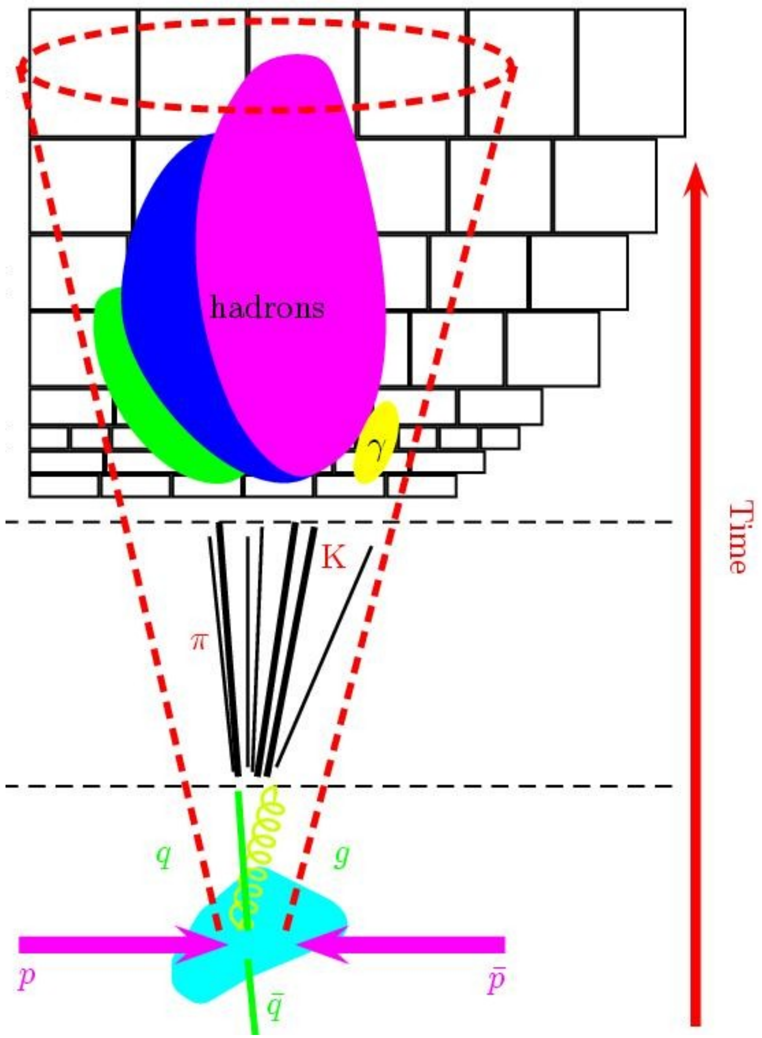
Jet Energy Scale at CDF and DØ

Bob Hirosky **The University of Virginia**

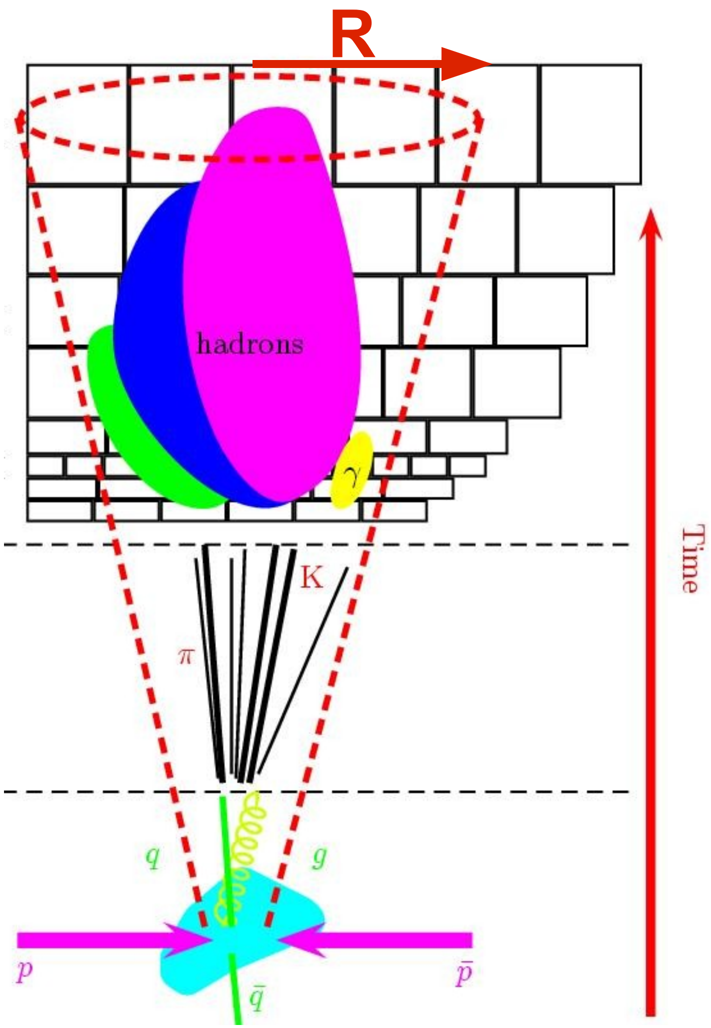


- Many physics measurements depend on accurate knowledge of energies of jets resulting from the fragmentation of quarks and gluons in the hard scattering process.

- A 1% uncertainty on the jet scale translates to ~10% uncertainty for jet C.S. ~500 GeV P_T and O(1%) on the top mass

- This talk will cover the approaches used by the CDF and DØ Experiments to derive their absolute energy scale corrections for jets.

The following concentrates on corrections for (iterative) cone-jet algorithms, though the methods are also generally applicable to recombinant, K_T-style, algorithms



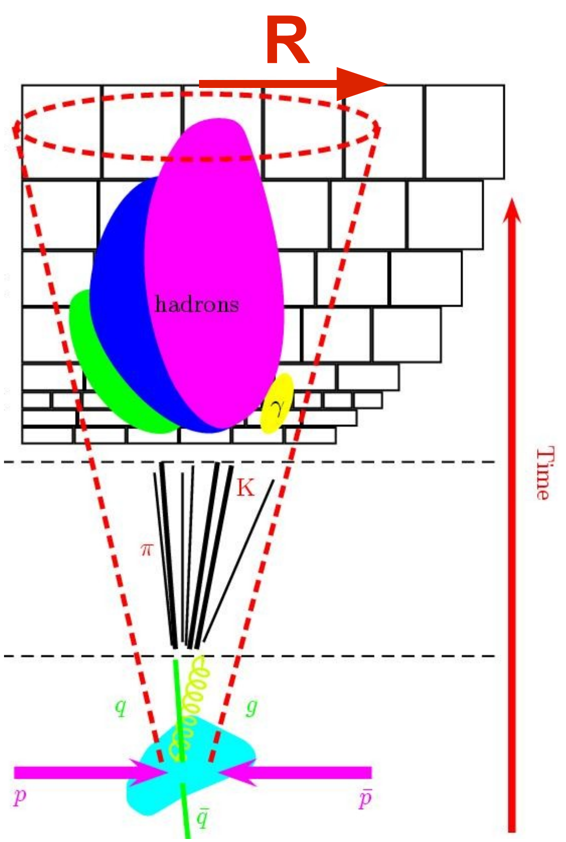
Both experiments use an iterative cone algorithm:

Starting with calorimeter "seed towers"

Neighboring towers lying within a cone radius, R, are combined to form a cluster.

A centroid is calculated and the position of the cone is iterated until the centroid and geometric center of the code are aligned

RunII Jet clustering schemes in the two experiments



DØ: clustering performed in E-Scheme[1]
- Centroids given by addition of tower 4-vectors
- Midpoints applied as additional starting points

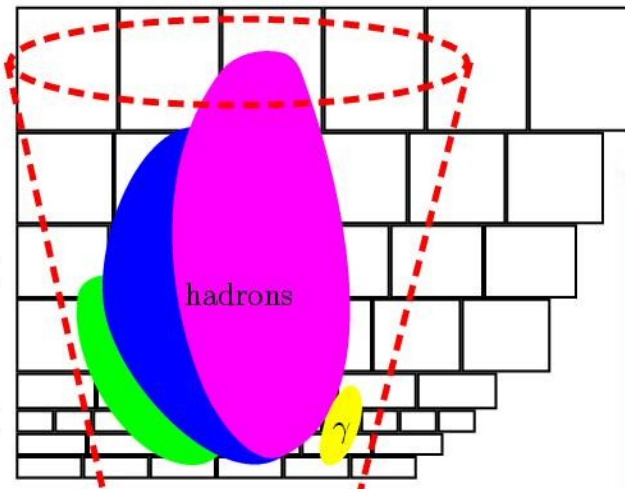
CDF: clustering performed in Snowmass Scheme[2]
- ET-weighted centroids
- No midpoints applied
- Final jet angles defined according to 4 vecs. of towers
- "Ratcheting" to limit cone drift during iterations

Minor algorithmic differences are unimportant for this discussion, however it should be clear that there are many potential jet scales, one for each algorithm.

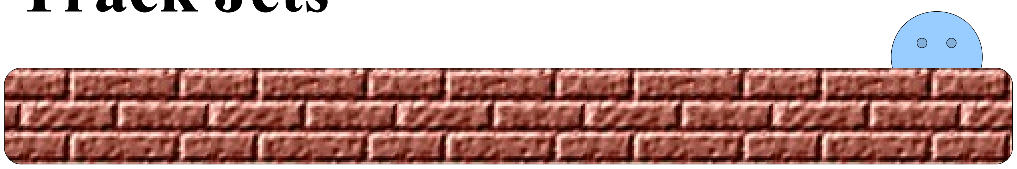
After all, a jet is what you define it to be!

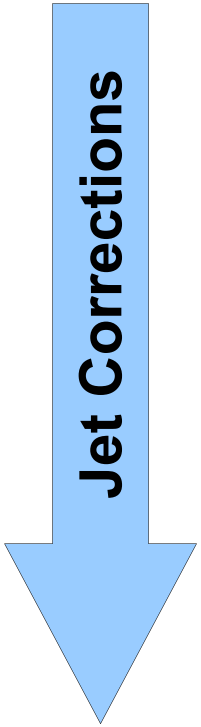
[1] FERMILAB-PUB-00-297 (2000).
[2] hep-ex/0510047 (2005), Huth et al. in Proceedings of Research Directions For The Decade: Snowmass 1990, World Scientific, 1992, p. 134.

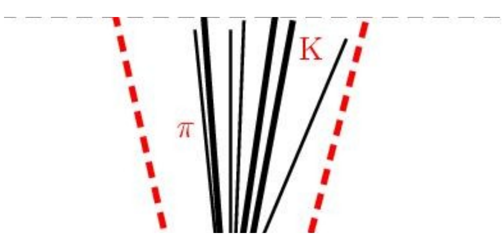
(Observed Energies)



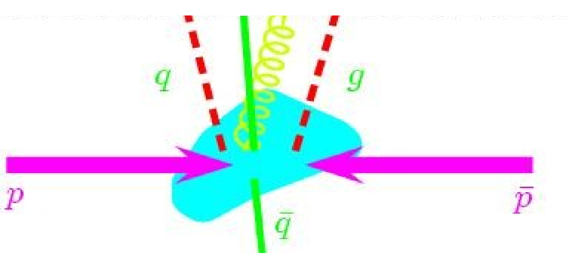
The algorithms are applied in data and (GEANT'd) MC at the detector: **Calorimeter Jets, Track Jets, Cal-Track Jets**





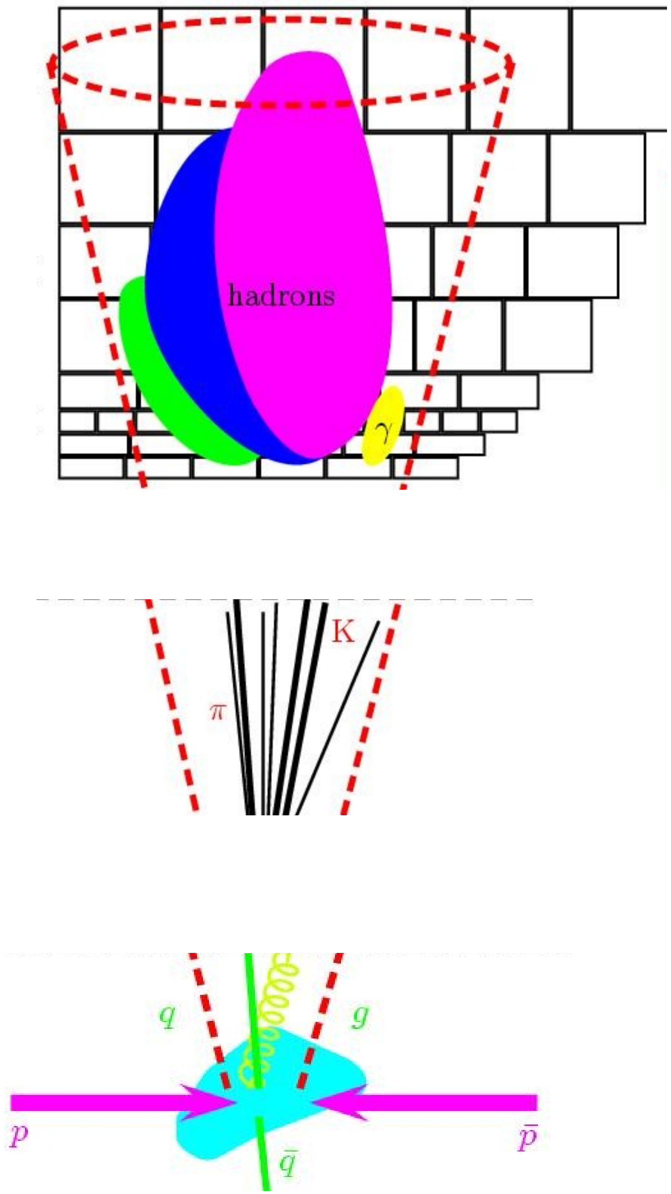


Particle-Level MC (e.g. Stable particle lists from Pythia/Herwig): **Particle Jets**



And may be applied directly to partons from the hard scatter before hadronization: **Parton Jets**

(Observed Energies)



The jet scale is a collection of a number of individual correction factors which may depend on:

- Jet properties: such as Energy, (pseudo)rapidity, longitudinal/transverse shapes (fragmentation/showering), heavy flavor tags, ...

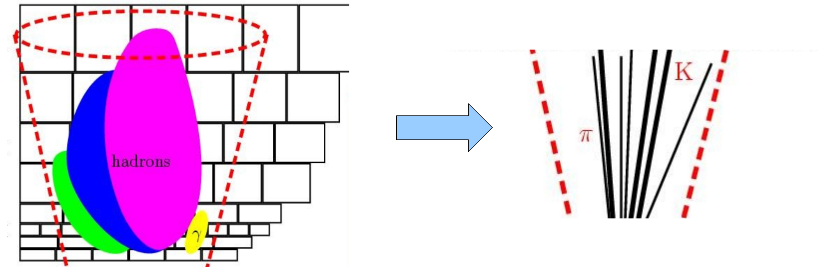
- Detector features: uniformity corrections and overall energy calibration

- Jet definitions: cone size, reconstruction thresholds, ...

- Effects of soft physics and noise: spectator and multiple hard interactions, detector noise, readout zero suppression, ...

