



Search for new physics in $t\bar{b}$ resonances

Top LHC France 2019



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- Beyond the Standard Model
- $W' \rightarrow t\bar{b}$ resonance searches
- Latest $W' \rightarrow t\bar{b}$ searches with ATLAS & CMS
- Conclusion

Beyond the SM

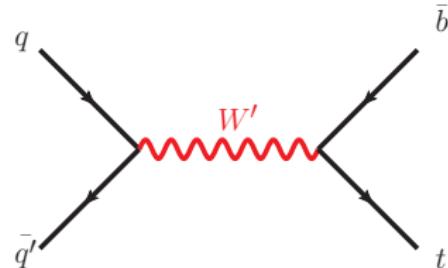
Many BSM theories introduce *new boson resonances*, massive enough to decay to $t\bar{b}$:

■ spin 1 vector boson W'^{\pm}

- Extended SM symmetries:
 - ▷ massive right-handed version of the W boson
- Universal extra-dimensions:
 - ▷ Kaluza-Klein excitations of the W boson
- ...

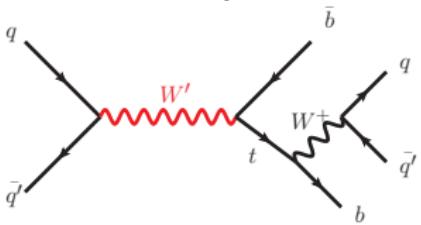
$W' \rightarrow t\bar{b}$ decay mode is interesting:

- can be fully reconstructed
- access to models with leptophobic W'
- W' is expected to couple more strongly to 3rd generation of quarks

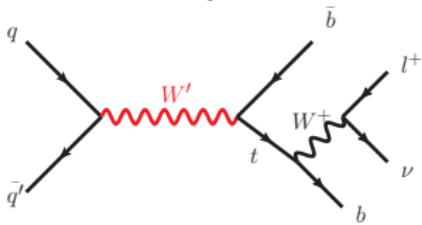


$W' \rightarrow t\bar{b}$ direct searches

0-lepton



1-lepton



Experiment	\sqrt{s}	Int. lumi.	0-lepton	Reference 1-lepton
CDF	1.96 TeV	1.9 fb^{-1}	–	PRL 103 (2009) 041801
DØ	2.3 fb^{-1}	–	–	PLB 699 (2011) 145
ATLAS	7 TeV	1.04 fb^{-1}	–	PRL 109 (2012) 081801
CMS	5.0 fb^{-1}	–	–	PLB 718 (2013) 1229
ATLAS*	8 TeV	20.3 fb^{-1}	EPJC 75 (2015) 165	PLB 743 (2015) 235
CMS	19.7/19.5 fb^{-1}	JHEP 02 (2016) 122	JHEP 05 (2014) 108	
ATLAS*	13 TeV	36.1 fb^{-1}	PLB 781 (2018) 327	PLB 788 (2019) 347
CMS	2.6/35.9 fb^{-1}	JHEP 08 (2017) 029	PLB 777 (2018) 39	
ATLAS*	14 TeV	3000 fb^{-1}	–	ATL-PHYS-PUB-2018-044
CMS	–	–	–	CMS-PAS-FTR-16-005

Covered in this talk

* LPC-Clermont contributions

Latest $W' \rightarrow t\bar{b}$ searches with both ATLAS & CMS

Theoretical model

PRD 66 (2002) 075011 PRD 86 (2012) 075018

$$\mathcal{L} = \frac{V'_{ij}}{2\sqrt{2}} \bar{f}_i \gamma_\mu [g'_R(1 + \gamma^5) + g'_L(1 - \gamma^5)] W'^\mu f_j + h.c.$$

Parameters

V'_{ij} : CKM(δ_{ij}) matrix for quarks(leptons)

$g'_R(g'_L)$: coupling to right-(left-) handed fermions

g' can be different from $SU(2)_L$ coupling g

arbitrary combinations of g'_R and g'_L are allowed:

W'_R, W'_L, W'_{LR}

If $g'_L \neq 0$ (W'_L, W'_{LR}), one must take into account interference with the SM W boson

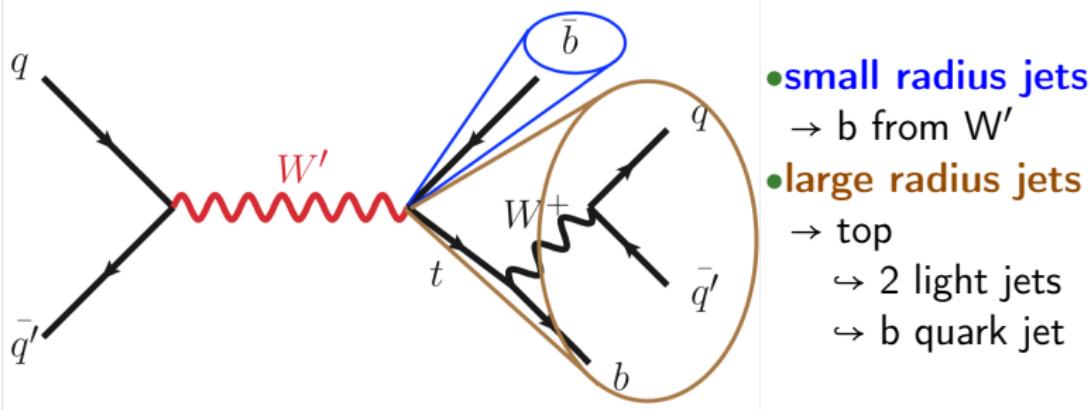
Two scenarios for W'_R : $m(\nu_R) > m(W'_R)$ or $m(\nu_R) \ll m(W'_R)$

