Search for new vector boson decaying to a top quark and bottom quark using 36.1/fb data with the ATLAS detector

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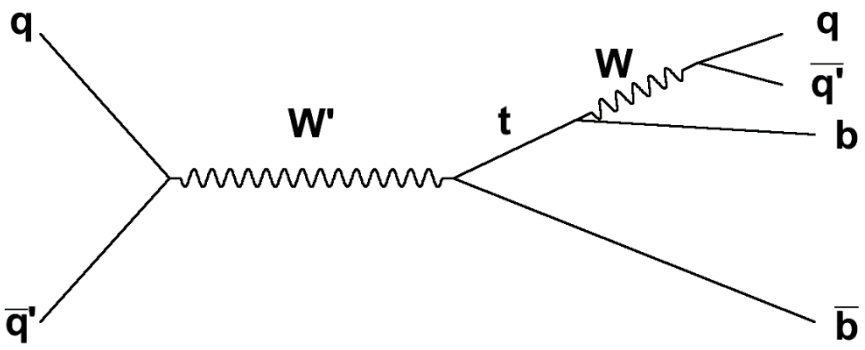
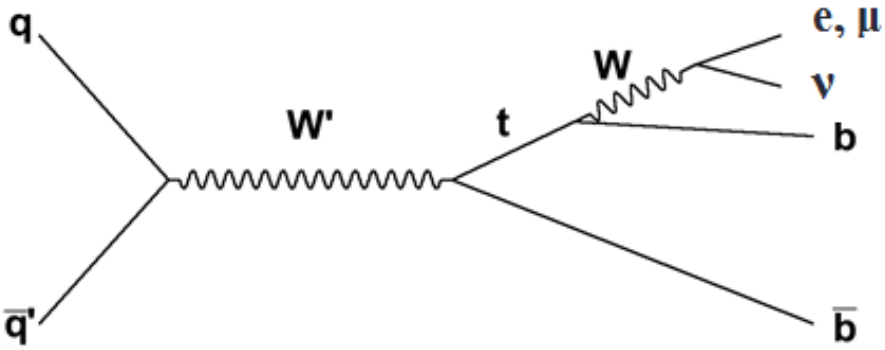
Outline

- Introduction
- $W' \rightarrow tb$ all-hadronic decay
  - Selection
  - Top tag
  - Background
  - W' mass spectrum
  - Limit
- $W' \rightarrow tb$ semi-leptonic decay
  - Selection & Reconstruction
  - Background
  - W' mass spectrum
  - Limit
- CMS result
  - W' mass spectrum
  - Limit
  - Key difference

$W' \rightarrow tb$: Introduction

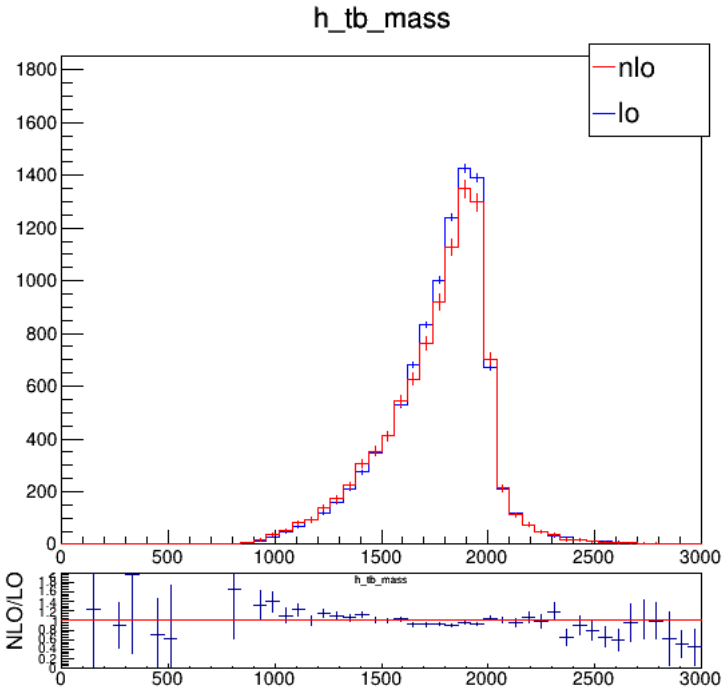
- Boson, spin 1, charge ±1, introduced by many BSM theories
- Chirality W'_L and W'_R
- W'_R can't decay to $l\nu$ if $m_{\nu_R} > m_{W'_R}$
- All-hadronic/semi-leptonic channel: decay mode of W boson comes from top
  - Hadronic: 1 top quark(include 1 b quark and 2 light quarks) + 1 isolated b quark
  - Leptonic: 2 b quarks + 1 lepton(e, μ) + 1 neutrino



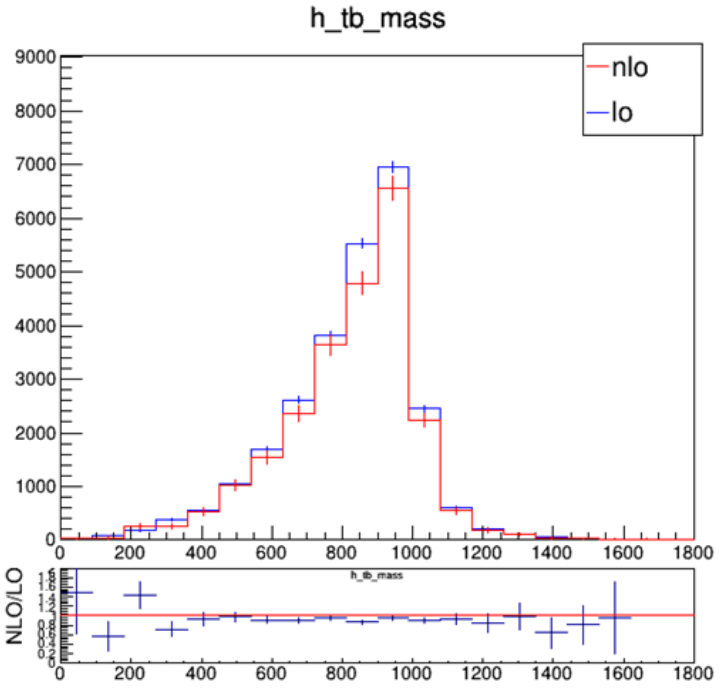


$W' \rightarrow tb$: Signal

- We use the signal sample generated at LO, and rescaled to NLO calculations using NLO/LO K-factors given by ZTOP (D. Duffty, Z. Sullivan, Phys. Rev. D 86 (2012) 075018)
- Generated by Madgraph5 at NLO is consistent with LO*K-factors on particle level(k-factors from 1.1 to 1.4 for semi-leptonic channel, 1.3 to 1.4 for all-hadronic channel)



all-hadronic, 3.5 TeV

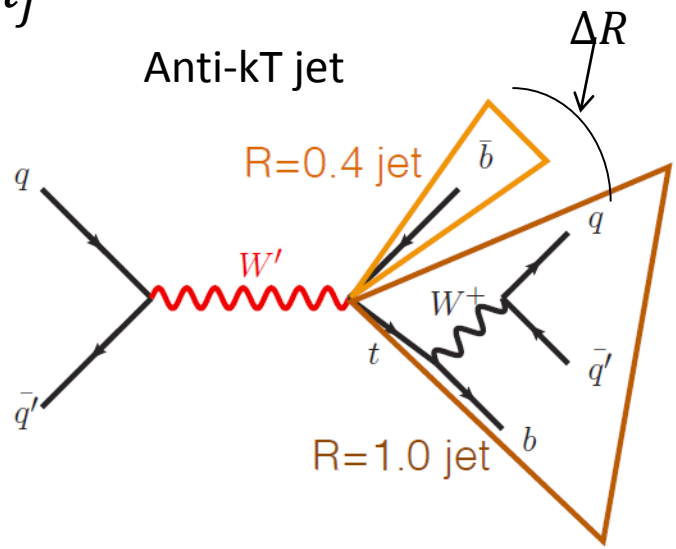


semi-leptonic, 1TeV,

W'_R, NLO compare to LO*K-factor, normalize to same luminosity

All-hadronic: Selection

- Data-driven method requires definition of top and bottom candidates before tagging
  - Effective mass: $m_{eff} = m_j + 0.15 * m_J$
  - J: R = 1.0 jet,
    j: highest p_{T} R = 0.4 jet
    among those of which are inside J
  - R=1.0 jet with the highest effective Mass -> top-candidate jet

