Calorimetry Lecture 1

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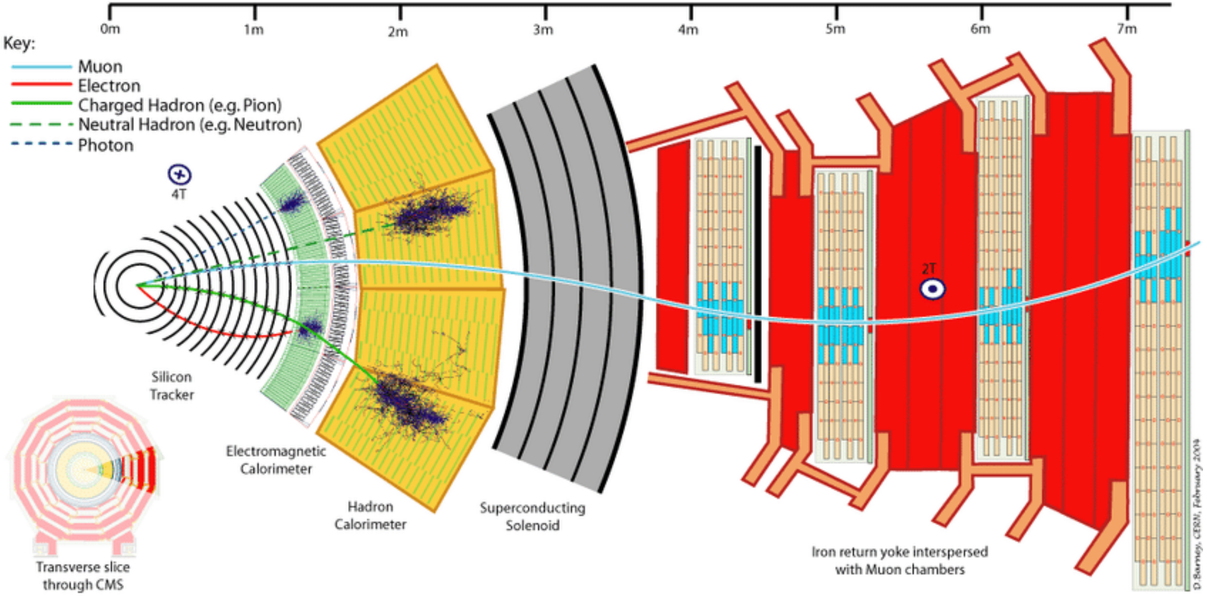
General purpose particle detectors : ATLAS and CMS

- General purpose collider detectors are an assembly of sub-systems providing complementary measurements of the components of the momentum four-vector of particles produced in collisions.

- Inner **trackers** make multiple non-destructive measurements of charged particles determine momentum.
- Outer **calorimeters** cause most particles to destructively deposit their energy to determine energy.



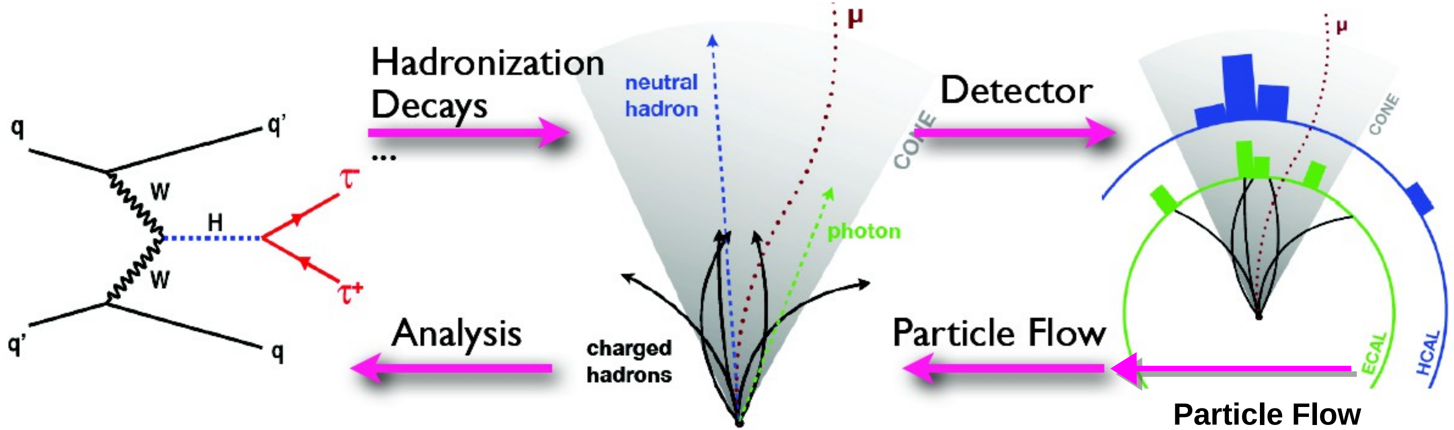
Outline

- Introduction
- Fundamental interactions : radiation, ionization, pair production, nuclear interactions
- Electromagnetic showers
- Hadronic showers
- Measuring the energy of showers
- Detector resolution
- Components of scintillator / light systems
- Next lecture

Particle flow reconstruction

- Information from all sub-systems used simultaneously to reconstruct electrons, photons, muons, charged hadrons, and neutral hadrons with optimal resolution.

- Calorimeters are essential for photons, neutral hadrons, and electrons
  - Also important for charged hadron reco and muon ID.



Electron, muon, tau, jet, & photon candidates

Particle Flow Candidates

What do we to measure with Calorimeters?

- **Charged particles** : Trackers provide primary measurement at low energies, but calorimeter resolution improves with energy (and tracking resolution degrades with energy)
- **Neutral particles** : Only detector that measures neutral energy
- **Invisible particles** (neutrinos, new particles) : Calorimeters are critical for hermetic detectors that can infer presence of undetected particles through transverse momentum imbalance

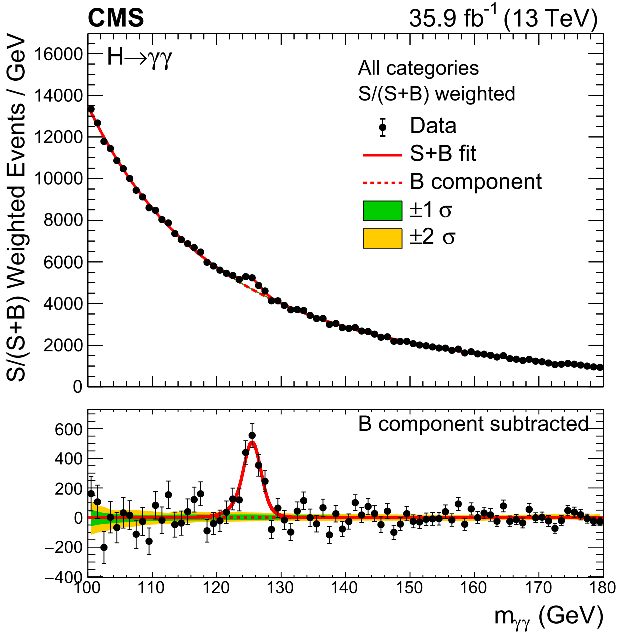
Other Calorimeter benefits

- Fast trigger
- Precise timing measurements

Challenges

- Energy calibration less straightforward than tracking
- Must be large (costly) for full particle shower containment.

LHC calorimeter success : 0.1% precision on Higgs mass

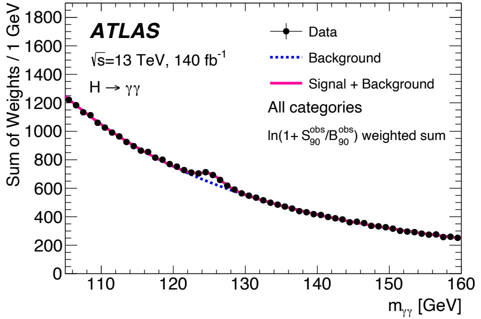


125.78 ± 0.18 (stat) ± 0.18 (syst) GeV

125.78 ± 0.26 GeV

125.22 ± 0.11 (stat) ± 0.09 (syst) GeV

125.22 ± 0.14 GeV



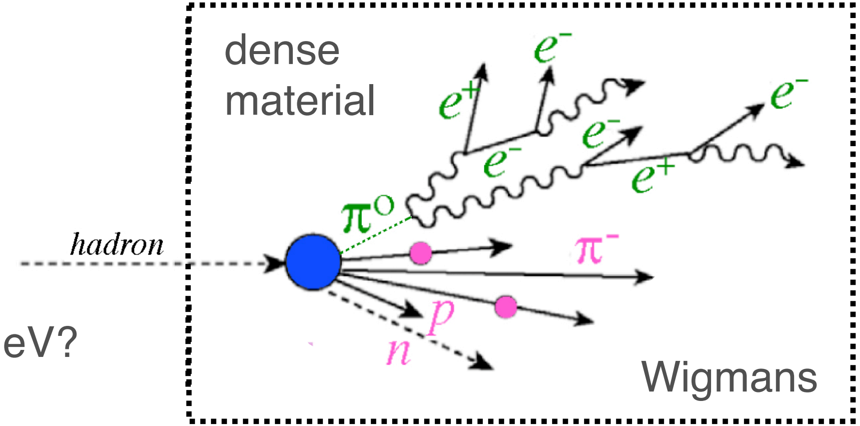
Source	Impact [MeV]
Photon energy scale	83
$Z \rightarrow e^+e^-$ calibration	59
E_T-dependent electron energy scale	44
$e^\pm \rightarrow \gamma$ extrapolation	30
Conversion modelling	24
Signal–background interference	26
Resolution	15
Background model	14
Selection of the diphoton production vertex	5
Signal model	1
Total	90

Key questions for understanding calorimetry

- **Tracking systems** : low mass to minimally perturb particle trajectories
- **Calorimeter systems** : maximum density to destructively **convert the energy of incident particle** into many lower energy particles (particle shower) and **count / measure the secondary particles** to determine the original particle energy.

Key questions:

- What type is incident particle?
- What interactions at each vertex of shower?
- What types of secondaries are produced?
- What signals do secondaries produce?
- How much signal do secondaries produce per GeV?
- How to measure signals of secondaries?



