



# ATLAS (Non-SUSY) Searches Related to the Third Generation



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# Outline

## ATLAS Searches for New Quarks

- Status of a Fourth Generation of Quarks
- Chiral vs. Vector-Like Quarks (VLQs), New Quark Production at the LHC
- A Search for Single VLQs Coupling to the 1<sup>st</sup> Gen. [ATLAS-CONF-2012-137](#) [7 TeV, 4.6/fb]
- A Search for  $b'b'$  with Same-Sign Leptons [ATLAS-CONF-2012-130](#) [7 TeV, 4.7/fb]
- A Search for  $t't'$  with One Lepton and Jets [PLB 718 \(2013\), 1284](#) [7 TeV, 4.7/fb]

## ATLAS Searches for Heavy Resonances Decaying to Top Pairs

- Some Motivations for a  $t\bar{t}$  Resonance Signal
- A Search in the One Lepton Final State [ATLAS-CONF-2012-136](#) [7 TeV, 4.7/fb]
- A Search in the Fully Hadronic Final State [arXiv:1211.2202 \(acc. by JHEP\)](#)[7 TeV, 4.7/fb]

## Conclusions

# Searches For New Quarks

# Status of a Simple Fourth Generation Extension to the SM

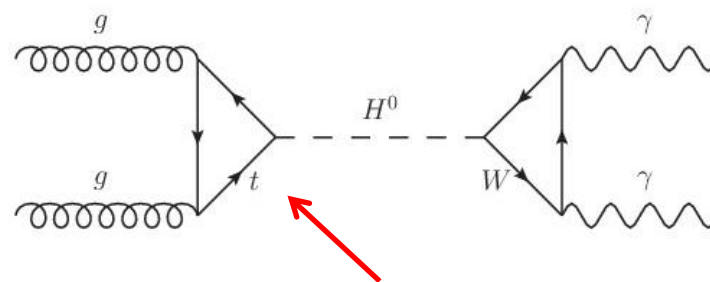
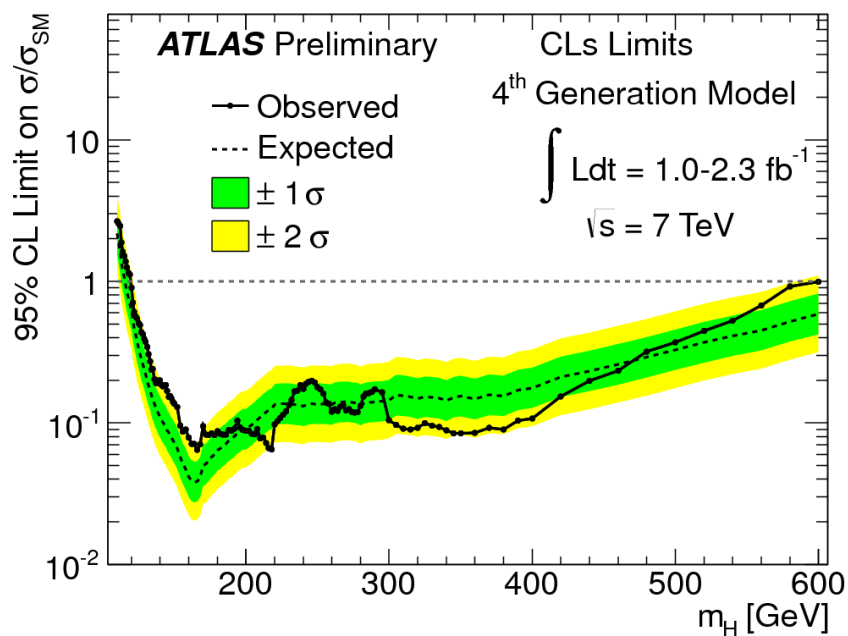
- A fourth **chiral generation** implies another  $SU(2)_L$  doublet of quarks and the corresponding right-handed singlets.
- The quarks are assumed to obtain mass via a single Higgs in the same way as the fermions of the other three generations.

$$\begin{pmatrix} t'_L \\ b'_L \end{pmatrix} \quad t'_R, b'_R$$

$$g\bar{\psi}_L\phi\psi_R \xrightarrow{\text{EWSB}} m\bar{\psi}_L\psi_R$$

2.4 MeV/c <sup>2</sup> 2/3 1/2 u up	1.27 GeV/c <sup>2</sup> 2/3 1/2 c charm	172.5 GeV/c <sup>2</sup> 2/3 1/2 t top	? 2/3 1/2 t' ?
4.8 MeV/c <sup>2</sup> -1/3 1/2 d up	104 MeV/c <sup>2</sup> -1/3 1/2 s strange	4.2 GeV/c <sup>2</sup> -1/3 1/2 b bottom	? -1/3 1/2 b' ?
< 2.2 eV/c <sup>2</sup> 0 1/2 ν <sub>e</sub> electron neutrino	< 0.17 MeV/c <sup>2</sup> 0 1/2 ν <sub>μ</sub> muon neutrino	< 15.5 MeV/c <sup>2</sup> 0 1/2 ν <sub>τ</sub> tau neutrino	? 0 1/2 ν <sub>4</sub> ?
0.511 MeV/c <sup>2</sup> -1 1/2 e electron	105.7 MeV/c <sup>2</sup> -1 1/2 μ muon	1,777 GeV/c <sup>2</sup> -1 1/2 τ tau	? -1 1/2 l <sub>4</sub> ?
0 0 1 γ photon	0 0 1 g gluon	80.4 GeV/c <sup>2</sup> ±1 1 W <sup>±</sup> W boson	91.2 GeV/c <sup>2</sup> 0 1 Z <sup>0</sup> Z boson

ATLAS-CONF-2011-135



- Gluon fusion diagram is enhanced by 9 by presence of new chiral quarks in loop.
- If 4<sup>th</sup> generation were quarks present, should've discovered SM Higgs much earlier.
- But situation is not so clear in 2HDMs ...

# Chiral vs. Vector-Like Quarks (VLQs)

- **Vector-like:** left and right handed component quantum numbers are the same, e.g. :

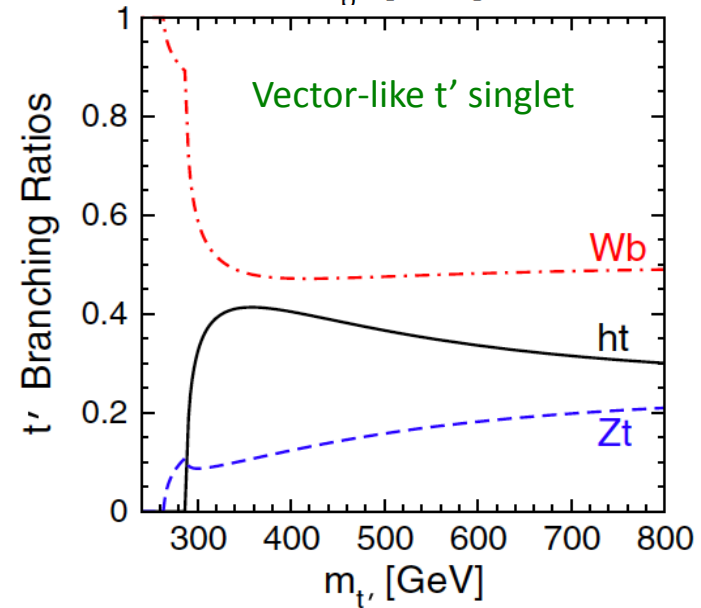
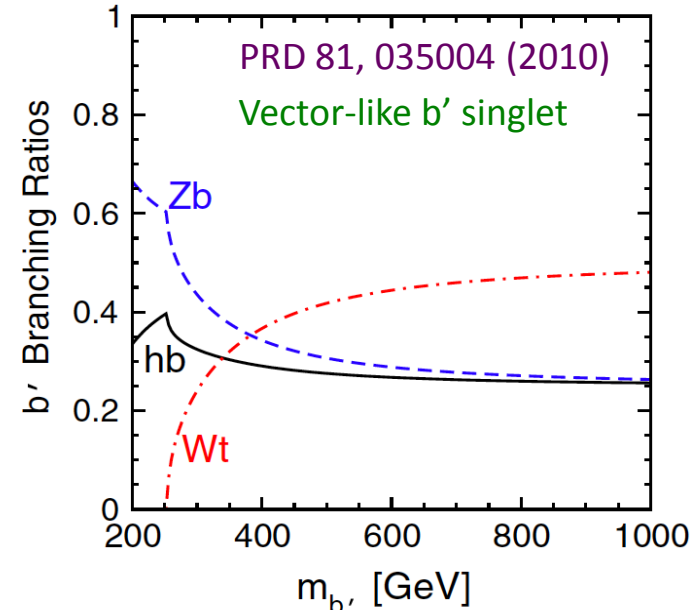
Vector-like singlets

$$t'_L \quad t'_R$$

Vector-like doublets

$$\begin{pmatrix} t'_L \\ b'_L \end{pmatrix} \quad \begin{pmatrix} t'_R \\ b'_R \end{pmatrix}$$

- Gauge invariant mass term independent of the SM Higgs  $M\bar{\psi}_L\psi_R$
- Mixing of weak eigenstates w/ different isospin breaks GIM and induces tree level FCNC.
- Mixing with 3<sup>rd</sup> generation generally preferred in most models (though caveats exist), and is experimentally less well constrained.
- Present in many BSM models: Little Higgs, Composite Top/Higgs, Extra Dims., GUTs, extended SUSY, ...

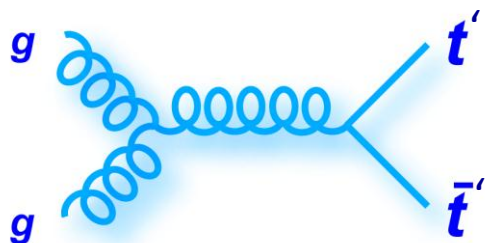


# New Quark Pair Production at the LHC

- New quarks can be produced singly or in pairs at the LHC.

