# Search for W' →tb

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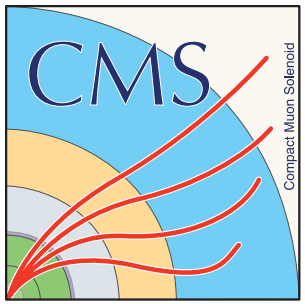
on behalf of ATLAS and CMS collaborations



# Outline

Introduction

W’ models

Hadronic analysis

Leptonic analysis

Results on couplings

Conclusion and Outlook

# Introduction

Massive charged gauge bosons W'

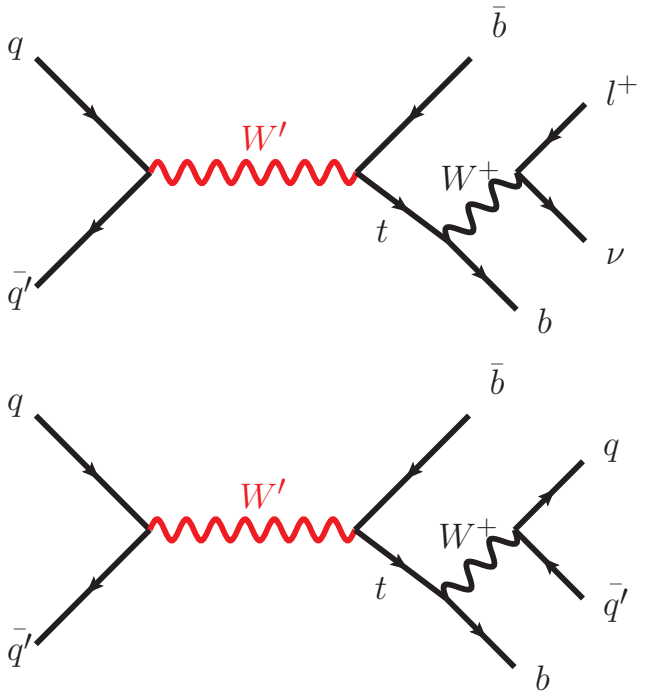
- Predicted by several Beyond Standard Model theories
  - Effective Left-Right model (Phys.Rev.D66:075011, PhysRevD.86.075018)
- Arise from additional symmetries

W'-> tb is an interesting channel:

- More model independent than leptonic decay
- Probe leptophobic sector
- BSM dynamics could explain high top mass
- Directly probes coupling to third generation
- Complementary to W'->lv and W'->VV searches

W' signal samples generation:

- ATLAS: MadGraph5 (LO) using FeynRules, with CTEQ6L1 PDF
- CMS: CompHEP (LO) with CTQ6M PDF



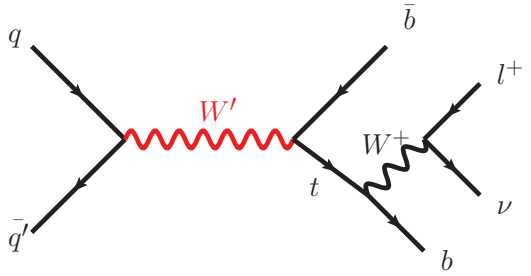
# W' models

$$\mathcal{L} = \frac{V_{f_i f_j}}{2\sqrt{2}} g_w \bar{f}_i \gamma_\mu \left[ a_R (1+\gamma^5) + a_L (1-\gamma^5) \right] \mathrm{W}'^{\mu} f_j + \mathrm{h.c.}$$

$V_{fifj}$ CKM matrix for quarks, $\delta_{ij}$ for leptons

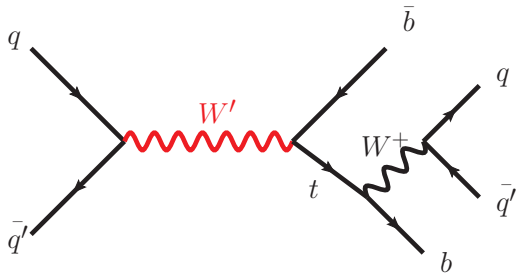
$g_W$ Standard Model weak coupling constant

$a_R$ coupling strength to right-handed fermions




If $a_L > 0$, one must take into account interference with the SM W boson

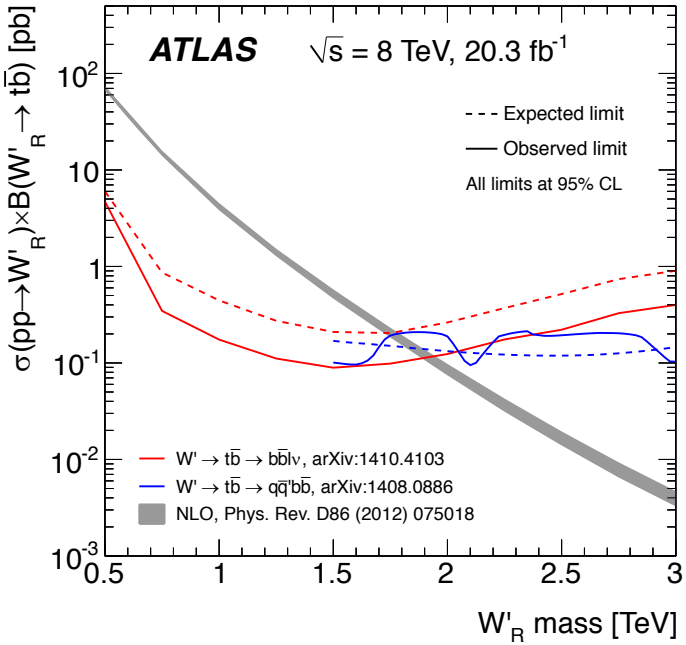
- W' with left and right handed couplings
- $m(W_R') \gg m(\nu_R)$
- $m(W_R') < m(\nu_R)$: $W_R' \rightarrow l\nu_R$ forbidden
  - $W_R'$ cross section * branching ratio is enhanced

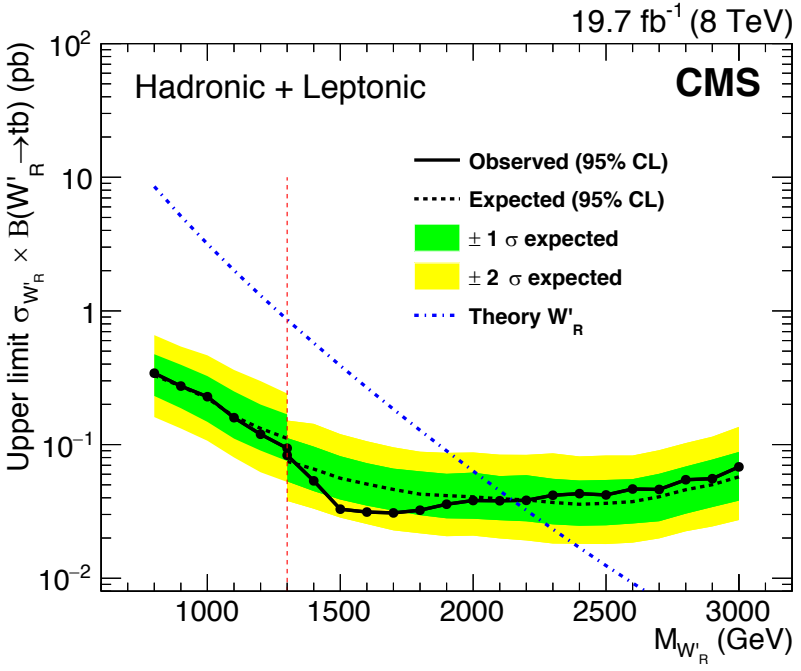


# W’ searches – 8 TeV results

In Run 1 both ATLAS and CMS performed searches for W’

- In both leptonic and hadronic channels
- No excess was found
- Results were interpreted in $W'_R$, $W'_L$ models and as limits on different couplings



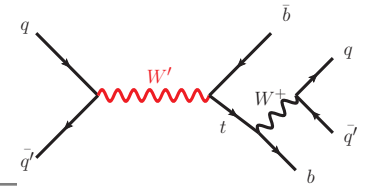

[Phys. Lett. B743 (2015) 235]

[JHEP02 (2016) 122]

# 13TeV analyses summary

| | CMS leptonic ($2.2fb^{-1}$) and hadronic ($2.6fb^{-1}$): :<br>◦ JHEP 08 (2017) 029 | CMS leptonic ($35.9fb^{-1}$):<br>◦ Electron and muon channels<br>◦ >=2jets: 1 or 2 b-jets<br>◦ TypeA, TypeB<br>◦ $p_T$(top), m(top), $p_T$(jet1, jet2)<br>◦ Phys. Lett. B 777 (2017) 39 | ATLAS hadronic ($36.1fb^{-1}$):<br>◦ Top tagging using shower deconstruction<br>◦ $p_T$(top), m(top), $p_T$(jet1, jet2)<br>◦ Phys. Lett. B 781 (2018) 327 |
|---|---|---|---|
| $m(W'_R)$ [TeV] | $m(W'_R)$ = 2.4 TeV | $m(W'_R)$ = 3.6 TeV | $m(W'_R)$ = 3 TeV |
| $m(W'_L)$ [TeV] | | | $m(W'_L)$ = 2.9 TeV |

# Event selection - hadronic

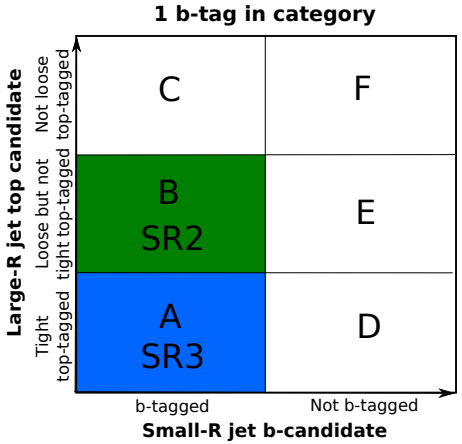



Dominant background is multijet production

- Estimated from data using a six-region "2D sideband" method that predicts both the shape and normalisation of the $m_{tb}$ distribution

