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

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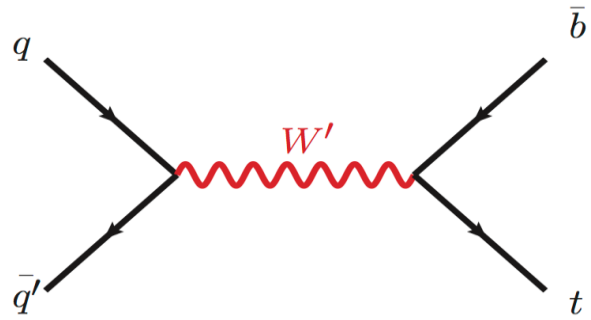
Outline

- Introduction
- Left-handed W'_L interference with SM W
- $W' \to tb \to l\nu bb$ channel
- Combination

Introduction

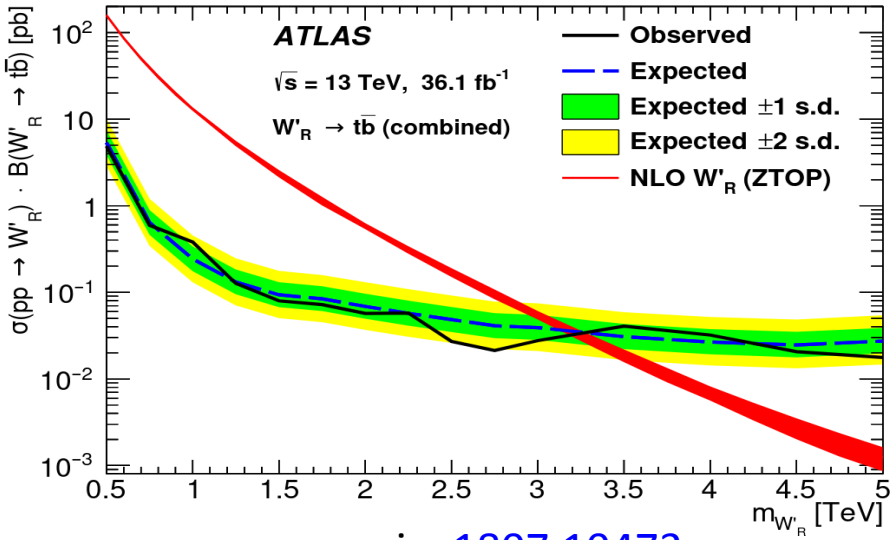
W' appears in several BSM scenarios: Extra dimensions, strong dynamics or composite Higgs. Some with preferential 3rd generation couplings



- **General Information**

- Two channels are studied separately, combined at the end
  - 0L(qqbb): public (CONF note)
  - 1L($l\nu bb$): target to finialize at the end of this year
- Final states:
  - 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

Signal model

- An effective Lagrangian is used to capture the relevant phenomenology of the Sequential Standard Model (SSM) signal

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

- Handeness and mass are free parameters, right-handed leptonic decay is forbidden
- A common factor multiplying all couplings (g'/g, or gF) is a free parameter.
  - The width is set to scale with square of g'/g
- W' generator

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

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

SM W

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

interference

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

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.

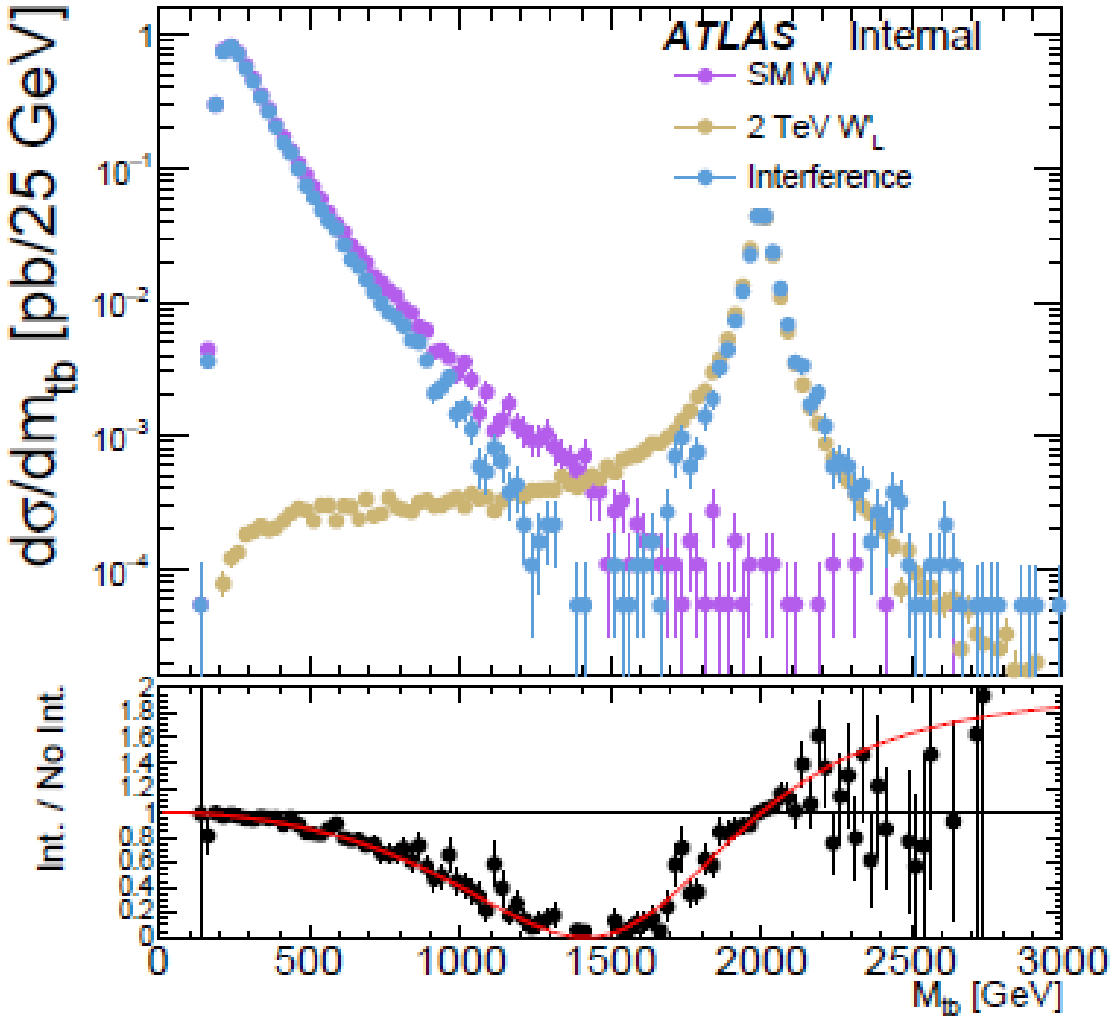
- Sub-process $ud -> tb$ partonic cross-section form as an example
- Don't need to produce separate interference-only samples which would be computationally costly
  - LO differential cross-section formula is used to re-weight
  - The ratio is implemented event by event

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

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)

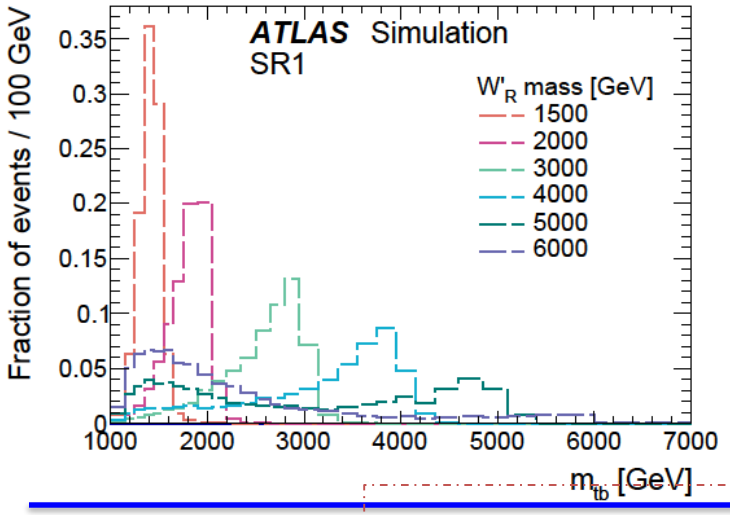


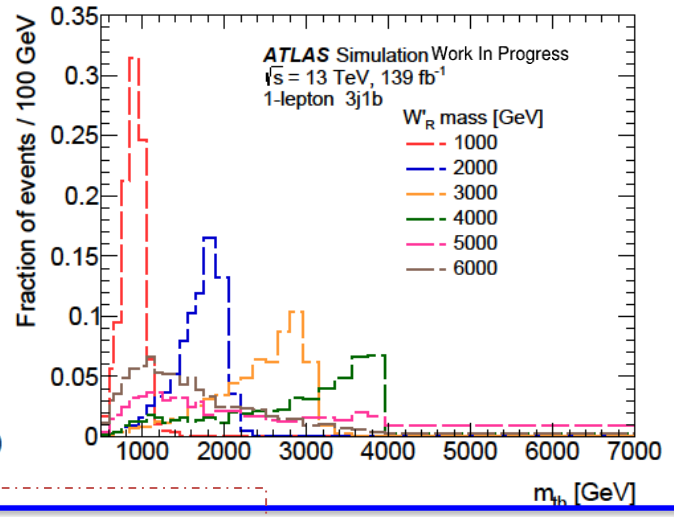
Signal samples

- Signal sample: Madgraph pp -> tb (only BSM vertex allowed)
  - Leading order scaled to NLO (k-Factor calculated by ZTOP: Phys.Rev.D86 (2012) 075018)
  - W'_L and W'_R (no mixture), 500 GeV – 6 TeV
  - Interferece taken into account in statistical analysis for W'_L
  - g'/g = 2.0
    - Madgraph reweighting available various couplings
    - Reweight to g'/g = 1.0 as nominal
    - Reweight to g'/g = 0.1~0.5(0.1 step), 1.0~5.0(0.5 step)
  - Width ~3.5 (2.5)% W' mass for left- (right-) handed (NLO values)

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	$0.00039\ ^{+0.00012}_{-0.00012}$	$0.000379^{+0.000085}_{-0.000085}$



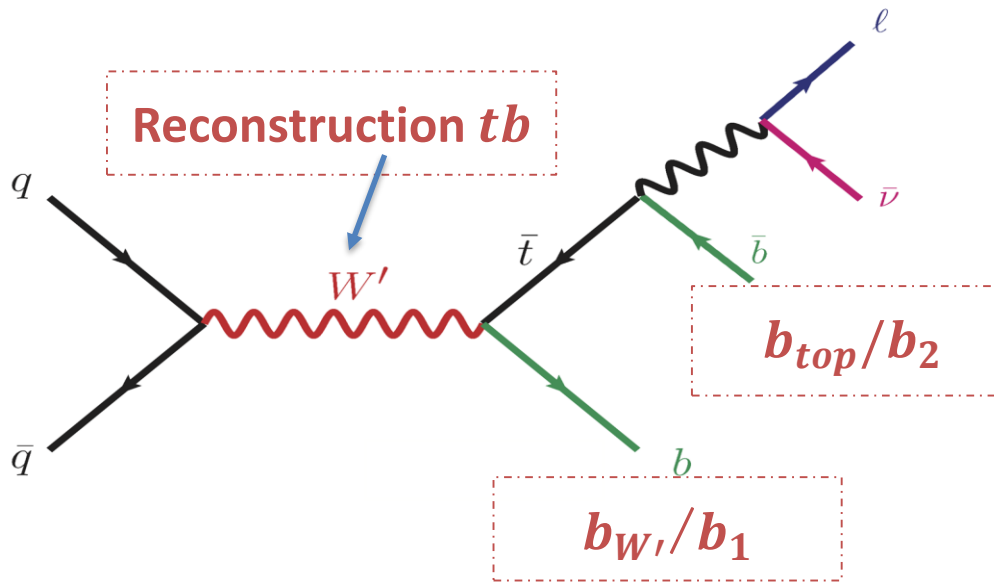


Reconstructed tb mass

ATLAS-CONF-2021-043

$W' \to tb \to l\nu bb$: Analysis strategy

- Final states: leptons (el or mu), MET and small-R jets (2 or more)
- Reconstructed m_{tb}:
  lep + MET -> W boson, W boson + b-jet -> top, top + b-jet -> W'
- Template fit (Multijet) + MC (ttbar/V+jets/single-top/diboson) for background estimation
- Profile-likelihood fit on the m_{tb} spectrum in 4 signal regions and 2 control regions



