ATLAS searches for vector-like quarks in single lepton final states, and the global search status

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on behalf of the ATLAS collaboration

What are vector-like quarks?

- SM quarks are chiral : the left-handed components transform as doublets under the weak-isospin gauge group, SU(2), while the right-handed components transform as singlets.

$$\begin{pmatrix} t_L \\ b_L \end{pmatrix} \qquad t_R \ , \ b_R$$

- A gauge invariant mass term for a chiral quark must originate from a Yukawa interaction with a scalar doublet, ϕ.

$$y_q \bar{Q}_L \phi q_R \overset{\text{EWSB}}{\rightarrow} m_q \bar{q}_L q_R$$

The observed rate of Higgs production severely constrains the existence of new chiral quarks.

- The left- and right-handed components of vector-like quarks (VLQs) transform the same way under SU(2), be that as singlets, doublets, or even triplets.

$$T_L \ , \ T_R$$

$$\begin{pmatrix} T_L \\ B_L \end{pmatrix}, \begin{pmatrix} T_R \\ B_R \end{pmatrix}$$

- This allows for a gauge invariant mass term independent of the Higgs and of some unspecified BSM origin.

$$M \bar{Q} Q$$

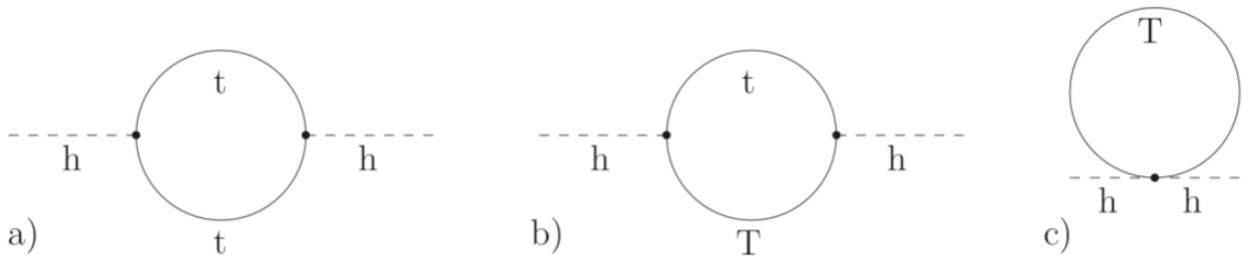


Figure 1. One-loop Higgs mass renormalization in a model with a fermionic top partner, such as the Littlest Higgs. arXiv:1205.0013 [hep-ph]

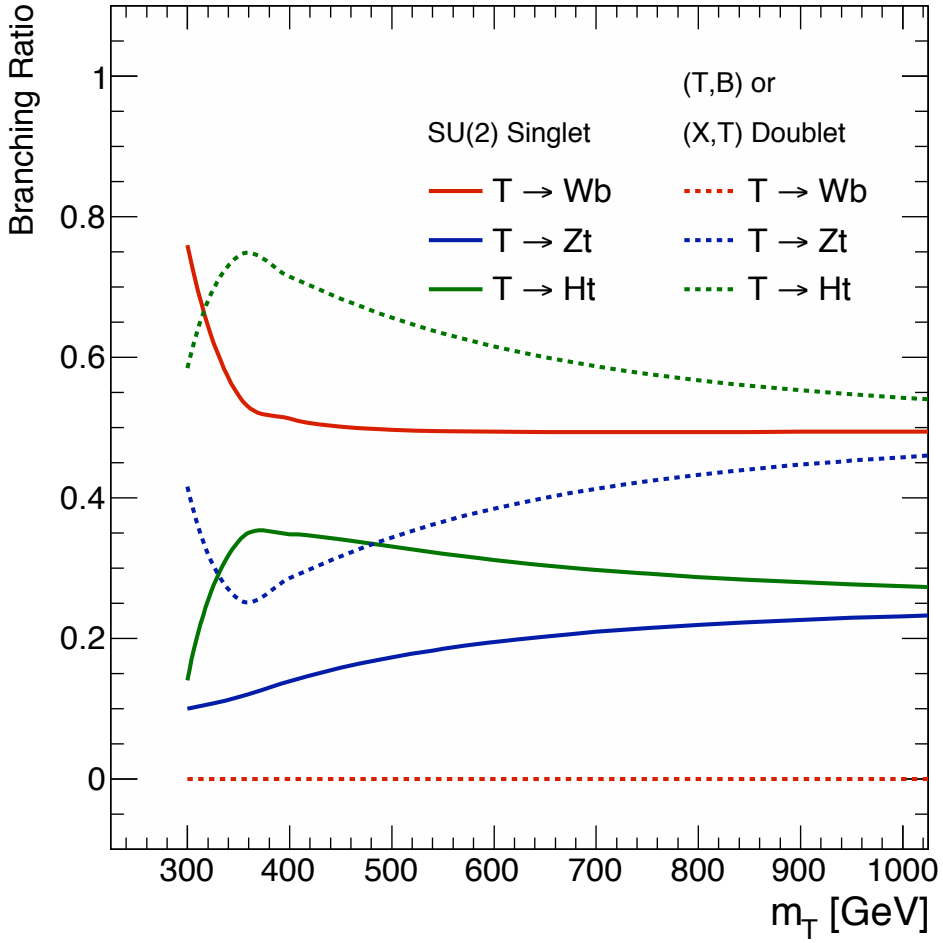
Vector-like quarks appear in many BSM theories, particularly those with strong EWSB.

A vector-like top can also stabilize the Higgs mass divergence, much like the stop in SUSY.

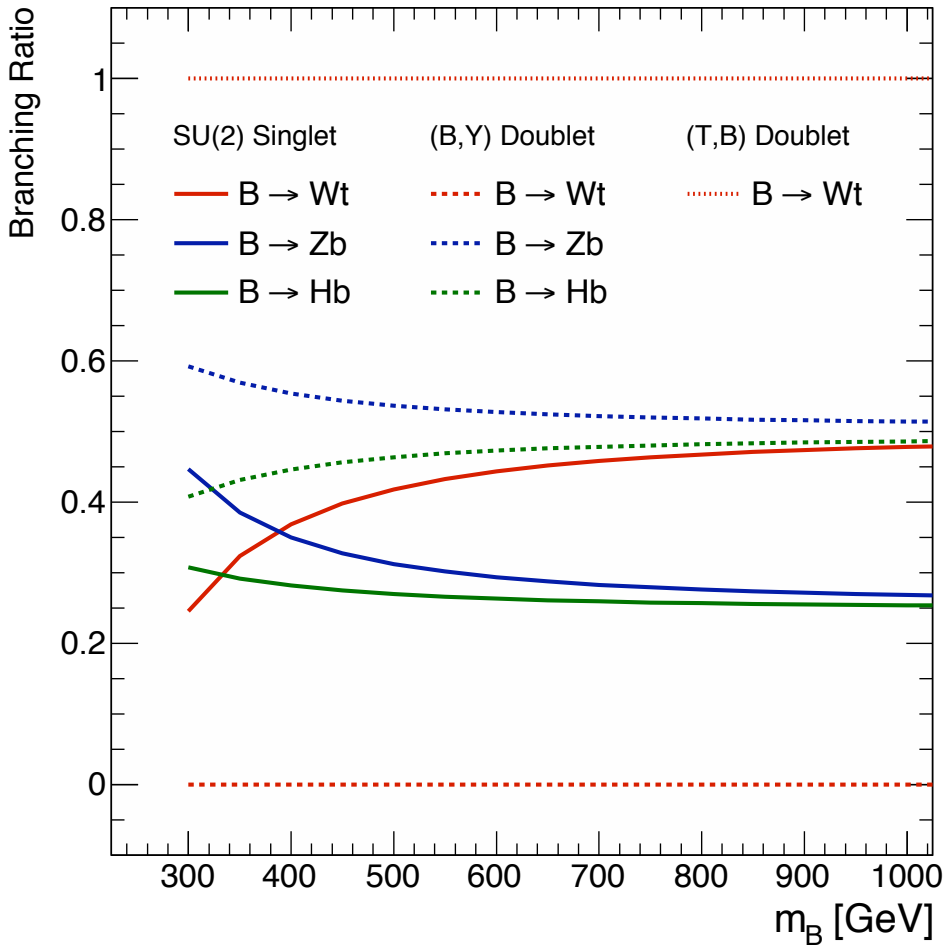
Vector-like quark branching ratios

- GIM mechanism is broken, tree level flavor changing neutral currents arise.
- Vector-like multiplets with new exotic charge quarks (+5/3 X, -4/3 Y) are allowed.
- Mixing primarily with 3rd generation generally assumed; natural, but not required.

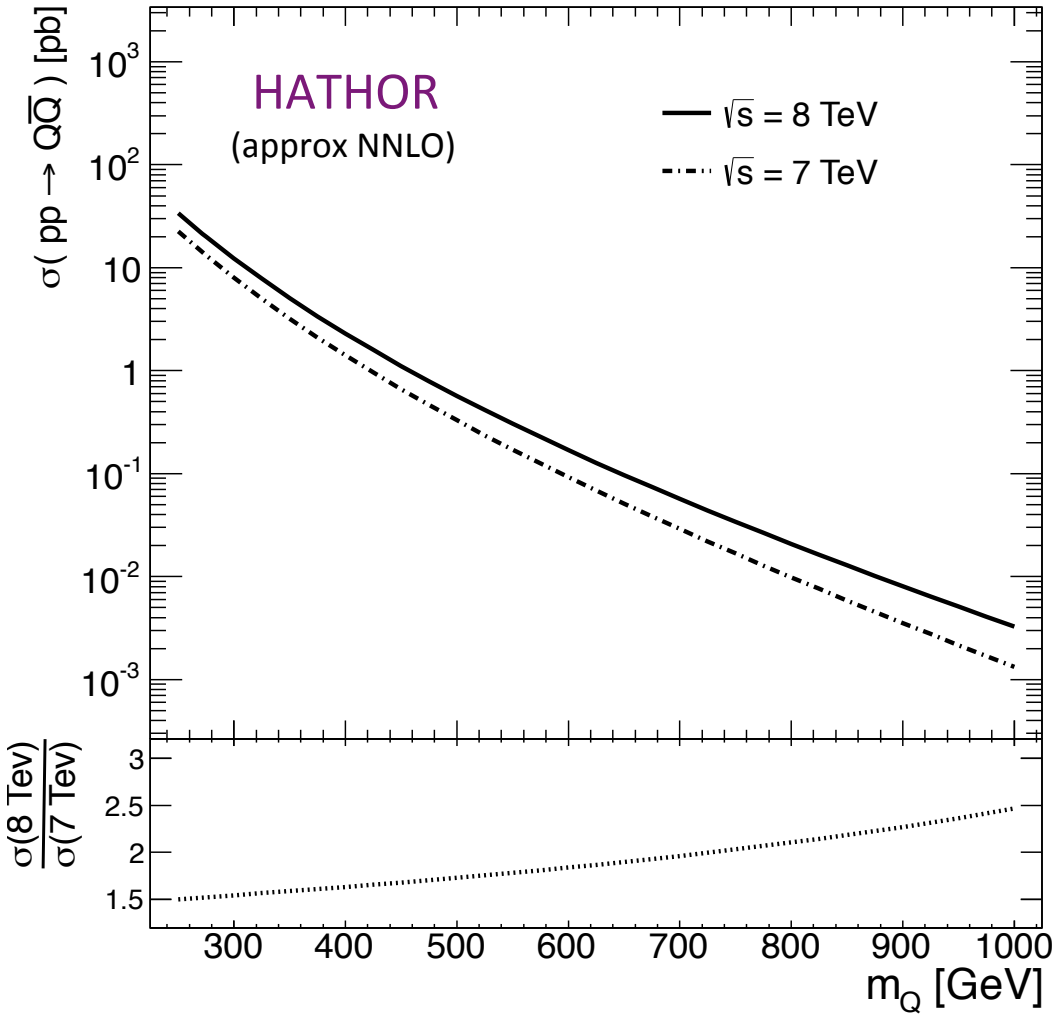
Vector-like Top

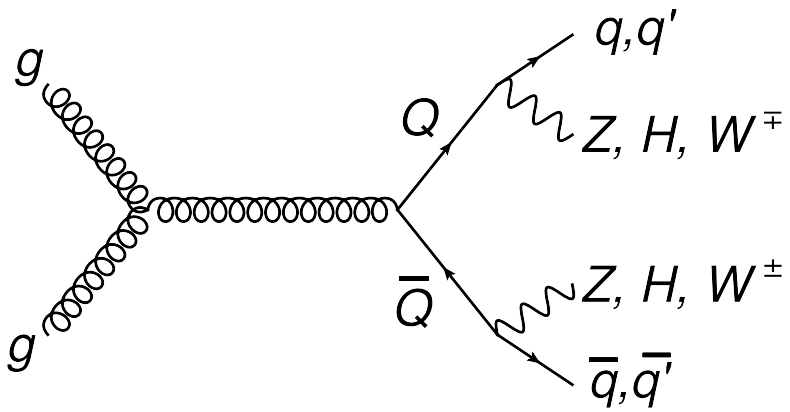


Vector-like Bottom



Heavy quark production at the LHC





- At the LHC, strong pair production is likely the dominant source for heavy quark masses below O(1 TeV).
- The HATHOR approx NNLO prediction is used, and is independent of the EW charges of the new quark.
- Uncertainties from scale choice and PDFs range from 10-20% over the 400 – 800 GeV mass range.

