# Searches for new heavy gauge bosons at the LHC

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on behalf of the ATLAS and CMS collaborations

BLV 2019

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# New heavy gauge bosons

Appear in many extensions of Standard Model:

- Theories with Extra Dimensions
- Theories with strongly-coupled sector
- Models with SM group extensions
  - Neutral gauge boson (Z′), singlet or triplet
    - decays to ll, jj, tt, WW, ZH
  - Charged gauge boson:
    - W′, triplet, coupling to left-handed fermions
      - decays to lν, jj, tb, WZ, WH, Wγ
    - $W_R$, hypercharged singlet, couples to right-handed fermions
      - decays to $l\nu_R$, jj, tb, WZ, WH, Wγ
- ...

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  - Charged gauge boson:
    - **W'**, triplet, coupling to left-handed fermions
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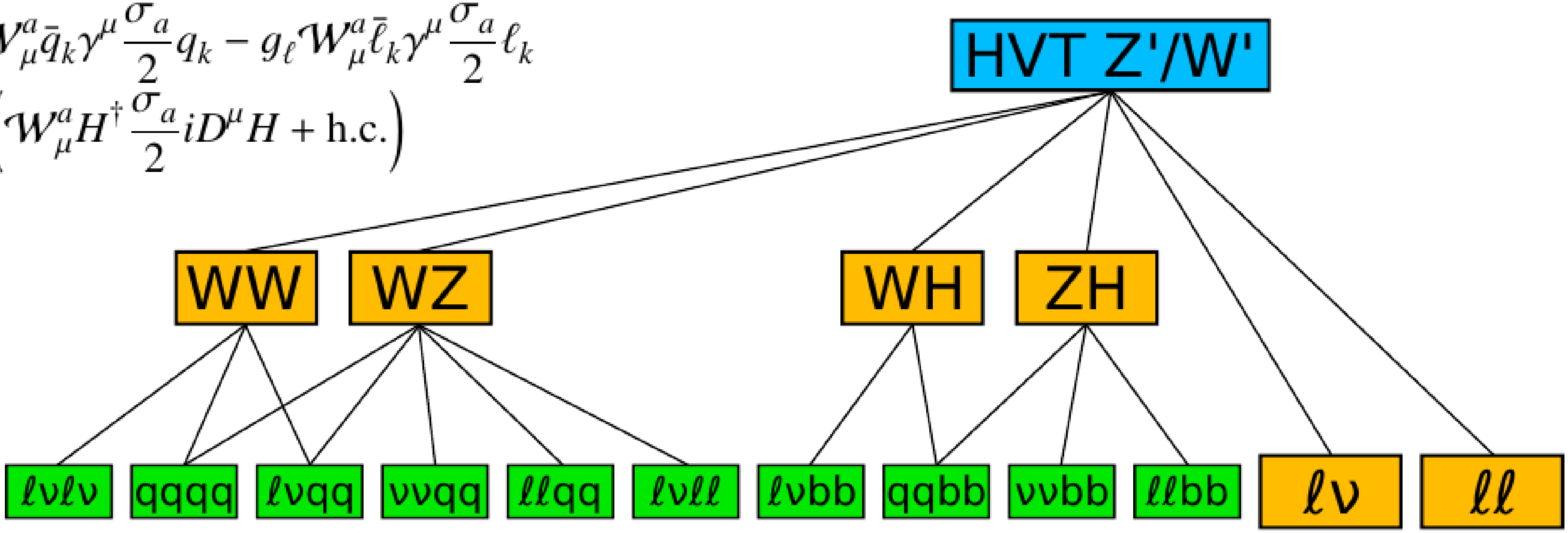
    - $\mathbf{W_R}$, hypercharged singlet, couples to right-handed fermions
      - decays to $\mathbf{l\nu_R}$, jj, tb, WZ, WH, Wγ
- ...

**+ combinations**

**This talk: focus on results from 2019 + combinations**

# Heavy Vector Triplet (HVT)

$$\mathcal{L}_{\mathcal{W}}^{\text{int}} = -g_q \mathcal{W}^a_\mu \bar{q}_k \gamma^\mu \frac{\sigma_a}{2} q_k - g_\ell \mathcal{W}^a_\mu \bar{\ell}_k \gamma^\mu \frac{\sigma_a}{2} \ell_k - g_H \left( \mathcal{W}^a_\mu H^\dagger \frac{\sigma_a}{2} i D^\mu H + \text{h.c.} \right)$$




- Simplified Heavy Vector Triplet (HVT) model
  - Triplet of colorless vector bosons $W'^{\pm}$, $Z'$
  - 4 free parameters (in universal case):
    - $g_q$ and $g_l$ : Universal coupling strength to quarks and leptons
    - $g_H$ : Coupling strength to Higgs field → enables diboson decays
    - $m_{V'}$: mass of W′ and Z′ bosons
    - Includes Sequential SM (SSM) W′: $g_q = g_l = 0.652$ & $g_H = 0$ (there is also a Z′ associated to this coupling point, but not SSM Z′ which is a singlet)

# More models

Heavy Vector Singlets Simplified approach

- In universal case 6 parameters ($g_H$, $g_l$, $g_e$, $g_q$, $g_u$, $g_d$, $m_{V'}$)
- Too many parameters to be usable

SSM Z′

- The same fermion couplings at the SM Z
- Width $\Gamma/m(Z')=3\%$
- Used as benchmark only

Grand Unification Model E6

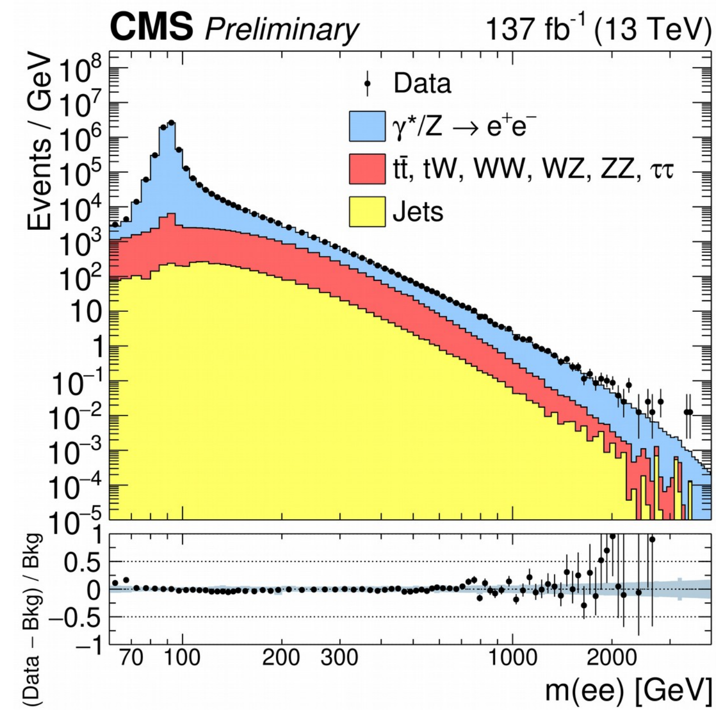
- E6 gauge group can be broken into SU(5) and two U(1): ψ and χ
  - $Z'(\theta_{E6}) = Z'_\psi \cos(\theta_{E6}) + Z'_\chi \sin(\theta_{E6})$, where mixing angle $0 \leq \theta_{E6} < \pi$
  - Width of resonances varies from 0.6% for $Z'_\psi$ to 1.2% for $Z'_\chi$
- E6 gauge group can be broken into SU(4), $SU(2)_L$, $SU(2)_R$ and a U(1)
  - This results in so-called left-right symmetric models with $W_R$ and various Z′s

