Searches for Heavy Quark States at ATLAS

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on behalf of the ATLAS collaboration

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Outline

- Overview of heavy quark searches at ATLAS
- Resonances searches
  - $t\bar{t}$ resonance (8 TeV and 13 TeV)
- Vector-Like Quarks (VLQs) searches
  - B searches
  - T searches
- Summary

Overview of heavy quark searches at ATLAS

Heavy quark searches at ATLAS are split in two main groups:

1. Model-agnostic searches in which we look for resonances:
   - $X \rightarrow t\bar{t}, t\bar{b}$ or single $t + E_T^{miss}$.

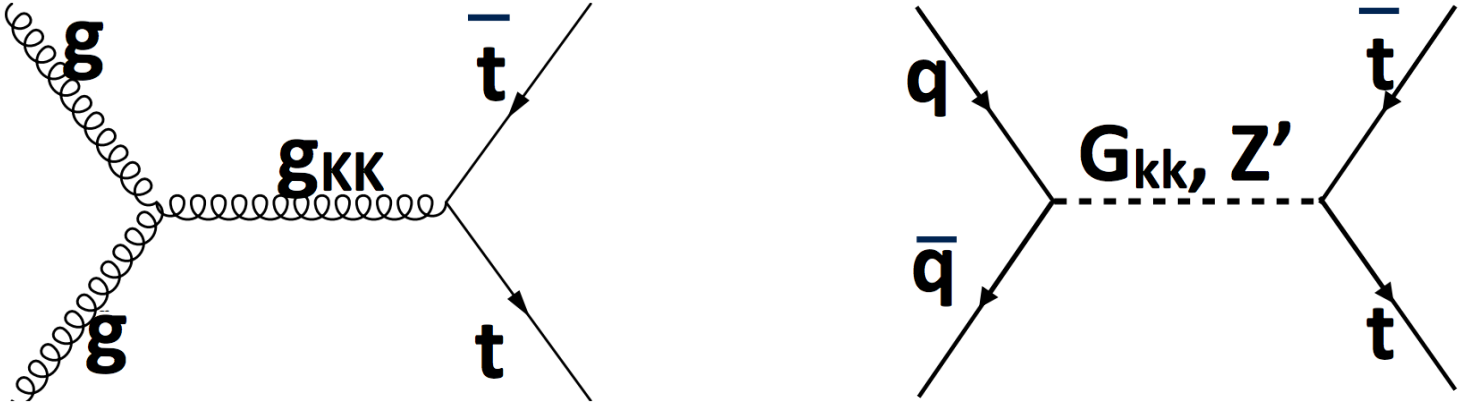
2. Vector-like quark (VLQ) searches, in which we look for either a pair of VLQ particles or a single VLQ particle production.

1. Resonances searches

- ATLAS has several searches for resonances:
  - Z', Gkk, gKK $\rightarrow t\bar{t} \rightarrow l$ + jets *at 8 TeV* :
    - ***JHEP08 (2015) 148***
  - $W' \rightarrow t\bar{b} \rightarrow l$ + jets *at 8 TeV*:
    - ***Physics Letters B 743 (2015) 235-255***
  - $W' \rightarrow t\bar{b} \rightarrow qqbb$ *at 8 TeV* :
    - ***Eur. Phys. J. C (2015) 75:165***
  - $Z' \rightarrow t\bar{t} \rightarrow l$ + jets *at 13 TeV:*
    - **ATLAS-CONF-2016-014**
- The $t\bar{t}$ resonance searches at 8 and 13 TeV are discussed in this talk.

$t\bar{t}$ resonance: motivations

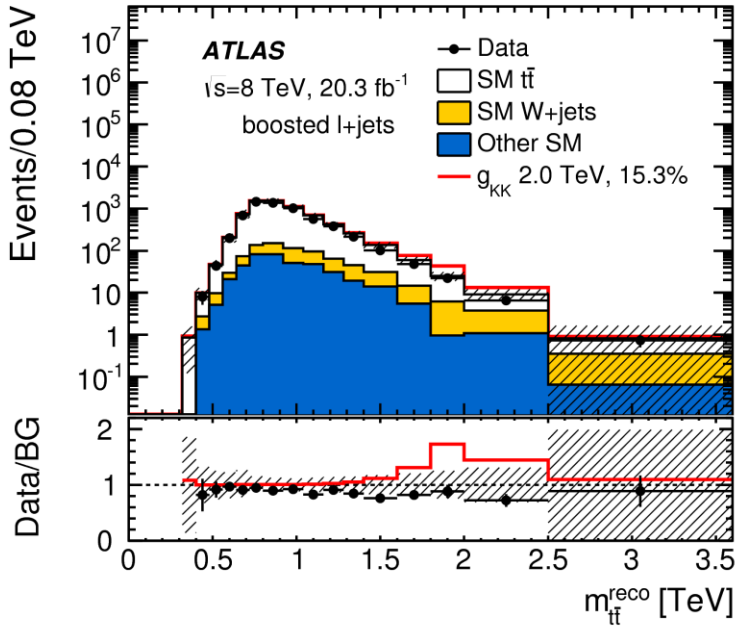
- Benchmark models predict new resonances decaying into $t\bar{t}$.
  - Topcolor-assisted technicolor: Z'→ $t\bar{t}$. (spin-1 color singlet)
  - Kaluza-Klein Randall-Sundrum model:
    - Gluon(g_{KK}) decays to $t\bar{t}$. (spin-1 color octet)
    - Excited graviton(G_{kk}) decays to $t\bar{t}$. (spin-2 color singlet)
  - Other color singlet scalar particles decay to $t\bar{t}$.

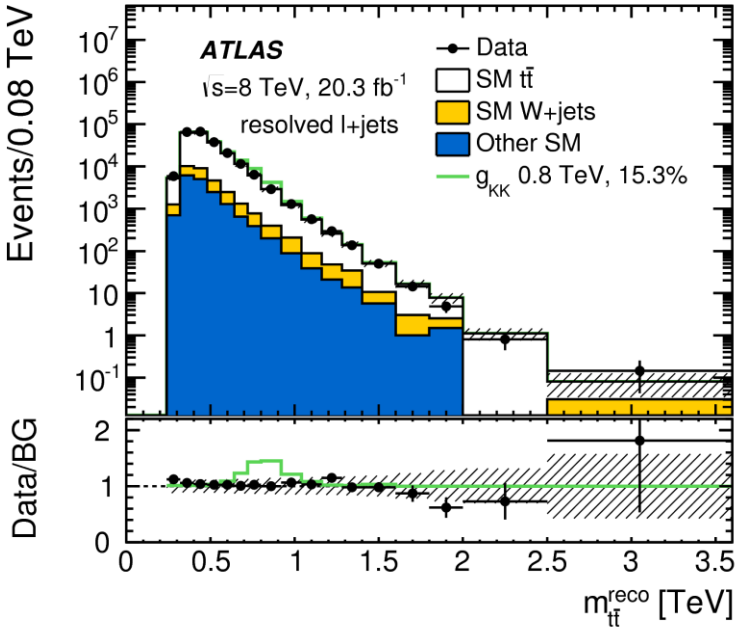


  - Strategy: Select $t\bar{t}$ events then reconstruct m($t\bar{t}$) and look for a mass peak.

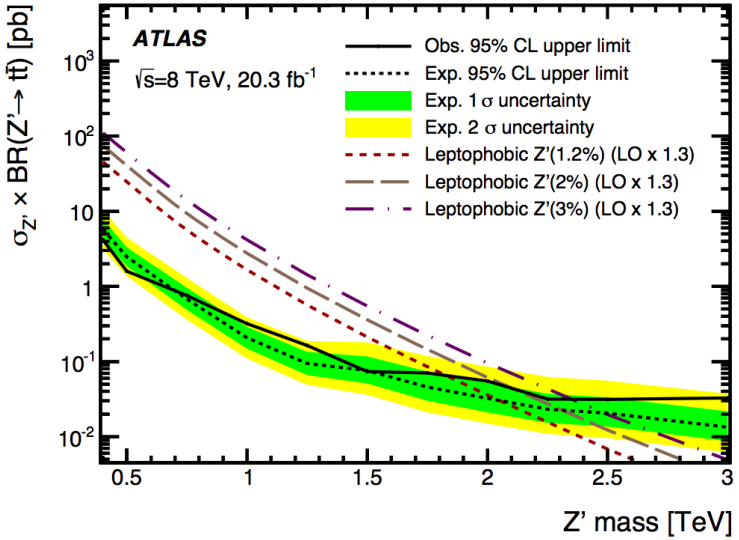
$t\bar{t}$ resonance: run 1

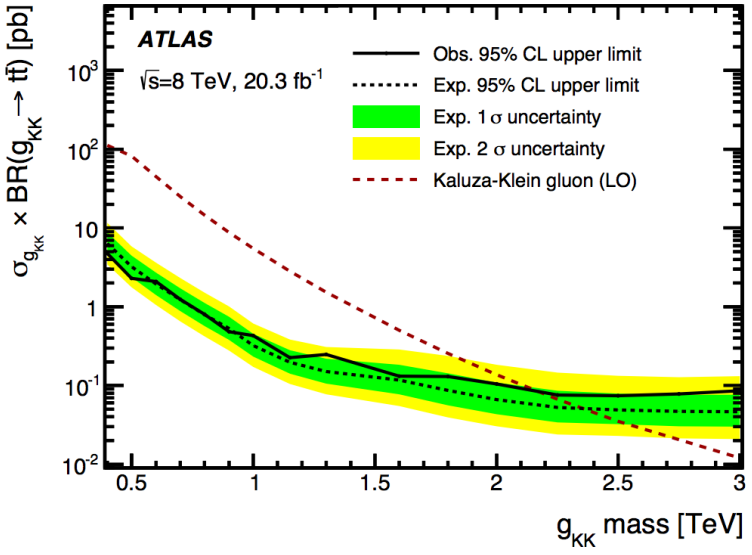
- ATLAS run1 data (20.3 fb^{-1}, $\sqrt{s}$= 8 TeV).
- **Boosted topology**
  - Hadronic top is reconstructed using the largest p_T large-R jet.
  - At least one small-R jets must be b-tagged and matched to at least one of the top candidates.
  - Semi-leptonic top is reconstructed using E_T^{miss} , lepton, and largest p_T small-R jet near jet.
- **Resolved topology**
  - At least 4 small-R jets.
  - At least one of them b-tagged.
- b-tagged jet has to match to had. top jet, lep. top jet or both, otherwise it is discarded.
- Reconstructed mass ($m_{t\bar{t}}^{reco}$) spectrum is scanned for deviations relative to expectation from background processes.





