Search for new heavy quarks in ATLAS

Moriond EW 2018

Nikiforos Nikiforou, UT Austin

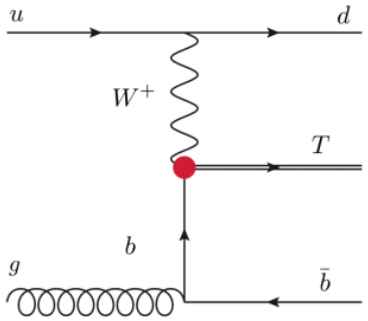
On behalf of the ATLAS collaboration

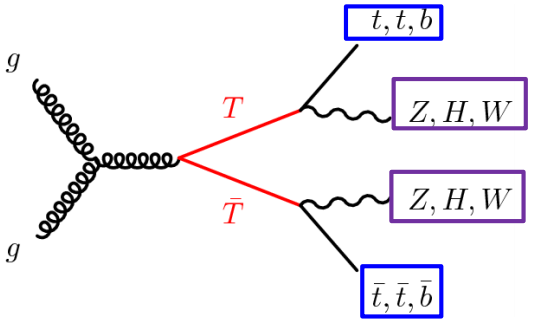
Physics motivation and general overview

- Although appealing, a straightforward inclusion of a 4th generation of quarks to extend the SM is excluded
  - Incompatible with observed Higgs production cross-section
- **Latest searches for new heavy quarks in ATLAS target <u>Vector-Like Quarks (VLQs)</u> (focus of this talk)**
- VLQs are proposed in various models of new physics
  - **Colored** spin-1/2 fermions and their L/R-handed components transform the same way under gauge transformations
  - Evade limitations on chiral quark extensions of the SM
- **VLQs could mix with their SM quark counterparts and regulate the Higgs mass-squared divergence**
  - Attractive mechanism to solve the hierarchy problem

A bit more about VLQs

- Can have $T_{2/3}, B_{-1/3}, X_{5/3}, Y_{-4/3}, \ldots$
- Could be ***singly***-produced or in **pairs**
  - Single production dominates for high VLQ masses
- Can be arranged in SU(2) singlets or multiplets
- Decays to W,Z, and H bosons with branching ratios which depend on the model
- Decays to 3rd generation quarks are favored
  - Usually assumed to couple only to t and b





Today's Menu: Pair-Produced Vector-like Quark searches

Focusing on latest ATLAS searches optimized for pair production of Vector-Like T and B:

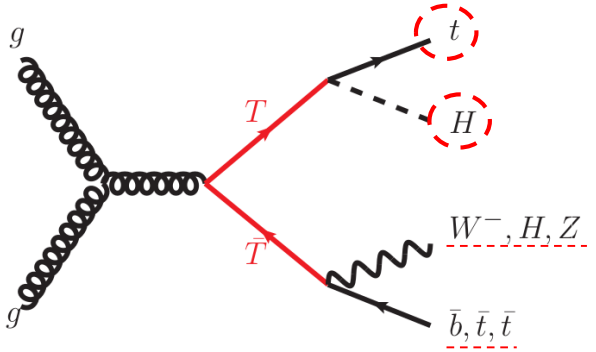
- $T\bar{T} \rightarrow Ht + X$: Up-type VLQ in events with multiple b-jets
  - EXOT-2016-13 **NEW!**

- $Q\bar{Q} \rightarrow Wb + X$: VLQ to High p_{T} W and b, lepton-plus-jets
  - JHEP10(2017)141/arxiv:1707.03347/EXOT-2016-14

The analyses are using the $\mathbf{36.1fb^{-1}}$ of proton-proton collisions delivered by the LHC at $\sqrt{s} = 13$ TeV in 2015 and 2016 and recorded by the ATLAS detector

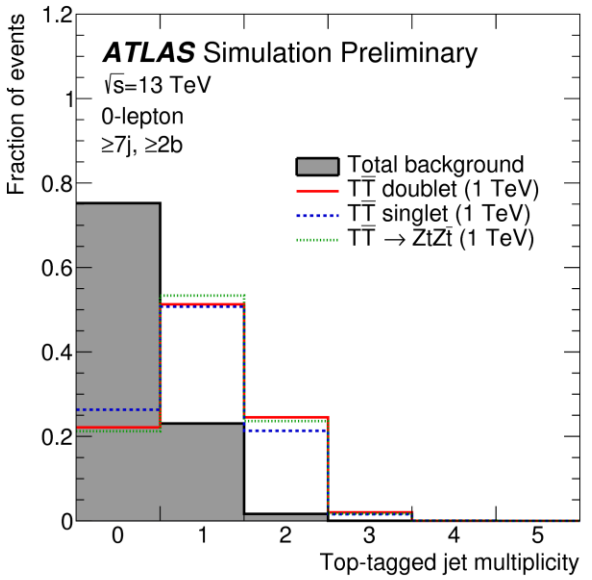
- You can always consult the latest ATLAS exotics publications here
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

$T\bar{T} \rightarrow Ht + X$
Strategy and preselection



- Targets $T\bar{T}$ pair production, a least one $T \rightarrow H(\rightarrow b\bar{b})t$ or $T \rightarrow Z(\rightarrow \nu\bar{\nu})t$
- Take advantage of presence of multiple jets, b-tagged jets, t-tagged jets, H-tagged jets, $E_{\mathrm{T}}^{\mathrm{miss}}$
- Split analysis into two channels
  - Preselection:

1-lepton channel	**0-lepton channel**
Single-lepton trigger **Exactly 1 isolated e or μ**	$E_{\mathrm{T}}^{\mathrm{miss}}$ trigger **Exactly 0** isolated e or μ
$E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV $E_{\mathrm{T}}^{\mathrm{miss}} + m_{\mathrm{T}}^{\mathrm{W}} > 60$ GeV	$\boldsymbol{E_{\mathrm{T}}^{\mathrm{miss}} > 200}$ **GeV** $\Delta\phi_{\mathrm{min}}^{4j} > 0.4$
≥ 5 jets	≥ 6 jets
≥ 2 b-tagged jets	



$$m_{\mathrm{T}}^{W} \equiv \sqrt{2\, p_{\mathrm{T}}^{\mathrm{lep}} E_{\mathrm{T}}^{\mathrm{miss}} [1 - \cos\Delta\phi]}$$

$\Delta\phi_{\mathrm{min}}^{4j}$: smallest separation in ϕ of $\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$ and 4 leading jets

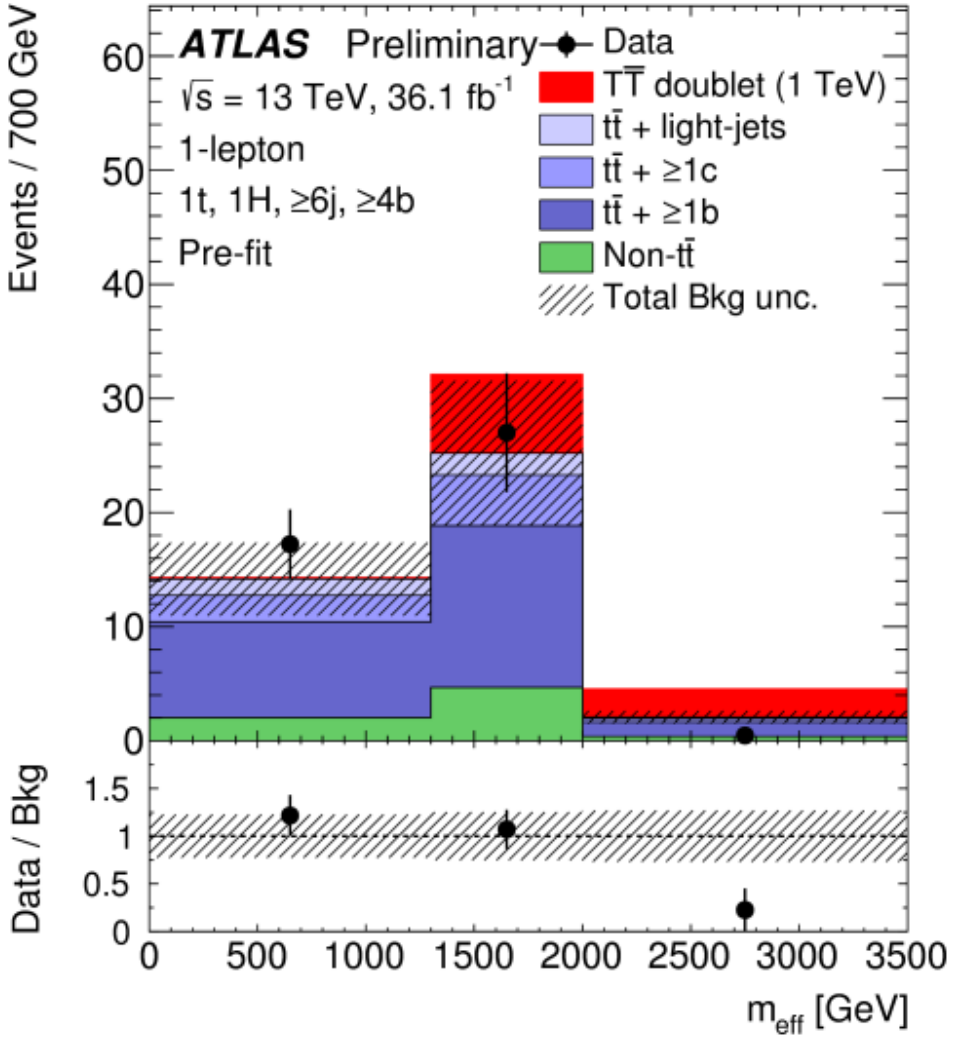
- Suppresses multijet background

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

Search regions and combined fit

- **Final discriminant: m_{eff}**
  - Scalar sum of p_{T} of lepton, jets, and $E_{\mathrm{T}}^{\mathrm{miss}}$
- Main background: $t\bar{t} + jets$
- "Non-$t\bar{t}$" includes:
  - $t\bar{t}V$
  - $t\bar{t}H$
  - single t
  - W\Z + jets
  - VV

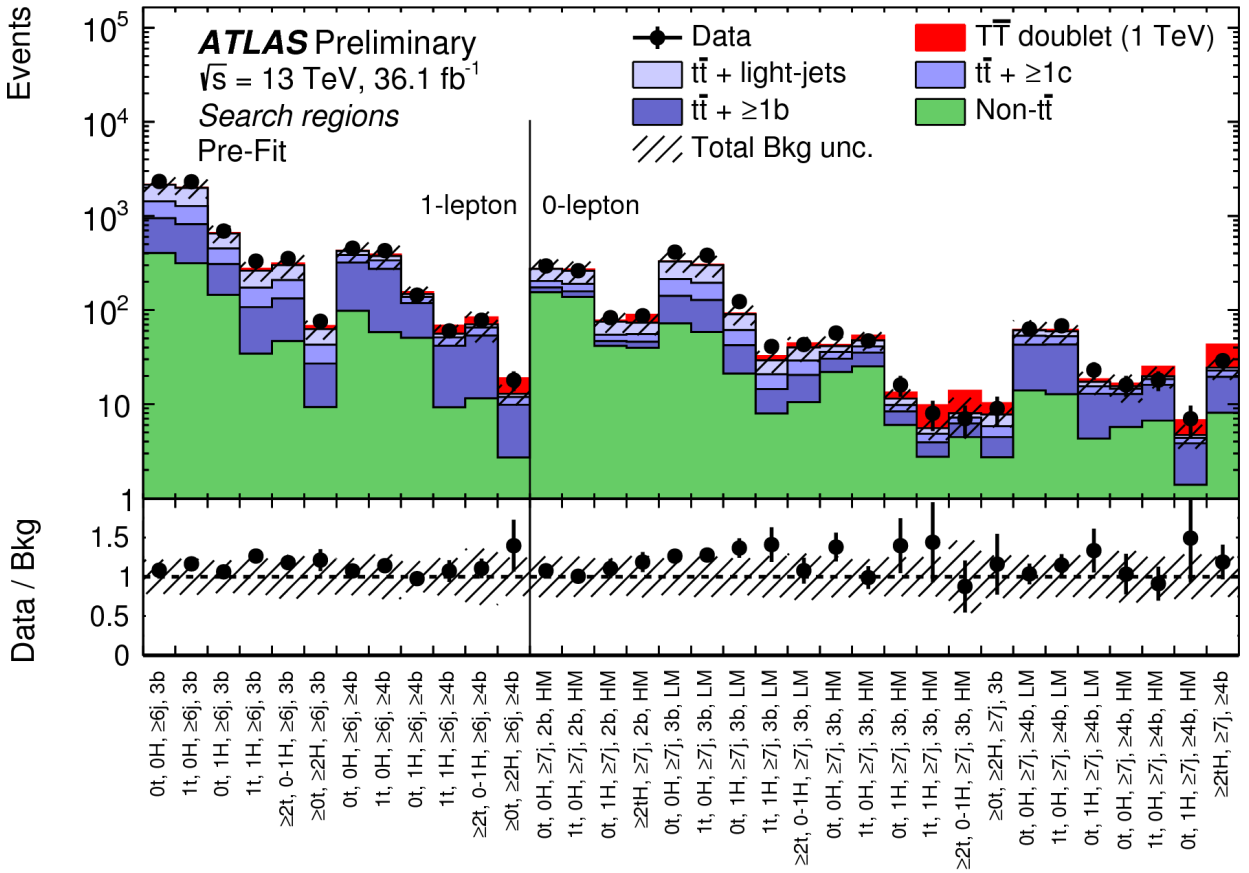
  } MC
  - Multijet: data-driven methods
    - Matrix Method (1ℓ)
    - Fit to $\Delta\phi_{\mathrm{min}}^{4j}$ (0ℓ)



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

Search regions and combined fit

- The two channels are further divided into search regions
- 12 (1ℓ) + 22 (0ℓ)
- Categorize according to N_t, N_H, N_b, N_j
- For 0-lepton also categorize in $m^b_{\mathrm{T,min}}$:
  - HM: $m^b_{\mathrm{T,min}} > 160$ GeV
  - LM: $m^b_{\mathrm{T,min}} < 160$ GeV