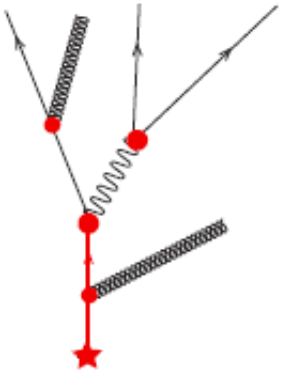


  - R=0.4 jet with the highest p_{T} and $\Delta R > 2$ -> b-candidate jet

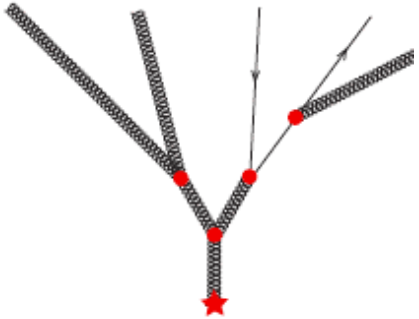
- 2 signal categories: 0 b-tag inside top-candidate jet and 1 b-tag inside top-candidate jet

All-hadronic: Top tag

- Top-tag method: Shower deconstruction
- Exclusive kT sub-jet inside 'top jet' (splitting scale threshold = 15 GeV)
- 2 sub-jets to match W mass plus 1 more sub-jet to match top-quark mass
- Estimate the likelihood of a top-quark decay vs that of a light-quark/gluon showering
- Better performance in high p_{T}



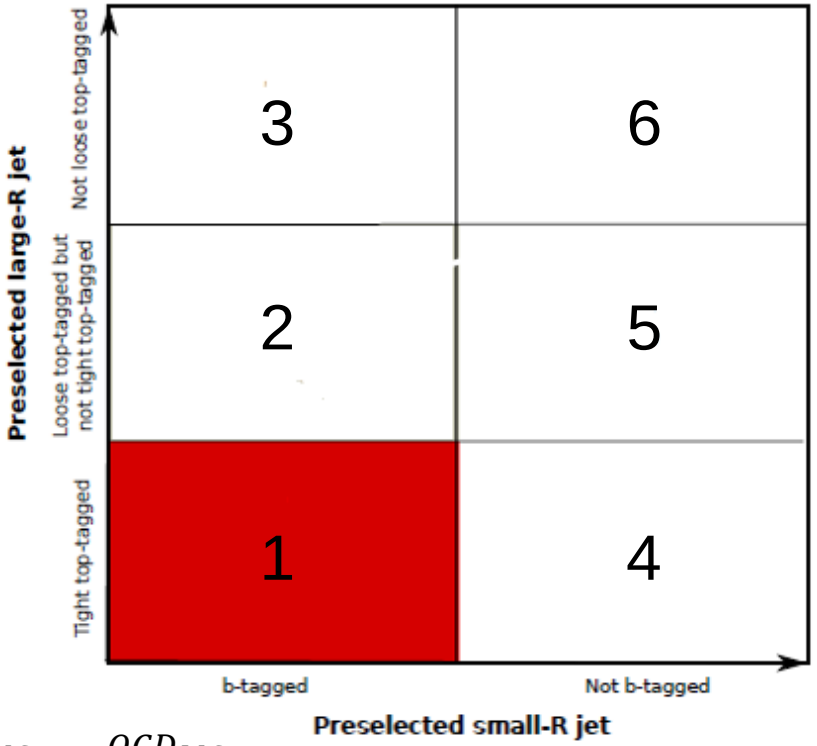
Top quark shower history



light jet shower history

All-hadronic: Background

- "2D sideband" method for estimating background
- Top-tag: loose/tight
- b-tag: tagged/not tagged
- Two taggers have non-negligible correlation. Correlation factors R are derived from QCD background simulation for each SR

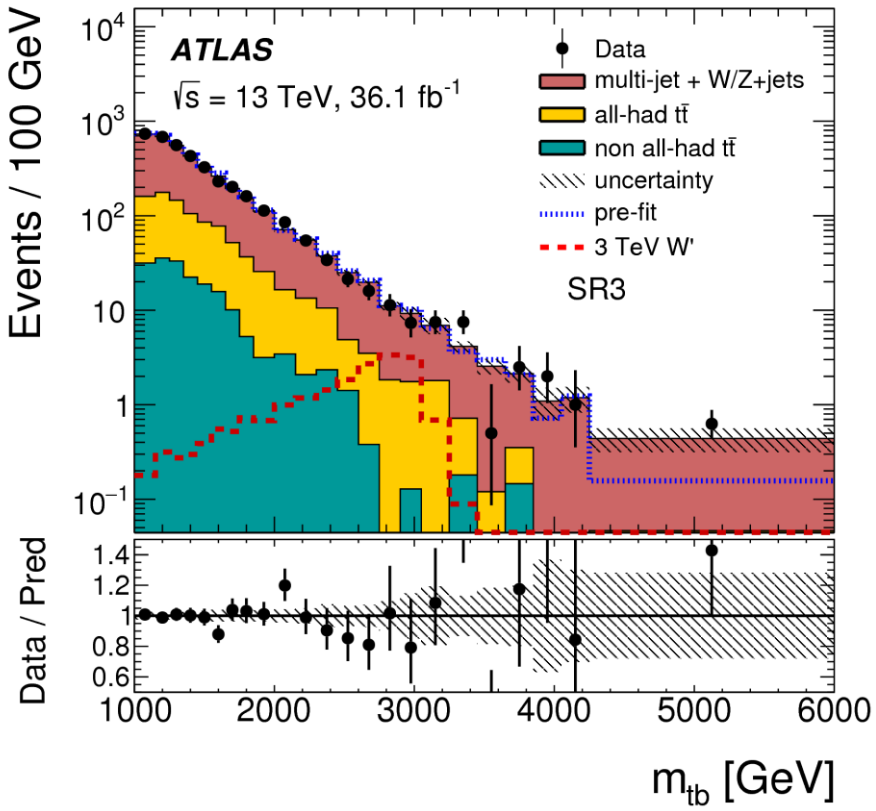


$$R_1^{corr} = \frac{N_1^{QCD_{MC}} \cdot N_6^{QCD_{MC}}}{N_3^{QCD_{MC}} \cdot N_4^{QCD_{MC}}}$$

$$N_1^{QCD} = R_1^{corr} \cdot \frac{N_3^{QCD} \cdot N_4^{QCD}}{N_6^{QCD}}, \; N_i^{QCD} = N_i^{Data} - N_i^{ttbar} \quad i = 3,4,5,6$$