0-lepton analysis @ 13 TeV

- using 36.1 fb^{-1} with ATLAS
- using 2.6 fb^{-1} with CMS

PLB 781 (2018) 327
JHEP 08 (2017) 029

boosted top \rightarrow *collimated top decays*



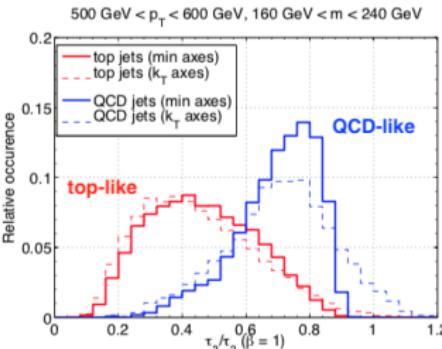
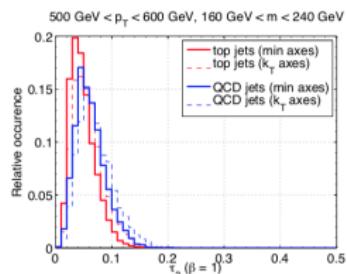
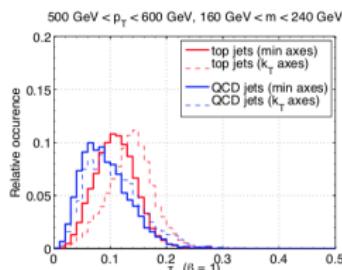
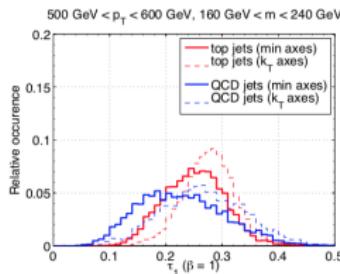
Top tagging: sensitive variables to characteristics of substructure of the large radius jet

N-subjettiness (τ_N) [JHEP03\(2011\)015](#), [JHEP 02 \(2012\) 093](#)

$$\tau_N = \frac{1}{d} \sum_i p_{T,i} \times \Delta R_{i,\text{axis of closest subjet}} \quad \text{with } d = \sum_i p_{T,i} \times R$$

τ_N quantifies to what degree a given jet can be regarded as a jet composed of N subjets.

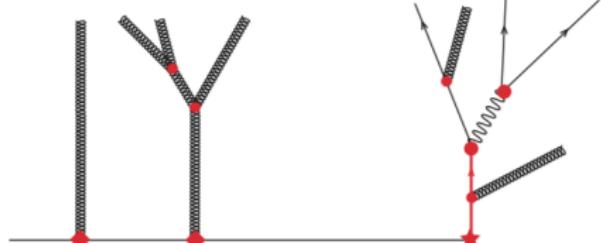
Jets with $\tau_N \simeq 0$ have all their radiation aligned with the candidate subjet directions



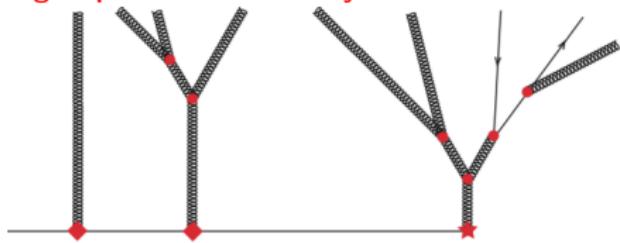
The ratio τ_N/τ_{N-1} is the preferred discriminating variable

shower deconstruction (SD) [PRD 84 \(2011\) 074002](#), [PRD 87 \(2013\) 054012](#)

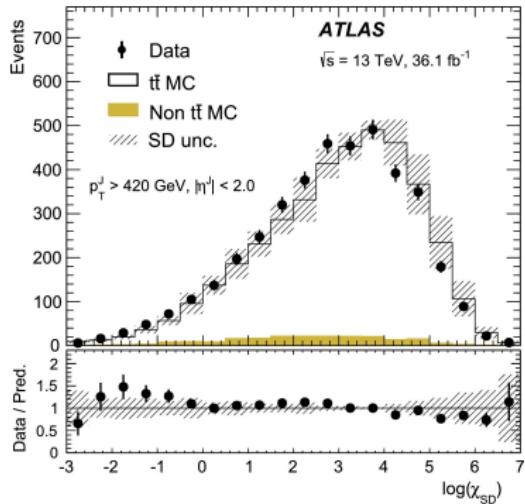
Top-quark shower history



Light-quark shower history



$$\chi_{\text{SD}}(\{p_i^k\}) = \frac{\sum P(\{p_i^k\} | \text{top-quark})}{\sum P(\{p_i^k\} | \text{gluon/light-quark})}$$

