Boosted Heavy Particles and Jet Substructure

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on behalf of the ATLAS Collaboration

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arXiv:1306.4945

Introduction

At LHC, √s >> electroweak scale

Massive particles like top, W, Z and Higgs are often produced with significant boost

- E.g. at √s = 7 TeV, there are 1000 ttbar/fb^{-1} with p_T^t > 300 GeV

Decay products are Lorentz-boosted in the same direction

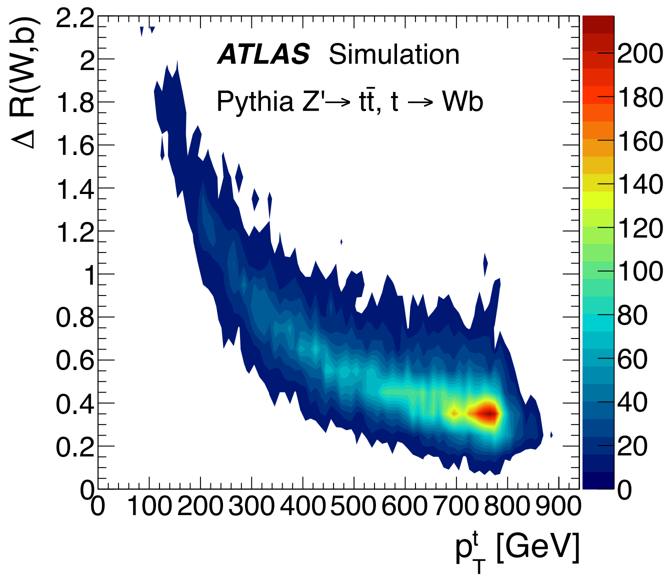
- Separation $\Delta R \approx 2m/p_T$

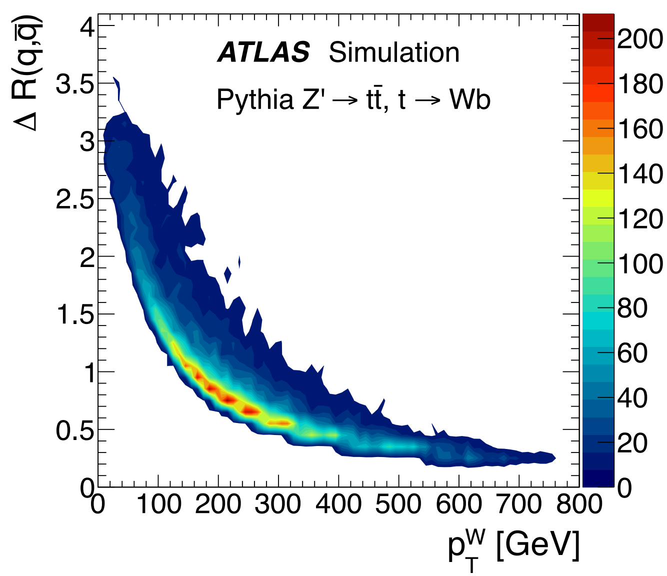
Hadronic decays cannot be reconstructed using separate jets, since these begin to merge

⇒use substructure techniques to look inside the merged jet and reconstruct the object of interest

Important to explore this kinematic regime

- Extend understanding of the Standard Model
- Search for new physics





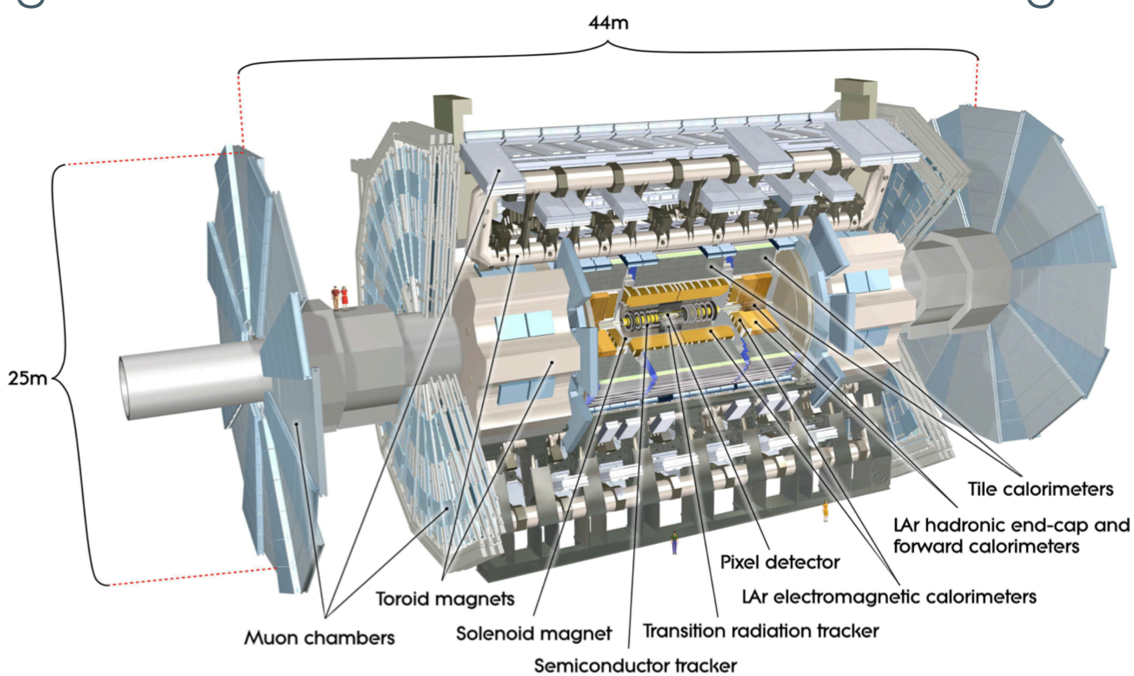
ATLAS Detector

ATLAS is well suited to reconstructing boosted heavy particles using jet substructure techniques

Excellent tracking

Highly granular, hermetic calorimeter covering $|\eta| < 4.9$

- Good jet energy resolution: $\sigma/E \approx 50\%/\sqrt{E} + 3\%$ ($|\eta| < 3.2$)
- Good longitudinal containment: 9.7 interaction lengths



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ATLAS Calorimeter

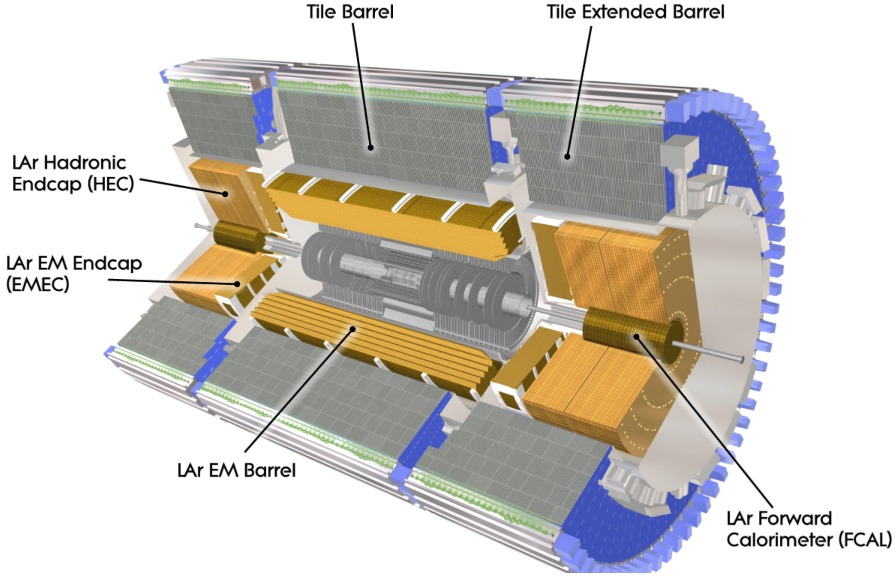
High granularity

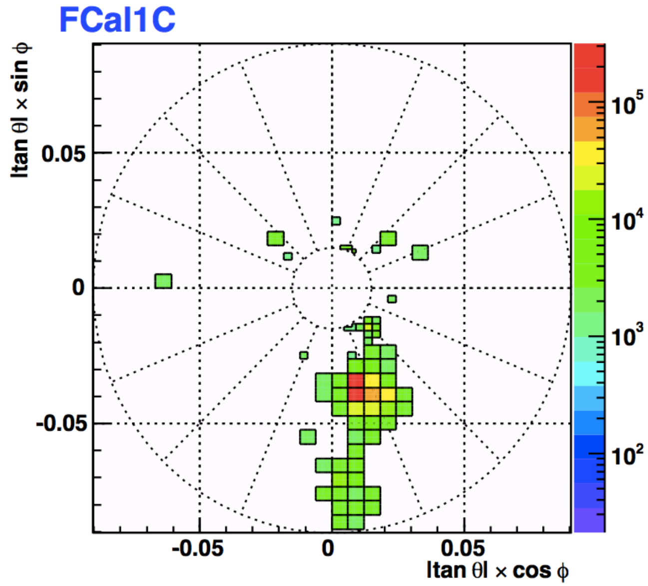
- Electromagnetic calorimeter (EMCAL): $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$
- Hadronic calorimeter (HCAL): $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$

Segmentation in depth to track shower development

- 3 layers for EMCAL and HCAL
- Improves energy resolution

Energy of hadrons is reconstructed by forming 3D topological clusters of energy





Jet Reconstruction

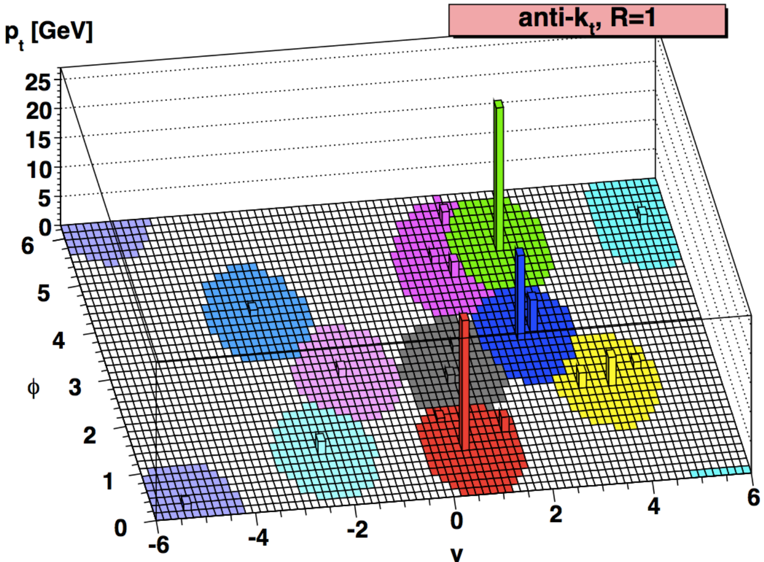
Topological energy clusters are combined into jets, using the generalized distance measure:

$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \frac{\Delta R_{ij}^2}{R^2} \qquad \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

The definition of p leads to the three algorithms that are commonly used in ATLAS

- $p = 1$: k_T
- $p = 0$: Cambridge-Aachen
- $p = -1$: anti-k_T

Large R parameters of ~1 are used to reconstruct heavy boosted objects



G. Salam arXiv:0906.1833v2 [hep-ph]

Jet Substructure

Jets containing the decay products of a massive particle will be distinct from those typically caused by a light parton

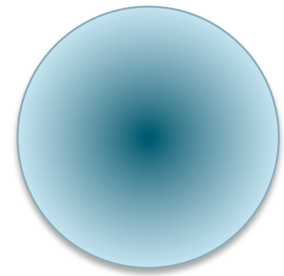
- Significant jet mass
- Hard 2- or 3-body substructure

These differences may be obscured by

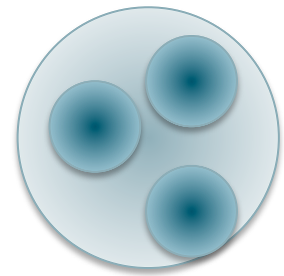
- QCD radiation
- Pile-up and Underlying event