Other important background is $t\bar{t}$ production

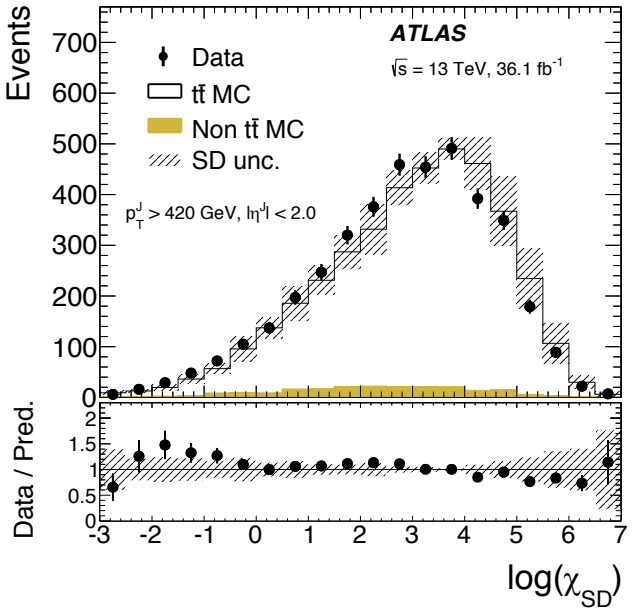
- Monte Carlo estimate using Powheg-Box v2




Top-tagger

- Boosted-top identification using shower deconstruction (SD)
- The SD tagger calculates likelihoods that a given large-*R* jet originates from a hadronic top-quark decay or from a high-momentum light quark or gluon
- $\chi_{SD}$ is defined as the ratio of the sum of the signal-hypothesis weights to the sum of the background-hypothesis weights

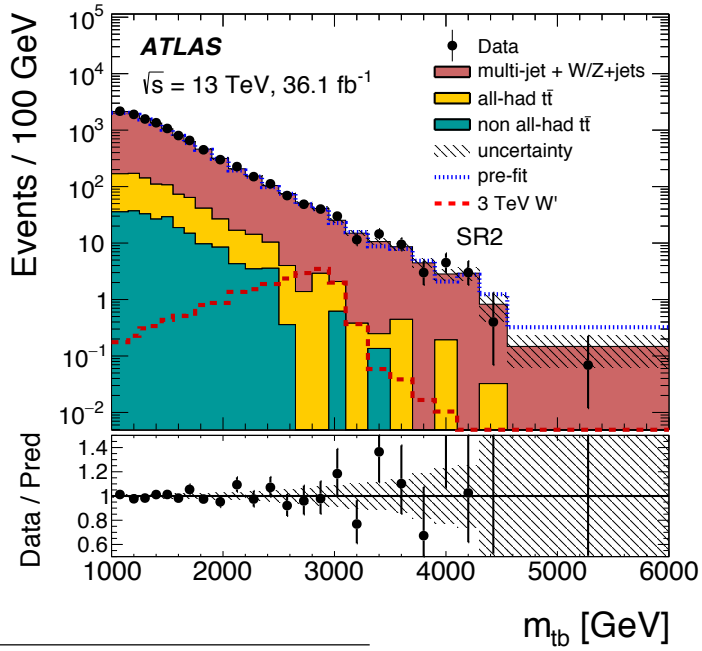
$$\chi_{SD}(\{p_i^k\}) = \frac{\sum_{perm} P(\{p_i^k\}|\text{top-quark jet})}{\sum_{perm} P(\{p_i^k\}|\text{gluon/light-quark jet})}$$



# m(tb) hadronic analyses 13 TeV

## Event selection:

- Veto events with leptons (e or μ)
- One large-R jet (R=1.)
  - at least three subjets
  - two or more subjets must have a combined invariant mass centered on the *W*-boson mass
  - at least one more subjet can be added to obtain a total mass centered on the top-quark mass
- Categorise events depending number of b-tagged jets
  - Using 77% efficiency working point



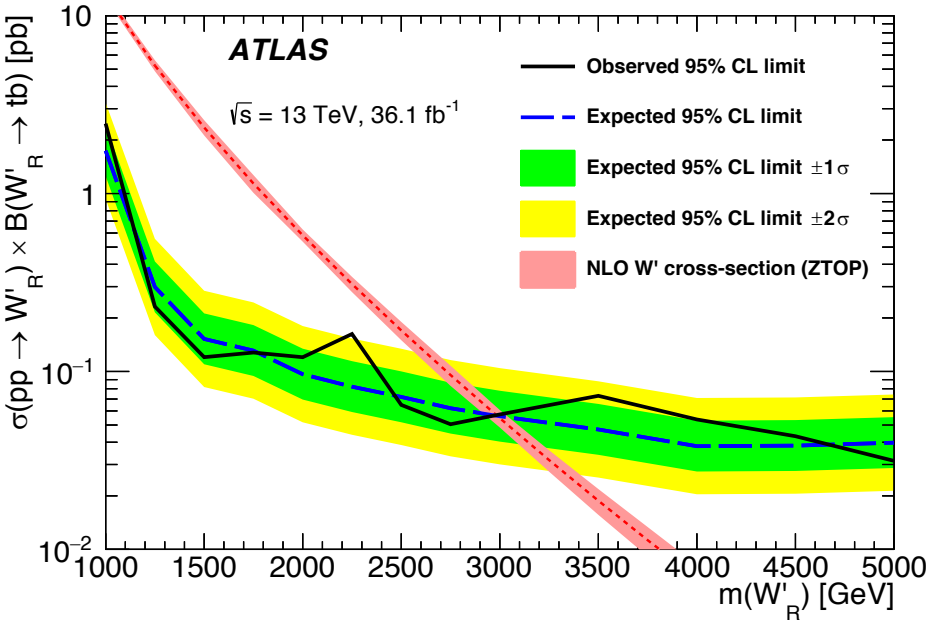

| Event reconstruction and selection | |
|---|---|
| Large-$R$ jet ($J$) | $p_{\mathrm{T}}^{J} > 420$ GeV, $\lvert\eta\rvert < 2.0$ |
| Small-$R$ jet ($j$) | $p_{\mathrm{T}}^{j} > 25$ GeV, $\lvert\eta\rvert < 2.5$ |
| Top-quark jet candidate ($J_{\mathrm{top}}^{\mathrm{cand}}$) | jet $J$ with highest $m_j + 0.15 \times m_J$ |
| $b$-quark jet candidate ($j_b^{\mathrm{cand}}$) | highest-$p_{\mathrm{T}}$ jet $j$ with $p_{\mathrm{T}}^{j} > 420$ GeV, $\Delta R(J_{\mathrm{top}}^{\mathrm{cand}}, j) > 2.0$ |
| Lepton veto | zero leptons with $p_{\mathrm{T}} > 25$ GeV, $\lvert\eta\rvert < 2.5$ |
| $b$-quark jet candidate $\eta$ | zero $j_b^{\mathrm{cand}}$ with $\lvert\eta\rvert > 1.2$ |
| 0 $b$-tag in | zero $b$-tagged jets $j$ with $\Delta R(J_{\mathrm{top}}^{\mathrm{cand}}, j) < 1.0$ |
| 1 $b$-tag in | exactly one $b$-tagged jet $j$ with $\Delta R(J_{\mathrm{top}}^{\mathrm{cand}}, j) < 1.0$ |

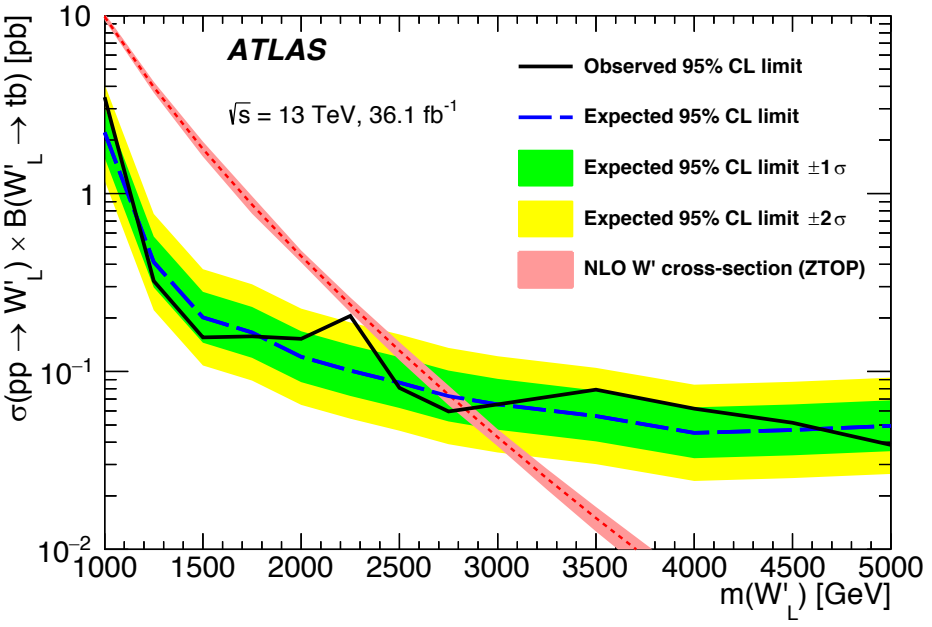
# Results hadronic analysis 13 TeV

The observed $m_{tb}$ spectrum is consistent with the background-only prediction

Exclusion limits at 95% CL are set on the W'-boson production cross- section times branching ratio to $t\bar{b}$

- excluding W' bosons with right-handed couplings with masses below 3.0 TeV
- excluding W' bosons with left-handed couplings with masses below 2.9 TeV



# Event selection - leptonic

## Selection:

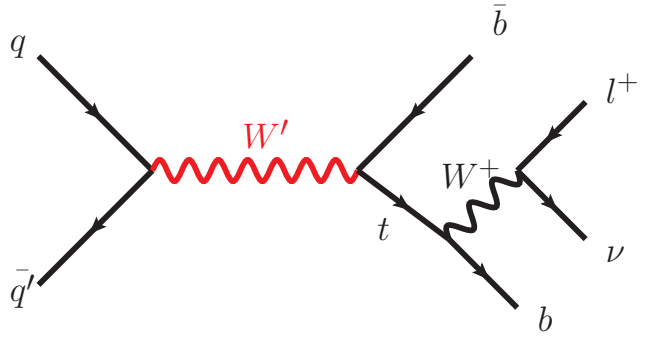
- ==1 lepton (e or μ) with $p_T$ > 180GeV (dilepton veto)
- ≥2 central jets with $p_T$ > 30 GeV
- Leading jet $p_T$ > 350 (450) GeV in the e (μ) channel
- top quark from the W' decay is highly boosted
  - causing the b-jet and lepton to be close to each other
  - leptons are not required to be isolated
- High $E_T^{miss}$ > 120(50)GeV in the e (μ) channel
- Events in the e channel $|\Delta\varphi(e, E_T^{miss})| < 2$ radians