$t\bar{t}$ resonance: run 1 results





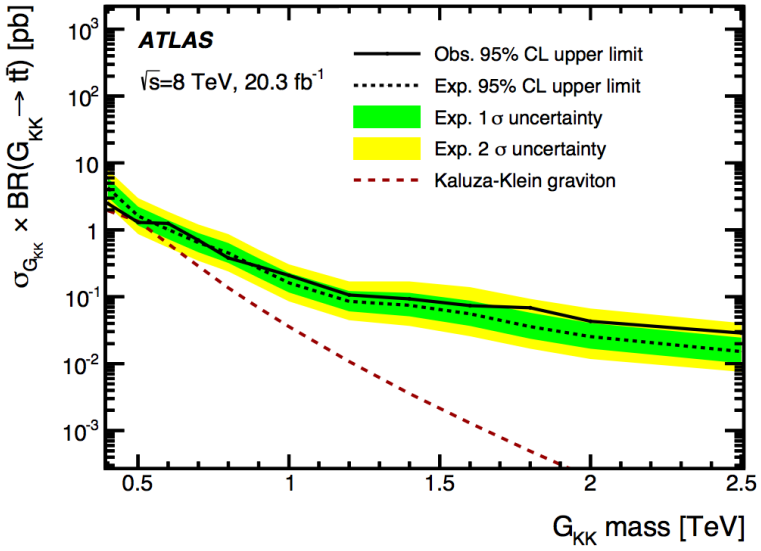
Kaluza-Klein excitations of graviton G_{KK}

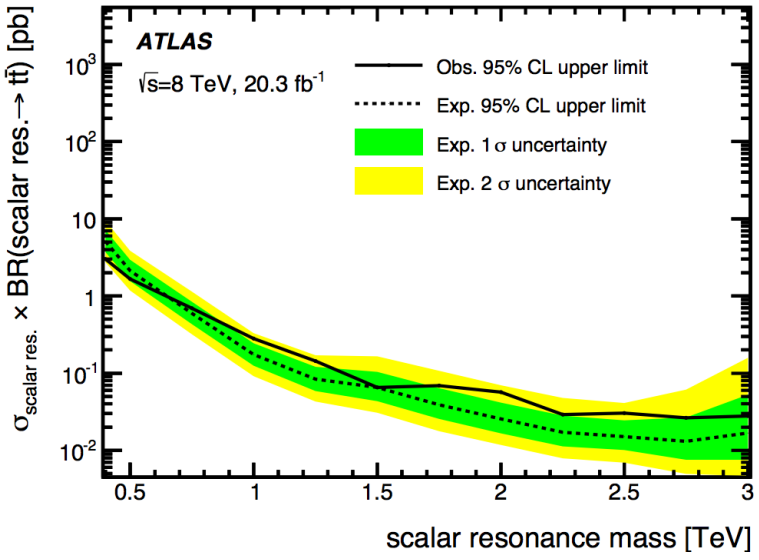
Topcolor-assisted technicolor Z'_{TC} :
excluded **0.4 TeV < $m_{Z'}$ < 1.8 TeV** (95% CL)

- **No excess beyond SM prediction was observed.**
- **Cross section limit set to different benchmark models.**

Color singlet scalar particle:
No interference is assumed between the scalar resonance and the SM $t\bar{t}$

Kaluza-Klein gluons in Randall-Sundrum model g_{KK}:
excluded **0.4 TeV < m_{gKK} < 2.2 TeV** (95% CL)



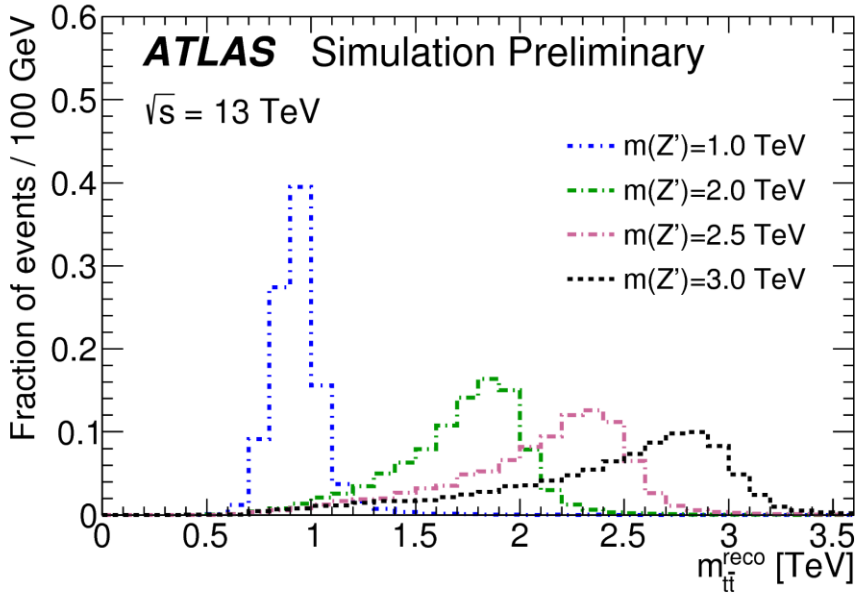


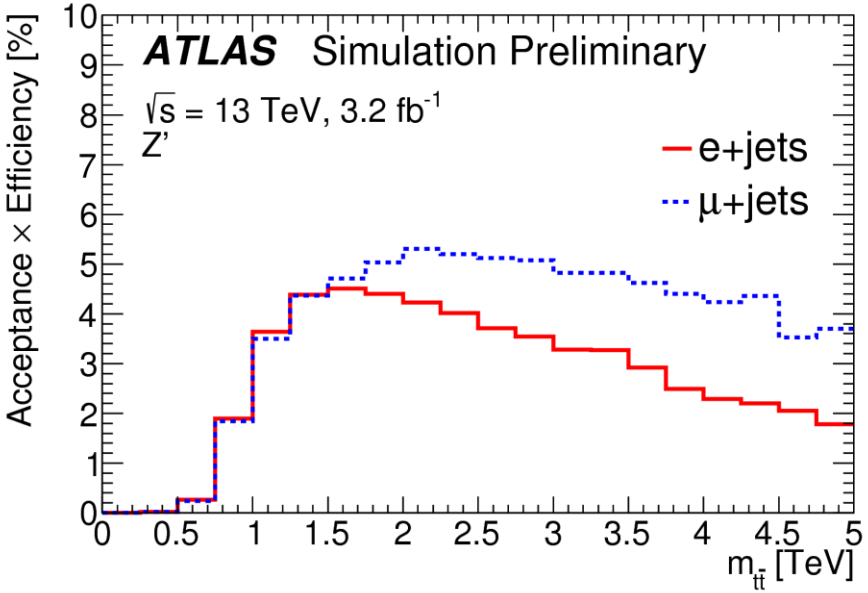
$t\bar{t}$ resonance: run 2

- ATLAS run2 2015 data (3.2 fb^{-1}, $\sqrt{s}$= 13 TeV).
- Only lepton+jet channel is shown here.
- Event selection:
  - Exactly 1 lepton ($e^{\pm}$, $\mu^{\pm}$) is reconstructed, must match candidates that triggered the event.
  - Leptonic-top b-jet:

    At least 1 small-R jet is reconstructed in $\Delta R(l, \text{jet}) < 1.5$.
  - Hadronic-top jet:

    At least 1 top-tagged large-R jet is reconstructed in the $\Delta\phi(l, \text{large-R jet}) > 2.3$ and $\Delta\phi(\text{lep. jet, large-R jet}) > 1.5$ region.
  - At least 1 b-tagged small-R jet is reconstructed.

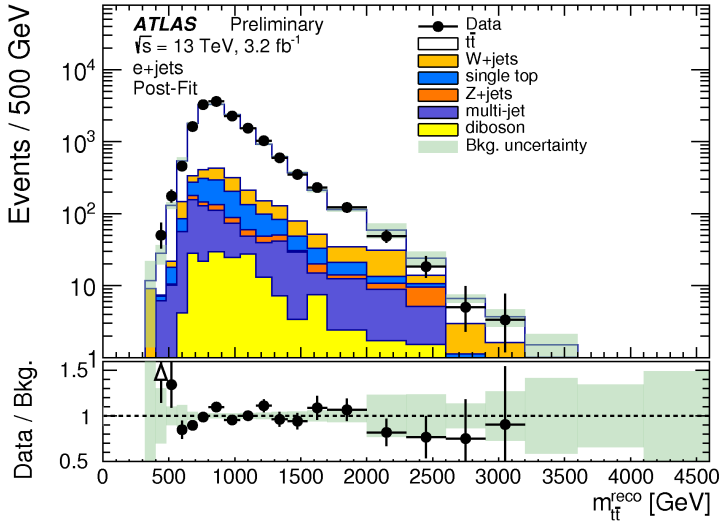


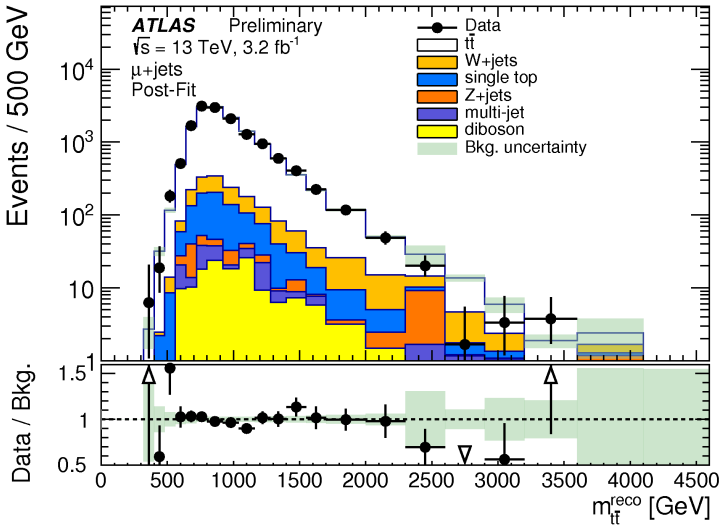


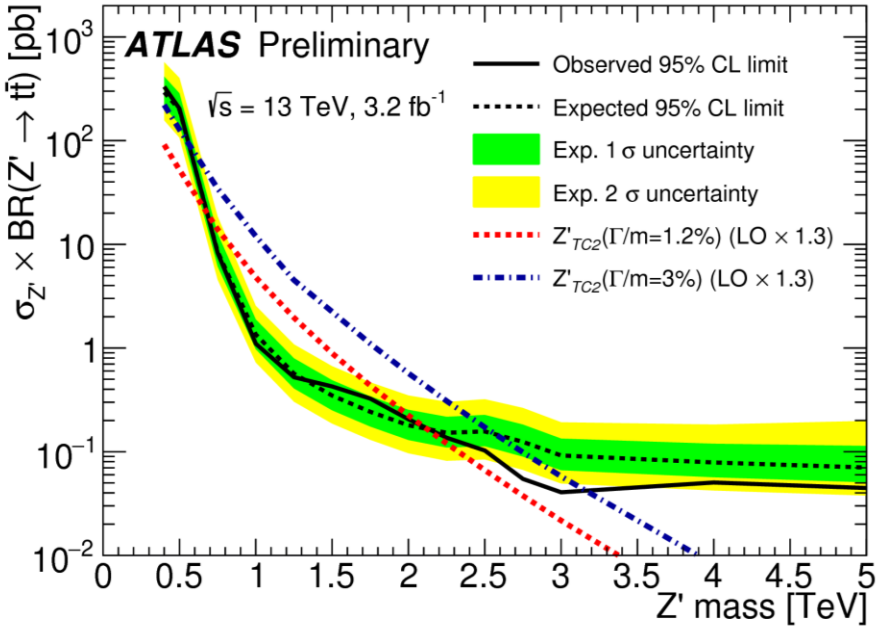
$t\bar{t}$ resonance: run 2 results

Main systematics:

Large-R JES, light flavor and charm jet mistag rate, luminosity



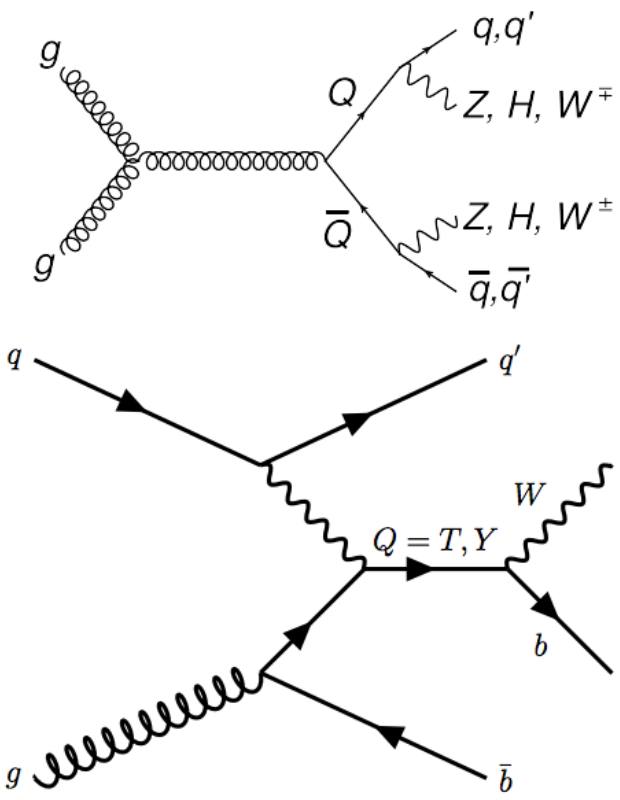




No excess beyond SM prediction was observed.

