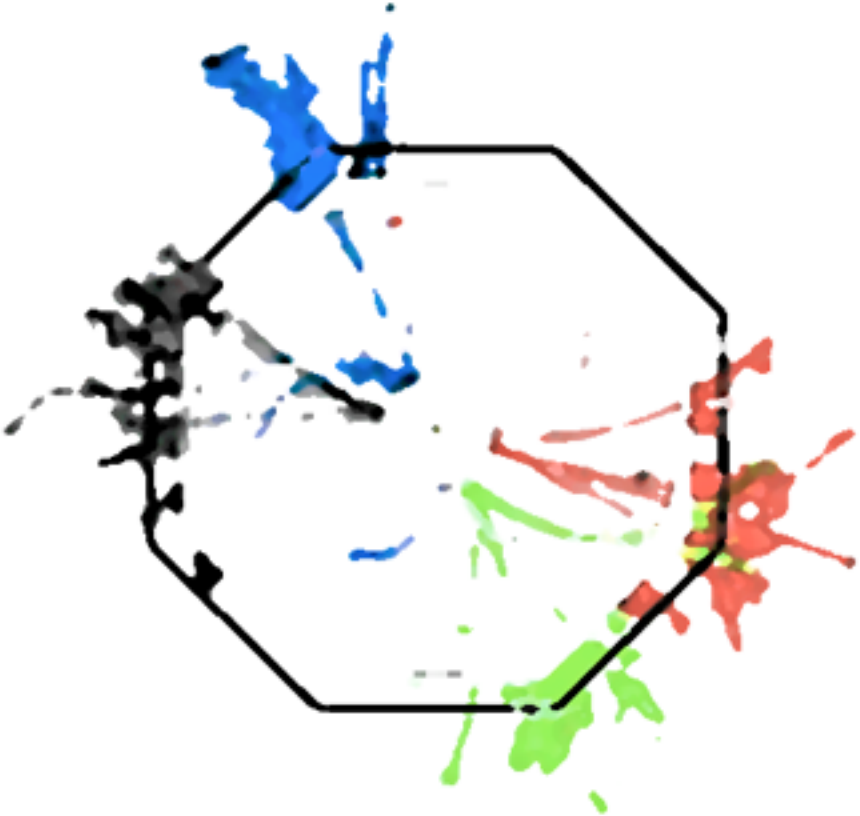

Calorimeters
- Part I -

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DER FORSCHUNG | DER LEHRE | DER BILDUNG

Outline

- Lecture 1 – Basics of calorimetry for HEP
  - Signal generation
  - Electromagnetic and hadronic processes
  - Sampling vs homogeneous calorimeters
  - 4D shower development
  - Signal detection
  - Response linearity and energy resolution

- Lecture 2 – Future of calorimetry for HEP
  - Highly granular calorimeters
  - The particle flow concept
  - …
  - Calorimeters for medicine (a glimpse…)

Key questions:

- What is a calorimeter used for (in HEP)?

  Measure particle energy

- Of which particles is possible to measure the energy ?

  Stable charged and neutral particles with sufficiently long lifetime of $c\tau > 500\mu m$:

  $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, $p^{\pm}$, K^0, n, γ

- How is the energy of a particle measured?

  Total absorption (destructive process) / conversion into measurable signal

  (NB. issue of muons)

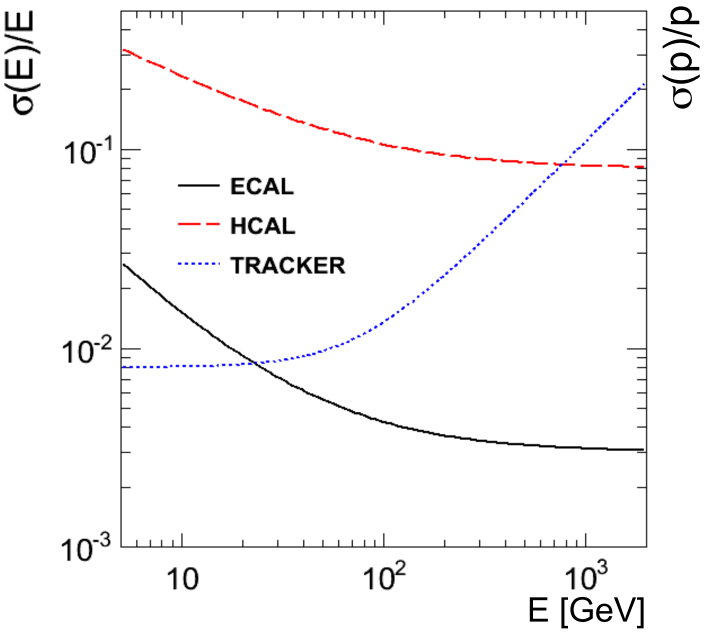
- What is the basic assumption in this method?

  $S = aE$

why calorimeters?

- Measure *charged + neutral* particles

- Performance of calorimeters *improves with energy* and is ~constant over 4π
(Magn. Spectr. anisotropy due to B field)



Calorimeter: $\frac{\sigma_E}{E} \sim \frac{1}{\sqrt{E}}$

e.g. ATLAS:

$\frac{\sigma_E}{E} \approx \frac{0.1}{\sqrt{E}}$

i.e. $\sigma_E/E = 1\%$ @ 100 GeV

Gas detector: $\frac{\sigma_p}{p} \sim p$

e.g. ATLAS:

$\frac{\sigma_p}{p} \approx 5 \cdot 10^{-4} \cdot p_t$

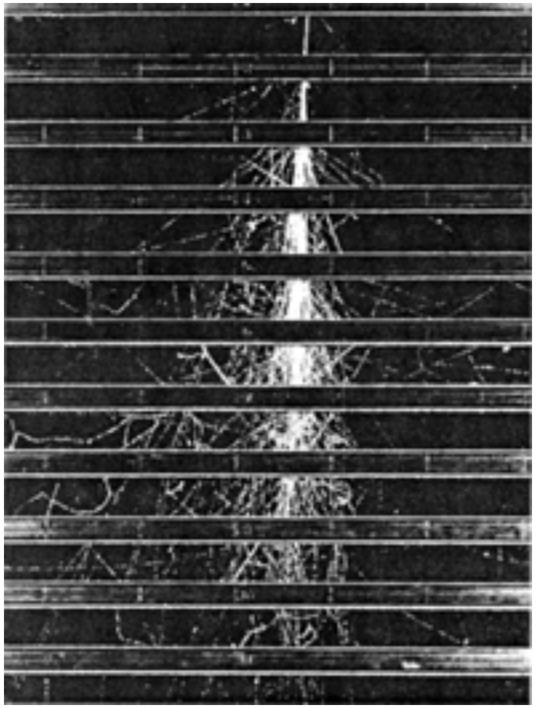
i.e. $\sigma_p/p = 5\%$ @ 100 GeV

- Obtain information *fast* (<100ns feasible)
recognise and select interesting events in real time (*trigger*)

Signal generation

1. A particle deposits its full energy in the calorimeter media

2. The energy is converted into a measurable signal



Signal generation

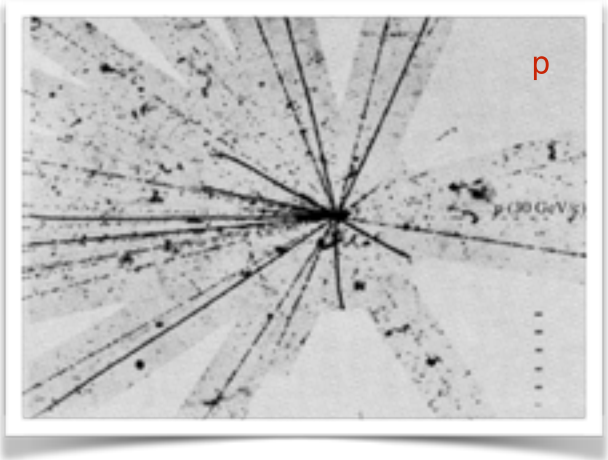
1. A particle deposits its full energy in the calorimeter media

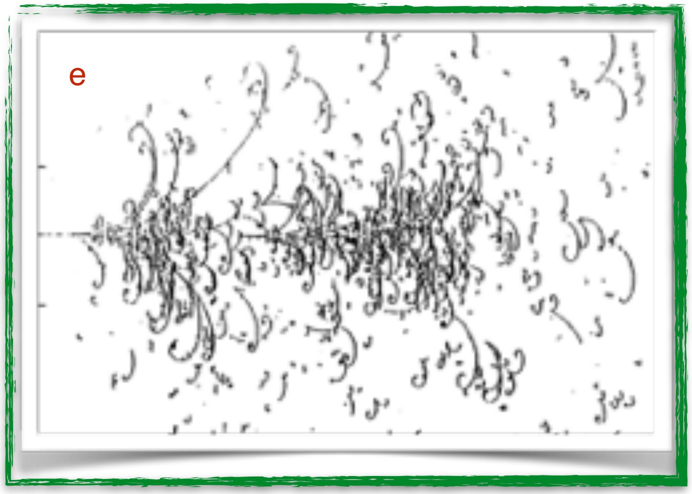
Interaction of particles & matter:

Process are particle & energy dependent

It depends on the kind of material the calorimeter is made of

Analytical description exists for electromagnetic (EM) processes but not for hadronic (HAD) processes





Electromagnetic Showers

Dominant processes at high energies (E > few MeV) :

Photons : Pair production

$$\sigma_{\text{pair}} \approx \frac{7}{9}\left(4\,\alpha r_e^2 Z^2 \ln\frac{183}{Z^{\frac{1}{3}}}\right)$$

$$= \frac{7}{9}\frac{A}{N_A X_0}$$

[X_0: radiation length]
[in cm or g/cm^2]

Absorption coefficient:

$$\mu = n\sigma = \rho\frac{N_A}{A}\cdot\sigma_{\text{pair}} = \frac{7}{9}\frac{\rho}{X_0}$$

X_0 = radiation length in [g/cm^2]

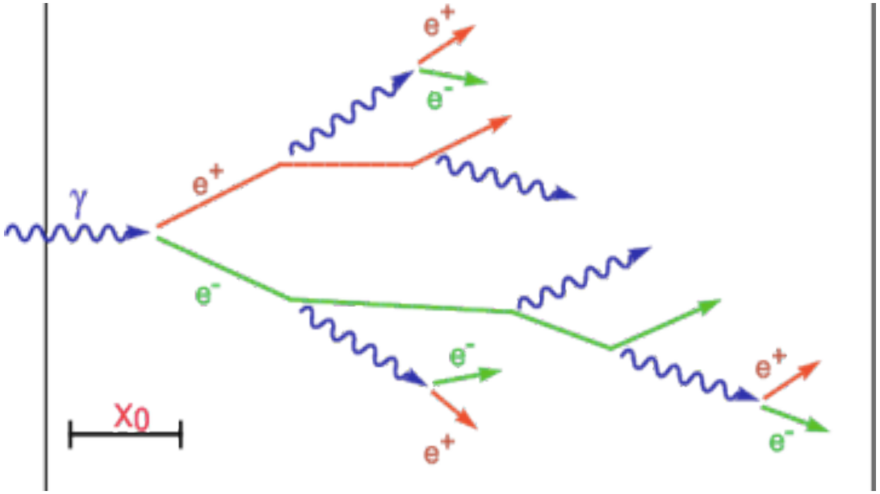
$$\boxed{X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln\frac{183}{Z^{1/3}}}}$$

Electrons : Bremsstrahlung

$$\frac{dE}{dx} = 4\alpha N_A\,\frac{Z^2}{A} r_e^2 \cdot E\ \ln\frac{183}{Z^{\frac{1}{3}}} = \frac{E}{X_0}$$

$$\rightarrow\ E = E_0 e^{-x/X_0}$$

After passage of one X_0 electron has only (1/e)th of its primary energy ...
[i.e. 37%]



Electromagnetic Showers

An alternating sequence of interactions leads to a cascade

Simplified shower model [Heitler]

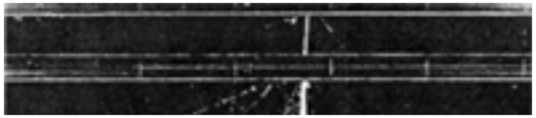
$E > E_c$: shower development governed by X_0

e^- loses energy via Bremsstrahlung

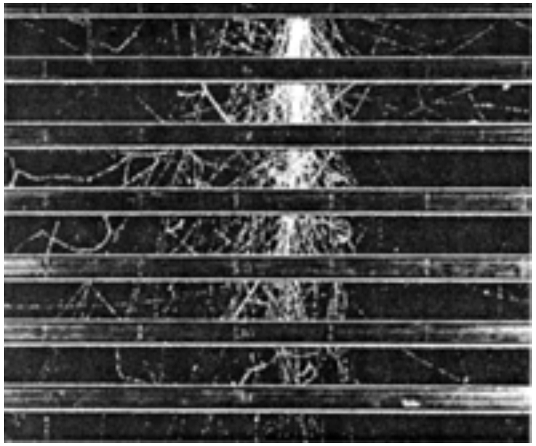
γ pair production with *mean free path* 9/7 X_0

Number of particles doubles every X_0 of material,

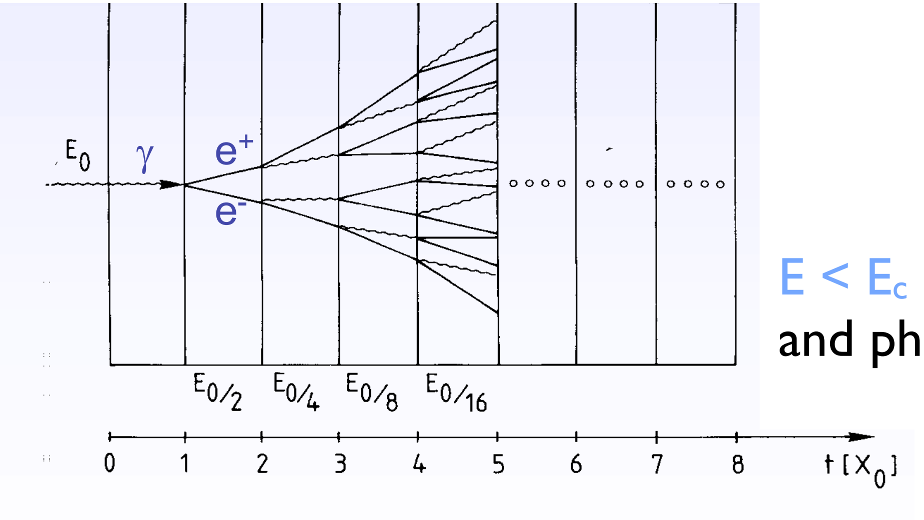
till the particles energy reaches E_c



Cloud chamber photo of electromagnetic cascade between spaced lead plates.



Pic: MIT cosmic ray group



$$\boxed{N_{\max} = 2^{t_{\max}} = \frac{E_0}{E_c}}$$

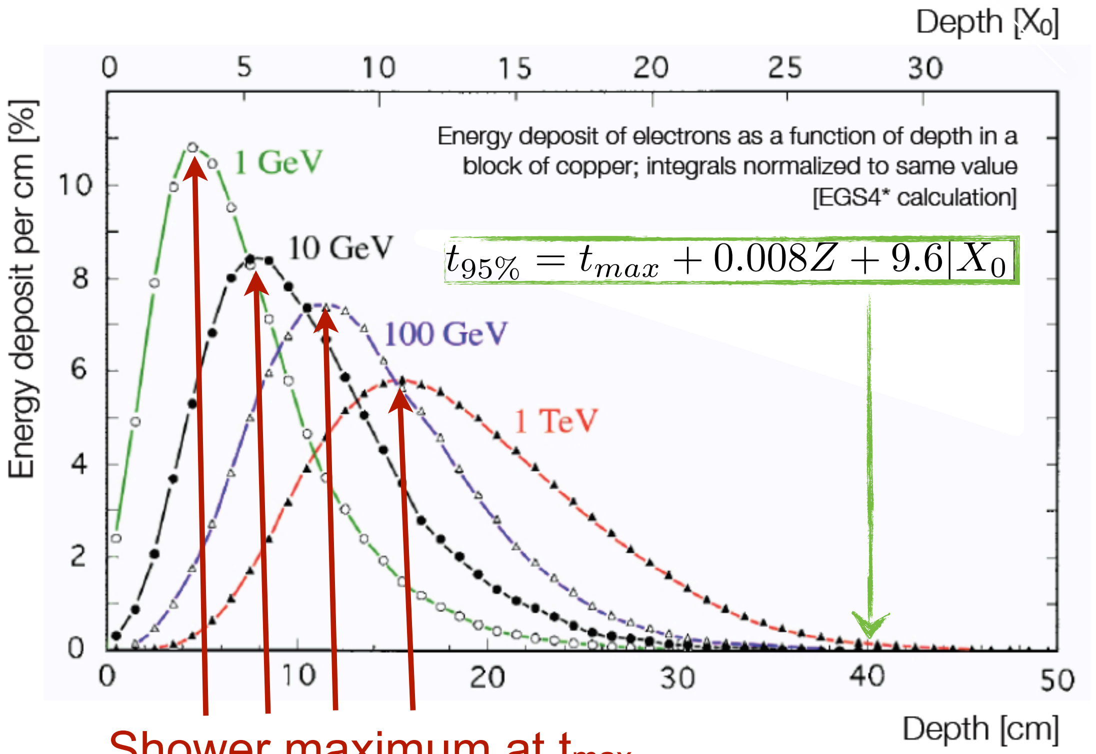
$E < E_c$: energy loss only via ionization/excitation and photo- absorption

EM Shower Properties

- Shower continues until energy of particles below critical energy

$$t_{max} = \frac{\ln \frac{E_0}{E_c}}{\ln 2} \qquad N_{max} \simeq \frac{E_0}{E_c}$$

Key feature in calorimetry:
Shower increases longitudinally with the logarithm of the incident particle energy
➡ Calorimeters can be compact



Energy deposit of electrons as a function of depth in a block of copper; integrals normalized to same value [EGS4* calculation]

$t_{95\%} = t_{max} + 0.008Z + 9.6\,[X_0]$

Shower maximum at t_{max}

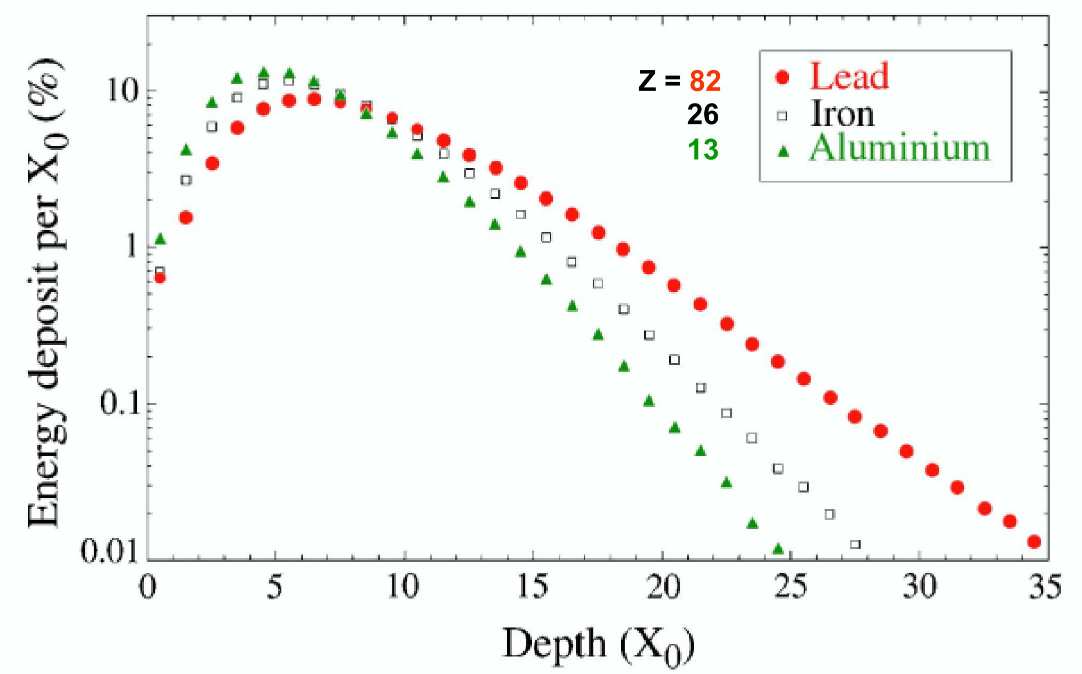
Some numbers: $E_c \approx 10$ MeV, $E_0 = 1$ GeV ➝ $t_{max} = \ln 100 \approx 4.5$; $N_{max} = 100$ $t_{95\%} \sim 10\ X_0$
$E_0 = 100$ GeV ➝ $t_{max} = \ln 10000 \approx 9.2$; $N_{max} = 10000$ $t_{95\%} \sim 20\ X_0$

	Szint.	LAr	Fe	Pb	W
X_0(cm)	34	14	1.76	0.56	0.35

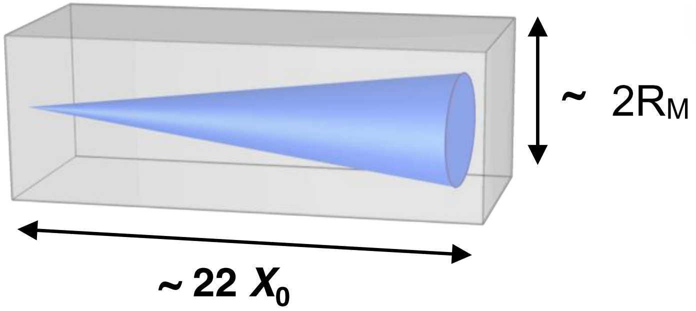
➔ 100 GeV electron contained in 16 cm Fe or 5 cm Pb

EM shower - a more complex reality

- Shower maximum depends slightly on material
- After maximum the shower decays via ionization and Compton scattering
- The process is slower for high-Z materials NOT proportional to X_0



EM Shower Properties

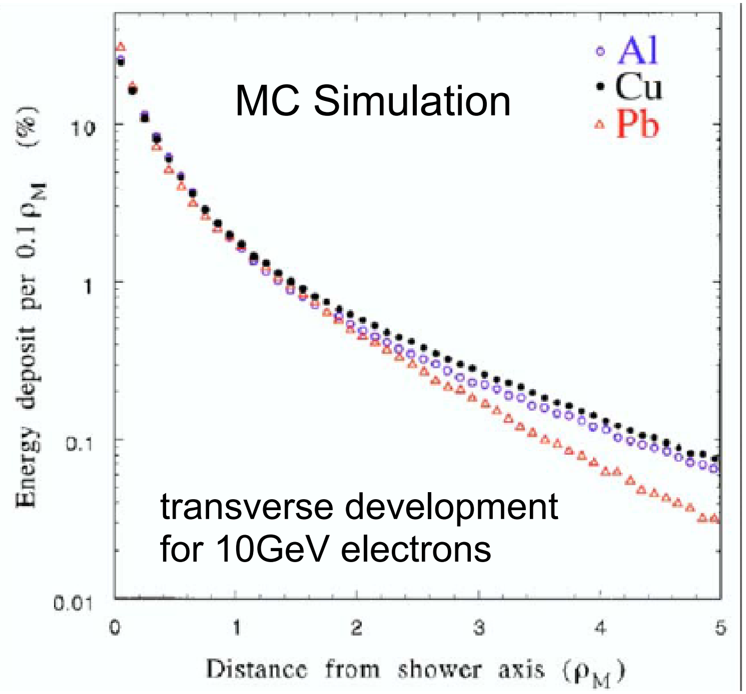


- Longitudinal development governed by the radiation length X_0
- Lateral spread due to electron undergoing multiple Coulomb scattering [Molière theory]: 95% of the shower cone is located in a cylinder with radius 2 R_M

$$R_M = \frac{E_s}{E_c} X_0 \approx \frac{21MeV}{E_c} X_0$$

$$E_s = \sqrt{\frac{4\pi}{\alpha}}(m_e c^2) = 21.2\ \text{MeV}$$

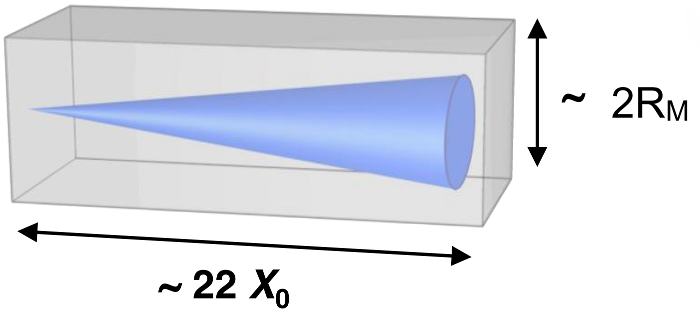
[Scale Energy]



- Lateral width scales with the **Molière radius R_M**
- Important parameter for shower separation

Example

electron with $E_0 = 100$ GeV
in lead glass $E_c = 11.8$ MeV
$X_0 \approx 2$ cm



$$t_{max} = \frac{\ln \frac{E_0}{E_c}}{\ln 2}$$

~ 13 X_0 = 26 cm

$$t_{95\%} = t_{max} + 0.008Z + 9.6[X_0]$$

~ 23 X_0 = 46 cm

$$N_{\max} = 2^{t_{\max}} = \frac{E_0}{E_c}$$

~ 8000

$$R_M = \frac{E_s}{E_c} X_0 \approx \frac{21MeV}{E_c} X_0$$

~ 3.6 cm

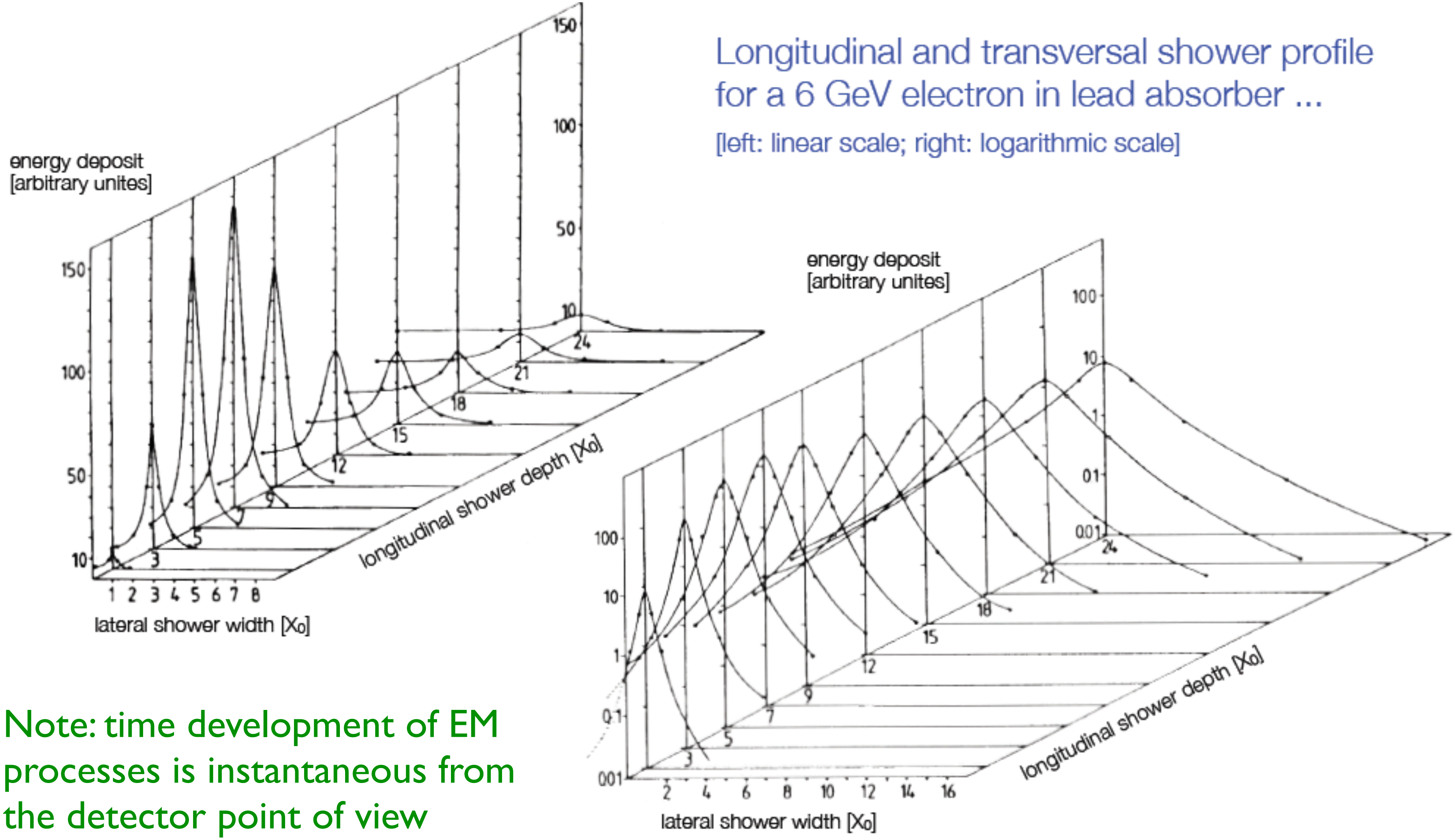
$R(95\%) = 2\ R_M$

~ 7.2 cm

3D development of EM showers

Longitudinal and transversal shower profile for a 6 GeV electron in lead absorber ...

[left: linear scale; right: logarithmic scale]



Note: time development of EM processes is instantaneous from the detector point of view

Signal generation

1. A particle deposits its full energy in the calorimeter media

2. The energy is converted into a measurable signal (charge / light / sound / heat)

- The most used materials:
  - gases / semiconductors / scintillators
- ... but also:
  - Cherenkov radiators / water - ice / antennas / metals or liquids ...

Principle of energy conversion

COST:

- semiconductors: dE/dx or photo-absorption
  + drift of e-h
  eV per e-hole pair

- gases: dE/dx or photo-absorption
  + charge diffusion
  20-40 eV per e-ion pair

- scintillators: dE/dx or photo-absorption
  + light emission
  400-1000 eV per photon

⇨ generated charges or photons yield the measurable signal:
statistical process = the more the better !

Historically

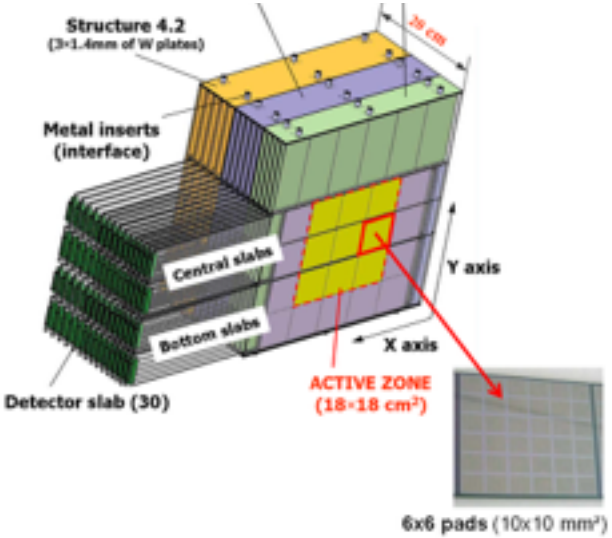
- semiconductors & gas mainly used in tracker detectors
  ➔ p measurement (+ dE/dx)

- scintillators (organic/inorganic) mainly used in calorimeters
  ➔ E measurement

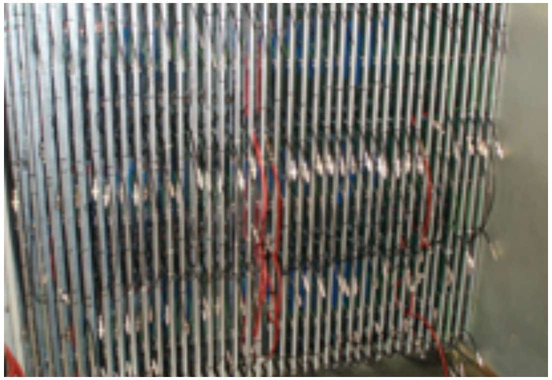
- ... but exceptions exist

as detector developer be open minded and daring !

