Lectures on calorimetry

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Lecture 2









Ρ3

Plan of lectures

Lecture 1	Lecture 2	
Why/what calorimeters ?	Example of Calorimeter	
Physics of EM & HAD showers	Calorimeter Objects & Triggering	
Calorimeter Energy Resolution	Exercises	

Lecture 3

Future of calorimetry

Lecture 4

Example of calorimeters (suite)

Exercises



- > Measure energy of charged (p, π , K, e, ...), and neutral (γ , n,...) particles
- Precision improves with energy
- Position Measurement
 - Important for neutral particles
- Particle ID
 - Longitudinal (if sampling calorimeter) and lateral profiles different for e and π .
- > Timing
- > Triggering
- > Can be built at 4π detectors
 - Hermiticity ! Important for missing energy measurement (see later)

Two types of calorimeters

- > Two types of calorimeters:
 - Homogenous:
 - Absorber == active medium
 - Material dense enough to contain shower, scintillating and transparent (for light transportation) or non-scintillating Cerenkov
 - Ex: CMS (PbWO4 scintillating crystals), L3 (BGO scintillating crystals), Lead Glass (Cerenkov), ...



Sampling

- Sandwich of high-Z absorber (Pb, W, Ur,...) and low-Z active media (liquid, gaz, ...)
 - Ex: ATLAS (Pb/LAr), DØ (Ur/LAr), ...
- Longitudinal segmentation
 - Good for particle ID, position measurement,...
- Cheaper than homogenous...
- ... but worst resolution (only part of the shower is sampled)





1. Particles interact with matter

depends on particle and material

Hadronic Showers

HAD showers have two components:



Electromagnetic component:

- Electrons, photons (from excitation, radiation, decay of hadrons, photo-effect, ...)
- Neutral pions (eg, $\pi^0 \rightarrow \gamma\gamma$, $\eta \rightarrow \gamma\gamma$)

Hadronic component:

- Charged hadrons π[±], K[±], p, …
 - ionization, excitation, nuclei interaction (spallation p/n production, evaporation n, spallation products)
- Neutrons,
 - Elastic collisions, thermalization+capture (=>γ's)
- Break-up of nuclei
- Part of the energy is lost in breaking nuclei (nuclear binding energy)
 Invisible part of the shower ! Only part of the shower energy is sampled !
- Large, **non-Gaussian** fluctuations of each component (EM vs non-EM)
- Large, non-Gaussian fluctuations in "invisible" energy losses.

Hadronic Showers properties

- The hadronic shower is governed by the interaction length λ_{int}
 - λ_{int} : Mean free path between inelastic interaction

$$\lambda_{\rm int} \approx 35 A^{1/3} (g.cm^{-2})$$

> Need about ~10 λ_{int} to contain most of the hadronic showers

- Lateral containment increases with energy !
 - Transverse radius for 95% containment ~ 1.5 λ_{int}





Compensation

$$\frac{e}{\pi} = \frac{(e/h)}{1 - f_{EM}(1 - e/h)}$$

 π : response to pions-induced showers e: response to em shower component h: response to non-em shower component

- Compensation if e/h = 1
- If compensated calorimeter
 - Same energy scale for electrons/photons and hadrons
 - Calibrate with electrons and you are done !
 - Better resolution on hadrons
 - Response linearity
- ≻ How?
 - Build a sampling calorimeter
 - Boost the non-EM response
 - Amplify neutron and soft photons component
 - fission, content of H in active material to capture neutrons,...
 - long integration time in electronics
 - Suppress EM response
 - Offline compensation

Calorimeters: example





ATLAS & CMS Calorimeters in details in Appendix

The CMS detector

Inner tracker 75M silicon pixels and strips

Electromagnetic calorimeter (ECAL) 76,000 PbWO₄ crystals

Hadronic calorimeter (HCAL) sbrass / plastic scintillator

Superconducting solenoid providing 3.8 T magnetic field

Muon chambers embedded in the steel return yoke outside the calorimeter =>compact calorimeters !