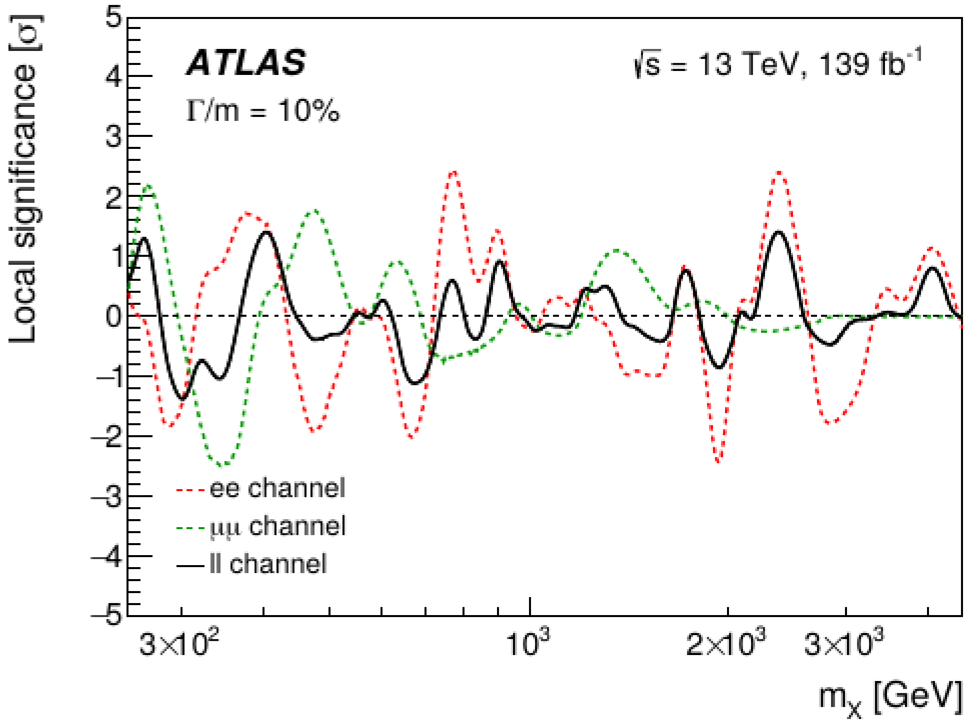
# Z’→ dileptons (l=e, μ)

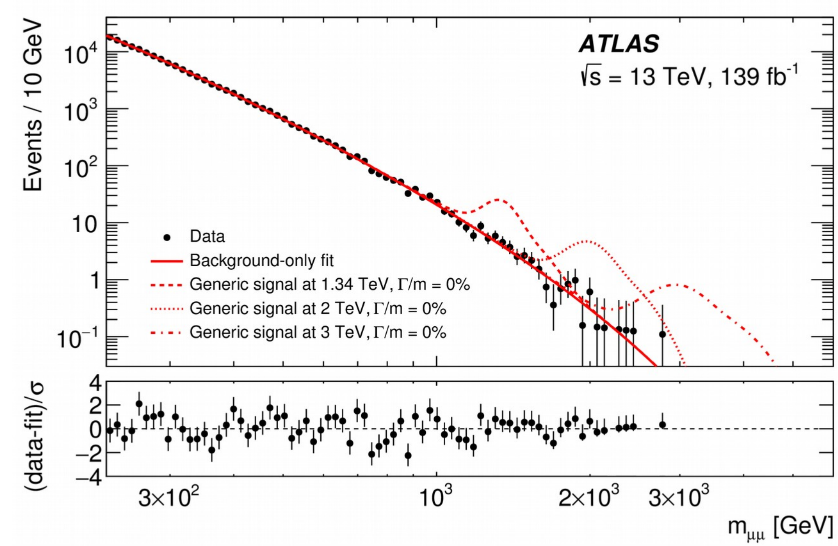
Phys. Lett. B 796 (2019) 68, CMS-PAS-EXO-19-019

# Z'→ dileptons (l=e, μ)

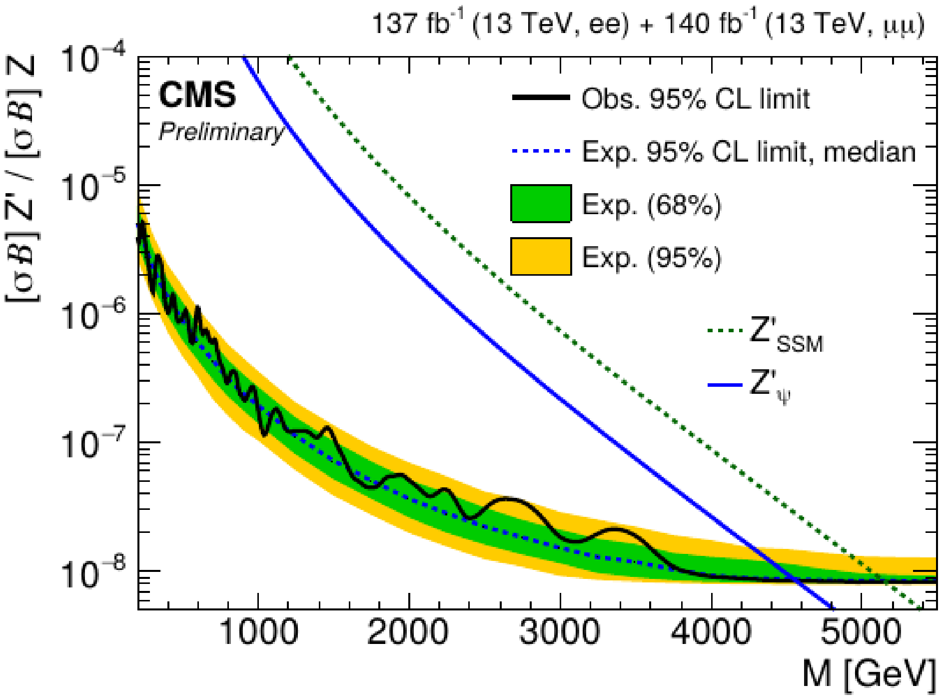
- Inclusive dilepton selection
- Signal model: Breit-Wigner⊗Resolution
  - ATLAS Γ=0-10%; CMS Γ=0.6%
- Background model:
  - CMS: discovery MC-based; limit sliding window fit
  - ATLAS: global $m_{ll}$ spectra fit in data (0.25-6TeV)
- No evidence for new ll resonances in Run 2 data