- Topcolor Z'_{TC} was excluded:
  - **0.7 TeV < $m_{Z'}$ < 2.0 TeV** (95% CL)

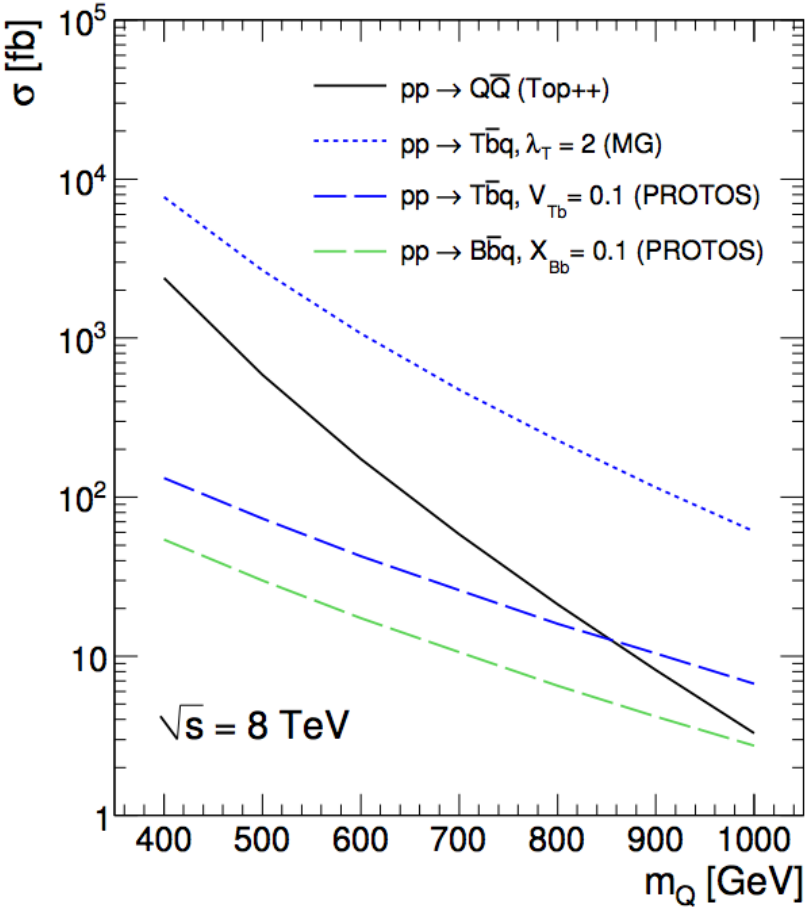
2. VLQ: Theoretical Motivations



- **VLQ in Little Higgs or Composite Higgs models:**
  - No Yukawa coupling to Higgs.
  - Mix with third gen. quarks, modify couplings to W, Z and Higgs.
  - Decay to qW, qZ, qH.
  - Pair produced via QCD below 1 TeV.
  - Singly produced may dominate at higher mass, depending on weak couplings to gauge bosons.
- **Depending on the models, 4 types of VLQ exists:**

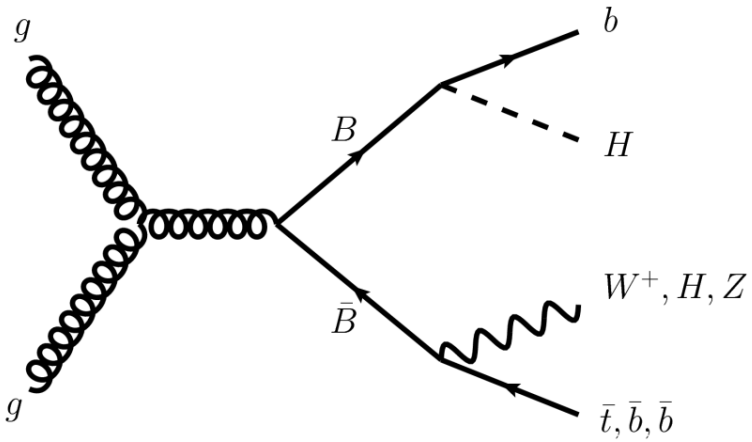
  T: charge +2/3 B: charge -1/3

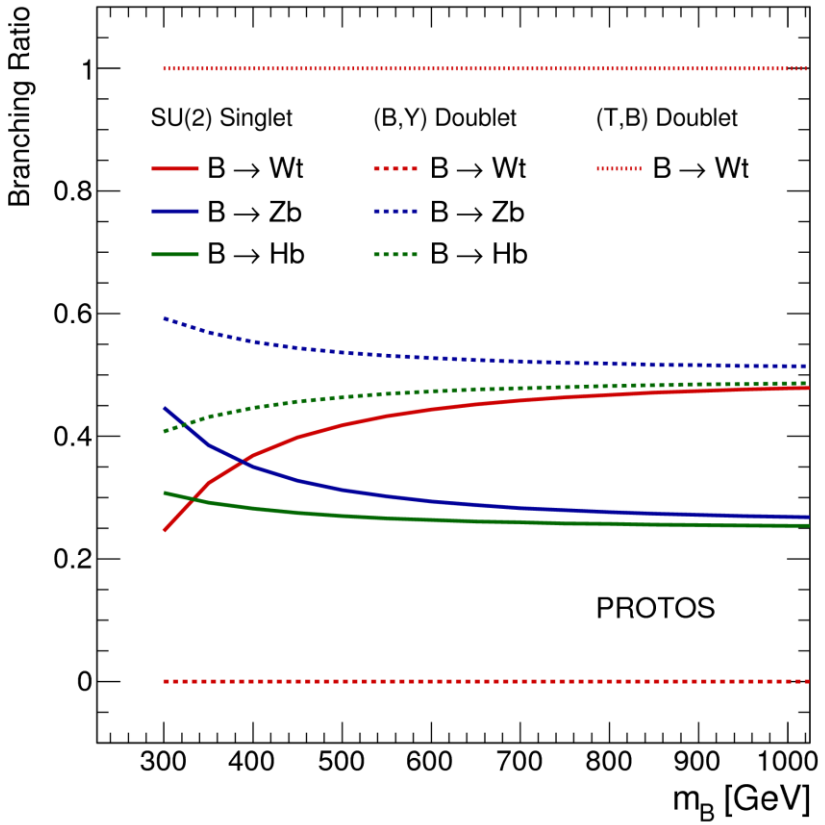
  X: charge +5/3 Y: charge -4/3



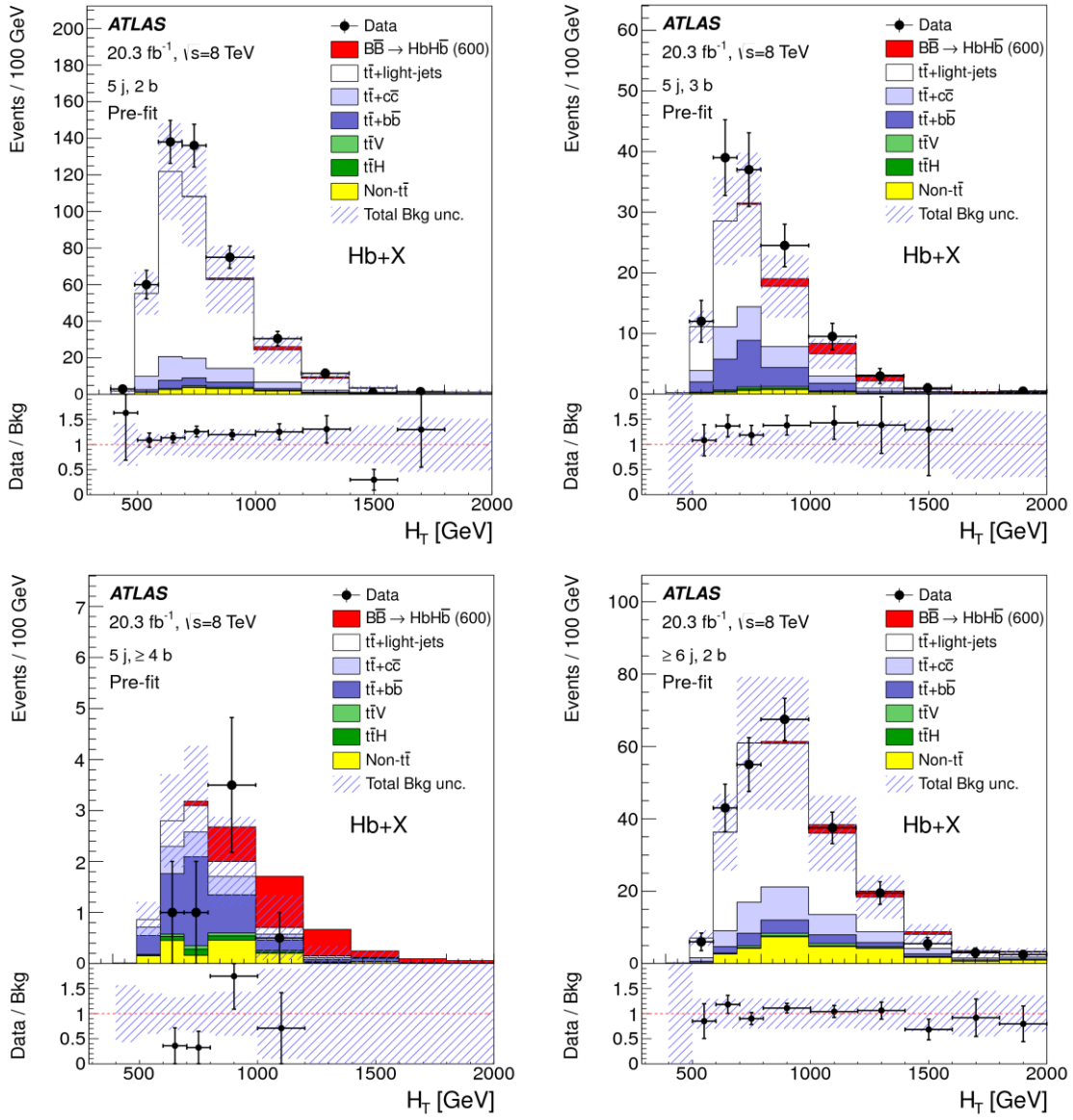
VLQ: B searches

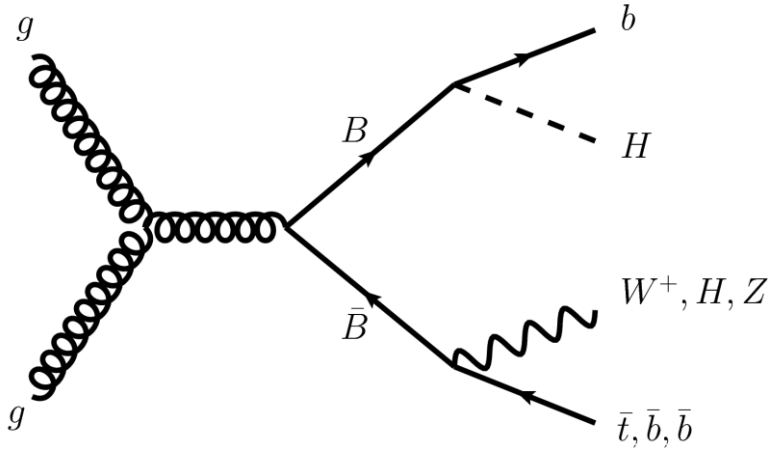
- ATLAS has several searches for pair production of B quarks, each sensitive to different decay modes:
  - $Zb + X$ for large $\mathcal{BR}(B \to bZ)$ at 8 TeV :
    - JHEP 1411 (2014) 104
  - $l^{\pm} l^{\pm} + b$ for large $\mathcal{BR}(B \to tW)$ at 8 TeV:
    - JHEP 1510 (2015) 150
  - $Hb + X$ for large $\mathcal{BR}(B \to bH)$ at 8 TeV:
    - JHEP 1508 (2015) 105
- The latter search is discussed in this talk.





