

# Search for $t+b$ resonances in the leptonic final state with the CMS experiment

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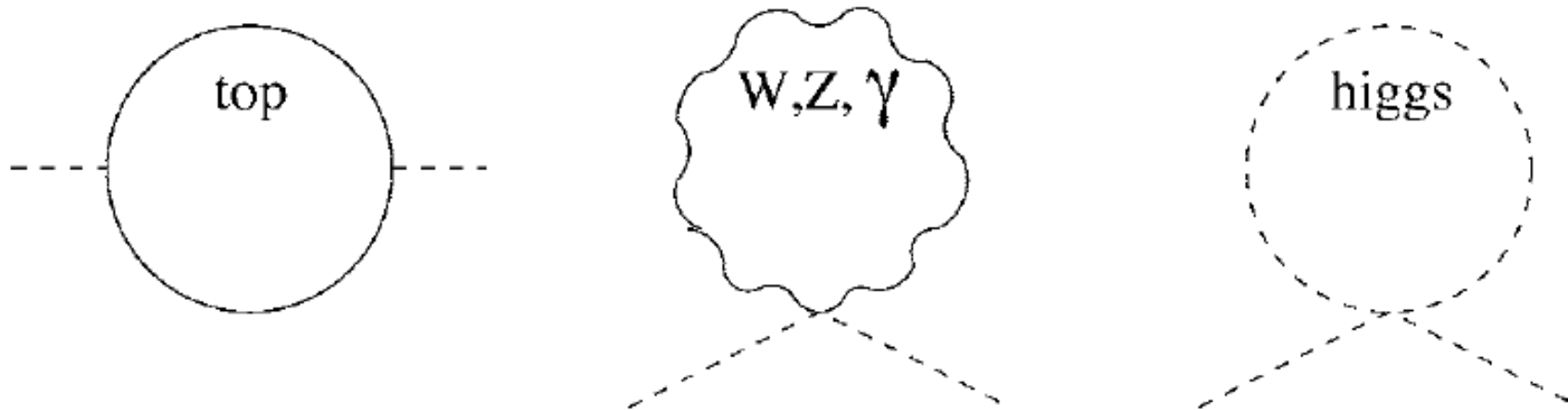
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*On behalf of the CMS collaboration*



- Motivation
- Method
- Previous results
- Data analysis
  - Event selection
  - Mass reconstruction
  - Systematic Uncertainties
- Mass limits for generalized coupling strengths
- Cross section limits for right-handed  $W'$ 
  - BDT analysis
- Conclusion / Outlook

- The CMS and ATLAS collaborations have observed a new boson with mass  $\sim 125$  GeV
- Fundamental scalar particles such as the Standard Model Higgs receive divergent corrections to their mass from other SM particles:



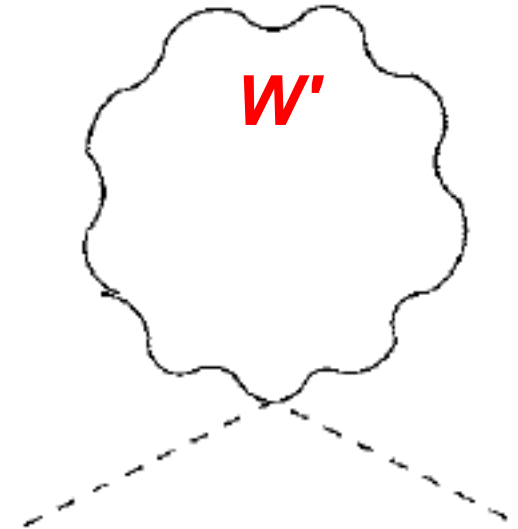
- Restricting fine tuning to the 10% level requires new physics which cuts off these divergent contributions [1]:

$$\Lambda_{top} \lesssim 2 \text{ TeV}$$

$$\Lambda_{gauge} \lesssim 5 \text{ TeV}$$

$$\Lambda_{Higgs} \lesssim 10 \text{ TeV}$$

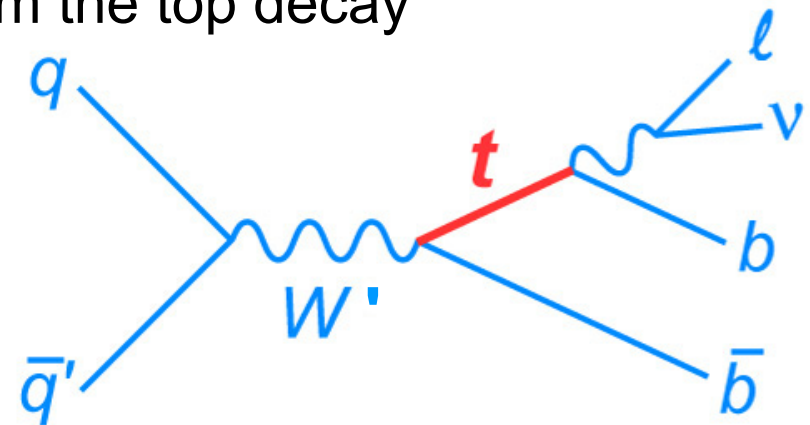
- Many new physics models which explain the light Higgs mass introduce new particles which cancel the divergences of the top, gauge, and self-coupling loops
- Our search focuses on a heavy new charged gauge boson, referred to as a  $W'$ , which is predicted by many theories, for example:
  - Little Higgs [1]
  - Extra Dimensions [2,3]
  - Extended Technicolor [4]
  - Left-Right Symmetry [5]
- We perform a model independent search for a  $W'$  boson which decays to a top+bottom quark pair