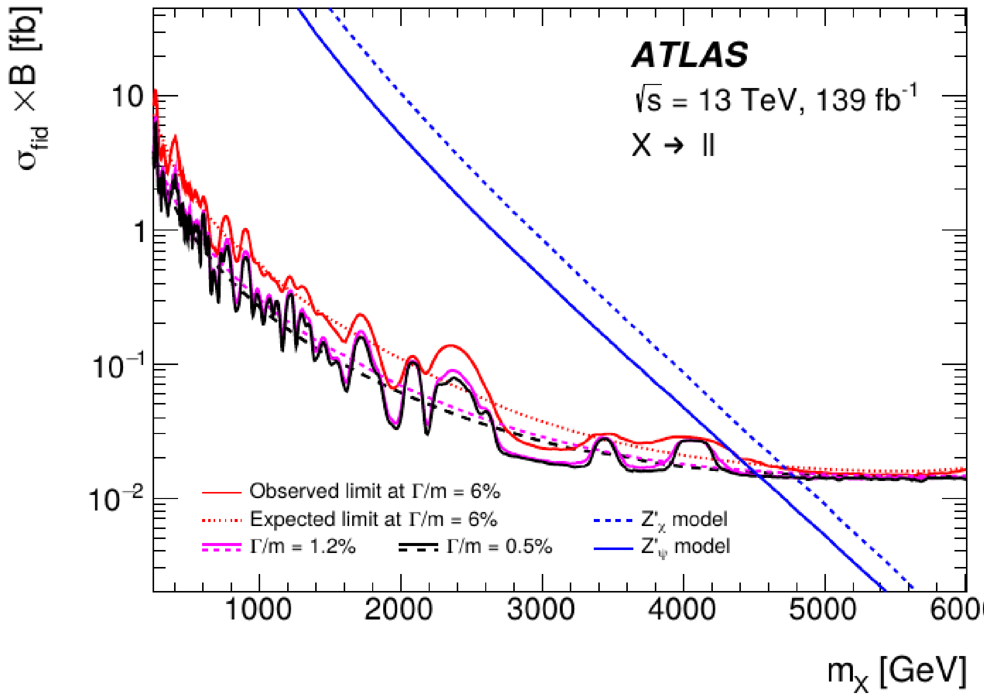


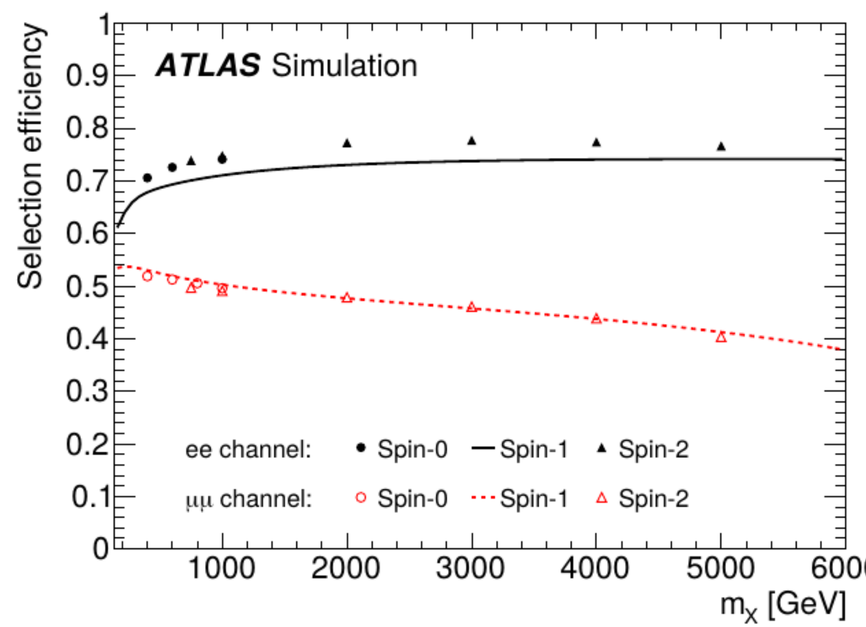



# Z’→ dileptons (l=e, μ)




- Observed limits on $Z'_\psi \to ll$:
  - CMS 4.56, ATLAS 4.5 TeV
- Easily reinterpretable to any model
  - ATLAS fiducial σ×B limits applicable to spin-0/1/2 signals
  - CMS efficiency ee (μμ) 60-67 (93)%
  - Available in ee and μμ channels
- No unfolded results available yet, but possibility to “fold” new BSM models
  - Parametrisation of dilepton resolution as a function of $m_{ll}$ available on HEPdata

# W'→ lν (l=e, μ)

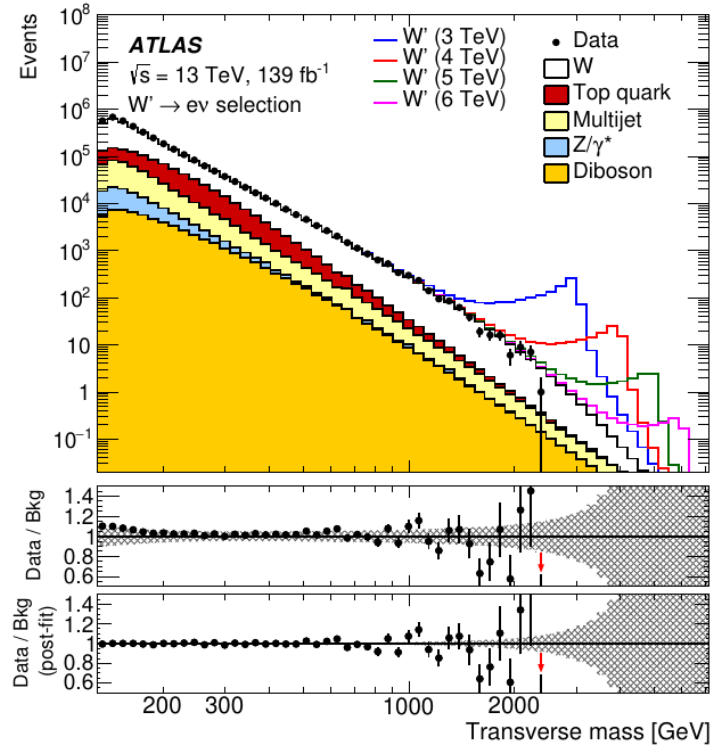
Phys. Rev. D 100 (2019) 052013

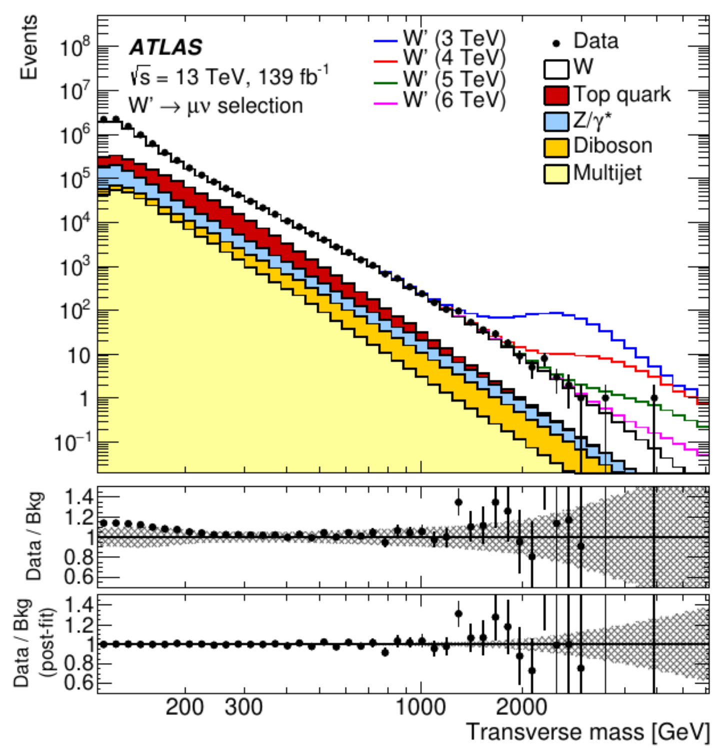
# W’→ lν (l=e, μ)

- Lepton +$E_t^{miss}$ requirement
  - $E_T^{miss}$= | $\Sigma_{vec}p_T$(signal leptons + photons + jets) | +(soft term)
  - Veto on second isolated lepton
  - Transverse mass:

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

- MC used for all bkgs except for fake electrons contributions
- Global significance for lowest p-value
  - eν (μν) at m(W') = 625 GeV (200 GeV): 1.3 (0.4) standard deviations.
  - lν at m(W') = 625 GeV is -0.5 standard deviations.
- Interference between W’ signal and SM Drell-Yan background is neglected



