Search for pair production of new heavy quarks that decay to a Z boson and a third generation quark in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

The ATLAS Collaboration

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DPF 2013 Santa Cruz, Ca

Overview

See M.S.Cooke's talk

- Introduction and Motivation
- Strategy
- Signal and Control Regions
- Systematic Uncertainties
- Results and Conclusions

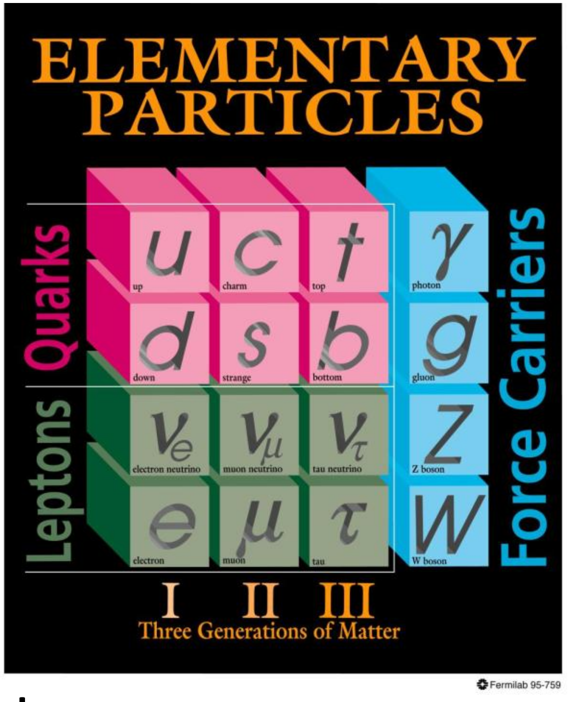
- Analysis uses 14.3 fb^{-1} of 2012 data at 8 TeV
- Use M_Q = 600 GeV as representative example
  - Analysis covers 350 GeV ≤ M ≤ 850 GeV

Analysis Object Definitions

- Light leptons (electrons and muons)
  - pT ≥ 25 GeV
  - Isolation: ΔR ≥ 0.4 to any jet
  - Electrons have |η| < 2.47 and exclude crack (1.37 < |η| < 1.52)
  - Muons have |η| < 2.5
- Jets
  - Anti-Kt algorithm with Radius Parameter D=0.4
  - pT ≥ 25 GeV
  - |η| < 2.5
  - Overlap removal against electrons using ΔR = 0.2
- B-tagging
  - Using a multivariate tagger based on track impact parameter and displaced secondary vertices (MV1)
  - MV1 weight at 70% operating point (MV170)
- u, d, c, s, b denote Standard Model (SM) quarks
- T, B denote new t-like, b-like quarks, respectively

Standard Selection Criteria

Introduction



- Standard Model (SM) contains 3 generations of leptons and quarks
- Fermions are chiral
  - Left-handed fermions transform as doublets under EW gauge group $(u,d)_L$
  - Right-handed fermions transform as singlets u_R d_R
- Many beyond-SM models include new breed of quarks (fermions) where both left- and right-handed components transform in the same manner
  - Vector-like

See M.S.Cooke's talk

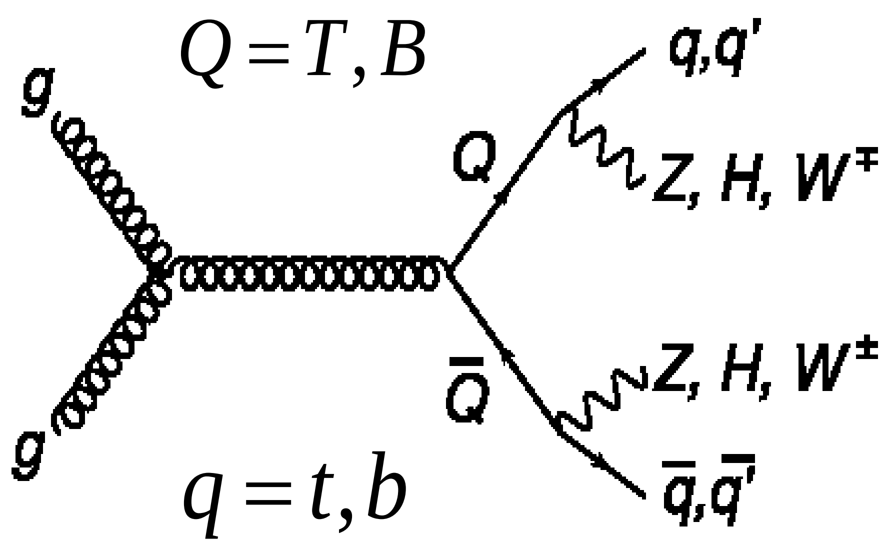
Flavor Changing Neutral Currents?

- Strong constraints on FCNC for chiral fermions
  - 2 and 3 generations → GIM-suppression
  - 4^{th} generation somewhat less stringent
- Chiral fermion FCNC constraints not applicable to vector-like fermions
  - F. del Aguila, M. Perez-Victoria and J. Santiago, Observable contributions of new exotic quarks to quark mixing, JHEP 09 (2000) 011, arXiv:hep-ph/0007316
  - J.A. Aguilar-Saavedra, R. Benrik, S. Heinemeyer, M. Perez-Victoria, A handbook of vector-like quarks: mixing and single production, arXiv:1306.0572

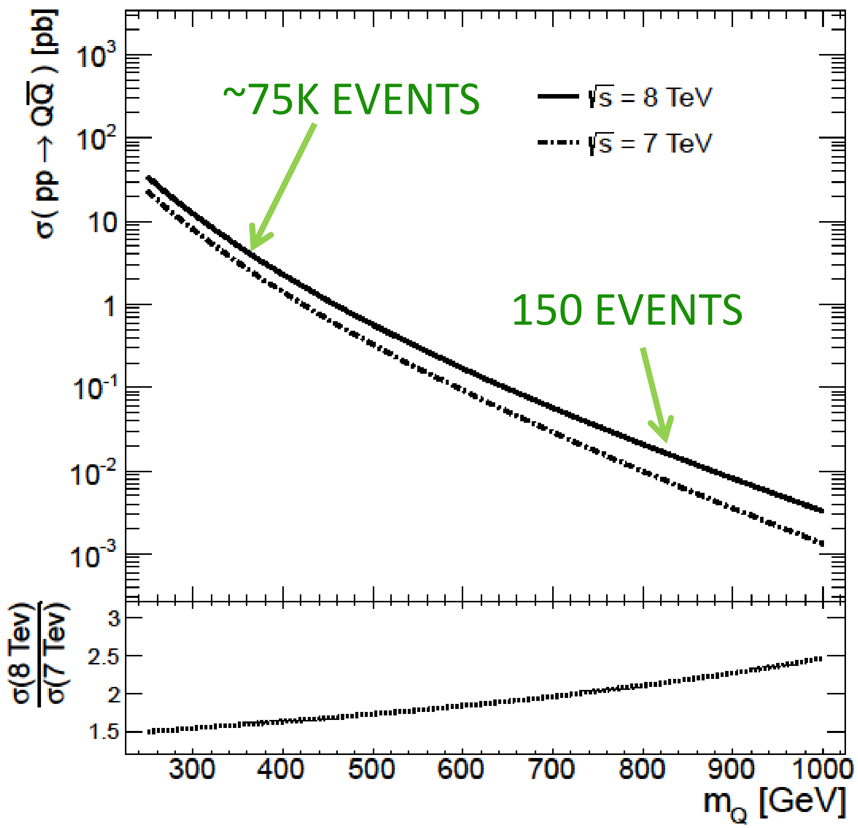
OUR SEARCH FOCUSES ON DECAYS VIA THE Z^0 BOSON

New Heavy Vector-Like Quark (VLQ) Production

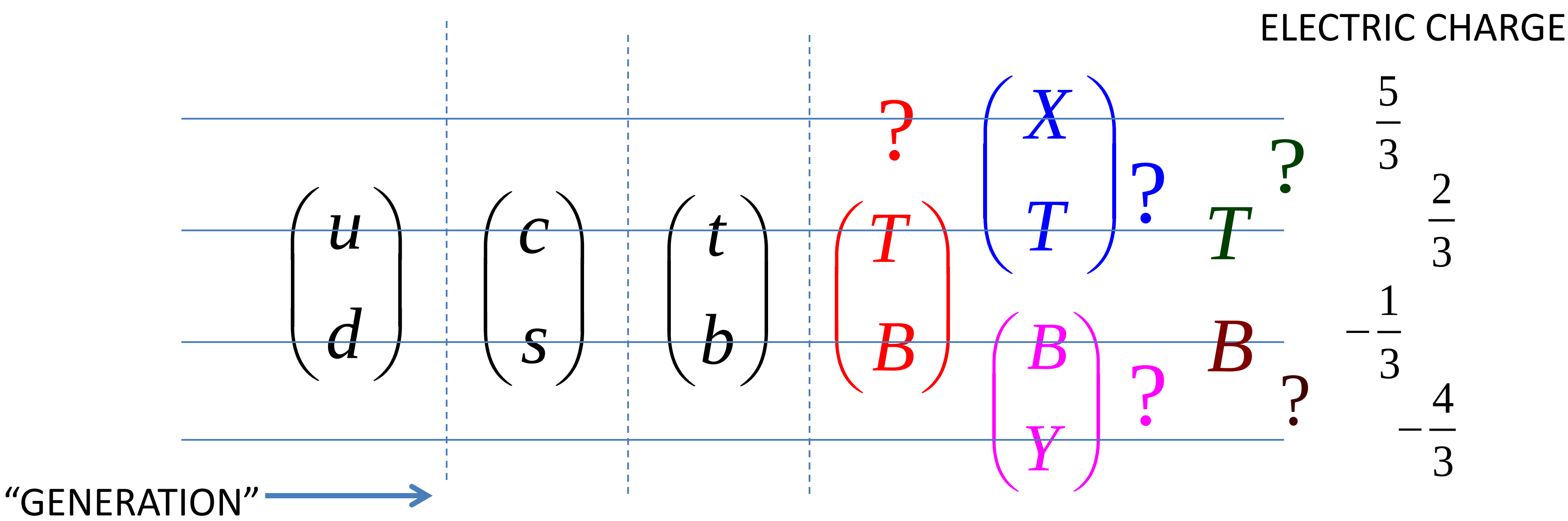
FOR MASS ≤ 1 TeV PREDOMINANTLY PAIR PRODUCED



