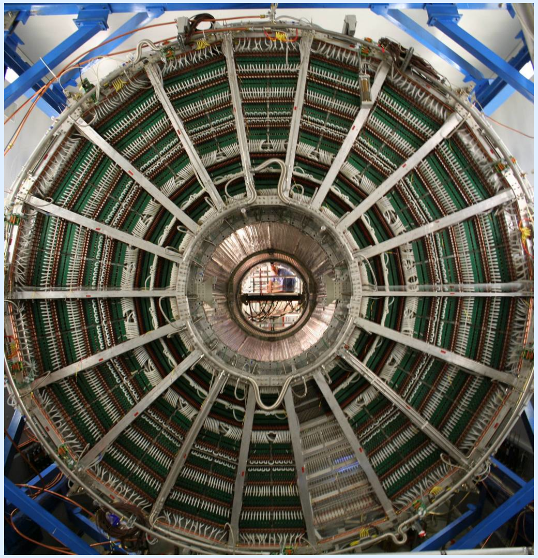

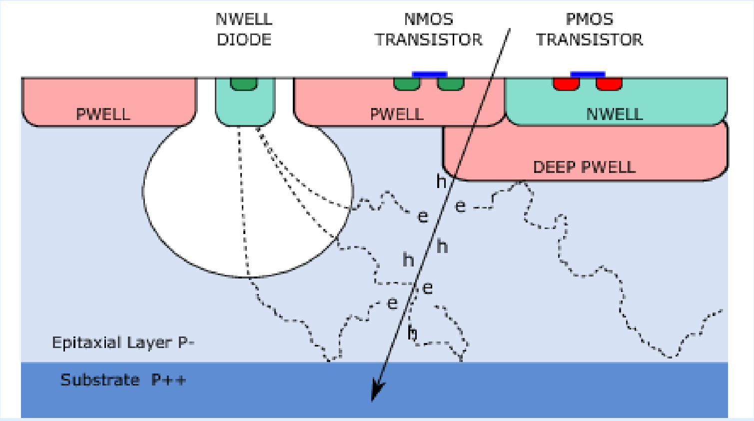

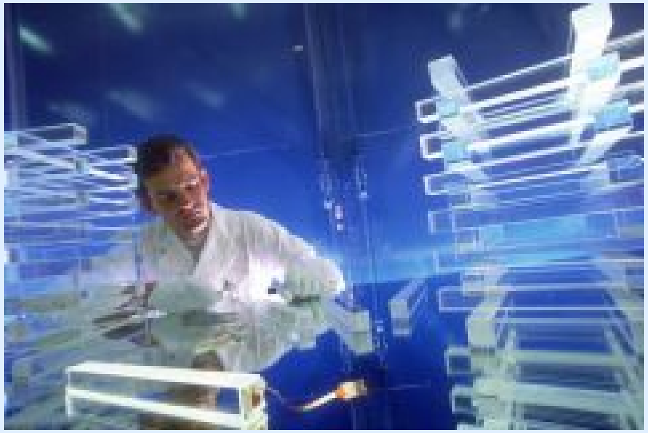

Electromagnetic calorimeters

Silvia Masciocchi,
GSI and University of Heidelberg

SS2017, Heidelberg
June 28, 2017

Calorimetry

Experimental technique in nuclear and particle physics in which the detection of a particle and the measurement of its properties is based on ABSORPTION in the detector volume (partial or total)

This is a DESTRUCTIVE process:

The particle's energy is converted in a detectable signal until the particle is absorbed

Another note: calorimetry is addressed also to neutral particle (not only charged one, see magnetic spectrometer)

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Outline

- Introduction
  - Energy measurement: total absorption of the particle energy via shower production ...
  - … particularly targeted to high momentum/energy particles

- Electromagnetic shower
  - Electron bremsstrahlung and photon pair production
  - Transverse and longitudinal shower development

- Electromagnetic calorimeters
  - Homogeneous and sampling calorimeters
  - Energy resolution

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Introduction

Measurement of energy or momentum of particles:

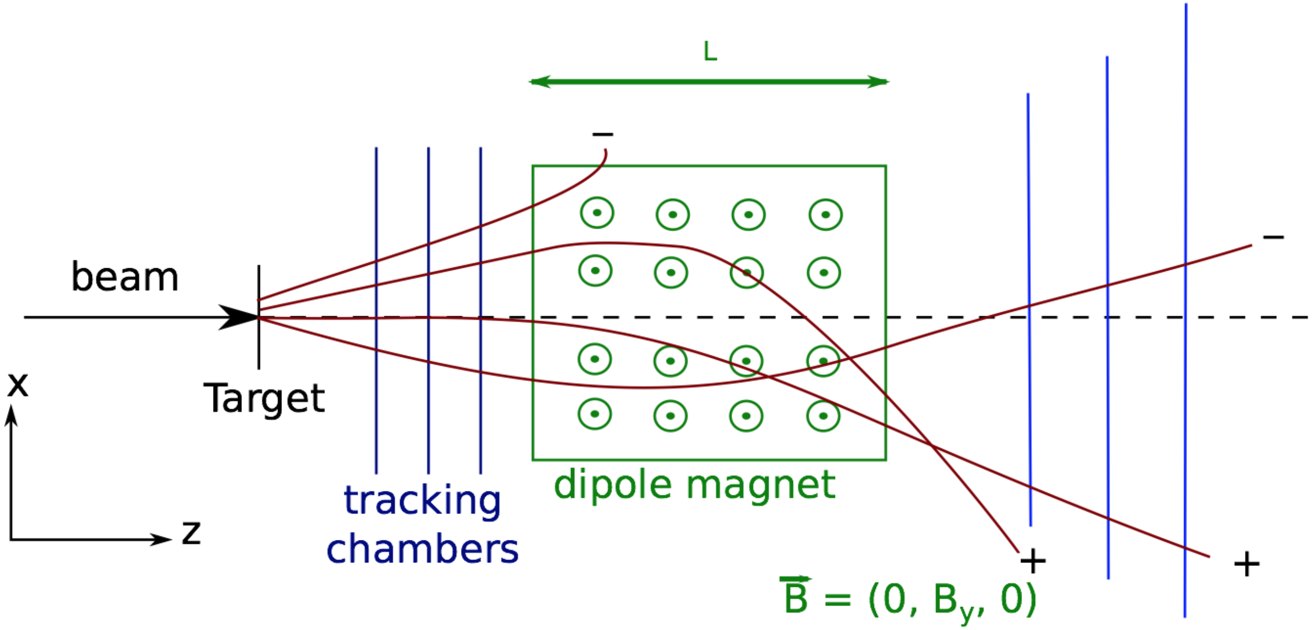
Let's focus on high energy particles (hadrons, leptons, (photons))

You will see next week:

Magnetic spectrometers

Momentum of charged particles is measured in magnetic field, with tracking detectors to determine the trajectory

$$\frac{\sigma_p}{p} \propto \frac{p}{L^2}$$



This is NOT the best choice to measure high energy particles.

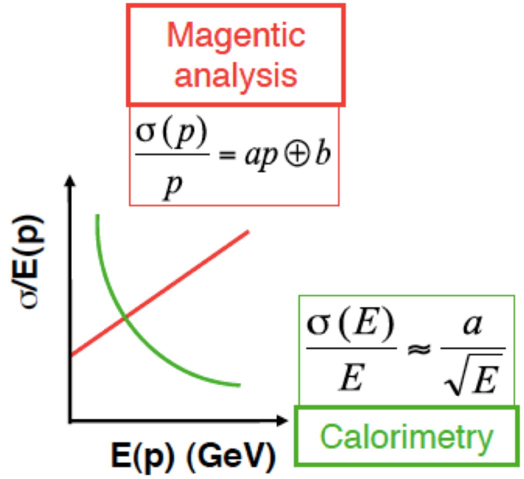
With increasing p (or E), the momentum resolution gets worse, or an impossibly long lever arm L is needed → switch to **calorimeters** !

Introduction

Calorimeters are the ideal instrument to measure the full energy of particles, particularly at high momentum

$$\frac{\sigma_E}{E} \propto \frac{1}{\sqrt{E}}$$

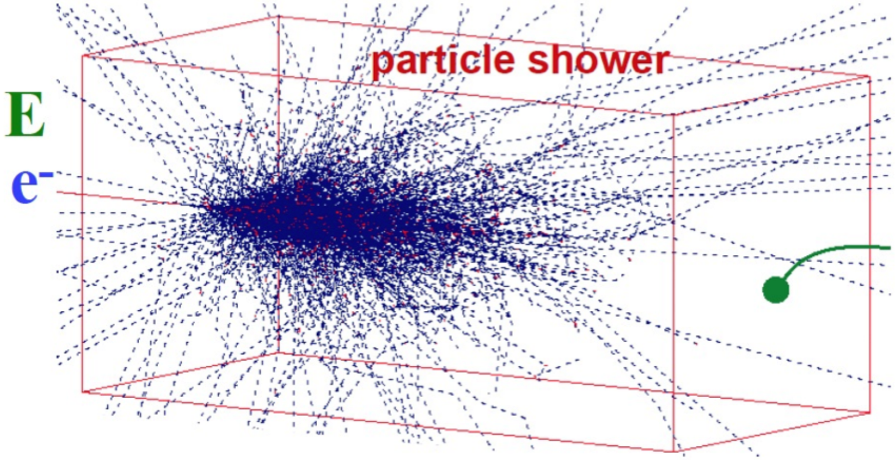
Resolution improves with energy!



Other advantages:

- Depth of shower ∝ ln (E/E_0) → grows only with ln(E) (while the momentum resolution would be "controlled" only by L^2 → unfeasible in reality)
- Calorimeter can cover full solid angle
- Fast timing signal from calorimeter → can be used for triggering!
- Distinction of hadronic and electromagnetic showers using segmentation in depth

What do calorimeters measure?



- An incident particle interacts with the calorimeter active and passive material
- A cascade process is initiated: shower development depends on particle type and on detector material
- Visible energy deposited in the active media of the calorimeter produces a detectable signal, proportional to the total energy deposited by the particle
- Essential to CALIBRATE the calorimeter, namely establish a precise relationship between the “visible energy” detected and the energy of the incoming particle

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Introduction: classification of calorimeters

TODAY !!

By particle type:

- Electromagnetic calorimeters: electrons, positrons, photons, π^0
- Hadronic calorimeters: charged and neutral hadrons, jets

By construction techniques:

- Homogeneous calorimeters: full absorption detectors, fully active medium for both energy degradation and signal generation
- Sampling calorimeters: alternate layers of absorber material to degrade the particle energy and active media to provide the detectable signal

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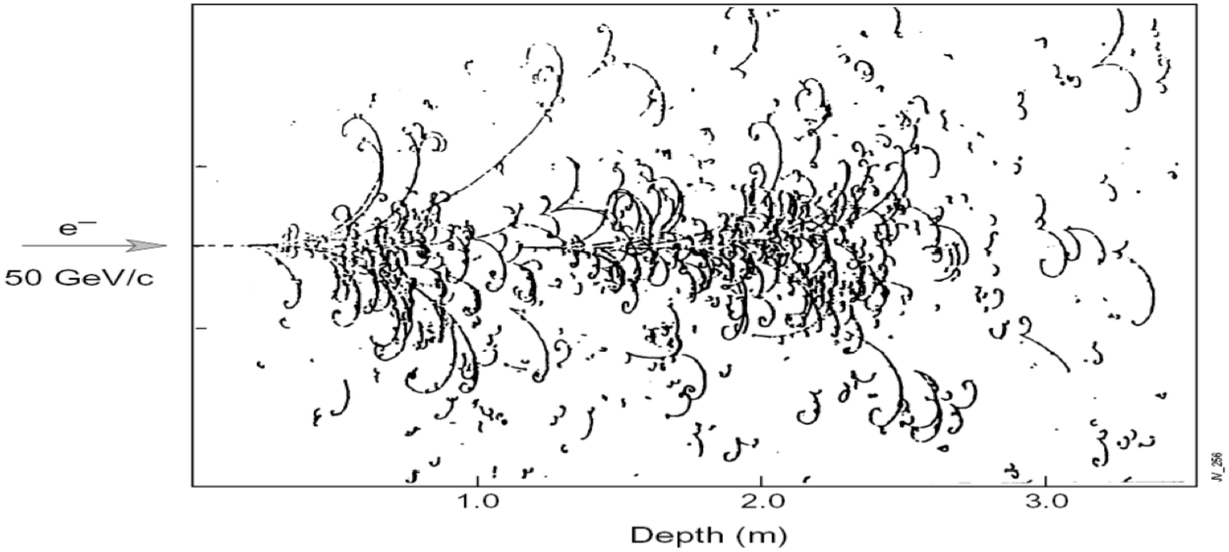
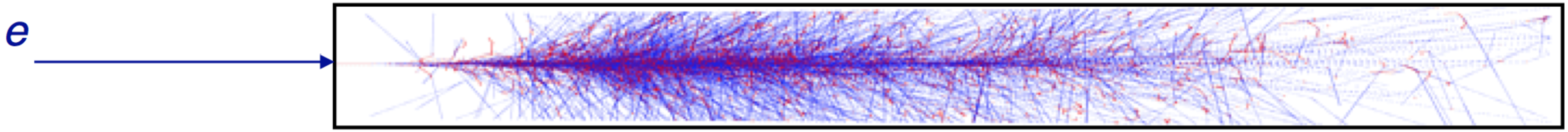
Electromagnetic shower

Electrons (positrons) and photons interacting with matter

Big European Bubble Chamber filled with Ne:H_2 = 70%:30%, 3T Field, L=3.5 m, X_0≈34 cm, 50 GeV incident electron

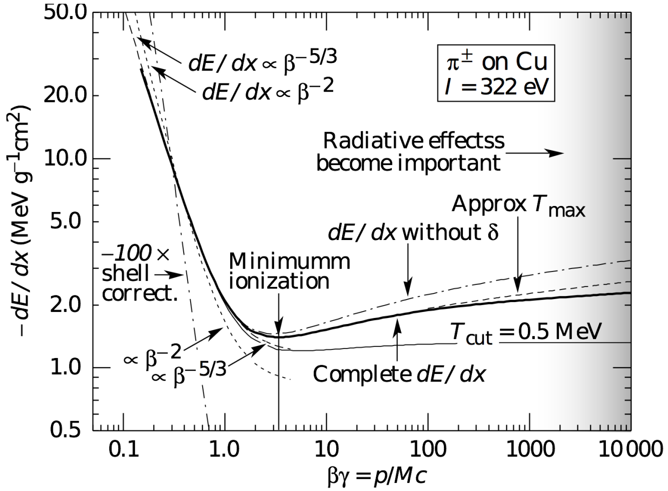


$PbW0_4$ CMS, X_0=0.89 cm



Electromagnetic shower: electrons

Electrons have two dominant effects through which they loose energy in their interaction with matter:



