XIII MEXICAN SCHOOL OF PARTICLES AND FIELDS

UNIVERSITY OF SONORA & SAN CARLOS, SONORA, MEXICO.

OCTOBER 2008 2-11

The Mexican School of Particles and Fields is a biennial conference organized by the Division of Particles and Fields of the Mexican Physical Society, designed to gather specialists in different areas of high energy physics to discuss the latest developments in the field. The format of the conference will consist of morning sessions devoted to theoretical and experimental reviews and afternoon thematic sessions.

Jet Reconstruction at the LHC (Lecture 3)

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ATLAS

THE UNIVERSITY OF ARIZONA. Arizona's First University.

UAPhysics THE UNIVERSITY OF ARIZONA College of Science

Remember

- **Environment plays important role in jet reconstruction**
  - Underlying events add energy and small fluctuations to hard scatter
  - Multiple interactions add fluctuations and little energy to hard scatter
- **Calorimeter signal choice important**
  - Different noise contributions from towers and clusters
  - No hadronic energy scale for towers
    - View does not follow shower structures!
- **Two different jet calibration models**
  - Find jet first in uncalibrated (electromagnetic energy scale) signals, then calibrated in jet context to jet energy scale
  - Calibrate calorimeter signals first, then find jet, then correct from hadronic to jet energy scale

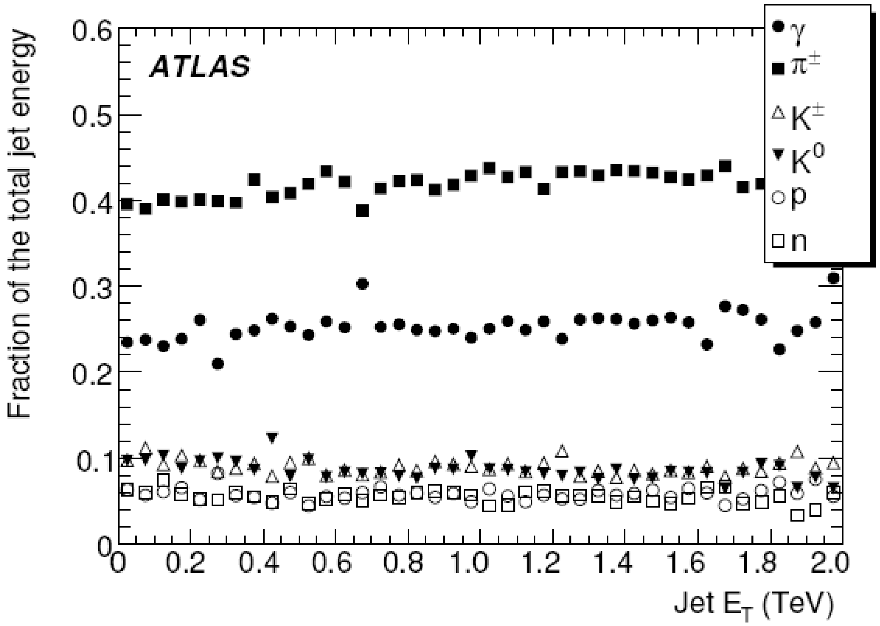
Overview

- **Lecture 1 (Saturday, October 4th, 2008, 12:30-13:30): Signals from particle jets**
  - Experimentalist view on jets
  - Brief review of the basics of calorimetric energy measurement
  - Jet response of a non-compensating calorimeter
  - Calorimeter signal reconstruction: cells, towers, clusters
- **Lecture 2 (Sunday, October 5th, 2008, 12:30-13:30): Jet algorithms and reconstruction**
  - Physics environment for jet reconstruction at LHC
  - Jet algorithms and reconstruction guidelines
  - Jet calibration strategies
  - Jet Reconstruction Performance
- **Lecture 3 (Sunday, October 5th, 2008, 17:00-18:00): Refinement of jet reconstruction at LHC**
  - Refined calibration using other detectors
  - Tagging jets from pile-up
  - The origin of jets: masses and shapes
  - AOB

Refined Jet Calibration With Other Detectors

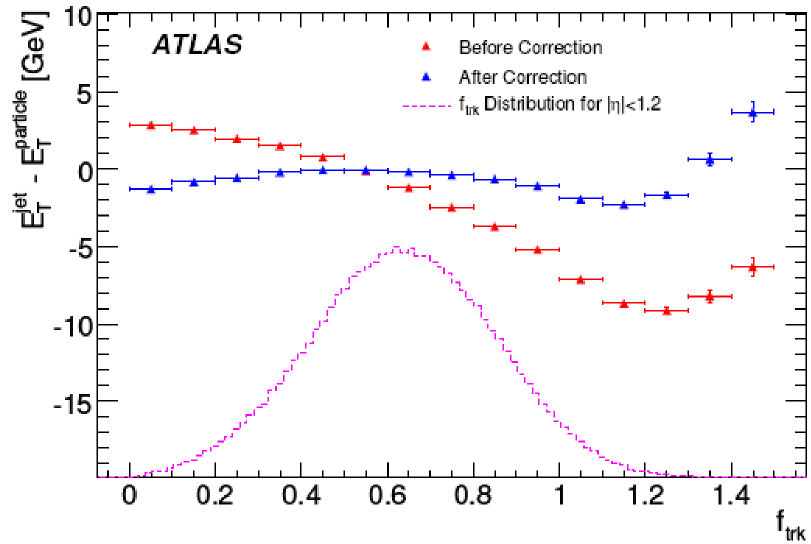
Recall Jet Composition

- **Charged particles carry large fraction of total jet energy on average**
  - ~60% from charged pions, Kaons, protons
- **These particles can leave a track in the inner detector**
  - Momentum (pT) measurement
  - pT fraction carried by reconstructed tracks is observable
- **They are all hadrons**
  - Jet with a large fraction of pT carried by charged particles is more hadronic
  - Sensitivity of calibrated calorimeter signal to this fraction?

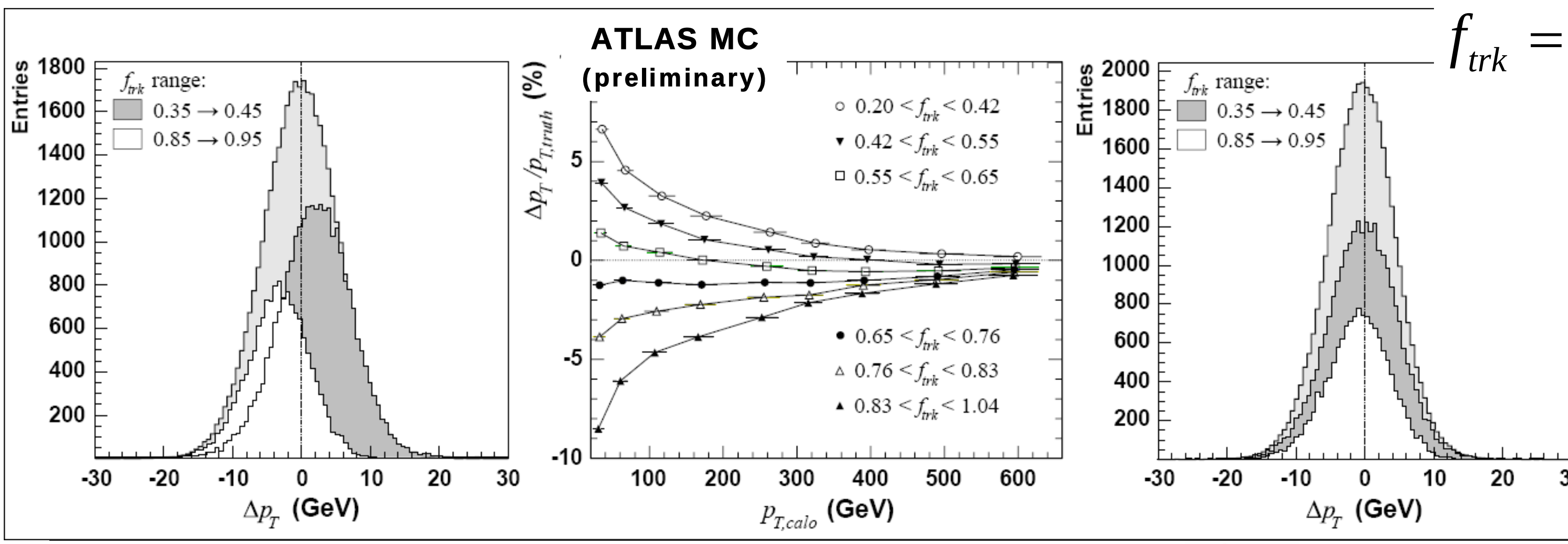


Track Jets

- **Aim: relative improvement of the jet energy resolution**
  - Jet-by-jet correction
- **Reconstruct jets from inner detector tracks**
  - Match track jets with calorimeter jets
  - Calculate pT fraction carried by tracks
- **Determine correction as function of pT fraction**