All-hadronic: Mass Spectrum

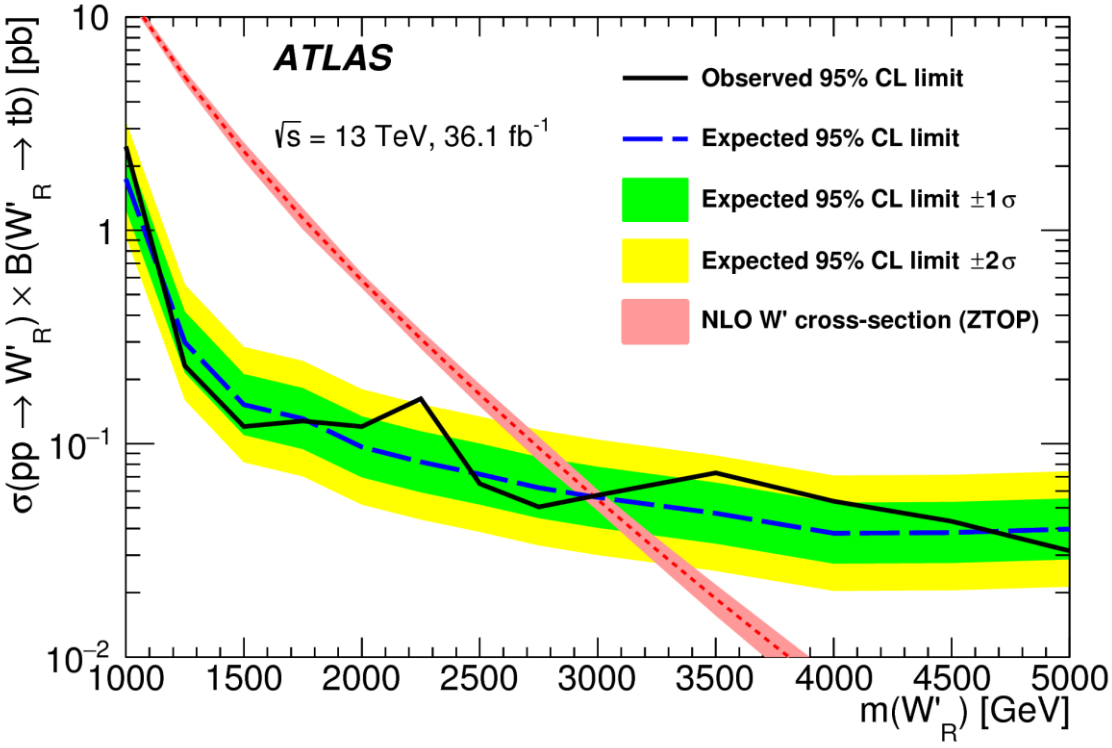
- 3 Signal regions
  - Tight top tag, 0 b-tag in
  - Loose top tag, 1 b-tag in
  - Tight top tag, 1 b-tag in
- Profile likelihood fit
- Most significant systematic uncertainties
  - 2D sideband correlation factors and b-tagging
- No excess found



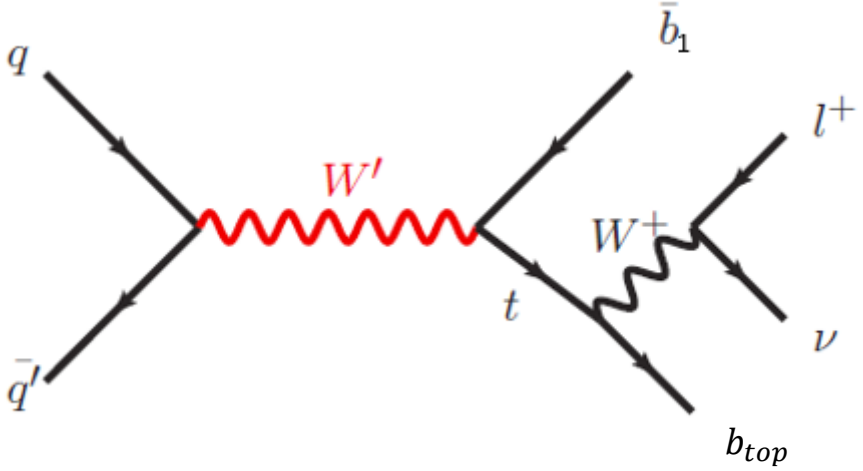
Tight top tag, 1 b-tag in

All-hadronic: Limits Setting

- Limits for W'_R on cross-section*BR
- Exclude W'_R mass up to 3 TeV at 95% CL
- Exclude W'_L mass up to 2.85 TeV 95% CL
- Run 1 ($\sqrt{s}$ = 8TeV) limits of W'_R: 1.76 TeV, 95% CL



Semi-leptonic: Selection & Reconstruction



- Neutrino p_z calculation
  - Estimated from MET and W mass constraint
- Top and W' reconstruction
  - Find jet that gives $m_{l\nu b}$ closest to top-quark mass: jet "b from top"
  - Assign highest p_T remaining jet to W' decay: jet "b from W' "

Signal Region	VR_{pretag}	$VR_{t\bar{t}}$	VR_{HF}
2 or 3 jets	2 or 3 jets	4 jets	2 or 3 jets
1 or 2 b-jets	pretag	1 or 2 b-jets	1 b-jet
$\Delta R(\ell, b_{top}) < 1.0$			$\Delta R(\ell, b_{top}) > 2.0$
$m_{tb} > 500$ GeV			$\Delta R(b_1, b_{top}) > 1.5$

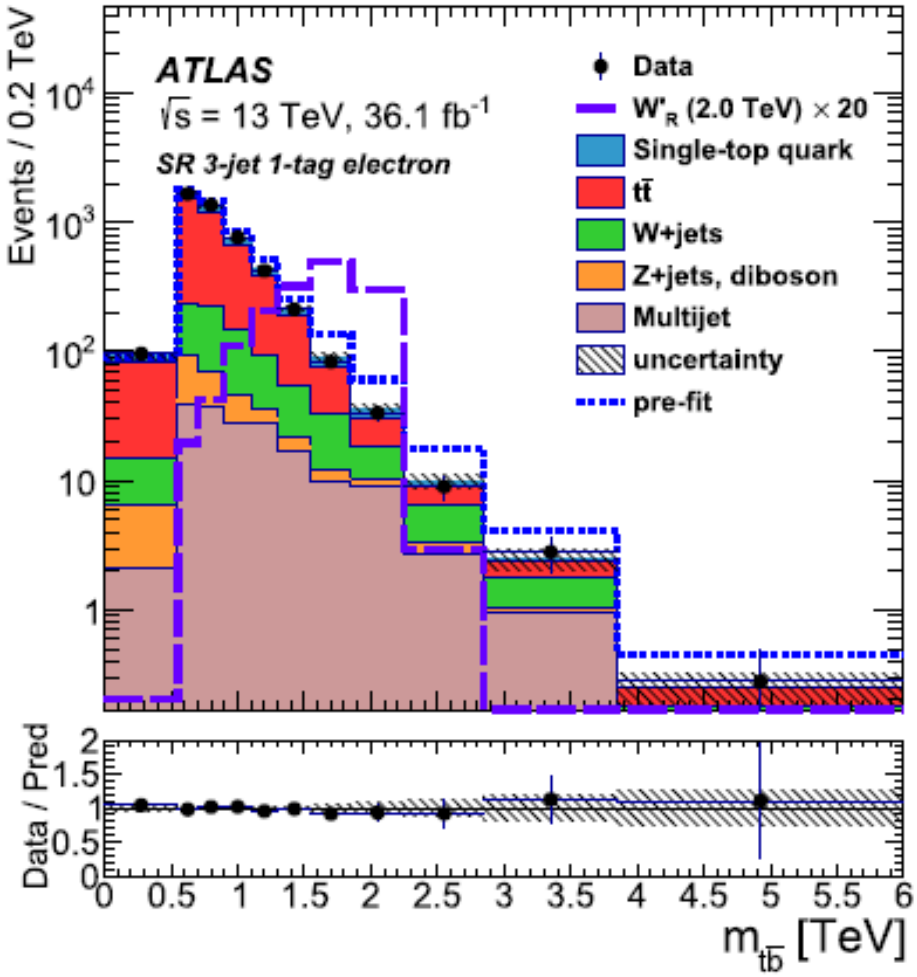
Semi-leptonic: Background

- *ttbar,* single-top, diboson and W+jets backgrounds
  - Modeled using the simulated MC samples
  - Dominant in signal regions: *ttbar* and *W*+jets production, the normalization of these backgrounds is allowed to float freely in fit