- ionization / excitation of atoms → Bethe-Bloch

  after the minimum around $\beta\gamma \approx 3$, the rise is weak and the dE/dx remains relatively low

- Bremsstrahlung:

  X_0 = radiation length

$$\frac{dE}{dx} = -\frac{E}{X_0}$$

$$E = E_0 \exp(-x/X_0)$$

Moliere radius (relevant for transverse size of the shower)

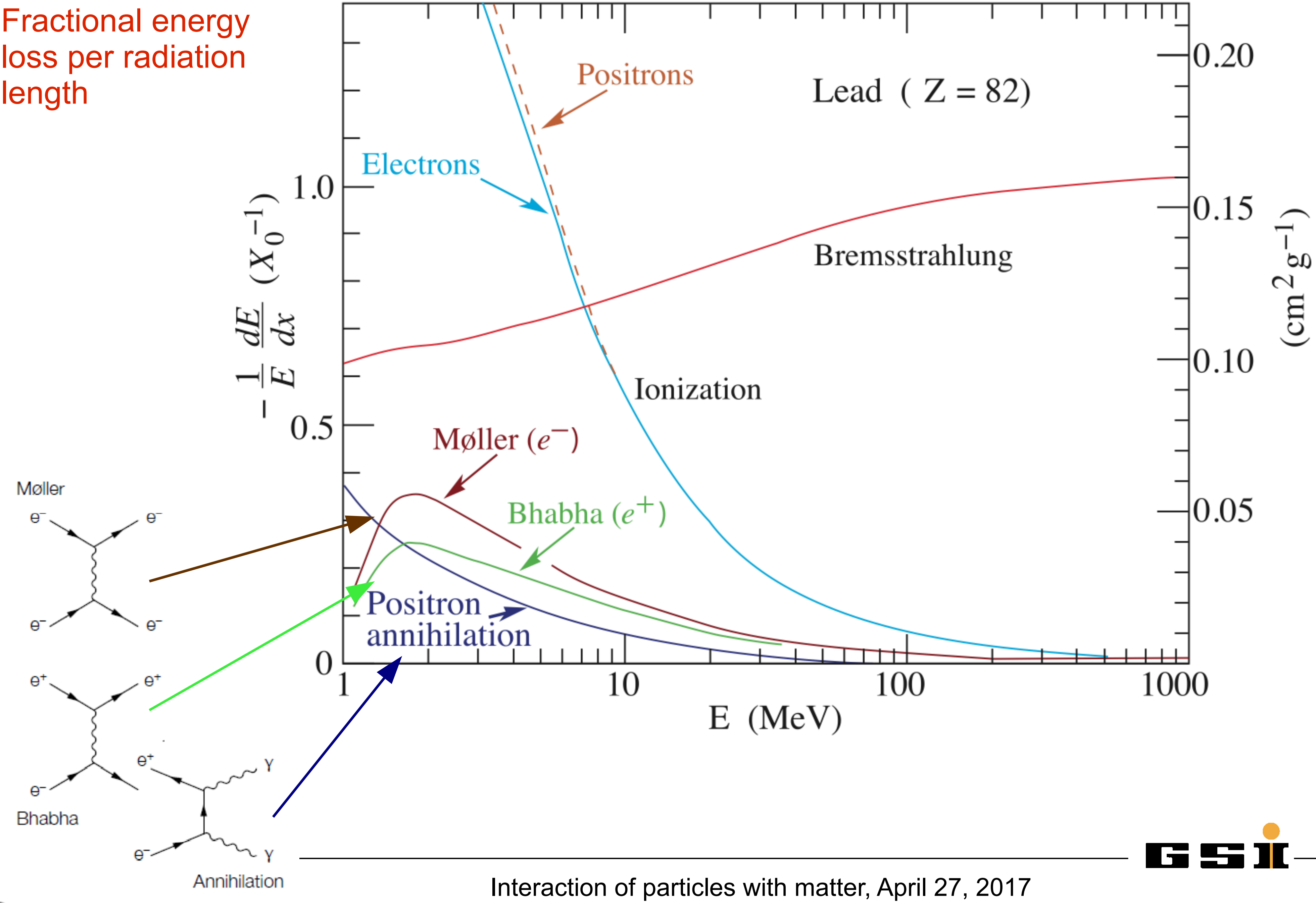
$$R_M = \frac{21.2\,\mathrm{MeV}}{E_c} \cdot X_0$$

→ Critical energy E_c !!

Overview: energy loss by electrons

From the 3rd lecture!!!

Fractional energy loss per radiation length



Critical energy

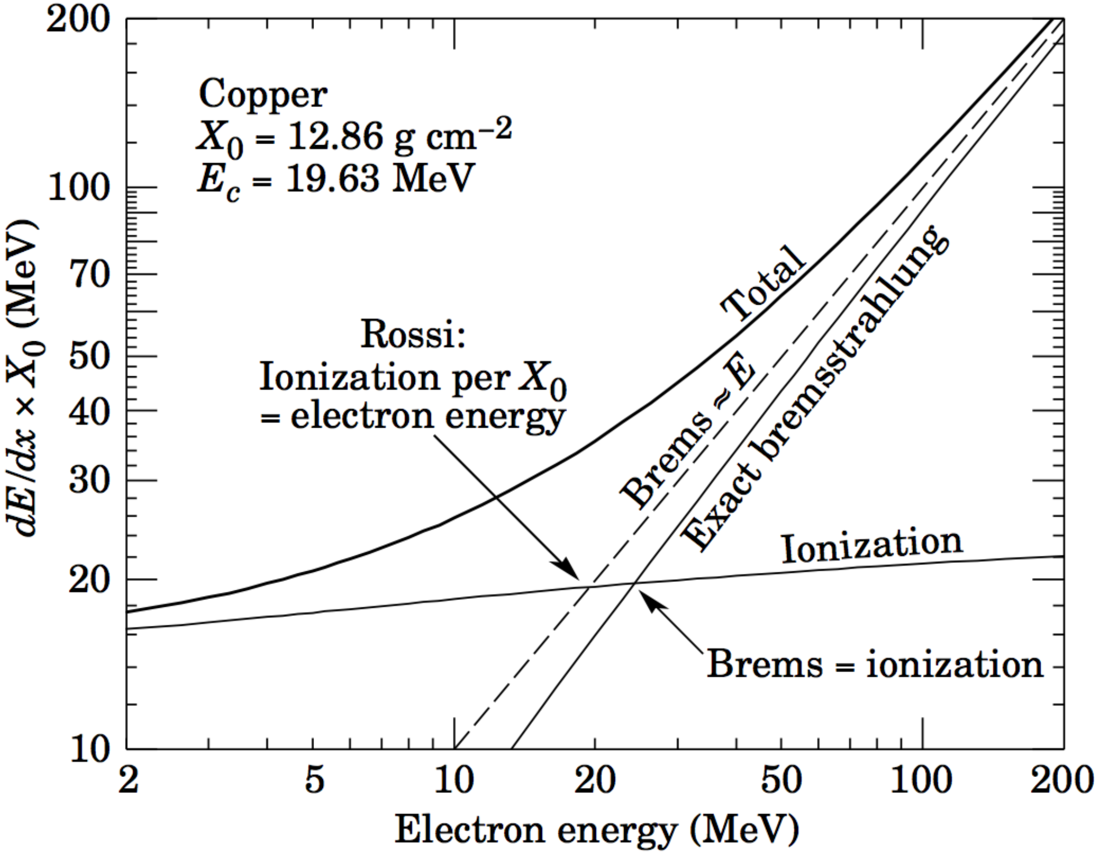
From the 3rd lecture!!!

Total energy loss of electrons:

$$\left(\frac{dE}{dx}\right)_{Tot} = \left(\frac{dE}{dx}\right)_{Ion} + \left(\frac{dE}{dx}\right)_{Brems}$$

Critical energy:

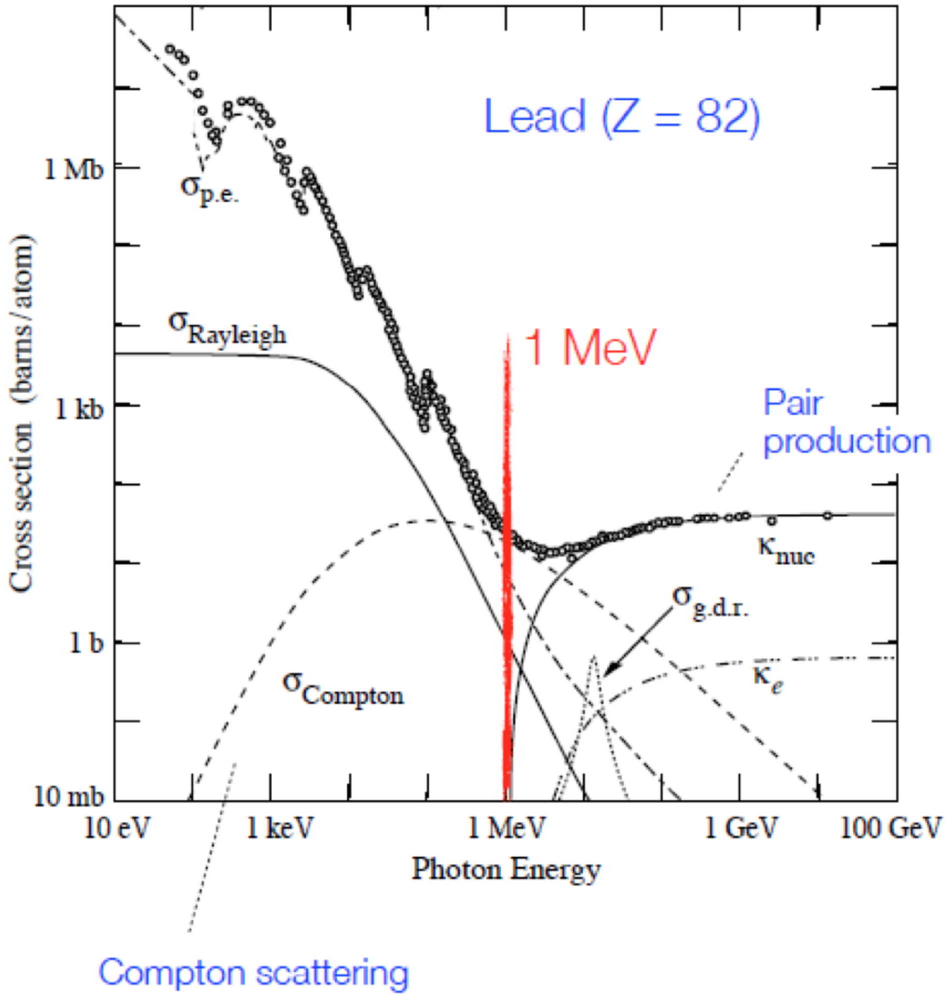
$$\left(\frac{dE}{dx}(E_c)\right)_{Brems} = \left(\frac{dE}{dx}(E_c)\right)_{Ion}$$



Example: Cu $E_c \approx 610/30$ MeV ≈ 20 MeV

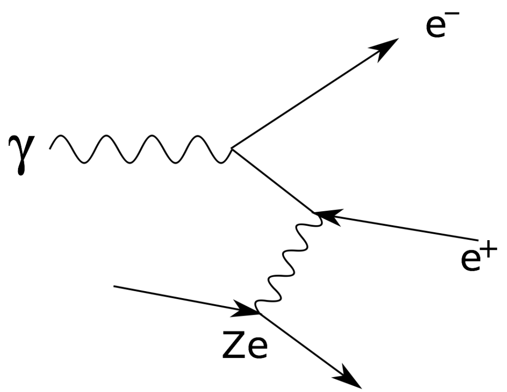
For E > E_c Bremsstrahlung dominates !!!

