Search for a new heavy boson W' decaying to a top quark and a bottom quark with the ATLAS detector

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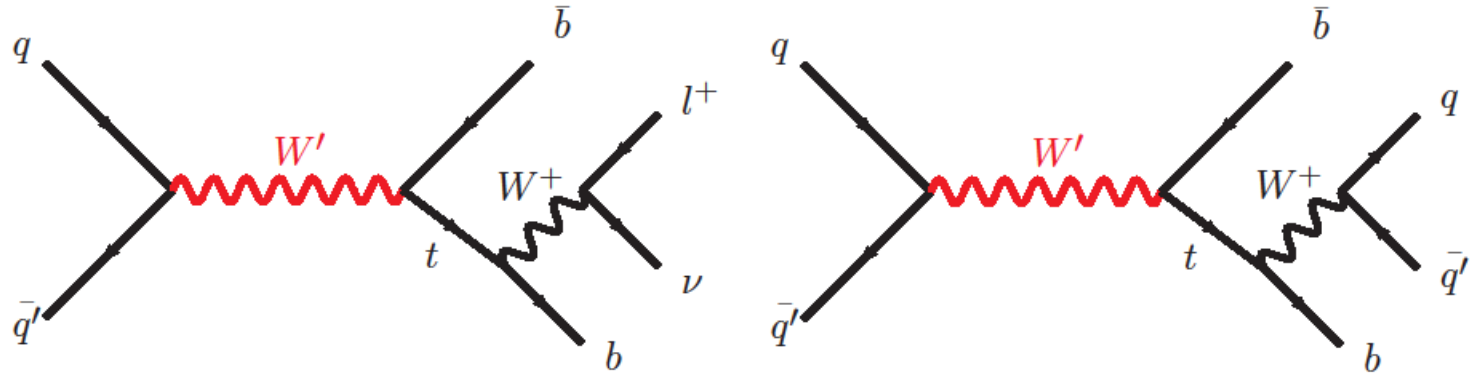
CLHCP2023, 19th November

Overview

Full Run-2 data W' search

in tb final states

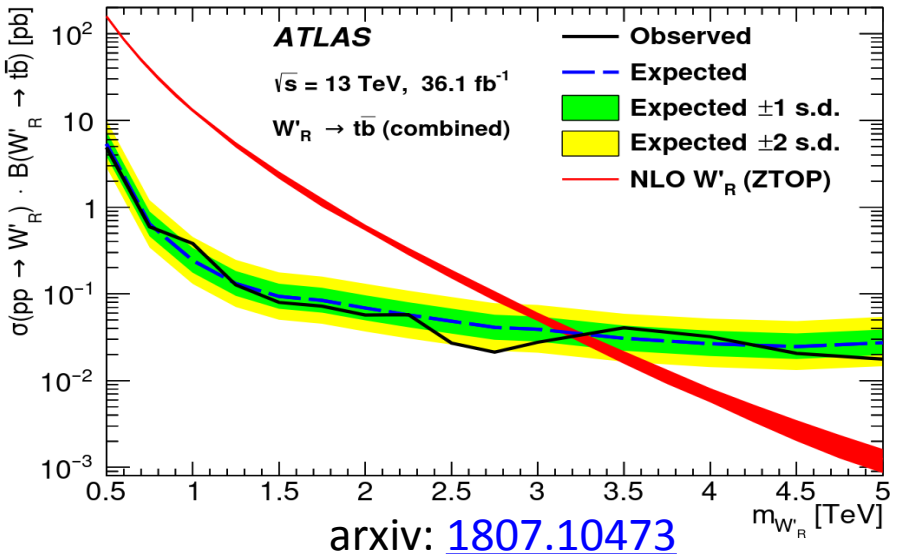
$qqbb$ and $lvbb$ channel



General Information

- Two channels are studied separately, combined at the end
  - 0L: 1 top-quark (AntiKt10 jet) and 1 b-quark (AntiKt4 jet)
  - 1L: 2 b-quark (AntiKt4 jet), 1 lepton and 1 neutrino (E_T^{miss})
- Reconstruct mass of tb
- MC + Data-driven estimated background
- Profile-likelihood fit on the m_{tb} spectrum

Previous Result



arxiv: 1807.10473

Outline

- $W' \rightarrow tb$ simulation

- Analysis strategy:
  - $W' \rightarrow tb \rightarrow qqbb$ (0L)
  - $W' \rightarrow tb \rightarrow l\nu bb$ (1L)

- Results, in terms of upper limit
  - 0L, 1L and combination
  - Right-handed and Left-handed
  - 1D and 2D

Signal model and sample

W' appears in several BSM scenarios, such as extra dimensions, strong dynamics or composite Higgs
W' is the mediator of a new massive charged vector current

- An effective Lagrangian is used to capture the relevant phenomenology of a W' decaying into tb

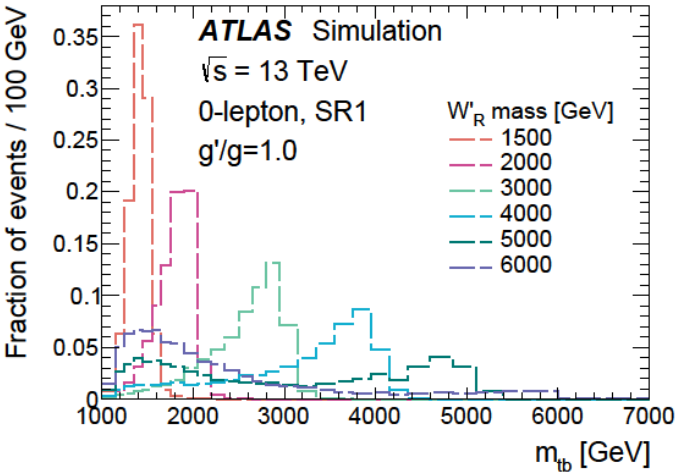
$$\mathcal{L} = \frac{V'_{ij}}{2\sqrt{2}} \bar{f}_i \gamma_\mu \left(g'^R_{i,j}(1+\gamma^5) + g'^L_{i,j}(1-\gamma^5) \right) W'^\mu f_j + h.c.$$

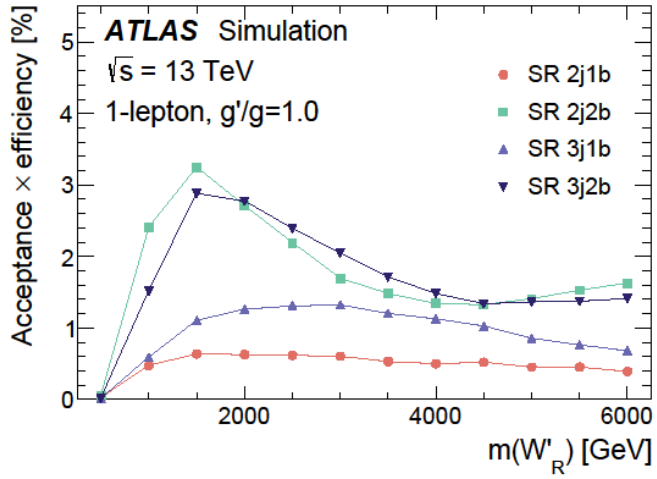
- Handeness and mass are free parameters, right-handed leptonic decay is forbidden ($m_{\nu_R} \gg m_{W'_R}$)

- The width is set to scale with square of g'/g: 2.6% (RH) or 3.5% (LH) $* M_{W'} * (g'/g)^2$

Phys.Rev.D86 (2012) 075018

- Signal sample: Madgraph pp $\rightarrow$ W' $\rightarrow tb$
  - Leading order scaled to NLO (k-Factor calculated by **ZTOP**)
  - W'_L and W'_R (no mixture), 500 GeV – 6 TeV in 1-lepton channel and 1.5 TeV – 6 TeV in 0-lepton channel
  - g'/g = 2.0 and 0.5 as starting point
    - Reweight to g'/g = 0.1~0.5 (0.1 step), 1.0~5.0 (0.5 step)





Xsec list & more plots

W'_L Interference with SM s-ch single top process

$$\hat{\sigma}(\hat{s}) = \frac{\pi\alpha_W^2}{6} V_{tb}^2 V_{ud}^2 \frac{(\hat{s}-M_t^2)^2(2\hat{s}+M_t^2)}{\hat{s}^2} \left[\frac{1}{(\hat{s}-m_W^2)^2+\gamma_W^2 m_W^2} + \right.$$

$$+2a_{ud}^L a_{tb}^L \frac{(\hat{s}-m_W^2)(\hat{s}-M_{W'}^2)+\gamma_W^2\Gamma_{W'}^2}{((\hat{s}-m_W^2)^2+\gamma_W^2 m_W^2)((\hat{s}-M_{W'}^2)^2+\Gamma_{W'}^2 M_{W'}^2)} +$$

$$\left. + \frac{({a_{ud}^L}^2 {a_{tb}^L}^2 + {a_{ud}^R}^2 {a_{tb}^R}^2 + {a_{ud}^L}^2 {a_{tb}^R}^2 + {a_{ud}^R}^2 {a_{tb}^L}^2)}{(\hat{s}-M_{W'}^2)^2+\Gamma_{W'}^2 M_{W'}^2} \right]$$

SM W

interference

W'_L

DOI: 10.1016/j.physletb.2007.03.064

$$\frac{\hat{\sigma}_{int}}{\hat{\sigma}_{sig}} = \frac{2}{(g'/g)^2} \frac{(\hat{s}-m_W^2)(\hat{s}-M_{W'}^2)+\gamma_W^2(g'/g)^4\Gamma_{W'}^2}{(\hat{s}-m_W^2)^2+\gamma_W^2 m_W^2}$$

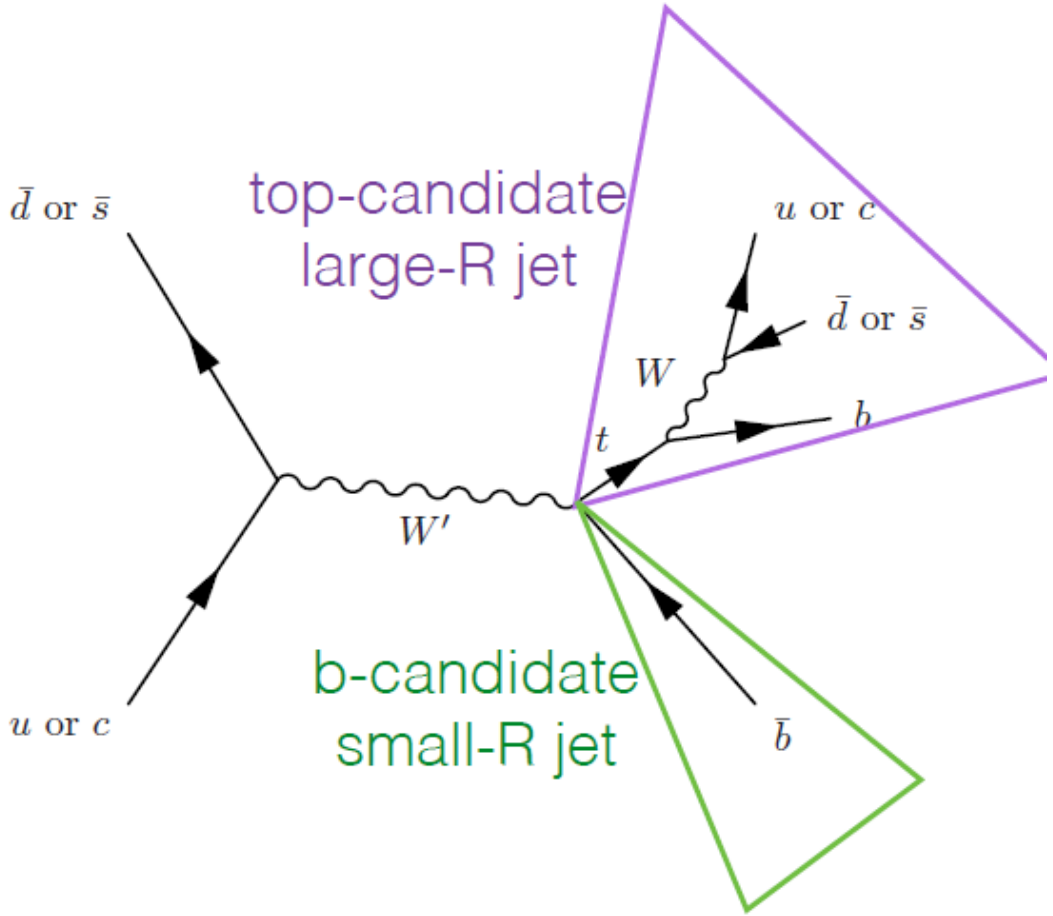
$\Gamma_{W'} = 3.45\,\% M_{W'}$; $\gamma_W = 2.09$ GeV; $m_W = 80.38$ GeV.

