Outline of Lecture 2

- Specific Calorimeters at the Tevatron and LHC
  - Design Choices and Physics Optimization
- Imperfect Detectors
  - Understanding Potential Limitations
  - A Historical Example
Tevatron Calorimeters

- Main calorimeter parameters were decided ~25 years ago in preparation for Run I (or even earlier for CDF)
  - Readout (and trigger) parameters needed adjustment for Run II detector upgrades due to bunch-crossing time modifications from 3.4 $\mu$s in Run I to 396 ns (and once falsely planned for even shorter spacing 132 ns)
  - New tracking (and for D0 a solenoid magnet) introduced new material in front of the calorimeters
  - CDF upgraded plug detectors (same technology used for CMS HCAL), added preshower and installed timing readout to the central EM calorimeter section

- Tevatron detectors have more time between crossings compared to the LHC, **no radiation hardness requirements**, somewhat smaller dynamic range and are optimized for SM
  - Tevatron calorimeters are well understood, operating well and have done amazing things (and still will)
Some Turn-on History

- Things started slowly and expectations (this is a 1999 slide) were still big, overestimating Run II.

Many explorations limited by available luminosity => Improve this for Run II!

- 1985: first collisions
- 1987: 30 nb\(^{-1}\)
- 1988-89: 4.7 pb\(^{-1}\)
- 1992-96: Run I 110 pb\(^{-1}\)
- 2001-02: Run II 2 fb\(^{-1}\)
- 2003-07: Run II >15 fb\(^{-1}\)

Possible luminosity evolution:
D0 LAr Calorimeter

D0 liquid Argon calorimeter:
- Conception started in 1983
- Uranium/Liquid Argon em calorimeter
- Copper/Stainless Steel had calorimeter

⇒ ”compensating” e/π ≈ 1 (with 3.4μs integration time)

- 55,000 read-out cells
  ⇒ 4 em layers (2, 2, 7, 10 X₀),
  ⇒ shower-max (EM3): 0.05 × 0.05
  ⇒ 4-5 hadronic layers (FH + CH)
  ⇒ λₚ > 7.2 (total)

- 5000 semi-projective trigger towers
  ⇒ Δη×Δφ = 0.1×0.1
- Hermetic:
  ⇒ |η| < 4.2 (θ ≈ 2°),
- single particle resolution from test beam
  e: σₑ/E = 15% /√E + 0.3%
  π: σₑ/E = 45% /√E + 4%
D0 LAr Calorimeter

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  ⇒ 4-5 hadronic layers (FH + CH)
  ⇒ λ_{int} > 7.2 (total)

- 5000 semi-projective trigger towers
  ⇒ Δη x Δφ = 0.1 x 0.1
- Hermetic:
  ⇒ |η| < 4.2 (θ ≈ 2°),
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  π: σ_{E}/E = 45% /√E + 4%
D0 Calorimeter Pseudo-Projective Towers

- Calorimeter cells make up pseudo-projective towers
- Four electromagnetic layers ($\approx 20 \times_0$)
- Three (central) or four (endcaps) finely segmented hadronic layers followed by one coarser hadronic layer. Hadronic depth $> 7.2$ ($8.0$) interaction lengths.
- Significant material in front of calorimeter: $\approx 4 \times_0$ (solenoid, preshowers, trackers)

Preshower detector
- Scintillating fibers
- Used to improve photon identification

Note, ICD Region
Dead Material In Front of Calorimeter

- Fine-Segmentation (0.5x0.5) in EM3 Section lost to the tail of the shower in Run II
  - Reduced power of EM shower ID parameters
  - Reweighted EM1 layer to try to account for dead material and added in preshower energies
  - Result on performance: Raised Energy Resolution Constant Term
Most Unexpected Changed

- The decrease in charge integration time (and faster pulse shaping – aimed at 132 ns bunch spacing) exposed non-uniformities in the original construction of the LAr gap spacings
  - Jet energy resolution constant term increased to ~8%

[Diagrams showing signal from ideal and distorted geometry with finite integration time]
The CDF Calorimeters

