Searches for vector-like quarks with the ATLAS detector

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On behalf of the ATLAS Collaboration

SUSY2016 at The University of Melbourne
Australia
3-8 July 2016

Vector-Like Quarks

- Many models beyond the Standard Model predict the existence of vector-like quarks (VLQ) to cancel the quadratic divergences arising from radiative corrections of Higgs mass
  - e.g. Little Higgs, Composite Higgs, Extra-dimensions, etc
- VLQ: spin 1/2, color-triplet, L&R-handed components under SU(3)xSU(2)xU(1)
  - Mix with SM quarks by Yukawa coupling, and allowed from experimental constraints (EW/Higgs measurement) unlike 4th generation of quarks

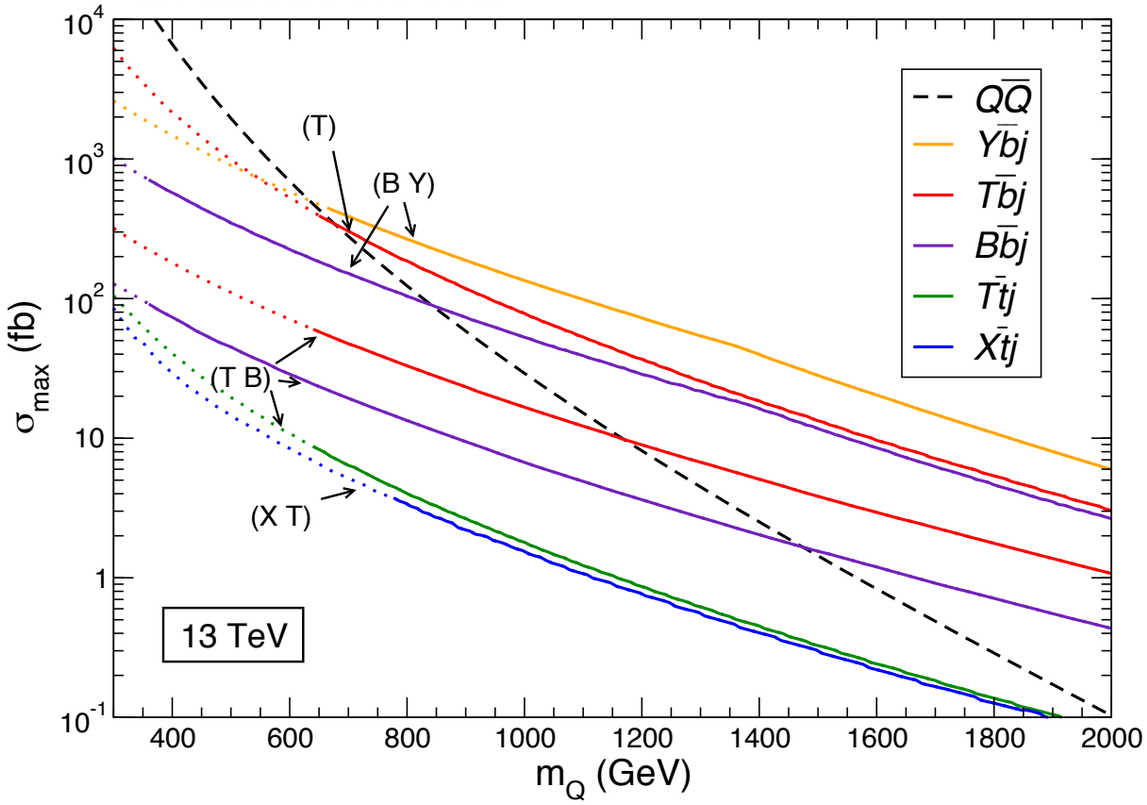
		SM	SU(2) Singlet	SU(2) Doublet	SU(2) Triplet
EM charge	5/3			$\begin{pmatrix} X \\ T \end{pmatrix}$	$\begin{pmatrix} X \\ T \\ B \end{pmatrix}$
	2/3	$\begin{pmatrix} u \\ d \end{pmatrix}\begin{pmatrix} c \\ s \end{pmatrix}\begin{pmatrix} t \\ b \end{pmatrix}$	(T)	$\begin{pmatrix} T \\ B \end{pmatrix}$	
	-1/3		(B)	$\begin{pmatrix} B \\ Y \end{pmatrix}$	$\begin{pmatrix} T \\ B \\ Y \end{pmatrix}$
	-4/3				
Mass		from Higgs	e.g.) generated by Yukawa coupling to a scalar singlet with VEV v' >> v(=246 GeV)		

Production & Decay

Production

- Pair production via strong interaction
  - Higher cross-section at low mass
  - Depends on just mass (model independent)
- Single production via EW interaction
  - Dominant at high mass
  - Depends on mass, mixing-angle, EM charge (more model dependent)

arXiv:1306.0572

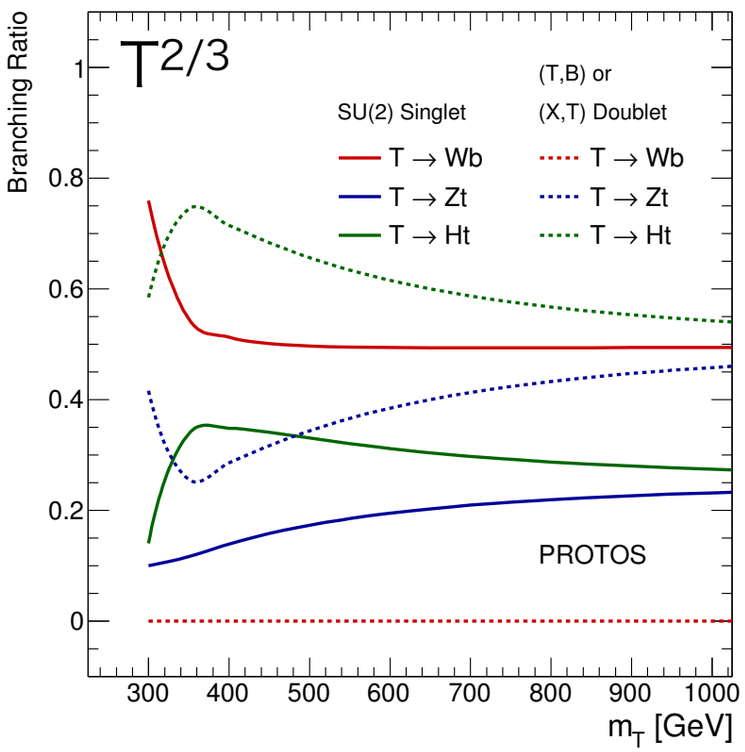


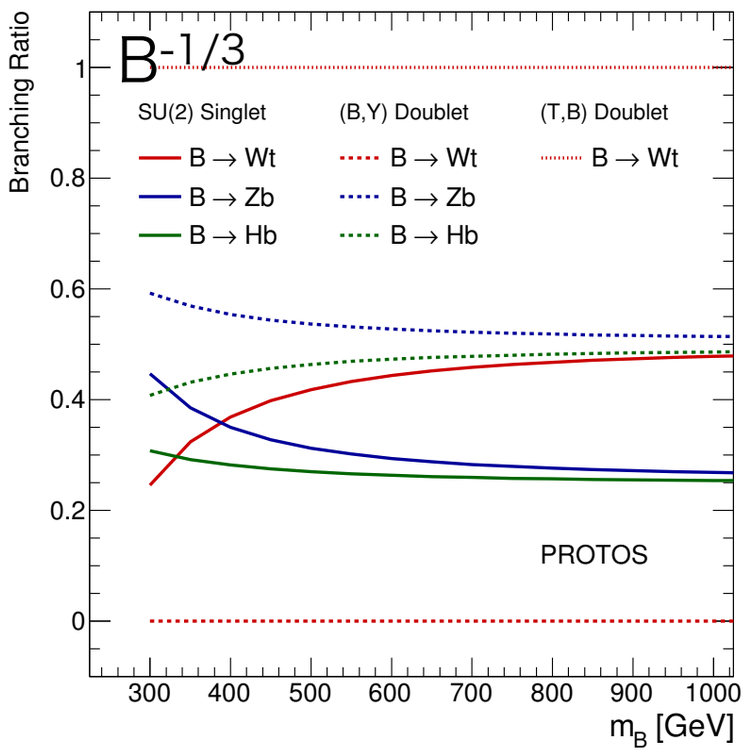
Decay

Coupling with SM quarks
(FCNC decays are allowed)

- $T^{2/3} \rightarrow$ Wb, Zt, Ht
- $B^{-1/3} \rightarrow$ Wt, Zb, Hb
- $T^{5/3} \rightarrow$ Wt
- $Y^{-4/3} \rightarrow$ Wb

