Searches for $t\bar{t}$ Resonances and Vector-Like Quarks in Atlas

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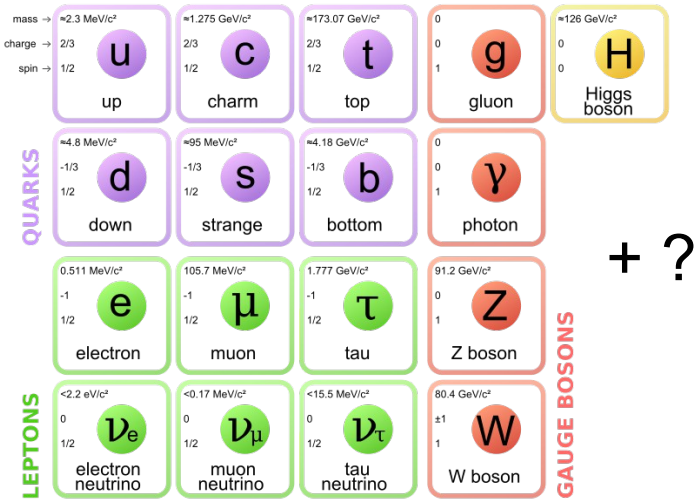
Motivation

- Several unanswered questions in the Standard Model:
  - Fermion generations and mass hierarchy
  - Matter-Antimatter asymmetry (extra CP violation?)
  - Fine tuning
  - Dark Matter
  - ....



+ ?

- Top quark is leading contributor to Higgs quadratic divergence mass quadratic divergence
  - ➔ New physics in the top sector can play an important role in regulating the Higgs mass

- Many proposed BSM models predict new physics to be found in the top sector
  - Topcolor, Little Higgs, Composite Higgs, Randall-Sundrum (with warped extra dimensions),...

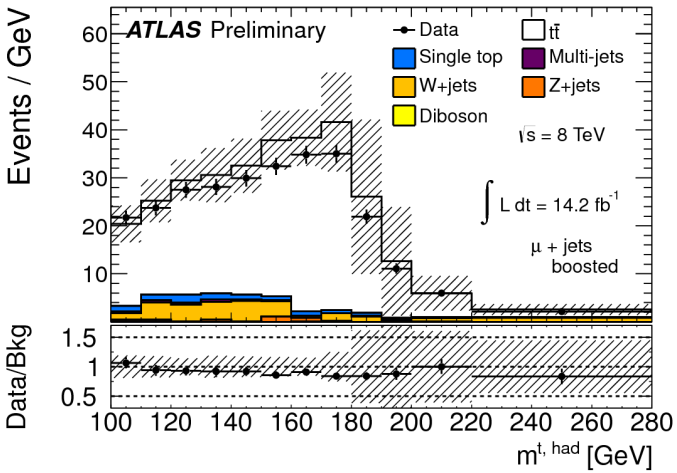
Overview

- Several searches will be presented featuring similar phenomenological characteristics
  - Top quark pairs (same or opposite signs)
  - Heavy quark pairs decaying into 3rd generation quark + boson
  - Four top final states

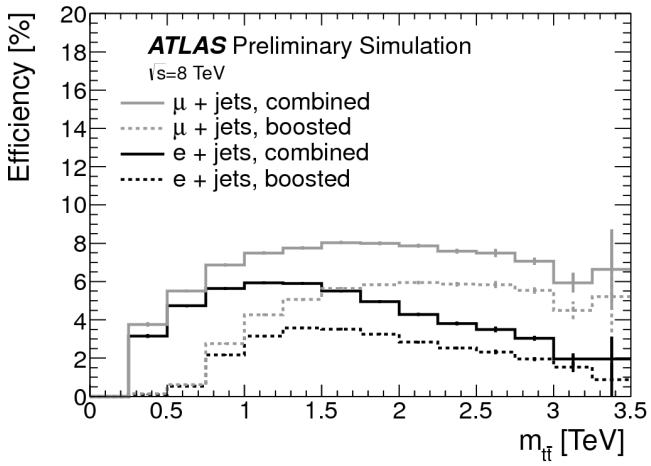
- All results shown for 14.3 fb^{-1} of data at 8 TeV taken by the Atlas Experiment between April and October 2012

Semileptonic $t\bar{t}$ Resonance Search

- Search for heavy particles decaying into top quark pairs
- Resolved and Boosted channels for low and high mass signal regions
  - Resolved channel: hadronic top decaying into 2-3 Anti-k_T R=0.4 jets
  - Boosted Channel: hadronic top decaying into a single large radius jet (Anti-k_T R=1.0)
    - High p_T top decay products can not be resolved separately
    - $p_T \geq 300$ GeV, $m_{jet} \geq 100$ GeV, Split12* ≥ 40 GeV
    - Jet trimming reduces the impact of pileup by removing soft components of a jet
- Leptonic top reconstructed from lepton+jet+Missing E_T
- Require large separation between hadronic and leptonic top constituents in boosted channel
- Only events which fail boosted selection are considered for the resolved channel



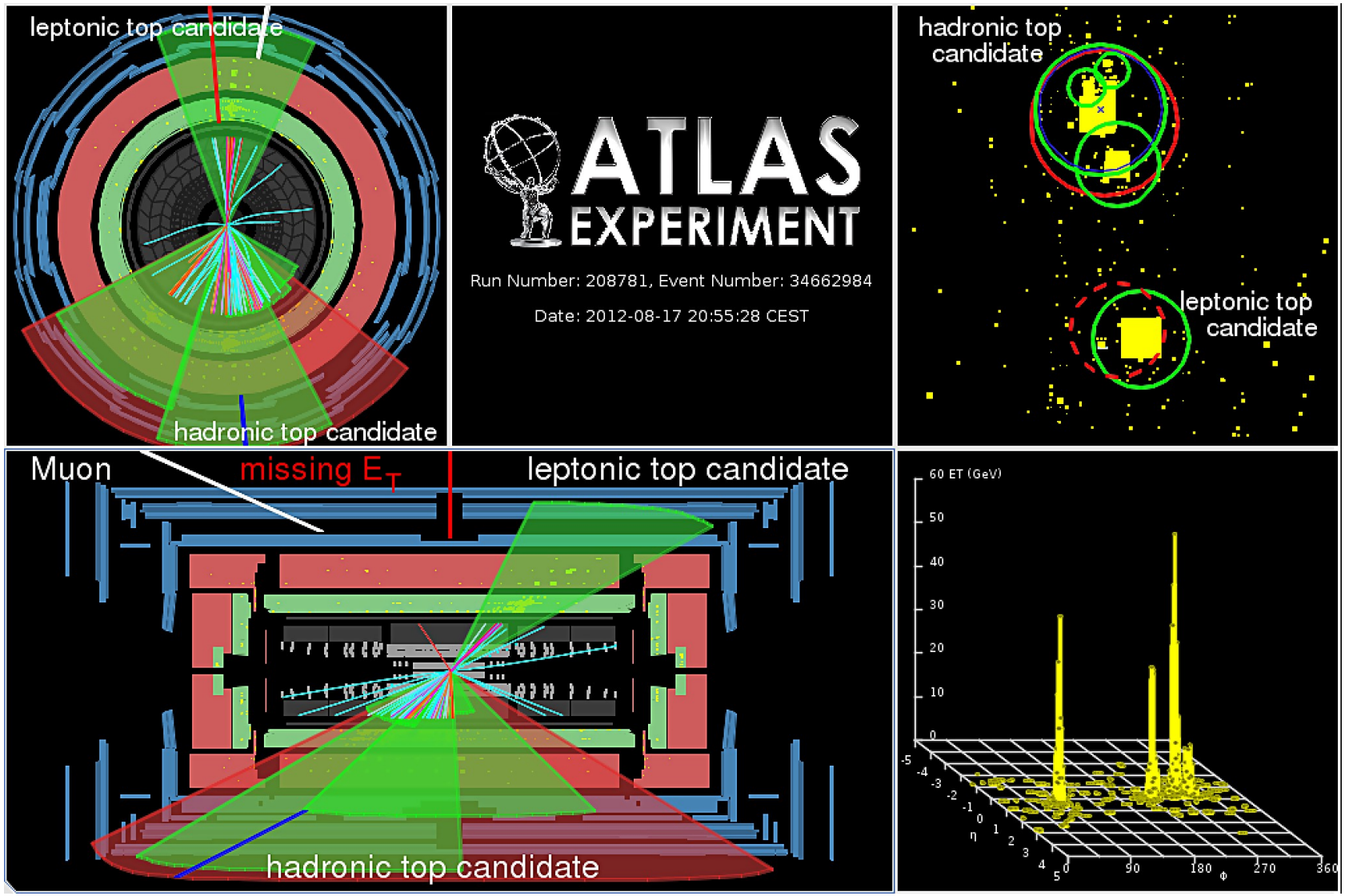
Reconstructed hadronic top mass, boosted muon channel



Event Selection Efficiency
Boosted (Dashed)
Combined (Solid)

* Split12 = k_T splitting scale between final 2 subjets after reclustering with k_T jet algorithm

Semileptonic $t\bar{t}$ Resonance Search: Event Display



Green cone:
R=0.4 jets

Red cone:
R=1.0 jet

White:
lepton (muon)

