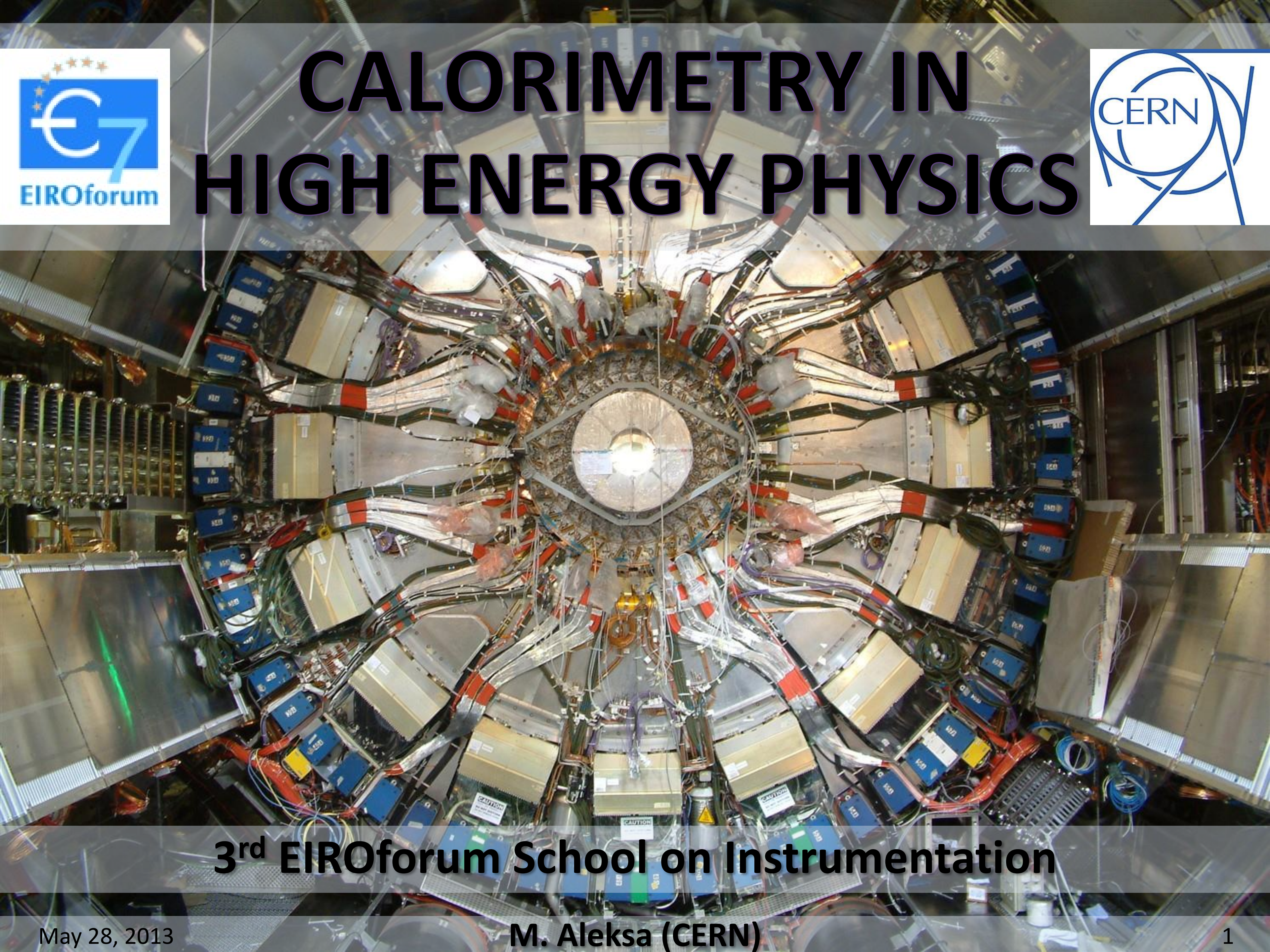


CALORIMETRY IN HIGH ENERGY PHYSICS

3rd EIROforum School on Instrumentation

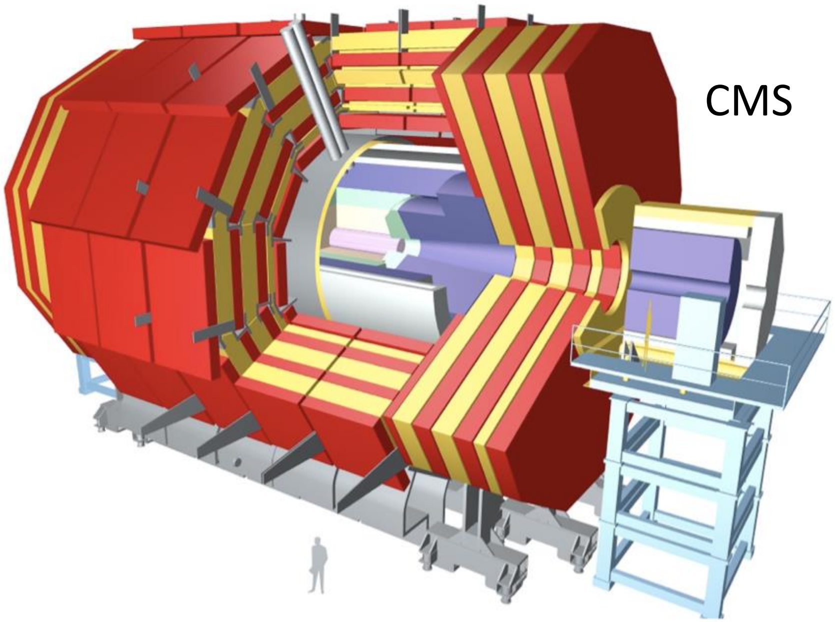
M. Aleksa (CERN)

Outline

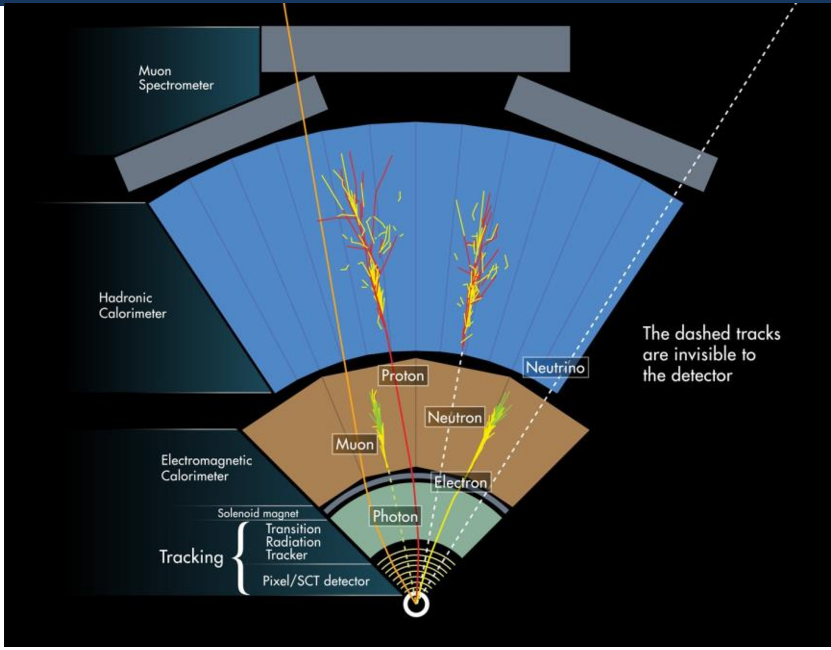
- Introduction
- Physics of Electromagnetic Showers
- Electromagnetic Calorimeters
- The Hadronic Cascade – Hadron Calorimeters
- Active Materials – Signal Detection
- Examples in High Energy Physics
- References

INTRODUCTION

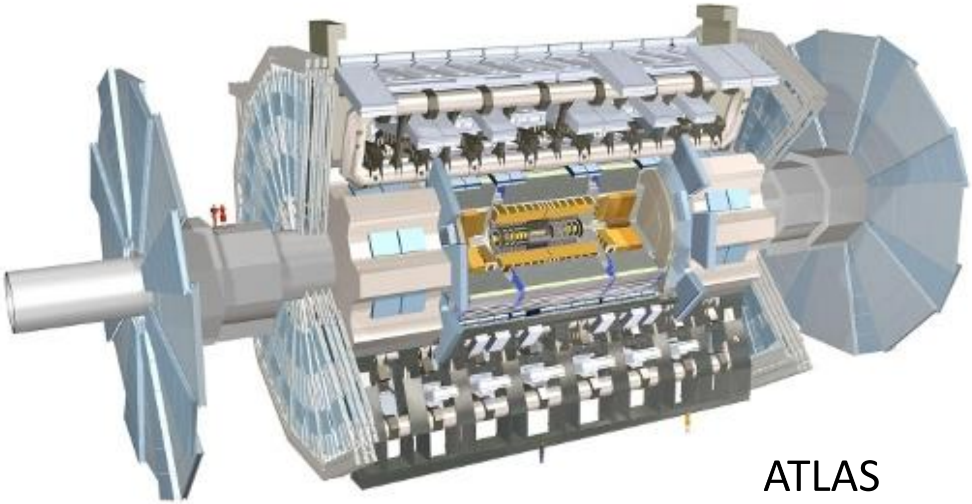
Particle Detection in High Energy Physics