Considering key questions

- Key questions generally motivate development of two complementary types of calorimeters:

Calo Type	Target Primaries	Interactions	Secondaries	Signals	Measurement Strategy	Typical active material
EM	$e^\pm$, γ	EM	$e^\pm$, γ	• Cerenkov radiation • ionization, • scintillation	• total absorption • sampling	• liquid argon • scintillating crystal • Cerenkov glass • silicon
Hadron	Hadrons	EM + strong	• $\pi^0 \to \gamma\gamma$ • $\pi^\pm$, $K^\pm$ • neutrons, soft γ • nuclear fragments, protons • binding energy		• sampling	• plastic scintillator • silicon

Fundamental interactions

Charged particle interactions with matter

- NB y-axis units: energy loss scales with density

Ionization :

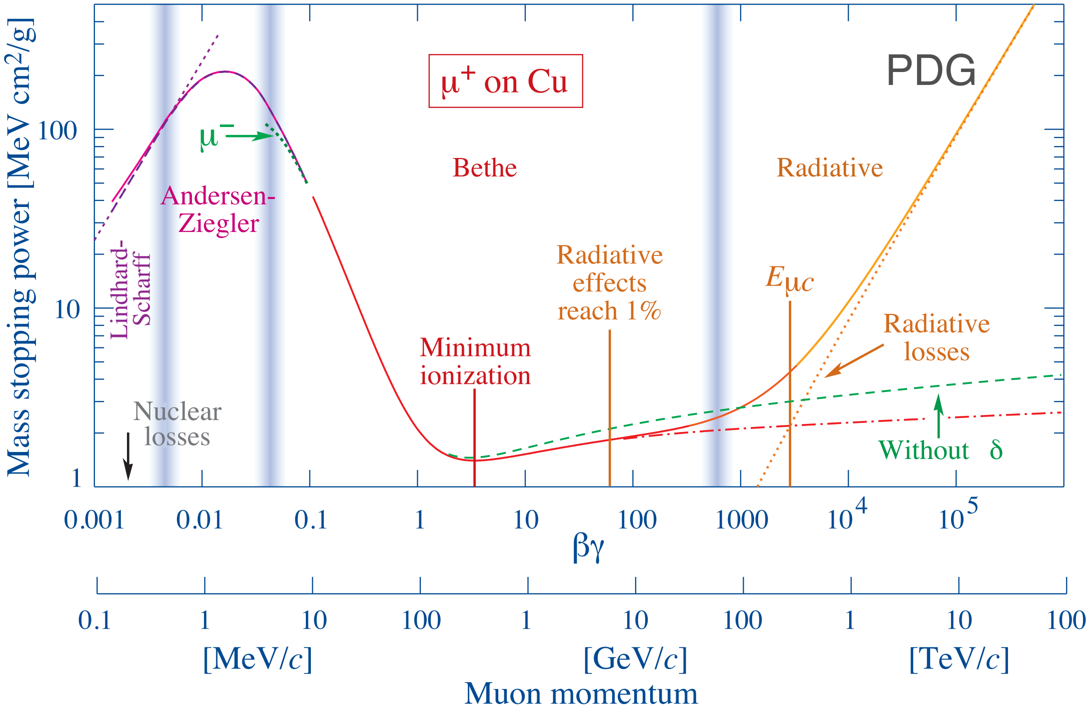
- dominates at low momentum
- Gives rise to scintillation in appropriate materials

Radiation / Bremsstrahlung:

- dominates at high momentum
- initiates particle showers

Radiation / Cherenkov:

- Smaller energy loss than ionization, but useful for detection



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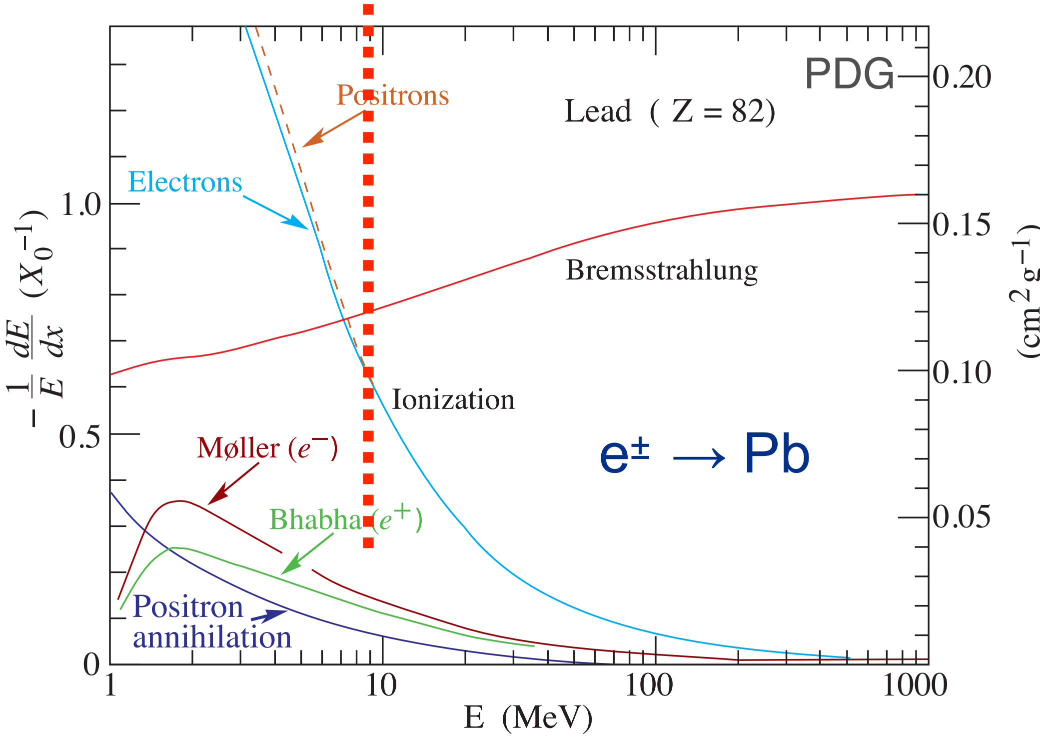
Radiation dominates for
e± with E > 10 MeV



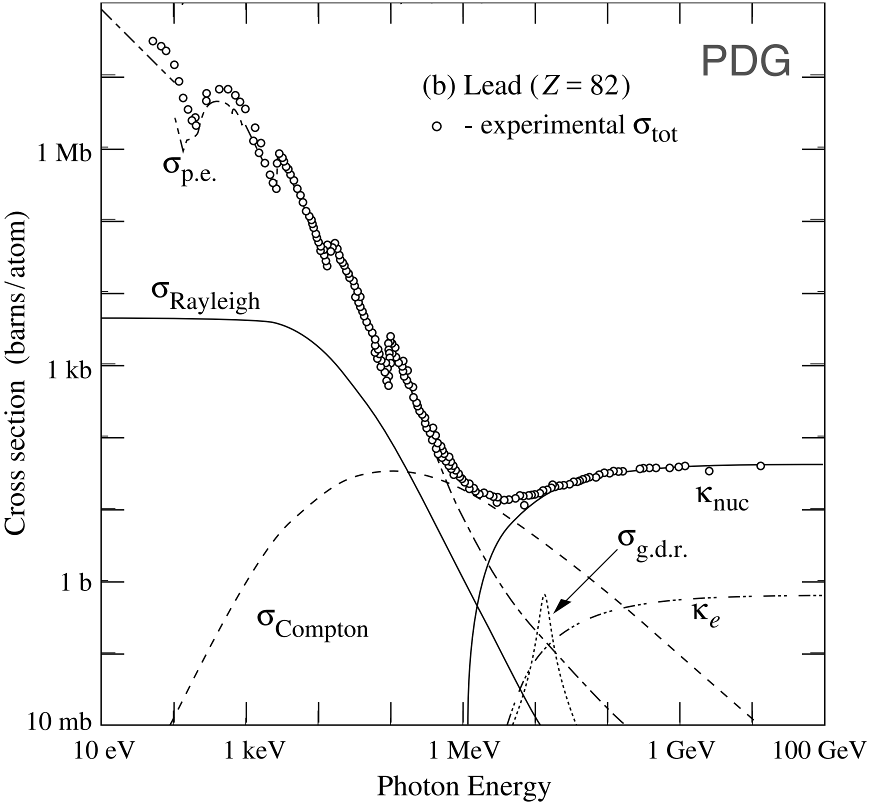
Photon interactions with matter

Pair production

- dominates at LHC energies
- initiates photon showers

Compton scattering & photoelectric effect

- dominates below ~1 MeV



$\sigma_{\text{p.e.}}$ = Atomic photoelectric effect (electron ejection, photon absorption)
σ_{Rayleigh} = Rayleigh (coherent) scattering–atom neither ionized nor excited
σ_{Compton} = Incoherent scattering (Compton scattering off an electron)
κ_{nuc} = Pair production, nuclear field
κ_e = Pair production, electron field
$\sigma_{\text{g.d.r.}}$ = Photonuclear interactions, most notably the Giant Dipole Resonance

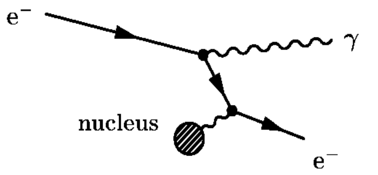
Electromagnetic showers

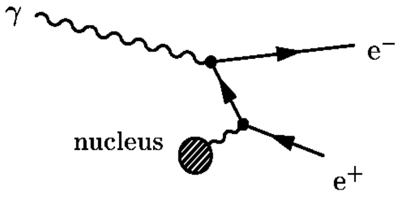
“Simple” case : electromagnetic shower

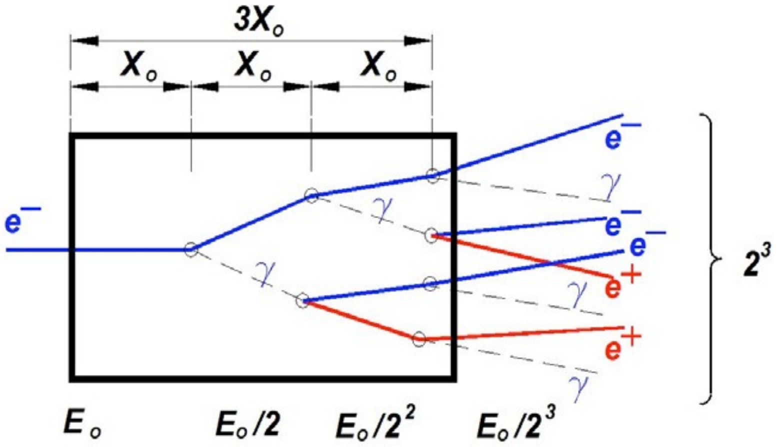
- At LHC energies, primary **electrons / photons** interact with matter dominantly through **bremsstrahlung / pair production**
  - Alternating sequence → **EM shower**

- Shower development characterization:
  - Longitudinal : cross section → radiation length (X_0)
  - Transverse : electron multiple scattering → Moliere radius (R_M)

- EM showers are compact and relatively uniform
  - Reconstruction of shower shape used to distinguish e+ from overlapping $\pi^0 \to \gamma\gamma$





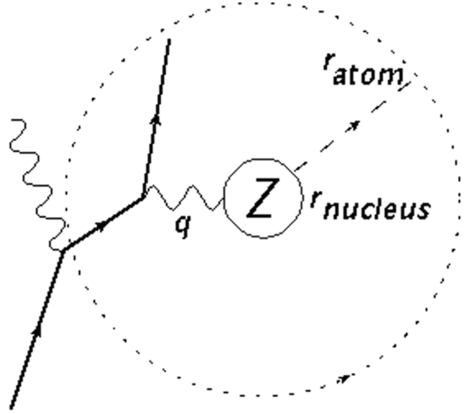


Radiative interactions

- Electron interacting with material sees distribution of high charge, high mass nuclei screened by diffuse cloud of electrons.

- Cross section to radiate determined by
  - classical electron radius
  - α x (photon propagator integral over the region of unscreened nuclear charge)

- Cross section scaling:
  - With square of nuclear charge (Z^2)
  - Dominated by low momentum exchange ($1/q^2$)



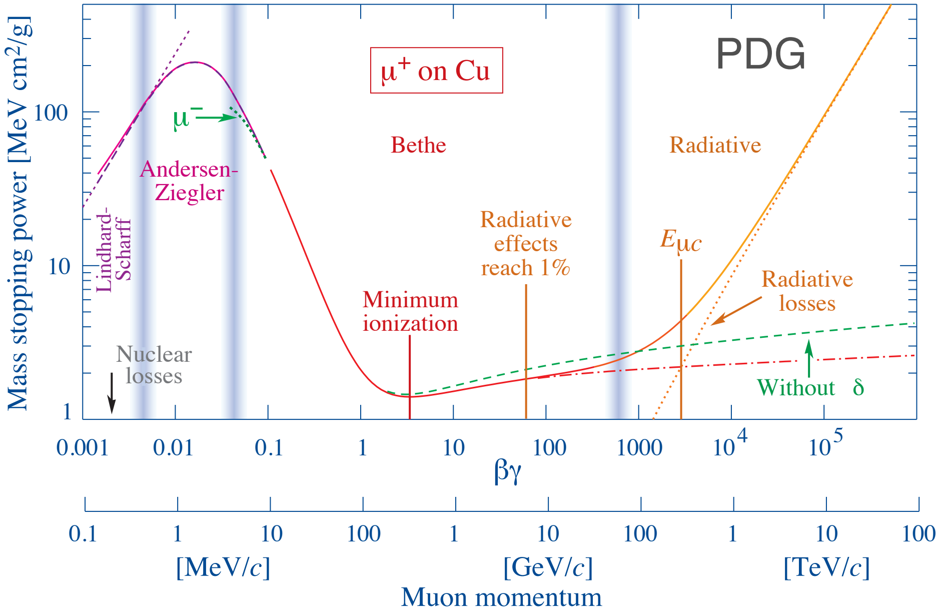
$$\sigma_{radiative} \approx \pi r_e^2 \left[\left(\frac{\alpha}{\pi}\right) Z^2 \int_{1/r^2_{atom}}^{1/r^2_{nucleus}} \frac{dq^2}{q^2} \right]$$

$$\sigma_{radiative} \approx 4 \alpha r_e^2 Z^2 \ln\left(\frac{r_{atom}}{r_{nucleus}}\right)$$

$$\sigma_{radiative} \approx 4 \alpha r_e^2 Z^2 \ln\left(\frac{183}{\sqrt[3]{Z}}\right)$$

Ionization

- When not radiating, charged particles deposit energy via ionization.
- This energy gives rise to measurable signals in active material of calorimeter by
  - Producing charge
  - Producing scintillation light
- Radiation drives shower development and ionization provides signal.