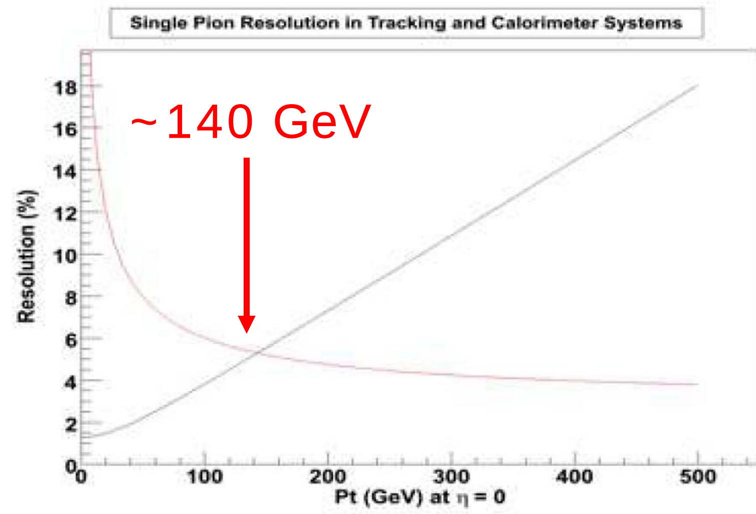


$$f_{trk} = \frac{p_{T,track}}{p_{T,calo}}$$



Energy Flow Reconstruction (1)

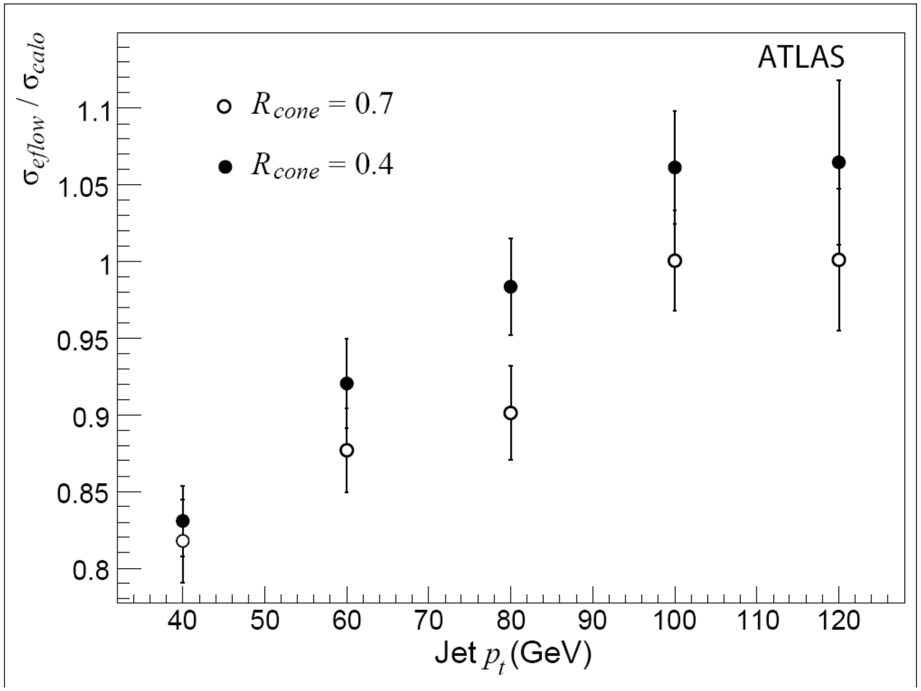
- **Combine reconstructed track with calorimeter cluster**
  - Use track measurement if favoured by detector resolution



  - Need to remove "charged response" from calorimeter if track is used
    - Basically remove cells around extrapolated track
  - Works well in low occupancy environments
    - LEP, HERA, even Tevatron
  - Not so obvious at LHC
    - Lots of tracks and calorimeter signal (shower) overlap

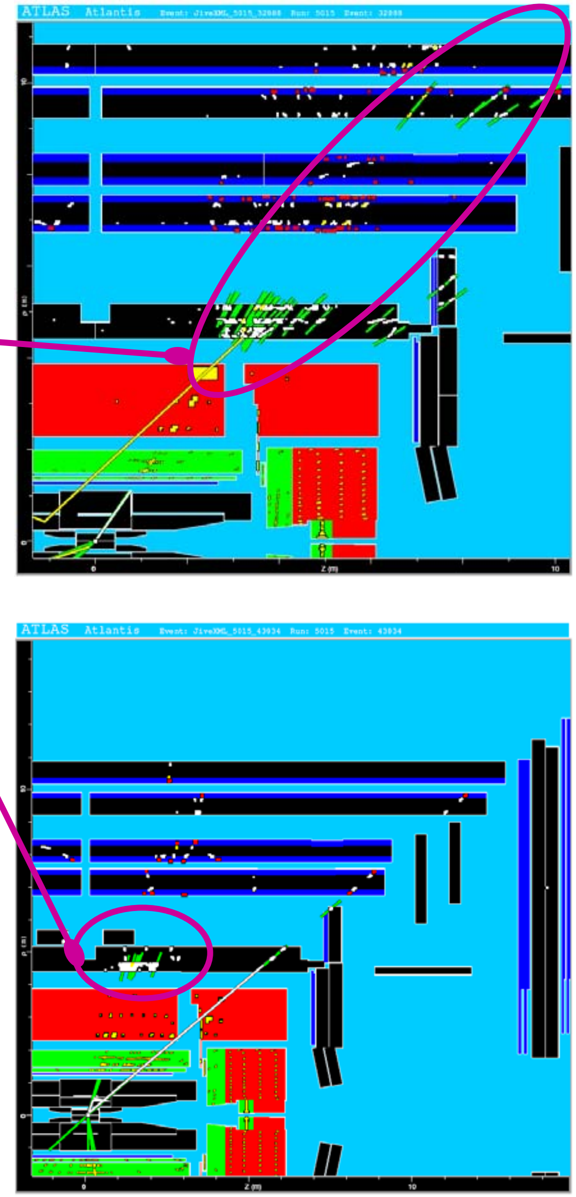
Energy Flow Reconstruction (2)

- **Studied in ATLAS**
  - Indicates resolution improvements for low pT jets (<80 GeV)
  - May be interesting for ttbar, for example
- **Is a basic tool in CMS**
  - x2 solenoid field increases tracking precision reach!
- **Careful evaluation in busy environments needed**
  - Removing wrong calorimeter signal decreases high energy resolution ("confusion term")



