Jet Energy Scale measurement at DØ

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Jet Reconstruction and Spectroscopy at Hadron Colliders
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Outline

1. Instrumentation
2. Reconstruction algorithms
3. Jet Energy Scale
    - Energy offset
    - Calorimeter response
    - Out-of-cone energy
4. Uncertainties
5. Summary

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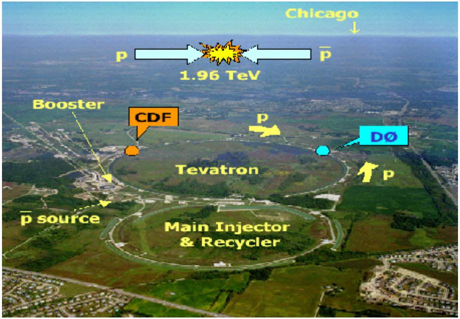
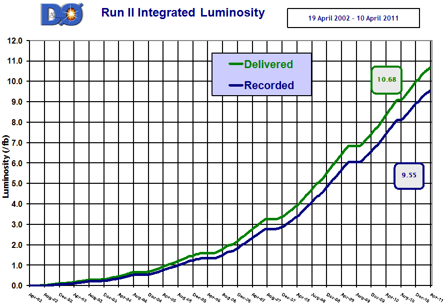
The Tevatron



- hadronic collider ($p\bar{p}$) at $\sqrt{s} = 1.96$ TeV
- more than 10 fb^{-1} expected to be recorded by CDF and DØ before October 2011
- initial instantaneous luminosity $\mathcal{L}$ often at $300 \cdot 10^{30}\ \text{cm}^{-2}\text{s}^{-1}$



Tevatron parameters (RunII)

$\sqrt{s}$	1.96 TeV
$\sigma(p\bar{p})$	≈ 60 mb
bunch crosses	≈ 1.7 MHz
$\mathcal{L}$	$10^{32}\ \text{cm}^{-2}\text{s}^{-1}$
$p\bar{p}$ interactions	≈ 4

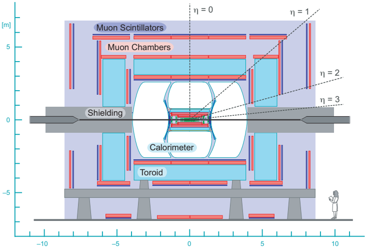
The DØ calorimeter

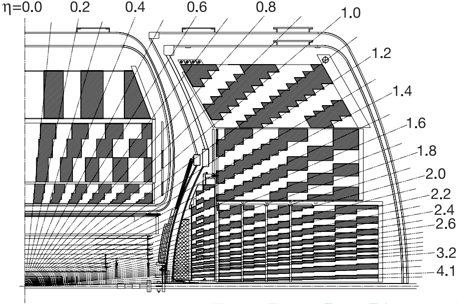
The DØ detector calorimeter(s):

- sampling calorimeter: liquid argon/uranium CC ($|\eta_\mathrm{d}| < 1.1$) and EC ($1.5 < |\eta_\mathrm{d}| < 4.2$)
- inter-cryostate region equipped with silicon detectors
- scintillator preshower detectors
- longitudinally segmented:

  electro-magnetic : $20X_0$

  hadronic : $7.2 \div 8.0\lambda_I$
- cells are $\approx \Delta\eta \times \Delta\varphi = 0.1 \times 0.1$
- $\approx 4X_0$ of material in front
- wrapping a 2 T magnetic field





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DØ jet algorithm

DØ uses a fixed-cone algorithm to build jets out of calorimeter cells:

- the algorithm is iterative and includes "mid-points"
- cells are considered to be massless
- the "E-scheme" is used: $\left(E_{\text{jet}}, \vec{p}_{\text{jet}}\right) = \sum_{c \in \text{cells}} \left(E_c; E_c \hat{u}_c\right)$
- we use two cone sizes, defined by the parameter $\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\varphi^2}$:

$\Delta R = 0.5$	is used for most of the analyses
$\Delta R = 0.7$	is used mostly for di- and tri-jet analyses which have lower final state multiplicity and care more of collecting all the energy of the jets

Jet energy scale correction is different for each of the two cone sizes.

An equivalent algorithm can be applied *in simulation* starting from stable particles (except μ and ν) instead of calorimeter cells.
We call this a *particle jet*.

