Searches for vector-like quarks with the ATLAS detector

Antonella Succurro

on behalf of
the ATLAS collaboration

EPS 2013, Stockholm, July 18th-24th

Outline

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]

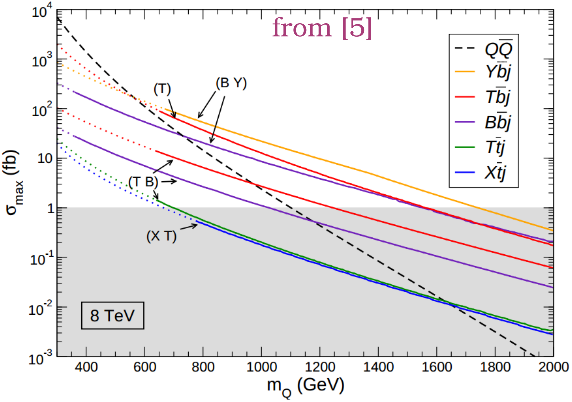
- Not chiral[(a)]: chiral 4th generation would change the Higgs SM cross section and B.R.
- Vector-like: left and right components transform the same under $SU(2) \times U(1)$
- Weak-isospin singlets, doublets or triplets

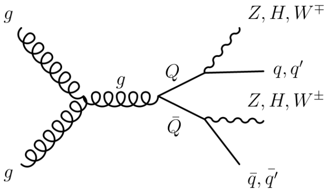
naturally solve the hierarchy problem,
like a stop squark in SUSY

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		

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

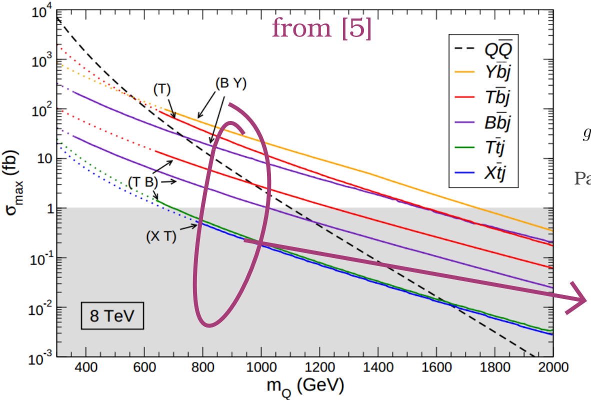
Heavy quark production

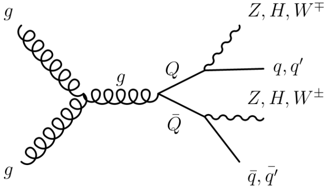




Pair-production via strong interaction

Heavy quark production





Pair-production via strong interaction

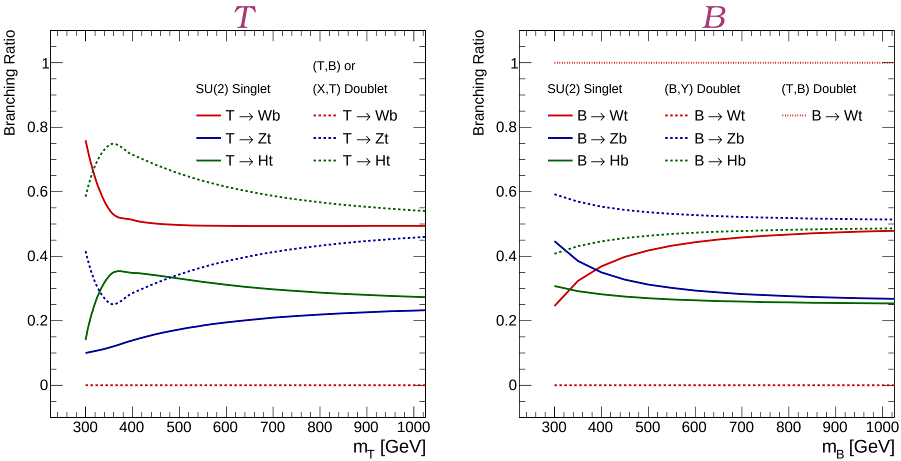
EW single production
could dominate at high mass