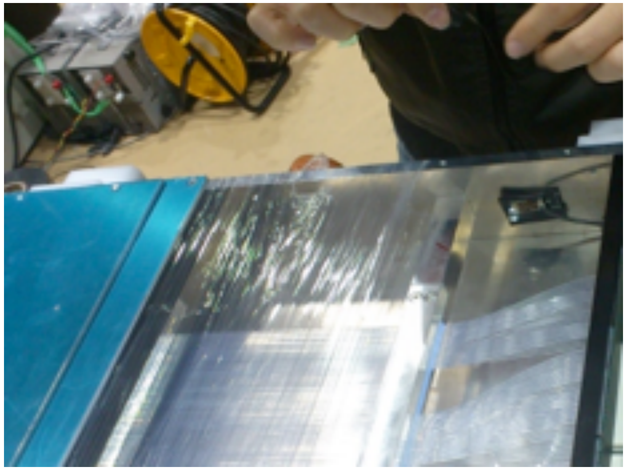
Silicon - ECAL



Gas readout for HCAL

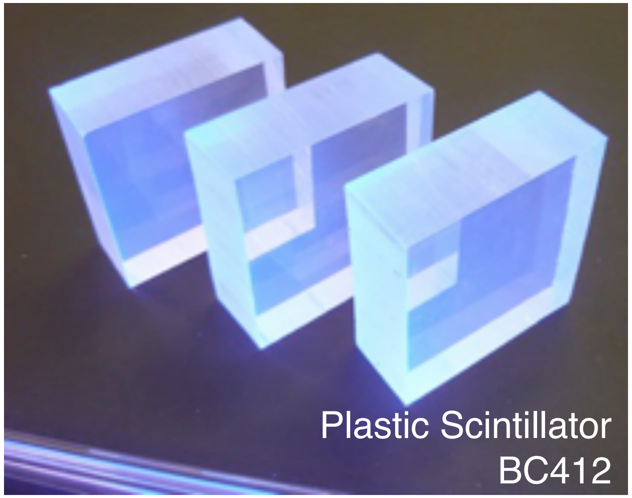


Fiber tracker

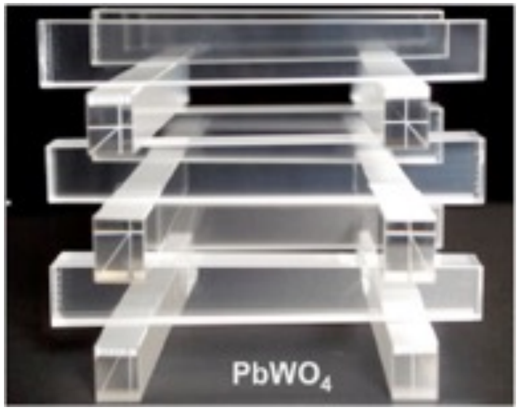


Physics of scintillators

- Emission of photons (UV-visible) by excited atoms
  - observed in noble gases (even liquid !)
  - Aromatic Hydrocarbons (Naphtalen, Anthrazen, organic scintillators) ➔ Most important category
    - Large scale industrial production, mechanically and chemically quite robust.
  - Inorganic Crystals ➔ Substances with largest light yield. Used for precision measurement of energetic photons and in Nuclear Medicine (100-500 keV).



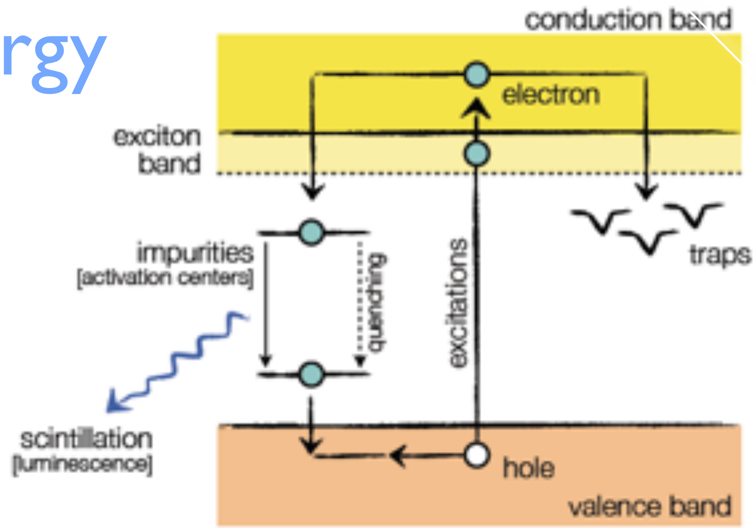
- Very fast (1 ns), plastic scint:
  - Density ~ 1.2 g/cm^3
  - high light yield: ~ 2x10^4 γ / MeV



Inorganic crystals have very high light yield 30x10^4 γ / MeV, but are slow (40-50 ns) or

- $PbWO_4$: Fast (6 ns), dense scintillator,
  - Density ~ 8.3 g/cm^3 (!)
  - but low light yield: ~ 10 photons / MeV

Scintillators to measure the energy



nds in
crystal
scence,
quenching and trapping

Inorganic scintillators

- Fluorescence is known in many natural crystals
  - UV light absorbed → Visible light emitted
- Artificial scintillators + doping impurities
  - Improve visible light emission

Detectors for calorimetry laboratory (day 3 and 4): CsI, BaF2 and LYSO

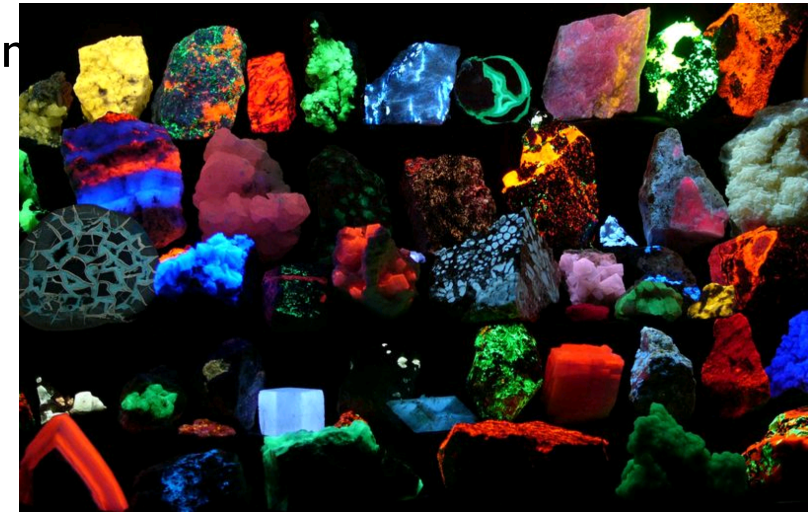
Detection mechanism:

An incident photon or particle ionizes the medium

Ionized electrons slow down causing excitatio

Energy transfer to impurities

Radiation of scintillation photons



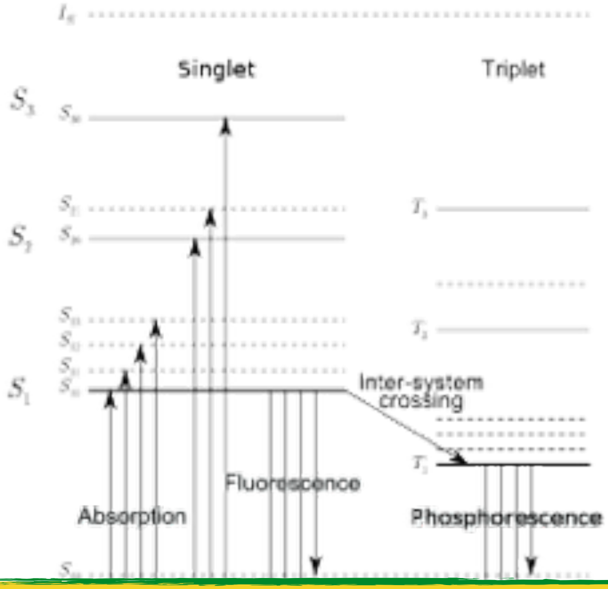
time constants:

Fast: recombination of activation centers [ns … μs]

Slow: recombination due to trapping [ms … s]

Scintillators to measure the energy

Organic scintillators



source: Wikipedia

- Emit light when traversed by ionizing particles (not dense enough for energetic photons)
- Excited states radiate photons in the visible and UV spectra.

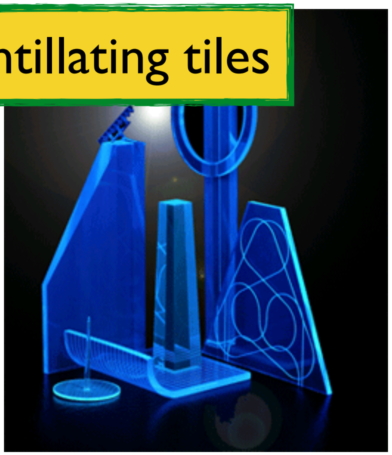
Fluorescence $S_1 \rightarrow S_0$ [$< 10^{-8}$ s]

Phosphorescence $T_1 \rightarrow S_0$ [$> 10^{-4}$ s]

Very fast! [Decay times of O(ns)]

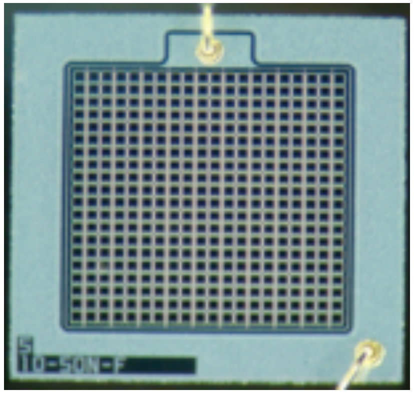
Detectors for calorimetry laboratory (day 1): SIPMs as readout of scintillating tiles

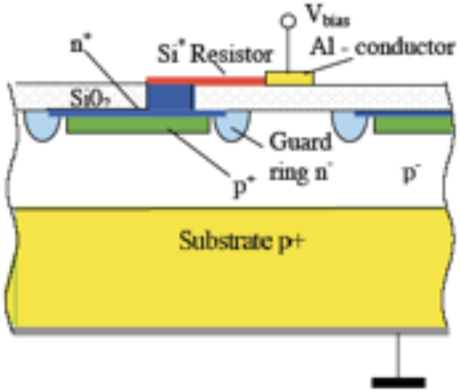
- Organic scintillators can be mixed with polystyrene to form a rigid plastic.
  - Easy to mold
  - Cheaper than crystals
  - Used as slabs or fibers

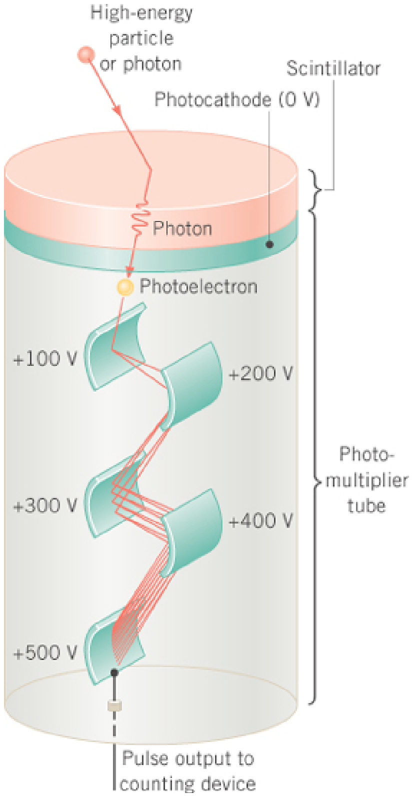


Detecting the light

- Light guided to a photo-detector (i.e. photomultiplier tube, silicon photomultiplier) and converted into charge:
  - Conversion of a photon into electrons via photo-electric effect
  - Amplification of the electron signal by factor 10^5-10^6 via secondary emissions on dynodes or avalanche multiplication in silicon







Source: Cutnell and Johnson, 7th edition image gallery

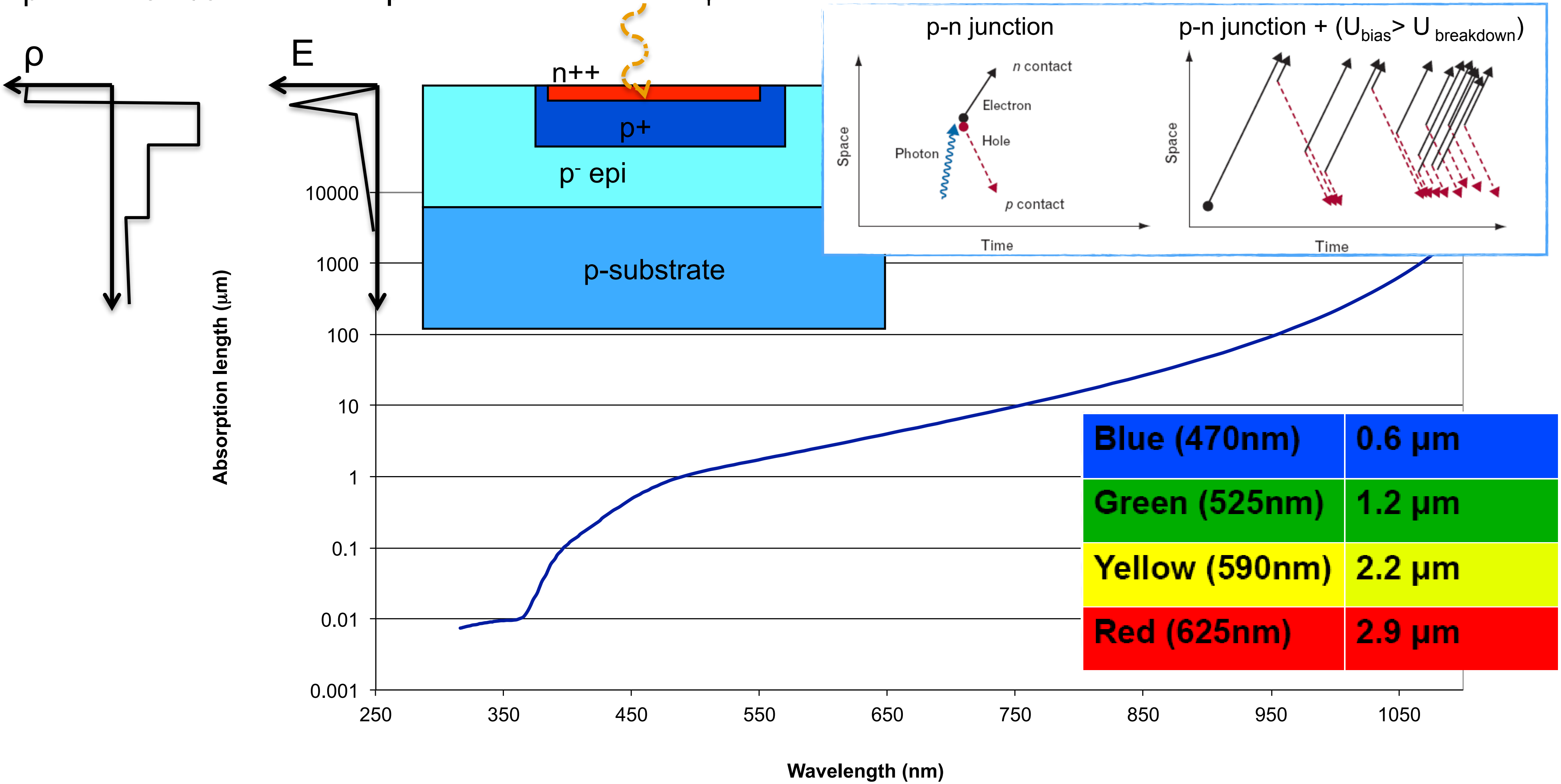
- Photo-detector requirements:
  - cover a large range of wave lengths (UV to IR)
  - good efficiencies, single photon detection possible
  - cover large active areas (SuperKamiokande O 46cm)

Photon absorption in Silicon

Si: ~ 5×10^{22} atoms/cm³
n++: ~ 10^{19} /cm³
p+: ~ 10^{16} /cm³

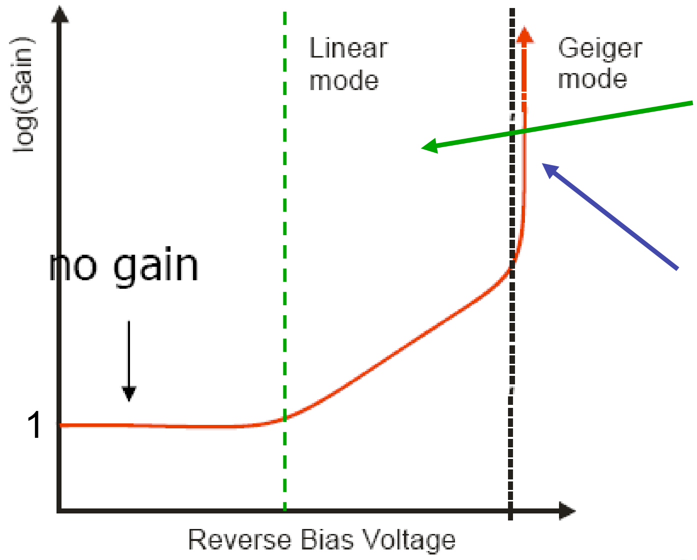
multipl. region ~ 2μm
E field ~3×10^{5} V/cm
μ ~ 10^{7} cm/s

E_γ~1.7-3 eV penetrate ~ 1-5 μm in Si



Blue (470nm)	**0.6 μm**
Green (525nm)	**1.2 μm**
Yellow (590nm)	**2.2 μm**
Red (625nm)	**2.9 μm**

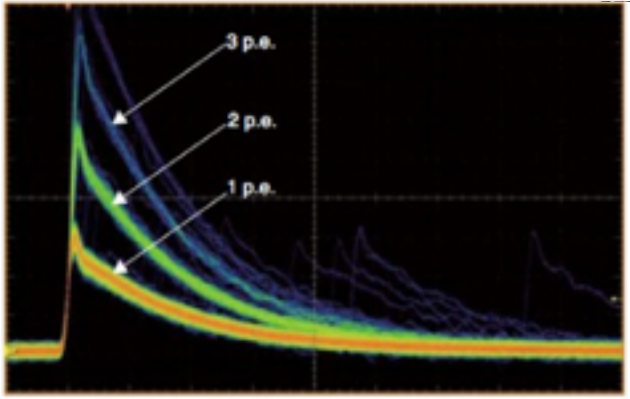
Photon detection in Silicon



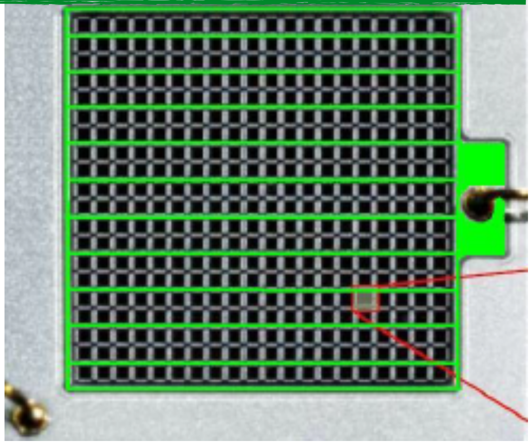
Avalanche Photo-Diode (APD)
operated in linear mode ~ AMPLIFIER (Gain ~ 50-500)
- signal proportional to number of photons deposited (used in CMS ECAL)

Geiger mode Avalanche Photo-Diode (GAPD)
operate above breakdown voltage (Gain ~$1*10^6$)
- a BINARY device
- for practical application use ARRAY of single GAPDs: the Silicon Photo-Multiplier (SiPM)

Detectors for calorimetry laboratory: SIPMs & APD



- all GAPDs connected in parallel, $S = \Sigma S_i$
- Non-linear response: S from Nγ in the same GAPD = S of one γ

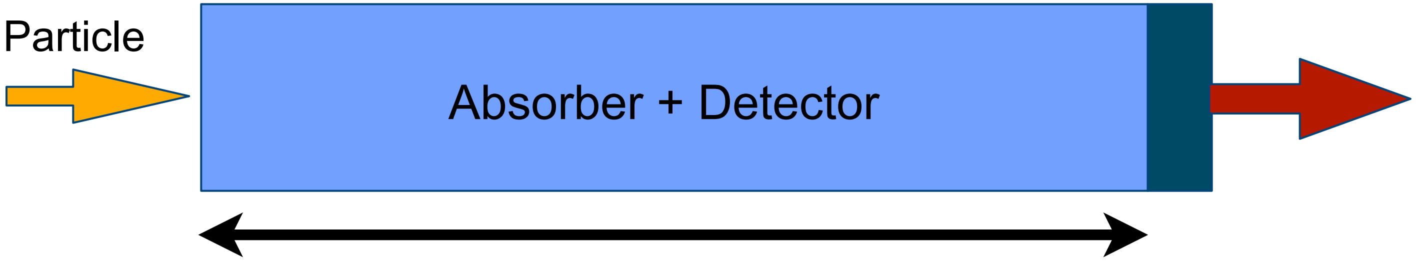


Calorimeter Types

- Most commonly used: Homogeneous and Sampling Calorimeter

Homogeneous Calorimeter

- The absorber material is active; all deposited energy is converted into signal
- Pro: very good energy resolution
- Contra: segmentation difficult, selection of material is limited, expensive

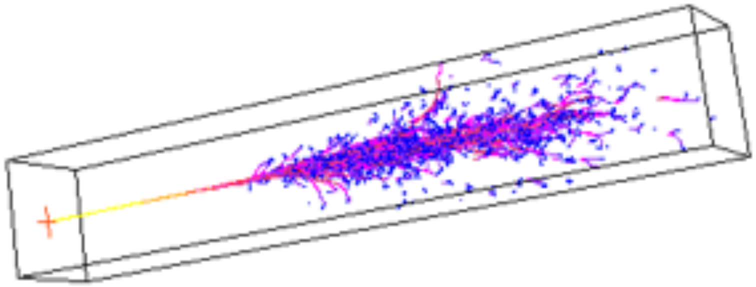


Particle

Absorber + Detector

Read out

long enough to absorb the cascade



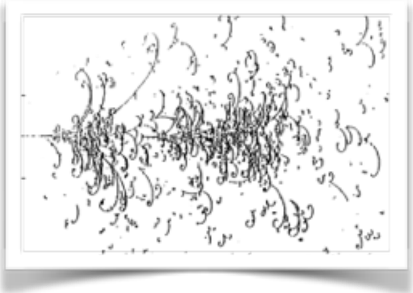
Pic: Cornell

Example: CMS electromagnetic calorimeter

design not suitable for hadronic calorimeters

Calorimeter Types

- Most commonly used: Homogeneous and Sampling Calorimeter



Homogeneous Calorimeter

Pro: very good energy resolution - **why ?**

- Detectable signal is proportional to the total track length of e+ and e- in the active material
- Intrinsic limit on $\sigma(E)/E$ due to fluctuations in the fraction (f_s) of initial energy that generates detectable signal, or the detectable portion of track

$$\frac{\sigma(E)}{E} \propto \frac{\sigma(T_r)}{T_r} \propto \frac{1}{\sqrt{T_r}}$$

$T_r = f_s T_0$

$$T_0 = N_{tot} X_0 \approx \frac{E_0}{E_C} X_0$$

E_C = critical energy (ionization = Bremsstrahlung)

$$\frac{\sigma(E)}{E} \propto \frac{1}{\sqrt{f_s}}\sqrt{\frac{E_C}{X_0}} \propto \frac{1}{\sqrt{f_s}}\sqrt{\frac{Z}{A}}$$

- minimize Z/A
- maximize f_s

$$f_s = \frac{E_0 - N_{max} E_{th}}{E_0}$$

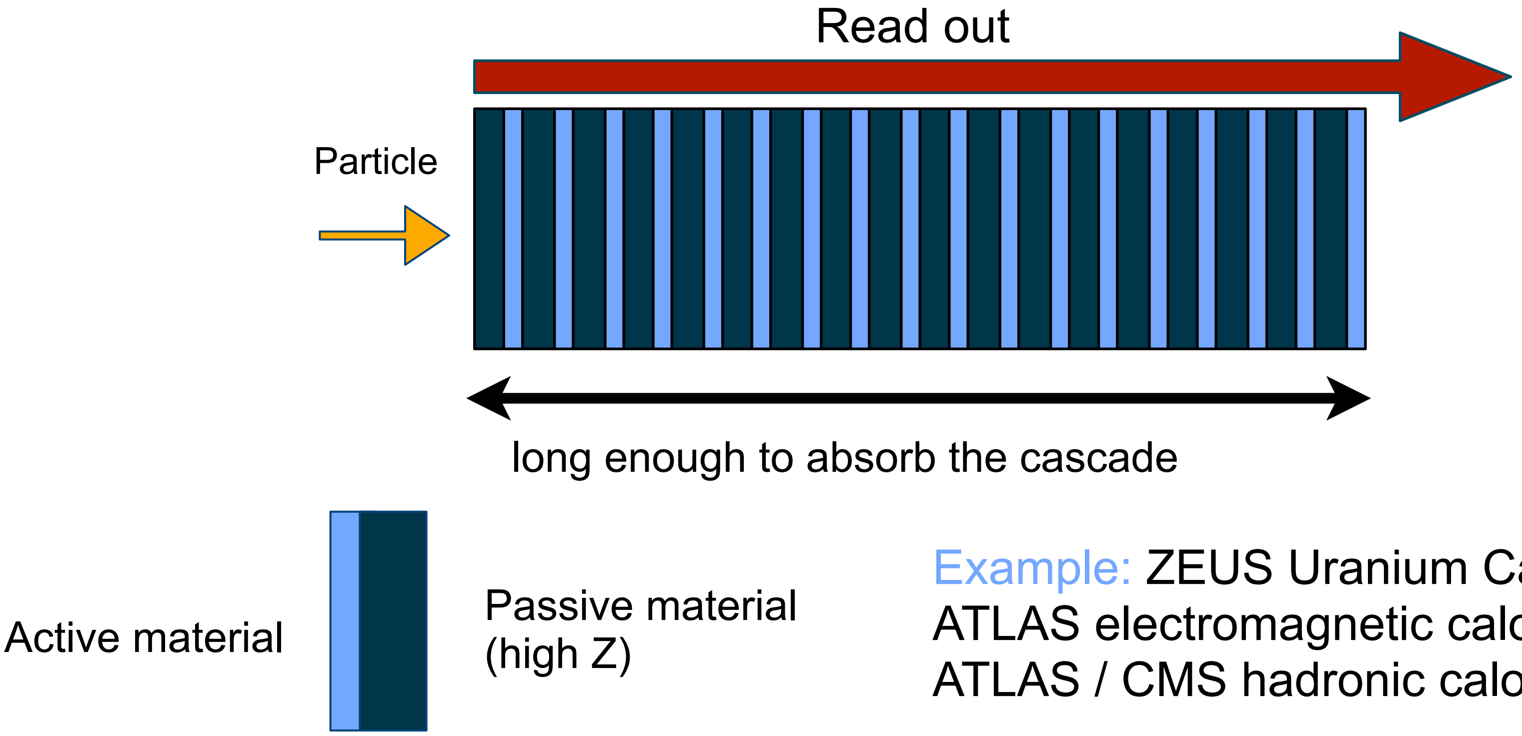
- Homogeneous calorimeter all e+e- over threshold produce signal

  i.e. scintillating crystals E_s~eV, 10^2-10^4 γ/MeV ➔ $\sigma(E)/E \sim 1\text{-}3\% / \sqrt{(E)}$

Calorimeter Types

Sampling Calorimeter

- A structure of passive and active material; a fraction (**Sampling Fraction, f_S**) of the deposited energy is detected (1-5%)
- Pro: Segmentation, compact detectors by the usage of dense materials (W, U)
- Contra: Energy resolution is limited by fluctuations



Example: ZEUS Uranium Calorimeter,
ATLAS electromagnetic calorimeter
ATLAS / CMS hadronic calorimeters, ...

