Overview of LHC Calorimetry

SNIC06
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CONTENT

- LHC Project
- Calorimetry in LHC $4\pi$ pp Detectors
  - Physics requirements
  - ATLAS calorimeters
  - CMS calorimeters
- ALICE & LHCb Calorimetry
- Conclusions
• $\sqrt{s} = 14$ TeV  
  (7 times higher than Tevatron/Fermilab)  
  → search for new massive particles up to $m \sim 5$ TeV

• $L_{\text{design}} = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$  
  (>10$^2$ higher than Tevatron/Fermilab)  
  → search for rare processes with small $\sigma$ ($N = L\sigma$)

ATLAS and CMS: pp, general purpose

ALICE: heavy ions

27 km ring used for $e^+e^-$ LEP machine in 1989-2000

LHC pp  Start 2007

LHCb: pp, B-physics
Cross Sections and Production Rates

Rates for $L = 10^{34}$ cm$^{-2}$ s$^{-1}$ at LHC

- Inelastic proton-proton reactions: $10^9$ / s
  - $b\ b$ pairs: $5 \times 10^6$ / s
  - $t \ t$ pairs: 8 / s
  - $W \rightarrow e \ \nu$: 150 / s
  - $Z \rightarrow e \ e$: 15 / s
  - Higgs (150 GeV): 0.2 / s
  - Gluino, Squarks (1 TeV): 0.03 / s

LHC is a factory for:
- top-quarks, b-quarks, $W$, $Z$, Higgs, ...
Requirements E.m. Calorimeters

- Most of the requirements come from the $H\rightarrow\gamma\gamma$ and the $H\rightarrow4e$ channels and have driven the calorimeter design. Here e.g. the ATLAS choice, CMS optimized differently.
- Large acceptance: $|\eta|<3.2$ (precision physics $|\eta|<2.5$)
- Energy resolution: $\rightarrow$ mechanics / electronics calibration
  - Stochastic term: $a \leq 10\% \, \text{GeV}^{1/2}$
  - Noise term: $b \leq 300 \, \text{MeV}$
  - Constant term: $c = 0.7\%$
- Linearity: 0.1\% or better: $\rightarrow$ presampler for dead material
  - 0.02\% for high precision measurement, e.g. $M_W$
- Angular resolution: $\sigma(\theta) \approx 50 \, \text{mrad} / \sqrt{E}$
  $\rightarrow$ lateral / longitudinal segmentation ($\Delta\eta \times \Delta\phi = 0.25 \times 0.25$)
- Particle identification capabilities:
  - $e / \text{jet}$,
  - $\gamma / \text{jet}$ (in particular $\gamma/\pi^0$ separation for isolated hi-$p_T \pi^0 > 3$)
- Time resolution: 100 ps
- Large dynamic range: 20 MeV-$\rightarrow$2TeV $\rightarrow$ electronic read-out
Requirements Hadronic Calorimeters

- Hadronic Calorimeters (HCAL) play an essential role in identification and measurement of quarks, gluons, and neutrinos by measuring energy and direction of jets and of missing transverse energy flow in events.
- Jet energy resolution: Stochastic term ~50%, constant term ~2%
- Missing energy forms a crucial signature of new particles, like the supersymmetric partners of quarks and gluons. For good missing energy resolution, a hermetic calorimetry coverage up to $|\eta|=5$ is required.
- HCAL will aid in the identification of electrons, photons and muons in conjunction with the tracker, e.m. calorimeter, and muon systems. Need longitudinal and transversal segmentation (e.g. 3-/4-fold longitudinal, $\Delta\eta*\Delta\phi = 0.1 * 0.1$)
- Radiation hard technology for calorimeters in end-cap and forward regions (e.g. expect up to $10^{15}$ n/cm$^2$-year, 20 Mrad/year)
LHC Detectors are large!

ATLAS
superimposed on the 5 floors of CERN building 40!
ATLAS Detector

- **Length**: ~ 46 m
- **Radius**: ~ 12 m
- **Weight**: ~ 7000 tons
- **~ 10^8** electronic channels
- **~ 3000 km** of cables

**Tracking** ($|\eta| < 2.5$, $B=2T$):
- Si pixels and strips
- Transition Radiation Detector ($e/\pi$ separation)

**Calorimetry** ($|\eta| < 5$):
- EM: Pb / Liquid Argon (LAr)
- HAD: Fe / scintillator (central), Cu - W / LAr (fwd)

**Muon Spectrometer** ($|\eta| < 2.7$):
- Air-core toroids with muon chambers
ATLAS LAr and Tile Calorimeters
ATLAS E.m. Accordion Calorimeter

