Boosting new physics searches at ATLAS

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Particle Physics Seminar
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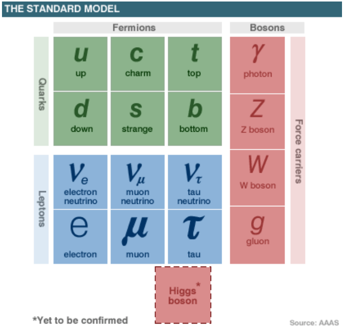
Outline

- Why do we need boosted object identification?
- Calibrating large-R jets
- Tagging jets containing heavy objects
- Outlook

Will focus on the details of ATLAS studies - CMS also has an active and productive boosted object search programme

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)

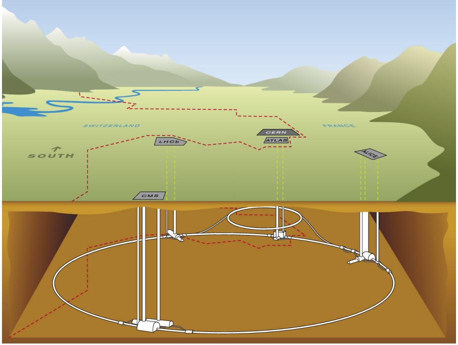
So what's wrong with the Standard Model?

- 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?

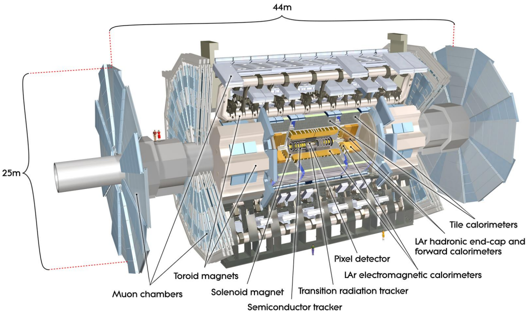
Where to look for answers? The Large Hadron Collider at CERN

- 27 km circumference ring
- Currently collides protons at centre-of-mass energy 8 TeV
- Four detectors installed around the ring
- An excellent environment to test the Standard Model and search for new Physics
- Triviality/Unitarity constraints on some SM cross sections imply a Higgs Boson or <u>something else</u> at an energy scale $< 800\,\mathrm{GeV}$



What equipment to use? A Toroidal Large ApparatuS (ATLAS)

- 4 Detectors:
  - 2 General Purpose
    - **ATLAS**
    - CMS
  - Two Specialised
    - ALICE - Heavy ion
    - LHCb - CP violation



ATLAS with full solid angle coverage, excellent charged particle tracking, particle ID and energy measurement is well-suited for TeV-Scale physics (and so is CMS of course)

Many candidates for new physics, some leading candidates:

- **Fermion/boson symmetry**: New scalar tops, other new heavy particles
- **Extra dimensions (ED)**: New TeV scale bosons and fermions, Heavy quarks that like to decay to 3rd generation quark + EW bosons
- **Compositeness/ Warped ED**: New heavy particles that prefer to couple to heavy SM particles e.g. resonance to $t\bar{t}, WW, ZZ, WZ, HH, ZH$
- **Exotics Higgs:** New charged and neutral scalars that prefer to decay to heavy SM particles

Exclusion limits are pushing towards very high-mass scales

Searches Status

ATLAS Exotics Searches* - 95% CL Exclusion

Status: April 2014

ATLAS Preliminary

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

	Model	ℓ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\,dt$[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 $\ell\ell/\gamma\gamma$	2γ or $2e, \mu$	–	–	4.7	M_S 4.18 TeV	$n = 3$ HLZ NLO	1211.1150
	ADD QBH $\to \ell q$	1 e, μ	1 j	–	20.3	M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD BH high N_{trk}	2 μ (SS)	–	–	20.3	M_{th} 5.7 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	1308.4075
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	20.3	M_{th} 6.2 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	ATLAS-CONF-2014-016
	RS1 $G_{KK} \to \ell\ell$	2 e, μ	–	–	20.3	G_{KK} mass 2.47 TeV	$k/\overline{M}_{Pl} = 0.1$	ATLAS-CONF-2013-017
	RS1 $G_{KK} \to ZZ \to \ell\ell qq/\ell\ell\ell\ell$	2 or 4 e, μ	2 j or –	–	1.0	G_{KK} mass 845 GeV	$k/\overline{M}_{Pl} = 0.1$	1203.0718
	RS1 $G_{KK} \to WW \to \ell\nu\ell\nu$	2 e, μ	–	Yes	4.7	G_{KK} mass 1.23 TeV	$k/\overline{M}_{Pl} = 0.1$	1208.2880
	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, μ	≥ 1 b, ≥ 1J/2j	Yes	14.3	g_{KK} mass 0.5-2.0 TeV	BR = 0.925	ATLAS-CONF-2013-052
	S^1/Z_2 ED	2 e, μ	–	–	5.0	$M_{KK} \approx R^{-1}$ 4.71 TeV		1209.2535
	UED	2 γ	–	Yes	4.8	Compact. scale R^{-1} 1.41 TeV		ATLAS-CONF-2012-072
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	20.3	Z' mass 2.86 TeV		ATLAS-CONF-2013-017
	SSM $Z' \to \tau\tau$	2 τ	–	–	19.5	Z' mass 1.9 TeV		ATLAS-CONF-2013-066
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	20.3	W' mass 3.28 TeV		ATLAS-CONF-2014-017
	EGM $W' \to WZ \to \ell\nu\,\ell'\ell'$	3 e, μ	–	Yes	20.3	W' mass 1.52 TeV		ATLAS-CONF-2014-015
	LRSM $W'_R \to t\bar{b}$	1 e, μ	2 b, 0-1 j	Yes	14.3	W' mass 1.84 TeV		ATLAS-CONF-2013-050
CI	CI $qqqq$	–	2 j	–	4.8	Λ 7.6 TeV	$\eta = +1$	1210.1718
	CI $qq\ell\ell$	2 e, μ	–	–	5.0	Λ 13.9 TeV	$\eta_{LL} = -1$	1211.1150
	CI $uutt$	2 e, μ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	Λ 3.3 TeV	$\lvert C\rvert = 1$	ATLAS-CONF-2013-051
DM	EFT D5 operator	–	1-2 j	Yes	10.5	M_* 731 GeV	at 90% CL for $m(\chi) < 80$ GeV	ATLAS-CONF-2012-147
	EFT D9 operator	–	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 μ	≥ 2 j	–	1.0	LQ mass 685 GeV	$\beta = 1$	1203.3172
	Scalar LQ 3rd gen	1 e, μ, 1 τ	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, μ	≥ 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, μ	≥ 1 b, ≥ 3 j	Yes	14.3	T mass 670 GeV	isospin singlet	ATLAS-CONF-2013-060
	Vector-like quark $BB \to Zb + X$	2 e, μ	≥ 2 b	–	14.3	B mass 725 GeV	B in (B,Y) doublet	ATLAS-CONF-2013-056
	Vector-like quark $BB \to Wt + X$	2 e, μ (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 γ	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	–	13.0	q^* mass 3.84 TeV	only u^* and d^*, $\Lambda = m(q^*)$	ATLAS-CONF-2012-148
	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, μ, 1 γ	–	–	13.0	ℓ^* mass 2.2 TeV	$\Lambda = 2.2$ TeV	1308.1364
Other	LRSM Majorana ν	2 e, μ	2 j	–	2.1	N^0 mass 1.5 TeV	$m(W_R) = 2$ TeV, no mixing	1203.5420
	Type III Seesaw	2 e, μ	–	–	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, μ (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

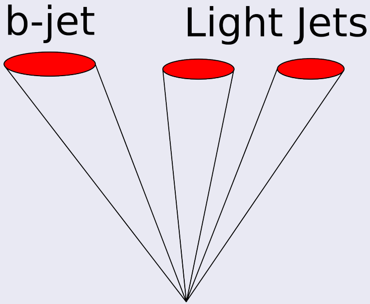
10^{-1} 1 10 Mass scale [TeV]

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

When pushing to higher energies, new factors come into play e.g. for top quarks:

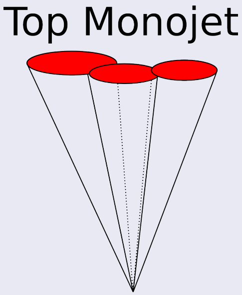
Low-energy tops

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



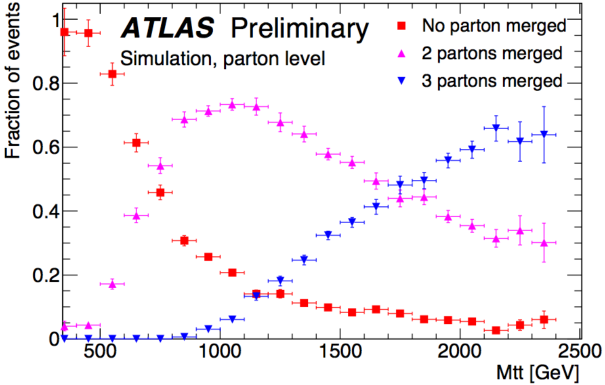
High-energy tops

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



Need new techniques to identify these boosted objects

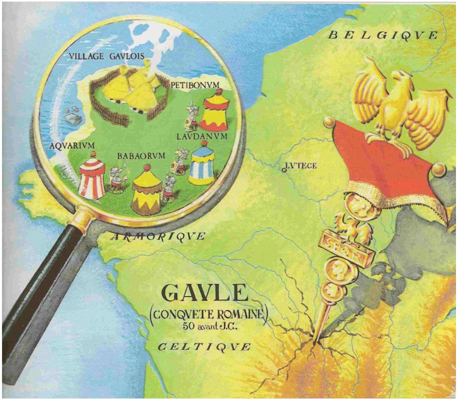
Merging of some description occurs for SM $t\bar{t}$ production:



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

Question: How can we handle this merging ?

Answer: Probe the substructure of the jets!



- Select a large radius jet to ensure you capture all particles of interest
- Resolve the image at a smaller scale to identify interesting substructure
- Or use well chosen variables that highlight characteristic features of EW decays vs QCD jet formation

Large-radius jets and substructure

Jets formed by the successive recombinations of pairs of particles:

Distance parameter

$$d_{ij} = \min(k_{T,i}^{2p}, k_{T,j}^{2p}) \frac{(\Delta\phi_{i,j}^2 + \Delta y_{i,j}^2)}{R^2}$$

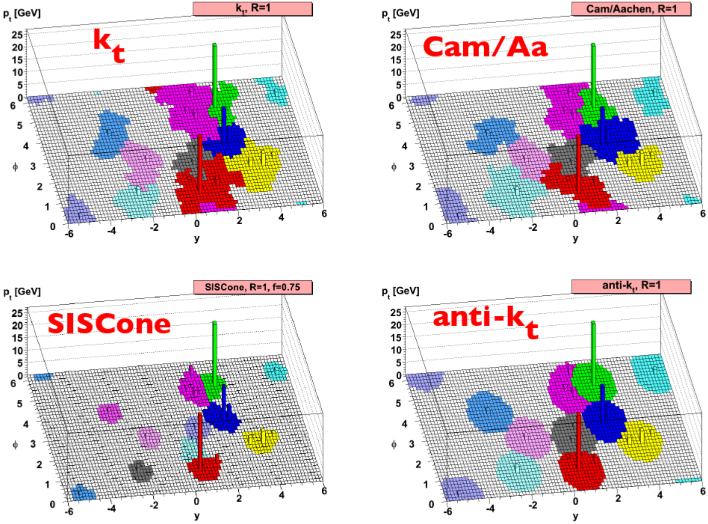
- $p = 1$ - k_T algorithm
- $p = 0$ - Aachen/Cambridge algorithm
- $p = -1$ - Anti-k_T algorithm

- Find pair with smallest d_{ij}
- if $d_{iB} = k_{T,i}^2 < d_{ij}$ then i is a *jet* and is no longer considered
- Else, replace pair with one *pseudojet* with four-momentum $k_i + k_j$

All of these algorithms are infra-red and collinear safe.
Jets in event depend on R and algorithm choice

Clustering History conveys information about the jet, d_{ij} tends to increase ∼monotonically throughout the procedure:

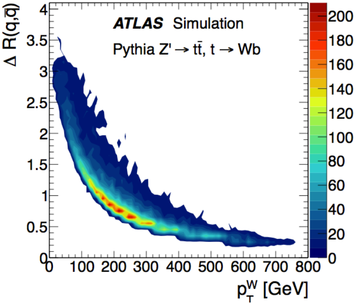
- k_t merges softest particles first - at last stage of merging pseudojets have high-p_T and large spatial separation
- C/A merges spatially-closest pairs of particles first - at last stage of merging pseudojets are widest angle pair
- Anti-k_t finds hardest particle and clusters the spatially closets particles with $\Delta R < R$ - at last stage of merging particle with largest spatial distance to centre of jet is combined with central core



M. Cacciari, G.P.Salam,G. Soyez. JHEP **0804** (2008) 063

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



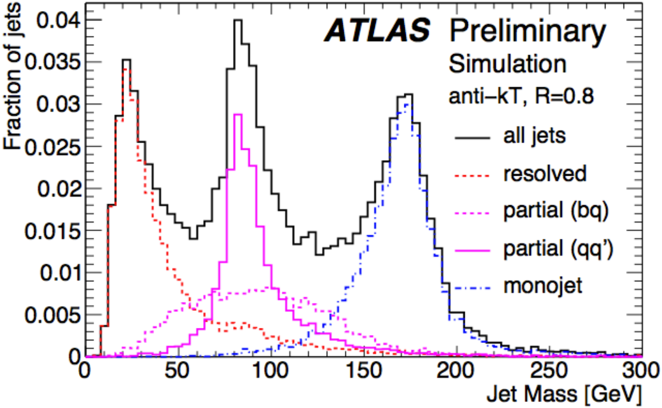
What kind of substructure variables can we use?

- The jet mass
- Values related to d_{ij} in the cluster history
- Jet shape variables such as *N-subjettiness* constructed from all constuents of the jet

Combinations also possible, e.g. minimum pairwise mass of hardest three subjets, etc.

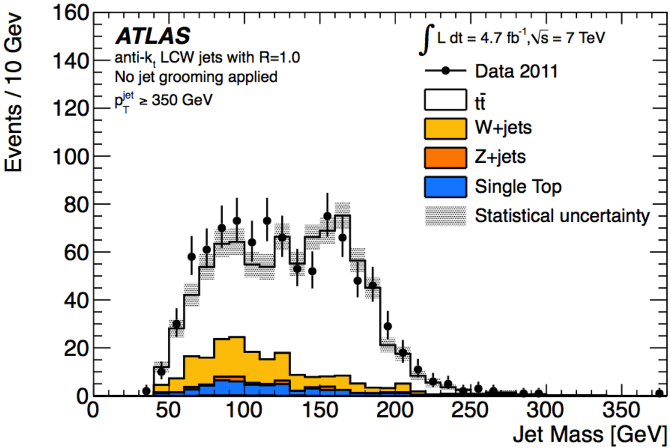
Jet Mass

The simplest choice, jet invariant mass:



W and top peaks clearly visible, QCD shape selection dependent

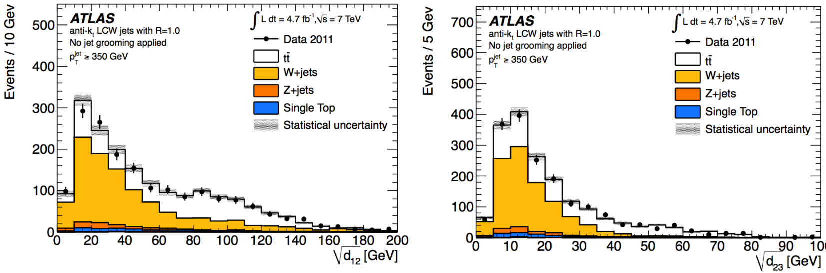
How does it look compared to data?



d_{ij} and Friends

Example of a variable that uses the cluster history is d_{12}:

- Recluster the original jet with the k_t algorithm
- Force the relustering to stop when there are two pseudojets left
- Calculate $d_{12} = \min(p_{T,1}, p_{T,2})\Delta R_{12}$
- Gives a "splitting scale" variable once raised to power $1/2$
- Analagous variables: d_{23} for three pseduojets and so on
- Less scale dependent variables can be constructed by dividing by jet Energy, jet p_T, jet mass or $\sqrt{m^2 + d_{ij}}$ (also sometimes known as z_{12})


