On behalf of the CMS collaboration

Outline

The particle-flow algorithm: overview
Performance on simulation
Commissioning on data
Conclusion

Material

CMS-PAS-PFT-10-002
CMS-PAS-PFT-10-003
CMS-PAS-PFT-09-001
The list of individual particles is then used to build jets, to determine the missing transverse energy, to reconstruct and identify taus from their decay products, to tag b jets …
Track-cluster link

ECAL surface

HCAL surface

* Two photons (ECAL clusters not linked to any track)  
  plus a $\pi^-$ and a $\pi^+$
Event Display, transverse view (2.36 TeV data)

Charged hadron
Event Display, transverse view (2.36 TeV data)

Charged hadron
Photon (dashed line)
Event Display, transverse view (2.36 TeV data)

Charged hadron
Photon (dashed line)
Neutral hadron (dotted line)
Event Display, transverse view (2.36 TeV data)

Charged hadron
Photon (dashed line)
Neutral hadron (dotted line)

Sum$E_T$ : 178 GeV
MET : 1.9 GeV

$$\overrightarrow{\text{MET}} = - \sum_{i=0}^{N_{\text{particles}}} \vec{E}_T^i$$
Particles clustered in jets

Jet 1 $p_T = 22$ GeV/c
Jet 2 $p_T = 42$ GeV/c
Jet 3 $p_T = 38$ GeV/c
MET: 1.9 GeV

Sum$E_T$: 178 GeV
MET: 1.9 GeV
Jet Algo: anti-Kt R=0.5
Three jets with $p_T > 20$ GeV/c
About 90% of the jet energy is carried by charged-hadrons and photons.

Even in high-$p_T$ jets, the average $p_T$ of the stable particles is around 10 GeV/c.
Jet energy response & resolution

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Simulated QCD-multijets events
barrel: $|\eta| < 1.5$

95-97% of the $p_T$ reconstructed, over the whole range

Very large improvement at low $p_T$, thanks to the tracks
Commissioning with $\pi^0 \rightarrow \gamma\gamma$

Data

- $m^{\text{phys}} = 135.2 \pm 0.1 \text{ MeV/}c^2$
- $\sigma_{m_{\gamma\gamma}} = 13.2 \pm 0.1 \text{ MeV/}c^2$
- 7-TeV Data, 0.1 nb

Simulated with CMS Preliminary 2010

- $m^{\text{phys}} = 136.9 \pm 0.2 \text{ MeV/}c^2$
- $\sigma_{m_{\gamma\gamma}} = 12.8 \pm 0.2 \text{ MeV/}c^2$

Agreement within ~1% of the PDG value in data

- Demonstrates the suitability of the absolute ECAL calibration
The calorimeter response to hadrons is well simulated.
The hadron response in the calorimeters is adequate at the 5% level
(similar agreement in the end-caps)
Jet composition

Jet energy fraction carried by particles within jets

Particle energy scale uncertainty:
- 65% charged hadrons: high precision
- 25% photons: 1%
- 10% neutral hadrons: 5%

Legitimate JES systematic uncertainty target ~ 1%

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Jet kinematics

- Require at least 2 jets with $p_T>25$ GeV and $\Delta \phi > \pi - 0.5$ and fill histograms with these 2 jets

Jet spectrum reproduced over several order of magnitudes

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**Di-jet events**

\[ E_T^{\text{miss}} = - \sum_{i=1}^{N_{\text{particles}}} E_T^i \]

\[ \Sigma E_T = \sum_{i=1}^{N_{\text{particles}}} E_T^i \]

- Agreement over 3 orders of magnitude for the $E_T^{\text{miss}}$
- Even more challenging: $\Sigma E_T$ (where no cancellation can occur)

All together, a remarkable agreement is obtained for these quantities, known to be challenging to reproduce at hadron colliders:
- Robustness of the algorithm
- A precise detector simulation
The $E_T^{\text{miss}}$ resolution is improved by a factor $\sim 2$ wrt the calorimeter-based $E_T^{\text{miss}}$.
A dedicated electron reconstruction algorithm has been developed to cope with low $p_T$ and non-isolated electrons. A sample of $J/\Psi \rightarrow ee$ is used for the commissioning. With a simple selection, a nice $J/\Psi \rightarrow ee$ peak is obtained.

The electron quality multivariate estimator agrees between data and simulation within $\sim 1\%$ of the PDG value.
High $p_T$ muons, electrons and $E_T^{\text{miss}}$

W leptonic decays are an ideal source for high $p_T$ leptons and neutrinos

$W \rightarrow \mu \nu$  No muon isolation applied  

$W \rightarrow e \nu$  Electron isolation applied

- Good agreement for the signal
- The agreement between data and simulation demonstrates the reliability of the Particle Flow $E_T^{\text{miss}}$ and lepton reconstruction
High $p_T$ leptons and $E_T^{\text{miss}}$

Average $E_T^{\text{miss}}$ as a function of the leading isolated lepton $p_T$.

