How to Calibrate Jet Energy Scale?

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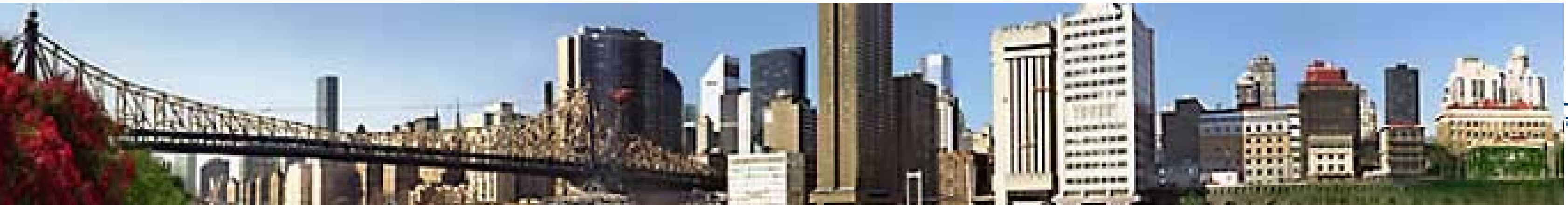


Jets in Top Quark Measurements

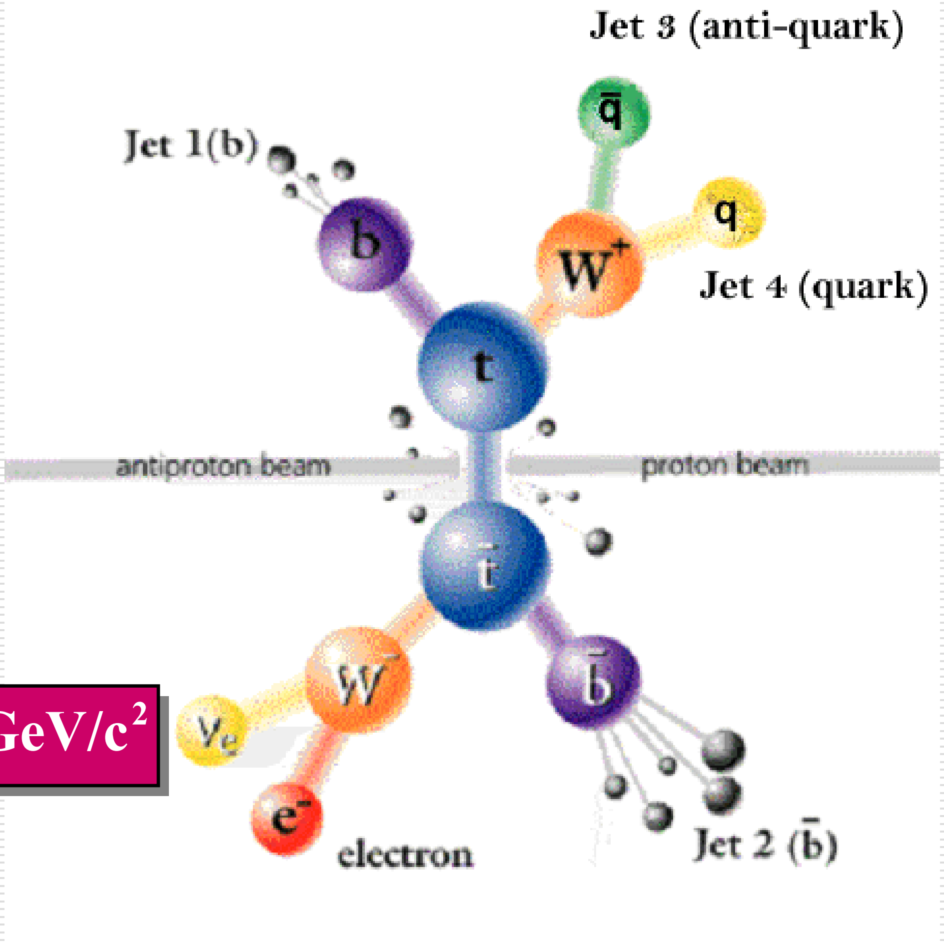
- All measurements of the top quark rely on the measurement of jets.
  - $t \rightarrow Wb$ (~ 100%), $W \rightarrow jj$ (~ 67%)
- Jet energy scale (JES) is the largest systematic uncertainty in the Run 1 CDF + D0 combined result on the top quark mass:

$$M_{top} = 178.0 \pm 2.7(\text{stat.}) \pm 3.3(\text{syst.})\ \text{GeV}/c^2$$

(hep-ex/0404010)

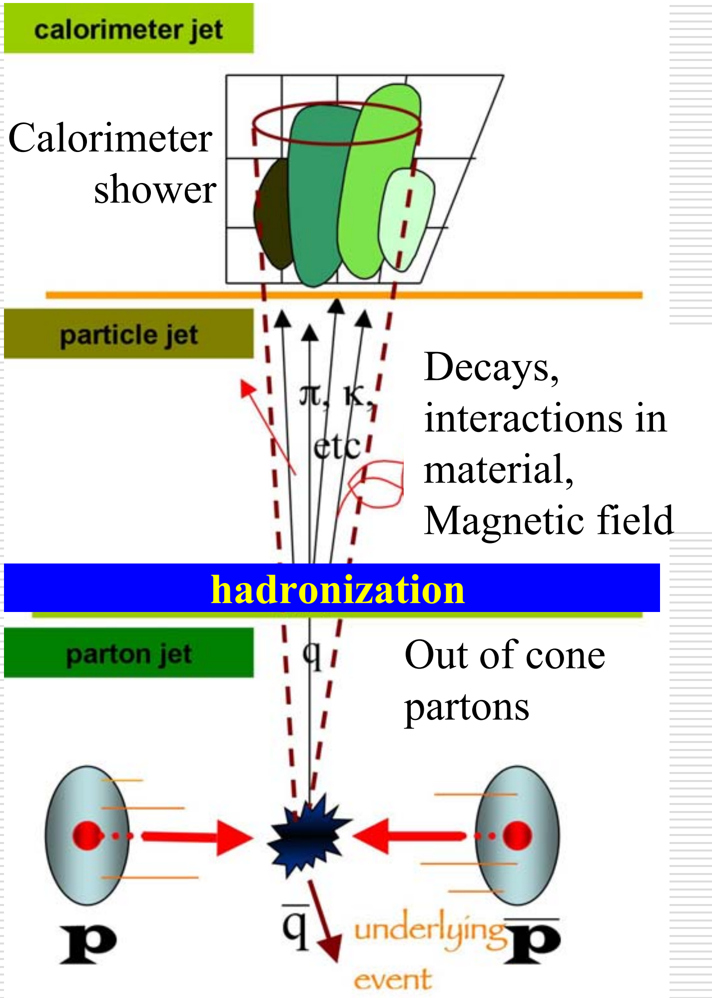
↑ JES = 2.6 GeV/c²

tt pair lepton + jets decay



Jets at the Hadron Colliders

Why is the jet energy scale determination difficult?



Instrumental effects

- non-linear response to hadrons
- different response to electrons and hadrons
- un-instrumented regions
- large fluctuations in deposited energy especially for hadrons

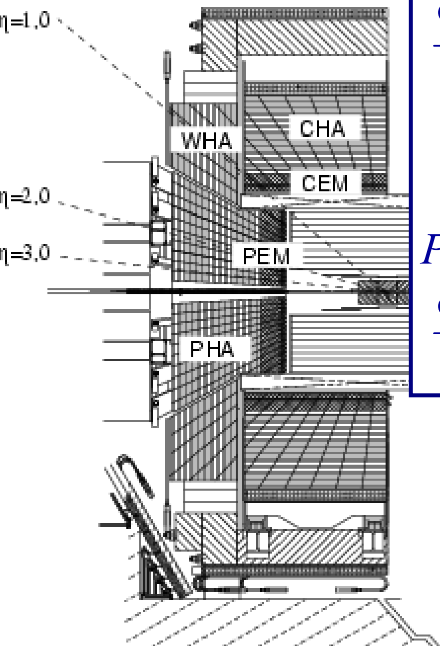
Physics effects

- fragmentation and hadronization
- spectator interaction energy
- initial and final state gluon radiation
- flavor of parent parton

CDF and D0 Calorimeters

CDF: scintilating tile with lead/iron absorbers $|\eta|<3.6$.

- Non-linear response to hadrons (non-compensating)
- Different response to electrons and hadrons
- Coarse granularity ($\Delta\eta \times \Delta\phi \sim 0.1 \times 0.26$ in central)
- Low noise



Electrons :

$$\frac{\sigma_{E_T}}{E_T} = \frac{13.5\%}{\sqrt{E_T}} \oplus 1.5\% \quad \text{(CEM)}$$

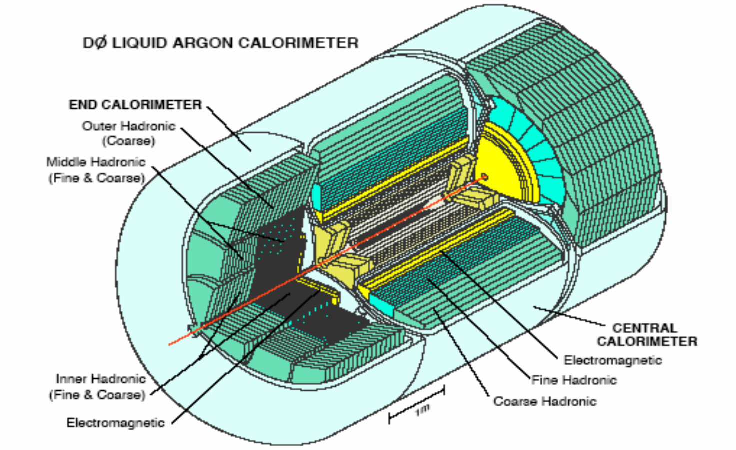
$$\frac{\sigma_E}{E} = \frac{16\%}{\sqrt{E}} \oplus 1\% \quad \text{(PEM)}$$

Pions :

$$\frac{\sigma_E}{E} \approx \frac{80\%}{\sqrt{E}}$$

D0: Uranium - liquid Argon calorimeter $|\eta|<4.2$.

