

# Search for heavy vector-like top with the ATLAS detector

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*on behalf of*  
the ATLAS collaboration

CPAN 2013, Santiago de Compostela, November 25th-27th

# Outline

## Introduction

### General Strategy

$$T\bar{T} \rightarrow Ht + X$$

### Same-sign dileptons

$$B\bar{B}(T\bar{T}) \rightarrow Zb(t) + X$$

$$T\bar{T} \rightarrow Wb + X$$

## Conclusions

# Standard Model as an effective theory

The Standard Model does not provide answers to the following questions

- ▶ Where does the baryon asymmetry come from?
- ▶ What is Dark Matter?
- ▶ How to solve the hierarchy problem?

*Supersymmetry is not the only possible solution...*

Extra-dimensions [1], composite Higgs [2] models  
with **new heavy quarks predicted** [3]

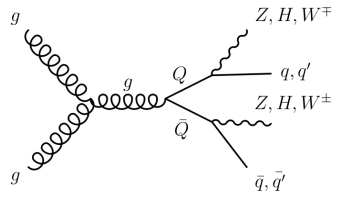
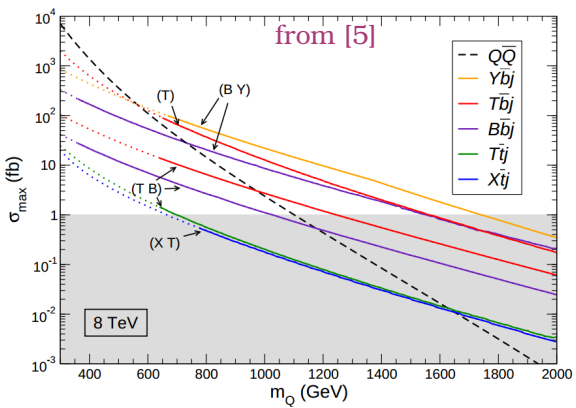
- ▶ Not chiral<sup>(a)</sup>: chiral 4th generation would change the Higgs SM cross section and B.R.
- ▶ Vector-like: left and right components transform the same under  $SU(2) \times U(1)$
- ▶ Weak-isospin singlets, doublets or triplets

*naturally solve the hierarchy problem,  
like a stop squark in SUSY*

<sup>(a)</sup> still, some models allow for a chiral fourth generation, see e.g. [4]

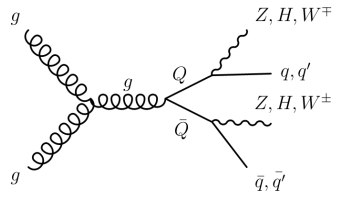
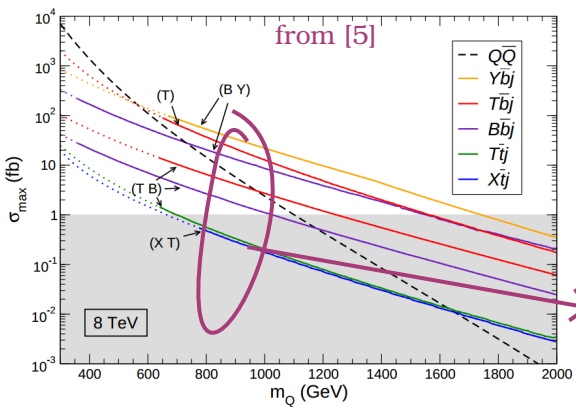
Singlet	Decay modes	Doublets	Decay modes
$T(+2/3)$	$W^+ b, Ht, Zt$	$\begin{pmatrix} T \\ B \end{pmatrix}$	$W^+ b, Ht, Zt$ $W^- t, Hb, Zb$
$B(-1/3)$	$W^- t, Hb, Zb$	$\begin{pmatrix} T \\ X \end{pmatrix}$	$Ht, Zt$ $W^+ t$
$X(+5/3)$	$W^+ t$	$\begin{pmatrix} B \\ Y \end{pmatrix}$	$Hb, Zb$ $W^- b$
$Y(-4/3)$	$W^- b$		

# Heavy quark production



Pair-production via **strong interaction**

# Heavy quark production



Pair-production via **strong interaction**

**EW single production**  
 could dominate at high mass

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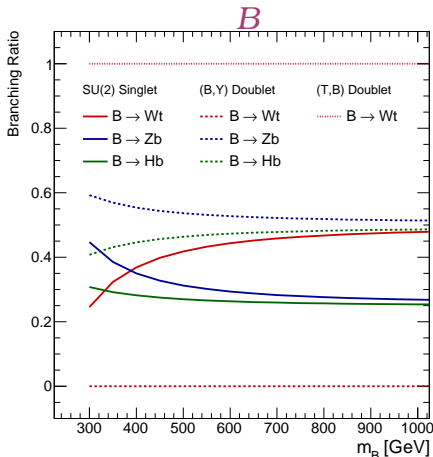
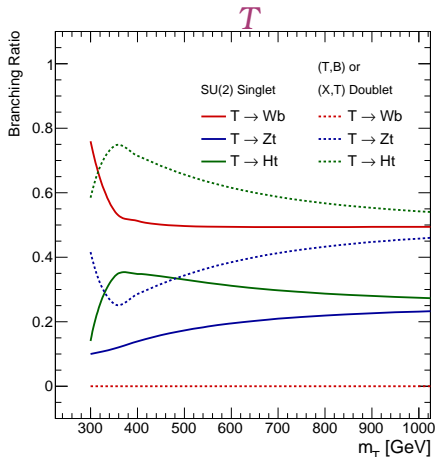
$$T\bar{T} \rightarrow Wb + X$$

Conclusions

# Heavy quark decay modes

B.R.s are very model dependent

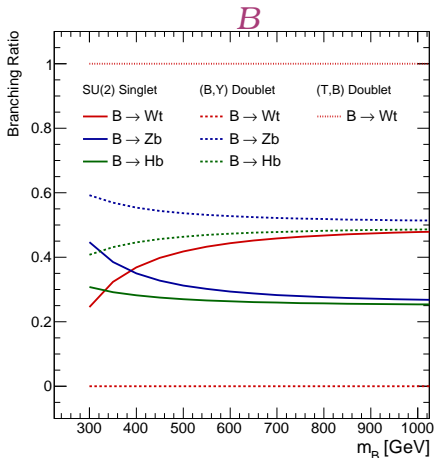
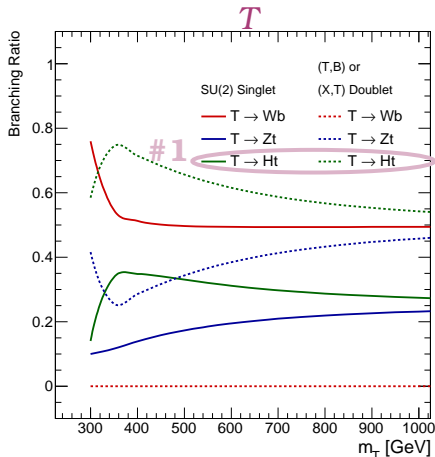
- ▶ most analyses optimized for specific decay channels