Photons



Dominant effect for energies above a few MeV:

Pair production

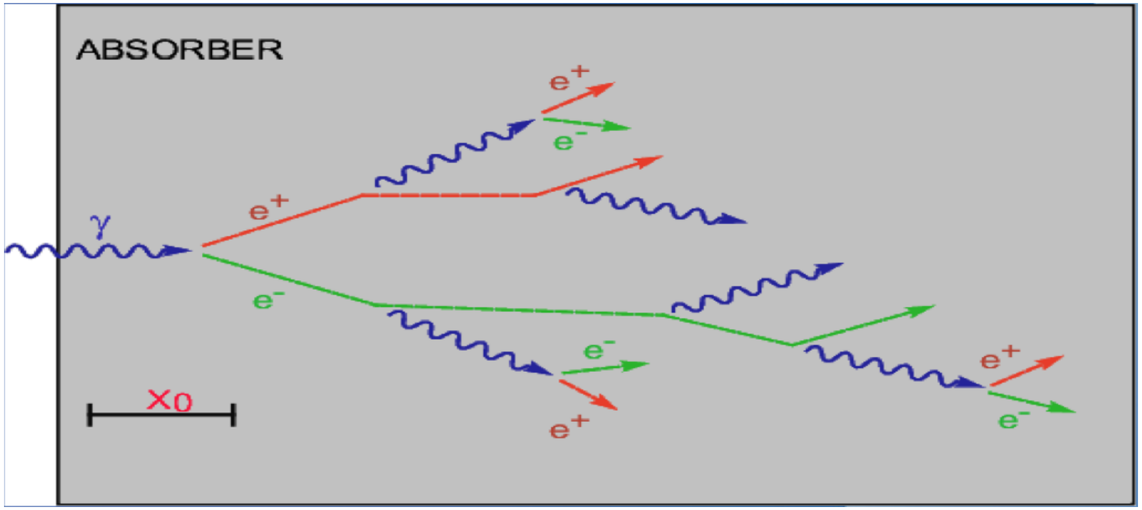


Probability for pair production (PP):

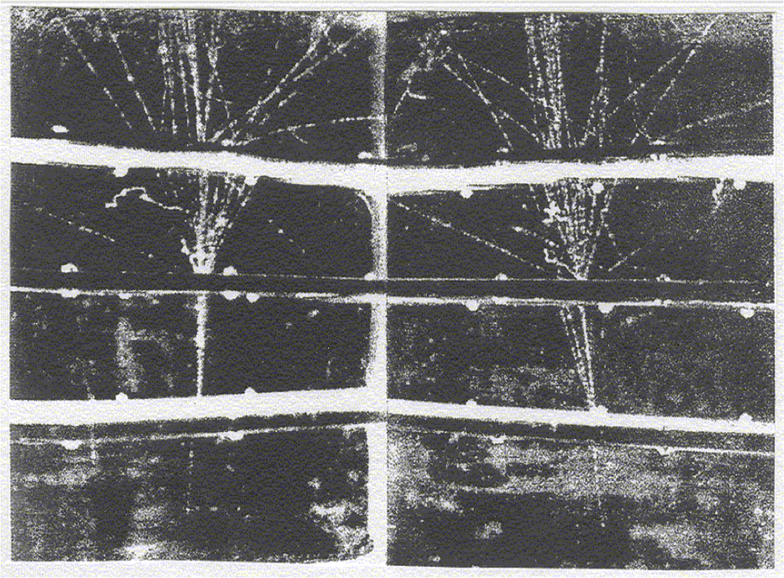
$$\frac{d\omega}{dx} = \frac{1}{\lambda_{PP}} e^{-x/\lambda_{PP}} \quad \rightarrow \quad \lambda_{PP} = \frac{9}{7} X_0$$

Electromagnetic shower

X_0 is the characteristic scale

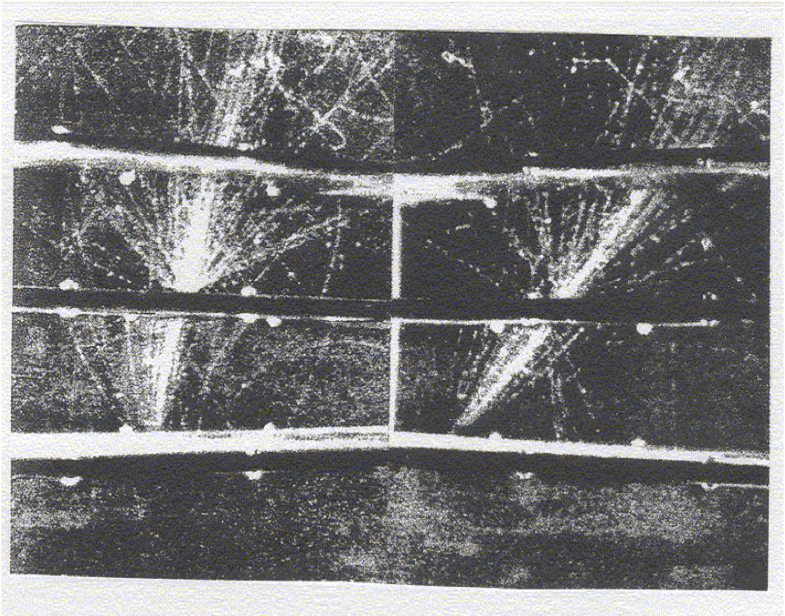


L.Fussel 1939



Electron Shower

L.Fussel 1939



Photon Shower

Examples of used materials

material	Z	X_0 [g cm^{-2}]	X_0 [cm]	E_c [MeV]	R_M [cm]
plastic scint.			34.7	80	9.1
Ar (liquid)	18	19.55	13.9	35	9.5
Fe	26	13.84	1.76	21	1.77
BGO		7.98	1.12	10	2.33
Pb	82	6.37	0.56	7.4	1.60
U	92	6.00	0.32	6.8	1.00
Pb glass (SF5)			2.4	11.8	4.3

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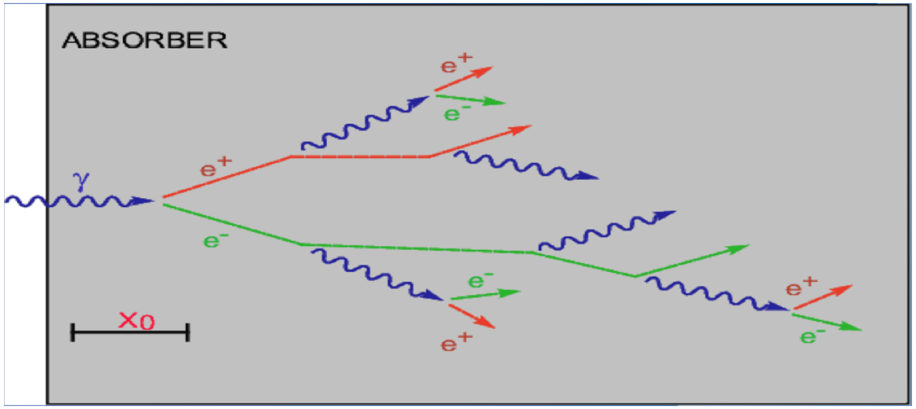
Analytic model of electromagnetic shower

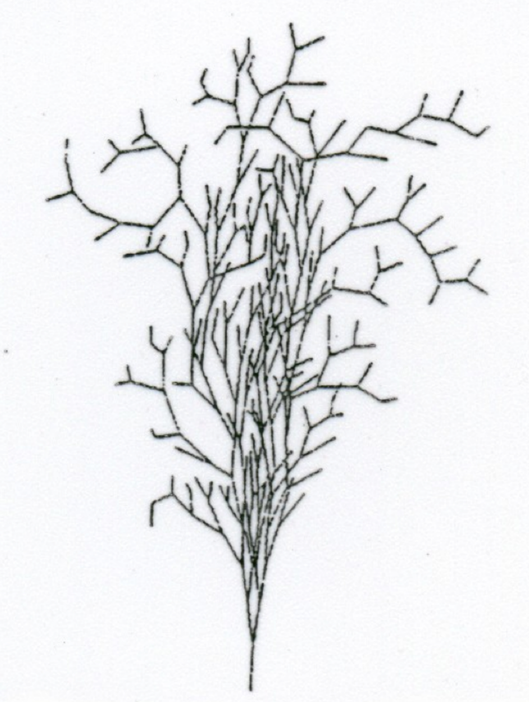
A high energy electron/photon (above ~100 MeV) enters matter:

- Electron looses energy by Bremsstrahlung
  e + nucleus → e + γ + nucleus
- Photon is absorbed by pair production
  γ + nucleus → $e^+ + e^-$ + nucleus



Approximate model:

- Over distance X_0, electron reduces via bremsstrahlung its energy to 1/e: $E_1 = E_2/e$
- Over distance ~X_0, photon converts to e^+e^-
  Energy of electron and positron: $E_\pm \simeq E_0/2$
  (precisely $\lambda_{PP} = 9/7 X_0$. Pair production probability in X_0 is P = 1 - exp(-7/9)=0.54)



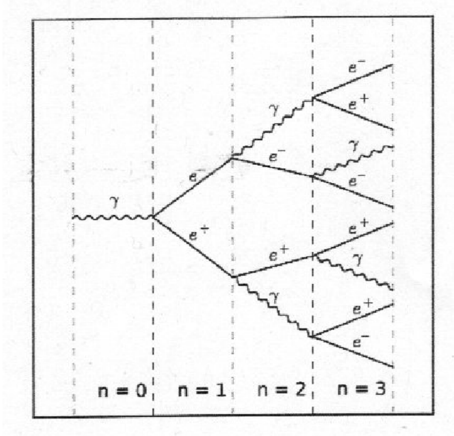
Assumptions:

- For $E>E_c$ no energy loss by ionization/excitation
- For $E<E_c$ electrons loose energy only via ionization/excitation

Analytic model of electromagnetic shower

An electromagnetic shower is characterized by:

- Number of particles in the shower
- Location of shower maximum
- Longitudinal shower distribution
- Transverse shower distribution



Simplified model (assuming e ≈ 2):

Introduce longitudinal variable $t = x/X_0$

Number of particles after traversing depth t:

$$N(t) = 2^t$$

Each particle has energy:

$$E(t) = \frac{E_0}{N(t)} = \frac{E_0}{2^t} \rightarrow t = \ln(E_0/E)/\ln 2$$

The shower ends approximately when $E \approx E_c$:

$$E_c = E(t_{max}) = \frac{E_0}{2^{t_{max}}}$$

$$2^{t_{max}} = E_0/E_c$$

Maximum shower depth:

$$t_{max} = \ln(E_0/E_c)/\ln 2$$

Maximum number of particles in shower:

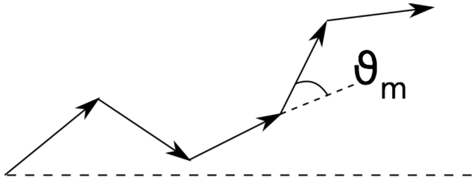
$$N_{max} = \exp(t_{max} \ln 2) = E_0/E_c$$

Example: 1 GeV photon in CsI crystal: $E_c \simeq 10$ MeV, $N_{max} = E_0/E_c \simeq 100$, $t_{max} \simeq 6.6\ X_0$

Transverse shower development

- Emission of bremsstrahlung under SMALL angle $\langle \theta^2 \rangle \approx \frac{m}{E} = \frac{1}{\gamma^2}$
- 3D multiple scattering of electron in Moliere theory

$$\langle \theta_m^2 \rangle = \left(\frac{21.2\,\mathrm{MeV}}{\beta p c}\right)^2 t$$



Multiple scattering dominates the transverse shower development!!

The main contribution comes from low energy electrons, assuming approximate range of electrons to be X_0

Moliere radius: $$R_M = \sqrt{\langle \theta^2 \rangle_{x=X_0} \cdot X_0} \approx \frac{21\,\mathrm{MeV}}{E_c} X_0$$

Transverse shower development

Useful relations:

$$X_0 = \frac{180A}{Z^2}(\text{g cm}^{-2})$$

$$E_c = \frac{580 \text{ MeV}}{Z}$$

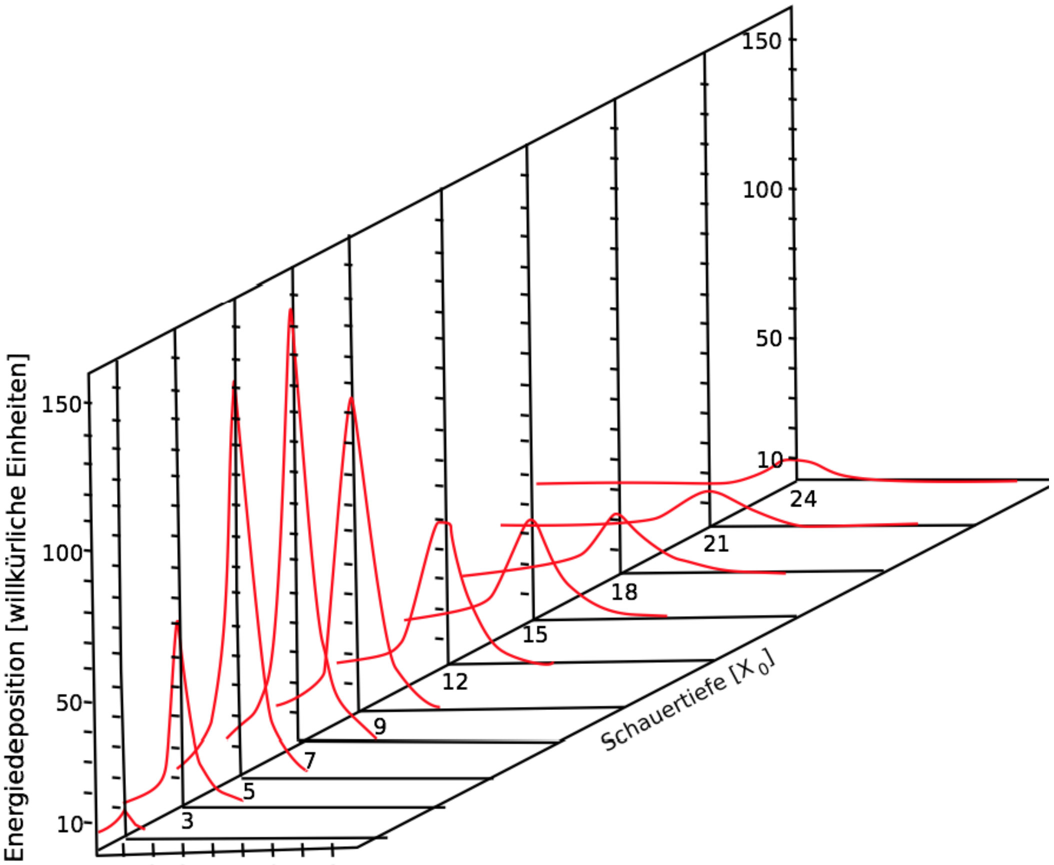
$$t_{max} = \ln\frac{E}{E_c} - \begin{cases} 1 & e \text{ induced shower} \\ 0.5 & \gamma \text{ induced shower} \end{cases}$$

95% of energy within:

$L(95\%) = t_{max} + 0.08\,Z + 9.6\,X_0$

$R(95\%) = 2\,R_M$

a 6 GeV electron in lead

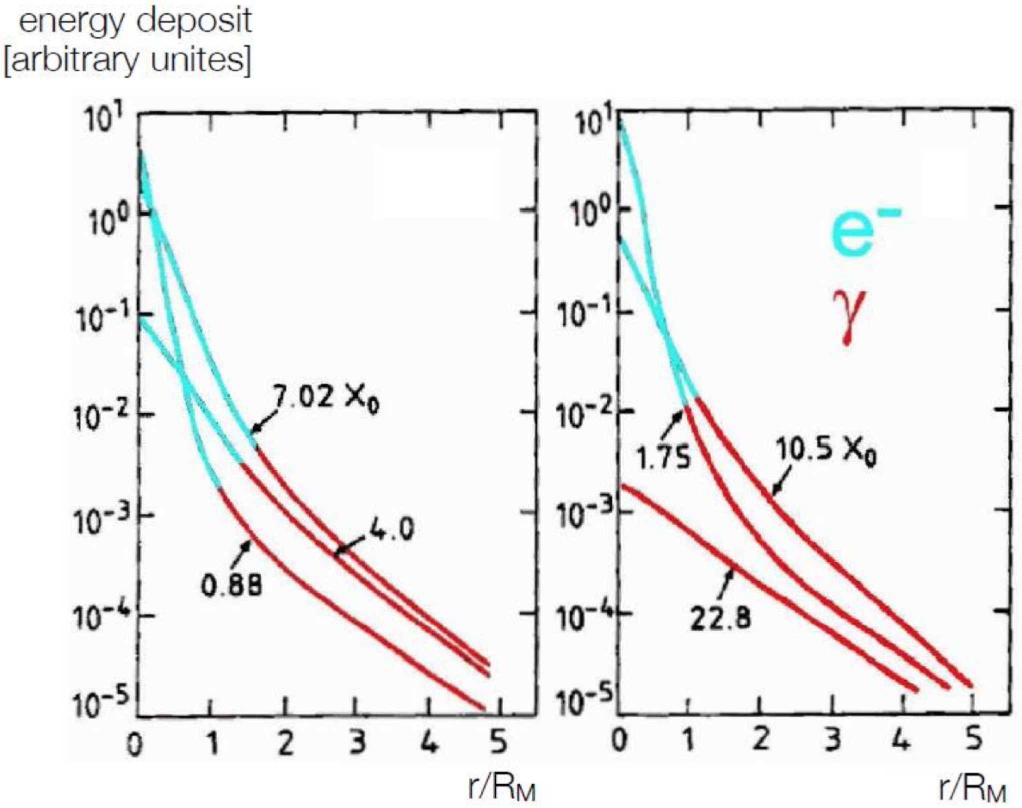


Laterale Schauerbreite [X_0]

Transverse shower profile

Lateral width increases with increasing longitudinal shower depth

- Central part: multiple Coulomb scattering of electrons (positrons) mostly "early" in the shower development
- Tail: low energy photons (and electrons) produced in Compton scattering and photoelectric effect, mostly late in the shower evolution



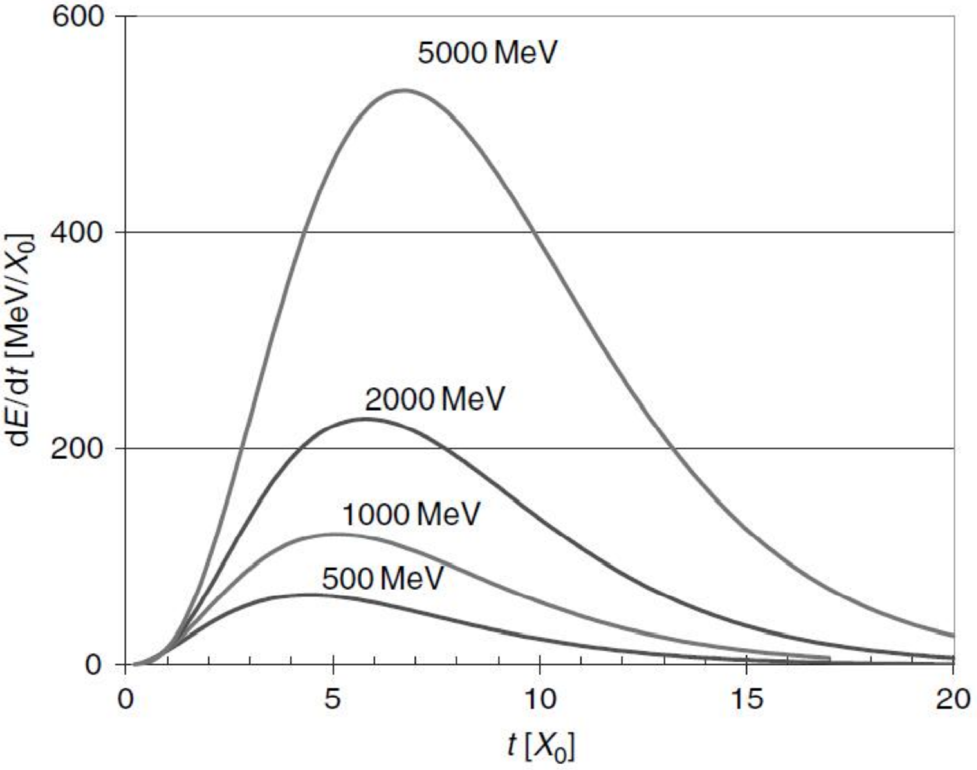
Longitudinal shower profile

Parametrization (Longo 1975)

$$\frac{dE}{dt} = E_0 t^{\alpha} \exp(-\beta t)$$

- First increase of secondaries
- Then absorption dominates

Energy deposit



Remember:

- Most of the energy of the incident γ is absorbed in 10-15 X_0
- The max position increases slowly with E_0 (~ lnE, not E!)
- Energy leakage mostly due to soft photons at the sides and the back

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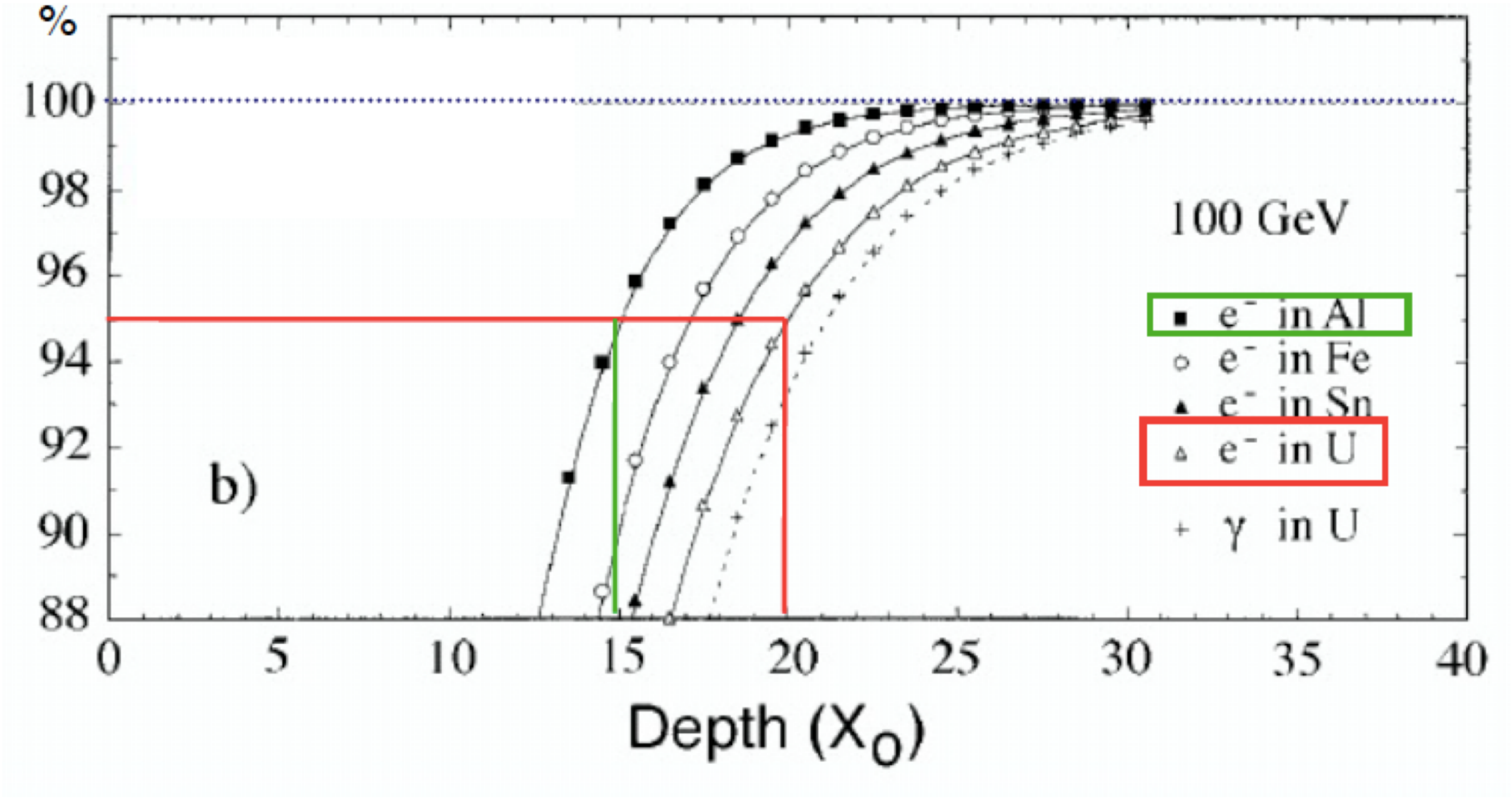
Longitudinal shower profile

Shower containment:



$$L(95\%) = t_{max} + 0.08\,Z + 9.6\,X_0$$

Electromagnetic calorimeters

- Homogeneous calorimeters: full absorption detectors, fully active medium for both energy degradation and signal generation
- Sampling calorimeters: alternate layers of absorber material to degrade the particle energy and active media to provide the detectable signal

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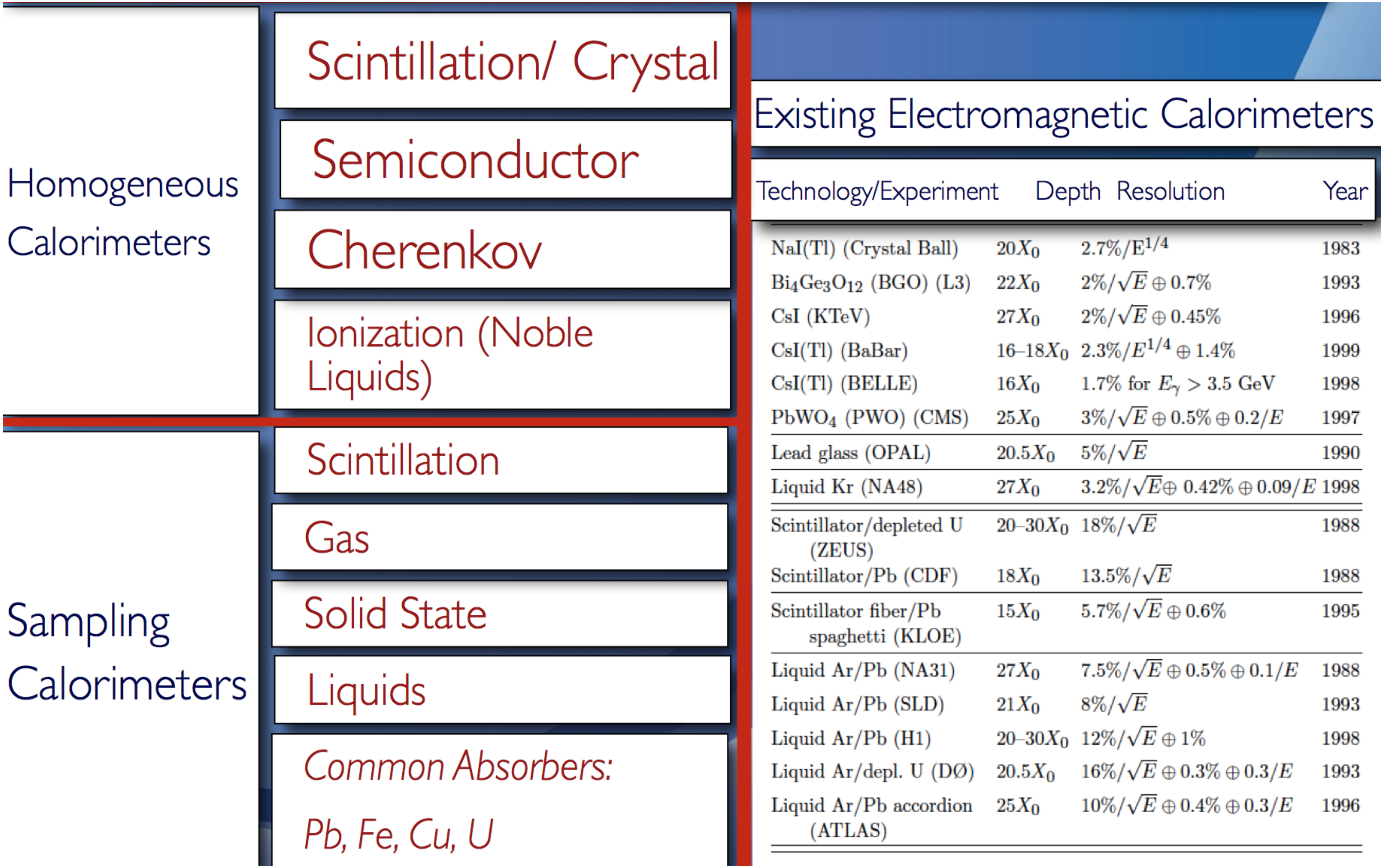
Electromagnetic calorimeters



Homogeneous Calorimeters

- Scintillation/ Crystal
- Semiconductor
- Cherenkov
- Ionization (Noble Liquids)

Sampling Calorimeters

- Scintillation
- Gas
- Solid State
- Liquids

Common Absorbers:

Pb, Fe, Cu, U

Existing Electromagnetic Calorimeters

Technology/Experiment	Depth	Resolution	Year
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/E^{1/4}$	1983
$Bi_4Ge_3O_{12}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	$16–18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl) (BELLE)	$16X_0$	1.7% for $E_\gamma > 3.5$ GeV	1998
$PbWO_4$ (PWO) (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997
Lead glass (OPAL)	$20.5X_0$	$5\%/\sqrt{E}$	1990
Liquid Kr (NA48)	$27X_0$	$3.2\%/\sqrt{E} \oplus 0.42\% \oplus 0.09/E$	1998
Scintillator/depleted U (ZEUS)	$20–30X_0$	$18\%/\sqrt{E}$	1988
Scintillator/Pb (CDF)	$18X_0$	$13.5\%/\sqrt{E}$	1988
Scintillator fiber/Pb spaghetti (KLOE)	$15X_0$	$5.7\%/\sqrt{E} \oplus 0.6\%$	1995
Liquid Ar/Pb (NA31)	$27X_0$	$7.5\%/\sqrt{E} \oplus 0.5\% \oplus 0.1/E$	1988
Liquid Ar/Pb (SLD)	$21X_0$	$8\%/\sqrt{E}$	1993
Liquid Ar/Pb (H1)	$20–30X_0$	$12\%/\sqrt{E} \oplus 1\%$	1998
Liquid Ar/depl. U (DØ)	$20.5X_0$	$16\%/\sqrt{E} \oplus 0.3\% \oplus 0.3/E$	1993
Liquid Ar/Pb accordion (ATLAS)	$25X_0$	$10\%/\sqrt{E} \oplus 0.4\% \oplus 0.3/E$	1996

Homogeneous em calorimeters

Absorbing material ≡ detection material

- Scintillating crystals (sodium iodide NaI, bismuth germanate BGO, caesium iodide CsI, lead tungstate $PbWO_4$, etc.)