- LO differential cross-section formula is used to re-weight
- The ratio (as a function of truth m_{tb}) is implemented event by event

The interference component can be obtained from the signal sample we already had

Validation plots

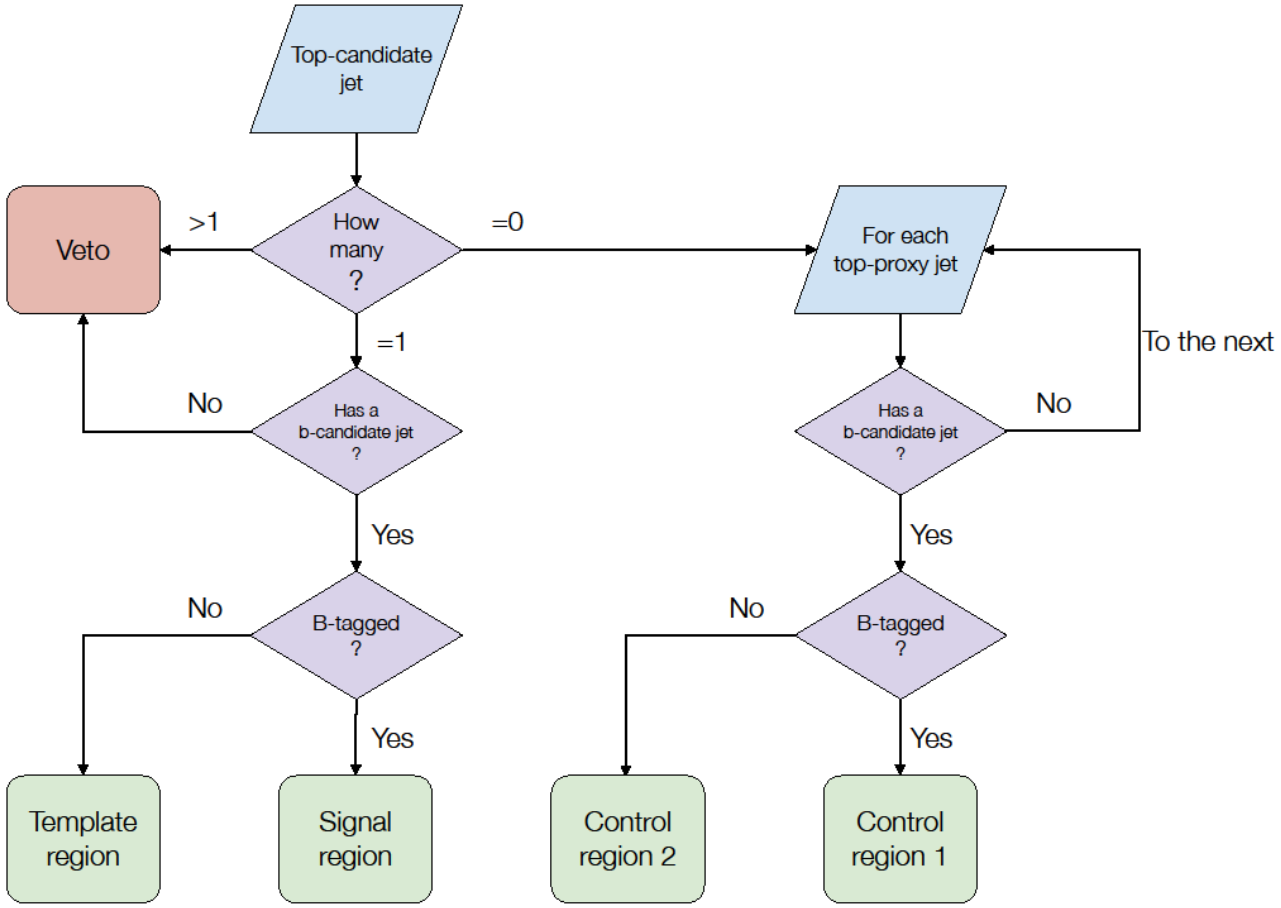
0-lepton: Object



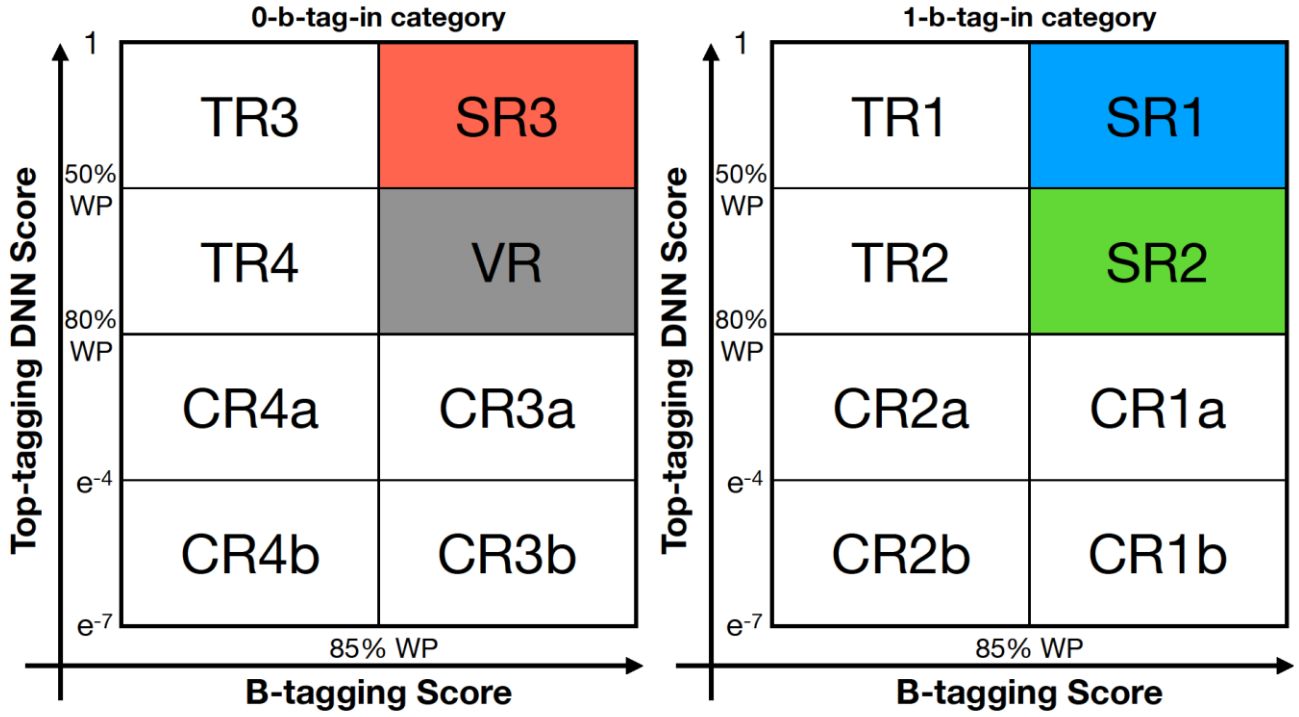
- Jet:
  - AntiKt10LCTopo large-R jet
    - DNN based top-tag: 50% WP (tight), 80% WP (loose)
  - PFlow small-R jet
    - DL1r b-tag 85% WP

0-lepton: Analysis strategy

- Select pairs of large-R jet + small-R jet
  - large-R jet: $p_T^J > 500$ GeV
    - If top-tagged (loose) -> top-candidate
    - If not top-tagged -> top-proxy
  - small-R jet leading small-R jet with $|\Delta\Phi(j,J)| > 2.0,\ p_T^j > 500$ GeV
    - -> b-candidate
- Categorisation: number of top-candidates
  - > 1: reject
  - = 1: keep and assign to SR/VR/TR
  - = 0: each pair of top-proxy and b-candidate -> CR
- $|\Delta\eta(t,b)| < 2$: suppress multijet background



0-lepton: Categorisation and Background estimation



- 3 SR -> Search regions, sensitive to W'
- VR -> Validate background estimation
- TR and CR -> Data-driven background estimation

- Background:
  - ttbar: MC, negligible in CR
  - QCD Multijet: Modified ABCD, data-driven

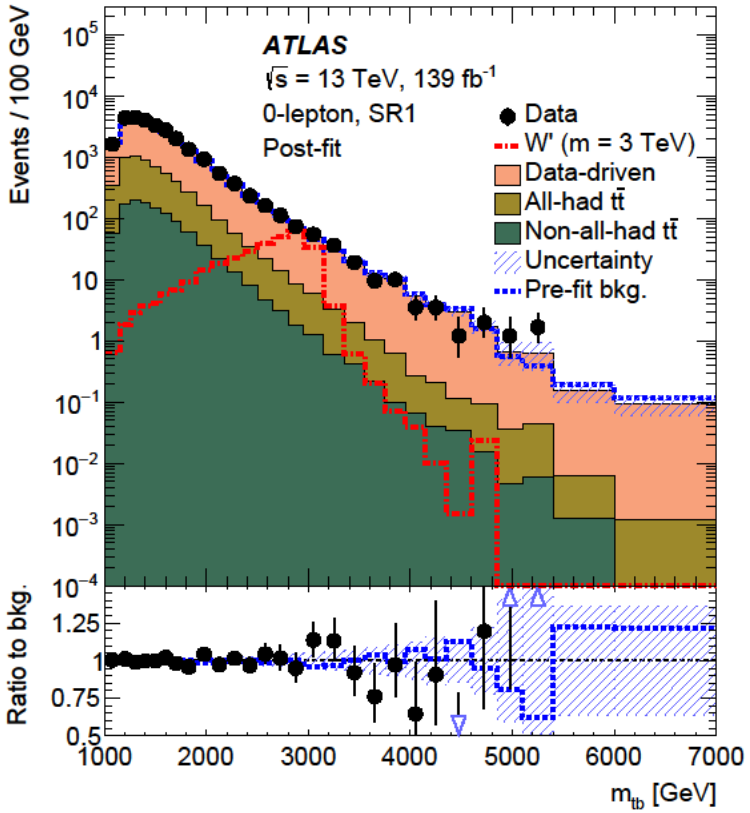
$$N^{\text{data-driven-background}}_{\text{SR1,SR2}}(i) = R^{1}_{\text{corr}}(i) \times \left(N^{\text{obs}}_{\text{TR1,TR2}}(i) - N^{t\bar{t}}_{\text{TR1,TR2}}(i)\right) \times \frac{N^{\text{obs}}_{\text{CR1a}}(i)}{N^{\text{obs}}_{\text{CR2a}}(i)}$$

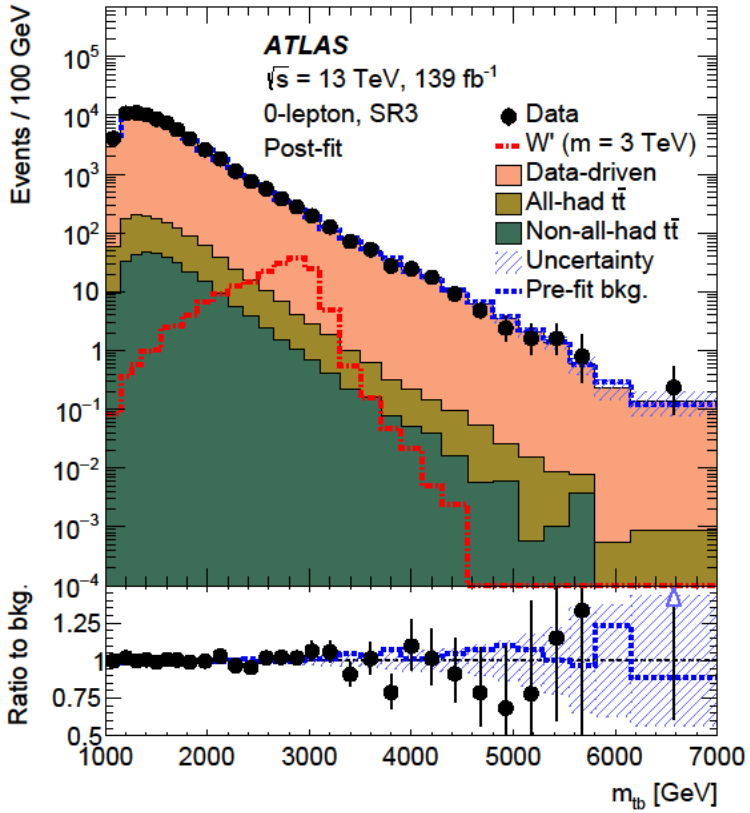
Details

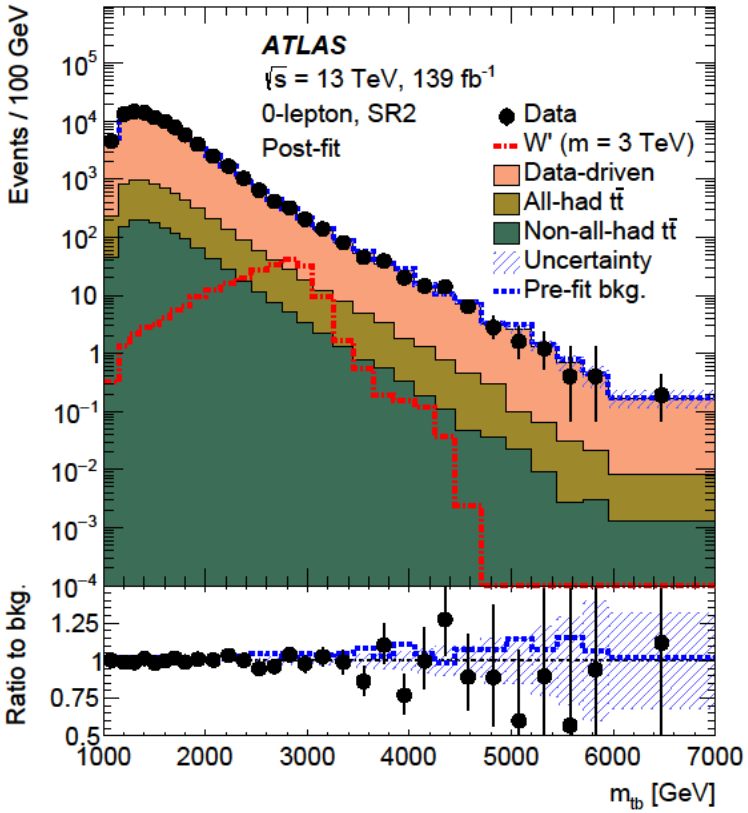
- Uncertainty estimated by CR a/b

$$\left|\frac{CR1a}{CR2a} \div \frac{CR1b}{CR2b} - 1\right|$$

0-lepton: Post-fit

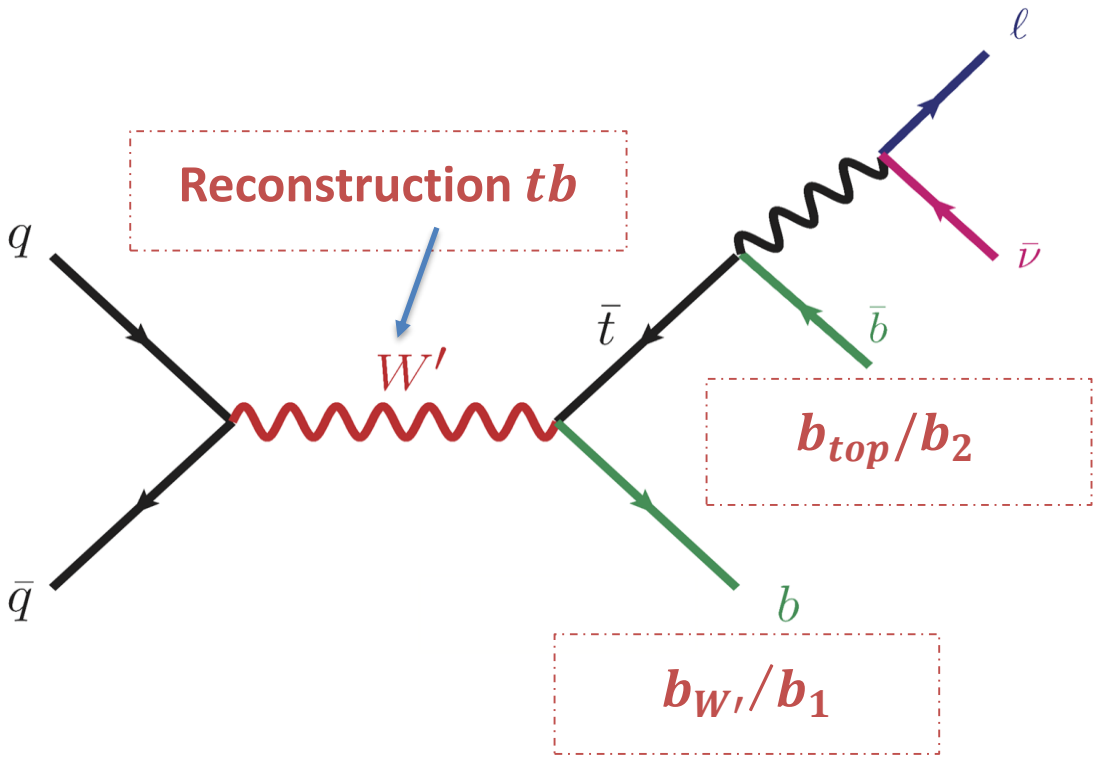






Good agreement
across the board
in all fit regions

1-lepton: Object and Pre-selection



- Jet:
  - same small-R jet & b-tagging
  - Variable-R re-clustered jet for semi-leptonic ttbar veto
    - $\rho = 2 * m_{top}, R_{eff}(p_T) = \rho/p_T$