- Multijet background
  - Estimate from data using Matrix Method

Semi-leptonic: Mass Spectrum

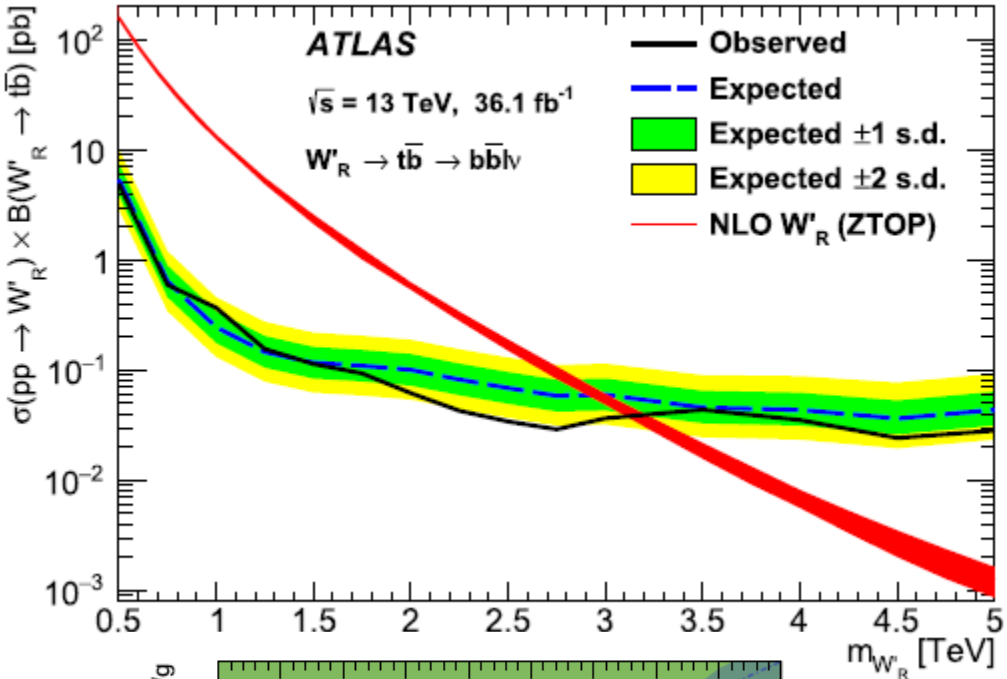
- SR: 2/3jets+1/2b-tag+e/μ
- Below masses of 2 TeV the dominant uncertainty: *ttbar* normalization and shape modeling
- At higher masses the dominant source of uncertainty: multijet background and b-tagging uncertainty

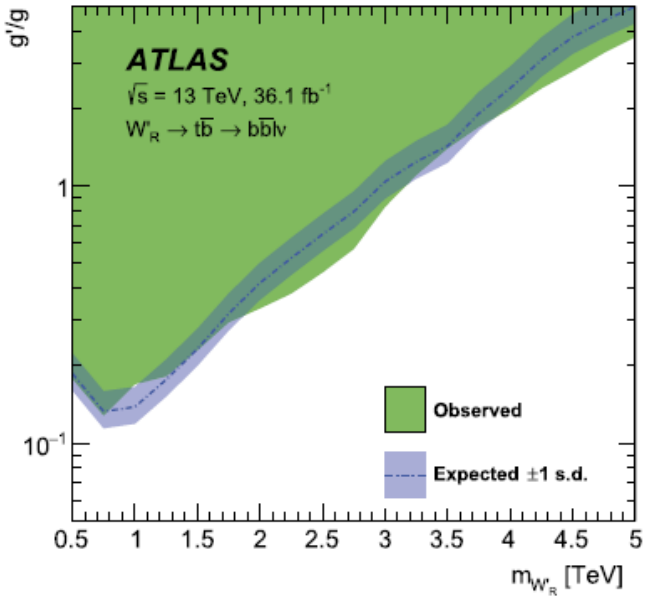


3-jet, 1 b-tag, electron

Semi-leptonic: Limit Setting

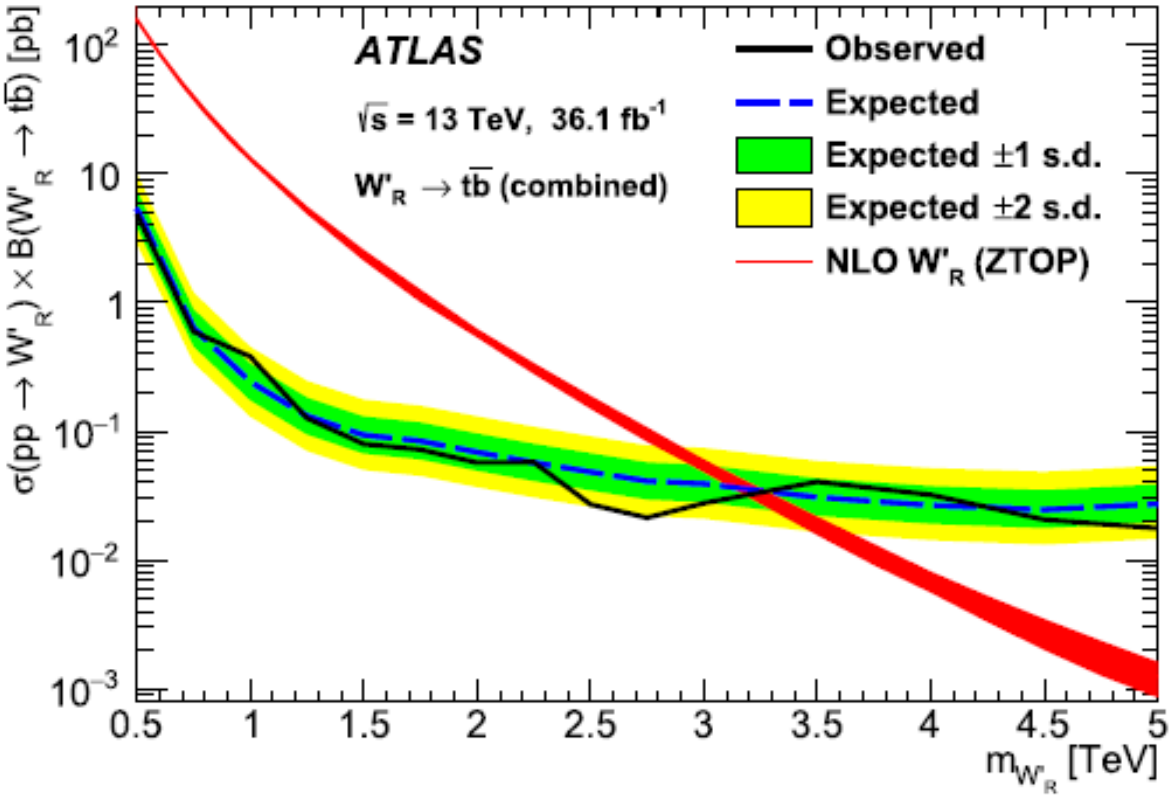
- Limits on W'_R cross-section * BR
- Exclude W'_R mass up to 3.15 TeV at 95% CL
- Run 1 ($\sqrt{s}$ = 8TeV) limits of W'_R: 1.92 TeV, 95% CL
- Limits on the ratio of couplings g′/g are derived from the limits on the W′ cross-section





Combined W'$_R$ limit

- Exclude W'_R mass up to 3.25 TeV at 95% CL, combined with W'->tb hadronic channel result



