Jet energy scale calibration at D0

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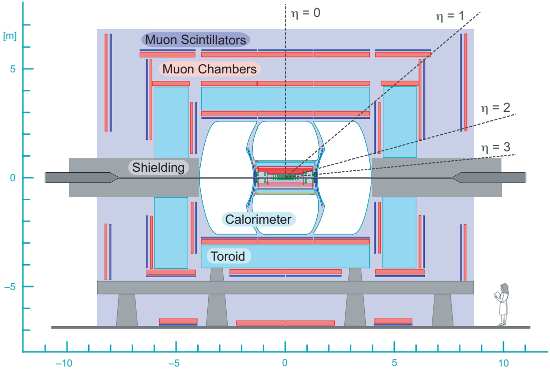
Outline

- Introduction
  - The D0 calorimeter system
- Jet energy scale calibration
  - Jet energy scale subcorrections
  - Combined jet energy scale corrections
- Inclusive jet cross section
- Summary

Motivation

- Most physics analyses involve jets, esp. QCD, top physics and new phenomena searches
- The 1 fb^{-1} Run IIa data set allows for very detailed studies in calibration samples (photon+jet, di-jet) over wide η and p_T ranges
- Many analyses using the Run IIa data set are already systematics limited
- Beautiful training grounds to perfect techniques and simulation before the jump to the LHC

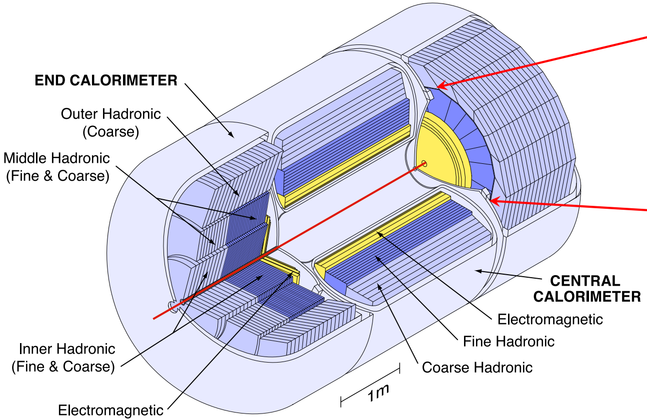
The D0 experiment at Fermilab

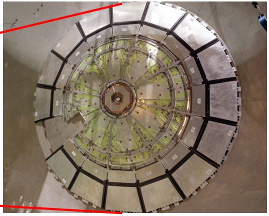


Located in the Fermilab Tevatron collider ring:

- $p\bar{p}$ at $\sqrt{s} = 1.96$ TeV
- bunch separation: 396 ns
- Run IIa: instantaneous luminosities up to $175 \cdot 10^{30}$ cm^{-2} s^{-1}
- On average $\approx$ 5 interactions per bunch crossing

The D0 calorimeter system





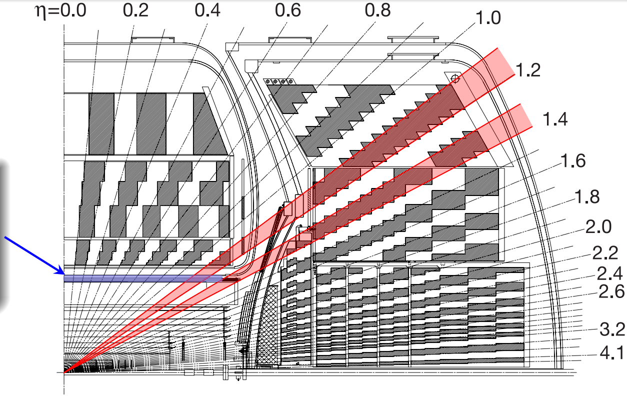
- Uranium/liquid argon calorimeter
- Hermetic coverage up to $|\eta| < 4.2$
- Scintillator based inter-cryostat detector improves coverage ($1.1 < |\eta| < 1.4$)
- Finely segmented: $\Delta\phi \times \Delta\eta = 0.1 \times 0.1$ and 0.05×0.05 at EM shower maximum

