Instrumentation in High Energy Physics - ECAL D. Lelas, University of Split, FESB

Sarajevo School of High Energy Physics 10 October 2022

Outline:

 \odot Instrumentation in HEP:

- ECAL (D. Lelas)
- Muon, HCAL (K. Cankocak)
- Tracker (A. Starodumov)
- Trigger/DAQ (S. Morović)

Brief introduction

Basics of electromagnetic calorimetry

Wonders of the World



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Instrumentation in a nutshell

LHC•



Large Hadron Collider (LHC) collisions and detectors



1 KHz 100 KHz mar.capeans@cern.ch 29/10/2014 1 MB/evt **High-Level** Offline 40 MHz trigger reconstruction L1 trigger Trigger and data acquisition **Computing time** 1 ns 1 µs 100 ms 1 s latency AND throughput latency constraint throughput constraint constraint

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The CMS detector: transverse view



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Why Calorimetry?

- Measure both *charge + neutral* particles
- Obtain information *fast*

recognize and select interesting events in real time (trigger)

• Performance of calorimeters *improves with energy*

($\sim E^{-1/2}$ if statistical processes are the limiting factor)

Important calorimeter features

- Energy resolution
- Position resolution (need 4-vectors for physics)
- Signal speed
- Particle ID capability

Calorimetry: Basic Principles

Calorimetry = Energy measurement by total absorption, usually combined with spatial reconstruction.

- LHC beam: Total stored beam energy: $E = 10^{14} \text{ protons} \times 14 \cdot 10^{12} \text{ eV} \approx 1 \cdot 10^8 \text{ J}$
- Which mass of water M_{water} could one heat up ($\Delta T = 100$ K) with this amount of energy ($c_{water} = 4.18$ J g-1 K-1) ? $M_{water} = E / (c\Delta T) = 239$ kg
- What is the effect of a 1 GeV particle in 1 liter of water (at 20° C)? $\Delta T = E / (c \cdot M_{water}) = 3.8 \cdot 10 - 14 \text{ K }!$

There must be more sensitive methods than measuring ΔT !

latin: calor = heat

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Calorimetry: Basic Principles

• Basic mechanism for calorimetry in particle physics: formation of

- electromagnetic
- or hadronic showers.

• Finally, the energy is converted into ionization or excitation of the matter.

Charge

Cherenkov light

Calorimetry is a "destructive" method. The energy and the particle get absorbed!

- Detector response $\propto E$
- Calorimetry works both for:
 ⇒ charged (e± and hadrons)
 ⇒ and neutral particles (n,γ)

Complementary information to p-measurement

Scintillation light

Only way to get direct kinematical information for neutral particles

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Interaction of charged particles

Detection of charged particles

Particles can only be detected if they deposit energy in matter. How do they lose energy in matter ?

Discrete collisions with the atomic electrons of the absorber material.



$$\left\langle \frac{dE}{dx} \right\rangle = -\int_0^\infty NE \frac{d\sigma}{dE} \hbar \, d\omega$$

N: electron density

Collisions with nuclei not important ($m_e << m_N$) for energy loss.

If $\hbar\omega$, $\hbar k$ are in the right range \rightarrow **ionization**.

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Interaction of charged particles: Bethe-Bloch formula

Energy loss by ionization only: <u>Bethe-Bloch formula</u>

$$\left\langle \frac{dE}{dx} \right\rangle = -4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \gamma^2 \beta^2}{I^2} T^{\max} - \beta^2 - \frac{\delta}{2} \right]$$

- dE/dx in [MeV g⁻¹ cm²]
- Valid for "heavy" particles $(m \ge m_{\mu})$.
- dE/dx depends only on β, independent of m !
- First approximation: medium simply characterized by Z/A ~ electron density



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Interaction of charged particles: Bremsstrahlung

Energy loss by bremsstrahlung

Radiation of real photons in the Coulomb field of the nuclei of the absorber medium:

$$-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} z^2 \left(\frac{1}{4\pi\varepsilon_0} \frac{e^2}{mc^2}\right)^2 E \ln\frac{183}{Z^{\frac{1}{3}}} \left(\propto \frac{E}{m^2} \right)^2$$

Effect plays a role only for e± and ultra-relativistic μ (>1000 GeV)

For electrons

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e

Interaction of charged particles: Critical energy E_c

• Critical energy E_c



Unlike electrons, muons in multi-GeV range can travers thick layers of dense matter. Find charged particles traversing the calorimeter? \rightarrow most likely a muon \rightarrow Particle ID

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Interaction of photons: Photo-electric effect

In order to be detected, a photon has to create charged particles and/or transfer energy to charged particles

Photo-electric effect:

(already met in photocathodes of photodetectors)



Only possible in the close neighborhood of a third collision partner \rightarrow photo effect releases mainly electrons from the K-shell.

