Jet Energy Calibration

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Outline

• Introduction
• CDF and D0 calorimeters
• Response corrections
• Multiple interactions
• $\eta$-dependent corrections
• Underlying event and Out-of-cone energy
• Other calibration signals
• Conclusions

• Disclaimer:
  – Most discussion here valid for cone jets
    • Will make some comments on $k_T$ jets
  – Will discuss CDF and D0 procedures as examples
    • ATLAS and CMS have no settled yet
Partons are produced in hard scatter

- Would like to know the energy of these partons
The parton will hadronise

- Hadronization is non-perturbative QCD phenomenon:
  - Phenomenological models implemented in MC:
    - Lund-Strong Model: PYTHIA
    - Cluster fragmentation: HERWIG

- Depends on energy and quark type
Multiple pp Interactions

- Overlapping interactions can overlap the jet
- Number of extra interactions depends on luminosity
  - LHC:
    - Low lumi \((L=1\times10^{33} \text{ cm}^{-2}\text{s}^{-1})\): \(<N>=2.3\)
    - High lumi \((L=1\times10^{34} \text{ cm}^{-2}\text{s}^{-1})\): \(<N>=23\)
  - Tevatron:
    - \(L=2\times10^{32} \text{ cm}^{-2}\text{s}^{-1}\): \(<N>=6\)

Offset depending on number of interactions
More than one parton per proton interacts

- Spectator partons can interact also and put energy into the same area as hard interaction

Offset, can depend on physics process
Hadrons enter calorimeter

- Calorimeter response determines what we measure

Correction depends on jet energy
Calorimeter response depends on angle

- Often calorimeters are different in forward vs central region
- There are often poorly instrumented regions (cracks) that have lower response

Correction depends on jet angle and energy
Noise can overlap with jet

- Depending on noise level in calorimeter the noise overlapping with our jet can be significant.

Offset depending on calorimeter noise level.
CDF calorimeter

• **Central and Wall (|\(\eta\)|<1.2):**
  - Scintillating tile with lead (iron) as absorber material in EM (HAD) section
  - Coarse granularity: \(\sim 800\) towers
  - Non-compensating
    • non-linear response to hadrons
  - Rather thin: 4 interaction lengths
  - Nearly no noise
  - Resolutions:
    • EM energies: \(\sigma/E=13.5\% / \sqrt{E} \oplus 1.5\%\)
    • HAD energies: \(\sigma/E=50\% / \sqrt{E} \oplus 3\%\)

• **Plug (1.2<|\(\eta\)|<3.6):**
  - Similar technology to central
  - Resolution:
    • EM energies: \(\sigma/E=16 \% / \sqrt{E} \oplus 1\%\)
    • HAD energies: \(\sigma/E=80 \% / \sqrt{E} \oplus 5\%\)
  - Thicker: 7 interaction lengths
DØ Calorimeter

- Same technology in central and forward calorimeter:
  - Liquid Argon with iron (stainless) as absorber in EM (HAD) calorimeter
  - Fine granularity: ~50K cells
  - Depth:
    - 7.2-8.0 interaction lengths
  - Compensating:
    - Compromised in Run 2:
      - Integrate charge only in 260ns due to shorter bunch spacing
  - Resolutions:
    - EM energies: $\sigma/E = 15\% / \sqrt{E} \oplus 0.3\%$
    - HAD energies: $\sigma/E = 50\% / \sqrt{E} \oplus 4\%$

Online calibration: see N. Hadley’s lecture
In Situ Calorimeter Calibration: Hadronic Energy

- Minimum Ionising Particle (MIP):
  - \( J/\psi \) and \( W \) muons
  - peak in HAD calo: \( \approx 2 \) GeV (in CDF)
  - Check time stability
- Minimum bias events
  - E.g. \( N_{\text{tower}}(E_T > 500 \text{ MeV}) \)
In Situ Calorimeter Calibration: EM Energy

