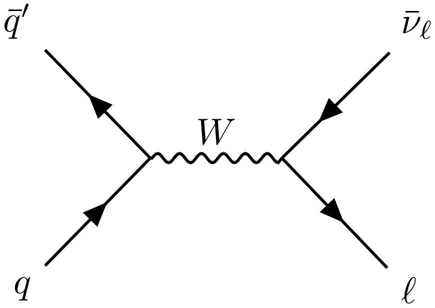
  - Z' couplings to fermions determined by the symmetry breaking and value of E_6
- Heavy Vector Triplet
  - Z'_{HVT} is neutral member of a new $\mathrm{SU}(2)$ group resulting in being part of a triplet
  - Cannot exist without $W'^{\pm}_{\mathrm{HVT}}$ that should be nearly degenerate in mass
- Dark matter mediator
  - Z'_{DMM} is member of a new $\mathrm{U}(1)$ group

Compositness of quarks

- Substructure of quarks would lead to contact interactions at high energy scales between the constituents
- Lead to deviations from the expected QCD scattering behaviour, which would be most visible in:
  - Inclusive jet cross section at high p_T
  - Dijet invariant mass distribution
  - Dijet angular distributions of jets in the parton-parton centre-of-mass system

Drell-Yan Backgrounds





Dilepton: Background functional form

[Phys. Lett. B 796 (2019) 68]

$$f_{\ell\ell}(m_{\ell\ell}) = f_{\mathrm{BW,Z}}(m_{\ell\ell}) \cdot (1 - x^c)^b \cdot x^{\sum_{i=0}^{3} p_i \log(x)^i}$$

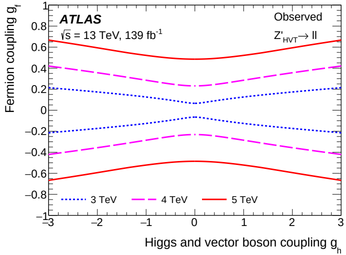
for $x = m_{\ell\ell}/\sqrt{s}$ and parameters b and p_i with $= 0, \cdots, 3$ are left free in the fit to data and independent for dielectron and dimuon channels. The parameter c is 1 for the dielectron and $1/3$ for the dimuon channel. $f_{\mathrm{BW,Z}}(m_{\ell\ell})$ is the non-relativistic Breit-Wigner with $m_Z = 91.1876$ GeV and $\Gamma_Z = 2.4952$ GeV.

Dilepton: $m_{\ell\ell}$ fit range starts at 225 GeV

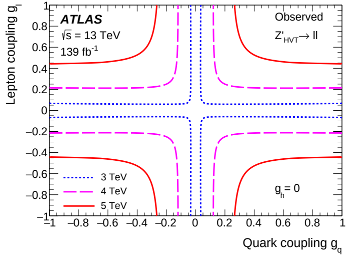
[Phys. Lett. B 796 (2019) 68]

The chosen fit range of $m_{\ell\ell} \in [225\ \text{GeV}, 6\ \text{TeV}]$ is mainly affected by the Z peak region, which starts to modify the spectrum towards lower $m_{\ell\ell}$. Studies with modified fit ranges show that a lower starting point of the fit yields higher spurious signal values.

- Dilepton upper limits converted to exclusion contours in the HVT model coupling space
- g_i are coupling strength between the triplet field for
  - g_ℓ: leptons
  - g_q: quarks
  - g_h: Higgs
- Area outside of curves is excluded at the 95% CL



$\{g_h, g_f\}$ with $g_f \equiv g_\ell = g_q$



$\{g_q, g_l\}$ with $g_h = 0$

Lepton + MET: high p_T single-lepton triggers [Phys. Rev. D 100 (2019) 052013]

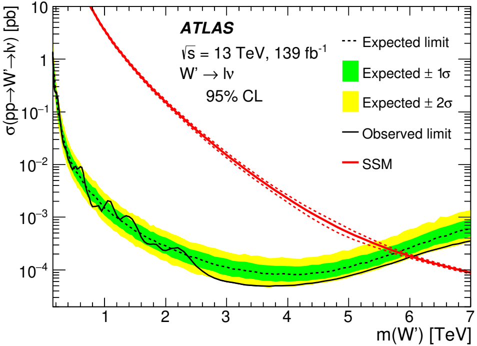
- Uses high p_T single-electron or single-muon triggers to fight against Drell-Yan W background
  - e: $p_T > 60$ GeV
  - e: $p_T > 140$ GeV (worse electron id)
  - μ: $p_T > 50$ GeV