	NaI(Tl)	BGO	CsI(Tl)	$PbWO_4$
density (g/cm^3)	3.67	7.13	4.53	8.28
X_0 (cm)	2.59	1.12	1.85	0.89
R_M (cm)	4.5	2.4	3.8	2.2
dE/dx_{mip} (MeV/cm)	4.8	9.2	5.6	13.0
light yield (photons/MeV)	$4 \cdot 10^4$	$8 \cdot 10^3$	$5 \cdot 10^4$	$3 \cdot 10^2$
energy resolution σ_E/E	$1\%/\sqrt{E}$	$1\%/\sqrt{E}$	$1.3\%/\sqrt{E}$	$2.5\%/\sqrt{E}$

- Energy loss by ionization (noble liquids)
- Cherenkov (lead glass SF5)

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Energy resolution of homogeneous calo

Contributions to the energy resolution σ_E/E:

- Shower fluctuations (intrinsic) stochastic term $\propto \frac{1}{\sqrt{E}}$
- photon/electron statistics in photon detector $\propto \frac{1}{\sqrt{E}}$
- Electronic noise $\propto \frac{1}{E}$
- Leakage, calibration $\simeq$ constant

Total energy resolution of electromagnetic calorimeter:

$$\boxed{\frac{\sigma_E}{E} = \frac{A}{\sqrt{E}} \oplus \frac{B}{E} \oplus X}$$

Examples

- PHOS in ALICE ($PbWO_4$ crystals)
- $PbWO_4$ calorimeter in CMS
- Alternative to scintillators → Cherenkov radiator e.g. lead glass

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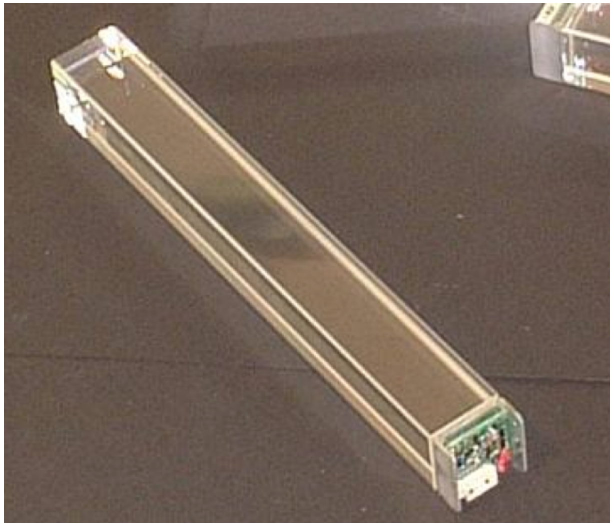
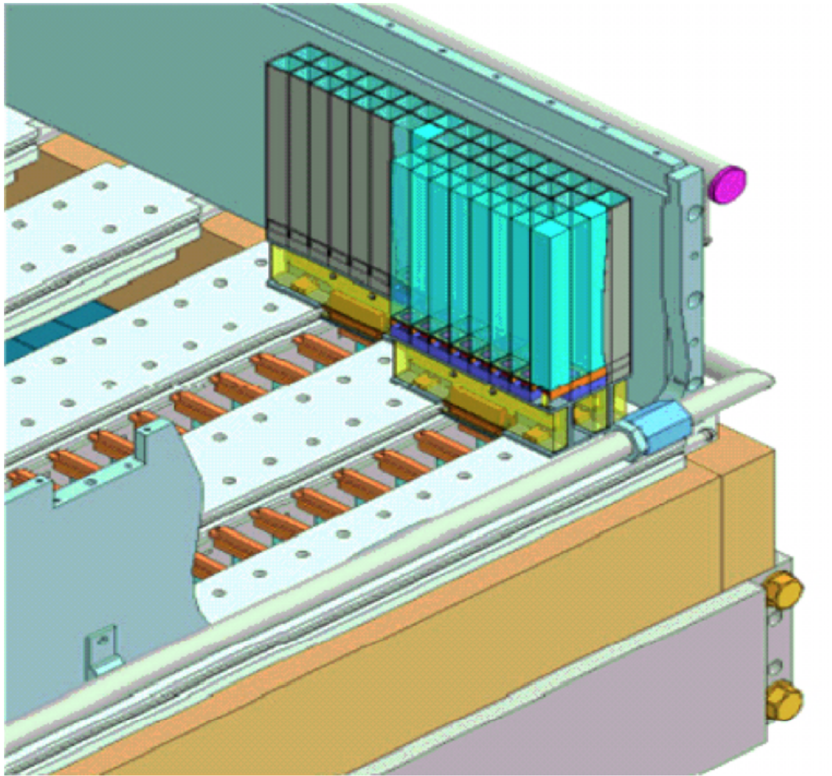
Electromagnetic calorimeters, June 28, 2017

PHOS: PHOton Spectrometer in ALICE





Array of 22 x 22 x 180 cm^3 $PbWO_4$ crystals.
Depth = 20 X_0. Total ~ 18,000 crystals.

Characteristics: dense, fast, relatively radiation hard

Emission spectrum: 420-550 nm

Readout: 5x5 mm^2 avalanche photodiodes, Q=85%

Light yield of $PbWO_4$ relatively low and strongly temperature dependent!!

Operate detector at -25° C, need to stabilize to 0.3° C (monitor with resistive temperature sensors)

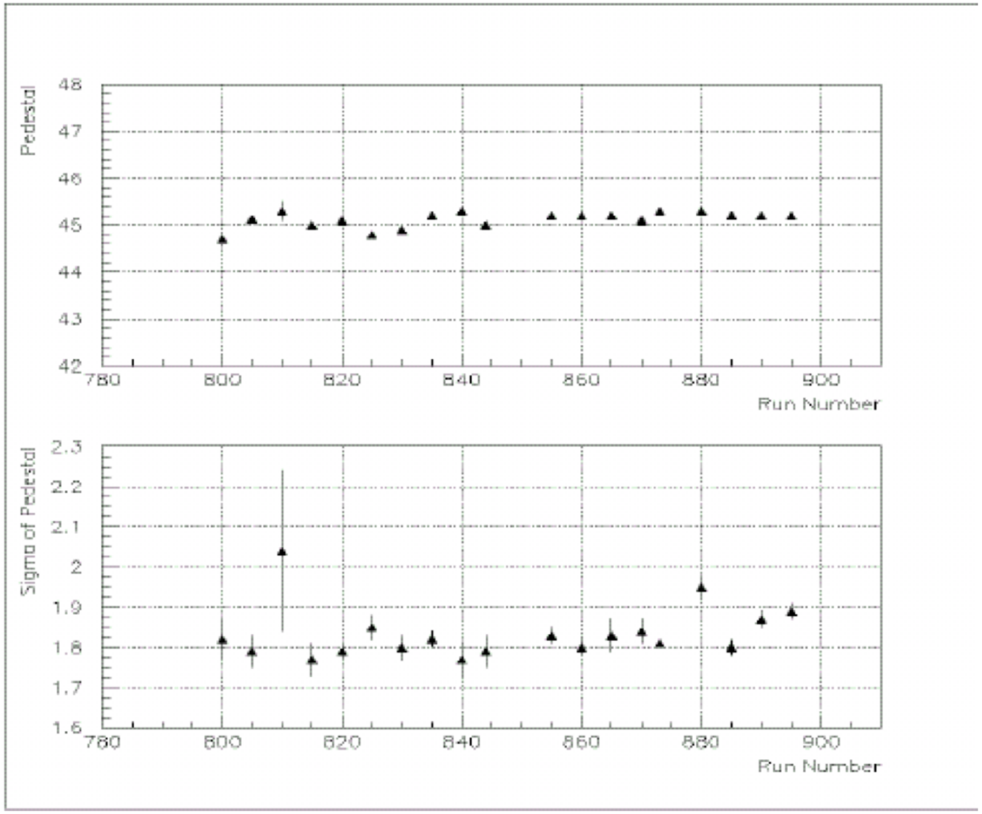
Crystals cold, electronics warm

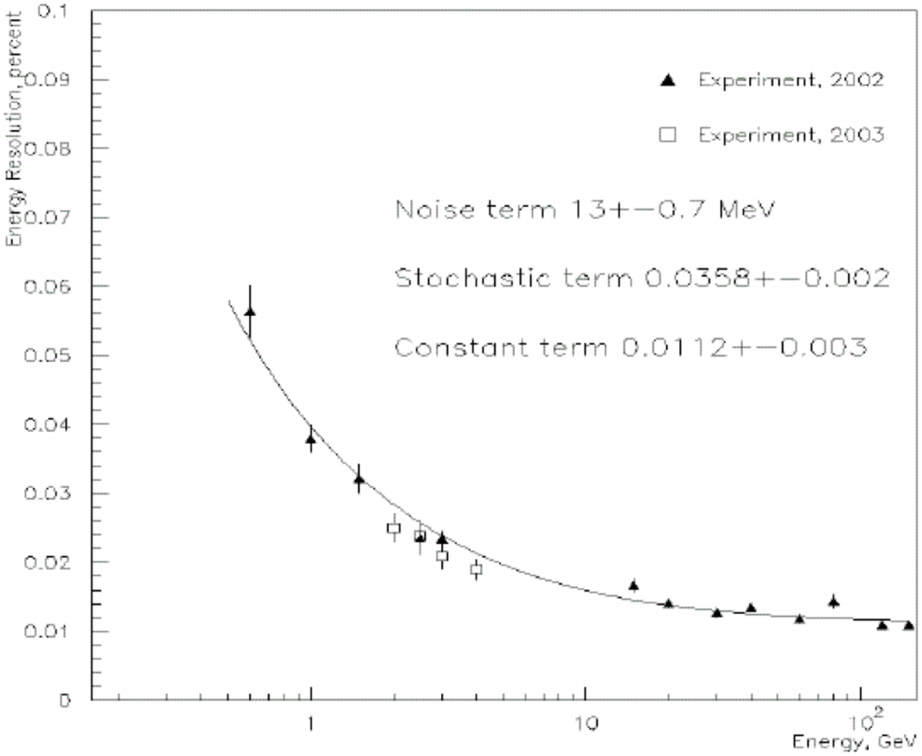
PHOS in ALICE

12.5 t of crystals, covering 8m^2 at 4 m from beam line

In front: charged particle veto – MWPC with cathode pad readout

Test beams of pions and electrons at CERN PS and SPS: 0.6 – 150 GeV





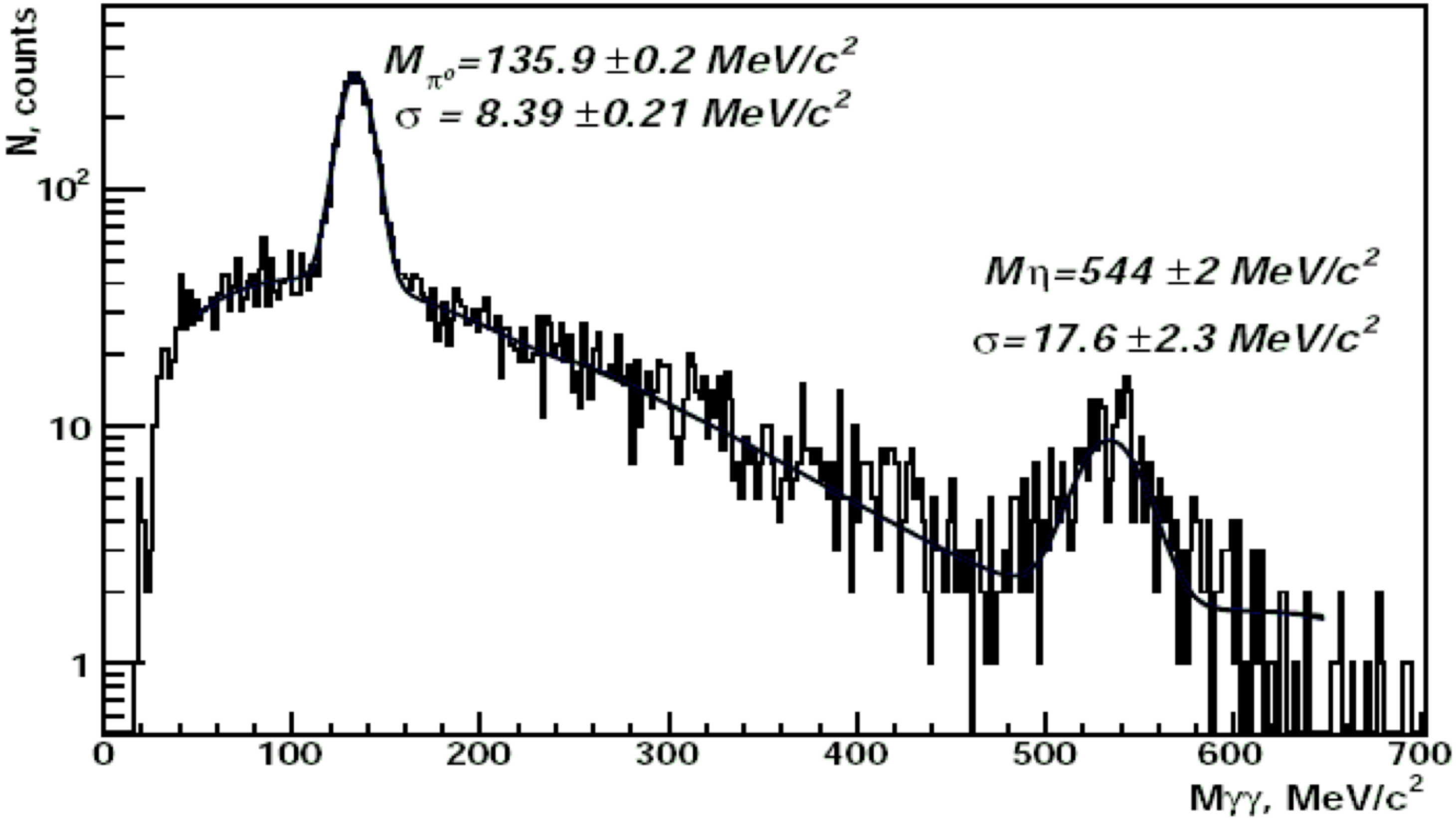
electronic noise:
1 ch = 400 e → noise about 700 e

$$\frac{\sigma_E}{E} = \frac{3.6\%}{\sqrt{E}} \oplus \frac{1.3\%}{E} \oplus 1.1\%$$