- **MIP peak:**
  - If visible (CDF at 300 MeV)
- **Z→ee peak:**
  - Set absolute EM scale in central and plug
- **E/p for electrons**
  - After having calibrated p and material (see M. Shapiro’s lecture)
- **Minimum Bias events:**
  - Occupancy above some threshold: e.g. 500 MeV
Calibrating jets at a Hadron Collider

- **Hadron collider:**
  - Physics processes span entire jet $E_T$ range: $0 < E_T < \sqrt{s}/2$
  - Calibration processes (photon-jet) run out of steam much earlier:
    - E.g. $d\sigma(\gamma)/dp_T = 0.001 \cdot d\sigma(\text{jet})/dp_T$
    - Unlike at HERA (NC process) or LEP/SLC (Z-resonance)
Two different approaches

- CDF and DØ use very different approaches
  - Documented in
    - CDF Run 2: hep-ex/0510047 (accepted by NIM)
    - DØ Run 2: http://www-d0.fnal.gov/phys_id/jes/public/plots_v7.1/index.html

- Main difference:
  - CDF uses test beam and single particles measured in-situ to understand absolute response of single particles
    - deduce jet response using simulation
    - Cross check with calibration processes like photon-jet data
  - DØ uses photon-jet data to measure absolute response
    - Extra correction for “showering” necessary

- Other differences:
  - CDF corrects separately for underlying event, multiple interactions, out-of-cone energy
  - DØ includes all these effects into one correction factor
Overview: CDF and DØ

• CDF calibrates $P_T$

$$P_{T, jet}^{corr} = \frac{P_{T, jet}^{raw} \times F_\eta - MI}{R}$$

• $P_T^{corr}$: calibrated jet $P_T$
• $P_T^{raw}$: raw jet $P_T$
• $F_\eta$: eta-dependent correction
• R: absolute response
• MI: multiple interactions

• DØ calibrates Energy

$$E_{jet}^{corr} = \frac{E_{jet}^{raw} - O}{F_\eta \times R \times S}$$

• $E^{corr}$: calibrated jet E
• $E^{raw}$: raw jet E
• $F_\eta$: eta-dependent correction
• R: absolute response
• O: offset energy
  – includes MI, noise, UE
• S: showering corrections

- Systematic error associated with each step
- additional corrections to get to parton energy
CDF: Detector to Particle Level

• Do not use data since no high statistics calibration processes at high $E_T > 100$ GeV
• Extracted from MC ⇒ MC needs to
  1. Simulate accurately the response of detector to single particles (charged pions, photons, protons, neutrons, etc.):
     CALORIMETER SIMULATION
     (CDF uses fast parameterization GFLASH, D0 uses GEANT3)
  2. Describe particle spectra and densities at all jet Et:
     FRAGMENTATION
     – Measure fragmentation and single particle response in data and tune MC to describe it
     – Use MC to determine correction function to go from observed to “true”/most likely Et:

\[ E^{\text{true}} = f (E^{\text{obs}}, \eta, \text{conesize}) \]
Single Particle Response Simulation

- Single particle response:
  - Test beam
  - In situ:
    - Select “isolated” tracks and measure energy in tower behind them
    - Dedicated trigger
    - Perform average BG subtraction
  - Tune simulation to describe E/p distributions at each p (use π/p/K average mixture in MC)
Single Particle Response Simulation

- **MC models**
  - Hadron response at low $p_T$ (in situ data) and high $p_T$ (test beam data)
  - Electron response

Typical jet composition:
- 60% charged particles
- 10% protons
- 90% pions
- 30% neutral pions ($\rightarrow \gamma\gamma$)
- EM response
- 10% other (neutrons, ...)

