



ATLAS Searches with Boosted Tops

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on behalf of the ATLAS collaboration

20.08.2014

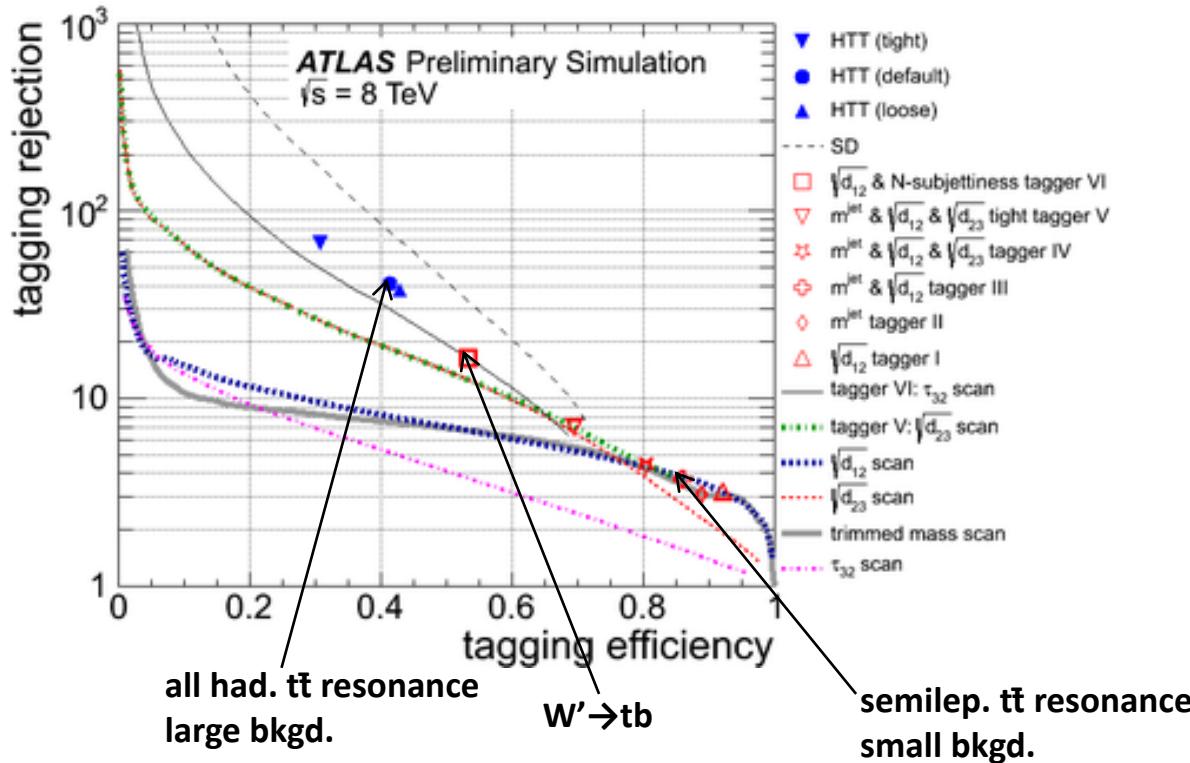
Outline

- Introduction
- Search for $t\bar{t}$ resonances
 - All-hadronic channel
 - Semi-leptonic channel
- Search for $W' \rightarrow tb$
- Search for direct $\tilde{t}_1 \tilde{t}_1$ production
 - 0-lepton channel
 - 1-lepton channel
- Summary

Introduction

- Top quarks and new physics
 - Large mass => special role in EWSB sector
 - Many BSM models predict final states with top quarks from decays of heavy states
 - Top quarks emerge in **boosted** states when these states at TeV-scale
- Searches with boosted top quarks
 - Extend reach to higher energy scales
 - Simplify object reconstruction in busy, multijet final states
 - e.g. all-hadronic $t\bar{t}$, tb resonances

Boosted Top Quark Tagging



- Choice of tagger highly dependent on analysis
 - Level of background contamination
 - Type of background
 - QCD jets, other boosted objects

Search for $t\bar{t}$ Resonances

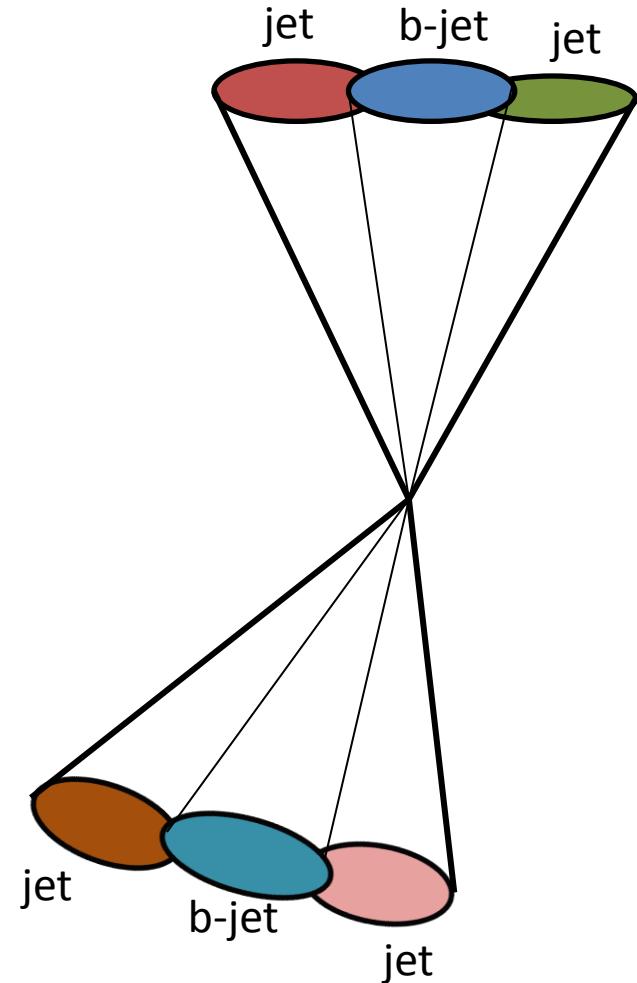
- 7 TeV search in all-hadronic channel
- 8 TeV search in semi-leptonic channel

Search for $t\bar{t}$ Resonances (All-hadronic)

$\sqrt{s} = 7 \text{ TeV}, \int L dt = 4.7 \text{ fb}^{-1}$

Event Selection

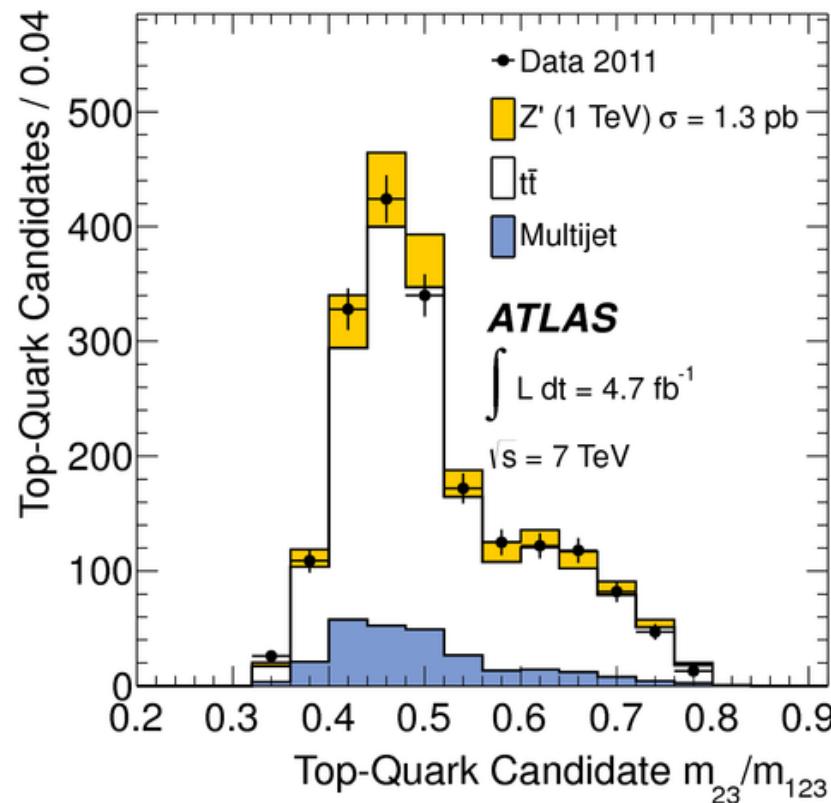
- 2 top-tagged high-pT fat ($R \geq 1.0$) jets
- No good leptons
- Two different top taggers
 - **HEPTopTagger** (moderate pT)
 - **Top Template Tagger** (high pT)
- Match top candidates to b-tagged small-R jets



Search for $t\bar{t}$ Resonances (All-hadronic)

Top Tagging - HEPTopTagger

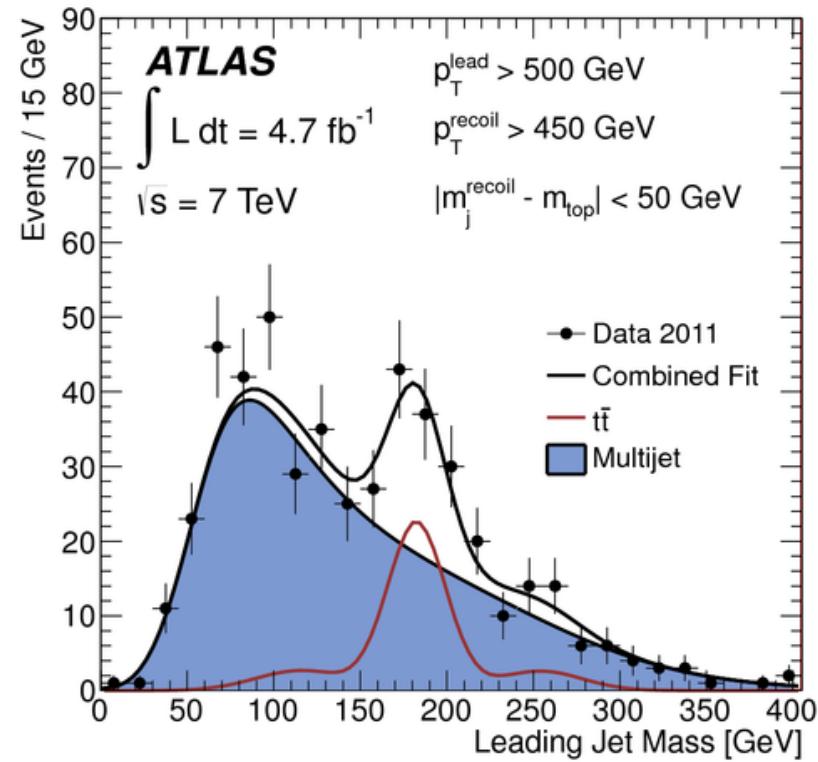
- Cambridge-Aachen R=1.5 jets
 - $pT > 200 \text{ GeV}$
- Decluster jet and try to reconstruct top and W decays from filtered subjets
 - Selection on subjet mass ratios and final candidate mass
- Sensitive to lower pT ($pT \sim 200 \text{ GeV}$) “moderately” boosted top quarks
- Tagging variables well-modelled in Monte Carlo



Search for $t\bar{t}$ Resonances (All-hadronic)

Top Tagging – Top Template Tagger

- Anti- k_T R=1.0 jets
 - $p_T > 450$ GeV
- Match energy flow inside jet to top decay configurations in partonic phase space.
 - Additional cut on pile-up corrected jet mass ($140 < m < 210$ GeV)
- Sensitive at higher top p_T ($>\sim 500$ GeV)
- Validation in data:
 - Observation of top peak in leading jet mass spectrum after tagging recoil jet

