Searches for new physics with top– and bottom–quark signatures using the ATLAS detector

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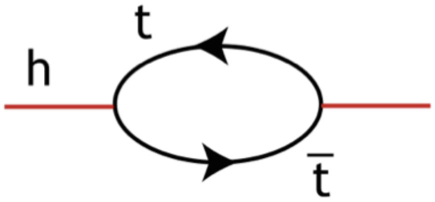
Introduction

- **The discovery of a 125 GeV Higgs boson is established.**
- However, there are many problems with the Standard Model (SM).
  - Hierarchy Problem,
  - Neutrino Oscillation,
  - Dark matter/Dark Energy,
  - Matter-Antimatter Asymmetry, Higgs mass stability, …
- **One of the primary goals of LHC, is to search for New Physics Beyond the SM (BSM).**
- Top quark still the heaviest fundamental particle; largest correction to the Higgs mass-squared
  - Top quark plays an important role in searches for physics BSM



BSM theories

- Some propositions for BSM physics:
  - Super symmetry, Extra dimensions,
  - Higher symmetry/Unified model, ….
- Many possible extensions of the SM (non-SUSY)
  - GUT, Extra-dimension(s), Little Higgs, composite Higgs, …
- Predict new particles, coupling preferentially to the third generation
- Focus on searches with third generation quarks:
  - New coloured fermions: Vector-Like Quarks (VLQ)
  - New bosons: decaying to $t\bar{t}$
    - Run 1 physics results: large dataset (20.3 fb^{-1});
    - Results published or publication ready

In this talk

Vector like quarks

Top/Bottom Partners aka VLQs

- Predicted in various BSM models, including composite Higgs, can solve naturalness problem without SUSY
- Left and right-handed components transform in the same way under the EW group (SU(2)) → Interesting properties:
  - Gauge invariant mass term independent of Higgs.
  - A vector-like top can play a similar role as the stop in regulating Higgs mass divergence.

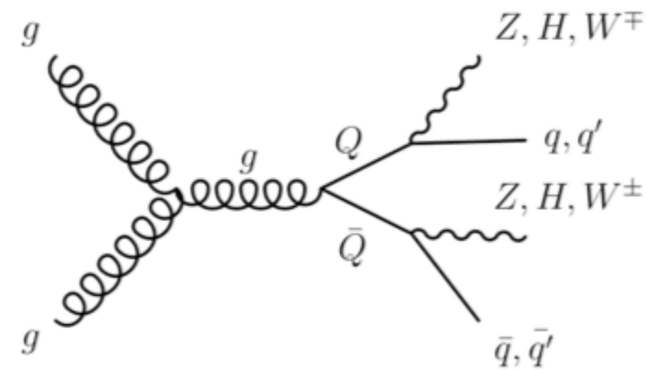
JHEP 11, 030 (2009) *(triplets not included)*

	Label	Charge	Decay mode
T singlet	T_S	+2/3	$T \to W^+b$, Zt, ht
B singlet	B_S	-1/3	$B \to W^-t$, Zb, hb
(T,B) doublet	TB_d	(+2/3, -1/3)	$T \to W^+b$, Zt, ht $B \to W^-t$, Zb, hb
(X,T) doublet	XT_d	(+5/3, +2/3)	$X \to W^+t$ $T \to Zt$, ht
(B,Y) doublet	BY_d	(-1/3, -4/3)	$B \to Zb$, hb $Y \to W^-b$

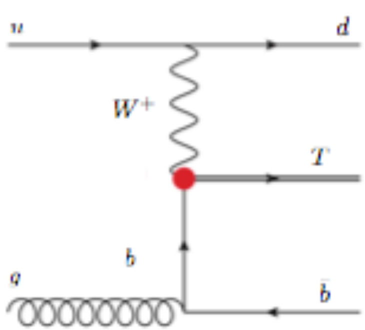
- Couple preferentially with 3*rd* generation quarks
- Considering four different kinds of Vector Like Quarks with different charge
- May come in singlets, doublets, triplets

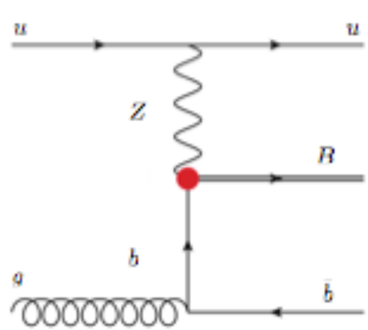
VLQs production mode at LHC

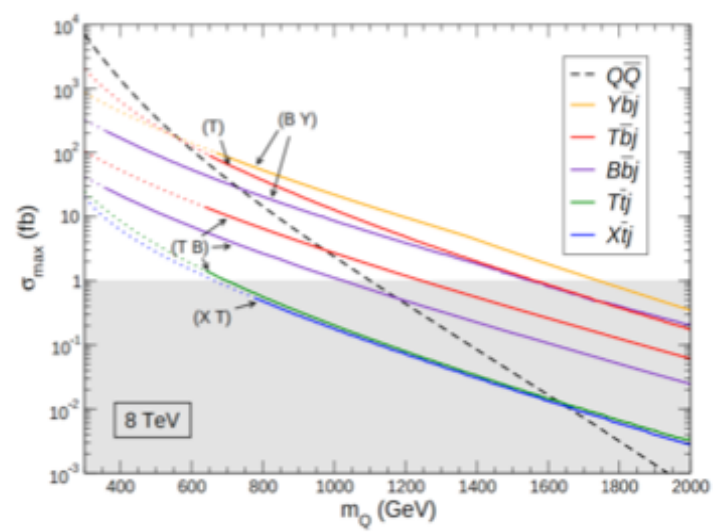
- **Strongly produced in pairs**: large $Q\overline{Q}$ cross section only dependent on mass (just like $t\bar{t}$)
  - Run-1 focus on **pair-production**



- **Single production** dependent on mass, charge, coupling (like single top)
  - dominant for large VLQ masses:

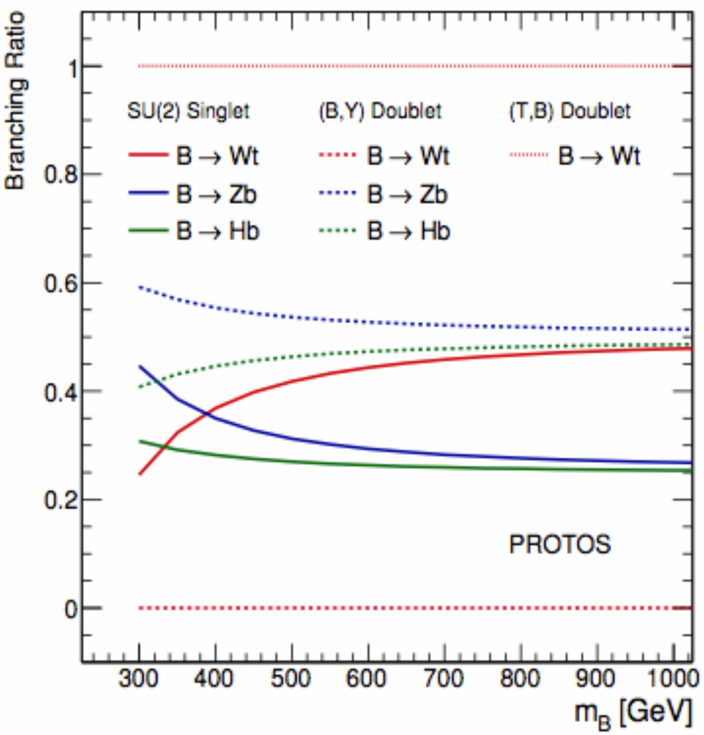


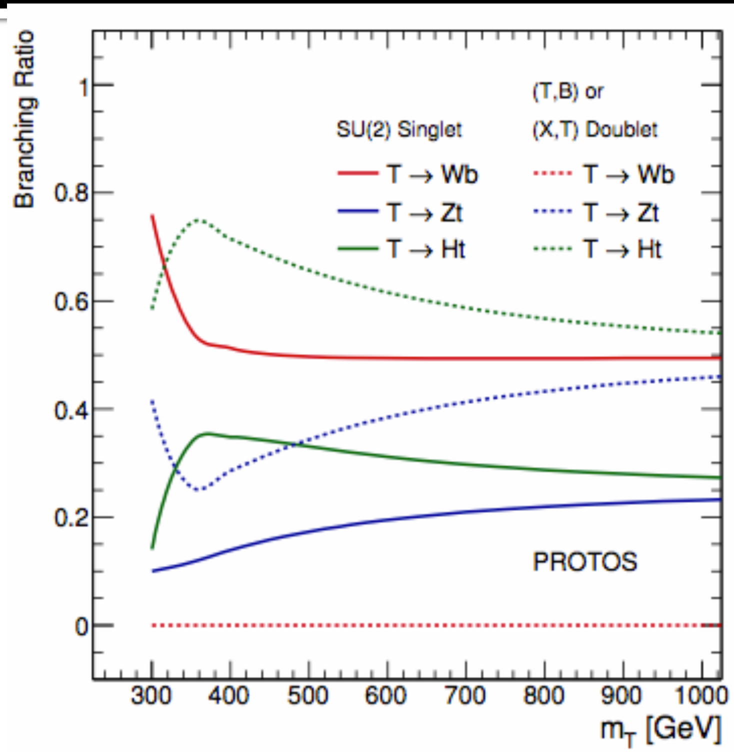




VLQ Decay Modes

- Three decay modes:
  - $T \rightarrow Wb$, $T \rightarrow Zt$, $T \rightarrow Ht$
  - $B \rightarrow Wt$, $B \rightarrow Zb$, $B \rightarrow Hb$