Searches for a vector-like top in single lepton final states

This talk presents preliminary results of two ATLAS searches for a vector-like top quark in single lepton final states using 14.3/fb of 8 TeV data.

1. Search for heavy top-like quarks decaying to a Higgs boson and a top quark in the lepton + jets final state …. (ATLAS-CONF-2013-018, a.k.a. Ht+X)

   - Target events with ≥ 6 jets, and ≥ 2 b-tagged jets (main signal region has ≥ 4 tags)
   - Test the H_T distribution for signal-like excess over background prediction

2. Search for pair production of a heavy top-like quark decaying to a high-p_T W boson and a b quark in the lepton + jets final state ….
   (ATLAS-CONF-2013-060, a.k.a. Wb+X)

   - Target events with ≥ 4 jets, and ≥ 1 b-tagged jets
   - Veto events with ≥ 6 jets, and ≥ 3 b-tagged jets (to remain orthogonal to Ht+X)
   - Require a high-p_T hadronically decaying W boson candidate
   - Reconstruct WbWb system, test heavy top-like quark mass distribution

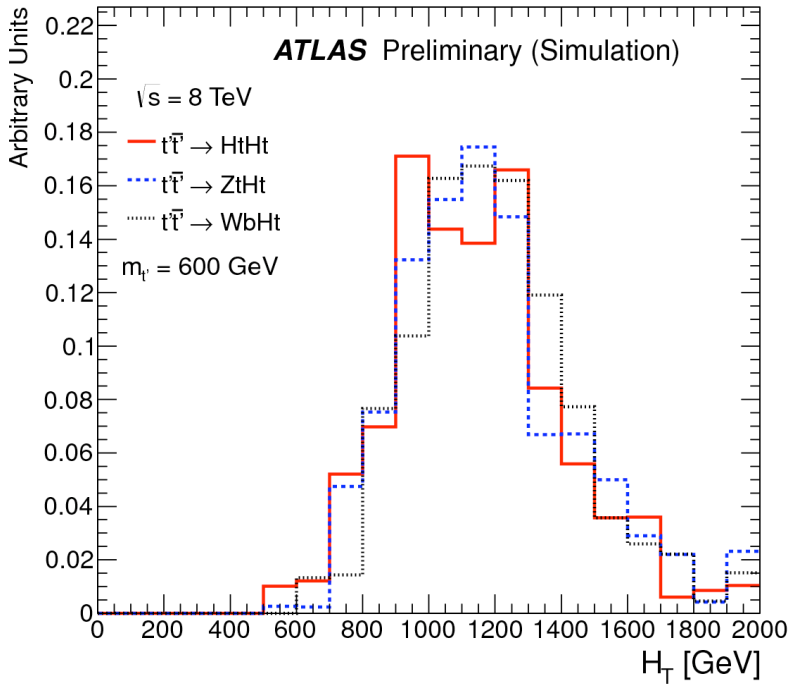
Higgs + top quark targeted search : strategy

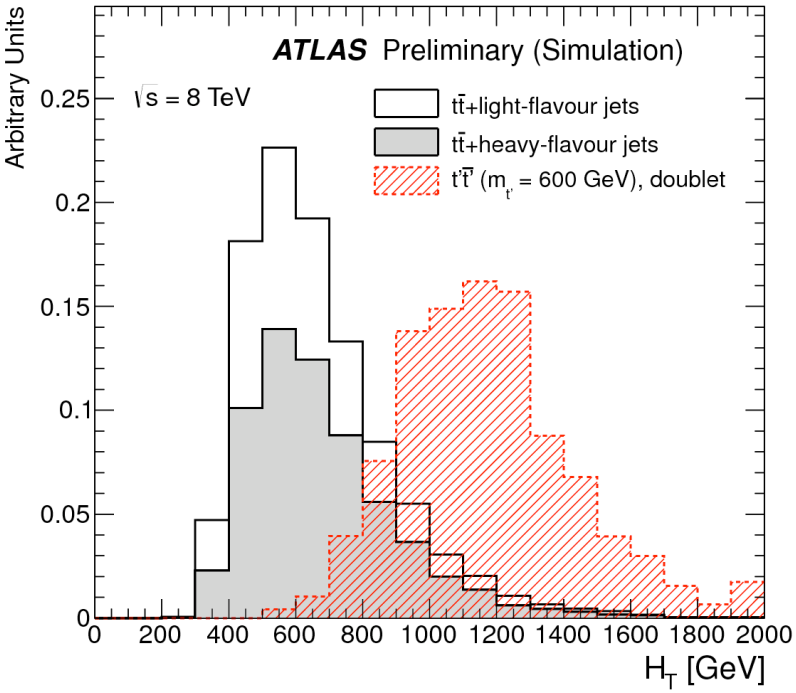
- Exactly one electron or muon candidate, $p_T > 25$ GeV, $|\eta| < 2.5$.
- Missing transverse energy, $ME_T > 20$ GeV.
- Transverse mass, m_T, and ME_T satisfying $ME_T + M_T > 60$ GeV.
- At least 6 jets (anti-kt, R=0.4); at least two b-tagged using a 70% efficient operating point.
- The strategy of the analysis is to test an H_T variable defined as:

$$H_T = p_T^{\text{lep}} + \not{E}_T + \sum p_T^{\text{jets}}$$

in bins of N_{tag} = 2, =3, and ≥ 4.

Good discrimination between HtHt signal and background, and also robust for mixed signals (HtZb and HtWb).

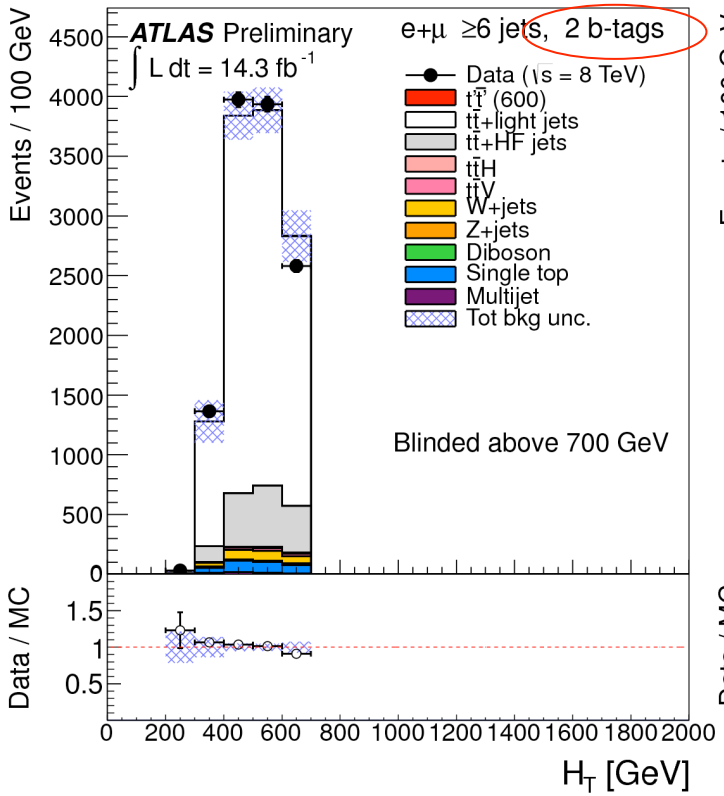


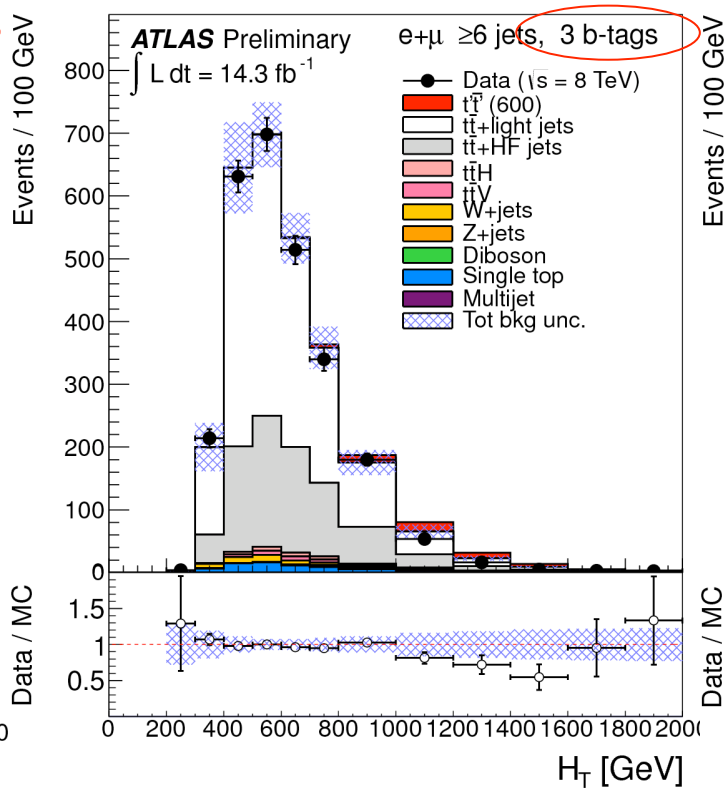


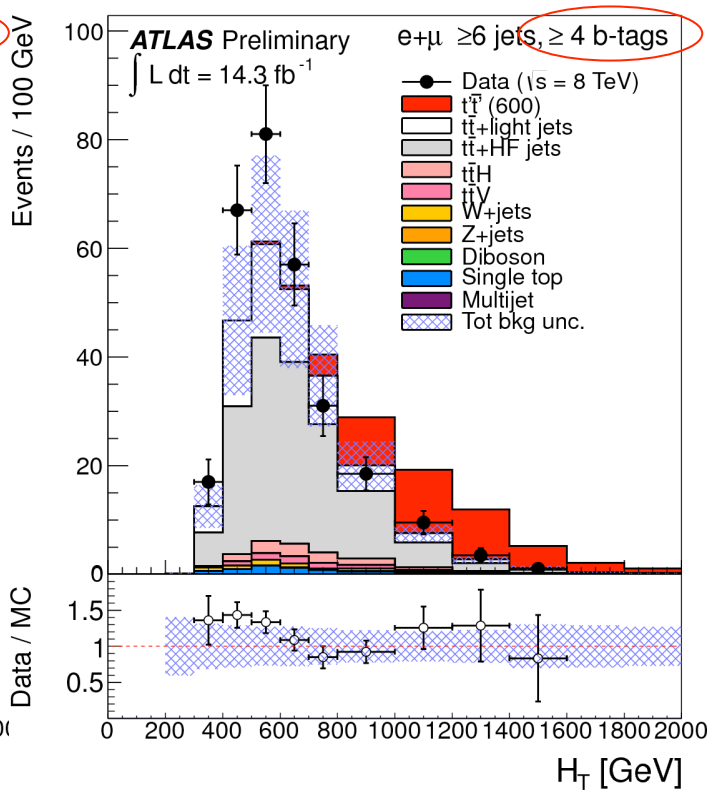
Higgs + top quark targeted search : data and predictions

- ALPGEN (LO) is used to model the dominant top quark pair background in association with additional light- and heavy-flavor jets.

- The $t\bar{t} + \text{jets}$ prediction is improved by performing a simultaneous fit to the H_T distribution in the N_{tag} = 2, 3, ≥ 4 bins, allowing the overall scale of + light jets and + heavy-flavor jets top pair processes to deviate from the nominal prediction.