Categorization

Region	SR	VR_{W+jets}	CR_{W+jets}	$VR_{t\bar{t}}$
Trigger	E_T^{miss} OR one-lepton			
N_{jets}	$= 2, = 3$			
N_{bjets}	$= 1, = 2$		$= 1$	$= 2$
$\Delta R(l, b_{top})$	< 1.0	$> 1.0, <= 1.5$	$> 1.5, <= 2.4$	$> 1.0, <= 2.4$
p_T^{lep}	> 50 GeV			
E_T^{miss}	> 100 GeV			
$p_T^{b_{W'}}$	> 200 GeV			
p_T^{top}	> 200 GeV			
m_{tb}	> 500 GeV			
m_T^W (in 1-tag)	> 20 GeV			
$\Delta\eta(t, b_{W'})$	< 2.0			
b-tagging (in 2-jet)	$b_{W'}$ is b-tagged			
b-tagging (in 3-jet)	J_3 is not b-tagged			
variable-R reclustered jet (in 3-jet)	veto 140 GeV $< m_{VRCJ} <$ 200 GeV			

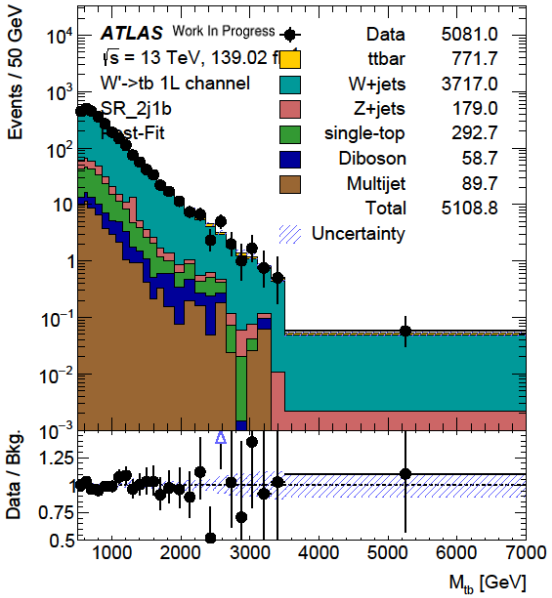
Regions for different jet multiplicities and different number of b-tagged jets

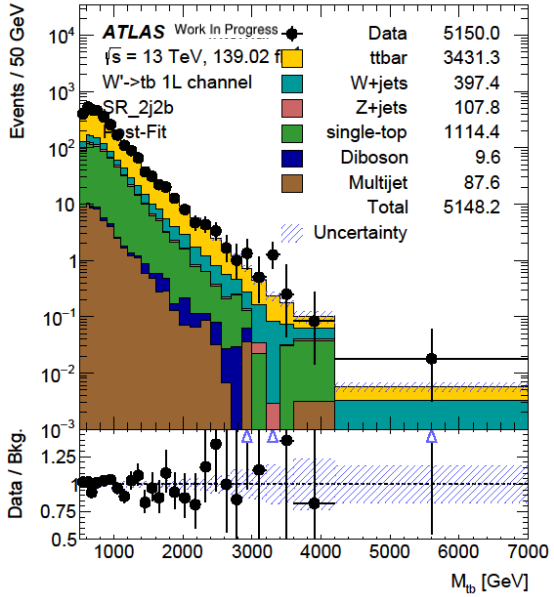
Angular variables to improve signal significance in the signal regions or W+jets purity in the control regions

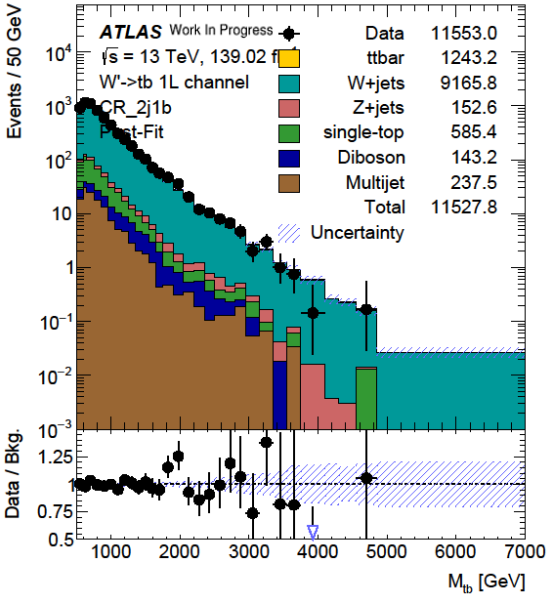
m_T^W cut reduces Multijet contribution

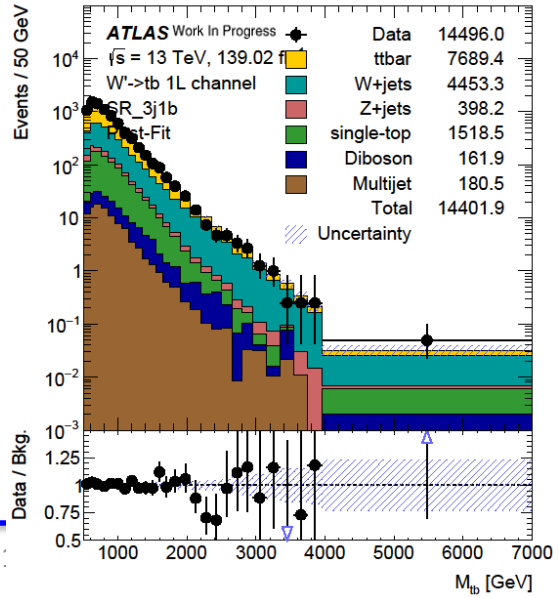
Strengthening Rejection of dominant backgrounds

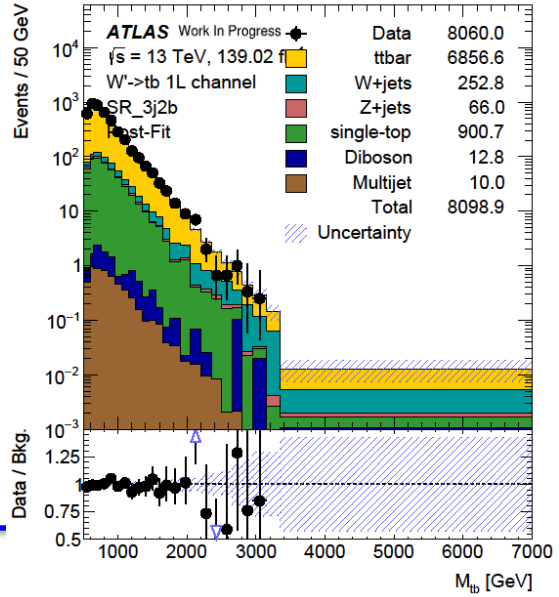
Post-fit

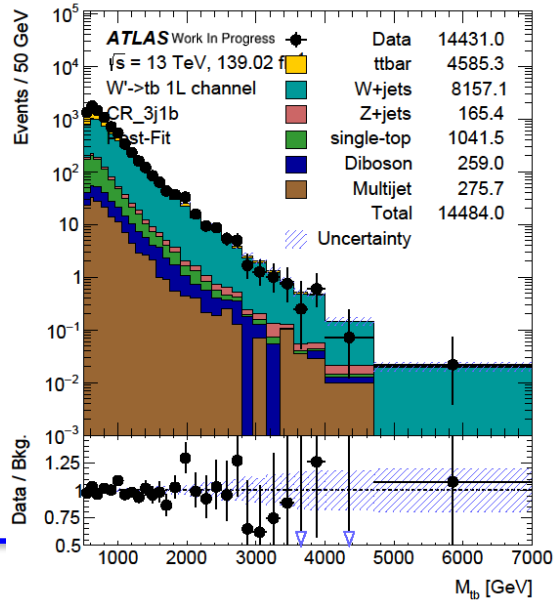

ATLAS Work In Progress
√s = 13 TeV, 139.02 f
W'->tb 1L channel
SR_2j1b
Post-Fit
Data 5081.0
ttbar 771.7
W+jets 3717.0
Z+jets 179.0
single-top 292.7
Diboson 58.7
Multijet 89.7
Total 5108.8
Uncertainty
Events / 50 GeV
Data / Bkg.
M_tb [GeV]


ATLAS Work In Progress
√s = 13 TeV, 139.02 f
W'->tb 1L channel
SR_2j2b
Post-Fit
Data 5150.0
ttbar 3431.3
W+jets 397.4
Z+jets 107.8
single-top 1114.4
Diboson 9.6
Multijet 87.6
Total 5148.2
Uncertainty
Events / 50 GeV
Data / Bkg.
M_tb [GeV]


ATLAS Work In Progress
√s = 13 TeV, 139.02 f
W'->tb 1L channel
CR_2j1b
Post-Fit
Data 11553.0
ttbar 1243.2
W+jets 9165.8
Z+jets 152.6
single-top 585.4
Diboson 143.2
Multijet 237.5
Total 11527.8
Uncertainty
Events / 50 GeV
Data / Bkg.
M_tb [GeV]

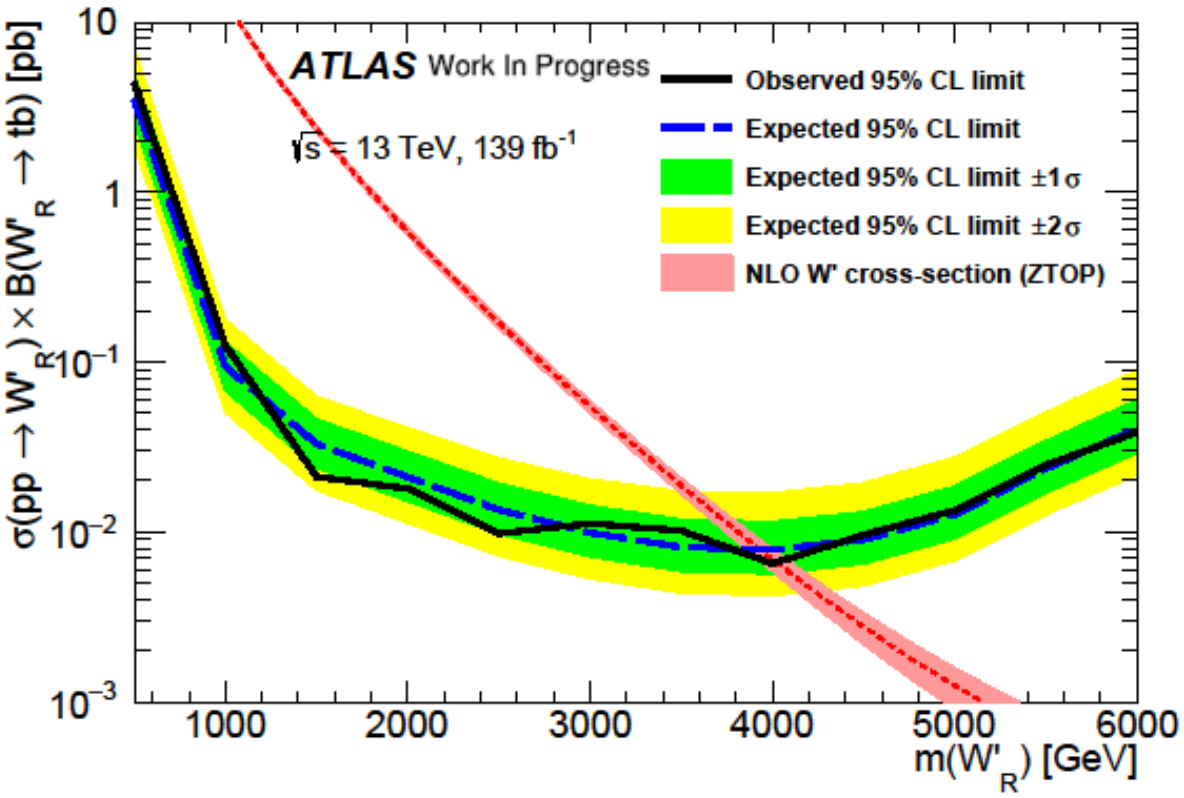

ATLAS Work In Progress
√s = 13 TeV, 139.02 f
W'->tb 1L channel
SR_3j1b
Post-Fit
Data 14496.0
ttbar 7689.4
W+jets 4453.3
Z+jets 398.2
single-top 1518.5
Diboson 161.9
Multijet 180.5
Total 14401.9
Uncertainty
Events / 50 GeV
Data / Bkg.
M_tb [GeV]