Many techniques exist to “tag” and “groom” jets

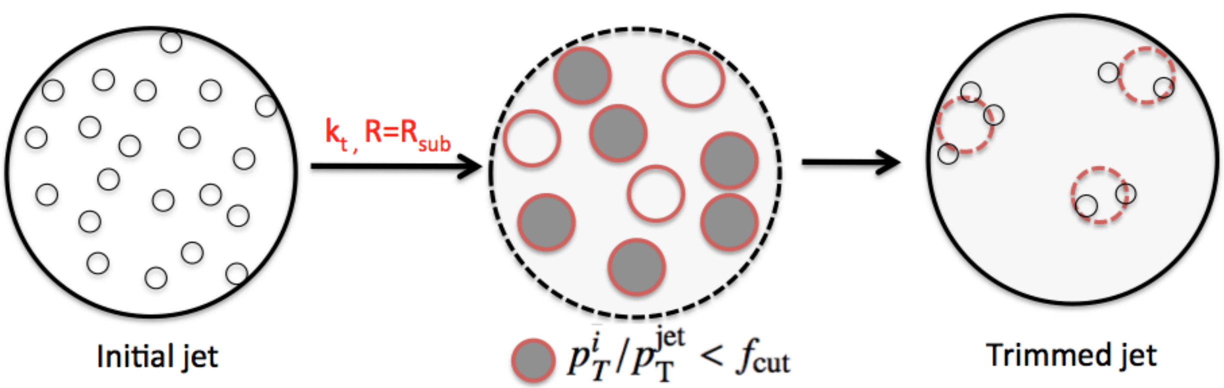
- identify and retain hard substructure
- reduce impact of soft QCD radiation

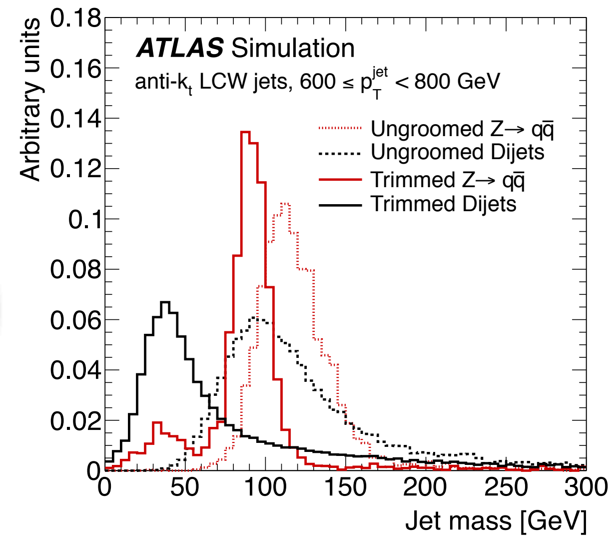


light parton jet



top jet





ATLAS Experimental Programme

- Measure the jets and their substructure observables
  - Required extensive work to calibrate observables and to estimate uncertainties
  - Validation of Monte Carlo simulation
- Test tagging and grooming techniques in data
  - Effective with finite resolution, pile-up etc.?
  - Understand their relative performance and correlations
- Use as tools for physics measurements
  - Standard Model measurements
  - Searches for new physics

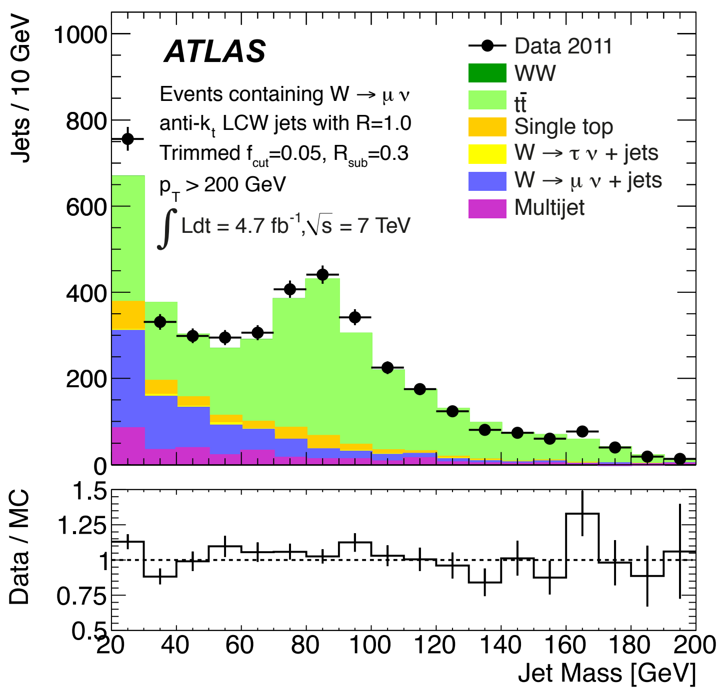
Jet Mass

arXiv:1306.4945 and
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/JetEtmissApproved2013Jms

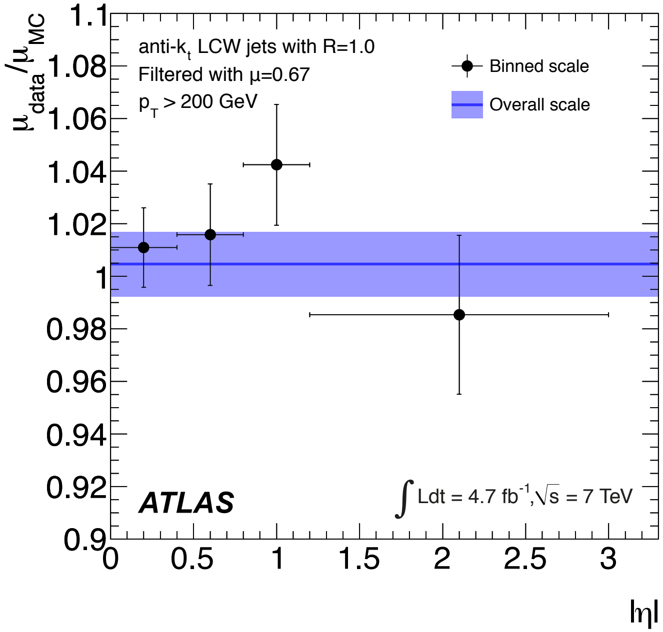
Jet mass calibration validated using
- Comparison to track-jets reconstructed in inner detector
- Hadronic W bosons selected from semi-leptonic ttbar events

Mass scale uncertainties
- < 3% in 2011 for hadronic W bosons (p_T > 200 GeV)
- < 5% in 2012 for hadronic top-jet (p_T > 500 GeV)

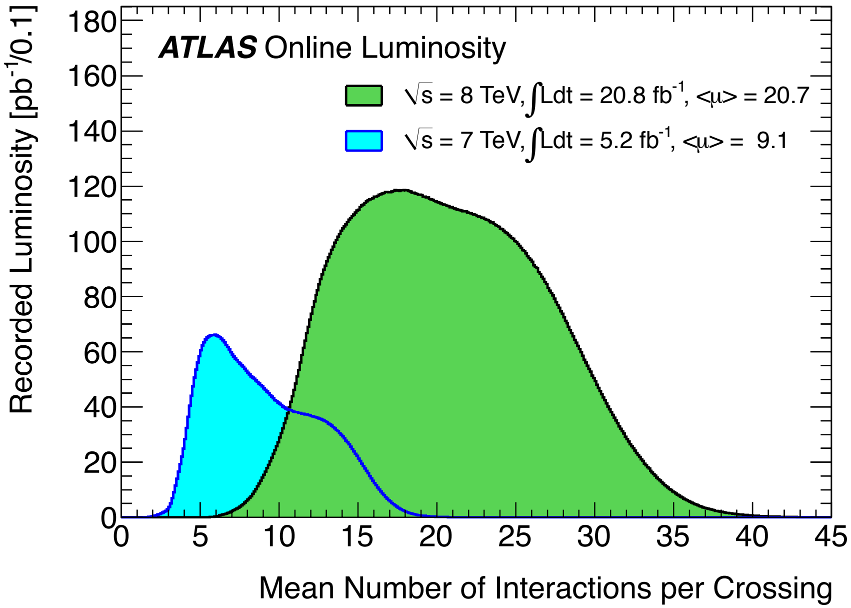
Precision physics possible with large-R jets!