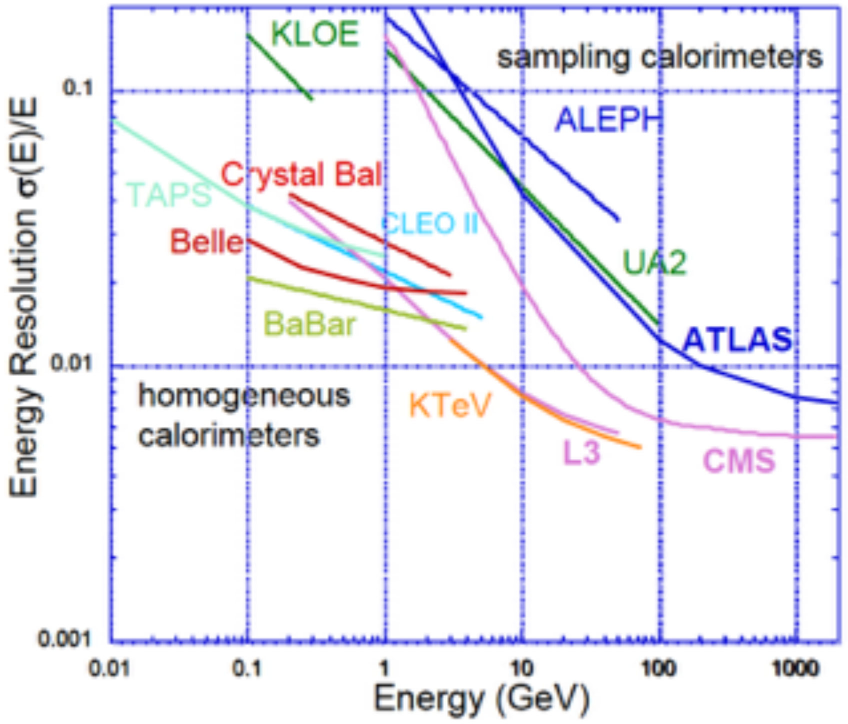
Calorimeter Types

Sampling Calorimeter

- A structure of passive and active material; a fraction (**Sampling Fraction, *fs***) of the deposited energy is detected (1-5%)

$$\frac{\sigma(E)}{E} \propto \frac{\sigma(T_r)}{T_r} \propto \frac{1}{\sqrt{T_r}}$$

$$T_r = f_s T_0 = f_s N_{tot} X_0^{abs} \approx f_s \frac{E}{E_C^{abs}} X_0^{abs}$$



Resolution scales with absorber thickness $t_{abs}=d/X_0$

$$\frac{\sigma(E)}{E} \propto \frac{1}{\sqrt{N_r}} \propto \frac{1}{\sqrt{f_s}}\sqrt{\frac{E_C t_{abs}}{E}}$$

$\sigma(E)/E \sim 10\text{-}20\% / \sqrt{E}$

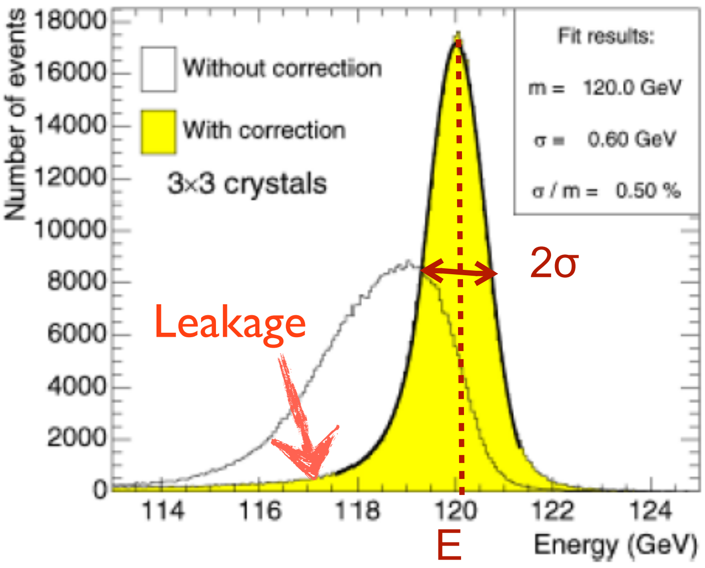
➔ Each system optimised to the energy range & physics of interest for the experiment

Energy resolution

- The **energy resolution** is parametrized as:

$$\frac{\sigma(E)}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + \left(\frac{b}{E}\right)^2 + c^2}$$

or $$\boxed{\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c}$$

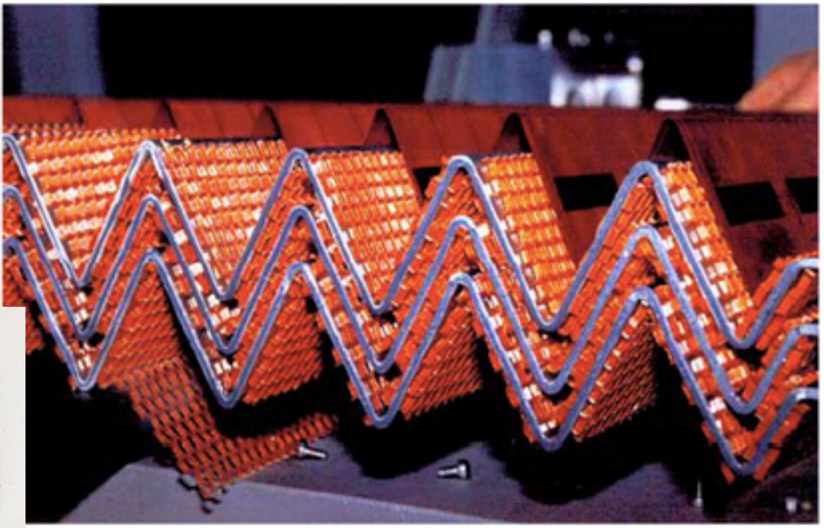


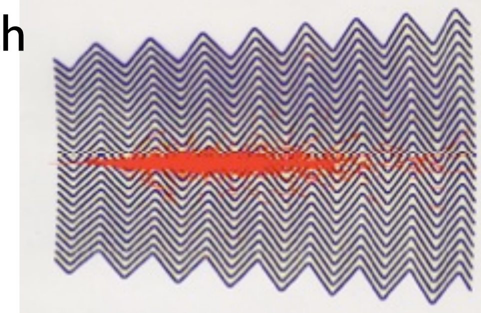
- Stochastic term **a**
  - E ∝ N ➔ σ ∝ 1/√N : all statistical effects contribute
    i.e. intrinsic and sampling fluctuations, photoelectron statistics
- Noise term **b** (energy independent term) relevant at low E
  - Electronic noise, radioactivity
- Constant term **c** (linearly dependent of energy) dominates at high E
  - inhomogeneities, calibration uncertainties, radiation damage, (leakage), ...

Examples of electromagnetic calorimeters

ATLAS EM barrel calorimeter

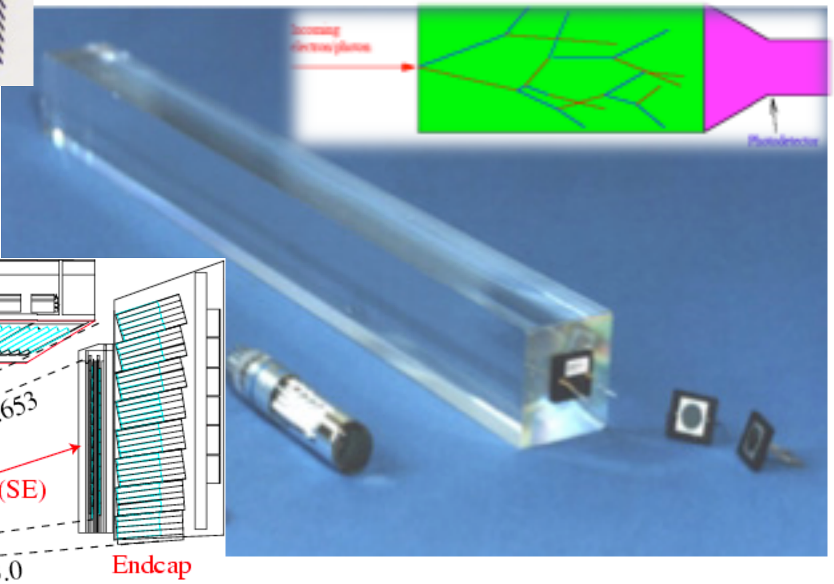
- Honeycomb spacers position the electrodes between the lead absorber plates
- Liquid Argon at 90°K flows through.
- Radiation resistant, no cracks in η
- Accordion structure with Pb-LAr sampling

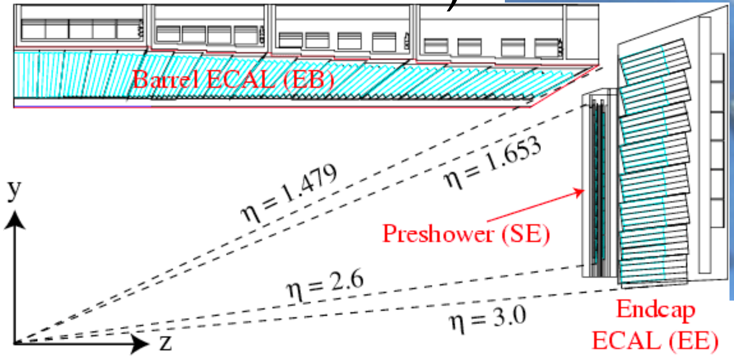




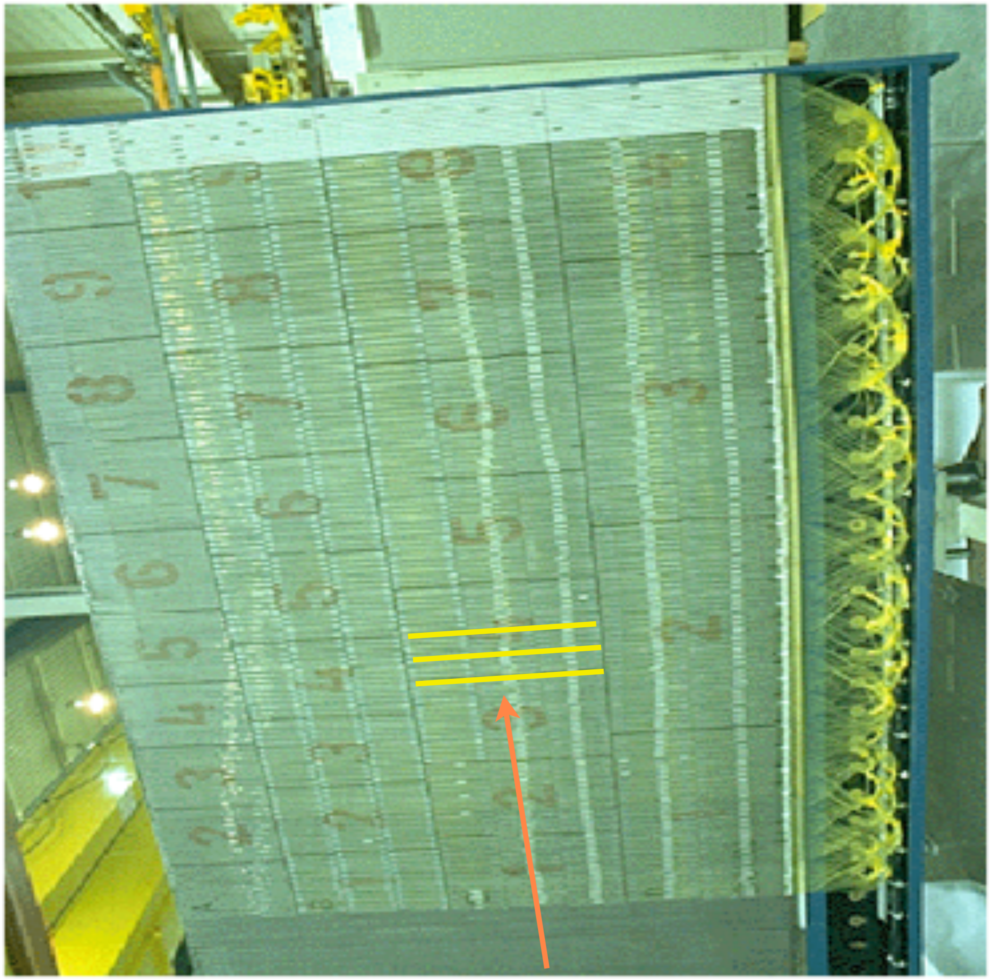
CMS EM barrel calorimeter

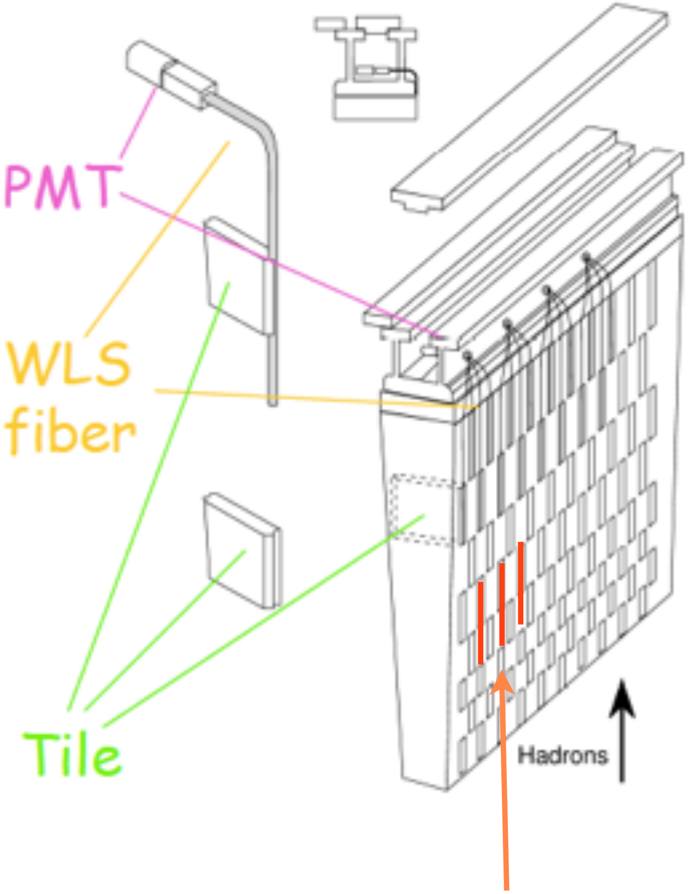
- PbWO4 crystals (230x22x22 mm³)
- Read out by APD (Avalanche PhotoDiodes)
- Homogeneous





Examples of hadronic calorimeters





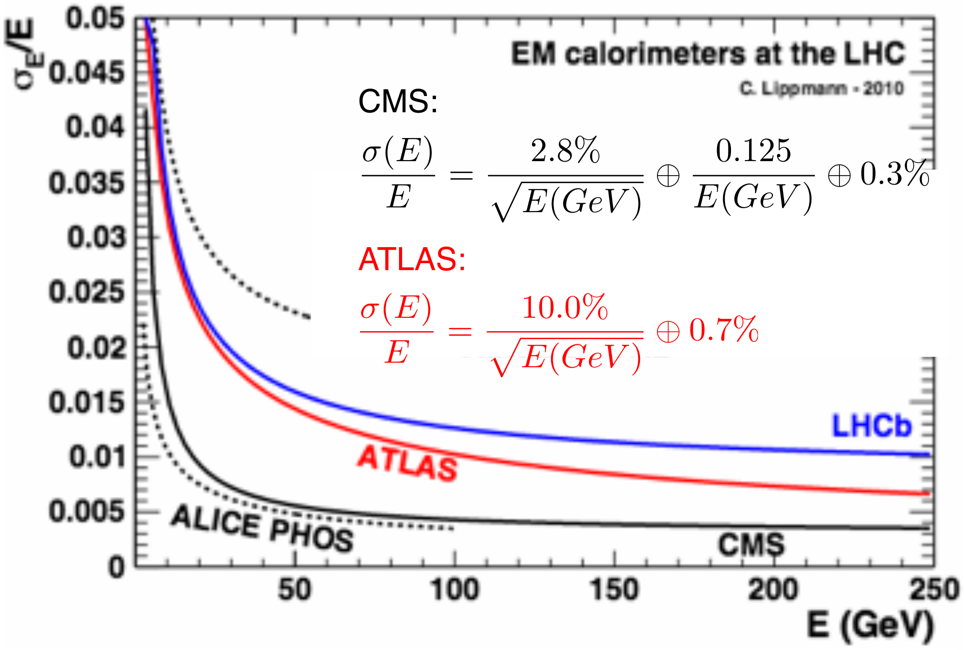
CMS: Brass/scintillator
longitudinal orientation

ATLAS: Fe/scintillator
vertical orientiation

Resolution comparison

Reported energy resolutions for single particles from test beam measurements:

electrons



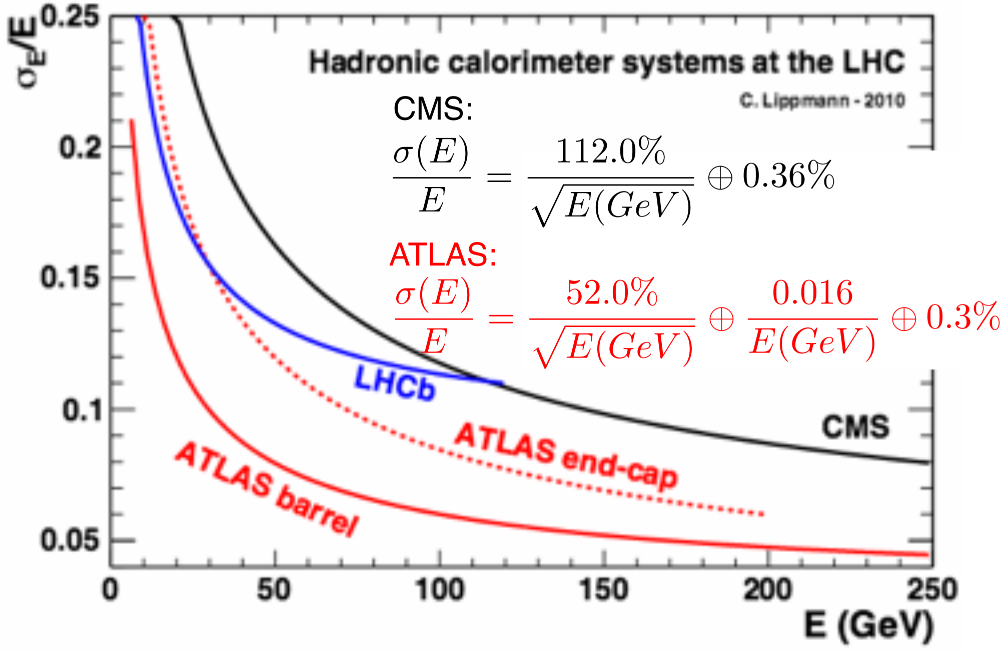
CMS:

$$\frac{\sigma(E)}{E} = \frac{2.8\%}{\sqrt{E(GeV)}} \oplus \frac{0.125}{E(GeV)} \oplus 0.3\%$$

ATLAS:

$$\frac{\sigma(E)}{E} = \frac{10.0\%}{\sqrt{E(GeV)}} \oplus 0.7\%$$

pions



CMS:

$$\frac{\sigma(E)}{E} = \frac{112.0\%}{\sqrt{E(GeV)}} \oplus 0.36\%$$

ATLAS:

$$\frac{\sigma(E)}{E} = \frac{52.0\%}{\sqrt{E(GeV)}} \oplus \frac{0.016}{E(GeV)} \oplus 0.3\%$$

Material upstream the calorimeter degrades E resolution performance:
loss of energy in tracker / support structure / cables /cooling / readout electronics

Why are hadronic calorimeters worse than EM ones?
Signal generation

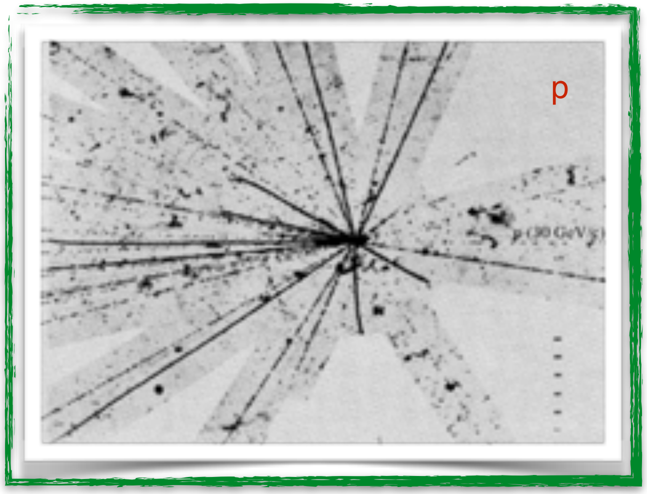
1. A particle deposits its full energy in the calorimeter media

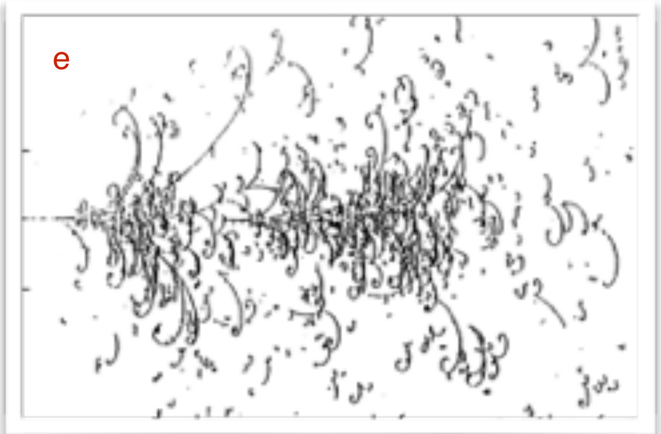
Interaction of particles & matter:

Process are particle & energy dependent

It depends on the kind of material the calorimeter is made of

Analytical description exists for electromagnetic (EM) processes but not for hadronic (HAD) processes





Hadronic shower

Extra complication: *The strong interaction* with detector material.

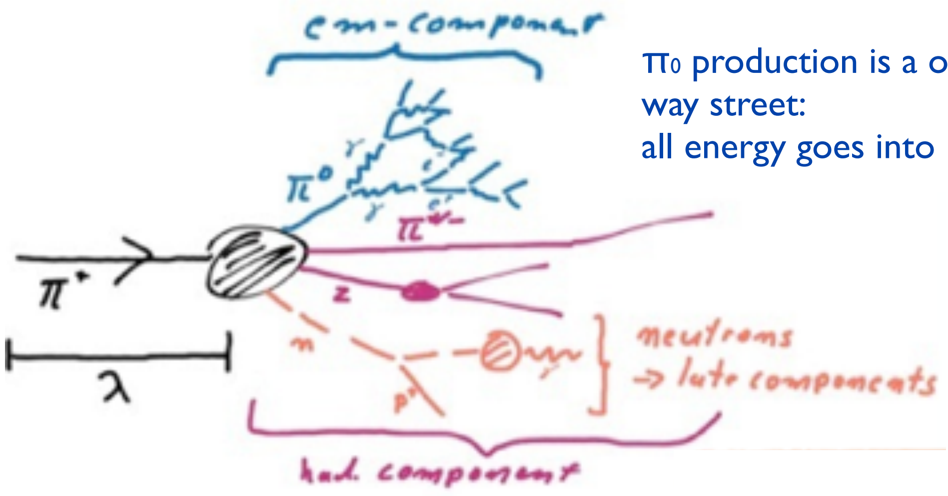
Produced in nuclear collisions:

- high energetic secondary hadrons [O(GeV)]
- electromagnetically decaying particles (π_0,η) initiate EM showers
- spallation p/n and nuclear excitation from soft nuclear processes [O(MeV)]
- part of the energy is invisible: binding energy of nuclei, ν, μ, soft γ's

Different scale: hadronic interaction length $\lambda_l = \frac{A}{N_A \sigma_{total}}$

σ_{tot} = total cross section for nuclear processes

	λ_I	X_0
Polystyren	81.7 cm	43.8 cm
PbWO	20.2 cm	0.9 cm
Fe	16.7 cm	1.8 cm
W	9.9 cm	0.35 cm

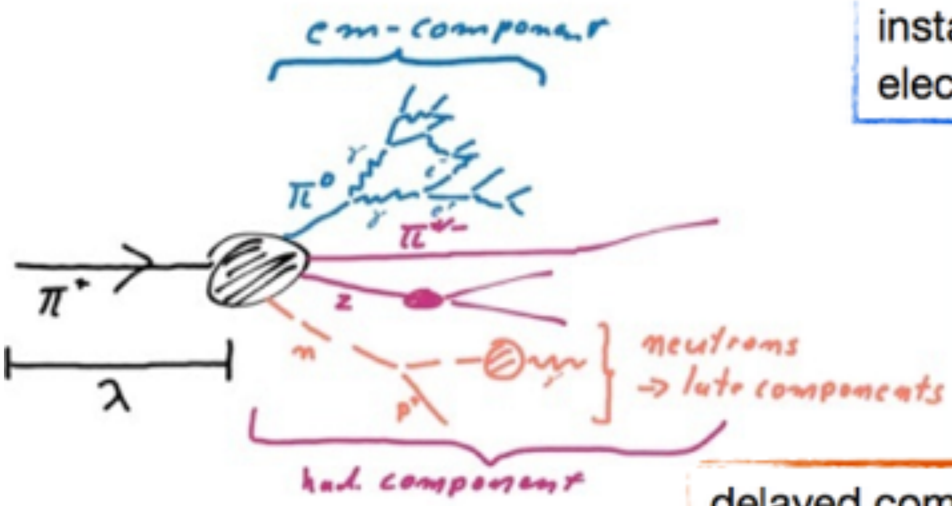


π_0 production is a one way street:
all energy goes into EM

Compare X_0 for high-Z materials, we see that the size needed for hadron calorimeters is large compared to EM calorimeters.

The structure of hadronic showers

- hadronic showers have a complex structure also in time



instantaneous, detected via energy loss of electrons and positrons in active medium

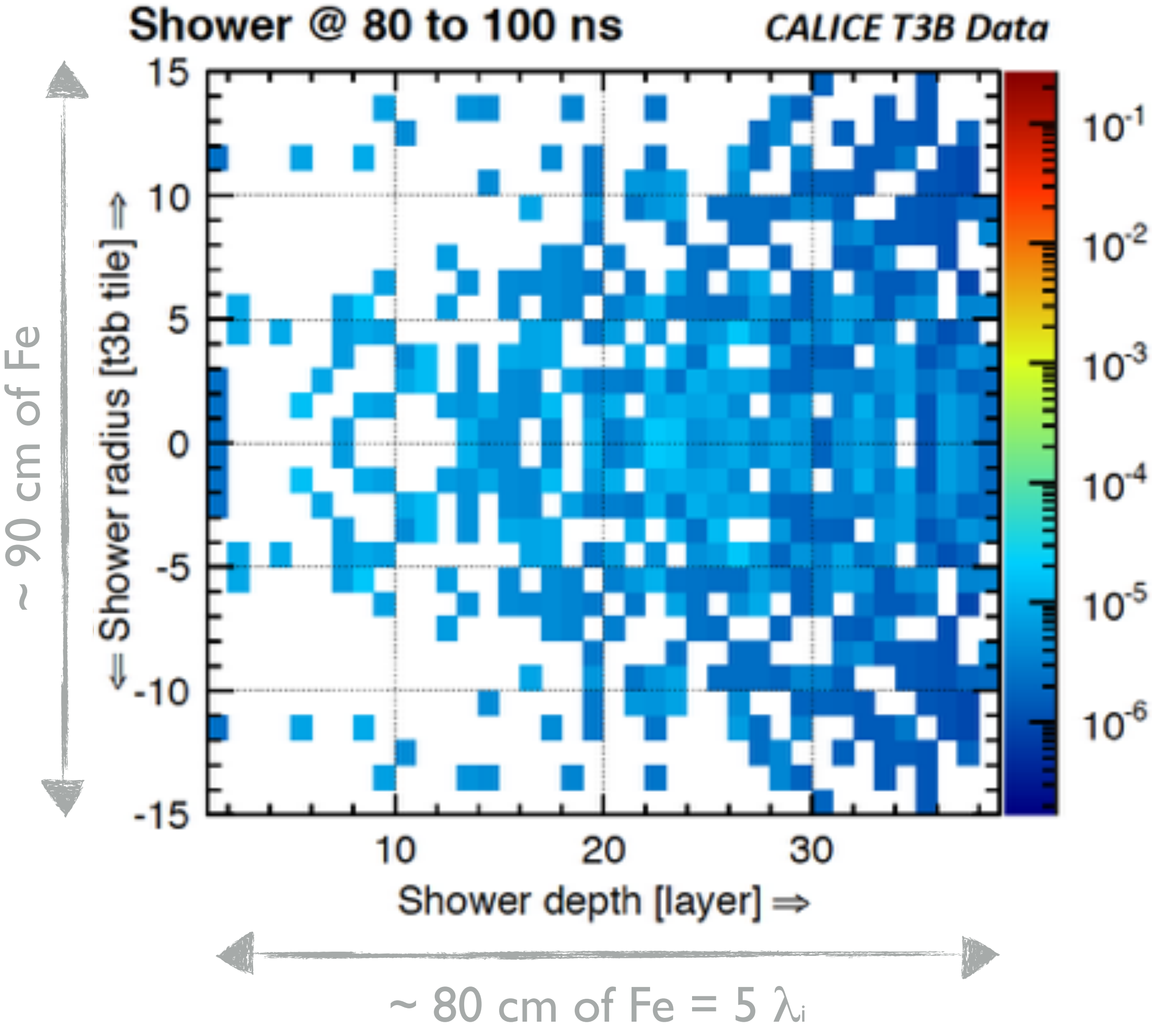
instantaneous component: charged hadrons detected via energy loss of charged hadrons in active medium

f_{EM} = fraction of primary hadron energy deposited via EM processes

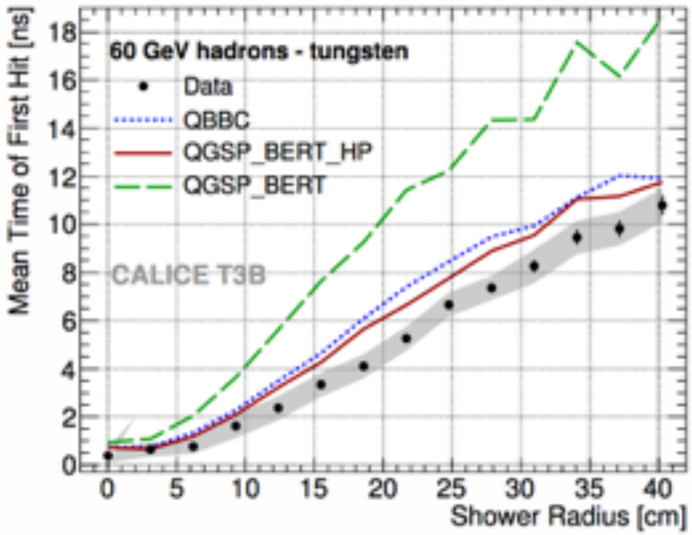
delayed component:
- neutrons from evaporation and spallation
- photons, neutrons, protons from nuclear de-excitation following neutron capture
- momentum transfer to protons in hydrogenous active medium from slow neutrons

- Importance of delayed component strongly depends on target nucleus
- Sensitivity to time structure depends on the choice of active medium

4D development of HAD showers



- 60 GeV pion shower in a highly segmented Fe/scint calo.
- 5 λ_i not sufficient for longitudinal containment (~11 λ_i necessary)
- Significant portion of energy deposited at t > 25 ns
- Not always well described in MC



C. Adloff et al. (CALICE), JINST 9 (2014) P0702

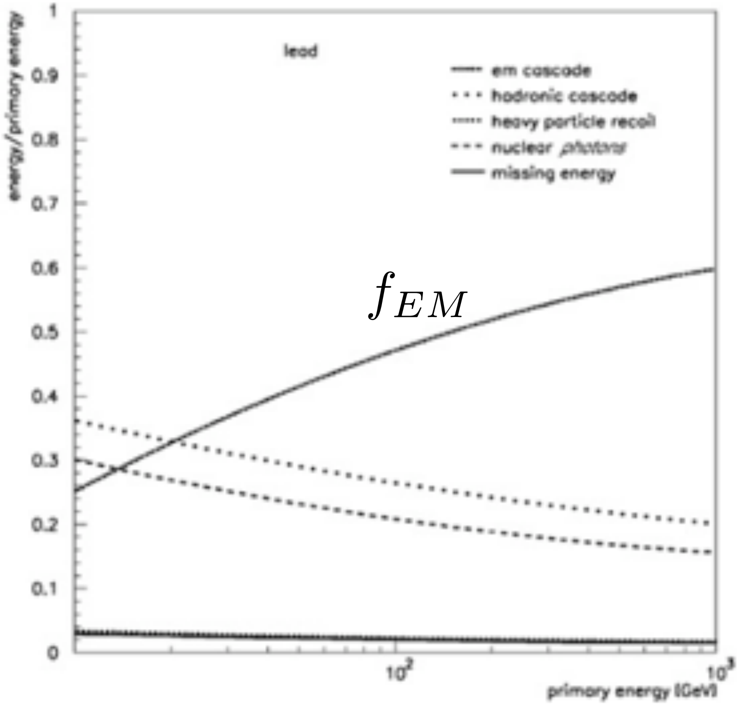
Hadronic calorimeter

The concept of compensation

- A hadron calorimeter shows in general different response to hadronic and electromagnetic shower components

$$R_h = eE_e + hE_h$$

- The fraction of the energy deposited hadronically depends on the energy



$$\frac{E_h}{E} = 1 - f_{EM} = 1 - k ln E(GeV) \quad k \approx 0.1$$

C. Fabjan, F. Gianotti, Rev. Mod. Phys. 75, 1243 (2003)

Hadronic calorimeter

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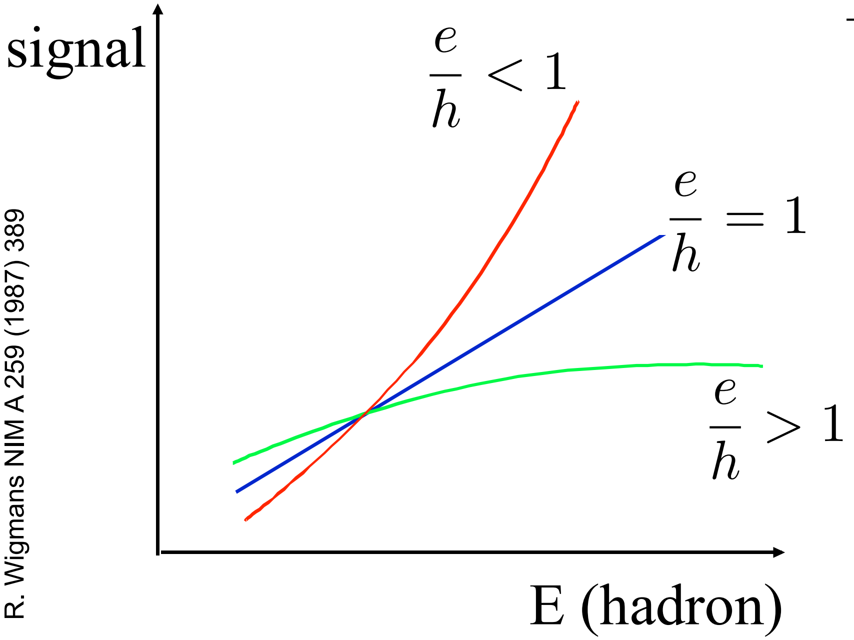


R. Wigmans NIM A 259 (1987) 389

$$\frac{E_h}{E} = 1 - f_{EM} = 1 - k ln E(GeV) \quad k \approx 0.1$$

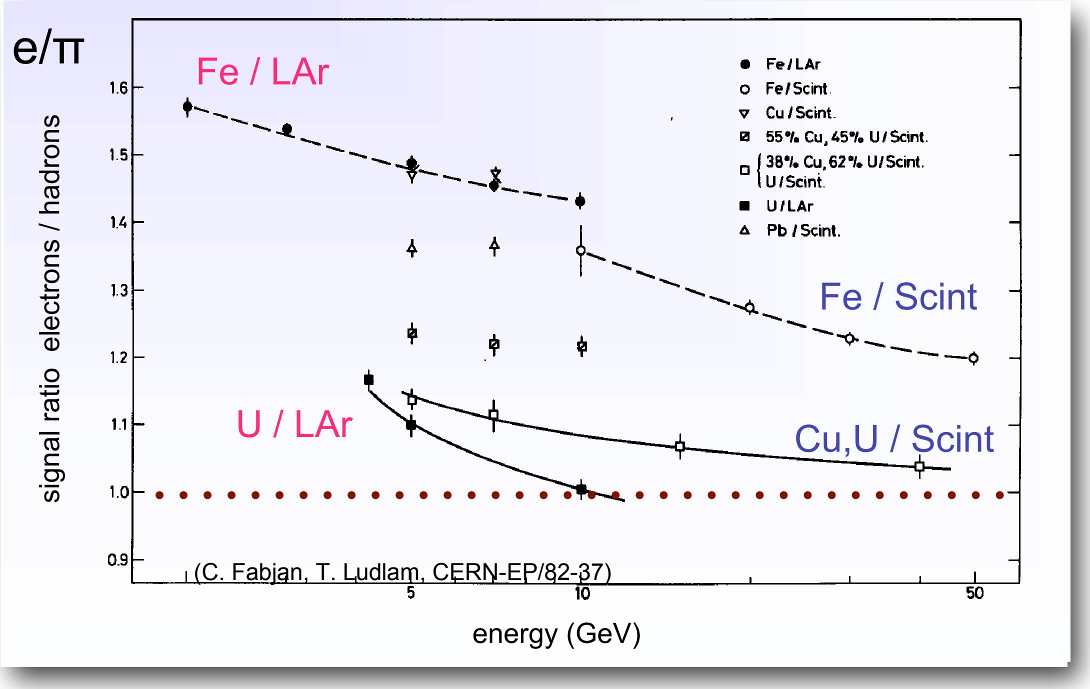
Response of calorimeter to hadron shower becomes non-linear

Energy resolution degrades

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} + d\left(\frac{e}{h} - 1\right)$$

Improved Energy Resolution: Compensation

- The detector parameter e/h is defined by geometry and material
- Typically to reach compensation (e/h = 1), the hadron signal has to be increased, by:
  - enhance sensitivity to slow neutrons, i.e. H-enriched scintillator, more $n + p \rightarrow n + p$
  - increasing of the neutron activity by use of a special absorber i.e. Uranium
  - choosing the right sampling-fraction ...