- The most general, lowest-order Lagrangian which describes the  $W'$  coupling to fermions can be written as [6]: *Z. Sullivan, Phys. Rev. D 66 (2002) 075011*

$$\mathcal{L} = \frac{V_{f_i f_j}}{2\sqrt{2}} g_w \bar{f}_i \gamma_\mu \left( a_{f_i f_j}^R (1 + \gamma^5) + a_{f_i f_j}^L (1 - \gamma^5) \right)^\mu f_j + \text{H.c.}$$

- Both left- and right-handed couplings are allowed, and if the left-handed coupling is non-zero, the  $W'$  will interfere with the SM  $W$
- We focus on the top+bottom quark decay mode, with a leptonic (electron/muon) decay of the  $W$  boson from the top decay
  - Complimentary to leptonic channel
  - Small QCD background compared to light quark decays
  - Extremely important if leptonic channel is suppressed, or coupling to third generation is enhanced [7]

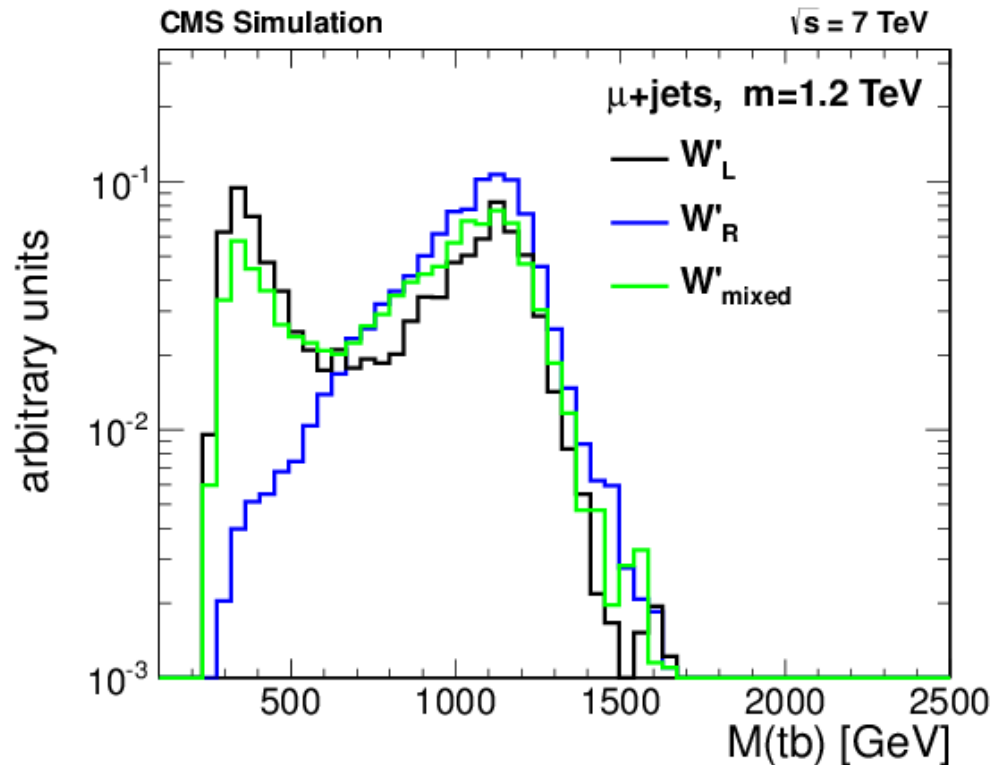


• The full effect of interference can be taken into account by simulating three different signal samples [8]:

- “SM+W’<sub>L</sub>” i.e.  $a_{ud}^L = a_{cs}^L = a_{tb}^L = 1, a_{ud}^R = a_{cs}^R = a_{tb}^R = 0$
- “W’<sub>R</sub>” i.e right-handed W’ with  $a_{ud}^L = a_{cs}^L = a_{tb}^L = 0, a_{ud}^R = a_{cs}^R = a_{tb}^R = 1$
- “SM+W’<sub>mixed</sub>” i.e.  $a_{ud}^L = a_{cs}^L = a_{tb}^L = 1, a_{ud}^R = a_{cs}^R = a_{tb}^R = 1$

• We search for a W’ with an arbitrary combination of left- and right-handed couplings