Outline

Heavy quark decay modes

B.R.s are very model dependent

- most analyses optimized for specific decay channels

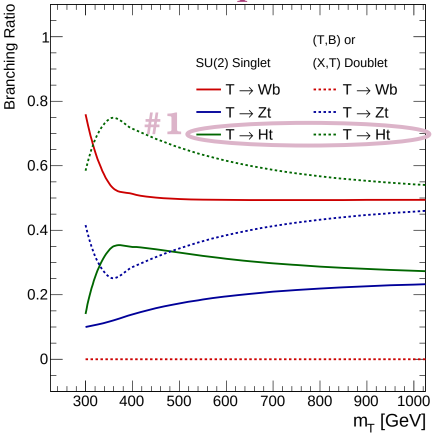


Heavy quark decay modes

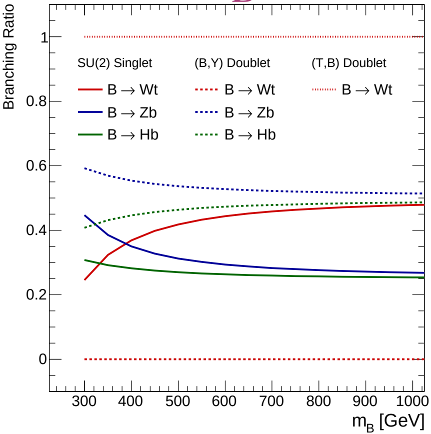
B.R.s are very model dependent

- most analyses optimized for specific decay channels

T



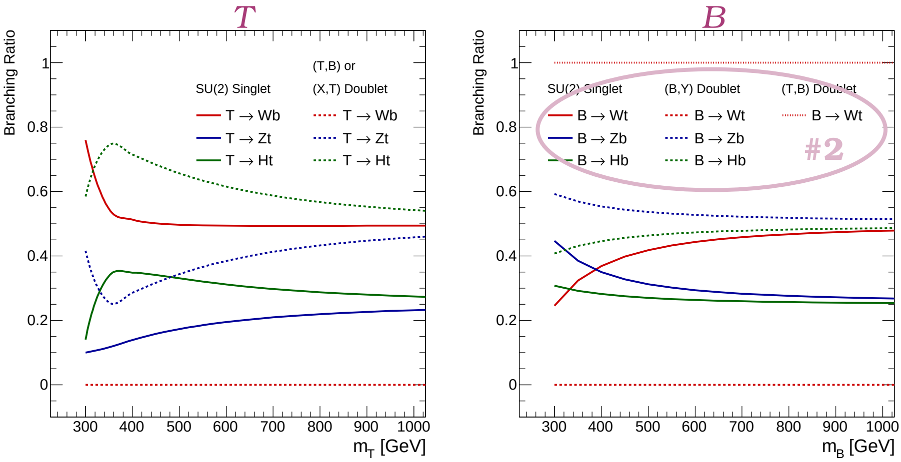
B



Heavy quark decay modes

B.R.s are very model dependent

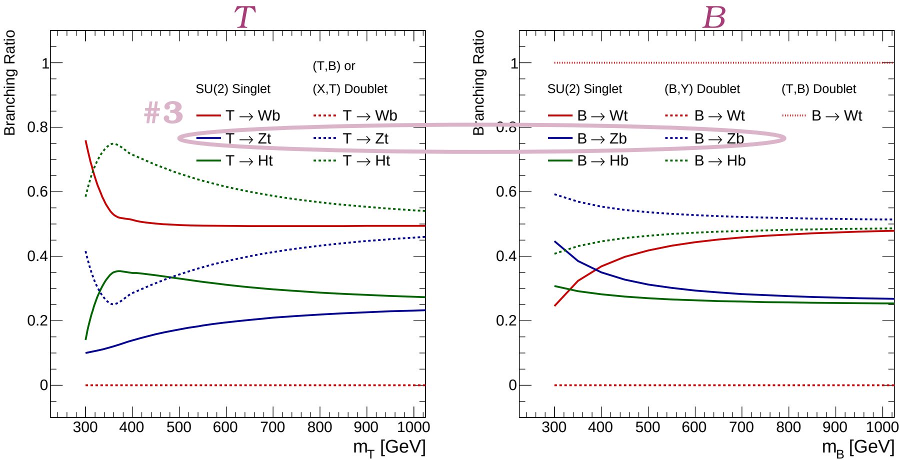
- most analyses optimized for specific decay channels



Heavy quark decay modes

B.R.s are very model dependent

- most analyses optimized for specific decay channels

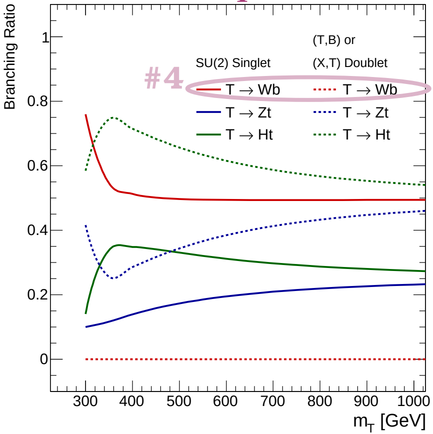


Heavy quark decay modes

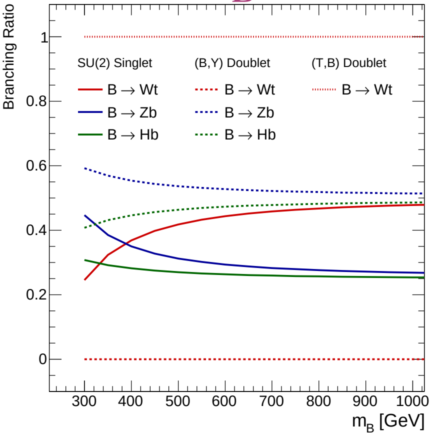
B.R.s are very model dependent

- most analyses optimized for specific decay channels

T



B

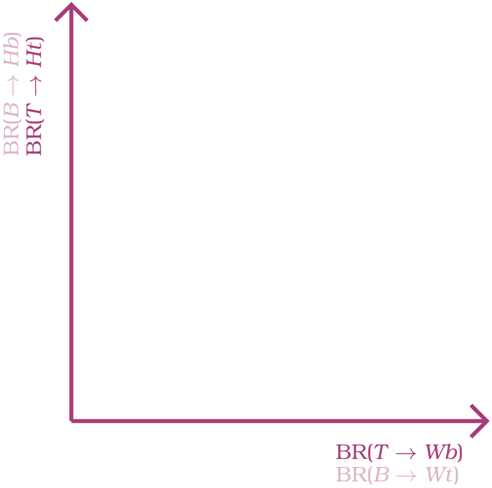


Model Independent Strategy . . . since Oct 2012 [8]!

- Build a 2-dim plane to scan model mixing

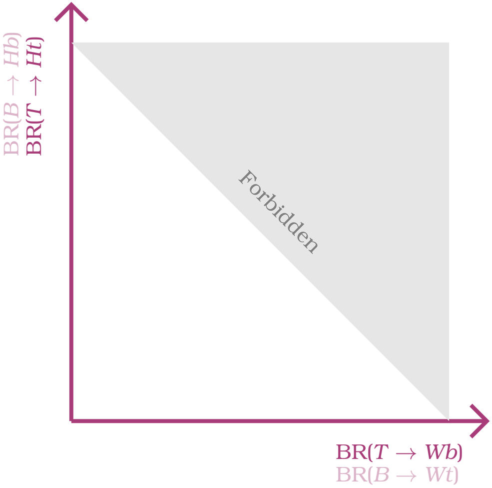
BR($T \to Wb$)
BR($B \to Wt$)

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



- Build a 2-dim plane to scan model mixing

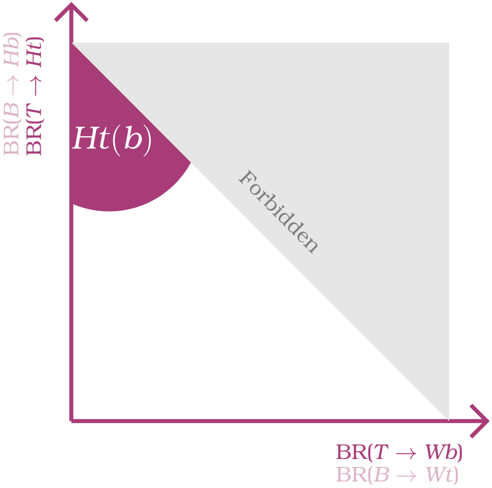
Model Independent Strategy ... since Oct 2012 [8]!



- Build a 2-dim plane to scan model mixing
- Sum of BRs is 1[a]

[a] BR($T/B \to Zt/b$) = 1 - BR($T/B \to Ht/b$) - BR($T/B \to Wb/t$)

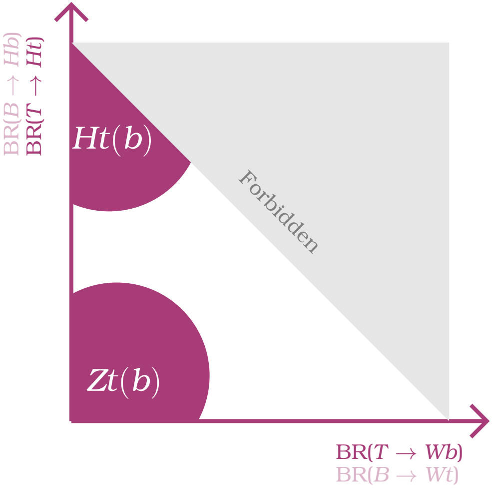
Model Independent Strategy ... since Oct 2012 [8]!