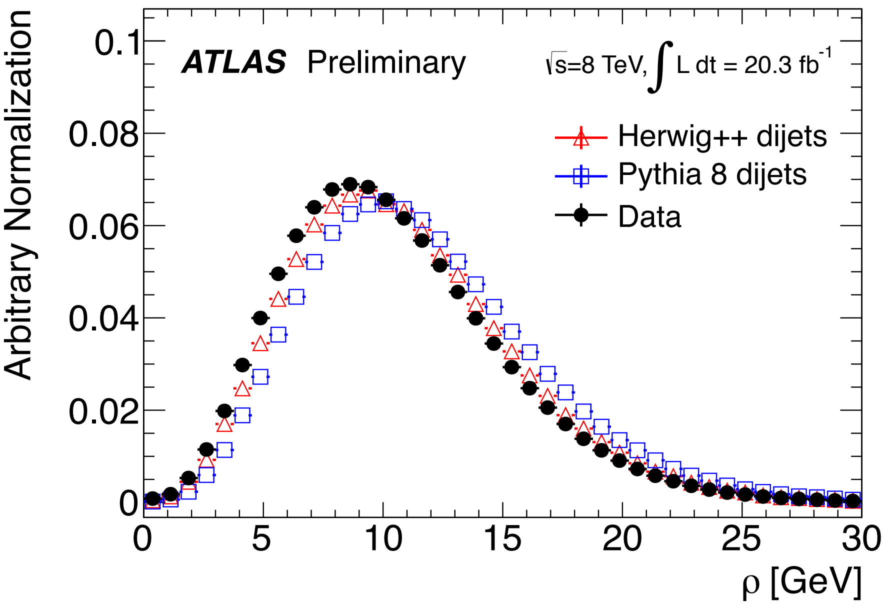


Data-MC Comparison of W peak position



Pile-Up

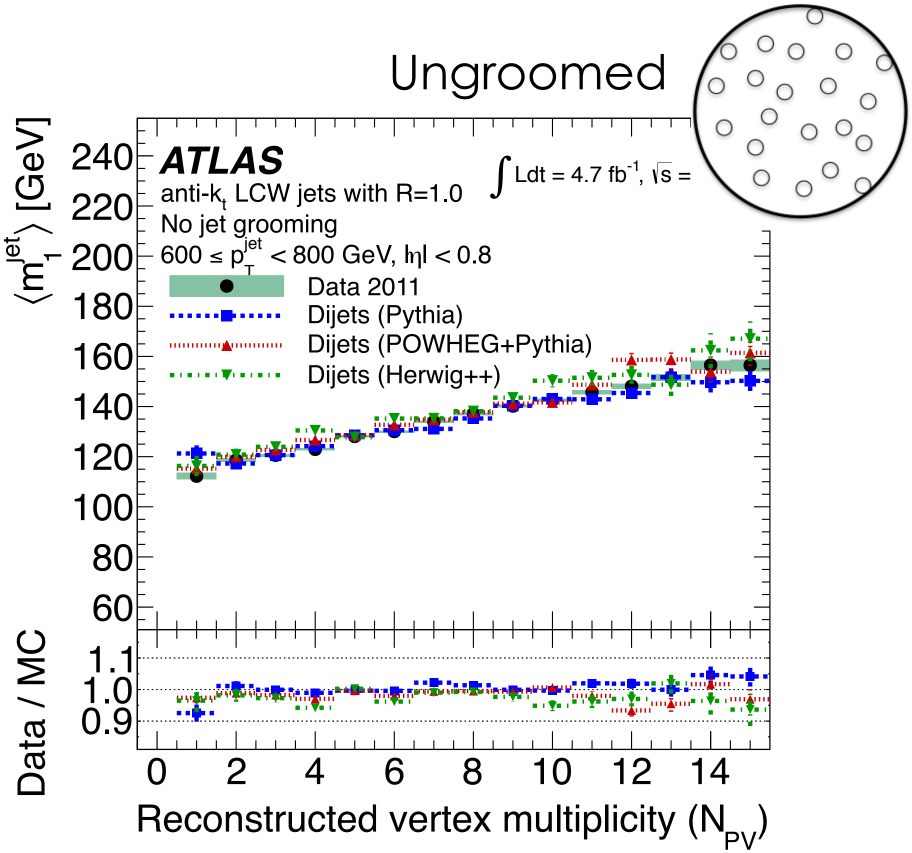




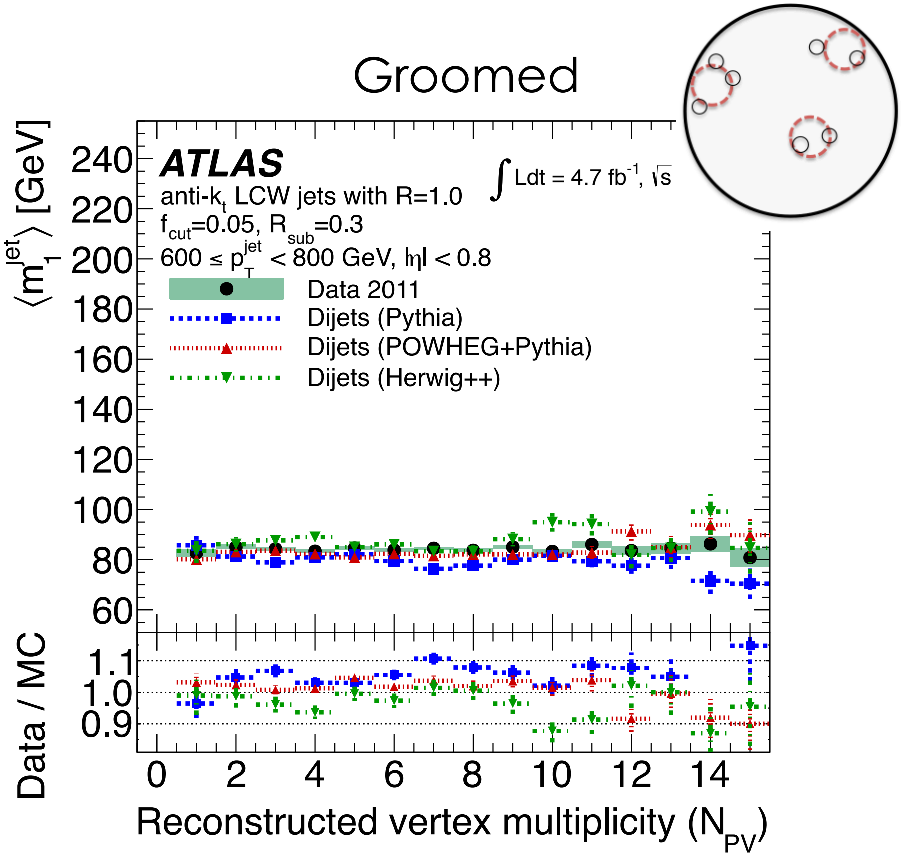
- High instantaneous luminosity causes many interactions per bunch crossing
- These pile-up interactions produce many low p_T particles leading to a substantial background energy density, ρ
- Large-R jets have a large "catchment" area
- ⇒suffer from large modifications of kinematics and substructure observables

Mitigating the Effects of Pile-Up: Grooming

Ungroomed



Groomed



Grooming reduces the effective jet area, rejecting soft energy deposits

This helps to uncover any hard substructure in the jet

Another Approach: Pile-Up Subtraction

Many fake particles – "ghosts" – with very low momenta, g_T, are clustered into each jet

- These mimic soft pile-up particles
- Individual ghost area is A_g

Sensitivity to pile-up of a given substructure variable, $V(\rho, g_T)$ is estimated by varying the energy of these ghosts by infinitesimal amount, δ

- $V(\rho, g_T + \delta.A_g) = V(\rho + \delta, g_T)$

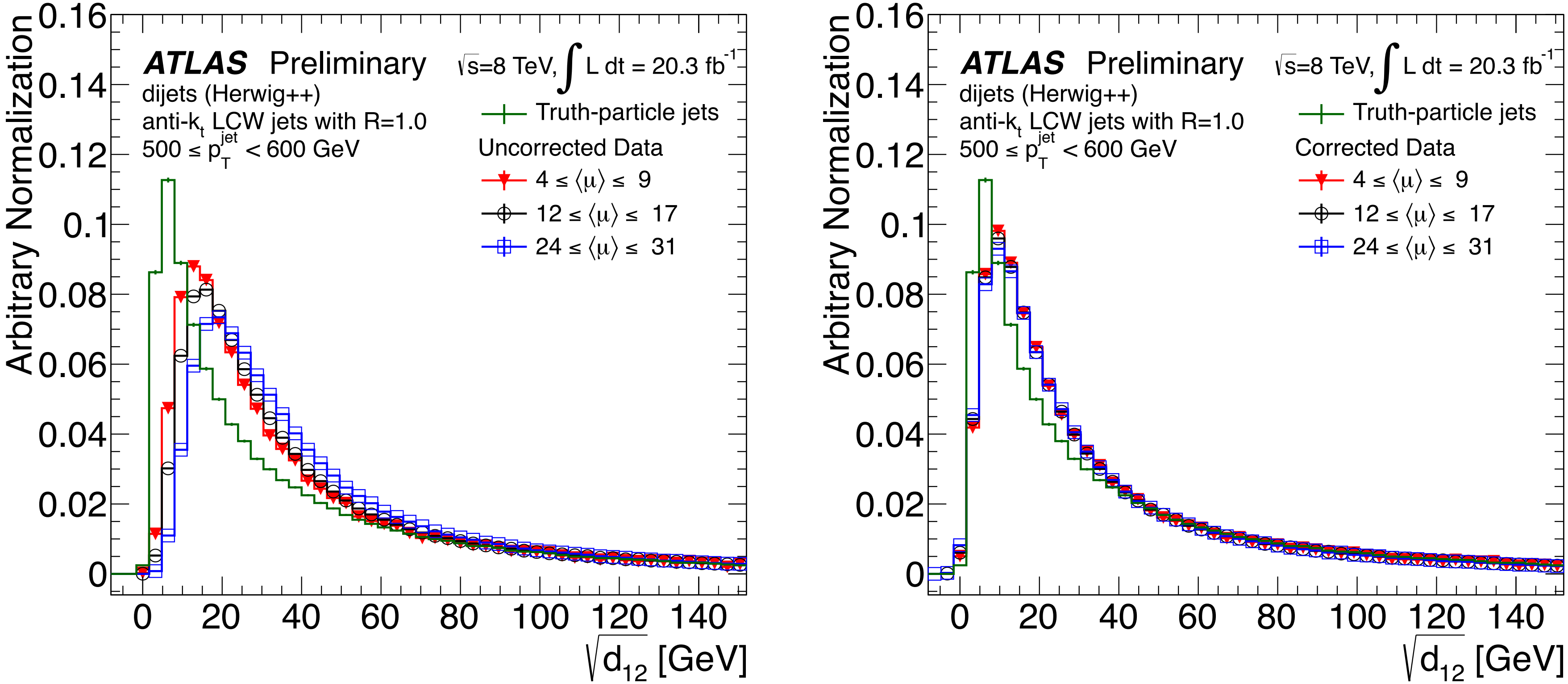
Correction is then

- $V_{corr} = V(\rho=0, g_T=0) = V(\rho = \rho_0, g_T = -\rho_0.A_g)$

V_{corr} is evaluated using a Taylor expansion

This method can be used for many jet shapes and substructure observables

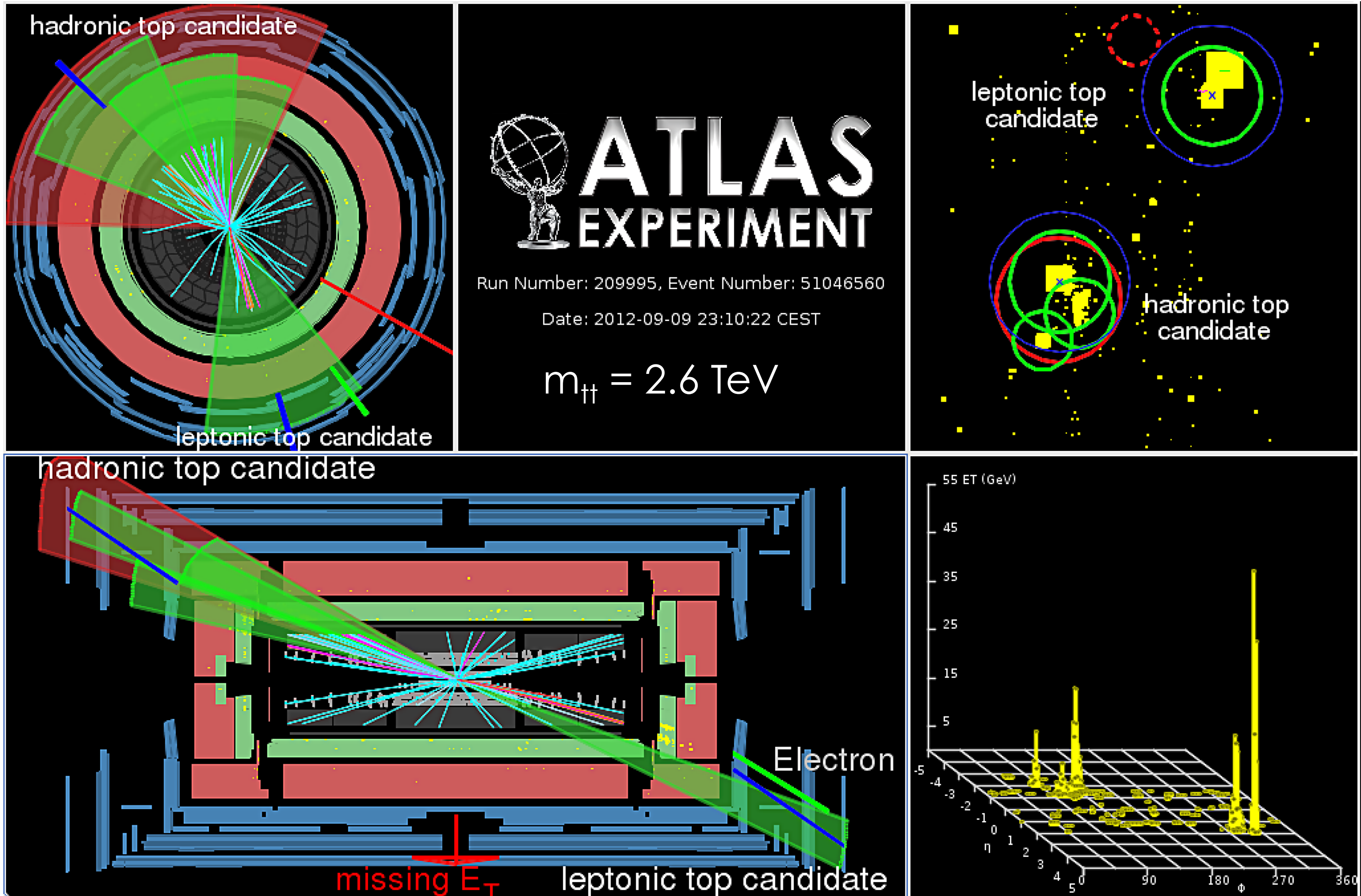
Pile-Up Subtraction for Substructure



Pile-up subtraction effectively removes pile-up effects from substructure observables

