Vector-Like Quarks at ATLAS

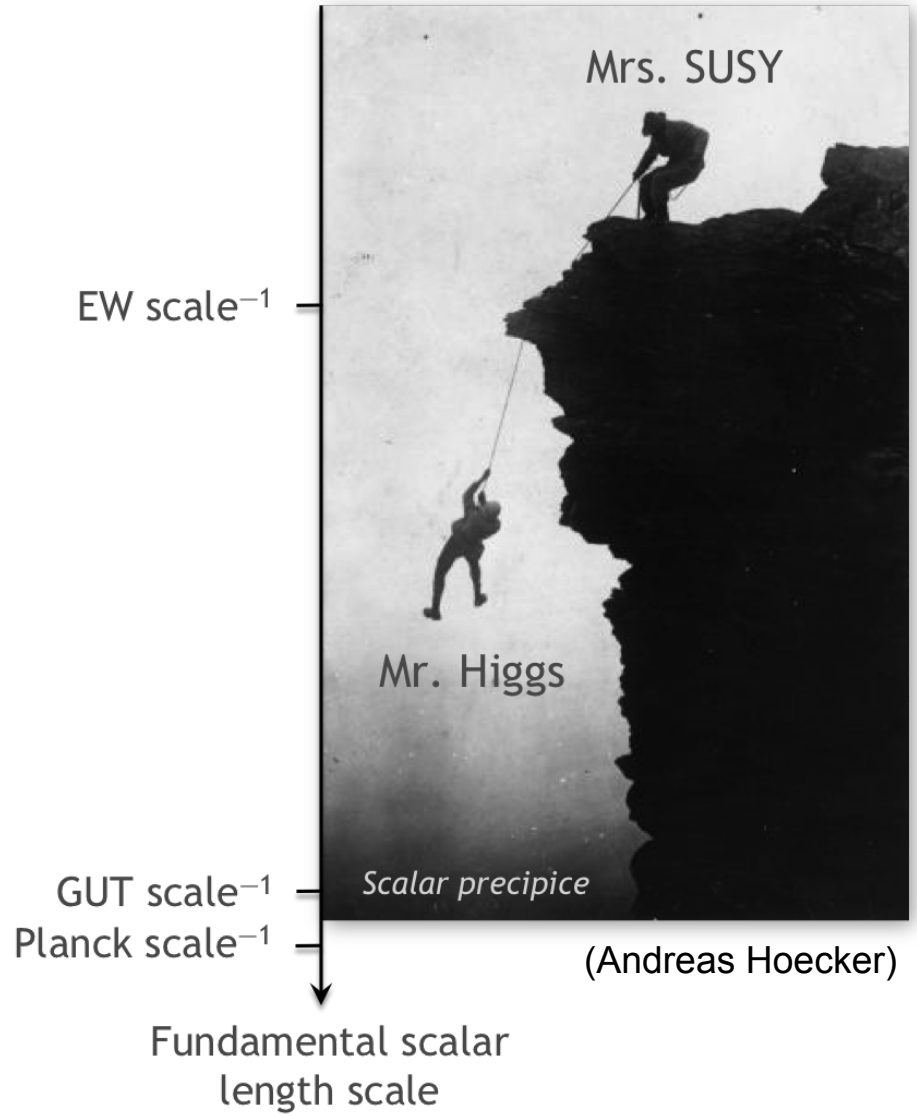
Tobias Golling (Yale)

LPC Workshop on Exotic Top Partners

Fermilab, Sep 26-27 2013

Higgs – Manifestation of Hierarchy Problem

$$\Delta m_H^2/m_H^2 \sim 10^{32}\ !$$



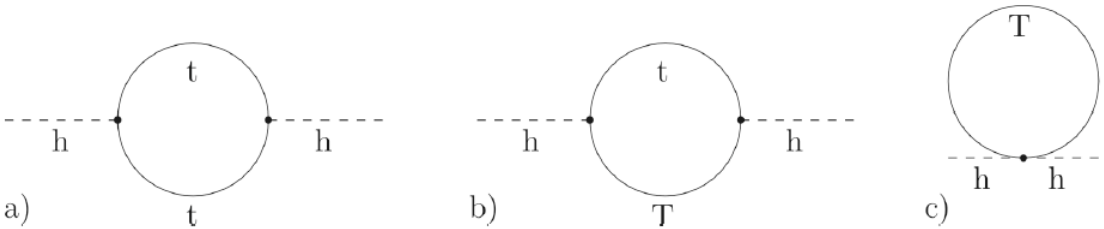
(Andreas Hoecker)

Higgs – Manifestation of Hierarchy Problem

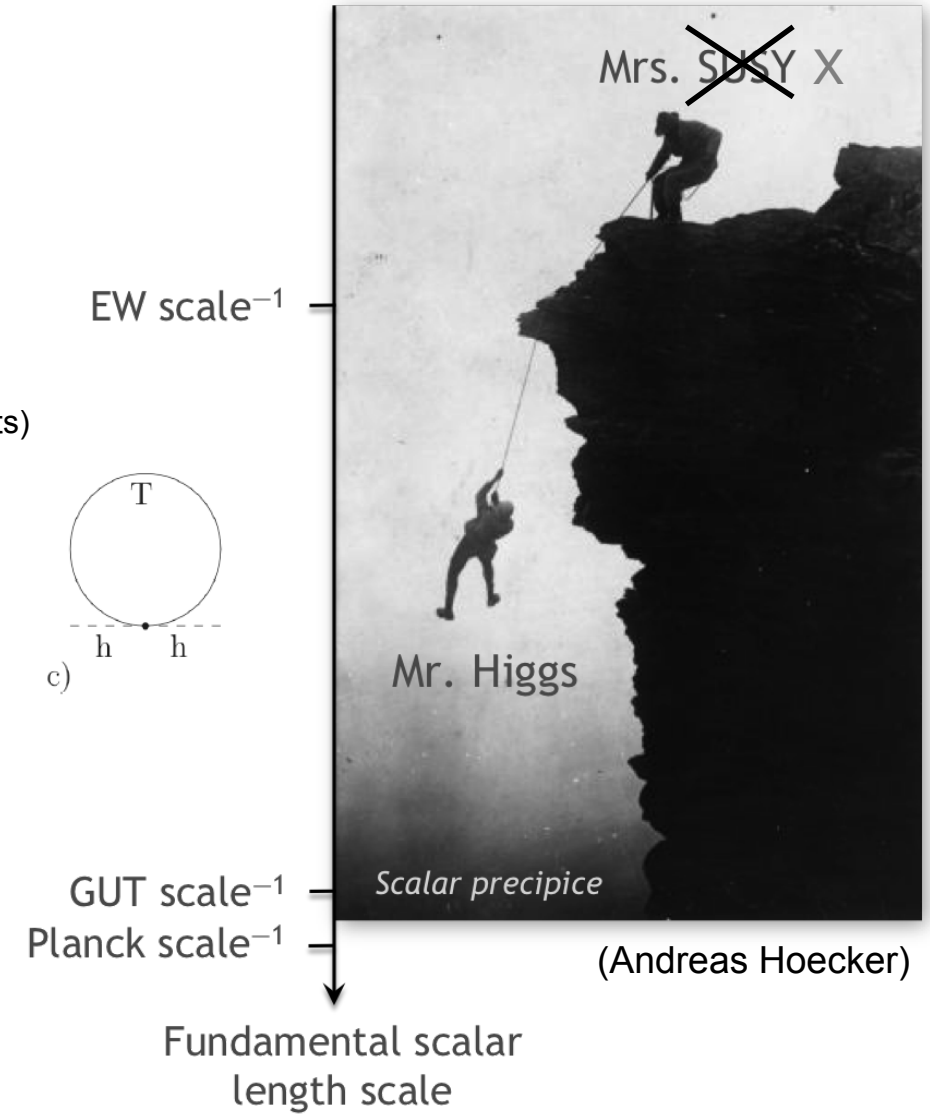
$$\Delta m_H^2/m_H^2 \sim 10^{32}\ !$$

Not only SUSY to rescue!
⇒ Vector-Like Quarks (VLQs)

(VLQ: same electroweak charges for LH and RH components)



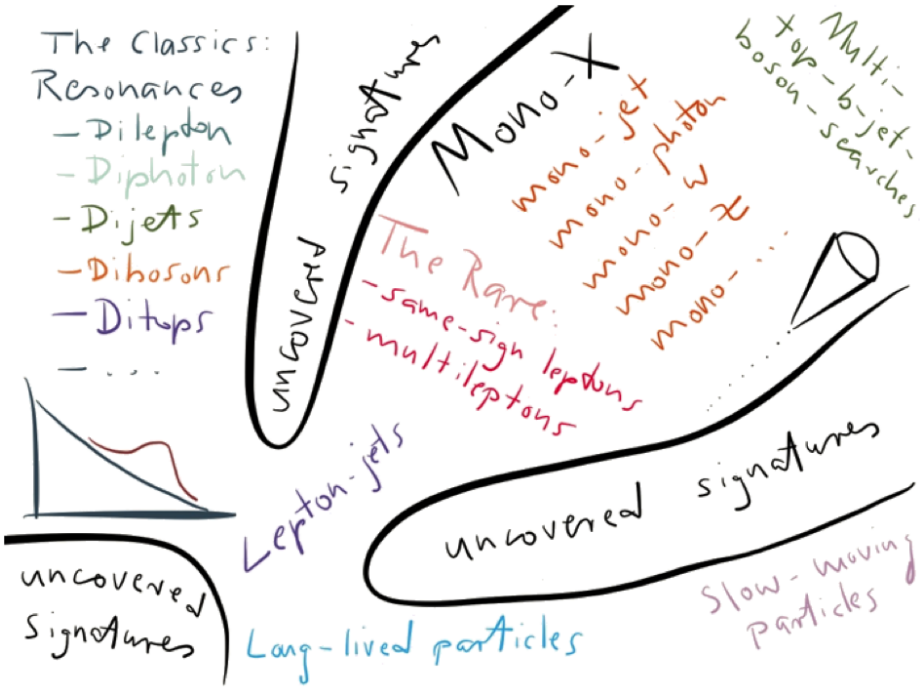
The quadratically divergent contribution to the Higgs mass from the top loop is canceled by the T loop.



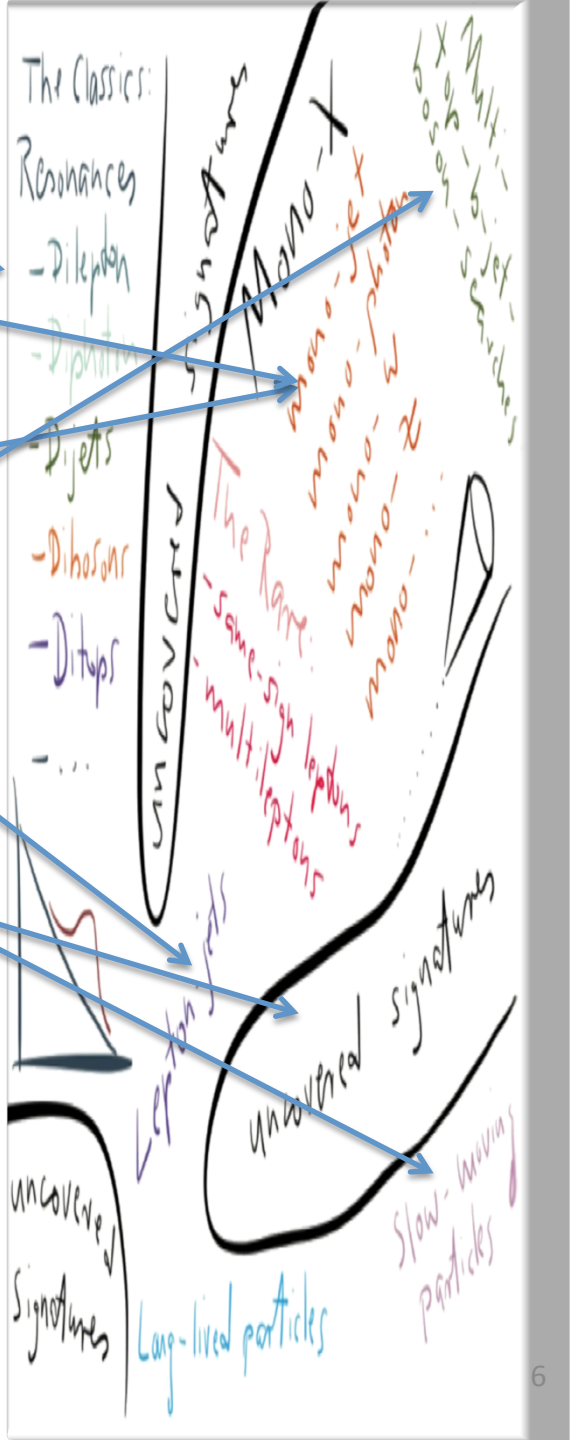
(Andreas Hoecker)

(Hitoshi Murayama)

(Hitoshi Murayama)



NOT YET
THOUGHT
OF
NOT YET
THOUGHT OF


The Classics:
Resonances
-Dileptons
-Diphotons
-Dijets
-Dibosons
-Ditops
-...
unconvered signatures
Mono-X
The Rare:
'same-sign leptons'
'multi-leptons'
mono-jet
mono-photon
mono-W
mono-Z
mono-...
Lepton jets
uncovered signatures
uncovered signatures
Long-lived particles
Slow-moving particles

Signature-Driven Searches

(Henry Bachacou)

- Many extensions of the SM have been developed over the past decades:
- Supersymmetry
- Extra-Dimensions
- Technicolor(s)
- Little Higgs
- No Higgs
- GUT
- Hidden Valley
- Leptoquarks
- Compositeness
- 4th generation (t', b')
- LRSM, heavy neutrino
- etc...

- 1 jet + MET
- jets + MET
- 1 lepton + MET
- Same-sign di-lepton
- Dilepton resonance
- Diphoton resonance
- Diphoton + MET
- Multileptons
- Lepton-jet resonance
- Lepton-photon resonance
- Gamma-jet resonance
- Diboson resonance
- Z+MET
- W/Z+Gamma resonance
- Top-antitop resonance
- Slow-moving particles
- Long-lived particles
- Top-antitop production
- Lepton-Jets
- Microscopic blackholes
- Dijet resonance
- etc...
- Uncovered signature
- …

- Not yet though of

!

- We know that each single model is probably "wrong"
- Use models as guidance where to look
- Try to cover all possible signatures
- Interpret results using benchmarks

VLQs

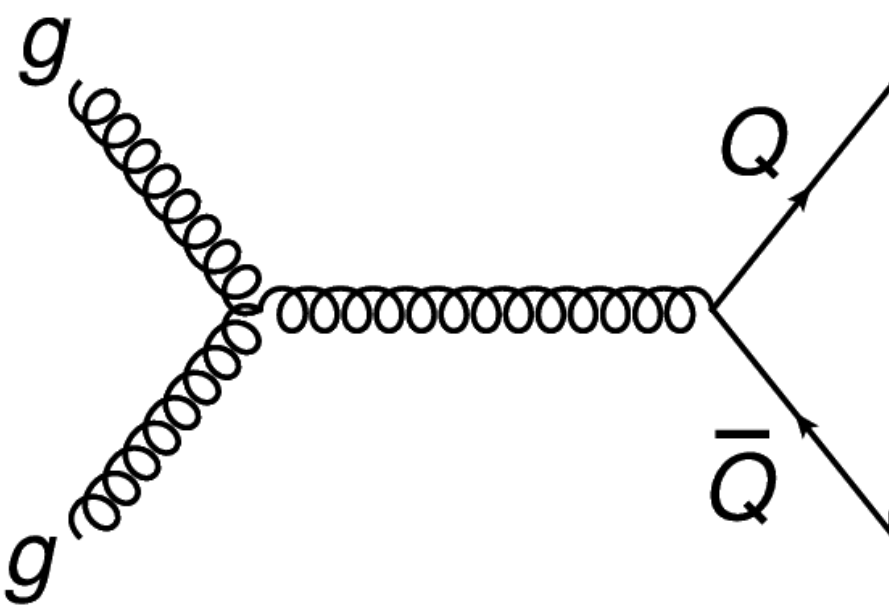
- Start by considering four different kinds of VLQs with different charge:
  - T (+2/3)
  - B (-1/3)
  - X (+5/3) – aka $T_{5/3}$
  - Y (-4/3)

JHEP 11, 030 (2009) *(triplets not included)*

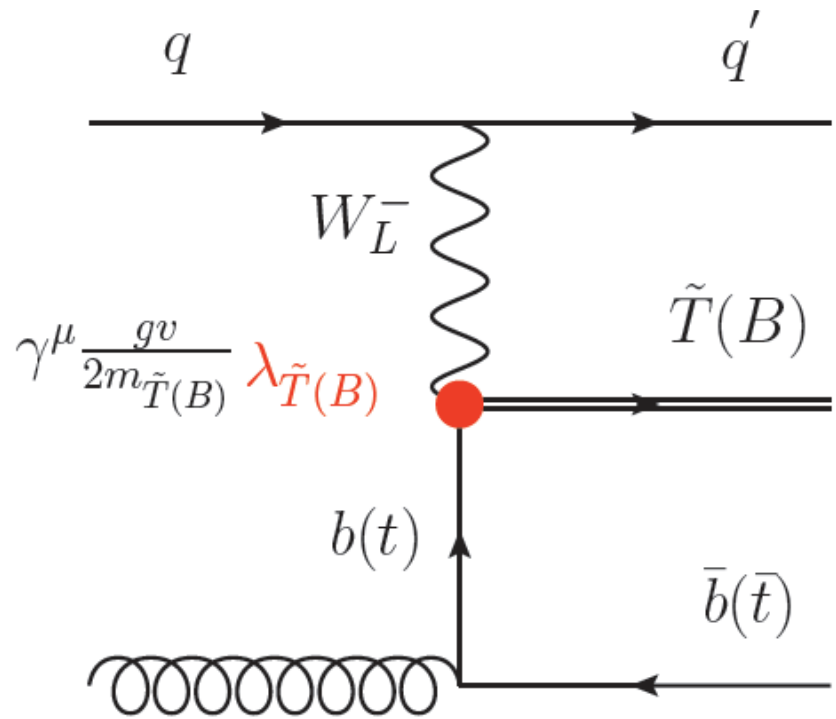
	Label	Charge	Decay mode
T singlet	T_S	+2/3	$T \to W^+b$, Zt, ht
B singlet	B_S	-1/3	$B \to W^-t$, Zb, hb
(T,B) doublet	TB_d	(+2/3, -1/3)	$T \to W^+b$, Zt, ht $B \to W^-t$, Zb, hb
(X,T) doublet	XT_d	(+5/3, +2/3)	$X \to W^+t$ $T \to Zt$, ht
(B,Y) doublet	BY_d	(-1/3, -4/3)	$B \to Zb$, hb $Y \to W^-b$

VLQ Production Modes at the LHC

- **Strongly produced in pairs**: large $Q\bar{Q}$ cross-section only dependent on mass (just like $t\bar{t}$)