The D0 calorimeter system

- Calorimeter cells make up pseudo-projective towers
- Four electromagnetic layers ($\approx 20\ X_0$)
- Three (central) or four (endcaps) finely segmented hadronic layers followed by one coarser hadronic layer. Hadronic depth > 7.2 (8.0) interaction lengths.
- Significant material in front of calorimeter: $\approx 4\ X_0$ (solenoid, preshowers, trackers)

Preshower detector

- Scintillating fibers
- Used to improve photon identification



Jet energy scale calibration

D0 uses the 'Run II midpoint cone algorithm' [1]

- Cone sizes 0.5 and 0.7
- $E_{\mathrm{T,\,jet}} \geq 6$ GeV

- Seed-based algorithm, use all particles (or partons, or calorimeter towers) as seeds
  - make cone of radius $\Delta R = \sqrt{\Delta y^2 + \Delta\eta^2} < \mathcal{R}_{\mathrm{cone}}$ arond seed direction
  - proto-jet: add particles within cone in the 'E-scheme' (four-vector addition)
  - iterate until stable solution is found (cone axis = jet axis)
- Use all midpoints between jet pairs as additional seeds for infrared safety
- Combine solutions from the above two steps
  - remove identical solutions
  - remove proto-jets with $E_{\mathrm{T}} < E_{\mathrm{T,\,min}}$
- Treat jets with overlapping cones (split/merge)
  - merge jets if more than 50% of the lowest jet p_{T} is contained in the overlap
  - otherwise split jets and assign particles in overlap to nearest jet

[1] G.C. Blazey et al., Proc. of the QCD and Weak Boson Physics in Run II Workshop (Batavia 1999), [hep-ex/0005012]

Jet energy scale calibration

Goal of the jet energy scale calibration:

To correct the calorimeter jet energy back to the stable-particle jet level before interaction with the detector

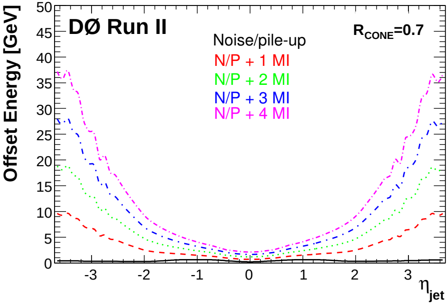
$$E_{\mathrm{jet}}^{\mathrm{ptcl}} = \frac{E_{\mathrm{jet}}^{\mathrm{meas}} - O}{F_{\eta} \cdot R \cdot S} \cdot k_{\mathrm{bias}}$$

- O Offset subtraction removes all energy not associated with the hard scatter
- R Absolute calorimeter response
- F_{η} η-Dependent inter-calibration of response
- S Correction for detector showering effects

Offset subtraction

Subtract all energy inside the jet cone not related to the hard interaction:

- electronics and uranium noise
- multiple $p\bar{p}$ interactions in the same bunch crossing
- left-overs from previous bunch crossings (pile-up)



Noise/pile-up

Estimated using zero-bias data; data triggered on the presence of bunch crossings and vetoing any hard interactions

Multiple interactions

Measured in minimum-bias data; data triggered using the luminosity monitors to signal potential inelastic scatters. Contribution from additional interactions determined from:

$$\text{MI}(N_{PV}, L) = \text{MinBias}(N_{PV}, L) - \text{MinBias}(N_{PV} = 1, L)$$

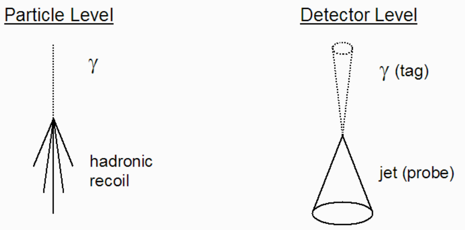
Absolute response measurement

Use a very tight photon+jet sample

- one photon within $|\eta| < 1.0$
- one jet within $|\eta| < 0.4$
- $\Delta\phi(\text{photon}, \text{jet}) > 3.0$