- Build a 2-dim plane to scan model mixing
- Sum of BRs is 1[(a)]
- Different analyses are sensitive to different areas

(a) BR($T/B \to Zt/b$) = 1 - BR($T/B \to Ht/b$) - BR($T/B \to Wb/t$)

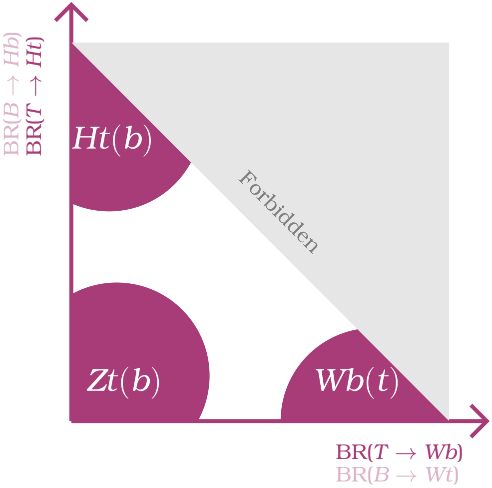
Model Independent Strategy ...since Oct 2012 [8]!



- Build a 2-dim plane to scan model mixing
- Sum of BRs is 1[a]
- Different analyses are sensitive to different areas

[a] $BR(T/B \to Zt/b)$ = 1 - $BR(T/B \to Ht/b)$ - $BR(T/B \to Wb/t)$

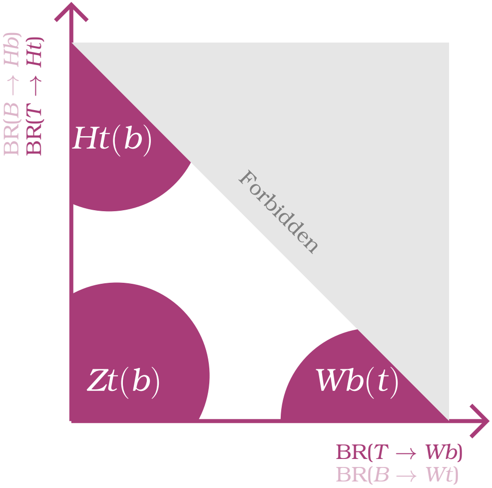
Model Independent Strategy ...since Oct 2012 [8]!



- Build a 2-dim plane to scan model mixing
- Sum of BRs is 1[(a)]
- Different analyses are sensitive to different areas

[(a)] BR($T/B \to Zt/b$) = 1 - BR($T/B \to Ht/b$) - BR($T/B \to Wb/t$)

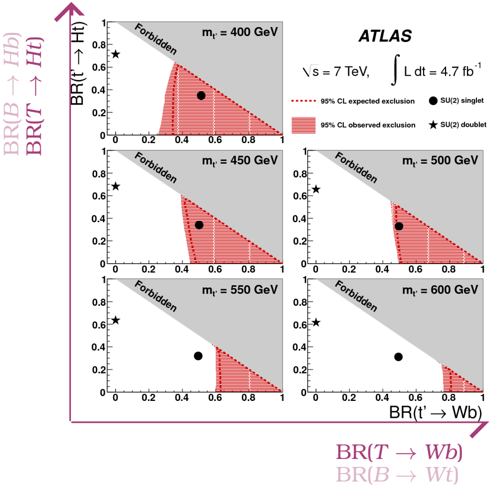
Model Independent Strategy ... since Oct 2012 [8]!



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

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

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



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

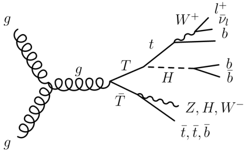
[(a)] BR($T/B \rightarrow Zt/b$) = 1 - BR($T/B \rightarrow Ht/b$) - BR($T/B \rightarrow Wb/t$)

Outline

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

ATLAS-CONF-2013-018 [9]

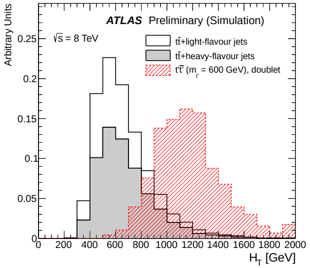
Channel with high jet and b-tagged jet multiplicity ($H \to bb$, $t \to Wb$)

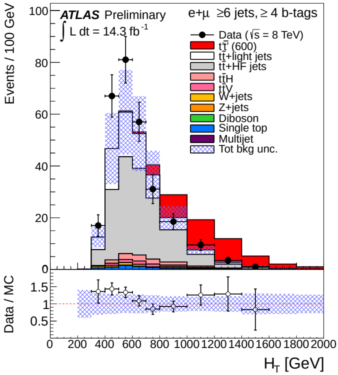


Three channels:
$= 2$, $= 3$, ≥ 4 b-tagged jets

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

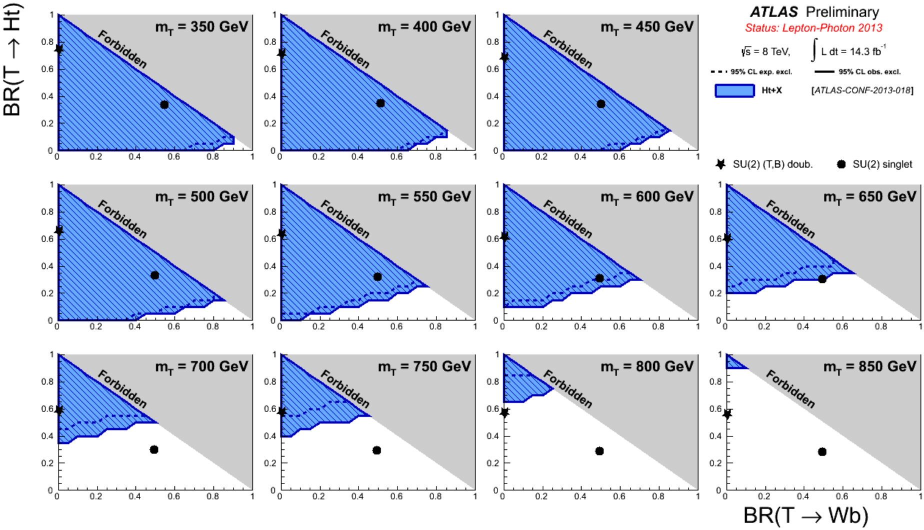
- At least 6 jets with $p_T > 25$ GeV
- Exactly one well reconstructed, isolated lepton (e or μ)
- $E_T^{\text{miss}} > 20$ GeV
- $E_T^{\text{miss}} + m_T(W) > 60$ GeV





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

T exclusion plane [10] I

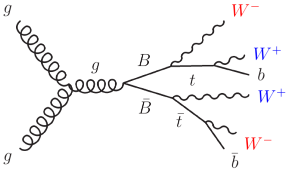


Outline

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, $t\bar{t}t\bar{t}$, $\tilde{g}$