$\sqrt{d_{12}}$ = the k_T distance between the two final clusters in jet

Boosted Top


hadronic top candidate
leptonic top candidate
ATLAS EXPERIMENT
Run Number: 209995, Event Number: 51046560
Date: 2012-09-09 23:10:22 CEST
m_{tt} = 2.6 TeV
leptonic top candidate
hadronic top candidate
hadronic top candidate
Electron
missing E_T
leptonic top candidate
55 ET (GeV)
45
35
25
15
5
η
φ

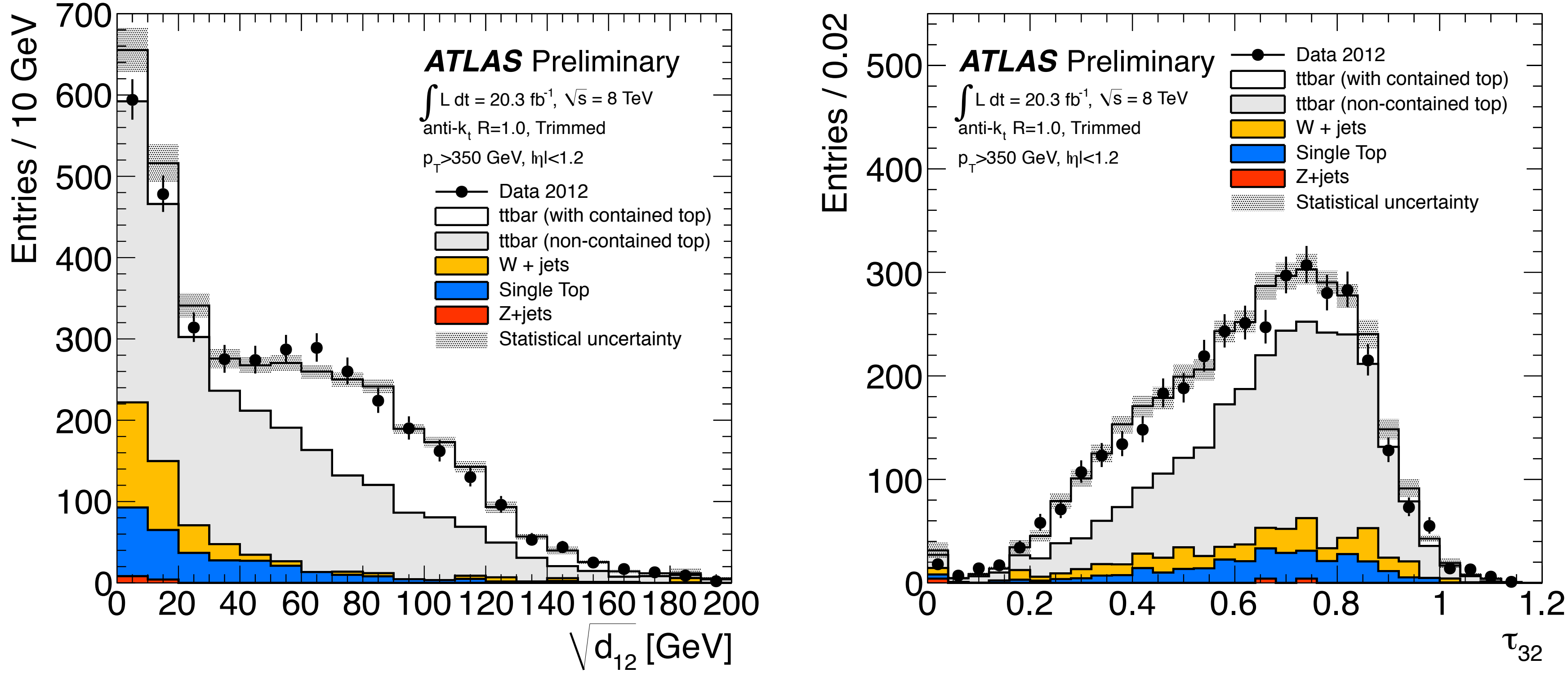
Introduction to ttbar Resonance Searches

- Many models of new physics predict heavy resonances with large couplings to top quarks
  - These heavy resonances will decay to boosted tops
- ATLAS has searched for two benchmark models
  - Z': predicted by some leptophobic topcolour models
    - colour singlet
    - narrow resonance: $\Gamma/m = 1.2\%$
  - g_{kk} boson: predicted by Randall-Sundrum models
    - colour octet
    - broad resonance: $\Gamma/m = 15.3\%$
- ATLAS have tested several algorithms to identify boosted tops
  - HEPTopTagger, Top Template Tagger
  - Substructure variable cuts: k_T splitting scales, n-subjettiness, mass
- Searches performed in fully- and semi-leptonic channels
  - Fully-hadronic with $\int Ldt = 4.7\ fb^{-1}$ ($\sqrt{s} = 7$ TeV)
  - Semi-leptonic with $\int Ldt = 14.3\ fb^{-1}$ ($\sqrt{s} = 8$ TeV) and $\int Ldt = 4.7\ fb^{-1}$ ($\sqrt{s} = 7$ TeV)

JHEP01(2013)116, arXiv:1305.2756, ATLAS-CONF-2013-052, ATLAS-CONF-2013-084

ATLAS-CONF-2013-084

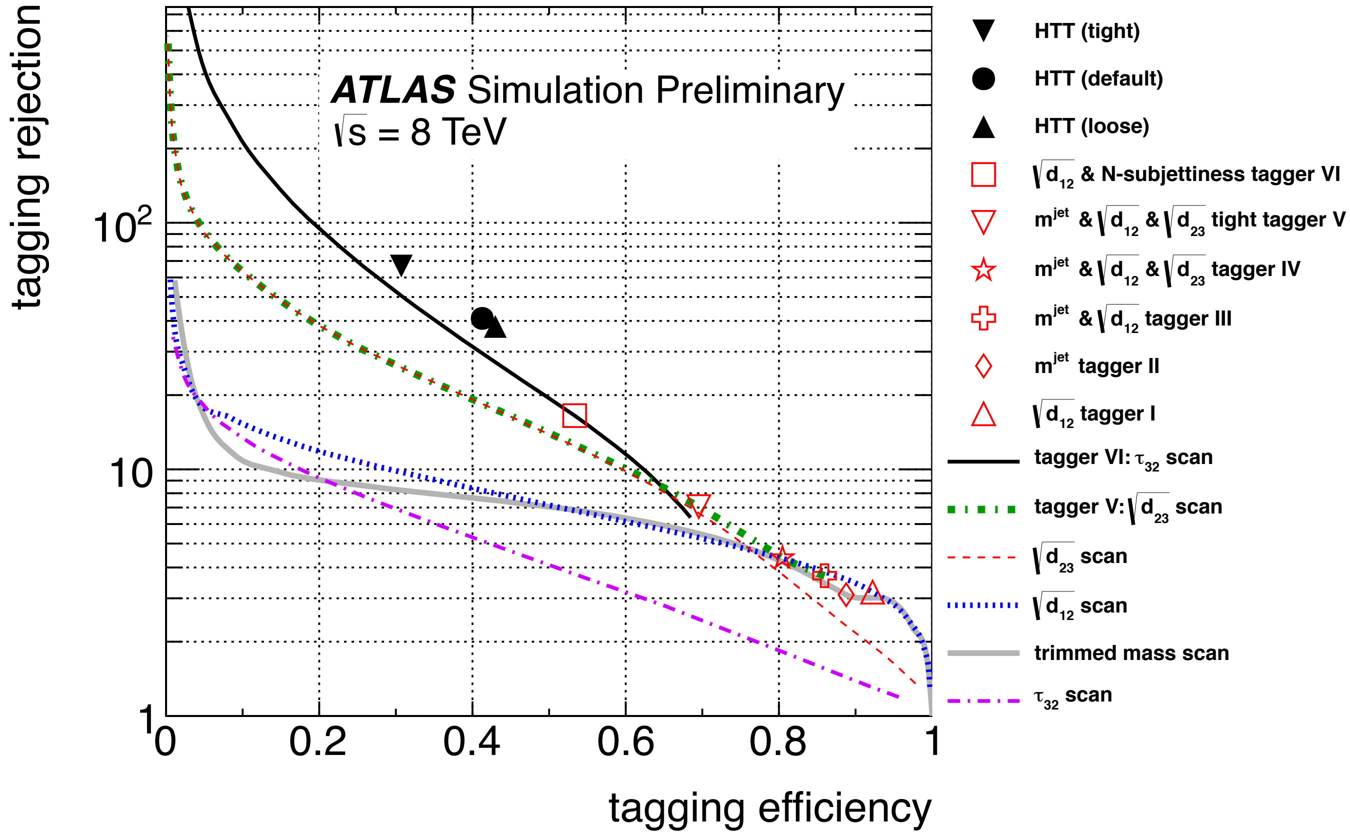
k_T Splitting Scale and N-Subjettiness



N-subjettiness , τ_N, evaluates how well the jet can be described as containing ≤ N subjets

- Ratios $\tau_{NM} = \tau_N / \tau_M$ give additional rejection power vs light parton jets

Comparison of Tagging Techniques

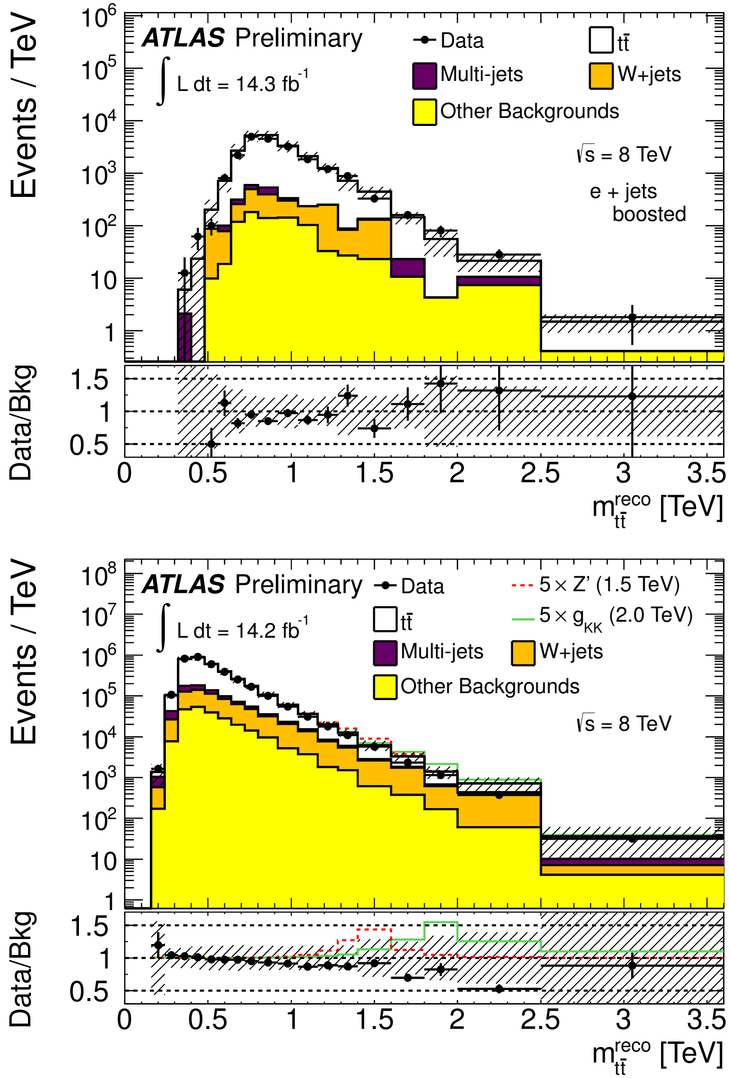


Broad spectrum of potential working points

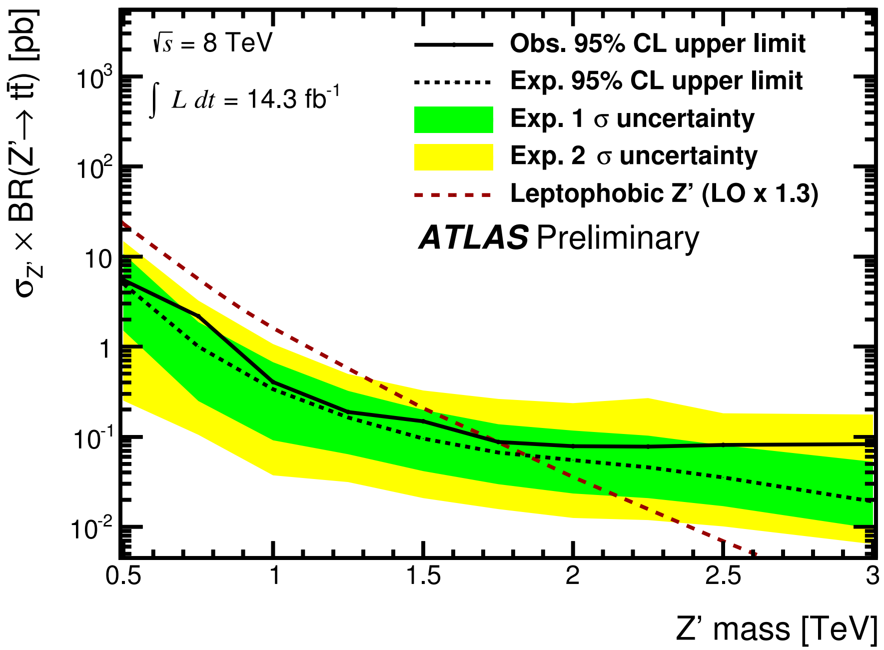
- Optimum choice is analysis dependent
- HTT, $\sqrt{d_{12}}$ and top template tagger have been used so far