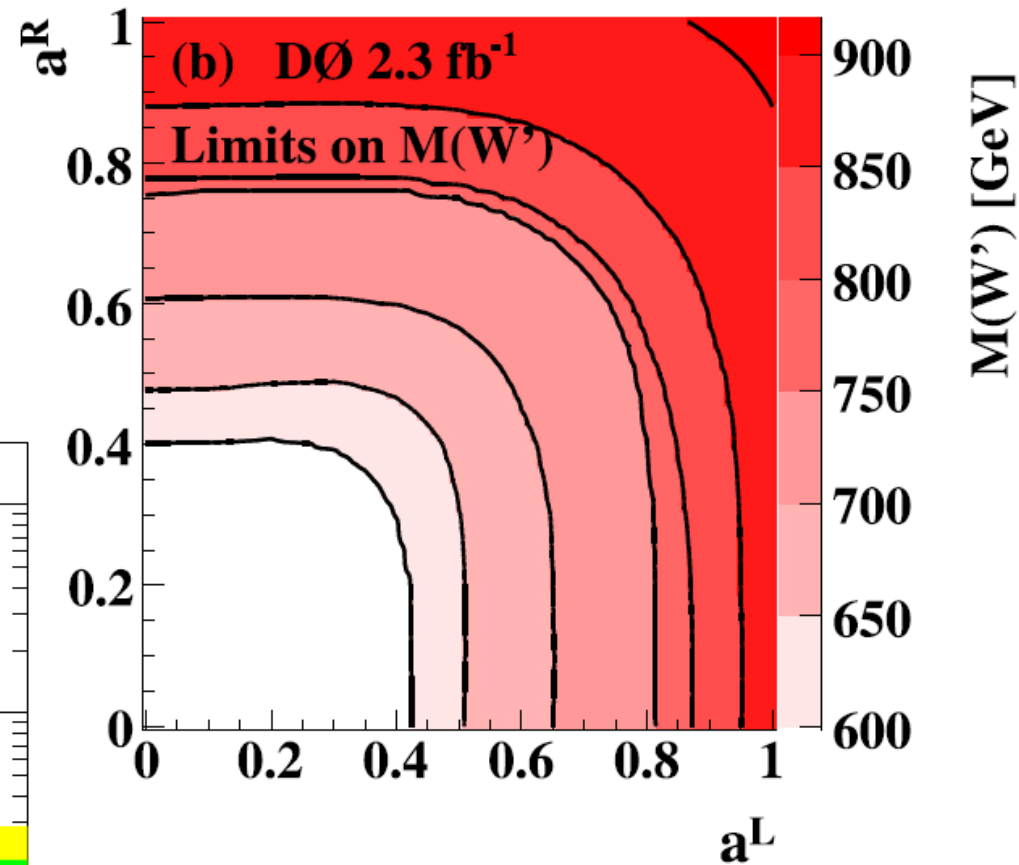
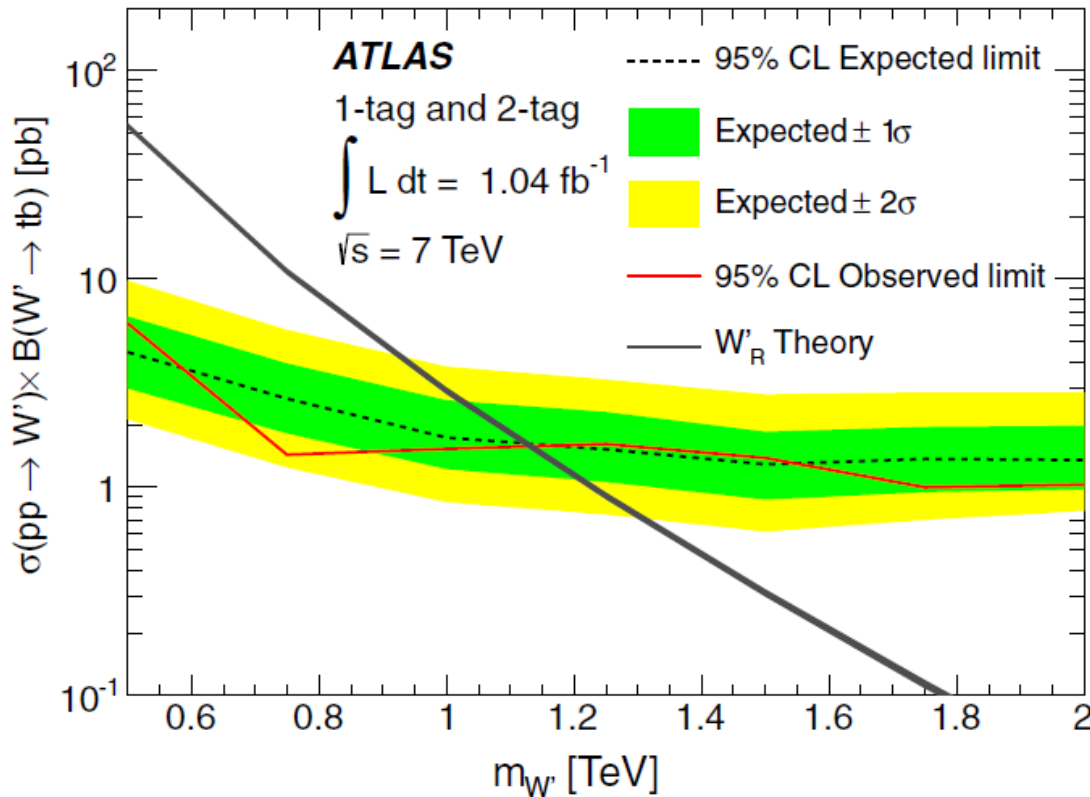
- Set limits on the mass for a given combination of couplings
- Also set limits on the cross section for a W’ with only right-handed couplings



# Previous Results (Other Experiments)



- Previous results have been presented by the D0 collaboration [9] including the effect of interference, and a mass limit of 890 GeV for right-handed  $W'$



- Search by ATLAS with 1.04 fb<sup>-1</sup> set a limit of 1.13 TeV for a right-handed  $W'$  [10]



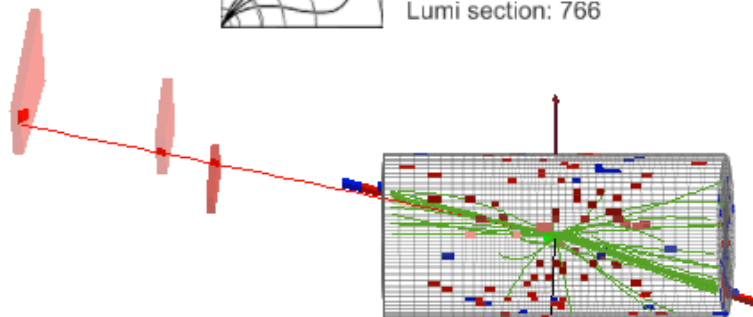
Search has been performed using 5.0 fb-1 of 7 TeV data