Both CDF and DØ use similar* parameterizations in their scale corrections

To get back to the particle level



CDF:

1) Corrects observed P_T for detector non-uniformity (C_η)
2) Removes energy associated w/ additional hard scatters (C_{MI})
3) Applies absolute scale (C_{abs})

$$P_T^{ptcl} = [P_T^{jet} \times C_\eta(\Delta R, \eta, P_T) - C_{MI}(\# Vtx)] \times C_{abs}$$

DØ:

1) Removes energy associated w/ ULE, additional hard scatters/Noise (E_{offset})
2) Corrects observed E for detector non-uniformity (R_η)
3) Applies absolute scale (R_{jet})
3) Corrects for shower leakage out of / into jet cone (R_{cone})

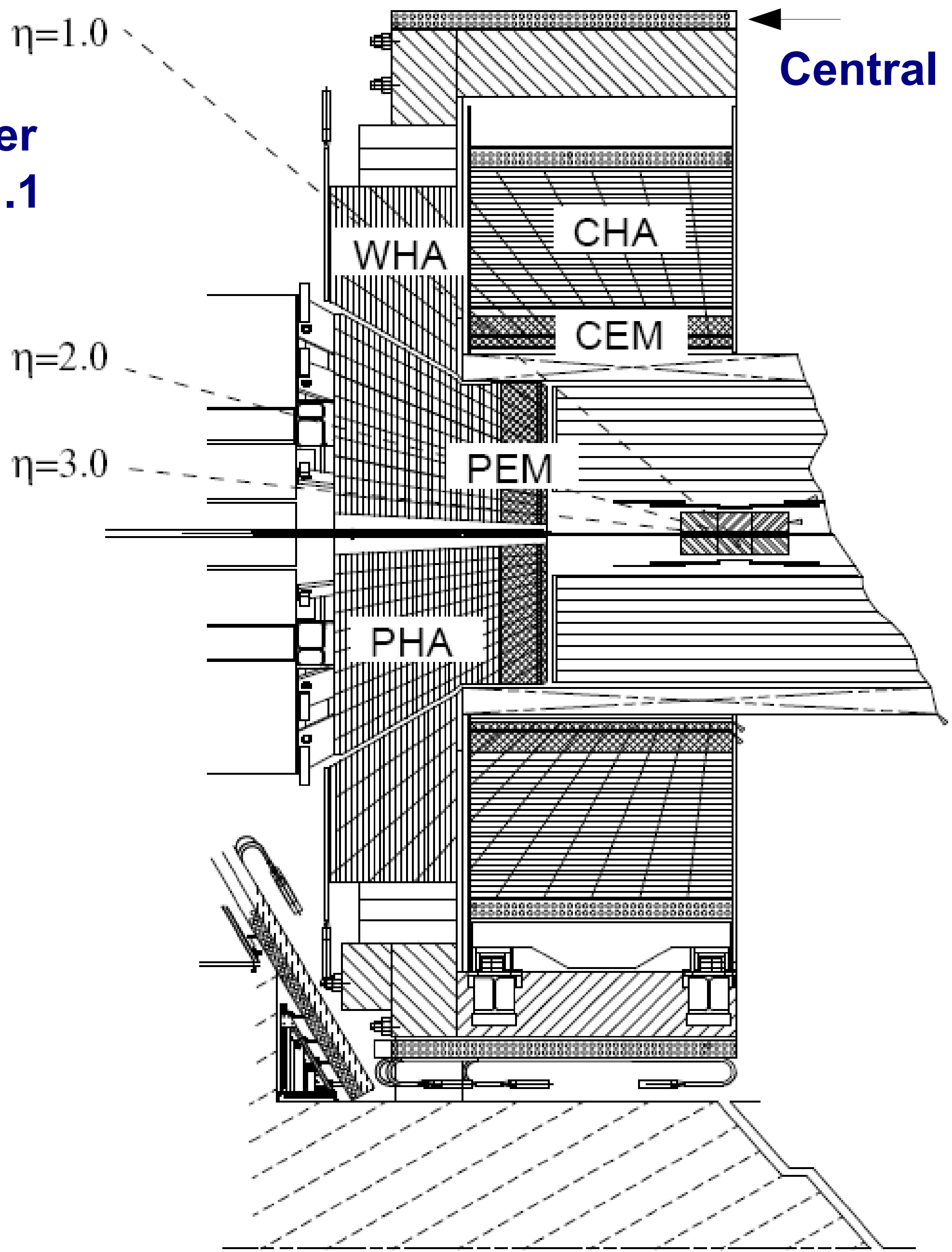
$$E_{jet}^{ptcl} = \frac{E_{jet}^{meas} - E_{Offset}(\Delta R, \# Vtx)}{R_\eta(\Delta R, E, \eta) \times R_{jet}(\Delta R, E) \times R_{cone}(\Delta R, E, \eta)}$$

*but methods are quite different

Non-uniform regions

Central gap $\eta = 0.0$

Inter-Calorimeter gap $|\eta| \sim 1.1$



CDF

Calorimetry:
- 4.5 absorption lengths
- $|\eta| < 3$

Tracking: 1.4T
- 8-lyr silicon
  $1.5\text{cm} < R < 28\text{cm}$
- 96-lyr drift chamber
  $R < 137$ cm
- coverage $|\eta| < 2$
  $|\eta| < 2.8$ (partial)

CDF Detector: NIM A387-403 (1988)
FERMILAB-PUB-96-390-E (1996)

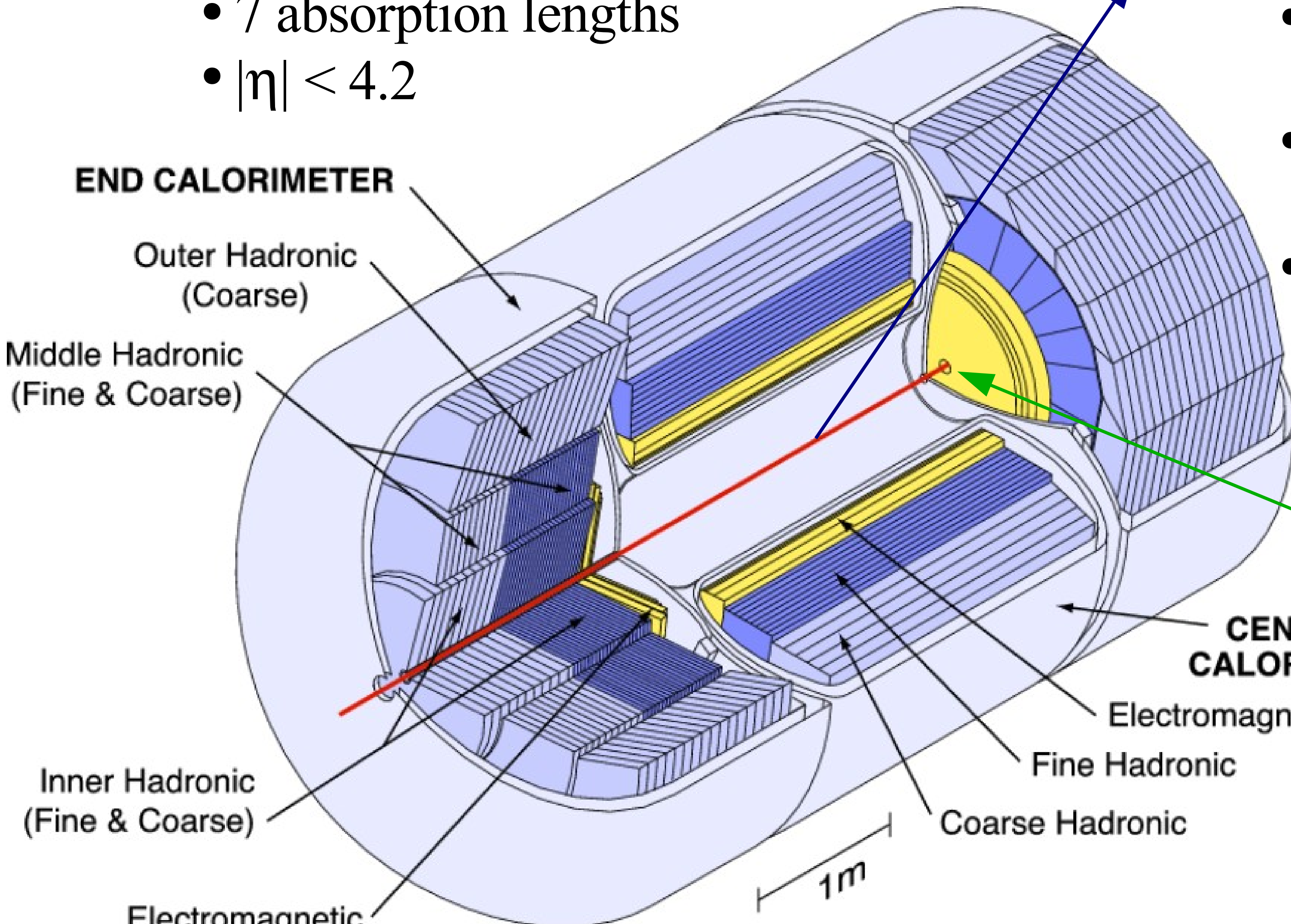
DØ

Inter-Cryostat Region (ICR) $|\eta| \sim 1.2$

Non-uniform region

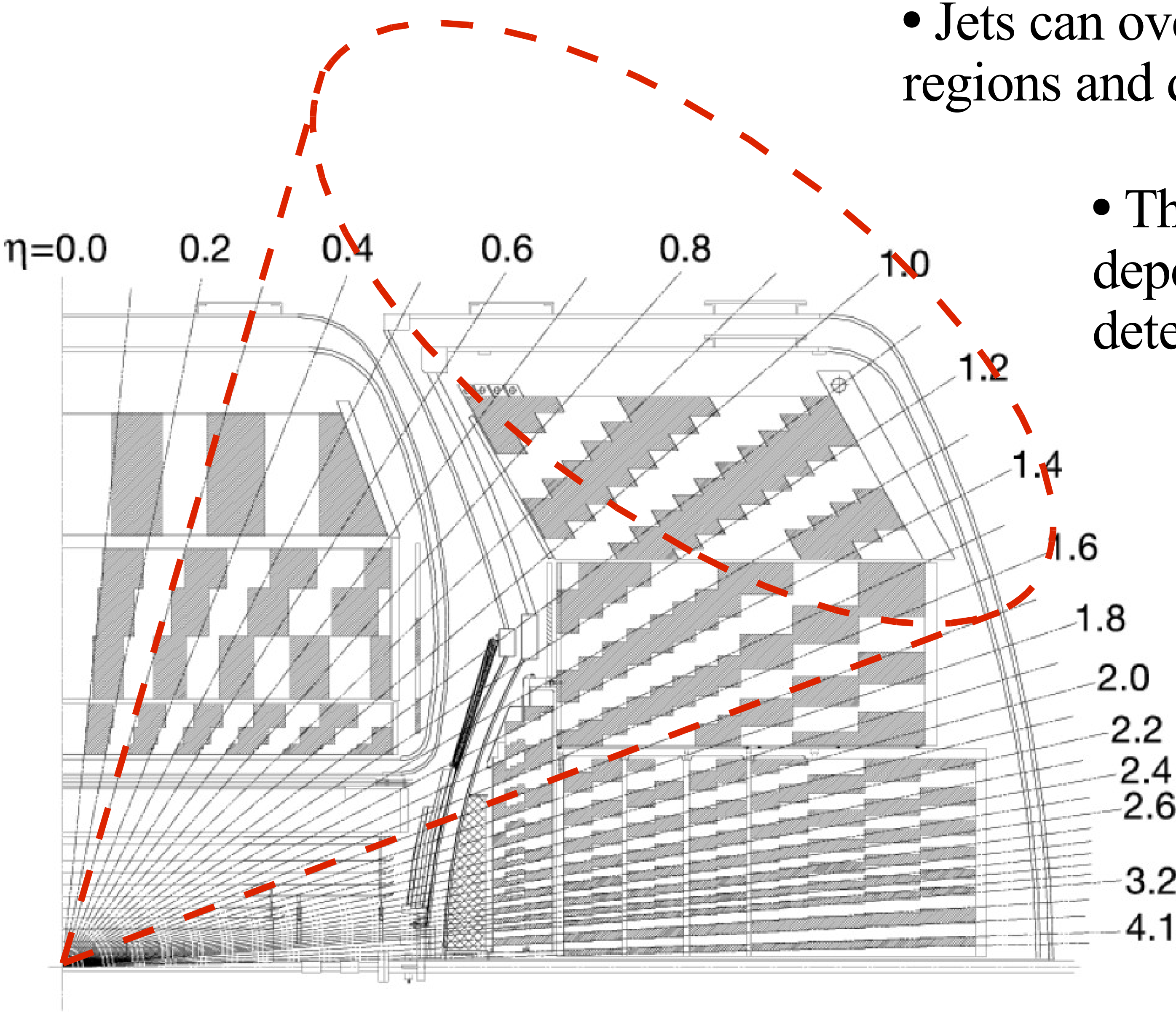
Calorimetry:
- 7 absorption lengths
- $|\eta| < 4.2$

Tracking: 2.0T
- 6-lyr silicon
  2.7cm < R < 9.4cm
- 16-lyr fiber tracker
  R < 52 cm
- coverage $|\eta| < 3.2$
  (not shown)



Location of Level0 (L0) Trigger Hodoscope Lumi. Monitor

¼ view of DØ Calorimetry with illustration of R=0.7 Cone Jet



- Jets can overlap many fiducial regions and detector technologies
- The jet scale therefore can depend on many complex detector systematics
- The mix of these effects varies w/ the location and shower development of the jet

CDF

CDF and DØ use somewhat different techniques to arrive at their absolute scale corrections for jets these will be presented separately in the following discussion.