•

CMS ECAL

Homogenous calorimeter made from 75848 PbWO₄ scintillating crystals





- Barrel (|η|<1.48), ~67 t
- 61200 crystals over 36 super-modules

- Endcaps (1.48<|η|<3), ~23 t
- 14648 crystals over 4 Dees (2 per endcap)
- Preceded by Pb/Si Pre-Shower

CMS crystals: PbWO₄

Excellent energy resolution $X_0 = 0.89$ cm \rightarrow compact calorimeter (28 cm for 26 X₀) $R_M = 2.2$ cm \rightarrow compact shower development Fast light emission (80% in less than 15 ns) Radiation hard (10⁵Gy) But

Low light yield (150 γ/MeV) Response varies with dose Response temperature dependance

CMS ECAL Construction



CMS ECAL: monitoring



CMS ECAL: performance

Stand-alone performance assessed during extensive test Beam campaigns at CERN...

Combined performance measured in-situ



Calorimeter Objects



- In hadron colliders, calorimeters are meant to trigger, reconstruct, identify and measure energy of charged and neutral particles produced during the collisions:
 - Electrons & photons
 - Jets
 - Neutrinos (and other invisible particles)

- Real conditions are different from standalone device or test beams:
 - Magnetic field (constraint for the readout electronics, photodetectors, ...)
 - Material in front of the calorimeter
 - Radiations,
 - (inter-)calibrations,
 - Pile-up,
 - ...

=> Degrade ultimate performance.

Electrons/Photons at LHC (1)

3500

ATLAS

Data

Sig+Bkg Fit (m_=126.5 GeV)

Final states with electrons and photons are **major experimental signatures at LHC**: \geq

- $H \rightarrow \gamma \gamma$
- $H \rightarrow ZZ^* \rightarrow 4$ leptons (e, μ)
- SUSY \rightarrow multileptons cascade





Naively:

Photon = (isolated) energy deposited in ECAL only (not leakage in HCAL), no track Electrons = (isolated) energy deposited in ECAL only + associated track (from Tracking detector)

Electrons/Photons at LHC (2)

> Material in front of calorimeter: cables, cooling, mechanical support, ...

+ **B-field** (radiated energy spread in φ)



 \Rightarrow Identification and efficiency problems, charge mis-identification

The photons convert (e.g. 20-40%) in e+e- pairs before reaching the ECAL

Electrons/Photons at LHC (3)

- > Electrons (and photons) undergo **complicated pattern**:
 - electrons radiates brem photons, which may convert in e+e-, possibly also "breming", and subsequent photon convert, ... BEFORE reaching the ECAL surface



Need to develop complex reconstruction algorithm to collect brem/conversion: super-clustering, extension of Kalman filter, …

From single hadrons to Jets



- At (hadrons) colliders, quarks & gluons produced a collection of particles via fragmentation.
- This (collimated) sum of particles (pions, kaons, p, n, electron/γ, ..) is called a jet.
- Reconstructed with "cone" algorithms
 - Various flavors…
- Jets are important signatures at LHC too (dijet resonance, VBF, …)

Jets vs single particle resolution

Jets at CDF @ TeVatron



Jets performance in calorimeter worst than single hadron performance

Contribution from physics (parton shower/fragmentation, ISR/FSR, Underlying Event, ...), detector (granularity, resolution, ...) and clustering algorithm (out of "cone" energy losses) !

- > Neutrinos produced in collisions escape detection: $W \rightarrow e_{\nu}, Z \rightarrow \nu_{\nu}, ...$
- > Many BSM processes involves "invisible" particles: Dark Matter, Neutralinos from SUSY, ...



> Way to quantify these "invisible" particles, Missing Transverse Energy (MET):

$$\vec{E}_T^{miss} = -\sum_i \vec{E}_T^i + \frac{1}{1}$$

final states particles transverse momenta (or the way they are reconstructed in a given device: calo cluster/tower, ...)

Missing Transverse Energy (1)

> In practice, very difficult quantity to understand, calibrate, ...