Longitudinal Leakage

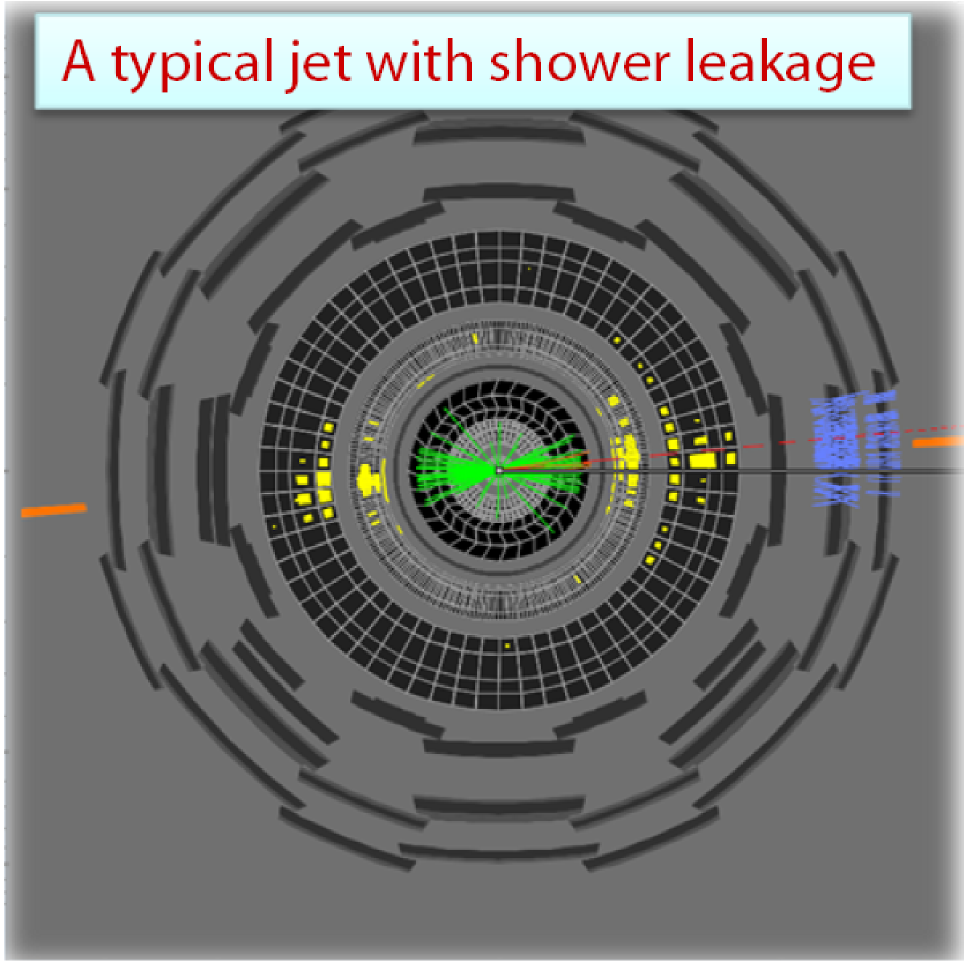
- **Indicated by increased number of hits in muon spectrometer behind the calorimeter**
  - Dangerous! Changes jet pT cross-section shape at high pT -> fake compositeness signal?
- **First studies to understand energy loss correlation with muon spectrometer signal**
  - Quite new stuff, no strong correlation expected
  - Helps to tag suspicious jets, at least
- **Not to forget: real muon may be inside jet**
  - b decay



Frank Paige, ATLAS T&P Week February 2006

Longitudinal Leakage (cont'd)

- **Note missing Et direction!**
  - Indicates mis-calibration of high energetic jet!



A Word Of Caution

- **Inner detector acceptance in ATLAS is limited to within +/-2.5 in pseudorapidity**
  - No tracks beyond this range, but still plenty of jets!
- **The muon detector has a similar reach in ATLAS**
  - Highest energies go even more forward
  - Need to explore correlation between energy sharing in calorimeter samplings and leakage, too!

Tagging Jets From Pile-Up

Jets Not From Hard Scatter

Dangerous background for W+n jets cross-sections etc.

- Lowest pT jet of final state can be faked or misinterpreted as coming from multiple interactions
- Usually taken care off by applying efficiency and purity estimates and correct cross-sections accordingly

Jet-by-jet handle

- Classic indicator for multiple interactions is number of reconstructed vertices in event
  - Tevatron with RMS(z_vertex) ~ 30 cm
  - LHC RMS(z_vertex) ~ 8 cm
- If we can attach vertices to reconstructed jets, we can in principle identify jets not from hard scattering
  - Limited to pseudorapidities within 2.5!

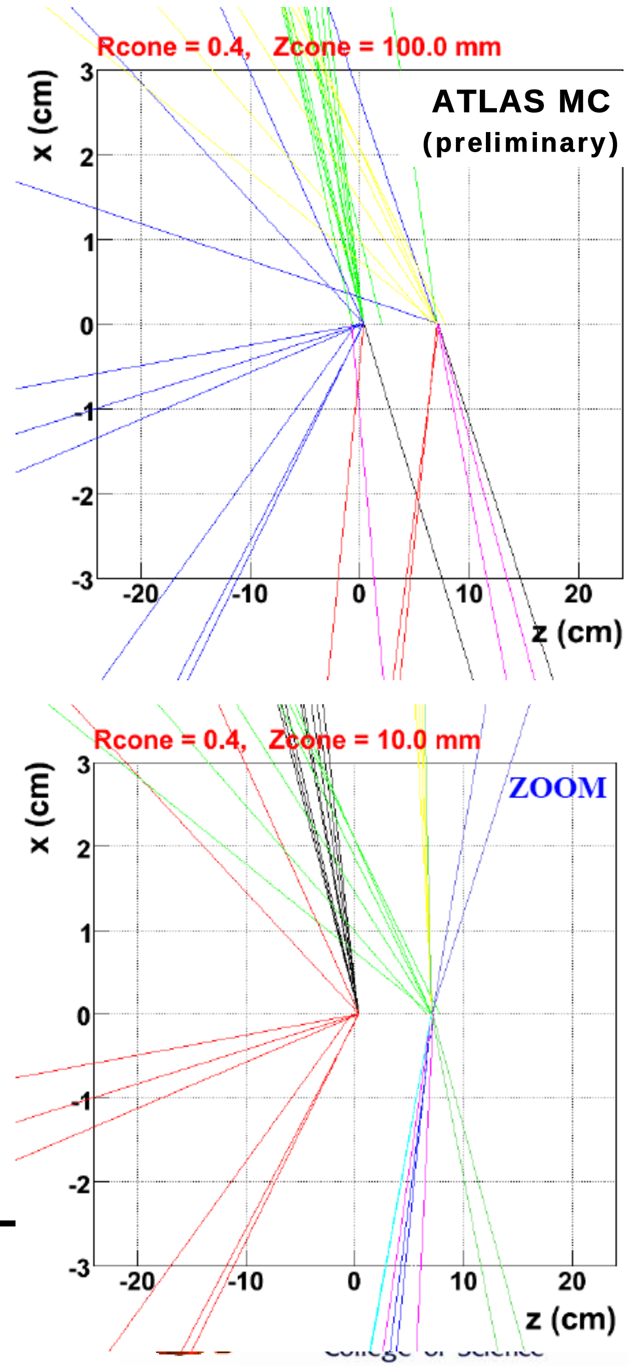
First Task: TrackJets With Vertex

Find jets in tracks

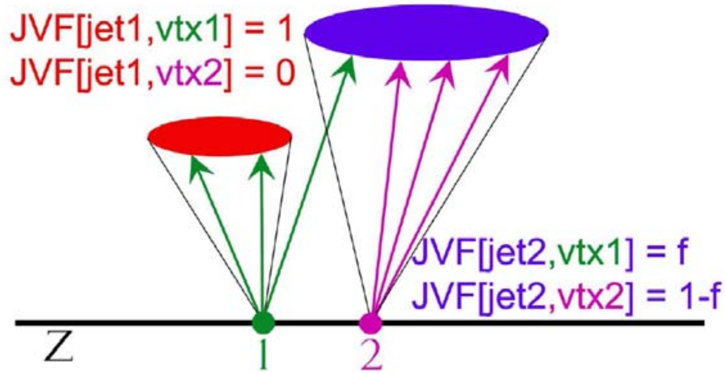
- Hint to calorimeter inefficiencies
  - Cracks with calorimeter signal below threshold
- Tracks have vertices -> assign vertex to jet!