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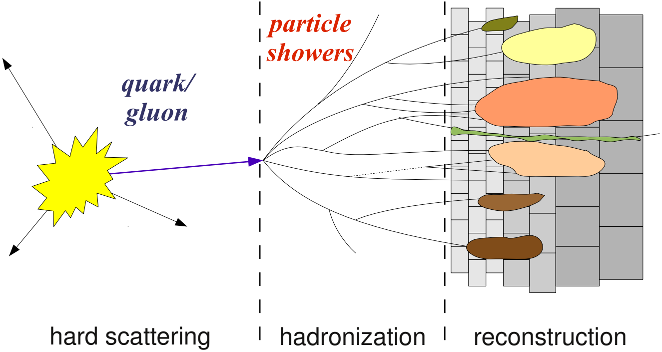
Quarks, particle jets, reconstructed jets



The goal:

The DØ JES aims to correct the reconstructed energy back to the energy of the particles, which can in principle be directly measured. It does *not* try to quantify the energy of the original gluon or quark.

Jet energy scale correction

The Jet Energy Scale correction is summarized in this formula:

$$E_{\text{jet}}^{\text{ptcl}} = \frac{E_{\text{jet}}^{\text{meas}} - E_{\text{O}}}{R_{\text{jet}}\, S_{\text{jet}}} \tag{1}$$

The jet energy at level of particles, $E_{\text{jet}}^{\text{ptcl}}$, is computed

- from the detected energy $E_{\text{jet}}^{\text{meas}}$ (sum of energy from jet cells)
- subtracting the "offset" energy E_{O} from activity alien to the jet
- correcting for the calorimeter response R_{jet} to the jet particles
- including the energy S_{jet} from partices fallen out of the jet cone

Jet energy scale correction

The Jet Energy Scale correction is summarized in this formula:

$$E_{\mathrm{jet}}^{\mathrm{ptcl}} = \frac{E_{\mathrm{jet}}^{\mathrm{meas}} - \hat{E}_{\mathrm{O}}}{\hat{R}_{\mathrm{jet}}\,\hat{S}_{\mathrm{jet}}} \cdot \frac{k_{\mathrm{O}}}{k_{\mathrm{R}}} \tag{1}$$

The jet energy at level of particles, $E_{\mathrm{jet}}^{\mathrm{ptcl}}$, is computed

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- including the energy S_{jet} from partices fallen out of the jet cone
- with additional correction factors for zero-suppression, response and offset biases

Energy offset correction

Offset energy:

Energy deposited in the calorimeter, which does not come from the primary interaction

+ includes apparent energy from calorimeter (esp. uranium) and electronic noise
+ includes effects from the slow response of calorimeter electronics (“pile-up”)
+ includes energy from additional $p\bar{p}$ interactions (*MI*)
− does *not* include energy deposited by the $p/\bar{p}$ remnants not involved in the hgh Q^2 scattering

Energy offset correction: method

The correction is extacted based on:

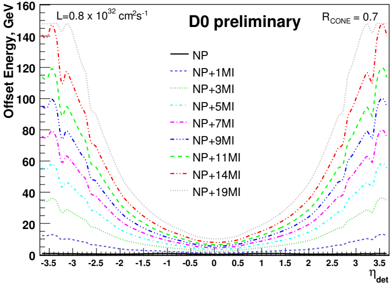
$$\hat{E}_{\mathrm{O}}^{\mathrm{ring}}(\eta, n_{\mathrm{PV}}, \mathcal{L}) = \hat{E}_{\mathrm{NP}}^{\mathrm{ring}}(\eta, \mathcal{L}) + \hat{E}_{\mathrm{MI}}^{\mathrm{ring}}(\eta, n_{\mathrm{PV}}, \mathcal{L}) \tag{2}$$

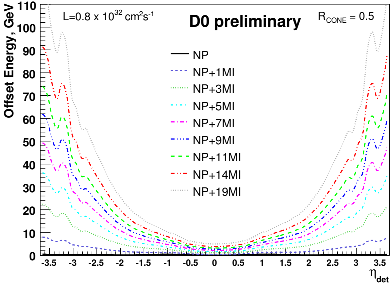
- the noise and pile-up energy $\hat{E}_{\mathrm{NP}}^{\mathrm{ring}}$ is obtained from “Zero Bias” events (triggered at a random bunch-crossing) with no reconstructed primary vertex
- the energy from multiple interactions $\hat{E}_{\mathrm{MI}}^{\mathrm{ring}}$ is obtained from “Minimum Bias” events (triggered by an elastic scattering at high η); to correct a triggered physical event with n_{PV} primary vertices, the energy $\hat{E}_{\mathrm{MI}}^{\mathrm{ring}}(\eta, n_{\mathrm{PV}}, \mathcal{L}) - \hat{E}_{\mathrm{MI}}^{\mathrm{ring}}(\eta, n_{\mathrm{PV}} = 1, \mathcal{L})$ is used, to exclude the contribution from the interesting event

The energy offset $\hat{E}_{\mathrm{O}}$ of a jet is computed as sum of $\hat{E}_{\mathrm{O}}^{\mathrm{ring}}$ according to its cone radius, either $\Delta R = 0.5$ or 0.7.