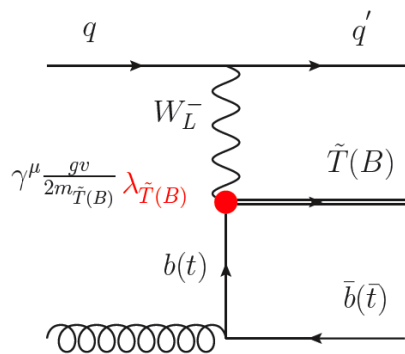
## Pair Production

(like heavy  $t\bar{t}$ )



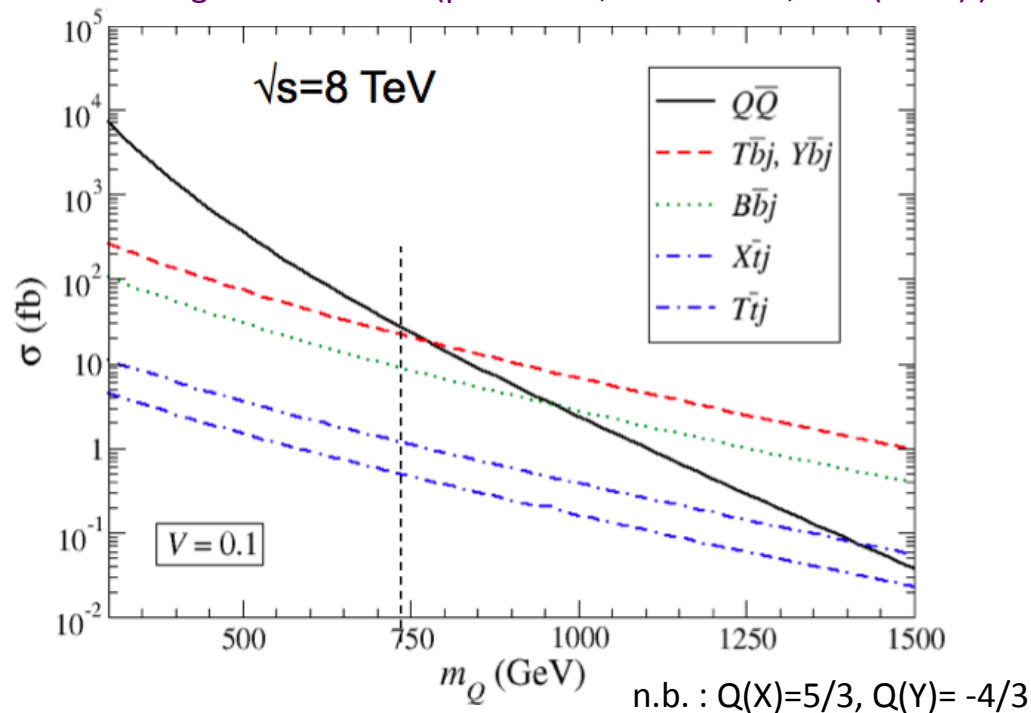
## Single Production

(depends on charge, coupling)



1207.0830

J.A. Aguilar-Saavedra (priv. com., c.f. JHEP 11, 030 (2009) )

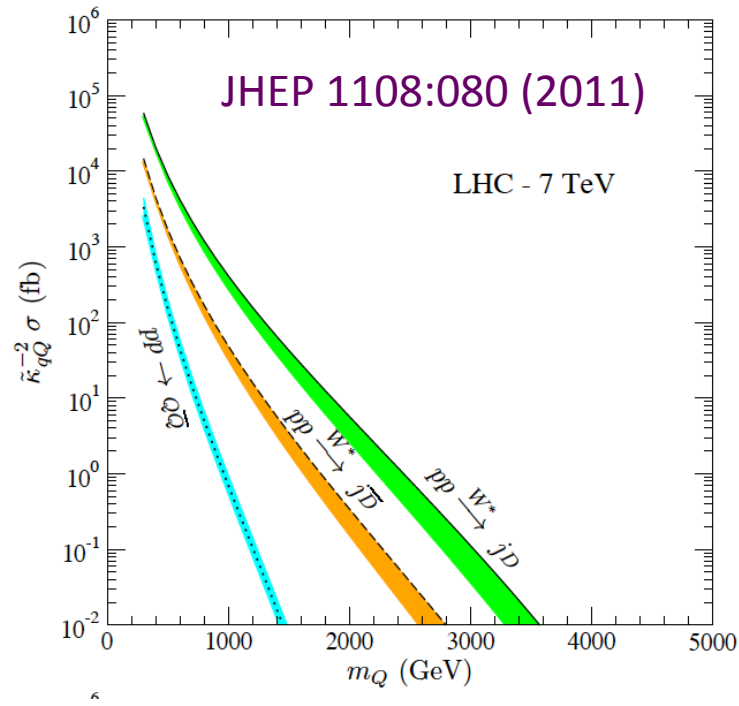
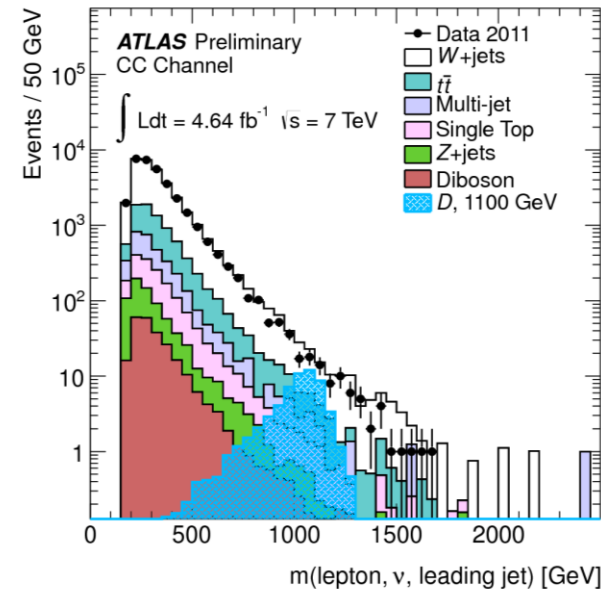
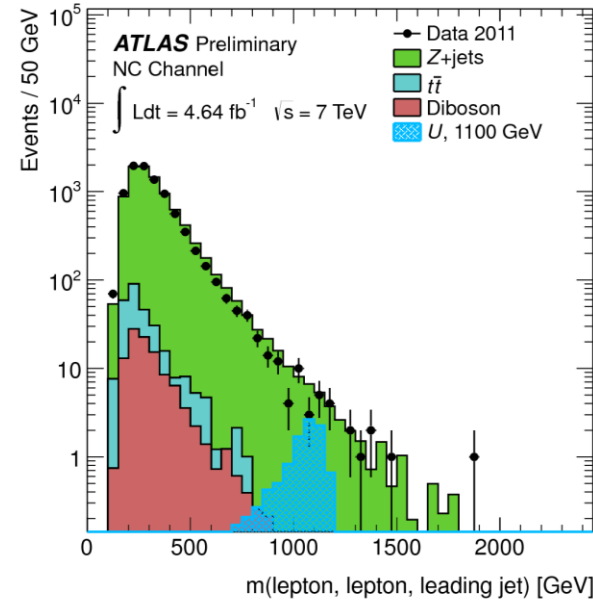
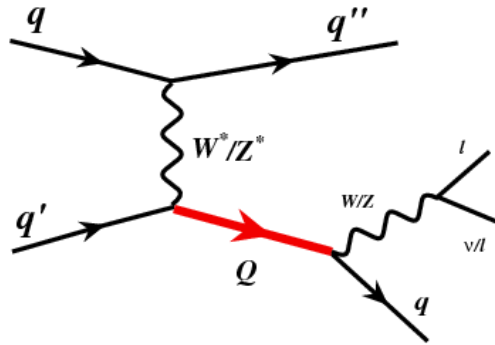


- ATLAS searches primarily targeting pair production at present.
- Signal yields are normalized to the HATHOR approx. NNLO prediction.

# Single Vector-Like Quarks Coupling to the First Generation

- Although precision EW observables generally constrain coupling to light quarks, caveats exist.
- Example : degenerate vector-like bi-doublets w/ hypercharges 1/6 and 7/6.

ATLAS-CONF-2012-137  
[7 TeV, 4.6/fb]



• Final state consists of vector boson and high  $p_T$  jet from the VLQ decay, plus a lower  $p_T$  associated jet.

• Search performed in CC (W) and NC (Z) channels.





# ATLAS

EXPERIMENT

Run Number = 189288

Event Number = 2779906

Z(ee)+jet mass = 1858.8 GeV

leading jet

associated jet

electrons

Leading electron  $p_T = 485.1$  GeV

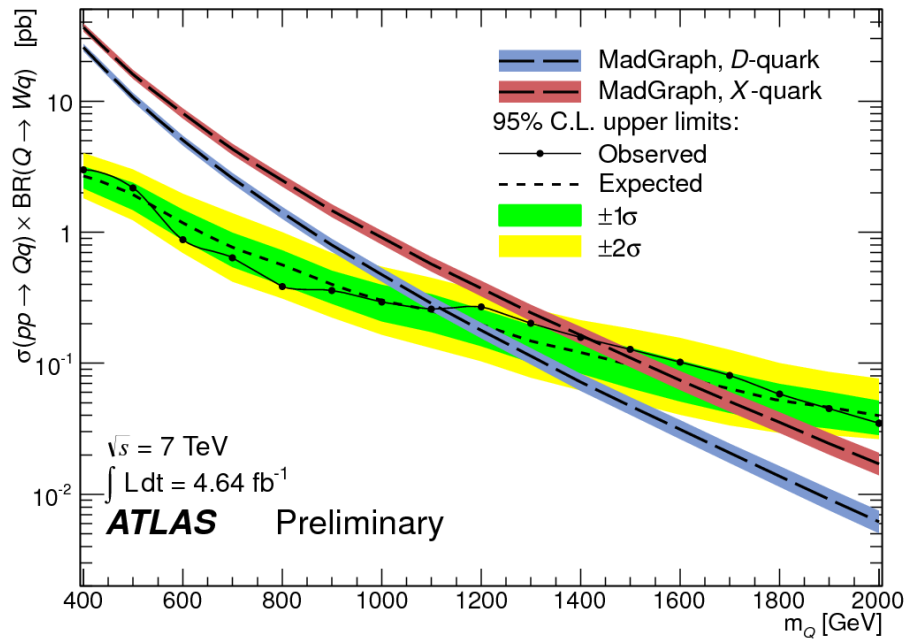
Second electron  $p_T = 335.1$  GeV

Leading jet  $p_T = 905.8$  GeV

Associated jet  $p_T = 96.5$  GeV



# Single Vector-Like Quarks Coupling to the First Generation



- Limits above assume the normalized coupling (by Higgs vev divided by heavy quark mass) is equal to 1.
- Limit on arbitrary coupling provided as a function of the heavy quark mass.