Red:
Missing E_T

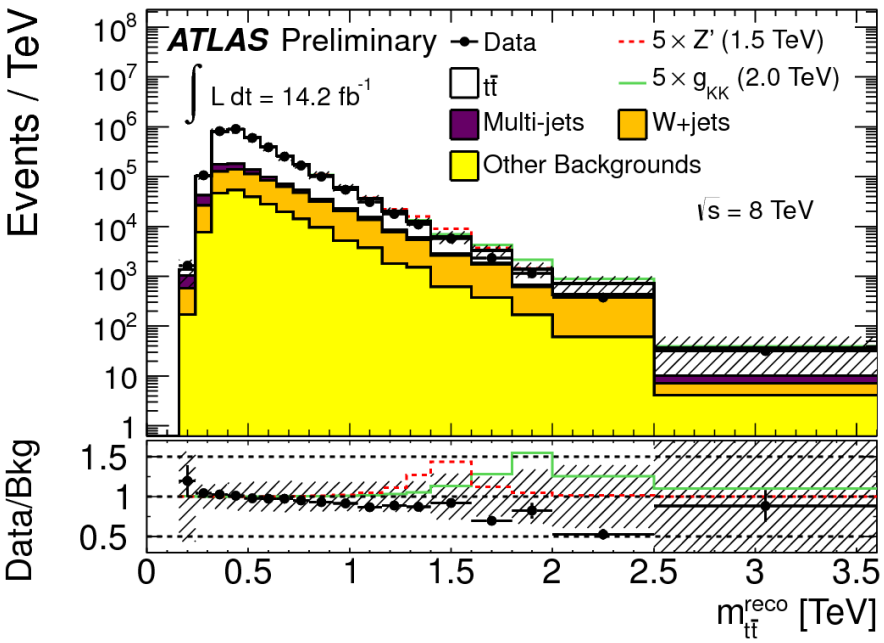
Blue:
b-tagged jet

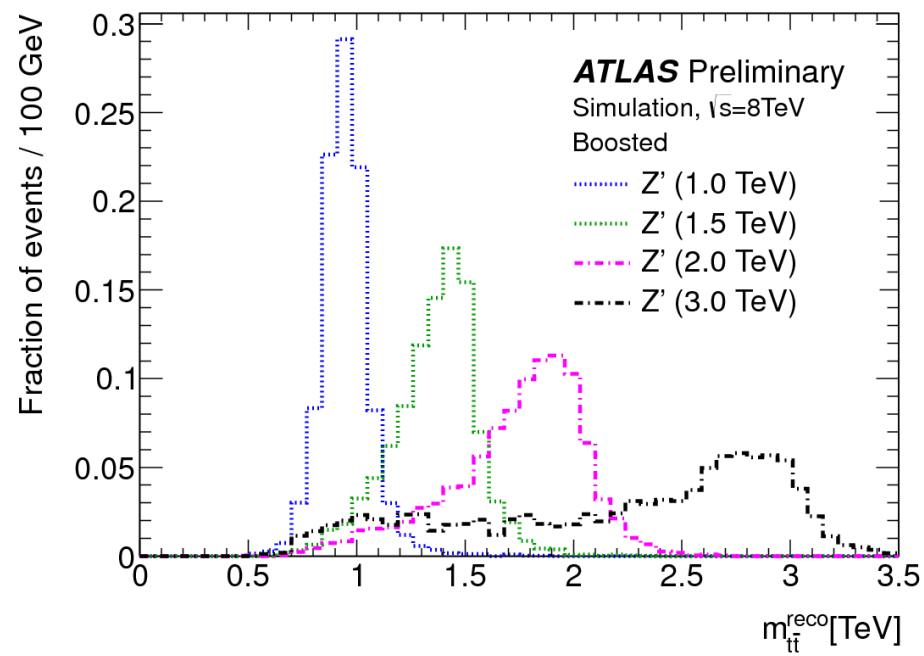
$m_{t\bar{t}}^{reco}$ = 2.5 TeV $t\bar{t}$ candidate in boosted channel.

Semileptonic $t\bar{t}$: Event Reconstruction

- Resolved channel: χ^2 algorithm used to pick combination of jets most consistent with $t\bar{t}$ decay
- Boosted channel: highest p_T jets satisfying selection are chosen
- Bayesian limit setting proceeds using reconstructed $m_{t\bar{t}}$ as a discriminant

$$\chi^2 = \left[\frac{m_{jj} - m_W}{\sigma_W}\right]^2 + \left[\frac{m_{jjb} - m_{jj} - m_W}{\sigma_{th-W}}\right]^2 + \left[\frac{m_{jl\upsilon} - m_{tl}}{\sigma_{tl}}\right]^2 + \left[\frac{(p_{T,jjb} - p_{T,jl\upsilon}) - (p_{T,th} - p_{T,tl})}{\sigma_W}\right]^2$$

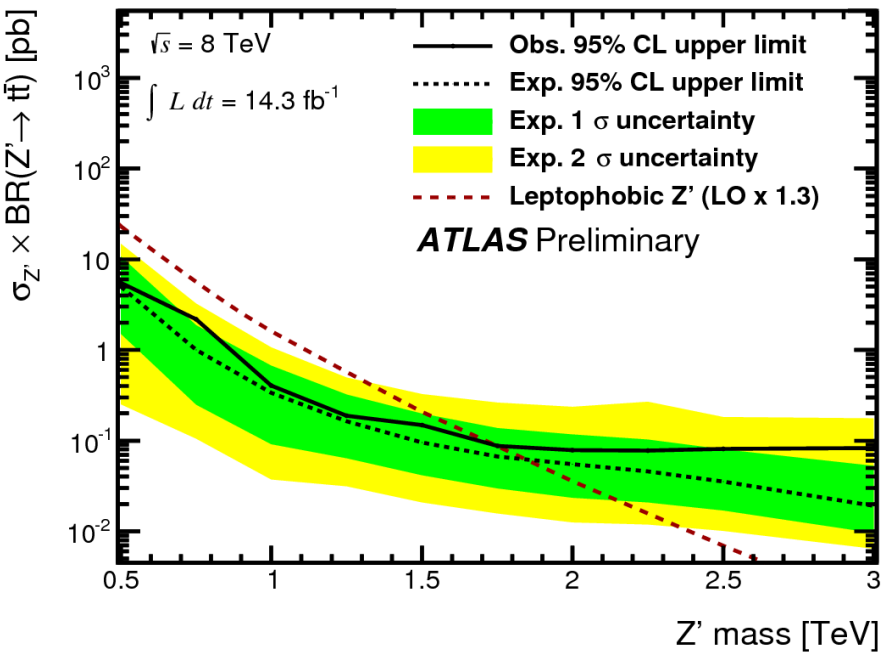




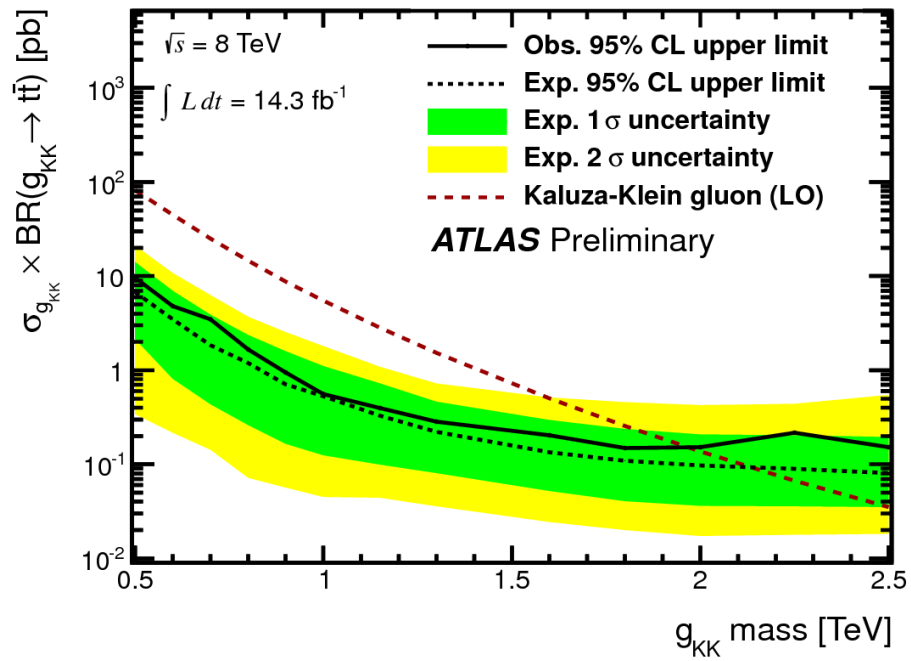
$t\bar{t}$ Resonance Search

- 2 Benchmark models for resonances decaying to $t\bar{t}$:
  - Narrow width leptophobic Z' (Γ/m = 1.2%)
    - Topcolor
  - Wide width Kaluza-Klein gluon (Γ/m = 15.3%)
    - Randall-Sundrum model

- 95% CL Limits:



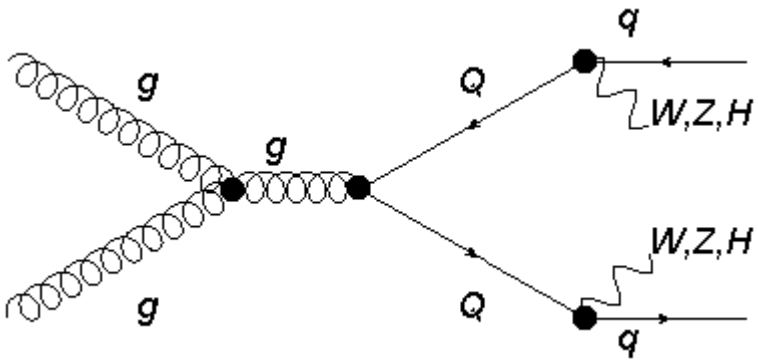
$m_{Z'}$ > 1.9 TeV

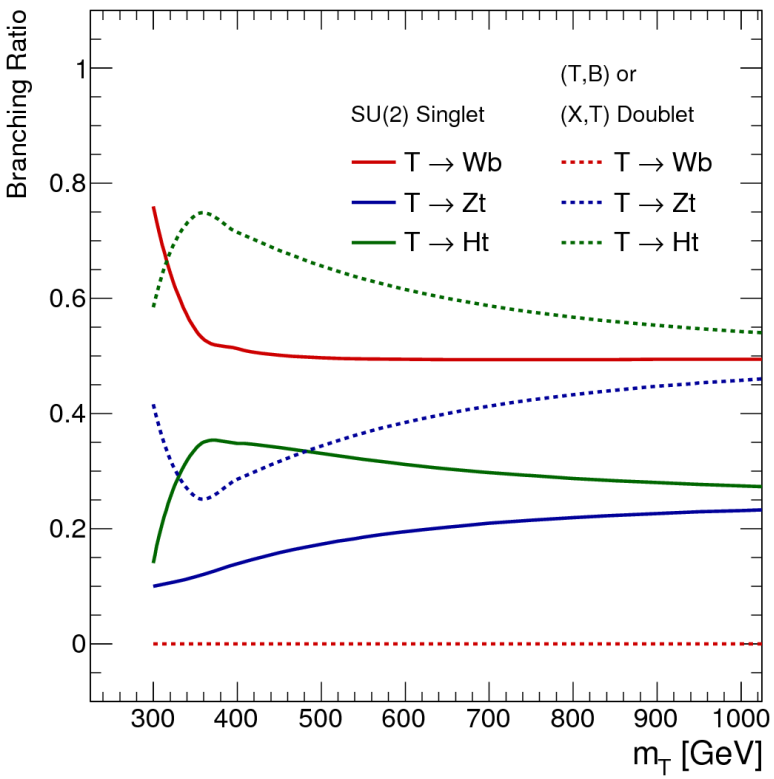


m_{gKK} > 2.1 TeV

Vector-Like Quarks

- Left and right handed components have identical electroweak gauge transformations
- Top partner may play an important role in regulating the Higgs mass
- Charged and neutral current decay modes possible:
  - T → Wb, T → Zt, T → Ht
  - B → Wt, B → Zb, (B → Hb)
- Pair production (via QCD) dominates at masses less than 1 TeV
- Decays to third generation dominant in most scenarios

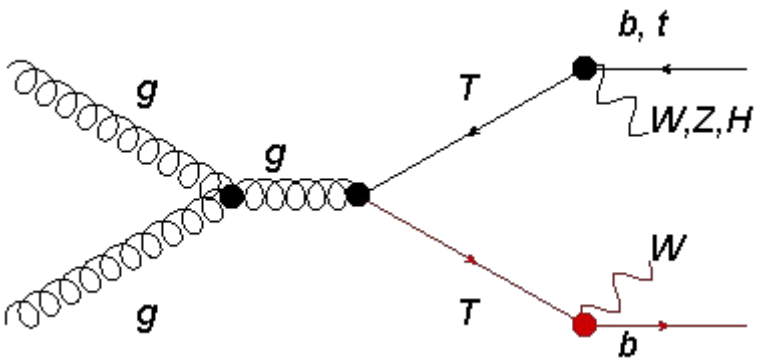




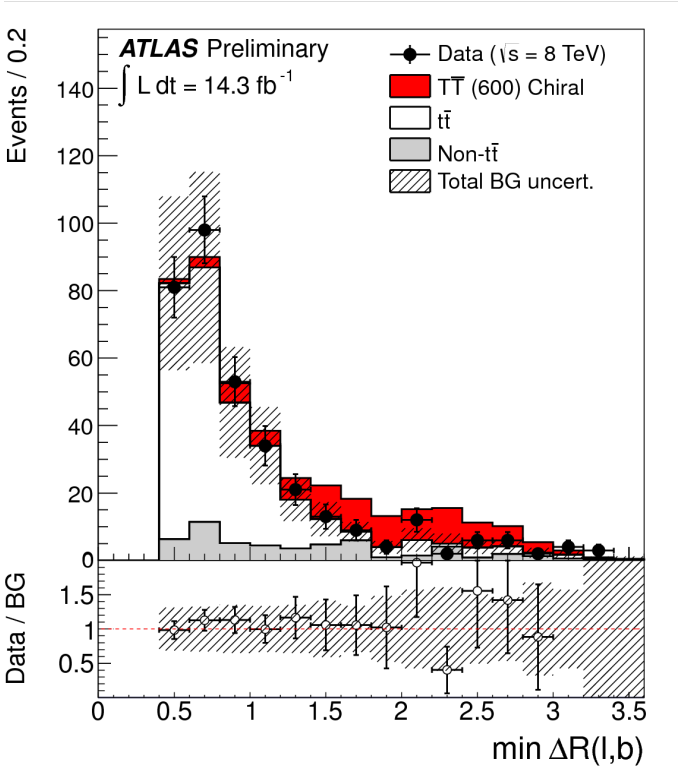
Branching ratio's at varying m_T

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

- Sensitive to either a Chiral or Vector-Like heavy quark

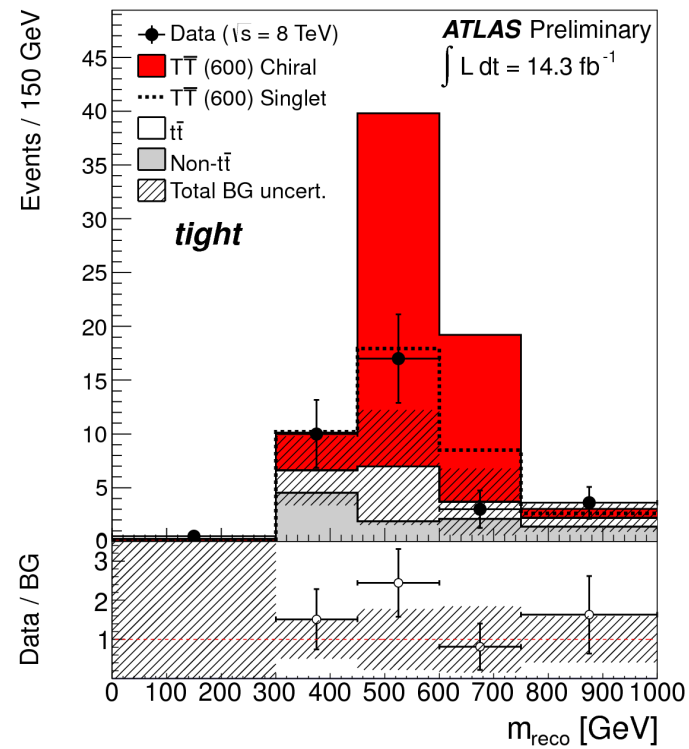


- Event Selection:
  - 4 jets, at least 1 b-tagged
    - Consider 2 jets with highest b-tag weight as b-candidates
  - 1 Reconstructed leptonic W
    - Lepton + Missing E_T
  - 1 Reconstructed hadronic W
    - Type 1: Single merged jet, (60< m <120 GeV, p_T > 250 GeV)
    - Type 2: Two jets with dR < 0.8
  - Large separation between W_{had}/lepton and closest b-candidate (dR>1.4)
  - H_T > 800 GeV
  - Reject events with ≥6 jets and ≥3 b-tagged jets
    - Overlap with $T\bar{T}$->Ht+X analysis



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

- m_T reconstructed from hadronic and leptonic W's and b-candidates
  - Permutation chosen which minimizes the difference between leptonic and hadronic m_T
- Limit setting proceeds via the frequentist CL_s method using $m_{T,Hadronic}$ as the final discriminant

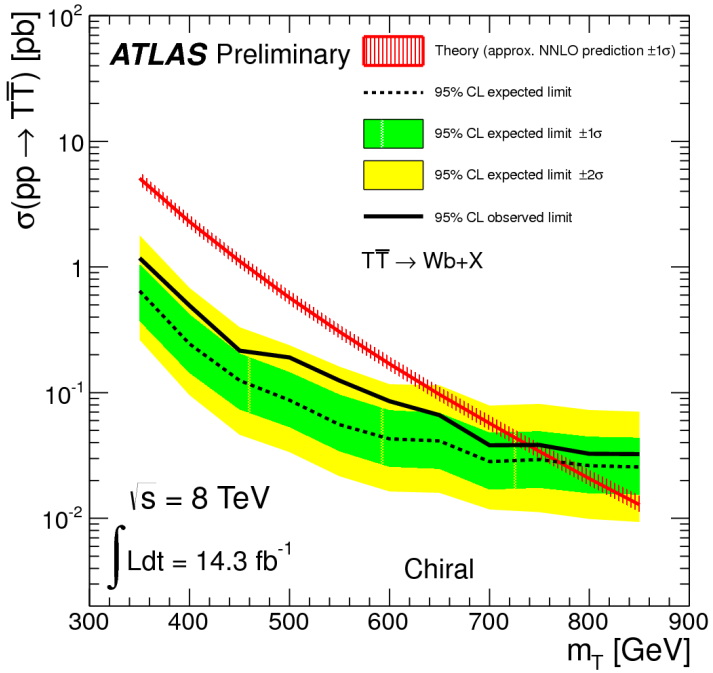


Selection efficiency by decay mode

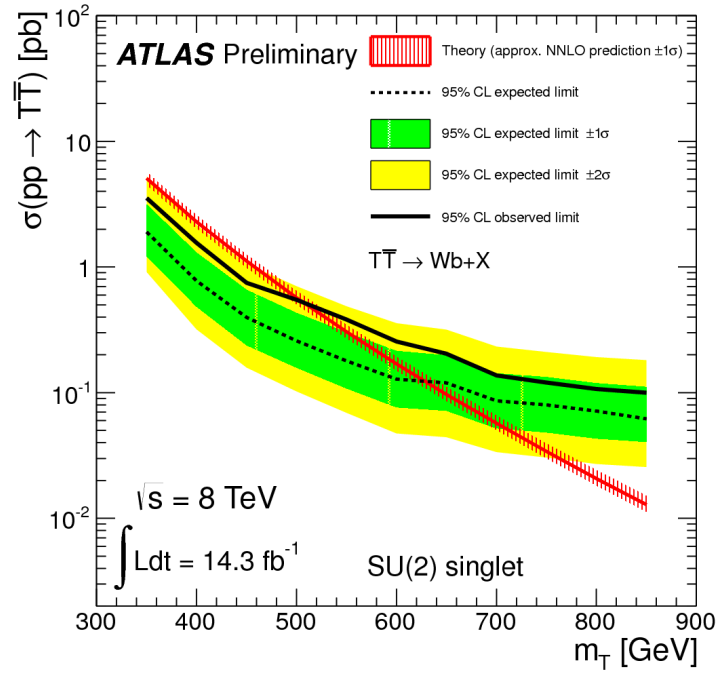
	WbWb	WbZt	WbHt	ZtZt	ZtHt	HtHt
Efficiency	2.45%	0.64%	0.47%	0.10%	0.18%	0.16%

Efficiency shown for m_T=600 GeV. Although search is optimized for WbWb, other channels contribute as well.