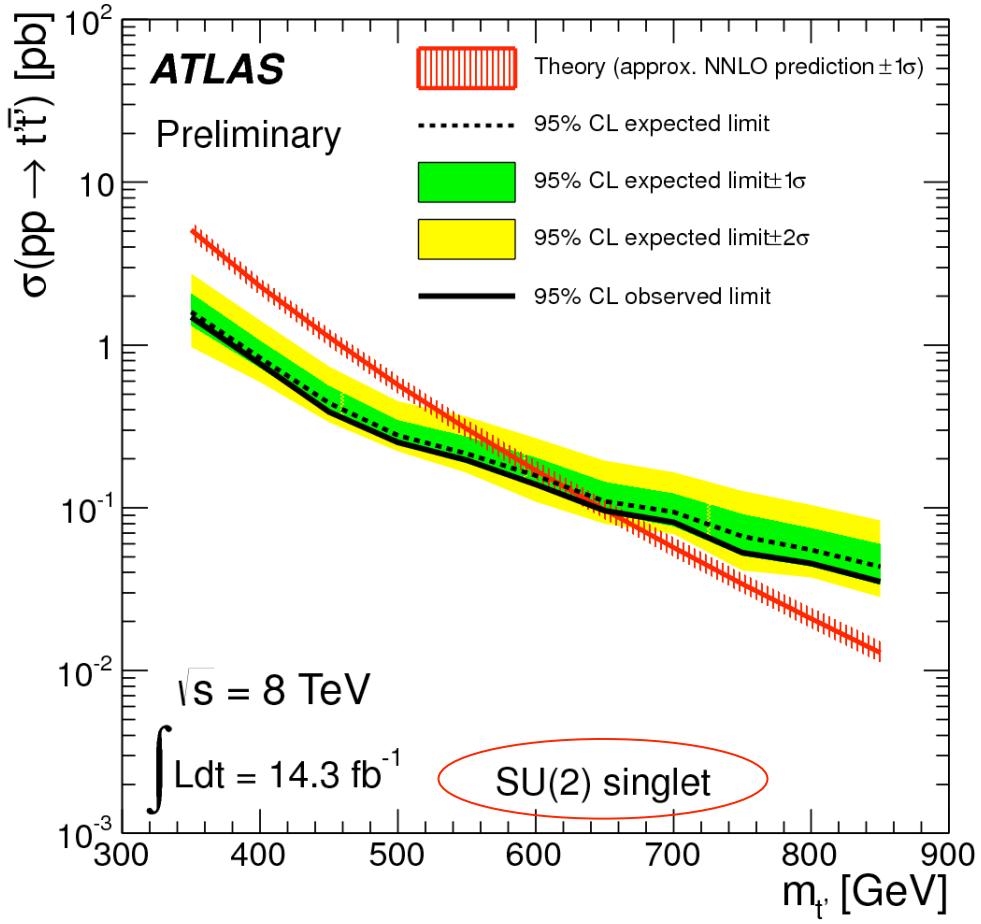




Higgs + top quark targeted search : singlet and doublet limits

Singlet T:

BR(Wb, Ht, Zt) ≈ 50%, 25%, 25%

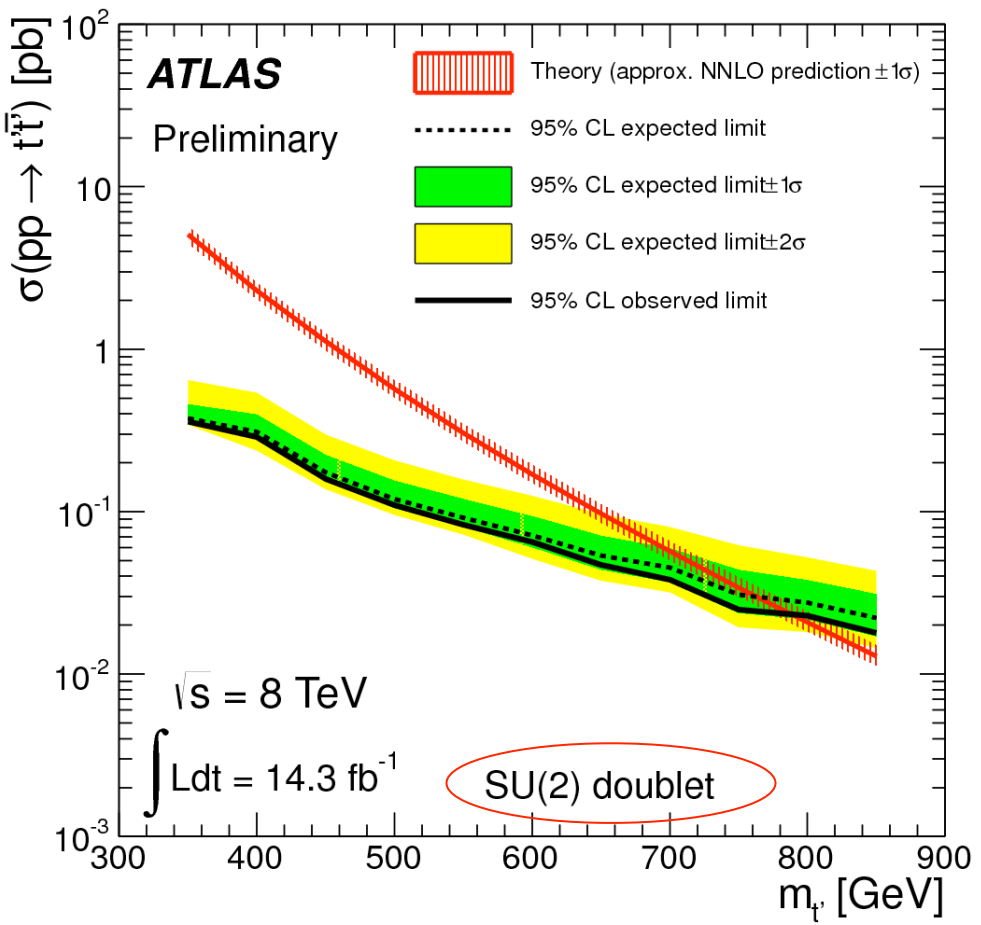


Upper limits on mass at 95% CL

m_T < **640** (615) **GeV**, **obs** (exp)

T in a doublet:

BR(Wb, Ht, Zt) ≈ 0%, 50%, 50%



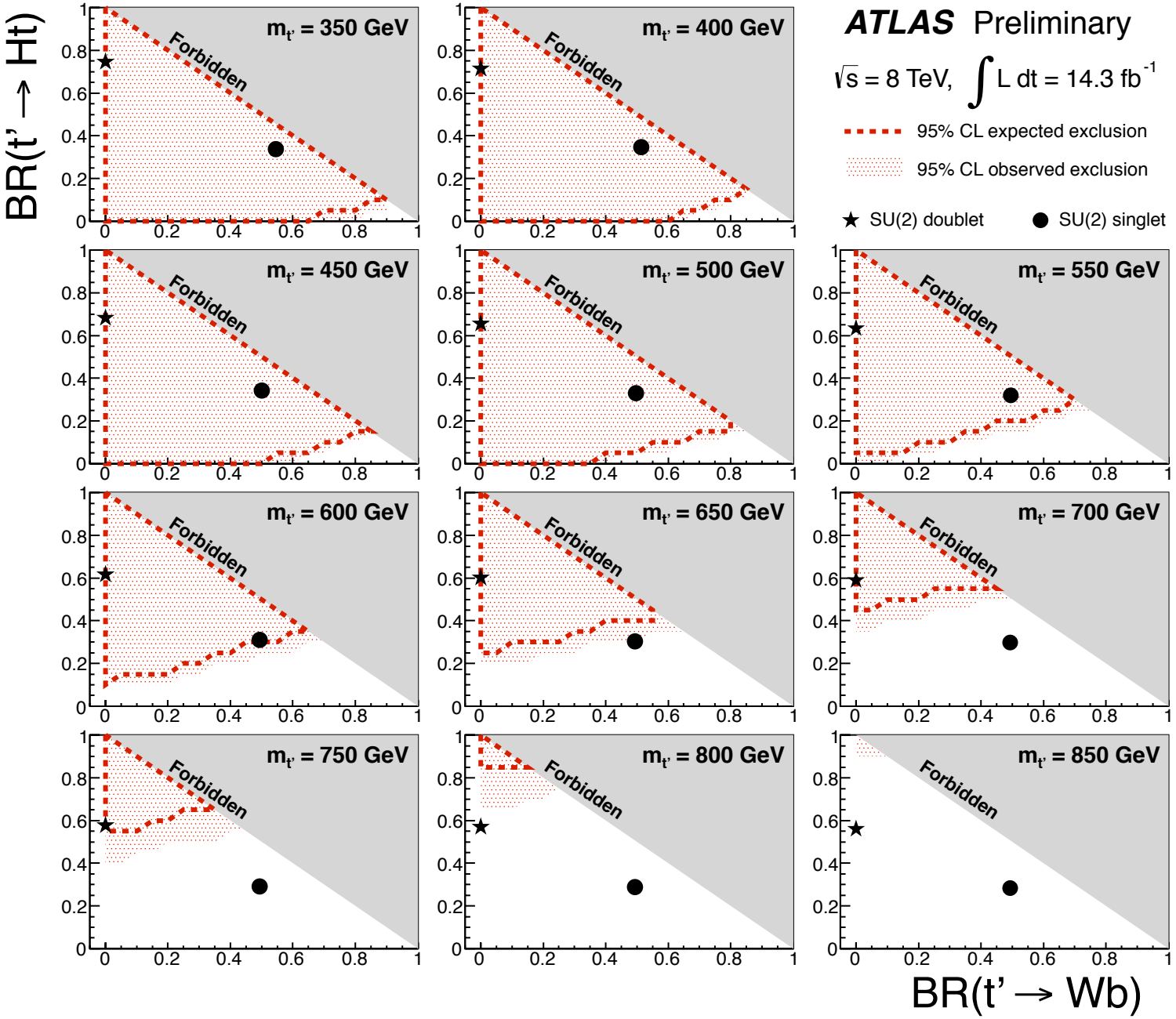
m_T < **790** (745) **GeV**, **obs** (exp)

Higgs + top quark targeted search : arbitrary branching ratios

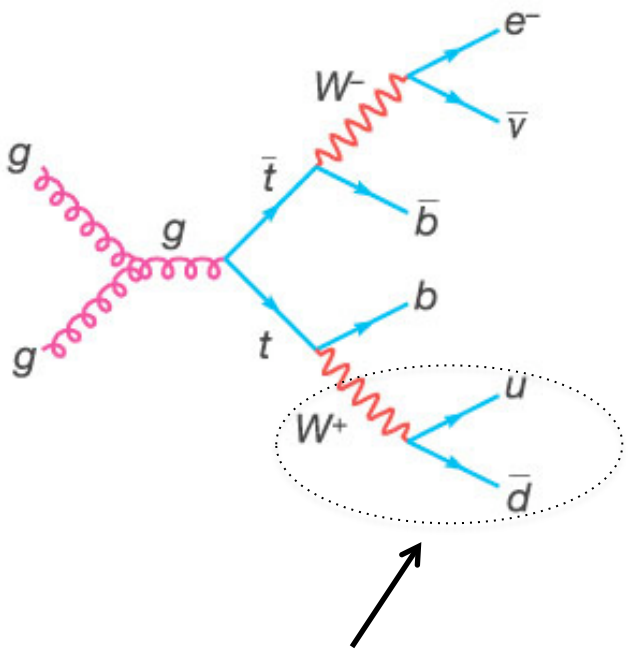
Limits also assessed for arbitrary branching ratios at a given mass and presented in the (Wb,Ht) BR plane.
[Recall BR(Zt) is determined, as the three sum to unity]

As expected, Ht+X analysis is most sensitive in the Ht corner

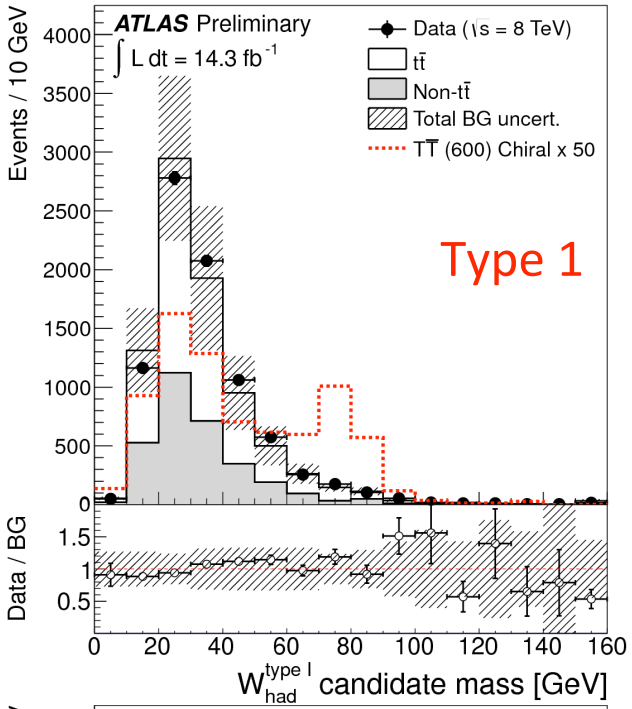
First such interpretation presented in the 7 TeV Wb+X publication.
[PLB 718 (2013) 1284, arXiv 1210.5468]



W boson + bottom quark targeted search : strategy



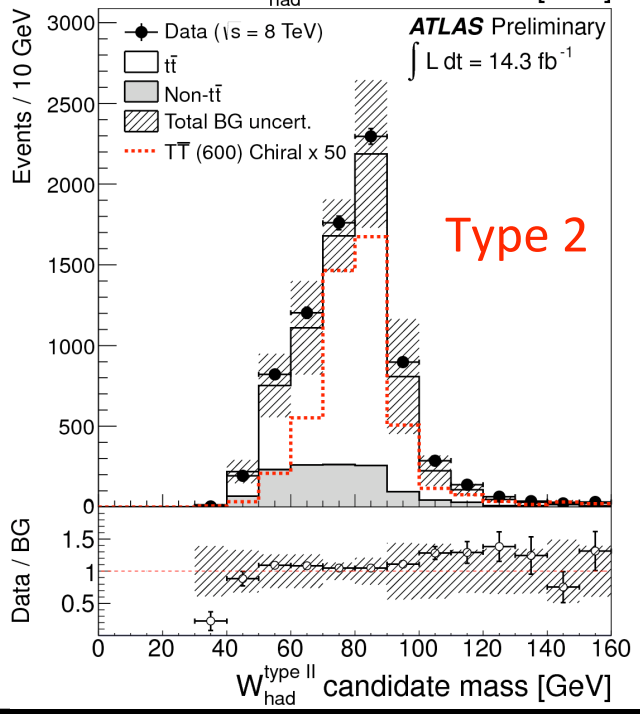
- Selection for the leptonic side of event is the same as in the Ht+X search.
- At least one explicitly b-tagged jet; treat 2nd highest b-tag weight jet in the event as 2nd b-jet.



