Jet Energy Resolution at the ILC.

FLC Group

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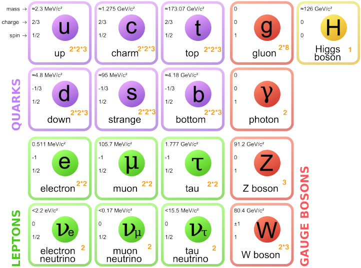
HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

The Future of High Energy Physics

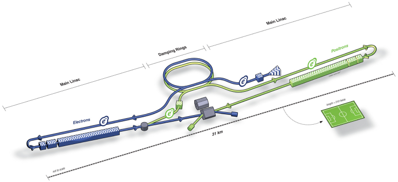
- The Standard Model is the best theoretical description of particle physics, and successfully models every accepted high energy physics experimental result
- However, it is incomplete
  - It does not include gravity
  - It doesn't contain any candidates for dark matter particles
- So, we must continue to probe for experimental disagreements which could lead to a new theory



Source: `https://commons.wikimedia.org/wiki/File:Standard_Model_of_Elementary_Particles.svg`

Why the International Linear Collider (ILC)?

- Complement the physics program of the LHC by allowing more precise measurements of the properties of particles such as the H and W bosons and the top quark
- Produce new physics, e.g. search for further Higgs particles or dark matter candidates, measure H self coupling
- Technical Specifications:
  - $\sqrt{s} = 200$ to 500 GeV, future 1 TeV upgrade
  - Peak luminosity of $2 \times 10^{34}\ cm^{-2}s^{-1}$
  - Highly polarised beam for maximising process cross sections and background suppression: $\pm 80\%$ for e^-, $\pm 30\%$ for e^+
  - 5 Hz bunch train frequency - allows passive cooling of detectors
  - No pileup
  - Uses superconducting RF cavities for acceleration - same as FLASH, XFEL



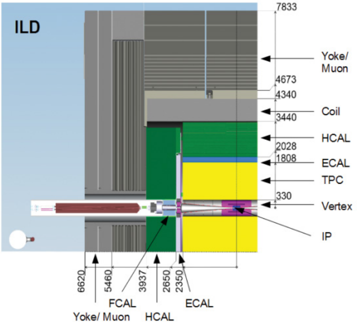
ILC Schematic

RF Accelarating Cavity

Source: `https://www.linearcollider.org`

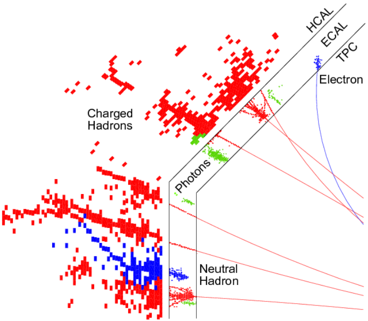
The International Large Detector (ILD)

- First high energy physics detector capable of particle flow reconstruction (discussed later)
- The ILD will consist of several sub-detectors:
  - Vertex detector plus a few layers of Si tracker
  - Time Projection Chamber (TPC), giving **dE/dx particle identification** - momentum resolution of $\sigma_{p_t}/p_t^2 = 2x10^{-5} GeV^{-1}$
  - **Highly segmented** calorimeter tiles
    - electromagnetic: 5mm x 5mm, resolution of $\sigma_E/E = 10\%/\sqrt{\mathrm{E(GeV)}}$
    - hadronic: 30mm x 30mm, resolution of $\sigma_E/E = 60\%/\sqrt{\mathrm{E(GeV)}}$
  - 3.5T axial **B** field produced by a large superconducting coil, encased in a yoke - which functions as a muon detector
  - Forward region calorimeters for 4π angular coverage and luminosity measurements via Bhubha scattering
- ILD will be switched with Silicon Detector (SiD) every few weeks via push-pull system



Particle Flow Reconstruction

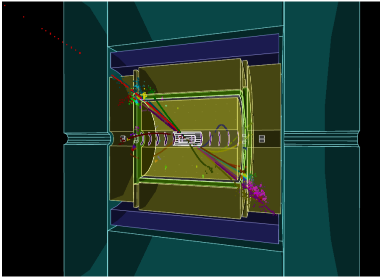
- Approach to calorimetry which improves jet energy resolution by reconstructing individual particles rather than just jets
- Made possible by combination of **highly granular** calorimeters and **complex pattern recognition** algorithms
  - For each particle, an energy measurement can be taken from only the **most accurate detector subsystem** with which it interacts
  - Jet composition is generally: 65% charged particles, 25% photons and 10% neutral hadrons
- Result is a collection of Particle Flow Objects (PFOs)
  - Possible to attempt to even identify the type of particle - important for detector calibration



Brief Overview: 1

What is a jet?

