Calorimetry Lecture 3: Using Calorimeter Information

Simulated 130 GeV Higgs decaying to two photons

Higgs signal

Events / 500 MeV for 10^5 pb-1

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Topics in Lecture 3

- Using calorimeter information
  - Calibration
  - Complementarity of tracking and calorimetry

- Reconstruction of jets
  - Algorithms
  - Jet Energy Corrections
Calibration and Linearity

- Goal: uniform and known response to a given calorimeter signal
- For example, signal (charge) from detector is in pC, digitized to ADC counts
  - want linear response
  - channel-to-channel differences: leakage, upstream material, electronics
- Calibrations:
  - Relative calibration normalizes the response between all channels
  - Absolute calibration translates it to energy units (from ADC counts)
- How-to: testbeam, electronics calibration, in-situ, simulation
To get to physics, first must calibrate

- **Component calibration**
  - For example, all PMT’s are tested standalone

- **Testbeam** – operate detector (or part of) in a known-energy, known-species beam
  - In addition to R&D for new detectors, provide a testbench for the final modules of the calorimeter

- **In-situ calibration**
  - Pulse detector with known energy, measure response
  - Cosmic muons, single particles

- **Physics object calibration**
  - “tag and probe”, dijet balance, photon+jet balance, W in top events
Component testing and calibration

- Example – PMT’s for CMS HCAL (HF)
  - Test station – dark box, laser input
  - Individual testing, relative calibration
  - PMT’s characterized, data put into database for later calibration input:
    - Double-pulse linearity,
    - Gain vs HV
    - Single photoelectron spectrum
    - X-Y scan (spatial uniformity)
    - Lifetime, pulse width, rise time
    - Transit time and spread
    - Anode dark current
    - Relative gain coupled with cathode sensitivity
    - Pulse linearity
    - Quality control decision

- All (or as many as possible) components of detector are calibrated long before they are integrated into detector

Pulse width for 1550 PMT’s
In-situ Detector/Electronics Calibration

- Example: inject known-energy pulse (e.g., from radioactive source or laser), then normalize readout of all channels.
- Example: Atlas and CMS -- similar methods:

![Atlas Source Path](image)

Response by location
Calibration with Muons

- Use muons from cosmic rays, testbeam, or physics events
  - Will give MIP response in calorimeter cell
  - Equalize channel-to-channel response

- CDF:
  - select muons from J/ψ and W
  - peak in HAD calo: ≈2 GeV (in CDF)
- Check time stability
In Situ Calorimeter Calibration: EM Energy

- **MIP peak:**
  - CDF → 300 MeV

- **Z→ee peak:**
  - Set absolute EM scale in central and endcap

- **E/p for electrons**
  - After having calibrated p and material, see response in E

![Graph showing MIP peak at 300 MeV and Z→ee peak]
Single Particle Response Simulation

- Single particle response:
  - Measure with test beam
  - In situ:
    - Select “isolated” tracks and measure energy in tower behind them
  - Tune simulation to describe E/\rho \text{ distributions at each } \rho \text{ (use } \pi/\rho/K \text{ 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**

In-situ

Test beam
CMS ECAL calibration

- Startup calibration based on 10 years of test beam and cosmic ray pre-calibration, $\pi^0$ calibration
- Precision of startup calibration
  - ECAL Barrel 0.5 – 2.2%
    → 1.2% in central region
  - ECAL Endcap 5%
  - Target with 10/pb: 0.5% EB, 1-2% in EE
- Calibration validated by observation of $\pi^0$ and $\eta \rightarrow \gamma\gamma$
Single-particle response in CMS

- Compare response of isolated tracks with low ECAL energy in MinBias events with single pions from Monte Carlo

Mean response in Data and MC agree within 2-3% in barrel region. In endcap, simulation is lower than data (~4%)
Jets from Collisions

