Searches for vector-like quarks in dilepton/multilepton final states in ATLAS

Duc Bao Ta – Michigan State University

Vector-like quark workshop Hamburg 2014

reminder from Clement's talk

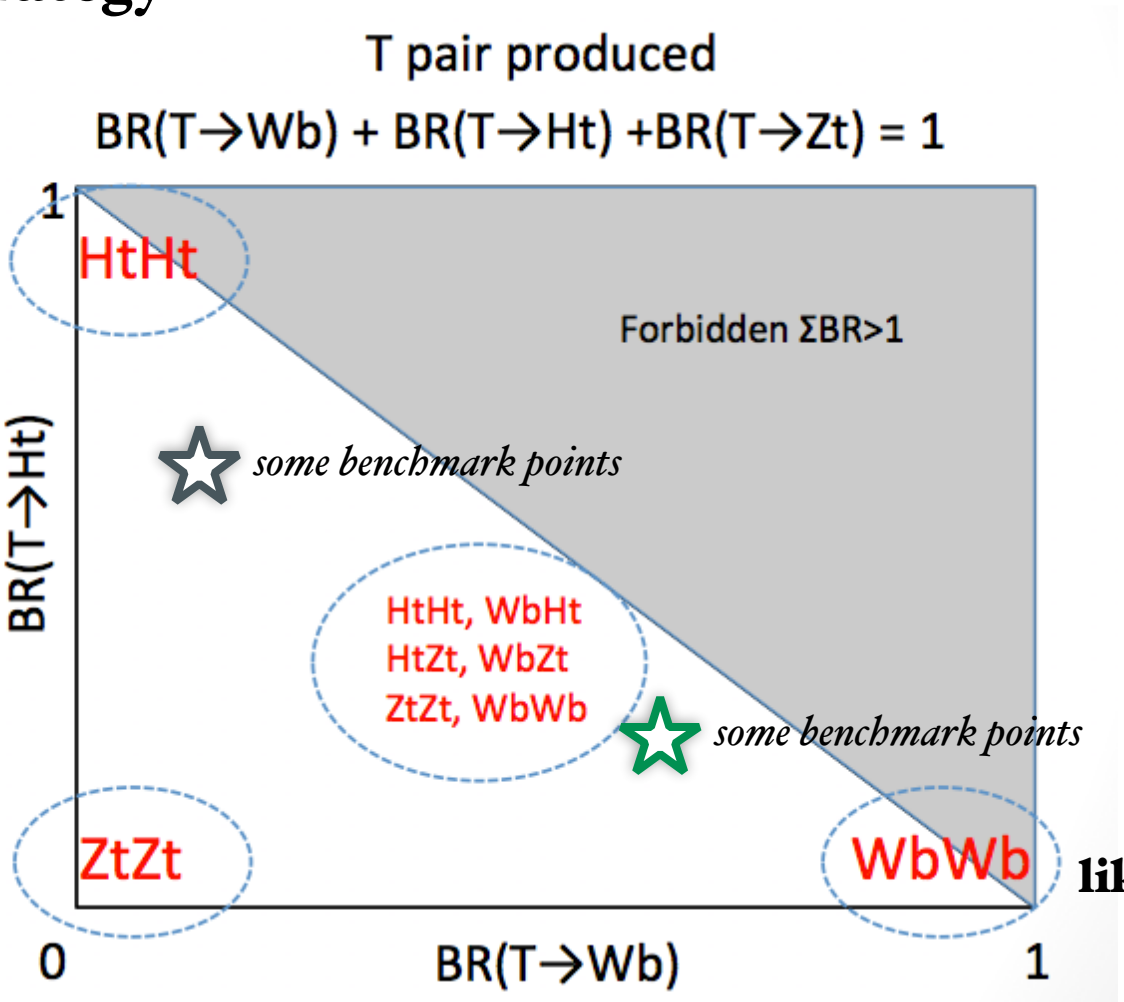
Vector like quark searches in different final states

		T_S	B_S	TB_d	XT_d	BY_d
4 leptons	4l (2Z)	TT	BB	TT,BB	TT	BB
	4l (1Z)	TT	BB	TT,BB	TT	BB
	4l (0Z)	TT	BB	TT,BB	TT,XX	BB
3 leptons	3l (1Z)	TT	BB	TT,BB	TT	
	3l (0Z)	TT	BB	TT,BB	TT,XX	
OS leptons	l^+l^- (1Z)	TT	BB	TT,BB	TT	BB
	l^+l^- (0Z)	TT	BB	TT,BB	TT,XX	BB,YY
SS leptons	$l^\pm l^\pm$		BB	BB	XX	
L+jets	$l^\pm$ (4j)	TT		TT		
	$l^\pm$ (≥6j)	TT	BB	TT,BB	TT,XX	

plus single production!

reminder from Clement's talk

ATLAS strategy

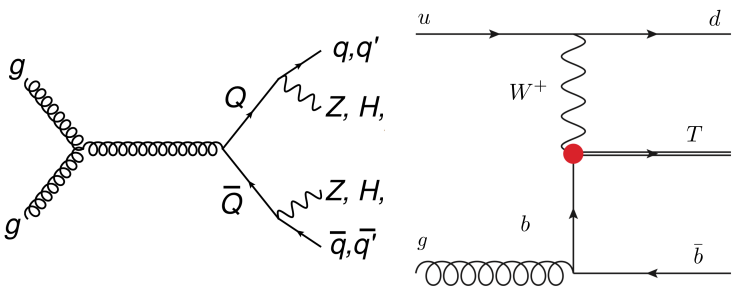


likewise for B

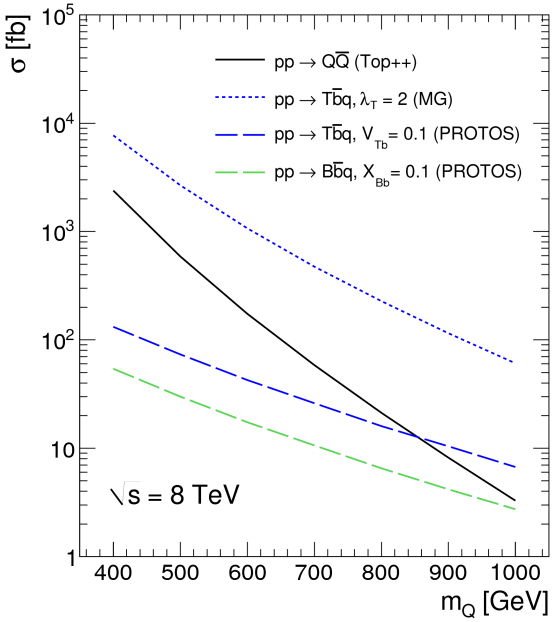
T->Zt, B->Zb pair and single T production

ATLAS-CONF-2014-036

- **Search in dilepton or trilepton final states using full 8TeV dataset, target T/B pair and single production**
- **Signal models and MCs**
  - T/B pair production generated using Protos, cross section from Top++
  - single T production: Madgraph for composite Higgs model with coupling parameter λ_T parameter, kinematics comparable with Protos
  - single production B using Protos with mixing parameter V_{Tb} and X_{Bb} at the upper bound from precision EW measurements
  - BR from Protos with benchmark models with mixings close to the upper bound from EW precision measurements
- **Background modelling**
  - Z+jets and Z+HF, diboson: Sherpa, ttV: Madgraph, ttbar: Powheg+Pythia, single top: MC@NLO/AcerMC, fake or mis-id leptons negligible



Phys. Rev. D86, 075017(2012), arXiv:1207.0830



T->Zt, B->Zb pair and single T production

ATLAS-CONF-2014-036

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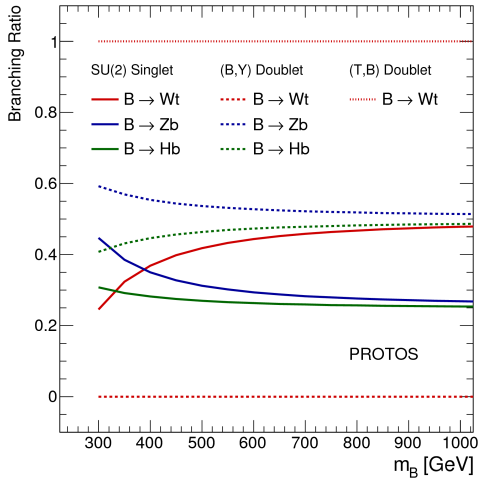

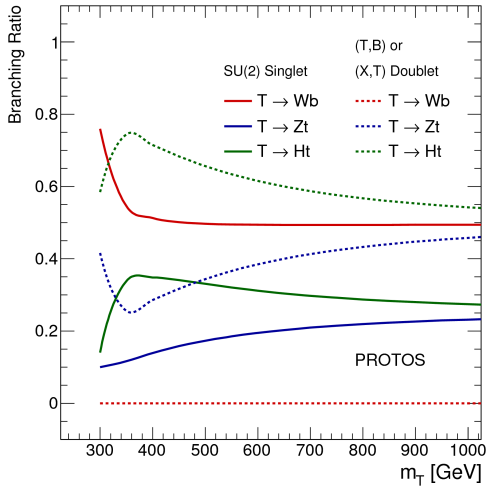

$V_{Tb} << V_{tB}$

T->Zt, B->Zb pair and single T production

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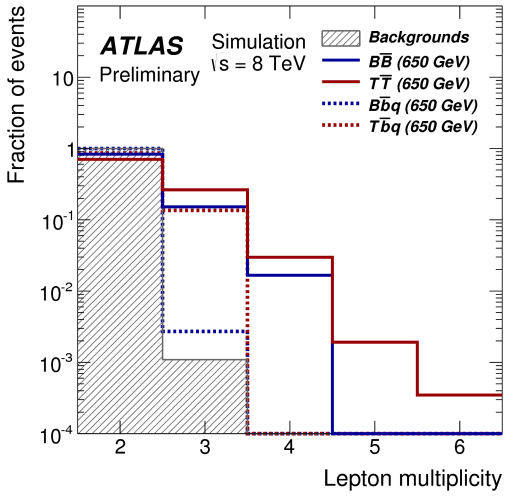
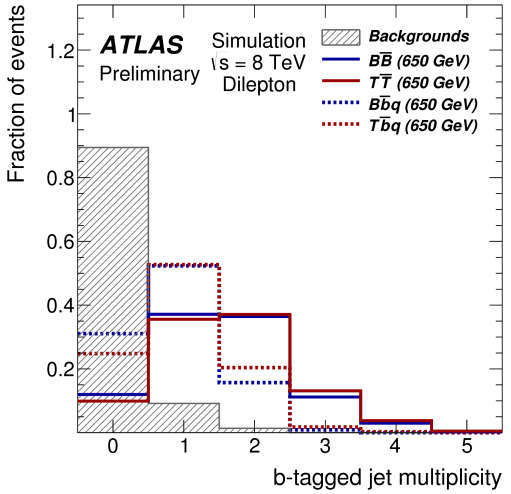
- **Object selection**
  - **Electron selection,** central electron, requirements on EM cluster and associated track, track and calorimeter isolation required
  - **Muon selection,** central muon, p_T dependent track isolation
  - **Lepton p_T>25GeV**
    - looser selection for electrons from Z, no isolation required
  - **Jet selection**, anti-k_T0.4, central jets, p_T>25 GeV
    - overlap removal between jets and lepton in small cone, between electron and jet in larger cone
  - **b-tagging**, 70% efficiency, 130 (5) light (charm) rejection factor