## Neutrino $p_Z$ calculation

- Estimated from $E_T^{miss}$ and W mass constraint
- Neutrino $p_z$ reconstruction

## Top and W' reconstruction

- Find jet that gives m(lvb) mass closest to top-quark
- Assign highest $p_T$ remaining jet to W' decay




Dominant backgrounds:

- $t\bar{t}$, W+jets production

Subdominant backgrounds:

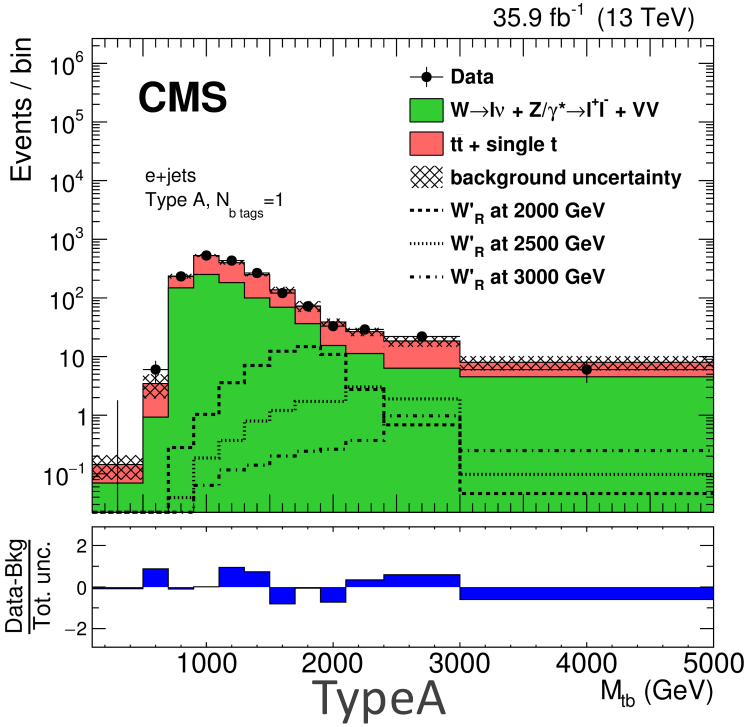
- single top (s-, t-channel), Wt, Z/γ*+jets, diboson production

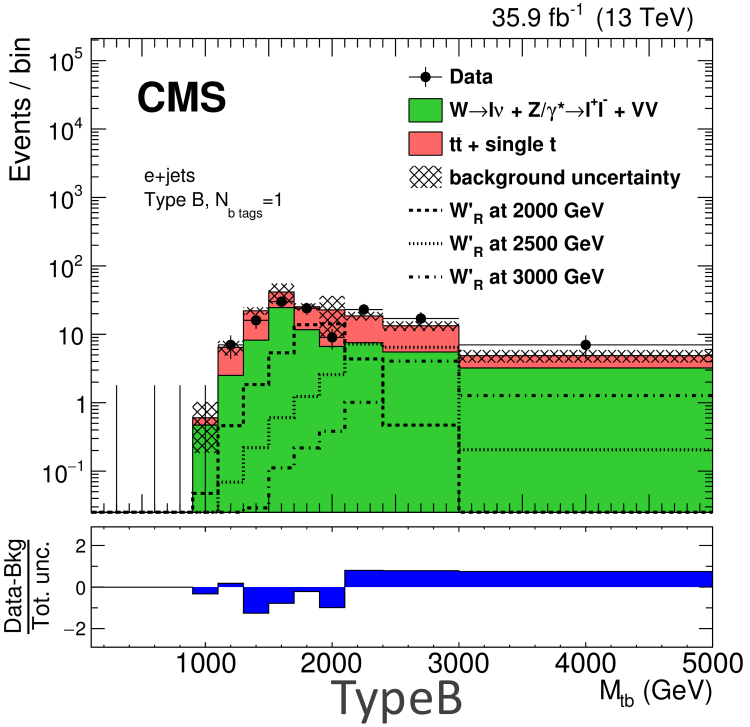
All backgrounds estimated from Monte Carlo

# m(tb) leptonic channel 13 TeV

Categories are created according to:

- lepton type (e or μ)
- number of b-tagged jets among the first two leading $p_T$ jets (1 or 2)
  - allows the analysis to maintain acceptance for signal events where one of the jets is not correctly b tagged
- $p_T^t$ and $p_T^{j1+j2}$ (Type A or B)
  - allows the analysis to perform well over a large range of possible signal masses



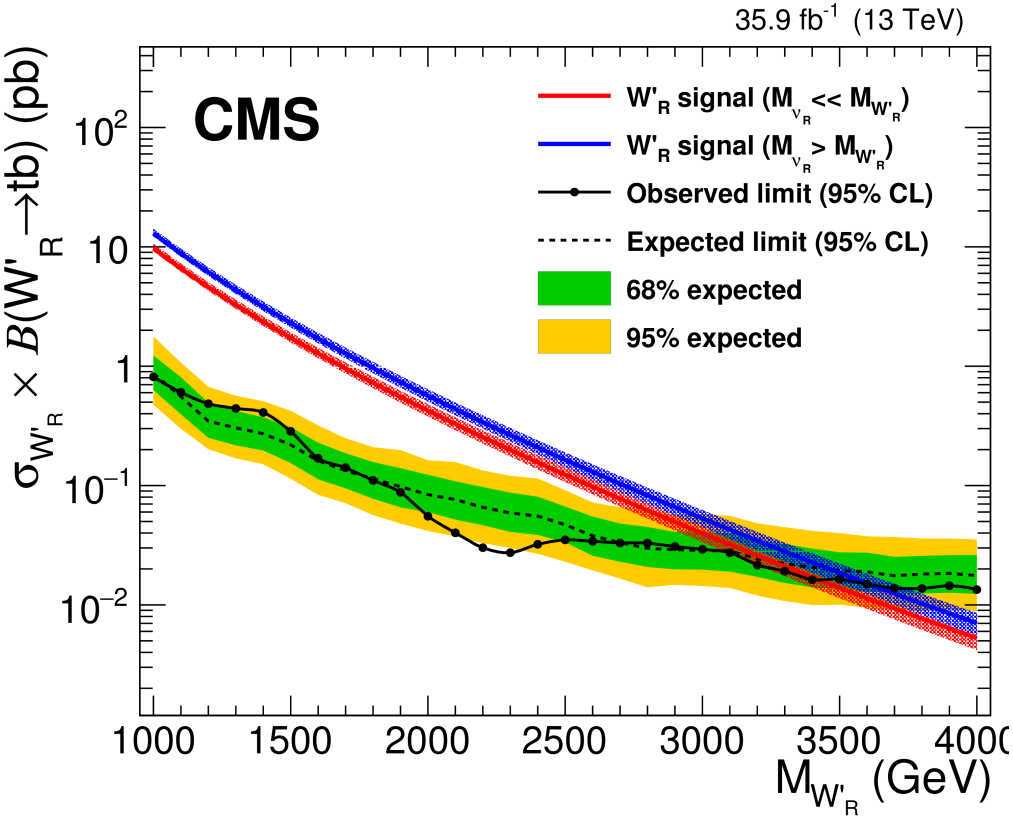



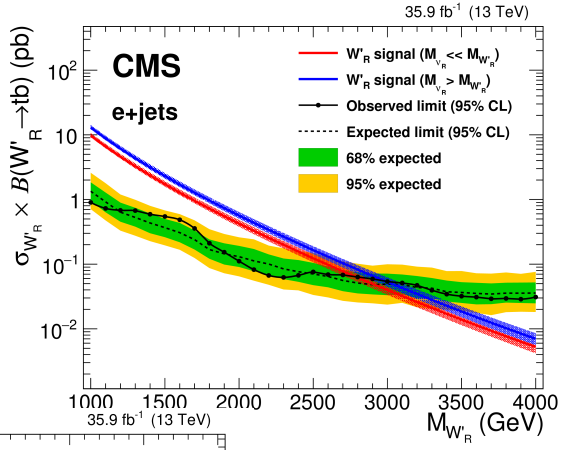
# $W'_R$ – leptonic channel 13 TeV

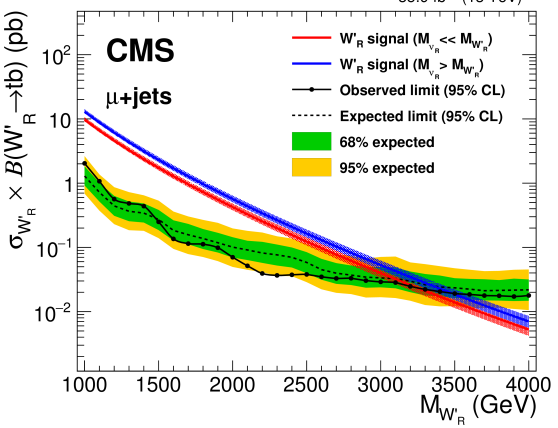
Data agree with the predicted SM background processes

