Searches for exotic heavy particles with ATLAS

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DESY-Hamburg Seminar
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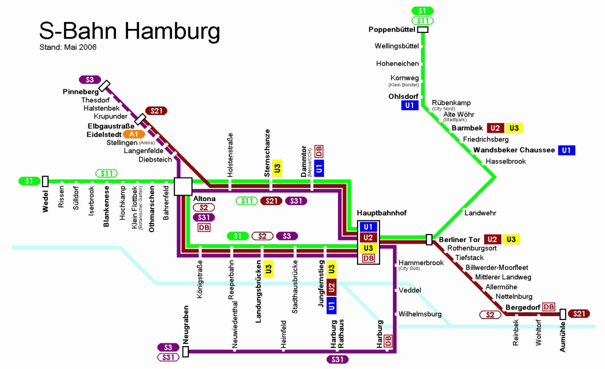
Outline

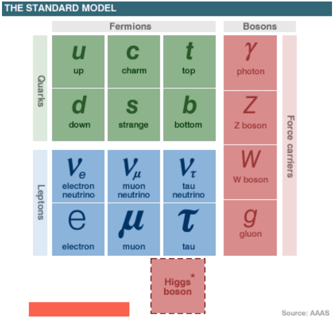
- Introduction
- Run-1 search Highlights
- A brief look towards run-II
- Conclusion and Outlook



The Standard Model (SM) of particle physics:

- Fermionic matter:
  - Three generations of **quarks**
  - Three generations of **leptons**
- Gauge Bosons:
  - Four Force carriers : γ(EM), $W^{\pm}$, Z (Weak), g (strong)
  - The Higgs Boson to give mass

"Was she pretty?" asked the bigger of the small girls. "Not as pretty as any of you," said the bachelor, "but she was horribly good."
The storyteller - H. H. Munro (Saki)



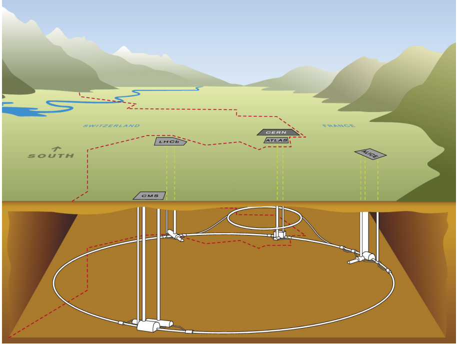
So what's wrong with the Standard Model?

- No Dark Matter candidates
- Not enough CP violation to explain the observed matter-antimatter imbalance
- ~~The Higgs boson has still not been observed~~
- No gravity
- Particle masses are not understood

Is there physics beyond the Standard Model?

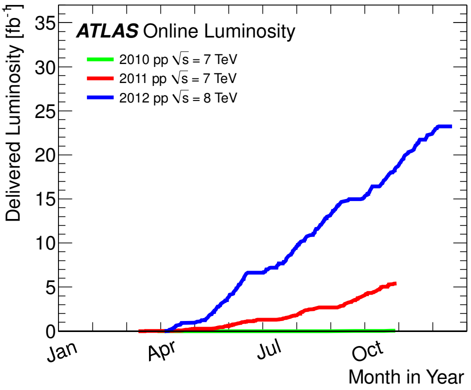
- Searches for Exotic (Non-SUSY) BSM physics are a large part of the LHC Programme:
  - 79 (75) ATLAS Exotics (CMS Exotica+B2G) Publications (2011-2014)
- Easy for a seminar discussing this wide programme to become a fashion parade of exotic models and searches
- Here I will present what I consider to be the edited highlights: concentrating on searches for new heavy bosons and fermions
- Will discuss topics that I think are of particular relevance for run-II
- Will present the results of the run-I searches in approximately the order I expect the results to appear from LHC Run-II

- 27 km circumference ring
- So far collided protons at centre-of-mass energies 7 and 8 TeV, expecting 13 TeV in run-II
- Four detectors installed around the ring
- An excellent environment to test the Standard Model and search for new Physics



The LHC performed excellently in 2010-2012:

- $\sim 35\,\mathrm{pb}^{-1}$ of 7 TeV *pp* collisions/experiment 2010
- $\sim 5\,\mathrm{fb}^{-1}$ of 7 TeV *pp* collisions/experiment 2011
- $\sim 20\,\mathrm{fb}^{-1}$ of 8 TeV *pp* collisions/experiment 2012

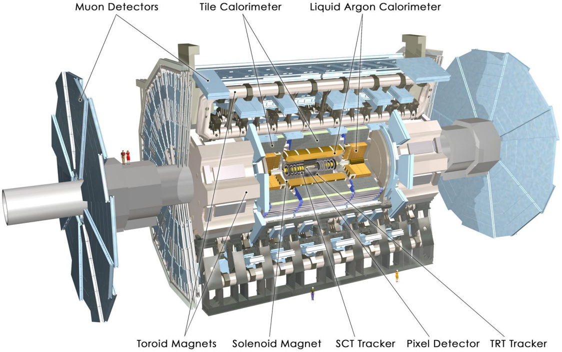


Introduction

The ATLAS detector at the LHC:

- precise calorimetry:
  - Hadronic jets
  - electrons
- Precise tracking:
  - Muons
  - *b*-jet tagging
- Excellent solid-angle coverage:
  - E_T^{miss}

Versatile detector for finding new physics in a variety of final states



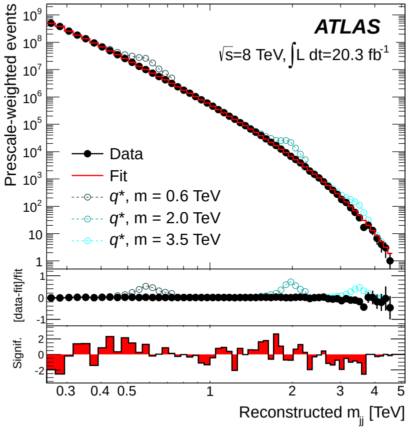
- First go for the potential early discoveries:
  - large-cross-section processes
  - simple final states
- Then tougher targets:
  - smaller cross-sections
  - complex signatures
- Make sure to check the rest with:
  - model independent searches
  - precision measurements

First, the low hanging fruit:

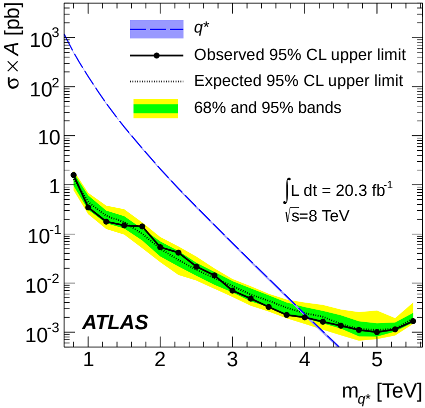
- large cross section:
  - dijets
- simple (clean) final states
  - l^+l^-
  - $l\nu$

Search for new physics in dijets
20 fb^{-1} @ 8 TeV: arXiv:1407.1376

- Require two central jets
  $|y| < 2.8$, $p_T > 50$ GeV
- Reduce t-channel-like processes
  $|y_{1,2}| < 2.8$, $|y^*| < 0.6$
- $|m_{jj}| > 250$ GeV
- Search for a bump in the m_{jj} spectrum



- limits set on specific models to quantify performance of the search
- Furthermore minimally model-dependent limits (assuming a Gaussian signal, or Breit-Wigner convolved with falling parton luminosity) set
- Application to set limits on NP models beyond those directly considered is possible



Dijets

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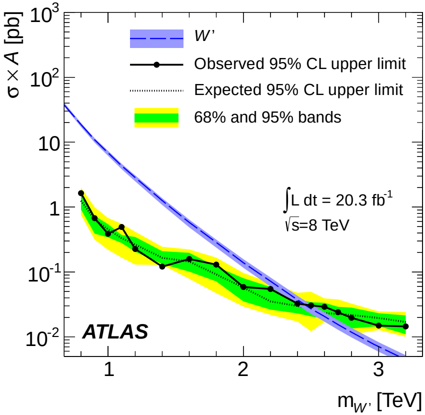

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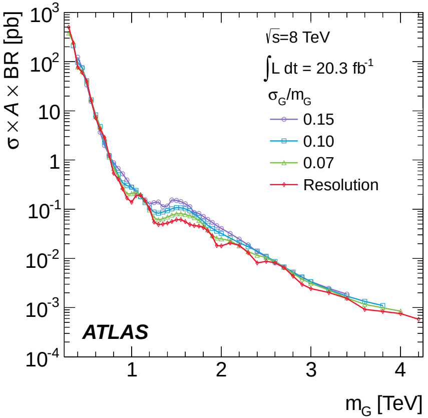

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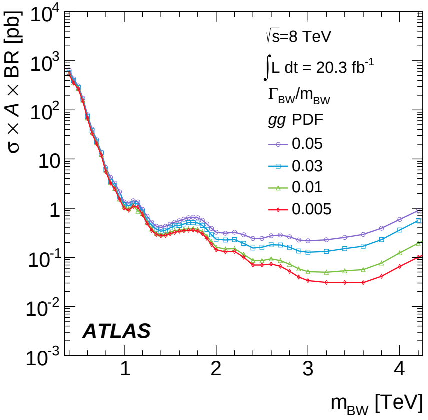