arXiv:1505.04306

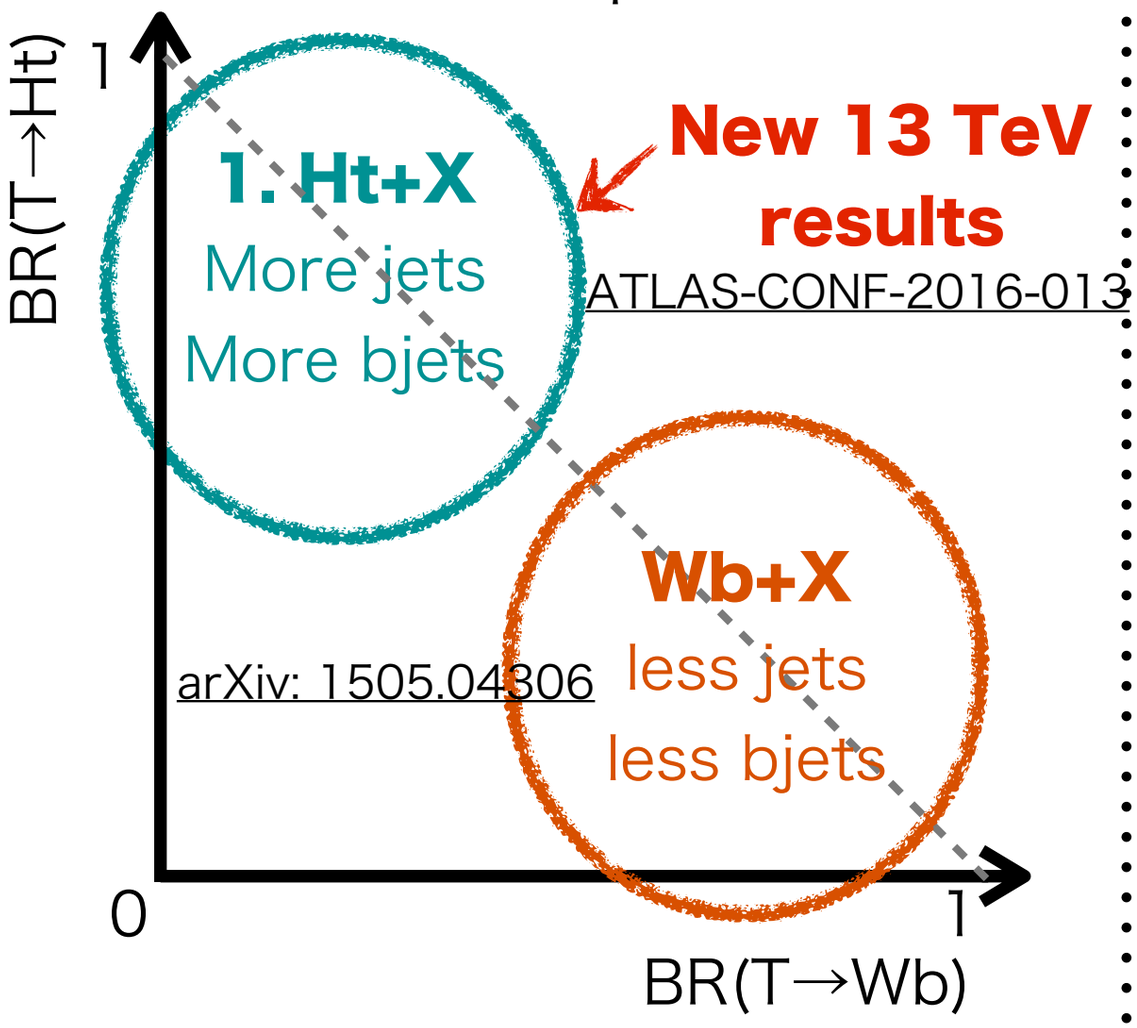




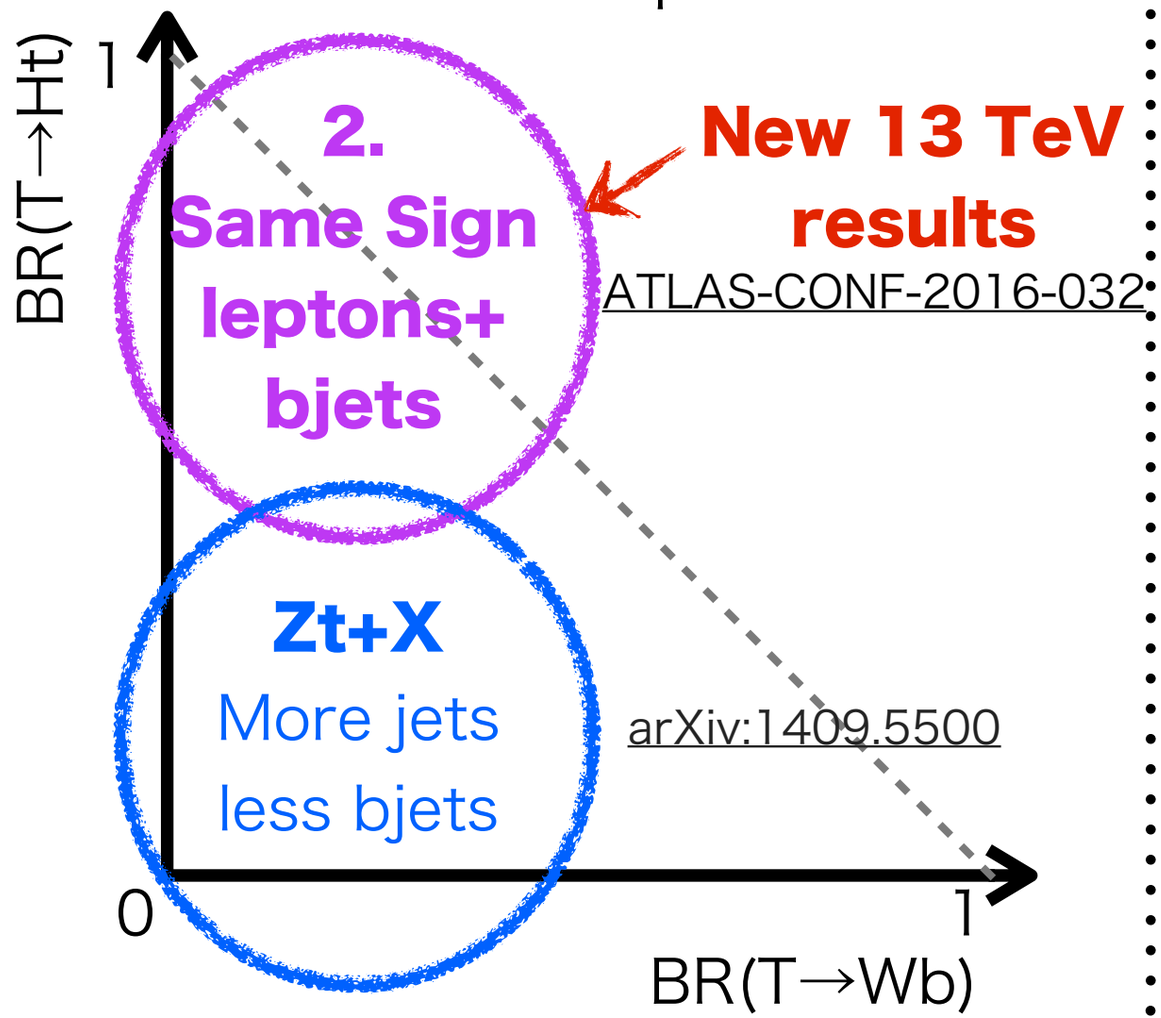
Search for VLT at ATLAS

Pair Production

One lepton



Multi-lepton



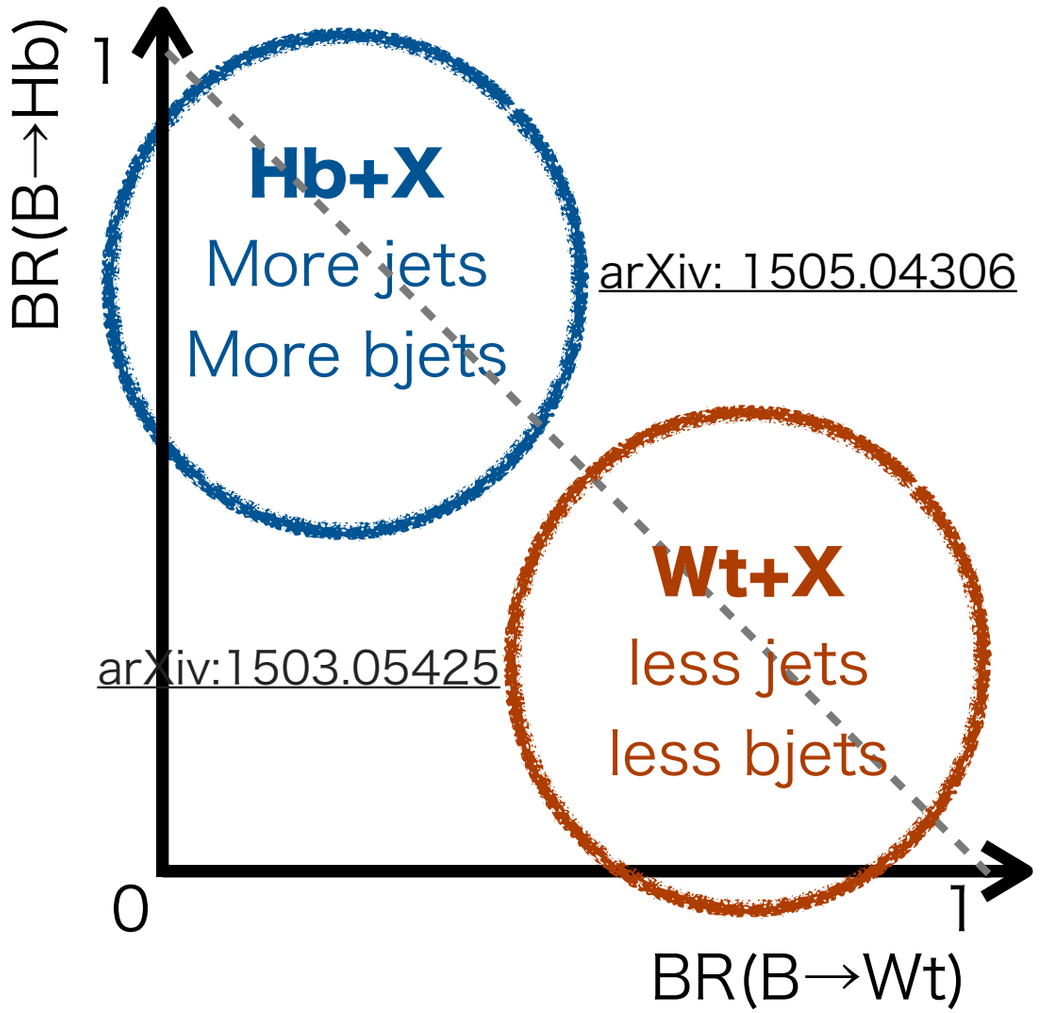
Single Production

- 3. T→Wb arXiv: 1602.05606 ← **New 8 TeV results**
- T→Zt arXiv:1409.5500

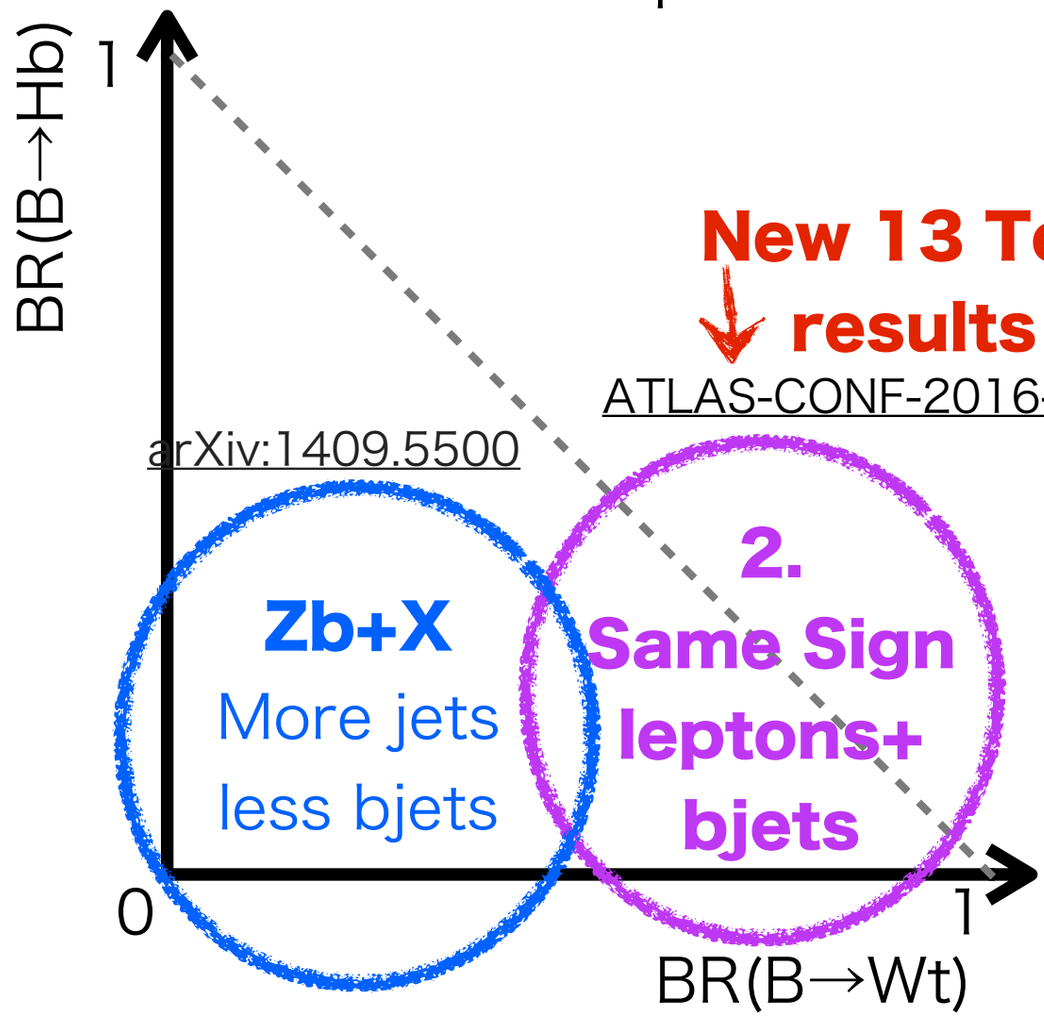
Search for VLB at ATLAS

Pair Production

One lepton



Multi-lepton

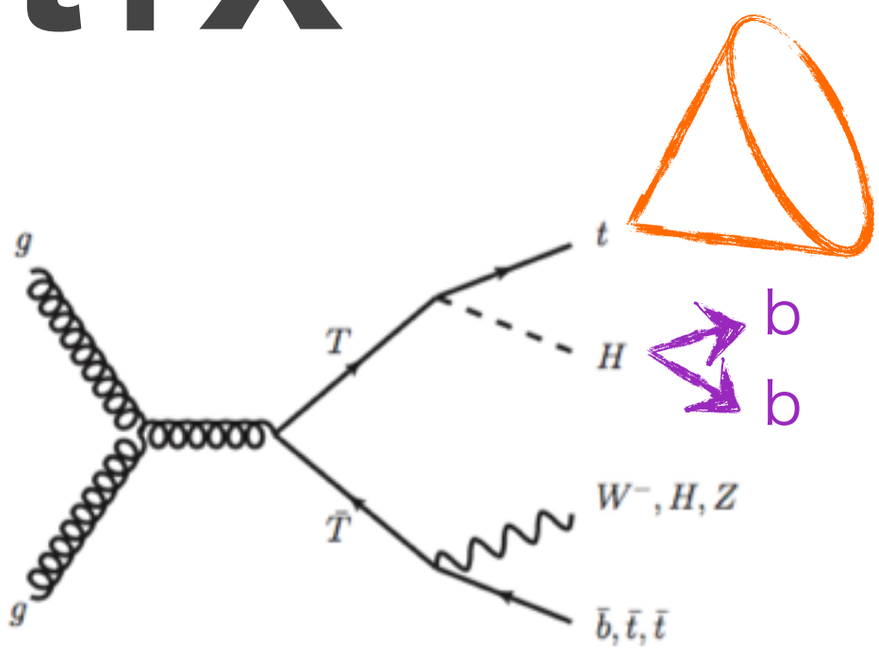


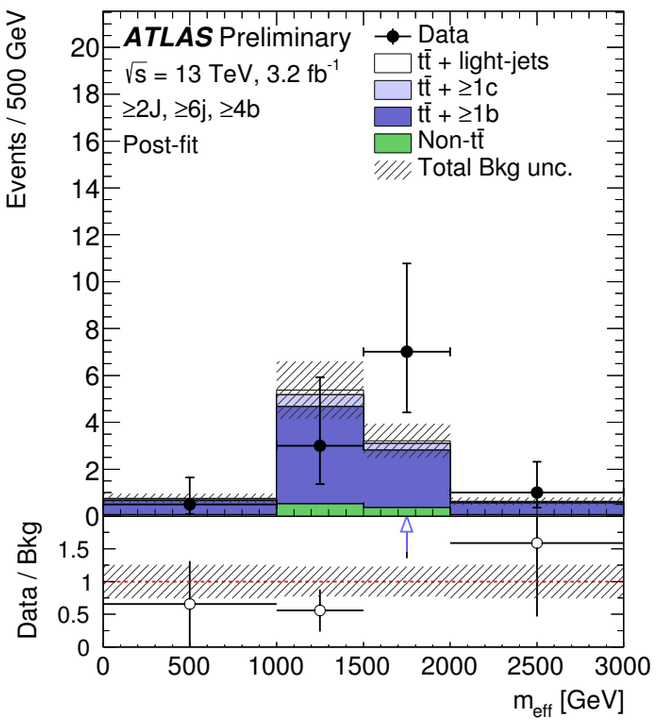
Single Production

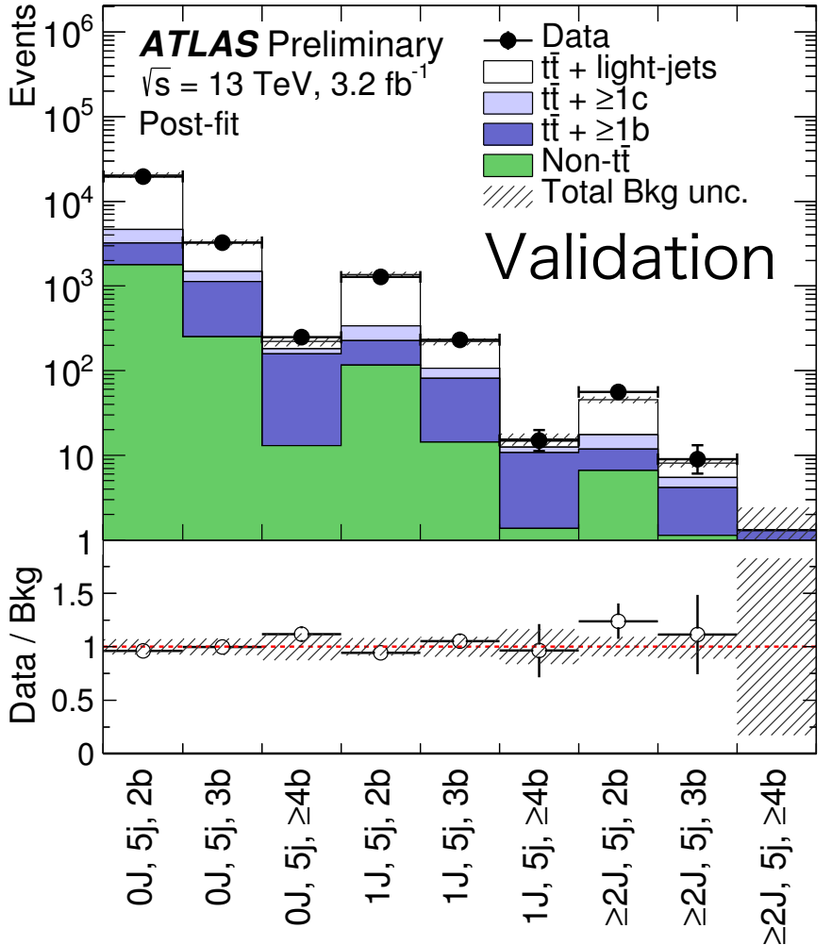
- B→Wt arXiv: 1510.02664 ← **New 8 TeV results**
- B→Zb arXiv:1409.5500

1. TT → Ht+X

- **New result with 13 TeV data (3.2 fb^{-1})**
- Sensitivity: VLT, (B)SM 4-top production
- Simple Pre-selection
  - 1 lepton, ≥5 jets, ≥2 bjets,
    E_T^{miss} > 30 GeV, E_T^{miss} + M_T^W > 60 GeV
- Event classification : N_{jet}, N_{bjets}, $N_{mass\text{-}tagged}$
  - mass-tagged jet : Large-R(R=1.0) jet
    with m > 100 GeV, p_T > 300 GeV, $|\eta| < 2.0$
    - To identify collimated heavy objects (higgs, tops)
- Fitting m_{eff}
  (= $\Sigma p_T^{jets} + p_T^{lepton} + E_T^{miss}$)
  - 5jets ... Validation
    - Good agreement between data and MC
  - ≥6 jets ... CR/SR
    - No excess

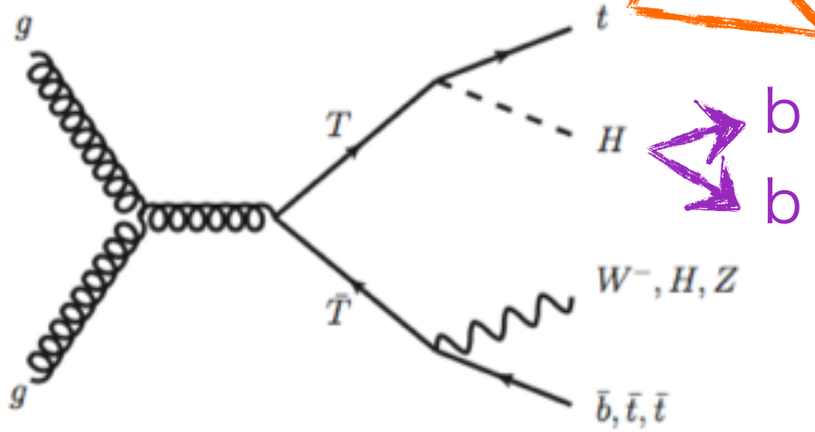




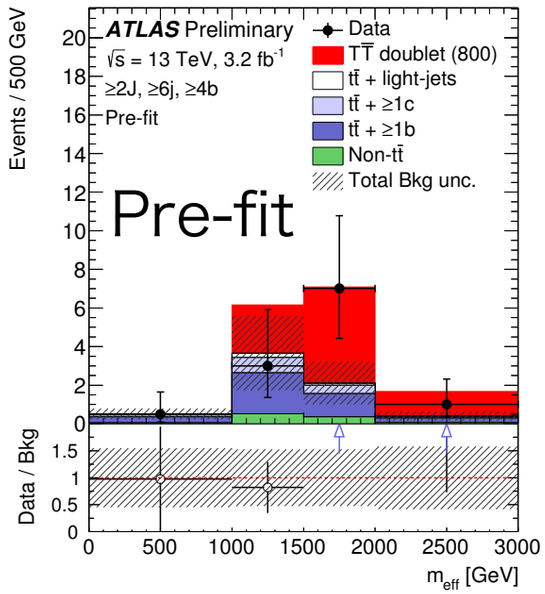


1. TT → Ht+X

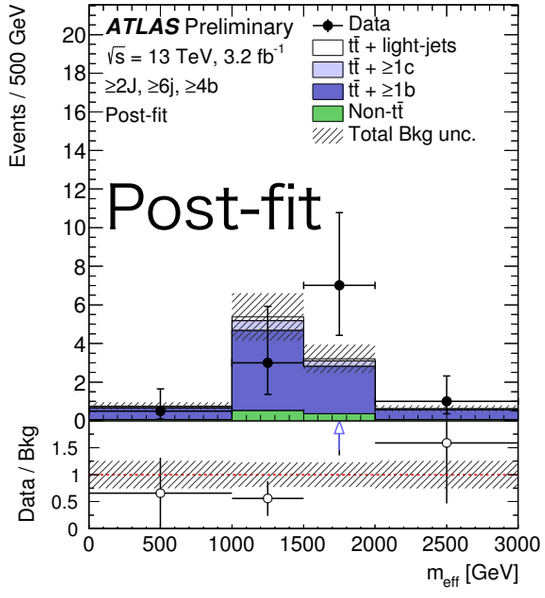
- Main Background
  - tt (using NLO MC simulation)
    - Normalized to NNLO cross section (832 pb)
    - Events categorized according to flavor content
      tt+light, tt+cc and tt+bb
    - tt+bb is dominant background for the most sensitive region



- Dominant Systematic Uncertainty
  - tt+jets (mainly tt+bb)
    - Normalization (tt+bb and tt+cc uncorrelated): 50%
    - m_{eff} Shape (including PDF, scale variation, ...)
    - Fit the m_{eff} distribution to data
      → Reduce the uncertainty significantly
      e.g. 55% → 24% for the most sensitive region



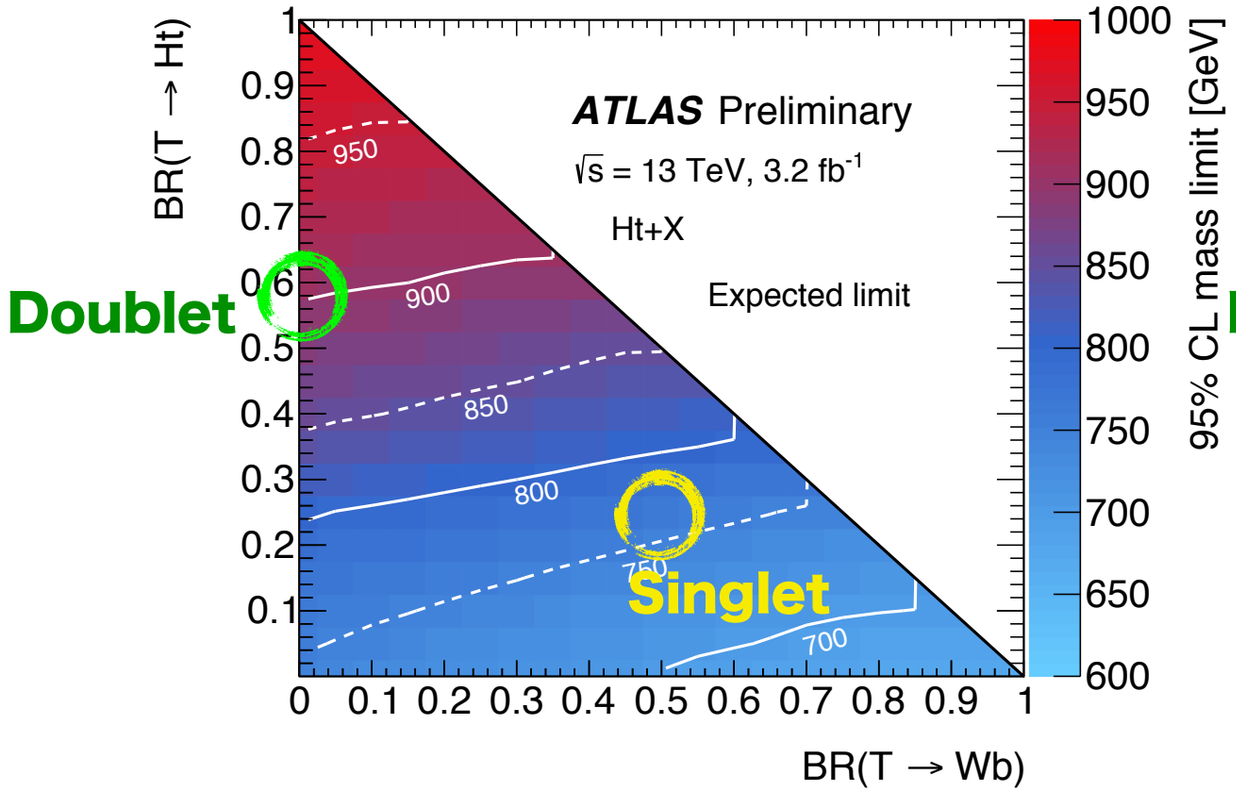
55%

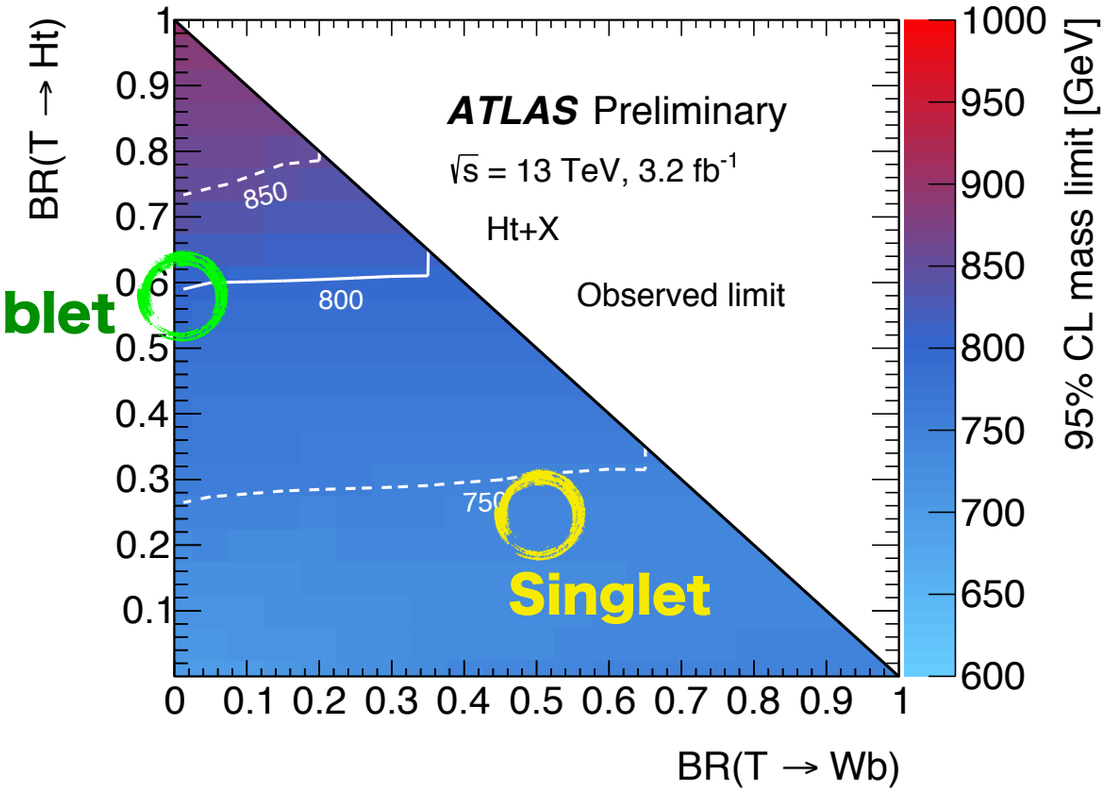


24%

1. TT → Ht+X

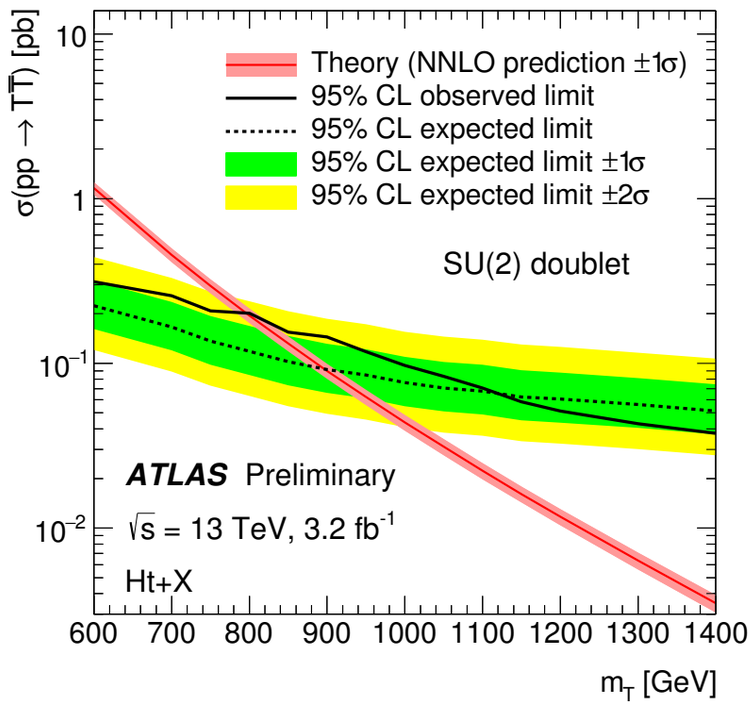
- Limit Setting





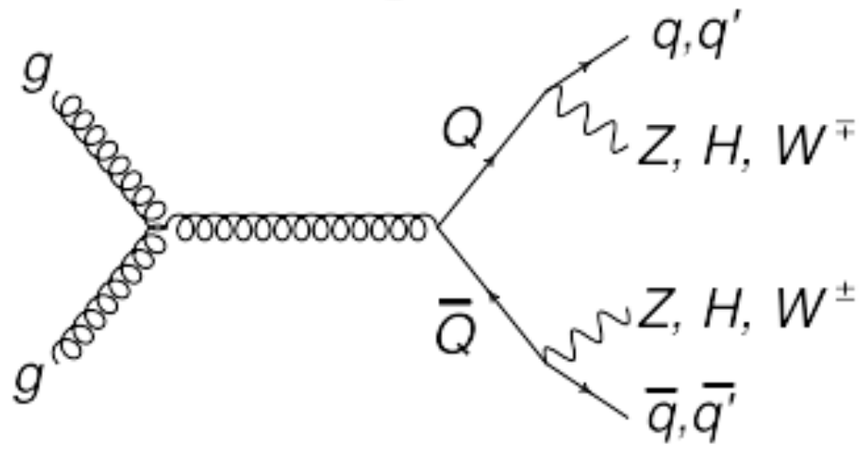
obs.(exp.)

- Doublet: m_T > 800(900) GeV
  Run1 .... 854(819)
- Singlet: m_T > 750(780) GeV
  Run1 ... 766(722)
- Improved the sensitivity by ~80 GeV
- 4-top results: see Rui's talk (link)

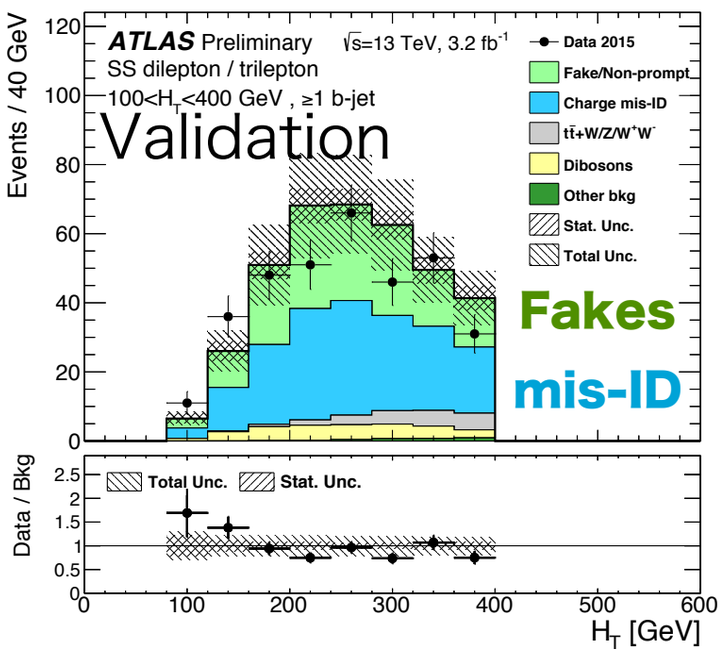


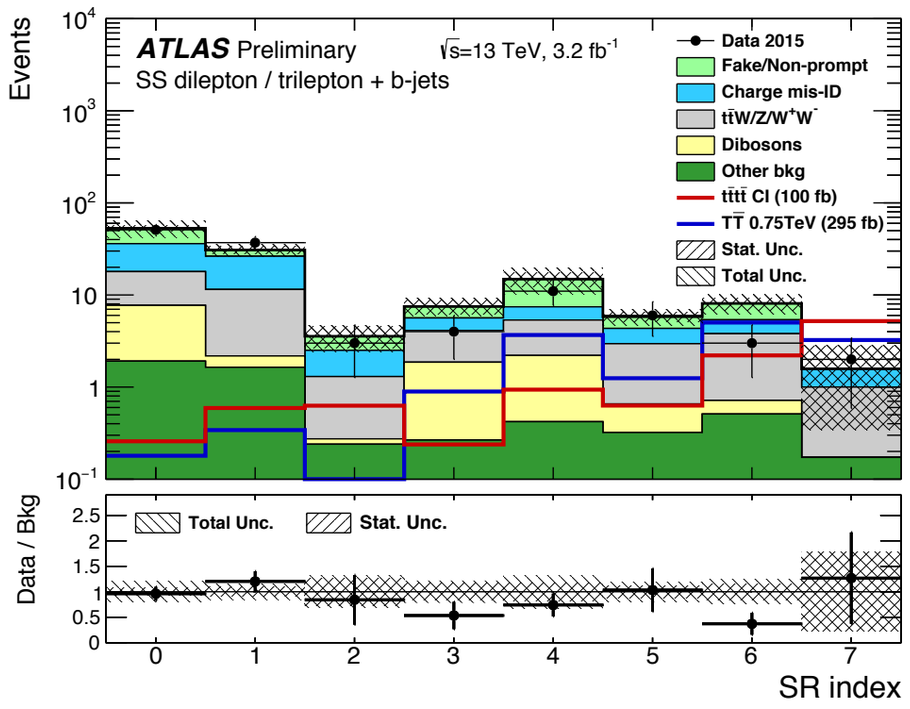
2. SS dilepton + bjets

- **New result with 13 TeV data (3.2 fb^{-1})**
- Sensitivity
  - $T^{2/3}\,T^{2/3}$, $B^{-1/3}\,B^{-1/3}$, $T^{5/3}\,T^{5/3}$ (→WtWt)
  - 4-top production (SM, BSM)
- Event Selection (Right table)
- Main Background:
  - Physics: tt+W/Z (Use MC simulation)
  - Detector: charge mis-ID & fakes
    - Data-driven estimate
    - Good agreement
- Count Analysis
  - No excess
  - Set the limit

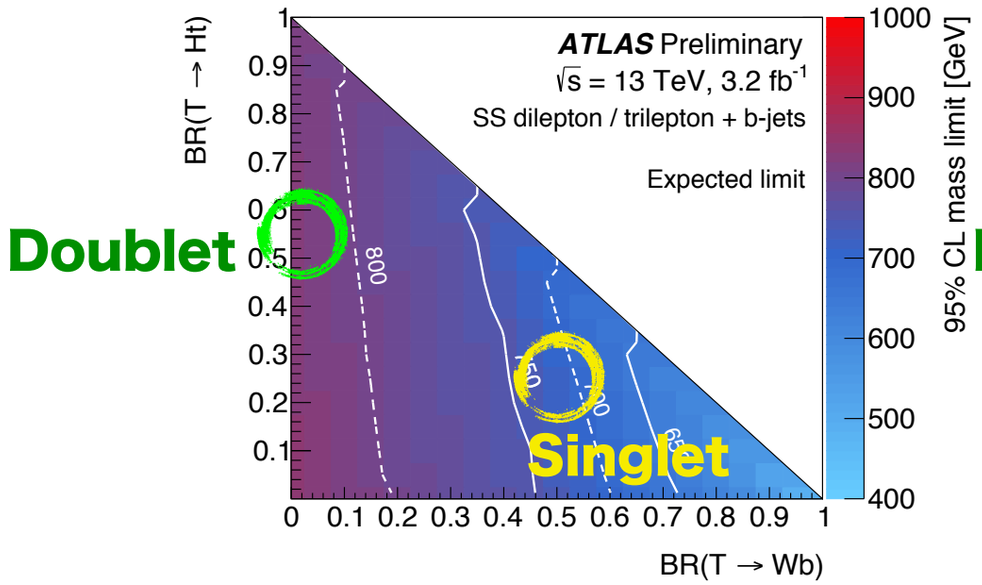


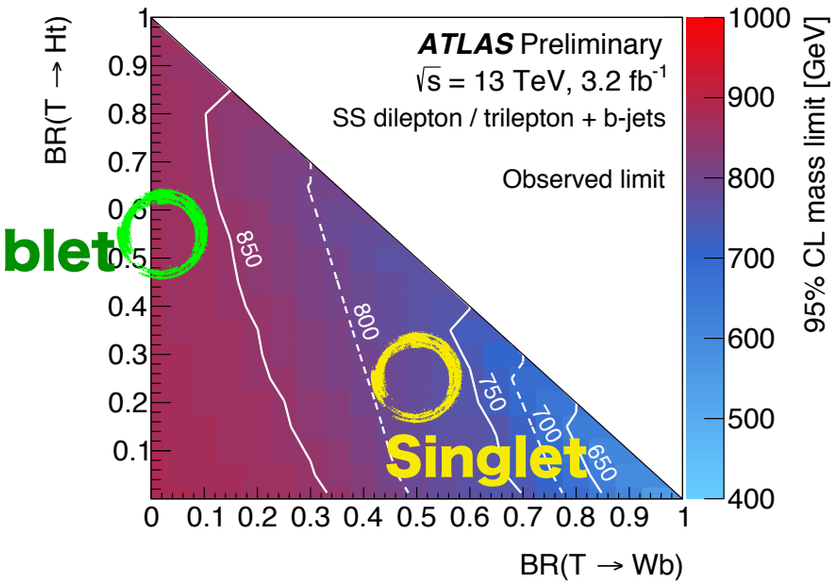
Definition			Name
$e^{\pm}e^{\pm} + e^{\pm}\mu^{\pm} + \mu^{\pm}\mu^{\pm} + eee + ee\mu + e\mu\mu + \mu\mu\mu$, $N_{\text{jets}} \geq 2$			
$400 < H_{\text{T}} < 700GeV$	$N_b = 1$	$E_{\text{T}}^{\text{miss}} > 40$ GeV	SR0
	$N_b = 2$		SR1
	$N_b \geq 3$		SR2
$H_{\text{T}} \geq 700\ GeV$	$N_b = 1$	$40 < E_{\text{T}}^{\text{miss}} < 100GeV$	SR3
		$E_{\text{T}}^{\text{miss}} \geq 100\ GeV$	SR4
	$N_b = 2$	$40 < E_{\text{T}}^{\text{miss}} < 100GeV$	SR5
		$E_{\text{T}}^{\text{miss}} \geq 100\ GeV$	SR6
	$N_b \geq 3$	$E_{\text{T}}^{\text{miss}} > 40$ GeV	SR7

