Jet Calibration at the TeVatron

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for the CDF and D0 collaboration

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Jets at the TeVatron

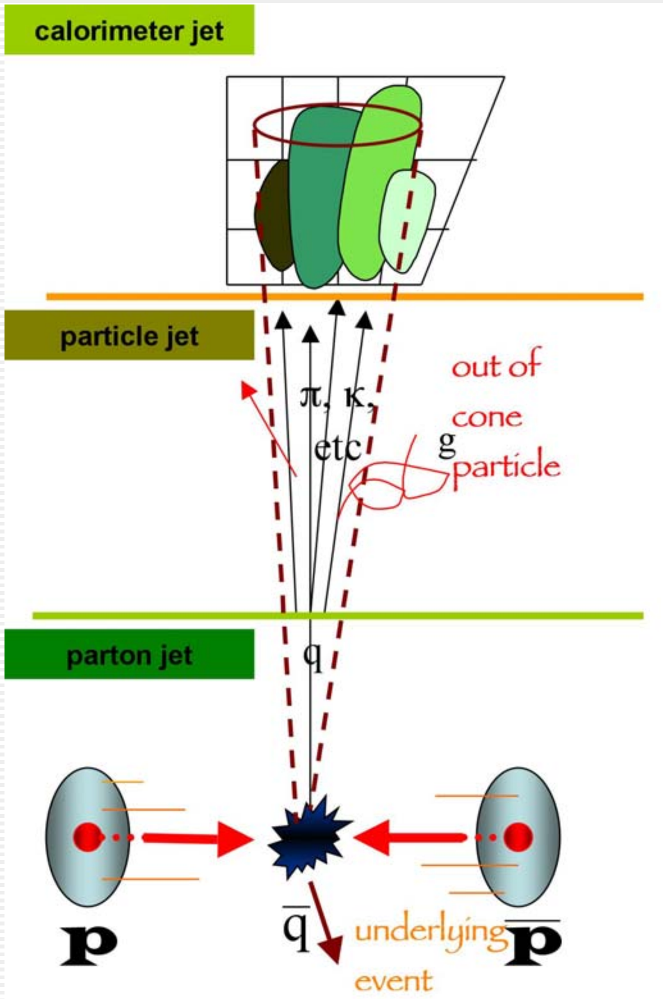
- Jets are complicated objects measured with a calorimeter and defined by algorithm

Complex detector properties

- energy response could be non-linear
- there are non-instrumented regions
- larger particle shower widths worse energy measurement
- jet may not contain low energy deposition

Need to correct for detector, algorithm and physics effects to obtain the true energy of the jets:

Jet Energy Scale (JES)



Algorithms with complex behavior such as cone, cone-midpoint, KT

- might not capture all particles
- low energy jets might not be possible to define
- algorithm must handle merging and splitting of jets

Complex underlying physics

- events contain spectator interactions
- partons radiate initial and final state gluons
- might contain energy from different ppbar interactions
- there are different types of jets: light quarks, gluons, b/c/τ

Physics with Jets

- Much of the interesting physics at the TeVatron is done with jets
- Some of them require a better (or different) knowledge of the jet energies

- QCD
  - more sensitive to different jet algorithms
  - energy scale should cover a wide P_T range
  - understand jet energy scale in the forward region
- Searches (Higgs)
  - need good jet energy resolution
  - energy scale should cover a wide P_T range
  - interplay with Missing E_T (MET) is important
  - parton-level corrections
- Top
  - mainly central jets
  - usually smaller cone sizes since they are crowded events
  - parton level corrections
    - not needed for cross section
    - necessary for top mass

- CDF and D0 make use of generic jet corrections for all physics groups and all jets (with exceptions of b-specific corrections in some physics groups)

Top Quark Mass

- Jet energy scale is the largest uncertainty in the best top mass measurement (D0)

M_{top} = 180 ± 3.6 (stat.) ± 3.9 (syst.) GeV/c^2

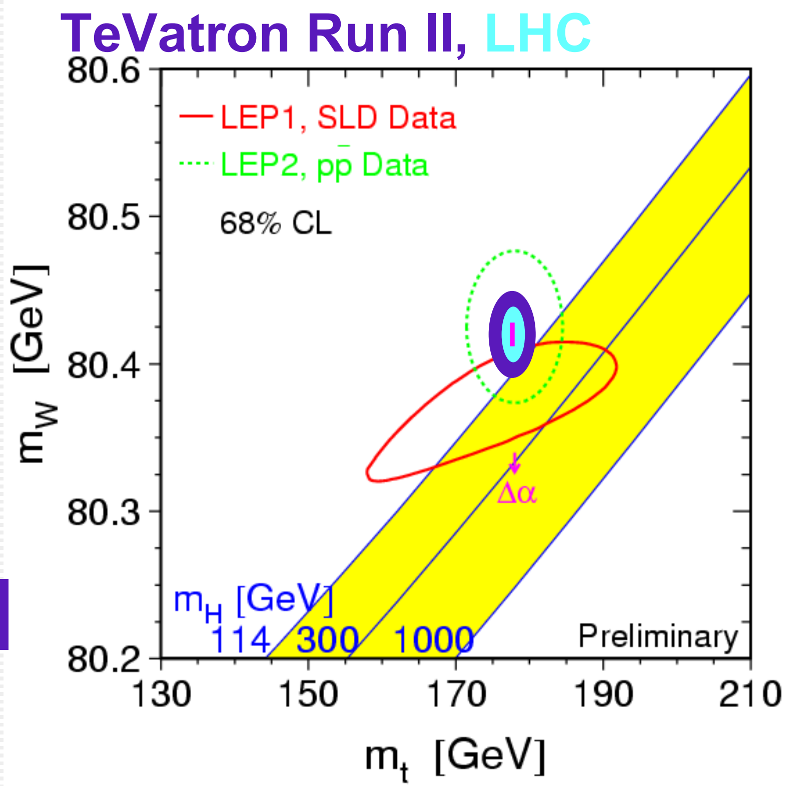
JES = 3.3 GeV

- In the most precise Run II result the jet energy scale is already the largest uncertainty (CDF)

M_{top} = 180 +4.5-5.0 (stat.) ± 6.2 (syst.) GeV/c^2

JES = 5.3 GeV

- Run II expected error 2 GeV: very challenging!

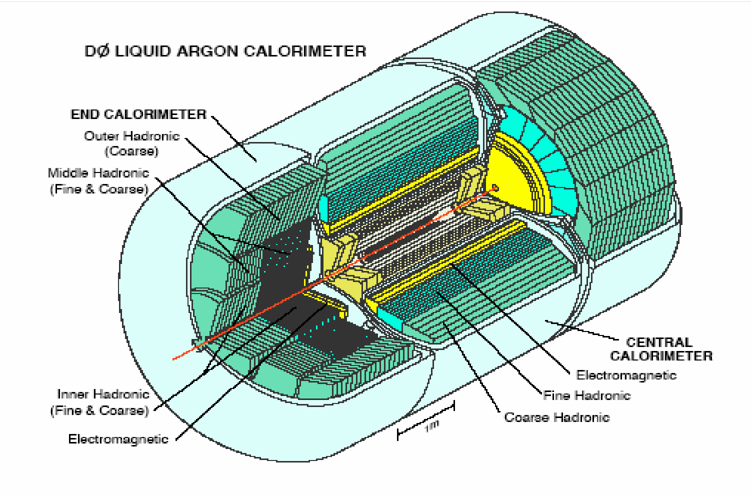


TeVatron calorimeters

- D0 Uranium-Liquid Argon sampling calorimeter $|\eta|<4.2$:
  - nearly compensating $e/\pi < 1.05$ E>30 GeV
  - uniform response & hermetic
  - nearly solid angle coverage
  - fine spatial segmentation

Electrons: $\sigma_E / E = 15\% / \sqrt{E} \oplus 0.3\%$

Jets: $\sigma_E / E \sim 80\% / \sqrt{E}$

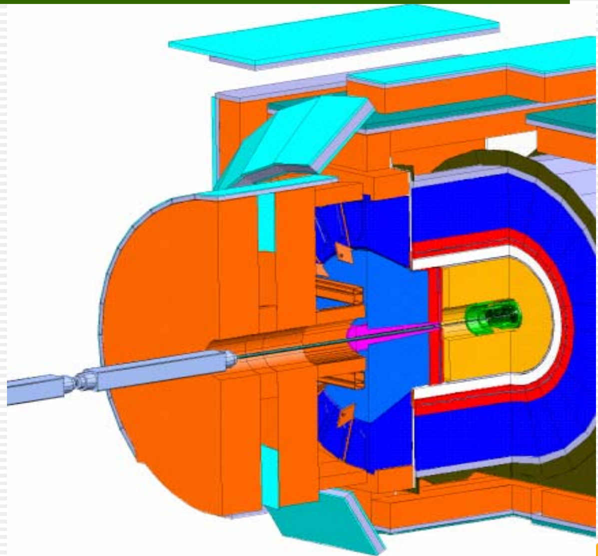


- CDF Scintillating time with lead/iron absorbers $|\eta|<3.6$:
  - non-compensating (non-linear response to hadrons)
  - coarse granularity
  - new plug (more linear)