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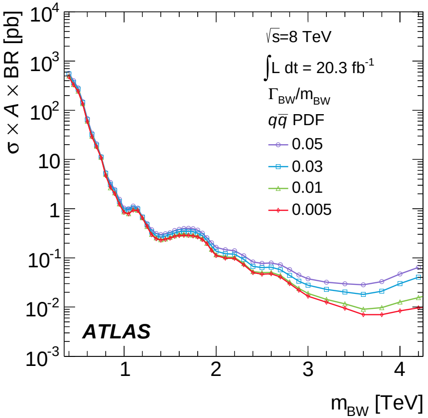
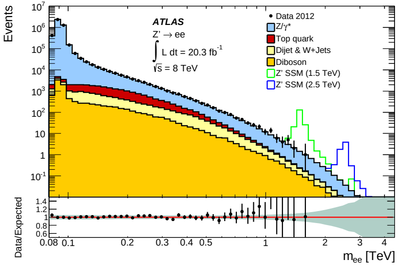
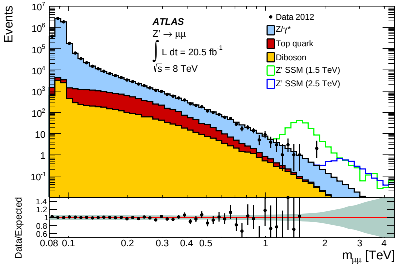
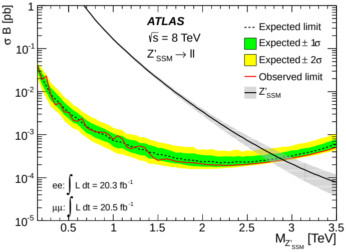


Another early search channel is l^+l^-: (Phys Rev D90, 052005 (2014))

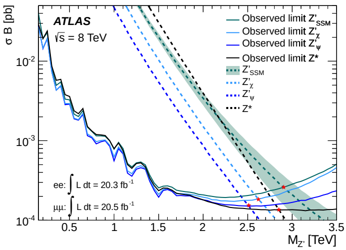
- Select two high p_T leptons
- Search invariant mass spectrum
- Set limits on models



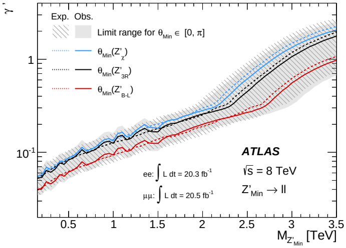




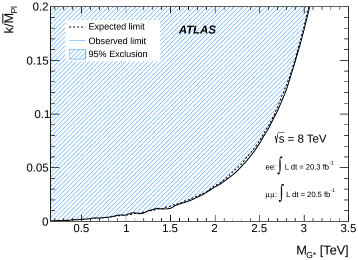
ATLAS
√s = 8 TeV
Z'SSM → ll
Expected limit
Expected ± 1σ
Expected ± 2σ
Observed limit
Z'SSM
ee: ∫ L dt = 20.3 fb-1
μμ: ∫ L dt = 20.5 fb-1
σ B [pb]
MZ'SSM [TeV]



ATLAS
√s = 8 TeV
Observed limit Z'SSM
Observed limit Z'χ
Observed limit Z'ψ
Observed limit Z*
Z'SSM
Z'χ
Z'ψ
Z*
ee: ∫ L dt = 20.3 fb-1
μμ: ∫ L dt = 20.5 fb-1
σ B [pb]
MZ' [TeV]



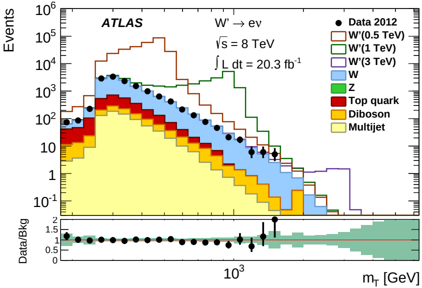
γ'
Exp. Obs.
Limit range for θMin ∈ [0, π]
θMin(Z'χ)
θMin(Z'3R)
θMin(Z'B-L)
ATLAS
√s = 8 TeV
Z'Min → ll
ee: ∫ L dt = 20.3 fb-1
μμ: ∫ L dt = 20.5 fb-1
MZ'Min [TeV]



k/M̄Pl
Expected limit
Observed limit
95% Exclusion
ATLAS
√s = 8 TeV
ee: ∫ L dt = 20.3 fb-1
μμ: ∫ L dt = 20.5 fb-1
MG* [TeV]

Usually slower to access: $l\nu$ (E_T^{miss})

- JHEP 1409 (2014) 037
- Select a high-p_T lepton
- Require E_T^{miss} that balances p_T^l
- Search m_T distribution for excesses
  - e-channel
  - μ-channel



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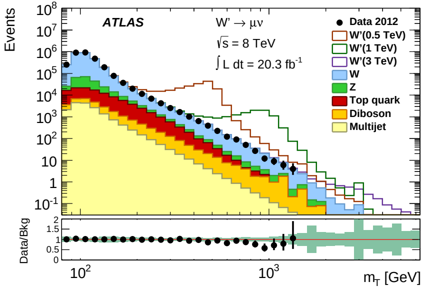
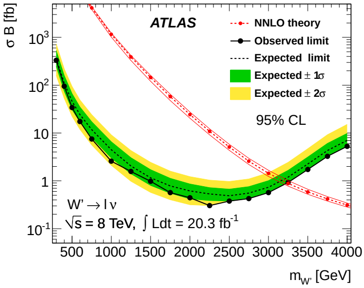
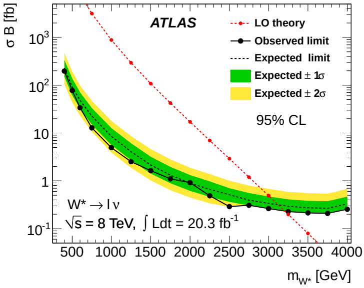



ATLAS
NNLO theory
Observed limit
Expected limit
Expected ± 1σ
Expected ± 2σ
95% CL
W' → l ν
√s = 8 TeV, ∫ Ldt = 20.3 fb⁻¹
σ B [fb]
m_W' [GeV]

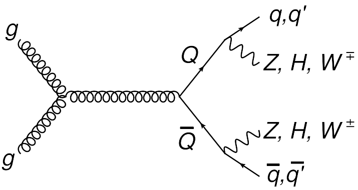

ATLAS
LO theory
Observed limit
Expected limit
Expected ± 1σ
Expected ± 2σ
95% CL
W* → l ν
√s = 8 TeV, ∫ Ldt = 20.3 fb⁻¹
σ B [fb]
m_W* [GeV]

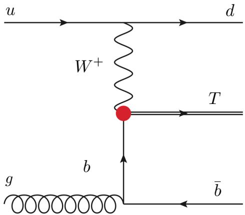
As data sets become better understood, more challenging quarry can be approached:

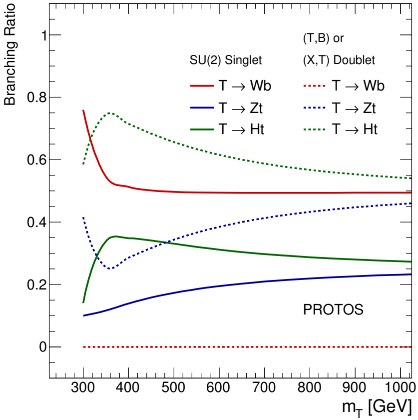
- More complex observables (e.g. Eur. Phys. J. C (2014) 74 3134)
- Final states with τs and bs (e.g. JHEP 1411 (2014) 056)
- Complex multi-object final states
- Processes with very small expected cross sections
- Final states with boosted heavy objects
- Long-lived particle searches, (e.g. arXiv:1501.04020)

Examples of models that produce many-particle final states:

- Compositeness scenarios and Extra dimension models produce Vector-Like quarks
- Such scenarios can also produce resonances that decay to pairs of vector bosons such as were searched for in arXiv:1409.6190 (as can various BSM Higgs bosons)

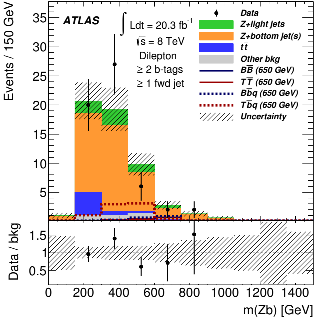


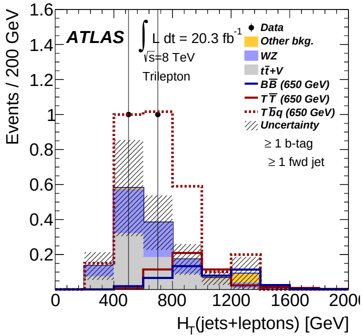


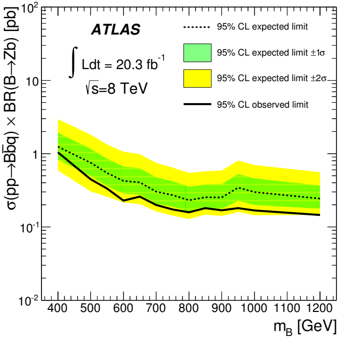


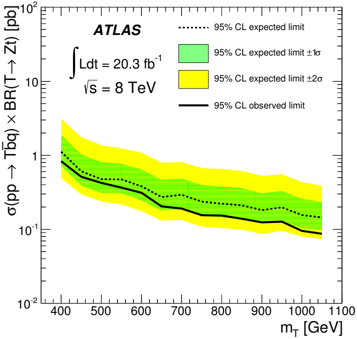
- Most recent result, search for $T \rightarrow tZ$ (JHEP 1411 (2014) 104)
- Small branching ratio but clean signature