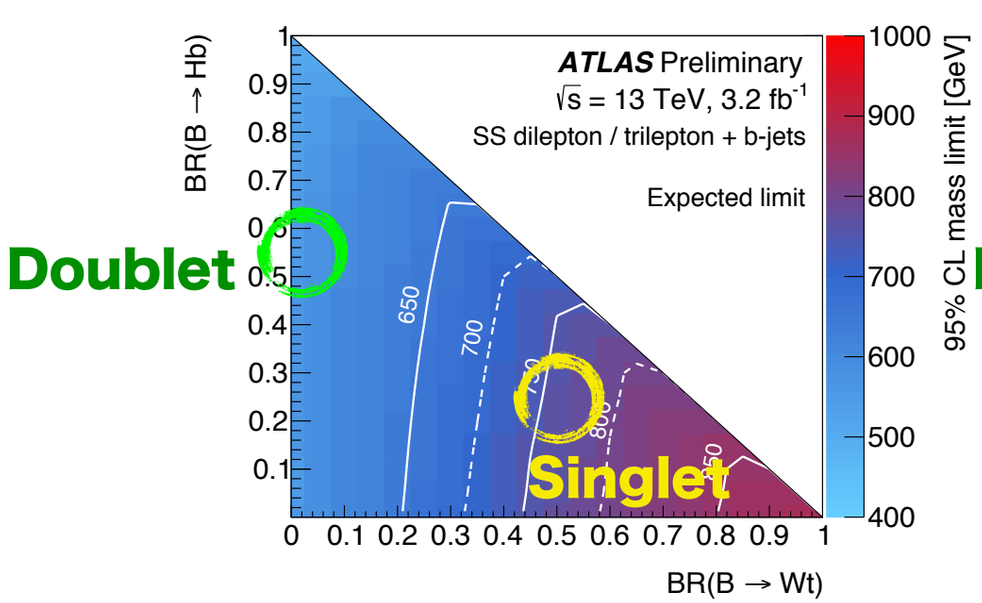


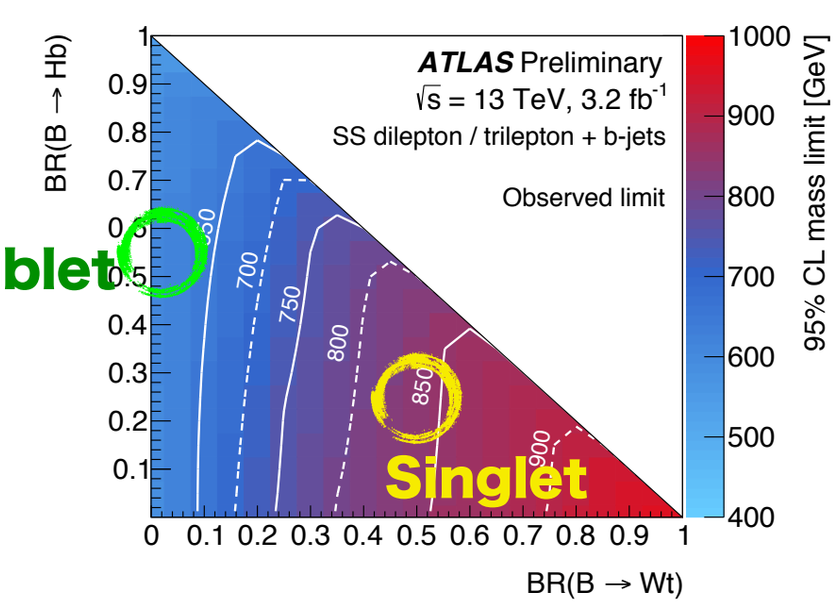


2. SS dilepton + bjets









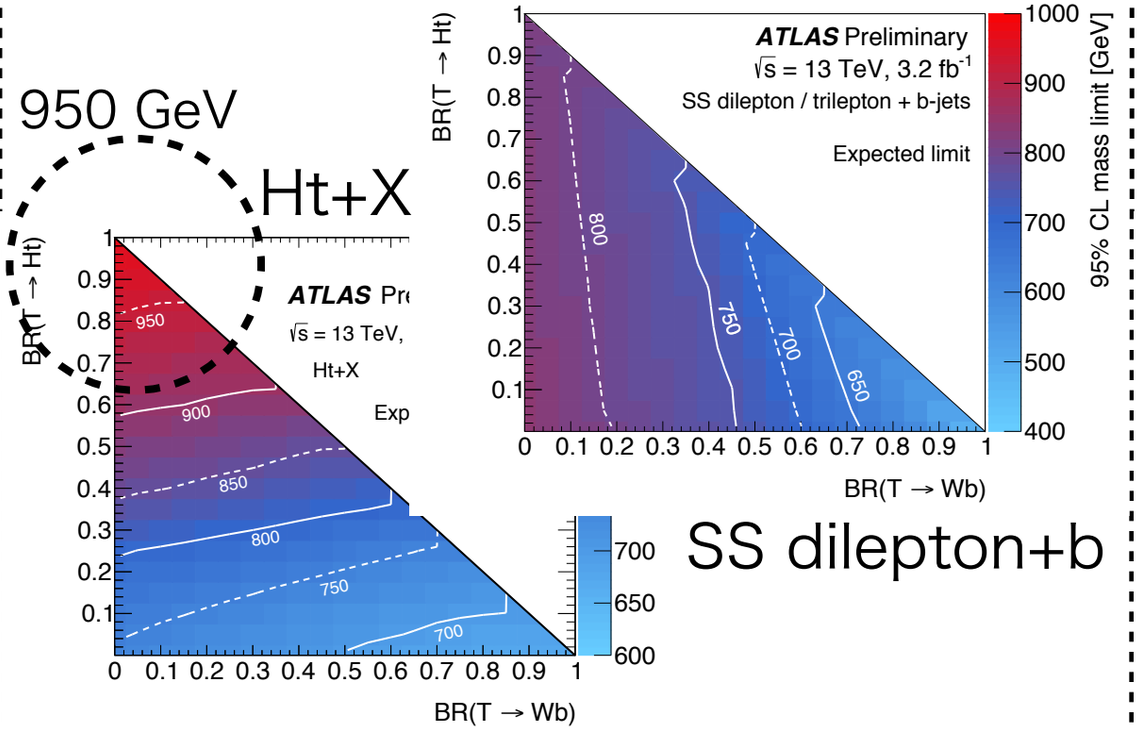
- Singlet: m_T > 780 (730) GeV & m_B > 830 (750) GeV ↑ Improved the sensitivity
  Run1 590 (660) GeV 620 (690) GeV ↑ by ~60 GeV
- Interpretation for $T^{5/3}$: $m_{T5/3}$ > 990 (920) GeV
- For 4top: σ_{SM} < 95 (107) fb, σ_{BSM} < 67 (79) fb (see Rui's talk (link))

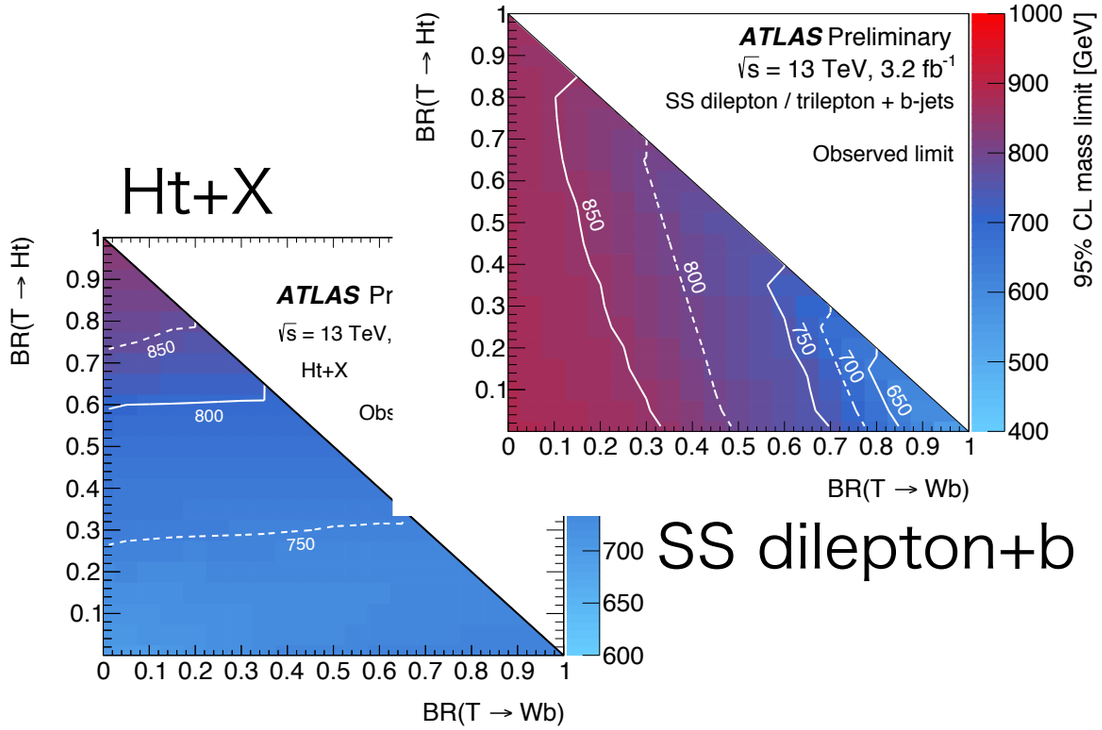
VLT mass limit (pair production)

Expected

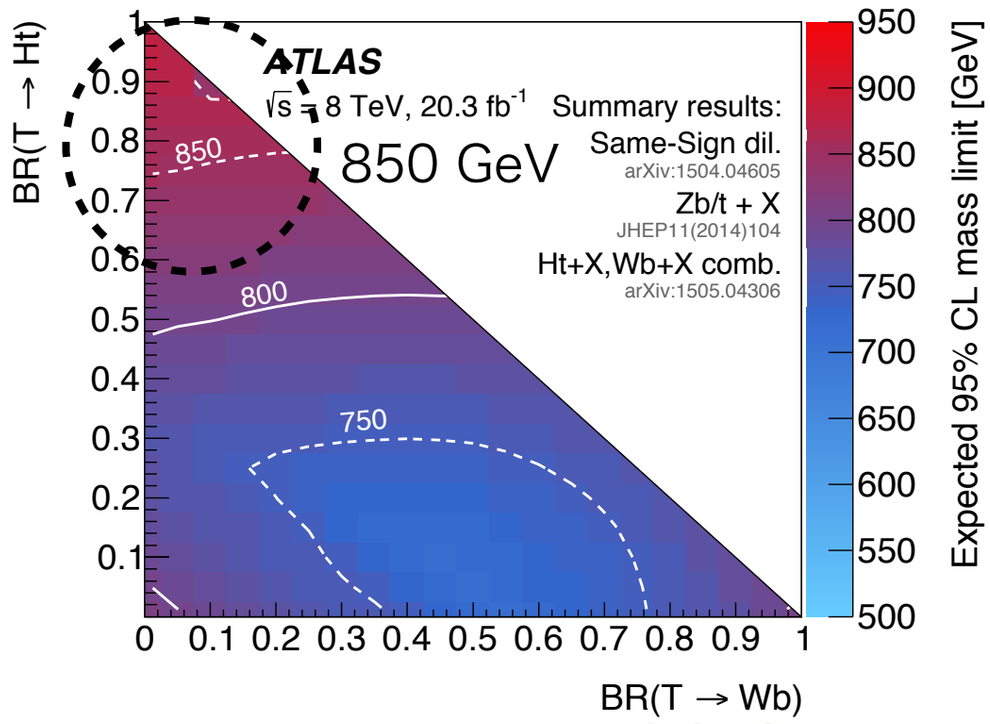
Observed

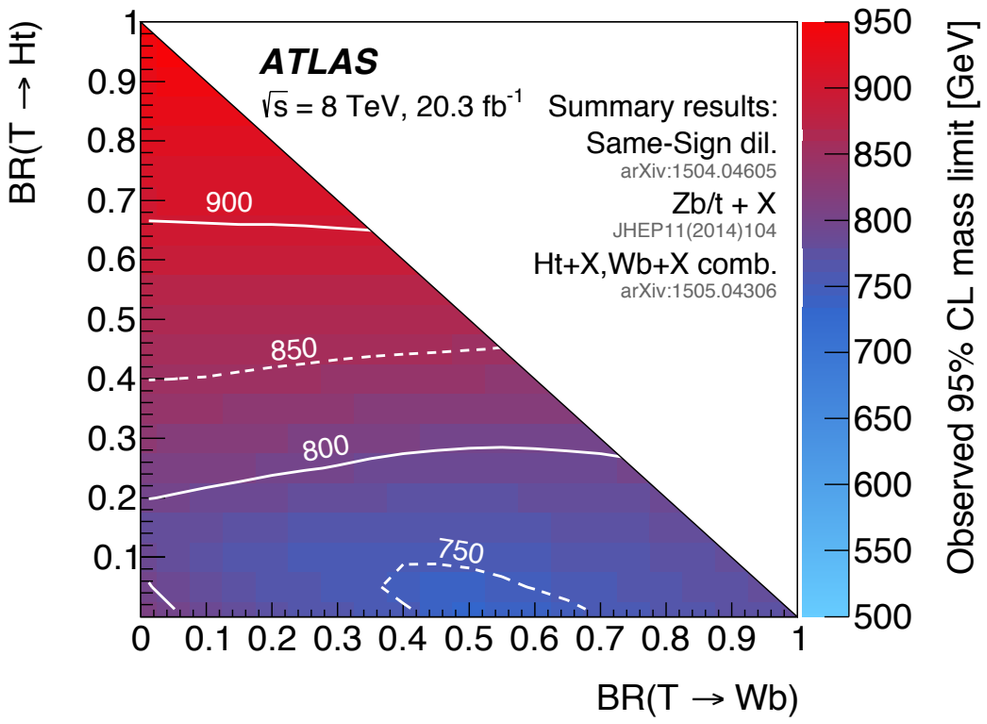
13 TeV





8 TeV





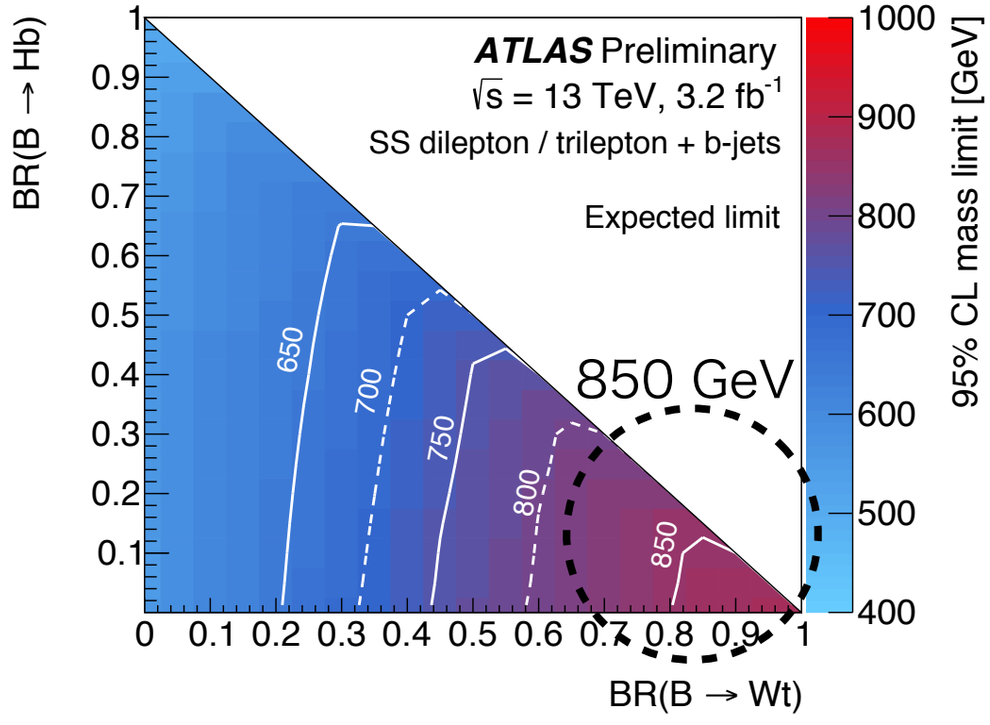
Improved by ~100 GeV

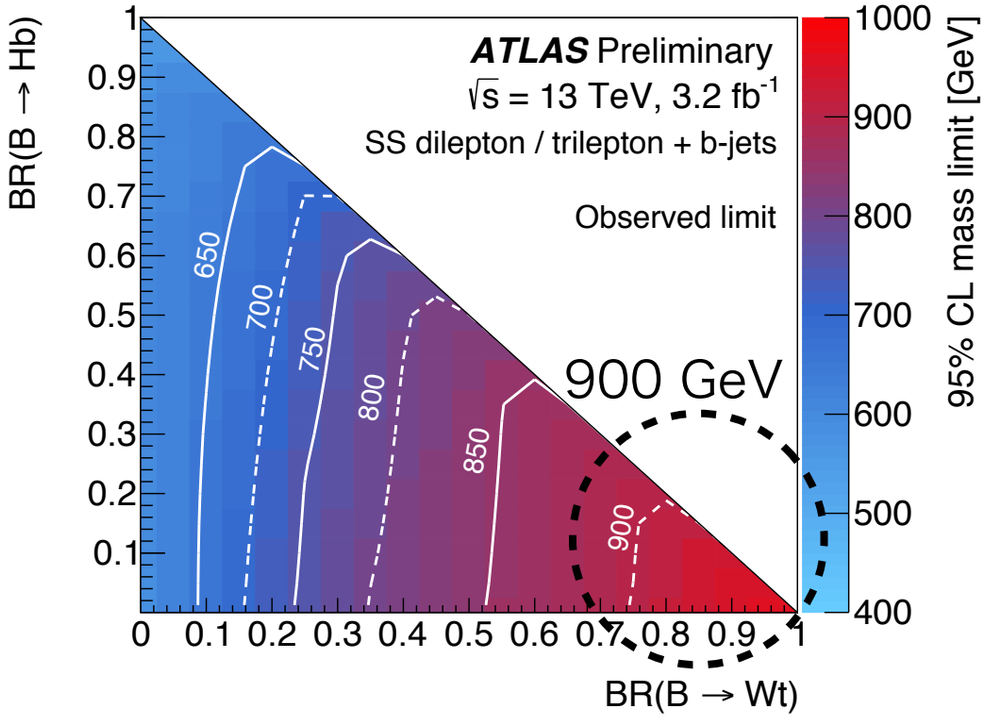
VLB mass limit (pair production)