Electrons: $\sigma_E / E = 13.5\% / \sqrt{E}$ **(central)**

$\sigma_E / E = 16\% / \sqrt{E}$ **(plug)**

Jets: $\sigma_E / E \sim 80\% / \sqrt{E}$



2 Different Approaches

D0 jet energy scale

- Calorimeter jet ->Particle jet

NIM #A424:352 (1999)

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

  - **Offset O**: calorimeter Ur noise, energy from the underlying event, pile-up and contributions of additional ppbar interactions
  - **Response R_{jet}**: change in scale due to e/π and non-uniformity in the detector:
    - EM part calibrated using Z->ee mass peak
  - **Showering S_{cone}**: fraction of the particle jet energy that is deposited outside the algorithm cone (not fot KT)

  Mostly based on data, exploiting conservation of transverse momentum through an accurate determination of the particle level MET

- Parton level corrections applied only for some analyses (and analysis-specific)

CDF Jet Energy Scale Method

- **(f_{rel}) Relative Corrections**
  - Make response uniform in η
- **(*UEM*) Multiple Interactions**
  - Energy from different ppbar interaction increases jet energy
- **(f_{abs}) Absolute (Calorimeter-to-Particle) Corrections (central region)**
  - Calorimeter is non-linear and non-compensating
- **(*UE*) Underlying Event**
  - Energy associated with the spectator partons in a hard collision
- **(*OOC*) Out-of-Cone (Particle-to-Parton)**
  - **Particle level to parton level**

$$P_T(R) = \left[P_T^{raw}(R) \times f_{rel} - UEM(R)\right] \times f_{abs}(R) - UE(R) + OOC(R)$$

- Systematic uncertainties at each step:
  - Differences between Monte Carlo and data: since we use Monte Carlo (generators, CDF simulation) we need to treat jets in data and in Monte Carlo on equal footing
  - Uncertainties from the method used to obtain the corrections

Correcting for detector effects

D0

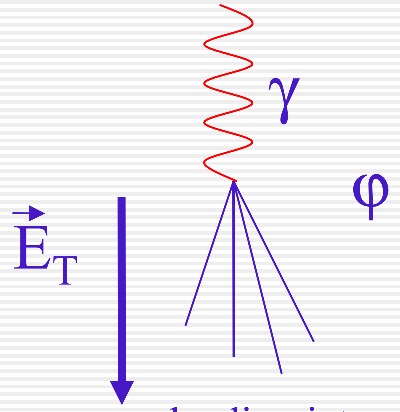
Method

Correction is obtained from data and Monte Carlo using photon+jet events

- Determined from the P_T imbalance in photon+jet events: Missing E_T Projection Method

$$E_T^{\gamma} + E_T^{recoil} = 0$$ <- ideal

$$R_{\gamma} E_T^{\gamma} + R_{recoil} E_{Trecoil} = -\not{E}_T$$ <- real



- After EM energy calibration from Z->ee mass peak (R_{γ}=1)

$$R_{recoil} = 1 + \frac{n_T^{\gamma} \bullet \not{E}_T}{E_T^{\gamma}}$$

- Select back-to-back, γ+jet events

$$R_{jet} = R_{recoil}$$

- Events are placed in various E' bins

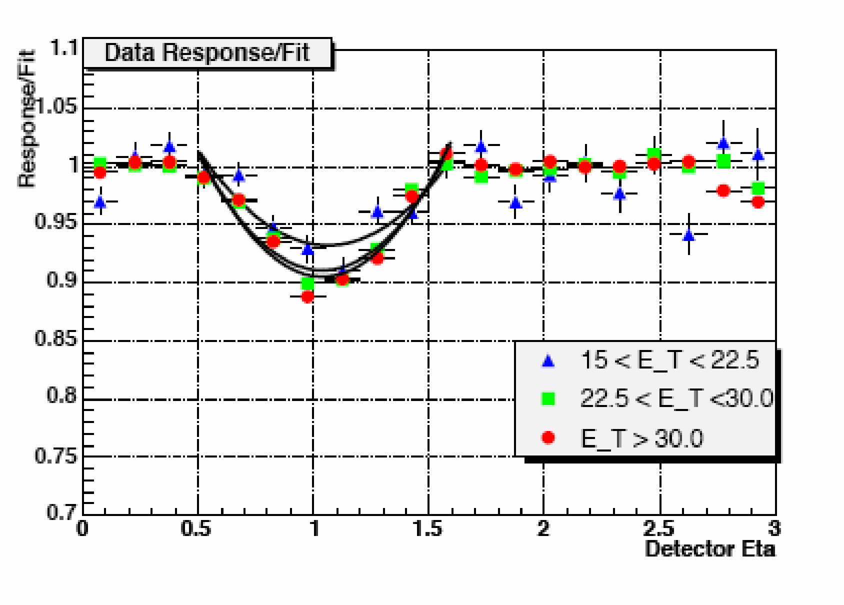
$$E' = E_T^{\gamma} \cosh(\eta_{jet})$$

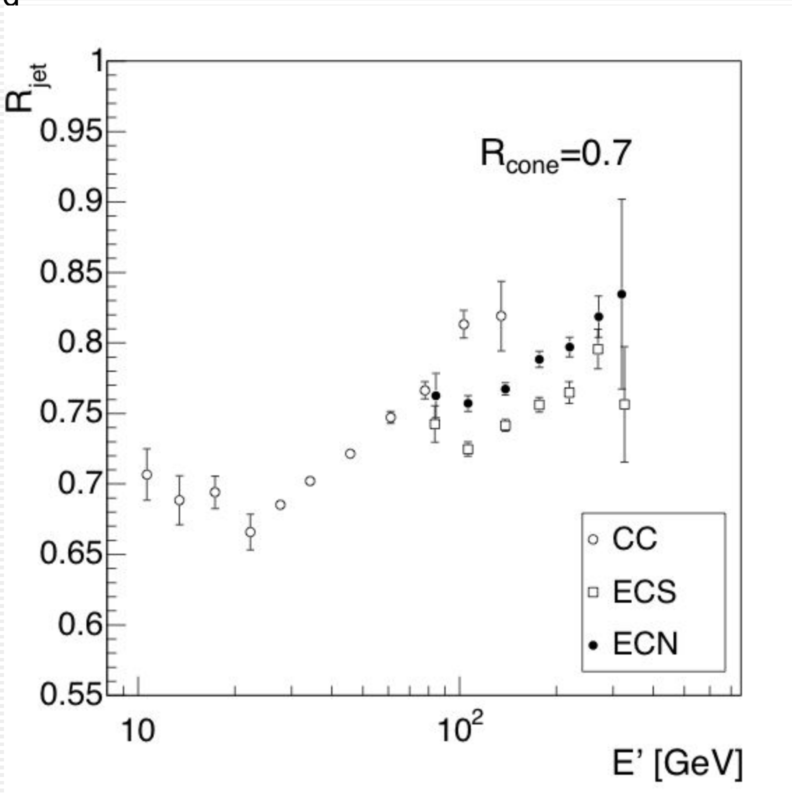
  - photon energy and jet direction are well measured quantities
  - smearing effects are minimized

Non-central regions

Different response in central than in forward calorimeter

- Correction factor defined as Rjet central/Rjet forward
- CC= central calorimeter
- ECS = south end-cap calorimeter
- ECN = north end-cap calorimeter