CMS

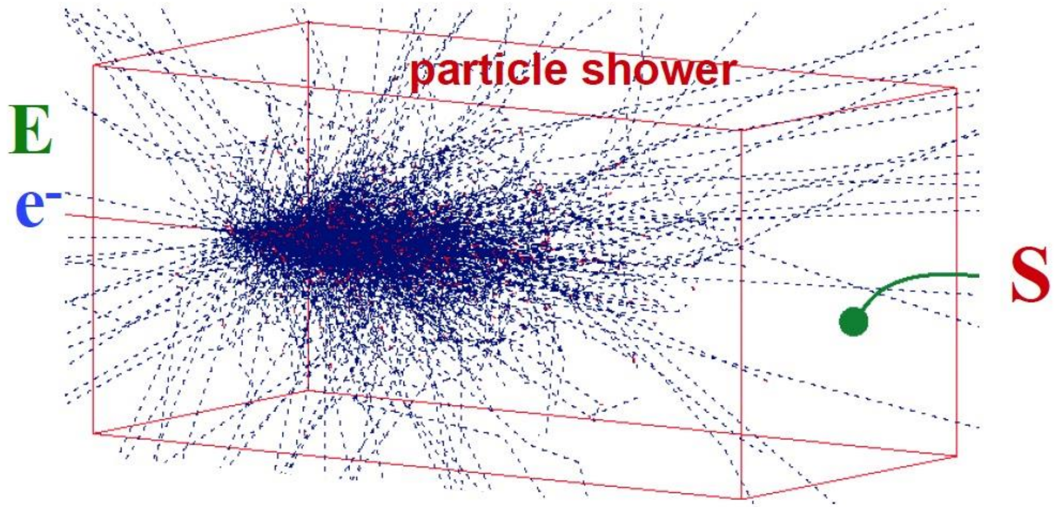


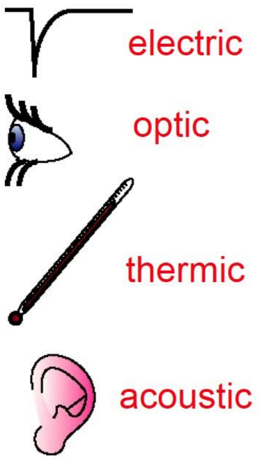
- The characteristics of particles are measured by different types of detectors and identified thanks to their different interactions with matter
- Calorimeters detect: photons (γ), electrons (e), protons, neutrons, jets (q, g), missing energy (e.g. ν)



ATLAS

Calorimetry: Basic Concept Very Simple





- **Energy measurement** via **total absorption** of the incoming particles
- **Principle of operation:**
  - Incoming particle interacts with calorimeter material → particle shower
    - Shower composition and dimension depend on particle type and detector material
  - Energy deposited in form of heat, ionization, excitation of atoms (e.g. scintillation), Cherenkov light…
    - Different calorimeter types use different kinds of these signals to measure total energy.
- **Important: Signal (S) is proportional to total deposited energy (E)**
  - Scale factor obtained by calibration

Why Calorimetry?

- Calorimeters measure **charged** and **neutral** particles
- Obtain information on **energy flow**: Total (missing) transverse energy, jets, …
- Dimensions necessary to contain the particle showers proportional to lnE → **compactness**
  - Calorimeter: $L \propto \ln E$
- Calorimeters have a **high rate capability** and are **fast** and can therefore recognize and select interesting events in real time → **Trigger**
- Longitudinal and lateral segmentation → Measurement of **position and direction**. Also **particle ID** on topological basis
- Detection based on stochastic processes → **precision increases with energy** $\frac{\sigma_E}{E} \propto \frac{1}{\sqrt{E}}$

Compare with spectrometer:

Only charged particles

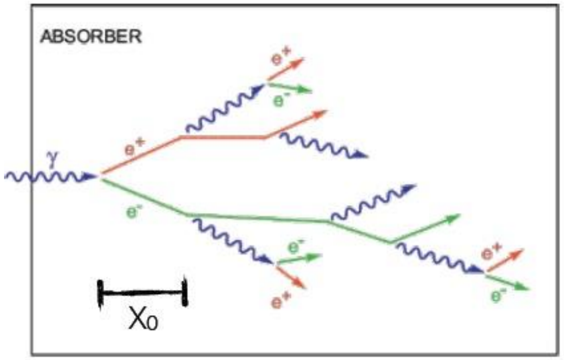
To keep same resolution $L \propto \sqrt{p_T}$

Tracking reconstruction needs more computing resources (usually possible in higher level trigger only)

$$\frac{\sigma_p}{p} \propto \frac{p_T \sigma_x}{L^2 B}$$

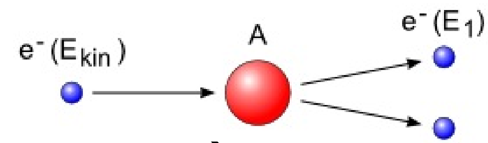
PHYSICS OF ELECTROMAGNETIC SHOWERS

Electromagnetic Showers

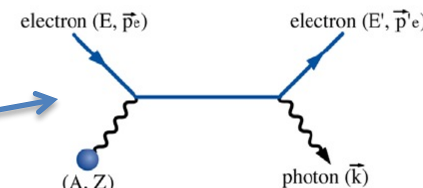


… let's start with **electrons** and **photons** – how do they loose energy due to their **interactions** with **nuclei and atomic electrons**?

- **Electrons**:
  - Ionization (atomic electrons)
  - Bremsstrahlung (nuclear)
    - dominant at high energies
- **Photons**:
  - Photoelectric effect (atomic electrons)
  - Compton scattering (atomic electrons)
  - Pair production (nuclear)
    - dominant at high energies

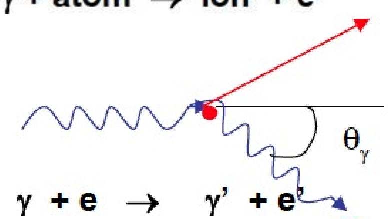


$e^- + \text{atom} \rightarrow \text{ion}^+ + 2e^-$
need energy W (1—100 eV) to produce e-ion pair

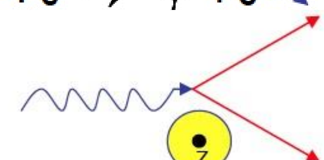


$e^- + \text{Coul. Field} \rightarrow e^- + \gamma$

$\gamma + \text{atom} \rightarrow \text{ion}^+ + e^-$



$\gamma + e \rightarrow \gamma' + e$



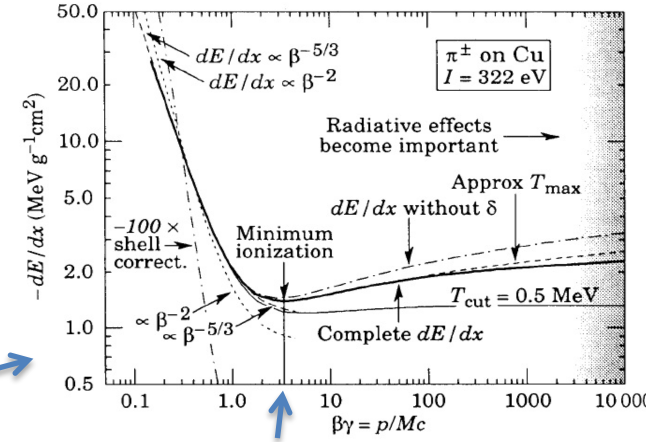
$\gamma + \text{Coul. Field} \rightarrow e^+ + e^-$

Ionization Energy Loss

- **Bethe-Bloch Formula** (energy loss for heavy charged particles → not for electrons!)
  - Interaction dominated by elastic collisions with electrons

PDG 2010

$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$



βγ ~ 3, β = 0.95

$K = 4\pi N_A r_e^2 m_e c^2 = 0.307$ MeV g^{-1} cm^2

$T_{max} = 2m_ec^2\beta^2\gamma^2/(1 + 2\gamma m_e/M + (m_e/M)^2)$

[Max. energy transfer in single collision]

z : Charge of incident particle

M : Mass of incident particle

Z : Charge number of medium

A : Atomic mass of medium

I : Mean excitation energy of medium

δ : Density correction [transv. extension of electric field]

$N_A = 6.022\cdot 10^{23}$

[Avogardo's number]

$r_e = e^2/4\pi\varepsilon_0 m_e c^2 = 2.8$ fm

[Classical electron radius]

$m_e = 511$ keV

[Electron mass]

$\beta = v/c$

[Velocity]

$\gamma = (1-\beta^2)^{-1/2}$

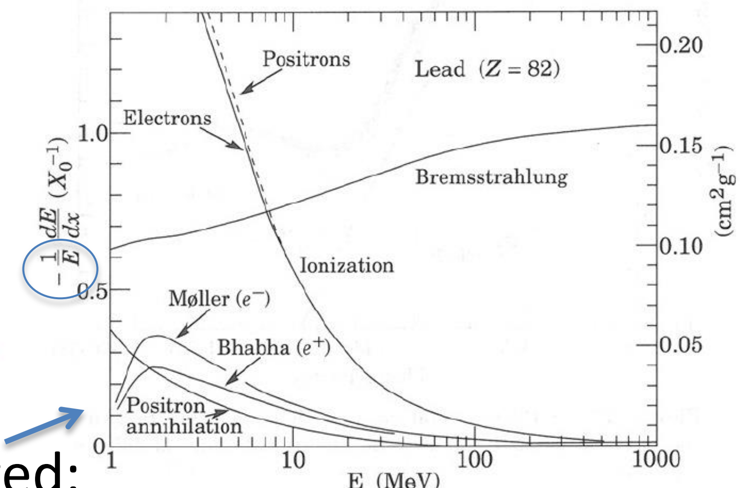
[Lorentz factor]

Validity:

$.05 < \beta\gamma < 500$

$M > m_\mu$

Courtesy calorimetry lecture H.-C. Schultz-Coulon



Relative energy loss of e$^\pm$

- **Ionization for electrons** is more complicated:

$$-\frac{dE}{dx} = k \frac{Z}{A} \frac{1}{\beta^2} \left\{ \ln \frac{\gamma m_e c^2 \beta \sqrt{\gamma - 1}}{I\sqrt{2}} + \frac{1}{2}(1-\beta^2) - \frac{2\gamma - 1}{2\gamma^2} \ln 2 + \frac{1}{16}\left(\frac{\gamma-1}{\gamma}\right)^2 \right\} \; (\mathrm{MeV/(g/cm^2)})$$

Bremsstrahlung - Electrons

Bremsstrahlung

Arises if particles are accelerated in Coulomb field of nucleus

$$-\frac{dE}{dx} = 4\alpha N_A \frac{z^2 Z^2}{A}\left(\frac{1}{4\pi\epsilon_0}\frac{e^2}{mc^2}\right)^2 E\ \ln\frac{183}{Z^{\frac{1}{3}}} \propto \frac{E}{m^2}$$

→ energy loss proportional to $(Z^2/A)(E/m^2)$

$$-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^2 \cdot E\ \ln\frac{183}{Z^{\frac{1}{3}}}$$

$$-\frac{dE}{dx} = \frac{E}{X_0} \quad \text{with} \quad X_0 = \frac{A}{4\alpha N_A\ Z^2 r_e^2\ \ln\frac{183}{Z^{\frac{1}{3}}}} \quad \Rightarrow \quad E = E_0 e^{-x/X_0}$$

[Radiation length in g/cm²]