ATLAS Work In Progress
√s = 13 TeV, 139.02 f
W'->tb 1L channel
SR_3j2b
Post-Fit
Data 8060.0
ttbar 6856.6
W+jets 252.8
Z+jets 66.0
single-top 900.7
Diboson 12.8
Multijet 10.0
Total 8098.9
Uncertainty
Events / 50 GeV
Data / Bkg.
M_tb [GeV]

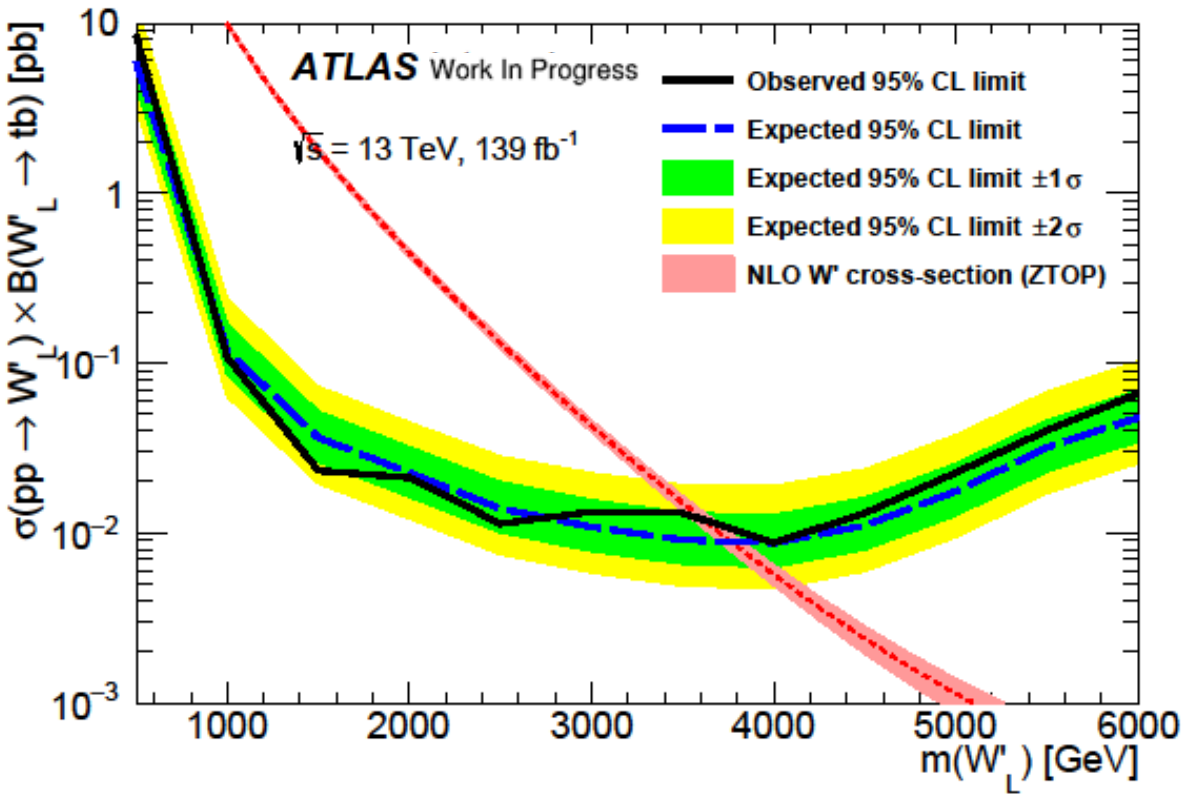

ATLAS Work In Progress
√s = 13 TeV, 139.02 f
W'->tb 1L channel
CR_3j1b
Post-Fit
Data 14431.0
ttbar 4585.3
W+jets 8157.1
Z+jets 165.4
single-top 1041.5
Diboson 259.0
Multijet 275.7
Total 14484.0
Uncertainty
Events / 50 GeV
Data / Bkg.
M_tb [GeV]

