Studies of the internal properties of jets with the ATLAS Detector

Jets, jet shapes and jet substructure

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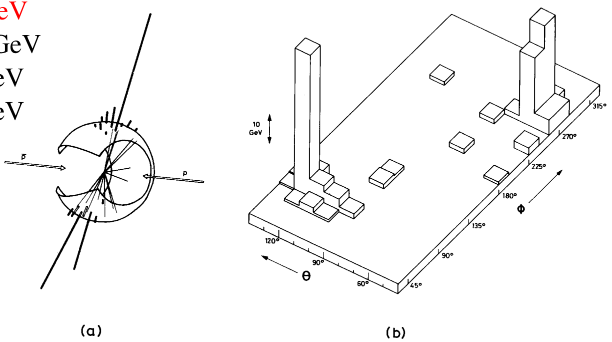
Evidence for jet production at CERN's UA2 (1982)

First observation at a hadron collider

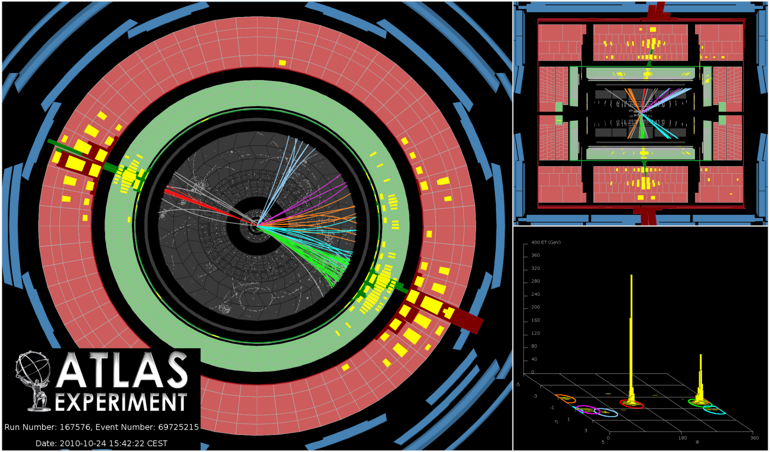
$\sqrt{s} = 540$ GeV
$m_{1,2} = 140$ GeV
$p_{T,1} = 60$ GeV
$p_{T,2} = 57$ GeV



First evidence for hadronic jet production in the UA2 experiment in 1982. (a) Charged tracks pointing to the inner face of the central calorimeter of the UA2 detector are shown together with calorimeter cell energies (indicated by heavy lines with lengths proportional to cell energies). (b) The cell energy distribution as a function of polar angle θ and azimuthal angle ϕ.

Entering a new era for hadronic final states: ATLAS (2010)

Our window into the Terascale!