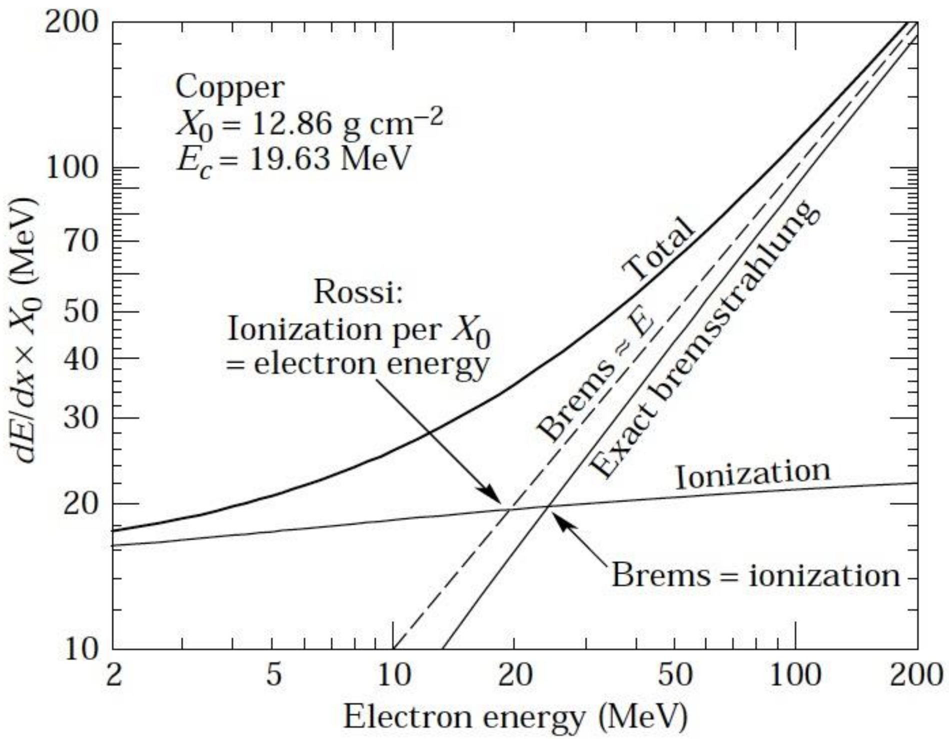
Radiation length X_0 is the thickness of material that reduces the mean energy of a beam of high energy electrons by a factor e. Approx.: $X_0 \cong 180A/Z^2$ g cm^{-2}

Critical Energy - Electrons

- **Critical energy** E_C:

$$\frac{dE}{dx}(E_c)\Big|_{\text{Brems}} = \frac{dE}{dx}(E_c)\Big|_{\text{Ion}}$$

$$E_c = \frac{610 \text{ MeV}}{Z + 1.24}$$ parameterization for solids and liquids



- **Electrons irradiate photons** until their energy becomes **less than** $\boldsymbol{E_C}$ (z.B. $E_C \cong$ 7MeV for Pb).

Photons

- Photo-electric effect:

$$\sigma_{pe} \approx Z^5 \alpha^4 \left(\frac{m_e c^2}{E_\gamma} \right)^{\frac{7}{2}}$$ → σ ≈ Z^5, $E^{-3.5}$

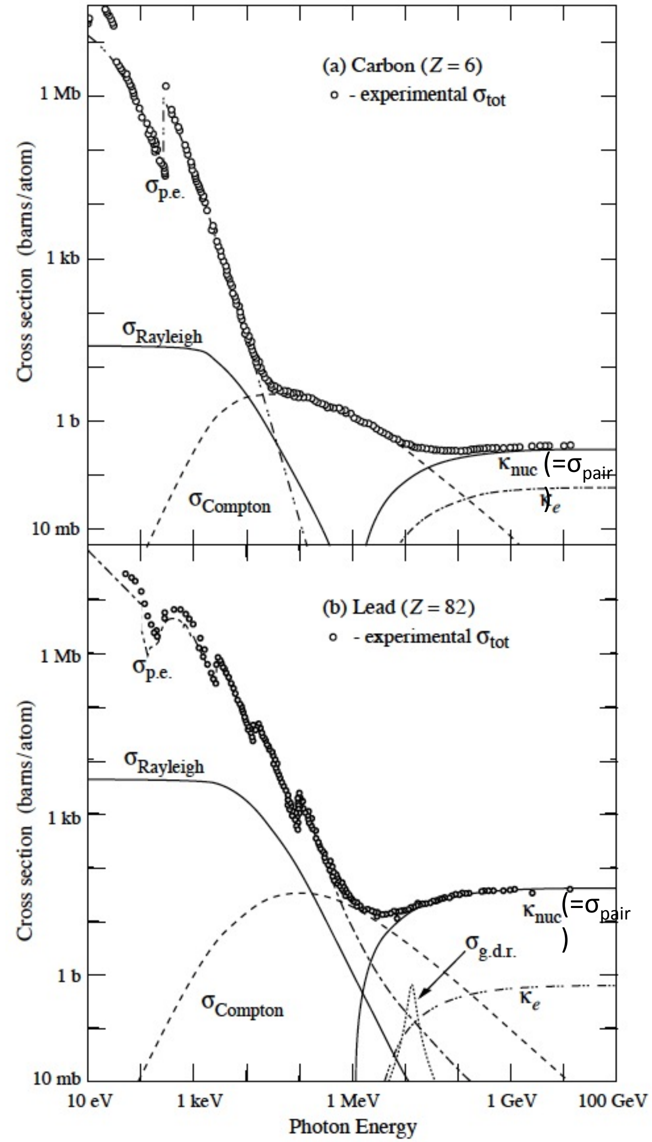
- Compton scattering:

$$\sigma_{Compton} \approx Z \frac{\ln E_\gamma}{E_\gamma}$$ → σ ≈ Z, E^{-1}

- Pair-production
  - if $E_\gamma > 2m_ec^2 = 1.022$MeV

$$\sigma_{pair} \approx \frac{7}{9} \frac{A}{N_A} \frac{1}{X_0}$$ → σ ≈ Z(Z+1), $\ln E/m_e$ (<1GeV), then constant (>1GeV)

  - Probability of conversion in 9/7 X_0 is (1-1/e) (mean free path)



Summary – EM Showers

Electromagnetic showers are showers of Electrons and Photons

The most important processes at high energies are

- **Electrons/Positrons: Bremsstrahlung**
- **Photons: Pair production**

The typical length for these processes is the radiation length X_0.

All charged particles (here electrons and positrons) loose energy by ionization. For $E < E_C$ ionization dominates

ELECTROMAGNETIC CALORIMETERS

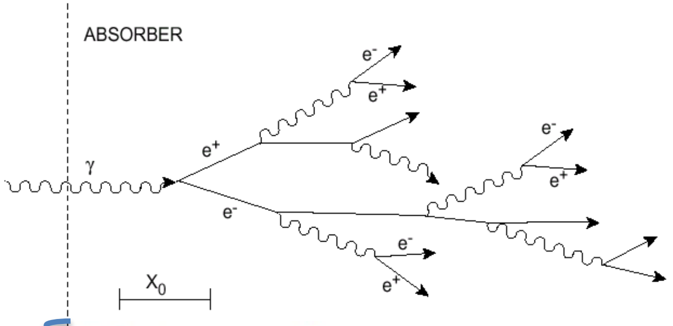
Electromagnetic Showers Characteristics

- For $E > E_C$ **two dominant interactions**:
  - **Pair production and Bremsstrahlung**
  - Shower development **governed by X_0**
    - After distance X0 electrons remain with 1/e of their primary energy (rest lost by Bremsstrahlung)
    - Those Bremsstrahlungs photons produce e^+e^--pair after $9/7\ X_0 \approx X_0$.
  - In 0th approximation after $1X_0$ number of shower particles N(t) has doubled ($t=x/X_0$)
- **Transverse shower development**:
  - Dominated by multiple scattering but also contribution due to Bremsstrahlung and Compton scattering
  - **Molière radius R_M** characterizes lateral shower spread (90% E_0 within cylinder with $1R_M$)

$$R_M = \langle\theta\rangle_{x=X_0} \cdot X_0 \approx \frac{21\mathrm{MeV}}{E_C} X_0$$

- **Longitudinal shower development** (reasonably well described by: Longo-Sestili NIM 128)

$$\frac{dE}{dt} = E_0\, t^{\alpha} e^{-\beta t}$$



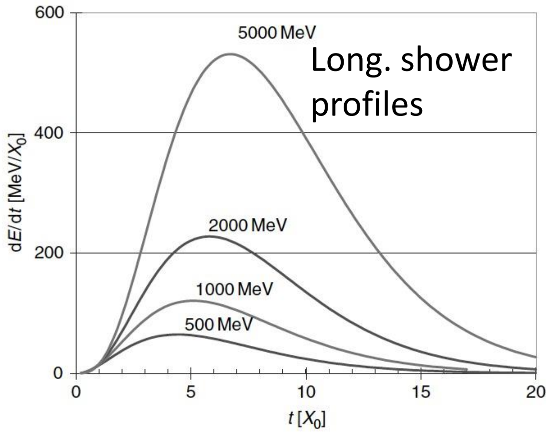
$$N(t) = 2^t$$

Energy per particle:

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

Shower maximum:

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



Some Material Examples

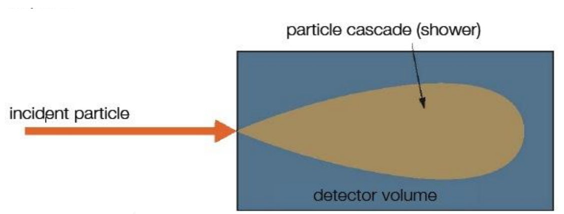
Typical values for X_0, E_C, R_M, λ_{int} and dE/dx of materials used in calorimeters