Expected

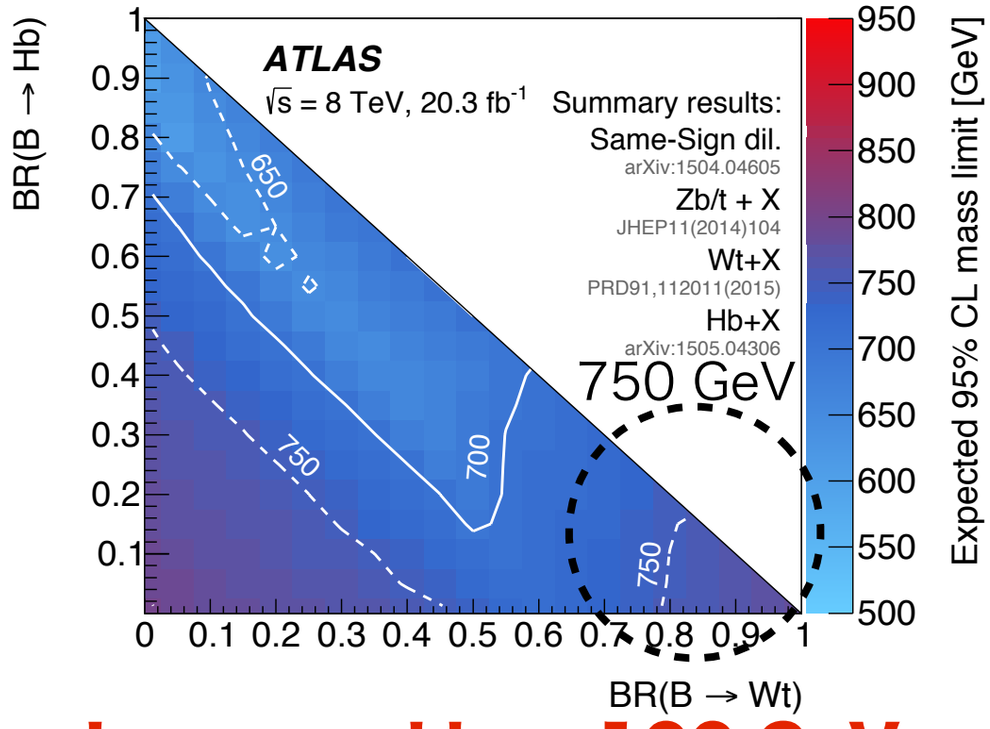
Observed

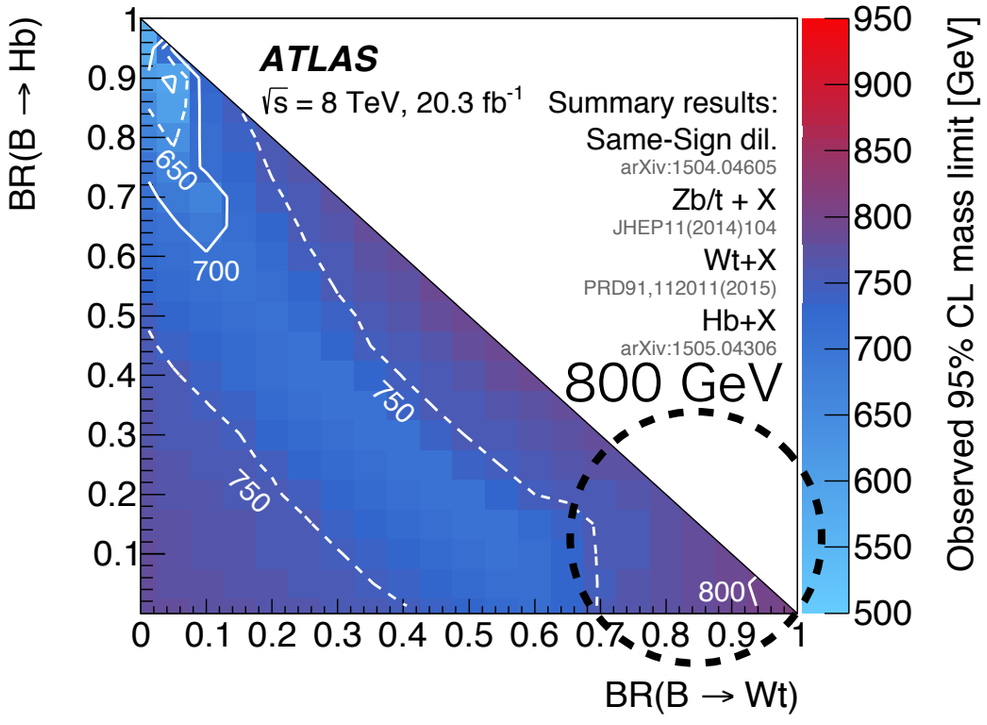
13 TeV





8 TeV

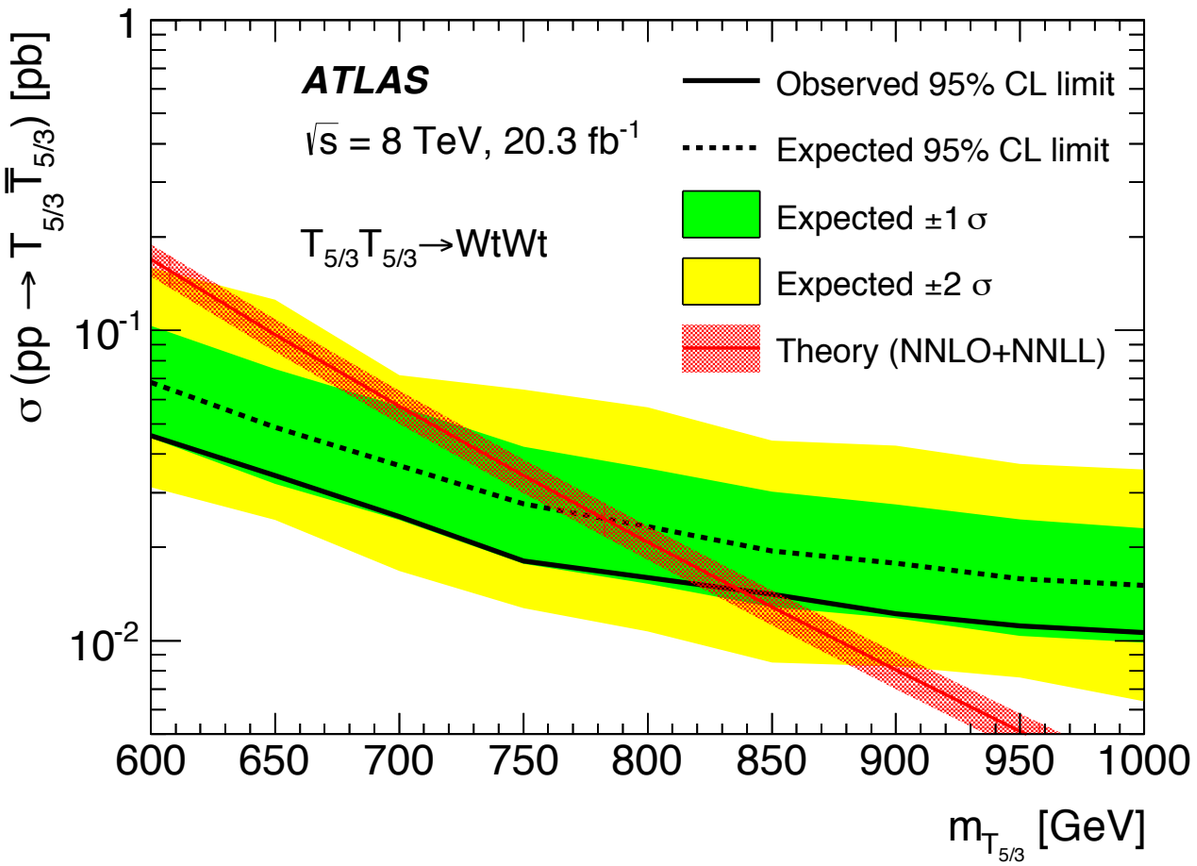


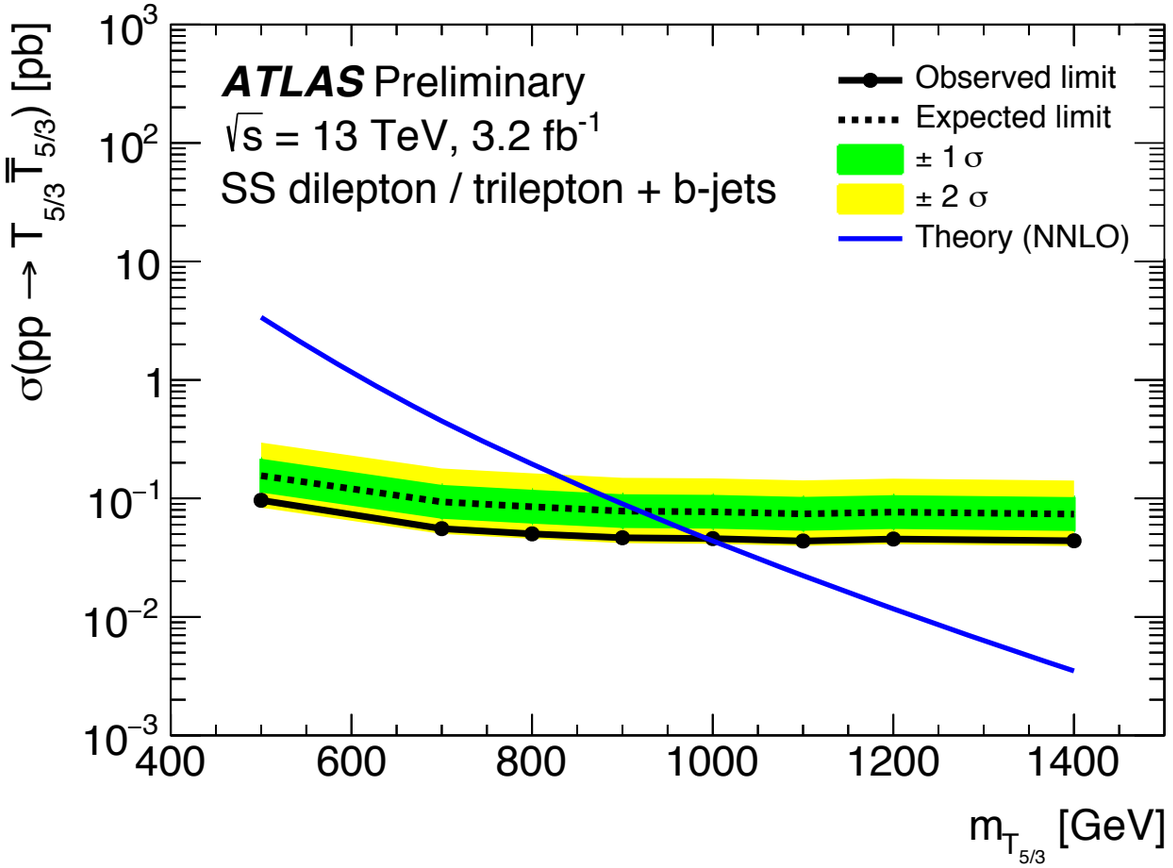


Improved by ~100 GeV

$T^{5/3}$ mass limit

- **Result with 8 TeV data (20.3 fb^{-1})**
  - BB→Wt+X has the most sensitivity for $T^{5/3}$
    - $m_{T5/3}$ > 840 (780) GeV
- **Result with 13 TeV data (3.2 fb^{-1})**
  - SS dilepton + bjets
    - $m_{T5/3}$ > 990 (920) GeV





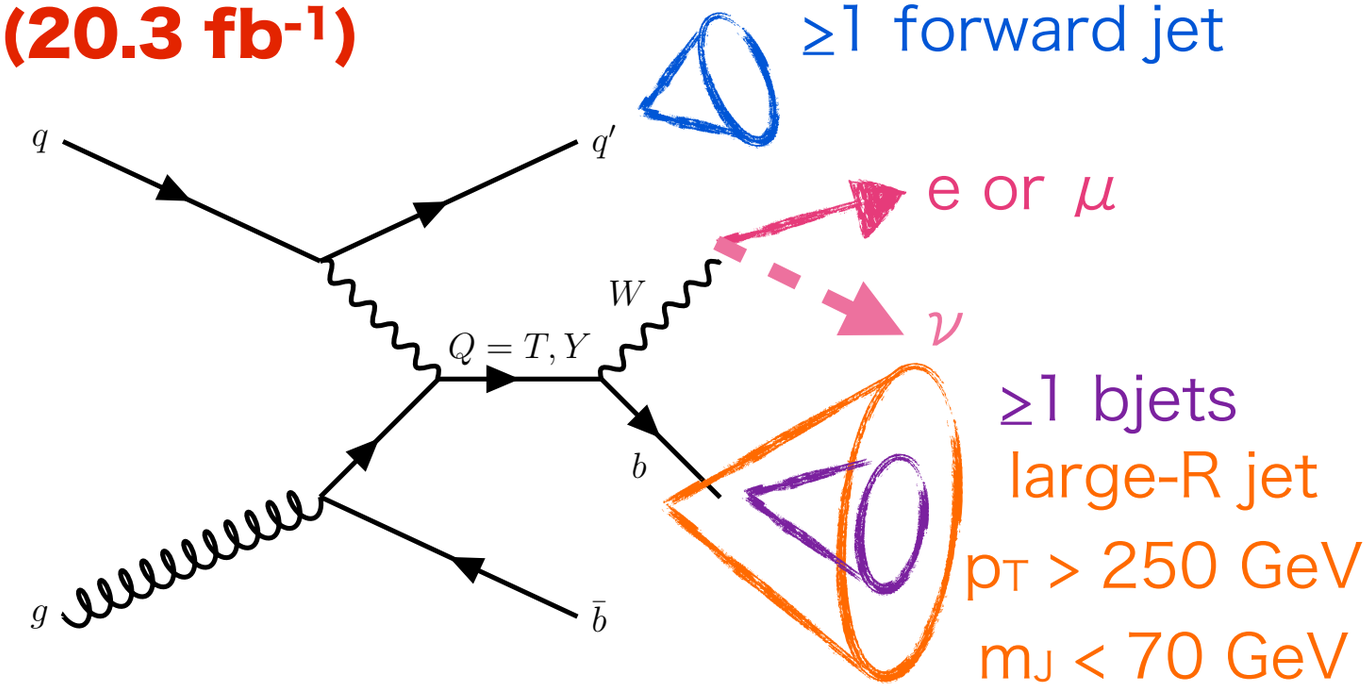
3. T→Wb

- **New results with 8 TeV data (20.3 fb^{-1})**
  arXiv: 1602.05606

- Event selection

  - Pre-selection
    1 lepton, ≥2 jets, ≥1 large-R jet,
    E_T^{miss} > 20 GeV, $E_T^{miss}+M_T^W$ > 60 GeV

  - Signal Region
    $\Delta\phi$ (lep, large-R jet) > 1.5
    Reject events with any jets with p_T > 75 GeV & $|\eta|$ < 2.4 outside large-R jet

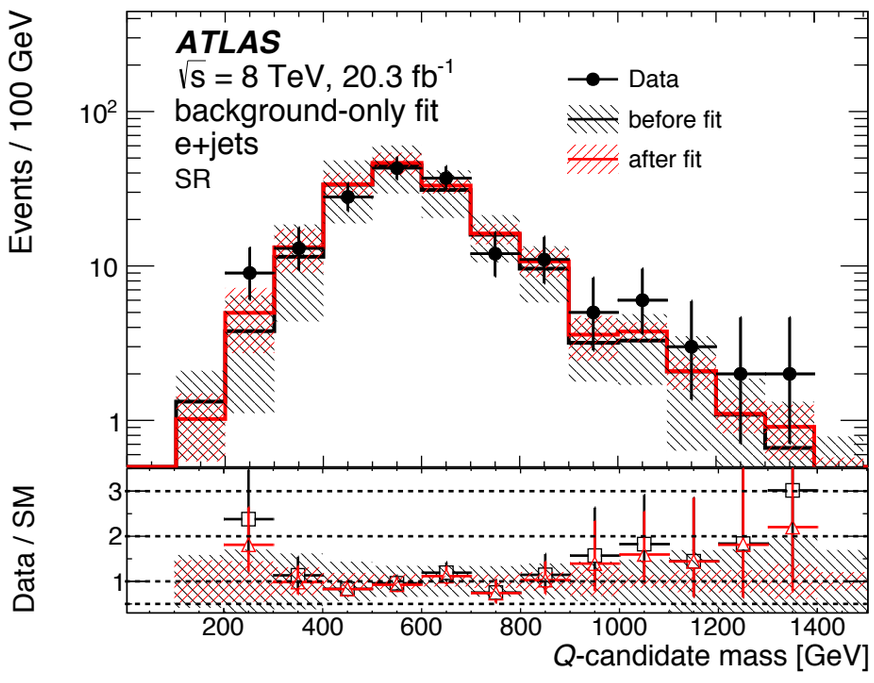


- Fit the m(Q), reconstructed with leptonic W and bjet

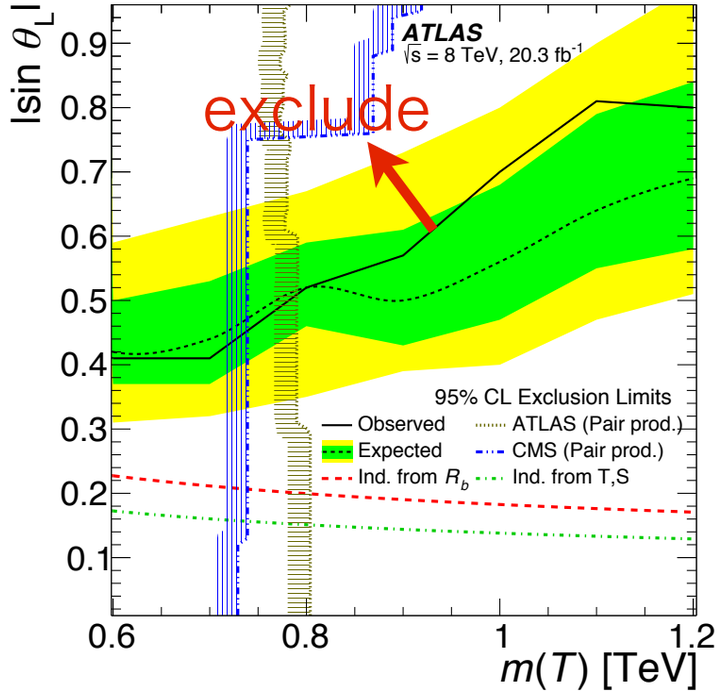
- Systematic Uncertainty

  - tt, W+jets normalization
  - Large-R jet uncertainties

- No excess
  Set exclusion limit
  on the plane of
  mixing angle and VLT mass



mixing angle between T and t



QQ → WqWq

- **New result with 8 TeV data (20.3 fb^{-1})**
  arXiv: 1509.04261

- Pair production of vector-like light flavor quark(Q) decaying to Wq

- Event selection

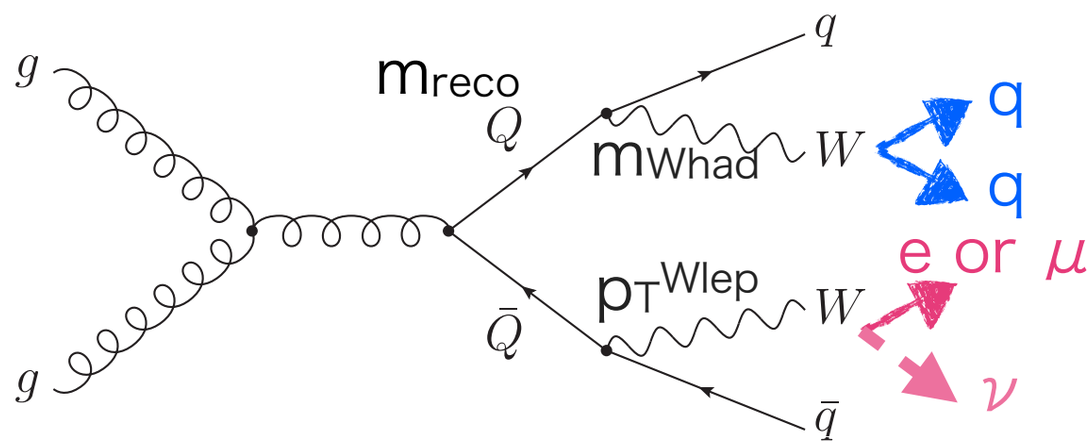
  - 1lepton, ≥4 non b-jets(bjet veto),
    E_T^{miss} > 30 GeV, E_T^{miss}+M_T^W > 60 GeV

  - 1st leading p_T^{qjet} > 160 GeV
    2nd leading p_T^{qjet} > 120 GeV

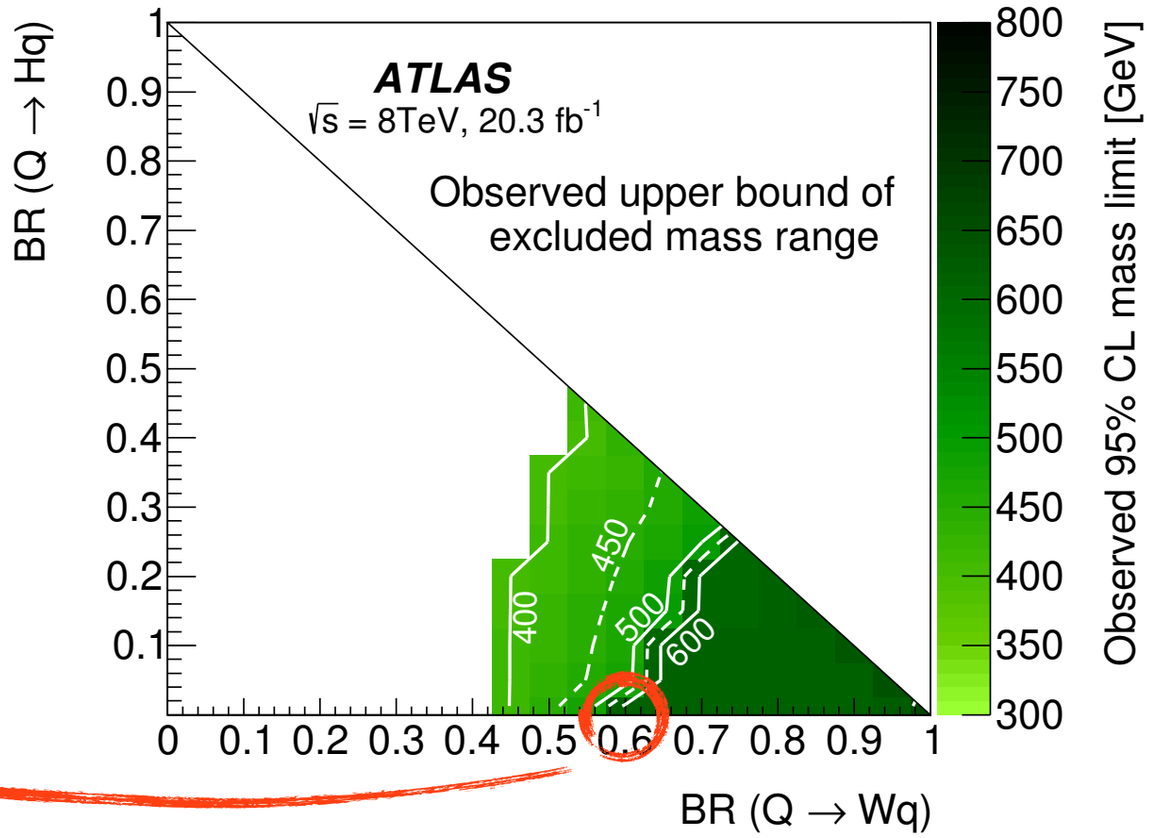
  - $|m_Q - m_Q| < 120$ GeV
    $2.0 < \Delta R(Q, Q) < 4.2$

- Final Discriminant: m_{reco} (hadronic Q mass)

- No significant excess
  Limit : m_Q > 610 (690) GeV
  ($BR_{(Q\to Wq)}$ = 0.6, $BR_{(Q\to Zq)}$ = 0.4)



65 < m_{Whad} < 100 GeV
p_T^{Wlep} > 125 GeV
p_T^{lep} + E_T^{miss} + p_T^{Whad} + p_T^{qjets} > 1100 GeV



Summary

- Searches for vector-like quarks have been carried out with different final states at ATLAS in Run1&2, including pair and single production

- Analysis strategies are optimized for each channel. ATLAS results have been published with 20 fb^{-1}(Run1 8 TeV) and with 3.2 fb^{-1} (Run2 13 TeV)
  VLQs have NOT been discovered so far

		SU(2)Singlet Obs.(Exp.)	SU(2) Doublet Obs.(Exp.)
$T^{2/3}$	13 TeV	780 (730) GeV ...SSl+b	800 (900) GeV ...Ht+X
	8 TeV	~800(~750) GeV ...comb	~850(~800) GeV ...comb
$B^{-1/3}$	13 TeV	830 (750) GeV ...SSl+b	~600(~550) GeV ...SSl+b
	8 TeV	~750(~700) GeV ...comb	~750(~750) GeV ...comb
$T^{5/3}$	13 TeV	990 (920) GeV	
	8 TeV	840 (780) GeV	
Q	8 TeV	610 (690) GeV ($BR_{(Q\to Wq)}$ = 0.6, $BR_{(Q\to Zq)}$ = 0.4)	

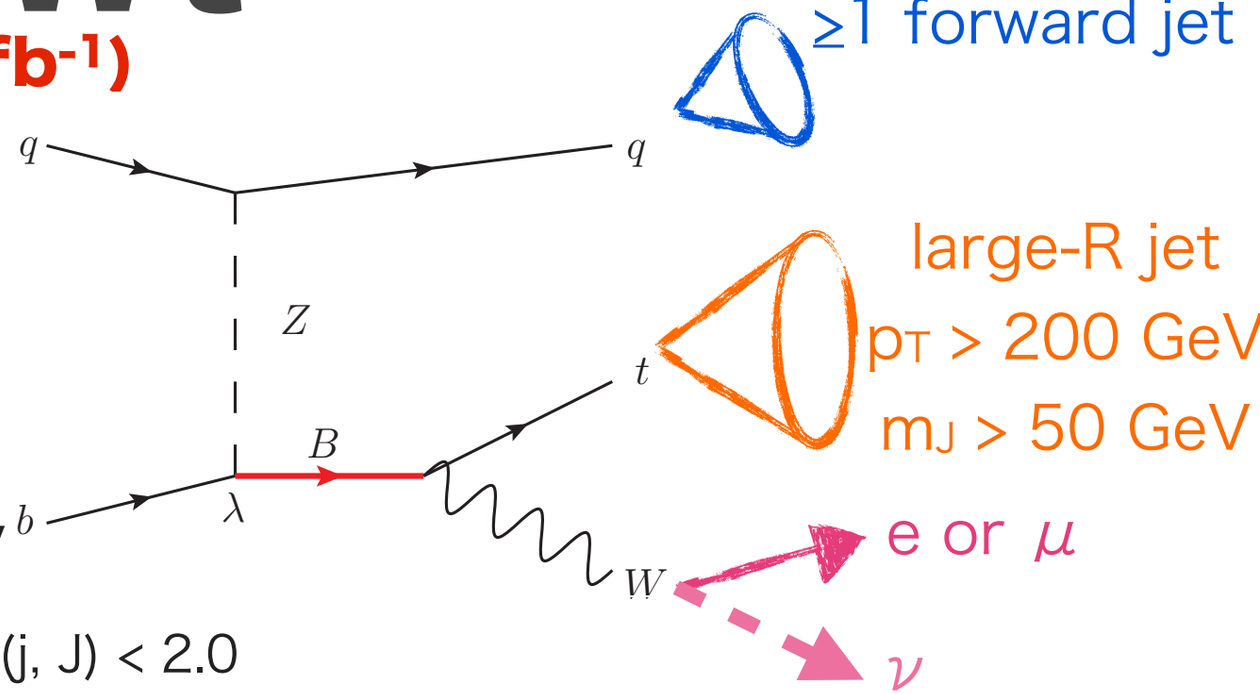
- Many analysis has been carried out with 13 TeV data in Run2
  Stay tuned for new VLQ results!!