- Almost compensating ($e/\pi<1.05$ for $E>30$ GeV)
- Fine segmentation ($\Delta\eta \times \Delta\phi = 0.1 \times 0.1$)
- Uranium noise



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

$$\textit{Pions}: \sigma_E / E \approx 45\% / \sqrt{E} \oplus 4\%$$

Overview:
Jet Energy Scale Determination

Jets used in CDF & D0 top quark measurements

	CDF	D0
Jet algorithm	Cone, R_{cone}=0.4	Cone, R_{cone}=0.5
Main calibration source(s) for absolute scale:	In-situ single track & test beam data + jet fragmentation model	Photon+jet P_T balance

D0 Jet Energy Scale

- Calorimeter jet → Particle jet (without underlying event)

$$E_{jet}^{particle} = \frac{E_{jet}^{measured} - E_o}{R_{jet} \cdot S}$$

- ***E_o*: Offset** – for Uranium noise, energy from previous bunch crossing, additional *p-pbar* interactions, and underlying event. Determined from the min.-bias & zero-bias data.
- ***R_{jet}*: Jet response** – Calorimeter response to jets.
  Equalize jet response along η using P_T balance in dijet events.
  Absolute scale determined from P_T balance in photon+jet events.
  EM scale determined using *Z→ee* mass.
- ***S*: Showering correction** – for energy emitted outside jet cone due to detector effects (does not correct for "physics" showering). Determined from energy density outside the jet cone in data and MC.

- Corrections mostly determined based on data using conservation of transverse momentum.
- Separate corrections for data and MC.

CDF Jet Energy Scale

$$P_{T,jet}^{particle} = \left[P_{T,jet}^{measured} \times f_{rel} - MI\right] \times f_{abs}, \qquad P_T^{parton} = P_{T,jet}^{particle} - UE + OOC$$

corrections for detector effects

corrections for physics effects
(some analyses use analysis-specific corrections)

- f_{rel}: **Relative correction -** make jet response uniform in η. Determined from dijet P_T balance.
- ***MI*: Multiple interaction correction -** for energy of other *p-pbar* interactions. From data.
- f_{abs}: **Absolute correction -** for calorimeter response to jets. From simulated dijet events. The single particle response in the simulation tuned to the in-situ single track & test beam data.
  - **particle jet (including UE)**
- ***UE*: Underlying event correction -** for beam remnants, multiple parton scattering… From data.
- ***OOC:* Out-of-cone correction** - for energy outside jet cone due to physics showering. Determined based on the MC parton shower & hadronization model.
  - **parent parton**

Systematic uncertainties:

- Differences between MC and data.
- Uncertainties from the method used to obtain the corrections.

Jet Energy Corrections

D0: Response Function, R_{jet}

R_{jet} obtained from data and MC separately using missing E_T projection fraction (MPF).

In photon+jet events: (for absolute jet response)

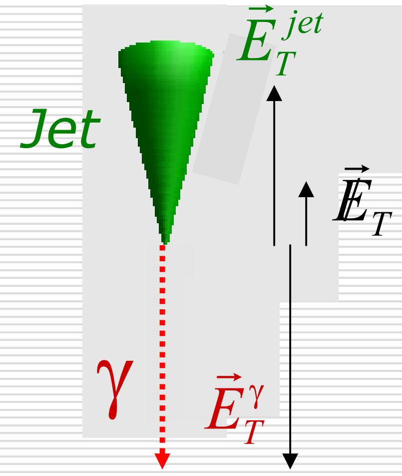
$$\vec{E}_T^{\gamma} + \vec{E}_T^{recoil} = 0 \quad \text{theoretically}$$

$$R_{\gamma}\vec{E}_T^{\gamma} + R_{recoil}\vec{E}_T^{recoil} = -\vec{\not E}_T \quad \text{in practice}$$

- After EM energy calibration, $R_{\gamma}=1$.

$$R_{recoil} = 1 + \frac{\vec{\not E}_T \cdot \vec{n}_T^{\gamma}}{E_T^{\gamma}} \Rightarrow R_{jet}$$

(in back-to-back photon+jet events)



- Perform the study as a function of

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

  - E_T^{γ}, η_{jet} better measured than E_{jet}
  - less sensitive to jet energy resolution
  - map from E' to E_{jet}

In dijet events: (for relative jet response)

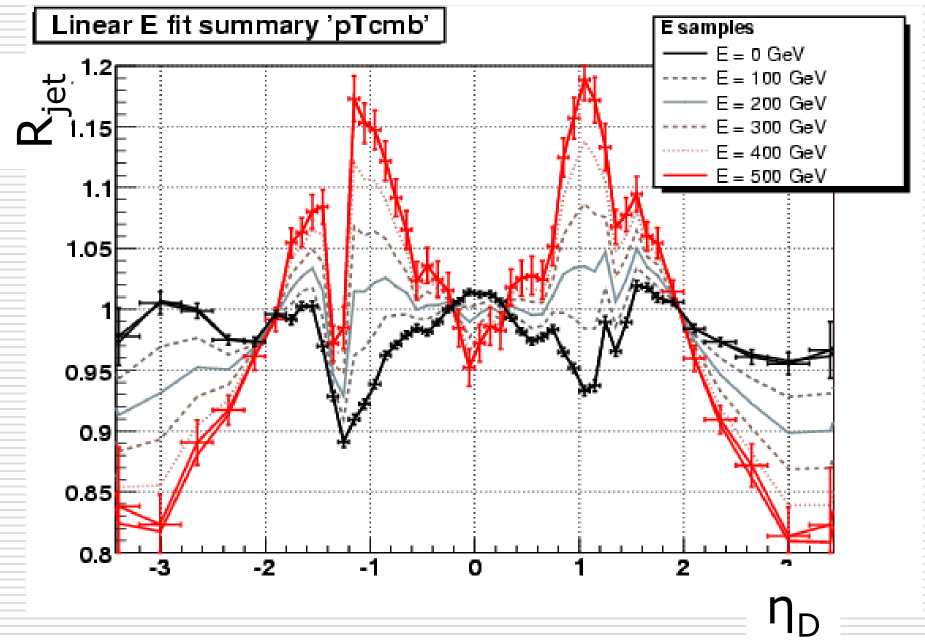
$$R_{jet} = 1 + \frac{\vec{\not E}_T \cdot \vec{n}_T^{central\ jet}}{E_T^{central\ jet}}$$