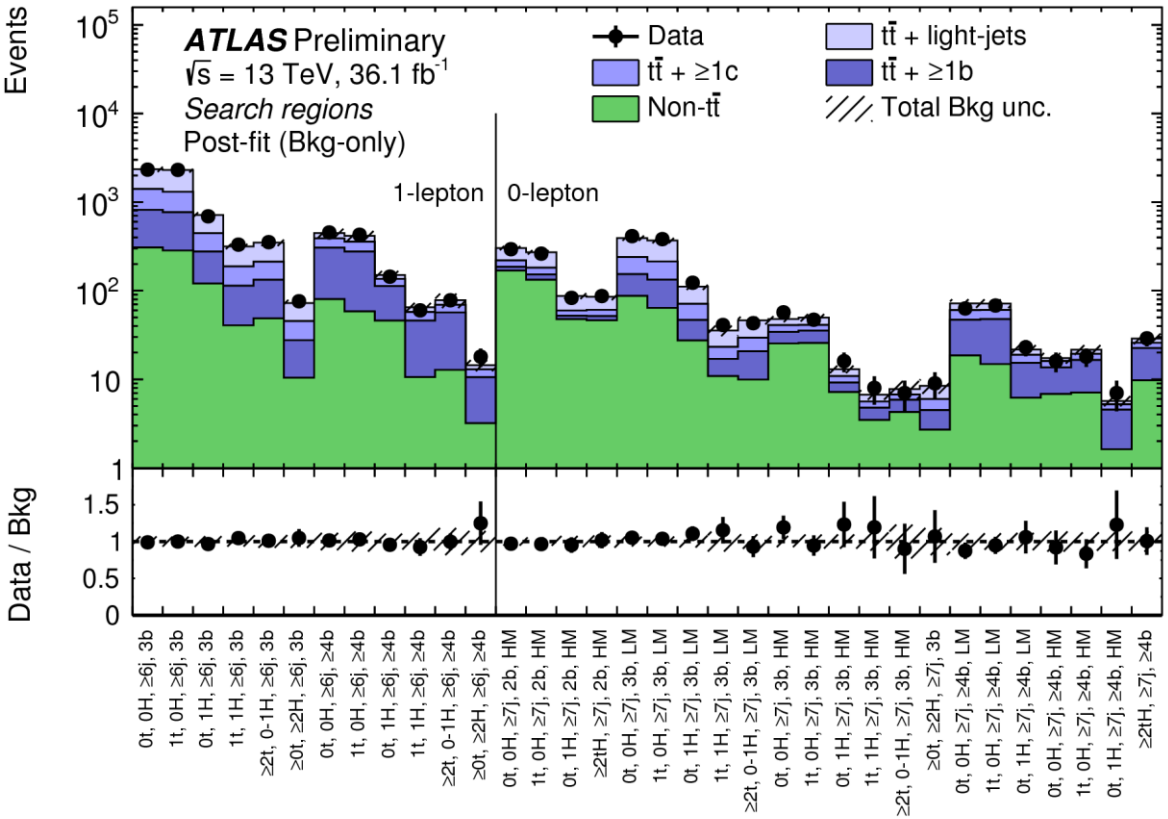


Perform Combined Maximum likelihood fit of m_{eff} distribution in all search regions

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

Search regions and combined fit

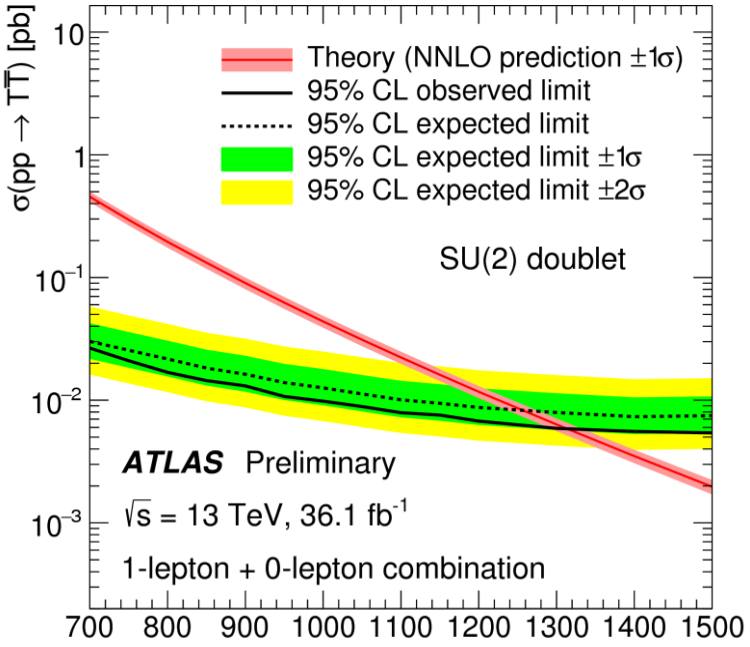
- **Very good agreement of the data with the background expectation**
- Check background in orthogonal validation regions: 10 (1ℓ) + 16 (0ℓ)
  - Use number of jets ($\equiv 5$ or $\equiv 6$)
- Main systematic uncertainties (vary by search region):
  - $t\bar{t}$ modeling, flavor tagging uncertainties, background normalization uncertainties



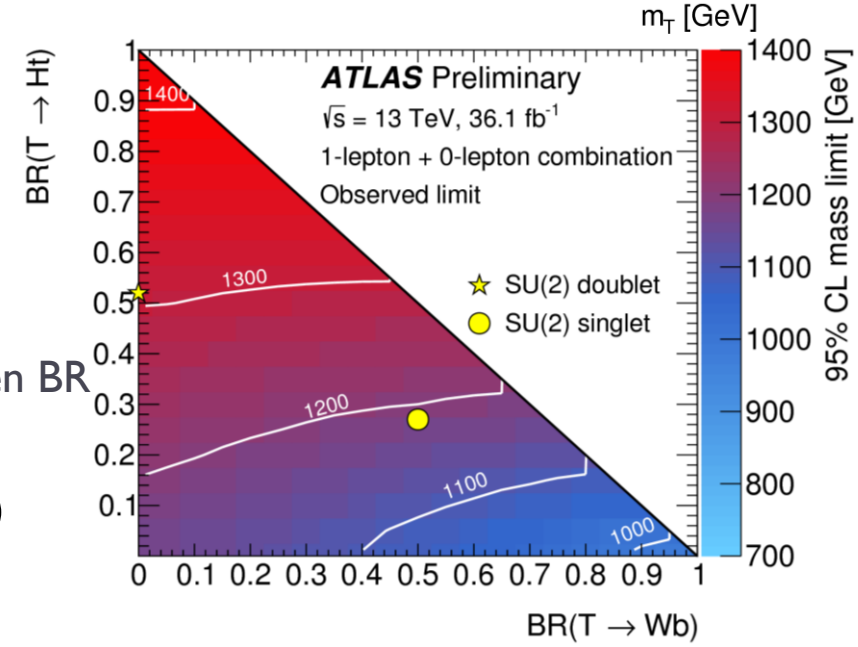
Proceed to set limits (next slide)

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

- Exclusion limits are set both separately for each channel and **combined**
- **Under different BR assumptions, VLT masses are excluded up to, e.g.:**
  - **$\sim$1.4 TeV (100% BR $T \rightarrow Ht$)**
  - **$\sim$1.3 TeV (Doublet)**



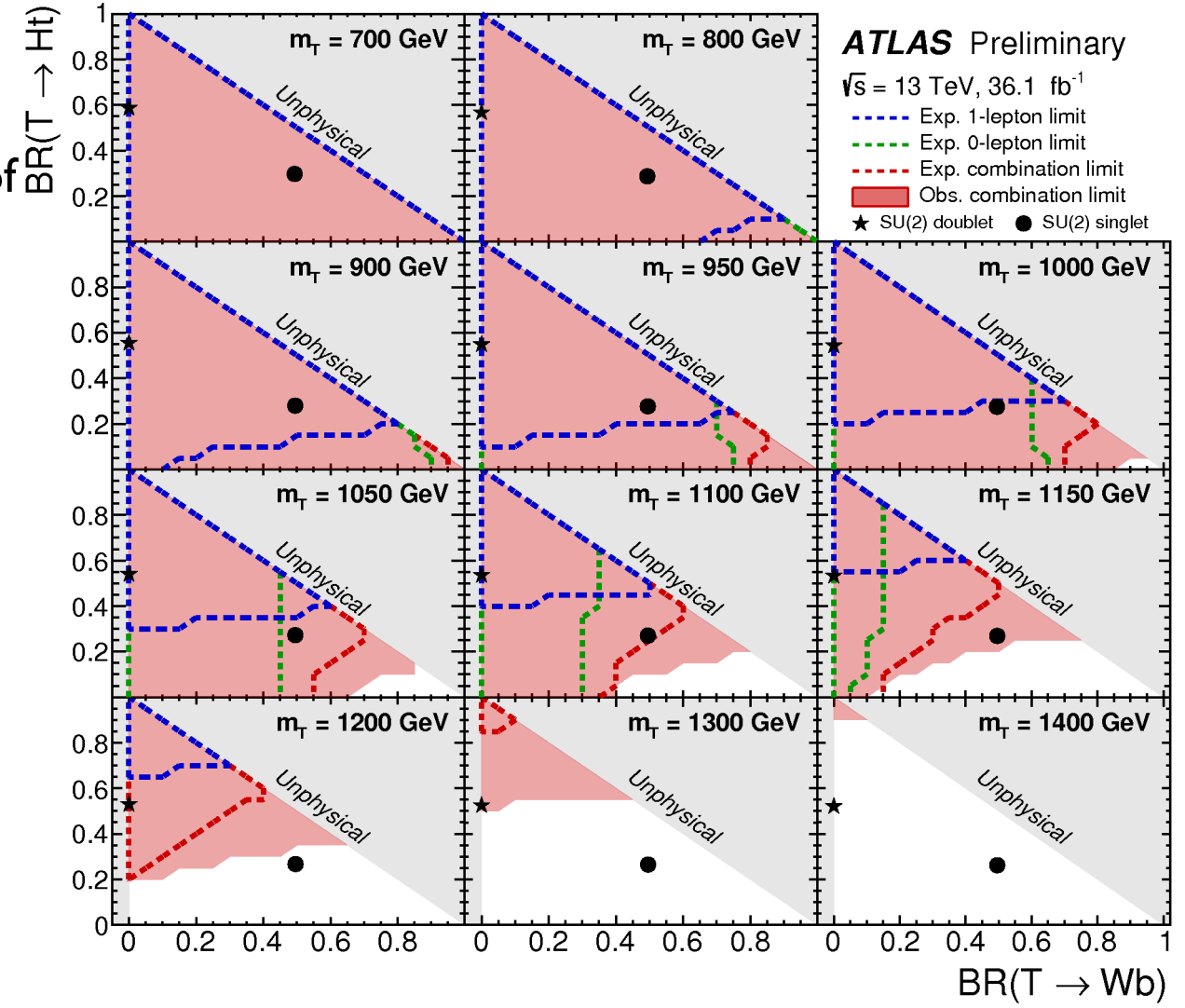
- Reweight signal samples to other BR compositions to obtain 2D limits
  - Assumes $BR(T \rightarrow Ht) + BR(T \rightarrow Wb) + BR(T \rightarrow Zt) = 1$
  - Heat map: highest excluded VLT mass at the given BR composition
- Notice increased sensitivity near point (0,1) where $BR(T \rightarrow Ht) = 1$



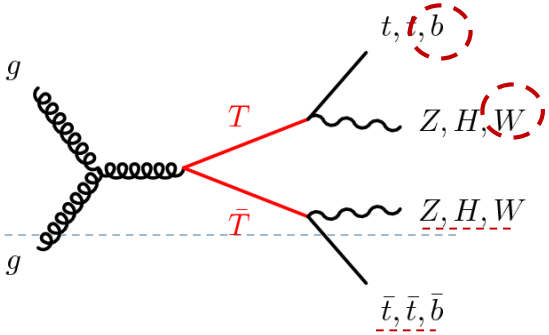
$T\bar{T} \rightarrow Ht + X$

Summary of individual and combined results

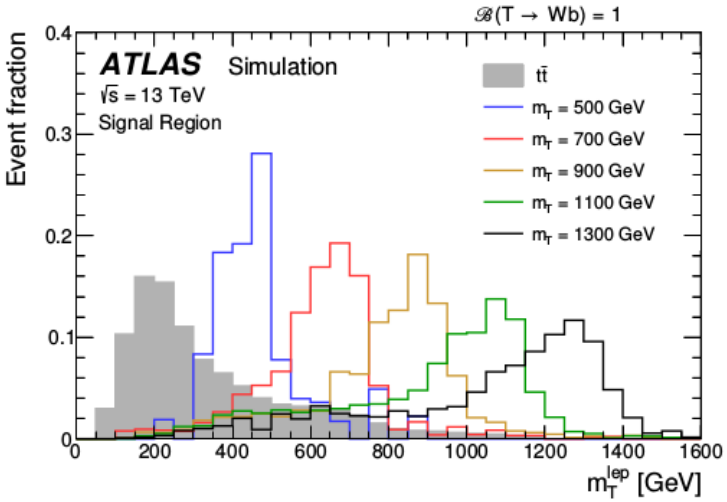
- For each mass point, expected exclusion reach on the BR plane of each channel (1ℓ, 0ℓ) separately and their combination (dotted lines)
- **Combined Observed limit**: pink shaded area
- **~500 GeV** improvement compared to previous 8 TeV ATLAS result [JHEP 08 (2015) 105]

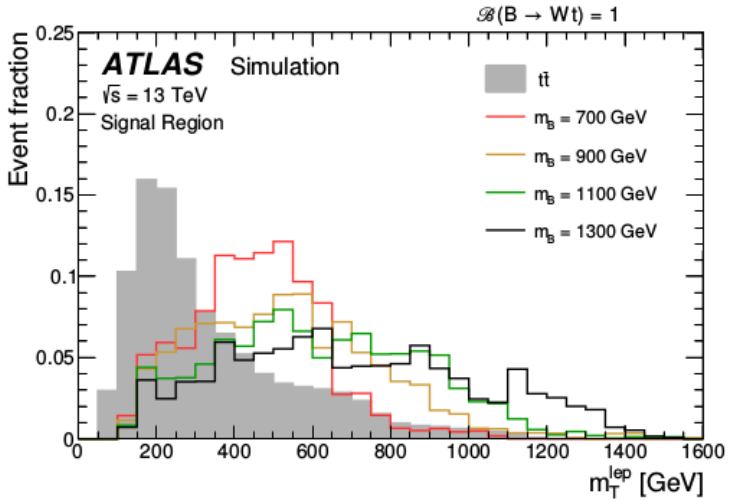


$Q\bar{Q} \rightarrow Wb+X$
Analysis strategy



- Targets $T\bar{T}$ pair production, a least one $T \rightarrow Wb$
- $\equiv 1\ \ell\ (e\ or\ \mu), \geq 3j, \geq 1\ b, E_{\mathrm{T}}^{\mathrm{miss}} > 60$ GeV
- ≥ 1 boosted hadronic W candidate (W_{had})
- **Selection optimized for for $T\bar{T} \rightarrow W_{\mathrm{had}} W_{\mathrm{lep}} bb$**
- Final discriminant: reconstructed semi-leptonic T mass m_T^{lep}
- Reconstruct two T candidates minimizing $|m_T^{\mathrm{had}} - m_T^{\mathrm{lep}}|$
  - Make all combinations of W candidates with b or other jets





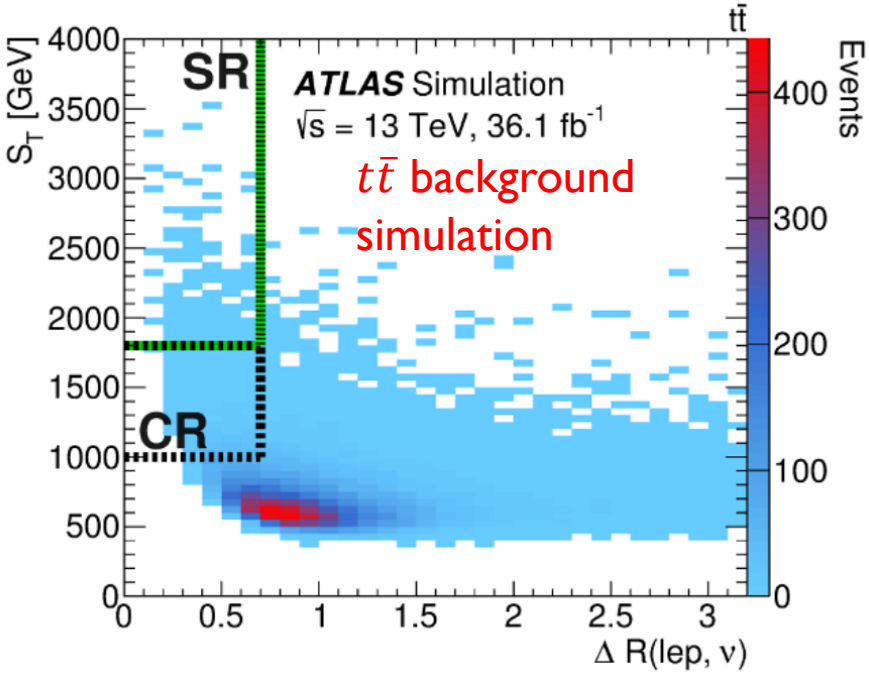
Bonus: Same procedure applied to search for $B \rightarrow Wt$ without need for further optimization