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



Chiral T



Singlet Vector-Like T

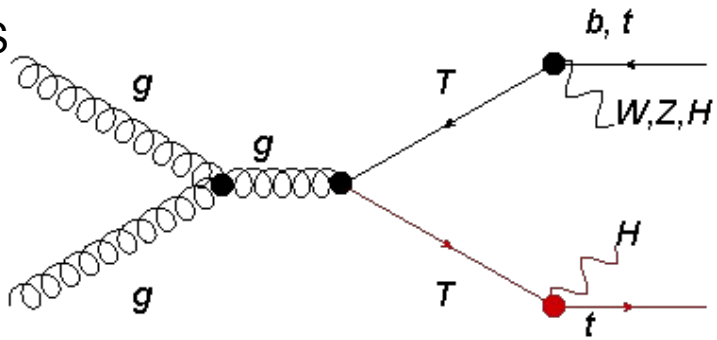
- Expected and observed 95% CL limits on the $T\bar{T}$ cross section times branching fraction for a chiral (left) and vector-like singlet (right) T quark.

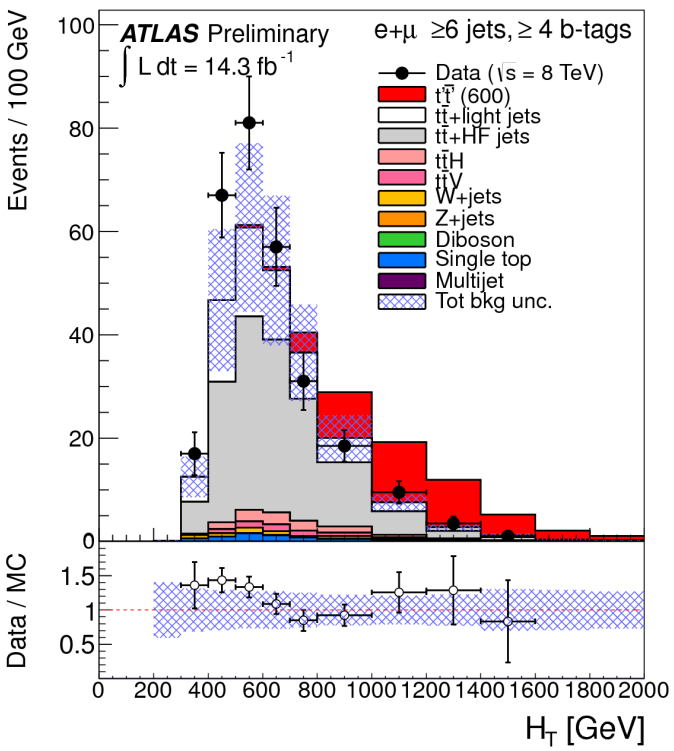
- Observed limits: $m_T > 740$ (505) GeV for chiral (vector-like singlet) T quark

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

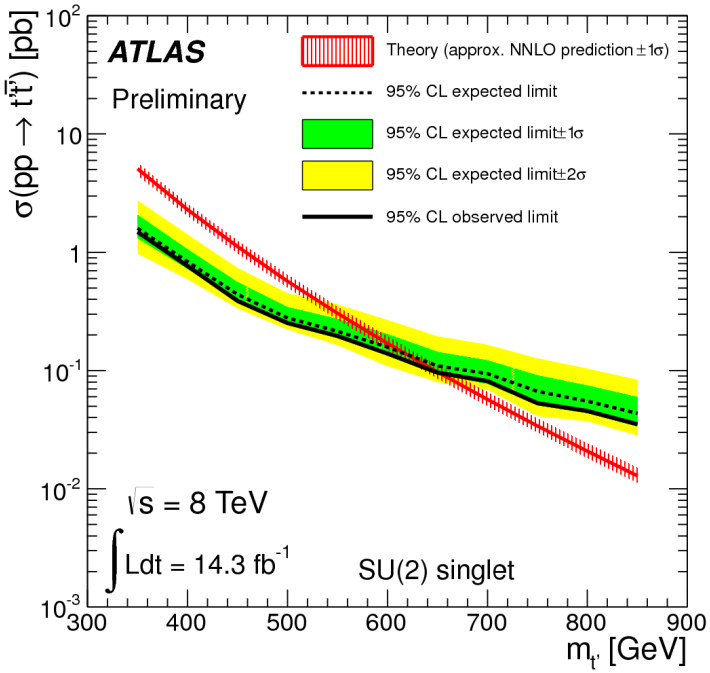
- Assume
  - 125 GeV Higgs consistent with observations at Atlas and CMS
  - H->$b\bar{b}$, and at least one $W \rightarrow l\nu$
- Signal characteristics
  - Exactly one lepton, Missing E_T
  - At least 6 jets, and 4 b-tags
- 2 and 3 b-tag events also considered as control regions to constrain systematics
  - Especially $t\bar{t}$+ light/heavy flavor jet composition
- H_T chosen as final discriminant for sensitivity to multiple decay modes
  - $T\bar{T} \rightarrow (Ht\bar{Ht})$, $(Ht\bar{Zt})$, (HtWb)
  - Peaks at about 2 m_T for signal events

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

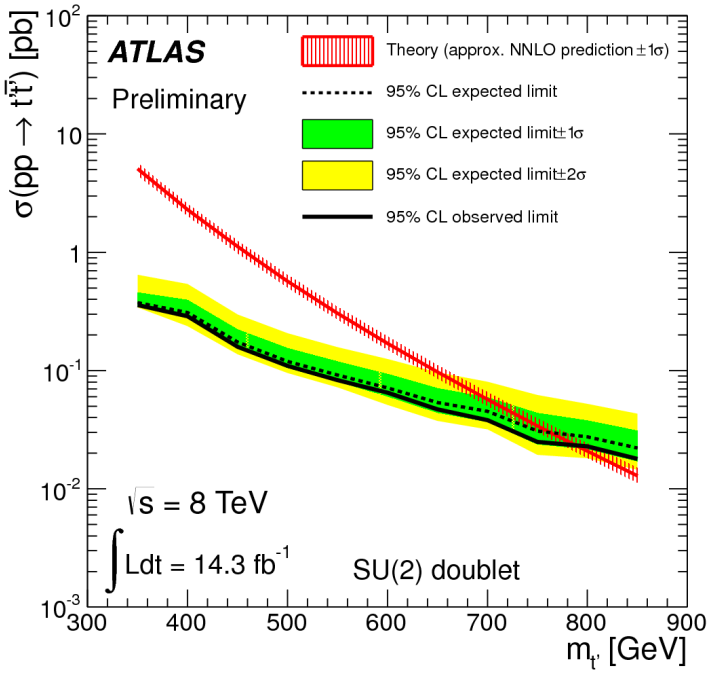




$T\overline{T} \rightarrow Ht+X$: Results



Singlet Vector-Like T



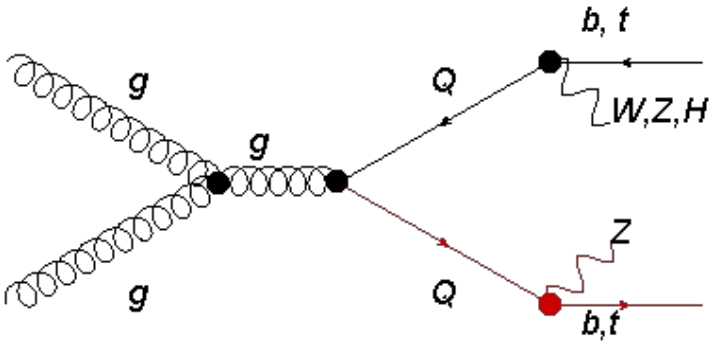
Doublet Vector-Like T

- Expected and observed 95% CL limits on the $T\overline{T}$ cross section times branching fraction for a vector like doublet (left) and singlet (right) T quark.