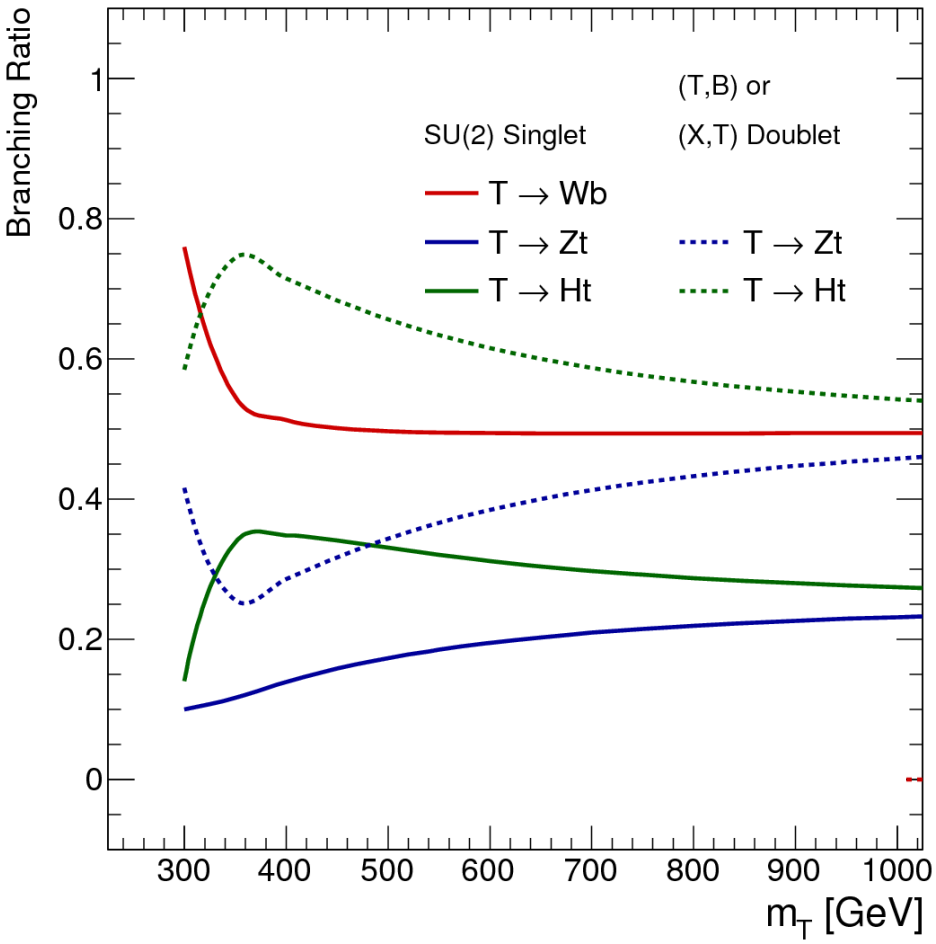


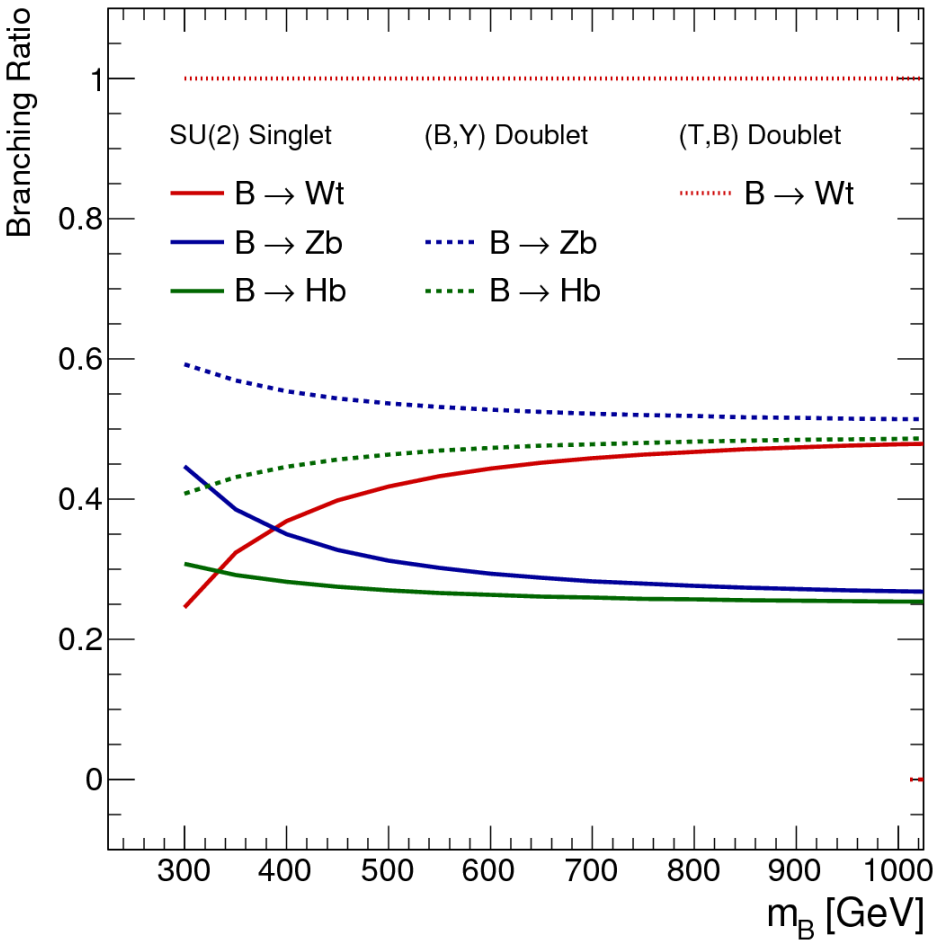
- **Single production** dependent on mass, charge, coupling



VLQ Decay Modes

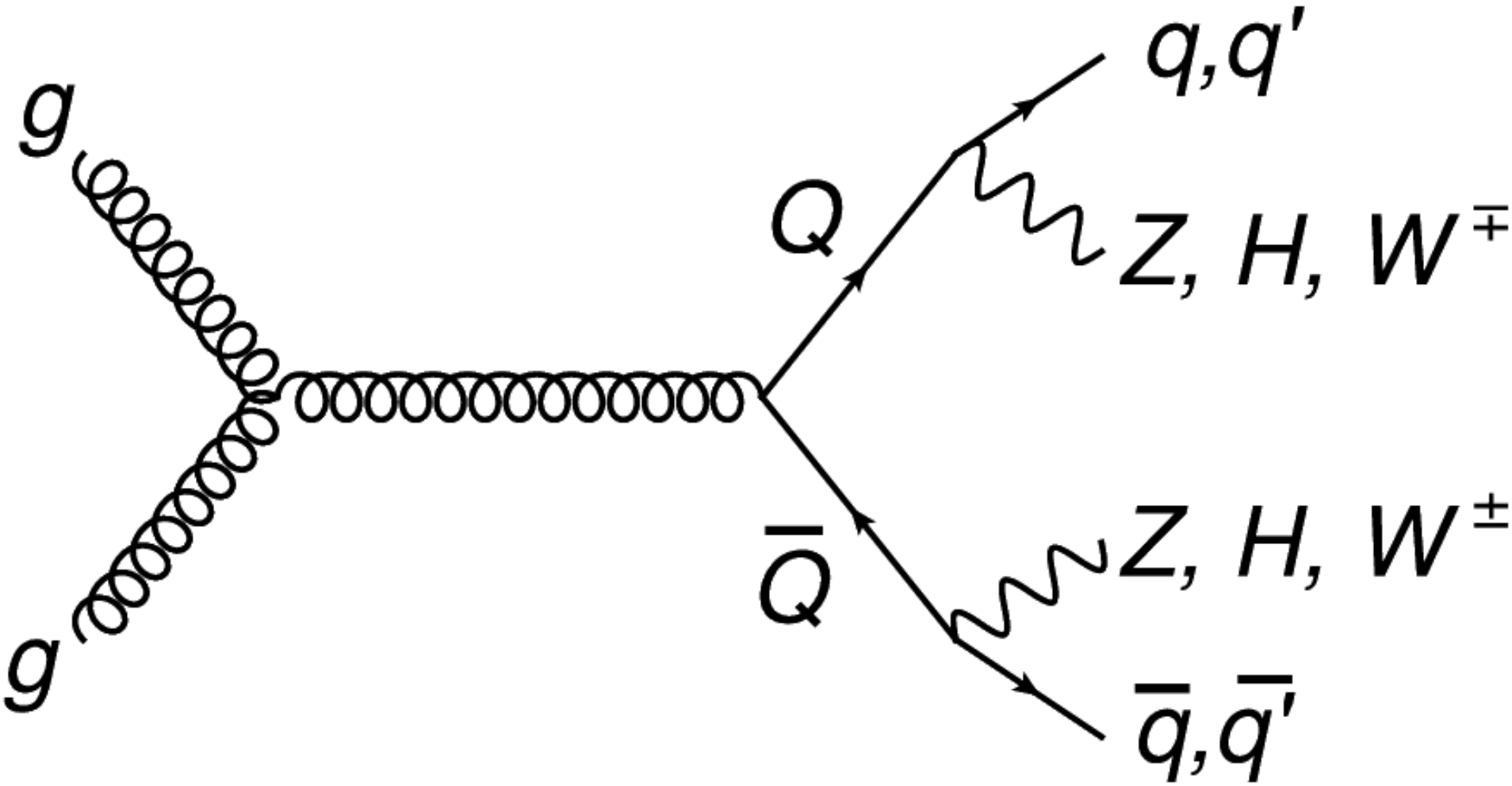
For (T,B) doublet assume $V_{Tb} << V_{tB}$



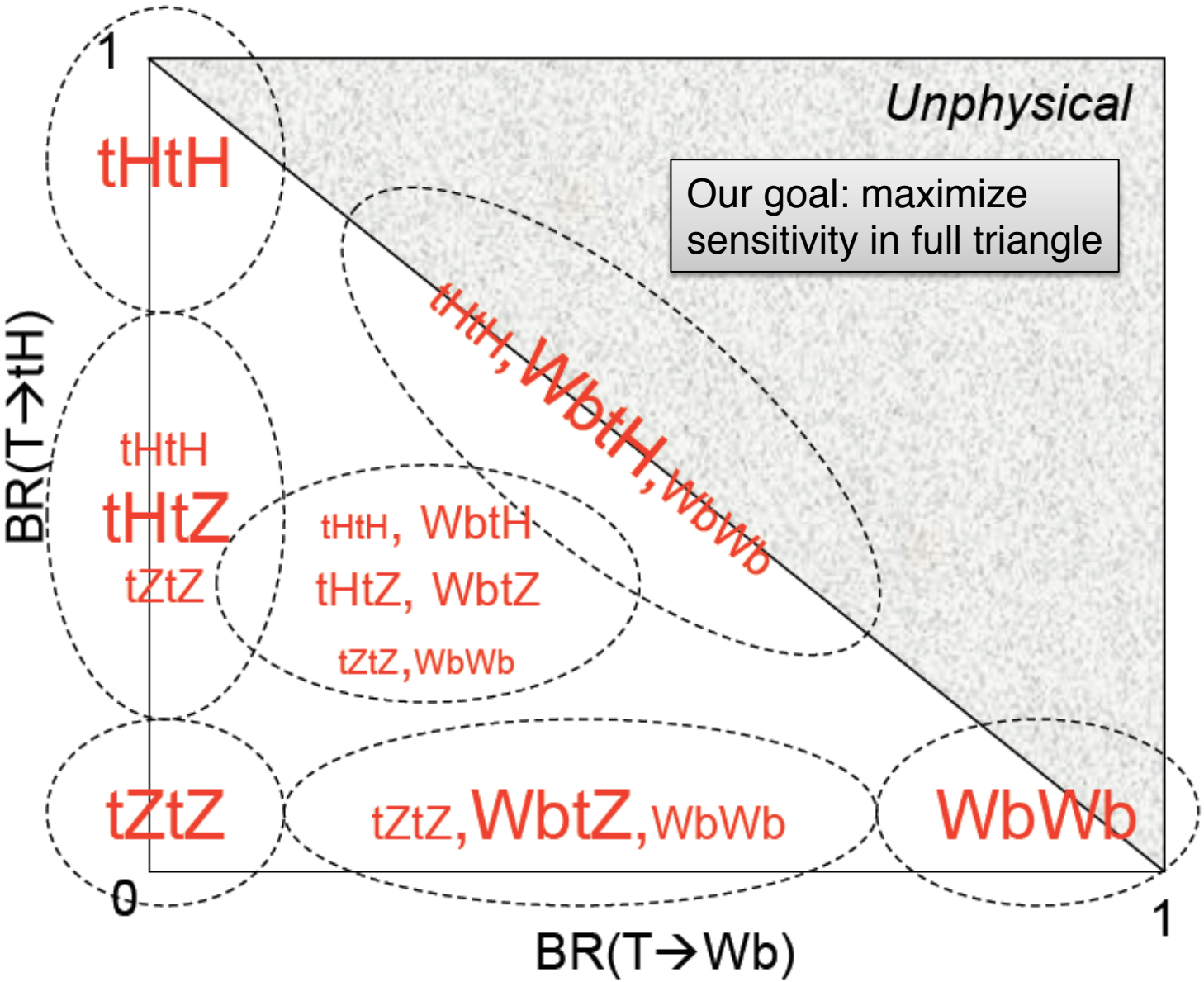


VLQ Pair Production

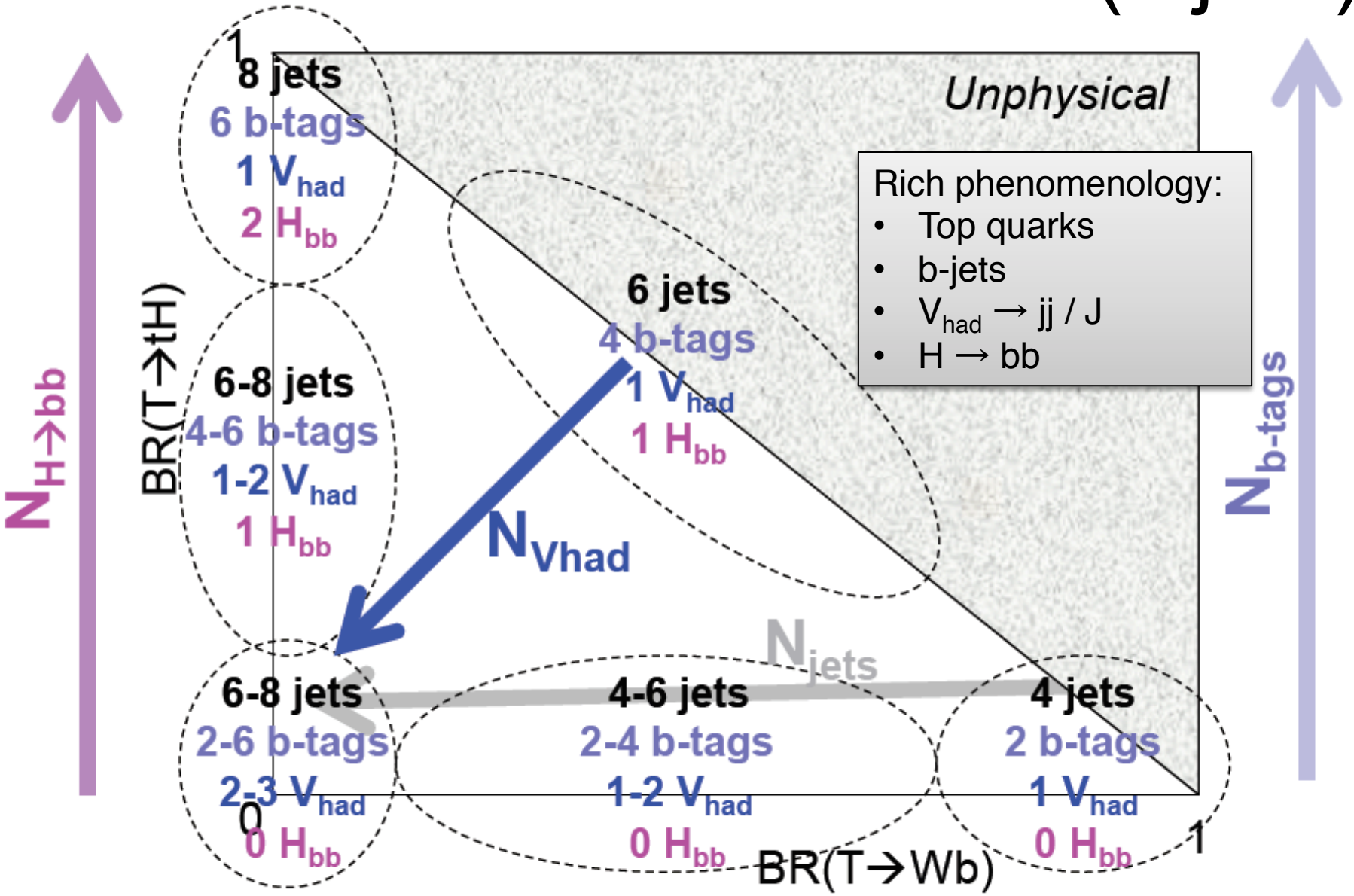
Spectacular signatures: boosted b-jets, tops, W, Z, H bosons



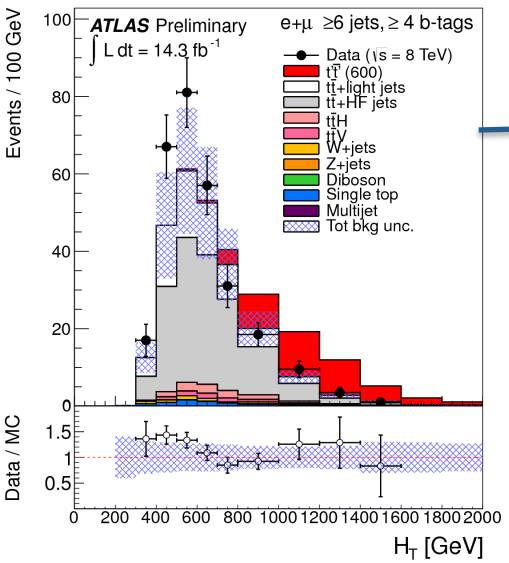
VLQ Pair Production: $T\bar{T}$



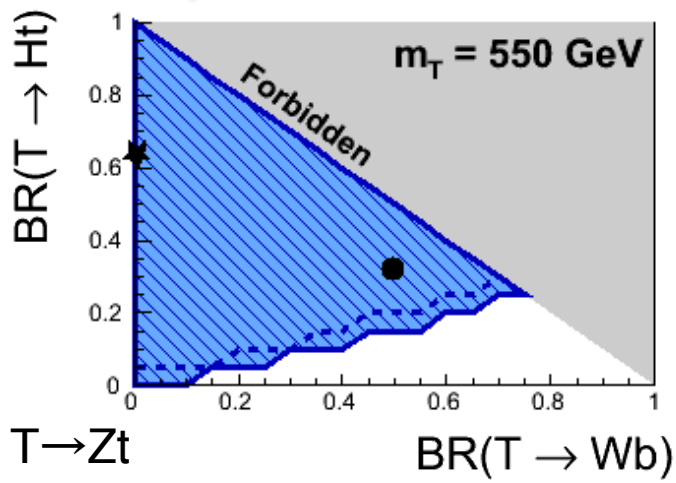
Possible Final States for $T\bar{T}$ (l+jets)