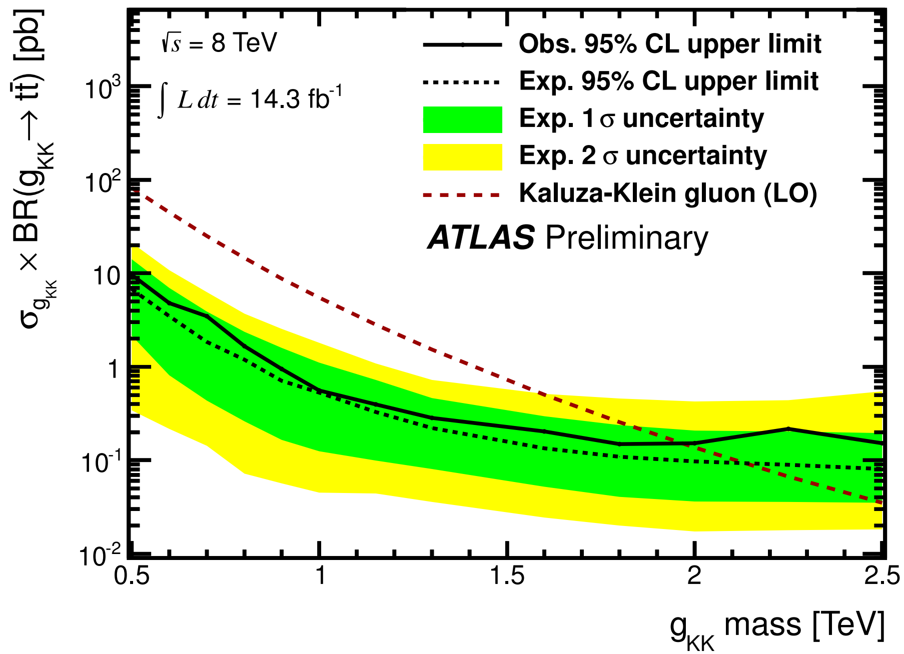
Search in Semi-Leptonic Channel

- Dataset: ∫Ldt = 14.3 fb^{-1} at $\sqrt{s}$ = 8 TeV
- ≥1 b-tagged R = 0.4 jet
- Selection for Leptonic top decay
  - W candidate: lepton + ME_T
  - R=0.4 jet, ΔR(jet,lepton) < 1.5
- Selection for hadronic top decay
  - Trimmed R=1.0 jet, p_T > 300 GeV, m > 100 GeV
  - $\sqrt{d_{12}}$ > 40 GeV
- $\Delta\Phi$ (lepton, had. top) > 2.3
- To extend searches to lower resonance masses, a complementary resolved jet is used



Search in Semi-Leptonic Channel





No significant excess was seen, so 95% C.L. limits are set
- 0.5 – 1.8 TeV for narrow, Z'-like resonances
- 0.5 – 2.0 TeV for broad, g_{KK}-like resonances

Semi-leptonic search with $\int Ldt$ = 4.7 fb^{-1} at $\sqrt{s}$ = 7 TeV (*arXiv: 1305.2756*) set similar limits

A complementary search for fully hadronic ttbar resonances (*JHEP01(2013)116*) saw no excess either

Conclusions

- High LHC collision energy means heavy particles are often highly boosted
  - Within the Standard Model and in new physics models
- Specialized substructure techniques can be used to reconstruct these highly boosted particles
- ATLAS has a comprehensive programme
  - To calibrate and understand substructure observables
  - To meet experimental challenges such as high pile-up
  - To measure Standard Model processes with boosted particles
  - To search for new physics with boosted particles
- Many interesting studies: these slides are only a selection
- Lots of new results coming soon

Some ATLAS Papers on Substructure and Boosted Heavy Particles

Performance and Validation of Q-Jets at ATLAS	ATLAS-CONF-2013-087
Jet Charge Studies in ATLAS	ATLAS-CONF-2013-086
Performance of Pile-up Subtraction for Jet Shapes	ATLAS-CONF-2013-085
Performance of Boosted Top Quark Identification	ATLAS-CONF-2013-084
Pile-Up Subtraction and Suppression for Jets	ATLAS-CONF-2013-083
Performance of Jet Substructure Techniques for Large-R Jets	arXiv:1306.4945
Jet Mass and Substructure of Inclusive Jets	JHEP 05 (2012) 128
Search for Resonances Decaying into Top-Quark Pairs Using Fully Hadronic Decays	JHEP 01 (2013) 116
ATLAS Measurements of Properties of Jets For Boosted Particle Searches	Phys. Rev. D 86 072006
A Search for ttbar Resonances in the Lepton Plus Jets Final State with ATLAS using 14 fb^{-1}	ATLAS-CONF-2013-052

ADDITIONAL MATERIAL

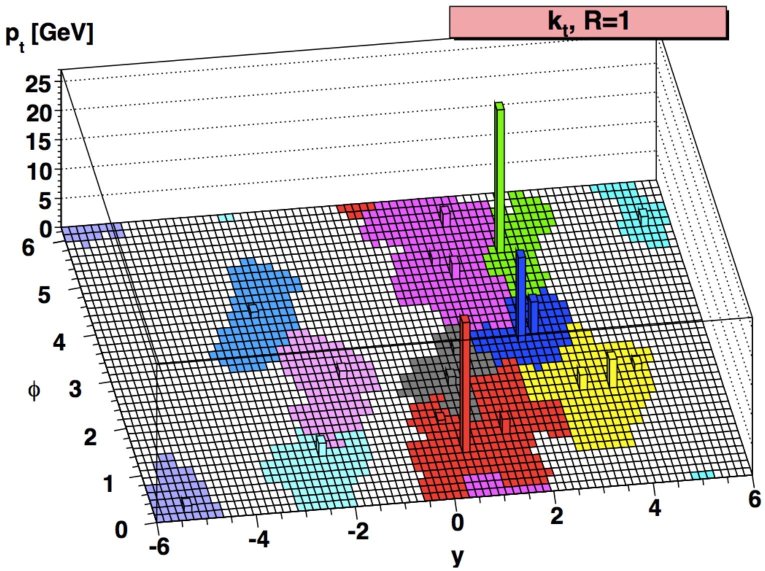
ATLAS Coordinate System

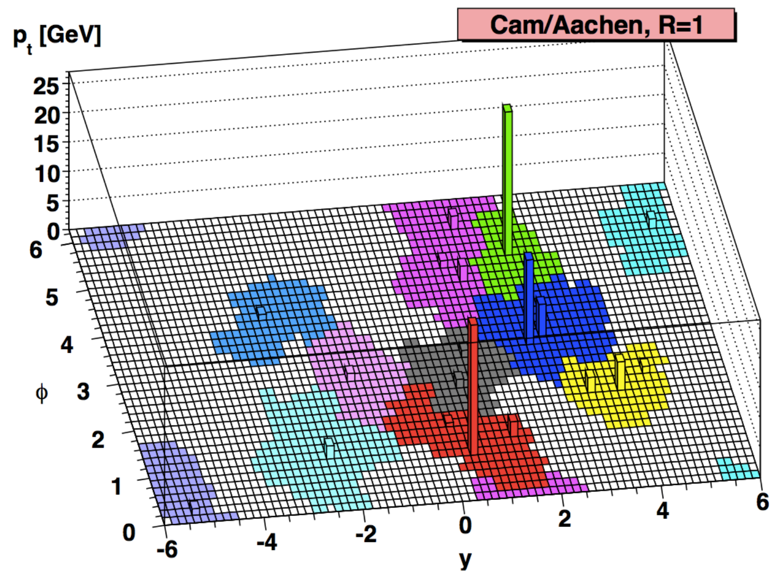
- Right-handed system with x-axis pointing to the LHC centre and y-axis pointing upwards
- Polar angle, θ , is measured w.r.t. LHC beamline
- Azimuthal angle, ϕ , is measured w.r.t. x-axis
- Rapidity $y = 0.5 \ln[(E + p_Z)/(E - p_Z)]$
- Pseudorapidity, η
  - is approximation of rapidity, y, in high energy limit
  - $\eta = -\ln \tan(\theta/2)$
- $p_T = p \sin \theta$, $E_T = E \sin \theta$