[11] **CMS Collaboration, Phys. Lett. B (2013) 718 (EXO-12-001)**

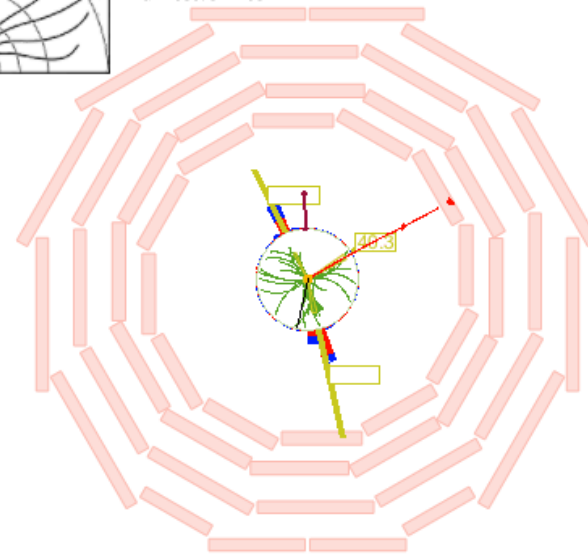
- 1 tight electron (muon) with  $P_t > 35(32)$  GeV, and  $|\eta| < 2.5(2.1)$
- 2 jets with  $P_t > 100$  GeV and  $> 40$  GeV
  - At least one of the jets is “tagged” as a b-jet
- Missing transverse energy  $> 20(35)$  GeV
- Same event selection is applied to samples of simulated events to estimate the backgrounds
  - SM  $V$ +jets
  - SM top pair production+single top
- Corrections derived using control regions in data are applied to the MC to account for different reconstruction and identification efficiencies
  - The fraction of  $W$ +heavy flavor jets
  - Shape of  $M(tb)$  in data vs.  $W$ +jets MC



CMS Experiment at LHC, CERN  
Data recorded: Mon Sep 19 02:53:21 2011 CDT  
Run/Event: 176702 / 1256852370  
Lumi section: 766



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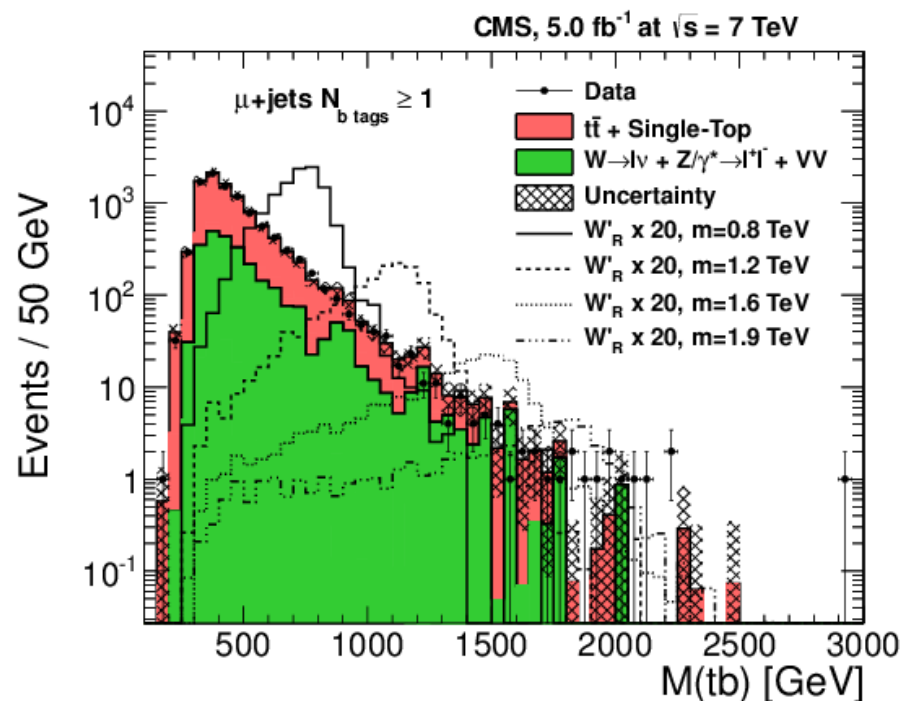
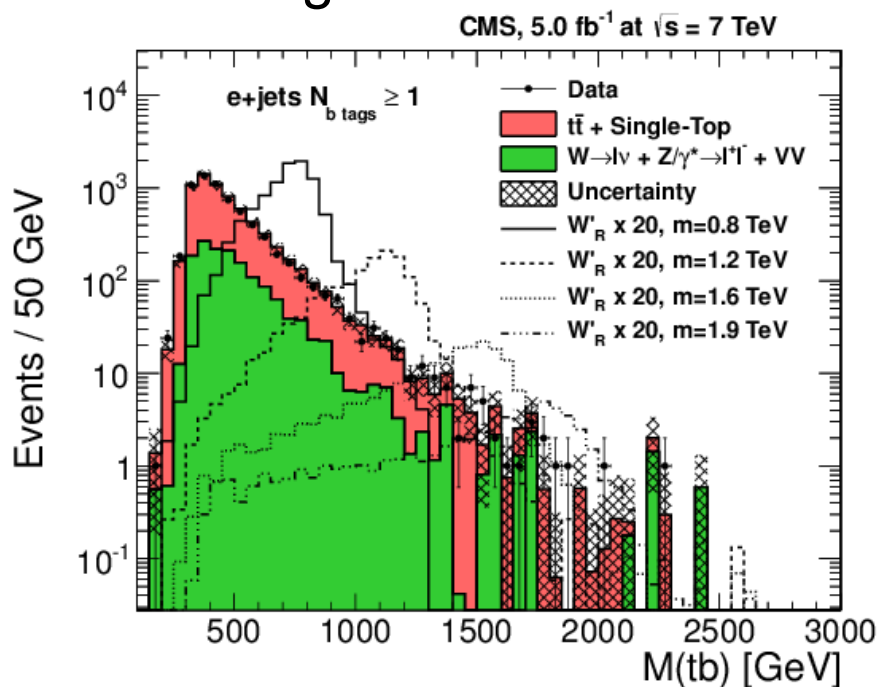


# Mass Reconstruction



- The neutrino z momentum is determined by using the W-mass constraint
- W candidates are combined with the “best” jet in the event, which gives the closest reconstructed top mass
- M(tb) found by combining top candidate with the highest pT remaining jet
- For the final generalized couplings analysis, additional cuts are made to further reduce the background and enhance the signal:

**$130 < m(\text{top}) < 210 \text{ GeV}$**   
 **$pt(\text{top}) > 75 \text{ GeV}$**   
 **$pt(j1, j2) > 100 \text{ GeV}$**



- **Normalization**

- Luminosity (2.2%)
- Trigger (3%) and ID (3%) efficiencies
- Top pair cross section (15%)

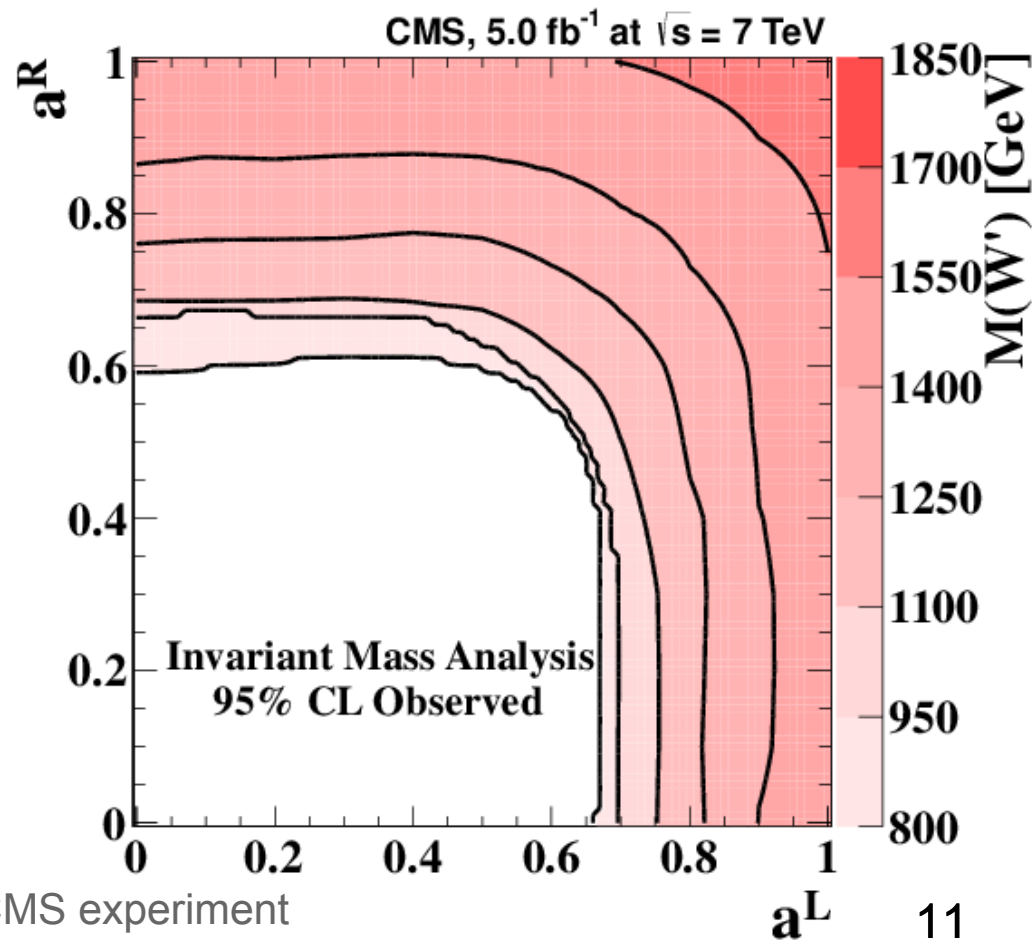
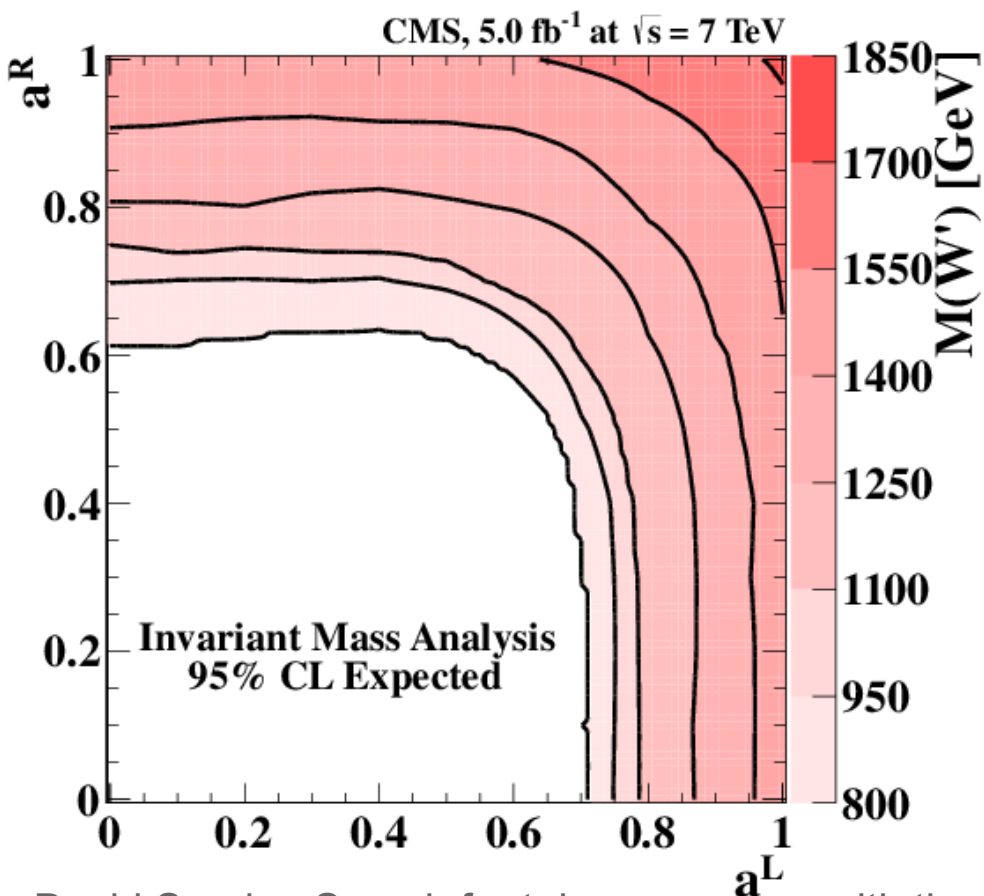
- **Shape**