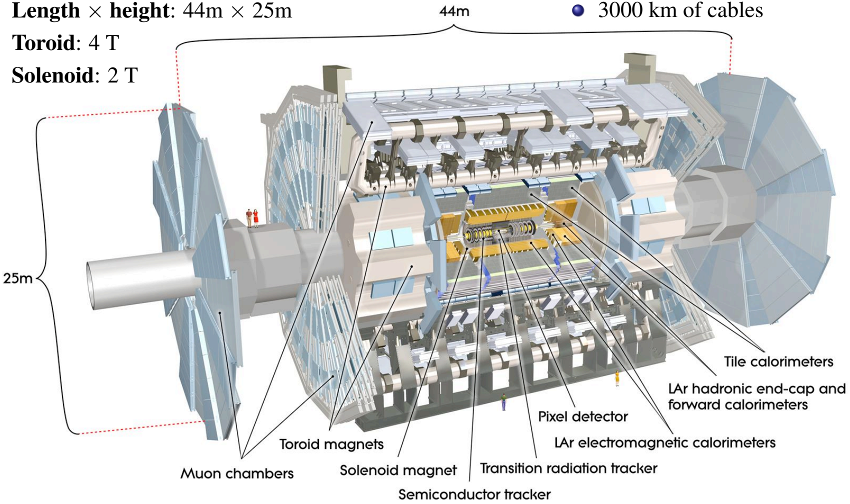


$\sqrt{s} = 7$ TeV

$\mathbf{m_{1,2} = 2.6}$ **TeV**, $p_{T,1} = 1.3$ TeV, $p_{T,2} = 1.2$ TeV

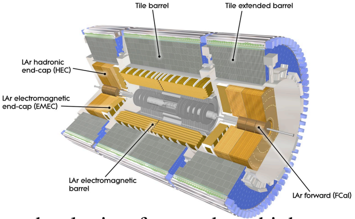
The ATLAS detector at the LHC

- **Weight**: 7000 tons
- **Length** × **height**: 44m × 25m
- **Toroid**: 4 T
- **Solenoid**: 2 T
- 100,000,000 electronic channels
- 3000 km of cables



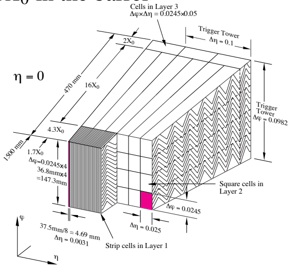
But the whole is more than just the sum of its parts...

The ATLAS calorimeter system and jet reconstruction

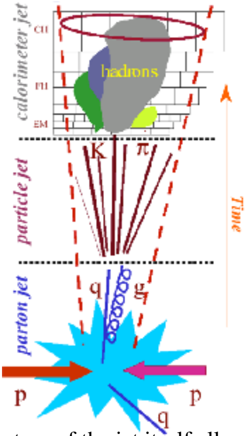


Well known technologies, fast readout, high granularity.

- Highly granular EM calo with longitudinal segmentation
- $\Delta\eta \times \Delta\phi \approx 0.025 \times 0.025$ (central)
- $22X_0 - 33X_0$ in the barrel



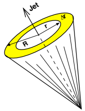
Jets are collections of final state particles which are *defined as comprising a single identifiable object*

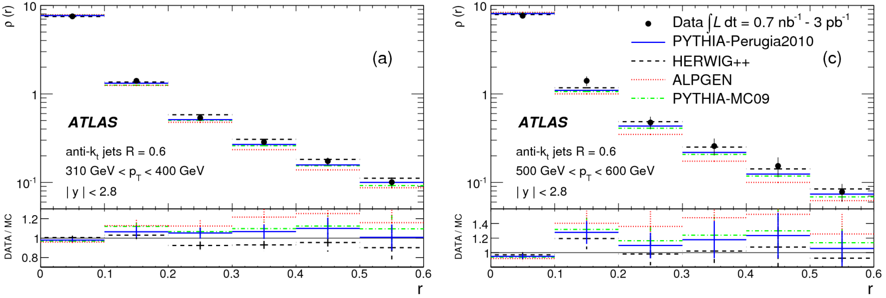


The structure of the jet itself allows for much **more** than just a simple 4-vector description.

Internal "classical" jet shapes with 2010 data

Using the anti-k_t $R = 0.6$ jet algorithm (Phys. Rev. D 83, 052003 (2011))