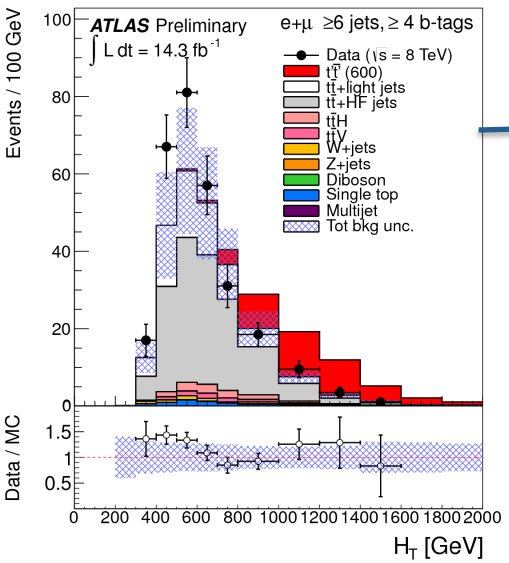
VLQ $T\bar{T}$ Search Strategy



Ht+X (l+jets)

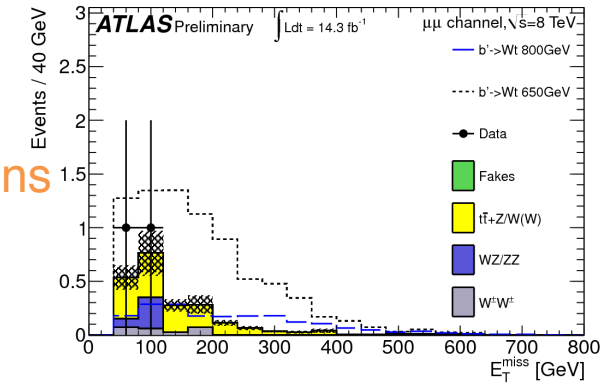


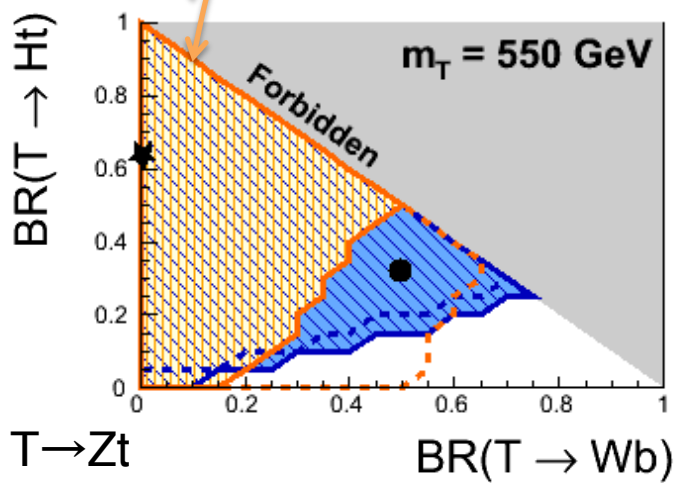
VLQ $T\bar{T}$ Search Strategy



Ht+X (l+jets)

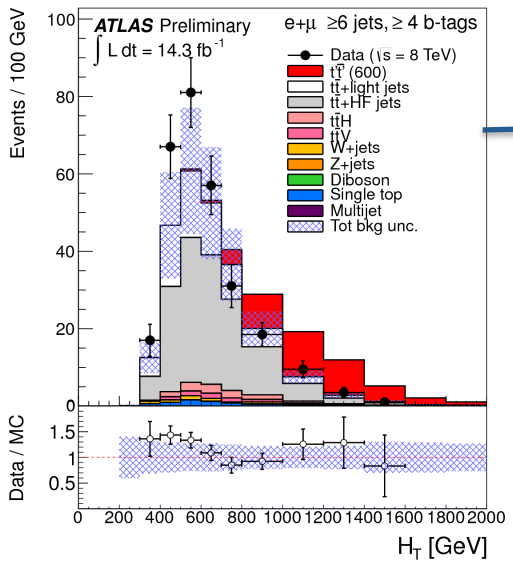
Same-sign leptons





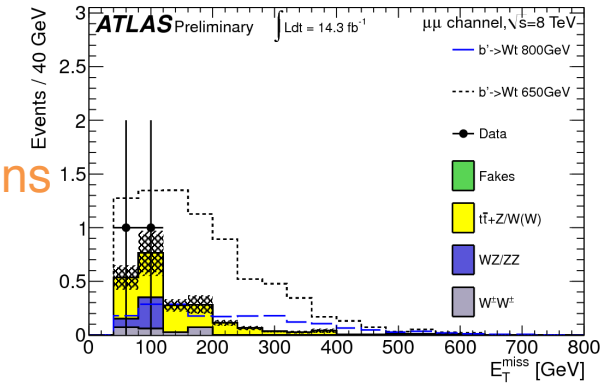
(not a combination, just overlaying results)

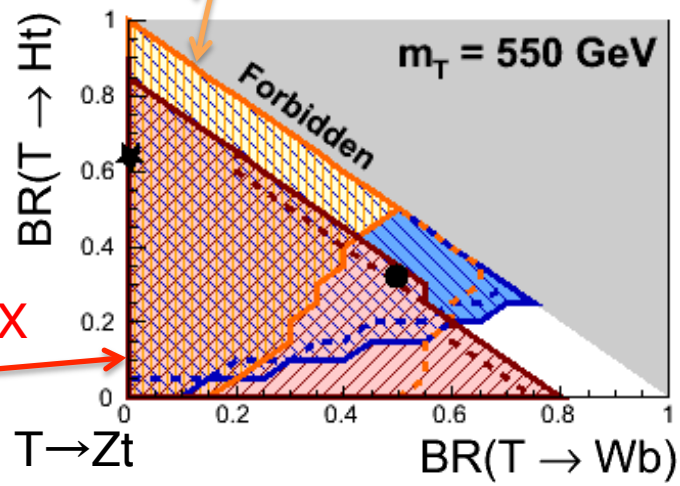
VLQ $T\bar{T}$ Search Strategy



Ht+X (l+jets)

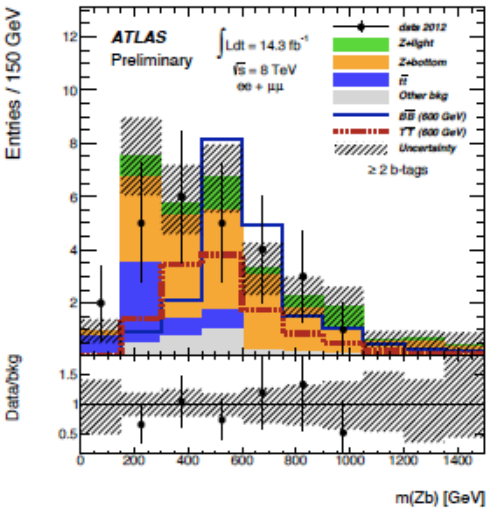
Same-sign leptons



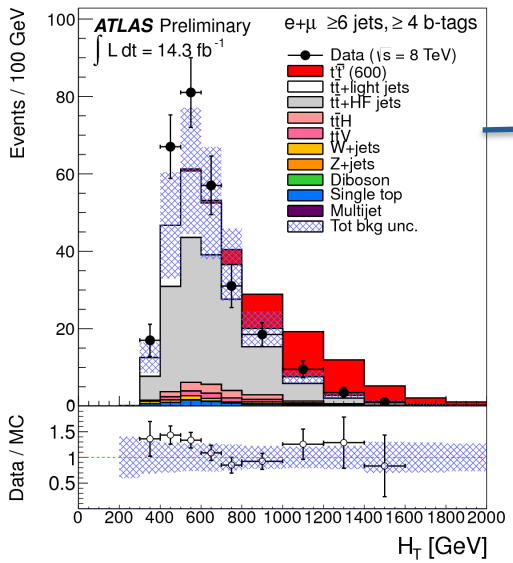


Zt+X

T→Zt

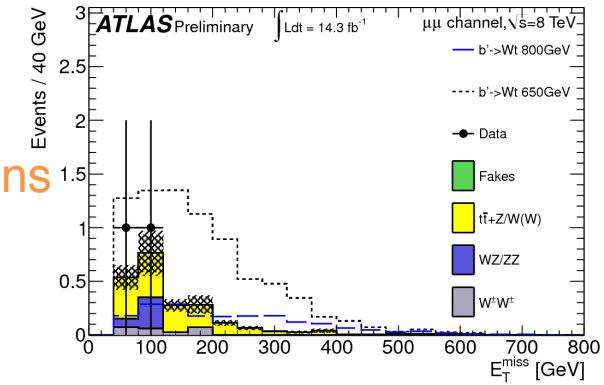


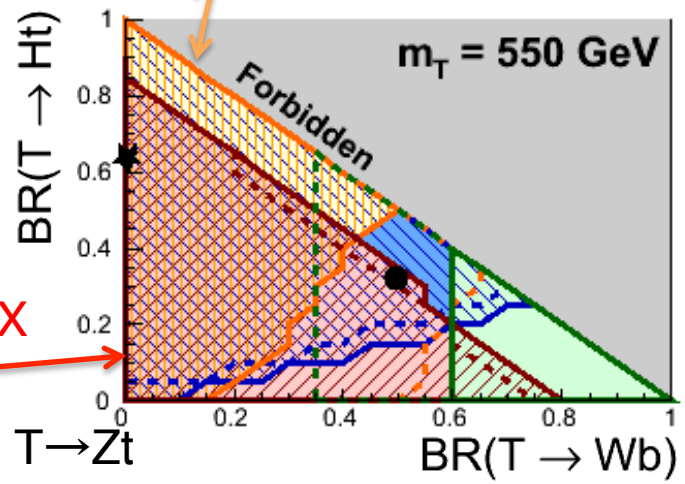
VLQ $T\bar{T}$ Search Strategy



Ht+X (l+jets)

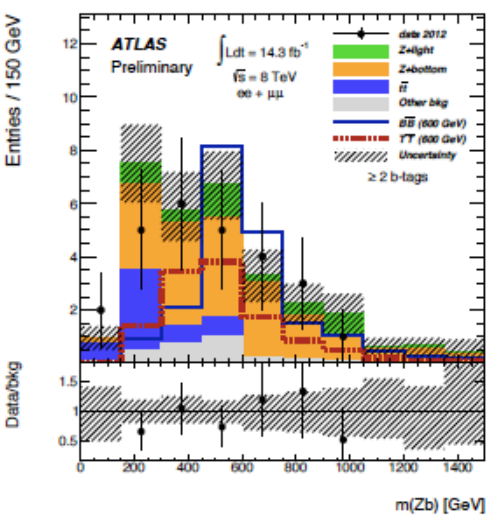
Same-sign leptons

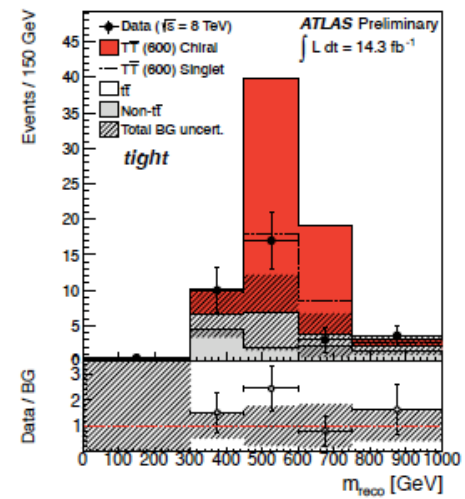




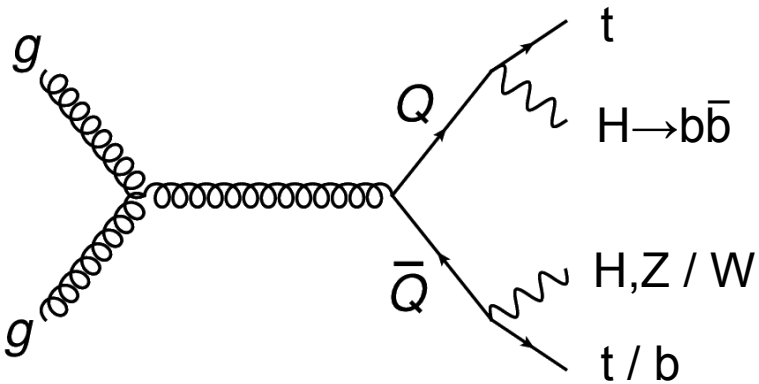
Zt+X

Wb+X (l+jets)

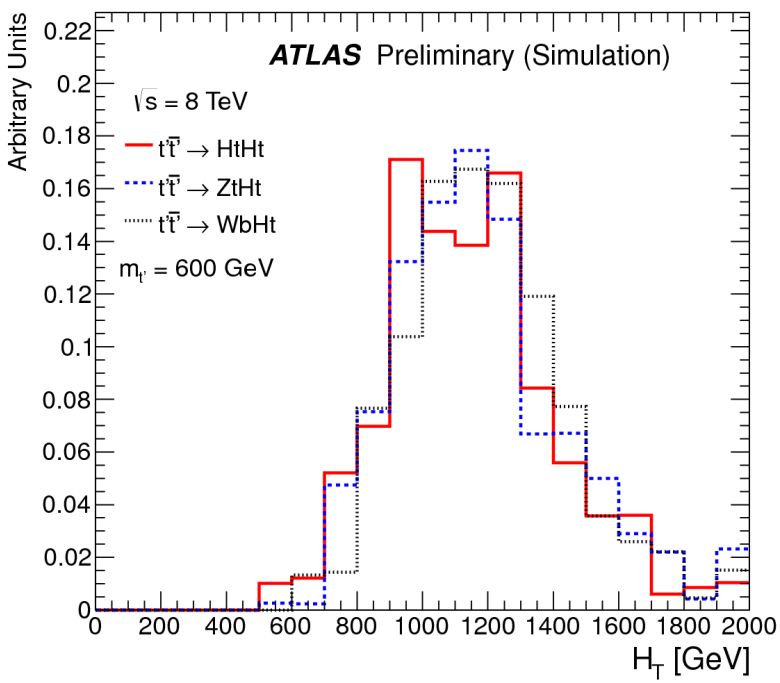


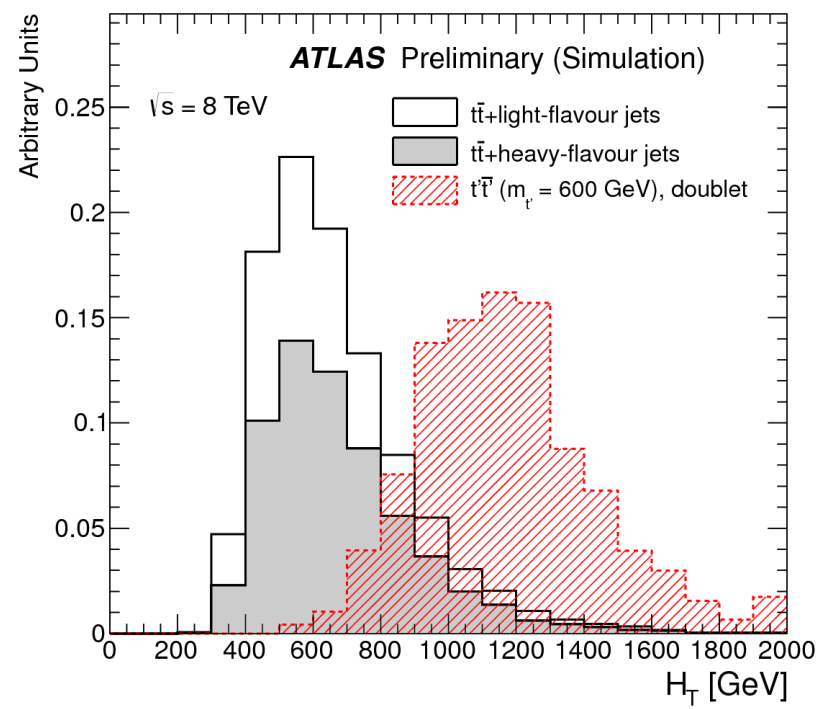


$T\bar{T} \rightarrow Ht+X$ Search Strategy



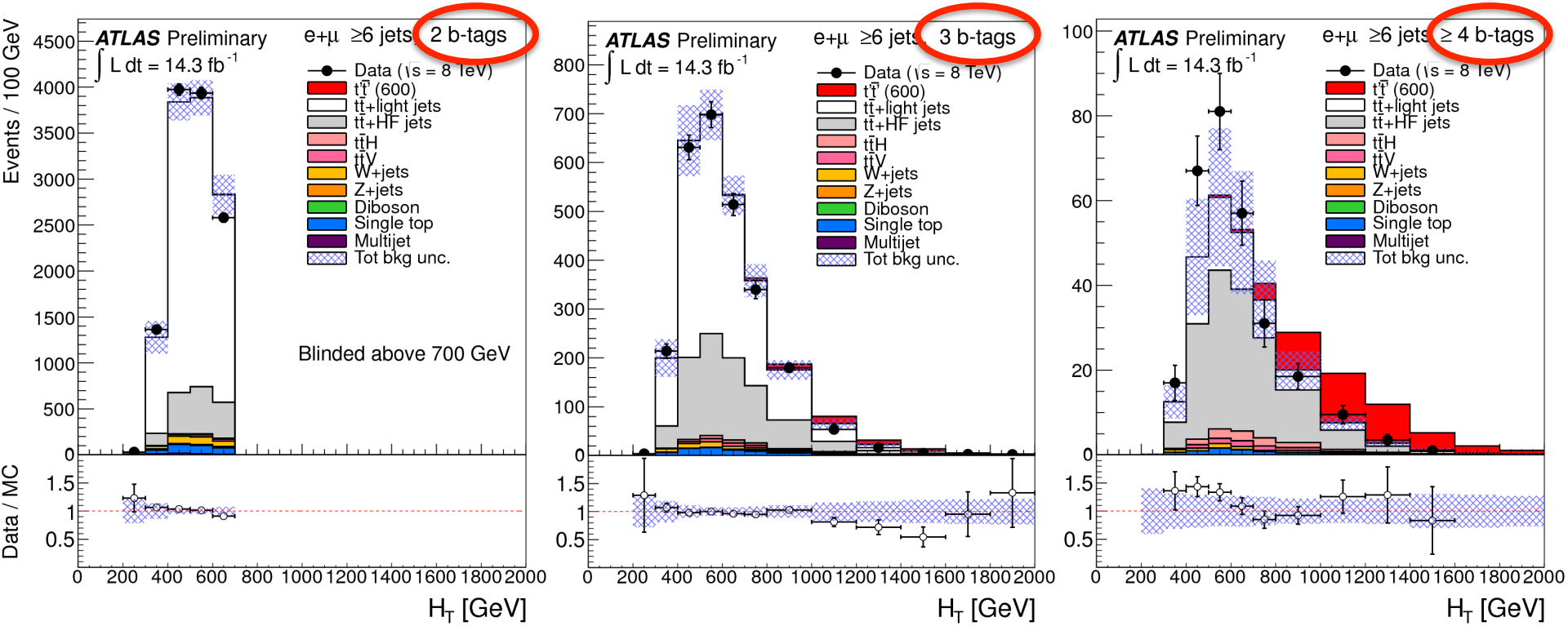
- Require lepton and MET ($W \rightarrow l\nu$)
- ≥ 6 jets
- ≥ 4 b-jets
- Final discriminant: H_T(l,ν,jets)