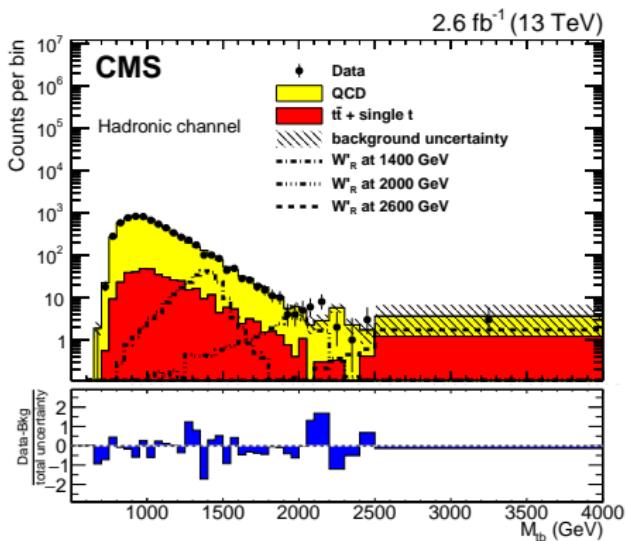
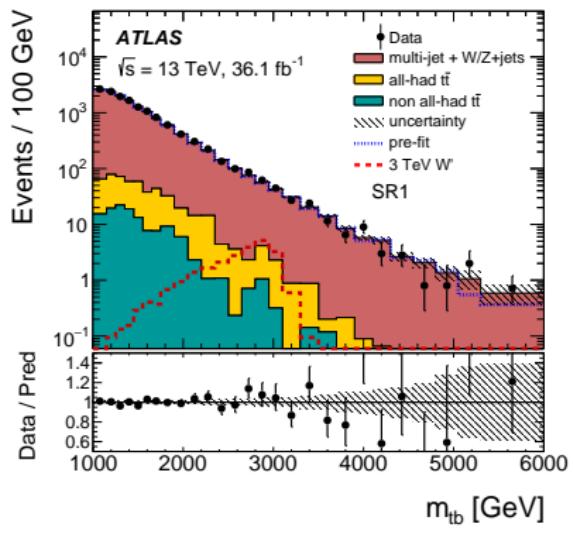


Sum over all the shower histories in which signal processes lead to the subjet configuration $\{p_i^k\}$

The large radius jet is tagged as a top-quark jet if χ_{SD} is larger than a given value

$W' \rightarrow tb$: 0-lepton

$m(tb)$ distribution

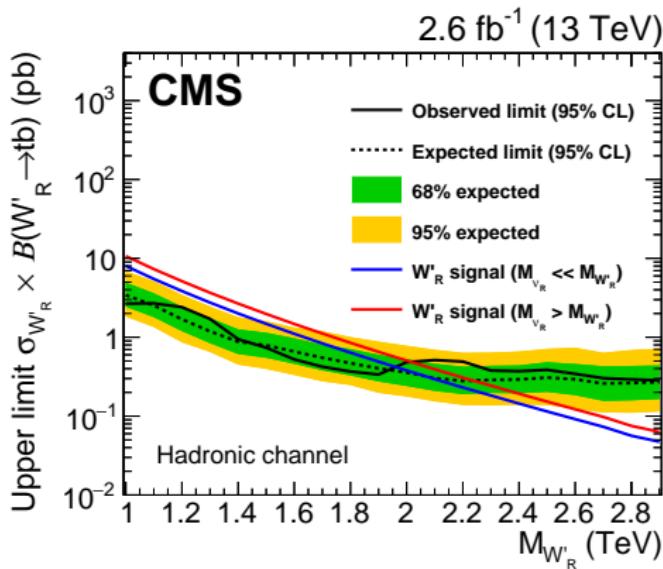


Main background: multi-jet, $t\bar{t}$
multi-jet ($t\bar{t}$) estimated from data (MC)

Data is consistent with the background-only prediction

Limit setting on $\sigma(W') \times \text{BR}$

- W' with pure right coupling
- $m(\nu_R) > m(W'_R)$ or $m(\nu_R) \ll m(W'_R)$
- $g' = g$

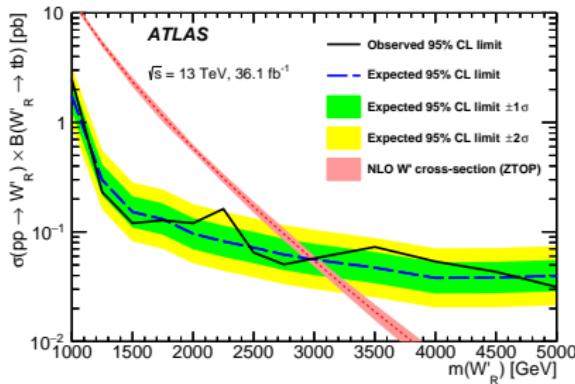
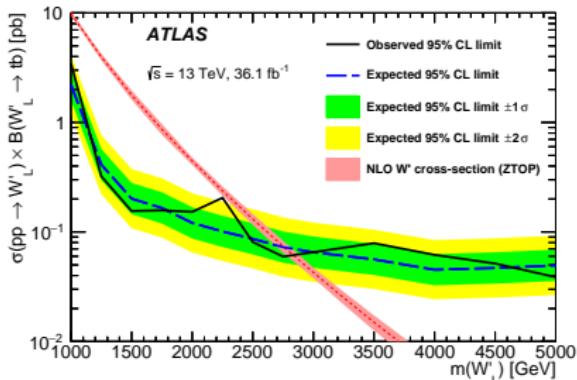


excluded up to: 2 TeV

- Large systematic uncertainties: top quark tagging and normalizations

Limit setting on $\sigma(W') \times \text{BR}$

- W' with pure left- or right-handed coupling
- $m(\nu_R) > m(W'_R)$
- $g' = g$



excluded up to: 2.9 (3) TeV for W'_L (W'_R)