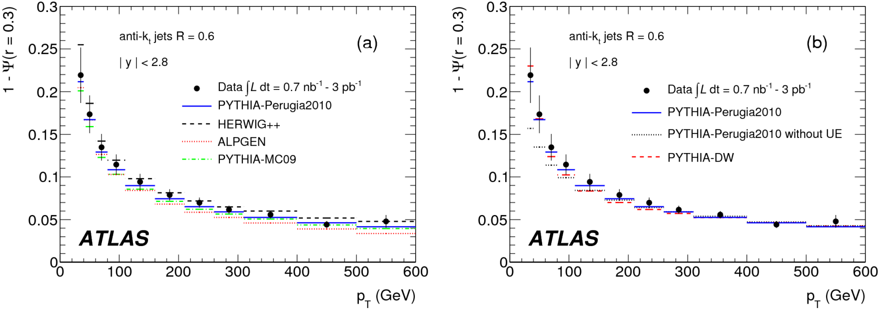




- Differential anti-k_t $R = 0.6$ jet shape densities – per annulus – demonstrate clear **jet-like structure** (dense core and diffuse periphery).
- Tests of different Monte Carlo generators (2 PYTHIA versions, ALPGEN, HERWIG++) show varying levels of agreement.
- Perugia 2010 tune of PYTHIA and HERWIG++ consistently describe the data very well.

Internal "classical" jet shapes vs. p_T in 2010

Using the anti-k_t $R = 0.6$ jet algorithm (Phys. Rev. D 83, 052003 (2011))



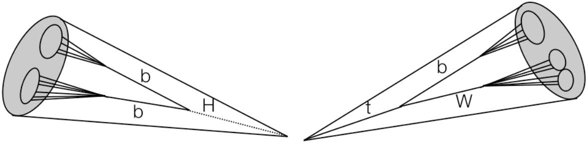
- $\Psi(r = r_0)$ represents the integrated energy within a given cone.
- $1 - \Psi(r = 0.3)$ represents the energy *outside* the core of the jet.
- Consistently see that most standard MC tunes (ALPGEN, PYTHIA) underestimate the amount of soft, wide-angle contributions to the jet.

What the energy frontier offers

With **new theoretical tools, advanced detectors, and experimental methods** in hand, we will be able to treat the jet as more than simply a 4-vector surrogate for a parton and to even search *inside* the jet.

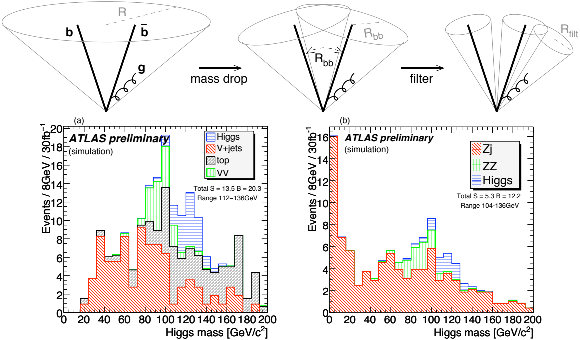
Here are a few examples of cases in which these techniques will be essential to study the Standard Model in a new energy regime, or even to discover new physics.

- Light Higgs decays to two *b*-quarks: **JET MASS**
- High mass SUSY particles which violate R-parity, producing highly boosted hadronic decays: **JET SPLITTING SCALES**
- Boosted top quarks with decay products merged into a single jets: **JET MASS AND SUBSTRUCTURE**



Recovering lost Higgs channels

A light Higgs decay to two b-quarks, $H \to b\bar{b}$, was thought to be completely lost in the QCD background. With **substructure techniques**, this channel may be recoverable.



$pp \to ZH/WH$
$H \to b\bar{b}$
ATL-PHYS-PUB-2009-88

Combined $llb\bar{b}$, $l\nu b\bar{b}$, $\nu\nu b\bar{b}$ channels may yield an observation (3.7σ) with 30 fb^{-1} .

At this luminosity, methods to understand, mitigate and correct for ***pile-up*** *will be essential.*

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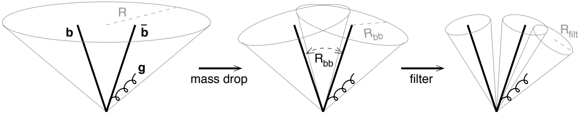
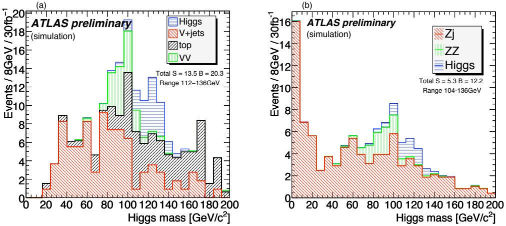
Crucial to remove soft radiation: jet filtering