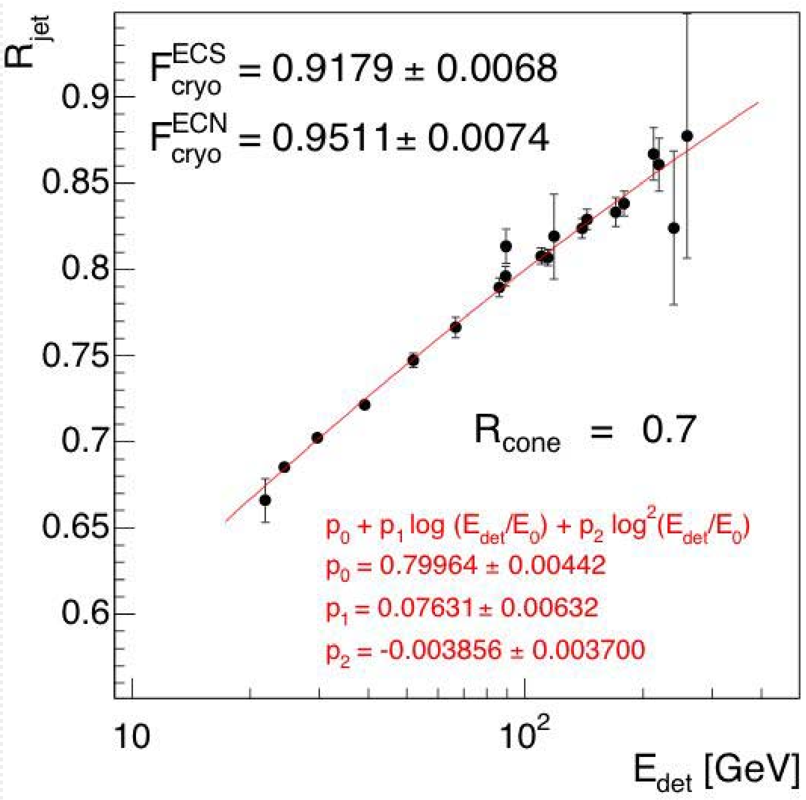
ICR (crack between central and forward calorimeters)

- η dependent correction
- Obtained from photon+jet

Response and uncertainties

- Mapping from E' to measured energies E_{det} to obtain the final calorimeter response

- Uncertainties:
  - statistical error
  - systematic error
    - variation of cuts
    - closure tests on MC and different data samples