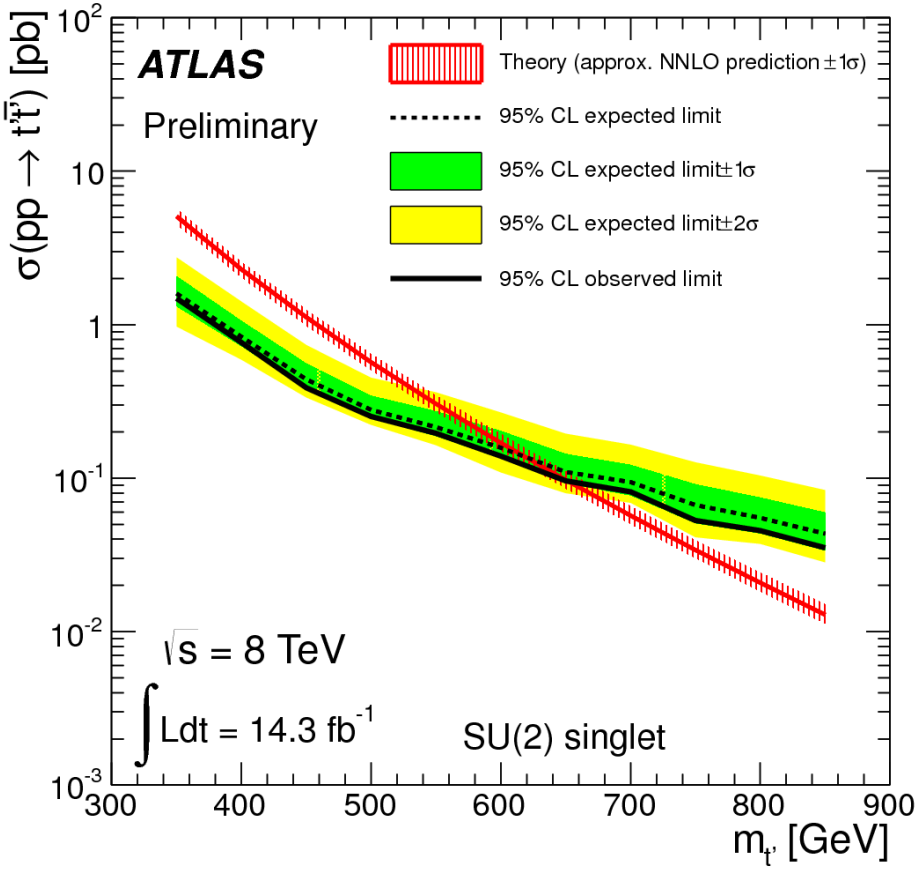
[ATLAS-CONF-2013-018]

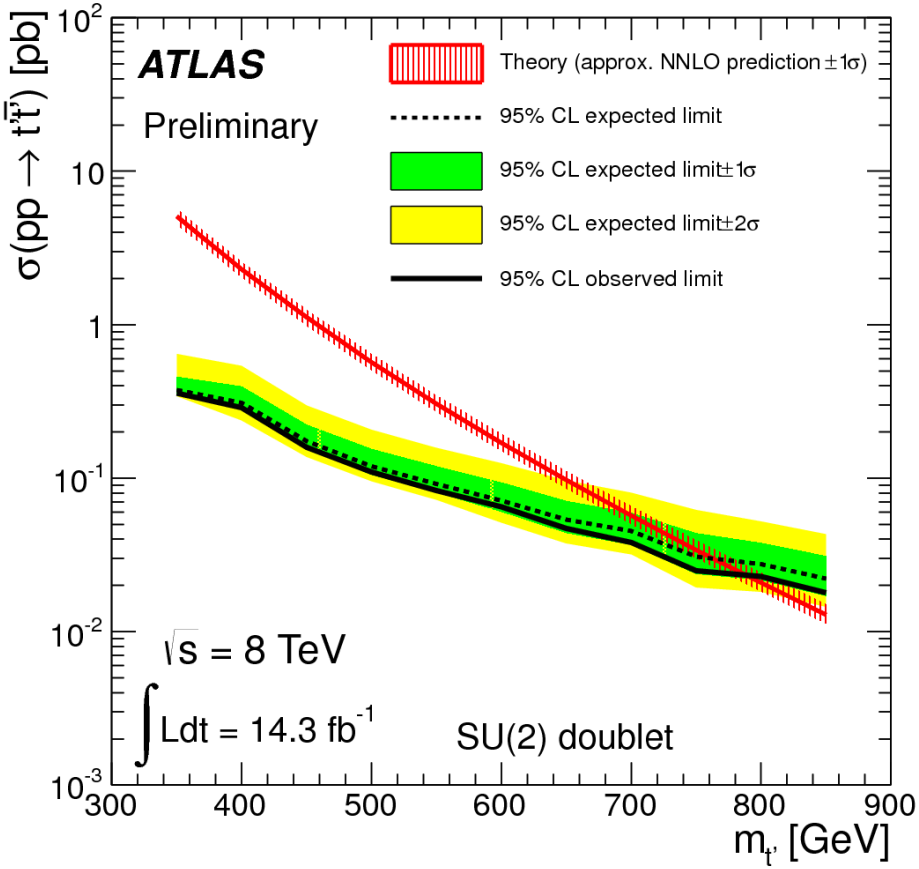
$T\bar{T} \rightarrow$ Ht+X Results



[ATLAS-CONF-2013-018]

$T\bar{T} \rightarrow$ Ht+X Limits on VLQ Singlet & Doublet

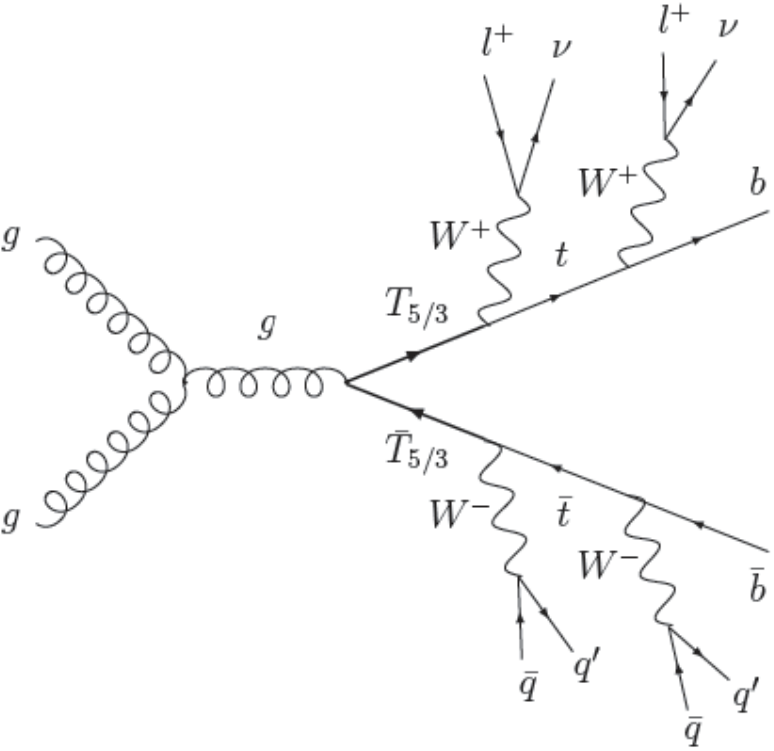


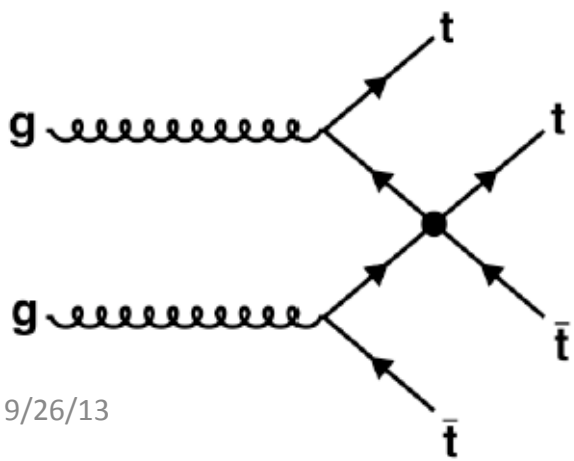


- Exclude @ 95% singlet with mass < 640 GeV
- Exclude @ 95% doublet with mass < 790 GeV

[ATLAS-CONF-2013-018]

Same-Sign Leptons Search Strategy





- Very Low SM backgrounds
  - 2 leptons of same charge
  - Large MET
  - 2 b-jets
  - Large H_T
- Many NP scenarios (including SUSY)
  - $B\bar{B}$, $T\bar{T}$, $T_{5/3}$, tt, 4-tops, gluino-mediated stop, H++/--, heavy neutrino (seesaw), TeV-scale gravity (mini-black holes),…
- Background estimate
  - Data-driven fakes-lepton estimate
  - Charge flip (e only), determined using Z events
  - Irreducible VV and $t\bar{t}$+V background

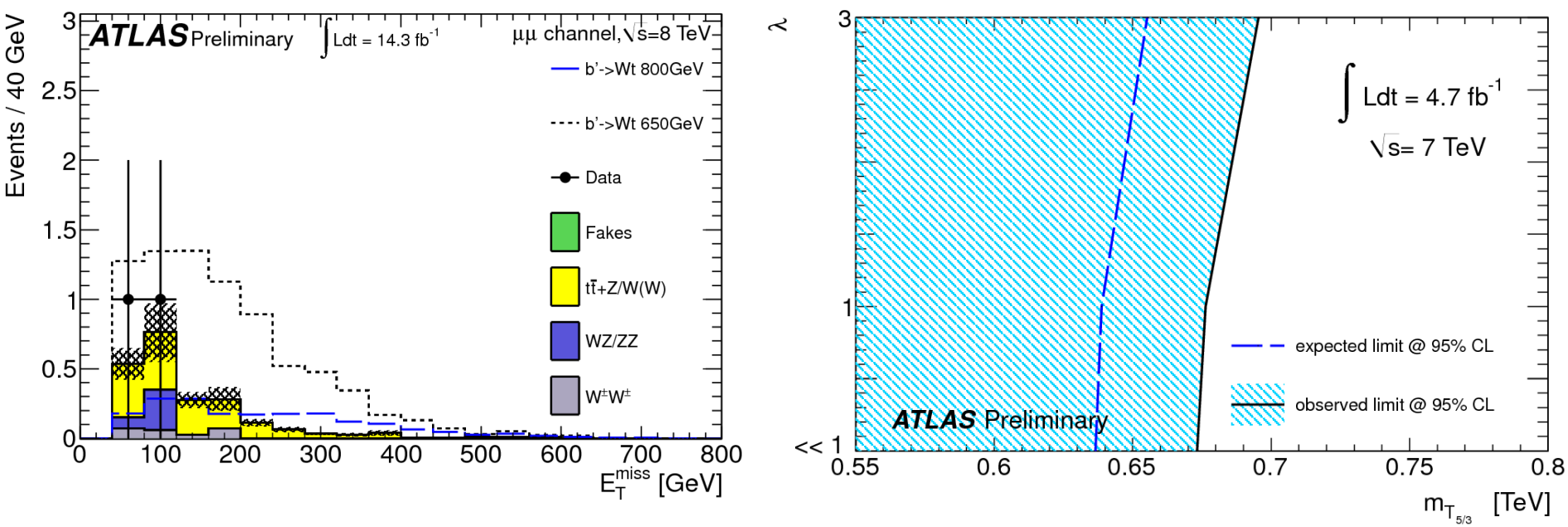
[ATLAS-CONF-2012-130]
[ATLAS-CONF-2013-051]

Same-Sign Results

Two examples:

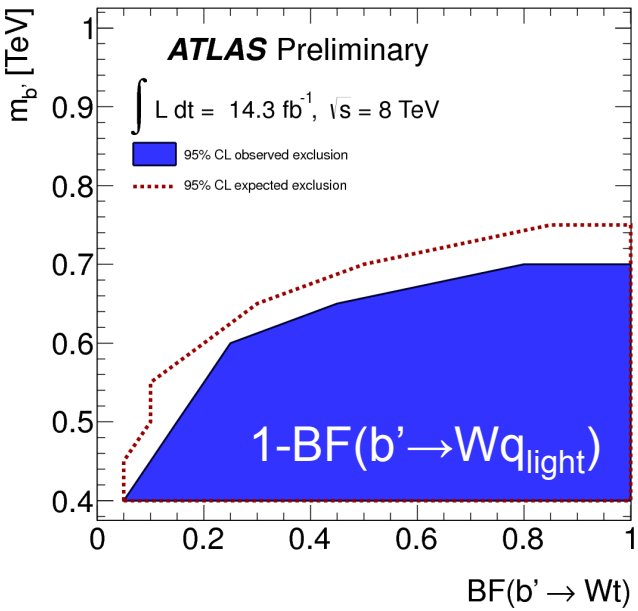
- B doublet or chiral b' pair production (left)
- $T_{5/3}$ pair and single production (right)

[ATLAS-CONF-2013-051]

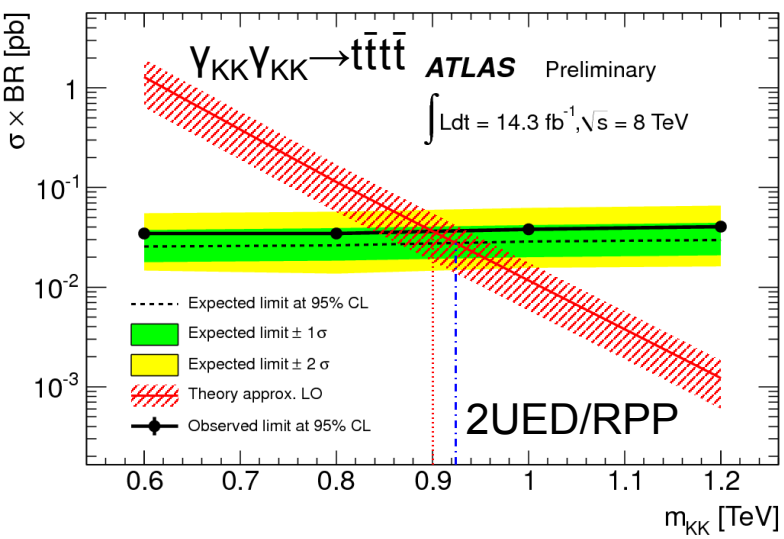


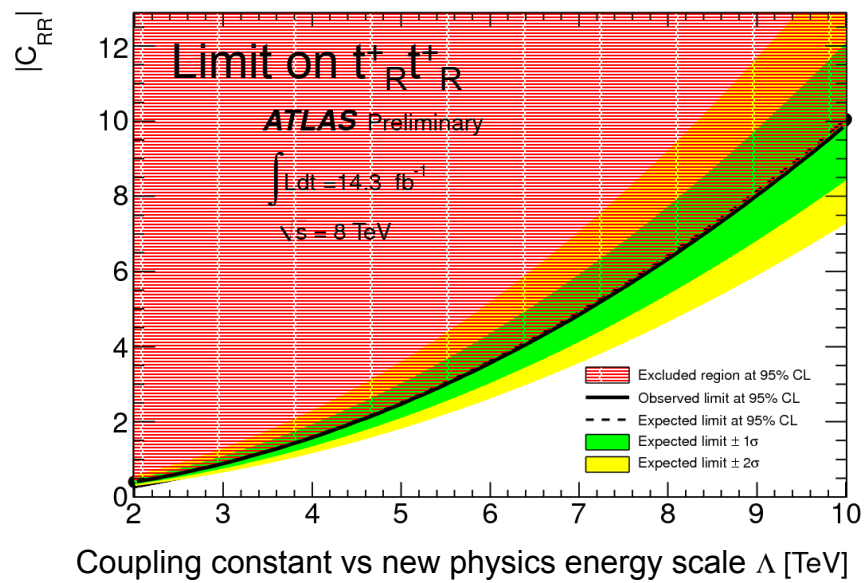
[ATLAS-CONF-2012-130]

Beautiful Set of Same-Sign Interpretations



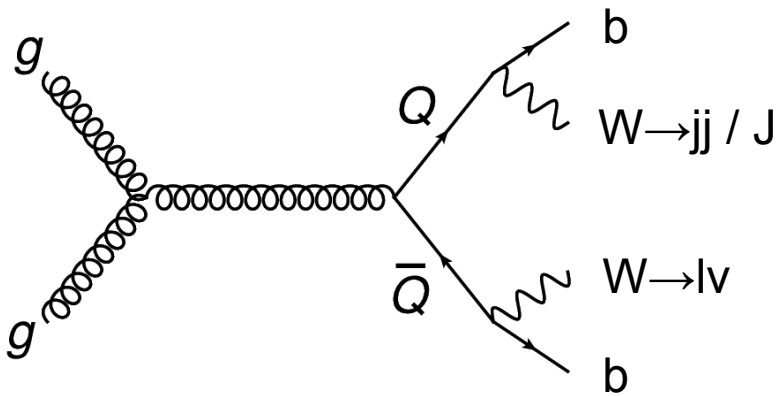
- Exclude @ 95% CL
  - m($T_{5/3}$/B doublet/b') < 720 GeV
  - m(B singlet) < 590 GeV
  - m(T singlet) < 540 GeV
  - …
  - More VLQ limits later



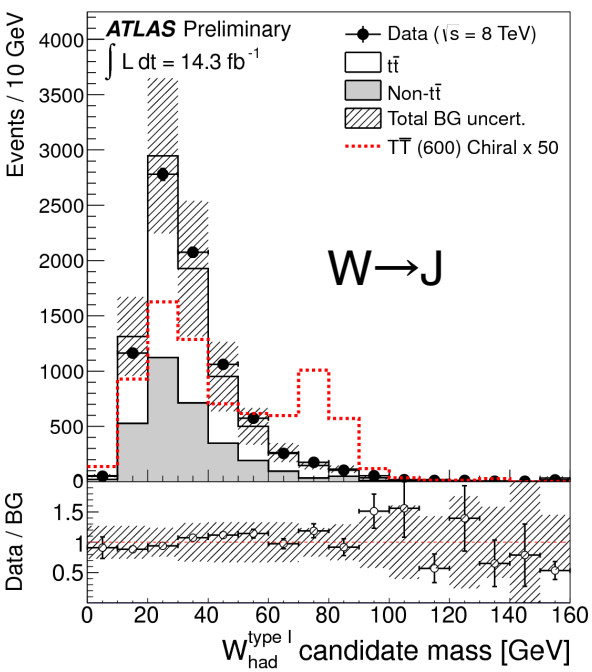


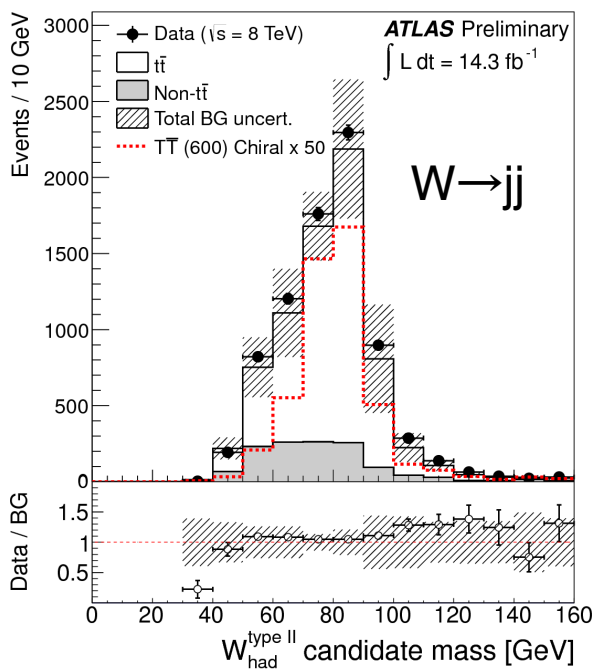
[ATLAS-CONF-2013-051]