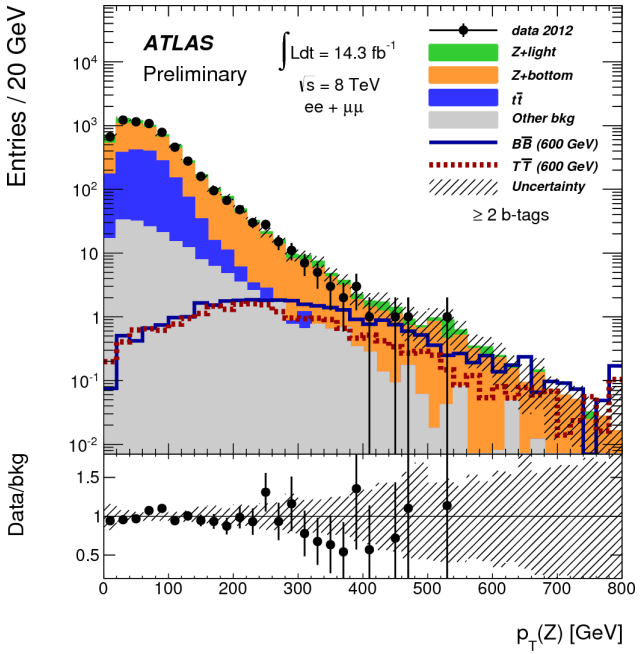
- Observed limits: m_T> 640 (790) GeV for singlet (doublet) vector-like T quark

$T\bar{T} \rightarrow Zt+X$, $B\bar{B} \rightarrow Zb+X$

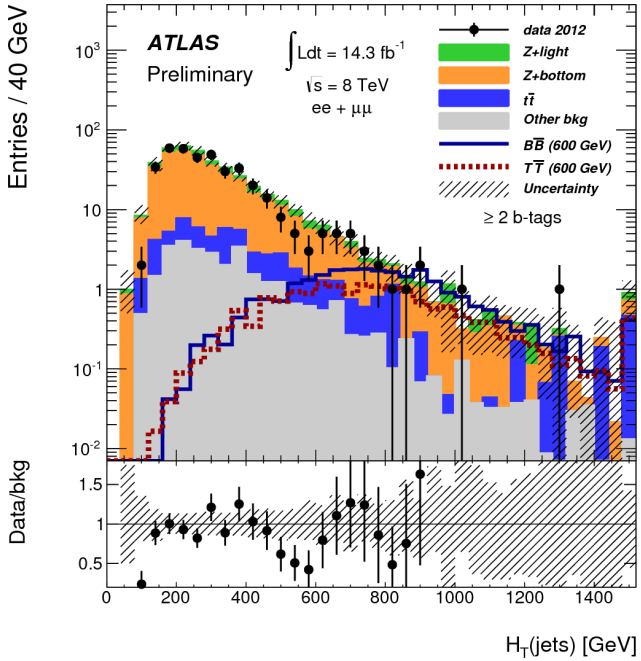
- Sensitive to both T and B vector-like heavy quarks pairs
- Event Selection:
  - High p_T leptonically decaying Z boson (p_T>150 GeV)
  - At least 2 b-tagged jets
  - H_T(jets) > 600 GeV
- m(Zb) used as discriminant for CL_s limit setting



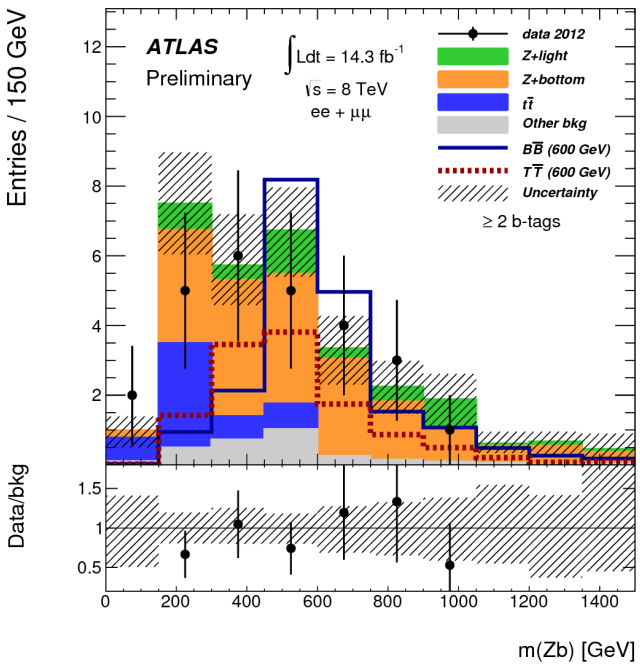
$P_T(Z)$



H_T(jets)



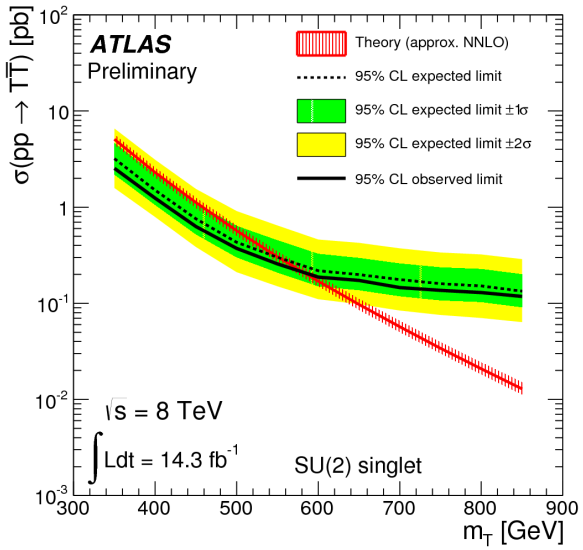
m(Zb)



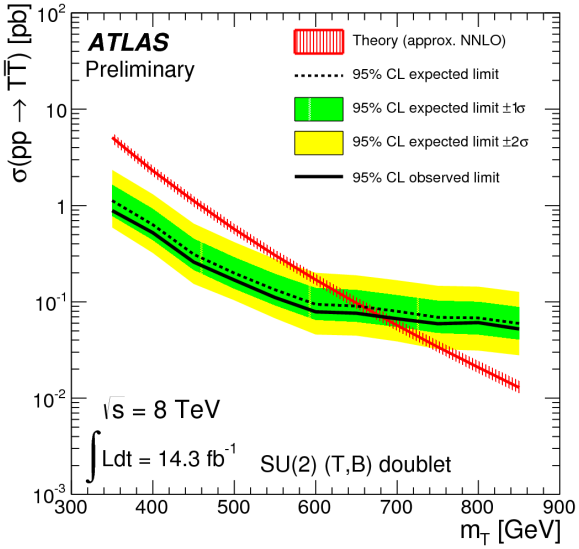
$T\bar{T}\rightarrow Zt+X$, $B\bar{B}\rightarrow Zb+X$: Results

- Observed Limits:
  - Singlet T: 585 GeV
  - Singlet B: 645 GeV
  - Doublet (T,B): 680 GeV
  - Doublet (B,Y): 725 GeV

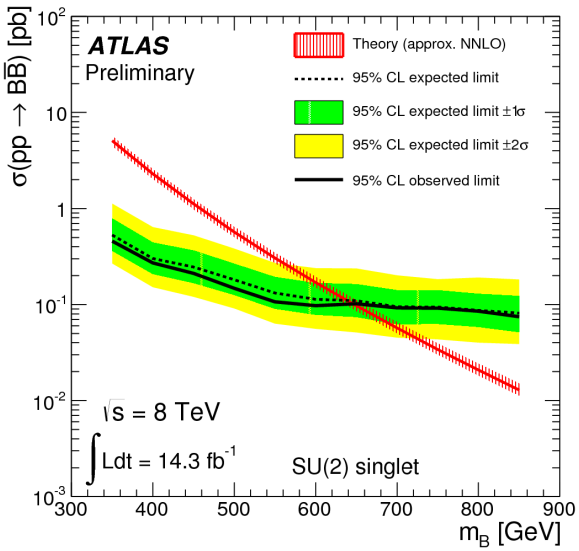
SU(2) Singlet (T)



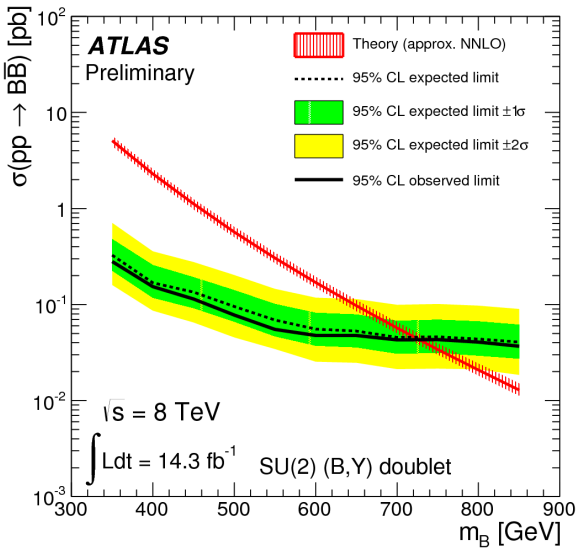
SU(2) doublet (T,B)



SU(2) Singlet (B)

