



*Jet substructure and hadronic event shapes  
at high  $Q^2$  in ATLAS*

David W. Miller  
on behalf of the ATLAS Collaboration

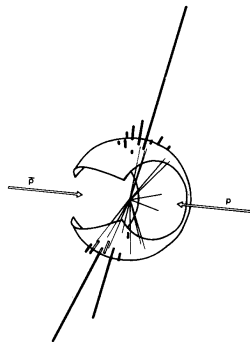
SLAC National Accelerator Laboratory and Stanford University  
(now at the University of Chicago)

2011 Meeting of the Division of Particles and Fields  
of the American Physical Society  
August 9-13, 2011 in Providence, RI



# Jet production at hadron colliders

*Our window into the Terascale!*



UA2,  $S\bar{p}pS$ , 1982

$\sqrt{s} = 540 \text{ GeV}$

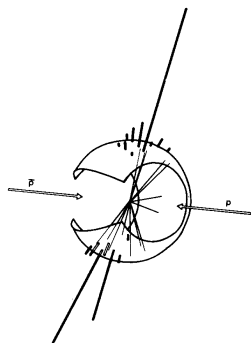
$m_{1,2} = 140 \text{ GeV}$

$p_{T,1} = 60 \text{ GeV}$

$p_{T,2} = 57 \text{ GeV}$

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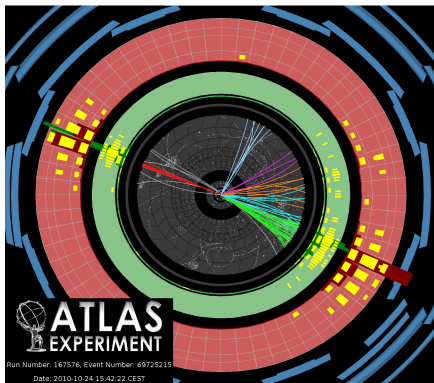
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ATLAS, LHC, 2010

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

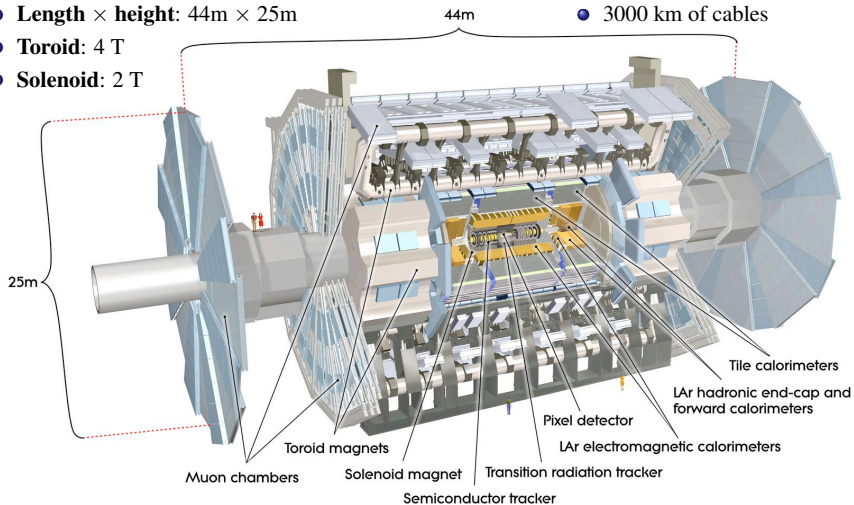
$$m_{1,2} = 2.6 \text{ TeV}$$

$$p_{T,1} = 1.3 \text{ TeV}$$

$$p_{T,2} = 1.2 \text{ TeV}$$

## The ATLAS detector at the LHC

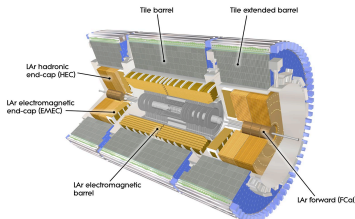
- **Weight:** 7000 tons
- **Length × height:** 44m × 25m
- **Toroid:** 4 T
- **Solenoid:** 2 T
- 100,000,000 electronic channels
- 3000 km of cables



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

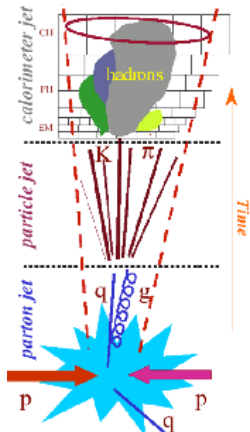
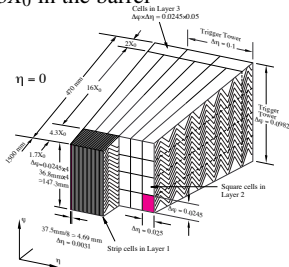
# The ATLAS calorimeter system and jet reconstruction

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



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



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

## Multi-jet event shapes and QCD at $\sqrt{s} = 7$ TeV

Multi-jet final states and event shapes have a long history at both hadron and lepton colliders.

