Jet Energy Scale Determination at CDF

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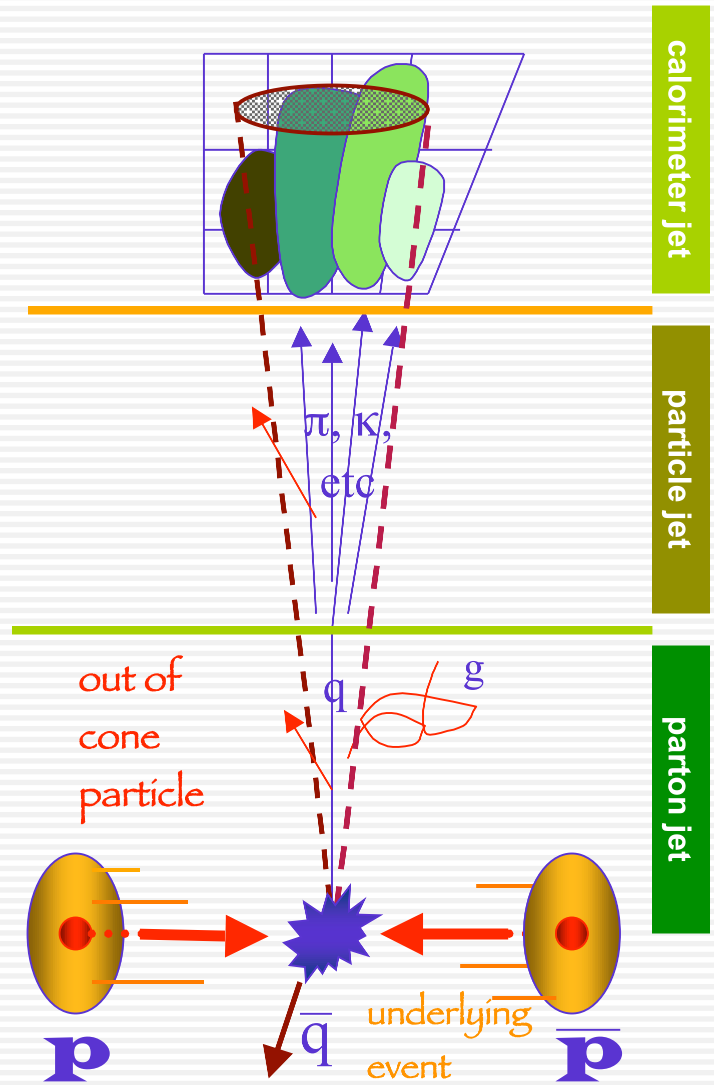
Talk Overview

- Introduction
  - Jets
  - Physics with jets
- Corrections and uncertainties
  - Different levels of jets
  - Does the Monte Carlo reproduce the data?
- Tests and cross-checks
  - Are the corrections accurate?
  - Are the uncertainties believable?
- Conclusions

Jets

- Measurements of hard scattering processes in ppbar collisions depend on the determination of the 4-momenta of quarks and gluons produced in the hard scatter
- The measurement of these 4-momenta relies on the reconstruction of hadronic jets resulting from the quark or gluon fragmentation
- Jets are complicated objects measured by calorimeter towers and defined by a clustering algorithm
- To convert jet energies to parton energies we need to correct for:
  - Instrumental effects
  - Physics effects
  - Jet algorithm effects

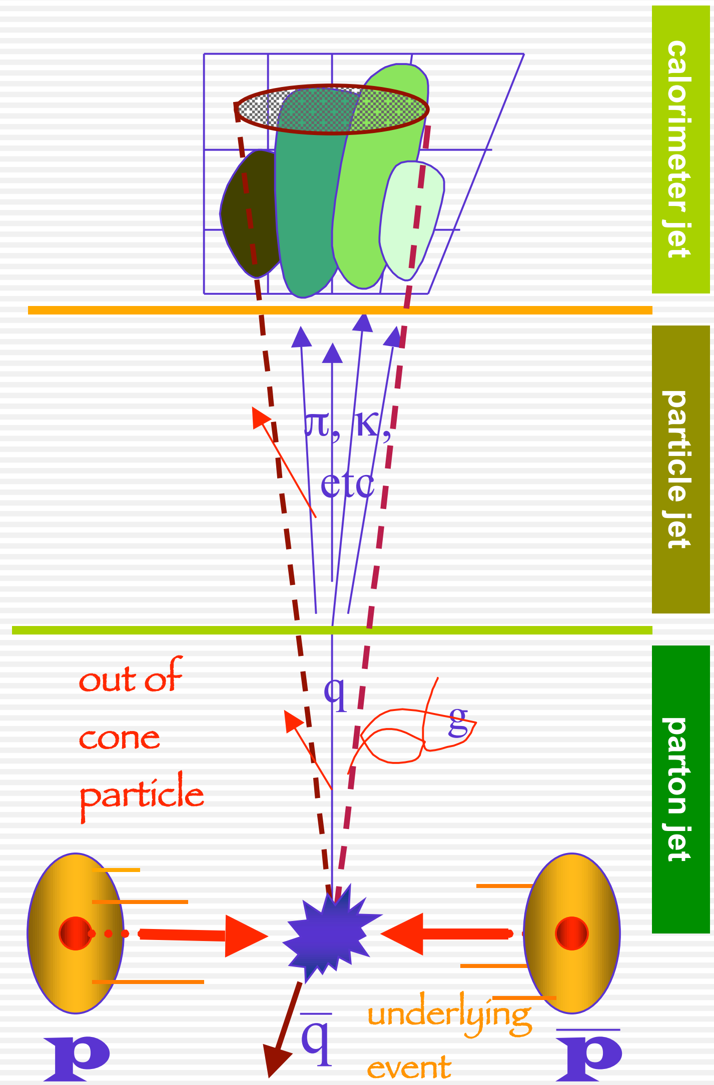


Jets

Instrumental effects:
- non-linear calorimeter
- non-instrumented regions
- non-compensating calorimeter
- may not contain low energy deposition

Algorithm effects:
- might not capture all particles
- low energy jets might not be possible to define

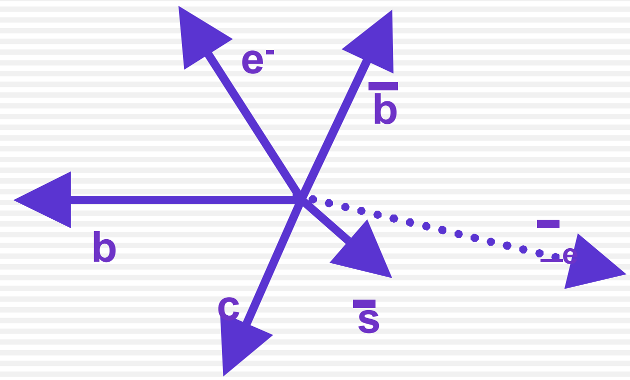
Physics effects:
- hadronization
- spectator interactions
- radiation
- multiple ppbar interactions
- flavor of the parent parton



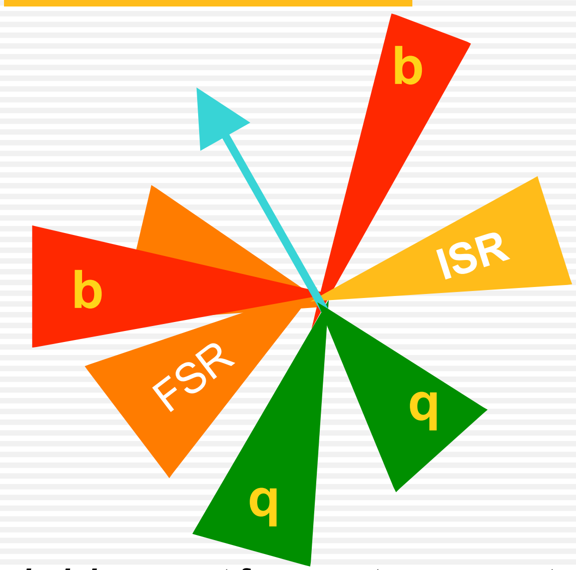
Physics with Jets

- **Much interesting physics is done with jets. Some analyses require a better (or different) knowledge of the jet energies**
- **QCD**
- **Searches**
- **Top**
  - mainly central jets (with the exception of single-top)
  - usually smaller cone sizes since they are crowded events
  - parton-level corrections
    - not needed for cross section
    - necessary for top mass

Final State from LO Diagram



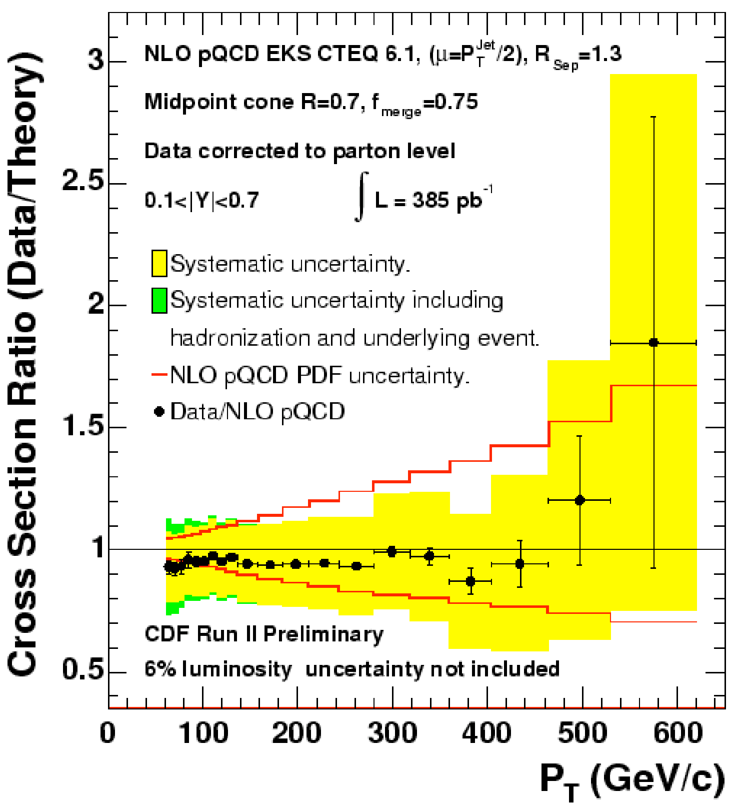
What we measure

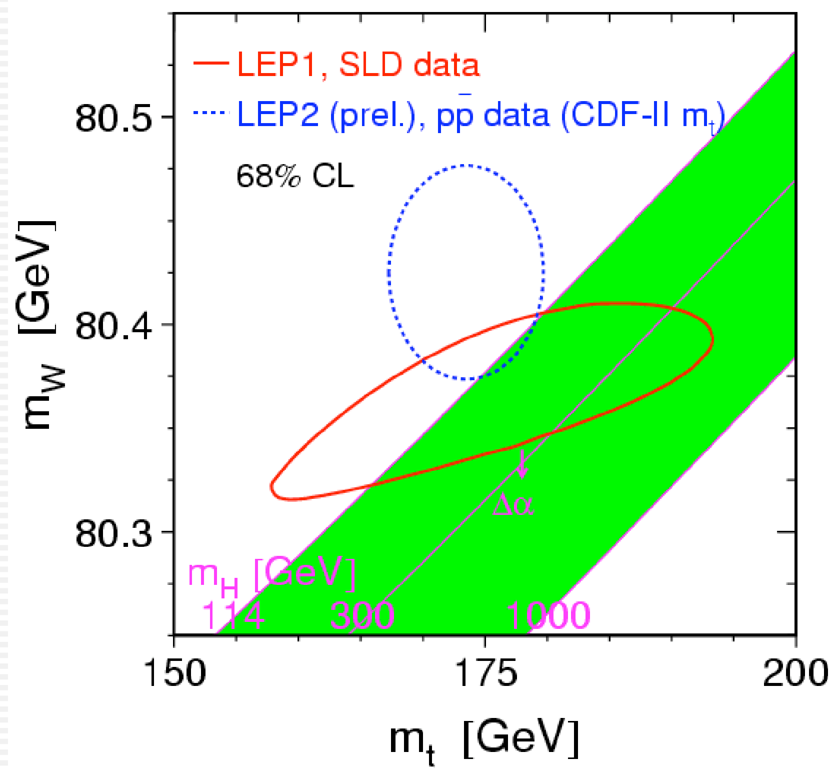


+ underlying event from proton remnants + multiple interactions!

Physics with Jets

Precision on the determination of jet energies is required by many analyses





1% uncertainty in jet => ~10% uncertainty in jet cross section

$$M_{top} = 173.5^{+2.7}_{-2.6}(\text{stat.}) \pm 2.5(\text{JES}) \pm 1.7(\text{syst.})\,\text{GeV}/c^2$$

CDF Jet Energy Scale Philosophy

- To accommodate the needs of different physics analyses:
  - Corrections from 8 GeV to 600 GeV
  - Corrections for different jet clustering algorithms: Cone 0.4, 0.7, 1.0, Midpoint, K_T
  - Different levels of jet energy corrections
  - Obtained from "generic" flavor jets
- They are obtained from Monte Carlo (generators+CDF simulation):
  - Need good models of hadronization and radiation in generators (Pythia, Herwig)
  - Need good CDF detector simulation (GFLASH)

Jet Energy Corrections Overview

- **Calibration**:
  - Calorimeter energy scale
  - Detector simulation
  - Physics models

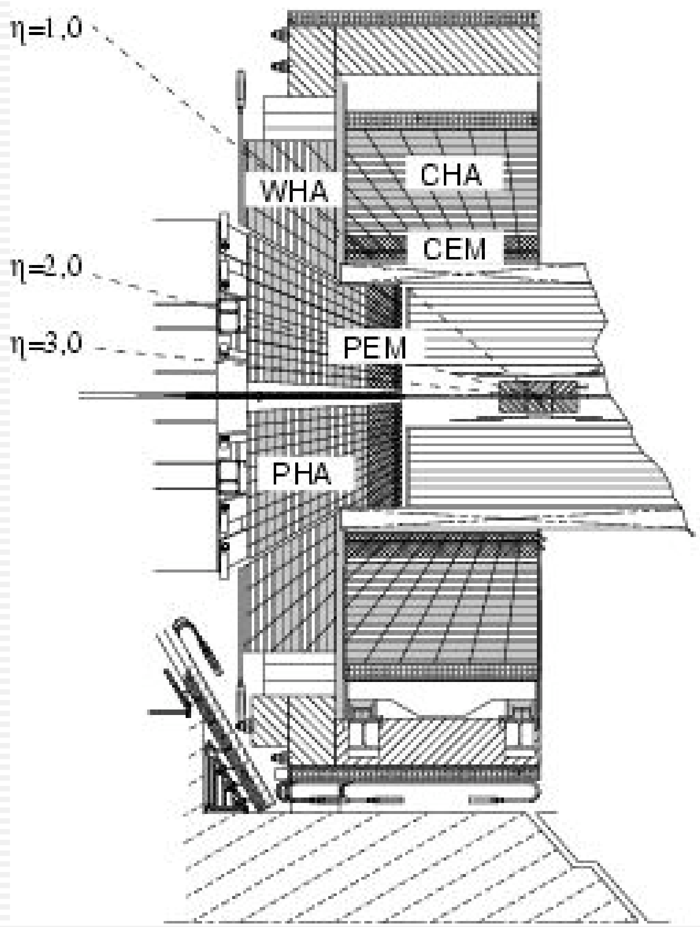
- **Corrections**:
  - Obtain calorimeter-to-particle corrections using simulated dijet events (C_{Abs})
  - Obtain particle-to-parton corrections using Monte Carlo shower in dijet events (C_{OOC})
  - Make jet energy scale uniform in η using dijet balance (data and Monte Carlo) (C_{Rel})
  - Pile-up and underlying event are measured from data (C_{MI} and C_{UE})

$$P_{Parton} = \left[P_{jet} \times C_{Rel} - C_{MI}\right] \times C_{Abs} - C_{UE} + C_{OOC}$$

- **Uncertainties**:
  - Differences between Monte Carlo and data
  - Uncertainties from the method used to obtain the corrections

CDF Calorimeter

- Jets are measured with a calorimeter …
- Scintillating tile with lead/steel absorbers $|\eta|<3.6$:
  - CEM = 18 X_0; CHA = 4.7 λ ($0.0<|\eta|<1.0$)
  - PEM = 23 X_0; PHA = 7 λ ($1.3<|\eta|<3.6$)
  - Projective Towers $\Delta\eta=0.11$; $\Delta\phi=2\pi/24$ (central), $\Delta\phi=2\pi/48$ (plug)
- Non-linear response to hadrons
- Linear response to electrons
- Coarse granularity
- Very low noise



Electrons and Photons:

$\sigma_{ET} / E_T = 13.5\% / \sqrt{E_T} \oplus 1.5\%$ **(central)**

$\sigma_{ET} / E_T = 16\% / \sqrt{E_T} \oplus 1\%$ **(plug)**

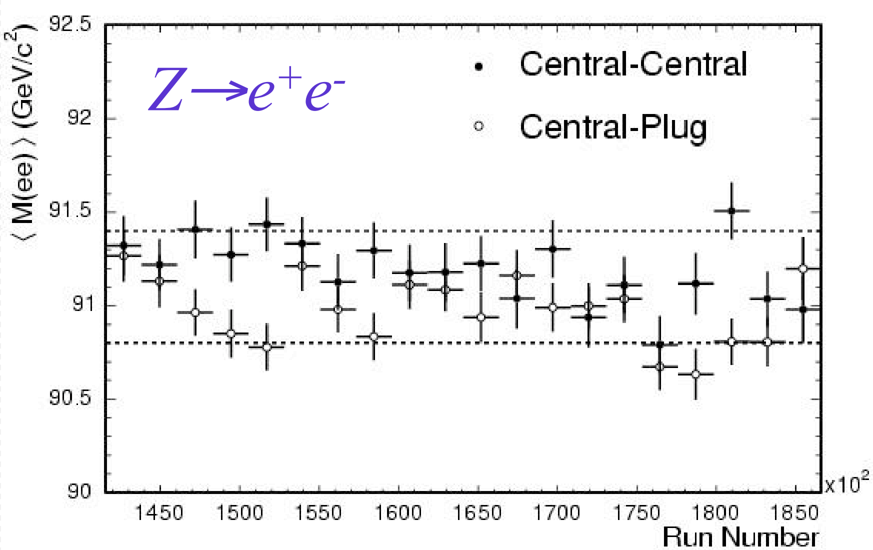
Charged Pions:

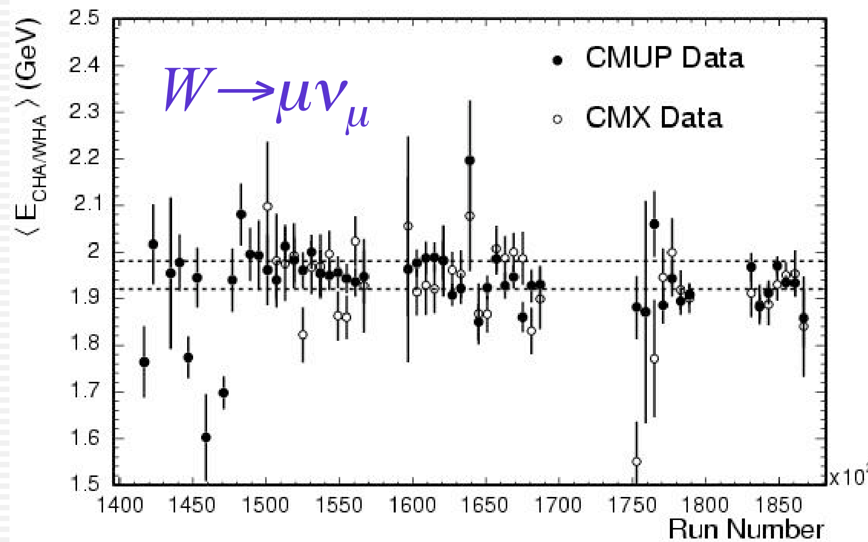
$\sigma_E / E_T = 50\% / \sqrt{E} \oplus 3\%$ **(central)**

$\sigma_E / E = 80\% / \sqrt{E} \oplus 5\%$ **(plug)**

Calorimeter Energy Scale

- **Scale**
  - CEM and PEM set using $Z \rightarrow e^+e^-$ = LEP measurement
  - CHA and PHA set using test beam pions (57 GeV)
  - Maintained using *in-situ* and test beam measurements
- **Stability**
  - Scales decrease due to aging of photomultipliers and scintillators
  - Online response is kept stable better than 3%
  - Offline response is kept stable better than 0.3% for CEM, PEM and 1.5% for CHA, WHA, PHA

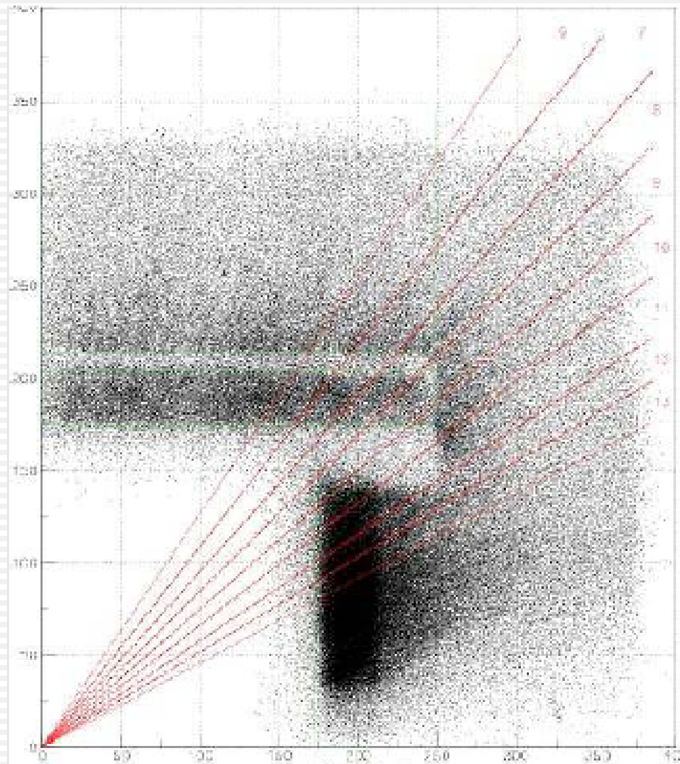




Calorimeter Simulation

- **CDF Run II simulation:**
  - GEANT 3 propagates particles up to the first inelastic interaction in the calorimeter
  - GFLASH (from H1) parameterize the electromagnetic and hadronic showers shapes in the calorimeter

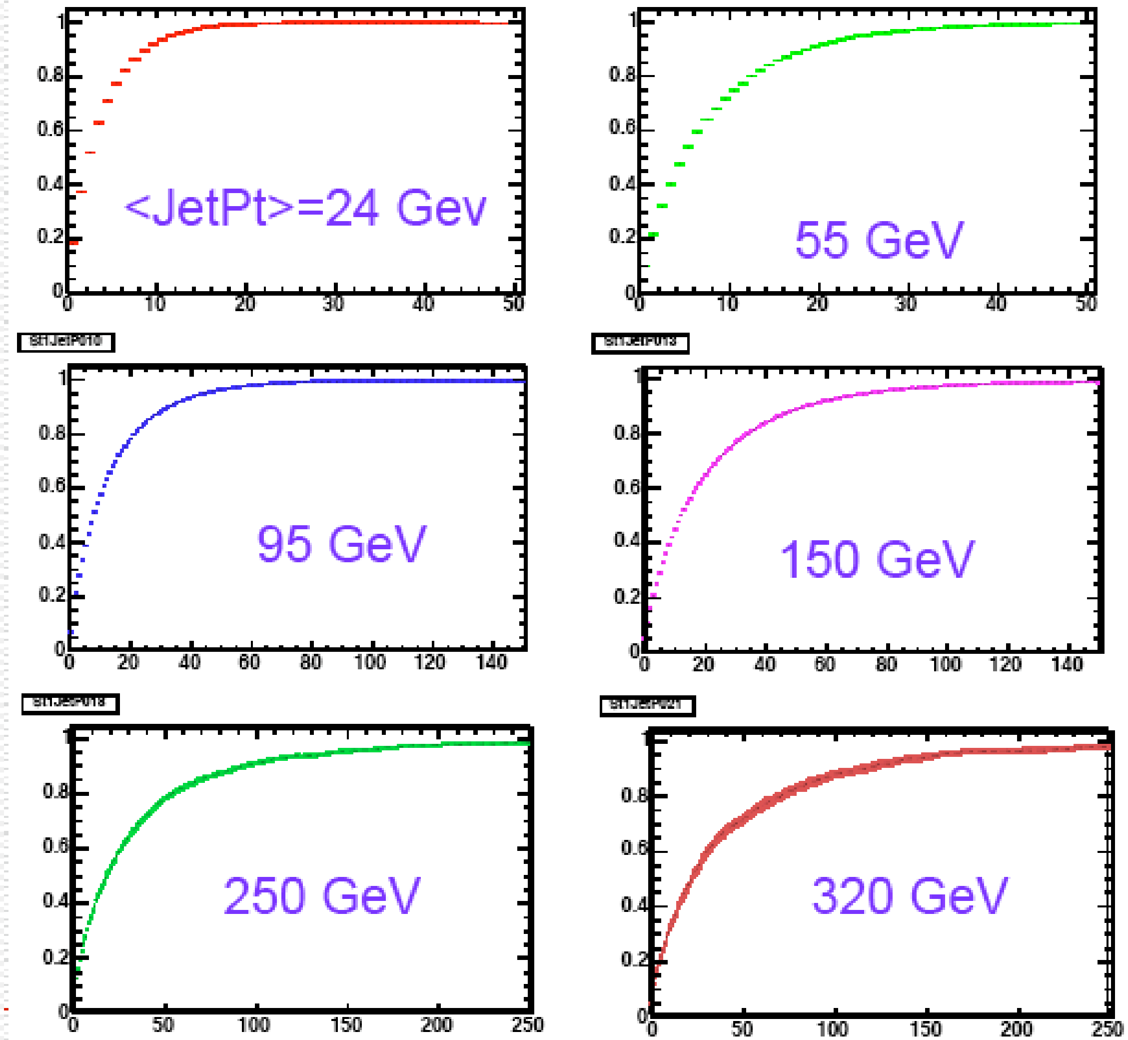
- **Calorimeter simulation (GFLASH) :**
  - Calculates spatial distribution of energy deposited by a shower and the energy which is visible to the active medium (using sampling fractions, 2 parameters)
  - Longitudinal shower profile (18 parameters)
  - Lateral shower profile (14 parameters)
  - Energy is summed into towers based on the CDF calorimeter tower segmentation
  - Parameters are modified to reproduce energy deposition from data
  - Only a fraction of the available parameters are tuned, rest using default setting by H1 collaboration



Tuning of the Calorimeter Simulation

- Method uses mixture of in-situ and test beam data:
  - Calorimeter energy E
  - Reconstructed track momentum p
- How far do we need to tune the simulation?
  - For 95 GeV jet ~70% of the energy is in particles with p<20 GeV
- Different tuning for:
  - Central and Plug
  - EM and HAD particles

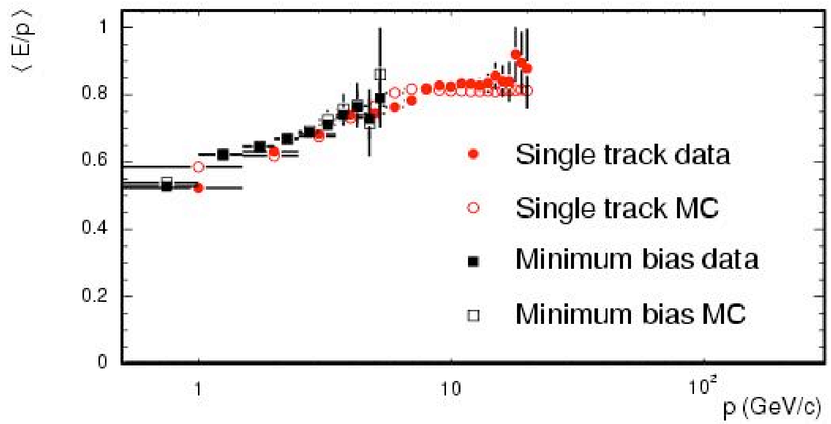
p_T of tracks in a cone of 0.7 around the jet axis

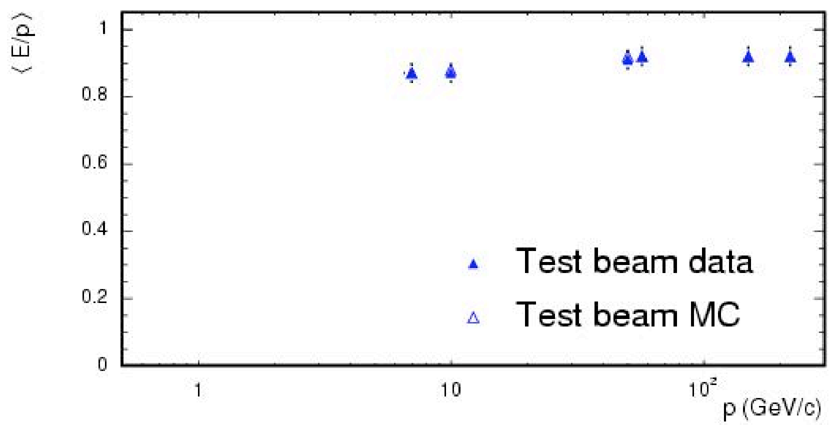


Single Particle Response - Central Region

- **HAD particles:**
  - Isolated single track data from minimum bias (0.5<p<2.5 GeV) and pion test beam data (7<p<227 GeV)
  - For testing the tuning, single track data up to p<20 GeV is used

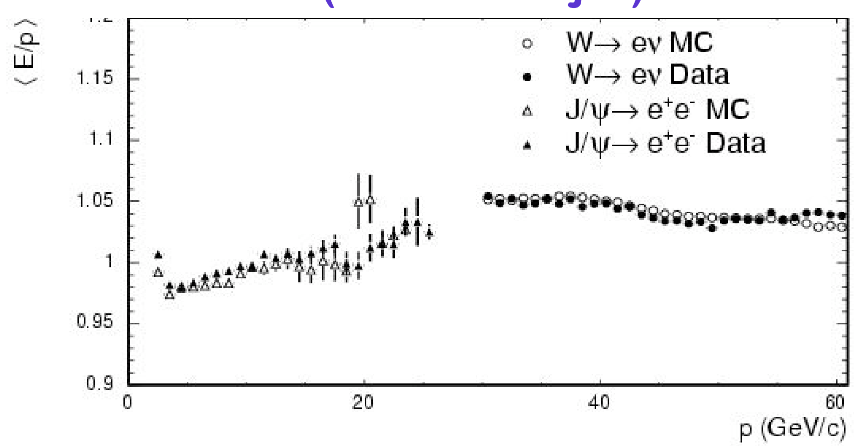
HAD (~70% of a jet)



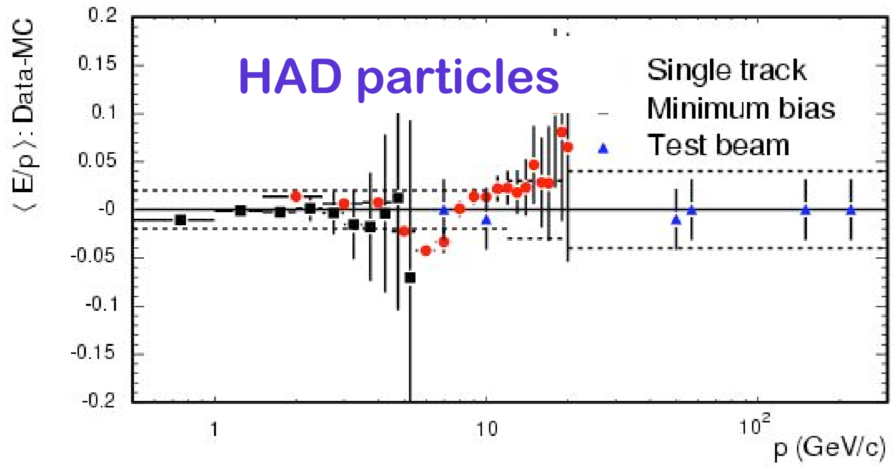


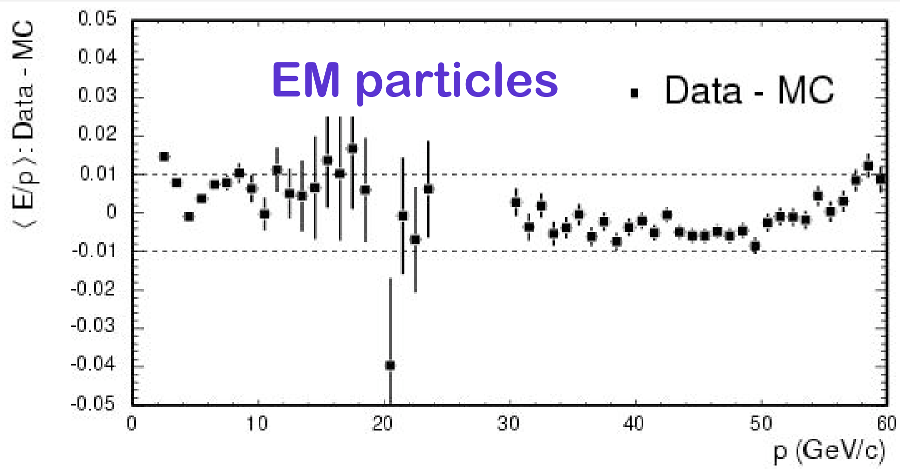
- **EM particles:**
  - *Z->e⁺e⁻* in situ data
  - Electrons from test beam