Electromagnetic Barrel EMB

Electromagnetic End-cap EMEC

Half Barrel Assembly

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Lead/Liquid argon sampling calorimeter with accordion shape:

- Full azimuthal coverage
- Rapidity coverage up to 3.2
- High granularity (~200000 channels)
- Longitudinal segmentation
- Presampler for $\eta < 1.8$

Barrel: gap = 2.1mm @ 2000 V
lead 1.5 (1.1) mm for $\eta < 0.8$ (>0.8)
End-cap: gap varies with radius 3.1->0.9 mm
variable HV by steps
Detector design dictated by physics goals (high energy EM final states)

\[ H^0 \rightarrow \gamma\gamma, H^0 \rightarrow ZZ \rightarrow 4e, W' \rightarrow ev, Z' \rightarrow ee \]

Accordion structure chosen to ensure azimuthal uniformity (no cracks)

Liquid argon chosen for radiation hardness and speed
ATLAS EMB

32 modules produced and tested at cold between 2001-2003
Assembly/insertion in cryostat end 2003

Presampler
ATLAS EM Barrel

- **Feedthrough**
- **Calorimeter**
- **Presampler**
- **Solenoid**
ATLAS EMB Linearity / E-scale

- Needed a dedicated TB set-up in 2002 to measure the beam energy
- e linearity is better than 0.1% in the energy range 20-180 GeV
- Caveats:
  - Check done at one $\eta$ position
  - Less material than in ATLAS
- Performance adequate for most ATLAS measurements.

- W mass
  - if one wants to improve over LEP + Tevatron, one needs to know energy scale to $\sim$0.02%
  - Energy scale set by $Z \rightarrow ee$
  - Will need combination with tracking detector to extrapolate from $Z$ to $W$ with such precision

Except for $E=10$ GeV, all energy points are within 0.1%
ATLAS LAr End-Cap Calorimeters

Hadronic Endcap Calorimeter

Cryogenic feedthroughs

Electromagnetic Endcap Calorimeter

Forward Calorimeter
ATLAS Hadronic End-Cap Calorimeter HEC

LAr-Cu sampling calorimeter covering $1.5 < \eta < 3.2$

Composed of 2 wheels per end, 32 modules per wheel

HEC Module Structure
(ATLAS HEC Insertion into Cryostat)

HEC wheel 1 insertion

HEC wheel 2 insertion

EMEC

HEC1
ATLAS Forward Calorimeter FCal

Novel electrode structure → thin annular gaps formed by an tubes in an absorber matrix, which are filled with anode rods of slightly smaller radius. Gap maintained by helically-wound radiation hard plastic fibre (PEEK).

Three modules: 1 EM, 2 Hadronic (ease of construction, depth segmentation)

<table>
<thead>
<tr>
<th>Type</th>
<th>Absorber</th>
<th>Gap (µm)</th>
<th>Number of Electrodes</th>
</tr>
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<tbody>
<tr>
<td>FCal1</td>
<td>EM</td>
<td>250</td>
<td>12000</td>
</tr>
<tr>
<td>FCal2</td>
<td>HAD</td>
<td>375</td>
<td>10000</td>
</tr>
<tr>
<td>FCal3</td>
<td>HAD</td>
<td>500</td>
<td>8000</td>
</tr>
</tbody>
</table>

Matrix and rods are part of the detector ‘absorber’ and are composed of the same material.
FCal 2/3 Structure and Assembled Module

Liquid Argon Gap

Tungsten Rod
ATLAS LAr Read-out Electronics

Common readout electronics for all LAr Calorimetry except for cold (GaAs) preamplifier for Hadronic Endcap Calorimeter

Installation and testing of Front-End Crates currently underway in ATLAS cavern
ATLAS LAr Commissioning Plans

- Cold testing of the three cryostats at the surface after detector integration (complete)
- Warm testing (calibration signals, read-out) in the ATLAS cavern
- Cold testing in the ATLAS cavern
- Electronic calibration, noise studies including magnet operation
- Commissioning / integration with trigger / DAQ systems
- Data taking with cosmic rays (begins 2006)
  - LAr Barrel ~June 2006 (cool-down will start next week)
  - LAr End-caps ~Sept 2006
- Commissioning with single beams in summer 2007 (?)
- Commissioning with colliding beams in fall 2007 (?)
ATLAS TileCal Performance for Pions

- Testbeam results:
  - linearity studies show $e/h = 1.36$
  - uniformity of response over several modules at the level of 1.5%

Good agreement with latest G4 MC (4.7.1 QGSP)
ATLAS Calorimeter Installation Status