Lepton + MET: low m_T MC/data discrepancy [Phys. Rev. D 100 (2019) 052013]

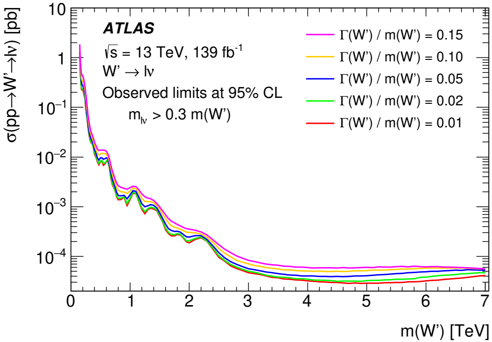
Throughout Run-2, a modeling issue has been observed, leading to a higher yield in data than in MC in the low end of the signal region m_T distribution. The issue has been observed in both the electron and muon channels, and is assumed to be predominantly due to an issue with the modeling of the non-leptonic event activity, such as jet emissions, parton shower, and/or underlying event, and/or the corresponding modeling of the detector response to this activity (jet reconstruction, E_T^{miss} soft term, etc.). Indeed it is the systematic uncertainties related to these effects, in particular to the jet energy resolution and E_T^{miss} soft term that allows a suitable description of the mismodeling in terms of nuisance parameter pulls in the statistical analysis. A large component of the mismodeling seems to be a better E_T^{miss} resolution in MC than in data, leading to a wider reconstructed W boson mass peak in the data than in MC, and a corresponding overshoot of data over MC in the steeply falling region at the high end of the peak.

Lepton + MET: Non-zero Width Limits

[Phys. Rev. D 100 (2019) 052013]



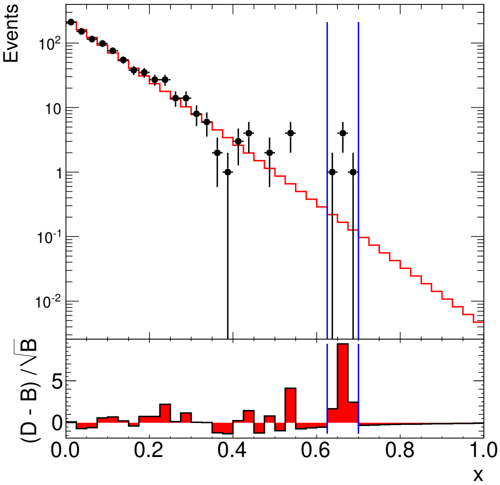
Combined upper limits on the SSM W' model



Combined upper limits on the SSM W' model for various widths

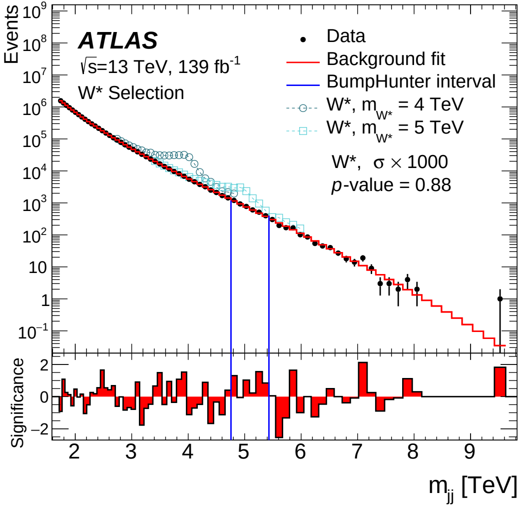
BumpHunter Algorithm

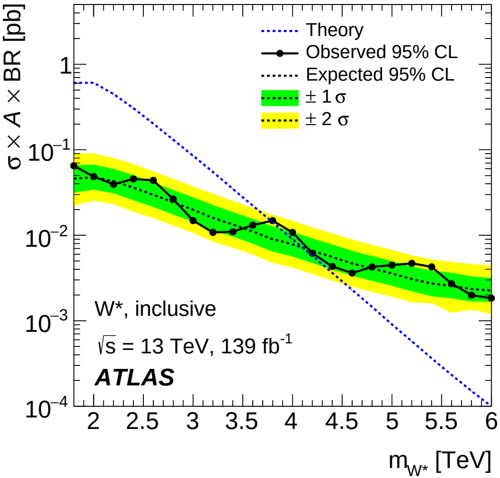
- PHYSTAT2011, arXiv:1101.0390
- BumpHunter: fit in varying width window to find region of data most discrepant with model and calculates global p-value (accounts for “look elsewhere effect”)