vs $\eta^{non\text{-}central\ jet}$

D0: Response Function, R_{jet}

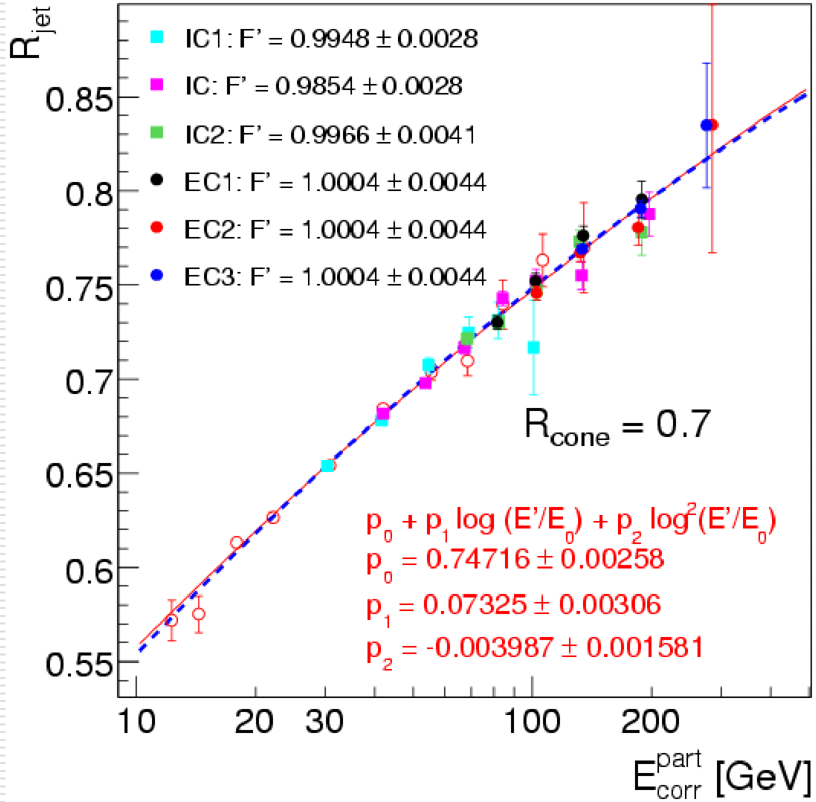
Relative jet response vs η_{jet}

- Corrections from dijet events
- Cross-checked in γ+jet events at low P_T



Absolute jet response vs E_{jet}

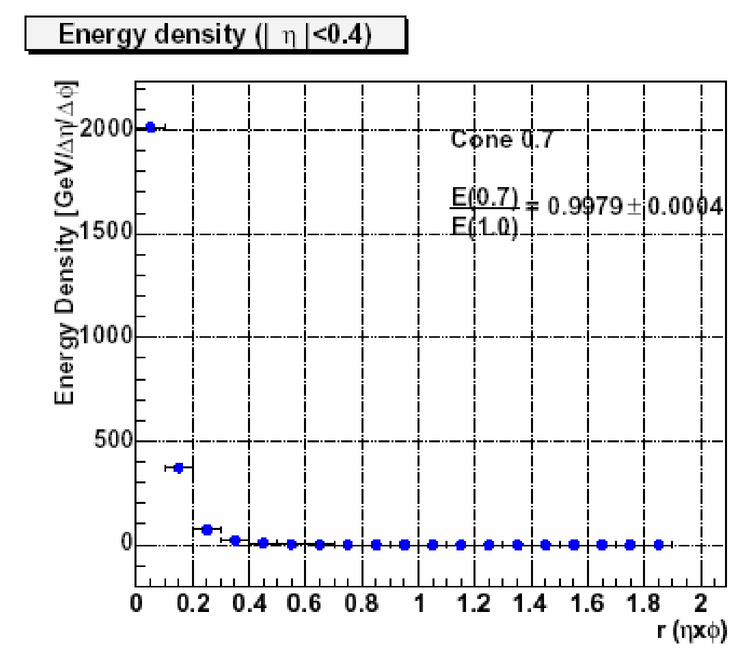
- Corrections from γ+jet events

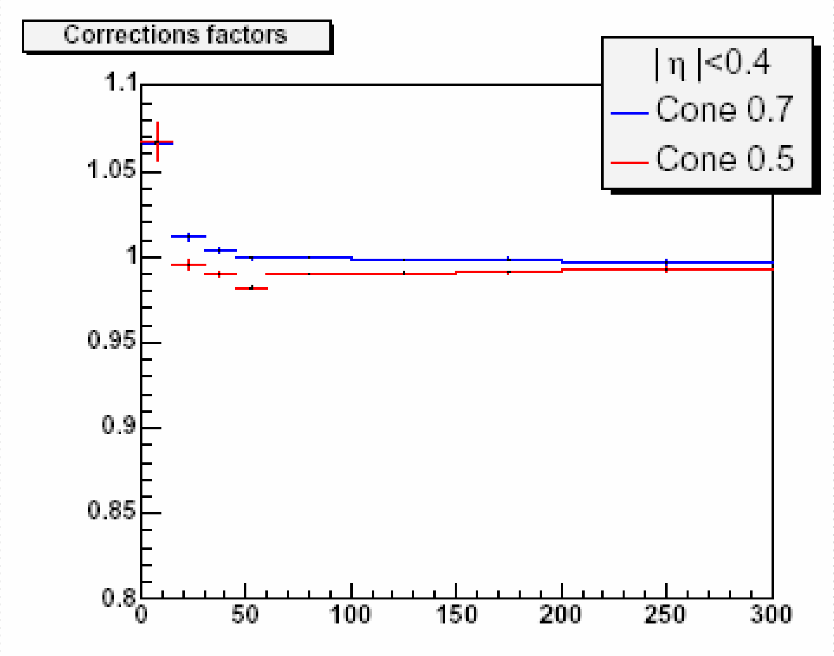


D0: Showering Correction

Shower particles can leak outside the jet clustering cone.

- Measure the energy flow vs distance from the jet axis, *R*.
- Subtract "offset" energy due to noise, UE etc.
- Subtract the physics showering contribution estimated from MC.

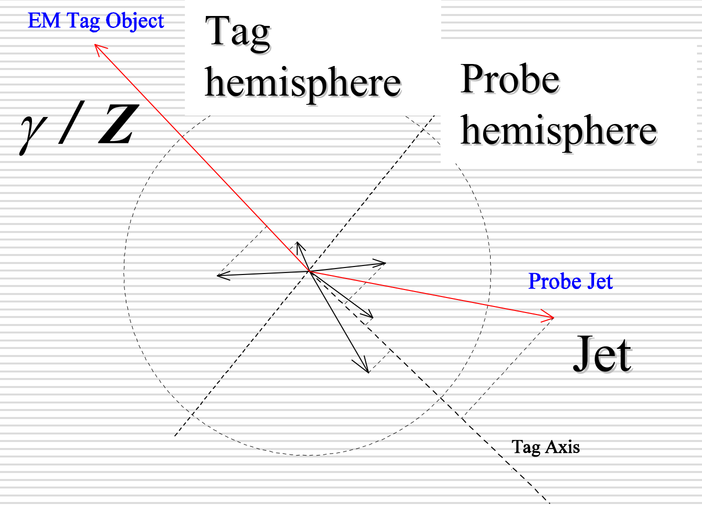




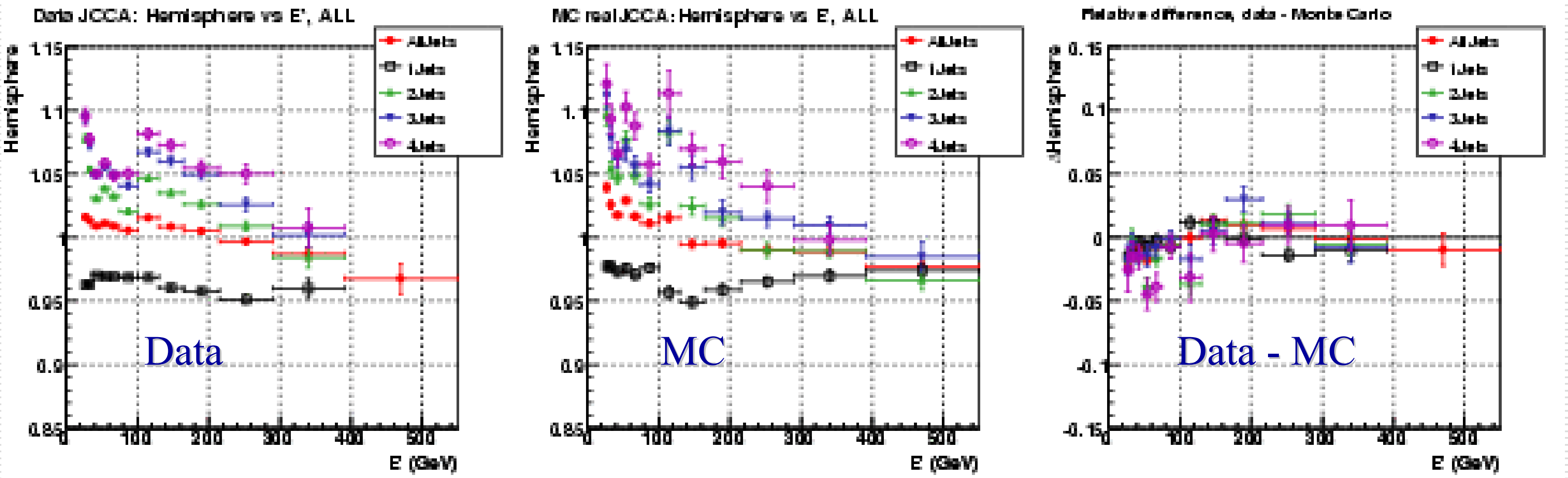
D0: Closure Test – Hemisphere Method

Hemisphere variable:

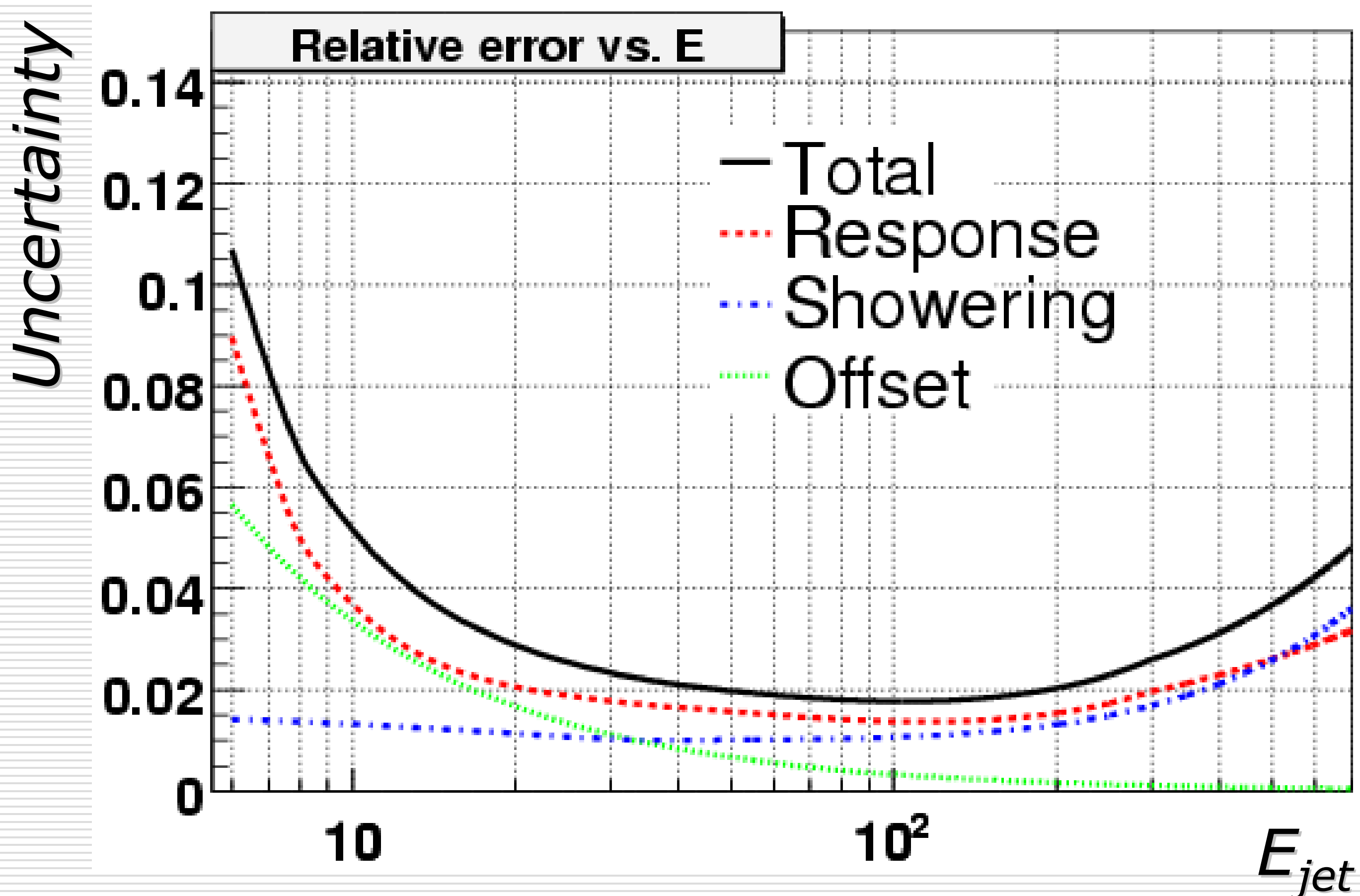
$$H = \frac{\sum_{Probe\ hemi} |\vec{P}_T \cdot \vec{n}_T^{\gamma}|}{\sum_{Tag\ hemi} |\vec{P}_T \cdot \vec{n}_T^{\gamma}|}$$



- All corrections lead to "closure" in data and MC?