CDF's jet scale builds on top of a parameterized shower simulation

This parameterization (GFLASH[1]) is tuned to describe the observed response of the calorimeter for *single particles*

Data sets used in the tuning include:

- Test beam data
- Minbias and *high*-P_T single track-selected data from the collider
- $J/\Psi \to ee$ & $Z \to ee$ data from the collider (to tune EM showers)

[1] N.I.M. A 290, 469 (1990)

CDF

Simulation of EM and Hadronic showers involves two steps

(1) GFLASH calculated spatial distribution of energy, E_{dp}, deposited by a shower w/in the calorimeter volume:

$$dE_{dp}(\vec{r}) = \frac{E_{dp}}{2\pi} L(z) T(r) \, \mathrm{d}z \mathrm{d}r$$

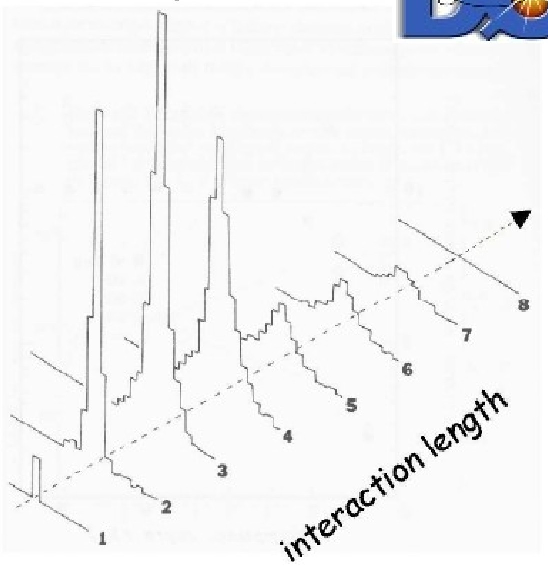
Longitudinal profile → $L(z)$ Transverse profile → $T(r)$

depends on incident particle energy, shower fluctuations, sampling structure of detector

(2) Fraction of deposited energy visible to active medium, $E_{vis}(\vec{r})$, is calculated. Depends on relative sampling fractions of MIPs, EM and Hadronic particles: S_e/S_{mip} , S_{had}/S_{mip} (tunable parameters)

CDF

Longitudinal shower profiles modeled with Γ-distribution



$$L_{em}(z) = \frac{x^{\alpha_{em}-1}e^{-x}}{\Gamma(\alpha_{em})} \qquad x = \beta_{em} z(X_0)$$

Hadronic showers classified 3-ways:

- Purely hadronic (***h***), scales w/ absorption length, λ_0
- Showers w/ π_0 produced in 1st inelastic collision (***f***)
- Showers w/ π_0 produced in later inelastic collision (***l***)

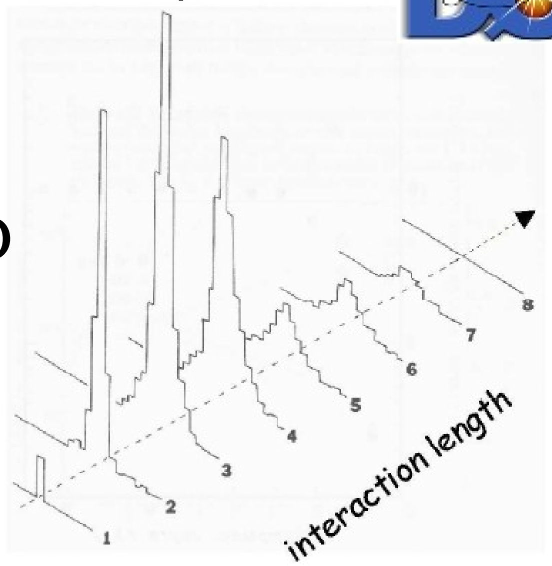
$$\mathcal{L}_{h}(x_h) = \frac{x_h^{\alpha_h-1}e^{-x_h}}{\Gamma(\alpha_h)} \qquad x_h = \beta_h z(\lambda_0)$$

$$\mathcal{L}_{f}(x_f) = \frac{x_f^{\alpha_f-1}e^{-x_f}}{\Gamma(\alpha_f)} \qquad x_f = \beta_f z(X_0)$$

$$\mathcal{L}_{l}(x_l) = \frac{x_l^{\alpha_l-1}e^{-x_l}}{\Gamma(\alpha_l)} \qquad x_l = \beta_l z(\lambda_0)$$

22 parameters total

CDF



Transverse/Lateral shower profiles for both EM and HAD particles are modeled with the Ansatz function:

$$T(r) = \frac{2rR_{50}^2}{(r^2 + R_{50}^2)^2}$$

$$\langle R_{50}(E,z)\rangle = [R_1 + (R_2 - R_3 \log E)z]^n \qquad n = 1, 2$$

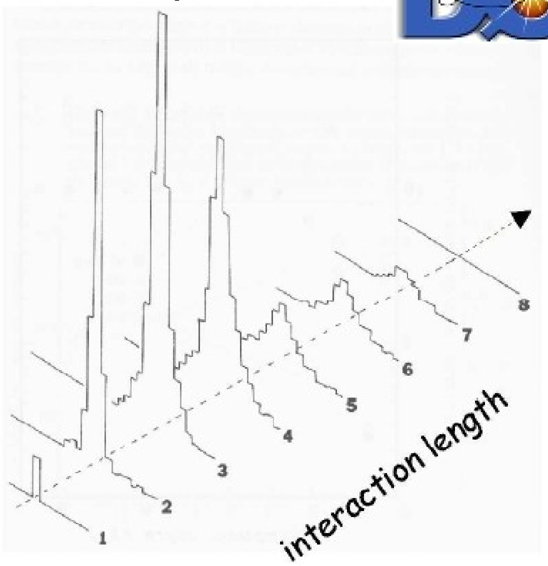
$$\sigma_{R_{50}}(E,z) = [(S_1 + (S_2 - S_3 \log E)z\langle R_0(E,z)\rangle]^2$$

R_{50} is given in units of Moliére Radius (R_M) / Absorption Length (λ_0) for EM/HAD showers respectively

The lateral spreading is taken to be linear (n=1) in HAD showers and quadratic (n=2) in EM showers.

14 parameters total

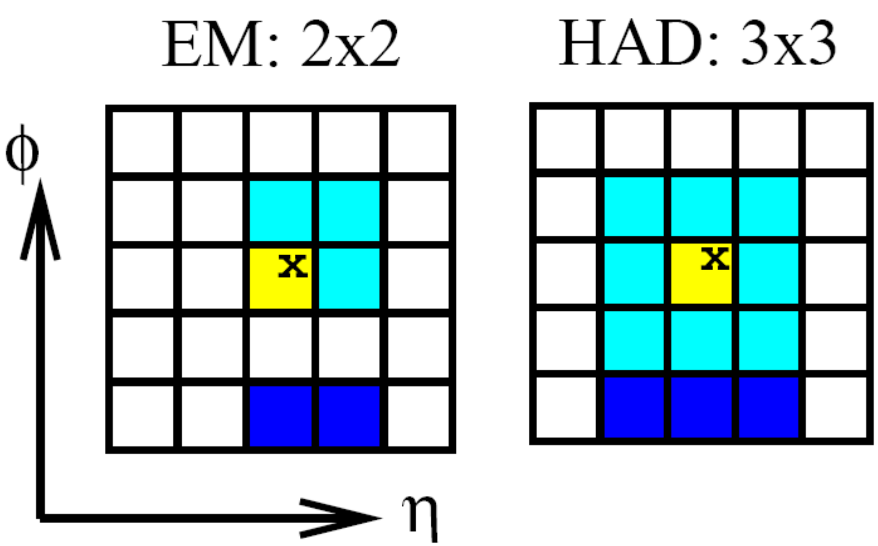
CDF



Possible 38 parameters:
11 are tuned for central calorimeter
7 are tuned for the plug (forward) calorimeter

Remaining parameters use default settings from H1 Collaboration (see GFLASH reference).

Relies on relative independence of shower profiles to particular calorimeter



Tuning in-situ w/ isolated track data

E/p measurements w/ isolated charged particles:

$$(\Delta\phi,\Delta\eta) = (30°,0.2)_{EM}, (45°,0.3)_{HAD}$$

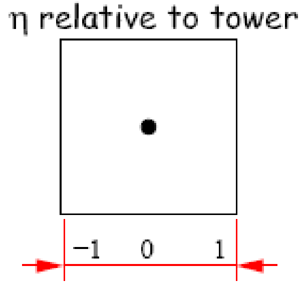
Signal Region

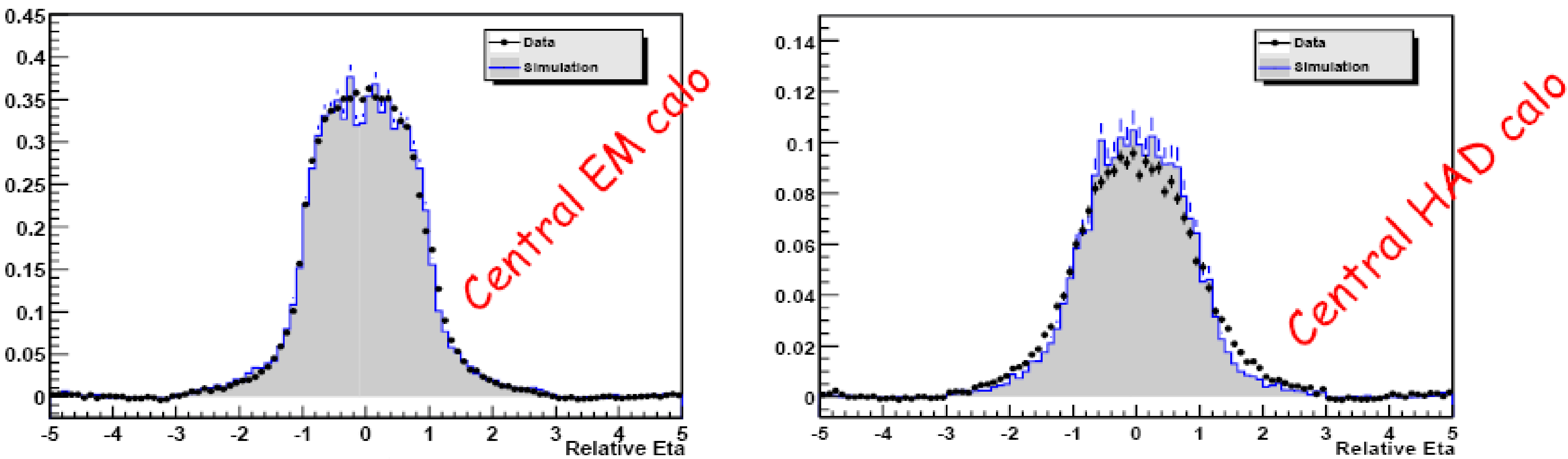
Background Region

CDF: Lateral Profiles

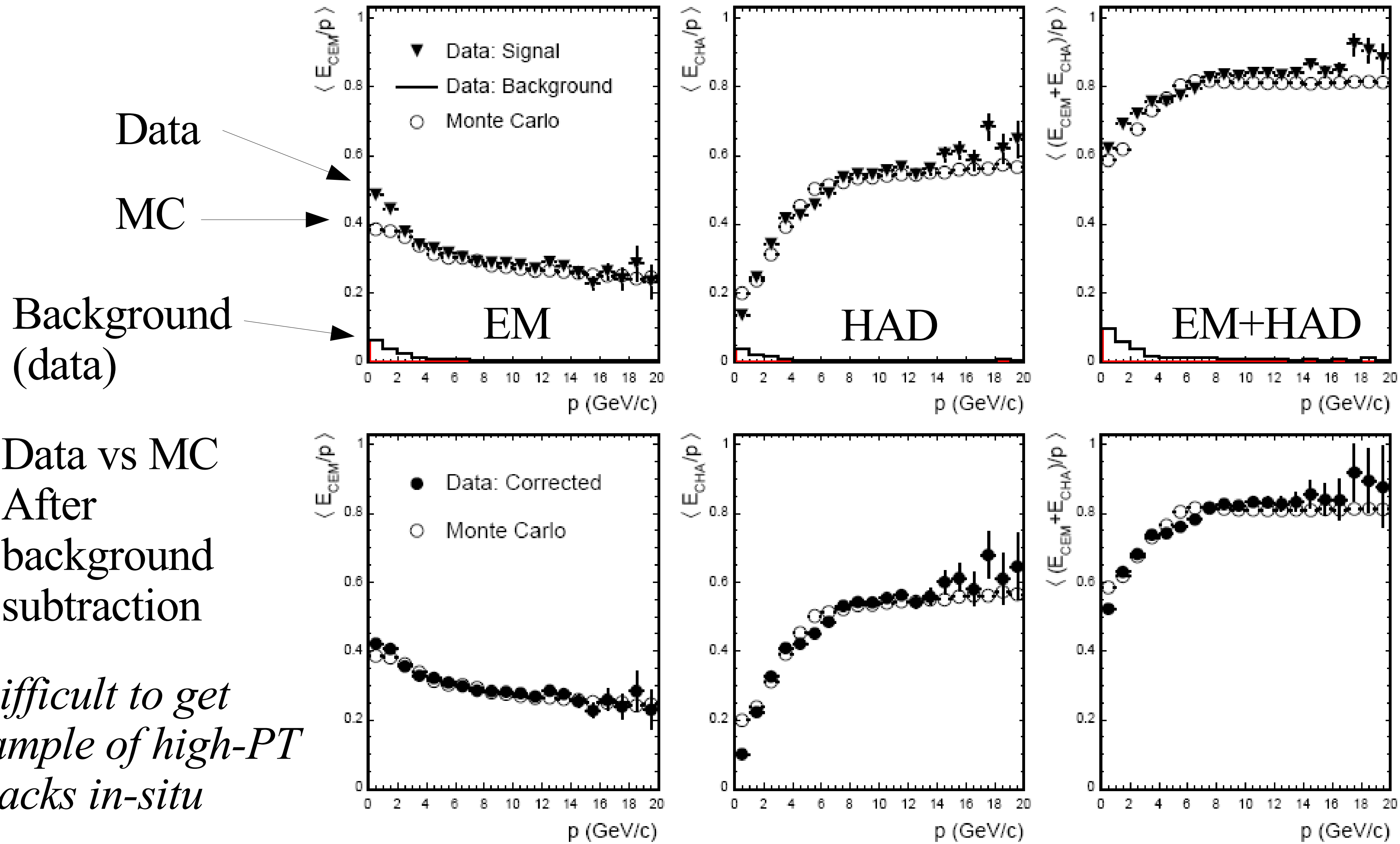
Comparison to MinBias tracks in central region: $0.5 < P_T < 2.5$ GeV/c

$$T(r) = \frac{2r R_{50}^2}{(r^2 + R_{50}^2)^2}$$





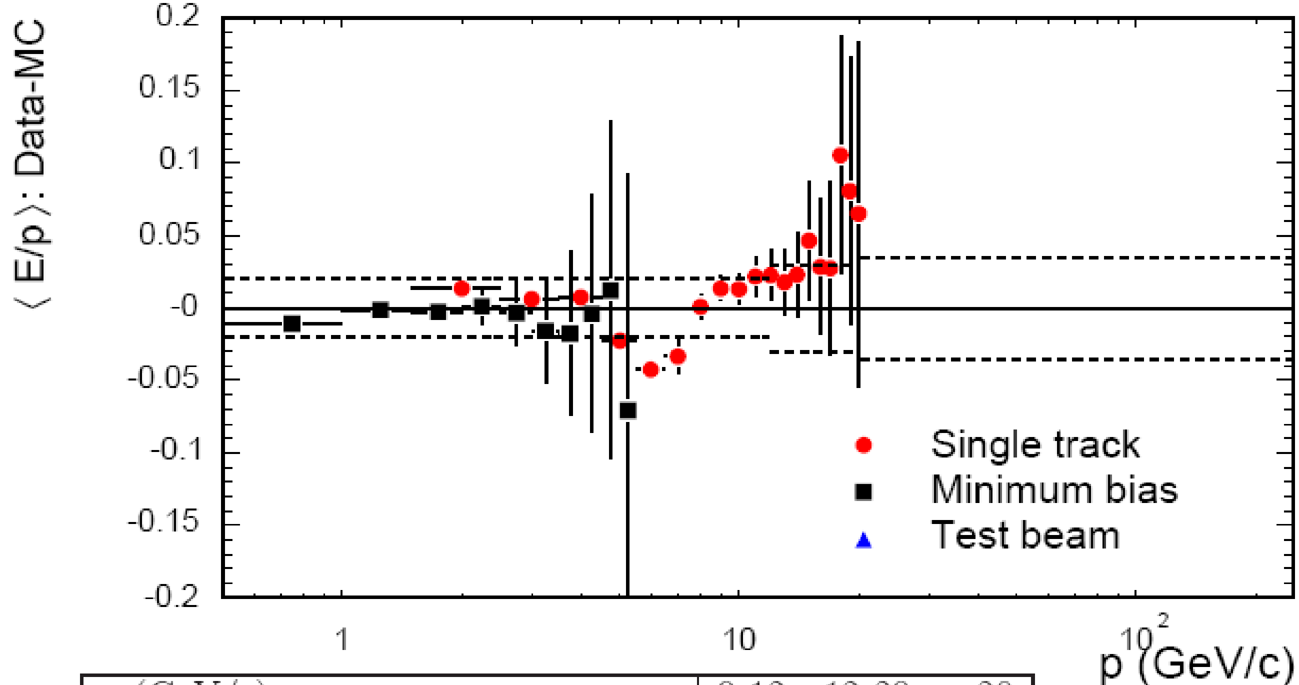
CDF: E_{obs} / p (central) 0.5<p<20 GeV/c