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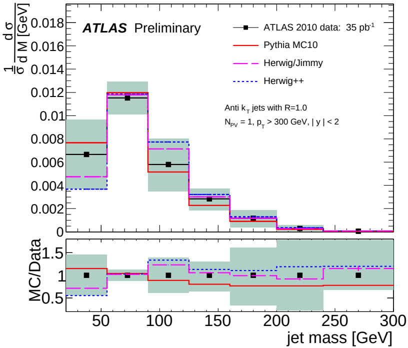
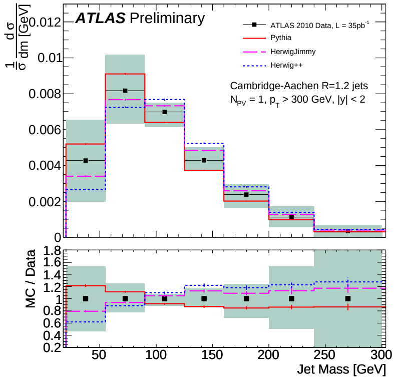
First measurements of "fat" jet mass at ATLAS in 2010

Using the anti-k_t, $R = 1.0$ and C/A, $R = 1.2$ "fat" jet algorithms (ATLAS-CONF-2011-073)

The individual jet mass encodes information about both the parton shower and the potential presence of heavy particle decays within the jet.



anti-k_t, $R = 1.0$ mass (35 pb^{-1})

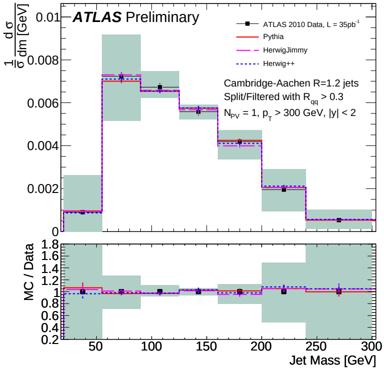


C/A, $R = 1.2$ mass (35 pb^{-1})

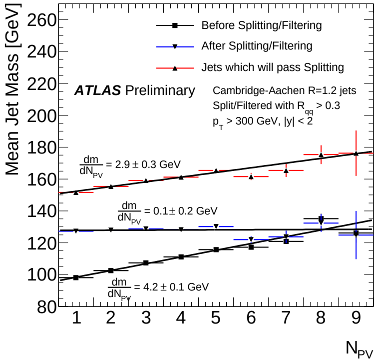
- Jet mass is unfolded to the particle level to correct for detector effects.

First measurements of filtered "fat" jet masses

By applying the jet filtering algorithm (necessary for mass resolution in boosted Higgs, $H \to b\bar{b}$), generator differences are reduced and impact of pile-up is removed.



C/A, $R = 1.2$ (filtered) mass (35 pb^{-1})



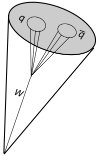
Impact of pile-up on mass w/ & w/o filtering

- World's first measurement of filtered jet mass. Agreement among MC is extremely good after filtering.