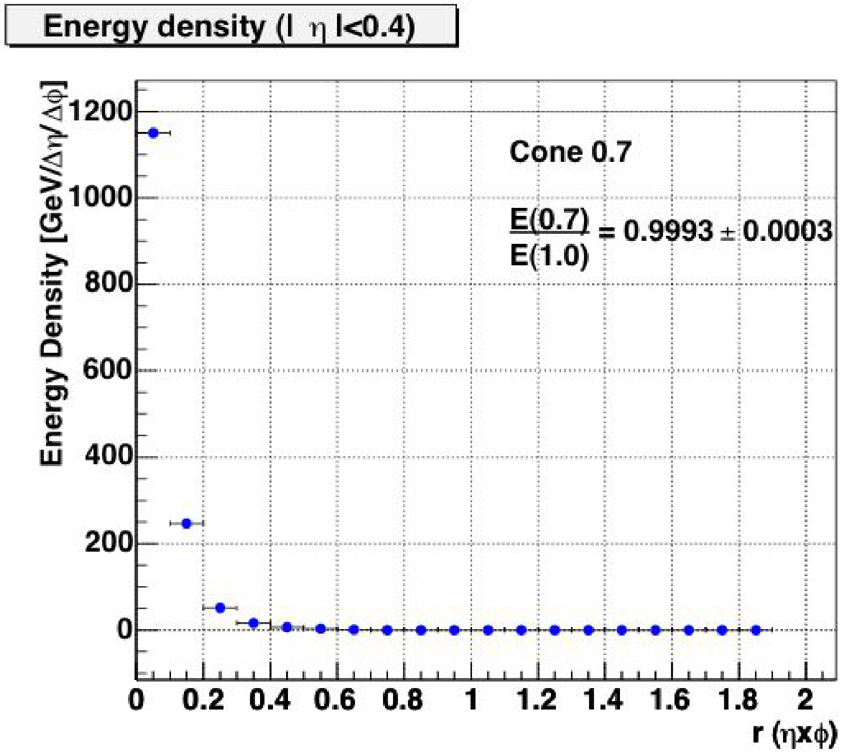


Showering

Energy losses outside the jet cone due to showering in the calorimeter

	Cone 0.7	Cone 0.5
Central	0.99	0.92
ICR	0.96	0.89
Forward	0.94	0.85

- Largest uncertainty at low P_T and high η



Correcting for detector effects

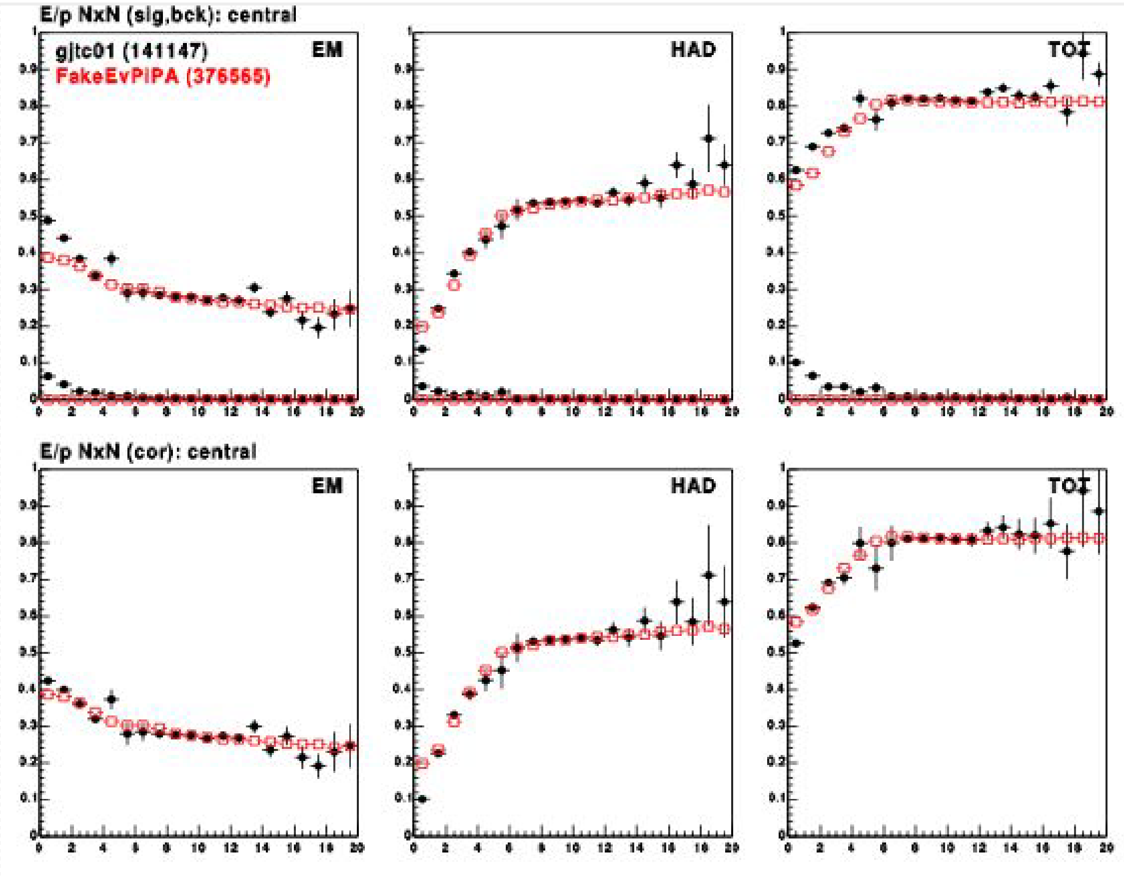
CDF

Method

Tune the CDF simulation using single particle response

Calorimeter response drops 30% between 10 and 1 GeV

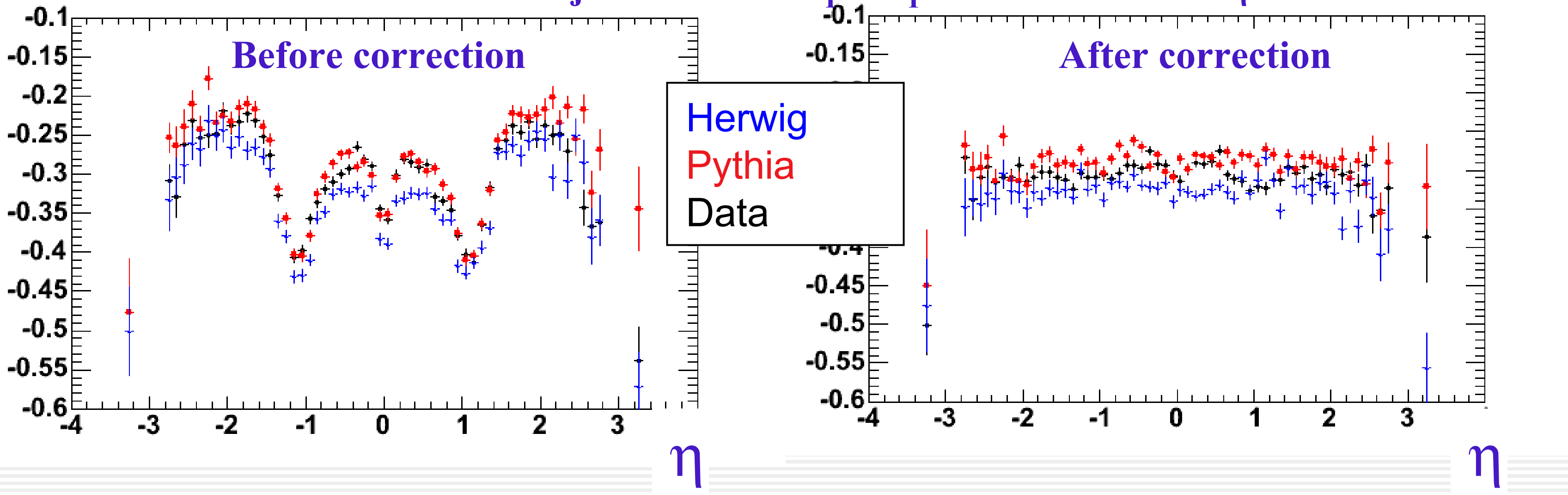
- Measure p using tracking. E from EM and HAD calorimeters
- Uses isolated tracks from minimum bias with a dedicated trigger
- E/p used to tune simulation: GFLASH parameterization for the calorimeter showers
- Difference between data and MC simulation => part of the systematic uncertainty of the jet energy scale



Non-central regions

- Two corrections: one for data and another for MC (derived with PYTHIA)
- Better understanding of the central calorimeter then we map jets in plug calorimeter and cracks w.r.t. central using dijet balance

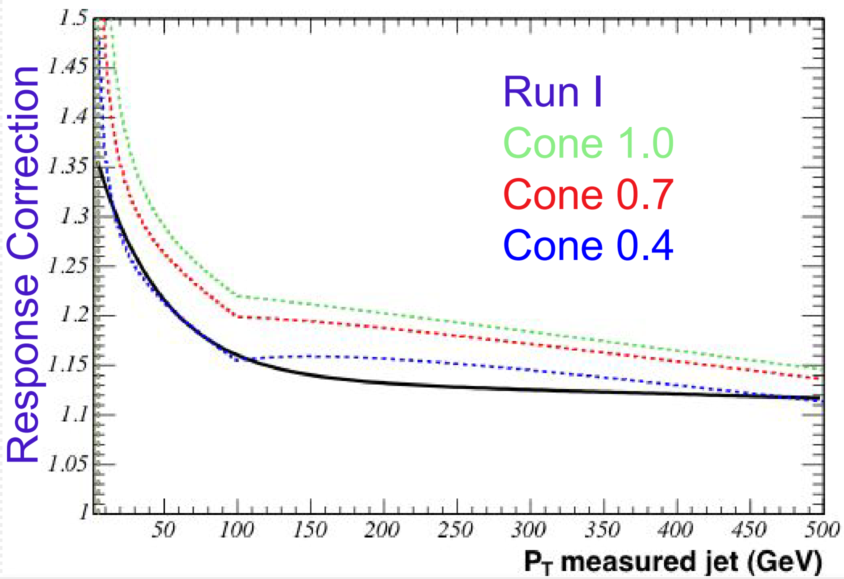
Photon+jet balance $1-P_T^{jet}/P_T^{\gamma}$ as a function of η

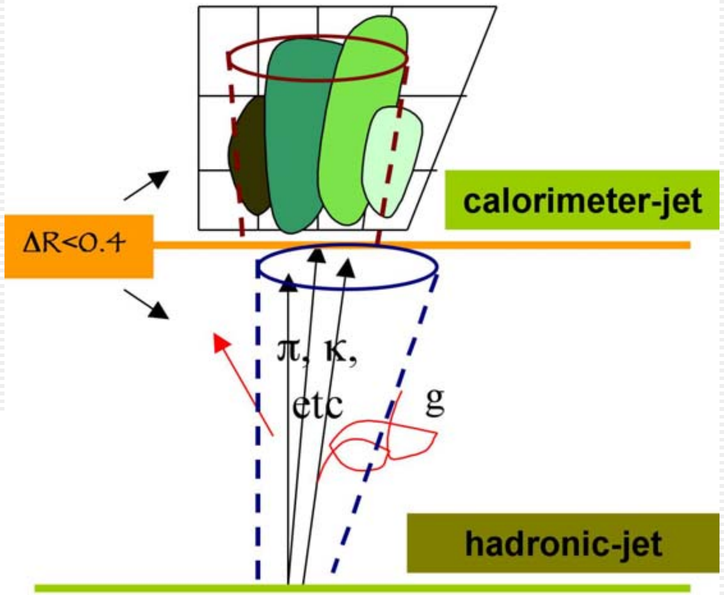


After this correction, non-central jets can be treated like any central jet

Response

- Once the MC simulation is tuned, the corrections are calculated using PYTHIA dijet events with different minimum P_T (0 - 600 GeV) and only in the central region
- We map the calorimeter-level jet P_T with the hadron-level jet P_T and obtain the probability of measuring P_T^{Cal} when P_T^{Had} was produced





After this correction, jets are independent of the calorimeter

Uncertainties

- Is the response of the calorimeter to single particles (pions, protons, neutrons, etc) simulated correctly?

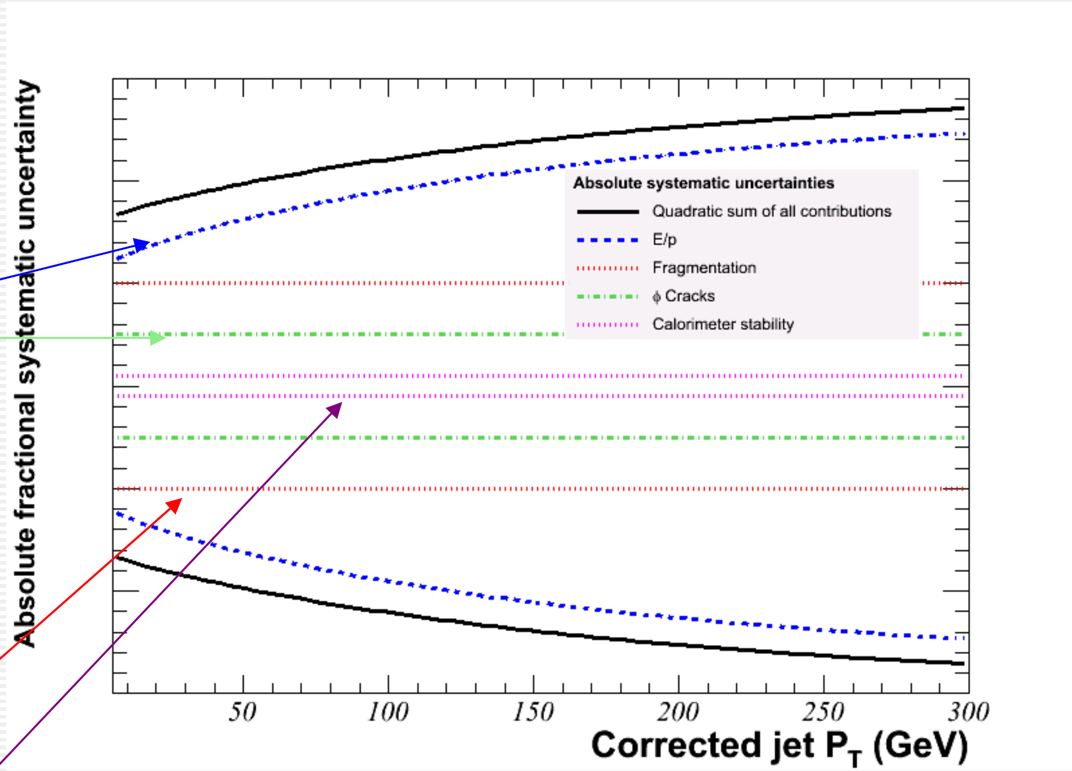
  CALORIMETER SIMULATION

- Does the Monte Carlo describe well particle spectra and densities at all jet E_T?

  FRAGMENTATION

- Is the calorimeter fully calibrated?