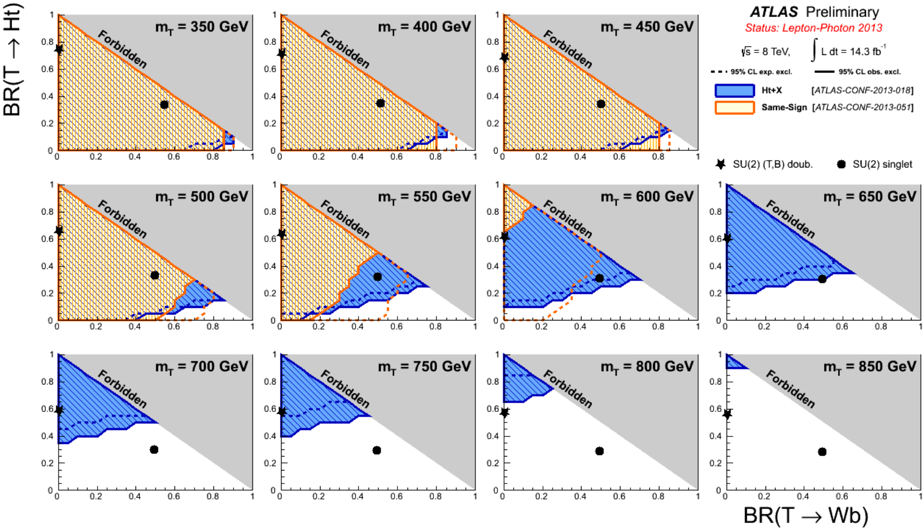


- Exactly 2 leptons (e or μ) with same electric charge
- Z veto in ee and $\mu\mu$ channels
- $\geq$ 2 jets with $p_T >$ 25 GeV
- $\geq$ 1 b-tagged jet
- $E_T^{miss} >$ 40 GeV
- $H_T^{(1)} >$ 650 GeV

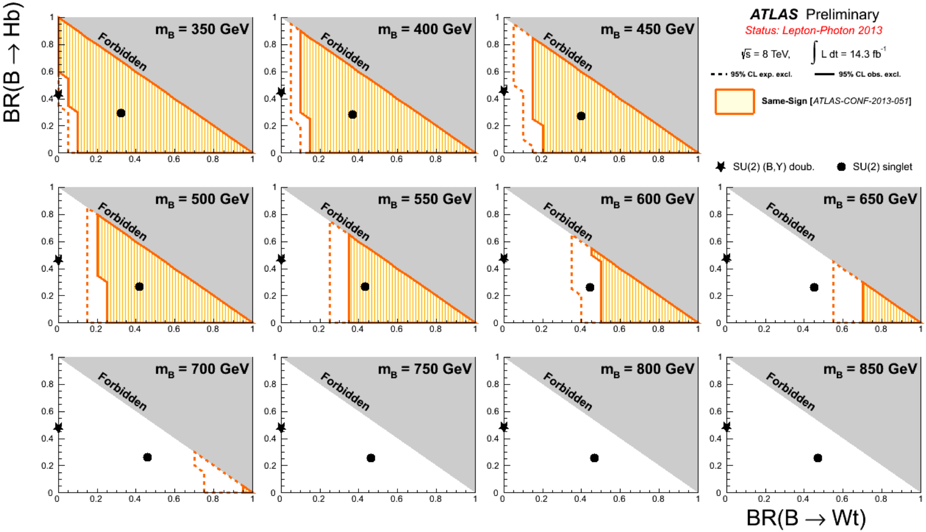
Backgrounds	Channel		
Samples	ee	$e\mu$	$\mu\mu$
Charge misidentification	$0.6 \pm 0.1 \pm 0.2$	$0.9 \pm 0.1 \pm 0.3$	—
Fakes	$0.8 \pm 0.4 \pm 0.3$	$0.2 \pm 0.4 \pm 0.1$	< 1.1
Diboson			
• WZ/ZZ+jets	$0.3 \pm 0.2 \pm 0.1$	$0.3 \pm 0.1^{+0.4}_{-0.2}$	$0.4 \pm 0.2 \pm 0.1$
• $W^\pm W^\pm$+2 jets	$0.17 \pm 0.09 \pm 0.05$	$0.3 \pm 0.2 \pm 0.1$	$0.2 \pm 0.1 \pm 0.1$
$t\bar{t} + W/Z$			
• $t\bar{t}W$(+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



B exclusion plane [10] I

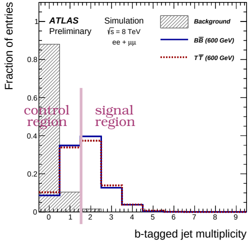


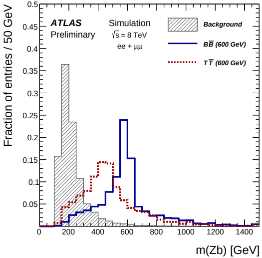
Outline

$B\bar{B}(T\bar{T}) \to Zb(t) + X$ ATLAS-CONF-2013-056 [13] update of [14]

Exploit ability to reconstruct Z bosons from OS dileptons (e and μ)

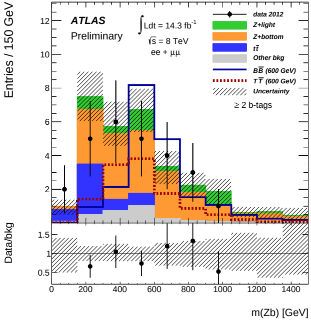
- Exactly two same flavor, opposite charge leptons
- Dilepton mass in a 15 GeV mass window around $m(Z)$
- At least two $b-$tagged jets





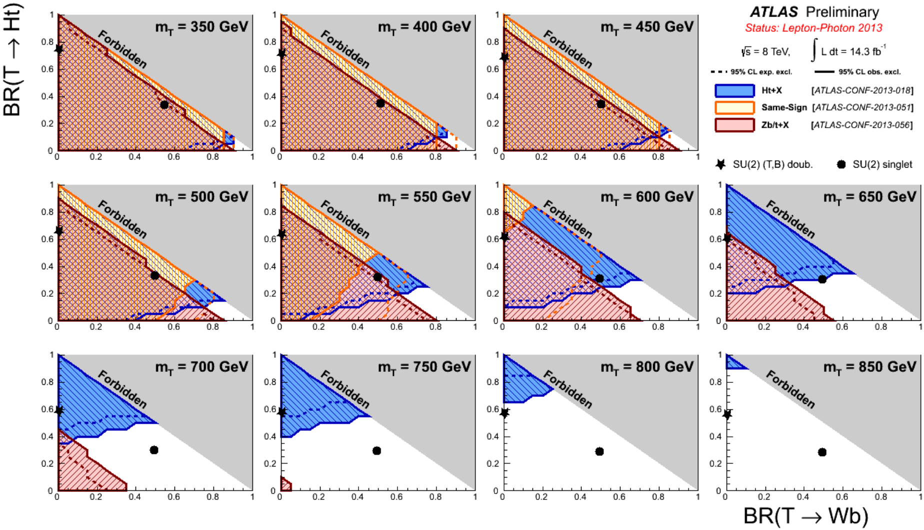
- $H_T^{(1)} > 600$ GeV
- $p_T(Z) > 150$ GeV