D0: Total JES Uncertainties

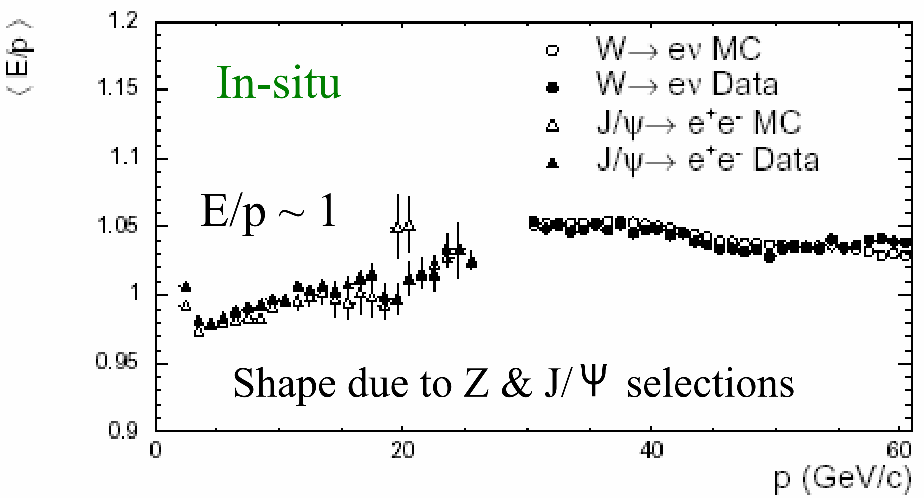


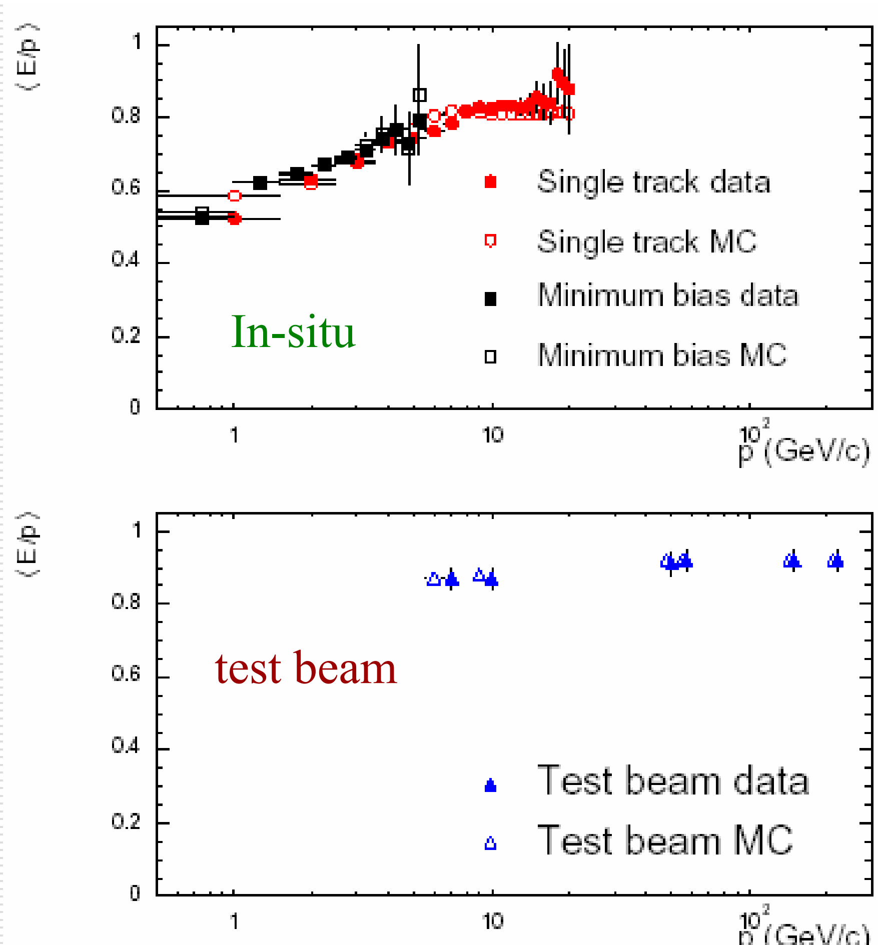
- The results are not final yet.
- The final JES results expected to come out in spring.

CDF: Single Particle Response

Electromagnetic particles (electrons, photons, π^0s)

Charged hadrons

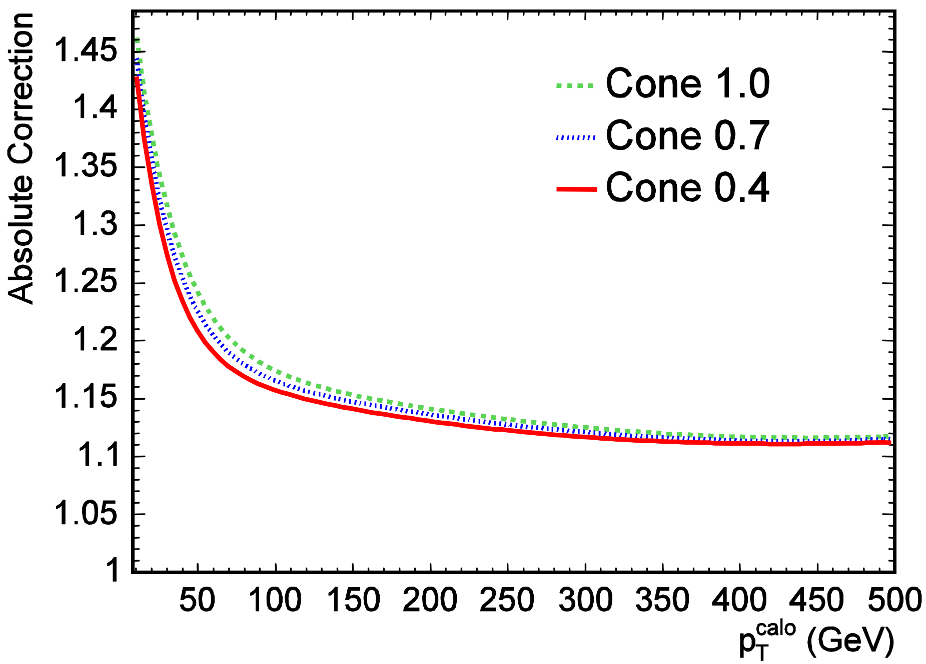


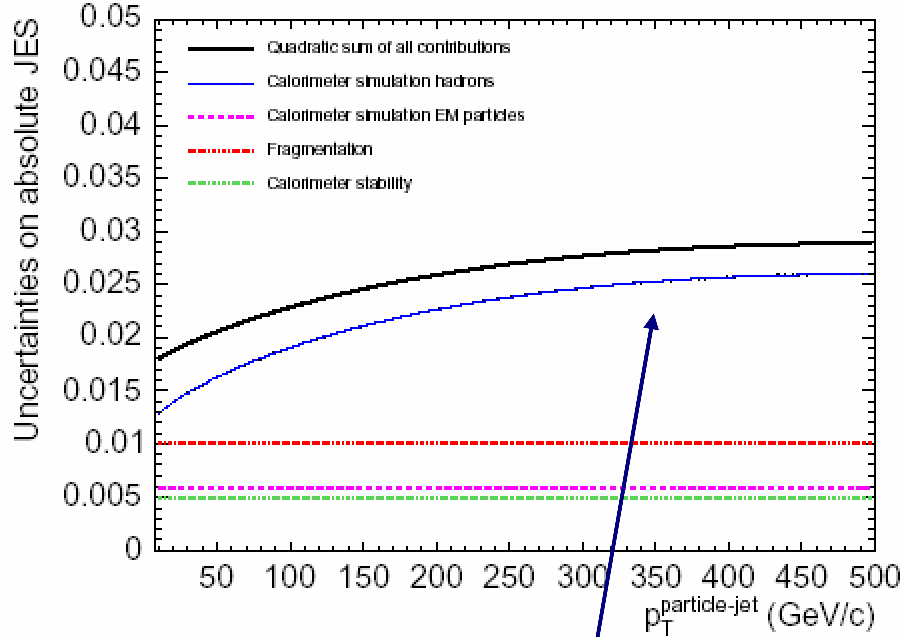


Currently extending in-situ calibration to higher p

CDF: Absolute (Response) Correction

- Map calorimeter jet P_T with particle jet P_T.
- Take the most probable value for the correction.
- After this correction, jets are independent of the CDF detector.



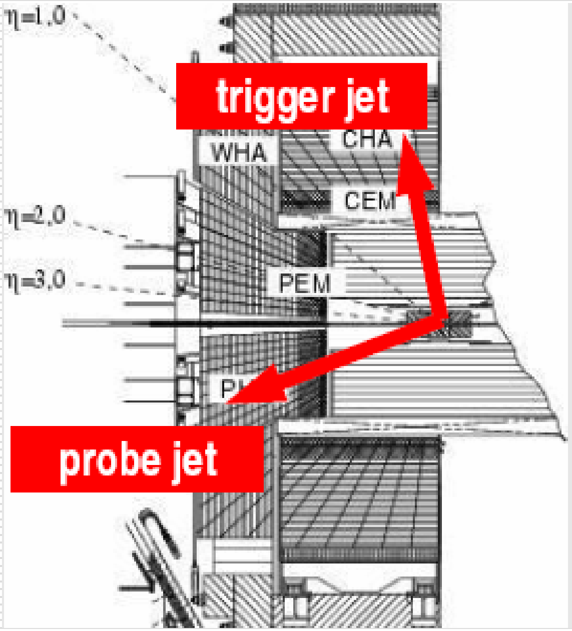


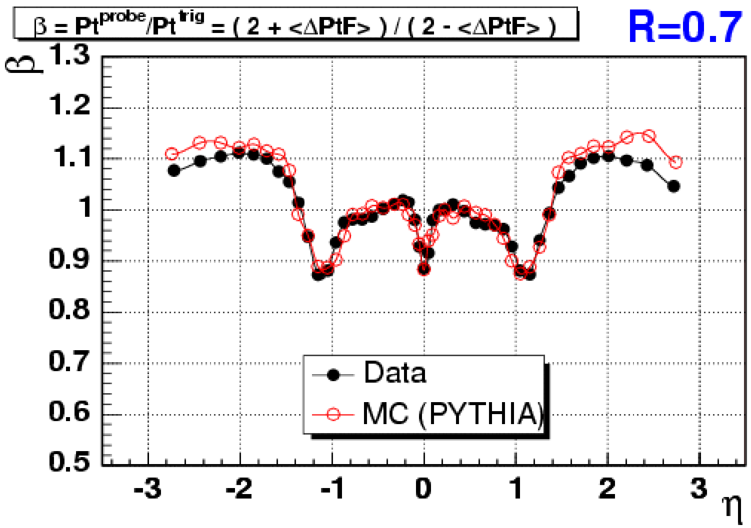
Uncertainty in single particle response measurements (in-situ and test beam) & tuning of the CDF simulation: dominant uncertainty at high P_T^{jet}