  STABILITY



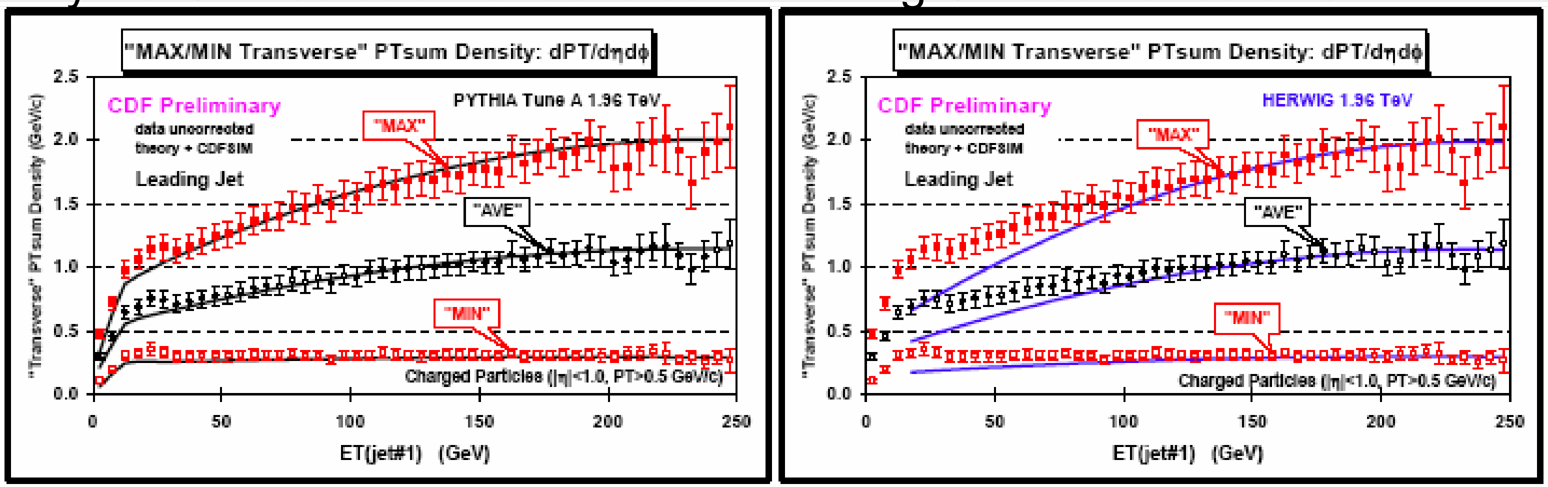
- Still using test beam results in some P_T regions (large uncertainties). More important for high P_T jets

Correcting for physics effects

Remove energy not associated with the hard interaction

- Both experiments subtract the energy from underlying event and multiple ppbar interactions in a similar way
  - using minimum bias
  - calculating energy densities
- Pile-up more important at D0, Ur noise only relevant to D0

- Pythia UE has been tuned to data. Herwig UE seems too small

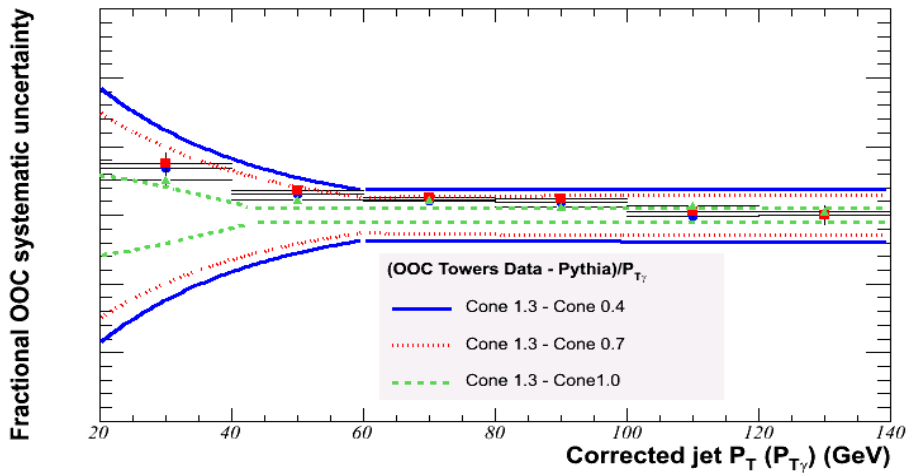


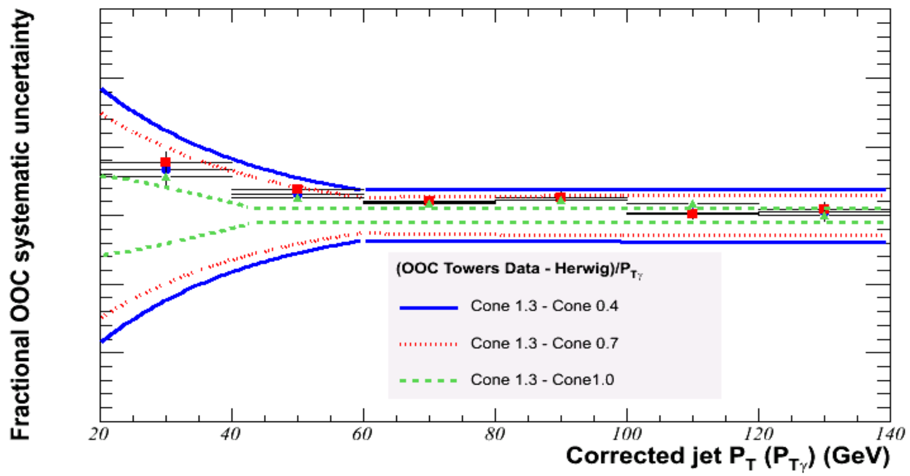
Charged particle density and PTsum density for "leading jet" events versus E_T(jet#1) for PYTHIA Tune A and HERWIG.

Out-of-Cone

Add energy from particles deposited outside the jet cone

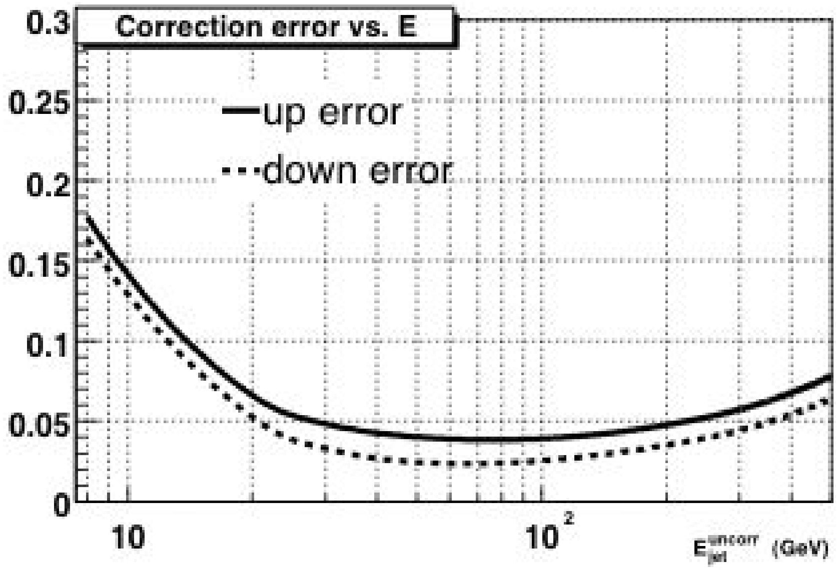
- Corrections applied only in som physics groups
  - some groups have their own correction
- Different than showering, contai effects at the particle level (physics out-of-cone)
- The uncertainty is difference in energy outside the jet cone between data and MC
  - obtained from photon+jet

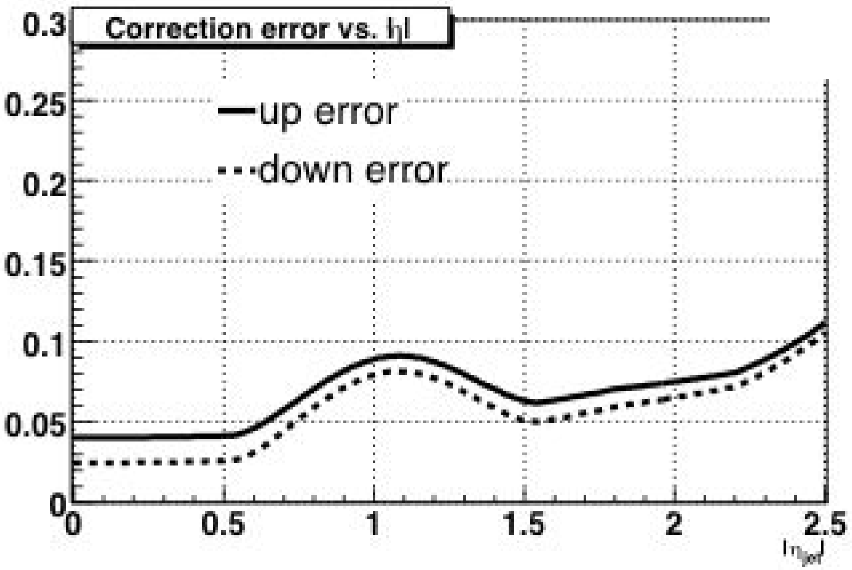




Total Uncertainties - D0

- Low energy uncertainty dominated by showering uncertainty
- Expect improvements in the next version => Approaching Run I uncertainty