T->Zt, B->Zb pair and single T production

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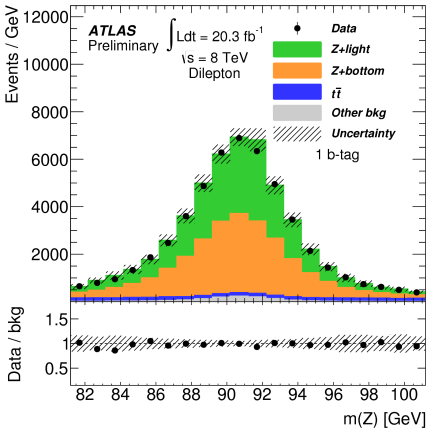
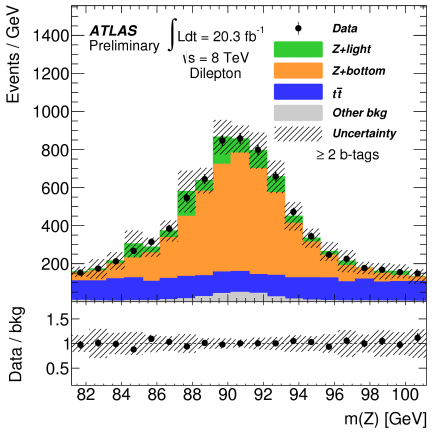
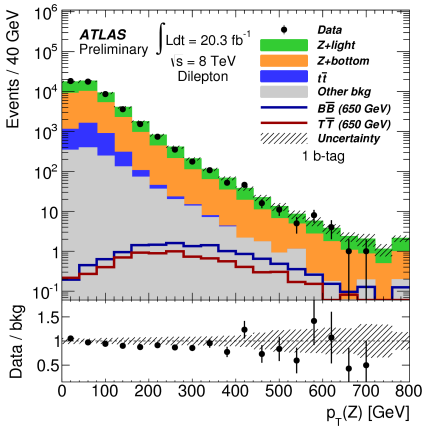
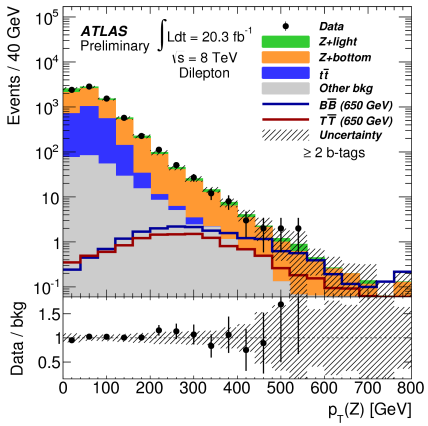
- **Background corrections and control region: dilepton**
  - signal region with 2-btags
  - scaling factor for Z+jets from region $p_T(Z)<100GeV$ separately for 1-tagged and >1-tagged events









- reweighting $p_T(Z)$ by polynomial fit function on residual $(N_{data}-N_{bkg})/N_Z$ of 1-bragged events
- other control regions: 0-tag events

T->Zt, B->Zb pair and single T production

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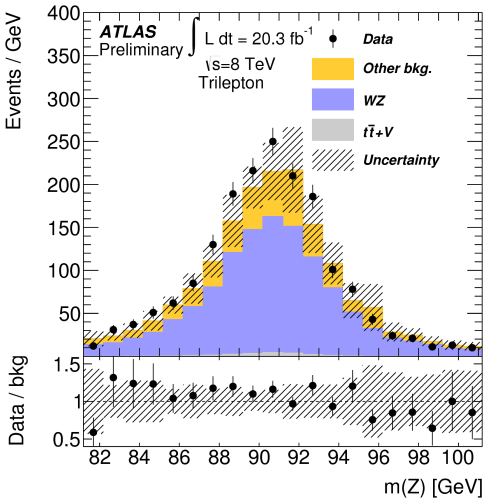
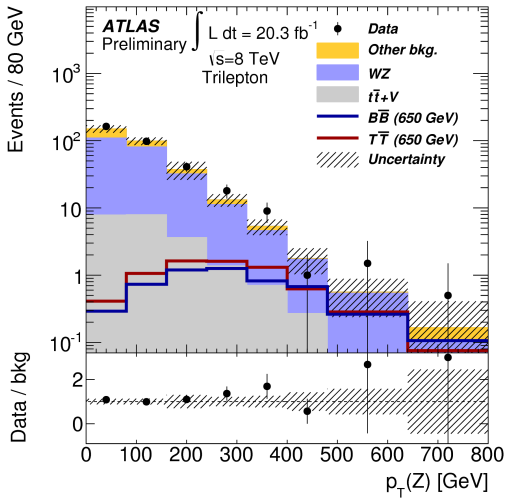
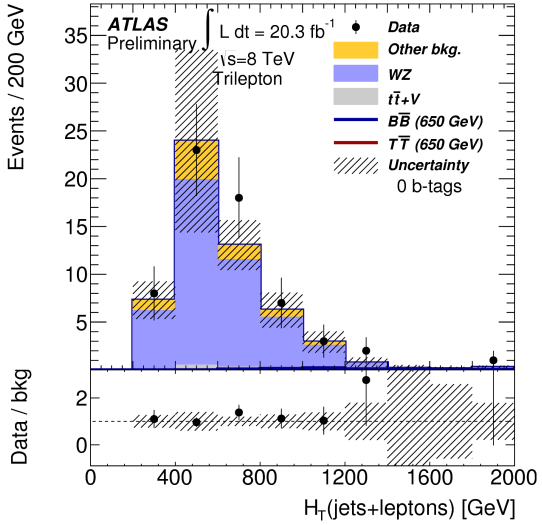
- **Control region: trilepton**
  - signal region with 1-brag
  - generally well modelled distributions invariant m_{ll} mass, $p_T(Z)$, jet and b-tag multiplicities, no correction needed







  - 0-tag control region also well modelled

T->Zt, B->Zb pair and single T production

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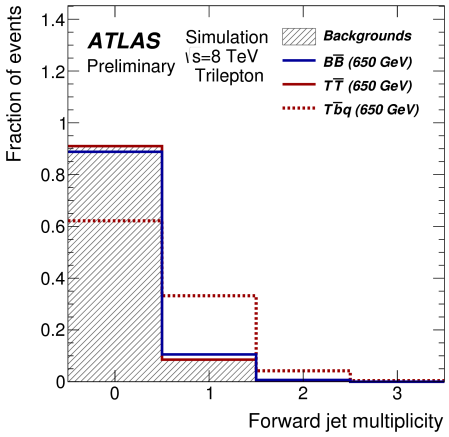
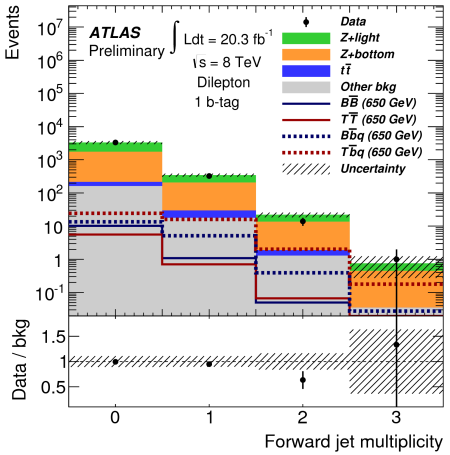
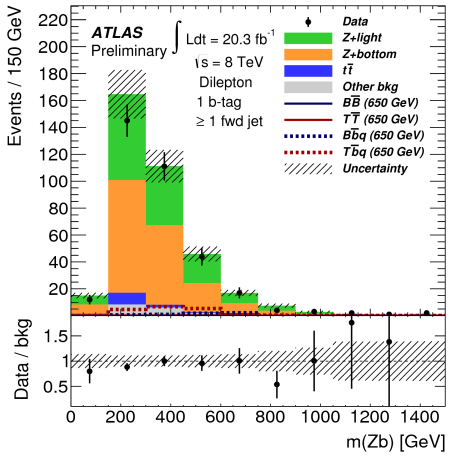
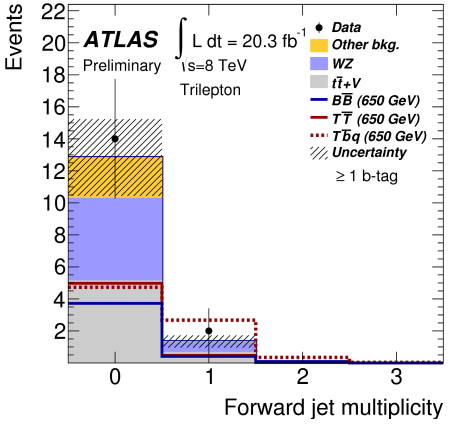
- **Control region: single production**
  - single production seems to favour forward jets compared to background (and pair production)
  - check forward jet modelling and distributions after forward jet requirement
  - generally well modelled distributions, no corrections needed





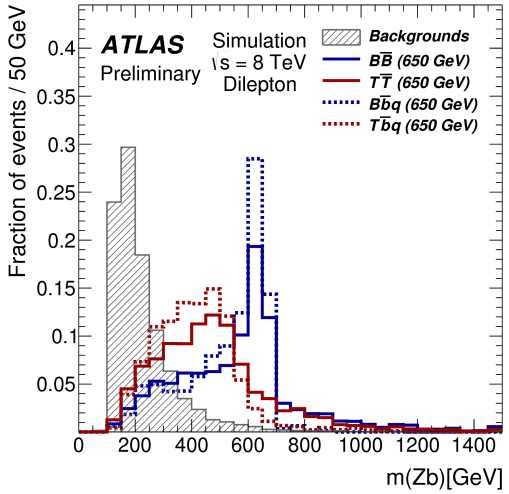




T->Zt, B->Zb pair and single T production

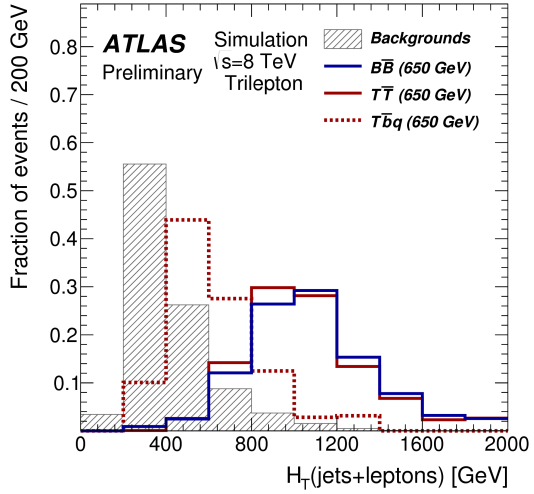
ATLAS-CONF-2014-036

Event selection			
Z boson candidate preselection ≥ 2 central jets $p_T(Z) \geq 150$ GeV			
Dilepton channel		**Trilepton channel**	
$= 2$ leptons		≥ 3 leptons	
≥ 2 b-tagged jets		≥ 1 b-tagged jet	
Pair production	**Single production**	**Pair production**	**Single production**
$H_T(\text{jets}) \geq 600$ GeV	≥ 1 fwd. jet	–	≥ 1 fwd. jet
Final discriminant			
$m(Zb)$		H_T(jets+leptons)	



dilepton event yields

	$Z+\geq 2$ jets ($N_{tag} \geq 2$)	$p_T(Z) \geq 150$ GeV	$H_T(\text{jets}) \geq 600$ GeV
Z+light	900 ± 210	63 ± 14	4.0 ± 1.3
Z+bottom	4420 ± 300	382 ± 49	19.3 ± 3.6
$t\bar{t}$	2190 ± 230	33.0 ± 8.0	4.6 ± 1.5
Other SM	270 ± 70	42 ± 11	4.0 ± 1.1
Total SM	7780 ± 440	519 ± 53	32.0 ± 4.2
Data	7790	542	31
$B\bar{B}(m_B = 650\ \text{GeV})$	18.7 ± 1.5	16.5 ± 1.4	14.2 ± 1.3
$T\bar{T}(m_T = 650\ \text{GeV})$	12.1 ± 0.8	10.0 ± 0.7	8.6 ± 0.7