PRODUCTION CROSS SECTION



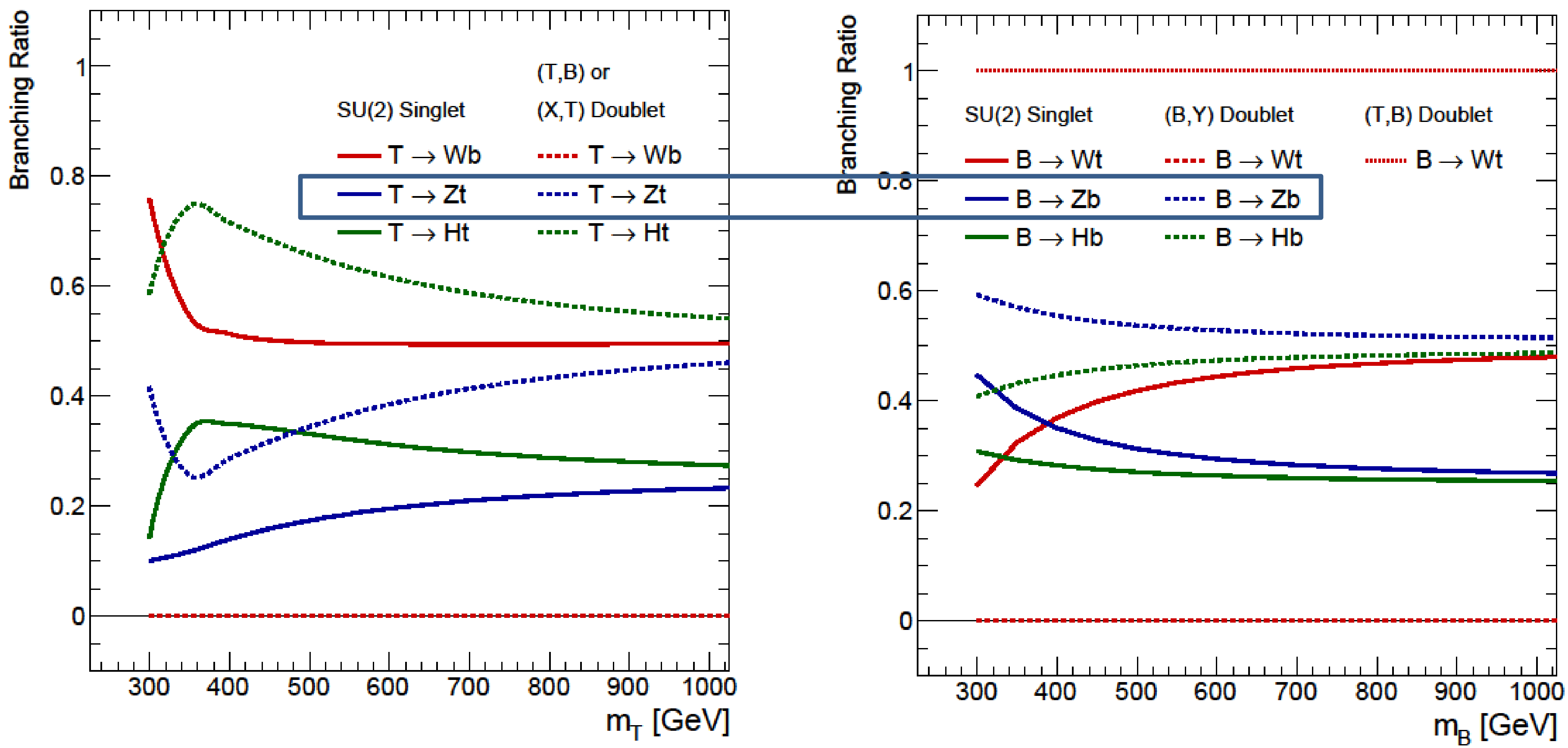
Vector-Like Quarks
What Would They Look Like?



- (T, B) form a weak-isospin doublet?
- (X,T) and/or (B,Y) for weak-isospin doublet?
- T and/or B singlets?

SEARCH STRATEGY IS THE SAME FOR ALL SCENARIOS
WHERE NEUTRAL CURRENT DECAYS ARE POSSIBLE

Heavy VLQ Decays
Branching Ratios

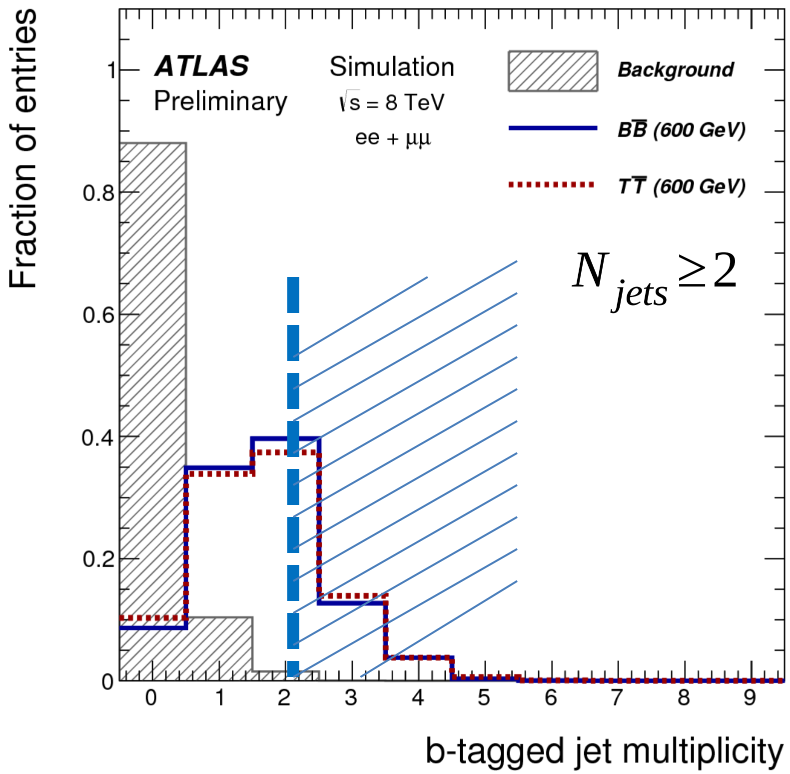


- Reasonable neutral current branching ratios
  - Better for B than for T

Heavy Vector-Like Quark Signature "Broad Strokes" Picture - Strategy

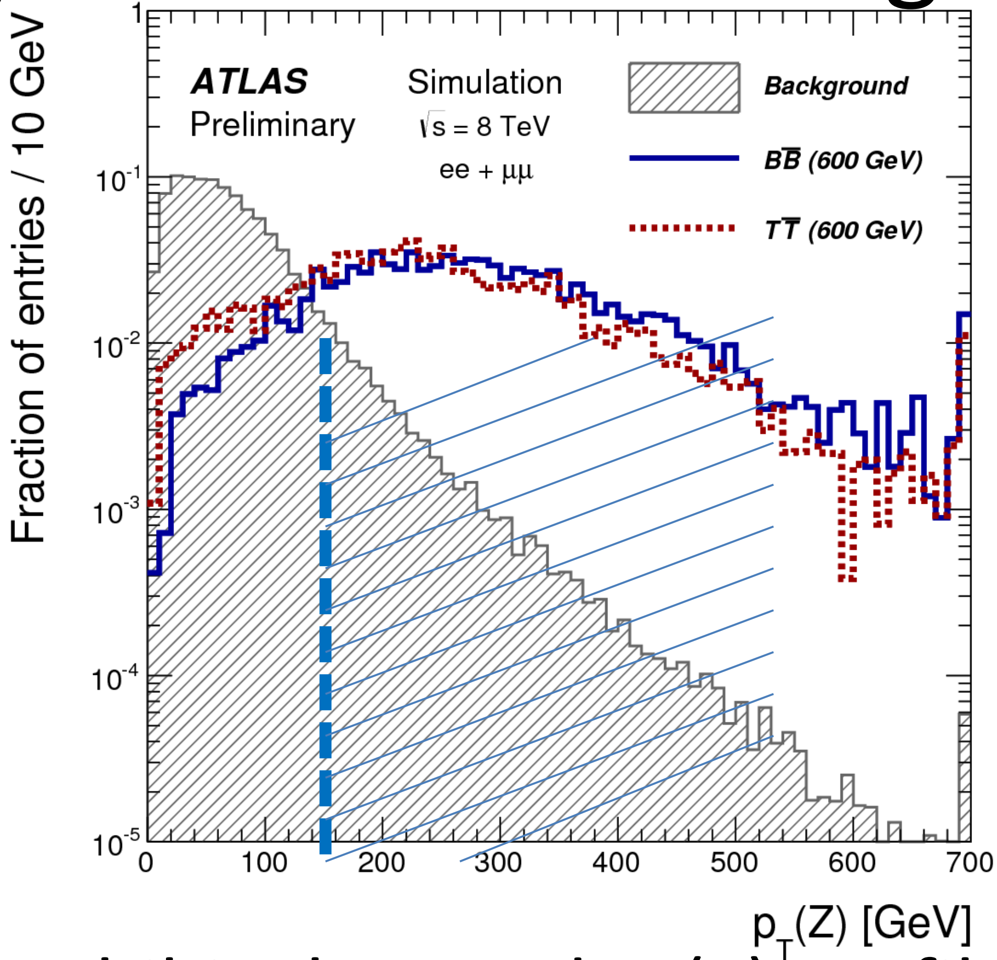
- On-shell, high P_T (boosted) leptonic Z
  - $76\text{ GeV} \leq M_Z \leq 106\text{ GeV}$
  - $pT(Z) \geq 150\text{ GeV}$
- Select events with ≥2 jets
- Two SM b-quarks →b-jets
- Large additional energy – $H_T = \Sigma_{jet} p_T$
- Quark mass gives structure to invariant mass of decay products - M(Zb)