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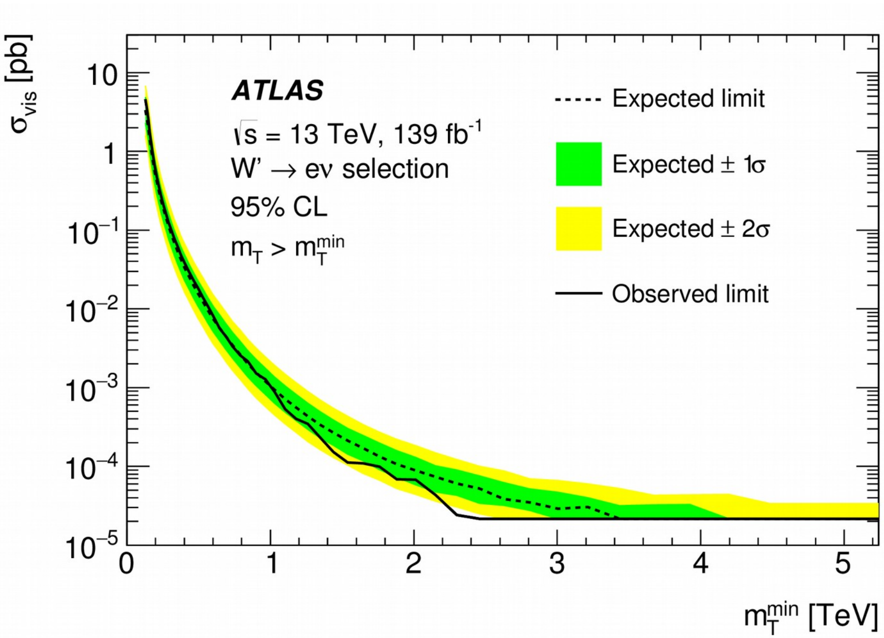
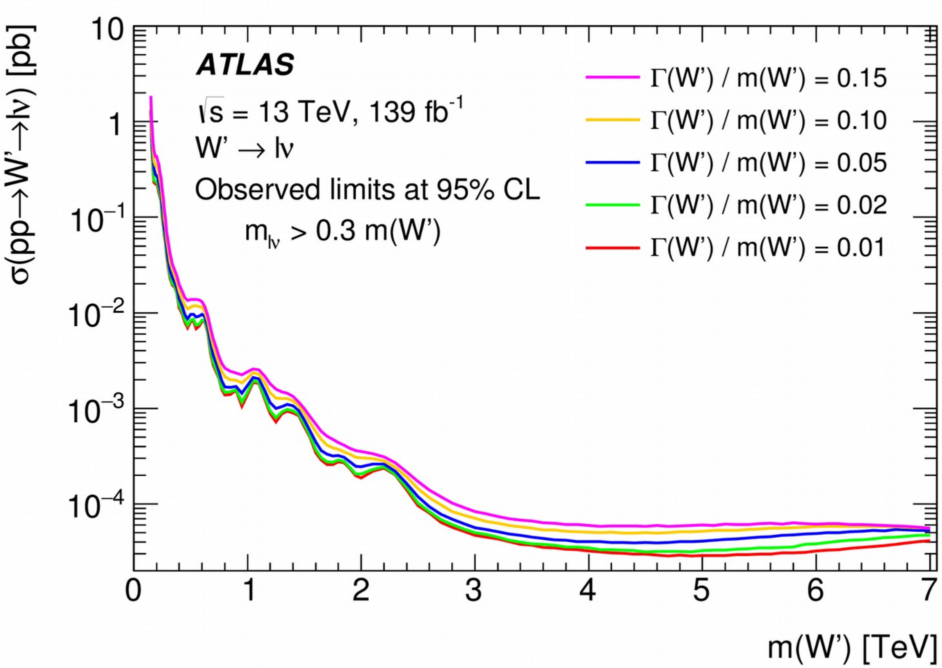
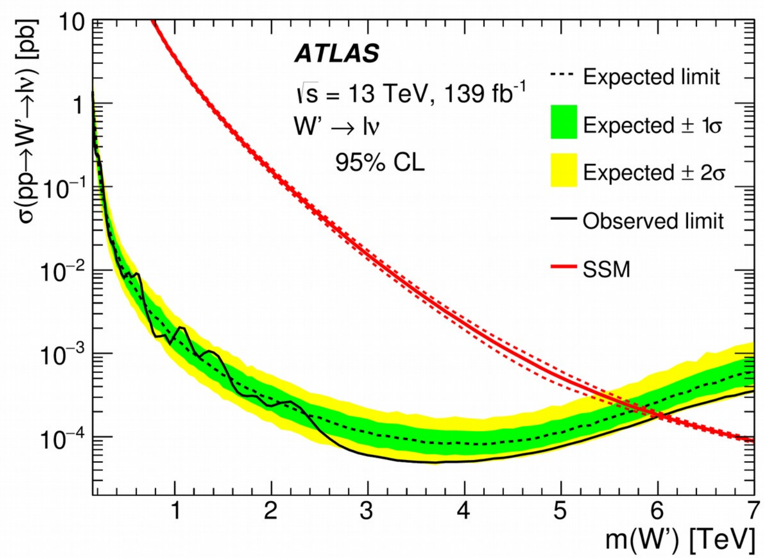



- Provided model-indepedent single-bin cross-section limits ($N_{sig}$/Lumi)
  - $m_T^{min}$ varies in 0.13(0.11)-5.127GeV range for eν(μν) channels
- Generic cross-section limits for Γ/M=1-15% in 0.15-6TeV range



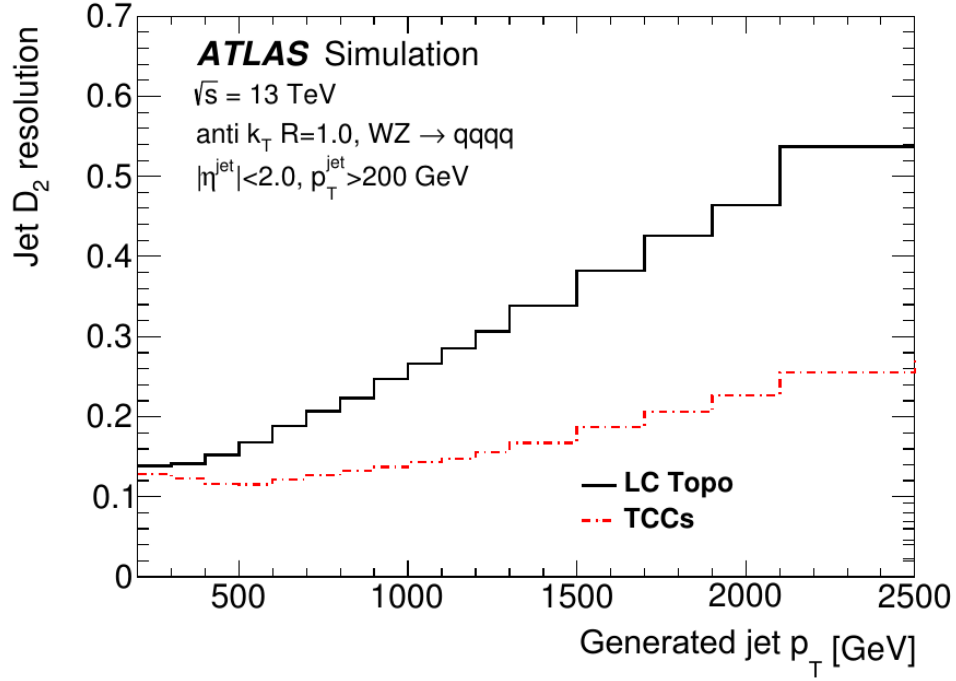

| Decay | $m(W')$ lower limit [TeV] Observed | Expected |
|---|---|---|
| $W' \to e\nu$ | 6.0 | 5.7 |
| $W' \to \mu\nu$ | 5.1 | 5.1 |
| $W' \to \ell\nu$ | 6.0 | 5.8 |