Need dedicated jet finder

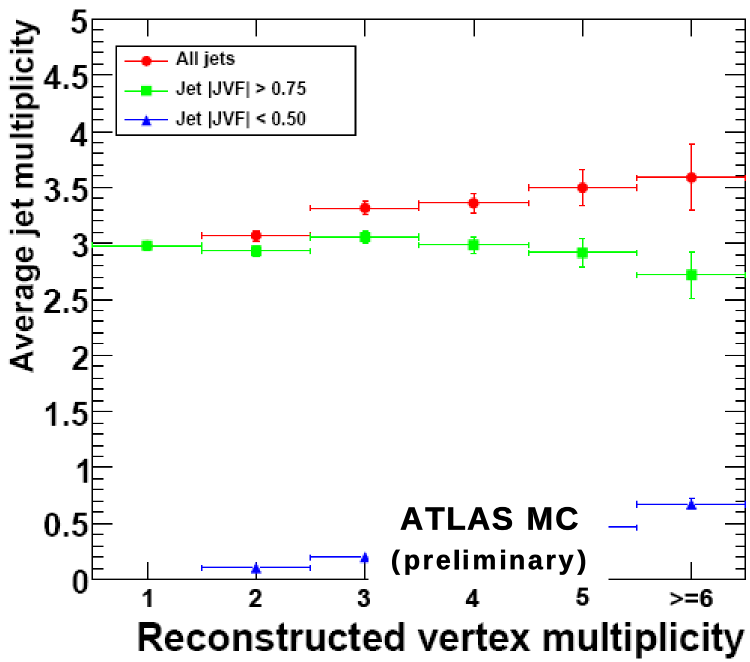
- Typically clustering in two variables (η,φ)
- Use third variable z_{vertex} to assign correct vertex



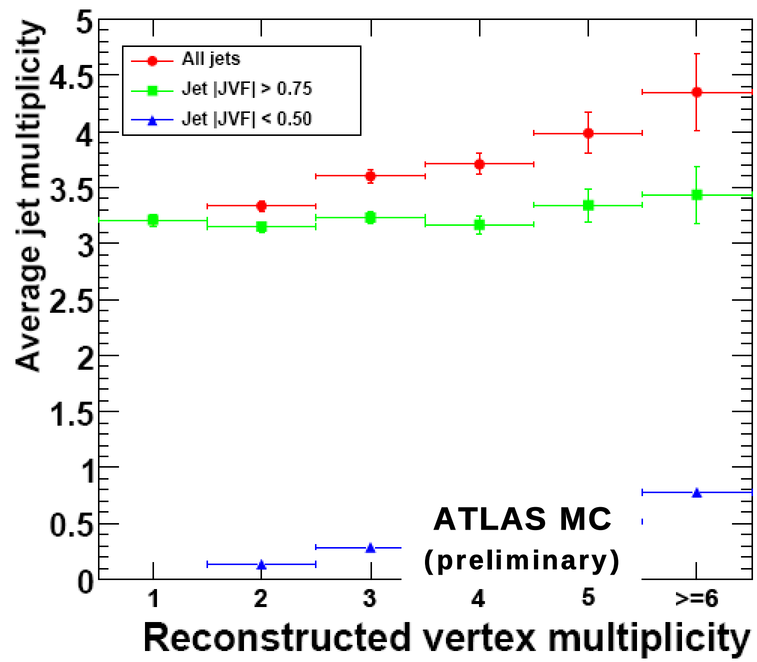
Application of Trackjets



- **Match tracks in track jet with calorimeter jet**
  - Calculate pT fraction coming from each vertex for given jet
  - Jets with little pT from primary vertex are likely from multiple interactions (e.g. pile-up)

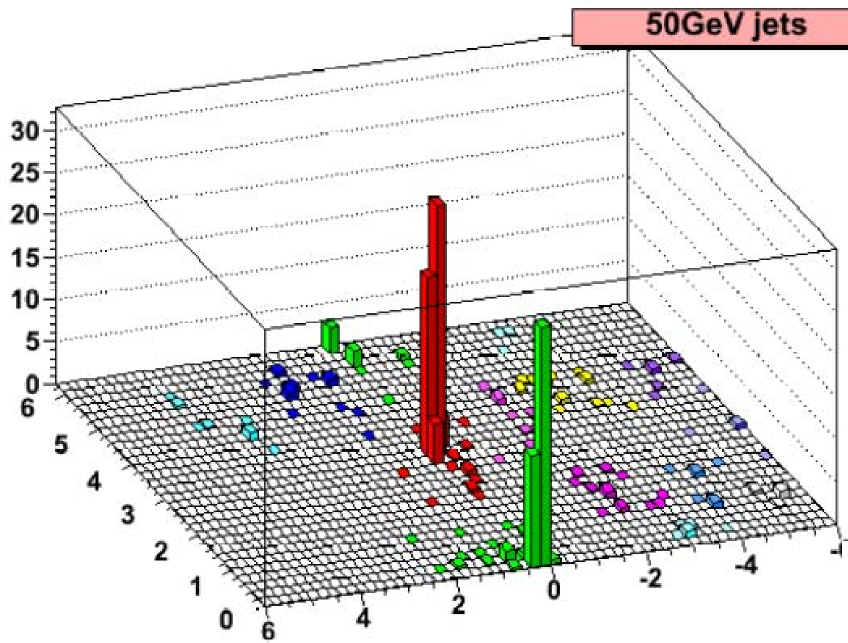


(c) Di-jet (J6)



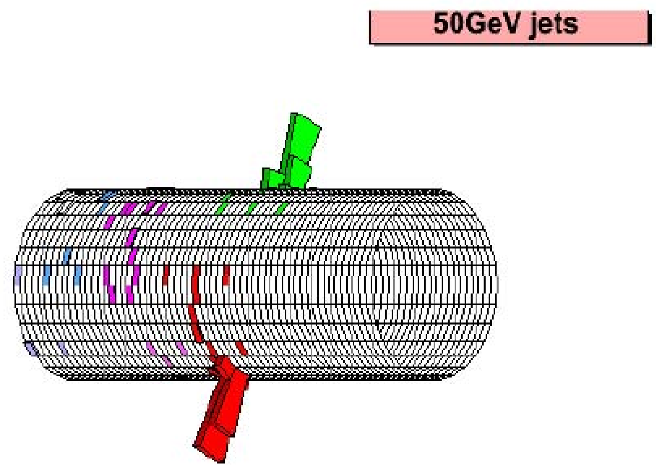
(d) $t\bar{t}$, $W \rightarrow$jets

Jet Areas (1)



kT jets only!

'Standard hard' event
Two well isolated jets

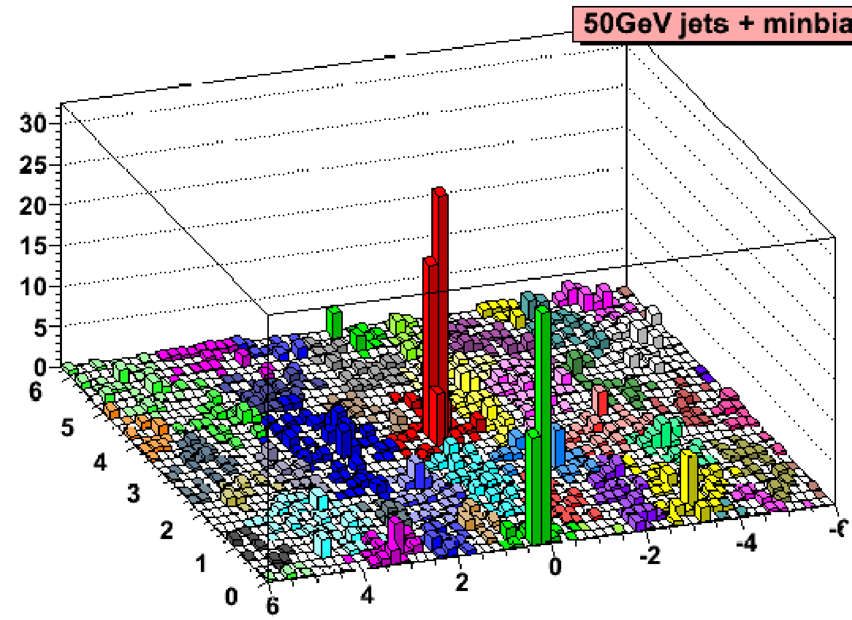


$\sim$ 200 particles

Clustering takes $\lesssim 1ms$

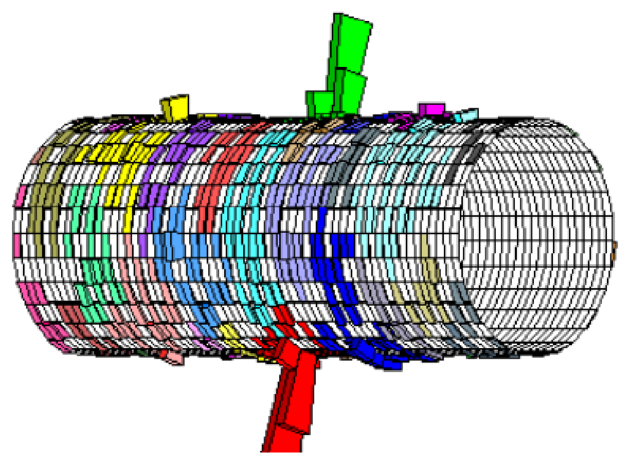
(Gavin Salam)

Jet Areas (2)



kT jets only!