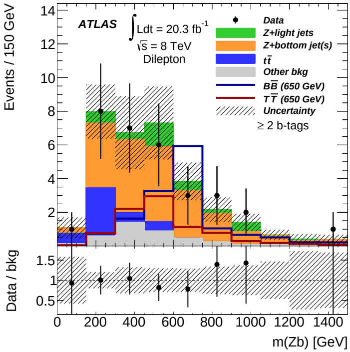
<table>
<tr><th colspan="4">Event selection</th></tr>
<tr><td colspan="4">Z boson candidate preselection
≥ 2 central jets
$p_{\mathrm{T}}(Z) \geq 150$ GeV</td></tr>
<tr><td colspan="2">Dilepton channel</td><td colspan="2">Trilepton channel</td></tr>
<tr><td colspan="2">$= 2$ leptons</td><td colspan="2">≥ 3 leptons</td></tr>
<tr><td colspan="2">≥ 2 b-tagged jets</td><td colspan="2">≥ 1 b-tagged jet</td></tr>
<tr><td>Pair production</td><td>Single production</td><td>Pair production</td><td>Single production</td></tr>
<tr><td>H_{T}(jets) ≥ 600 GeV</td><td>≥ 1 fwd. jet</td><td>–</td><td>≥ 1 fwd. jet</td></tr>
<tr><th colspan="4">Final discriminant</th></tr>
<tr><td colspan="2">$m(Zb)$</td><td colspan="2">H_{T}(jets+leptons)</td></tr>
</table>

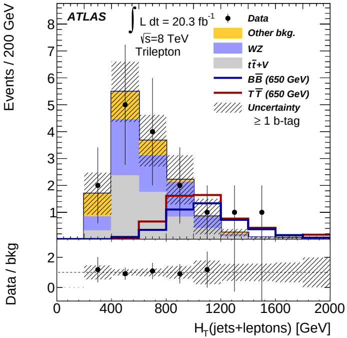

ATLAS
$\int$ Ldt = 20.3 fb^{-1}
$\sqrt{s}$ = 8 TeV
Dilepton
≥ 2 b-tags
≥ 1 fwd jet
Data
Z+light jets
Z+bottom jet(s)
$t\bar{t}$
Other bkg
$B\bar{B}$ (650 GeV)
$T\bar{T}$ (650 GeV)
$B\bar{b}q$ (650 GeV)
$T\bar{b}q$ (650 GeV)
Uncertainty
Events / 150 GeV
Data / bkg
m(Zb) [GeV]

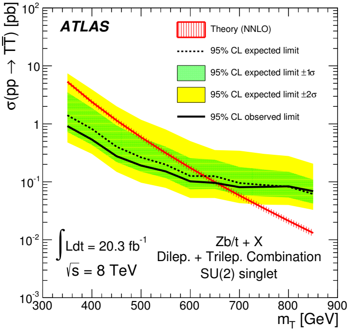

ATLAS
$\int$ L dt = 20.3 fb^{-1}
$\sqrt{s}$=8 TeV
Trilepton
Data
Other bkg.
WZ
$t\bar{t}$+V
$B\bar{B}$ (650 GeV)
$T\bar{T}$ (650 GeV)
$T\bar{b}q$ (650 GeV)
Uncertainty
≥ 1 b-tag
≥ 1 fwd jet
Events / 200 GeV
H$_T$(jets+leptons) [GeV]

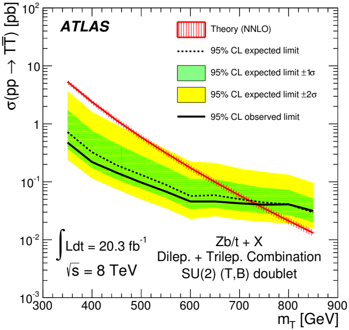

ATLAS
$\int$ Ldt = 20.3 fb^{-1}
$\sqrt{s}$=8 TeV
95% CL expected limit
95% CL expected limit ±1σ
95% CL expected limit ±2σ
95% CL observed limit
σ(pp→B$\bar{b}$q) × BR(B→Zb) [pb]
m$_B$ [GeV]
10^{2}
10
1
10^{-1}
10^{-2}
400
500
600
700
800
900
1000
1100
1200

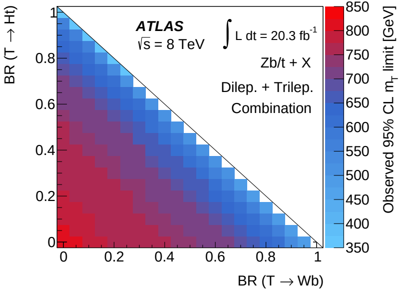

ATLAS
$\int$ Ldt = 20.3 fb^{-1}
$\sqrt{s}$ = 8 TeV
95% CL expected limit
95% CL expected limit ±1σ
95% CL expected limit ±2σ
95% CL observed limit
σ(pp → T$\bar{b}$q) × BR(T→ Zt) [pb]
m$_T$ [GeV]
10^{2}
10
1
10^{-1}
10^{-2}
400
500
600
700
800
900
1000
1100

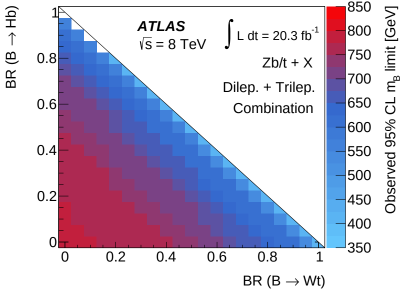

ATLAS
$\int$Ldt = 20.3 fb^{-1}
$\sqrt{s}$ = 8 TeV
Dilepton
Data
Z+light jets
Z+bottom jet(s)
$t\bar{t}$
Other bkg
$B\bar{B}$ (650 GeV)
$T\bar{T}$ (650 GeV)
Uncertainty
≥ 2 b-tags
Events / 150 GeV
Data / bkg
m(Zb) [GeV]

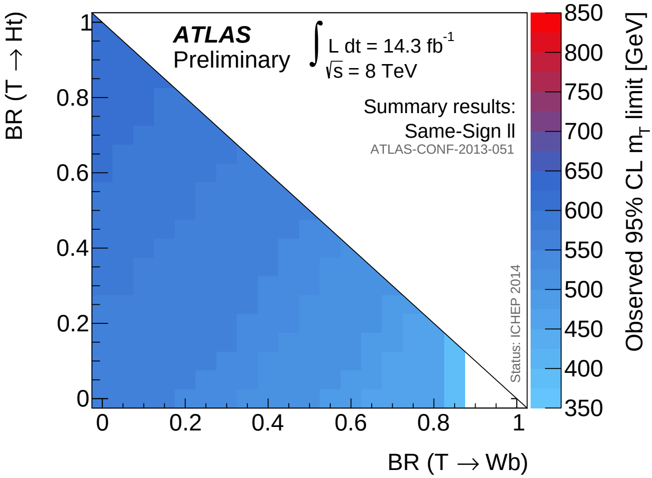

ATLAS
$\int$L dt = 20.3 fb^{-1}
$\sqrt{s}$=8 TeV
Trilepton
Data
Other bkg.
WZ
$t\bar{t}$+V
$B\bar{B}$ (650 GeV)
$T\bar{T}$ (650 GeV)
Uncertainty
≥ 1 b-tag
Events / 200 GeV
Data / bkg
H_T(jets+leptons) [GeV]

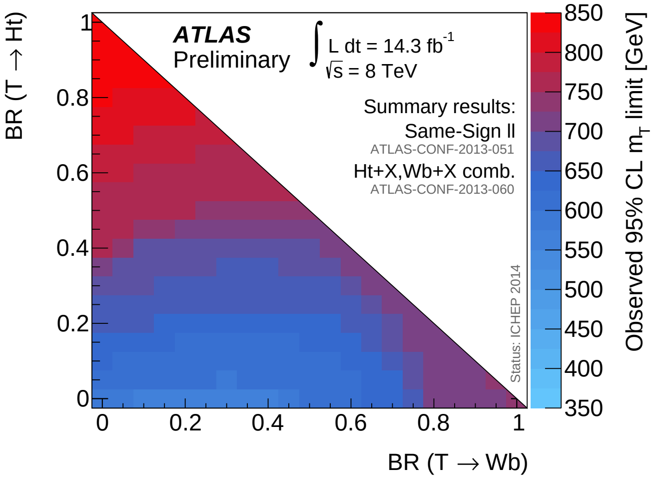

ATLAS
Theory (NNLO)
95% CL expected limit
95% CL expected limit ±1σ
95% CL expected limit ±2σ
95% CL observed limit
∫Ldt = 20.3 fb^-1
√s = 8 TeV
Zb/t + X
Dilep. + Trilep. Combination
SU(2) singlet
σ(pp → TT̄) [pb]
m_T [GeV]


ATLAS
Theory (NNLO)
95% CL expected limit
95% CL expected limit ±1σ
95% CL expected limit ±2σ
95% CL observed limit
∫Ldt = 20.3 fb^-1
√s = 8 TeV
Zb/t + X
Dilep. + Trilep. Combination
SU(2) (T,B) doublet
σ(pp → TT̄) [pb]
m_T [GeV]


ATLAS
$\sqrt{s}$ = 8 TeV
$\int$ L dt = 20.3 fb^{-1}
Zb/t + X
Dilep. + Trilep.
Combination
BR (T → Ht)
BR (T → Wb)
Observed 95% CL m_T limit [GeV]
0
0.2
0.4
0.6
0.8
1
350
400
450
500
550
600
650
700
750
800
850


ATLAS
$\sqrt{s}$ = 8 TeV
$\int$ L dt = 20.3 fb^{-1}
Zb/t + X
Dilep. + Trilep.
Combination
BR (B → Hb)
BR (B → Wt)
Observed 95% CL m_B limit [GeV]
0
0.2
0.4
0.6
0.8
1
350
400
450
500
550
600
650
700
750
800
850


ATLAS Preliminary
$\int L\,dt = 14.3\ fb^{-1}$
$\sqrt{s} = 8$ TeV
Summary results:
Same-Sign ll
ATLAS-CONF-2013-051
Status: ICHEP 2014
BR (T → Ht)
BR (T → Wb)
Observed 95% CL m_T limit [GeV]
0
0.2
0.4
0.6
0.8
1
350
400
450
500
550
600
650
700
750
800
850