Back up

B→Wt

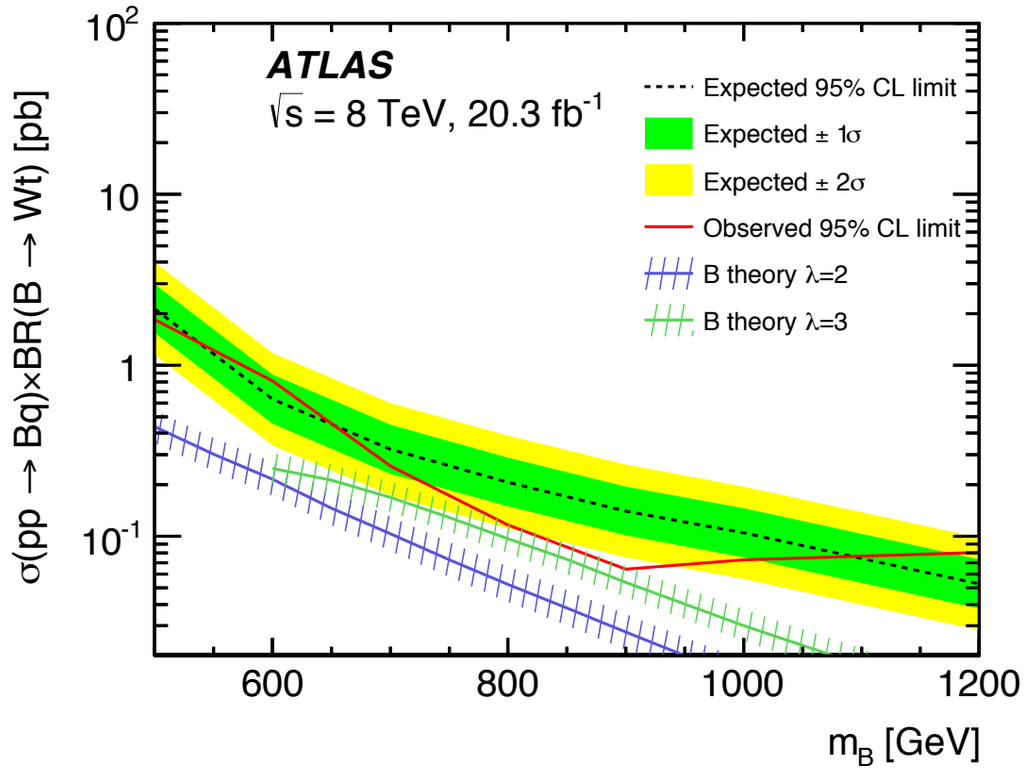
- **New result with 8 TeV data (20.3fb^{-1})**
  arXiv: 1510.02664

- Categorize events
  - 1 lepton, 2 or 3 jets,
    ≥1 large-R jets, $\Delta\phi$(lep, J) > 1.5
    E_T^{miss} > 20 GeV, $E_T^{miss}+M_T^W$ > 60 GeV
    - "1L hadT": minΔR(lep. j) > 1.5 & maxΔR(j, J) < 2.0
      "1L hadW": minΔR(lep. j) < 1.5 & maxΔR(j, J) > 2.0
    - Final discriminant: m_B from jets, lepton, E_T^{miss}
  - 2 leptons $e^{\pm}\mu^{\mp}$
    1 or 2 jets, one b-tagged
    one additional jet with $1.5 < \eta < 4.5$
    "2L 1jet 1tag" or "2L 2jet 1tag"
    - Final discriminant: m_T
      from the leading jet, lepton, E_T^{miss}



- Fit m_B in 1 lepton channel
  and m_T in 2 lepton channel

- No excess and No limit on VLQ mass



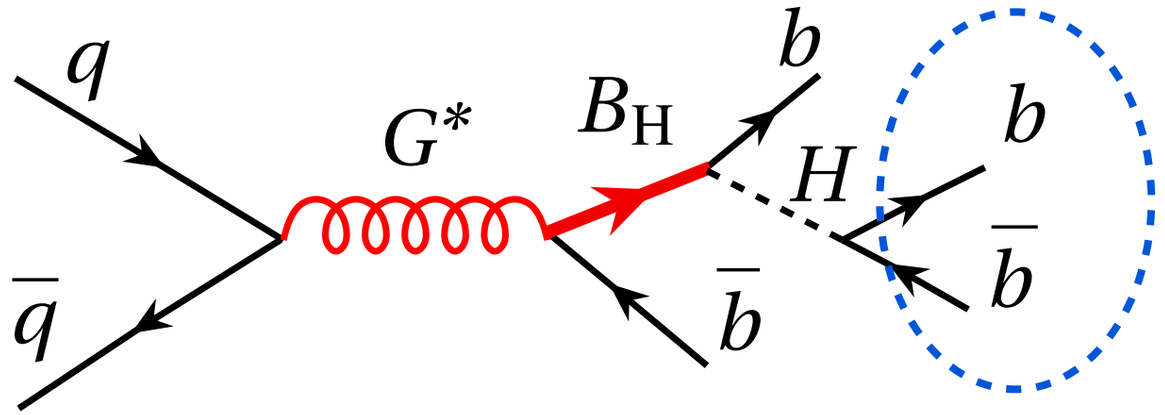
B→Wt (8 TeV)

Systematic uncertainty

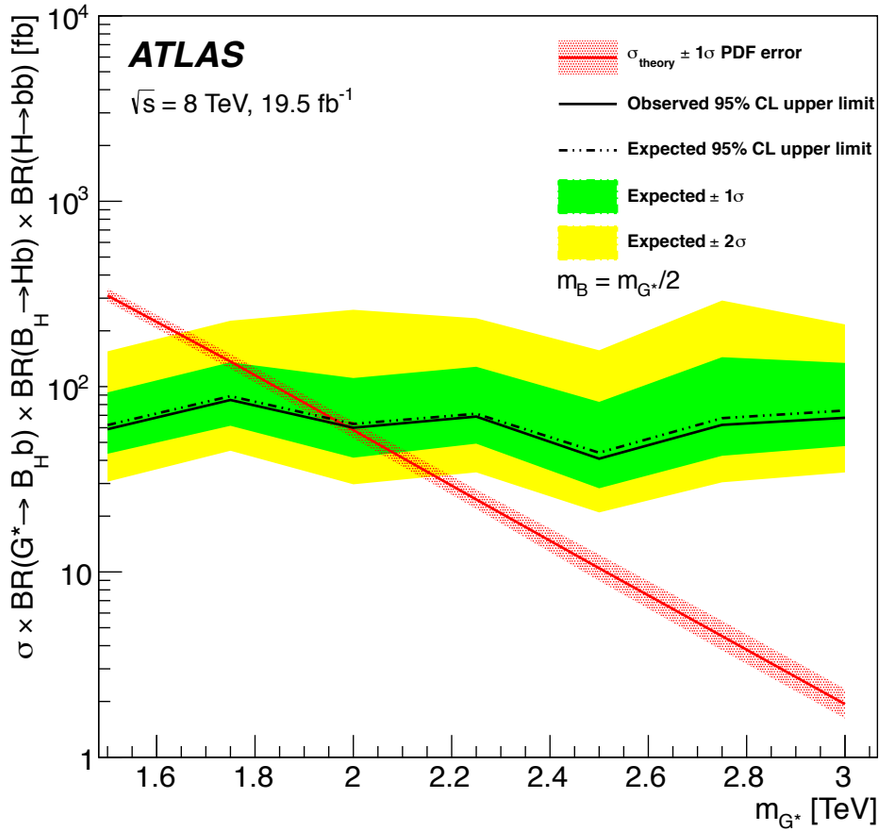
	b^*		B	
	Pre-fit [%]	Post-fit [%]	Pre-fit [%]	Post-fit [%]
Jet uncertainties	14.0	6.5	12.0	6.2
b-tagging uncertainties	3.3	3.0	2.8	2.5
Lepton uncertainties	1.6	1.5	1.6	1.6
Fake-lepton uncertainties	2.6	2.4	2.9	2.6
Theory uncertainties				
• Top-quark pair	3.2	1.8	9.4	3.4
• W+jets	9.1	3.6	9.6	4.9
• Single top	0.0	0.0	0.1	0.1
• Diboson	0.5	0.5	0.2	0.2
• Z+jets	0.5	0.5	0.7	0.7

G*→Bb→Hbb→bbbb

- New results: 8 TeV data (19.5 fb^{-1})
  arXiv:1602.06034
- Composite Higgs scenarios predicts heavy color octet vector G* decays $B^{-1/3}b$ ($B^{-1/3}\rightarrow Hb$)
- Main background: QCD multi-jets
  - 'ABCD' data driven method
- Event Selection
  ≥3 b-jets & lepton veto
  invariant mass of all jets > 600 GeV
  - Merged or Resolved
  - Classify events with reconstructed m_{G^*} & m_B
- No significant excess
  - Limit : $m_{G^*} > 2.0$ TeV ($m_{G^*} = 2m_B$)



- Merged into a fat jet including one b-jet
  $90 < m_J < 140$ GeV
- Resolved
  $90 < m_{jj} < 140$ GeV



Snowmass 2013 arXiv: 1311.2028

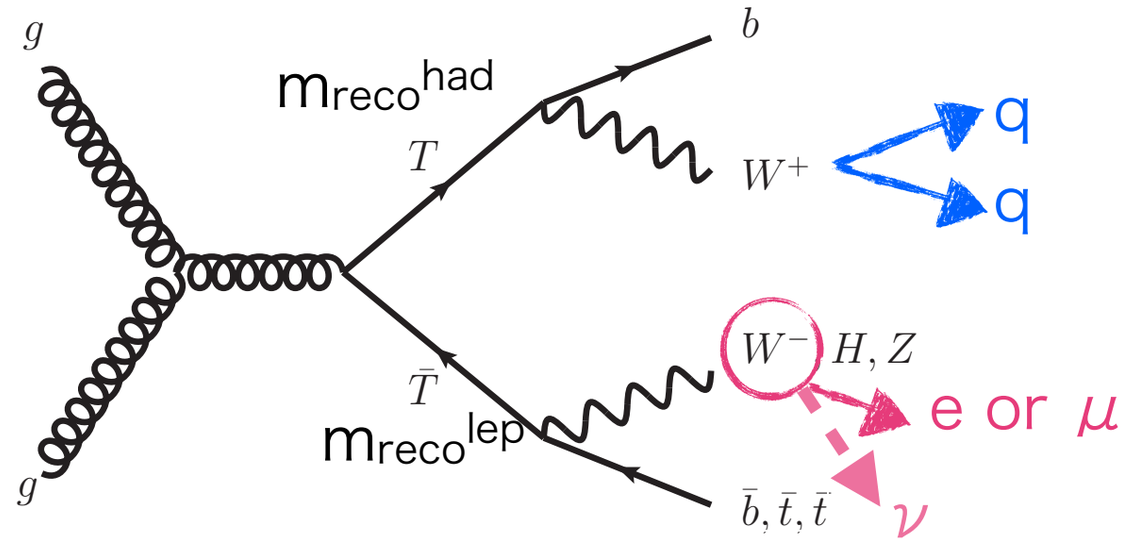
Collider	Luminosity	Pileup	3σ evidence	5σ discovery	95% CL
top-partner pair production					
LHC 14 TeV	300 fb^{-1}	50	1340 GeV	1200 GeV	1450 GeV
LHC 14 TeV	3 ab^{-1}	140	1580 GeV	1450 GeV	1740 GeV
LHC 33 TeV	3 ab^{-1}	140	2750 GeV	2400 GeV	3200 GeV
top-partner single production					
LHC 14 TeV	300 fb^{-1}	50	1275 GeV	1150 GeV	
LHC 14 TeV	3 ab^{-1}	140	1130 GeV	1000 GeV	
LHC 33 TeV	3 ab^{-1}	140	1350 GeV	1220 GeV	
LHC 100 TeV	3 ab^{-1}	50	1750 GeV	1600 GeV	
LHC 100 TeV	3 ab^{-1}	140	1750 GeV	1575 GeV	
bottom-partner pair production					
LHC 14 TeV	300 fb^{-1}	50	1210 GeV	1080 GeV	1330 GeV
LHC 14 TeV	3 ab^{-1}	140	1490 GeV	1330 GeV	>1500 GeV
LHC 33 TeV	300 fb^{-1}	50	> 1500 GeV	> 1500 GeV	> 1500 GeV
Charge 5/3 fermion pair production					
LHC 14 TeV	300 fb^{-1}	50	1.51 TeV	1.39 TeV	1.57 TeV
LHC 14 TeV	3 ab^{-1}	140	1.66 TeV	1.55 TeV	1.76 TeV
LHC 33 TeV	3 ab^{-1}	140	2.50 TeV	2.35 TeV	2.69 TeV

Table 1-15. *Expected mass sensitivity for heavy top and bottom partners, based on various studies for the Snowmass process.*

2. TT → Wb+X

- 8 TeV data (20.3 fb^{-1})
  arXiv: 1505.04306

- Event Selection (optimized for WbWb)
  Boosted W and large separation to the bjet

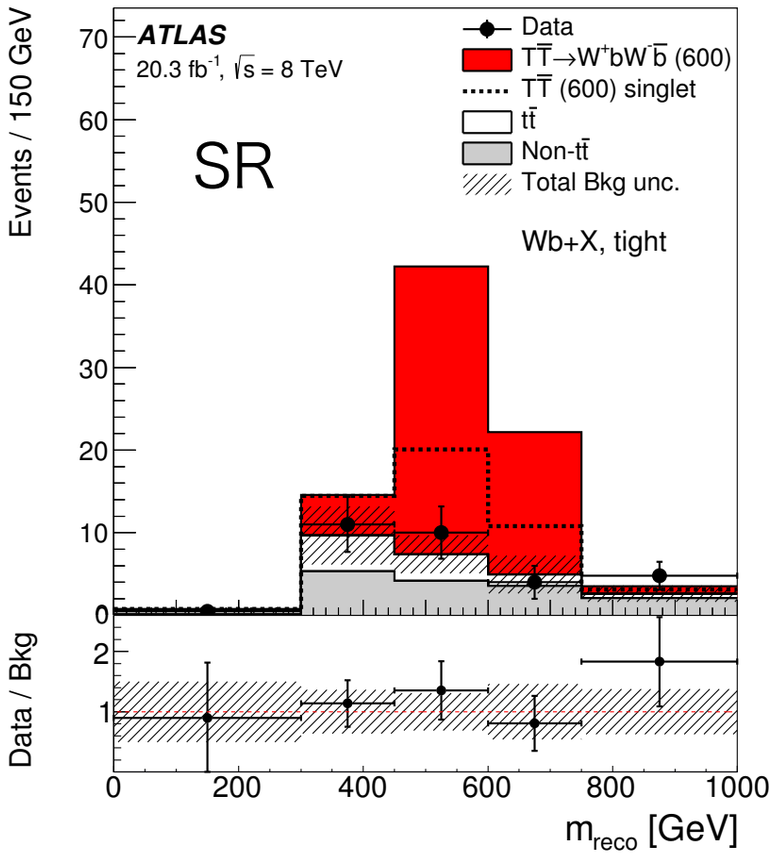


  - Reconstruct boosted hadronic W
    - Type1: reconstruct as one single jet with p_T > 400 GeV
    - Type2: dijet system with p_T > 250 GeV, $\Delta R(j, j) < 0.8$, $60 < m_{jj} < 120$ GeV

Selection	Requirements
Preselection	Exactly one electron or muon $E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV, $E_{\mathrm{T}}^{\mathrm{miss}} + m_{\mathrm{T}}^{W} > 60$ GeV $\geq$4 jets, $\geq$1 b-tagged jets
Loose selection	Preselection $\geq$1 W_{had} candidate (type I or type II) $H_{\mathrm{T}} > 800$ GeV $p_{\mathrm{T}}(b_1) > 160$ GeV, $p_{\mathrm{T}}(b_2) > 110$ GeV (type I) or $p_{\mathrm{T}}(b_2) > 80$ GeV (type II) $\Delta R(\ell, \nu) < 0.8$ (type I) or $\Delta R(\ell, \nu) < 1.2$ (type II)
Tight selection	Loose selection $\min(\Delta R(\ell, b_{1,2})) > 1.4$, $\min(\Delta R(W_{\mathrm{had}}, b_{1,2})) > 1.4$ $\Delta R(b_1, b_2) > 1.0$ (type I) or $\Delta R(b_1, b_2) > 0.8$ (type II) $\Delta m < 250$ GeV (type I) [see text for definition]

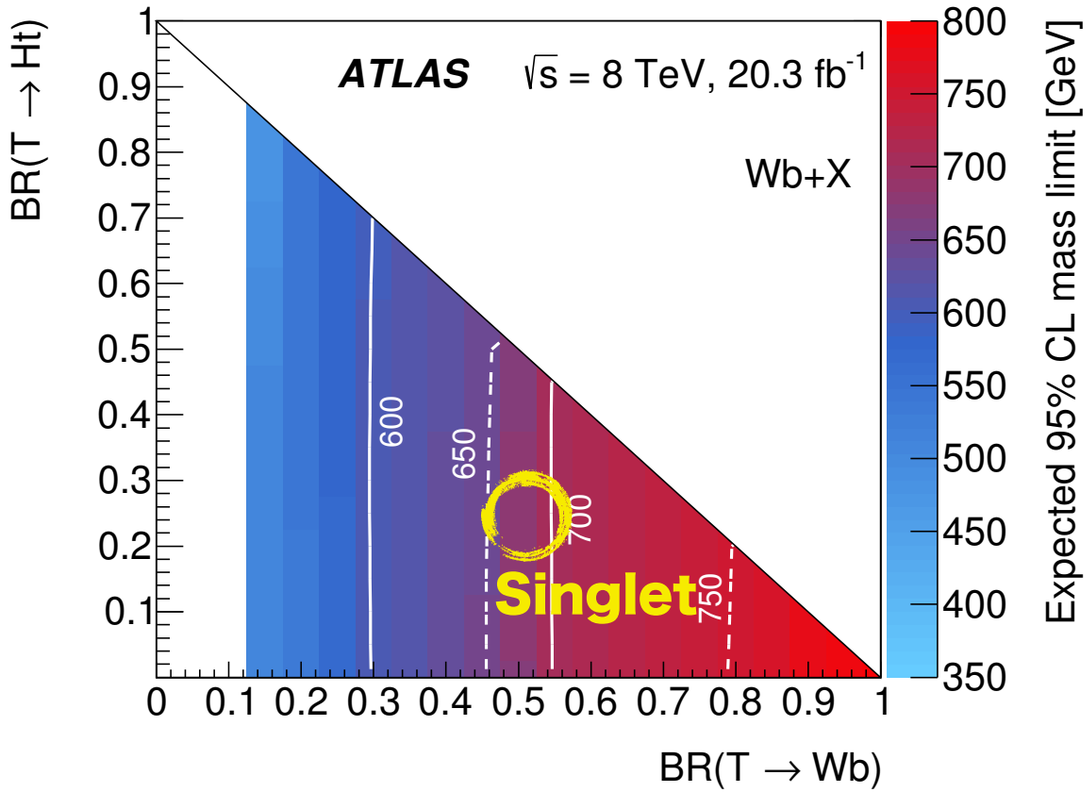
$\Delta m = \min |m_{reco}^{lep} - m_{reco}^{had}|$

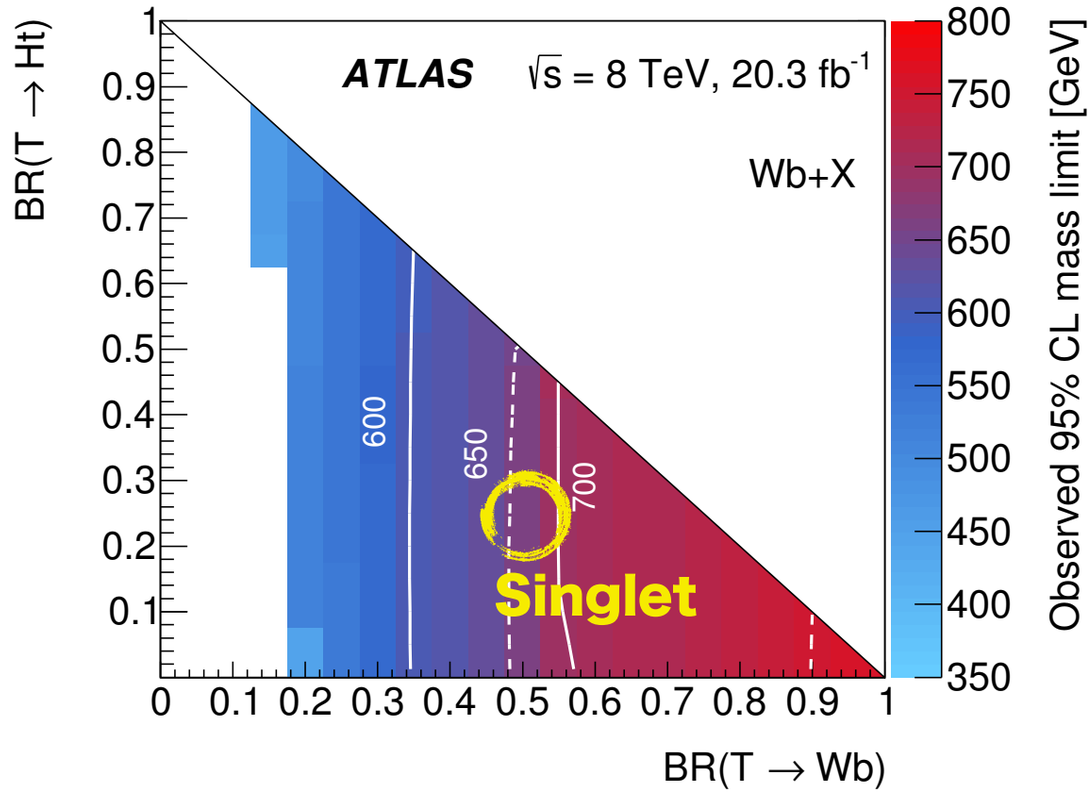
- Final discriminant: m_{reco}
  reconstructed T mass from hadronic W



2. TT → Wb+X

- Limit Setting

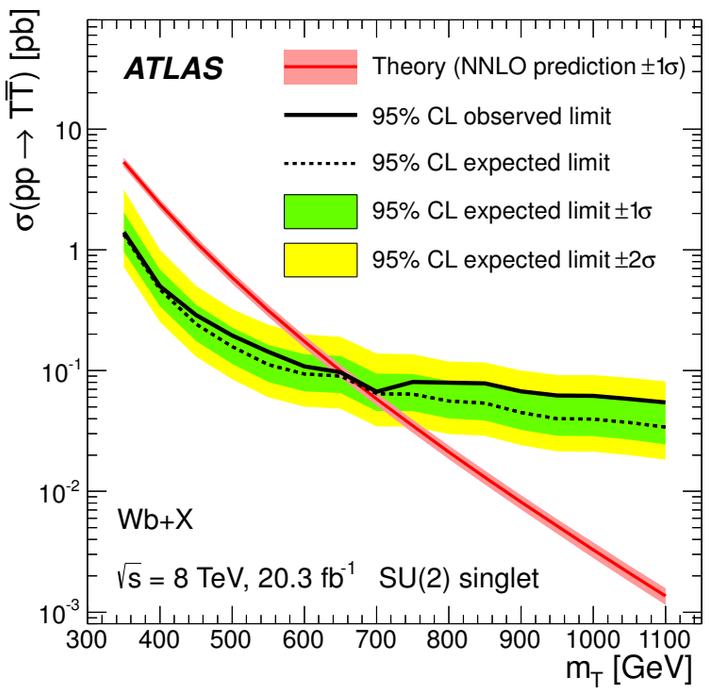




obs.(exp.)

- Singlet: m_T > 650(650) GeV
  7 TeV (4.7fb^{-1}): m_T > 500(500) GeV
  arXiv: 1210.5468v1

- Improved the exclusion limit by 150 GeV



- Analysis on 13 TeV data is on-going

TT/BB → Zt/b+X

- 8 TeV data (20.3fb^{-1})
  arXiv:1409.5500

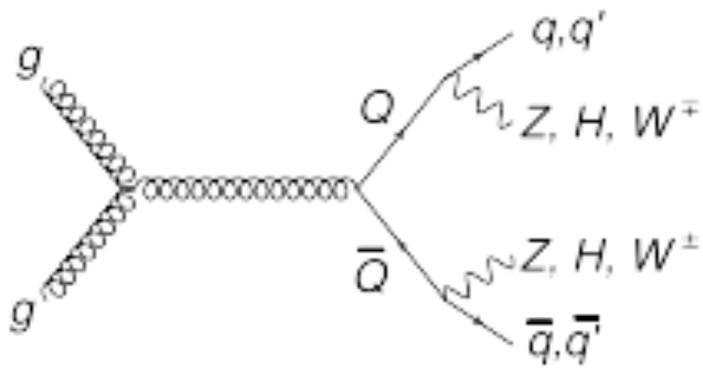
- Sensitive for pair & single production with dilepton and trilepton
  - Interpretation for single production is shown in back up

- Z is reconstructed from $e^{\pm}e^{\mp}$ or $\mu^{\pm}\mu^{\mp}$ with $|m - m_Z| < 10$ GeV

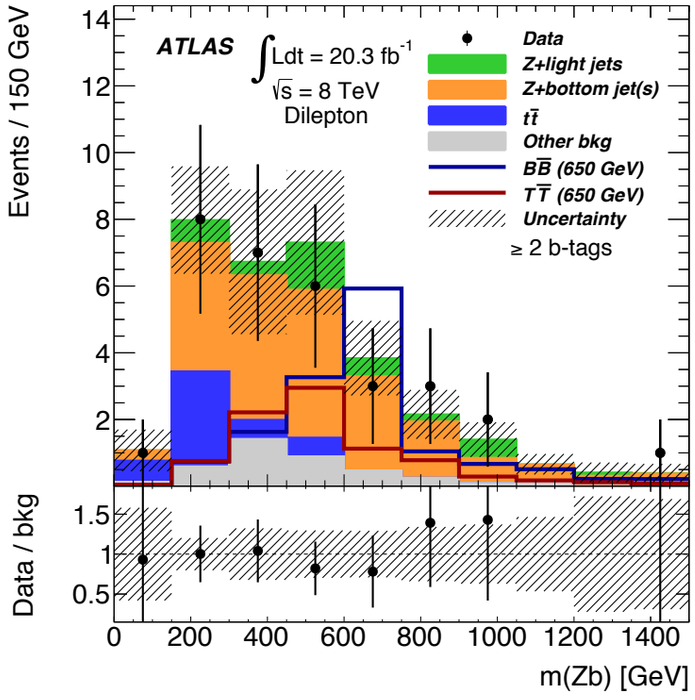
- Event selection

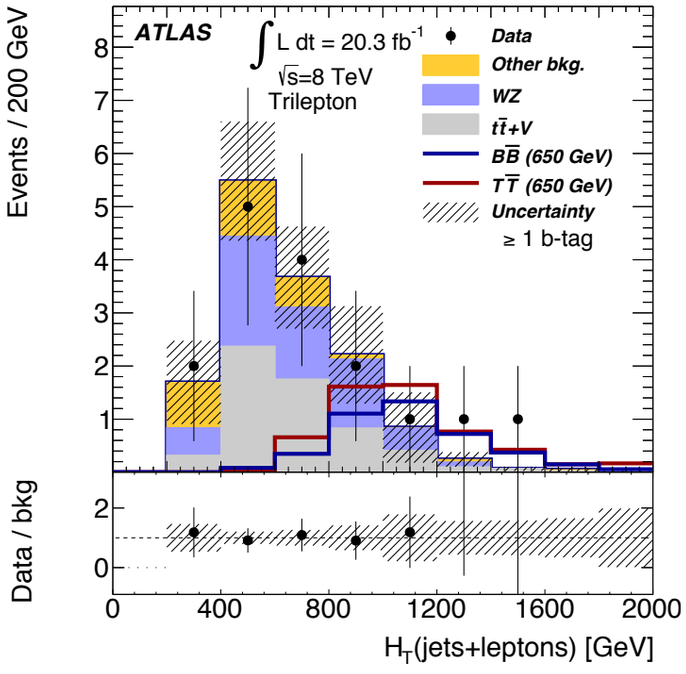
- A binned Poisson likelihood test on the final discriminant distribution