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



- Reconstruct boosted W→jj / J
  - W→J: p_T>250 GeV, 60<m<120 GeV
  - W→jj: ΔR(j,j)<0.8, p_T>200 GeV, 60<m<120 GeV
  - Both j and J are akt 0.4 jets





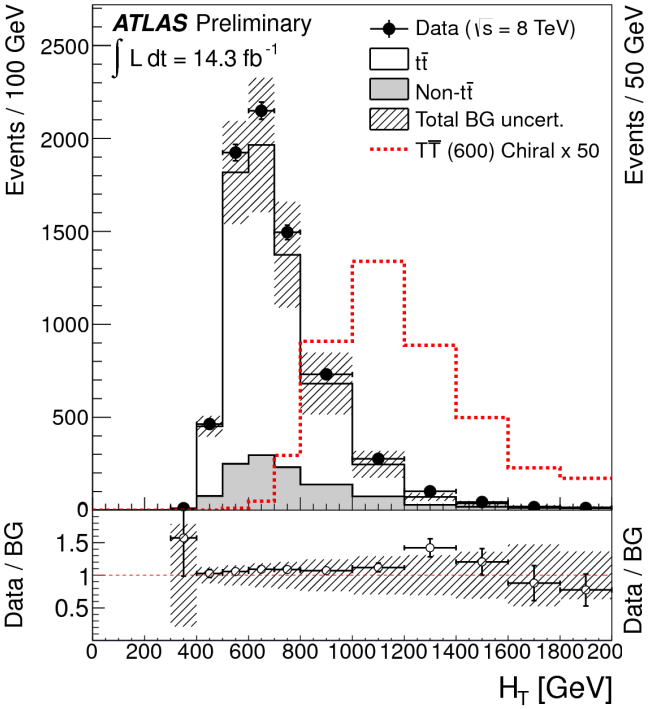
Additional selection:

- b-jet candidates: 2 jets with highest b-tag discriminant
- Kinematic cuts
- Discriminant: reconstructed mass of T using kinematic fit

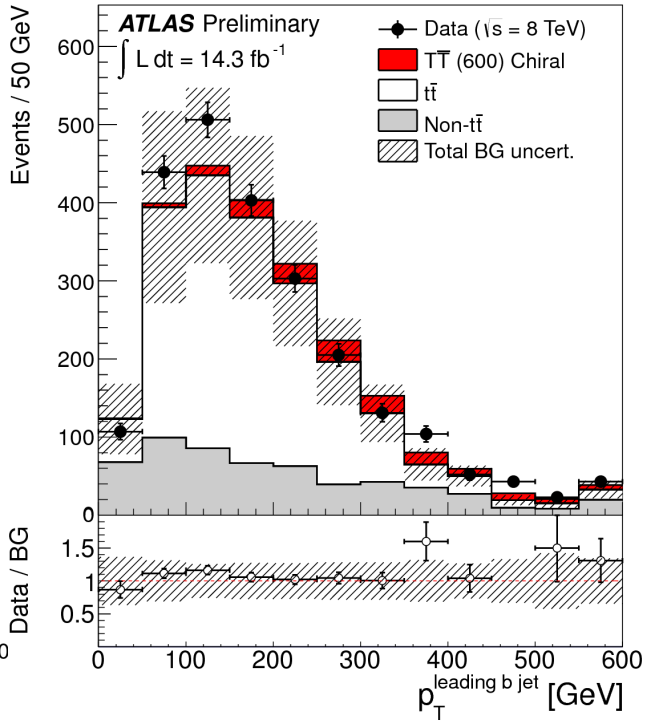
[ATLAS-CONF-2013-060]

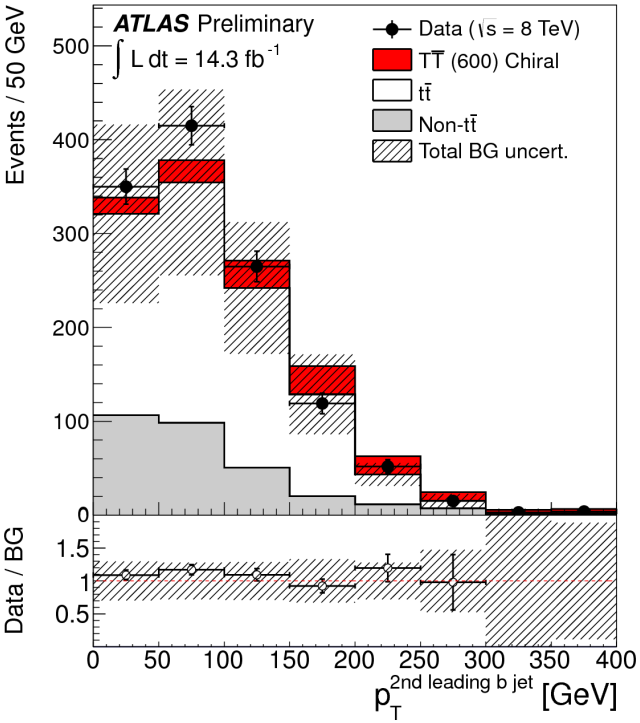
$T\bar{T} \rightarrow Wb+X$ Search Strategy

H_T(l,v,jets) > 800 GeV



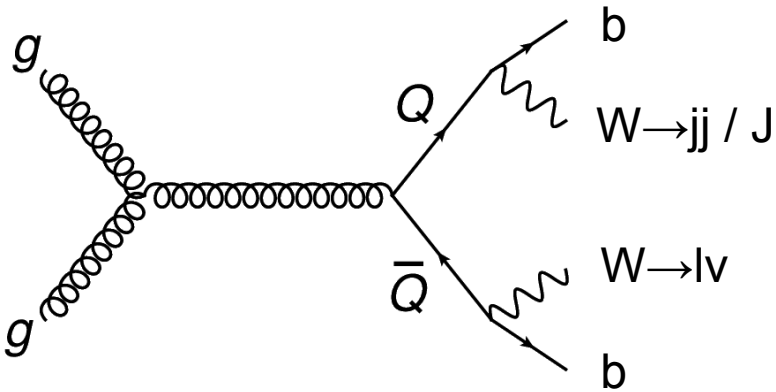
Large b-jet p_T



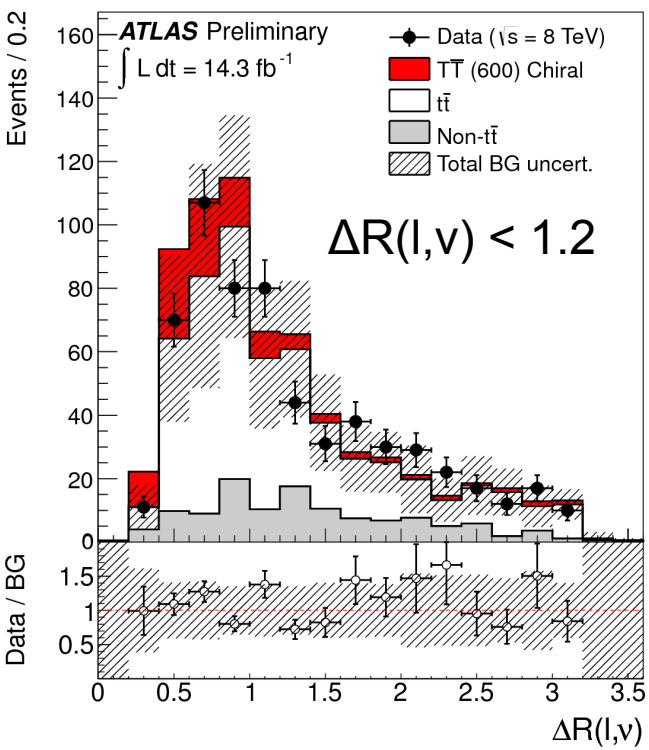


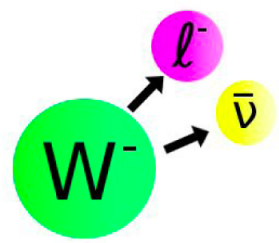
[ATLAS-CONF-2013-060]

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

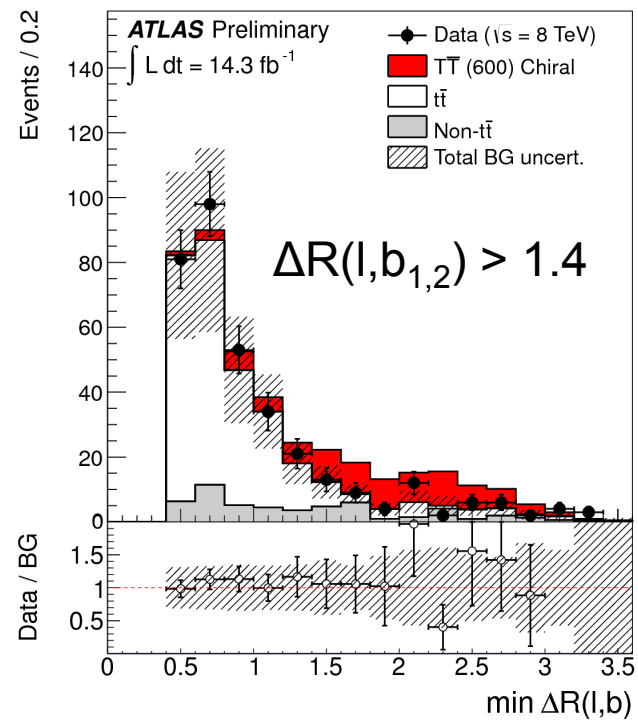


$\Delta R(W_{had}, b_{1,2}) > 1.4$





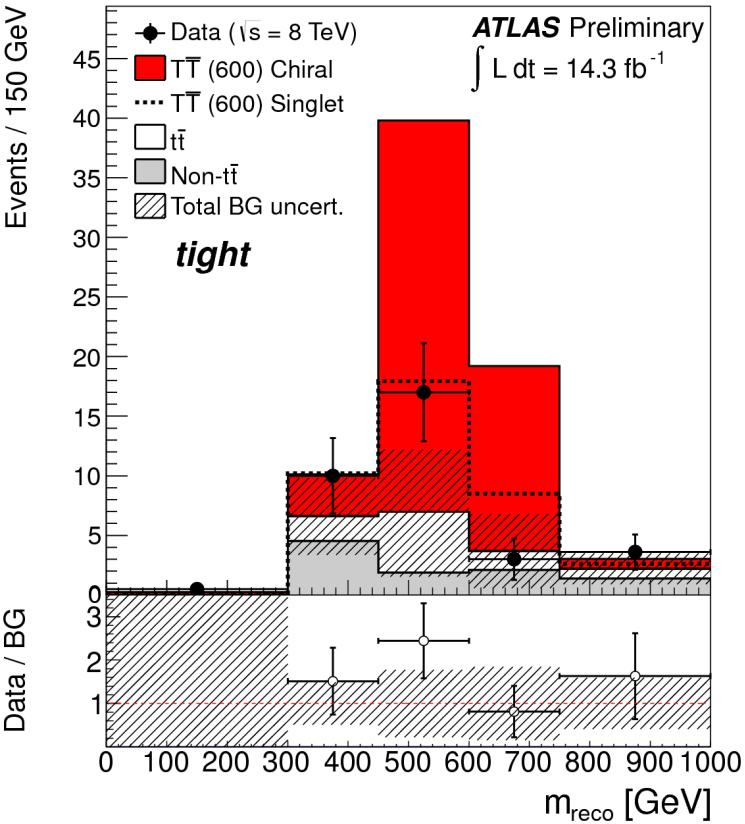
Boosted W decay products are collinear in the lab frame

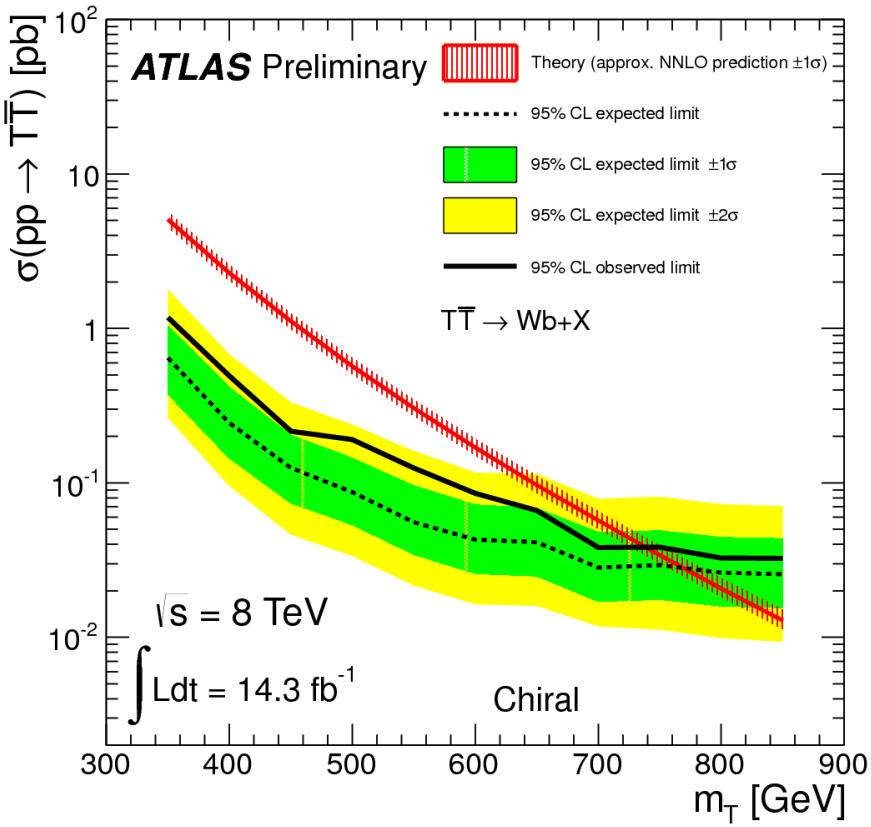


[ATLAS-CONF-2013-060]

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

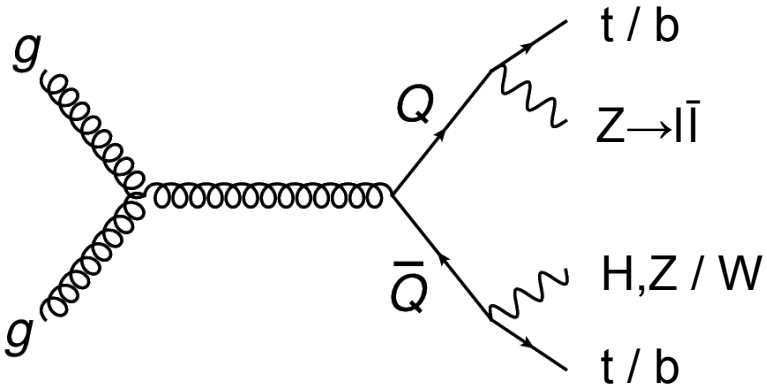
- Exclude @ 95% CL
  - m(chiral t') < 740 GeV
  - m(singlet T) < 510 GeV
  - m(singlet T) < 670 GeV (combination with Ht+X)





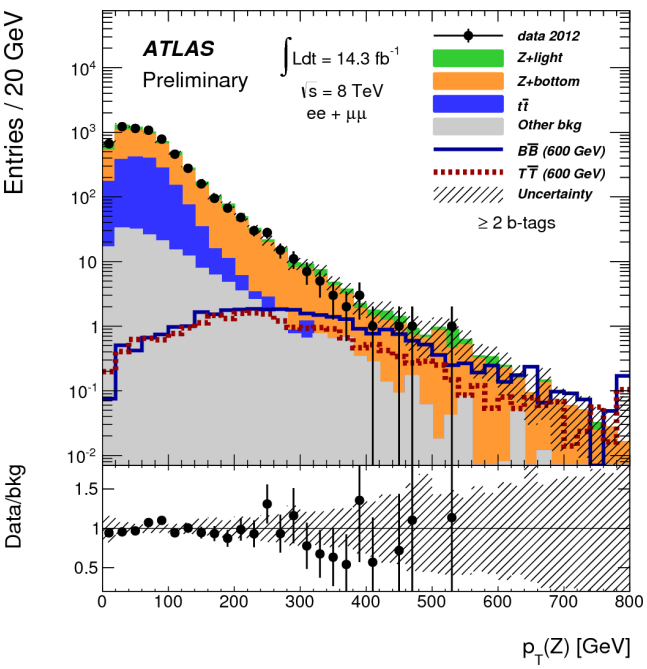
[ATLAS-CONF-2013-060]

$T\bar{T}$ / $B\bar{B}$→ Zt / Zb+X Search Strategy

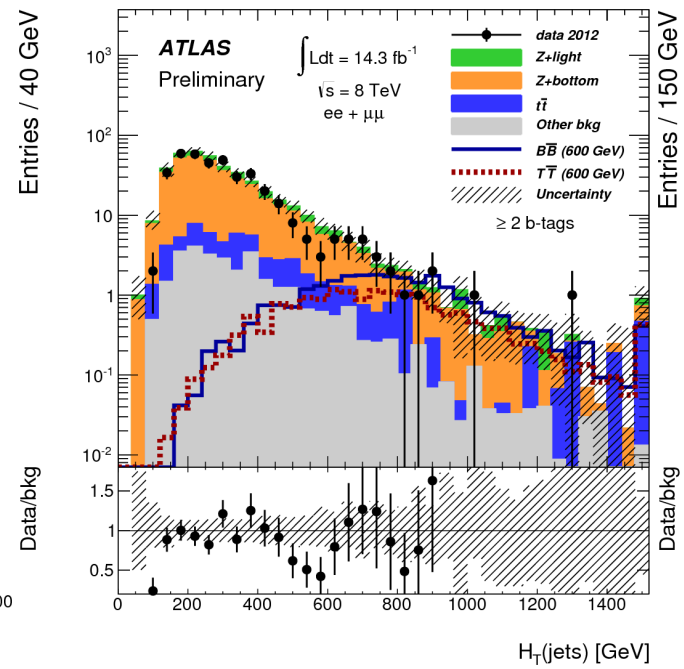


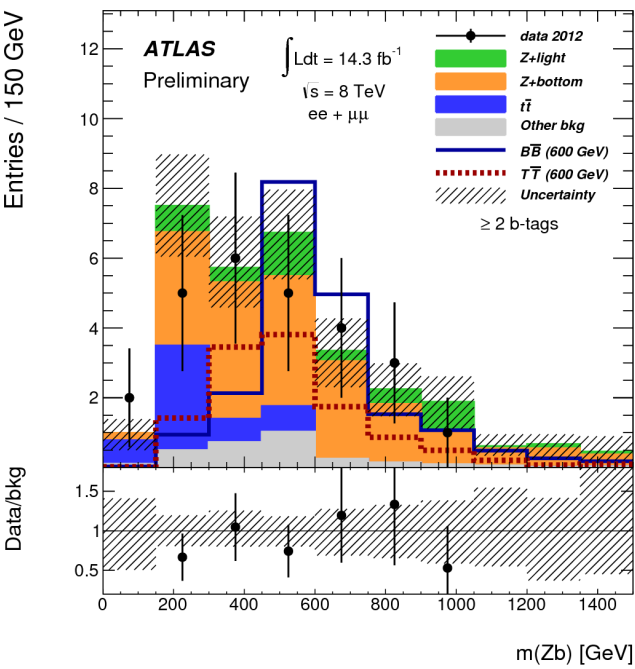
- Select Z→l$\bar{l}$ and 2 b-jet
  - $p_T(Z)$ > 150 GeV
  - H_T > 600 GeV
- Discriminant: m(Zb)