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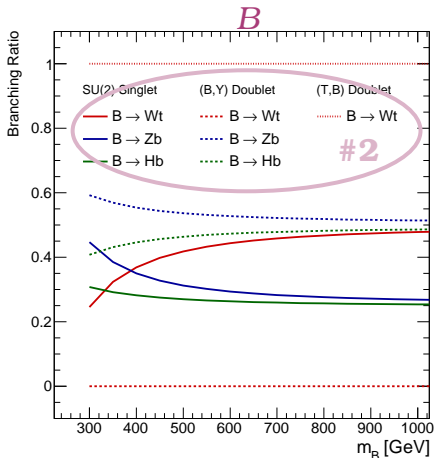
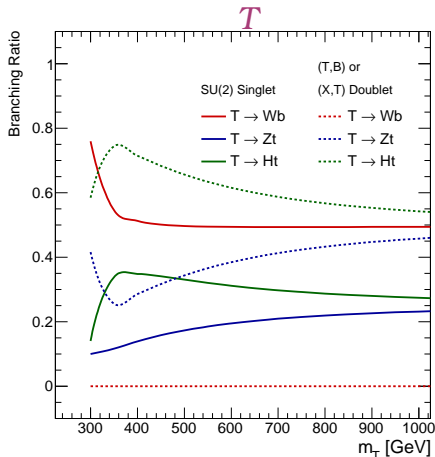
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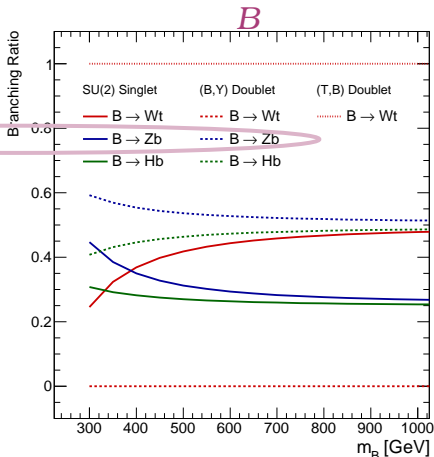
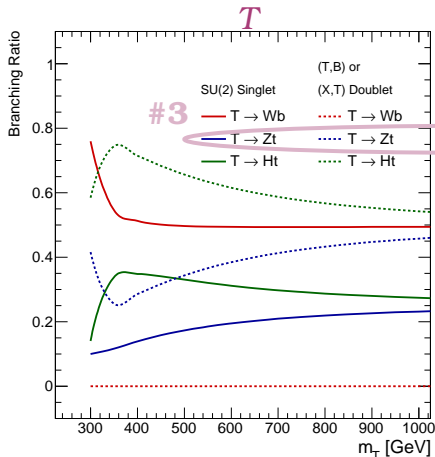
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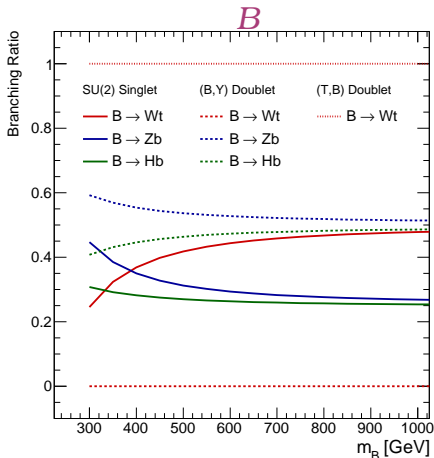
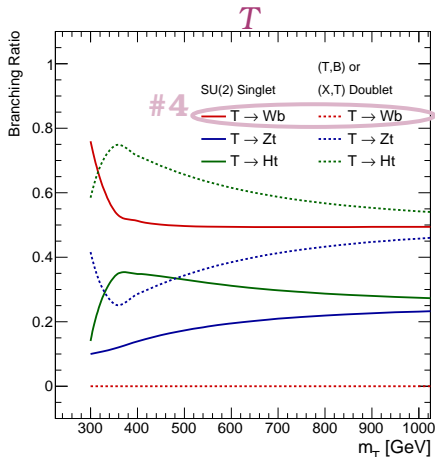
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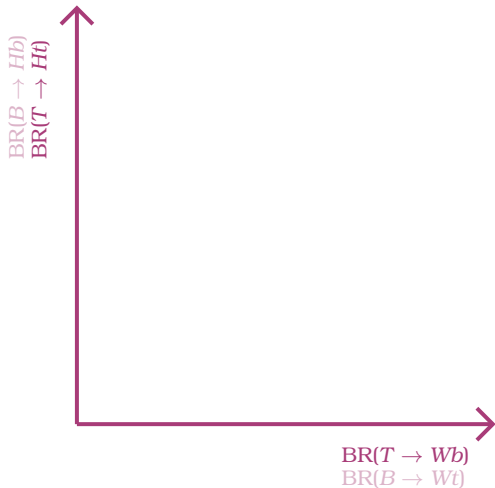
# Model Independent Strategy ... since Oct 2012 [8]!

- Build a 2-dim plane to scan model mixing



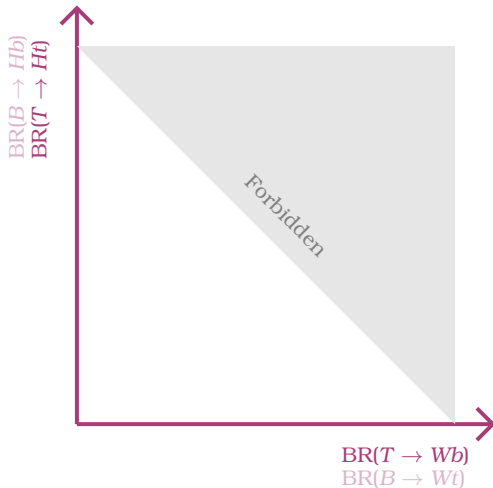
$BR(T \rightarrow Wb)$   
 $BR(B \rightarrow Wt)$

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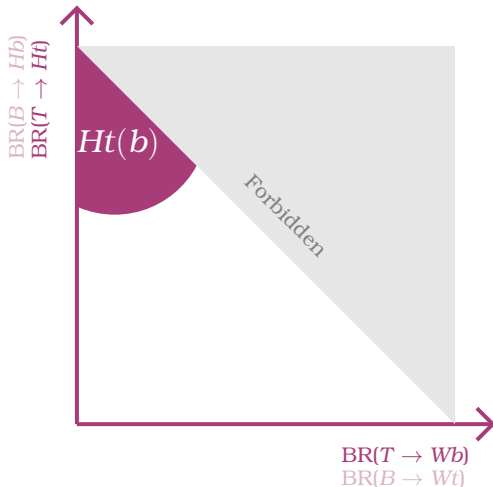
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- Build a 2-dim plane to scan model mixing
- Sum of BRs is 1<sup>(a)</sup>

$$^{(a)}\text{BR}(T/B \rightarrow Zt/b) = 1 - \text{BR}(T/B \rightarrow Ht/b) - \text{BR}(T/B \rightarrow Wb/t)$$