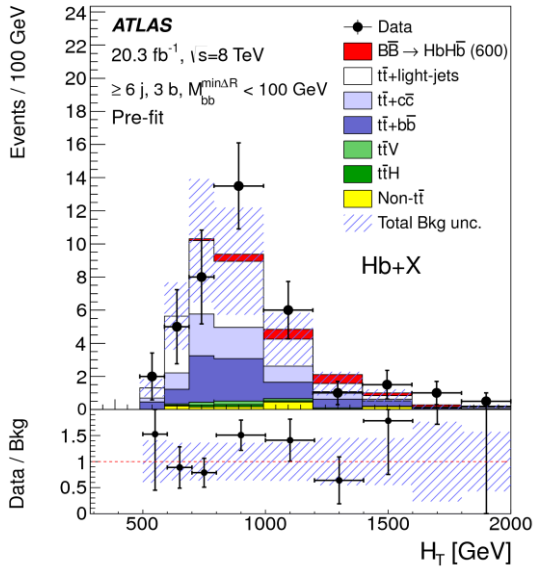
VLQ: B searches (Hb + X)

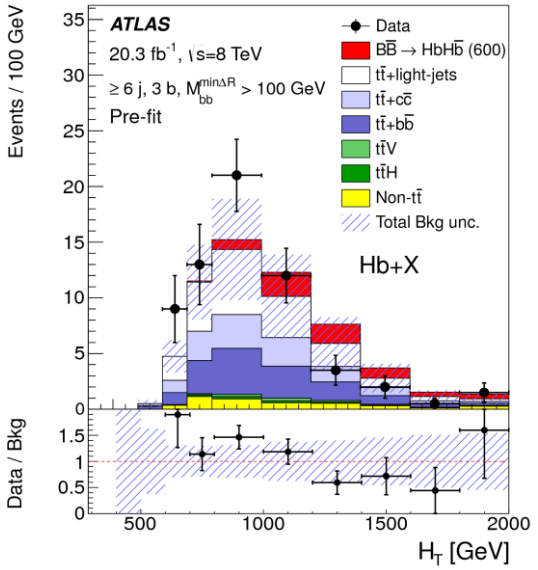


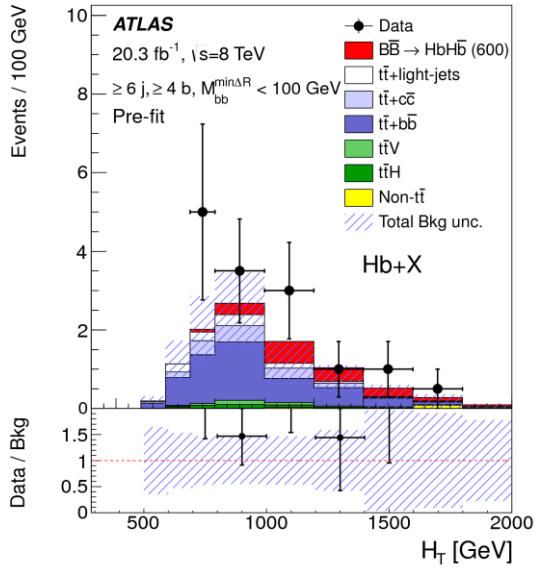


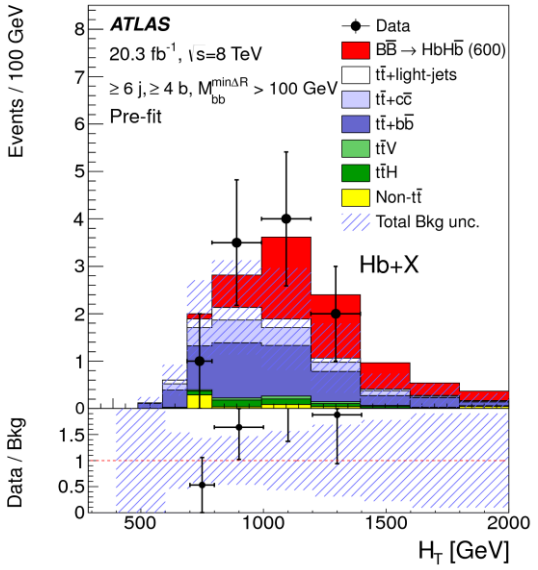
- Select sample dominated by $t\bar{t}$.
- Subdivide into 8 categories by n_{jets}, b–multiplicity and mass of closest two b jets.
- Background rich regions have low b–multiplicity.
- Signal rich regions have high b–multiplicity.
- Search using distribution of **scalar sum of transverse momentum of jets, $l^{\pm}$ and E_T^{miss} (H_T).**

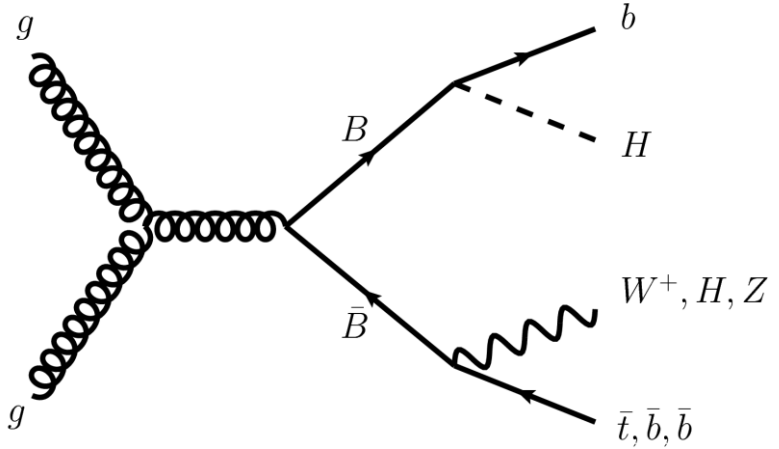
VLQ: B searches (Hb + X)











- Select sample dominated by $t\bar{t}$.
- Subdivide into 8 categories by n_{jets}, b–multiplicity and mass of closest two b jets.
- Background rich regions have low b–multiplicity.
- Signal rich regions have high b–multiplicity.
- Search using distribution of **scalar sum of transverse momentum of jets, $l^{\pm}$ and E_T^{miss} (H_T).**

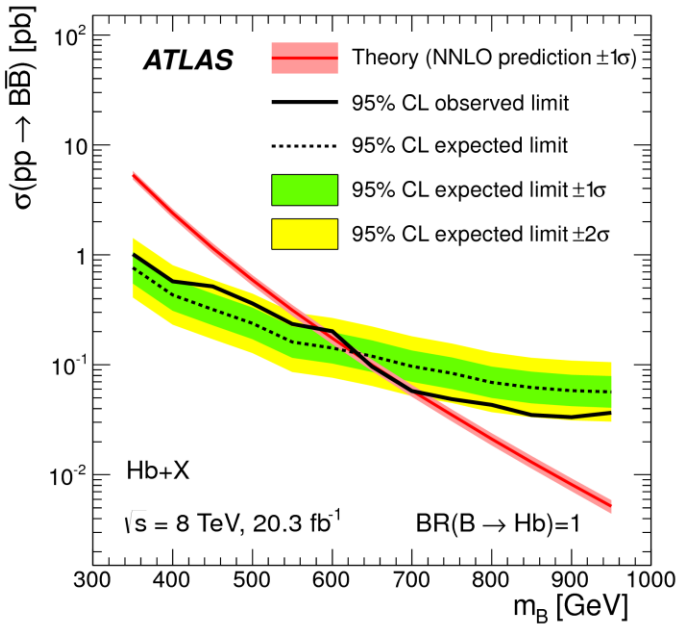
VLQ: B searches (Hb + X)

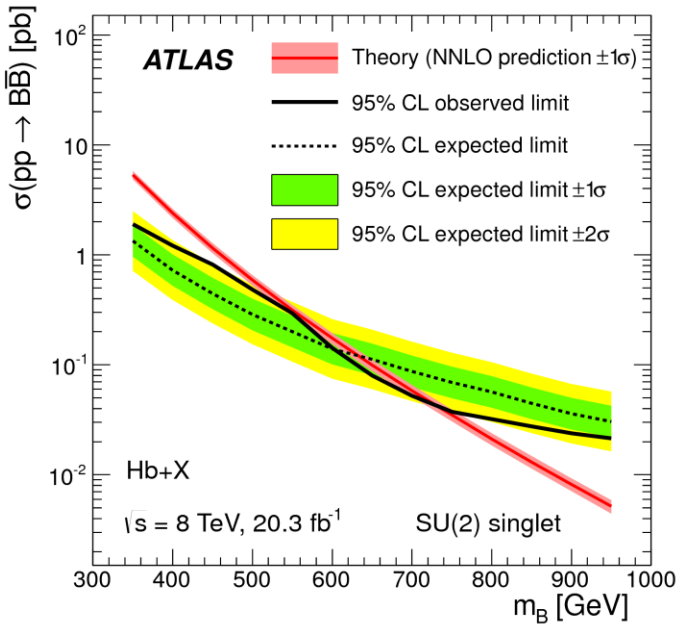
Main systematics:

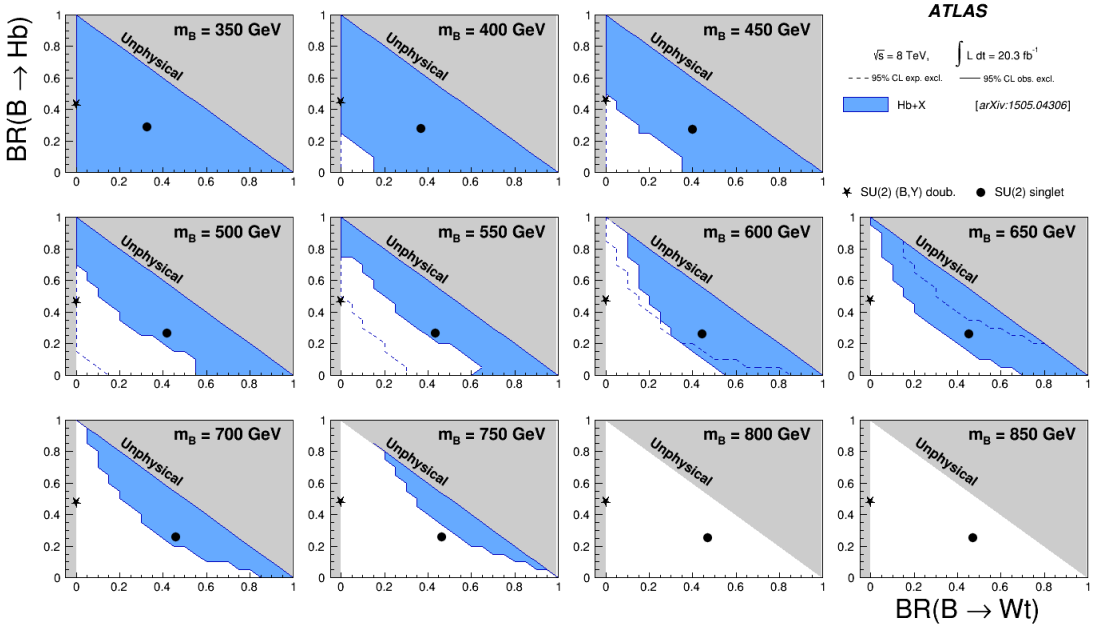
JES, theoretical cross section

- No excess beyond SM is observed.
- $\mathcal{BR}(B \to Hb) = 1$:

  excluded **350 < m_B < 580 and 635 < m_B < 700 (< 625) GeV** (95% CL).
- SU(2) Singlet B: excluded **m_B < 735 (635) GeV** (95% CL).