- **Measure the relationship of hadronic final state objects (jets) to one another, in a new energy regime.**

### The observables

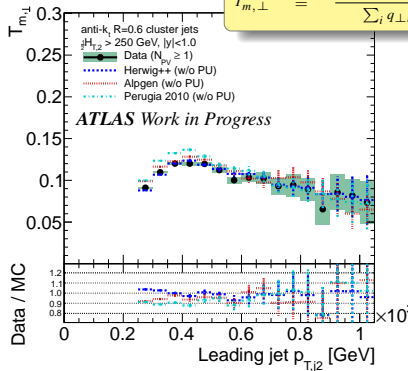
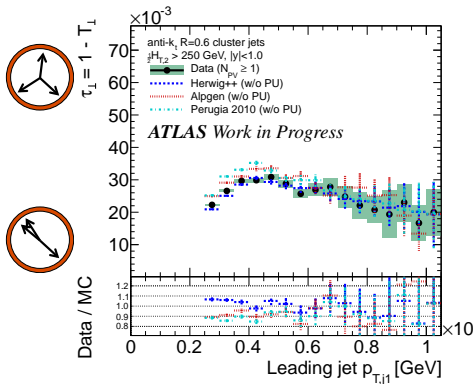
- **Transverse thrust, thrust minor** ( $\tau_{\perp}, T_{m,\perp}$ ): measure aspects of the “three-jettiness” of an event by looking for the magnitude of the multi-jet axis with respect to the hardest two jets.
  - Sensitive to “in-plane” and “out-of-plane” radiation.
- **(Transverse) sphericity**,  $S^{\text{spheri}}, S_{\perp}^{\text{spheri}}$ : measure **circular symmetry** of the event using eigenvalues of the jet momentum tensor,  $M_{xyz}$ .
- **Three-jet resolution** ( $y_{23}$ ): measures the **momentum content of the 3rd jet** ( $p_{T,3}^2$ ) in relation to the sum of the first two, or  $Q^2 = (p_{T,1} + p_{T,2})^2$

# Detector-level distributions: $\tau_{\perp}$ and $T_{m,\perp}$

$$T_{\perp} \equiv \frac{\max_{\hat{n}_{\perp}} \sum_i |\vec{q}_{\perp i} \cdot \hat{n}_{\perp}|}{\sum_i q_{\perp i}}$$

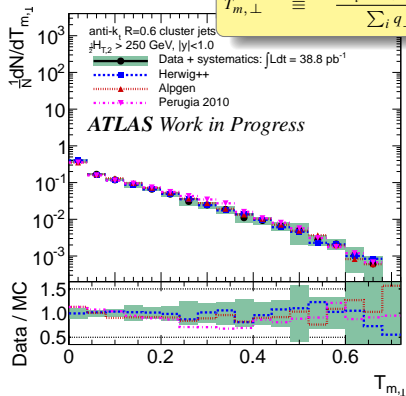
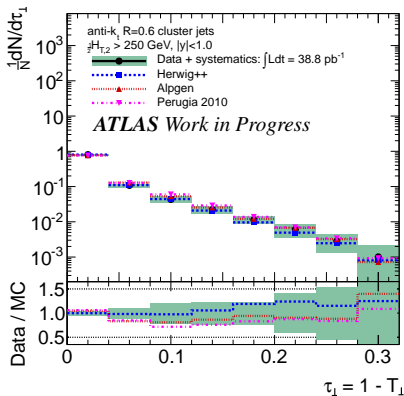
$$\tau_{\perp} \equiv 1 - T_{\perp}$$

$$T_{m,\perp} \equiv \frac{\sum_i |\vec{q}_{\perp i} \times \hat{n}_{\perp}|}{\sum_i q_{\perp i}}$$



- The slightly worse agreement of PYTHIA (Perugia 2010) is most in the kinematic evolution of the thrust and thrust minor component.
- In the region where the multijet description dominates, PYTHIA deviates in just the *mean* thrust minor (roughly, the out-of-plane jet activity) by 10%.