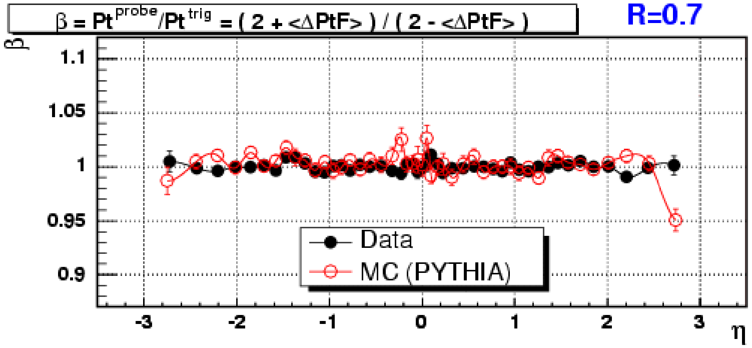
CDF: Corrections for Non-Central Jets

- The single particle response tuning is limited in precision in non-central regions due to detector geometry/tracking coverage.
  - **dijet P_T balance method**

$$f_b \equiv \frac{\Delta P_T}{P_T^{ave}} = \frac{p_T^{probe} - p_T^{trigger}}{(p_T^{probe} + p_T^{trigger})/2}, \quad \beta \equiv \frac{p_T^{probe}}{p_T^{trigger}} = \frac{2 + \langle f_b \rangle}{2 - \langle f_b \rangle}$$

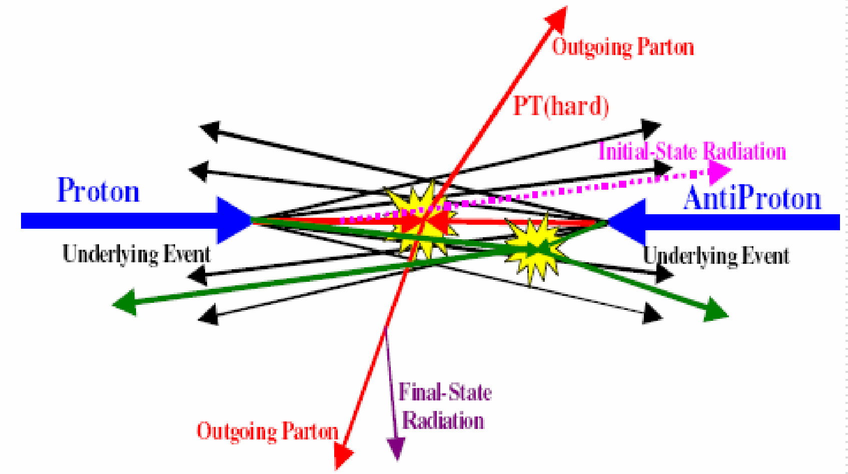


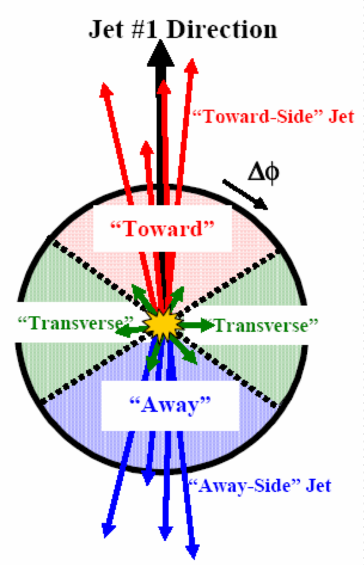


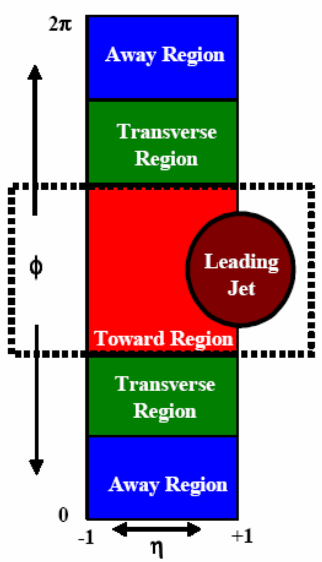


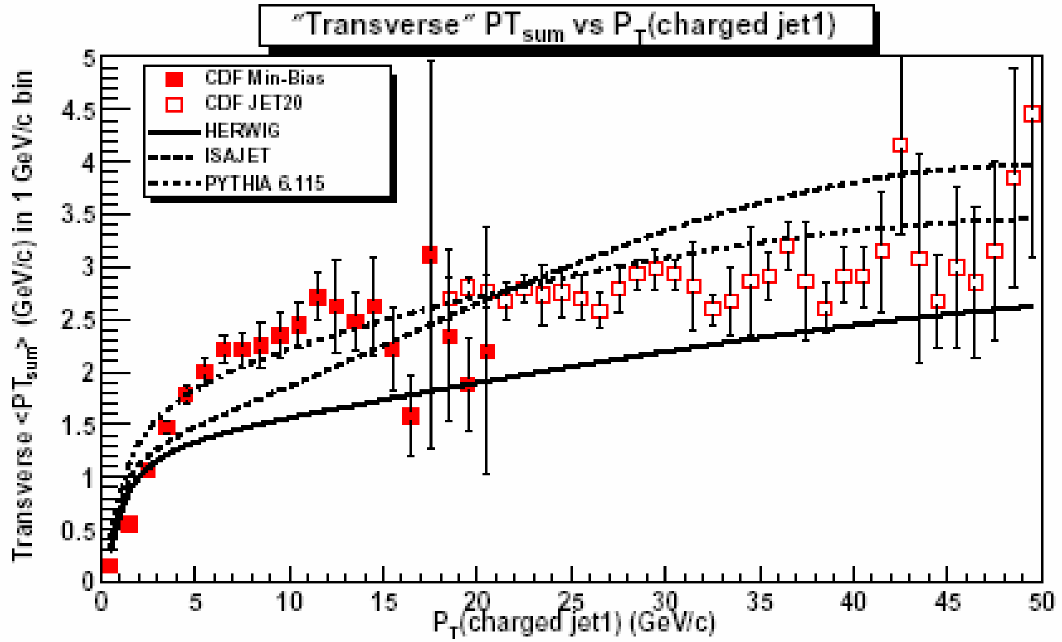
CDF: Underlying Event (UE) Tuning in MC

- Underlying Event: particles not associated with the hard scatter.
  - Beam remnants
  - Multiple parton Interactions
  - Initial state soft radiations
- Tune charged particles in MC in the "transverse" region (sensitive to UE) in dijet events.









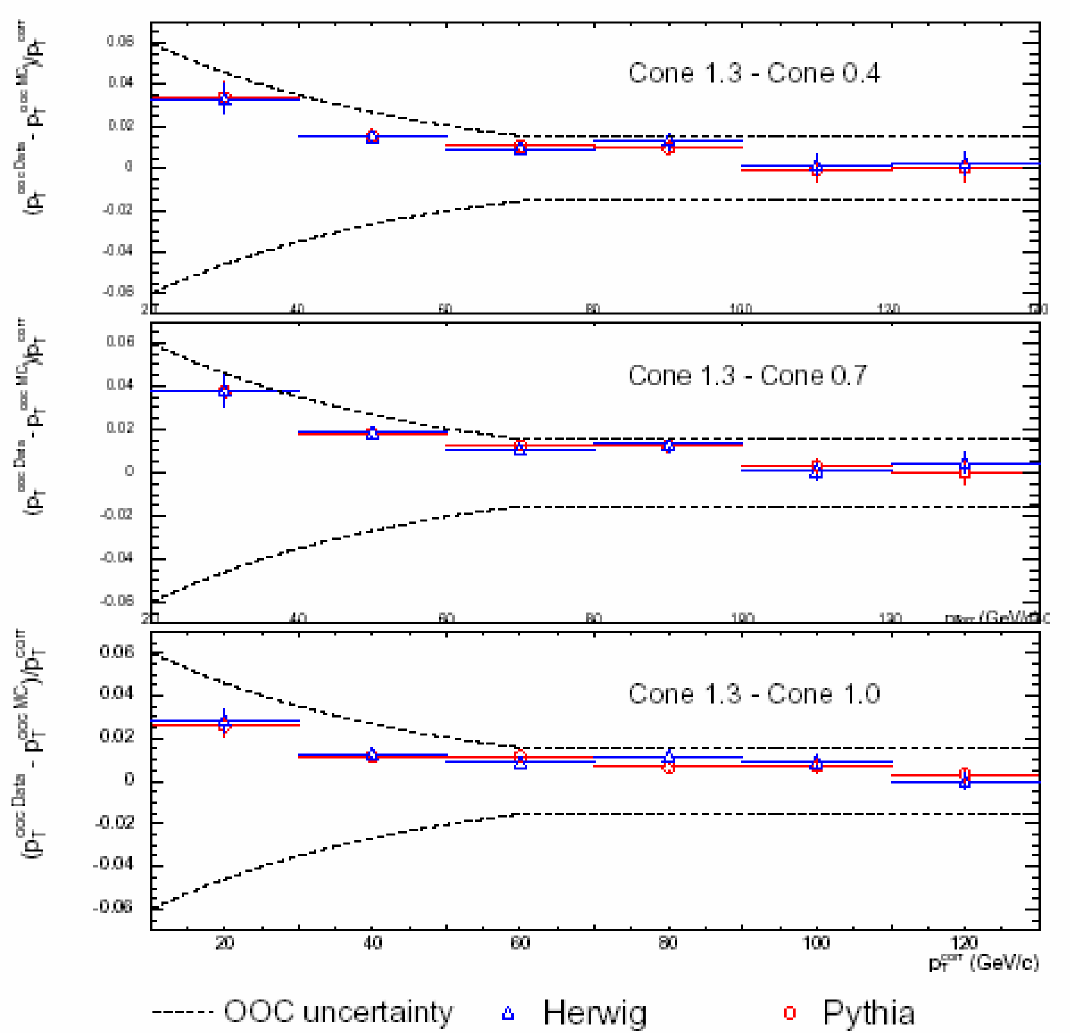
CDF: Out-of-Cone Correction & Uncertainty

Correction:

- Add energy of particles leaking outside the jet cone due to physics showering.
- Some analyses use the analysis-specific correction.