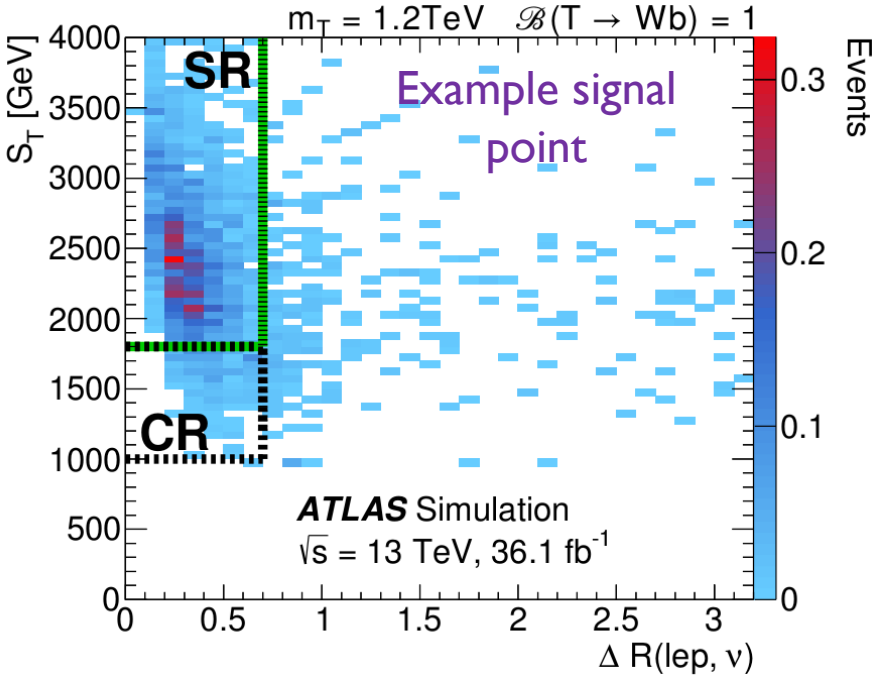
JHEP10(2017)141

TEXAS The University of Texas at Austin

$Q\bar{Q} \rightarrow Wb+X$
Signal and Control Region definitions

- Main background: $t\bar{t}$, constrained by dedicated CR
  - Define SR and CR using scalar sum of $E_{\mathrm{T}}^{\mathrm{miss}}$ and p_{T} of leptons and jets, S_{T}, and separation between lepton and neutrino, $\Delta R(lep, \nu)$



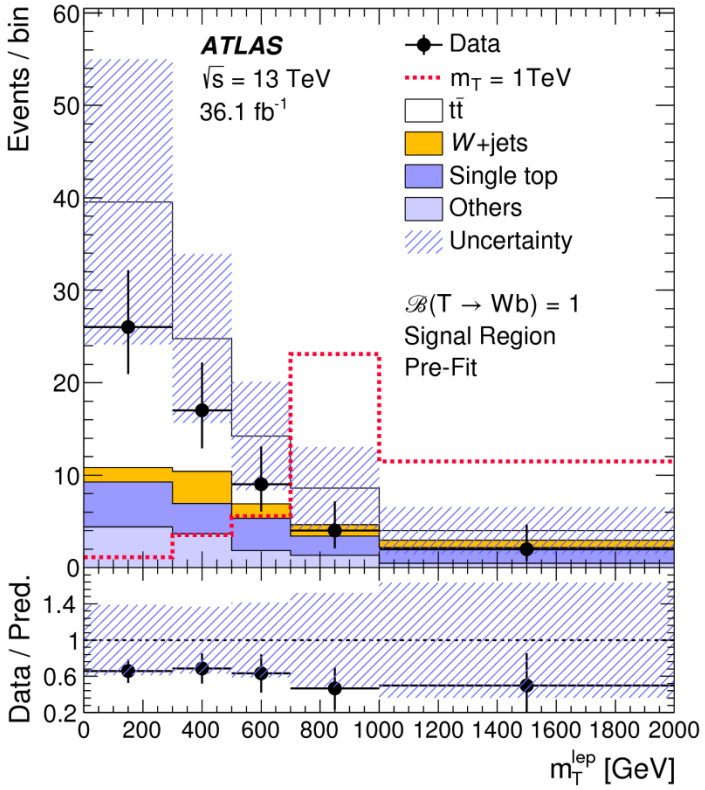


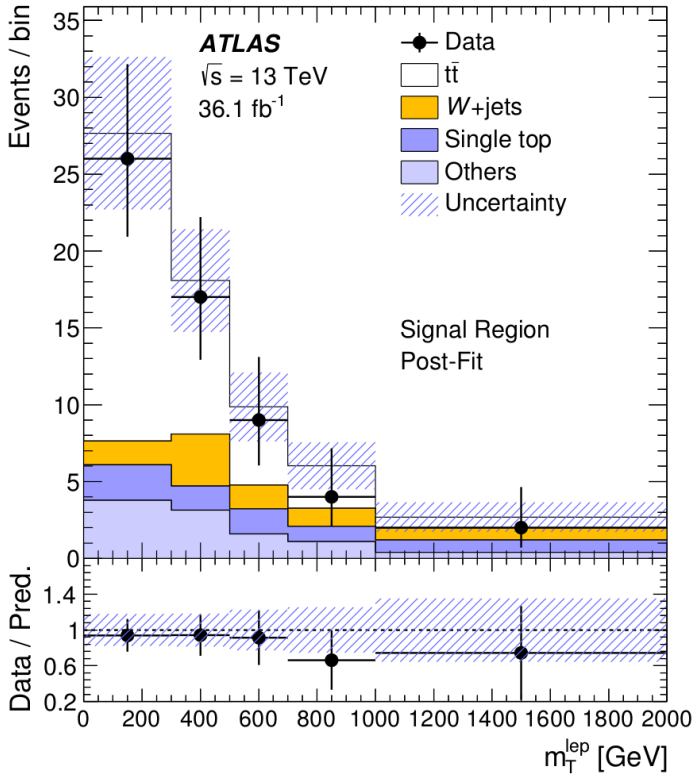
- Subdominant backgrounds
  - Multi-jets: estimated with Matrix Method
  - SM backgrounds (W + jets, single t, Z + $jets$, ttV) estimated with MC

JHEP10(2017)141

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

SR distributions before and after bkg-only fit

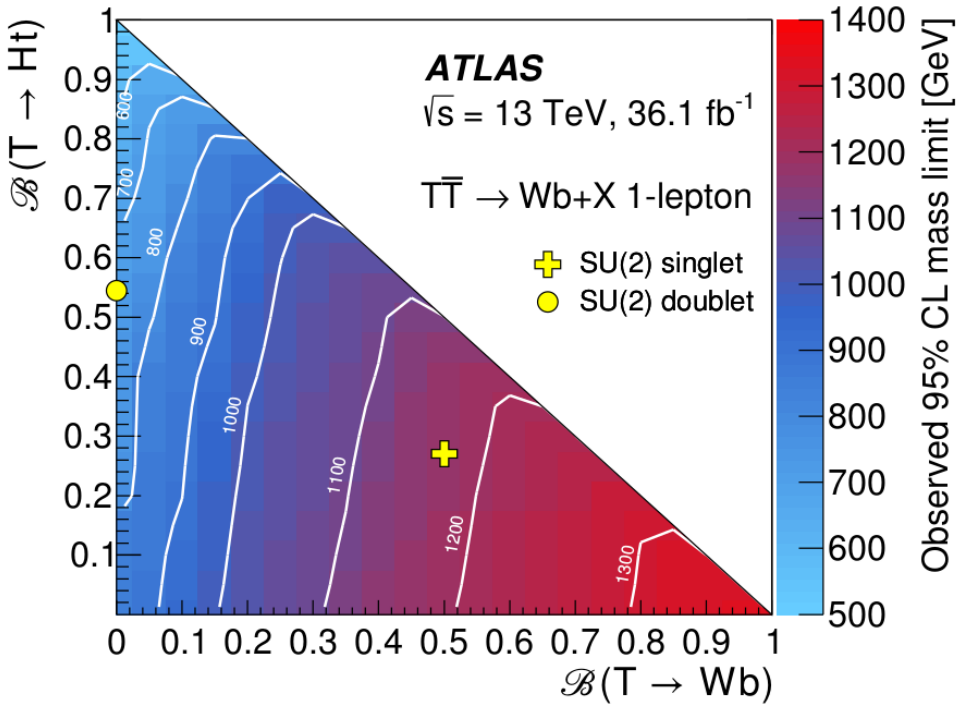




- Very good agreement with the background expectation
  - Proceed to set limits (next slide)
- Main systematics: single t and $t\bar{t}$ modeling uncertainties, Jet Energy Resolution

$Q\bar{Q} \rightarrow Wb+X$
2D limits on T BRs

Assumes
$BR(T \rightarrow Ht) + BR(T \rightarrow Wb) + BR(T \rightarrow Zt) = 1$



- Notice increased sensitivity near point (1,0)
  - Larger BR to Wb
- Limits for particular BR assumptions:

Model	Obs. 95% CL lower mass limit [GeV]
100% $T \rightarrow Wb$	**1350**
Singlet T	**1170**

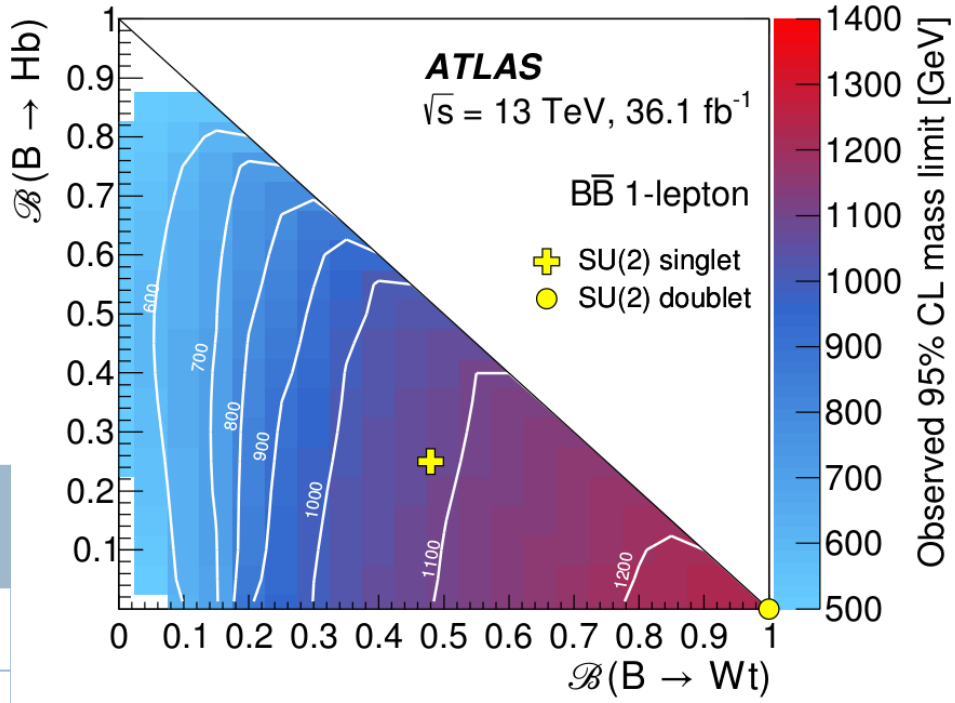
- **Bonus**: 100% $T \rightarrow Wb$ limits are applicable to VL Y (q=-4/3)
  - The Y decays exclusively to Wb
  - Excluded for masses below 1350 GeV

$Q\bar{Q} \rightarrow Wb+X$
2D limits on B BRs

Assumes
$BR(B \rightarrow Wt) + BR(B \rightarrow Hb) + BR(B \rightarrow Zb) = 1$

- Notice increased sensitivity near point (1,0)
  - Larger BR to Wt
- Limits for particular BR assumptions:

Model	Obs. 95% CL lower mass limit [GeV]
100% $B \rightarrow Wt$	**1250**
Singlet B	**1080**



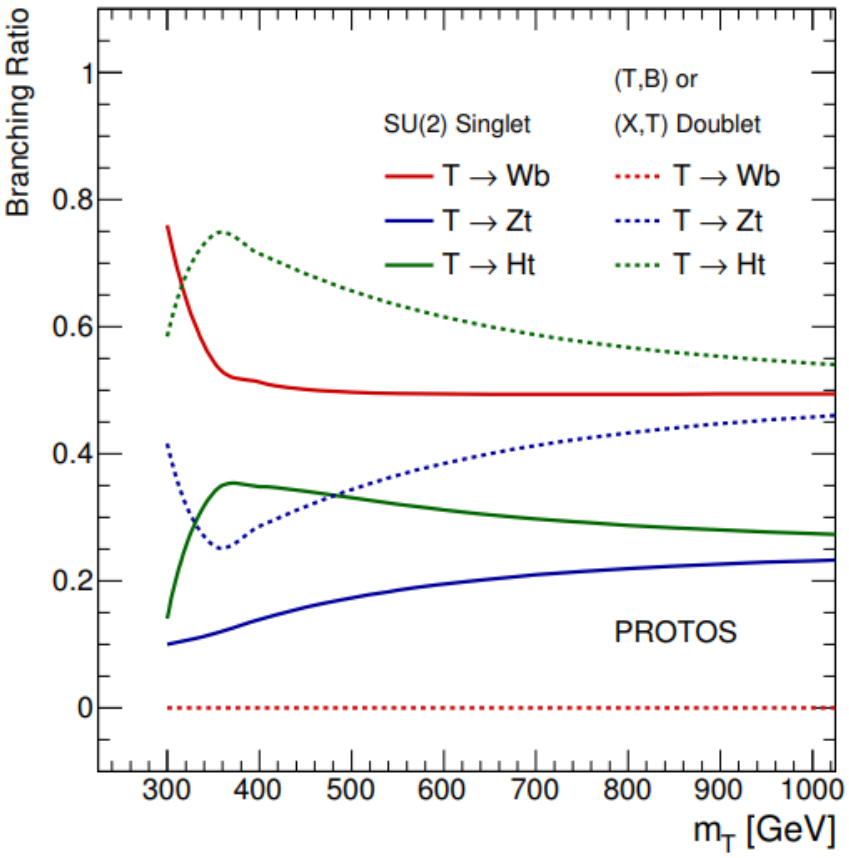
- **Bonus**: 100% $B \rightarrow Wt$ limits are applicable to VL X (q=5/3)
  - The X decays exclusively to Wt
  - Excluded for masses below 1250 GeV