Limit at 95% CL: W'_R and W'_L with g'/g = 1.0

No excess observed, set upper limit and exclude mass range for theory

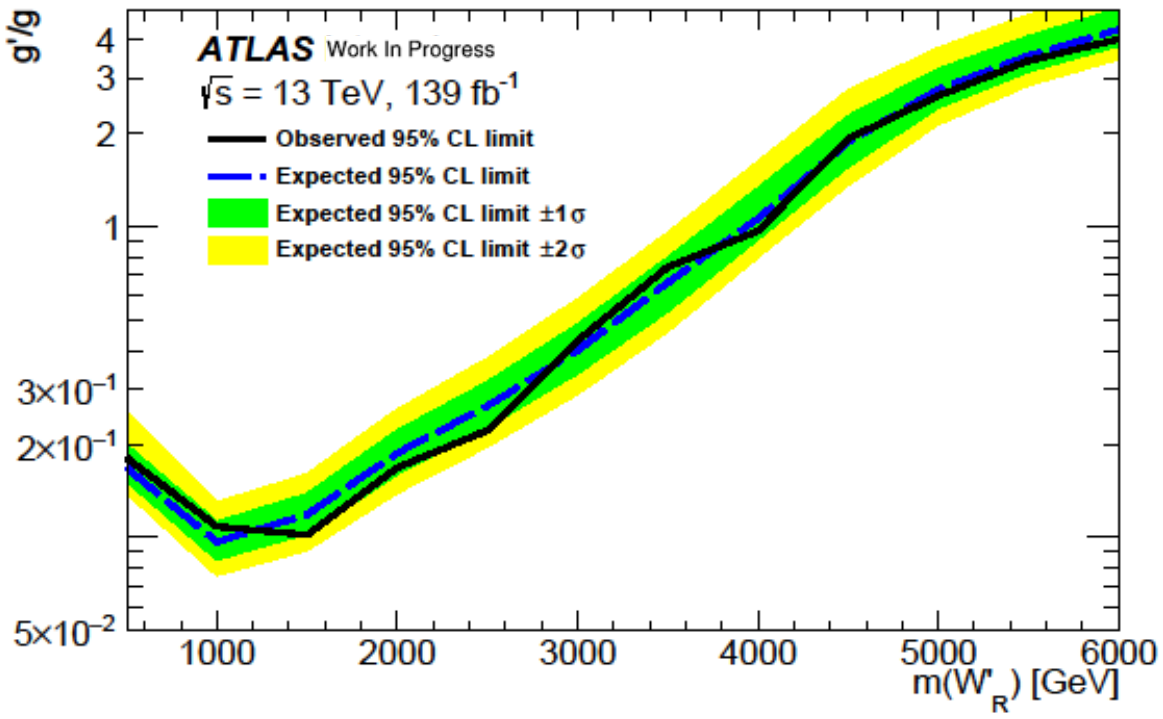


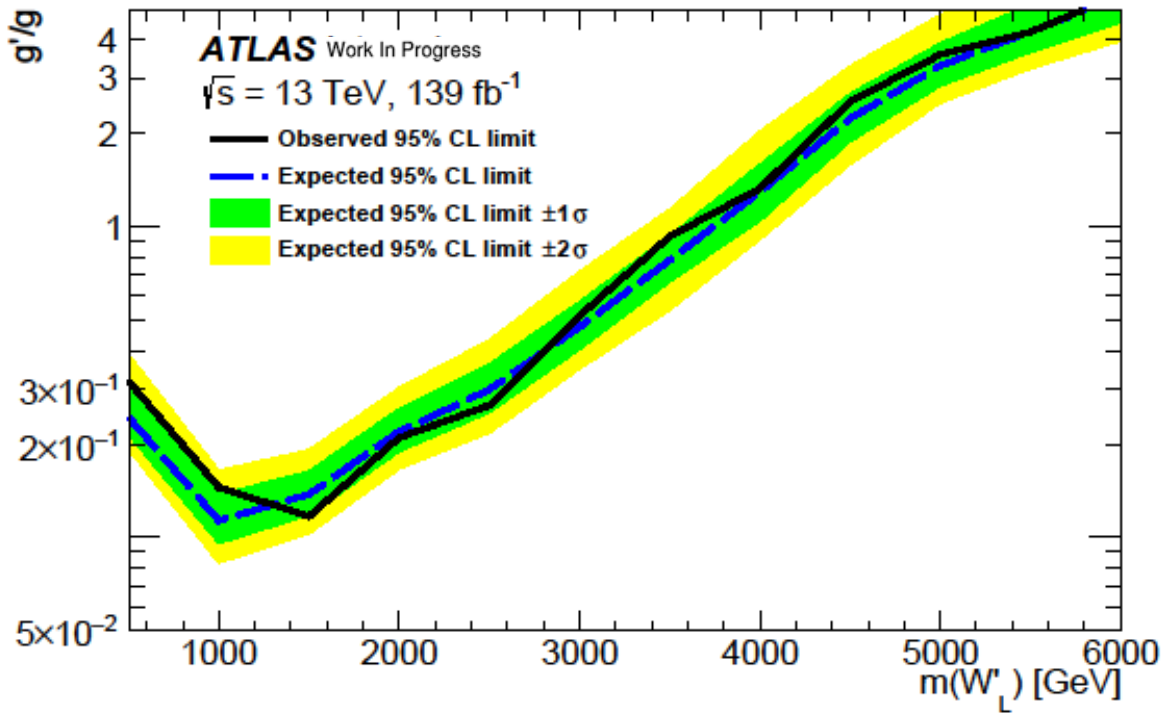
4.07 (3.96) TeV



3.70 (3.84) TeV

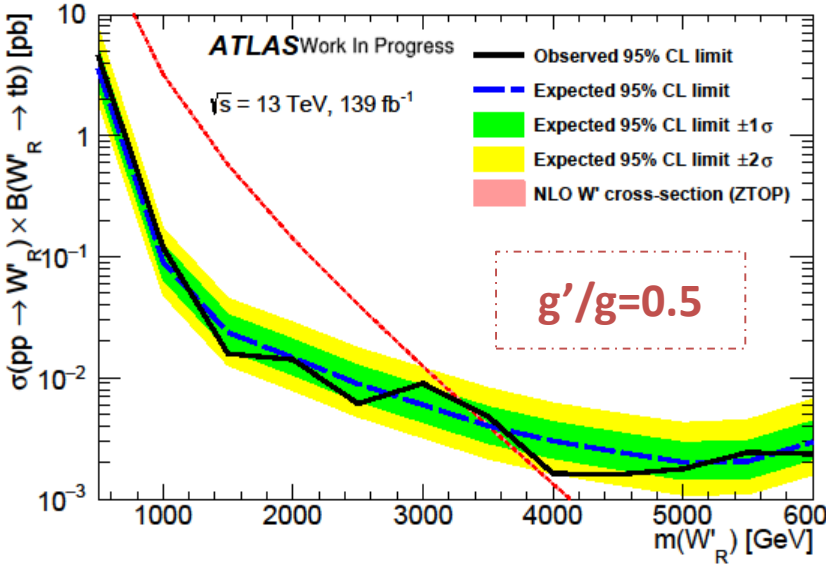
2D Limit

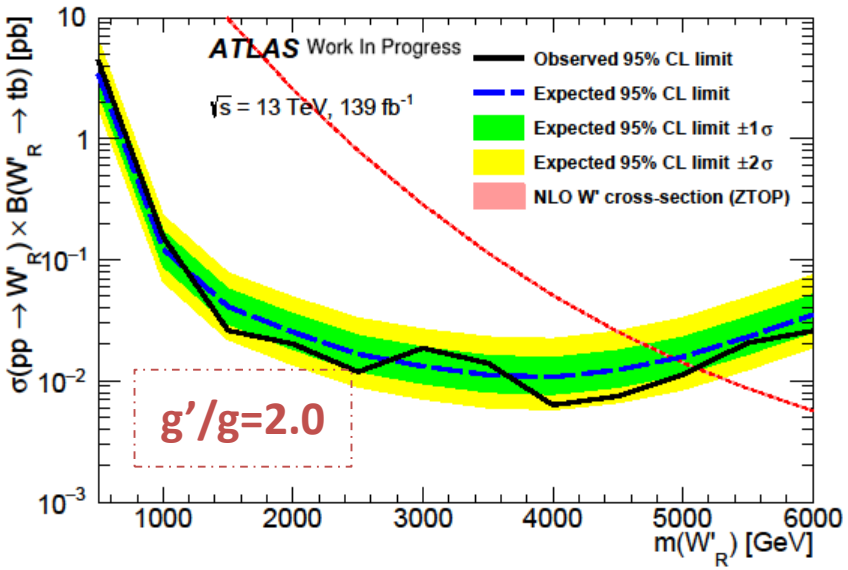


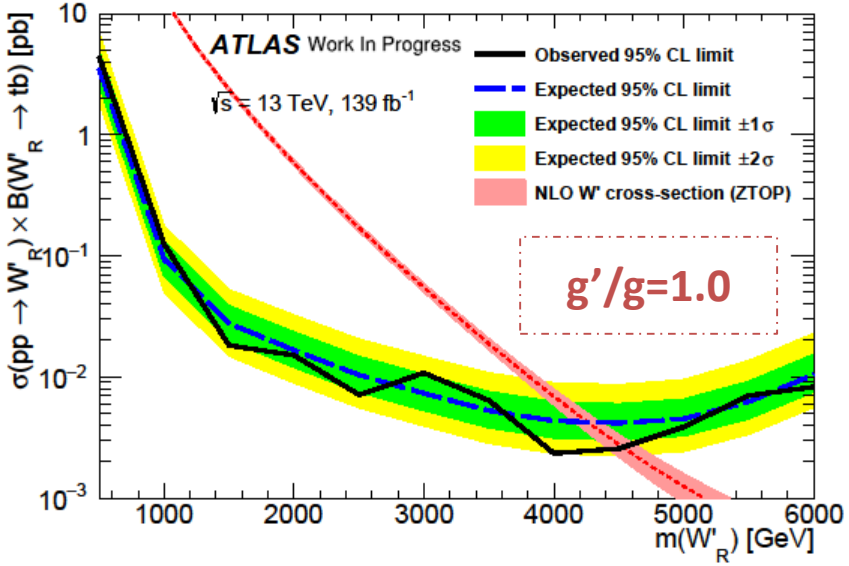


Coupling fraction vs m_{tb} 2D plane, points are obtained from 1D limit, theory excluded cross-point
Region above the contour is excluded

Combination Limit: W'_R



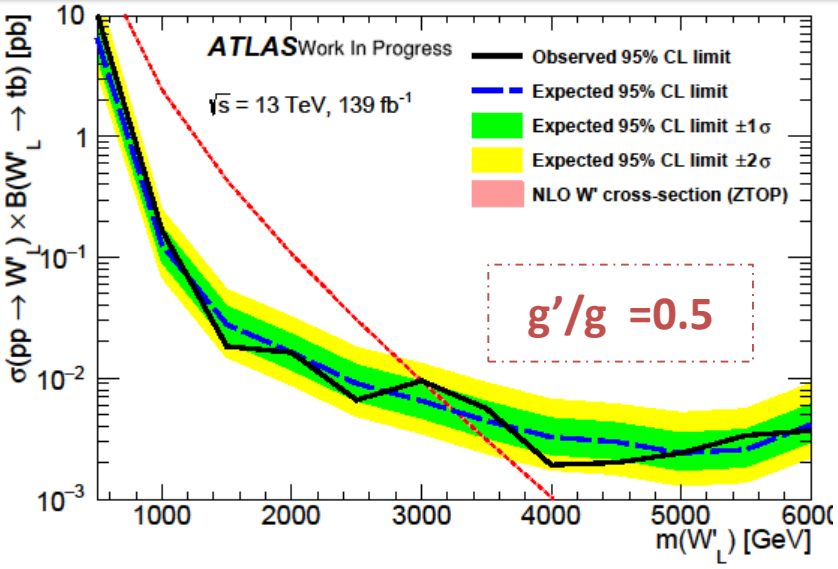


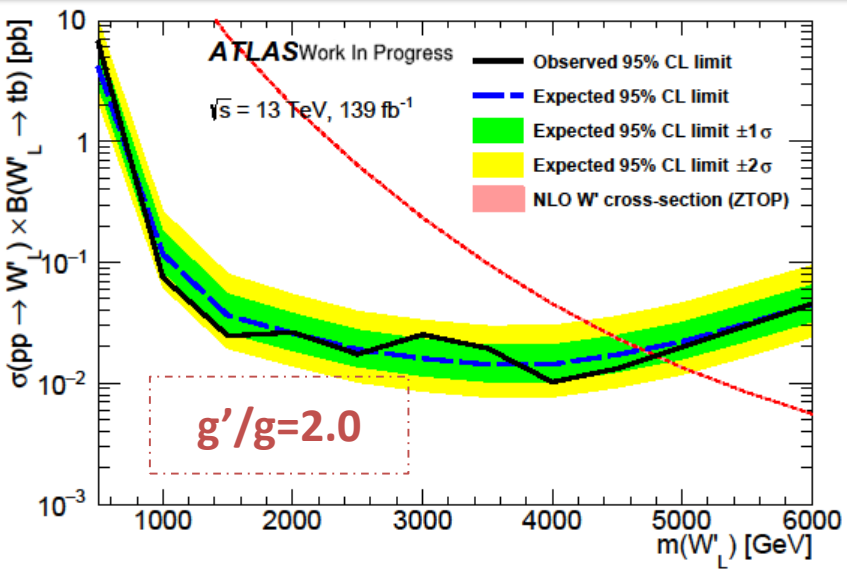


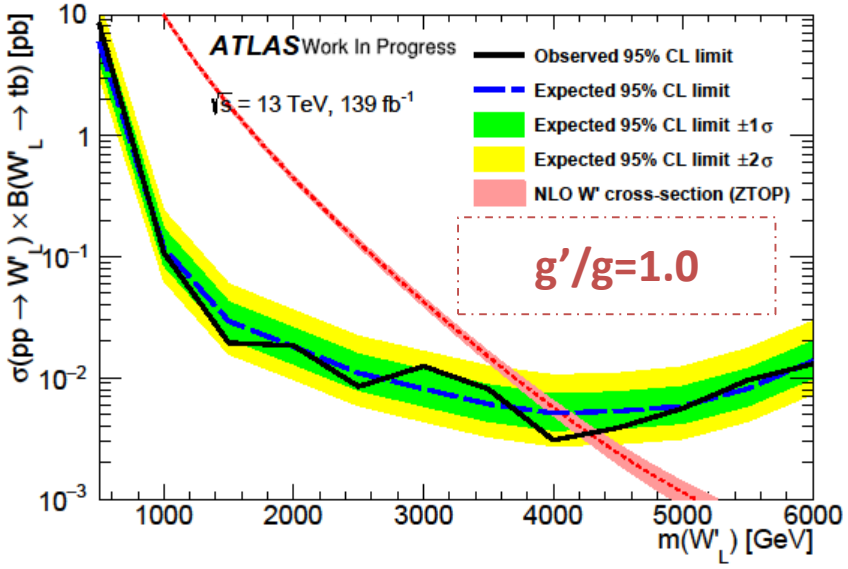
- Simultaneous fit of 1L regions and 0L regions
  - 4 SR + 2CR in 1L channel
  - 3 SR in 0L channel [ATLAS-CONF-2021-043]
  - VR won't contribute to constraint

