ATLAS Searches for New Quarks after the Observation of a Standard Model Higgs-like Particle

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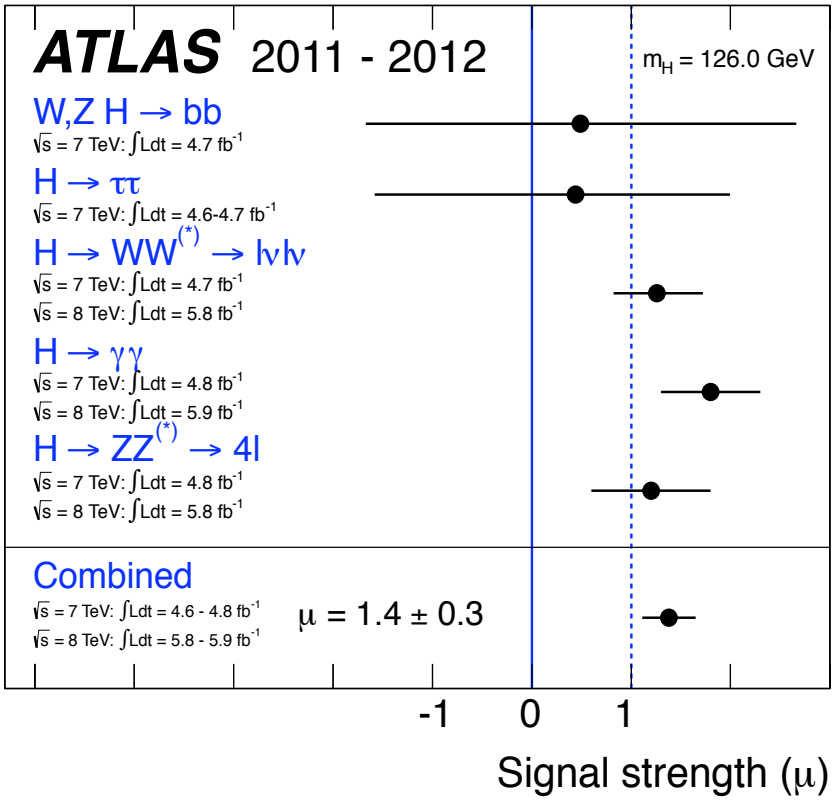
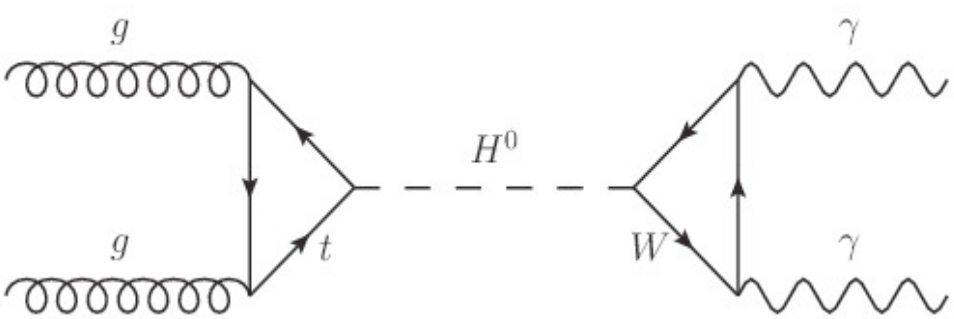
ATLAS

Observation of a Higgs-like Particle : Is it Consistent with SM?

Phys. Lett. B 716 (2012) 1-29

- Observation of a new particle in the search for the Standard Model (SM) Higgs Boson.
- ATLAS Significance: 5.9σ
- Mass: 126.0 ± 0.4 (stat) ± 0.4 (sys) GeV
- Question: Is the observed strength in each channel consistent with the SM Higgs Boson?





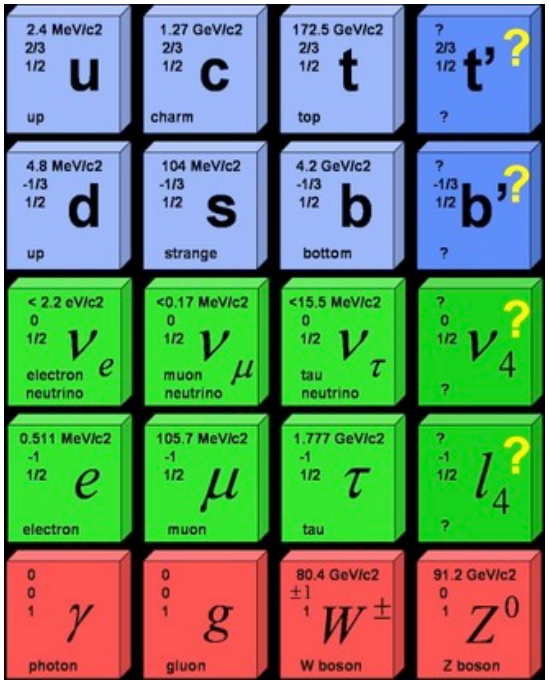
- Very early in the game, but deviations from the expected signal strengths could indicate beyond SM particles entering the Higgs production and decay diagrams.

A Fourth Generation of Chiral Fermions (SM4)

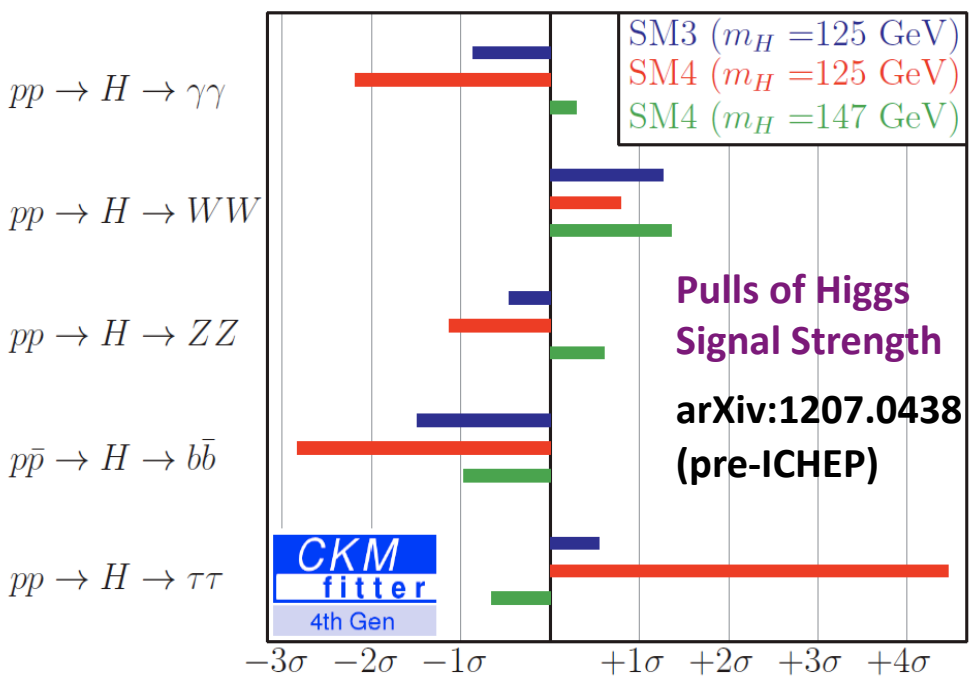
- A Chiral 4th Generation: Example of a set of new particles that would affect the Higgs signal strengths.