- Exactly 1L with P_T > 50 GeV
- E_T^{miss}> 30 GeV
  - MET triggers only for E_T^{miss} > 200 GeV
- Two or more jets with P_T > 30 GeV
- One or more jets b-tagged

1-lepton: Reconstruction and Selection

- Neutrino reconstructed: solve the equation for four-momentum conservation between W and $l + \nu$ with m_w (80.4 GeV) as constraint
- W'= top + b = Single lepton + neutrino + jet that provides the closest m_{top} + Remaining leading jet

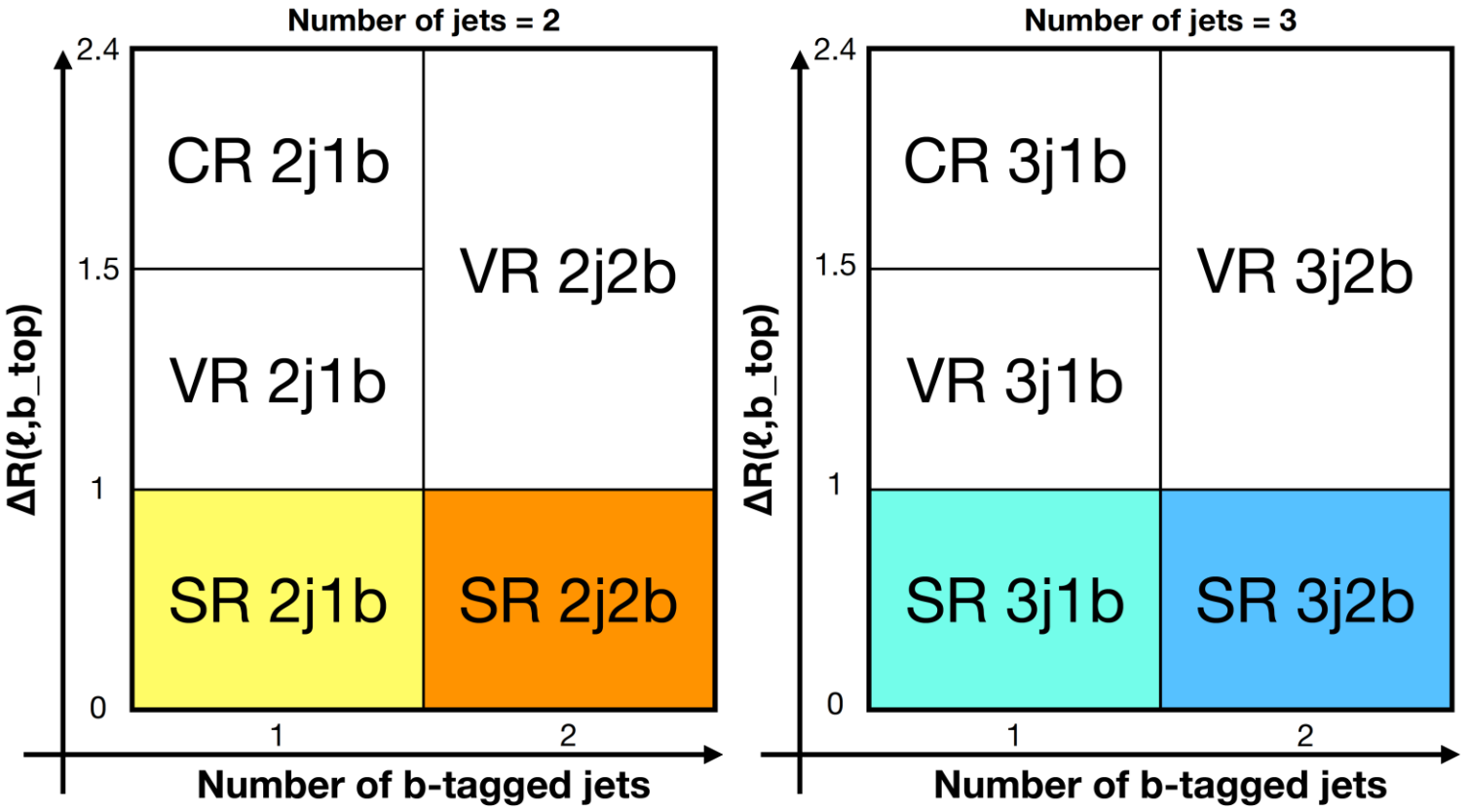
Regions	SR SR 2j1b, SR 2j2b, SR3j1b, SR3j2b	$CR_{W+\text{jets}}$ CR 2j1b, CR 3j1b	$VR_{W+\text{jets}}$ VR 2j1b, VR 3j1b	$VR_{t\bar{t}}$ VR 2j2b, VR 3j2b
Trigger	$E_{\text{T}}^{\text{miss}}$ OR one-lepton			
N_{jets}	2, 3			
$N_{b-\text{jets}}$	1, 2	1	1	2
p_T^{lepton}	> 50 GeV			
$E_{\text{T}}^{\text{miss}}$	> 100 GeV			
m_{T}^{W} (in 1-tag)	> 20 GeV			
$p_{\text{T}}^{b_{W'}}$	> 200 GeV			
$p_{\text{T}}^{\text{top}}$	> 200 GeV			
m_{tb}	> 500 GeV			
$\lvert\Delta\eta(\text{top}, b_{W'})\rvert$	< 2.0	n/a	n/a	n/a
$\Delta R(l, b_{\text{top}})$	< 1.0	> 1.5, < 2.4	> 1.0, < 1.5	> 1.0, < 2.4
b-tagging (2-jet regions)	$b_{W'}$ is b-tagged			
b-tagging (3-jet regions)	third jet is not b-tagged			
vRC-jet (3-jet regions)	veto events with 140 GeV < $m_{\text{vRC-jet}}$ < 200 GeV			

Angular variables to improve signal significance in the signal regions or dominant components' purity in the control regions

m_T^W cut reduces Multijet contribution

Strengthening Rejection of dominant backgrounds

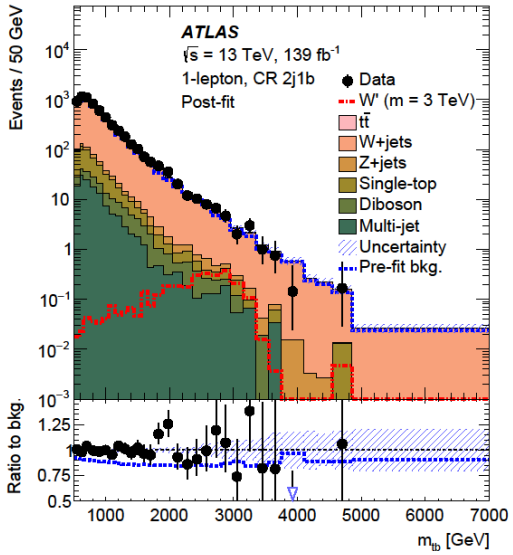
1-lepton: Categorization and Background

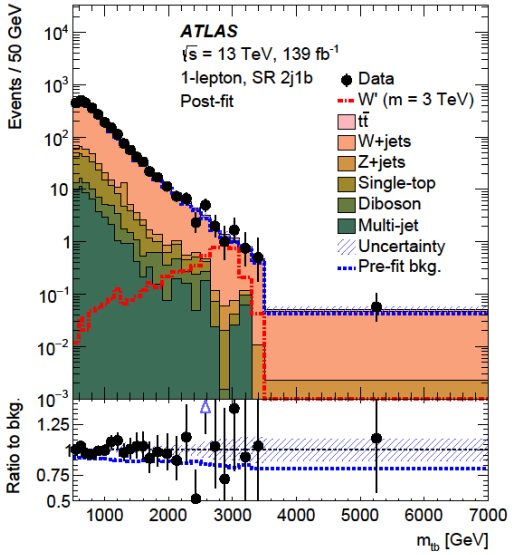


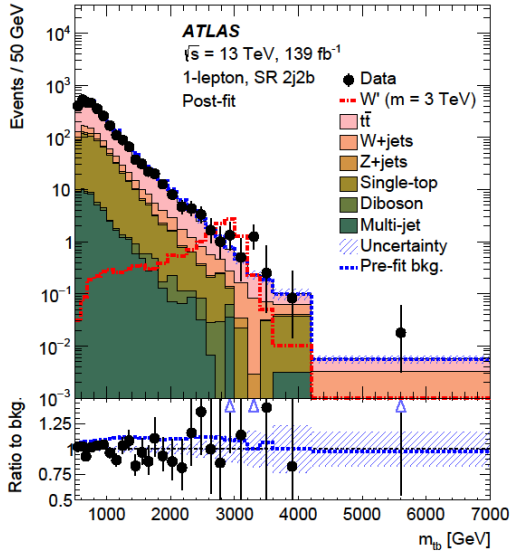
- MC: ttbar/Wjets/singletop/diboson/ Zjets, ttbar/Wjets are dominant
- Multijet: data-driven template fit
  - Very small
  - m_T^W and m_{tb} distribution from loose-not-tight regions (Loose-not-tight lepton definition): multijet_template
  - Fit of m_T^W in the analysis regions using the multijet_template (only normalization, no shape)

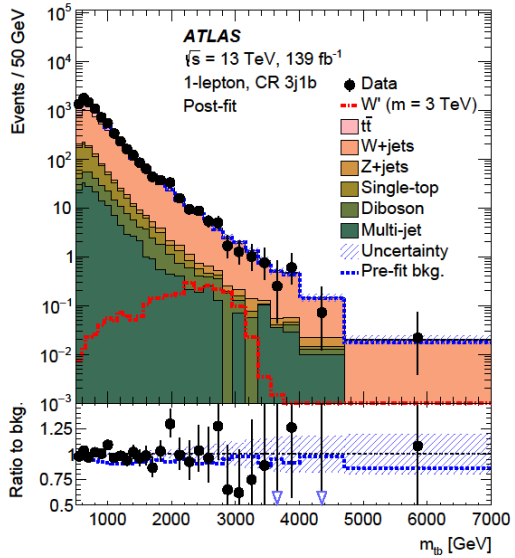
Details

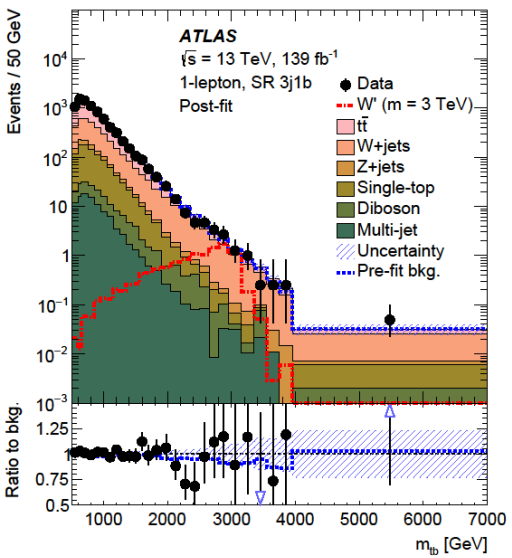
1-lepton: Post-fit

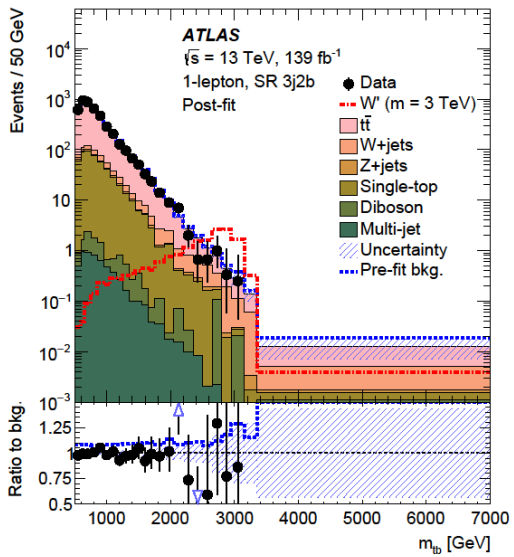










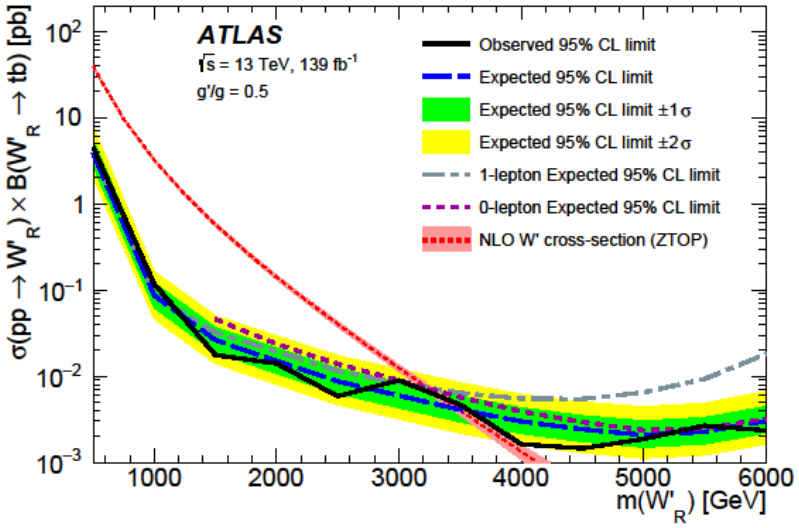


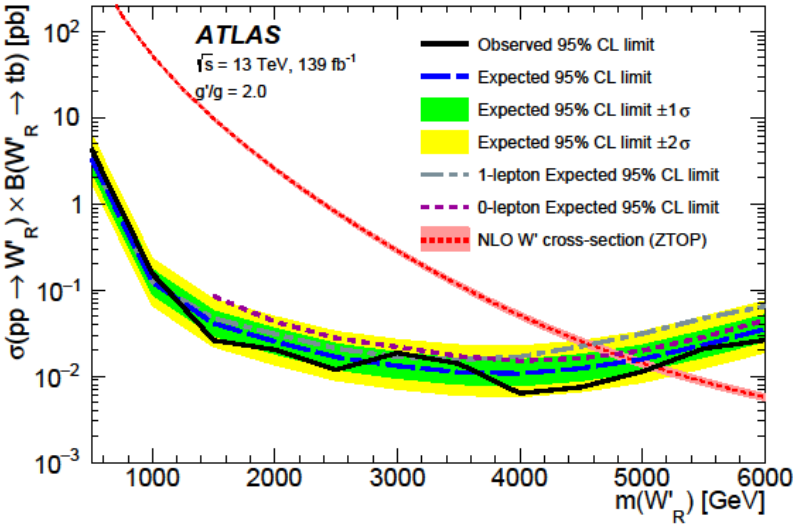
Good agreement across the board in all fit regions