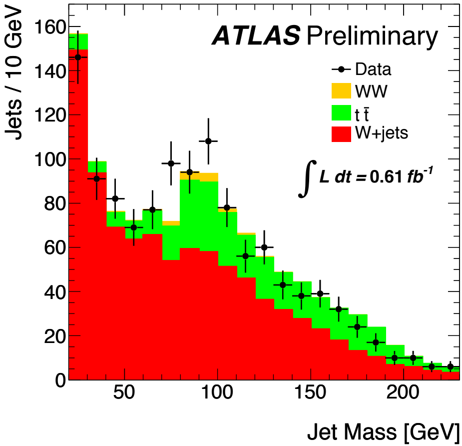
ATLAS-CONF-2011-073

Single jet hadronic W mass in $H \to b\bar{b}$ search

ATLAS-CONF-2011-103



- Events are selected to be consistent with $W \to l\nu$+1 jet, with $p_T^{\text{jet}} > 180$ GeV and $\Delta\phi_{W,\text{jet}} > 1.2$
  - Jet filtering procedure is used with C/A, $R = 1.2$ jets
  - No b-tagging is applied
- Uncorrected $t\bar{t}$, W+jets, and SM WW processes are included and normalized to the highest order cross-section available.
- These first results are encouraging, promising new results with boosted jet substructure techniques in the near future.

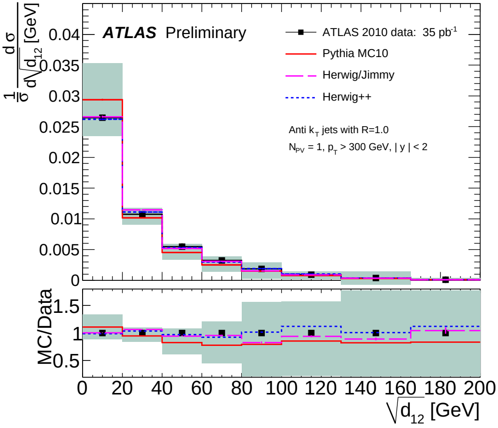


Uncorrected jet mass in $W \to l\nu$ events

First measurements of "fat" jet splitting scale at ATLAS

ATLAS-CONF-2011-073 (35 pb^{-1})

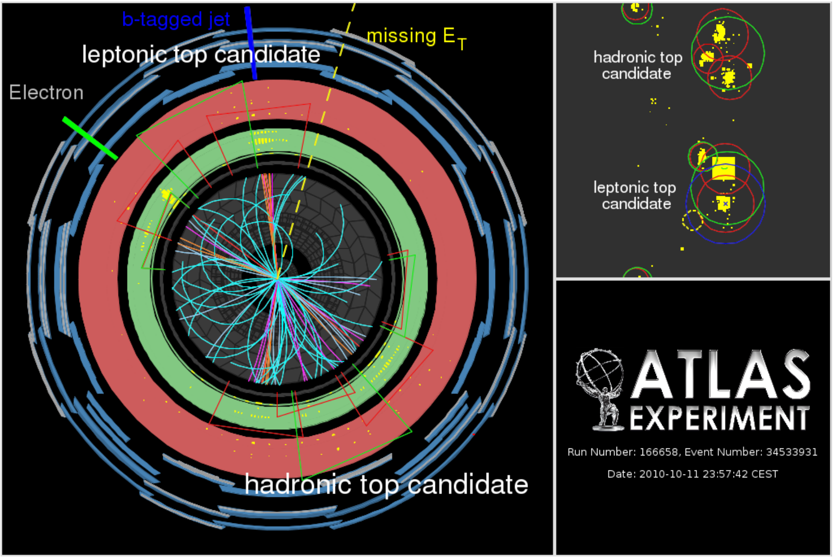
$$\sqrt{d_{12}} = \min(p_{T,1}, p_{T,2})\delta R_{12}$$



The **splitting scale** represents the kinematic threshold at which a jet can be broken into sub-components – the level at which structure begins to form.