- Barrel part of the calorimeter (Tile + LAr cryostat) is at its final position.
  - Tile FE electronics in the modules certified.
  - LAr electronics being installed and commissioned.
- End-cap C (Tile with gap scintillators + LAr cryostat) in its garage position
  - FE electronics certified.
- End-cap A being lowered
  - Tile bottom 1/3 lowered.
  - LAr cryostat will be lowered week after Easter.
ATLAS Barrel Calorimeter at IP
(LAr and Tile calorimeters, including central solenoid)
moved on air pads into its final position at the centre of the ATLAS detector

4th November 2005
ATLAS Hadronic Calibration: Concept

- Goal is to obtain for each calo cell optimum estimate of deposited energy: 'local calibration'
- Start with em scale
- Weighting approach:
  Energy density in individual cell yields good estimate of em fraction

A hadronic shower consists of:
- EM energy (e.g. \( \pi^0 \rightarrow \gamma \gamma \)) \( O(50\% ) \)
- visible non-EM energy (e.g. \( dE/dx \) from \( \pi^\pm, \mu^\pm \), etc.) \( O(25\% ) \)
- invisible energy (e.g. breakup of nuclei and nuclear excitation) \( O(25\% ) \)
- escaped energy (e.g. \( \nu \)) \( O(2\% ) \)

Each fraction is energy dependent and subject to large fluctuations.
ATLAS Hadronic Calibration: Concept

- E.m. topo cluster: Use general cluster moments to get probability for a cluster to be almost pure e.m. type: Assign e.m. scale.
- Dead material corrections: Use correlations with layer/cell deposits in neighbouring topo clusters.
- Energy corrections step by step and uncorrelated: if problems in situ (simulation ↔ data) have better chance to identify source of problem.
- Validation of MC using testbeam data is a vital step in the procedure!
Apply single pion weights to jets

- ratios of $E_{\perp}$ for the matched jets as function of $E_{\perp}^{\text{truth}}$ (left) and $\eta^{\text{truth}}$ (right) for:
  - calibrated topo jets over the calibration hit truth (full blue dots)
  - raw topo jets over the calibration hit truth (full red dots)
  - calibrated topo jets over the matched particle truth (open blue dots)
  - raw topo jets over the matched particle truth (open red dots)

Still ongoing: get weights from jets directly and compare!
CMS Detector

- Solenoidal magnetic field (4T) in inner tracking detector and in calorimeters.
  - Momentum measurement in ID
  - Muon measurement

- ID: High resolution semiconductor detectors: 9,7 Mio. channels, 210 m²

- ECAL: Energy measurement in Lead –Tungstate crystals (excellent E-resolution for Photons)

- HCAL: Hermetic coverage to $|\eta|=5$
CMS Detector
CMS E.m. Calorimeter: ECAL

- **Principal design objective:** Construct a very high performance e.m. calorimeter of scintillating crystal calorimeter (PbWO$_4$ lead-tungstate).
- **Excellent e.m. energy resolution** (stochastic term $\sim$3%) since almost all of the energy of electrons and photons is deposited within the crystals.
- **Lead tungstate crystals:** high density, small Moliere radius, low $X_0$.
- **High-resolution crystal calorimeter chosen to enhance the $H\rightarrow\gamma\gamma$ discovery potential at the initially lower luminosities at the LHC**
CMS ECAL

61200 barrel crystals

14648 endcap crystals
To avoid the design and construction of a very large quantity of radiation-hard electronics, the data are transported from the on-detector electronics immediately after the digitization step, to the counting room by fiberoptic links.
CMS ECAL Status

- **Crystals**
  49000 barrel crystals (80%) delivered

- **Bare Supermodules**
  25 (out of 36) bare SMs assembled.

- **Photodetectors**:  
  All 130k APDs and 11000 VPTs (~70%) delivered

- **Electronics**:  
  Most on-board electronics in-hand, Off-detector electronics in good shape.

- ‘Dressed’ Supermodules (equipped with electronics, cabling)
  - Good results from first fully ‘dressed’ SM in Oct-04 Beam test.
  - 7 (out of 36) SMs dressed
  - 3 dressing lines operational. 3 SMs being dressed now.
  - Finalize 1 SM/week.

- **SM installation in several phases**  
  One half (18 SM) in Aug-06, several in Oct-06, completion in May-07.

- **Concern**  
  Crystals: delivery defines ECAL critical path.
CMS ECAL Supermodule Assembly

SM with Cooling System

Monitoring fibres
CMS ECAL: Energy resolution over large areas

- Corrections for “local containment” (not hitting the crystals in the middle) work as well as previous results and Monte-Carlo studies suggest.
- Also corrections for losses close to 6 mm inter-module voids.