- Require a hadronically decaying W boson candidate.

  Type 1: Single jet, $p_T > 250$ GeV, jet mass within 60-120 GeV

  Type 2: Jet pair, $\Delta R(j,j) < 0.8$, $p_T(j,j) > 200$ GeV, m(j,j) within 60-120 GeV

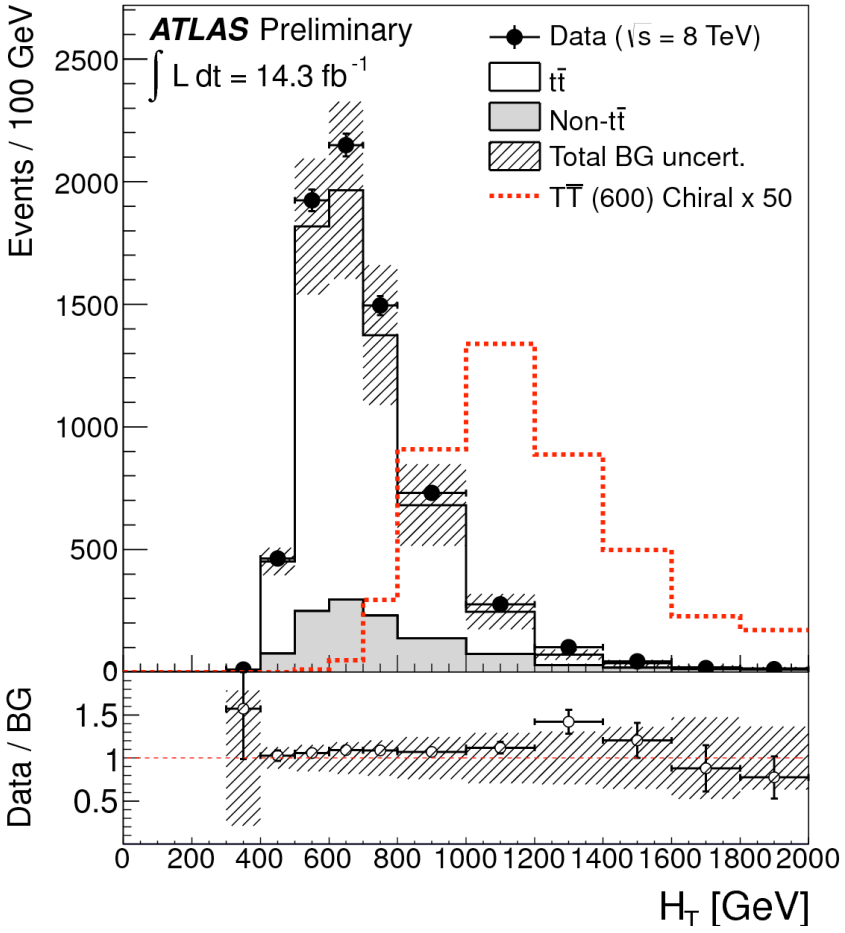


- $t\bar{t} + \text{jets}$ modeling: 2 NLO generators compared, MC@NLO and Powheg. Data generally bracketed by the two, w/ MC@NLO (default) providing a better description. Largest systematic uncertainty in analysis associated w/ difference.

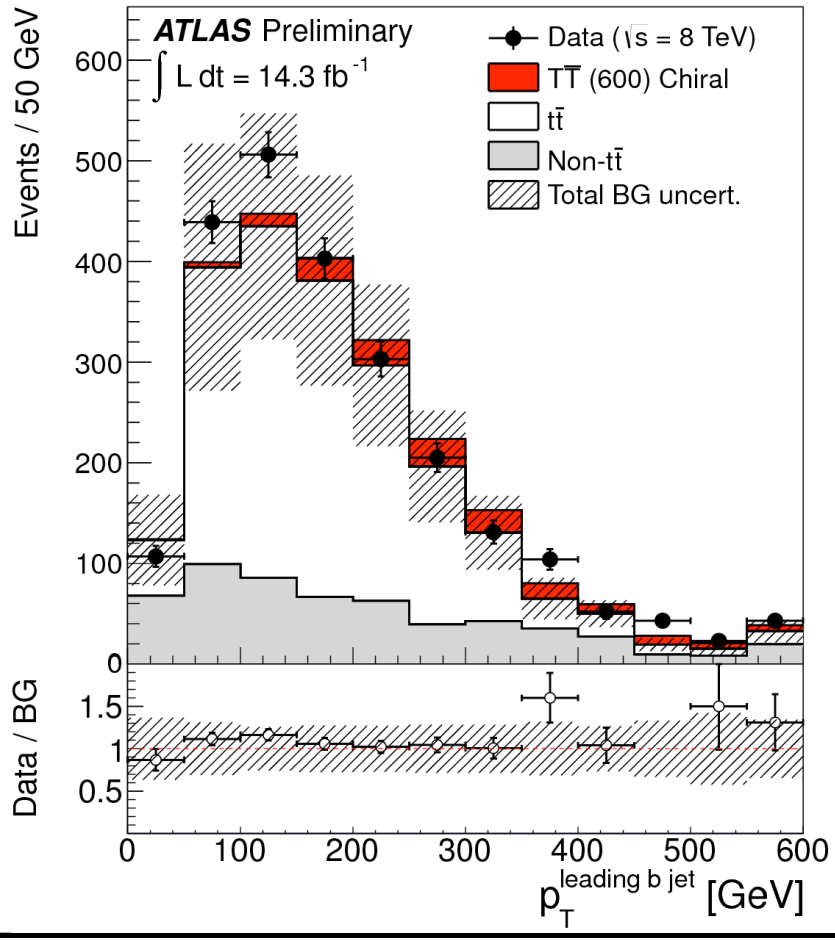
W boson + bottom quark targeted search : loose selection

- After preselection, $t\bar{t} + \text{jets}$ is the dominant background.
- Reduce with requirements on H_T (here w/ using 4 highest p_T jets), and p_T of b-jets.

Require $H_T > 800$ GeV



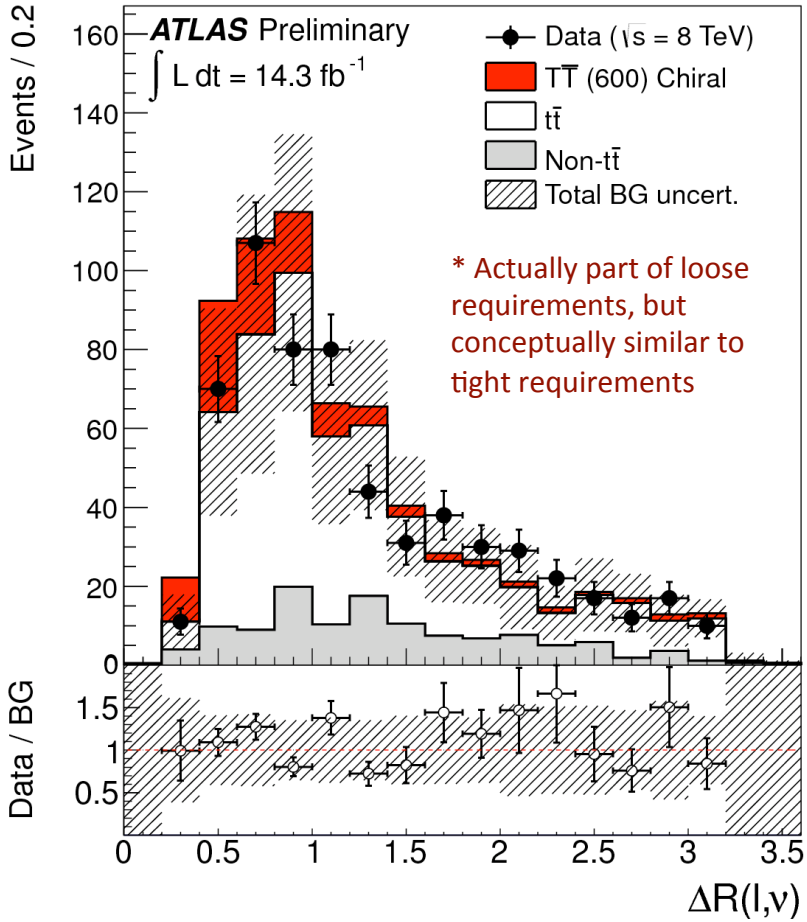
Require b_1, b_2 $p_T > 160, 80$ GeV



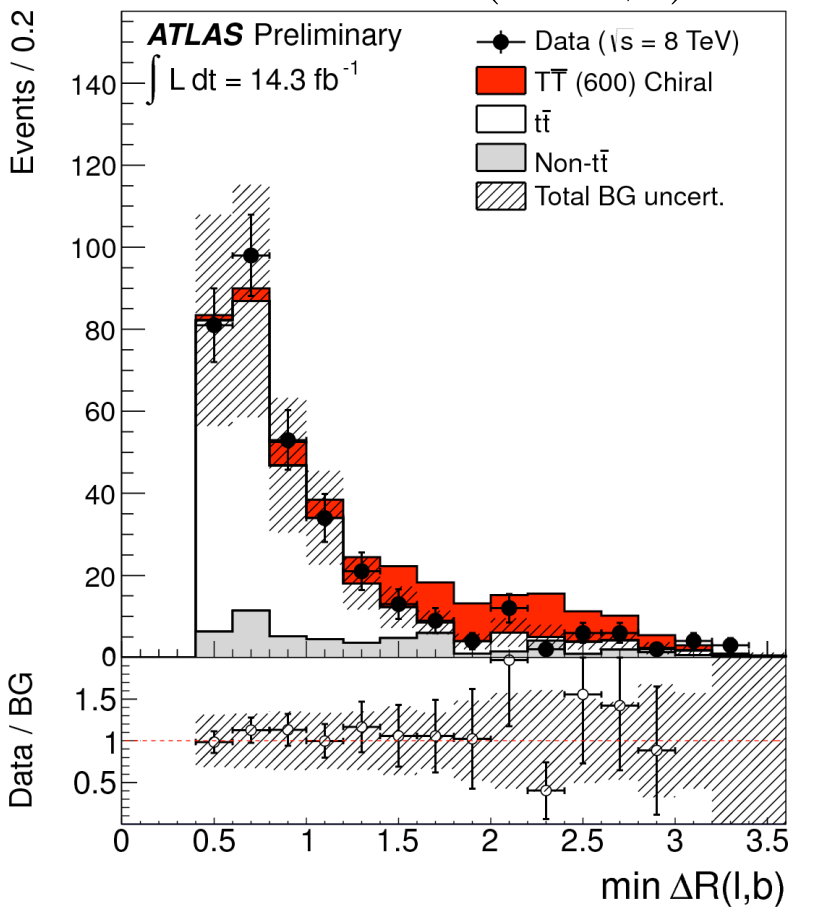
W boson + bottom quark targeted search : tight selection

- After H_T and b-jet p_T requirements, remaining $t\bar{t}+\text{jets}$ bkg is boosted.
- W_{lep} even more boosted for signal.
- W bosons and b-jets are closer to each other in background events.