ATLAS Preliminary
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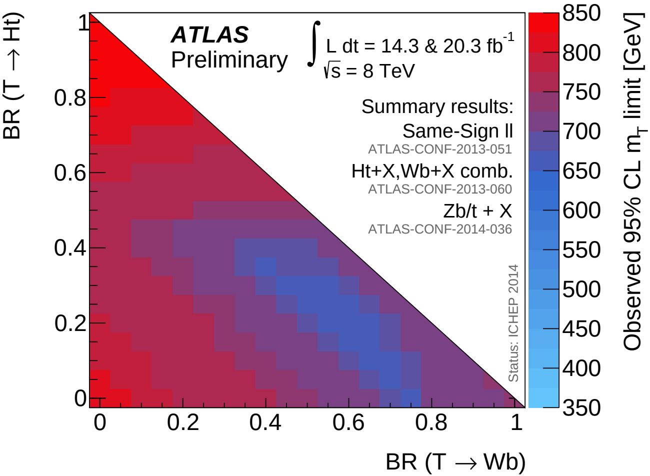
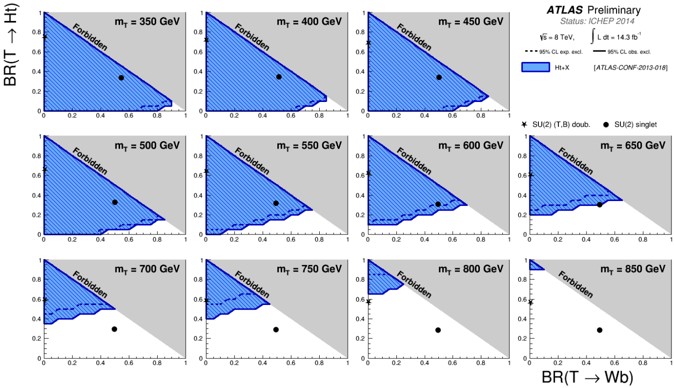
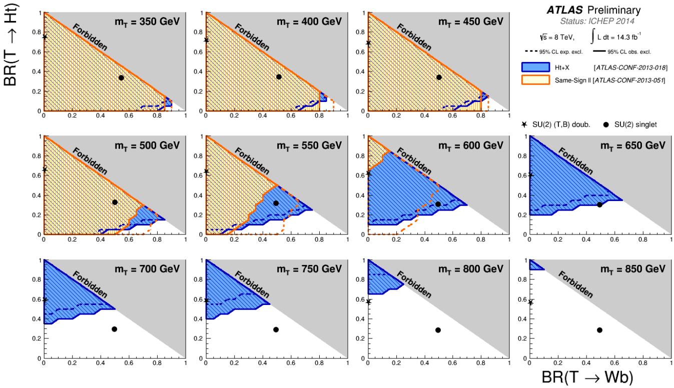
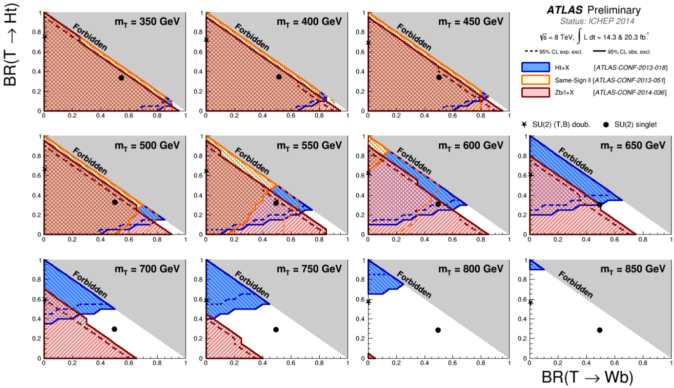
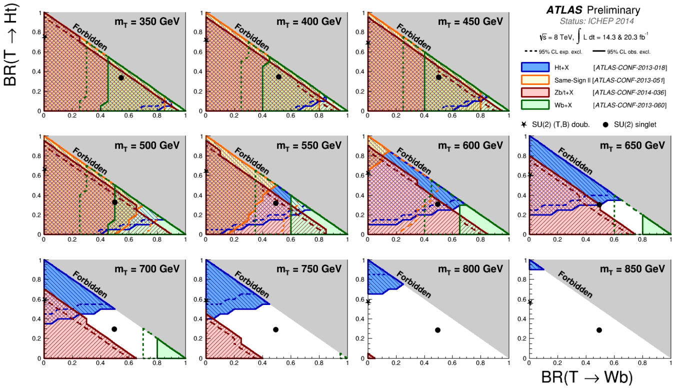
$\sqrt{s}$ = 8 TeV
Summary results:
Same-Sign ll
ATLAS-CONF-2013-051
Ht+X,Wb+X comb.
ATLAS-CONF-2013-060
Status: ICHEP 2014
BR (T → Ht)
BR (T → Wb)
Observed 95% CL m_T limit [GeV]
0
0.2
0.4
0.6
0.8
1
350
400
450
500
550
600
650
700
750
800
850

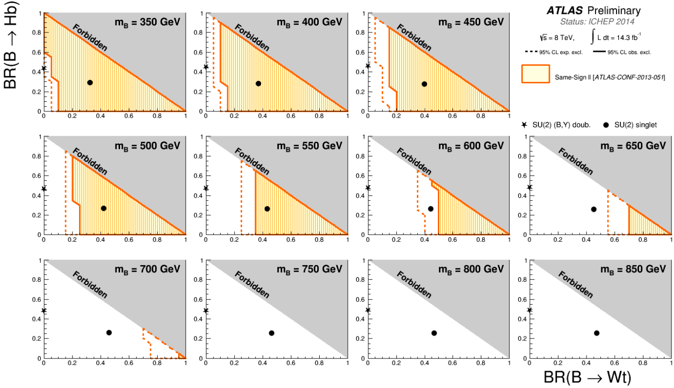

ATLAS Preliminary
∫ L dt = 14.3 & 20.3 fb^{-1}
√s = 8 TeV
Summary results:
Same-Sign ll
ATLAS-CONF-2013-051
Ht+X,Wb+X comb.
ATLAS-CONF-2013-060
Zb/t + X
ATLAS-CONF-2014-036
Status: ICHEP 2014
BR (T → Ht)
BR (T → Wb)
Observed 95% CL m_T limit [GeV]
0
0.2
0.4
0.6
0.8
1
350
400
450
500
550
600
650
700
750
800
850

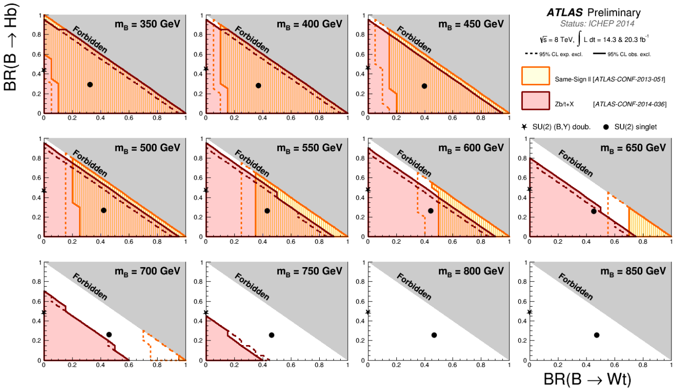

ATLAS Preliminary
Status: ICHEP 2014
√s = 8 TeV, ∫ L dt = 14.3 fb⁻¹
95% CL exp. excl.
95% CL obs. excl.
Ht+X
[ATLAS-CONF-2013-018]
SU(2) (T,B) doub.
SU(2) singlet
m_T = 350 GeV
m_T = 400 GeV
m_T = 450 GeV
m_T = 500 GeV
m_T = 550 GeV
m_T = 600 GeV
m_T = 650 GeV
m_T = 700 GeV
m_T = 750 GeV
m_T = 800 GeV
m_T = 850 GeV
Forbidden
BR(T → Ht)
BR(T → Wb)


ATLAS Preliminary
Status: ICHEP 2014
√s = 8 TeV, ∫ L dt = 14.3 fb⁻¹
95% CL exp. excl.
95% CL obs. excl.
Ht+X [ATLAS-CONF-2013-018]
Same-Sign ll [ATLAS-CONF-2013-051]
SU(2) (T,B) doub.
SU(2) singlet
m_T = 350 GeV
m_T = 400 GeV
m_T = 450 GeV
m_T = 500 GeV
m_T = 550 GeV
m_T = 600 GeV
m_T = 650 GeV
m_T = 700 GeV
m_T = 750 GeV
m_T = 800 GeV
m_T = 850 GeV
Forbidden
BR(T → Ht)
BR(T → Wb)


ATLAS Preliminary
Status: ICHEP 2014
√s = 8 TeV, ∫ L dt = 14.3 & 20.3 fb⁻¹
95% CL exp. excl.
95% CL obs. excl.
Ht+X [ATLAS-CONF-2013-018]
Same-Sign ll [ATLAS-CONF-2013-051]
Zb/t+X [ATLAS-CONF-2014-036]
SU(2) (T,B) doub.
SU(2) singlet
m_T = 350 GeV
m_T = 400 GeV
m_T = 450 GeV
m_T = 500 GeV
m_T = 550 GeV
m_T = 600 GeV
m_T = 650 GeV
m_T = 700 GeV
m_T = 750 GeV
m_T = 800 GeV
m_T = 850 GeV
Forbidden
BR(T → Ht)
BR(T → Wb)


ATLAS Preliminary
Status: ICHEP 2014
√s = 8 TeV, ∫ L dt = 14.3 & 20.3 fb⁻¹
95% CL exp. excl.
95% CL obs. excl.
Ht+X [ATLAS-CONF-2013-018]
Same-Sign ll [ATLAS-CONF-2013-051]
Zb/t+X [ATLAS-CONF-2014-036]
Wb+X [ATLAS-CONF-2013-060]
SU(2) (T,B) doub.
SU(2) singlet
m_T = 350 GeV
m_T = 400 GeV
m_T = 450 GeV
m_T = 500 GeV
m_T = 550 GeV
m_T = 600 GeV
m_T = 650 GeV
m_T = 700 GeV
m_T = 750 GeV
m_T = 800 GeV
m_T = 850 GeV
Forbidden
BR(T → Ht)
BR(T → Wb)