- set 95% CL upper limits on the W' boson production cross section

Right-handed $W'_R$ bosons with masses below 3.4 TeV are excluded at 95% CL



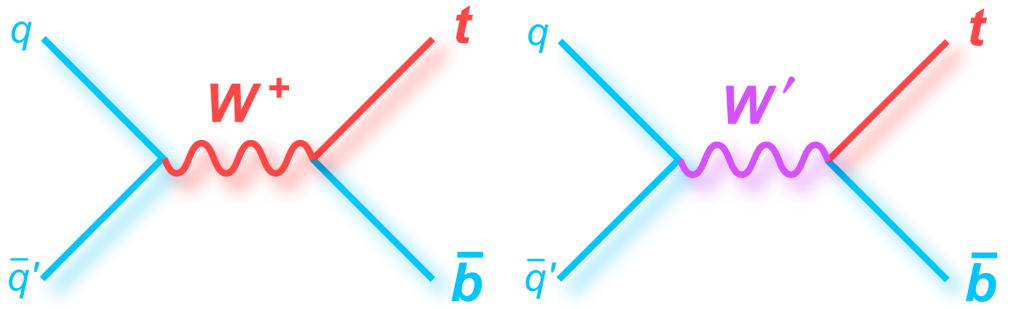



# Interference

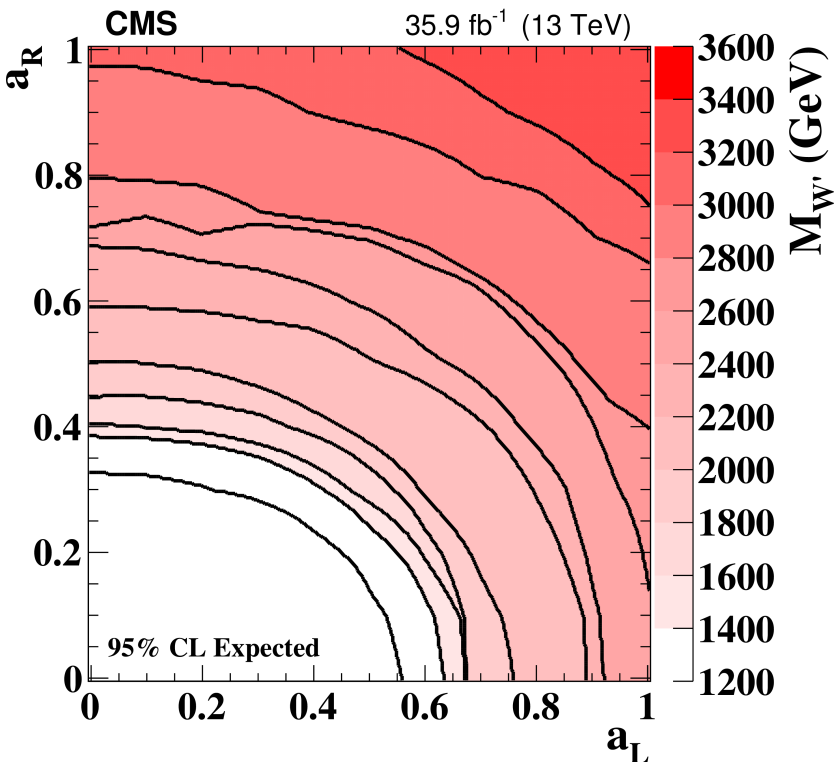
W'$_L$ couple to same fermion multiplets as Standard Model W boson
- Interference between s-channel single top production via W and W'$_L$ bosons
- Interference can be constructive and destructive
  - We consider only destructive interference
- These processes are generated together

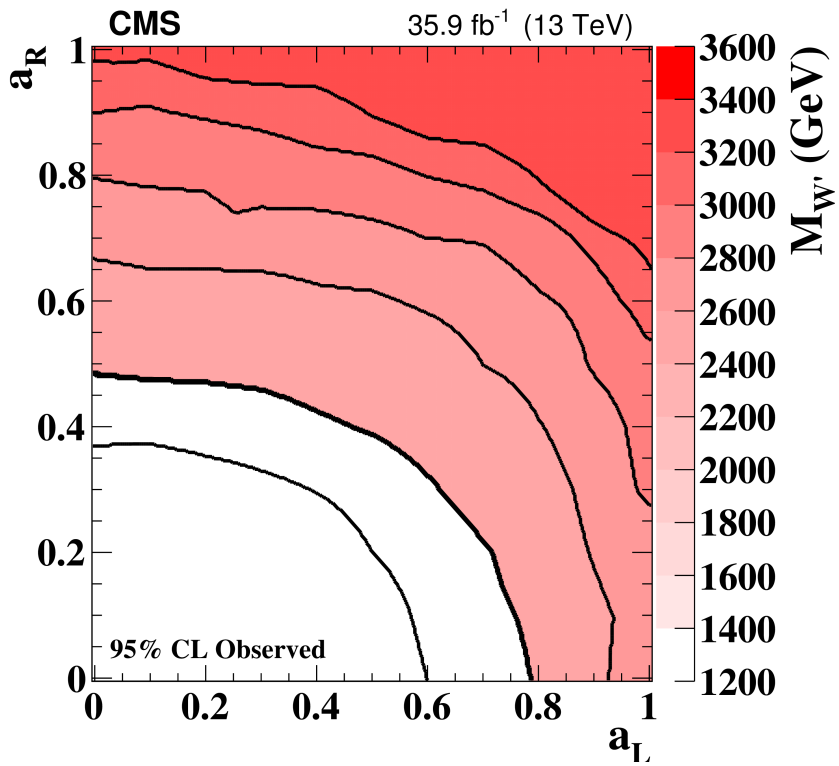
For W'$_L$ search s-channel single top production enters into signal
- Wt and t-channel single top productions are considered as backgrounds
- Limits are set on the pp-> W'$_L$/W->tb process considered as unique signal




$$|\mathcal{M}|^2 = |\mathcal{M}_{SM}|^2 + |\mathcal{M}_{BSM}|^2 + 2\Re(\mathcal{M}^*_{SM}\mathcal{M}_{BSM})$$

# Results on couplings 13 TeV




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

where $\sigma_L$, $\sigma_R$, $\sigma_{LR}$, $\sigma_{SM}$ are obtained from simulation (including interference)

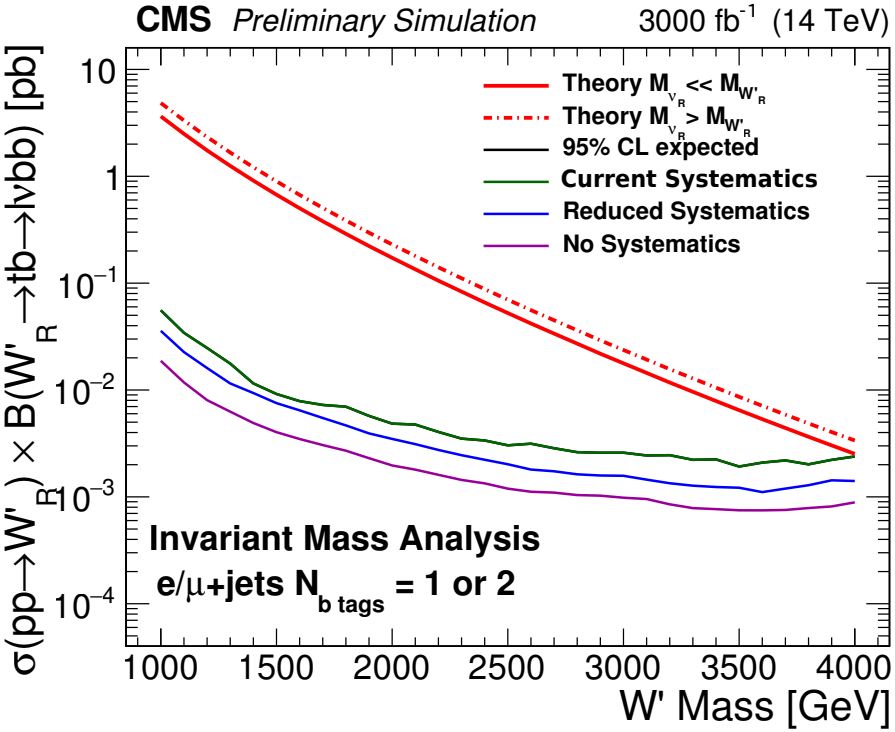
Mixed-coupling signal: ($a_L$, $a_R$) = (1/ √ 2, 1/ √ 2) instead of previously (1,1) to ensure that widths are similar for all samples

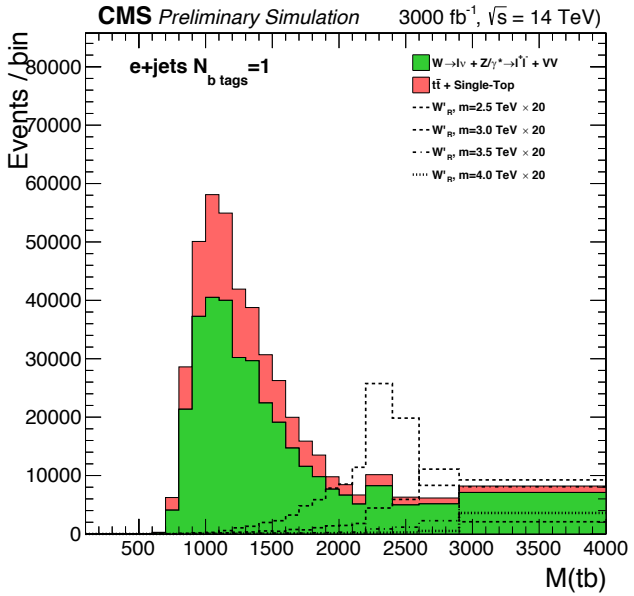
# Leptonic channel 14 TeV

Projections for upgrade

CMS leptonic 14TeV (3000fb$^{-1}$ @ HL-LHC):

- CMS-PAS-FTR-16-005
- Projections obtained by extrapolation of 13 TeV analysis
- Scaling of background and signal cross-sections
- 1tag, 2tag, e and μ channels




Current systematics

- Keep the values from the Run13TeV analysis

Reduced systematics

- Cross section, PDF, and *Q*2 uncertainties scale down by a factor of 2
- The top $p_T$ uncertainty scaled down by a factor of 3
- the luminosity uncertainty is reduced to 1.5%
- jet energy scale uncertainty and the b-tag uncertainty is set to 1%
- The mis-tag uncertainty stay unchanged
- All other uncertainties scaled down by factor $\sqrt{\mathcal{L}}$