CDF
electrons

test beam

In-situ
Fragmentation

- Due to non-linearity of calorimeters, big difference between e.g.
  - one 10 GeV pion: ~8 GeV
  - ten 1 GeV pions: ~6 GeV

- Measure $P_T$ spectra of particles in jets at different $E_T$ values as function of track $P_T$:
  - Typically mean rather low
  - Requires understanding track efficiency inside jets
Jet Correction to Particle Level

- MC convolutes response and particle momentum spectrum for us
  - Use tuned and validated MC to compare measured jet to jet at particle level
  - Systematic uncertainty given by how well MC simulation and fragmentation reproduced data
• Nearly independent of cone size
  – Response about 80% at $p_T=50$ GeV, 87% at $p_T=300$ GeV
Response correction using prompt photons

• Prompt photon process:
  – Photon well measured in calorimeter
    • Calibrated using electrons
  – Constraint: $E_T(\gamma) = E_T(\text{jet})$

• Complications:
  – Number of events at high $E_T$ rather low:
    • $E_T(\gamma) > 300$ GeV, $\int L dt = 1$ fb$^{-1}$: 40 events
  – Background due to $\pi^0$’s
    • Purity: 30-80% for $E_T(\gamma) = 20$-100 GeV
  – Higher order processes:
    • Photon + 2 jets
DØ using prompt photons

• Reduce “physics effects”:
  – “MPF method”:
    • MPF=Missing Et Projection Fraction
  – Require jet to be back-to-back with photon:
    • $\Delta \phi > 3$ radians (>172°)

• Reach high $E_{T,\text{jet}}$:
  – Calibrate versus energy $E_{\text{jet}}$
    • Exploiting similarity between forward and central calorimeters
    – $\eta_{\text{jet}} \approx 0$: $E_{\text{jet}} \approx E_{T,\text{jet}}$
    – $\eta_{\text{jet}} \approx 2$: $E_{\text{jet}} \approx 3 E_{T,\text{jet}}$
Syst. Uncertainties on Response

• Varying assumptions gives systematic uncertainty
• In analysis data/MC difference counts in most cases
  – Same procedure done for MC
Multiple Interactions (MI)

- Need to know how many interactions there were:
  - # of z-vertices ~ # of interactions
- Throw random cones in Minimum Bias events
  - Determine average $E_T$ per cone, e.g., CDF: 1 GeV for $R=0.7$
The complication for $k_T$ algorithm

- Multiple Interactions are main reason for the difficulties with the $k_T$ algorithm at hadron colliders
  - The method of throwing a random cone does not work:
    - they are not cone jets
  - $k_T$ algorithm biases itself to go where the energy is and picks up energy from MI
- $k_T$ algorithm has now been used by CDF in Run 2 for the jet cross section:
  - Empirical correction factor using fact that cross section independent of inst. luminosity
Relative Corrections

\[ \beta = \frac{p_T^{\text{probe}}}{p_T^{\text{trigger}}} \]
Relative Corrections

- Mapping out cracks and response of calorimeter
- Central at $\sim 1$ by definition
- D0:
  - Response similar in central and forward
  - Two rather large cracks
- CDF:
  - Response of forward better than of central
  - Three smaller cracks
- Difficulties:
  - depends on $E_T$
  - Can be (most often is initially) different for data and MC
Corrections from Particle Jet to Parton

• Underlying event (UE) and Out-of-cone (OOC) energy
  – Only used if parton energy is wanted
  – Requires MC modeling of UE and OOC
    • Differences are taken as systematic uncertainty

\[ P_{T, \text{parton}} = P_{T, \text{particle}} - UE + OOC \]
Underlying event definition:
- “beam-beam remnants”: energy from interaction of spectator partons
- “Initial state radiation”: energy radiated off hard process before main interaction
  - Not wanted when e.g. measuring the top quark mass

Can be estimated using Monte Carlo
- Measurements led to tuning of MC generators: PYTHIA, Herwig+Jimmy
Many studies exist about underlying event:
  - Checkout talks by Rick Field/U. of Florida

At LHC we will need to measure it:
  - Expect it to be much harder than at Tevatron

“Transverse” region very sensitive to the “underlying event”!
Out of Cone Energy (OOC)

- **Out-of-Cone Energy:**
  - Original parton energy that escapes the cone
    - E.g. due to gluon radiation
  - Jet shape in MC must describe data:
    - measure energy flow in annuli around jet
- **Differences between data and MC**
  - Lead to rather large systematic uncertainty
• CDF and DØ achieve similar uncertainties after following very different paths before
• Both collaborations have plans to improve further
Compare data and MC after calibration