- Chiral means an $SU(2)_L$ doublet w/ corresponding right handed singlets. E.g.

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



- Constraints exist from precision electro-weak and flavor observables, direct searches, and now the Higgs search.



- If a chiral 4th generation exists below 1 TeV, we should have seen the Higgs much earlier.
  - 4th generation quarks increase gluon fusion Higgs production rate by a factor of 9.
  - HWW, HZZ, and Hγγ couplings are suppressed by the new fermions, but not Hττ.

Vector-like Fermions

- Vector-like (VL): Left and right handed components transform the same way under $SU(2)_L$

Vector-like singlets $\quad t'_L \qquad t'_R$

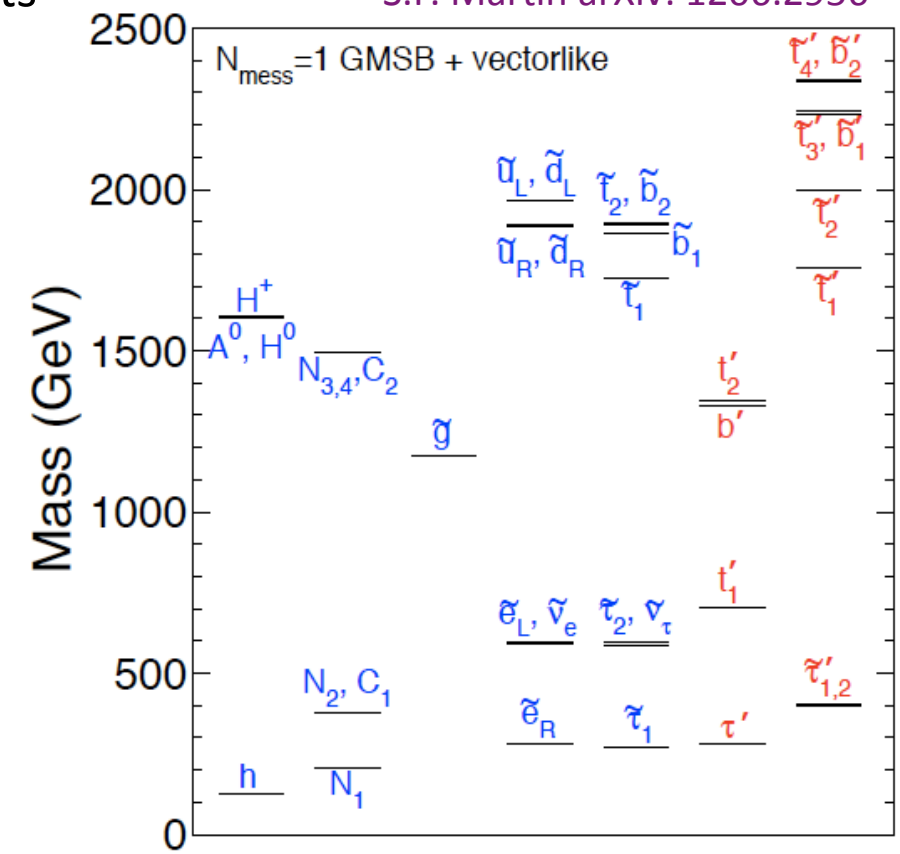
Vector-like doublets $\quad \begin{pmatrix} t'_L \\ b'_L \end{pmatrix} \qquad \begin{pmatrix} t'_R \\ b'_R \end{pmatrix}$

- VL fermions appear in many SM extensions:
  - Little Higgs, composite Higgs
  - Top color, top condensate
  - Extra dimensions, GUTS, SUSY extensions

- VL quarks less constrained by precision electro-weak and flavor measurements; more subtly modify Higgs signal strengths.

E.g. S. Dawson and E. Furlan, PRD 86, 015021 (2012)
arXiv: 1112.3142, 1112.5653, 1207.4235, 1207.4482.