- **Cone** of particles, formed by the hadronisation of a quark or a gluon
- For example, when a $q\bar{q}$ pair are pulled apart, they undergo QCD process to form a parton shower, which then hadronises into two jets



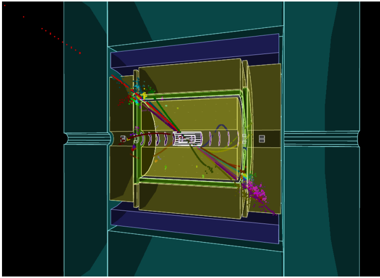
Why do we care about jets?

- Some particles are too short lived to be measured directly; only possibly to observe their decay products which can often result in jets
- So, want good jet energy resolution for precise measurements of e.g. Higgs properties

Brief Overview: 2

The $Z^{'} \rightarrow q\bar{q}$ Event

- Simulate a stationary fictional Z boson with whatever $\sqrt{s}$ we require, which decays to $q\bar{q}$ back to back
- These then decay to form two jets
- Only consider uds to minimise neutrinos (compared to heavy quark events)



Why Do We Do This?

- Allows us to measure the **jet energy resolution and scale** of the detector and reconstruction algorithms, with no background
- This gives a comparison between different detector models/reconstruction **performances**
- Currently used method is an **approximation** to jet energy resolution

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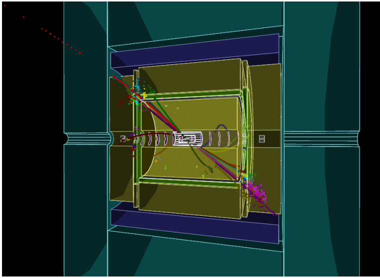

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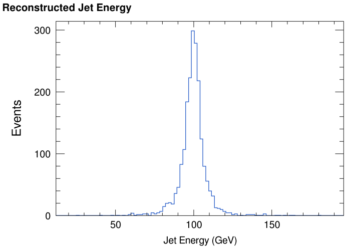
The aim of this project was to develop a more accurate method

Jet Energy Resolution

- Measure of how well we can identify the difference between two jets of similar energy
- Calculate based on the width of a distribution of measured energies, for jets of the same true energy, as:

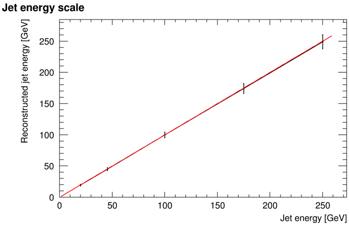
$$\text{resolution} = \frac{\text{rms}_{90}}{\text{mean}_{90}} \tag{1}$$

- Where $\text{rms}_{90}, \text{mean}_{90}$ are the rms and mean of a modified distribution containing only the central 90% of measurements



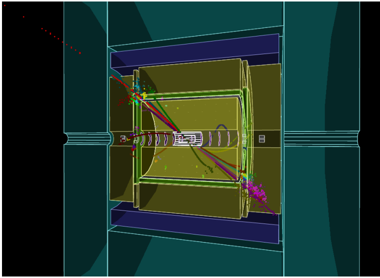
Jet Energy Scale

- Measure of how accurately our detector measures jets of known energy
- Easy way to check this is to plot reconstructed jet energy against true jet energy
- For a well calibrated detector, this plot will agree with the line $y = x$



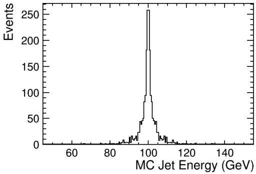
Methods

- Total Energy Method
  - Take all PFOs, sum reconstructed energy and divide by two (**Assumption**: reconstructed jet energies are equal)
- Monte Carlo (MC) Clustering
  - Begin by looking at MC particles in event simulation, split initial particles into two jets and then iterate over these until we have all MC particles in each jet
  - *This is where most of my work was focused*
- Durham Clustering Method
  - Define a 'distance' between PFOs - $d_{ij} = 2\min(E_i^2, E_j^2)(1 - \cos\theta_{ij})$
  - Iteratively add particles together until we have only two jets