Uncertainty:

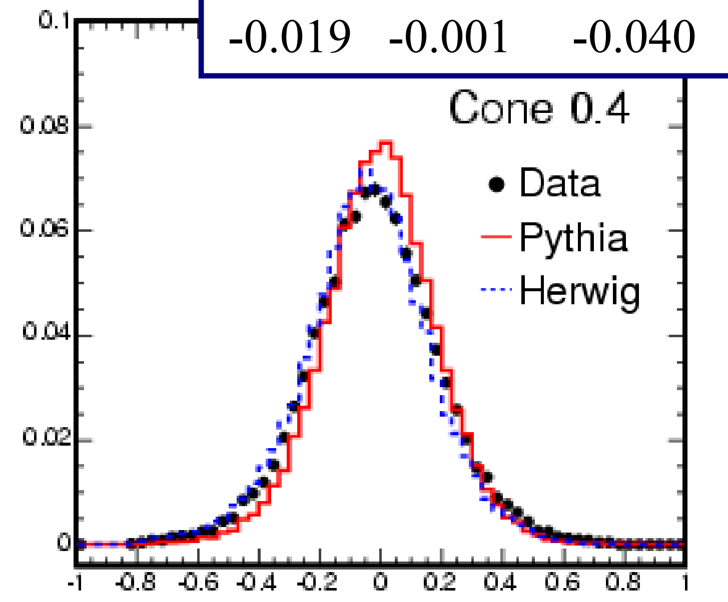
- Differences in energy outside the jet cone up to R=1.3 in data and MC samples in photon+jet events.
- Main uncertainty at low P_T^{jet}.



Photon-jet and *Z*-jet Balancing

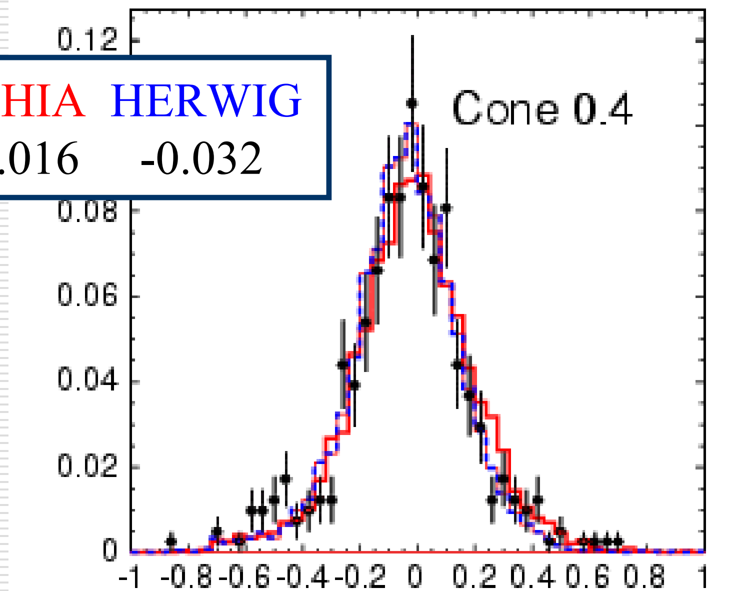
- Good samples to test JES as photon/*Z* energy is well measured
- Results depend on event selection cuts, e.g. 2nd jet P_T and photon/*Z*-jet opening angle. Data and MC disagree to 2% even with tight cuts.

Data	PYTHIA	HERWIG
-0.019	-0.001	-0.040

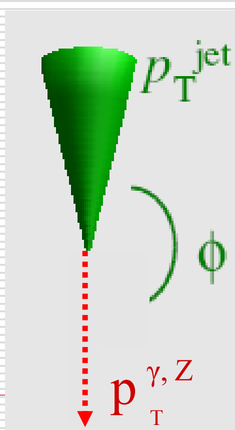


$$p_T \text{ balance } = p_T^{jet} / p_T^{\gamma} - 1$$

Data	PYTHIA	HERWIG
-0.026	-0.016	-0.032

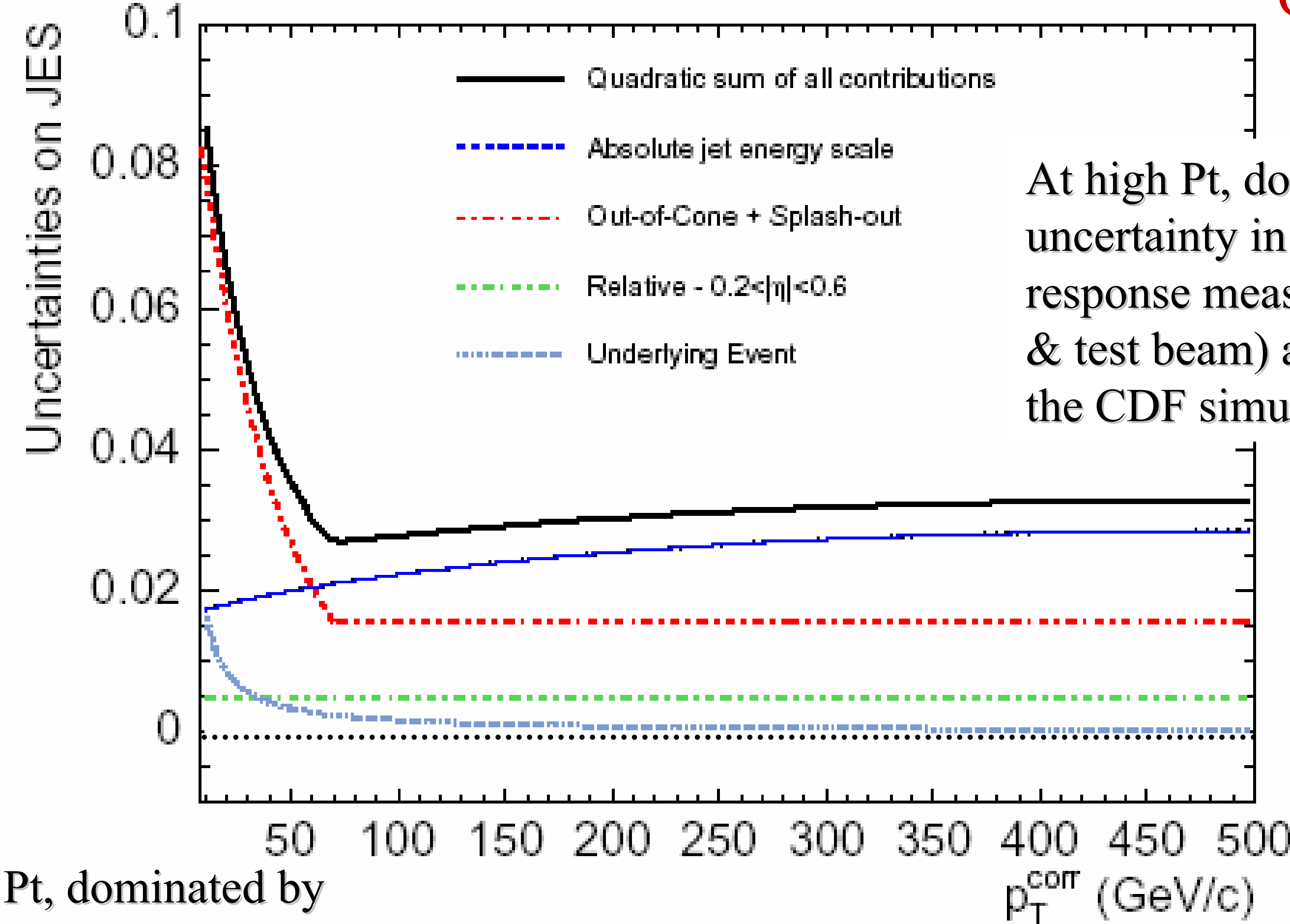


$$p_T \text{ balance } = p_T^{jet} / p_T^{Z} - 1$$



CDF: Total JES Uncertainty

Central jets



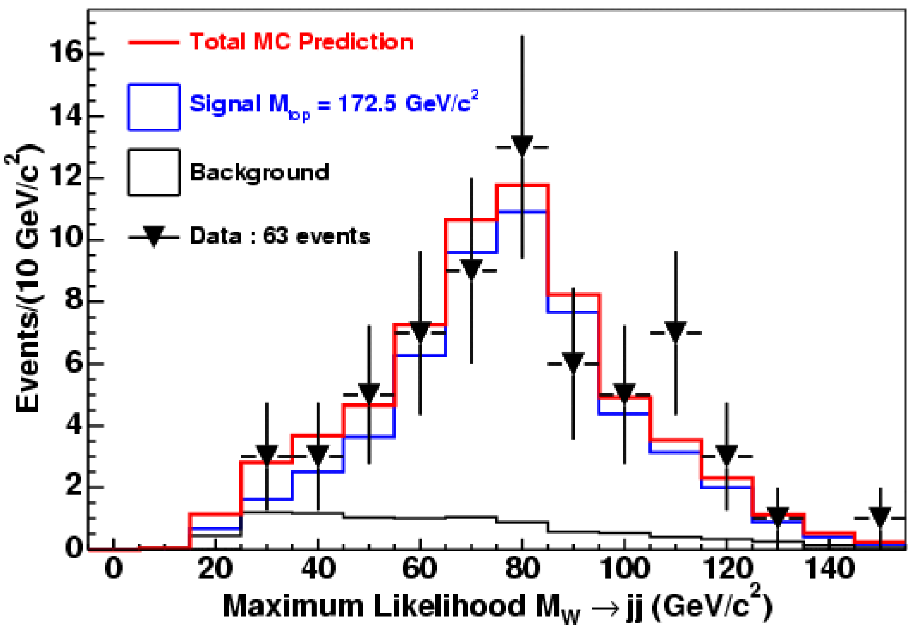
At high Pt, dominated by uncertainty in single particle response measurements (in-situ & test beam) and tuning of the CDF simulation