EM (~30% of a jet)



Single Particle Response - Central Region





- **Sources of uncertainty:**
  - **data-MC (low p)**
  - **statistical precision (medium p)**
  - **test beam momentum scale (high p)**
  - **test beam calibration stability (high p)**
  - **tower boundaries**
- **Uncertainties for single particle response:**
  - **HAD particles**
    - **1.5% for p<12 GeV**
    - **2.5% for 12<p<20 GeV**
    - **3.5% for p>20 GeV**
  - **EM particles**
    - **1% for all p**
- **E/p only sensitive to ~80% of the calorimeter towers. ϕ-boundaries uncertainties:**
  - **HAD = 1.9%; EM =1.6%**

Uncertainties from Single Particle Response

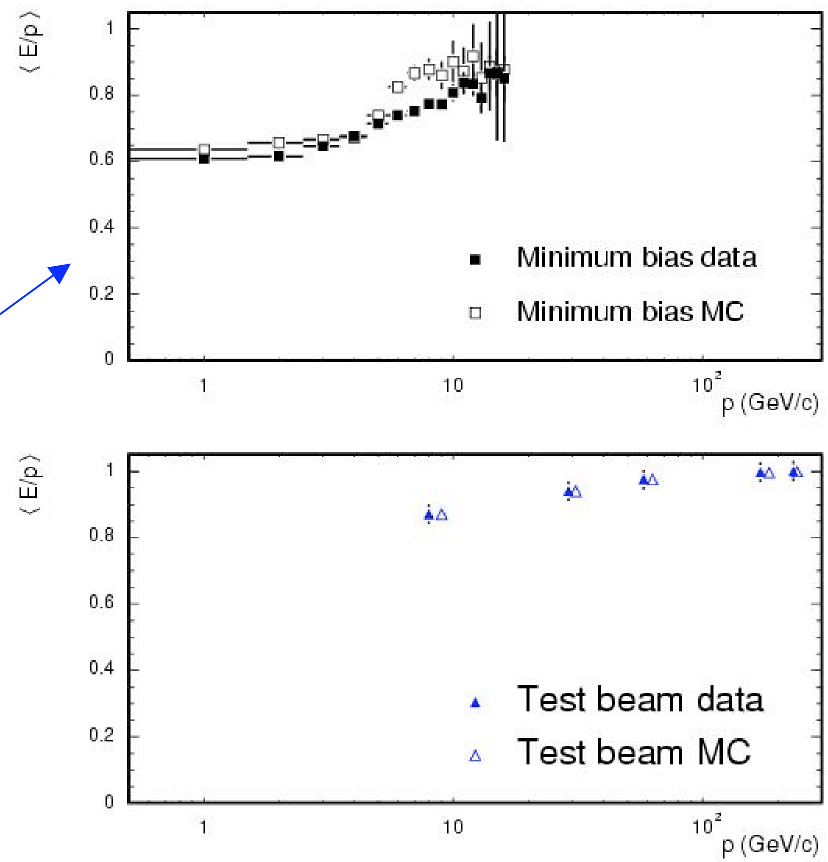
Central region

p(GeV/c)	0-12	12-20	>20
<E/p> response to hadrons			
in inner 81% (%)	1.5	2.5	3.5
in 19% near phi and eta boundaries (%)	1.9	1.9	1.9
Total hadrons (%)	2.5	3.0	4.0
<E/p> response to EM particles			
in inner 84% tower (%)	1.0	1.0	1.0
in 16% near phi boundary (%)	1.6	1.6	1.6
Total EM particles (%)	1.7	1.7	1.7

These numbers will be passed to the jet scale uncertainty

Calorimeter Simulation in the Forward Region

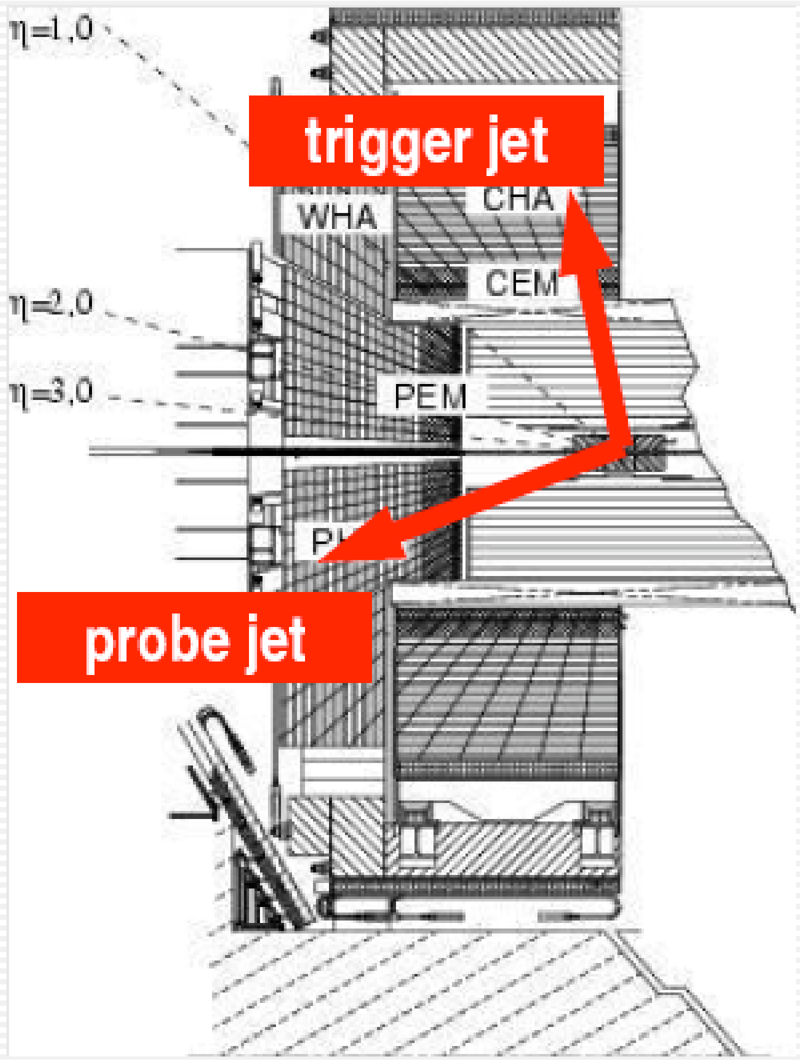
- Compared to the central region:
  - Tracking efficiency is lower
  - Momentum resolution for tracks is poorer
  - Background is larger
- Simulation has been tuned mostly to pion test beam (8.6<p<231 GeV) and some minimum bias data
- Previously only high momentum track trigger available up to |η|<1.0: new trigger available now
- Working on improving forward simulation with new data
- For now, forward region is not used for obtaining JES corrections or uncertainties (replaced by η-dependent corrections)



η-dependent Corrections

- Recalibrate energy of non-central jets (“probe jet”) with energy of central jet (“trigger jet”) using dijet balance:
  - Trigger jet: $0.2<|\eta|<0.6$
  - Dijet balance:

$$\beta = \frac{p_T^{probe}}{p_T^{trigger}} = \frac{2+\langle \Delta p_T f \rangle}{2-\langle \Delta p_T f \rangle} \qquad \Delta p_T f = \frac{p_T^{probe} - p_T^{trigger}}{(p_T^{probe} + p_T^{trigger})/2}$$



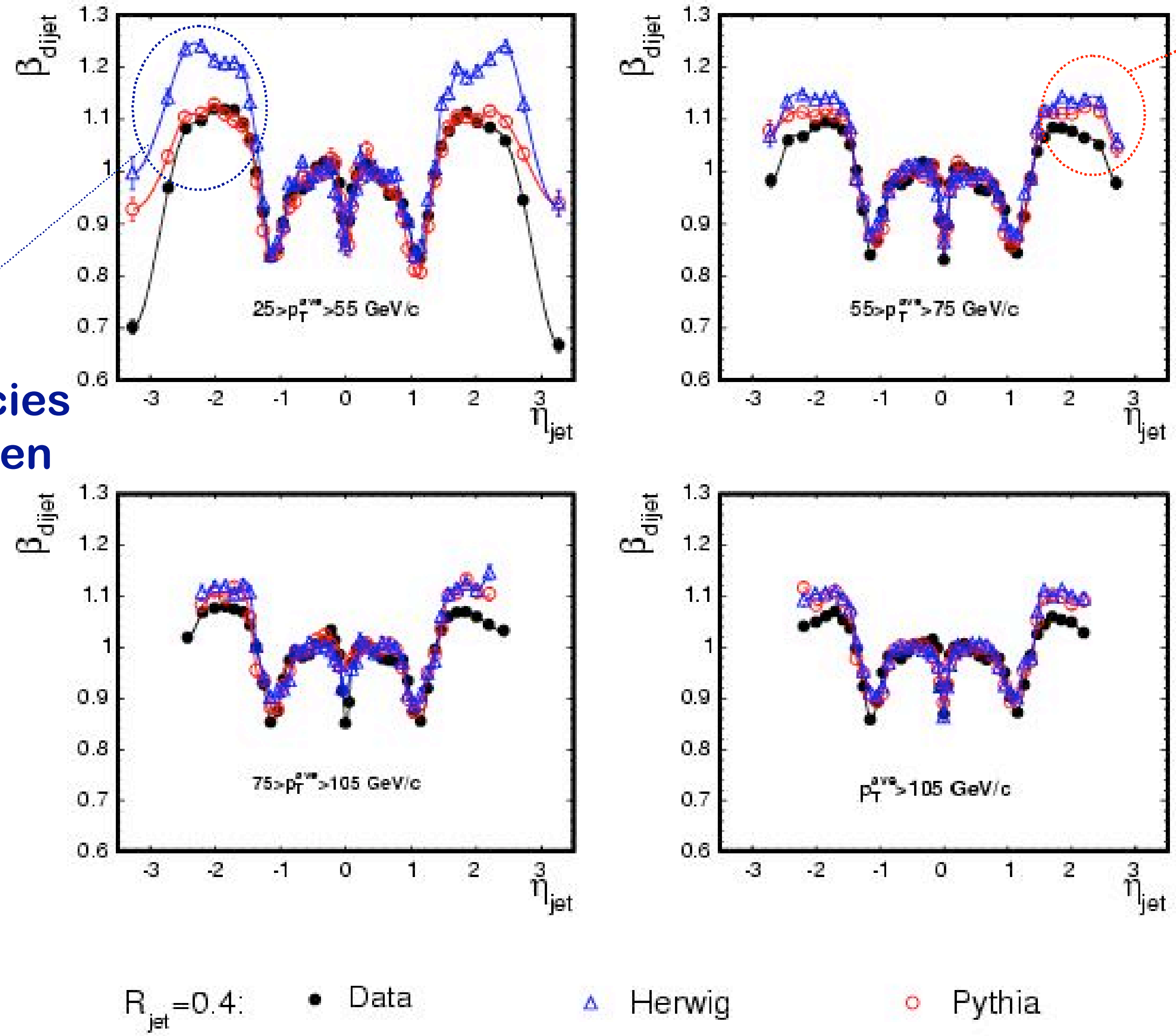
- Reduce effects from QCD radiation and ensure p_T probe = p_T trigger
  - $\Delta\phi$(jet probe, jet trigger)>2.7
  - 3rd jet p_T<7, 8, or 10 GeV
  - p_T^{ave} = (p_T trigger+p_T probe)/2 > (5 + jet p_T trigger threshold)

- Two corrections, one for data and another one for MC (Pythia)

η-dependent Corrections

- Dijet balance as a function of η

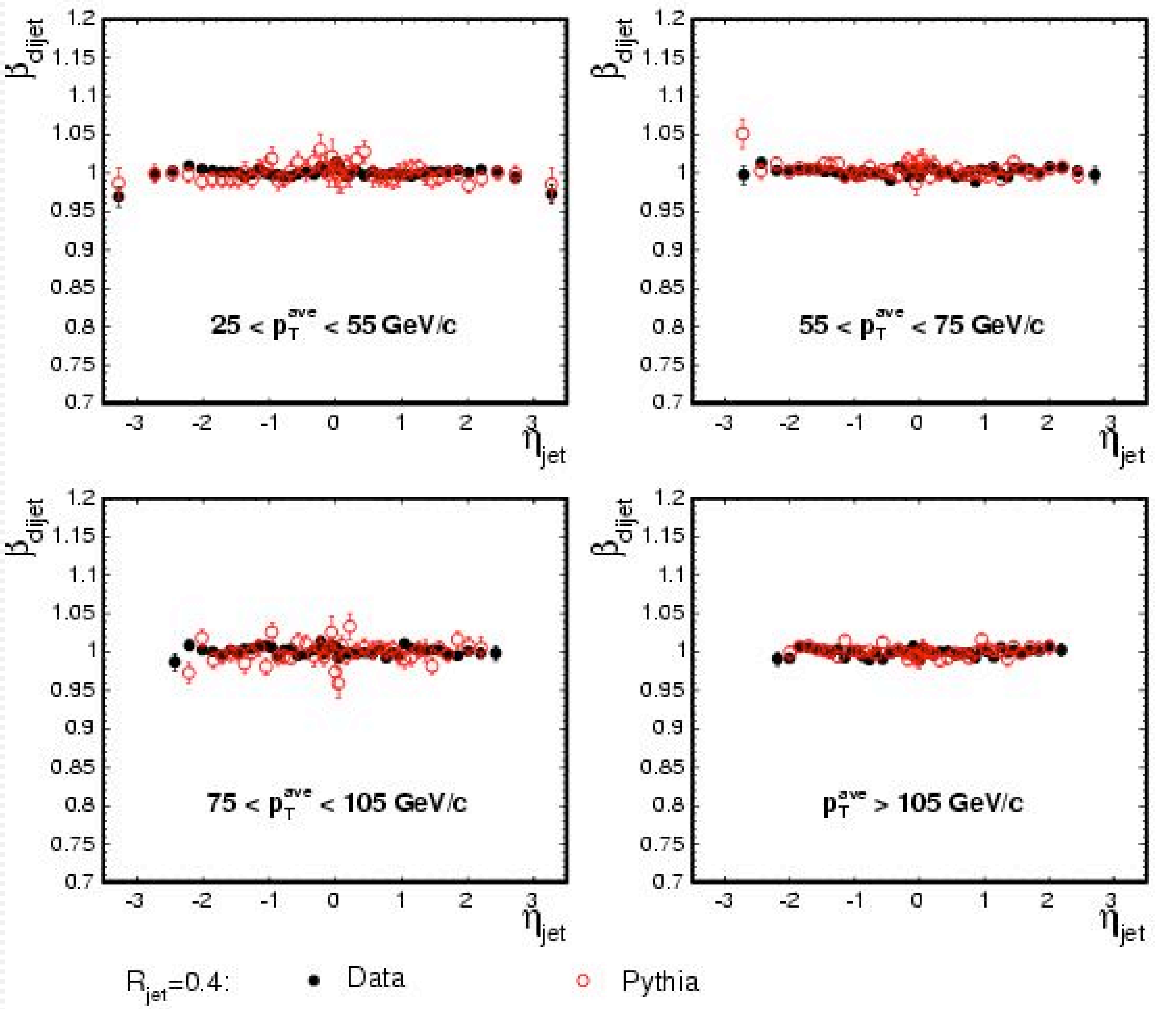
Herwig discrepancies are only seen in dijet samples