S.P. Martin arXiv: 1206.2956

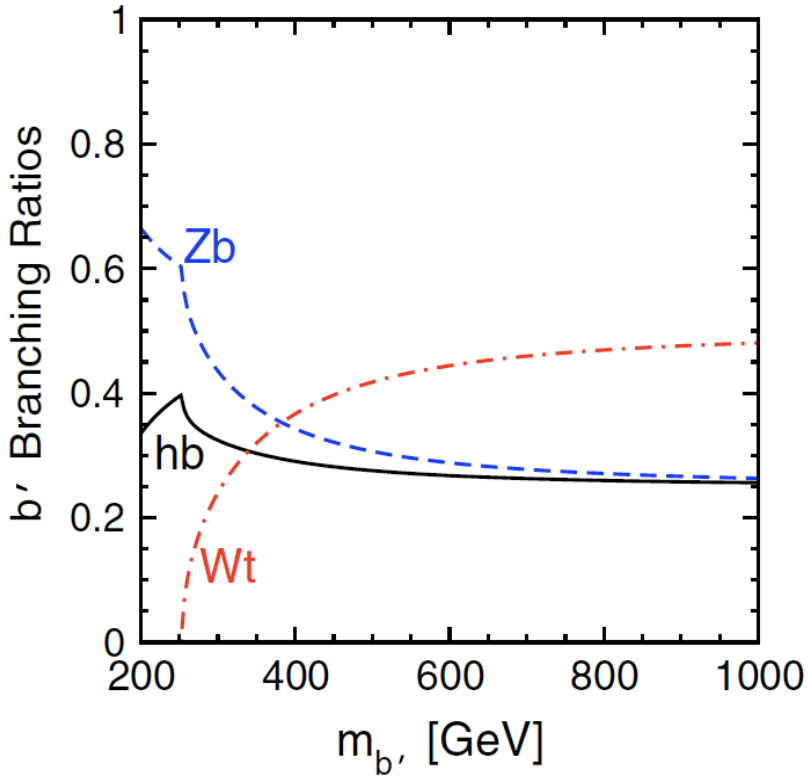


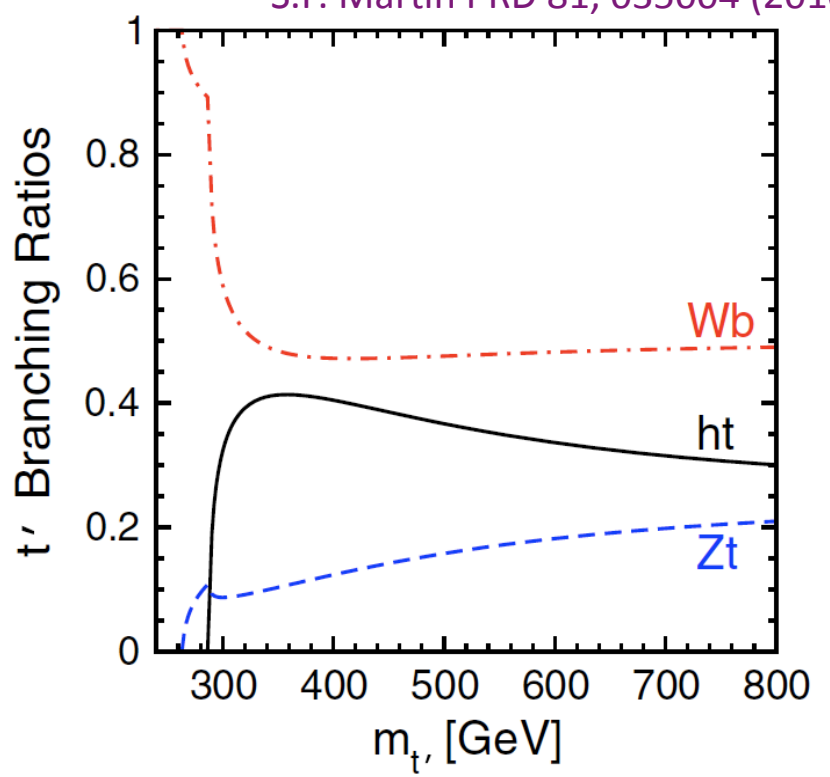
- Some SUSY models (e.g. mGMSB) cannot yield a 126 GeV Higgs. VL matter bring mass from ~115 GeV to 126 GeV, expand particle spectrum.

Vector-like Quarks : Branching Ratios

- Vector-like quarks break the Glashow-Iliopolous-Maiani mechanism.
- Flavor-changing neutral-current decays to a Z boson or Higgs boson occur at tree level.
- The "chiral" charged current modes (Wt/Wb) are still important, but no longer 100%.
- Goldstone Boson Equivalence limit (W:h:Z) = (2:1:1) reached at high mass.
- Mixing with 3rd generation more favored by flavor constraints.

S.P. Martin PRD 81, 035004 (2010)



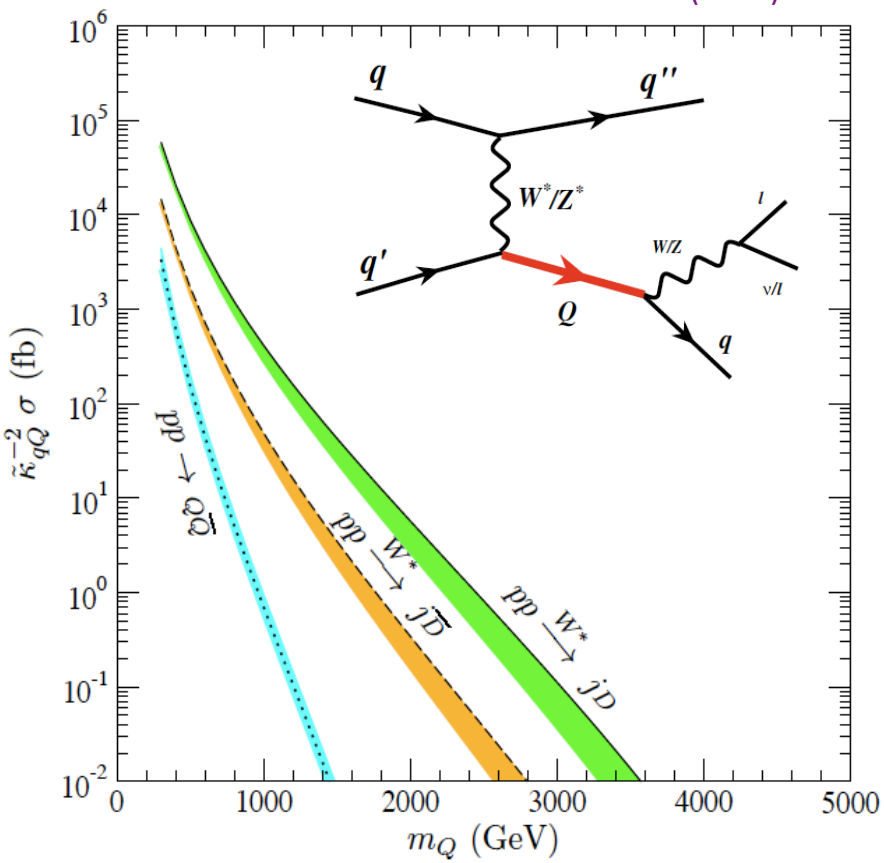


Heavy Quark Production at the LHC

Electroweak single production of vector-like quarks coupling to light generations.