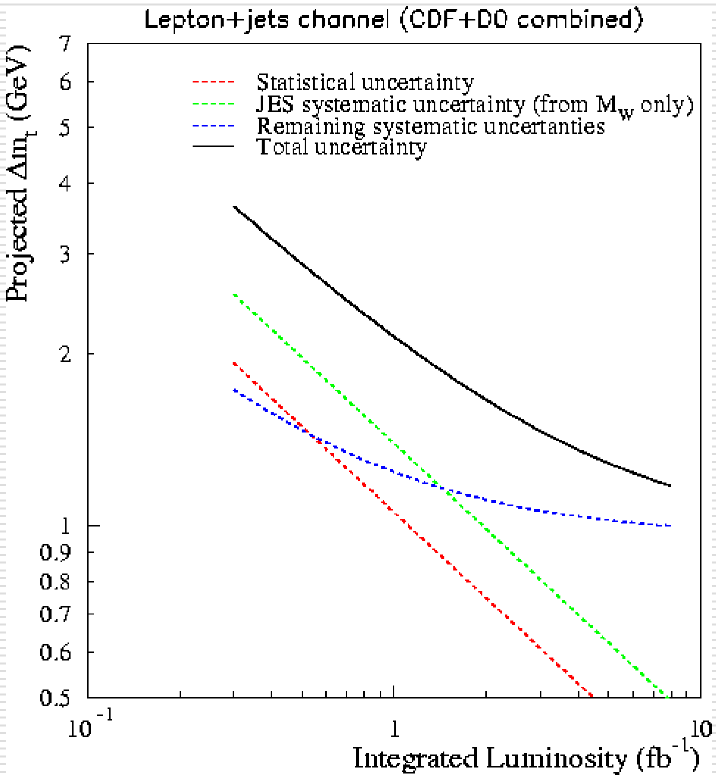
At low Pt, dominated by out-of-cone uncertainty (physics modeling uncertainty)

Constraining JES with Dijet Mass Resonances & *b*-jet Energy Scale

W Mass Resonance in *tt* Events

- Both CDF and D0 use $W \to jj$ mass in *tt* events to constrain JES in M_{top} measurements in lepton+jets channel.
- M_{top} measurement sensitive primarily to *b*-jet energy scale; however, most uncertainty is shared by "generic" jets & *b*-jets.

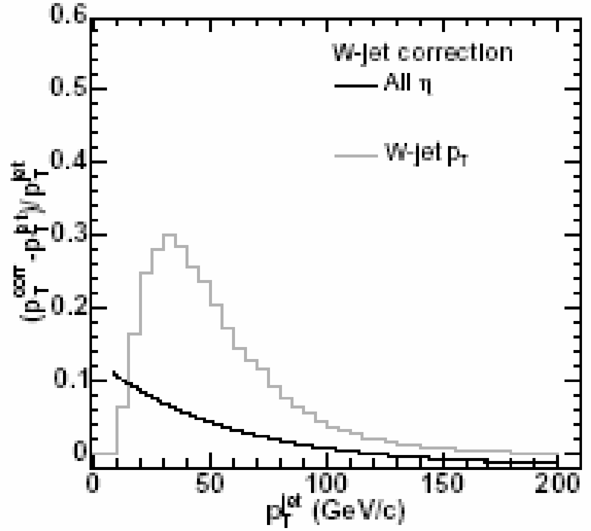


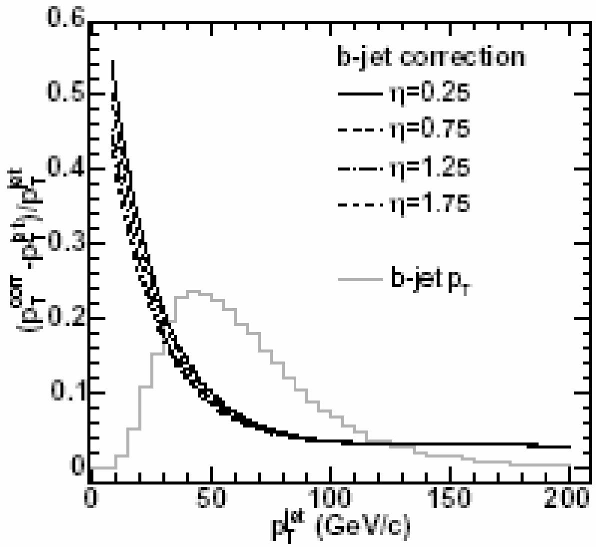


- The uncertainty reduces with increasing integrated luminosity ☺.
- "One point" calibration: cannot constrain JES over wide P_T range.

b-jet Energy Scale

- *b*-jets have different characteristics from generic jets
  - Harder fragmentation
  - *B* hadron decays
- CDF and D0 use MC to model *b*-jet response. In M_{top} measurements, use:
  - Generic jet energy corrections
  - Additional corrections (from MC) to correct *b*-jets back to the parent *b*-quark
- Additional uncertainties for *b*-jets (0.6%) based on constraints from other experiments



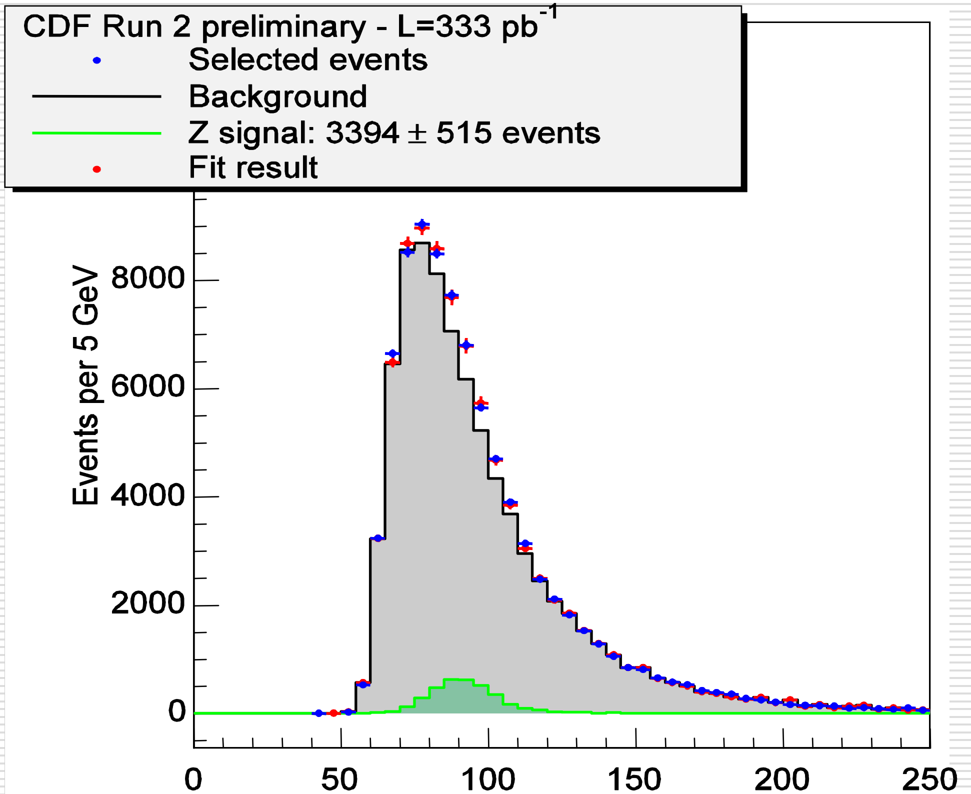


Work in progress:

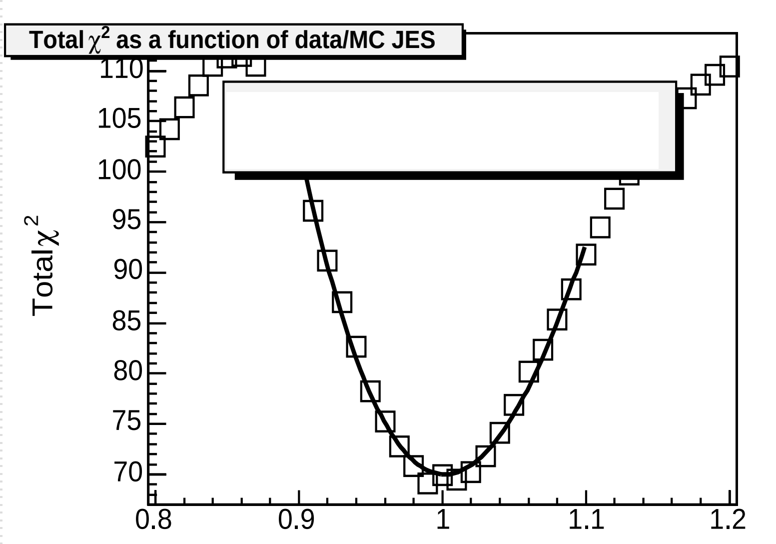
- Test *b*-jet energy scale directly in data, with photon–*b*-jet P_T balance & $Z \to bb$

CDF: Extraction of $Z \rightarrow bb$ Signal

- Great tool to test *b*-jet energy scale and for extraction of *bb* resonances ($H \rightarrow bb$)
- Use two *b*-tagged jet events, apply kinematic cuts to improve *S/B*
- Fit signal and background (direct QCD production) templates, and vary JES



Dijet invariant mass GeV/c^2



Data/MC relative *b*-jet scale

Current status:

- Evaluating systematic biases (if any)
- Integrating more data

Conclusions

- The jet energy scale is the dominant uncertainty in many measurements of the top quark.
- CDF and D0 use different approaches to determine the jet energy scale and uncertainty:
  - CDF: Scale mainly from single particle response + jet fragmentation model. Cross-checked with photon/*Z*-jet P_T balance etc.
  - D0: Scale mainly from photon-jet P_T balance. Cross-checked with the closure tests in photon/*Z*+jet events etc.
- CDF achieved ~3% uncertainty in Run 2. Further improvements in progress.
- D0 new result in Run 2 (uncertainty ~ 2%) will come out soon.
- In-situ M_W calibration has been successfully used to improve JES by both CDF and D0 in M_{top} measurements.
- Expect result on the *b*-jet energy scale from photon–*b*-jet P_T balance & $Z \to bb$ soon.