Energy offset correction: results

The observed energy offset can become huge in extreme conditions, but it is usually below 25 GeV for most of the jets used in the physics analyses.





Systematic errors on this correction are very small and dominated by the error on the bias correction.

Response correction

Calorimeter response:

Fraction of the energy of the jet particles which is converted and measured

+ difference in energy response for different particles (esp. hadrons vs. electrons, since the calorimeter is *non-compensating*)
+ energy loss due to inactive material (cracks) or uninstrumented region (inter-cryostate gap)
+ non-linearity caused by zero-suppression
+ energy not detected because converted in nucleon mass
+ non-uniformity of response in different regions of the calorimeter
+ energy leaking beyond the calorimeter (“punch through”)
− undetected energy from muons and neutrinos is not added at this stage

Two-body processes X+jet

To evaluate the calorimeter response, a tag and probe method is used; we use two-body events, which have the simplest topology:

- γ+jet is the most important process, defining a relation between jet energy and another energy, the one supposedly well measured of the photon. Photon identification criteria used here are very tight
- di-jet is used to enhance statistics for the estimation of the uniformity of the response

$Z(\rightarrow e^+e^-)$+jet has not been used because of low statistics

Events are required to have a very low number of reconstructed primary vertices and the two bodies are required to be back to back ($\Delta\varphi \geq 3$ rad).

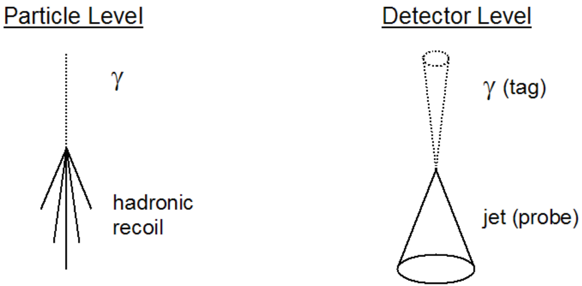
Instead of the jet energy, subject to conspicuous uncertainties, to parametrize our corrections we use the quantity:

$$E' \equiv p_T^{\text{tag}} \cosh \eta^{\text{probe}} \tag{3}$$

where the momentum of the tag is fully corrected.

Response: Missing E_T Projection Fraction

Missing E_T Projection Fraction Method: γ+jet



$$\vec{p}_{T,\gamma} + \vec{p}_{T,had} = \vec{0}$$

$$\vec{p}_{T,\gamma} + R_{had}\vec{p}_{T,had} = -\vec{\not{E}}_T$$

$$R_{had} = 1 + \frac{\vec{\not{E}}_T \cdot \vec{p}_{T,\gamma}}{\vec{p}^{\,2}_{T,\gamma}}$$

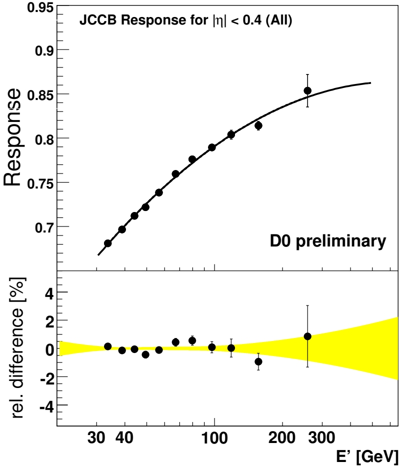
For back-to-back events: $R_{jet} \approx R_{had}$

- the MPF provides an estimation of the ratio between the response of the probe and the tag
- it does not depend on the probe jet algorithm
- the jet response R_{jet} is equal to the recoil response R_{had} not better than at percent level

Response in the central calorimeter

The first step for the response correction is the absolute response:

- exclusively from very clean γ+jet events (and di-jet contamination is corrected for)
- relates the response of very central jets ($|\eta| \leq 0.4$) to the well known photon energy
- increases with the energy (because of more $\pi^0 \to \gamma\gamma$)
- parametrized as $P_2(\log E'/E_0)$
- main uncertainties: γ energy and di-jet contamination

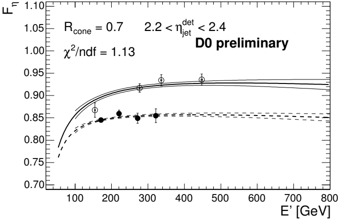


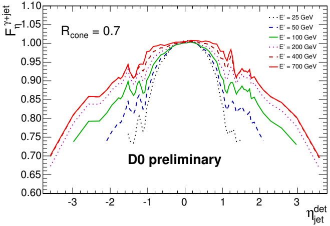
This response is extrapolated to higher energies using simulation.