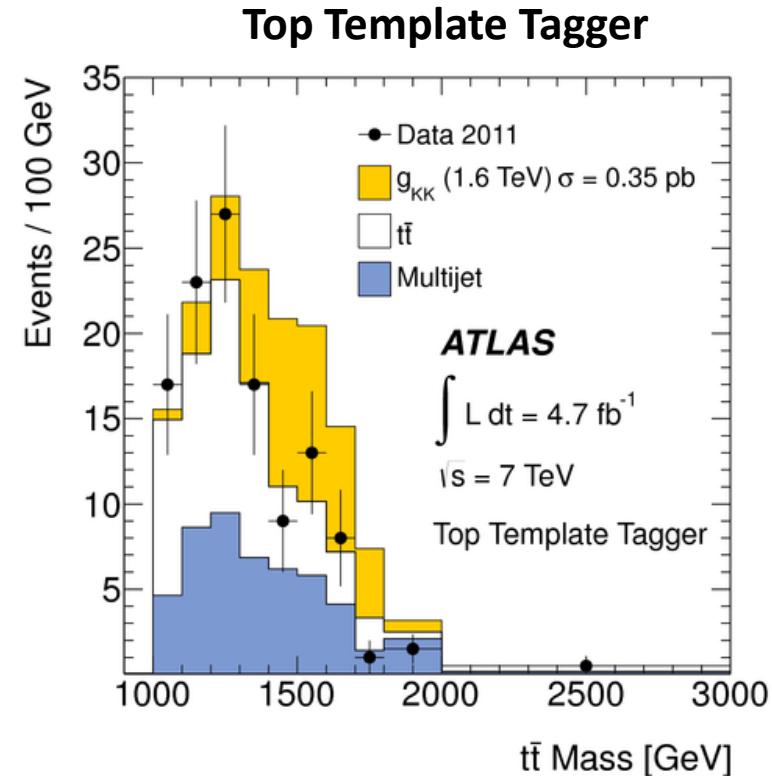
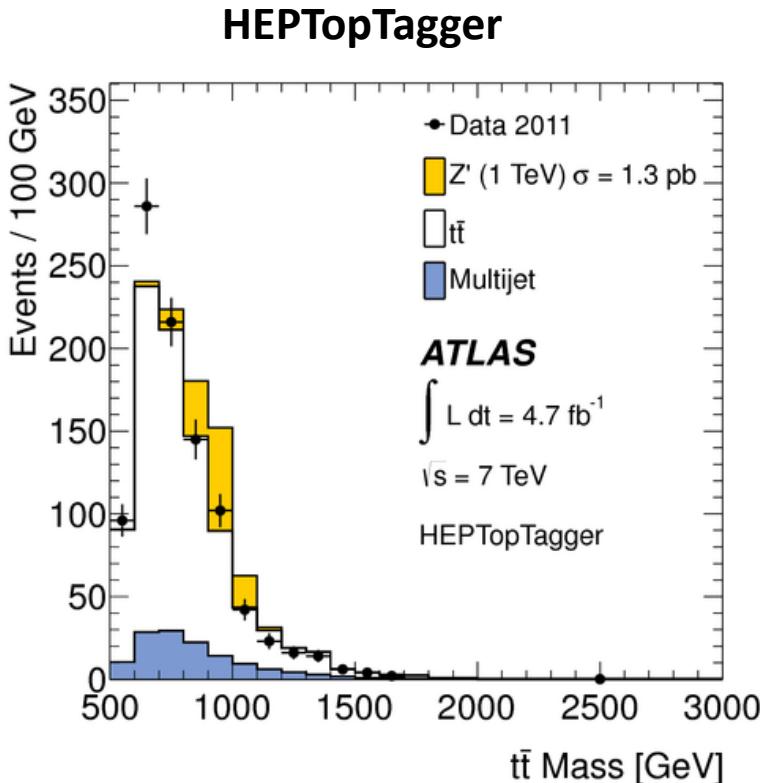


Search for $t\bar{t}$ Resonances (All-hadronic)

- No significant excess in $t\bar{t}$ invariant mass spectrum

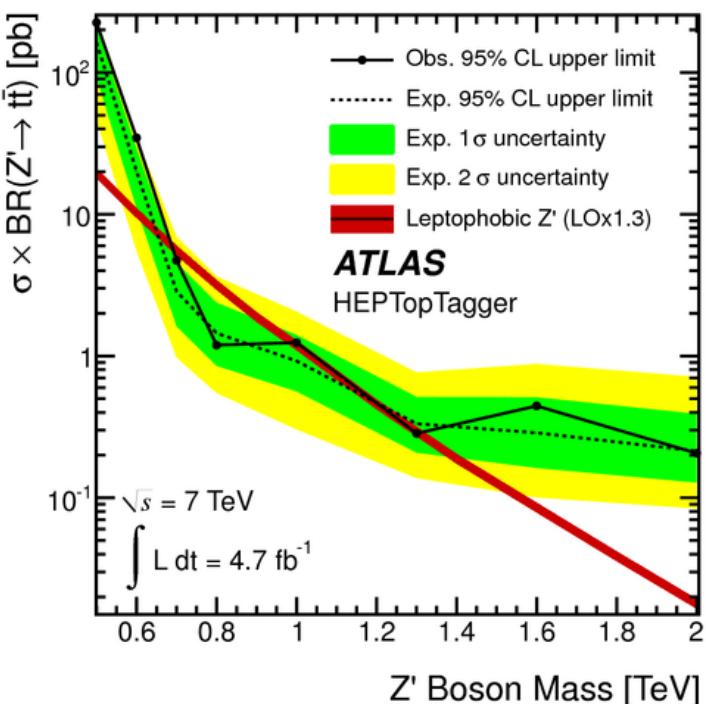
Backgrounds

- SM $t\bar{t}$ (MC simulation + normalisation from data)
- QCD multijet (data sidebands)

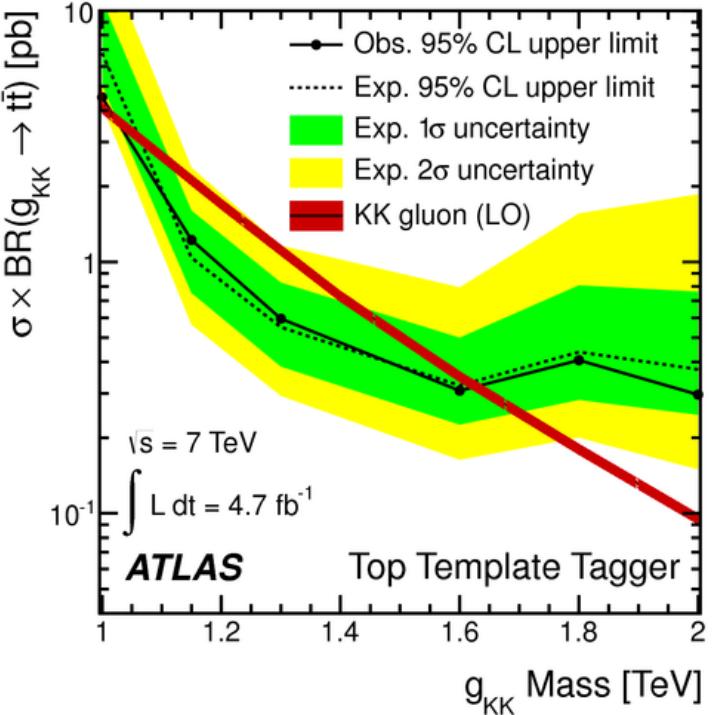


Search for $t\bar{t}$ Resonances (All-hadronic)

- Limit in each mass range set with technique with best sensitivity in that range
 - $M < 1.3 \text{ TeV}$: HEPTopTagger
 - $M > 1.3 \text{ TeV}$: Top Template Tagger
- Observed limits:
 - **0.70-1.00 TeV; 1.28-1.32 TeV (leptophobic Z')**
 - **0.7-1.62 TeV (KK gluon)**



BOOST 2014, London

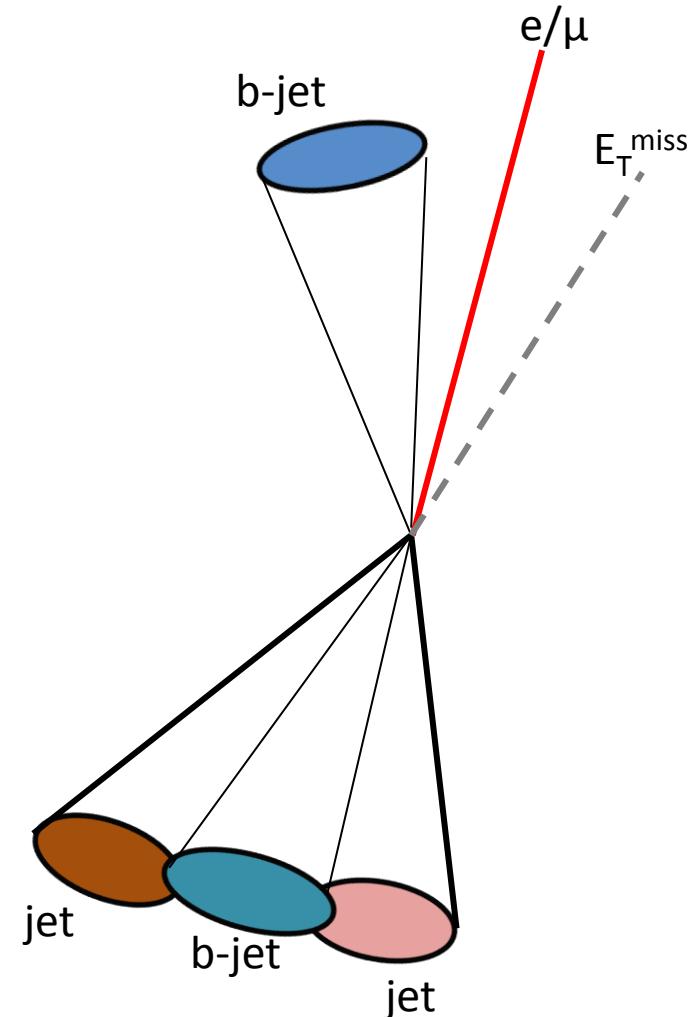


Search for $t\bar{t}$ Resonances (Semileptonic)

Event Selection – Boosted Analysis

- 1 “mini-isolated” lepton with $pT > 25 \text{ GeV}$
- Presence of significant E_T^{miss}
- ≥ 1 b-tagged Anti-kT R=0.4 jet close to lepton
- ≥ 1 Anti-kT R=1.0 trimmed jet; $\Delta\Phi(\text{jet}, \text{lepton}) > 2.3$
 - Top tagging:
 - $m_{\text{jet}} > 100 \text{ GeV}, \sqrt{d}_{12} > 40 \text{ GeV}$

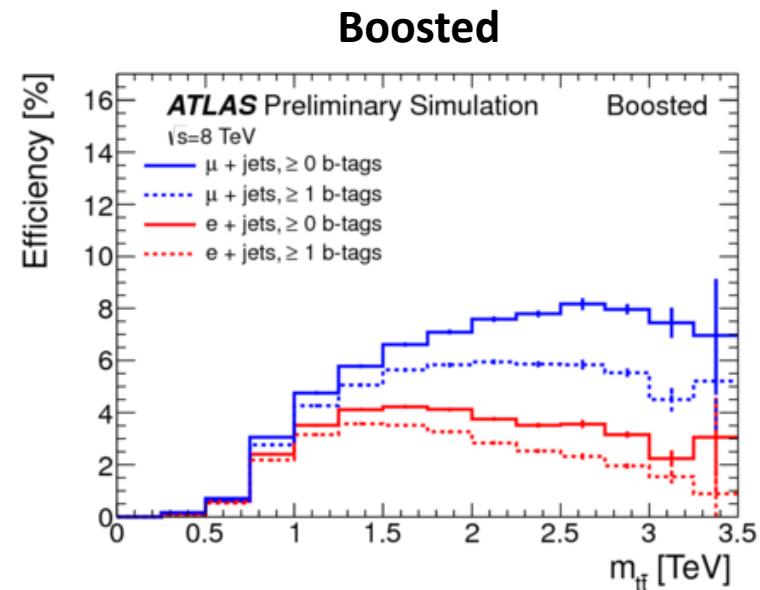
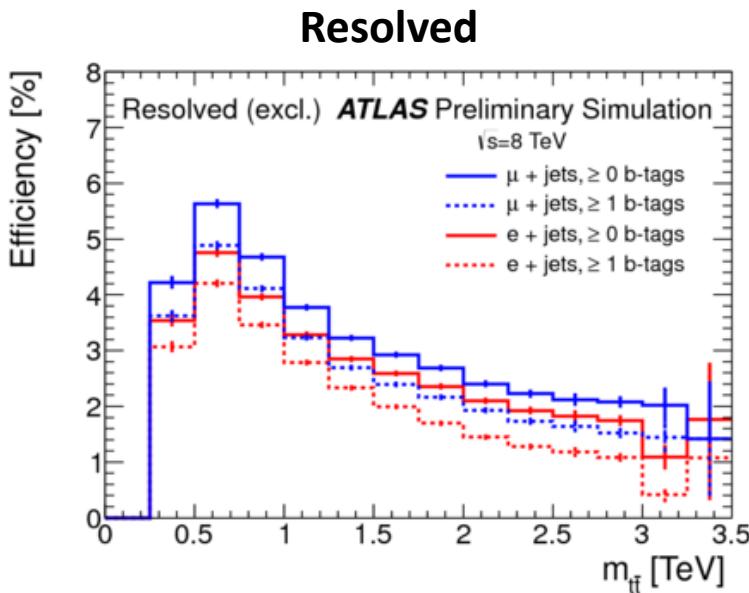
$\sqrt{s} = 8 \text{ TeV}, \int L dt = 14.3 \text{ fb}^{-1}$



- Events failing boosted selection are passed through traditional resolved $t\bar{t}$ selection
- Limits are combined

Search for $t\bar{t}$ Resonances (Semileptonic)