$p_T(Z)$ > 150 GeV



H_T > 600 GeV

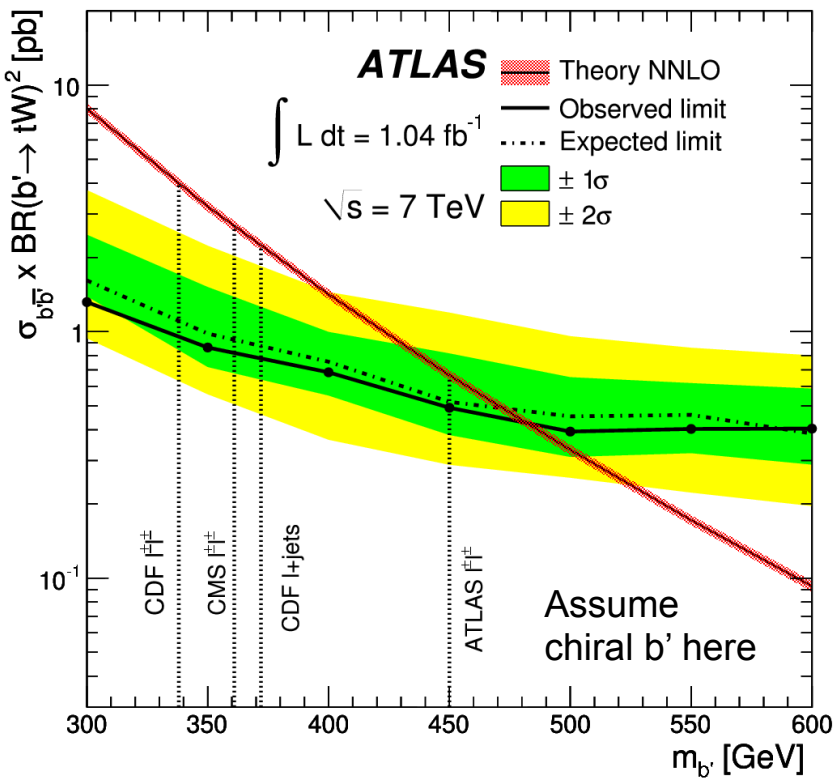


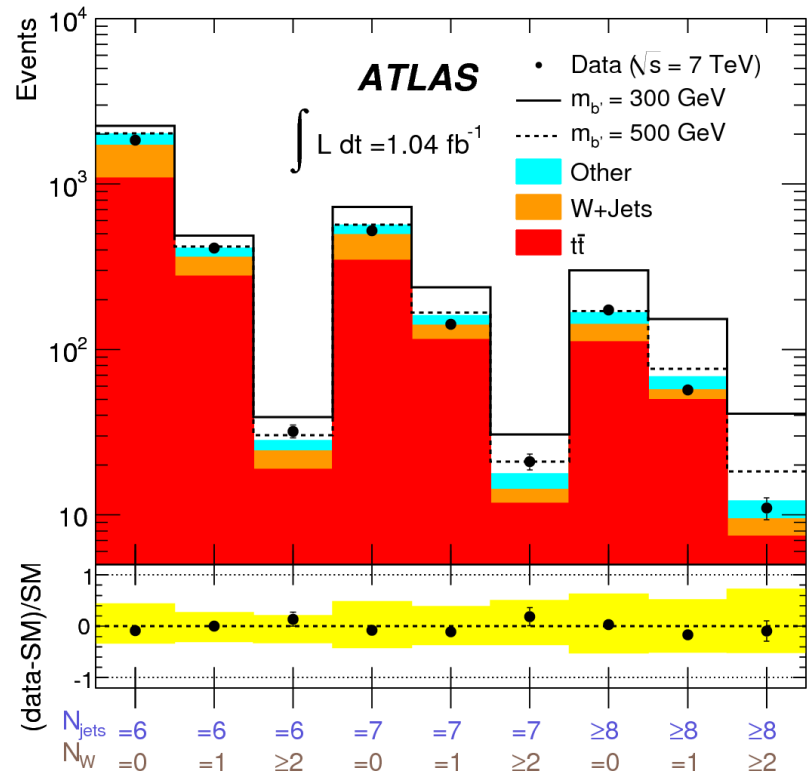


[ATLAS-CONF-2013-056]

$B\bar{B} \rightarrow WtW\bar{t}$ Search Strategy

- $B\bar{B} \rightarrow WtW\bar{t} \rightarrow WWWWbb$ (l+jets channel)
- Selection: high jet multiplicity, no b-tagging, semi-boosted $W \rightarrow jj$
- Discriminant: number of jets and number of semi-boosted $W \rightarrow jj$ ($70\ \text{GeV} < m_{jj} < 100\ \text{GeV}$, $\Delta R(j,j) < 1.0$)

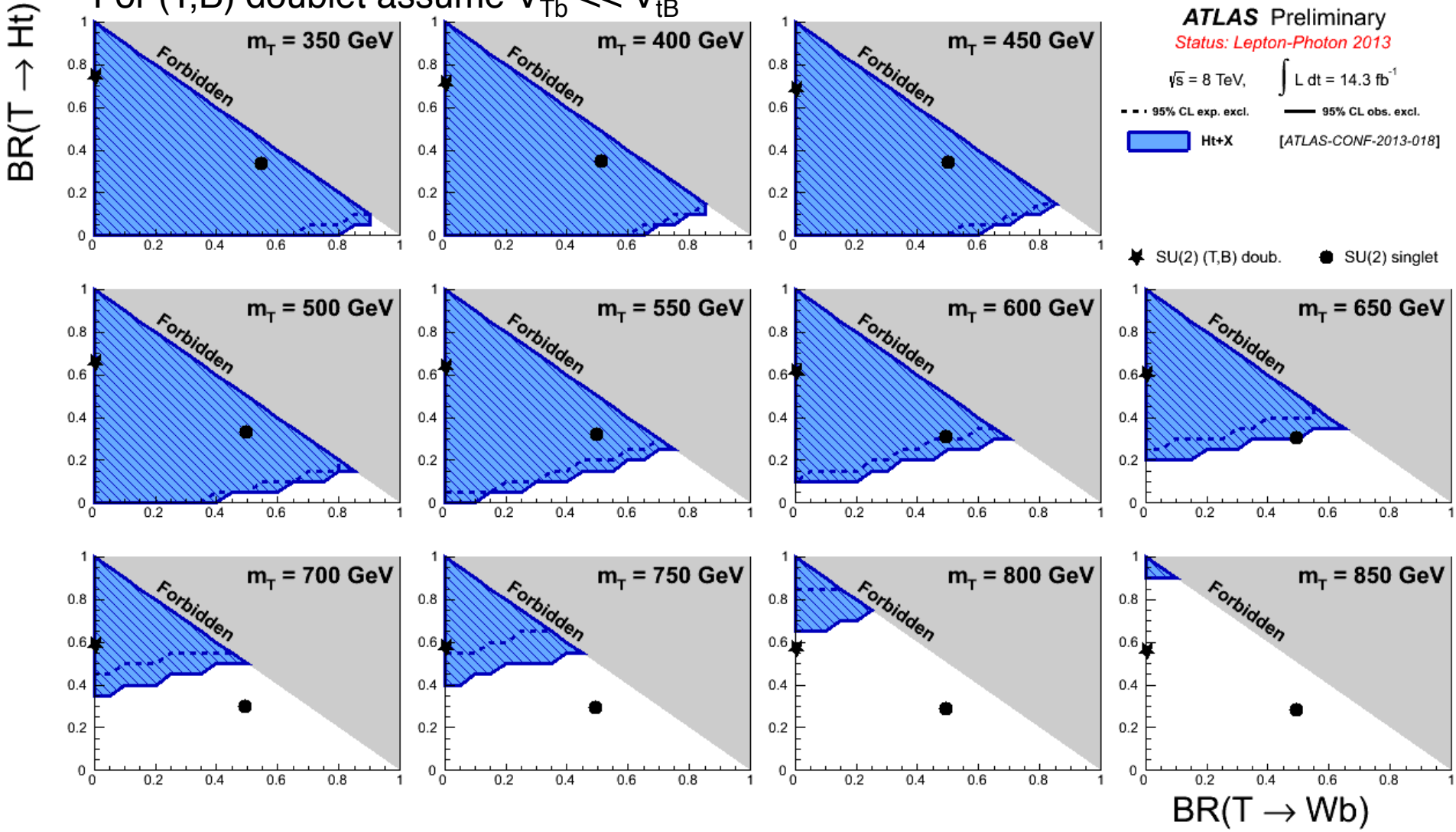




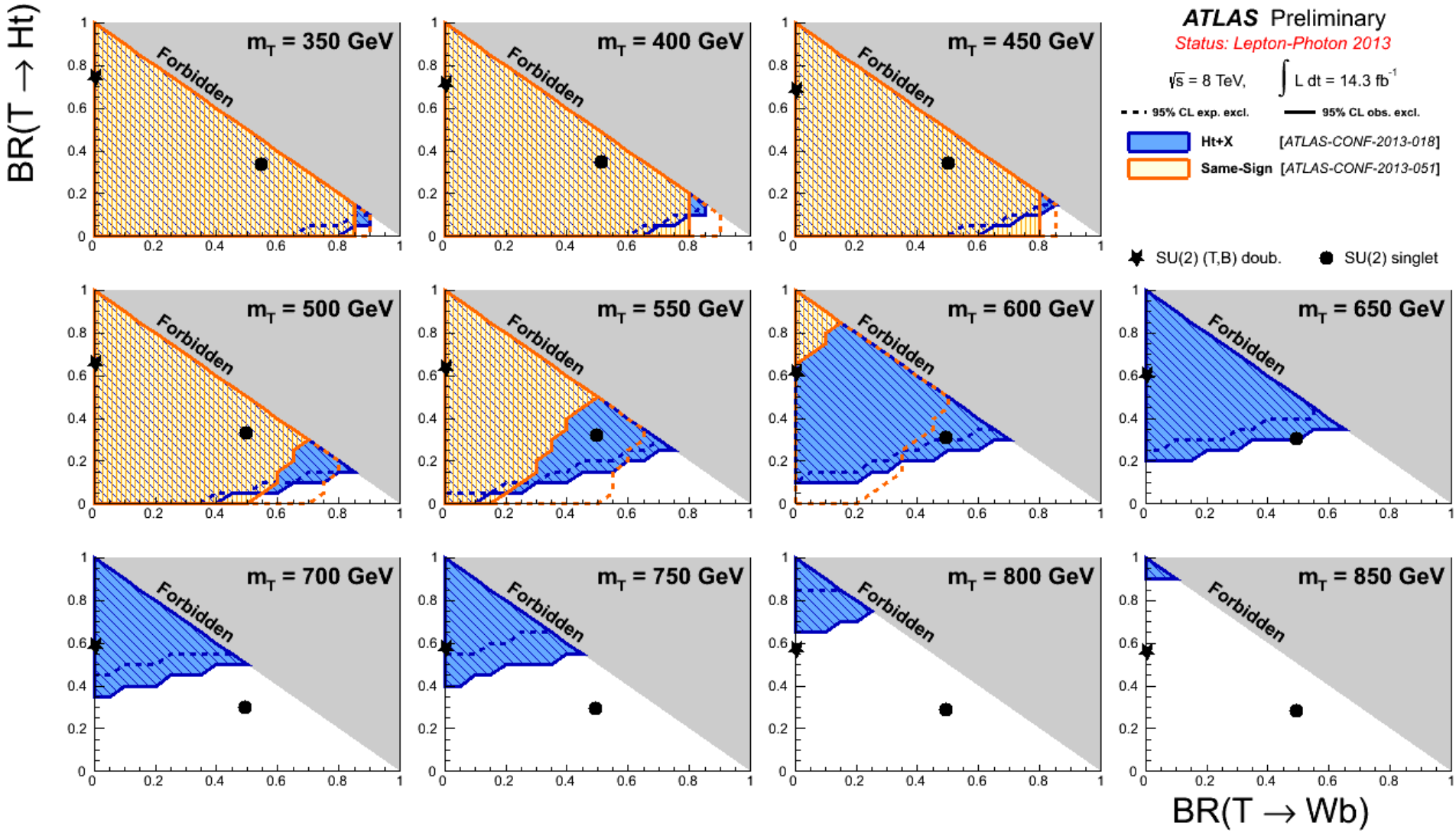
[Phys.Rev.Lett. 109 (2012) 032001, arXiv:1202.6540]

Vector-Like T Limits

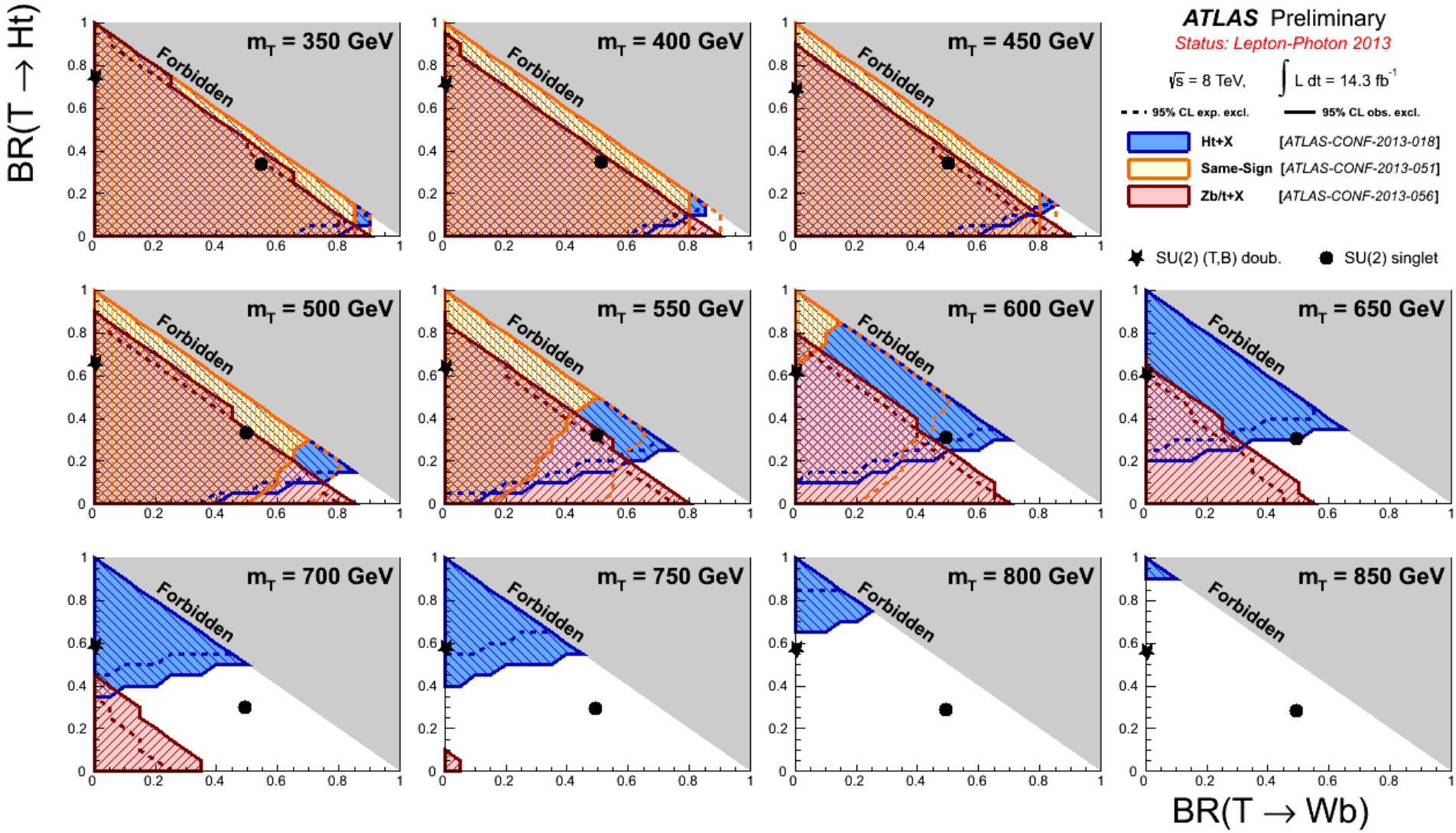
For (T,B) doublet assume $V_{Tb} << V_{tB}$