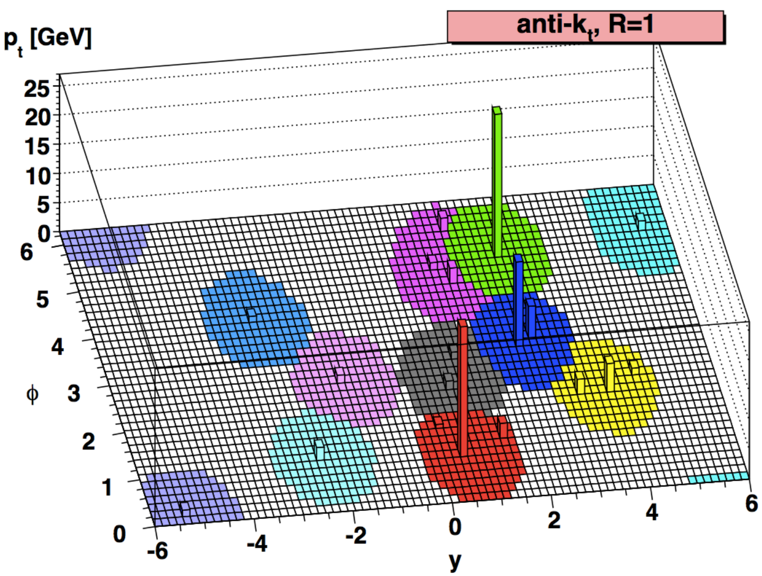
Topoclustering

Different Jet Clustering Algorithms

G. Salam
arXiv:0906.1833v2 [hep-ph]







Mass Calibration Validation using Track-Jets

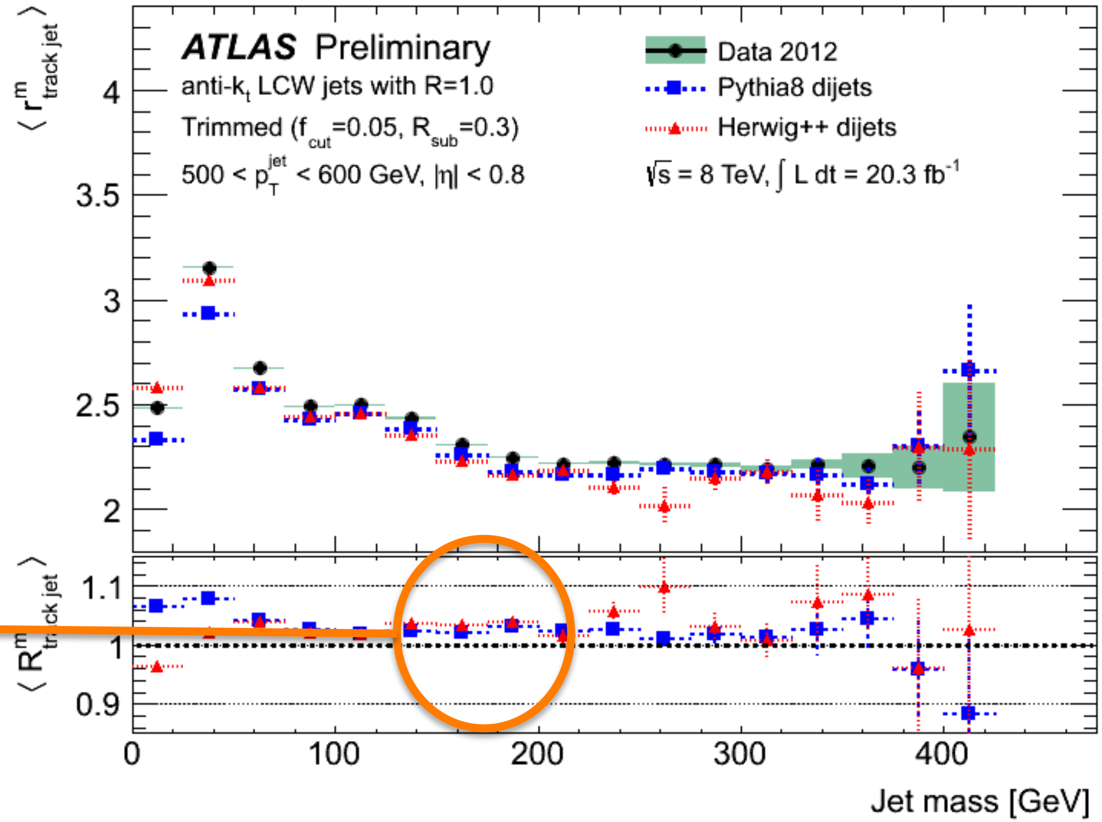
Jet mass scale validated by comparing to jets reconstructed from tracks

- uncorrelated systematics: tracker vs calorimeter
- pile-up reduced by using only tracks from hard scatter vertex

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

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

jet mass uncertainty < 5% in 2012 for hadronic top-jet (p_T > 500 GeV)

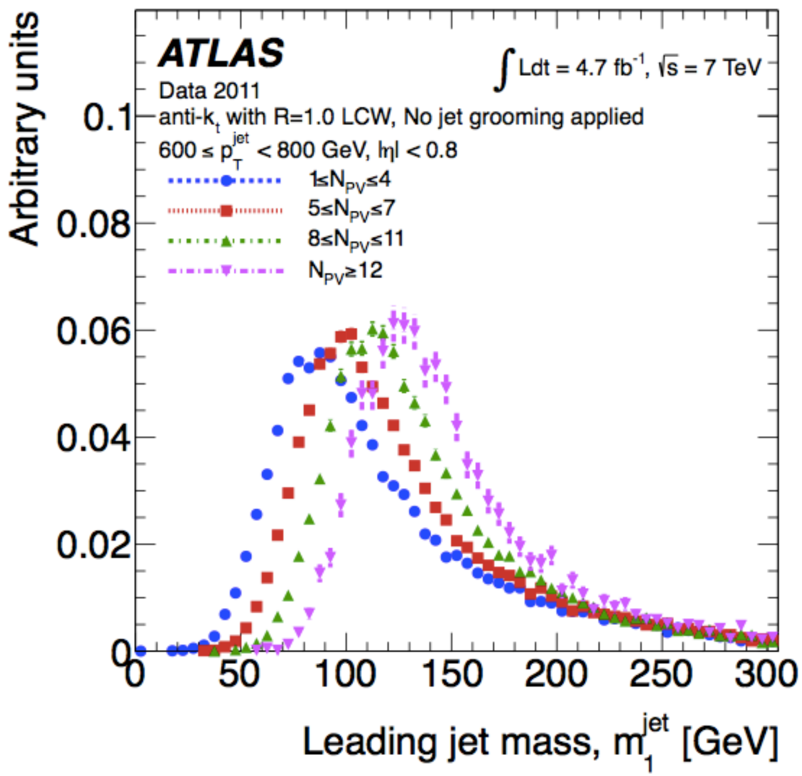


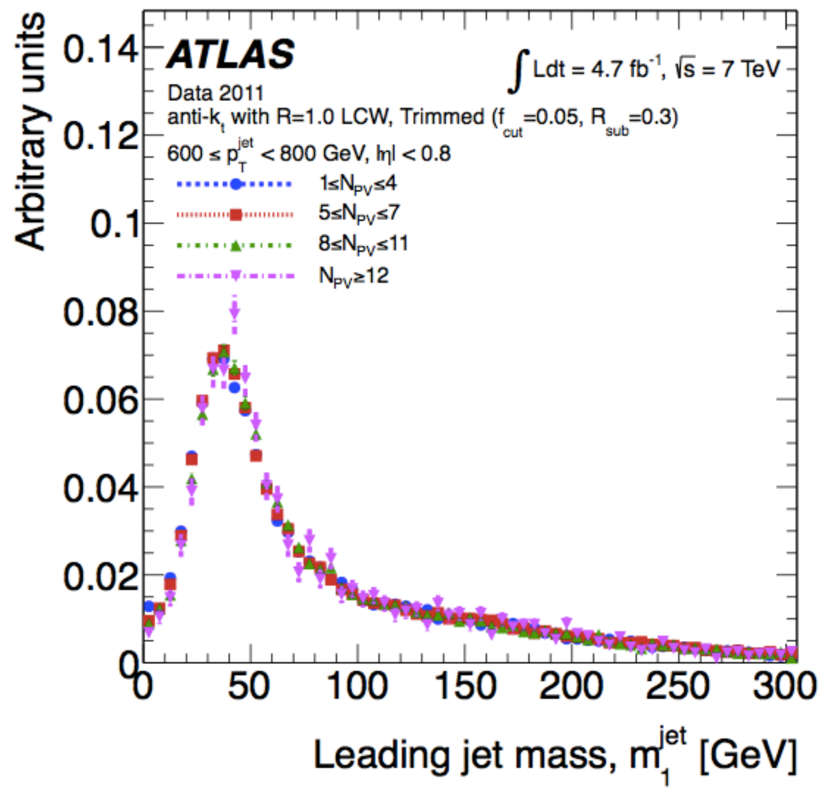
Mitigating the Effects of Pile-Up: Grooming

Ungroomed

Groomed

arXiv:1306.4945



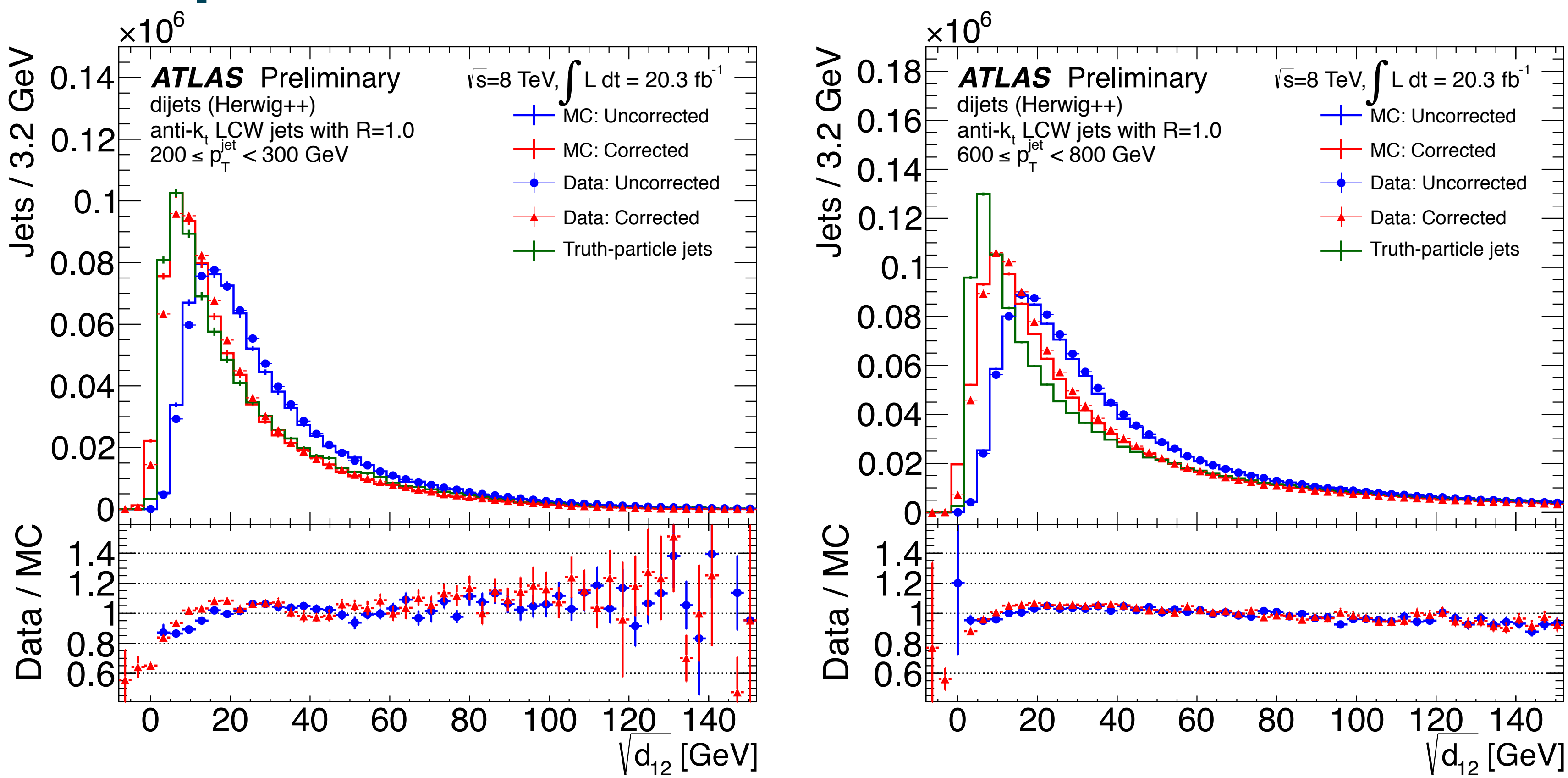


By reducing the effective jet area, grooming effectively eliminates the impact of pile-up