N_{tag} as Discriminating Variable



- Events with Z + ≥2 jets
- Signal rich in b-jets
- Background relatively poor

$p_T(Z)$ as a Discriminating Variable



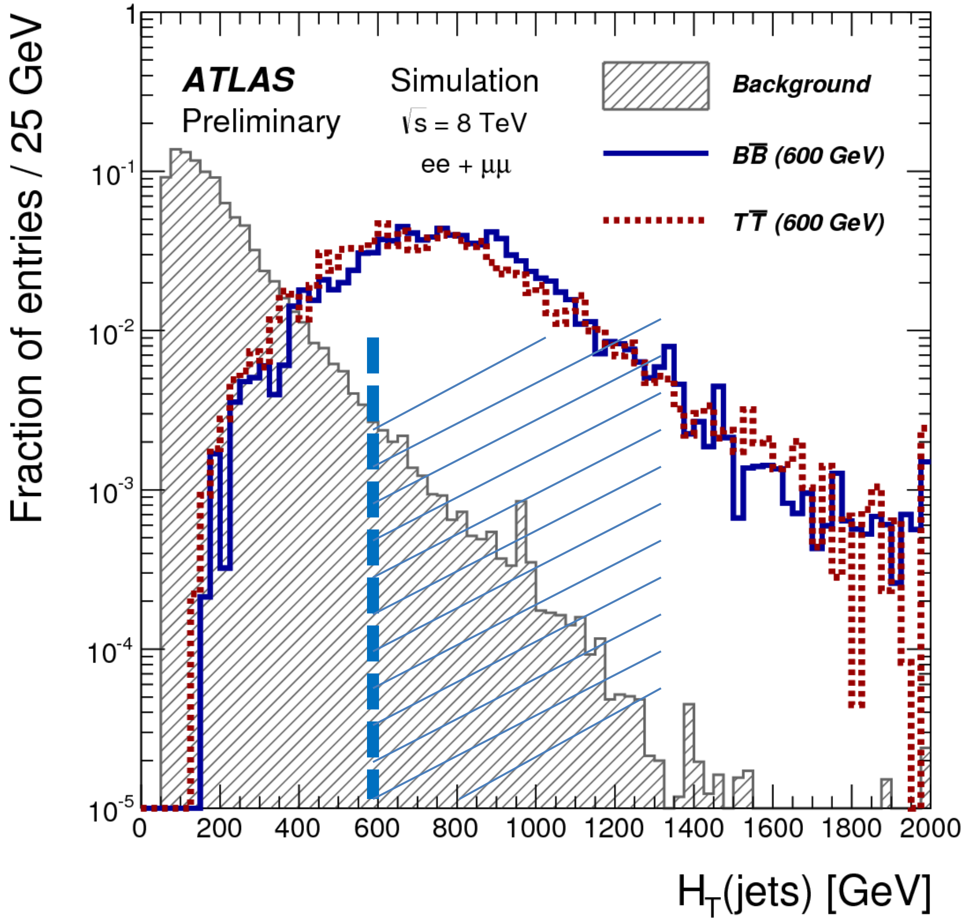
$N_{tag} \geq 2$

$p_T(Z) \geq 150 GeV$

- Signal exhibits boosted $p_T(Z)$ profile
- Background much softer

H_T as a Discriminating Variable

$$H_T = \sum_{jets} p_T^{jet}$$



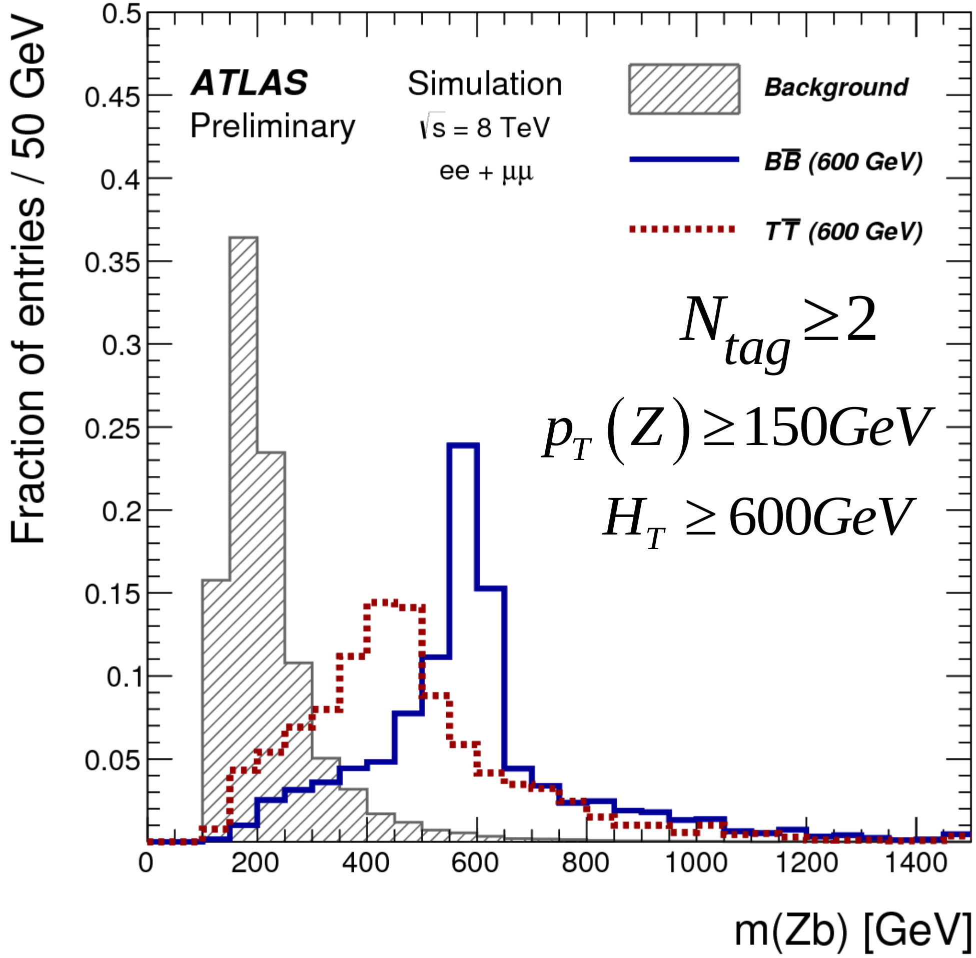
$$N_{tag} \geq 2$$

$$p_T(Z) \geq 150 GeV$$

$$H_T \geq 600 GeV$$

- Signal exhibits enhanced structure at large H_T

Invariant Mass of Zb System



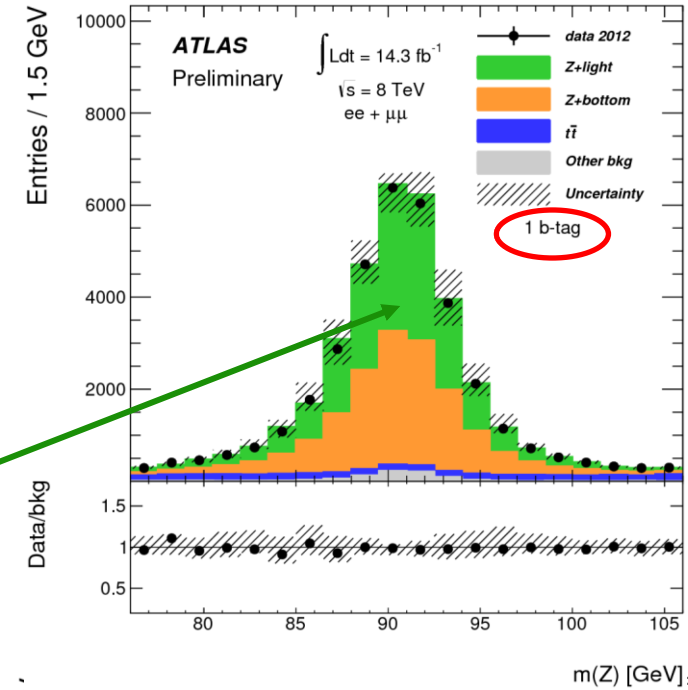
- Signal exhibits structure in invariant mass distribution
- Choose highest p_T b-jet as b-candidate
- Works for both T and B

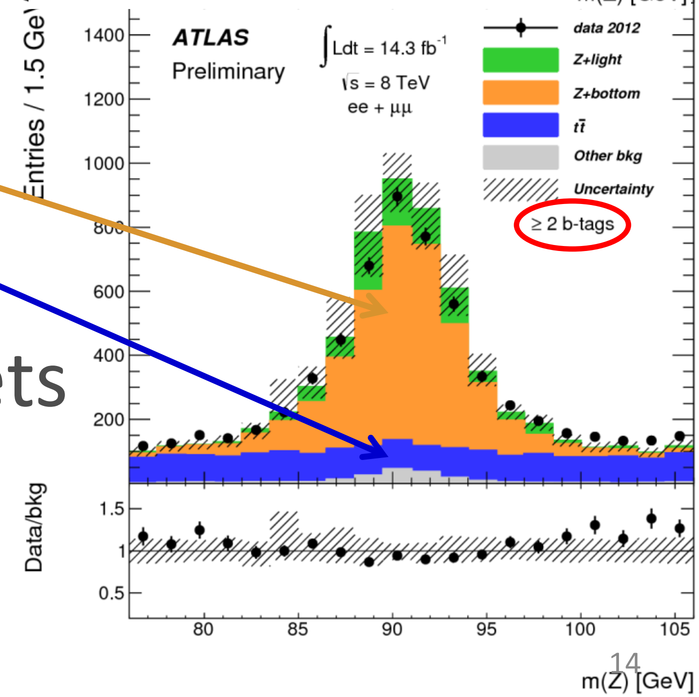
Backgrounds

- Z+jets – dominant
  - Z+light flavor (u,d,s)
  - Z+charm
  - Z+bottom
- top/anti-top quark + jets

OTHER BCK.