Missing transverse energy projection fraction method

- independent of the jet algorithm
- requires calibrated EM objects



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

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

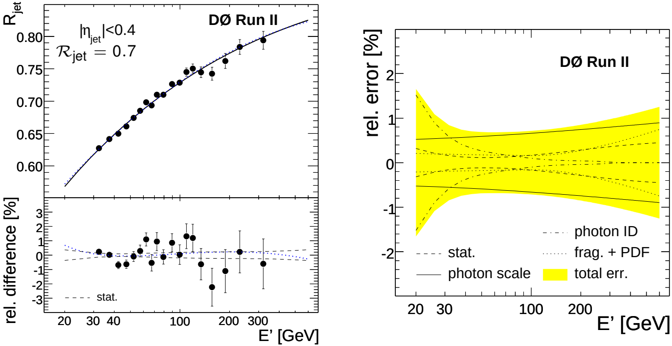
$$R_{\text{had}} = 1 + \frac{\vec{\not{E}}_{\text{T}} \cdot \vec{p}_{\text{T},\gamma}}{\vec{p}^{\,2}_{\text{T},\gamma}}$$

For tightly back-to-back objects:

$$R_{\text{jet}} \approx R_{\text{had}}$$

Absolute response measurement

The ≈ 25% correction to the response is the largest of all energy scale contributions

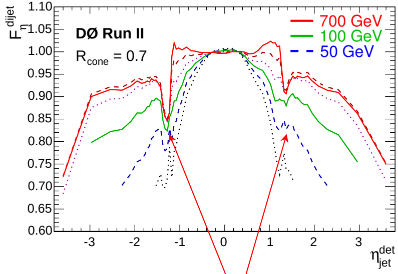


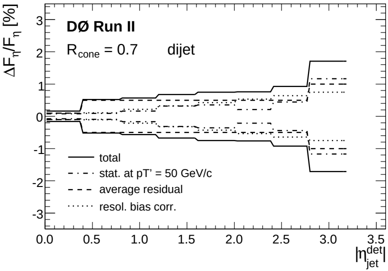
- Only ≈ 1.2% uncertainty at $p_T = 600$ GeV/c
- The di-jet contamination in the photon+jet sample is measured in MC, verified in data and explicitly corrected for
- Parameterization vs. $E' \equiv p_{T,\gamma} \cosh \eta_{jet}$ suppresses effects of jet energy resolution

η-Dependent response corrections

Calibrate forward jets with respect to central ones

- **photon+jet**: one tag photon within $|\eta| < 1.0$, contributes to low p_T region
- **di-jet**: one tag jet within $|\eta| < 0.4$, contributes to high p_T region





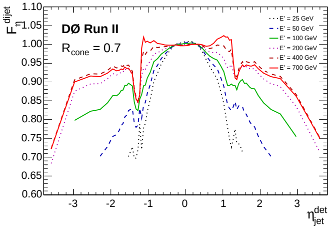
inter-cryostat region 'cracks'

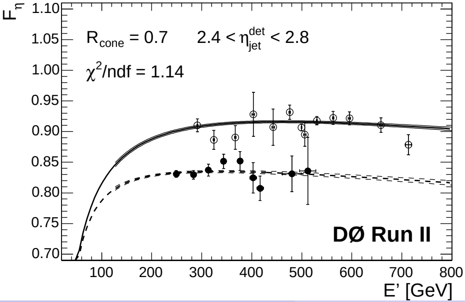
η-Dependent response corrections

Sample dependence

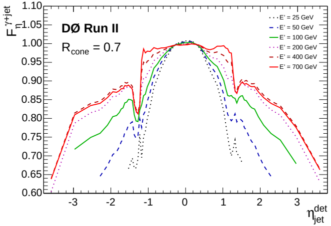
- Different response for gluon vs. quark jets
- Response difference increases going forward
- Relative quark/gluon contributions differ strongly between di-jet/photon+jet
- Di-jet sample used to extract shape of p_T dependence

di-jet





photon+jet



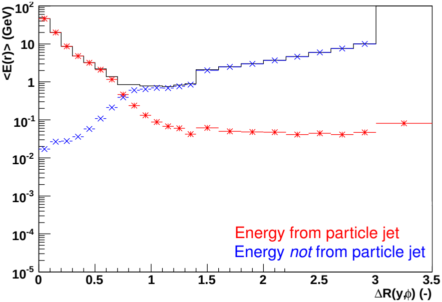
Detector showering corrections

Correct for instrumental showering effects: magnetic field bending, shower development in the calorimeter, ...