All scintillator-based sampling calorimeters

| $|\eta|$ Range | $\Delta \phi$ | $\Delta \eta$ |
|------------|-------------|-------------|
| 0. - 1.1 (1.2 h) | $15^\circ$ | $\sim 0.1$ |
| 1.1 (1.2 h) - 1.8 | $7.5^\circ$ | $\sim 0.1$ |
| 1.8 - 2.1 | $7.5^\circ$ | $\sim 0.16$ |
| 2.1 - 3.64 | $15^\circ$ | 0.2 - 0.6 |

Table 1.2: CDF II Calorimeter Segmentation

Coarse Granularity in $\phi$
**CDF EM Calorimeter**

**Central Electromagnetic Calorimeter (CEM)**

<table>
<thead>
<tr>
<th>Thickness</th>
<th>18X₀, 11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abs. (pb) layer</td>
<td>1/8” (4.2 mm, 0.6 X₀)</td>
</tr>
<tr>
<td>Scint. layer</td>
<td>5 mm, polystyrene (SCSN-38)</td>
</tr>
<tr>
<td>w.l.s.</td>
<td>3 mm Y7 acrylic sheet</td>
</tr>
<tr>
<td>PMT</td>
<td>Ham. R580 (1.5”)</td>
</tr>
<tr>
<td>light yield</td>
<td>&gt;100 p.e./GeV/pmt</td>
</tr>
<tr>
<td>resolution</td>
<td>13.5/\sqrt{Eₜ}</td>
</tr>
</tbody>
</table>

Shower Max Detector (Gas Strip Chamber) at EM Shower Max

Added Timing Info in Run II
CDF Plug Calorimeter

Plug Hadronic Calorimeter (PHA)

30° Megatiles

Same technology as CMS HCAL

Fiber bending
Radius limits
ϕ-Segmentation at high eta
ATLAS Pb/LAr EM

- Length: at least $22 \times X_0$ (47 cm)
- 3 longitudinal layers (+presampler)
- $4 \times X_0$ rejection of $\pi^0$ in two photons
- $16 \times X_0$ for shower core
- $2 \times X_0$ evaluation of late showers

170,000 channels
Spacing Held with Honeycomb Structure

$|\eta| < 1.475$

- Cu/kapton electrode
- Honeycomb spacer
- Stainless-steel-clad Pb absorber plates
CMS ECAL

Barrel: $|\eta| < 1.48$
36 Super Modules
61200 crystals ($2\times2\times23\text{cm}^3$)

EndCaps: $1.48 < |\eta| < 3.0$
4 Dees
14648 crystals ($3\times3\times22\text{cm}^3$)
Atlas/CMS ECAL Resolutions

Global Constant Term less than 0.5%

\[
\frac{\sigma}{E} = \frac{2.8\%}{\sqrt{E\text{ (GeV)}}} \oplus \frac{125}{E\text{ (MeV)}} \oplus 0.3\%
\]

Atlas EM Resolution

Global Constant Term 0.6-0.7%

Data noise subtracted

TB2002

2004 TB

Atlas EM Resolution

Global Constant Term less than 0.5%
Why ECAL Resolution so critical?