- > Fake MET thus appears naturally from various sources.
 - Need dedicated cleaning in order NOT to make fake discoveries (e.g., BSM models tends to produced very high MET signals)

Missing Transverse Energy (2)



Triggering



Why Trigger ?

- > It's a question of:
 - rate of experiment,
 - physics processes to look at,
 - Storage & computing capacity
 - (<=> cost)

In general:

- CANNOT record all data
- and... DON'T WANT to record all data ("new physics" buried under tons of "old" physics)
- > Need an **online** filtering.

data not recorded is lost forever!

In the following, mainly focus on LHC experiments where challenges are by far the more important.

A bit of history (1)

Early Accelerator Expts: Bubble Chambers

[page from: Babukhadia et al. "Triggering in Particle Physics Experiments", IEEE Nuclear Science Sypmosium, 10 Nov 2002]

Bubble Chambers, Cloud Chambers, etc

- DAQ was a stereo photograph
- Effectively no Trigger:
 - Each expansion was photographed (based on accelerator cycle)
 - High-level trigger was human (scanning teams)
- Slow repetition rate (observe only most common processes)
- Later some triggering attempts with higher repetition rate (> 40 Hz)

Emulsions still used in some experiments (e.g. CHORUS, DONUT)

Events selected with electronically readout detectors
 → scanning of emulsion seeded by external tracks



K⁰ mixing event, Graham Thompson, 1971 (careful, this is fixed target – example for photograph only!)

Un bit of history (2)

Early Fixed Target Trigger

[page from: Babukhadia et al. "Triggering in Particle Physics Experiments", IEEE Nuclear Science Sypmosium, 10 Nov 2002]

Cronin-Fitch *et al.* experiment 1964 – discovery of *CP* violation

- K_L mesons produced from protons bombarding Be target
- Two arm spectrometer with Spark Chambers, Chernkov counters and Trigger scintillators
- Spark chambers require fast (~20ns) HV pulse to develop spark, followed by triggering camera to photograph tracks
- Trigger on coincidence of Scintillators and Water Cherenkov counters
- Only one trigger level
- Dead-time incurred while film advances





Measurement of opening angle of pion tracks and their invariant mass to spot $K_L \rightarrow \pi\pi$ decay

Val Fitch

Collisions at the LHC



Proton - Proton2804 bunch/beamProtons/bunch1011Beam energy7 TeV (7x1012 eV)Luminosity1034cm-2s-1

Crossing rate 40 MHz Collisions every 25ns !

Collision rate ≈ 10⁷-10⁹

	√s	Peak L	Bunch Crossing period
LEP (e+e-)	~90-200 GeV	10 ³² cm ⁻² s ⁻¹	22 µs
Tevatron (p-pbar)	1.96 TeV	3.5x10 ³² cm ⁻² s ⁻¹	392 ns
FC-hh (pp)	100 TeV	5-29x10 ³⁴ cm ⁻² s ⁻¹	5-25 ns

For comparison:

LHC: the rate/selectivity problem



Need a inhuman rejection factor of more than 10 orders of magnitude !!!

LHC: the data storage problem

	Bunch Crossing Rate	Event size	Trigger Rate Output	Data rate without trigger (PB/year*)	Data rate with trigger (PB/year*)
LEP	45 kHz	~ 100 kB	~ 5 Hz	O(100)	O(0.01)
Tevatron	2.5 MHz	~ 250 kB	~ 50-100 Hz	O(10 000)	O(0.1)
HERA	10 MHz	~ 100 kB	~ 5 Hz	O(10000)	O(0.01)
LHC	40 MHz	~ 1 MB	~ 100-200 Hz	O(100 000)	O(1)



+ problem to have the CPU capacity to process them...

LHC: the Pile-Up problem !

> At LHC, each bunch crossing contains on average 25-50 additional interactions ("pile-up")

In-time" pile-up: particles from the same crossing but from a different pp interaction

- Long detector response/pulse shapes:
 - "Out-of-time" pile-up: left-over signals from interactions in previous crossings
 - Need "bunch-crossing identification"



t (25ns units)



t (25ns units)

> Detectors must have fast response

- Take fast decision (new data every 25 ns!)
- Minimize out-of-time PU effect
 - Challenges for the electronics !