Cross section shows strong modulation if $E_{\gamma} \approx E_{shell}$

$$\sigma_{photo}^{K} = \left(\frac{32}{\varepsilon^{7}}\right)^{\frac{1}{2}} \alpha^{4} Z^{5} \sigma_{Th}^{e} \qquad \varepsilon = \frac{E_{\gamma}}{m_{e}c^{2}} \qquad \sigma_{Th}^{e} = \frac{8}{3}\pi r_{e}^{2} \quad \text{(Thomson)}$$

At high energies (E>>1)

$$\sigma_{photo}^{K} = 4\pi r_{e}^{2} \alpha^{4} Z^{5} \frac{1}{\varepsilon}$$

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 $\sigma_{photo} \propto Z^5$

Interaction of photons: Compton scattering



0.15-

0.075

0.05-

0.15-0.125-0.1-0.1-

Klein-Nishina
$$\frac{d\sigma}{d\Omega}(\theta,\varepsilon)$$
 \rightarrow

At high energies approximately

$$\sigma_c^e \propto \frac{\ln \varepsilon}{\varepsilon}$$

Atomic Compton cross-section:

 $\sigma_c^{atomic} = Z \cdot \sigma_c^e$

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Interaction of photons: Pair production



 $\gamma + nucleus \rightarrow e^+e^- + nucleus$

Only possible in the Coulomb field of a nucleus (or an electron) if $E_{\gamma} \ge 2m_e c^2$

Cross-section (high energy approximation)



Interaction of photons: Summary



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Reminder: basic electromagnetic interactions



Electromagnetic cascades (showers)



Electromagnetic shower in a cloud chamber with lead absorbers

Simple qualitative model



$$N(t) = 2^t$$
 $E(t) / particle = E_0 \cdot 2^{-t}$

Process continues until $E(t) \le E_c$

$$N^{total} = \sum_{t=0}^{t_{max}} 2^{t} = 2^{(t_{max}+1)} - 1 \approx 2 \cdot 2^{t_{max}} = 2\frac{E_{0}}{E_{c}}$$
$$t_{max} = \frac{\ln E_{0}/E_{c}}{\ln 2}$$

After $t = t_{max}$ the dominating processes are ionization, Compton effect and photo effect \rightarrow absorption of energy.



Electromagnetic shower development



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46 cm

Calorimeter energy resolution



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Calorimeter types: Homogeneous calorimeters

Homogeneous calorimeters: Detector = absorber

⇒ good energy resolution

- ⇒ limited spatial resolution (particularly in longitudinal direction)
- ⇒ only used for electromagnetic calorimetry

	Scintillator	Density	X ₀	Light Yiel	ld τ ₁ [1	ns] λ_1 [nm	1] Rad.	Co	omments
		$[g/cm^3]$	[cm]	γ/MeV			Dam.		
				(rel. yield	*)		[Gy]		
rwo main types.	NaI (Tl)	3.67	2.59	$4{\times}10^4$	230	415	≥10	hy	droscopic,
								fra	gile
	CsI (Tl)	4.51	1.86	5×10^{4}	100	5 565	≥10	Sli	ghtly
1. Scintillators				(0.49)			,	hy	groscopic
	CSI pure	4.51	1.86	4×10^{4}	10	310	103	Sli	ghtly
				(0.04)	36	310		hy	groscopic
	BaF_2	4.87	2.03	104	0.6	220	105		
				(0.13)	620	310			
	BGO	7.13	1.13	8×10 ⁵	300	480	10		
Charankay daviasa	$PbW0_4$	8.28	0.89	≈100	440	broad band	1 104	lig	ht yield $= f(T)$
					530	broad band			
X				* Relativo	e light yie	eld: rel. to N	val(TI) rea	dout wit	h PM (bialkali PC
	Material	Density	X ₀ [cm]	n	Light yi	eld	$\lambda_{\rm cut} [{\rm nm}]$	Rad.	Comments
in both cases the signal		$[g/cm^3]$			[p.e./Ge	V]		Dam.	
consists of photons					(rel. p.e.	*)		[Gy]	
consists of photons.	SF-5	4.08	2.54	1.67	600	-1.	350	10*	
Readout via photomultiplier	Lead glass		1.00		(1.5×10^{-1})	-4)			
dia da Aria da ADD UDD	SF-6	5.20	1.69	1.81	900	-4.	350	102	
-aloae/trioae, APD, HPD	Lead glass		0.05	1.00	(2.3×10 ⁻	¬)		103	
	PDF ₂	7.66	0.95	1.82	2000			10-	Not available
and the second s					(5×10))			

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Homogeneous calorimeters: CMS ECAL