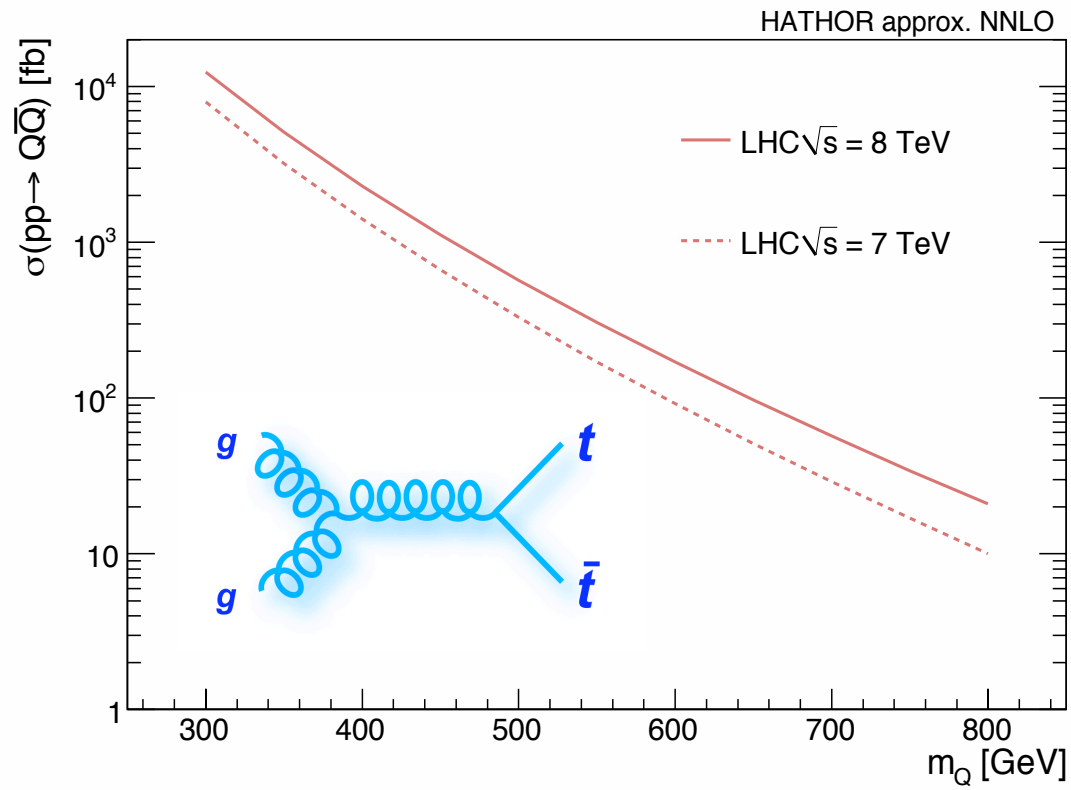
(Heavy D-type quark via charged current is shown, strong pair production also shown for reference.)

JHEP 08 (2011) 080



Strong production of chiral and vector-like quarks.

(Equivalent to heavy top quark pair production).



ATLAS Searches for new Heavy Quarks with 7 TeV Data

1. *Search for singly produced vector-like quarks coupling to light quarks.*

   Phys. Lett. B 712 (2012) 22-39 [1.0/fb]; ATLAS-CONF-2012-137 [4.7/fb] New!

2. *Search for b'b' production in events with two same charge leptons.*

   JHEP 04 (2012) 069 [1.0/fb]; ATLAS-CONF-2012-130 [4.7/fb] New!

3. *Search for b'b' production in single lepton events with hadronic W candidates.*

   Phys. Rev. Lett. 109, 032001 (2012) [1.0/fb]

4. *Search for b'b' production with a b' decaying to a b-quark and a Z boson.*

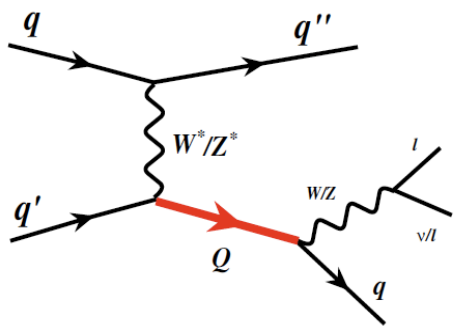
   Phys. Rev. Lett. 109, 071801 (2012) [2.0/fb]

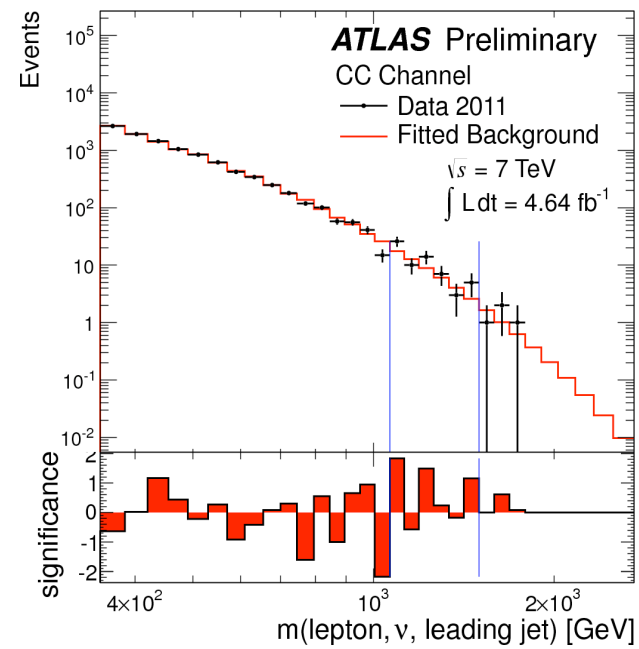
5. *Search for t't' production in single leptons events.*

   Phys. Rev. Lett. 108, 261802 (2012) [1.0/fb]; EXOT-2012-007 (to be submitted to PLB) [4.7/fb] New!

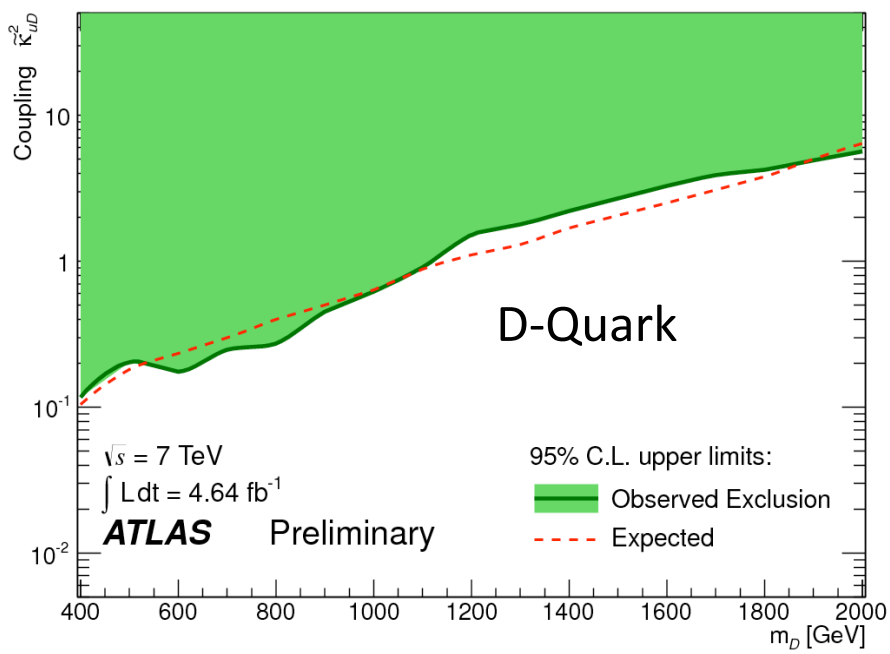
Search for Singly Produced Vector-Like Quarks Coupling To Light Quarks