- Jet Energy Scale
- Jet Energy Resolution
- B-tagging efficiency and mistag rate
- W+jets heavy flavor fraction
- Jet parton matching
- Factorization scale
- W+jets 0-tag Shape data vs simulation

Shape systematic uncertainties are evaluated by raising or lower the corresponding parameter by  $1\sigma$  and repeating the analysis

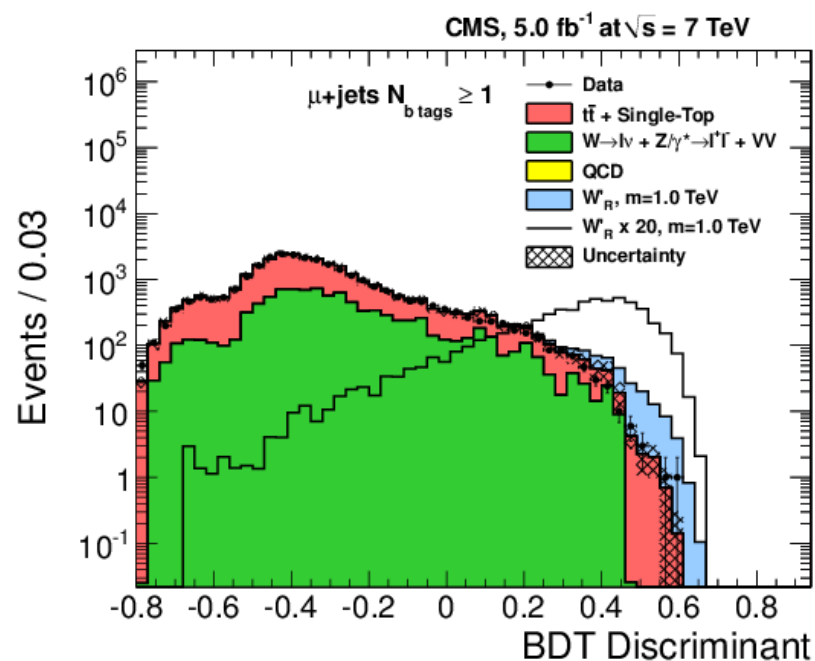
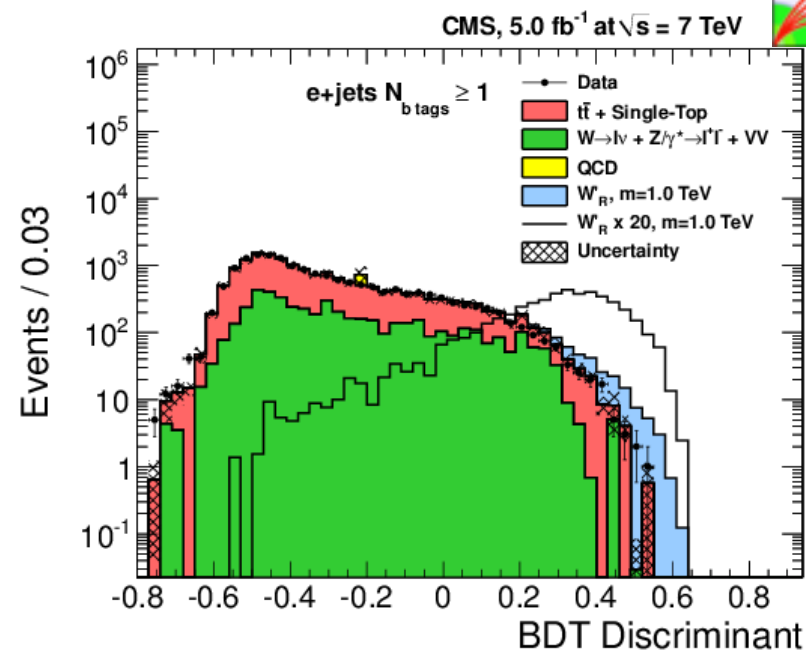
- The cross section for  $pp \rightarrow W/W' \rightarrow tb$  with arbitrary left- and right-handed  $W'$  couplings can be written as:
- For each point determine the mass limit

$$\begin{aligned} \sigma &= \sigma_{SM} + a_{ud}^L a_{tb}^L (\sigma_L - \sigma_R - \sigma_{SM}) \\ &+ \left( (a_{ud}^L a_{tb}^L)^2 + (a_{ud}^R a_{tb}^R)^2 \right) (\sigma_R) \\ &+ \frac{1}{2} \left( (a_{ud}^L a_{tb}^R)^2 + (a_{ud}^R a_{tb}^L)^2 \right) (\sigma_{LR} - \sigma_L - \sigma_R) \end{aligned}$$