## Results at particle level: $\tau_{\perp}$ & $T_{m,\perp}$



$$T_{\perp} \equiv \frac{\max_{\hat{n}_{\perp}} \sum_i |\vec{q}_{\perp i} \cdot \hat{n}_{\perp}|}{\sum_i q_{\perp i}}$$

$$\tau_{\perp} \equiv 1 - T_{\perp}$$

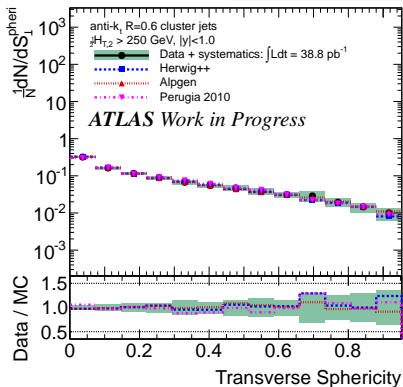
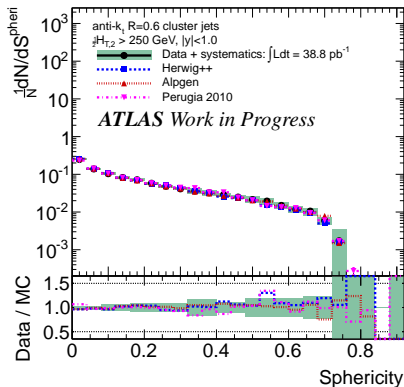
$$T_{m,\perp} \equiv \frac{\sum_i |\vec{q}_{\perp i} \times \hat{n}_{\perp}|}{\sum_i q_{\perp i}}$$

- The thrust generally well described by each of the three generators, although both ALPGEN and PYTHIA (Perugia 2010) show slight deviations in the midrange of the thrust, and is slightly worse for  $T_{m,\perp}$ , suggesting that the out-of-plane activity is not as well described.

# Results at particle level: $S^{\text{spheri}}$ & $S_{\perp}^{\text{spheri}}$

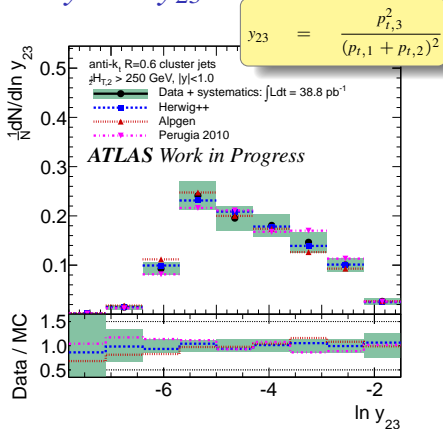
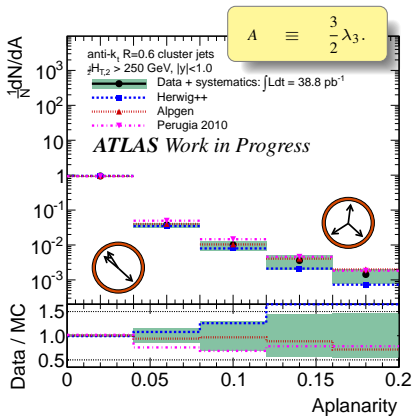
$$S^{\text{spheri}} \equiv \frac{3}{2}(\lambda_2 + \lambda_3),$$

$$S_{\perp}^{\text{spheri}} \equiv \frac{2\lambda_2}{\lambda_1 + \lambda_2},$$



- Sphericity and transverse sphericity are both well described by all three generators with comparatively small systematic uncertainties.

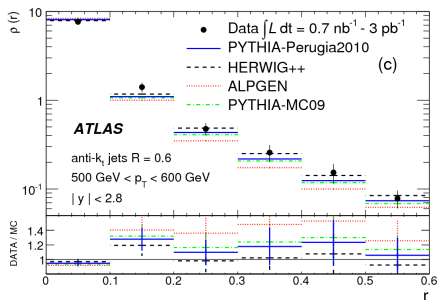
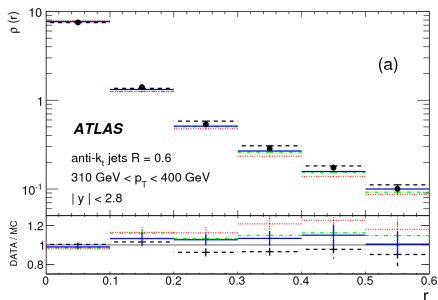
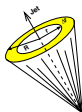
## Results at particle level: aplanarity and $y_{23}$



- After correcting for detector effects, HERWIG++ is quite discrepant at high  $A$ . ALPGEN models the data slightly better than PYTHIA (Perugia 2010) in the lower and mid-range.
- Good agreement for  $y_{23}$  with all generators, although HERWIG++ does seem to follow the data the best, but all are within systematics here.