Longitudinal shower development : Mean Free Path

- How far does an electron travel before radiating?
- Electron mean free path (λ) can be written in terms of number of atoms per unit volume (n) and cross section for radiation (σ)

$$\lambda = (n\sigma)^{-1} = (\frac{N_A\rho}{A}\sigma)^{-1} = \frac{A}{4\alpha r_e^2\ N_A\rho\ Z^2\ \ln[183\ Z^{-1/3}]}$$

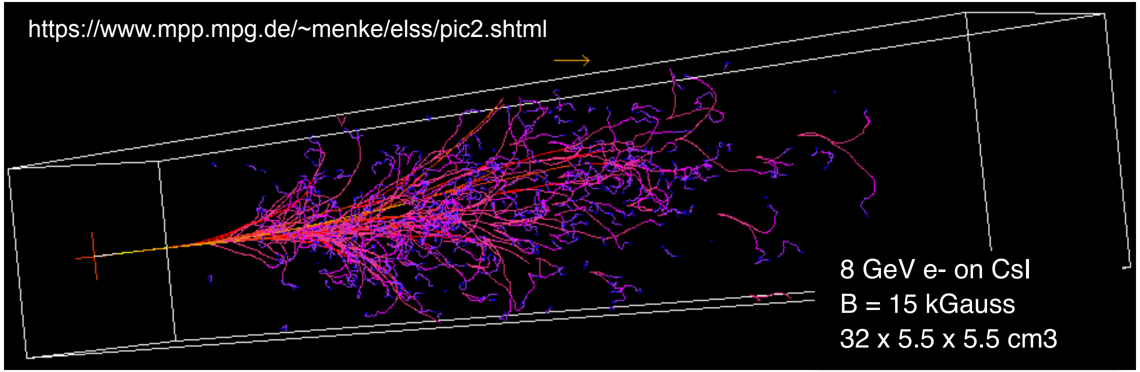
- With nuclear charge (Z), molar mass (A), classical electron radius (r_e=2.8x1013 cm), fine structure constant (α=1/137), and Avogadro's number (N_A=6x10^{23}/mol):

Longitudinal shower development : Radiation length

- Radiation length (X_0) is mean distance over which electron loses 1/e of energy to radiation
- Commonly parameterized for different materials (A, Z) in units of g cm^{-2} (divide by density to obtain length in cm) as :

$$X_0 = \frac{A\ [\text{g mol}^{-1}]}{(4\alpha\ r_e^2\ [\text{cm}^2]\ N_A\ [\text{mol}^{-1}])\ Z(Z+1)\ \ln(287/\sqrt{Z})} = \frac{716.4\ A}{Z(Z+1)\ln(287/\sqrt{Z})}[\text{g cm}^{-2}]$$

- Proportional to $1/Z^2$ just like mean free path.
- Mean free path for pair production by high energy photon $\lambda(\gamma \rightarrow e^+e^-) \sim 9/7\ X_0$

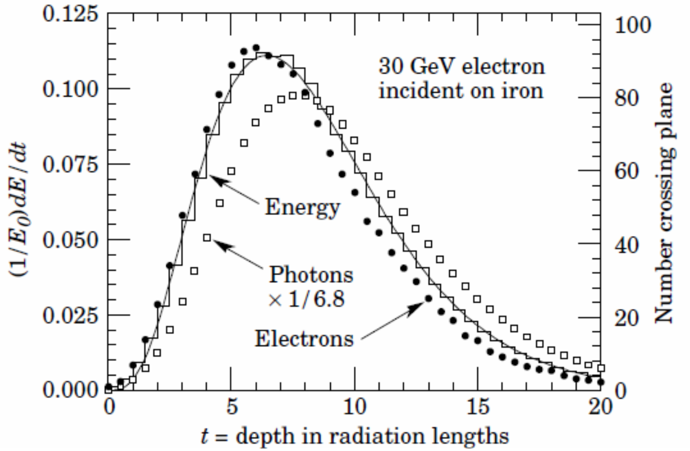

https://www.mpp.mpg.de/~menke/elss/pic2.shtml

8 GeV e- on CsI
B = 15 kGauss
32 x 5.5 x 5.5 cm3

Longitudinal shower development : Shower max

- Shower max = transverse plane with the largest number of particles flowing through it

Average secondary particle energy : E_C
Number of secondary particles : $N_{max} = E_i / E_C$
Depth of shower max : $L_{max} \sim \ln(E_i / E_C)\, X_0$



E_i is energy of incident particle

E_C is energy at which brem and ionization rates are equal

$E_c \propto 1/Z$ [7 MeV for Pb, 22 MeV for Fe]

Implications

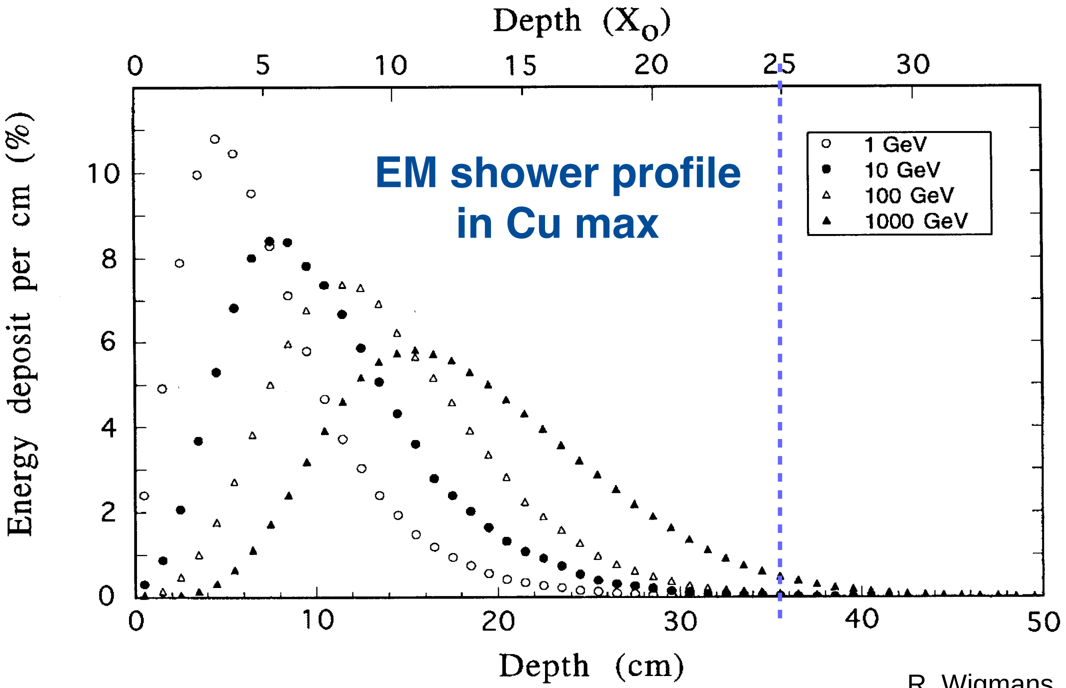
- "MIP counting" : energy of incident particle can be estimated from N_{max}
- In sampling calorimeter, L_{max} is critical to instrument most finely

Longitudinal development

- On average, 20-30% of energy deposited in few cm around shower max.

- Shower dissipates as the average secondary particle energy decreases
  - Pair production → Compton / photoelectric processes
  - Radiation → ionization

- EM calorimeters have typical depth of ~25 X_0



R. Wigmans

Transverse shower development : Moliere radius

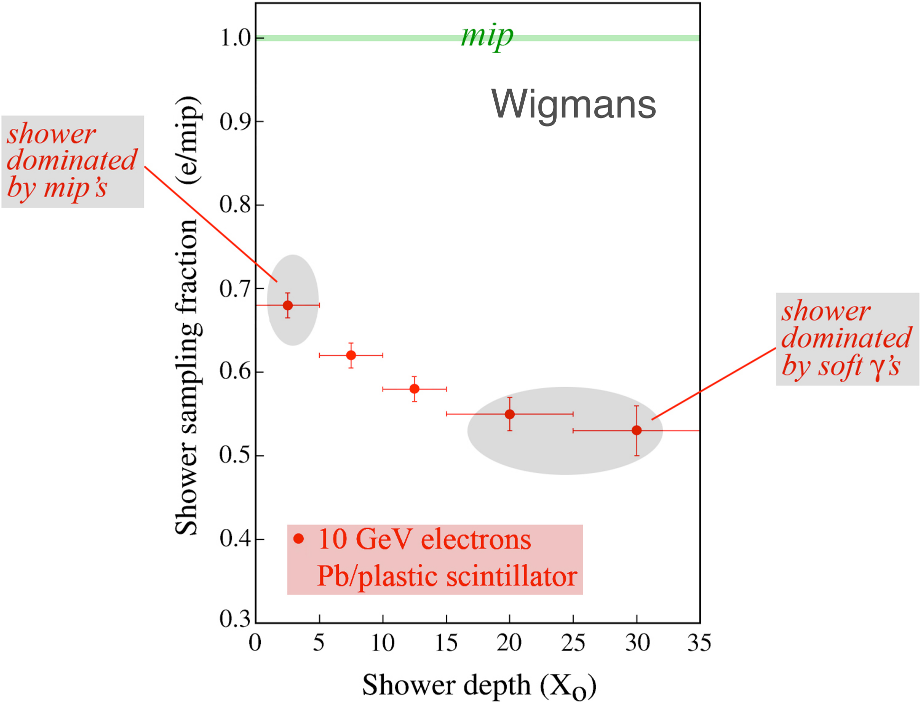
- Moliere radius (R_M) is radius of cylinder containing 90% of EM shower in a material.
  - Proportional to 1/Z (since $X_0 \propto Z^{-2}$ and $E_C \propto Z^{-1}$)
- Calorimeter transverse segmentation should be finer than but on same order as R_M
  - With signal sharing between calo cells, shower position can be determined to within small fraction of cell size
- Transverse shower shapes are critical for identifying merged neutral pions $\pi^0 \rightarrow \gamma\gamma$

$$R_M = [21\ \mathrm{MeV}]\ \frac{X_0}{E_C}$$

Material	**R_M [cm]**
Tungsten	0.9
Copper	1.6
LYSO	2.1
$PbWO_4$	2.2
Liquid Argon	9
Earth atmosphere (sea level)	79

Even EM showers are not so simple …

- Early part of shower dominated by ionization from MIPs
- Late part of shower dominated by soft photons
- In principle, this simple fact complicates
    - use of depth segmentation
    - understanding longitudinal effects like radiation damage



Aside : What about muon showers?