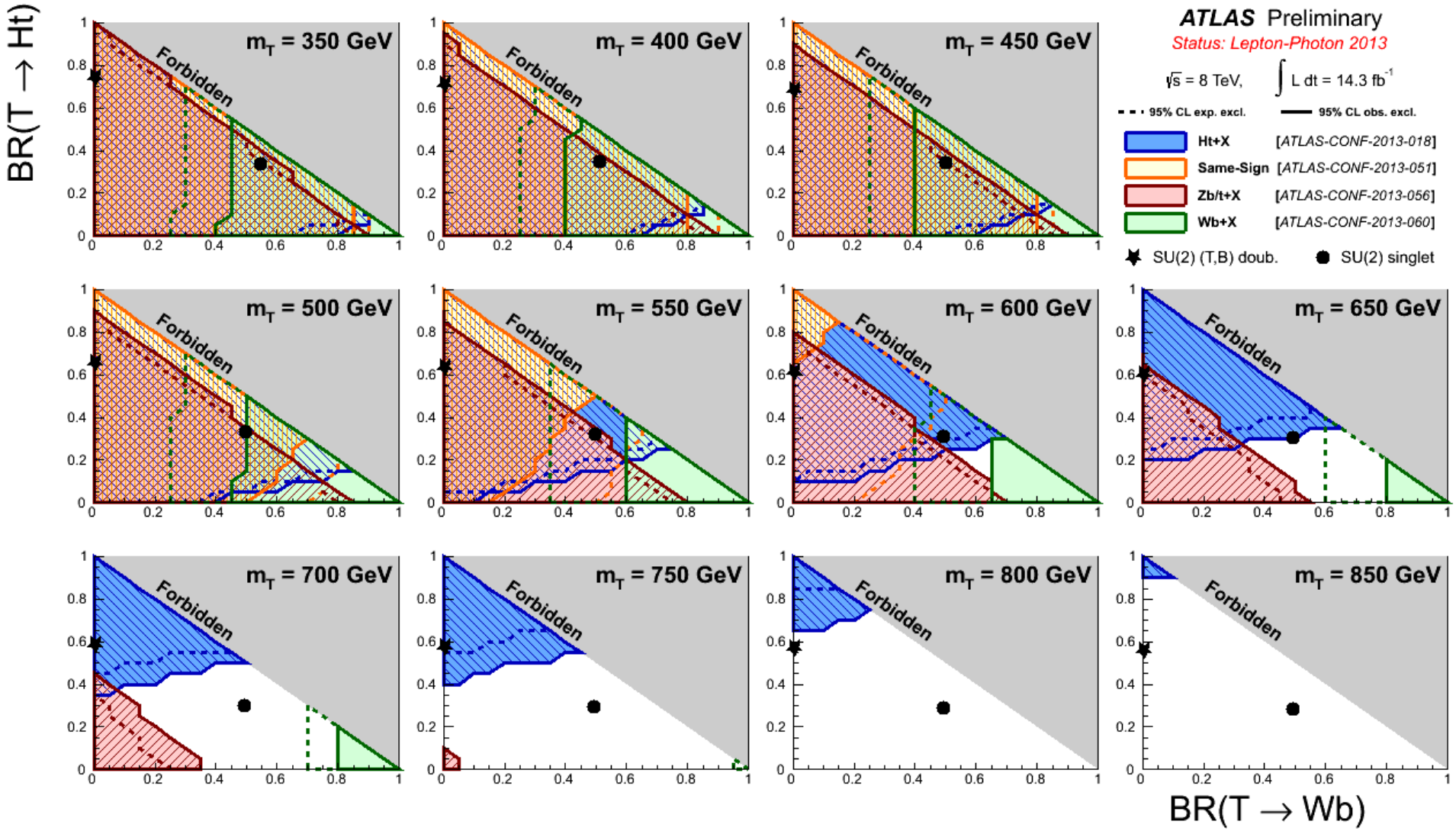
Vector-Like T Limits



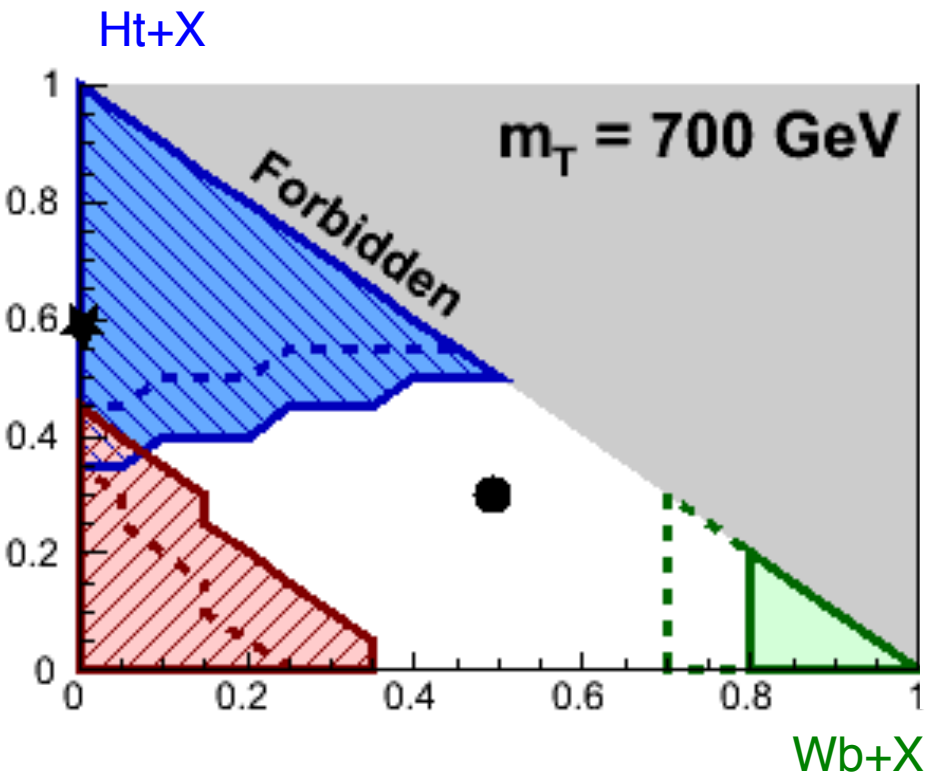
Vector-Like T Limits

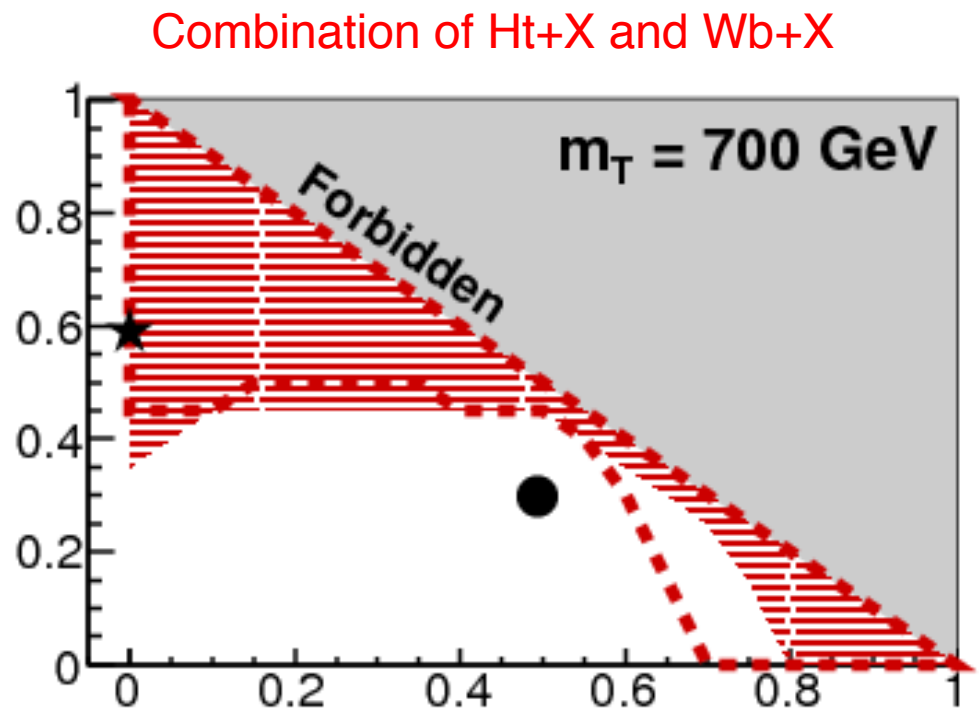


Vector-Like T Limits



Combination of Ht+X and Wb+X

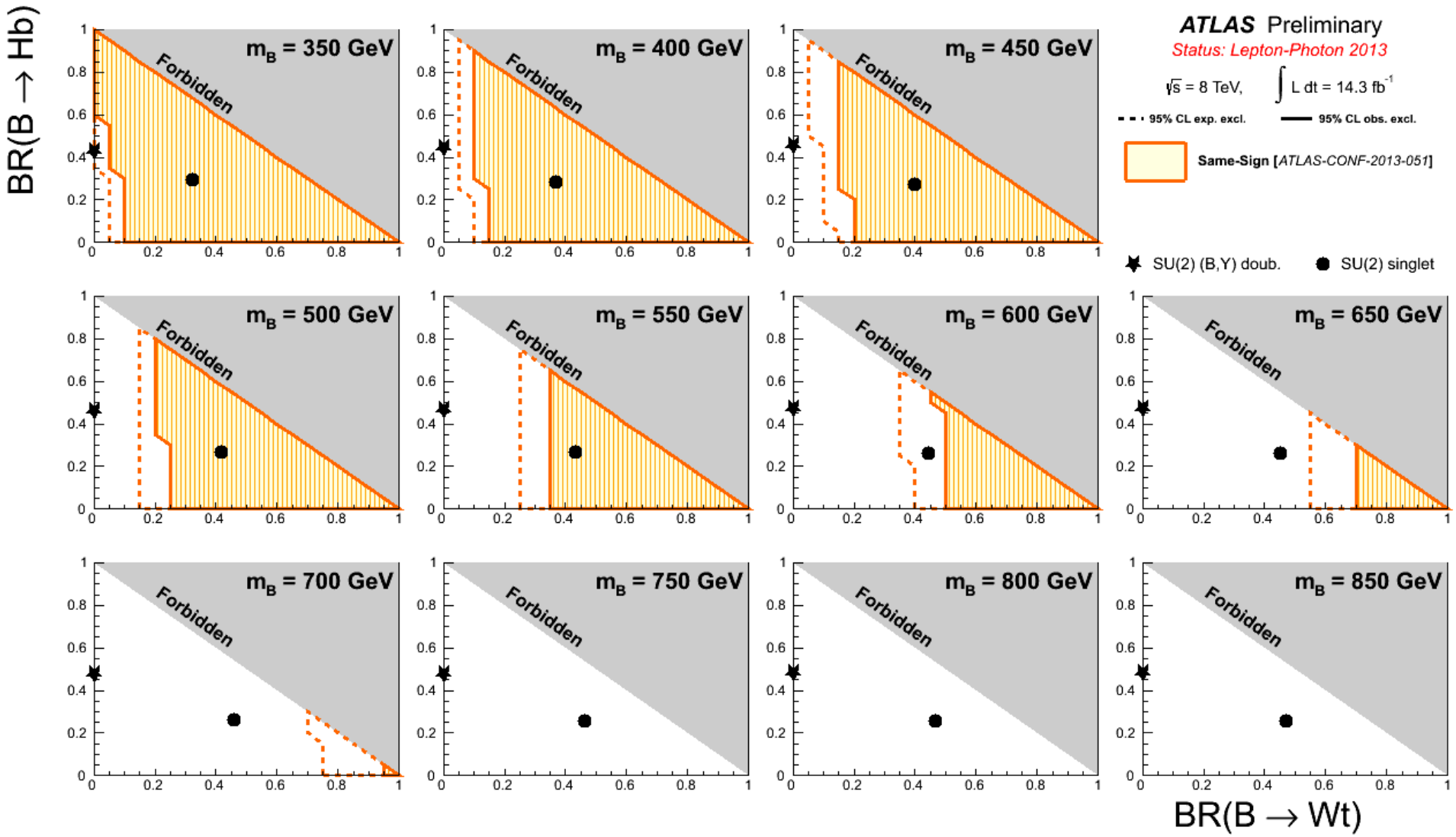




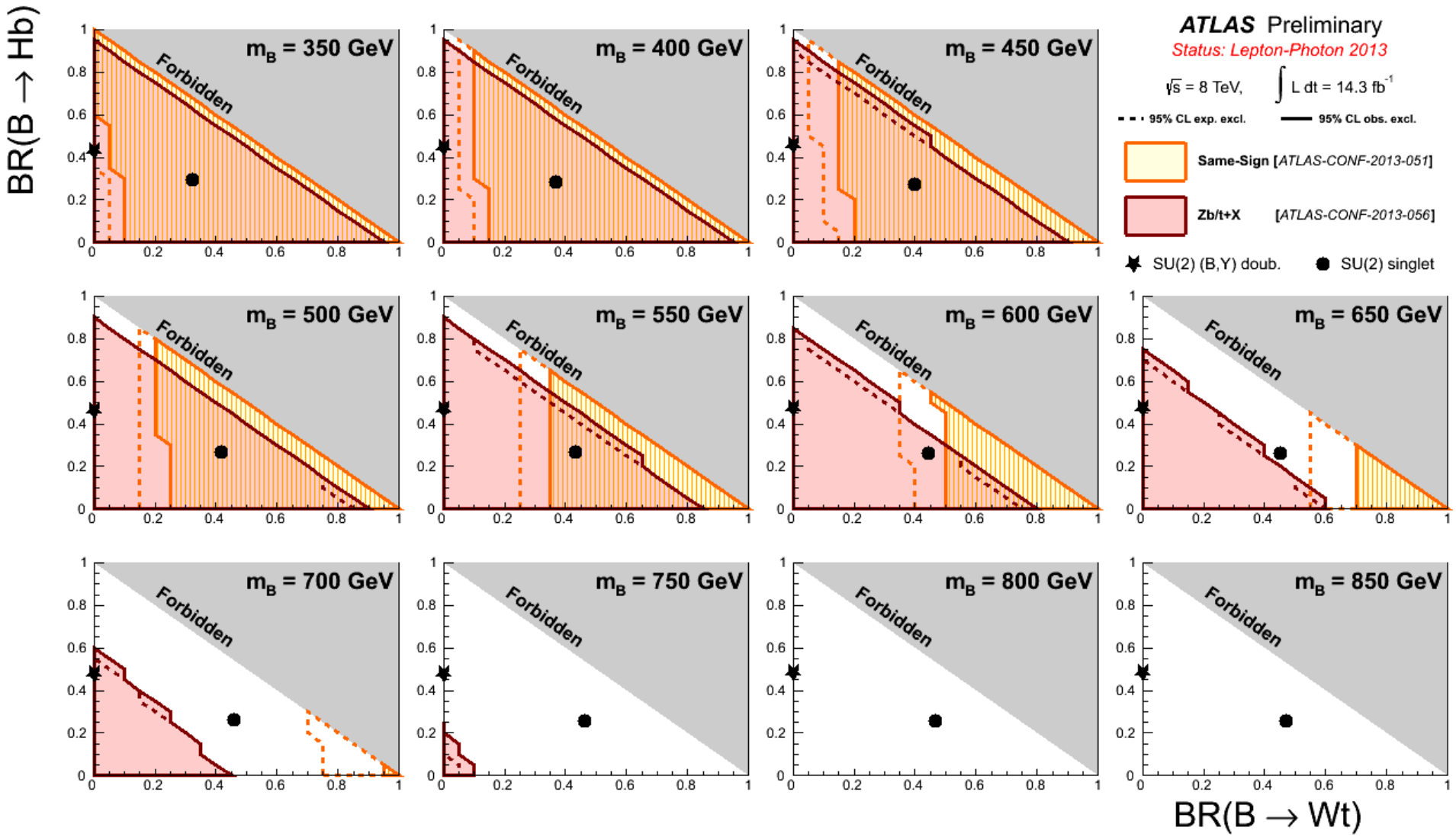
Combination of “blue” and “green” shown on the right (example mass m=700 GeV)

[ATLAS-CONF-2013-060]

Vector-Like B Limits



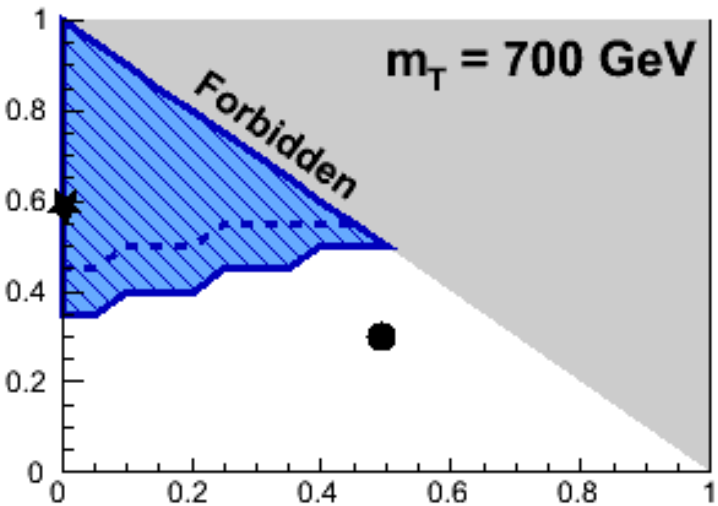
Vector-Like B Limits

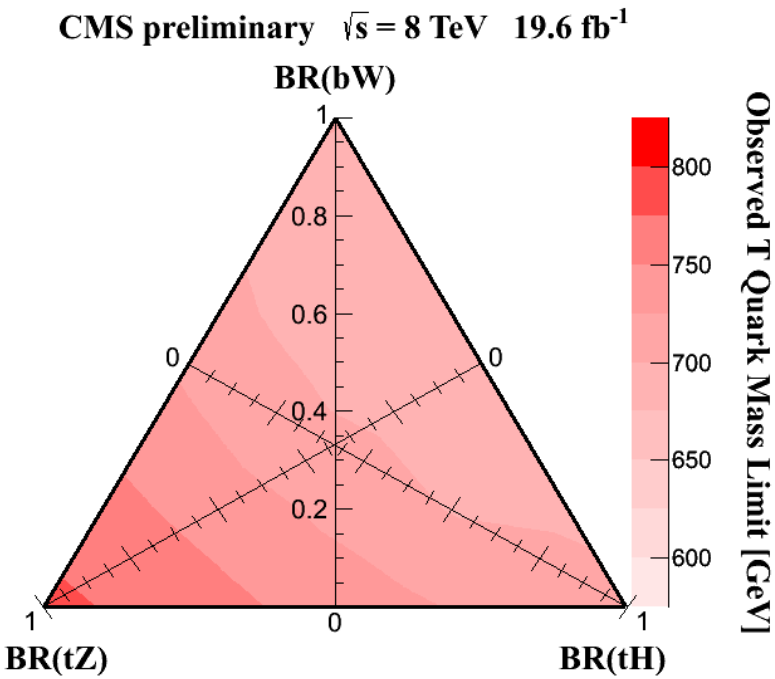


A Comment on these Results

- Masses within isospin multiplets are predicted to be nearly degenerate
  - **Our limits are conservative in this sense**
  - **Could do additional interpretation assuming both B and T present**
- While additional interpretations provide further information they don't change the core message that *we have not seen signs of VLQs* ***yet***

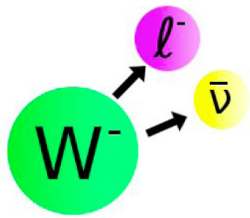
Express Yourself





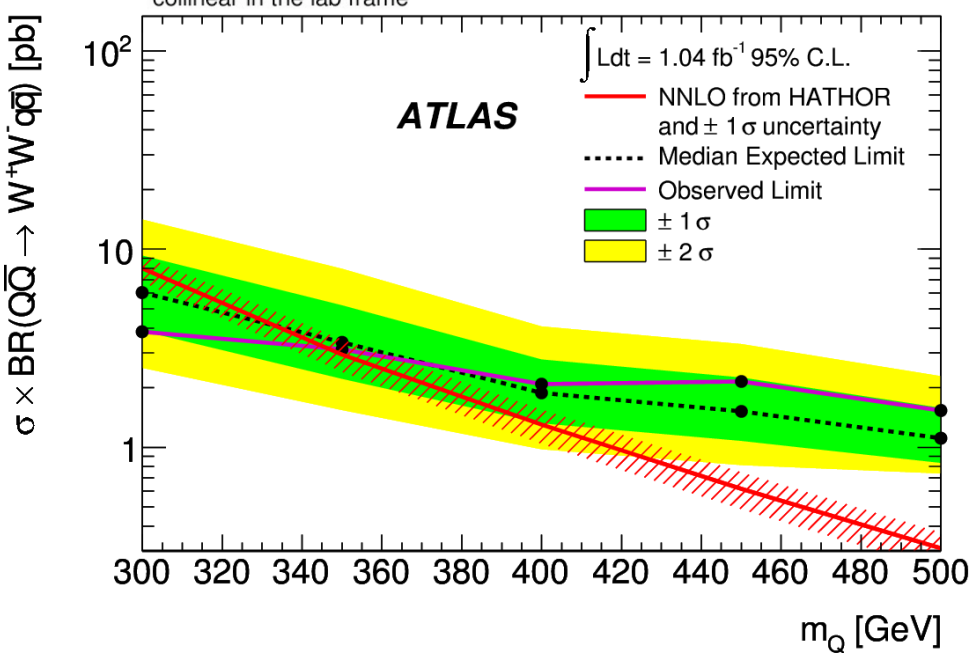
Light Flavor: $Q\bar{Q} \rightarrow WqW\bar{q}$