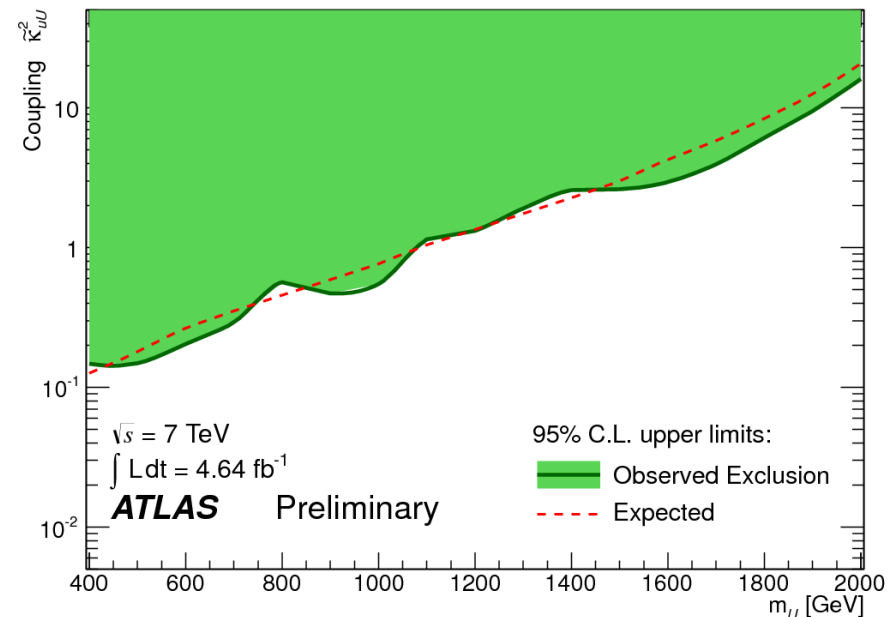
$W \rightarrow l\nu$  Channel

D-quark ( $Q = -1/3$ ): **> 1120 GeV**

X-quark ( $Q = 5/3$ ): **> 1420 GeV**

$Z \rightarrow ll$  Channel

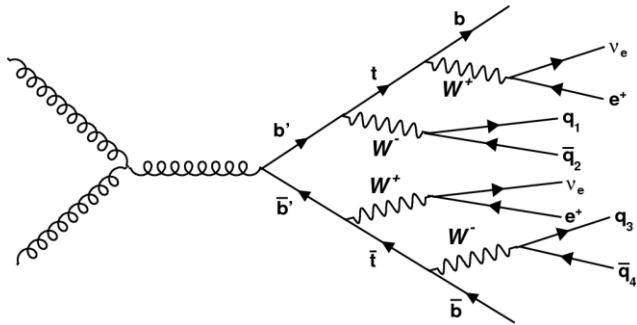
U-quark ( $Q = 2/3$ ): **> 1080 GeV**



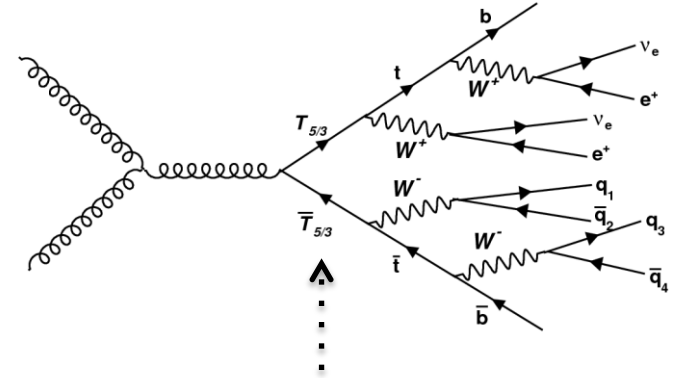
# $b'b'$ (and $T_{5/3}$ , and 4-tops) with Same-Sign Leptons

ATLAS-CONF-2012-130 [7 TeV, 4.7/fb]

Several Signal Models Considered

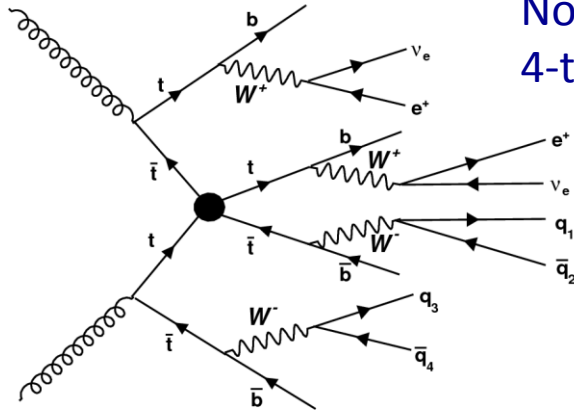


Chiral-Like  $b'$



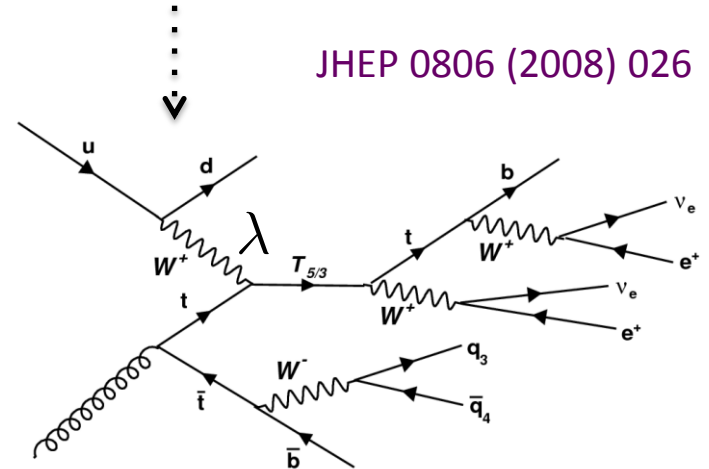
$T_{5/3}$  Single and Pair Production

JHEP 0806 (2008) 026



Non-resonant  
4-top production

JHEP 1103 (2011) 125



# $b'b'$ (and $T_{5/3}$ , and 4-tops) with Same-Sign Leptons

## Selection

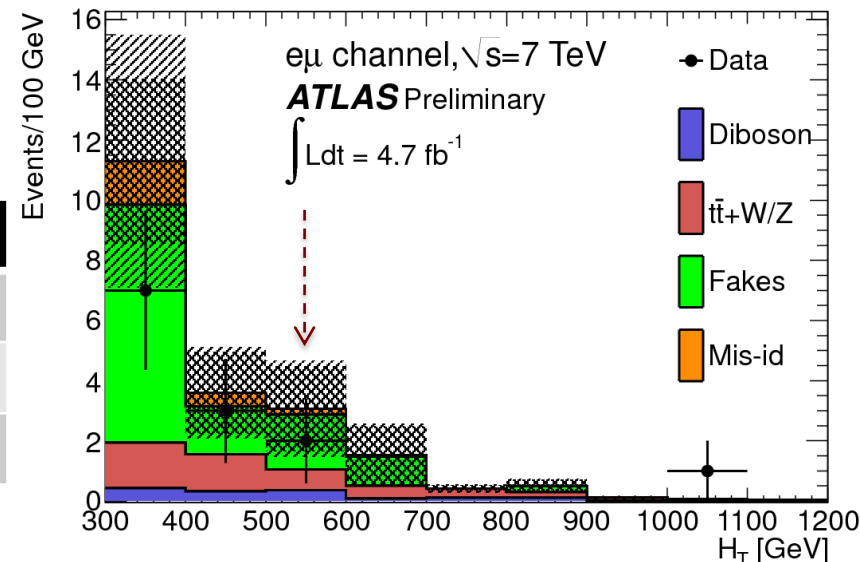
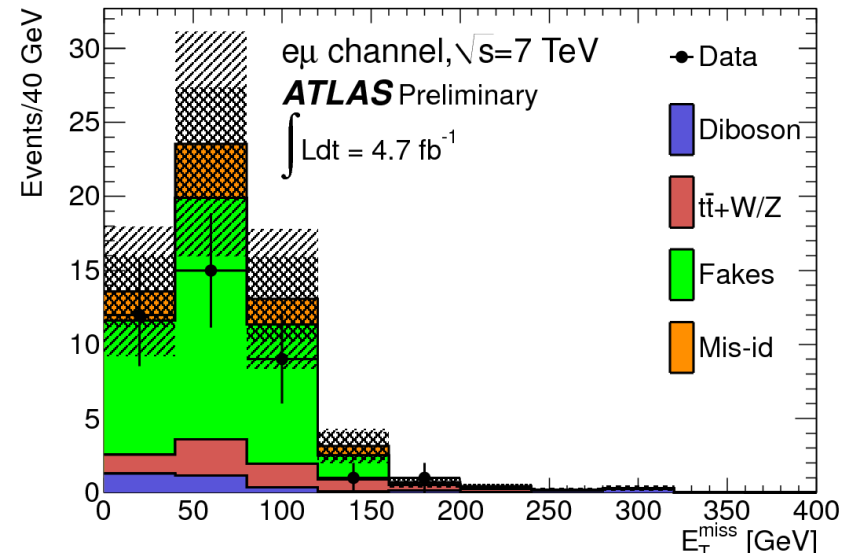
- At least two same-sign leptons
- At least two jets w/  $p_T > 25$  GeV
- At least one b-tagged (70% eff.) jet
- $H_T(\text{lep+had}) > 550$  GeV

## Background Sources

- Charge mid-ID (data driven, several methods)
- Fake leptons (data driven, matrix method)
- Di-Bosons
- $tt+V$

## Final yields in signal region

Channel	$ee$	$e\mu$	$\mu\mu$
Tot. Exp. Bkgd	$1.3 \pm 1.1 \pm 0.3$	$2.9 \pm 1.1 \pm 0.5$	$1.4 \pm 0.3 \pm 0.3$
Obs. Events	2	2	0
$b'b'$ (650 GeV)	$0.98 \pm 0.04$	$3.06 \pm 0.08$	$2.00 \pm 0.07$



# $b'b'$ (and $T_{5/3}$ , and 4-tops) with Same-Sign Leptons

- Chiral  $b'$  Limit (i.e.  $BR(Wt) = 100\%$ ):