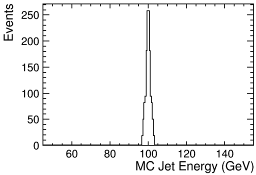


MC Jet Difference Cuts

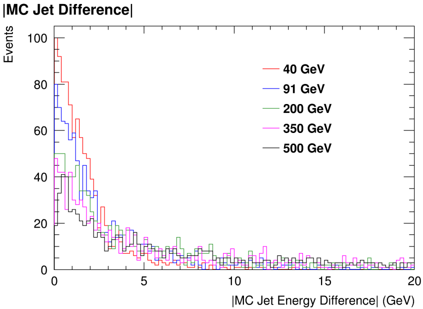
- We want a distribution of reconstructed energy for a **single** true (MC) jet energy to measure jet energy resolution - but simulated events have a **spread** of true jet energy (always sum to $\sqrt{s}$)
  - Must apply a cut to eliminate events where jet energy is not close enough to $\sqrt{s}/2$



No cut, 1000 events



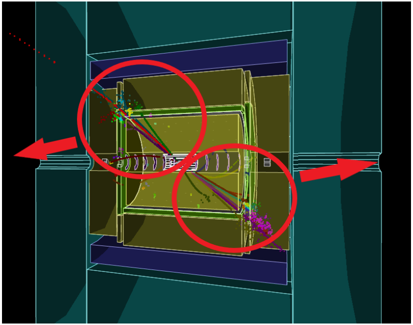
$E_{mc\ diff} \leq 3\%\sqrt{s}$, 685 events



Example Event

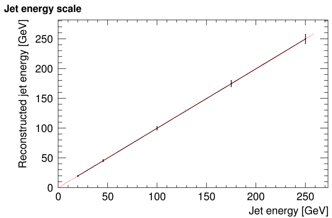
Consider the following situation for a $\sqrt{s} = 100$ GeV event ($E_{pfo\ total} = 98$ GeV):

$E_{mc\ 1} = 50 GeV$
$E_{rec,mc\ 1} = 45 GeV$
$E_{rec,Dur.\ 1} = 49 GeV$

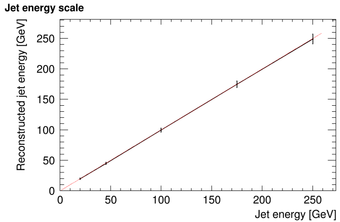


$E_{mc\ 2} = 50 GeV$
$E_{rec,mc\ 2} = 53 GeV$
$E_{rec,Dur.\ 2} = 49 GeV$

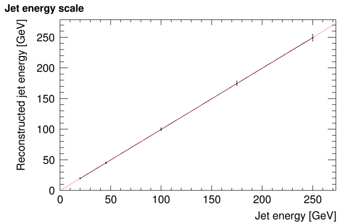
Final Results - Jet Energy Scale



MC Clustering

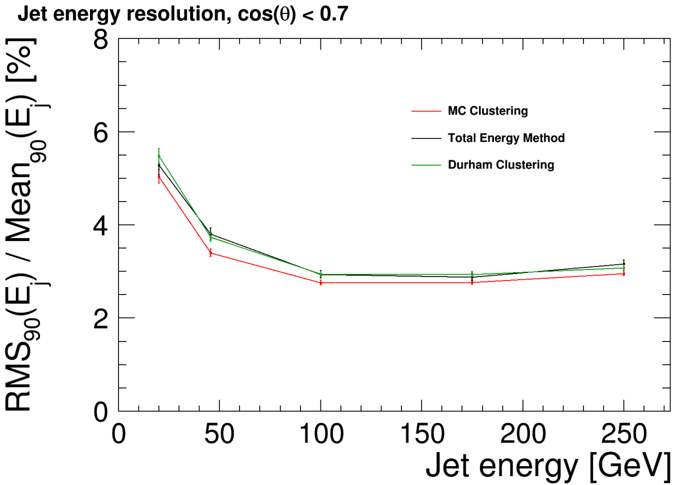


Durham Clustering



Total Energy Method

Final Results - Jet Energy Resolution



Conclusions

- A fair comparison of the total energy method and jet clustering methods **cannot be obtained**
  - The total energy method makes an approximation which can't be guaranteed
- MC clustering gives the **best obtainable** jet energy resolution for a specific detector model and reconstruction configuration; Durham clustering gives a *slightly* poorer resolution, as expected for such simple di-jet events
- The ILC would provide an ideal platform for more precise measurements of SM quantities and to probe beyond the SM physics
- **Highly granular calorimeters** and **complex pattern recognition algorithms** in **Particle Flow** reconstruction at the ILD would allow better jet energy resolution than any previous experiment

Any questions?