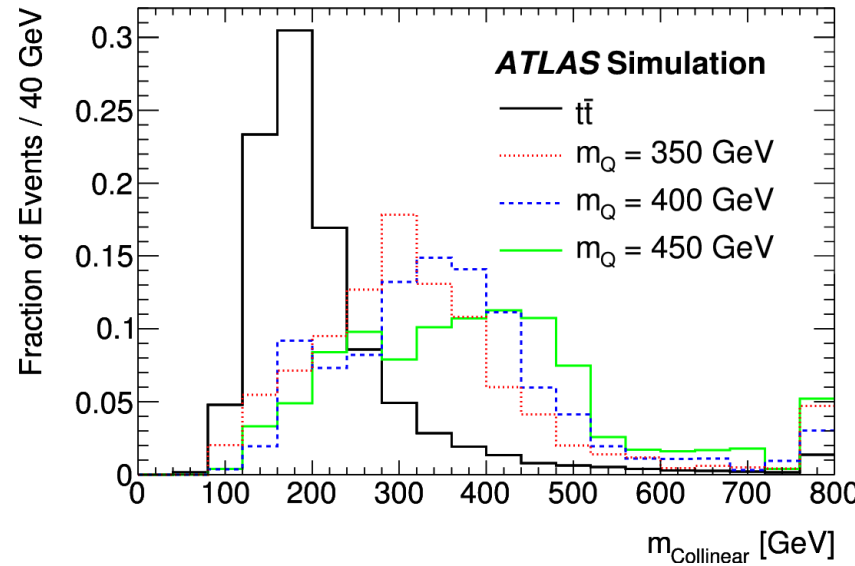
- $Q\bar{Q} \rightarrow WqW\bar{q}$ (dilepton channel)
- Selection: 2 leptons, no b-tagging
- Discriminant: collinear mass

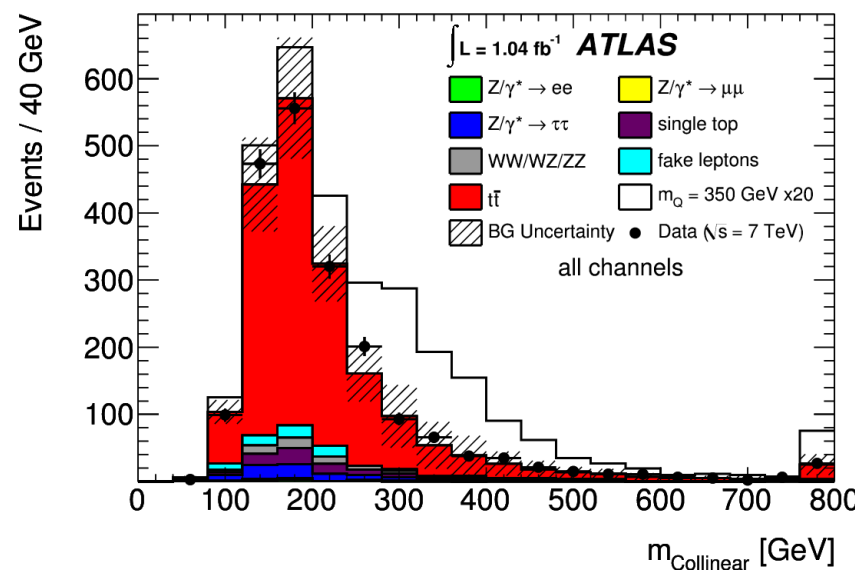


Boosted W decay products are collinear in the lab frame

Exlude @ 95% CL:
m(Q) < 350 GeV

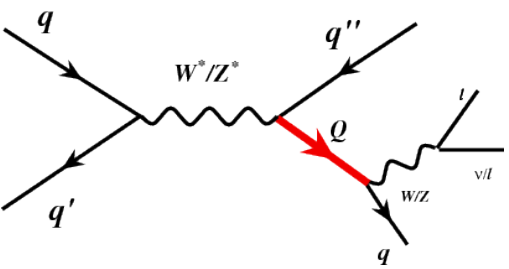




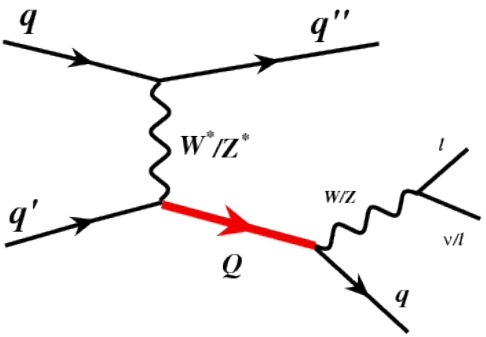


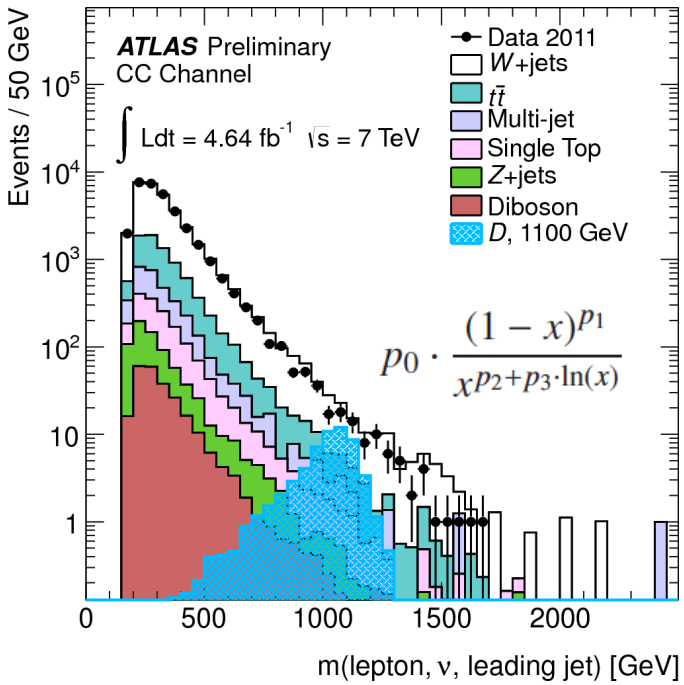
[Phys.Rev. D86 (2012) 012007, arXiv:1202.3389]

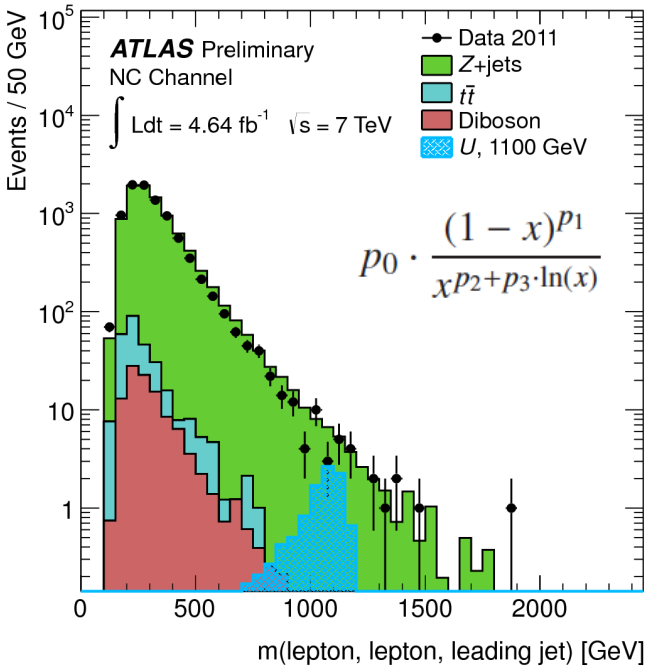
Light Flavor Single VLQ



- Select W→lν / Z→l$\bar{l}$ and 2 jets
- Apply kinematic cuts
- Reconstruct m(Q)=m(W/Z+jet)
- Phenomenological fit to m(Q)

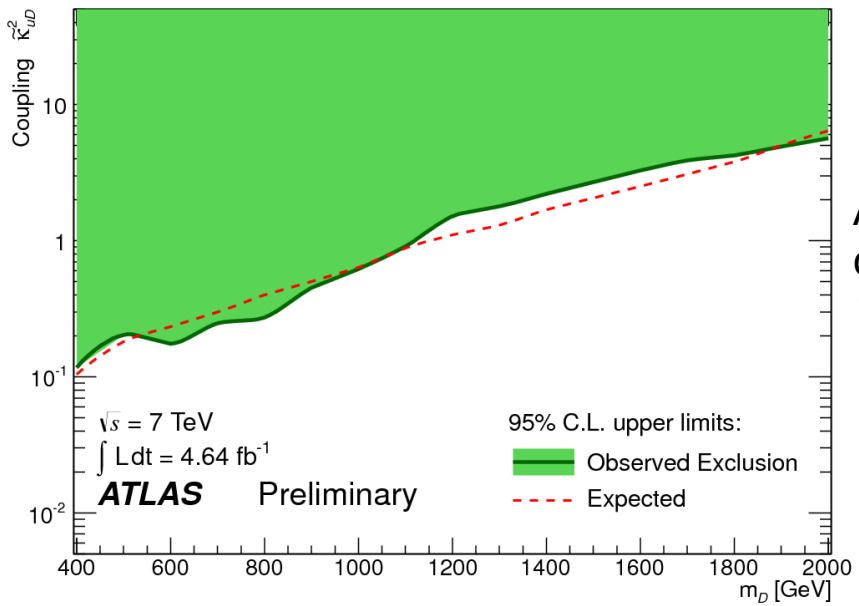




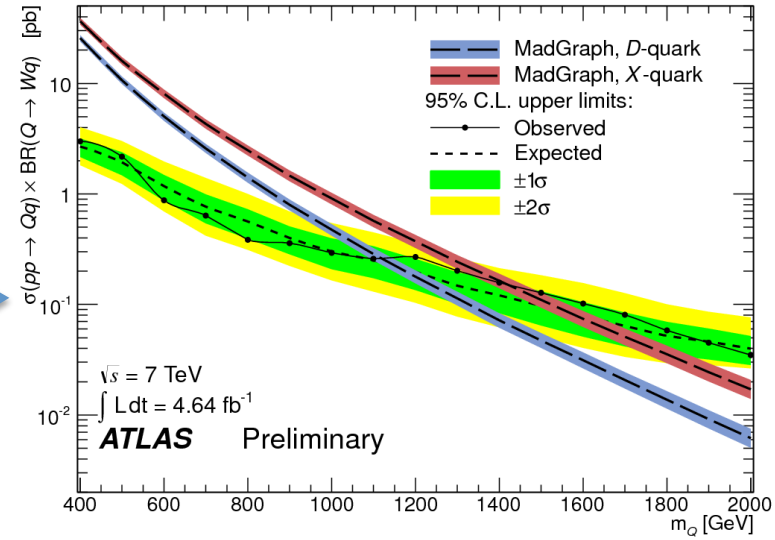


[ATLAS-CONF-2012-137]

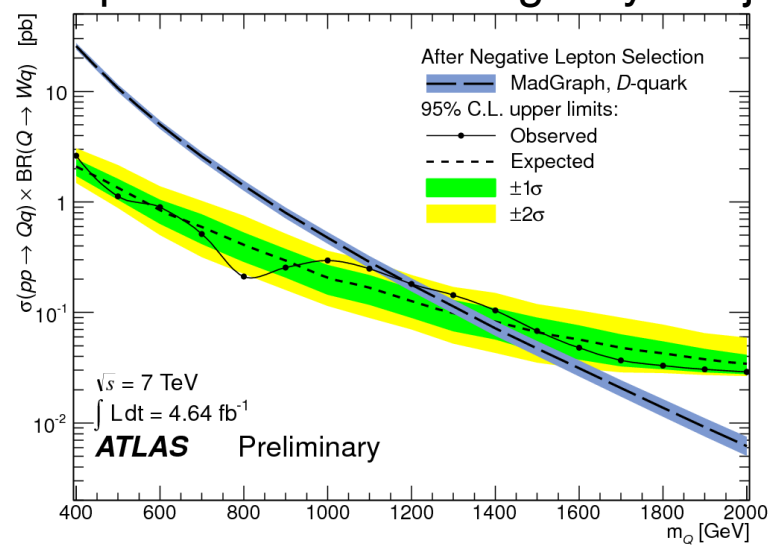
Light Flavor Single VLQ Limits



Assume coupling =1



Improved D limits using only W$^-$+jets

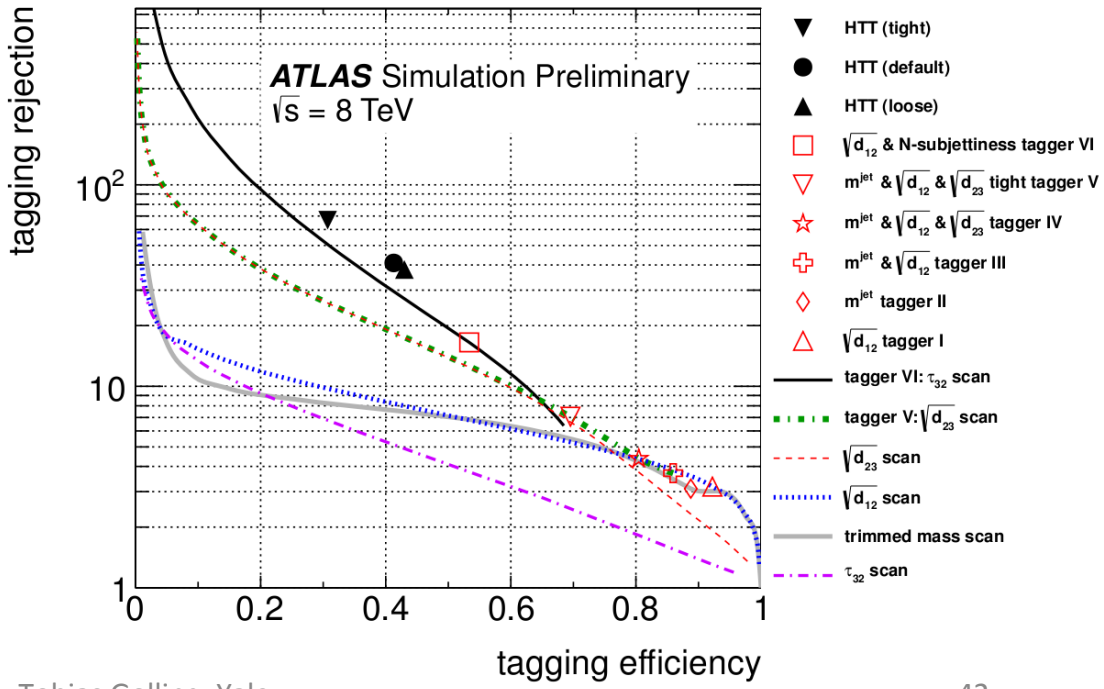


- Exclude @ 95% CL
  - m(U) < 1120 GeV
  - m(D) < 1080 GeV
  - m(X) < 1420 GeV

[ATLAS-CONF-2012-137]

VLQ – What's Next?

- Keep searches general/signature based
  - Remain sensitivity in full BR phase space
- Extend searches on single VLQ and light-flavor VLQ
  - Consider more complex NP flavor structure
- Boosted top quarks, W, Z, H boson are essential and will remain a focus



[ATLAS-CONF-2013-084]

Conclusions

- Cover all possible NP signatures in our searches
  - **Are we missing anything?**
- Still 8 TeV analyses in pipeline where NP might hide
- Ramp-up 14 TeV – big jump in sensitivity
  - Boosted objects even more important
- So far mainly results based on one signature at a time
  - Move to Run I legacy / combination papers
  - **Feedback always welcome regarding presentation or combination of results**

Don’t Give Up Looking!

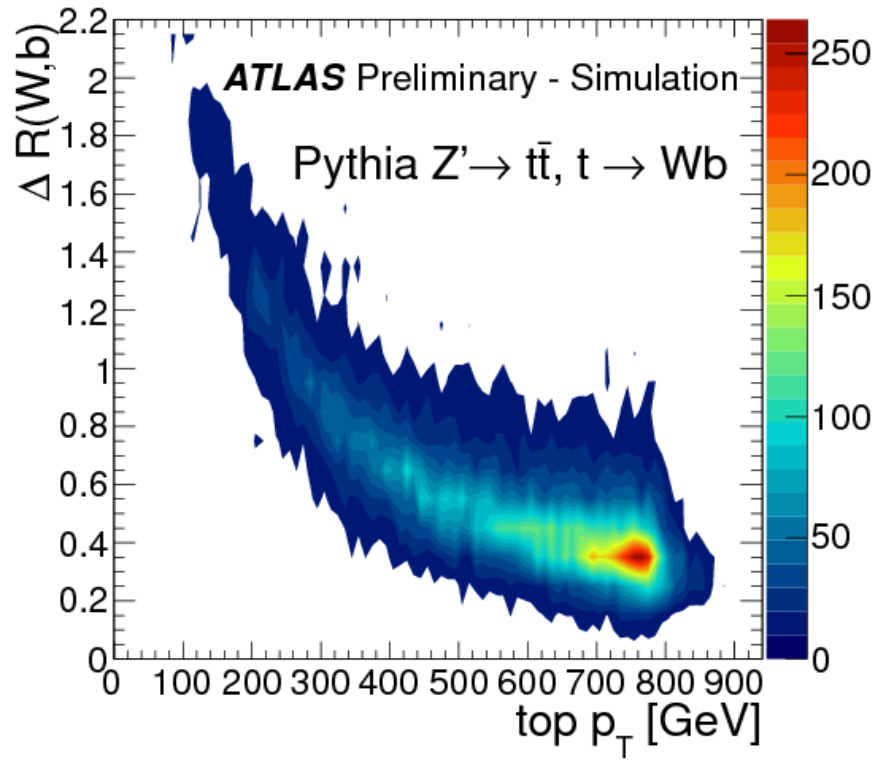
Thank You!

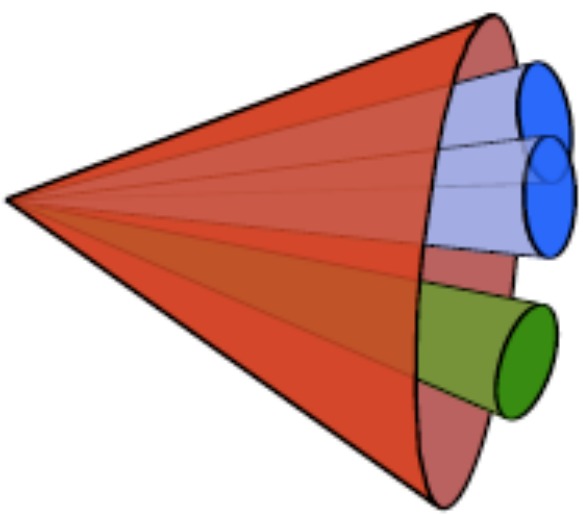
Backup

Jet Substructure

- Use jets with large radii (e.g. anti-k_T, R = 1.0) to collect all products of hadronic top decays

- Rule of thumb: $\Delta R \sim 2M/p_T$





- Investigate substructure

- Jets with larger radii suffer more from contamination by underlying event and pile-up
  - ✓ "Grooming" allows to remove soft radiation