(C. Fabjan, T. Ludlam, CERN-EP/82-37)

but:

careful with amount of material in front of calorimeter!

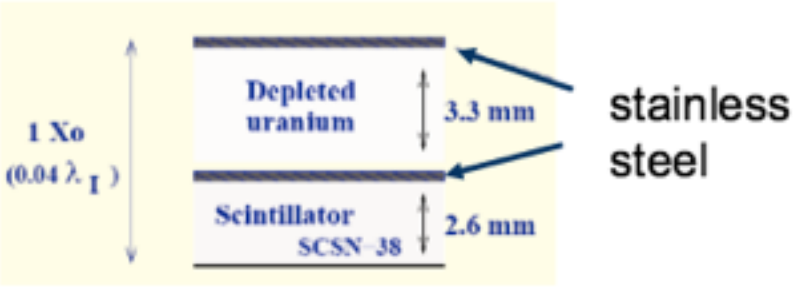
$$\frac{e}{\pi} = \frac{e}{h} \cdot \frac{1}{1 + f_{em}(e/h-1)}$$

Compensating calorimeters - The ZEUS example

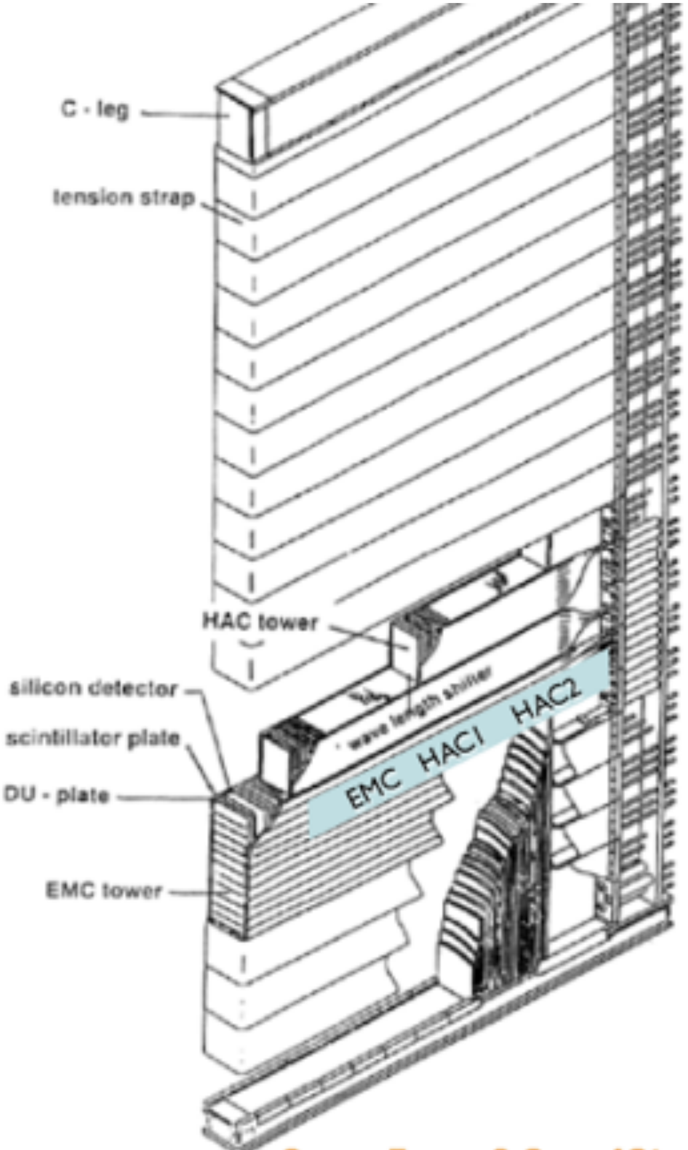
Highly-segmented, uranium scintillator sandwich calorimeter r/o by 12,000 photomultiplier tubes:

- compensation
- high Z material = compact size
- natural radioactivity provides means of calibration

Layers:



proper choice of active and passive thicknesses gives compensation (e/h = 1.0)



3m x 5m x 0.2m, 12tons
total of 80 modules

Compensating calorimeters - The ZEUS example

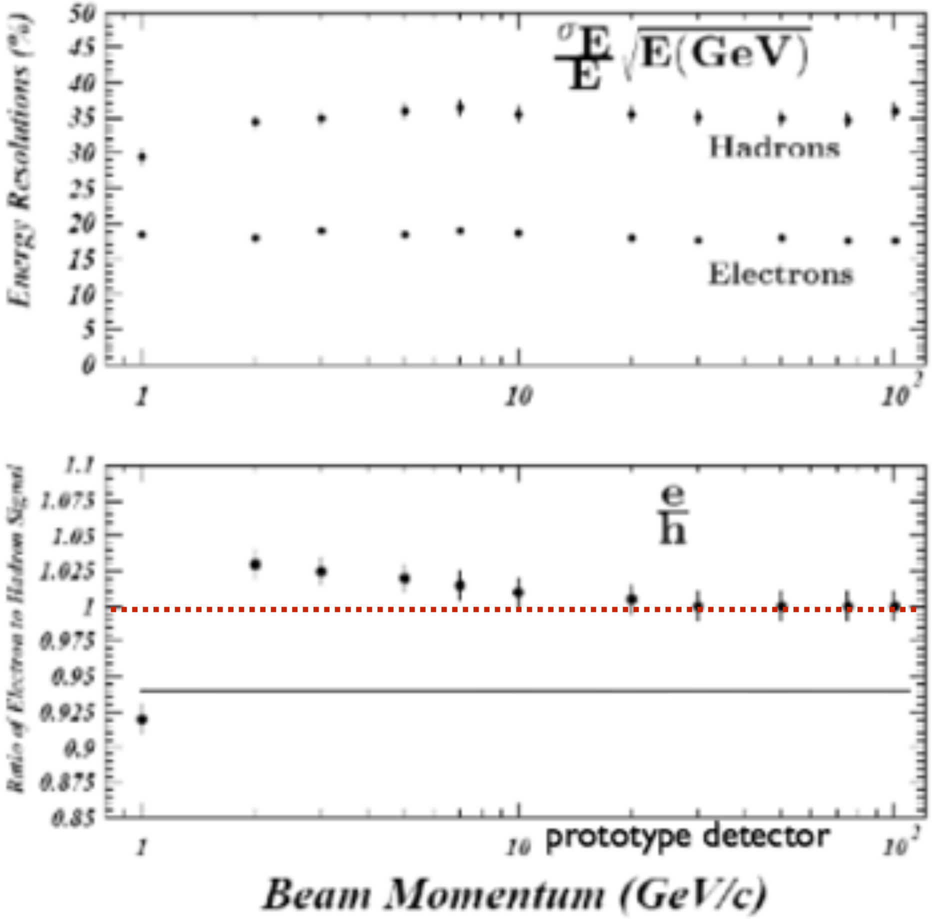
Highly-segmented, uranium scintillator sandwich calorimeter r/o by 12,000 photomultiplier tubes

Electrons: $\frac{\sigma(E)}{E} = \frac{18\%}{\sqrt{E(GeV)}}$

Hadrons: $\frac{\sigma(E)}{E} = \frac{35\%}{\sqrt{E(GeV)}}$

Best hadronic resolution ever !!

proper choice of active and passive thickness gives compensation (e/h = 1.0)



prototype detector

Summary

Calorimeters serve to measure the energy of charged and neutral particles

Electromagnetic Calorimeters

- to measure electrons and photons through their EM interactions.

Hadron Calorimeters

- to measure hadrons through their strong and EM interactions.

Two types of calorimeters classified into:

Homogeneous Calorimeters

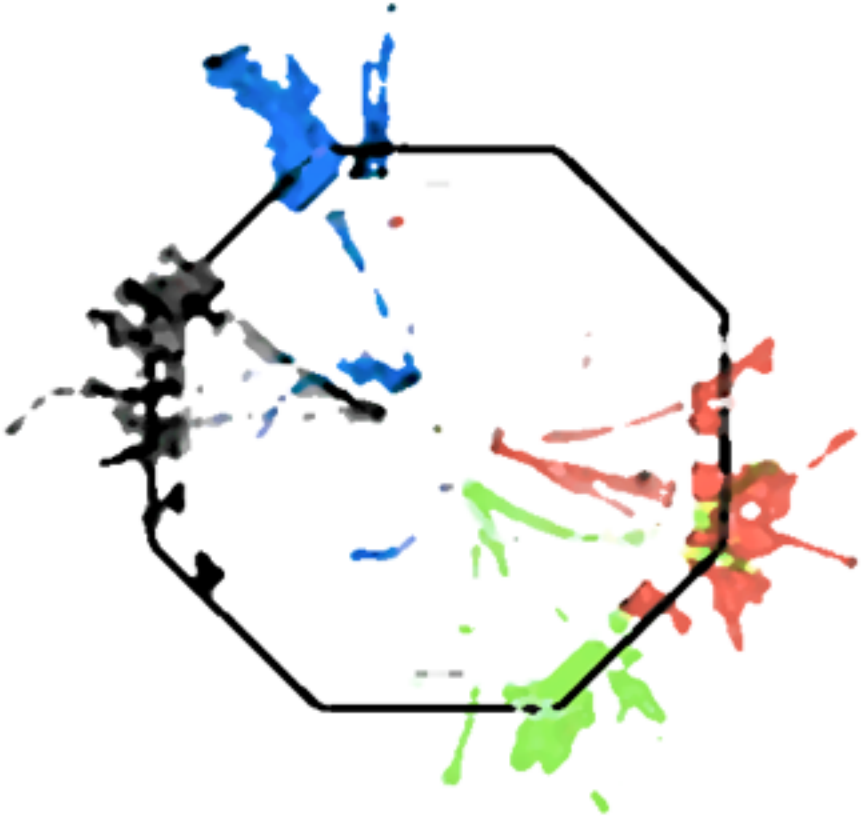
- only one material for two tasks, energy degradation and signal generation.

Sampling Calorimeters

- alternating layers of absorber material to degrade the energy of the incident particle, and active material that provides the detectable signal.

Energy resolution

- dominated by fluctuations



Calorimeters
- Part 2 -

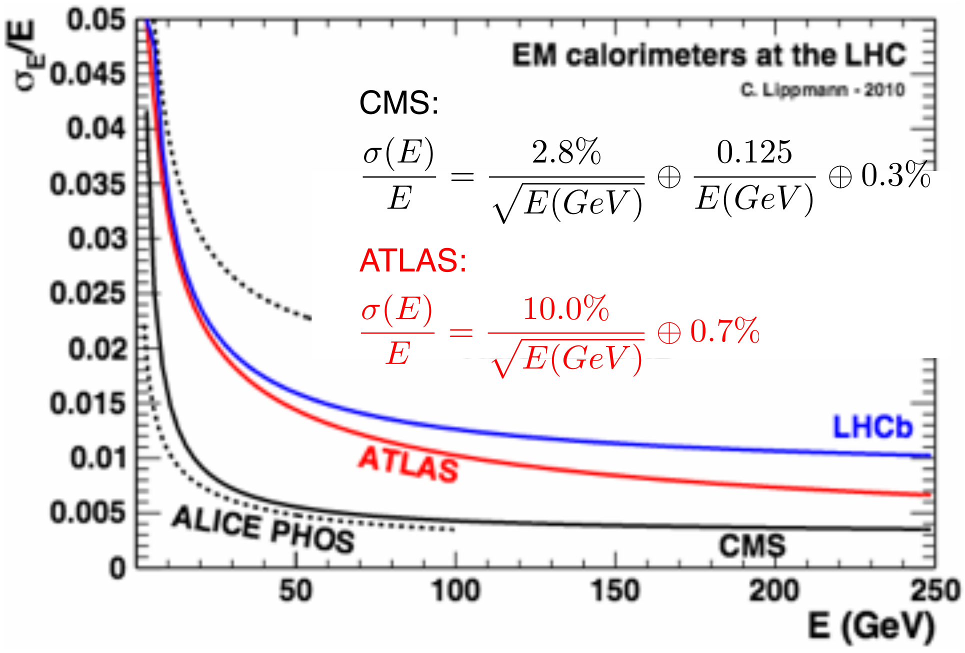
Erika Garutti

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Resolution comparison

Reported energy resolutions for single particles from test beam measurements:

electrons



CMS:

$$\frac{\sigma(E)}{E} = \frac{2.8\%}{\sqrt{E(GeV)}} \oplus \frac{0.125}{E(GeV)} \oplus 0.3\%$$

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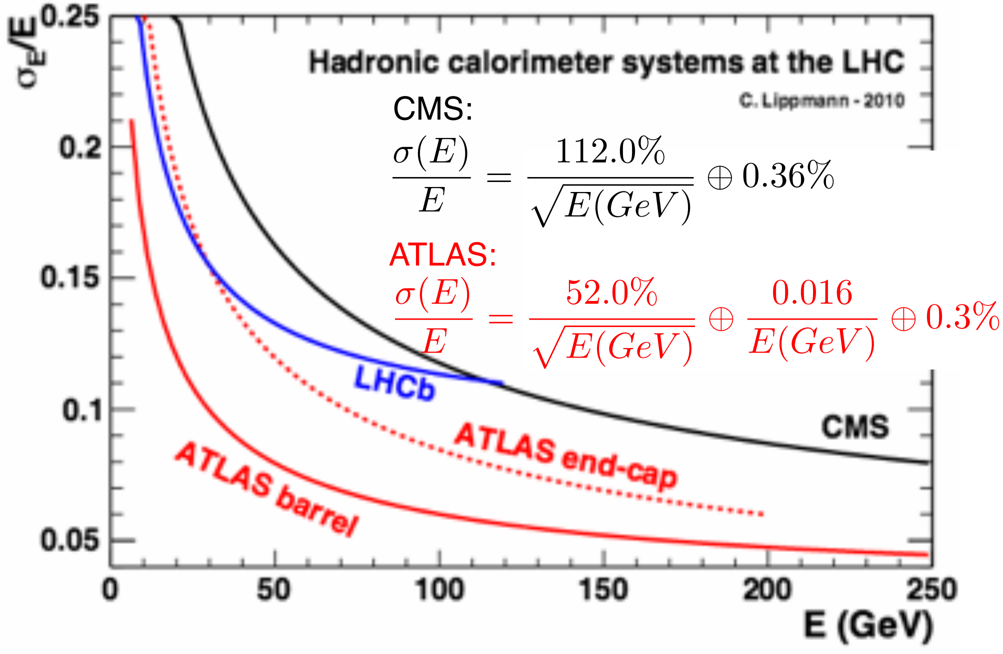
$$\frac{\sigma(E)}{E} = \frac{10.0\%}{\sqrt{E(GeV)}} \oplus 0.7\%$$

pions



CMS:

$$\frac{\sigma(E)}{E} = \frac{112.0\%}{\sqrt{E(GeV)}} \oplus 0.36\%$$

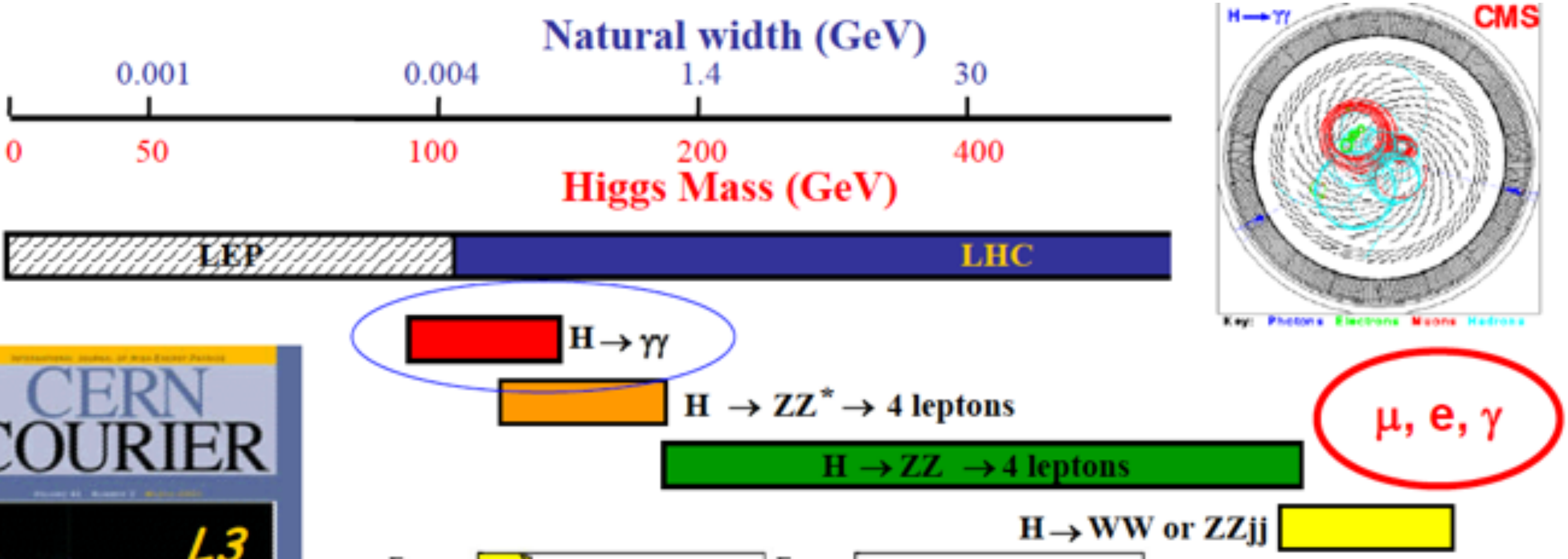
ATLAS:

$$\frac{\sigma(E)}{E} = \frac{52.0\%}{\sqrt{E(GeV)}} \oplus \frac{0.016}{E(GeV)} \oplus 0.3\%$$

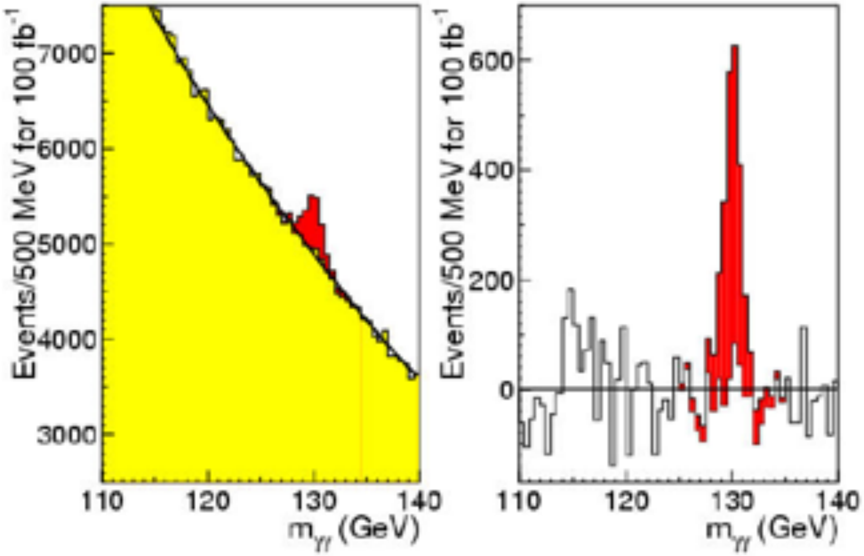
Are these the relevant numbers for calorimetry in HEP detectors?

What is the relevant physics?

What is the relevant physics? - LHC



LEP observed an excess of events around 115 GeV



Only precision in γ detection will tell a peak (H →γγ signal) from a huge background

CERN 8-9 Feb 2011

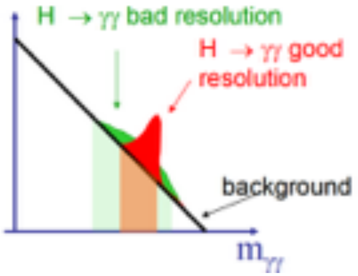
H ➔ γγ : ECAL benchmark

Light Higgs scenario ($m_H \sim 100$ GeV)
the precision will be given by exp. resolution

$$\Gamma_H(m_H \simeq 100GeV) \simeq 2 - 10MeV$$

$$m_{\gamma\gamma} = 2 E_1 E_2 (1 - \cos\theta_{\gamma\gamma})$$

$$\frac{\sigma_m}{m} = \frac{1}{2}\left[\left(\frac{\sigma_1}{E_1}\right)^2 + \left(\frac{\sigma_2}{E_2}\right)^2 + \left(\frac{\sigma_\theta}{tg\theta/2}\right)^2\right] \longrightarrow \boxed{\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c}$$



CMS:
Homogeneus calo **a** ~ 2%,
which for E_γ~ 50 GeV means:

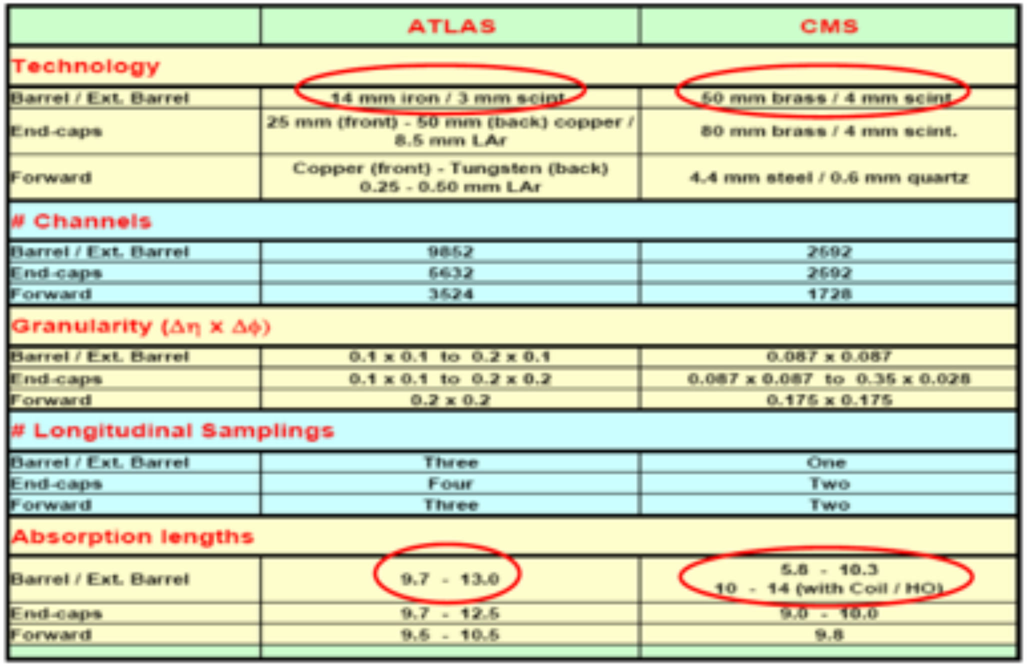
b ~ 200 MeV
! don't forget c ~ 0.3% = 150 MeV
and angular resolution σ_θ~ 50 mrad/√E

ATLAS:
Sampling calo **a** ~ 10%,
which for E_γ~ 50 GeV means:

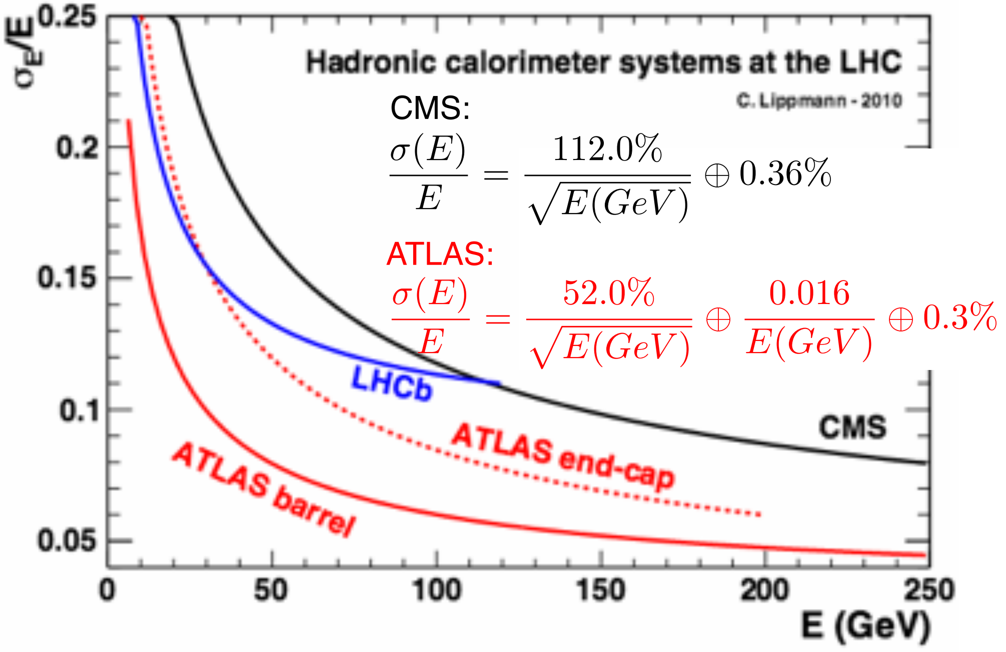
b ~ 300 MeV
! don't forget c ~ 0.7% = 350 MeV
and angular resolution σ_θ~ 50 mrad/√E

CMS Collaboration, 14 May 2014, Phys. Lett. B 736 (2014) 64: "… A simultaneous maximum likelihood fit to the measured kinematic distributions near the resonance peak and above the Z-boson pair production threshold leads to an upper limit on the Higgs boson width of $\Gamma_H < 22$ MeV at a 95% confidence level …"

What about hadronic physics at LHC?