T->Zt, B->Zb pair and single T production

ATLAS-CONF-2014-036

Event selection			
Z boson candidate preselection ≥ 2 central jets $p_{\mathrm{T}}(Z) \geq 150$ GeV			
Dilepton channel		**Trilepton channel**	
$= 2$ leptons		≥ 3 leptons	
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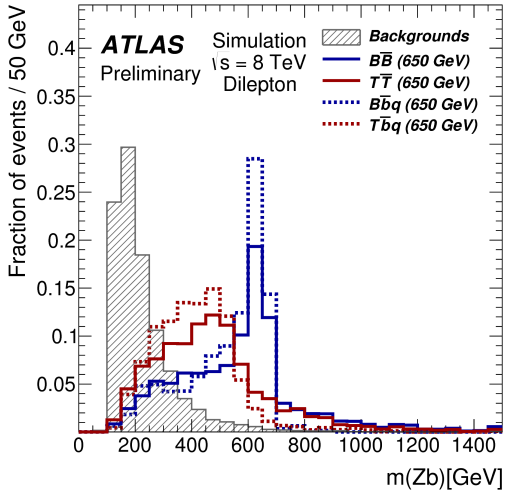
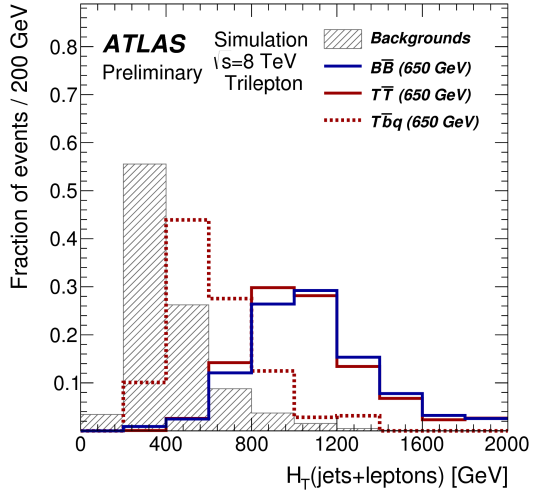
Pair production	**Single production**	**Pair production**	**Single production**
$H_{\mathrm{T}}(\mathrm{jets}) \geq 600$ GeV	≥ 1 fwd. jet	–	≥ 1 fwd. jet
Final discriminant			
$m(Zb)$		H_{T}(jets+leptons)	



trilepton event yields

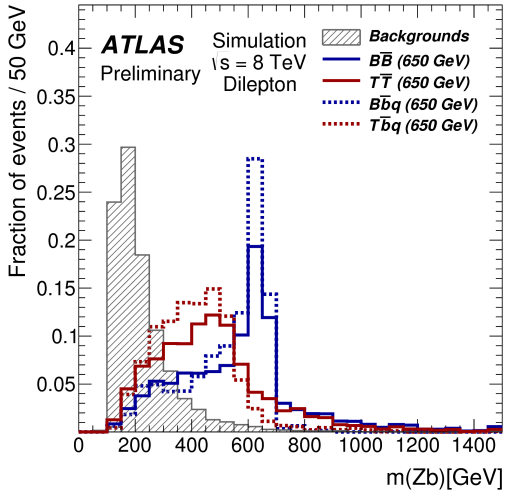
	Trilepton ch.	≥ 2 central jets	$p_{\mathrm{T}}(Z) > 150$ GeV	$N_{\mathrm{tag}} \geq 1$
WZ	1170 ± 130	219 ± 32	51.5 ± 8.9	5.8 ± 1.4
$t\bar{t}+X$	23.5 ± 6.7	22.0 ± 6.3	7.0 ± 2.1	5.8 ± 1.8
Other SM	435 ± 50	67 ± 13	10.4 ± 9.2	2.6 ± 1.3
Total SM	1630 ± 170	309 ± 39	69 ± 14	14.3 ± 2.6
Data	1760	334	78	16
$B\bar{B}$ (m_B=650 GeV)	5.8 ± 0.4	5.7 ± 0.4	4.75 ± 0.31	4.17 ± 0.30
$T\bar{T}$ (m_T=650 GeV)	7.4 ± 0.5	7.4 ± 0.5	6.1 ± 0.5	5.5 ± 0.4



T->Zt, B->Zb pair and single T production

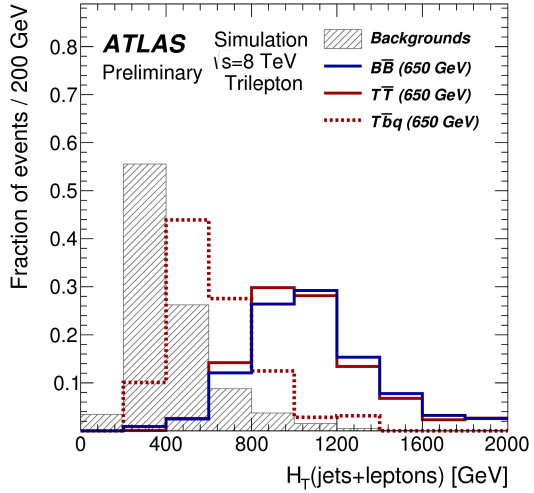
ATLAS-CONF-2014-036

Event selection			
Z boson candidate preselection ≥ 2 central jets $p_T(Z) \geq 150$ GeV			
Dilepton channel		**Trilepton channel**	
$= 2$ leptons		≥ 3 leptons	
≥ 2 b-tagged jets		≥ 1 b-tagged jet	
Pair production	**Single production**	**Pair production**	**Single production**
H_T(jets) ≥ 600 GeV	≥ 1 fwd. jet	–	≥ 1 fwd. jet
Final discriminant			
$m(Zb)$		H_T(jets+leptons)	



single production event yields

Dilepton channel		Trilepton channel	
Z+light	7.3 ± 2.0	WZ	0.62 ± 0.27
Z+bottom	40 ± 10	$t\bar{t}+V$	0.74 ± 0.24
$t\bar{t}$	5.2 ± 2.1		
Other SM	3.8 ± 1.3	Other SM	0.07 ± 0.10
Total SM	56 ± 12	Total SM	1.4 ± 0.4
Data	57	Data	2
$B\bar{b}q$ ($m_B = 650$ GeV, $X_{bB} = 0.5$)	1.88 ± 0.27		
$T\bar{b}q$ ($m_T = 650$ GeV, $\lambda_T = 2$)	7.7 ± 1.0	$T\bar{b}q$ ($m_T = 650$ GeV, $\lambda_T = 2$)	3.1 ± 0.5
$B\bar{B}$ ($m_B = 650$ GeV)	1.53 ± 0.24	$B\bar{B}$ ($m_B = 650$ GeV)	0.45 ± 0.10
$T\bar{T}$ ($m_T = 650$ GeV)	1.08 ± 0.15	$T\bar{T}$ ($m_T = 650$ GeV)	0.50 ± 0.10



T->Zt, B->Zb pair and single T production

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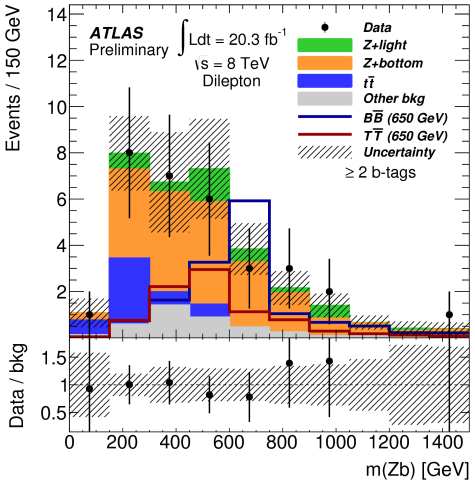
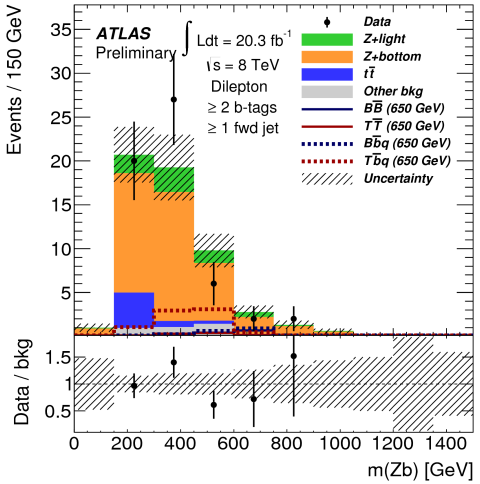
Pair production selection

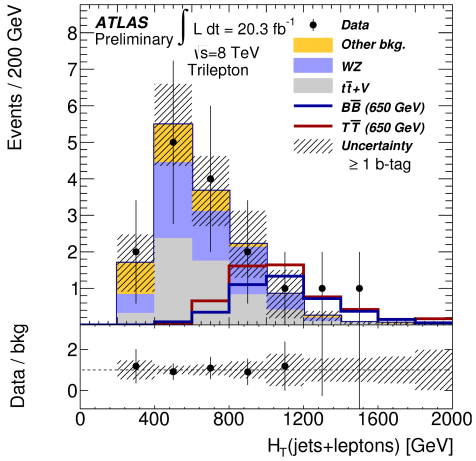
Single production selection

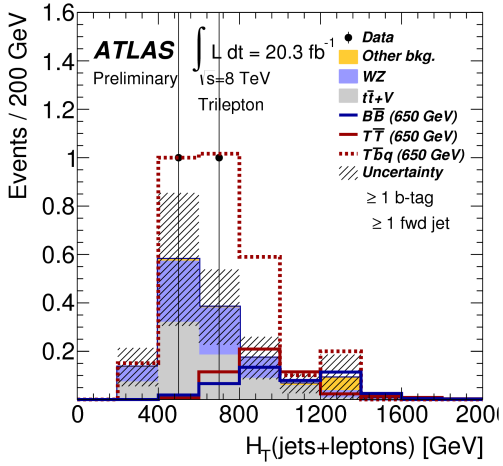
dilepton





trilepton





T->Zt, B->Zb pair and single T production

ATLAS-CONF-2014-036

- **Systematics**
  - dominant systematics: cross section uncertainties
    - ttV: 30%
    - WZ+jets: 50% HT/1TeV
    - other processes theoretical uncertainties

Fractional uncertainties (%): dilepton channel						
	Z+jets	$t\bar{t}$	Other bkg.	Total bkg.	$B\bar{B}$	$T\bar{T}$
Luminosity	1.4	2.8	2.8	0.3	2.8	2.8
Cross section	5.5	6.4	29	0.7	-	-
Jet reconstruction	13	10	14	11	2.0	2.1
b-tagging	9.1	13	9.9	5.7	7.2	5.9
e reconstruction	2.9	16	5.9	4.6	2.5	1.5
μ reconstruction	3.8	7.8	7.2	4.2	3.2	1.3
Z+jets $p_{\mathrm{T}}(Z)$ correction	9.0	-	-	6.5	-	-
Z+jets rate correction	6.9	-	-	5.0	-	-
MC statistics	5.0	25	12	5.4	2.4	2.9