- No excess

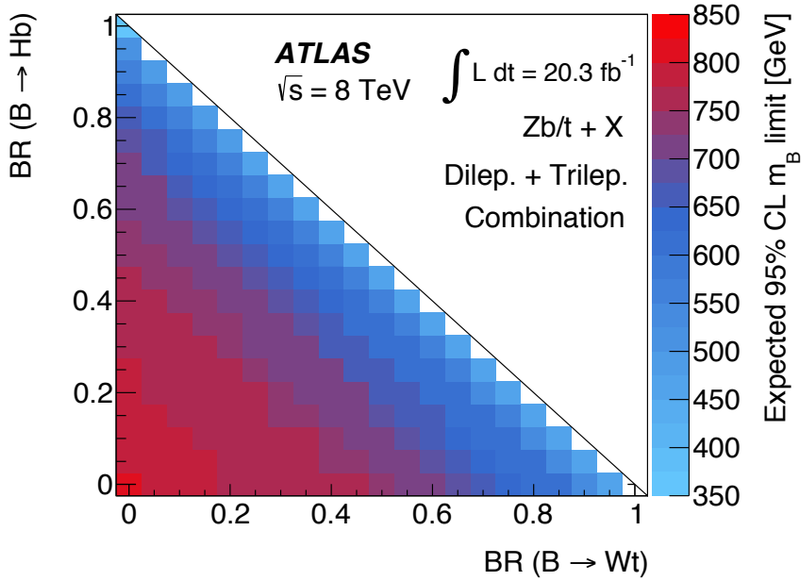


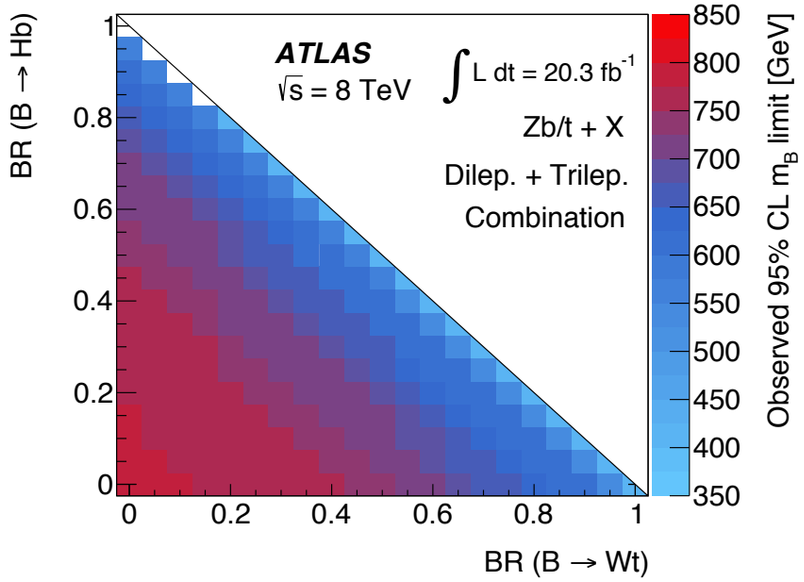
Event selection			
Z boson candidate preselection ≥ 2 central jets $p_{\mathrm{T}}(Z) \geq 150$ GeV			
Dilepton channel		**Trilepton channel**	
$= 2$ leptons		≥ 3 leptons	
≥ 2 b-tagged jets		≥ 1 b-tagged jet	
Pair production	**Single production**	**Pair production**	**Single production**
$H_{\mathrm{T}}(\mathrm{jets})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

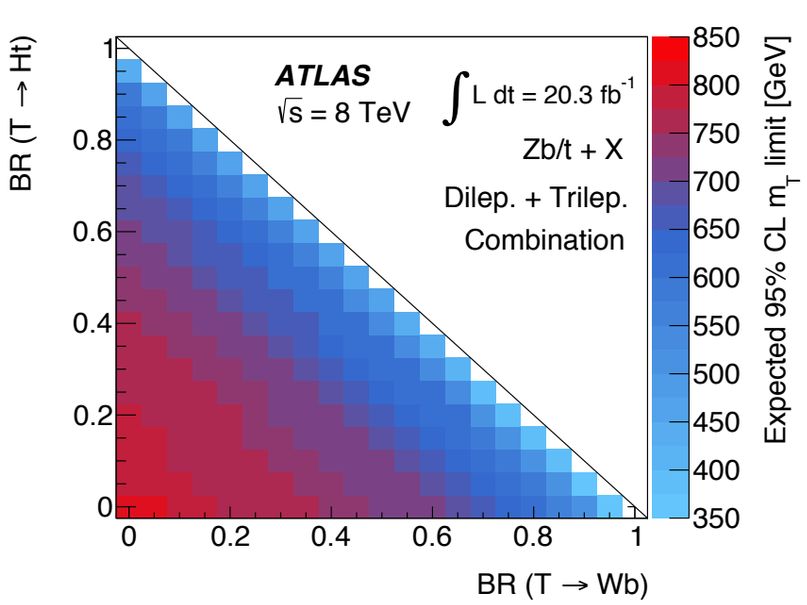


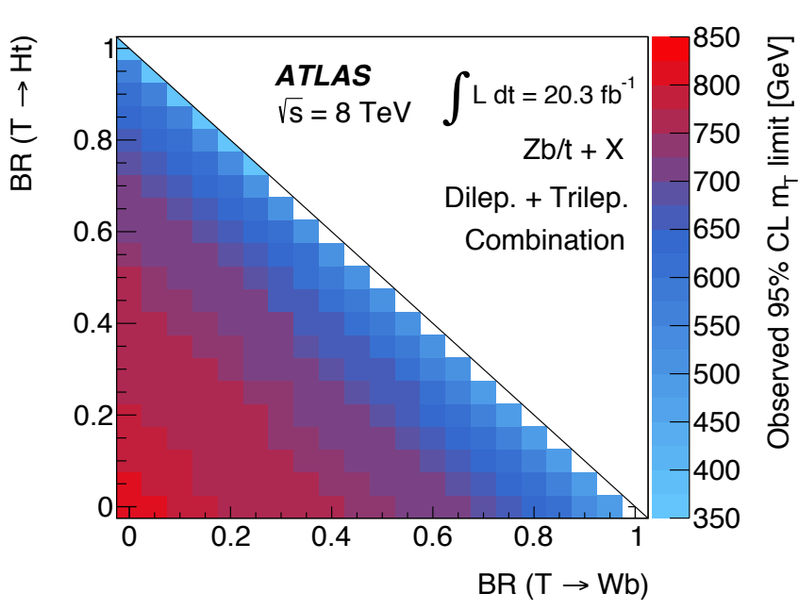


TT/BB → Zt/b+X







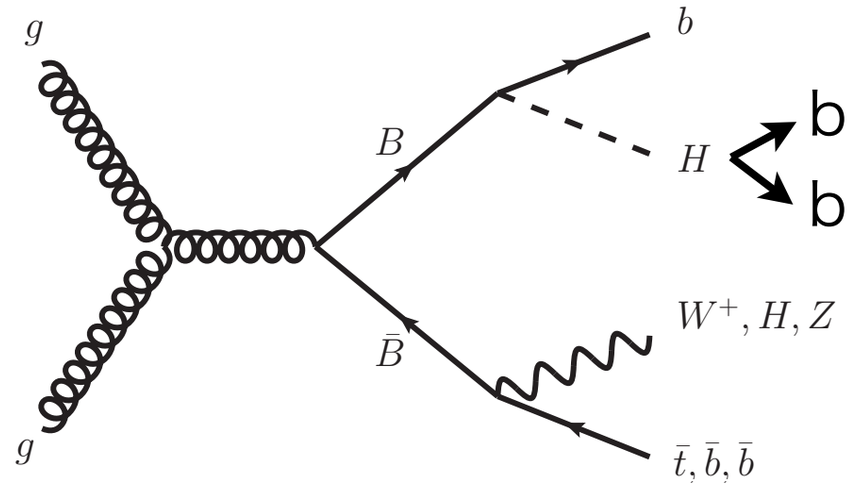


	Singlet mass limit [GeV]			Doublet mass limit [GeV]		
Hypothesis	Dilepton	Trilepton	Comb.	Dilepton	Trilepton	Comb.
$B\bar{B}$	690 (665)	610 (610)	685 (670)	765 (750)	540 (530)	755 (755)
$T\bar{T}$	620 (585)	620 (620)	655 (625)	705 (665)	700 (700)	735 (720)

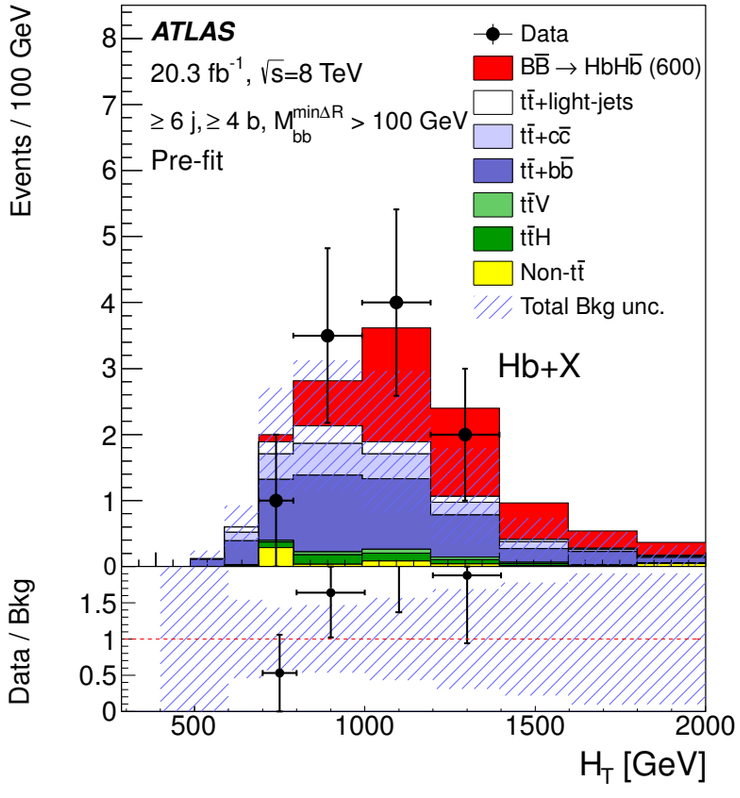
BB → Hb+X

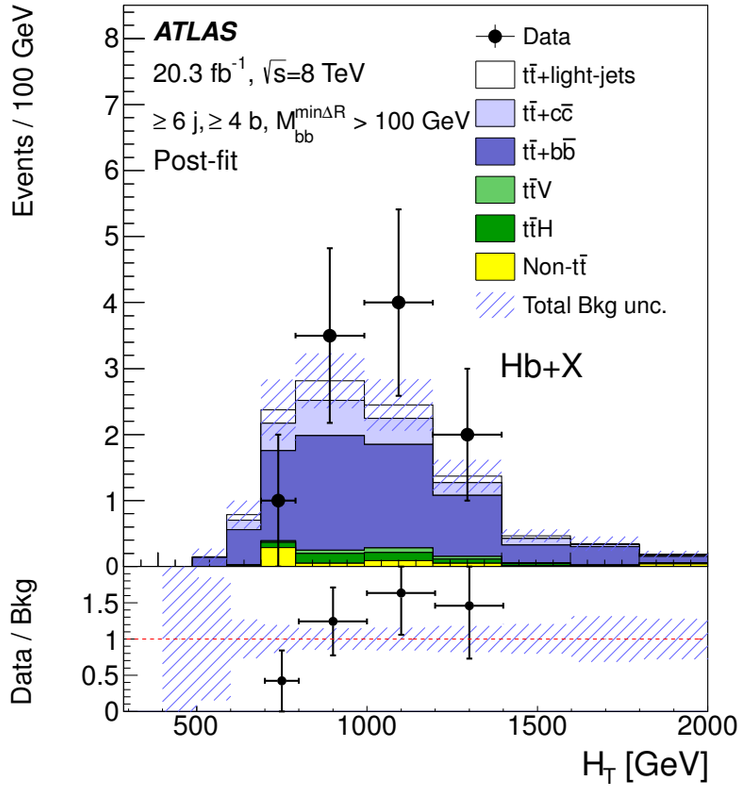
- 8 TeV data (20.3 fb^{-1})
  arXiv: 1505.04306

- Event Selection (basically same as Ht+X)
  - 1 lepton, ≥5 jets, ≥2 bjets
  - 2nd leading bjet p_T > 150 GeV
    (b-quark from T decay has high p_T)
  - Classify events with N_{jets}, N_{bjets}, M_{bb}
    M_{bb}: invariant mass with nearest bjet pair
    - 5jets: Validation
    - ≥6jets: CR/SR



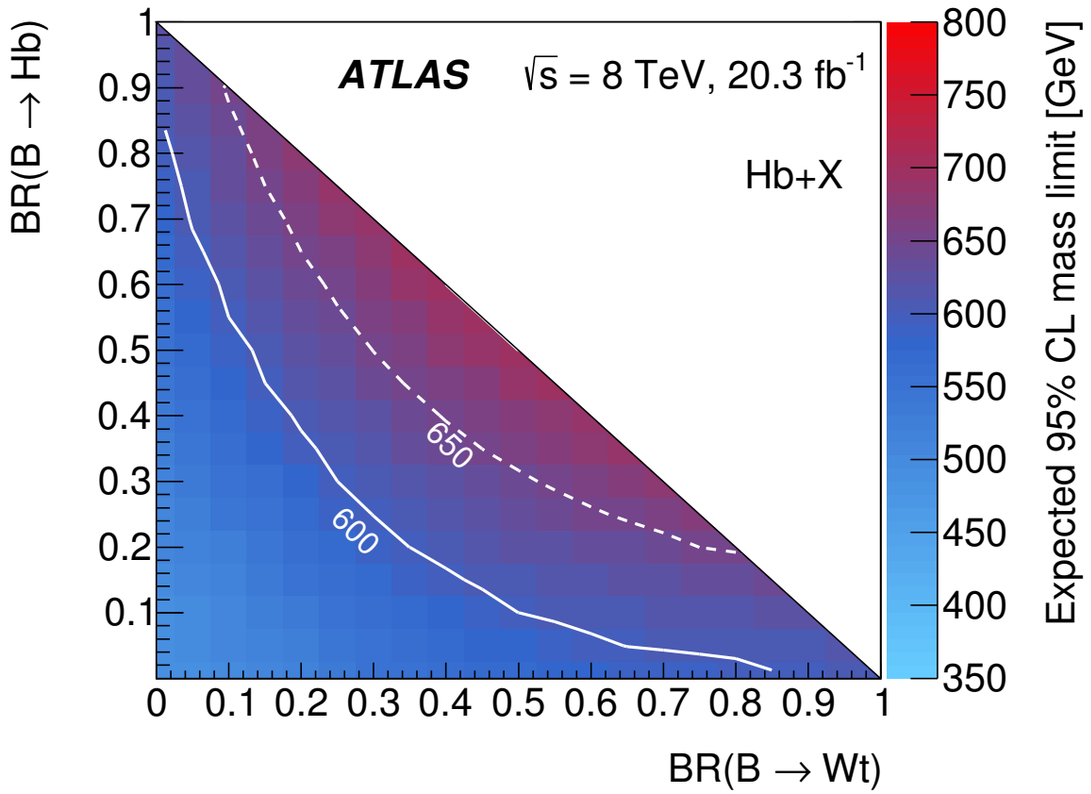
- Final discriminant:
  $H_T = \Sigma p_T^{jets} + p_T^{lep} + E_T^{miss}$
  - Fit the H_T distribution

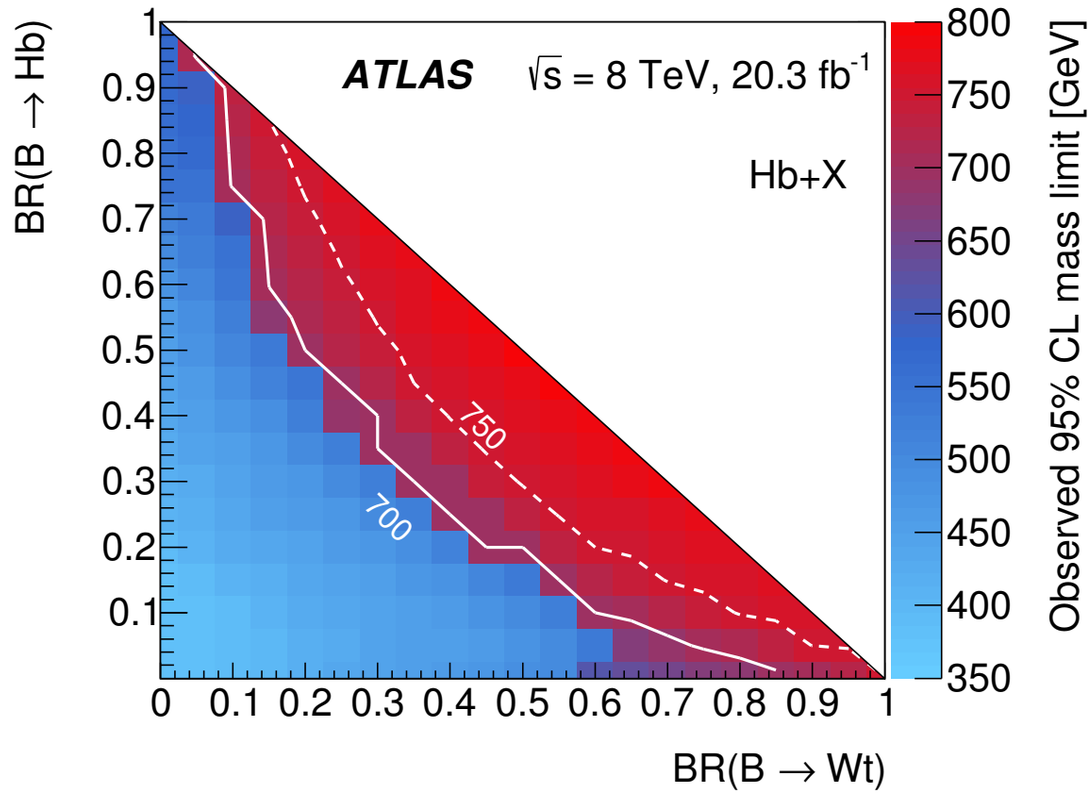




BB → Hb+X

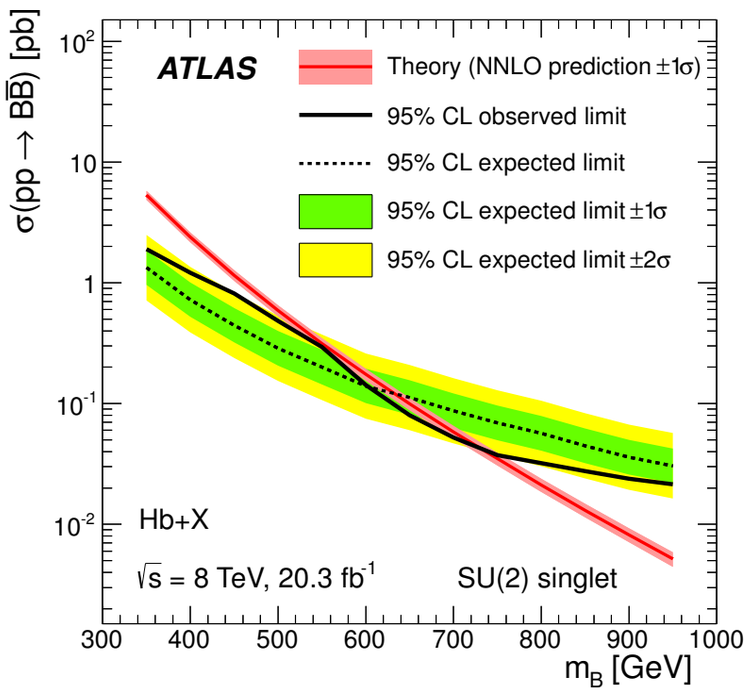
- Limit setting





obs.(exp.)

- Singlet: m_B > 735 (635) GeV



BB → Wt+X

- 8 TeV data (20.3 fb^{-1})
  arXiv:1503.05425

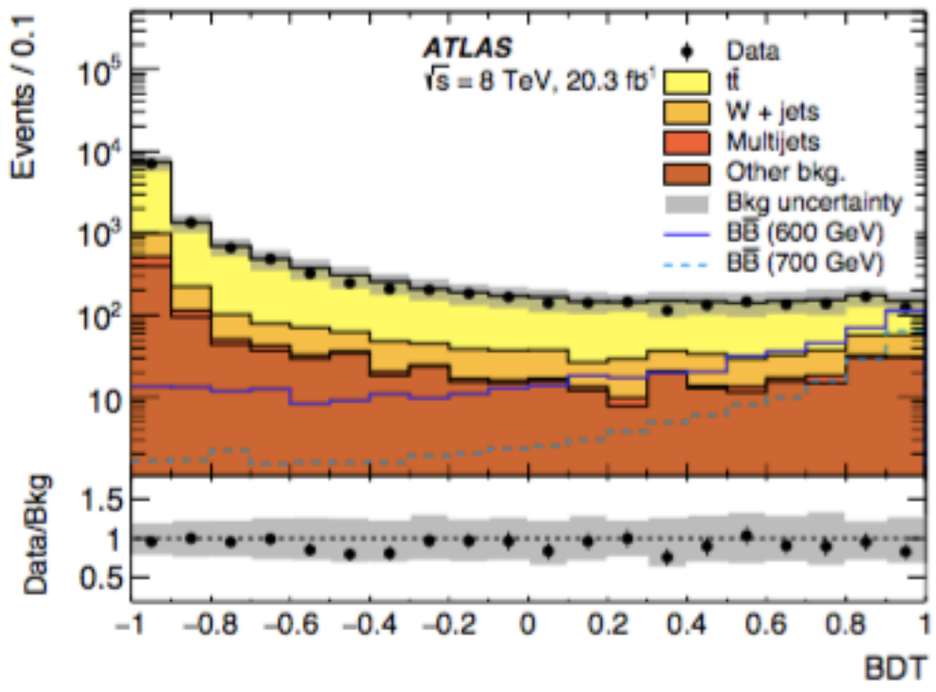
- Multi-variate Analysis (BDT)

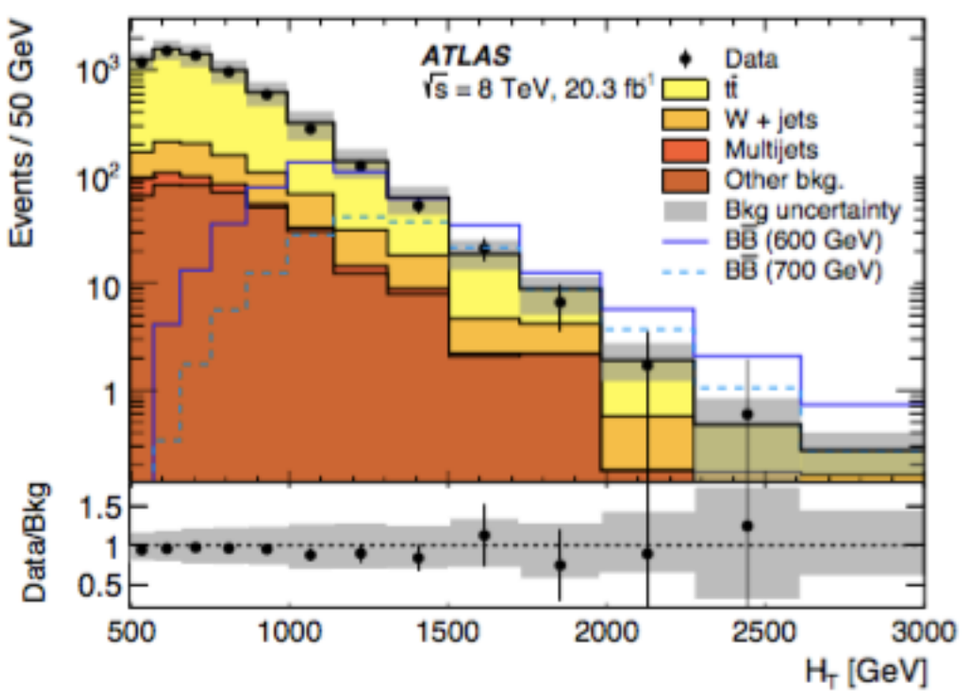
  - H_T, $\Delta R(l, bjet^{1st})$, M_T, $p_T(W^{lep})$
    $\min \Delta R(l, W^{had})$, $E^{bjet1st}$,
    Average $\Delta R(j, j)W^{had}$, $N_{W/Z}$,
    N_{jets}, N^{bjets}, p_T^{lep}, E_T^{miss}