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

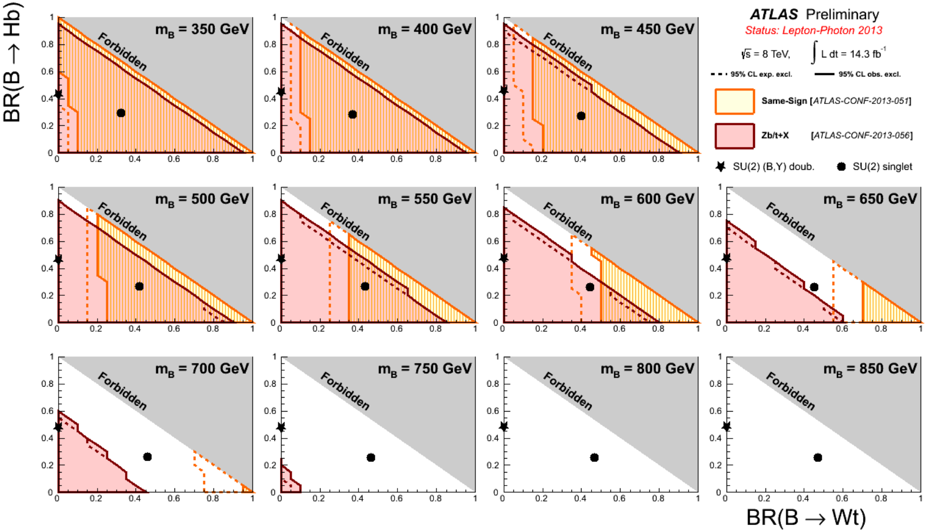


$m(Zb)$ is the final test variable: invariant mass of the Z candidate paired with the highest p_T b-tagged jet

T exclusion plane [10] III



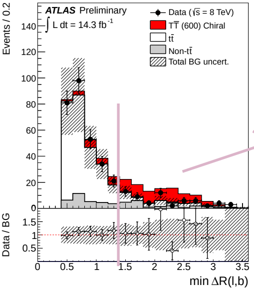
B exclusion plane [10] II

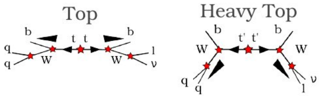


Outline

$T\bar{T} \to Wb + X$ ATLAS-CONF-2013-060 [15] update of [8]

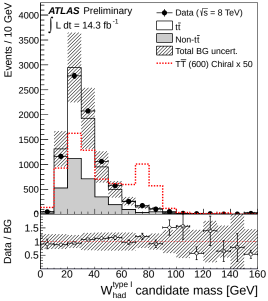
Exploit T's boosted kinematics to reconstruct W bosons

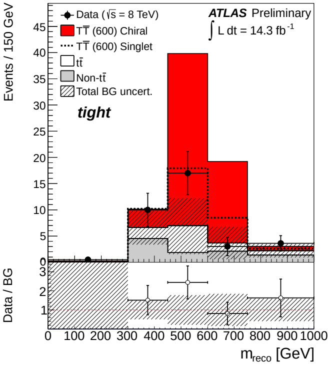




- $\Delta R(l, \nu) < 1.2$
- $min(\Delta R(l, b_{1,2})) > 1.4$
- $min(\Delta R(W_{had}, b_{1,2})) > 1.4$

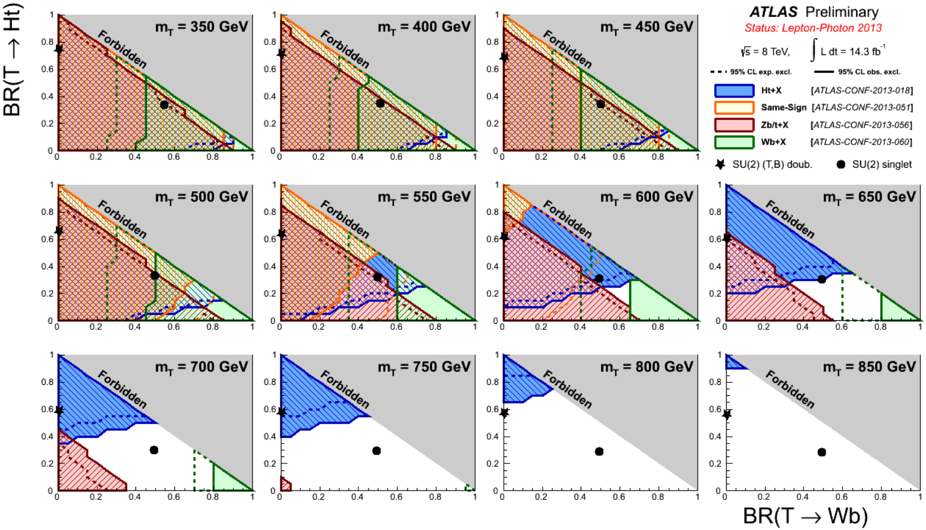
- W_{had}^{typeI}: single merged jet ($p_T > 250$ GeV, $m_j \in [60, 110]$ GeV)
- W_{had}^{typeII}: two close-by jets ($\Delta R(j, j) < 0.8$, $p_T > 150$ GeV, $m_{jj} \in [60, 110]$ GeV)





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



Outline

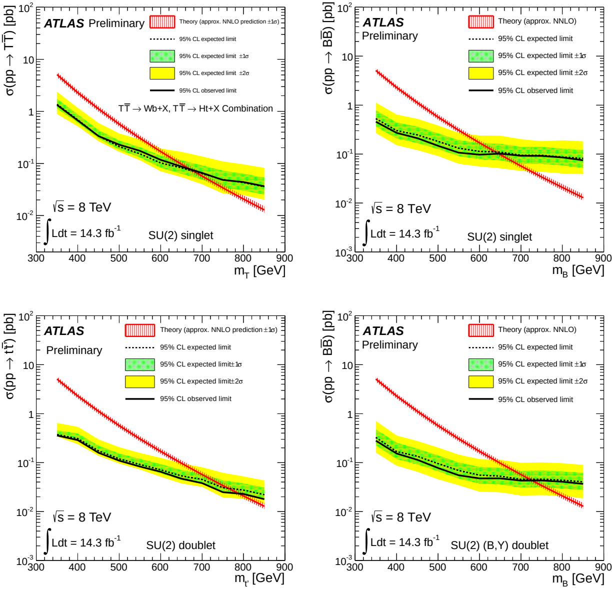
Conclusions

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

- Updating $\sqrt{s} = 7$ TeV analyses

Considering a few benchmark points, at 95% CL we exclude:

- Singlet T with mass up to 670 GeV [9, 15]
- Singlet B with mass up to 645 GeV [13]
- Doublet T with mass up to 790 GeV [9]
- Doublet B with mass up to 725 GeV [13]



References I

[1] Csaba Csaki.
TASI lectures on extra dimensions and branes.
pages 605–698, 2004.

[2] Maxim Perelstein.
Little Higgs models and their phenomenology.
Prog.Part.Nucl.Phys., 58:247–291, 2007.

[3] J.A. Aguilar-Saavedra.
Identifying top partners at LHC.
JHEP, 0911:030, 2009.