Add 10 min-bias events
(moderately high lumi)

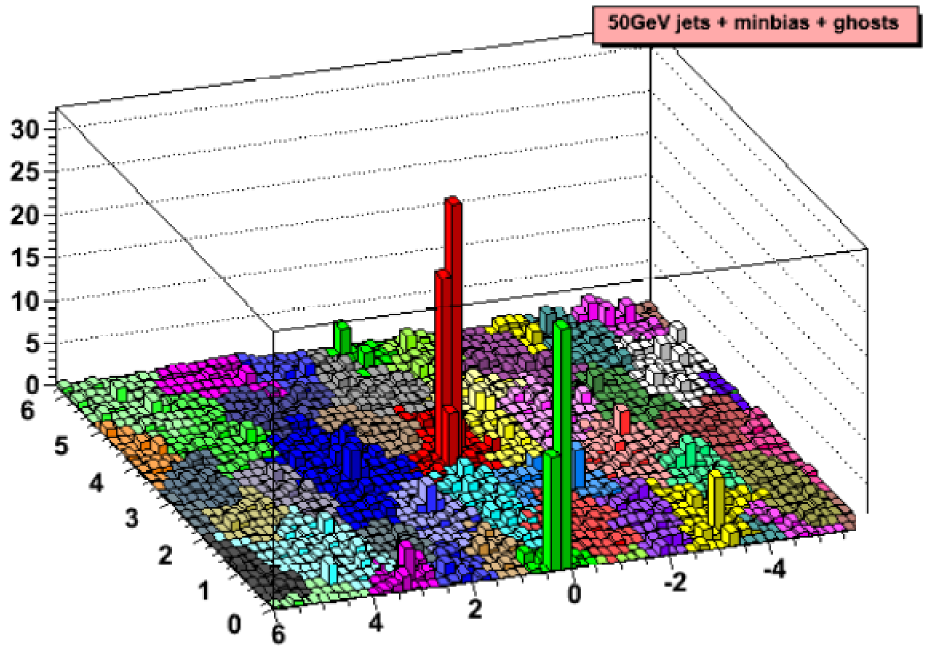


$\sim$ 2000 particles

Clustering takes $\sim 10ms$

(Gavin Salam)

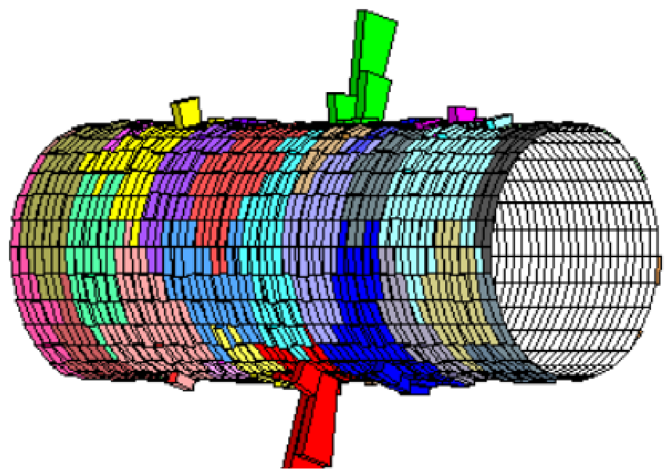
Jet Areas (3)



kT jets only!

Add dense coverage of infinitely soft *"ghosts"*

See how many end up in jet to measure jet area



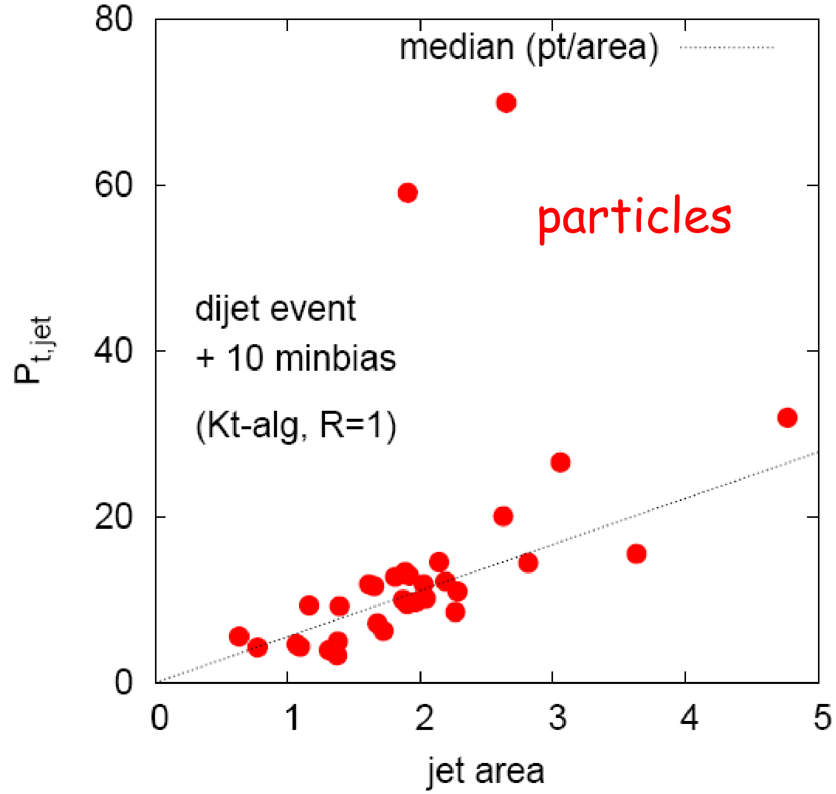
∼ 10000 particles

Clustering takes ∼ 0.2*s*

(Gavin Salam)

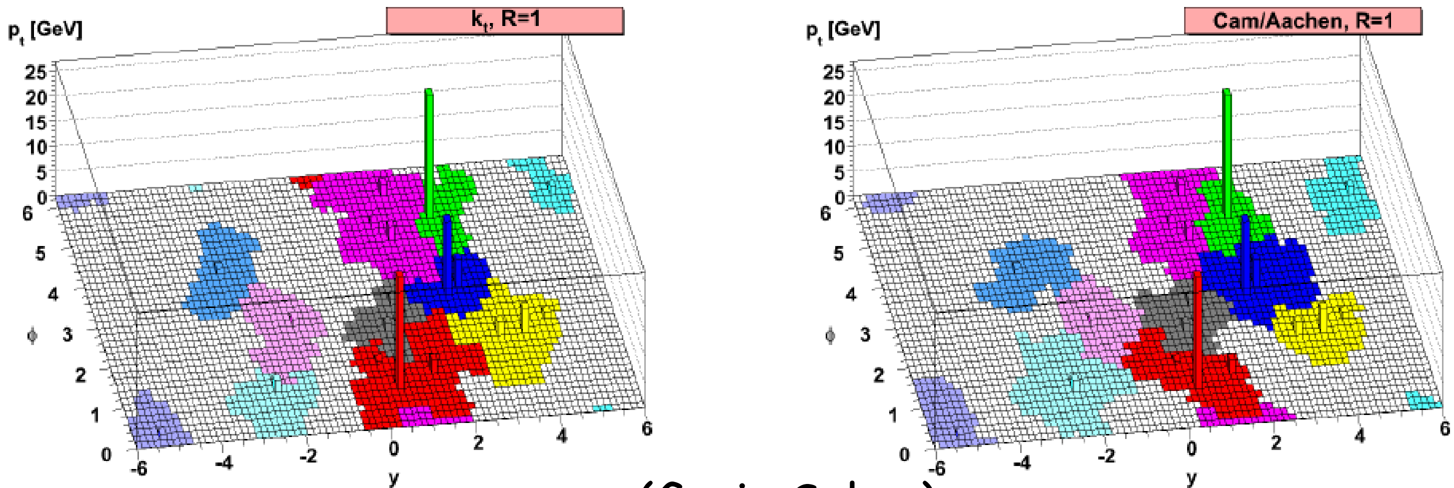
Jet Area And Multiple Interactions

- **pT area density for each jet in an event if good indicator of multiple interation/underlying event activity**
  - At least at particle level!
- **Jet area is challenging for calorimeter jets**
  - Showers can increase lateral jet size
    - Most prominent in forward direction
  - Cluster better than towers?
- **Not yet fully understood for calorimeter signals**
  - Sounds promising, though!