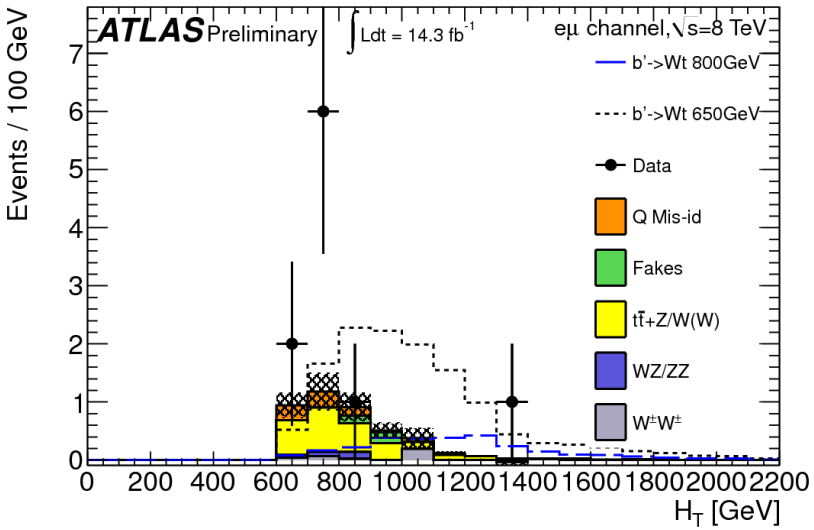


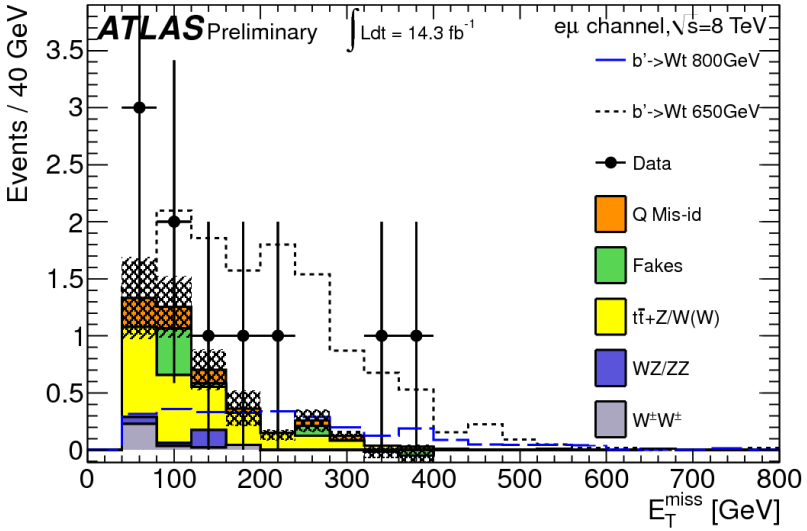
SU(2) doublet (B,Y)



Same-Sign Dileptons + b-Jets

- Tiny production cross section in the Standard Model
- Possible signature for several varieties of new physics
  - Chiral or Vector-Like heavy quarks
    - $B\bar{B}$>Wt+x, $T\bar{T}$->Zt+x ,$T\bar{T}$->Ht+x
  - Enhancement of four top production
  - Positively charged top quark pair production
    - uu → tt mediated by new heavy particle
- Baseline event selection
  - Exactly 2 same sign leptons
    - Z mass window veto in same flavor case
  - At least 2 Jets, 1 b-tagged
  - $E_T^{Miss} \geq 40$ GeV, $H_T > 550$ GeV,
- Additional selection for each signal models
  - Heavy Quark: $H_T > 650$ GeV
  - tt: positive leptons only
  - $t\bar{t}t\bar{t}$: $H_T > 650$ GeV, 2 b-tagged jets

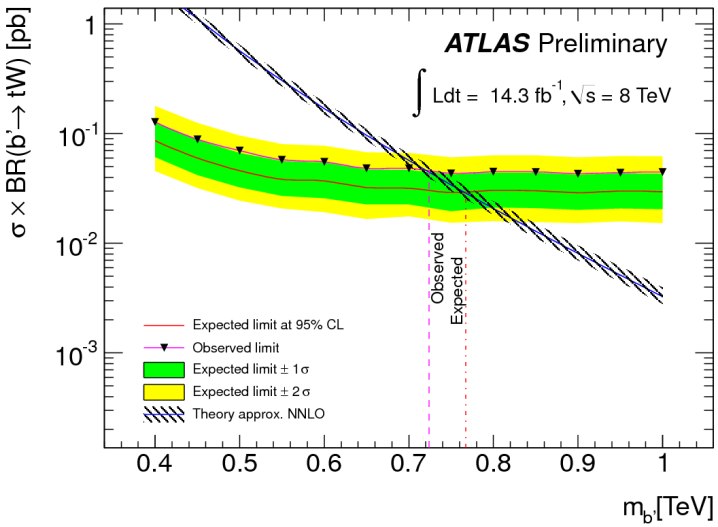




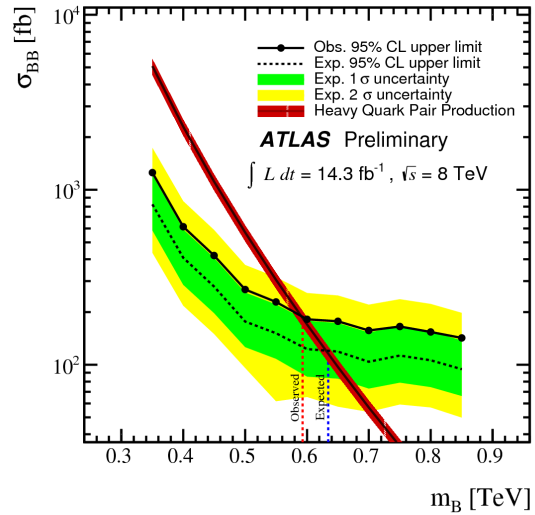
eμ channel, heavy quark selection

Same-Sign Dileptons: Heavy Quark Results

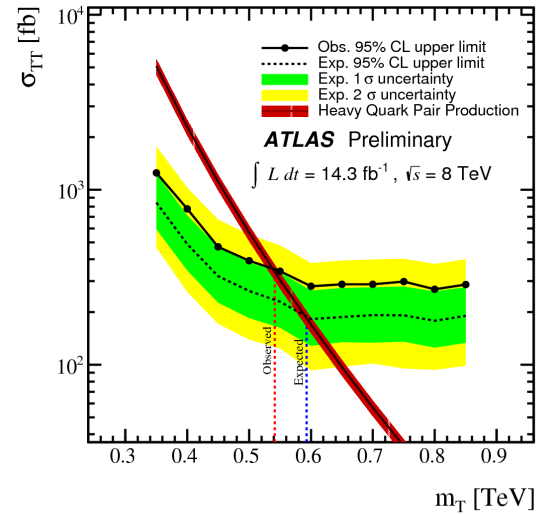
Chiral B quark



Vector-Like B quark



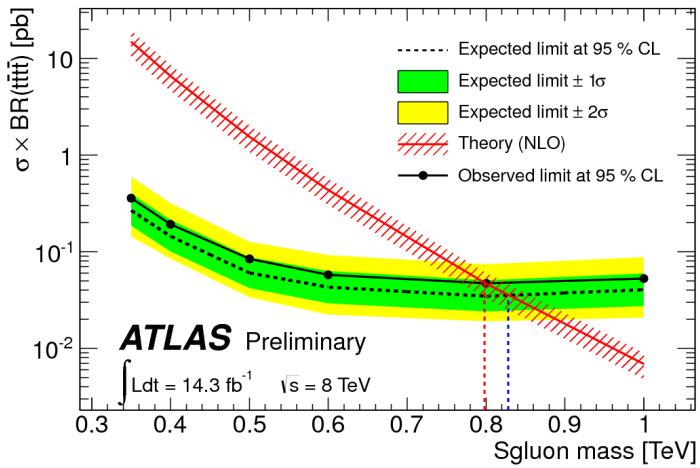
Vector-Like T quark



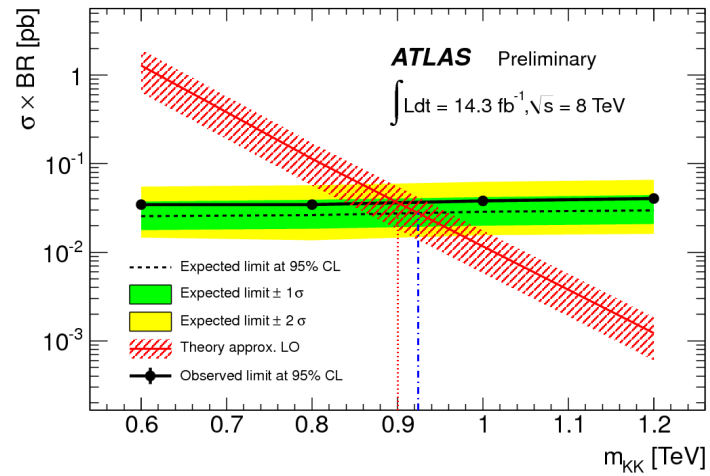
- Limit setting on the final event yields proceeds via a frequentist approach (CL_s)
- Limits:
  - Chiral B: m> 720 GeV
  - Vector-Like B(singlet): m>590 GeV
  - Vector-Like T(singlet): m>540 GeV