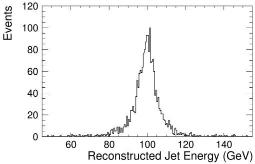
Backup Slides 1

Number of events remaining after each cut

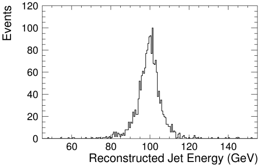
Energy (GeV)	$E_{mc\ diff} \leq 1\%\sqrt{s}$	$E_{mc\ diff} \leq 3\%\sqrt{s}$	$E_{mc\ diff} \leq 10\%\sqrt{s}$
40	986	2475	4463
91	1499	3176	4358
200	2047	3437	4585
350	2244	3491	4596
500	2353	3614	4608

Backup Slides 2

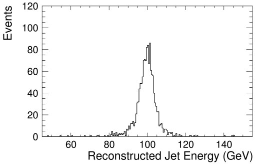
Reconstructed jet energy distribution after cuts (MC Clustering) for $\sqrt{s} = 200$ GeV event



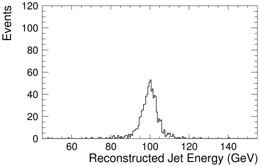
No cut, 1000 events, $\mathrm{rms}_{90} = 4.97$



$E_{mc\ diff} \leq 10\%\sqrt{s}$, 930 events, $\mathrm{rms}_{90} = 4.27$



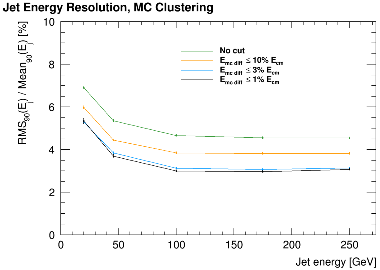
$E_{mc\ diff} \leq 3\%\sqrt{s}$, 685 events, $\mathrm{rms}_{90} = 3.45$

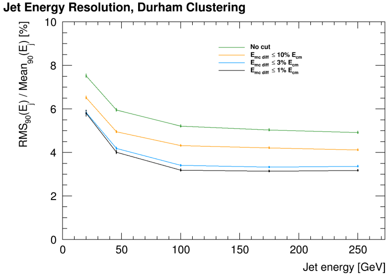


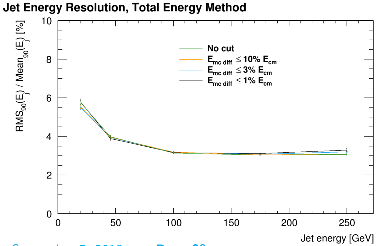
$E_{mc\ diff} \leq 1\%\sqrt{s}$, 415 events, $\mathrm{rms}_{90} = 3.44$