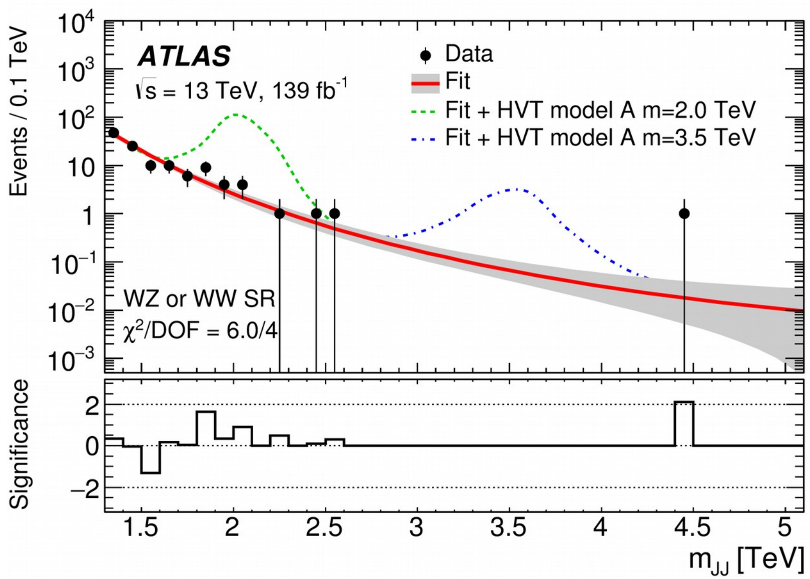
# V’→ JJ (V’=Z’ or W’)

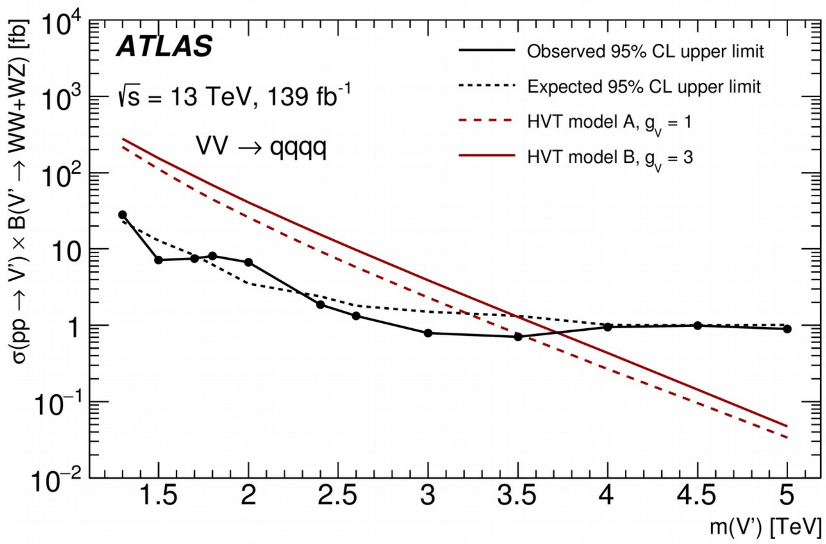
- High momentum hadronic decays of the W/Z are very collimated – use large R = 0.8 or 1 fat jets
- Main background: QCD multijets
- JHEP 09 (2019) 091 and arXiv:1906.05977

# ATLAS V’→ JJ (V’=Z’ or W’)

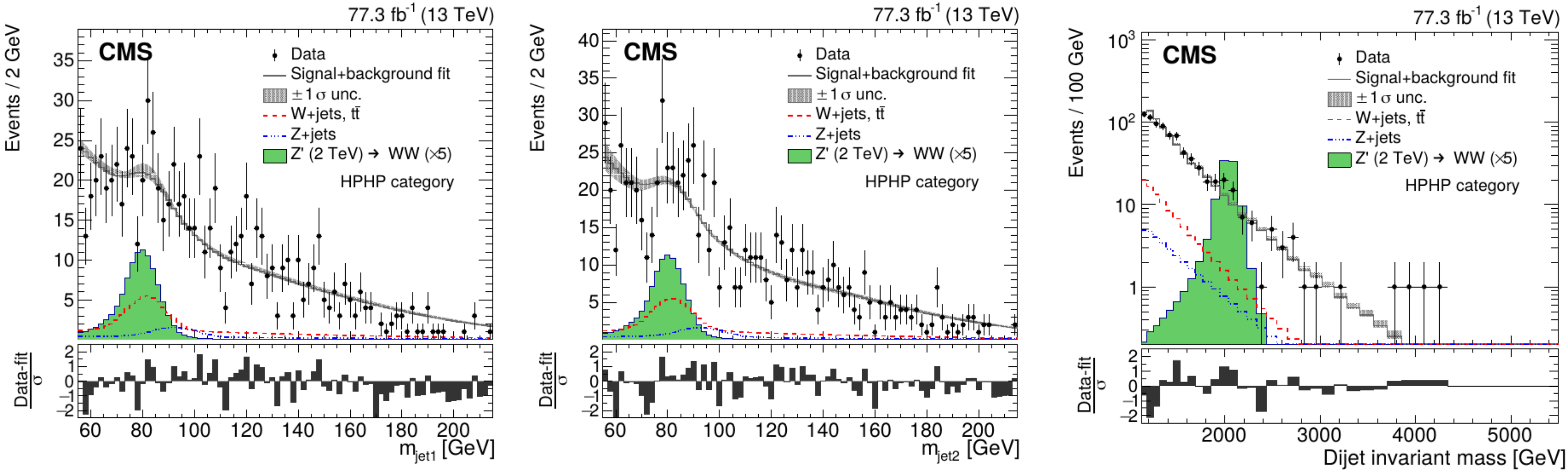
- Granularity limits of calorimeter – use angular track information to improve spatial resolution
  (Track-CaloClusters, TCC)
  - Remove soft components from pileup (trimming)
- New W/Z boson taggers use jet substructure (jet mass, $D_2$ and number of tracks)
  - charged hadron multiplicity to reduce multi-jet background with radiated gluon that can mimic 2 prong structure

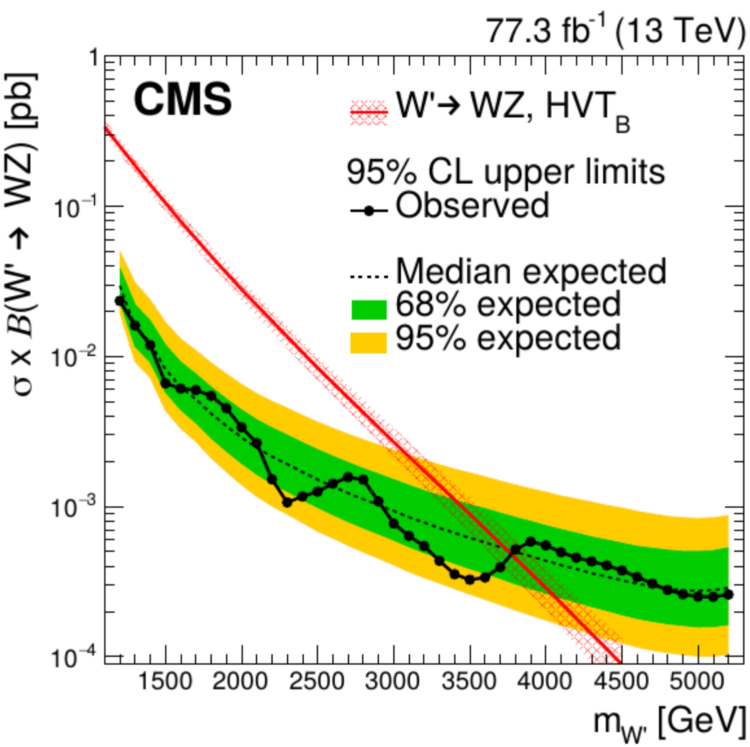


# CMS V'→ JJ (V'=Z' or W')



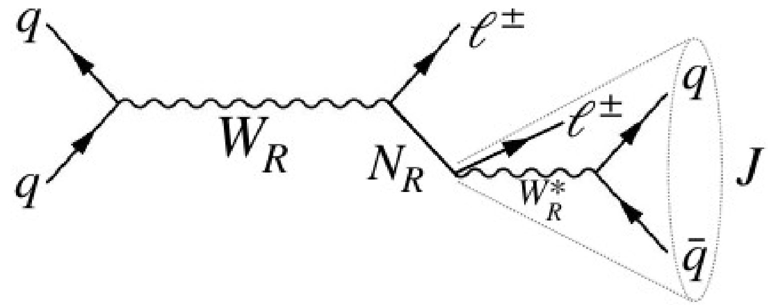

- Jets are groomed with soft-drop (modified mass-drop) tagger, removing soft radiation constituents
  - Jet mass from 4-momentum of groomed jet
- Use „designed decorrelated tagger" (DDT) method to decorrelate n-subjettiness ratio from jet mass and $p_T$
- 3D fit in $m_{jet1}$, $m_{jet2}$ and $m_{jj}$
- No excess over background stimation
- CMS limits m($W'_{HVT}$)>3.8TeV ($77fb^{-1}$)
  - The same as ATLAS limit on $140fb^{-1}$
  - Limits on $Z'_{HVT}$ also available