120 GeV electrons

Area covered

S9 120 GeV Xtal 1104 with gaps correction all area of Xtal

<table>
<thead>
<tr>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>112.4</td>
<td>1.189</td>
</tr>
</tbody>
</table>

Centre

all

120 GeV electrons

σ/E = 0.52 %

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CMS ECAL: Inter-Calibration of Crystals

- Inter-Calibration known to 4.4% from laboratory measurements (Light Yield, Light Transmission, APD response)

- Target precision (~0.5%) makes the job hard, not just quantitatively but qualitatively
  - More and more effects become no longer negligible as the target precision is increased

- Essential issue is inter-calibration
  - In both time and space: energy reconstructed at \( \eta = 0.5 \) last Tuesday, must give the same response as energy reconstructed \( \eta = -1.3 \) next Friday

- During inter-calibrate with physics events everything must remain constant (or be corrected by independent measurement) \( \Rightarrow \) laser monitoring
  - So it must not take too long. Target: couple of months (one year ?)
- **Hadronic barrel and end-cap calorimeters** are sampling calorimeters with 50 mm thick copper absorber plates interleaved with 4 mm thick scintillator sheets.
- **Forward calorimeters** are sampling calorimeters with steel absorbers and scintillating fibers for read-out.
CMS HCAL Barrel / End-cap

- Copper as absorber material because of density.
- Barrel HCAL constructed of two half-barrels each of 4.3 m length.
- End-cap HCAL consist of two large structures at each end of the barrel within the region of high magnetic field.
- Barrel HCAL inside the coil not sufficiently thick, additional scintillation layers placed just outside the magnet coil.
- Full depth of the combined barrel detectors ~11 \( \lambda \).

- Megatiles large sheets of plastic scintillator
- Subdivided into tiles of size \( \Delta \eta \times \Delta \phi = 0.87 \times 0.87 \)
- Scintillation signals from megatiles detected using waveshifting fibers.
- Fibre diameter ~1 mm.

- Light emission from tiles in the blue-violet (410-425 nm).
- Light wavelength shifted via fibers to green (490 nm).
- Green light transported via clear fiber waveguides to connectors at the ends of the megatiles.
CMS HCAL Status

- **Assembly and Installation**
  - Absorbers and optics of all HCAL complete. 2nd HF being mounted.

- **Electronics**:
  - Almost all HPDs and HF_PMTs delivered.
  - Installation of readout boxes in progress.
  - Off-detector: Expect to produce and burn-in all 270 HTR cards by end of summer.

- **Source Inter-calibration**
  - Carry out HB, HE and HF inter-calibrations in 2005/06 before lowering into UX5

- **Test Beam 2004**
  - Results using low energy beam have been used to tune G4 simulation.
  - Need Test beam in 2006 to carry out combined final ECAL+HCAL measurements

- **Concerns: None**
LHCb Detector
LHCb Detector

- Experiment to investigate CP-violation in B-Meson system
- High event rates expected: $10^{12}$ bb-pairs / year @ $L = 10^{32}$
- Important precision measurements
LHCb ECAL

- Shashlik type technology
- 3 regions with different cell size
- 3.3 k modules, 6.0 k electronics channels

Integration of ECAL modules into the detector wall
LHCb ECAL: Stack assembly

Steel pressing matrix
Plastic matrix
Steel stretching tape

Tong
Flanch of tong

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LHCb ECAL Module

Pb/Sc stack

OUTER MODULE

MIDDLE MODULE

INNER MODULE

R/O part

All ECAL modules produced

Z = 12520 mm

[Diagram showing LHCb ECAL Module with dimensions and labels]
LHCb Calorimeter Installation in IP8

E-cal

H-cal
The ALICE Collaboration is building a dedicated heavy-ion detector to exploit the unique physics potential of nucleus-nucleus interactions at LHC energies.

- Aim is to study the physics of strongly interacting matter at extreme energy densities, where the formation of a new phase of matter, the quark-gluon plasma, is expected.
ALICE PHOS

PHOS tasks to investigate:
- Initial phase of collision of heavy nuclei via direct single photons and diphotons,
- Jet-quenching as probe of deconfinement, studied via high $p_T$ $\gamma$ and $\pi^0$,
- Signals of chiral-symmetry restoration.