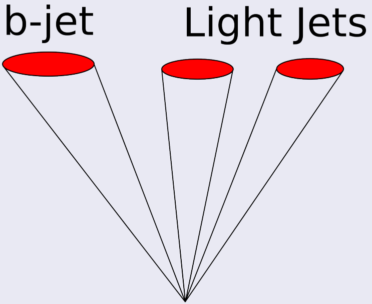

ATLAS Preliminary
Status: ICHEP 2014
√s = 8 TeV, ∫ L dt = 14.3 fb⁻¹
95% CL exp. excl.
95% CL obs. excl.
Same-Sign ll [ATLAS-CONF-2013-051]
SU(2) (B,Y) doub.
SU(2) singlet
BR(B → Hb)
BR(B → Wt)
m_B = 350 GeV
m_B = 400 GeV
m_B = 450 GeV
m_B = 500 GeV
m_B = 550 GeV
m_B = 600 GeV
m_B = 650 GeV
m_B = 700 GeV
m_B = 750 GeV
m_B = 800 GeV
m_B = 850 GeV
Forbidden


ATLAS Preliminary
Status: ICHEP 2014
√s = 8 TeV, ∫ L dt = 14.3 & 20.3 fb⁻¹
95% CL exp. excl.
95% CL obs. excl.
Same-Sign ll [ATLAS-CONF-2013-051]
Zb/t+X [ATLAS-CONF-2014-036]
SU(2) (B,Y) doub.
SU(2) singlet
m_B = 350 GeV
m_B = 400 GeV
m_B = 450 GeV
m_B = 500 GeV
m_B = 550 GeV
m_B = 600 GeV
m_B = 650 GeV
m_B = 700 GeV
m_B = 750 GeV
m_B = 800 GeV
m_B = 850 GeV
Forbidden
BR(B → Hb)
BR(B → Wt)

When pushing to higher energies, new factors come into play:

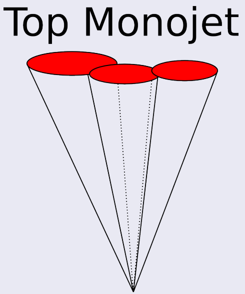
Low Energy tops

$t \to bW, W \to qq'$ gives three distinct "jets":



High Energy tops

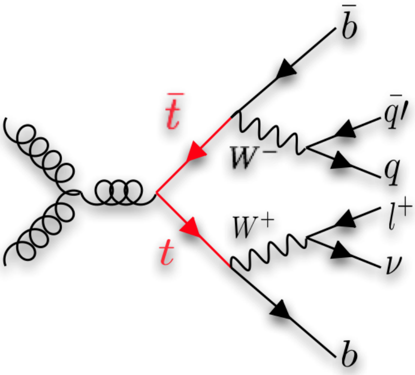
top decay system is highly boosted and reconstructed as only one jet:



Need new techniques to identify these boosted objects

An ideal test case is a search for high-mass particles decaying to $t\bar{t}$:

- Use the l+jets topology
- Lepton and E_T^{miss} cuts ensure sample is quite pure
- Can search for new physics
- Can verify that jet substructure variables are well described

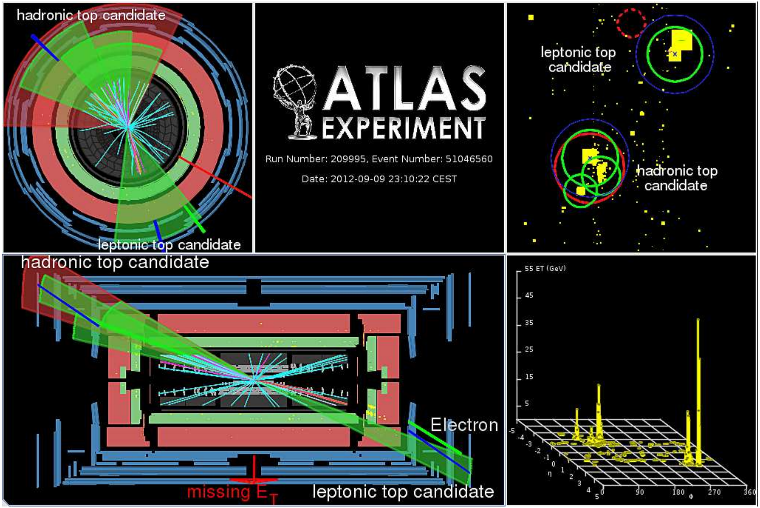


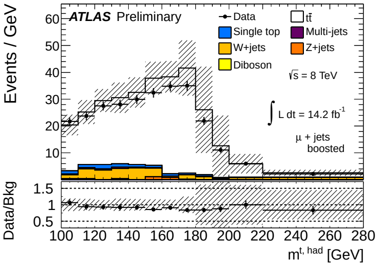
ATLAS-CONF-2013-052

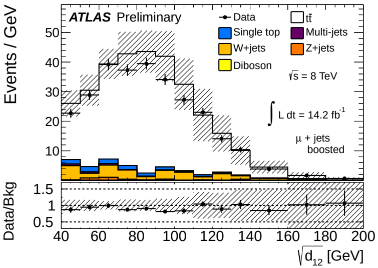
Search strategy adopted by ATLAS, combines two selections:

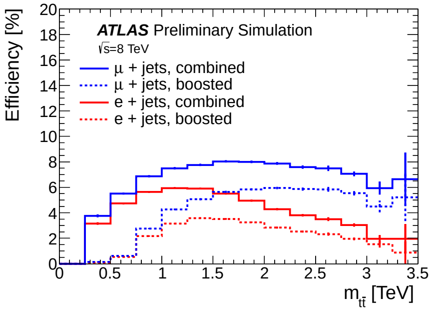
- **Resolved**
  - lepton
  - E_T^{miss}
  - ≥ 3 jets
  - ≥ 1 b-jet
- **Boosted:**
  - lepton
  - E_T^{miss}
  - ≥ 1 large-R jet with $p_T > 350$ GeV and large jet-mass
  - ≥ 1 b-jet

Example Event

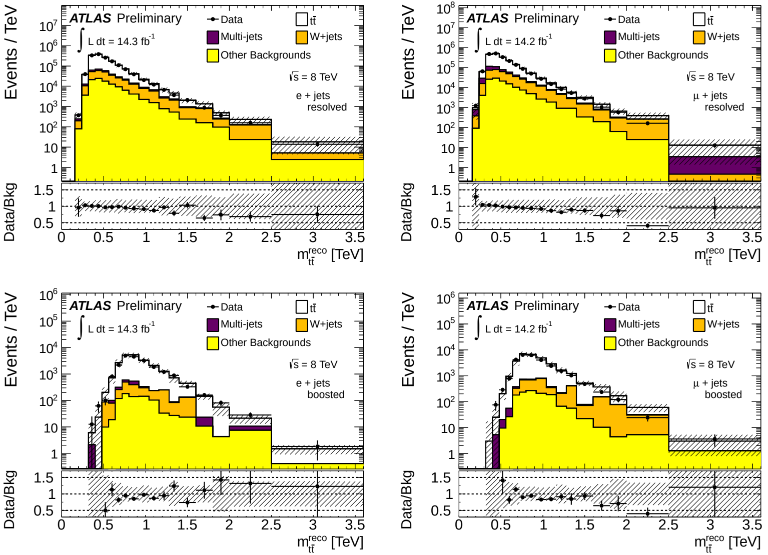


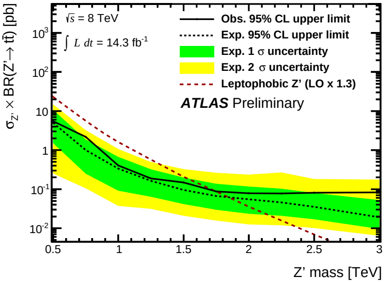


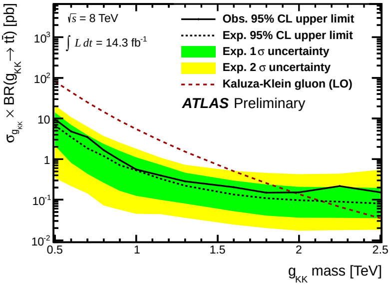




- Jet Mass and k_t splitting scale used to identify top-jet candidates
- Resulting *boosted* selection provides most of the efficiency for $m_{t\bar{t}} > 1\,\mathrm{TeV}$.