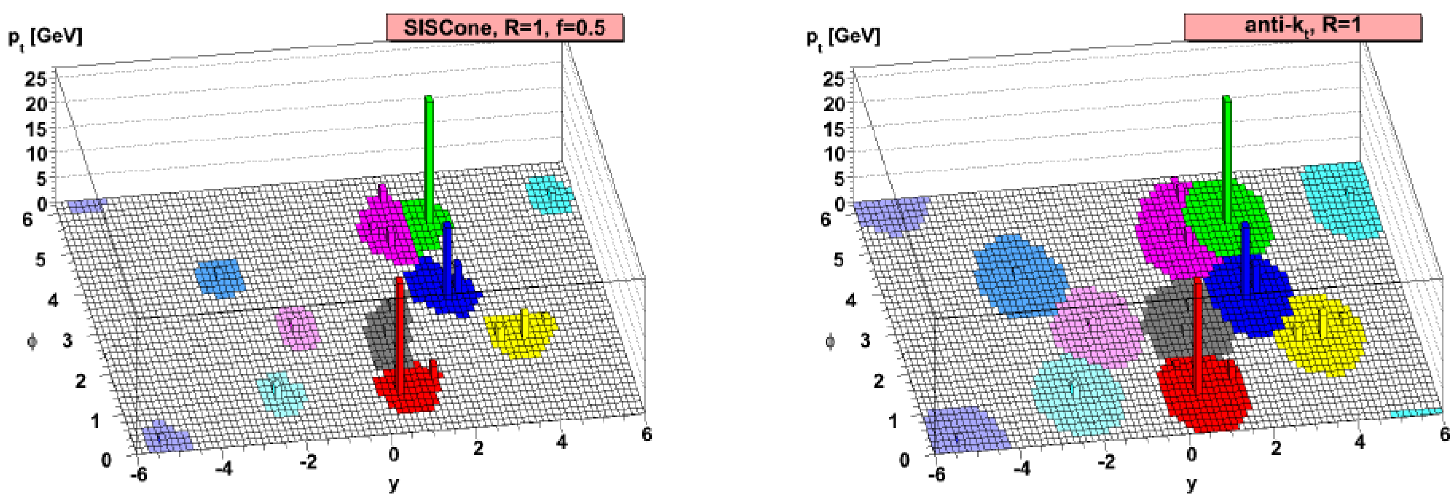


(Salam/Cacciari)

Jet Areas For Various Algorithms



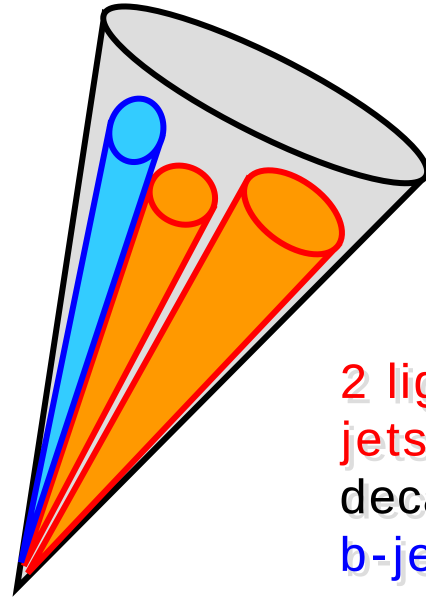
(Gavin Salam)



The Origin Of Jets: Masses And Shapes

Jet Mass

- **Gained interest at LHC**
  - Decay products of highly boosted heavy particles all reconstructed as one (narrow) jet
    - E.g. top quark
  - Indication of source from jet mass requires high resolution of spatial structures
    - Jet mass measurement notoriously difficult due to (hadronic) shower spread
- **We try to understand sensitivities**
  - Dependence on calorimeter signal choice
  - Prominent constituent reconstruction
- **Other sub-structures…**