4.56 (4.33) TeV

Combination Limit: W'_L

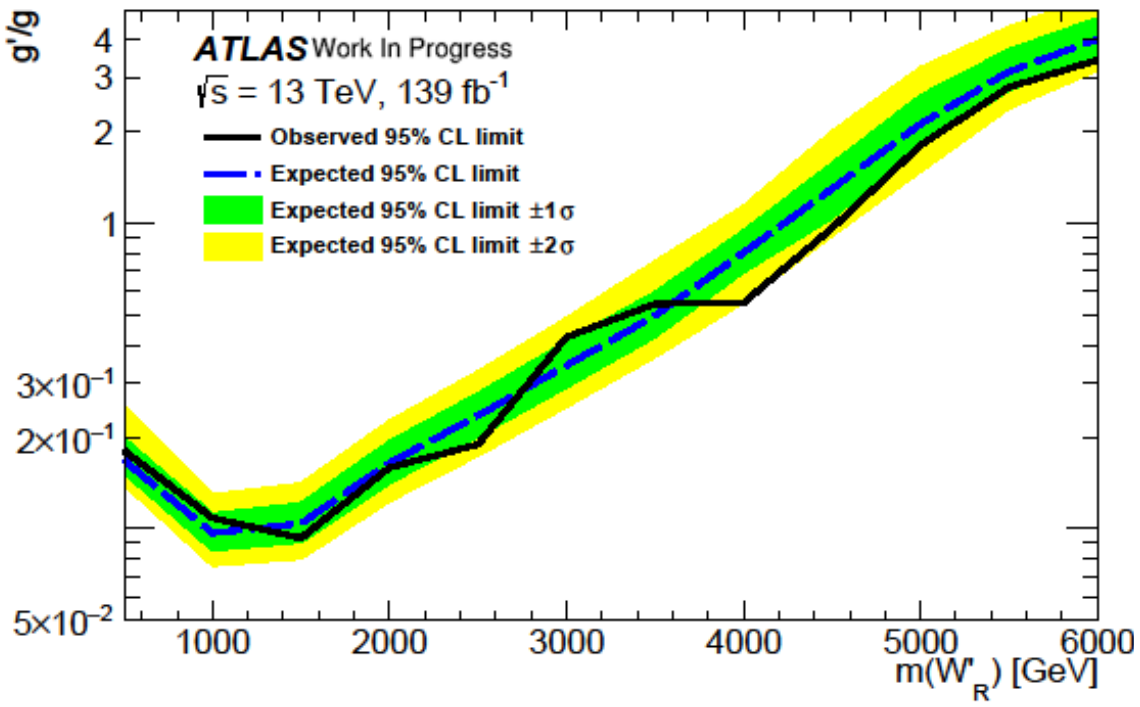


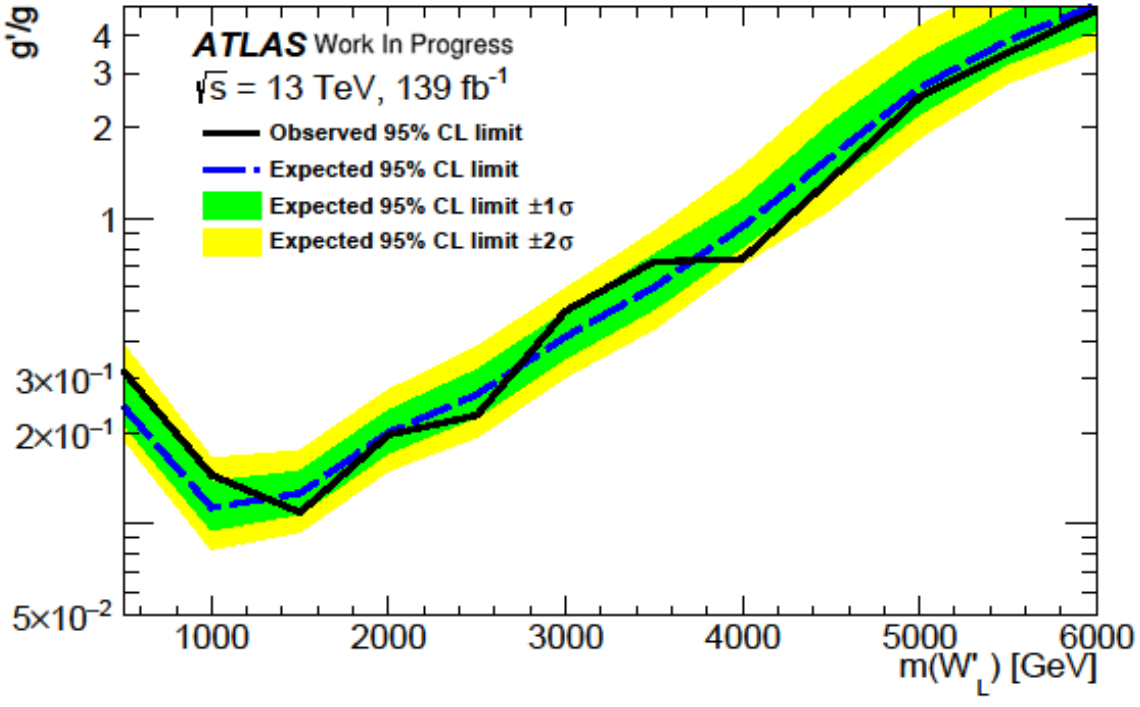




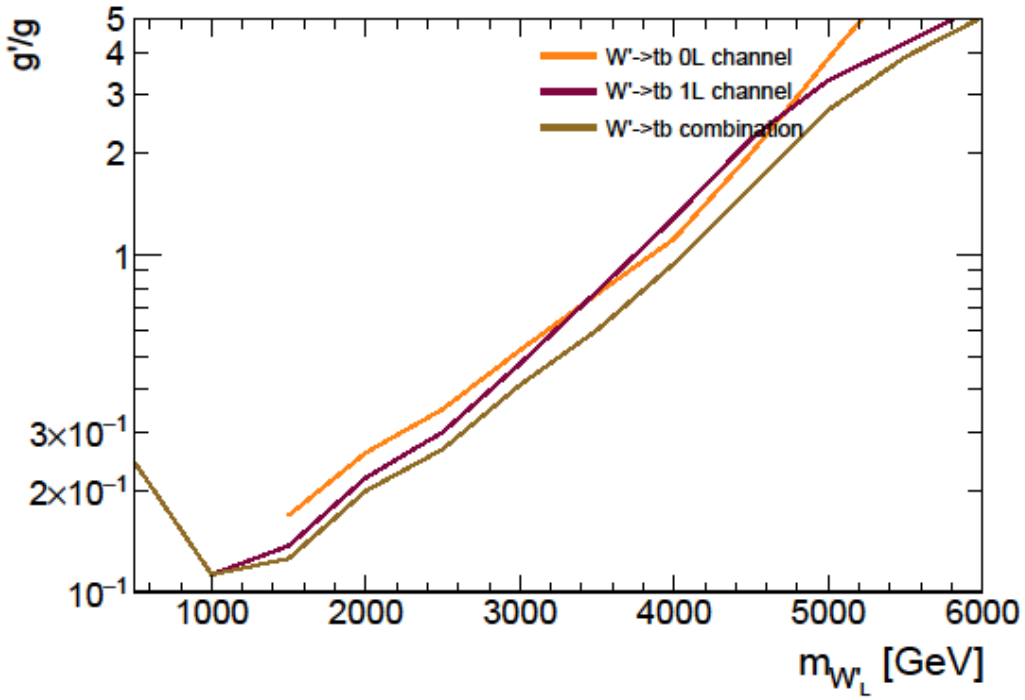
4.32 (4.09) TeV

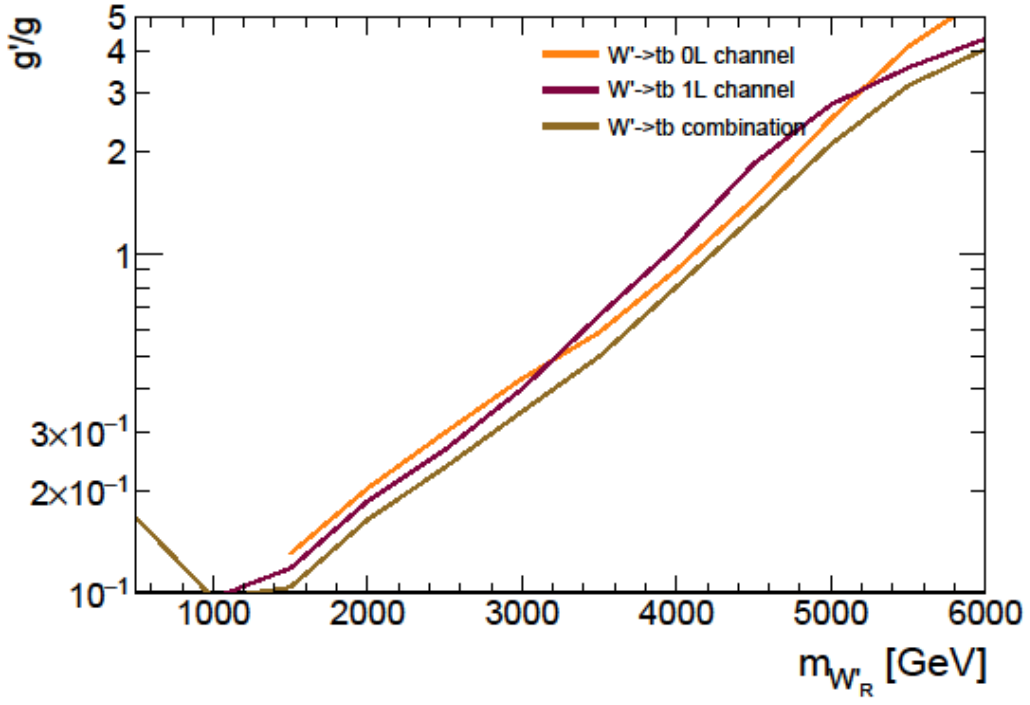
2D Limit


g'/g
ATLAS Work In Progress
√s = 13 TeV, 139 fb-1
Observed 95% CL limit
Expected 95% CL limit
Expected 95% CL limit ±1σ
Expected 95% CL limit ±2σ
4
3
2
1
3×10−1
2×10−1
5×10−2
1000
2000
3000
4000
5000
6000
m(W'R) [GeV]


g'/g
ATLAS Work In Progress
√s = 13 TeV, 139 fb-1
Observed 95% CL limit
Expected 95% CL limit
Expected 95% CL limit ±1σ
Expected 95% CL limit ±2σ
4
3
2
1
3×10−1
2×10−1
5×10−2
1000
2000
3000
4000
5000
6000
m(W'L) [GeV]

2D Limit Comparison





- At very high W' mass and high coupling regimes, the significance contributed by the predicted peak (which is very degraded and mostly disappears completely) is very small. The low mtb tail becomes the more significant region and the 1L channel has better sensitivity for low m_{tb}

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}:
  - 4.56 TeV exclusion for W'_R
  - 4.32 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

Summary

- Present the studies of the heavy boson W' decaying to a top and a bottom quark
  - Combination of $W' \to tb \to qqbb$ and $W' \to tb \to l\nu bb$
- Large improvement from 36.1 fb^{-1} results
- Very extended Interpretation strategy
  - Interference added to left-handed interpretation
  - 2D scan of g'/g from 0.1 to 5.0 to obtain the 2D contour

Thank you~

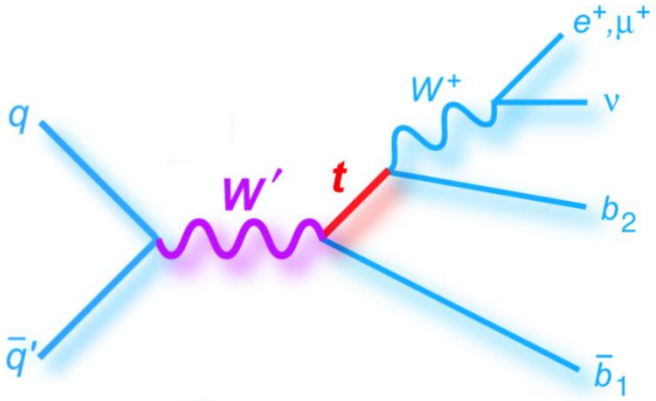
Backup

$W' \to tb \to l\nu bb$: Reconstruction

Reconstruction

- Neutrino reconstruction algorithm using m_w (80.4 GeV) and the missing energy
- W reconstruction: Single lepton + neutrino
- Top reconstruction: jet that provides the closest m_{top} = 172.5 GeV -> b_{top}
- W' reconstruction: Remaining jet with highest P_T -> $b_{W'}$

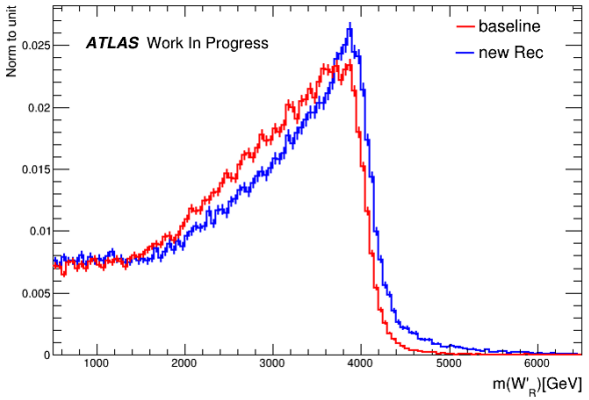
$$p_{z,\nu}^{\pm} = \frac{\mu \cdot p_{z,l}}{p_{T,l}^2} \pm \sqrt{\frac{\mu^2 \cdot p_{z,l}^2}{p_{T,l}^4} - \frac{E_l^2 \cdot p_{T,\nu}^2 - \mu^2}{p_{T,l}^2}}$$



Alternative method

- Consider the neutrino momentum should satisfy both of the W boson and top reconstruction at same time
- Solution should be a group of points (if exist) on the intersection of these two ellipsoids described by the equations
- Choose the point closest to the MET and the projection of the ellipse onto the transverse plane, define the distance as D_ν
- Choose the jet with smallest D_ν as b-candidate
- Better resolution, but less events,
  hurt the significance, especially at high mass region