- Corrected to particle level for detector effects
- Expected to be significantly different between signal and background for boosted objects
- Well described by MC + detector simulation

Boosted SM top quarks observed in the data



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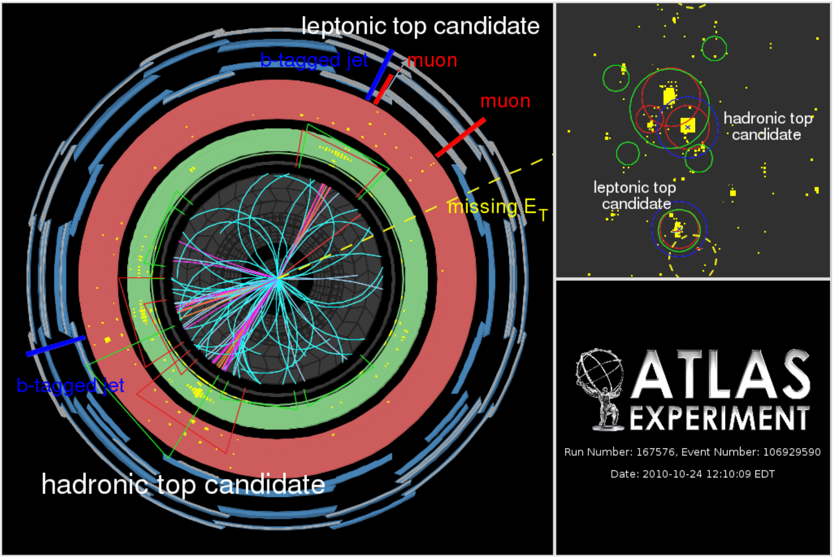
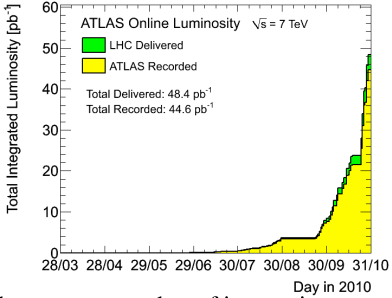
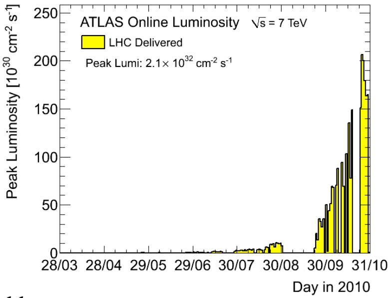


Status and future jet physics at ATLAS

- The physics program is well underway at ATLAS
  - Many of the first results based on hadronic final states
- Advanced experimental and theoretical tools expose the wealth of information *inside* of jets at the energy frontier.
  - Jets are more than just a simple 4-vector
- Have shown the canonical measurements of inclusive QCD **jet shapes** and first measurements of **fat jet mass, splitting scales, and internal structure**
  - Results are in good agreement with expectations from MC, while crucial differences between MC models have been uncovered.
- Already applying these advanced techniques to searches for new physics in boosted hadronic final states
  - **First hints of hadronic W decays into a single jet and candidate boosted top quark events**

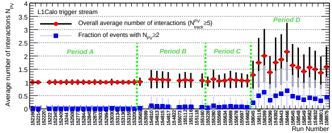
LHC operation in 2010



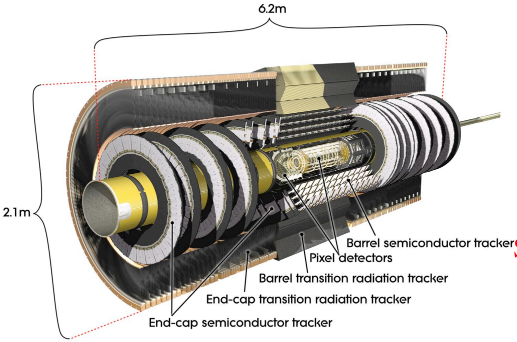


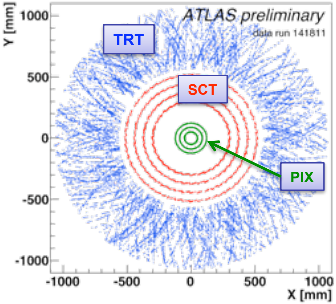
The average number of interactions measured by the reconstructed primary vertex multiplicity in calorimeter triggered events as a function of time throughout 2010.