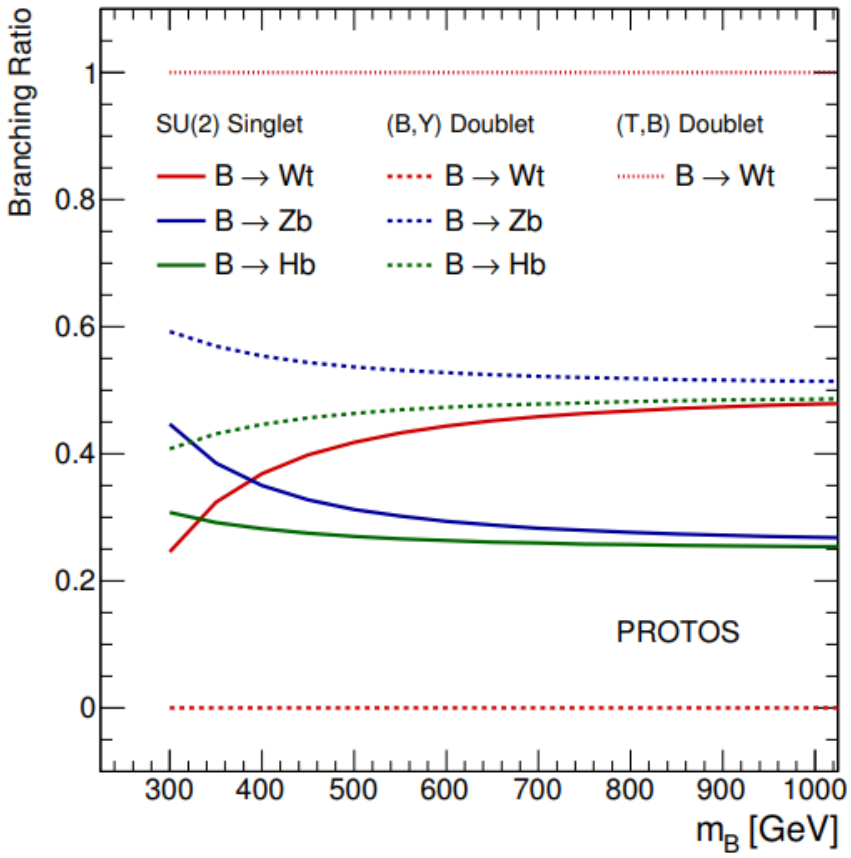
Summary

- Latest ATLAS searches for new heavy quarks have focused on Vector-Like Quarks
  - Broad program targeting both pair- and single-production
- Analyses can be optimized for VLQ decays via the W, Z or H bosons
  - Latest results for all three have been presented today
- VL T masses up to ~**1.2** to **1.4** **TeV** are excluded assuming 100% BR to Zt, Wb, or Ht
- VL B masses up to **1.25** **TeV** are excluded assuming 100% BR to Wt
- Limits are also provided for models with intermediate BR values

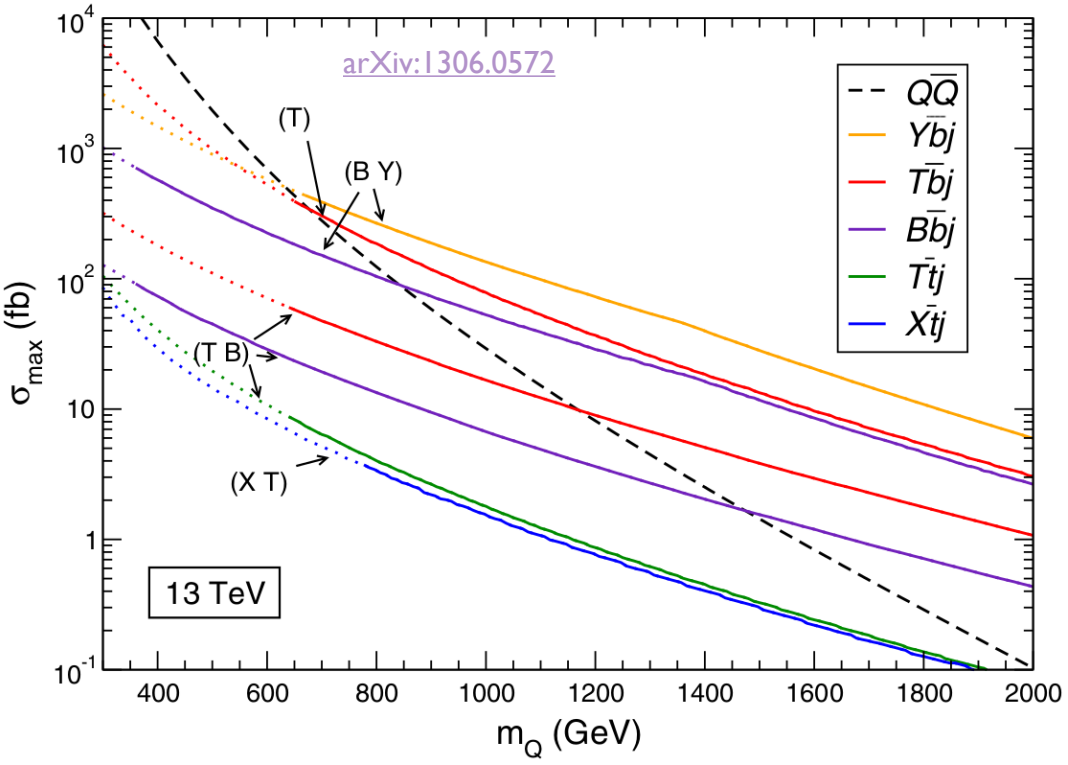
Supplementary Material

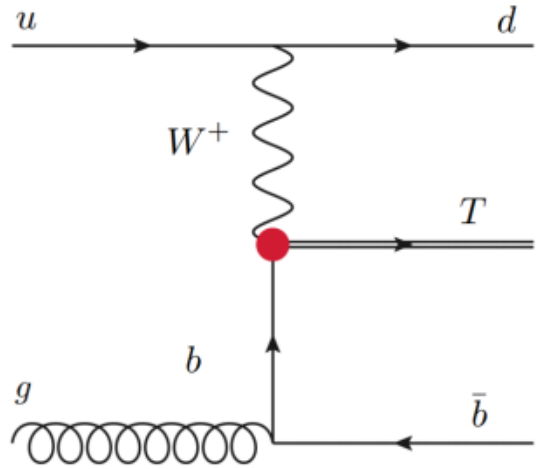
VLT and VLB BR

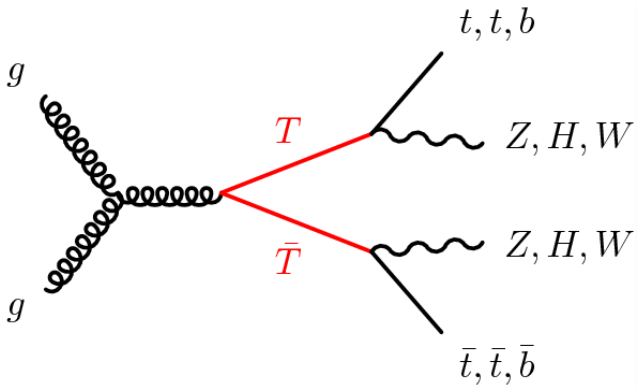




Single vs pair production

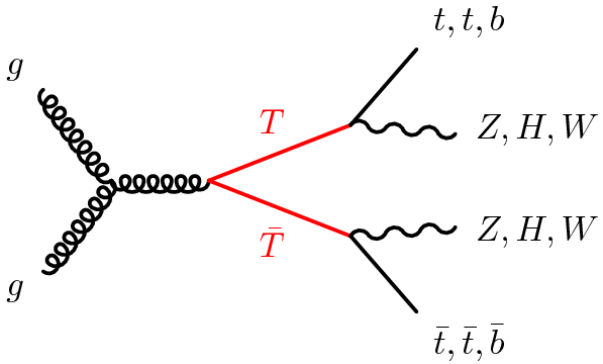


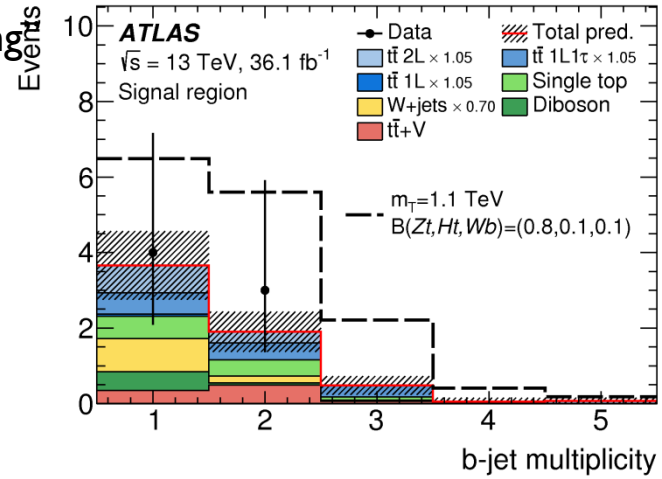




Generic VLQ search recipe

- Features in signal exploited by VLQ searches (and used by the analyses presented today)
  - Presence of leptons
  - High ("small-Radius") jet multiplicity
  - High b-tagged jet multiplicity
    - Typically tagged using a WP with 77% efficiency measured in simulated $t\bar{t}$ events
  - Presence of "large-Radius" jets
    - Typically reconstructed with R=1.0 either by "reclustering" small-R jets or original calorimeter clusters
  - High H_{T}, m_{eff}
    - Scalar sums of the transverse momenta of the objects in the event
  - Presence of missing transverse energy, $E_{\mathrm{T}}^{\mathrm{miss}}$



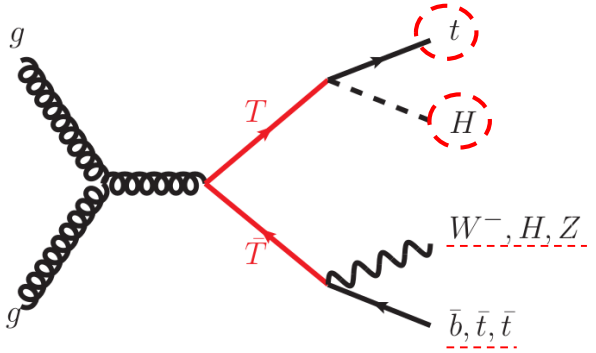


Recent ATLAS VLQ publications

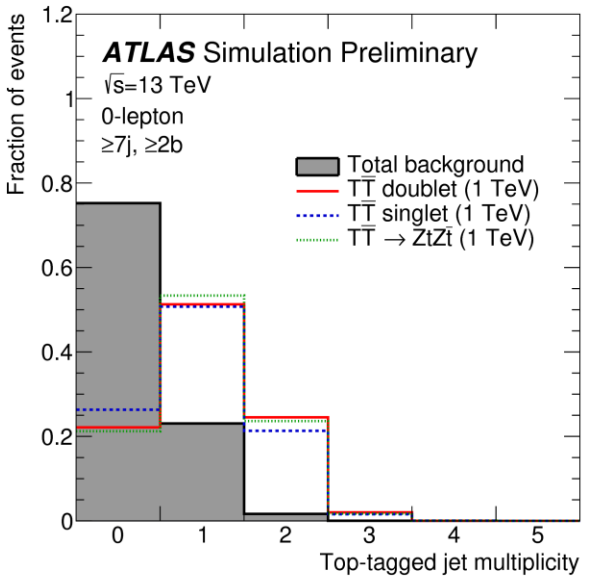
Short Title	Journal reference	Date	√s (TeV)	L
VLQ Pair Production Ht+X 13 TeV 2016 (PRELIMINARY)	**EXOT-2016-13**	**---**	**13**	**36.1 fb^{-1}**
VLQ pair production Wb+X 13 TeV 2016	**JHEP 10 (2017) 141**	**11-JUL-17**	**13**	**36.1 fb^{-1}**
VLQ pair production Zt+X lepton + MET 13 TeV 2016	JHEP 08 (2017) 052	30-MAY-17	13	36.1 fb^{-1}
Stop pair; 1 lepton, b-jets	Phys. Rev. D 94 (2016) 052009	13-JUN-16	13	3.2 fb^{-1}
Single VLQ search with heavy gluon 8 TeV 2012	Phys. Lett. B758 (2016) 249	18-FEB-16	8	20.3 fb^{-1}
Search for single VLQ in Wb 8 TeV 2012	Eur. Phys. J. C76 (2016) 442	17-FEB-16	8	20 fb^{-1}
Search for the production of single vector-like and excited quarks in the WtWt final state in pppp collisions at √s=8 TeV with the ATLAS detector	JHEP02(2016)110	09-OCT-15	8	20 fb^{-1}
Search for VLQs decaying to light quarks 8 TeV 2012	Figures | Phys. Rev. D 92, 112007 (2015)	14-SEP-15	8	20 fb^{-1}
Search for production of vector-like quark pairs and of four top quarks in the lepton-plus-jets final state in ppppcollisions at √s=8 TeV with the ATLAS detector	Figures | JHEP 08 (2015) 105	16-MAY-15	8	20 fb^{-1}
Same-sign dilepon plus b-jet search 8 TeV 2012	JHEP 10 (2015) 150	17-APR-15	8	20.3 fb^{-1}
Search for vector-like BB quarks in events with one isolated lepton, missing transverse momentum and jets at √s=8 TeV with the ATLAS detector	Phys. Rev. D 91, 112011 (2015)	18-MAR-15	8	20 fb^{-1}

- You can always consult the latest ATLAS exotics publications here
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

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



- Targets $T\bar{T}$ pair production, a least one $T \rightarrow H(\rightarrow b\bar{b})t$ or $T \rightarrow Z(\rightarrow \nu\bar{\nu})t$
- Take advantage of presence of multiple jets, b-tagged jets, t-tagged jets, H-tagged jets, $E_{\mathrm{T}}^{\mathrm{miss}}$
- Split analysis into two channels
  - Exactly 1 lepton
  - **NO** lepton



Preselection requirements

Requirement	1-lepton channel	0-lepton channel
Trigger	Single-lepton trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$ trigger
Leptons	=1 isolated e or μ	=0 isolated e or μ
Jets	≥5 jets	≥6 jets
b-tagging	≥2 b-tagged jets	≥2 b-tagged jets
$E_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} > 200$ GeV
Other $E_{\mathrm{T}}^{\mathrm{miss}}$-related	$E_{\mathrm{T}}^{\mathrm{miss}} + m_{\mathrm{T}}^{W} > 60$ GeV	$\Delta\phi_{\mathrm{min}}^{4\mathrm{j}} > 0.4$

$$m_{\mathrm{T}}^{W} \equiv \sqrt{2\, p_{\mathrm{T}}^{\mathrm{lep}} E_{\mathrm{T}}^{\mathrm{miss}} [1 - \cos\Delta\phi]}$$

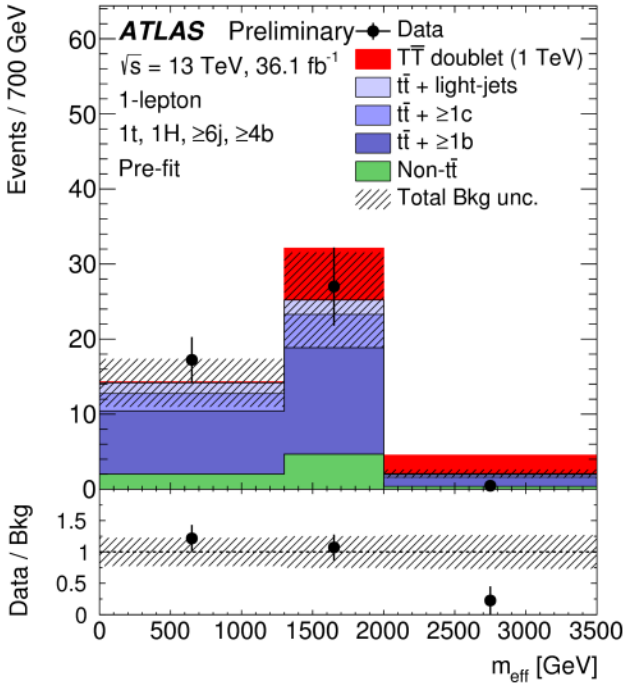
$\Delta\phi_{\mathrm{min}}^{4j}$: smallest separation in ϕ of $\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$ and 4 leading jets