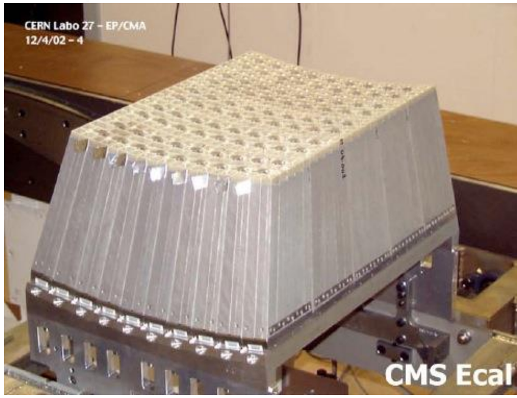
Material	Z	Density	E_C	X_0	R_M	λ_{int}	$(dE/dx)_{mip}$
		(g cm^{-3})	(MeV)	(mm)	(mm)	(mm)	(MeV cm^{-1})
Al	13	2.70	43	89	44	390	4.36
Fe	26	7.87	22	17.6	16.9	168	11.4
Cu	29	8.96	20	14.3	15.2	151	12.6
Sn	50	7.31	12	12.1	21.6	223	9.24
W	74	19.3	8.0	3.5	9.3	96	22.1
Pb	82	11.3	7.4	5.6	16.0	170	12.7
^{238}U	92	18.95	6.8	3.2	10.0	105	20.5
Concrete	-	2.5	55	107	41	400	4.28
Glass	-	2.23	51	127	53	438	3.78
Marble	-	2.93	56	96	36	362	4.77
Si	14	2.33	41	93.6	48	455	3.88
Ge	32	5.32	17	23	29	264	7.29
Ar (liquid)	18	1.40	37	140	80	837	2.13
Kr (liquid)	36	2.41	18	47	55	607	3.23
Polystyrene	-	1.032	94	424	96	795	2.00
Plexiglas	-	1.18	86	344	85	708	2.28
Quartz	-	2.32	51	117	49	428	3.94
Lead-glass	-	4.06	15	25.1	35	330	5.45
Air 20°, 1 atm	-	0.0012	87	304 m	74 m	747 m	0.0022
Water	-	1.00	83	361	92	849	1.99

Courtesy calorimetry lecture D. Fournier

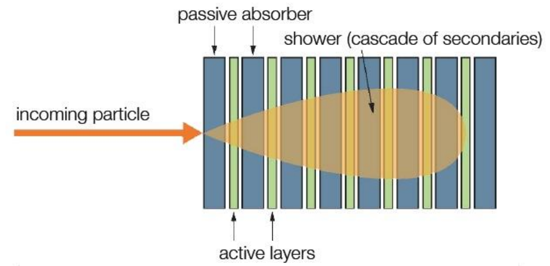
Homogeneous and Sampling Calorimeters

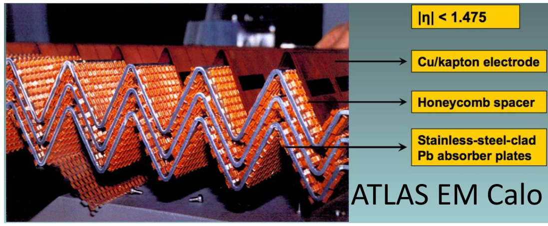
- In a **homogeneous calorimeter** all the energy is deposited in the active medium (**absorber = active medium**)
  - Excellent energy resolution (stochastic term down to 1% possible)
  - Used exclusively for EM calorimeters
  - Difficult to segment in 3 dimensions → often no information on longitudinal shower shape
  - Radiation damage is a problem
  - Signal:
    - Scintillation light: high density crystals e.g. $PbWO_4$ (8.3 g/cm^3, X_0 = 8.9mm, R_M=2.2cm), e.g. BGO, BaF_2, CeF_3, CsI, NaI(Tl)
    - Cherenkov light: e.g. lead glass
    - Ionization signal: e.g. liquid nobel gases (Ar, Kr, Xe)





- **Sampling calorimeter: stack of passive and active layers**
  - Limited energy resolution (stochastic (sampling) term >8%)
    - Only part of the energy is actually deposited in the active layer (typically a few %) → **sampling fraction f_s**.
    - Sampling fluctuations deteriorate energy resolution
  - Compact calorimeters possible (high density absorber material), also hadron calorimeters
  - Detailed shower shape information
  - Absorber: e.g. Fe, Cu, Pb, W, U
  - Active material: plastic scintillators, silicon detectors, liquid nobel gases, gases





EM Calorimeter Energy Resolution

- **Simple shower model**: The detectable signal is proportional to the total number of produced signal quanta *N* (e.g. e⁻-ion pair, scintillation photon)
- An estimation of the **energy resolution** is given by the **fluctuations of** the number ***N*** of produced signal quanta in the active medium (*N*: Poisson distributed). Need **average energy *W*** to produce 1 signal quantum.

Silicon detectors:	$W \approx 3.6$eV
Gas detectors:	$W \approx 30$eV
Plastic scintillators:	$W \approx 100$eV
Liquid Ar:	$W \approx 23.3$eV
Scint. crystal NaI:	$W \approx 25$eV
Scint. crystal $PbWO_4$:	$W \approx 10$keV

Paremetrization of resolution:

$$\frac{s_E(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

stochastic/sampling term

noise term

constant term

$$N \gg \frac{E}{W}$$

$$\frac{s(E)}{E} \mu \frac{s_N}{N} \gg \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}}$$

$$\frac{s_E}{E} \mu \sqrt{\frac{W}{E}}$$

Relative resolution improves with $1/E^{½}$

- Very simple model, reality is more complicated since the fluctuations are not independent (e.g. sum of deposit is *E* → Fano factor *F*<1)

$$\frac{s_E}{E} \mu \sqrt{\frac{FW}{E}}$$

EM Calorimeter Energy Resolution

- **Stochastic term *a***: accounts for any kind of **Poisson-like fluctuation**
  - Additional contribution to this term if only part of the energy is deposited in the active material (e.g. sampling calorimeters)
- **Noise term *b***: responsible for degradation of low-energy resolution
  - Main contribution is the energy equivalent of the **electronics noise**
  - In high luminosity environment also the **pile-up** contributes to this term: Pile-up noise comes from fluctuations of energy entering the measurement area from sources other than the primary particle (e.g. additional particles from other collisions in the same bunch crossing or in the bunch crossings before).
- **Constant term *c***: dominates at high energy
  - Main contribution is the uniformity and stability of the energy response (excellent calibration necessary to keep this term low).
  - Contributions from energy leakage, non-uniformity of signal generation and/or collection (construction!), loss of energy in dead materials,…

Paremetrization of resolution:

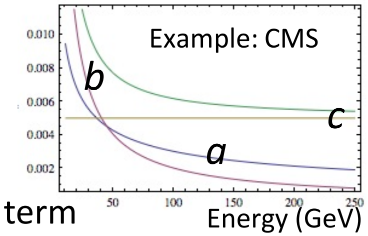
$$\frac{\sigma_E(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

stochastic/sampling term

noise term

constant term

$$x \oplus y \equiv \sqrt{x^2 + y^2}$$



Technology (Experiment)	Depth	Energy resolution	Date	
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/E^{1/4}$	1983	Homogeneous
$Bi_4Ge_3O_{12}$ (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	Sampling
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	

Summary – EM Calorimeters

Homogeneous calorimeters: All energy is deposited in active material

Sampling calorimeters: Stack of active and passive layers

Resolution: Governed by

- **stochastic/sampling term (fluctuations)**
- **noise term (electronics and pile-up noise)**
- **constant term (stability, precision, dead material).**
  - **Determines resolution at high energies**

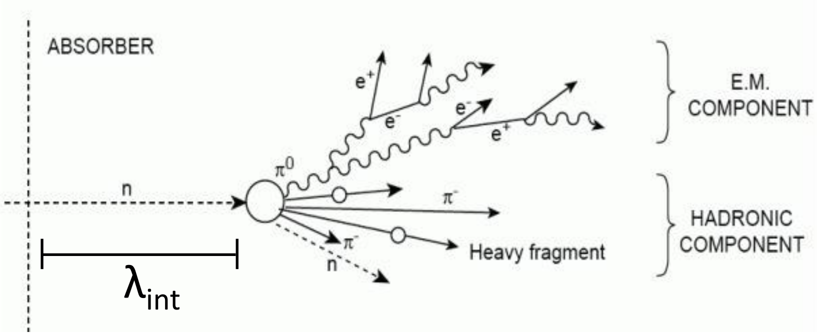
THE HADRONIC CASCADE – HADRON CALORIMETERS

Physics of the Hadronic Cascade

- Energy loss of **high-energy hadrons** in an absorber material is mostly due to **strong interactions**
- Two classes of effects:
  - Production of **energetic hadrons**, typically mesons (e.g. $\pi^\pm$, π^0, K, …) with momenta of typically a fair fraction of the primary hadron momentum (i.e. at the GeV scale) → in turn interact with further nuclei
    - **⅓ of pions produced will be π^0** which will decay into two photons ($\pi^0 \rightarrow \gamma\gamma$) → **electromagnetic cascade** (will not contribute further to hadronic processes) → **EM fraction F_{EM}**
    - After each "generation" EM fraction will increase → the higher the incident energy, the higher the EM fraction
  - A significant part of the primary energy is diverted to **nuclear processes** such as excitation, nucleon evaporation, spallation, etc., resulting in particles with characteristic nuclear energies at the MeV scale → high number of low-energy neutrons (~20-40 n/GeV in Pb) which will be captured leading to delayed (µs timescale) nuclear photon emission → in general not detected ("invisible", ~ ⅓ of non-EM fraction)

Nuclear interaction length λ_{int}:

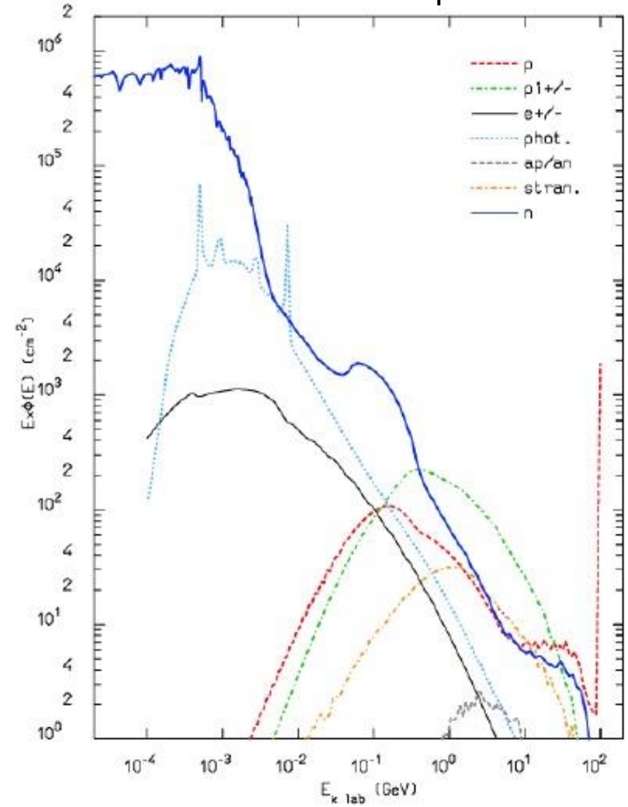
$$\lambda_{\text{int}} = \frac{A}{N_A \sigma_{\text{int}}} = \frac{A}{N_A R^2 \pi} \propto A^{1/3}$$



Fluctuations of EM fraction!

