Search for heavy particles decaying to top and bottom quarks with the CMS Detector

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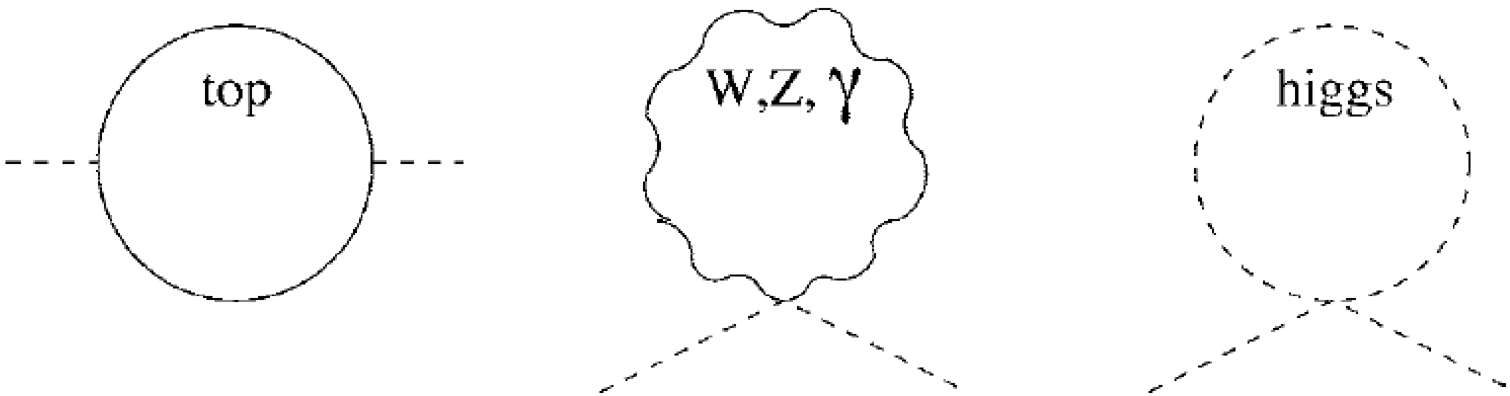
Beyond the Higgs

- The CMS and ATLAS collaborations have observed a new boson with mass ~125 GeV, consistent with the type predicted by Brout, Englert, Higgs, Guralnik, Hagen, Kibble, et. al. ***Nobel Prize in Physics, 2013***

- Fundamental scalar particles such as the Standard Model Higgs receive divergent corrections to their mass from other SM particles:



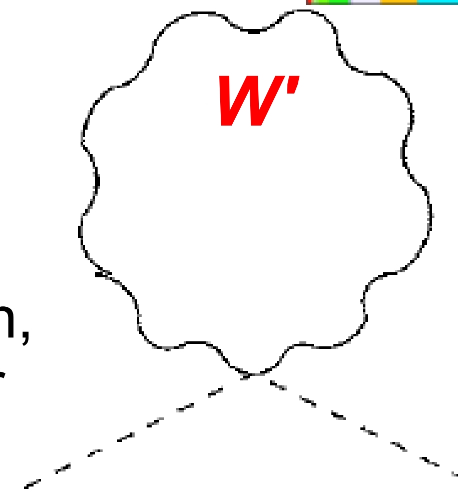
- Restricting fine tuning to the 10% level requires new physics which cuts off these divergent contributions [1]:

$$\Lambda_{top} \lesssim 2\ \mathrm{TeV} \qquad \Lambda_{gauge} \lesssim 5\ \mathrm{TeV} \qquad \Lambda_{Higgs} \lesssim 10\ \mathrm{TeV}$$

There is strong motivation for beyond the Standard Model new physics at energy scales accessible by the LHC!

Motivation for W' particles

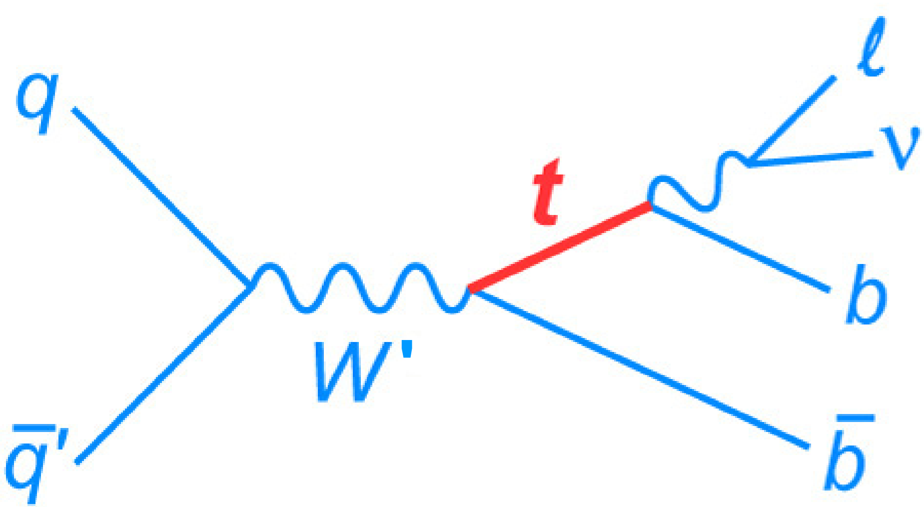
• Many new physics models which explain the light Higgs mass introduce new particles which cancel the divergences of the top, gauge, and self-coupling loops



• 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 search for a W' boson which decays to a top+bottom quark pair



- Complimentary to searches in other channels such as W' → ℓν, W' → WZ
- Small QCD background compared to light quark decays W' → qq'
  → The couplings to third generation fermions may also be enhanced [6]
- *Extremely important in models with a right-handed neutrino*

Method

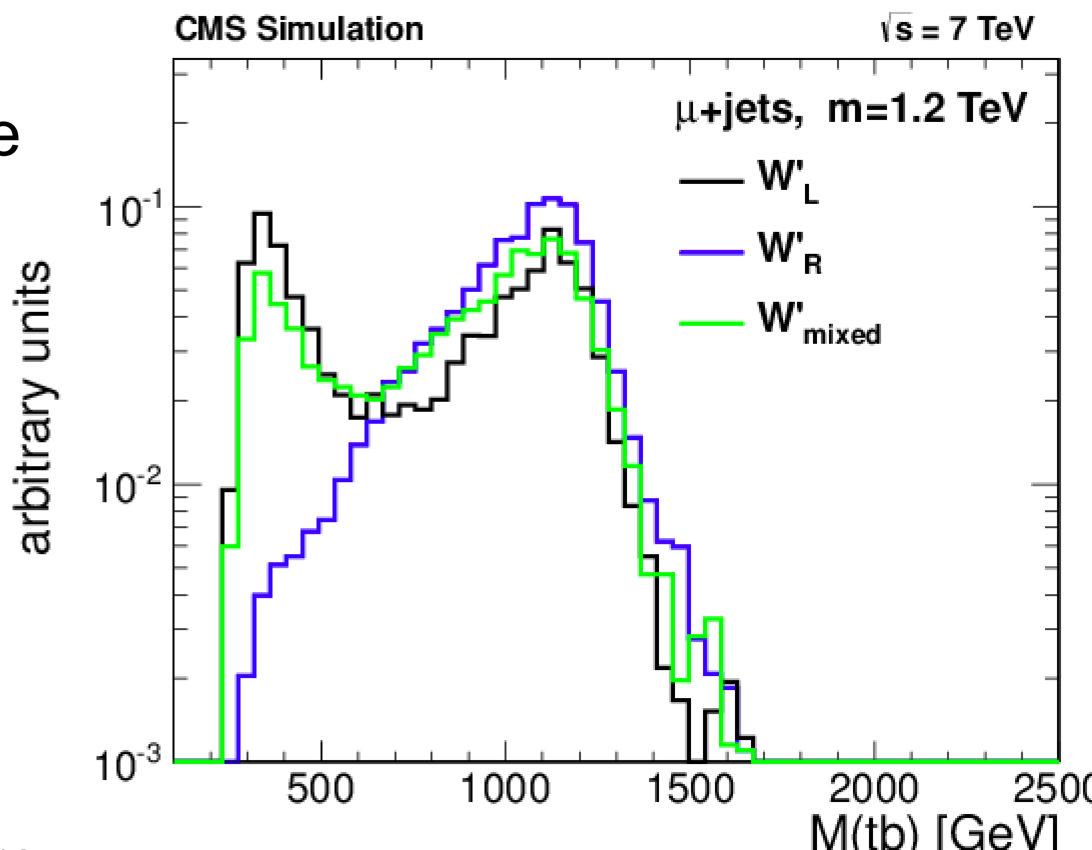
• The most general, lowest-order Lagrangian which describes the W' coupling to fermions can be written as [7]:

$$\mathcal{L} = \frac{V_{f_i f_j}}{2\sqrt{2}} g_w \overline{f}_i \gamma_\mu \left(a^R_{f_i f_j} (1+\gamma^5) + a^L_{f_i f_j} (1-\gamma^5) \right)^\mu f_j + \mathrm{H.c.}$$