- VV+jets (V=W,Z)
- top/anti-top quark + V + jets
- W+jets





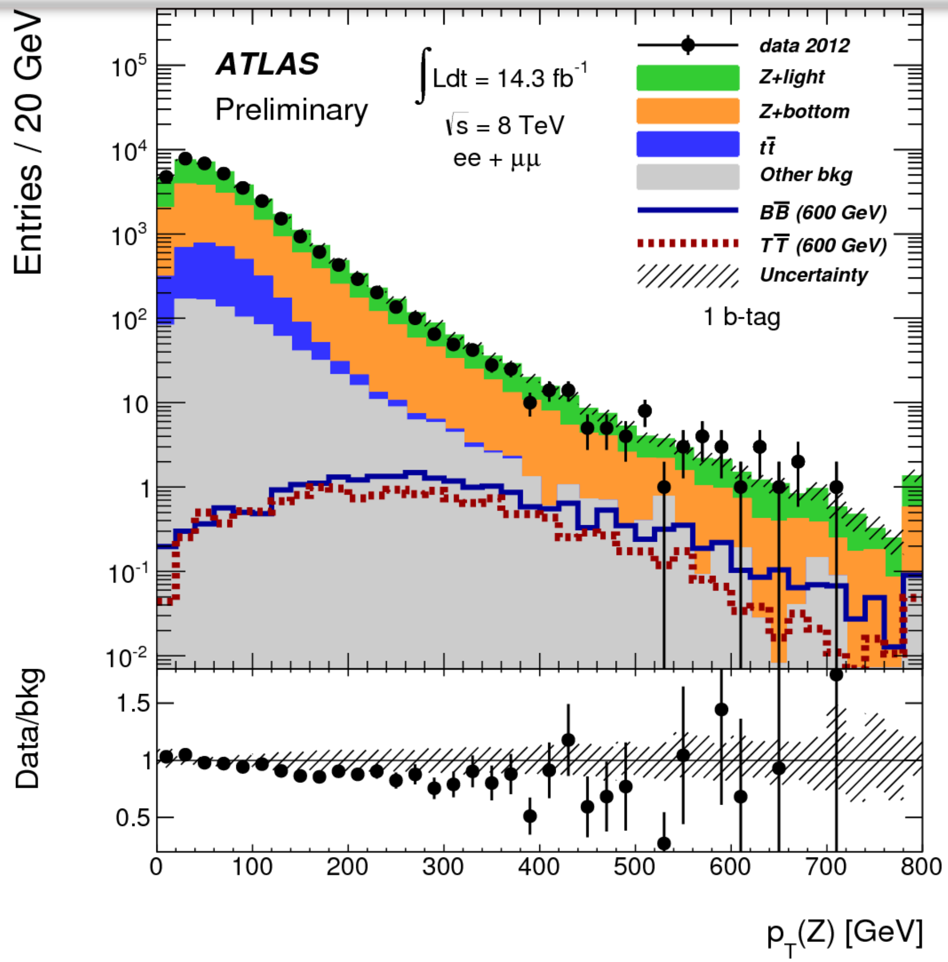
Background Details

- Z+jets modelled with Sherpa and AlpGen
  - Sherpa used for baseline analysis
  - Extensive comparisons of Sherpa and AlpGen
  - Sherpa uses CT10NLO Parton Distribution Function (PDF)
  - AlpGen uses CTEQ6L1 PDF

DOMINANT BACKGROUND

- Top/anti-top matrix element (ME) modelled by POWHEG
  - Parton Shower (PS) and Hadronization by Pythia
  - CT10NLO PDF
- Diboson ME modelled by AlpGen
  - PS and Hadronization by HERWIG
- Wt and s-channel single top ME production modelled by MC@NLO
  - PS and Hadronization by HERWIG
- t-channel single top ME modelled by ACER MC
  - PS and Hadronization by Pythia
- All backgrounds normalized to NLO cross sections

Monte Carlo Modelling of Background



SLOPE DIRECTLY IMPACTS BACKGROUND PREDICTION IN SIGNAL REGION

- Implement correction process to bring MC closer to data
- MC shapes and rates should agree w/data close to signal region
- Minimize signal contamination in the control region (defined next)

Control Regions/Monte Carlo Corrections

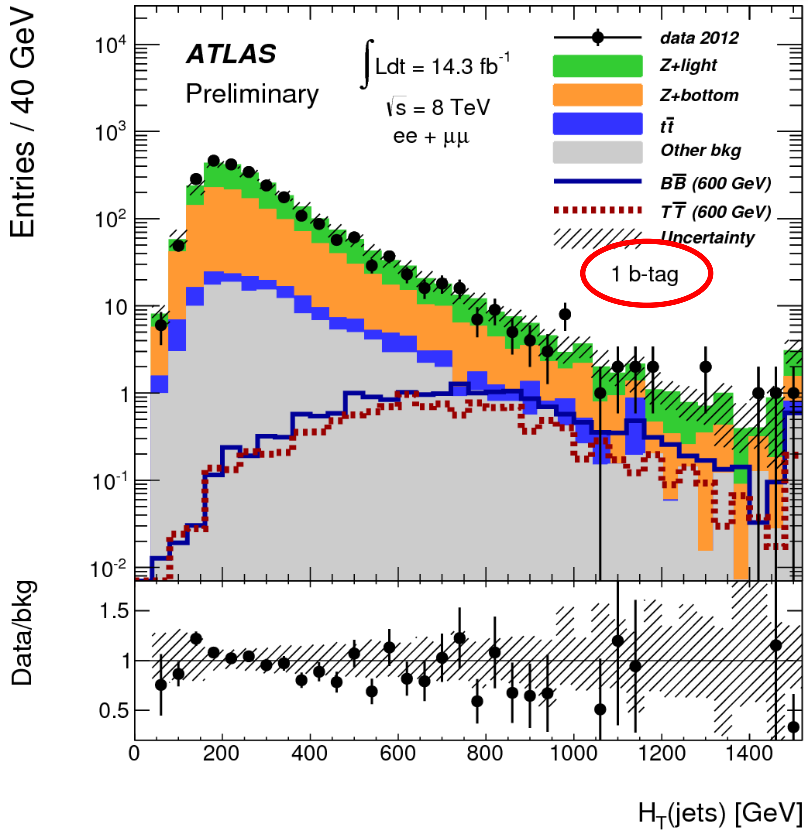
- Reminder: events selected with Z + ≥2 jets
- Z+jets sample binned into N_{tag}=0, 1 or ≥2
- Z+jets normalized so that total background prediction for $p_T(Z) \leq 100$ GeV agrees with data in each N_{tag} bin

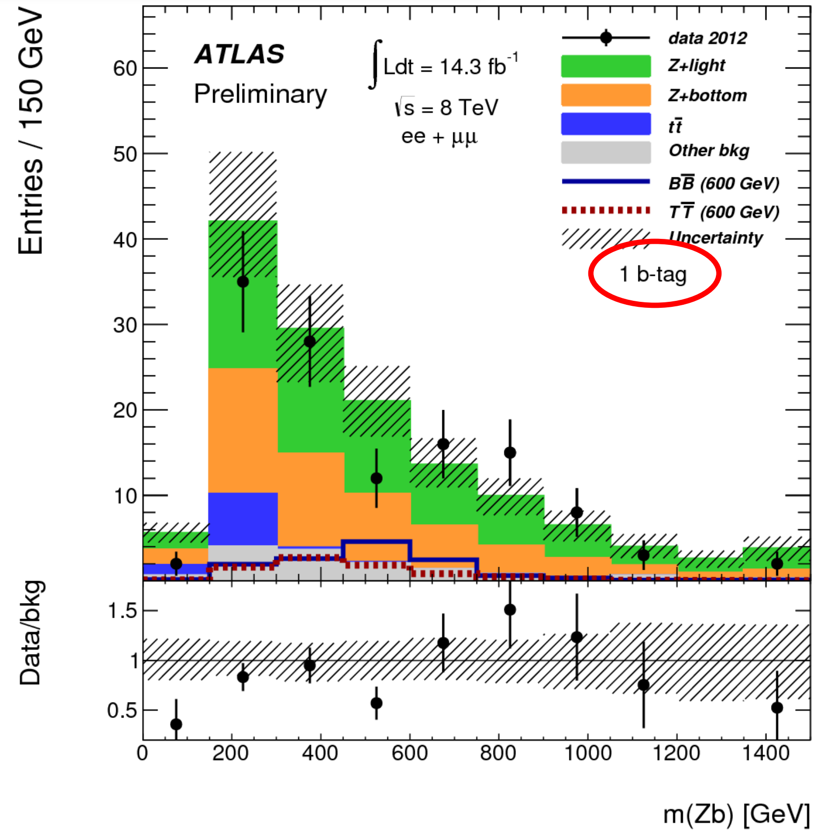
CONTROL REGIONS

- Significant residual slope in $p_T(Z)$ distribution observed (previous slide)
  - Similar slope in each N_{tag} bin
  - Derive new reweight function $F(p_T)$ in N_{tag}=1 bin
  - Apply $F(p_T)$ to N_{tag}≥2 bin
- Results of reweights shown next