To get agreement on these plots:
- the $E_T^{\text{miss}}$ should be correctly reproduced in the simulation
- the W/multi-jet event yields should be correctly reproduced.
Combining the various CMS sub-detectors, the particle-flow event reconstruction allows for a much better reconstruction of the jets, the $E_T^{\text{miss}}$, (and $\tau$)
- up to 3 times better resolution in jets
- on average 2 times better resolution in $E_T^{\text{miss}}$

The particle flow algorithm commissioning is ongoing and going well
- the energy scale of jets, $E_T^{\text{miss}}$, electrons, photons, muons is under control at the percent level

The particle-flow event reconstruction is keeping up with the LHC challenge
- the algorithms proves to be robust and reliable
Backup slides
The CMS Detector

- **Silicon Tracker**
  - Pixels (100 x 150 μm²)
  - ~1m², 66M channels
  - Microstrips (50-100μm)
  - ~210m², 9.6M channels

- **Crystal Electromagnetic Calorimeter (ECAL)**
  - 76k scintillating PbWO₄ crystals

- **Preshower**
  - Silicon strips
  - ~16m², 137k channels

- **Superconducting Solenoid**
  - Niobium-titanium coil carrying ~18000 A

- **Steel Return Yoke**
  - ~13000 tonnes

- **Total weight**: 14000 tonnes
- **Overall diameter**: 15.0 m
- **Overall length**: 28.7 m
- **Magnetic field**: 3.8 T

- **Hadron Calorimeter (HCAL)**
  - Brass + plastic scintillator

- **Forward Calorimeter**
  - Steel + quartz fibres

- **Muon Chambers**
  - Barrel: 250 Drift Tube & 500 Resistive Plate Chambers
  - Endcaps: 450 Cathode Strip & 400 Resistive Plate Chambers

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Why Particle Flow in CMS

Tracker: large acceptance and efficiency

ECAL: Good granularity

Solenoid: Large field

Muon system: Excellent efficiency
Hadron calibration - End-caps

CMS Preliminary 2010 (End-caps)

Calibrated Calo Energy (GeV) vs. Track momentum (GeV/c)

- Red line: 7-TeV Data, 7.5 nb⁻¹ (Calibrated)
- Black line: 7-TeV Data, 7.5 nb⁻¹ (Uncalibrated)
Jet variables

CMS Preliminary 2010
\( \sqrt{s} = 7 \text{ TeV}, L = 6.2 \text{ nb}^{-1} \)

- Data
- Simulation

Anti-\( k_T \) 0.5 PFJets
\( p_T^{\text{corr}} > 25 \text{ GeV/c} \)

Jet \( \eta \)

Jet \( \phi \)
Jet variables

CMS Preliminary 2010
$\sqrt{s} = 7$ TeV, $L = 6.2$ nb$^{-1}$

- Data
- Simulation

Anti-$k_T$ 0.5 PFJets
$|\eta| < 3.0$
$p_T^{\text{corr}} > 25$ GeV/c

Jet Momentum / Invariant Mass

10^4
10^3
10^2
10
1

0 20 40 60 80 100 120 140 160 180 200

1800
1600
1400
1200
1000
800
600
400
200
0

0 5 10 15 20 25 30 35 40

N Candidates
Barrel

Charged hadron energy

CMS Preliminary 2010
$\sqrt{s} = 7$ TeV, $L = 6.2$ nb$^{-1}$

$\text{Anti-}k_{t}$, 0.5 PFJets
$|\eta| < 1.4$
$p_{T}^{\text{corr}} > 25$ GeV/c

Photons energy

CMS Preliminary 2010
$\sqrt{s} = 7$ TeV, $L = 6.2$ nb$^{-1}$

$\text{Anti-}k_{t}$, 0.5 PFJets
$|\eta| < 1.4$
$p_{T}^{\text{corr}} > 25$ GeV/c

Neutral hadron energy

CMS Preliminary 2010
$\sqrt{s} = 7$ TeV, $L = 6.2$ nb$^{-1}$

$\text{Anti-}k_{t}$, 0.5 PFJets
$|\eta| < 1.4$
$p_{T}^{\text{corr}} > 25$ GeV/c
**End-caps**

- Charged hadron energy
- Photon energy
- Neutral hadron energy

![Graphs showing charged hadron energy, photon energy, and neutral hadron energy distributions.](image-url)
**Tau reconstruction**

**CMS Preliminary**

![Graph 1](image1)

- $|\eta| < 1.4$

![Graph 2](image2)

- $1.6 < |\eta| < 2.4$

**Tau visible energy**