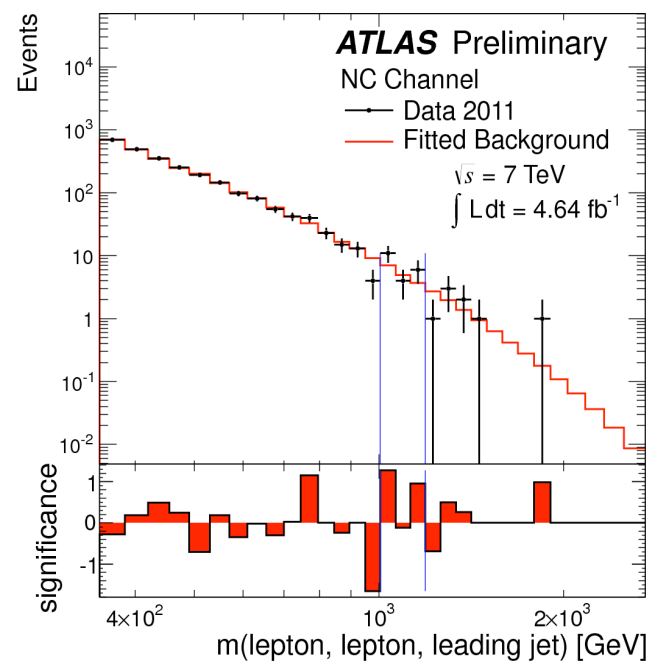
- Final state consists of vector boson and high p_T jet from the VLQ decay, plus a lower p_T associated jet.
- Search performed in CC (W) and NC (Z) channels. Analytic fit function to model the candidate mass spectrum, test data for evidence of a resonance.



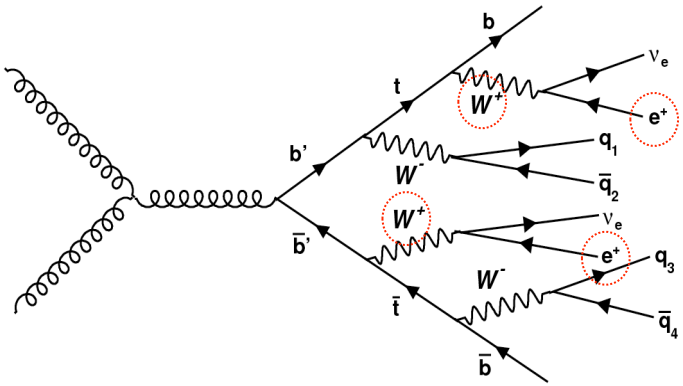


- Limits derived on U (Q=+2/3), D (Q=-1/3), and X (Q=+5/3) quarks.
- Limits presented as function of model-independent coupling vs. mass.



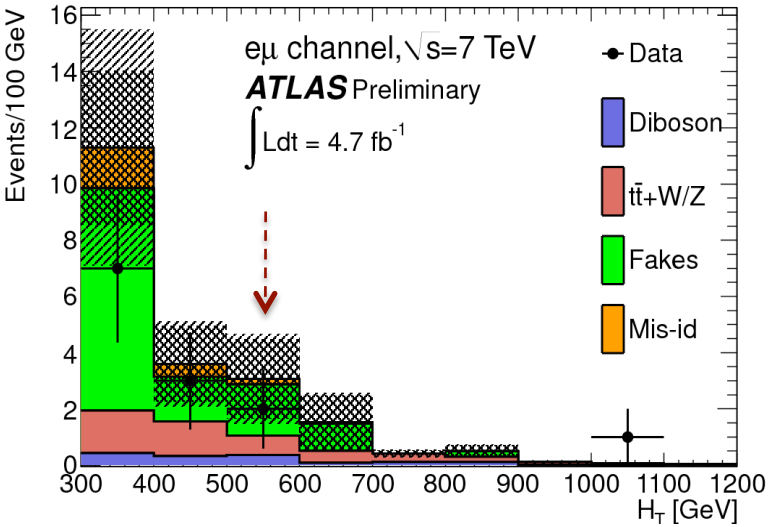


Search for b'b' in Events with Two Same Charge Leptons

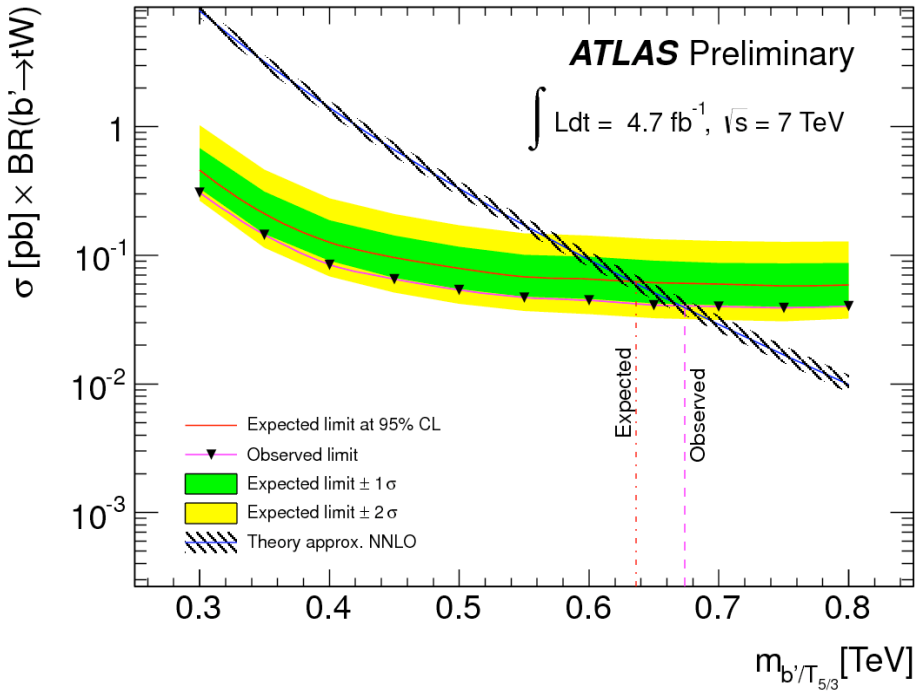


$$b'\bar{b}' \rightarrow W^- t W^+ \bar{t} \rightarrow W^- W^+ W^+ W^- b\bar{b}$$

- If Wt decay mode dominates, final state has 2 same-sign W's.
- Require two same-sign leptons and missing E_T > 40 GeV.
- Require two or more jets, with at least one jet tagged as a b-jet.
- Require event H_T > 550 GeV.
- b' masses < 670 GeV are excluded (BR(Wt) = 100%).