CORRECTIONS

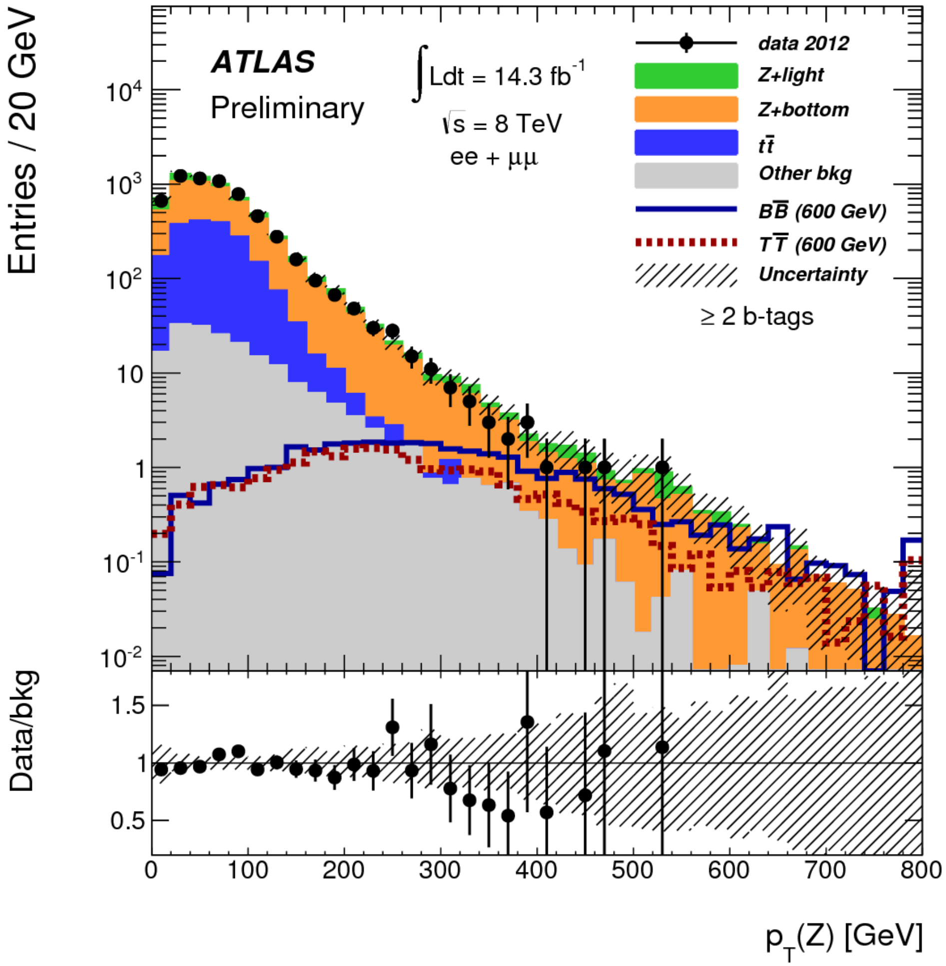
Control Regions

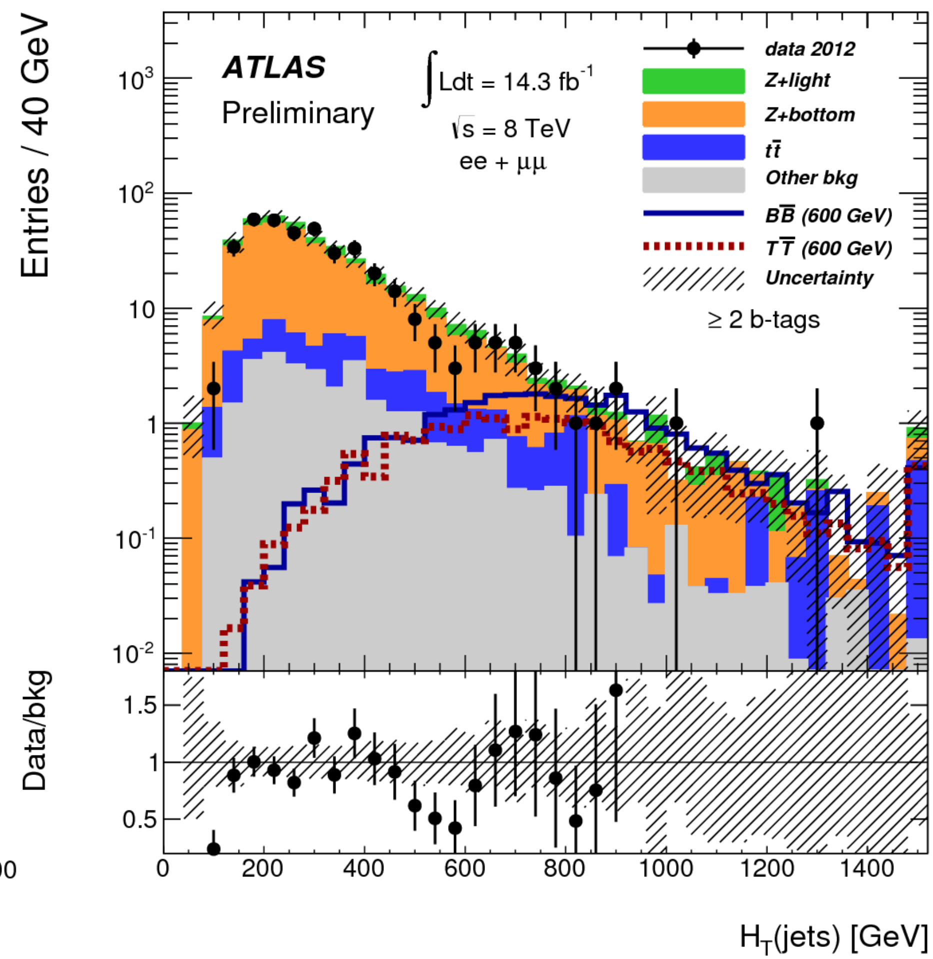




- N_{tag}=0, 1
- $p_T(Z) < 100$ GeV
- LHS is H_T after $p_T(Z)$ correction
- RHS is M(Zb) after $p_T(Z)$ correction