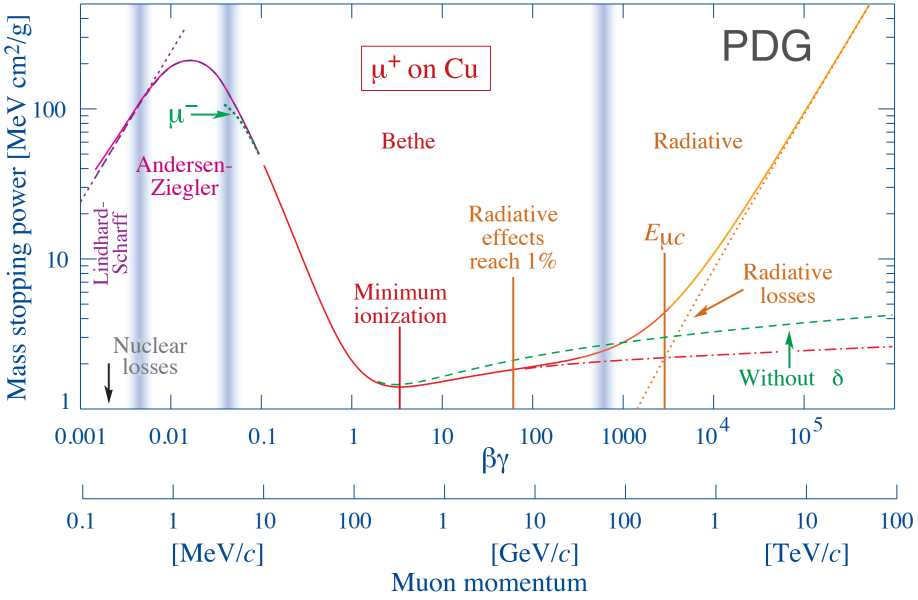
- Probability for an EM particle to radiate a photon (initiating an EM shower) goes as 1/m^2.

$$\sigma_{\text{radiative}} \propto {r_e}^2 \propto {m_e}^{-2}$$

$$\frac{\sigma^{\mu}_{\text{radiative}}}{\sigma^{e}_{\text{radiative}}} = \frac{{m_e}^2}{{m_\mu}^2} = 0.000025$$

- Muons are minimum ionizing in collider experiments and identified by their ability to fully penetrate the calorimeters.

- Muons will radiate and shower at high enough energies, but not typical collider energies of 1-100 GeV.

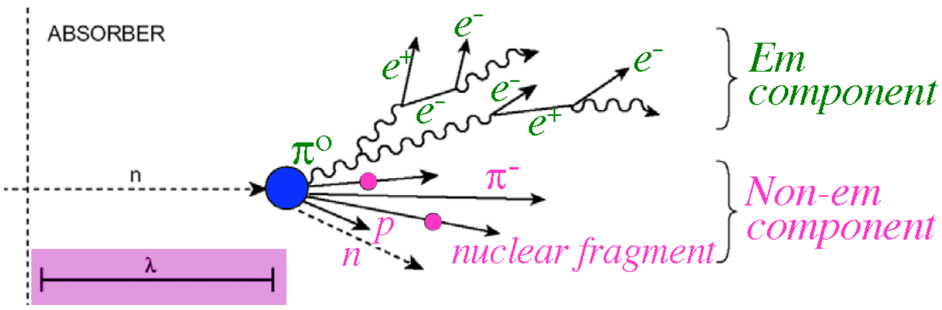


Hadronic showers

Hadronic shower

- Radiative processes for charged hadrons ($\pi^{\pm}$, $K^{\pm}$) experience same mass suppression as muons → strong interactions dominate
  - $\sigma(\pi p) = 26$ mb; $\sigma(pp) = 40$ mb; constant with q^2

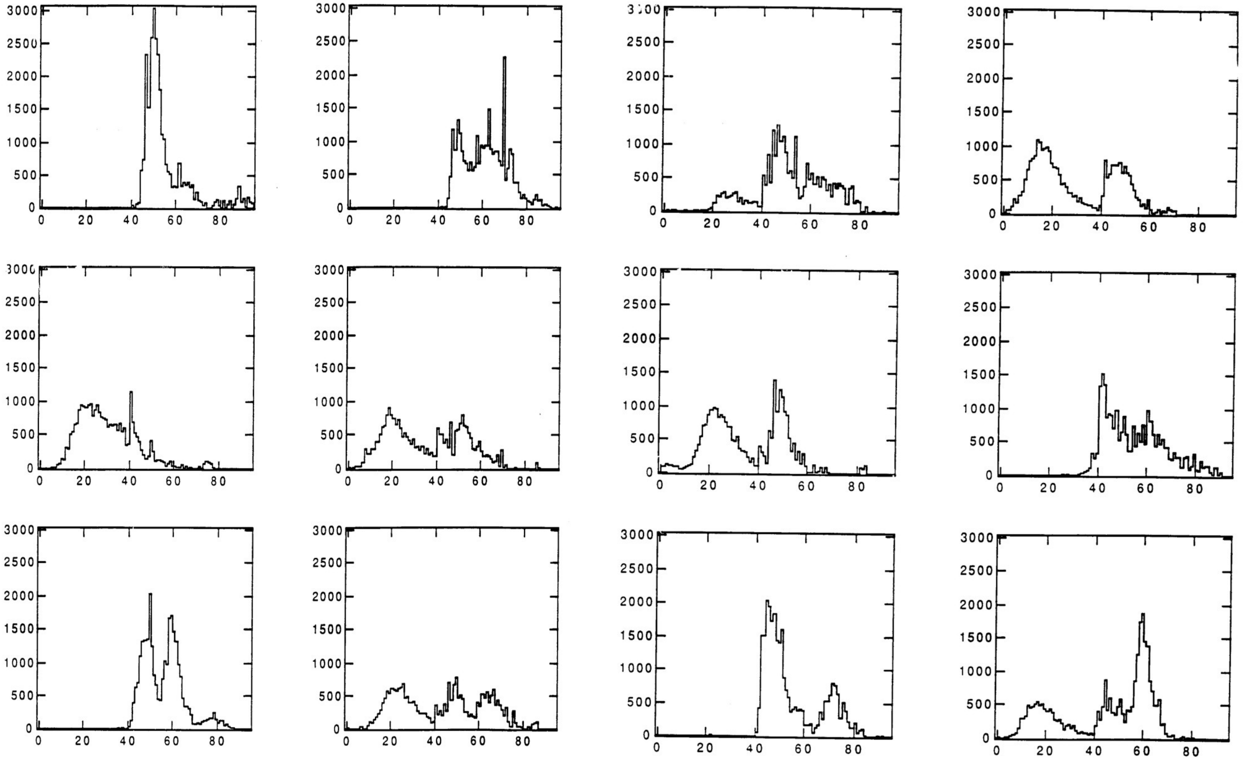
Wigmans



- Hadron showers consist of two components
  - **EM component** : $\pi^0 \rightarrow \gamma\gamma$
  - **Hadron (non-EM) components** :
    - Charged hadrons $\pi\pm$, $K\pm$
    - Nuclear fragments, protons
    - Neutrons, soft γ
    - Nuclear binding energy (invisible)

- Hadron showers much less regular than EM showers
  - Lower cross sections for nuclear interaction
  - Fluctuations of EM vs. non-EM components
  - Fluctuations of invisible components

Hadronic shower fluctuations : longitudinal shapes from CMS beam test



270 GeV pions

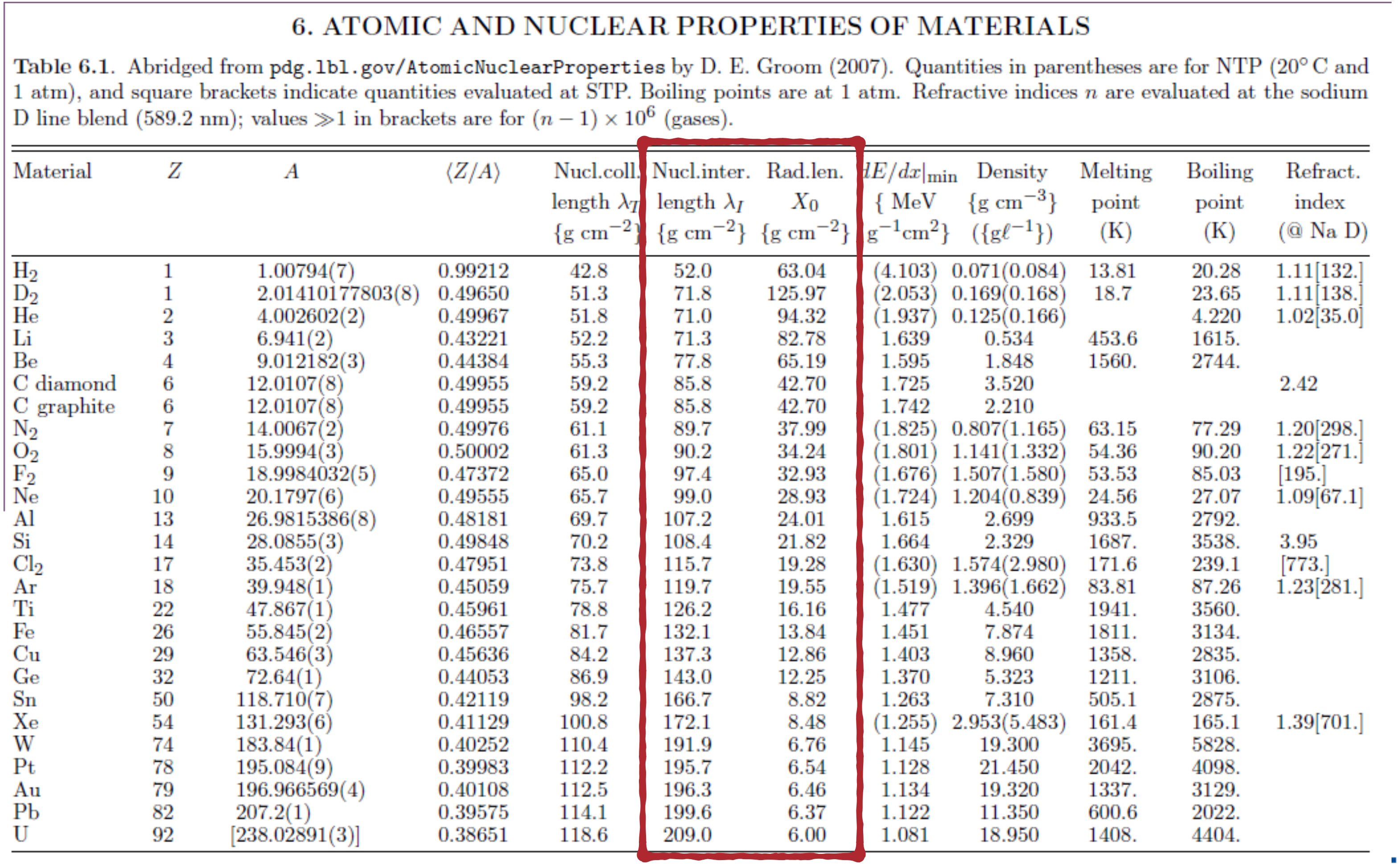
Hadronic shower : longitudinal development

- Longitudinal development characterized by nuclear interaction length (λ) ~ mean free path for nuclear interaction

$$\lambda_{int} = \frac{A[\mathrm{g\ mol}^{-1}]}{N_A[\mathrm{mol}^{-1}]\ \sigma(pp)[\mathrm{cm}^2]}$$

- 95% longitudinal containment for thickness of
  - $L_{95\%} = 1 + 1.35 \ln(E\,[\mathrm{GeV}])\ [\lambda_{int}]$
  - $L_{95\%} \sim 10\ \lambda_{int}$ for $E \sim 1$ TeV

- Since ($\lambda_{int} \propto A$) and ($X_0 \propto AZ^{-2}$) ➔ $\lambda_{int} >> X_0$ for high Z material
  - $\lambda_{int}(\mathrm{Fe}) = 10 \times X_0\,(\mathrm{Fe})$



6. ATOMIC AND NUCLEAR PROPERTIES OF MATERIALS

Table 6.1. Abridged from `pdg.lbl.gov/AtomicNuclearProperties` by D. E. Groom (2007). Quantities in parentheses are for NTP (20° C and 1 atm), and square brackets indicate quantities evaluated at STP. Boiling points are at 1 atm. Refractive indices n are evaluated at the sodium D line blend (589.2 nm); values $\gg 1$ in brackets are for $(n-1)\times 10^6$ (gases).