# Internal “classical” jet shapes with 2010 data

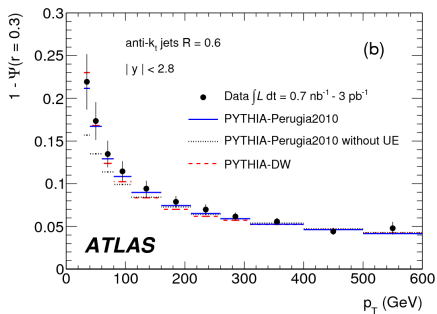
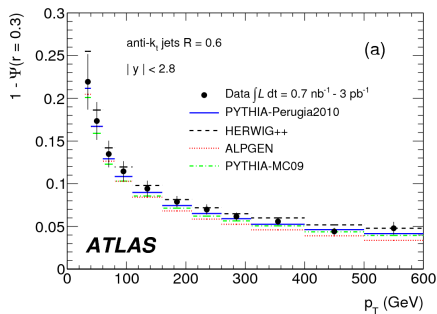
Using the anti- $k_t$   $R = 0.6$  jet algorithm (*Phys. Rev. D* 83, 052003 (2011))



- 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- $k_r$   $R = 0.6$  jet algorithm (*Phys. Rev. D* 83, 052003 (2011))



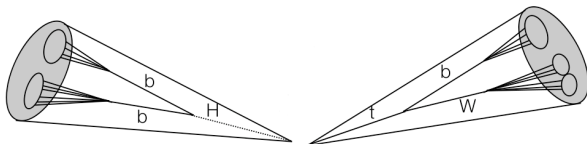
- $\Psi(r = r_0)$  represents the integrated energy within a given cone.
- $1 - \Psi(r = 0.3)$  represents the energy *outside* the core of the jet.
- Consistently see that most standard MC tunes (ALPGEN, PYTHIA) **underestimate** the amount of soft, wide-angle contributions to the jet.

## 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.

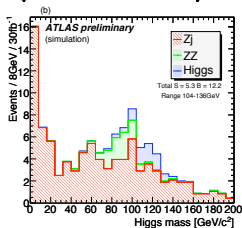
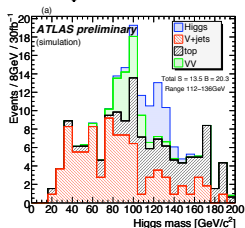
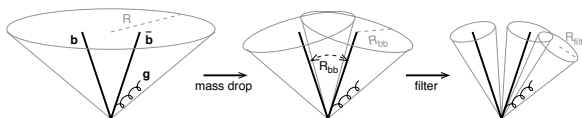
Here are a few examples of cases in which these techniques will be essential to study the Standard Model in a new energy regime, or even to discover new physics.

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



$pp \rightarrow ZH/WH$   
 $H \rightarrow b\bar{b}$

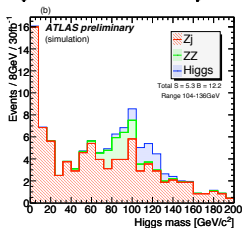
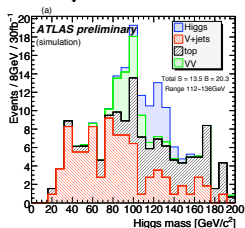
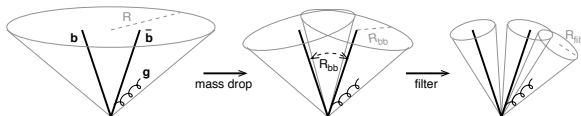
ATL-PHYS-PUB-2009-88

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



$pp \rightarrow ZH/WH$   
 $H \rightarrow b\bar{b}$

ATL-PHYS-PUB-2009-88

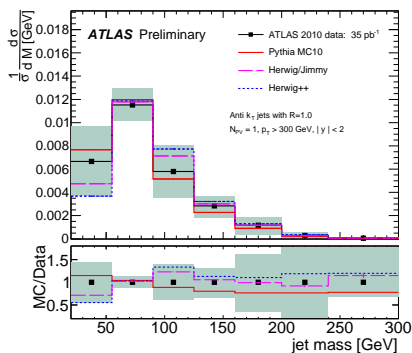
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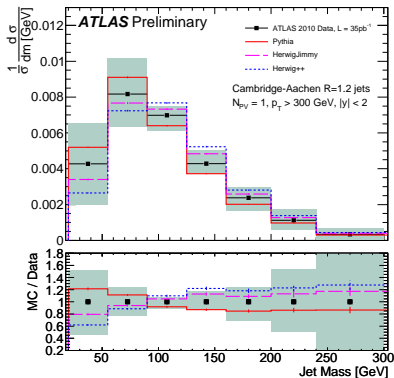
# First measurements of “fat” jet mass at ATLAS in 2010

Using the anti- $k_r$ ,  $R = 1.0$  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- $k_r$ ,  $R = 1.0$  mass ( $35 \text{ pb}^{-1}$ )