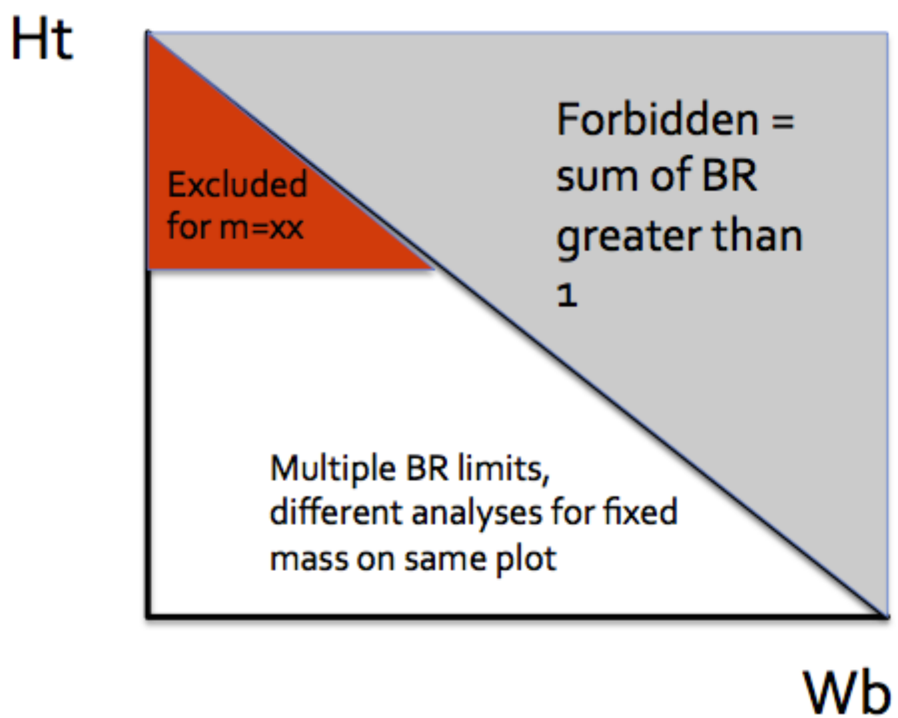


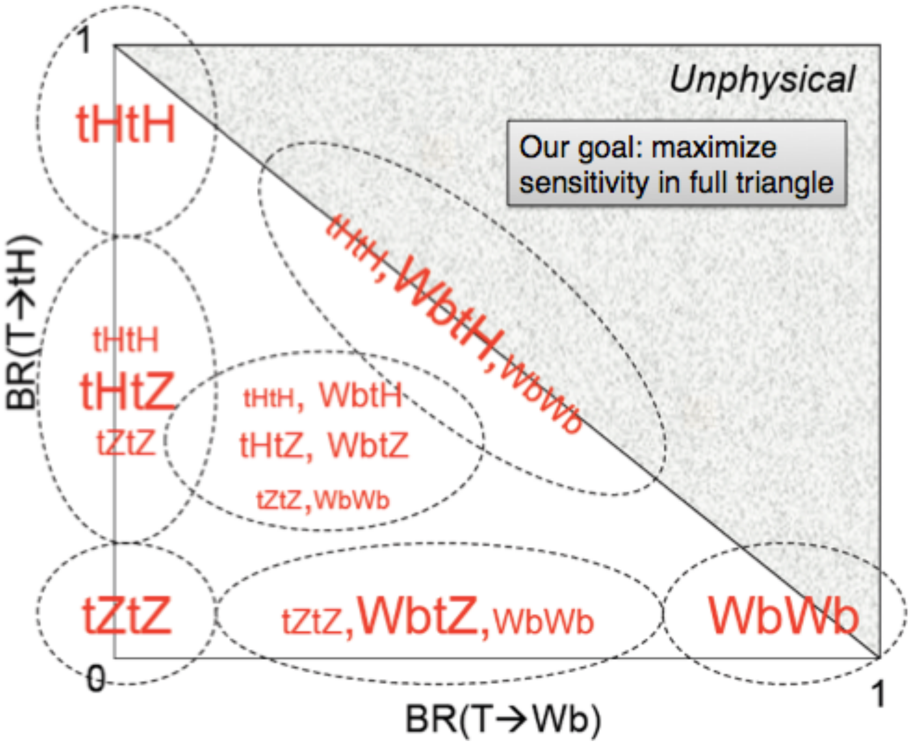


- Branching Ratios (BR) are very model dependent, hence different general analyses were developed to cover all the possible decays

ATLAS Style limit plot

- 2D–BR plane for a given VLQ mass for many analyses





Pair VLQs production: $T\bar{T} \rightarrow Wb+X$

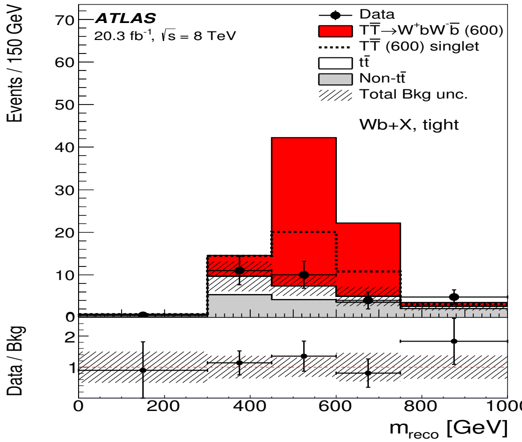
arXiv:1505.04306

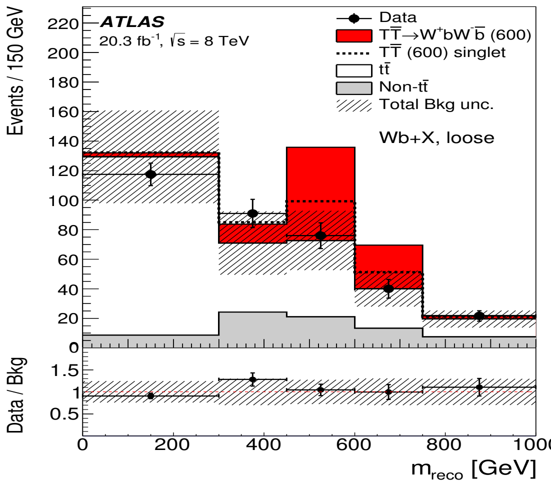
- **Event selection**

Exactly one electron or muon
$E_T^{\mathrm{miss}} > 20$ GeV, $E_T^{\mathrm{miss}} + m_T^W > 60$ GeV
≥ 4 jets, ≥ 1 b-tagged jets

- **Apply technique to identify hadronic W_{had} :**
  - Exploit T's boosted kinematics to reconstruct W bosons.
  - Two types of W_{had} candidates are defined :
    - W_{had}^{typeI} : single merged jet, $(p_T > 400 GeV, \Delta R \leq \Delta R_{cone} = 0.4)$
    - W_{had}^{typeII}: two close-by jets, $(p_T > 250 GeV, \Delta R(j,j) < 0.8, m_{jj} = 60 - 120 GeV)$.
  - For W_{lep} candidates, is reconstructed using the lepton and E_T^{miss}.

- **m_{reco} from had W+bjet (*) of tight selection is chosen to derive final results; better sensitivity**



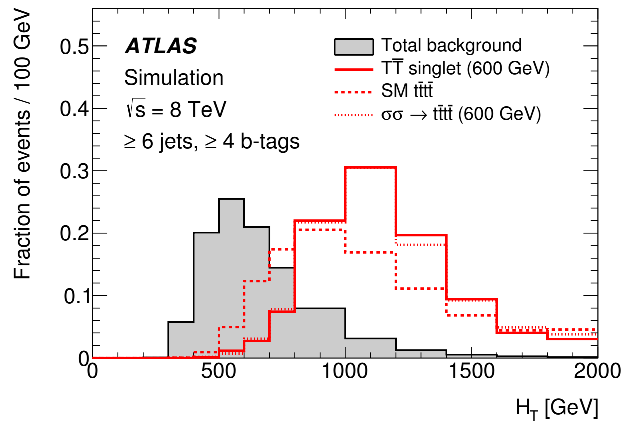


* $\boxed{\text{sum of } W_{\mathrm{had}}^{\mathrm{type\ I}} \text{ and } W_{\mathrm{had}}^{\mathrm{type\ II}} \text{ events}}$

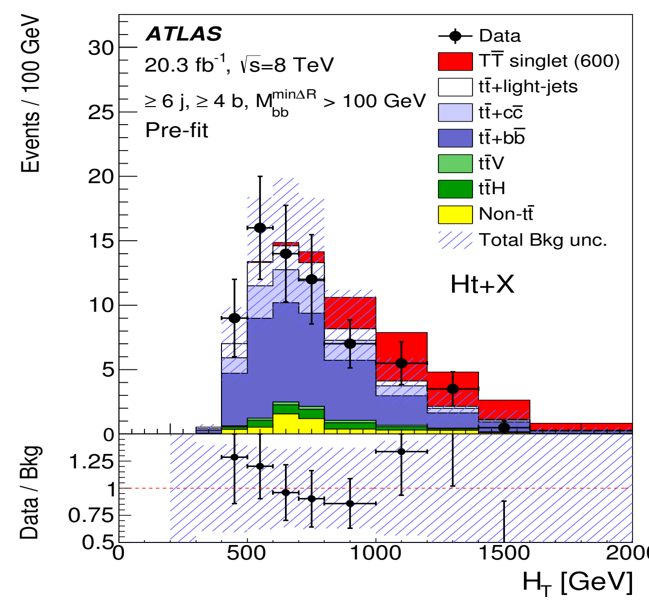
Pair VLQs production: $T\bar{T} \to Ht+X$

arXiv:1505.04306

- $T\bar{T}$ production search, $T \to H(\to b\bar{b})t$
- Possible final states:
  - $HtH\bar{t}$, $HtZ\bar{t}$, $HtWb$
- **Selection:**