ATLAS
anti-k_t LCW jets with R=1.0
No jet grooming applied
$p_T^{jet} \geq 350$ GeV
$\int L\,dt = 4.7$ fb^{-1}, $\sqrt{s} = 7$ TeV
Data 2011
$t\bar{t}$
W+jets
Z+jets
Single Top
Statistical uncertainty
Events / 10 Gev
$\sqrt{d_{12}}$ [GeV]
ATLAS
anti-k_t LCW jets with R=1.0
No jet grooming applied
$p_T^{jet} \geq 350$ GeV
$\int L\,dt = 4.7$ fb^{-1}, $\sqrt{s} = 7$ TeV
Data 2011
$t\bar{t}$
W+jets
Z+jets
Single Top
Statistical uncertainty
Events / 5 Gev
$\sqrt{d_{23}}$ [GeV]

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:

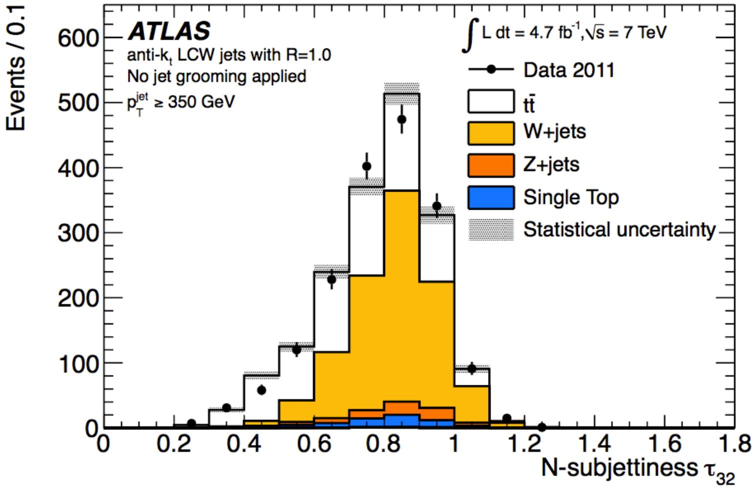
$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \times \min(\Delta R_{1,k}, \Delta R_{2,k}, ..., \Delta R_{3,k})$$

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

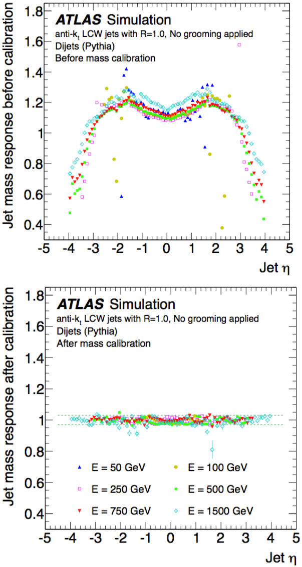
N-Subjettiness



The large-R jets are calibrated using a Monte-Carlo based method:

- Locally calibrated clusters of energy from the calorimeter are fed to the jet algorithms (corrections applied based on response from single-pion MC)
- Jet response to p_T and **m** is corrected using relationship between true and reconstructed jet values in MC

(ATLAS Coll., JHEP09 (2013) 076)



Validation

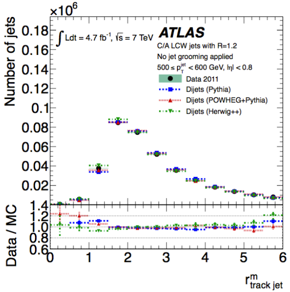
The calibration is mainly validated using track-jets:

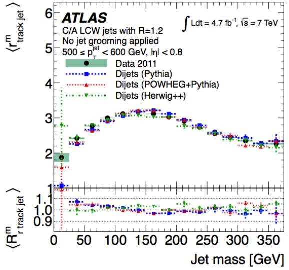
- Use ratio calorimeter to track based quantities:

$$r^{m}_{\text{track jet}} = \frac{m^{\text{jet}}}{m^{\text{track jet}}}$$

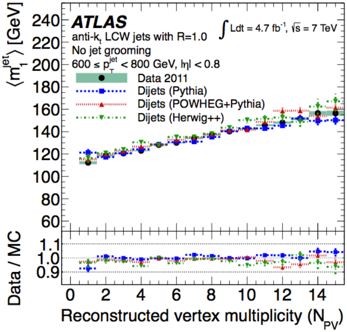
- In particular, the double ratio is used to quantify uncertainties:

$$R^{m}_{r\text{track jet}} = \frac{r^{m,\text{data}}_{\text{track jet}}}{r^{m,\text{MC}}_{\text{track jet}}}$$





Grooming

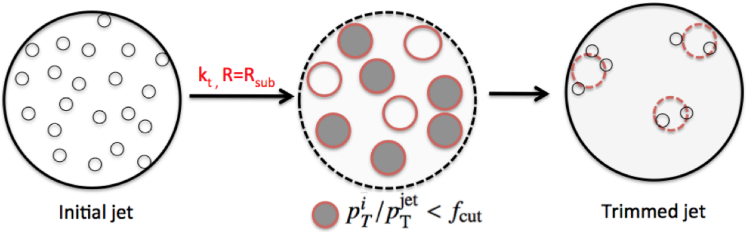


Additional challenge for large-radius jets:

- Mass (and other substructure) is sensitive to pile-up
- Need a way to mitigate this effect

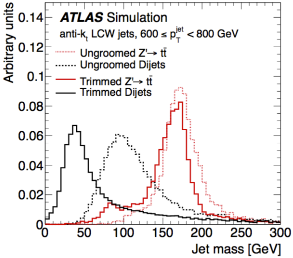
Common techniques: *Trimming*, *Pruning*, *mass-drop filtering*

Trimming

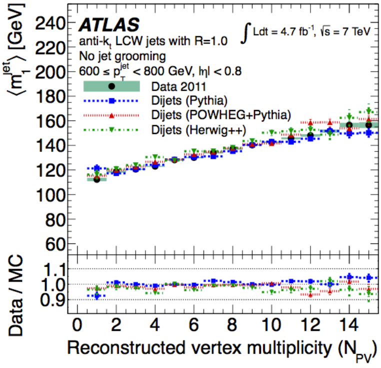


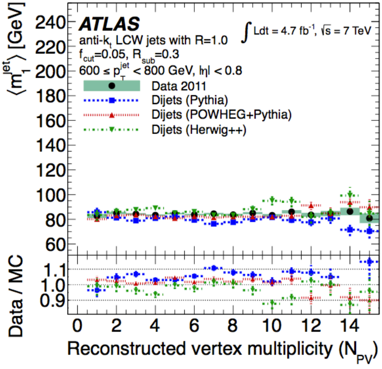
Typical example parameters for ATLAS:

- Intial jet: $R = 1.0$ Anti-k_t
- $f_{\mathrm{cut}} = 0.05$
- $R_{\mathrm{sub}} = 0.3$

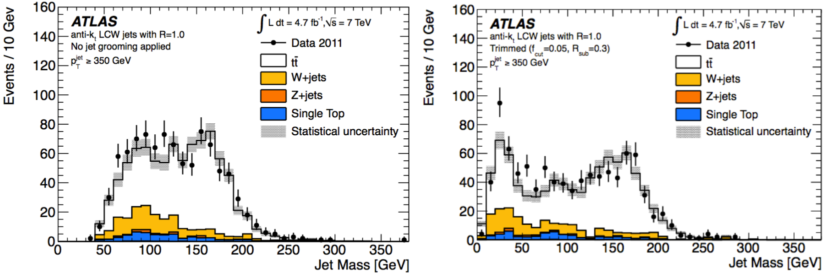


Trimming performance





Trimming performance

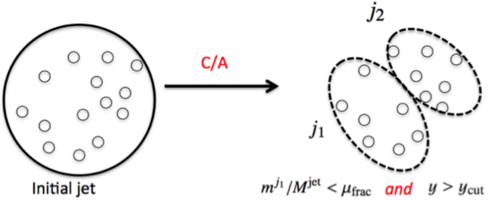


Tagging jets from boosted tops and EW bosons

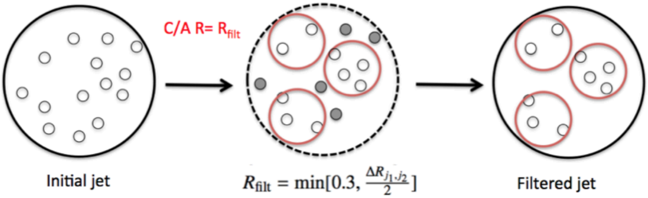
- Boosted-object taggers have been extensively studied at ATLAS
- I will discuss three taggers
  - The BDRS Tagger (Mass-Drop Filter)
  - The HepTopTagger
  - Shower Deconstruction
- Other dedicated taggers are available
- One can also use cuts on substructure to tag jets