Fractional uncertainties (%): trilepton channel						
	WZ	$t\bar{t}+V$	Other bkg.	Total bkg.	$B\bar{B}$	$T\bar{T}$
Luminosity	2.8	2.8	2.8	2.8	2.8	2.8
Cross section	17	30	8.9	21	-	-
Jet reconstruction	5.4	1.2	8.1	3.1	4.0	1.8
b-tagging	13	3.6	13	6.7	5.6	5.5
e reconstruction	9.3	3.9	37	11	5.9	12
μ reconstruction	14	3.9	18	4.2	6.2	5.7
MC statistics	11	3.1	27	6.6	4.8	8.3

T->Zt, B->Zb pair and single T production

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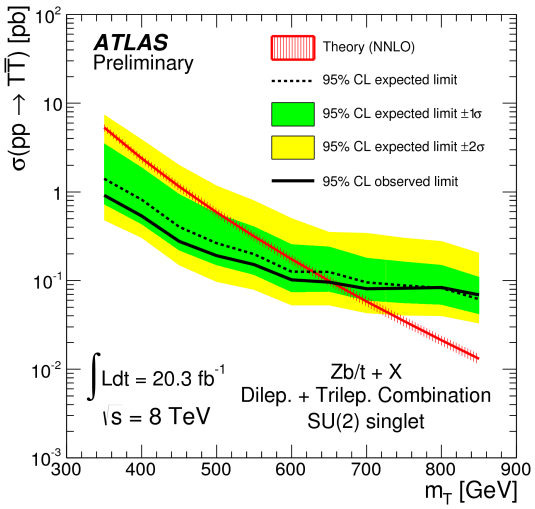
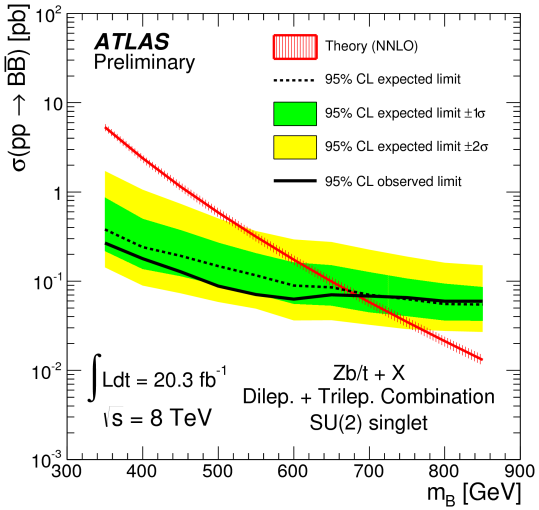
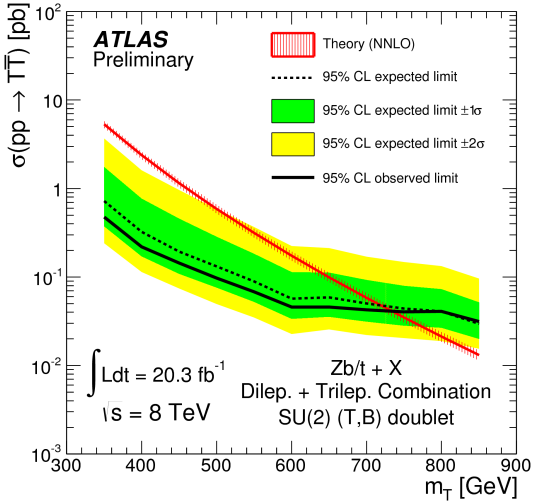
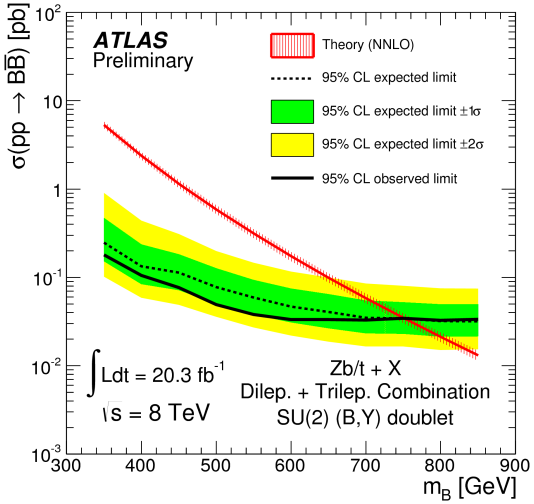
- **Limits on VLQ pair production**
  - m(B singlet)>685GeV (670GeV)
  - m(B doublet)>755GeV (755GeV) (B,Y)
  - m(T singlet)>655GeV (625GeV)
  - m(T doublet)> 735GeV (720GeV) (T,B)



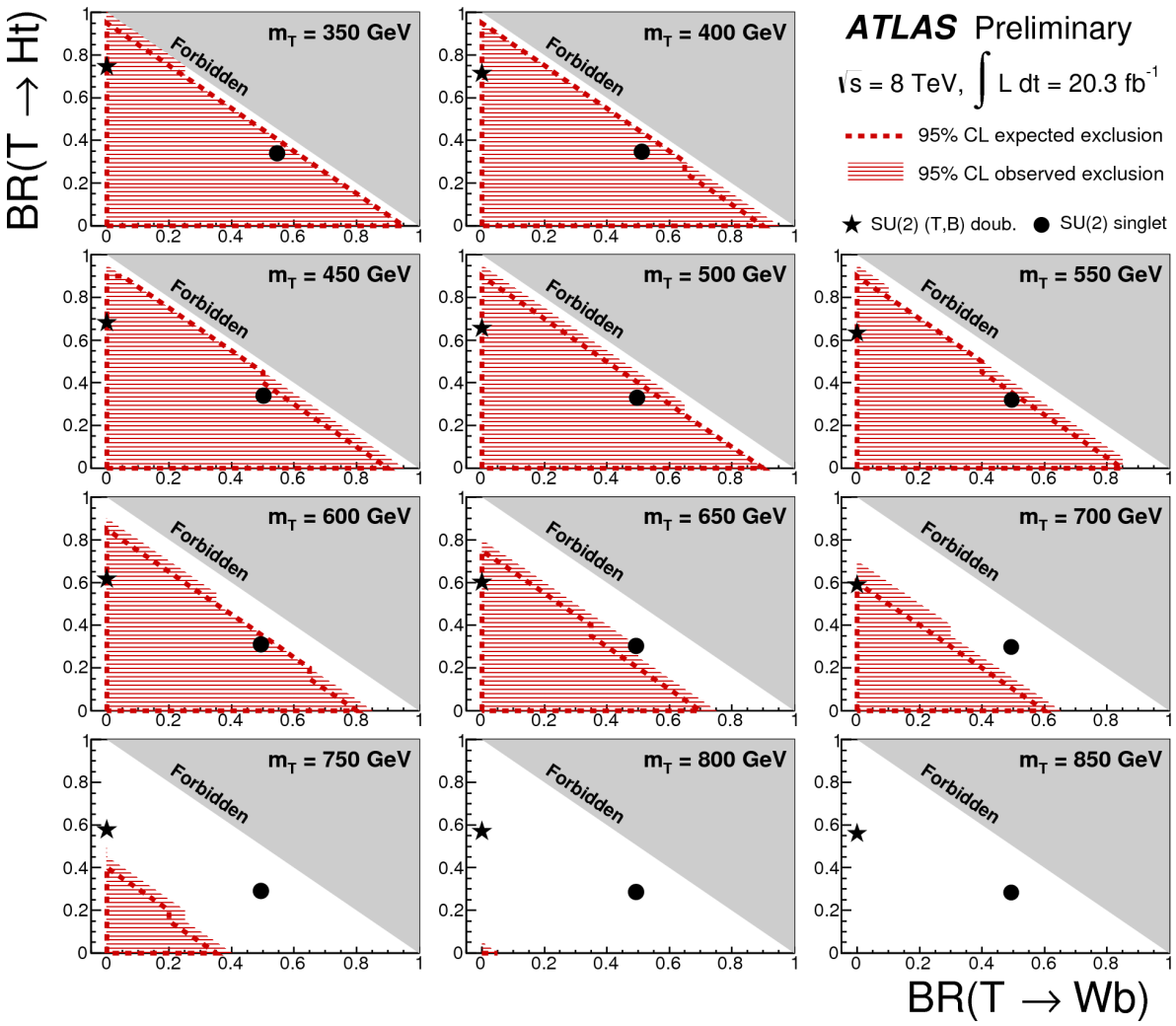






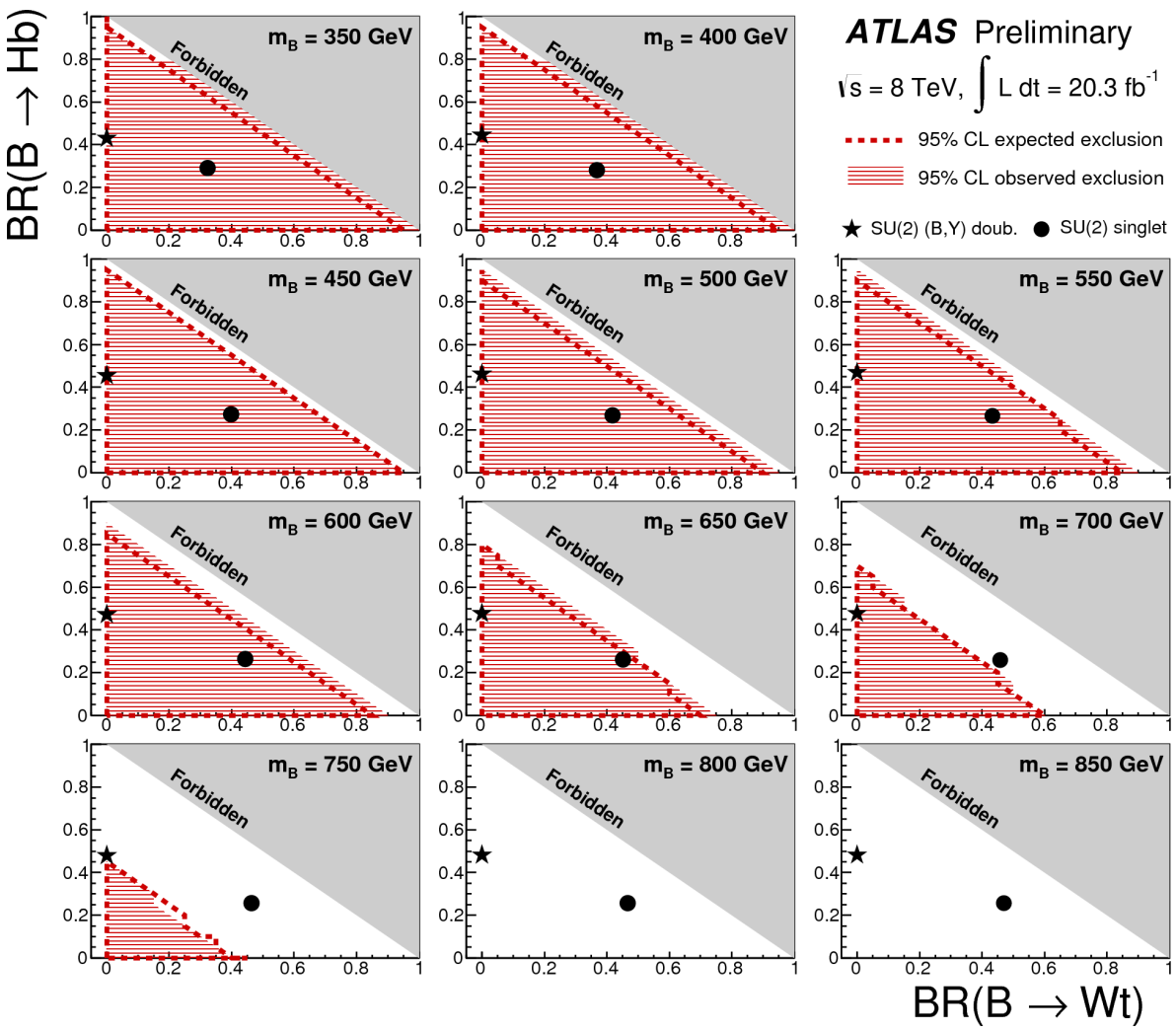
T->Zt, B->Zb pair and single T production