Example from PHYSTAT2011, arXiv:1101.0390

[arXiv:1910.08447]

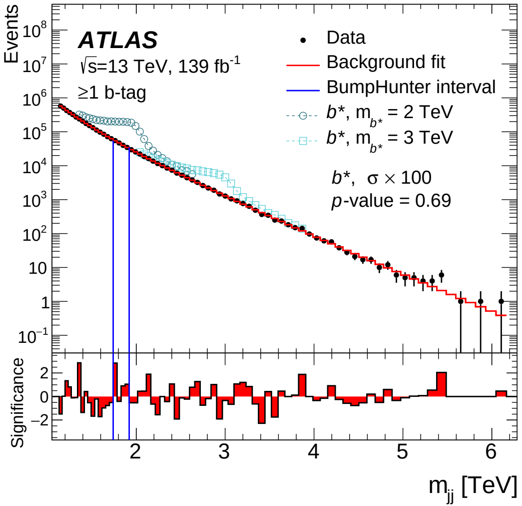


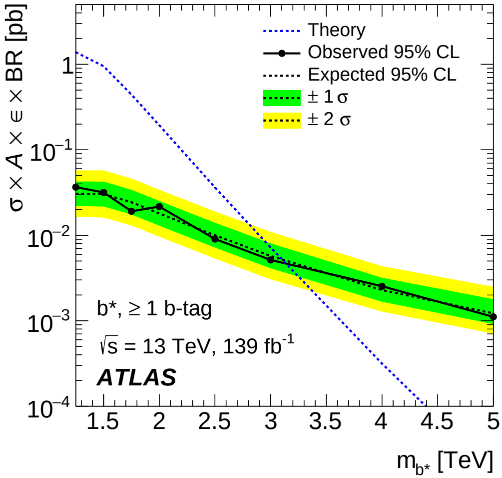


95% CL lower limit on m_{W^*} of 3.9 TeV

Dijet: b^* Limits

[arXiv:1910.08447]

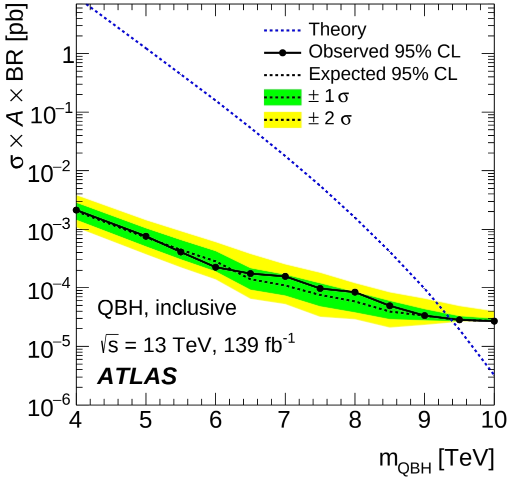




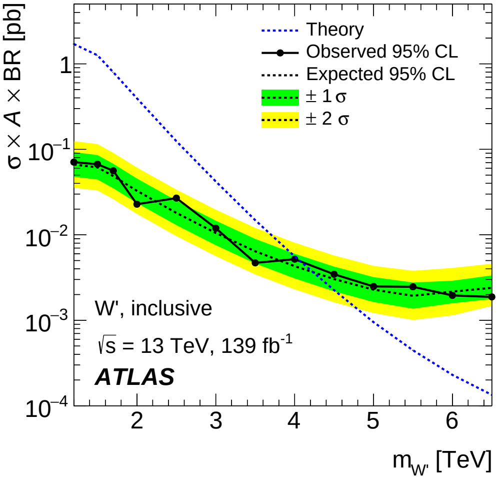
95% CL lower limit on m_{b^*} of 3.2 TeV

Dijet: QBH and W' Limits

[arXiv:1910.08447]