	ATLAS	CMS
Technology		
Barrel / Ext. Barrel	14 mm iron / 3 mm scint	50 mm brass / 4 mm scint
End-caps	25 mm (front) - 50 mm (back) copper / 8.5 mm LAr	80 mm brass / 4 mm scint.
Forward	Copper (front) - Tungsten (back) 0.25 - 0.50 mm LAr	4.4 mm steel / 0.6 mm quartz
# Channels		
Barrel / Ext. Barrel	9852	2592
End-caps	5632	2592
Forward	3524	1728
Granularity ($\Delta\eta \times \Delta\phi$)		
Barrel / Ext. Barrel	0.1 x 0.1 to 0.2 x 0.1	0.087 x 0.087
End-caps	0.1 x 0.1 to 0.2 x 0.2	0.087 x 0.087 to 0.35 x 0.028
Forward	0.2 x 0.2	0.175 x 0.175
# Longitudinal Samplings		
Barrel / Ext. Barrel	Three	One
End-caps	Four	Two
Forward	Three	Two
Absorption lengths		
Barrel / Ext. Barrel	9.7 - 13.0	5.8 - 10.3 10 - 14 (with Coil / HO)
End-caps	9.7 - 12.5	9.0 - 10.0
Forward	9.5 - 10.5	9.8

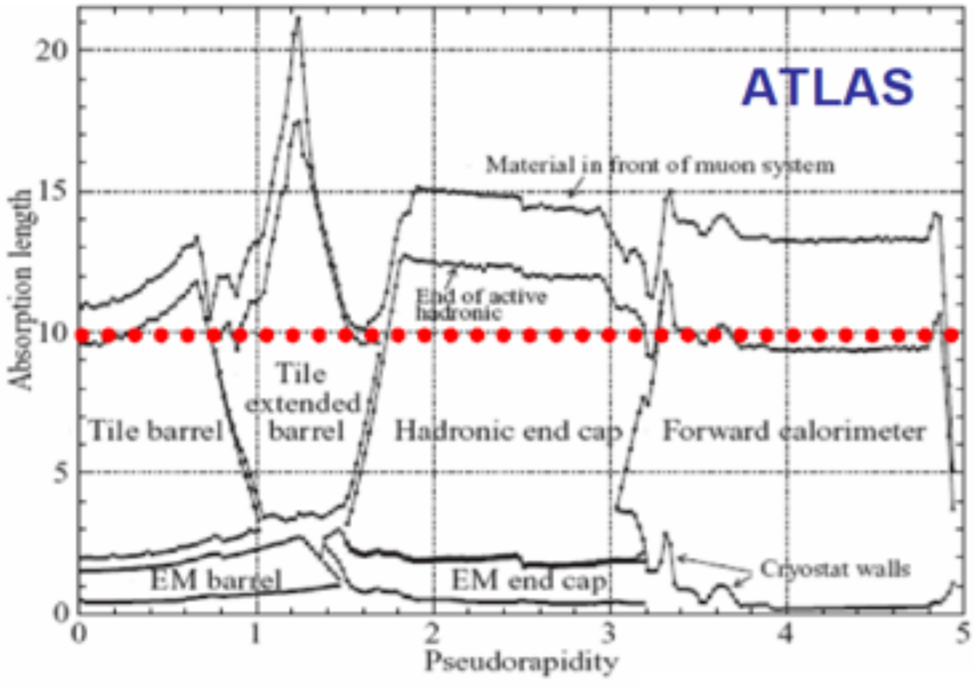


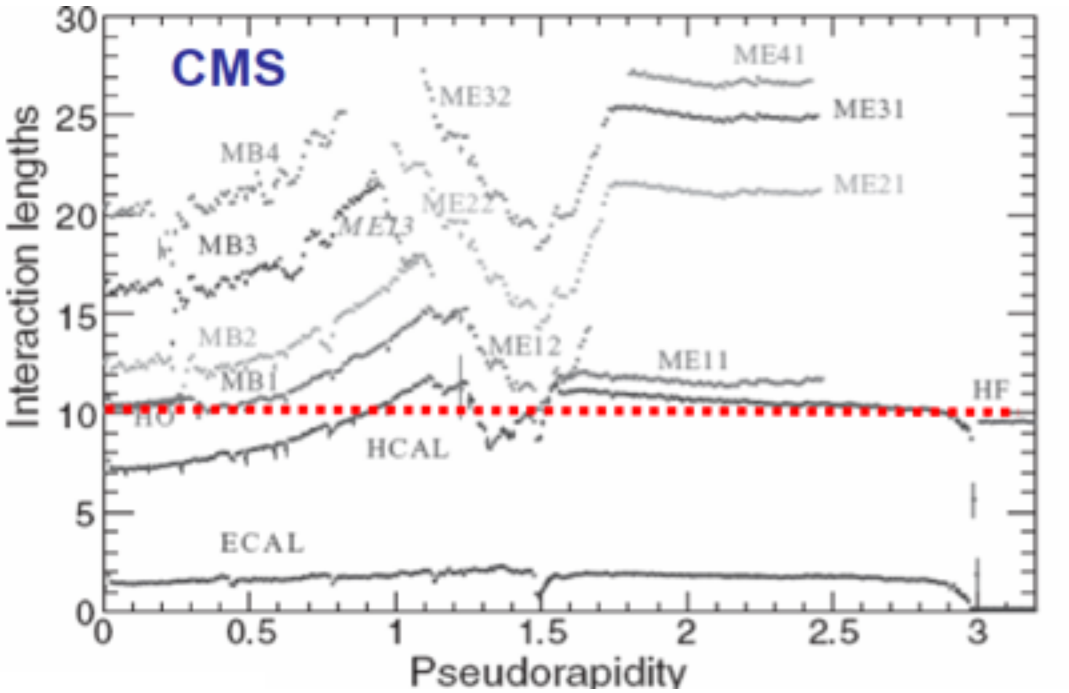
The choices made for the hadronic central section by ATLAS and CMS are similar: sampling calorimeters with scintillator as active material.

- In both cases the dominant factor on resolution and linearity is the e/h ≠ 1
- ATLAS & CMS: $e/h_{had} \approx 1.4$
- ATLAS higher segmentation and containment gives better total resolution

CMS barrel HCAL

What about hadronic physics at LHC?





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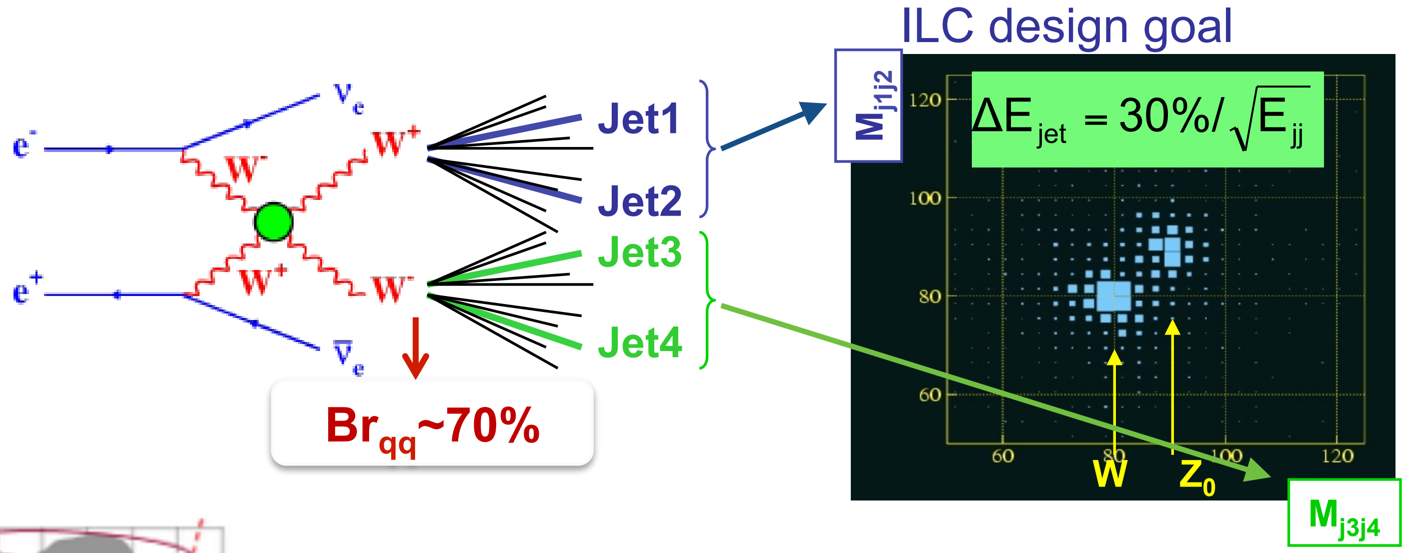
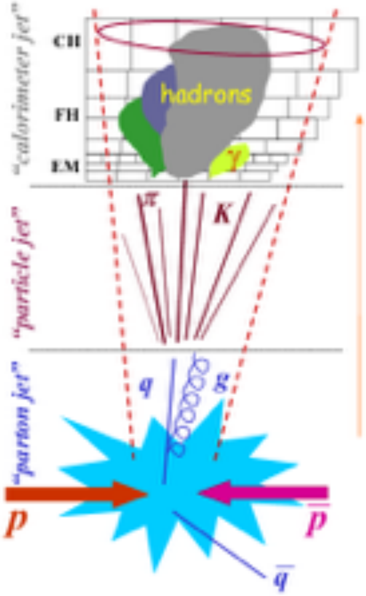
What is the relevant physics?

At high energy collider experiments no single hadrons but "jets"



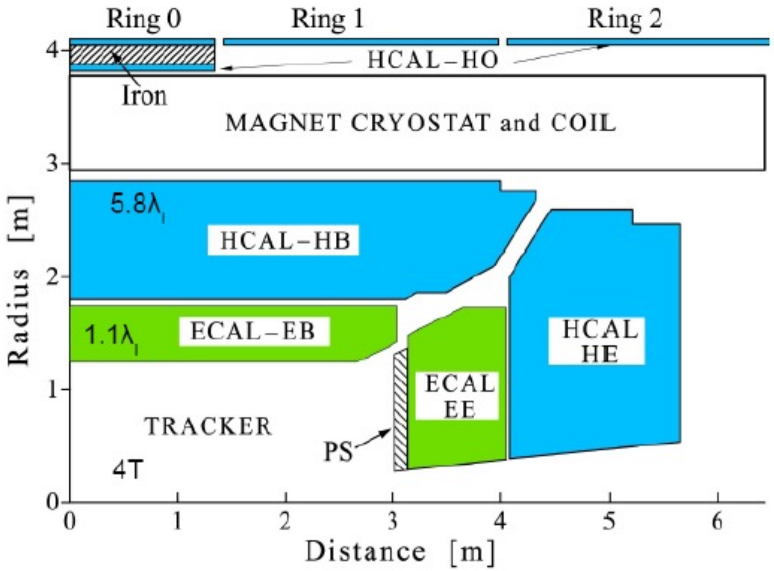


Discovery & precision physics requires excellent jet energy resolution

A jet is a ill defined object:
Contribution from
Physics: Parton shower & fragmentation, underlying events, Initial & Final State Radiation, pileup form minimum bias events
Detector: Resolution, granularity
Clustering: Out of "cone" energy losses

Jet energy resolution @ LHC

CMS

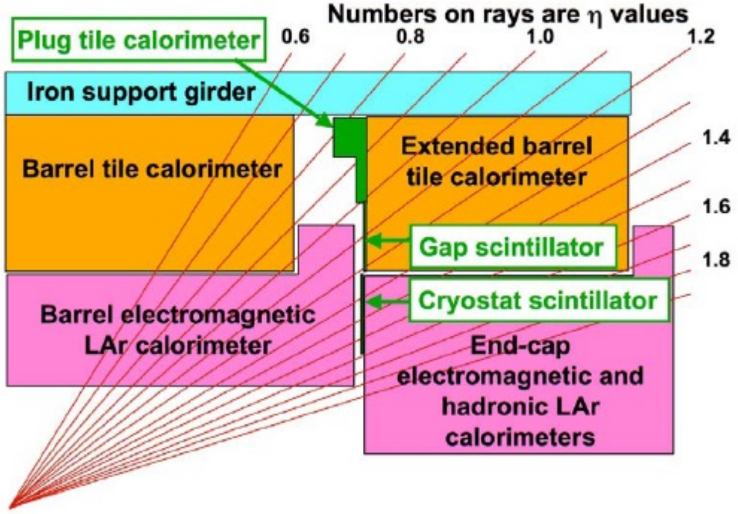


5 cm brass / 3.7 cm scint.
Embedded fibres, HPD readout

Expected jet resolution:

$$\frac{\sigma}{E} = \frac{125\%}{\sqrt{E}} \oplus \frac{5.6\ \mathrm{GeV}}{E} \oplus 3.3\%$$

ATLAS



14 mm iron / 3 mm scint.
sci. fibres, read out by phototubes

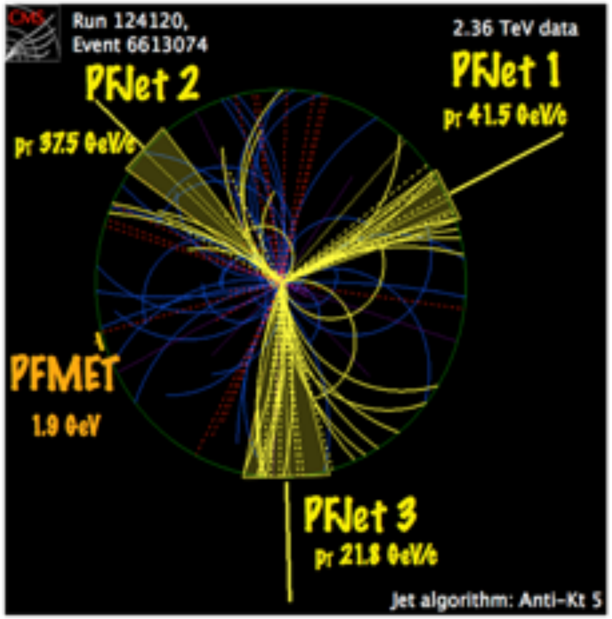
Jet resolution with weighting:

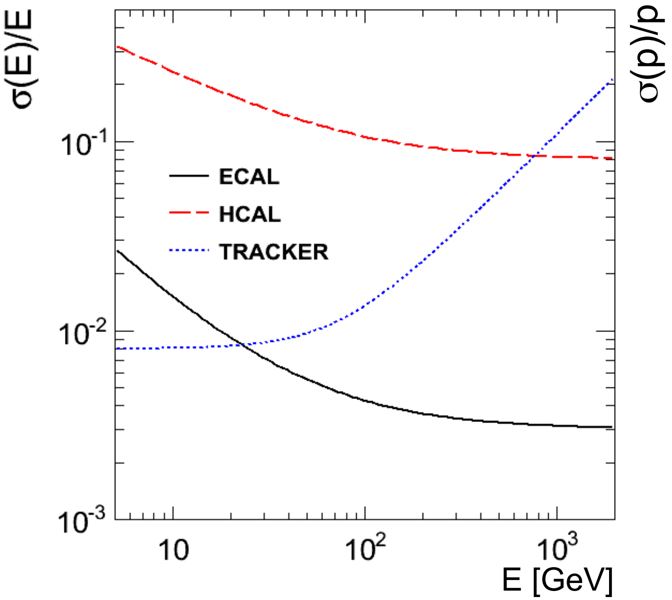
$$\frac{\sigma}{E} = \frac{60\%}{\sqrt{E}} \oplus 3\%$$

Jet energy resolution generally worse that for single hadrons ➜ how to improve ?

Particle Flow

- Improve the jet energy resolution of a HEP detector combining detector design + sophisticated reconstruction software
- Attempt to measure the energy/momentum of each particle with the detector subsystem providing the best resolution





Identification and reconstruction of:

- charged hadrons in tracker ~60% E_{jet}
- photons in ECAL ~30% E_{jet}
- neutral hadrons in HCAL ~10% E_{jet}

then cluster single particles in jets

➜ HCAL E resolution still dominates E_{jet} resolution
But much improved resolution (only 10% of E_{jet} in HCAL)

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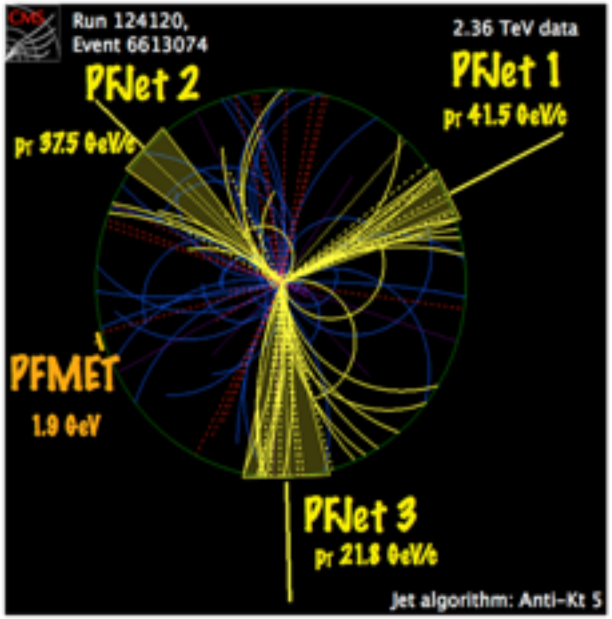
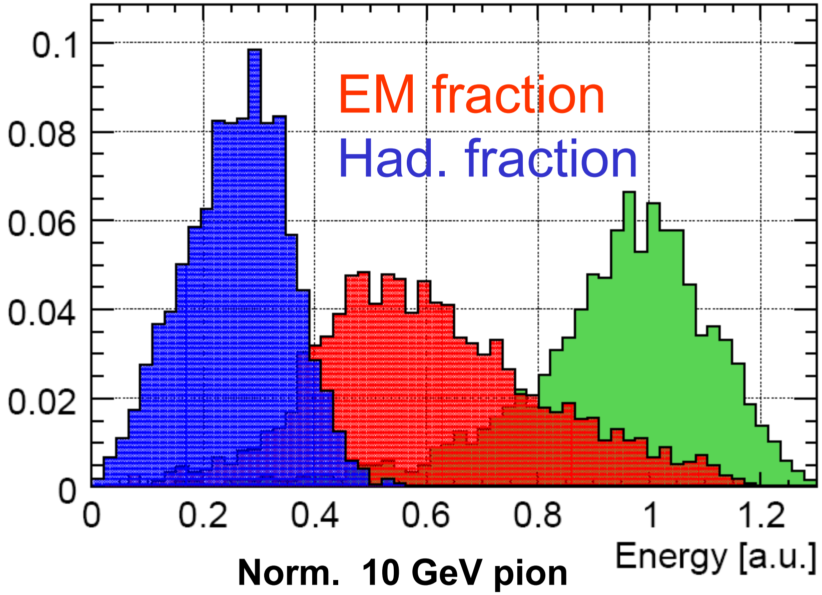




Identification and reconstruction of:

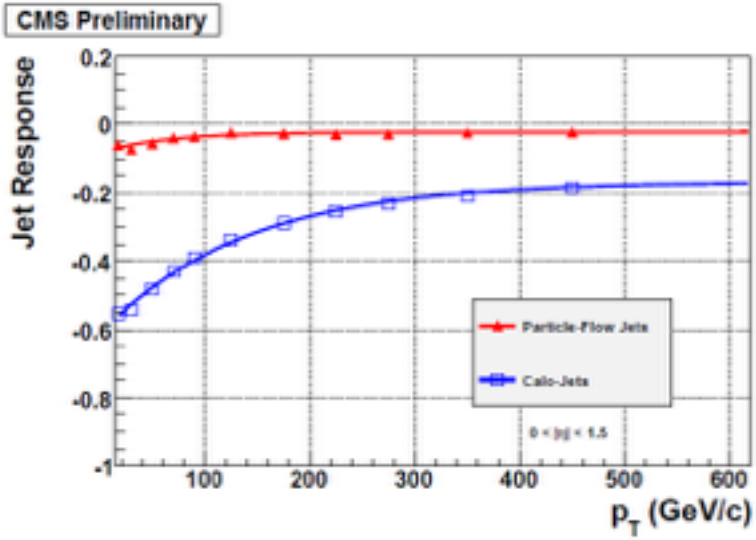
	in average:
charged hadrons in tracker	~60% E_{jet}
photons in ECAL (f_{EM})	~30% E_{jet}
neutral hadrons in HCAL	~10% E_{jet}

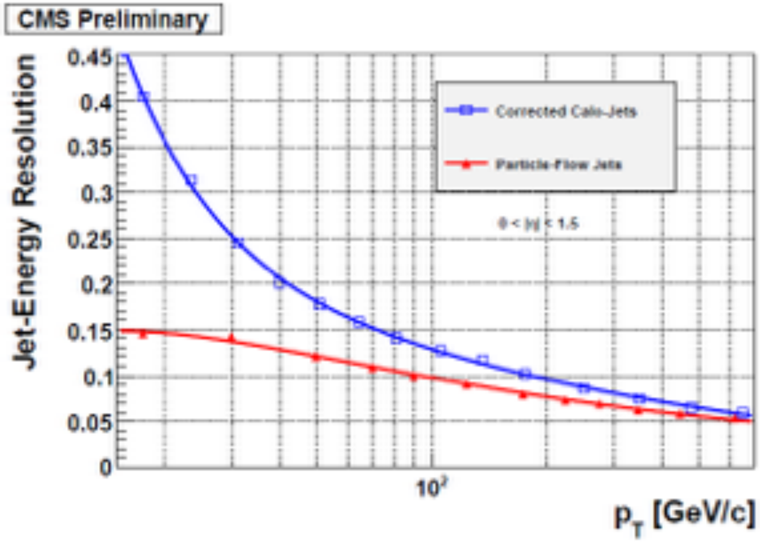
warning large fluctuations !!!

then cluster single particles in jets

➜ HCAL E resolution still dominates E_{jet} resolution
But much improved resolution (only 10% of E_{jet} in HCAL)

Particle Flow @ LHC - Performance





Jet response:

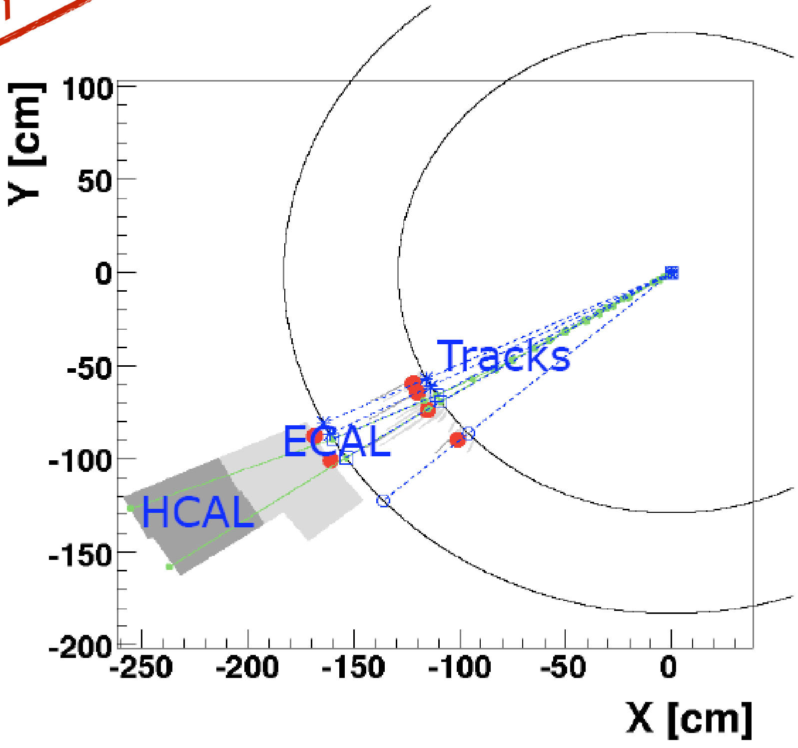
$$(p_T^{rec} - p_T^{gen})/p_T^{gen}$$

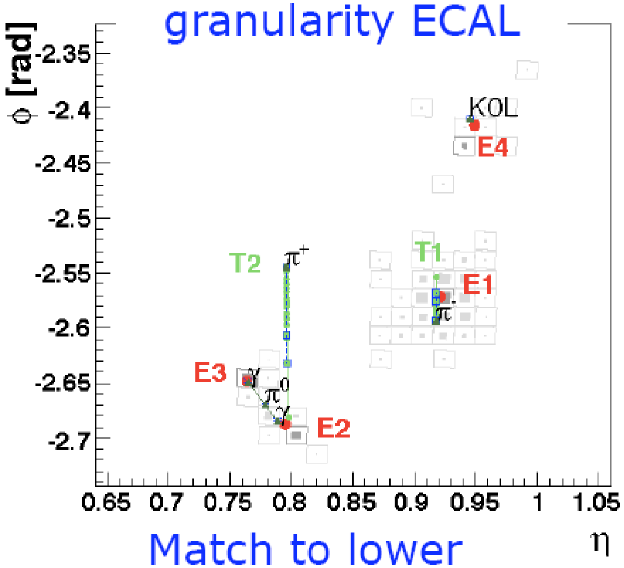
Jet resolution:

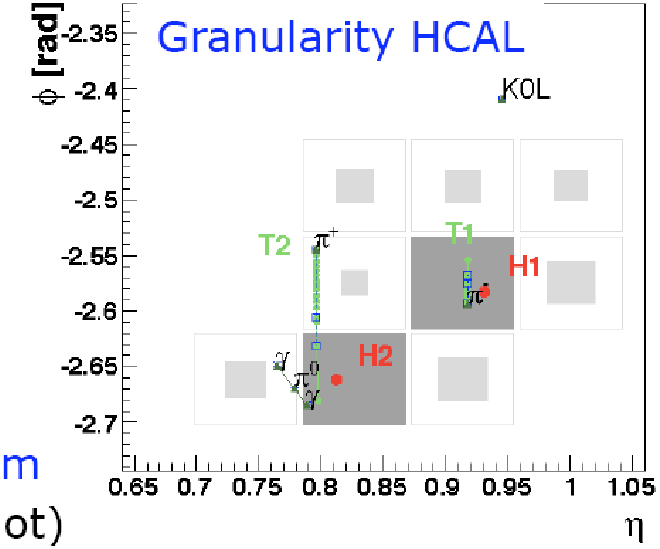
- profits of excellent momentum resolution in tracker
- for very high energy Jets no significant improvement
- energy dependence does not follow $1/\sqrt{E}$

Particle flow @ LHC - Limitations

need higher granularity !!!



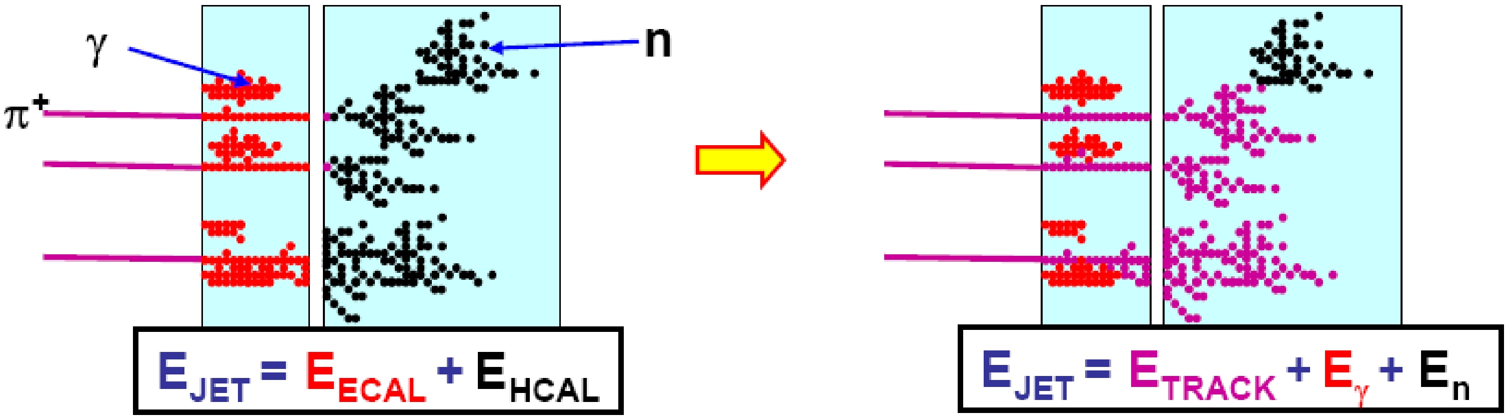

Match track to high granularity ECAL


Match to lower Granularity HCAL

1) Leverage High Precision Tracking
2) And High Resolution ECAL EM-Showers
3) Match and Discard Charged Hadron Showers Replacing with Track Momentum

(Courtesy of P. Janot)

Particle Flow limitations - Confusion



$E_{JET} = E_{ECAL} + E_{HCAL}$

$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

If particles are too close they cannot be separated …

granularity is more important than energy resolution !