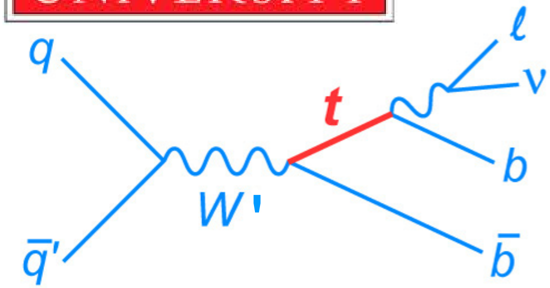
- Both left- and right-handed couplings are allowed, and if the left-handed coupling is non-zero, the W' will interfere with the SM W

• Interference effects significantly change the shape of the M(tb) distribution

•The full effect of interference can be taken into account by simulating three different signal samples with left-handed, right-handed, or left- and right-handed fermionic couplings [8]

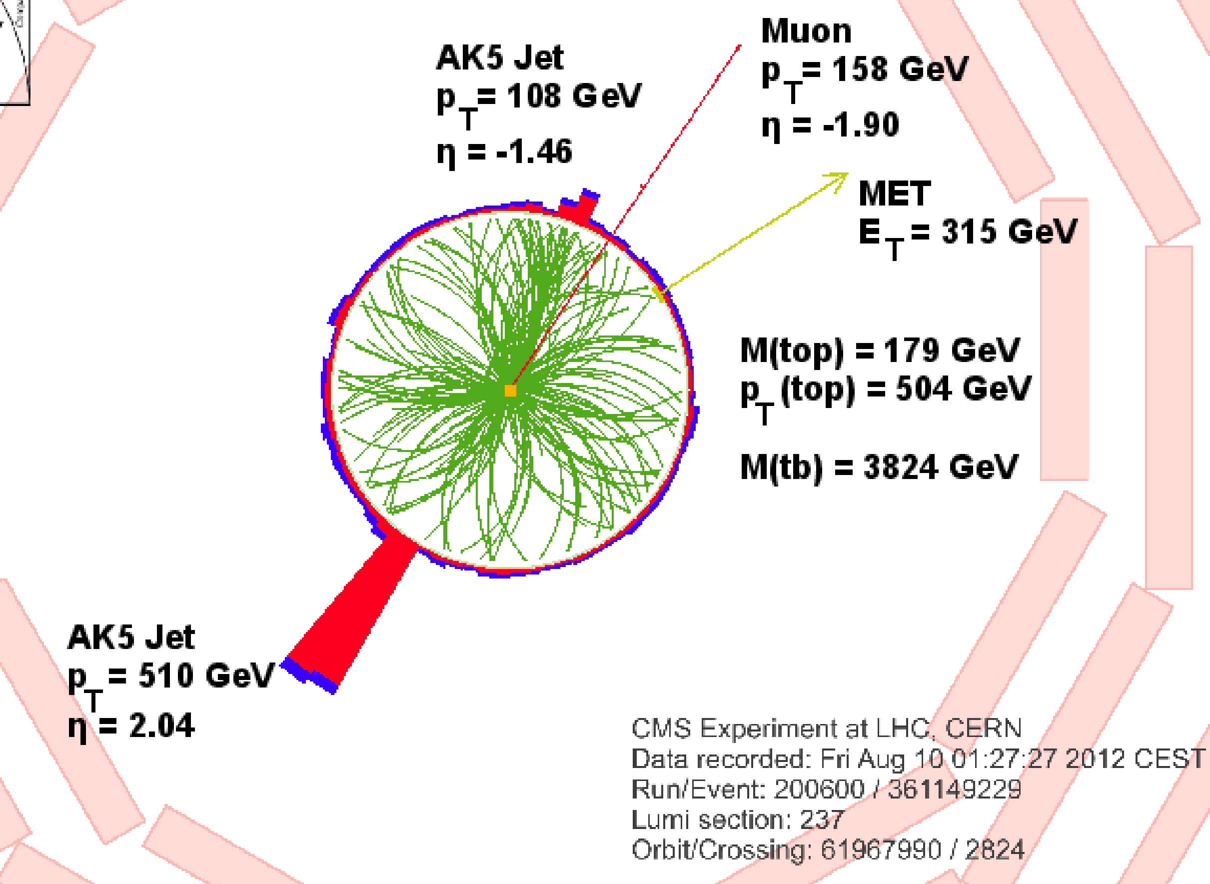


8 TeV Analysis: Event Selection



CMS-PAS-B2G-12-010

19.6 fb-1 @ 8 TeV



Lepton Selection:

- Exactly 1 electron(muon) with pT > 50 GeV, and |η| < 2.5(2.1)

Jet Selection:

- Require at least 2 jets with leading jet pT > 120 and 2nd leading jet pT > 40 GeV

MET Selection:

- Require MET > 20 GeV

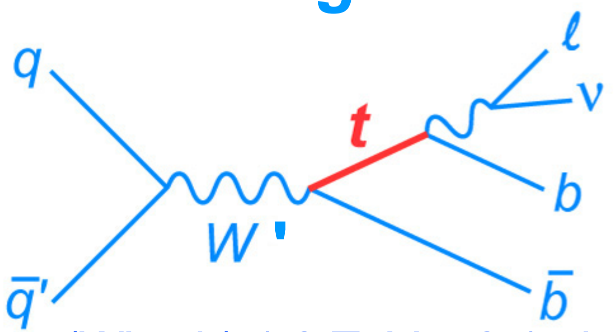
B-tagging Selection:

- Require at least one of the leading two jets to be b-tagged

The top quark 4-momentum can be reconstructed by combining the lepton and MET (constrained to the W boson mass), and a jet which gives a mass closest to the nominal top quark mass.
The W' 4-momentum is determined by combining the top quark candidate with the highest pt remaining jet

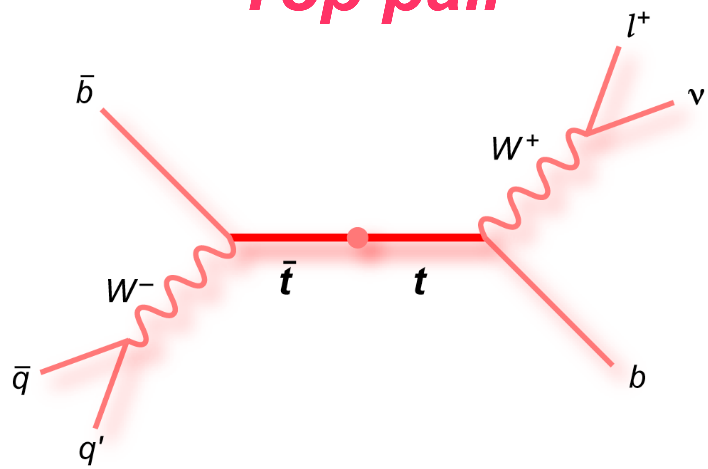
Standard Model Backgrounds

W' Signal

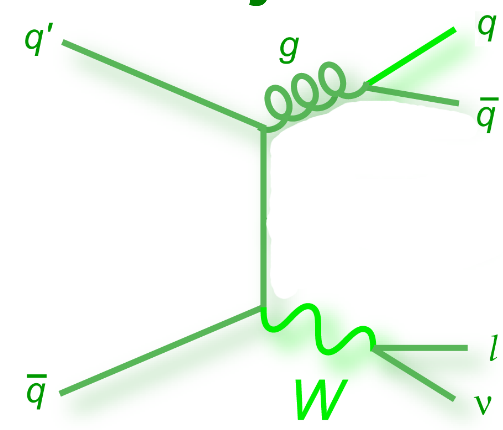


σ(W'→tb) 1.0 TeV ~ 3.1 pb
σ(W'→tb) 2.0 TeV ~ 0.062 pb
σ(W'→tb) 3.0 TeV ~ 0.003 pb