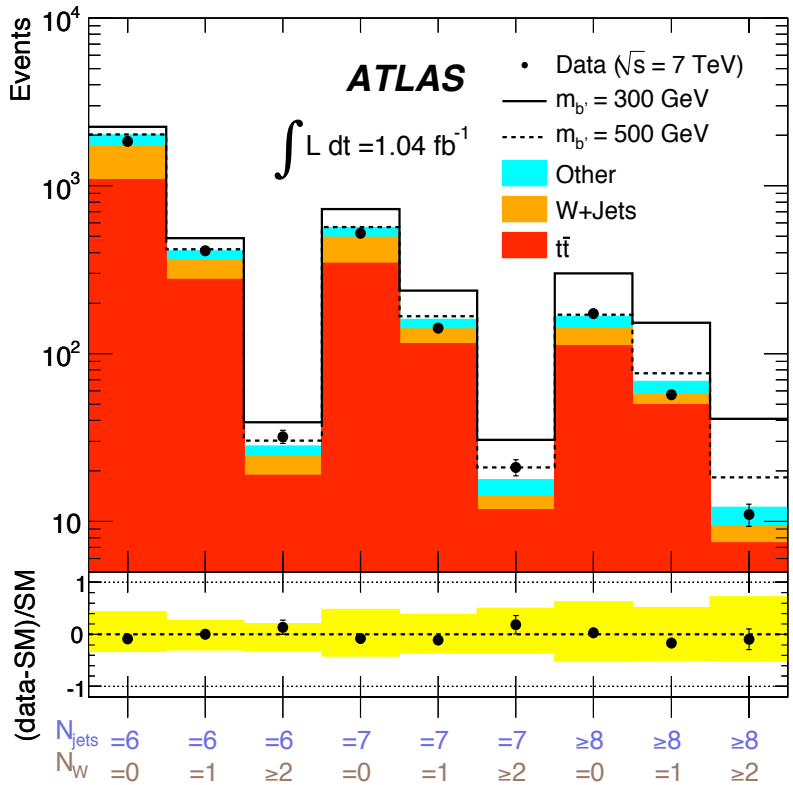
Channel	ee	eμ	μμ
Tot. Exp. Bkgd	1.3 ± 1.1 ± 0.3	2.9 ± 1.1 ± 0.5	1.4 ± 0.3 ± 0.3
Obs. Events	2	2	0
b'b' (650 GeV)	0.98 ± 0.04	3.06 ± 0.08	2.00 ± 0.07

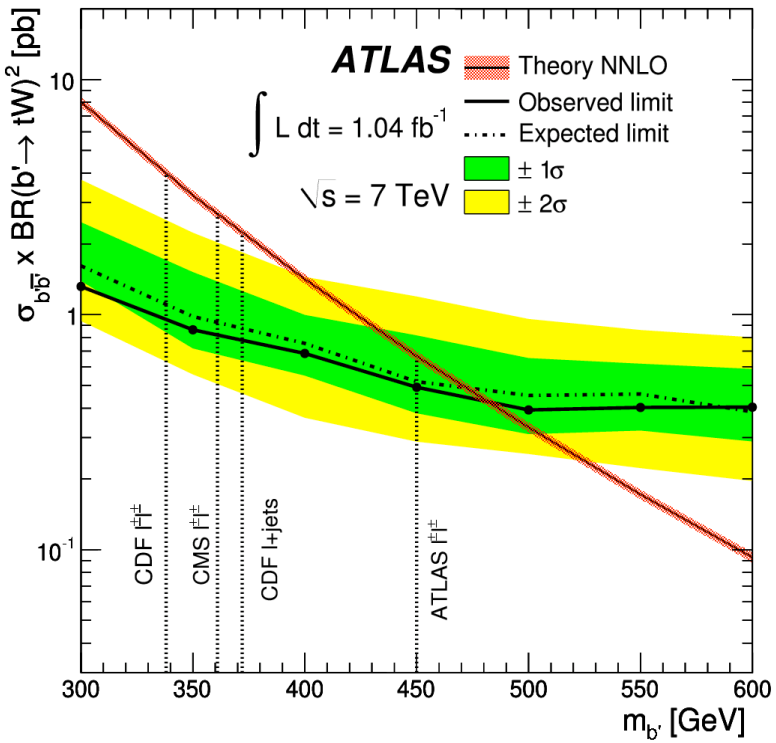


Search for b'b' in Single Lepton Events With Hadronic W Candidates

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

- The 4 W + 2-b-jet final state also allows for a single lepton analysis in high jet multiplicity events.
- Similar selection to di-top in lepton+jets. Use jets to tag hadronic W candidates.
- Promising analysis to update with the 8 TeV data set and to consider also tagging hadronic Z and Higgs boson decays to provide more sensitivity to vector-like quark decays.