- Use back-to-back photon+jet events and remove offset
- Map average energy deposited by jet particles vs. radial distance away from the jet
- Fitting the jet/not-jet energy templates to the data allows measurement of

$$S = \frac{\int_0^\infty E(\text{jet})}{\int_0^{\mathcal{R}_\text{jet}} \left(E(\text{jet}) + E(\text{not-jet})\right)}$$

$\mathcal{R}_\text{jet} = 0.7$, $|\eta_\text{d}| < 0.4$, $100 < p_\text{T}^{\prime} < 130$ GeV/c



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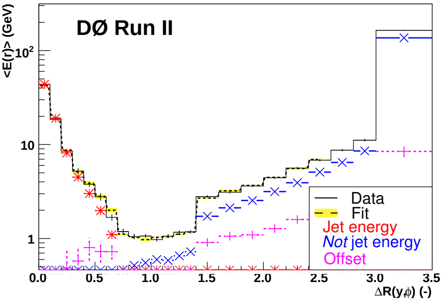

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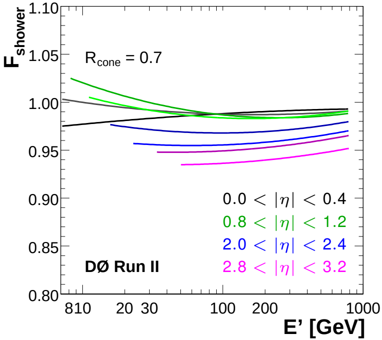
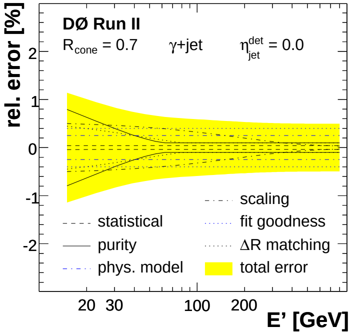




- Calibrated using true showering in Monte Carlo
- Very small corrections compared to offset and response
- More prominent for smaller jet cone sizes
- Larger corrections for forward jets

- Main systematic uncertainties:
  - quality of the fit
  - photon purity (at low p_T)
  - jet fragmentation model (at high p_T)

Additional bias corrections

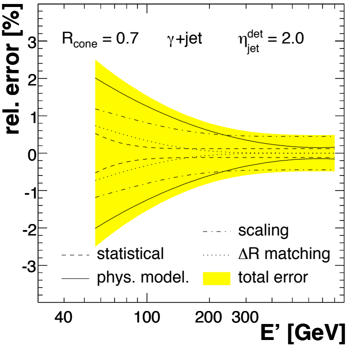
Side-effects of zero-suppression:

- The offset energy inside a jet is larger than the offset energy estimated in the absence of jets
- The compactness of photons with respect to jets makes photons less sensitive to zero-suppression effects: the MPF method underestimates the jet response.

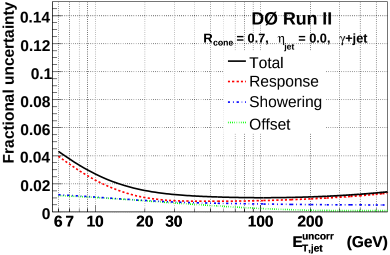
The above effects compensate to a large extent. The remaining effect is studied in MC by comparing offset and response for the same jets with and without ZB overlay.