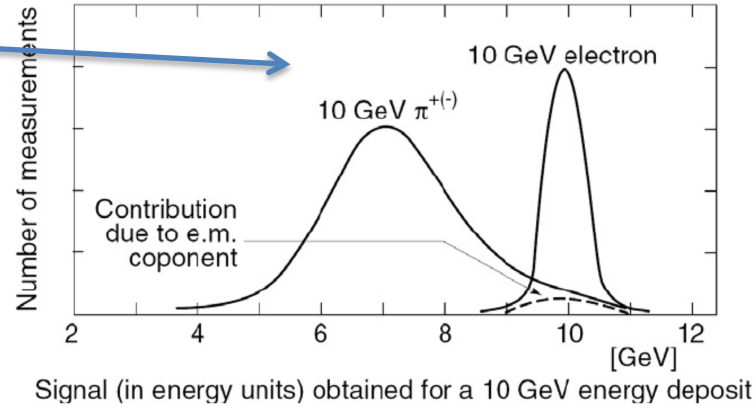
Fluctuations of "invisible" energy!

FLUKA simulations of 100GeV proton in Pb



Hadron Calorimeter Energy Resolution

- **Electromagnetic** (EM) component and **non-EM** component usually have **different response** (e.g. e/h > 1)
- If e/h ≠ 1 the fluctuations in the em-fraction F_{EM} (**non-Gaussian** fluctuations → not described by $1/E^{½}$) lead to additional degradation of energy resolution and to a non-linearity in energy response (since F_{EM} increases with higher incident energy)
  - If possible identifying EM and non-EM part of the hadronic cascade with help of fine segmentation, classification according to energy density



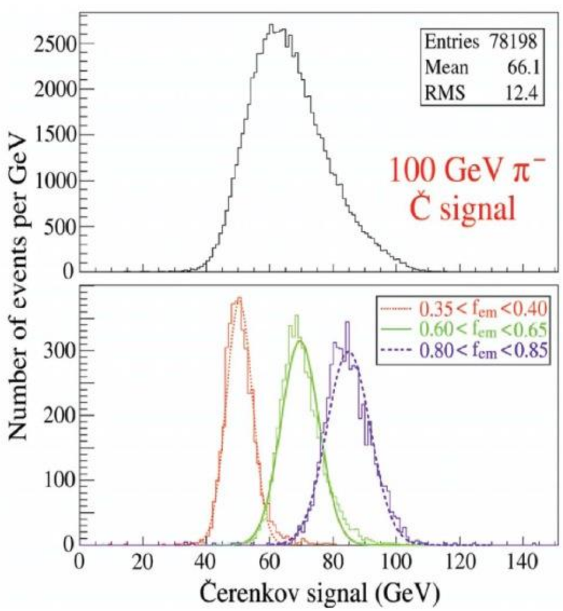
→ *a* ~ 50% - 100%

- How to obtain e/h = 1 (**compensation**)?
  - Suppress EM component (e.g. high Z absorber)
  - Enhance response to neutrons by using hydrogen close to active material (n-p scatter → recoil proton has a range of e.g. 20µm in scintillator)
  - Enhance neutron production by fission (U absorbers, e.g. ZEUS)

→ *a* ~ 35%

- Other ideas to improve energy resolution: **Dual readout** (e.g. Dream), difficult in collider environment
  - e.g. in quartz fiber calorimeter (e/h ~ 5)
  - Read-out of Cerenkov light (threshold β>1/n, i.e. 200keV of electrons, 400MeV for protons) → mainly EM component.
  - Read-out scintillation light → all components.
  - → Combine information to get F_{EM} and E.

→ *a* ~ 15%



Summary – Hadron Calorimeters

Hadronic cascades: Energy loss of hadrons governed by strong interaction

- **Showers have EM component and hadronic component (part of hadronic component is in general "invisible")**

Typical length: Interaction length λ_{int}.

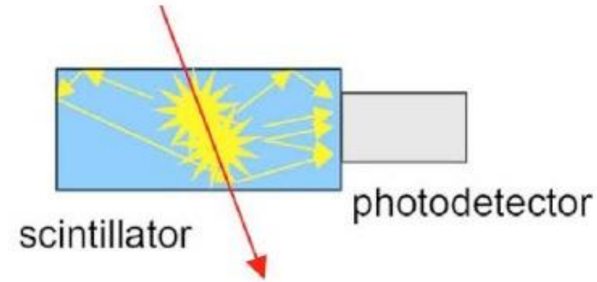
Resolution of hadron calorimeters:

- **Fluctuations of "invisible" energy and of EM component**
- **Difference in response between EM and hadronic component (e/h>1)**
- **Can be improved by compensation (e/h=1) or other ideas (e.g. dual readout)**

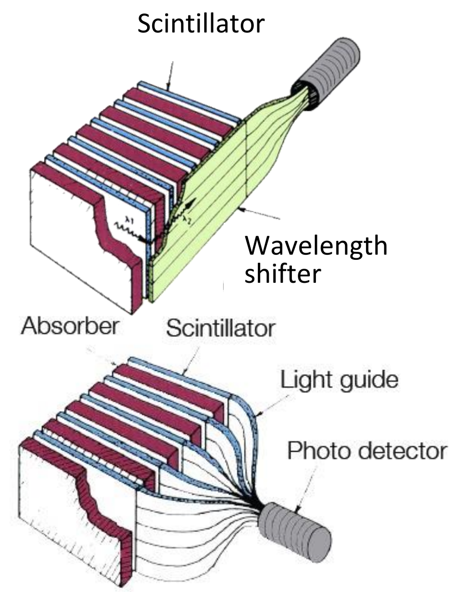
ACTIVE MATERIAL – SIGNAL DETECTION

Scintillation and Čerenkov Light

- **Čerenkov light**: Emitted by relativistic particles (e.g. $e^{\pm}$) $\beta>1/n$ (e.g. quartz n=1.45). Light is emitted at well defined angle
- **Scintillation light**: Some materials emit light when traversed by ionizing particles. Scintillation is caused by excited molecules falling back to ground state.
  - Organic scintillators
    - up to 10000 photons/MeV
    - decay time O(ns)
    - low Z, relatively low density
    - doped, large choice of emission wavelength, cheap, easy to manufacture, scintillation is single molecular process
  - Inorganic scintillators (crystals) – e.g. homogeneous calorimeters
    - High light yield, up to 40000 photons/MeV (NaI)
    - decay time O(ns to µs)
    - high Z, large variety of Z and density
    - difficult to grow, expensive. Require crystal latice to scintillate
- **Photodetectors** (used to detect scintillation light and also Čerenkov light):
  - Photocathode + secondary emission multiplication
    - e.g. photomultiplier (PMT)
  - Solid-state devices
    - Photodiodes (no gain), avalanche photodiodes APD (gain 10 – 100), solid state photomultipliers (e.g. SiPM)

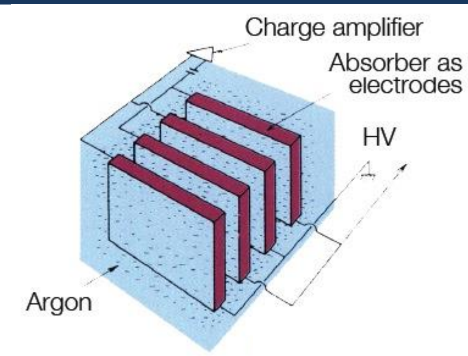


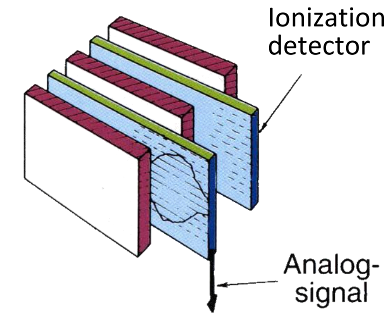
Light is guided out of the detector using light guides and wavelength shifters.



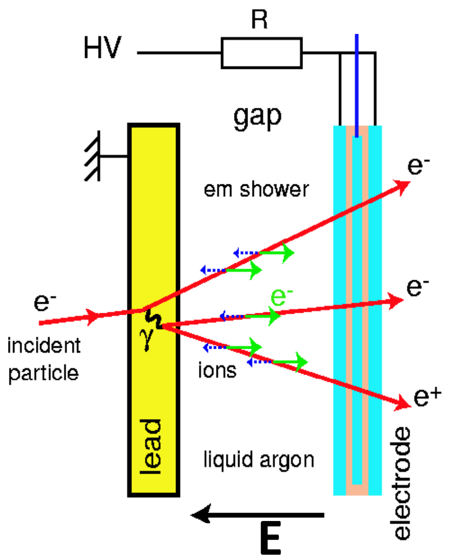
Ionization Detectors

- **Different types** depending on active material:
  - Liquids (noble liquids) - Cryogenic system! (~ 80K)
  - Solid materials (semiconductors)
  - Gaseous detectors (less used in sampling calorimeters for high energy physics, low density → small f_s)
- Typically **no charge amplification** (ionization mode)