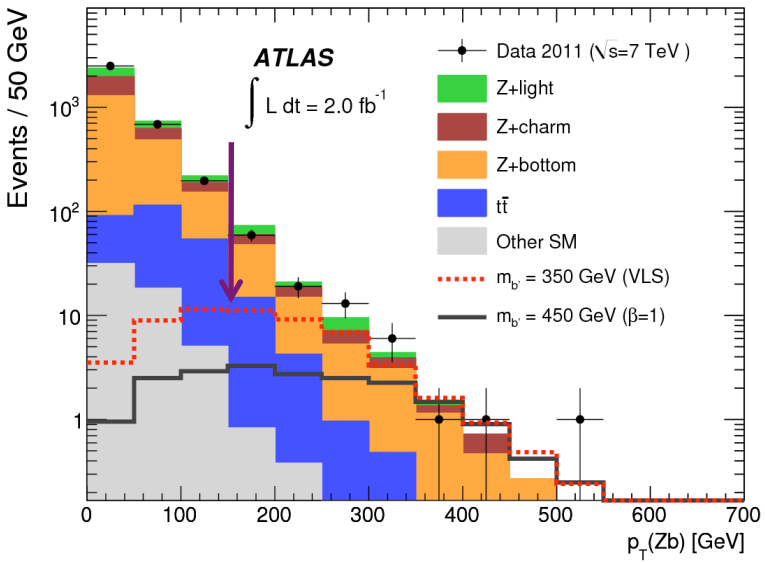




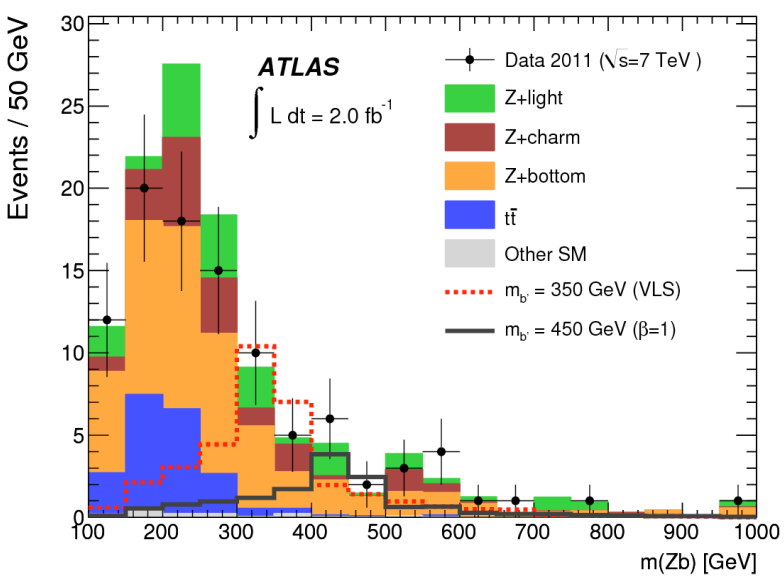
Search for b'b' Production with a b' Decay to b quark and Z boson

$$b'\bar{b}' \rightarrow Zb + X$$

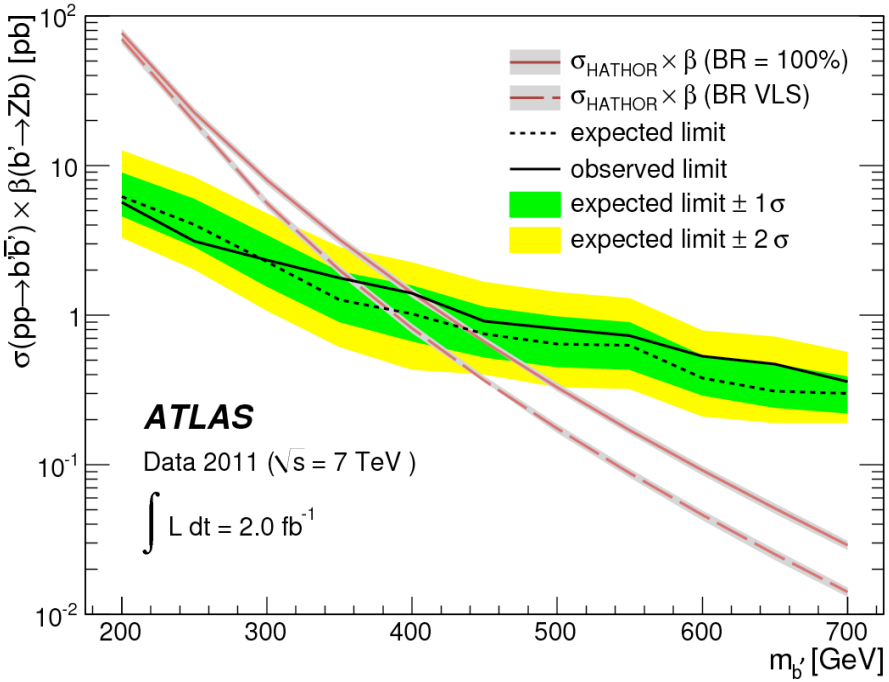
P_T of the Zb Candidate



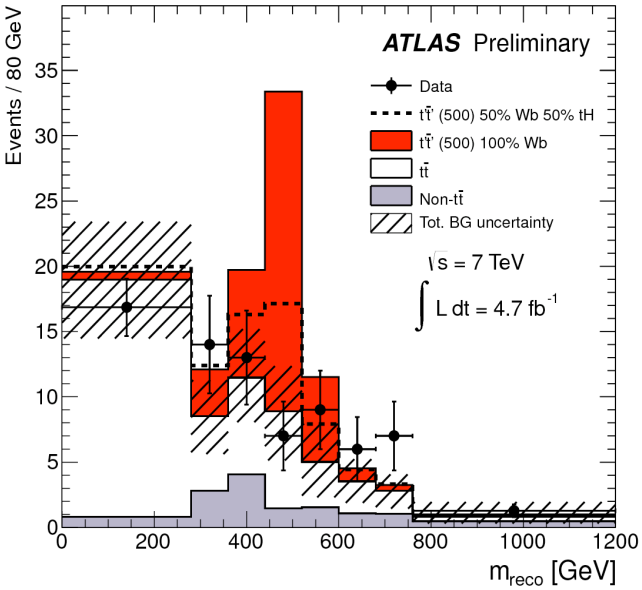
Mass of the Zb Candidate



- Select events with a leptonic Z candidate and a b-tagged jet.
- Form $b' \rightarrow Zb$ candidate.
- Require $p_T(Zb) > 150\ \mathrm{GeV}$ to reduce bkgd, then examine mass.
- Remain agnostic to " X = the decay of the other b' ".
- Exclude b' masses < 400 GeV in the case of BR(Zb) = 100%, masses < 358 GeV in the case of a vector-like singlet.