although at cost of some information about jet

Pile-Up Subtraction for Substructure

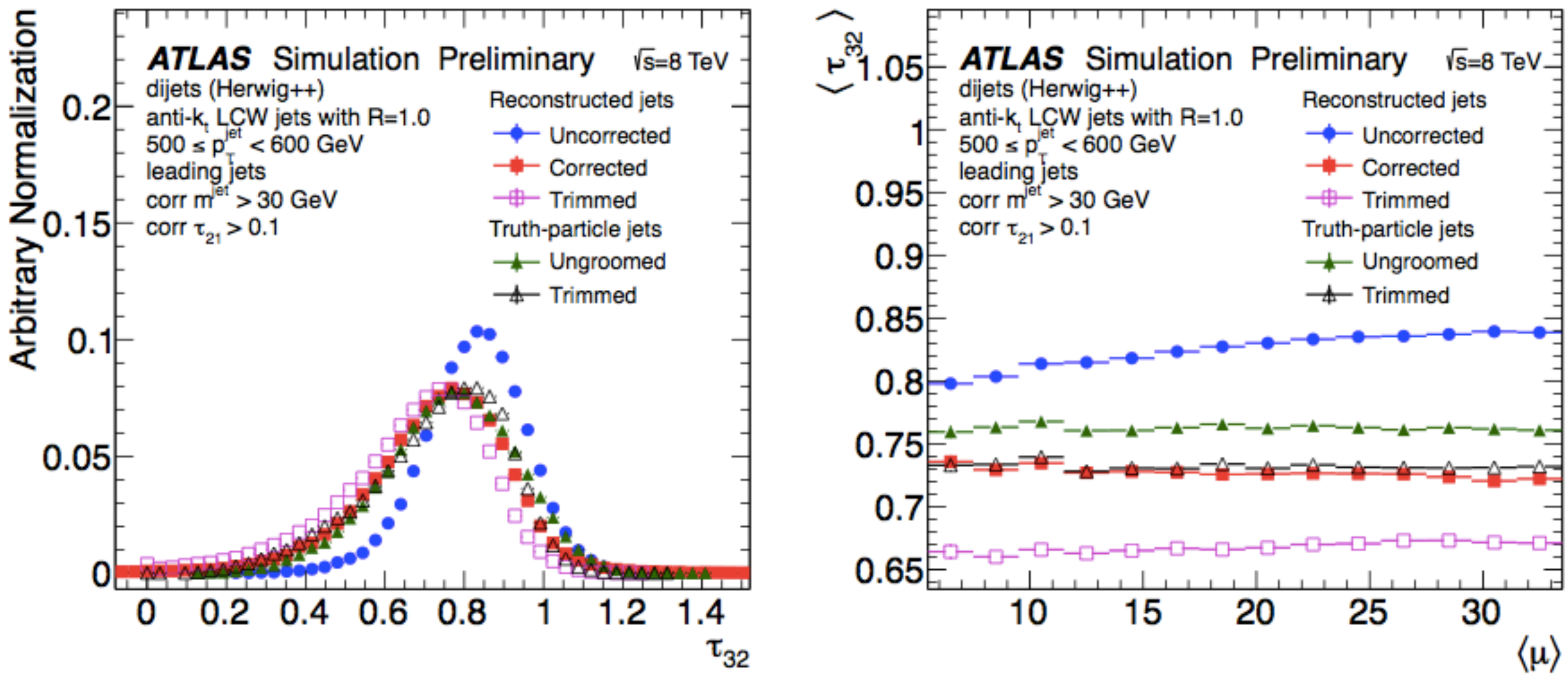
ATLAS-CONF-2013-085



Pile-up subtraction effectively removes pile-up effects from substructure observables

$\sqrt{d_{12}}$ = the k_T distance between the two final clusters in jet

Comparison of Trimming and Subtraction



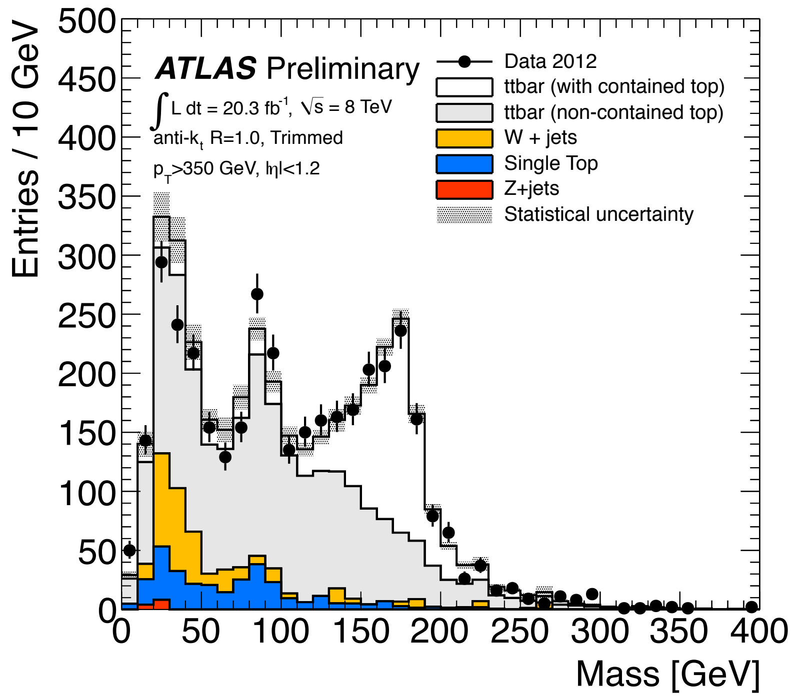
Both methods perform well

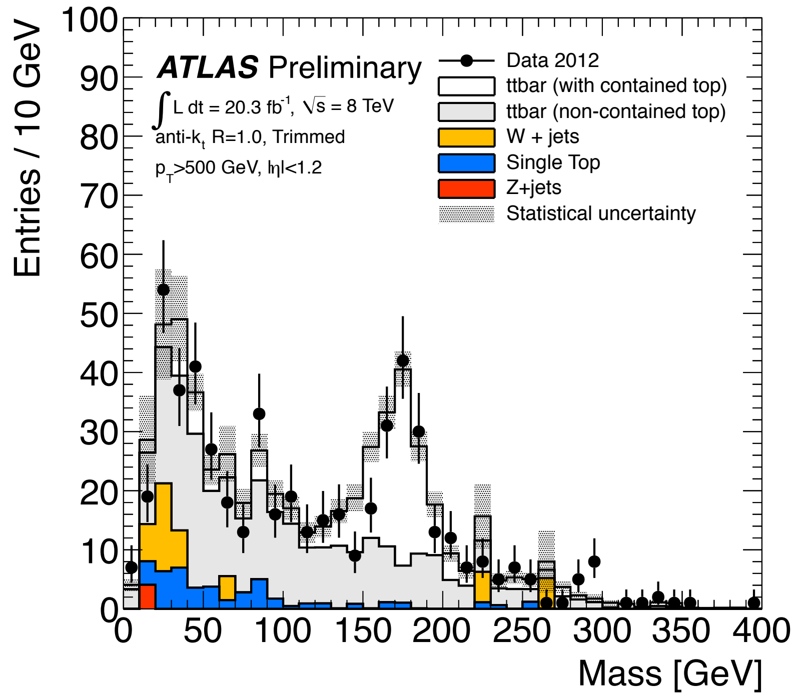
Different advantages/disadvantages

Jet substructure techniques possible in a high pile-up environment

Bodes well for LHC Run 2 and beyond

Jet Mass





Decay product separation $\Delta R \approx 2m/p_T$

For $p_T > 350$ GeV, clear top peak in mass spectrum

- From events where all top decay products are contained
- W peak from events where b is not contained within R=1.0 jet

For $p_T > 500$ GeV, top decay products are contained more often

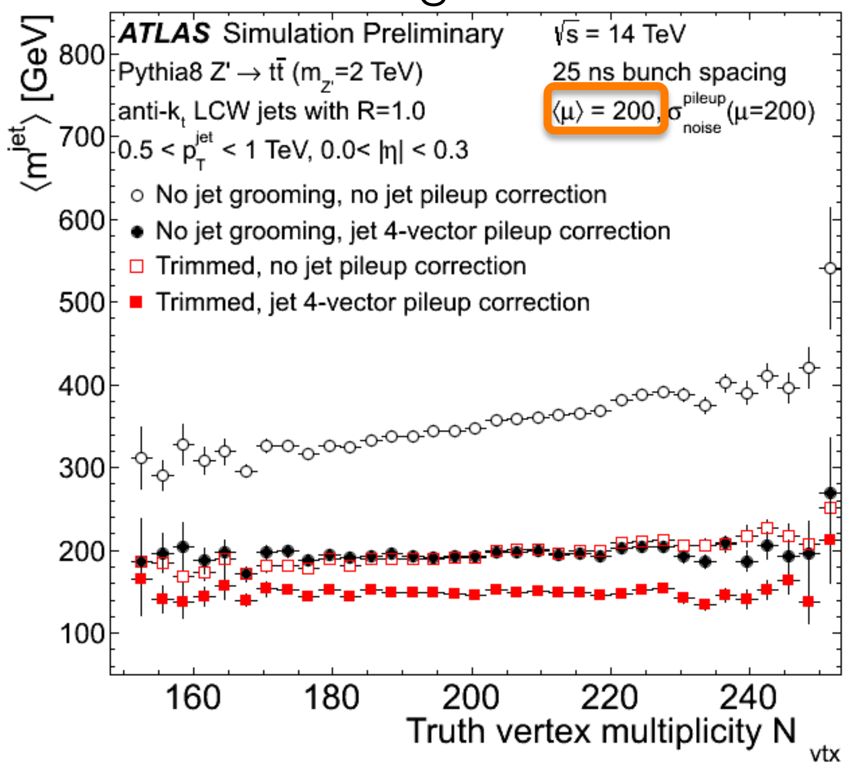
- W peak further suppressed as R = 0.3 subjets merge

Dealing with HL-LHC Pile-Up

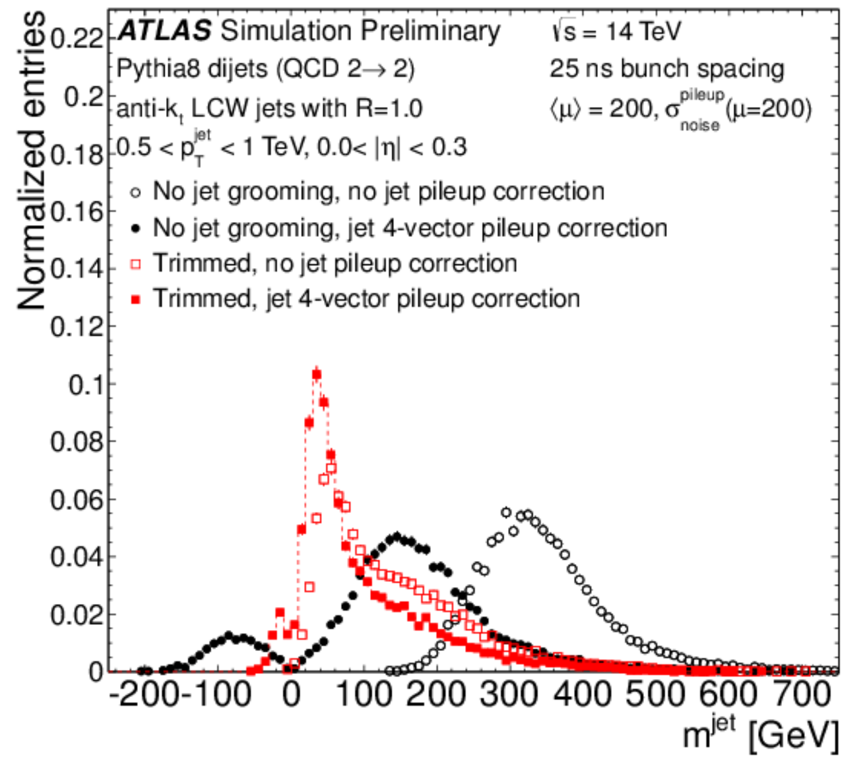
Planned upgrades of the LHC in the 2020s will see the luminosity increase to $L = 5\times10^{34}\ cm^{-2}s^{-1}$

MC studies indicate that large-R jets and substructure techniques can be used in this environment