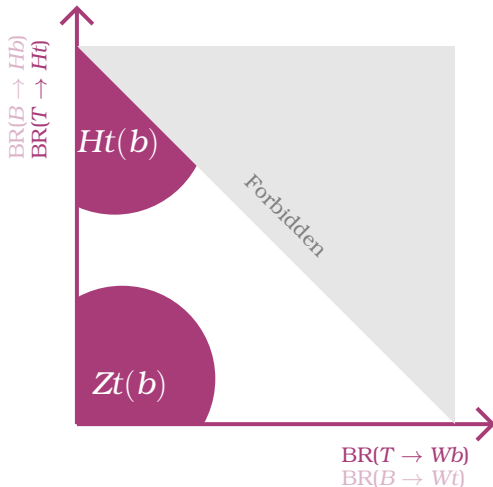
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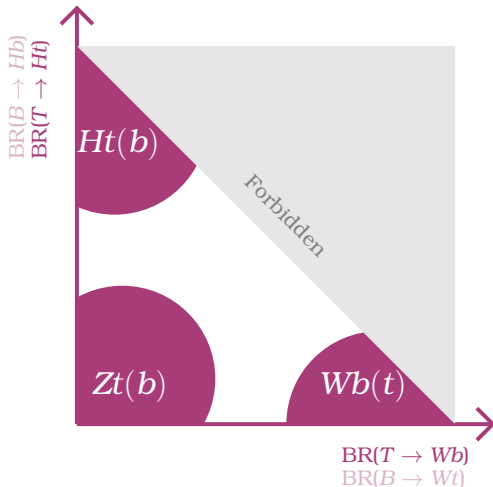
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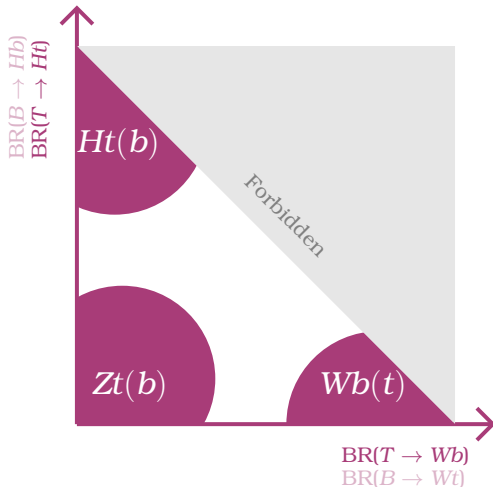
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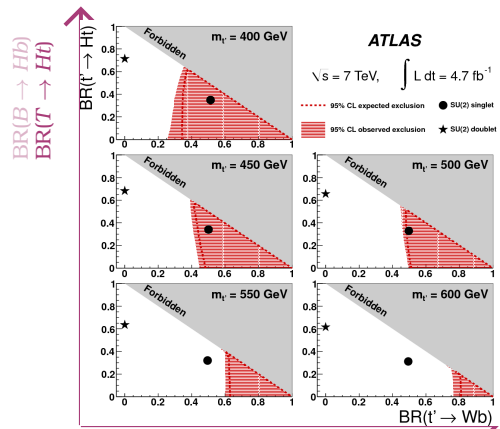
# Model Independent Strategy ... since Oct 2012 [8]!



- Build a 2-dim plane to scan model mixing
- Sum of BRs is 1<sup>(a)</sup>
- Different analyses are sensitive to different areas
- Set exclusion using  $CL_s$  technique [6, 7]
- Using  $14.3 \text{ fb}^{-1}$  of 2012 data

$$^{(a)}\text{BR}(T/B \rightarrow Zt/b) = 1 - \text{BR}(T/B \rightarrow Ht/b) - \text{BR}(T/B \rightarrow Wb/t)$$

# Model Independent Strategy ... since Oct 2012 [8]!



$$\frac{BR(T \rightarrow Wb)}{BR(B \rightarrow Wt)}$$

- Build a 2-dim plane to scan model mixing
- Sum of BRs is 1<sup>(a)</sup>
- Different analyses are sensitive to different areas
- Set exclusion using *CL<sub>s</sub>* technique [6, 7]
- Using 14.3 fb<sup>-1</sup> of 2012 data
- Updating 7 TeV results

$$^{(a)} BR(T/B \rightarrow Zt/b) = 1 - BR(T/B \rightarrow Ht/b) - BR(T/B \rightarrow Wb/t)$$

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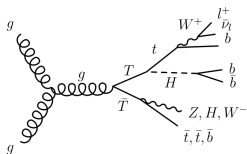
$$T\bar{T} \rightarrow Wb + X$$

Conclusions

# $T\bar{T} \rightarrow Ht + X$

ATLAS-CONF-2013-018 [9]

Channel with high jet and  $b$ -tagged jet multiplicity ( $H \rightarrow bb, t \rightarrow Wb$ )

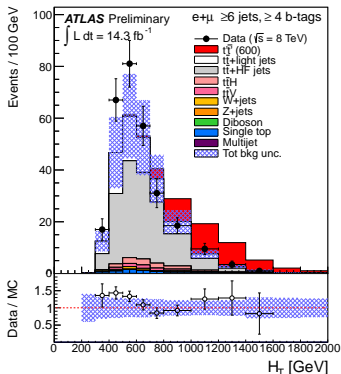
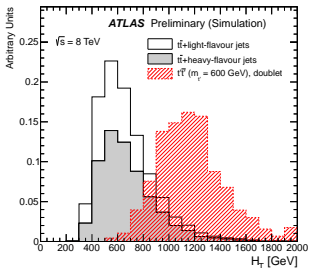


Three channels:  
 $= 2, = 3, \geq 4$   $b$ -tagged jets

Discriminant variable:

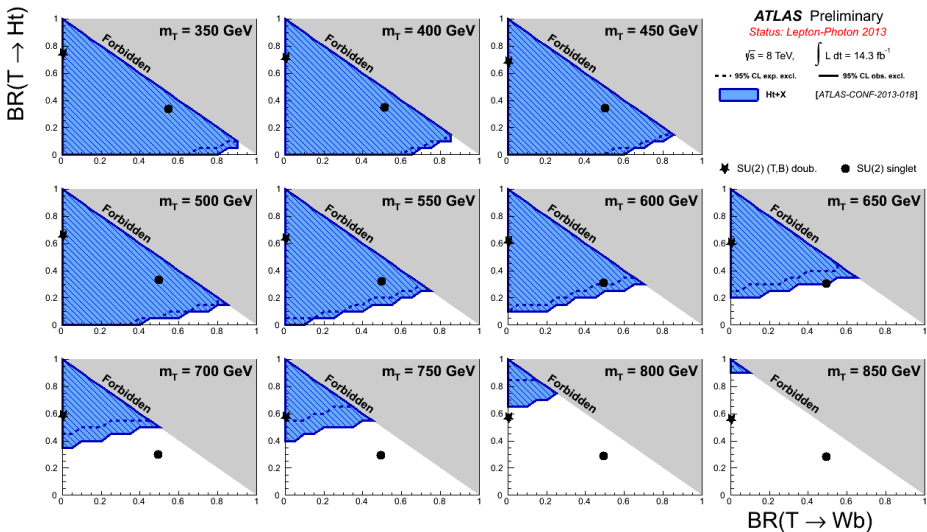
$$H_T = \sum_j p_T(j) + p_T(l) + E_T^{\text{miss}}$$

- ▶ At least 6 jets with  $p_T > 25$  GeV
- ▶ Exactly one well reconstructed, isolated lepton ( $e$  or  $\mu$ )
- ▶  $E_T^{\text{miss}} > 20$  GeV
- ▶  $E_T^{\text{miss}} + m_T(W) > 60$  GeV



$N_{\text{tag}} = 2, 3$  help constrain background systematics

# T exclusion plane [10] I



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$$T\bar{T} \rightarrow Ht + X$$

**Same-sign dileptons**

$$B\bar{B}(T\bar{T}) \rightarrow Zb(t) + X$$

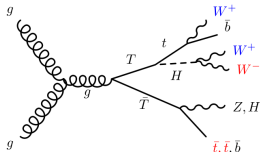
$$T\bar{T} \rightarrow Wb + X$$

Conclusions

# Same-sign dileptons

ATLAS-CONF-2013-051 [11] update of [12]

Channel with very small contamination from SM backgrounds: sensitive to many possible new physics signals like vector-like  $B$  and  $T$ ,  $t\bar{t}t$ ,  $\tilde{g}$