Same-Sign Dileptons: tt and $t\bar{t}t\bar{t}$ results

Sgluon pair→$t\bar{t}t\bar{t}$



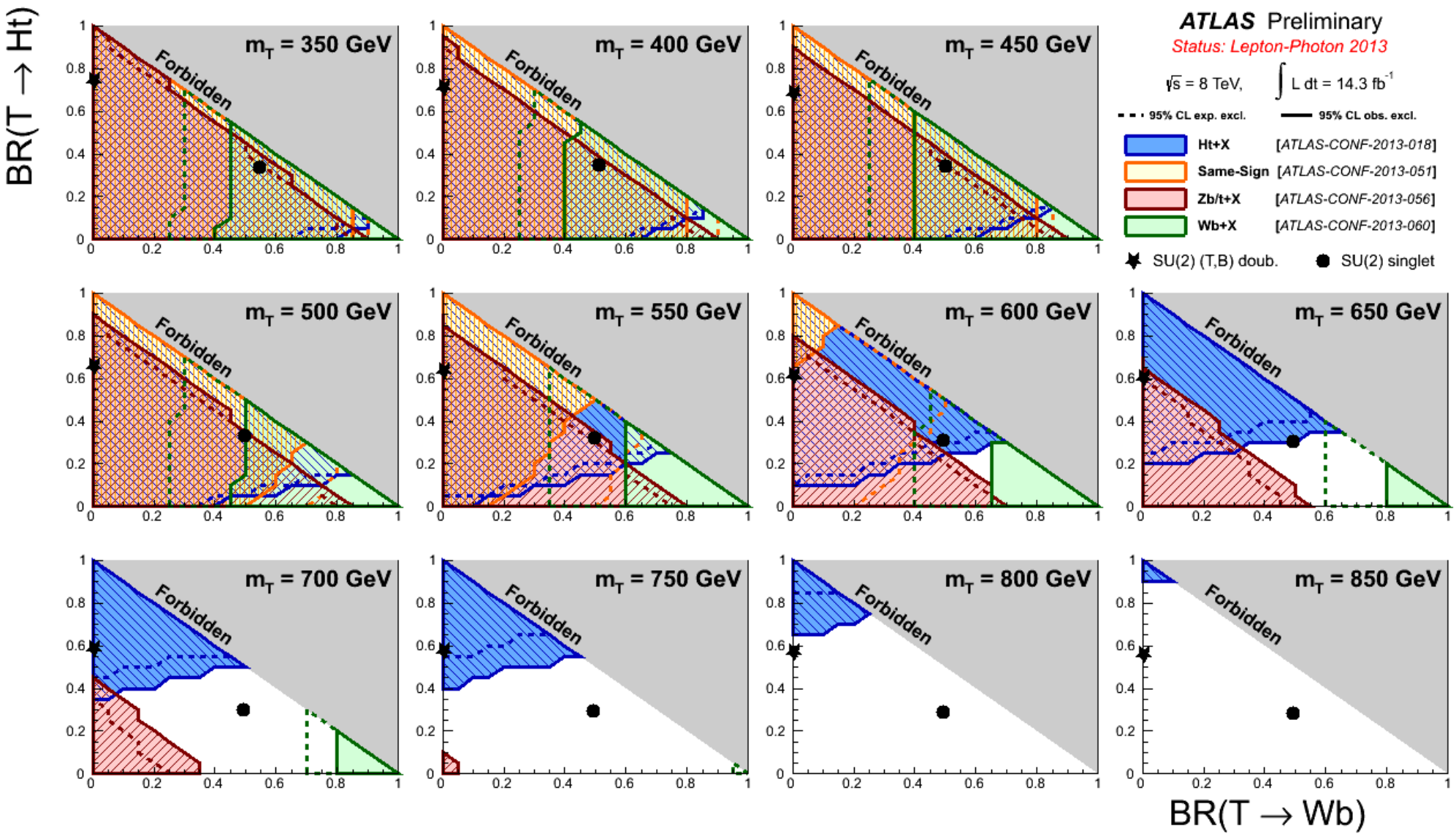
Kaluza-Klein Gluon Pair → $t\bar{t}t\bar{t}$
(2UED/RPP model)



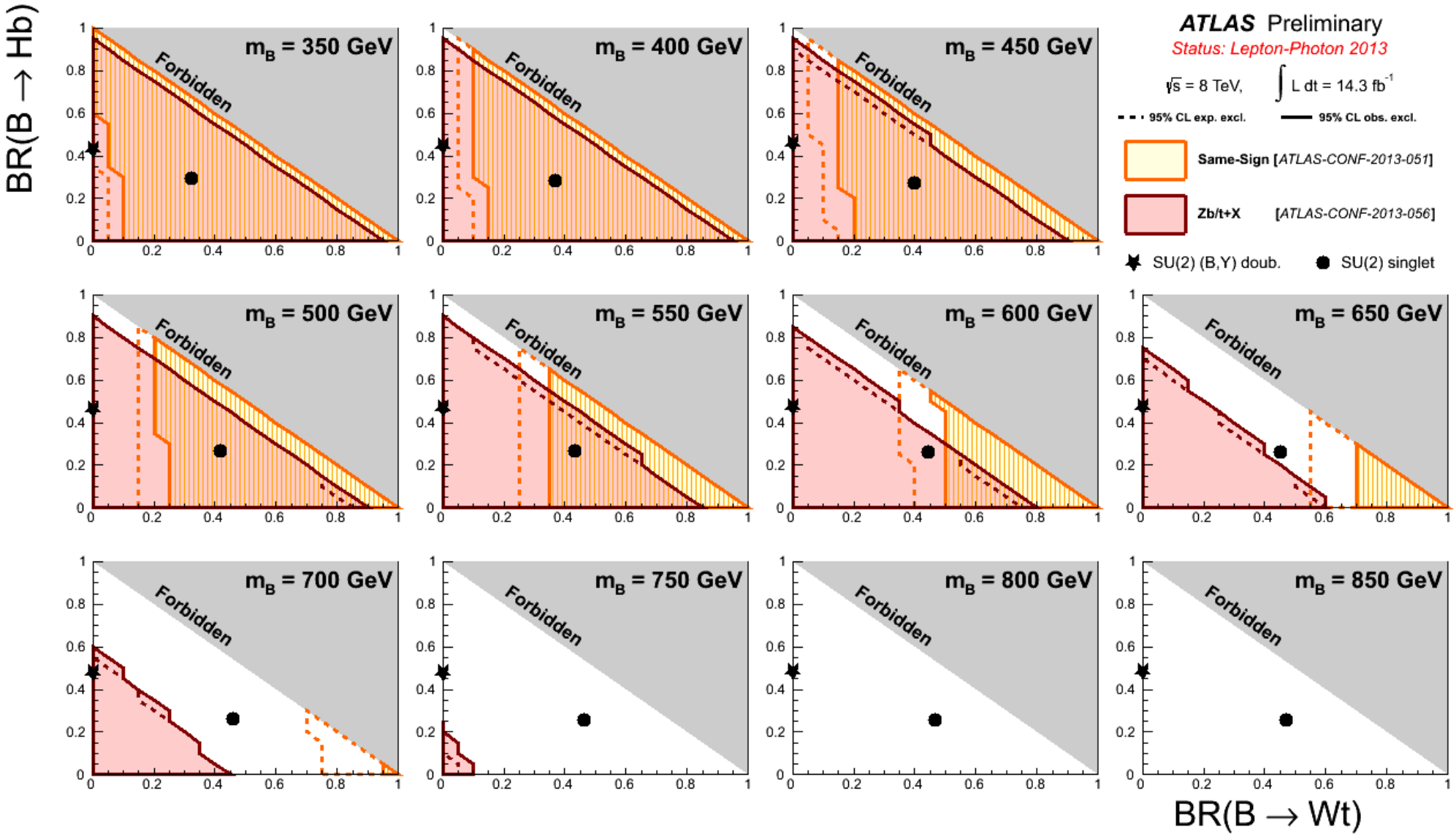
- $\sigma(t\bar{t}t\bar{t}) < 59$ fb (four top contact interaction)

- Same-Sign tt Cross Section:
  - 19,20,21 fb for left-left, left-right, or right-right chiralities

Vector-Like T Summary



Vector-Like B Summary

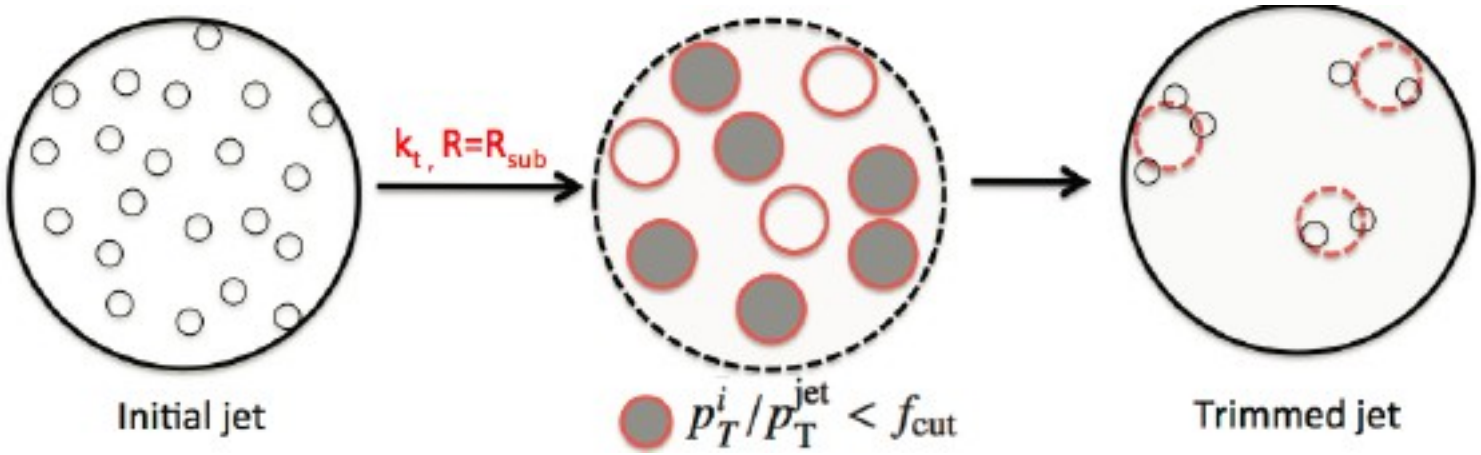


Conclusions

- Several searches for physics beyond the standard model have been presented
- Results are consistent with expectations based on the Standard Model
- Competitive limits set on numerous final states displaying similar phenomenology:
  - Vector-like heavy quarks (singlets and doublets)
  - Chiral heavy quarks
  - $t\bar{t}$ resonances
    - Z', Kaluza-Klein gluon, sgluon
  - Four top contact interactions
- We look forward to continuing to improve our sensitivity in the future!