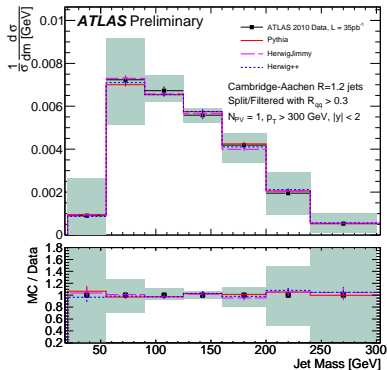


C/A,  $R = 1.2$  mass ( $35 \text{ pb}^{-1}$ )

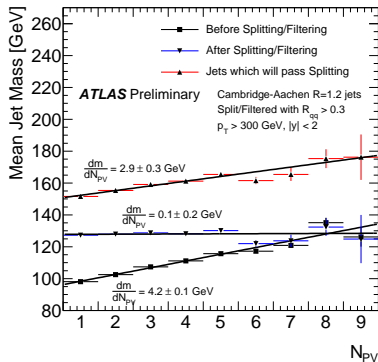
- Jet mass is unfolded to the particle level to correct for detector effects.

# First measurements of *filtered* “fat” jet masses

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



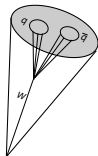
C/A,  $R = 1.2$  (filtered) mass ( $35 \text{ pb}^{-1}$ )



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.

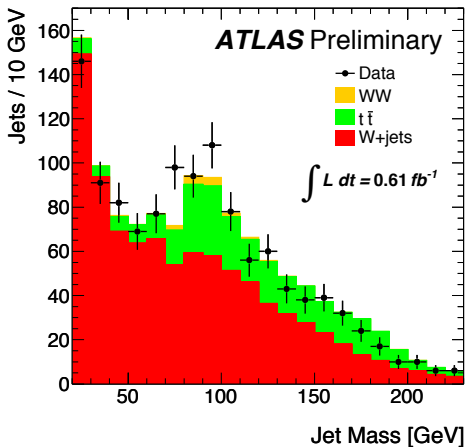
ATLAS-CONF-2011-073



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

ATLAS-CONF-2011-103

- Events are selected to be consistent with  $W \rightarrow l\nu + 1$  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.

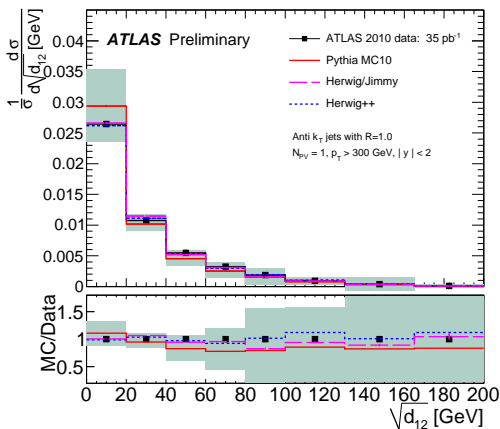


Uncorrected jet mass in  $W \rightarrow l\nu$  events

# First measurements of “fat” jet splitting scale at ATLAS

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

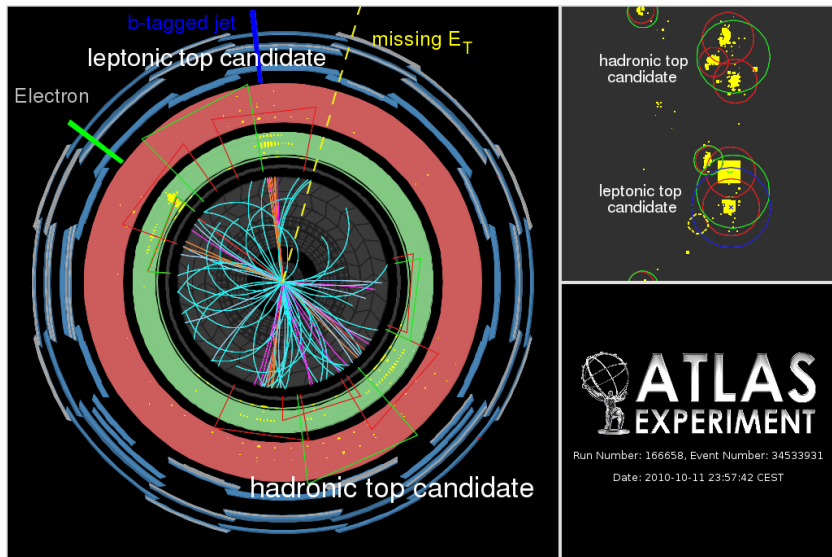
$$\sqrt{d_{12}} = \min(p_{T,1}, p_{T,2}) \delta R_{12}$$