> Detectors must have high granularity

- To improve separation of particles
 - high number of electronic channels !

> Architecture must be flexible

Data taking conditions are changing often during a year...

> Various detectors have to be synchronized !

> In general, only calorimeter and muon system enters in the first steps of the trigger decision

Multi-Stage Trigger

Conflict between:



ATLAS & CMS Concepts

- Level 1: reduced granularity, reduced resolution, simplified algorithms.
- High Level Trigger: CPU's farms. As close as possible as offline.



Level 1 Calorimeter Objects & Algorithms (CMS Run I example)



L1 Triggers: where in the detector ?



Level 1 Latency



(stolen from A. David: "LHC Physics 2013")

Performance of Calorimeter Triggers with real data





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Impact of Calorimeter Trigger

Calorimeter Trigger is essential for discovery !!!



Calibration



- Reconstructing Energy With ECAL





Rafael Teixeira de Lima (NEU) - CALOR 2016, Daegu - South Korea

ECAL CRYSTAL RESPONSE MONITORING



Laser Monitoring

- ECAL crystals change response due to radiation exposure (time dependent): change in crystal transparency and VPT response in endcaps
- Response is **monitored with a laser** system injecting light in every ECAL crystal
- PbWO₄ crystals partially recover during periods with no exposure
- Monitoring corrections obtained/ applied promptly (~48h)
- Stability: interpolate 2nd of 3 consecutive readings << required 0.2%

Effect of monitoring corrections by comparing energy of electron reconstructed by ECAL (E) and tracker (p)



17/09

24/09

01/10

08/10

15/10

1.0

CMS Preliminary

13 TeV

08/15

0.001537

0.006944

0.9401

Mean

RMS

Mean

RMS

200

0

400

29/10

date (day/month)

22/10

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Relative Calibration of Single Channel Response



Intercalibration (IC)

- Equalizes the response of each single crystal to the deposited energy
 - Constants are normalized not to interfere with absolute scale

Intercalibration strategy same as in Run I



Method	Description	Timescale	Run I Precision (20 fb ⁻¹)
ф-symmetry	Energy flux around φ rings (constant η) should be uniform - IC corrects for non- uniformity	gs (constant η) rrects for non- ~days Endcap: < 109	
п ⁰ /η→ γ γ	In a ϕ ring, use IC to improve M($\gamma\gamma$) resolution for π^0 and η resonances	~months	Barrel: <1.5% Endcap: < 10%
E/p	Compare isolated electron energy from ECAL and Tracker, calculate IC to correct discrepancies	statistically limited	Barrel: <2% Endcap: < 10%

Rafael Teixeira de Lima (NEU) - CALOR 2016, Daegu - South Korea

Absolute Calibration and η Scale



Calibration with $Z \rightarrow ee$

- Electrons from Z→ee events are used to calibrate the η dependence of the energy reconstruction and its absolute scale
- The Z peak is used to fix the overall absolute calibration (ADC to GeV), matching data to a detailed simulation of the detector
- Z peaks reconstructed with electrons in a single ϕ ring are used to correct the relative scale between different η regions



0T: no energy loss in reconstruction due to bremsstrahlung → better resolution

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- CLUSTERING RECONSTRUCTION AND CORRECTIONS

Events / GeV



Cluster Corrections

- Large amount of material before ECAL - high probability of bremsstrahlung emission for electrons and conversion for photons
- Clustering algorithm gathers clusters of energy deposit into superclusters to recover that information
- Supercluster's energy is corrected following a multivariate approach see J. Bendavid's talk



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ECAL ENERGY RESOLUTION WITH 2015 DATA@3.8T

- The relative resolution is extracted from an unbinned likelihood fit to Z→ee events, using a Breit-Wigner function convoluted with a Gaussian as the signal model
- Large improvement by recalculating calibration with 2015 data (winter re-reconstruction) with respect to initial calibration (prompt) with Run I values for intercalibration/calibration constants