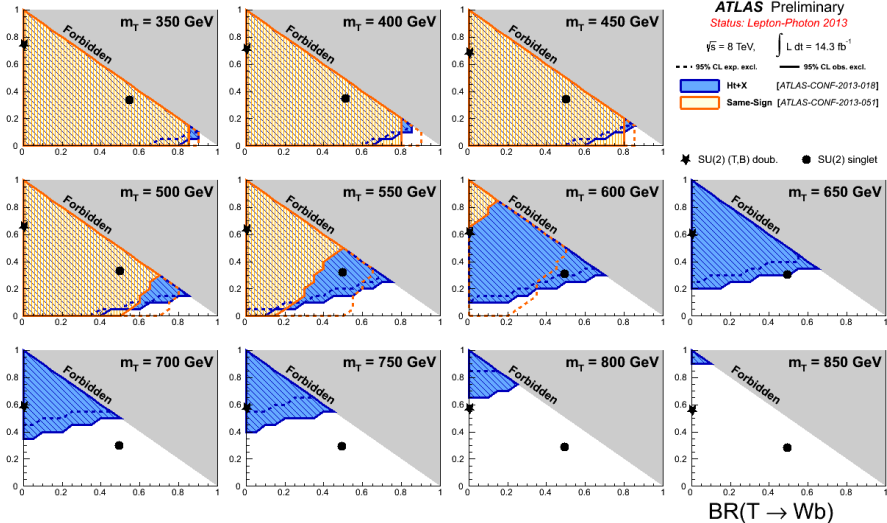
- ▶ Exactly 2 leptons ( $e$  or  $\mu$ ) with same electric charge
- ▶  $\geq 2$  jets with  $p_T > 25$  GeV
- ▶  $E_T^{\text{miss}} > 40$  GeV
- ▶ Z veto in  $ee$  and  $\mu\mu$  channels
- ▶  $\geq 1$   $b$ -tagged jet
- ▶  $H_T^{(1)} > 650$  GeV

Backgrounds	Channel		
	$ee$	$e\mu$	$\mu\mu$
Samples			
Charge misidentification	$0.6 \pm 0.1 \pm 0.2$	$0.9 \pm 0.1 \pm 0.3$	—
Fakes	$0.8 \pm 0.4 \pm 0.3$	$0.2 \pm 0.4 \pm 0.1$	$< 1.1$
Diboson			
• $WZ/ZZ$ +jets	$0.3 \pm 0.2 \pm 0.1$	$0.3 \pm 0.1^{+0.4}_{-0.2}$	$0.4 \pm 0.2 \pm 0.1$
• $W^\pm W^\pm$ +2 jets	$0.17 \pm 0.09 \pm 0.05$	$0.3 \pm 0.2 \pm 0.1$	$0.2 \pm 0.1 \pm 0.1$
$t\bar{t} + W/Z$			
• $t\bar{t}W$ (+jet(s))	$0.6 \pm 0.2 \pm 0.3$	$1.9 \pm 0.2 \pm 0.6$	$1.3 \pm 0.2 \pm 0.4$
• $t\bar{t}Z$ (+jet(s))	$0.18 \pm 0.03 \pm 0.06$	$0.66 \pm 0.05 \pm 0.22$	$0.31 \pm 0.04 \pm 0.10$
• $t\bar{t}W^+W^-$	$0.024 \pm 0.003^{+0.010}_{-0.007}$	$0.072 \pm 0.005^{+0.028}_{-0.020}$	$0.055 \pm 0.004^{+0.022}_{-0.016}$
Total expected background	$2.7 \pm 0.5 \pm 0.4$	$4.4 \pm 0.5^{+0.9}_{-0.7}$	$2.3 \pm 1.2 \pm 0.5$
Observed	3	10	2

(1)  $H_T = \sum_j p_T(j) + p_T(l_1) + p_T(l_2)$

# T exclusion plane [10] II

BR(T → Ht)



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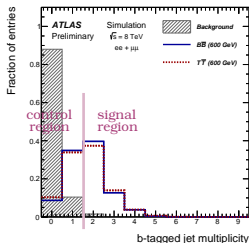
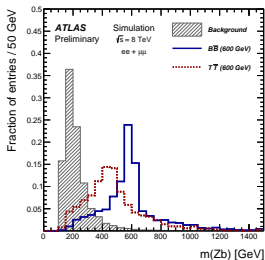
Conclusions

$B\bar{B}(T\bar{T}) \rightarrow Zb(t) + X$ 

ATLAS-CONF-2013-056 [13] update of [14]

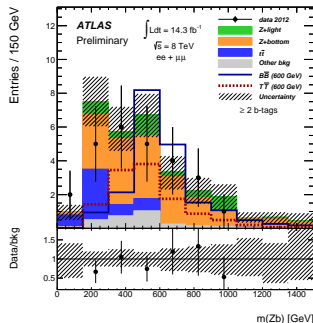
 Exploit ability to reconstruct  $Z$  bosons from OS dileptons ( $e$  and  $\mu$ )

- ▶ Exactly two same flavor, opposite charge leptons
- ▶ Dilepton mass in a 15 GeV mass window around  $m(Z)$
- ▶ At least two  $b$ -tagged jets



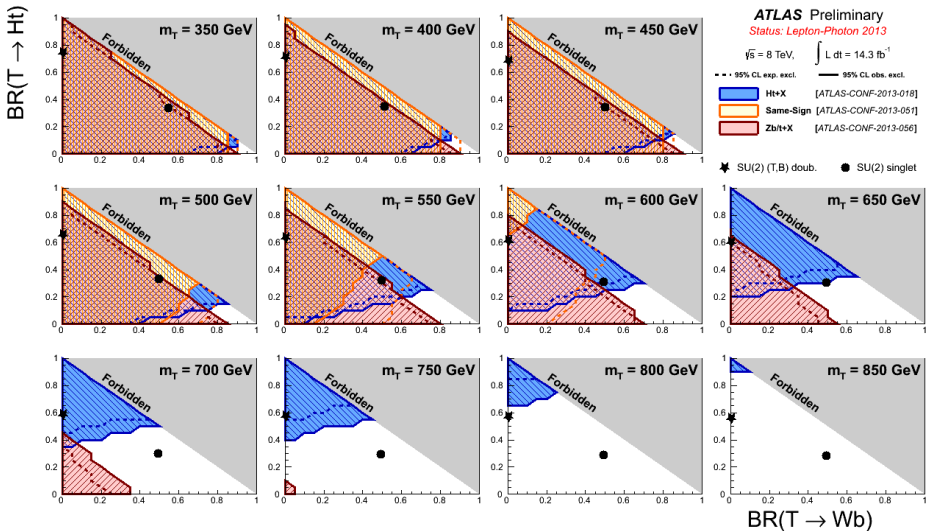
- ▶  $H_T^{(1)} > 600$  GeV
- ▶  $p_{T(Z)} > 150$  GeV

$$H_T^{(1)} = \sum_{\text{jets}} p_T(j)$$



$m(Zb)$  is the final test variable:  
invariant mass of the  $Z$  candidate  
paired with the highest  $p_T$   $b$ -tagged jet

# T exclusion plane [10] III



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Same-sign dileptons

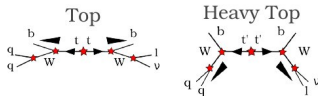
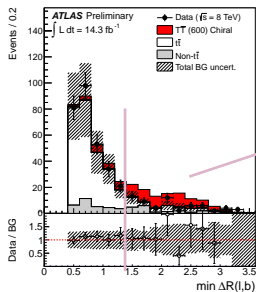
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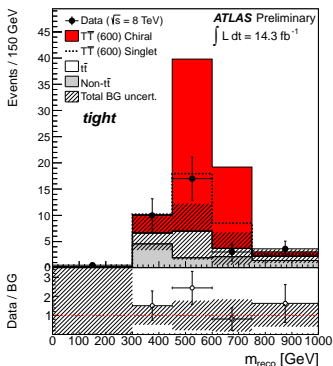
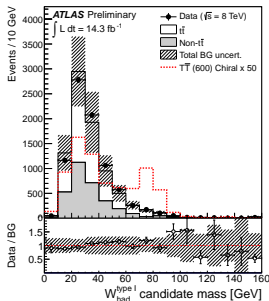
Conclusions

$T\bar{T} \rightarrow Wb + X$ 

ATLAS-CONF-2013-060 [15] update of [8]