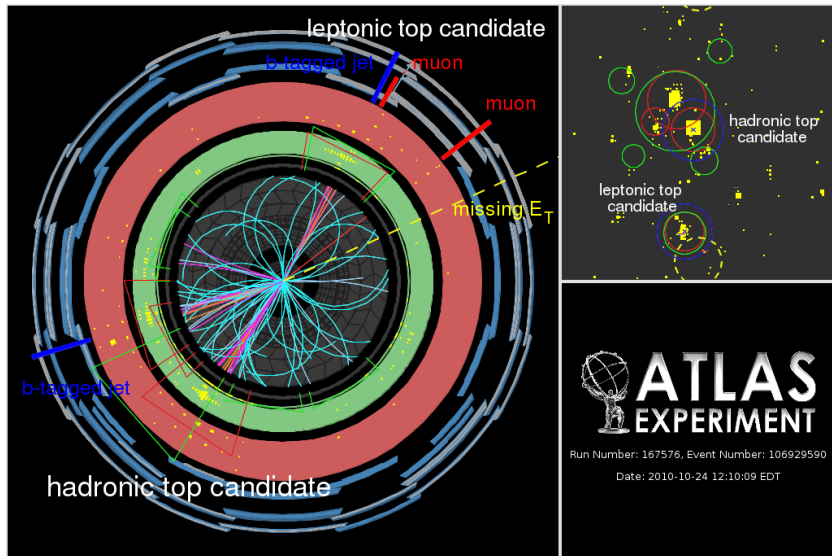


The **splitting scale** represents the kinematic threshold at which a jet can be broken into sub-components – the level at which structure begins to form.

- 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



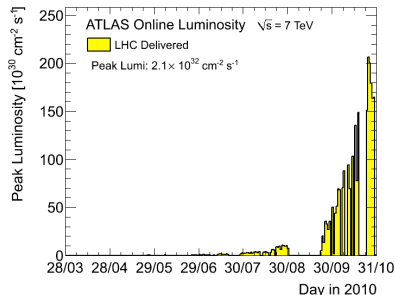
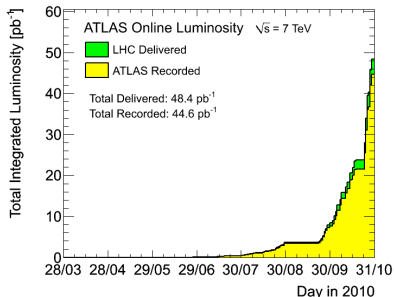
*Boosted SM top quarks observed in the data*

## 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 *between* and *inside* of jets at the energy frontier.
  - Jets are more than just a simple 4-vector
- Have shown the canonical measurements of **high- $p_T$  event shapes**, 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**

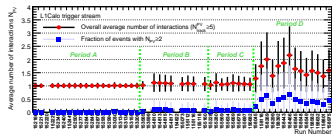
# Additional Material

# LHC operation in 2010

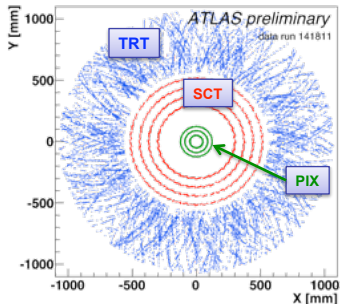
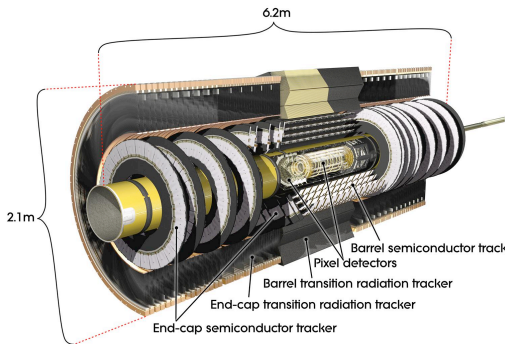


The average number of interactions measured by the reconstructed primary vertex multiplicity in calorimeter triggered events as a function of time throughout 2010.

- **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
- $\sigma_{r\phi} \sim 17\mu\text{m}$ ,  $\sigma_z \sim 580\mu\text{m}$
- 6.3M channels

## Silicon Pixels (PIX)

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

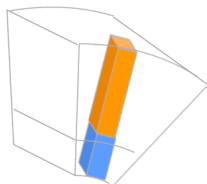
## Transition Radiation Drift Tubes (TRT)

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

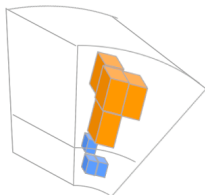
Excellent position resolution, tracking efficiency, vertexing performance.