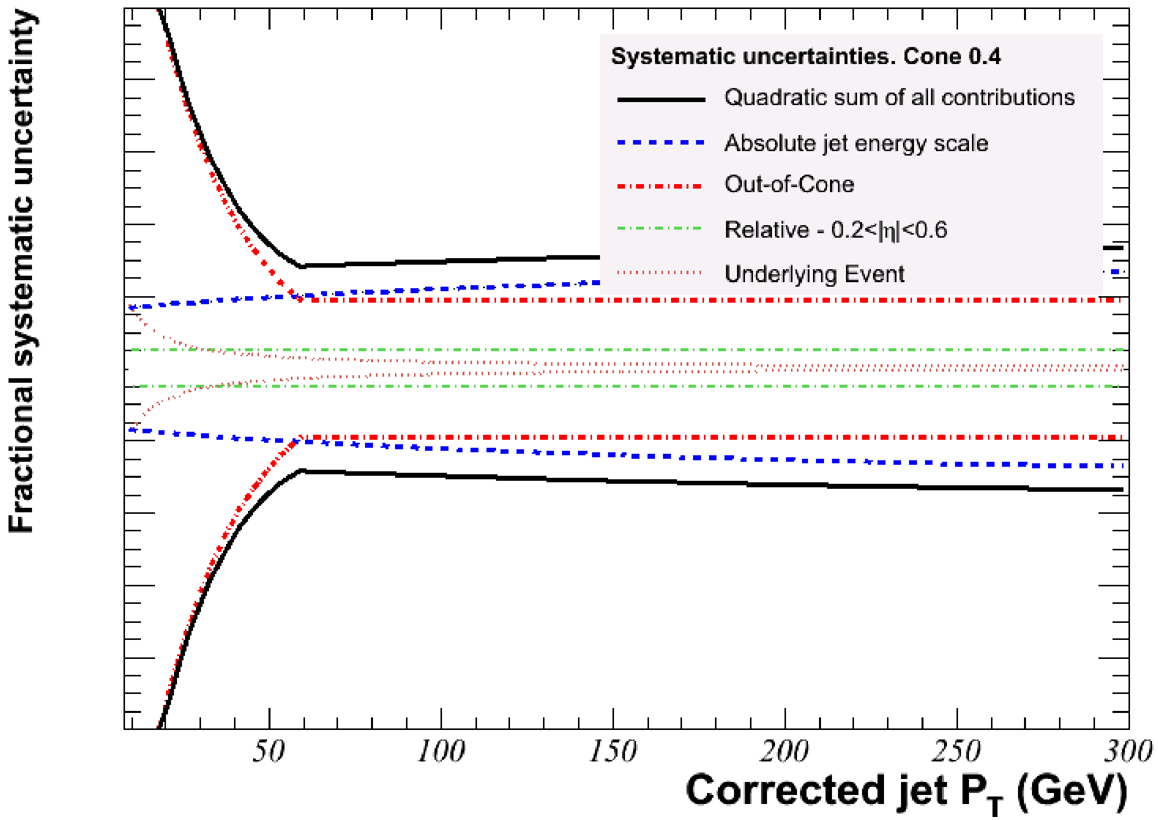




- For the top mass, particle-to-parton corrections are derived from ttbar MC. Corrections are applied to photon+jet, difference between MC and data is taken as the JES uncertainty.

Total Uncertainties - CDF

- Similar as in Run I
- Note that this plot contains also the out-of-cone uncertainty



Systematic Checks

- γ-Jet:
  - highest statistics ☺
  - systematically limited (kt-kick, BG contributions: π^0) ☹
  - Not available for E_T<25 GeV (trigger) ☹
- Z-Jet:
  - Usable at lower E_T values than γ-Jet ☺
  - lower statistics than γ-Jet at high P_T ☹
  - No kt-kick effect ☺
- Z-bb:
  - Nice to have calibration peak ☺
  - Only for b-jets and difficult to trigger 😐
  - Small signal on large background ☹
- W-jj in double b-tagged top events:
  - Expect 250 double-b-tagged top events in 2/fb → 1-2 % precision? ☺

BUT none of them can test jets with E_T>200 GeV ☹

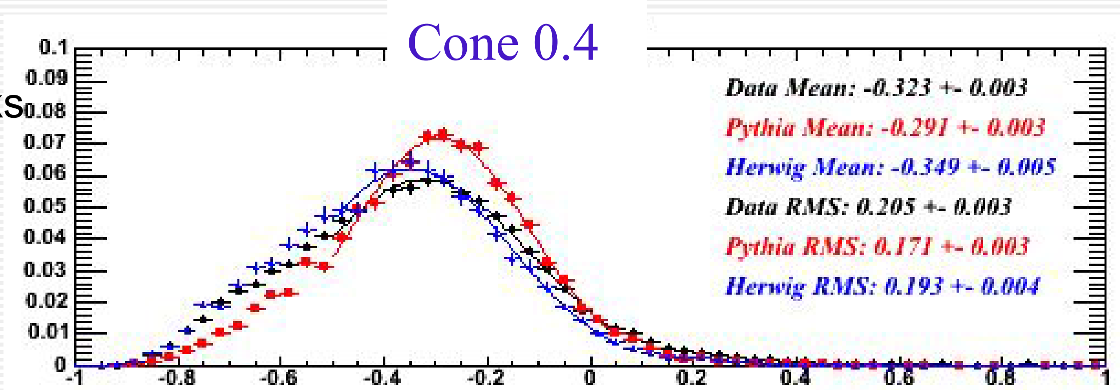
Photon+jet

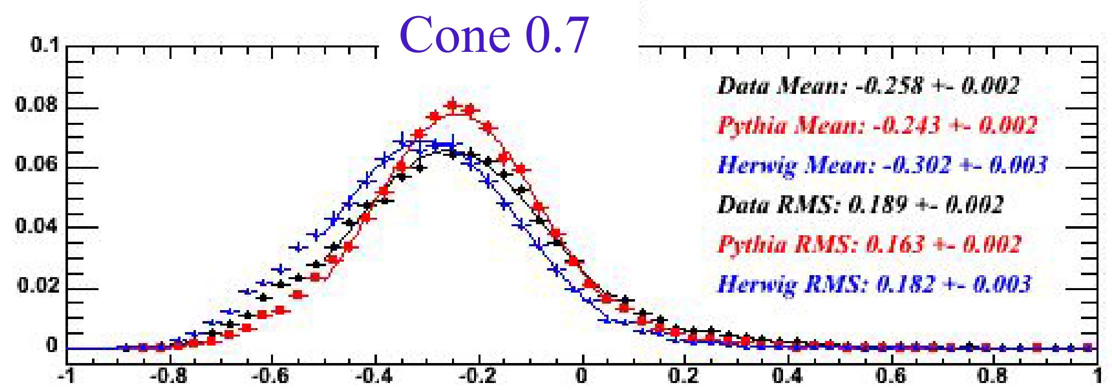
- Some systematic uncertainties (CDF) or corrections (D0) are derived from photon+jet