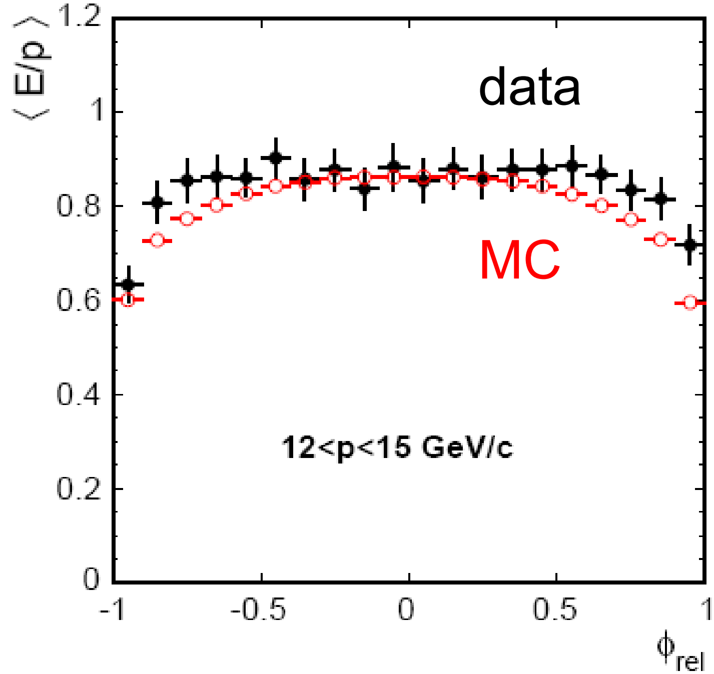
Difficult to get sample of high-PT tracks in-situ

CDF: Uncertainties in modeling of single particles

Data- MC Overall E/p agreement



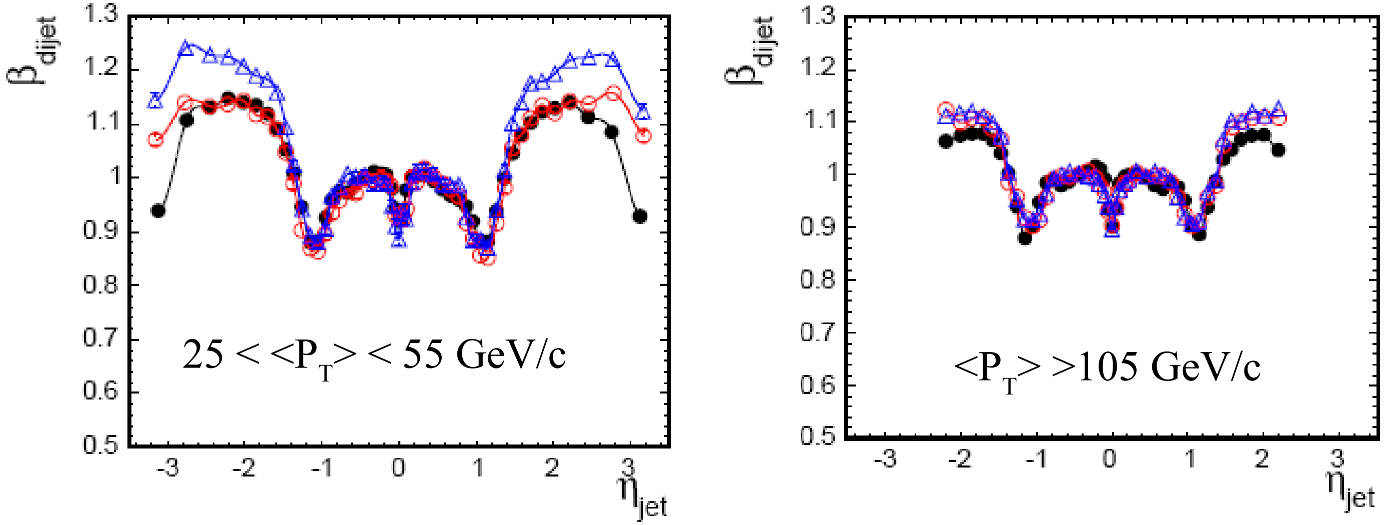
Agreement at cell boundaries



p (GeV/c)	0-12	12-20	>20
$\langle E/p \rangle$ response to hadrons			
Total tower (%)	1.5	2.5	3.5
Near tower ϕ and η-boundaries (%)	1.9	1.9	1.9
→ Total for hadrons(%)	2.5	3.0	4.0
$\langle E/p \rangle$ response to EM particles			
Total tower (%)	1.0	1.0	1.0
Near tower ϕ-boundary (%)	1.6	1.6	1.6
→ Total for EM particles(%)	1.7	1.7	1.7

Note: central calorimeter only. Due to reduced momentum resolution and MC discrepancies forward calorimetry is calibrated relative to central.

CDF: η-dependent Corrections



R_{jet}=0.7: ● Data △ Herwig ○ Pythia

Non-uniformities in η arise from separations of calorimeter components and the joining of different detector elements

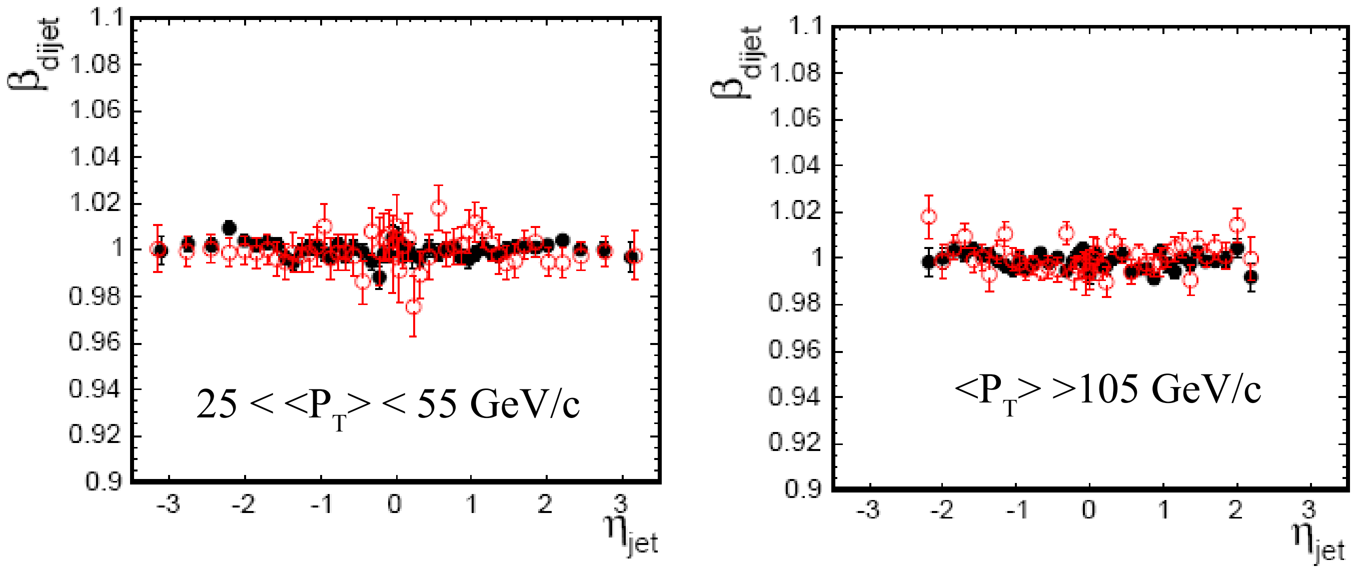
A di-jet P_T-balancing method is used w/ where a *trigger* jet is required in 0.2<η<0.6 and a probe jet is allowed to sweep through the detector

Balance Fraction

$$f_b \equiv \frac{\Delta p_T}{p_T^{ave}} = \frac{p_T^{probe} - p_T^{trigger}}{(p_T^{probe} + p_T^{trigger})/2}$$

Correction Factor $$\beta_{dijet} \equiv \frac{2 + \langle f_b \rangle}{2 - \langle f_b \rangle}$$

CDF: η-dependent Corrections



After Corrections
R=0.7

Data
Pythia

P_T-balancing also used to implicitly correct for transverse spreading of calorimeter showers outside jet cone + any η dependence of gluon radiation and multiple parton interactions

Uncertainties

$\lvert\eta\rvert$ range	0.0 – 0.2	0.2 – 0.6	0.6 – 0.9	0.9 – 1.4	1.4 – 2.0	2.0 – 2.6	2.6 – 3.6
$p_T < 12$ GeV/c	1.5 %	0.5 %	1.5 %	2.5 %	1.5 %	5.0 %	7.5 %
$12 \leq p_T < 25$ GeV/c	1.5 %	0.5 %	1.5 %	1.5 %	1.5 %	3.0 %	6 %
$25 \leq p_T < 55$ GeV/c	1.0 %	0.5 %	1.0 %	1.0 %	0.5 %	1.5 %	6 %
$p_T \geq 55$ GeV/c	0.5 %	0.5 %	0.5 %	0.5 %	0.5 %	1.5 %	6 %

CDF: Absolute Scale

After the response is made uniform in η, an absolute scale is applied to transform the jet energy to correspond to the underlying particle jet

The absolute scale is based on the most probable observed jet transverse momentum, P_T^{jet}, given a particle jet w/ fixed value $P_T^{particle}$

The probability density $d\mathcal{P}(P_T^{particle}, P_T^{jet})$ is parameterized as:

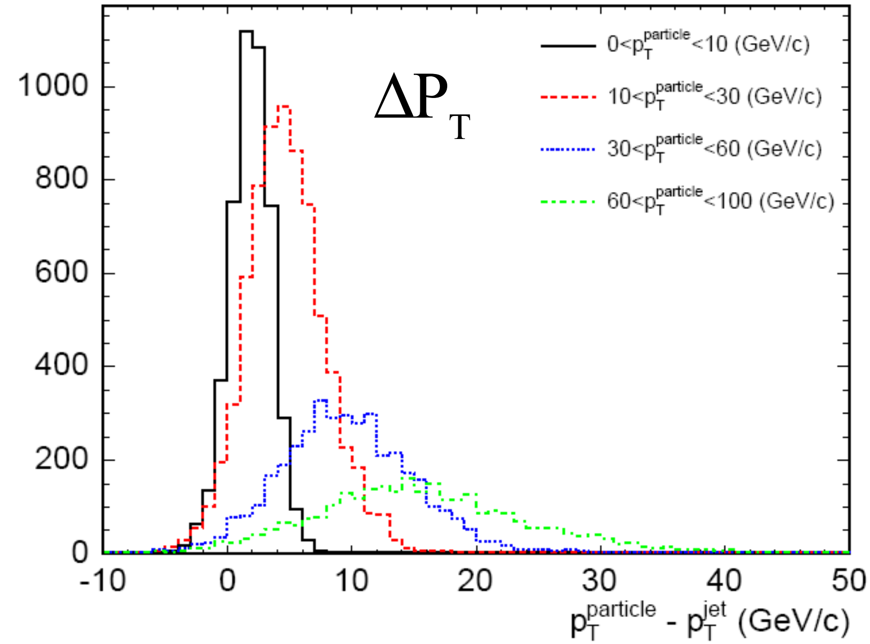
$$d\mathcal{P}(p_T^{particle}, p_T^{jet}) = f(\Delta p_T)dp_T^{particle}dp_T^{jet}$$

$$f(\Delta p_T) = \frac{1}{\sqrt{2\pi}(\sigma_1 + N_2\sigma_2)}[e^{-\frac{1}{2}(\frac{(\Delta p_T - \mu_1)}{\sigma_1})^2} + N_2 e^{-\frac{1}{2}(\frac{\Delta p_T - \mu_2}{\sigma_2})^2}]$$

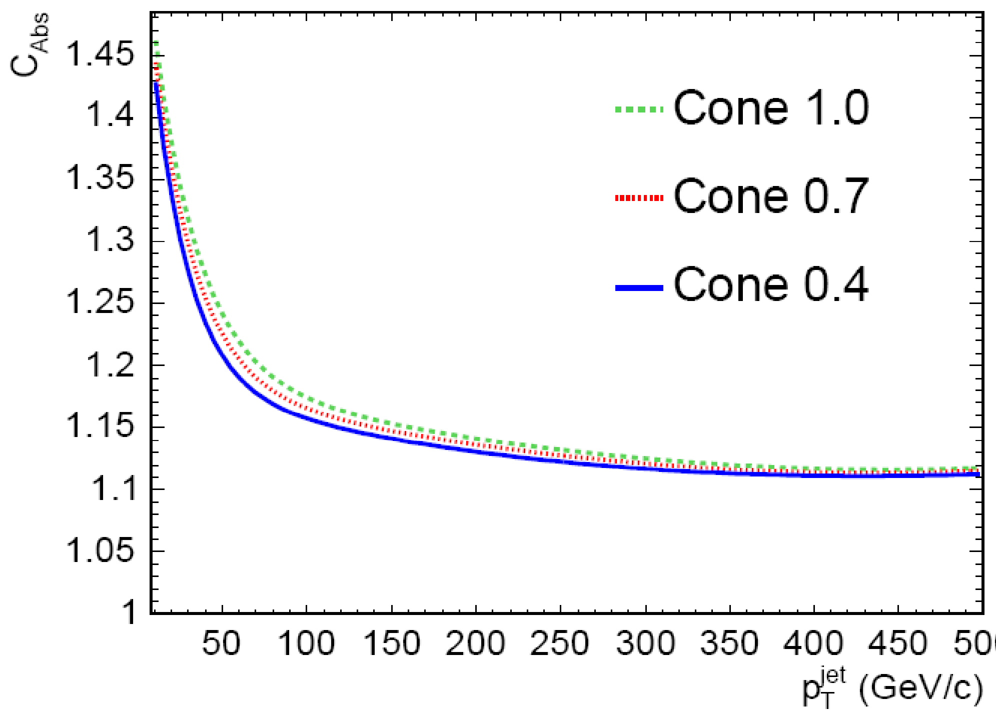
Where $\Delta P_T = (P_t^{particle} - P_T^{jet})$ and the remaining parameters are used to model a double Gaussian function representing a *core* response and *tails*