Relative response anywhere in the calorimeter

The second step for the response correction is the relative response:

- from very clean γ+jet and di-jet events
- relates the response of any part of the calorimeter to the very central one
- the tag object has $|\eta| \leq 0.4$, the probe jet can be up to $|\eta| \leq 3.6$
- shows strongly reduced response in the inter-cryostate region
- response from γ+jet and di-jet events is very different due to the different jet composition
- the main uncertainty comes from the response parametrization in E' and η





Out-of-cone energy

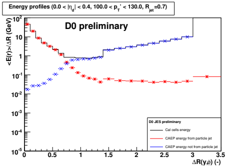
Out-of-cone energy:

Energy contributed or lost due to the cone geometry.

- \+ energy of particles from the jet which fell outside the jet cone
- \+ energy of particles alien to the jet which fell inside the jet cone
- \+ energy of particles from the jet so weak that they never reached the calorimeter due to the magnetic field
- − does not include energy from gluon radiation at large angles

Out-of-cone energy estimation method

- a energy profile is defined as the energy of particles within a given radius δR from the jet axis: $E\left(R\right) = \sum_{\delta R<R} E_{\text{particles}}$
- three profiles are extracted from simulation for:
  - particles from the jet: $E^{\text{MC}}_{\text{from-jet}}\left(R\right)$
  - particles not from the jet: $E^{\text{MC}}_{\text{non-jet}}\left(R\right)$
  - offset energy: $E^{\text{MC}}_{\text{ofs}}\left(R\right)$



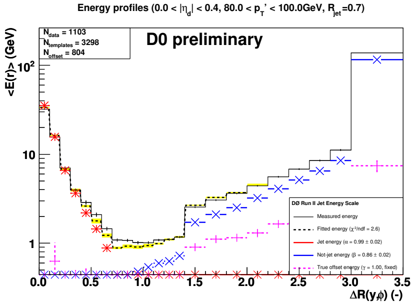
The correction for a jet of cone ΔR (either 0.5 or 0.7) is:

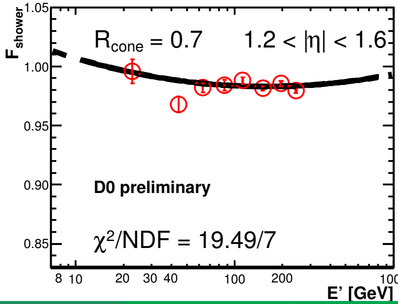
$$\hat{S}_{\text{jet}} = \frac{E^{\text{MC}}_{\text{from-jet}}\left(\delta R < \Delta R\right)}{E^{\text{MC}}_{\text{from-jet}}} + \frac{\alpha}{\beta}\frac{E^{\text{MC}}_{\text{non-jet}}\left(\delta R < \Delta R\right)}{E^{\text{MC}}_{\text{from-jet}}} \tag{4}$$

The first and second ratio describe the fraction of the *measured energy* of the particles, respectively from the jet and alien to the jet, falling inside the ΔR cone. The global parameters α and β are simulation-to-data energy scale factors for the two categories of particles.

Out-of-cone energy measurement

- γ+jet sample is used for data and for the simulation
- an energy profile is extracted from data as well
- the energy scale parameters α and β are estimated by a template fit on E^{MC} $(\delta R < 0.2)$
- the correction is extracted for different E' and η
- some relevant uncertainties are the simulation of the gluon radiation, statistics for templates and the purity of the γ+jet sample





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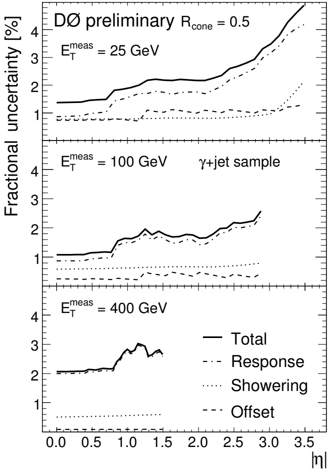
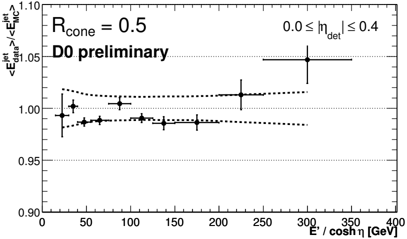
Jet Energy Scale uncertainty