Top pair



W+jets

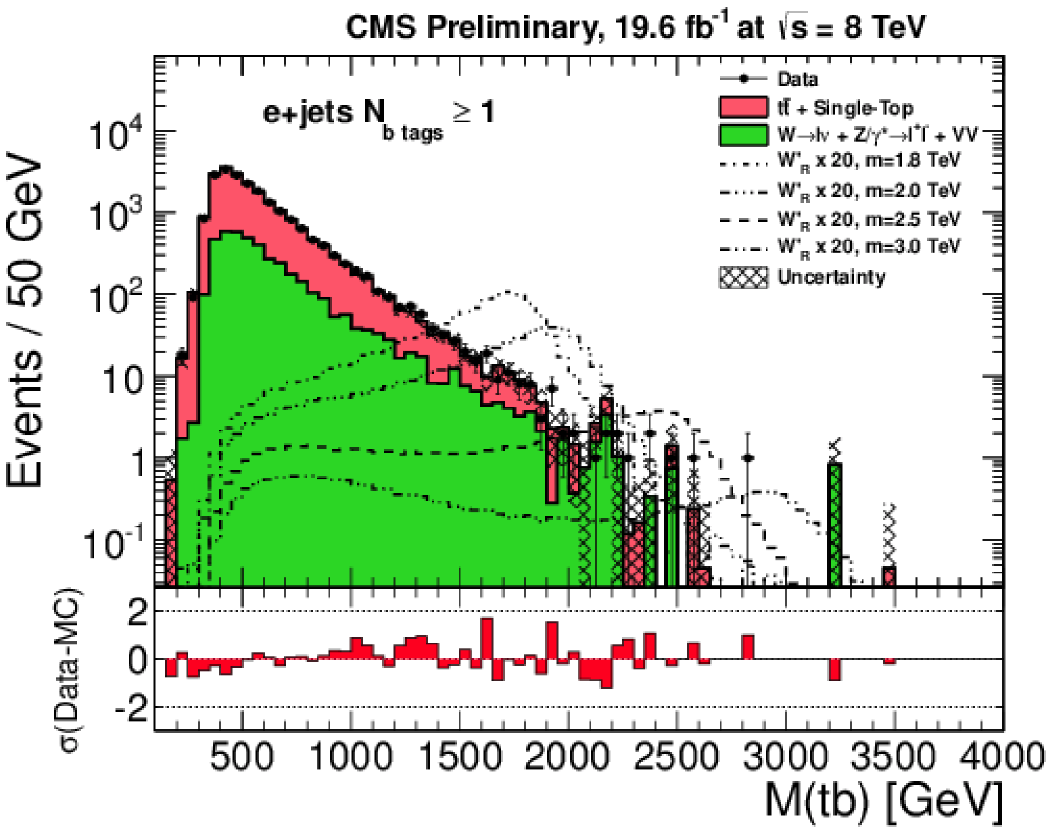


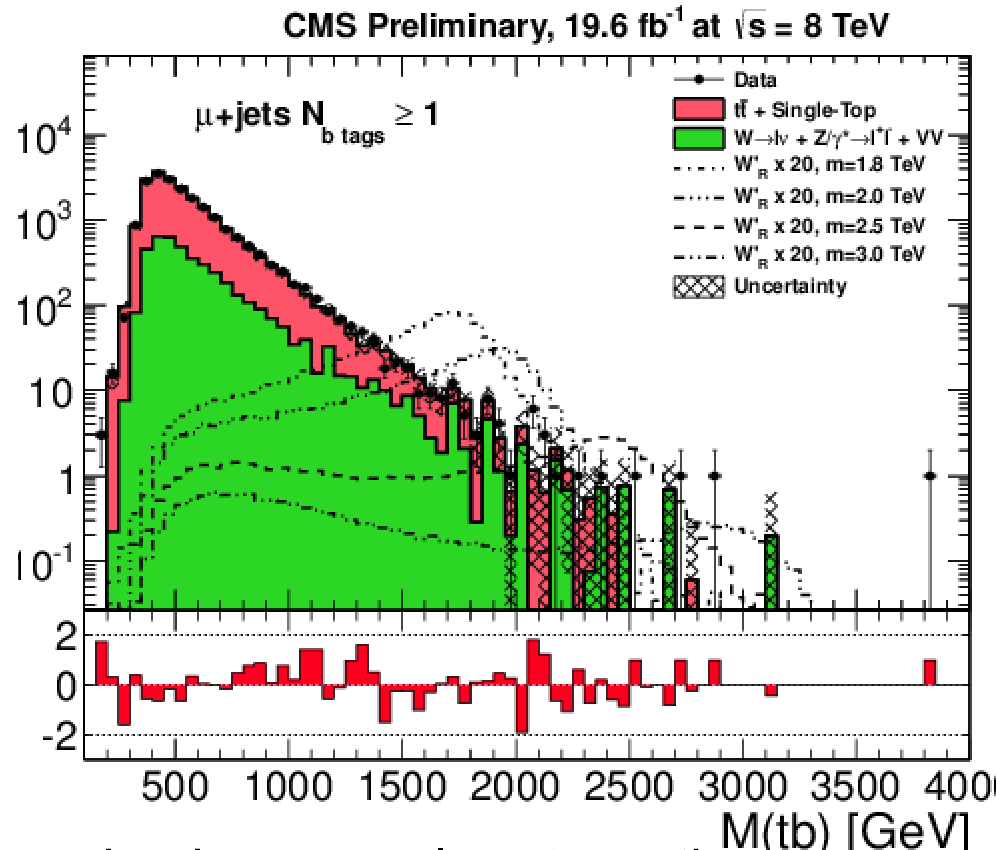
Top pair + single top: Normalized to ~NNLO cross section, shape taken from simulation and checked in control region

W+jets: Shape from MC and checked in a control region, normalization derived from the data

Process	σ (pb)
tt	234 (~NNLO)
Single top $t-$channel (tqb)	56.4 (~NNLO)
Single top $t-$channel ($\bar{t}q\bar{b}$)	30.7 (~NNLO)
Single top $tW-$channel	11.1 (~NNLO)
Single top $\bar{t}W-$channel	11.1 (~NNLO)
$W(\rightarrow)\ell\nu$+jets	37509.0 (NNLO)
$Z/\gamma^*(\rightarrow \ell\ell)$+jets ($M_{\ell\ell} > 50$)	3503.71 (NNLO)
WW	54.838 (NLO)
Single top $s-$channel ($t\bar{b}$)	3.79 (~NNLO)
Single top $s-$channel ($\bar{t}b$)	1.76 (~NNLO)