- ➔ large jet and **b-jet multiplicity**
- ➔ **event categories**: n jets (5, ≥6)/n b-tags(2, 3, ≥4)
- ➔ Higgs-candidate from b-jets with min ∞R
- ➔ two channels based on $\mathbf{m}_{bb}^{\min\Delta R}$ (> or < 100 GeV)
- ➔ limits from $\mathbf{H}_T = \Sigma\, p_T(\text{jets}) + p_T(\text{leptons}) + E_T^{miss}$

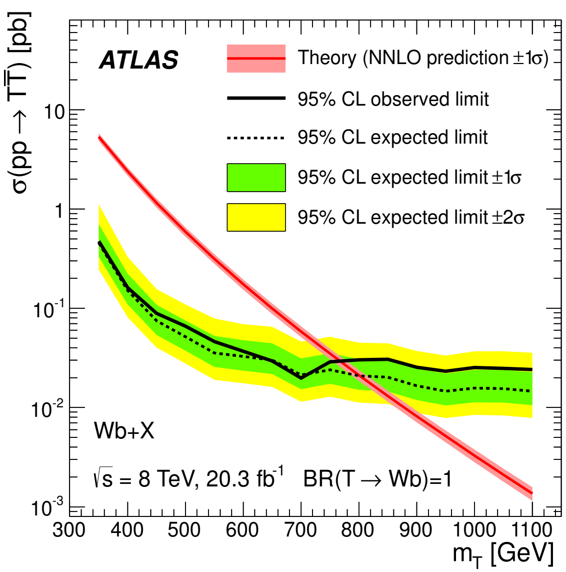


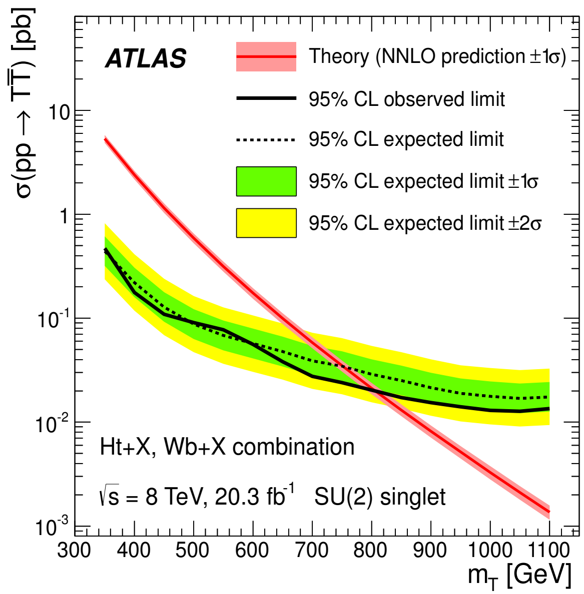
- ***tt̄* dominant background**
- H_T excellent discriminating variable

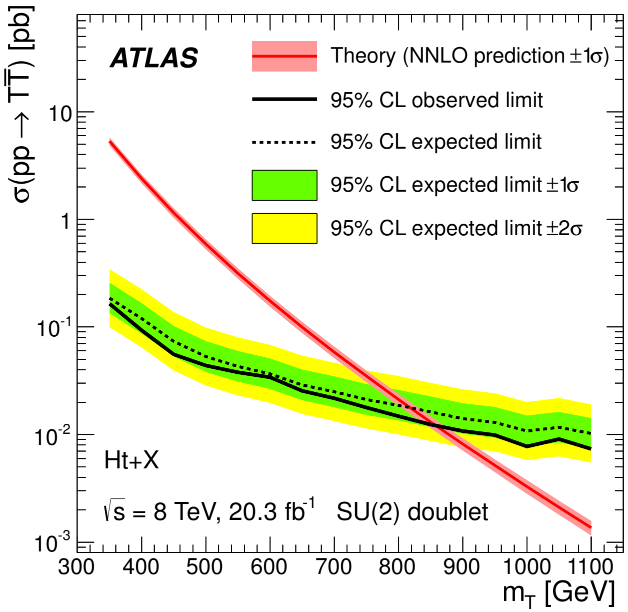
Limits on the $T\bar{T}$ cross-section

Pair VLQs production: limits on $T\bar{T}$

arXiv:1505.04306







- Exclusion @95% CL
- BR(T→Wb=1) case
- obs (exp) limit:
  - m_T >770(795) GeV

- Exclusion @95% CL
- SU(2) singlet case
- obs (exp) limit:
  - m_T > 800(755) GeV
- Combination TT→(Wb+X) & TT→(Ht+X)

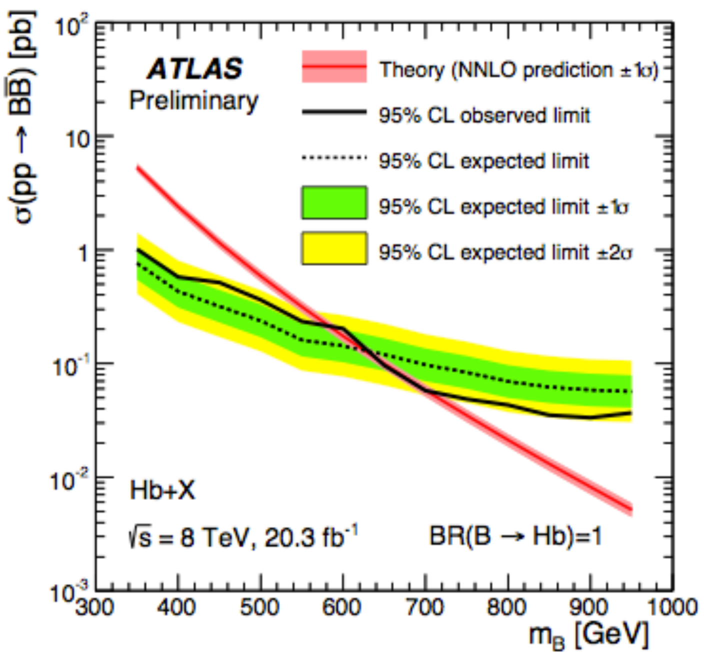
- Exclusion @95% CL
- SU(2) doublet case
- obs (exp) limit:
  - m_T > 855(820) GeV

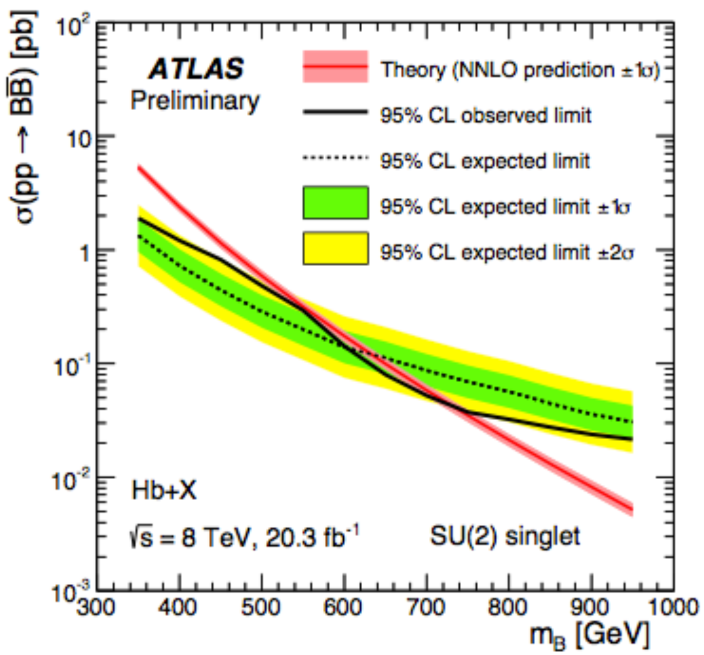
Limits on the $B\bar{B}$ cross-section

Pair VLQs production: $B\bar{B} \rightarrow Hb+X$ & Limits

arXiv:1505.04306

- $BB \rightarrow Hb + X$: same analysis as $TT \rightarrow Ht + X$
- only minor change on p_T leading b-jets (more boosted)





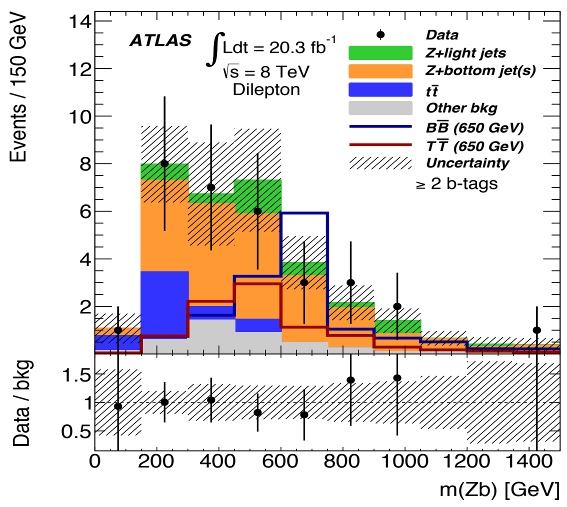
- $BR(B \rightarrow Hb=1)$ case $\rightarrow$ Exclusion @95% CL limit $m_B > 625$ GeV
- SU(2) singlet case $\rightarrow$ Exclusion @95% CL limit $m_B > 635$ GeV