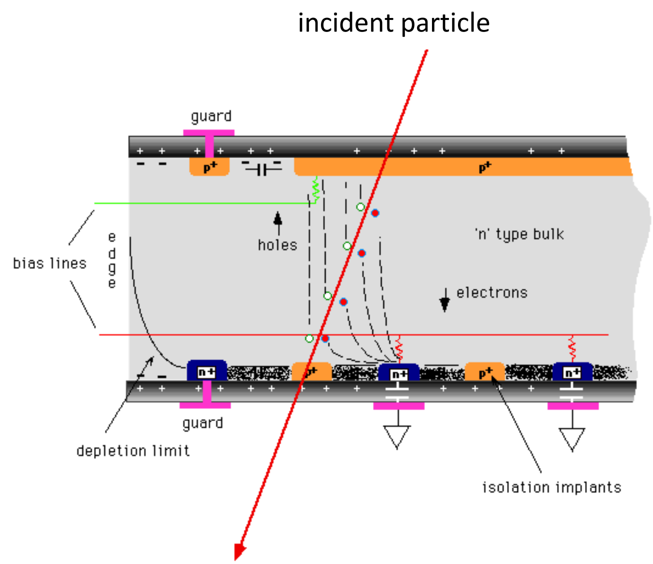




Liquids: Liquid Argon (LAr), liquid Krypton, liquid Xenon



Semiconductors: Silicon (strips, pixels), GaAs, Diamond



Summary – Signal Detection

Either detect light signal with photo-detectors

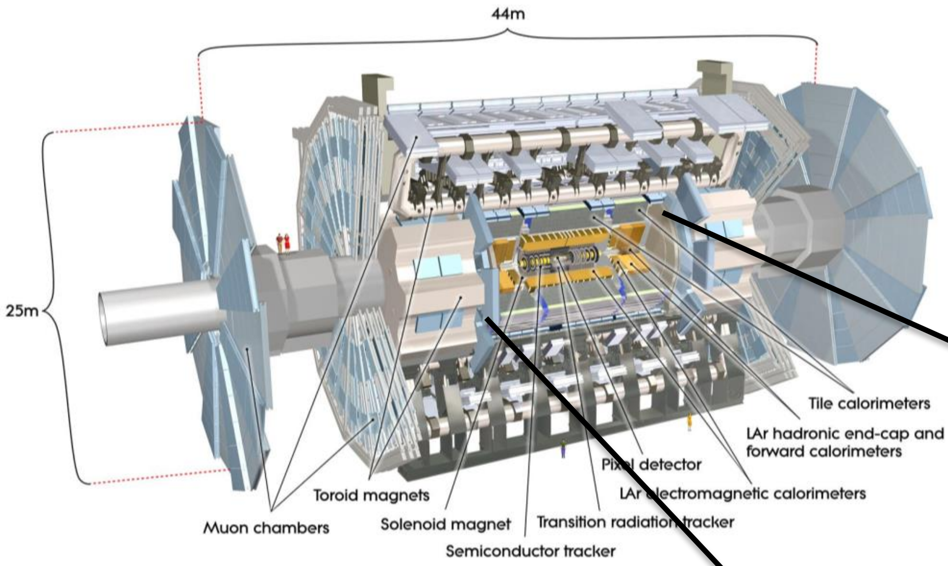
- **Čerenkov light**
- **Scintillation light**

… or ionization signal with ionization detectors

- **Nobel liquids as active material**
- **Semiconductors**

EXAMPLES IN HIGH ENERGY PHYSICS

The ATLAS Calorimeter System



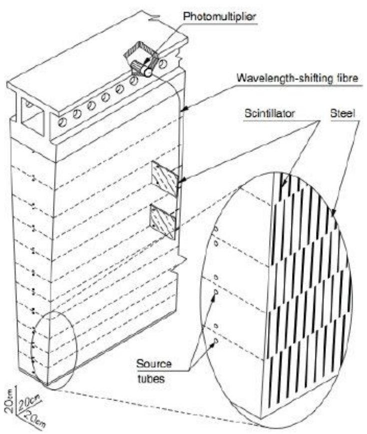
The Liquid Argon (LAr) calorimeter:

EM calorimeter: (|η|<3.2)

- Pb-LAr sampling calorimeter
- Presampler, fine segmentation first layer, 3 layers in total in central reg.
- Design EM resol.: $\frac{s(E)}{E} = \frac{10\%}{\sqrt{E}} \oplus \frac{0.2}{E} \oplus 0.7\%$

Hadronic end-caps: 1.5<|η|<3.2: Cu-LAr

Forward: 3.1<|η|<4.9: Cu,W-LAr



The Tile calorimeter:

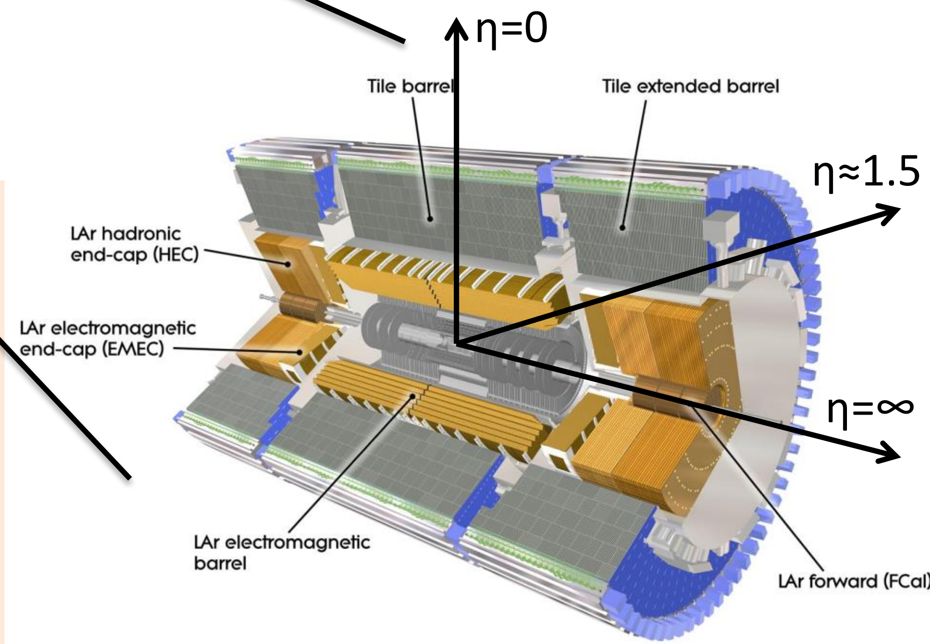
Hadronic calorimeter

Steel absorber plates and plastic scintillator tiles

- Coverage: |η| < 1.7
- Three longitudinal layers, total thickness of about 7λ

Design jet resolution (LAr+Tile):

$$\frac{s(E)}{E} = \frac{50\%}{\sqrt{E}} \oplus 3\%$$



The ATLAS EM Calorimeter

Sampling calorimeter

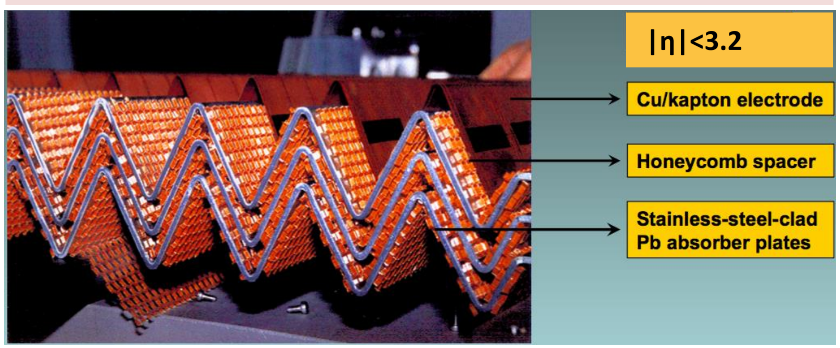
- with Pb absorbers and active LAr gaps (2mm in barrel, 1.2 – 2.7mm in endcap)

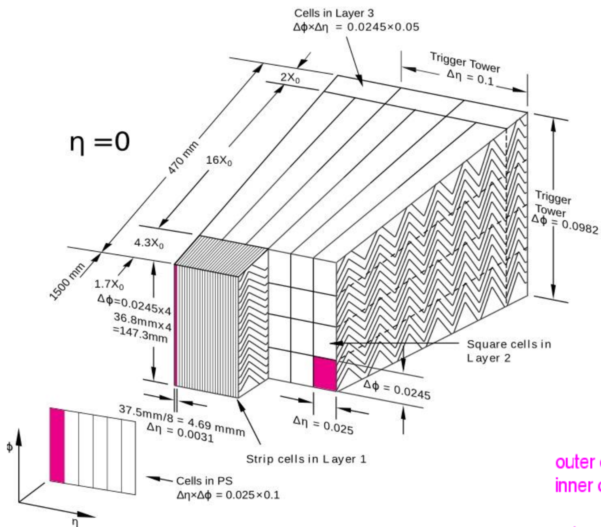
Advantages of **liquid argon (LAr) as active material**

- linear behavior
- stability of the response over time
- radiation tolerance

Advantages of **accordion geometry**

- it allows a very high granularity and longitudinal segmentation
- it allows for very good hermeticity since HV and signal cables run only at the front and back faces of the detector
- it allows for a very high uniformity in ϕ

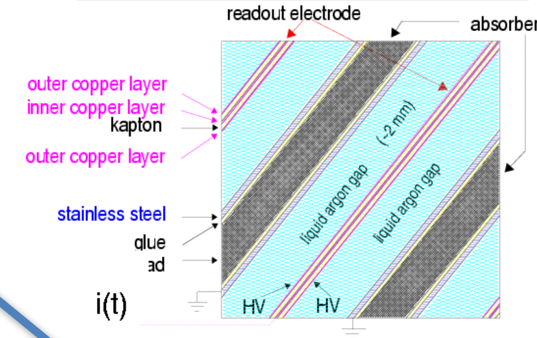


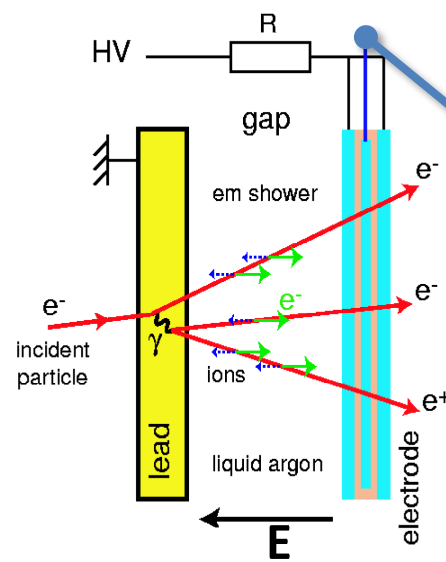


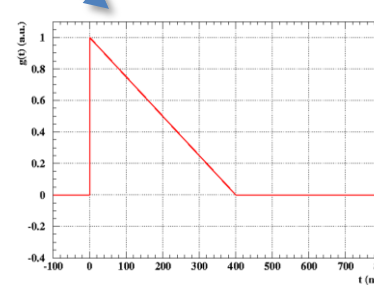
Incident electrons create **EM showers** in Pb (X_0=0.56cm) and LAr gaps (X_0=14.2cm)

secondary e^+ and e^- create e^-– ion pairs in LAr (W=23.3eV)