Selection Efficiencies



Boosted selection has higher efficiencies for $M > 1 \text{ TeV}$

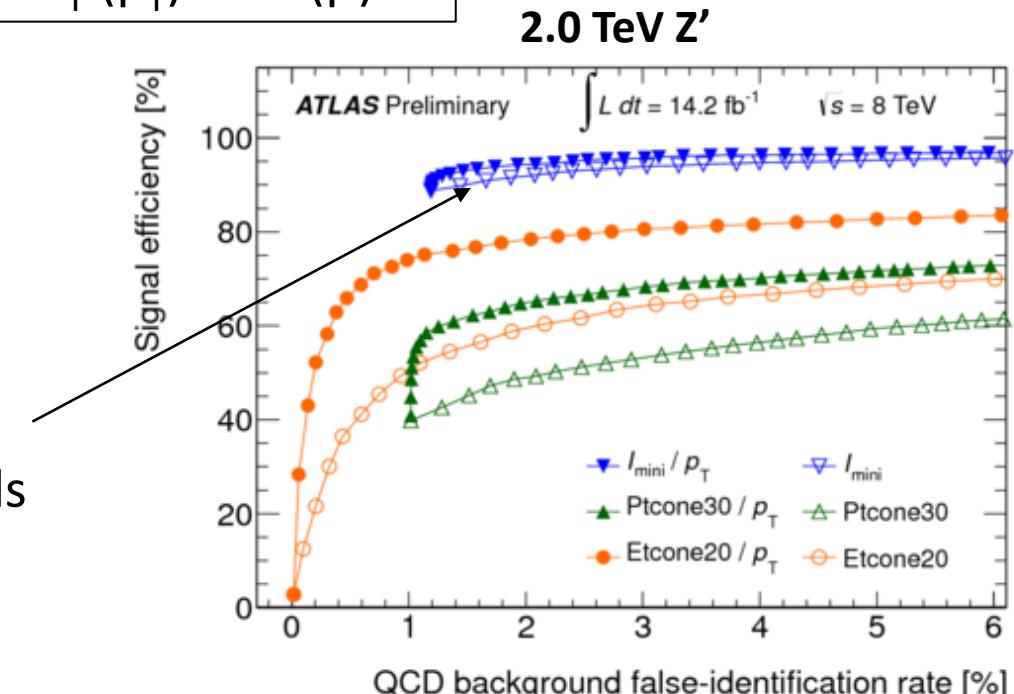
Search for $t\bar{t}$ Resonances (Semileptonic)

Lepton Isolation in Boosted Topologies

- Leptonic top $p_T \uparrow \Rightarrow \Delta R(\text{lepton}, \text{b-jet}) \downarrow$
- Isolation requirement for lepton must vary as function of p_T .
 - “Mini”-isolation $I_{\text{mini}} < 0.05 * E_T(p_T)$ for $e(\mu)$

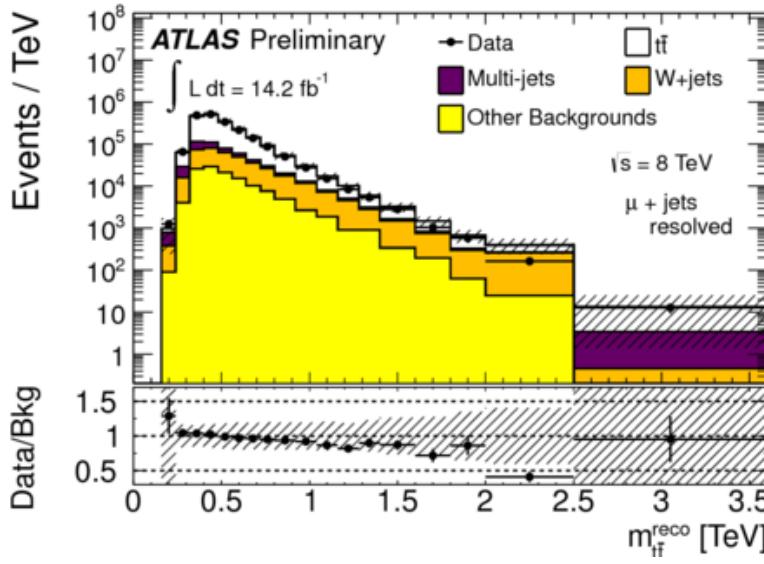
- Significant improvement in efficiency vs. rejection over fixed cone isolation methods

$$\begin{aligned} I_{\text{mini}} &= \sum p_{\text{track}}^T ; \text{track } \notin \text{lepton}; \\ \Delta R(\text{track, lepton}) &< 10 \text{ GeV} / E_T^{\text{lepton}} \end{aligned}$$

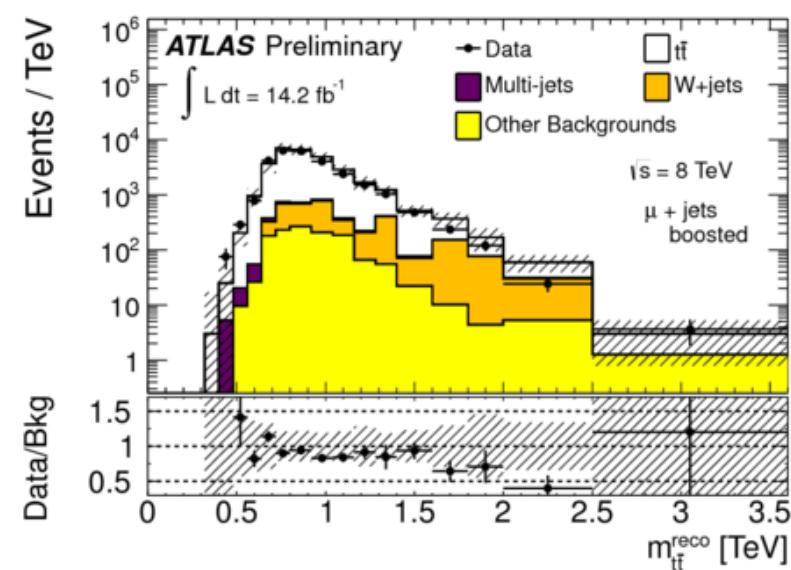


Search for $t\bar{t}$ Resonances (Semileptonic)

Resolved



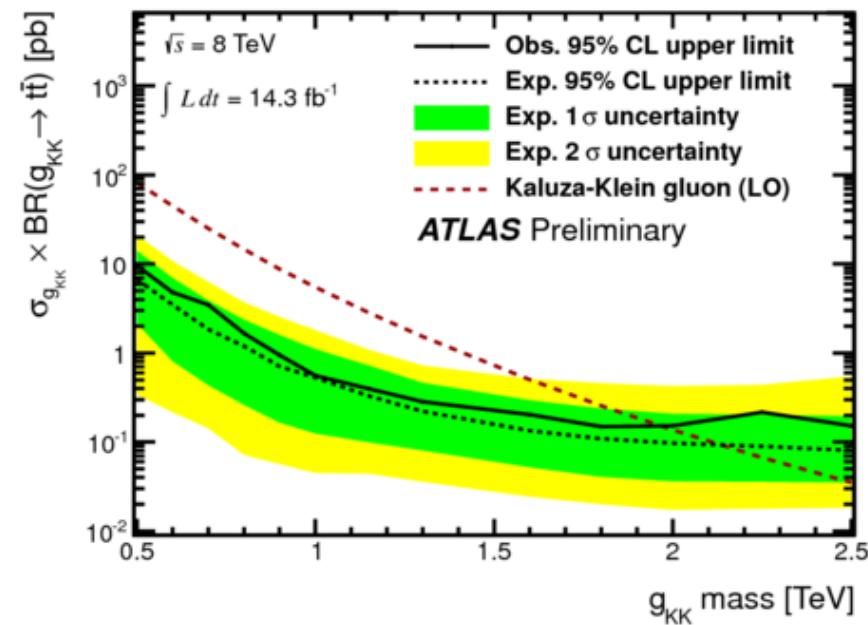
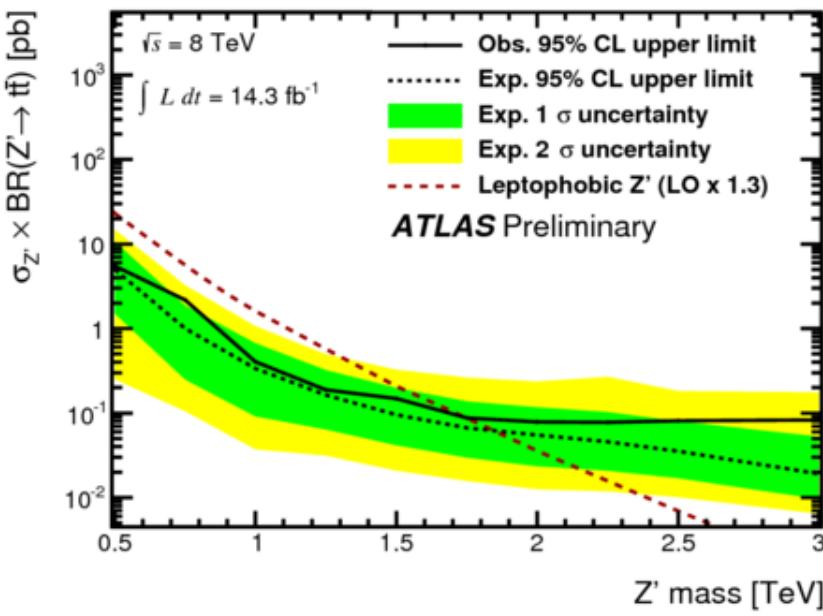
Boosted



- No significant excess in $t\bar{t}$ invariant mass spectrum

Search for $t\bar{t}$ Resonances (Semileptonic)

- Observed limits (boosted + resolved combination):
 - 0.5-1.8 TeV (leptophobic Z')**
 - 0.5-2.0 TeV (KK gluon)**



Search for $W' \rightarrow tb$

$\sqrt{s} = 8 \text{ TeV}, \int L dt = 20.3 \text{ fb}^{-1}$

- Predicted by
 - GUT, technicolour, little Higgs
- Preferential coupling of W' to third generation in some models
- This search : fully hadronic final state
- Sensitive for $m_{W'} > 1.5 \text{ TeV}$

Event Selection

- $H_T^{\text{jets}} > 850 \text{ GeV}$
- Exactly 1 **W' top-tagged** Anti-kT R=1.0 trimmed jet with $pT > 350 \text{ GeV}$
- 1 b-tagged Anti-kT R=0.4 jet with $pT > 350 \text{ GeV}$
- $\Delta R(\text{b-jet, large-R jet}) > 2.0$

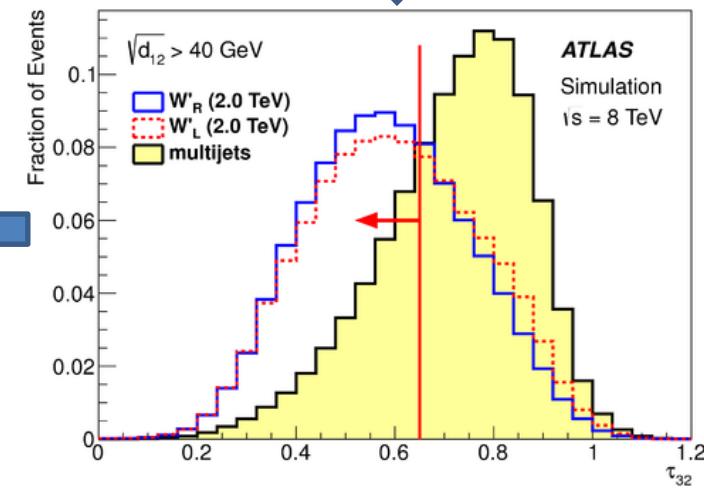
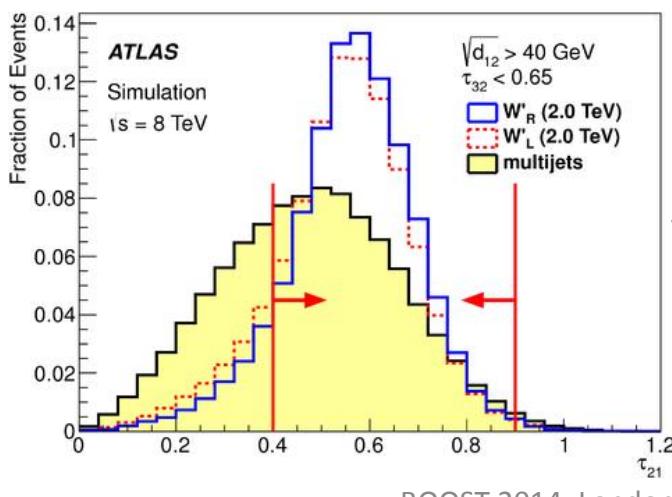
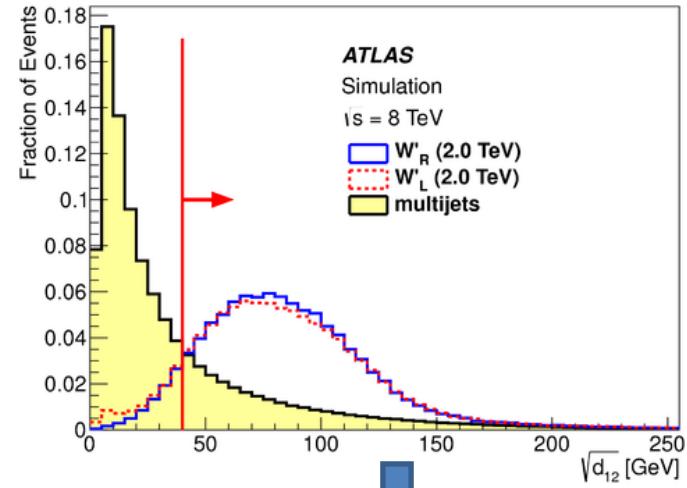
Further classification:

- Additional b-jet with $\Delta R(\text{b-jet, large-R jet}) < 1.0$: **2 b-tag**
- Else : **1 b-tag**

Search for $W' \rightarrow tb$

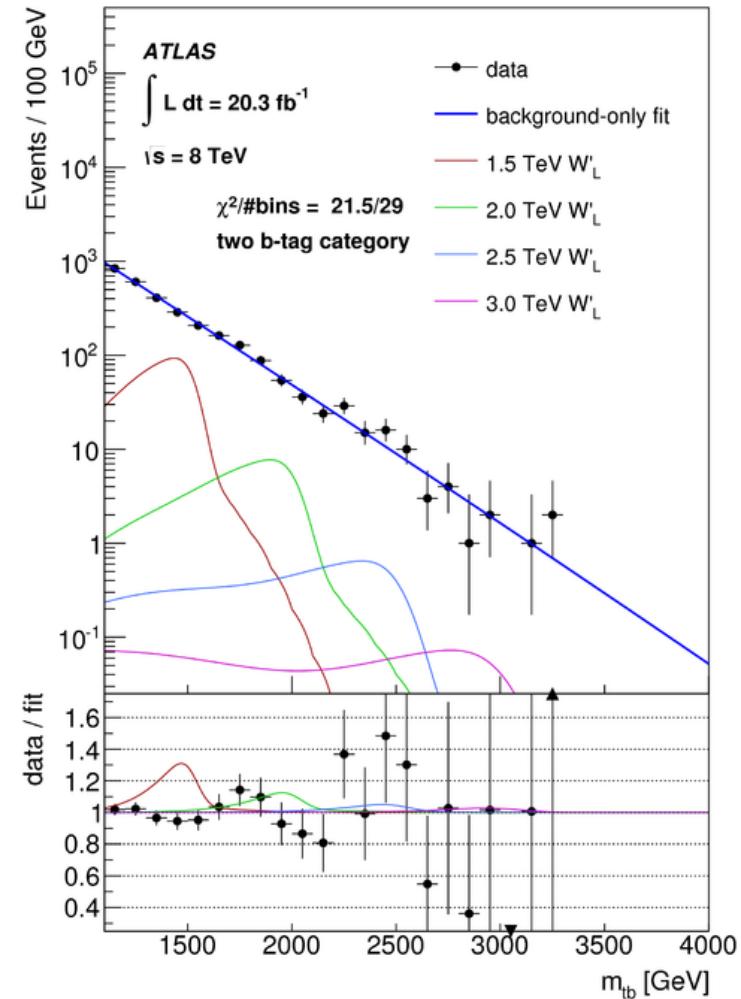
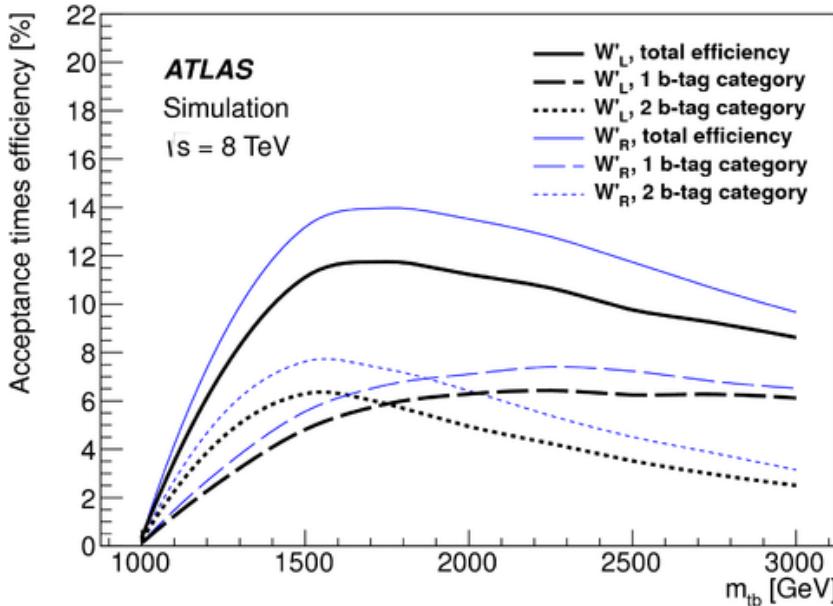
The W' Top Tagger

- Apply set of cuts on jet substructure observables:
 - $\sqrt{d}_{12} > 40$ GeV
 - $\tau_{32} < 0.65$
 - $0.4 < \tau_{21} < 0.9$
- Selects jets with symmetric splittings and 3-pronged substructure
- Top-tagging efficiency > 0.5 for $pT > 500$ GeV
- Fake rate < 0.1



Search for $W' \rightarrow tb$

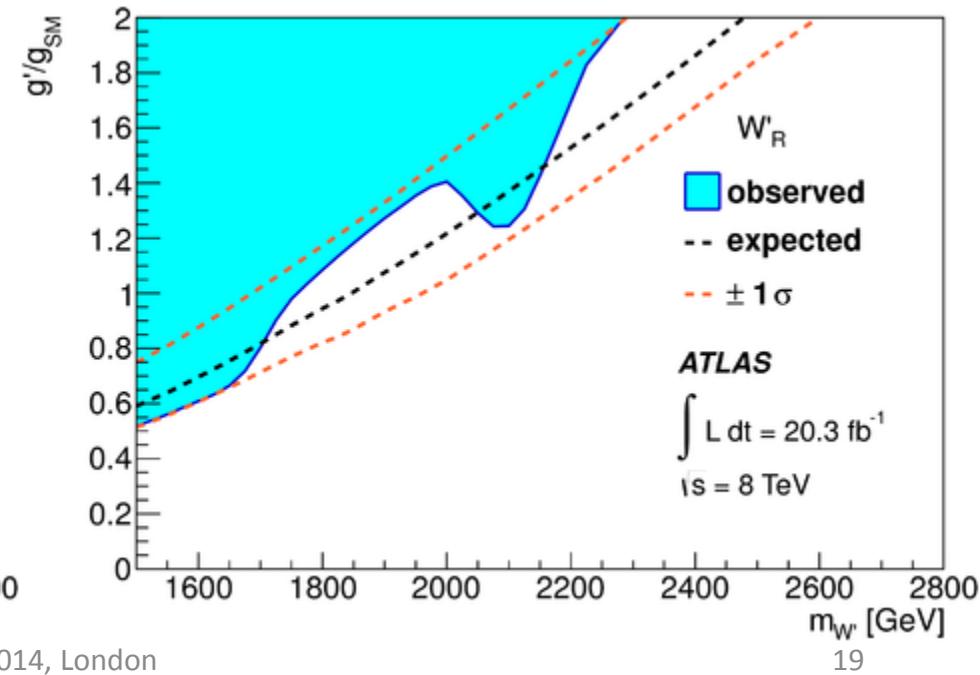
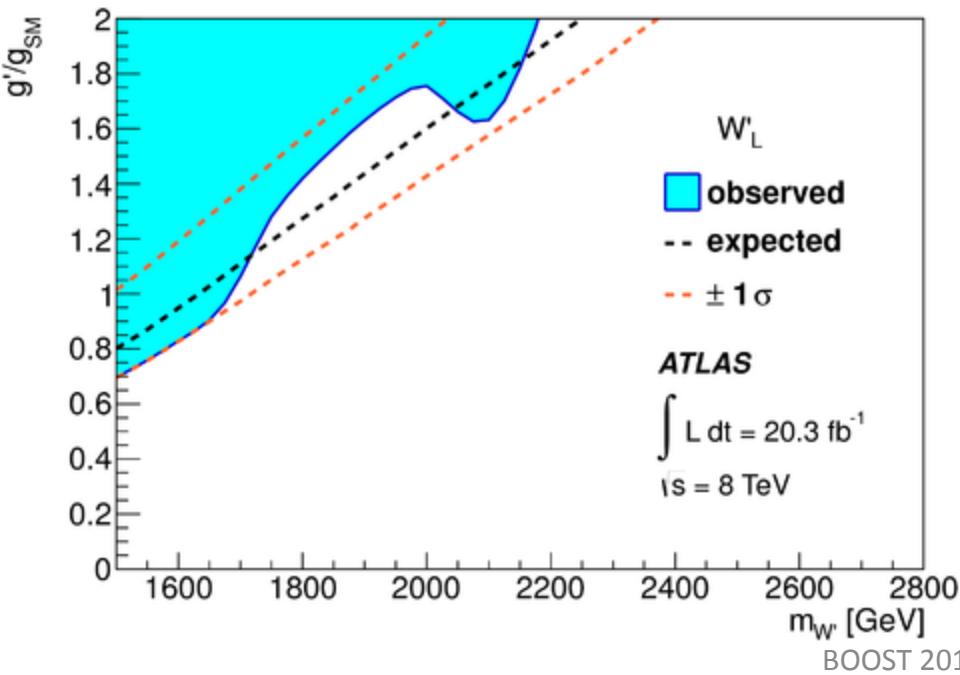
- Backgrounds:
 - QCD multijet
 - SM $t\bar{t}$
 - Estimated from analytic fit to m_{tb} spectrum in data
- Events observed with m_{tb} upto 3 TeV
- Good agreement with SM



Search for $W' \rightarrow tb$

- Observed limits on g'/g_{SM} for W'_L and W'_R as function of $m_{W'}$

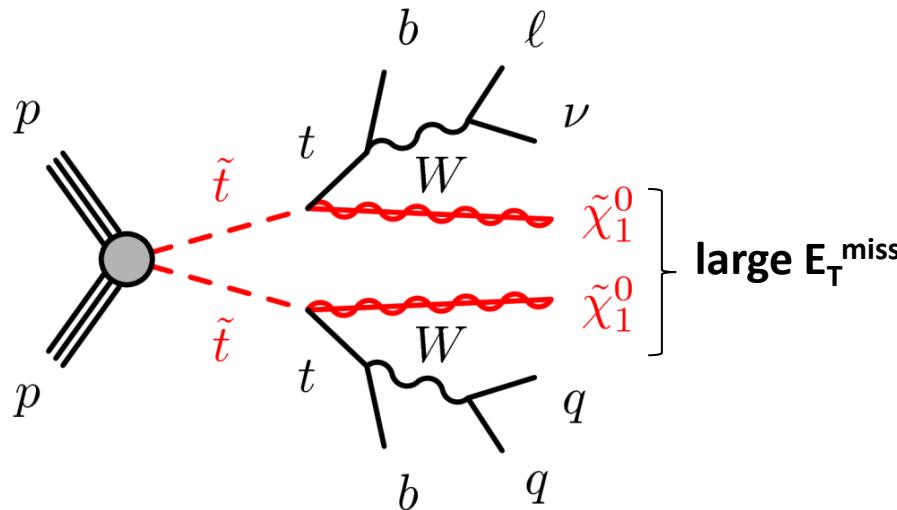
$$\mathcal{L} = \frac{V'_{ij}}{2\sqrt{2}} \bar{f}_i \gamma^\mu \left(g'_{R_{i,j}} (1 + \gamma^5) + g'_{L_{i,j}} (1 - \gamma^5) \right) W'^\mu f_j + h.c.$$