Pair VLQs production: $T\bar{T}/B\bar{B} \rightarrow Z(t/b)+X$

***JHEP* 11 (2014) 104**

Event selection

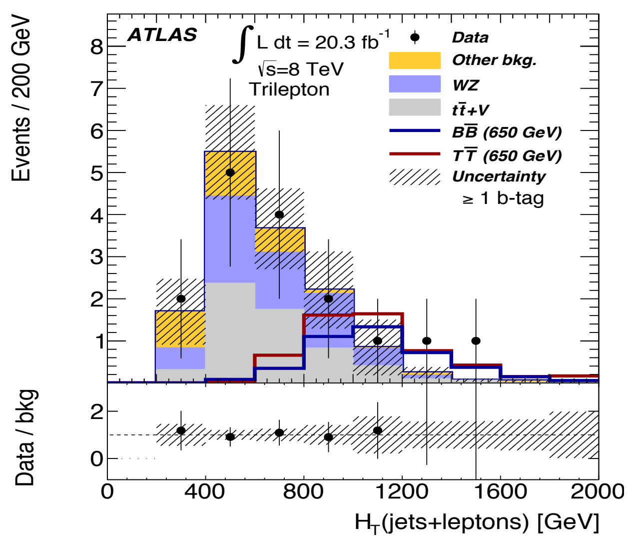
- Single e or μ trigger (24 GeV)
- At least e^+e^- or $\mu^+\mu^-$ with $|m_{\ell^+\ell^-} - m_Z| < 10$ GeV, $p_T(\ell^+\ell^-) \geq 150$ GeV
- At least 2 central jets
- Two channels:
  - **dilepton** (exactly 2 leptons), at least 2 b-tagged jets
  - **trilepton** (at least 3 leptons), at least 1 b-tagged jet



→ targets also single VLQ production: **forward jet requirement**

→ di-lepton: targets Z decays, T→Zt, B→Zb, observable **m(Zb)**

→ tri-lepton: targets multi-boson final states (W, Z, H), observable **H_T**



Pair VLQs production: $T\bar{T}/B\bar{B} \rightarrow Z(t/b)+X$
Limits on $T\bar{T}$ & $B\bar{B}$

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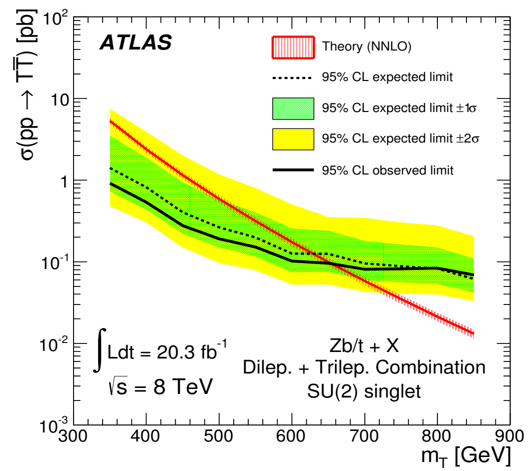
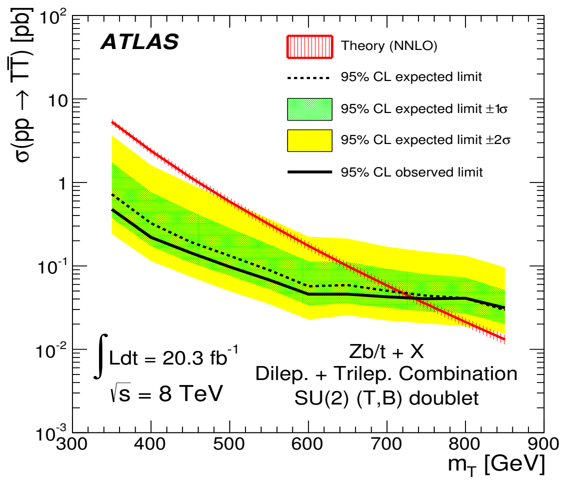
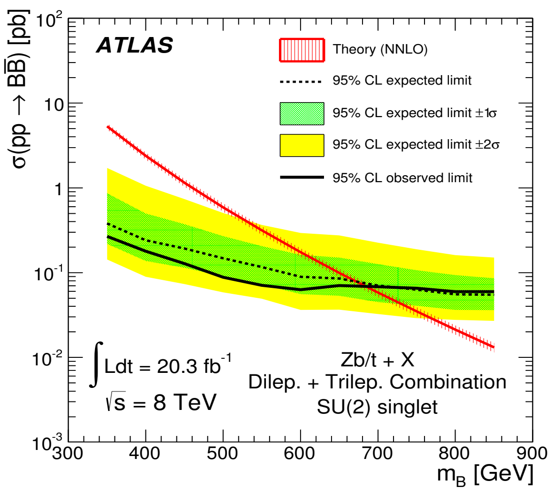
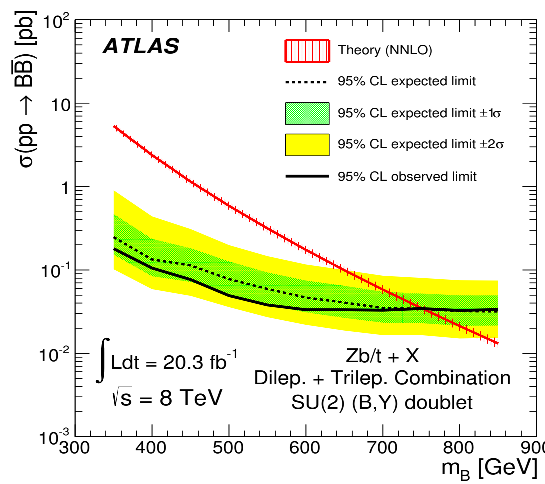




- Exclusion @95% CL limit
- $T\bar{T}$ singlet/doublet excluded to
  - **655/735 GeV**





- Exclusion @95% CL limit
- $B\bar{B}$ singlet/doublet excluded to
  - **685/755 GeV**

Single VLQs production: T/B→Z(t/b)+X

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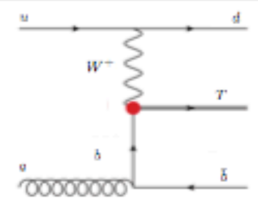
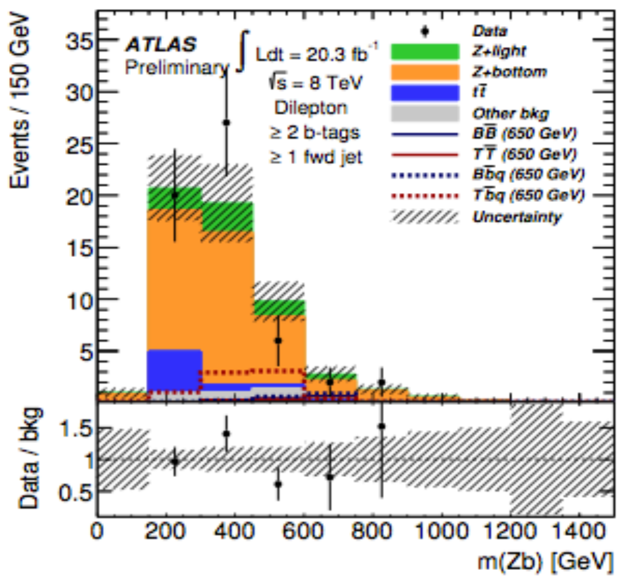
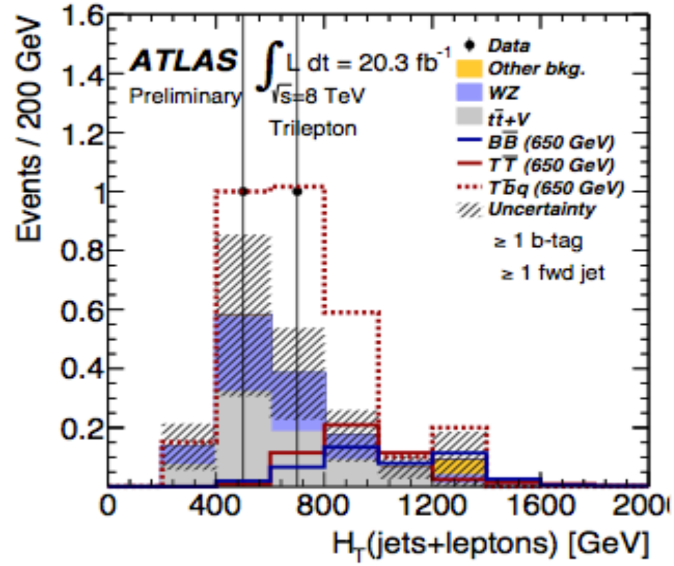
Single production: discriminating variables