ATLAS Preliminary
∫ L dt = 14.3 fb⁻¹
Data
tt̄
Multi-jets
W+jets
Other Backgrounds
√s = 8 TeV
e + jets resolved
Events / TeV
Data/Bkg
m_tt̄^reco [TeV]
ATLAS Preliminary
∫ L dt = 14.2 fb⁻¹
μ + jets resolved
ATLAS Preliminary
∫ L dt = 14.3 fb⁻¹
e + jets boosted
ATLAS Preliminary
∫ L dt = 14.2 fb⁻¹
μ + jets boosted

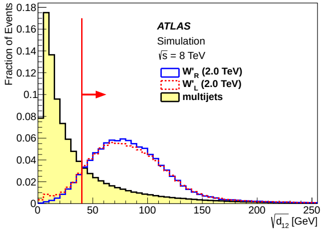

√s = 8 TeV
∫ L dt = 14.3 fb⁻¹
Obs. 95% CL upper limit
Exp. 95% CL upper limit
Exp. 1 σ uncertainty
Exp. 2 σ uncertainty
Leptophobic Z' (LO x 1.3)
ATLAS Preliminary
σ_Z' × BR(Z'→tt̄) [pb]
Z' mass [TeV]

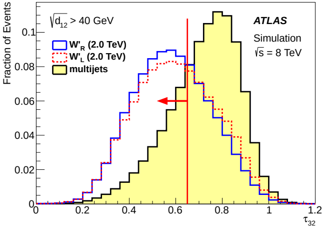

√s = 8 TeV
∫ L dt = 14.3 fb⁻¹
Obs. 95% CL upper limit
Exp. 95% CL upper limit
Exp. 1σ uncertainty
Exp. 2σ uncertainty
Kaluza-Klein gluon (LO)
ATLAS Preliminary
σ_gKK × BR(g_KK→tt̄) [pb]
g_KK mass [TeV]

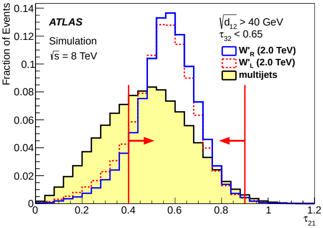
- Choice of substructure variables in $X \to t\bar{t}$ analysis employed a very loose top-tagging selection.
- More discriminating, but less efficient, tagging can also be applied
- A nice example is the search for $W' \to tb$

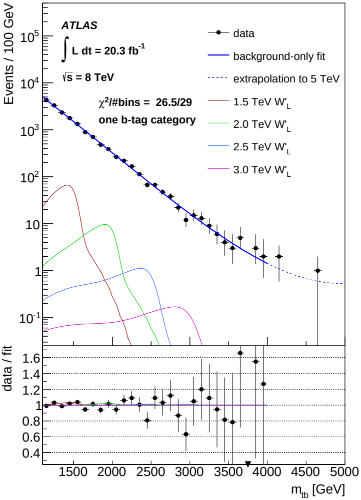
arXiv:1408.0886

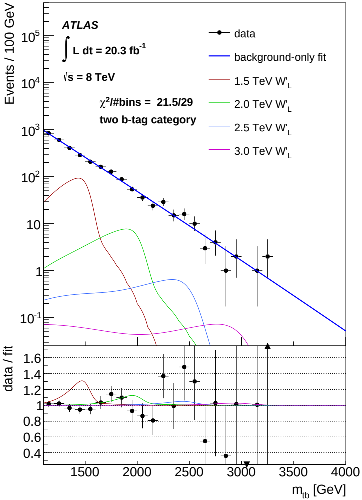
$W' \rightarrow tb$



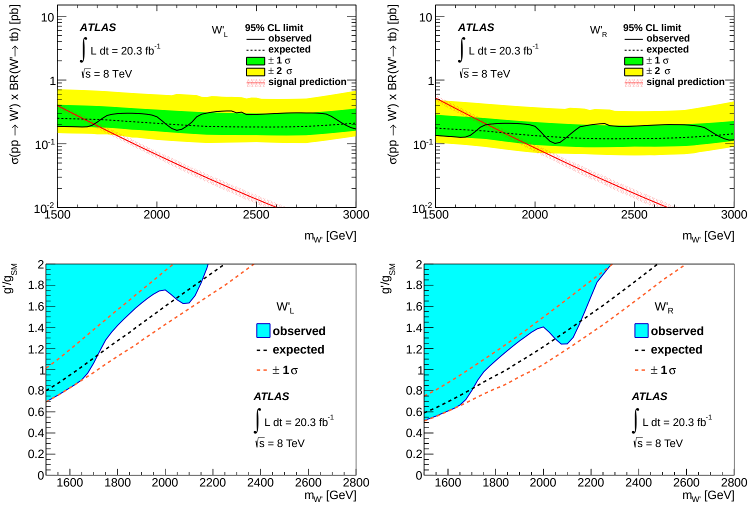


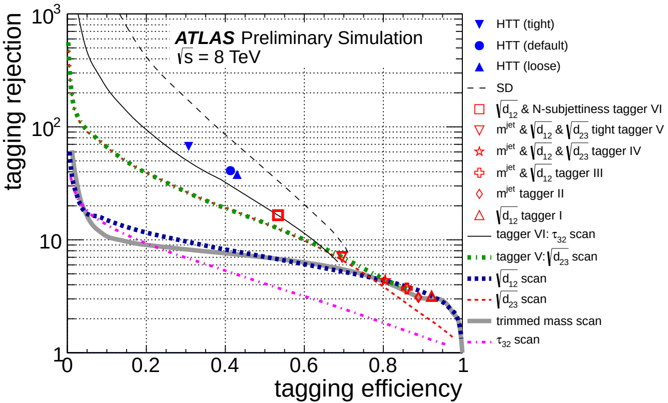



ATLAS
∫ L dt = 20.3 fb⁻¹
√s = 8 TeV
χ²/#bins = 26.5/29
one b-tag category
data
background-only fit
extrapolation to 5 TeV
1.5 TeV W'L
2.0 TeV W'L
2.5 TeV W'L
3.0 TeV W'L
Events / 100 GeV
data / fit
m_tb [GeV]


ATLAS
∫ L dt = 20.3 fb⁻¹
√s = 8 TeV
χ²/#bins = 21.5/29
two b-tag category
data
background-only fit
1.5 TeV W'L
2.0 TeV W'L
2.5 TeV W'L
3.0 TeV W'L
Events / 100 GeV
data / fit
m_tb [GeV]

$W' \to tb$


ATLAS
∫ L dt = 20.3 fb^{-1}
√s = 8 TeV
W'$_L$
W'$_R$
95% CL limit
observed
expected
± 1 σ
± 2 σ
signal prediction
σ(pp → W') x BR(W'→ tb) [pb]
m$_{W'}$ [GeV]
g'/g$_{SM}$
observed
expected
± 1σ



Many different top-taggers on the market, possible to choose the best working point for any given search (ATLAS-CONF-2013-084 ATLAS-CONF-2014-003)

As well as relatively dedicated searches, there is an increasing trend towards producing results that are more widely applicable:

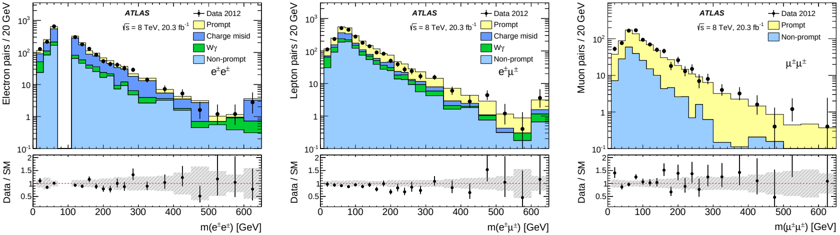
- Fiducial cross section limits
- Limits associated with parametrised efficiency
- Global searches for any discrepancies

These offer the chance to catch new physics that we hadn't thought of and they give others the potential to test new models against existing searches.

Many models predict signatures with same-sign leptons in the final state, but

- There are too many models to test each individually
- So instead of optimising on many models, ATLAS chooses to set fiducial limits

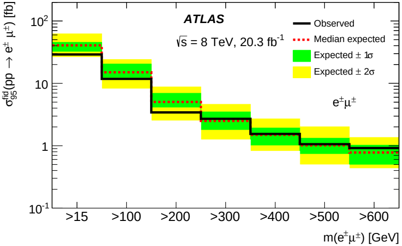
arXiv:1412.0237

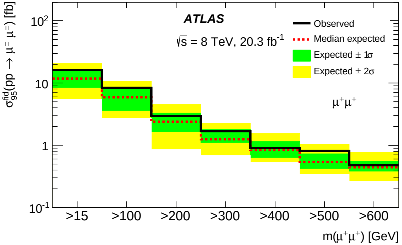


- Select events with like-sign lepton pairs $ee,\mu\mu.e\mu$
- in *ee* channel exclude mass window around *Z* (large charge-flip background there)
- No requirement on E_T^{miss}

Common particle-level and reconstruction level selection is used:

Selection	Electron requirement	Muon requirement
Leading lepton p_T	$p_T > 25$ GeV	$p_T > 25$ GeV
Subleading lepton p_T	$p_T > 20$ GeV	$p_T > 20$ GeV
Lepton η	$\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.47$	$\lvert\eta\rvert < 2.5$
Isolation	$\sum p_T(\Delta R = 0.3)/p_T^e < 0.1$	$\sum p_T(\Delta R = 0.3)/p_T^\mu < 0.07$
Selection	**Event selection**	
Lepton pair	Same-sign pair with $m_{\ell\ell} > 15$ GeV	
Electron pair	Veto pairs with $70 < m_{\ell\ell} < 110$ GeV	
Event	No opposite-sign same-flavour pair with $\lvert m_{\ell\ell} - m_Z\rvert < 10$ GeV	



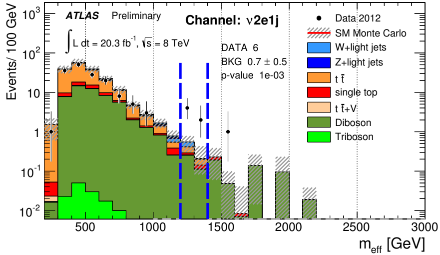


- Evaluate efficiency in fiducial region using several models:
  - S_{DQ} (Diquark)
  - $H^{\pm\pm}$
  - $W_R \rightarrow lN_R$
  - $b'b' \rightarrow WtWt$
- Use most conservative choice for fiducial limit
- Alternative approach for 3 lepton search in: arXiv:1411.2921:
  - σ_{vis} sections provided
  - Parametrised lepton efficiencies also given