$$m_W^2 = (P_\nu + P_l)^2$$
$$m_t^2 = (P_\nu + P_l + p_{b_2})^2$$



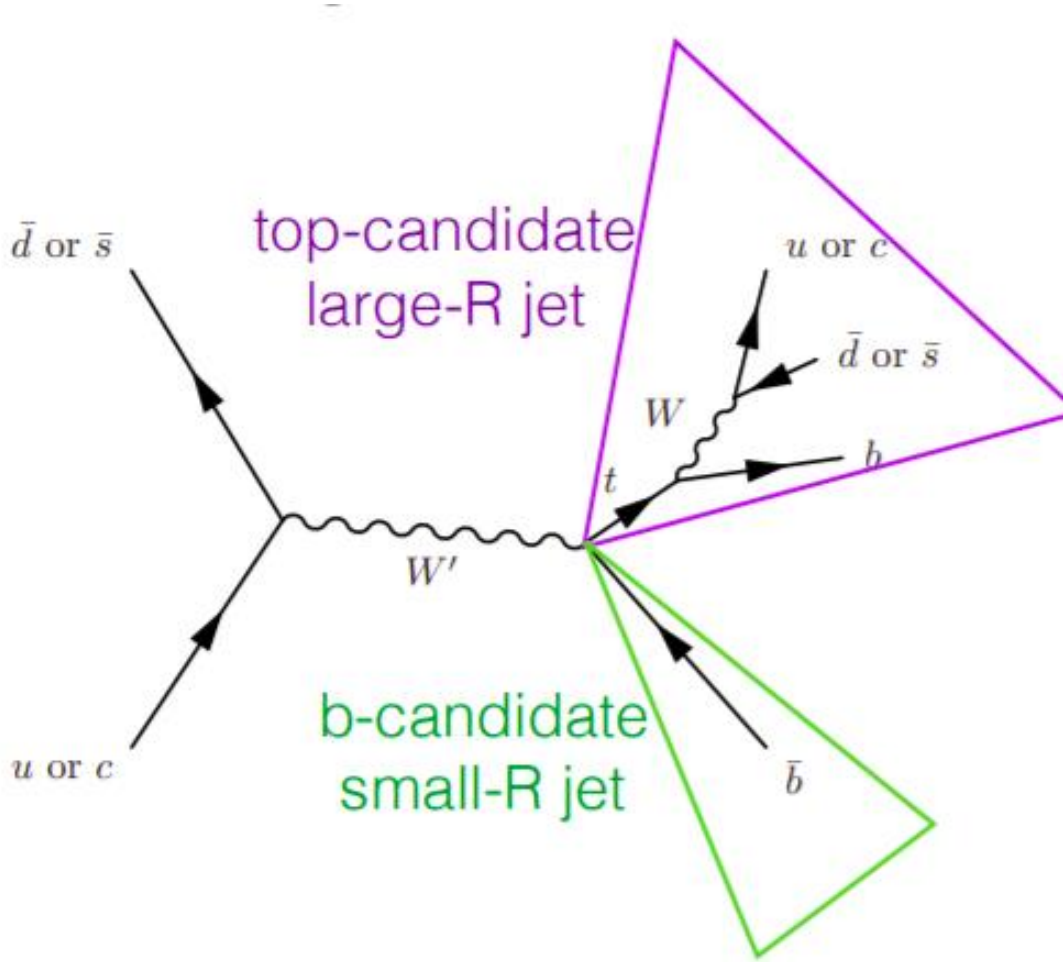
Background estimation

- MC for ttbar/Wjets/single-top/diboson/Zjets, ttbar/Wjets are dominant
- 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 = Data – MC in loose-not-tight regions
  - Fit m_T^W multijet_template with normal MC and Data (tight), get initial norm_SF for multijet
  - Implement the norm_SF on m_{tb} multijet_template distribution. And include in the final fit

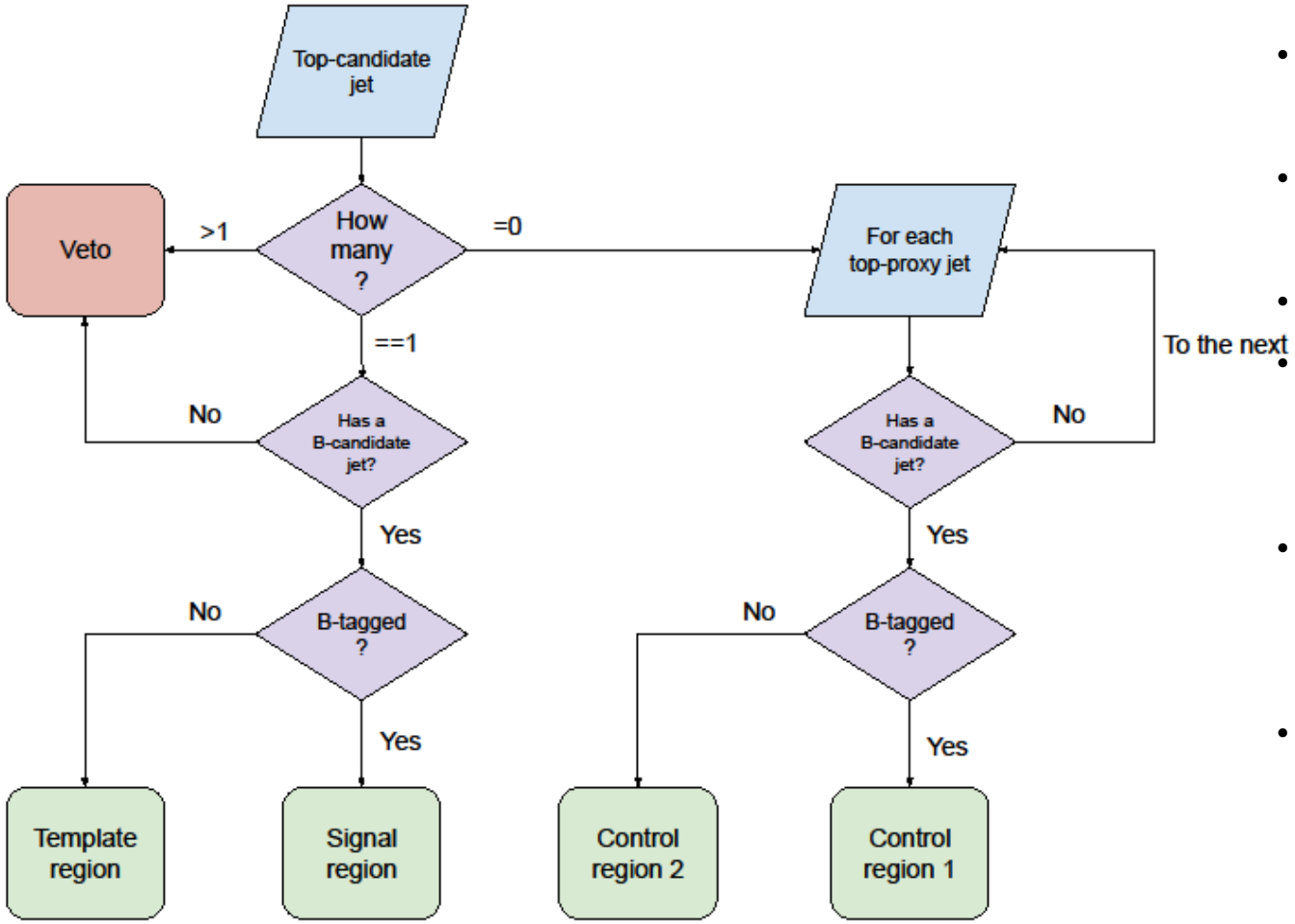
$W' \to tb \to qqbb$: Analysis strategy

- Boosted hadronically decaying top-quark
  -> one large-R jet (AntiKt10) as top-candidate
- b-quark from W'
  -> small-R jet (AntiKt4) as b-candidate
- Categorization based on top-tagging and b-tagging

  top-tagging: large-R jets identified as coming from a top-quark
  b-tagging: small-R jets identified as coming from b-quark
  Both are DNN based
- Backgound:
  - MC ttbar
  - Data-driven QCD multi-jet



$W' \to tb \to qqbb$: Analysis strategy



CONF Note: ATLAS-CONF-2021-043

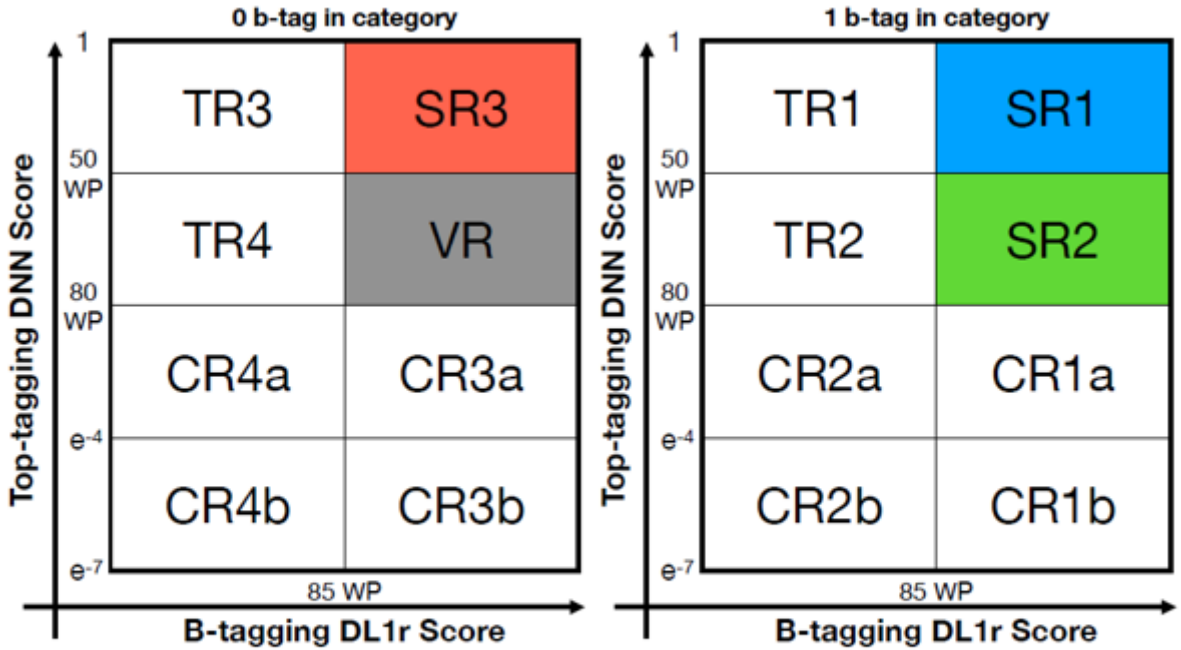
- Request at least 1 small-R jet and 1 large-R jet
- DNN based top-tag

- Top-tagged large-R jet -> top-candidate
- Not top-tagged large-R jet -> top-proxy (could have more than 1 in a event)

- Veto events w/ two top-candidate jets (mostly ttbar)

- Top-proxy jets
  - Control regions for data-driven background estimation
  - All top-proxy jets and paired b-candidate jets are considered

$W' \to tb \to qqbb$: Categorisation

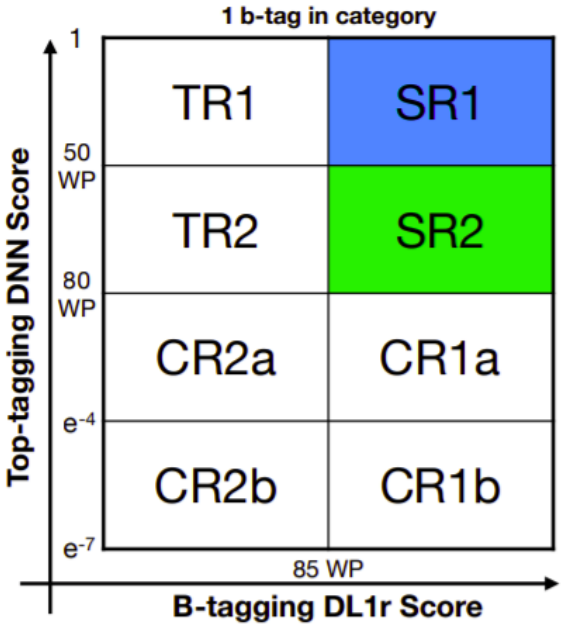


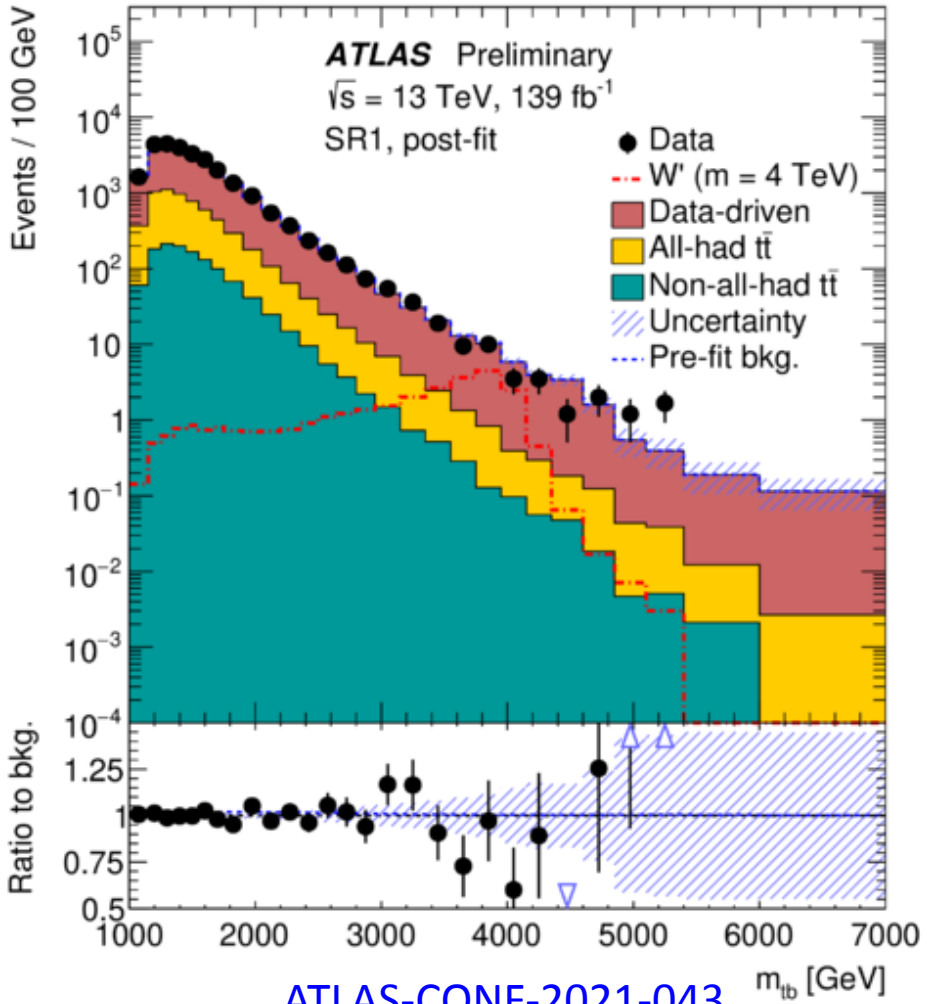
VR = validation region; TR = template region