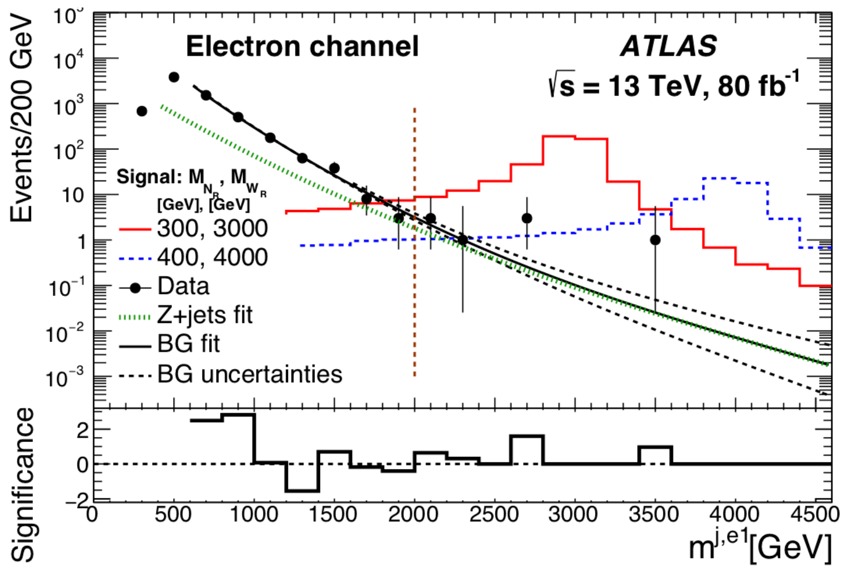
# $W_R \to lN_R \to llqq$

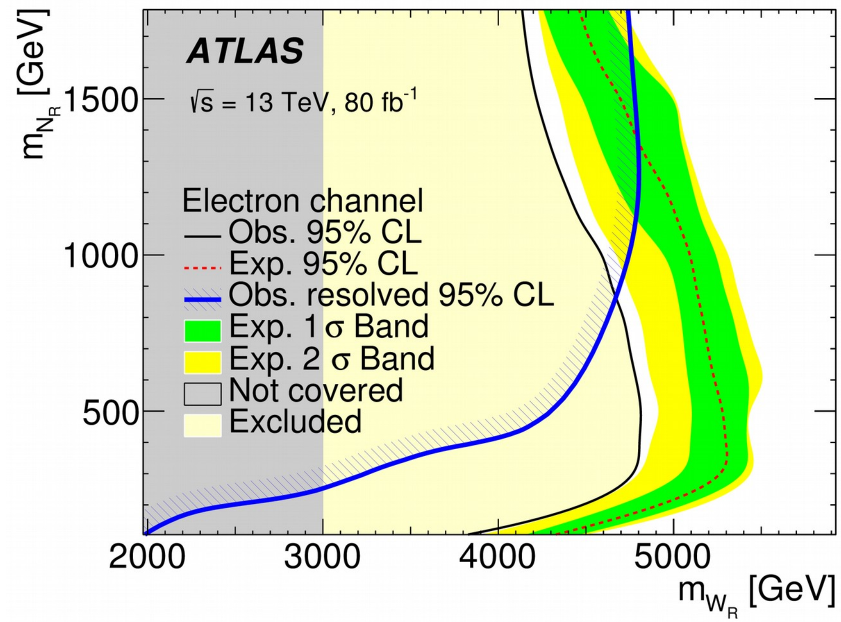
Phys. Lett. B 798 (2019) 134942

# $W_R \rightarrow l N_R \rightarrow llqq$

- Framework of L-R symmetric models
  - SM-singlet heavy neutrinos $N_R$
- Focus on $m(N_R)/m(W_R) \leq 0.1$
  - $N_R$ can be highly boosted
  - quarks merge: large-R jets
  - electrons: $m(N_R) = m(J)$
  - muons: $p(N_R) = p(J)+p(\mu_2)$
- SR: $m(W_R)$>2 TeV, same-flavour leptons, single bin search
  - dominant bkg is ttbar, fitted in $m(W_R)$<2 TeV, extrapolated to SR
- Excluded region extends to $m(W_R)$~5 TeV for both channels, for $m(N_R)$ of 0.4-0.5 TeV
- Much more sensitive with respect to the resolved channel at small $N_R$ masses (JHEP 01 (2019) 016)
- Muon channel in backup





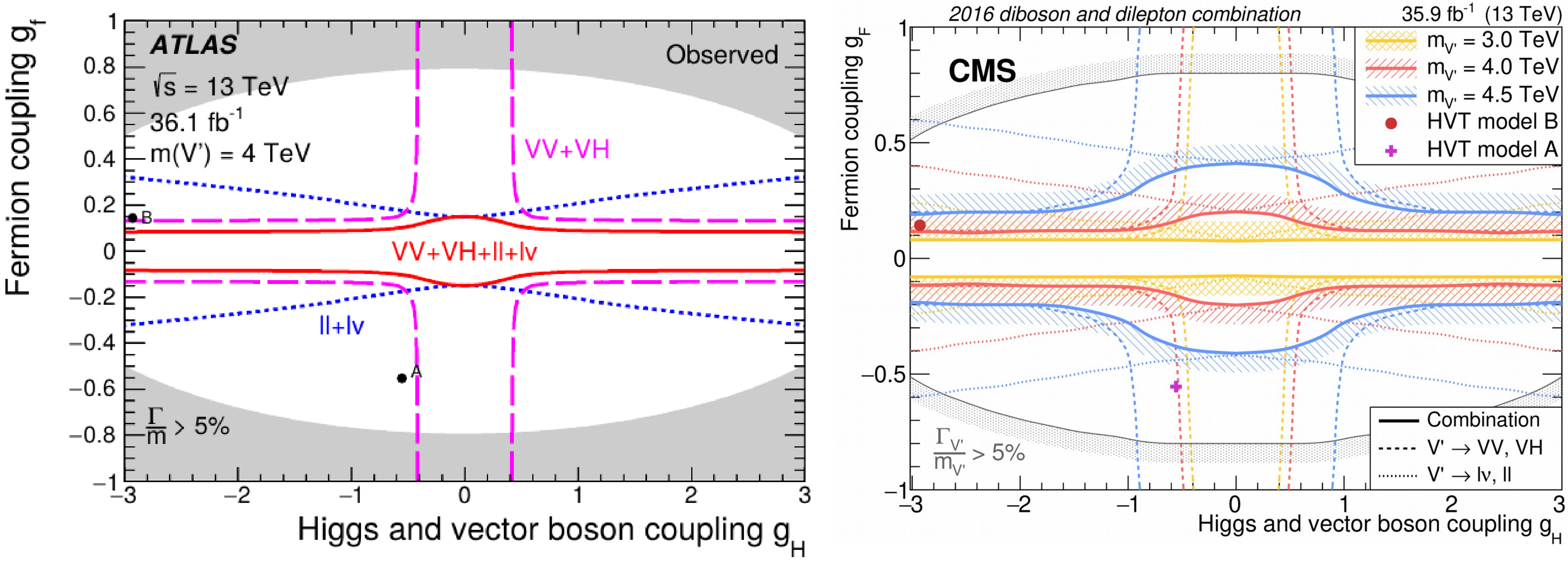
# Combinations

PRD 98(2018)052008 and PLB 798 (2019) 134952

- Heavy new resonances might decay into various final states
- Combination allows to increase sensitivity