M(tb) after all selection cuts



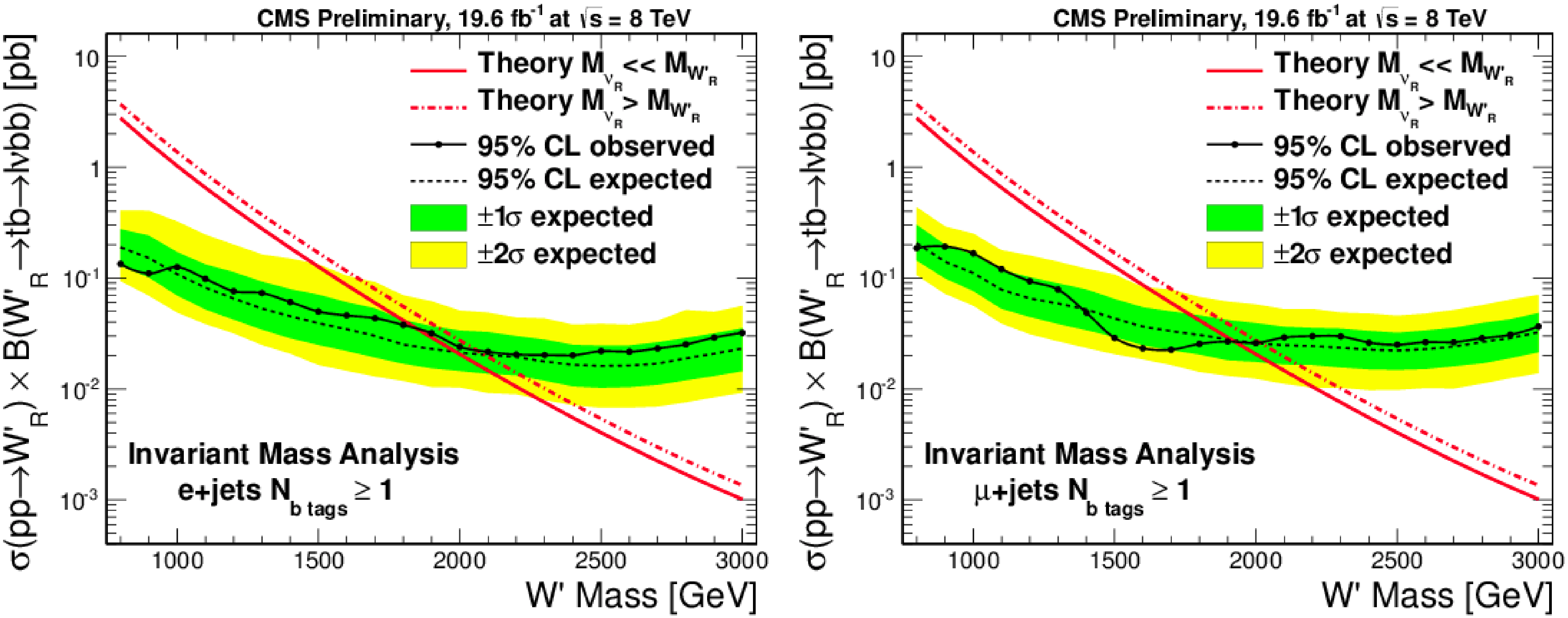


- To further increase the signal to background ratio, we apply cuts on three additional variables
- Optimized cut values to improve expected sensitivity

130 < m(top) < 210 GeV   pt(top) > 85 GeV   pt(j1,j2) > 140 GeV

The tb invariant mass spectrum is also well described by the background prediction → no evidence for resonant tb production

Cross section Limits

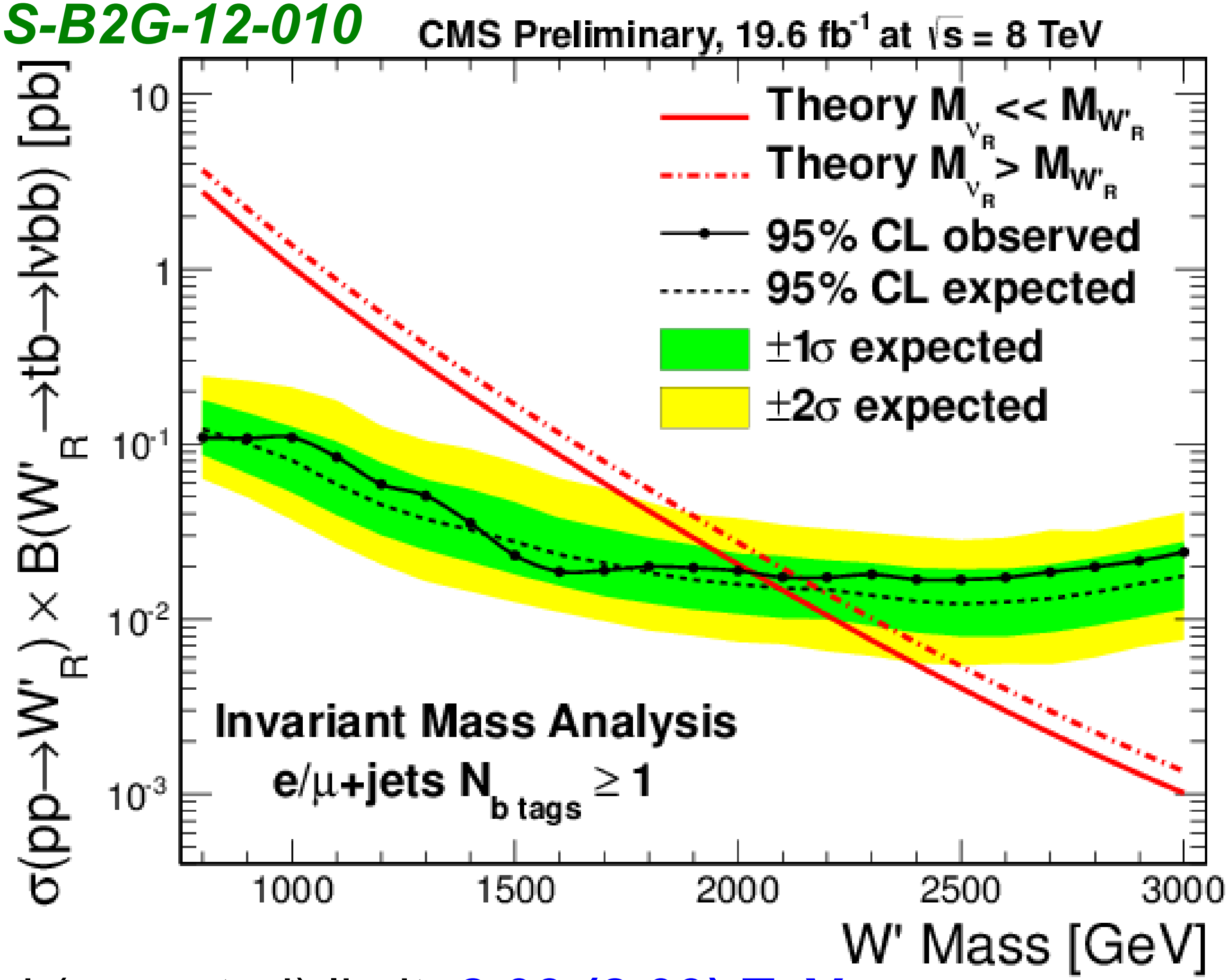


Resonant tb production with a cross section greater than the solid black line is disfavored at 95% confidence level

Theoretical cross section is shown in red, for two different right handed neutrino mass hypotheses

Combined Limit

CMS-PAS-B2G-12-010



Observed (expected) limit: **2.03 (2.09) TeV**

Most stringent limit to date in this channel!

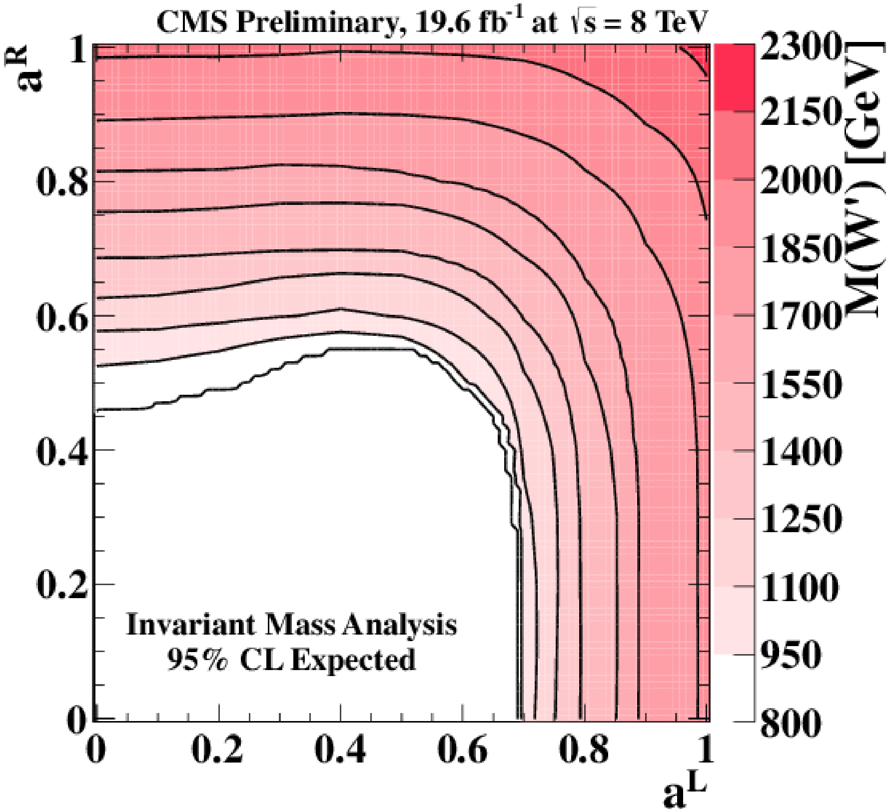
Aside: indirect theoretical limit from neutral kaon mass difference → $M_{W_R} \gtrsim 2.4\,\mathrm{TeV}$