Search for Direct $\tilde{t}_1\tilde{t}_1$ Production

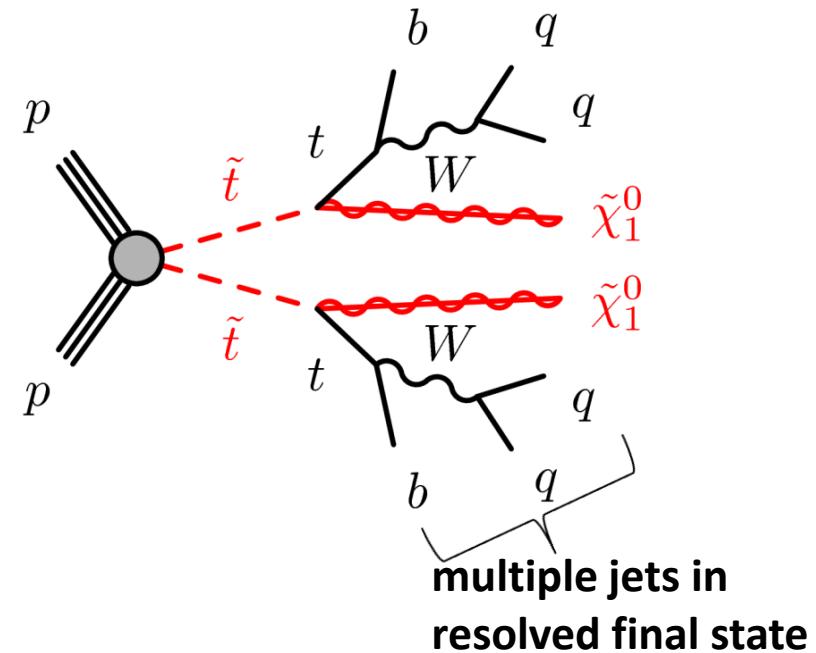
$\sqrt{s} = 8 \text{ TeV}, \int L dt = 20.1 \text{ fb}^{-1}$

- **1-lepton Search**
- Dedicated search region for “partially-resolved” top quarks employing **jet reclustering**



- Main Backgrounds:
- $t\bar{t}$ ($\tau + \text{jets}$), $t\bar{t}Z(\nu\nu)$
 - $W/Z + \text{jets}$

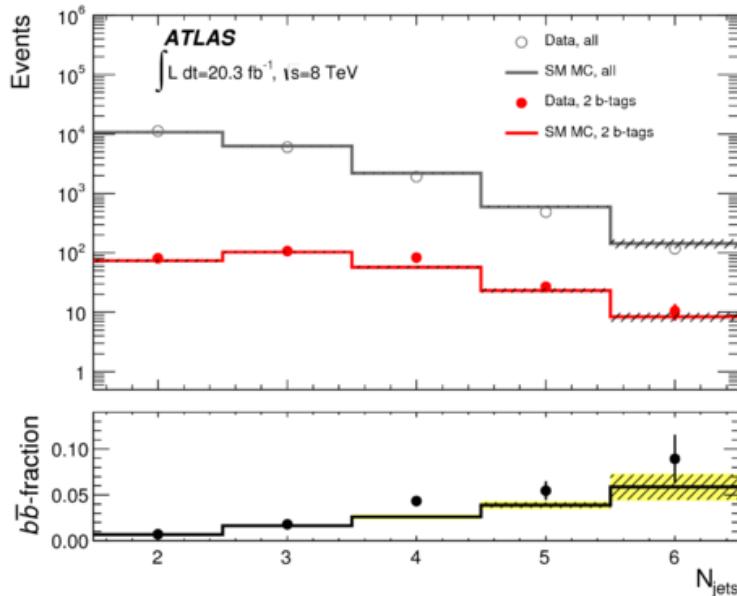
- **0-lepton Search**
- Boosted signal region using trimmed large-R jets



Search for $\tilde{t}_1 \tilde{t}_1$ (0-lepton)

Event Selection

- No good leptons
- At least two b-tagged AntikT R=0.4 jets ($p_T > 35$ GeV)
- $E_T^{\text{miss}} > 150$ GeV; $\min(m_{\text{b-jet}}, E_T^{\text{miss}}) > 175$ GeV



SRA (Fully Resolved)

≥ 6 jets, at least 2 with $p_T > 80$ GeV

SRB (Partially Resolved)

< 6 jets

SRB1

SRB2

- 4 or 5 jets, ≥ 2 with $p_T > 80$ GeV
- $*A_{m_t} < 0.5 \Rightarrow$ two well-reconstructed top quarks

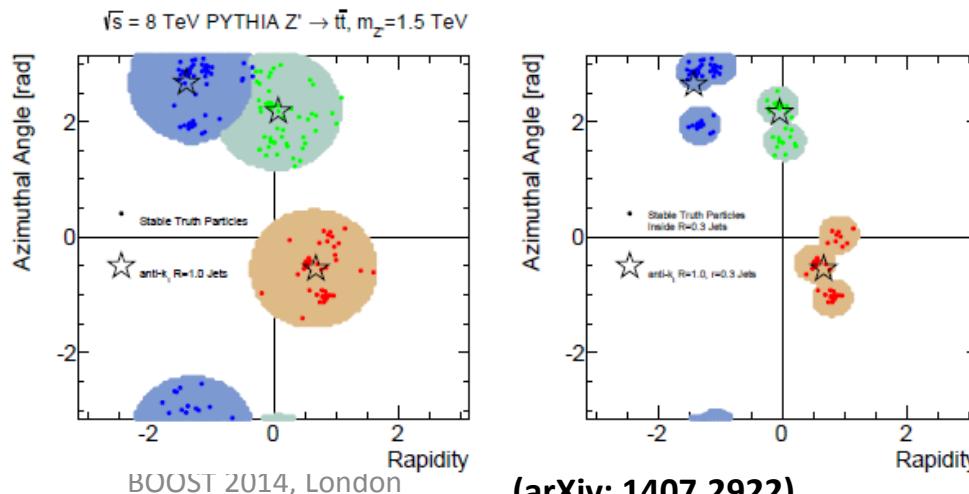
- 5 jets, ≥ 2 with $p_T > 100$ GeV
- $A_{m_t} > 0.5 \Rightarrow$ one or more top quarks not well-reconstructed

$*A_{m_t}$: Top Mass Asymmetry Variable

Search for $\tilde{t}_1 \tilde{t}_1$ (0-lepton)

Jet reclustering

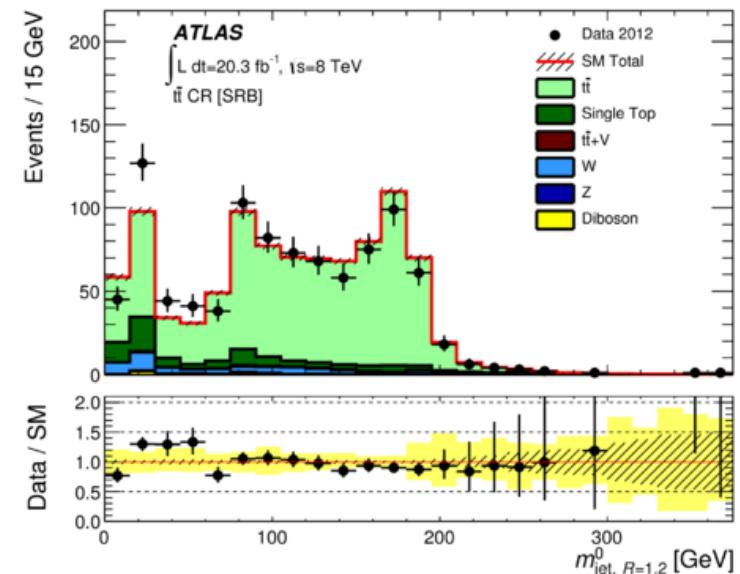
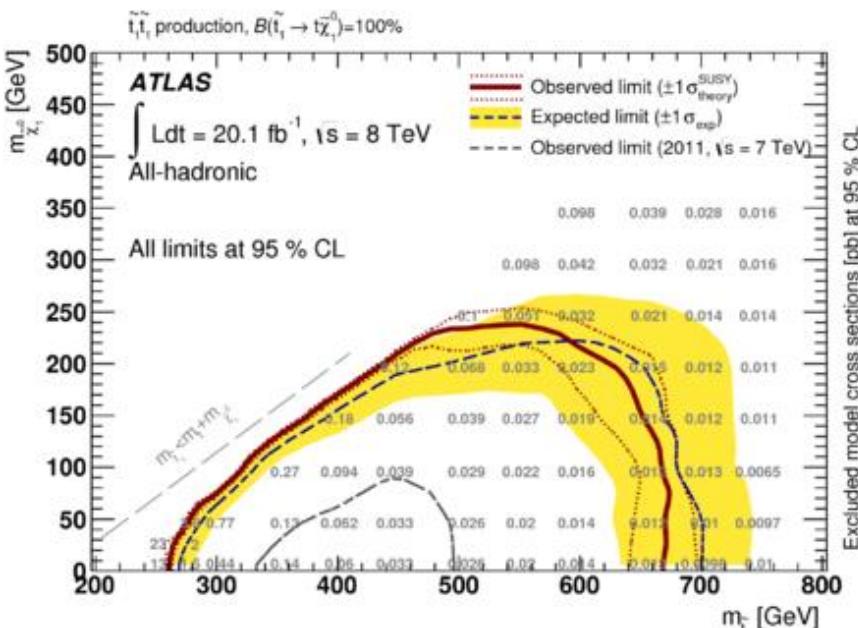
- Run anti-kT algorithm with R=0.8 and R=1.2 **with the Anti-kT R=0.4 jets as input**
- Require ≥ 2 reclustered R=1.2 jets in final state (top candidates)
- SRB1 ($A_{m_t} < 0.5$):
 - $m_{\text{lead}} > 80 \text{ GeV}, 60 < m_{\text{sublead}} < 200 \text{ GeV}$
 - $m_{\text{lead}}^{\text{R}=0.8} > 50 \text{ GeV}$
- SRB2 ($A_{m_t} > 0.5$):
 - $pT_{\text{lead}} > 350 \text{ GeV}$
 - $140 < m_{\text{lead}} < 500 \text{ GeV}$
 - $70 < m_{\text{lead}}^{\text{R}=0.8} < 300 \text{ GeV}$



Search for $\tilde{t}_1 \tilde{t}_1$ (0-lepton)

- Profile likelihood fits performed in each signal region with simultaneous background fit in defined control regions

Observed Limits

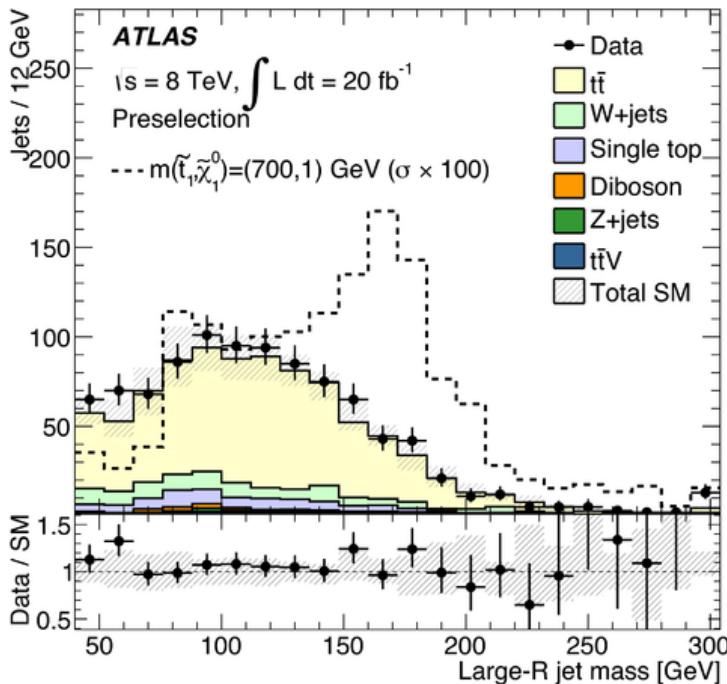


Leading R=1.2 jet mass in $t\bar{t}$ control region

Search for $\tilde{t}_1 \tilde{t}_1$ (1-lepton)

- Several SR optimised for different areas of parameter space
- Boosted SR:
 - Sensitive to $m_{\tilde{t}_1} > 600$ GeV