Dilepton



Trilepton



Not sensitive to $B\bar{b}q$

At least 1 forward jet

Single VLQ production: limits on T & B

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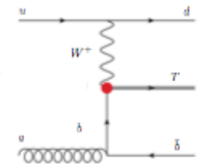
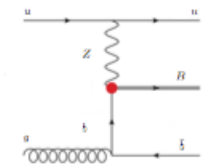
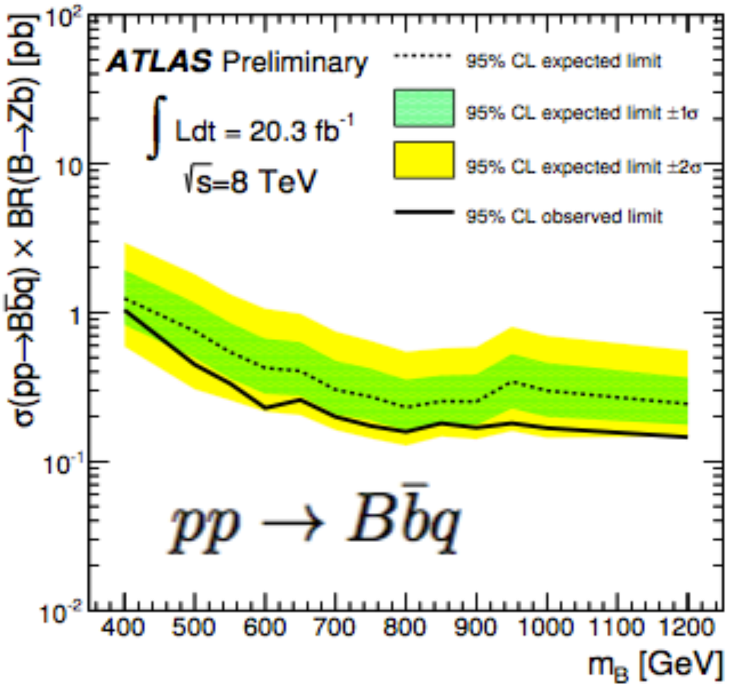
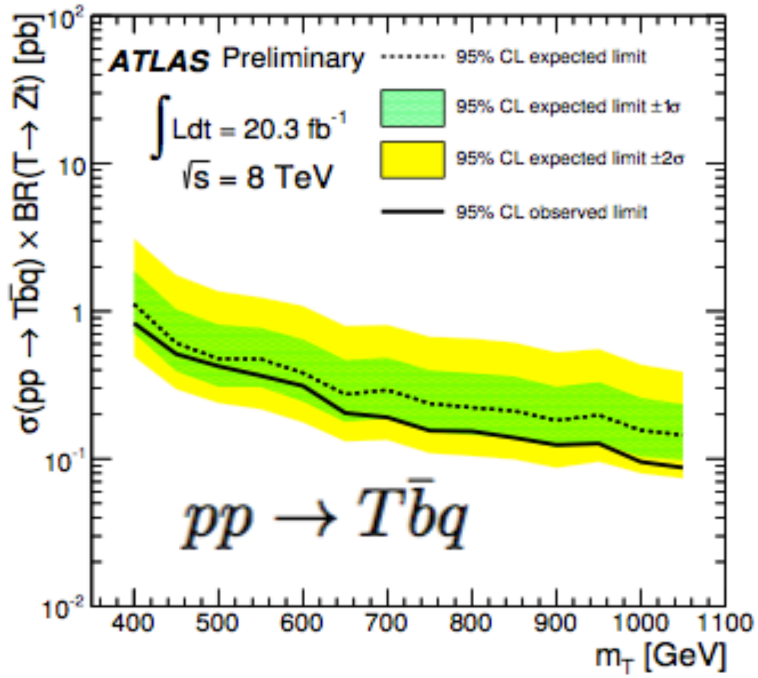




- First LHC cross section limit on single VLQ production
- Sensitivity not sufficient to constrain electroweak couplings TWb & BZb
  - **Single VLQ not quite yet competitive with pair production**





Pair VLQs production: $B\bar{B} \to Wt+X$

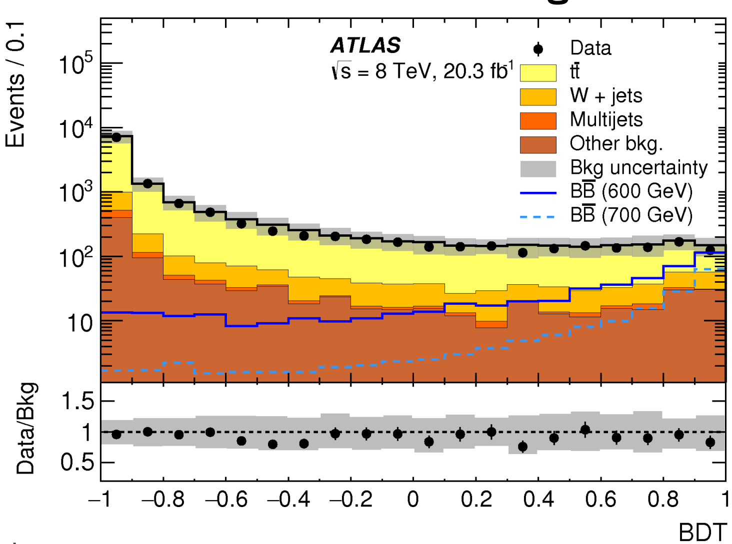
Phys. Rev. D 91, 112011 (2015)

- **Event selection**
  - 1 lepton (e, μ), E_T^{miss}, jets
  - **categories**: N jets, N hadronic W/Z, N b-jets, H_T
  - **BDT** with 12 variables, most discriminating:
    - H_T, ΔR (lep, b-jet 1), M_T(W lep)

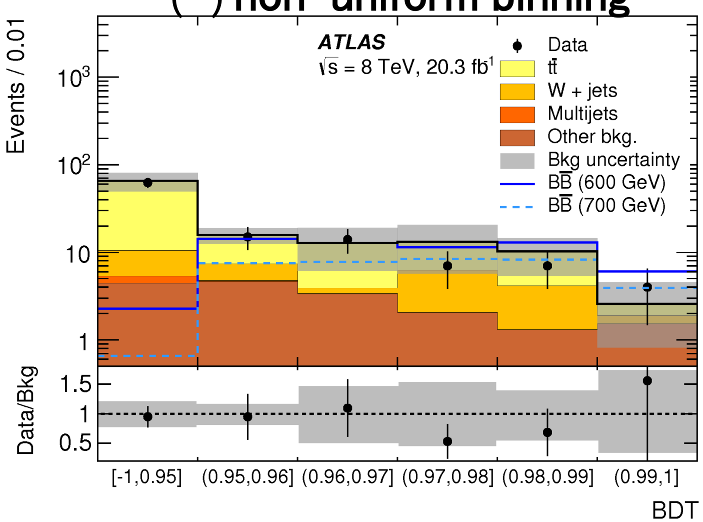
- BDT **cross-checked**
- With **cut-based analysis**

- **The output of the BDT is shown for the two different signal categories:**

Uniform binning



(*) non-uniform binning

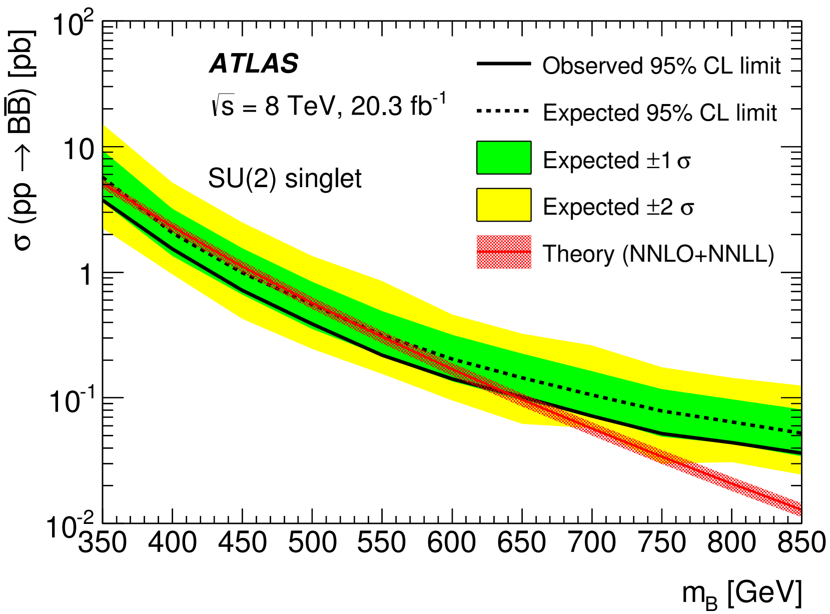


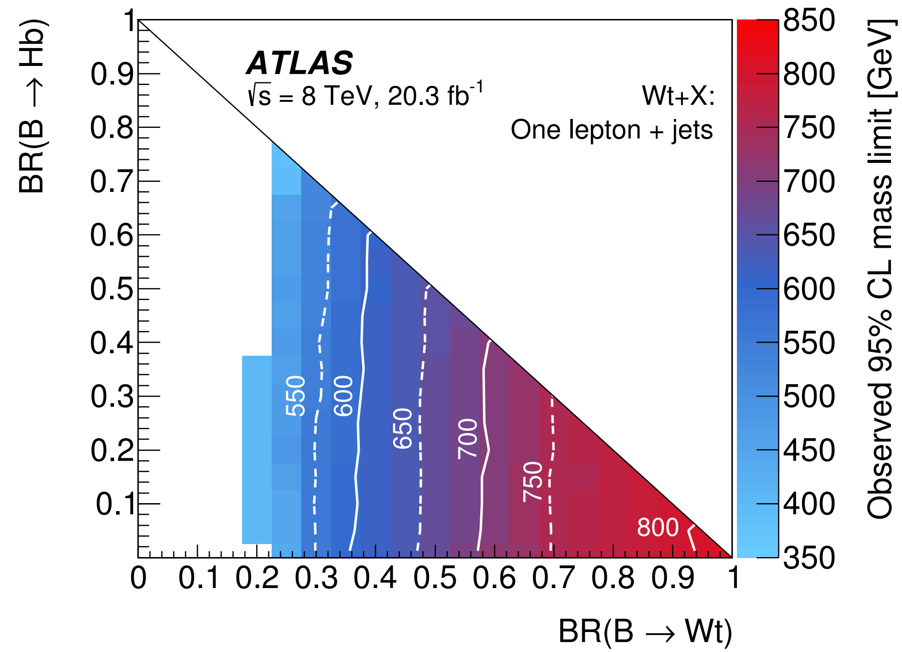
(*) Used to determine the final exclusion limits

Pair VLQs production: $B\bar{B} \rightarrow Wt+X$

Limits on $B\bar{B}$

Phys. Rev. D 91, 112011 (2015)





- Exclusion @95% CL limit
  - SU(2) singlet case
  - observed (expected) limit:
    - m_B > 640 (505) GeV