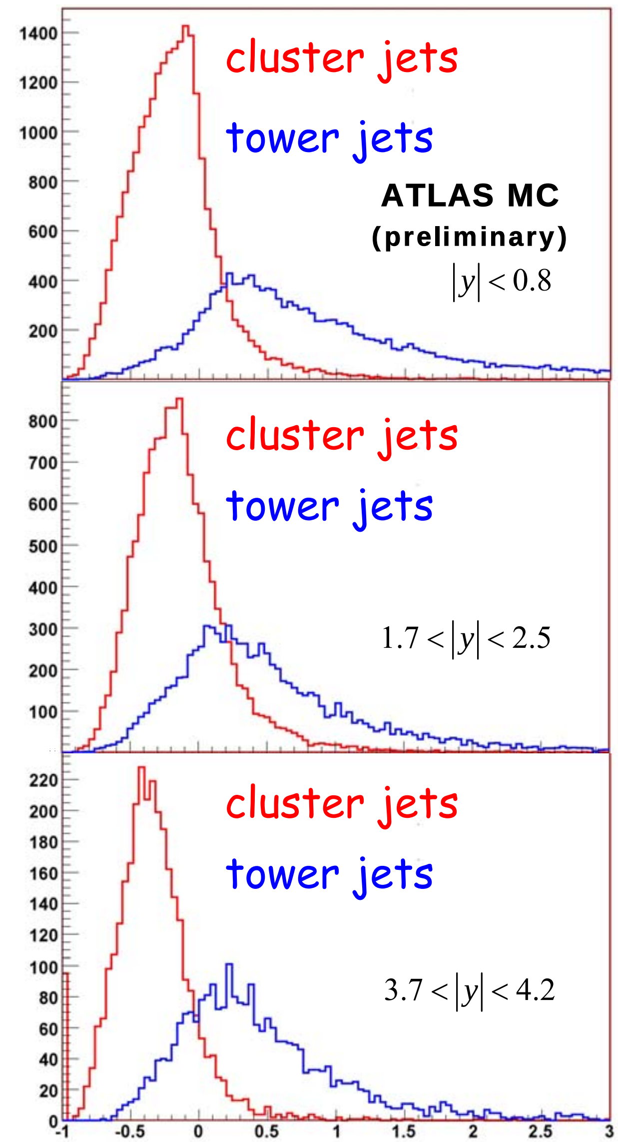


2 light quark jets from W decay and 1 b-jet

Jet Masses

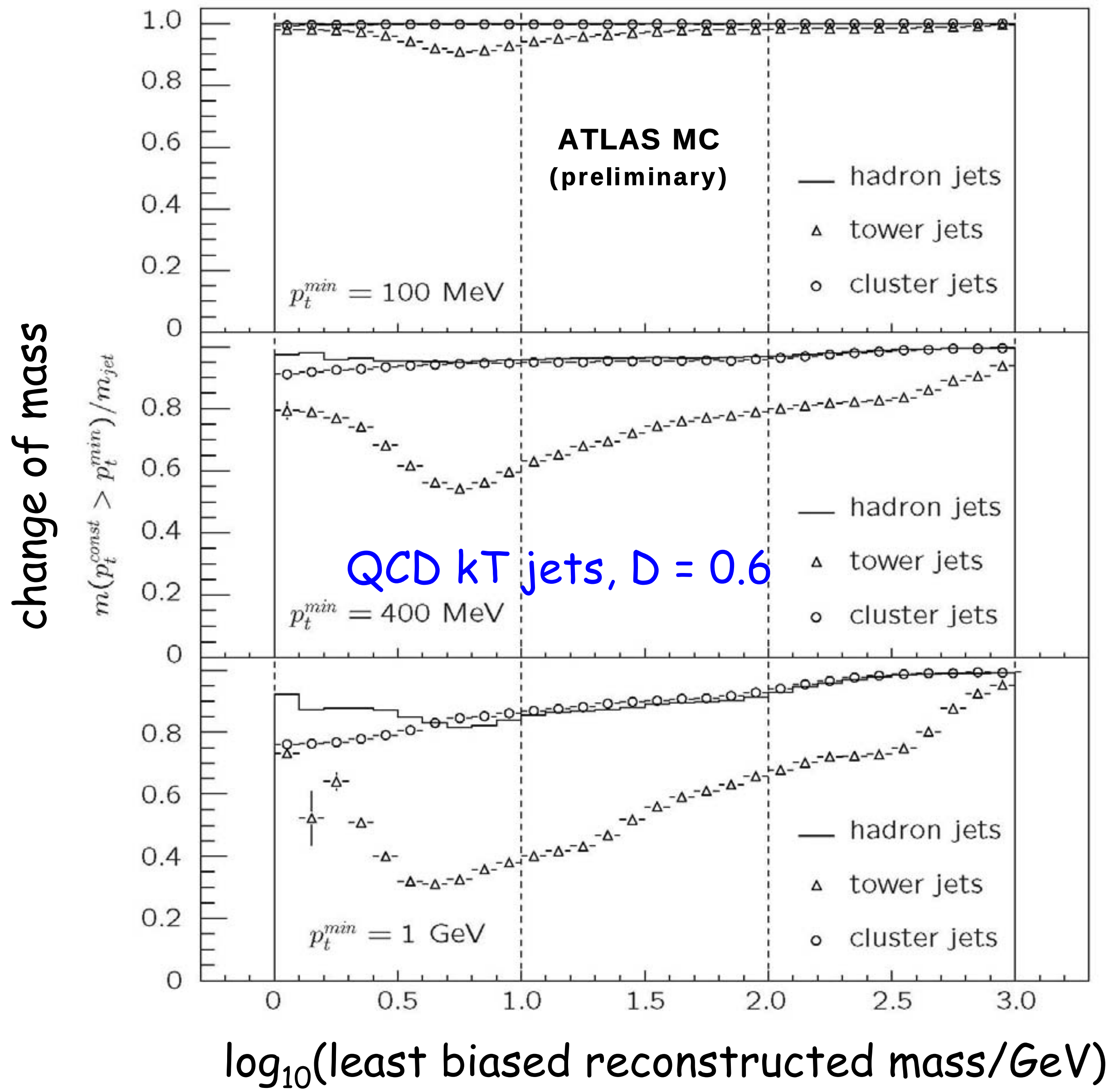
Mass measurement challenging

- Particle jet level mass is reference
  - Simulations only!
- Mass of calorimeter jet is affected by shower spreads
  - Enters: signal definition dependence, cluster shapes/overlap, noise,…
- Sensitivity to losses of soft particles
  - Magnetic field, dead material,…



relative mass difference

Mass Sensitivity

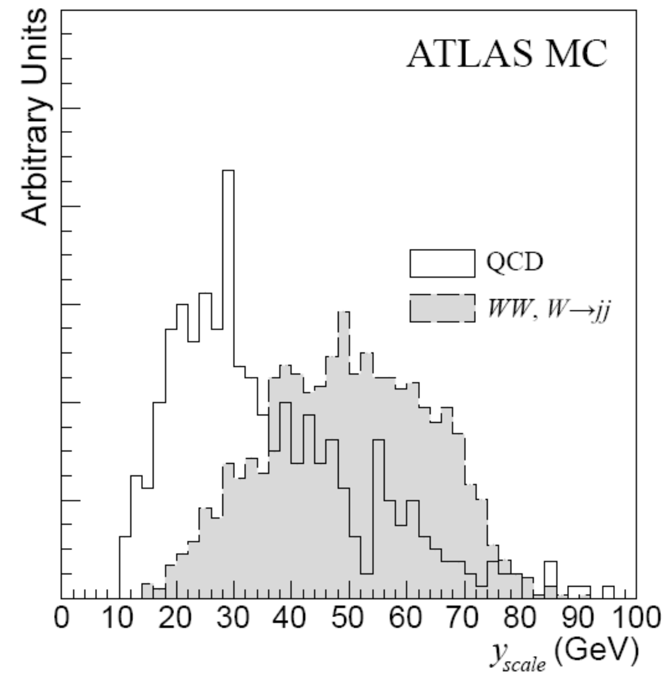


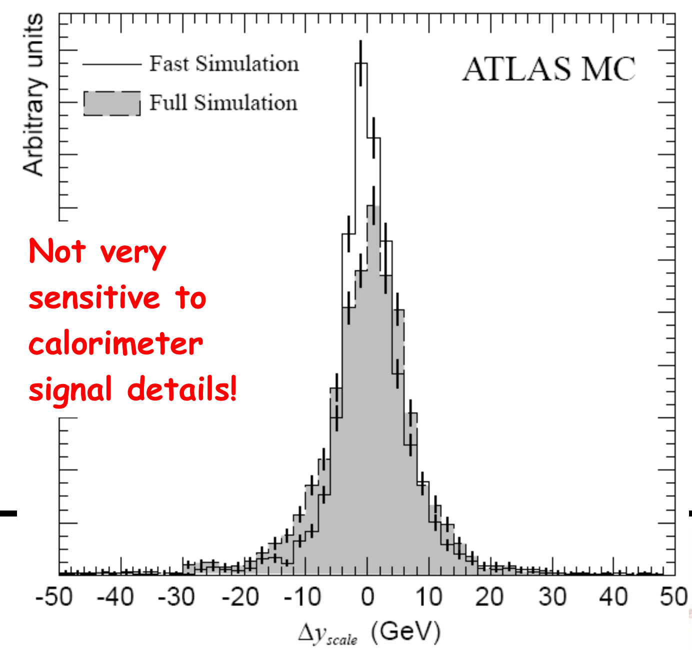
Jet Substructure

- **Mass too complex?**
  - Can be too sensitive to small signals in jets
    - UE, pile-up, other noise
- **Use YSplitter to detect substructure**
  - Determines scale y for splitting a giving jet into 2,3,… subjects, as determined by y_{cut}, from

$$y = \sqrt{y_{cut}} \times p_T^{jet}$$

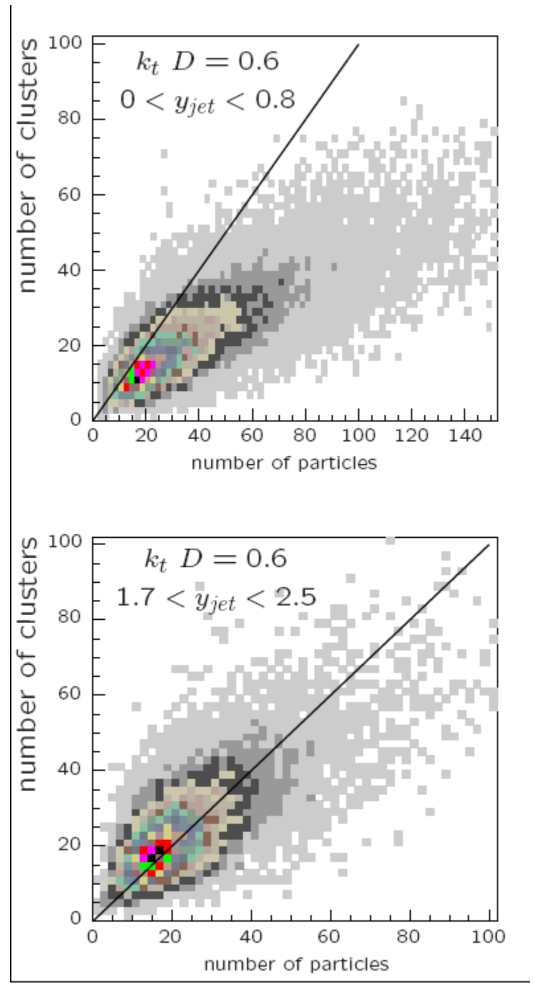
  - More stable as only significant constituents are used ?
  - At least additional information to mass
- **Other option:**
  - Look at mass of 2…n hardest constituents (Ben Lillie,ANL)