VR post-fit plots

Combination Limit: Right-handed

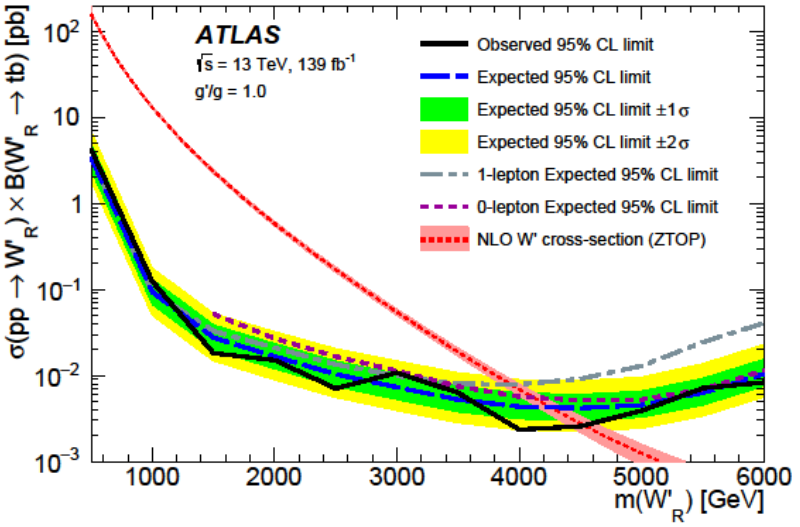
g’/g=0.5





g’/g=2.0

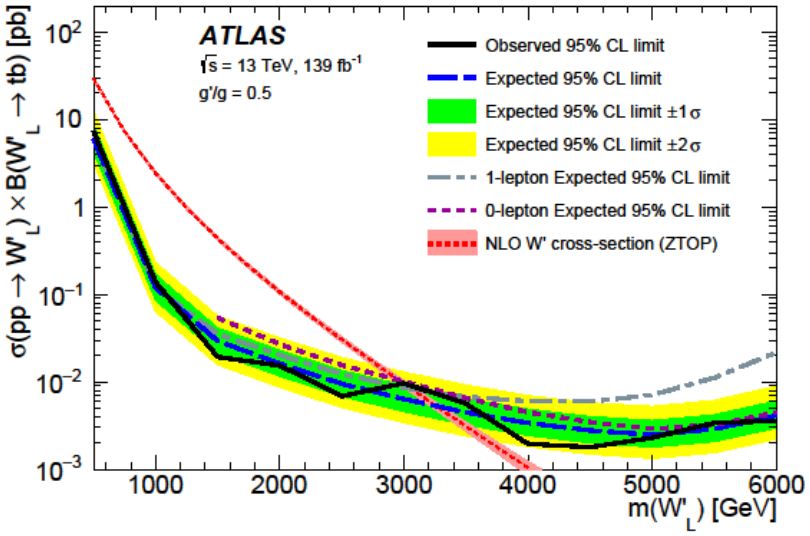
g’/g=1.0



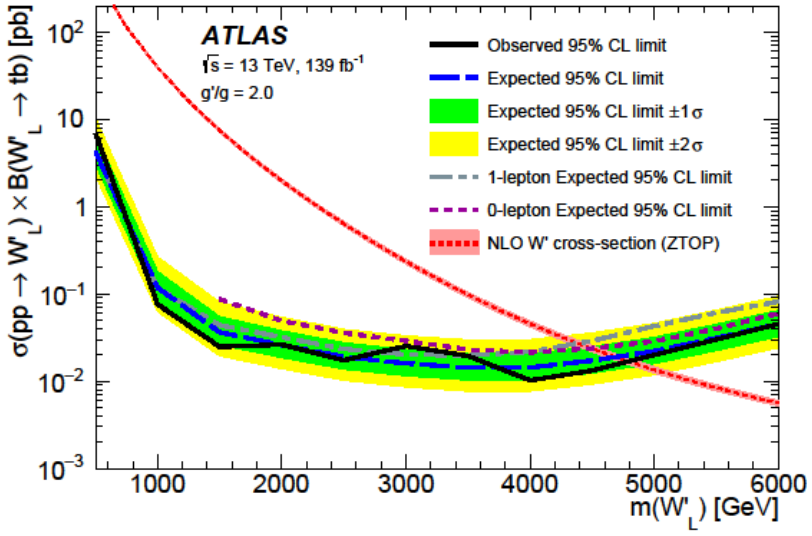
4.6 (4.2) TeV

Combination Limit: Left-handed

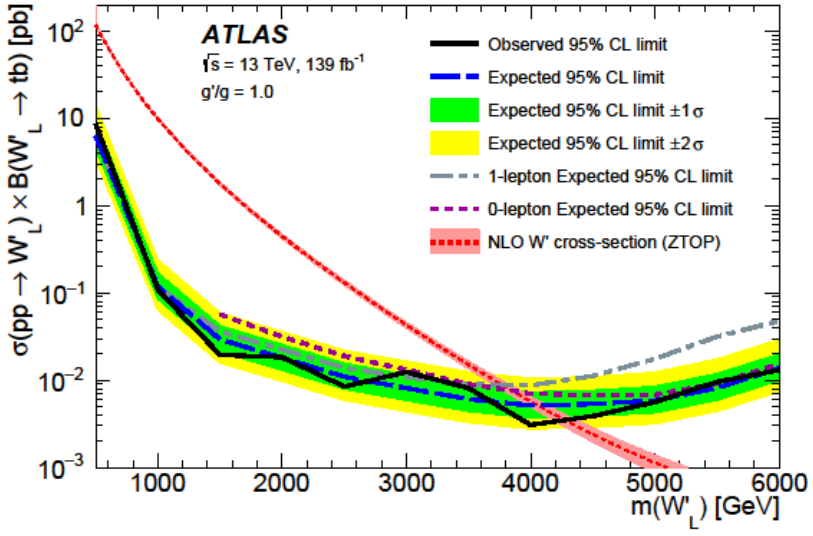
g’/g =0.5



g’/g=2.0

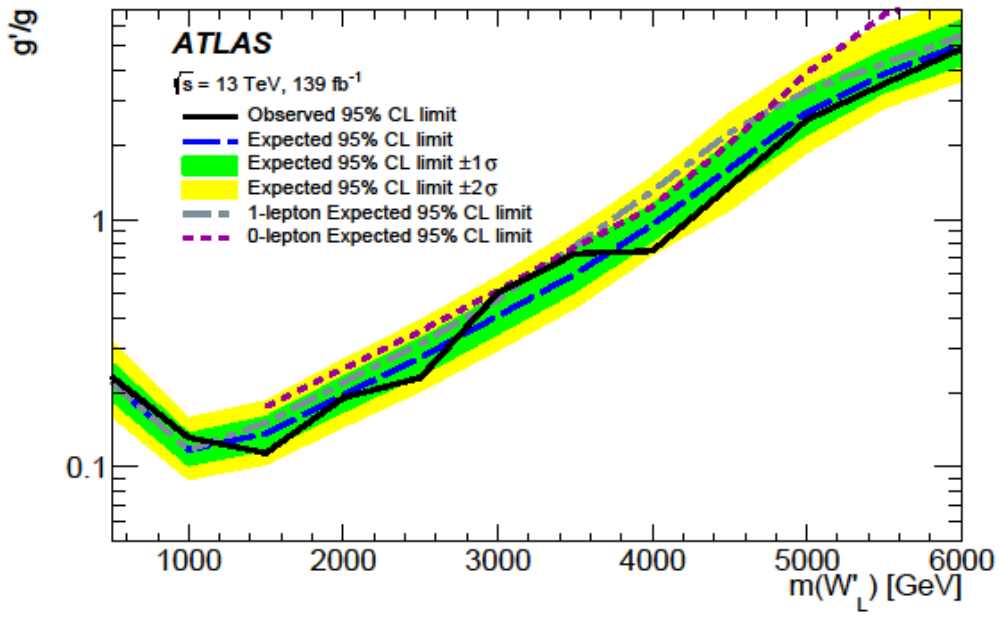


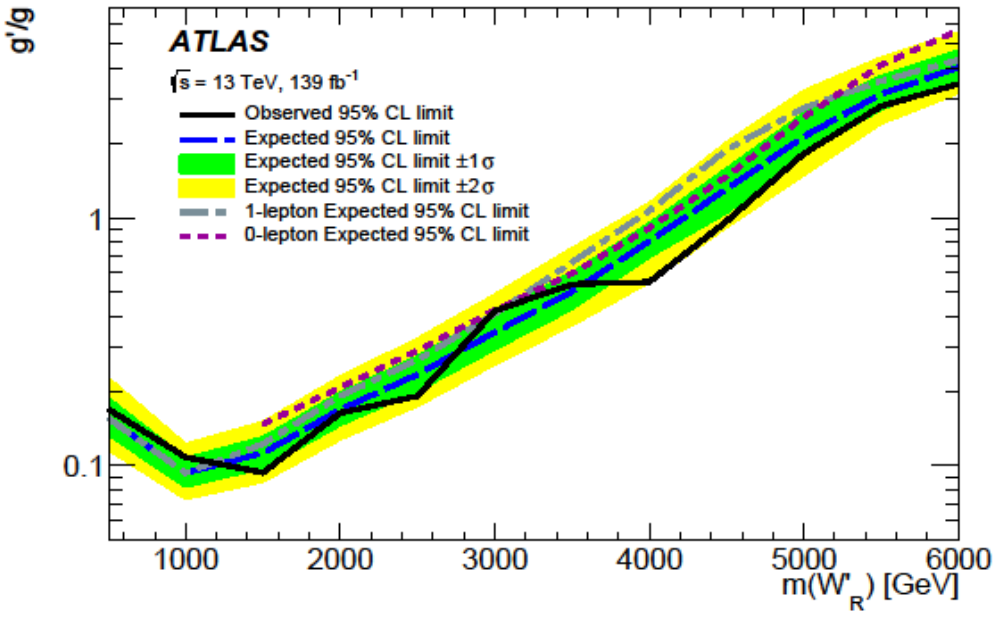
g’/g=1.0



4.2 (4.1) TeV

2D Limit





Coupling fraction vs $m_{W'}$, 2D plane,
points are obtained from crossing between 1D limit and theory lines
Region above the contour are excluded

Summary

- $W' \rightarrow tb$ analysis is done by using ATLAS full Run-II $139 fb^{-1}$ data
  - Resonance search in the reconstructed m_{tb}
  - Monte Carlo background + data-driven Multijet background (ABCD in 0L and template fit in 1L)
  - arxiv:2308.08521

- Comprehensive interpretation strategy
  - 0L+1L Combination results, right-handed W' mass is excluded up to 4.6 (4.2) TeV
  - Interference added to ${W'}_L$ interpretation, with mass exclusion up to 4.2 (4.1) TeV
  - Exclusion contour of g'/g = 0.1 to 5.0 vs. W' mass