 Exploit  $T$ 's boosted kinematics to reconstruct  $W$  bosons


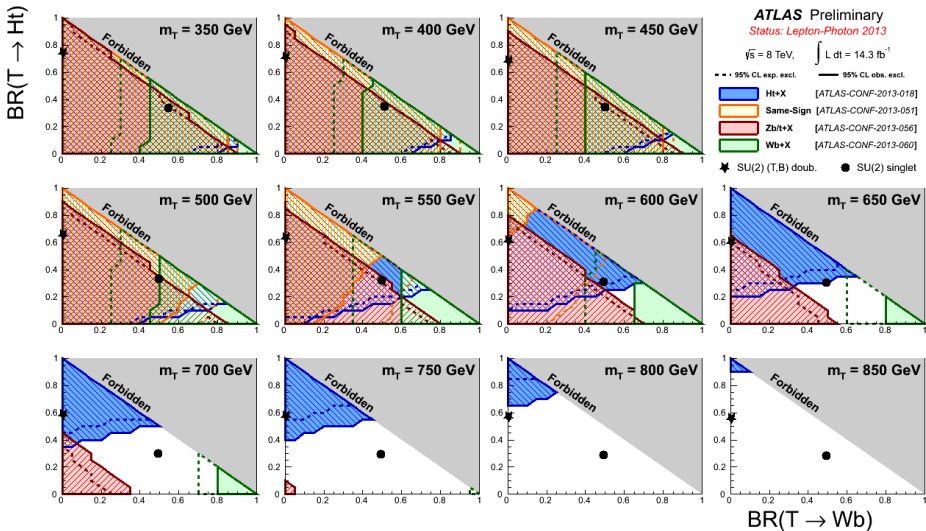
- ▶  $\Delta R(l, \nu) < 1.2$
- ▶  $\min(\Delta R(l, b_{1,2})) > 1.4$
- ▶  $\min(\Delta R(W_{had}, b_{1,2})) > 1.4$



- ▶  $W_{had}^{typeI}$ : single merged jet  
 $(p_T > 250 \text{ GeV}, m_j \in [60, 120] \text{ GeV})$
- ▶  $W_{had}^{typeII}$ : two close-by jets  
 $(\Delta R(j, j) < 0.8, p_T > 200 \text{ GeV}, m_{jj} \in [60, 120] \text{ GeV})$

The reconstructed  $W$  boson is matched to the  $b$ -tagged jets that gives the lowest mass difference between the leptonical and hadronical leg

# T exclusion plane [10] IV



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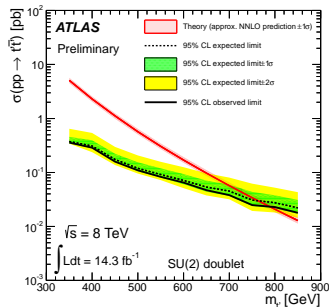
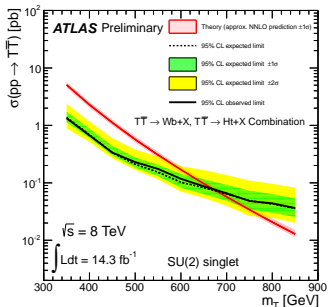
Conclusions

# Conclusions

Using  $14 \text{ fb}^{-1}$  of  $\sqrt{s} = 8 \text{ TeV}$  2012 LHC data, ATLAS performed four preliminary **model independent** and **complementary** searches for heavy quarks

At 95% CL we exclude:

- ▶ Singlet  $T$  with mass up to 670 GeV [9, 15]
- ▶ Doublet  $T$  with mass up to 790 GeV [9]
- ▶ Chiral fourth-generation top quarks with mass up to 740 GeV [15]



Stay tuned for the  $20 \text{ fb}^{-1}$  updates!

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- [8] ATLAS Collaboration.  
Search for pair production of heavy top-like quarks decaying to a high-pT  $W$  boson and a  $b$  quark in the lepton plus jets final state at  $\sqrt{s} = 7$  TeV with the ATLAS detector.  
*Phys.Lett.*, B718:1284–1302, 2012.

## References III

[9] ATLAS collaboration.

Search for heavy top-like quarks decaying to a higgs boson and a top quark in the lepton plus jets final state in  $pp$  collisions at  $\sqrt{s} = 8$  tev with the atlas detector.

*ATLAS-CONF-2013-018*, Mar 2013.

[10] ATLAS Collaboration.

ExoticsVLQSummary (short url: <http://goo.gl/QahRE>).

[11] ATLAS collaboration.

Search for anomalous production of events with same-sign dileptons and  $b$  jets in  $14.3 \text{ fb}^{-1}$  of  $pp$  collisions at  $\sqrt{s} = 8$  tev with the atlas detector.

*ATLAS-CONF-2013-051*, May 2013.

[12] ATLAS collaboration.

Search for exotic same-sign dilepton signatures ( $b'$  quark,  $T_{5/3}$  and four top quarks production) in  $4.7/\text{fb}$  of  $pp$  collisions at  $\sqrt{s} = 7$  TeV with the ATLAS detector.

*ATLAS-CONF-2012-130*, Sep 2012.

## References IV

[13] ATLAS Collaboration.

Search for pair production of new heavy quarks that decay to a  $Z$  boson and a third generation quark in  $pp$  collisions at  $\sqrt{s} = 8$  TeV with the ATLAS detector.

*ATLAS-CONF-2013-056*, Jun 2013.

[14] ATLAS Collaboration.

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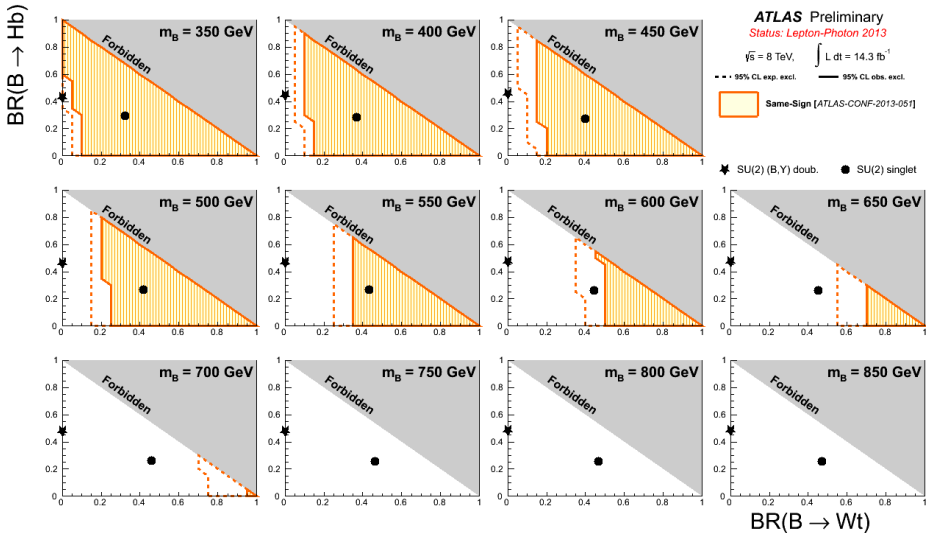
[15] ATLAS Collaboration.

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*ATLAS-CONF-2013-060*, Jun 2013.