- **March-June** $\langle N_{PV} \rangle \approx 1.05 - 1.1$ (fraction with $N_{PV} \geq 2$: <10%)
- **June-October** $\langle N_{PV} \rangle \approx 1.5 - 2.0$ (fraction with $N_{PV} \geq 2$: 40-60%)



The ATLAS tracking system





Silicon Strips (SCT)

- 4 barrel layers, 2x9 end-cap disks
- $\sigma_{r\phi} \sim 17\mu$m, $\sigma_z \sim 580\mu$m
- 6.3M channels

Transition Radiation Drift Tubes (TRT)

- 73 barrel straws, 2x160 end-cap disks
- $\sigma_r \sim 130\mu$m, particle ID
- 350k channels

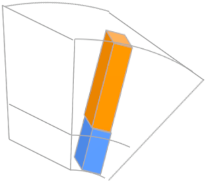
Silicon Pixels (PIX)

- 3 barrel layers, 2x3 end-cap disks
- $\sigma_{r\phi} \sim 10\mu$m, $\sigma_z \sim 115\mu$m
- 80M channels

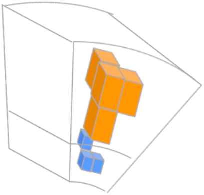
Excellent position resolution, tracking efficiency, vertexing performance.

Inputs to jet reconstruction

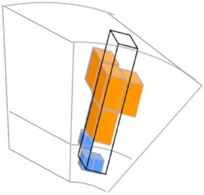
ATLAS has a highly flexible and robust set of input signals to consider for jet reconstruction:



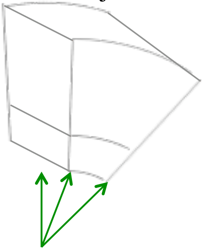
Towers without noise suppression



Topological clusters



Towers with noise suppression

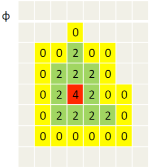


Tracks

Each of these has been studied in detail in the data in order to *ensure a thorough understanding of the jet reconstruction* itself and the signal model being used to form the basis for physics measurements.

- ATLAS-CONF-2010-18
- ATLAS-CONF-2010-53

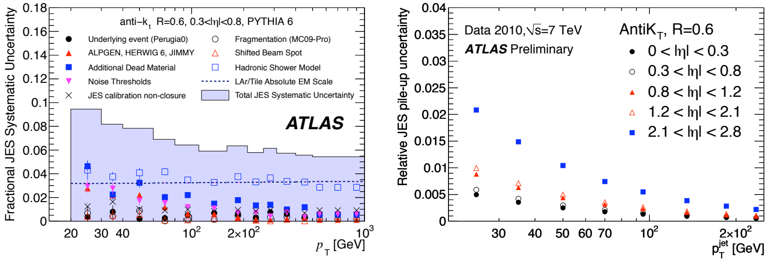
Topological clustering for noise suppression



Jet energy scale uncertainty

ATLAS-CONF-2010-056

The JES uncertainty is the single largest uncertainty for any analysis I will present.



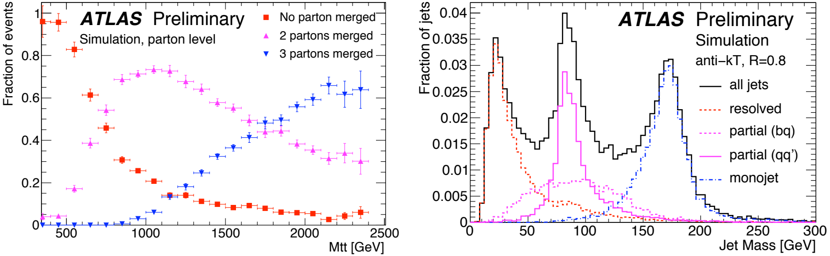
- It is crucial to determine each component *systematically* and to provide a **well-understood uncertainty**, over and above a *small uncertainty*.
- 8-9% at low p_T

Focus on the component known to change over time, and to become ever more important as the luminosity of the machine increases to its nominal value:

the uncertainty due to multiple interactions in same bunch crossing: pile-up.