Require* $\Delta R(l,\nu) < 1.2$

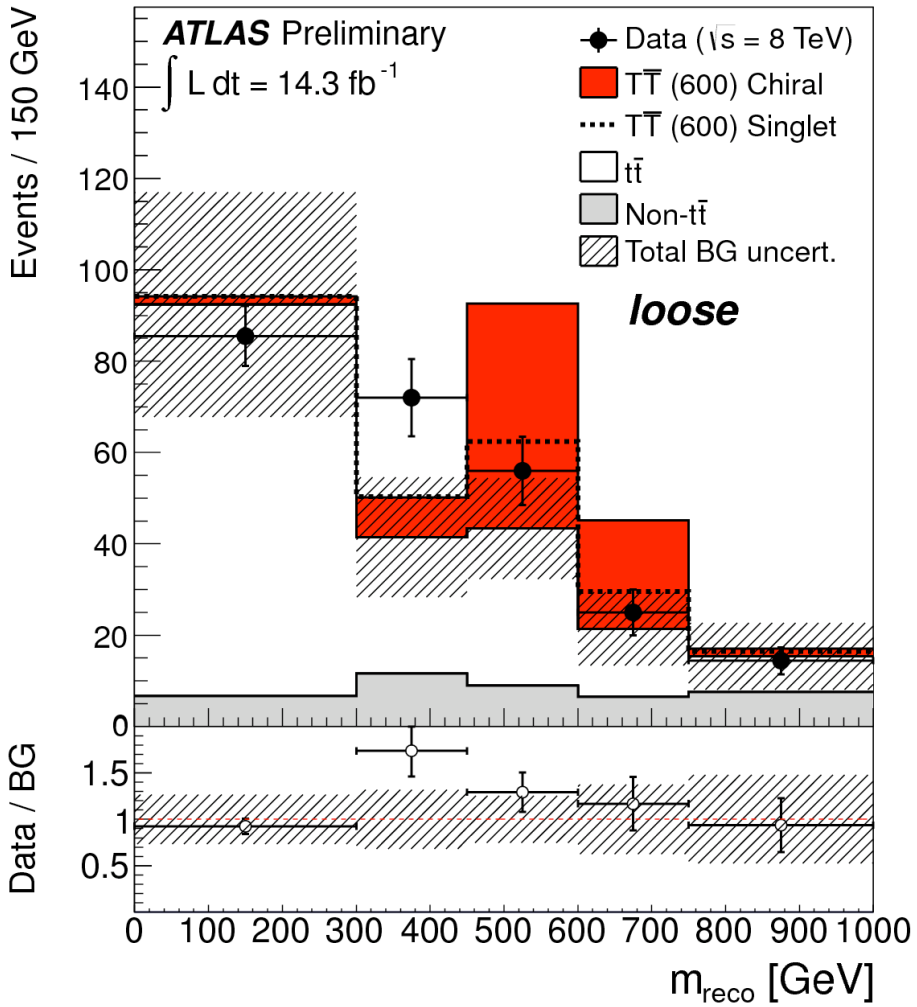


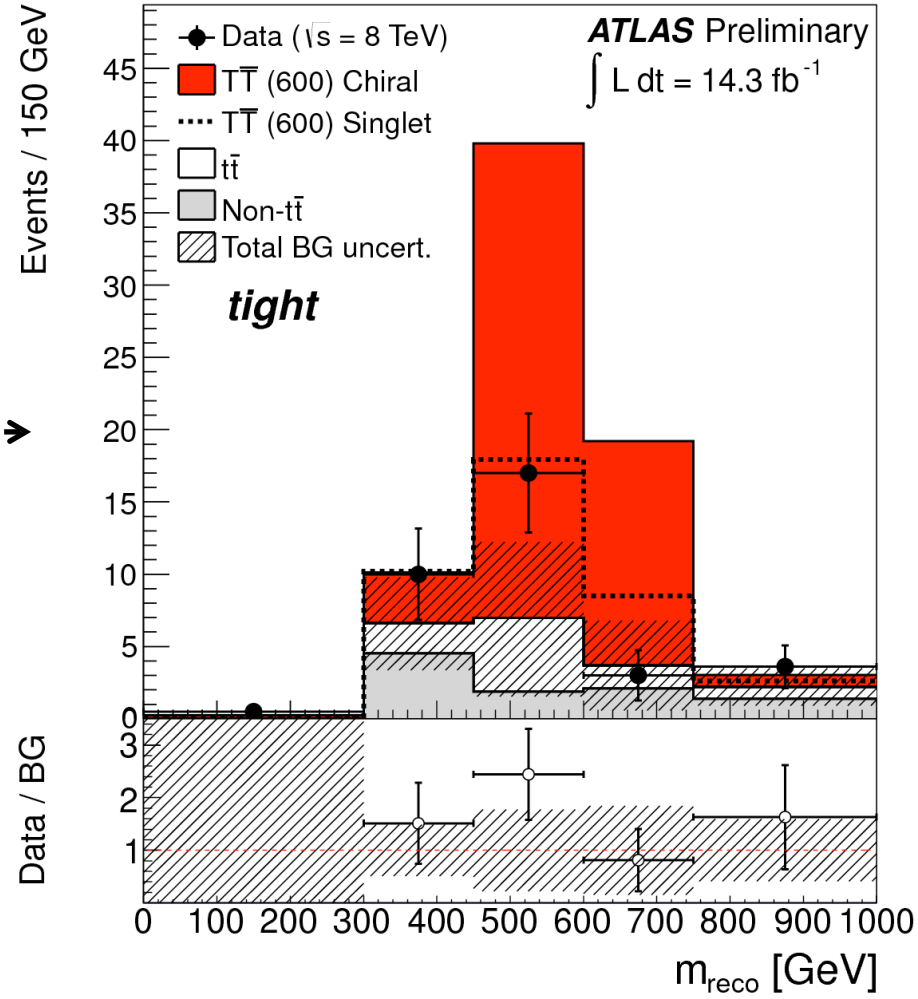
Require $\min \Delta R(l,b) > 1.4$
and $\min \Delta R(W_{\text{had}},b) > 1.4$



W boson + bottom quark targeted search : reconstructed mass

- Reconstructed heavy quark mass (m_{reco}) built from W_{had} and one of the b-jets.
- Typically two solutions for W_{lep} , and two ways to pair W cands w/ b-jets.
- Among all possibilities, choose comb that minimizes lep and had heavy quark mass diff.

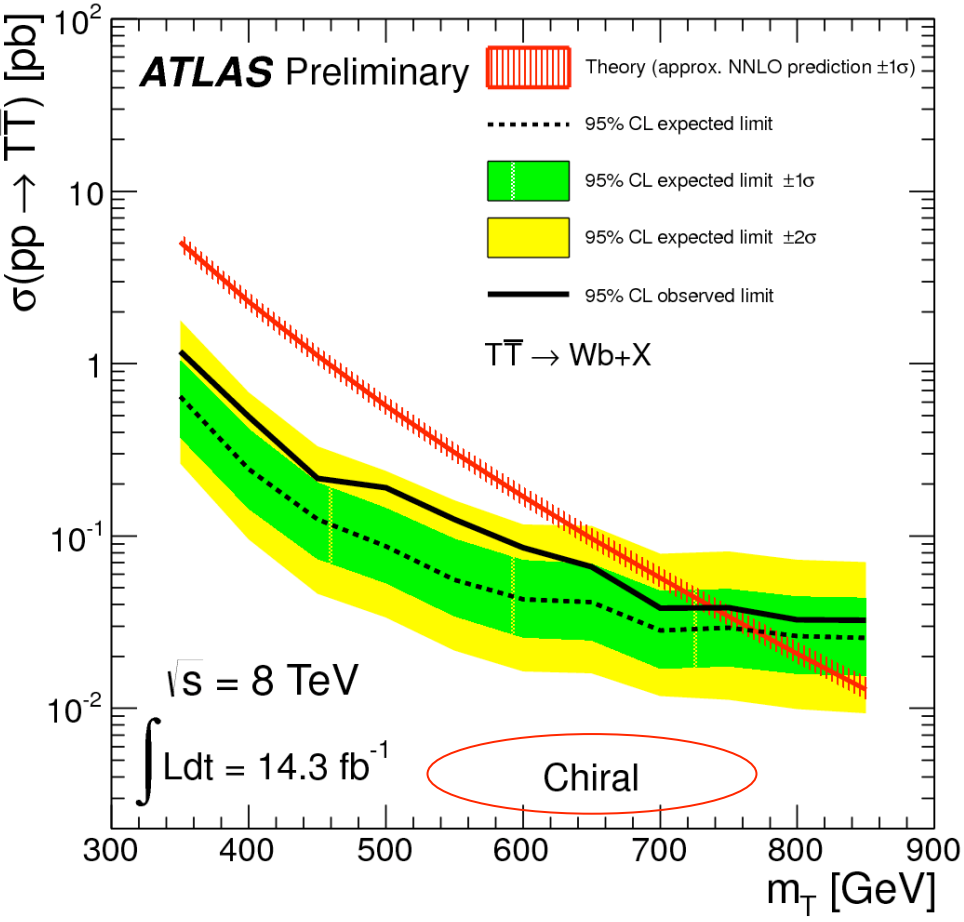




W boson + bottom quark targeted search : chiral and singlet limits

Chiral T:

BR(Wb, Ht, Zt) ≈ 100%, 0%, 0%

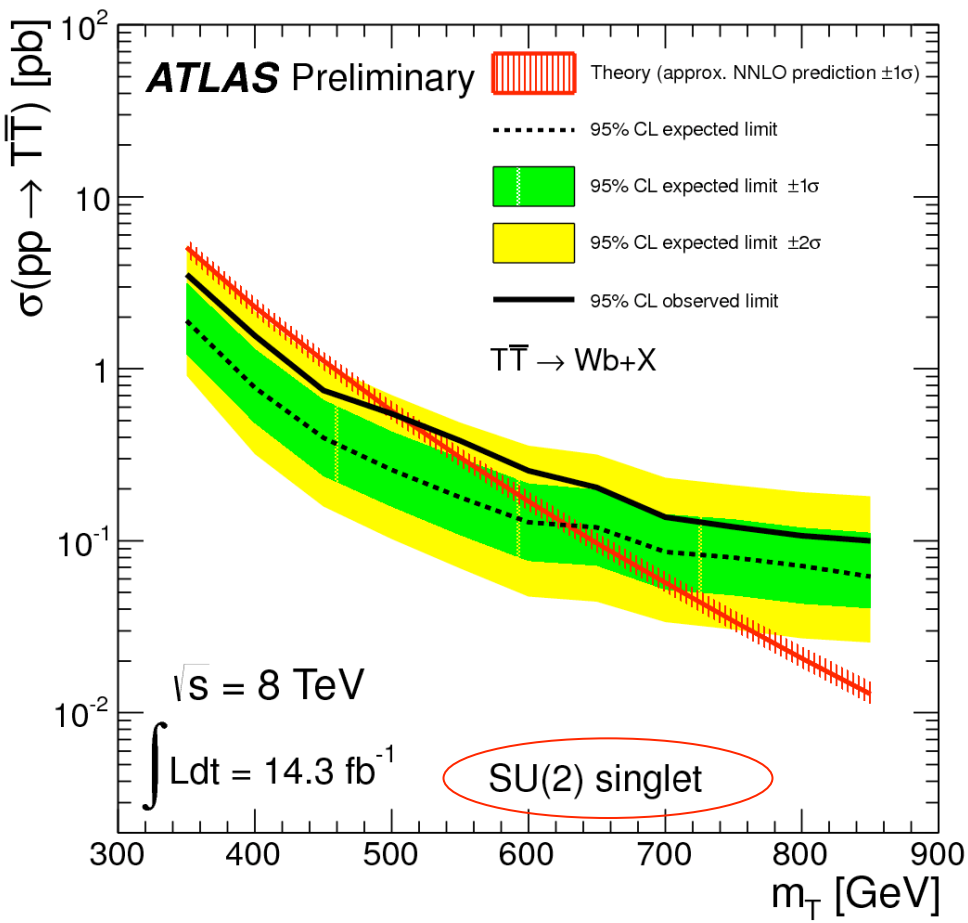


Upper limits on mass at 95% CL

m_T < **740** (770) **GeV**, **obs** (exp)

Singlet T:

BR(Wb, Ht, Zt) ≈ 50%, 25%, 25%

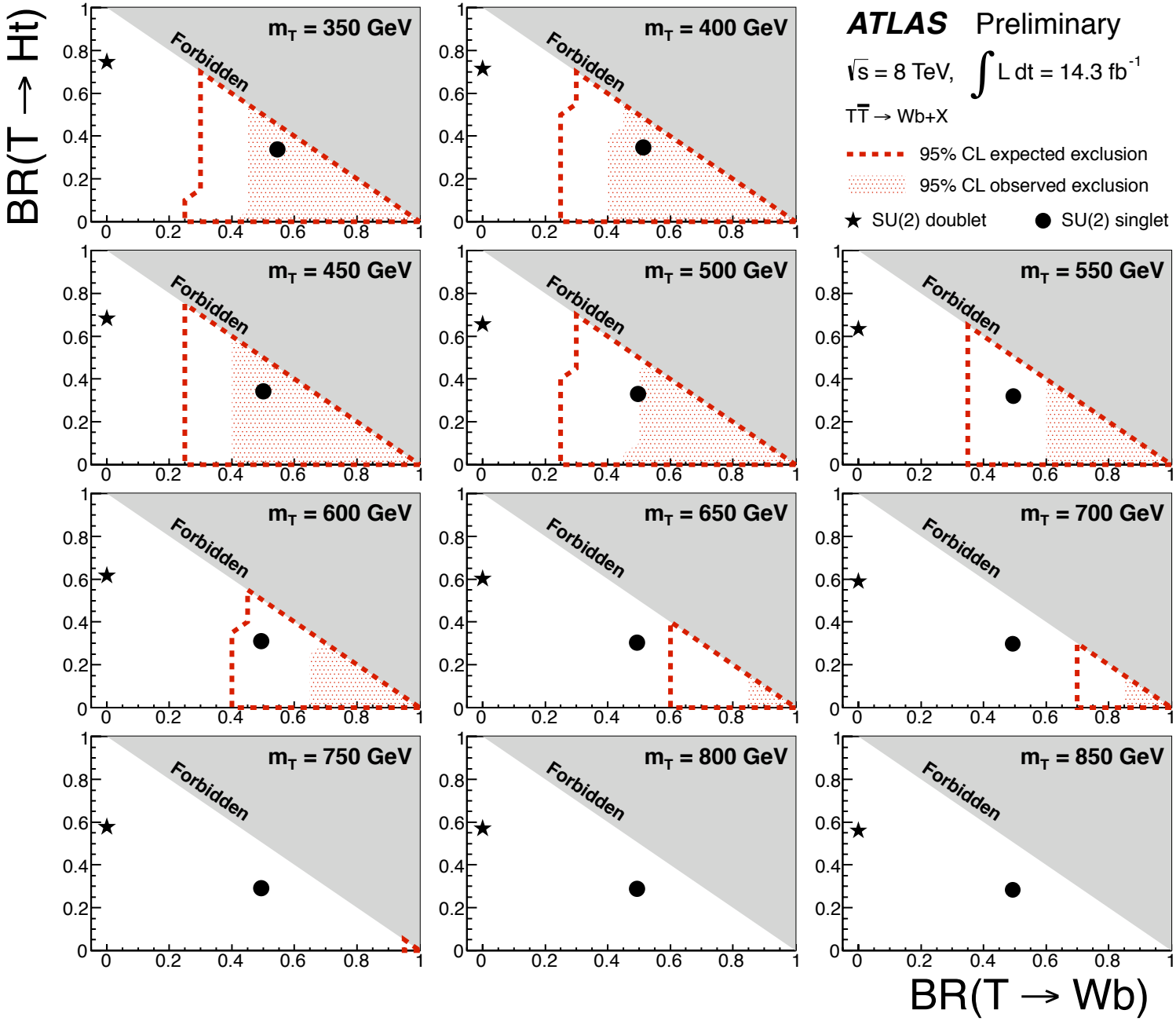


m_T < **505** (630) **GeV**, **obs** (exp)

W boson + bottom quark targeted search : arbitrary branching ratios

Limits also assessed for arbitrary branching ratios at a given mass and presented in the (Wb,Ht) BR plane.
[Recall BR(Zt) is determined, as the three sum to unity]

As expected, Wb+X analysis is most sensitive in the Wb corner



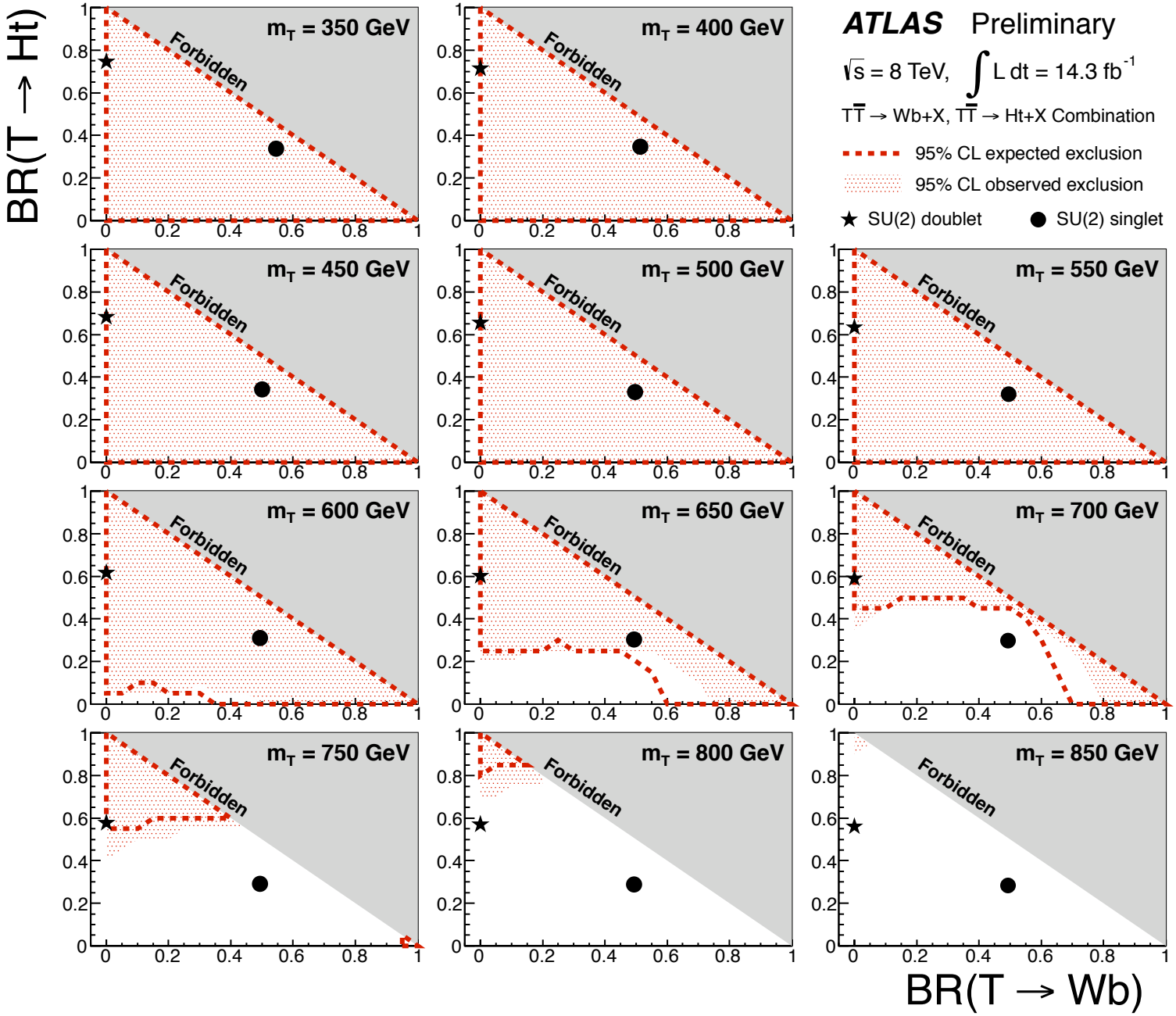
Combination of single lepton results

A preliminary combination of the Ht+X and Wb+X analyses has been performed.
[the two analyses do not overlap, and common sources of sys. uncert. are treated as fully correlated]

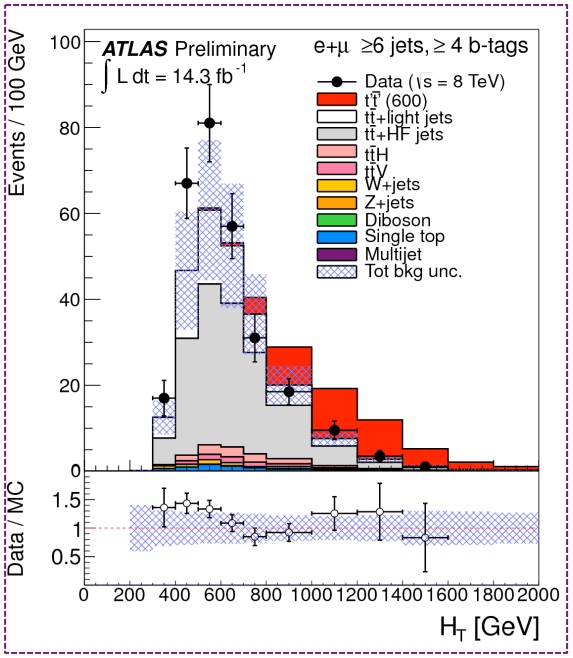
Combined limit on a singlet T:

m_T < **670** (675) **GeV**, **obs** (exp)

After combination, the BR(Zt) corner is the least well covered, but ATLAS has additional searches to cover it!



ATLAS VLQ results with single and multiple leptons



Ht+X

- Single lepton + missing E_T
- At least 4 jets, one or (many) more b-jets

≥ 6 jets

≥ 4 b-tags

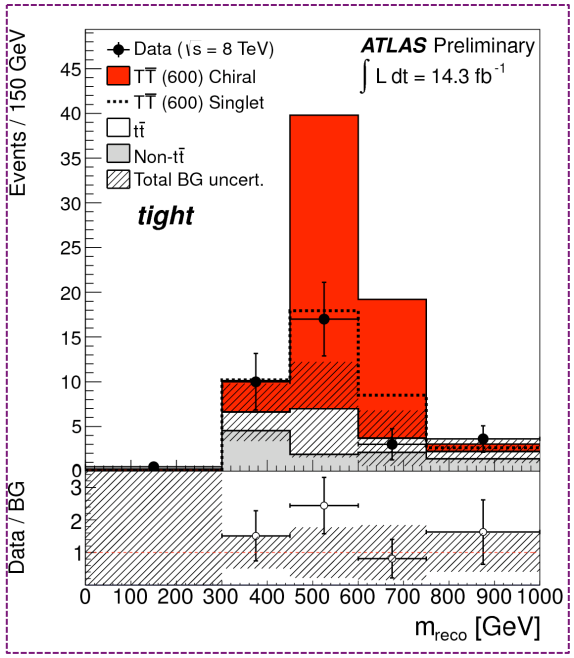
Test H_T(all)

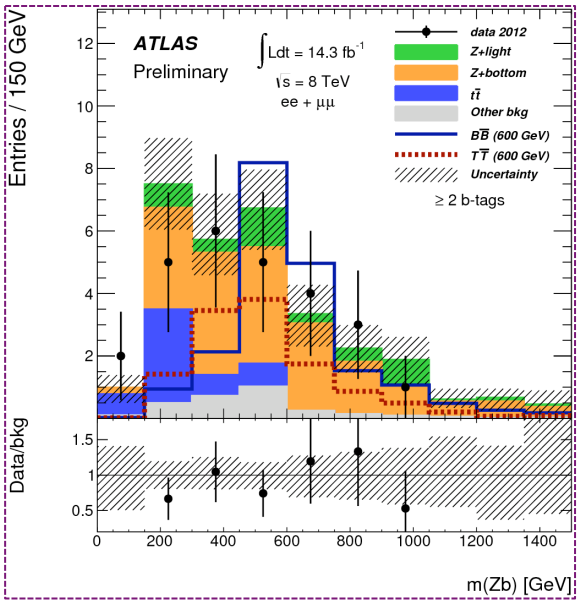
Wb+X

Reco W_{had}

Reco WbWb

Test Mass





Zb/t+X

ATLAS-CONF-2013-056

see J. Virzi's talk

- OS/SF leptons
- Z candidate
- High p_T(Z)
- ≥ 2 b-jets
- Large H_T(jets)

Test m(Zb)