Large-R jet mass in preselected sample



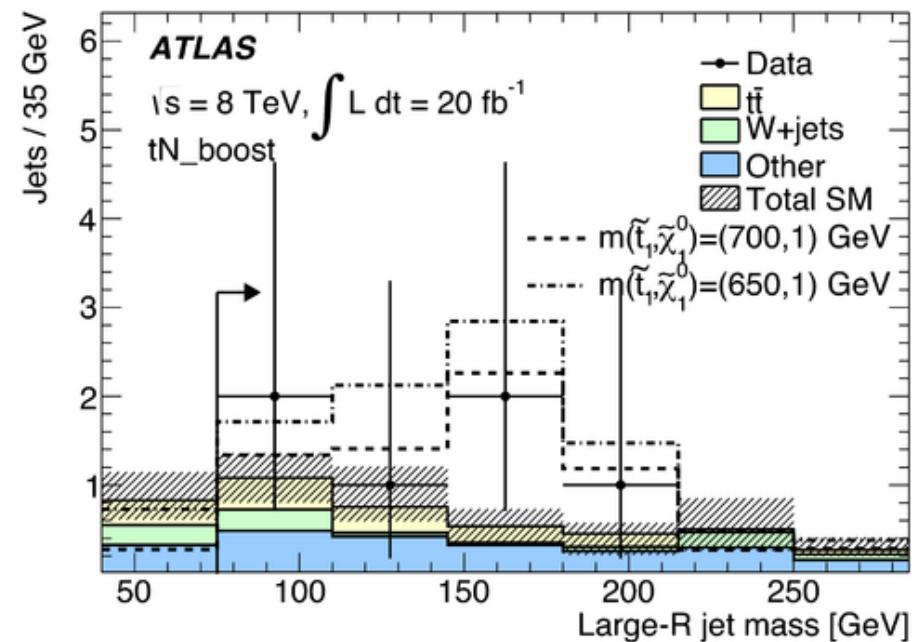
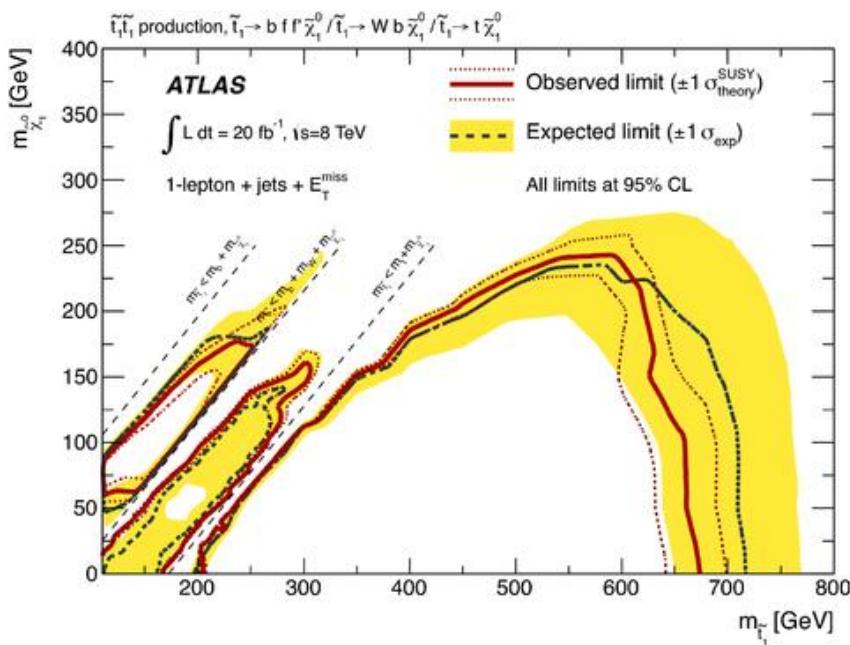
Event Selection for Boosted SR

- One good lepton
- ≥ 4 AntikT R=0.4 jets
 - ≥ 1 b-tagged jet; $\Delta R(b, \text{lep}) < 2.6$
- $E_T^{\text{miss}} > 315$ GeV;
- Req. on $m_T(\text{lep}, E_T^{\text{miss}})$, E_t^{miss} significance, etc. (see backup)
- ≥ 1 Anti-kT R=1.0 trimmed jet
 - $pT > 270$ GeV, $m_{\text{jet}} > 75$ GeV

Search for $\tilde{t}_1 \tilde{t}_1$ (1-lepton)

- Profile likelihood fit on number of events in signal region and defined background control regions

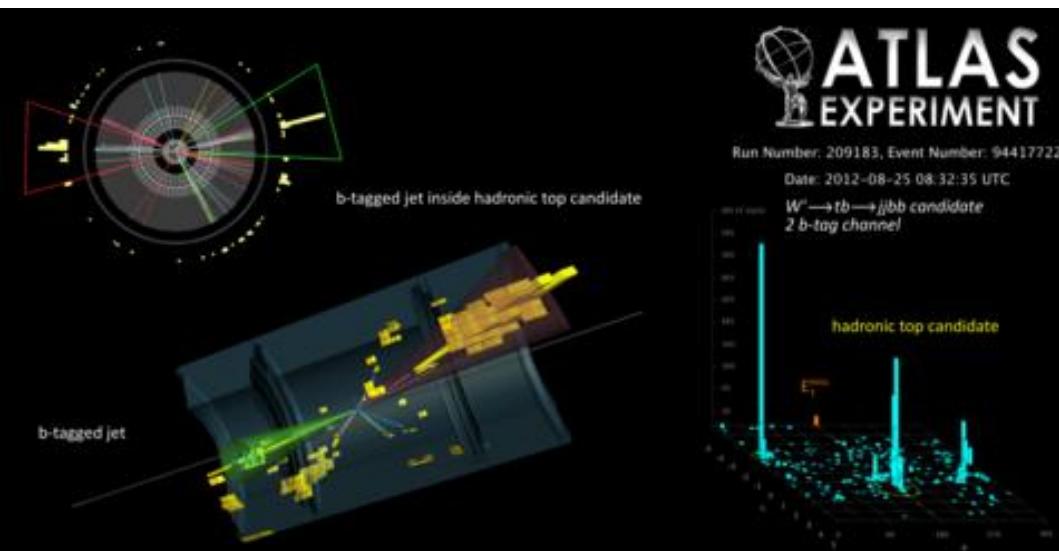
Observed Limits



Large-R jet mass in Boosted SR

Summary

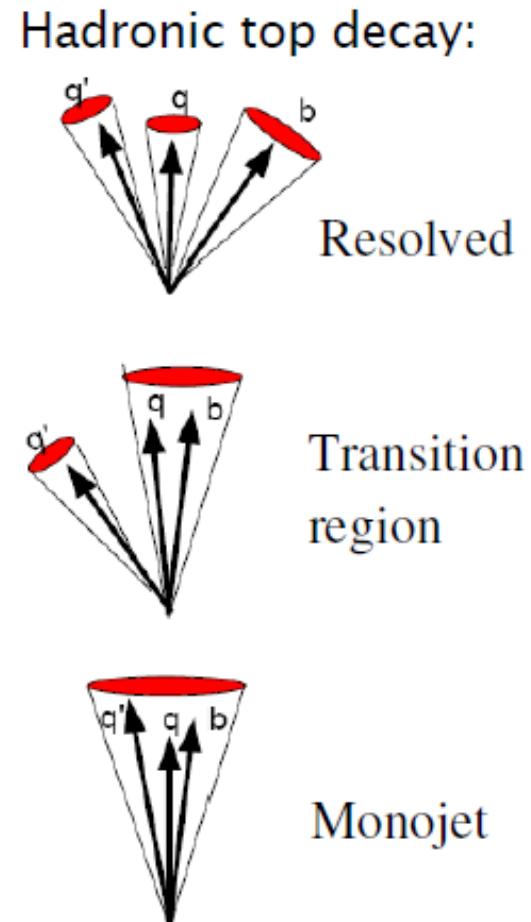
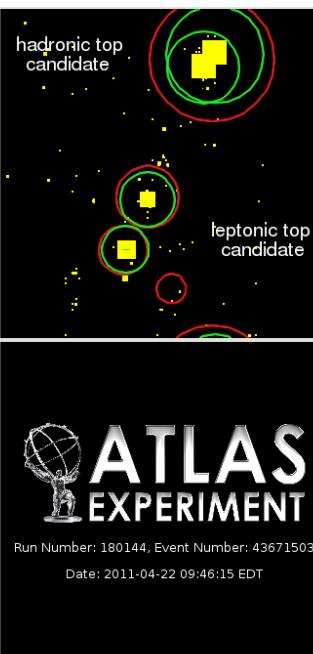
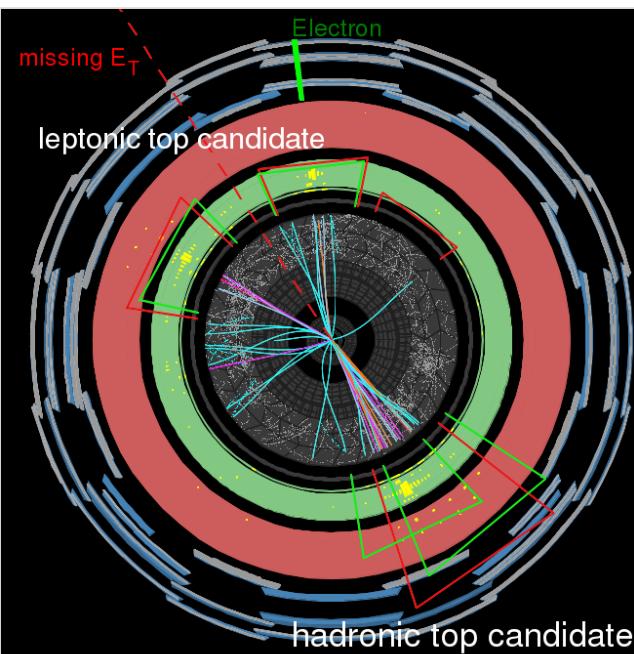
- Boosted top quark identification is well-established in ATLAS
 - Different choices of taggers appropriate for different analyses
 - Has extended the reaches of many searches
 - Of increasing importance as we probe higher energy scales
 - Will be essential in Run II



BACKUP SLIDES

Boosted Top Quarks

- Large $m_{\text{top}}/p_T \Rightarrow$ boosted in lab frame
 - ⇒ Collimated decay products ($R \sim 2m_{\text{top}}/p_T$)
 - ⇒ Hadronic top quark decays can be reconstructed as single “**top quark jet**”
 - ⇒ Better sensitivity with increasing p_T
- Large background from QCD multijet events
 - Suppressed using distinctive **substructure** of top quark jets compared to light quark/gluon jets



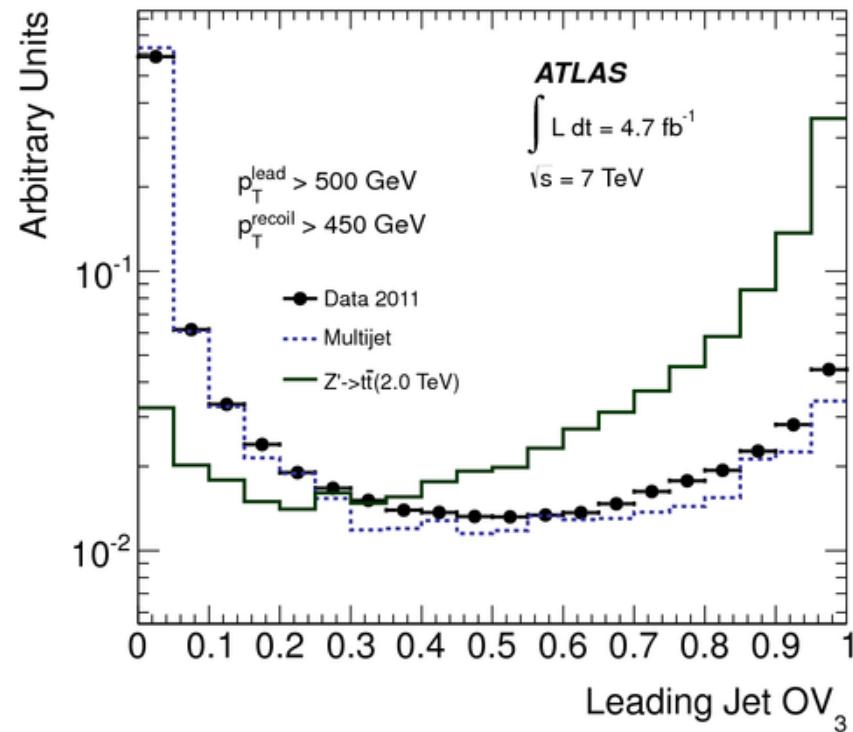
The Top Template Tagger

- Match energy flow in candidate “**top-quark jet**” to 3-parton top quark decays
 - Large number of decay “templates” cover full phase space
- Overlap function measures agreement between candidate jet and each template
- Max. overlap (OV_3) over template set used to discriminate top quark jets from QCD jets