Not optimal MC tuning in plug region

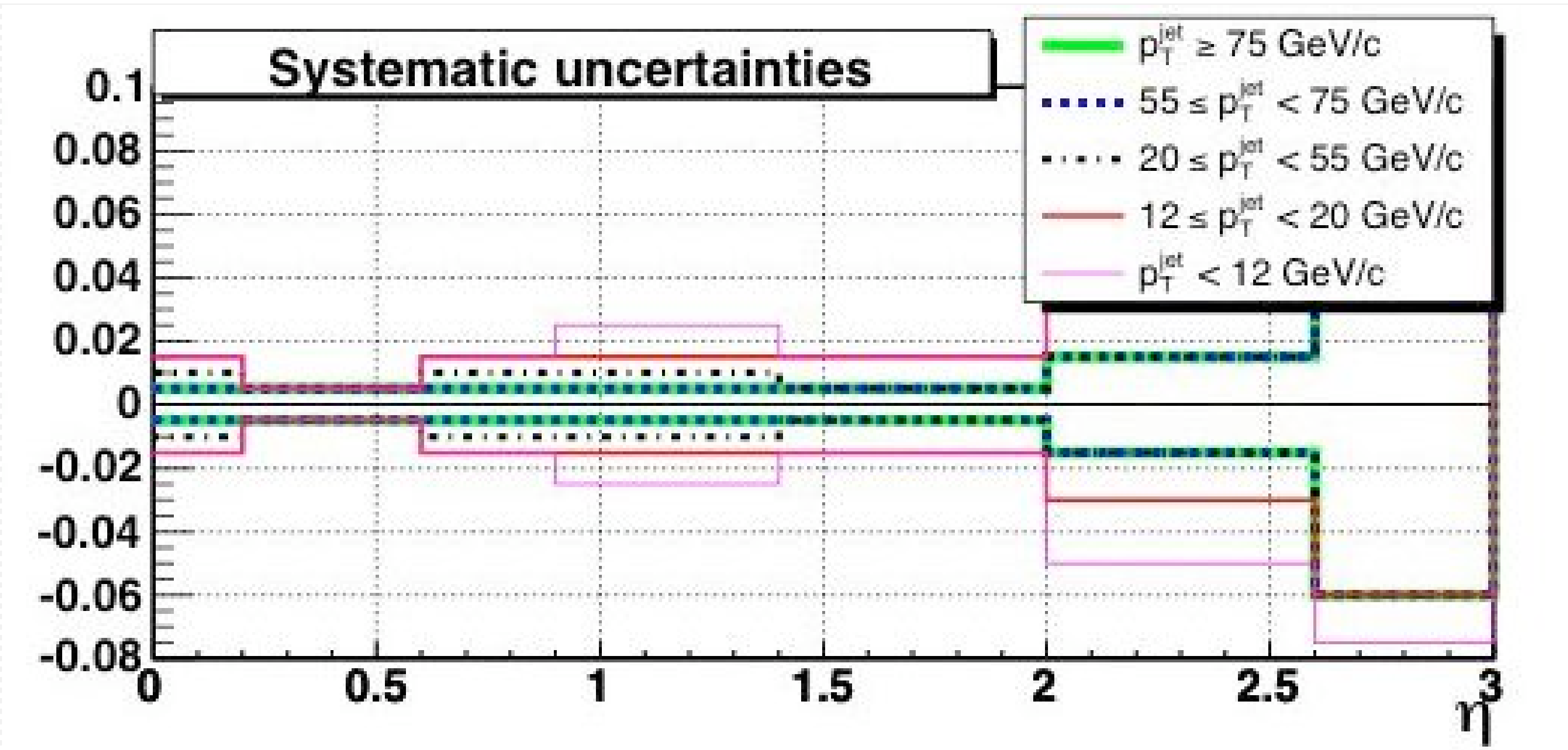
η-dependent Corrections

- Dijet balance as a function of η after corrections



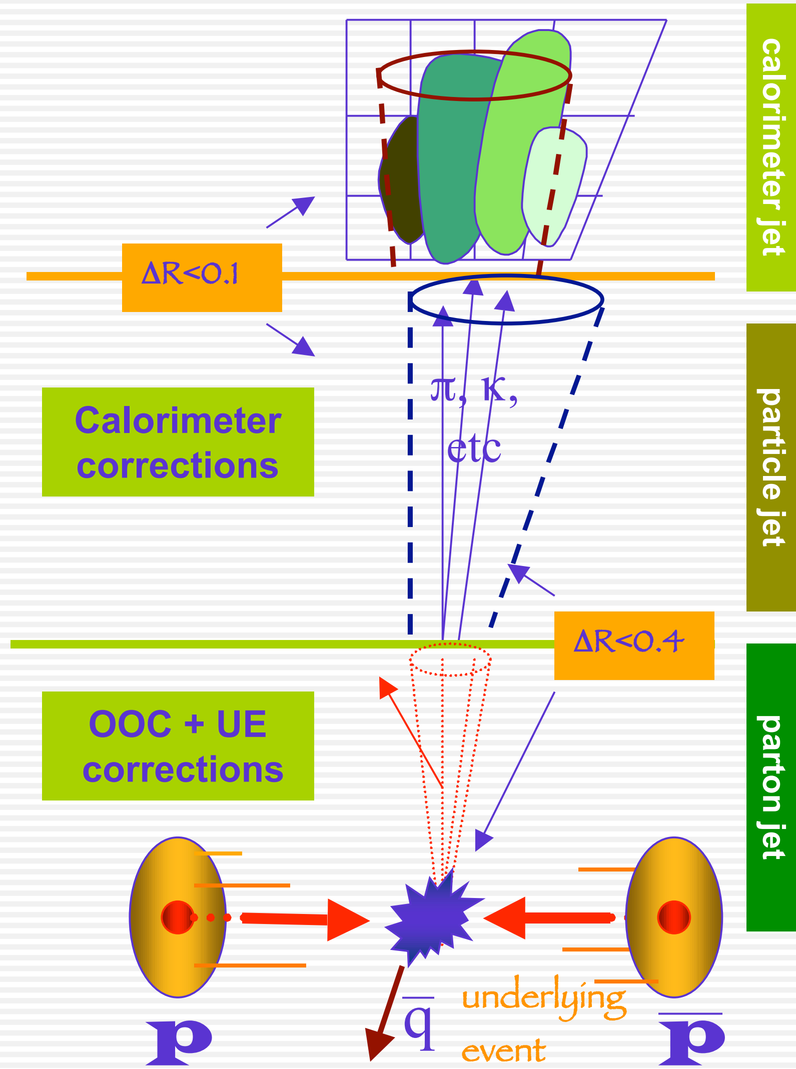
η-dependent Uncertainties

- Deviation of corrected response from unity
- Determined varying the selection cuts and the fitting procedure
- Difference between data and simulation in photon+jet events is also added to the uncertainties (certain P_T range)



Jet Energy Scale Corrections

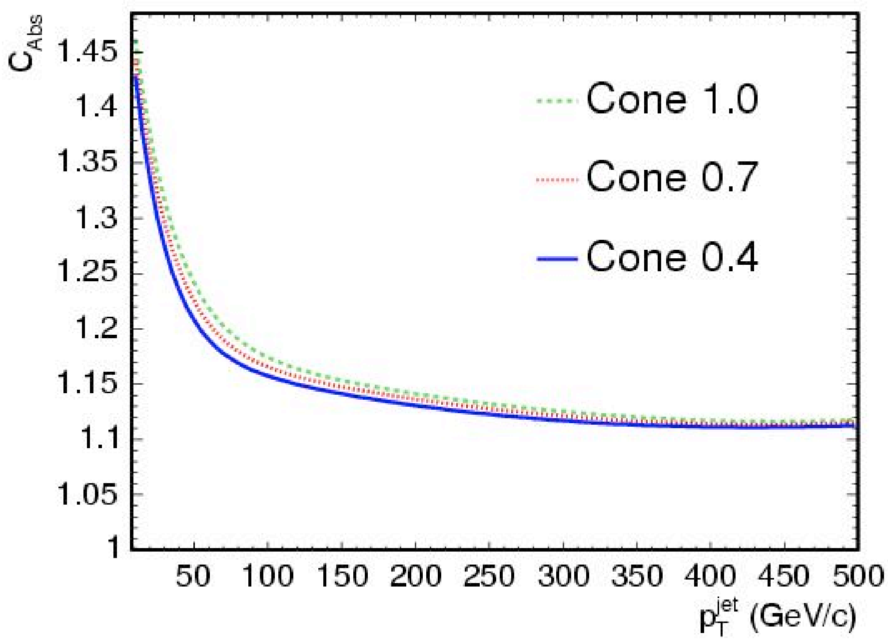
- Once the calorimeter simulation is done and the p_T response is uniform in η we need to correct for calorimeter effects
- Only obtained with central jets ($0.2<|\eta|<0.6$)
- Corrections obtained using two leading jets in MC PYTHIA dijet events with difference minimum P_T (0-600 GeV)
- Parameterize difference between calorimeter jet and particle jet (calorimeter corrections) and particle jets and parton (OOC+UE corrections)



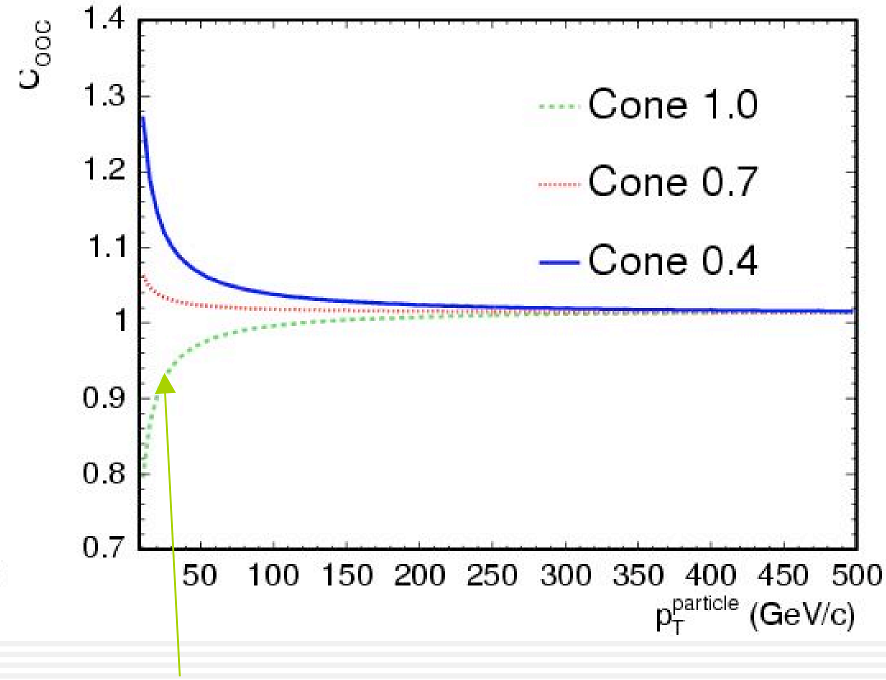
Jet Energy Scale Corrections

- Corrections are the **most probable value** for $\Delta p_T/p_T$(particle) for a given p_T(particle)

Calorimeter Corrections



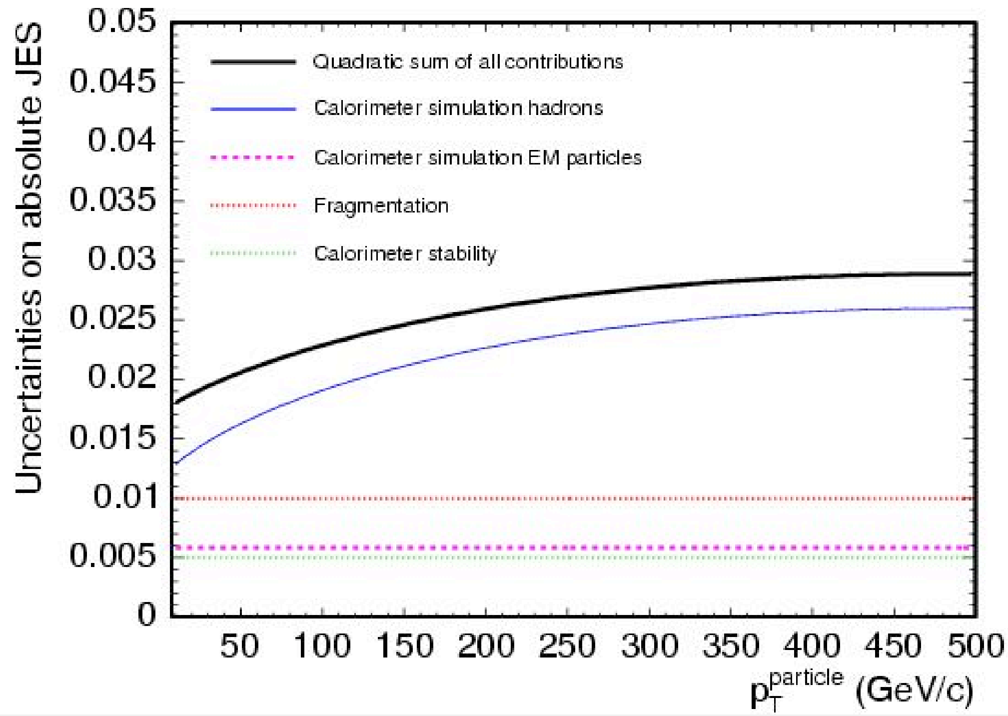
OOC+UE Corrections



More energy from UE in the jet than lost outside the jet

Calorimeter Uncertainties

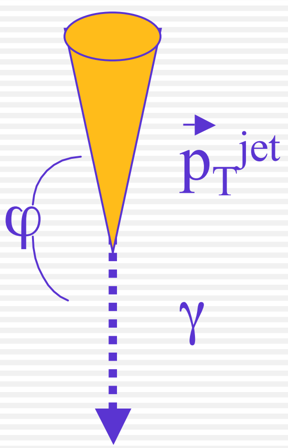
- Is the calorimeter energy scale stable?
  - Yes, up to 0.3%
- Are the jets well modeled by the simulation?
  - Is the response of the calorimeter to an individual particle correctly simulated?
    - Propagate EM and HAD single particle response uncertainty E/p to jets
  - Is the multiplicity and p_T spectrum of particles inside a jet the same for data and MC?
    - Propagate the difference between particle multiplicity in data and MC to jets



$$R_{jet} = \frac{\sum_{i=1}^{Ntracks} p_{T,i} R_{single-particle}(p_{T,i})}{\sum_{i=1}^{Ntracks} p_{T,i}}$$

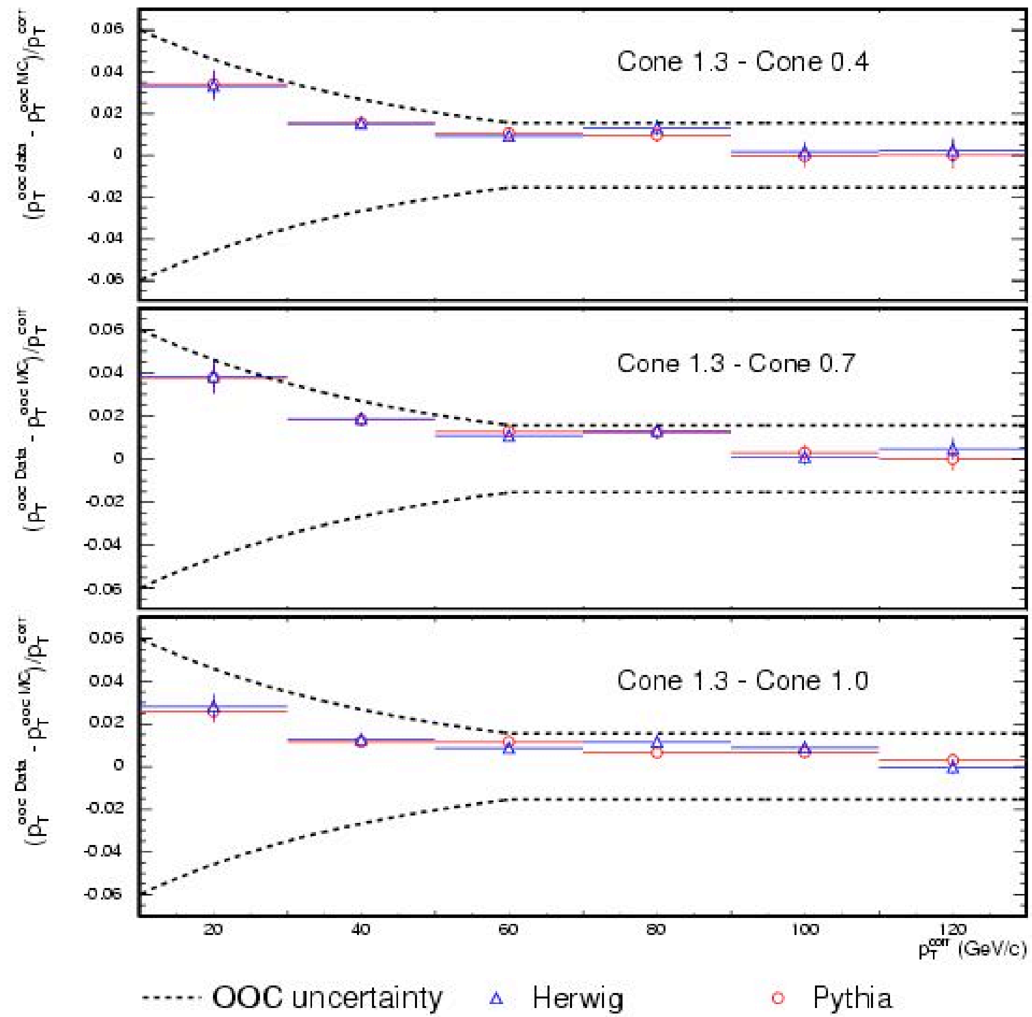
Out-of-Cone Uncertainties

- **Compare energy flow in annuli around the cone up to R=1.3 between data and MC in photon+jets events at the calorimeter level**
- **Photon p_T should balance unknown jet parent parton p_T**