ATLAS studies from: ATLAS - JHEP 1309 (2013) 076, ATLAS-CONF-2013-084, ATLAS-CONF-2013-087, ATLAS-CONF-2014-003, ATLAS-PHYS-PUB-2014-004

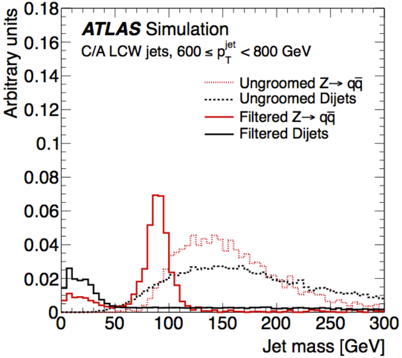
Developed for $H \to b\bar{b}$ (BDRS, PRL **100** (2008) 242001)

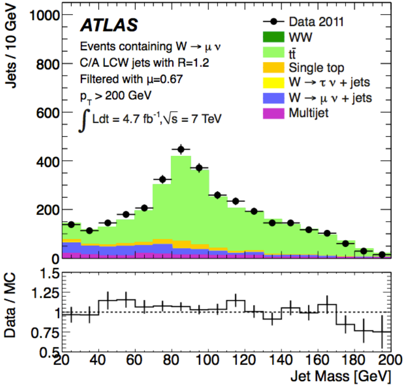


(a) The mass-drop and symmetric splitting criteria.

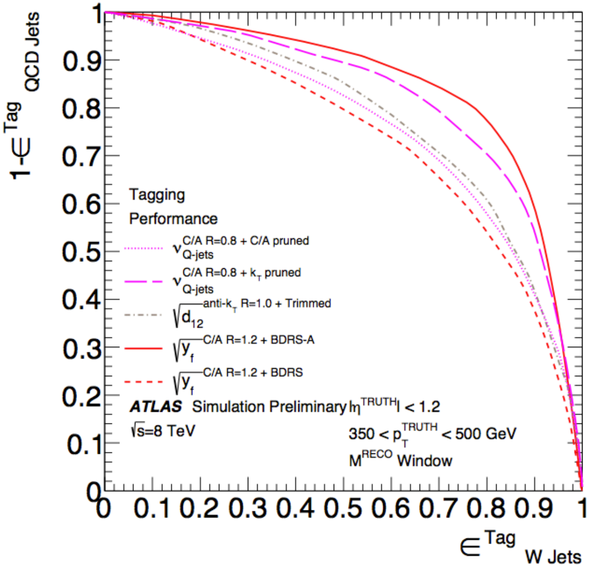


(b) Filtering.

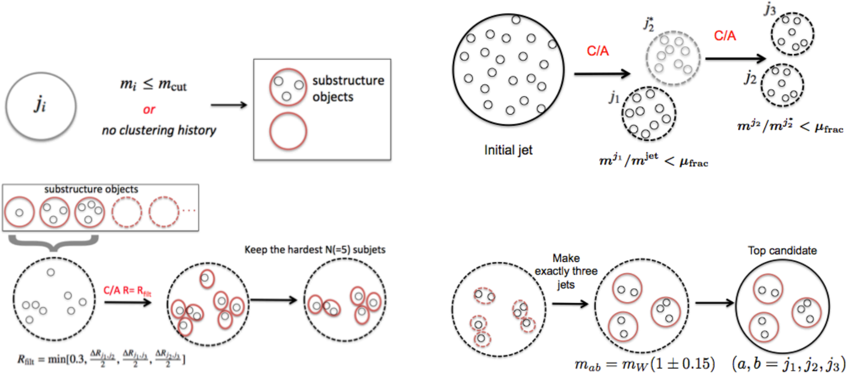

ATLAS Simulation
C/A LCW jets, 600 ≤ p_T^{jet} < 800 GeV
Ungroomed Z→ qq̄
Ungroomed Dijets
Filtered Z→ qq̄
Filtered Dijets
Arbitrary units
Jet mass [GeV]


ATLAS
Events containing W → μ ν
C/A LCW jets with R=1.2
Filtered with μ=0.67
p_T > 200 GeV
$\int$ Ldt = 4.7 fb^{-1}, $\sqrt{s}$ = 7 TeV
Data 2011
WW
tt̄
Single top
W → τ ν + jets
W → μ ν + jets
Multijet
Jets / 10 GeV
Data / MC
Jet Mass [GeV]

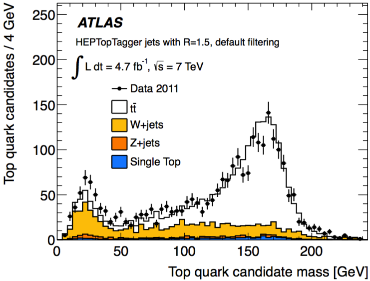
Boson-tagging Performance

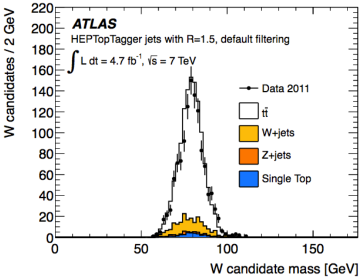


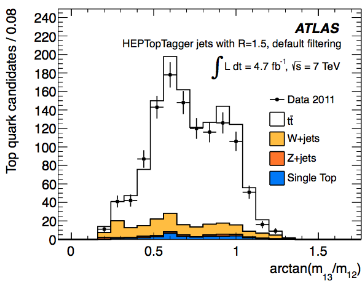
Tagger proposed by Plehn, Salam, Spannowsky, PRL. **104** (2010) 111801

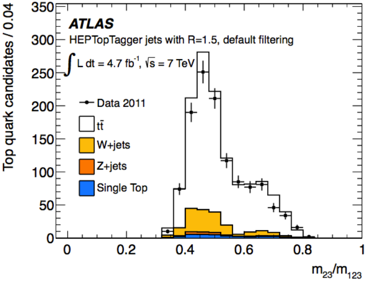


HepTopTagger

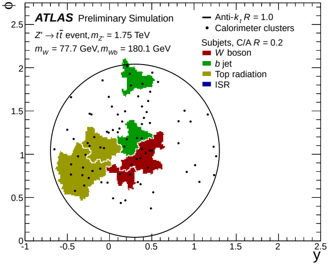


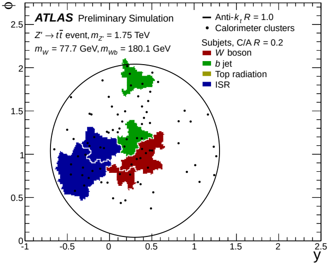


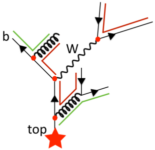


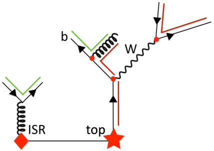


Shower Deconstruction Proposed by Soper and Spannowsky[1]

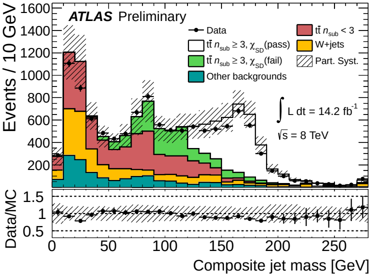


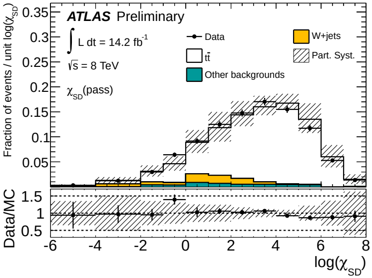


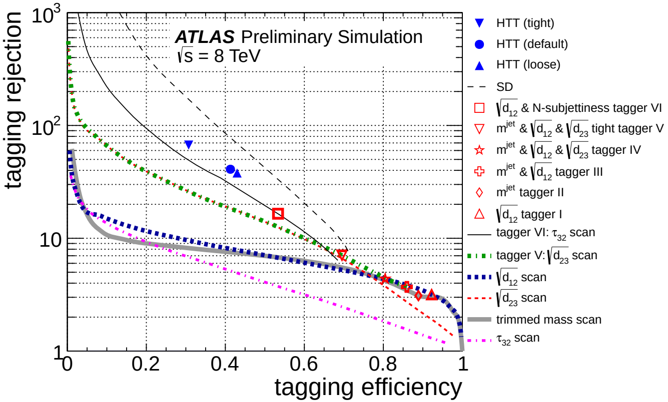




[1]For Higgs: Phys.Rev. D84 (2011) 074002
For top: Phys.Rev. D87 (2013) 5, 054012