$\sigma^2_{jet} = \sigma^2_{h\pm} + \sigma^2_{\gamma} + \sigma^2_{h0} + \sigma^2_{confusion}$ + …

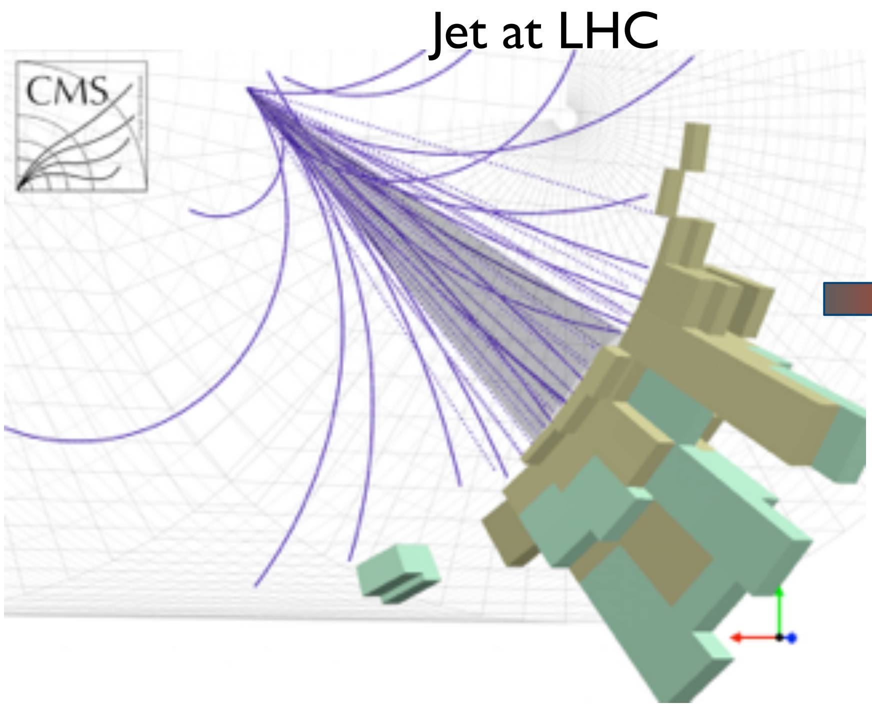
CMS example:

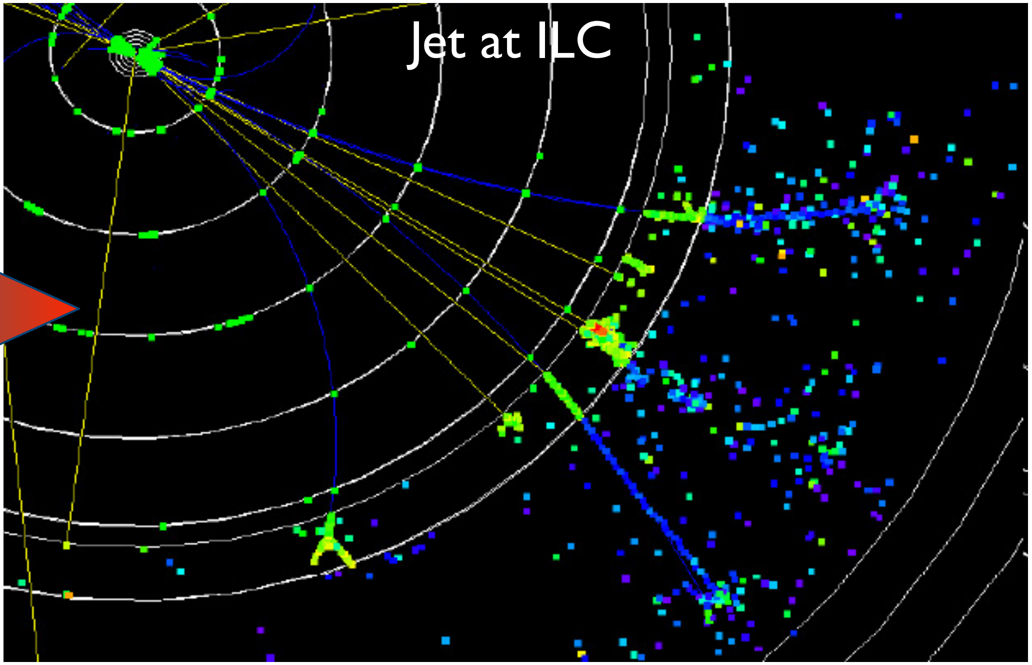
Component	Detector	Fraction	Part. resolution	Jet E resolution
Charged ($h_{+/-}$)	tracher	60%	10^{-4} $E_{h+/-}$	negligible
Photons	ECAL	30%	$0.02/\sqrt{E_h}$	$0.01/\sqrt{E_{jet}}$
Neutral h (h_0)	E/HCAL	10%	$1.1/\sqrt{E_h}$	$0.35/\sqrt{E_{jet}}$

expected: $\sigma^2_{h\pm} + \sigma^2_{\gamma} + \sigma^2_{h0} = (0.35/\sqrt{E_{jet}})^2$ measured: $\sigma^2_{jet} = (1.0/\sqrt{E_{jet}})^2$ at E_{jet} = 100 GeV

➜ $\sigma_{confusion} \simeq 100\%$ at E_{jet} = 100 GeV

Future of calorimeters


Jet at LHC

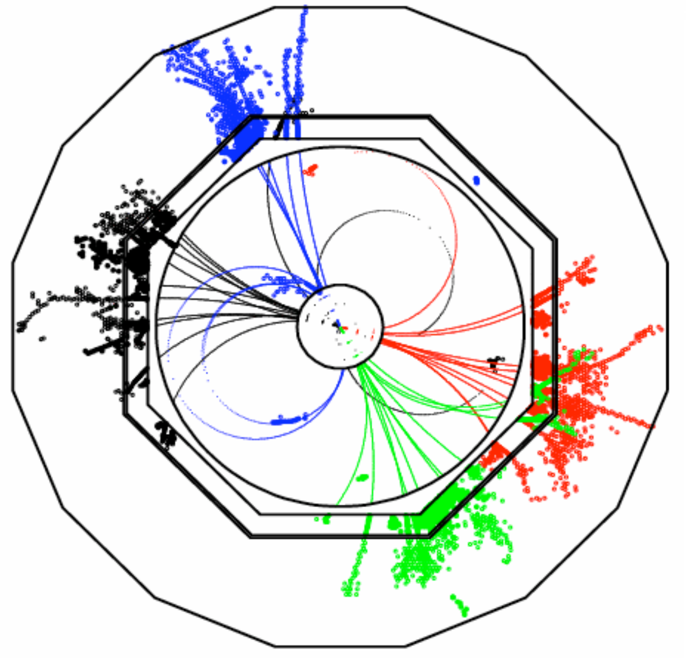

Jet at ILC

- Tower-wise readout: light from many layers of plastic scintillators is collected in one photon detector (typically PMT) O(10k) channels for full detectors

- Extreme granularity to see shower substructure: small detector cells with individual readout for Particle Flow O(10M) channels for full detectors

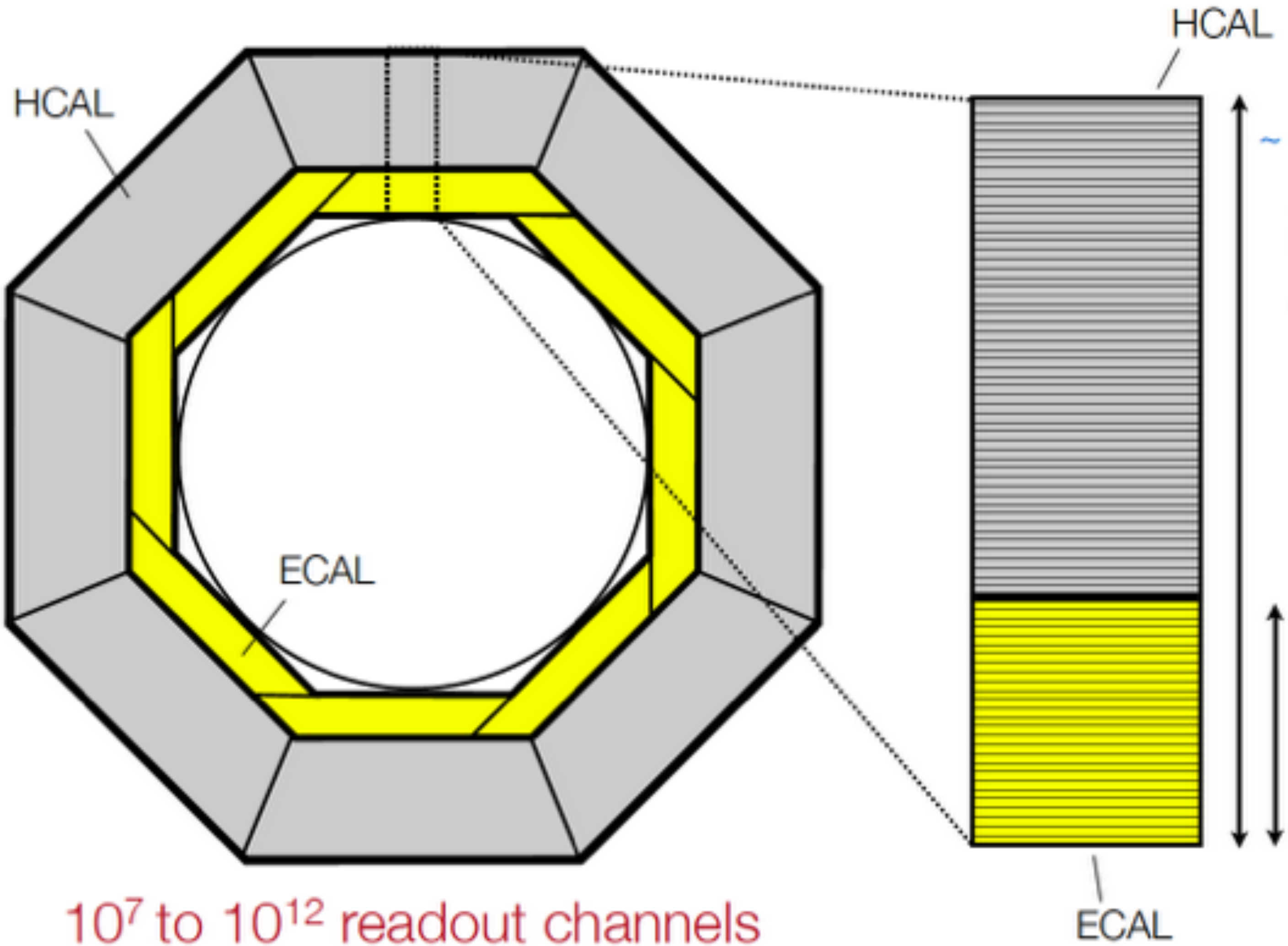
Particle Flow Calorimeter

- Improve the jet energy resolution of a HEP detector combining detector design + sophisticated reconstruction software
- Attempt to measure the energy/momentum of each particle with the detector subsystem providing the best resolution



- EM calorimeter optimized for photon ID and E res.
  ➡ extreme segmentation ~ 0.5 cm or smaller
  ➡ but $\sigma_E/E \simeq 15\%/\sqrt{E}$
- HAD calorimeter optimized for shower separation (measure only neutral hadrons)
  ➡ high segmentation ~ 1-3 cm
  ➡ and $\sigma_E/E \simeq 50\%/\sqrt{E}$

Overall calorimeter design



~ 5 λ

40 extra layers
[2.5 cm/layer]

Granularity:
- 3x3 cm^2 to 20x20 cm^2 (analog)
- 1x1 cm^2 (digital)

~ 24 X_0

30 - 40 layers
[0.6 – 1.2 X_0]

Granularity:
- 5x5 mm^2 (analog)
- 50x50 μm^2 (digital)

10^7 to 10^{12} readout channels

[high-level of integration, low power consumption]

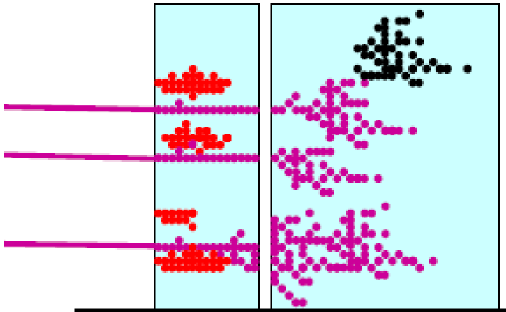
How to read out a high granular calorimeter

- $O(10^7\text{-}10^{12})$ channels to be read out

- Key calorimeter paradigm:

$$\boxed{E \propto \sum N_i}$$

- If granularity high enough Number of particles in the shower is proportional to E



$$\boxed{E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}}$$

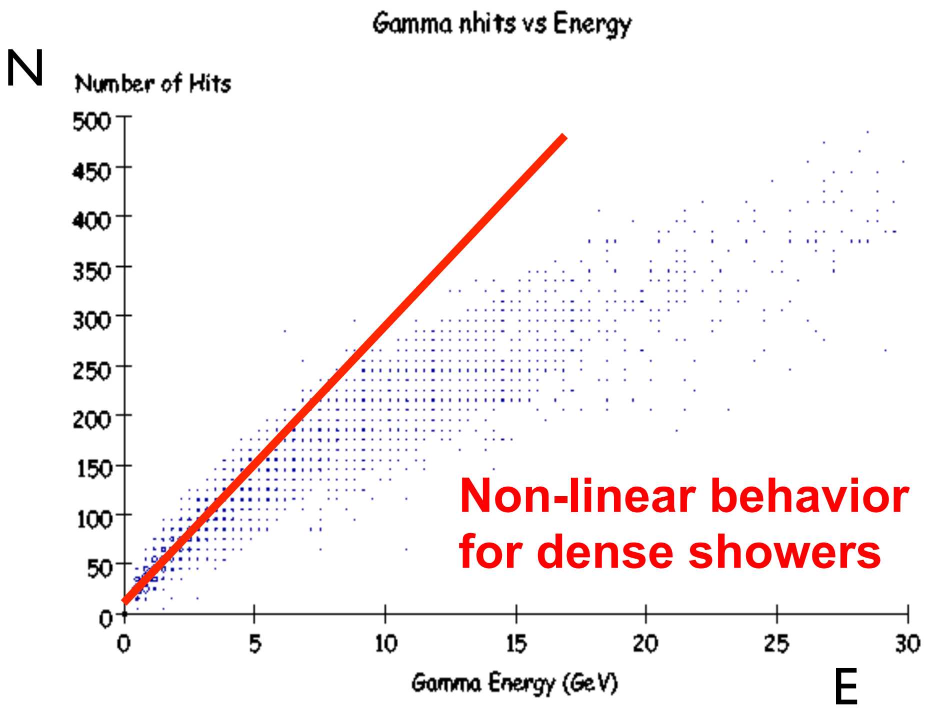
- Analog or digital r/o of individual channels are possible

The challenge of high granularity

photon analysis

$$E_\gamma \neq \sum N_i$$

ECAL: Analog readout required

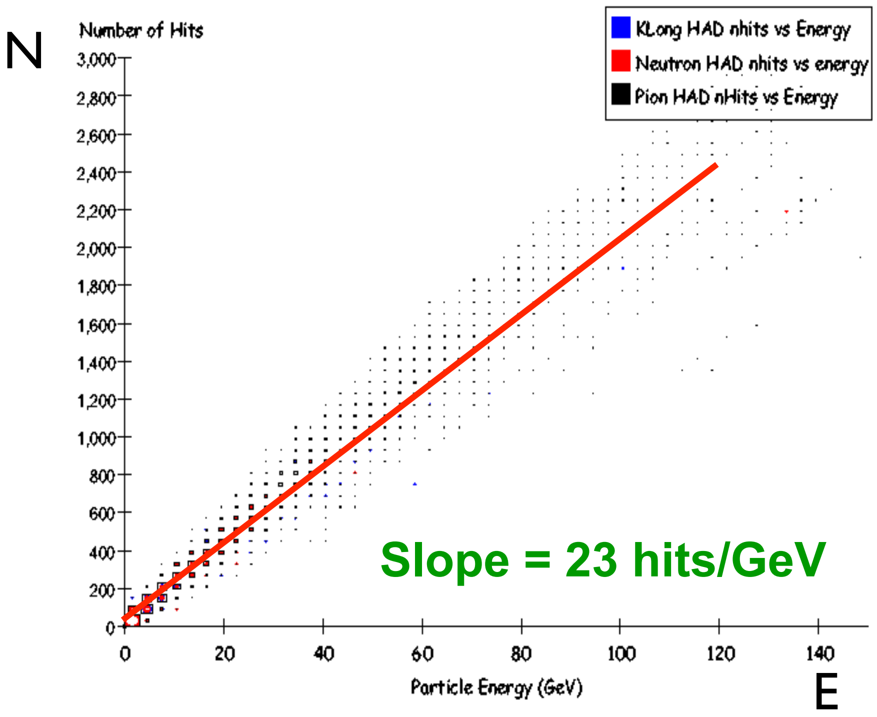


Non-linear behavior for dense showers

hadron analysis

$$E_h \propto \sum N_i$$

HCAL: either Analog or Digital readout



Slope = 23 hits/GeV

Calorimeter cell size 1x1cm^2

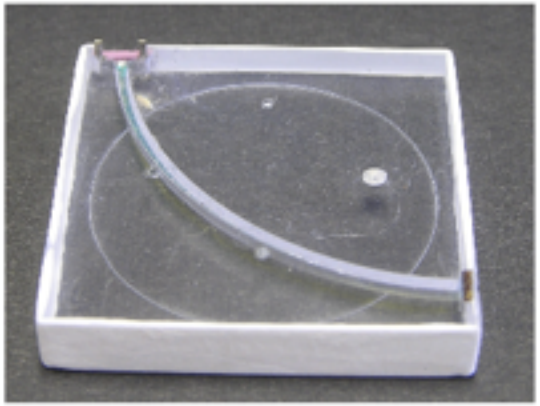
Scintillator + PM readout

Well established technology for calorimeters

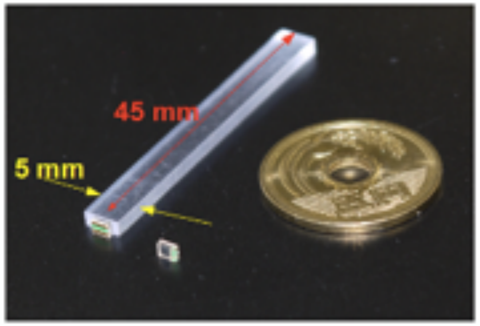
Key features:

- high segmentation possible using SiPM
- large dynamic range

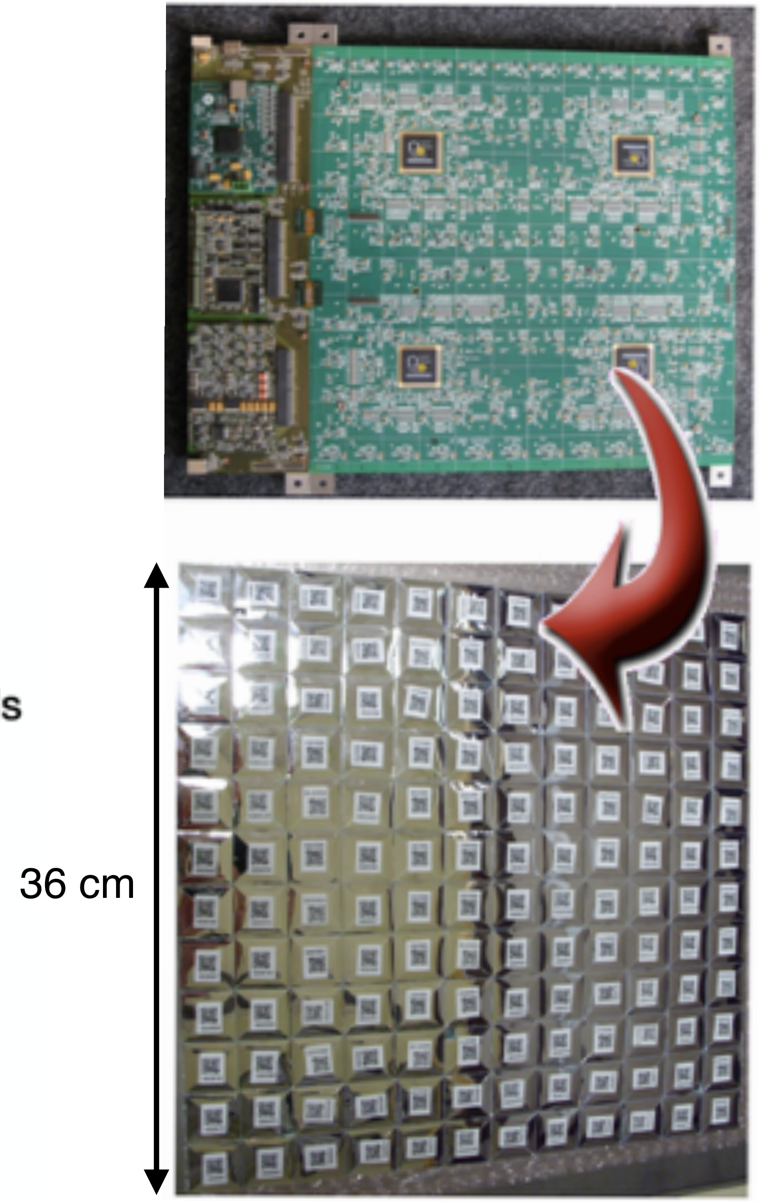
Used in EM and HAD calorimeters



AHCAL physics prototype:
$3 \times 3 \times 0.5$ cm^3 cells
first large-scale use of SiPMs



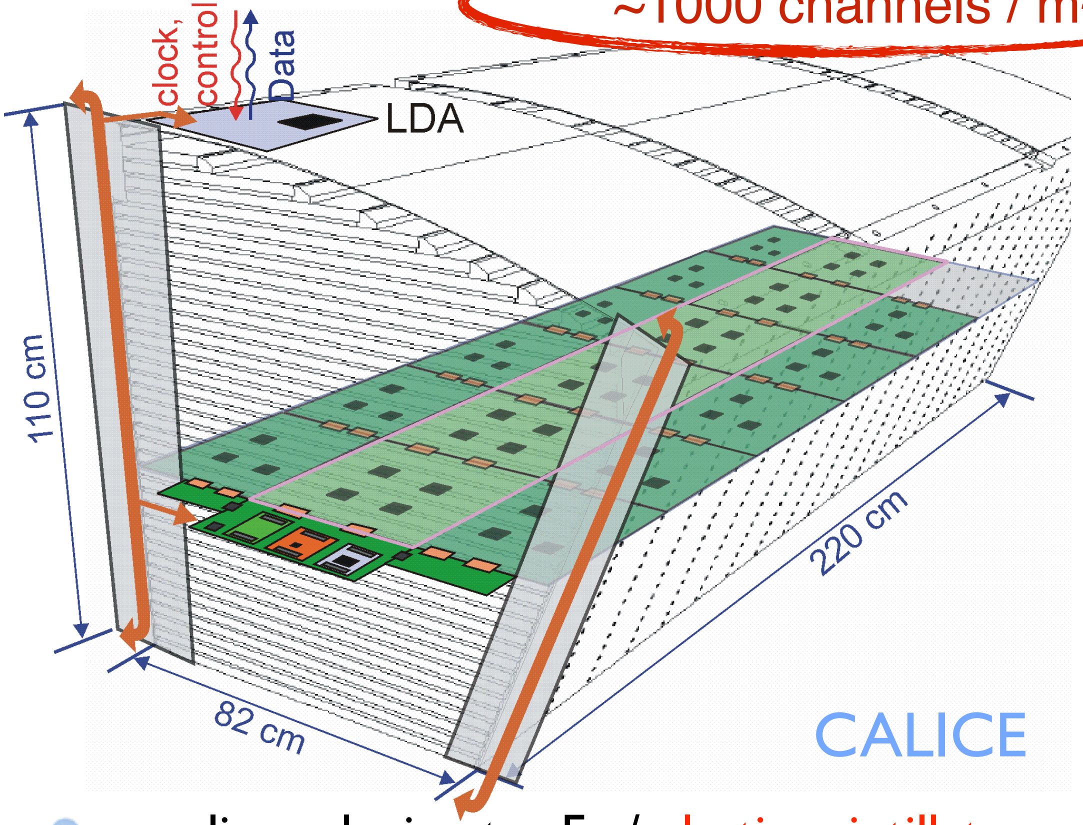
ScECAL prototype:
$45 \times 5 \times 2$ mm^3 strips
crossed layers to
achieve effective
5×5 mm^2 granularity

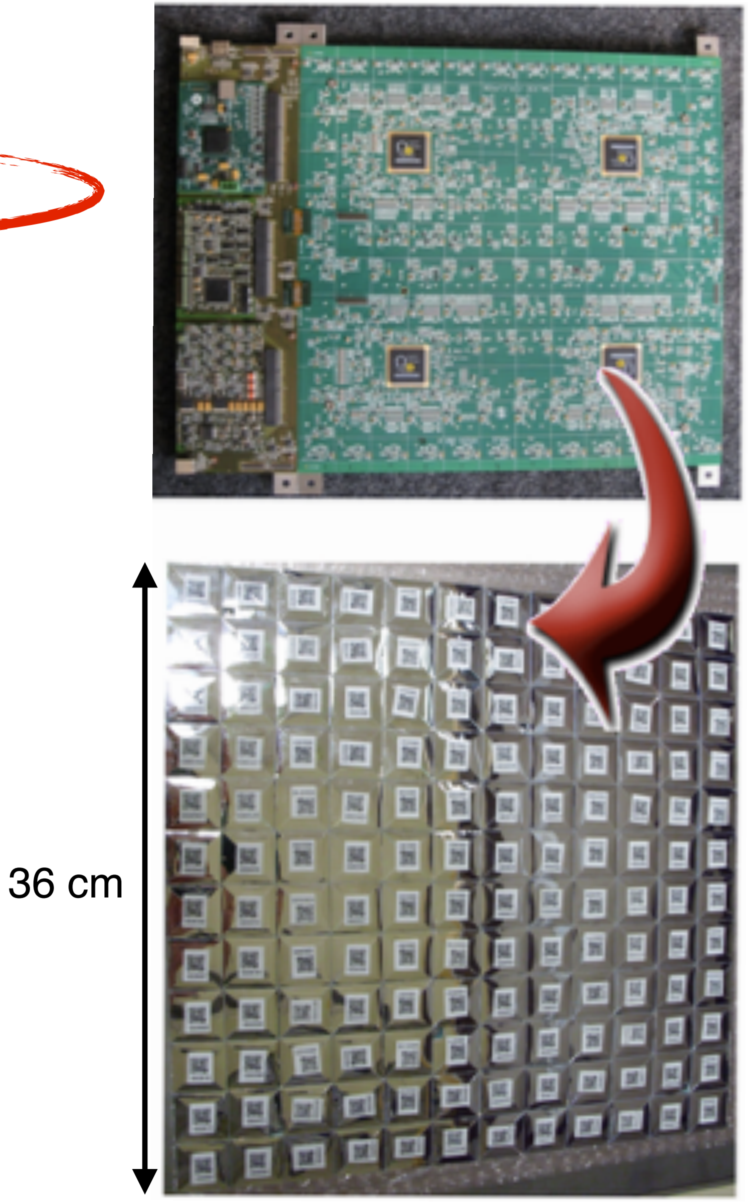


Highly integrated r/o electronics mandatory

Scintillator based analog HCAL

~1000 channels / m²





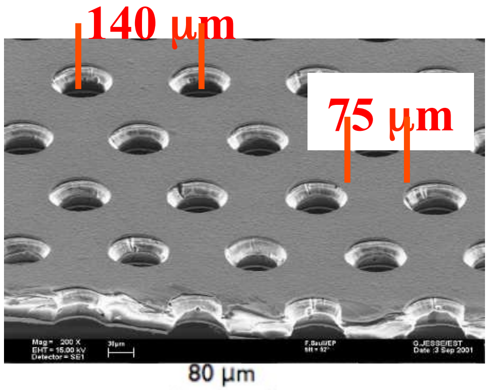
- sampling calorimeter Fe / plastic scintillator
- ~ 48 layers ~ 6 λ
- Front end electronics integrated in active layer

Highly integrated r/o electronics mandatory

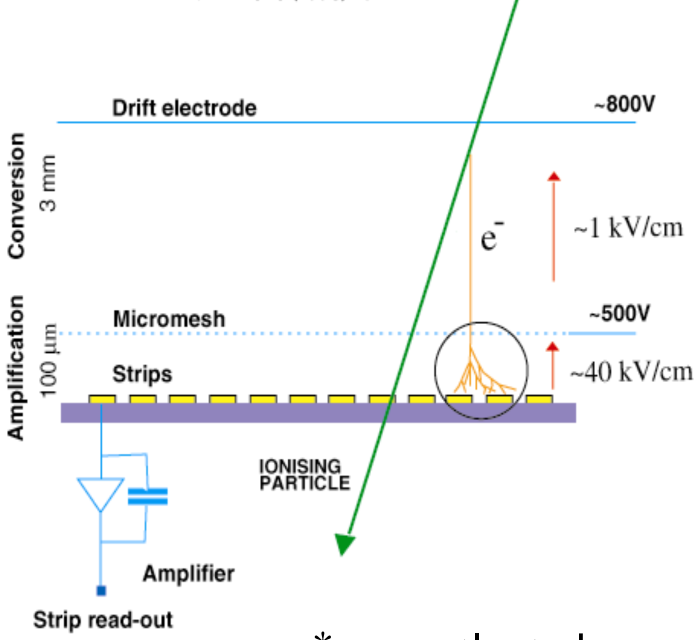
Gaseous readout

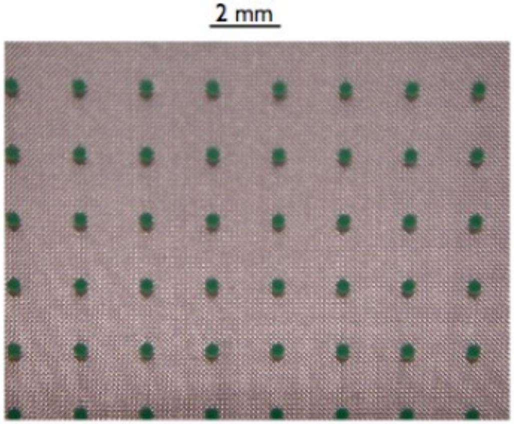
- Digital readout is required to reach 1x1 cm^2 granularity *
- Technique for the active media:
  - ionization-gas chambers with charge amplification (RPC, GEM, MicroMegas)
  - digital readout on pads 1x1cm^2
  - integrated electronics inside active layer
  - high level of data concentration (~0.5 M channels / m^3)

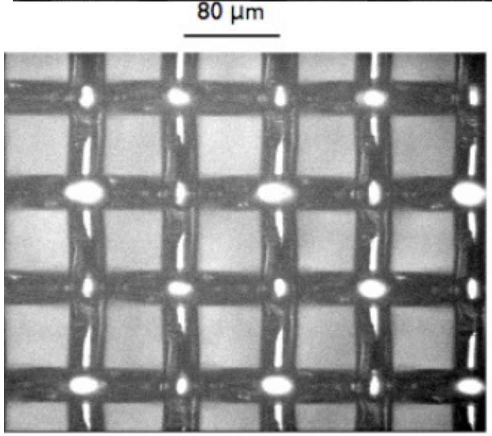
Gas Electron Multiplier foil



Y.Giomataris, Ph. Rebourgeard, J.P Robert and G. Charpak
NIM A376 (1996) 29



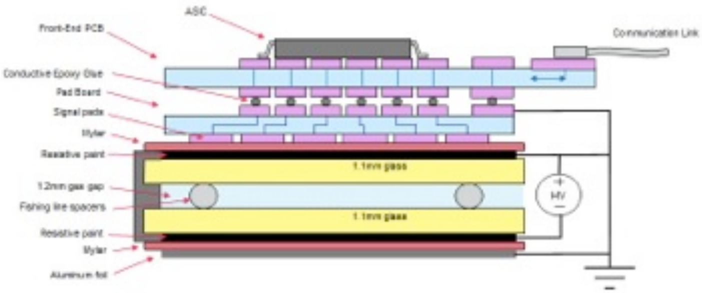




* currently study ongoing to test also 1x1 cm^2 scintillator tiles with SiPM readout

Gaseous based digital HCAL

~ 10,000 calorimeter cells / m^2

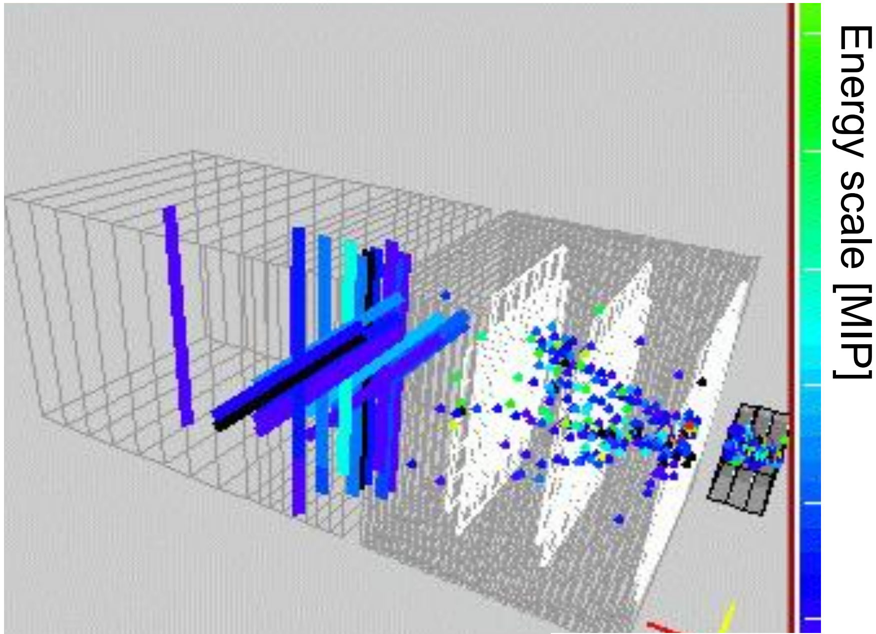


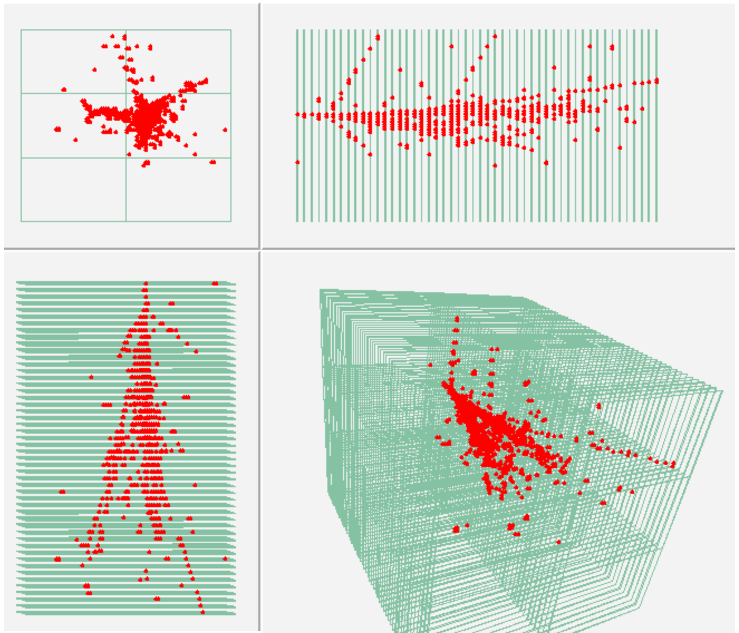
- sampling calorimeter Fe / gas layer (RPC)
- ~ 48 layers ~ 6 λ
- Front end electronics integrated in active layer