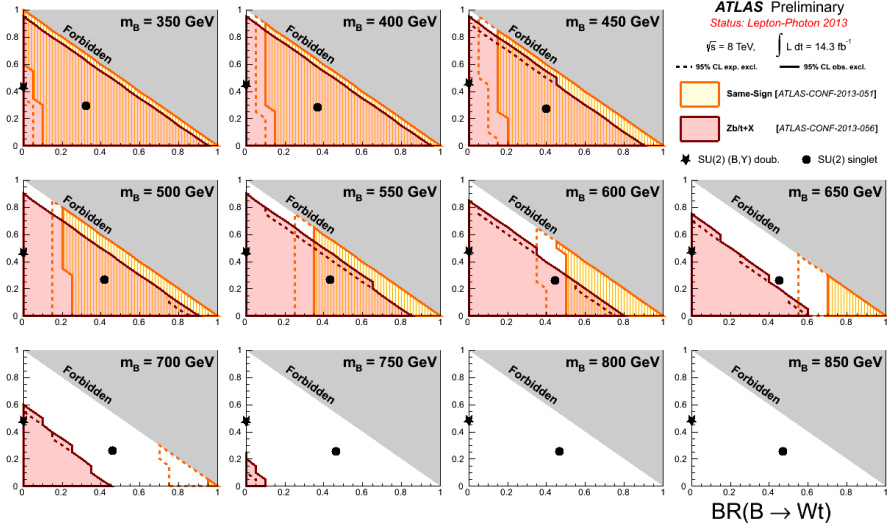
## **BACKUP SLIDES**

# B exclusion plane [10] I



# B exclusion plane [10] II

BR(B → Hb)



# Event preselection

ATLAS working groups defined standard object definitions  
analyses use in general these definitions, as well as common selections

## Object definitions

- ▶ **Jets:** Topological clusters reconstructed with the AntikT4 algorithm ( $p_T > 25$  GeV,  $|\eta| < 2.5$ ,  $JVF > 0.5^{(a)}$ )
- ▶ **Electrons:** Well isolated calo object matched to track ( $E_T > 25$  GeV,  $|\eta|$  in  $[0, 2.47]$  removing  $[1.37, 1.52]$ ,  $z_0 < 2$  mm<sup>(b)</sup>)
- ▶ **Muons:** Segment in the tracker and muon detector, isolated track ( $p_T > 25$  GeV,  $|\eta| < 2.5$ ,  $z_0 < 2$  mm<sup>(b)</sup>)

If jets within  $\Delta R < 0.2$  of an electron, the closest jet is discarded; Leptons within  $\Delta R < 0.4$  of a jet are removed

## Event pre-selection

- ▶  $\geq 5$  tracks from the Primary Vertex (Cosmics and Pileup rejection)
- ▶ If more vertices, choose the one with largest sum of  $p_T^2$
- ▶ Single lepton triggers: isolated electron with  $p_T > 24$  GeV OR electron with  $p_T > 60$  GeV OR isolated muon with  $p_T > 24$  GeV OR muon with  $p_T > 36$  GeV

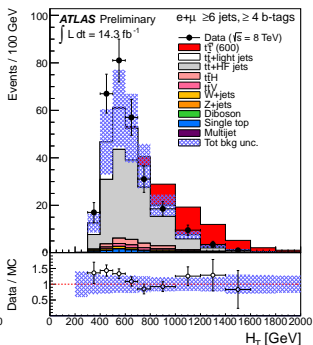
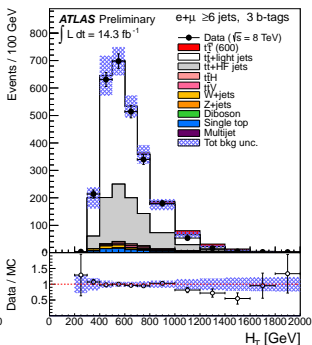
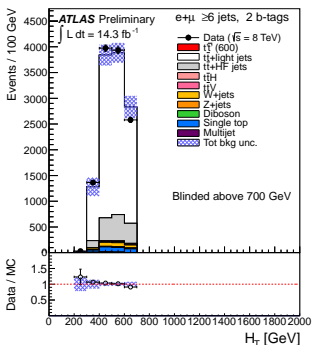
If the analysis requires one or more leptons, at least one of them must match the single lepton trigger

<sup>(a)</sup> the jet vertex fraction is defined as the fraction of summed  $p_T$  ( $> 0.5$  GeV) of tracks associated to the jet that come from the primary vertex

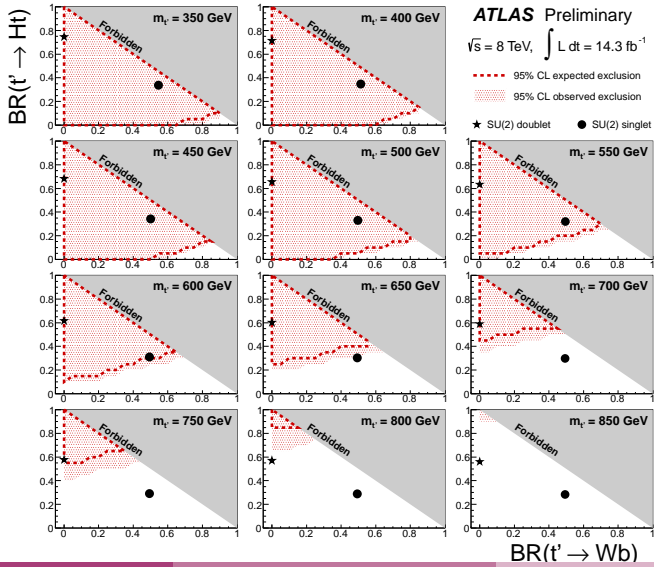
<sup>(b)</sup>  $z_0$  is the longitudinal impact parameter of the track wrt the primary vertex

$$\bar{T}\bar{T} \rightarrow Ht + X \text{ [9]}$$

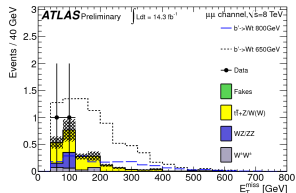
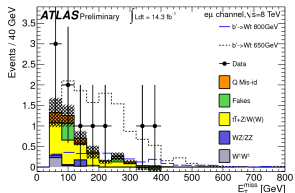
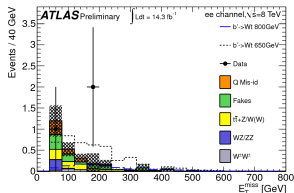
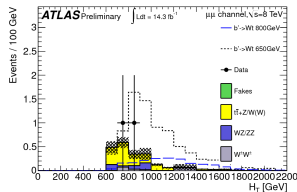
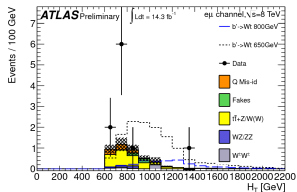
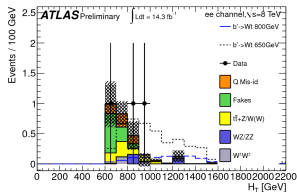
Three channels:  
 $= 2, = 3, \geq 4$  *b*-tagged jets



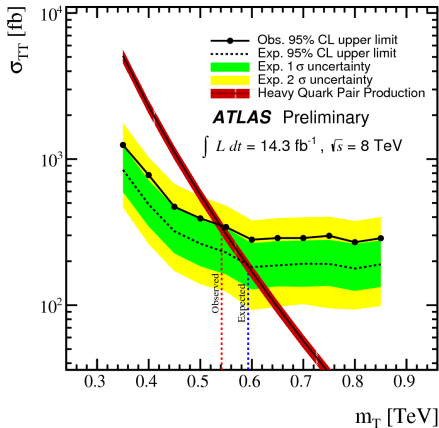
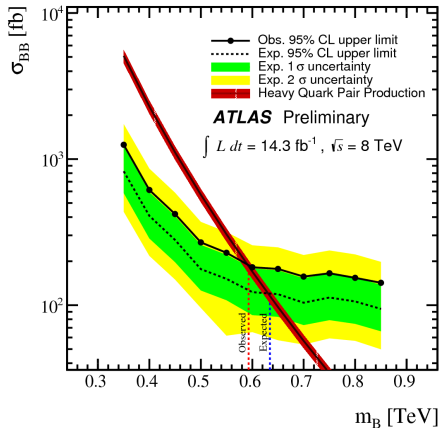
$T\bar{T} \rightarrow Ht + X$  [9]