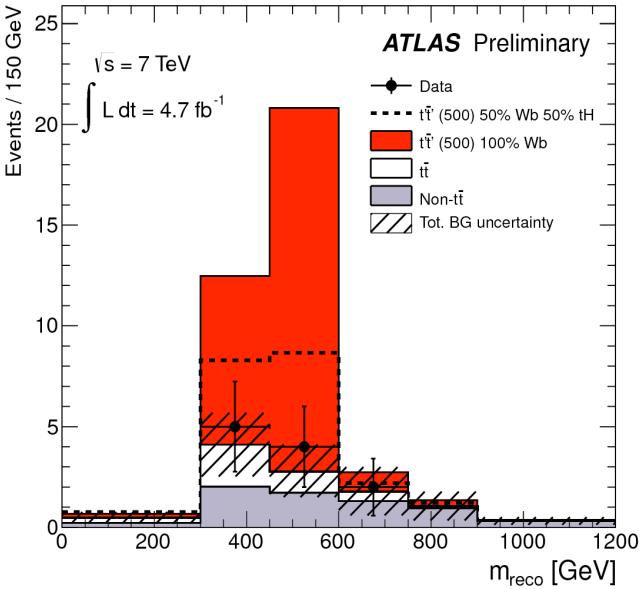


Search for t't' in the Events with One Lepton



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

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



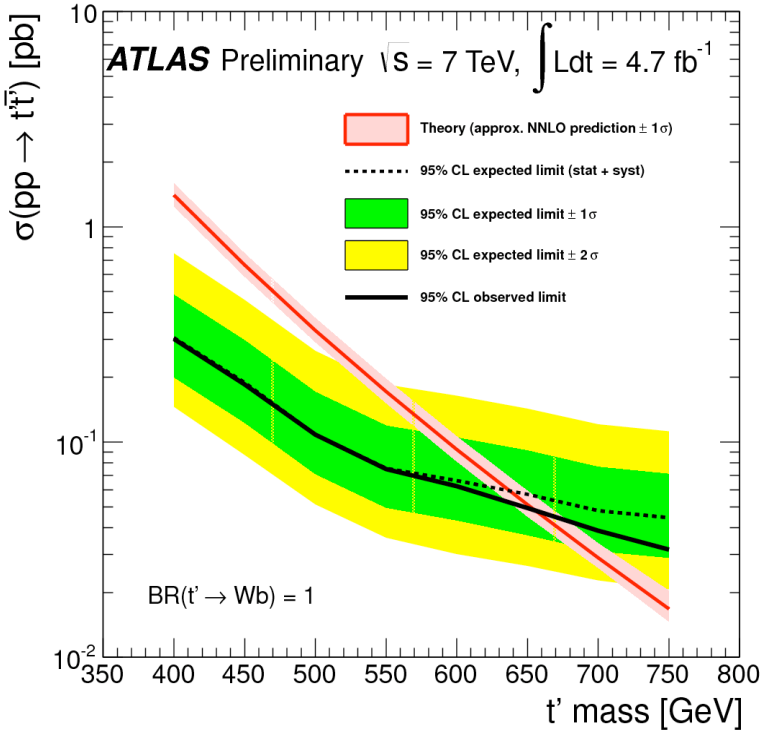
$$t'\bar{t}' \rightarrow W^+ b W^- \bar{b}$$

- Events w/ 1 lepton, missing E_T, and at least 3 jets selected.
- Require 1 hadronic W candidate, identified as either a single jet or a di-jet.
- 1 explicitly b-tagged jet. Also consider jet with next highest b-tag weight.
- b_1 p_T > 160 GeV, and b_2 p_T > 60 GeV. Event H_T > 750 GeV.
- Reconstruct heavy quark candidate mass.

- Top bkgd. reduced by requiring lepton & W_{had} well separated from b-jets.

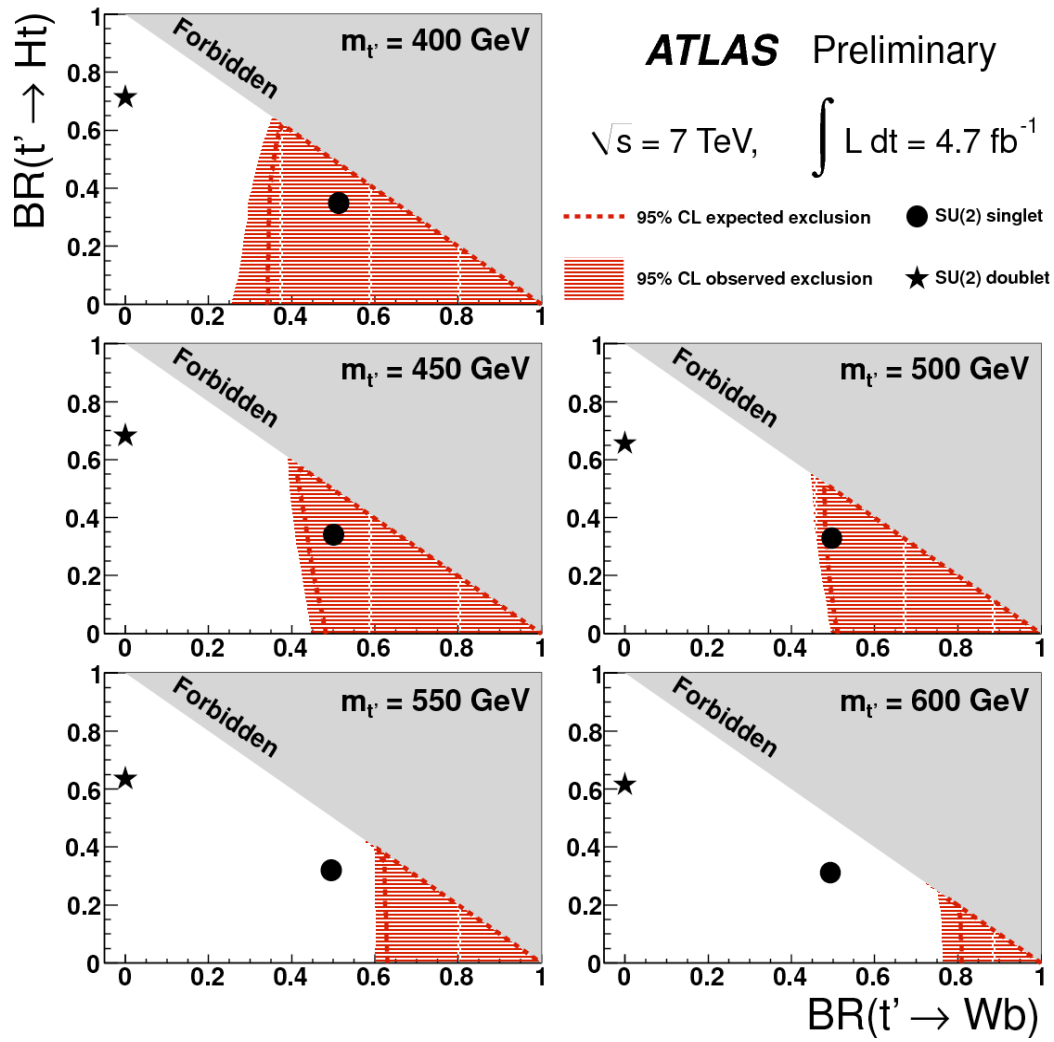
- t' masses < 656 GeV are excluded (BR(Wb) = 100%).

- Sensitivity to vector-like models (Ht and Zt) also assessed (next slide).



Conclusions

- After the discovery of a Higgs-like particle, attention is turning to whether the signal strengths are compatible with the SM.
- New fermions would modify the signal strengths.
- The newly observed particle is already SM-like enough to strongly disfavor a 4th chiral generation.
- ATLAS direct searches for new quarks also rule out chiral quarks at the 600-700 GeV scale.
- Vector-like quarks degrade these limits, as more complex final states are allowed.
- Studies of vector-like fermion phenomenology show that they subtly modify Higgs properties, fix problems with SUSY, and arise in many other SM extensions.



- Therefore, with the 8 TeV dataset, ATLAS aims to cover more of the currently allowed parameter space of vector-like quark decay modes.