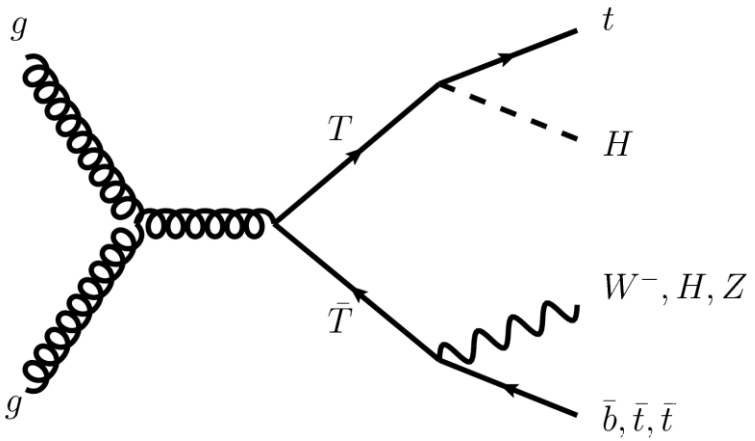


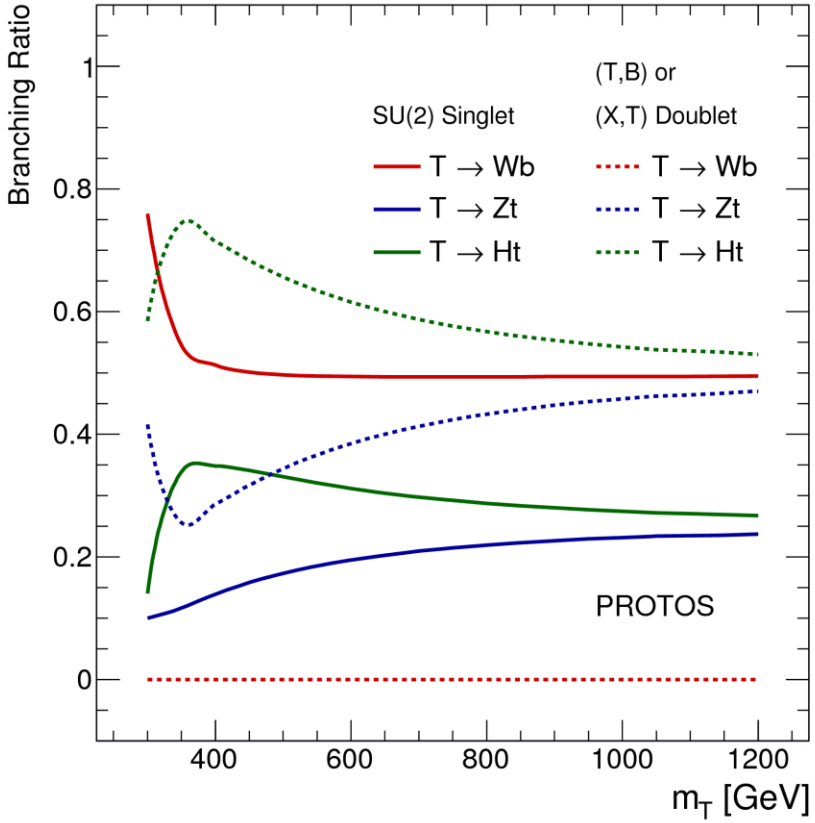




VLQ: T searches

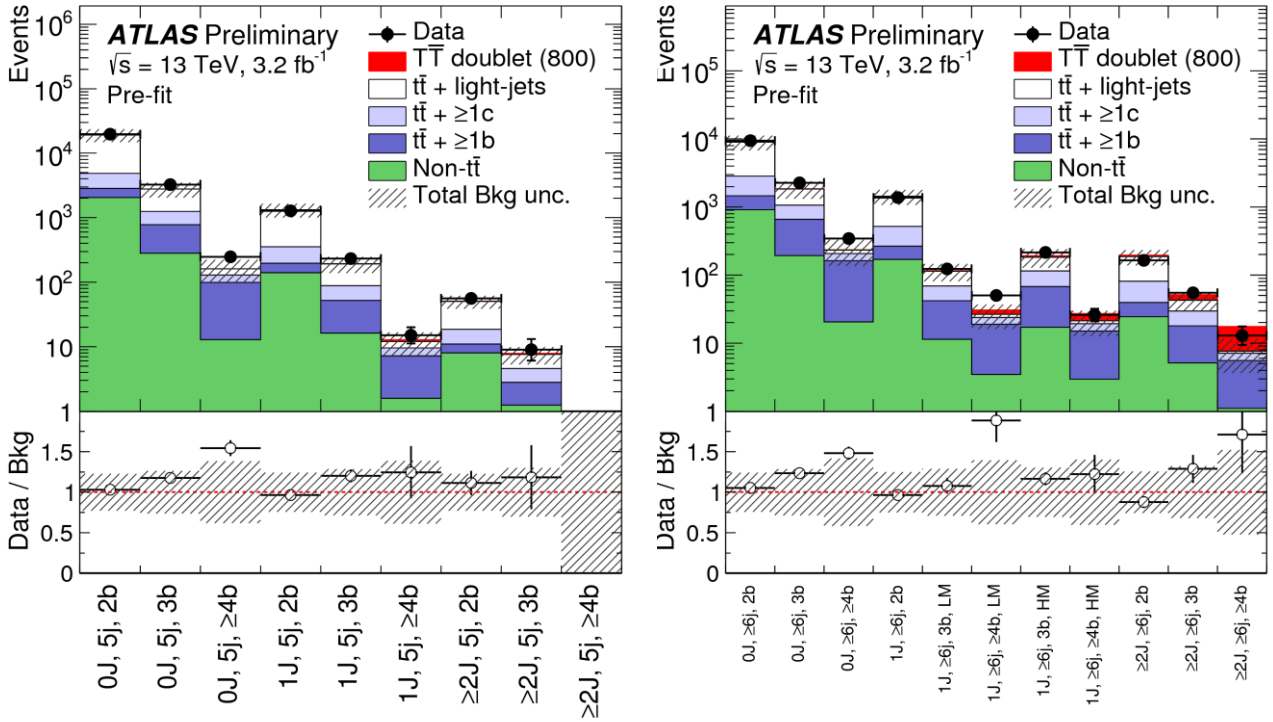
- ATLAS has several searches for pair production of T quarks, each sensitive to different decay modes:
  - $Zt + X$ for large $\mathcal{BR}(T \to tZ)$ at 8 TeV:
    - JHEP 1411 (2014) 104
  - $l^{\pm} l^{\pm} + b$ for large $\mathcal{BR}(T \to tZ, tH)$ at 8 TeV:
    - JHEP 1510 (2015) 150
  - $Wb + X$ for large $\mathcal{BR}(T \to Wb)$ at 8 TeV:
    - JHEP 1508 (2015) 105
  - $Ht + X$ for large $\mathcal{BR}(T \to tH)$ at 13 TeV:
    - ATLAS-CONF-2016-013
- The latter search is discussed in this talk.

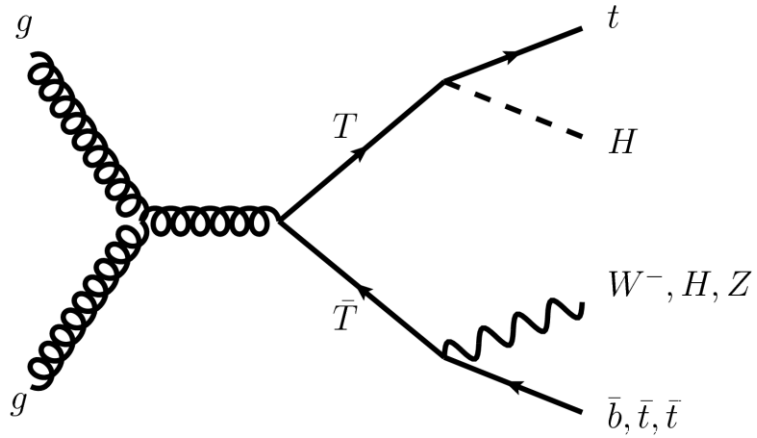




VLQ: T searches (Ht + X)

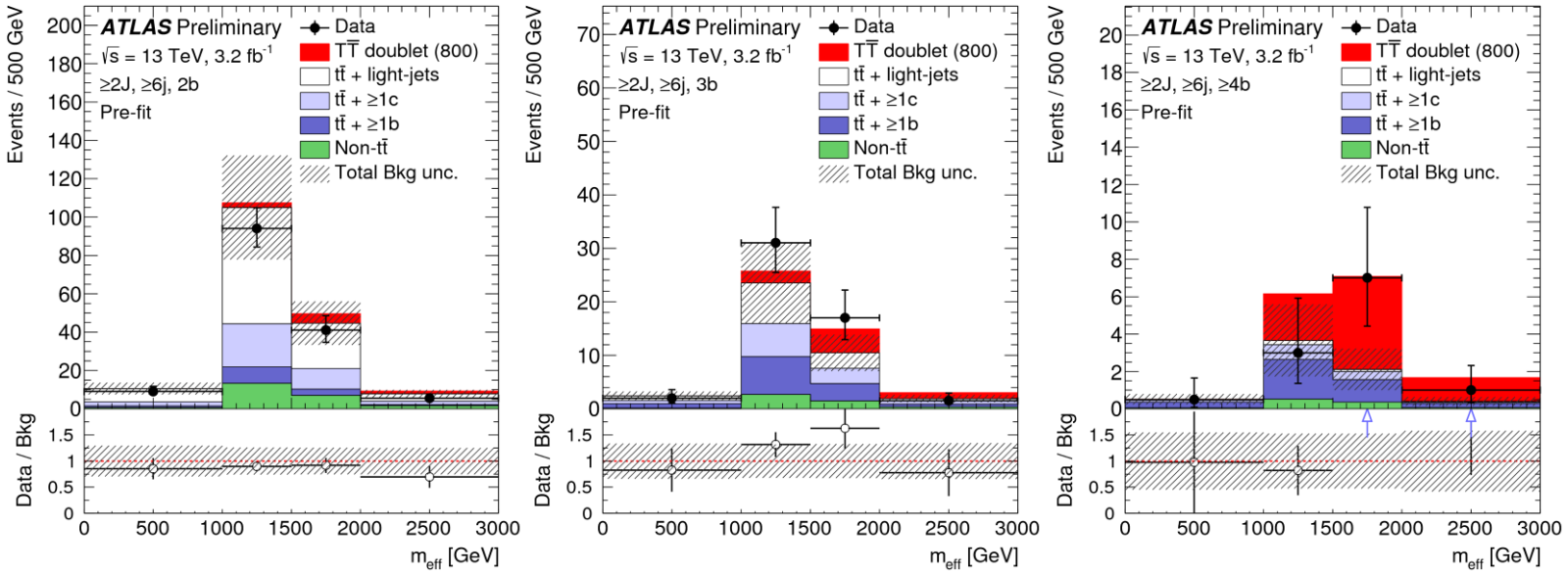
ATLAS run2 2015 data (3.2 fb^{-1}, $\sqrt{s}$= 13 TeV).