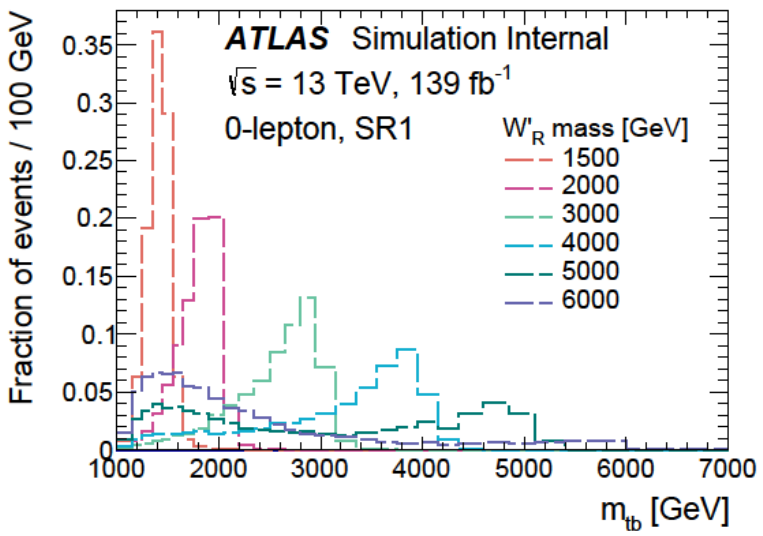
Backup

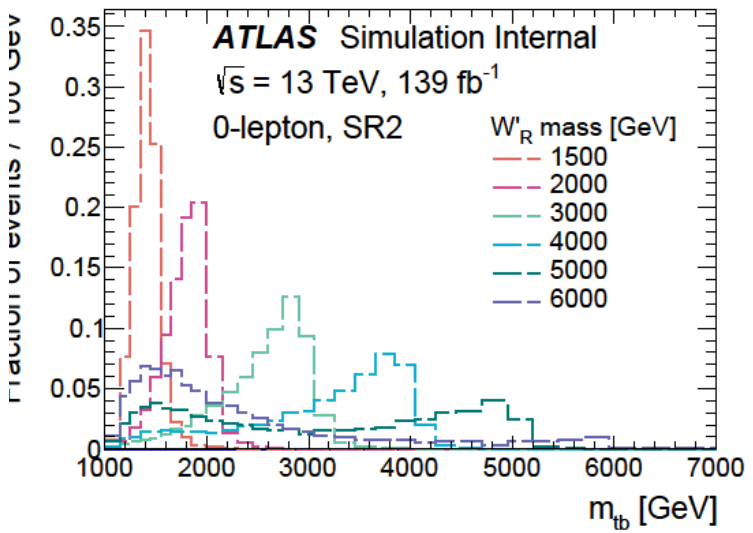
Signal simulation

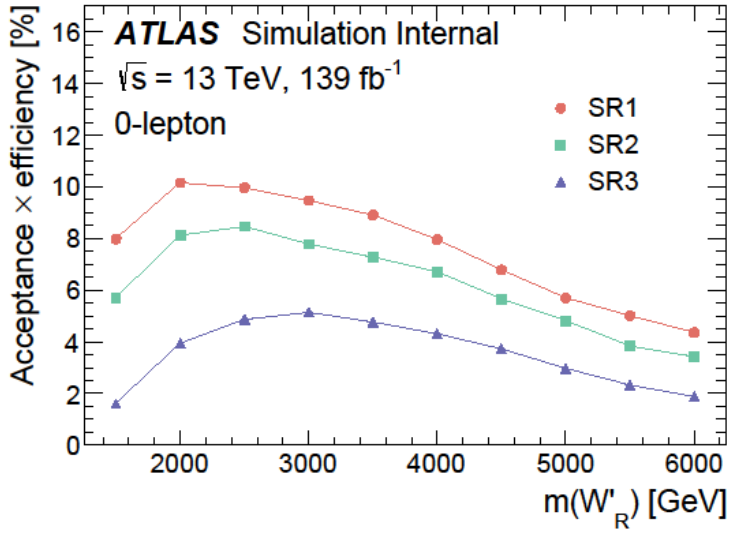
NLO cross-section

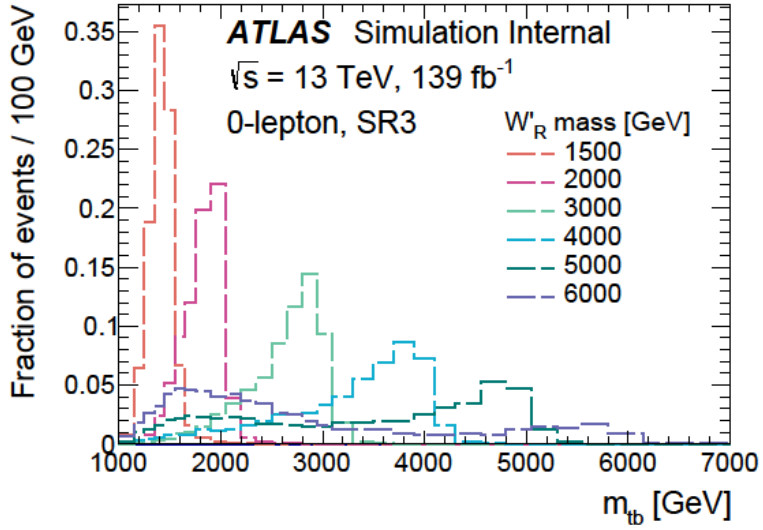
Mass (GeV)	$\sigma_{W'_R} \times \mathcal{B}(W'_R \to t\bar{b})$ [pb]	$\sigma_{W'_L} \times \mathcal{B}(W'_L \to t\bar{b})$ [pb]
500	$158.5\ ^{+3.6}_{-3.4}$	$117.9^{+2.7}_{-2.5}$
1000	$13.08\ ^{+0.43}_{-0.42}$	$9.86^{+0.33}_{-0.32}$
1500	$2.35\ ^{+0.11}_{-0.11}$	$1.781^{+0.079}_{-0.078}$
2000	$0.5826\ ^{+0.0329}_{-0.0331}$	$0.4443^{+0.0247}_{-0.0249}$
2500	$0.1701\ ^{+0.0115}_{-0.0116}$	$0.1310^{+0.0089}_{-0.0089}$
3000	$0.0547\ ^{+0.0045}_{-0.0046}$	$0.0427^{+0.0034}_{-0.0035}$
3500	$0.0188\ ^{+0.0020}_{-0.0020}$	$0.0150^{+0.0015}_{-0.0016}$
4000	$0.006890\ ^{+0.001020}_{-0.001023}$	$0.00570^{+0.00078}_{-0.00078}$
4500	$0.00276\ ^{+0.00058}_{-0.00058}$	$0.00239^{+0.00044}_{-0.00044}$
5000	$0.00125\ ^{+0.00034}_{-0.00034}$	$0.00113^{+0.00026}_{-0.00026}$
5500	$0.00065\ ^{+0.00020}_{-0.00020}$	$0.00062^{+0.00015}_{-0.00015}$
6000	$0.00039\ ^{+0.00012}_{-0.00012}$	$0.000379^{+0.000085}_{-0.000085}$

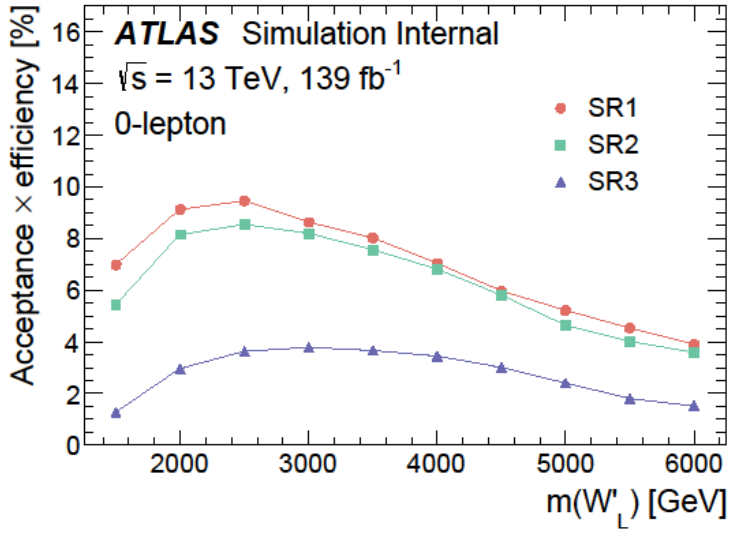
Signal simulation: 0-lepton signal shape and efficiency



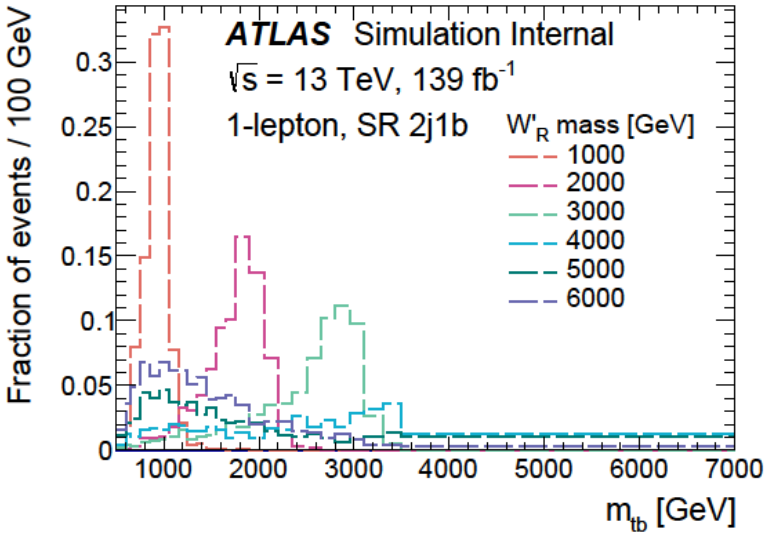


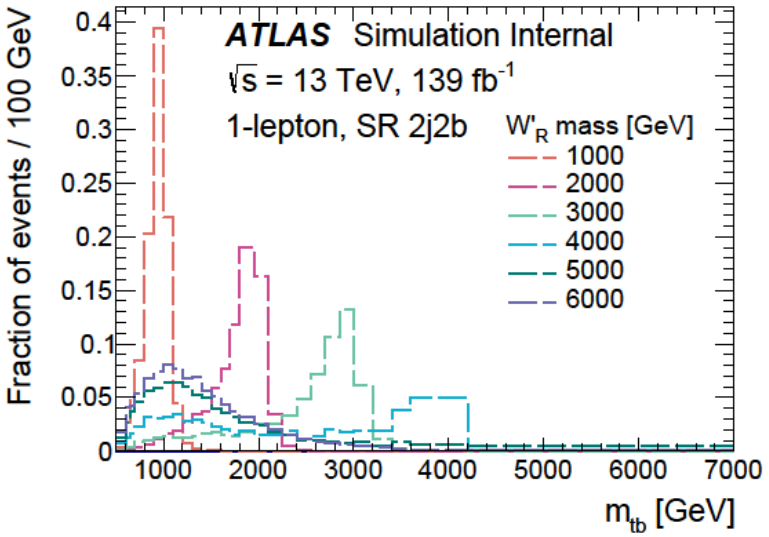


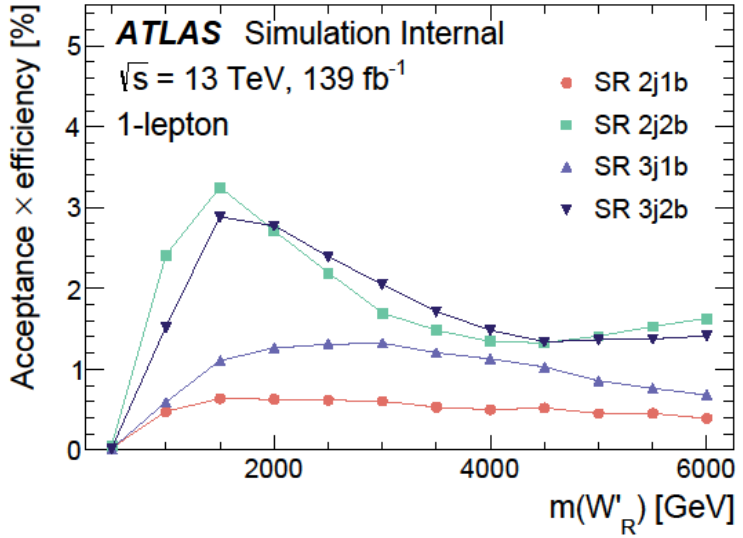


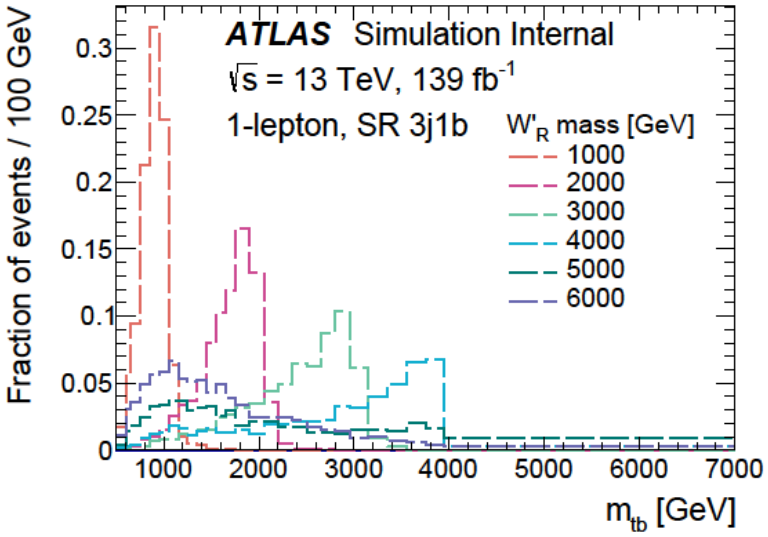


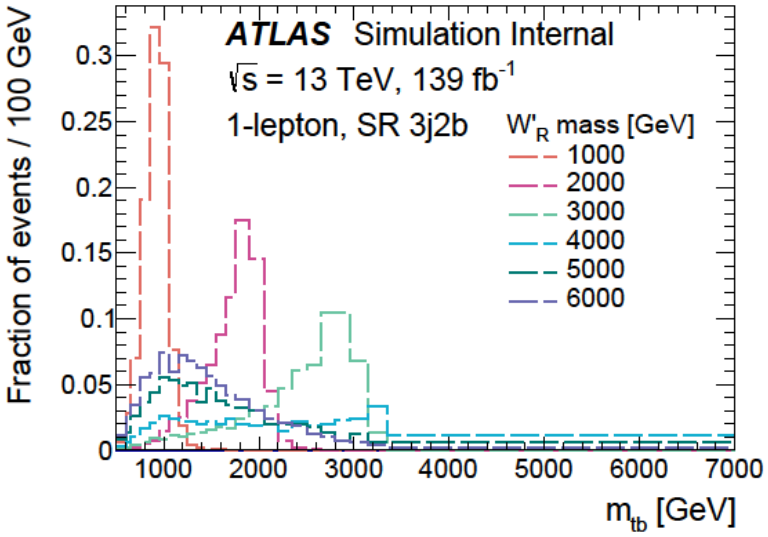
Signal simulation: 1-lepton signal shape and efficiency