Final Signal Region Distributions

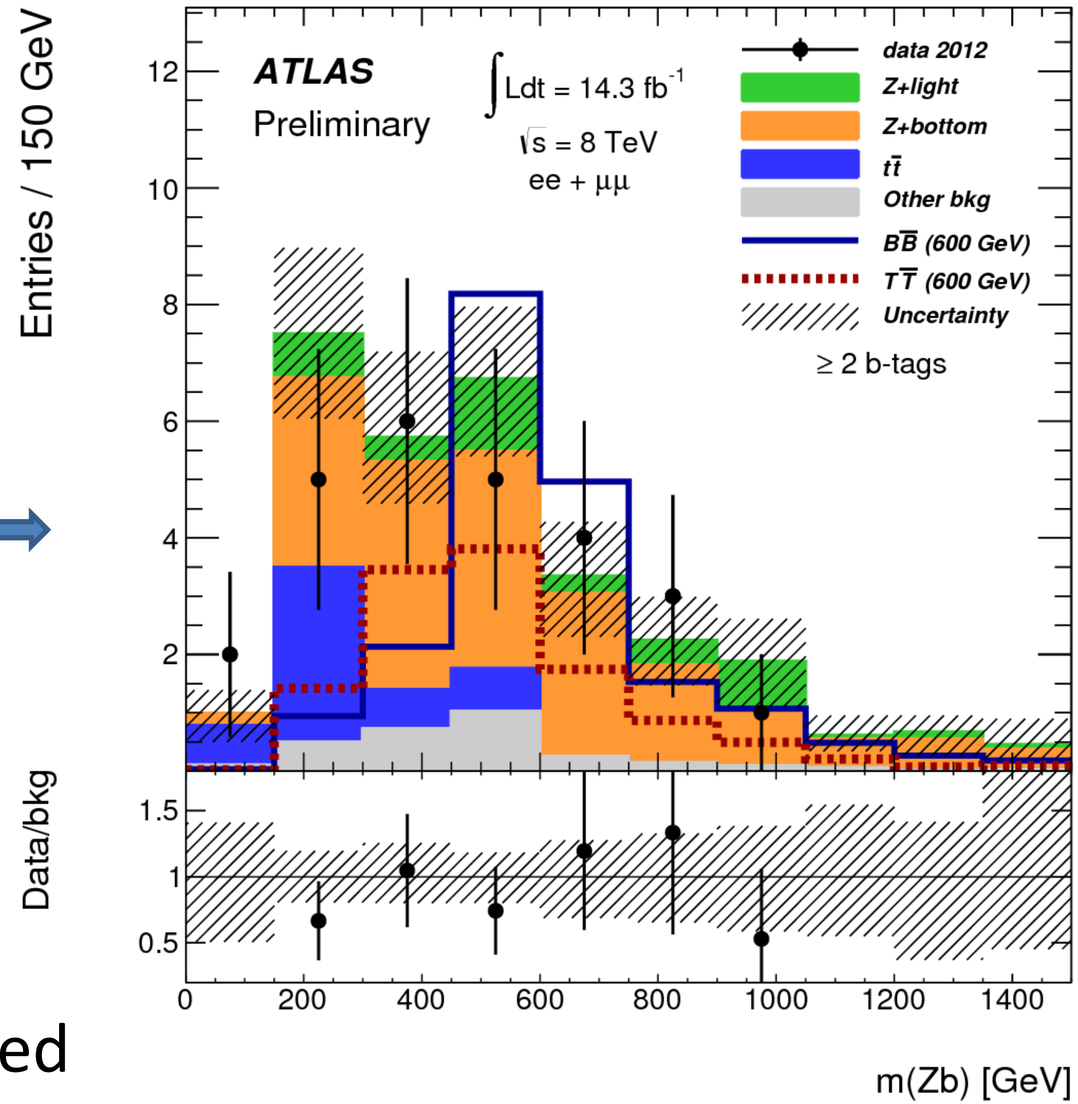




- All corrections applied

Final M(Zb) Distribution

- ≥2 b-tagged jets
- $p_T(Z) \geq 150$ GeV
- $H_T \geq 600$ GeV



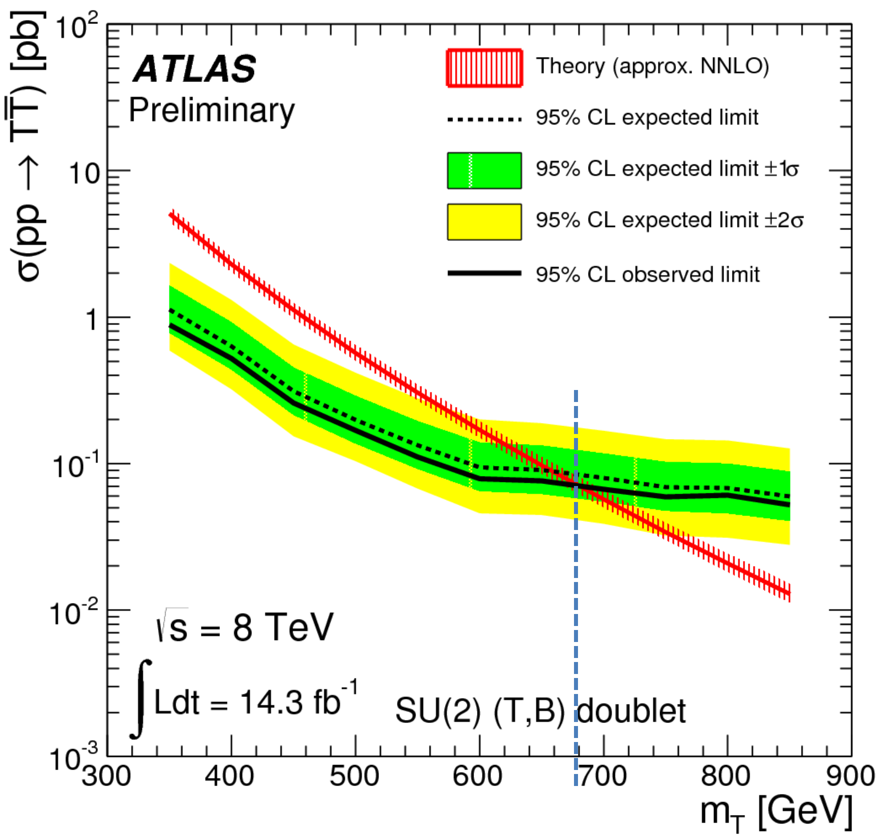
- All corrections applied
- Observed distribution consistent with SM prediction

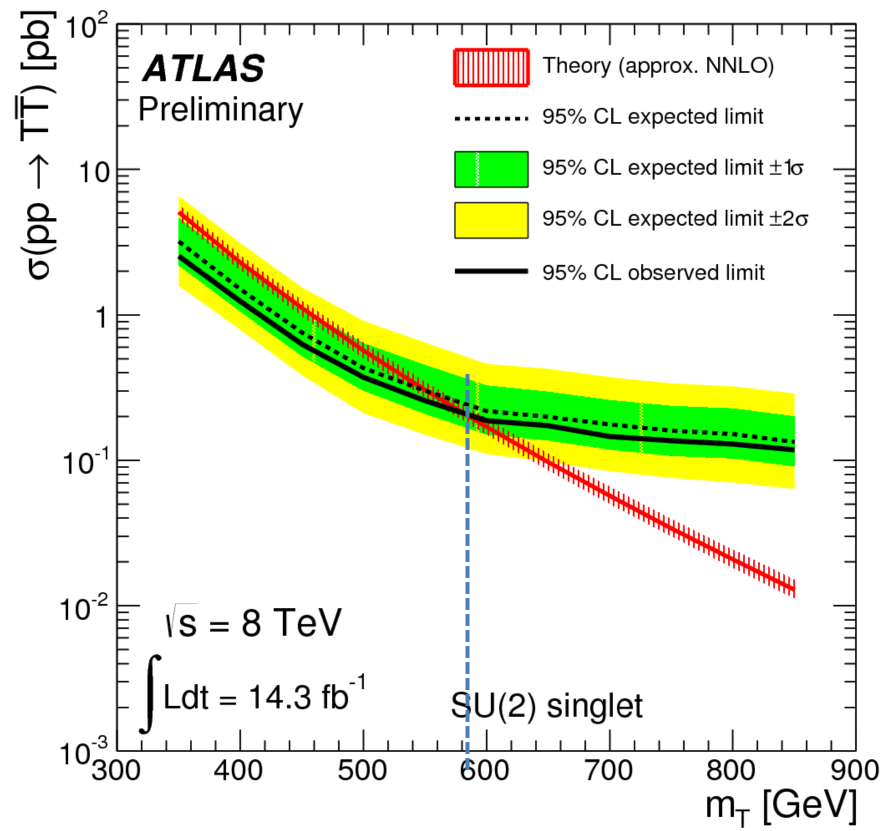
Systematic Uncertainties in the M(Zb) Normalization

	Z+ jets	$t\bar{t}$	Other bkg.	$B\bar{B}$ (600 GeV)	$T\bar{T}$ (600 GeV)
Luminosity	1.7	3.6	3.6	3.6	3.6
Cross section	7.0	11	28	-	-
Jet Reco.	12	14	15	4.8	5.8
b-tagging	7.1	13	13	11	10
e Reco.	1.8	6.8	3.0	3.9	3.8
μ Reco.	1.8	2.3	4.9	4	4.2
Z+ jets rate corr.	9.1	–	–	–	–
Z+ jets $p_T(Z)$ corr.	19	–	–	–	–

- Relative uncertainties in %
- Z+jets rate correction uses $p_T(Z) \leq 100$ GeV in N_{tag}=1 bin
  - Uncertainty assessed by comparing use of $50 \leq p_T(Z) \leq 150$ GeV instead
- Z+jets $p_T(Z)$ correction uses reweighting, derived in the N_{tag}=1 bin, applied to N_{tag}=2 bin
  - Uncertainty assessed by comparing use of N_{tag}=0 bin instead
  - Large statistical component

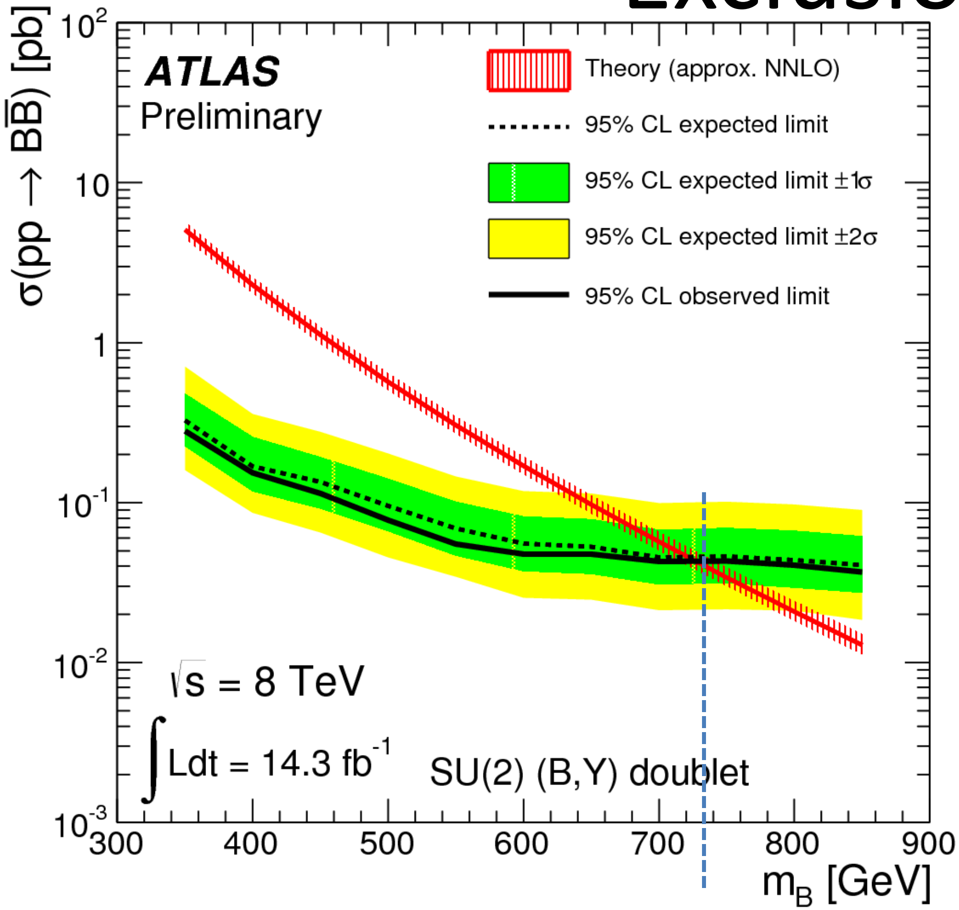
Results for T
Exclusion Limits

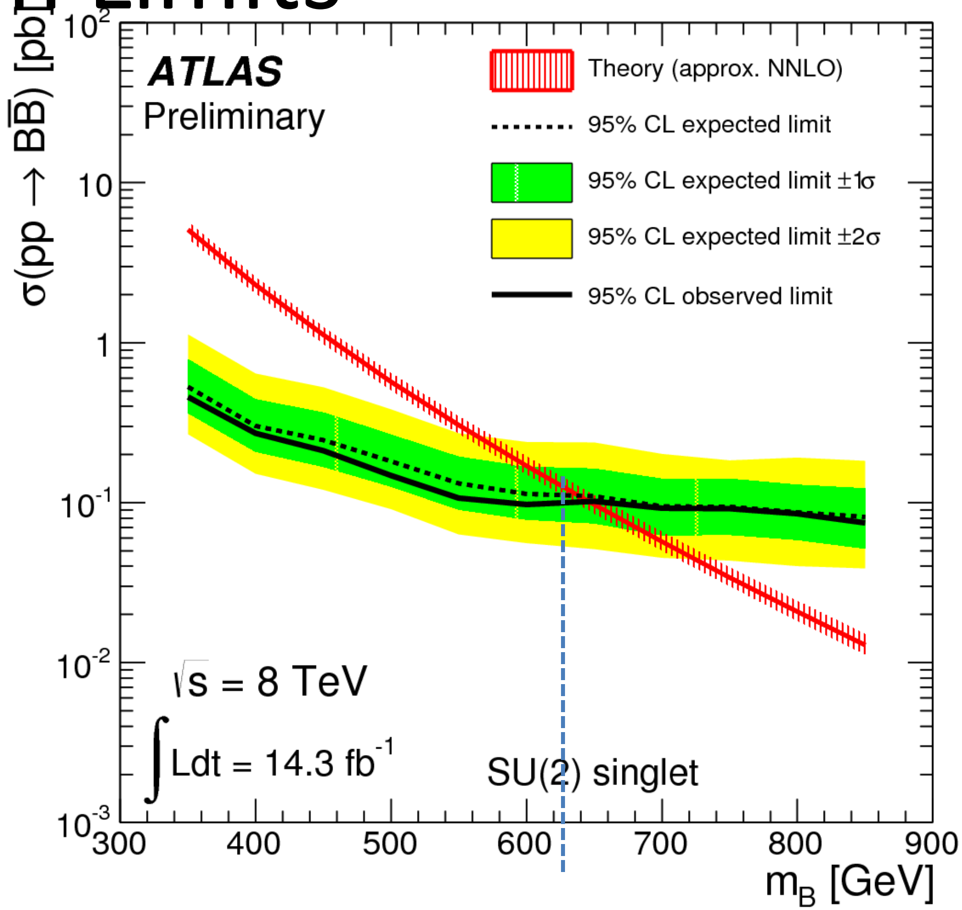




- (T,B) doublet scenario – M(T) ≤ 680 GeV excluded at 95% CL
- T singlet scenario – M(T) ≤ 585 GeV excluded at 95% CL