Current resolution is close to what is expected after calibration with 20 fb⁻¹ of data





BACK UP SLIDES

Cannot use PMT (affected by magnetic field) or PIN photodiodes (no internal amplification, too sensitive to charged particles)

Barrel crystals read by Avalanche Photo Diode

Endcap crystals read by Vacuum Photo Triode

CMS Electronics chain



FIG. 3.2: Électronique de lecture du ECAL, en partant d'un cristal et son photodétecteur à gauche. Une carte VFE contient un pré-amplificateur à multi-gain (MGPA) et un convertisseur Analogue vers Digital (ADC) par cristal. La carte FE, qui contrôle 5 cartes VFE, enregistre les signaux provenant des cristaux individuel sur une mémoire tampon (buffer) en attendant un signal d'acceptation L1A. Chaque carte FE produit des primitives (pré-primitives dans les bouchons) de déclenchement (TPG) et les transmet à une carte TCC via des liens optiques GOH.

Nadir Daci's thesis

CMS L1 Trigger Chain



FIG. 3.5: Système de déclenchement de niveau 1. Chaque carte FE calcule des primitives (pré-primitives dans les bouchons) de déclenchement, encodant l'énergie transverse totale déposée dans chaque tour (resp. pseudo-bande) dans le tonneau (resp. les bouchons). La carte TCC finalise les primitives de déclenchement et compresse les données. Le déclenchement calorimétrique régional (RCT) construit, dans plusieurs régions du détecteur, des candidats L1 EG (resp. Jets, Tau) à partir de primitives provenant du ECAL (resp. HCAL). Le déclenchement calorimétrique global (GCT) transmet les quatre candidats L1 EG d'énergie transverse maximale au GT. Le GT reçoit les candidats L1 EG, Jets, Tau et Muons et prend la décision finale en appliquant les algorithmes de sélection L1.

High-level trigger

Final selection in software triggers using large commercial PC farms

- acces to full granularity and offline reconstruction-like algorithms
- extremely flexible
- slow (1-100+ ms latency), so use many PCs at the same time

Events are independent, so trivially parallelizable on PC cluster

ATLAS HLT farm:



LHCb readout switch:



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Calorimeters in space: FERMI/LAT



Fermi Satellite with Large Area Telescope (LAT) instrument.

- Gamma-Ray Telescope
 - (200 MeV < γ < 300 GeV)
- Launched June 11 2008
- Consists of:
 - Tracker: Pb foils + Si strips
 - Calorimeter (see next slide)
 - Anticoincidence Detector : plastic scintillator tiles



Calorimeters in space: FERMI ECAL

Homogenous calorimeter made from 1728 CsI(TI) scintillating crystals

7 | incoming gamma ray



- > 18 modules (400mmx400mmx250mm) ~100 kg each
- > 1 module:
 - carbon-fiber alveolar structure +
 - 96 Csl(Tl) crystals (2.7 cm x 2.0 cm x 32.6 cm)
 - arranged in 8 layers of 12 crystals each
- Each module aligned 90° wrt its neighbors, forming x,y (hodoscopic) array
 - Depth: 8.6 X₀ (10.1 including tracker)
 Need shower leakage correction



Calorimeters in space: AMS-02

> Alpha Magnetic Spectrometer (AMS):

- HEP-like detector operating as external module on ISS¹
- Launched in 2011
- Search for Dark Matter, anti-matter, precise study of high energy cosmic ray (flux, composition), gamma rays.





AMS: A TeV precision, multipurpose, magnetic spectrometer



The AMS-02 ECAL

Sampling calorimeter made from Lead + Scintillating fibers

3-D imaging of shower development

- 9 Super-Layers (SL) alternatively oriented along X and Y axis (5 SL along X, 4 long Y)
- ➤ 1 Super-Layer (~18.5mm):
 - 11 grooved, Pb foils (1mm thick) interleaved with 10 layers of scintillating fibers (Ø~1mm) glued by epoxy-resin

Depth: ~17 X0

Fibers read by PMT





ECAL support structure

65 cm