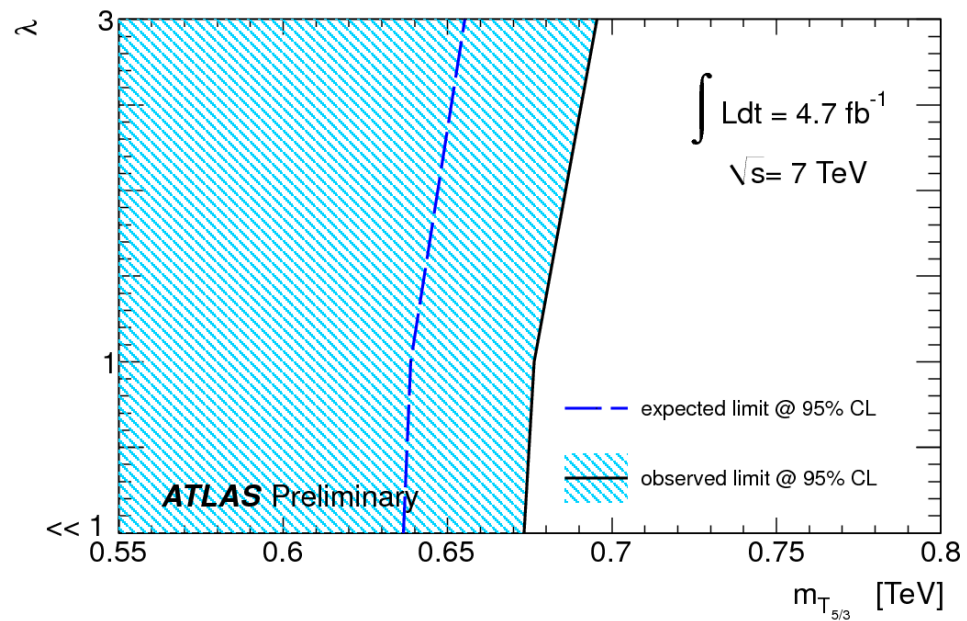
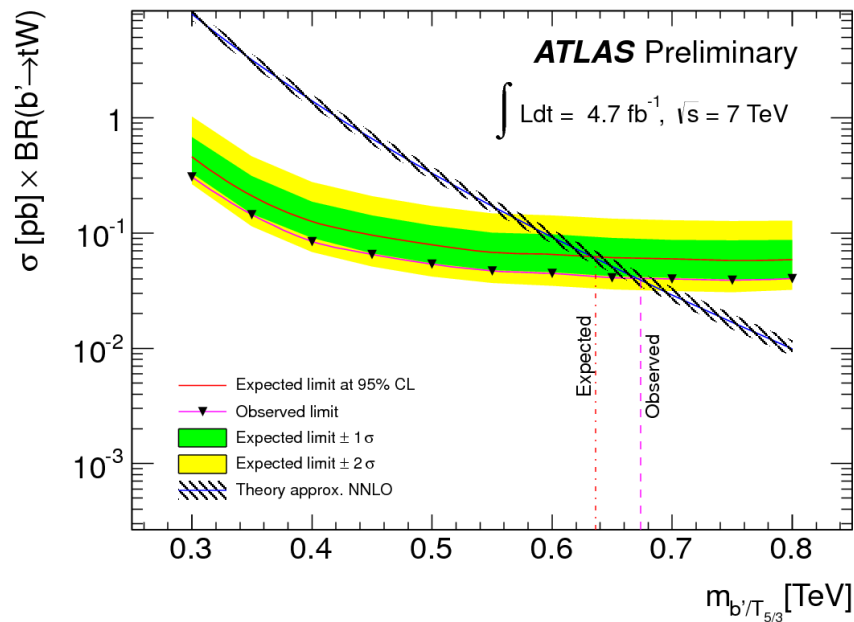
> 640 GeV (exp)

> 670 GeV (obs)

- Results to left apply to  $T_{5/3}$  in limit  $\lambda \ll 1$

$\lambda = 1$  > 680 GeV (obs)

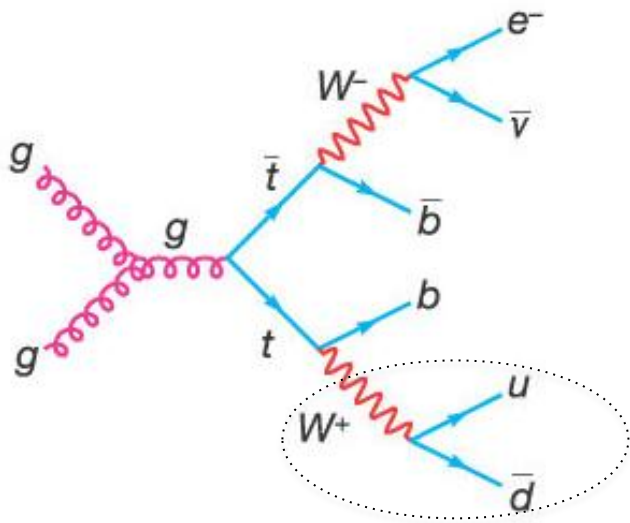
$\lambda = 3$  > 700 GeV (obs)



- Limit on four top production: 61 fb (exp), 90 fb (obs). n.b. : SM is order few fb.

# $t't'$ with One Lepton + Jets

PLB 718 (2013), 1284 [7 TeV, 4.7/fb]



Search begins by targeting the final state:

$$t't' \rightarrow W^+ b W^- \bar{b}$$

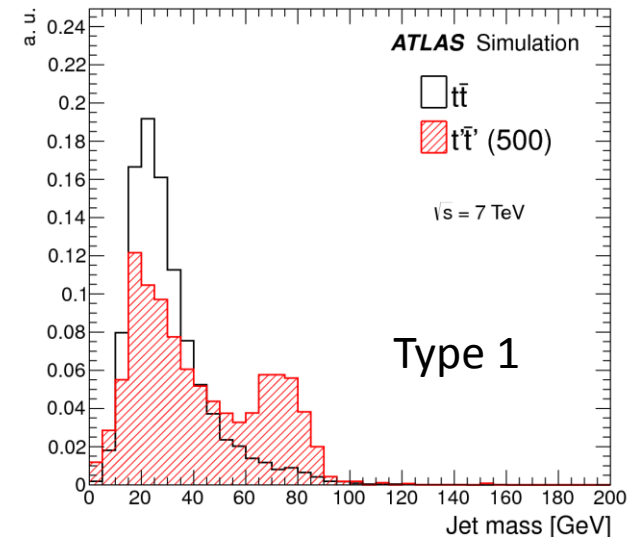
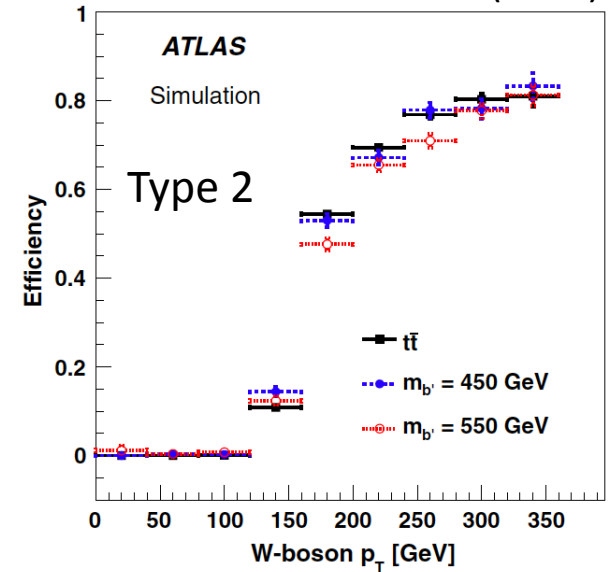
Selection:

- = 1 Lepton
- Missing  $E_T$ ,  $M_T$
- At least 3 anti-kt 0.4 jets
- 1 explicit b-tag
- 1 hadronic boson candidate.
- $H_T > 750$  GeV

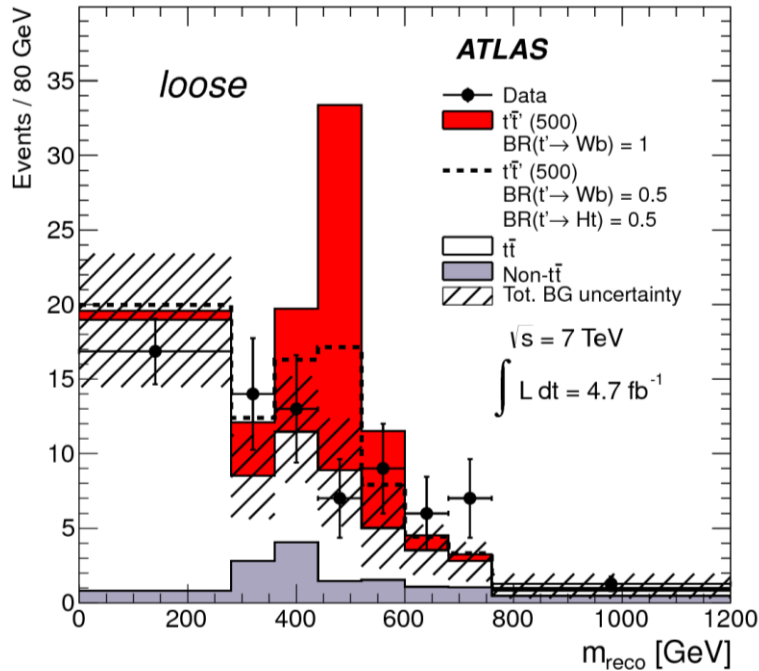
Two types of hadronic boson candidates:

- Type 1: single  $p_T > 250$  GeV, jet mass 60-110 GeV.
- Type 2: two jets w/  $\Delta R < 1.0$ , and di-jet system  $p_T > 150$  GeV and mass 60-110 GeV.

PRL 109 032001 (2012)



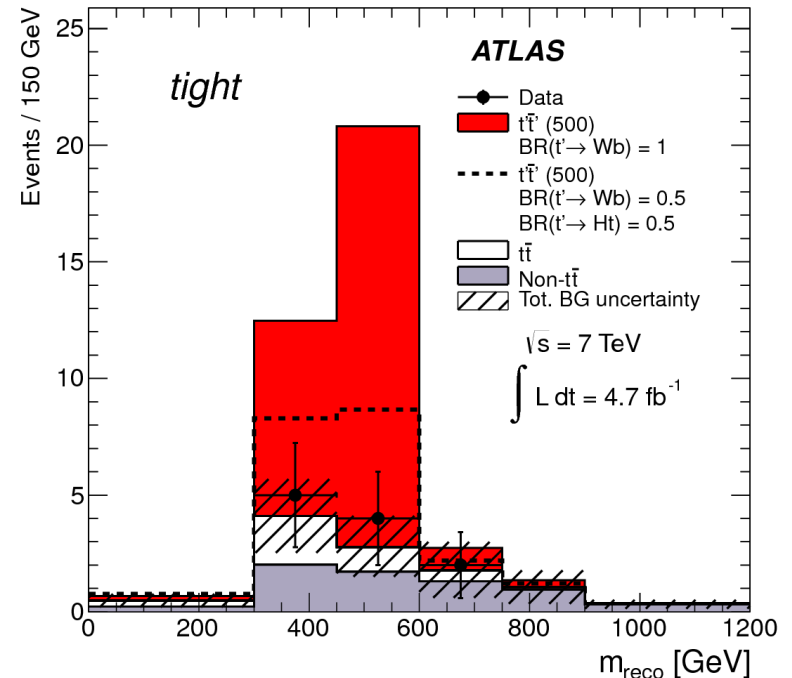
# $t\bar{t}'$ with One Lepton + Jets



Require W and b candidates to be well separated to reduce background.