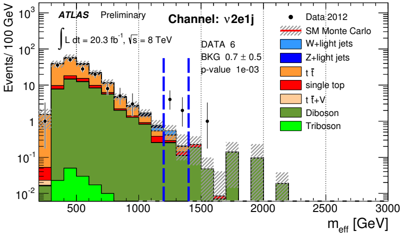
Making sure we don't miss anything big: ATLAS-CONF-2014-006

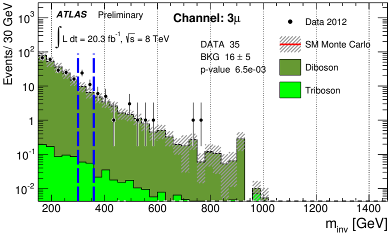
Define physics objects:

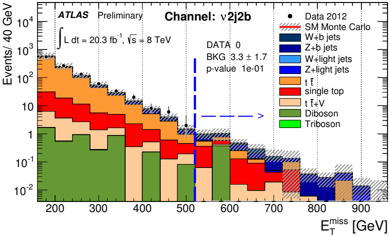
- **electrons**: $p_T > 25$ GeV , $|\eta| < 2.47$
- **muons** : $p_T > 25$ GeV , $|\eta| < 2.4$
- **jets** : $p_T > 50$ GeV , $|\eta| < 2.8$
- **b-jets** : b-tagged jet, $|\eta| < 2.5$
- **photons** : $p_T > 40$ GeV , $|\eta| < 2.37$
- **neutrinos** : $E_T^{\text{miss}} > 150$ GeV

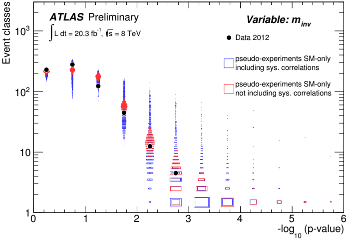


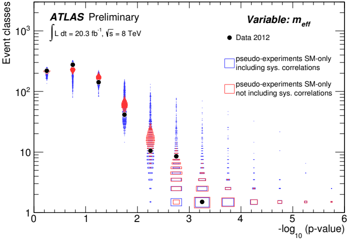
Systematically look at all possible multi-object final states for regions of largest discrepancy (697 with > 0.1 even expected, 573 with data events)

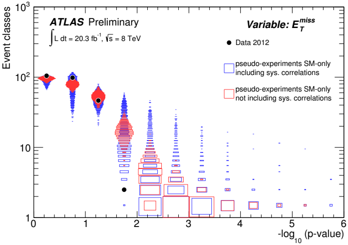

ATLAS Preliminary
Channel: ν2e1j
∫L dt = 20.3 fb-1, √s = 8 TeV
DATA 6
BKG 0.7 ± 0.5
p-value 1e-03
Data 2012
SM Monte Carlo
W+light jets
Z+light jets
t t̄
single top
t t̄+V
Diboson
Triboson
Events/ 100 GeV
m_eff [GeV]


ATLAS Preliminary
Channel: 3μ
∫L dt = 20.3 fb-1, √s = 8 TeV
DATA 35
BKG 16 ± 5
p-value 6.5e-03
Data 2012
SM Monte Carlo
Diboson
Triboson
Events/ 30 GeV
m_inv [GeV]


ATLAS Preliminary
Channel: ν2j2b
∫L dt = 20.3 fb-1, √s = 8 TeV
DATA 0
BKG 3.3 ± 1.7
p-value 1e-01
Data 2012
SM Monte Carlo
W+b jets
Z+b jets
W+light jets
Z+light jets
t t̄
single top
t t̄+V
Diboson
Triboson
Events/ 40 GeV
E_T^miss [GeV]


ATLAS Preliminary
∫L dt = 20.3 fb⁻¹, √s = 8 TeV
Variable: m_inv
Data 2012
pseudo-experiments SM-only including sys. correlations
pseudo-experiments SM-only not including sys. correlations
Event classes
-log10 (p-value)


ATLAS Preliminary
∫L dt = 20.3 fb⁻¹, √s = 8 TeV
Variable: m_eff
Data 2012
pseudo-experiments SM-only including sys. correlations
pseudo-experiments SM-only not including sys. correlations
Event classes
-log10 (p-value)


ATLAS Preliminary
∫L dt = 20.3 fb⁻¹, √s = 8 TeV
Variable: E_T^miss
Data 2012
pseudo-experiments SM-only including sys. correlations
pseudo-experiments SM-only not including sys. correlations
Event classes
-log10 (p-value)

ATLAS Exotics Searches* - 95% CL Exclusion

Status: ICHEP 2014

ATLAS Preliminary

$\int \mathcal{L}\,dt = (1.0 - 20.3)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV

	Model	ℓ,γ	Jets	E_T^{miss}	$\int \mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	1-2 j	Yes	4.7	M_D 4.37 TeV	$n = 2$	1210.4491
	ADD non-resonant $\ell\ell$	$2e,\mu$	–	–	20.3	M_S 5.2 TeV	$n = 3$ HLZ	ATLAS-CONF-2014-030
	ADD QBH $\to \ell q$	$1\ e,\mu$	1 j	–	20.3	M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	20.3	M_{th} 5.82 TeV	$n = 6$	to be submitted to PRD
	ADD BH high N_{trk}	$2\ \mu$ (SS)	–	–	20.3	M_{th} 5.7 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	1308.4075
	ADD BH high $\sum p_T$	$\geq 1\ e,\mu$	≥ 2 j	–	20.3	M_{th} 6.2 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	1405.4254
	RS1 $G_{KK} \to \ell\ell$	$2\ e,\mu$	–	–	20.3	G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \to WW \to \ell\nu\ell\nu$	$2\ e,\mu$	–	Yes	4.7	G_{KK} mass 1.23 TeV	$k/\overline{M}_{Pl} = 0.1$	1208.2880
	Bulk RS $G_{KK} \to ZZ \to \ell\ell qq$	$2\ e,\mu$	2 j / 1 J	–	20.3	G_{KK} mass 730 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-039
	Bulk RS $G_{KK} \to HH \to b\bar{b}b\bar{b}$	–	4 b	–	19.5	G_{KK} mass 590-710 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-005
	Bulk RS $g_{KK} \to t\bar{t}$	$1\ e,\mu$	≥ 1 b, $\geq$ 1J/2j	Yes	14.3	g_{KK} mass 2.0 TeV	BR = 0.925	ATLAS-CONF-2013-052
	S^1/Z_2 ED	$2\ e,\mu$	–	–	5.0	$M_{KK} \approx R^{-1}$ 4.71 TeV		1209.2535
	UED	$2\ \gamma$	–	Yes	4.8	Compact. scale R^{-1} 1.41 TeV		ATLAS-CONF-2012-072
Gauge bosons	SSM $Z' \to \ell\ell$	$2\ e,\mu$	–	–	20.3	Z' mass 2.9 TeV		1405.4123
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	19.5	Z' mass 1.9 TeV		ATLAS-CONF-2013-066
	SSM $W' \to \ell\nu$	$1\ e,\mu$	–	Yes	20.3	W' mass 3.28 TeV		ATLAS-CONF-2014-017
	EGM $W' \to WZ \to \ell\nu\,\ell'\ell'$	$3\ e,\mu$	–	Yes	20.3	W' mass 1.52 TeV		1406.4456
	EGM $W' \to WZ \to qq\ell\ell$	$2\ e,\mu$	2 j / 1 J	–	20.3	W' mass 1.59 TeV		ATLAS-CONF-2014-039
	LRSM $W'_R \to t\bar{b}$	$1\ e,\mu$	2 b, 0-1 j	Yes	14.3	W' mass 1.84 TeV		ATLAS-CONF-2013-050
	LRSM $W'_R \to t\bar{b}$	$0\ e,\mu$	≥ 1 b, 1 J	–	20.3	W' mass 1.77 TeV		to be submitted to EPJC
CI	CI $qqqq$	–	2 j	–	4.8	Λ 7.6 TeV	$\eta = +1$	1210.1718
	CI $qq\ell\ell$	$2\ e,\mu$	–	–	20.3	Λ 21.6 TeV	$\eta_{LL} = -1$	ATLAS-CONF-2014-030
	CI $uutt$	$2\ e,\mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	Λ 3.3 TeV	$\lvert C\rvert = 1$	ATLAS-CONF-2013-051
DM	EFT D5 operator (Dirac)	$0\ e,\mu$	1-2 j	Yes	10.5	M_* 731 GeV	at 90% CL for $m(\chi) < 80$ GeV	ATLAS-CONF-2012-147
	EFT D9 operator (Dirac)	$0\ e,\mu$	1 J, ≤ 1 j	Yes	20.3	M_* 2.4 TeV	at 90% CL for $m(\chi) < 100$ GeV	1309.4017
LQ	Scalar LQ 1st gen	$2\ e$	≥ 2 j	–	1.0	LQ mass 660 GeV	$\beta = 1$	1112.4828
	Scalar LQ 2nd gen	$2\ \mu$	≥ 2 j	–	1.0	LQ mass 685 GeV	$\beta = 1$	1203.3172
	Scalar LQ 3rd gen	$1\ e,\mu, 1\ \tau$	1 b, 1 j	–	4.7	LQ mass 534 GeV	$\beta = 1$	1303.0526
Heavy quarks	Vector-like quark $TT \to Ht + X$	$1\ e,\mu$	≥ 2 b, ≥ 4 j	Yes	14.3	T mass 790 GeV	T in (T,B) doublet	ATLAS-CONF-2013-018
	Vector-like quark $TT \to Wb + X$	$1\ e,\mu$	≥ 1 b, ≥ 3 j	Yes	14.3	T mass 670 GeV	isospin singlet	ATLAS-CONF-2013-060
	Vector-like quark $TT \to Zt + X$	$2/\geq 3\ e,\mu$	$\geq 2/\geq 1$ b	–	20.3	T mass 735 GeV	T in (T,B) doublet	ATLAS-CONF-2014-036
	Vector-like quark $BB \to Zb + X$	$2/\geq 3\ e,\mu$	$\geq 2/\geq 1$ b	–	20.3	B mass 755 GeV	B in (B,Y) doublet	ATLAS-CONF-2014-036
	Vector-like quark $BB \to Wt + X$	$2\ e,\mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	B mass 720 GeV	B in (T,B) doublet	ATLAS-CONF-2013-051
Excited fermions	Excited quark $q^* \to q\gamma$	$1\ \gamma$	1 j	–	20.3	q^* mass 3.5 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1309.3230
	Excited quark $q^* \to qg$	–	2 j	–	20.3	q^* mass 4.09 TeV	only u^* and d^*, $\Lambda = m(q^*)$	to be submitted to PRD
	Excited quark $b^* \to Wt$	1 or 2 e,μ	1 b, 2 j or 1 j	Yes	4.7	b^* mass 870 GeV	left-handed coupling	1301.1583
	Excited lepton $\ell^* \to \ell\gamma$	$2\ e,\mu, 1\ \gamma$	–	–	13.0	ℓ^* mass 2.2 TeV	$\Lambda = 2.2$ TeV	1308.1364
Other	LSTC $a_T \to W\gamma$	$1\ e,\mu, 1\ \gamma$	–	Yes	20.3	a_T mass 960 GeV		to be submitted to PLB
	LRSM Majorana ν	$2\ e,\mu$	2 j	–	2.1	N^0 mass 1.5 TeV	$m(W_R) = 2$ TeV, no mixing	1203.5420
	Type III Seesaw	$2\ e,\mu$	–	–	5.8	$N^\pm$ mass 245 GeV	$\lvert V_e\rvert$=0.055, $\lvert V_\mu\rvert$=0.063, $\lvert V_\tau\rvert$=0	ATLAS-CONF-2013-019
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	$2\ e,\mu$ (SS)	–	–	4.7	$H^{\pm\pm}$ mass 409 GeV	DY production, BR($H^{\pm\pm} \to \ell\ell$)=1	1210.5070
	Multi-charged particles	–	–	–	4.4	multi-charged particle mass 490 GeV	DY production, $\lvert q\rvert = 4e$	1301.5272
	Magnetic monopoles	–	–	–	2.0	monopole mass 862 GeV	DY production, $\lvert g\rvert = 1g_D$	1207.6411