- Large systematic uncertainties: multi-jets bkg estimation and b-tagging

1-lepton analysis @ 13 TeV

- using 36.1 fb^{-1} with ATLAS
- using 35.9 fb^{-1} with CMS

PLB 788 (2019) 347

PLB 777 (2018) 39

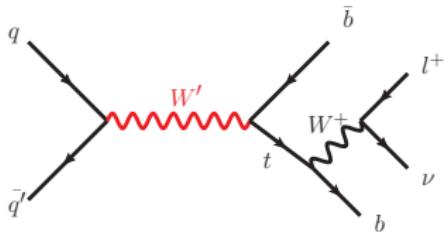
At high pt \rightarrow the lepton is close to jets

ATLAS

- isolated lepton $e(\mu)$
- Large E_T^{miss} $>80(30)$ GeV
- $E_T^{\text{miss}} + m_T^W >100$ GeV
- 2 or 3 jets (1 or 2 b tagged)

CMS

- non-isolated lepton $e(\mu)$ +tighter p_T cuts
- Large E_T^{miss} $>120(50)$ GeV
- $|\Delta\phi(e, E_T^{\text{miss}})| < 2$
- ≥ 2 jets (≥ 1 of the 2 leading jets b tagged)



- $p_z(\nu)$: constrain $m(\ell\nu)$ to $m(W)$
- top: 4-momenta of W with jet that gives $m(W+\text{jet})$ closest to $m(\text{top})$
- W' : 4-momenta of top with highest p_T remaining jet

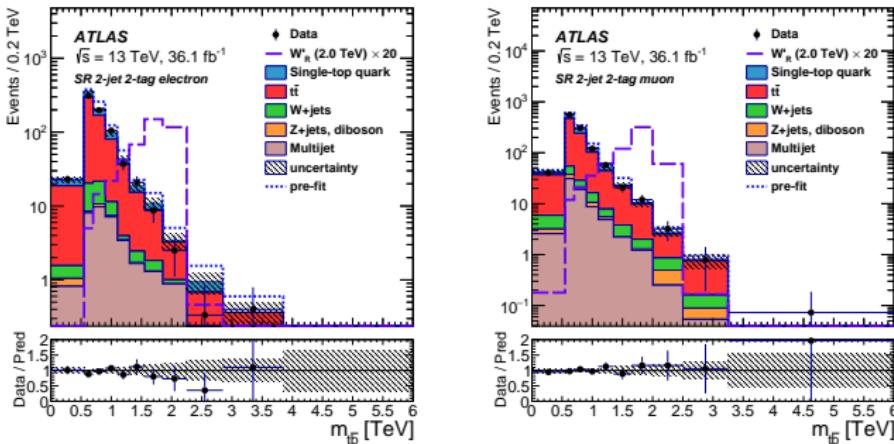
Additional tighter cuts are used to define **8 independent regions**:

- ATLAS: 2/3 jet, 1/2 tag, e/μ
- CMS: Type A/B, 1/2 tag, e/μ

Type A (B) : low (high) p_T^{top} and $p_T^{j_1+j_2}$

$W' \rightarrow t\bar{b}$: 1-lepton

$m(t\bar{b})$ distribution



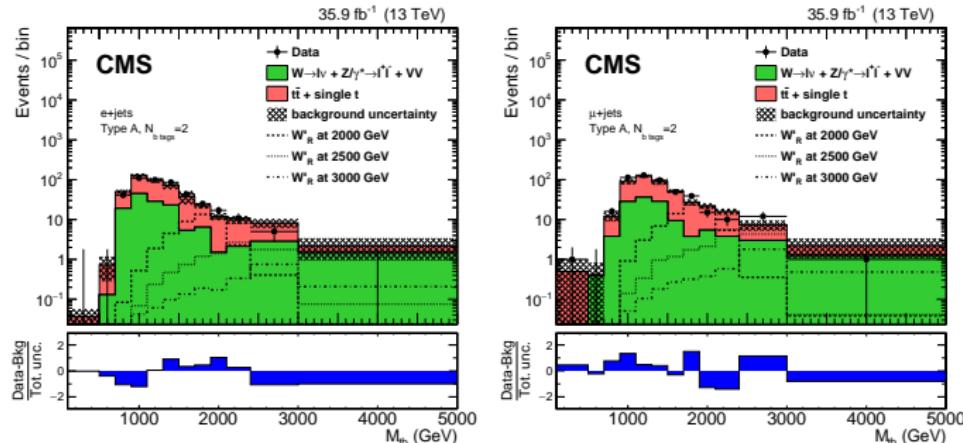
Dominant backgrounds: $t\bar{t}$, W+jets