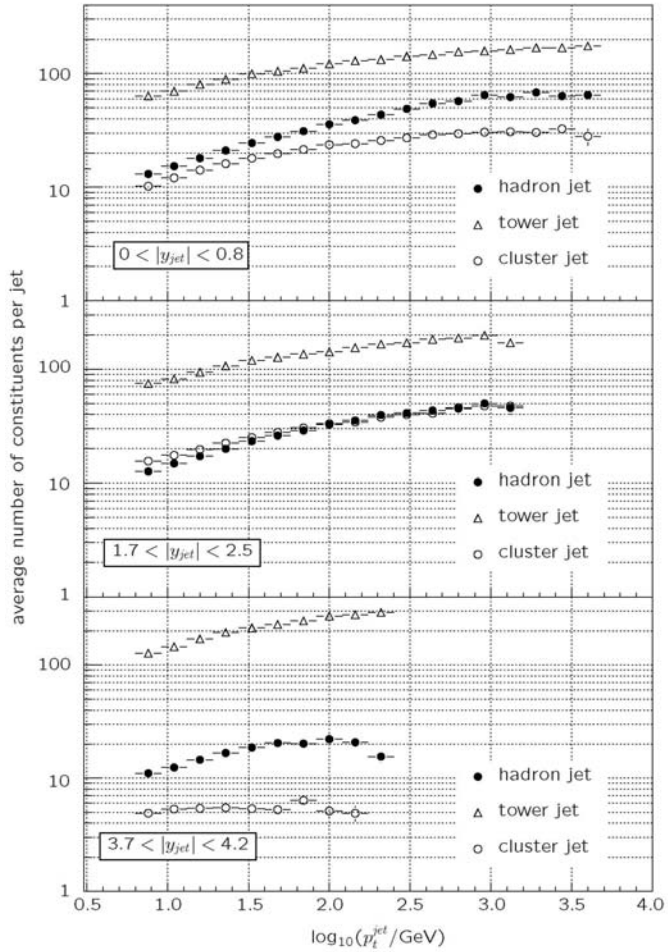
Jet Composition

- **We expected clusters to represent individual particles**
  - Cannot be perfect in busy jet environment!
    - Shower overlap in finite calorimeter granularity
  - Some resolution power, though
    - Much better than for tower jets!
  - ~1.6:1 particles:clusters in central region of ATLAS
  - ~1:1 in ATLAS endcap region
    - Best match of readout granularity, shower size and jet particle energy flow

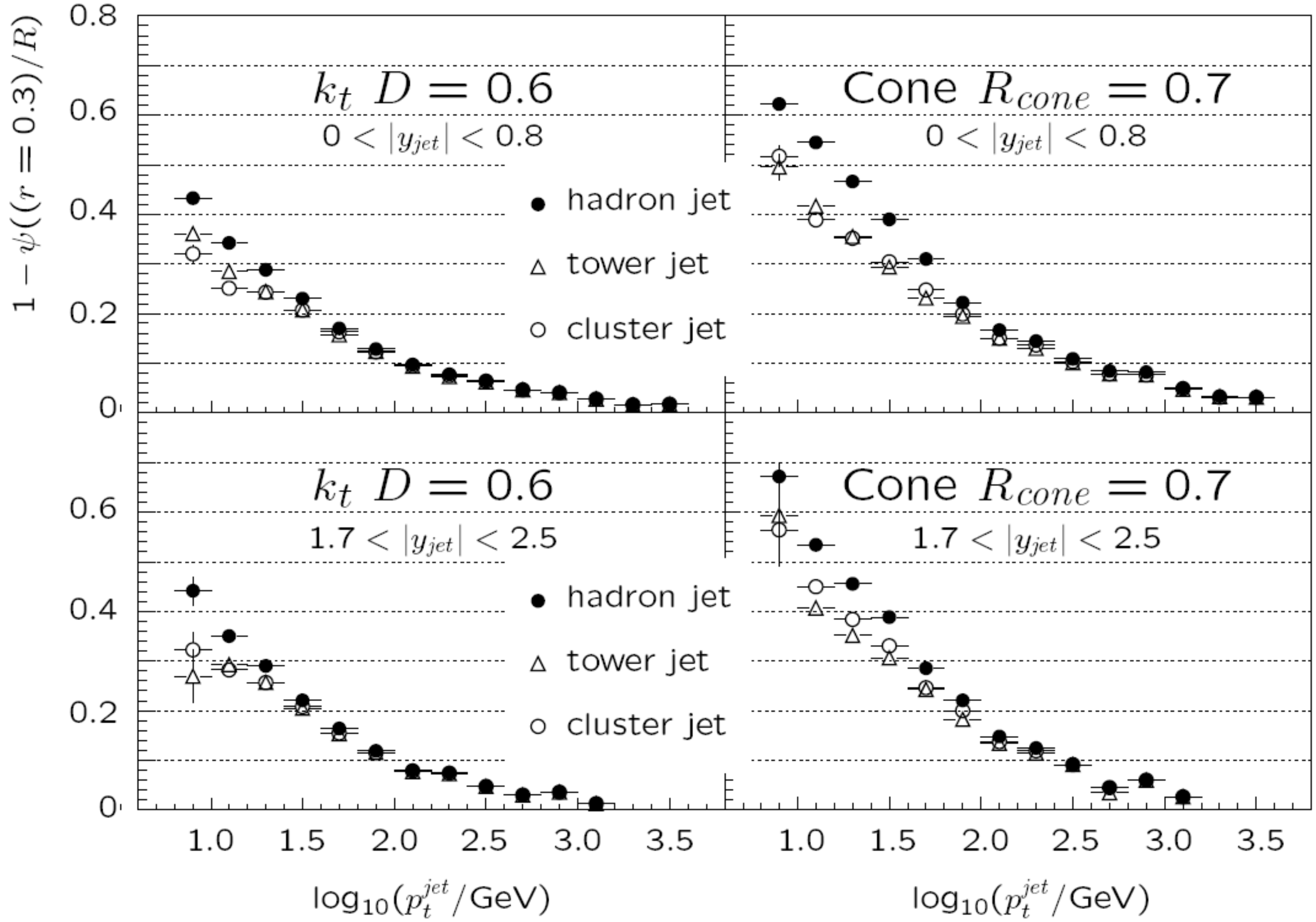


Number Of Jet Constituents

- **Note that this not really a relevant variable!**
  - But it can be understood as hint to support signal definition choices!



Jet Energy Density



Post Mortem

Conclusions

- **Jet reconstruction from detector signals is challenging**
  - Limited energy resolution
  - Limited spatial resolution
  - Change of jet shape by detector
- **A lot of the detector effects can be unfolded within limitations**
  - Highest level of factorization desirable to implement corrections and calibrations which can be independently tested
  - Limitations depend on detector designs
- **There is no universal jet calibration**
  - Many jet finder strategies and configurations
  - Each may need a corresponding calibration strategy
    - Especially in a high precision measurement
- **We are looking into new things to get from jet reconstruction**
  - Origin from reconstructed mass and/or substructure
  - Jet shapes for improved calibration and fragmentation tests

What I Did Not Say

- **What are the precision requirements for jet reconstruction?**
  - ~<1% systematic error (top mass, mass spectrum at the end of a long decay chain in SUSY…)
    - This is VERY challenging!
  - It took running experiments O(10 years) of data taking to understand their detectors at this level
    - And often not for all final states!
  - It is quick to go from 10% to 5% once we have data
  - It is going to take some time to go from 5% down to 3%
  - It is going to take even more time to go from 3% down to 1%
- **Why did I not show you the current estimates for jet reconstruction performance in ATLAS and CMS?**
  - First of all, it's all based on simulations – better to wait for a reasonable amount of good data for a better answer
  - I do not believe you will or want to remember these numbers anyway
    - If you need to know them, please contact me for references
  - Especially, I do not want to compare the ATLAS and CMS performance
    - It would lead to the wrong conclusions at this time!

I said in the beginning that the subject deserves a whole semester of lectures –
I hope you now have at least a bit of an idea why!

Thank you very much!