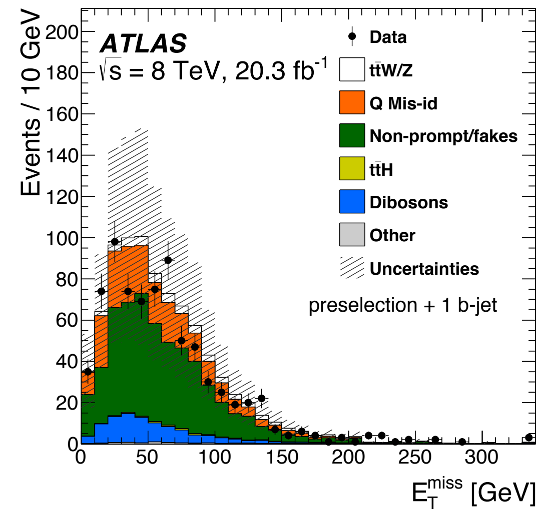
- Best sensitivity in bottom-right corner where BR(B → Wt)=100%
  - Exclusion @95% CL limit
  - observed (expected) limit:
    - m_B > 810 (760) GeV

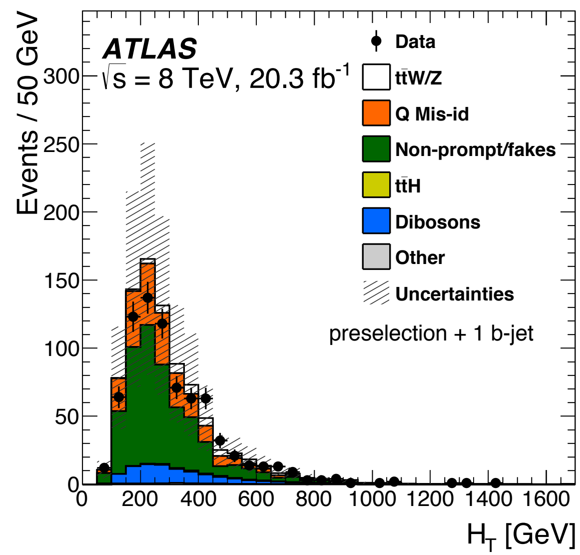
Same−sign dileptons and b−jets

arXiv:1504.04605

- Very small cross section in the Standard Model
- **Exotic Models:**
  - Pair production of chiral *b′* quarks
  - Pair production of VLQ
  - 4 top quark production
  - Same-sign top quark production
- **Pre-selection:**
  - 2 same flavor leptons with same electric charge
    $m_{ll} > 15$ GeV, Z veto $|m_{ll} - m_Z| > 10$ GeV
  - ≥ 2 jets and ≥ 1 b-tag

- Selection optimized for different signal regions
  - event categories based on H_T, N b−jets, E_{miss}
- **~2 σ excess** in categories with large H_T

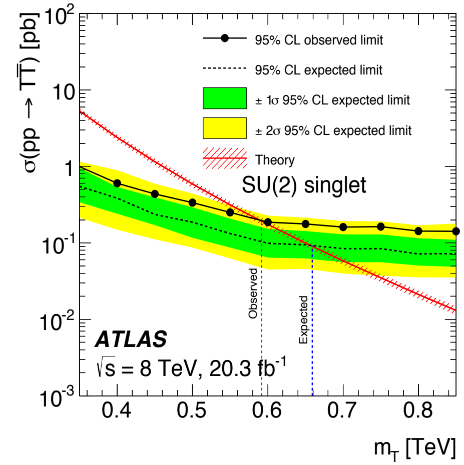




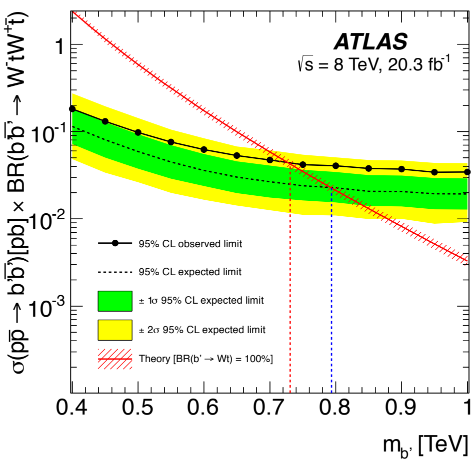
Same-sign dileptons and b-jets Exlusion limits for Different Signals

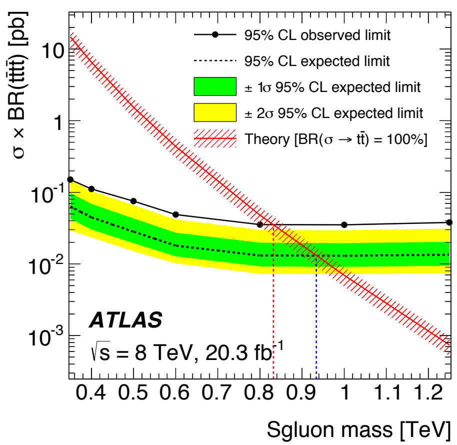
arXiv:1504.04605

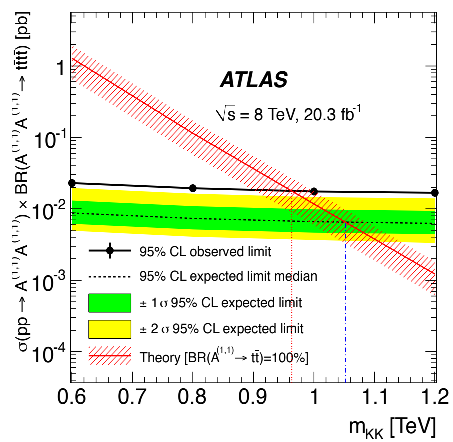
- Absence of any significant data excess in the H_T spectra
- Interpretation of several new physics models

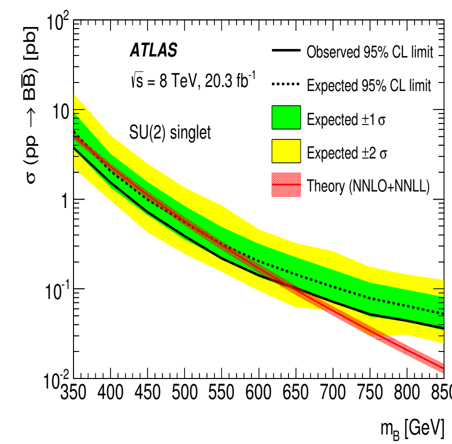


- Exclusion @95% CL limit
  - m_B >0.62 TeV
  - m_T >0.59 TeV
- Exclusion @95% CL limit
  - $m_{b'}$ > 0.73 TeV
  - m_{Sgloun} > 0.83TeV
  - m_{KK} > 0.96TeV





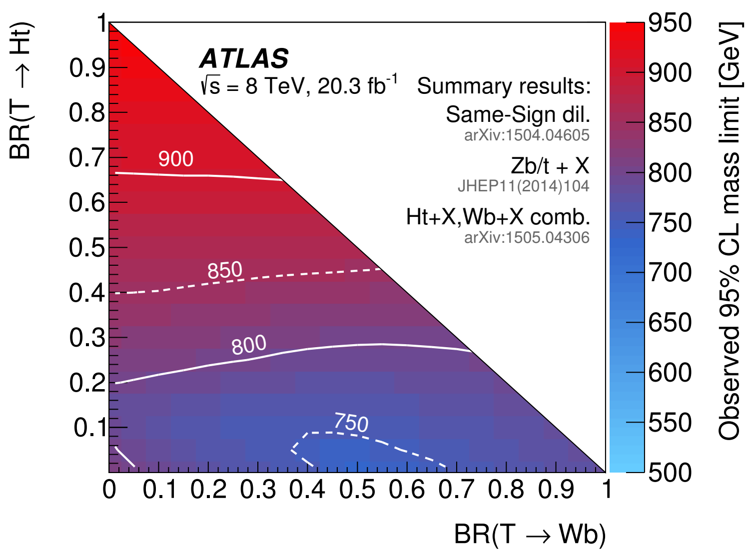




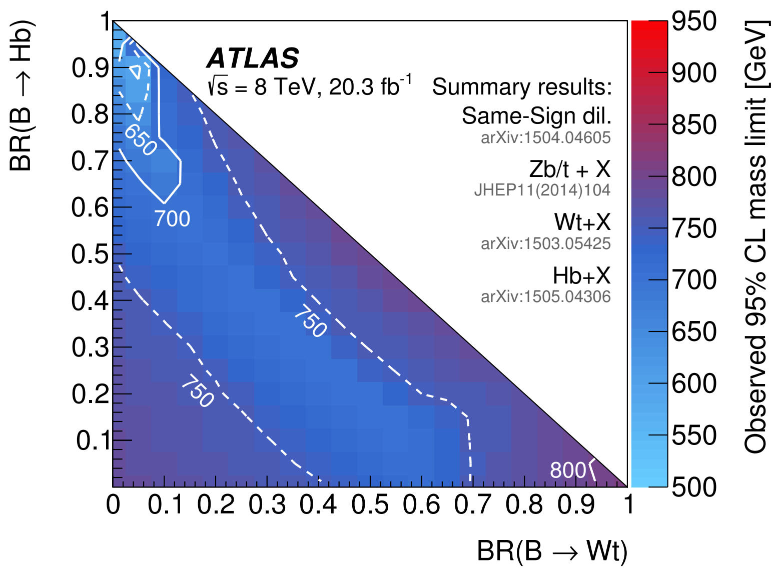
Pair VLQs production: generic limits

arXiv:1505.04306

- **Exclusion @95% CL limit**
  - Expected: 715–885 GeV
  - Observed: 730–950 GeV