Ionized electrons and ions drift in electric field (2kV for 2mm gaps in barrel) and **induce triangular signal** (≈450ns drift time)







$t_{drift} \approx 450$ ns

CMS EM Calorimeter

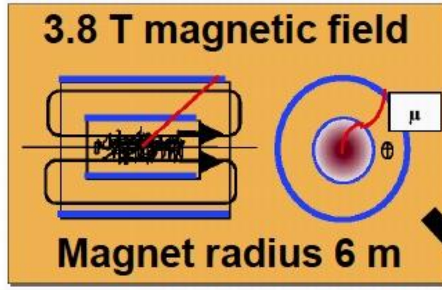
Homogenous $PbWO_4$ (PWO) ECAL:

- very low stochastic term, excellent energy resolution, but response impacted by radiation (laser correction necessary)
- $PbWO_4$: 8.3g/cm^3, X_0=8.9mm, R_M=22mm, Refr. index: 2.3, light yield: 100γ/MeV.
- Readout via Avalanche photodiodes (APD) in the barrel and Vacuum phototriodes (VPT) in the endcaps

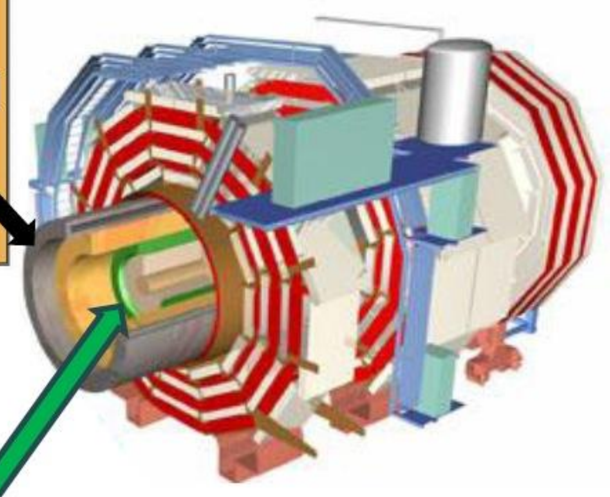
No longitudinal segmentation

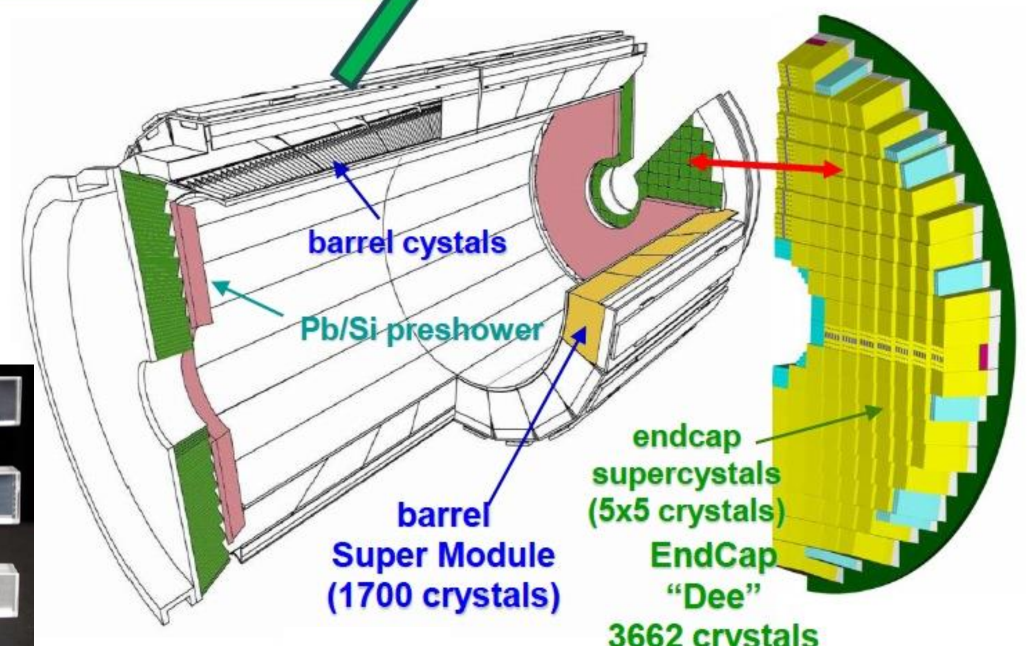
Coverage: $|\eta|<3.0$, Preshower $1.65<|\eta|<2.6$

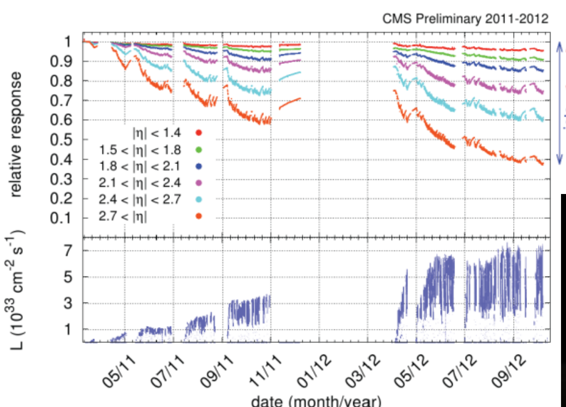
Design res.: $$\frac{\sigma(E)}{E}=\frac{3\%}{\sqrt{E}}\oplus\frac{0.2}{E}\oplus 0.5\%$$

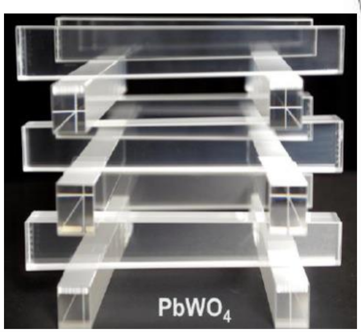


- Tk coverage $|\eta| < 2.5$
- Calo inside the coil
- Designed for: 14 TeV, 10^{34} cm^{-2}s^{-1} & 500fb^{-1}









Comparing ATLAS and CMS EM Calo

ATLAS

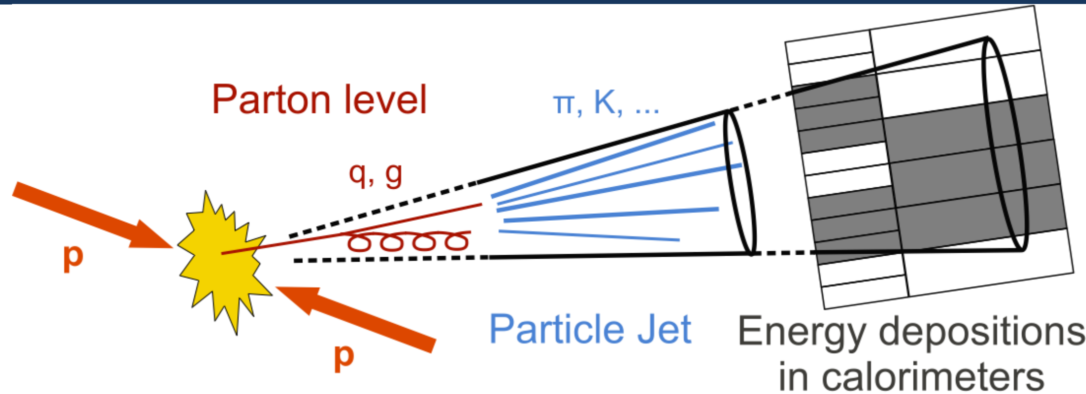
- Sampling calorimeter (LAr-Pb), 3 longitudinal layers + presampler, 173000 channels), E range MIP – TeV
- High lateral granularity
  - $\Delta\eta=0.0031$, $\Delta\phi=0.025$
- Radiation resistance
- Good energy resolution
- Very stable response in time
  - rms in time $\approx 3\times10^{-4}$
- Outside solenoid field (behind the coil) → 3 – 6 X_0 in front
- Main correction: dead material correction using presampler
- Strength: background rejection (e.g. π^0), stability, photon vertex measurement

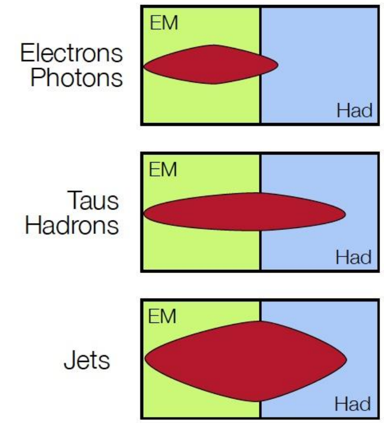
CMS

- Homogeneous calorimeter (75000 $PbWO_4$ crystals + PS in forward direction), E range MIP – TeV
- High lateral granularity
  - $\Delta\eta=\Delta\phi=0.0175$
- Radiation resistance
- Excellent energy resolution
- Response impacted by radiation
  - after laser correction rms $\approx 2\times10^{-3}$
- Inside strong solenoid field → only 0.4 – 1.9 X_0 in front
- Main correction: Laser correction to compensate impact of radiation
- Strength: little material in front, energy resolution

→ ≈ Same significance for H→γγ signal

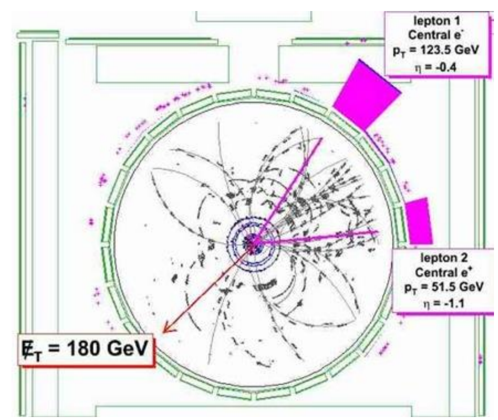
Measurement of Physics Objects in HEP





- In high energy physics (HEP) we **don't just measure single hadrons**!
- Quarks and gluons produced in the p-p collisions have a colour charge and hence cannot exist freely (colour confinement) → they hadronize into colour neutral hadrons and form **particle jets**