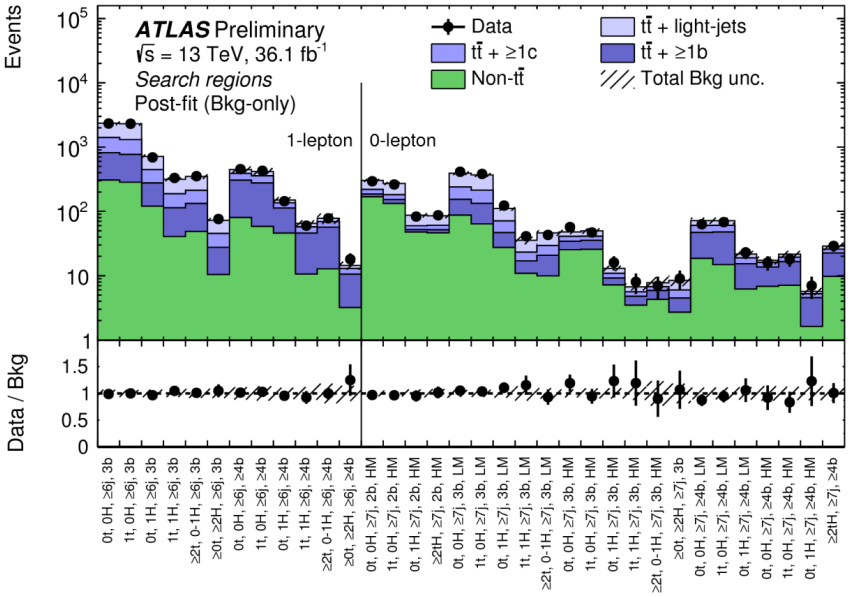
- Suppresses multijet background

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

Search regions and combined fit

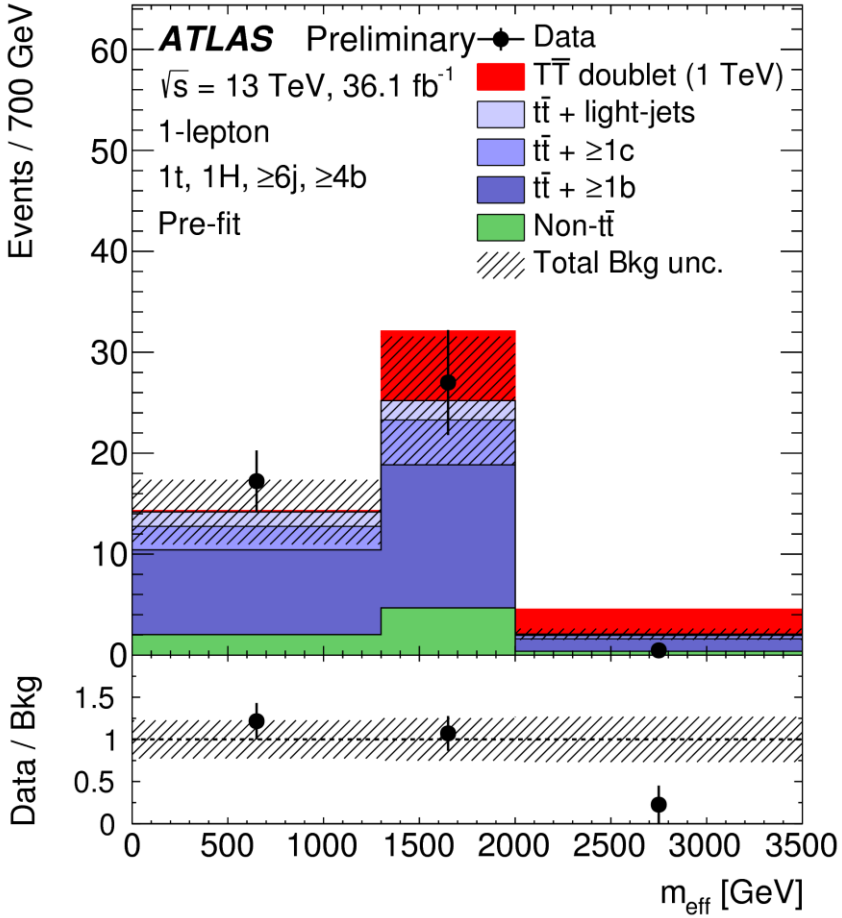
- Final discriminant: m_{eff}
  - Scalar sum of p_{T} of lepton, jets, and $E_{\text{T}}^{\text{miss}}$
- Main background: $t\bar{t} + jets$
  - "Non-$t\bar{t}$" includes $t\bar{t}V$, $t\bar{t}H$, single t, W\Z + jets , VV, multijet
- The two channels are further divided into search regions: 12 (1ℓ) + 22 (0ℓ)
  - N_t, N_H, N_b, N_j and High/Low-$m_{\text{T,min}}^{b}$
- **Combined Maximum likelihood fit of m_{eff} distribution in all search regions**
- Check background in orthogonal validation regions: 10 (1ℓ) + 16 (0ℓ)
  - Use number of jets ($\equiv 5$ or $\equiv 6$)
- Main systematic uncertainties (vary by search region):
  - $t\bar{t}$ modeling, flavor tagging uncertainties, background normalization uncertainties

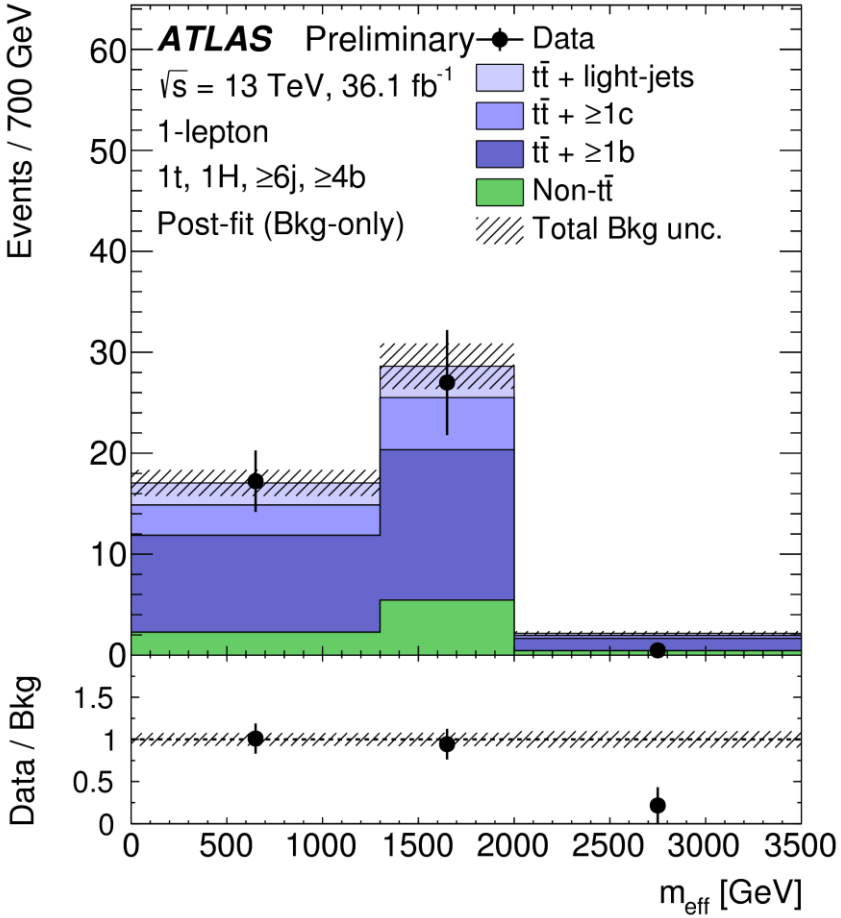




$T\bar{T} \rightarrow Ht + X$

Pre-/post-fit Comparison in one Search Region





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

Search regions and **prefit** Data/Bkg comparison

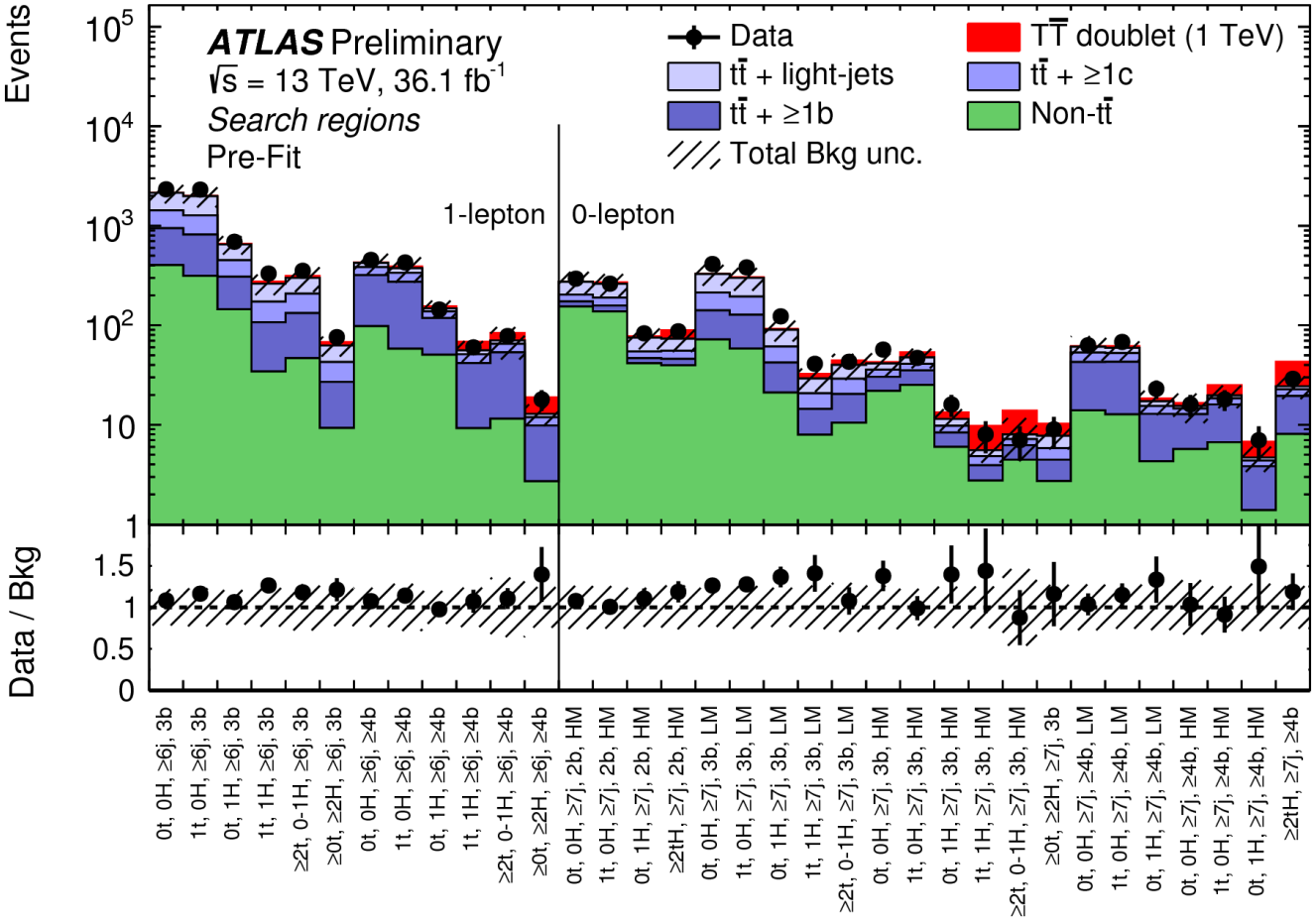
For 0-lepton:

LM: $m_{\mathrm{T,min}}^{b} < 160$ GeV

HM: $m_{\mathrm{T,min}}^{b} > 160$ GeV

Where $m_{\mathrm{T,min}}^{b}$ is the minimum transverse mass formed with the $E_{\mathrm{T}}^{\mathrm{miss}}$ and any of the 2 (or 3) b-jets

- Bounded from above by m_t for semileptonic $t\bar{t}$
- Can have high values for $T\bar{T}$ signal due to $T \rightarrow Z(\rightarrow \nu\nu)t$ and $T \rightarrow W(\rightarrow \ell\nu)b$

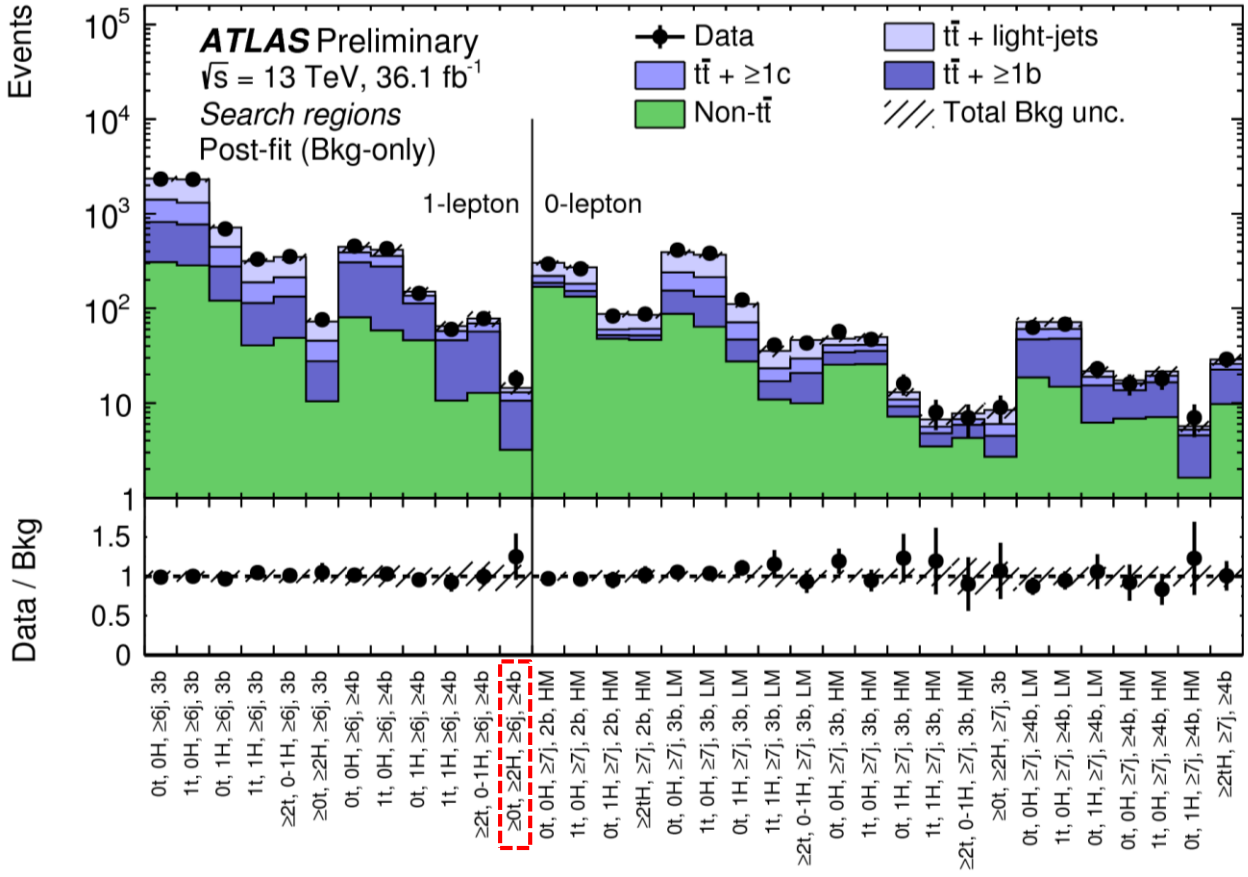


$T\bar{T} \rightarrow Ht + X$

Search regions and **postfit** Data/Bkg comparison

- Notice constrain of post-fit uncertainties
- E.g. for the region $\geq 0t, \geq 2H, \geq 6j, \geq 4b$:
  - 25% -> 10% for the uncert. on the bkg normalization