- QCD interactions $\rightarrow$ Jets
- Types of Jets
  - Parton level – quarks/gluons from initial collision
  - Hadron level – fragmentation, decay, hadronization produce particles
  - Experimental – what we see in the calorimeter, and how we interpret it
- Goal – take detector information, reconstruct parton level physics
Jet Algorithms

- Procedure to turn recorded detector info into jets
  - Or, looking at it from the other way, turn partons into jets

- Constraints:
  - Infrared and collinear safe (see next slide)
  - Invariant under boost (important for hadron colliders)
  - Independent of level (parton, hadron, calorimeter) and detector
  - Easy to implement and use (computer resources), calibrate
Technical terms

- Infrared safe – same jets even if one of the partons emits a soft gluon

- Collinear safe – same jets even if outgoing partons split

Graphics from Kerstin Perez, ISSP 2009
Jet Algorithms used at Hadron Colliders

- Choice of jet algorithms is an involved topic – theorists and experimentalists have been working together for years to find the perfect scheme
  - True to parton-level
  - True to experimental (detector) level
  - Taking into account detector effects, pileup, etc.

- There are many possible algorithms to choose from – we won’t cover them all
  - Here are examples from CMS: Anti-kT, SISCone and kT jet algorithms:
    - Then, generator jets, calorimeter jets, calorimeter+track, and particle-flow jets for these jet algorithms
Cone Algorithms

- Cone (traditional)
  - clusters nearby in angular space
  - Problem: seeded – introduces bias especially with pileup
  - Problem: needs merging/overlap scheme, which every experiment implements differently
    -> Difficult to compare, feedback to theorists

- If you don’t seed the jets, takes $N 2^N$ time to find jets among $N$ particles (“unseeded”)
  - unusable at hadron level (think of “simple” event with 100 particles…)
  - reduce to $N^2 \ln(N)$ time – SISCones algorithm
Clusters nearby in momentum space

Based on JADE or Durham algorithm -- exclusive iterative pairwise clustering scheme

- JADE algorithm uses test variable $y_{ij}$, and a combination procedure.
- Test if objects $i$ and $j$ should be combined according to whether $y_{ij} < y_{cut}$.
- Also, consider next pair to combine (smallest value of $y_{ij}$).
- Original JADE $y_{ij} = M^2_{ij}/Q^2$ where $Q$ is the hard scale (i.e. the centre-of-mass in $e^+e^-$ annihilation) and $M^2_{ij} = 2E_iE_j(1 - \cos \theta_{ij})$, (invariant mass-squared)
- Repeated until no objects can be combined further

- Problem with JADE – not IR, collinear safe

- Durham mod -- consists of replacing $M^2_{ij}$ in test variable by $k^2_{Tij}$,
  - $k^2_{Tij} = 2\min\{E_i, E_j\}^2(1 - \cos \theta_{ij})$ -- relative transverse momentum-squared of $i$ and $j$. 

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kT and anti-kT

- **Advantages of kT**
  - Jet identification is unique – no merge/split stage

- **Disadvantage of kT**
  - Resulting jets are more amorphous, energy calibration difficult (subtraction for UE?), and analysis can be very computer intensive (time grows like $N^3$)

- **Anti-kT**
  - Like kT, only uses $1/p_T$ as the distance parameter
  - Improves performance with pileup
Testing Jet Definitions

- See this very nice webpage http://www.lpthe.jussieu.fr/~salam/jet-quality/
  - You choose two jet algorithms, set the parameters, and it compares dijet mass distributions with your conditions

Your input – twice for comparison
Example: compare $k_T$ to anti-$k_T$
More on jet algorithms

- Algorithms often designed from parton point of view
- From the detector point of view
  - What information goes into a jet?
    - Calorimeter, tracking
    - “Energy flow”
  - Jet corrections, systematics
  - Integration into experimental software.
For Example, CMS Jets

- CMS has chosen the anti-kT algorithm, with \( R=0.5 \), as the default. Then, 4 types of jets reconstructed:

  1. **Calorimeter Jets**
     - Jets clustered from ECAL and HCAL deposits (Calo Towers)
     - Accordingly:
       - Calo MET

  2. **Jet-Plus-Track Jets (JPT)**
     - Subtract average calorimeter response from CaloJet and replace it with the track measurement
     - Accordingly:
       - Tc MET

  3. **Particle Flow Jets (PF)**
     - Cluster Particle Flow objects: Unique list of calibrated particles “a la Generator Level”
     - Accordingly:
       - PF MET

  4. **Track Jets**
     - Reconstructed from tracks of charged particles, independent from calorimetric jet measurements

From Joanna Weng
Particle Flow Jets

- Combines info from all subdetectors to produce particles
  - Charged hadrons – from tracks
  - Photons, neutral hadrons from ECAL, HCAL energy
    - Clusters with no tracks
  - Neutral particle overlapping with charged particles – subtract charged pt from cluster, remaining is neutral particle

- Jets from resulting particles – charged hadrons and $\gamma$ are 90% of jet energy
Jet Energy Scale

- Determine the energy of the partons produced in the hard scattering process
- Corrections needed for:
  - Detector effects:
    - Non-linearity of calorimeter
    - Response to hadrons
    - Poorly-instrumented or non-functional regions
  - Physics effects:
    - Initial and final state radiation
    - Hadronization
    - Underlying event
    - Parton flavor
- Need corrections for data and MC, validate in both
Jet Corrections

- Use CMS as an example, also show others
  - CMS uses factorized approach

apply Jet Corrections as:

\[ \text{E}_{\text{corrected}} = (\text{E}_{\text{uncorrected}} - \text{E}_{\text{offset}}) \times C_{\text{rel}}(\eta, p''_T) \times C_{\text{abs}}(p'_T) \]

Where \( p''_T \) is the jet \( p_T \) corrected for offset, and \( p'_T \) is corrected for offset and \( \eta \) dependence (Relative corr).
Offset correction

- Measure noise with Zero Bias trigger, with Minimum Bias trigger vetoed (MinBias requires coincidence in Beam Scintillating counters, indicating pp interaction)
- Measure pileup – select MinBias events in early data (most events 0,1 int.)
- $E_{\text{offset}}$ -- average calorimeter energy summed in a cone of radius $R=0.5$ at a given $\eta$ -- Offset from noise is below 400 MeV in energy
- Offset from one pile-up event: Up to 7 GeV in energy
- Probability of pile-up in 2010 data typically $\sim$50%
- Correction is small -- not yet being applied on CMS jets
Relative Correction from Dijet pT balance

- Require at least 2 jets, one in central region (Tag)
- $\Delta\phi > 2.7$
- Veto 3rd jet ($p_T^{3rd}/p_T^{dijet} < 0.2$)
- Measure Balance variable $B$ in bins of $p_T(dijet)$ and $\eta$
- $\langle B \rangle$ in each bin is used to construct $r$
  - Measure of relative response
Relative response in $\eta$

- Same dijet balance is applied to simulation
- Good agreement Data/MC for $|\eta|<2$
- Calorimeter transition
  - Barrel to endcap at $|\eta|=1.3$
  - Endcap to forward at $|\eta|=3$
JPT and PF jets – rely on tracking with calorimetry – response reflects tracking detector coverage as well as calorimeter

⇒ Steep falloff in track efficiency and resolution for $|\eta|>2$, none for $|\eta|>2.5$
Relative JEC : Data/MC

- Good agreement up to $|\eta| = 2$
- Relative response in data ~10% higher compared to simulation for $|\eta| > 2$

$=>$ Data/MC close to unity after the residual correction
$=>$ Data/MC deviations are covered by conservative $\eta$-dependent systematic uncertainty of $\pm 2\% \times |\eta|$
Absolute Jet Energy Correction at CMS