Signal



Background



Top Template Tagger

Compares energy flow in jet to 300k simulated top templates

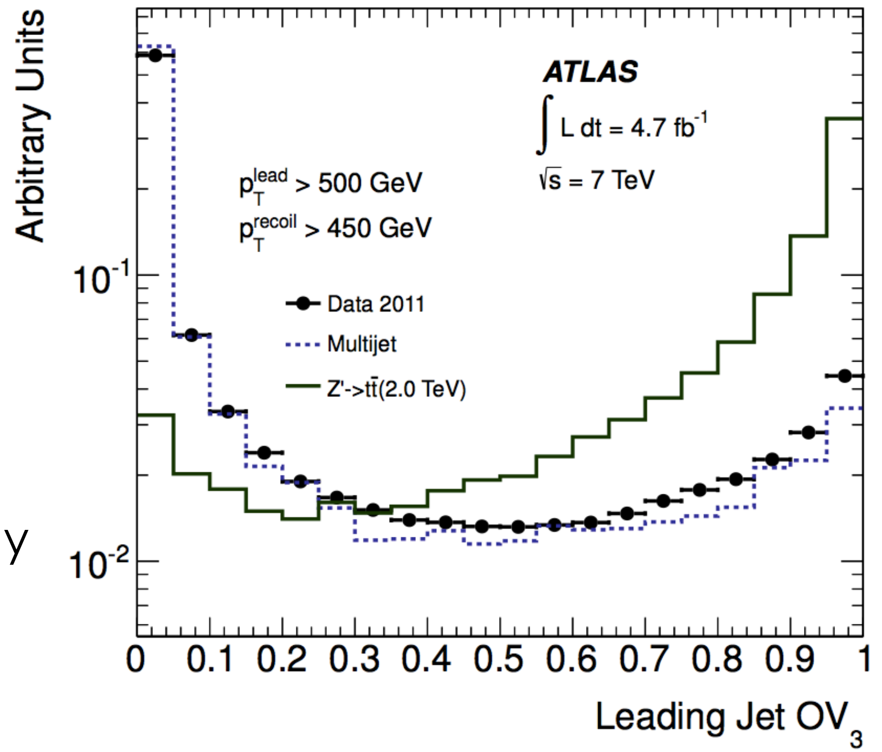
- jets with an overlap $OV_3 > 0.7$ are considered tagged

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

best template match is used

parton energy

cluster energy

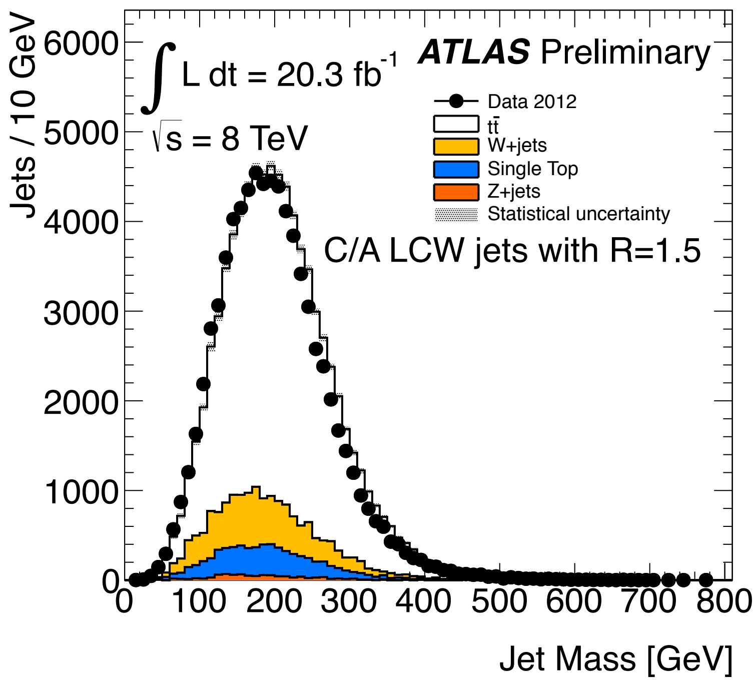


HEPTopTagger

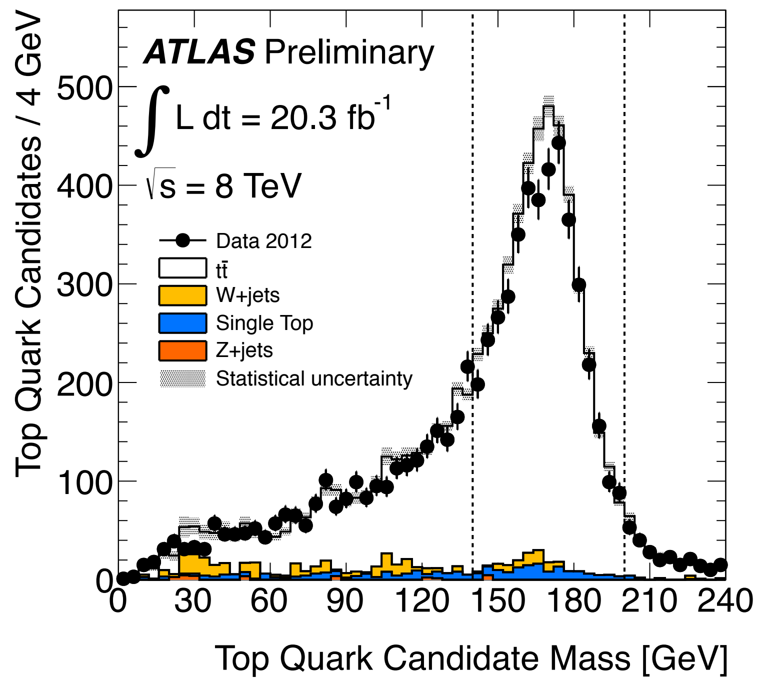
Divides C-A R=1.5 jets into subjets with small R-parameter

- Filters out soft contributions

Tests all combinations of three subjets for compatibility with hadronic top quark



Tag



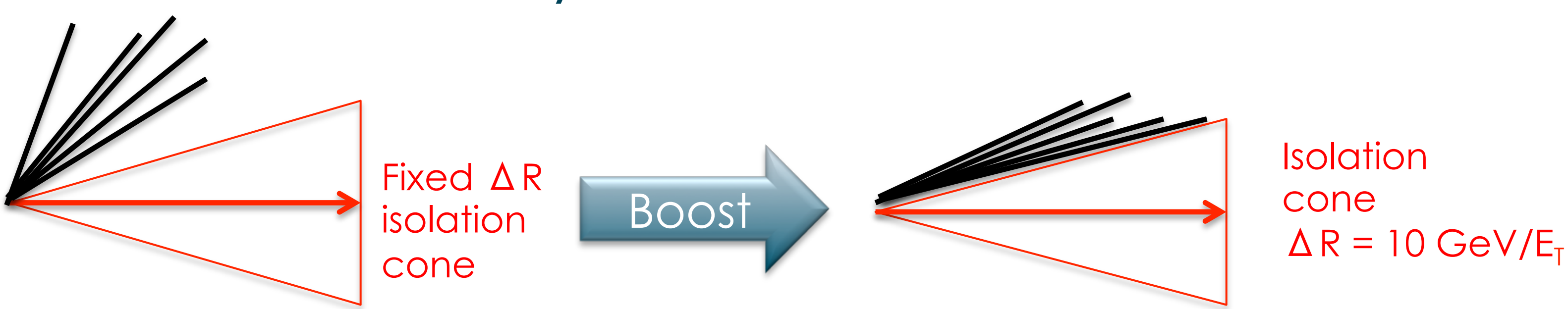
86% pure → 98% pure

Mini-Isolation

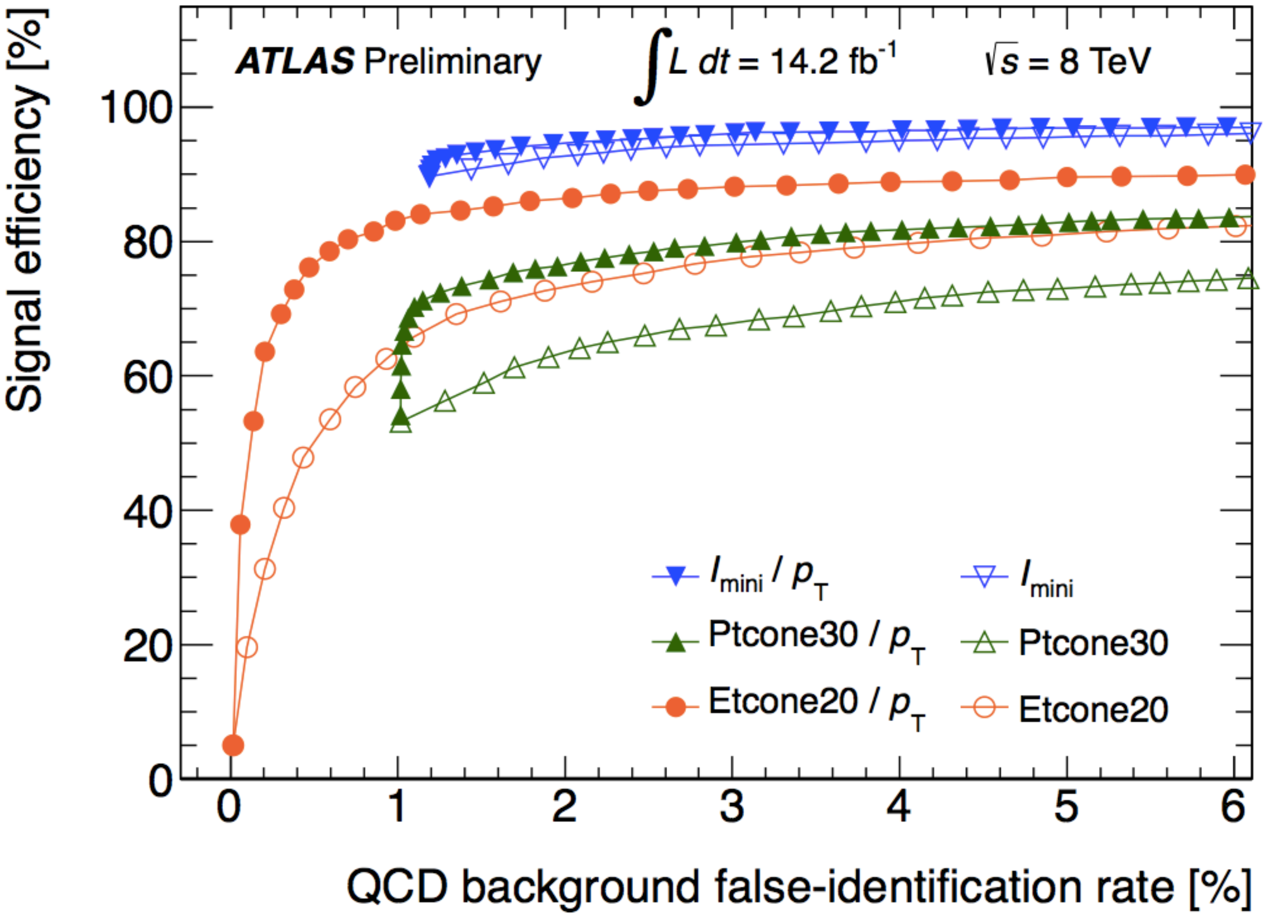
Leptonic decay products of top quark boosted too

Leads to a loss in isolation efficiency if fixed cone used

Define lepton p_T dependent isolation cone to maintain efficiency



Lepton Mini-Isolation Performance



Reducing isolation cone size improves signal efficiency

Jet Substructure

arXiv:1306.4945

Jets containing the decay products of a massive particle will be distinct from those typically caused by a light parton

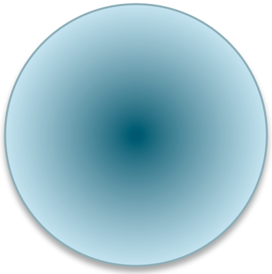
- Significant jet mass
- Hard 2- or 3-body substructure

These differences may be obscured by

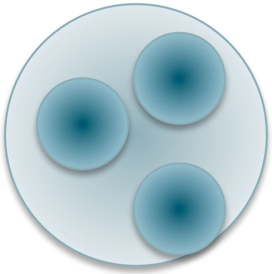
- QCD radiation
- pile-up and underlying event

Many techniques exist to “tag” and “groom” jets, aiming to

- Identify and retain hard substructure
- Reduce impact of soft QCD radiation



light parton jet



top jet