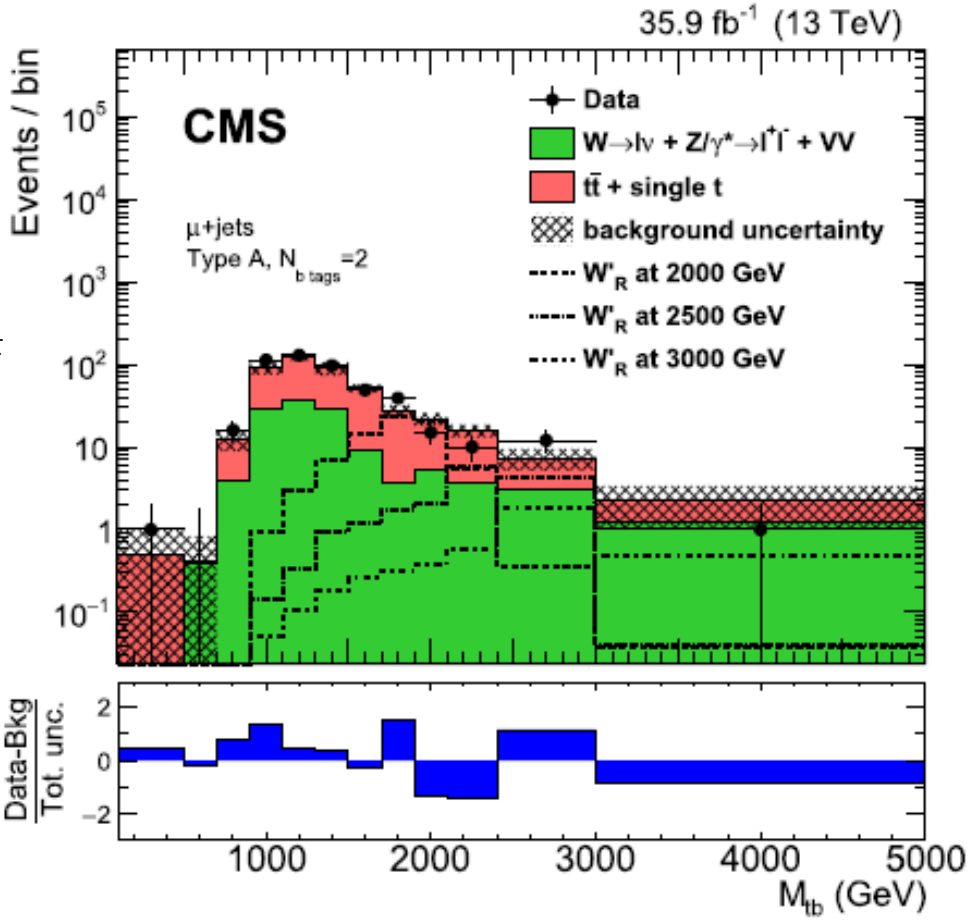
CMS: Mass Spectrum

- Study of the $W' \rightarrow tb$ in lepton + jets final state(Phys. Lett. B777 (2018) 39-63)

- An extra cut on P_T of the four-vector sum of the two leading P_T jets($P_T^{j_1+j_2}$), and set categorization based on P_T^t and $P_T^{j_1+j_2}$
  - Type A: P_T^t > 250 GeV, 100 < m_t < 250 GeV, $P_T^{j_1+j_2}$ > 350 GeV
  - Type B: P_T^t > 650 GeV, $P_T^{j_1+j_2}$ > 700 GeV