- Goal – want calorimeter energy response to a particle jet to be 1 and independent of pT
  - Absolute Jet Energy Correction
- When combined with offset and relative corrections, this is all that is needed for most analyses
- Use photon+jet events
  - γ+jet balance
  - MPF
- Start with isolated photon, pt>15 GeV, in barrel region (|η|<1.3), + 1 barrel jet
Absolute Correction from Photon + jet

- pT balance in back-to-back $\gamma$+jet events

  - $\gamma$ is the reference, test response $p_T/p_T^\gamma$

- Compare data, simulation to true from MC
- Bias due to soft veto on 2nd jet
- D0 – developed MPF method
- Missing ET Projection Fraction – uses MET to measure the balance, less sensitive to QCD radiation
Jet Response from MPF in $\gamma$+jet

- **Basics of MPF (Missing Momentum Fraction; developed at D0)**
  - Ideally: $\vec{p}_T^\gamma + \vec{p}_T^{\text{recoil}} = 0$

- Add in the detector: $R_\gamma \vec{p}_T^\gamma + R_{\text{recoil}} \vec{p}_T^{\text{recoil}} = -\vec{E}_T^{\text{miss}}$

- Solving: $R_{\text{recoil}} / R_\gamma = 1 + \frac{\vec{E}_T^{\text{miss}} \cdot \vec{p}_T^\gamma}{|\vec{p}_T^\gamma|^2} \equiv R_{\text{MPF}}$

  - $R_{\text{MPF}}$ is assigned as the response of the recoil jet

- **Advantage of MPF: Low sensitivity to extra radiation**
  - Smaller error bars: Widths of distributions are narrower $\rightarrow$ fewer fluctuations from the impact of extra radiation
  - Smaller bias wrt MC-truth than $p_T^{\text{jet}} / p_T^\gamma$ for current very loose cuts on extra radiation
  - Helps to fully exploit the accuracy of PF method

- **MPF method demonstrates the accuracy of JES for different types of jets more clearly than $\gamma$-jet balancing method does**
MPF at CMS

\[ \gamma + \text{jet} \rightarrow \text{MPF} \]

**Graphs:**

- Response vs \( p_T^\gamma \) (PF Jet)
- Distributions of "response sensitive" variable \( R_{\text{MPF}} \) vs \( p_T^\gamma \) (PF Jet)

**Equations:**

- \( \sqrt{s} = 7 \text{ TeV}, L = 67 \text{ nb}^{-1} \)

**Other Data:**

- CMS Preliminary 2010
- JME-10-003

**Fits:**

- Photon \( p_T \) [GeV/c]:
  - \( \text{FIT: } 0.926 \pm 0.017 \)
  - \( \text{FIT: } 0.992 \pm 0.010 \)
Absolute Correction Factors

- Absolute jet energy correction factors $C_{\text{abs}}$ derived from simulation for CaloJets, PF Jets, JPT jets, at 7 TeV, as a function of corrected jet $p_T$

Note large correction factors at low $p_T$ for CaloJets – due to non-compensation of CMS calorimeters
Correcting Simulated Jets

- Derive corrections for Monte Carlo jets – match reconstructed jets to MC-generator level jets
- In CMS, first three levels are put together in one correction (offset, relative, absolute)

![Jet Energy Correction Factor Graphs](image-url)
Jet Corrections/Calibrations from Tevatron

- Mature Tevatron experiments have sophisticated jet correction algorithms
  - Use some of the same that I showed for CMS
- I will show some examples
Multiple Interactions (MI) at the Tevatron

- 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
Relative Corrections

- Mapping out cracks and response of calorimeter
- Central at ~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 different for data and MC
Calibration Peaks from W’s and Z’s

- Would like to use W,Z for calibration – same mass scale as Higgs
- Difficult to see inclusive decays of W’s and Z’s to jets
  - Small signal on huge background
- Two best opportunities:
  - W in top quark decays
  - Z in bb decay mode
Jet Energy Scale Uncertainties