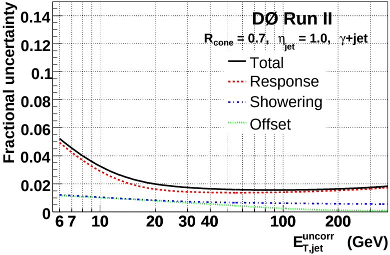
The MPF method is sensitive to additional activity in the event:

- jets below reconstruction threshold ($E_{\mathrm{T,\,min}} = 6$ GeV)
- event selection, especially the minimum $\Delta\phi(\mathrm{photon, jet})$ cut
- effects of jet splitting/merging
- underlying event

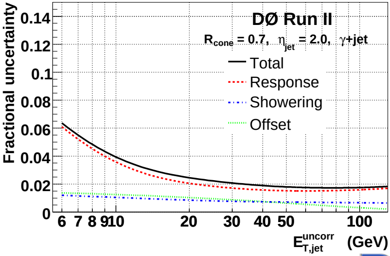


Combined jet energy scale corrections





Fractional jet energy scale uncertainties for $\mathcal{R}_{\text{jet}} = 0.7$ cone jets at various $\eta = 0.0/1.0/2.0$ as a function of uncorrected jet p_T



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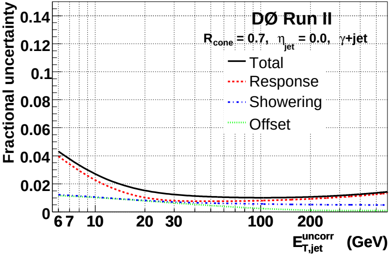
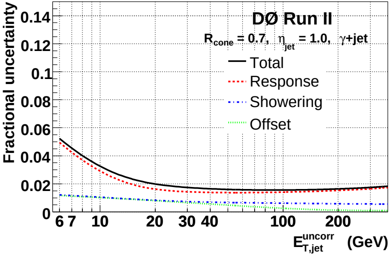
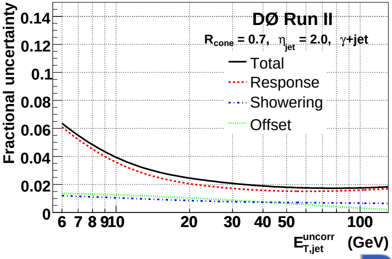




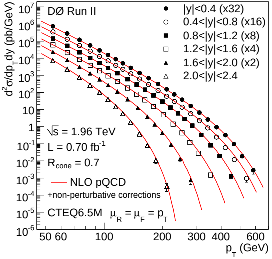
Dominant uncertainties:

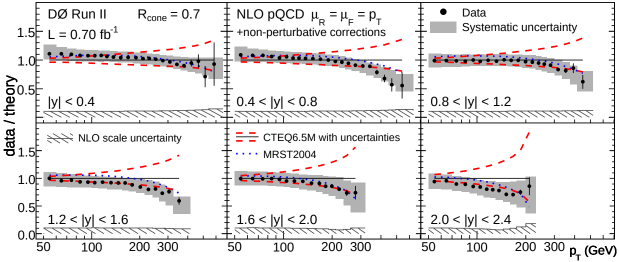
- Absolute EM energy scale
- Electron-to-photon energy scale
- Photon purity in the photon+jet sample (esp. at low p_T and very forward)
- Low statistics at high p_T



Inclusive jet cross section

- JES uncertainties have improved by a factor of two or more since the preliminary JES (2006).
- Inclusive jet cross section not published in forward regions before. JES improvements of a factor of ten now allow publication.





*Measurement of the inclusive jet cross section in ppbar scattering at sqrt(s)=*1.96 *TeV*, 0802.2400 [hep-ex], Submitted to PRL

Summary

- D0 employs a data-driven jet energy scale calibration method
- D0's jet energy scale calibration has reached a precision of 1–2% for jets over a wide kinematic range
- High precision jet energy scale calibration requires detailed understanding of many components: electronics calibration, photon energy scale, detector simulation, etc.
- D0 has gathered invaluable experience and methods for the understanding of jets in hadron interactions over a wide range of jet energies and rapidities
- A NIM paper describing the D0 JES calibration is in preparation
  - Detailed discussion of all results as functions of energy and pseudorapidity
  - Study of JES differences for quark- vs. gluon jets
  - Special jet energy scale for di-jet events
    $\rightarrow$ makes use of correlations between uncertainties to reduce overall uncertainty

For more details please visit the D0 jet energy scale page:
`http://www-d0.fnal.gov/phys_id/jes/public_RunIIa/`