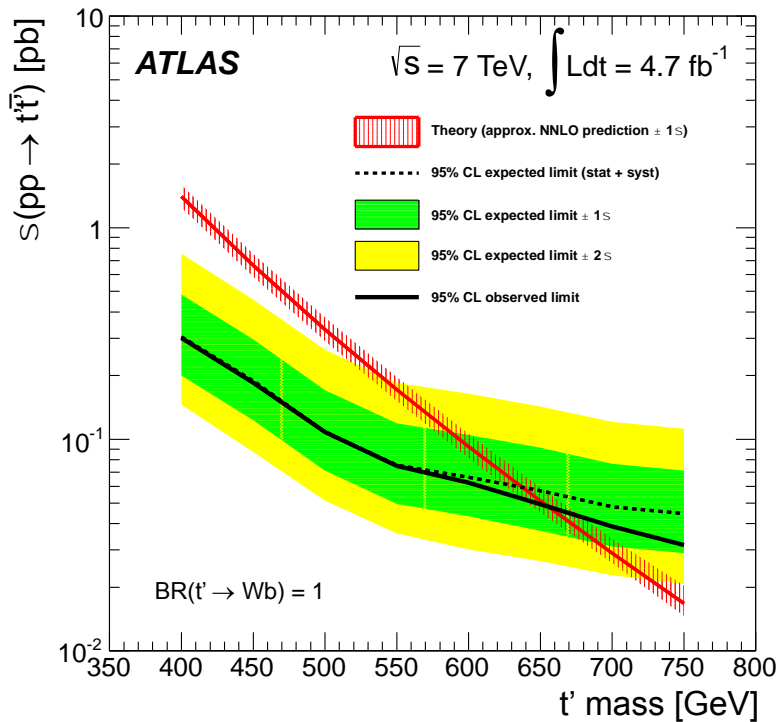
$$\min(\Delta R(W_{had}), b_{1,2}) > 1.4$$

$$\min(\Delta R(l, b_{1,2})) > 1.4$$

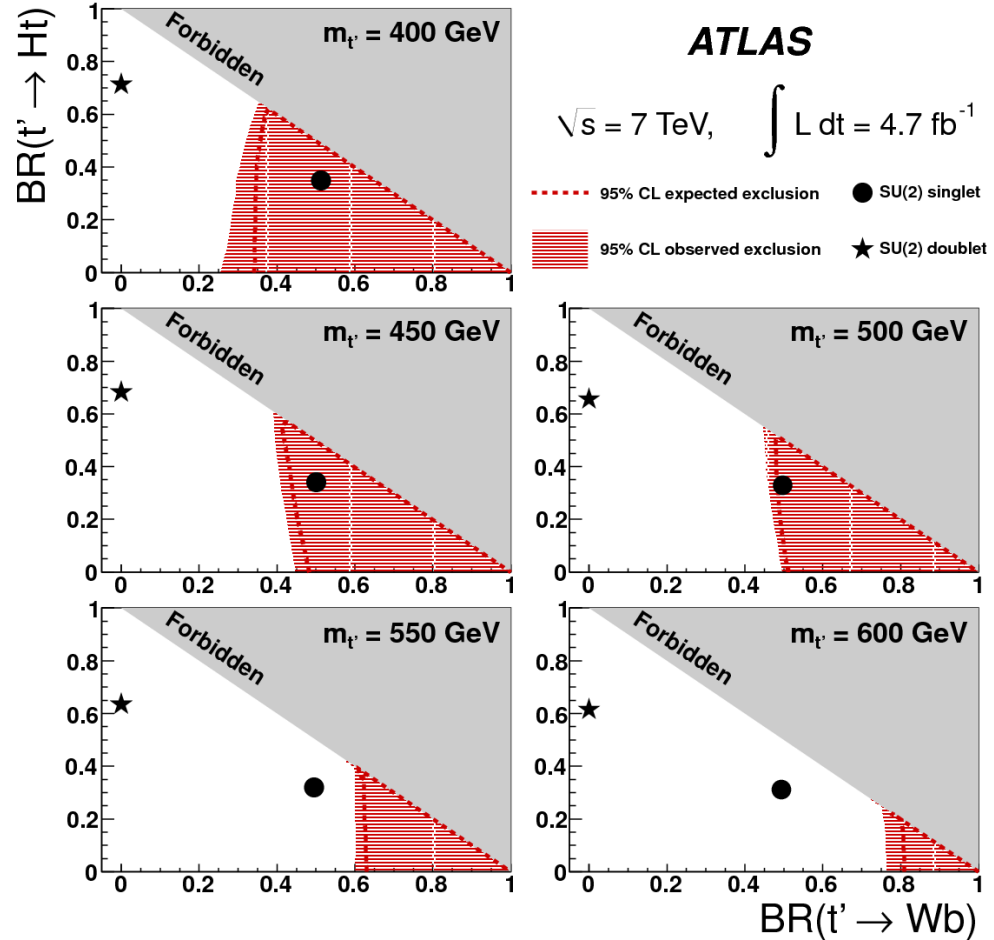


	<i>loose</i> selection	<i>tight</i> selection
$t\bar{t}$	$94 \pm 26$	$4.2 \pm 2.9$
$W$ +jets	$5.4 \pm 4.2$	$2.0 \pm 1.4$
$Z$ +jets	$0.5 \pm 0.4$	$0.2 \pm 0.2$
Single top	$7.2 \pm 1.7$	$1.1 \pm 0.5$
Dibosons	$0.1 \pm 0.1$	$0.04 \pm 0.04$
Multi-jet	$5.9 \pm 8.4$	$3.8 \pm 3.2$
Total background	$113 \pm 30$	$11.3 \pm 4.8$
Data	122	11
$t'\bar{t}'(500 \text{ GeV})$		
$Wb : Zt : Ht = 1.0 : 0.0 : 0.0$	$47.4 \pm 6.3$	$28.2 \pm 3.6$
$Wb : Zt : Ht = 0.5 : 0.0 : 0.5$	$25.4 \pm 3.6$	$11.2 \pm 1.5$

# $t't'$ with One Lepton + Jets



- Chiral  $t'$  Limit (i.e.  $BR(Wb) = 100\%$ ):
  - > 638 GeV (exp)
  - > 656 GeV (obs)



- Limits also assessed across full plane of VLQ branching ratios.



# Searches For Heavy Resonances Decaying to Top Pairs

# Motivation

- Many BSM models predict new heavy resonances decaying to  $t\bar{t}$ , perhaps preferentially.
- Some examples are:

Spin 0 : Lee-Wick Higgs

Spin 1 : Top Color (lepto-phobic)  $Z'$  , Randall-Sundrum bulk KK gluon.

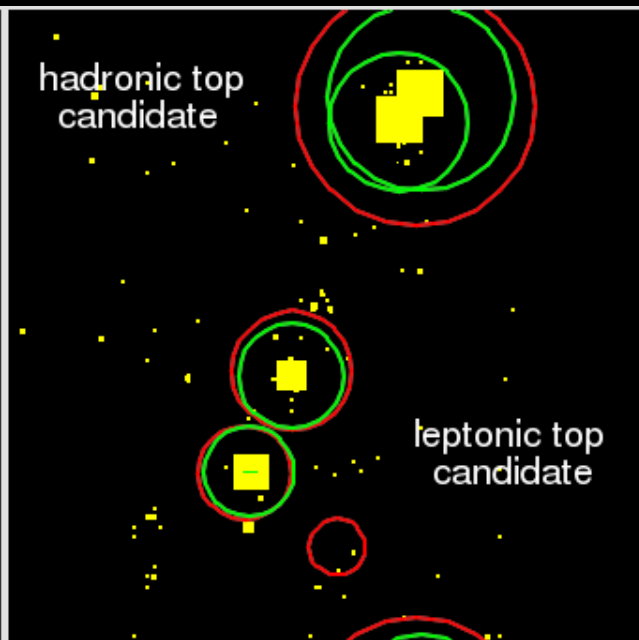
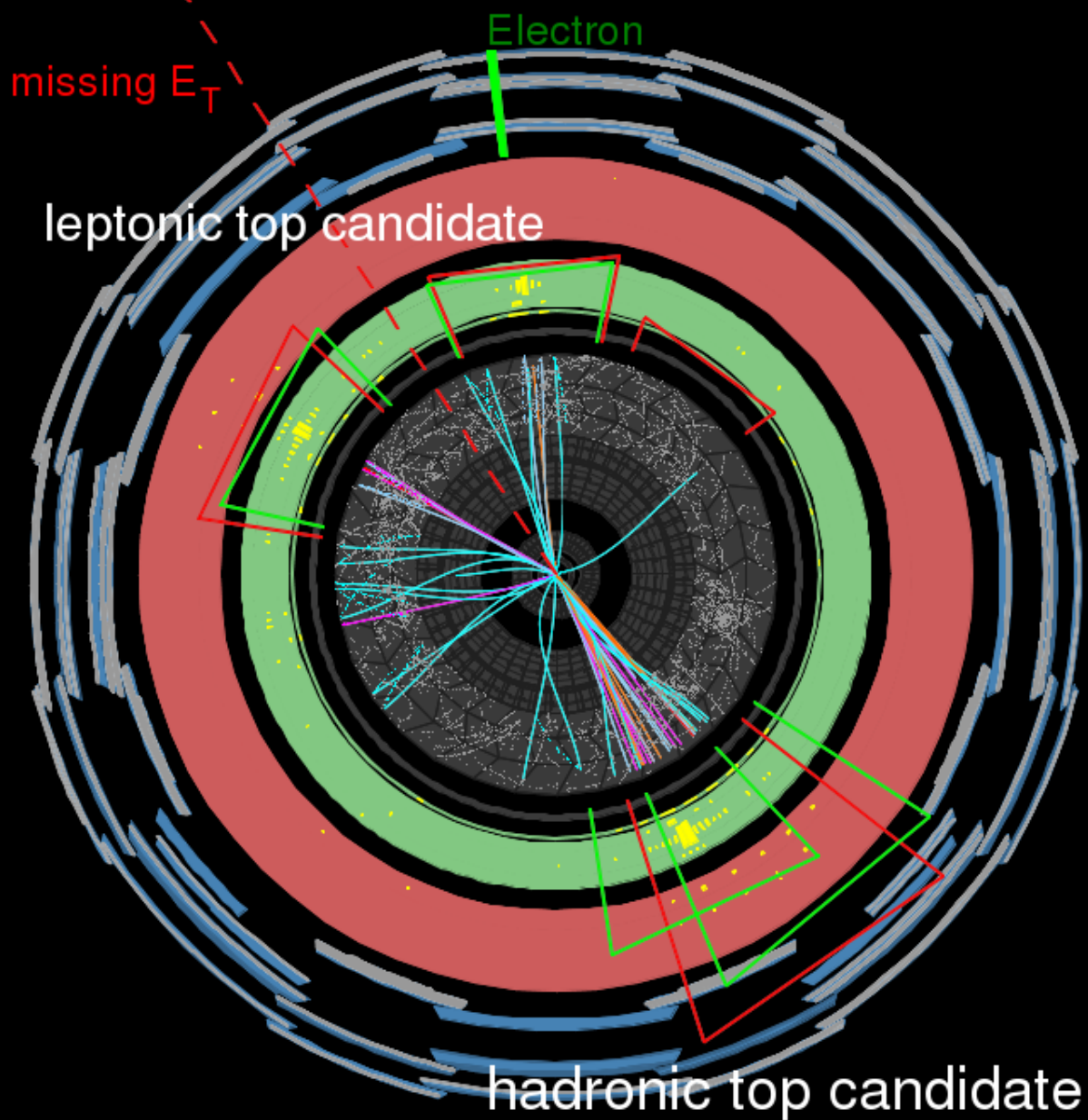
Spin 2 : Randall-Sundrum bulk KK graviton.