- Uncertainty on Jet Energy Scale determines how well you can measure mass (of W, H, new resonance, etc) – extremely important to reduce, and understand
- CDF and DØ achieve similar uncertainties
- CMS – 10% based on Monte Carlo studies – initial data validates that this is conservative → Will improve with more data
Summary

- I’ve tried to show aspects of calibration of calorimeters at many levels
  - detector components
    - Testbeam, in-situ
  - Single-particle
  - Physics objects

- Using calorimeter information
  - Jet construction algorithms

- Corrections at the physics level
  - It comes back to how the detector was designed and built
  - Important to physics results!
Thanks for your attention and participation!!
Enjoy the rest of the summer school!!
Extra slides
Backup: Anti K_T

\[ d_{ij} = \min \left( \frac{k_{T,i}^{-2}, k_{T,j}^{-2}}{R_i^2, R_j^2} \right) \frac{\Delta R_{ij}^2}{R^2} \]

\[ \Delta R_{i,j}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2 \]

- New development in the jet clustering theory.
- Tends to cluster the energy around the hardest particles.
  - essentially behaves like a cone algorithm giving perfectly round jet areas
- Belongs to the “k_T” family.
  - merging of 4-vector pairs based on transverse momentum weighted distance in y-\(\phi\) plane.
  - the clustering terminates when the weighted distance between particles is greater than a specific value \(R\) (resolution parameter).
  - the quantity \(R\) is of the order of unity.
- infrared and collinear safe (suitable for theory calculations).
Multiple pp Interactions

- Overlapping interactions can overlap the jet
- Number of extra interactions depends on luminosity
  - LHC:
    - Low lumi (L=1x10^{33} \text{ cm}^{-2}\text{s}^{-1}): \langle N \rangle = 2.3
    - High lumi (L=1x10^{34} \text{ cm}^{-2}\text{s}^{-1}): \langle N \rangle = 23
  - Tevatron:
    - L=2x10^{32} \text{ cm}^{-2}\text{s}^{-1}: \langle N \rangle = 6

Offset depending on number of interactions
**In-situ** Measurement of JES

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

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

$$\text{JES} \propto M(jj) - 80.4 \text{ GeV}/c^2$$

Measurement of JES scales directly with data statistics.
### W → 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!
Streamlined Seedless Algorithm

- Data in form of 4 vectors in $(\eta, \varphi)$

- Lay down grid of cells (~ calorimeter cells) and put trial cone at center of each cell

- Calculate the centroid of each trial cone

- If centroid is outside cell, remove that trial cone from analysis, otherwise iterate as before

- Approximates looking everywhere; converges rapidly

- Split/Merge as before
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

\[ P_{T,\text{parton}} = P_{T,\text{particle}} - UE + OOC \]
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
Underlying Event

- Consists of:
  - "beam-beam remnants": energy from interaction of spectator partons
  - "Initial state radiation": energy radiated off hard process before main interaction
Measuring the Underlying Event

“Transverse” region very sensitive to the “underlying event”!

**Leading Jet Direction**

- **“Toward”** Jet
- **“Away”** Jet
- **“Toward Side”** Jet
- **“Away Side”** Jet

**Charged Particle Density**

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**CDF Data**

- **630 GeV**
- **1.8 TeV**
- **14 TeV**

**Transverse** $P_{T_{sum}}$ vs $P_{T}$ (charged jet 1)

- **CDF MinBias**
- **CDF JET20**
- **HERWIG**
- **ISAJET**
- **PYTHIA 6.115**

**“Transverse” $P_{T}$ vs $P_{T}$** (charged jet 1) in 1 GeV/c bin

**Charged Particle Density**

- **Pythia 6.206 Set A**
- **|$\eta|$<1**

**Leading Jet Direction**

- **“Toward”** Jet
- **“Away”** Jet
- **“Toward Side”** Jet
- **“Away Side”** Jet