“Taus, Jets, & MET from Particle Flow Event Reconstruction with CMS”

R. Cavanaugh*
Fermi National Accelerator Laboratory
& University of Illinois at Chicago

SUSY09, Boston
6 June, 2009

- Introduction
- What is Particle Flow?
- How does it work?
- How well does it perform in CMS?

*On behalf of the CMS Collaboration
Particle Flow in CMS

- CMS ideally suited to reconstruct and identify particles!
  - Very Large Tracker; High B-Field
  - Large Lever-arm for High PT Muons
  - Fine Granularity, High Resolution ECAL
  - Nearly full solid-angle coverage HCAL
Goal of Particle-Flow

- Reconstruct & identify all particles
  - $\gamma, e, \mu$, charged hadrons, neutral hadrons, pileup particles, and even converted photons & nuclear interactions
  - Use the best combination of all CMS sub-detectors to get the best estimates of energy, direction, particle ID

- Provide consistent & complete list of ID’d & calibrated particles for
  - Tau reconstruction
  - Jet reconstruction
  - Missing Energy and total Visible Energy determination

- Use of Redundant Information: Calorimeter & Tracking
  - Good: Better Calibration (data driven) and Resolution possible
  - Challenge: Must have accurate accounting

- Very different from “Traditional” Tau, Jet, MET Reconstruction...
Basic Required Ingredients

- **Large Volume Tracker**
  - high precision, high efficiency tracking is critical
- **High Magnetic Field**
  - needed for good pT resolution
  - needed to separate charged from neutral particles
- **Highly Granular Calorimeter**
  - needed to separate charged from neutral particles
- **Good Calorimeter Energy Resolution is**:
  - needed for good photon, electron ET resolution
    - “interesting” photons/electrons tend to be prompt
  - not critical for Hadrons
    - individual hadrons tend to be lower in pT
Using the Detailed Full Detector

Muons

Electrons

$\Delta p/p$

$0.0 < \eta < 0.2$

Significant improvement achieved for leptons by using the Detailed Full Detector...

...why not also for taus, Jets & MET?
Calorimeter Tower
- 1 HCAL Cell
- 25 ECAL Crystals underneath (loss of granularity)

Calorimeter Jets
- Large Jet E Corr.
- Resolution HCAL
  \[ \sigma \approx 100\% \]
  \[ \frac{\sigma}{E} \approx \frac{100\%}{\sqrt{E}} \]
**Calorimeter Tower**
- 1 HCAL Cell
- 25 ECAL Crystals underneath (loss of granularity)

**Charged hadrons**
- Spread by high B-field
- Degrades angular resolution

**Calorimeter Jets**
- Large Jet E Corr.
- Resolution HCAL
  \[ \frac{\sigma}{E} \approx \frac{100\%}{\sqrt{E}} \]
Charged hadrons
○ 65% of jet E
○ direction at vertex
○ resolution tracker

Use B-field and hi-res tracker to our advantage!

Momentum Resolution
○ 1% for 100 GeV
Photons
○ 25% of jet E
○ resolution ECAL

Granularity
○ \( 0.02 (\Delta \eta \Delta \phi) \)

Energy Resolution
○ \( \approx 2\%/\sqrt{E} \)

Use granularity and resolution of ECAL to our advantage!

Separate
○ charged particles
○ neutral particles
Neutral Hadrons
○ 10% of jet E
○ resolution HCAL

Reduce dependence on HCAL

Granularity
○ $0.1 \Delta \eta \Delta \varphi$

Energy Resolution
○ $\approx 100\% / \sqrt{E}$
Particle Flow Algorithm
First Associate Hits within Each Detector

HCAL Clusters

ECAL Clusters

Tracks
Particle Flow Algorithm
Linking Across Detectors

HCAL Clusters

ECAL Clusters

Tracks
Basic Idea of Particle Flow:
Finally Apply Particle ID & Separation

HCAL Clusters

ECAL Clusters

Tracks

neutral hadron

\[ E_{\text{rec}}(\text{ECAL, HCAL}) > E_{\text{tracks}} \]
Very Basic View of Particle Flow

“Clean” the Event During Reconstruction!