Subdominant backgrounds: Multijet, Single top, Z+jets, diboson

All backgrounds estimated from Monte Carlo except for Multijet

$W' \rightarrow t\bar{b}$: 1-lepton

$m(t\bar{b})$ distribution



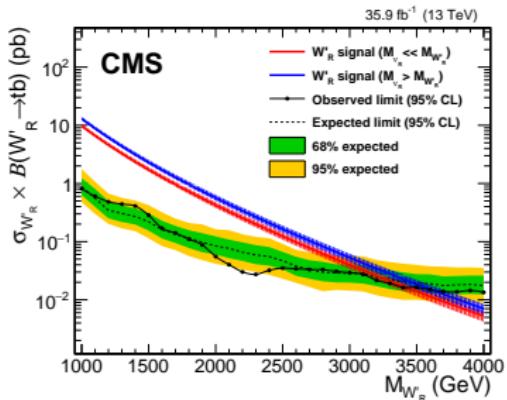
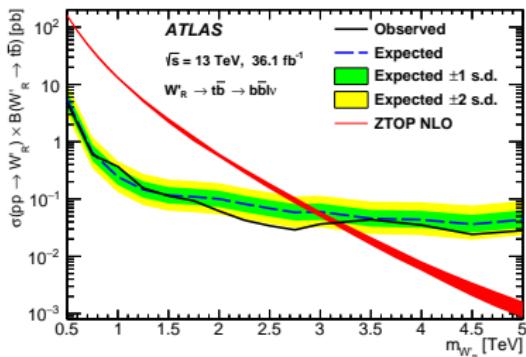
Dominant backgrounds: $t\bar{t}$, $W+jets$

Subdominant backgrounds: single top , Z/γ^*+jets , diboson

All backgrounds estimated from Monte Carlo

Limit setting on $\sigma(W') \times \text{BR}$, assuming $g' = g$

- ATLAS (CMS) considers W'_R in range 0.5-5 (1-4) TeV
 - ATLAS: $m(\nu_R) > m(W'_R)$
 - CMS : $m(\nu_R) > m(W'_R)$ or $m(\nu_R) \ll m(W'_R)$

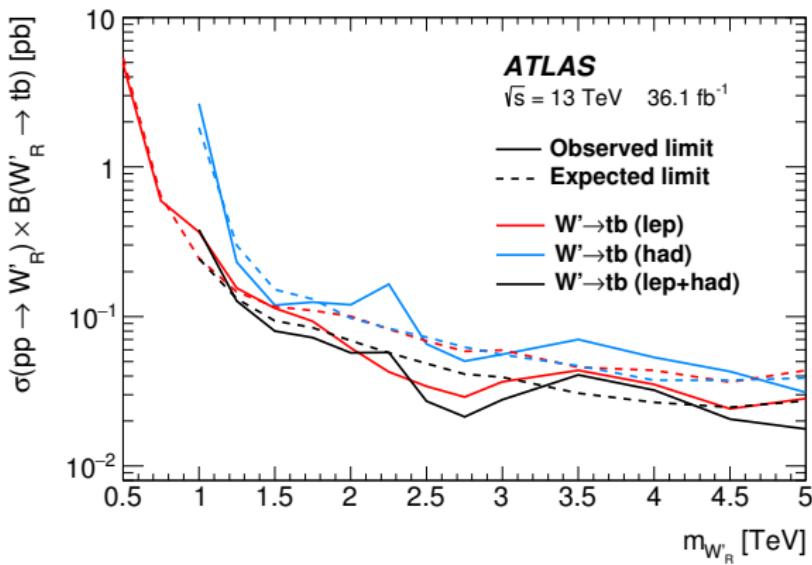


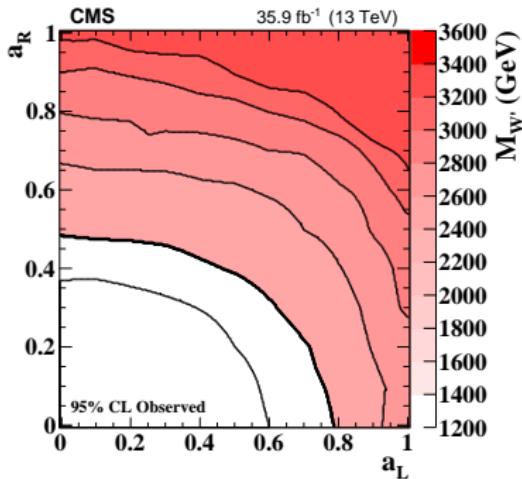
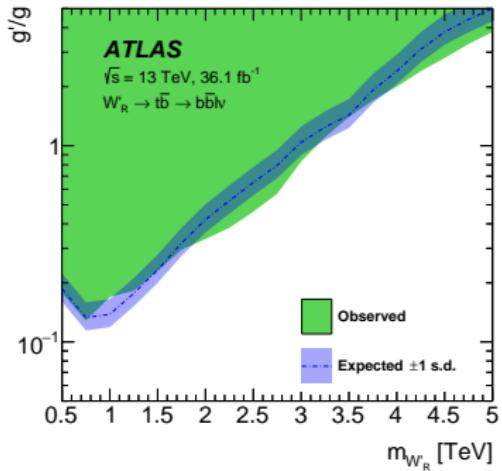
- Obs. limits:
 - 3.15 TeV: $m(\nu_R) > m(W'_R)$

- Obs. limits:
 - 3.6 TeV for $m(\nu_R) > m(W'_R)$
 - 3.4 TeV for $m(\nu_R) \ll m(W'_R)$