No systematics

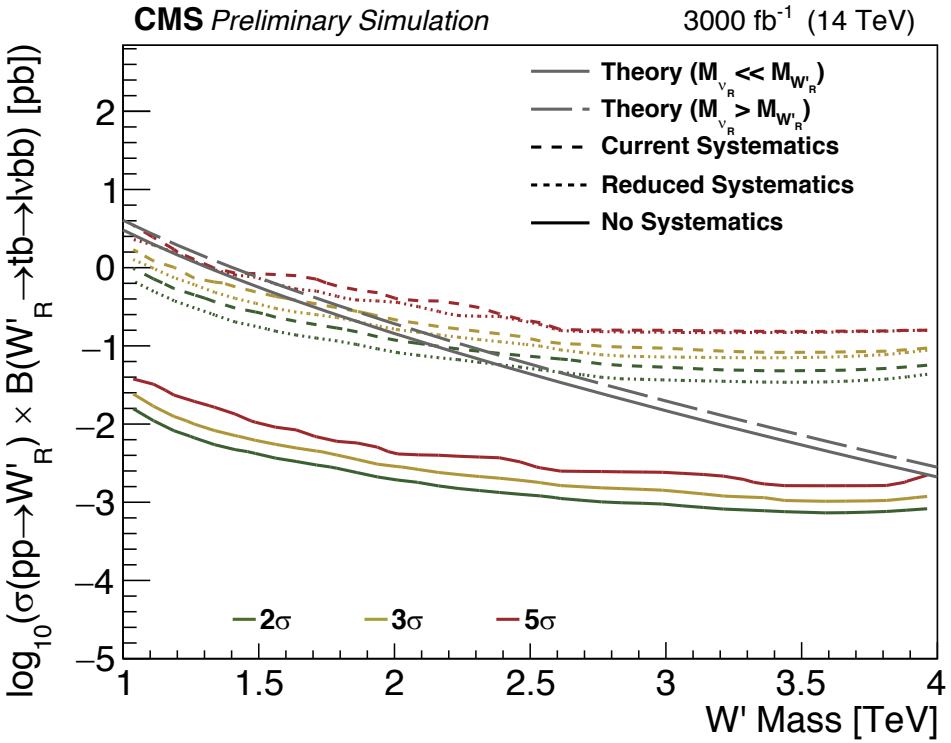
- corresponding to the best possible limit

# Leptonic channel 14 TeV

Projections for upgrade

A quasi-model-independent method is used:

- Projections are performed for arbitrary cross sections and resonance mass
- Toy datasets with different amounts of injected signal are studied
- The p-values for these hypothesized datasets compared to the null-signal hypothesis yield significances which are reported in units of standard deviations ($\sigma$)
- Three exemplary values of $2\sigma$, $3\sigma$ (corresponding to "evidence") and $5\sigma$ (corresponding to discovery)



# Conclusion and Outlook

Presented ATLAS and CMS results for W' searches for 2015 and 2016 data

No excess found

- Results are interpreted as limits on several W' models
- $W'_R$, $W'_L$
- Limits on couplings

Projections of the leptonic analysis at 14TeV

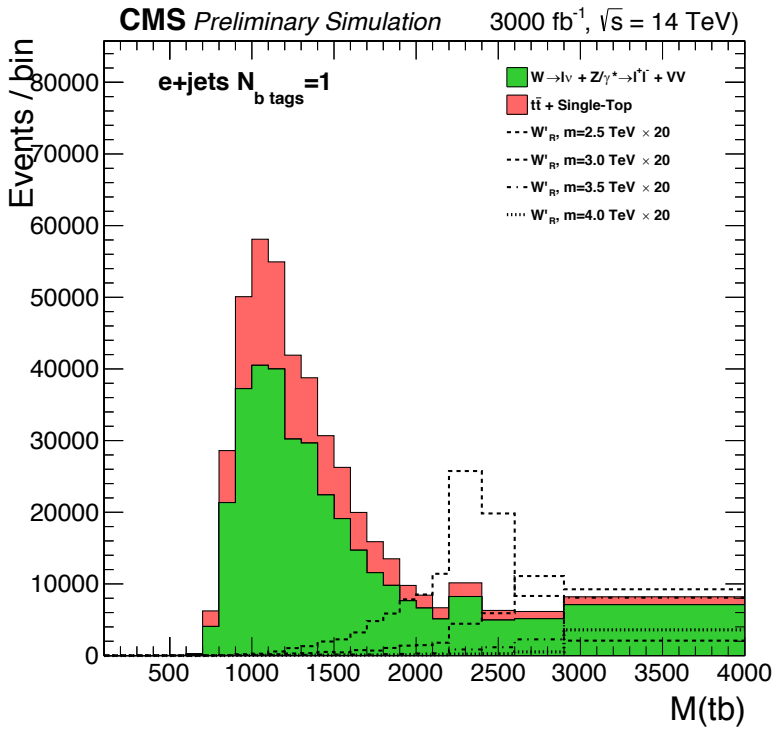
# Back up

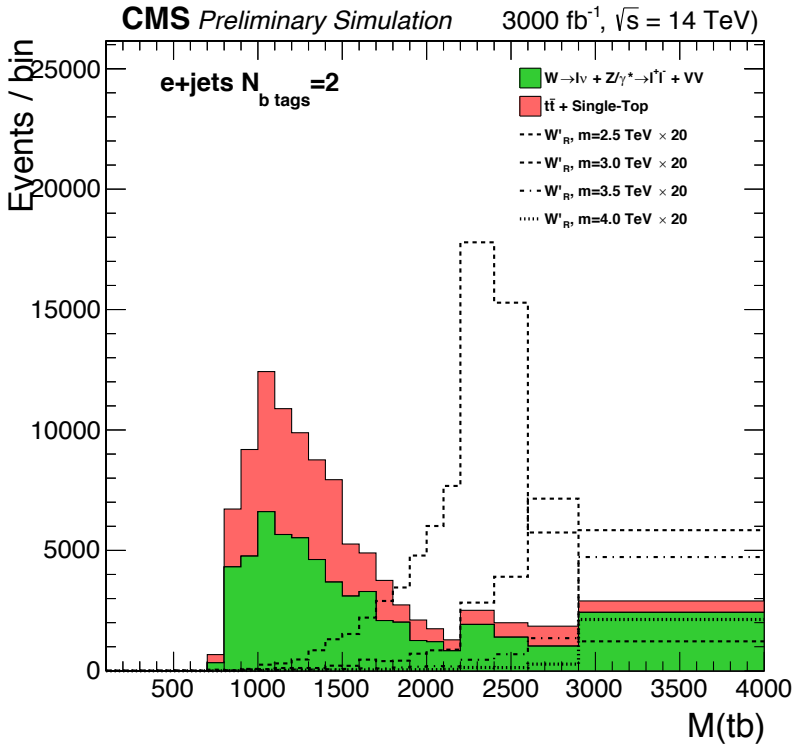
# m(tb) leptonic channel 14 TeV

CMS leptonic 14TeV (3000fb$^{-1}$):

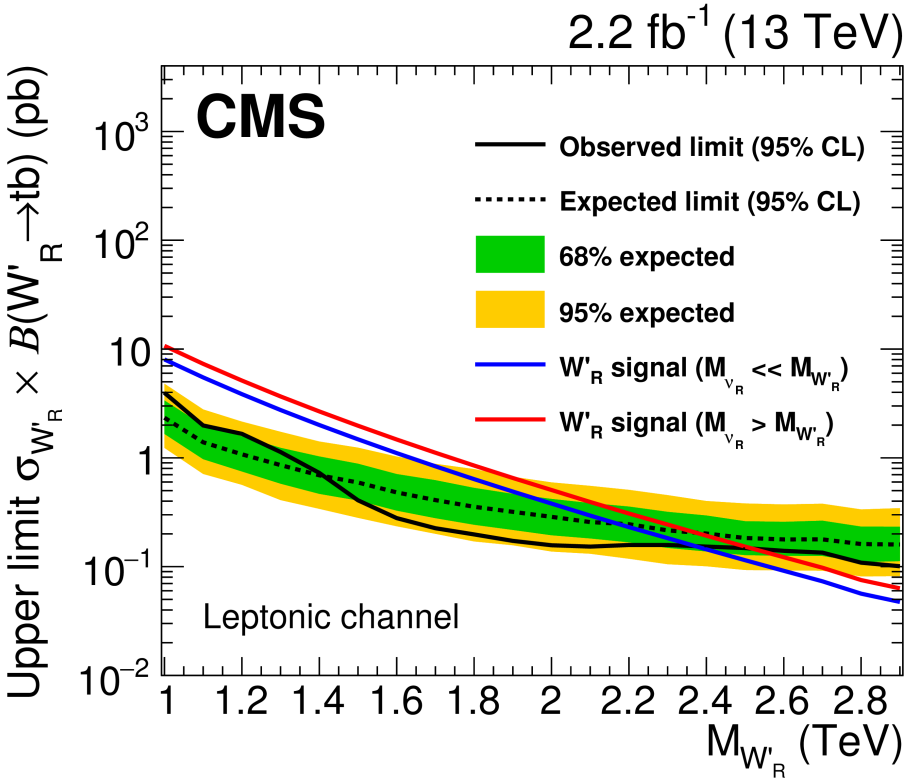
1tag, 2tag regions

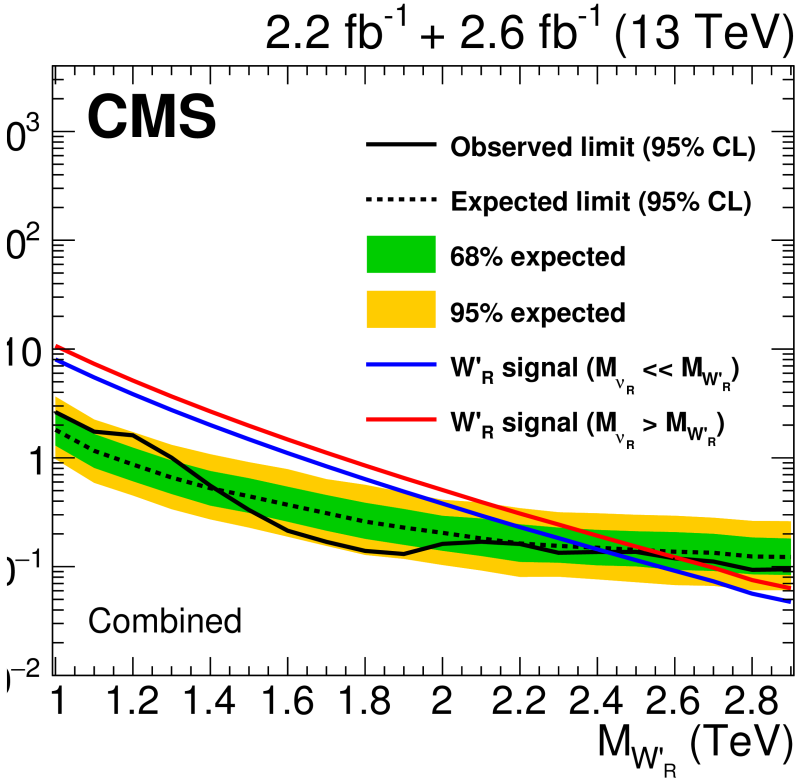
[CMS-PAS-FTR-16-005]