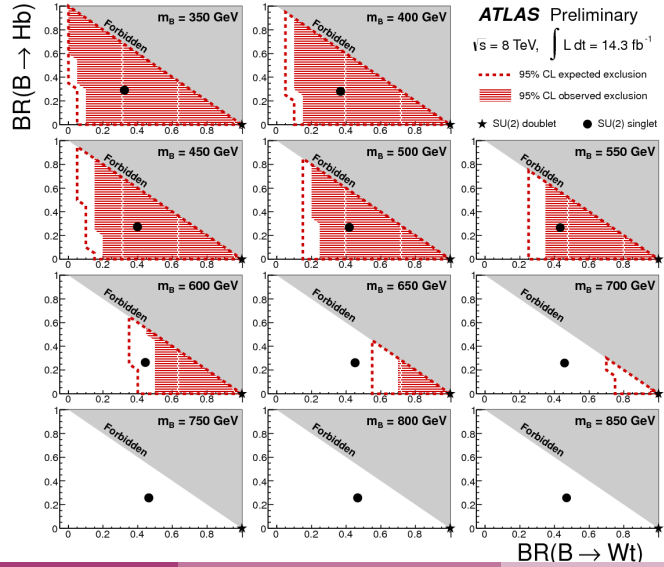
# Same-sign dileptons [11]



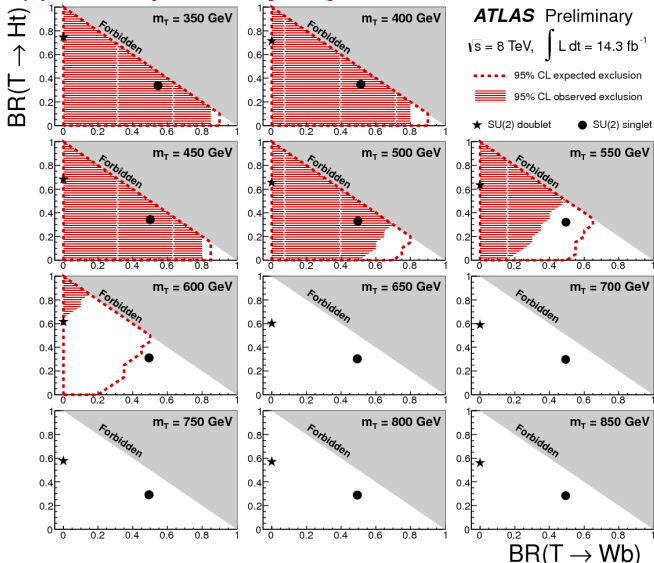
# Same-sign dileptons [11]



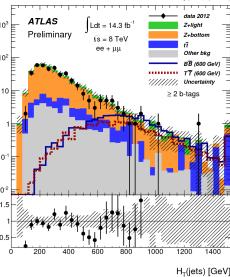
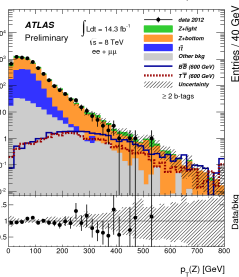
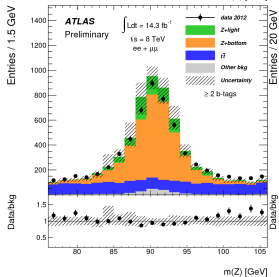
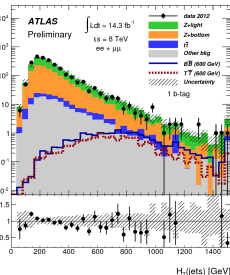
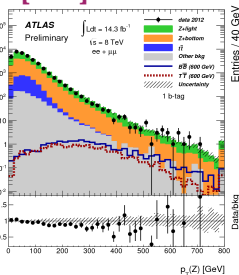
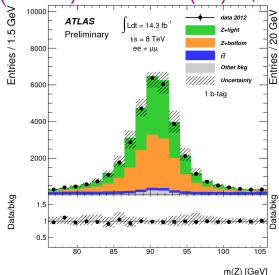
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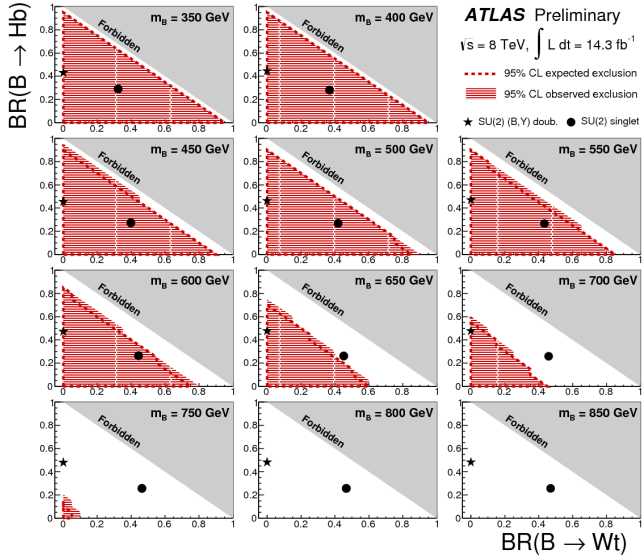
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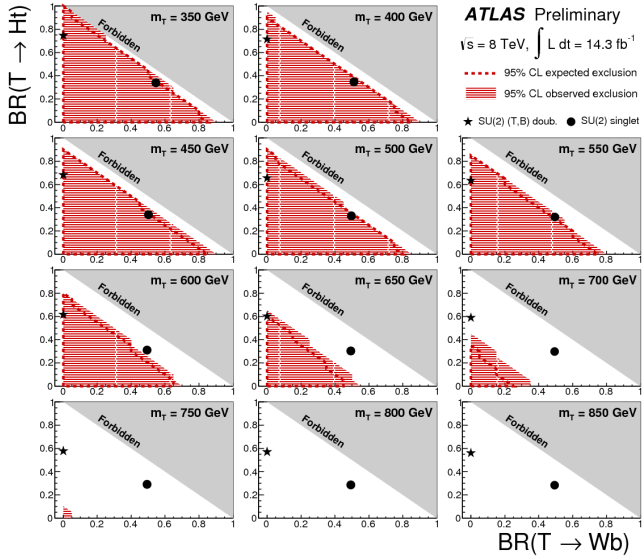
# $B\bar{B}(T\bar{T}) \rightarrow Zb(t) + X$ [13]



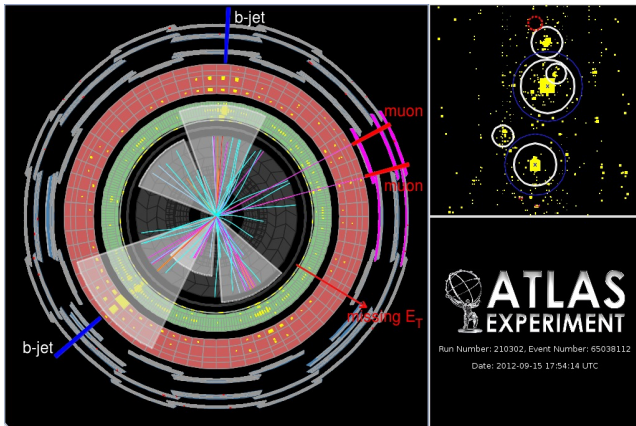
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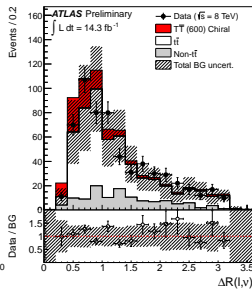
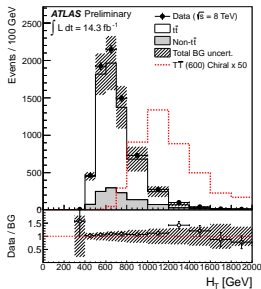