- This sample is also used for many cross checks

- Very useful sample since the photon is well measured

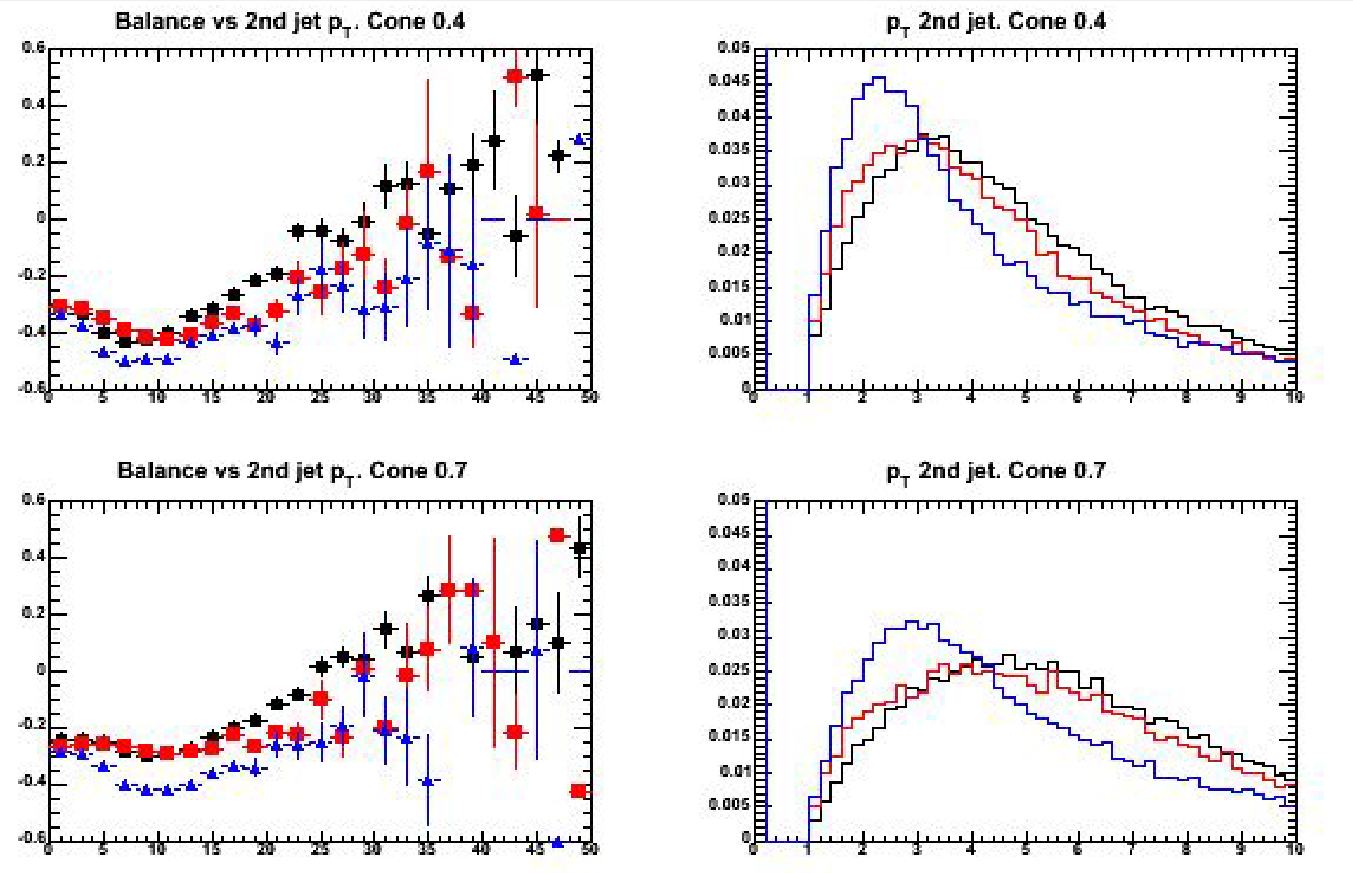
$$P_T balance = 1 - \frac{P_T^{jet}}{P_T^{\gamma}}$$





Photon+jet

- When calculating systematic uncertainties using a sample it is difficult to deconvolute physics effects

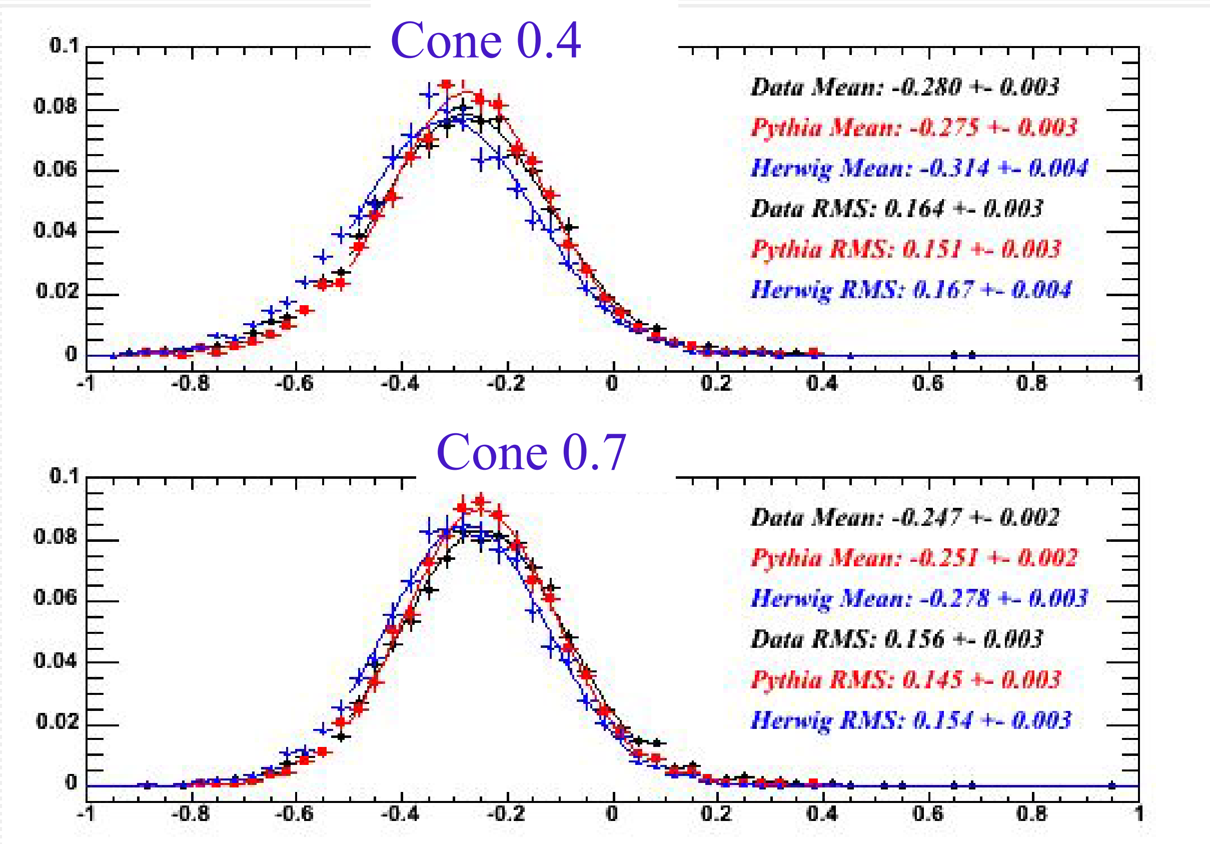


- Differences between physics effects can bias the estimate of uncertainties on JES and corrections

- A lot of effort trying to understand the physics in the MC

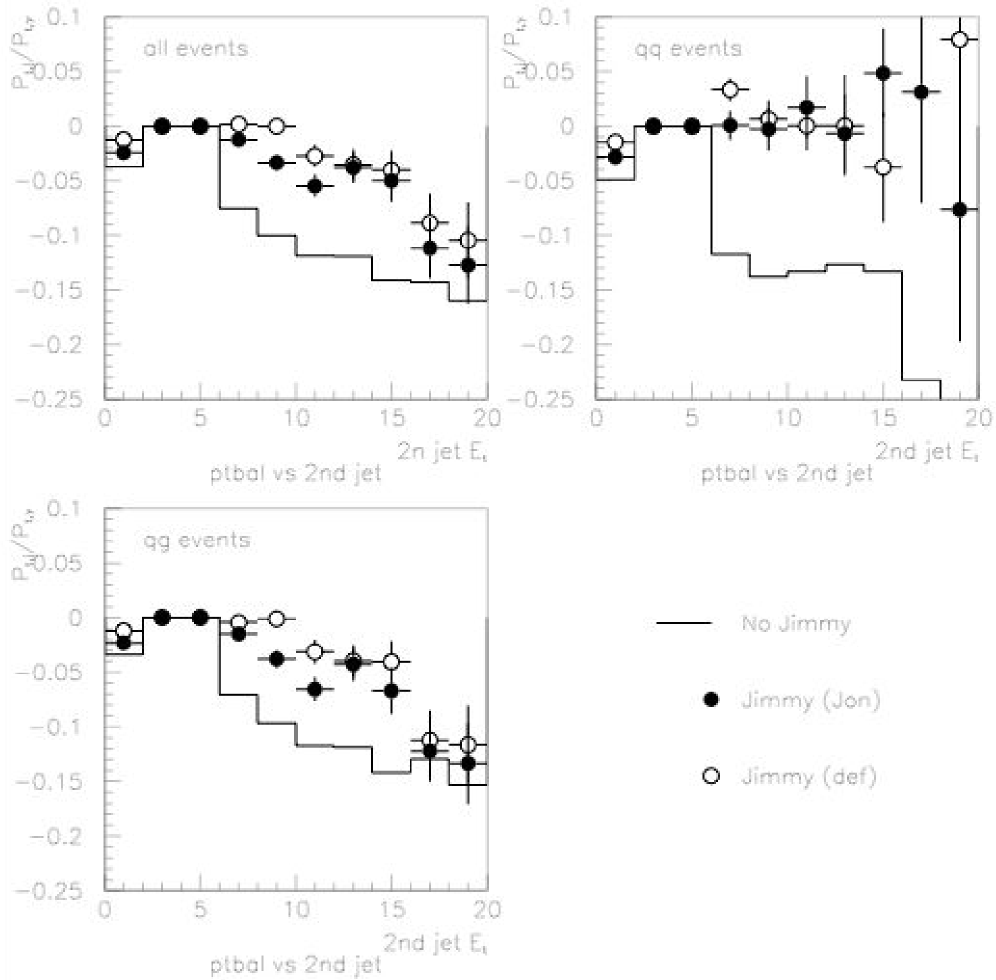
Photon+jet

- Applying cuts on the second jet P_T some physics effects are reduce
- Agreement still about 3% between Pythia, Herwig, data