Generalized Couplings Analysis

- The cross section for pp → W/W' → tb in the presence of a W' boson with left and right handed couplings can be written as:

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

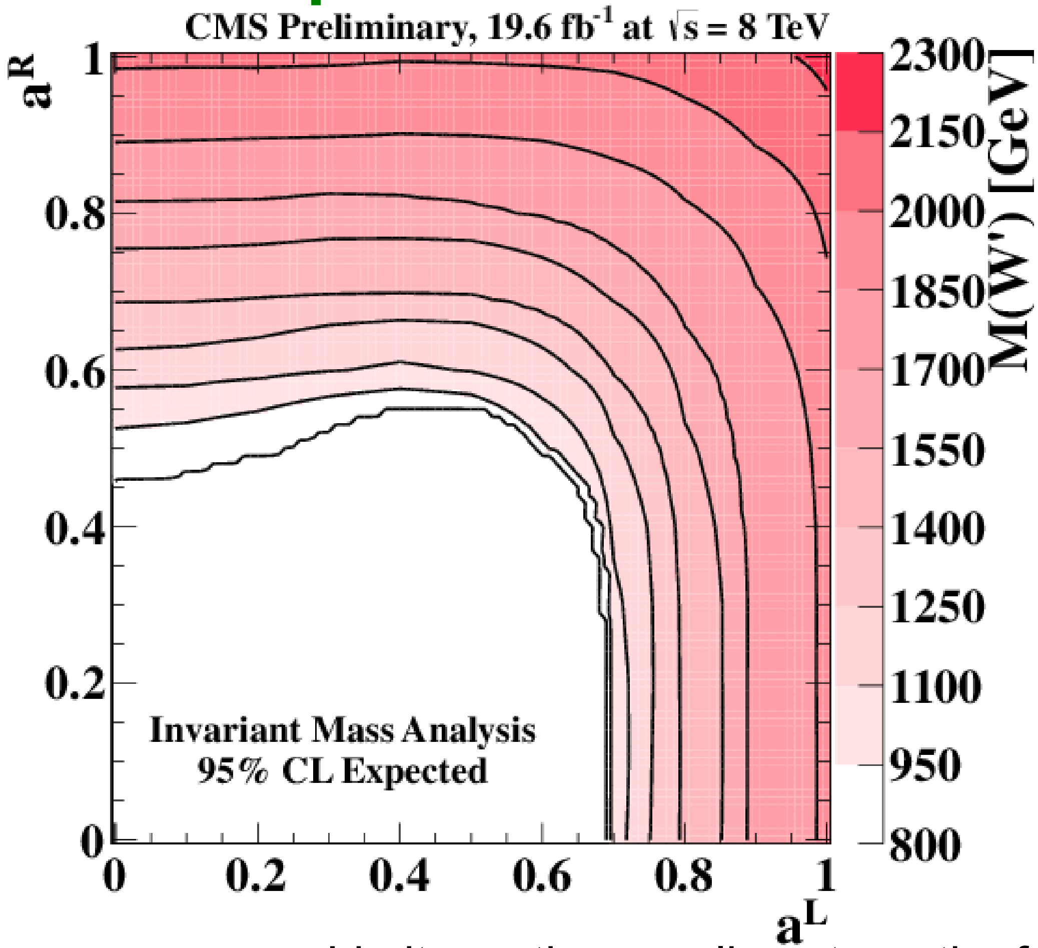
- Construct templates by weighting the signal distributions according this equation
- We scan the parameter space and for each set of couplings determine the mass a which the expected / observed limit equals the theoretical cross section and build contours



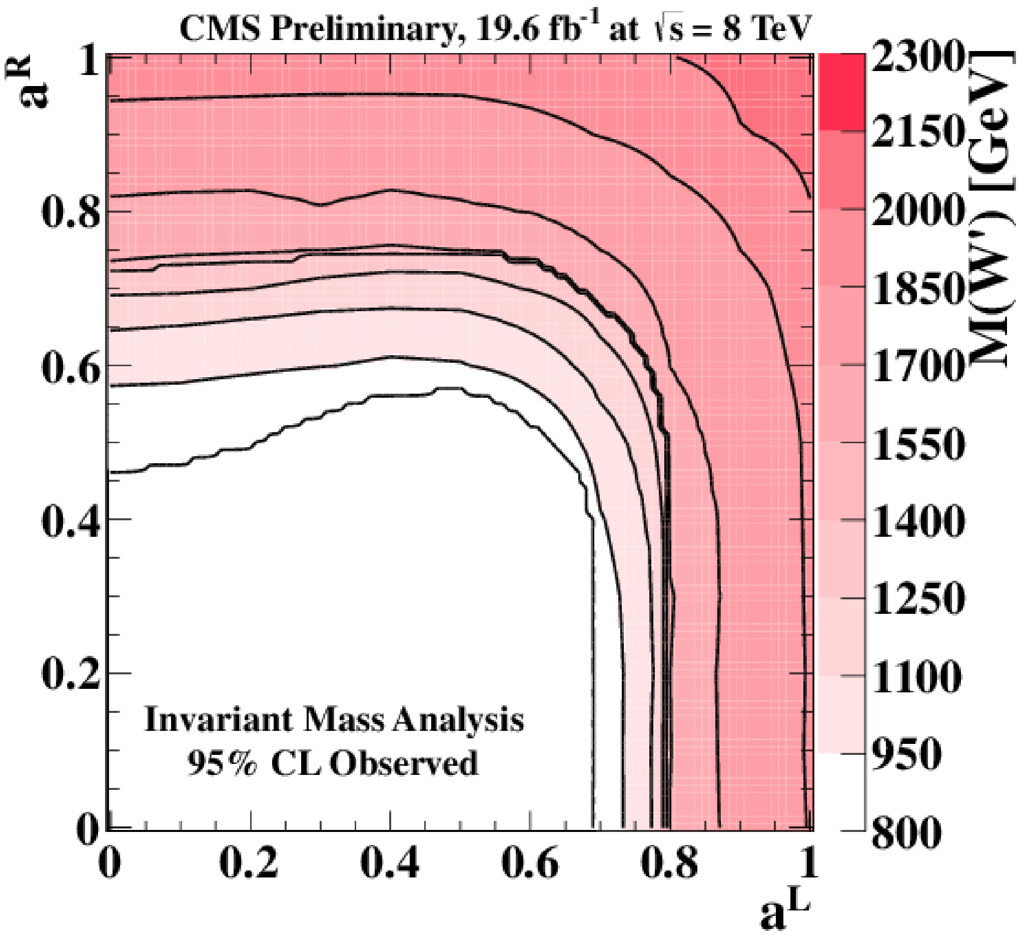
Expected Limits on left- and right-handed coupling strengths

Generalized Couplings Limits

Expected Limits



Observed Limits



Limits on the coupling strengths for different W' mass hypotheses
Black lines are iso-contours of the W' mass, 150 GeV intervals

Limits on coupling strengths can be used to constrain more general models of W' production

Conclusions

- We have performed a search for W' → tb analysis using the 8 TeV dataset
  - Several new physics models predict this type of resonance
  - For a W' with only right handed couplings, we exclude W' masses below 2.03 TeV, which is represents a significant improvement over the previous result and is the most stringent limit to date in this channel
    - Previous result: M(W') > 1.85 TeV
  - We have also set limits on the W' mass for an arbitrary combination of left- and right-handed coupling strengths
    → CMS is the only LHC experiment doing this analysis
  - Exciting times ahead when the LHC searches will start to be able to probe past the indirect theoretical bounds

References

[1] M. Schmaltz, D. Tucker-Smith, Ann. Rev. Nucl. Part. Sci. 55 (2005) 229
[2] T. Appelquist, H.-C. Cheng, B.A. Dobrescu, Phys. Rev. D 64 (2001) 035002
[3] H.C. Cheng et al, Phys. Rev. D64 (2001) 065007
[4] R.S. Chivukula, E.H. Simmons, J. Terning, Phys. Rev. D 53 (1996) 5258
[5] R.N. Mohapatra and J.C. Pati, Phys. Rev. D11 (1975) 566
[6] E. Malkawi, T. Tait, and C.P. Yuan, Phys. Lett. B385 (1996) 304
[7] Z. Sullivan, Phys. Rev. D 66 (2002) 075011
[8] E.E. Boos et. al, Phys. Atom. Nucl. 69 (2006) 1317