Material	Z	A	$\langle Z/A \rangle$	Nucl.coll. length λ_T {g cm^{-2}}	Nucl.inter. length λ_I {g cm^{-2}}	Rad.len. X_0 {g cm^{-2}}	$dE/dx\|_{\rm min}$ { MeV g^{-1}cm^2}	Density {g cm^{-3}} ({gℓ^{-1}})	Melting point (K)	Boiling point (K)	Refract. index (@ Na D)
H_2	1	1.00794(7)	0.99212	42.8	52.0	63.04	(4.103)	0.071(0.084)	13.81	20.28	1.11[132.]
D_2	1	2.01410177803(8)	0.49650	51.3	71.8	125.97	(2.053)	0.169(0.168)	18.7	23.65	1.11[138.]
He	2	4.002602(2)	0.49967	51.8	71.0	94.32	(1.937)	0.125(0.166)		4.220	1.02[35.0]
Li	3	6.941(2)	0.43221	52.2	71.3	82.78	1.639	0.534	453.6	1615.	
Be	4	9.012182(3)	0.44384	55.3	77.8	65.19	1.595	1.848	1560.	2744.	
C diamond	6	12.0107(8)	0.49955	59.2	85.8	42.70	1.725	3.520			2.42
C graphite	6	12.0107(8)	0.49955	59.2	85.8	42.70	1.742	2.210			
N_2	7	14.0067(2)	0.49976	61.1	89.7	37.99	(1.825)	0.807(1.165)	63.15	77.29	1.20[298.]
O_2	8	15.9994(3)	0.50002	61.3	90.2	34.24	(1.801)	1.141(1.332)	54.36	90.20	1.22[271.]
F_2	9	18.9984032(5)	0.47372	65.0	97.4	32.93	(1.676)	1.507(1.580)	53.53	85.03	[195.]
Ne	10	20.1797(6)	0.49555	65.7	99.0	28.93	(1.724)	1.204(0.839)	24.56	27.07	1.09[67.1]
Al	13	26.9815386(8)	0.48181	69.7	107.2	24.01	1.615	2.699	933.5	2792.	
Si	14	28.0855(3)	0.49848	70.2	108.4	21.82	1.664	2.329	1687.	3538.	3.95
Cl_2	17	35.453(2)	0.47951	73.8	115.7	19.28	(1.630)	1.574(2.980)	171.6	239.1	[773.]
Ar	18	39.948(1)	0.45059	75.7	119.7	19.55	(1.519)	1.396(1.662)	83.81	87.26	1.23[281.]
Ti	22	47.867(1)	0.45961	78.8	126.2	16.16	1.477	4.540	1941.	3560.	
Fe	26	55.845(2)	0.46557	81.7	132.1	13.84	1.451	7.874	1811.	3134.	
Cu	29	63.546(3)	0.45636	84.2	137.3	12.86	1.403	8.960	1358.	2835.	
Ge	32	72.64(1)	0.44053	86.9	143.0	12.25	1.370	5.323	1211.	3106.	
Sn	50	118.710(7)	0.42119	98.2	166.7	8.82	1.263	7.310	505.1	2875.	
Xe	54	131.293(6)	0.41129	100.8	172.1	8.48	(1.255)	2.953(5.483)	161.4	165.1	1.39[701.]
W	74	183.84(1)	0.40252	110.4	191.9	6.76	1.145	19.300	3695.	5828.	
Pt	78	195.084(9)	0.39983	112.2	195.7	6.54	1.128	21.450	2042.	4098.	
Au	79	196.966569(4)	0.40108	112.5	196.3	6.46	1.134	19.320	1337.	3129.	
Pb	82	207.2(1)	0.39575	114.1	199.6	6.37	1.122	11.350	600.6	2022.	
U	92	[238.02891(3)]	0.38651	118.6	209.0	6.00	1.081	18.950	1408.	4404.	

Hadron shower : transverse development

^{237}U is created by high-energy photon interactions (π^0 in core of shower)

Mo is created by fission events initiated by MeV neutrons

^{239}Np is created by capture of thermal neutrons

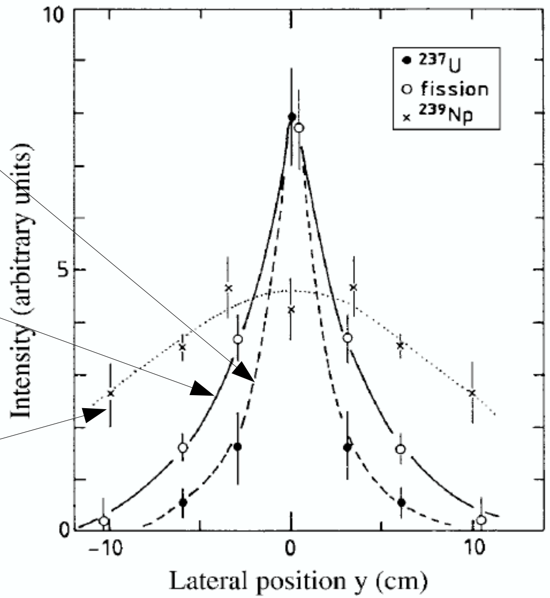
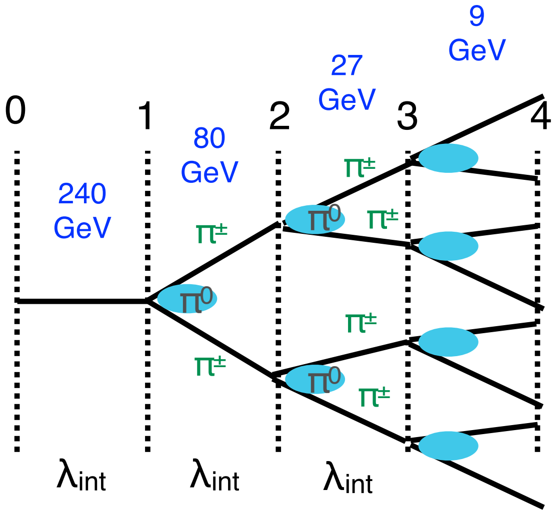


FIG. 2.34. Lateral profiles for 300 GeV π^- interactions in a block of uranium, measured from the induced radioactivity at a depth of $4\lambda_{\mathrm{int}}$ inside the block. The ordinate indicates the decay rate of different radioactive nuclides, produced in nuclear reactions by different types of shower particles. Data from [Ler 86].

Pion Cascade

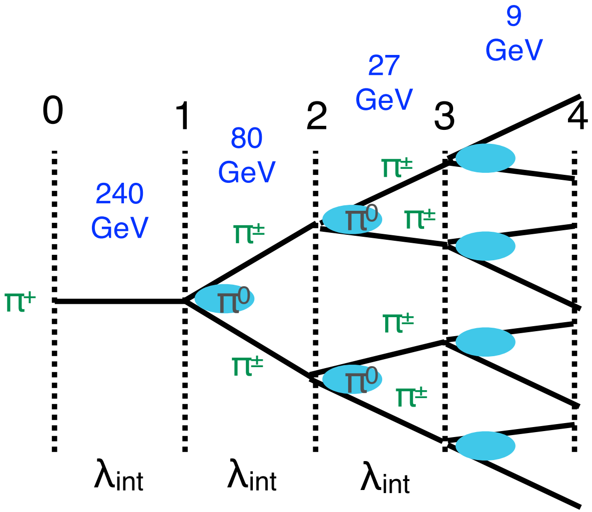
- Shower is series of hadronic interactions $\pi + N \rightarrow a\,\pi^0 + b\,\pi^+ + c\,\pi^- + X$
  - On average each interaction produces 1 π^0 and 2 $\pi^\pm$
  - π^0 deposit energy immediately by decaying $\pi^0 \rightarrow \gamma\gamma$ and creating EM showers
  - $\pi^\pm$ transport shower deeper into detector depositing ionization energy
  - X = nuclear fragments, neutrons, binding energy loss



Gen	N(π±)	N(π0)	E(π0) [GeV]	ΣE(π0) [GeV]	ΣE(π0) / total
0	1	0	0	0	0
1	2	1	80	80	33%
2	4	2	53	133	55%
3	8	4	36	169	70%
4	16	8	24	193	80%

Pion Cascade (2)

- Shower cuts off when particle energies < threshold to produce pions (few x M_π)
  - EM fraction (fraction of energy deposited by π^0) increases with each generation of cascade
  - Higher energy incident particles have more generations and larger EM fraction
- Toy model : start with 240 GeV π^+ and assume energy splits into 3 at each shower generation:



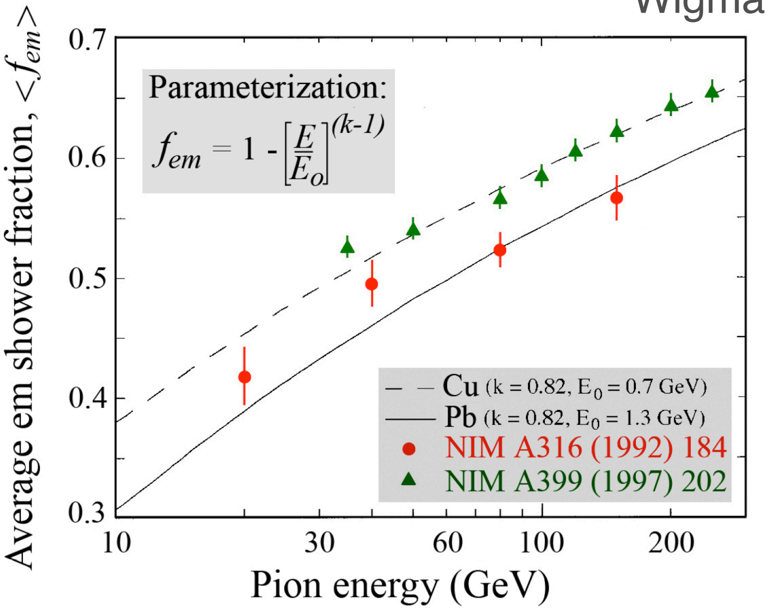
Gen	$N(\pi^\pm)$	$N(\pi^0)$	$E(\pi^0)$ [GeV]	$\Sigma E(\pi^0)$ [GeV]	$\Sigma E(\pi^0)$ / total
0	1	0	0	0	0
1	2	1	80	80	33%
2	4	2	53	133	55%
3	8	4	36	169	70%
4	16	8	24	193	80%

EM fraction (f_{EM}) depends on initial particle energy

- Parameterization is not simple 1/3 per generation because of energy loss and other processes.

- There are large fluctuations around the average behavior!