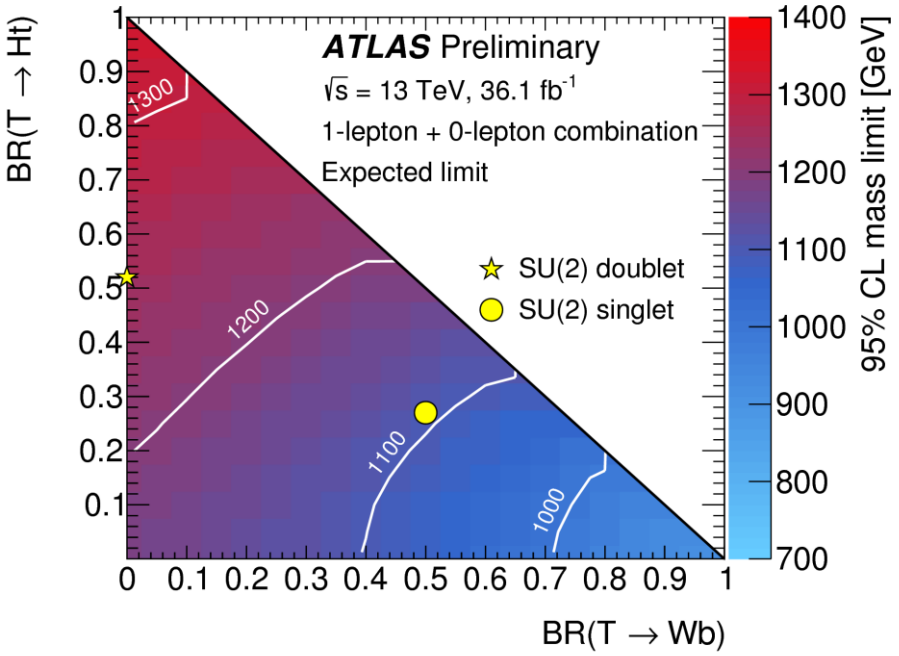
NB: $t\bar{t} + \geq 1b$ bkg normalization is determined from the fit (floating normalization)

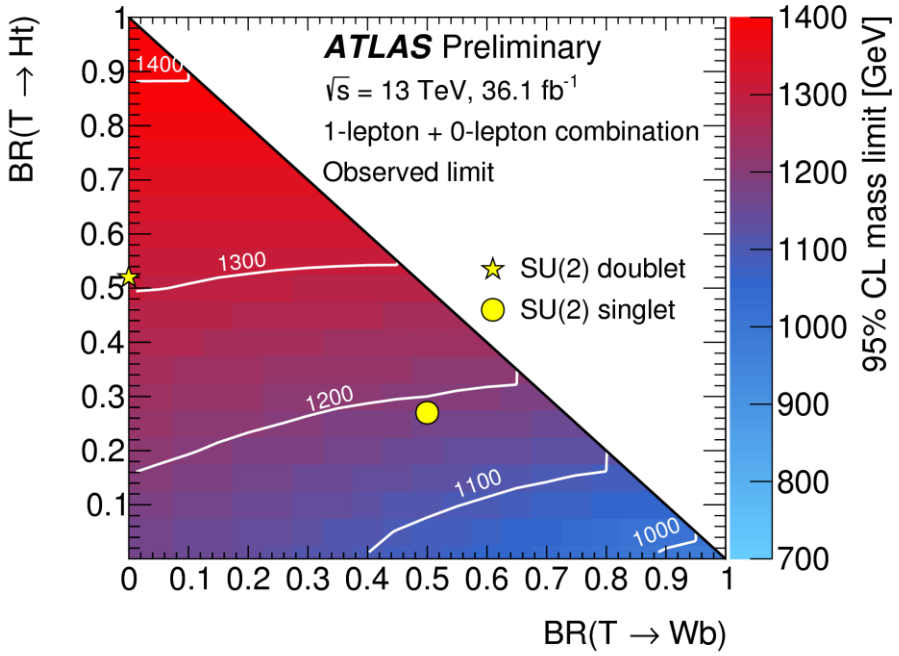


$T\bar{T} \rightarrow Ht + X$

Combined 2D limits on T BRs

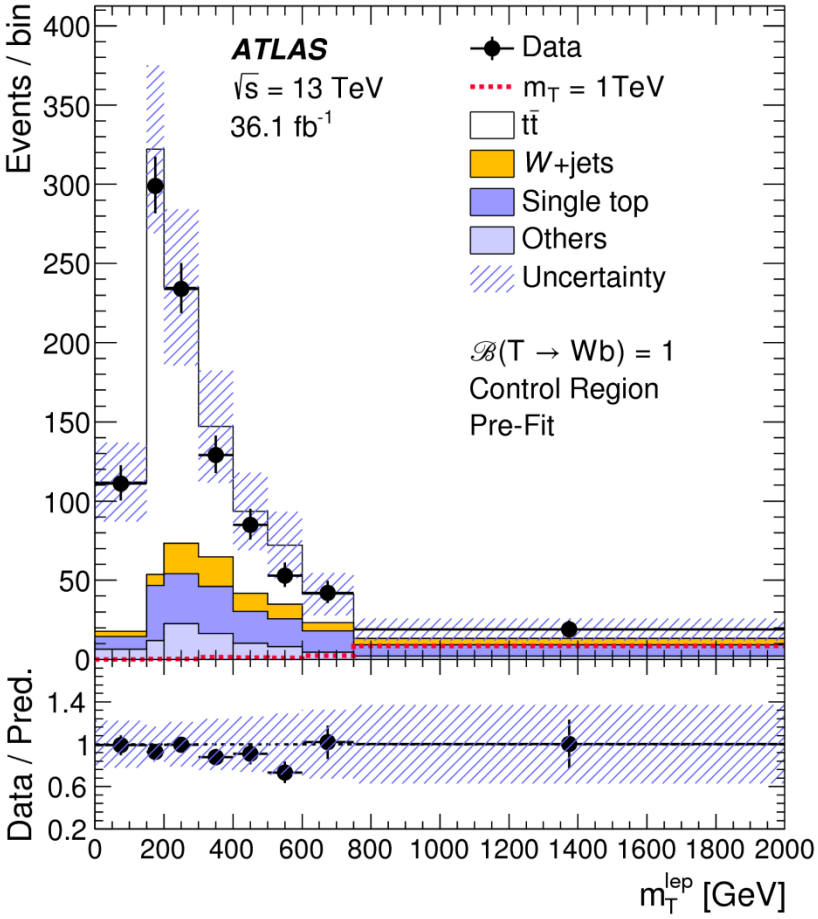
Reweight signal samples to other BR compositions to obtain 2D limits
Assumes $BR(T \rightarrow Ht) + BR(T \rightarrow Wb) + BR(T \rightarrow Zt) = 1$

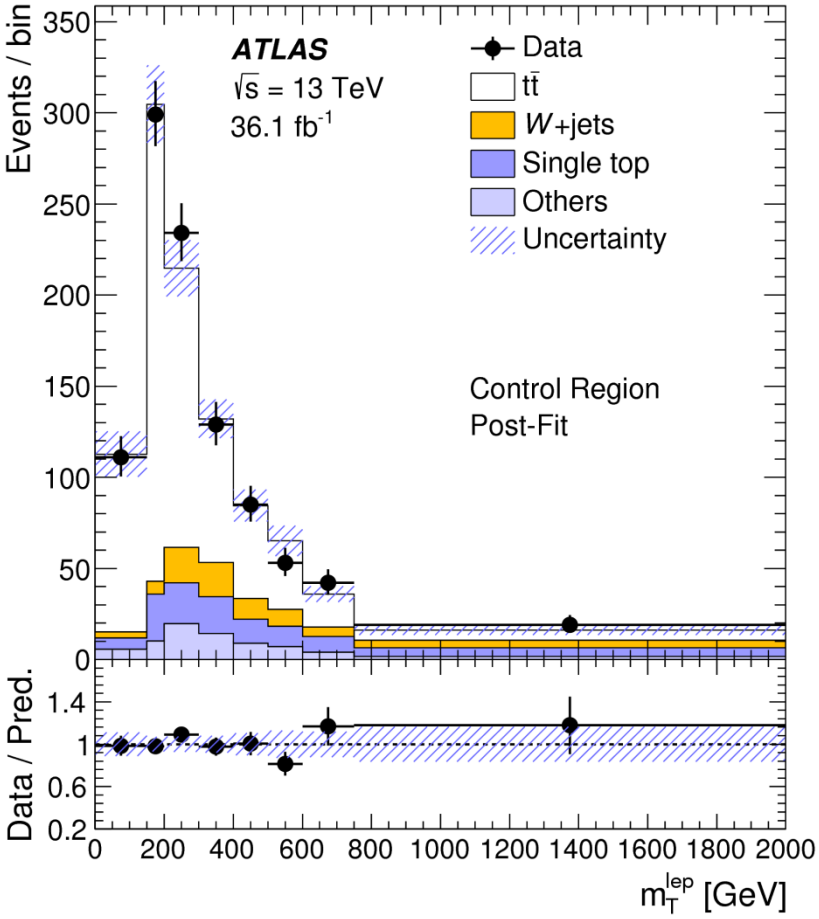




Notice increased sensitivity near point (0,1) due larger BR to Ht

$Q\bar{Q} \rightarrow Wb+X$
CR before and after bkg-only fit





JHEP10(2017)141

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

Signal and Control Region yields PREFIT

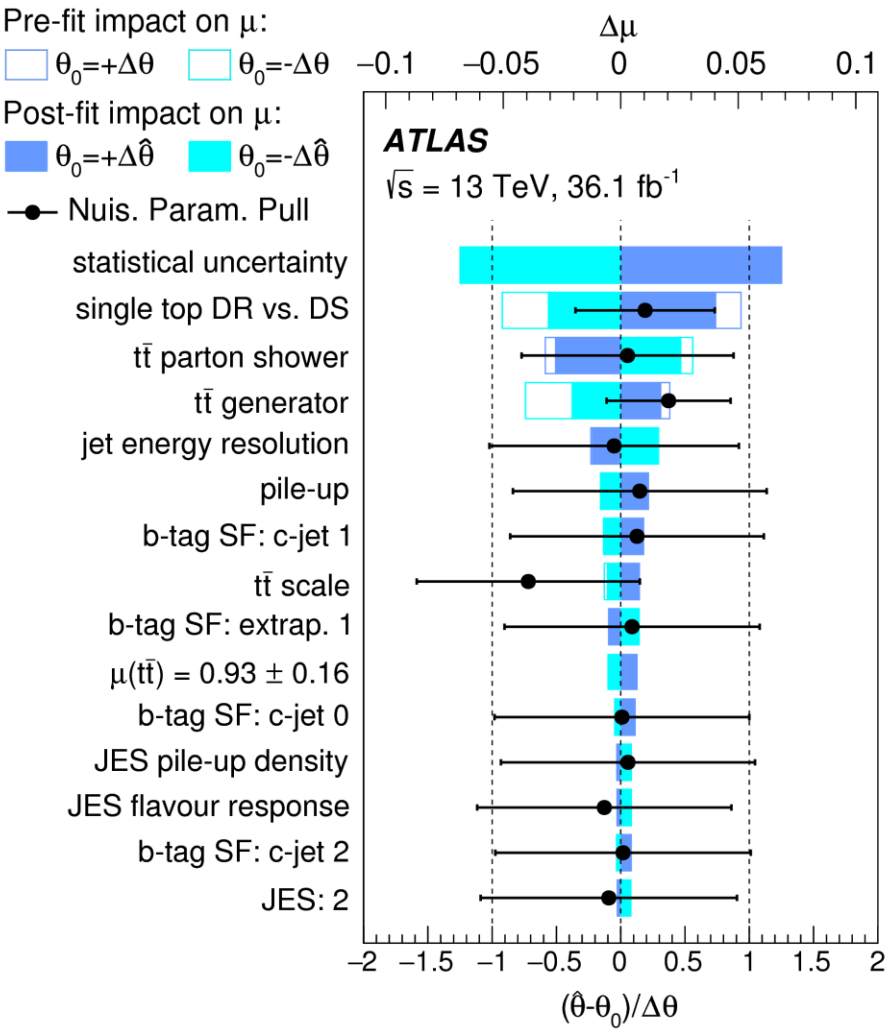
Sample	Signal region	Control region
$t\bar{t}$	55 ± 26	720 ± 130
W+jets	9 ± 4	78 ± 41
Single top	15 ± 15	160 ± 110
Others	12 ± 10	82 ± 66
Total Background	91 ± 35	1040 ± 200
Signal ($m_T = 1$ TeV, $\mathcal{B}(T \rightarrow Wb) = 1$)	45 ± 4	15 ± 2
Signal ($m_T = 1$ TeV, SU(2) singlet)	21 ± 2	8 ± 1
Signal ($m_B = 1$ TeV, $\mathcal{B}(B \rightarrow Wt) = 1$)	46 ± 4	21 ± 2
Signal ($m_B = 1$ TeV, SU(2) singlet)	18 ± 2	8 ± 1
Data	58	972

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

SR/CR yields after bkg only fit

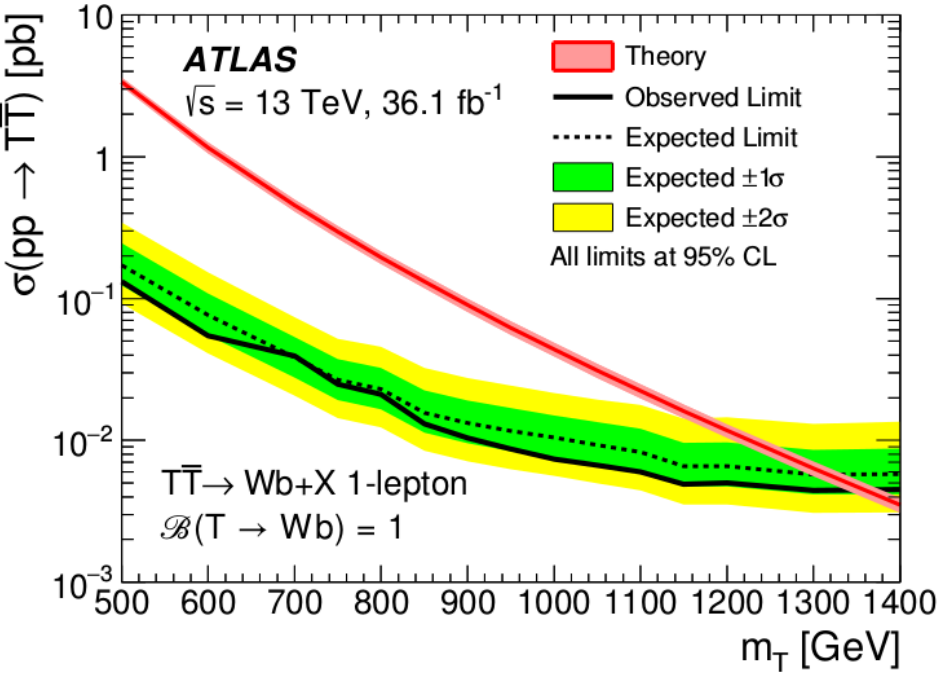
Sample	Signal region	Control region
$t\bar{t}$	39 ± 10	700 ± 70
W+jets	8 ± 4	78 ± 38
Single top	7 ± 4	110 ± 40
Others	10 ± 7	72 ± 48
Total background	64 ± 9	970 ± 50
Data	58	972