Backup Slides

Jet Trimming



- Use a k_t algorithm with radius R_{sub} to re-cluster jet constituents
- Remove any subjets with small p_T fraction

$$p_T^i \,/\, p_T^{jet} < f_{cut}$$

- Semileptonic $t\bar{t}$ resonance search uses Anti-k_t R=1.0 jets, trimmed with f_{cut}=0.05, R_{sub}=0.3

k_t Splitting Scale

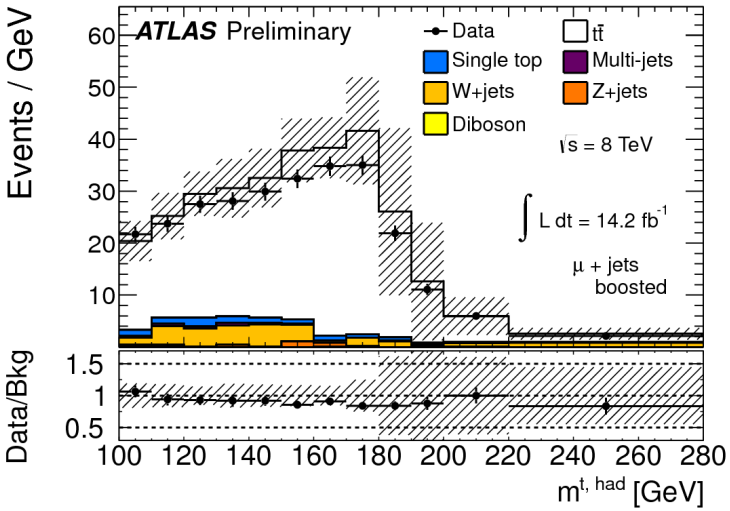
- Distance between last two remaining subjets after reclustering a jet with a k_t algorithm

$$Split12 = \min(p_{T1}, p_{T2}) \times \Delta R_{12}$$

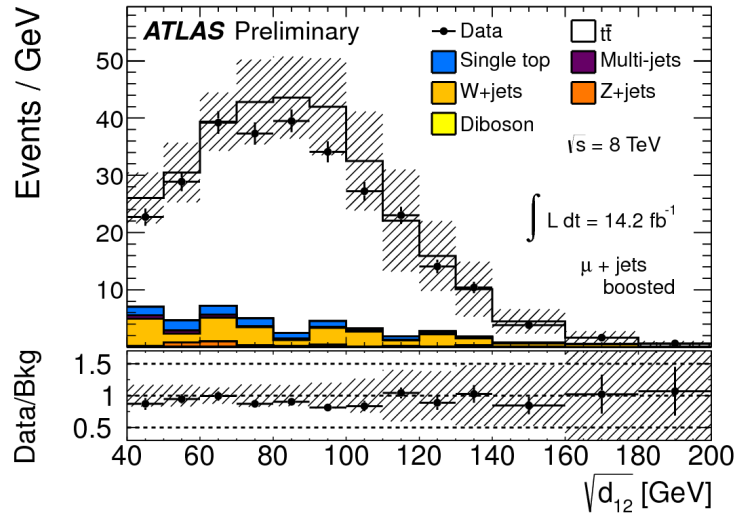
- Under the k_t algorithm, the hardest subjets tend to be merged last

- For a jet with substructure, we expect Split12~$m_{jet}/2$
- Many backgrounds expected to produce a steeply falling spectrum

Semileptonic $t\bar{t}$ Resonance Search

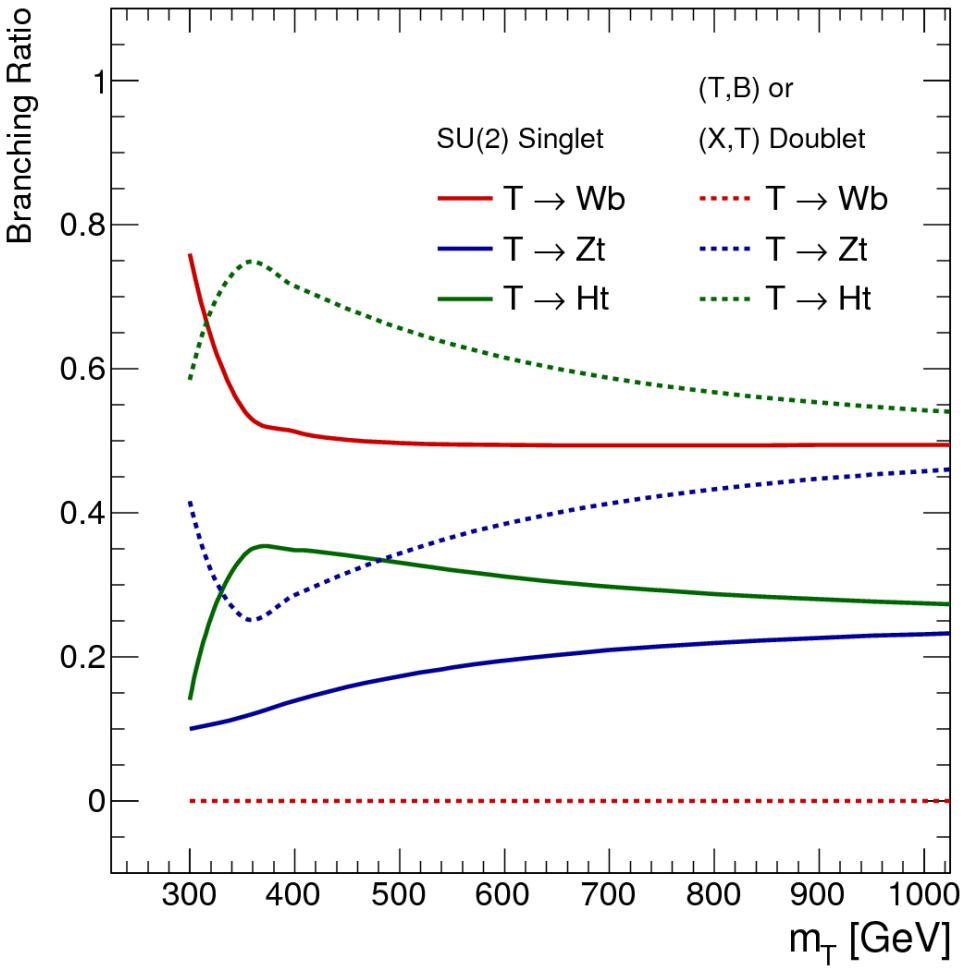


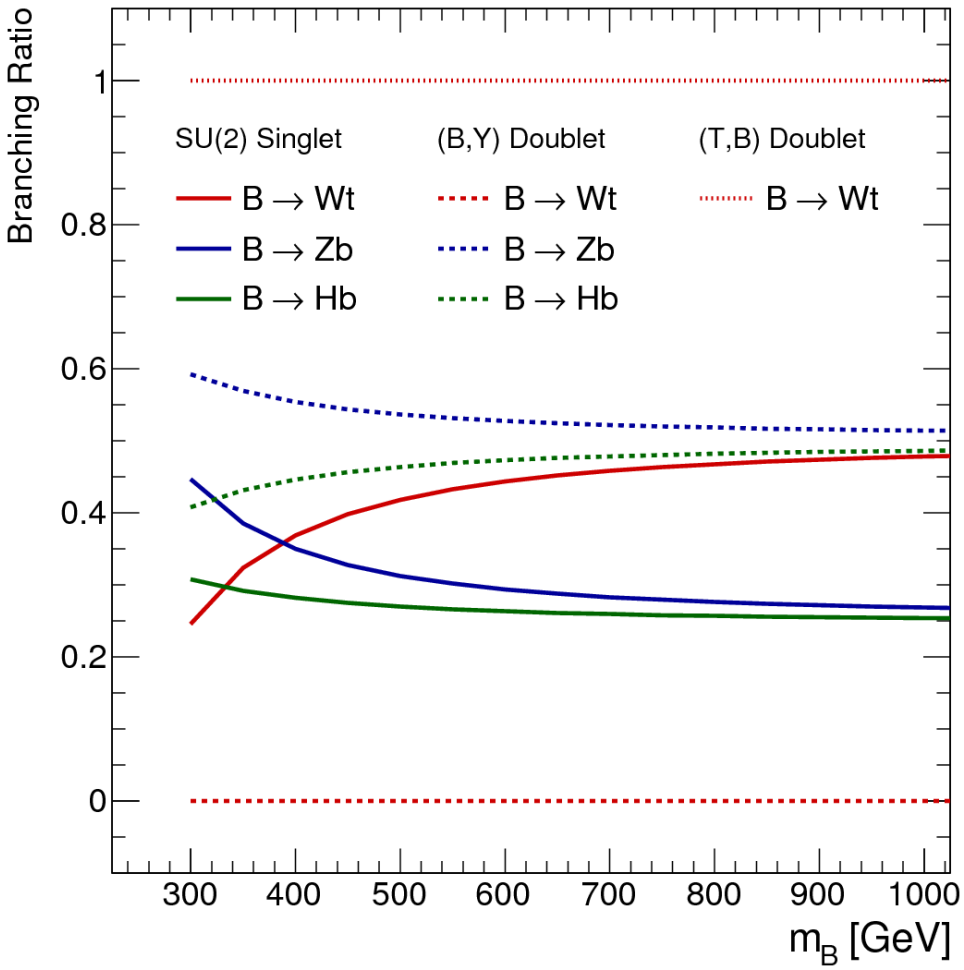
Mass of a hadronic boosted top jet candidate (muon channel)



Split12 of a hadronic boosted top jet candidate (muon channel)

Vector-Like Quarks – Branching Ratios





Branching Ratio's for VLQ at varying m_T