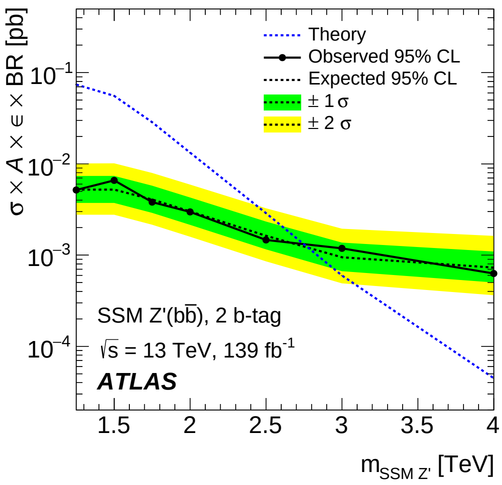
95% CL lower limit on m_{QBH} of 9.4 TeV



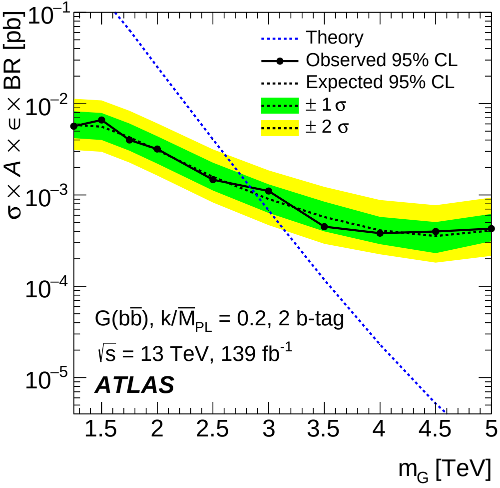
95% CL lower limit on $m_{W'}$ of 3.9 TeV

Dijet: Z'_{SSM} and Kaluza-Klein Graviton Limits

[arXiv:1910.08447]

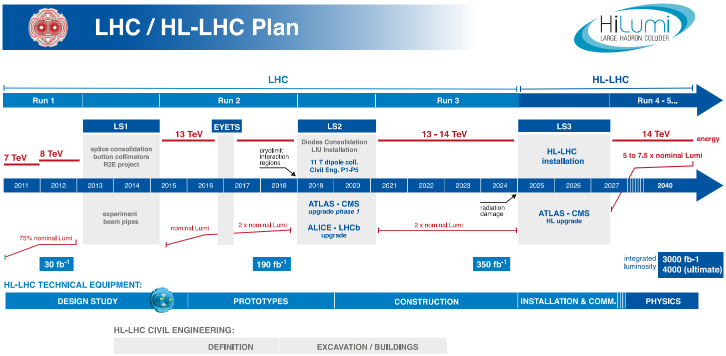


95% CL lower limit on $m_{Z'_{\mathrm{SSM}}}$ of 2.7 TeV



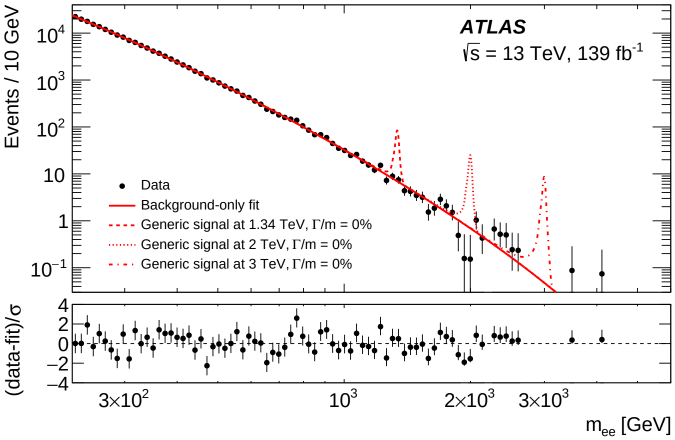
95% CL lower limit on m_G of 2.8 TeV

Long Shutdown 2, Run 3, and HL-LHC Schedule



The experiments would like to have more time to complete their upgrades. As a consequence, LS2 has been extended by two months [to May 2021], and LS3 has been delayed by one year [to 2025] to accommodate the extra time needed by ATLAS and CMS to finalise their Phase 2 upgrades while maximising the integrated luminosity from Run 3.
— Fabiola Gianotti, Director-General of CERN

Fractional Event Counts?



- Dilepton fit plots are representing events differential in mass (density not count)
- Plot has variable width bins, so the individual bin density (integer) needs to be scaled by the bin width scale factor to reach the plot density (Events/10 GeV)

$$\frac{\text{Events}}{10\text{ GeV}} = \frac{\text{Events}}{w\text{ GeV}} \cdot \left(\frac{10\text{ GeV}}{w\text{ GeV}}\right)$$