Backups

CDF Jet Energy Correction Scheme

Corrections for detector effects

For central jets:

- Tune the detector simulation to the real calorimeters.
  - Response to individual particles of each type, momentum and direction
- Simulate "jets" using a jet fragmentation model.
  - Particle composition, momentum and multiplicity distributions in a jet

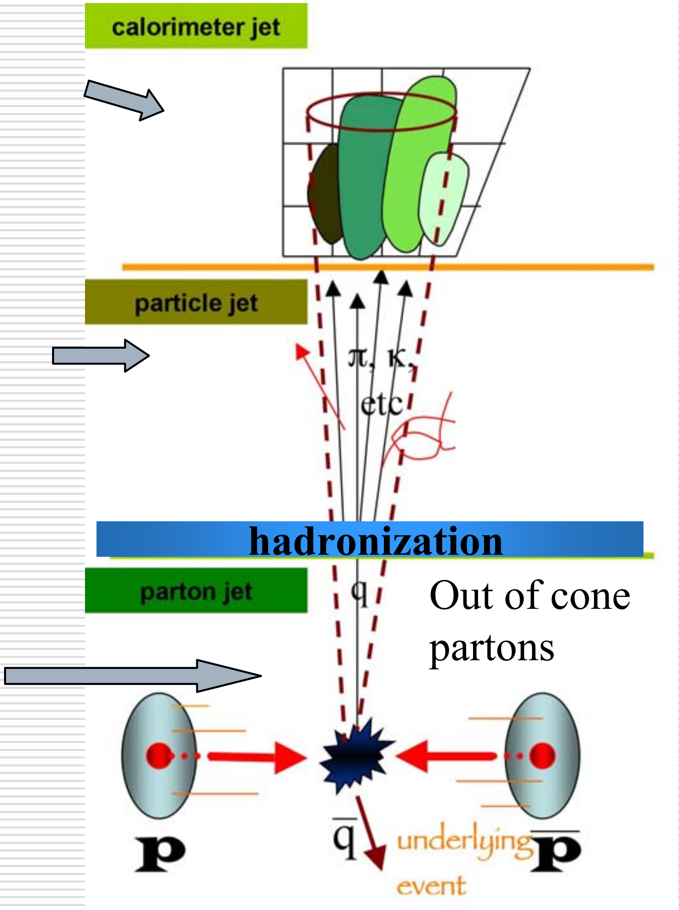
  Run them through the detector simulation
- Cluster particles (particle jet) & calorimeter towers (calorimeter jet), use P_T correlation for correction.

For non-central jets

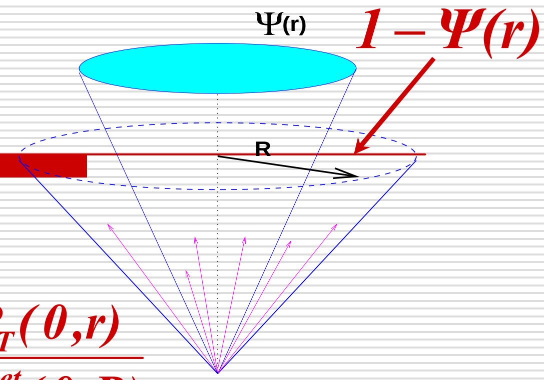
- Dijet P_T balance

Corrections for physics effects

- Tune MC generator to data in the "transverse" region which is sensitive to UE.
- Correlate P_T of the particle jet and its parent parton in the tuned MC generator.



CDF: Jet Fragmentation Study

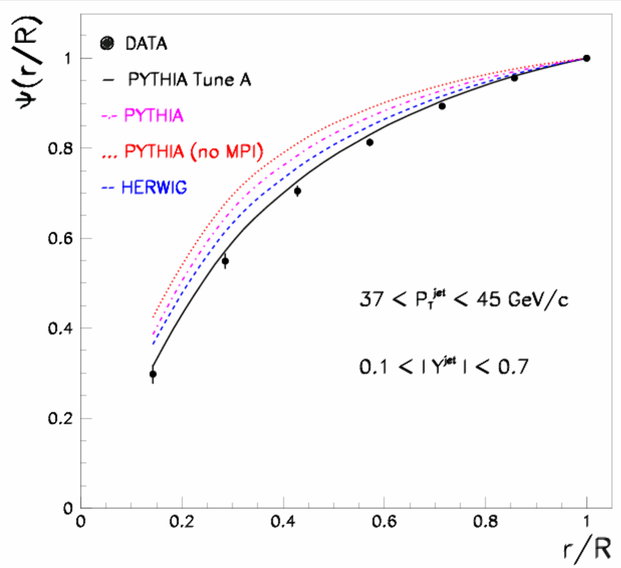


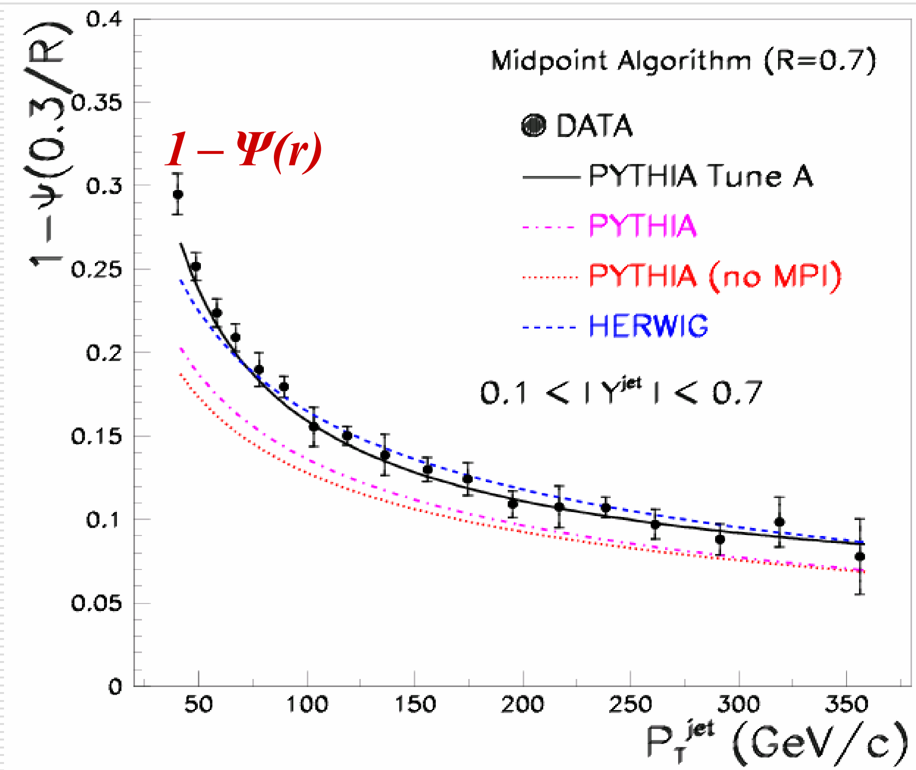
Need to simulate jets properly: particle composition, multiplicity, momentum distribution etc

$$\Psi(r) = \frac{1}{N_{jets}} \Sigma_{jets} \frac{P_T(0,r)}{P_T^{jet}(0,R)}$$

e.g. ***2 hadrons with p_T = 50 GeV/c***
≠ 20 hadrons with p_T = 5 GeV/c

due to calorimeter non-linearity

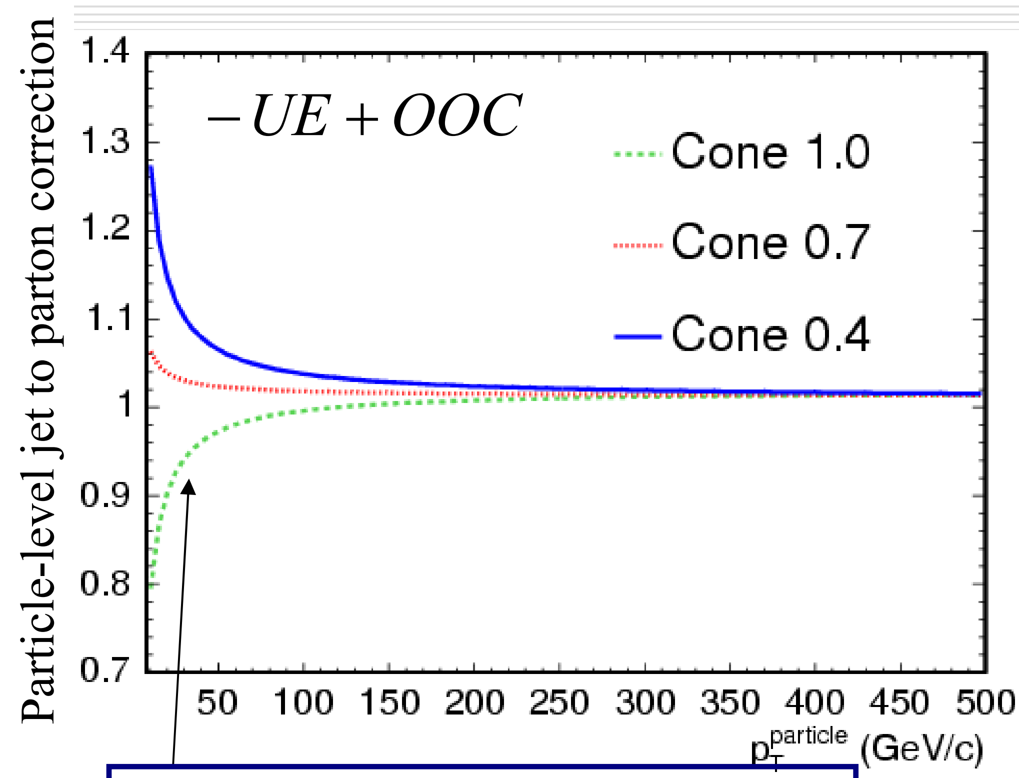




Tuned MC, PYTHIA tuneA (enhanced ISR + MPI), describes the data

CDF: Particle Jet to Parton Corrections

- Correct particle jet to the parent parton. Correcting for two effects:
  - Underlying event energy
  - Energy that leaks outside the jet clustering cone (out-of-cone)
- The corrections determined from PYTHIA tuneA dijet MC events. Many analyses determine corrections from their process samples; the corrections depend on process & parent parton type.



More energy from UE in the cone than energy leaking outside the cone