Photons high precision

leptons high precision
# Comparing Atlas/CMS ECAL Designs

<table>
<thead>
<tr>
<th></th>
<th>ATLAS Lead/L. Ar ECAL</th>
<th>CMS PWO Crystal ECAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Barrel</td>
<td>Endcaps</td>
</tr>
<tr>
<td># of Channels</td>
<td>110,208</td>
<td>83,744</td>
</tr>
<tr>
<td>Lateral Segmentation ($\Delta \eta \times \Delta \varphi$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Presampler</td>
<td>0.025 x 0.1</td>
<td></td>
</tr>
<tr>
<td>Strip/Preshower</td>
<td>0.003 x 0.1</td>
<td>0.005 x 0.1</td>
</tr>
<tr>
<td>Main Body</td>
<td>0.025 x 0.025</td>
<td>0.0175 x 0.0175</td>
</tr>
<tr>
<td>Back</td>
<td>0.05 x 0.025</td>
<td></td>
</tr>
<tr>
<td>Longitudinal Segmentation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Presampler</td>
<td>10 mm L. Ar</td>
<td>2 x 2 mm L. Ar</td>
</tr>
<tr>
<td>Strip/Preshower</td>
<td>~4.3 $X_0$</td>
<td>~4 $X_0$</td>
</tr>
<tr>
<td>Main Body</td>
<td>~16 $X_0$</td>
<td>~20 $X_0$</td>
</tr>
<tr>
<td>Back</td>
<td>~2 $X_0$</td>
<td>~2 $X_0$</td>
</tr>
<tr>
<td>Designed Energy Resolution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stochastic: a</td>
<td>10%</td>
<td>10 - 12%</td>
</tr>
<tr>
<td>Constant: b</td>
<td>0.7%</td>
<td>0.7%</td>
</tr>
<tr>
<td>Noise: C</td>
<td>0.25 GeV</td>
<td>0.25 GeV</td>
</tr>
</tbody>
</table>

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How about jet/MET resolution?

identify complex decay chains by measuring electrons, jets, missing transverse energy
Atlas Tile Calorimeter

Fe/Scint with WLS fiber Readout via PMT

Figure 5-15 Cell geometry of half of a barrel module. The fibres of each cell are routed to one PMT. The PMTs are located in the open circles shown in the girder region.

Figure 5-16 Proposed cell geometry for the extended barrel modules (version “a la barrel”).
CMS HCAL barrel

Layer to Tower Decoding Fiber

Optical cable

Optical Connector

Clear Fiber

Tile

Splice

Mirror

WLS fiber

HPD in REX

RRX

Image of CMS HCAL barrel
Not all Brass is Expense?
Swords to Plowshares
Swords to Plowshares
Crystal EM Endcap and Brass HCAL
## Comparing Atlas/CMS HCAL Designs

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Technology</strong></td>
<td>14 mm iron / 3 mm scint.</td>
<td>50 mm brass / 4 mm scint.</td>
</tr>
<tr>
<td>Barrel / Ext. Barrel</td>
<td>25 mm (front) - 50 mm (back) copper / 8.5 mm LAr</td>
<td>80 mm brass / 4 mm scint.</td>
</tr>
<tr>
<td>End-caps</td>
<td>Copper (front) - Tungsten (back) 0.25 - 0.50 mm LAr</td>
<td>4.4 mm steel / 0.6 mm quartz</td>
</tr>
<tr>
<td>Forward</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| **# Channels**       |                                |                              |
| Barrel / Ext. Barrel | 9852                           | 2592                         |
| End-caps             | 5632                           | 2592                         |
| Forward              | 3524                           | 1728                         |

| **Granularity (Δη x Δφ)** |                                |                              |
| Barrel / Ext. Barrel    | 0.1 x 0.1 to 0.2 x 0.1         | 0.087 x 0.087                |
| End-caps               | 0.1 x 0.1 to 0.2 x 0.2         | 0.087 x 0.087 to 0.35 x 0.028 |
| Forward                | 0.2 x 0.2                      | 0.175 x 0.175               |

| **# Longitudinal Samplings** |                                |                              |
| Barrel / Ext. Barrel      | Three                          | One                          |
| End-caps                  | Four                           | Two                          |
| Forward                   | Three                          | Two                          |

| **Absorption lengths**   |                                |                              |
| Barrel / Ext. Barrel      | 9.7 - 13.0                     | 5.8 - 10.3                   |
|                          | 10 - 14 (with Coil / HO)       |                              |
| End-caps                 | 9.7 - 12.5                     | 9.0 - 10.0                   |
| Forward                  | 9.5 - 10.5                     | 9.8                          |
Similar Radioactive Source Calibration

ATLAS Source Path

CMS source path

Wire source

Scintillator

signal

forward  backward

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Atlas/CMS Forward Calorimeters