- 2 categories: 0 or 1+ b-tag small-R jets inside the top-candidate (top-proxy) jet
- Signal/template region: top-candidate pass (fail) 50% WP top-tag -> tight (loose-but-not-tight) top-tag
- Control region “a” or “b”: top-proxy jet with DNN score > e^{-4} or $e^{-7} \sim e^{-4}$
  - CRa: nominal data-driven estimation

$W' \to tb \to qqbb$: Background estimation

- CRa: nominal data-driven estimation
- Subtract ttbar from data in TR
- SR1 = TR1*(CR1/CR2), bin-by-bin
- Systematic: |(CR1a/CR2a)/(CR1b/CR2b)-1|

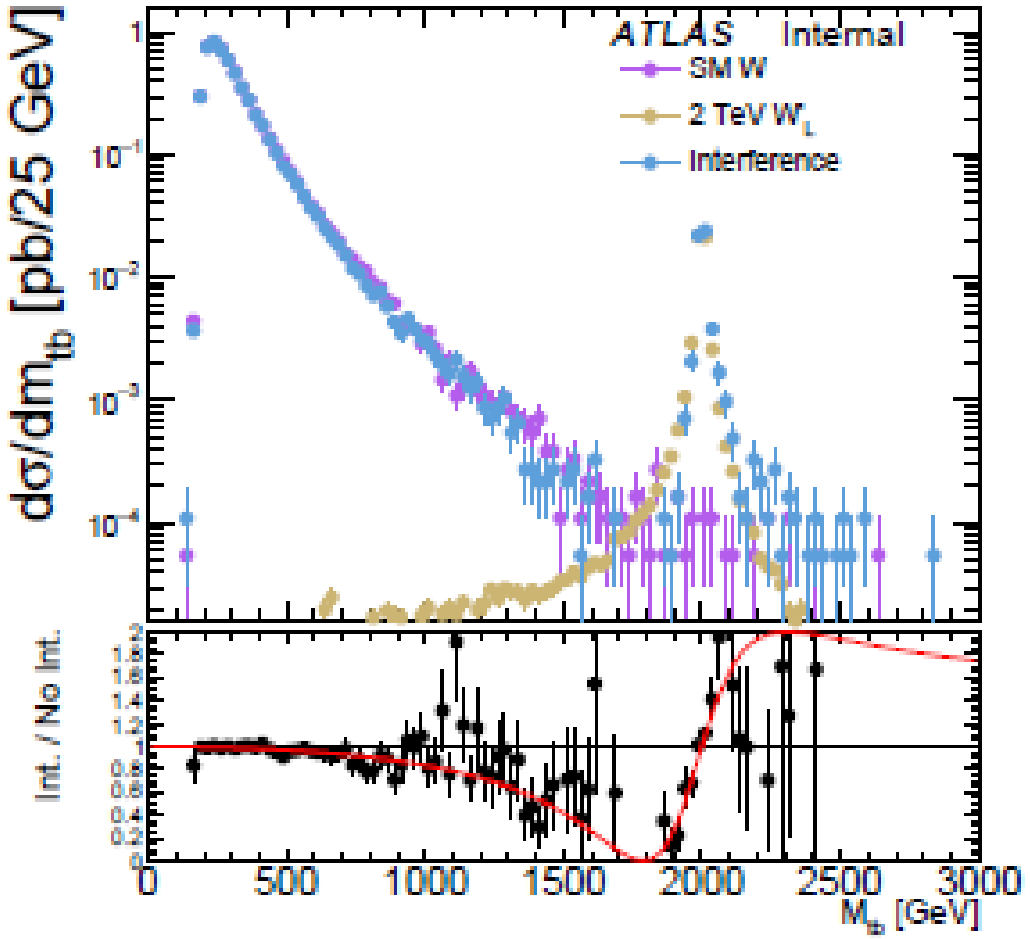




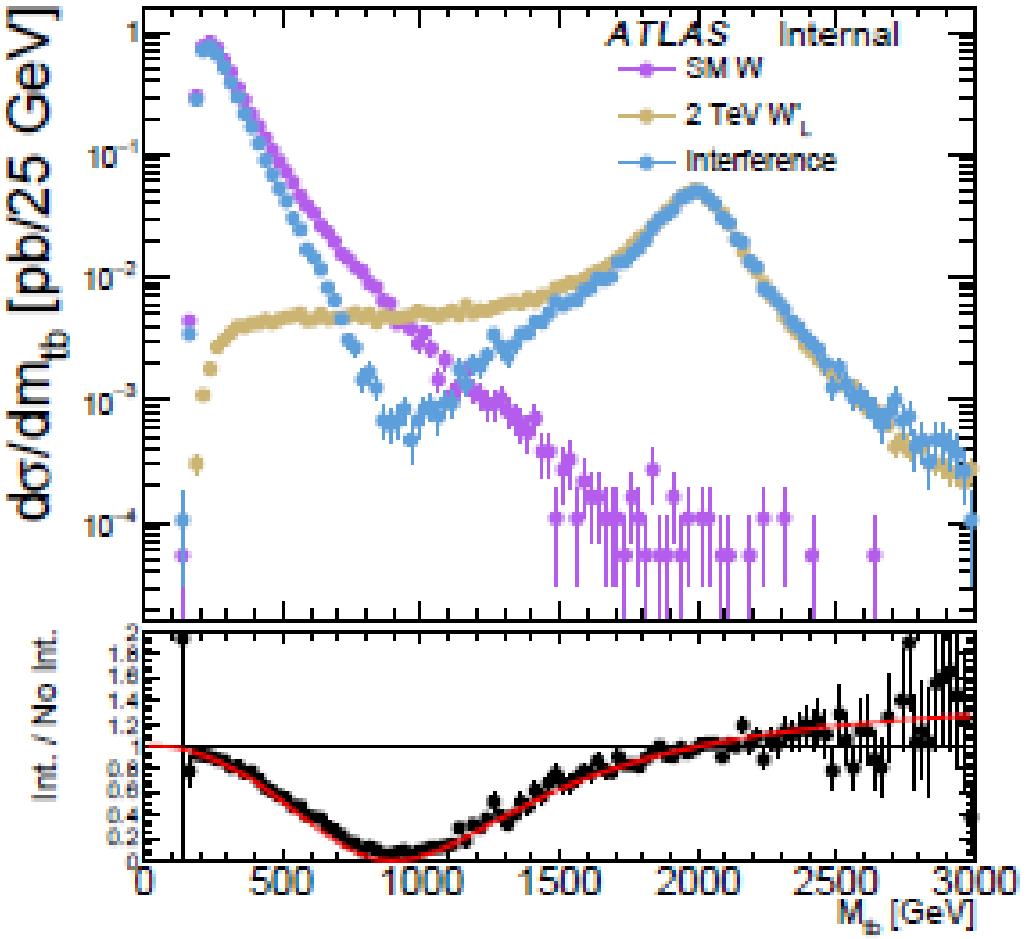
[ATLAS-CONF-2021-043]