[4] S.A. Cetin, G.W.S. Hou, V.E. Ozcan, A.N. Rozanov, and S. Sultansoy.
Status of the Fourth Generation: A Brief Summary of B3SM-III Workshop in Four Parts.
arXiv:1112.2907, 2011.

References II

[5] J.A. Aguilar-Saavedra, R. Benbrik, S. Heinemeyer, and M. Perez-Victoria.
A handbook of vector-like quarks: mixing and single production.
2013.

[6] Thomas Junk.
Confidence level computation for combining searches with small statistics.
Nucl.Instrum.Meth., A434:435–443, 1999.

[7] Alexander L. Read.
Presentation of search results: The CL(s) technique.
J.Phys., G28:2693–2704, 2002.

[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 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/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 $\mathbf{Z}$ boson and a third generation quark in $\mathbf{pp}$ collisions at $\sqrt{\mathbf{s}} = \mathbf{8}$ TeV with the ATLAS detector.
ATLAS-CONF-2013-056, Jun 2013.

[14] ATLAS Collaboration.
Search for pair production of a new quark that decays to a Z boson and a bottom quark with the ATLAS detector.
Phys.Rev.Lett., 109:071801, 2012.

[15] 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 in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector.
ATLAS-CONF-2013-060, Jun 2013.

BACKUP SLIDES

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$^{(b)}$)
- Muons: Segment in the tracker and muon detector, isolated track ($p_T > 25$ GeV, $|\eta|$ <2.5, $z_0 < 2$ mm$^{(b)}$)

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

- ≥ 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

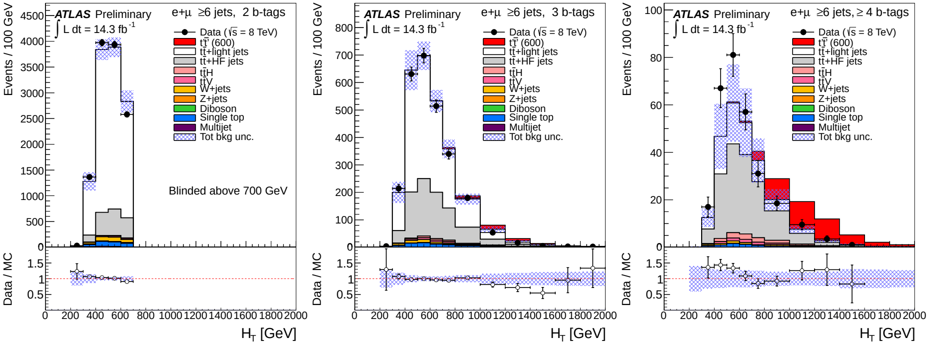
If the analysis requires one or more leptons, at least one of them must match the single lepton trigger

$^{(a)}$ 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

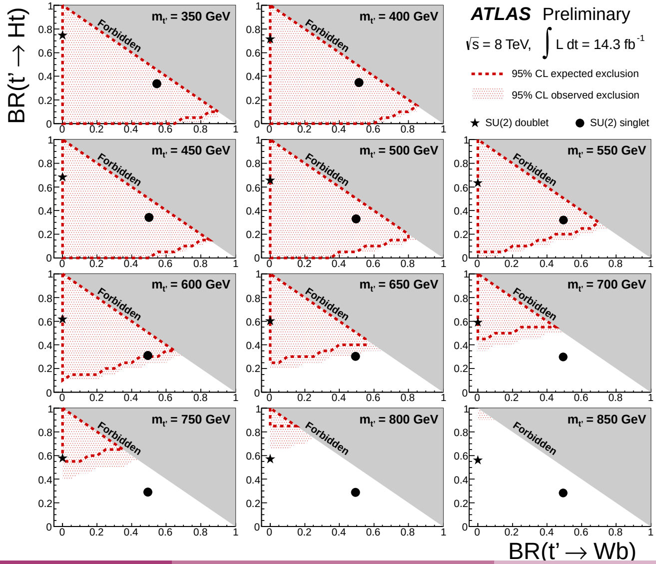
$^{(b)}$ z_0 is the longitudinal impact parameter of the track wrt the primary vertex

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

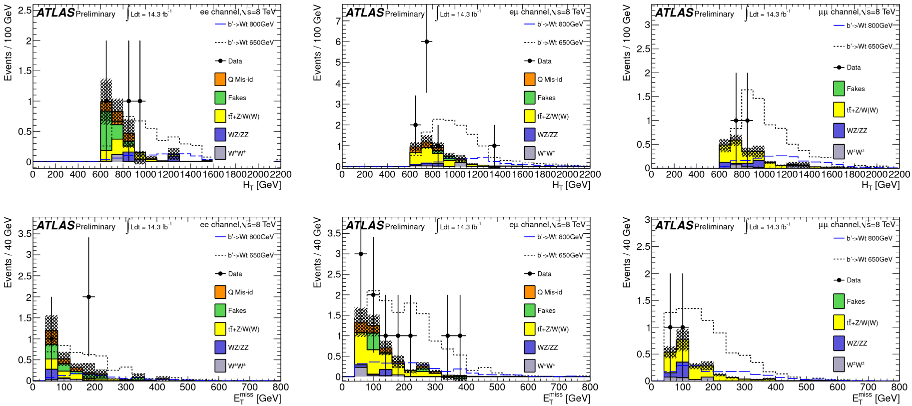
Three channels:
$= 2$, $= 3$, ≥ 4 *b*-tagged jets



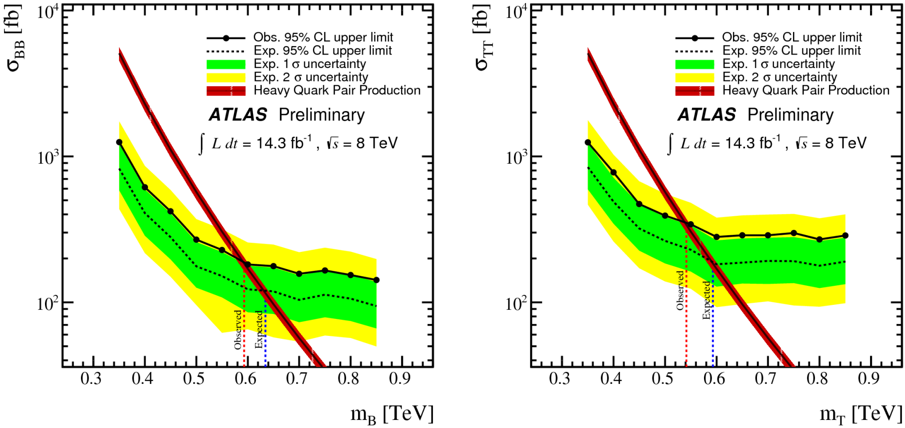
$T\bar{T} \rightarrow Ht + X$ [9]