- **Exclusion @95% CL limit**
  - Expected: 615–800 GeV
  - Observed: 575–813 GeV



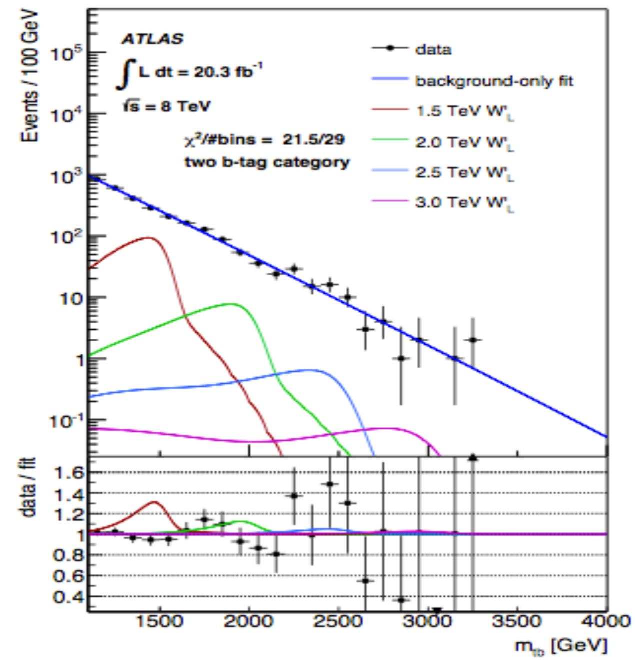
- Lower mass limits for individual limits from most restrictive searches
- Best sensitivity in upper-left corners where BR(T → Ht)=100%

W' resonances

Search for $t\bar{b}$ resonances

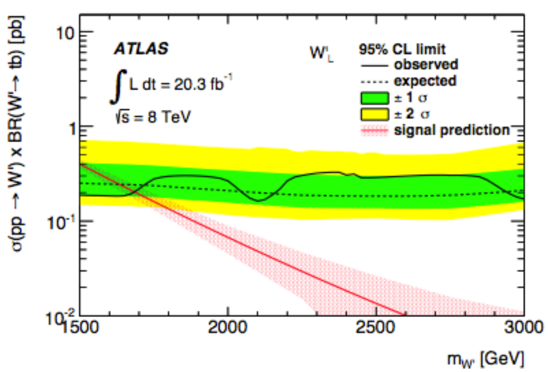
Eur. Phys. J. C (2015) 75:165; Physics Letters B 743 (2015) 235-255

- Full hadronic analysis
  - Target: $W' \to t(\to q\bar{q}'b)\bar{b}$ in the range [1.5,3] TeV
  - Decay of **boosted** top $\Rightarrow$ use of **large-R jets**
  - Two channels:
    - **one b-tag** (no additional b-tagged jet)
      - background: 99% multijet
    - **two b-tag** (one additional small-R b-tagged jet inside top-tagged jet)

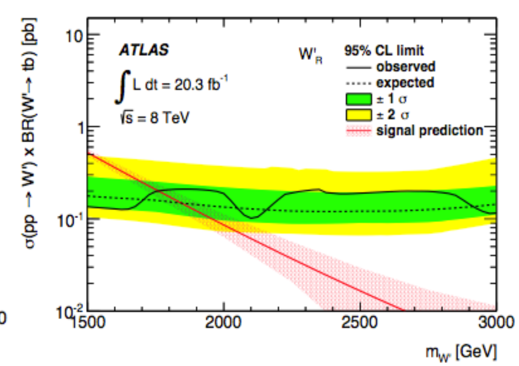


- Unbinned likelihood fit on m(tb)
- Background estimation fully from data
  - Exclusion @95% CL limit
  - $m_{W'_L} > 1.68$ TeV
    $m_{W'_R} > 1.76$ TeV
- Lepton+jets analysis
- *Phy. Lett. B 743 (2015) 235–255*

Left-handed



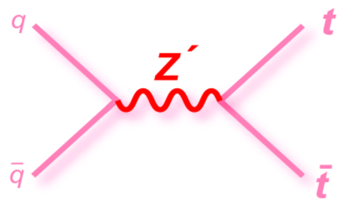
Right-handed



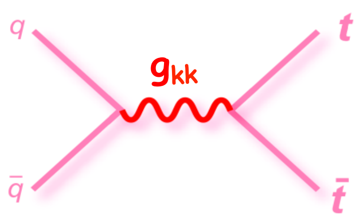
Search for ttbar resonances (lepton + jets)

$t\bar{t}$ resonances

- **Two theoretical benchmarks to quantify sensitivity:**
  - Narrow resonance (topcolor, leptophobic (Z'))
    - $\Gamma_{Z'}/m_{Z'}$=1.2% (or 1%) with K factor 1.3 [EPJ C72 (2012) 2072]



  - Broad resonance (Kaluza-Klein (KK) gluons) from Randall Sundrum
    - Γ_{ggKK}/m_{gKK}=15.3% (10-15%) with no K factor



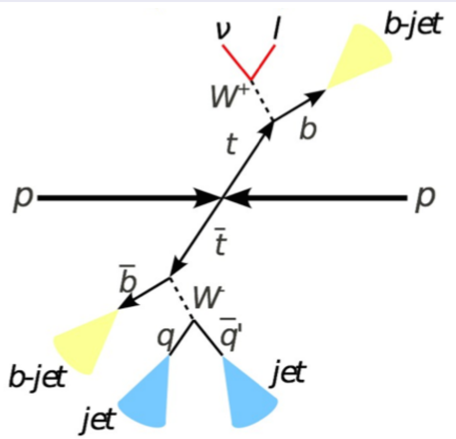
- Search for enhancement in the invariant mass ttbar spectrum

$t\bar{t}$ resonances

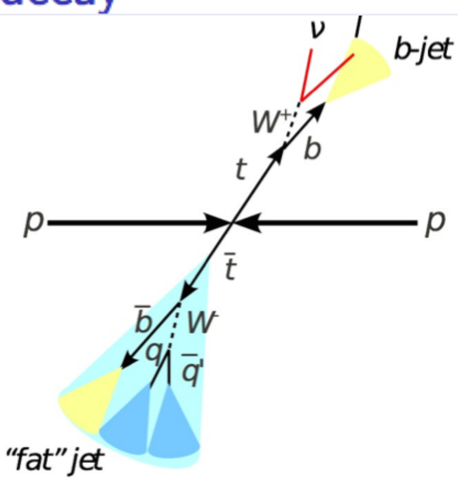
arXiv:1505.07018; accepted by JHEP

- **Analysis strategy**
  - The top pairs may decay in two main topologies: well separated jets and leptons, or boosted jet topologies → combined for limit setting.

A resolved top → *Wb* decay



A boosted top → *Wb* decay

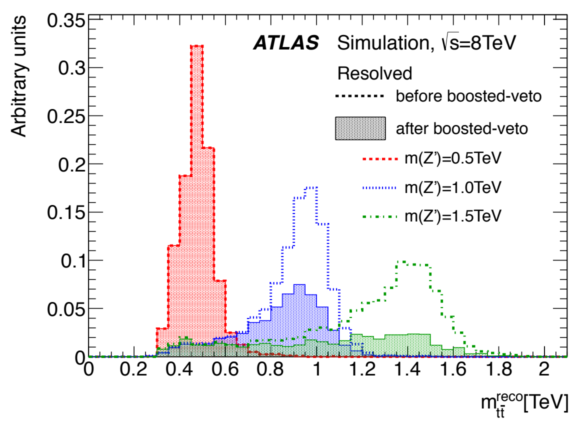


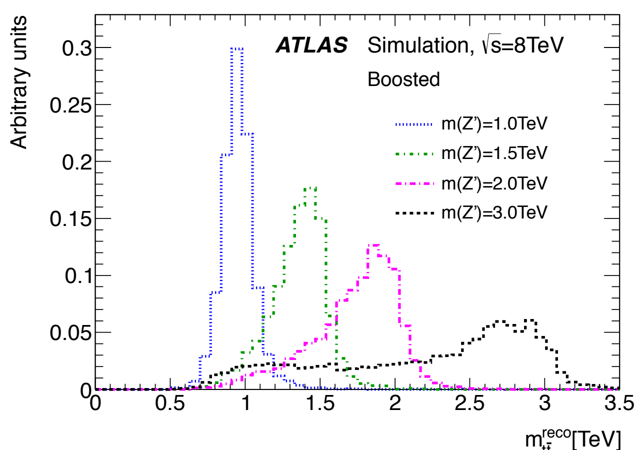
Two separate analyses for different topologies

Search for $t\bar{t}$ resonances

arXiv:1505.07018; accepted by JHEP

- Single-lepton (e/ μ) final state
- **Resolved + boosted selections**
  - **Resolved:** Reconstruct tt with l+MET+4 small radius jets (R=0.4); Choose kinematically best combinatorics
  - **Boosted:**
    - Leptonic top = l +MET + nearby small radius jet (R=0.4)
    - Hadronic top = large radius jet (R=1.0) with high mass, hard substructure