CDF: Absolute Scale

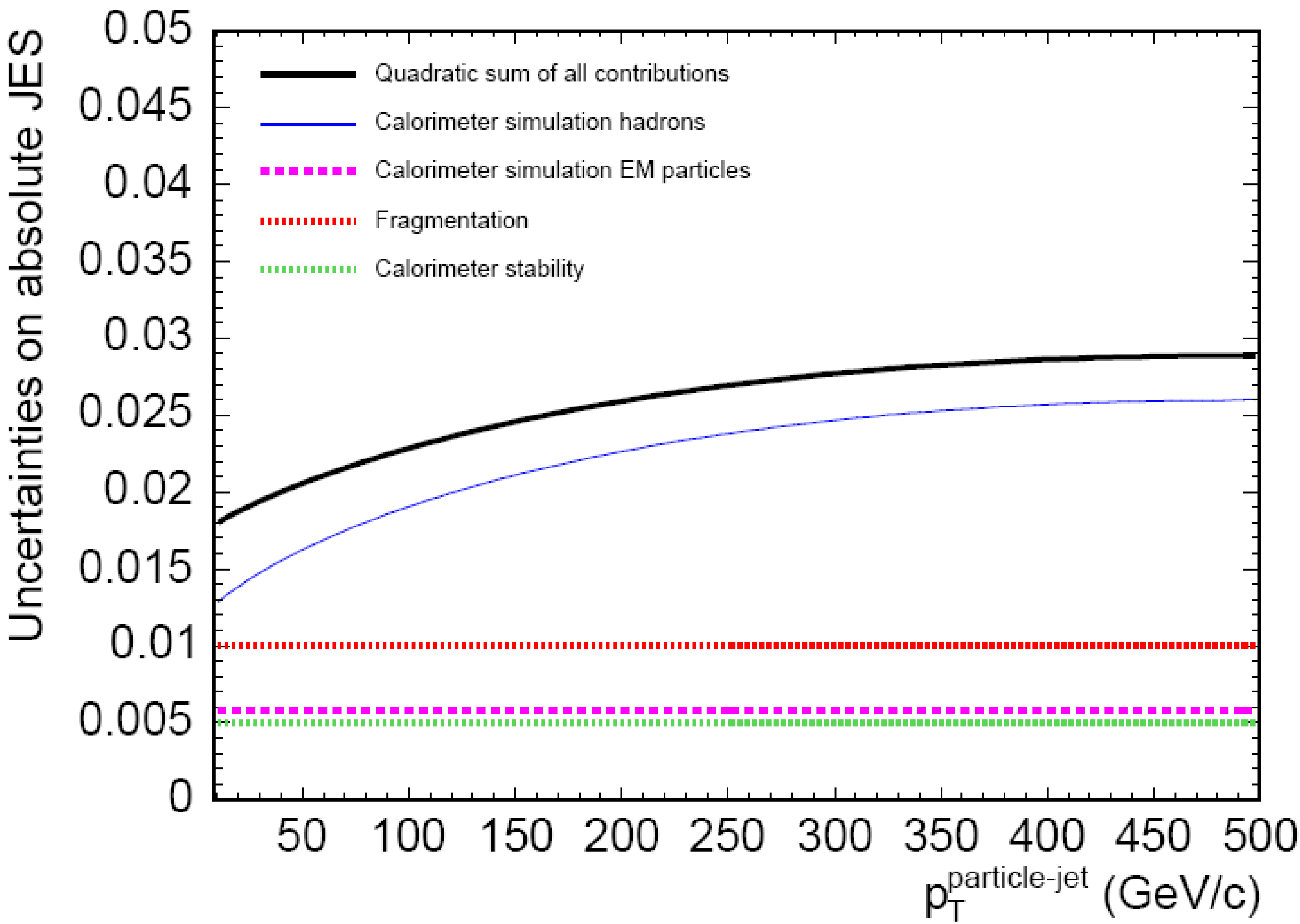
An unbinned likelihood fit is used to extract the response parameters using di-jet events generated in PYTHIA and reconstructed in the CDF calorimeter after detector simulation



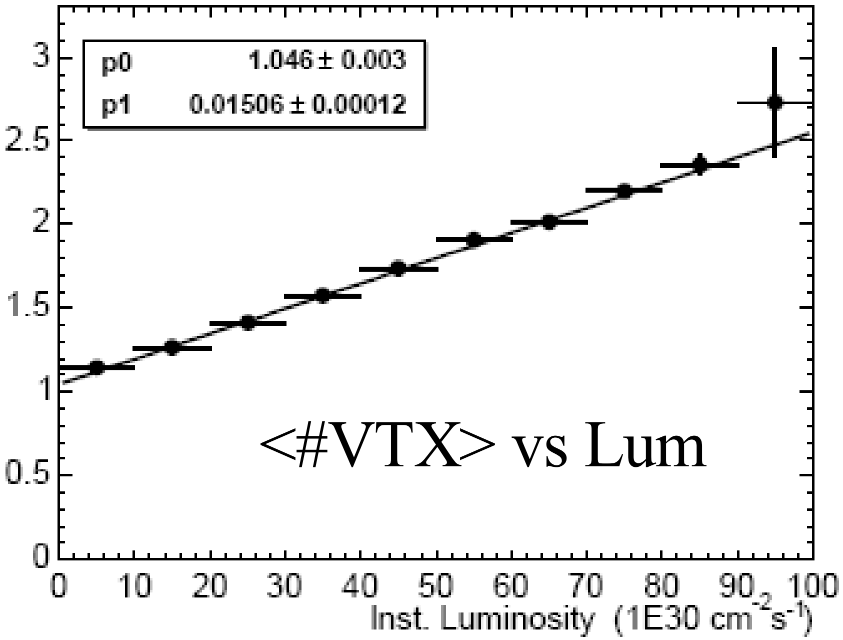
The resulting response is a convolution of the single particle response and the P_T spectrum of particles within a jet



CDF: Summary of absolute scale uncertainties

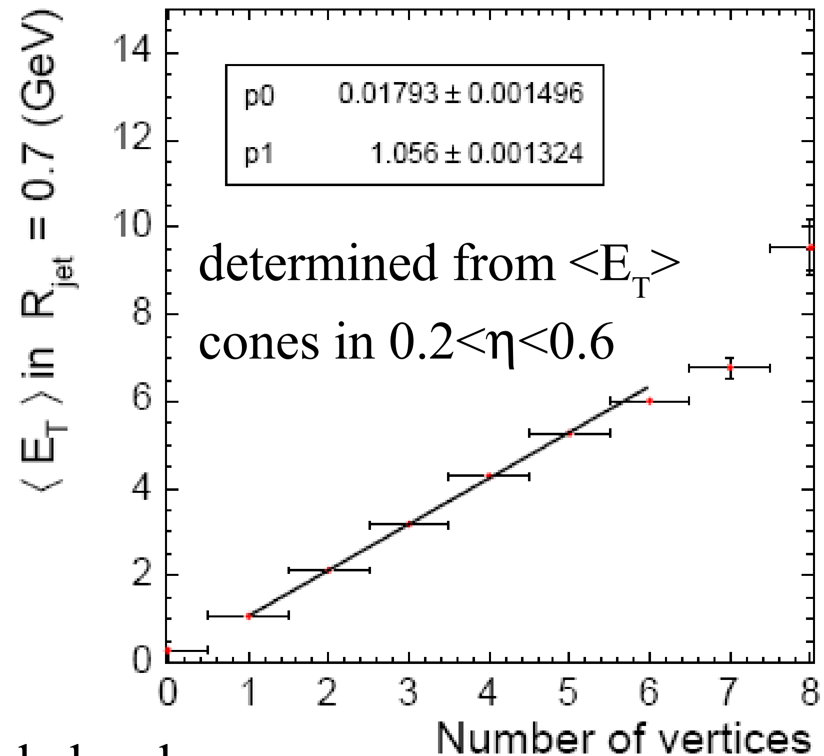


CDF: Multiple PPbar interactions



The probability for multiple PPbar collisions to occur increases linearly with luminosity, thus increasing the overall energy density observed in the detector

Average energy in a cone determined in MinBias data is used to derive correction for multiple PPbar interactions as a function of the number of reconstructed verticies



After this point, jet energies are corresponding to particle level

DØ Scale corrections

DØ relies as much as possible on in-situ techniques to determine the jet scale corrections

- Tower *inter-calibrations* are verified/corrected w/ a variety of data sets: Z, J/Ψ, MinBias, various specially trigger'd calorimeter data

- The overall calorimeter EM scale is fixed by $Z \rightarrow ee$ decays

- Photon scale is adjusted to account for e/γ showering differences from material in front of calorimeter

- Hadronic/Jet Scale is set relative to corrected photon response

DØ Scale corrections are applied as follows

(1) An offset correction removes additional energy w/in the jet associated with: multiple interactions, underlying (spectator) event, electronic/uranium noise, and pileup from previous bunch crossings

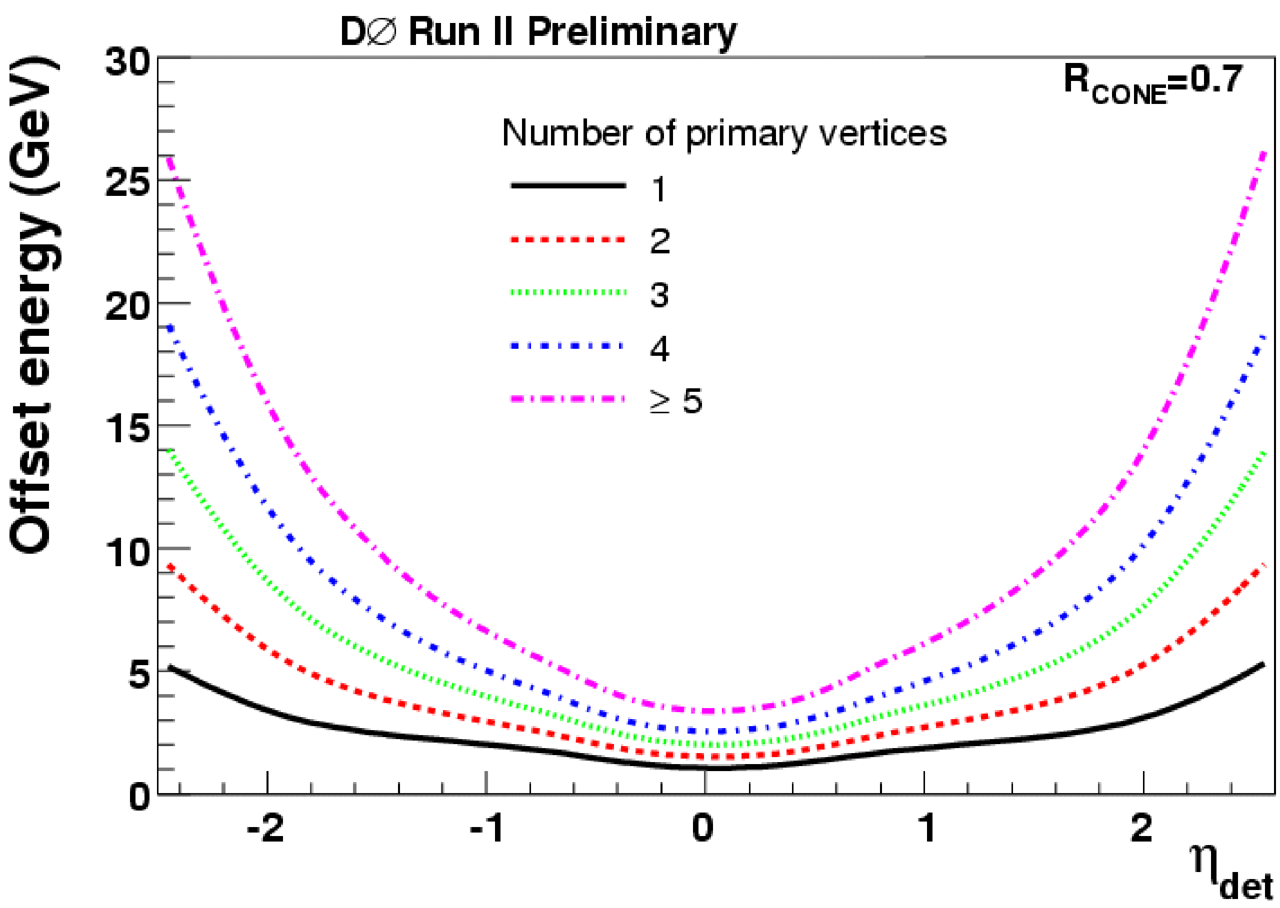
(2) An η-dependent correction corrects the relative response in η

(3) An absolute response correction brings the energy in the jet to coincide w/ the particle level energy

(4) A showering correction corrects for energy at the particle level that may leak into/out of the calorimeter jet

$$E_{jet}^{ptcl} = \frac{\overbrace{E_{jet}^{meas} - E_{Offset}(\Delta R, \#Vtx)}^{(1)}}{\underbrace{R_{\eta}(\Delta R, E, \eta)}_{(2)} \times \underbrace{R_{jet}(\Delta R, E)}_{(3)} \times \underbrace{R_{cone}(\Delta R, E, \eta)}_{(4)}}$$

DØ Offset correction



The DØ offset correction is determined from:

- ZeroBias Events (w/ no hard interaction tag at L0)
- MinBias events only requiring a L0 tag

Used to separate noise/zero sup. effects from soft underlying event contrib.

The correction is then parameterized in terms of BOTH number of reconstructed verticies and η for each jet cone size

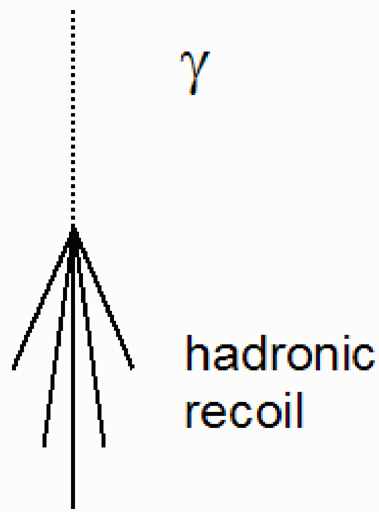
DØ Missing ET Projection Fraction (MPF)

The hadronic response of the DØ calorimetry is measured relative to the photon response using the MPF method in γ+jet events.