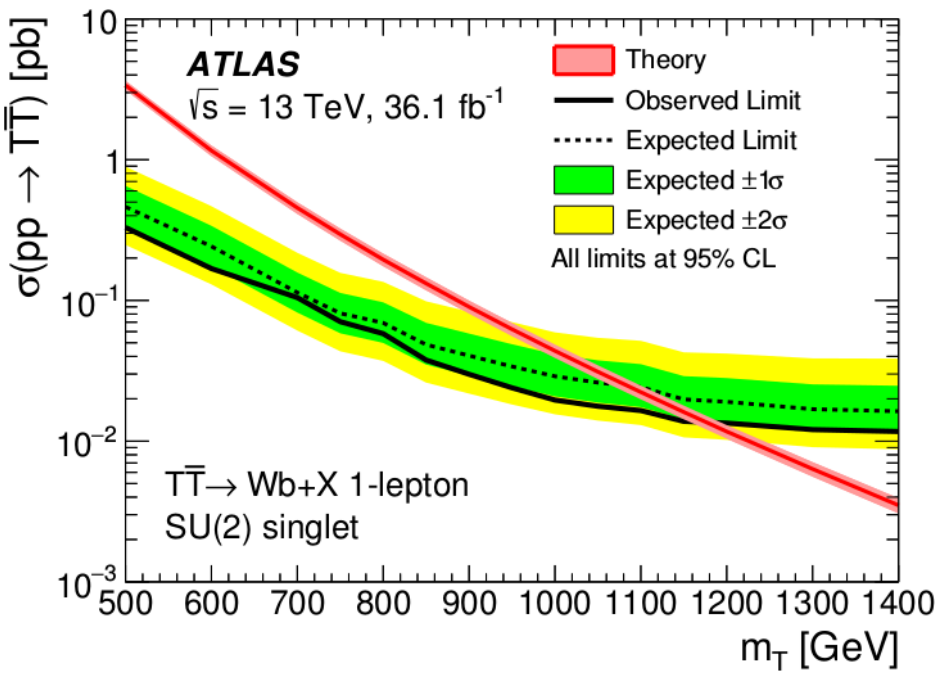
$Q\bar{Q} \rightarrow Wb+X$
Ranking plot



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

σ vs m limits for four models

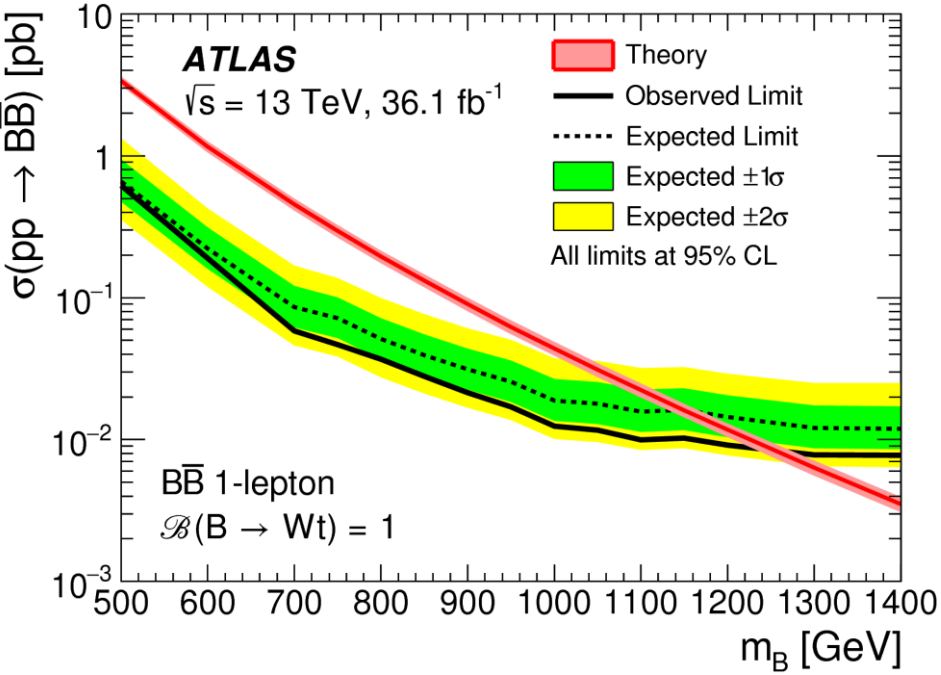


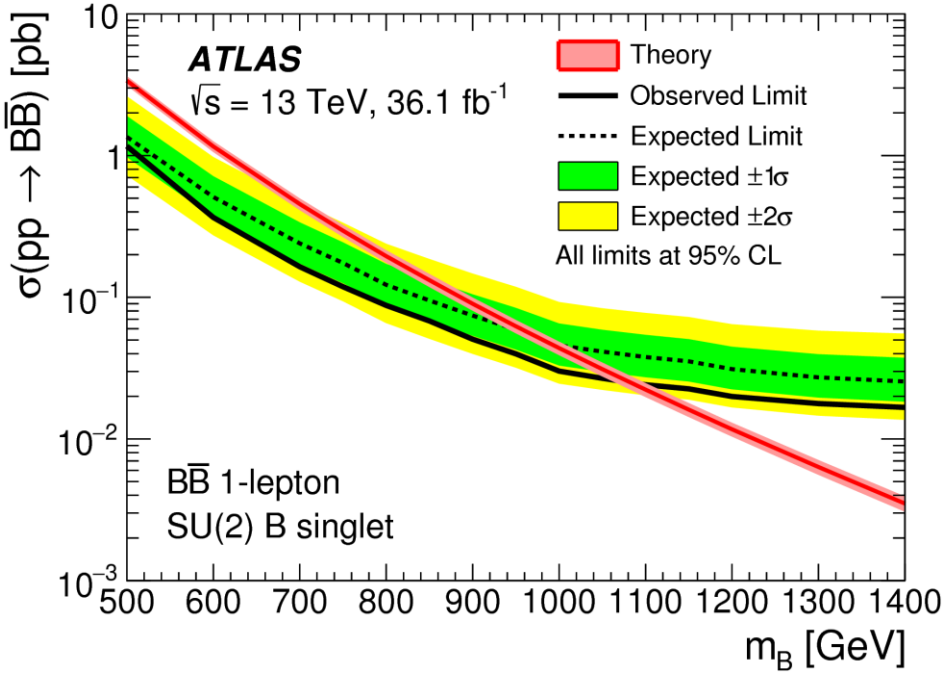


Model	Obs. 95% CL lower mass limit [GeV]	Exp. 95% CL lower mass limit [GeV]
100% $T \rightarrow Wb$	**1350**	1310
Singlet T	**1170**	1080
100% $B \rightarrow Wt$	**1250**	1150
Singlet B	**1080**	980

Main systematics: single t and $t\bar{t}$ modeling uncertainties, Jet Energy Resolution

$Q\bar{Q} \rightarrow Wb + X$
$B \rightarrow Wt$ limit plots



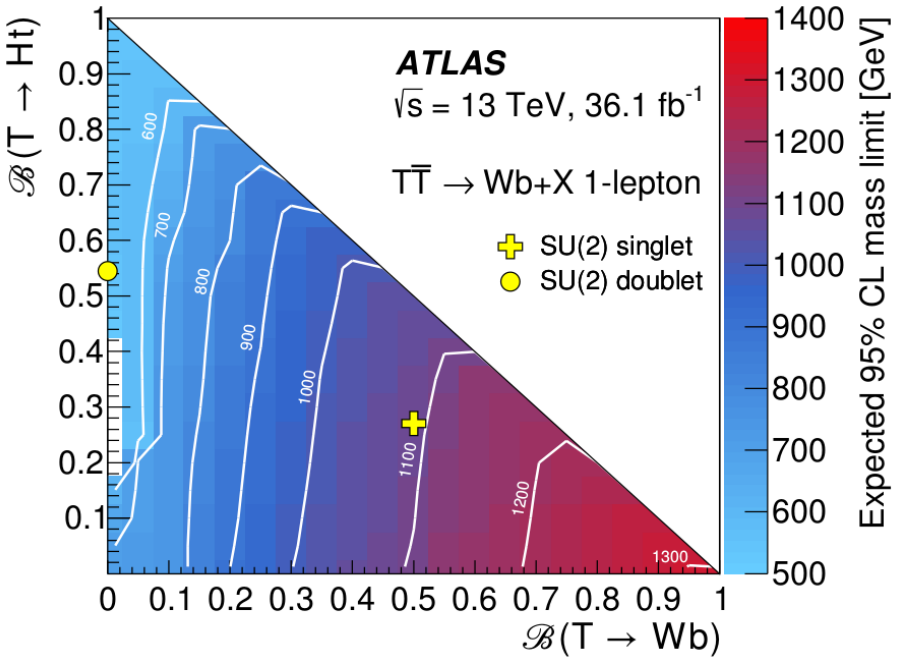


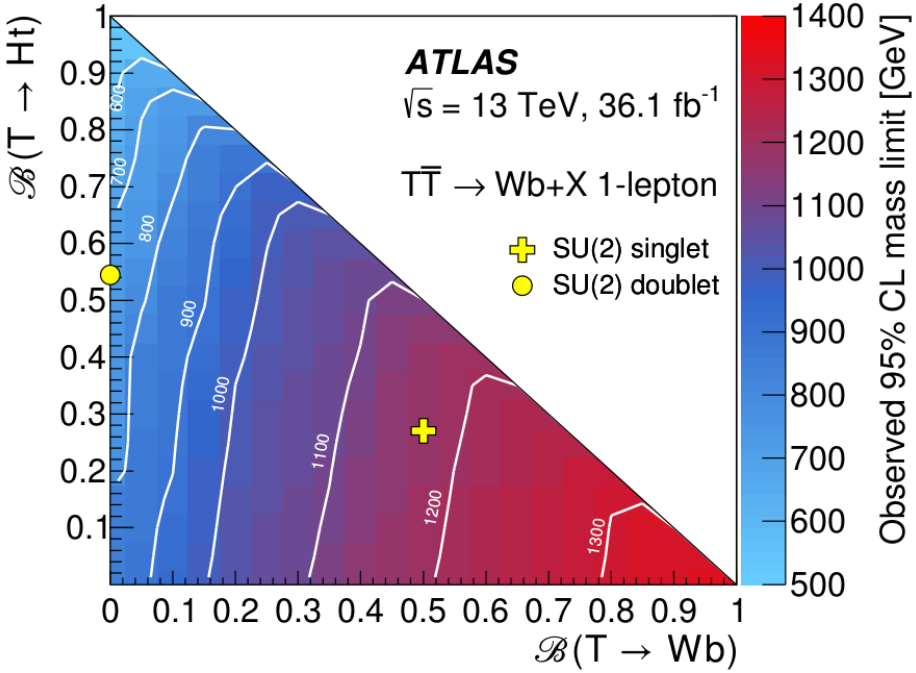
Model	Obs. 95% CL lower mass limit [GeV]	Exp. 95% CL lower mass limit [GeV]
$T \rightarrow Wb$	1350	1310
Singlet T	1170	1080
$B \rightarrow Wt$	1250	1150
Singlet B	1080	980

JHEP10(2017)141

$Q\bar{Q} \rightarrow Wb+X$
2D limits on T BRs

Assumes $BR(T \rightarrow Ht) + BR(T \rightarrow Wb) + BR(T \rightarrow Zt) = 1$

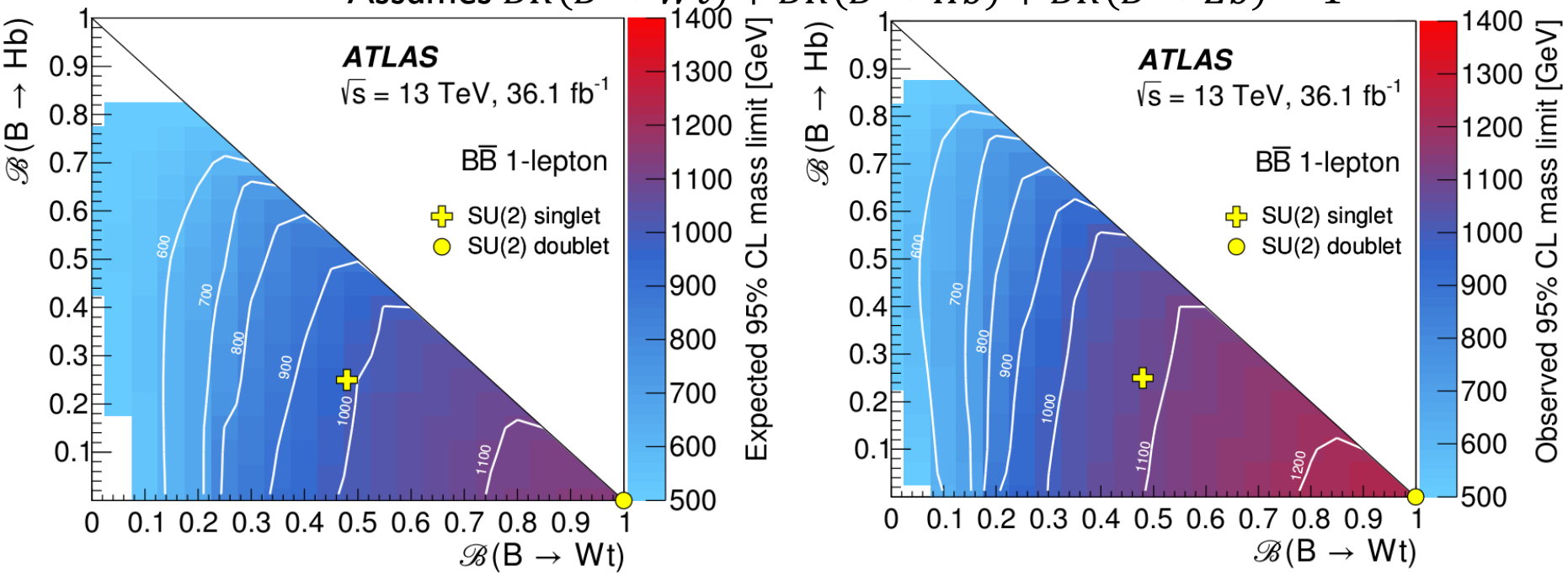




- Notice increased sensitivity near point (1,0) (larger BR to Wb)
- **Bonus** (since no assumption on q): $100\%\ T \rightarrow Wb$ limits are applicable to **VL Y (q=-4/3)** : excluded for masses below 1350 GeV