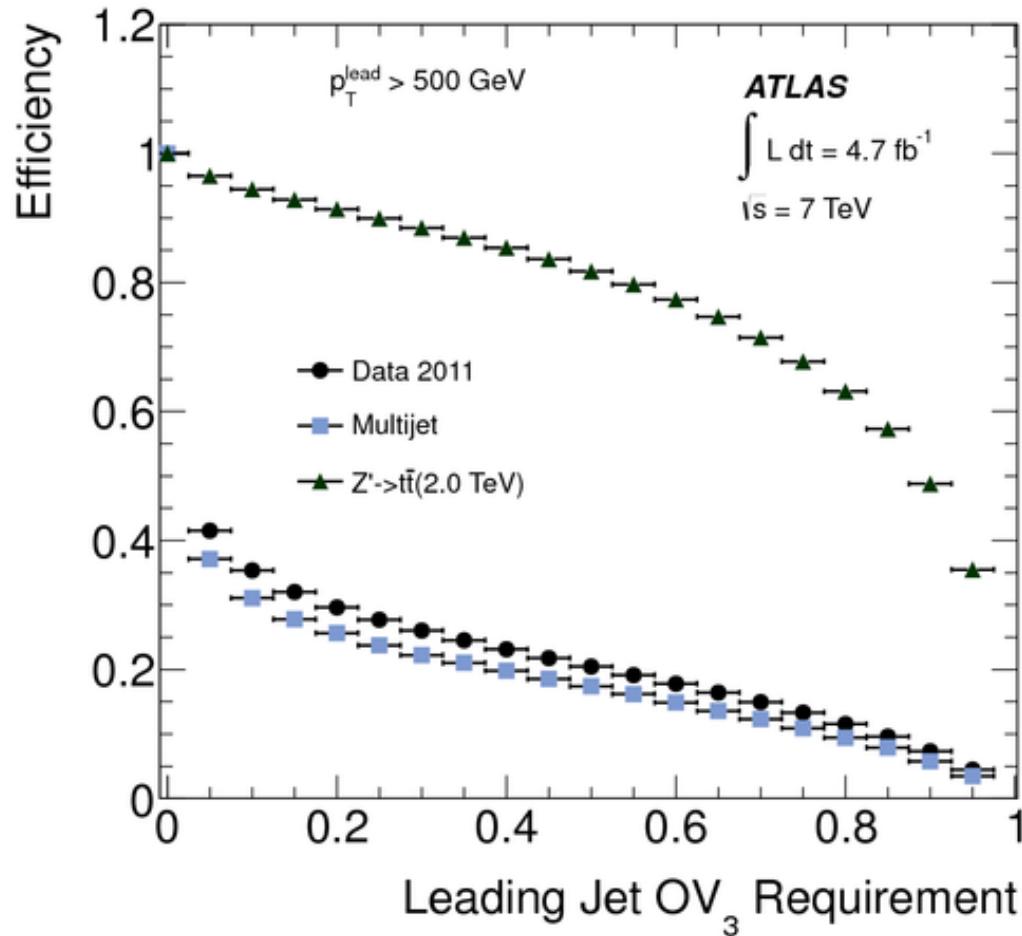
Template Overlap Function

$$OV_3 = \max_{\{\tau_n\}} \exp \left[- \sum_{a=1}^3 \frac{1}{2\sigma_a^2} \left(\sum_{\Delta R(\text{topo},a) < 0.2} E_{\text{topo}} - E_a \right)^2 \right]$$

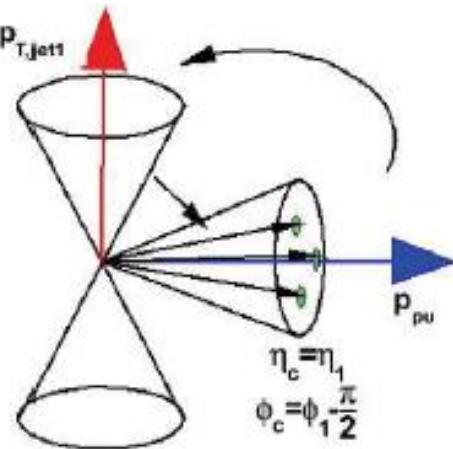
with $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, $\sigma_a = E_a/3$



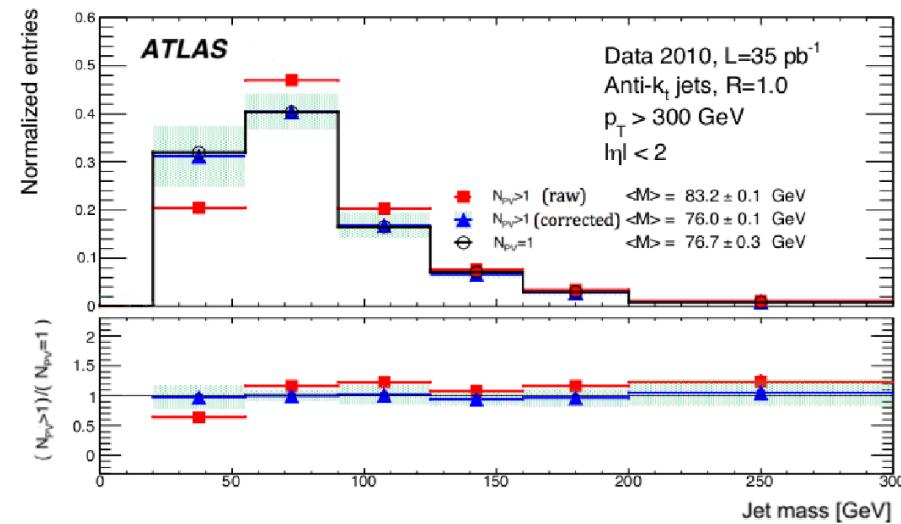
Top Template Tagger Efficiency



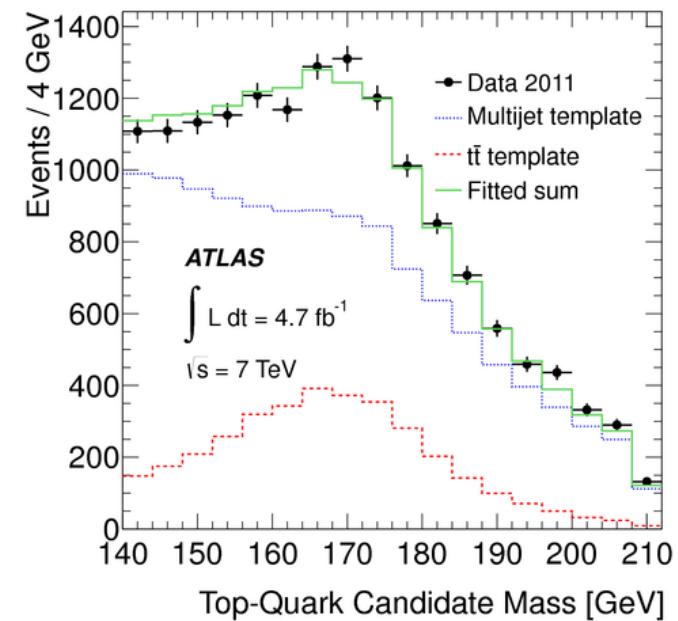
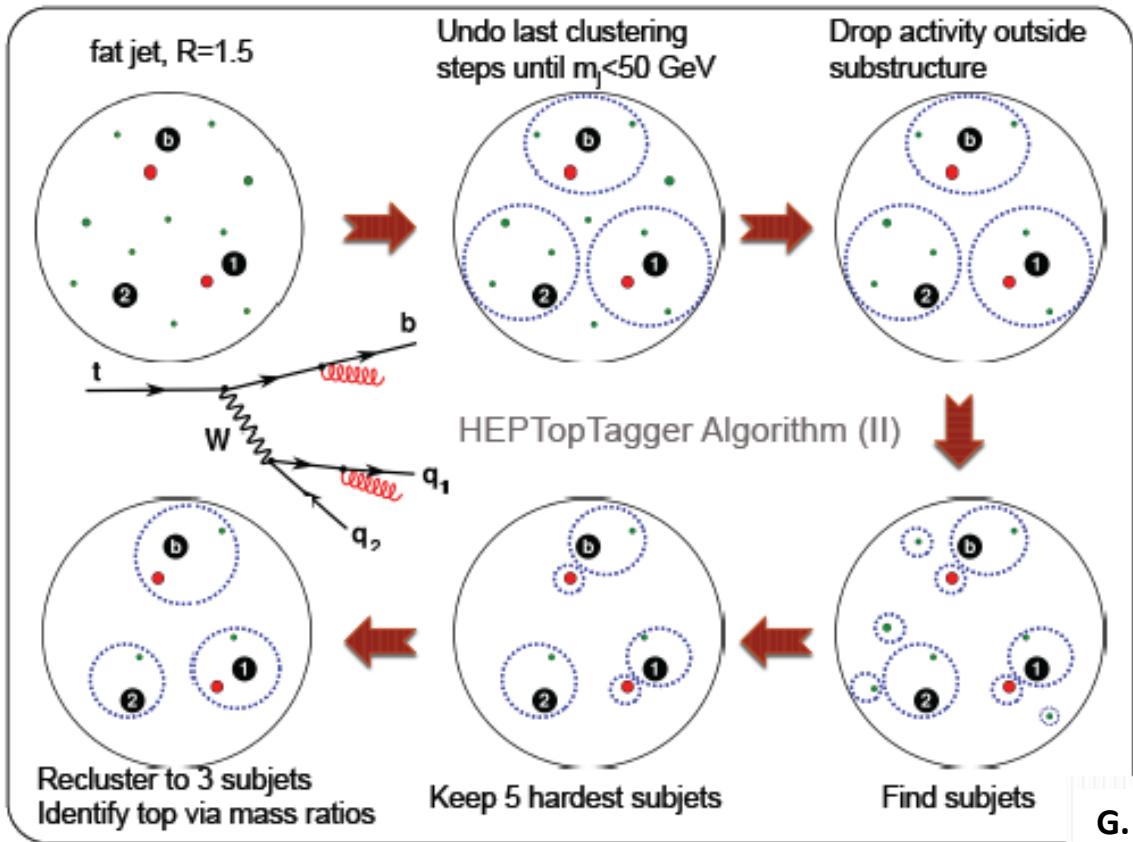
Data-driven Pile-up Corrections for Jet Mass and Substructure



- Soft energy flow from “pile-up” interactions alter the mass and substructure of jets
- Data-driven “**complementary cone**” corrections (**Phys. Rev. D 84, 114025**)
 - Clusters in transverse cone in dijet events added to leading jet
 - Shift in jet observable calculated and parametrised as function of the observable (and level of pile-up \sim NPV)
 - Corrections can be scaled according to jet area



The HEPTopTagger Algorithm



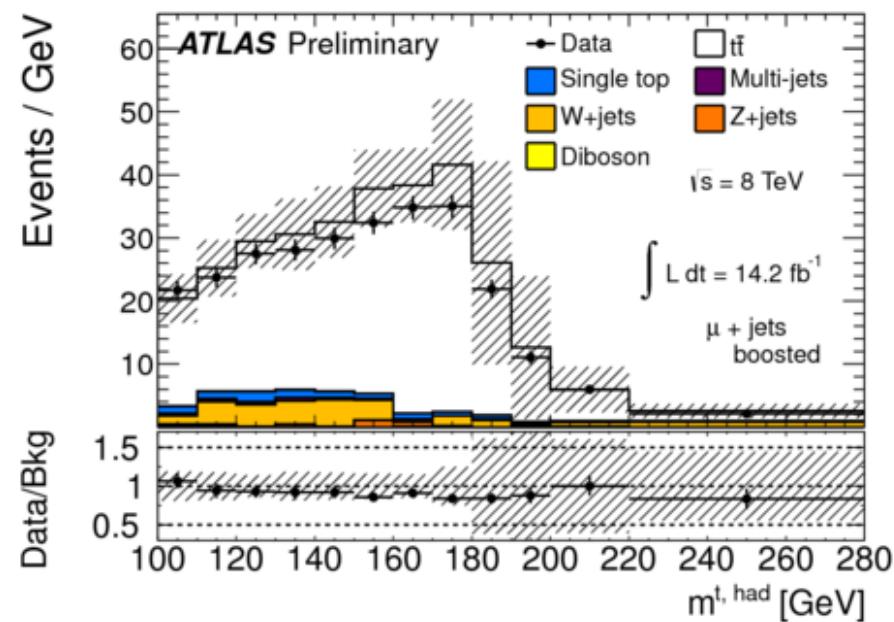
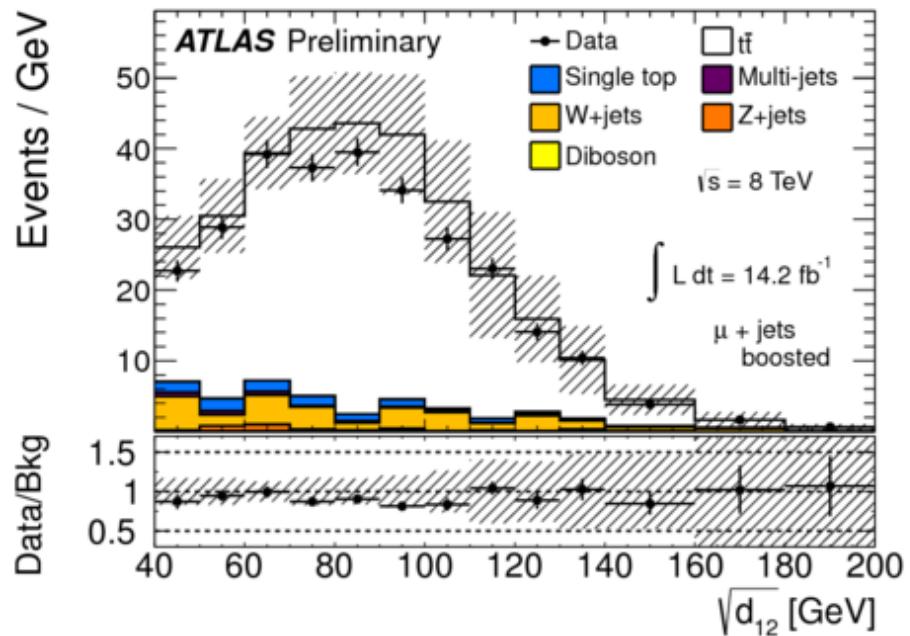
G. Kasieczka, BOOST 2012