Importance of energy resolution

Peaks sit on combinatorial background. S/B depends on resolution

$\pi^0, \eta \rightarrow \gamma\gamma$



Invariant mass spectrum from the inclusive reaction:

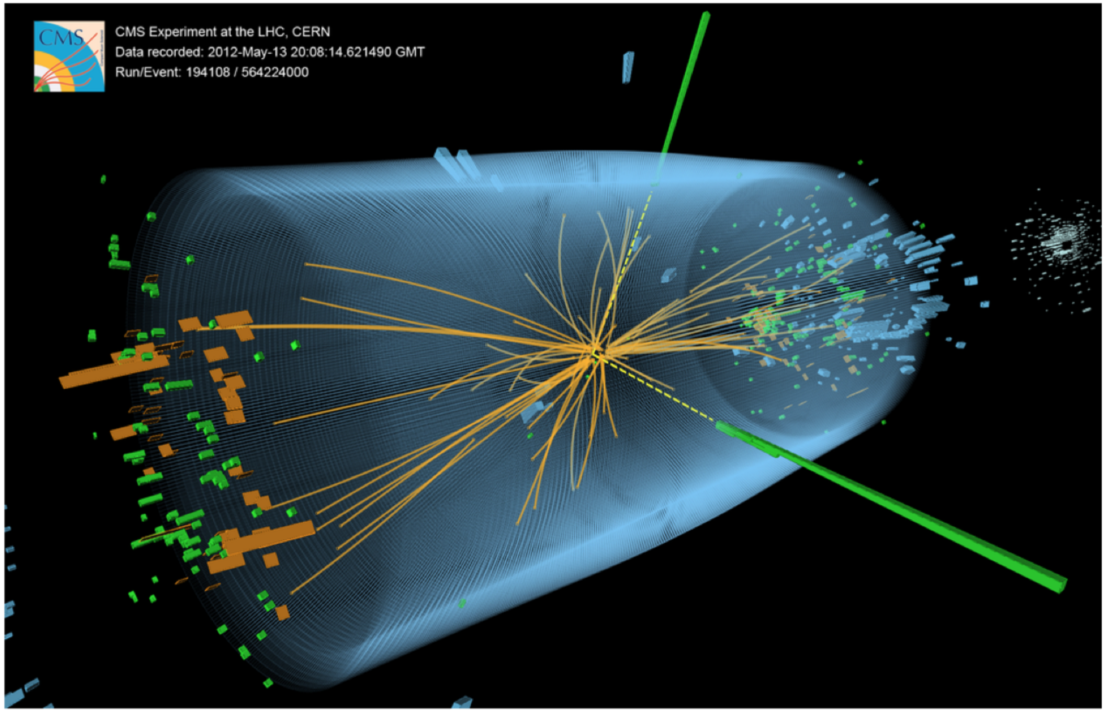
6 GeV/c $\pi^- + {}^{12}C \rightarrow \pi^0 + X$

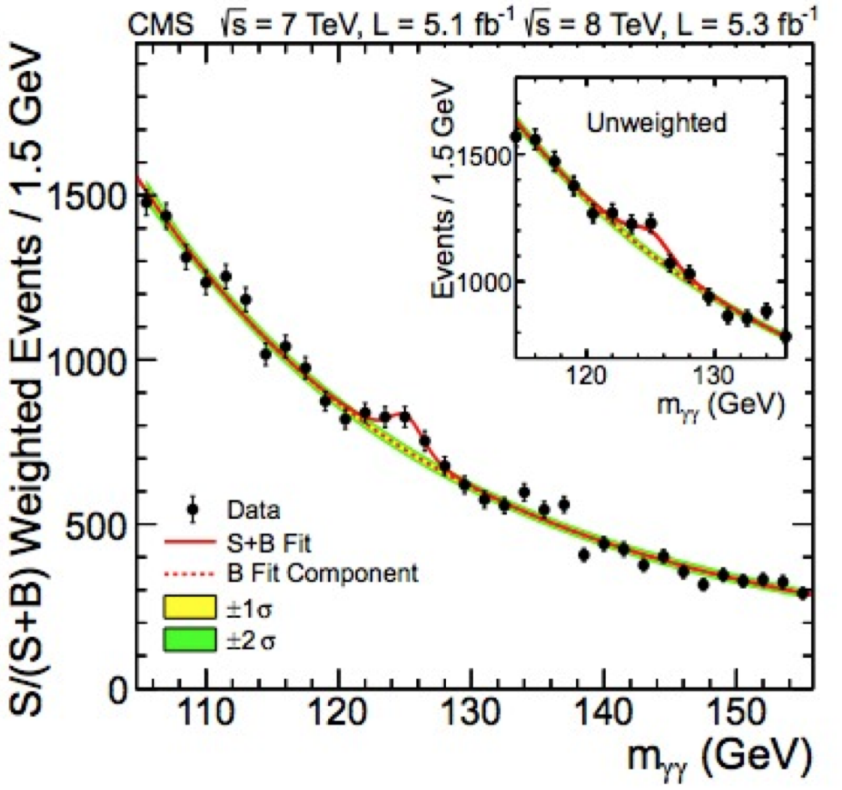
measured at 122 cm distance

CMS crystal calorimeter ($PbWO_4$)

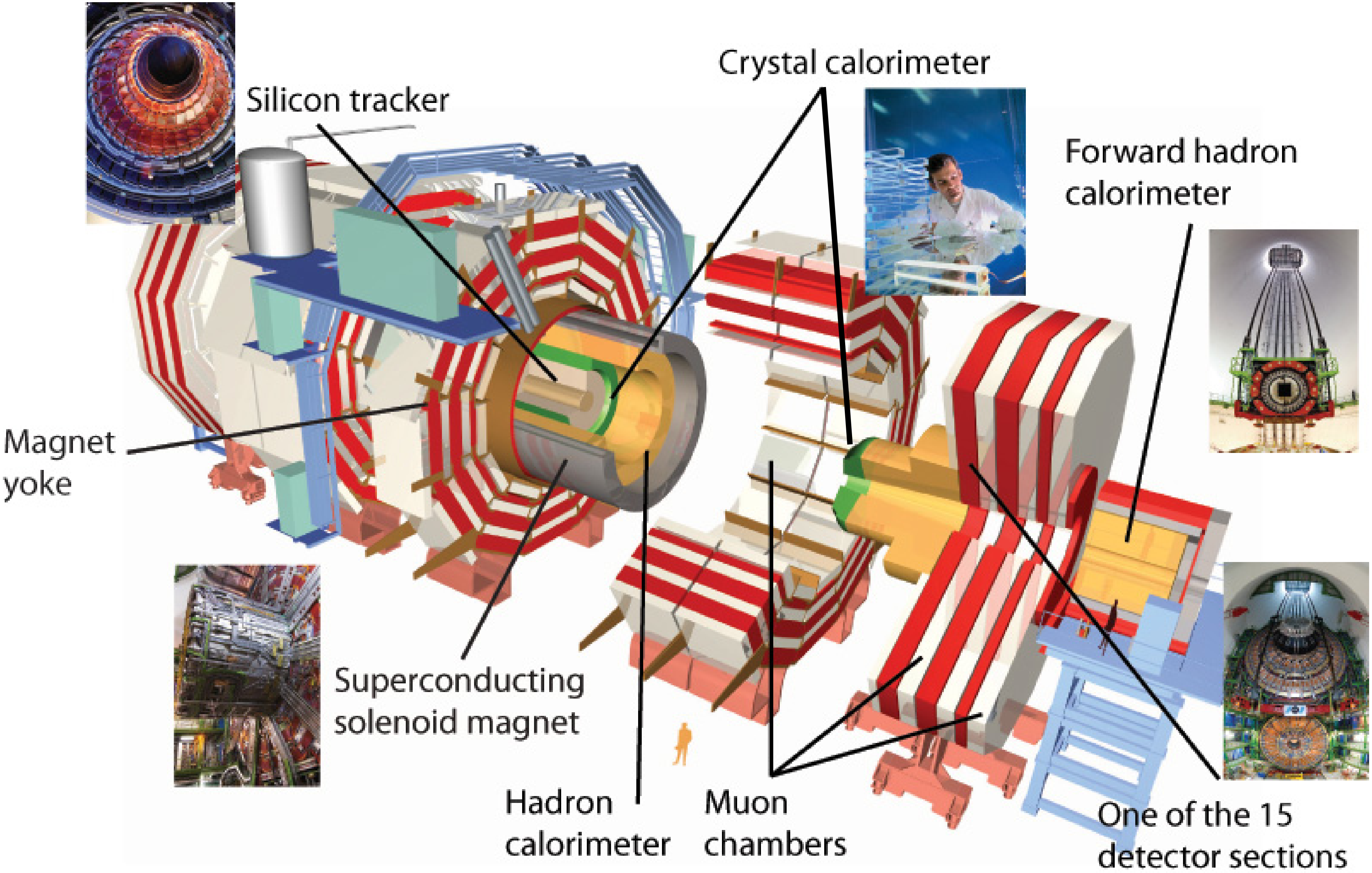
Most important Higgs discovery channel:

$H \rightarrow \gamma\gamma$

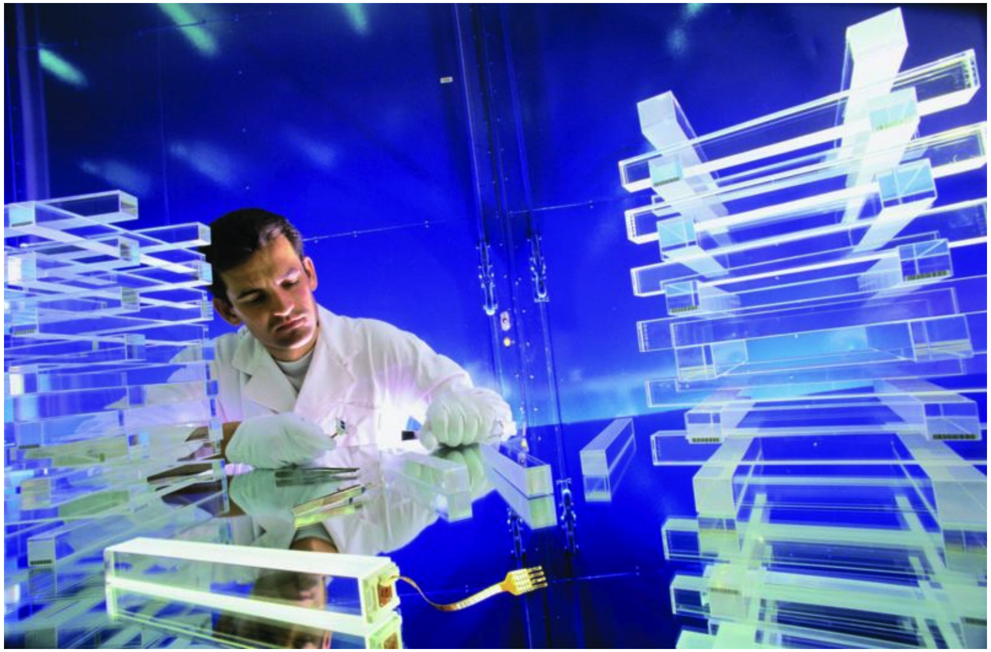




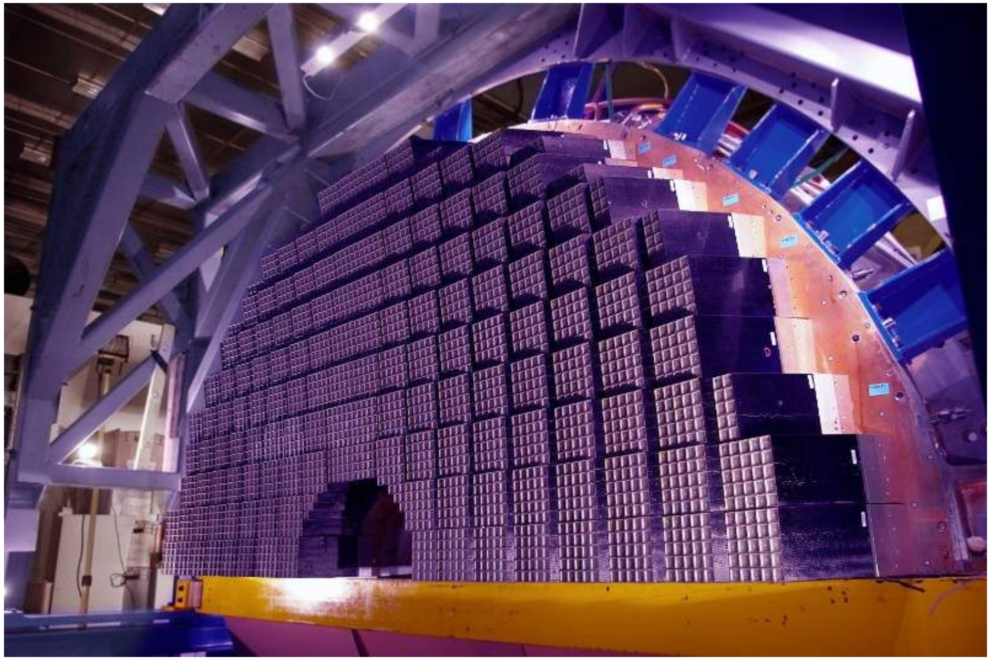
CMS crystal calorimeter ($PbWO_4$)



CMS crystal calorimeter ($PbWO_4$)



The crystals



End-cap electromagnetic calorimeter

Homogeneous calo: alternative to scintillators

DISADVANTAGE OF SCINTILLATING CRYSTALS: high costs and limitation in producing large volumes

Alternative: use Cherenkov radiator

Electrons and positrons of em shower emit Cherenkov light

- Number of photons is proportional to total path length of electrons and positrons: $N_{ph} \propto E_0$
- Resolution limited by photoelectron statistics (typical: about 1000 photo electrons per GeV shower energy)

Mostly used: lead glass, e.g. SF5: n=1.67, β_{thr}=0.6 or E_{thr}=0.62 MeV for electrons

Blocks of typical size 14 x 14 x 42 cm^3 → diameter 3.3 R_M and depth 17.5 X_0

Readout with photomultipliers.