- Very Different Design Approach
  - Weak Boson Fusion Tagging-Jets

![Diagram showing distribution of generated particles with peaks labeled as quark\(_{\text{min}}\), lepton\(\tau\) jet, and quark\(_{\text{max}}\).]
Compact LAr-Cu/LAr-W Calorimeter

**ATLAS forward calorimeter**

- tubular structure, very narrow LAr gaps
- 28 $X_0$ LAr-Cu: electromagnetic
- 2 x 3.7 $\lambda$ LAr-W: hadronic
- 3.2 < $|\eta|$ < 4.9
- Total number of channels: 2822
Compact size

Liquid Argon Gap

Tungsten Rod

Calorimetry Lecture 2
Complete Assembly

FCal support tube

Brass Plug Shielding
CMS Forward Calorimeter

- Quartz fibers are manually inserted in slots between iron plates
Cherenkov Light from Quartz Fibers

- In quartz \( (n=1.45\approx\sqrt{2}) \) charged particles with \( \beta > 1/n \) (0.7) emit Cherenkov light (Threshold 0.2 MeV for e, 400 MeV for p)
- Cherenkov angle \( \theta_c \) such that \( \cos \theta_c = (\beta n)^{-1} \) (~45° for \( \beta=1 \))
- Optical fibers only trap light emitted within the numerical aperture of the fiber \( \theta_T \) (~20° with axis of fiber)

Note, co-linear radiating particles do not produce captured light
Typical spectral response of QF shows reduced radiation damage effects in the region around maximum (420 nm) of PMT sensitivity (Quantum Efficiency); this is an important asset of quartz-fiber calorimetry.
Cherenkov Light is Intrinsically Fast

QIE pulse $\pi$ 50 GeV (1ns)

CMS HF Calorimeter
2003 Test Beam

25 ns
Sharper Shower Profiles

Hadronic showers are narrow in a Cherenkov (EM-only sensitive) detector.
Energy Resolution of Cherenkov Detectors

\[
\frac{\sigma(E)}{E} = \frac{N}{E} \oplus \frac{S}{\sqrt{E}} \oplus C
\]

- Electromagnetic energy resolution is **dominated by photoelectron statistics** and can be expressed in the customary form. The stochastic term \( S = 198\% \) and the constant term \( C = 9\% \).
- Hadronic energy resolution is largely determined by the fluctuations in the neutral pion production in showers, and when it is expressed as in the EM case, \( S = 280\% \) and \( C = 11\% \).
- Highly non-compensating: \( e/h \sim 5 \)
- Light yield \( \sim 0.3 \) pe/GeV
- Uniformity (transverse) \( \pm 10\% \)
- Precision in \( \eta \sim 0.03 \) and in \( \phi \sim 0.03 \) rad
Not So Compact (11.2 m from Int. Point)
Needs to be Raised to Beam Level

- Assembly is raised to beam level when being used
- And is lowered and stored in garages when CMS needs to be opened
  - One detector located on each side of the interaction region (11.2 meters from IP)
Electron and Jet Longitudinal Profiles

100 GeV electron shower
100 GeV proton shower
Hardware Compensation

- Cherenkov calorimeter has two fiber lengths (Long and Short) which are readout separately.
  - They are designed to give hardware e/h compensation at $\sim 50-150$ GeV.

**Total = L+S, EM = L-S, HAD = 2S**
LHCb Calorimeters

Muons System

Calorimeters:
PID: $e, \gamma, \pi^0$

Tracking Stations:
p of charged particles

VELO:
primary vertex
impact parameter
displaced vertex

PileUp System

RICHES:
PID: $K, \pi$ separation

Trigger Tracker:
p for trigger and $K_s$ reco
Wall Structures

HCAL

Shashlik ECAL

particles

spacers

scintillators

master plate

light guide

WLS fibers

PMT

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Master plates: 6 mm
Spacers: 4 mm
Scintillator: 3 mm
Sampling:
  - longitudinal: 20 cm
  - lateral: 2 cm