ATLAS Preliminary
Data
$t\bar{t}$ $n_{sub} < 3$
$t\bar{t}$ $n_{sub} \geq 3$, χ_{SD}(pass)
W+jets
$t\bar{t}$ $n_{sub} \geq 3$, χ_{SD}(fail)
Part. Syst.
Other backgrounds
$\int$ L dt = 14.2 fb^{-1}
$\sqrt{s}$ = 8 TeV
Events / 10 GeV
Data/MC
Composite jet mass [GeV]

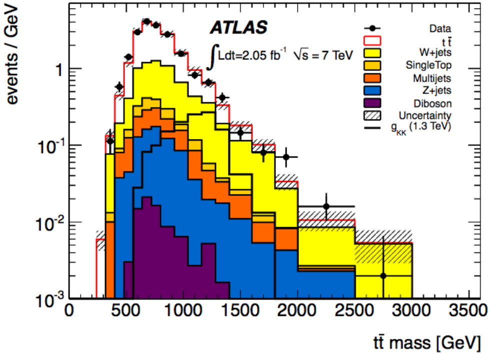

ATLAS Preliminary
$\int$ L dt = 14.2 fb^{-1}
$\sqrt{s}$ = 8 TeV
χ_{SD}(pass)
Data
W+jets
$t\bar{t}$
Part. Syst.
Other backgrounds
Fraction of events / unit log(χ_{SD})
Data/MC
log(χ_{SD})


ATLAS Preliminary Simulation
√s = 8 TeV
tagging rejection
tagging efficiency
HTT (tight)
HTT (default)
HTT (loose)
SD
√d12 & N-subjettiness tagger VI
mjet & √d12 & √d23 tight tagger V
mjet & √d12 & √d23 tagger IV
mjet & √d12 tagger III
mjet tagger II
√d12 tagger I
tagger VI: τ32 scan
tagger V: √d23 scan
√d12 scan
√d23 scan
trimmed mass scan
τ32 scan

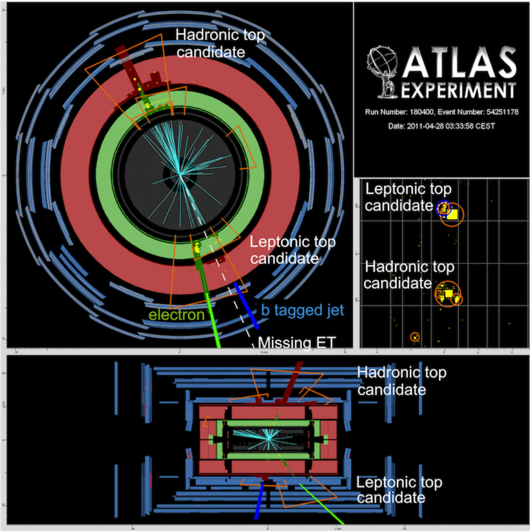
Searches with boosted tops and EW bosons

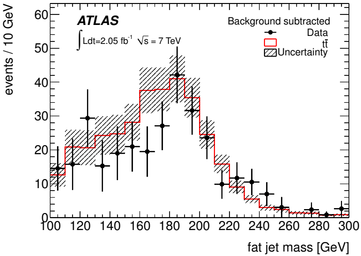
Boosted techniques into practice in: ATLAS - JHEP 1209 (2012) 041

- isolated lepton, missing E_T required
- No b-tag
- Look for boosted $t \to bqq$:
  - Large-R (1.0) anti-k_T jet
  - Require large jet mass ($> 100\,\text{GeV}$) and first k_T splitting scale ($\sqrt{d_{12}} > 40\,\text{GeV}$)
- Reconstruct $m_{t\bar{t}}$ from hadronic top cand +lepton, E_T^{miss} and nearest anti-k_T (R=0.4) jet

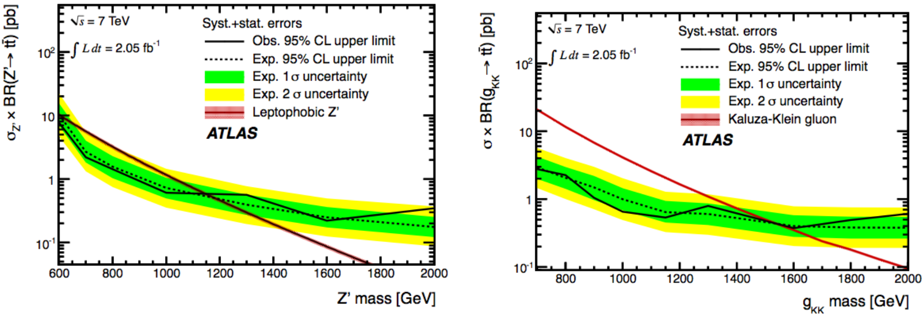


Candidate


Hadronic top candidate
Leptonic top candidate
electron
b tagged jet
Missing ET
ATLAS EXPERIMENT
Run Number: 180400, Event Number: 54251178
Date: 2011-04-28 03:33:58 CEST
Leptonic top candidate
Hadronic top candidate
Hadronic top candidate
Leptonic top candidate


ATLAS
∫Ldt=2.05 fb-1 √s = 7 TeV
Background subtracted
Data
tt̄
Uncertainty
events / 10 GeV
fat jet mass [GeV]
0
10
20
30
40
50
60
100
120
140
160
180
200
220
240
260
280
300

Extract limits on narrow (<3%) or Wide (∼10%) resonance $\rightarrow t\bar{t}$:



comfortably outperforming the conventional analysis at high $m_{t\bar{t}}$

The first search to fully combine boosted and resolved approaches: Phys. Rev. D 88, 012004 (2013)

- **Boosted:**
  - lepton
  - E_T^{miss}
  - ≥ 1 large-R jet with $p_T > 350$ GeV and large jet-mass and d_{12}
  - ≥ 1 b-jet
- **Resolved**
  - Fails boosted selection
  - lepton
  - E_T^{miss}
  - ≥ 4 jets or ≥ 3 jets and one jet has a mass > 60 GeV
  - ≥ 1 b-jet

included also several improvements compared to previous iterations

Building a better search:

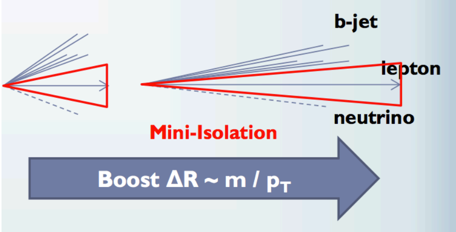
- **Resolved:** Improve $t\bar{t}$ reconstruction
- **Boosted:** Add b-tagging (reduce large W+jets background),
- **Both:** Improve isolation definition,

Lepton Isolation

Conventional lepton isolation is also a problem for boosted tops:

Standard isolation requirements:

- Require lepton and nearest jet well separated ($\Delta R(l,j) > 0.4$)
- require p_T within a small cone around the lepton track is less than some value

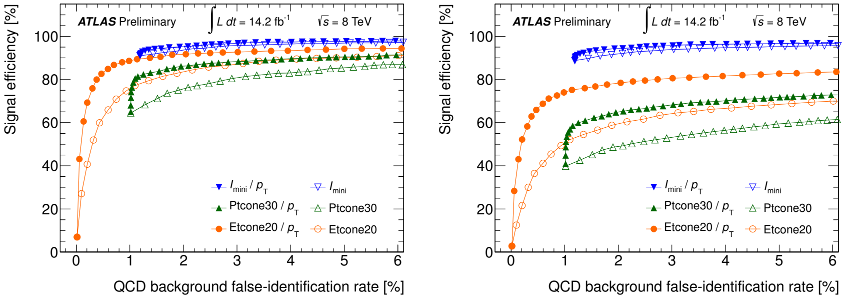


Solution: Adopt mini-isolation (JHEP 1103 (2011) 059)