- **Limits on T from pair production**
  - with varying BR



T->Zt, B->Zb pair and single T production

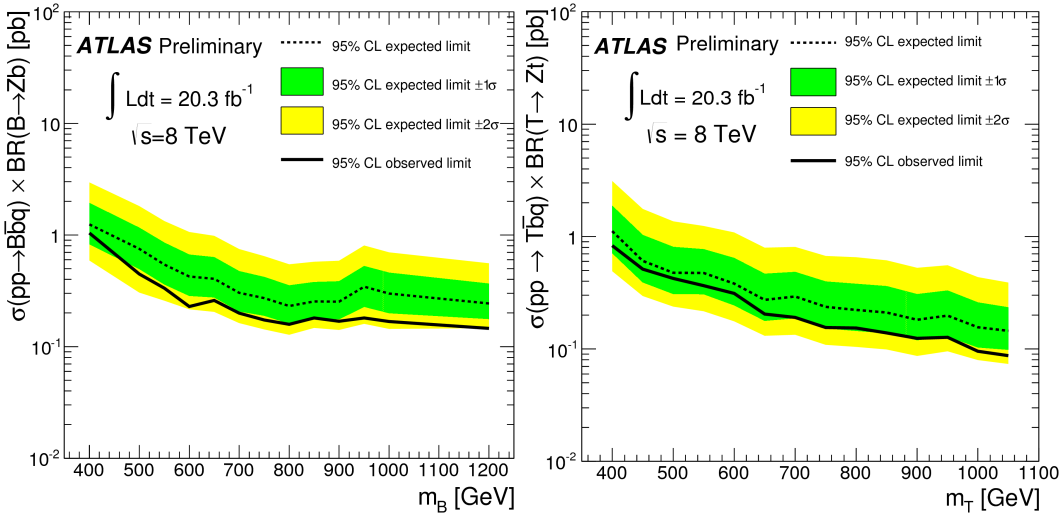
- **Limits on B from pair production**
  - with varying BR



T->Zt, B->Zb pair and single T production

ATLAS-CONF-2014-036

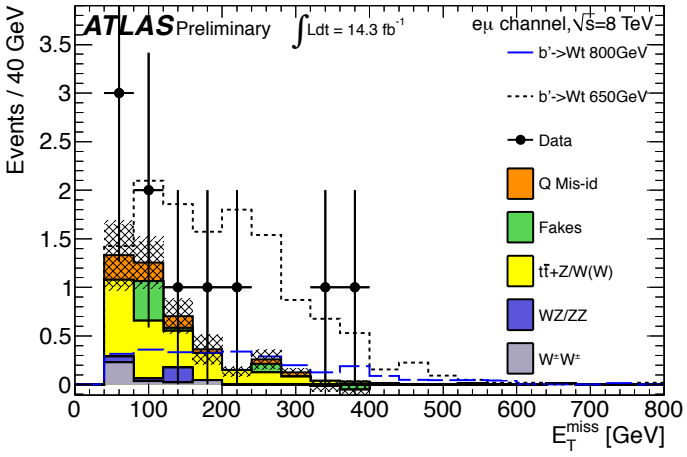
- **Limits on VLQ pair single production**
  - Limit on Bbq production from dilepton channel only
  - No sensitivity for single T production for λ_T<1.5
  - Mostly no sensitivity for single T production for V_{Tb}<1, but for V_{Tb}<0.7 in mass range 450-650GeV (downward fluctuation of data)
  - Mostly no sensitivity for single B production for V_{Bb}<0.5



same-sign dilepton with b-jets

ATLAS-CONF-2013-051

- **SS lepton selection in 14.3fb^{-1} 8 TeV data where SM has small contribution**
- **Analysis has multiple interpretations**
  - chiral b'->Wt pair production
  - non-resonant four-top (sgluon pair, KK excitation in 2UED/RPP model)
  - SS top (uu->tt via heavy particle)
  - **VLQ T/B pair production (e.g. B->Wt, T->Zt, T->Ht, all decay modes considered)**
    - NNLO cross section for b'/VLQ pair production from Hathor
    - BR according to Protos calculation



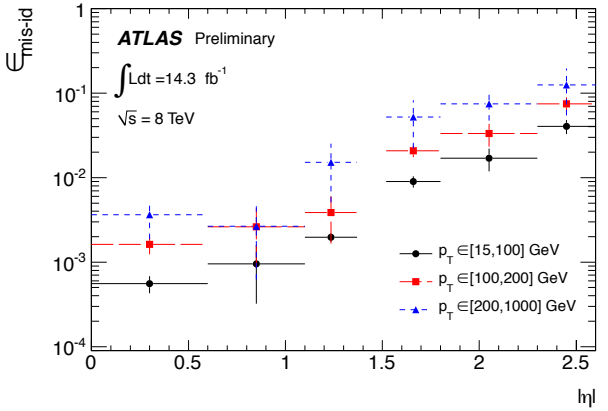
same-sign dilepton with b-jets

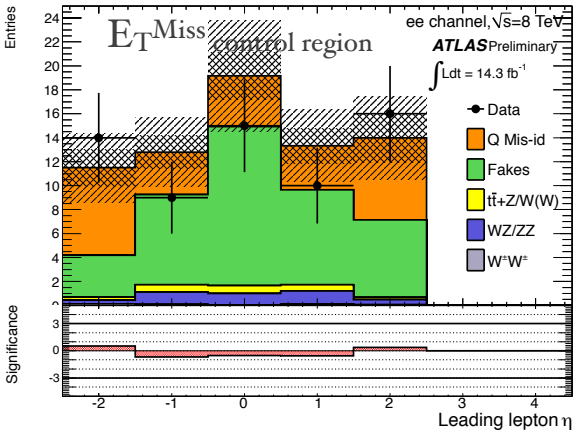
ATLAS-CONF-2013-051

- **Signal models and MCs (b'/VLQ)**
  - T/B pair production with Protos
- **Background modelling**
  - ttV/WW, WW+jj: Madgraph, WZ/ZZ+HF Sherpa
  - data driven method for fakes/mis-id: matrix method
    - measure *selection efficiency* $\epsilon_{fake,real}$ of loose->tight selection of single real/fake leptons in dedicated control regions
    - construct number of *tight selected leptons* N_{fake}^{tight} (lepton pairs) containing fake leptons (at least one fake lepton) from a selection of *tight and loose leptons* ($N^{tight,loose}$)
  - charge mis-id
    - for electrons using Z->ee data events, for high p_T electrons using ttbar MC scaled to match low p_T Z->ee data rate
    - remove trident events covered by fakes estimation
  - Validation regions
    - no req. on E_T^{Miss} and 100 < H_T < 400GeV, no req. on H_T and E_T^{Miss} <40GeV, zero b-tag region

$$N_{\text{fake,real}}^{\text{tight}} = \epsilon_{\text{fake,real}} \cdot N_{\text{fake,real}}^{\text{loose}}$$

$$N^{\text{tight,loose}} = N_{\text{fake}}^{\text{tight,loose}} + N_{\text{real}}^{\text{tight,loose}}$$



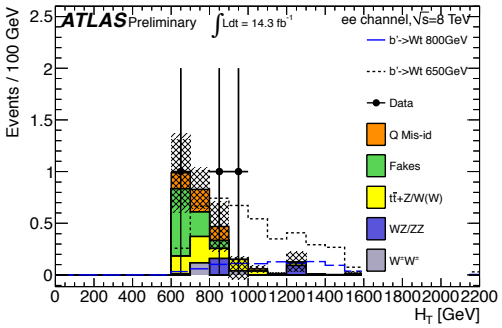


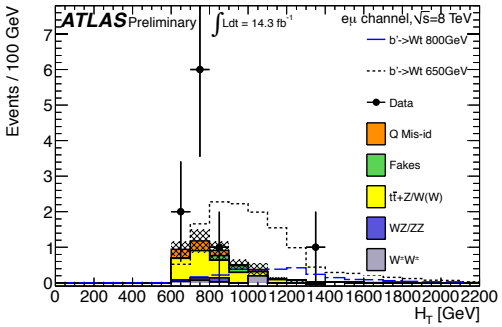
same-sign dilepton with b-jets

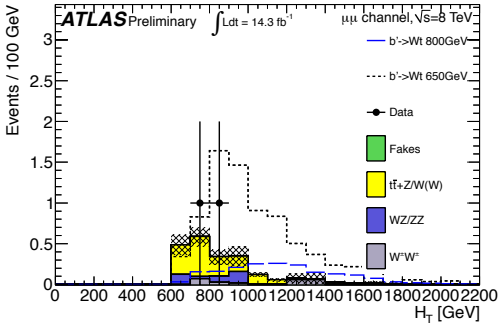
ATLAS-CONF-2013-051

- **Object selection**
  - follow the same object selection as previous analyses
- **Event selection**
  - one SS lepton pair, at least one b-tag
  - E_T^{Miss}>40GeV, m_{ll}>15GeV, outside of Z peak, H_T>550
  - H_T>650 GeV for b', VLQ (singlet)
  - other selection cuts for different interpretations

Backgrounds	Channel		
Samples	ee	$e\mu$	$\mu\mu$
Charge misidentification	$0.6 \pm 0.1 \pm 0.2$	$0.9 \pm 0.1 \pm 0.3$	—
Fakes	$0.8 \pm 0.4 \pm 0.3$	$0.2 \pm 0.4 \pm 0.1$	< 1.1
Diboson			
• WZ/ZZ+jets	$0.3 \pm 0.2 \pm 0.1$	$0.3 \pm 0.1^{+0.4}_{-0.2}$	$0.4 \pm 0.2 \pm 0.1$
• $W^{\pm}W^{\pm}$+2 jets	$0.17 \pm 0.09 \pm 0.05$	$0.3 \pm 0.2 \pm 0.1$	$0.2 \pm 0.1 \pm 0.1$
$t\bar{t}$ + W/Z			
• $t\bar{t}W$(+jet(s))	$0.6 \pm 0.2 \pm 0.3$	$1.9 \pm 0.2 \pm 0.6$	$1.3 \pm 0.2 \pm 0.4$
• $t\bar{t}Z$(+jet(s))	$0.18 \pm 0.03 \pm 0.06$	$0.66 \pm 0.05 \pm 0.22$	$0.31 \pm 0.04 \pm 0.10$
• $t\bar{t}W^+W^-$	$0.024 \pm 0.003^{+0.010}_{-0.007}$	$0.072 \pm 0.005^{+0.028}_{-0.020}$	$0.055 \pm 0.004^{+0.022}_{-0.016}$
Total expected background	$2.7 \pm 0.5 \pm 0.4$	$4.4 \pm 0.5^{+0.9}_{-0.7}$	$2.3 \pm 1.2 \pm 0.5$
Observed	3	10	2







same-sign dilepton with b-jets

ATLAS-CONF-2013-051

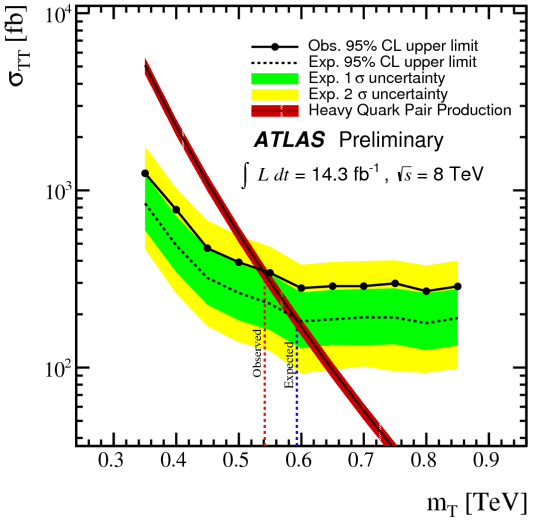
- **Systematic uncertainties**
  - ttbar+V - PDF and scales: 30%
  - WZ/ZZ - scales: 34%
  - WWjj - scales: 25%
  - ttWW - scales: -26%/+38%