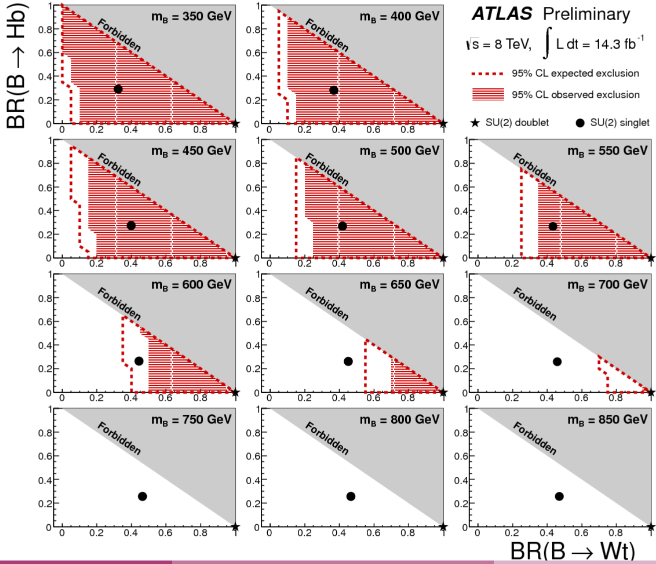
Same-sign dileptons [11]



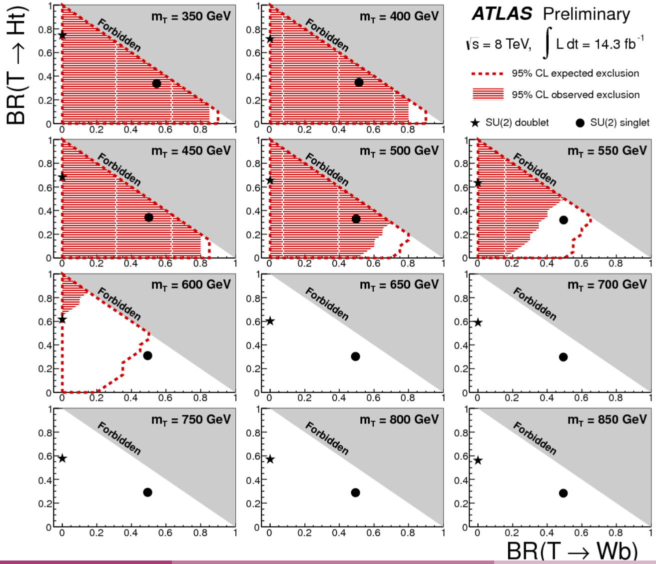
Same-sign dileptons [11]



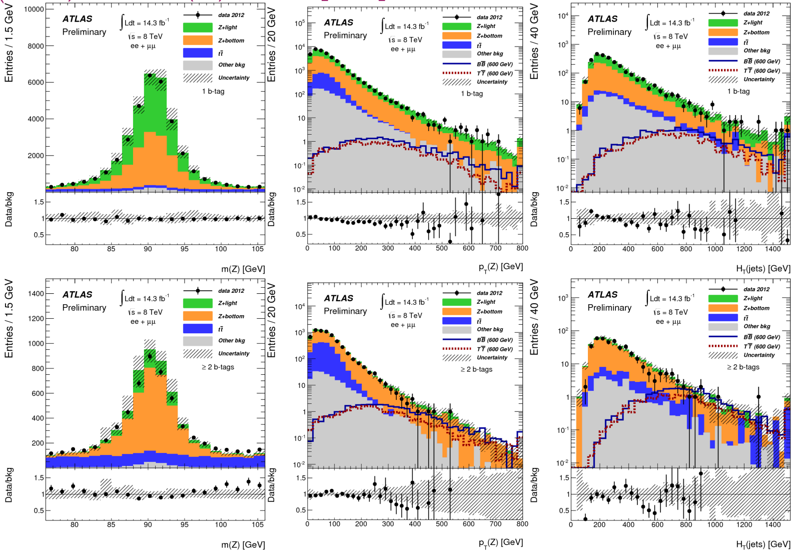
Same-sign dileptons [11]



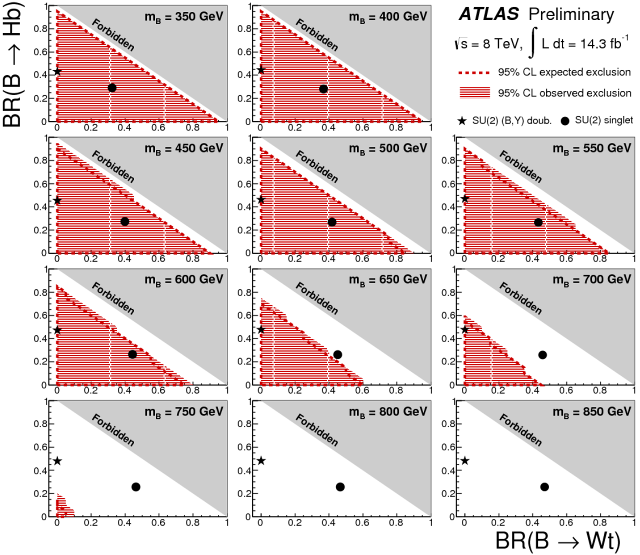
Same-sign dileptons [11]



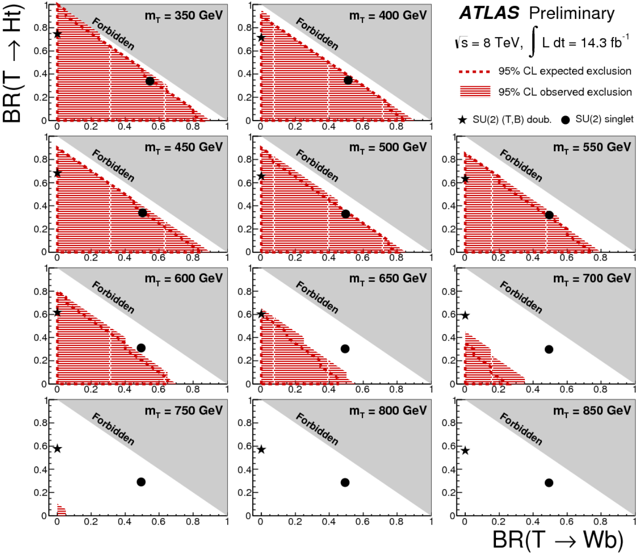
$B\bar{B}(T\bar{T}) \rightarrow Zb(t) + X$ [13]



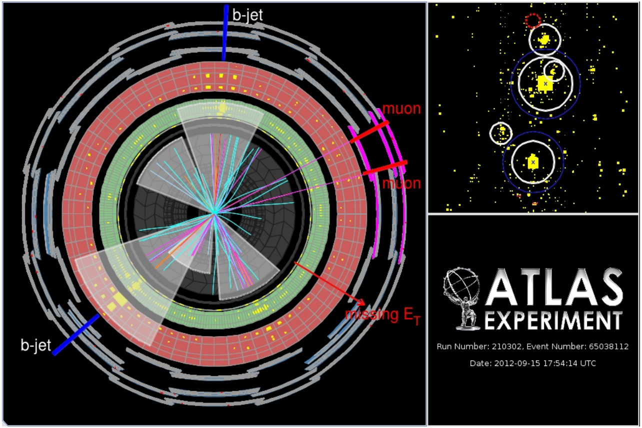
$B\bar{B}(T\bar{T}) \rightarrow Zb(t) + X$ [13]