- 2/1 b-tags + muon/electron

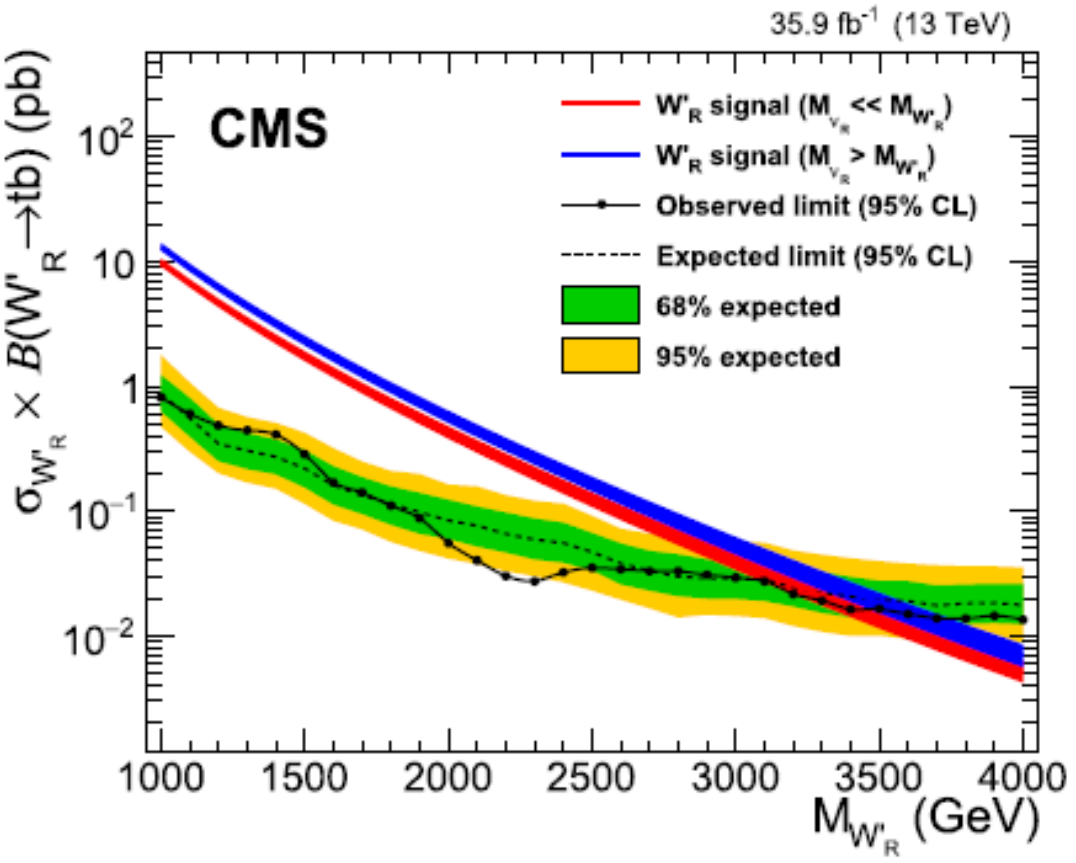
- Basically rejects multijet background



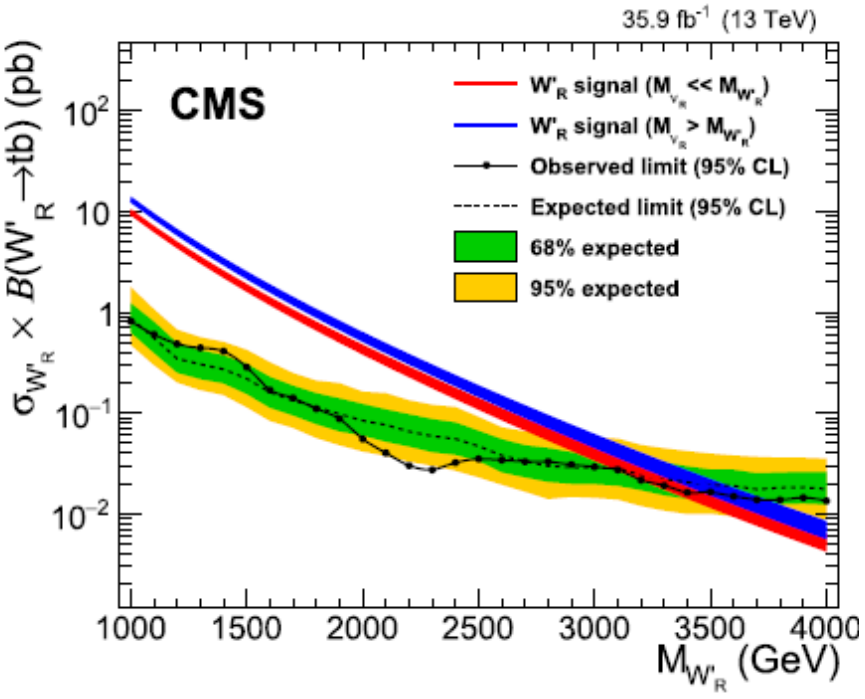
Type A, 2b-tag, μ channel

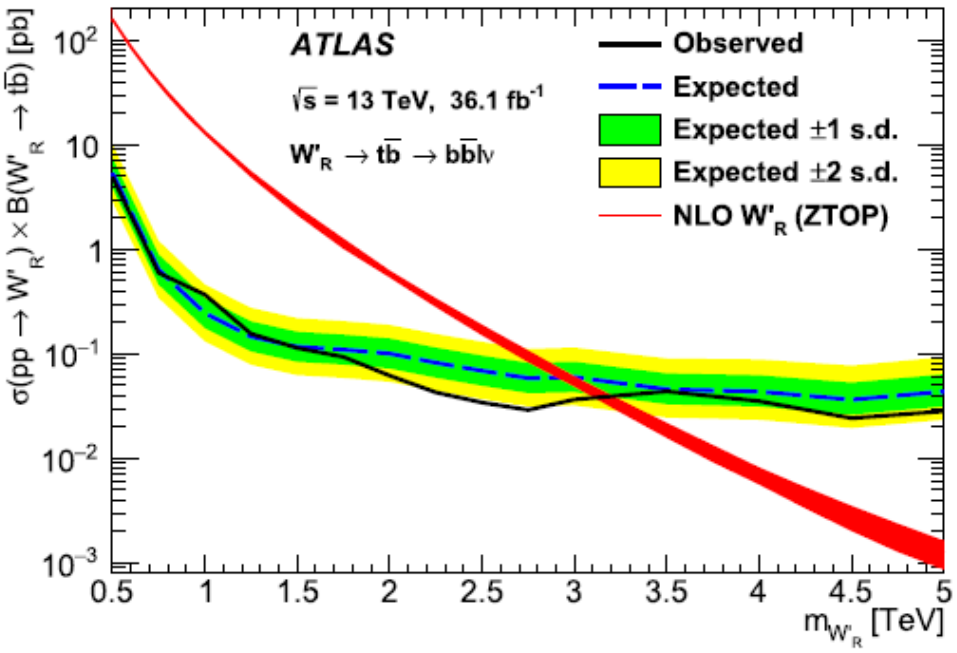
CMS: Limit

- Better exclusion result in muon channel
- Exclude W'_R mass up to 3.4TeV at 95% CL



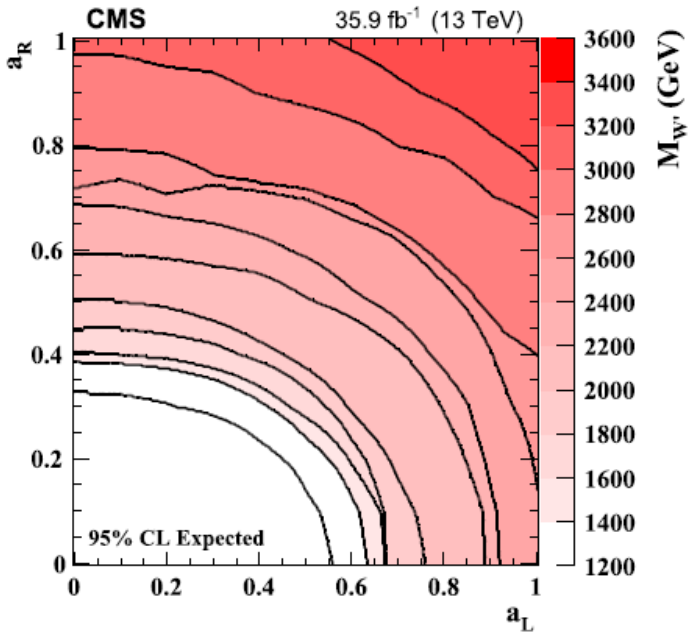
CMS: Key difference

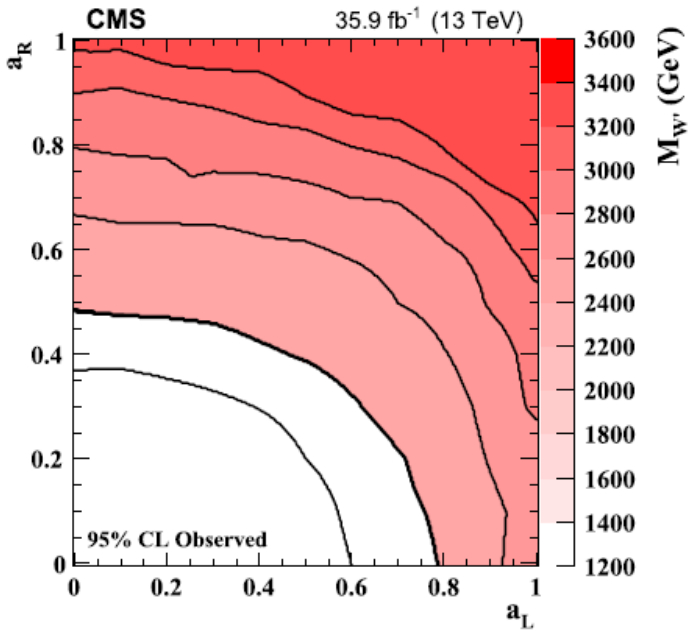




- Doesn't require leptons to be isolated, but with tighter cuts for leptons.
- Requires tighter cut on jets in μ channel than in e channel, and tighter cut on MET in e channel than in μ channel
- Better b-tagging efficiency at high P_T region

CMS: Limit





- Scan the a_R and a_L in 0.1 steps from 0 to 1 to produce cross section limits for arbitrary combinations of a_R and a_L.
- Black lines represent contours of equal W' boson mass separated by 200GeV.

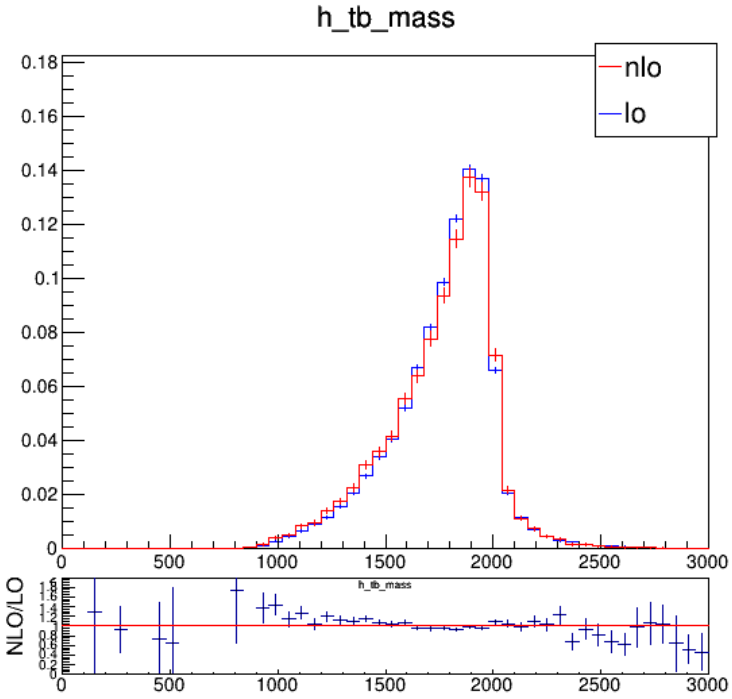
Summary

- Present 2 recent results of searching for heavy resonances decayed to top and bottom quark
  - $W' \rightarrow tb \rightarrow qqbb$
  - $W' \rightarrow tb \rightarrow l\nu bb$
- No significant deviation between data and background prediction
- Significant improvement on mass limits from Run 1 for both analyses
- CMS result shows better sensitivity in the study of lepton+jets final state
- The study of $W' \rightarrow tb$ with full Run2 data is on-going