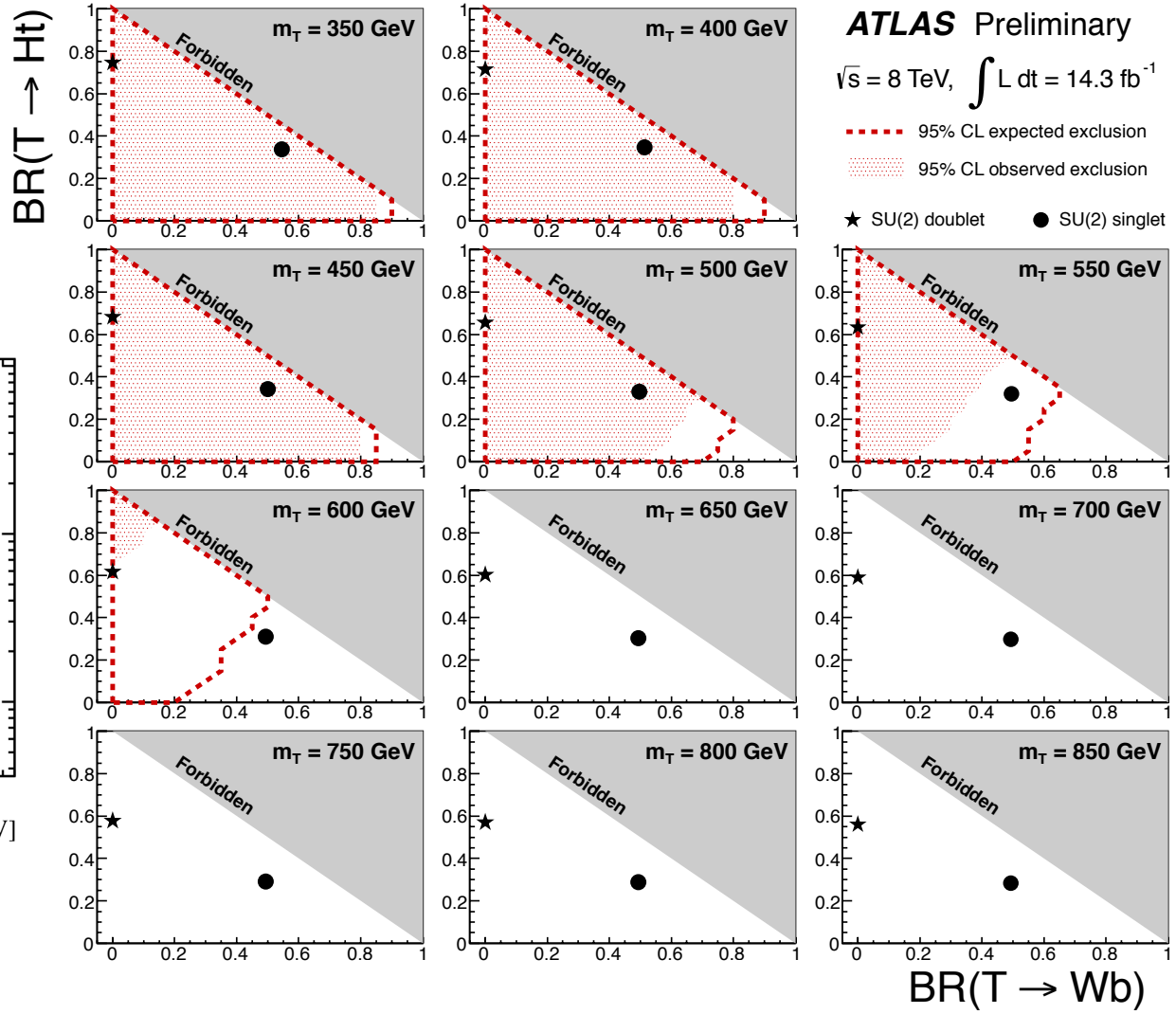
	Uncertainty in %					
	650 GeV b'			Background		
Source	ee	$e\mu$	$\mu\mu$	ee	$e\mu$	$\mu\mu$
Cross section	–	–	–	14.4	25.4	32.9
Fakes	–	–	–	9.7	1.4	10.1
Charge misidentification	–	–	–	7.2	7.1	–
Jet energy scale	4.6	2.5	0.2	3.5	10.2	4.4
ISR/FSR	6.0	6.0	6.0	2.6	4.5	4.0
b-tagging efficiency	4.6	3.1	3.0	2.1	4.4	4.0
Lepton ID efficiency	5.3	4.9	8.2	2.2	3.6	5.4
Jet energy resolution	0.8	0.9	0.3	0.9	2.7	2.0
Luminosity	3.6	3.6	3.6	1.6	2.7	3.6
Lepton energy scale	0.8	0.4	0.0	1.4	0.9	0.1
JVF selection efficiency	2.5	2.9	2.6	1.1	1.5	1.4