- Find and “remove” muons ($\sigma_{\text{track}}$)
- Find and “remove” electrons ($\min[\sigma_{\text{track}}, \sigma_{\text{ECAL}}]$)
- Find and “remove” converted photons ($\min[\sigma_{\text{track}}, \sigma_{\text{ECAL}}]$)
- Find and “remove” charged hadrons ($\sigma_{\text{track}}$)
- Find and “remove” V0’s ($\sigma_{\text{track}}$)
- Find and “remove” photons ($\sigma_{\text{ECAL}}$)
- Left with neutral hadrons (10%) ($\sigma_{\text{HCAL + fake}}$)

- Use above list of Reconstructed Particles to describe the entire event!
Tau Reconstruction

• Tau decay diagrams

• Excellent Laboratory for Particle Flow
  • Very clean environment
Tau Reconstruction

- Tau-jet (single+three prong) reconstruction at CMS benefits enormously from Particle Flow

- Better Resolution
  - Angular
  - Visible ET

- Less Bias
  - Angular
  - Visible ET

- Strong B-field
  - helps separation!
  - lowers density
  - improves Particle ID

CDF: Similar Tau Reconstruction Improvement also observed
Jet Reconstruction

- Approaching Self-calibration
  - much smaller residual corrections
    5% compared with 65% at 100 GeV
  - Nearly independent of Jet Flavour
- Better Energy Resolution
  - Factor 3 at 15 GeV (tracker dominates)
  - Converges to Calorimeter at high pT
- Better Angular Resolution
  - Especially in azimuth (B-Field)
  - Especially at low pT, but also at high pT
- Enables Better Jet Definitions
  - Clustering Algorithms:
    - smaller cone sizes possible
    - lower pT thresholds possible
  - Reduces isolated e/γ faking a jet
    - can be excluded from jet clustering
  - Particle Multiplicity and Content:
    - neutral hadronic, charged hadronic, photonic, leptonic, etc
Jet Reconstruction

- Approaching Self-calibration
  - much smaller residual corrections
  5% compared with 65% at 100 GeV
  - Nearly independent of Jet Flavour
- Better Energy Resolution
  - Factor 3 at 15 GeV (tracker dominates)
  - Converges to Calorimeter at high pT
- Better Angular Resolution
  - Especially in azimuth (B-Field)
  - Especially at low pT, but also at high pT
- Enables Better Jet Definitions
  - Clustering Algorithms:
    - smaller cone sizes possible
    - lower pT thresholds possible
  - Reduces isolated e/γ faking a jet
    - can be excluded from jet clustering
  - Particle Multiplicity and Content:
    - neutral hadronic, charged hadronic, photonic, leptonic, etc
Jet Reconstruction

- Approaching Self-calibration
  - much smaller residual corrections
    5% compared with 65% at 100 GeV
  - Nearly independent of Jet Flavour
- Better Energy Resolution
  - Factor 3 at 15 GeV (tracker dominates)
  - Converges to Calorimeter at high pT
- Better Angular Resolution
  - Especially in azimuth (B-Field)
  - Especially at low pT, but also at high pT
- Enables Better Jet Definitions
  - Clustering Algorithms:
    - smaller cone sizes possible
    - lower pT thresholds possible
  - Reduces isolated e/γ faking a jet
    - can be excluded from jet clustering
  - Particle Multiplicity and Content:
    - neutral hadronic, charged hadronic, photonic, leptonic, etc
MET Performance

- MET is the very last step
  - Benefits from all progress in the jets!
  - Will continue to benefit from further progress!