Wigmans



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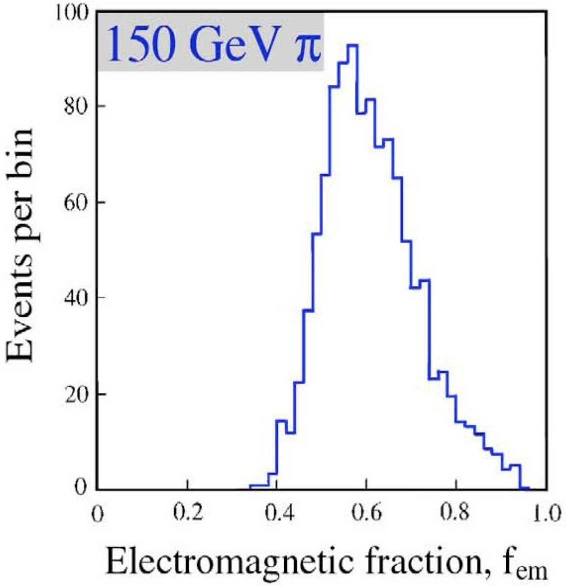
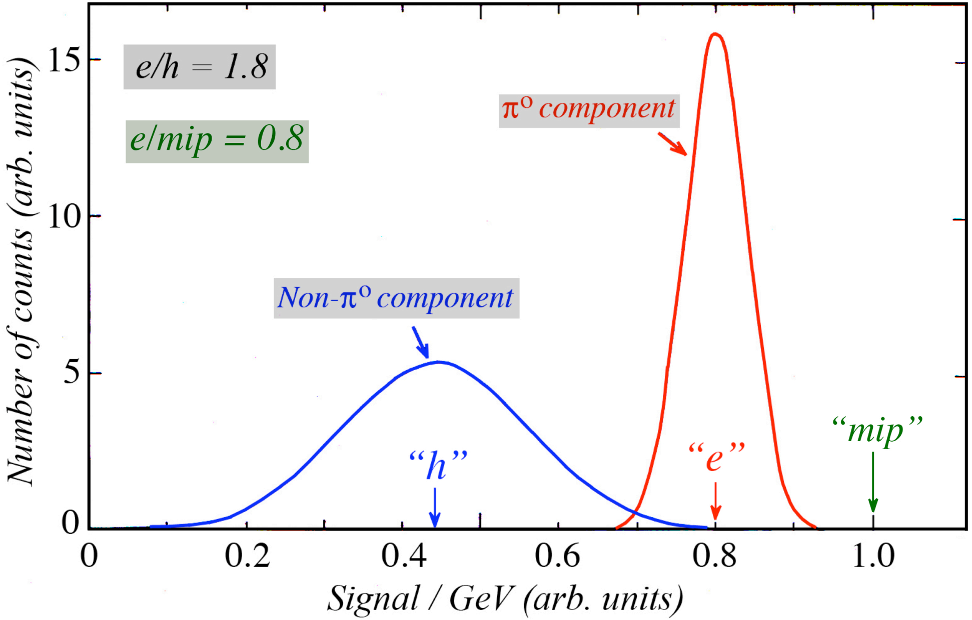


EM and non-EM responses are different

- **Calorimeter response** = the amount of signal (light, charge) produced for a given initial energy
- Calorimeter response to the EM and non-EM components is very different!
  - **e/h** = EM/(non-EM) response
  - Generally e/h > 1

Wigmans



Total response depends on initial particle energy

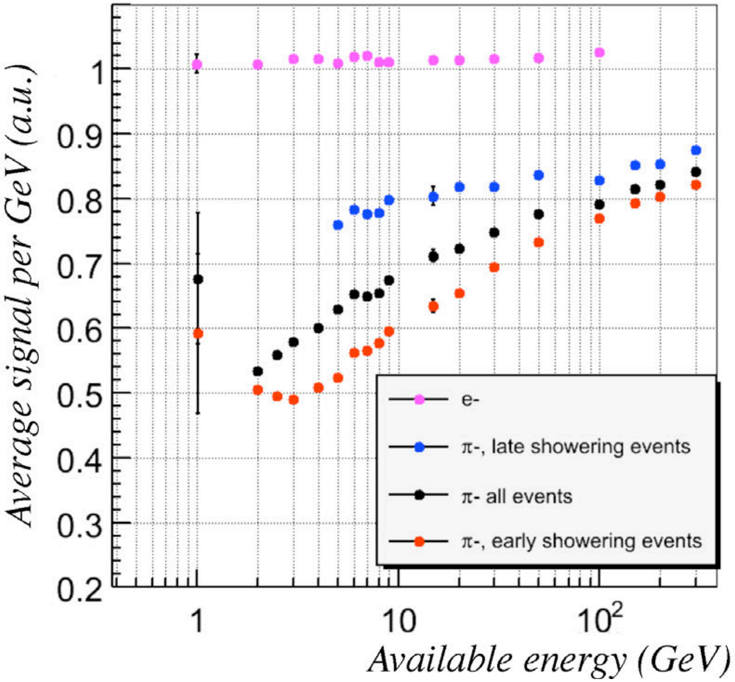
[e/h > 1] & f_{EM} energy dependence

➔

Calorimeter response depends on initial energy

- Calorimeters must be calibrated separately for wide range of energies and for a variety of particle species.
- So far considering single particle response — we also care about response to hadronic jets!
- Calorimeter systems are made from separate EM and hadronic calorimeters with different e/h!!
  - CMS ECAL e/h = 2.4
  - CMS HCAL e/h = 1.3

CMS Note 2007/012



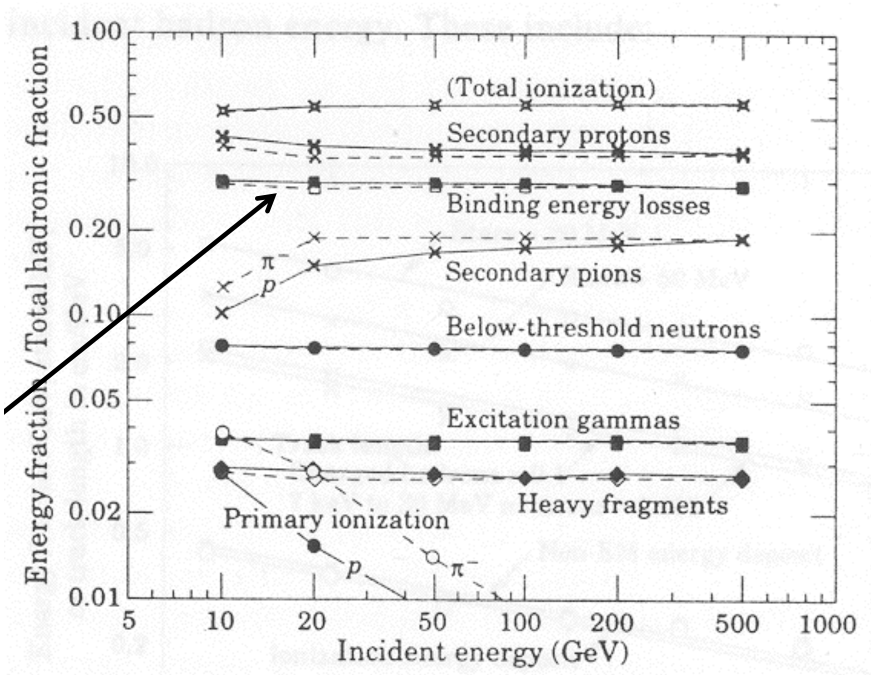
Where does the energy go?

For the hadronic part of the shower

- O(60%) : ionizing particles (**visible**)
- O(10%) : below-threshold neutrons (**somewhat visible, usually delayed**)
- O(30%) : nuclear binding energy and recoil (**invisible**)

Fluctuations about these averages are large!

CALOR MC



Measuring the energy of the showers

Measurement basics

- Goal is to use fundamental interactions to convert energy of original particle into **measurable signal** that is proportional to the original energy.
  - Already discussed : simple proportionality is not practically possible ➔ detailed calibration is required as function of energy.

- Even assuming calibration for the average response is perfect, **fluctuations** inherent to the measurement limit the precision / resolution.

- Key questions impacting detector design:
  - How will we calibrate?
  - How can we minimize the factors that limit the resolution?

What are the "measurable signals" and "active materials"?

Calorimeters use "active material" to produce light or charge

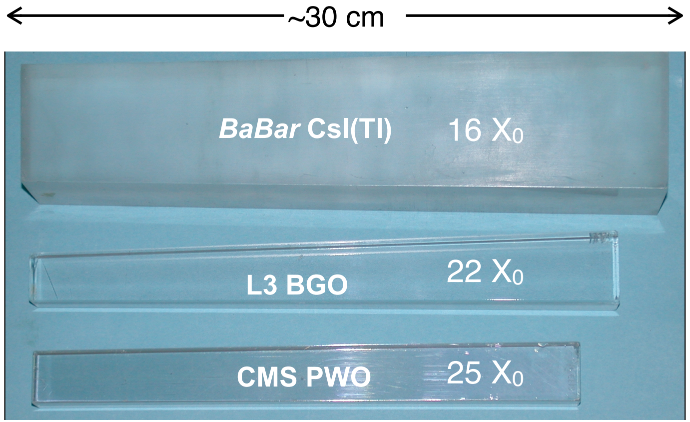
- Ionization in scintillator ➔ light ➔ photosensor ➔ charge
- Ionization in noble liquid or silicon sensor ➔ charge
- Cerenkov radiation ➔ light ➔ photosensor ➔ charge

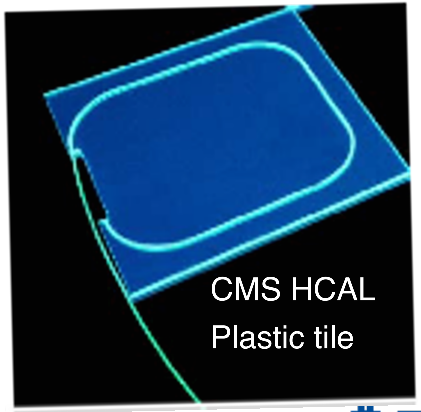
Charge-based active material

- **Silicon** : CMS HGCAL , CALICE
- **Liquid Argon** : ATLAS EM calorimeter

Light-based active material

- **Inorganic scintillating crystal** : CMS ECAL [$PbWO_4$], Babar [CsI(Tl)]
- **Plastic scintillator** : CMS HCAL + ATLAS Tile Cal [polystyrene]
- **Cerenkov** : CMS HF Forward Calorimeter [Quartz]





Crystals used in HEP Calorimeters

Crystal	NaI:Tl	CsI:Tl	CsI	BaF_2	BGO	LYSO:Ce	PWO	PbF_2
Density (g/cm^3)	3.67	4.51	4.51	4.89	7.13	7.40	8.3	7.77
Melting Point (°C)	651	621	621	1280	1050	2050	1123	824
Radiation Length (cm)	2.59	1.86	1.86	2.03	1.12	1.14	0.89	0.93
Molière Radius (cm)	4.13	3.57	3.57	3.10	2.23	2.07	2.00	2.21
Interaction Length (cm)	42.9	39.3	39.3	30.7	22.8	20.9	20.7	21.0
Refractive Index[a]	1.85	1.79	1.95	1.50	2.15	1.82	2.20	1.82
Hygroscopicity	Yes	Slight	Slight	No	No	No	No	No
Luminescence[b] (nm) (at peak)	410	550	420 310	300 220	480	402	425 420	-
Decay Time[b] (ns)	245	1220	30 6	650 0.9	300	40	30 10	-
Light Yield[b,c] (photons/MeV)	38,000	63,000	1,400 420	13,680 1,560	8,000	32,000	114 40	-
d(LY)/dT[b] (%/ °C)	-0.2	0.4	-1.4	-1.9 0.1	-0.9	-0.2	-2.5	-
Experiment	Crystal Ball	BaBar BELLE BES III	KTeV Mu2e	TAPS Mu2e-II	L3 BELLE	COMET CMS BTL PIONEER	CMS ALICE PANDA ePIC	A4 G-2

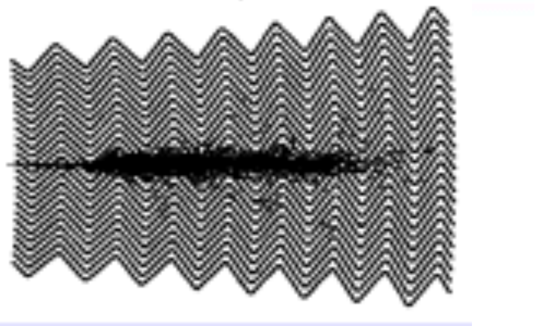
a. at emission peak; b. up/low row: slow/fast component; c. with QE of readout device taken out.