$$B\bar{B}(T\bar{T}) \rightarrow Zb(t) + X \text{ [13]}$$



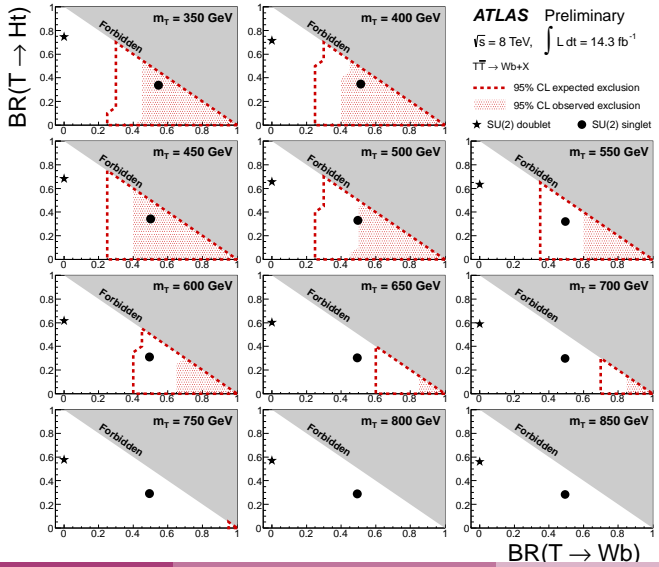
# $T\bar{T} \rightarrow Wb + X$ [15]

- ▶ one lepton ( $e$  or  $\mu$ ),  $E_T^{\text{miss}} > 20$  GeV,  $E_T^{\text{miss}} + m_T(W) > 60$  GeV
  - ▶  $\geq 3$  jets and one  $W_{had}^{typeI}$
- OR
- ▶  $\geq 4$  jets and one  $W_{had}^{typeII}$  and no  $W_{had}^{typeI}$
  - ▶  $\geq 1$   $b$ -tagged jet (consider also the 2nd highest  $b$ -tag weight jet)
  - ▶  $H_T^{(a)} > 800$  GeV
  - ▶  $p_T(b_1) > 160$  GeV,  $p_T(b_2) > 80$  GeV
  - ▶  $\Delta R(l, \nu) < 1.2$
  - ▶  $\min(\Delta R(l, b_{1,2})) > 1.4$
  - ▶  $\min(\Delta R(W_{had}, b_{1,2})) > 1.4$

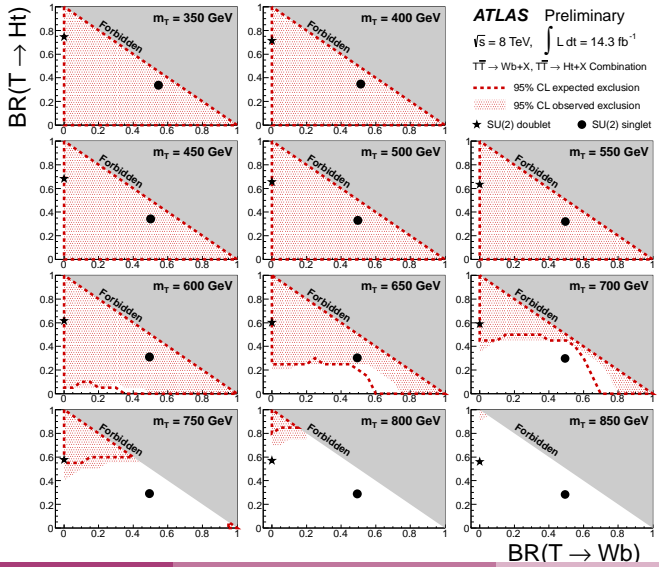


$$^{(a)}H_T = p_T(j_1) + p_T(j_2) + p_T(j_3) + p_T(j_4) + p_T(l) + E_T^{\text{miss}}$$

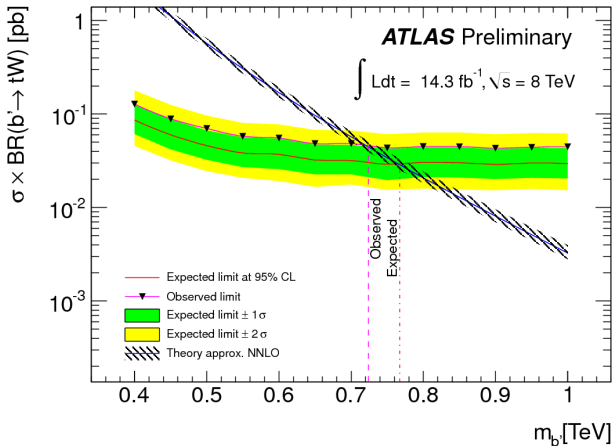
# $T\bar{T} \rightarrow Wb + X$ [15]



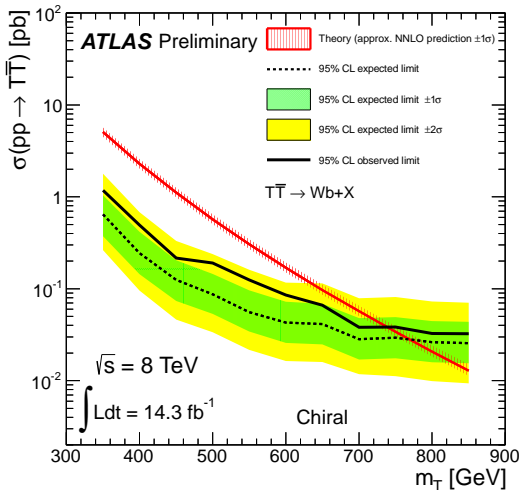
# combining $T\bar{T} \rightarrow Ht + X$ [9] and $T\bar{T} \rightarrow Wb + X$ [15]



# Results on chiral quarks: $b' \rightarrow Wt$ (100%) [11]



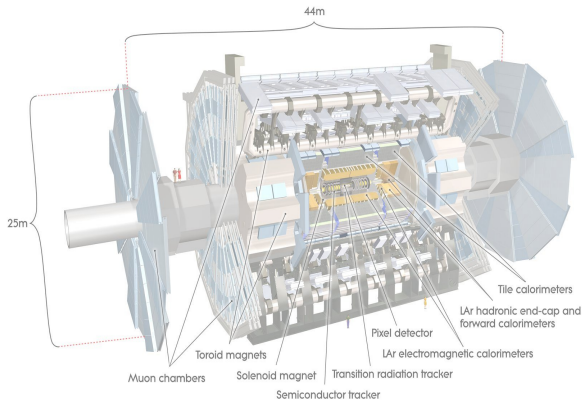
# Results on chiral quarks: $t' \rightarrow Wb$ (100%) [15]



# The ATLAS Detector

A general purpose experiment

- ▶ vertex detector and central tracker
- ▶ superconducting solenoid
- ▶ electromagnetic and hadronic calorimeters
- ▶ muon spectrometer
- ▶ superconducting toroids
- ▶ high hermeticity (full  $\phi$  and  $|\eta| < 5$ )

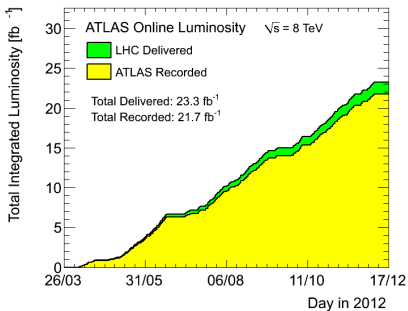


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In 2012  $21.7 \text{ fb}^{-1}$  collected at  $\sqrt{s} = 8 \text{ TeV}$ !



See [ATLAS public page](#)

Will present results obtained with  $14.3 \text{ fb}^{-1}$  of 2012 data