- Data and MC agree within systematic uncertainties
Photon-Jet $P_T$ balance

- Agreement within 3% but differences in distributions
  - Data, Pythia and Herwig all a little different
- These are physics effects!
• Better agreement of data and MC than in photon-jet data
  – In progress of understanding this better together with Herwig and Pythia authors
Calibration Peaks from W’s and Z’s

- Very, very difficult to see inclusive decays of W’s and Z’s to jets
  - Small signal on huge background
    - W+2 jets
    - Photon+2 jets (UA2)
- Two best opportunities:
  - W in top quark decays
  - Z in bb decay mode

UA2, S/B ~ 1/35, ~5000 Signal
\textit{In-situ} Measurement of JES

- Additionally, use $W \rightarrow jj$ mass resonance ($M_{jj}$) to measure the jet energy scale (JES) uncertainty.

Measurement of JES scales directly with data statistics.

2D fit of the invariant mass of the non-b-jets and the top mass:

$$\text{JES} \propto M(jj) - 80.4 \text{ GeV}/c^2$$
W$\rightarrow$jj Calibration in Top Events

- Fit for ratio of JES in data to JES in MC
  - CDF (1 fb$^{-1}$): $\delta_{\text{JES}} = 0.99 \pm 0.02$
  - DØ (0.3 fb$^{-1}$): $\delta_{\text{JES}} = 0.99 \pm 0.03$
- Constrain JES to 2% using 166 events

At LHC will have 45,000 top events/month!
• **Z→bb decay mode:**
  - Suppresses QCD background more than signal
  - Difficult to trigger
    - CDF uses secondary vertex trigger
    - D0 uses semi-leptonic decays collected by muon trigger

• Use this to measure difference between data and MC JES, e.g. DØ:
  - Data:
    - $\mu=81.0 \pm 2.2$
    - $\sigma=10.7 \pm 2.1$
  - MC:
    - $\mu=83.3$
    - $\sigma=13.0$
Conclusions

• Different calorimeters/collaborations can choose very different procedures:
  – CDF tunes simulation and then derives everything from MC
    • Systematic uncertainties depend on how well MC models data
  – DØ does a purely data based estimate
    • Systematic uncertainties depend on understanding of calibration process and sample composition

• Calibration signals:
  – MIP peak, E/p, Z→ee and Minimum Bias for calorimeter calibration
  – Di-jet balancing for relative response in cracks and in plug calorimeter
  – Isolated tracks for understanding calorimeter response to π’s
    • Fragmentation needs to be modeled well
  – Photon-jet balancing for relative and absolute response

• Independent channels used for cross checks/systematic error:
  – Photon-Jet and Z-jet balancing
  – Z→bb peak and W→jj peak in top events

• 3-4% systematic uncertainty achieved so far
  – Better for jets in top events (~2%)

Jets are very complex and rather tough to calibrate
Backup
Jet Energy Scale

- **Jet energy scale**
  - Determine the energy of the partons produced in the hard scattering process
  - **Instrumental effects:**
    - Non-linearity of calorimeter
    - Response to hadrons
    - Poorly instrumented regions
  - **Physics effects:**
    - Initial and final state radiation
    - Underlying event
    - Hadronization
    - Flavor of parton
- **Test each in data and MC**

\[
P_{T,\text{jet}}^{\text{particle}} = \left( P_{T,\text{jet}}^{\text{measured}} \times f_{\text{rel}} - MI \right) \times f_{\text{abs}},
\]

\[
P_{T,\text{parton}} = P_{T,\text{jet}}^{\text{particle}} - UE + OOC
\]
Offset correction in D0

Offset includes:
- Underlying event
- Multiple interactions:
  - # of Interactions ~ # of z-vertices
- Noise
- Pile-up from previous interaction
  - Due to long shaping time of preamplifier
- Measure
  - Minimum bias events per tower
  - Depending on number of vertices

![Graph showing offset energy vs. number of primary vertices](image)