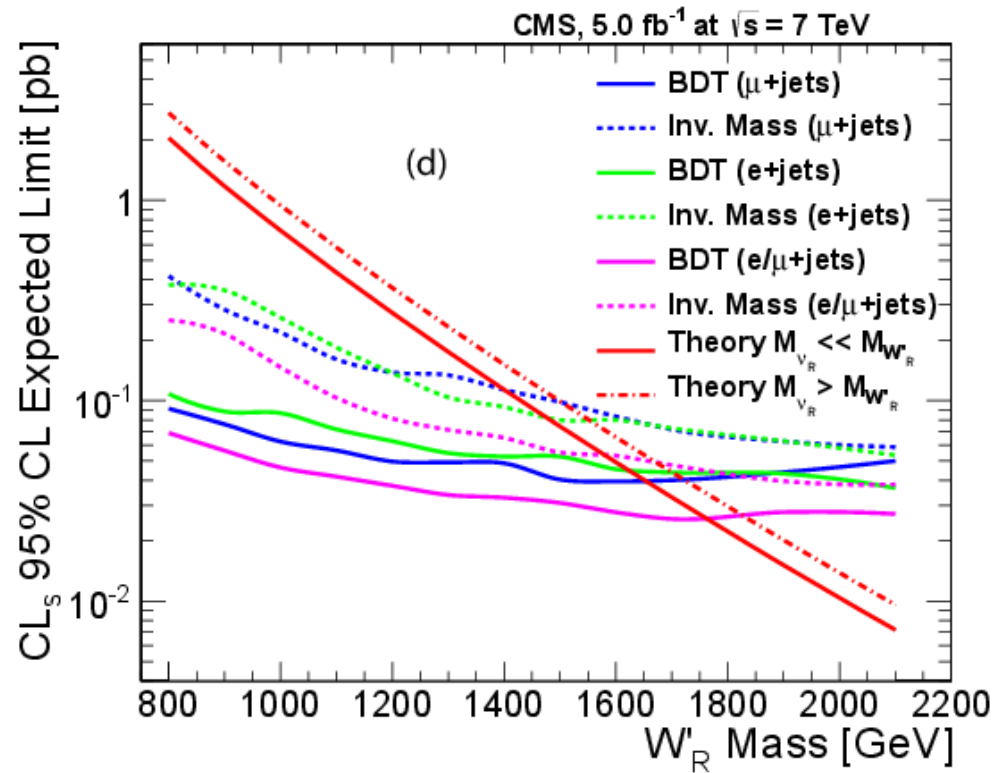
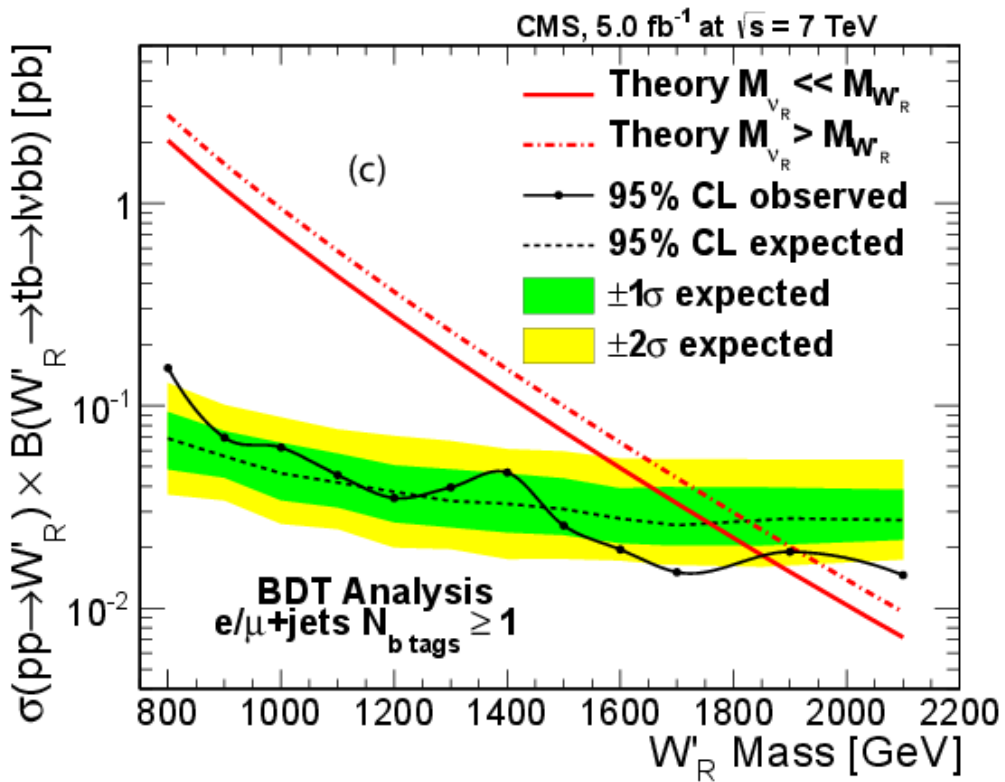


- For a  $W'$  with right-handed couplings, we perform a multivariate analysis with Boosted Decision Trees to obtain the best sensitivity
- Variables are chosen to optimize sensitivity and minimize correlation, and are checked in control regions dominated by  $W$ +jets (2 jets  $H_T < 300$  GeV) and top pairs ( $> 3$  jets)