$Q\bar{Q} \rightarrow Wb+X$
2D limits on B BRs

Assumes $BR(B \rightarrow Wt) + BR(B \rightarrow Hb) + BR(B \rightarrow Zb) = 1$

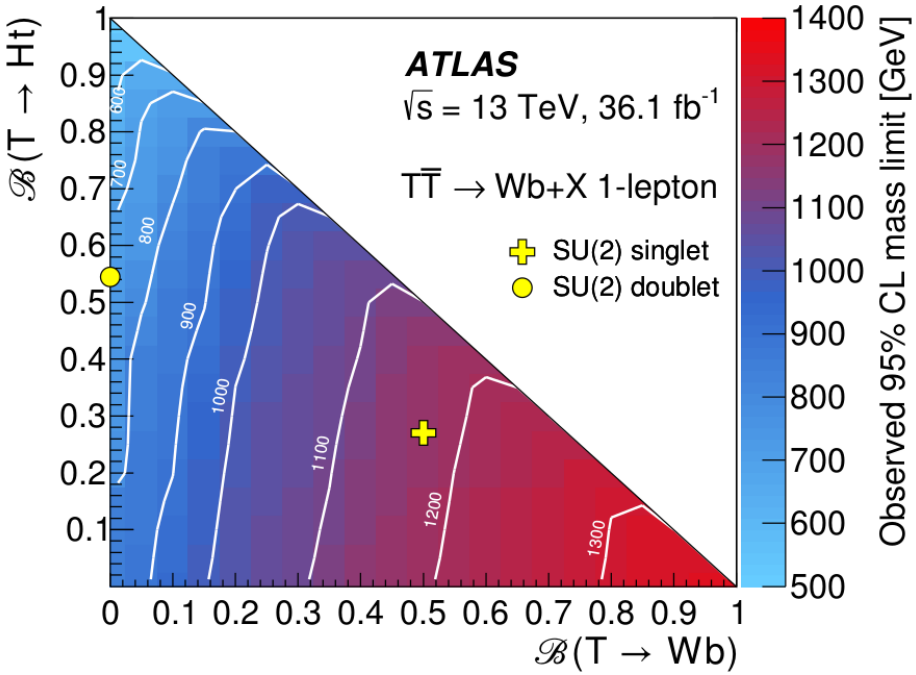


- Notice increased sensitivity near point (1,0) (larger BR to Wb)
- Bonus: 100% $B \rightarrow Wt$ limits are applicable to **VL X (q=5/3):** excluded for X masses below 1250 GeV

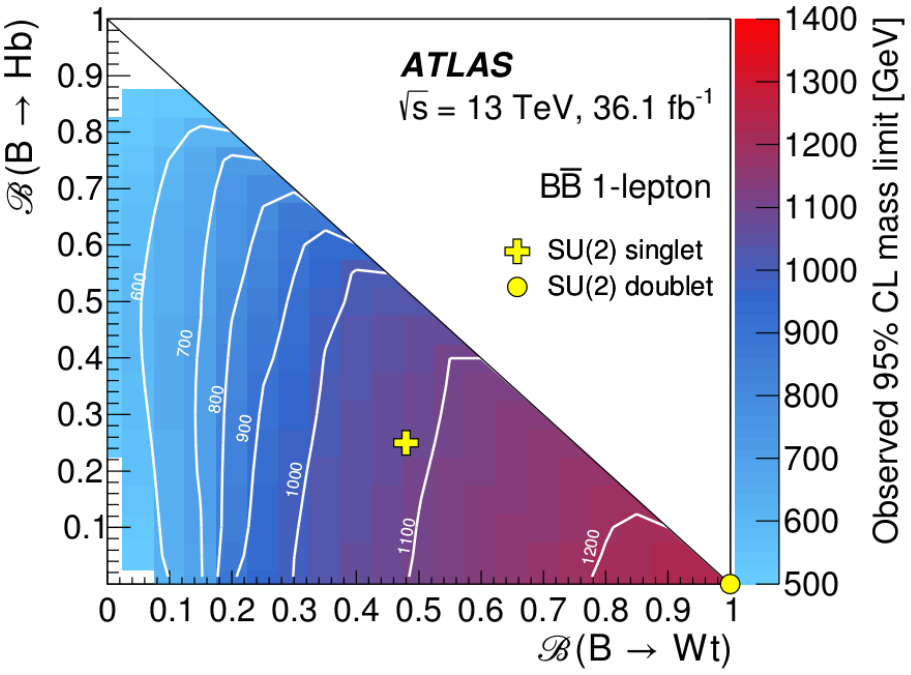
NB: The white regions are areas where the limit is below 500 GeV which was the lowest simulated signal mass

$Q\bar{Q} \rightarrow Wb+X$
2D limits on T BRs (left) and B BRs (right)

Assumes
$BR(T \rightarrow Ht) + BR(T \rightarrow Wb) + BR(T \rightarrow Zt) = 1$

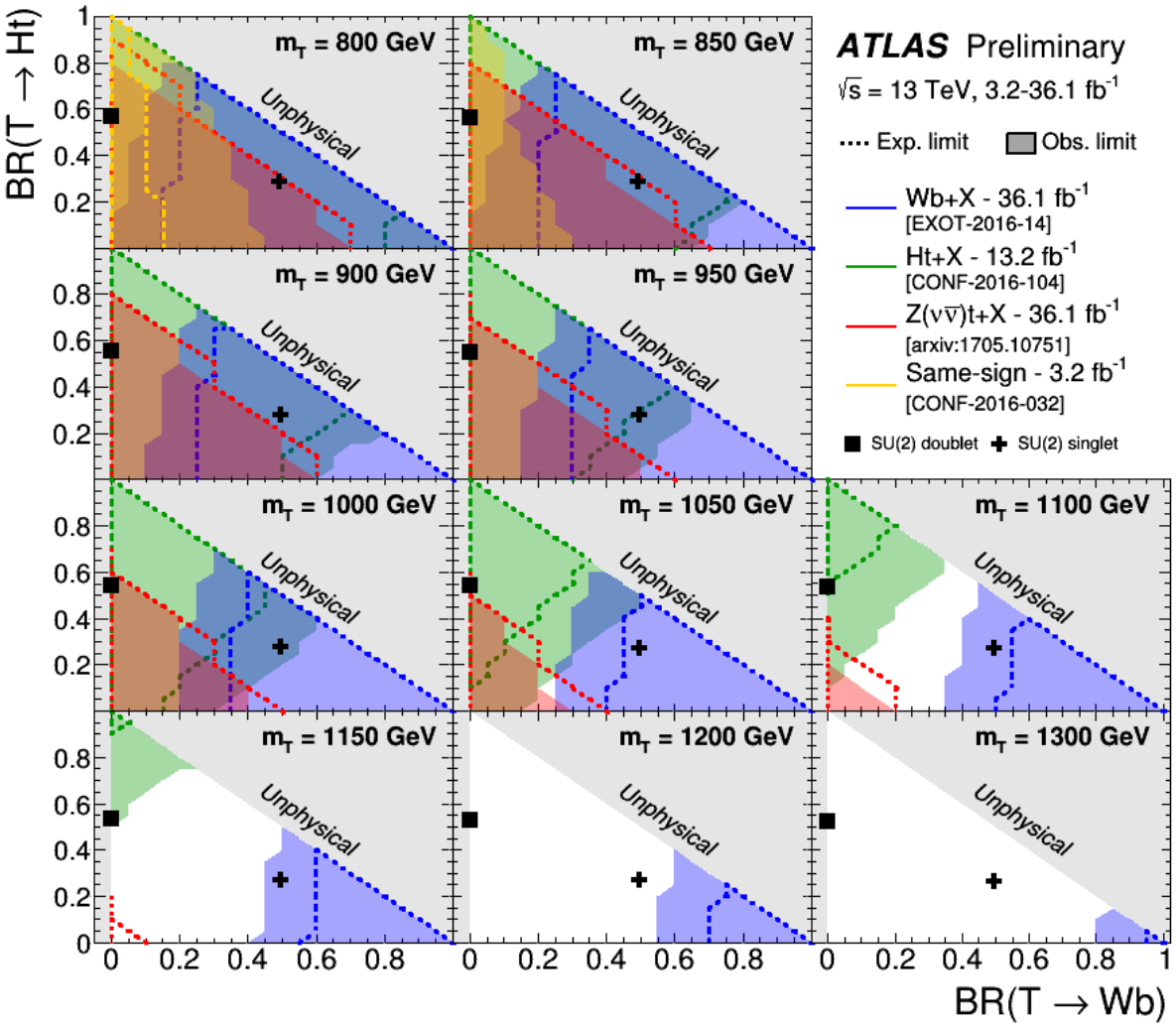


Assumes
$BR(B \rightarrow Wt) + BR(B \rightarrow Hb) + BR(B \rightarrow Zb) = 1$

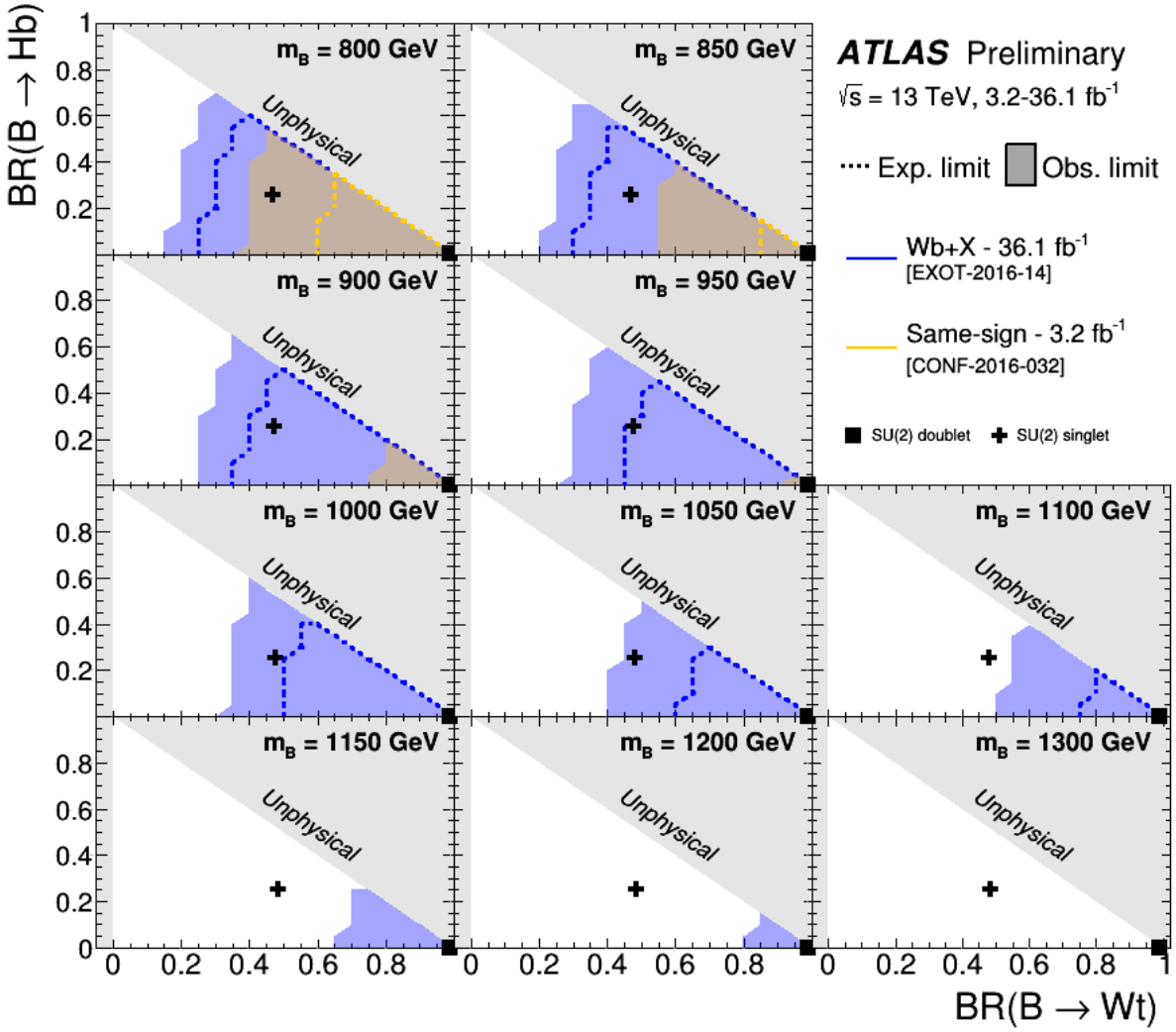


- Notice increased sensitivity near point (1,0) (larger BR to Wb/Wt)
- **Bonus**: 100% $T \rightarrow Wb$ limits are applicable to **VL Y (q=-4/3)** : excluded for masses below 1350 GeV and 100% $B \rightarrow Wt$ limits are applicable to **VL X (q=5/3):** excluded for X masses below 1250 GeV

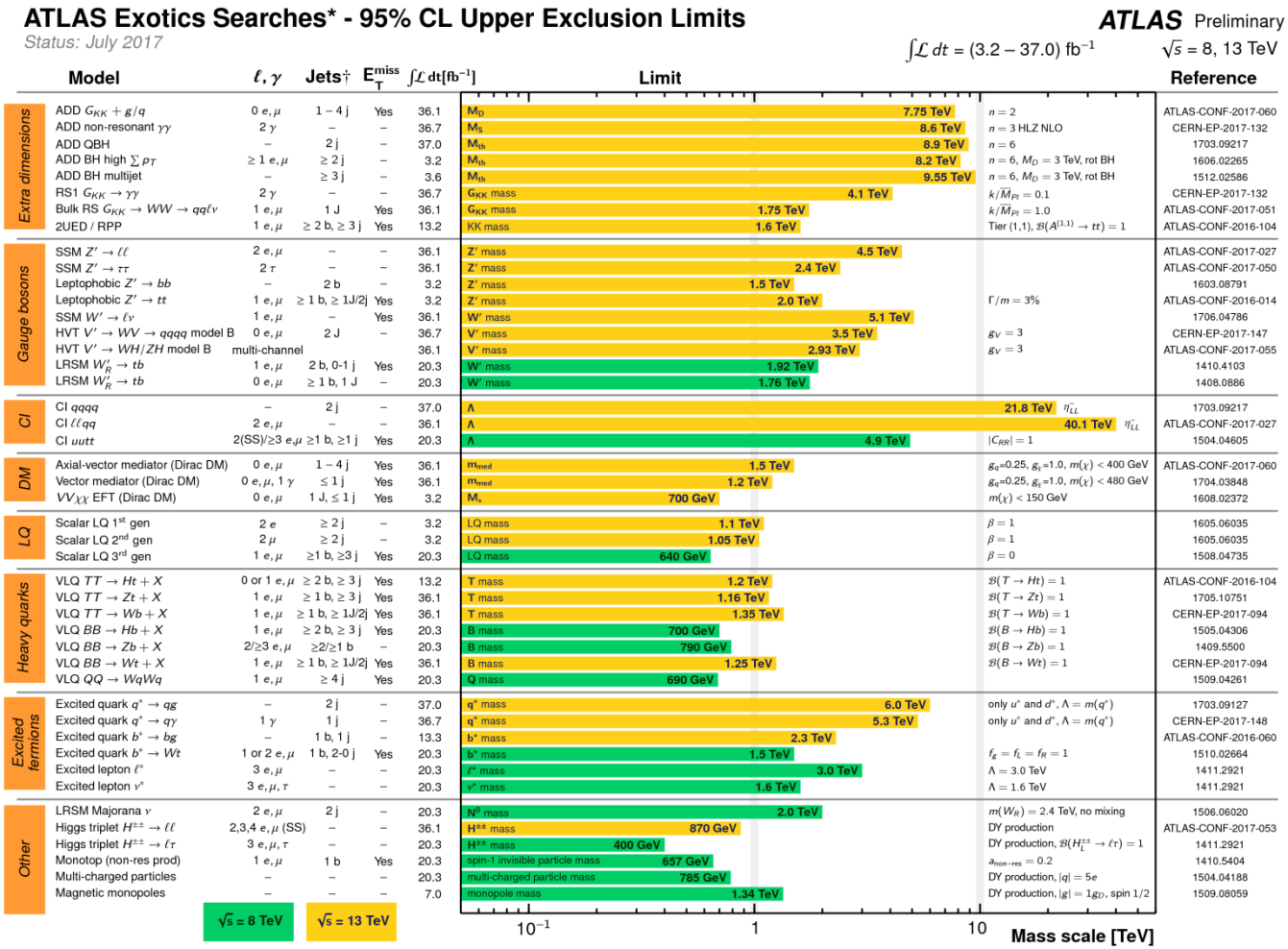
VLT Summary plot



VLB Summary plot



ATLAS Exotics summary (July 2017)



*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).