- The present ATLAS results consider the Top Color  $Z'$  and RS KK gluon:

Different widths:

- $Z'$  : 1.2% of mass
- $g_{\text{KK}}$  : 15.3% of mass

Mass	$Z' \rightarrow t\bar{t}$ $\sigma \times \text{BR} \times 1.3$ [pb]	$g_{\text{KK}} \rightarrow t\bar{t}$ $\sigma \times \text{BR}$ [pb]
$m = 500$ GeV	19.6	81.3
$m = 1000$ GeV	1.2	4.1
$m = 1500$ GeV	0.13	0.50
$m = 2000$ GeV	0.019	0.095
$m = 2500$ GeV	0.0030	0.026
$m = 3000$ GeV	0.00097	0.0097



**ATLAS**  
**EXPERIMENT**

Run Number: 180144, Event Number: 43671503

Date: 2011-04-22 09:46:15 EDT

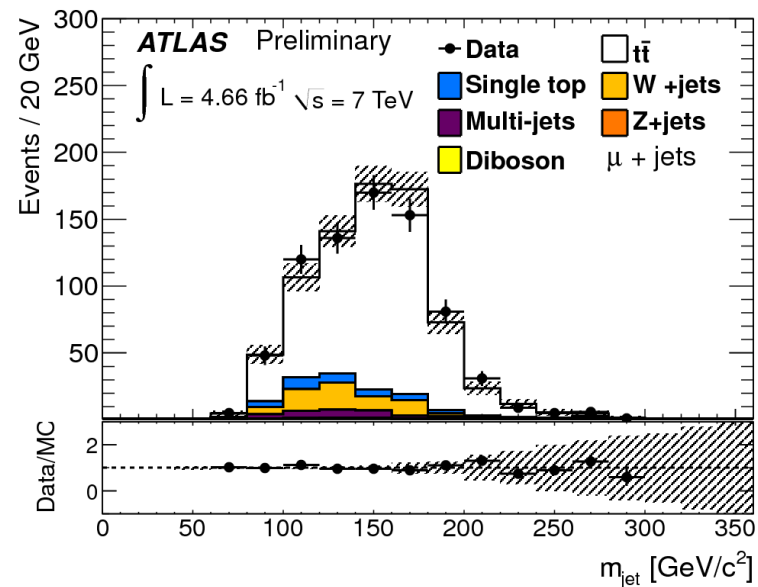
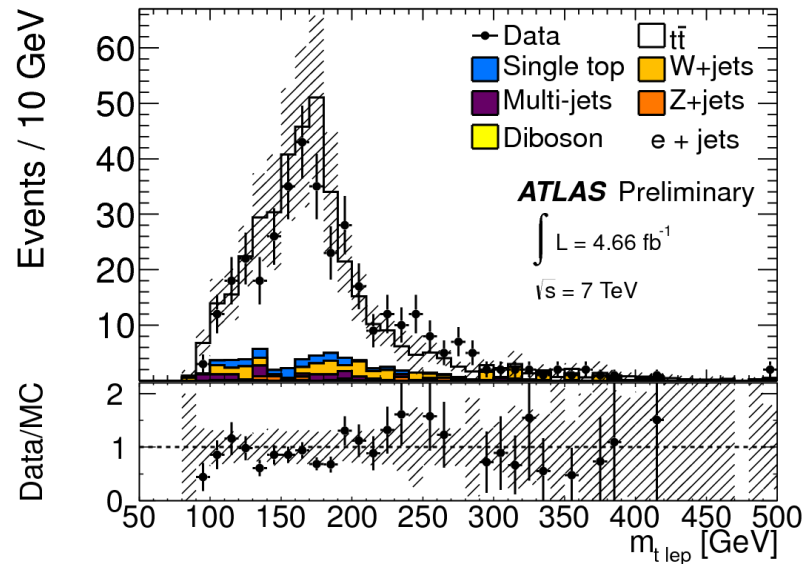
# Resonances Decaying to Top Pairs, Lepton + Jets

ATLAS-CONF-2012-136 [7 TeV, 4.7/fb]

- One lepton selection employing “mini-isolation”.
- Modest requirements on missing  $E_T$  and transverse mass.
- At least one b-tagged jet.
- Two selections (combined later):

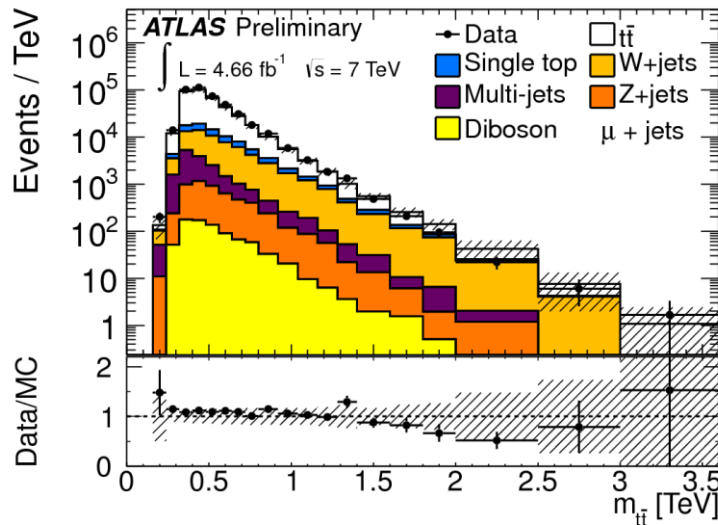
**Resolved** : 3 or 4 anti-kt  $R = 0.4$  jets.  $\chi^2$  algorithm to select jet assignments for mass reconstruction.

**Boosted** : anti-kt  $R=1.0$  jet for hadronic top.  $p_T > 350$  GeV, mass  $> 100$  GeV, first kt splitting scale  $> 40$  GeV. Plots on right show leptonic and hadronic top masses.

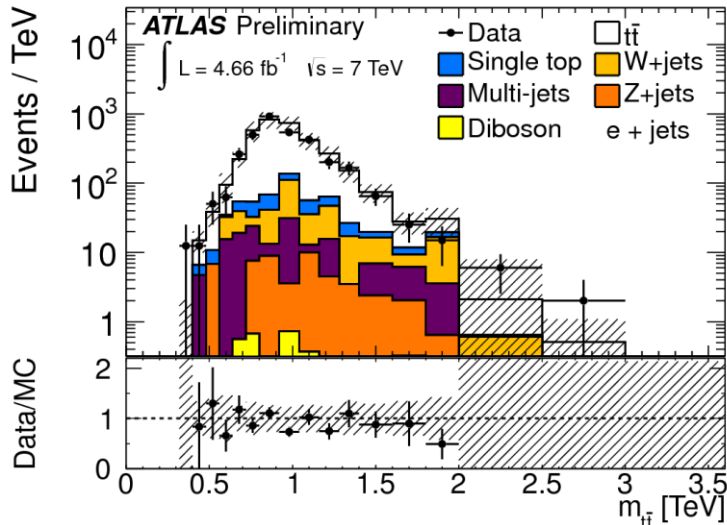


# Resonances Decaying to Top Pairs, Lepton + Jets

## Resolved Selection (muon channel)



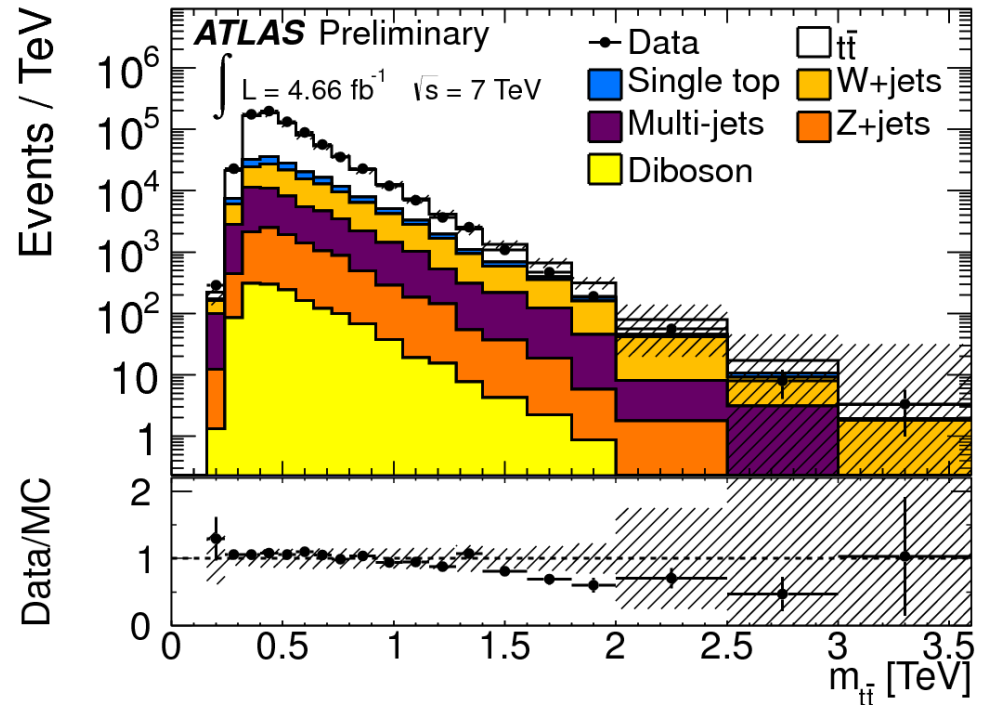
## Boosted Selection (electron channel)