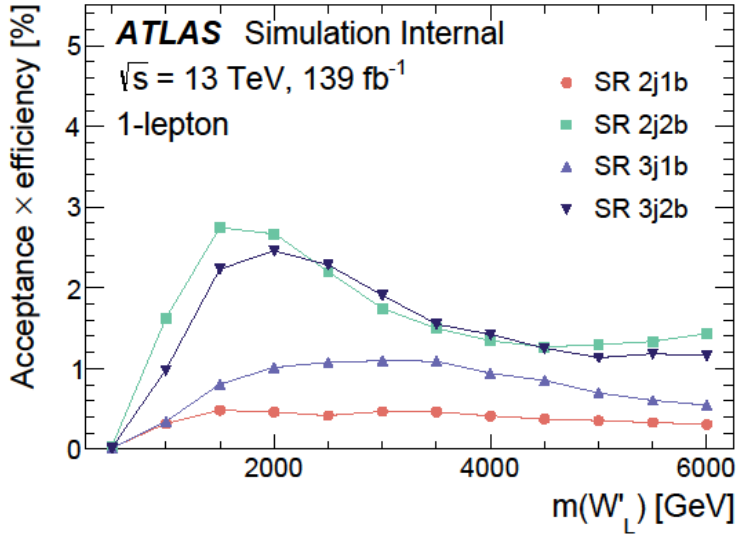








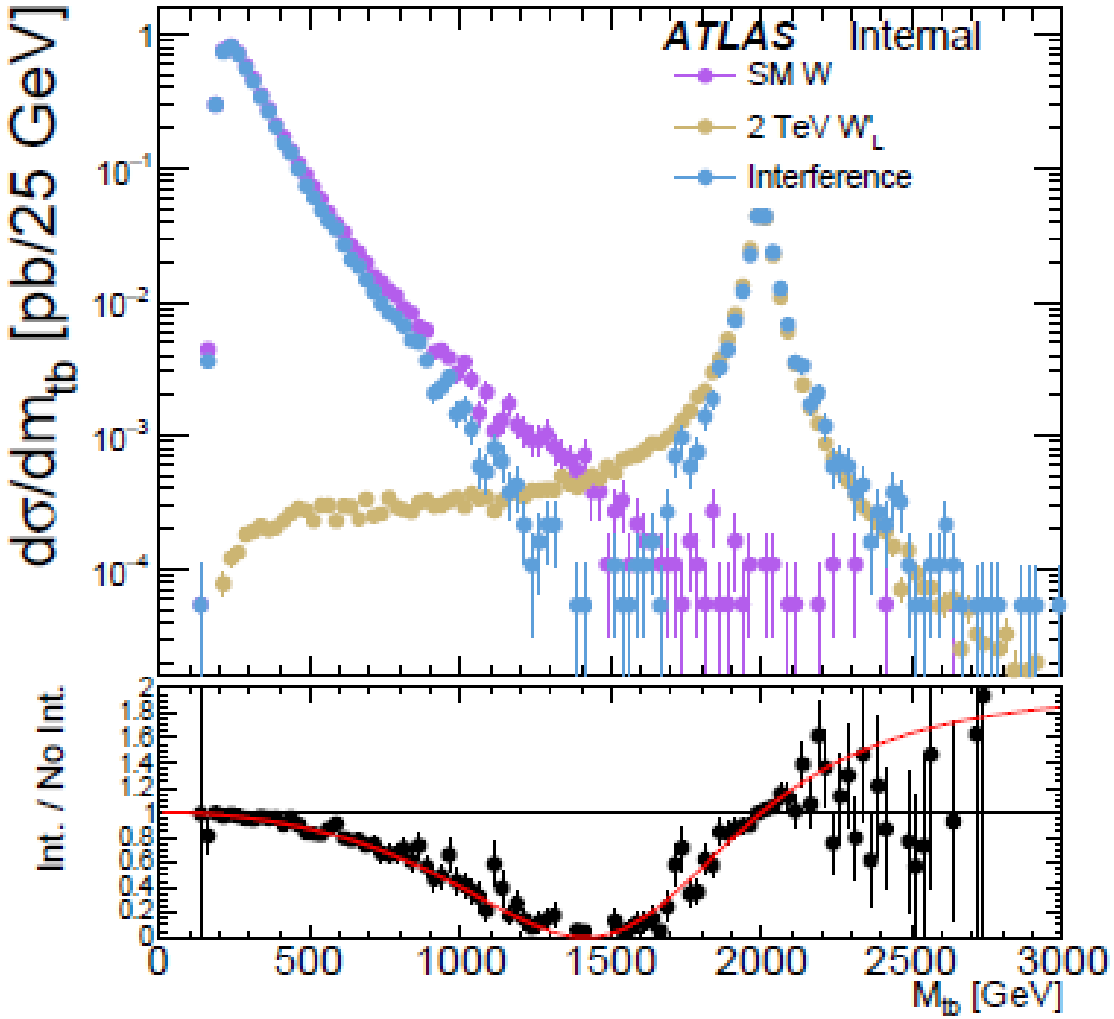




Interference formula validation

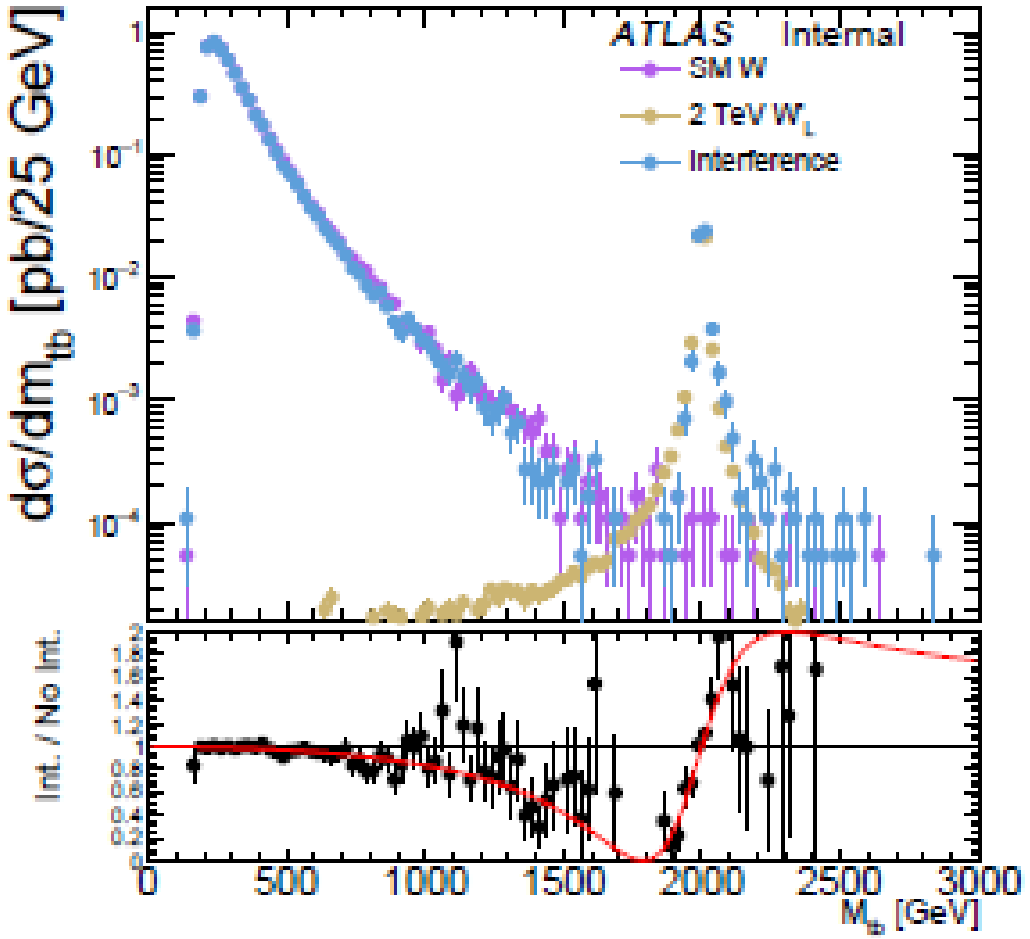
- Top pad: from production
  - Single-top (purple)
  - W'_L only (brown)
  - Single-top + interference + W'_L (blue)

- Bottom pad: Ratio
  - Red curve: formula of (W'+Int+W)/(W'+W)
  - Black dot: blue/(brown+purple)

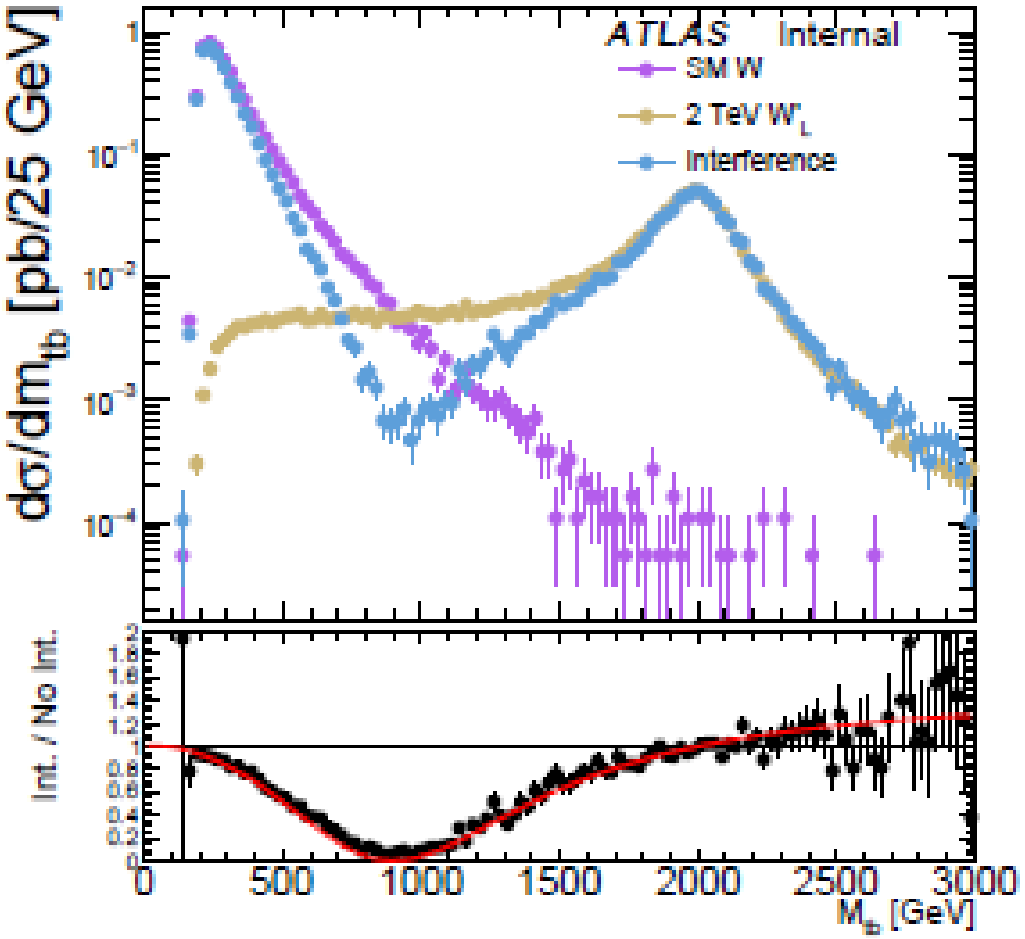


Interference formula validation for various g'/g

g'/g = 0.5



g'/g = 2.0

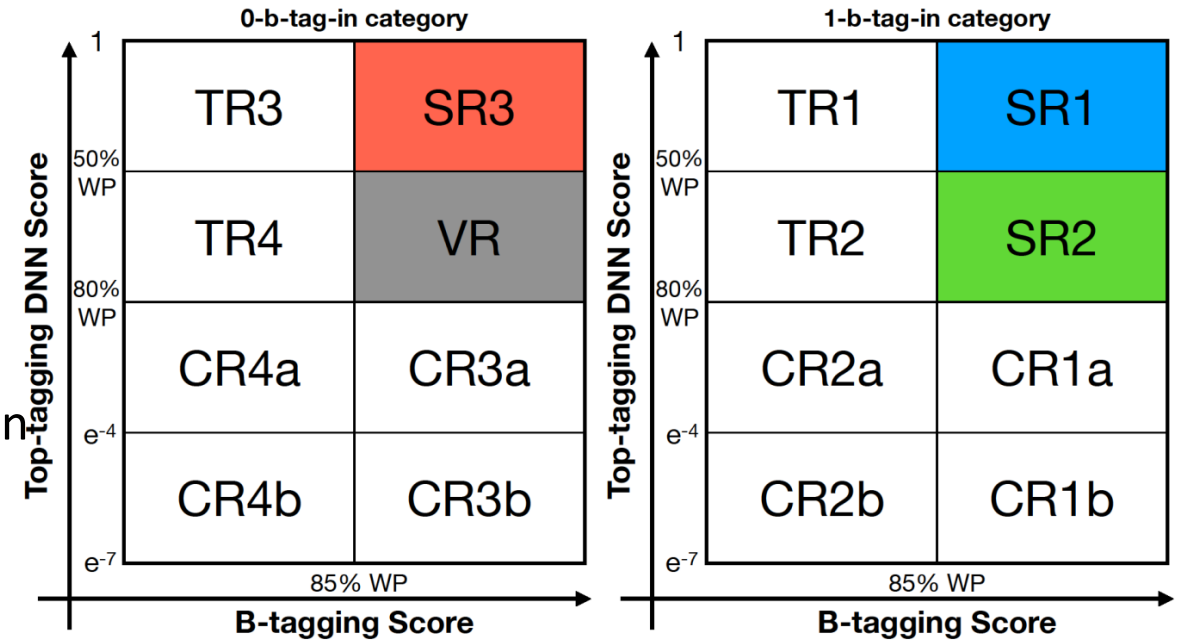


0-lepton: Categorisation details

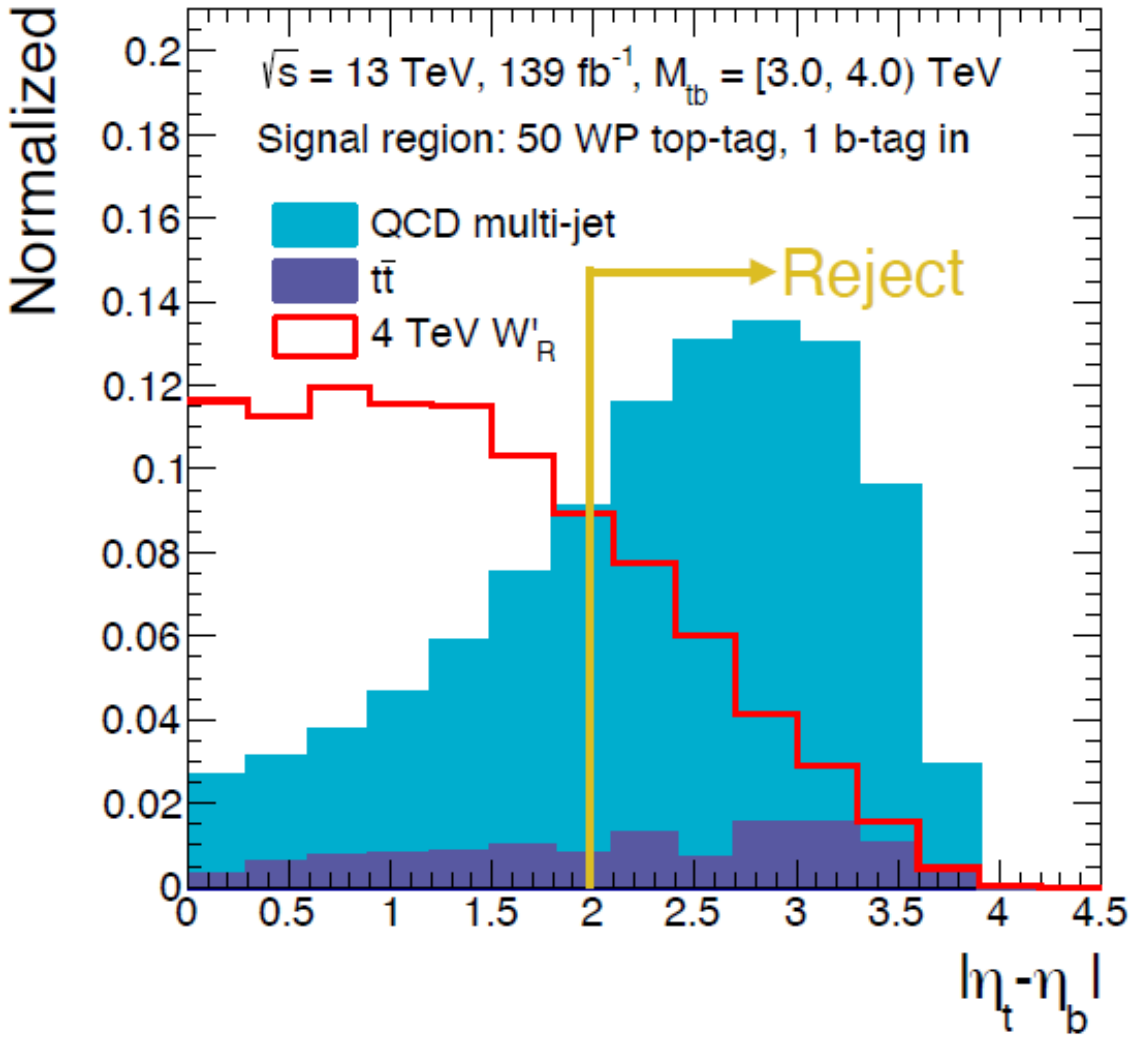
- 3 SR, no CR and VR included in fit
  - SR1: Tight top-tagged large-R jet with b-tagged inside
  - SR2: Loose-Not-Tight top-tagged with b-tagged inside
  - SR3: Tight top-tagged large-R jet without b-tagged inside
  - All SR need small-R jet b-tagged

- Background: ttbar (MC) and QCD Multijet (data-driven)
  - Modified ABCD method used for multijet estimation
    - Bin-by-bin in m_{tb} distribution
    - Subtract ttbar from data
    - SR1 = TR1*(CR1a/CR2a)
  - ttbar NNLO reweighting implemented