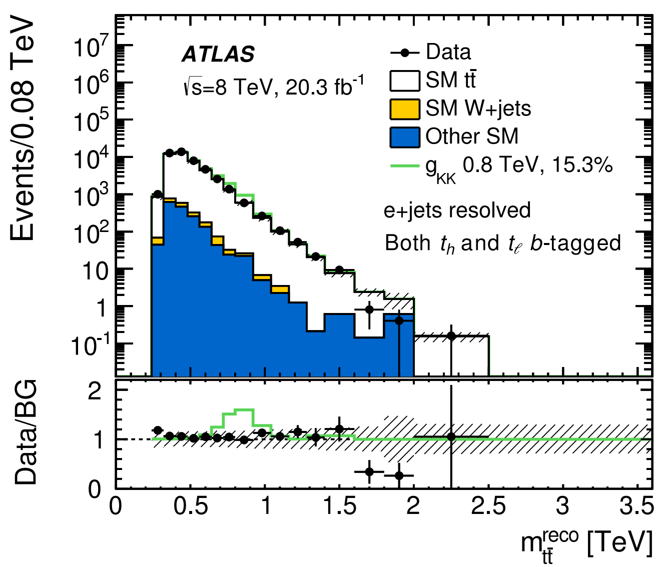


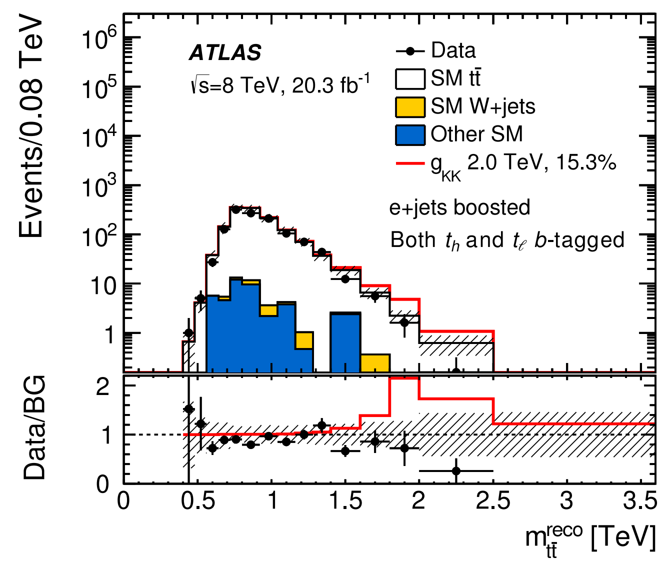
- **Boosted selection attempted first;**
- Events that fail the boosted selection are examined using the resolved selection

Search for $t\bar{t}$ resonances

arXiv:1505.07018; accepted by JHEP

- Focus on invariant mass spectrum (m_{tt})
- Combine 12 m_{tt} event categories
  - 3 b–tag categories for 2 selections and for 2 decay channels
    - b–tag: leptonic side/hadronic side/both
    - resolved/boosted regime
    - lepton channel (e/ μ)

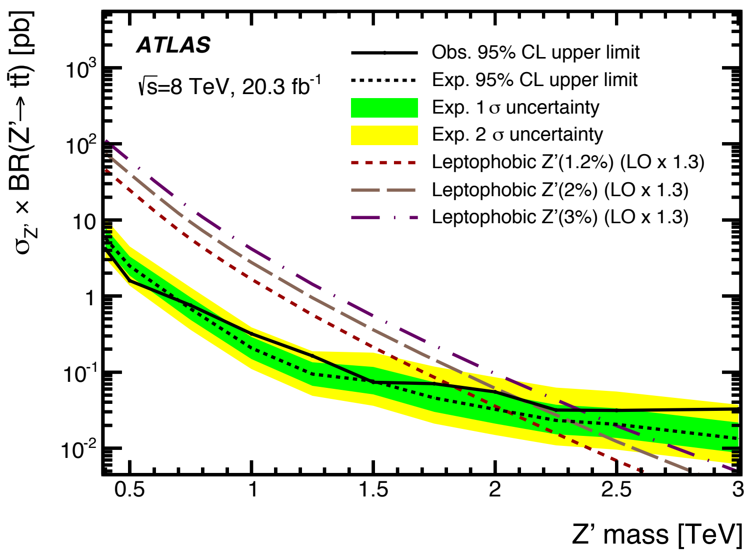


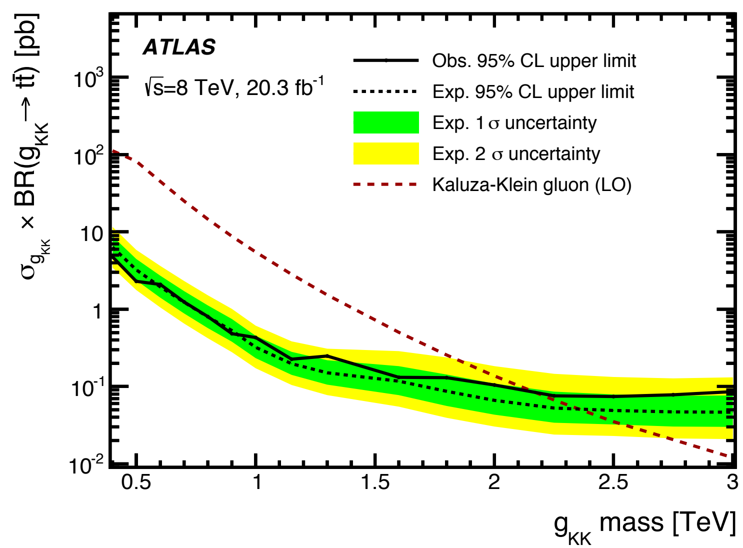


Search for $t\bar{t}$ resonances: results

arXiv:1505.07018; accepted by JHEP

- *No significant deviation* from the expected background is found
- Upper limits on the $\sigma_{Z'} \times BR(Z' \to t\bar{t})$ and $\sigma_{KKg} \times BR(KKg \to t\bar{t})$





- Exclusion @95% CL limit
- $m_{Z'} > 1.8$ TeV
  - (narrow leptophobic)

- Exclusion @95% CL limit
- $mg_{kk} > 2.2$ TeV
  - (Randall–Sundrum KK model)

Summary & outlook

- No hints of new physics yet!!!
- Recent results with 2012, 8TeV data are presented
- All results consistent with Standard Model so far
- Limits are set for new physics models/particles

- Exiting perspective
- LHC physics reach at TeV mass scale is greatly extended by the increased beam energy and intensity of Run 2

- ATLAS has been doing great…
  - Very competitive analyses in Exotica searches

Acknowledgements:

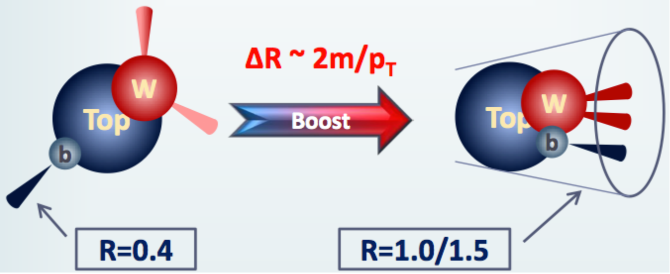
- We acknowledge the support of the Spanish R&D project of reference FPA2013-47424-C3-1-R

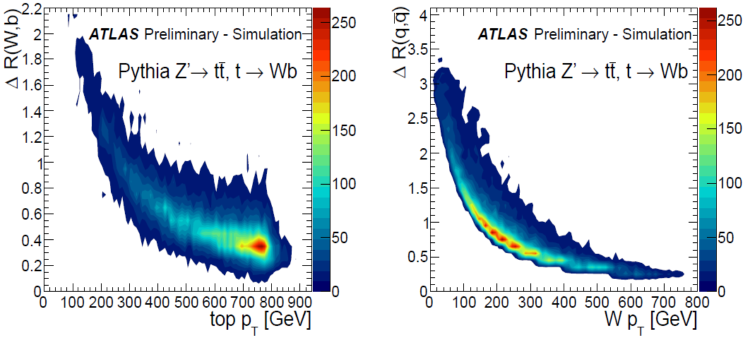
BACKUP

Top quarks in BSM searches

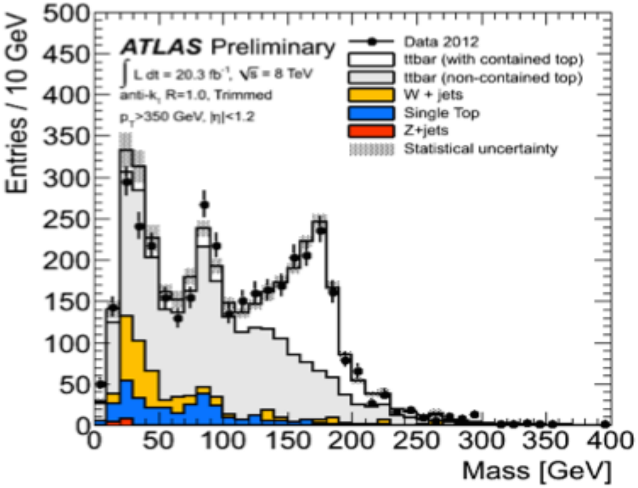
ATLAS-CONF-2013-084

- LHC searches entering TeV–scale: "Boosted" top quarks from BSM signals
  - Decay products of Boosted Tops collimated in direction of p_T
  - Separation can be described according to $\Delta R \approx m/p_T$





(a) $t \to Wb$ ATLAS-CONF-2012-065 (b) $W \to q\bar{q}$



- Efficient hadronic top tagging;
  - Large–radius jet as top candidate
    - Less combinatorics backgrounds
- Jet substructure can be exploited for powerful discriminants

Run-2 results so far

- Run 2 physics results:
  - limited dataset (<100 pb-1)
  - only a few weeks to "look" at data
  - mostly "retuning" searches for higher energies
  - no complete searches yet
  - higher energy extends mass range:
  - sensitivity soon competitive (for some searches)

Pair VLQs production: TT→Wb+X

arXiv:1505.04306

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 ≥ 4 jets, ≥ 1 b-tagged jets
Loose selection	Preselection ≥ 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]

Table 1: Summary of event selection requirements for the $T\bar{T} \rightarrow Wb$+X analysis (see text for details).