- Size of isolation cone shrinks with p_T , $\Delta R = k/p_T^l$ (in the case of ATLAS $k = 10\,\text{GeV}$ is used)
- Require p_T with that cone is less than some value (in the case of ATLAS $< p_T^l/20.0$)

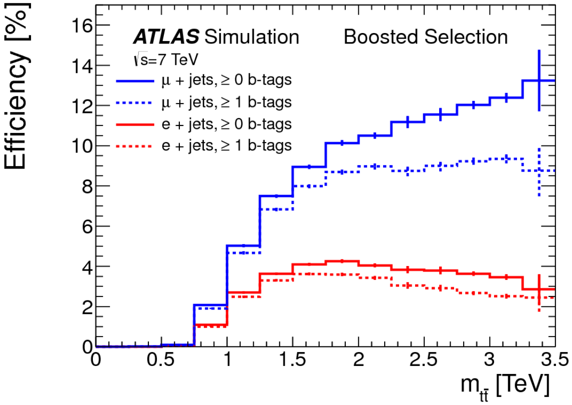
... and relax requirement on $\Delta R(l,j)$ in the μ channel.

Lepton Isolation



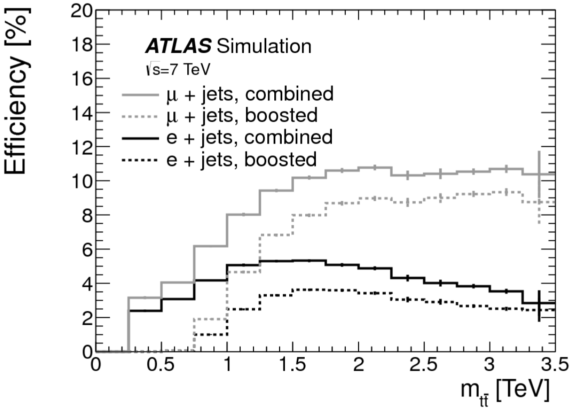
Performance of mini-isolation is very good and stable for different Z' masses (1.0 TeV (left) and 2 TeV (right))

Selection Efficiency

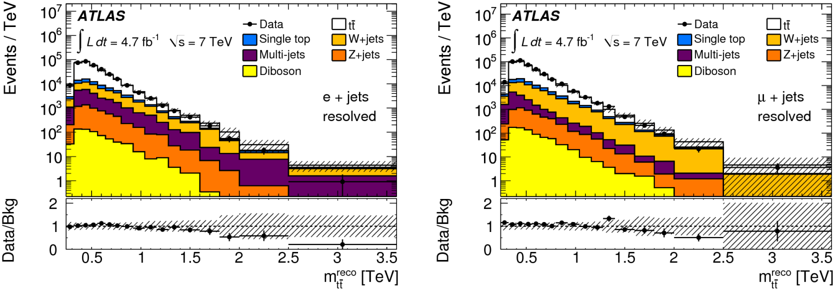


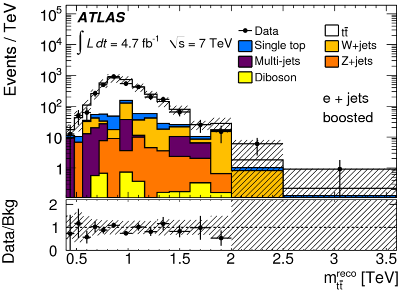
- Muon channel efficiency now rises with $m_{t\bar{t}}$
- Fall-off at high masses for electrons because $\Delta R(l,j)$ cut could not be relaxed

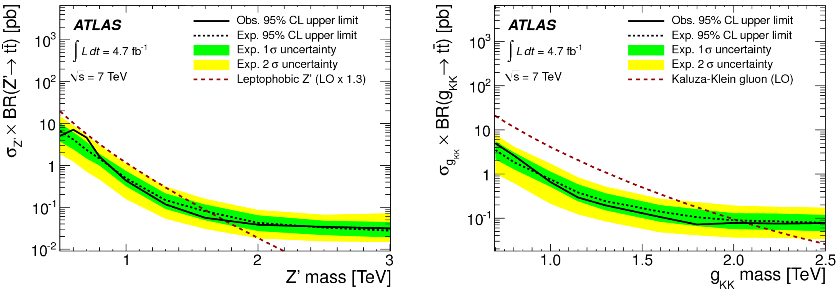
Selection efficiency



Overall signal efficiency is high (this value is relative to all $t\bar{t}$)


ATLAS
∫ L dt = 4.7 fb-1 √s = 7 TeV
Data
tt̄
Single top
W+jets
Multi-jets
Z+jets
Diboson
e + jets
resolved
Events / TeV
Data/Bkg
m_tt̄^reco [TeV]
ATLAS
∫ L dt = 4.7 fb-1 √s = 7 TeV
Data
tt̄
Single top
W+jets
Multi-jets
Z+jets
Diboson
μ + jets
resolved
Events / TeV
Data/Bkg
m_tt̄^reco [TeV]


ATLAS
∫ L dt = 4.7 fb-1 √s = 7 TeV
Data
Single top
Multi-jets
Diboson
tt̄
W+jets
Z+jets
e + jets
boosted
μ + jets
boosted
Events / TeV
Data/Bkg
m_tt̄^reco [TeV]

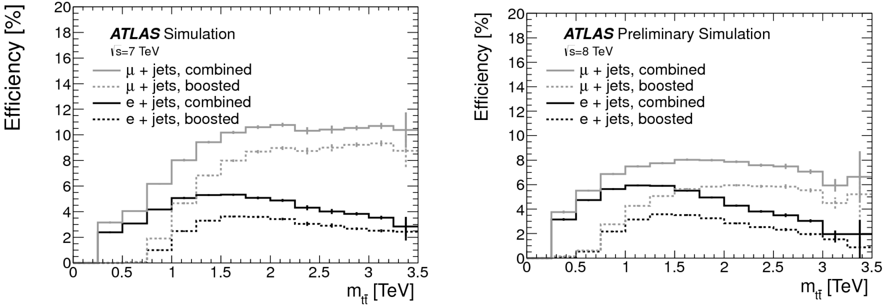


benchmark models excluded up to 1.75 TeV (Z') and 2.1 TeV (g_{KK})

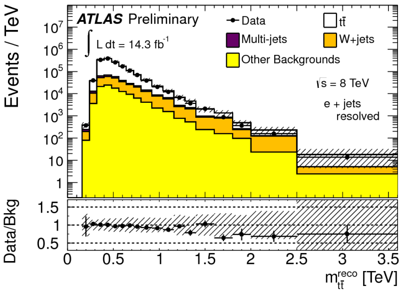
First ATLAS search using partial 8 TeV dataset:

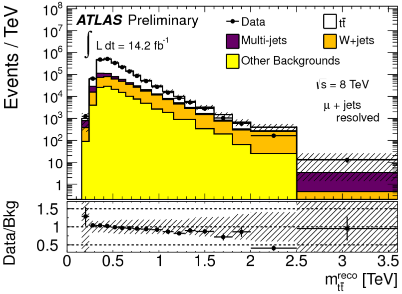
- **Improvements:**
  - Introduced Trimming of large-R jet to mitigate pile-up
- **Disadvantages:**
  - large-R jet triggers not available at this time (large hit in muon channel efficiency)

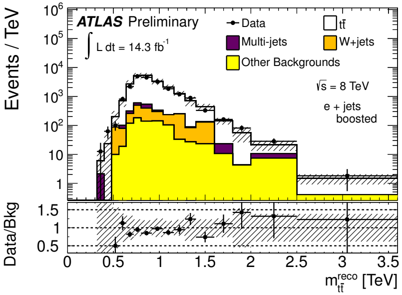
Selection Efficiency

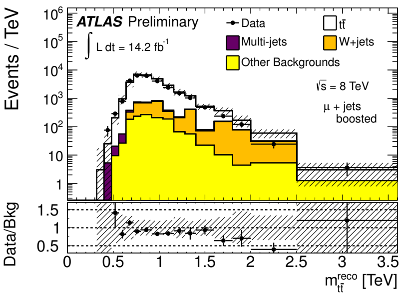


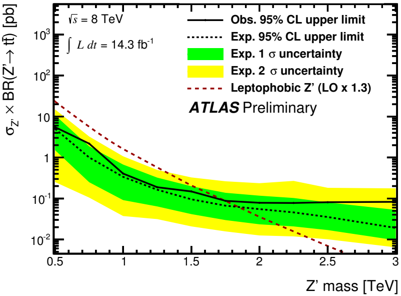
- Electron channel loss - due to trimming
- Muon channel loss - trimming and trigger
- Partly mitigated by some other gains in reconstruction