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



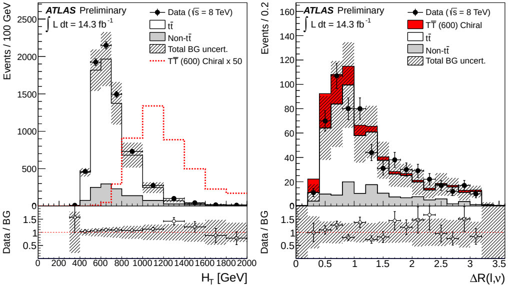
$B\bar{B}(T\bar{T}) \rightarrow Zb(t) + X$ [13]



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

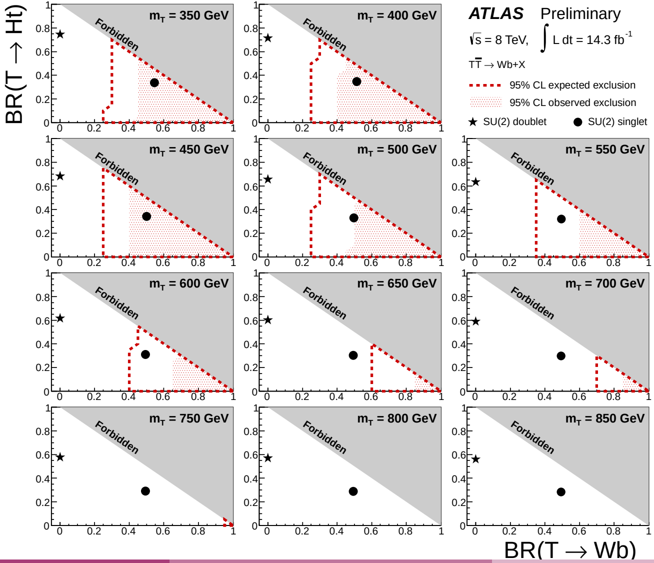
- one lepton (e or mu), E_T^{miss} >20 GeV, $E_T^{\text{miss}} + m_T(W)$ >60 GeV
- $\geq$3 jets and one W_{had}^{typeI}

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

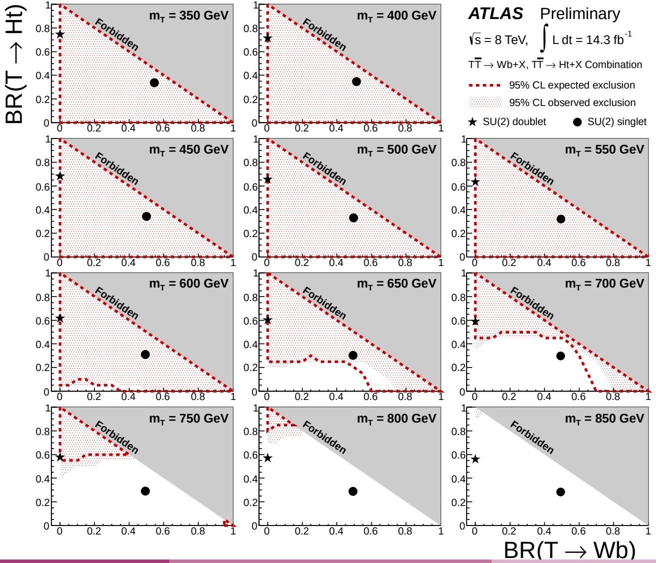


$$^{(a)}H_T = p_T(j_1) + p_T(j_2) + p_T(j_3) + p_T(j_4) + p_T(l) + E_T^{\text{miss}}$$

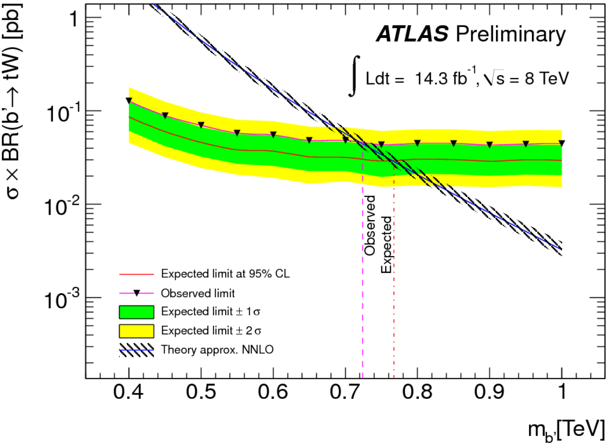
$T\bar{T} \rightarrow Wb + X$ [15]



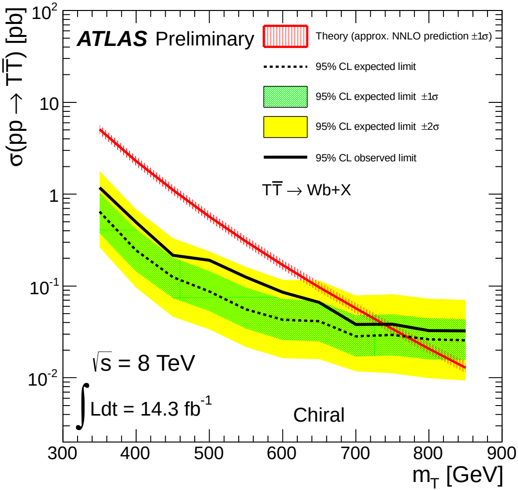
combining $T\bar{T} \to Ht + X$ [9] and $T\bar{T} \to Wb + X$ [15]



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



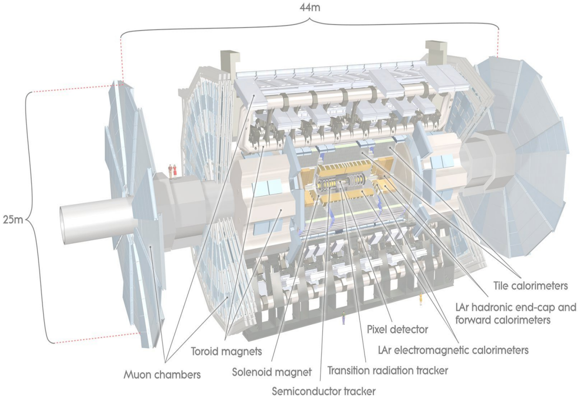
Results on chiral quarks: $t' \to Wb$ (100%) [15]



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 ϕ and $|\eta| < 5$)

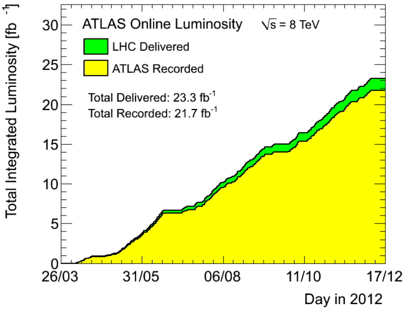


The ATLAS Detector

A general purpose experiment

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

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



See ATLAS public page

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