Interference formula validation for various g'/g

g'/g = 0.5

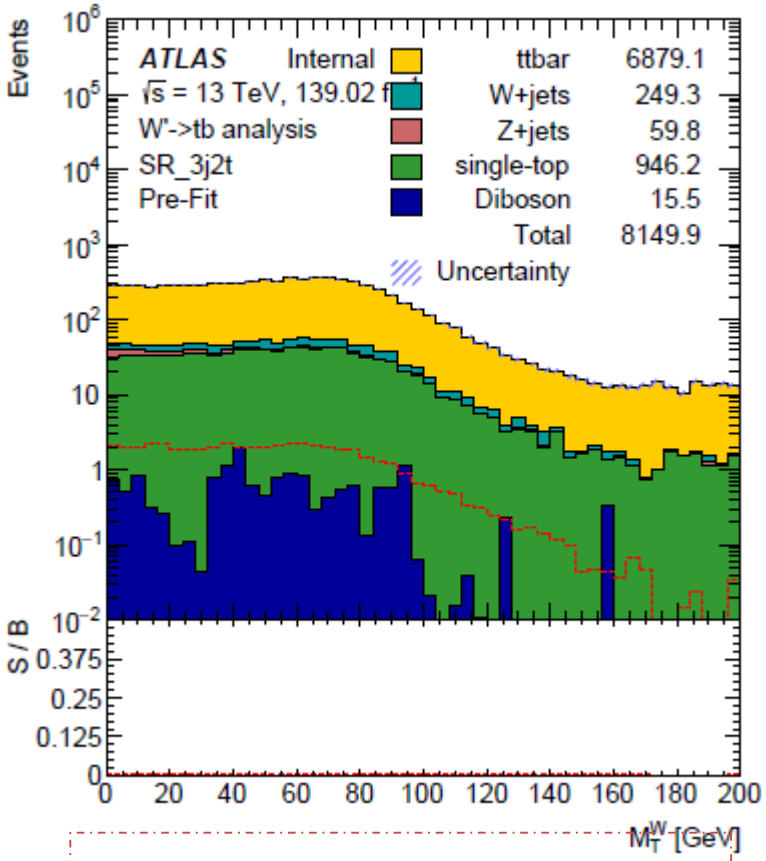


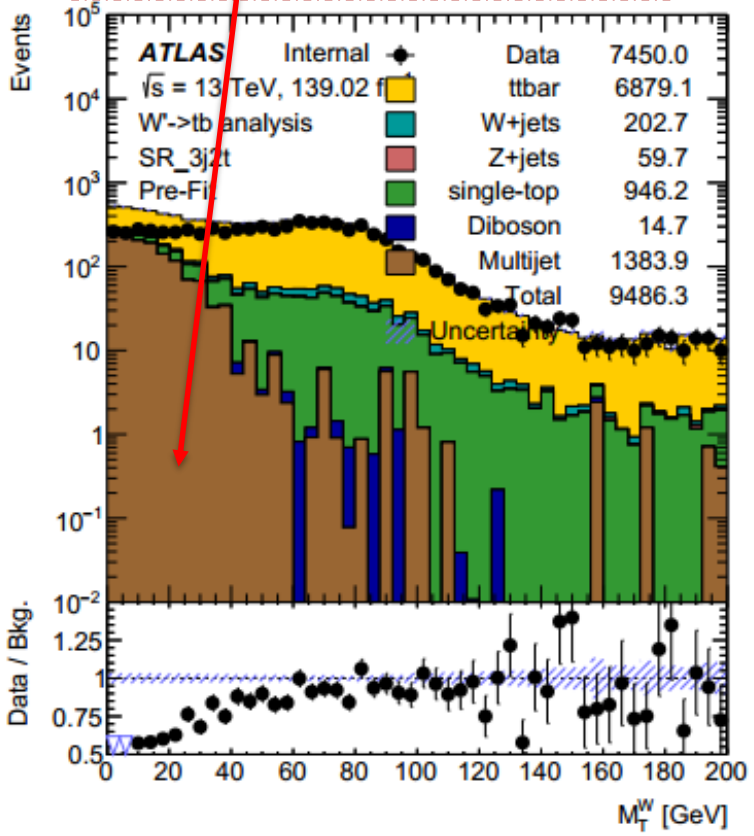
g'/g = 2.0

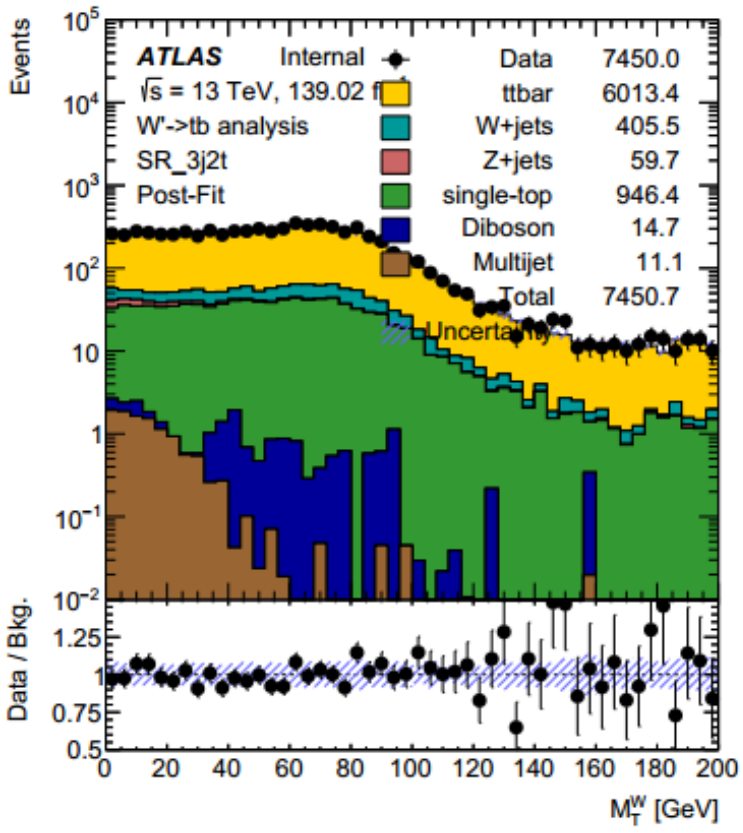


Multijet estimation: template fit

Template from loose-not-tight distribution



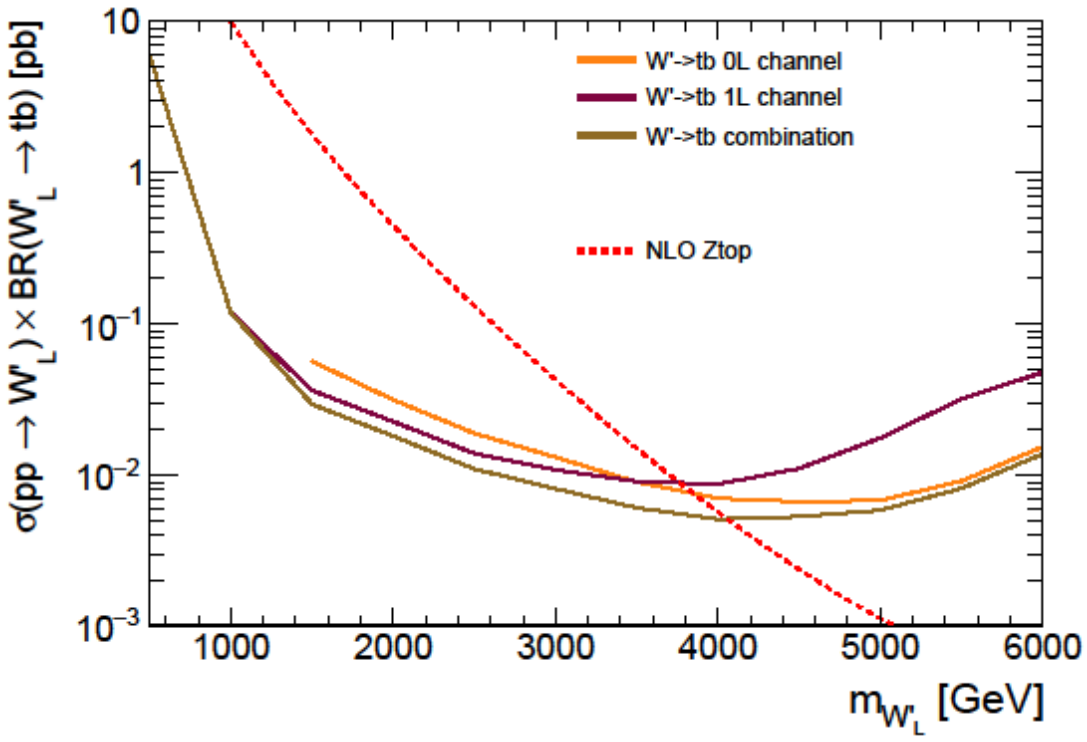


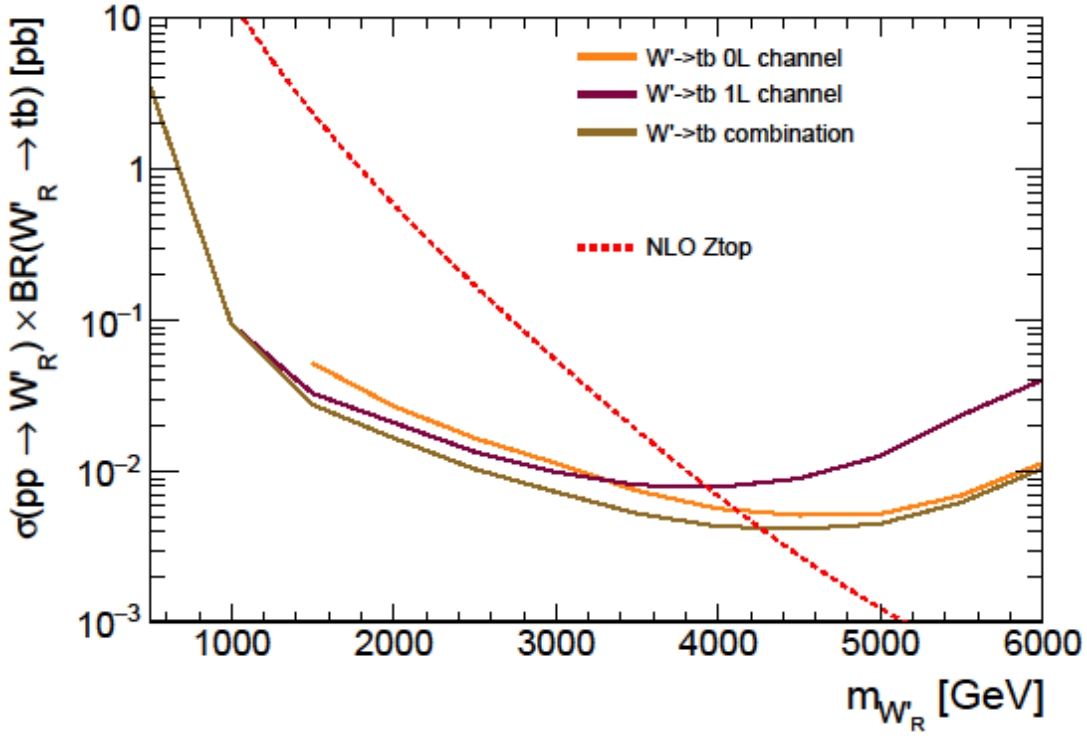


Sensitivity of mTW is studied first to ensure we can fit the SR safely

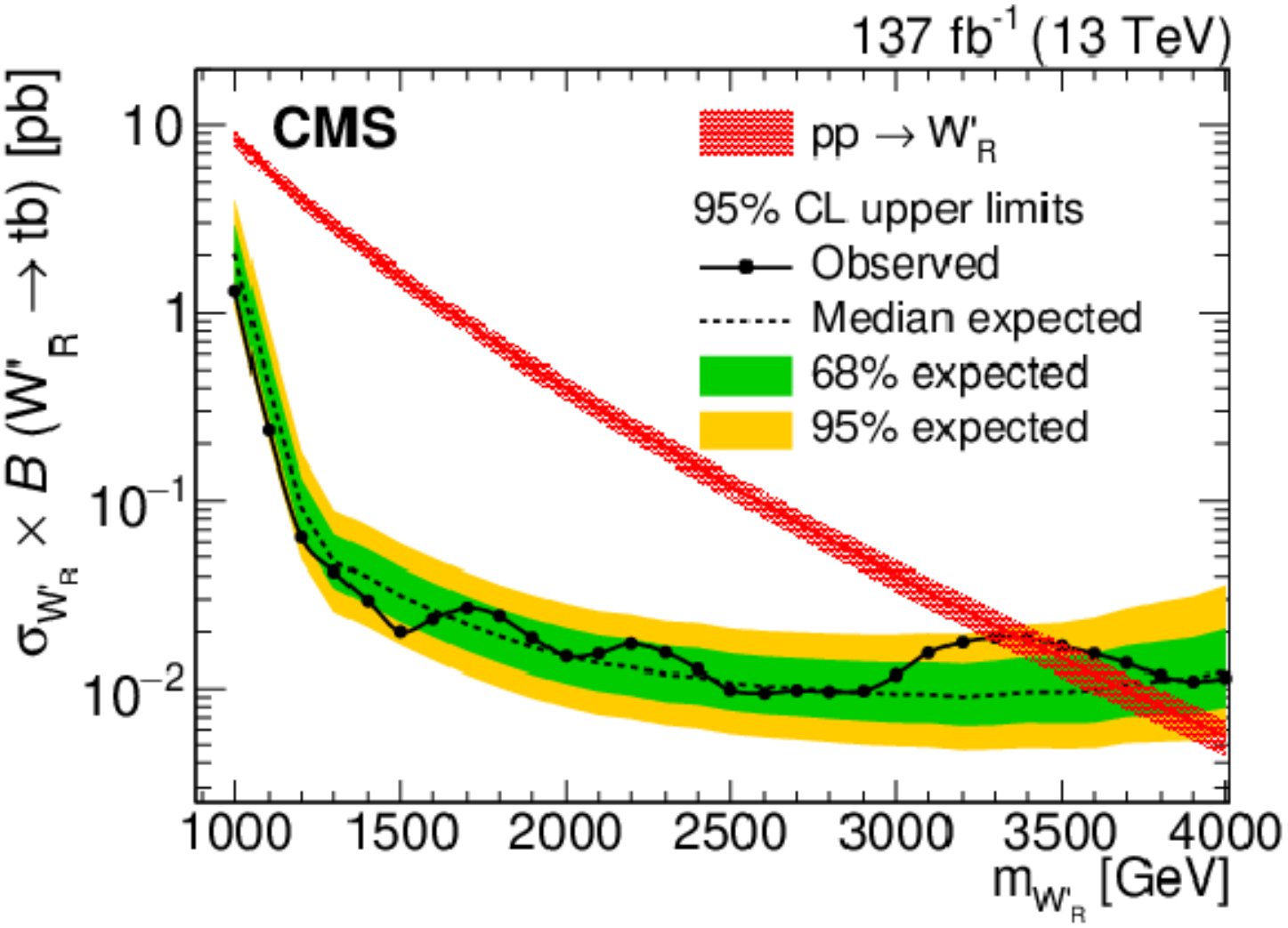
	SR 2j1b	SR 2j2b	SR 3j1b	SR 3j2b
Multijet	389.58 ± 49.30	84.56 ± 37.76	660.45 ± 89.89	11.12 ± 66.29
Total background	6277.36 ± 79.04	4371.80 ± 68.06	17684.50 ± 132.74	7450.75 ± 568.80

g'/g=1.0 Limit comparison





CMS result



arxiv: [2104.04831]