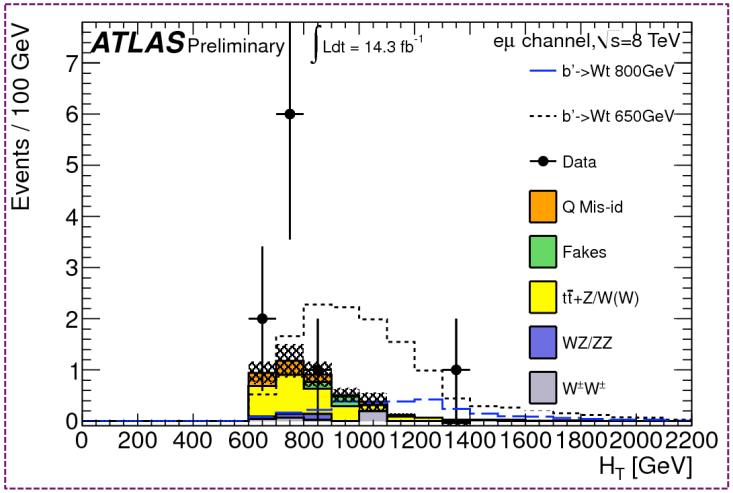
Same-Sign

ATLAS-CONF-2013-051

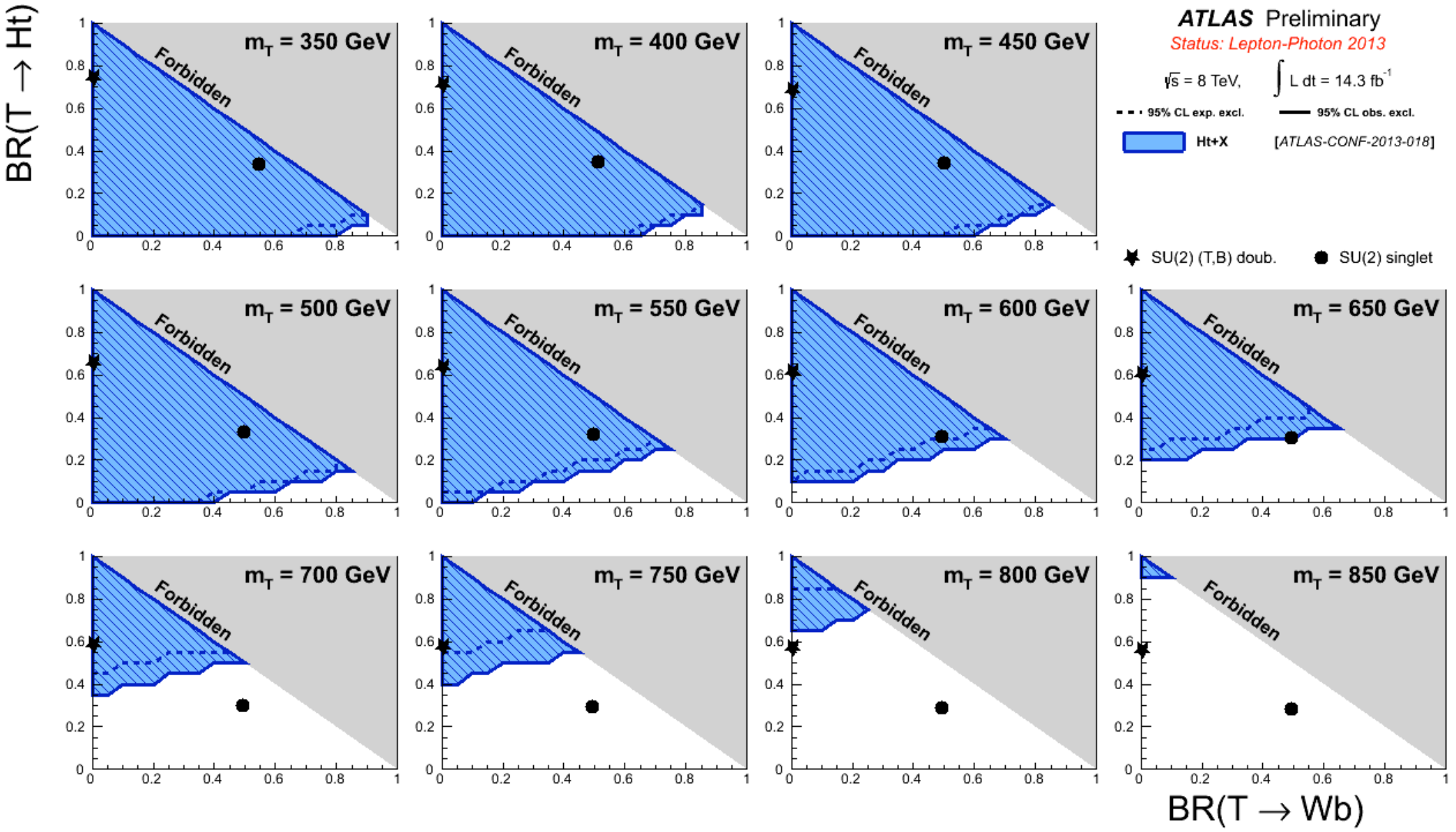
see X. Lei's talk

- SS leptons
- Missing E_T
- ≥ 2 jets
- ≥ 1 b-jets
- Large H_T(all)

Count

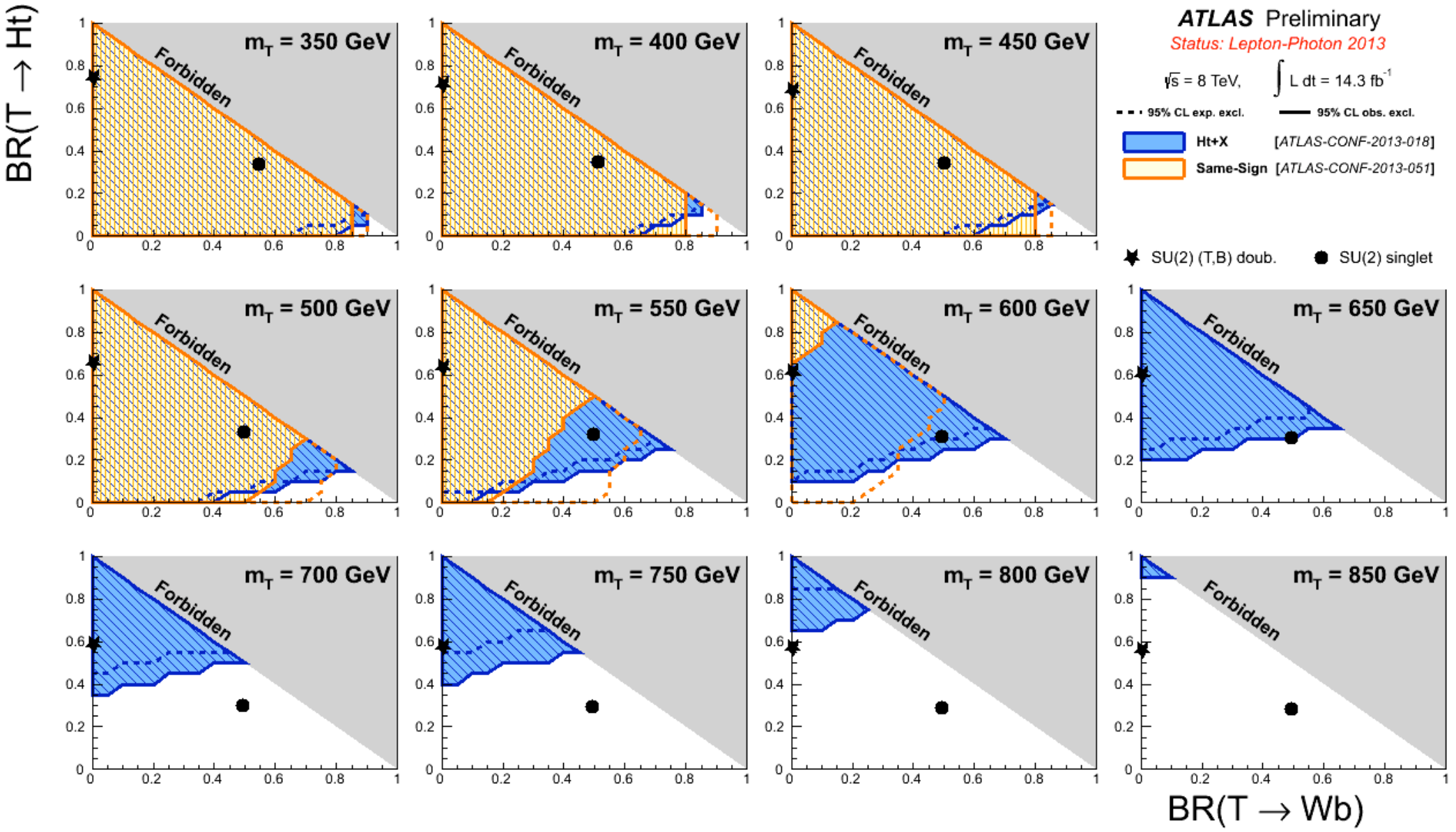


Vector-like T Summary Plots



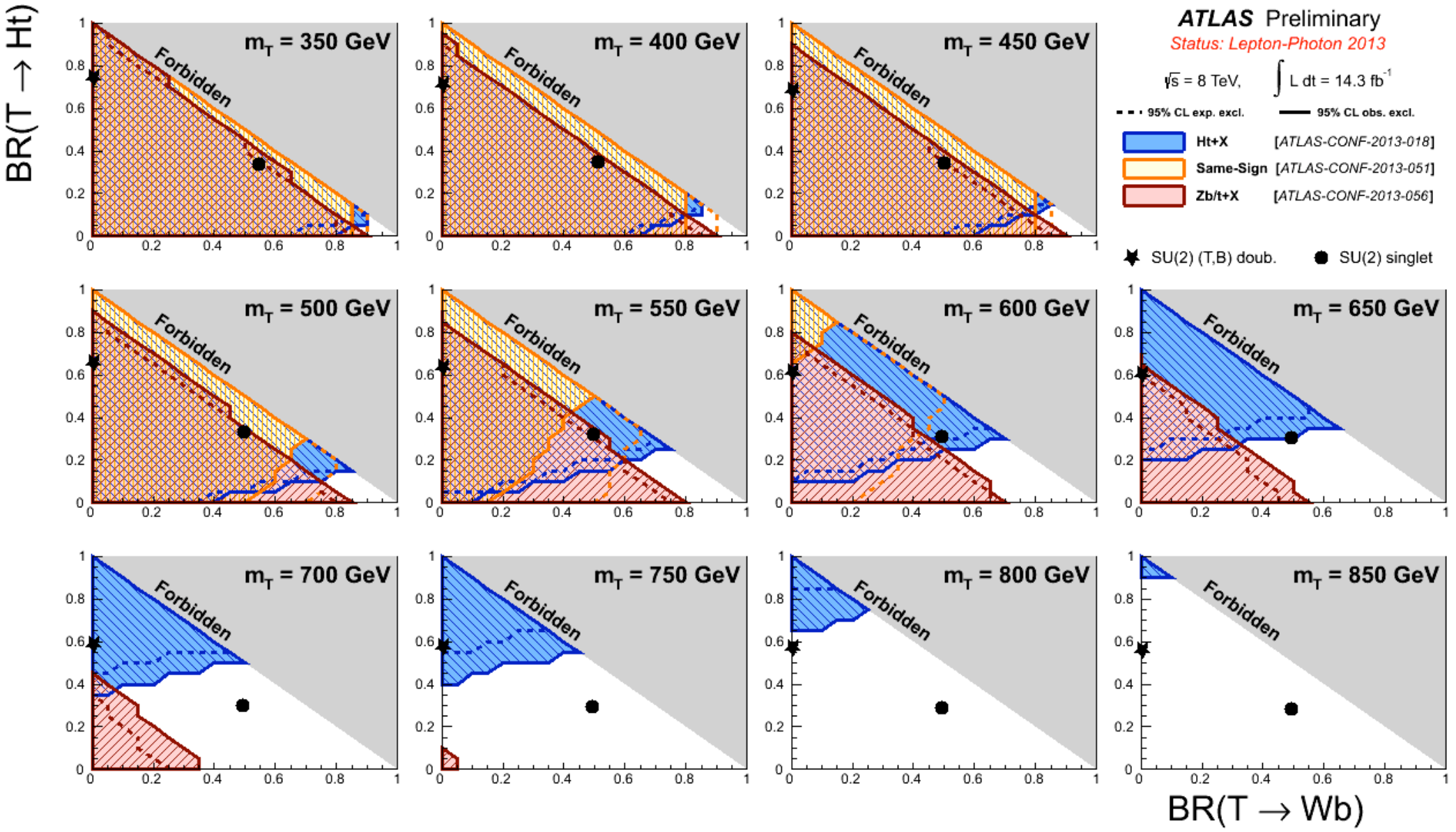
- In the T plane, the Ht+X analysis is particularly powerful in the Ht corner, but also has considerable sensitivity over a good portion of the full plane.