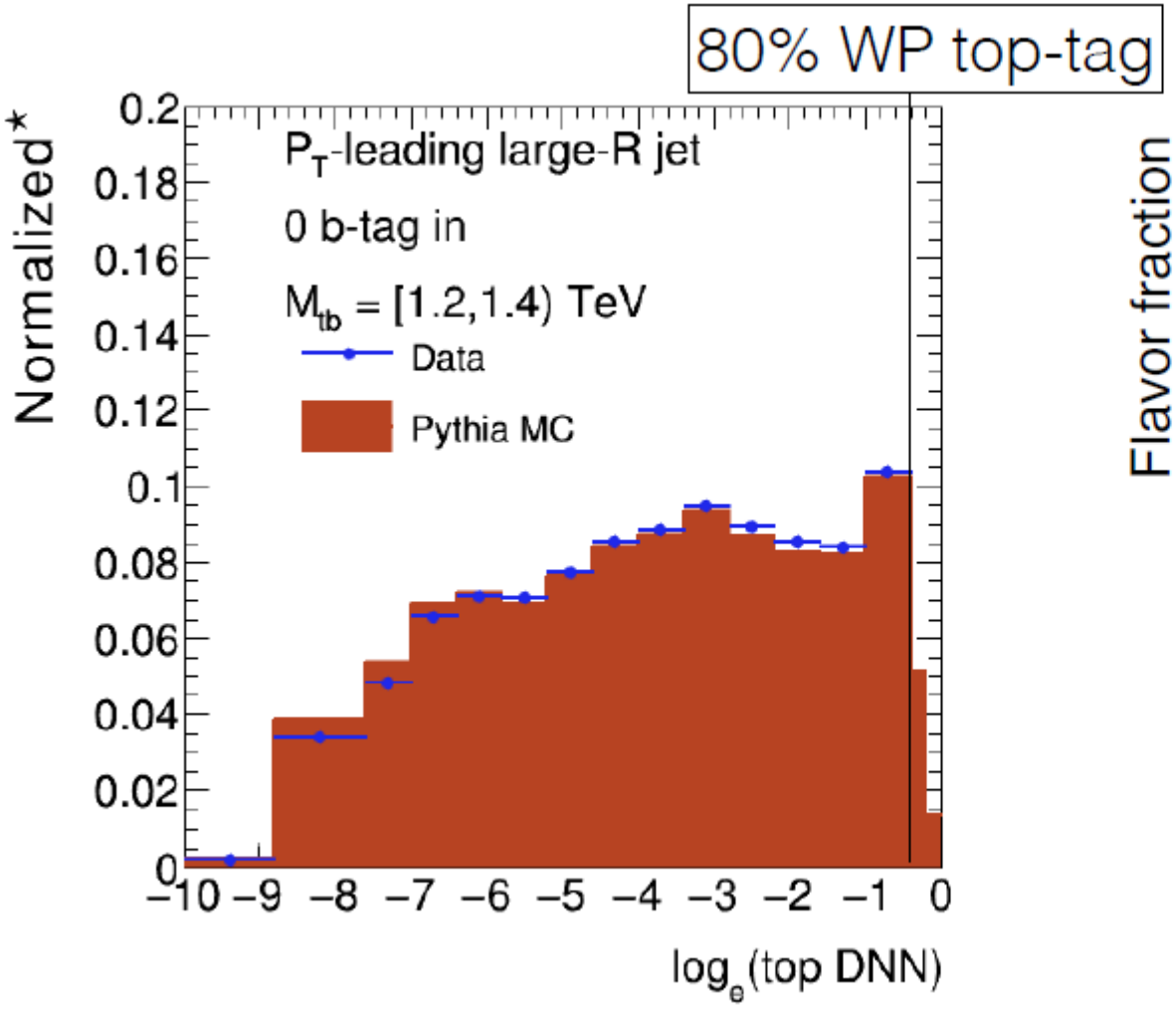
- Data-driven uncertainty estimated by CR a/b
  - |(CR1a/CR2a)/(CR1b/CR2b)-1|

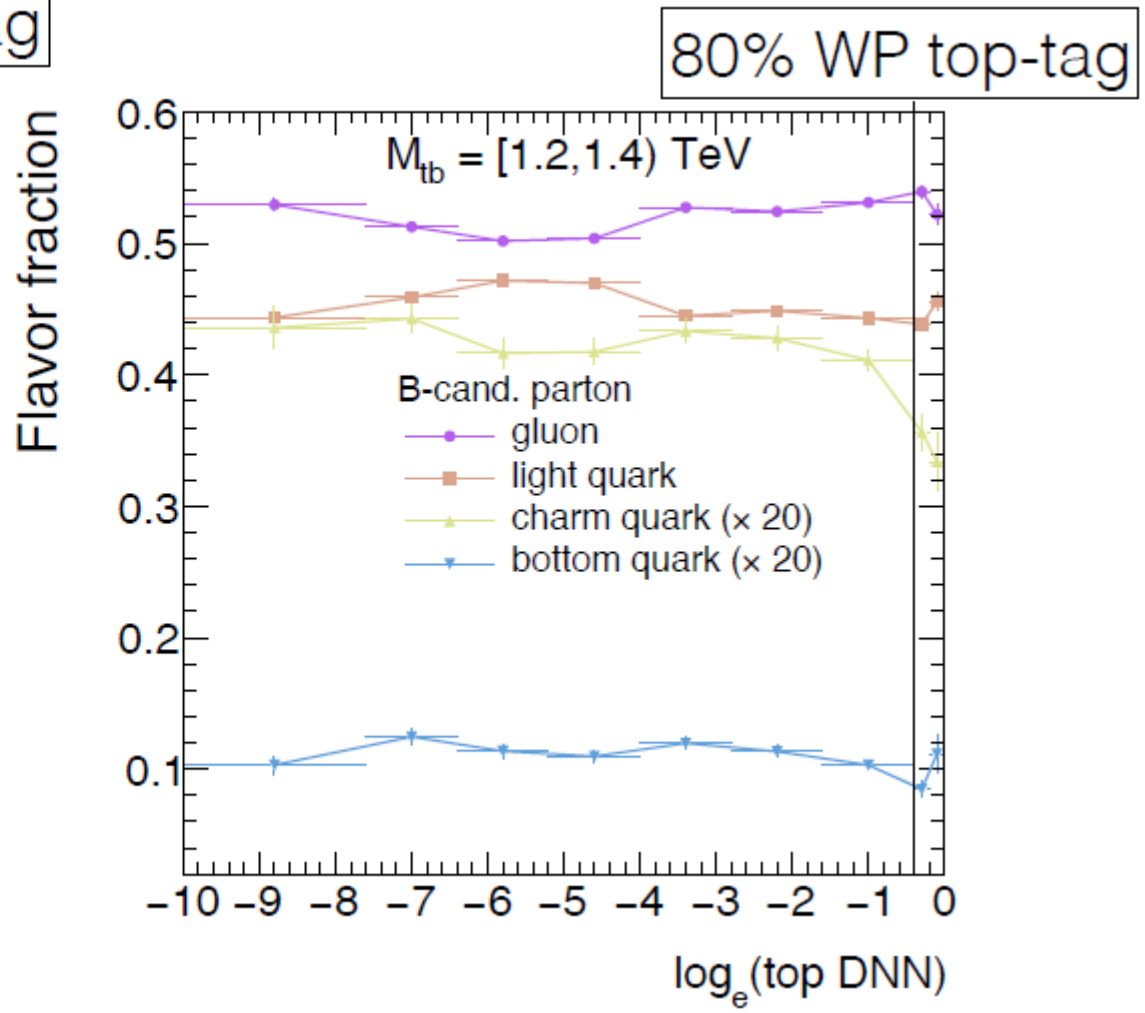


0-lepton: Cut

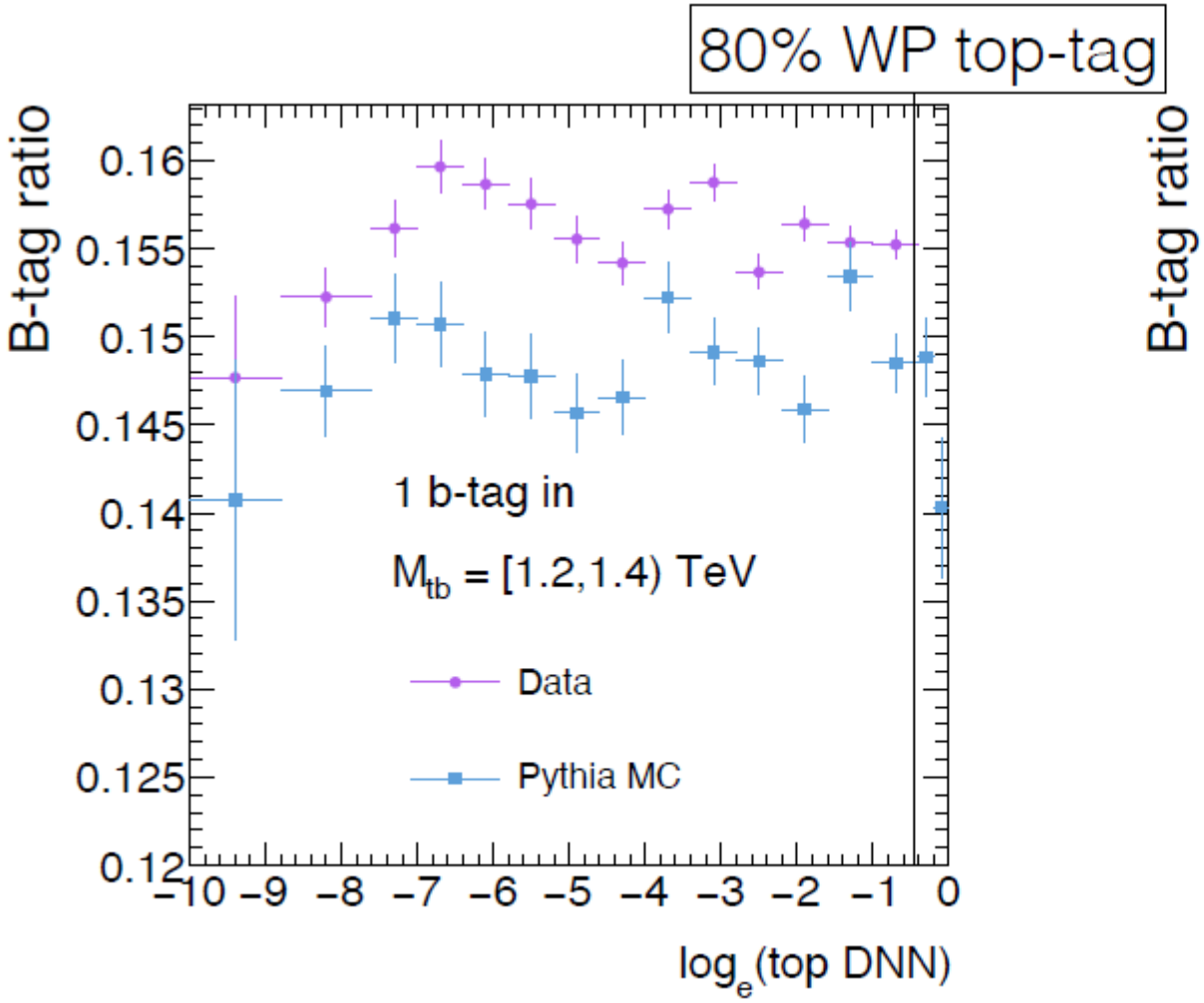

Normalized
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}, M_{tb} = [3.0, 4.0) TeV
Signal region: 50 WP top-tag, 1 b-tag in
QCD multi-jet
$t\bar{t}$
4 TeV W'_R
Reject
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
$|\eta_t - \eta_b|$