Results for B Exclusion Limits



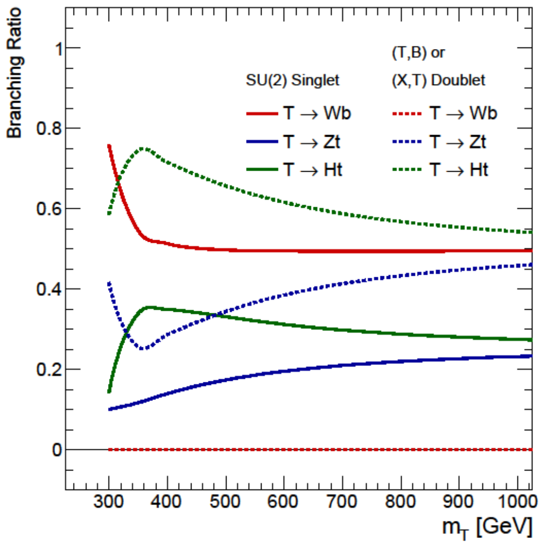


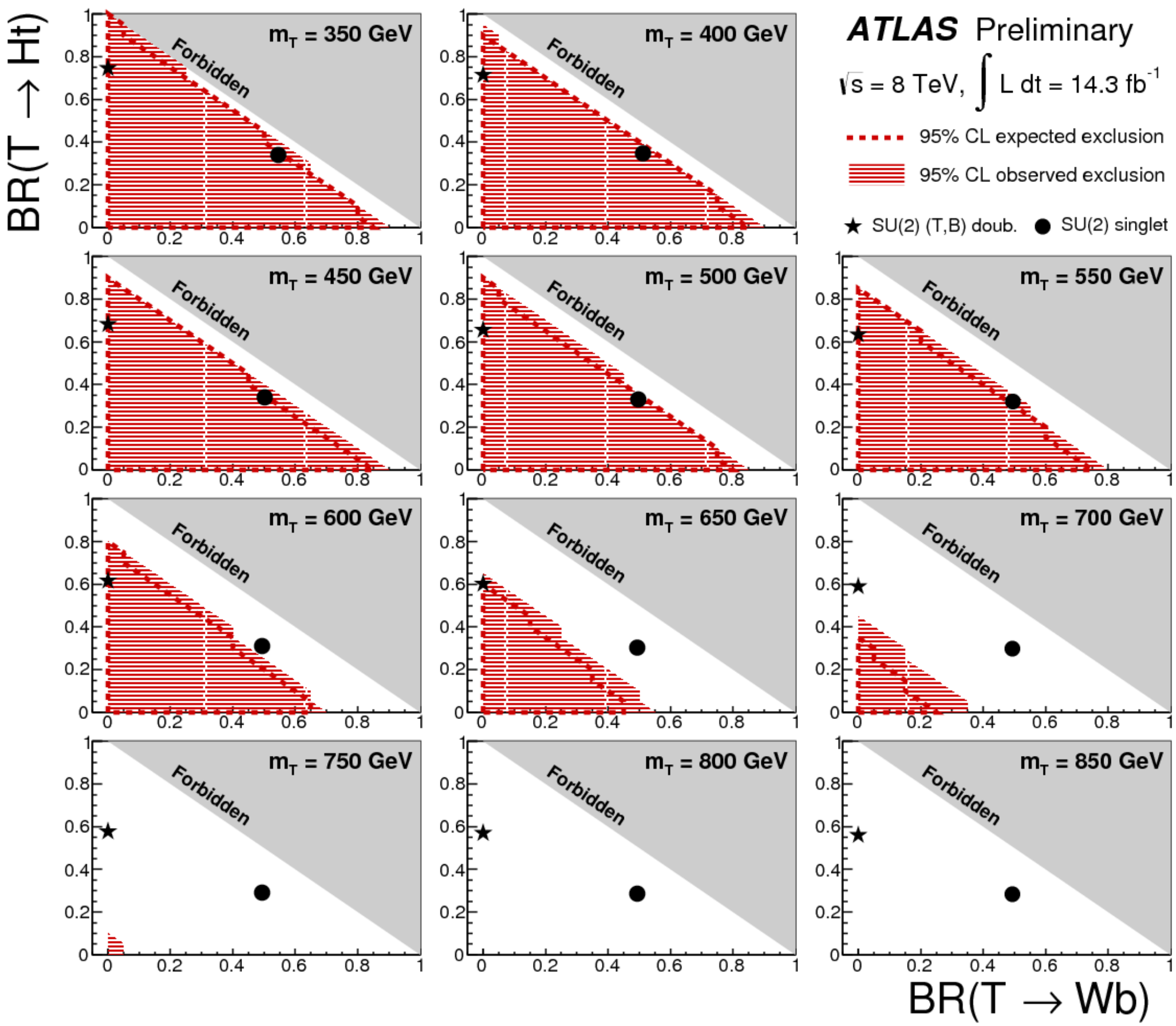
- (B,Y) doublet scenario M(B) ≤ 725 GeV excluded at 95% CL
- B singlet scenario M(B) ≤ 645 GeV excluded at 95% CL

Conclusions

- The search for Vector-Like Quarks did not produce a significant deviation from the predicted SM background in the M(Zb) distribution
- Cross section exclusion plots derived
  - Expected exclusion consistent with observed exclusion
- Branching ratio exclusion plots derived
- Assuming a T(B) singlet model, a new vector-like quark is excluded for with $M_Q \leq 585$ GeV(645 GeV)
- Assuming a (T, B) doublet model, a new vector-like quark is excluded with $M_Q \leq 680$ GeV(725 GeV)

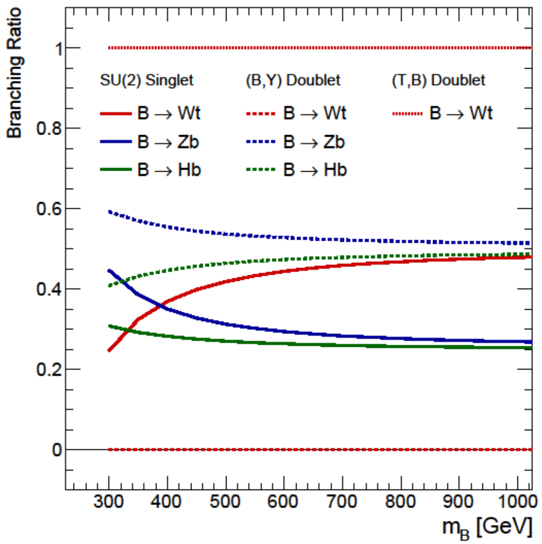
2D Exclusion Limits for Branching Ratios