same-sign dilepton with b-jets

ATLAS-CONF-2013-051

- **Limits on T from pair production**
  - m(T)>540GeV
  - with varying BR

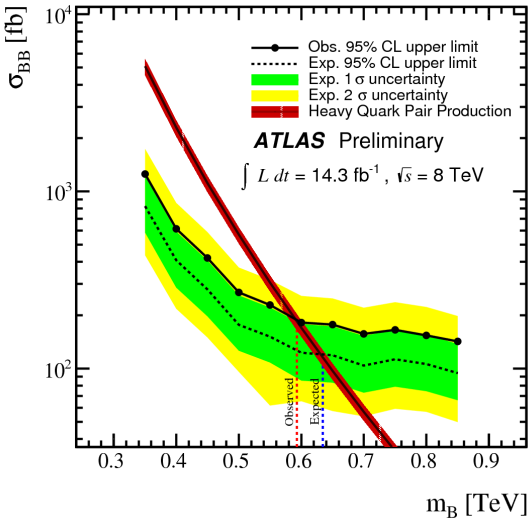


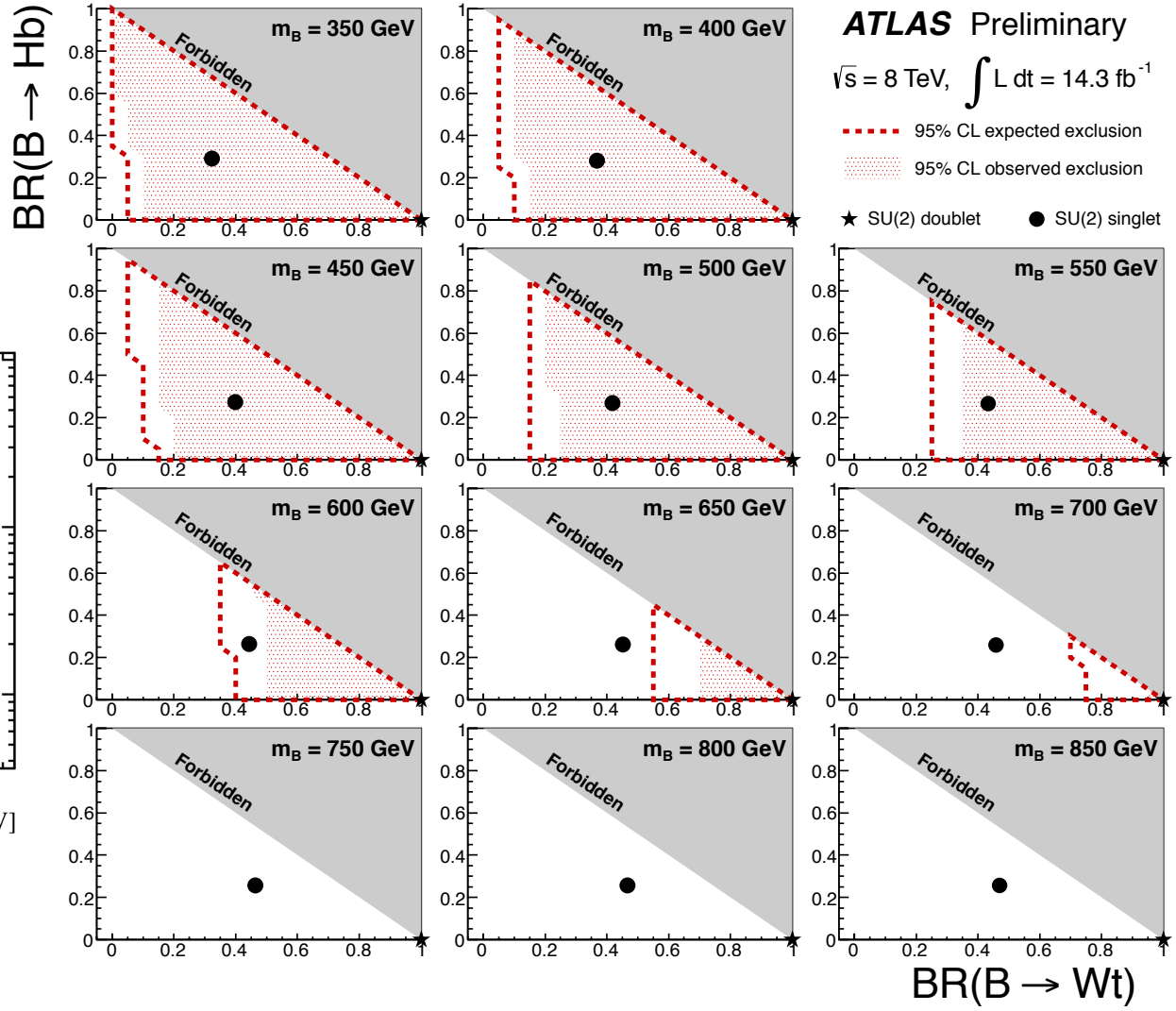


same-sign dilepton with b-jets

ATLAS-CONF-2013-051

- **Limits on B from pair production**
  - m(B)>590GeV
  - with varying BR





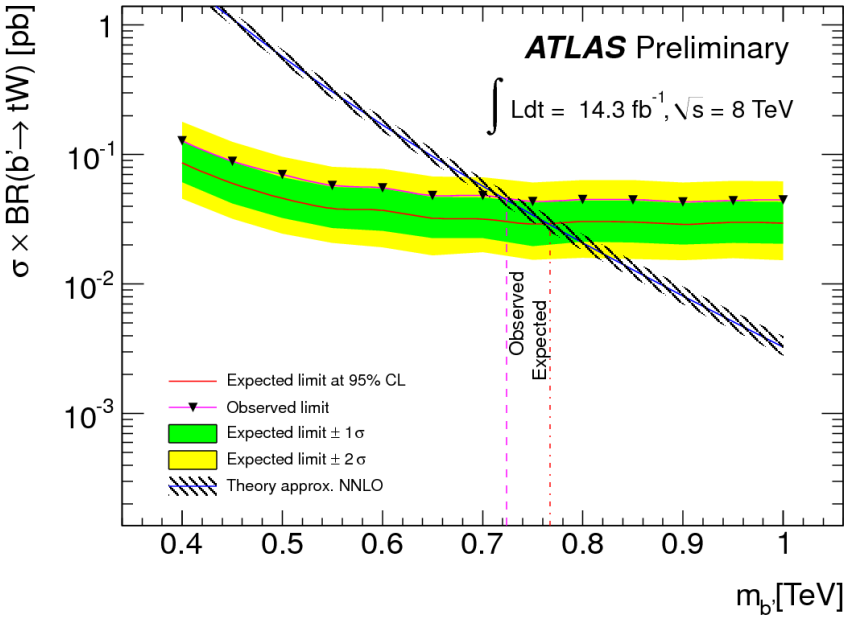
Summary

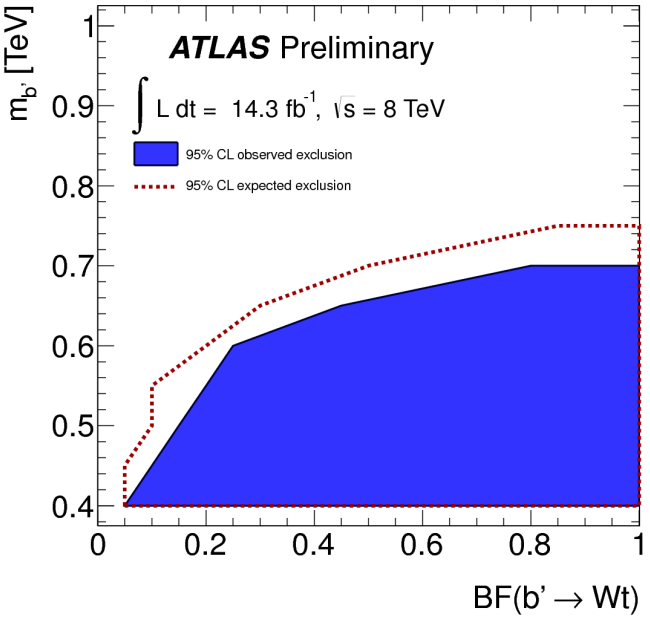
- **Vector-like quark searches in dilepton/multilepton final states**
  - Specific analysis for T->Zt, B->Zb pair and single T production search
  - Generic same-sign lepton search interpretation for VLQ
- **Limits for pair production at mixing values close to limit from EW measurement**
  - up to 755 GeV(B doublet)
  - also limits for different BRs
  - analysis not yet sensitive to single production, more specific analyses should take advantage of higher cross section at higher masses