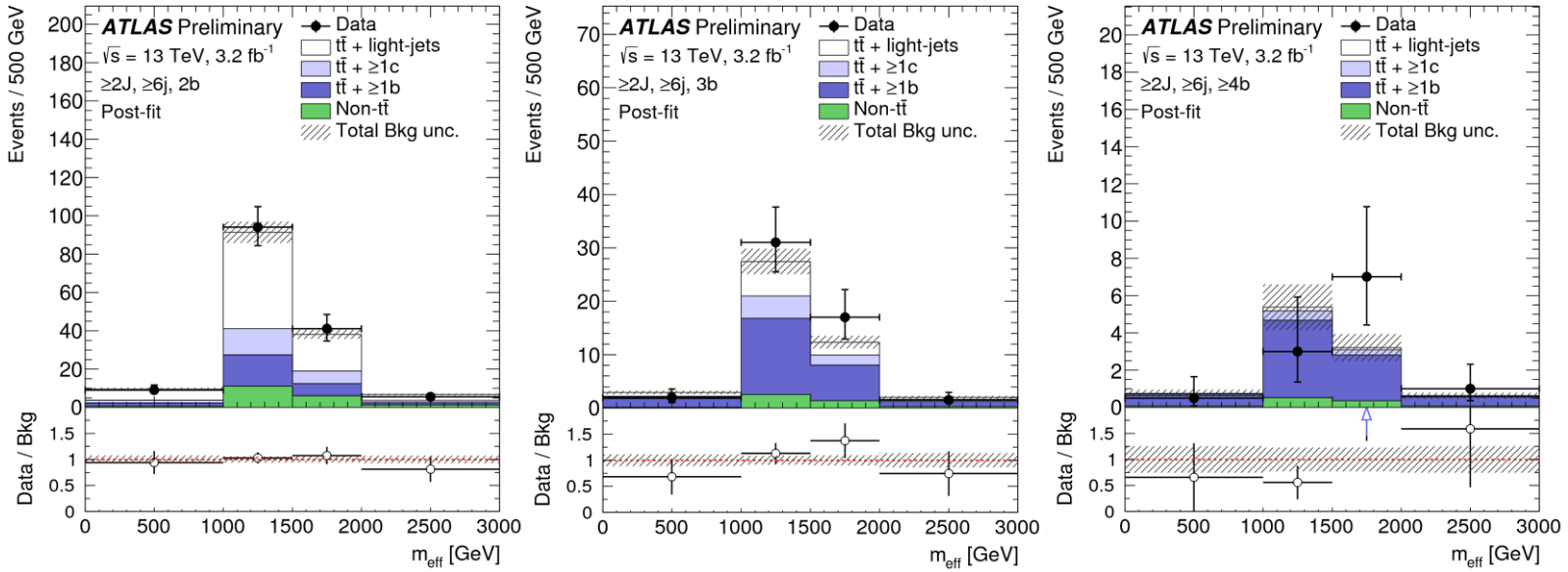




- Require (= 5 jets for valid.) ≥ 6 jets, ≥ 2 b-jets, $l^{\pm}$, E_T^{miss}.
- 20 categories by n_{jets}, b–multiplicity and mass of closest two b jets, number of large-R jets with mass > 100 GeV.
- Background rich regions have low b–multiplicity.
- Signal rich regions have high b–multiplicity.
- Search using distribution of scalar sum of transverse momentum of jets, $l^{\pm}$ and E_T^{miss}(m_{eff}).
- Presence of boosted, hadronically-decaying resonances reconstructed as large-R jets.

VLQ: T searches (Ht + X)





m_{eff} distributions from signal-sensitive regions before/after background-only hypothesis fit.

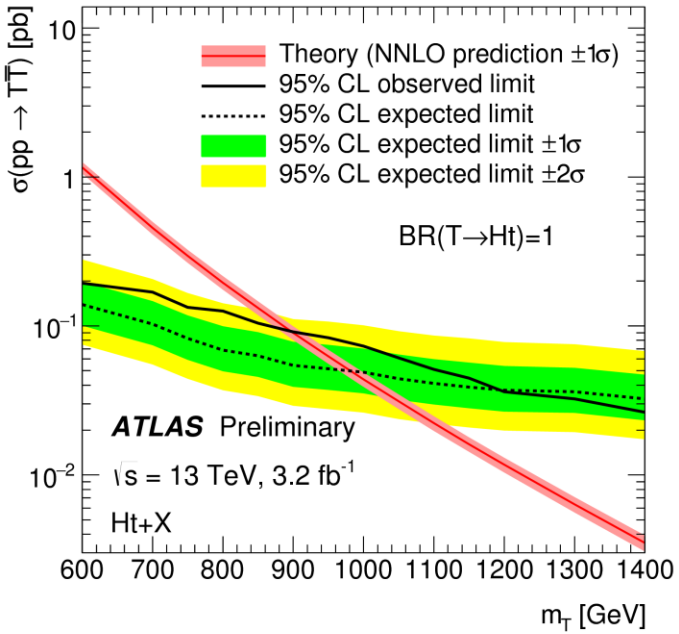
m_{eff} = scalar sum of transverse momentum of jets, $l^{\pm}$ and E_T^{miss}

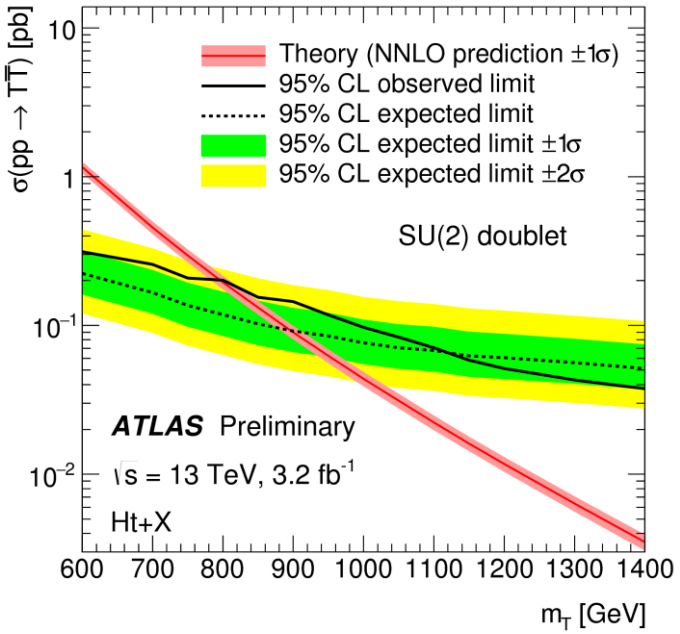
VLQ: T searches (Ht + X)

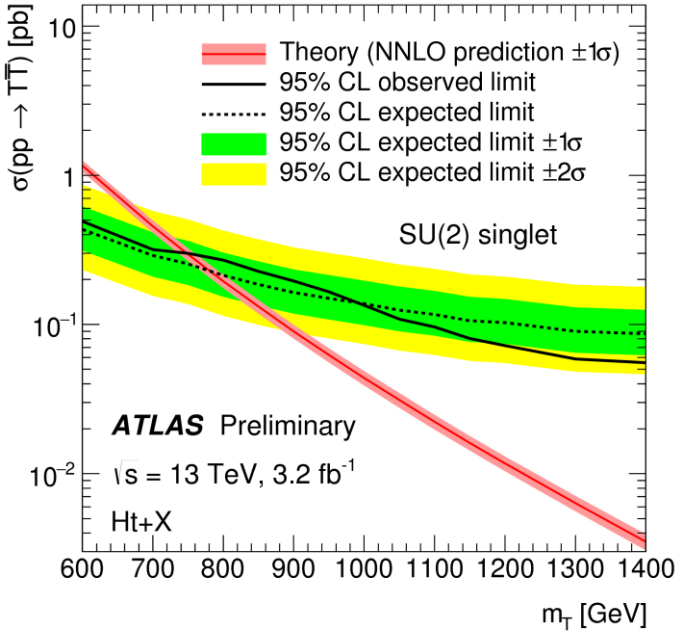
Main systematics:

Bkg prod. XS (incl. factorization and renormalization scales and PDF (NLO and NNLO) uncertainties), luminosity, JES

- No excess beyond SM is observed.
- Assuming $\mathcal{BR}(T \to Ht) = 1$: excluded **$m_T$ < 900 (980) GeV** (95% CL).
- SU(2) Singlet T: excluded **m_T < 750 (780) GeV** (95% CL).
- SU(2) Doublet T: excluded **m_T < 800 (900) GeV** (95% CL).

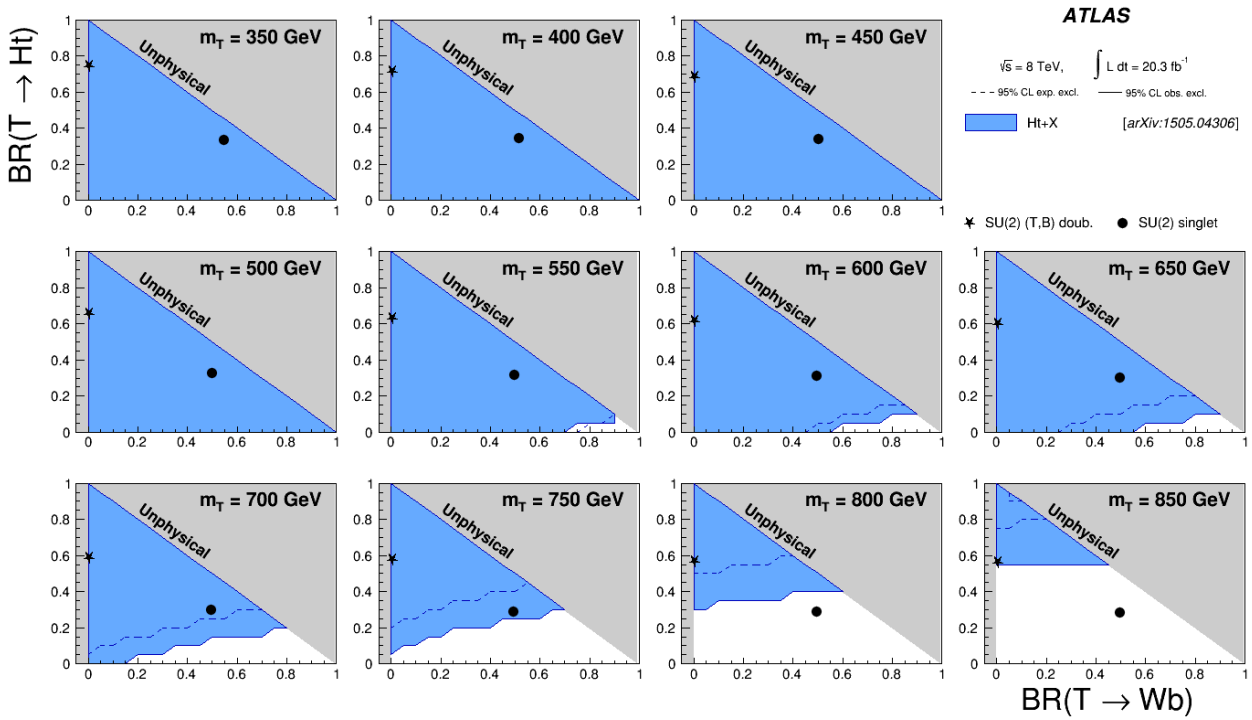


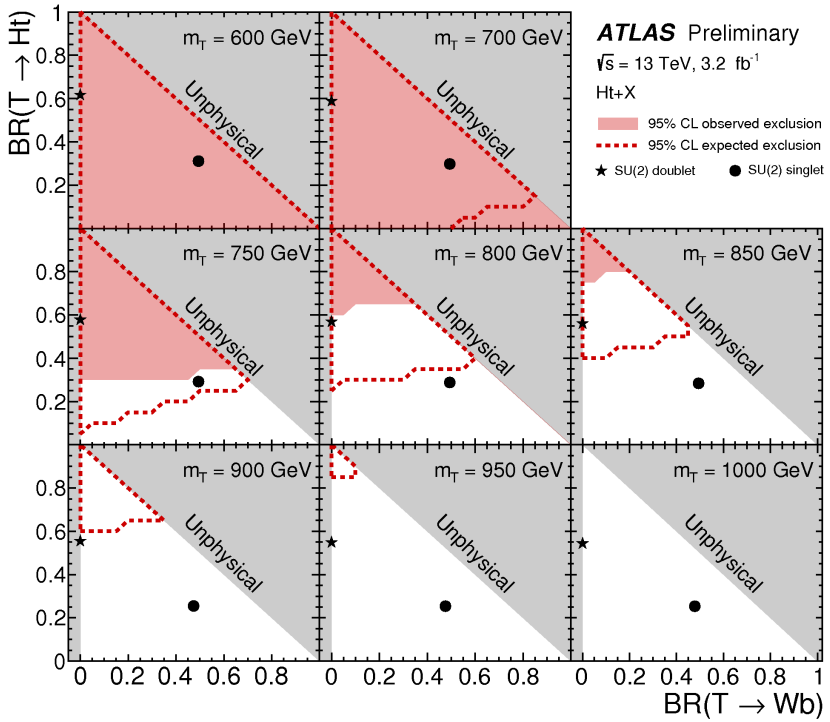




VLQ: T searches (Ht + X)