CMS PbW0₄ EM Calorimeter

vacuum chamber

central detector electromagnetic calorimeter hadronic calorimeter

superconducting

return yoke

muon chamber

76000 Lead tungstate crystals





Homogeneous calorimeters: CMS ECAL

CMS PbW0₄ Test Beam Performance



Alexandre Zabi

12th International Conference on Calorimetry in High-Energy Physics Chicago, Illinois, 6-9 June 2006

Calorimeter types: Sampling calorimeters

Sampling calorimeters = Absorber + detector (gaseous, liquid, solid)

- MWPC, streamer tubes
- warm liquids (TMP = tetramethylpentane, TMS = tetramethylsilane)
- cryogenic noble gases: mainly LAr (LXe, LKr)
- scintillators, scintillation fibres, silicon detectors





'Shashlik' readout D. Lelas, University of Split, FESB

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Sampling calorimeters: ATLAS ECAL

ATLAS electromagnetic Calorimeter

Accordion geometry absorbers immersed in Liquid Argon





Liquid Argon (90K)

- + lead-steal absorbers (1-2 mm)
- multilayer copper-polyimide readout boards
- \rightarrow lonization chamber.
- 1 GeV E-deposit \rightarrow 5 x10⁶ e⁻
- Accordion geometry minimizes dead zones.
- Liquid Ar is intrinsically radiation hard.
- Readout board allows fine segmentation (azimuth, pseudo-rapidity and longitudinal) acc. to physics needs



Spatial resolution ≈ 5 mm / \sqrt{E}

Test beam results
$$\sigma(E)/E = 9.24\%/\sqrt{E} \oplus 0.23\%$$

Calibration of calorimeter systems

• Determine relationship between *signal* (pC, p.e.) and *energy* (GeV)

• Fundamental problem in sampling calorimeters:

Different shower components are sampled differently Shower composition changes as shower develops

Sampling fraction changes with the shower age (also E dependent) How to intercalibrate the sections of a longitudinaly segmented calorimeter? (quite of a chalange...)

Calibration Techniques:

- Test Beams
- Cosmic muons
- Laser/LED Monitoring
- Guided 60 Co sources
- Low-level, stable radioactive background
- \circ Cell-weighting to optimize resolution, uniformity
- In situ physics:

- Electromagnetic part: $Z, J / \psi \rightarrow e^+ e^-; \pi^0, \eta \rightarrow \gamma \gamma$ - Hadronic part: $W, Z \rightarrow q\overline{q}; Z, \gamma - jet$ balancing'

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Future - CMS High Granularity Calorimeter

The High Granularity Calorimeter (HGCAL) will possess unprecedented spatial granularity

- 3D visualization of showers
- Excellent energy resolution
- Enables identification of electrons, photons, pions and even muons
- Timing capabilities allowing for the distinction of between spatially overlapping showers





Concluding remarks

Since the 1980's, calorimetric measurements have grown in importance with the expanding energy frontier in elementary-particle physics, becoming the precision instrument of choice due to their exploitation of high-statistics counting methods.

Intense R&D programs have improved quantitative understanding of the physics behind their operation and resulted in a huge variety of available calorimeter technologies.

Today's applications of calorimeters extend from medical diagnostics to neutrino astrophysics, from satellites to deep-sea arrays, from mountaintops to Antarctic ice.

Extensive detector-development programs are in preparation around the world, inspiring confidence in a bright future for progress in calorimetry and further expansion of its range of applications.

Materials based upon:

This presentation is widely based on:

C. Joram, Particle detectors : principles and techniques, Part 4, Calorimetry, CERN Academic training lectures 2005, <u>http://indico.cern.ch/conferenceDisplay.py?confld=a042932</u>

J. Crittenden, Calorimetry in High-Energy Elementary-Particle Physics, Joint Dutch Belgian German Graduate School, Bad Honnef, 8-9 September 2006,

R. Wigmans, LHC luminosity upgrade: detector challenges (3/5), CERN Academic training programme 2006, <u>http://indico.cern.ch/conferenceDisplay.py?confld=a056410</u>

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- P. B. Cushman, Electromagnetic and Hadronic Calorimeters, in Instrumentation in High Energy Physics, ed. F.Sauli (1992)
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- U. Amaldi, Calorimetry in High-Energy Physics, in Experimental Techniques in High-Energy Physics, ed. T.Ferbel (1987)
- R. Fernow, Introduction to Experimental Particle Physics (1986)
- C. Grupen, Particle Detectors (1996)

Interaction of charged particles: Multiple Scattering

- This process will turn out to be closely related to the transverse profile of electromagnetic showers.
- Coulomb-scattering scales with the squared charges, so scattering in matter is dominated by scattering off nuclei (rather than off electrons), for Z>10. Scattering of spin 0 (Rutherford) and spin 1/2 (Mott) particles are identical in a small-angle approximation.
- Result can be defined in terms of radiation length X₀, to be defined later.