Vector-like T Summary Plots



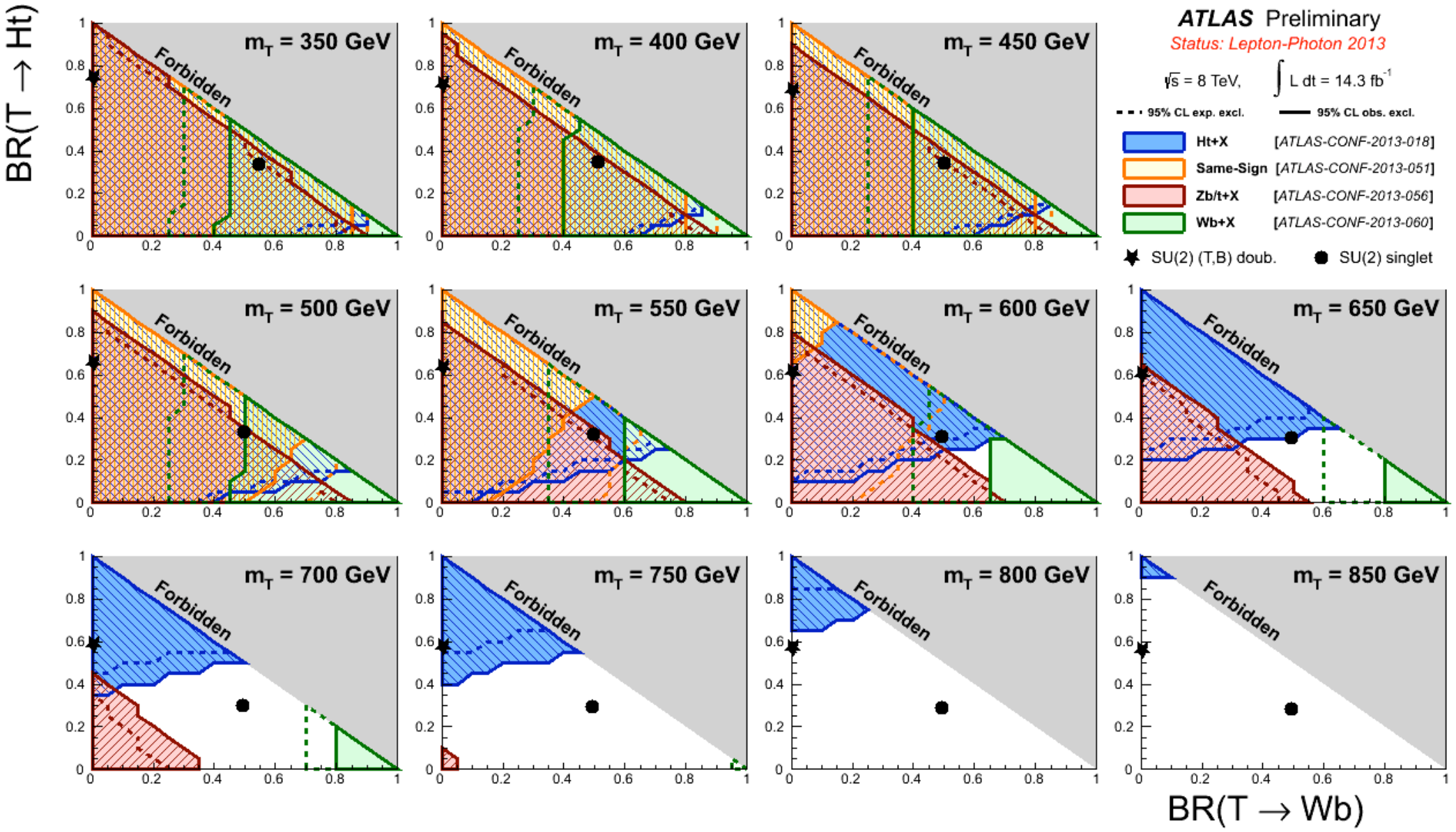
- In the T plane, the SS analysis complements the Ht+X analysis, adding a little more reach at low BR(Ht) for lower masses.

Vector-like T Summary Plots



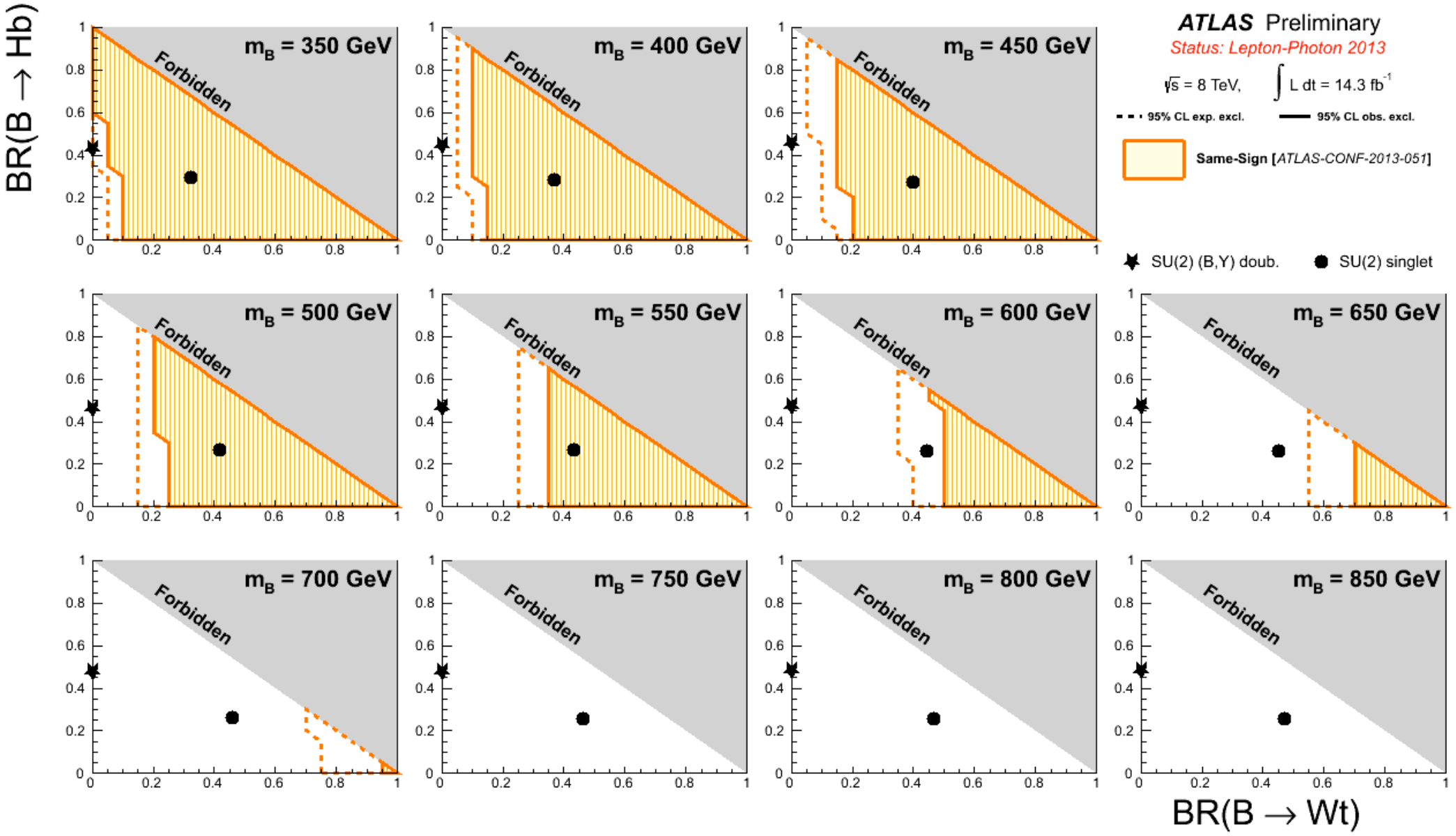
- However, the Zb/t+X provides the best sensitivity at low BR(Ht) in the T plane.

Vector-like T Summary Plots



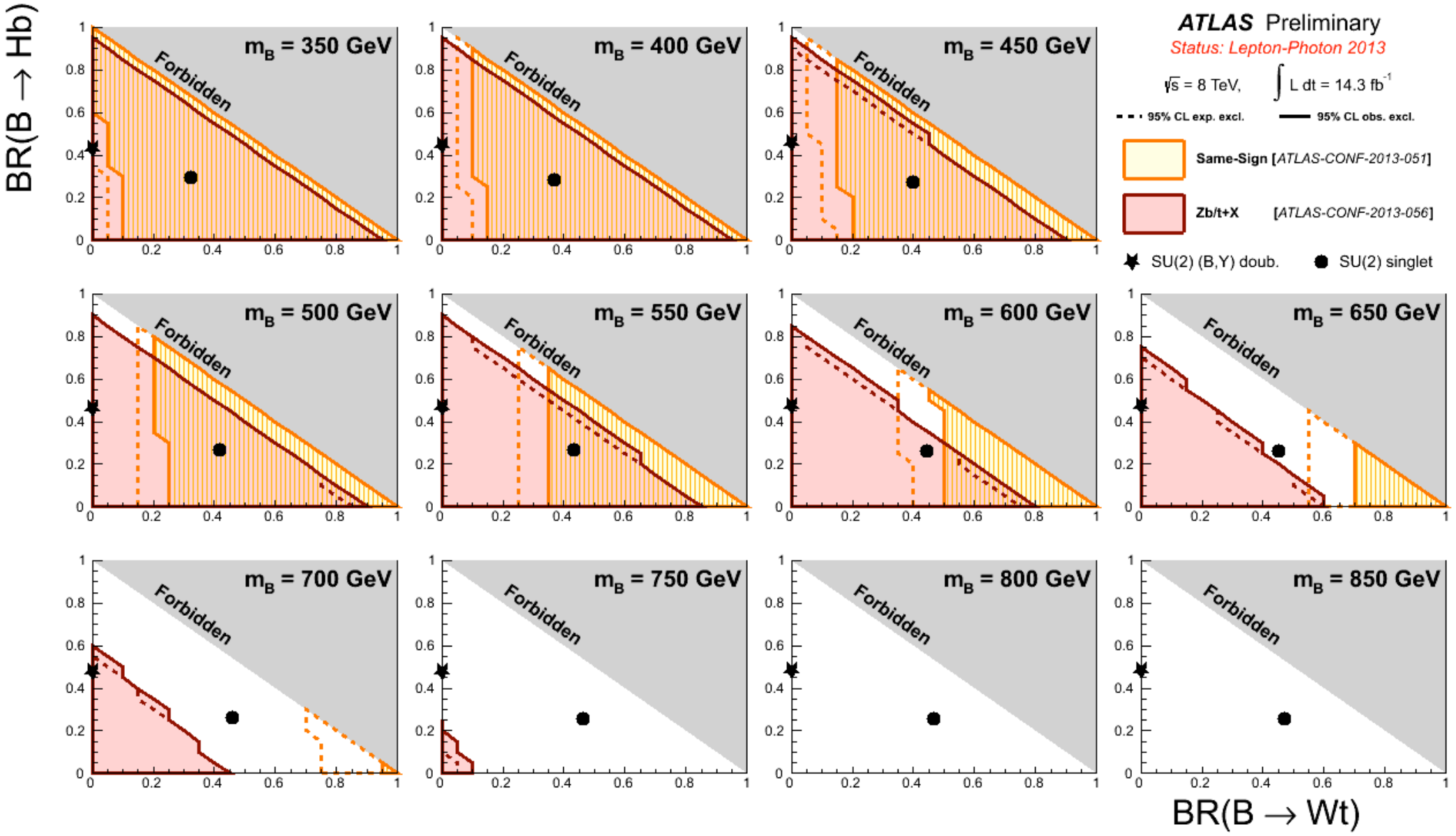
- And Wb+X fills in the remaining uncovered region, the charged-current corner.

Vector-like B Summary Plots



- In the B plane, the SS analysis covers well the charged current corner (4 W final state).

Vector-like B Summary Plots



- And the Zb/t+X covers well the neutral current side of the B plane.

Conclusions

- Two searches for heavy top-like quarks using 14.3/fb of 8 TeV data were described.
- Both were carried out in the single lepton final state, and are complementary.
- Ht + X targets the neutral-current decay to a top quark and a Higgs boson.
- Wb + X targets the charged-current decay to a bottom quark and a W boson.

Heavy Top Quark Summary

Heavy T quark type	Source	Obs. limit [GeV]	Exp. Limit [GeV]
vector-like singlet T	1-lep comb	670	675
T in vector-like (T,B) doublet	Ht + X	790	745
chiral	Wb +X	740	770

- These 1-lepton results are complemented by dilepton results that also set strong limits on new heavy bottom quarks.

Heavy Bottom Quark Summary

Heavy B quark type	Source	Obs. limit [GeV]	Exp. Limit [GeV]
vector-like singlet B	Zb/t+X	645	635
B in vector-like (T,B) doublet / chiral	SS	720	770
B in vector-like (B,Y) doublet	Zb/t +X	725	720