The MPF represents the missing E_T projected onto the photon direction

- Does not depend directly on jet algo
- Can be defined even if no jet is reconstructed

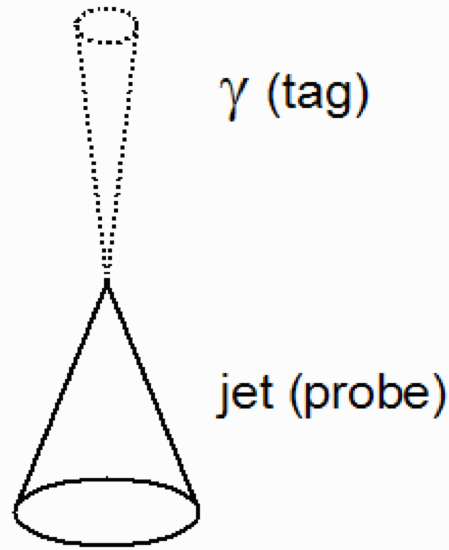
Particle Level



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

Response of hadronic recoil

Detector Level



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

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

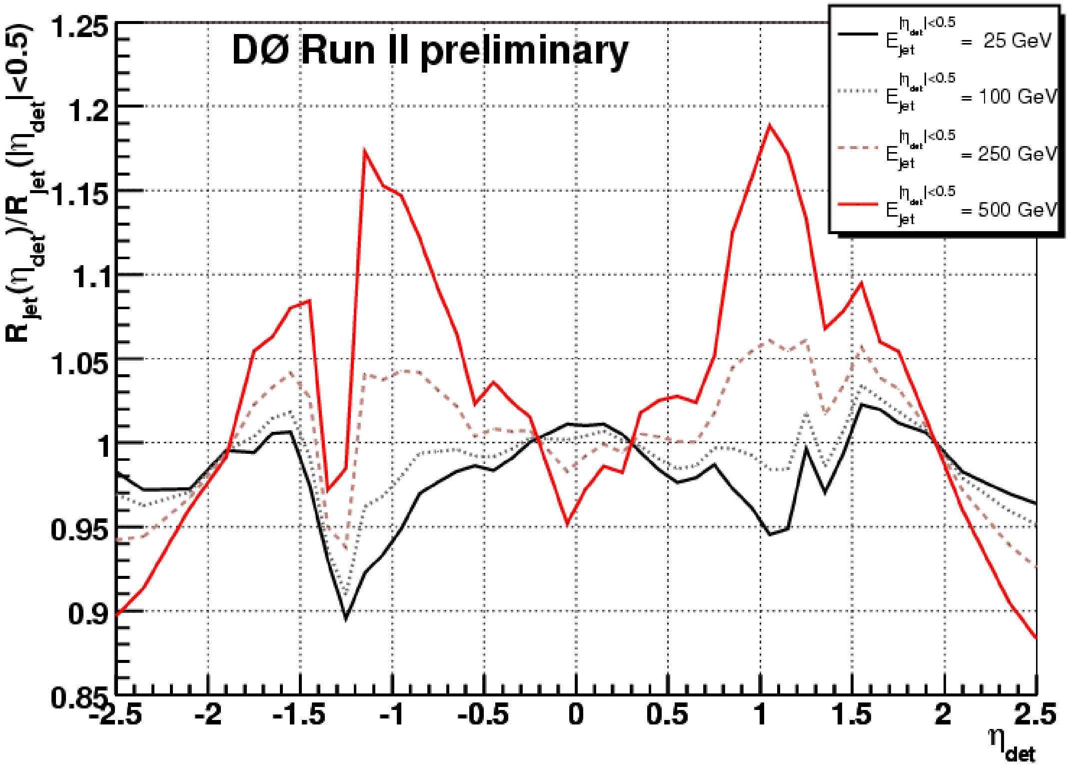
For back-to-back events: $R_{jet} \approx R_{had}$

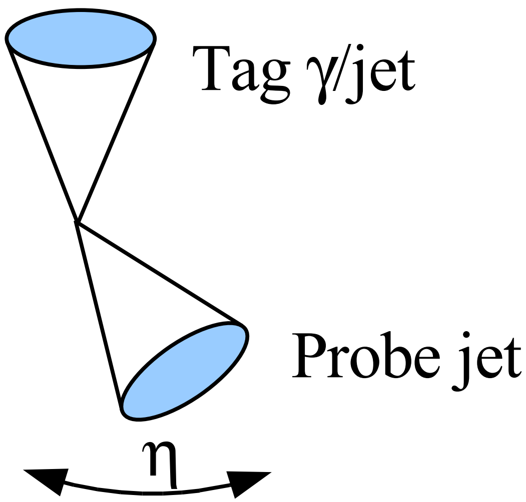
DØ MPF and η-dependence

MPF may also be applied to di-jet events to determine relative response (after correction for resolution-bias effects due to **E**-dependent jet resolutions)

A combination of γ+jet and di-jet data are used to determine η-dependent corrections relative to central calorimeter

Detector effects also separated from expected **E**-dependent jet response effects

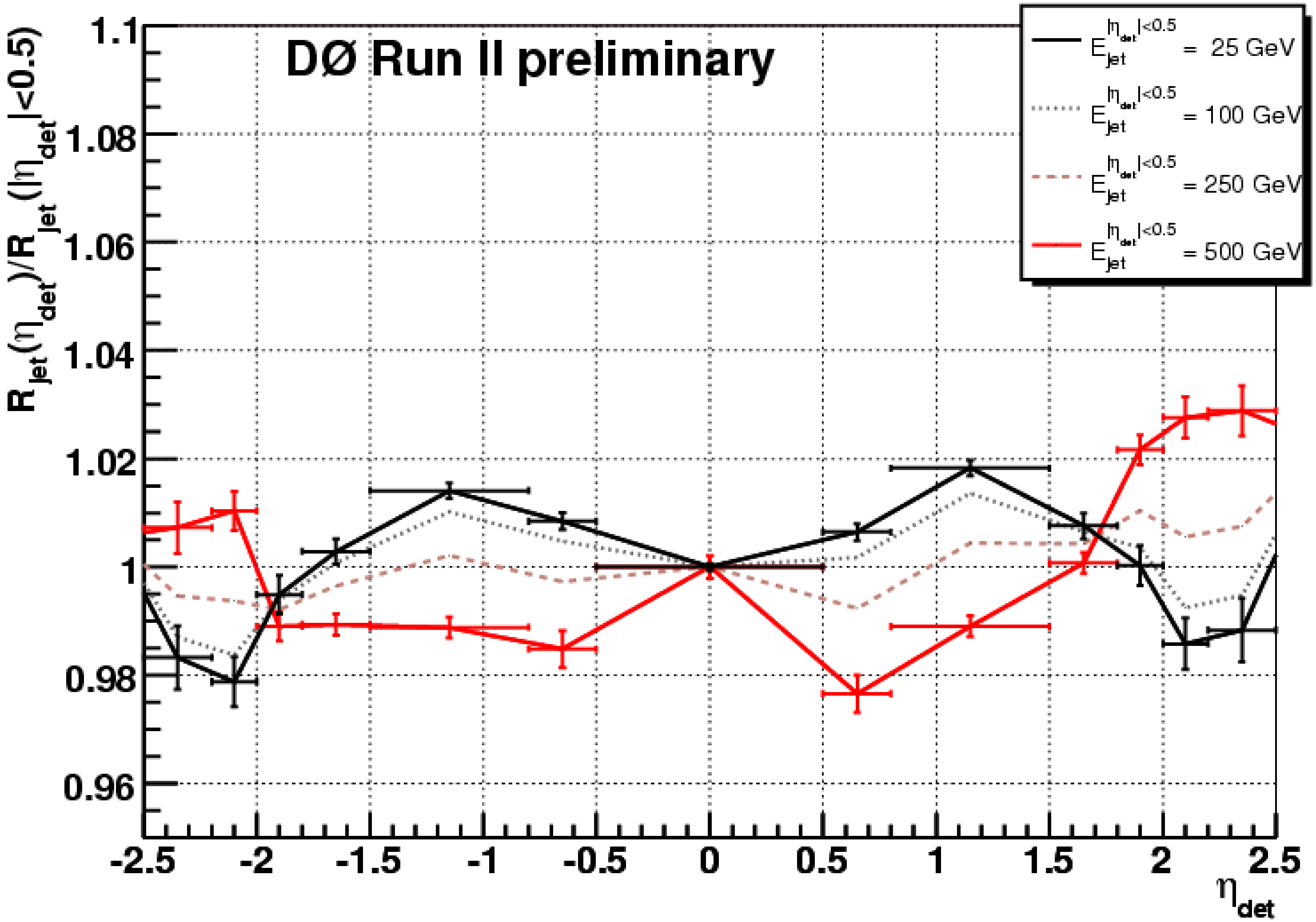




η-dependent corrections are parameterized wrt:
Energy, η, Cone Size

DØ Relative response after η-dep. correction

Typical closure to w/in <~2%



DØ Absolute Response

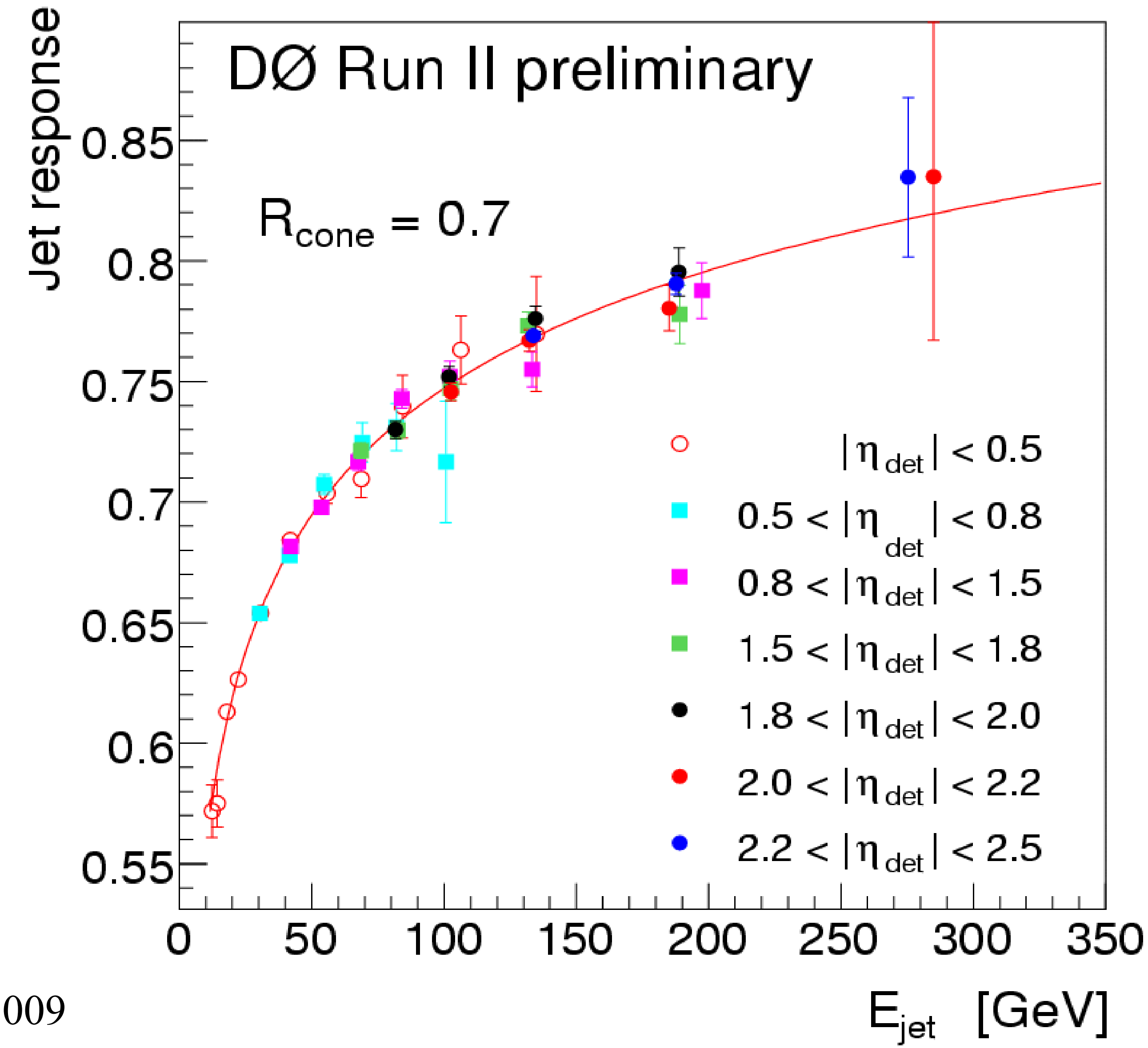
Next the absolute response correction can be determined in γ+jet data using a large fiducial region of the detector

Not covered here:

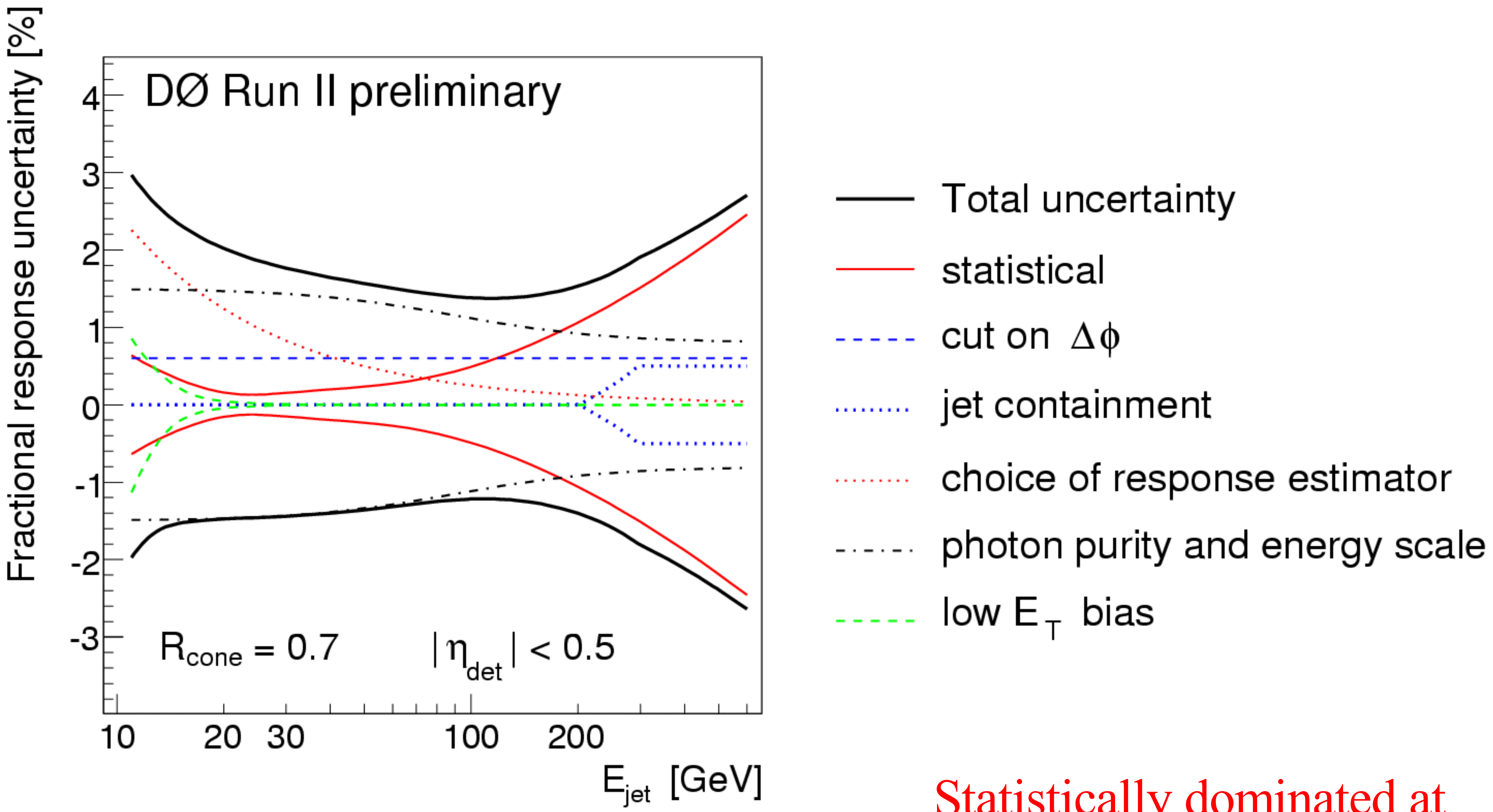
- E' parameterization to reduce resolution bias in response determination