6/11/2024

Presented by Ren-Yuan Zhu, Caltech, in the FCC Week 2024, San Francisco

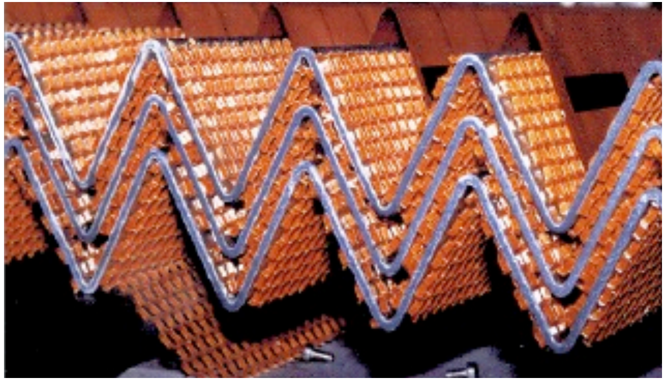
What are the "dense materials"? Total absorption vs. Sampling Calorimeters

Showers must be initiated by dense material since cross section for radiation ~ Z^2.



Total absorption calorimeter

- Dense material and active material is the same
- Transparent crystals with heavy element in matrix : **Pb**WO_4 , **Bi**$_4Ge_3O_{12}$, CsI(**Tl**)
- Appropriate materials are expensive ➔ only practical for EM cals ($\lambda_{\text{int}} \gg X_0$)



Sampling calorimeter

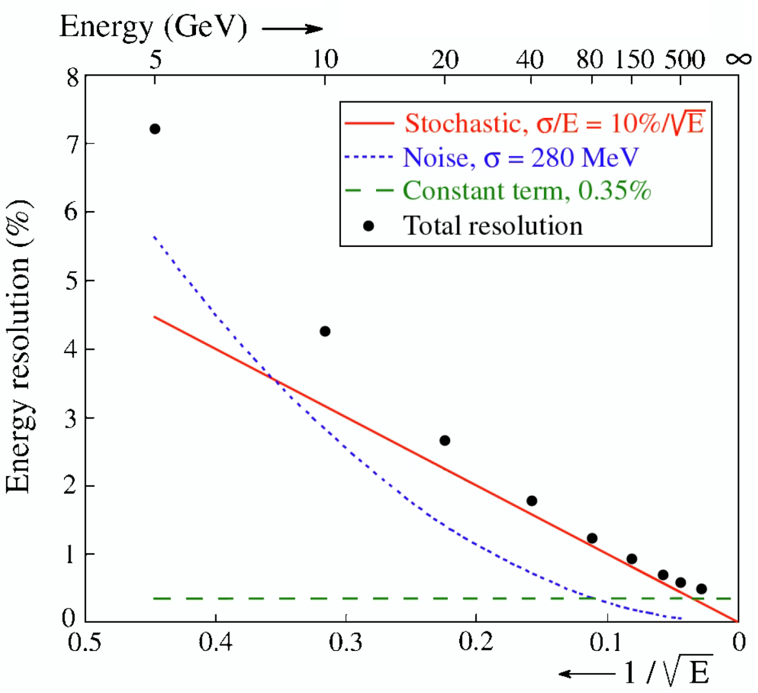
- Dense, inert "absorber" interleaved with light, active material
- CMS HCAL : 17 layers of brass (5-8cm) + plastic scintillator (3.7 mm)
- CMS HGCAL : 48 layers of CuW / stainless steel (4-10cm) + silicon sensors / plastic scintillator (few mm)
- ATLAS LAr ECAL : 2mm Pb "accordion" + 2mm LAr

Detector resolution

Detector resolution

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

- **Noise** term (**a**) fixed in energy
  - e.g. electronics noise
- **Stochastic** term (**b**) scales with √E
  - e.g. random fluctuations in sampling, counting, or path length
- **Constant** term (**c**) scale with E
  - e.g. mis-calibration, detector non-uniformity

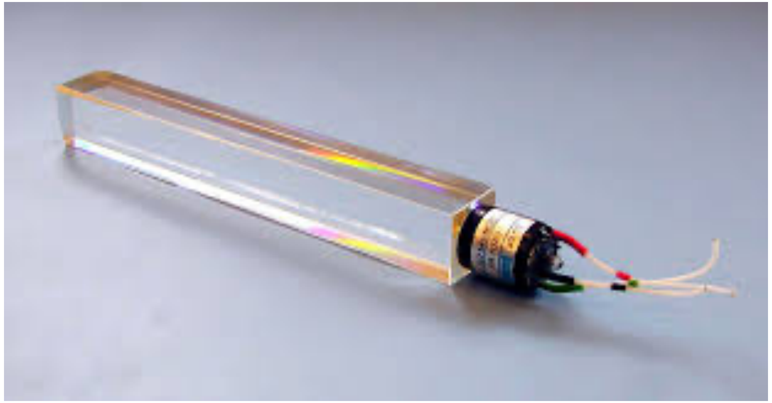


Resolution of ATLAS EM barrel calorimeter at η~0.3 [Gin 95]

Total absorption resolution (stochastic term) : CMS $PbWO_4$ ECAL (e.g.)

- 1 GeV photon incident on CMS ECAL PbWO4 crystal
  - 100,000 photons/GeV ➔ 1/sqrt(100k) = 0.3%
- 96% of photons are absorbed before reaching photon sensor or fail to produce a photoelectron in the sensor
  - 4000 p.e./GeV ➔ 1.6%
- Fluctuations in the photodetector generate additional factor sqrt(2)
  - 1.6% ➔ 2.2%
- Measuring shower in 5x5 crystal area (so that electronics noise does not dominate measurement) results in shower containment fluctuations of 1.5%
  - 2.2% ➔ 2.7%

From Mans



Sampling calorimeter resolution (stochastic term) : ATLAS LAr ECAL (e.g.)

- Almost all energy loss happens in the absorber with secondaries producing ionization in active material.
- Sampling calorimeter can be thought of as counting the number of produced secondaries, which behave as ~MIPs in active material.
  - dE/dx_{MIP} = 2-4 MeV/cm in active material

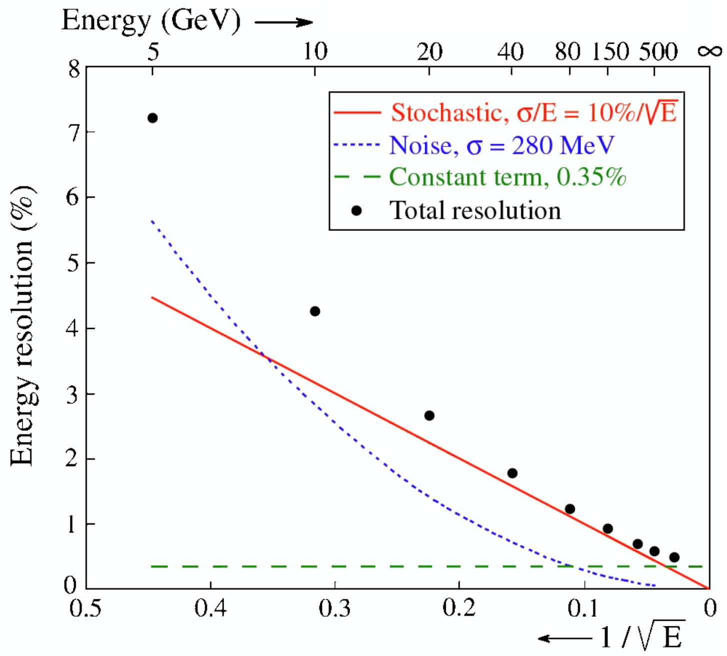
Consider ATLAS LAr ECAL with 2mm Pb absorber

- 1 GeV electron produces 128 secondary particles since $E_C(Pb)$ = 7.8 MeV.
- Each secondary measured by 3 layers of LAr since $X_0(Pb)$ = 6mm
- Thus, each electron is measured 384 times leading to a minimum resolution of

$$\sigma_{\min} = \frac{1}{\sqrt{384}} = 5.1\%$$

Mans

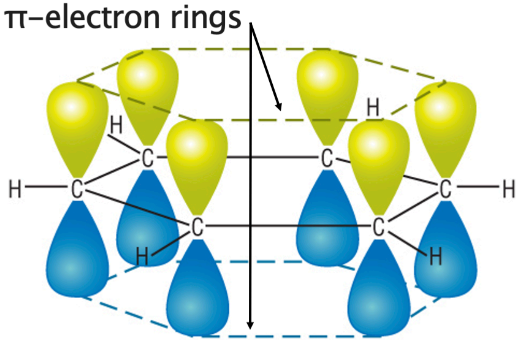
- Additional effects degrade actual stochastic term to ~10% at 1 GeV.



Components of scintillation / light systems

Scintillation : plastic scintillator (e.g.)

- **Base material** is excited by ionization at molecular level and emits UV light in de–excitation.
  - In general, base material is nearly opaque to initial UV light.
- **Secondary fluors** absorb primary UV light and re–emit in visible part of spectrum.
- Primary scintillation light (from base) results from excitation and de–excitation of **benzene** rings.
  - S1➔S0 decay is fast scintillation (nsec)
  - S1➔T1 decay is slow phosphoresence (msec)



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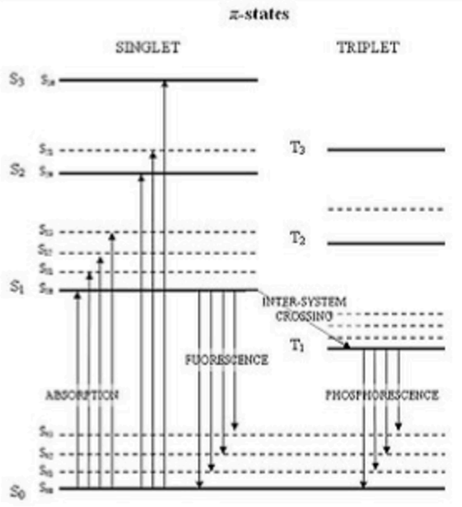
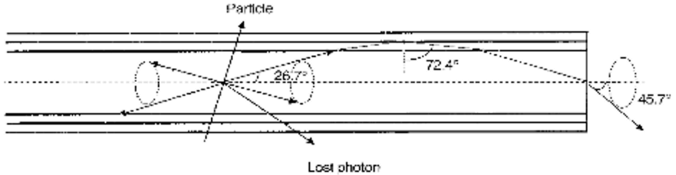
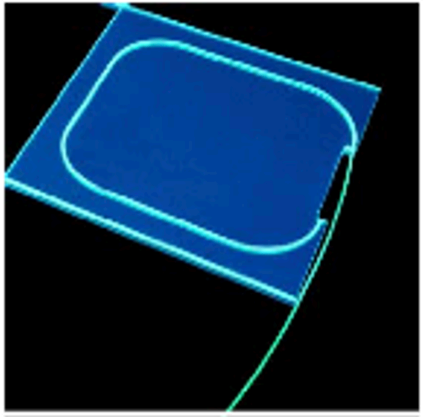


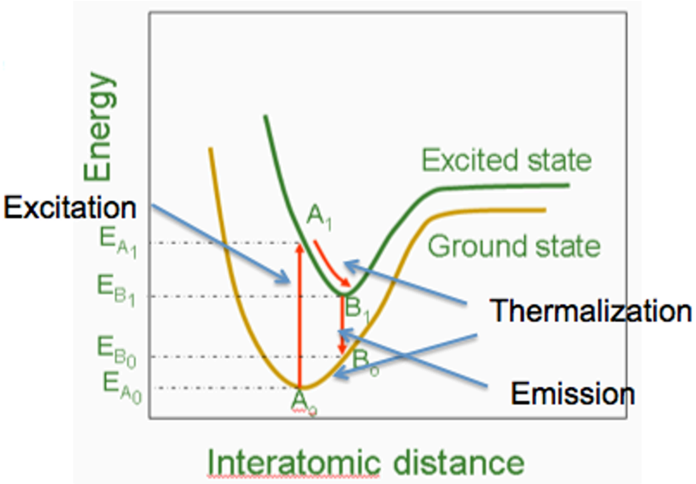
Wave-length shifting

- Scintillation light is **emitted isotropically** in HCAL tile.