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

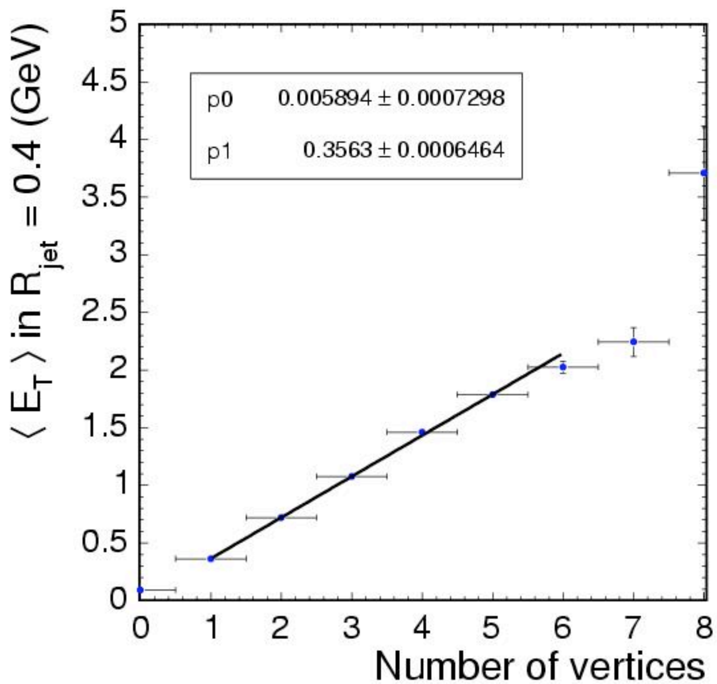
- **Uncertainty is the largest difference between data, Pythia and Herwig, scaled with C_{Abs}(p_T photon)**

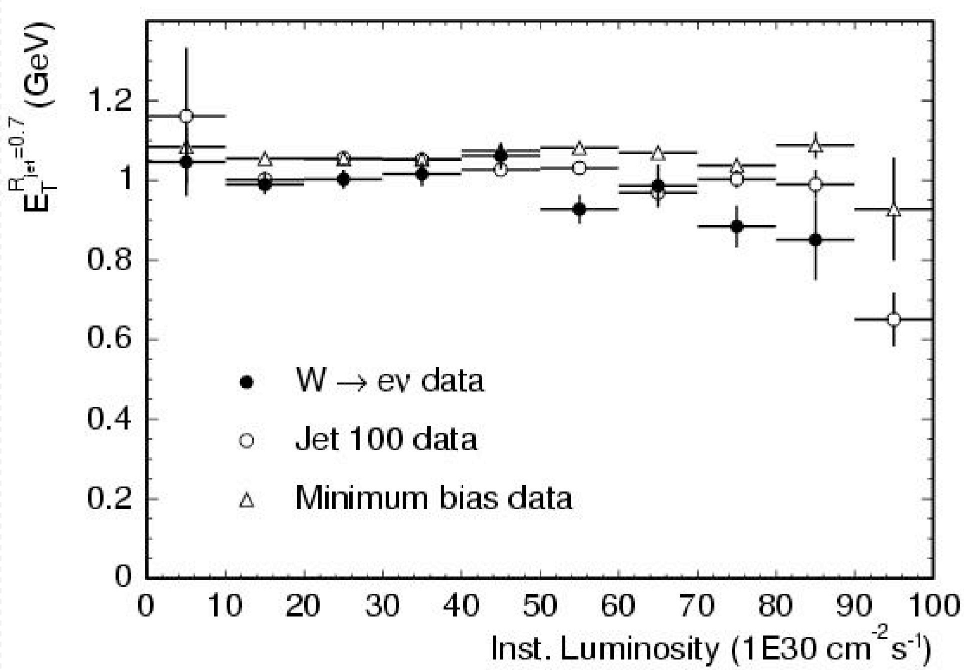


- **Additional "Splash-Out" uncertainty accounting for energy flow outside the cone of R=1.3: 0.25 GeV**

Physics Effects: Multiple Interactions

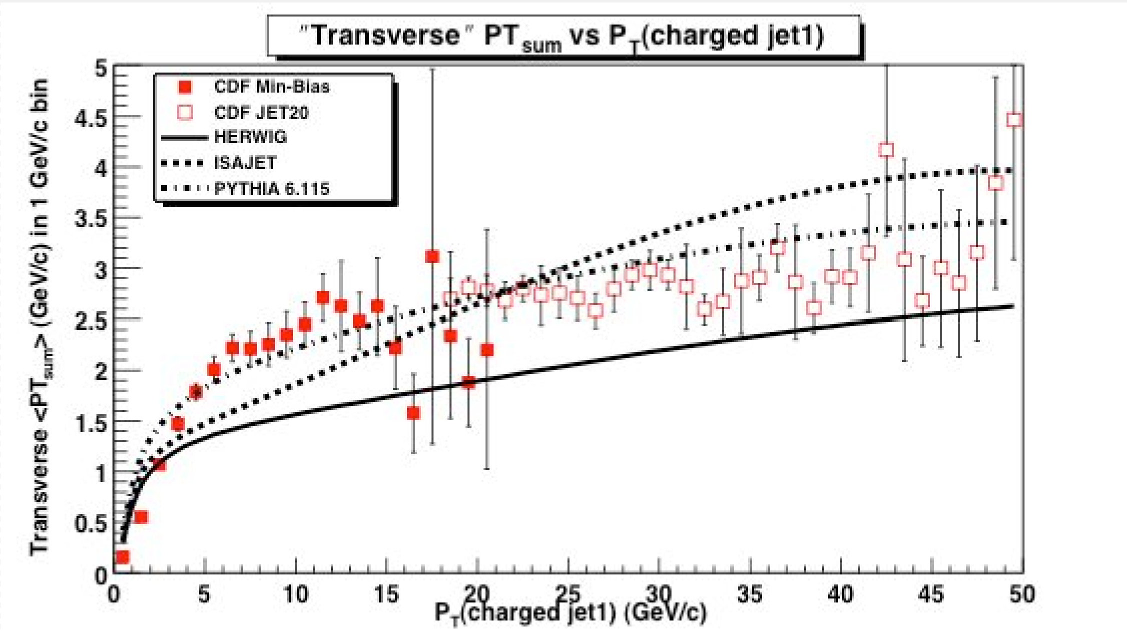
- **Correction:**
  - Energy in a random cone in minimum bias events as a function of the number of reconstructed vertices (N_{vtx})
  - Use parameterization to subtract corresponding energy
- **Uncertainty (15% of correction):**
  - Vertex reconstruction efficiency
  - Vertex fake rate





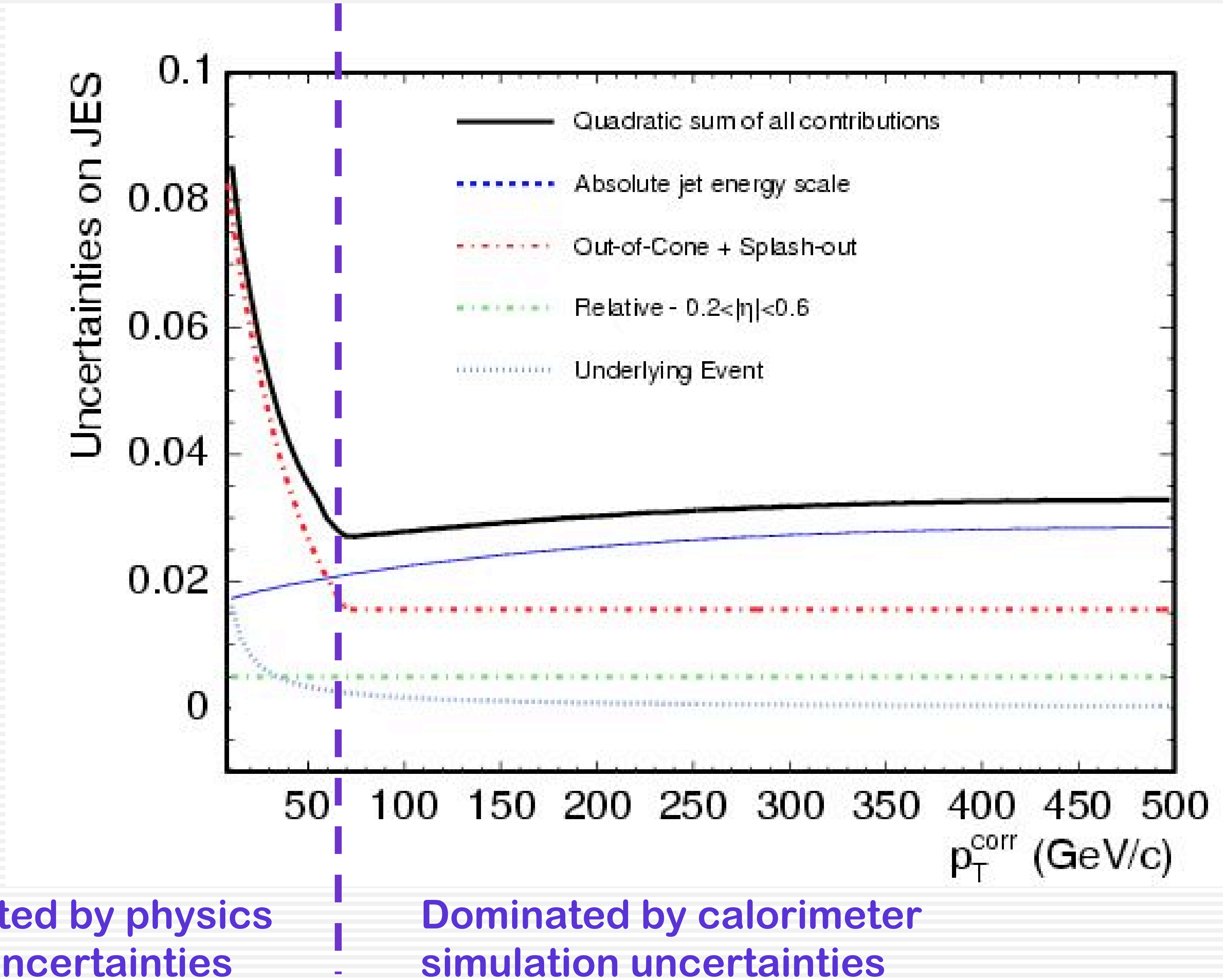
Physics Effects: Underlying Event

- **Correction**: Use Multiple Interactions correction at N_{vtx}=1
  - 0.11 GeV (R=0.4)
  - 0.32 GeV (R=0.7)
  - 0.66 GeV (R=1.0)
- **Uncertainty**: Quantify agreement between MC and data by comparing charged particle transverse energy densities in “transverse regions” w.r.t. leading jets in dijet events
  - 30% uncertainty of correction



- **Pythia UE** has been tuned to CDF data
- **Herwig UE** seems too small - we (Rick Field) are working on tuning Jimmy (Herwig UE model) to CDF Run II data

Total Uncertainties

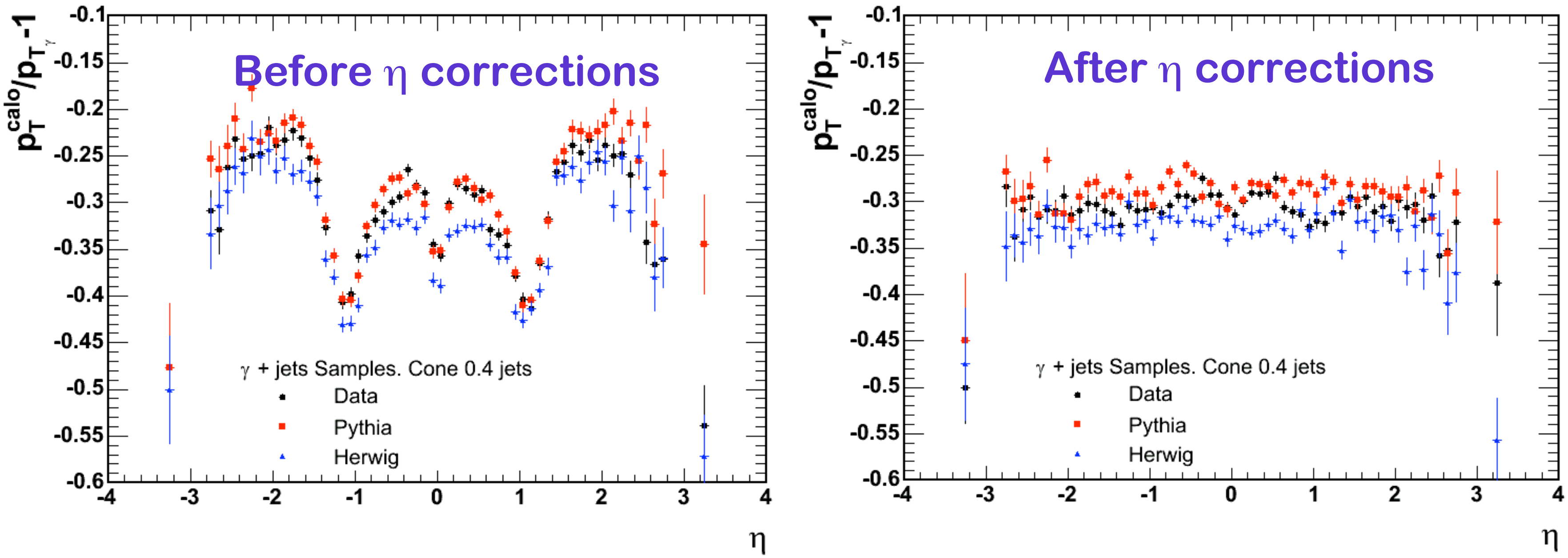


Dominated by physics model uncertainties

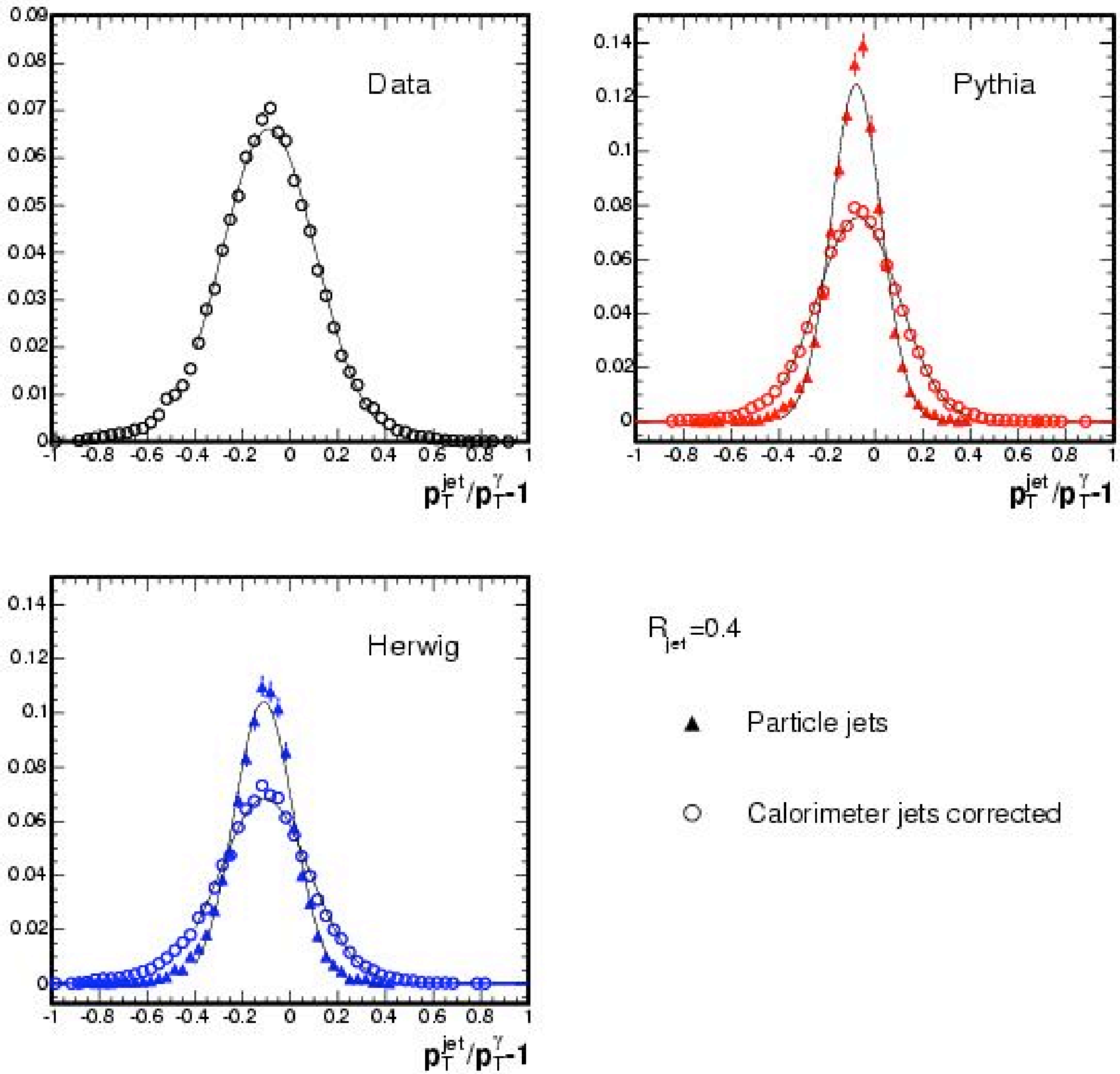
Dominated by calorimeter simulation uncertainties