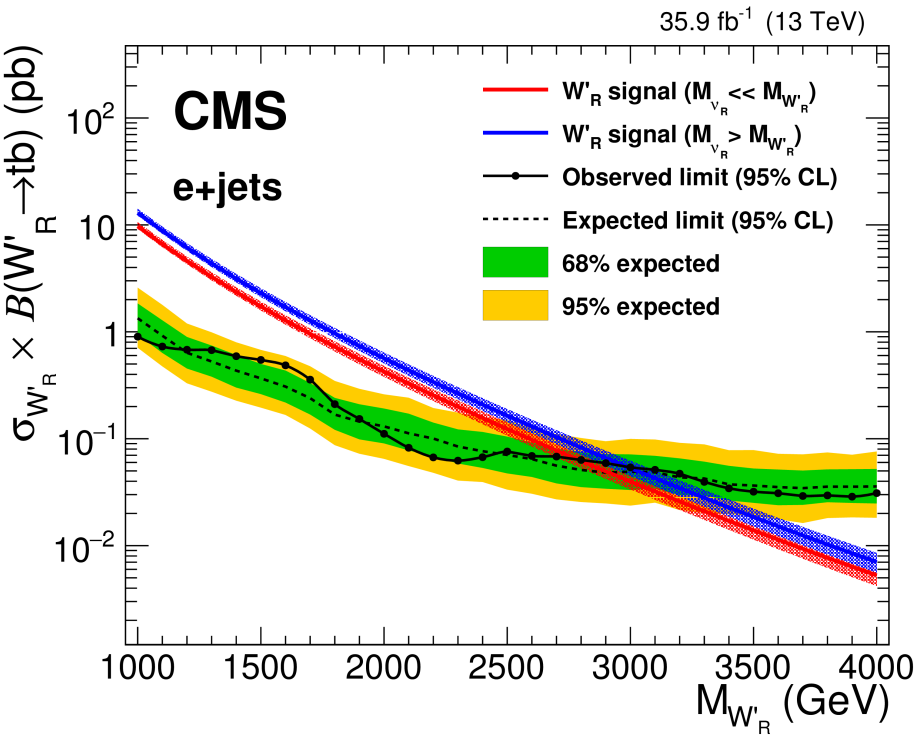



# $W'_R$ – combined 13 TeV

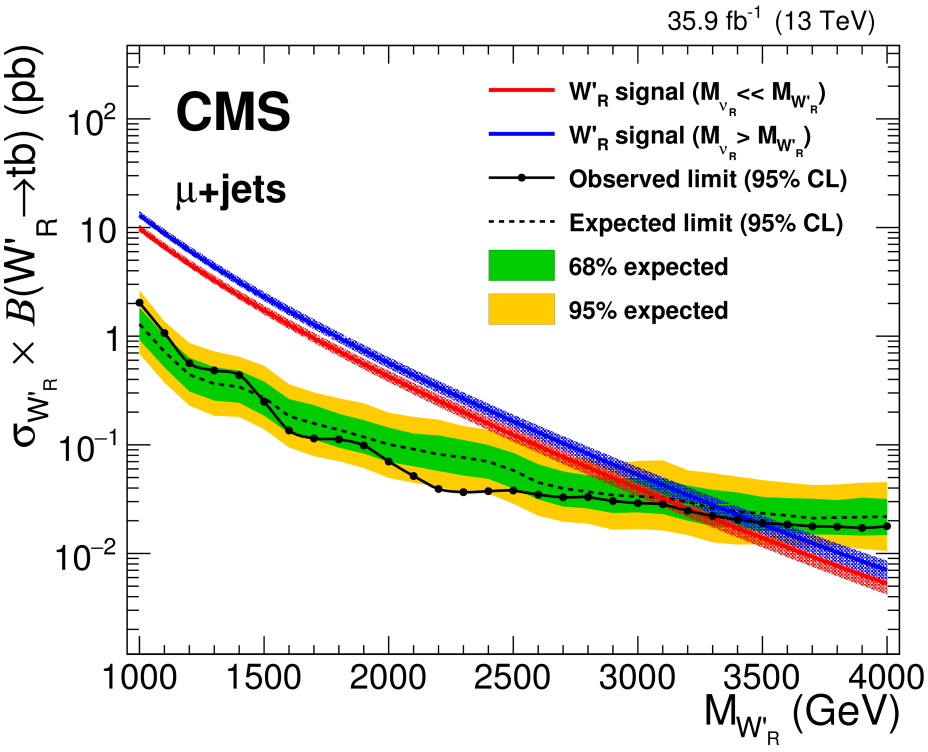


# m(tb) leptonic channel 13 TeV

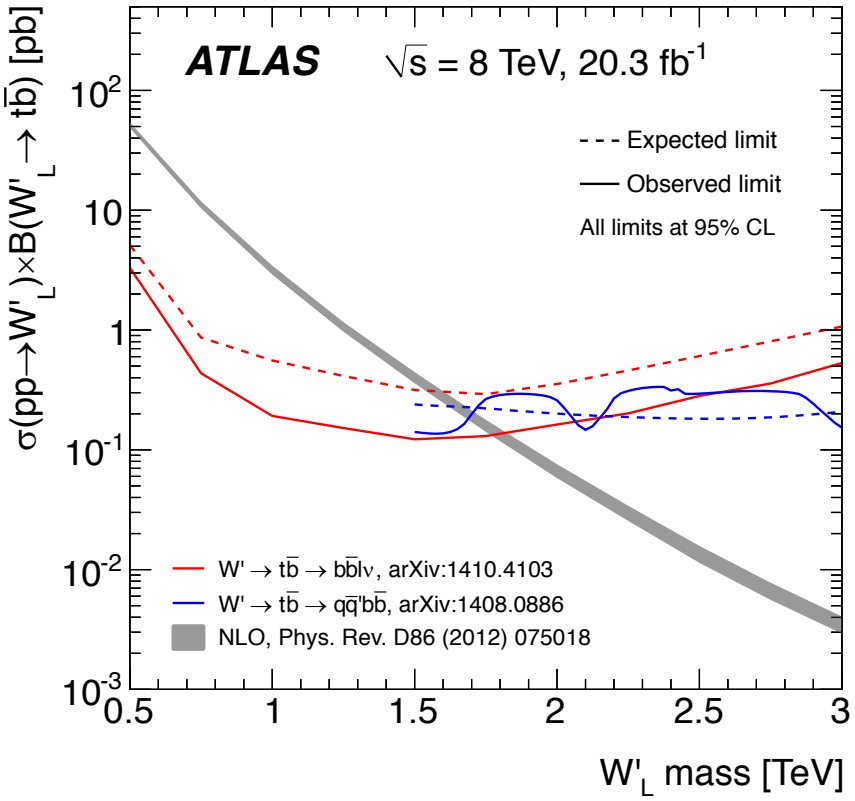



TypeA

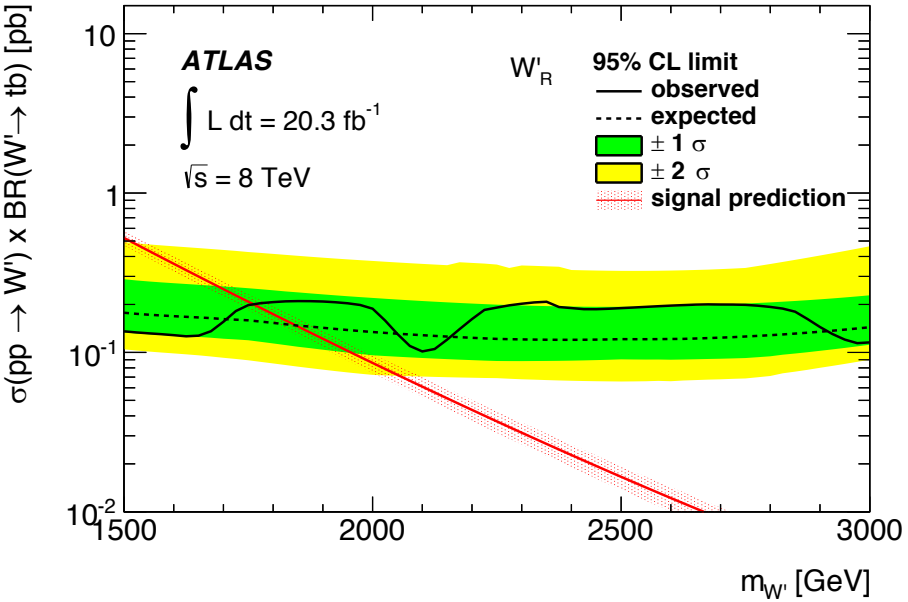


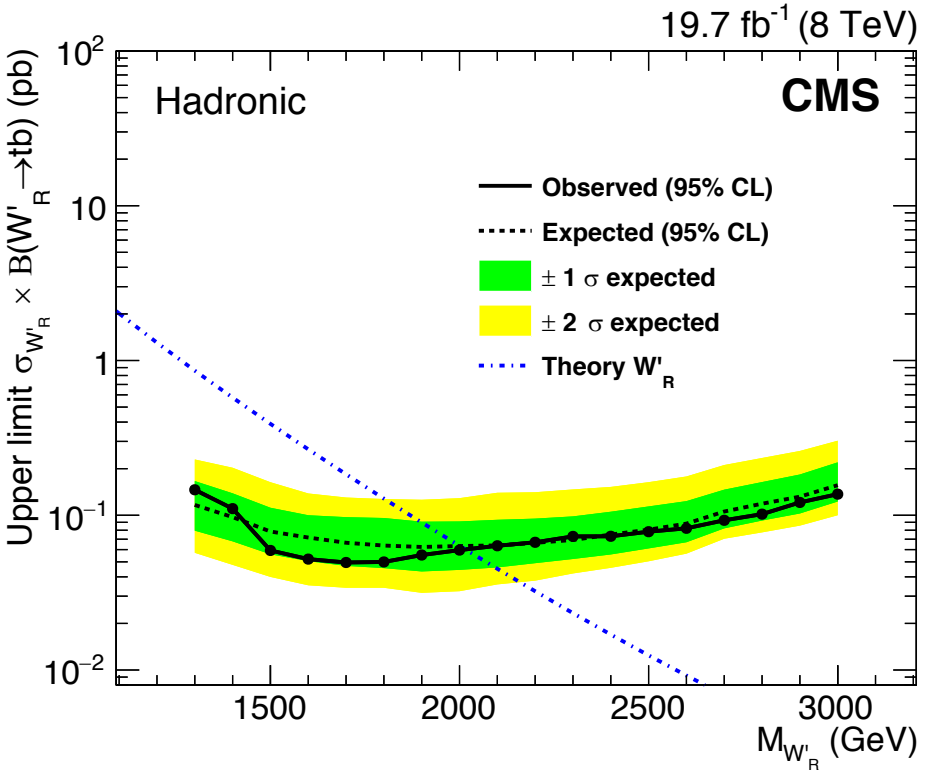

TypeB

# $W'_L$ - combined 8 TeV

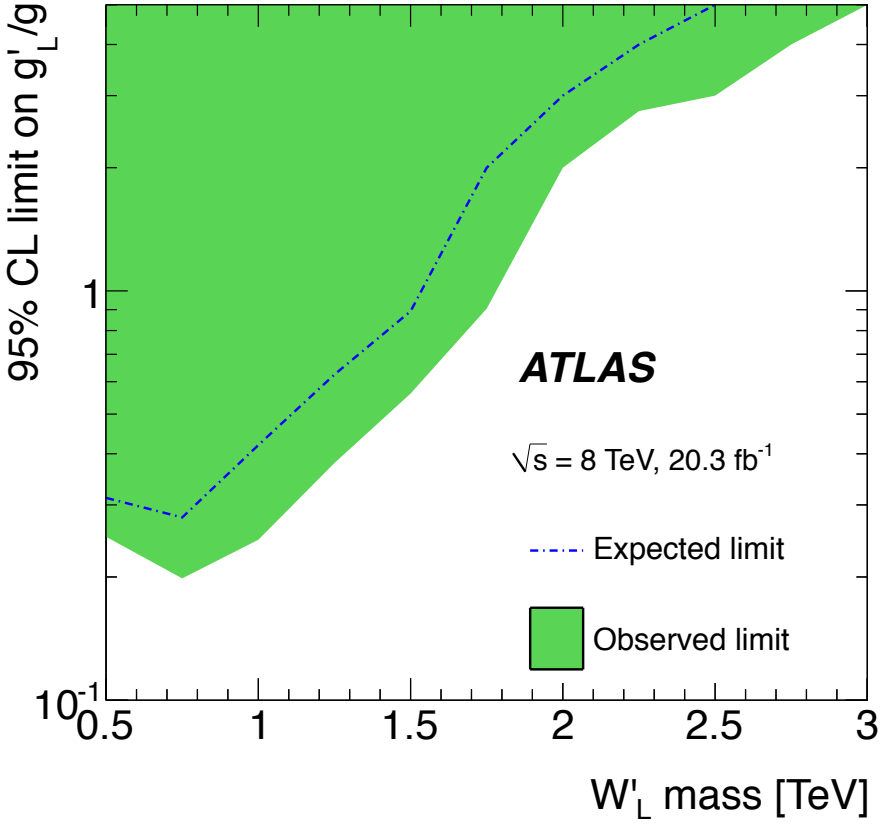


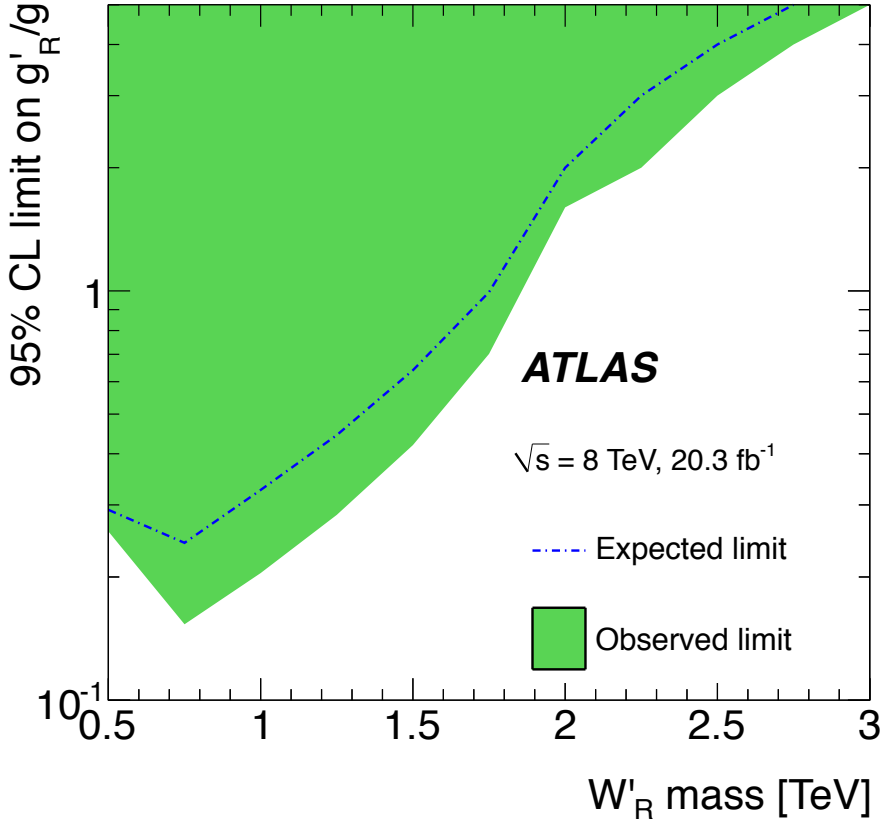
# Right-handed W' - hadronic



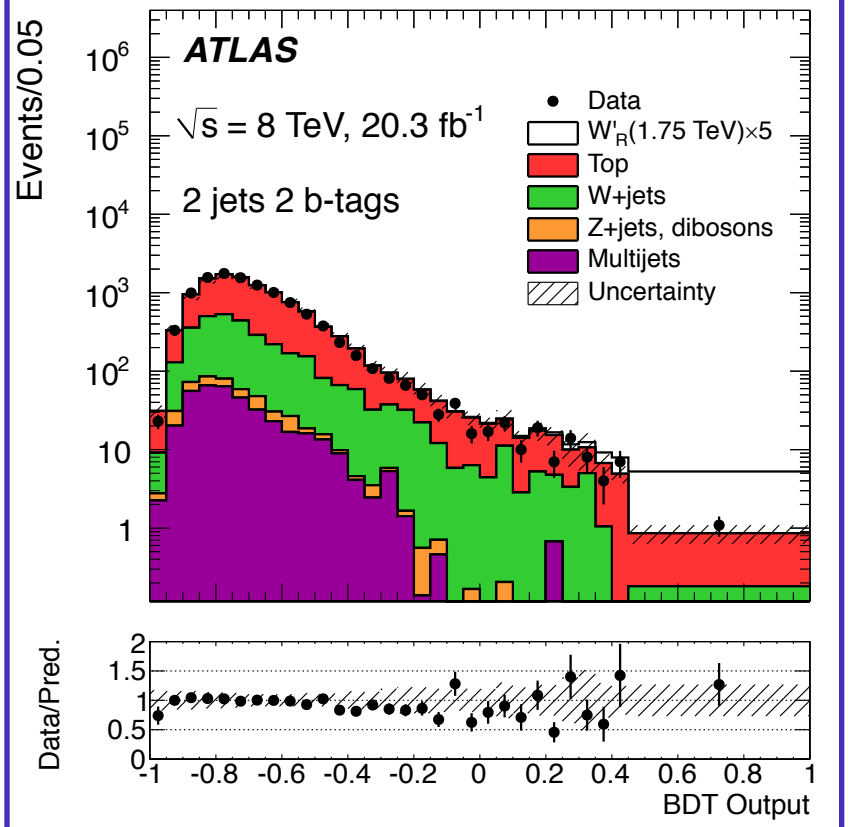