$\sigma(W') \times \text{BR}$ combination of 0-&1-lepton analysis

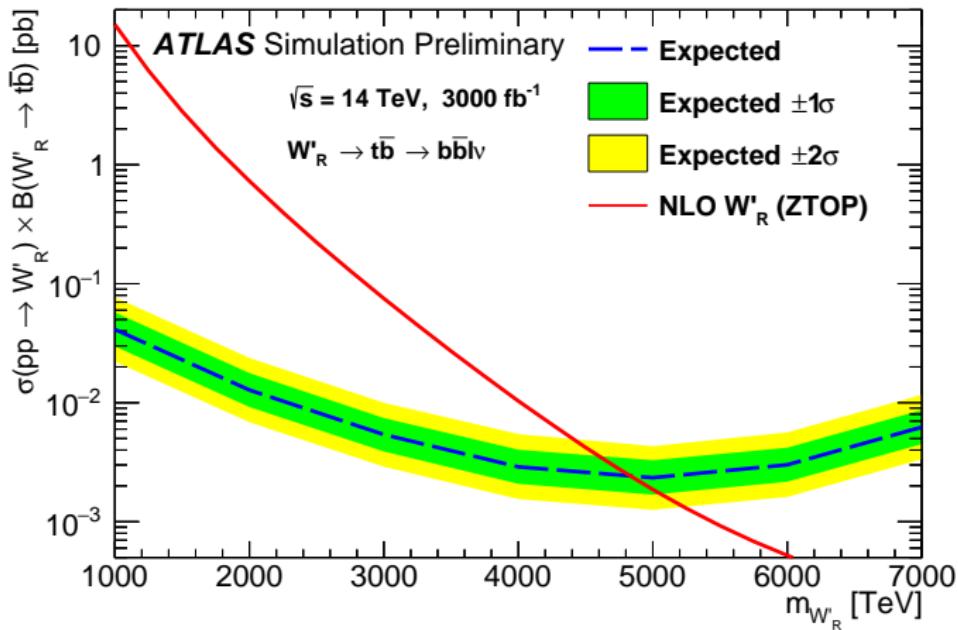
- same data collection
- orthogonal event selections
- correlation between systematics from common source





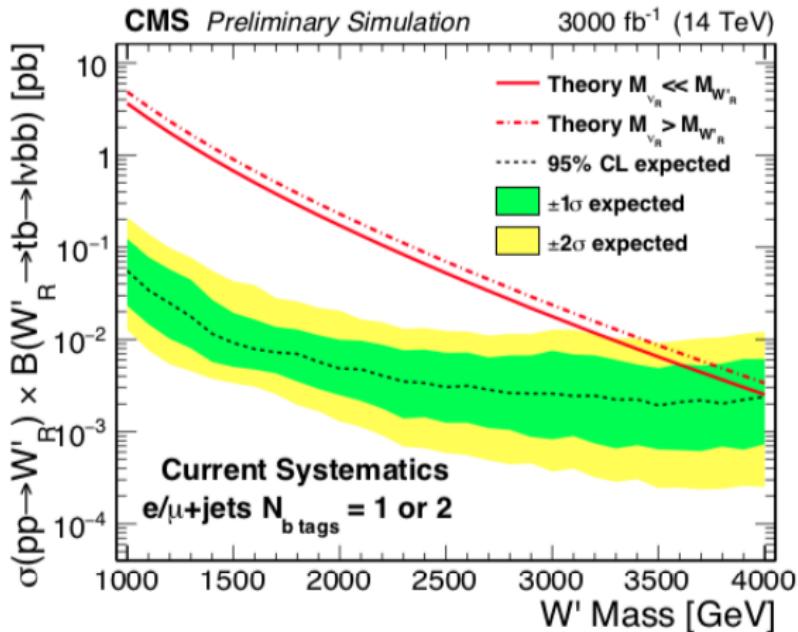
- pure R-handed coupling
- no interferences
- g'_R/g in range [0,5]
- L and R mixing
- interferences
- $a_{L,R} = g'_{L,R}/g$ in range [0,1]

ATL-PHYS-PUB-2018-044



- Scaling: background and signal cross-sections
- 8 SR selections
- **Systematics from Run 2** including dominant ones

CMS-PAS-FTR-16-005



- Scaling: background and signal cross-sections
- 1 or 2 tag, e and μ channels

- **Current systematics**
use the values from the Run 2 analysis

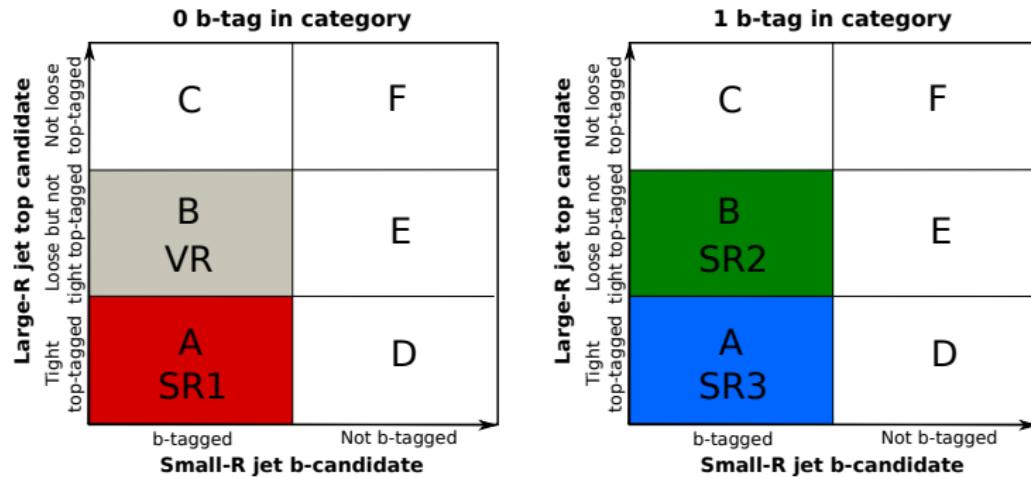
Conclusion: $W' \rightarrow t\bar{b}$ searches by ATLAS and CMS