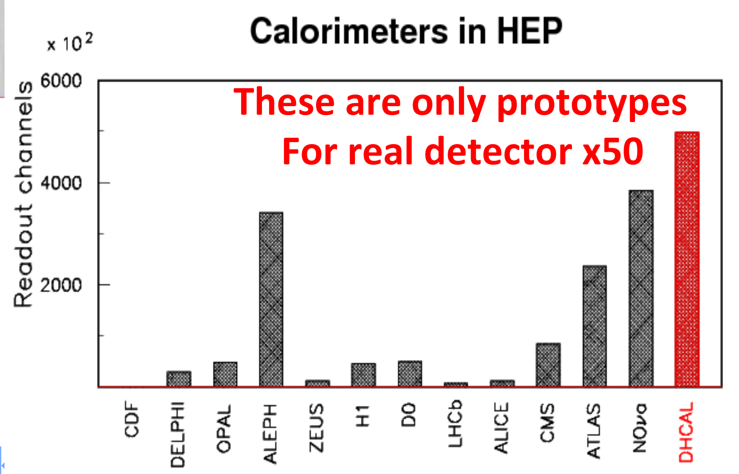
Single pion reconstruction with high granularity

Fe/scintillator with analog readout

Fe/gas with digital readout





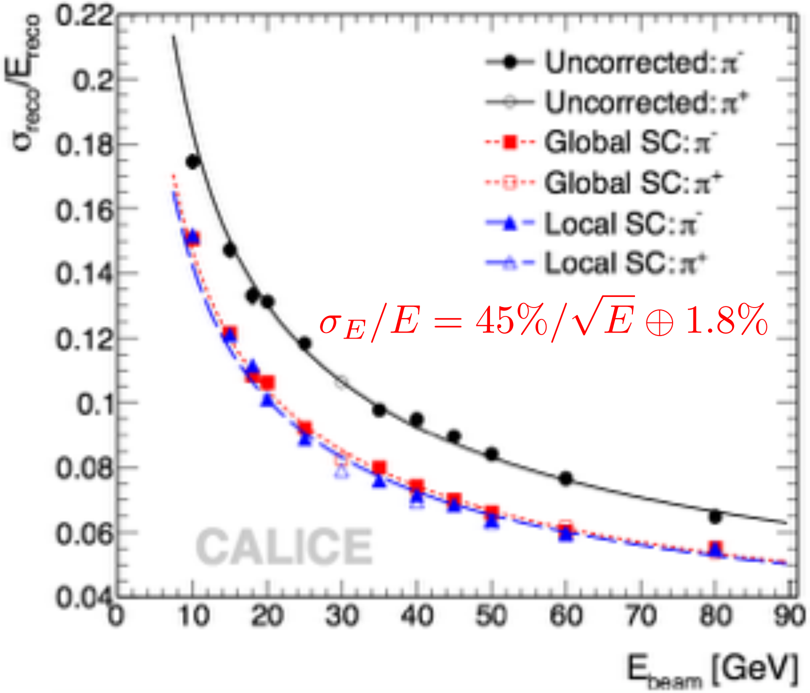


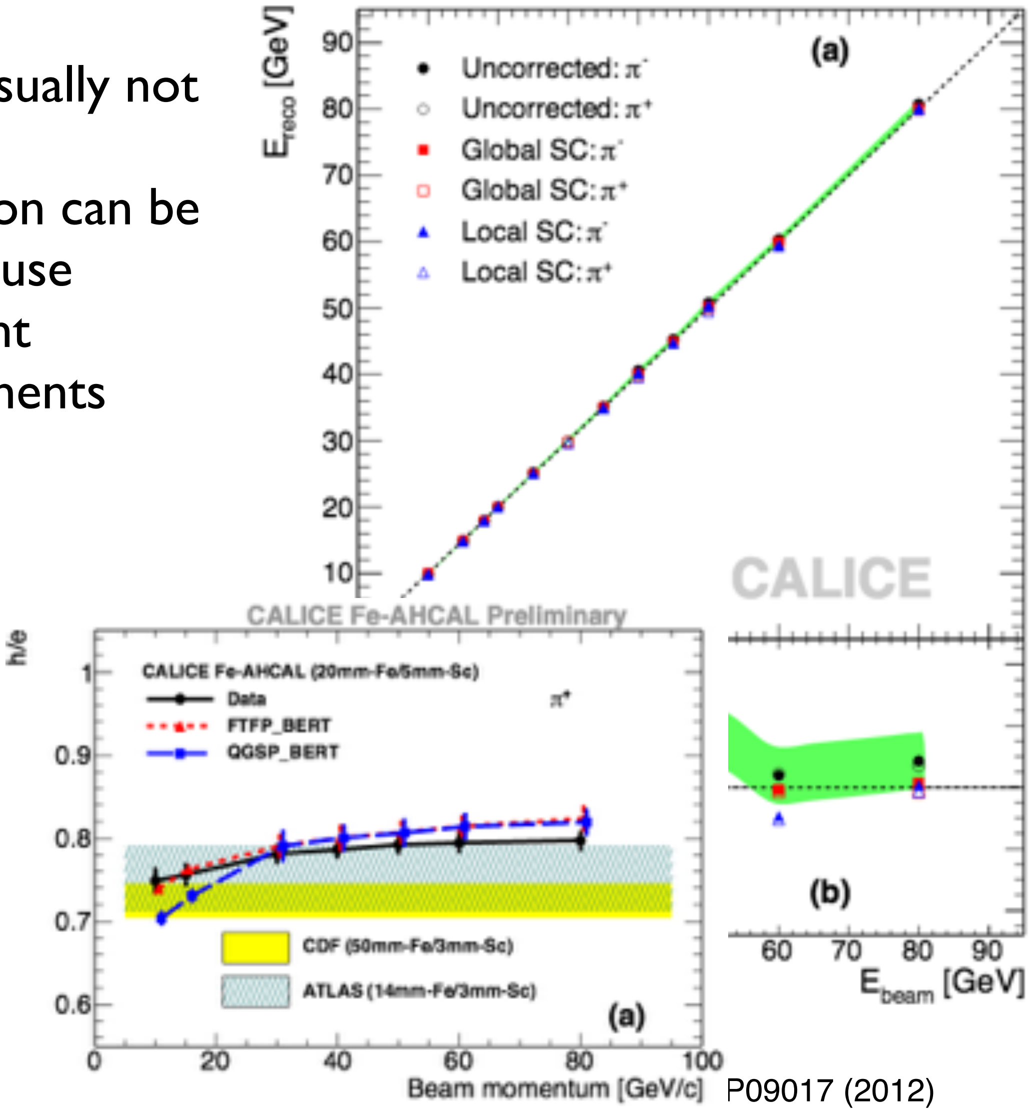
These are only prototypes
For real detector x50

CALICE

Performance of hadronic P-flow calorimeters

- Calorimeter response must be linear
- Sampling hadronic calorimeters are usually not compensating
- In high granular calorimeters resolution can be improved by software compensation: use shower density to correct for different response to em and hadronic components



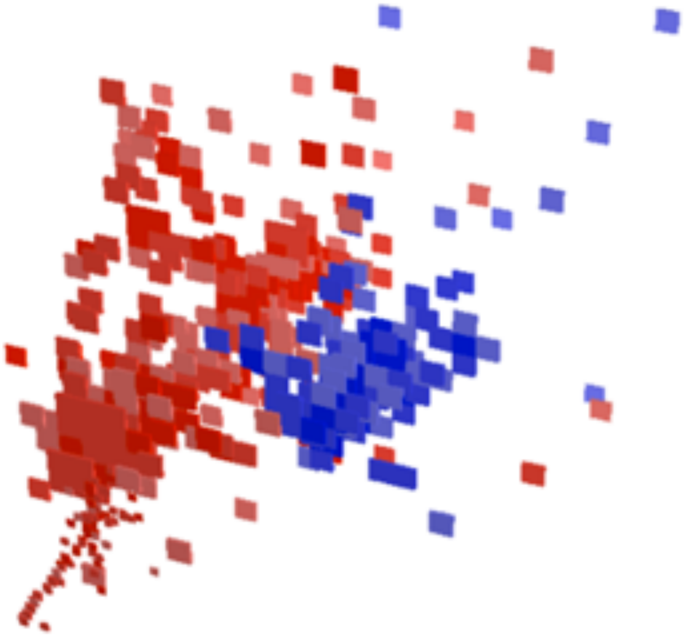


P09017 (2012)

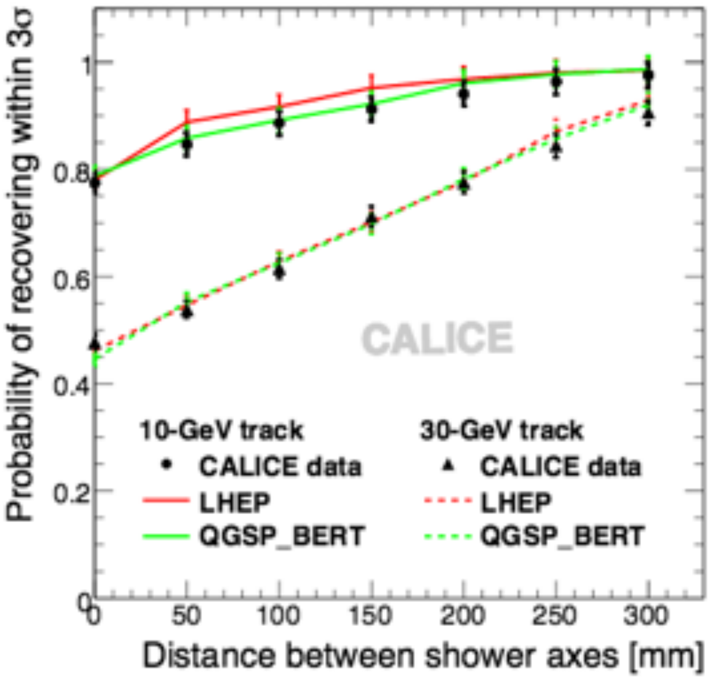
Particle flow performance

A key performance criterion is the separation of showers

‣ Use CALICE data projected into full detector geometry, apply P-flow to separate neutral from charged hadrons - validate MC prediction



Excellent reproduction of two-particle separation in SiW ECAL + Scint. AHCAL



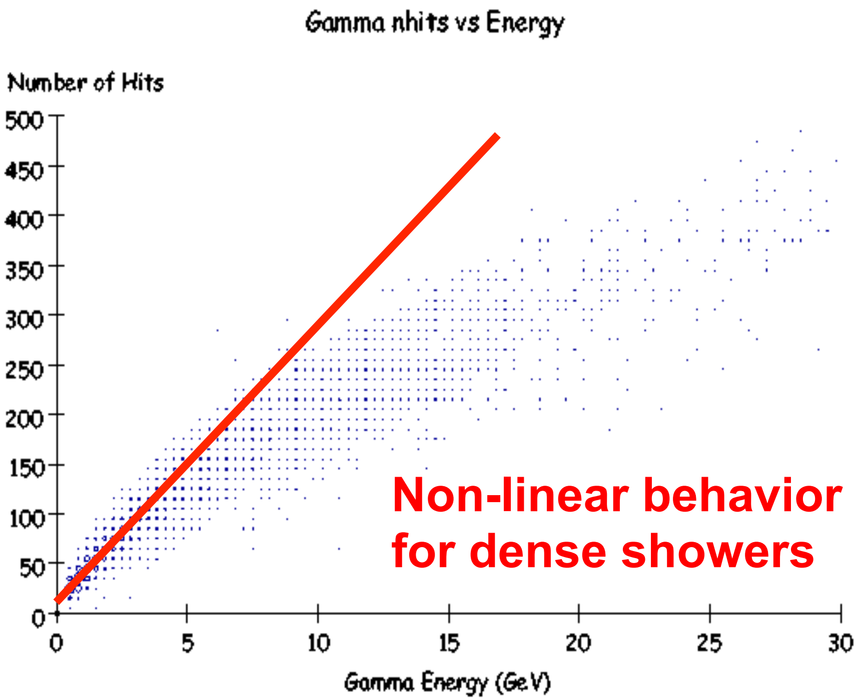
JINST 6, P07005 (2011)

The challenge of high granularity

photon analysis

$$E_\gamma \neq \sum N_i$$

ECAL: Analog readout required

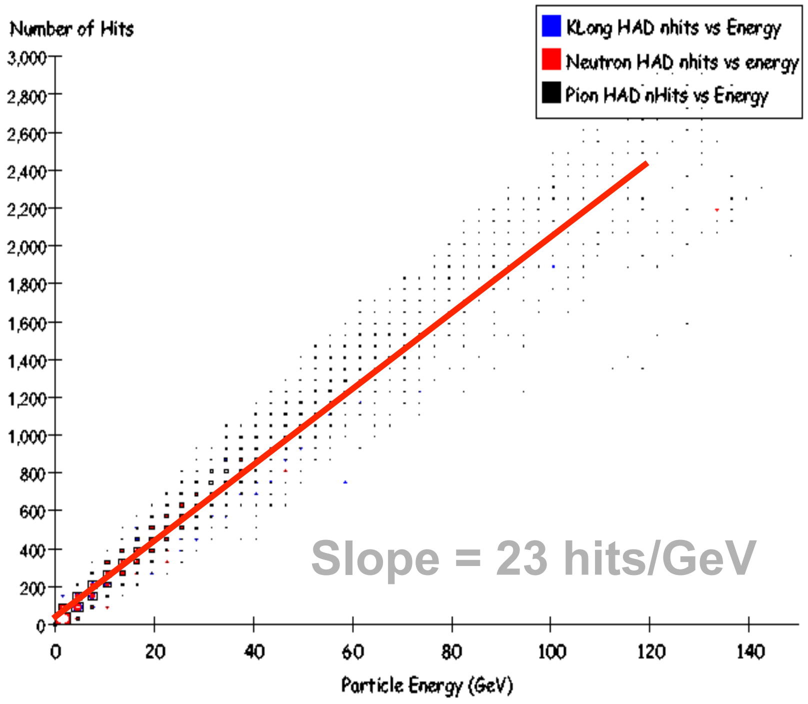


Non-linear behavior for dense showers

hadron analysis

$$E_h \propto \sum N_i$$

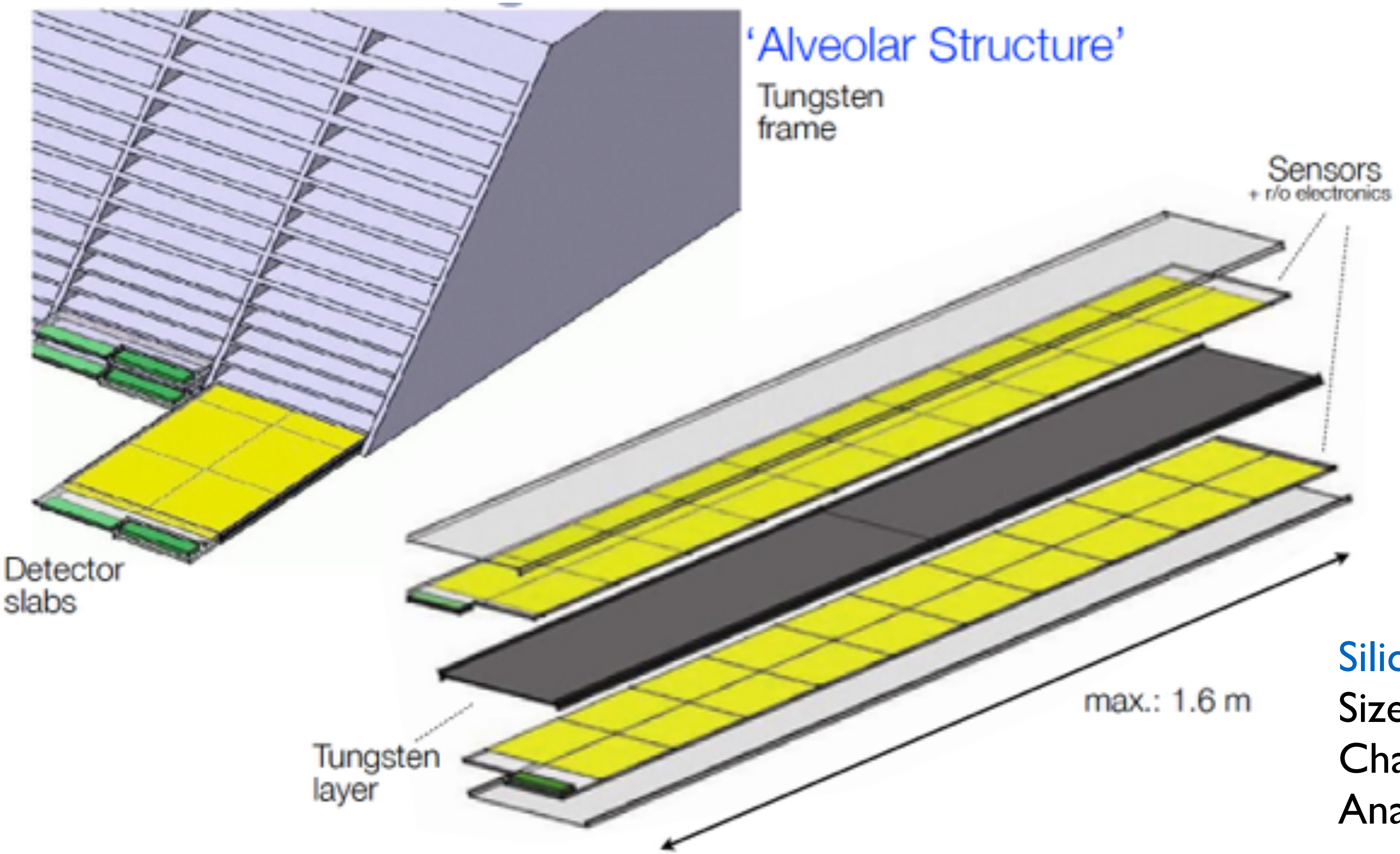
HCAL: either Analog or Digital readout



Slope = 23 hits/GeV

Calorimeter cell size 1x1cm^2

Silicon Tungsten - Analog ECAL



Silicon pads:
Size: 0.5 x 0.5 cm^2
Channel number: 10^7
Analog readout

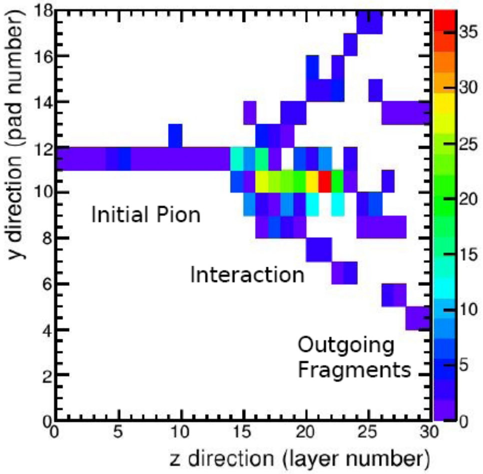
Advantages of Silicon:

- (relatively) high density, low required energy per e- /hole pair: large sampling fraction also for thin active layers, large signals
- high segmentation possible, stable against changing environmental parameters

Silicon Tungsten - Analog ECAL

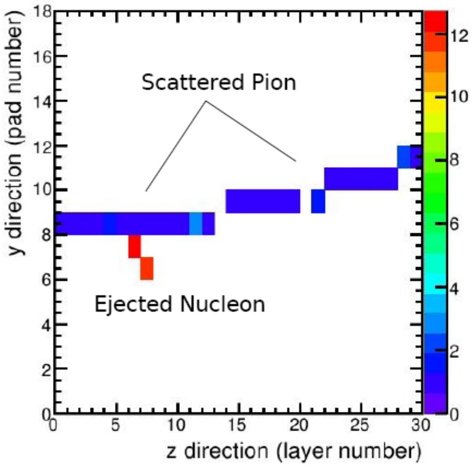
(Start of) Hadronic Showers in the SiW Ecal

Complex and Impressive



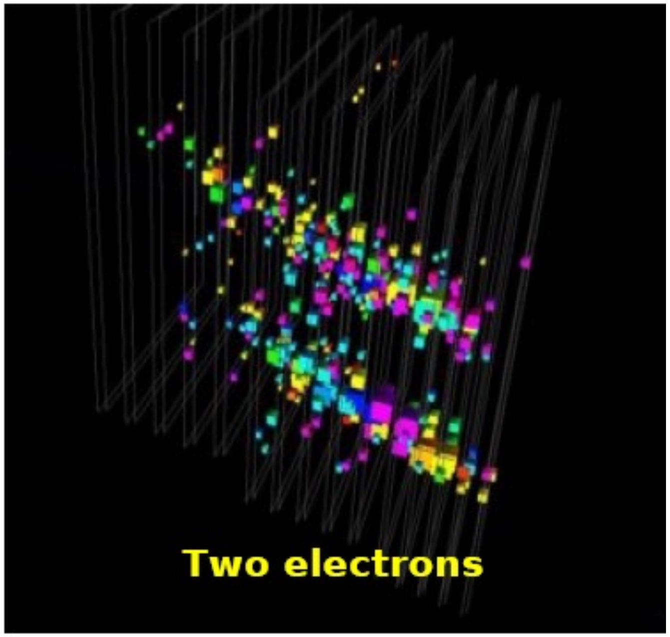
Inelastic Reaction in SiW Ecal

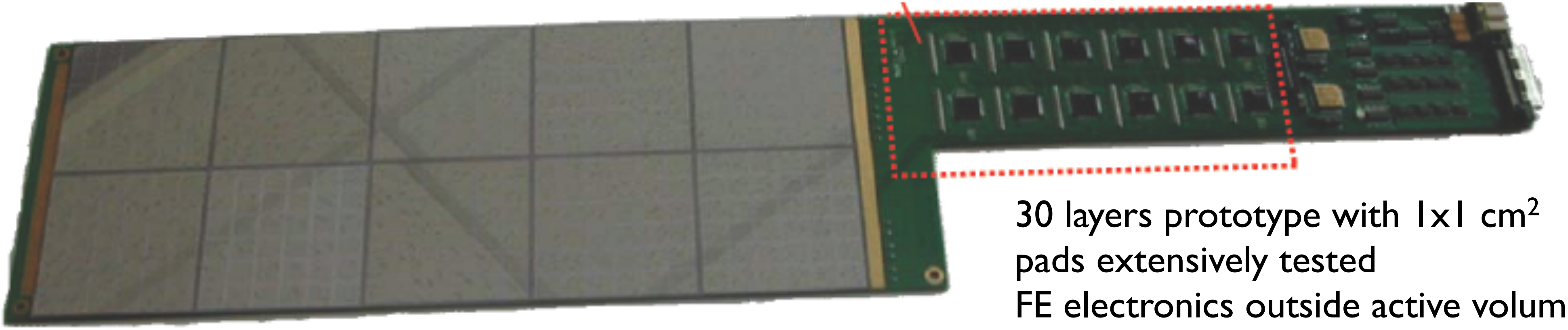
Simple but Nice



Nucleon Ejection in SiW Ecal

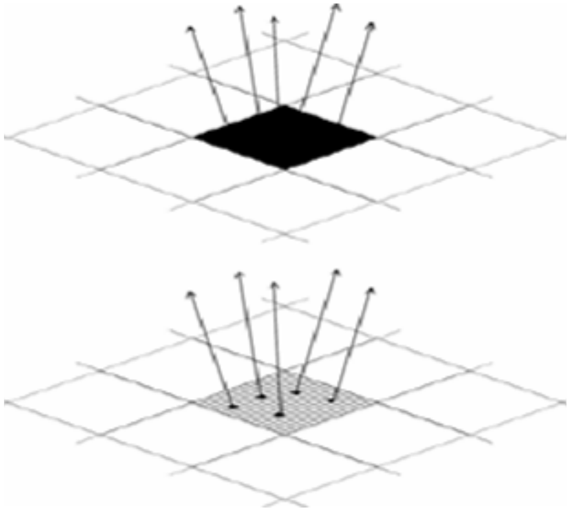
Particle Distance~ 5 cm
→ No Confusion !!!





30 layers prototype with 1x1 cm^2 pads extensively tested
FE electronics outside active volume

Digital ECAL



Next R&D challenge:

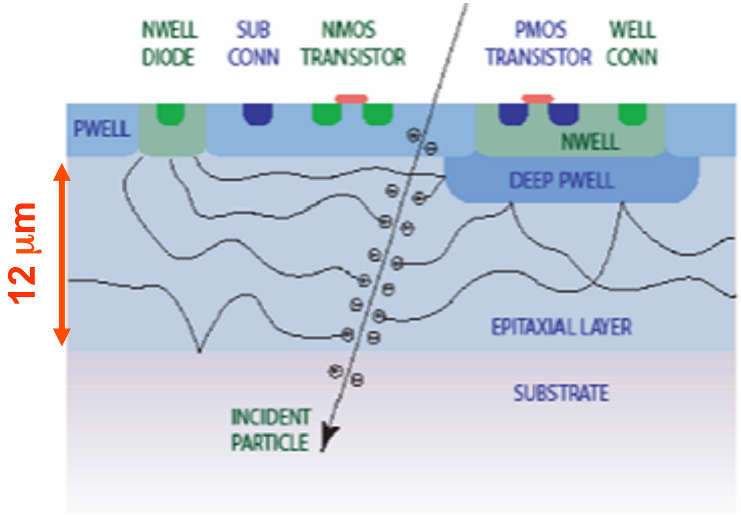
Substitute 0.5x0.5 cm^2 analog readout Si pads with smaller pixels readout digitally

"Small" = at most one particle/pixel

1-bit ADC/pixel, i.e. Digital !

How small should a pixel be?

- EM shower core density at 500GeV is ~100/mm^2
  Pixels must be <100×100μm^2
- Baseline: 50×50μm^2
- Gives ~10^{12} pixels for ECAL
  a "Tera-pixel calorimeter"
- Mandatory to integrate electronics on sensor
  MAPS (Monolithic Active Pixel Sensors)
  - developed for vertex detectors



Monolithic active pixels - Digital ECAL

MAPS:

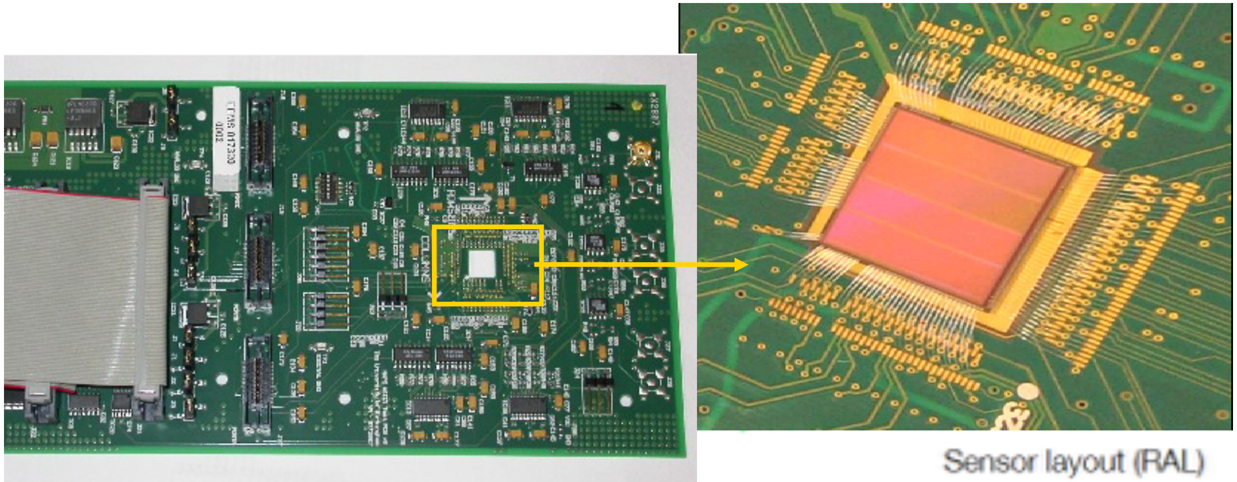
Monotlithic
Active Pixel Sensor

Pixel size: 40x40 μm^2
Channel number: 8x10^{11}
Absorber: Tungsten
Binary readout

Integration of
sensor and readout electronics

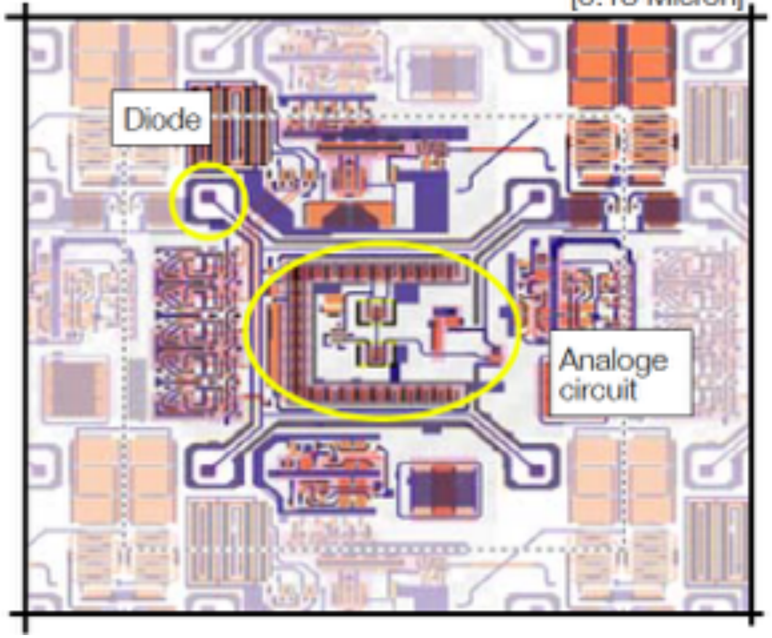
Manufactured in
standard CMOS process

Concerns:
Power consumption: 40 μW/mm^2
DAQ needs 400 Gbit/s

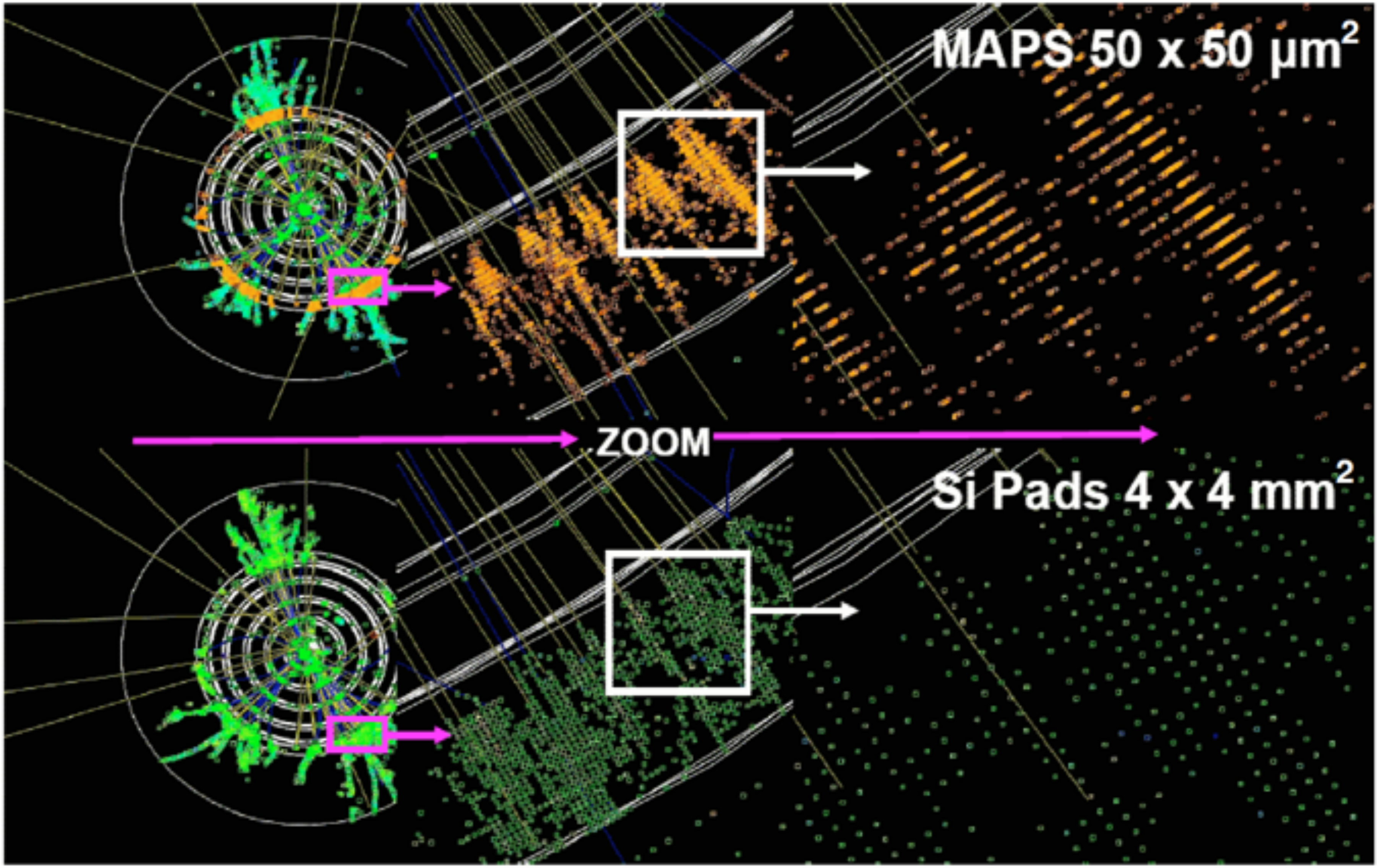


8.2 million transistors
28224 pixels; 50x50 μm^2

Sensor layout (RAL)
[0.18 Micron]