- Low E_T-bias correction for jets near reconstruction threshold

For more info see:
NIM A424, 352 (1999), hep-ex/9805009



DØ Absolute Response: Uncertainties

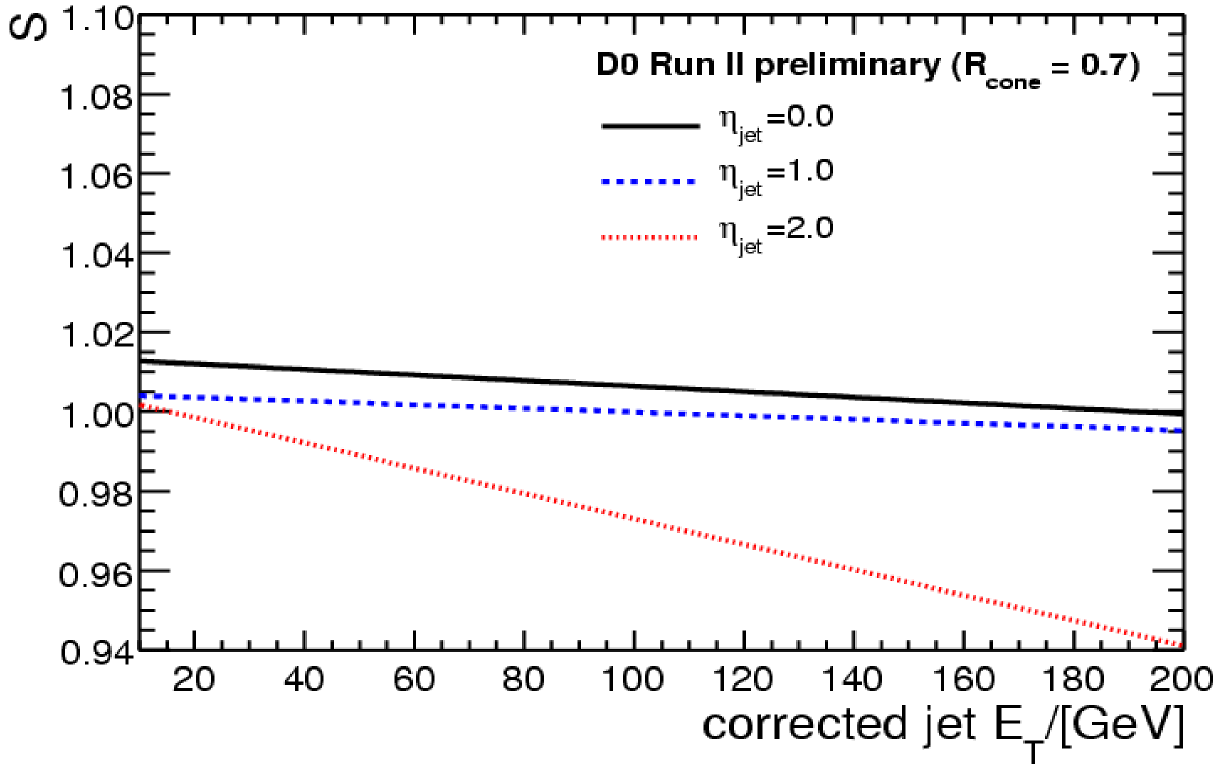


Statistically dominated at large energies

DØ Showering Correction

Finally we correct for *instrumental effects* of E-losses from cone via showering.

- Not a correction for *physics showering* (e.g. hard gluon radiation)
- Particles adjacent to the jet may also shower into the cone



The showering correction is determined in data by studying jet energy density profiles as a function of radial distance from the jet axis.

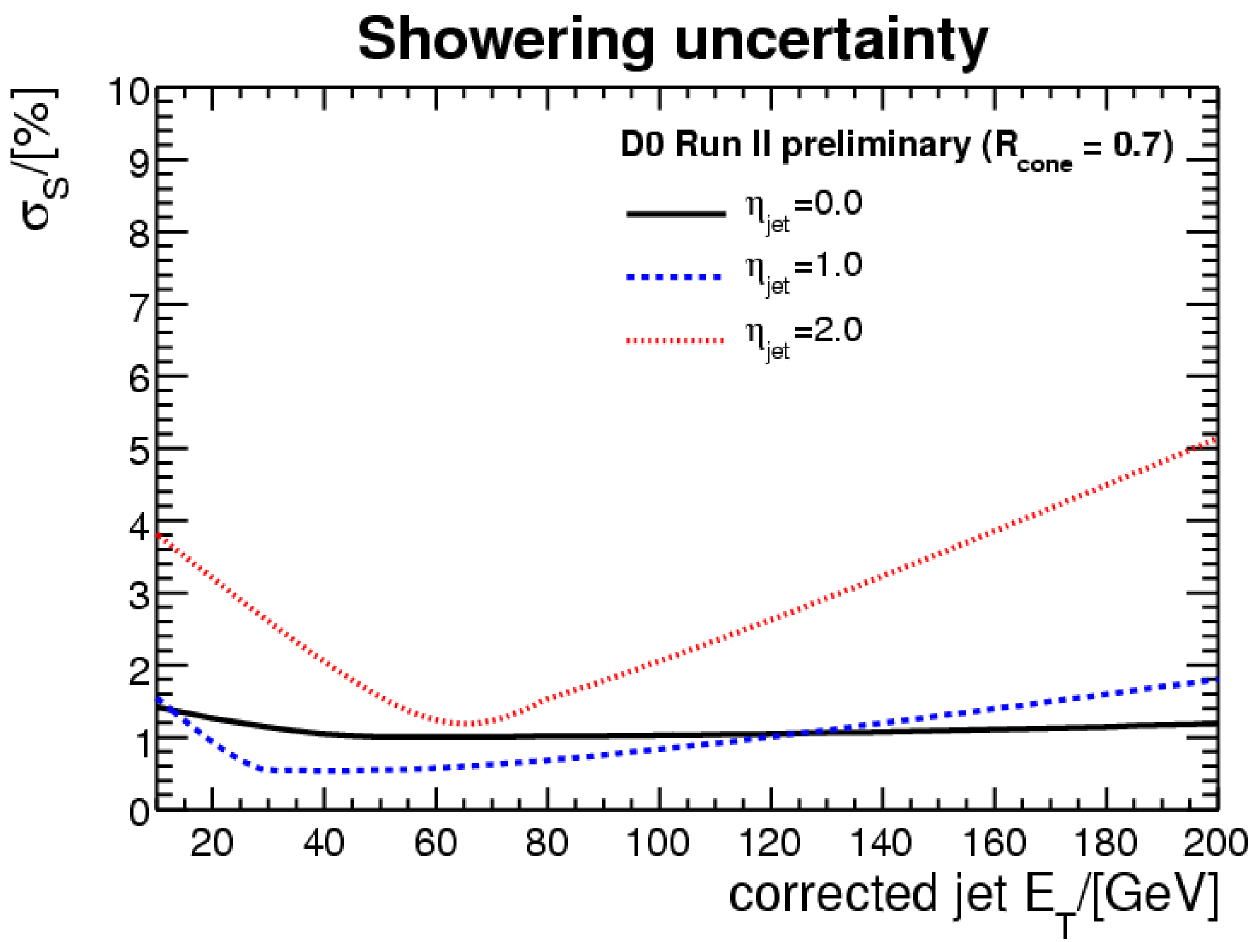
After correcting for baseline energy (E_{offset}), data are compared to MC model (PYTHIA) to separate energy lying adjacent to the cone through detector showering from physics-showering (particles w/ trajectories outside jet cone)

DØ Showering Correction: Uncertainty

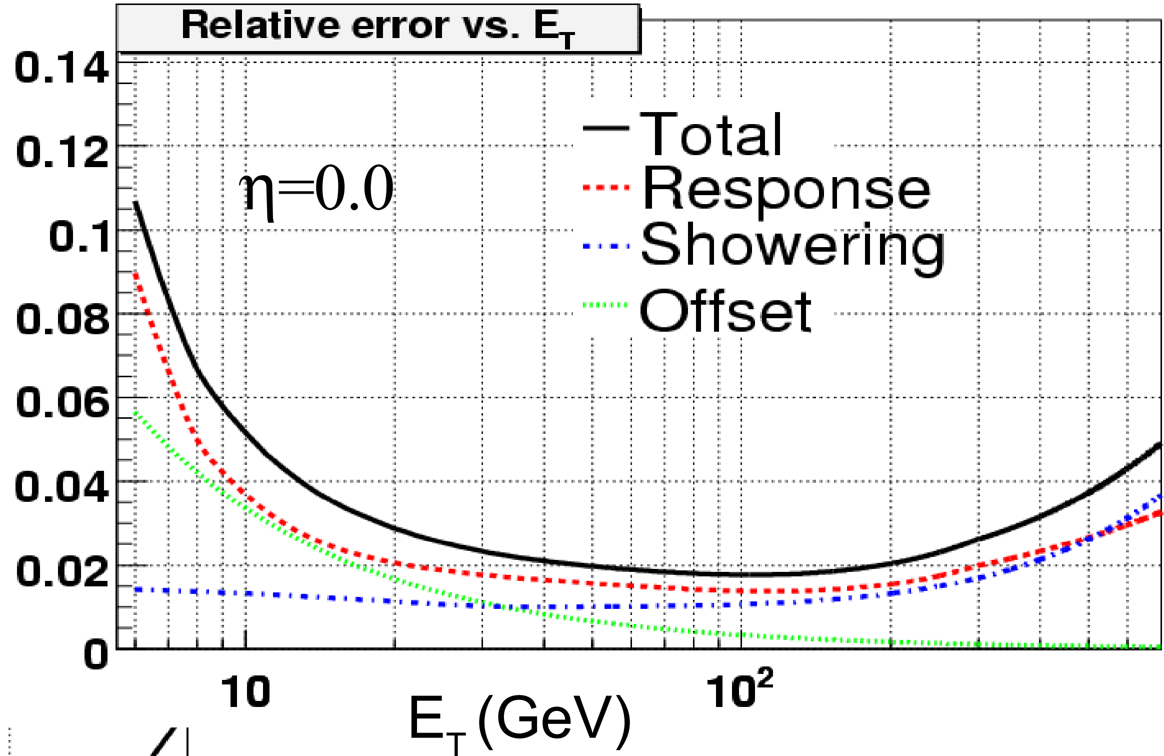
Most MC-dependent aspect of DØ jet scale, uncertainties dominated by:

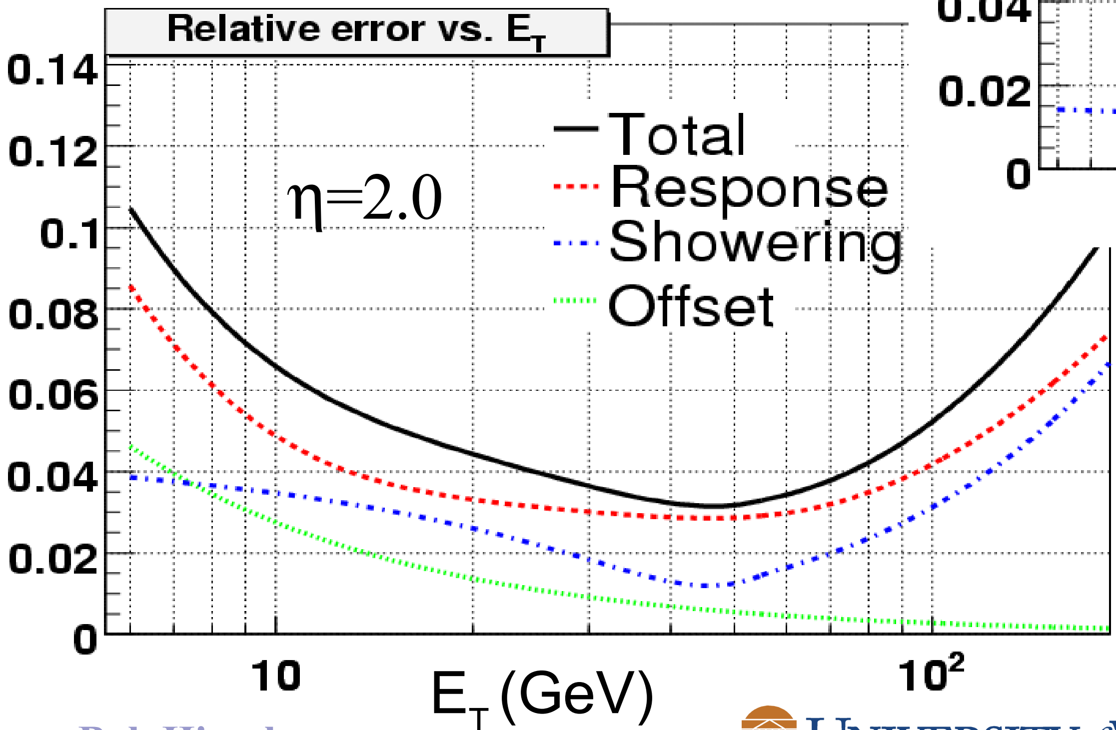
- Limits applied in studying jet energy profiles

- Uncertainties related to high E_T extrapolations, particularly in the forward region, due to limited statistics