Backup Slides 3

JER after various cuts

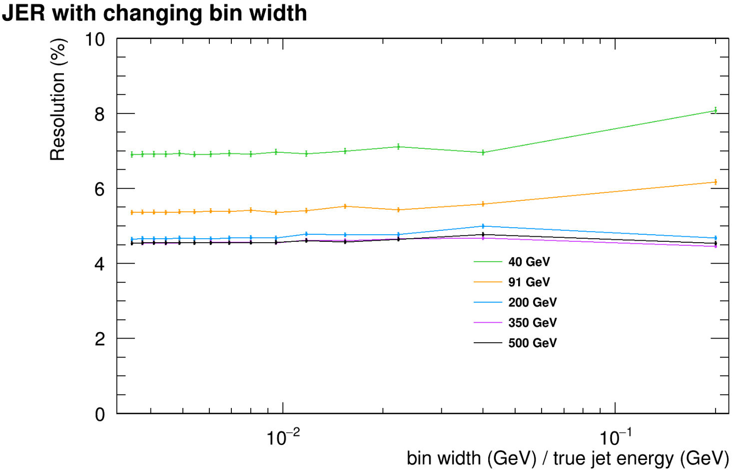






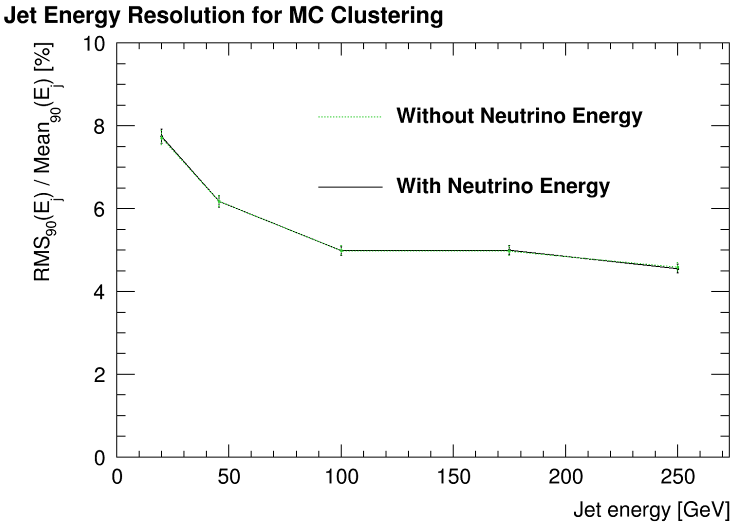
Backup Slides 4

Effect of bin width on calculated resolution, MC Clustering



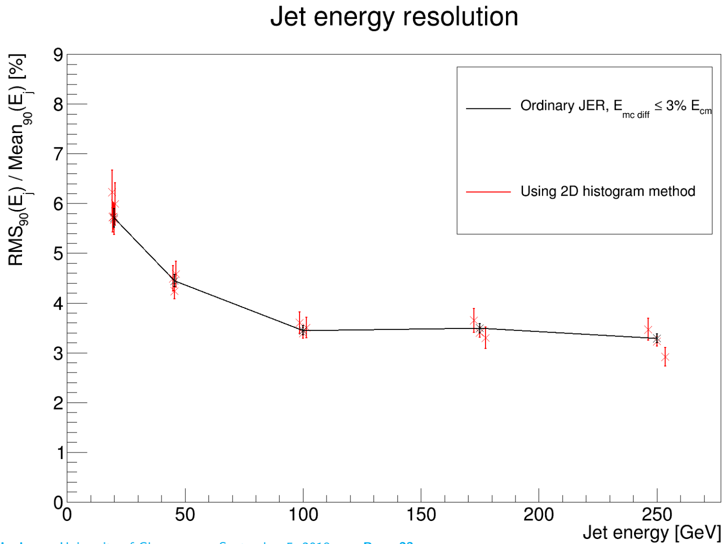
Backup Slides 5

Effect of neutrinos (missing energy), 1000 events



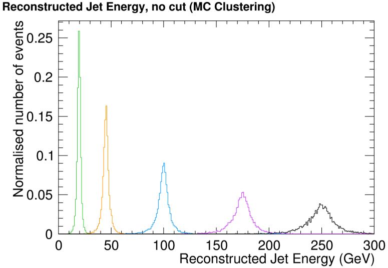
Backup Slides 6

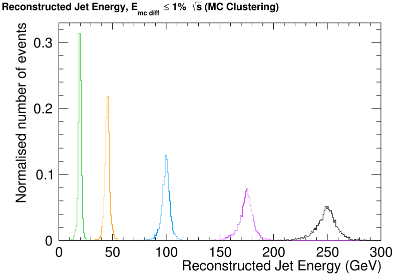
2D binning approach, MC Clustering



Backup Slides 7

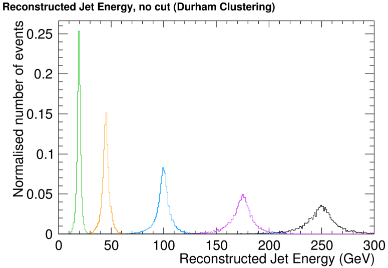
Reconstructed jet energy distributions - MC Clustering

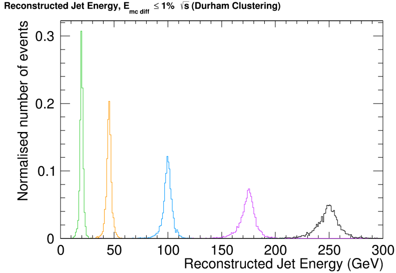




Backup Slides 8

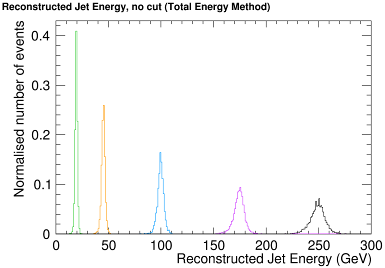
Reconstructed jet energy distributions - Durham Clustering