## Inputs to jet reconstruction

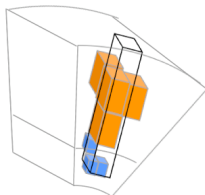
ATLAS has a highly **flexible and robust** set of input signals to consider for jet reconstruction:



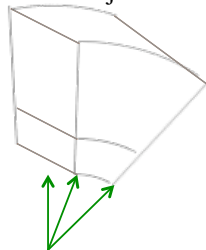
Towers without noise suppression



Topological clusters



Towers with noise suppression

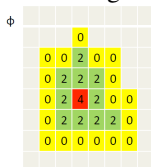


Tracks

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

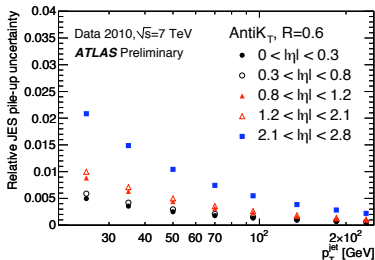
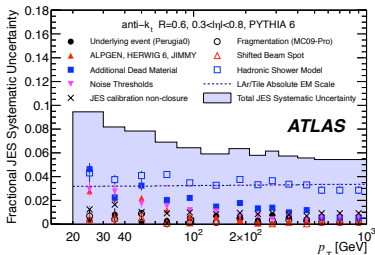
Topological clustering for noise suppression



# Jet energy scale uncertainty

ATLAS-CONF-2010-056

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

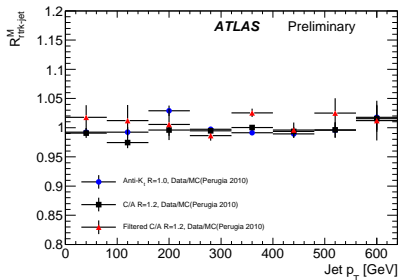


- It is crucial to determine each component *systematically* and to provide a **well-understood uncertainty**, over and above a *small uncertainty*.
- **8-9% at low  $p_T$**

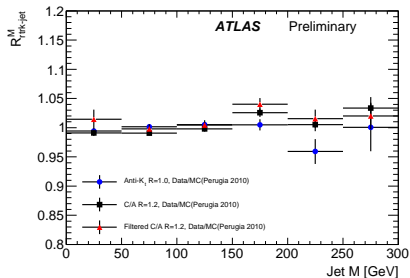
Focus on the component known to change over time, and to become ever more important as the luminosity of the machine increases to its nominal value:

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

# Fat jet momentum and energy scale uncertainty



$$R_{rtrack-jet}^{pT}$$



$$R_{rtrack-jet}^m$$

Figure:  $R_{rtrack-jet}^m$  versus  $p_T^{\text{jet}}$  and  $m^{\text{jet}}$  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%

## Definitions of the observables

Several observables are compared between data and MC, some of which are known to be perturbatively incalculable (such as  $S^{pheri}$ ) but are nonetheless considered as they are commonplace in some searches for new physics (e.g. microscopic black holes).

### *Three-jet resolution variant: $y_{23}$*

$$y_{23} = \frac{d_{23}}{Q^2}$$

$$\text{where } d_{23} = p_{t,3}^2$$

$$\text{and } Q^2 = (p_{t,1} + p_{t,2})^2$$

$y_{23}$  represents the threshold at which the event transitions from a di-jet event into a multi-jet (specifically three-jet) event

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**Sphericity and planarity:  $S^{\text{spheri}}$ ,  $S_{\perp}^{\text{spheri}}$ , and  $A$**

$$M_{\text{xyz}} = \frac{\sum_i p_{\alpha}^i p_{\beta}^i}{\sum_i (p^i)^2},$$

$$S^{\text{spheri}} \equiv \frac{3}{2}(\lambda_2 + \lambda_3),$$

$$S_{\perp}^{\text{spheri}} \equiv \frac{2\lambda_2}{\lambda_1 + \lambda_2},$$

$$A \equiv \frac{3}{2}\lambda_3.$$

Global information about the full jet momentum tensor of the event. They effectively measure the total transverse momentum with respect to the event axis.

## Definitions of the observables

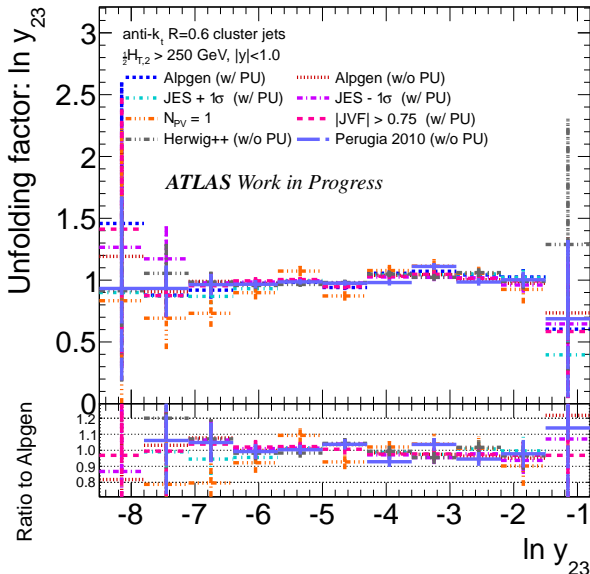
Several observables are compared between data and MC, some of which are known to be perturbatively incalculable (such as  $S^{pheri}$ ) but are nonetheless considered as they are commonplace in some searches for new physics (e.g. microscopic black holes).