- $t\bar{b}$ resonance searches probe a large variety of BSM theories
- Presented the latest results: 0-&1-lepton analysis @13TeV
 - No significant excess of data events above SM prediction
 - Results interpreted as limits
 - different hypothesis: L,R,L/R mixing,
 $m(\nu_R) > m(W'_R)$, $m(\nu_R) \ll m(W'_R)$
- HL LHC projection of 1-lepton analysis

Backup

Multi-jet background estimation & SRs definition

0-lepton analysis @ 13 TeV using 36.1 fb⁻¹ with ATLAS



not loose top-tagged: events where the selected top-quark jet candidate fails to meet the loose top-tagged (80% WP) identification criteria

loose-but-not-tight top-tagged: events where the selected top-quark jet candidate satisfies the loose top-tagged identification criteria but not the tight top-tagged (50% WP) criteria

tight top-tagged: events where the selected top-quark jet candidate satisfies the tight top-tagged criteria.

$$N_A^{\text{bkg}} = R_A^{\text{corr}} \cdot \frac{(N_C^{\text{data}} - N_C^{\bar{t}\bar{t}}) \cdot (N_D^{\text{data}} - N_D^{\bar{t}\bar{t}})}{N_F^{\text{data}} - N_F^{\bar{t}\bar{t}}}, \quad N_B^{\text{bkg}} = R_B^{\text{corr}} \cdot \frac{(N_C^{\text{data}} - N_C^{\bar{t}\bar{t}}) \cdot (N_E^{\text{data}} - N_E^{\bar{t}\bar{t}})}{N_F^{\text{data}} - N_F^{\bar{t}\bar{t}}}$$

R_X^{corr} : correlation between top and b tagging (QCD dijet MC)

Multi-jet background estimation

0-lepton analysis @ 13 TeV using 2.6 fb⁻¹ with CMS

- apply the b tagging criteria to the b-candidate jet in the event to measure the average b-tagging rate for multi-jet, assuming the rate is the same for multi-jet jets in the SR
- average b- tagging rate is parameterized as a function of the p_T of the b-candidate jets (which pass all requirements except the b tag) in three $|\eta|$ regions: $|\eta| < 0.5$, $0.5 \leq |\eta| \leq 1.15$, $1.15 \leq |\eta| \leq 2.40$

$$f(p_T) = \begin{cases} c_0 + c_1 p_T + c_2 (p_T - a)^2, & \text{if } p_T < a \\ c_0 + c_1 p_T + c_3 (p_T - a)^2, & \text{if } p_T \geq a. \end{cases}$$

where c_0 to c_3 are free coefficients determined in the fit.

$a = 500$, 500, and 550 GeV in $|\eta| < 0.5$, $0.5 \leq |\eta| \leq 1.15$, and $1.15 \leq |\eta| \leq 2.40$, respectively

- events in the SR that do not have b tagging applied are then weighted by this average b-tagging rate to estimate the multi-jet background contribution

$W' \rightarrow t\bar{b}$: 1-lepton Yields [ATLAS: 13TeV, 36.1 fb $^{-1}$]

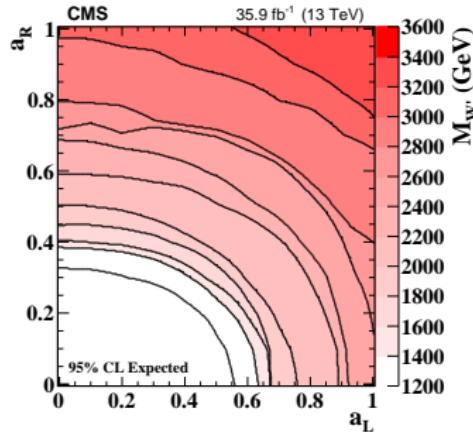
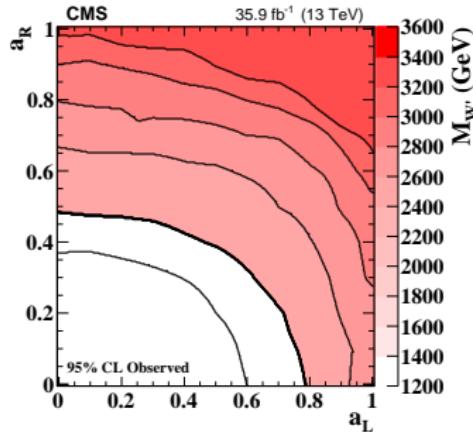
	2-jet 1-tag (e^\pm)			2-jet 1-tag (μ^\pm)			3-jet 1-tag (e^\pm)			3-jet 1-tag (μ^\pm)		
W'_R (1.0 TeV)	1517	\pm	32	2030	\pm	40	1159	\pm	31	1665	\pm	35
W'_R (2.0 TeV)	83.4	\pm	1.7	132.9	\pm	2.1	105.0	\pm	1.9	167.4	\pm	2.2
W'_R (3.0 TeV)	4.7	\pm	0.1	10.4	\pm	0.2	7.0	\pm	0.2	15.7	\pm	0.2
W'_R (4.0 TeV)	0.43	\pm	0.01	1.01	\pm	0.02	0.64	\pm	0.02	1.62	\pm	0.03
W'_R (5.0 TeV)	0.076	\pm	0.002	0.153	\pm	0.003	0.096	\pm	0.003	0.232	\pm	0.004
$t\bar{t}$	1112	\pm	23	1505	\pm	28	3220	\pm	50	4090	\pm	70
Single-top	472	\pm	20	657	\pm	25	482	\pm	21	624	\pm	24
W +jets	520	\pm	50	1280	\pm	120	550	\pm	40	1130	\pm	90
Multijets	358	\pm	35	630	\pm	100	196	\pm	20	390	\pm	60
Z +jets, diboson	129	\pm	14	211	\pm	19	128	\pm	12	242	\pm	20
Total background	2590	\pm	60	4290	\pm	160	4580	\pm	70	6470	\pm	130
Data	2622			4260			4555			6433		