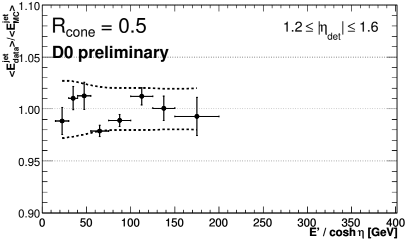
- at the end of the Jet Energy Scale measurement, dozens of sources of uncertainty can and have been identified and included
- the largest contribution to the uncertainty comes from the largest component of the correction, the *response*
- a few of the contributions can be reduced by expanding the simulation samples, much more by collecting and analysing more data
- as time goes, detector performances change, as do accelerator's: it is not always possible to combine additional data to the existing measurement



Comparison between data and simulation

- for a sizeable number of analyses the consistency of JES between data and simulation is *more important* than the correctness of its absolute scale
- consistency is verified on a γ+jets sample
- the simulated sample is contributed by both γ+jets and QCD processes, proportionally to the estimated purity in data





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Summary

- in an hadron collider, Jet Energy Scale is of capital importance for most analyses
- the complete treatment of the measurement is complex (and in this talk *a lot* of corrections were not even mentioned)
- at DØ we can estimate the Jet Energy Scale with a precision of $\mathcal{O}\,(2\%)$ in most of the regions
- we are updating the measurement as new data becomes available, although the combination of different data epochs can be tricky due to changes in configuration of the detector and simple aging

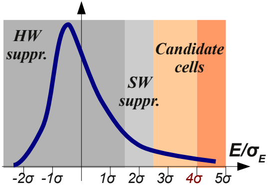
Backup

Calorimeter readout: zero suppression

To save bandwidth and storage space, calorimeter readout is «zero-suppressed»:

1. each cell has its noise (quantified as RMS σ of ADC count)
2. readings below 1.5σ are discarded by hardware
3. readings below 2.5σ are discarded by software
4. cells above 2.5σ are included only if they have a neighbor (in 3D) with reading above 4σ

This is a source of *energy loss* on reconstructed objects.

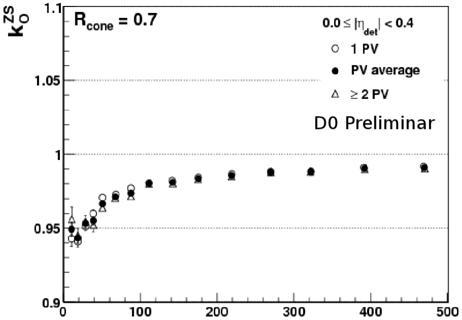


2.5σ	1σ	2σ	1.5σ	
-0.5σ	4.5σ	5σ	3σ	3.5σ
		1.5σ		1.5σ
	3σ		5σ	1.5σ
1σ	3σ	-2σ		

Energy offset correction: zero-suppression bias

Energy deposits from an interesting event which would be ignored because of the zero-suppression can be saved by the presence of additional energy from other interactions.

- in order to correct this bias, simulation is used, comparing the energy deposit of a γ+jet simulated event:
  - with no minimum bias overlay (the reference energy)
  - with minimum bias overlay (what we actually measure)



This bias (shown in the plot as function of jet energy) is found to be of a few percent.

DØ jet algorithm

The algorithm used in DØ is fixed-cone in $\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\varphi^2}$ with midpoints:

1. cell towers are defined as pseudo-projective groups of (unsuppressed) cells, with $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$
2. the reconstructed interaction vertex is then used as projection point
3. *proto-jets* are created drawing cones of radius ΔR around seeds (high-p_T towers, plus additional mid-points), using the «*E*-scheme» ($p_{\text{jet}} = \sum_{c \in \text{cells}} \left(E_c, \vec{p}_c\right)$, cells are massless)
4. the process is repeated using cones around the newjet axes until the result is stable
5. the overlapping proto-jets are either split or merged, depending on the shared energy
6. jets with $p_T < 6$ GeV/*c* are discarded

◂ back to algorithm summary

A photon

- a cluster of cells mostly (96%) in the e.m. calorimeter
- reconstructed within the fiducial region of the calorimeter
- associated with no tracks
- isolated respect to other clusters in the calorimeter
- isolated respect to reconstructed tracks
- has reconstructed positions from the preshower detector and from the calorimeter close (to suppress $\pi^0 \to \gamma\gamma$)