Validation of the η-dependent Corrections

P_T Balance = P_T^{Jet}/P_T^{γ} -1 in Photon+Jets events



Validation of the Calorimeter Corrections

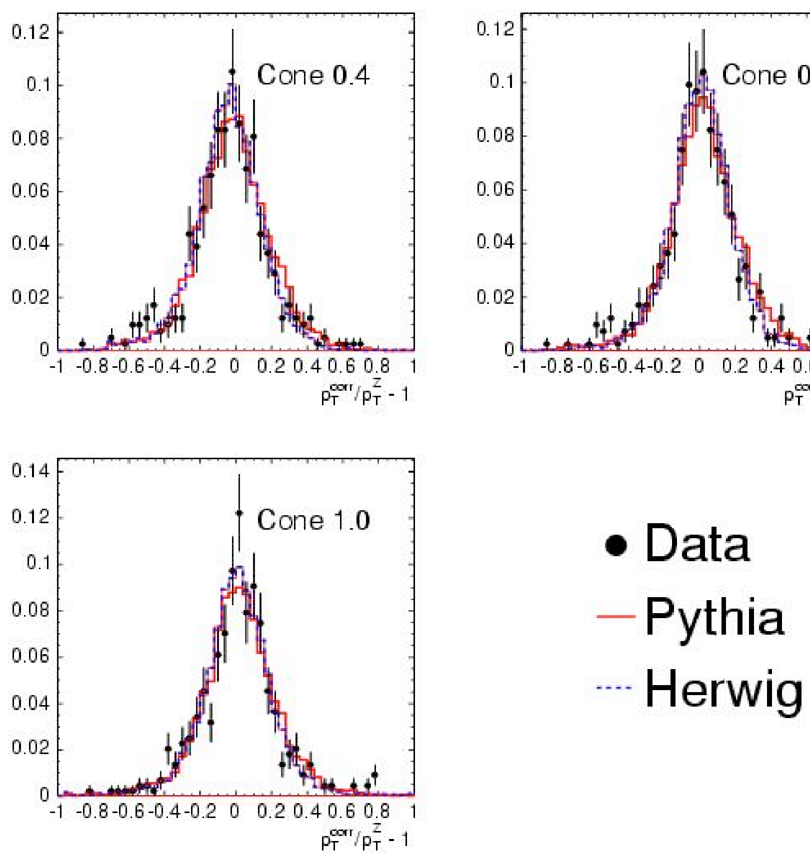


- Photon+jet data and MC after η-dependent and calorimeter corrections were applied to jets
- After corrections p_T balance of photon and jet should be similar to the particle level (p_T balance

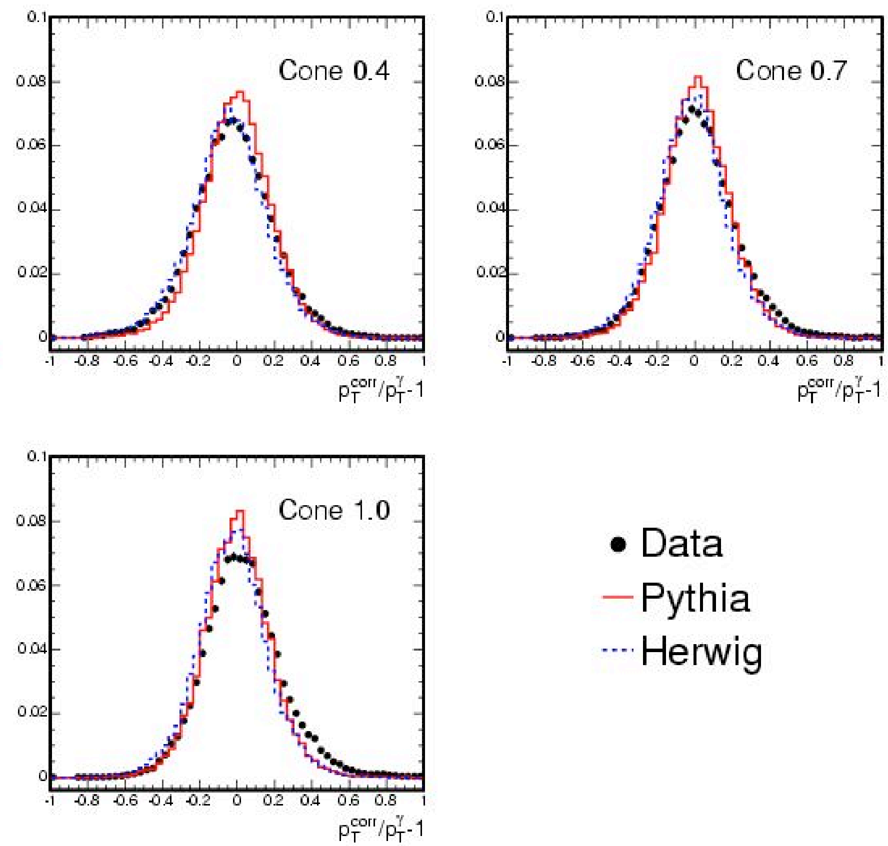
Validation of the OOC+UE Corrections

- After all corrections are applied the p_T balance between photon or Z and jet should be 0

Z+jets events

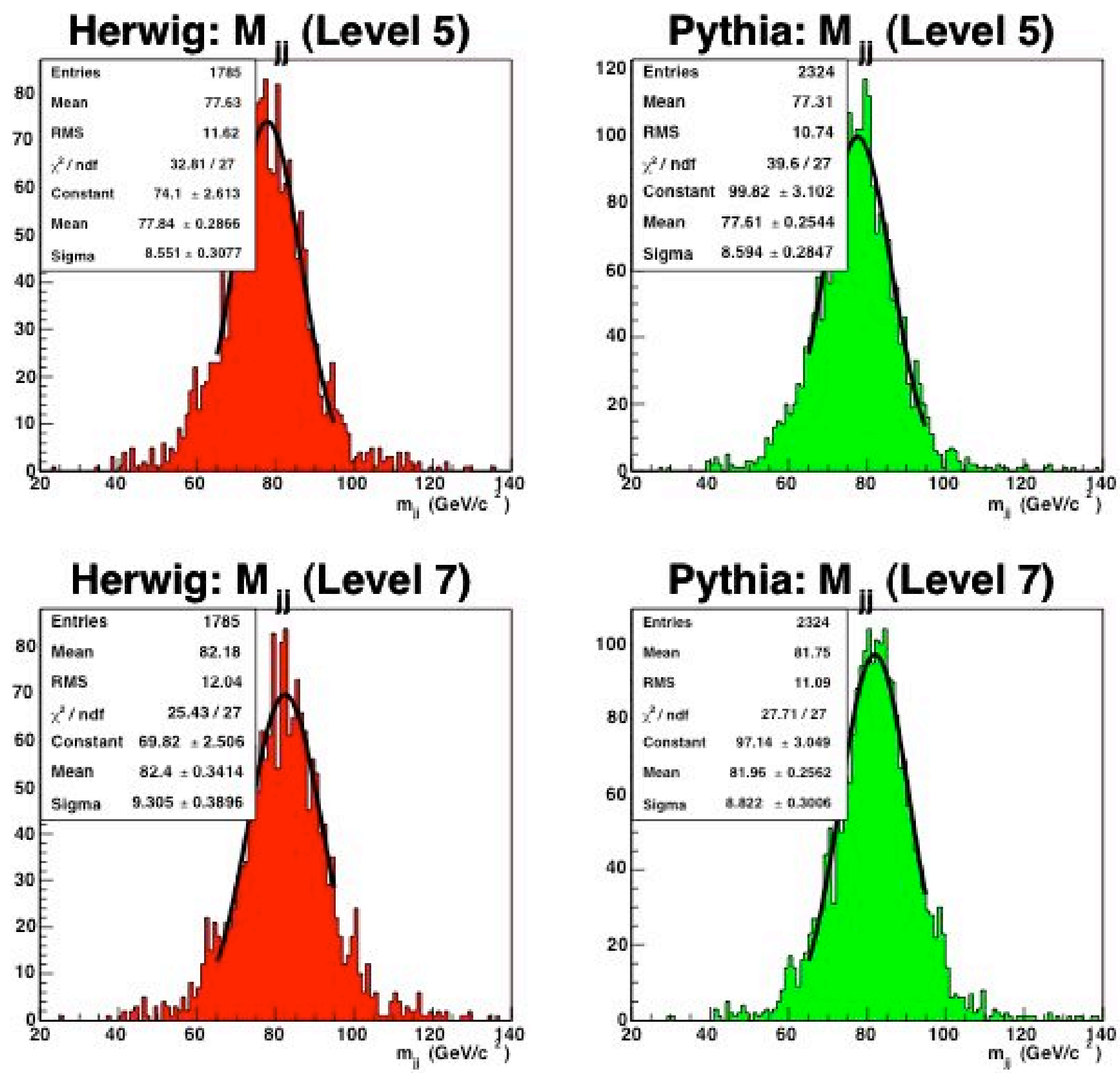


Photon+jets events

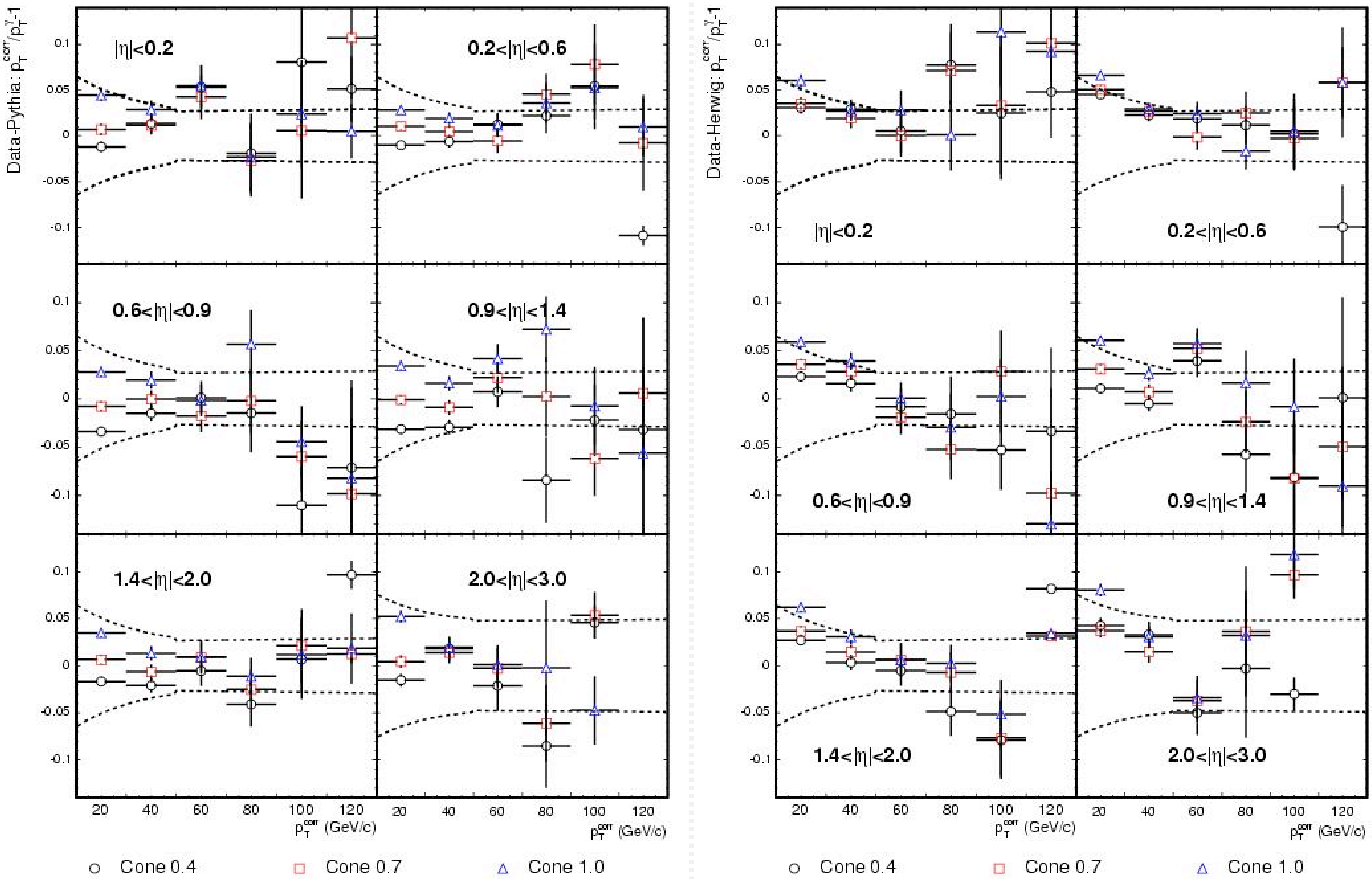


Corrections in ttbar Events

- Hadronic W mass after all corrections were applied to the jets

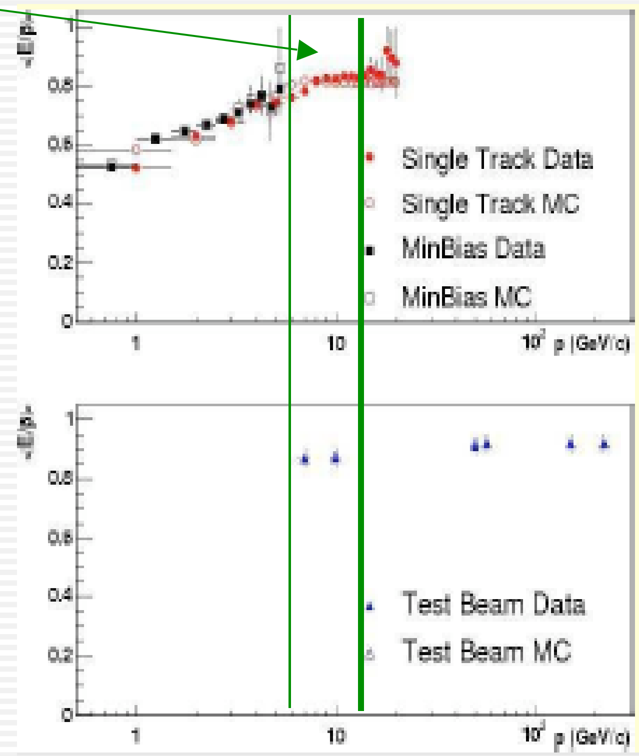


Are the uncertainties large enough?



Future Improvements

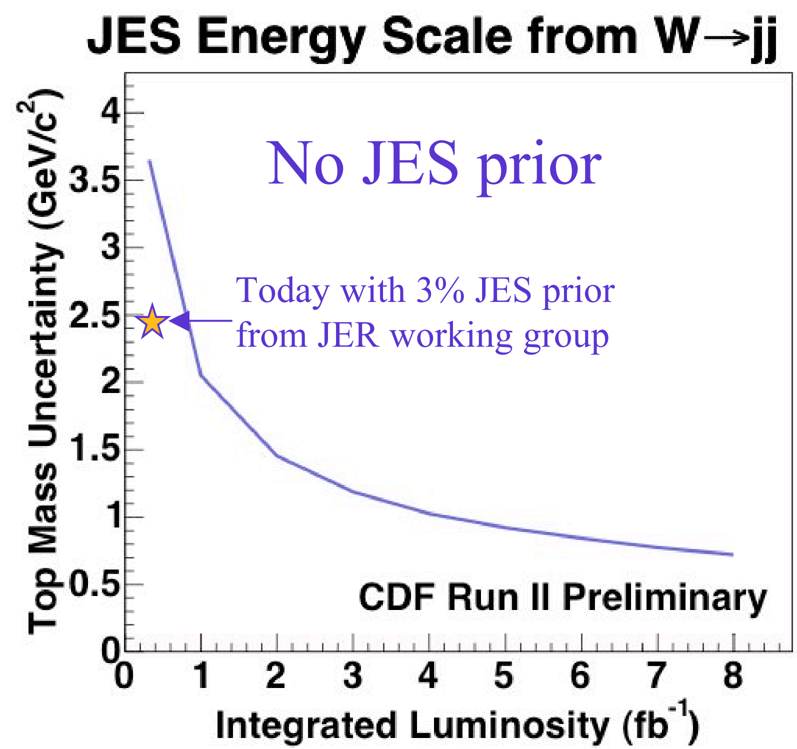
- Improve calorimeter simulation:
  - Lateral profile
  - Statistical precision of central calorimeter (medium p)
  - Extend tuning to higher p to avoid the use of test beam data
  - Measurement of single particle response in the plug calorimeter
  - Electron response in ϕ-boundaries



- Improve performance of physics generators:
  - better understanding of the underlying event, gluon radiation effects
  - tuning of Pythia, Herwig (Jimmy)
- Improve jet resolution
- Will Z->bbbar help with the JES in the near future?