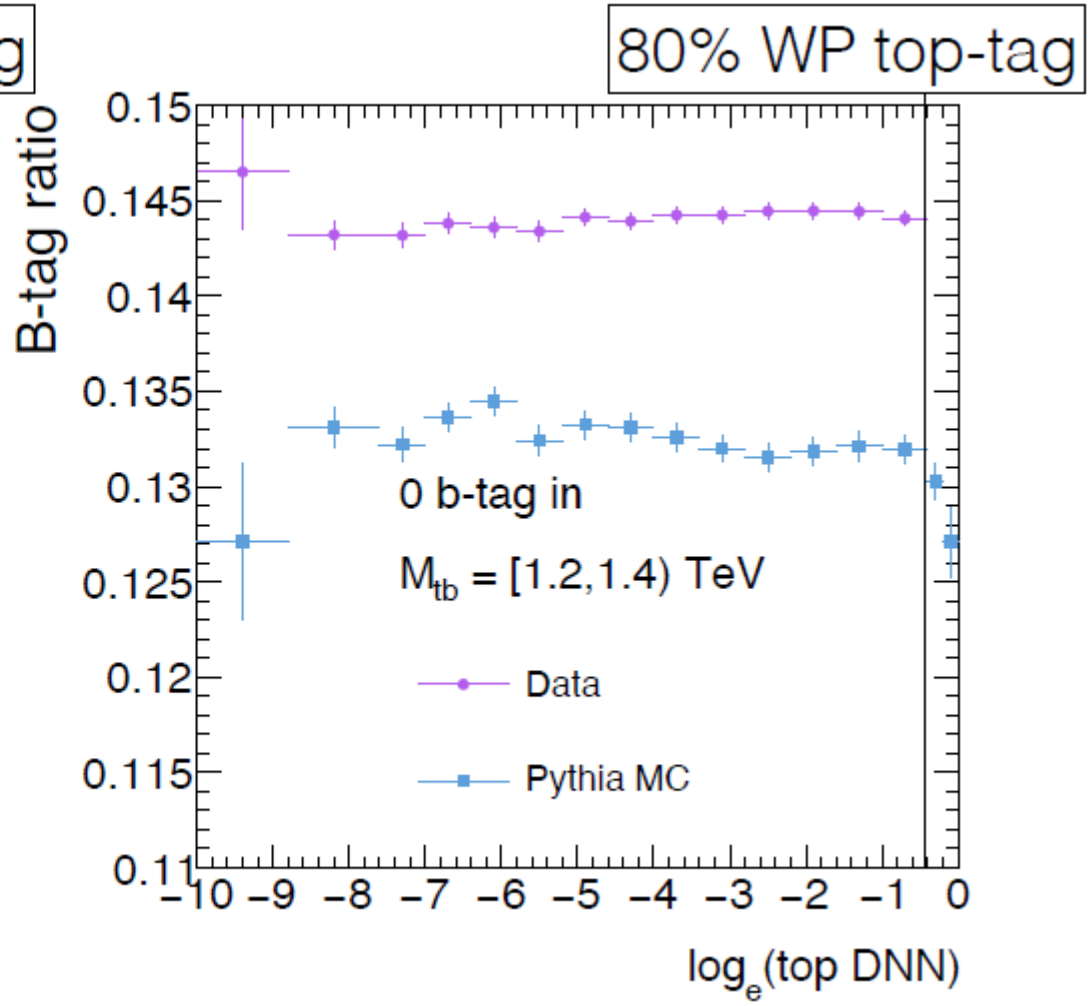
0-lepton: Data-driven study





0-lepton: Data-driven study

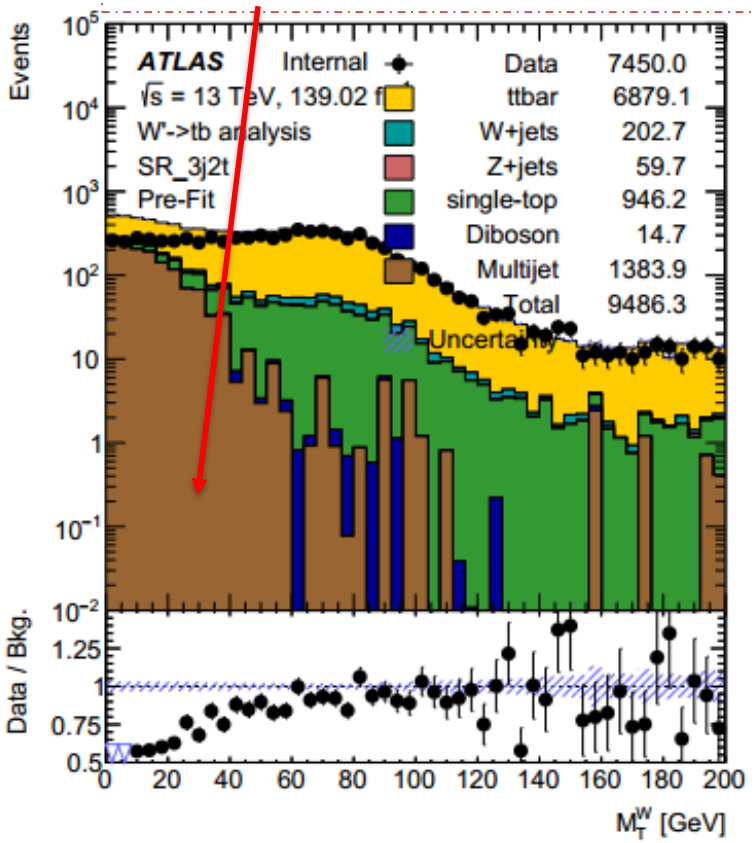


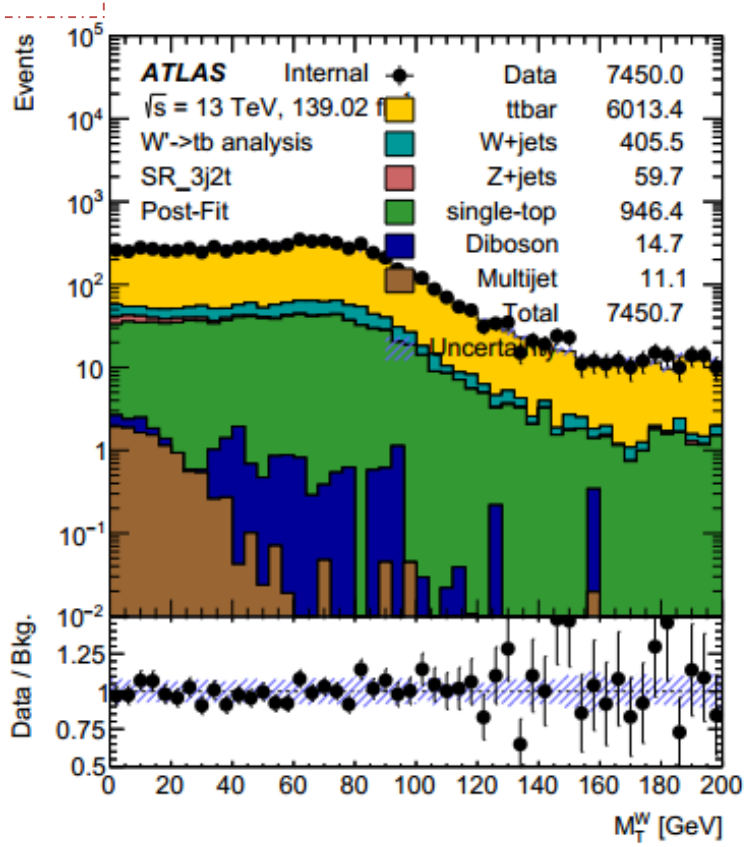


1-lepton: Background

- Multijet background uses data-driven estimation: template fit
- m_T^W and m_{tb} distribution from loose-not-tight regions (Loose-not-tight lepton definition): multijet_template
- Fit of m_T^W in the analysis regions using the multijet_template (only normalization, no shape)

Template from loose-not-tight distribution (Data-MC)





Multijet normalization from this fit used in final m_{tb} distributions

Fit strategy and systematic uncertainties

- Simultaneous fit on the m_{tb} distribution, scan g'/g 0.1 ~ 5.0
  - Profile likelihood fit
- 9 regions go into the fit: 0-lepton 3 SR & 1-lepton 4 SR + 2 CR
- Right-handed and Left-handed
  - LH: interference contribution is taken into account in the likelihood
- Wjets/ttbar freely float in 1L regions

- All experimental systematics are considered correlated between both channels
  - luminosity, pile-up reweighting, jet, jet flavor tagging, lepton ID, MET reconstruction

- All modelling systematics are de-correlated between two channels
  - Theoretical modelling uncertainties
    - ttbar (0L/1L), Wjets (1L), singletop(1L)
  - data-driven uncertainty
    - 0L: uncertainties on ttbar are propagated through the Data - MC_ttbar in TR
    - 0L: additional uncertainty of ABCD <- correlation between top-tag score and b-tag
    - 1L: small, given by the template fit along with the initial SF

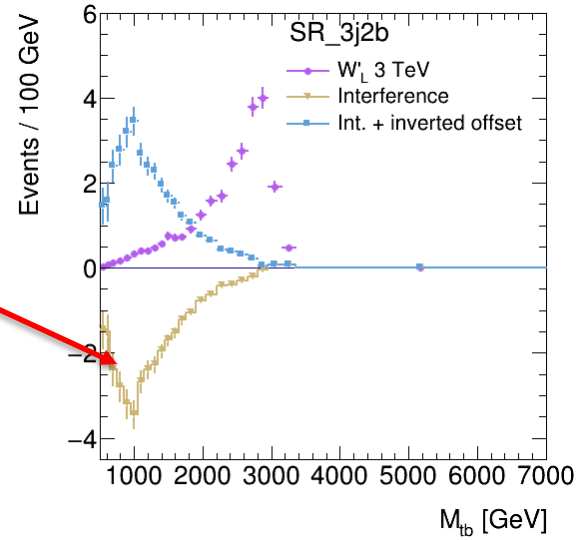
W'_L fit with interference

- Re-write the μS + B as:

$$\mu \cdot S + \sqrt{\mu} \cdot I + B$$

- Interference (I) obtained with the method described before
  - It could be negative, not allowed in the fit tool

Negative!

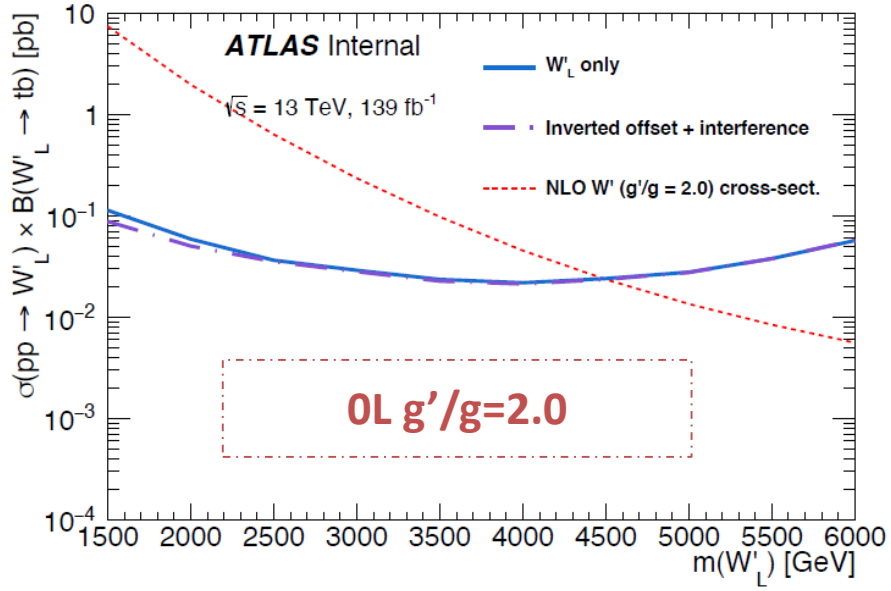


- An Offset is added in I so $S + I$ has all positive bin:

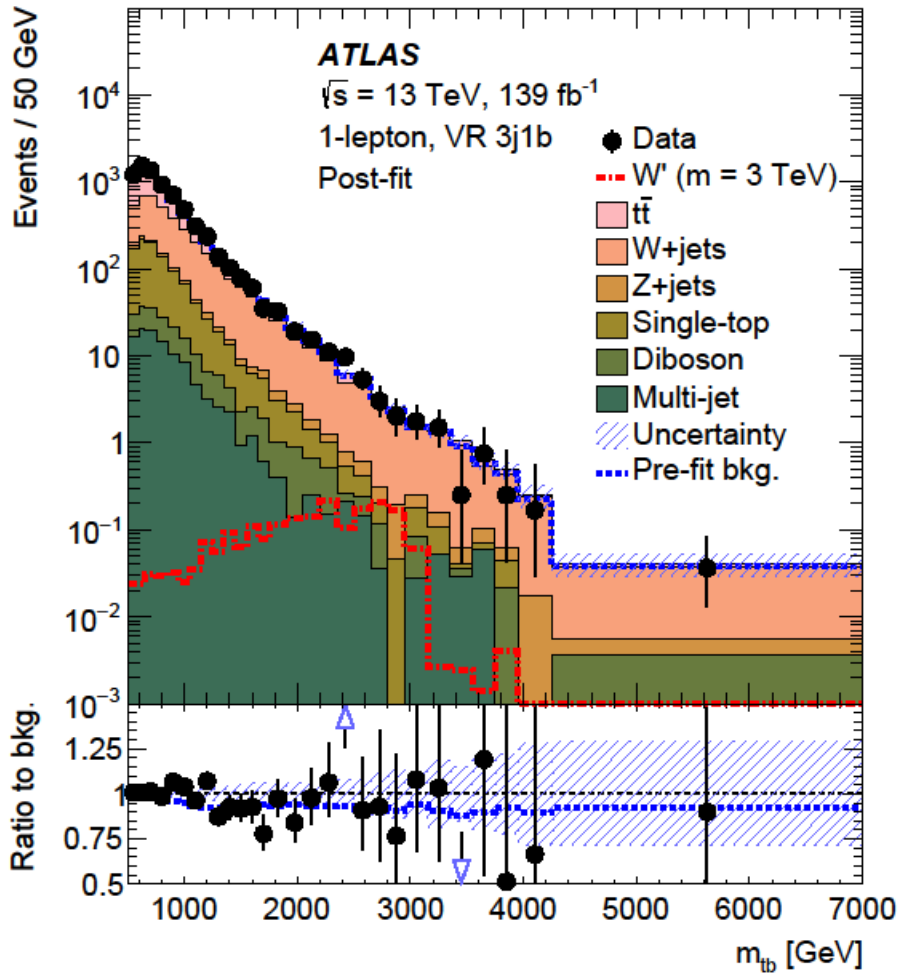
$$\mu \cdot S + \sqrt{\mu} \cdot [I + \mathtt{offset}] - \sqrt{\mu} \cdot \mathtt{counterterm} + B$$

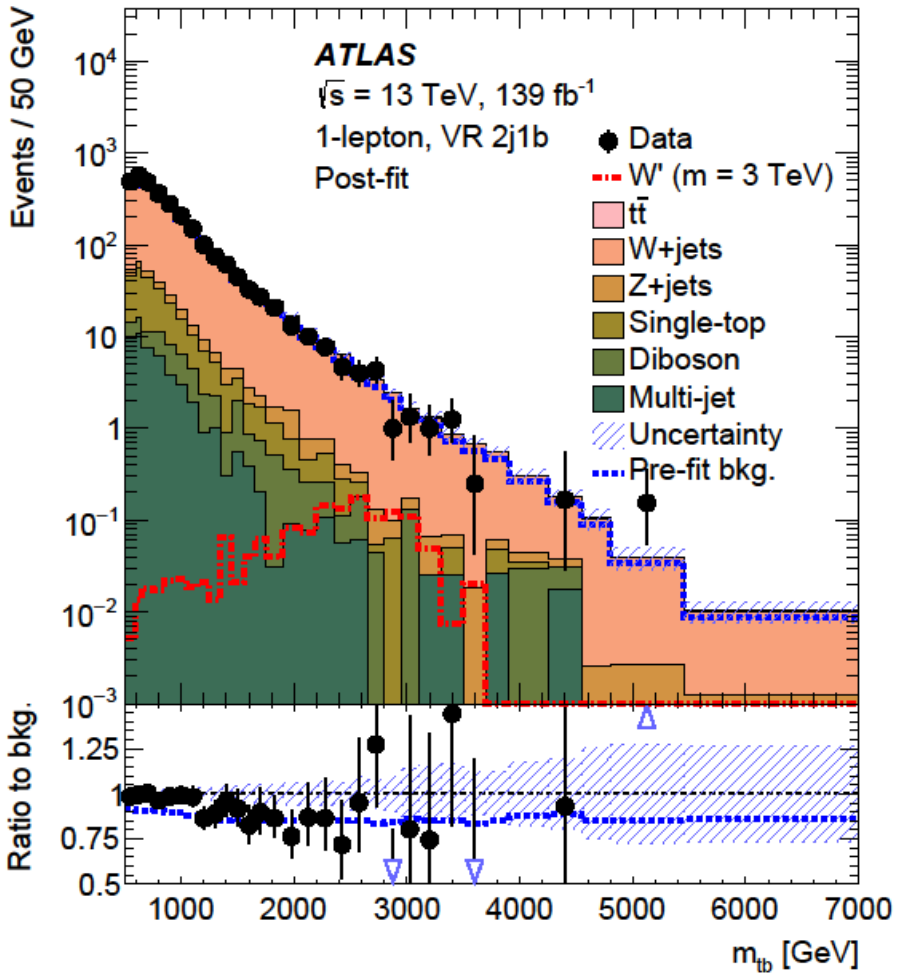
- Counter-term = Offset

- Effect of Interference is very small



1-lepton: Post-fit





Comparison with Latest results

- 1L 139 fb^{-1}:
  - 4.07 TeV exclusion for W'_R
  - 3.70 TeV exclusion for W'_L
- Combination 139 fb^{-1}:
  - 4.6 TeV exclusion for W'_R
  - 4.2 TeV exclusion for W'_L

- D0 and CDF: search under 1 TeV
- CMS 0L: full run-II, excluded up to 3.4 TeV
- CMS 1L: 35.9fb^{-1}, excluded up to 3.6 TeV
- ATLAS 1L+0L: 36.1fb^{-1}, 3.25 TeV exclusion for W'_R
- ATLAS 0L: 36.1fb^{-1}2.85 TeV exclusion for W'_L