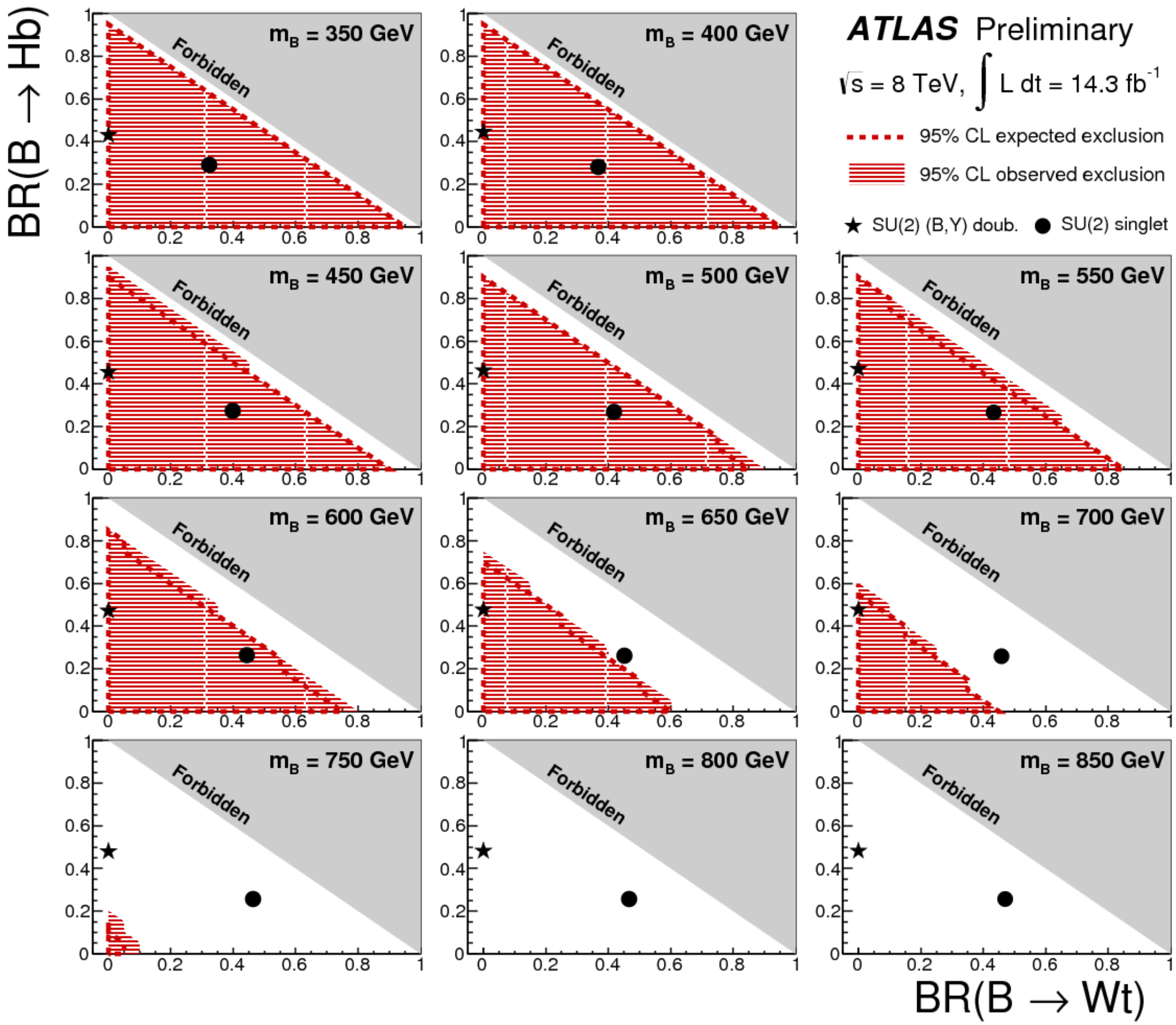




- Assumes BR(T→Ht)+BR(T→Wb)+BR(T→Zt)=1

2D Exclusion Limits for Branching Ratios





- Assumes BR(B→Hb)+BR(B→Wt)+BR(B→Zb)=1

Backup Slides

Some Previous Searches for New Heavy Quarks

- $T \rightarrow Wb$
  - ATLAS Collaboration
    - Phys.Lett. B 718 (2013) 1284 arXiv:12105468
  - ATLAS update https://cds.cern.ch/record/1553199

- $T \rightarrow Zt$
  - CMS Collaboration
    - Phys.Rev.Lett. 107 (2011)271802 arXiv:1109.4985

- $T \rightarrow Ht$
  - ATLAS-CONF-2013-018

- $T \rightarrow Zb$
  - ATLAS Collaboration
    - Phys.Rev.Lett. 109 (2012) 071801 arXiv:1204.1265

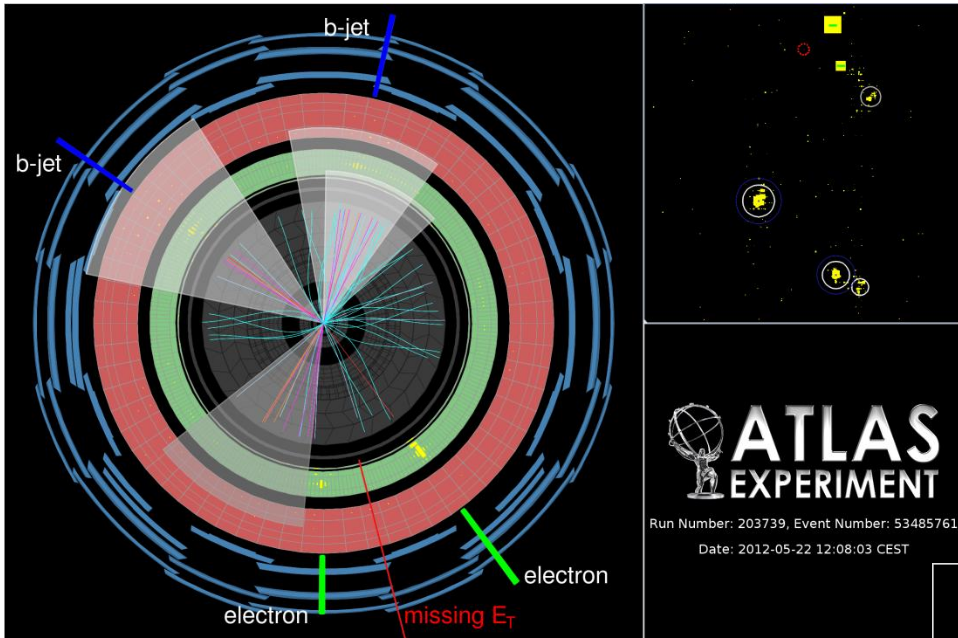
- $T \rightarrow Wb/tH/tZ$
  - CMS Collaboration
  - http://cds.cern.ch/record/1557571

The Analysis

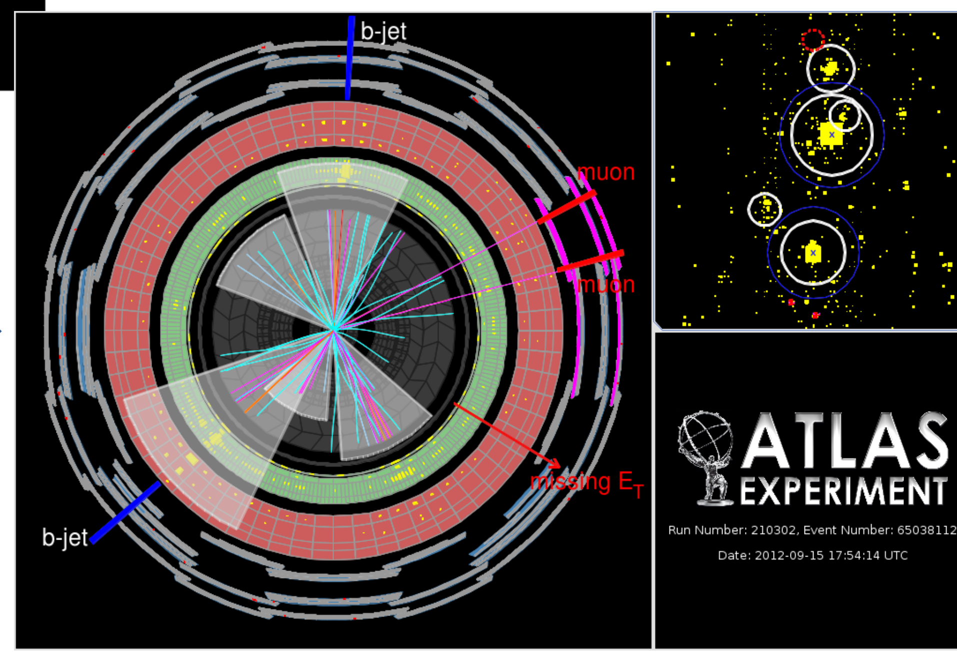
- Select events with Z and ≥2 jets
  - Z→ee (148K events)
  - Z→μμ (203K events)
  - 76 GeV ≤ M(Z →light leptons) ≤ 106 GeV
- Signal Region (SR) – details follow
  - Ntag ≥ 2
  - pT(Z) > 150 GeV
  - H_T > 600 GeV
- Discriminating variable is invariant mass of Z + hardest b-jet
  - M(Zb)
- Control Regions (CR)
  - Compare Monte Carlo (MC) modelling of background against data
  - pT(Z) < 100 GeV
  - Ntag = 0 or 1
- Normalization of Monte Carlo SM background to DATA
- CL_S exclusion using M(Zb) templates

WORKS FOR BOTH NEW TOP-LIKE AND BOTTOM-LIKE QUARKS!

Event Displays



pp→Zbb+jets→eebb+jets



pp→Zbb+jets→μμbb+jets

Event Yields Before/After Corrections

	$Z+\geq$ 2jets ($N_{tag}=1$)	$p_T(Z) > 150$ GeV	H_T(jets) > 600 GeV
Z+light (before p_T corr.)	$17,000 \pm 1,200$	$1,370 \pm 150$	78.3 ± 5.9
Z+light (after p_T corr.)	$16,700 \pm 1,500$	$1,170 \pm 190$	68.0 ± 15.3
Z+bottom (before p_T corr.)	$15,000 \pm 1,400$	$1,290 \pm 170$	56.3 ± 5.0
Z+bottom (after p_T corr.)	$14,700 \pm 1,400$	$1,110 \pm 180$	48.8 ± 11.1
$t\bar{t}$	$2,700 \pm 300$	61 ± 9	7.8 ± 2.1
Other SM	900 ± 300	135 ± 45	14.0 ± 5.2
Total SM (before p_T corr.)	$35,600 \pm 2,000$	$2,850 \pm 230$	156.4 ± 9.3
Total SM (after p_T corr.)	$35,000 \pm 2,000$	$2,470 \pm 265$	138.5 ± 19.6
Data	34,955	2,480	121
$B\bar{B}$ ($m_B = 600$ GeV)	22.5 ± 3.4	18.7 ± 2.9	13.0 ± 2.4
$T\bar{T}$ ($m_T = 600$ GeV)	15.2 ± 2.1	12.0 ± 1.6	8.0 ± 1.3

Event Yields After Selection

	$Z+\geq 2$jets ($N_{tag}\geq 2$)	$p_{\mathrm{T}}(Z)>150$ GeV	H_{T}(jets) >600 GeV
Z+light	850 ± 240	58 ± 17	4.3 ± 1.8
Z+bottom	3380 ± 470	301 ± 55	17.8 ± 4.8
$t\bar{t}$	1730 ± 320	31 ± 6	5.1 ± 1.4
Other SM	190 ± 60	29 ± 10	3.0 ± 1.2
Total SM	$6,150\pm 620$	419 ± 59	30.2 ± 5.3
Data	6,097	386	26
$B\bar{B}$ ($m_B=600$ GeV)	31.0 ± 4.3	25.7 ± 3.6	19.8 ± 2.7
$T\bar{T}$ ($m_T=600$ GeV)	21.9 ± 2.8	17.1 ± 2.2	12.2 ± 1.7