PHOS technical data:
- 17920 lead-tungstate crystals
- distance to IP 4400 mm
- coverage in $\eta$ -0.12;+0.12
- coverage in azimuth 100°
- crystal size 22x22x180 mm³
- depth in radiation length 20
- modularity 5 modules
- total area 8m²
- total crystal weight 12.5 t
- operating temperature -25 °C
- photoreadout APD

PHOS (PHOton Spectrometer) is a high resolution electromagnetic calorimeter consisting of 17920 detection channels based on lead-tungstate crystals (PWO).
**ALICE PHOS**

Modular structure

- 5 independent modules each of 3584 crystal detector units:
  - PWO crystal + APD + preamp.

PHOS module
Working temperature: -25 °C

PHOS Cradle

Crystal detector unit

Strip unit of 16 detector units
ALICE EMCal

Lead-scintillator sampling calorimeter
|\eta|<0.7, \Delta\phi=110^\circ
Shashlik geometry, APD photosensor
PHOS Readout electronics
~13K towers (\Delta\eta\times\Delta\phi\sim0.014\times0.014)
Detector concept defined

Full Scope:

\~13k towers
\phi = 0 to 110°
\eta = -0.7 to 0.7

11 super modules (10 +1/2+1/2)
LHC Start-up for Physics

I. Pilot physics run
   - First collisions
   - 43 bunches, no crossing angle, no squeeze, moderate intensities
   - Push performance (156 bunches, partial squeeze in 1 and 5, push intensity)
   - Performance limit $10^{32}$ cm$^2$ s$^{-1}$ (event pileup)

II. 75ns operation
   - Establish multi-bunch operation, moderate intensities
   - Relaxed machine parameters (squeeze and crossing angle)
   - Push squeeze and crossing angle
   - Performance limit $10^{32}$ cm$^2$ s$^{-1}$ (event pileup)

III. 25ns operation I
   - Nominal crossing angle
   - Push squeeze
   - Increase intensity to 50% nominal
   - Performance limit $2 \times 10^{33}$ cm$^2$ s$^{-1}$

IV. 25ns operation II
   - Push towards nominal performance
CONCLUSIONS

- LHC calorimeters are designed to cover a wide range of novel physics searches.
- They employ sophisticated, mature as well as newly developed techniques.
- Radiation hardness sets high requirements.
- Quality control during production is a must. It has rigorously been implemented in most cases, e.g. failure rates in the final calorimeters of ~0.1 % have been achieved.
- LHC collaborations try to have calorimeters ready for the start-up of the LHC machine in 2007.
- In some cases the efforts will have to be increased to cope with this deadline.
Back-up Slides
ATLAS LAr Bipolar Pulse Shaping

Pulse shape sampled every 25 ns (eg. once / bunch crossing)

Optimal shaping time is an optimization problem.
Clustering

- Cell-based topological nearest neighbor cluster algorithm
  - clusters are formed per layer using neighbours (that share at least one corner)
  - $E_{\text{seed}} > 4\sigma_{\text{noise}}$
  - $|E_{\text{cell}}| > 2\sigma_{\text{noise}}$
  - include neighbour cells with $|E_{\text{cell}}| > 3\sigma_{\text{noise}}$

180 GeV pion
CMS ECAL PbWO₄ Crystals

- schnelles Szintillationsmaterial
- hohe Dichte und kurze Strahlungslänge ($X_0$)

$$-\frac{dE}{dx} = \frac{E}{X_0} \Rightarrow E = E_0 e^{-\frac{x}{X_0}}$$

- in CMS: $26X_0$ ($\approx 23$ cm)
- kleiner Moliere-Radius:

$$R_M = X_0 \frac{21,2 \text{ MeV}}{E_c}$$

- Strahlungsfestigkeit
- finanzial möglich
CMS Schedule

- Magnet test on surface start: Nov 05
- Start Lowering CMS: Feb 06 (HF yoke mid Mar)
- ECAL barrel EB+ installation: Mar 06
- ECAL: last EB- installation & cabling: Oct 06
- Tracker installation + cabling start: Nov 06
- Beam pipe Installation: 07 Mar 07 (CP from 1 Apr)
- CMS “ready to close” for beam: 15 Jun 07
- CMS “ready for beam”: 30 Jun 07
- Det/Trig/DAQ continue integ/commiss.: Apr 07-Sep 07 (incl. Single beams)
- Data Taking (first collisions): Sep 07

During first shutdown after pilot physics run:
- Pixel Tracker installation: Dec 07 (rfi Jul 07)
- EE/ES installation: Dec 07/Feb 08 (+end rfi Sep 07)
CMS HCAL Forward

HF in Bat. 186: Start ‘burn-in’ of both HF in mid-2005
The two HF are the first elements to be lowered into UX