Data Region	N_{jets}	N_V	N_{bjets}	H_T (GeV)
SR (cuts-based)	≥ 6	≥ 1	≥ 1	> 800
SR (BDT)	≥ 6	≥ 1	≥ 1	> 500
WCR1	= 4, 5	-	= 0	-
TCR1	= 4, 5	-	≥ 1	-
WCR2	≥ 6	-	= 0	-
TCR2	≥ 6	-	≥ 1	< 500
TCR3	≥ 6	= 0	≥ 1	-

  - H_T: the most discriminating power

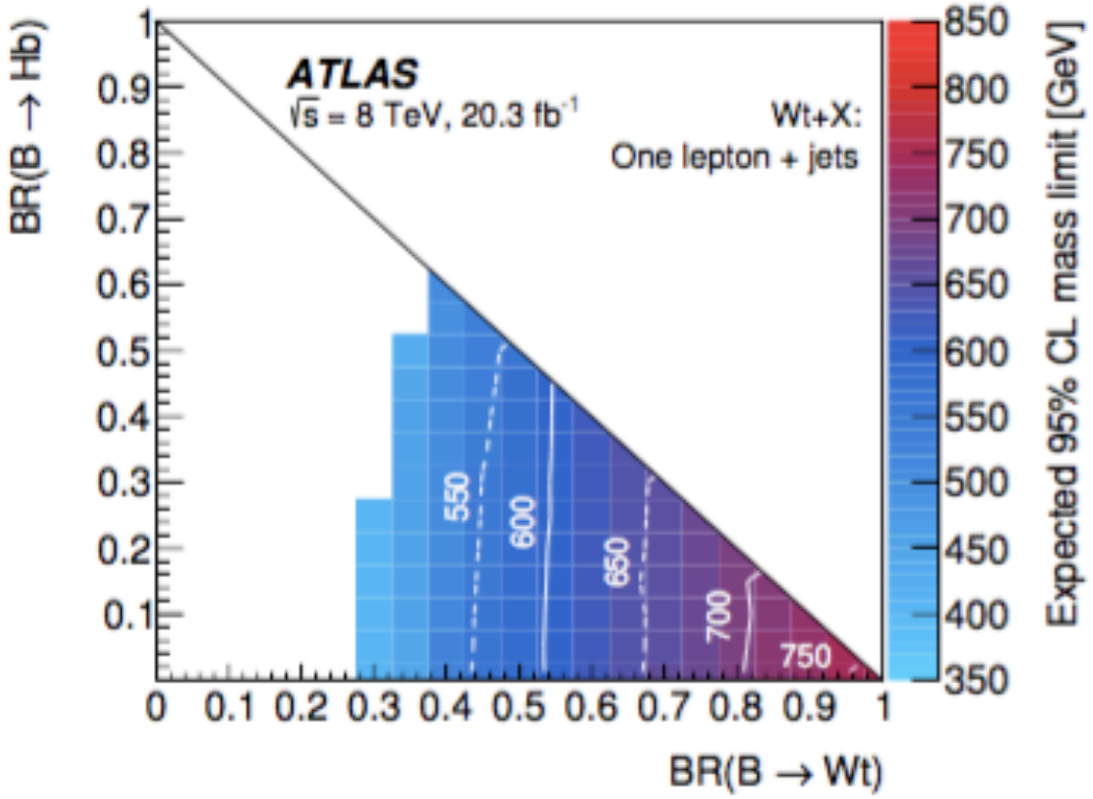
- Cross-check with cut-based analysis

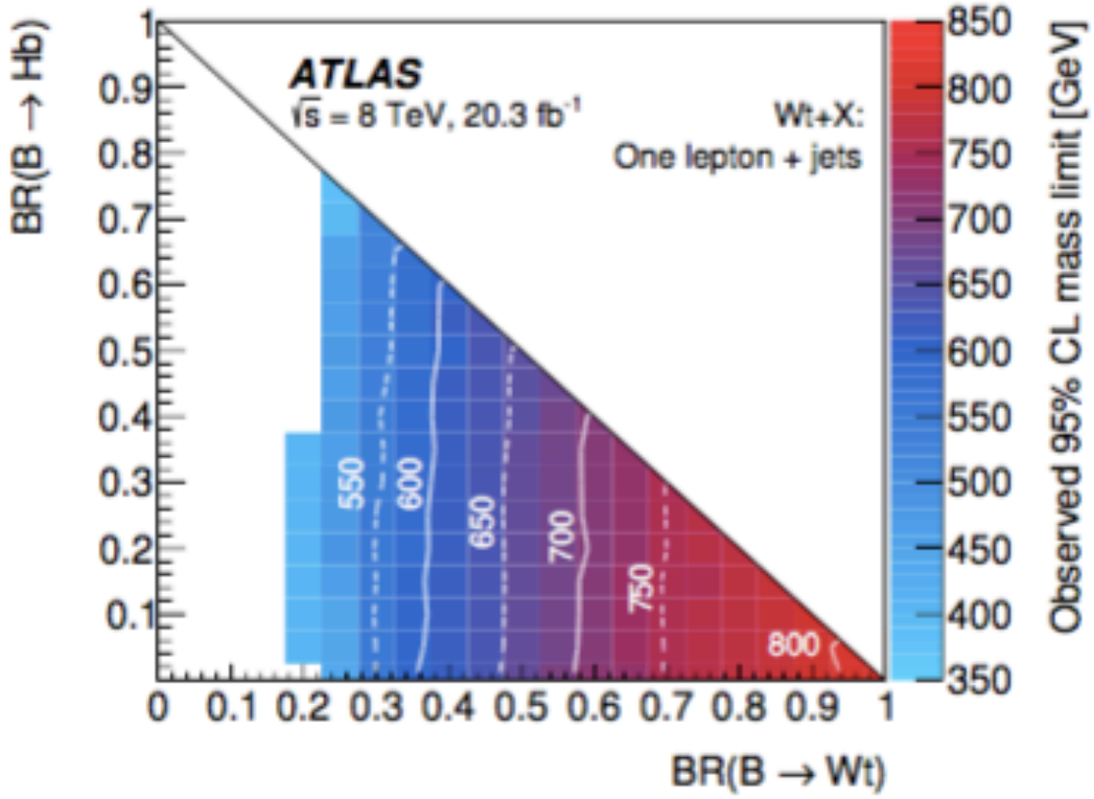




BB → Wt+X

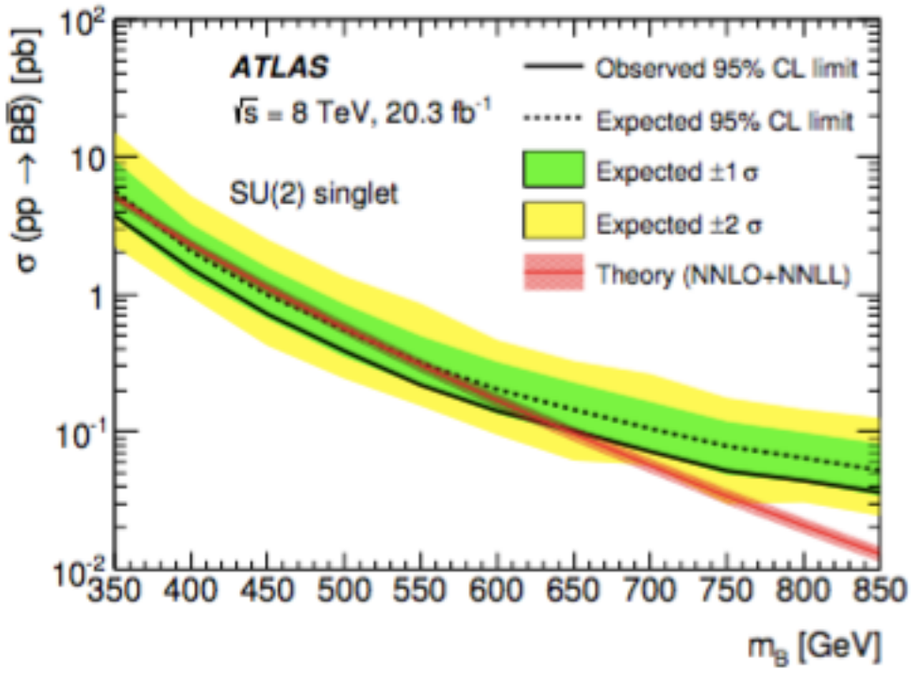
- Limit setting





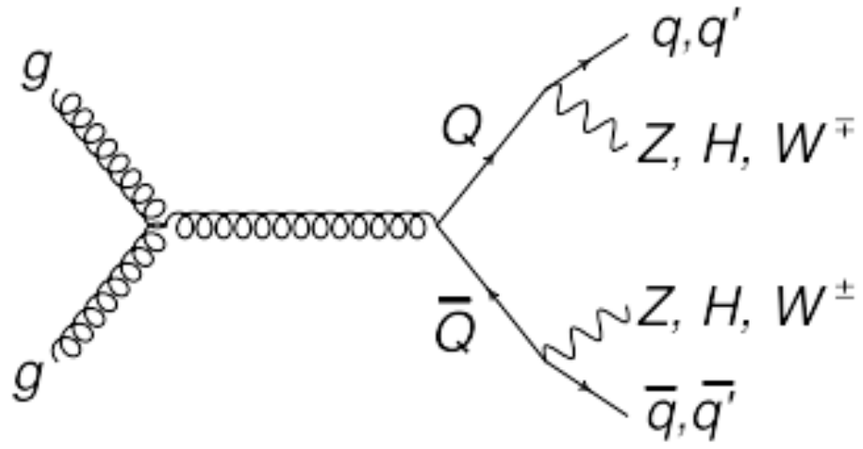
obs.(exp.)

- Singlet: m_B > 640(505) GeV
- $T^{5/3}$: m_B > 840(780) GeV
  the most sensitive for $T^{5/3}$ in Run1

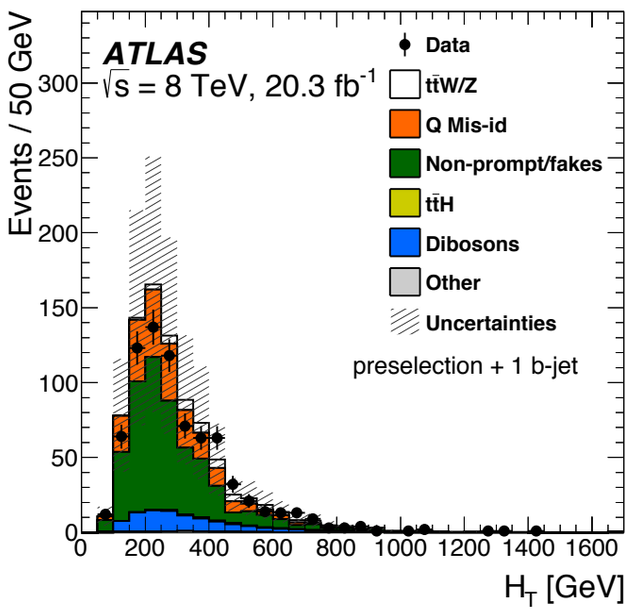


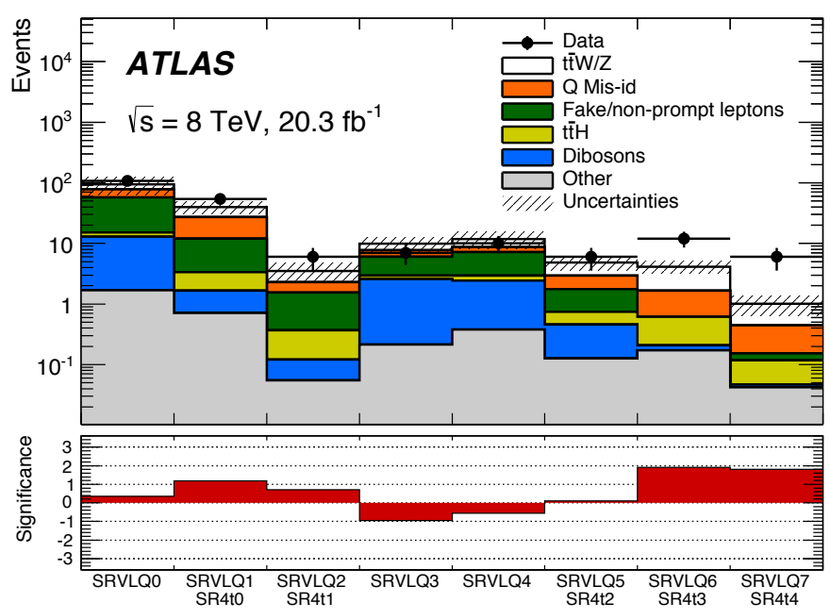
SS dilepton + bjets

- 8 TeV data (20.3 fb^{-1})
  arXiv: 1504.04605
- Pair production of $T^{2/3}/B^{-1/3}$, $T^{5/3}$ ($\rightarrow Wt$)
- Event Selection same-sign dilepton or multileptons
- Main Background:
  - Physics: tt+W/Z
    - Use MC simulation
  - Detector: charge mis-ID & fakes
    - Data-driven estimates
    - Good agreement
- Result ... no excess
  - Set the limit (next page)



Definition			Name	
$e^{\pm}e^{\pm} + e^{\pm}\mu^{\pm} + \mu^{\pm}\mu^{\pm} + eee + ee\mu + e\mu\mu + \mu\mu\mu$, $N_j \geq 2$				
$400 < H_{\mathrm{T}} < 700GeV$	$N_b = 1$	$E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV	SRVLQ0	
	$N_b = 2$		SRVLQ1	SR4t0
	$N_b \geq 3$		SRVLQ2	SR4t1
$H_{\mathrm{T}} \geq 700\ GeV$	$N_b = 1$	$40 < E_{\mathrm{T}}^{\mathrm{miss}} < 100GeV$	SRVLQ3	
		$E_{\mathrm{T}}^{\mathrm{miss}} \geq 100\ GeV$	SRVLQ4	
	$N_b = 2$	$40 < E_{\mathrm{T}}^{\mathrm{miss}} < 100GeV$	SRVLQ5	SR4t2
		$E_{\mathrm{T}}^{\mathrm{miss}} \geq 100\ GeV$	SRVLQ6	SR4t3
	$N_b \geq 3$	$E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV	SRVLQ7	SR4t4
$e^{+}e^{+}$, $e^{+}\mu^{+}$, $\mu^{+}\mu^{+}$, $N_j \in [2,4]$, $\Delta\phi_{\ell\ell} > 2.5$				
$H_{\mathrm{T}} > 450\ GeV$	$N_b \geq 1$	$E_{\mathrm{T}}^{\mathrm{miss}} > 40\ GeV$	SRttee, SRtteμ, SRtt$\mu\mu$	





SS dilepton + bjets

8 TeV

Uncertainty (%) on total background yield

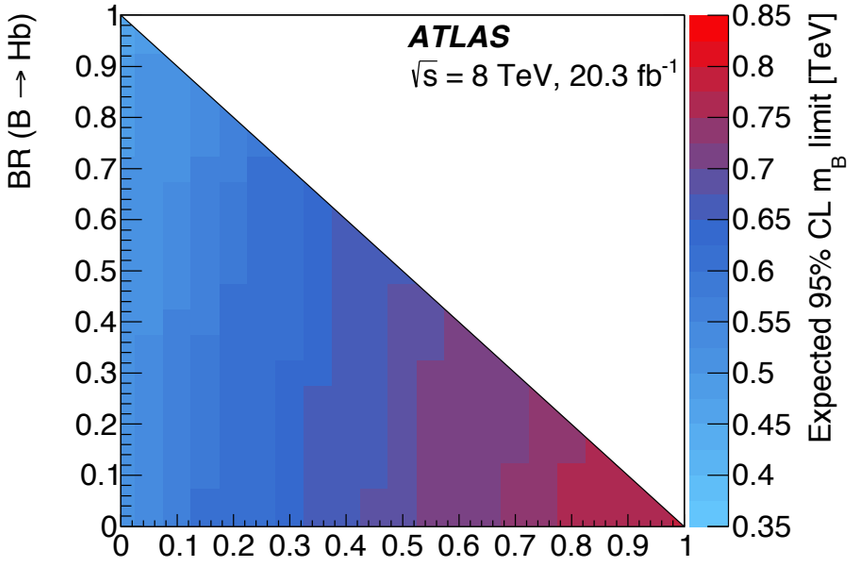
Source	VLQ signal region number							
	0	1	2	3	4	5	6	7
Cross section	±8.0	±13.6	±15.1	±11.1	±12.1	±16.8	±25.2	±23.8
Fake/non-prompt leptons	±33	±18	±25	±23	±26	±16	±1.5	±3.8
Charge misID	$^{+5.9}_{-5.7}$	$^{+9.3}_{-9.1}$	$^{+5.4}_{-5.1}$	$^{+7.4}_{-6.7}$	$^{+5.0}_{-4.6}$	$^{+8.7}_{-8.1}$	$^{+9.0}_{-8.5}$	$^{+11.0}_{-10.1}$
Jet energy scale	$^{+1.7}_{-1.6}$	$^{+1.2}_{-1.8}$	$^{+1.4}_{-1.7}$	$^{+1.8}_{-2.1}$	$^{+2.6}_{-4.2}$	$^{+3.8}_{-1.5}$	$^{+8.5}_{-4.8}$	$^{+7.3}_{-2.9}$
b-tagging efficiency	±1.0	±2.6	$^{+5.7}_{-5.5}$	$^{+1.9}_{-2.0}$	$^{+1.6}_{-1.7}$	$^{+3.8}_{-3.7}$	$^{+5.1}_{-5.0}$	$^{+8.3}_{-8.2}$
Lepton ID efficiency	±1.3	±1.6	±1.6	$^{+2.1}_{-2.0}$	$^{+2.1}_{-2.0}$	$^{+2.2}_{-2.1}$	$^{+2.8}_{-2.2}$	±2.5
Jet energy resolution	±0.5	±0.2	±3.1	±1.9	±0.3	±0.9	±0.8	±3.4
Luminosity	±0.9	±1.1	±1.3	±1.4	±1.5	±1.5	±2.1	±1.9

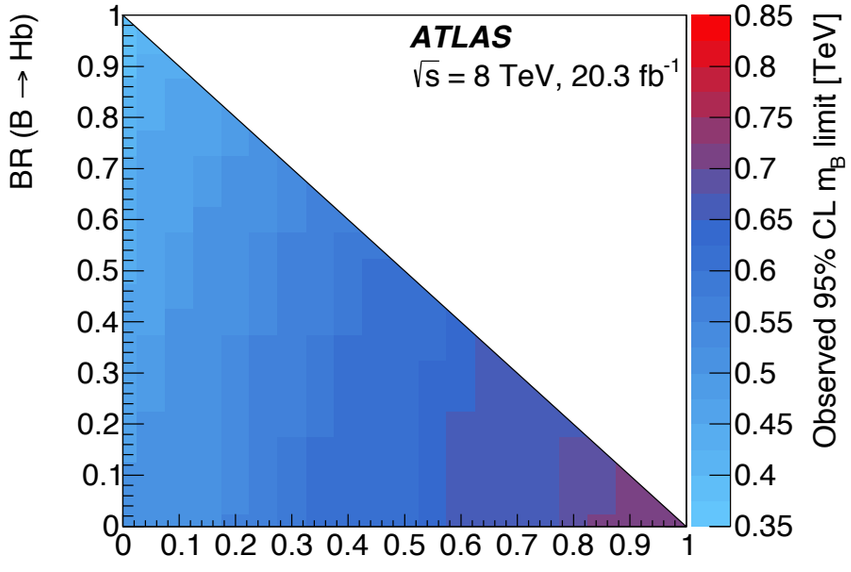
Uncertainty (%) on the yield of signal (BB m_B = 600GeV)

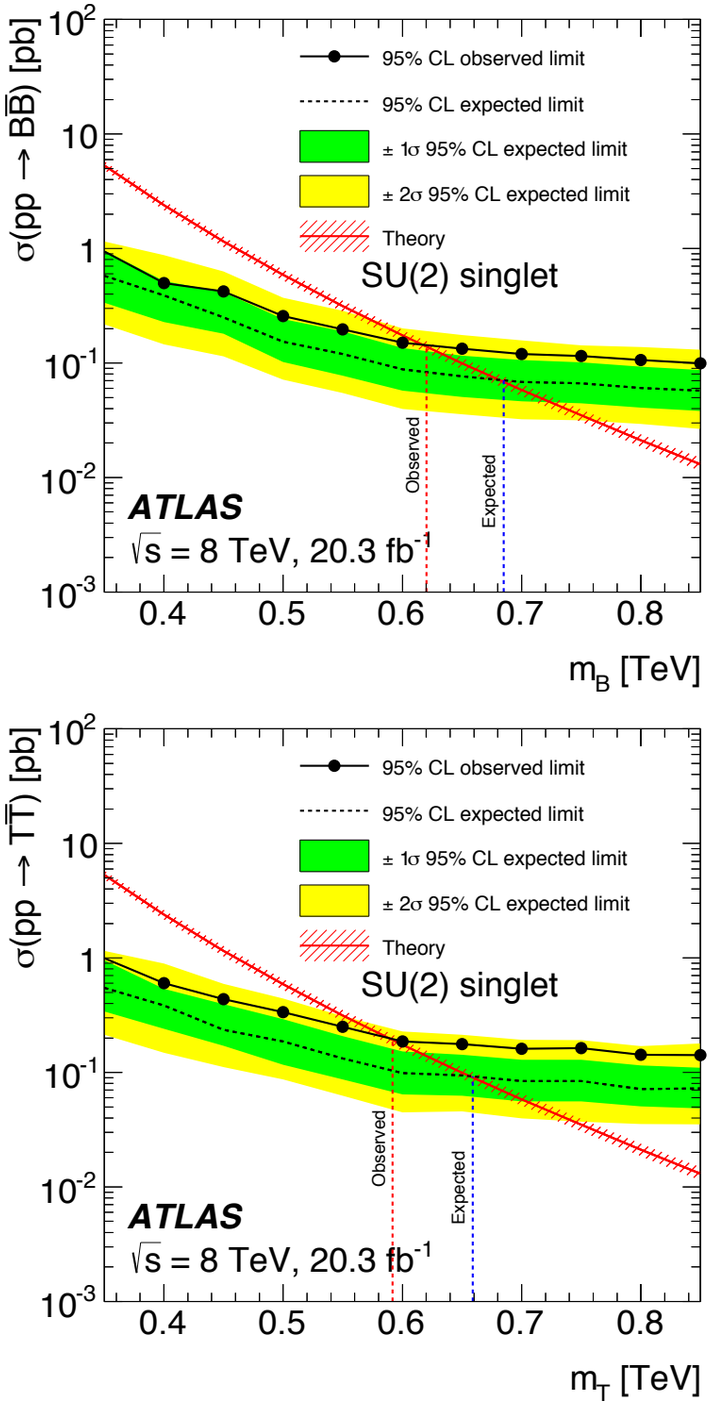
Source	VLQ signal region number							
	0	1	2	3	4	5	6	7
Jet energy scale	$^{+11.3}_{-9.0}$	$^{+11.5}_{-6.3}$	$^{+28.0}_{-17.3}$	$^{+3.7}_{-2.1}$	$^{+5.4}_{-2.4}$	$^{+3.9}_{-2.0}$	$^{+4.5}_{-6.5}$	$^{+6.6}_{-3.0}$
b-tagging efficiency	$^{+2.5}_{-3.0}$	$^{+6.3}_{-6.1}$	$^{+16.4}_{-15.9}$	$^{+3.1}_{-3.7}$	$^{+3.4}_{-4.0}$	$^{+7.4}_{-7.2}$	$^{+7.6}_{-7.4}$	$^{+12.1}_{-11.9}$
Lepton ID efficiency	±2.9	±2.9	±2.8	±2.9	$^{+3.2}_{-3.1}$	±2.9	$^{+3.2}_{-3.1}$	$^{+3.0}_{-2.9}$
Jet energy resolution	±0.8	±2.5	±3.9	±0.3	±0.7	±0.7	±1.0	±0.1
Luminosity	±2.8	±2.8	±2.8	±2.8	±2.8	±2.8	±2.8	±2.8