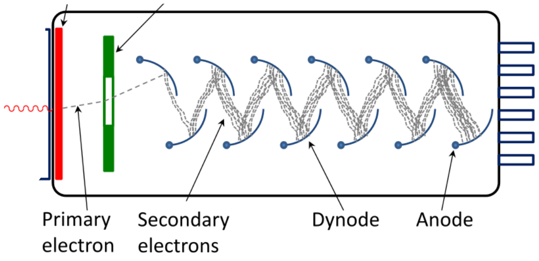
- How do we get it out?
  - **Optical fiber**, but any light that can enter fiber can also exit, so
  - **Wavelength shifting fiber** absorbs light and re-emits isotropically at longer wave so that ~5% is **captured through total internal reflection**.
- Wavelength shifting results from **Stokes shift**.





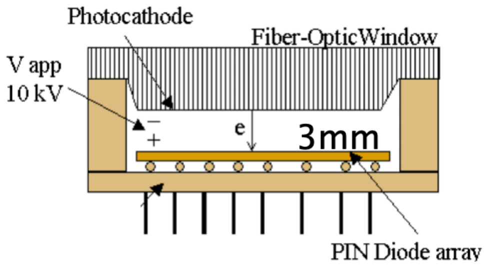
Photosensors

Photomultiplier Tube



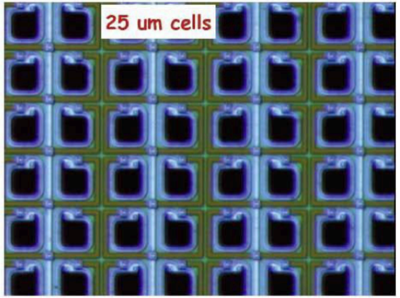
- p.e. accelerated over 2kV into dynode chain
- Secondary emission electrons provide gain 10^6

Hybrid Photodiode



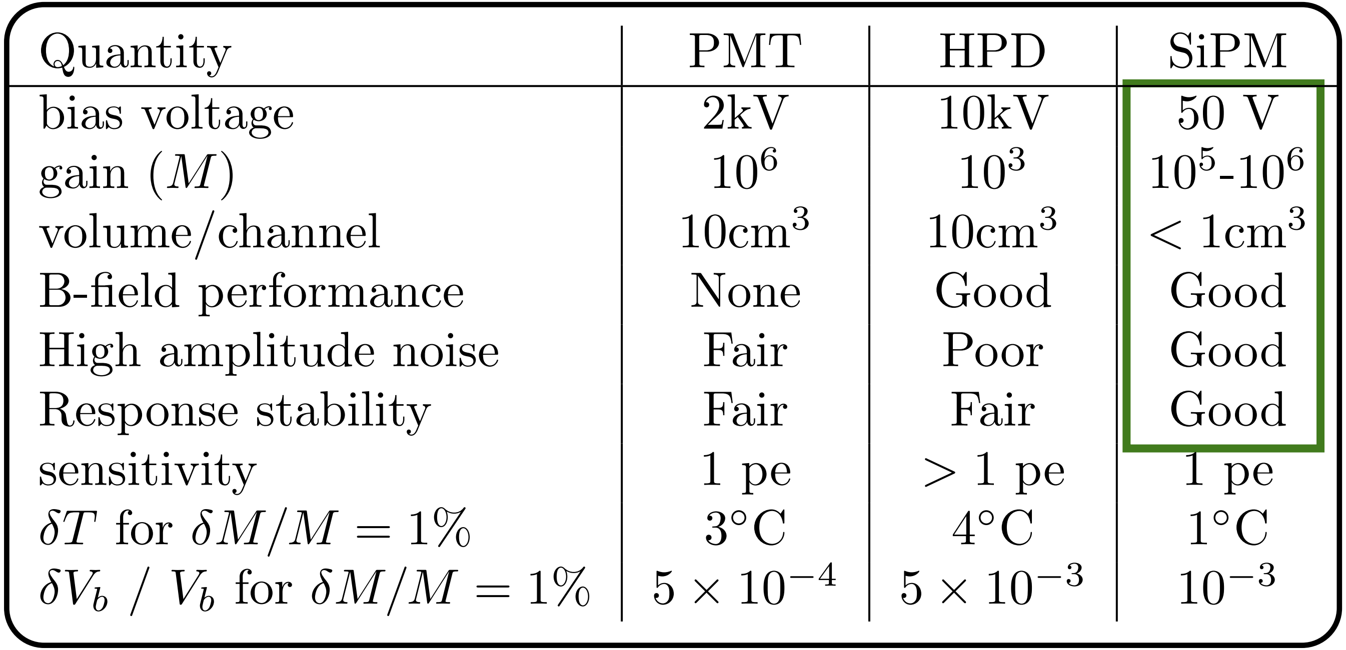
- photoelectron produced in photocathode
- accelerated over 10kV/3mm.
- gain = $V_{app}/3.6$ eV = 2000

Silicon Photomultiplier



- array of binary GAPD,
- gain = $C_{GAPD} \times (V_{op} - V_{bd})$
  $= 100$ fF (1V) $= 10^6$

Photosensors



Quantity	PMT	HPD	SiPM
bias voltage	2kV	10kV	50 V
gain (M)	10^6	10^3	10^5-10^6
volume/channel	10cm^3	10cm^3	$< 1\text{cm}^3$
B-field performance	None	Good	Good
High amplitude noise	Fair	Poor	Good
Response stability	Fair	Fair	Good
sensitivity	1 pe	$>$ 1 pe	1 pe
δT for $\delta M/M = 1\%$	3°C	4°C	1°C
$\delta V_b\ /\ V_b$ for $\delta M/M = 1\%$	5×10^{-4}	5×10^{-3}	10^{-3}

Biggest SiPM challenge is radiation-induced dark current

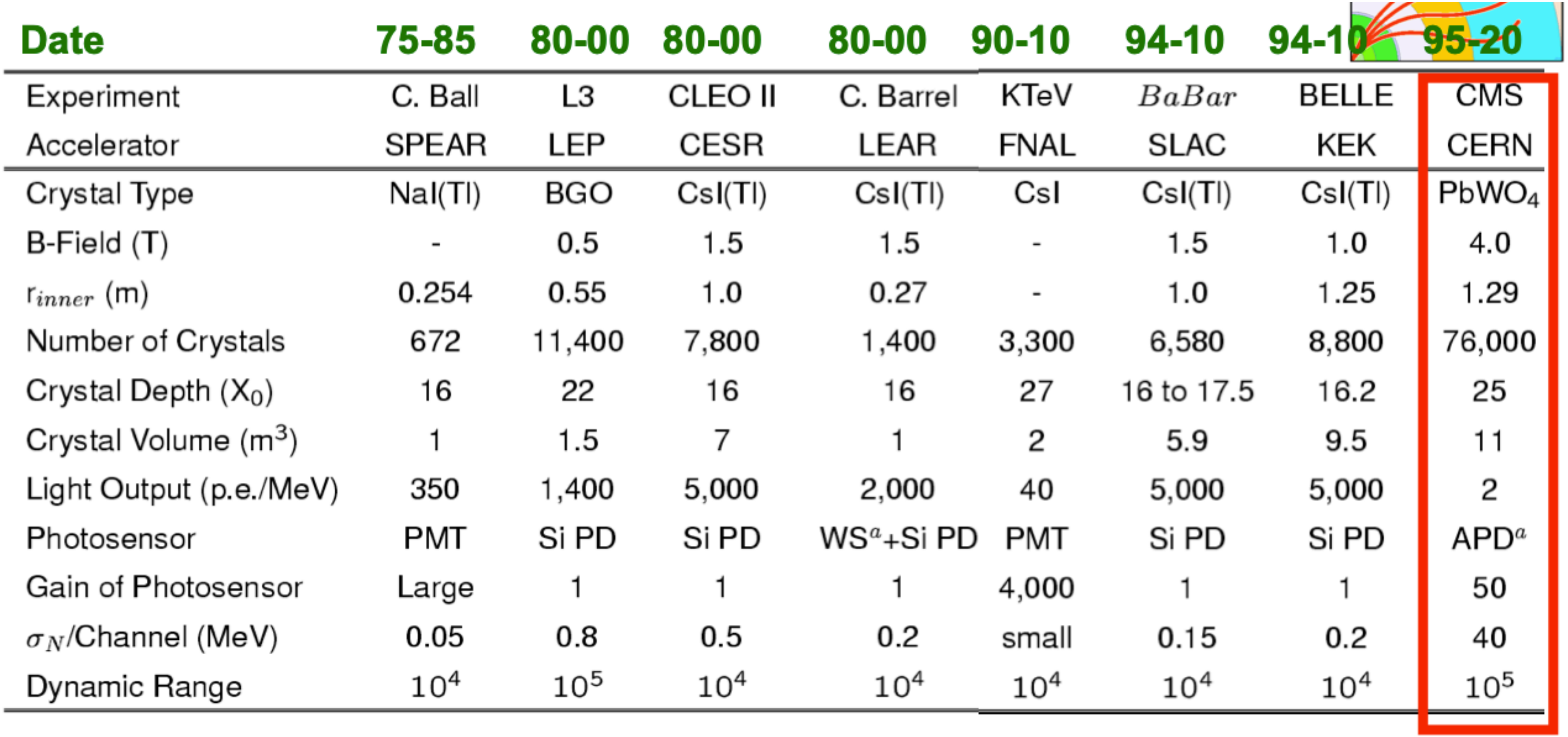
Next lecture on Friday

- Build on these basic elements of calorimetry
- Practical experience with existing LHC calorimeters
- Status and plans for the HL-LHC calorimeter upgrades
- Research directions for calorimeters at future colliders (e+e-, muon, pp)

Additional material

Crystal calorimeters in HEP

C Jessop



Date	75-85	80-00	80-00	80-00	90-10	94-10	94-10	95-20
Experiment	C. Ball	L3	CLEO II	C. Barrel	KTeV	*BaBar*	BELLE	CMS
Accelerator	SPEAR	LEP	CESR	LEAR	FNAL	SLAC	KEK	CERN
Crystal Type	NaI(Tl)	BGO	CsI(Tl)	CsI(Tl)	CsI	CsI(Tl)	CsI(Tl)	$PbWO_4$
B-Field (T)	-	0.5	1.5	1.5	-	1.5	1.0	4.0
r_{inner} (m)	0.254	0.55	1.0	0.27	-	1.0	1.25	1.29
Number of Crystals	672	11,400	7,800	1,400	3,300	6,580	8,800	76,000
Crystal Depth (X_0)	16	22	16	16	27	16 to 17.5	16.2	25
Crystal Volume (m^3)	1	1.5	7	1	2	5.9	9.5	11
Light Output (p.e./MeV)	350	1,400	5,000	2,000	40	5,000	5,000	2
Photosensor	PMT	Si PD	Si PD	WS^a+Si PD	PMT	Si PD	Si PD	APD^a
Gain of Photosensor	Large	1	1	1	4,000	1	1	50
σ_N/Channel (MeV)	0.05	0.8	0.5	0.2	small	0.15	0.2	40
Dynamic Range	10^4	10^5	10^4	10^4	10^4	10^4	10^4	10^5