Search for $t\bar{t}$ Resonances (Semileptonic)

- Event selection:
 - 1 “mini-isolated” lepton with $pT > 25 \text{ GeV}$
 - Significant E_T^{miss}
 - At least 1 b-tagged Anti-kT R=0.4 jet close to lepton
 - Electron channel:
 - $E_T^{\text{miss}} > 30 \text{ GeV}$, $m_T^W > 30 \text{ GeV}$
 - Muon channel:
 - $E_T^{\text{miss}} > 20 \text{ GeV}$, $E_T^{\text{miss}} + m_T^W > 60 \text{ GeV}$
 - At least 1 b-tagged Anti-kT R=0.4 jet with $\Delta R(l, \text{b-jet}) < 1.5$
 - At least 1 Anti-kT R=1.0 trimmed jet with

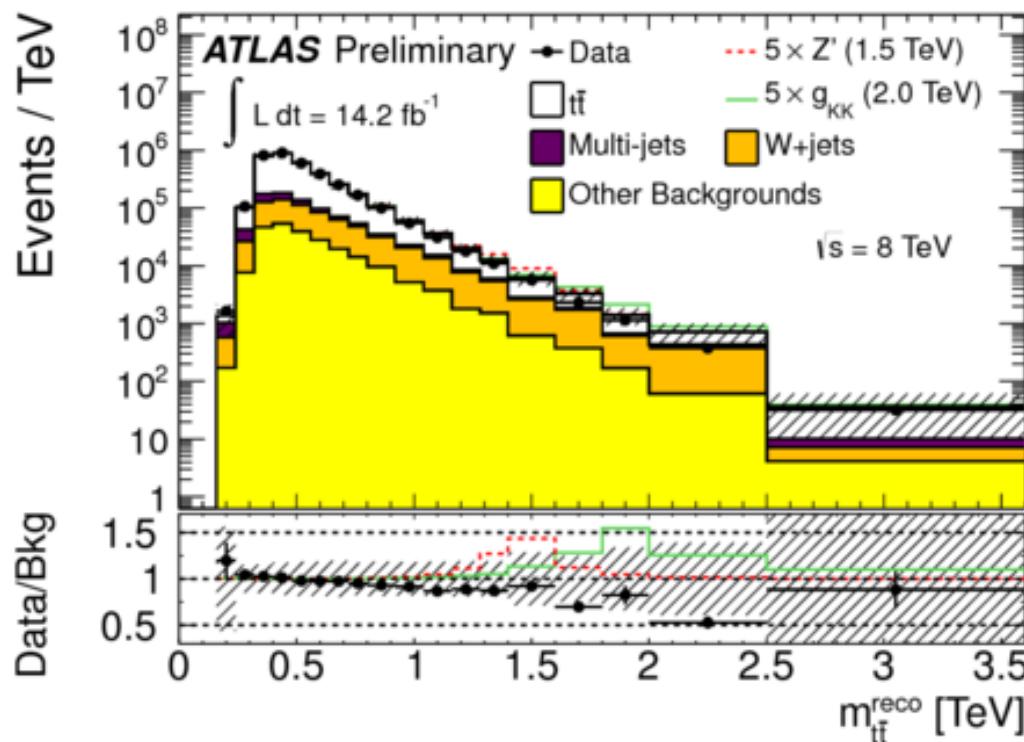
Search for $t\bar{t}$ Resonances (Semileptonic)

- Mjet and $\sqrt{d_{12}}$ distributions after boosted event selection



Search for $t\bar{t}$ Resonances (Semileptonic)

- Invariant mass of $t\bar{t}$ system after combination of resolved and boosted selection samples

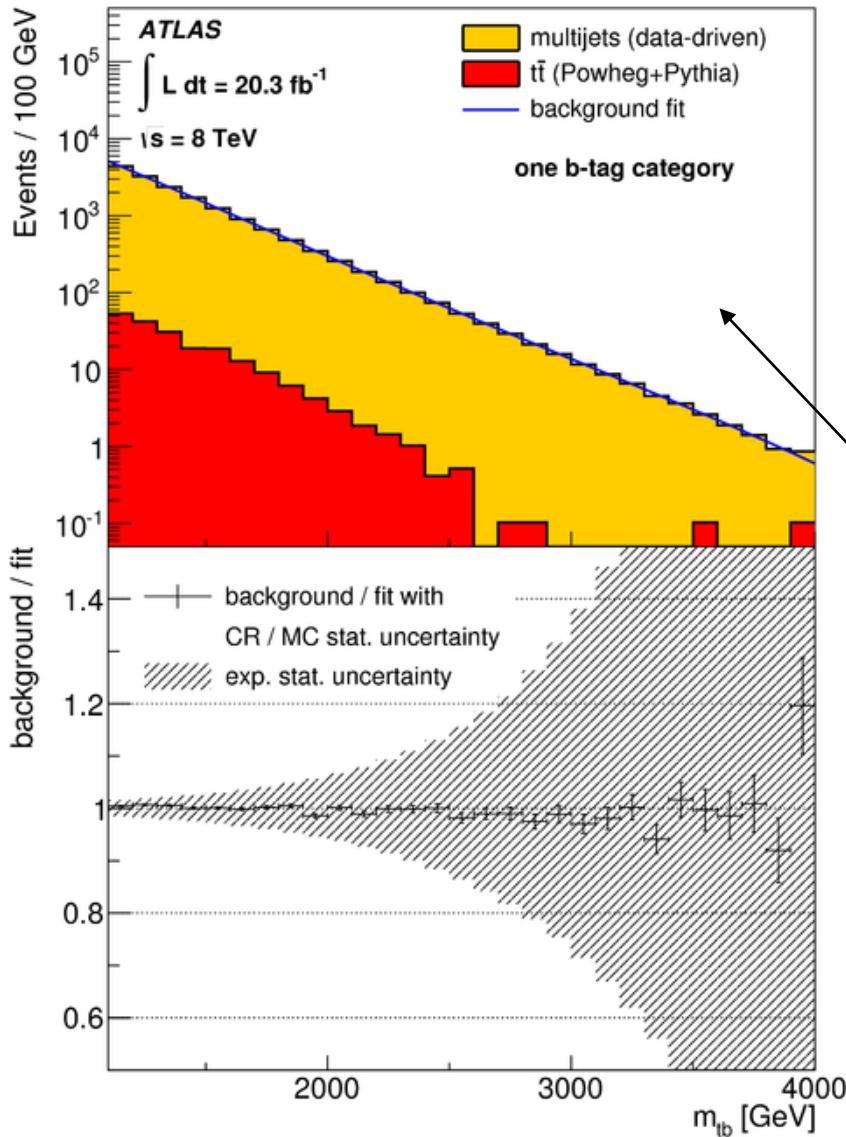


$W' \rightarrow tb$ Cutflow

ATLAS

Requirement	1.5 TeV W'_L	2.0 TeV W'_L	2.5 TeV W'_L	3.0 TeV W'_L
Trigger	80.7%	85.7%	82.6%	72.2%
Data quality requirements	80.4%	85.4%	82.3%	72.0%
$H_T > 850$ GeV	70.6%	79.6%	77.4%	66.4%
Lepton veto	70.6%	79.6%	77.4%	66.4%
Exactly one top candidate	30.0%	33.3%	31.7%	27.0%
Exactly one b candidate	11.0%	10.4%	8.7%	7.0%
$m_{tb} > 1.1$ TeV	9.9%	9.9%	8.3%	6.4%
One b -tag category	4.2%	5.4%	5.0%	4.1%
Two b -tag category	5.7%	4.5%	3.2%	2.3%
Requirement	1.5 TeV W'_R	2.0 TeV W'_R	2.5 TeV W'_R	3.0 TeV W'_R
Trigger	81.7%	86.6%	83.9%	73.5%
Data quality requirements	81.4%	86.3%	83.7%	73.3%
$H_T > 850$ GeV	71.9%	80.8%	78.9%	67.8%
Lepton veto	71.9%	80.8%	78.9%	67.8%
Exactly one top candidate	36.0%	40.5%	38.7%	32.7%
Exactly one b candidate	13.1%	12.6%	10.4%	7.9%
$m_{tb} > 1.1$ TeV	12.1%	12.3%	10.0%	7.3%
One b -tag category	5.1%	6.4%	5.9%	4.5%
Two b -tag category	7.0%	5.9%	4.1%	2.8%

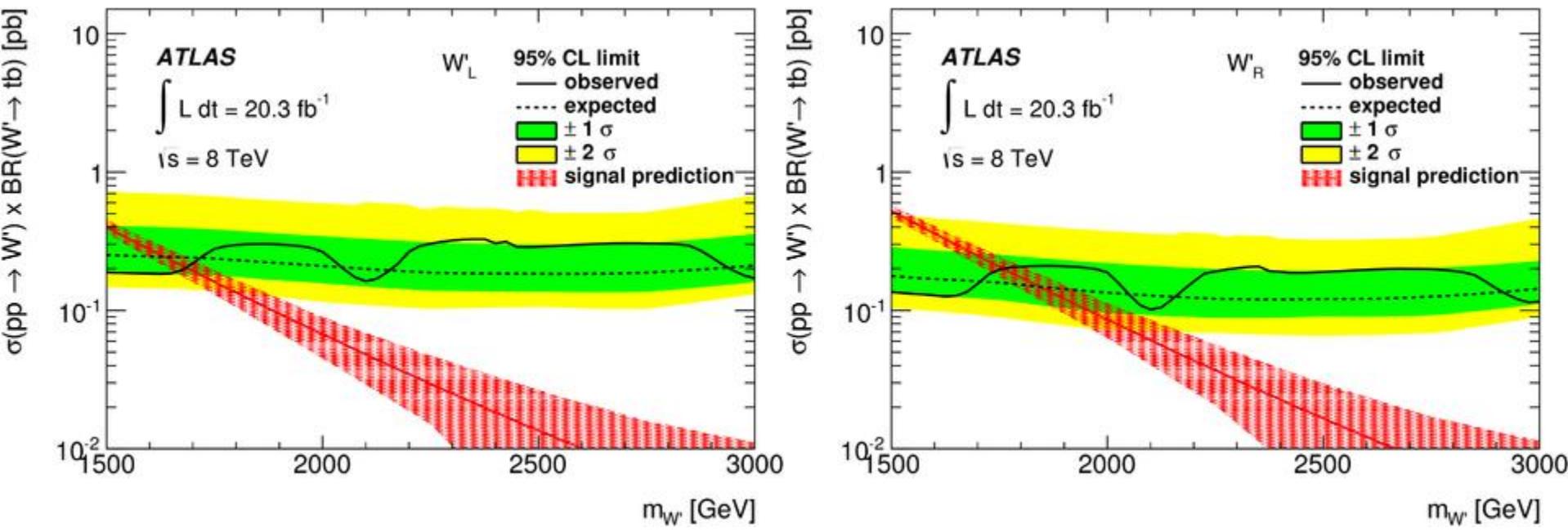
$W' \rightarrow tb$ Background Validation



- Final background estimate obtained from combined fit to SR in data
- Validated by fit to CR (multijet) + MC ($t\bar{t}$) initial background estimate

Search for $W' \rightarrow tb$

- Observed limits ($g' = g_{SM}$) :
 - $m_{W'_L} > 1.68 \text{ TeV}$
 - $m_{W'_R} > 1.76 \text{ TeV}$



Search for $\tilde{t}_1 \tilde{t}_1$ (0-lepton)

- Top mass asymmetry:

$$A_{m_t} = (m_{\text{lead}} - m_{\text{sublead}}) / (m_{\text{lead}} + m_{\text{sublead}})$$

- $A_{m_t} < 0.5 \Rightarrow$ two well-reconstructed top quarks (SRB1)
 - $m_{\text{lead}} > 80 \text{ GeV}, 60 < m_{\text{sublead}} < 200 \text{ GeV}$
 - $m_{\text{lead}}^{R=0.8} > 50 \text{ GeV}$
- $A_{m_t} > 0.5 \Rightarrow$ one or more top quarks not well-reconstructed (SRB2)
 - $140 < m_{\text{lead}} < 500 \text{ GeV}$
 - $pT_{\text{lead}} > 350 \text{ GeV}$
 - $70 < m_{\text{lead}}^{R=0.8} < 300 \text{ GeV}$

Search for $\tilde{t}_1 \tilde{t}_1$ (1-lepton)

- Expect subleading large-R jet to be well-separated from p_T^{miss} in signal
 - Discriminates against $t\bar{t}$ background