Object kinematics	Event kinematics
$\eta(\text{jet1})$	Aplanarity(alljets)
$p_T(\text{jet1})$	Sphericity(alljets)
$\eta(\text{jet2})$	Centrality(alljets)
$p_T(\text{jet2})$	$M(\text{btag1}, \text{btag2}, W)$
$\eta(\text{jet3})$	$M(\text{jet1}, \text{jet2}, W)$
$p_T(\text{jet3})$	$M(\text{alljets})$
$\eta(\text{jet4})$	$M(\text{alljets}, W)$
$\eta(\text{lepton})$	$M(W)$
$p_T(\text{lightjet})$	$M(\text{alljets}, \text{lepton}, E_T^{\text{miss}})$
$p_T(\text{lepton})$	$M(\text{jet1}, \text{jet2})$
$\eta(\text{notbest1})$	$M_T(W)$
$p_T(\text{notbest1})$	$p_T(\text{jet1}, \text{jet2})$
$p_T(\text{notbest2})$	$p_T(\text{jet1}, \text{jet2}, W)$
$E_T^{\text{miss}}$	$p_z/H_T(\text{alljets})$
Top quark reconstruction	Angular correlations
$M(W, \text{btag1})$ ("btag1" top mass)	$\Delta\phi(\text{lepton}, \text{jet1})$
$M(W, \text{best1})$ ("best" top mass)	$\Delta\phi(\text{lepton}, \text{jet2})$
$M(W, \text{btag2})$ ("btag2" top mass)	$\Delta\phi(\text{jet1}, \text{jet2})$
$p_T(W, \text{btag1})$ ("btag1" top $p_T$ )	$\cos(\text{best}, \text{lepton})_{\text{besttop}}$
$p_T(W, \text{btag2})$ ("btag2" top $p_T$ )	$\cos(\text{light}, \text{lepton})_{\text{besttop}}$
	$\Delta R(\text{jet1}, \text{jet2})$



# Right-handed W' Results



Analysis	$(a^L, a^R) = (0, 1)$		$(a^L, a^R) = (1, 0)$		$(a^L, a^R) = (1, 1)$	
	$M_{V_R} > M_{W'}$	$M_{V_R} \ll M_{W'}$	$M_{V_R} \ll M_{W'}$	$M_{V_R} \ll M_{W'}$	-	$M_{V_R} \ll M_{W'}$
BDT	1.91 TeV	1.85 TeV	-	-	-	-
Invariant mass	-	-	1.51 TeV	-	1.51 TeV	1.64 TeV

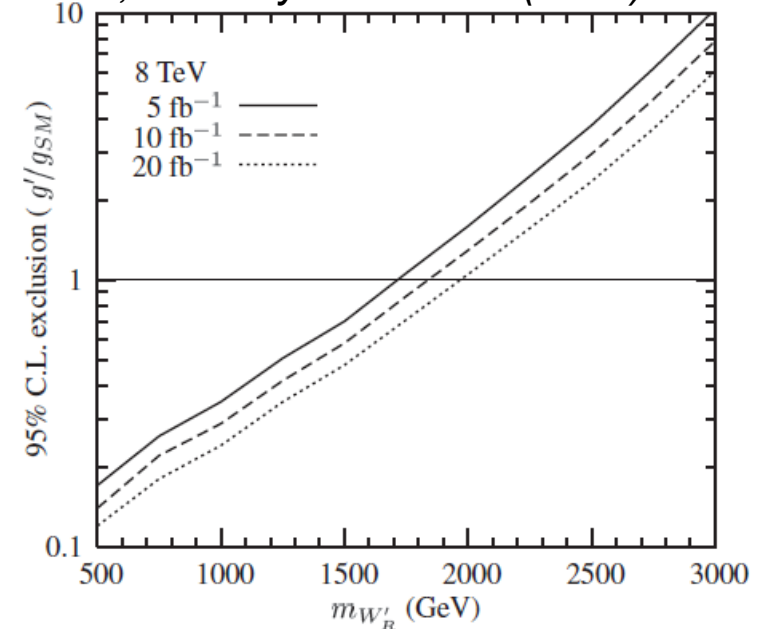
For W' bosons with right-handed couplings, **CMS excludes masses below 1.85 TeV**

***World's best limit in this decay channel!***



*D. Duffy and Z. Sullivan, 382 Phys.Rev. D86 (2012) 075018*

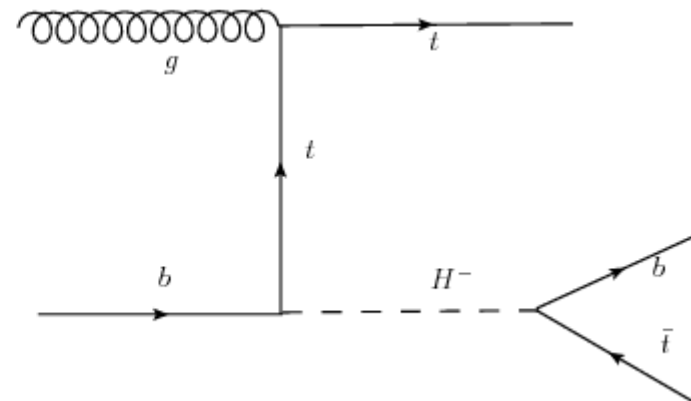
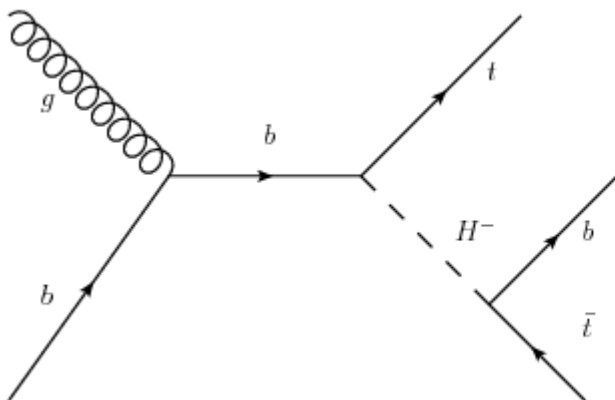
- CMS has searched for  $W'$  bosons decaying into top+bottom quark pairs
  - $W'$  boson with right-handed couplings is excluded below 1.85 TeV
  - Limits at 8 TeV should approach 2 TeV [13]
  - We have also set limits on the  $W'$  mass for an arbitrary combination of left- and right-handed coupling strengths
    - First analysis of its kind at the LHC



CMS will also start to explore other topologies with a t+b final state:

Charged Higgs particle  $H^+$  in SUSY theories can decay to t+b if it is heavier than the top quark

**Stay tuned!**





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