	2-jet 2-tag (e^\pm)			2-jet 2-tag (μ^\pm)			3-jet 2-tag (e^\pm)			3-jet 2-tag (μ^\pm)		
W'_R (1.0 TeV)	1584	\pm	35	2060	\pm	40	1241	\pm	30	1749	\pm	34
W'_R (2.0 TeV)	33.5	\pm	1.0	55.5	\pm	1.2	51.6	\pm	1.2	84.3	\pm	1.5
W'_R (3.0 TeV)	1.4	\pm	0.1	2.6	\pm	0.1	2.5	\pm	0.1	5.1	\pm	0.1
W'_R (4.0 TeV)	0.131	\pm	0.007	0.25	\pm	0.01	0.21	\pm	0.01	0.46	\pm	0.01
W'_R (5.0 TeV)	0.035	\pm	0.002	0.053	\pm	0.002	0.044	\pm	0.002	0.080	\pm	0.002
$t\bar{t}$	536	\pm	14	789	\pm	16	2459	\pm	31	3200	\pm	40
Single-top	121	\pm	6	176	\pm	10	235	\pm	12	347	\pm	17
W +jets	28	\pm	6	42	\pm	4.0	50	\pm	5	97	\pm	9
Multijets	36	\pm	6	71	\pm	13	95	\pm	11	135	\pm	22
Z +jets, diboson	2.5	\pm	0.4	11.5	\pm	1.3	21.2	\pm	2.1	26.9	\pm	2.3
Total background	723	\pm	16	1088	\pm	21	2859	\pm	33	3810	\pm	50
Data	683			1091			2869			3797		

$W' \rightarrow t\bar{b}$: 1-leptonYields [CMS: 13TeV, 35.9 fb $^{-1}$]

Process	Electron channel				Muon channel			
	Type A		Type B		Type A		Type B	
	1 b tag	2 b tags	1 b tag	2 b tags	1 b tag	2 b tags	1 b tag	2 b tags
Background								
t \bar{t}	760	249	69	22	731	263	75	30
tqb	14	6	1	0	14	6	1	0
tW	117	50	15	5	116	44	22	5
tb	2	2	0	0	3	1	0	0
W($\rightarrow \ell\nu$)+jets (LF)	189	17	16	2	177	16	15	1
W($\rightarrow \ell\nu$)+jets (HF)	581	98	52	7	631	107	51	8
Z($\rightarrow \ell\ell$)+jets	19	11	0	0	64	1	20	0
VV	35	9	2	0	33	1	5	4
Total background	1717 \pm 62	442 \pm 34	155 \pm 23	36 \pm 7	1769 \pm 70	439 \pm 30	189 \pm 22	48 \pm 9
Data	1750	437	133	40	1754	482	164	44
Signal								
$M_{W'_R} = 2000\text{ GeV}$	53	43	41	25	79	75	57	35
$M_{W'_R} = 2600\text{ GeV}$	8	6	16	10	14	12	24	15
$M_{W'_R} = 3200\text{ GeV}$	2	1	4	3	3	2	8	5

Black lines represent contours of equal $m(W')$ in step 200 GeV



Cross-section with arbitrary left- and right-handed couplings a_L, a_R :

$$\sigma = (1 - a_L^2)\sigma_{SM} + \frac{1}{a_L^2 + a_R^2} \left[a_L^2(a_L^2 - a_R^2)\sigma_L + a_R^2(a_R^2 - a_L^2)\sigma_R + 4a_L^2a_R^2\sigma_{LR} - 2a_L^2a_R^2\sigma_{SM} \right]$$

where $\sigma_L, \sigma_R, \sigma_{LR}, \sigma_{SM}$ are obtained from simulation

and $(a_L, a_R) = (1/\sqrt{2}, 1/\sqrt{2})$ to ensure similar widths for all samples

$H^\pm \rightarrow t\bar{b}$ direct searches

allowed if $m(H^\pm) > m(t) + m(b)$

received little attention so far

DØ @ 1.96 TeV: [PRL 102 \(2009\) 191802](#)

ATLAS @ 8 TeV: [JHEP 03 \(2016\) 127](#)

@ 8 TeV, ATLAS investigated $H^\pm \rightarrow t\bar{b}$ search through a reinterpretation of $W' \rightarrow t\bar{b}$ searches in ATLAS (both 0- and 1-lepton analysis).

No evidence for a charged Higgs boson was found yet