Boosted top decays at the LHC

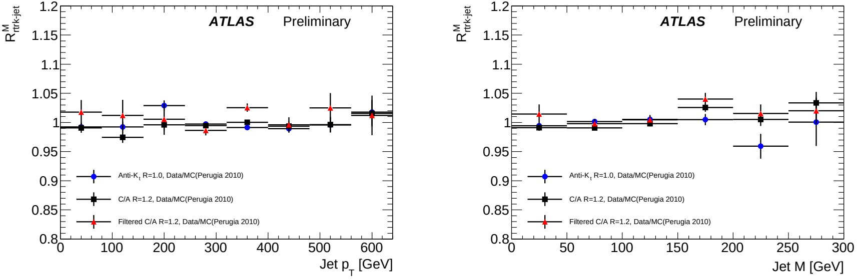
The LHC will offer many new arenas for measuring Standard Model processes, such as boosted $t\bar{t}$ decays. These same measurements serve as a **proving ground** for techniques to search for new physics in hadronic final states.



(left) Fraction of top quark decay products found within an anti-k_t jet of radius R=0.8. (right) Mass distribution of the lead jet in these events for different scenarios (ATLAS-PUB-2010-08)

The key is to pick apart this substructure correctly, which depends on excellent understanding of the calorimeter signals and the jet reconstruction itself.

Fat jet momentum and energy scale uncertainty



$R^{p_T}_{r\text{track}-\text{jet}}$. $R^{m}_{r\text{track}-\text{jet}}$.

Figure: $R^{m}_{r\text{track}-\text{jet}}$ versus p_T^{jet} and m^{jet} for jets reconstructed with the three algorithms considered.

Fat jet momentum and energy scale uncertainty

Table: Uncertainty on the p_T and mass scale of the three jet algorithms used in this study.

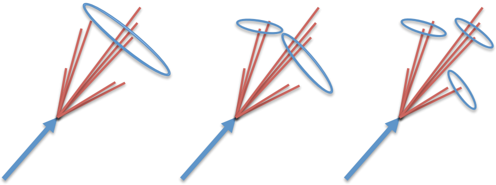
Jet Algorithm	JES	JMS	JER	JMR
anti-k_t, $R = 1.0$	5%	7%	20%	30%
C/A, $R = 1.2$	5%	6%	20%	30%
C/A, $R = 1.2$ (filtered)	6%	7%	20%	30%

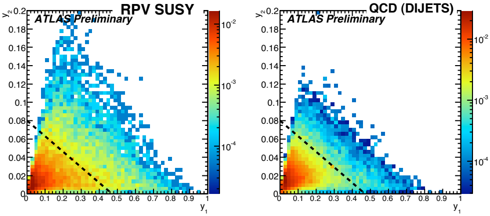
Table: Uncertainty on the scale and resolution of the k_T splitting scale variable.

	Scale	Resolution
$\sqrt{d_{12}}$	15%	30%

Searching for SUSY with substructure

In R-parity violating (RPV) SUSY, baryon number violation occurs and the decay $\overline{\chi}_1^0 \rightarrow qqq$ is possible, but buried under the QCD background.
Substructure-based analyses may be the only method to recover such a signal.





Approach:

1. Cluster jets with k_t, $R = 0.7$
2. Split the jets into the the last (y_1) and second to last (y_2) recombinations
   - $y_i = d_{i,i+1}/m_{\text{jet}}^2$
   - $d_{i,i+1} = \min(p_{T,i}^2, p_{T,i+1}^2)R_{i,i+1}^2/R^2$
3. Require $p_{T,\text{jet}} > 275$ GeV

ATL-PHYS-PUB-2009-076