Conclusions

- CDF has a set of corrections and uncertainties that are very solid
- The main component consist of tuning the calorimeter simulation to single particle response
- Uncertainties are about 3% and we are working on decreasing them as well improving our means
- Besides decreasing JES uncertainties, Improvements in JES benefit many analysis: better simulation, missing ET resolution, better physics models
- At 320pb^{-1}, the top mass in the golden channel, the JES plays an very important role reducing the error from W->jj. In the future, as more data is accumulated, the impact of JES will be limited in this channel comparing to W->jj

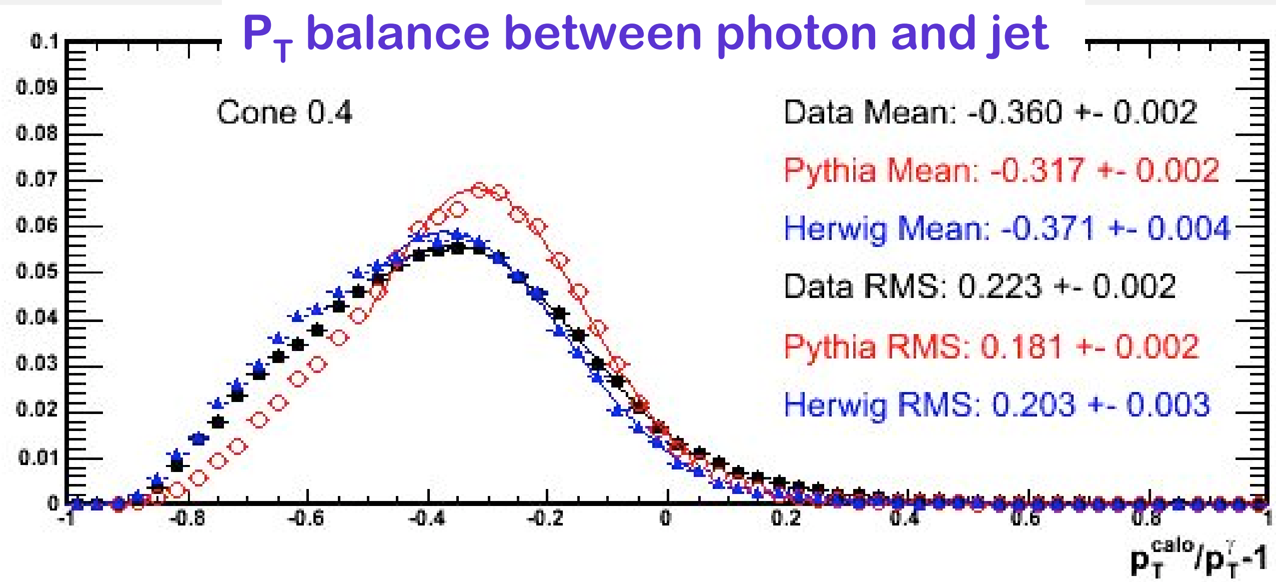


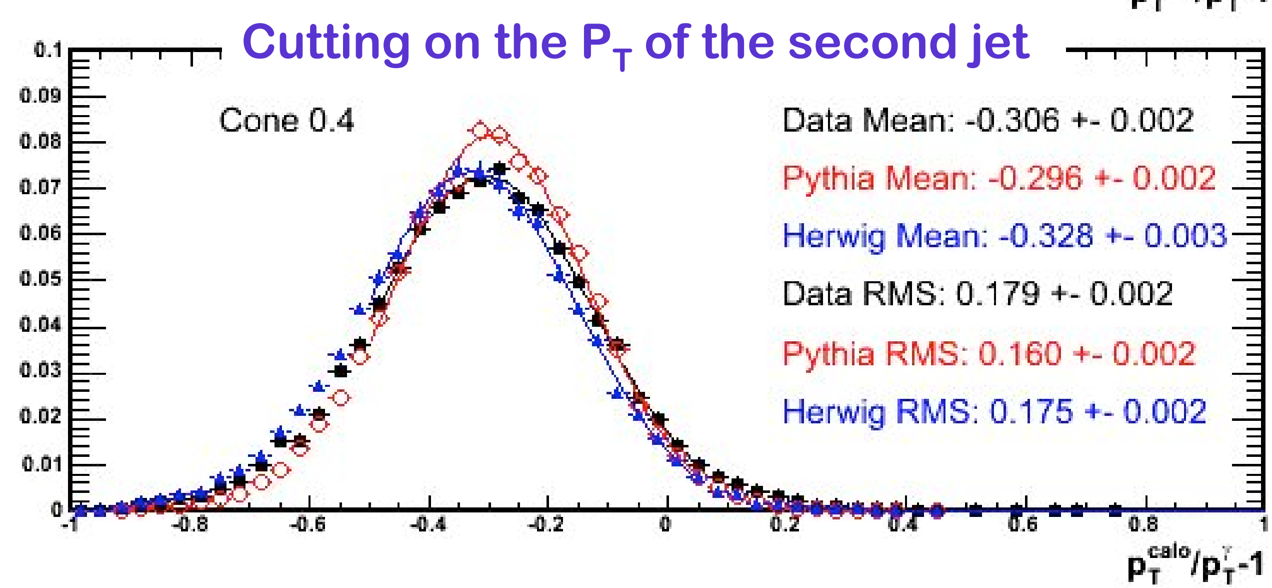
- Moreover, there are other analyses for which the JES will soon be an important uncertainty (if not yet)

More ! More !

Improvements - Monte Carlo

- Our understanding of the differences between data and MC in photon+jet is about 3%
- Decreasing the jet energy scale uncertainty means improve the Monte Carlo generators





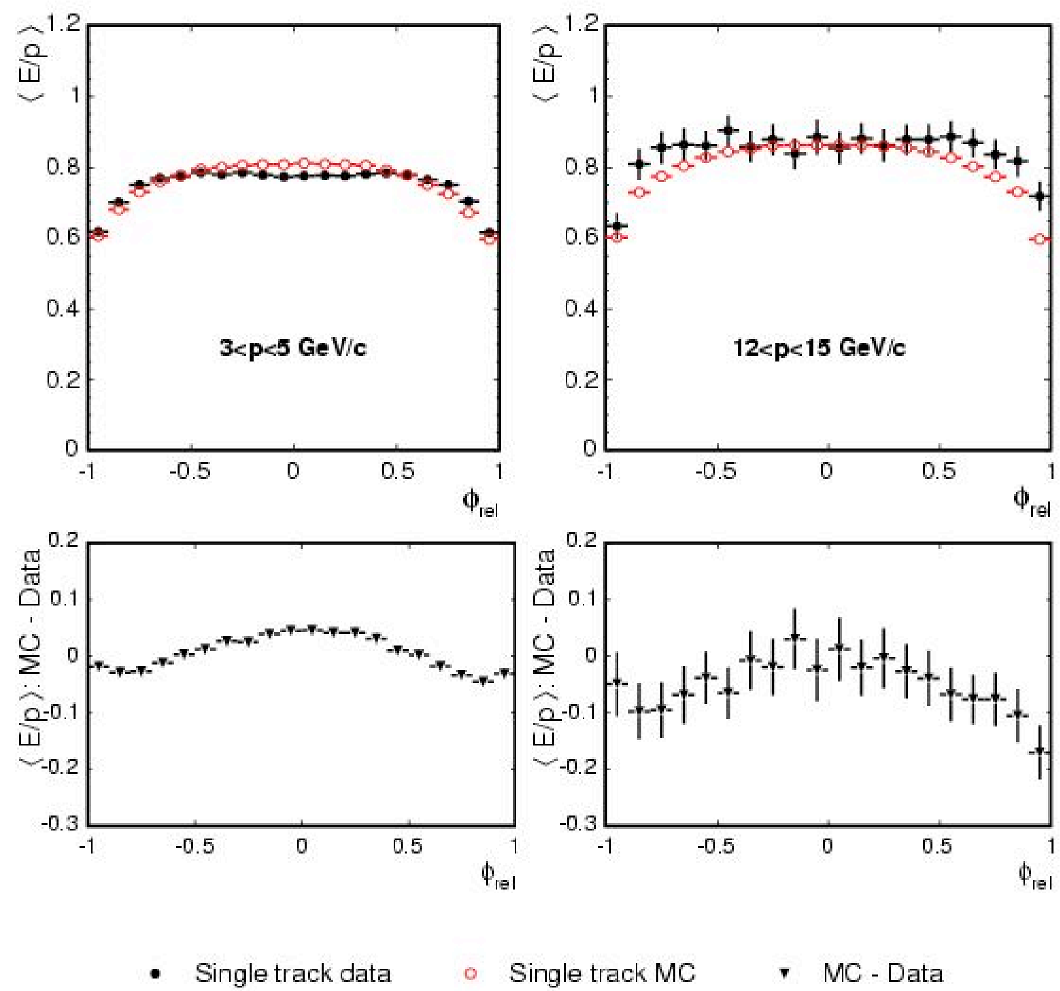
Improvements - Simulation

- Central:
  - For p<20 GeV
    - more statistics to evaluate E/p uncertainty
    - if the discrepancy is large, tune the Monte Carlo
  - For p>20 GeV
    - replace test beam measurement for in situ calibration
    - special trigger
  - Lateral profile:
    - could improve the calorimeter showering, decrease out-of-cone uncertainty
  - Need to tune simulation in ϕ cracks

- Plug:
  - Having a better forward simulation will allow us to be independent of the dijet balance method
  - p_T balance in dijet event is topology dependent and might create a bias
  - Will improve MET resolution

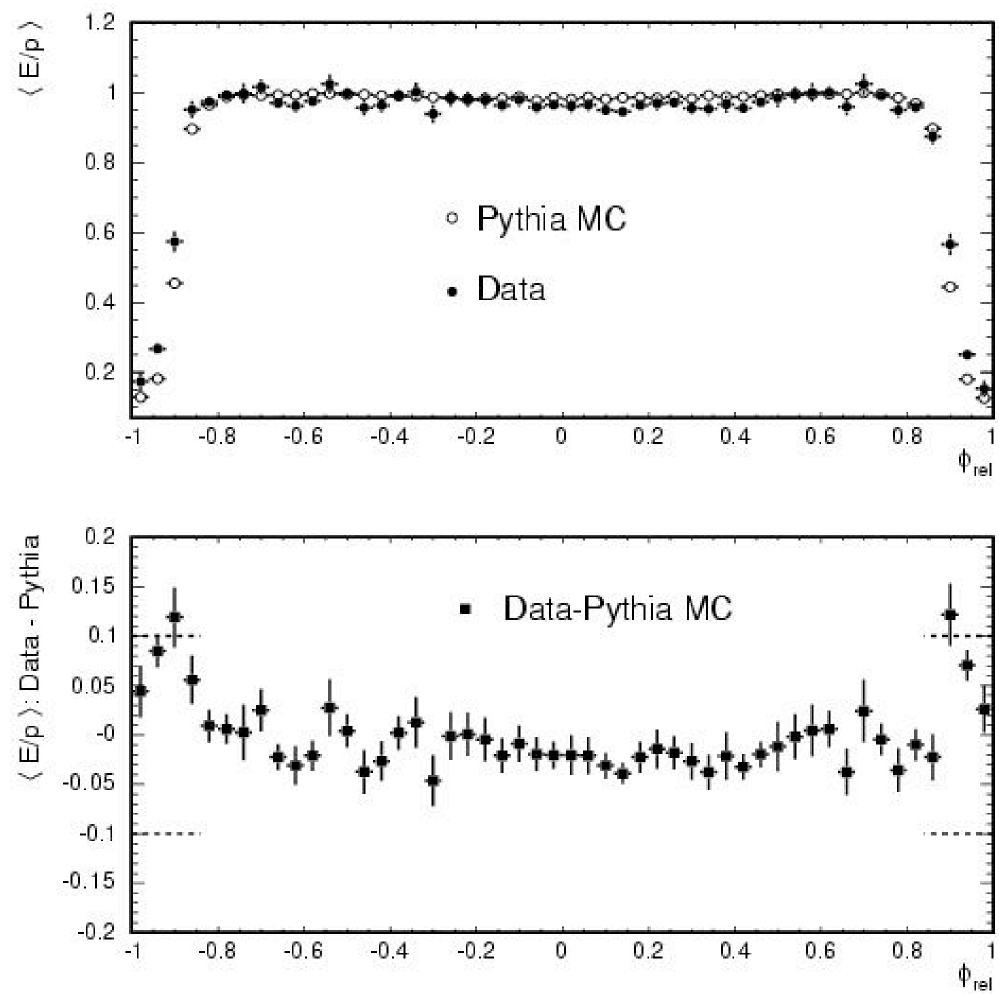
Single Particle Response - ϕ-boundaries

- **HAD particles**
- ϕ_{rel} azimuthal angle of the track impact point w.r.t. the target tower center
- Signal defined in only 81% of calorimeter HAD towers
- 10% discrepancy in 19% of the tower: 1.9% uncertainty in single particle response
- Similar effect seen at η-boundaries



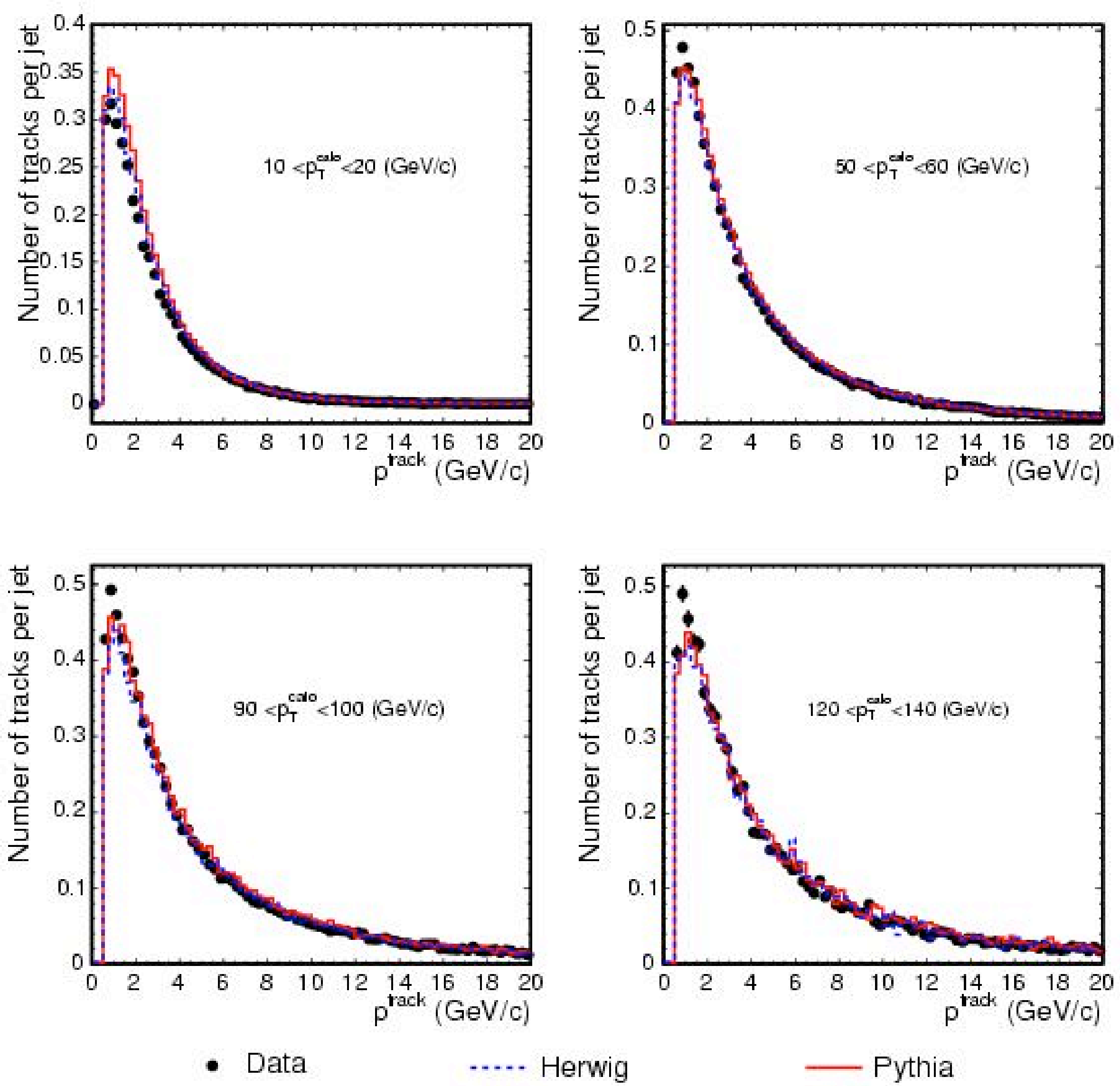
Single Particle Response - ϕ-boundaries

- **EM particles**
- **ϕ_{rel} azimuthal angle of the track impact point w.r.t. the target tower center**
- **Signal defined in 84% of calorimeter EM towers**
- **10% discrepancy in 16% of the tower: 1.6% uncertainty in single particle response**
- **Similar effect seen at η-boundaries**