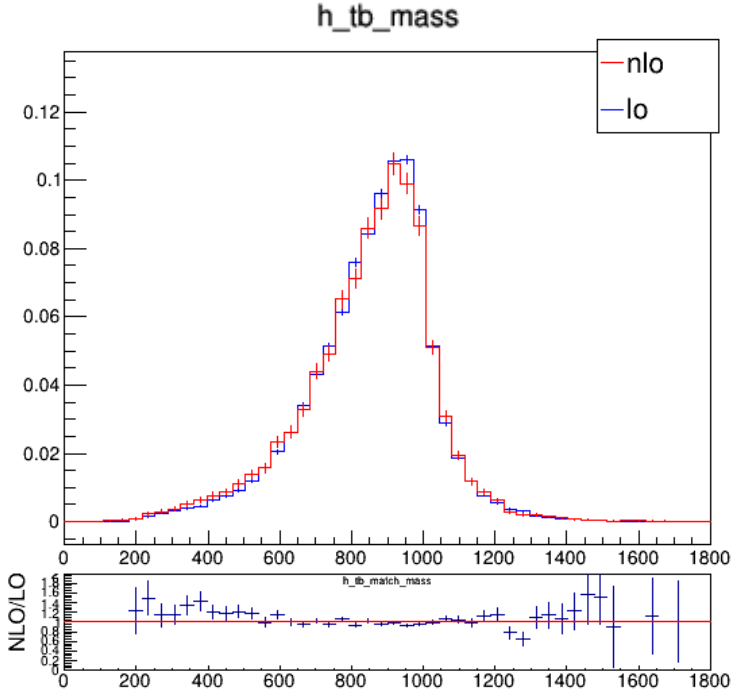
Backup

$W' \rightarrow tb$: Signal

- We use the signal sample generated at LO, and rescaled to NLO calculations using NLO/LO K-factors given by ZTOP (D. Duffty, Z. Sullivan, Phys. Rev. D 86 (2012) 075018)
- Generated by Madgraph5 at NLO is consistent with LO*K-factors on particle level(k-factors from 1.1 to 1.4 for semi-leptonic channel, 1.3 to 1.4 for all-hadronic channel)



all-hadronic, 2 TeV



semi-leptonic, 1TeV,

right-handed, normalize to same unity

Semi-leptonic: Reconstruction

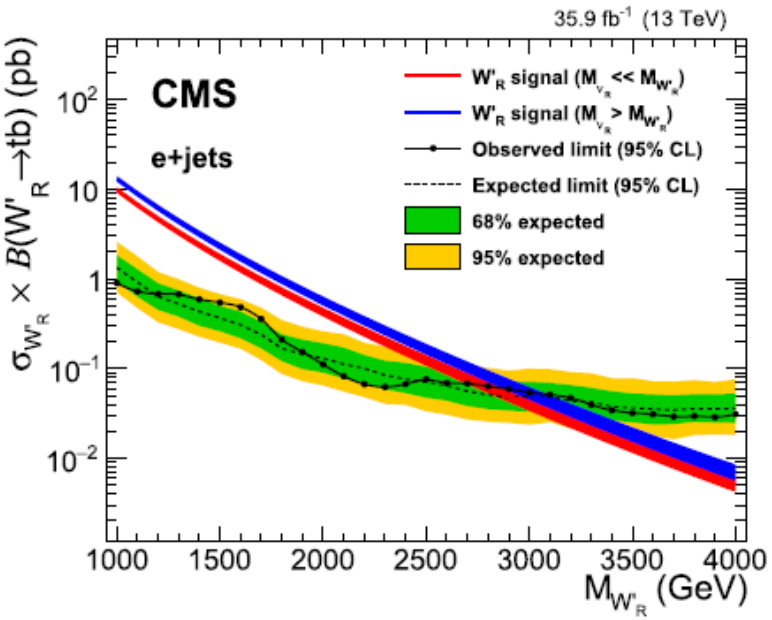
$$P_{z,\nu}^2 - 2 \cdot \frac{\mu \cdot P_{z,\ell}}{E_\ell^2 - P_{z,\ell}^2} \cdot P_{z,\nu} + \frac{E_\ell^2 \cdot P_{T,\nu}^2 - \mu^2}{E_\ell^2 - P_{z,\ell}^2} = 0, \quad (1)$$

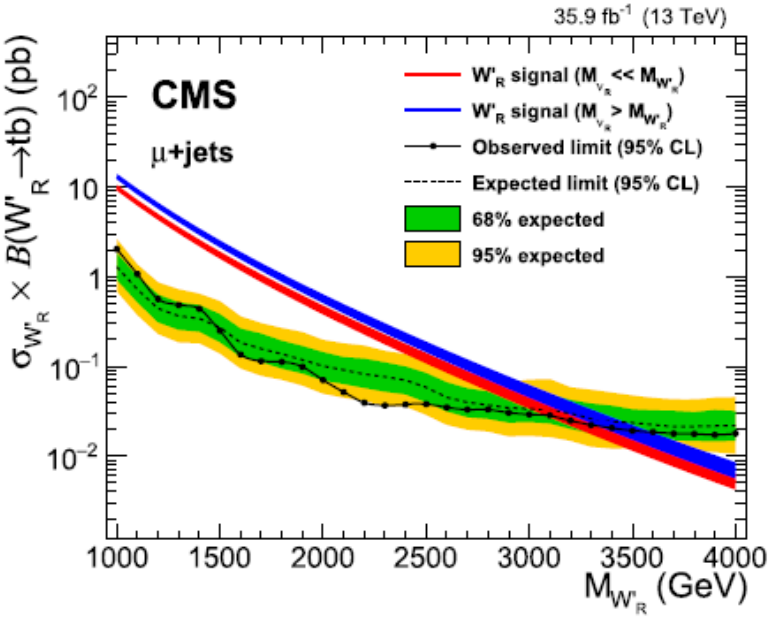
$$\text{with} \quad \mu = \frac{m_W^2}{2} + \cos\Delta\Phi \cdot P_{T,\ell} \cdot P_{T,\nu}. \quad (2)$$

$$p_{z,\nu}^{\pm} = \frac{\mu \cdot p_{z,l}}{p_{T,l}^2} \pm \sqrt{\frac{\mu^2 \cdot p_{z,l}^2}{p_{T,l}^4} - \frac{E_l^2 \cdot p_{T,\nu}^2 - \mu^2}{p_{T,l}^2}}. \quad (3)$$

- Neutrino p_z calculation
  - Estimated from MET and W mass constraint
  - Modify when discriminant < 0
- Top and W' reconstruction
  - Find jet that gives $m_{l\nu b}$ closest to top-quark mass: jet "b from top"
  - Assign highest pT remaining jet to W' decay: jet "b from W' "