Backup

Same-sign dilepton

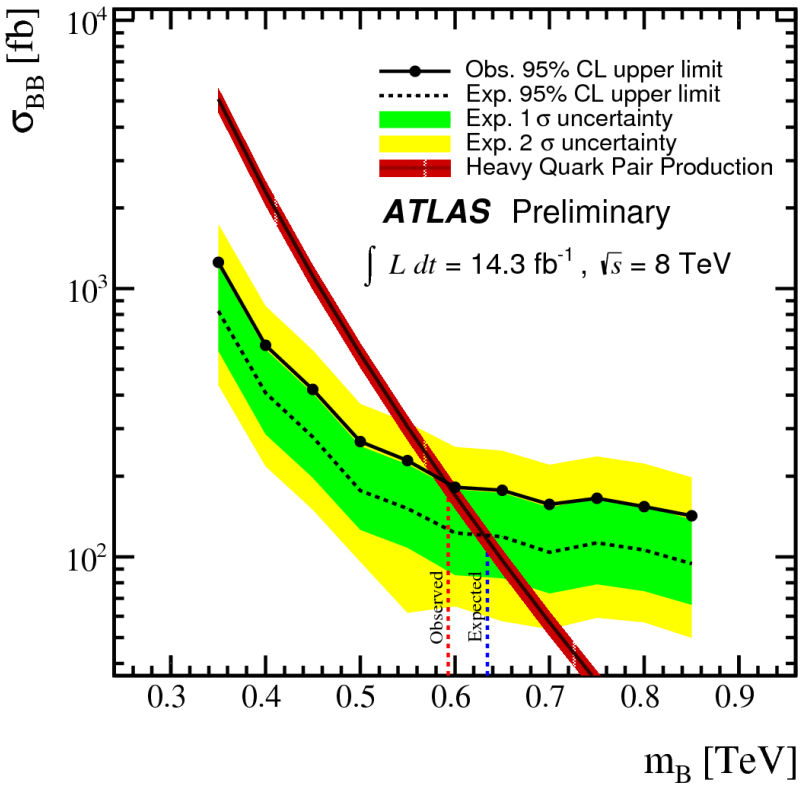
- **chiral B limit**

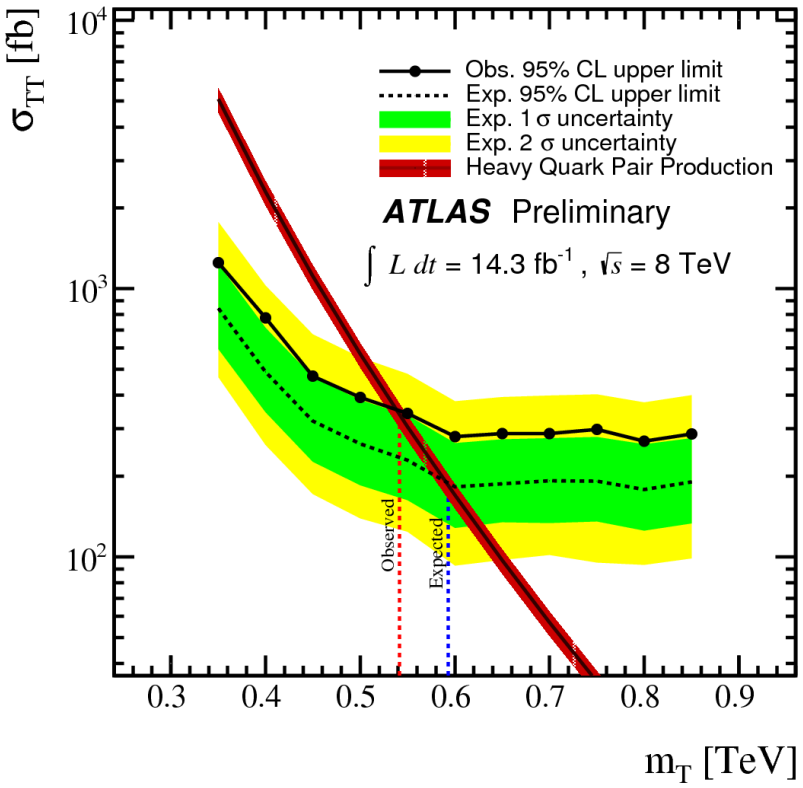




Same-sign dilepton

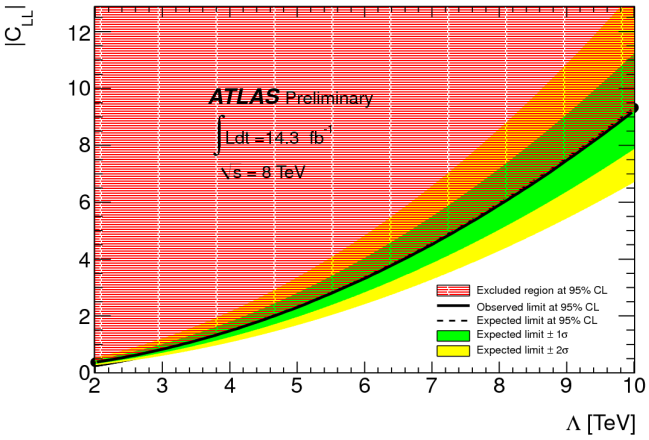
- **VLQ limits**

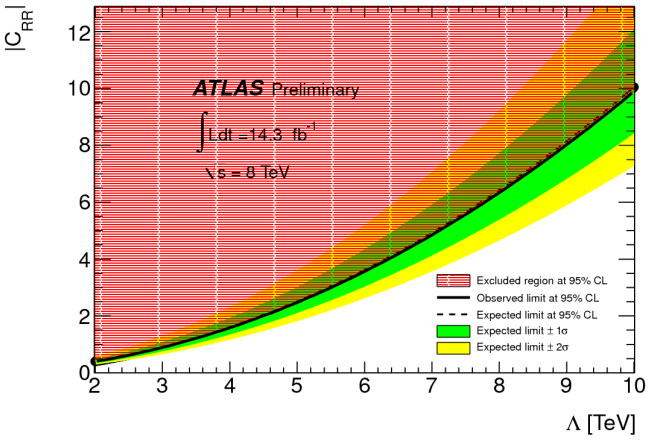


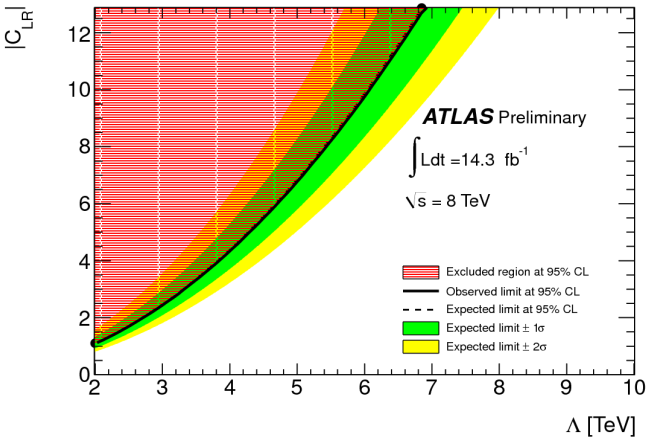


Same-sign dilepton

- **Limits on SS top-pair production**



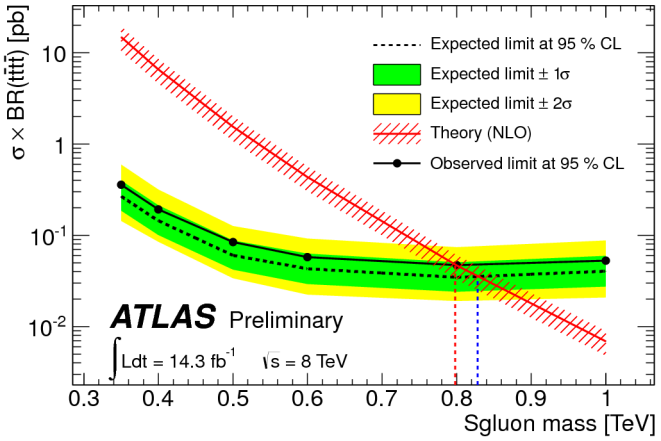


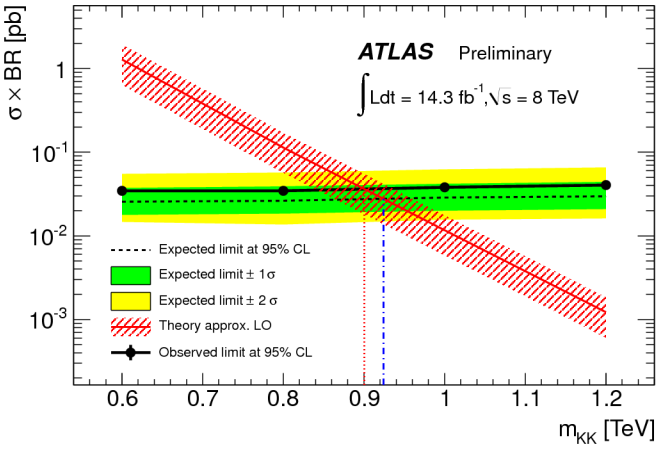


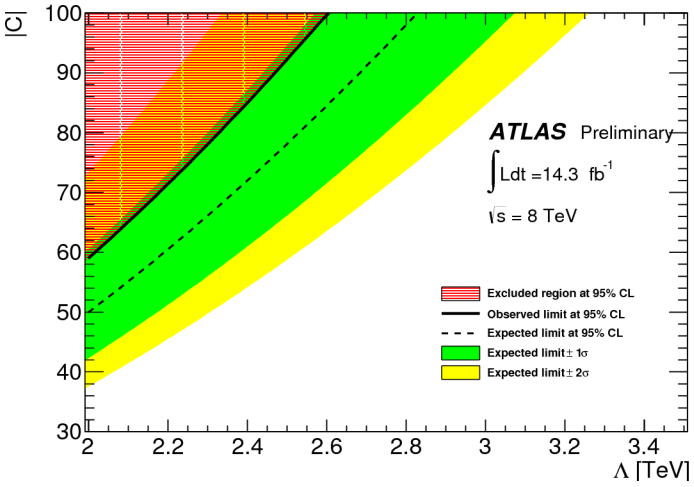
$$\mathcal{L}_{4F} = \frac{1}{2}\frac{C_{LL}}{\Lambda^2}(\bar{u}_L\gamma^\mu t_L)(\bar{u}_L\gamma_\mu t_L) + \frac{1}{2}\frac{C_{RR}}{\Lambda^2}(\bar{u}_R\gamma^\mu t_R)(\bar{u}_R\gamma_\mu t_R)$$
$$-\frac{1}{2}\frac{C_{LR}}{\Lambda^2}(\bar{u}_L\gamma^\mu t_L)(\bar{u}_R\gamma_\mu t_R) - \frac{1}{2}\frac{C'_{LR}}{\Lambda^2}(\bar{u}_{La}\gamma^\mu t_{Lb})(\bar{u}_{Rb}\gamma_\mu t_{Ra}) + \text{h.c.}$$

Same-sign dilepton

- **Effective four-top coupling** $\mathcal{L} = \mathcal{L}_{SM} + \frac{C}{\Lambda^2}(\bar{t}_R\gamma^\mu t_R)(\bar{t}_R\gamma_\mu t_R)$



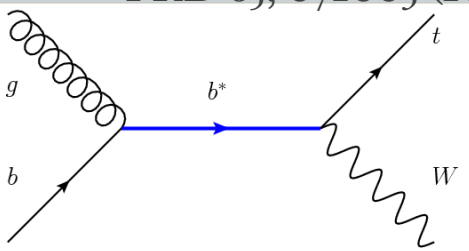


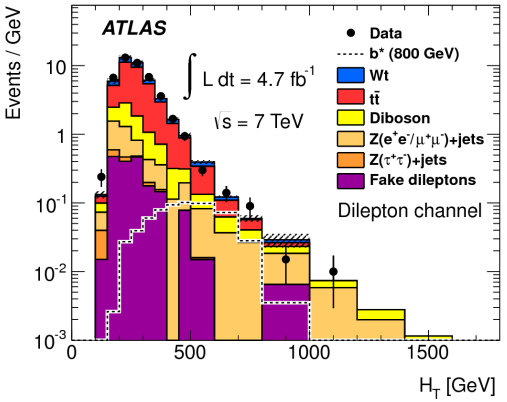


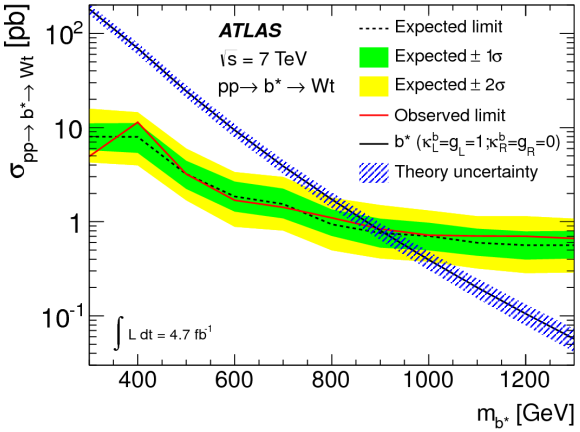
Excited b*->Wt search

PRD 85, 072003 (2012)

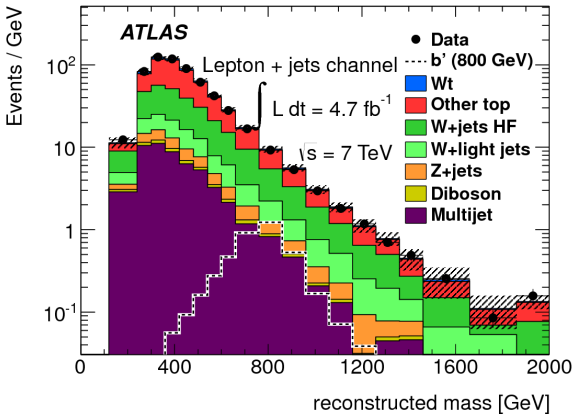
- **search for excited b* using full 7TeV dataset**
  - strong production of excited b*, coupling to third generation quarks, decay weakly to Wt
  - not directly a VLQ search, but also investigated right/left handed couplings
  - Interpretation for VLQ models as in the other analysis possible
- **dilepton and single lepton combined analysis**
  - single lepton selection, exactly three jets, exactly one b-tag
  - dilepton selection, exactly one jet, no b-tag requirement
  - sensitive distribution dilepton: H_T, single lepton: *reconstructed mass* of three jets, lepton and neutrino
- **Limits @95%CL on mass for maximally left- or/and right-handed coupling and coupling itself**
  - $m(b^*_{LH})>870(910)$GeV, $m(b^*_{LH})>920(950)$GeV, $m(b^*_{LH/RH})>1030(1030)$GeV

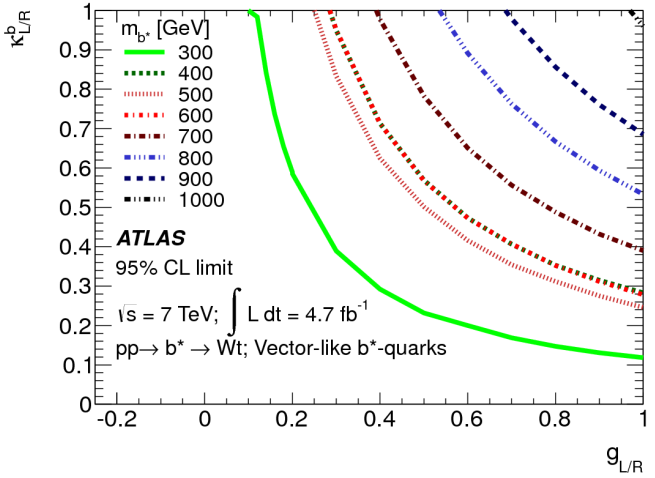




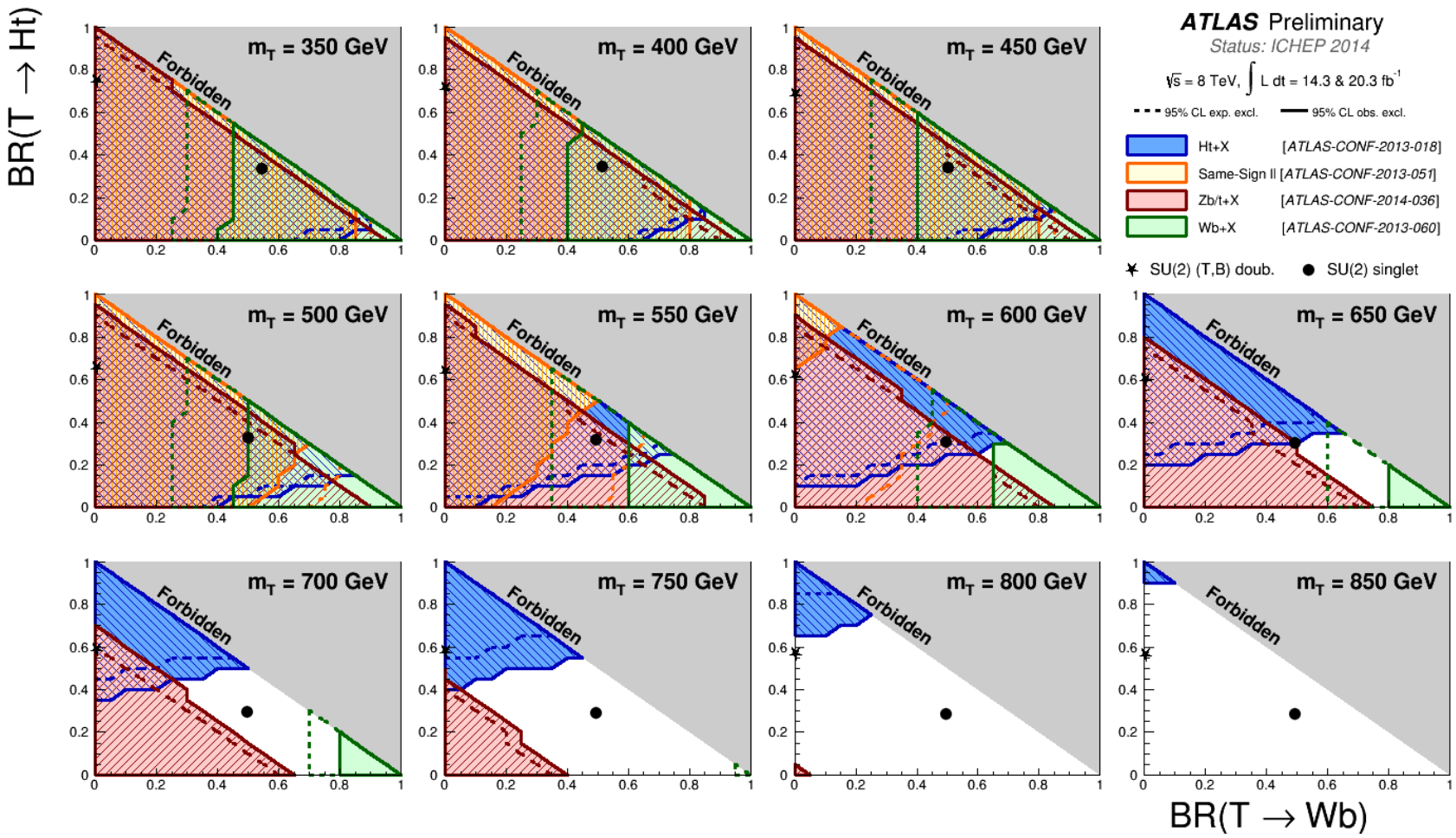


Excited b* search





Combination VLQ T



Combination VLQ B