- Better able to measure zero-MET (e.g. as in QCD)
  - Improved estimate of event visible energy
    - better measure of “zero” imbalance
  - 60% better at 500 GeV of Sum ET

- Better able to measure real-MET (e.g. as in ttbar)
  - Improved Energy Response
    - Calibrated within 5% above 20 GeV
  - Improved Energy Resolution
    - Nearly factor 2 near 100 GeV
    - About 60% better at 20 GeV
  - Improved Angular Resolution
    - Factor 2 up to (even >) 200 GeV
• MET is the very last step
  • Benefits from all progress in the jets!
  • Will continue to benefit from further progress!
• Better able to measure zero-MET (e.g. as in QCD)
  • Improved estimate of event visible energy
    • better measure of “zero” imbalance
  • 60% better at 500 GeV of Sum ET
• Better able to measure real-MET (e.g. as in ttbar)
  • Improved Energy Response
    • Calibrated within 5% above 20 GeV
  • Improved Energy Resolution
    • Nearly factor 2 near 100 GeV
    • About 60% better at 20 GeV
  • Improved Angular Resolution
    • Factor 2 up to (even >) 200 GeV
• MET is the very last step
  • Benefits from all progress in the jets!
  • Will continue to benefit from further progress!
• Better able to measure zero-MET (e.g. as in QCD)
  • Improved estimate of event visible energy
    • better measure of “zero” imbalance
  • 60% better at 500 GeV of Sum ET
• Better able to measure real-MET (e.g. as in ttbar)
  • Improved Energy Response
    • Calibrated within 5% above 20 GeV
  • Improved Energy Resolution
    • Nearly factor 2 near 100 GeV
    • About 60% better at 20 GeV
  • Improved Angular Resolution
    • Factor 2 up to (even >) 200 GeV
MET Performance

- MET is the very last step
  - Benefits from all progress in the jets!
  - Will continue to benefit from further progress!
- Better able to measure zero-MET (e.g. as in QCD)
  - Improved estimate of event visible energy
    - better measure of “zero” imbalance
  - 60% better at 500 GeV of Sum ET
- Better able to measure real-MET (e.g. as in ttbar)
  - Improved Energy Response
    - Calibrated within 5% above 20 GeV
  - Improved Energy Resolution
    - Nearly factor 2 near 100 GeV
    - About 60% better at 20 GeV
  - Improved Angular Resolution
    - Factor 2 up to (even >) 200 GeV
Summary

- Particle Flow is a fully generic description of the global event
  - not tuned to taus, Jets, or MET, but useful for each of them
  - can form complicated variables (event shapes variables, etc)
- Particle Flow enables rich menu of Physics at LHC
  - Improved reconstruction pT and angular performance
  - Improved composition information
- Significant Challenge in a Hadronic Environment!
  - Particle multiplicity $\rightarrow$ linking, particle ID, separation are keys!
- Significant Progress in CMS achieved!
  - Many interesting detector design subtleties $\rightarrow$ very interesting work!
- Significant Additional progress expected
  - Not the end of the game (many improvements already identified)

Eagerly Awaiting Performance on First Collision Data!
Backups - Systematic Checks

Jet Response

-0.5 -0.4 -0.3 -0.2 -0.1 0 0.1 0.2 0.3

-2 -1 0 1 2

△ Particle-Flow Jets
☐ Calo-Jets

η

X/X₀

 Beam Pipe
 Pixel
 Inner Silicon
 Outer Silicon
 Common
 Outside

η

26
Backups - Systematic Checks

CMS Preliminary

Jet Response vs. $p_T$ [GeV/c]
- Default Correction
- Correction ± 50%

CMS Preliminary

Jet Response vs. $p_T$ [GeV/c]
- Default Thresholds
- Thresholds ± 50%

CMS Preliminary

Jet Response vs. $p_T$ [GeV/c]
- Default Resolution
- Resolution ± 50%

CMS Preliminary

Jet Response vs. $p_T$ [GeV/c]
- Tracking0 Simulation
- Tracking5 Simulation