Particle Multiplicity

- p_T spectrum of particles inside a jet depends on fragmentation details
- Spectrum corrected for track inefficiencies and underlying event contribution
- Good agreement between MC and data for all jet p_T bins



Particle Multiplicity Uncertainties

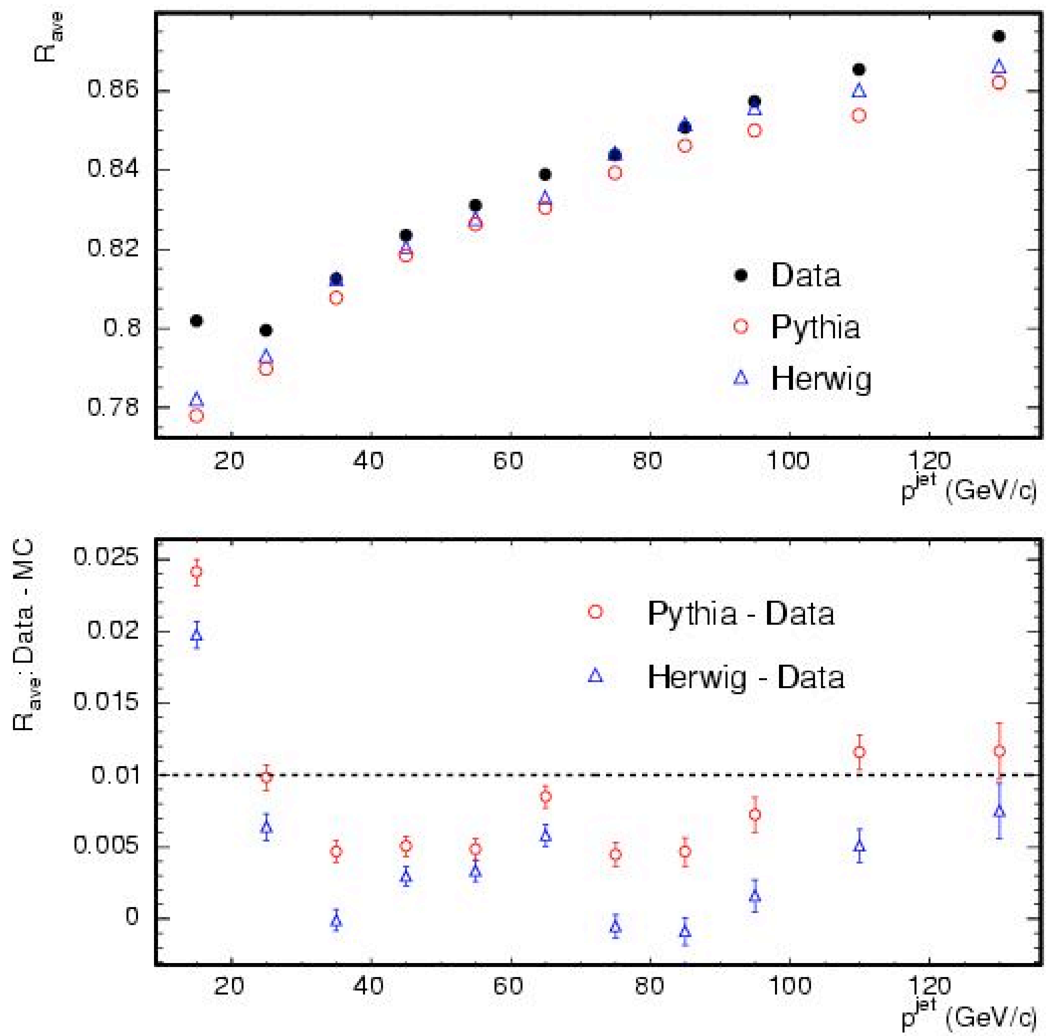
- Uncertainty derived from calculating

$$R_{jet} = \frac{\sum_{i=1}^{Ntracks} p_{T,i} R_{single-particle}(p_{T,i})}{\sum_{i=1}^{Ntracks} p_{T,i}}$$

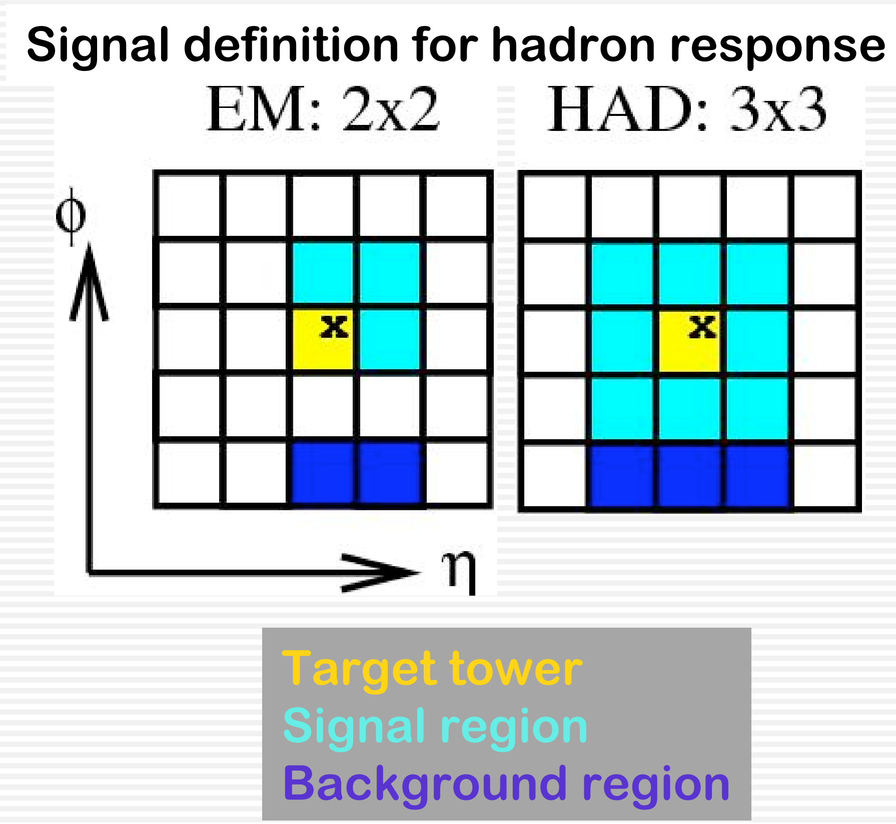
fixing the single particle response

- Pythia and data agree within 1% for 20-220 GeV jets, take as uncertainty

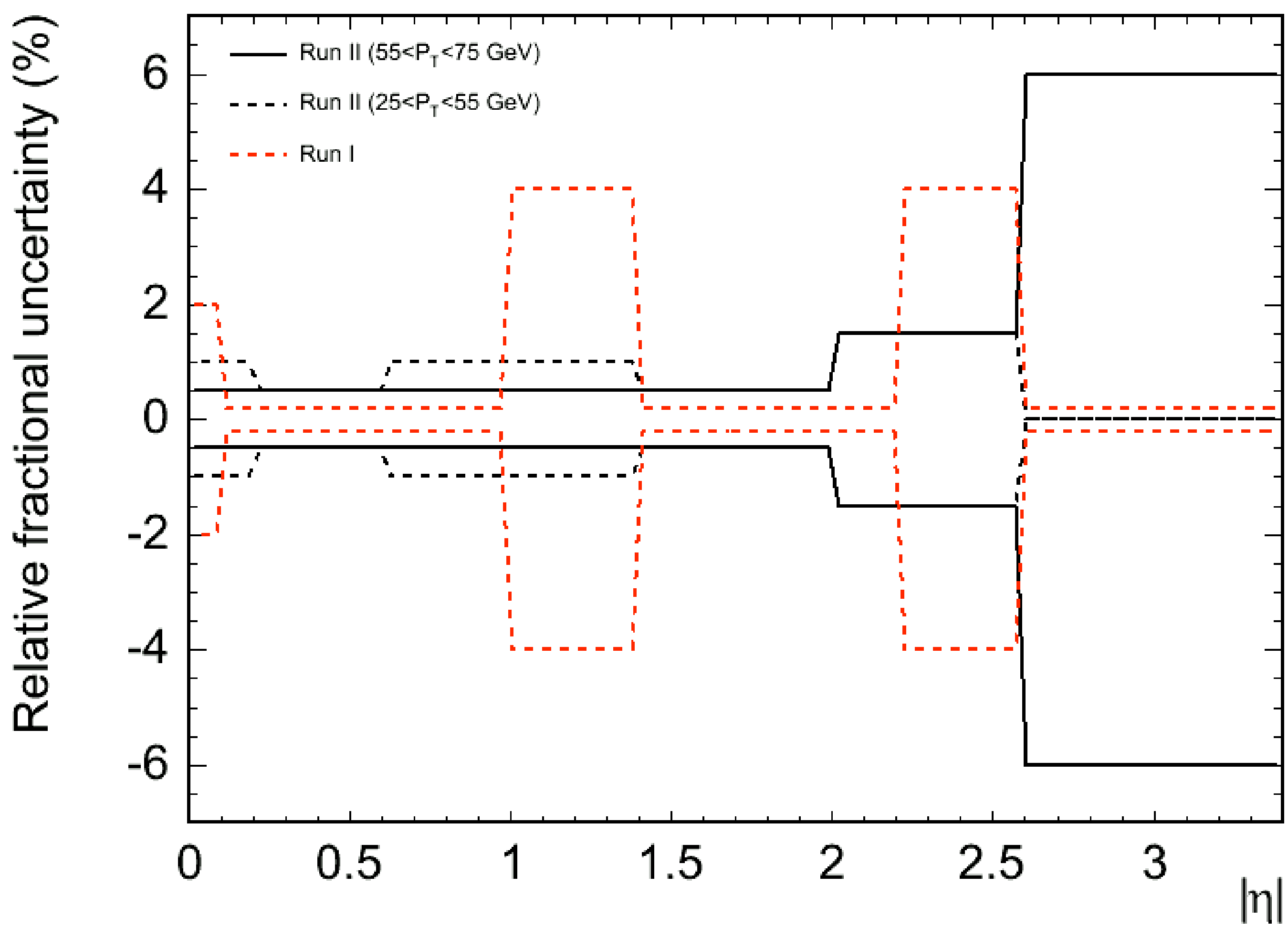
- Herwig and Pythia agree within <1%, not added to total uncertainty



Single Particle Response - Signal Definition



η-dependent Uncertainties Run I vs Run II



Gflash in a Nutshell

Parametrization of single particle response:

$$\propto a + b \tanh(c \ln E_{inc} + d)$$

simple model for incident energy dependence

fraction of deposited energy | relative sampling fractions

energy deposit

$$dE_{vis}(r) = E_{inc} f_{dep} \tilde{m} \left[\frac{\tilde{e}}{\tilde{m}} c_e f_e(r) + \frac{\tilde{h}}{\tilde{m}} c_h f_h(r) \right] dr$$

shower profile

$$f(r) \propto L(z) T(r)$$

z: shower depth

r: radial distance form shower center

longitudinal part:

- photons, electrons: $L(z) = \frac{(\beta z)^{\alpha-1} e^{-\beta z}}{\Gamma(\alpha)}$

2 parameters: α, β

- hadrons: sum of three subprofiles (all Γ functions):

$$L \propto c_h H(x)_h + c_f H_f(y) + c_l H_l(z)$$

pure hadronic shower

π^0 produced in *first* interaction

π^0 produced in *later* interactions

3×6 parameters: $\langle\alpha\rangle$, $\langle\beta\rangle$, σ_α, σ_β, $\langle f_{dep}\rangle$, $\sigma(f_{dep})$

mean and widths of 2 shower class fractions

lateral part:

$$T(r) = \frac{2 r R_0^2}{(r^2 + R_0^2)^2}$$

- R_0: log-normal distribution in units of Moliere radius
- photons, electrons: n=2
- hadrons: n=1

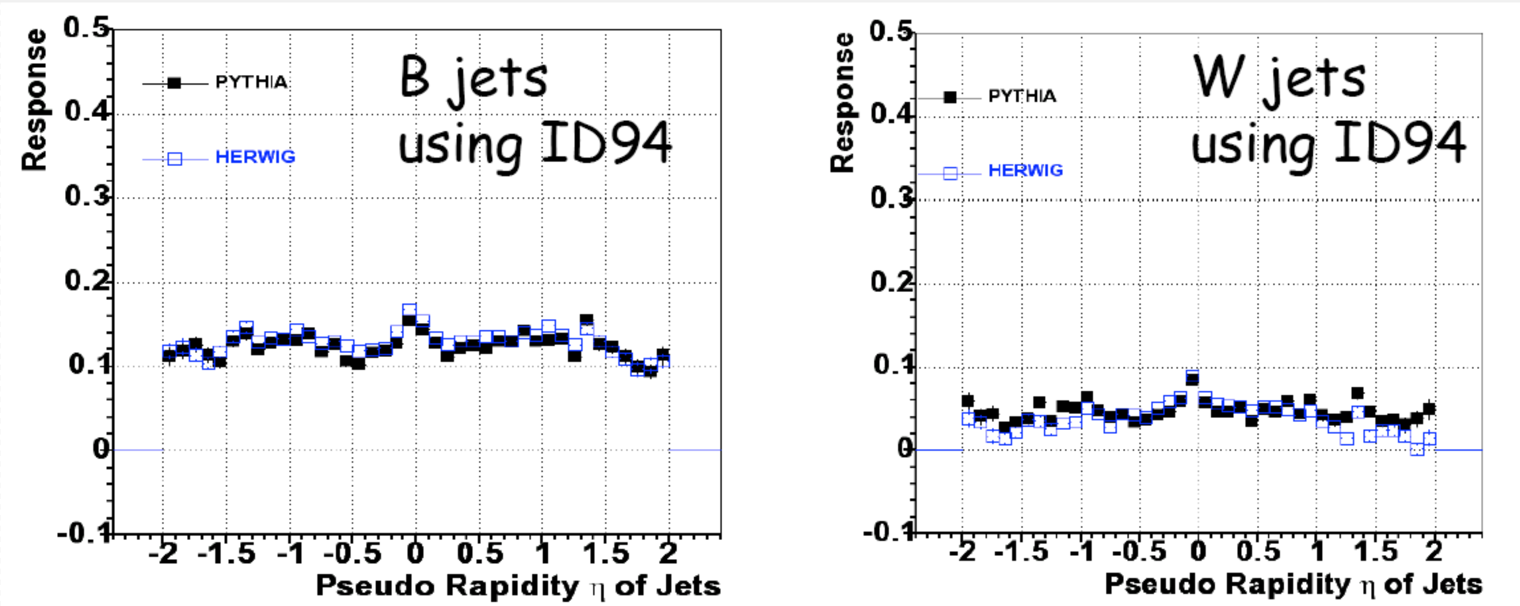
$$\langle R_0(E_{inc}, z)\rangle = [R_1 + (R_2 - R_3 \ln E_{inc}) z]^n$$

$$\frac{\sigma_{R_0}(E_{inc}, z)}{\langle R_0(E_{inc}, z)\rangle} = [(S_1 - S_2 \ln E_{inc})(S_3 + S_4 z)]^2$$

7 parameters: $R_1, R_2, R_3, S_1, S_2, S_3, S_4$

Corrections for b Jets

- The scale of b jets is different:
  - Taken into account when using top specific corrections or transfer functions



- But b and light jets seem to share similar characteristics:
  - In top analyses, we assign an small uncertainty of 0.6 GeV