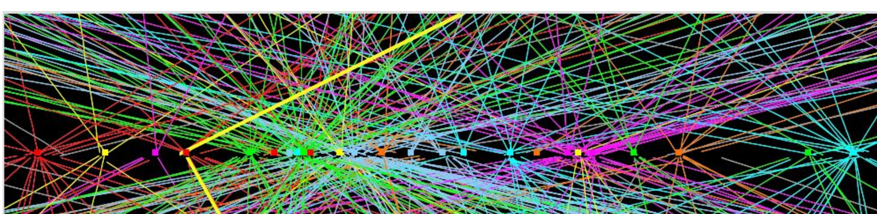
  → Measurement of quarks means measurement of many particles inside a cone
- Measurement of undetectable particles (e.g. neutrinos ν) → **missing E_T** (obtained by the negative vector sum of E_T)
- On top each event there is an underlying event (other particles from same p-p collision) and min. bias events from other simultaneous p-p collisions



Ways to cope with such a difficult environment:

- Weighting techniques for jet reconstruction
- Pile-up subtraction
- Particle flow (follow particles through different detectors and combine measurements) (e.g. CMS, CALICE)

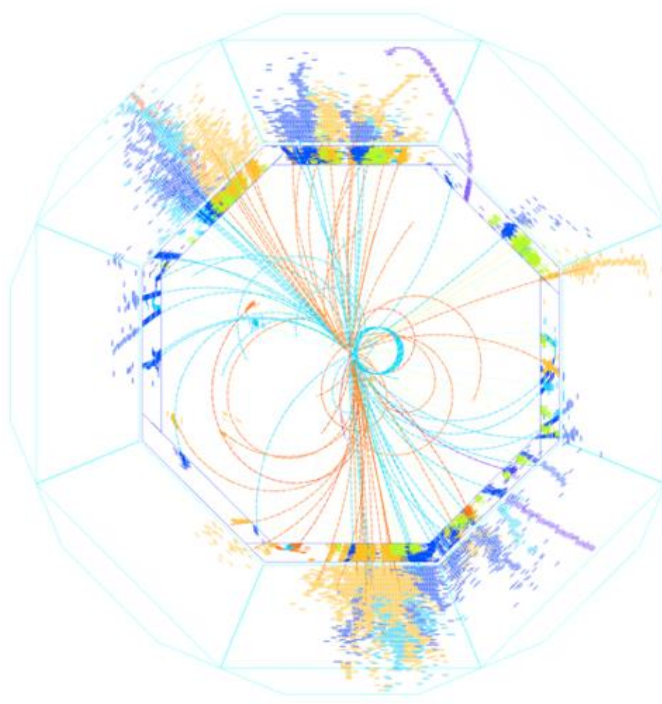
Known physics events used to calibrate (e.g. Z, W decays)



ATLAS: Z→μμ event from 2012 with 25 reconstructed vertices

Particle Flow

Component	Detector	Fraction	Part. resolution	Jet Energy Res.
Charged ($X^{\pm}$)	Tracker	60%	10^{-4} E_X	negligible
Photons (γ)	ECAL	30%	$0.1/\sqrt{E_\gamma}$	$.06/\sqrt{E_{jet}}$
Neutral Hadrons (h)	E/HCAL	10%	$0.5/\sqrt{E_{had}}$	$.16/\sqrt{E_{jet}}$



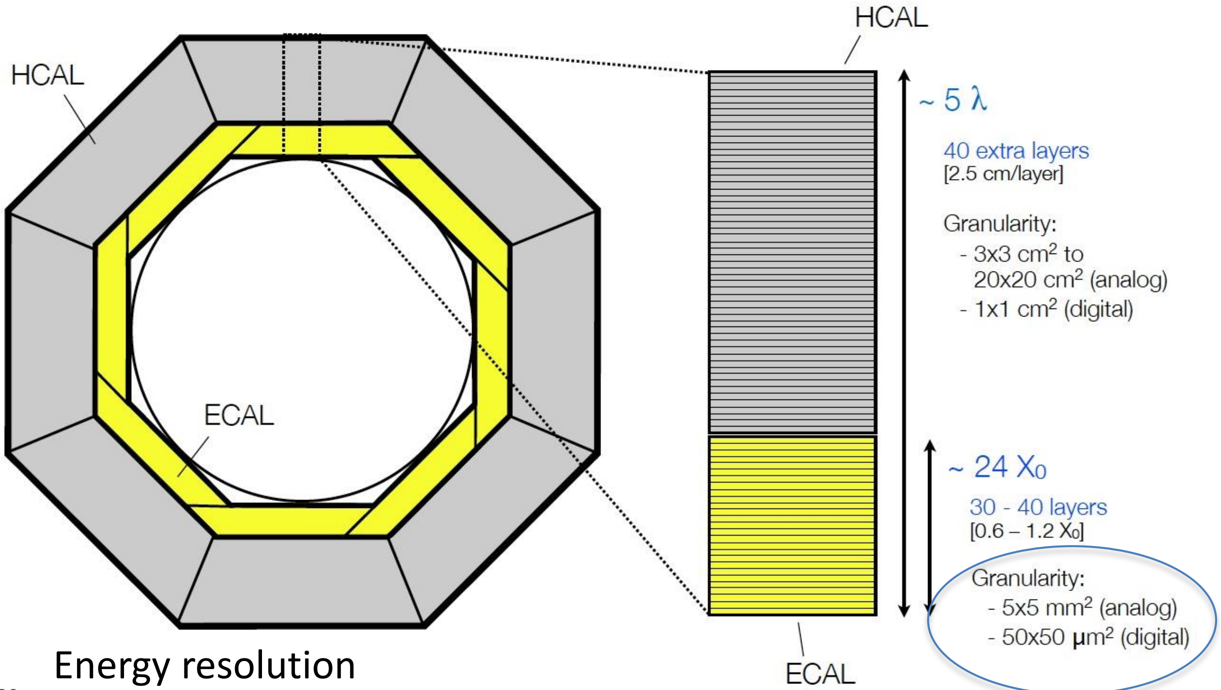
Choose **detector best suited** for particular **particle type**

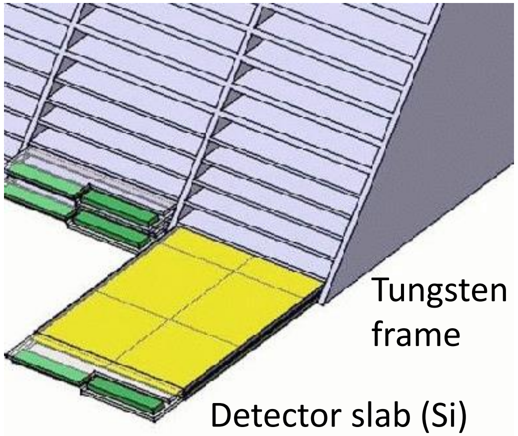
- Use tracks and distinguish "charged" from "neutral" energy to avoid double counting
- Distinguish electromagnetic and hadronic energy deposits in the calorimeter for software compensation

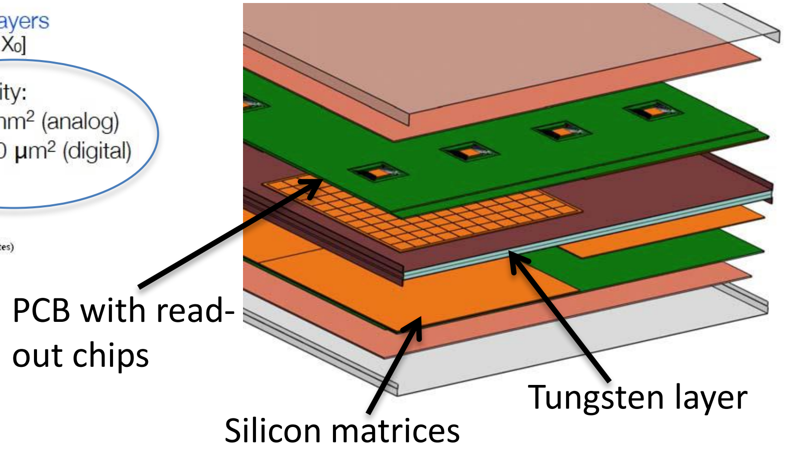
$$\sigma_{jet}^2 = \underbrace{\sigma_X^2 + \sigma_\gamma^2 + \sigma_h^2}_{\approx \frac{0.17}{\sqrt{E_{jet}}}} + \underbrace{\sigma_{confusion}^2 + \ldots}_{\approx \frac{0.25}{\sqrt{E_{jet}}}}$$

→ **Granularity more important than energy resolution!?**

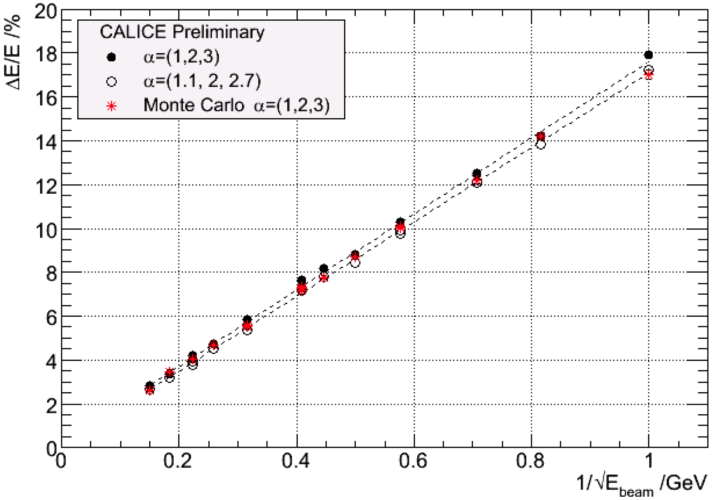
CALICE

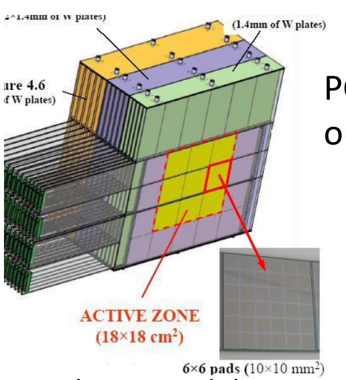






Energy resolution





Testbeam module

→ Achieved resolution in testbeams (pions) $< \frac{20\%}{\sqrt{E}}$

Few References and Further Literature

- R. Wigmans, “Calorimetry, Energy Measurements in Particle Physics”, Oxford science publications
- ATLAS & CMS Calorimeter TDRs
- ATLAS & CMS Detector Paper J. Instrum., 3 S08003 and 3 S08004 (2008)
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