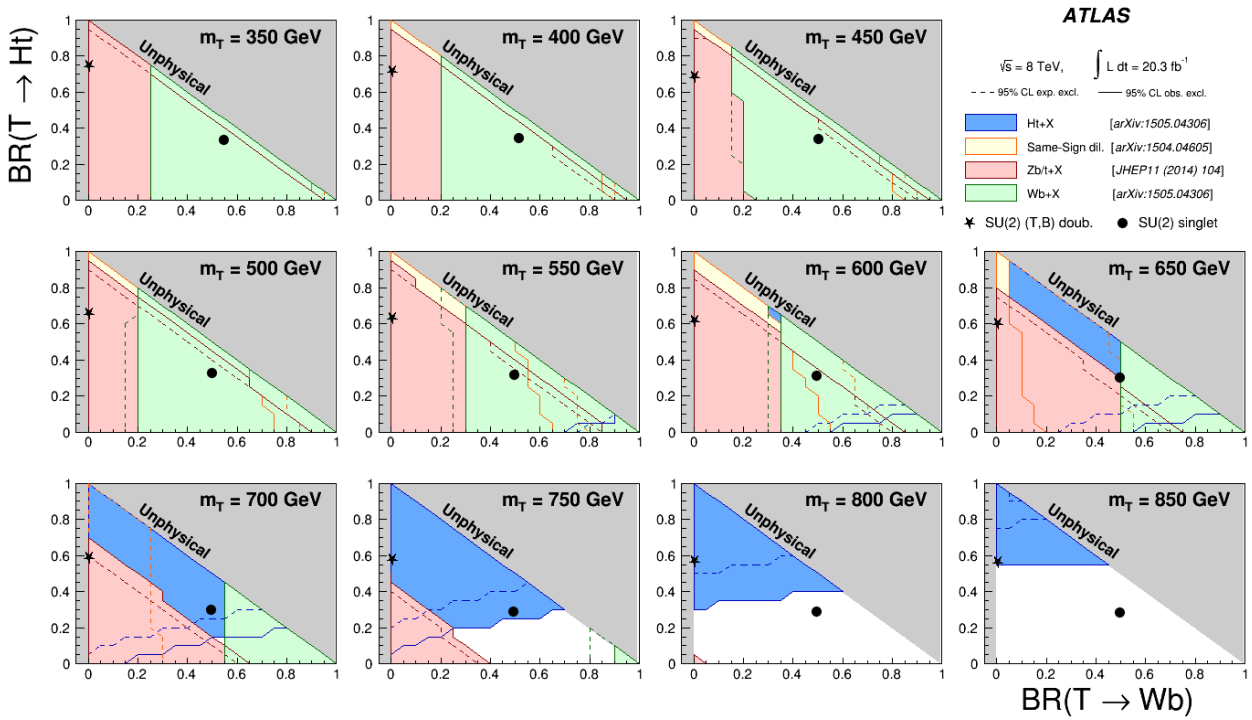
- 13 TeV analysis sensitivity reaches 950 GeV, exceeded that of 8 TeV analysis.
- Observed limits are weaker than expected above 700 GeV due to fluctuations in data.

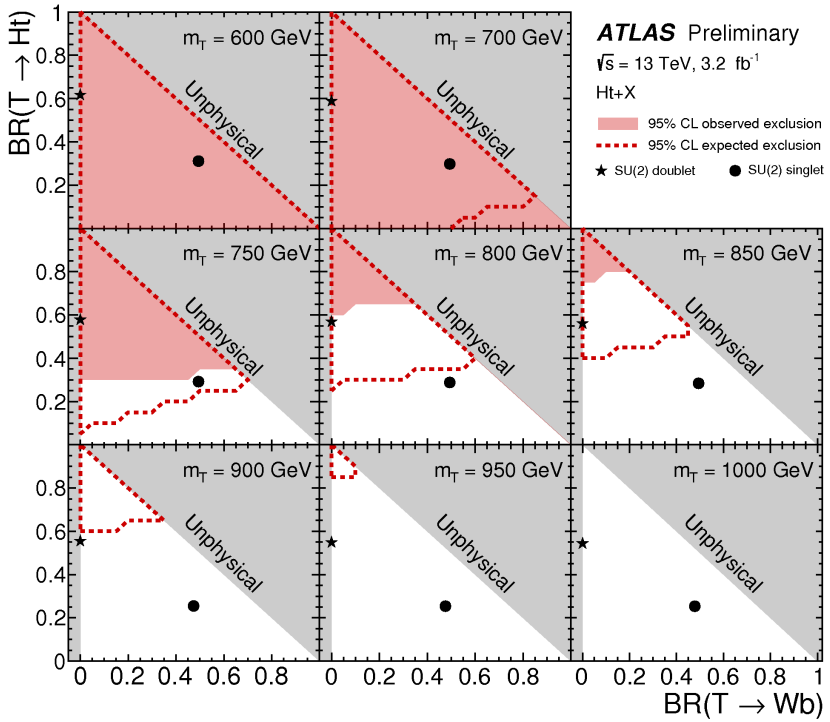




VLQ: T searches (Ht + X, SS dil., Zb/t + X, Wb + X)

- 13 TeV analysis sensitivity reaches 950 GeV, exceeded that of 8 TeV analysis.
- Observed limits are weaker than expected above 700 GeV due to fluctuations in data.

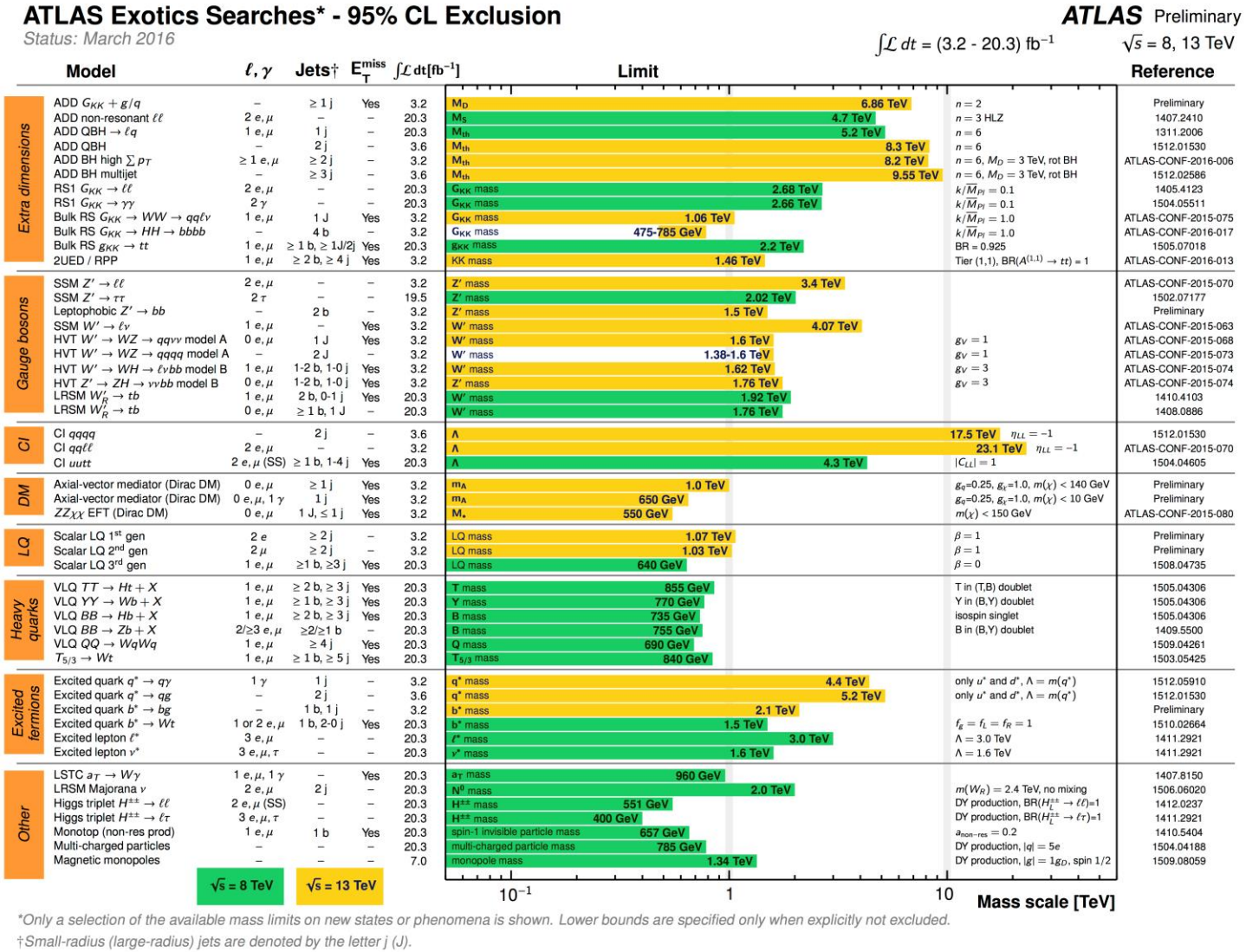




Summary

- No excess was found in any channel. Limit was set on cross sections.
- **$t\bar{t}$ resonance (8 TeV):**
  - Z'_{TC} : excluded **$0.4 < m_{Z'} < 1.8$ TeV** (95% CL)
  - g_{KK} : excluded **$0.4 < m_{gKK} < 2.2$ TeV** (95% CL)
- **$t\bar{t}$ resonance (13 TeV):**
  - Z'_{TC} : excluded **$0.7 < m_{Z'} < 2.0$ TeV** (95% CL)
- **VLQ (B searches):** obs.(exp.)
  - **8 TeV** assuming $\mathcal{BR}(B \to Hb) = 1$:
    excluded $\mathbf{m_B \in \{350, 580\} \cup \{635, 700\}}$ **(m_B <625) GeV** (95% CL)
  - **8 TeV** SU(2) singlet B: excluded **$m_B < 735(635)$ GeV** (95% CL)
- **VLQ (T searches):** obs.(exp.)
  - **8 TeV** SU(2) singlet T: excluded **$m_T < 800(755)$ GeV** (95% CL)
  - **8 TeV** SU(2) doublet T: excluded **$m_T < 855(820)$ GeV** (95% CL)
  - **13 TeV** SU(2) singlet T: excluded **$m_T < 750(780)$ GeV** (95% CL)
  - **13 TeV** SU(2) doublet T: excluded **$m_T < 800(900)$ GeV** (95% CL)