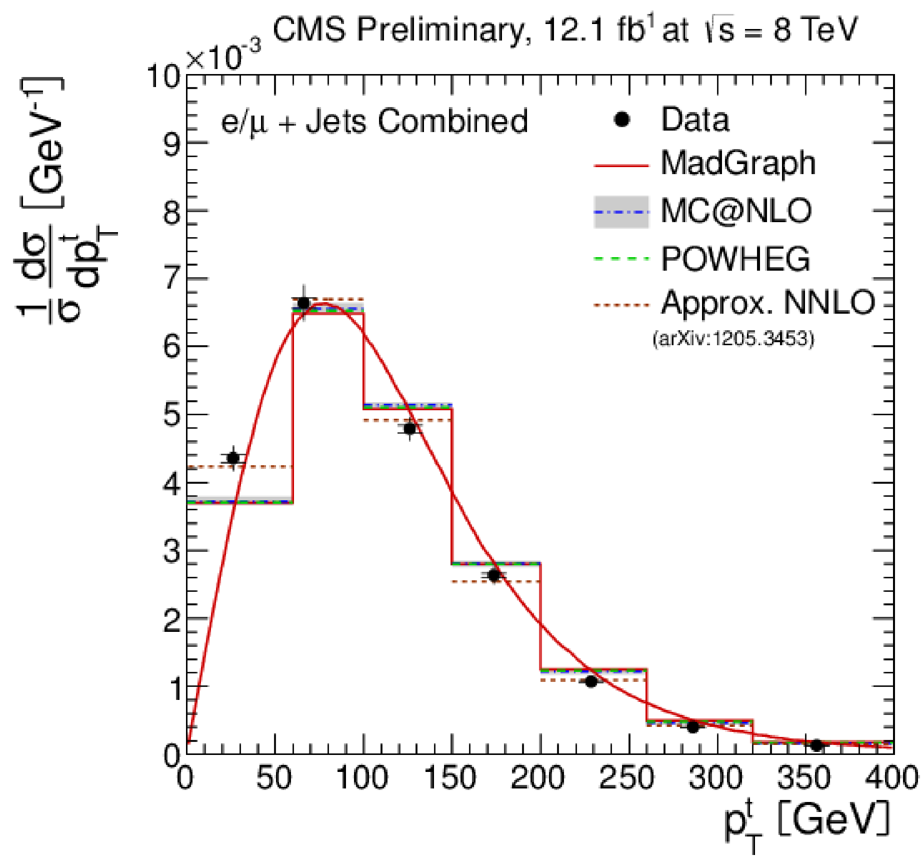
Backup Slides

[9] CMS Collaboration, CMS-PAS-TOP-12-027
[10] ATLAS Collaboration, ATLAS-CONF-2013-050
[11] CMS Collaboration, Phys. Lett. B (2013) 718
[12] A. Maiezza et al, Phys. Rev. D 82 (2010) 055022
[13] M. Nemevsek et al, Phys. Rev. D 83 (2011) 115014

Monte Carlo Validation

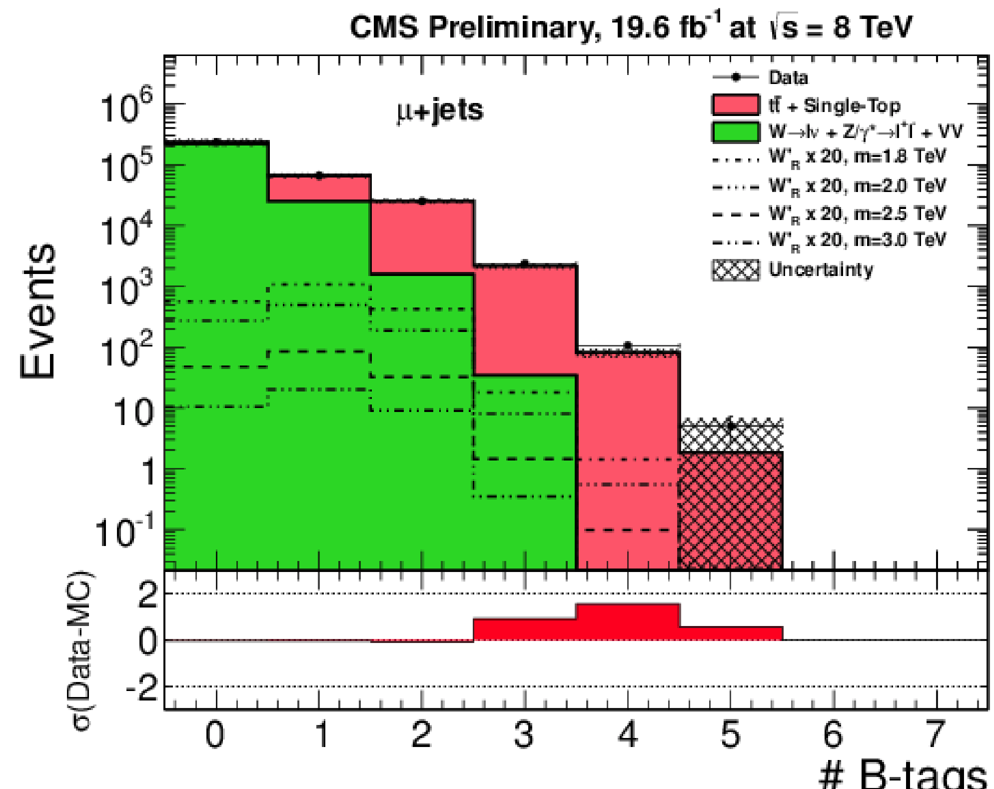
Top

• It has been observed that the pt(top) is not well described by the simulation [9]
• Therefore, we reweight the ttbar MC to match the top pt distribution observed in data



W+jets

• W+jets heavy flavor fractions derived from data using pre b-tag and 0 b-tag samples
•The W+jets shape in MC is also validated using the 0-tag sample from data after subtracting the other backgrounds



Uncertainties related to the determination of the background predictions from data are included in the limit setting procedure

Event Yields

Process	Number of Events					
	Electrons			Muons		
	b-tagged jets		Additional cuts	b-tagged jets		Additional cuts
	= 1	≥ 1		= 1	≥ 1	
Data	63050	72696	20238	62955	72820	20639
Signal:						
s-channel	176	269	86	197	299	96
$M(W'_R =)$ 1700 GeV	90	117	84	77	99	70
$M(W'_R =)$ 1900 GeV	41	52	37	35	44	31
$M(W'_R =)$ 2100 GeV	19	24	17	16	20	14
Background:						
$t\bar{t}$	36169	44575	14663	36989	45703	14923
t-channel	2124	2484	823	2287	2662	866
tW-channel	2571	2934	959	2659	3033	979
$W(\rightarrow \ell\nu)$+jets	19707	20263	3687	19438	20108	3717
$Z/\gamma^*(\rightarrow \ell\ell)$+jets	1492	1575	271	1505	1578	293
WW	206	216	50	220	226	49
Total Background	62269	72047	20452	63098	73310	20826
MC / Data	0.988	0.991	1.011	1.002	1.007	1.009

Observed number of events matches well with the background prediction

Limit Setting Procedure

- We perform a binned likelihood analysis to calculate the 95% confidence level upper limits on the W' production cross section
- Wide range of systematic uncertainties are incorporated into the limit setting procedure:

Systematic Uncertainties

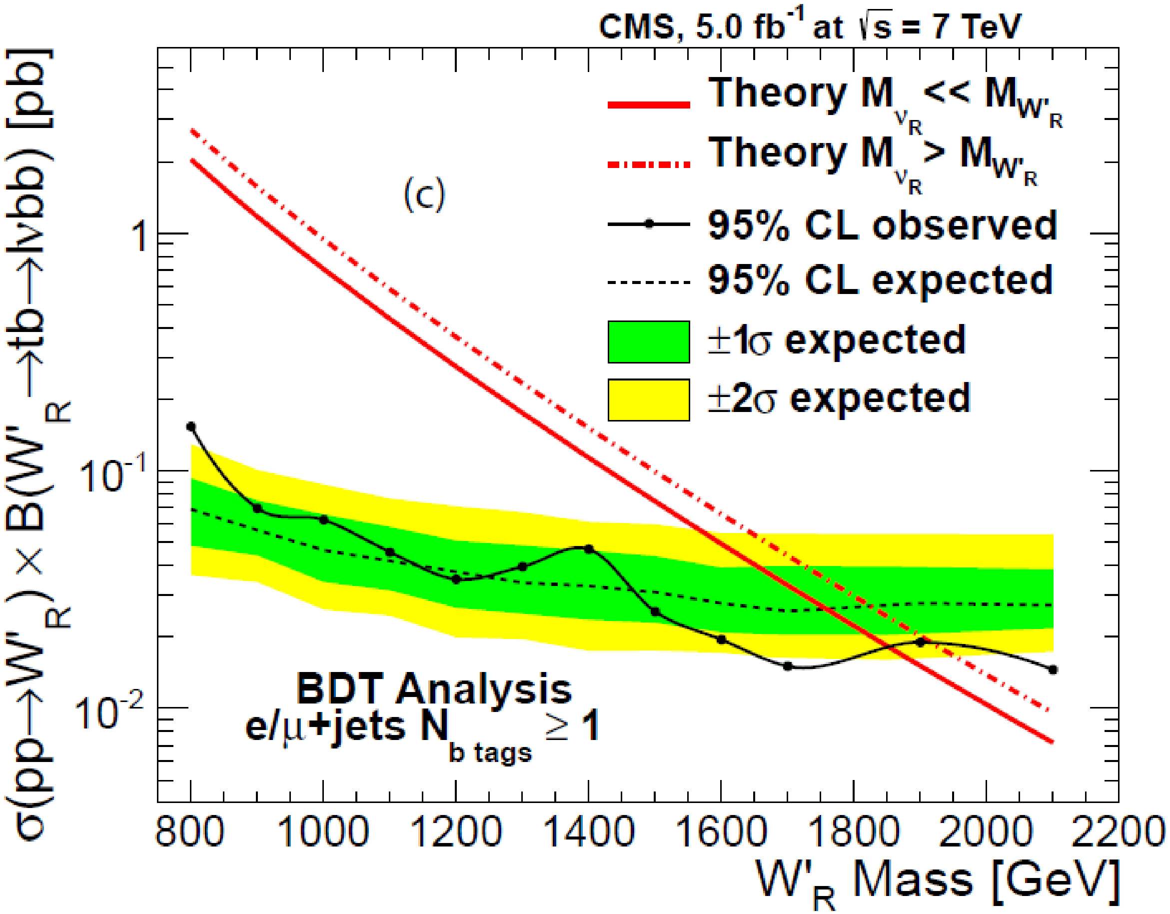
Dominant sources for the signal: Jet Energy Scale, B-tagging efficiency

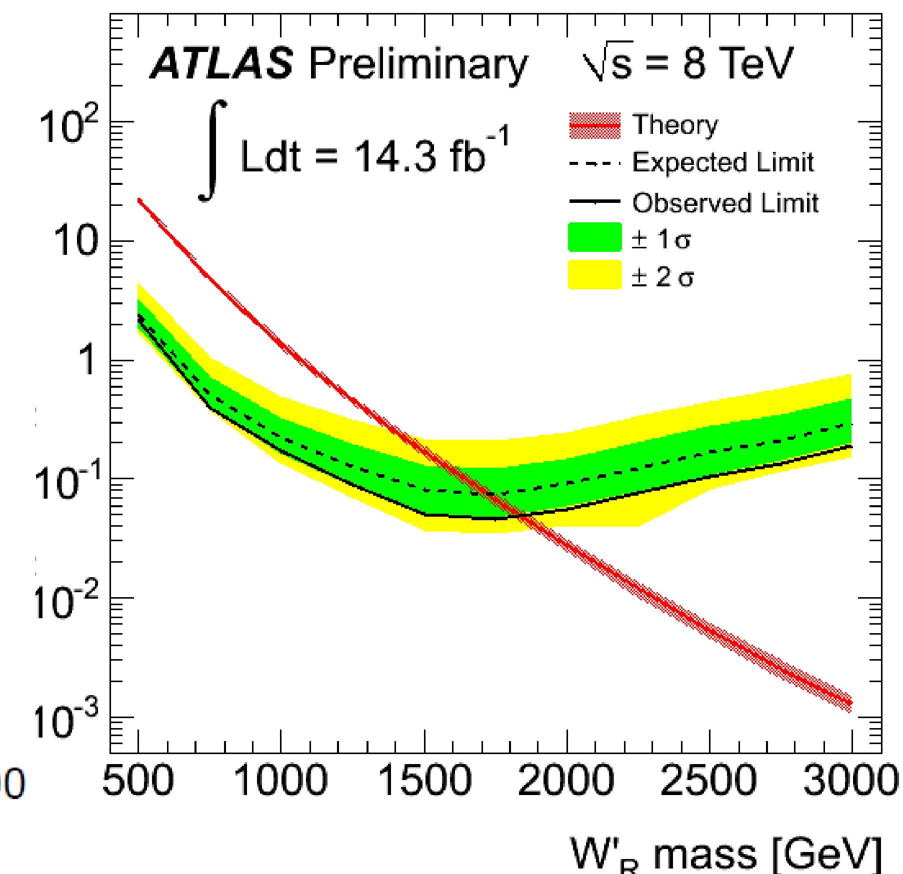
Dominant sources for the background: W+jets heavy flavor fraction, top pt reweighting

Source	Rate Uncertainty	Shape
Luminosity	4.4%	No
Trigger Efficiency	2%/1% (e/μ)	No
Lepton efficiencies	1%	No
Jet Energy Scale	$\pm 1\sigma(p_T, \eta)$	Yes
Jet Energy Resolution	$\pm 1\sigma(p_T, \eta)$	Yes
b-tagging (CSVM)	$\pm 1\sigma(p_T, \eta)$	Yes
c-tagging (CSVM)	$\pm 1\sigma(p_T, \eta)$	Yes
light quark mis-tagging (CSVM)	$\pm 1\sigma(p_T, \eta)$	Yes
matching and Q^2 scale	$\pm 1\sigma$	Yes
Pileup	$\pm 1\sigma$	Yes
W+ jets Heavy Flavor	$\pm 1\sigma$	Yes
W+jets Shape (data/MC diff using 0-btags)	$\pm 1\sigma$	Yes
Top p_T reweighting	$\pm 1\sigma$	Yes

Previous Results

- Search by ATLAS with 14.3 fb-1 at sqrt(s)=8 TeV set a limit of 1.84 TeV [10]
- Best published result comes from the CMS experiment at 7 TeV, excluding right-handed W' bosons with masses below 1.85 TeV [11]