# Combinations

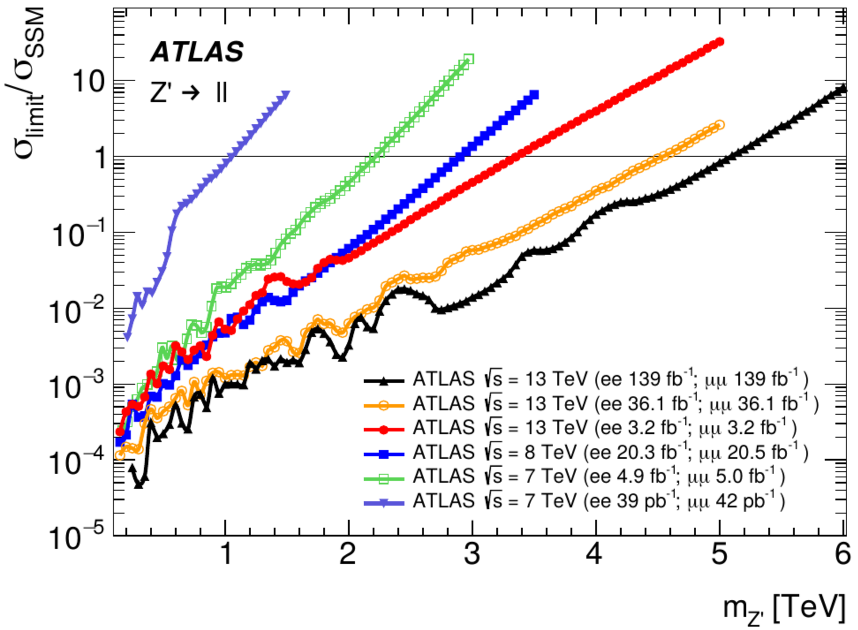
- Gain from statistical combination important where VV/VH and ll/lv are similarly sensitive
  - VV/VH: Excludes large $g_H$ regions; branching fracti ons → 0 for $g_H \to 0$
  - lv/ll: Provides sensitivity for small $g_H$ and high $g_F$




  - At high mass single channel full Run 2 limits from W′→lv are stronger than combination in certain areas of phase space
  - Important to keep up & extend this effort to include jj, bbar, ttbar, ττ etc. channels

# Conclusions

- Not many full Run 2 results yet directly relating to BLV in the sector of vector resonances
- These and other analyses can be found at
  - http://cms.web.cern.ch/news/cms-physics-results
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic

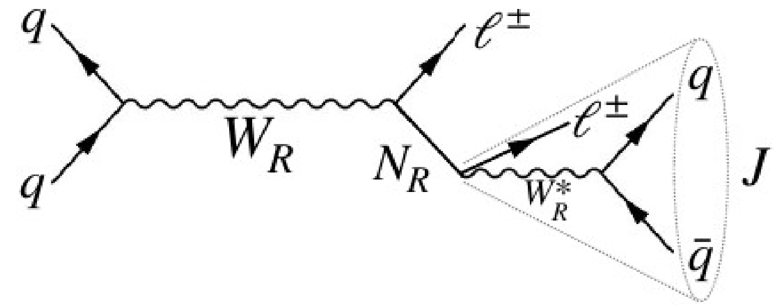


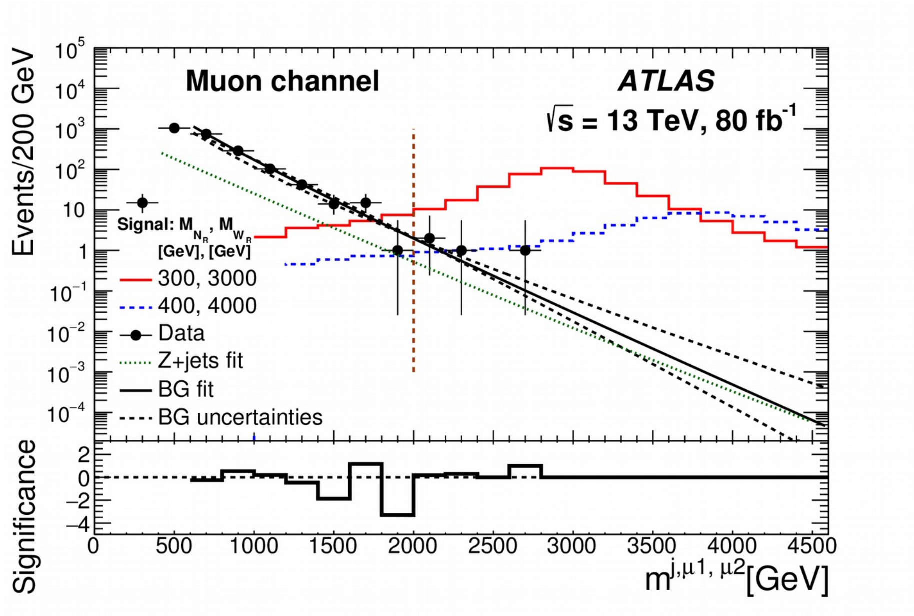

- More ATLAS and CMS results are soon to come
- Stay tuned!

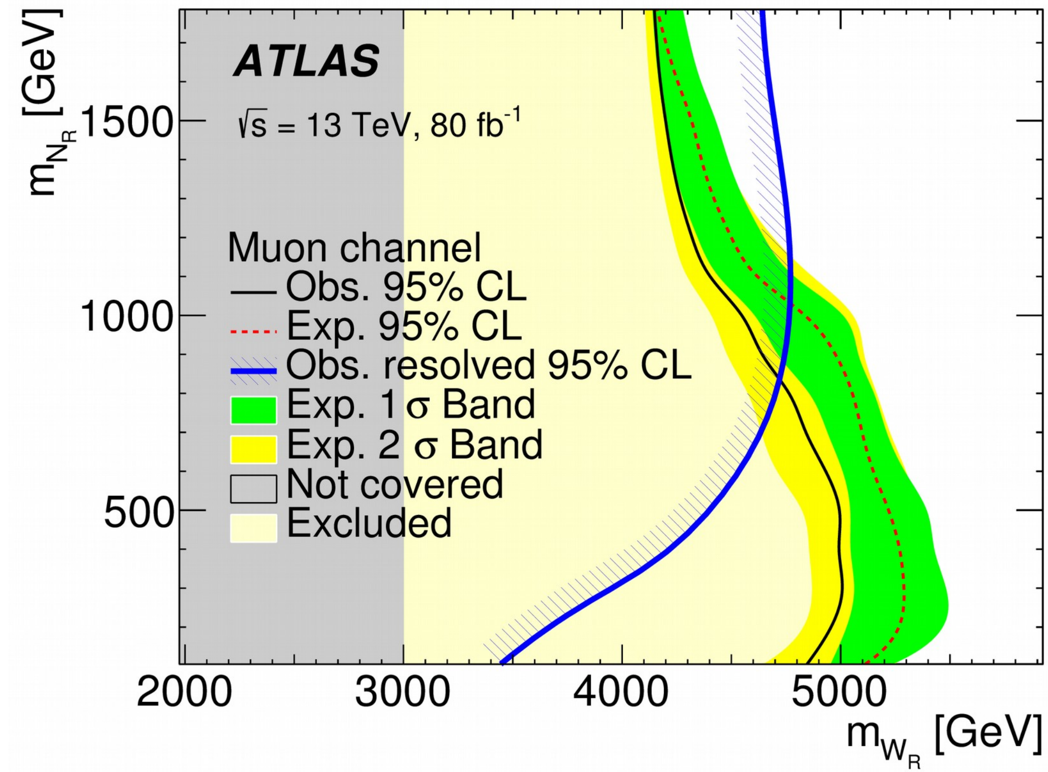
THANK YOU!