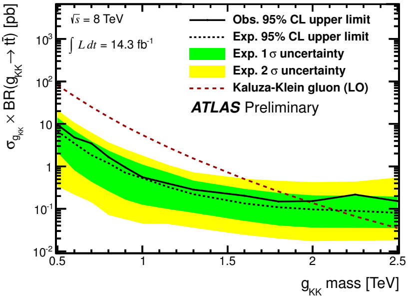

ATLAS Preliminary
∫ L dt = 14.3 fb⁻¹
Data
tt̄
Multi-jets
W+jets
Other Backgrounds
√s = 8 TeV
e + jets
resolved
Events / TeV
Data/Bkg
m_tt̄^reco [TeV]


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


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

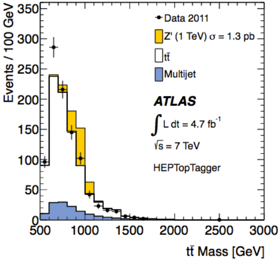

ATLAS Preliminary
∫ L dt = 14.2 fb⁻¹
Data
tt̄
Multi-jets
W+jets
Other Backgrounds
√s = 8 TeV
μ + jets
boosted
Events / TeV
Data/Bkg
m_tt̄^reco [TeV]

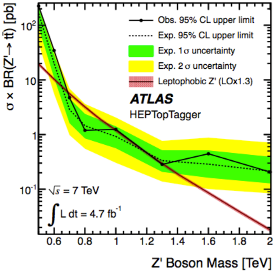


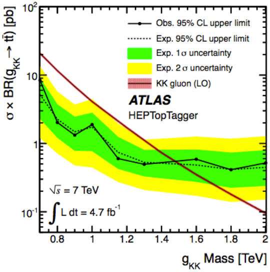


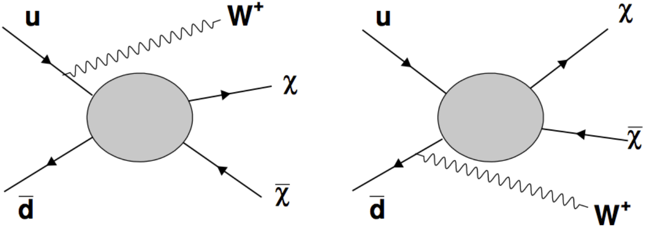
benchmark models excluded up to 1.8 TeV (Z') and 2.0 TeV (g_{KK})

For comparison, the ATLAS fully-hadronic channel result (JHEP 1301 (2013) 116)





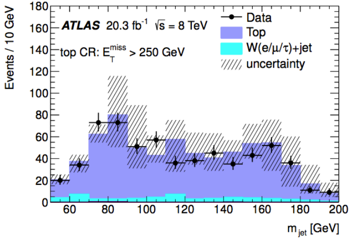




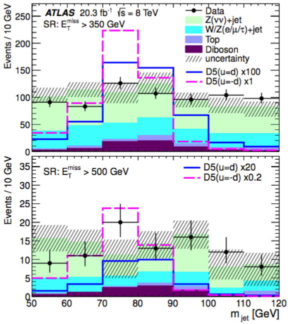
ATLAS Search for W plus missing transverse momentum events also used boosted-objects: arXiv:1309.4017

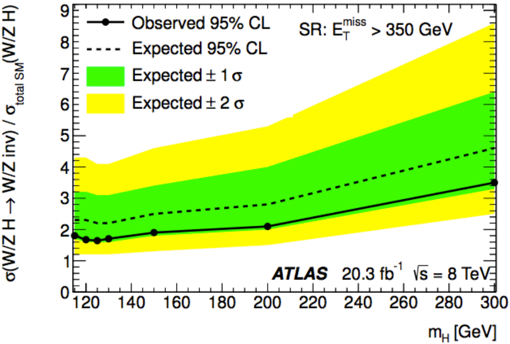
Can also be used to set limits on invisible Higgs decays

- Validate boosted W in top CR
  - one muon
  - one C/A R=1.2 jet $p_T > 250$ GeV
  - two extra anti k_t, R=0.4 jets , at least one b-tagged
  - $E_T^{\text{miss}} > 250$ GeV
- Main selection:
  - C/A R=1.2 jet (BDRS) with $p_T > 250$ GeV, $\sqrt{y} > 0.4$ and $50 < m < 120$ GeV required
  - Two SR are defined with $E_T^{\text{miss}} > 350, 500$ GeV



Mono-W


ATLAS 20.3 fb-1 √s = 8 TeV
SR: ETmiss > 350 GeV
Data
Z(νν)+jet
W/Z(e/μ/τ)+jet
Top
Diboson
uncertainty
D5(u=d) x100
D5(u=-d) x1
SR: ETmiss > 500 GeV
D5(u=d) x20
D5(u=-d) x0.2
Events / 10 GeV
mjet [GeV]


Observed 95% CL
Expected 95% CL
Expected ± 1 σ
Expected ± 2 σ
SR: ETmiss > 350 GeV
ATLAS 20.3 fb-1 √s = 8 TeV
σ(W/Z H → W/Z inv) / σtotal SM(W/Z H)
mH [GeV]

- ATLAS has commissioned many tools for identifying hadronically decaying boosted objects
- Performance of boson and top tagging now being systematically studied - expect publications on this topic in the not-so-distant future
- First uses in searches have been very successful
- Candidates for use will grow substantially in Run-II, expect more searches with boosted $W/Z/H/t$
- The machinery is now also well-enough tested for use in measurements

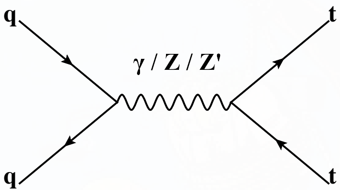
Back-up

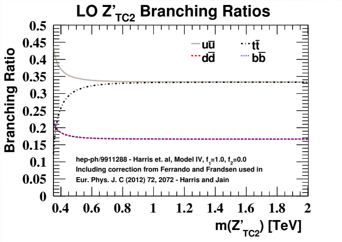
Many new physics scenarios predict heavy particles that decay to $t\bar{t}$:

- **Extra dimensions (Bulk RS)**: Excitations of gluon (g_{KK})/ graviton (G_{KK}) preferentially decay to $t\bar{t}$
- **Topcolor-assisted Technicolor**: Strong EWSB model via a top condensate - expect top-π (H-like) and top-ρ (Z'-like) the latter heavy enough to decay to $t\bar{t}$
- **Composite Higgs scenarios**: Usually require (naturalness) extra heavy-fermions, and commonly heavy "gluons" that decay to t_R or new heavy fermions depending on the masses
- **BSM Higgs**: New heavy pseudoscalar Higgs-like particles in, e.g. the MSSM, would also have a large $t\bar{t}$ branching ratio

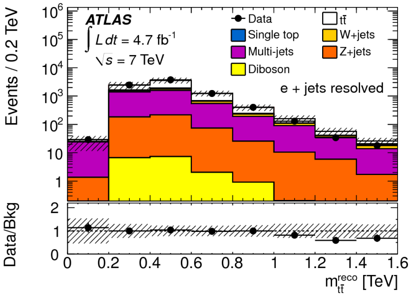
Searches so far have focused on two benchmark scenarios:

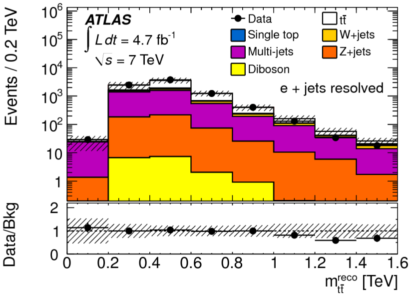
- Topcolor-assisted technicolor (TC2) $Z'_{\mathrm{TC2}} \to t\bar{t}$
  - Spin-1
  - Color singlet
  - Narrow width (1.2%) modelled with SSM Z' (3%) width
  - hep-ph/9911288, Eur. Phys. J. C (2012) 72 2072
- RS Kaluza-Klein Gluon $g_{\mathrm{KK}} \to t\bar{t}$
  - Spin-1
  - color octet
  - wide (10-15%)
  - $\mathcal{BR}(g_{\mathrm{KK}} \to t\bar{t}) \sim 92.5\%$
  - JHEP 0709 (2007) 074

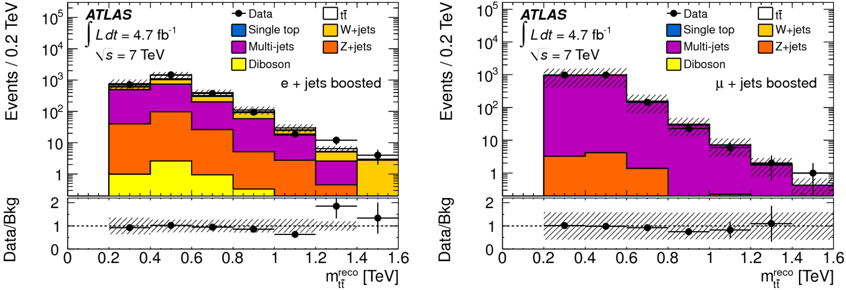


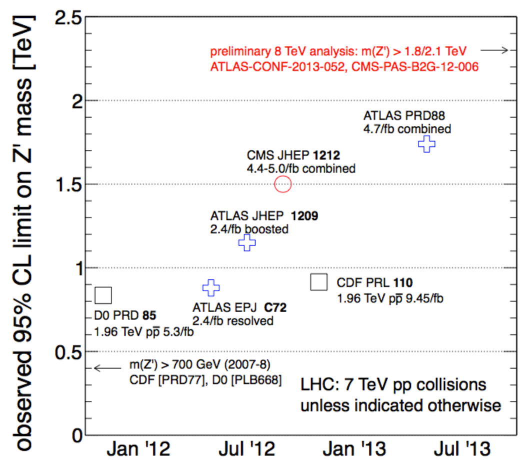


Backgrounds






ATLAS
∫ L dt = 4.7 fb-1
√s = 7 TeV
Data
Single top
Multi-jets
Diboson
tt̄
W+jets
Z+jets
e + jets boosted
μ + jets boosted
Events / 0.2 TeV
Data/Bkg
m_tt̄^reco [TeV]

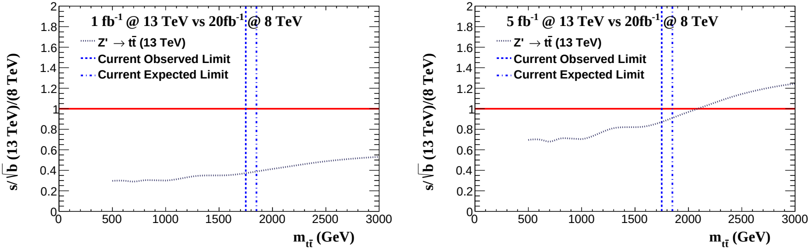


Boost 2012 report - arXiv:1311.2708

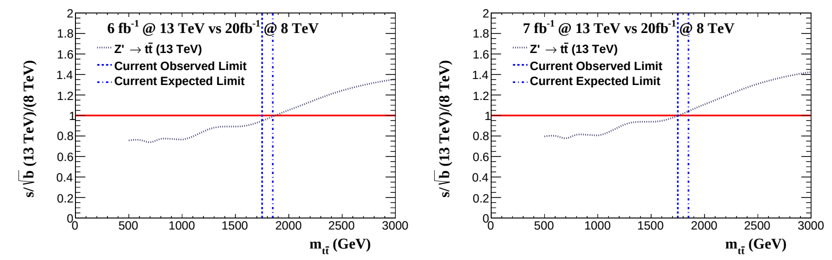
What's next?

- Towards LHC run-II
- Prospects with the upgraded LHC

How much luminosity is neeed at 13 TeV to be competitive with current data?



(simple extrapolation using cross sections for Z' and NLO $t\bar{t}$ in appropriate $m_{t\bar{t}}$ range)



Reach should start to increase as we approach 6-7 fb^{-1}

Upgrades

Example, ATLAS upgrade schedule:

Phase I

- **Installation Date:** 2018-19
- **Detector upgrades:** μ-trigger, L1 Calo-trigger, FTK, new Small wheel for muons , new forward detectors . Various readout improvements. (Maintain performance at higher luminosity)
- **Lumi** $2.2 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, 300-400 fb^{-1} by 2022, $\mu =$ 55-80

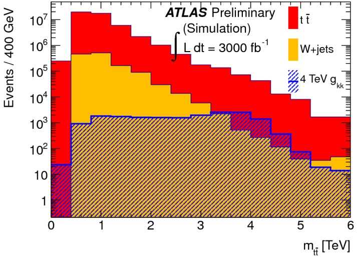
Phase II

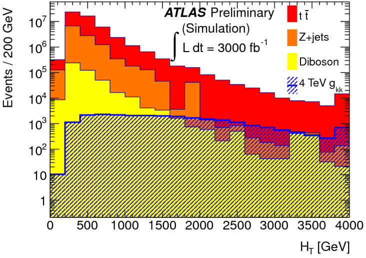
- **Installation Date:** 2022-24
- **Detector upgrades:** Split L0/L1 trigger, numerous trigger and readout upgrades, improved HLT, RPC precision upgrade, complete tracker replacement. (Maintain/improve performance at higher μ, improve resistance to radiation damage)
- **Lumi** $5 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, up to 3000 fb^{-1}, $\mu =$ 140-200

ATLAS upgrade performance and physics prospects have been studied in:

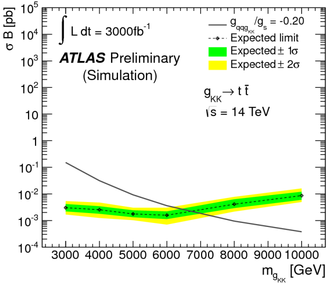
- Phase-I LOI: CERN-LHCC-2011-012
- Phase-II LOI: CERN-LHCC-2012-022
- $t\bar{t}$ resonance search: ATL-PHYS-PUB-2013-003

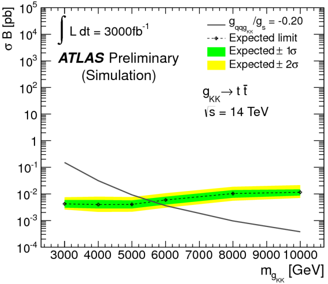
Studies of $t\bar{t}$ resonance searches done with a parametrisation of detector response, not at the full-simulation level.



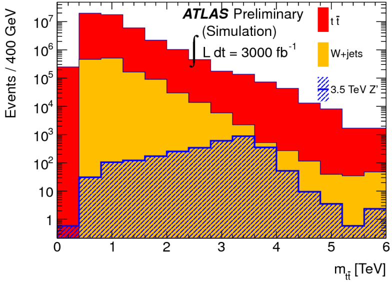


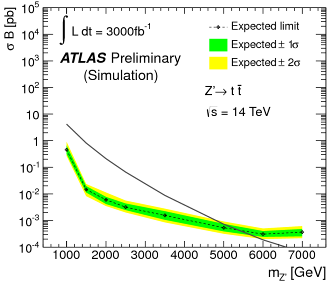
- $t\bar{t}$ in simplified l+jets (boosted) and dilepton selections





- $t\bar{t}$ in simplified l+jets (boosted) and dilepton selections





- $t\bar{t}$ in simplified l+jets (*boosted*) and dilepton selections

model	300 fb^{-1}	1000 fb^{-1}	3000 fb^{-1}
g_{KK}	4.3 (4.0)	5.6 (4.9)	6.7 (5.6)
Z'_{topcolor}	3.3 (1.8)	4.5 (2.6)	5.5 (3.2)

- $t\bar{t}$ in simplified l+jets (*boosted*) and dilepton selections
- Exclusion reach for benchmarks could extend as far as 5-6 TeV after the phase=II upgrade
- Of course we hope for a discovery before then