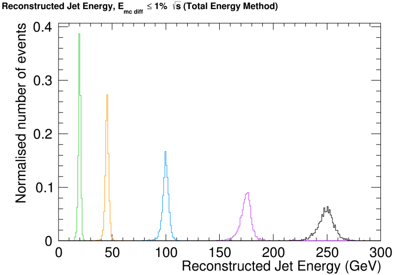




Backup Slides 9

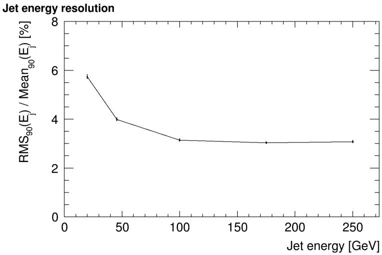
Reconstructed jet energy distributions - Total Energy Method

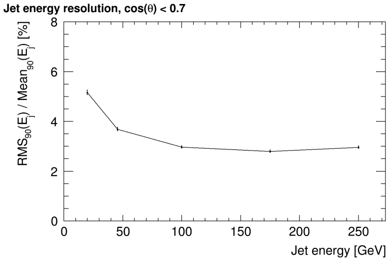


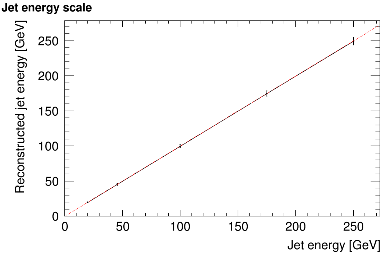


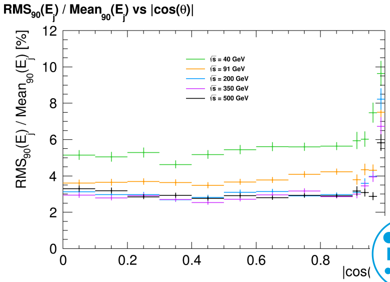
Backup Slides 10

Total Energy Method



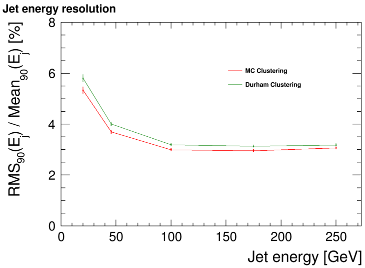


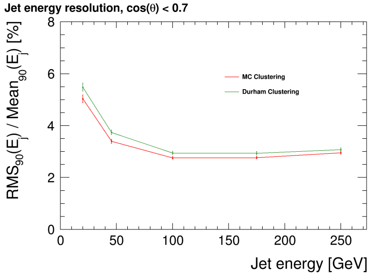


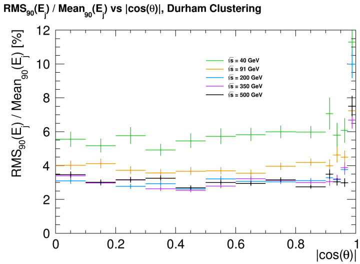


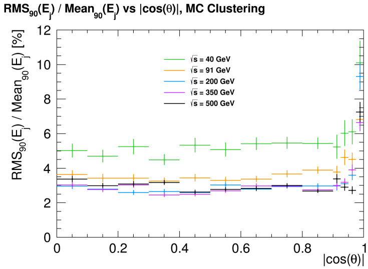
Backup Slides 11

Jet Clustering Methods - Resolution



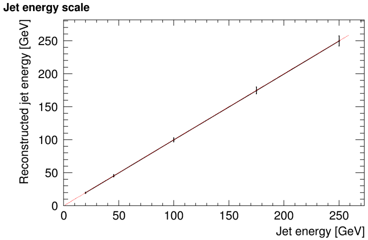




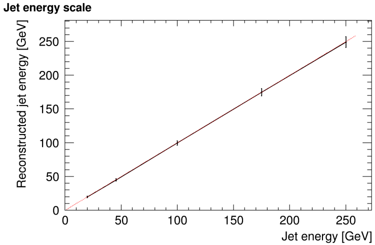


Backup Slides 12

Jet Clustering Methods - Scale



MC Clustering



Durham Clustering