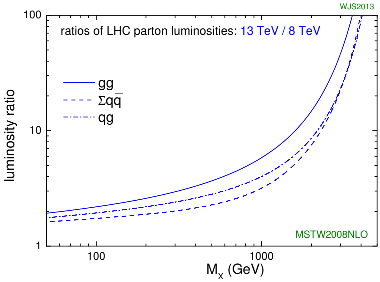
$\sqrt{s}$ = 7 TeV $\sqrt{s}$ = 8 TeV

Mass scale [TeV] (10^{-1}, 1, 10)

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

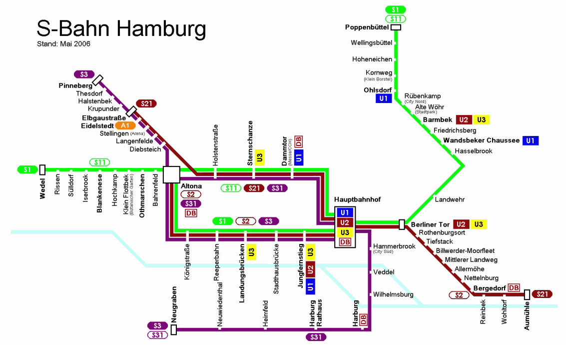
Run-II

- We expect $\mathcal{O}(10)\,\mathrm{fb}^{-1}$ luminosity in 2015
- Should quickly surpass new physics reach from run-I for $M_X > 2$ TeV within the first $5\,\mathrm{fb}^{-1}$
- Surpassed even at around $1\,\mathrm{fb}^{-1}$ for higher masses



  - Searches like dileptonand dijet resonance should come very early
  - But expect increasing number of studies of diboson resonances and third generation searches, these are important tests of compositeness
  - Expect increasing use of boosted techniques for such searches as we reach into the higher mass regime

- Wide range of NP signatures explored
- Extremely strong constraints on many benchmark models
- Still no sign of new physics
- Plenty to explore in the 13 TeV data



Need to look everywhere, surprises can always be lurking where you weren't expecting them...

We need to make sure the results can be interpreted in terms of future models

Conclusion

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- Extremely strong constraints on many benchmark models
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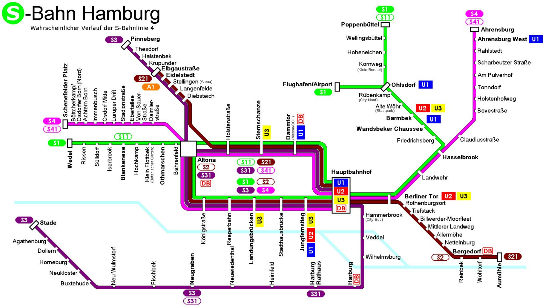


- Need to look everywhere, surprises can always be lurking where you weren't expecting them...
- We need to make sure the results can be interpreted in terms of future models

LHC Collaborations are pushing hard for new and updated results in the next few weeks!

Extra material follows...

N-subjettines variables , τ_N quantify how well jets can be described as containing N or fewer k_t subjets.

Recluster a jet up to N-subjets with the k_t algorithm then calculate τ_N:

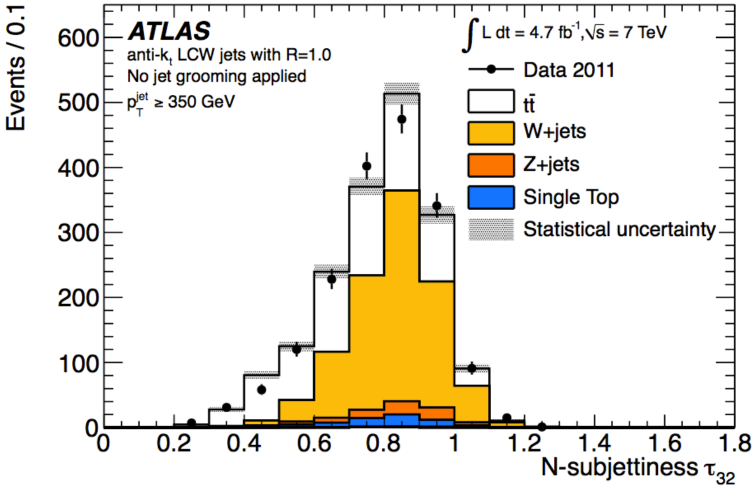
$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \times \min(\Delta R_{1,k}, \Delta R_{2,k}, ..., \Delta R_{3,k})$$

where $\Delta R_{i,k}$ here is the distance in the jet measure (d_{mn}), from subjet i to constituent k.

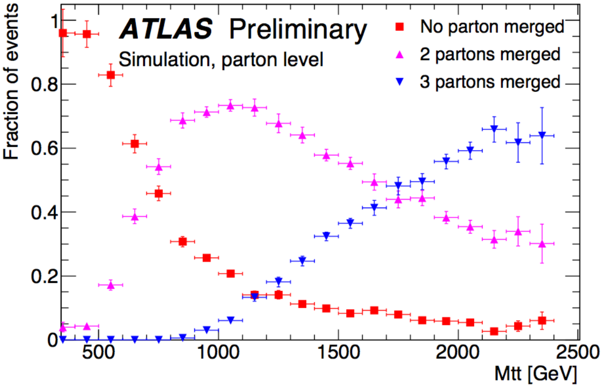
Ratios τ_i/τ_j are referred to as τ_{ij}

Other jet-shape type variables also exist and many have been tested

N-Subjettiness



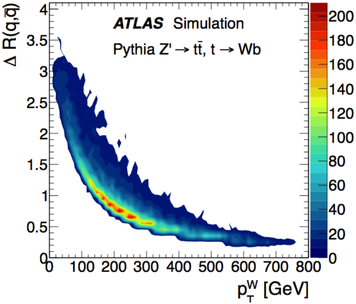
Merging of some description occurs for SM $t\bar{t}$ production:



Effect must be taken into account for SM measurements at higher P_T^t or $M_{t\bar{t}}$ (ATL-PHYS-PUB-2010-008)

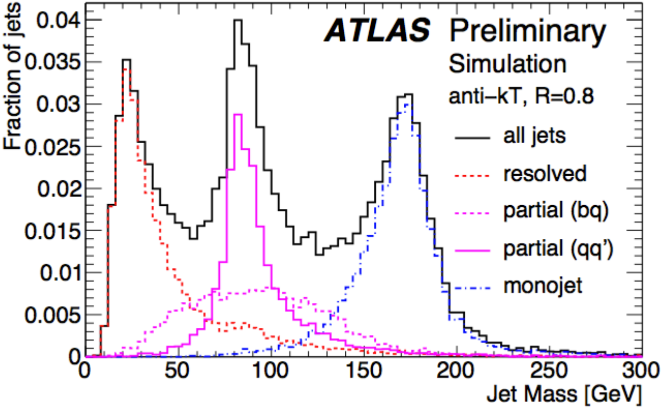
So how to choose the jet algorithm for boosted objects?

- Parameter R usually driven by considering that $\Delta R <\sim \frac{2m}{p_T}$ for a two body decay
  - Typically values $0.8 < R < 1.5$ used for boosted objects ($0.4 \geq R \leq 0.6$ used for "standard" jets)
- Calibration considerations:
  - Regular shape of anti-k_t jets makes calibration and correction for pile-up easier
- Substructure considerations:
  - k_t and C/A cluster history contains more physical information about the jet



Jet Mass

The simplest choice, jet invariant mass:



W and top peaks clearly visible, QCD shape selection dependent

$TT \rightarrow tZ + X$