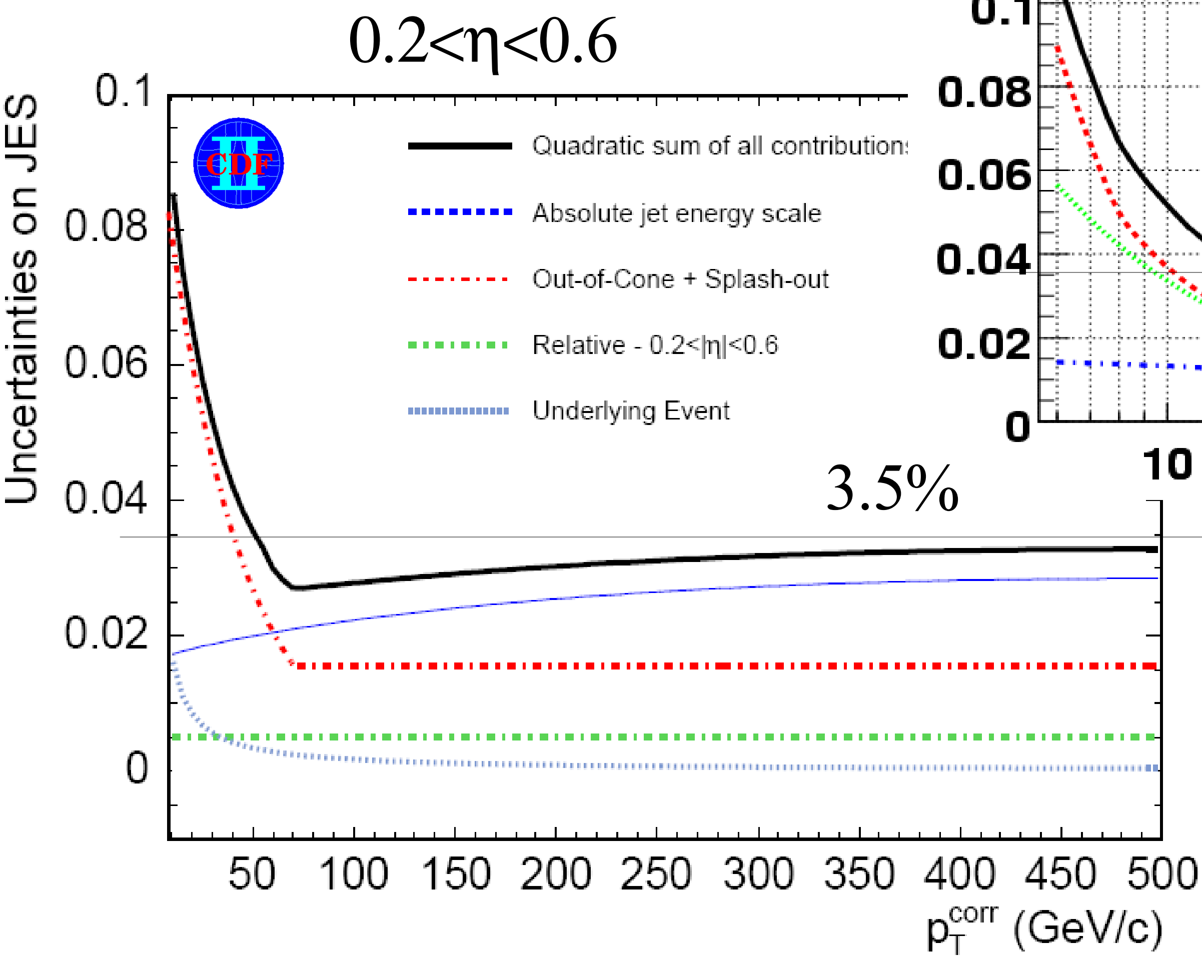


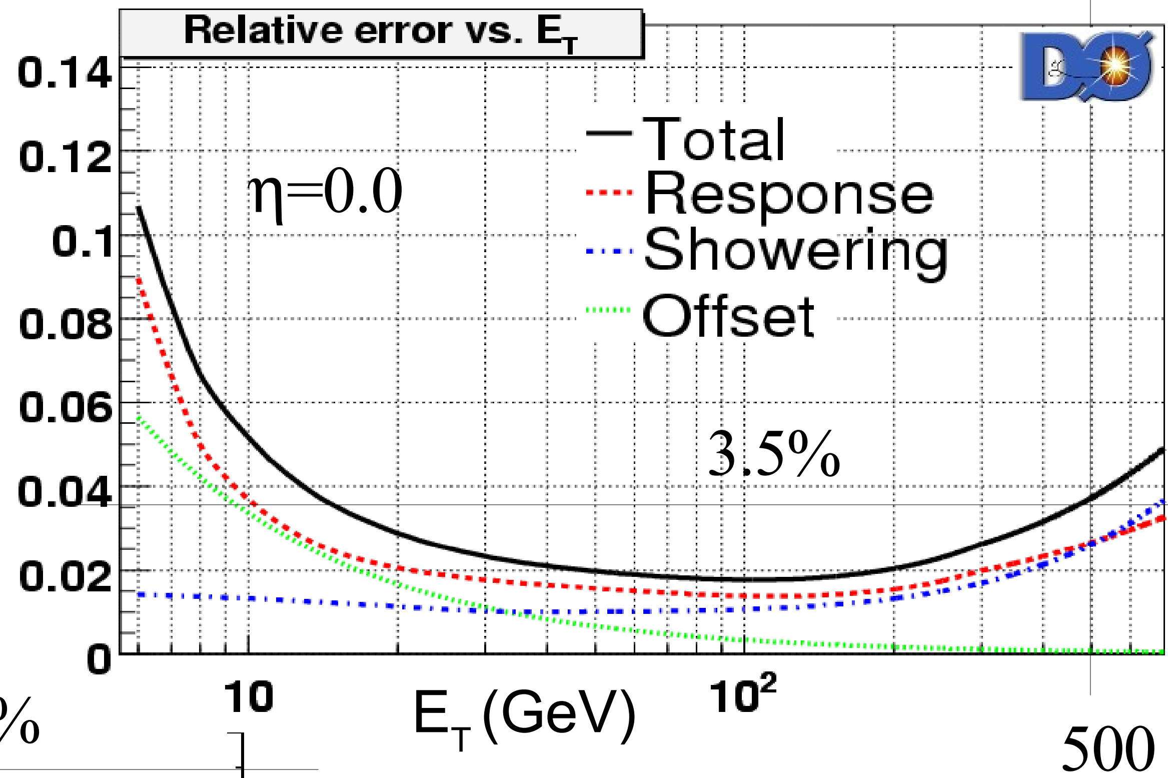
DØ Summary of Jet Scale Uncertainties vs E_T





Comparison of uncertainties for central Jets





Not quite ideal comparison CDF's OOC correction, includes additional systematics of correcting back to parton level...

Where do we go from here?

The analyses shown have thus far used only a subset of available RunII data:

CDF ~ 350 pb-1 DØ ~ 150pb-1

At present each experiment has ~1fb-1 of data, the full analysis of which offers a number of improvements:

CDF:
- Allows further tuning of single particle response
- May allow better understanding of FWD calo., now excluded from abs. scale determination

DØ:
Improve statistically limited measures:
- γ-jet scale at highest energies
- High E_T extrapolation of showering

Both:

Overall improvements in data-dominated uncertainties (η-dependence, etc)
Improvements in cross-check techniques (W/Z+jets, W→jj in ttbar, etc.)

Conclusion

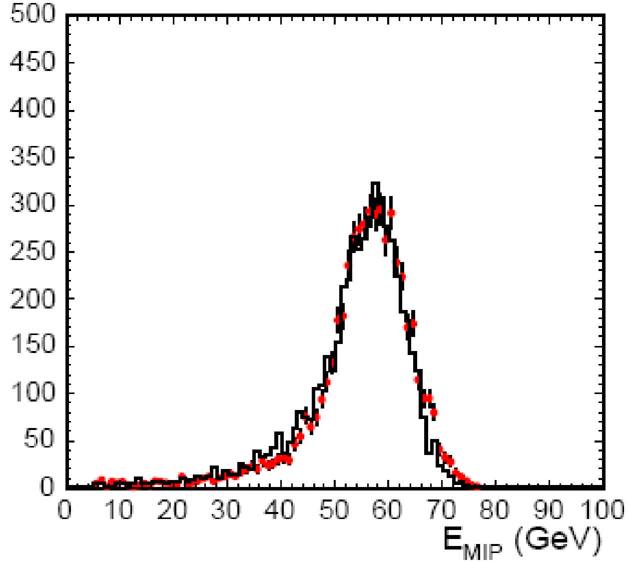
Run II systematics are already comparable to those in Run I.

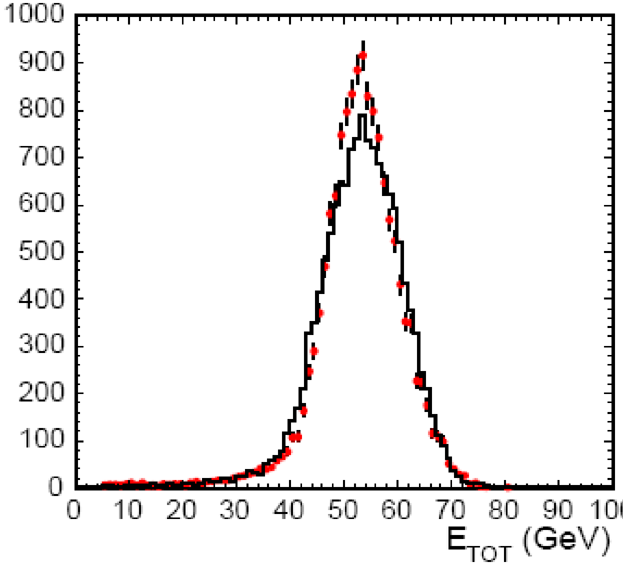
But we should expect significant progress with ever increasing data sets!

Additional Slides

CDF: Testbeam Data vs. MC for 57 GeV pions

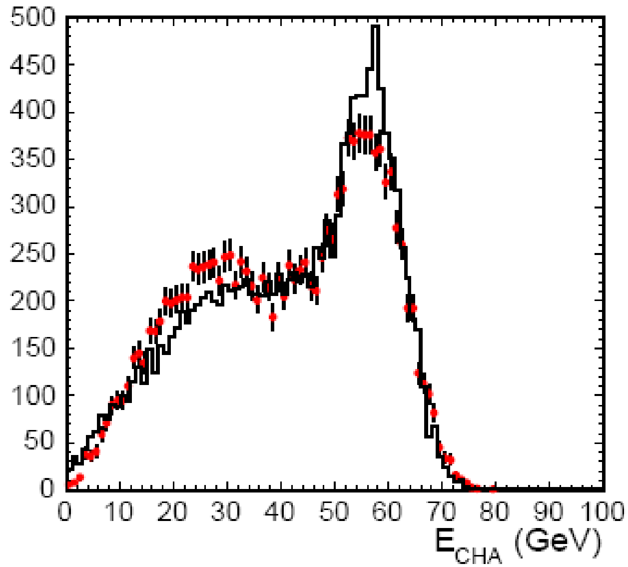
E_{CHA} if no inelastic interaction in E_{CEM}

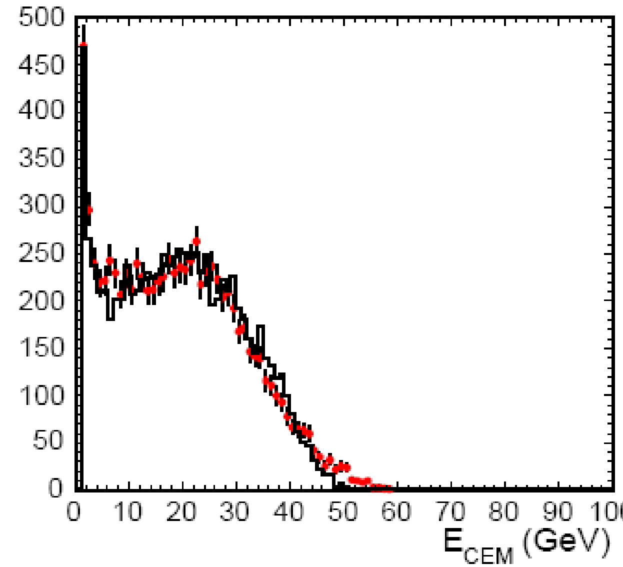




E_{Total}

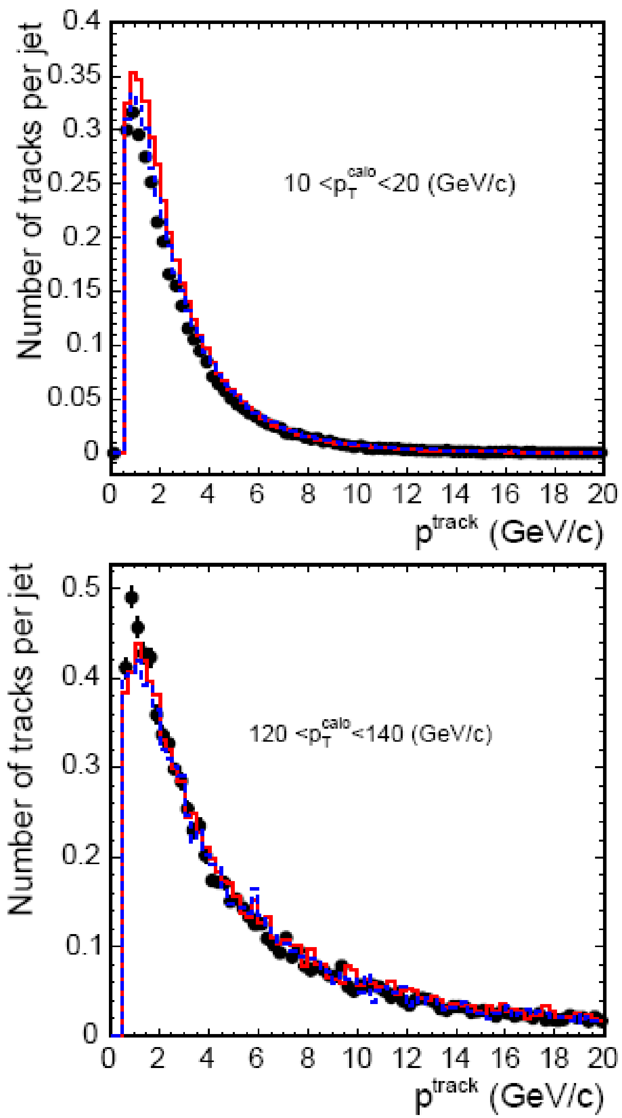
E_{CHA}



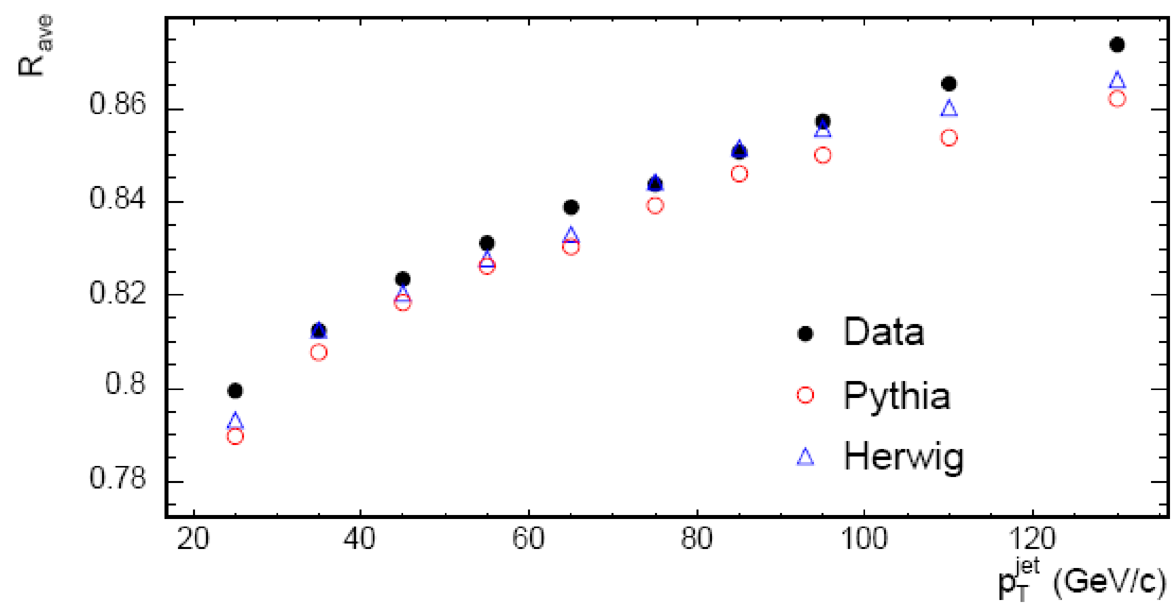


E_{CEM}

CDF: Particle momentum spectra Data V MC



And average response relative to charge tracks



Indirect test of scale

● Data ----- Herwig —— Pythia