EM Shower imaging



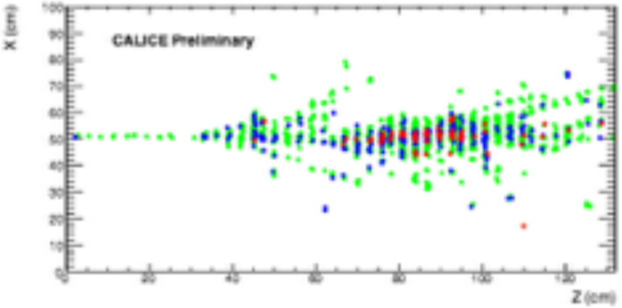
Simulation

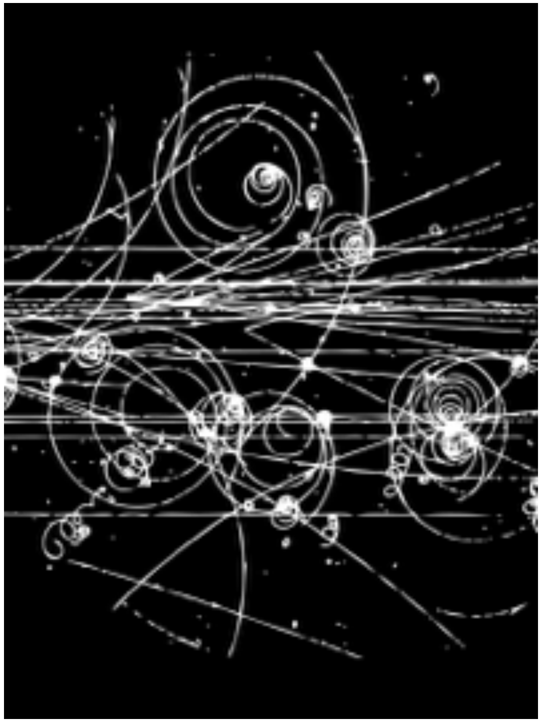
Particle flow - Summary

- A concept to improve jet energy resolution in collider experiments
- Based on synergy between high granular detectors and smart software
- Granularity more important than energy resolution

- Push technology limits on:
  - channel density
  - integrated electronics
  - cooling / power dissipation
  - minimal material budget

- Future:
  4D imaging calorimeters

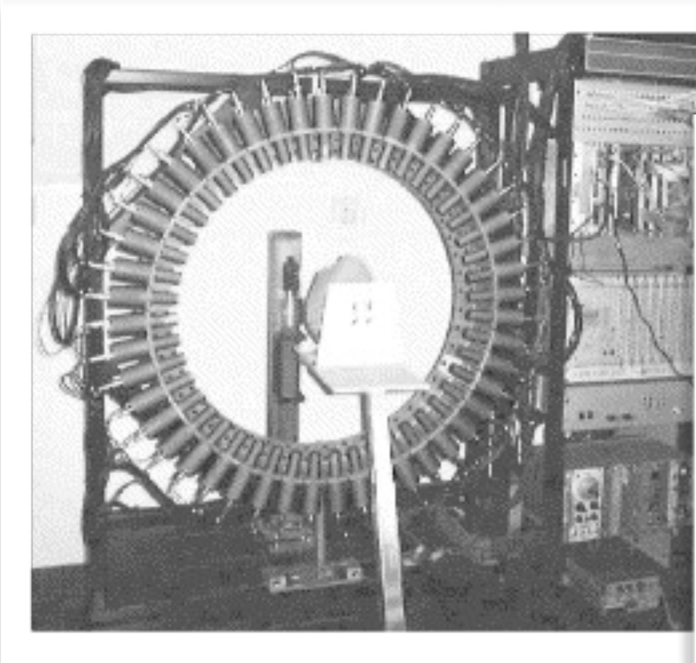




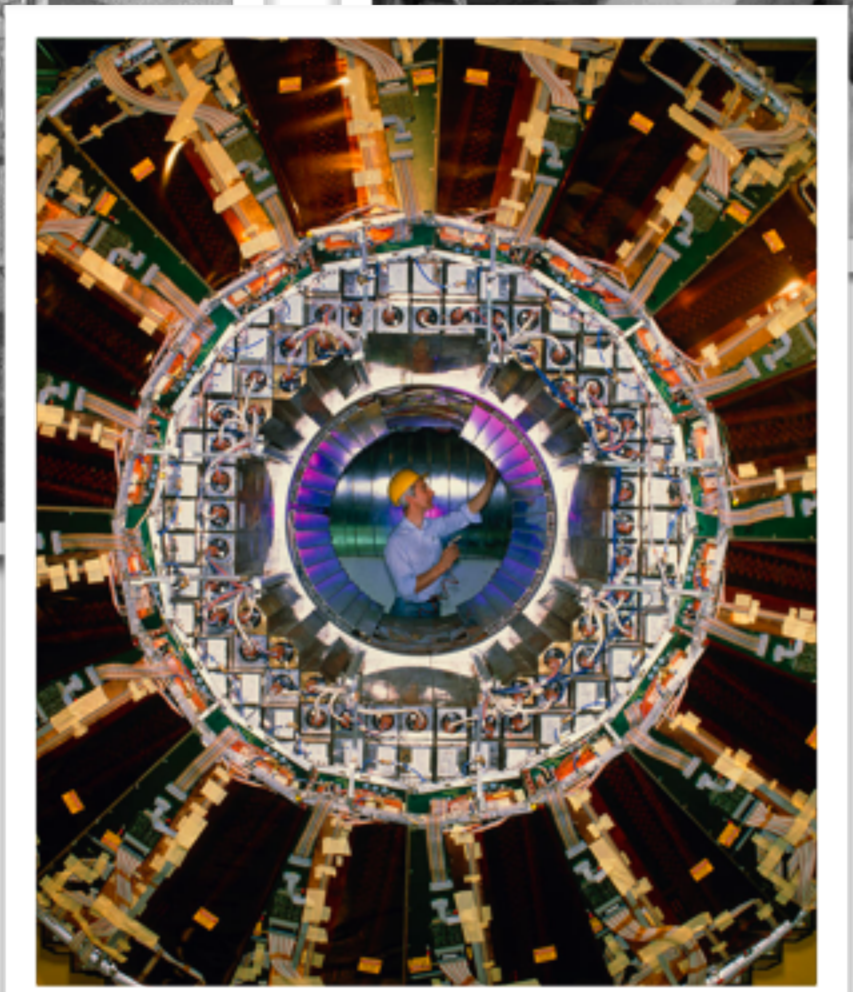
Calorimeters for medicine

The first PET scanners

'80s - '90s PET are mostly a research tool

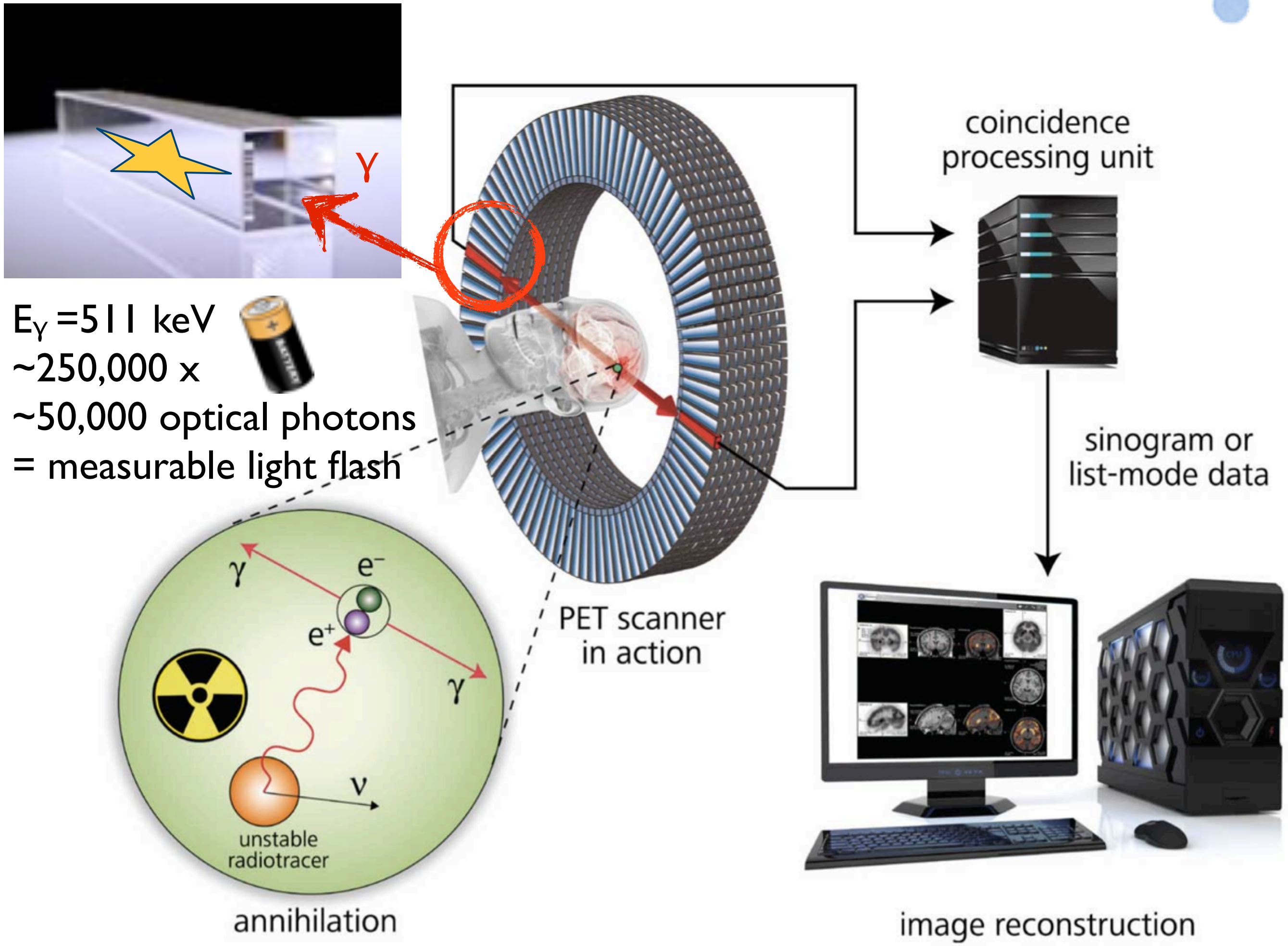


End of '90s construction of the OPAL detector at CERN



Positron Emission Tomography

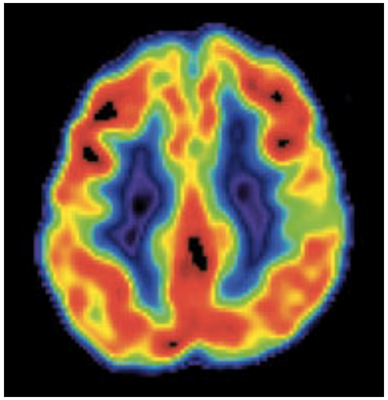
Since 2000 standard technique for cancer diagnostics in large hospitals



$E_\gamma = 511$ keV
~250,000 x
~50,000 optical photons
= measurable light flash

- Provides functional information:
  Blood flow
  Oxygen use
  Glucose metabolism
  Other metabolic functions
  (brain cognitive functions - serotonine, beast cancer - herceptin, prostate cancer - choline)

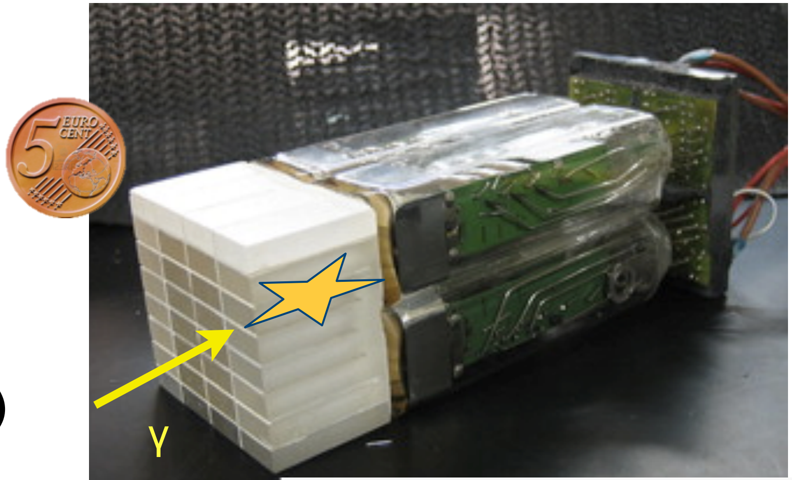
Brain slice



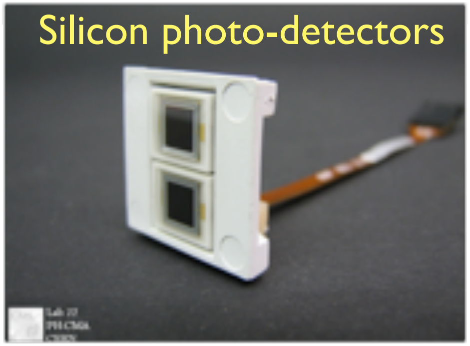
PET future improvements

Photon detection in a PET system:

- inorganic crystals to stop the photons (E = light)
- photo-detector to convert light into charge
- readout electronics to measure charge

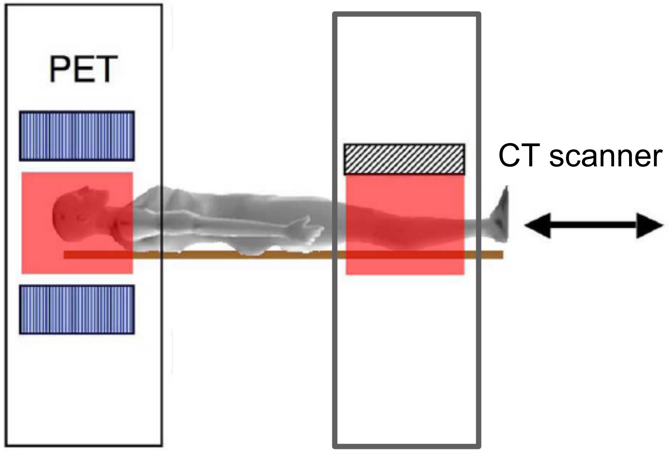


most commercial PET scanner are based on 30 years old technology (already spin-off from physics)



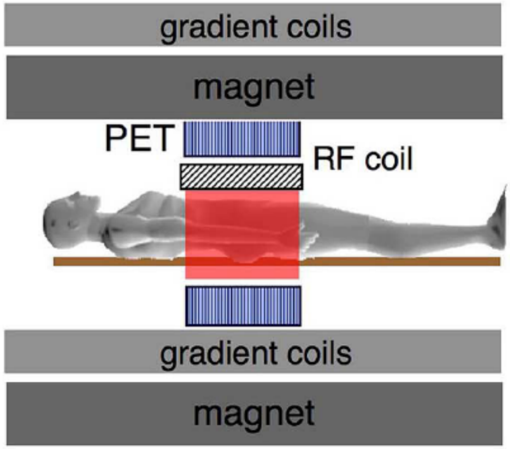
- High Energy Physics pushes particle detectors and read-out electronics beyond state-of-the-art to achieve the needed resolution, speed, granularity
- Clear benefits to the diagnostic tools in medical imaging

Next generation of multi-modality imaging



Sequential PET-CT technically simple

90 % oncology (whole body PET-CT)
CT low contrast in soft tissue (brain)
Sequential scanning (motion in between scans)
Radiation dose of CT is high (up to 30 mSv)
PET dose: 4 mSv (2 mSv natural radiation) = 200 MBq ^{18}F injected
For the hospital: 45 min/scan (2-3 h / patient), ~2000 Euro/scan

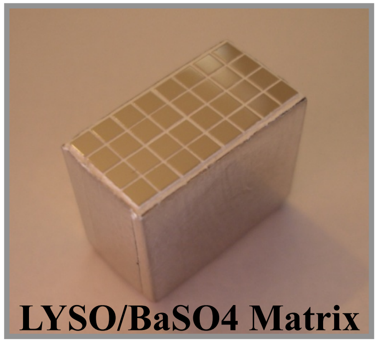


Simultaneous MR-PET technically challenging, but large potential

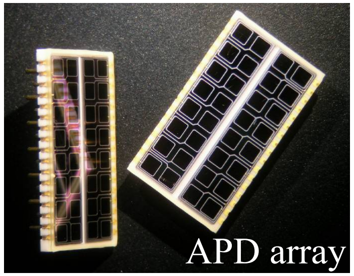
Clinical indications
- Neuro: Alzheimer, epilepsy, tumors,...
- Mammography
- Pediatric scans

Lower radiation dose (only PET)
For the hospital: slightly higher cost (MRI factor 2 more than CT)

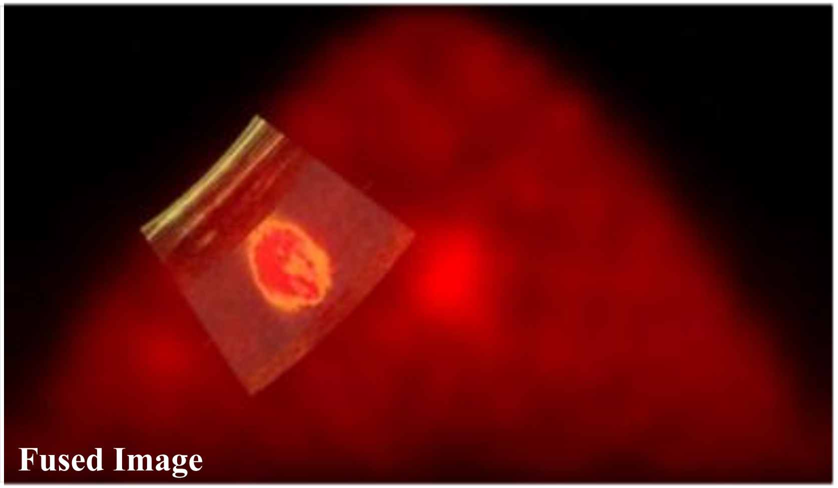
Novel instruments: ClearPEM-sonic

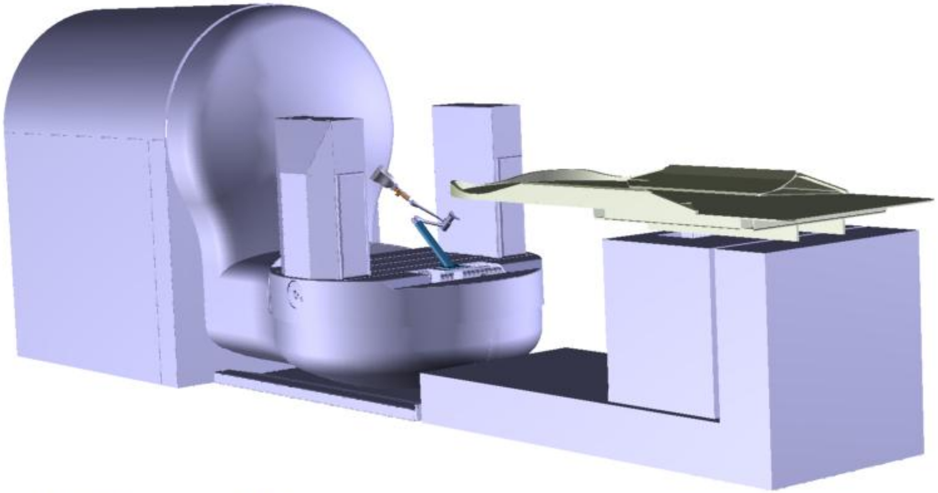

LYSO/BaSO4 Matrix

- A dedicated PET for mammography screening
- Employ the state of the art crystals and photo-detectors


APD array

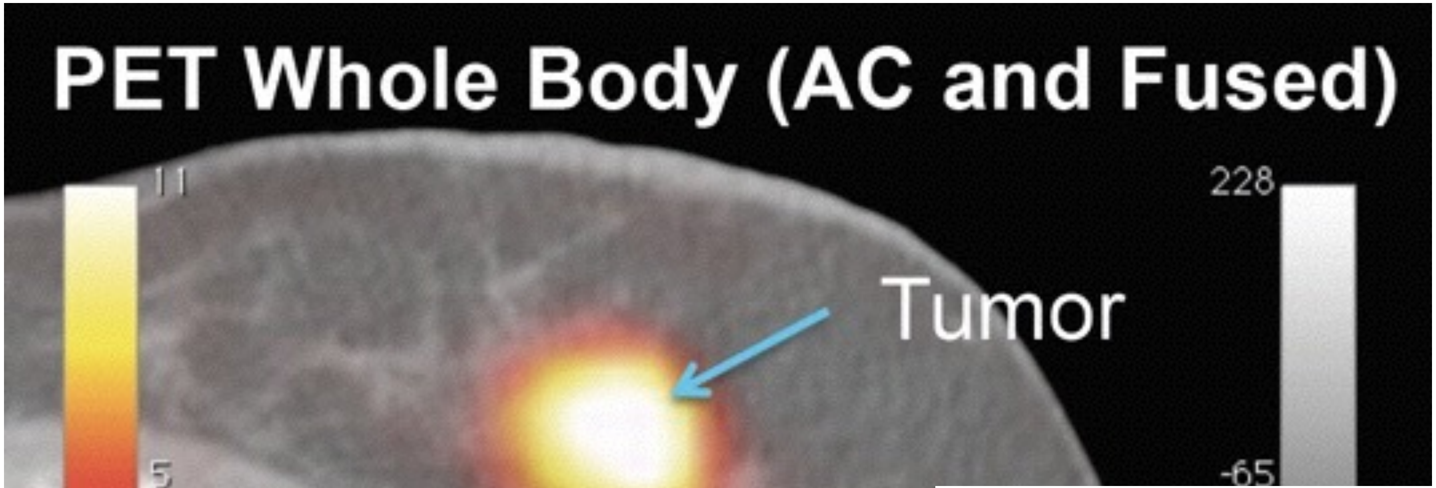
PET + UltraSound = functional + anatomical image

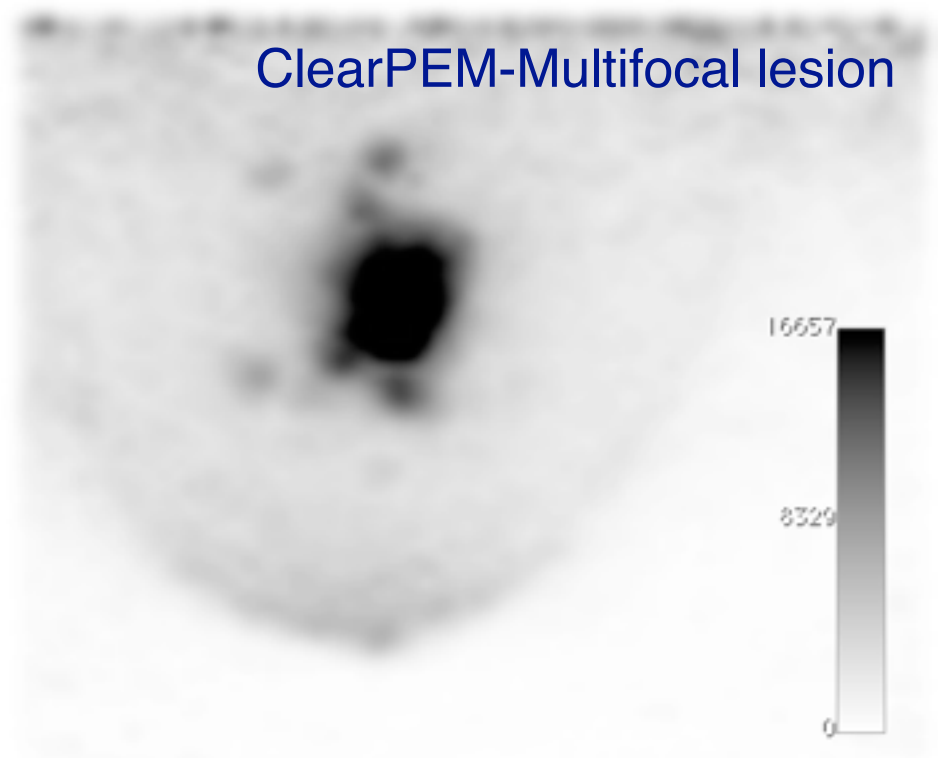

Fused Image



extensive tests at Timone hospital, Marseille now moved to San Girardo hospital, Milano for larger scale clinical trials

Clinical validation: ClearPEM-sonic




ClearPEM-Multifocal lesion

Successful identification of multifocal cancer not recognized by the PET/CT.

Very important information for the patient staging (first chemotherapy, then mastectomy).

Novel instruments: EndoscopicPET-UltraSound

PET = Coincidence between two detectors:

- One detector is external to the body (conventional PET)
- One detector is mounted on the tip of an ultrasound endoscope (miniaturized PET)

PET + UltraSound = functional + anatomical image

Courtesy DESY

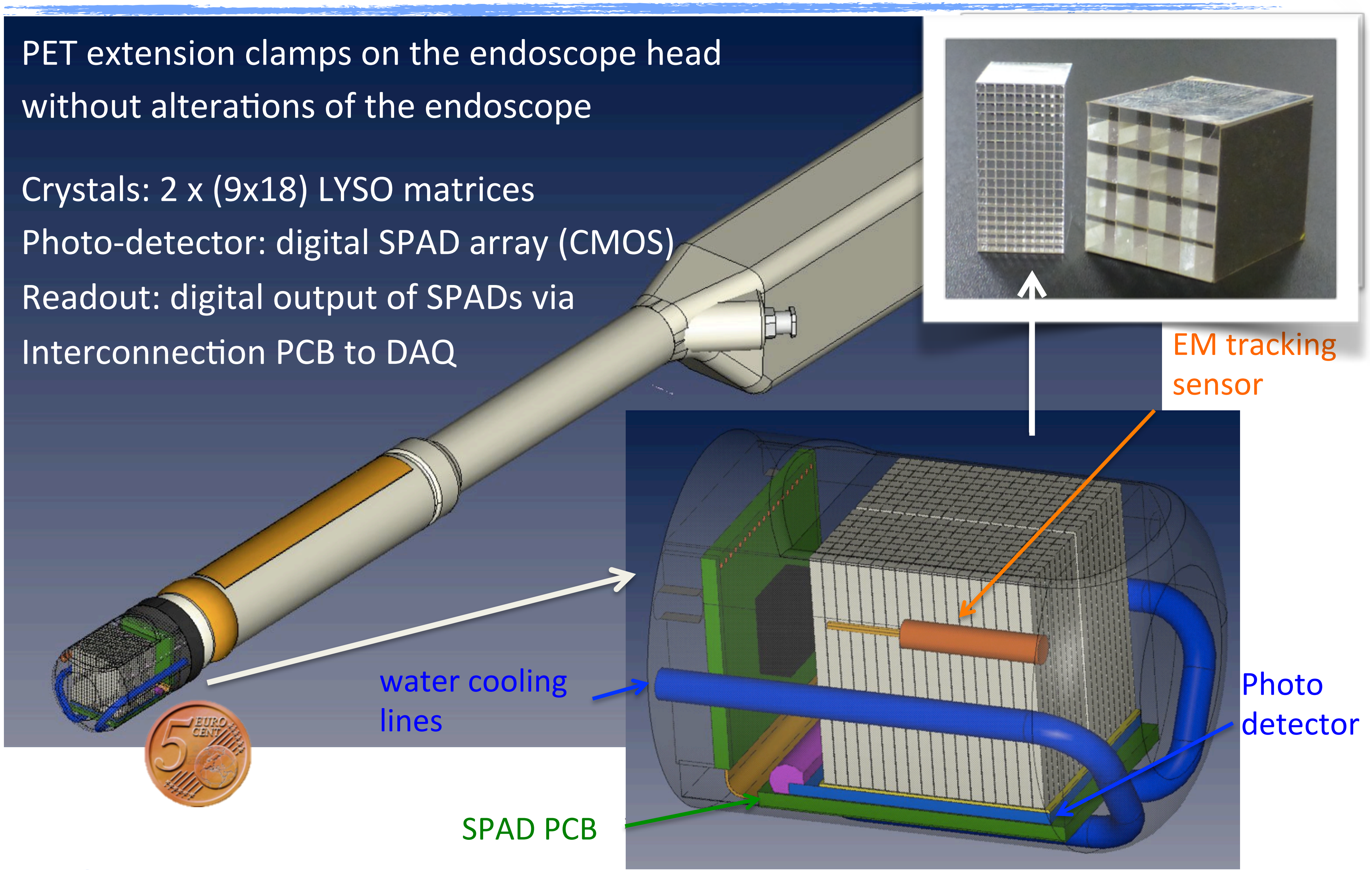
The smallest PET detector in the world

PET extension clamps on the endoscope head without alterations of the endoscope

Crystals: 2 x (9x18) LYSO matrices

Photo-detector: digital SPAD array (CMOS)

Readout: digital output of SPADs via Interconnection PCB to DAQ



Courtesy DESY