# Couplings ATLAS 8 TeV



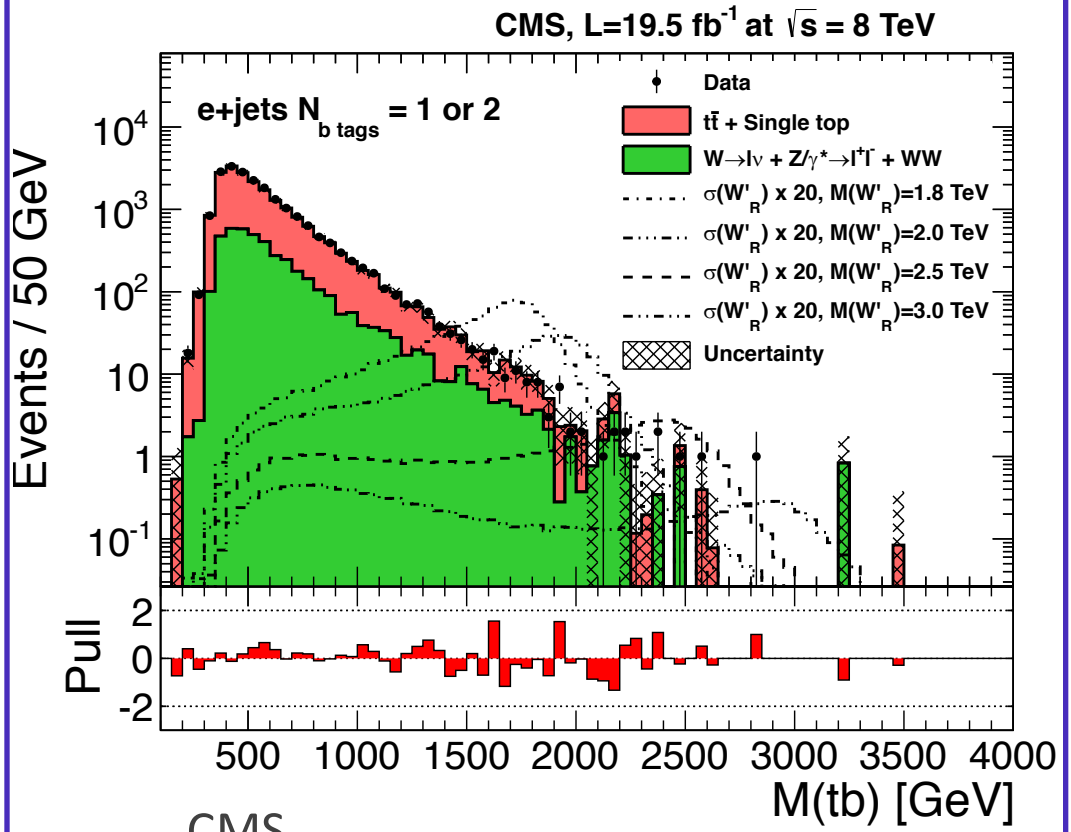



# m(tb) leptonic analyses 8 TeV




ATLAS

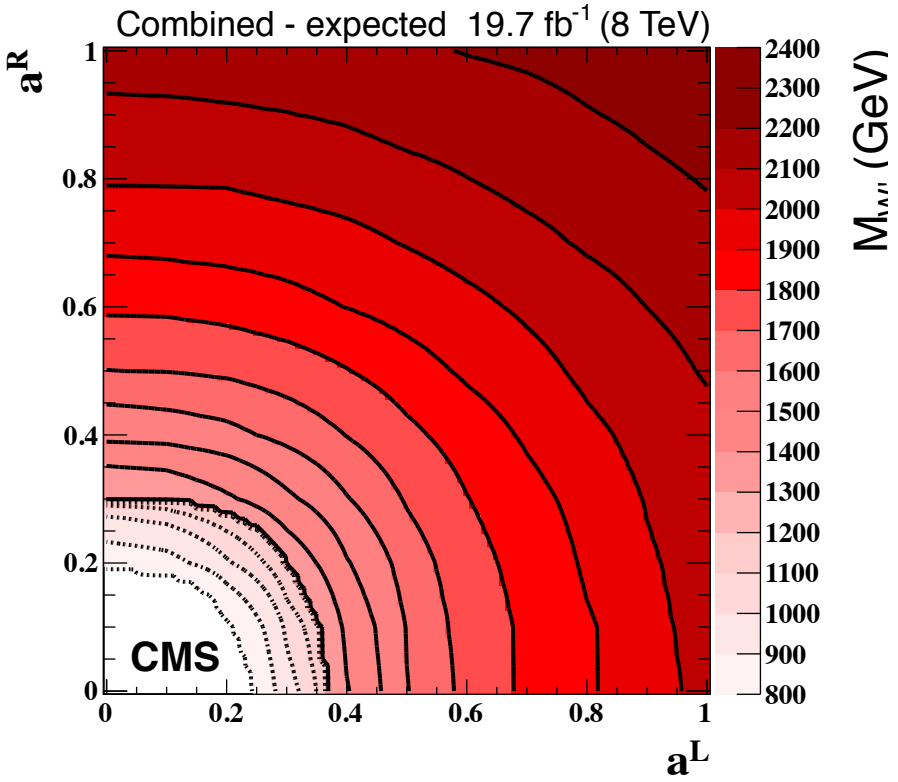
- Electron and muon channel
- 2 jets, 2 b-jets

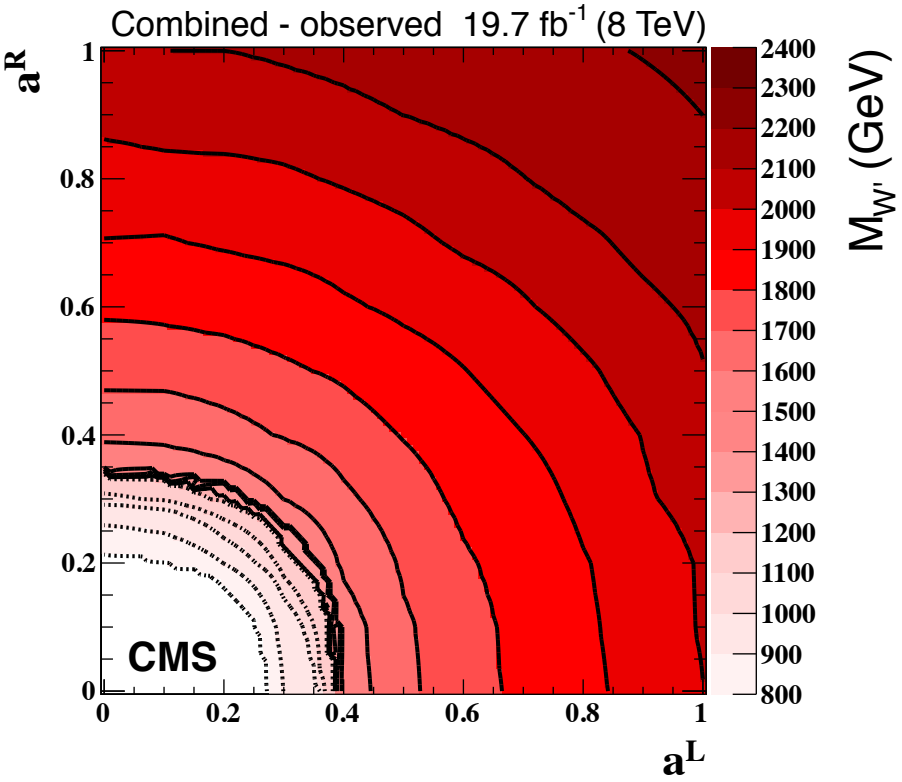



CMS

- Electron channel
- >=2jets: 1 or 2b-jets

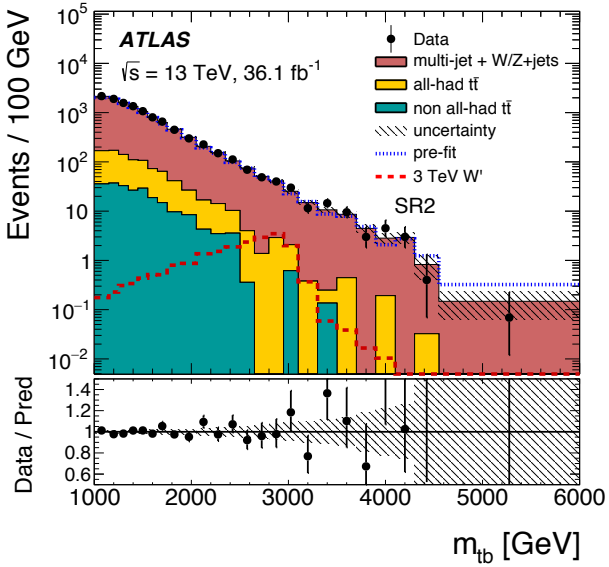
# Couplings CMS 8 TeV



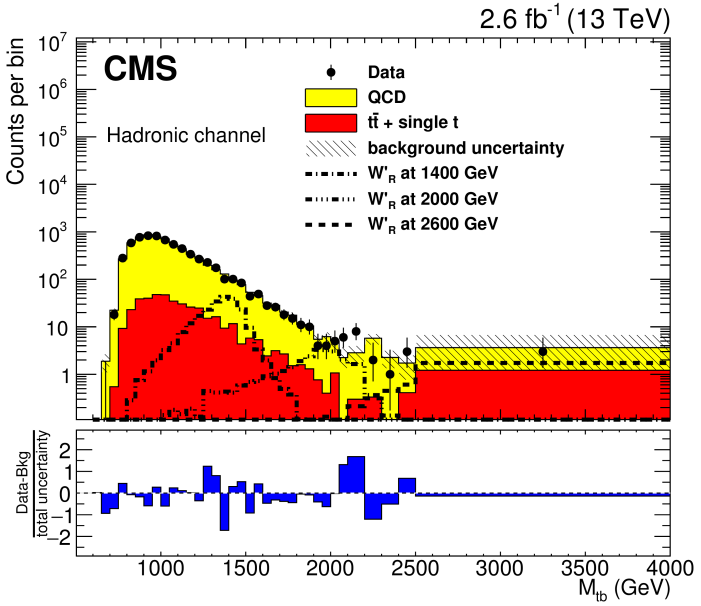

$$\sigma_{a_{ud}^L, a_{ud}^R, a_{tb}^L, a_{tb}^R} = \left(1 - a_{ud}^L a_{tb}^L\right)\sigma_t + a_{ud}^R a_{tb}^R \frac{a_{ud}^R a_{tb}^R - a_{ud}^L a_{tb}^L}{a_{ud}^L a_{tb}^L + a_{ud}^R a_{tb}^R}\sigma_{W'_R}$$
$$+ a_{ud}^L a_{tb}^L \frac{a_{ud}^L a_{tb}^L - a_{ud}^R a_{tb}^R}{a_{ud}^L a_{tb}^L + a_{ud}^R a_{tb}^R}\sigma_{W'_L} + 2\frac{a_{ud}^R a_{tb}^R a_{ud}^L a_{tb}^L}{a_{ud}^L a_{tb}^L + a_{ud}^R a_{tb}^R}\sigma_{W'_{LR}},$$

# m(tb) hadronic analyses 13 TeV




ATLAS

- Large R jet, top tagging
- 1tag, 2tag regions




CMS

- Large R jet, top tagging
- 2jets, 2tag region

# W'$_R$ – hadronic 13 TeV