**Thrust:**  $\tau_{\perp}$  and  $T_{m,\perp}$

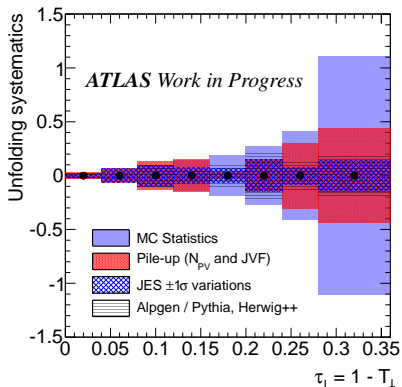
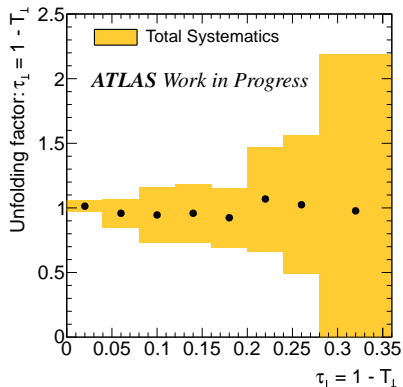
$$\begin{aligned} T_{\perp} &\equiv \max_{\hat{n}_{\perp}} \frac{\sum_i |\vec{q}_{\perp i} \cdot \hat{n}_{\perp}|}{\sum_i q_{\perp i}} \\ \tau_{\perp} &\equiv 1 - T_{\perp} \\ T_{m,\perp} &\equiv \frac{\sum_i |\vec{q}_{\perp i} \times \hat{n}_{\perp}|}{\sum_i q_{\perp i}}, \end{aligned}$$

The transverse thrust,  $T_{\perp}$ , and its minor component,  $T_{m,\perp}$ , attempt to define explicitly a thrust axis for the event that maximizes the total transverse momentum of the event.

# Unfolding factors: $\ln y_{23}$ as an example



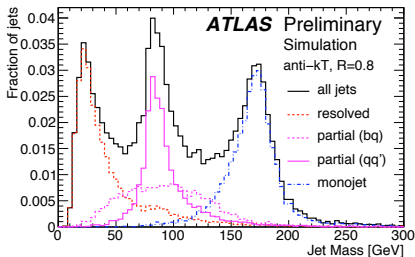
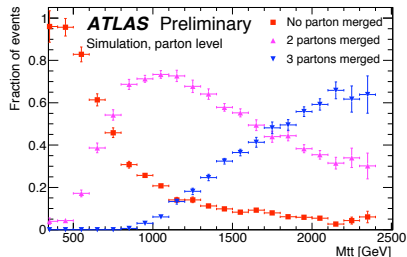
## Unfolding factors and systematic uncertainties: $\tau_{\perp}$



- The rightmost bin is combined in order to estimate the unfolding factor. However, only the  $\tau_{\perp} = 0.3$  bin is included in the final result.

## 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.



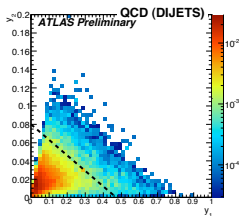
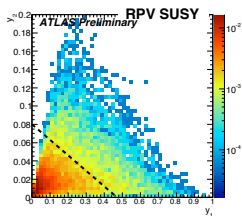
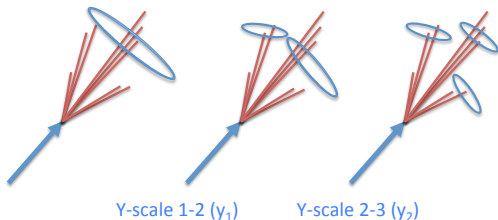
(left) Fraction of top quark decay products found within an anti- $k_r$  jet of radius  $R=0.8$ . (right) Mass distribution of the lead jet in these events for different scenarios (ATLAS-PUB-2010-08)

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

## Searching for SUSY with substructure

In **R-parity violating (RPV) SUSY**, baryon number violation occurs and the decay  $\bar{\chi}_1^0 \rightarrow qqq$  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

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