## Final Mass Distribution

(all channels)

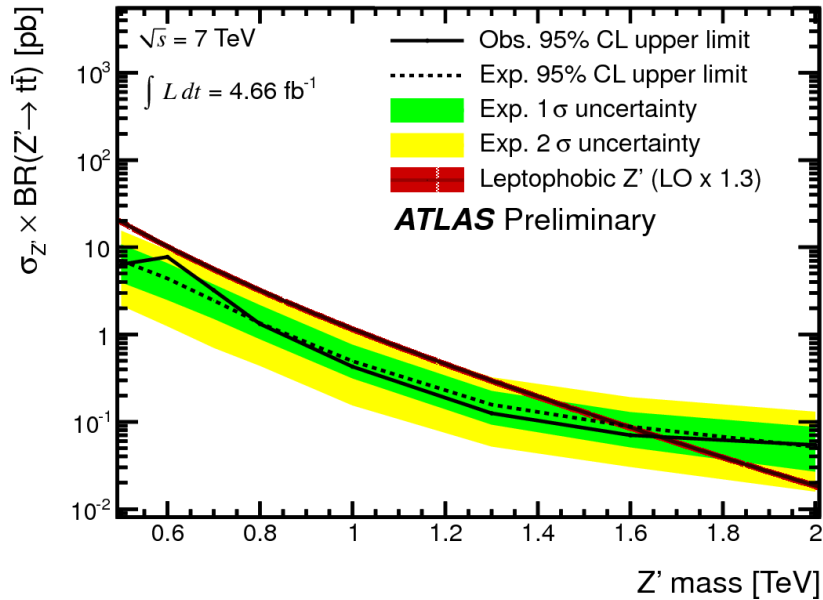
Combine selections according to:  
 Boosted + (Resolved & !Boosted)



# Resonances Decaying to Top Pairs, Lepton + Jets

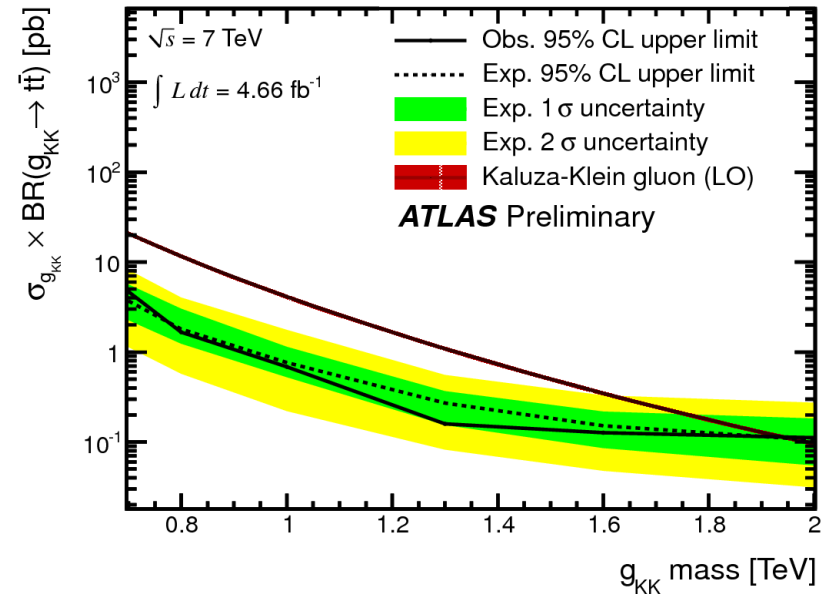
Results:

## Top Color $Z'$



Upper limits range from 3.2 pb at 0.7 TeV to 0.05 pb at 2.0 TeV.  
Exclude  $Z'$  masses between 0.5 TeV and 1.7 TeV.

## KK Gluon



Upper limits range from 4.7 pb at 0.7 TeV to 0.11 pb at 2.0 TeV.  
Exclude  $g_{KK}$  masses between 0.7 TeV and 1.9 TeV.

# Resonances Decaying to Top Pairs, Fully Hadronic

arXiv:1211.2202 [7 TeV, 4.7/fb]

- The same two signal models have been searched for in the fully hadronic state using two “Top Taggers”.

**HEPTopTagger** (tuned for  $p_T > 200$  GeV)

C/A algorithm,  $R = 1.5$  jets

Split into sub-jets, triplets tested as top cand.

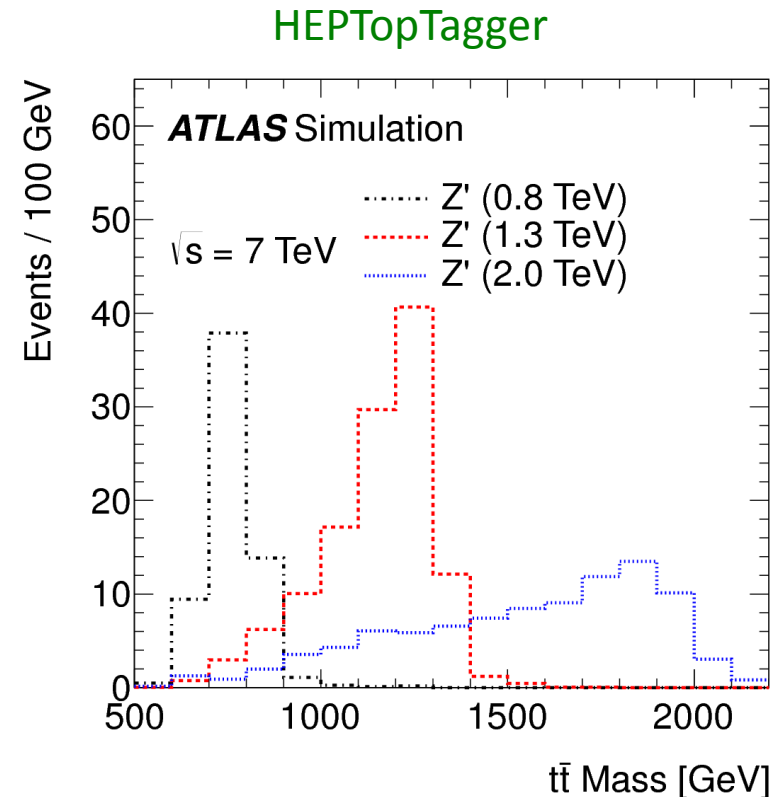
Test invariant mass ratios

**TopTemplateTagger** (tuned for  $p_T > 500$  GeV)

Anti-kt,  $R = 1.0$  jets

Construct an overlap function ( $OV_3$ ) that tests sub-jets compatibility with top daughters via a library of templates.

- Both analysis require two top tags that have also been b-tagged.

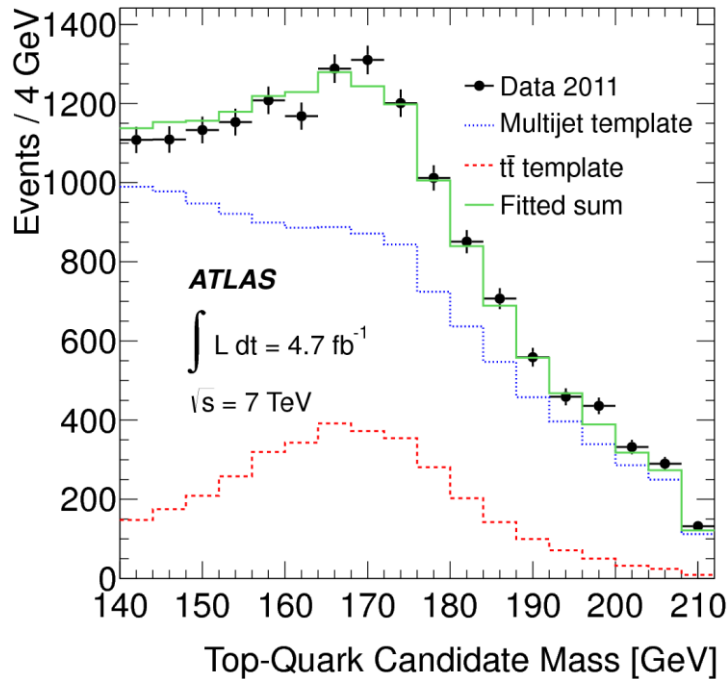




# Resonances Decaying to Top Pairs, Fully Hadronic

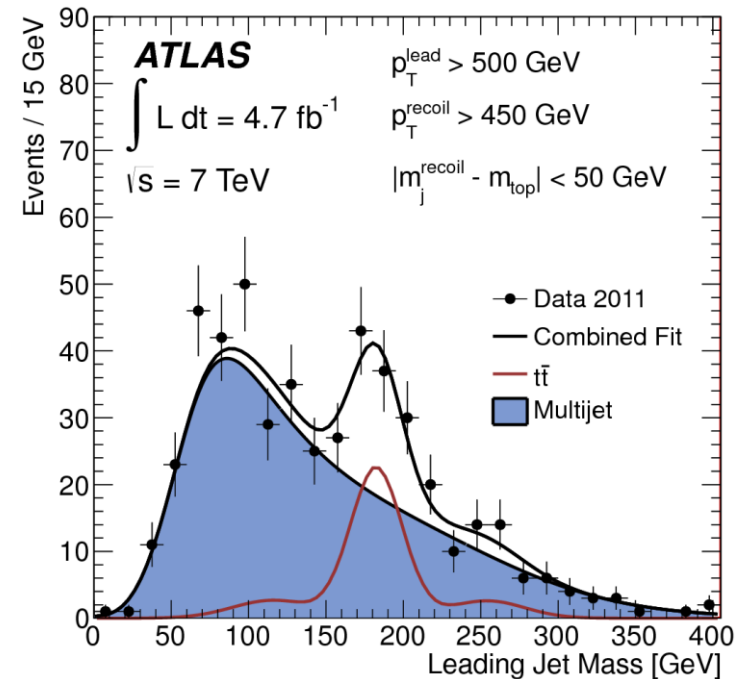
Top Mass in Control Regions:

HEPTopTagger



1 top tag control region

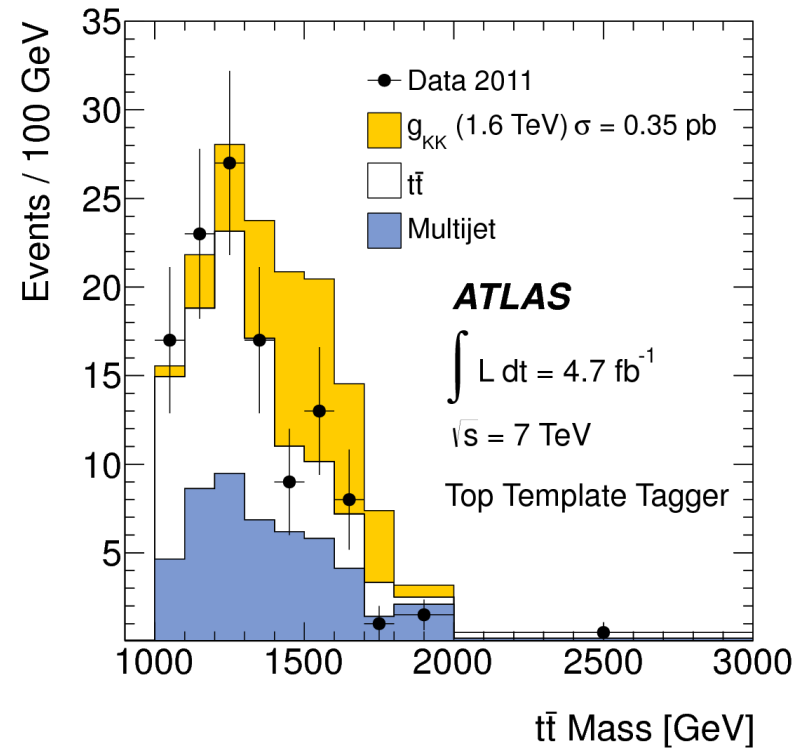
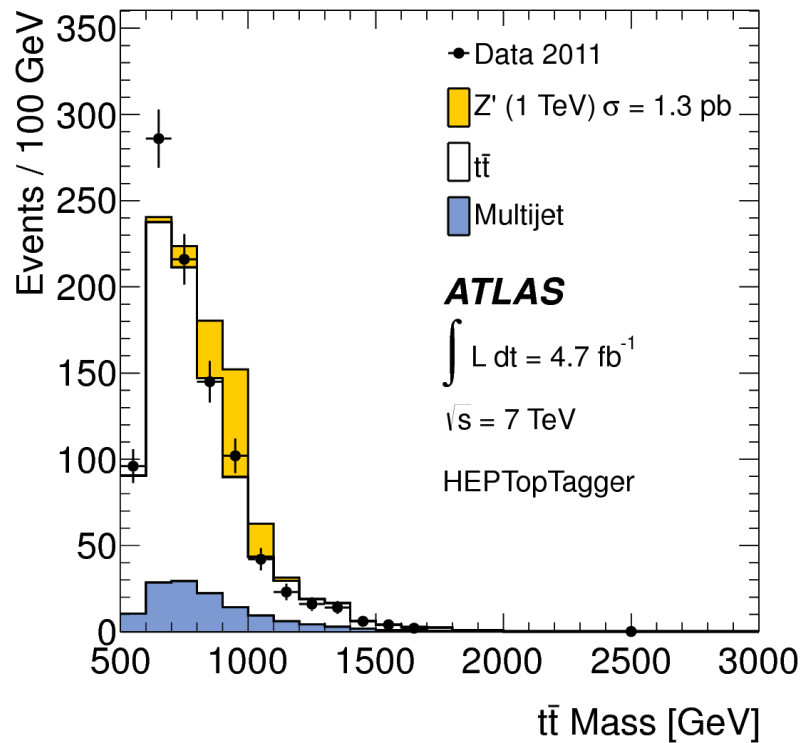
TopTemplateTagger



Dropping  $OV_3$  and jet mass requirements

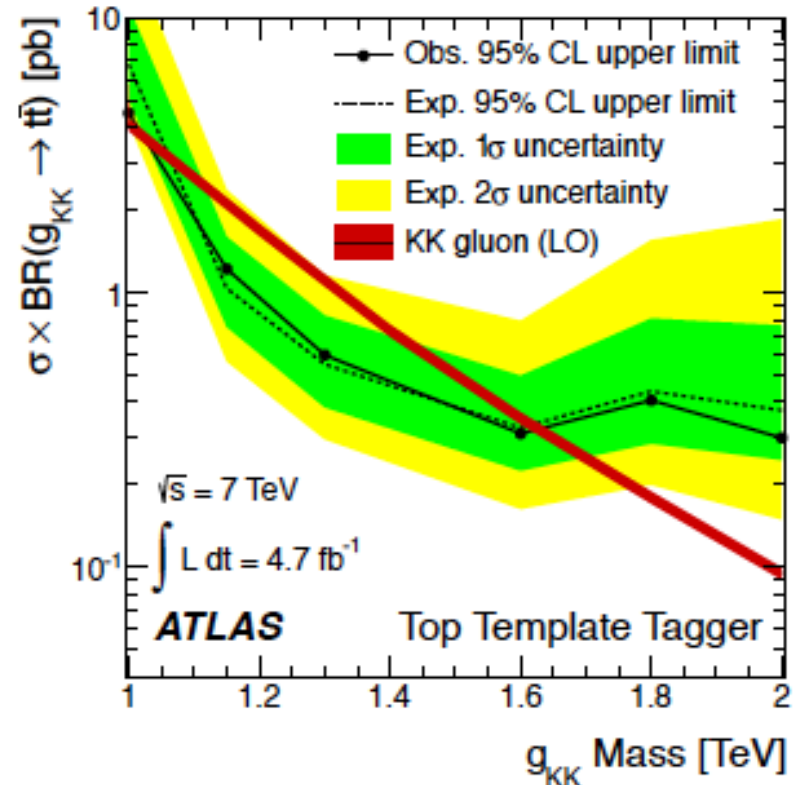
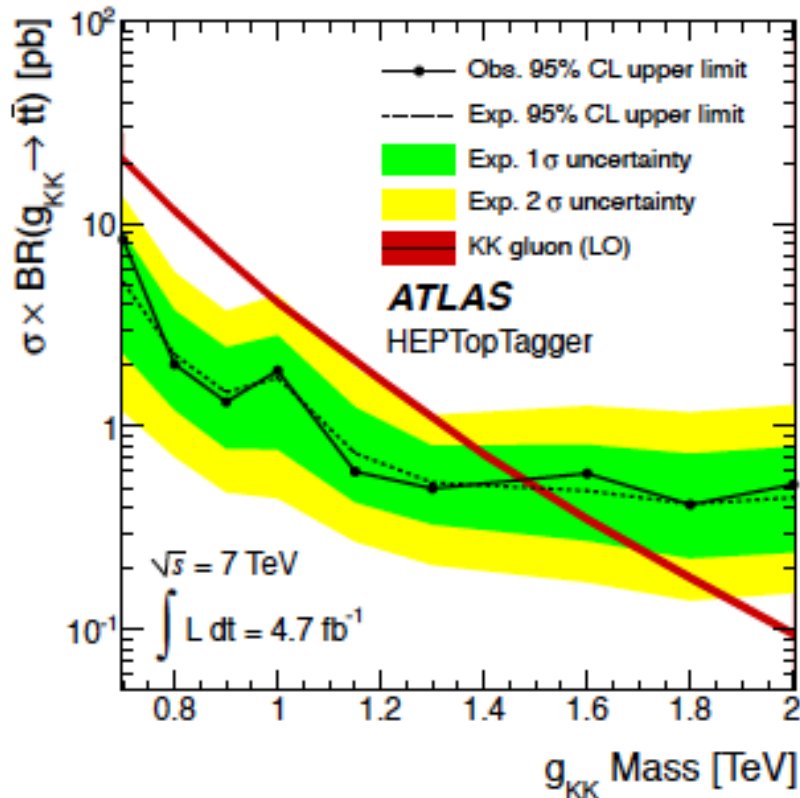
# Resonances Decaying to Top Pairs, Fully Hadronic

Final Mass Distributions in Signal Regions:



# Resonances Decaying to Top Pairs, Fully Hadronic

Results for KK gluon (see ref. for Z')



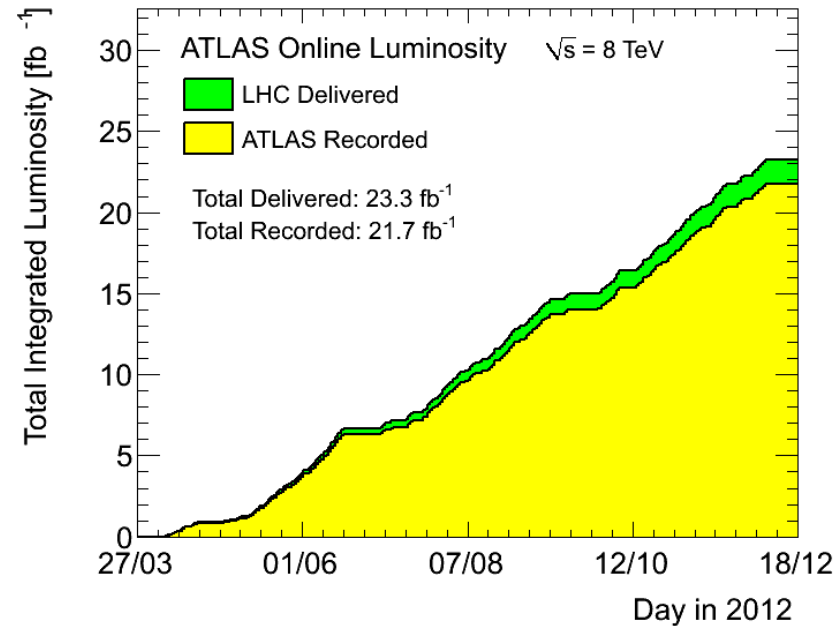
# Conclusions

## Searches for New Quarks

- Limits on VLQs coupling to light generations of order 1 TeV assuming unit coupling.
- Chiral  $t'$  and  $b'$  limits at about 650 GeV.
- The above  $t'/b'$  searches are moving towards VLQ and other interpretations.

## Searches for Heavy Resonances Decaying to Top Pairs

- Limits ranging from order pb around 1 TeV to order 0.1 pb at 2 TeV. Dependent on resonance width.



*Searches today performed  
with 7 TeV data ...  
Many new results and  
interpretations to come  
using 8 TeV data!*