More ATLAS Exotics Public Results



*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

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

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults#Exotics_Public_Results

Backup

Run1 $t\bar{t}$: systematics

Systematic Uncertainties	Resolved selection yield impact [%] total bkg.	Z'	Boosted selection yield impact [%] total bkg.	Z'
Luminosity	2.5	2.8	2.6	2.8
PDF	2.4	3.6	4.7	2.3
ISR/FSR	3.7	–	1.2	–
Parton shower and fragmentation	4.8	–	1.5	–
$t\bar{t}$ normalisation	5.3	–	5.5	–
$t\bar{t}$ EW virtual correction	0.2	–	0.5	–
$t\bar{t}$ generator	0.3	–	2.6	–
$t\bar{t}$ top quark mass	0.6	–	1.4	–
W+jets generator	0.3	–	0.1	–
Multi-jet normalisation, e+jets	0.5	–	0.2	–
Multi-jet normalisation, μ+jets	0.1	–	< 0.1	–
JES+JMS, large-radius jets	0.1	2.1	9.7	2.8
JER+JMR, large-radius jets	< 0.1	0.3	1.0	0.2
JES, small-radius jets	5.6	2.6	0.4	1.4
JER, small-radius jets	1.8	1.4	< 0.1	0.2
Jet vertex fraction	0.8	0.8	0.2	< 0.1
b-tagging b-jet efficiency	1.1	2.0	2.9	17.1
b-tagging c-jet efficiency	0.1	0.7	0.1	2.1
b-tagging light-jet efficiency	< 0.1	< 0.1	0.5	0.2
Electron efficiency	0.3	0.6	0.6	1.3
Muon efficiency	0.9	1.0	1.0	1.1
MC statistical uncertainty	0.4	6.0	1.3	1.8
All systematic uncertainties	10.8	8.8	13.4	18.0

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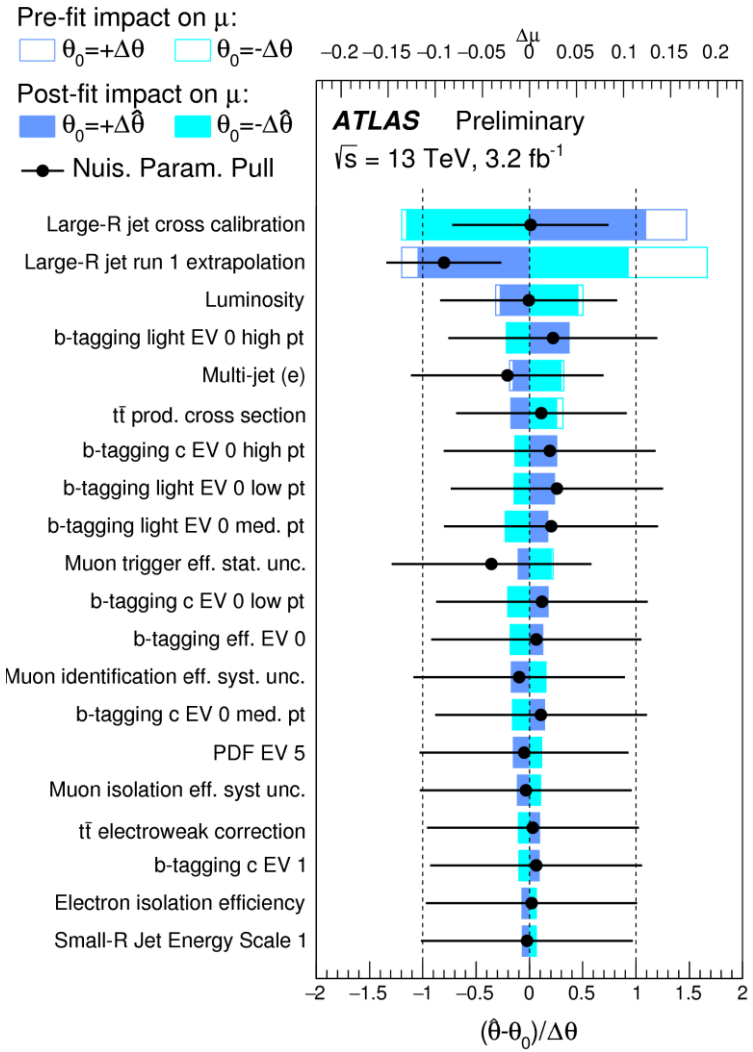
Run2 $t\bar{t}$: nuisance parameters of signal strength



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B search: yields and systematics

	5 j, 2 b	5 j, 3 b	5 j, ≥4 b	≥6 j, 2 b
$B\bar{B}$ ($m_B = 600$ GeV)				
BR($B \to Hb$) = 1	8.6 ± 1.1	9.3 ± 2.2	5.0 ± 1.4	11.9 ± 3.0
Singlet	12.2 ± 1.9	8.8 ± 1.7	3.4 ± 0.8	27.4 ± 4.3
(B,Y) doublet	8.5 ± 1.1	5.8 ± 1.4	2.8 ± 0.8	10.9 ± 2.1
$t\bar{t}$+light-jets	389 ± 93	72 ± 18	2.1 ± 0.7	234 ± 74
$t\bar{t} + c\bar{c}$	56 ± 42	23 ± 15	2.2 ± 1.5	55 ± 40
$t\bar{t} + b\bar{b}$	19 ± 14	25 ± 14	5.5 ± 3.2	22 ± 15
$t\bar{t}V$	4.2 ± 1.4	1.6 ± 0.5	0.3 ± 0.1	5.1 ± 1.7
$t\bar{t}H$	1.0 ± 0.1	1.1 ± 0.2	0.5 ± 0.1	1.5 ± 0.2
W+jets	21 ± 12	3.5 ± 2.1	0.6 ± 0.5	12.5 ± 7.9
Z+jets	8.2 ± 3.3	2.8 ± 2.8	0.5 ± 0.5	4.3 ± 4.1
Single top	41.3 ± 7.2	8.8 ± 1.9	0.6 ± 0.1	28.0 ± 6.8
Diboson	1.9 ± 0.9	0.5 ± 0.3	0.07 ± 0.07	1.2 ± 0.7
Multijet	< 0.01	< 0.01	0.4 ± 0.2	0.2 ± 0.1
Total background	540 ± 120	139 ± 35	12.8 ± 4.9	360 ± 100
Data	576	165	10	375

	≥6 j, 3 b low $M_{bb}^{\min\Delta R}$	≥6 j, 3 b high $M_{bb}^{\min\Delta R}$	≥6 j, ≥4 b low $M_{bb}^{\min\Delta R}$	≥6 j, ≥4 b high $M_{bb}^{\min\Delta R}$
$B\bar{B}$ ($m_B = 600$ GeV)				
BR($B \to Hb$) = 1	3.8 ± 0.6	13.1 ± 1.8	3.2 ± 0.7	9.6 ± 2.0
Singlet	7.1 ± 0.9	15.8 ± 2.5	4.6 ± 0.9	7.5 ± 1.5
(B,Y) doublet	2.7 ± 0.3	7.0 ± 1.3	2.3 ± 0.6	3.9 ± 0.9
$t\bar{t}$+light-jets	21.3 ± 9.0	32.8 ± 9.5	1.4 ± 0.5	1.5 ± 0.6
$t\bar{t} + c\bar{c}$	10.8 ± 7.5	20 ± 15	2.2 ± 1.6	2.9 ± 2.2
$t\bar{t} + b\bar{b}$	13.1 ± 8.5	24 ± 16	7.8 ± 4.8	8.1 ± 5.3
$t\bar{t}V$	1.1 ± 0.4	1.6 ± 0.6	0.6 ± 0.2	0.4 ± 0.2
$t\bar{t}H$	0.7 ± 0.1	1.4 ± 0.2	0.5 ± 0.1	0.9 ± 0.2
W+jets	2.0 ± 1.3	1.1 ± 0.8	0.3 ± 0.3	0.05 ± 0.05
Z+jets	0.11 ± 0.07	0.2 ± 0.1	< 0.01	< 0.01
Single top	3.2 ± 0.6	5.1 ± 2.2	0.8 ± 0.2	0.3 ± 0.2
Diboson	0.2 ± 0.1	0.09 ± 0.03	0.02 ± 0.01	< 0.01
Multijet	< 0.01	0.6 ± 0.2	< 0.01	0.4 ± 0.1
Total background	53 ± 18	87 ± 30	13.7 ± 5.9	14.5 ± 7.3
Data	62	103	23	20

≥6 j, ≥4 b, high $M_{bb}^{\min\Delta R}$

	Pre-fit				Post-fit		
	Signal	$t\bar{t}$+light-jets	$t\bar{t} + c\bar{c}$	$t\bar{t} + b\bar{b}$	$t\bar{t}$+light-jets	$t\bar{t} + c\bar{c}$	$t\bar{t} + b\bar{b}$
Luminosity	±2.8	±2.8	±2.8	±2.8	±2.7	±2.7	±2.7
Lepton efficiencies	±1.6	±1.4	±1.5	±1.7	±1.4	±1.5	±1.6
Jet energy scale	±5.6	±14	±14	±11	±13	±14	±11
Jet efficiencies	±3.1	±3.3	±1.0	±0.9	±3.2	±0.9	±0.8
Jet energy resolution	±0.1	±6.0	±1.1	±1.9	±4.5	±0.9	±1.5
b-tagging efficiency	±16	±7.6	±9.2	±16	±3.9	±5.2	±7.5
c-tagging efficiency	±1.0	±6.1	±15	±3.0	±5.8	±14	±2.8
Light-jet tagging efficiency	–	±19	±6.3	±2.4	±18	±5.8	±2.3
High-p_{T} tagging efficiency	±11	±2.7	±5.3	±5.0	±1.9	±3.8	±3.6
$t\bar{t}$: reweighting	–	±15	±16	–	±14	±15	–
$t\bar{t}$: parton shower	–	±22	±35	±26	±14	±33	±24
$t\bar{t}$+HF: normalisation	–	–	±50	±50	–	±44	±30
$t\bar{t}$+HF: modelling	–	–	±27	±24	–	±28	±21
Theoretical cross sections	–	±6.3	±6.2	±6.3	±5.9	±5.9	±5.9
Total	±21	±38	±73	±65	±24	±46	±27

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T search: predicted and observed yields

	0J, ≥6j, 2b	0J, ≥6j, 3b	0J, ≥6j, ≥4b
$t\bar{t}$+light-jets	6600 ± 420	880 ± 130	31 ± 12
$t\bar{t}$+≥1c	980 ± 270	303 ± 94	31 ± 11
$t\bar{t}$+≥1b	1080 ± 240	890 ± 170	270 ± 38
$t\bar{t}V$	49.5 ± 7.9	13.7 ± 2.4	3.28 ± 0.61
$t\bar{t}H$	27.4 ± 3.3	19.6 ± 2.5	8.4 ± 1.3
W+jets	110 ± 47	15.3 ± 8.2	1.14 ± 0.59
Z+jets	37 ± 23	4.8 ± 3.0	0.45 ± 0.28
Single top	322 ± 29	60.1 ± 8.0	6.6 ± 1.1
Diboson	37 ± 18	5.6 ± 2.9	0.81 ± 0.47
Multijet	229 ± 94	58 ± 28	–
Total background	9470 ± 270	2250 ± 80	352 ± 25
Data	9466	2279	345

	1J, ≥6j, 2b	1J, ≥6j, 3b LM	1J, ≥6j, 3b HM	≥2J, ≥6j, 2b
$t\bar{t}$+light-jets	887 ± 85	46.6 ± 7.8	71 ± 13	88 ± 12
$t\bar{t}$+≥1c	174 ± 60	18.5 ± 6.6	34 ± 12	24.9 ± 9.4
$t\bar{t}$+≥1b	193 ± 45	63 ± 13	100 ± 19	28.7 ± 7.6
$t\bar{t}V$	16.0 ± 2.6	1.82 ± 0.32	2.71 ± 0.49	3.46 ± 0.57
$t\bar{t}H$	7.21 ± 0.93	1.77 ± 0.26	3.21 ± 0.45	1.65 ± 0.24
W+jets	21.7 ± 9.2	1.47 ± 0.65	1.59 ± 0.87	4.7 ± 3.0
Z+jets	4.9 ± 3.0	0.20 ± 0.14	0.34 ± 0.22	1.19 ± 0.80
Single top	61.8 ± 6.0	4.26 ± 0.62	8.8 ± 1.3	7.38 ± 0.93
Diboson	10.8 ± 5.3	1.18 ± 0.63	0.69 ± 0.40	2.7 ± 1.4
Multijet	27 ± 14	–	–	–
Total background	1403 ± 53	138.9 ± 7.9	220 ± 10	162.3 ± 8.9
Data	1380	123	215	164

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