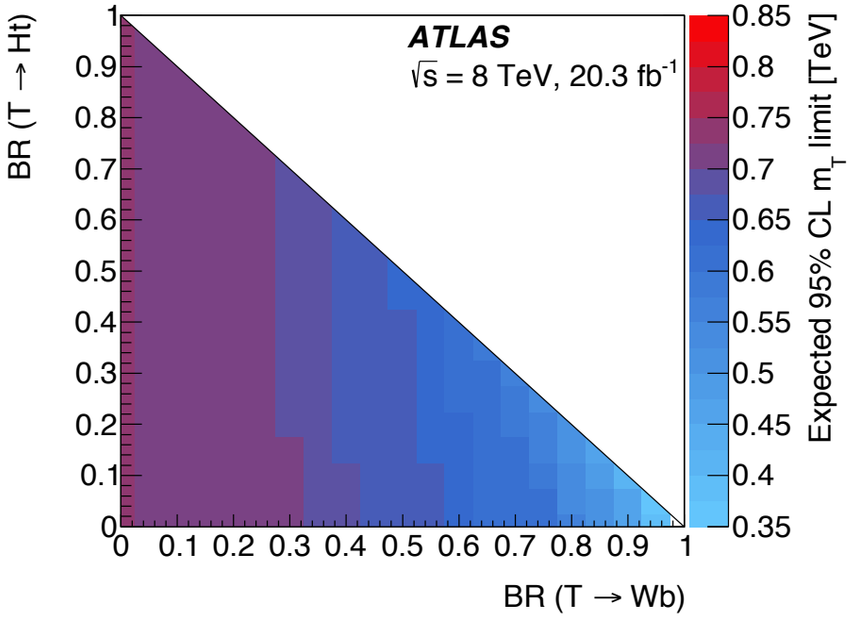
SS dilepton + bjets

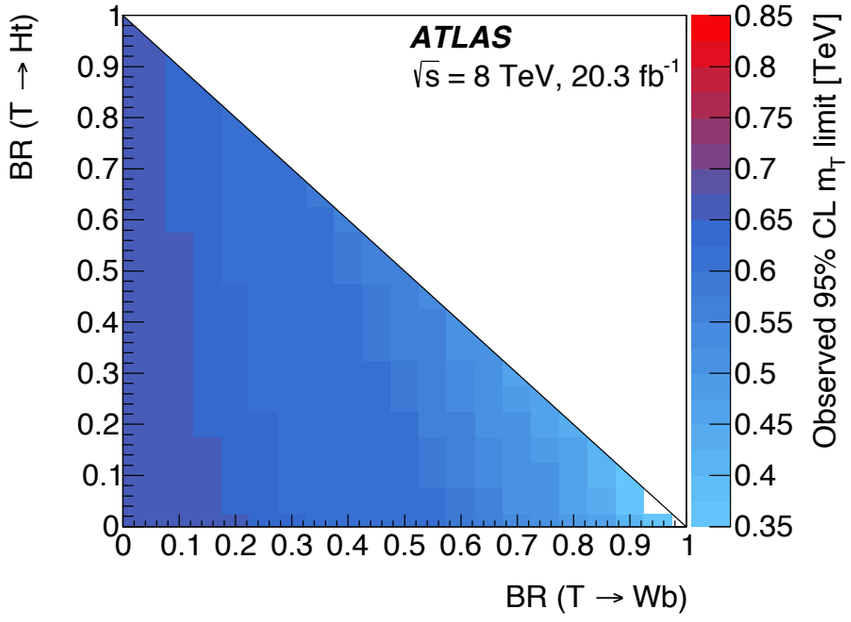
8 TeV









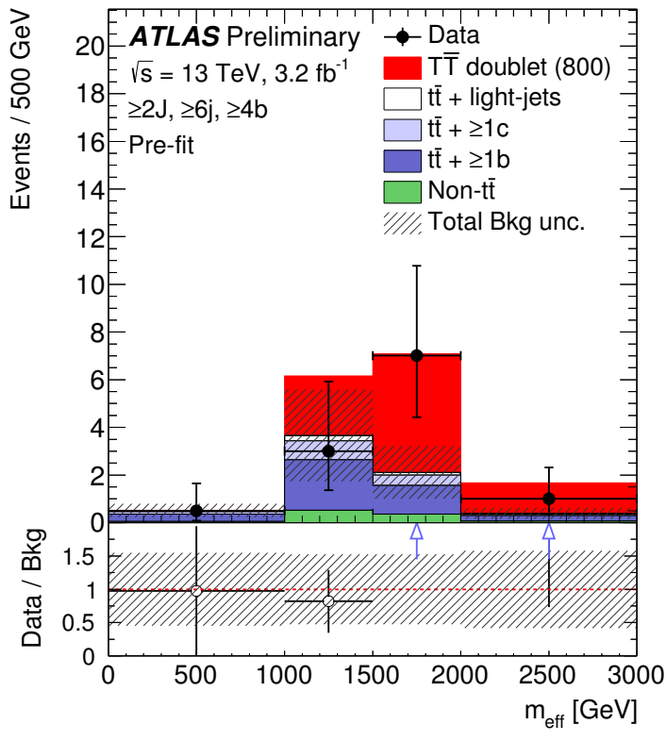


1. TT → Ht+X

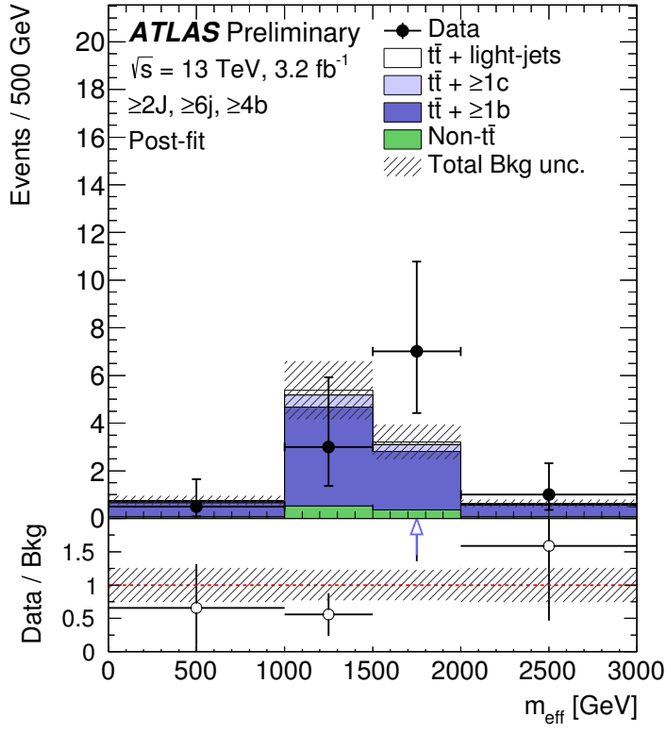
13 TeV

≥2 J, ≥6 jets, ≥4 bjets

Before fit



After fit



Leading Systematic Uncertainty

- tt+jets modeling including tt+HF
- b-tagging efficiency

	1J, ≥6j, ≥4b LM	1J, ≥6j, ≥4b HM	≥2J, ≥6j, 3b	≥2J, ≥6j, ≥4b
$T\bar{T}$ ($m_T = 800$ GeV)				
BR($T \to Ht$) = 1	5.52 ± 0.76	10.5 ± 1.4	12.2 ± 1.2	19.6 ± 2.7
(T, B) or (X, T) doublet	4.18 ± 0.53	6.00 ± 0.81	8.90 ± 0.70	10.0 ± 1.4
Singlet	1.90 ± 0.26	3.08 ± 0.50	4.83 ± 0.45	4.14 ± 0.65
SM $t\bar{t}t\bar{t}$	0.26 ± 0.03	0.27 ± 0.04	0.40 ± 0.04	0.30 ± 0.05
EFT $t\bar{t}t\bar{t}$ ($\lvert C_{4t}\rvert/\Lambda^2 = 4\pi$ TeV^{-2})	25.3 ± 3.8	36.7 ± 5.9	65.3 ± 5.3	45.9 ± 7.1
2UED/RPP $t\bar{t}t\bar{t}$+X ($m_{\mathrm{KK}} = 1$ TeV)	4.10 ± 0.57	10.3 ± 1.8	78.2 ± 4.7	60.5 ± 8.9
$t\bar{t}$+light-jets	2.7 ± 1.8	2.0 ± 1.3	13.2 ± 5.1	0.52 ± 0.45
$t\bar{t}$+≥1c	4.9 ± 3.4	4.2 ± 3.0	11.5 ± 7.3	1.5 ± 1.2
$t\bar{t}$+≥1b	15.5 ± 8.4	12.1 ± 6.8	13.0 ± 7.6	4.4 ± 3.5
$t\bar{t}V$	0.68 ± 0.15	0.36 ± 0.10	0.98 ± 0.22	0.22 ± 0.06
$t\bar{t}H$	1.06 ± 0.29	1.39 ± 0.33	0.99 ± 0.20	0.44 ± 0.13
W+jets	0.35 ± 0.25	0.19 ± 0.14	0.90 ± 0.61	0.08 ± 0.06
Z+jets	0.04 ± 0.04	0.02 ± 0.02	0.10 ± 0.10	< 0.01
Single top	1.03 ± 0.36	0.86 ± 0.27	1.74 ± 0.39	0.24 ± 0.11
Diboson	0.32 ± 0.31	0.15 ± 0.15	0.39 ± 0.26	0.11 ± 0.12
Multijet	–	–	–	–
Total background	27 ± 10	21.3 ± 8.6	43 ± 14	7.6 ± 4.0
Data	50	26	55	13

3. SS dilepton + bjets

13 TeV

Uncertainty (%) on the total background yield

Source	Signal region							
	SR0	SR1	SR2	SR3	SR4	SR5	SR6	SR7
Cross section	8	11	26	13	9	27	23	57
Jet energy scale	1	1	3	1	1	3	2	4
Jet energy resolution	<1	2	2	2	< 1	1	<1	3
b-tagging efficiency	1	2	5	3	1	2	2	7
Luminosity	1	1	1	1	1	1	1	1
Fake/non-prompt leptons	17	7	15	13	26	13	17	17
Charge misID	8	3	7	5	3	6	5	8

Uncertainty (%) on the yield of the signal (4-top quark production)

Source	Signal region							
	SR0	SR1	SR2	SR3	SR4	SR5	SR6	SR7
Jet energy scale	2	12	2	6	4	3	3	3
Jet energy resolution	16	6	7	16	14	11	1	2
b-tagging efficiency	8	5	5	21	14	15	5	5
Lepton ID efficiency	1	1	1	4	2	2	2	1
Luminosity	2	2	2	2	2	2	2	2

3. SS dilepton + biets

13 TeV

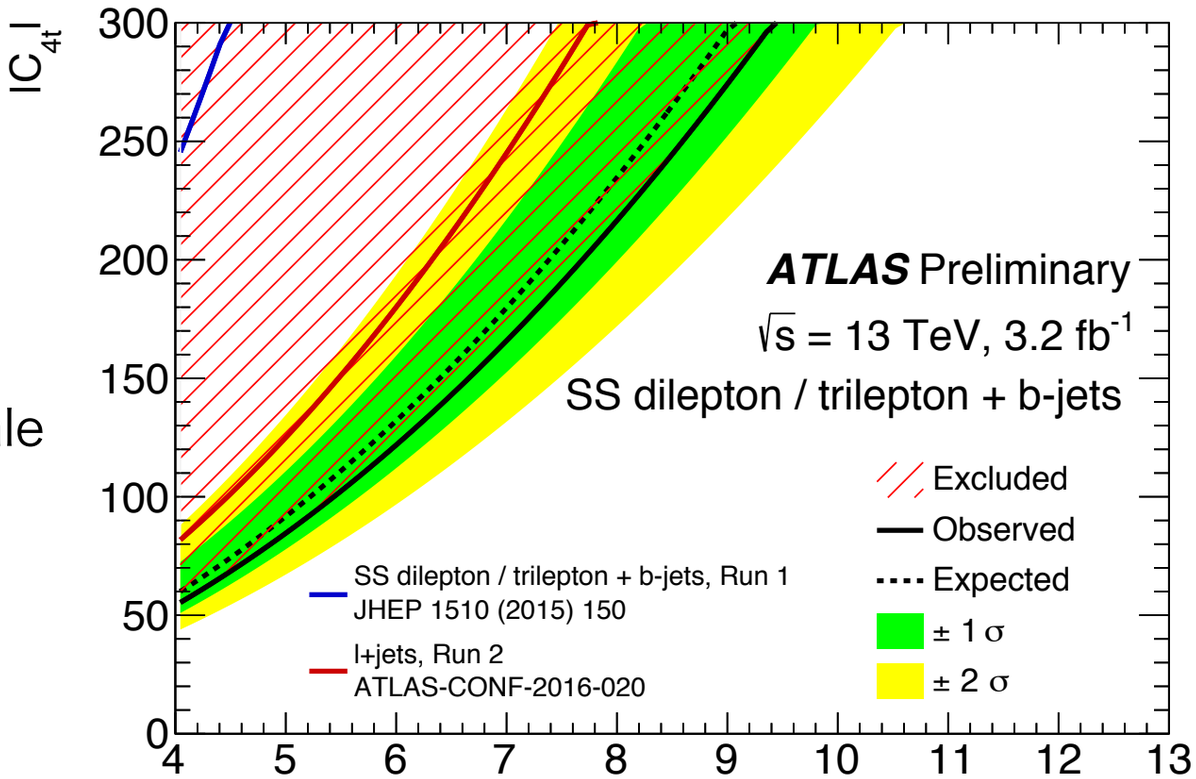
For 4top: $\sigma_{SM} < 95$ (107) fb, $\sigma_{BSM} < 67$ (79) fb

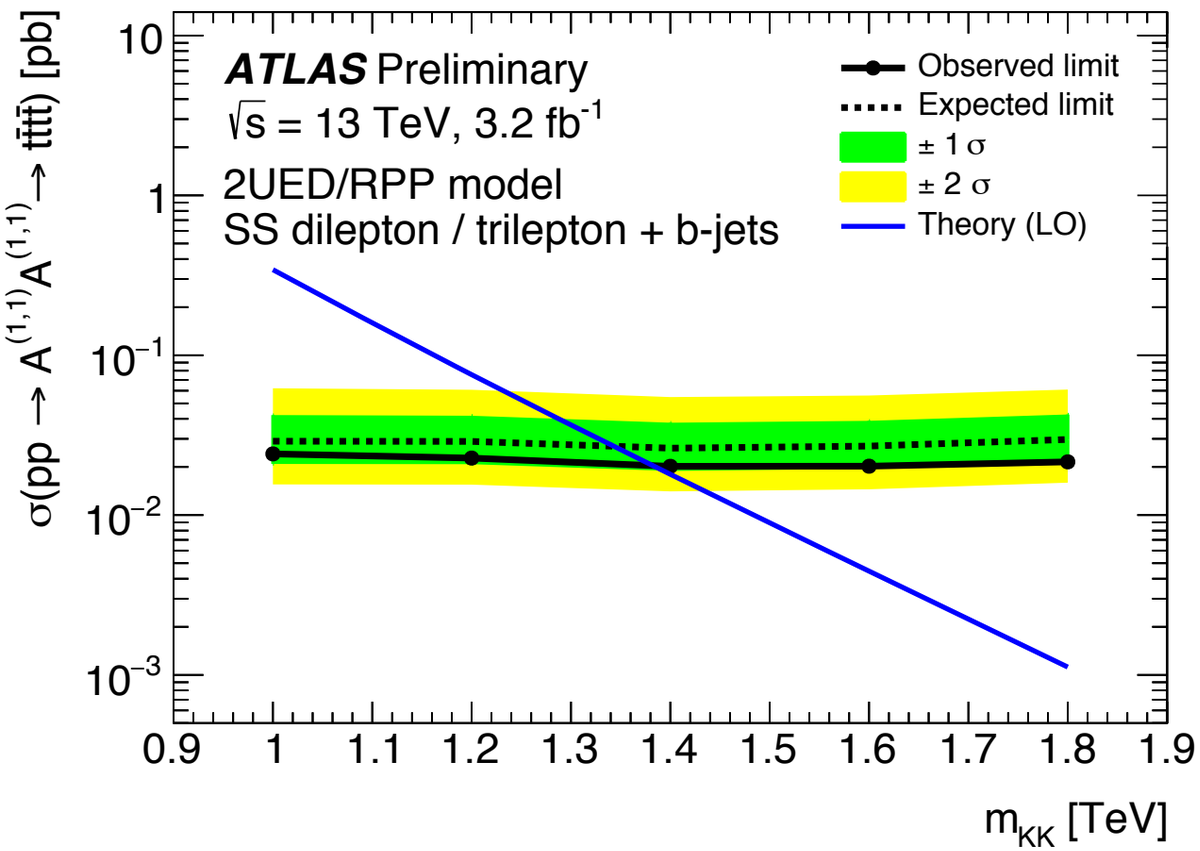
For contact interaction, $|C_{4t}|/\Lambda^2 < 3.5$ TeV^{-2}

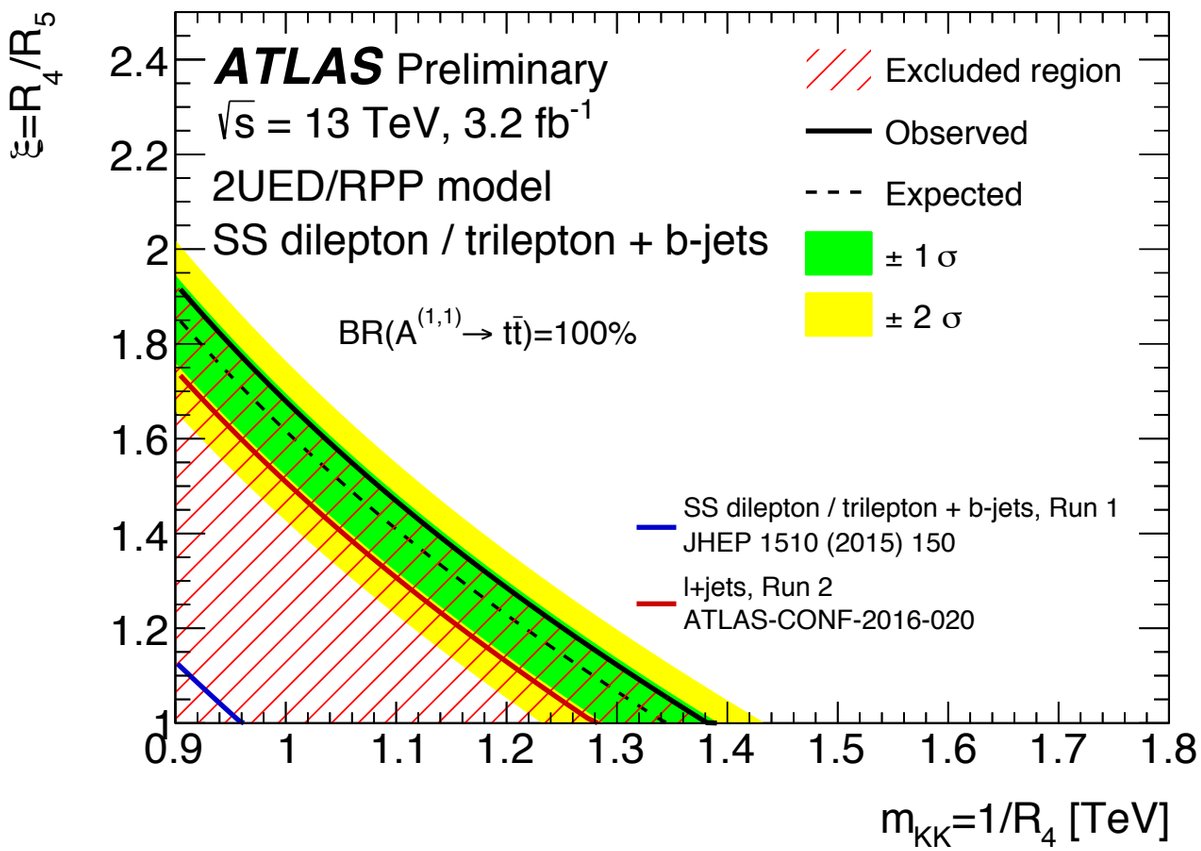
C_{4t}: coupling constant, Λ: BSM physics energy scale

For 2UED/RPP, $m_{KK} > 1.4$ TeV with

R4 = R5 & BR($A_\mu^{(1,1)} \rightarrow tt$) = 100%







2. TT → Wb+X

Systematic uncertainty [%] (8 TeV)

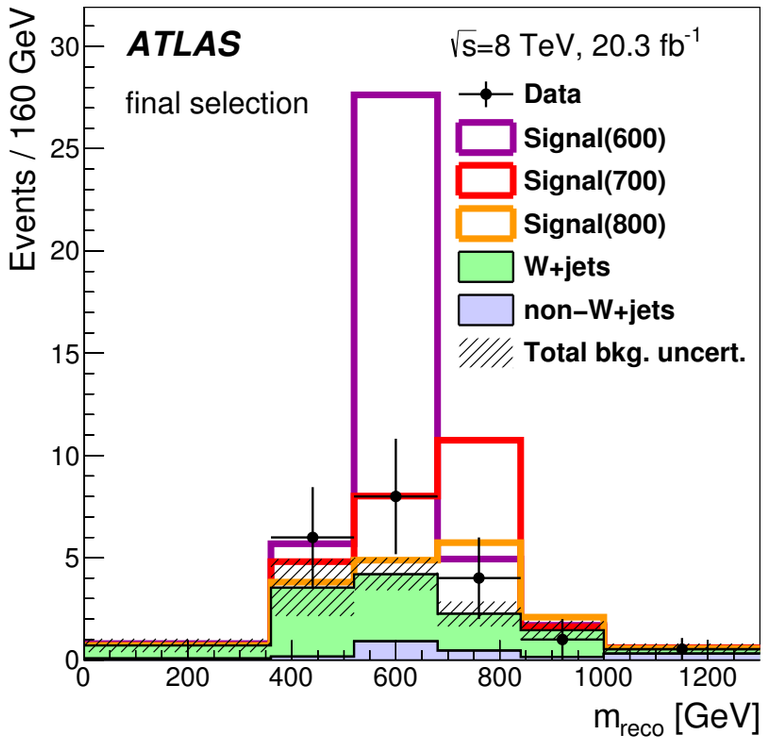
	Signal	$t\bar{t}$	Non-$t\bar{t}$	Total background
Luminosity	±2.8	±2.8	±2.8	±2.8
Lepton efficiencies	±1.6	±1.6	±1.5	±1.6
Jet energy scale	+3.4/−7.2	±16	+19/−9	+17/−12
Jet efficiencies	±1.5	±1.6	±1.6	±1.6
Jet energy resolution	±1.1	±0.6	±2.6	±1.8
b-tagging efficiency	±5.0	±0.7	±2.9	±2.0
c-tagging efficiency	±0.4	±1.2	±2.3	±1.9
Light-jet tagging efficiency	±0.2	±1.3	±1.6	±1.4
High-p_{T} tagging efficiency	±3.2	±1.3	±0.8	±1.1
Missing transverse momentum	–	±2.6	–	±1.0
$t\bar{t}$: reweighting	–	±15	–	±5.9
$t\bar{t}$: parton shower	–	±9.3	–	±3.6
$t\bar{t}$+HF: normalisation	–	+12.0/−5.5	–	+4.5/−2.1
$t\bar{t}$+HF: modelling	–	±30	–	±11
Theoretical cross sections	–	±6.0	±33	±20
Multijet normalisation	–	–	±2.9	±1.8
Non-$t\bar{t}$ modelling	–	–	±2.3	±1.4
Total	+7.7/−10.0	±40	±35	±29

4. T→Wb

Systematic uncertainty [%] (8 TeV)

Systematic uncertainty	Signal	Total bkg.
Modelling uncertainties [%]		
$t\bar{t}$ and W+jets normalisation	-	15
$t\bar{t}$ modelling	-	4.9
W+jets modelling	-	2.4
Single top modelling	-	6.3
Multijet estimate	-	2.6
Parton distribution functions	2.0	7.4
Experimental uncertainties [%]		
b-tagging	8.0	1.5
Small-R jets energy resolution	0.7	0.3
Small-R jets energy scale	3.3	3.6
JVF, small-R jets	< 0.1	0.2
Large-R jet energy and mass resolution	4.0	6.8
Large-R jet energy scale	7.2	9.7
Lepton id & reco	2.3	0.2
Missing transverse momentum	0.3	0.4
Luminosity	2.8	2.7

QQ → WqWq (8 TeV)



dominant systematic uncertainty [%]
(normalization)

	Signal ($m_Q = 700GeV$)	Non-W+jets	W+jets
Luminosity	+2.8/–2.8	+2.8/–2.8	+2.8/–2.8
Normalization		±15	+2.7/–4.4
Lepton identification	+1.6/–1.6	+1.5/–1.5	+1.4/–1.4
Jet energy resolution	+0.6/–0.6	+12/–12	+8.7/–8.7
Jet energy scale	+6.1/–4.3	+33/–34	+14/–18
b-tagging	+0.2/–0.2	+5.1/–5.3	+0.3/–0.3
c-tagging	+1.5/–1.5	+1.5/–1.5	+1.2/–1.2
Light-jet tagging	+1.0/–1.0	+0.9/–0.9	+1.0/–1.0
$p_{\mathrm{T}}^{\mathrm{truth}}(V)$ re-weighting			+5.7/–4.2

	Electron	Muon
W+jets	$5.6 \pm 1.5\ ^{+1.5}_{-1.2}$	$6.0 \pm 1.0\ ^{+2.2}_{-1.6}$
Non-W+jets	$1.2 \pm 0.5\ ^{+1.0}_{-0.4}$	$1.2 \pm 0.4\ ^{+0.8}_{-1.0}$
Total background	$6.8 \pm 1.6\ ^{+2.4}_{-1.5}$	$7.2 \pm 1.1\ ^{+2.5}_{-2.3}$
Signal ($m_Q = 700GeV$)	$7.0 \pm 0.6\ ^{+1.1}_{-1.3}$	$6.9 \pm 0.6\ ^{+1.0}_{-1.0}$
Data	9	11