CMS: Limit



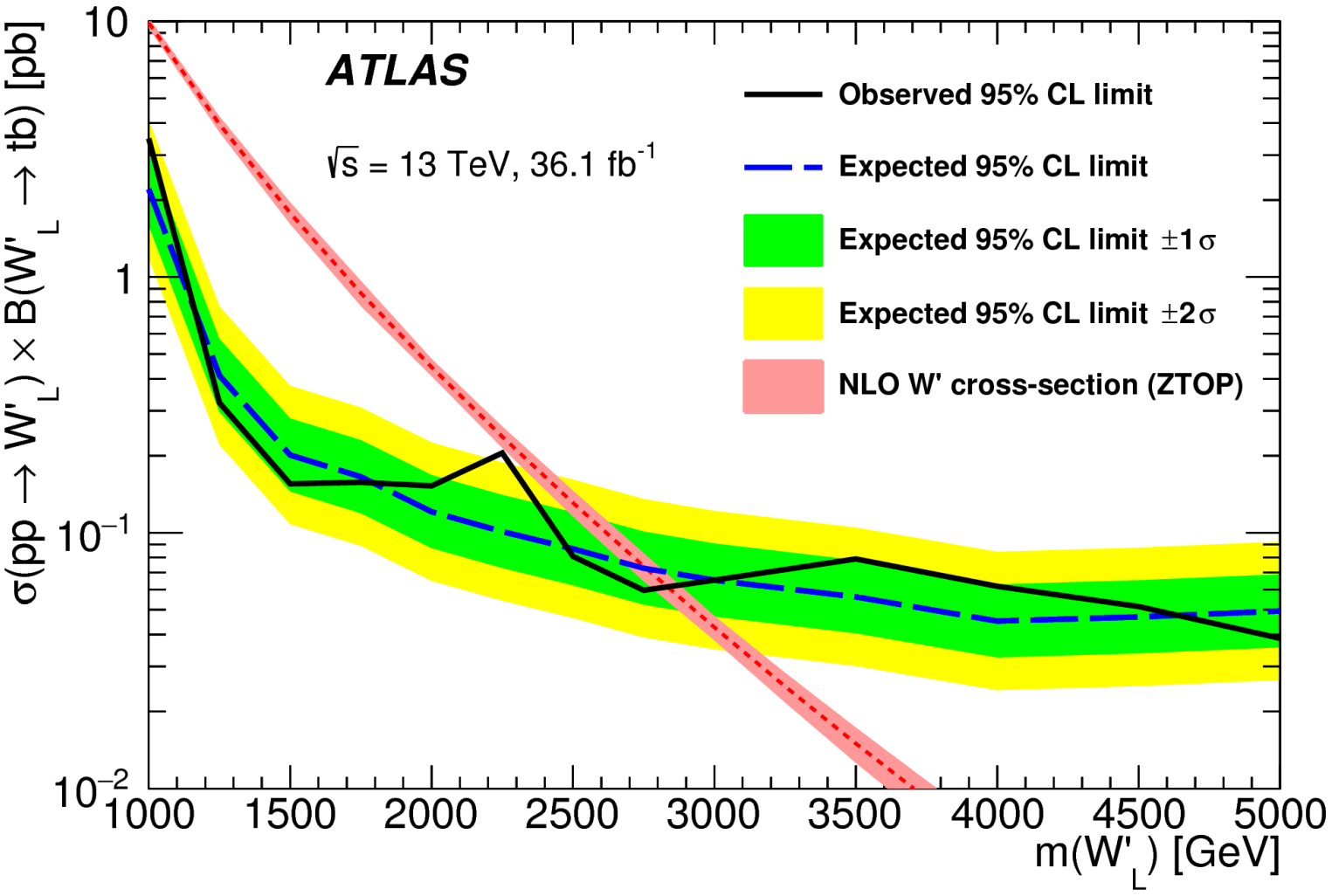


- Better exclusion result in muon channel
- Exclude W'_R mass up to 3.4TeV at 95% CL

All-hadronic: Event yields

"0 b-tag in" category						
	SR1	**QCD validation region**	**Region 3**	**Region 4**	**Region 5**	**Region 6**
Data	16333	57626	65600	267000	959000	12600000
QCD + V+jets(ABCD)	15247.40 (96.11%)	54474.10 (98.59%)				
$t\bar{t}$	616.57 (3.88%)	778.50 (1.41%)	1517.00	2372.50	3434.00	5066.00
"1 b-tag in" category						
	SR3	**SR2**	**Region 3**	**Region 4**	**Region 5**	**Region 6**
Data	4265	12834	78300	56000	188000	1220000
QCD + V+jets(ABCD)	3251.66 (74.45%)	11155.20 (99.69%)				
$t\bar{t}$	1115.72 (25.54%)	1144.43 (9.30%)	1116.00	5312.30	6700.00	5590.00

All-hadronic: W'$_L$ limit plot

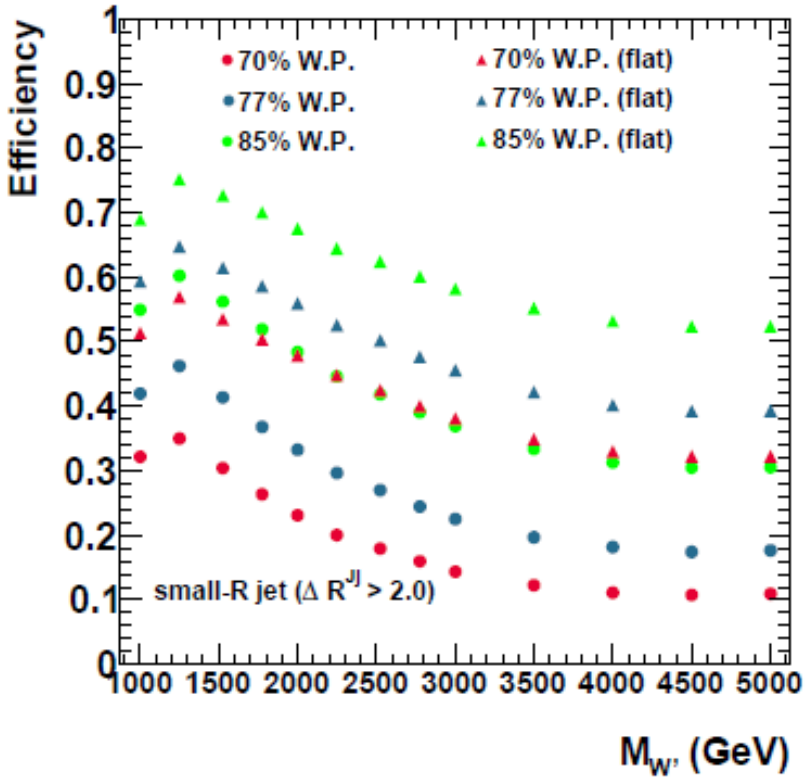


Semi-leptonic: Event yields

	2-jet 1-tag ($e^{\pm}$)	2-jet 1-tag ($\mu^{\pm}$)	3-jet 1-tag ($e^{\pm}$)	3-jet 1-tag ($\mu^{\pm}$)
W'_R (1.0 TeV)	1517 ± 32	2029 ± 39	1159 ± 31	1665 ± 35
W'_R (2.0 TeV)	83.4 ± 1.7	132.9 ± 2.1	105.0 ± 1.9	167.4 ± 2.2
W'_R (3.0 TeV)	4.7 ± 0.1	10.4 ± 0.2	7.0 ± 0.2	15.7 ± 0.2
W'_R (4.0 TeV)	0.4 ± 0.0	1.0 ± 0.0	0.6 ± 0.0	1.6 ± 0.0
W'_R (5.0 TeV)	0.1 ± 0.0	0.2 ± 0.0	0.1 ± 0.0	0.2 ± 0.0
$t\bar{t}$	1144 ± 24	1531 ± 30	3356 ± 57	4270 ± 78
Single-top	472 ± 20	655 ± 28	484 ± 23	639 ± 27
W+jets	500 ± 51	1285 ± 140	530 ± 45	1100 ± 100
Multijets	330 ± 37	640 ± 120	173 ± 20	394 ± 70
Z+jets	115 ± 17	179.4 ± 9.8	113 ± 13	215 ± 23
diboson	20.7 ± 1.7	34.4 ± 9.8	16.5 ± 2.2	28.5 ± 3.1
Total background	2583 ± 72	4320 ± 190	4672 ± 80	6650 ± 150
Data	2637	4307	4642	6606

	2-jet 2-tag ($e^{\pm}$)	2-jet 2-tag ($\mu^{\pm}$)	3-jet 2-tag ($e^{\pm}$)	3-jet 2-tag ($\mu^{\pm}$)
W'_R (1.0 TeV)	1584 ± 35	2055 ± 38	1241 ± 30	1749 ± 34
W'_R (2.0 TeV)	33.5 ± 1.0	55.5 ± 1.2	51.6 ± 1.2	84.3 ± 1.5
W'_R (3.0 TeV)	1.4 ± 0.1	2.6 ± 0.1	2.5 ± 0.1	5.1 ± 0.1
W'_R (4.0 TeV)	0.1 ± 0.0	0.3 ± 0.0	0.2 ± 0.0	0.5 ± 0.0
W'_R (5.0 TeV)	0.0 ± 0.0	0.1 ± 0.0	0.0 ± 0.0	0.1 ± 0.0
$t\bar{t}$	565 ± 15	810 ± 17	2582 ± 33	2737 ± 37
Single-top	125.6 ± 6.8	187 ± 12	242 ± 14	304 ± 18
W+jets	29.0 ± 6.0	38.9 ± 4.2	49.2 ± 4.9	79.4 ± 8.0
Multijets	33.4 ± 6.4	70 ± 15	84 ± 11	119 ± 22
Z+jets	2.2 ± 0.4	10.2 ± 1.5	11.8 ± 1.4	17.3 ± 2.1
diboson	0.0 ± 0.0	1.2 ± 0.2	11.5 ± 2.0	5.2 ± 0.7
Total background	755 ± 18	1117 ± 26	2980 ± 38	3262 ± 48
Data	706	1117	2976	3278

B-tag efficiency: ATLAS



B-tag efficiency: CMS