Photon+jet

- CDF is starting to look at adding Jimmy (multiparton interactions) to Herwig
- Seems to move the discrepancy of the second jet P_T in the right direction



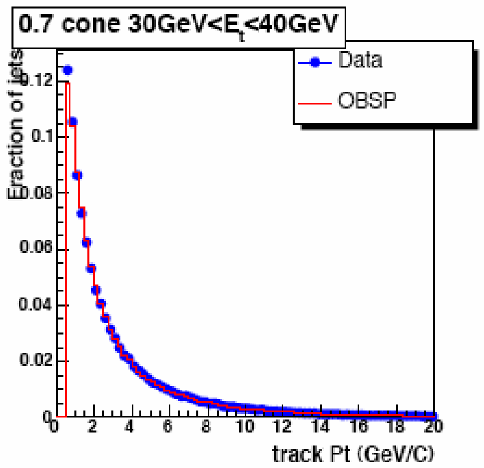
Conclusions

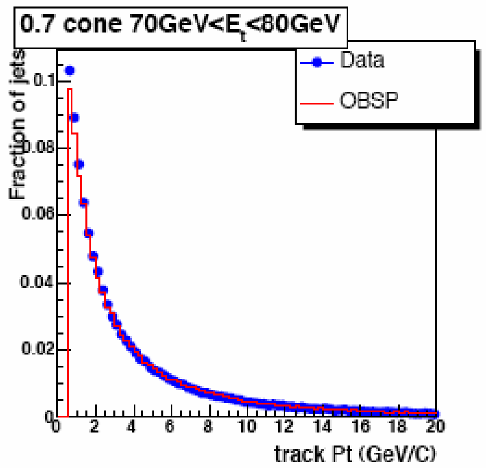
- Jet calibration at the TeVatron requires a big effort
- It is the major uncertainty in many measurements
- D0 and CDF are using similar methods to the ones employed in Run I to calculate corrections and uncertainties
- Although different, they achieved ~3% uncertainty in Run I
- Both experiments will achieve that level of uncertainty very soon
- Reducing the uncertainties will become even more challenging
  - Expect results on Z->bbbar, W->jj also soon!

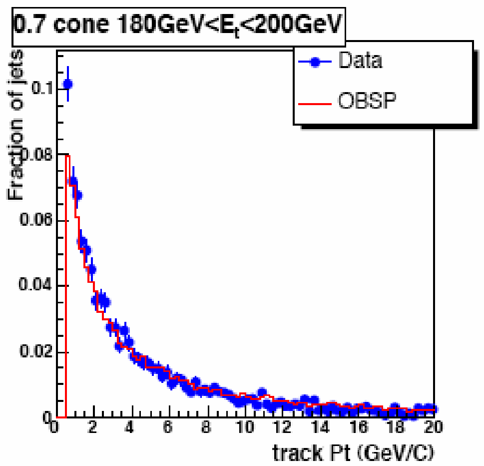
Thanks to: B. Kehoe, N. Parua, C. Royon, A. Kupco, B. Heinemann, A. Bhatti, L. Galtieri, S. Kuhlman, M. Shochet, K. Hatakeyama, R. Wallny

Fragmentation Uncertainty

- Due to non-linearity of CDF calorimeter big difference between e.g.
  - one 10 GeV pion
  - ten 1 GeV pions
- Pythia-Herwig negligible difference
- Measure number of and Pt spectra of particles in jets at different Et values as function of track Pt:
  - Requires understanding track efficiency inside jets
  - Ideally done for each particle type (π, p, K)

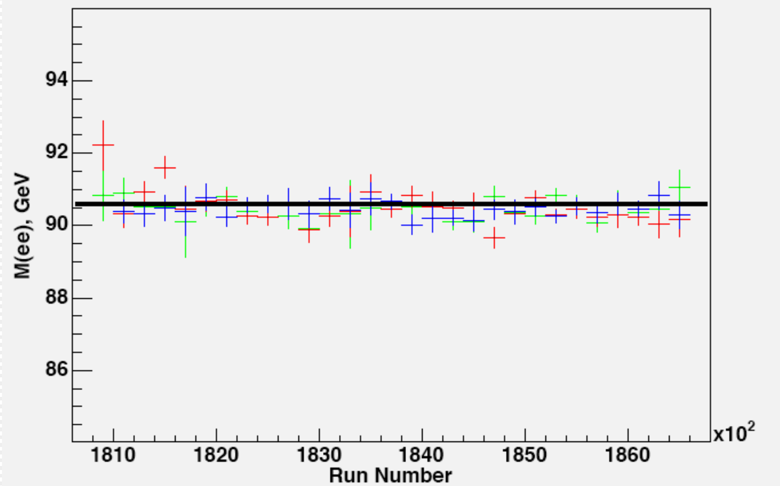




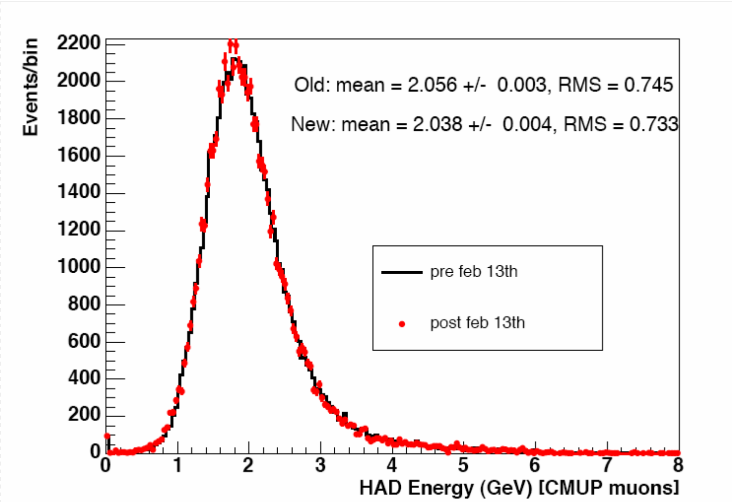


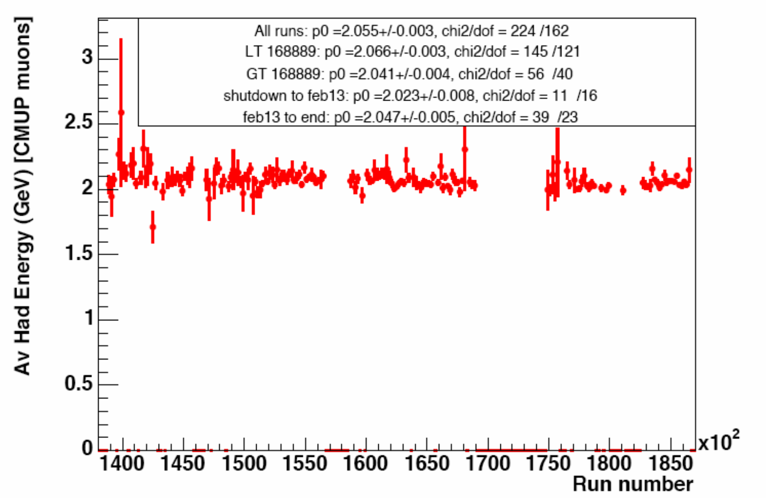
CDF Calibrations

- Z->ee mass peak stability
  - Sets the absolute scale
  - Compare data and MC
  - Check for time dependence



- Minimum Ionizing Particle (MIP)
  - J/Psi and W
  - Peak in HAD and EM
  - Check for time dependence





Photon+jet - all eta regions