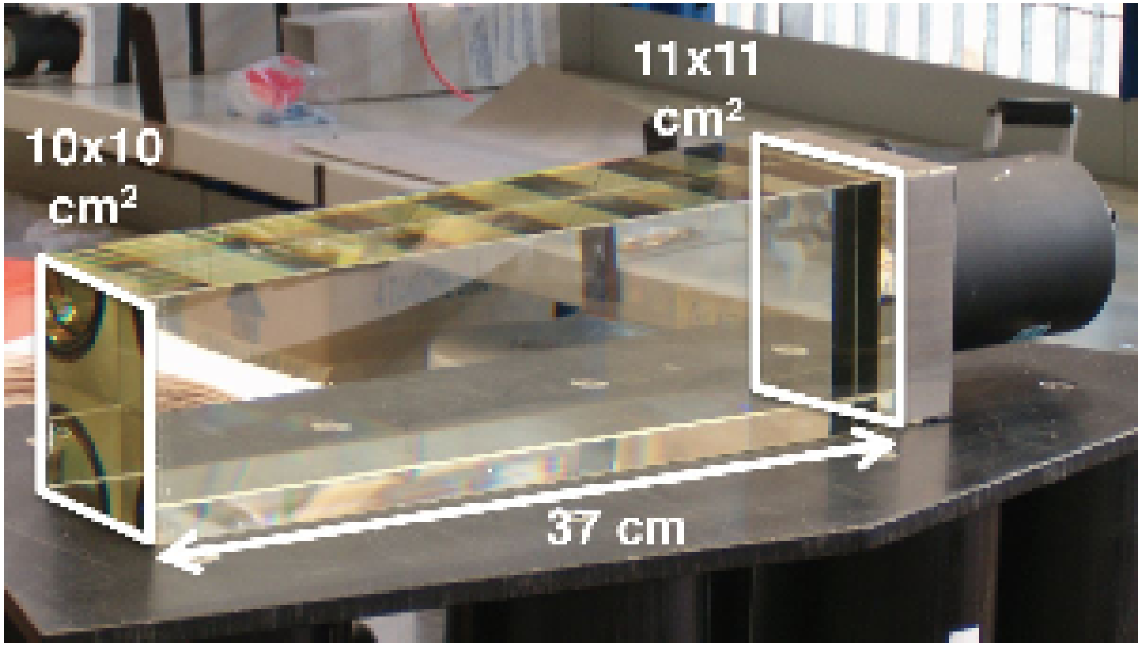
Typical performance:

$$\frac{\sigma_E}{E} = 0.01 + 0.05\sqrt{E(\mathrm{GeV})}$$

Lead glass calorimeter

Lead glass blocks from the OPAL calorimeter

Now recycled in NA62 (photon veto)

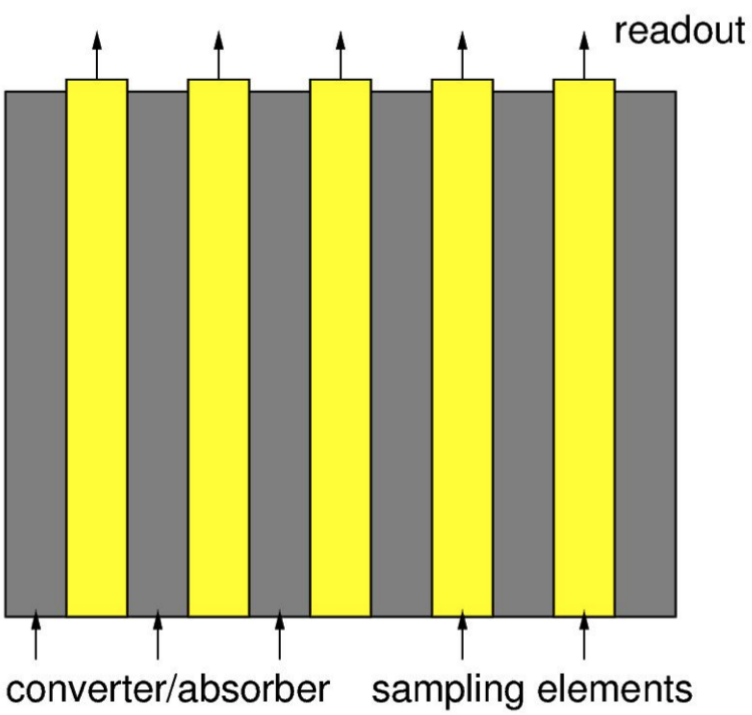


Sampling calorimeters

Signal generated in material different from material where the main energy loss occurs.

Shower (energy loss) only “sampled”

Simpler and more economical solution.



Converter medium:
Pb, W, U, Fe ← energy loss

Detection medium:
scintillator, liquid Ar ← sampling of shower

Longitudinal shower development:

Transverse shower development:

$$\left.\begin{array}{r} t_{max} = t_{max}^{abs}\dfrac{x+y}{x} \\ R(95\%) = 2R_M\dfrac{x+y}{x} \end{array}\right\} \begin{array}{ll} x = \sum x_i & \text{absorber} \\ y = \sum y_i & \text{detection element} \end{array}$$

Energy loss in absorber and detection medium varies event-by-event

SAMPLING FLUCTUATIONS: additional contribution to energy resolution

Sampling calorimeters

History:

- 1954: N.L. Grigorov put forward idea of sampling calorimeters using proportional counters and scintillation counters between thick iron sheets to measure cosmic ray particles with $E > 10^{14}$ eV
  - 1957: installation on Pamir mountains with 10m2 of double layer of emulsions to study cosmic ray showers

1960-70's: particle experiments at accelerators

- 1965: C. Heusch and C. Prescott in CALTECH studied em shower development in plastic scintillators + lead absorbers, and lucite-based materials with lead absorbers
- 1973: H. Schopper and his group in Karlsruhe made studies with similar detectors for a hadronic calorimeter

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Sampling fluctuations

Energy deposition is dominated by electrons at small energies

Range of 1 MeV electron in U: $R \simeq 0.4$ mm

For thickness d of absorber layers ≥ 0.4mm: only fraction f of these electrons reaches the detection medium

$$f(e, \mathrm{conv} \rightarrow \mathrm{det}) \propto 1/d \propto 1/t_{\mathrm{conv}}$$

Fraction of electrons generated in detection medium

$$f(e,\mathrm{det}) \propto \frac{t_{\mathrm{det}}}{t_{\mathrm{conv}}}$$

Number of charged particles in shower: $N \simeq E_0 / E_c$

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Sampling fluctuations

Fluctuations:

$$\frac{\sigma_E}{E} \propto \frac{1}{\sqrt{N}} \propto \sqrt{\frac{E_c}{E}} \sqrt{\alpha\, t_{conv} + (1-\alpha)\frac{t_{conv}}{t_{det}}}$$

$$\text{Fe:} \quad (1-\alpha) \gg \alpha \qquad \frac{\sigma_E}{E} \propto \frac{1}{\sqrt{E}} \sqrt{\frac{t_{conv}}{t_{det}}}$$

$$\text{Pb:} \quad (\text{١}-\alpha) \ll \alpha \qquad \frac{\sigma_E}{E} \propto \frac{1}{\sqrt{E}} \sqrt{t_{conv}}$$

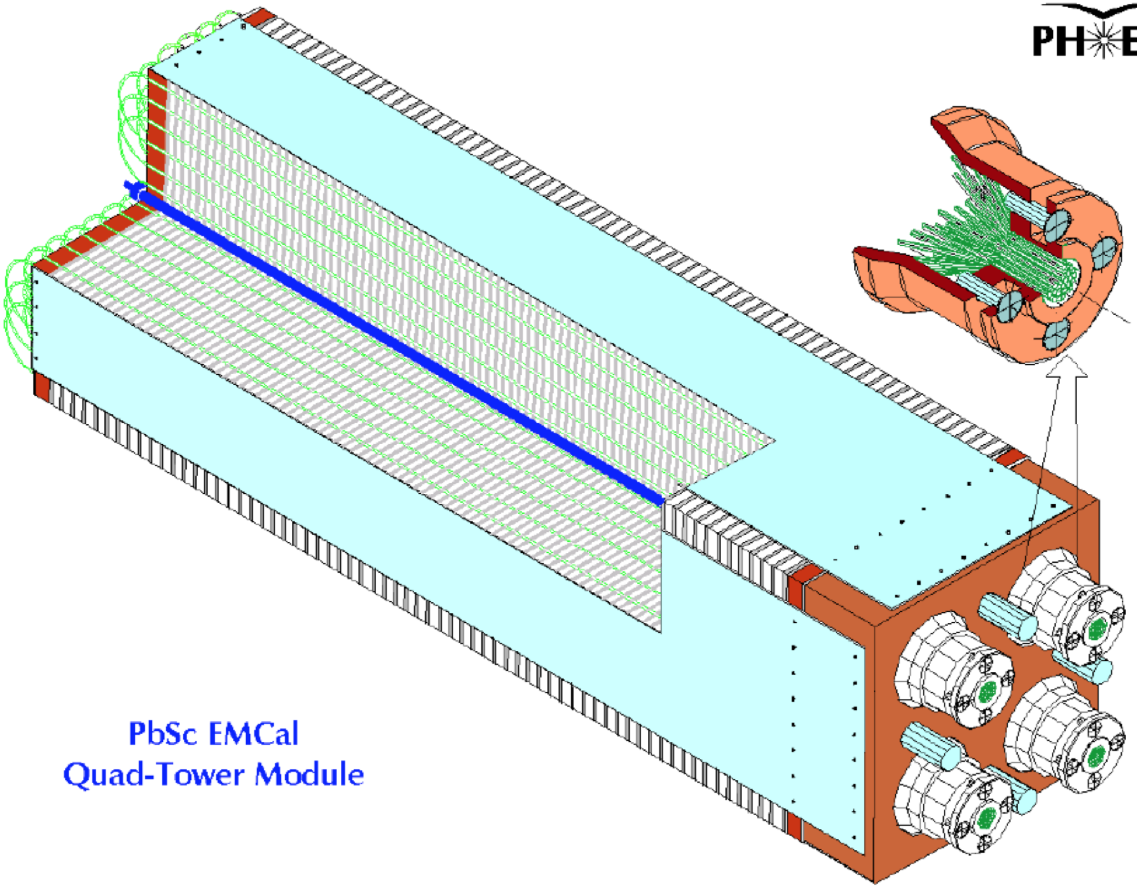
Common parametrization: $\dfrac{\sigma_E}{E} = 3.2\% \sqrt{\dfrac{E_c(\mathrm{MeV})}{F}} \sqrt{\dfrac{t_{conv}}{E(\mathrm{GeV})}}$

Good energy resolution for:

- E_c small ↔ Z large
- T_{conv} small: $x < X_0$, fine sampling

Example: PHENIX PbScint calorimeter

Alternating layers of Pb sheets and plastic scintillator sheets connected to PMT via scintillating fibres



individual towers 5 × 5 cm^2

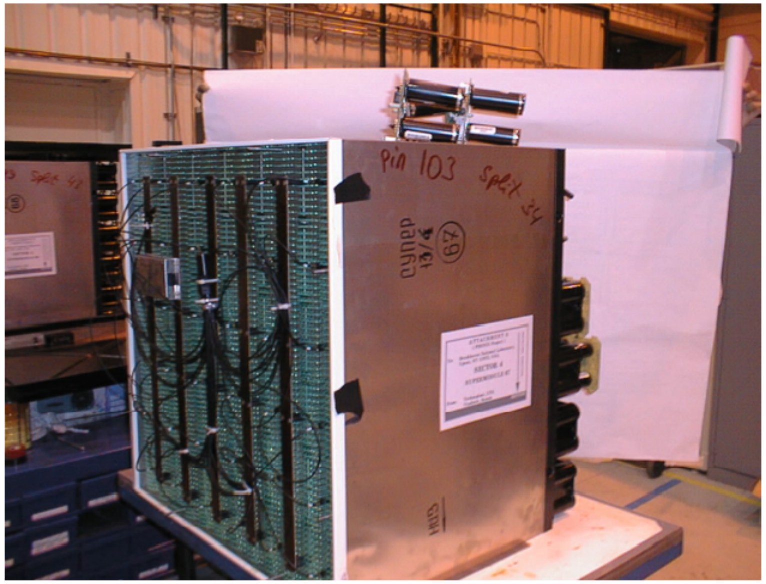
38 cm depth ($18X_0$)
66 sampling cells

in total covering 48 m^2
in 15552 individual towers

Parameter	Value
Lateral segmentation	5.535 x 5.535 cm^2
Active cells	66
Scintillator	4 mm Polystyrene (1.5% PT/0.01% POPOP)
Absorber	1.5 mm Pb
Cell thickness	5.6 mm (0.277 X_0)
Active depth	
(mm)	375 mm
(Rad. length)	18
(Abs. length)	0.85
WLS Fiber	1mm, BCF-99-29a
WLS fibers per tower	36
PMT type	FEU115 M, 30 mm
Photocathode	Sb-K-Na-Cs
Rise time (25% - 80%)	$\lesssim$ 5 ns