# Backups

# $W_R \to lN_R \to llqq$

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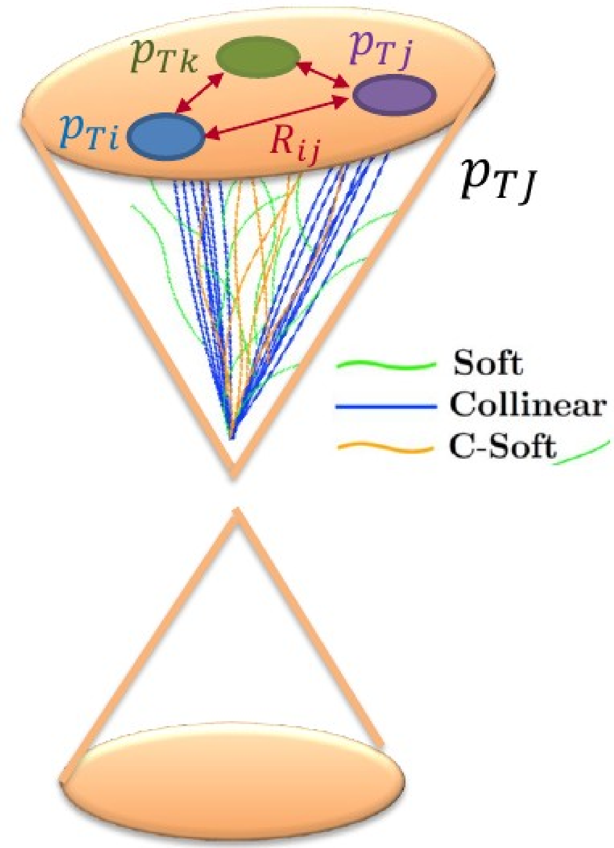
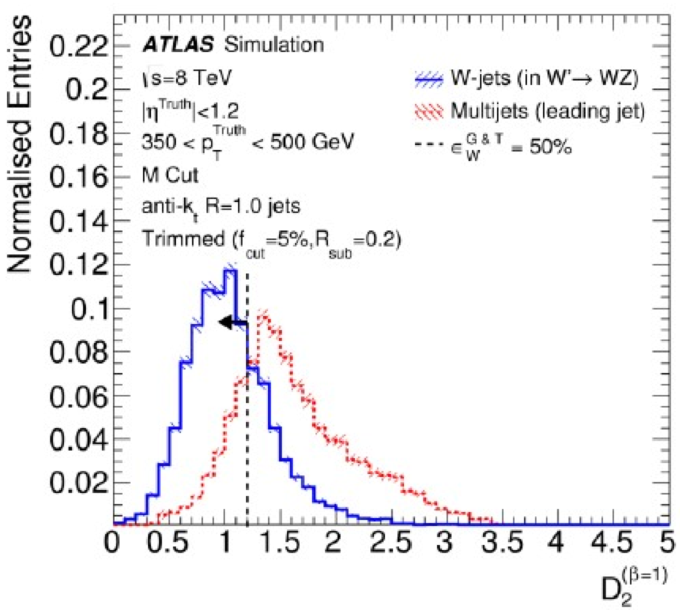
- Much more sensitive with respect to the resolved channel at small $N_R$ masses (JHEP 01 (2019) 016)

# ATLAS V'→ JJ (V'=Z' or W')

Diagram from N. Illic LHCP 2019

- Granularity limits of calorimeter – use angular track information to improve spatial resolution (Track-CaloClusters, TCC)
  - Remove soft components from pileup (trimming)
- New W/Z boson taggers use jet substructure (jet mass, $D_2$ and number of tracks)
  - charged hadron multiplicity to reduce multi-jet background with radiated gluon that can mimic 2 prong structure




$$e_2^{(\beta)} = \frac{1}{p_{TJ}^2} \sum_{1\le i<j\le n_J} p_{Ti}p_{Tj}R_{ij}^{\beta} \,,$$

$$e_3^{(\beta)} = \frac{1}{p_{TJ}^3} \sum_{1\le i<j<k\le n_J} p_{Ti}p_{Tj}p_{Tk}R_{ij}^{\beta}R_{ik}^{\beta}R_{jk}^{\beta}$$

$$D_2^{(\beta)} = \frac{e_3^{(\beta)}}{(e_2^{(\beta)})^3}$$

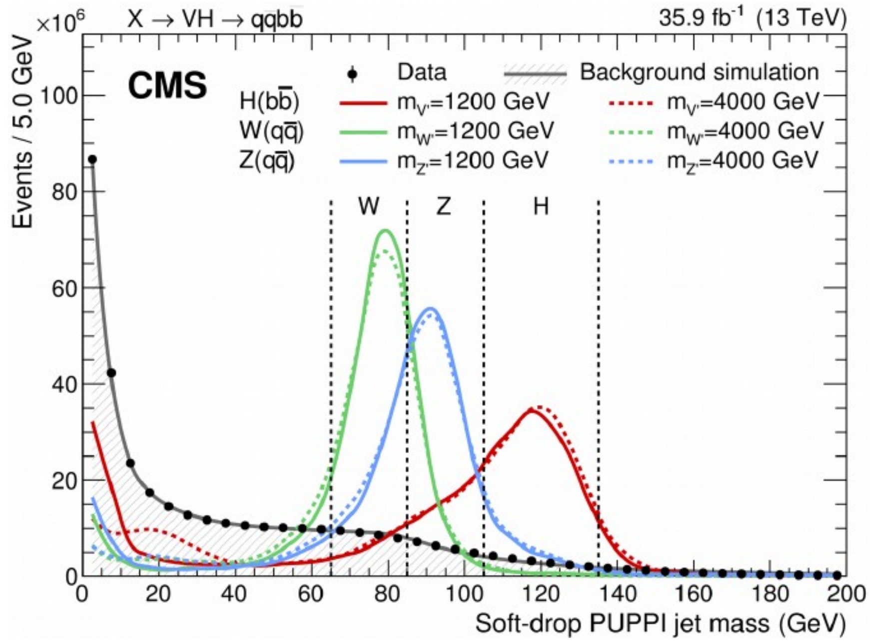
Energy correlation ratios

Eur. Phys. J. C (2016) 76:154

# CMS V'→ JJ (V'=Z' or W')

EPJC 77 (2017) 636

- Jets are groomed with soft-drop (modified mass-drop) tagger, removing soft radiation constituents
  - Jet mass from 4-momentum of groomed jet
- Use „designed decorrelated tagger" (DDT) method to decorrelate n-subjettiness ratio from jet mass and $p_T$
  - M=-0.08 (from MC), μ=1GeV




$$\tau_N = \frac{1}{r_0} \sum_k p_{T,k} \min(\Delta R_{1,k}, \Delta R_{2,k}, \ldots, \Delta R_{N,k}),$$

$$r_0 = R_0 \sum_k p_{T,k}$$

$$\tau_{21} = \tau_2/\tau_1$$

$$\tau_{21}^{DDT} = \tau_{21} - M\rho',$$

$$\rho' = \ln(m_{jet}^2/(p_T\mu))$$