Outline of Lecture 3

- Optimal Use of Calorimeter Information
  - Improving the Energy Measurement
  - Complementary Strengths of Tracking and Calorimetry

- Future Developments in Calorimetry
  - Dual-Readout Paradigm
  - New Detector and Photodetector Technologies
  - Upgrading Existing Calorimeters for Beyond $10^{34}\text{cm}^{-2}\text{s}^{-1}$
Summing Energies from Different Calorimeters

Perhaps one of the biggest challenges for calorimeter-only measurements is having to sum energies from different calorimeters:

- If calorimeters have a different e/h, then one suffers not only from non-compensating EM-fraction fluctuations within each calorimeter but also from the longitudinal fluctuations of the EM and HAD components of the shower between calorimeters.

- Many ECAL/HCAL transitions occur at $\lambda_{\text{int}} \approx 1\lambda_{\text{int}}$ right before the hadronic shower max (and unfortunately this is typically the location of dead material in the calorimeter).
Dual-e/h Response Compensation

Crystals+Tile Calorimetry

1) ECAL and HCAL clusters are matched

2) HCAL Tile Energy corrected for measured e/π in tile calorimeter (measured from HCAL only showers, MIP in ECAL)

3) ECAL Crystal Energy corrected for remaining e/π non-linearity in the beam energy minus the e/π-corrected HCAL energy

4) Corrected HCAL and ECAL energies for matched clusters are summed

(Courtesy of D. Green)
Dual-e/h Response Compensation

MIP in ECAL

“Banana Plots”

e/h=1 Line

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Dual-e/h Response Compensation

- Reduces stochastic term down to the level expected based on absorber thickness
  - Removes $e/\pi$ response non-linearity for isolated particles

\[
\sigma/E = a/\sqrt{E} + b
\]

- Linearity restored within 5% for $p \geq 5$ GeV and 2-3% for $p \geq 9$ GeV.

\[
\sigma/E = a/\sqrt{E} + b = 84\%/\sqrt{E} + 7\% \text{ in } P = 5-300 \text{ GeV/c}
\]

(idea developed by D. Green)
Hadron Showers: Layer Weighting and E-Density Weighting methods have been studied.
Clusters are reconstructed using “topological algorithm:
- seeds: highest energy > 4σ
- neighbors: energy > 2σ
Need to take care of overlapping clusters
Clusters can span over subdetectors!
T42 Noise Suppression

- Online noise suppression: only energies $|E| > 1.5 - 2.5 \sigma$ are read out.
- Offline T42 algorithm is applied:
  - All cells with $E > 4\sigma$ are kept.
  - All cells with $2\sigma < E < 4\sigma$ and a neighbor with $E > 4\sigma$.
  - Reduction of number of cells kept: 40%.

D0 Experiment

![Diagram showing noise suppression and data distribution with histograms and statistical values.]
1) Leverage High Precision Tracking
2) And High Resolution ECAL EM-Showers
3) Match and Discard Charged Hadron Showers Replacing with Track Momentum

(Courtesy of P. Janot)
Particle Flow

Jet Improvements

Response Linearity

Also, improves Jet Angle and Reco Turn-on Eff.

MET Improvements

Response Linearity

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Jet Plus Track

- No track-cluster matching required
  - Expected $e/\pi$ non-linearity is subtracted from calorimeter measurement and replaced with track momentum

Magnitude of improvement is much larger for calorimeters with large $e/\pi$ non-linearity
What’s on the horizon?

- **Dual-REAdout Method (DREAM Collaboration)**
  - Measure EM fraction cell-by-cell by comparing Cherenkov and dE/dx signals
  - Densely packed SPACAL calorimeter with interleaved Quartz(Cherenkov) and Scintillating Fibers
  - What is the dream? Measure jets as accurately as electrons

\[ \frac{\sigma_E}{E} \approx 15\% / \sqrt{E} \]

DREAM: Structure
New Method for Computing Energy

\[ S = E \left[ f_{\text{em}} + \frac{1}{(e/h)_S} (1 - f_{\text{em}}) \right] \]

\[ Q = E \left[ f_{\text{em}} + \frac{1}{(e/h)_Q} (1 - f_{\text{em}}) \right] \]

\[ \frac{Q}{S} = \frac{f_{\text{em}} + 0.21 (1 - f_{\text{em}})}{f_{\text{em}} + 0.77 (1 - f_{\text{em}})} \]

\[ E = \frac{S - \chi Q}{1 - \chi} \]

with \( \chi = \frac{1 - (h/e)_S}{1 - (h/e)_Q} \approx 0.3 \)

(Courtesy of R. Wigmans)
# New Detectors: Crystal Fibers

![Diagram of Crystal Fibers](image)

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g/cm³)</th>
<th>Radiation length X₀ (cm)</th>
<th>Refraction index n</th>
<th>Critical angle</th>
<th>Fundamental absorption (nm)</th>
<th>Čerenkov threshold e energy (KeV)</th>
<th>Relative photon yield *</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>2.2</td>
<td>12.7</td>
<td>1.46</td>
<td>47°</td>
<td>190</td>
<td>190</td>
<td>250</td>
</tr>
<tr>
<td>LuAP</td>
<td>8.34</td>
<td>1.1</td>
<td>1.95</td>
<td>59°</td>
<td>146</td>
<td>84</td>
<td>501</td>
</tr>
</tbody>
</table>

(Courtesy of P. Lecoq)
Quartz Plates

Blue : Clean Quartz
Green : ZnO (0.3 micron)
Red : PTP (2 micron)
Detecting UV Light

New Developments in Silicon Carbide avalanche photodiodes
QE of 60% peaking at 280nm
Perfect for Cherenkov
Blast from the Past

- Geiger Tube is Back!

- Reincarnated in Silicon

FBK: 625 Pixels

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Linear Array of SiPMs (MAPD)

Photon Counting

Zecotek Custom Device
15,000 pixels per mm²
Gain per pixel ~60,000
Operating Voltage +86V
Electron ID

Main backgrounds:
• overlay over a $\pi^0$ and a non-interacting $\pi^{+/-}$
• early showering $\pi^{+/-}$
• photon conversions

Calorimeter Isolation

Had/em Ratio

E/P matching

CDF

Dead material in front of the calorimeter induces Bremsstrahlung!
Replace Optical Addition of Layers

Layer to Tower Decoding Fiber

CMS HCAL

Optical cable

Optical Connector

Clear Fiber

Splice

Mirror

WLS fiber

Tile
More Depth Segmentation

**Current**

*18-Channel RMs*

**Upgrade**

*64-Channel HB RMs*

*48-Channel HE RMs*
Figure 2: Dose map (Gy per 500 fb\(^{-1}\)) in the endcap calorimetry for the reproduction of the HE calculations. Note the high resolution map in the HE up R=100 cm.
Final Remarks

- There is no great obstacle to producing physics measurements than an incomplete understanding of the detectors
  - Invest your time now and apply some of the basic principles from these and other lectures to estimate the expected behavior of the calorimeter you are using
  - Don’t let the Monte Carlo do everything for you
  - Always keep in mind ways of improving the measurements and reducing systematic uncertainties – do it now, and you’ll leave your mark on the experiment for years to come
SLIDE APPENDIX
Some trigger algorithms are based on finding local maxima in the calorimeter with a search algorithm known as the “sliding window”

- Despite the name, it’s more akin to bump hunting than, say, an iterative cone jet algo