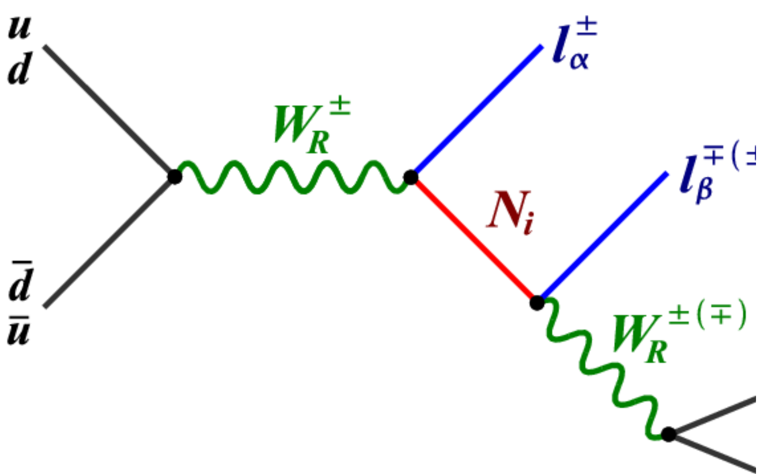


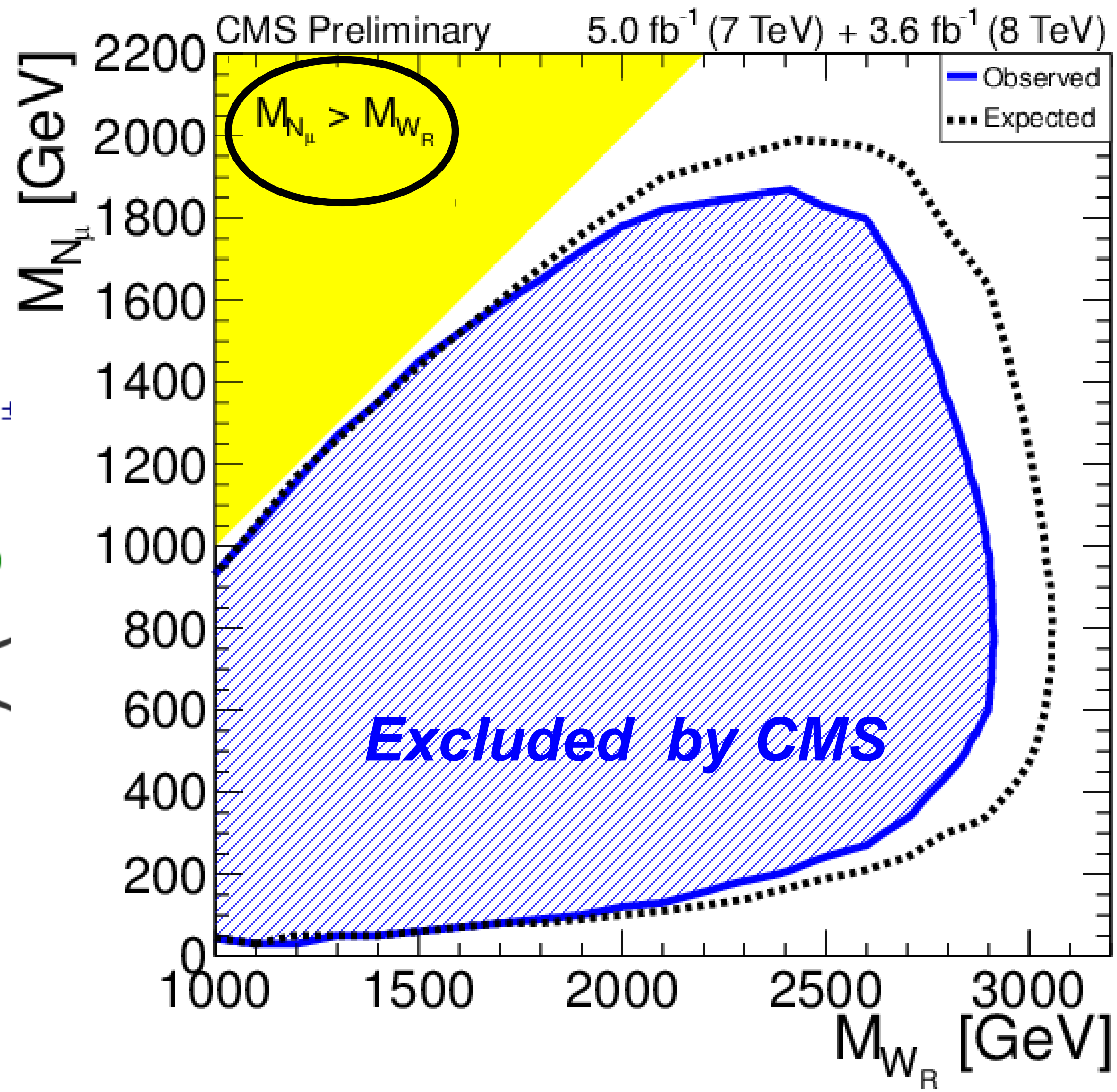
→ 8 TeV CMS exclusion limit (2.03 TeV) is the most stringent to date in this channel

Other Search Channels for right-handed W'

CMS EXO-12-017

Strongest constraints come from lepton number violating searches, but only when the right-handed neutrino mass is less the W' mass !





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Low Energy Constraints

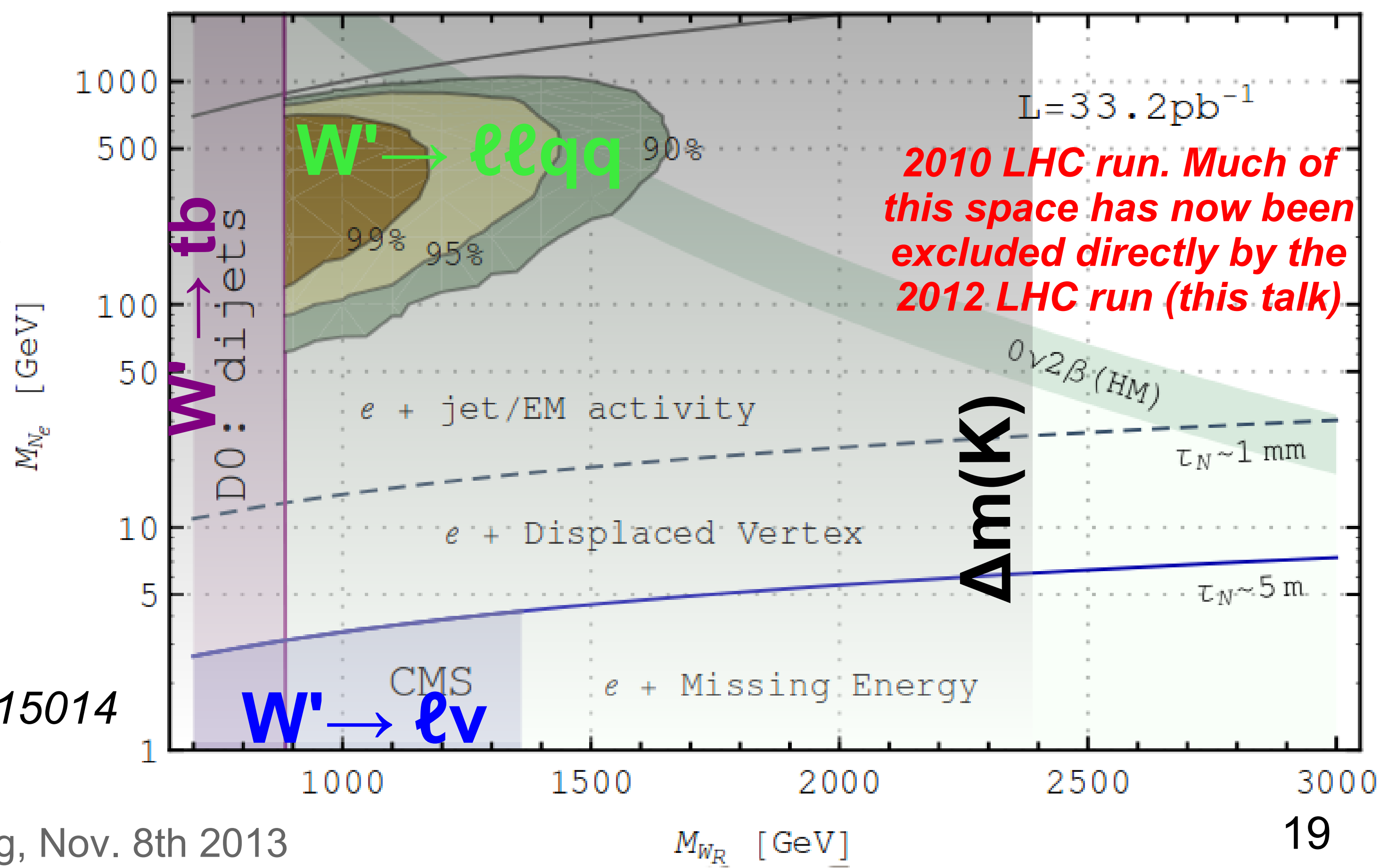
There are several low energy observables which would be modified by the presence of a right-handed W' boson [12,13]

In the minimal Left-Right model: *A. Maiezza et al, Phys. Rev. D 82 (2010) 055022*

By restricting the new physics contribution to the neutral kaon mass difference to be less than the measured difference → $M_{W_R} \gtrsim 2.4\,\mathrm{TeV}$

If neutrinoless double beta decay is observed, it would narrow greatly the allowed parameter space. Limits on lifetime can also set exclusions, along with LFV processes and cosmology, though these are more model dependent

M. Nemevsek et al, Phys. Rev. D 83 (2011) 115014



Updated Exclusions

S.P. Das et al, arxiv1206.0256