6 longitudinal sections (5.6 \( \lambda \))
(high energy showers not fully contained – but does not spoil the trigger operation)

**Module standing on end showing 6 longitudinal compartments**

**ECAL Resolution:**

\[
\frac{\sigma_E}{E} = \frac{(9.4 \pm 0.2)\%}{\sqrt{E}} \oplus (0.83 \pm 0.02)\%
\]

\[
\oplus \left( (145 \pm 13) \text{ MeV}/E \right)
\]

**HCAL Resolution:**

\[
\frac{\sigma}{E} = \frac{(69 \pm 5)\%}{\sqrt{E}} \oplus (9 \pm 2)\%
\]
ALICE EMCAL and PHOS
Alice PHOS with PbW0₄ Crystals

ALICE PHOS

To measure γ, π⁰ and η from 0.5 to 100 GeV

- coverage |Δη| < 0.12 and ΔΦ < 100°
- 18000 PWO crystals
- APD photodiodes
- distance to IP: 4.5m
- crystal size: 22×22×180 mm³
- Depth 20X₀
- operating temperature: -25 °C

1 module installed
2 more in first long shut down completed in 2010
Alice EMCAL with Shashlik

- 4 6x6 cm$^2$ towers/module
- WLS fiber readout on 1cm grid
- 5x5 mm$^2$ Hamamatsu S8148 APD
- ~4.5 photo-electrons/MeV
- Operated at nominal $M=30$
- Fullscale Energy = 250 GeV

- $\delta\eta = \delta\phi = 0.014$
- $20.1\ \chi_0$
- Pb:Sc = 1.44 : 1.76 mm
RETURNING TO ISSUES OF IMPERFECT DETECTORS
Material in front of Atlas/CMS ECALs

Amount of material in ATLAS and CMS inner trackers

ATLAS

CMS

Weight: 4.5 tons

Weight: 3.7 tons

LEP detectors
Photon Conversion Image of Material
Electrons are affected too

Effects of material in front

50% electrons undergo non-negligible bremsstrahlung

effect on resolution at $p_T$ 35 GeV:
0.7% → 1.06% (gauss) → 2.2% (effective)

dynamic clustering algorithms (superclusters) can resum photon energies

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Note, setting energy scale for tail catcher can be tricky because of e/π response energy dependence.
Barrel Geometry and Tail Catchers
Transition Regions

most significant $H\nu\nu$ candidate

$\sqrt{s} = 206.3$ GeV
Jet Energies $\sim 60$ GeV each, and $\sim 90$ GeV Missing Energy

Secondary vtx’s view

measured $H$ mass $= 114.4$ GeV
$H$ mass resolution $\sim 3$ GeV

L3 Higgs search

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Calorimetry Lecture 2
Dear Colleagues,

Today was the open session of the LEPC. The LEP Higgs Working Group made a clear recommendation for a further run in 2001 at 208 GeV with 200 pb-1 per experiment. Combining all experiments an excess of events of 2.9 sigma is reported for a Higgs mass at 115 GeV.

There is one new candidate from L3 in the channel H nu nu, with both jets in the instrumented cracks between barrel and end caps. There is no goldplated event in H ll. The most significant 4 jet events come all from ALEPH, but they found no new events since the LEP fest. If the effect is real a further run with 200 pb-1 per experiment in 2001 would enable to establish a combined 5 sigma effect.

This evening the LEPC in the closed session had a lively discussion. I understand the LEPC is not so convinced on the scientific evidence. They will probably make a neutral statement, allowing the Research board to decide anything.

The research Board meets next Tuesday. At the end the DG decides...

The 4 LHC spokespersons have requested to meet with CERN management. Obviously the LHC community is worried, whilst the LEP community pushes for further run... not simple. A large number belongs to both communities!

Have a nice week-end!
Absolutely no evidence of cracks in calorimeter

Jet Measurements
Z Calibration Data in 2000

Missing energy event has $\cos \theta_{\text{thrust}} = 0.77$ where the jet energy resolution is 13%.

L3 Higgs search