Example: PHENIX PbScint calorimeter

one module of PHENIX EMCal



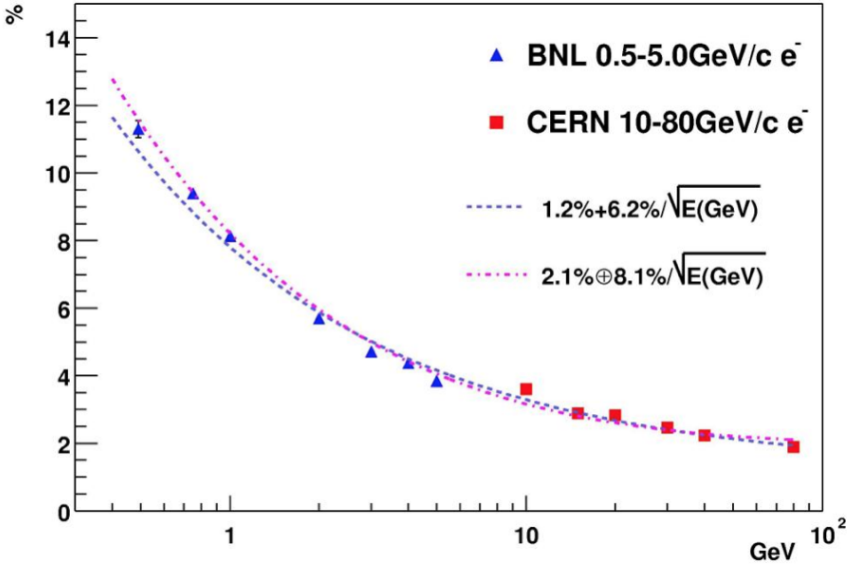
and entire WestArm

Example: PHENIX PbScint calorimeter

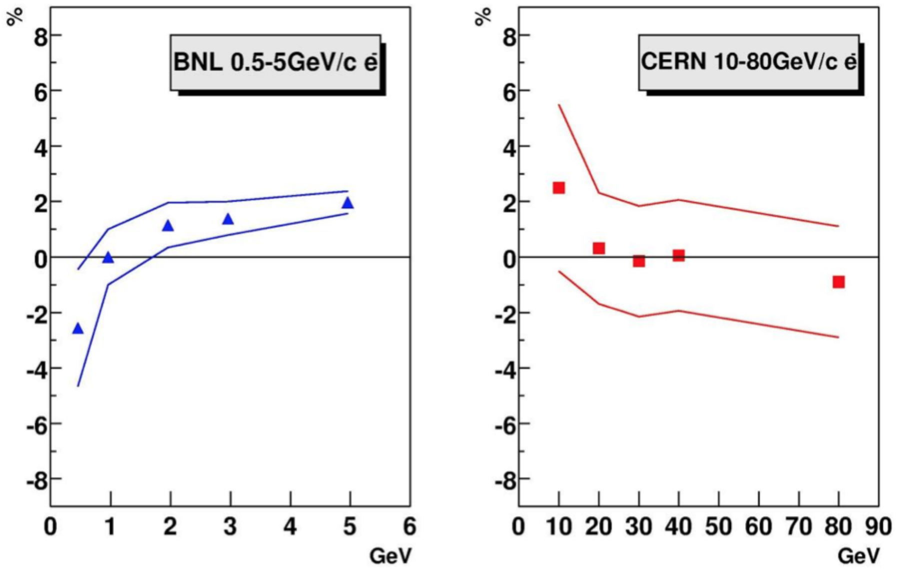
Nominal energy resolution: stochastic term: 8%/√E

Constant term: 2%

Time resolution: 200 ps



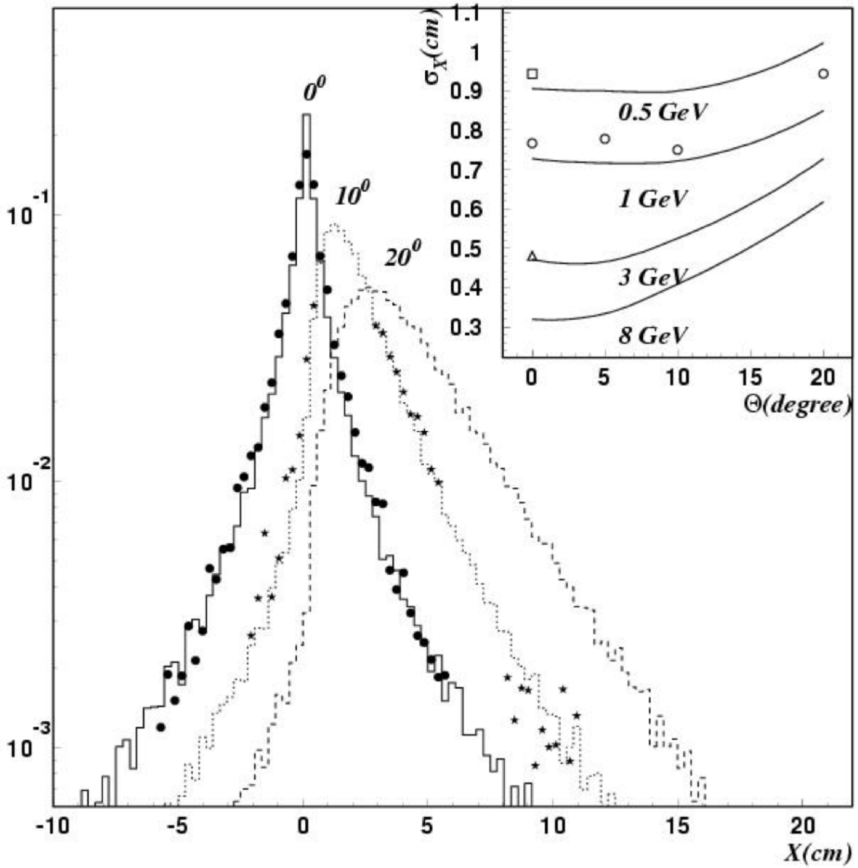
energy resolution

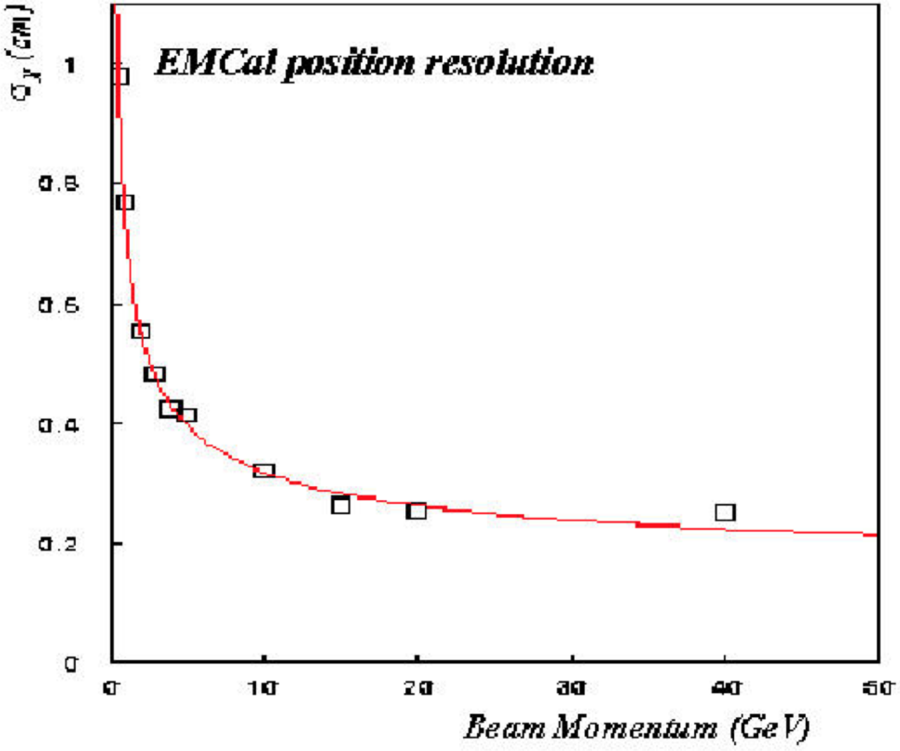


linearity of energy scale

Example: PHENIX PbScint calorimeter

Lateral shower profile well understood
→ position resolution in mm range





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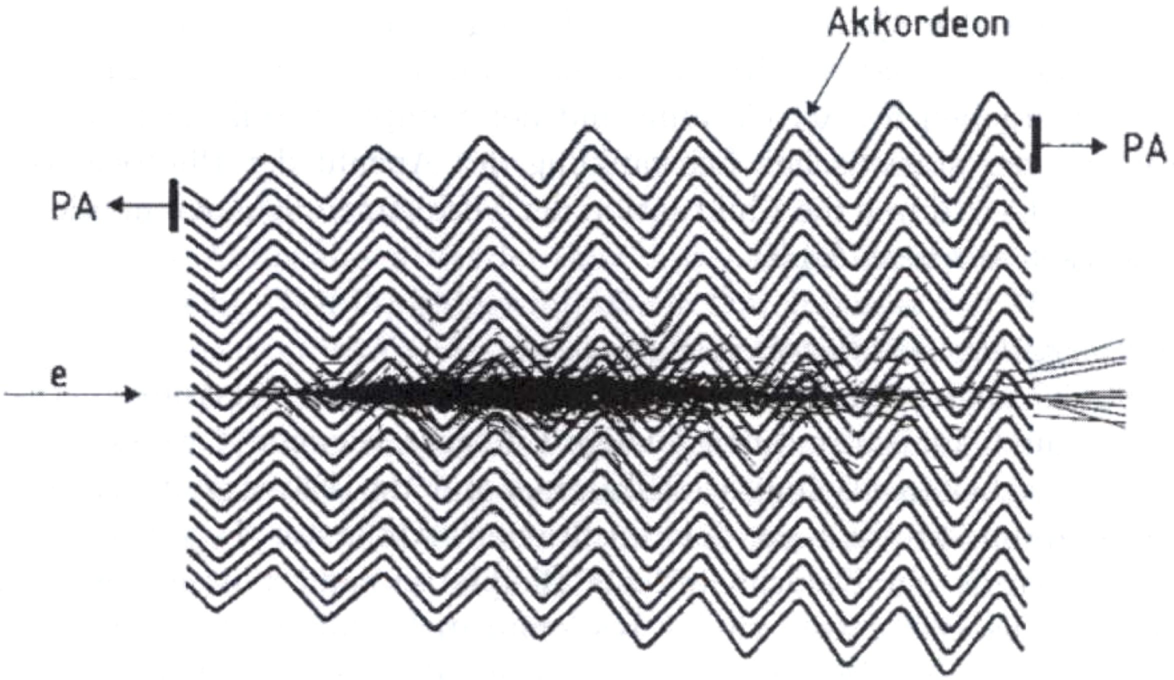
Liquid-argon sampling calorimeter

Alternative to scintillator and optical readout: use of liquid noble gas and operation of sampling sections as ionization chamber



For faster readout: interleave electrodes between metal plates and electronics directly on electrodes inside liquid

Example: electromagnetic calorimeter of ATLAS

Outlook

At TeV energies we can also do muon calorimetry → they loose energy proportionally to their energy → stopping them becomes possible

Example: Future Circular Collider → muons with energy > 1 TeV

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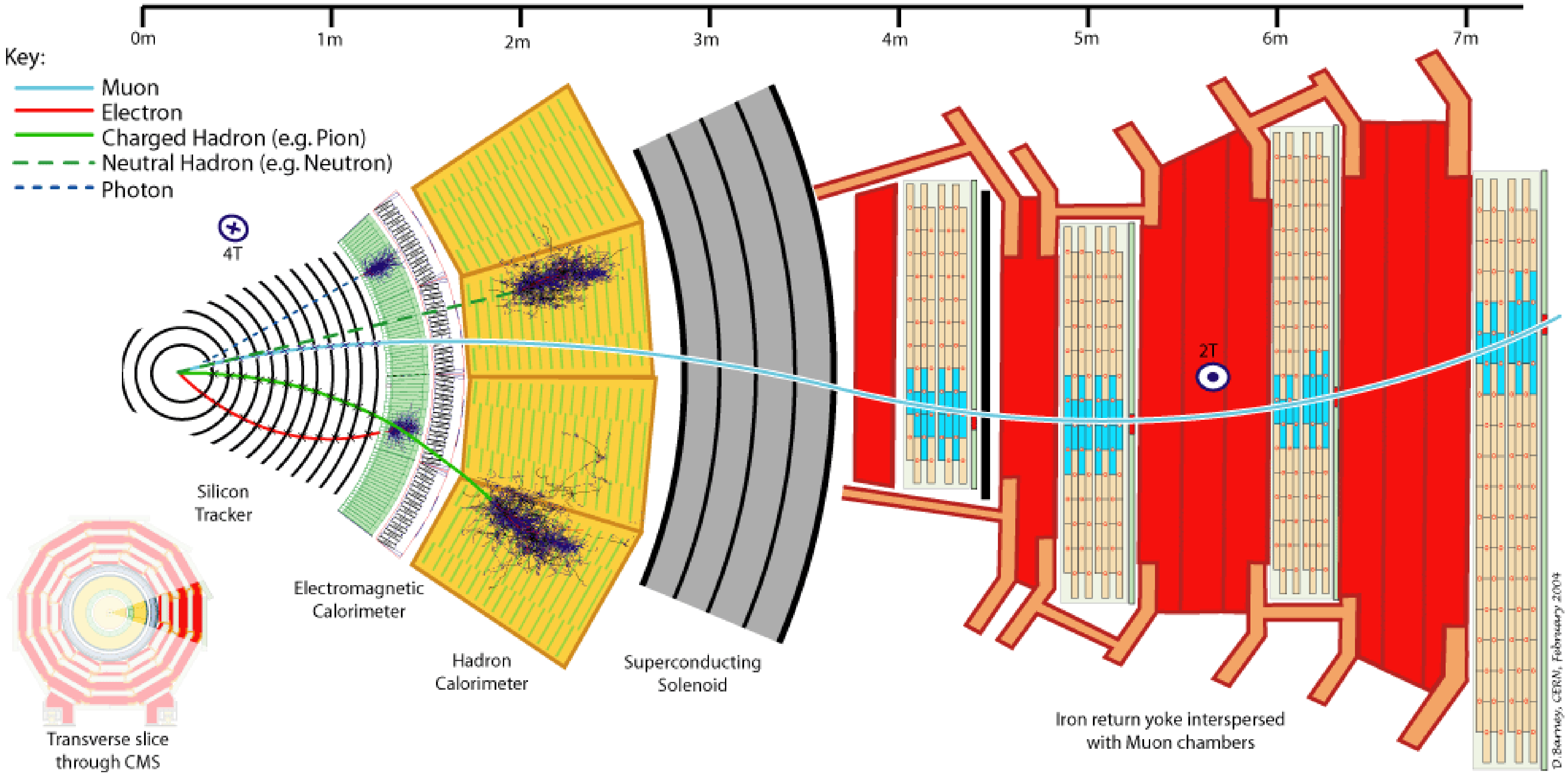
Calorimeters in a collider experiment: CMS



- Trackers
- Calorimeters
- Muon detectors

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