Particle interaction and detectors

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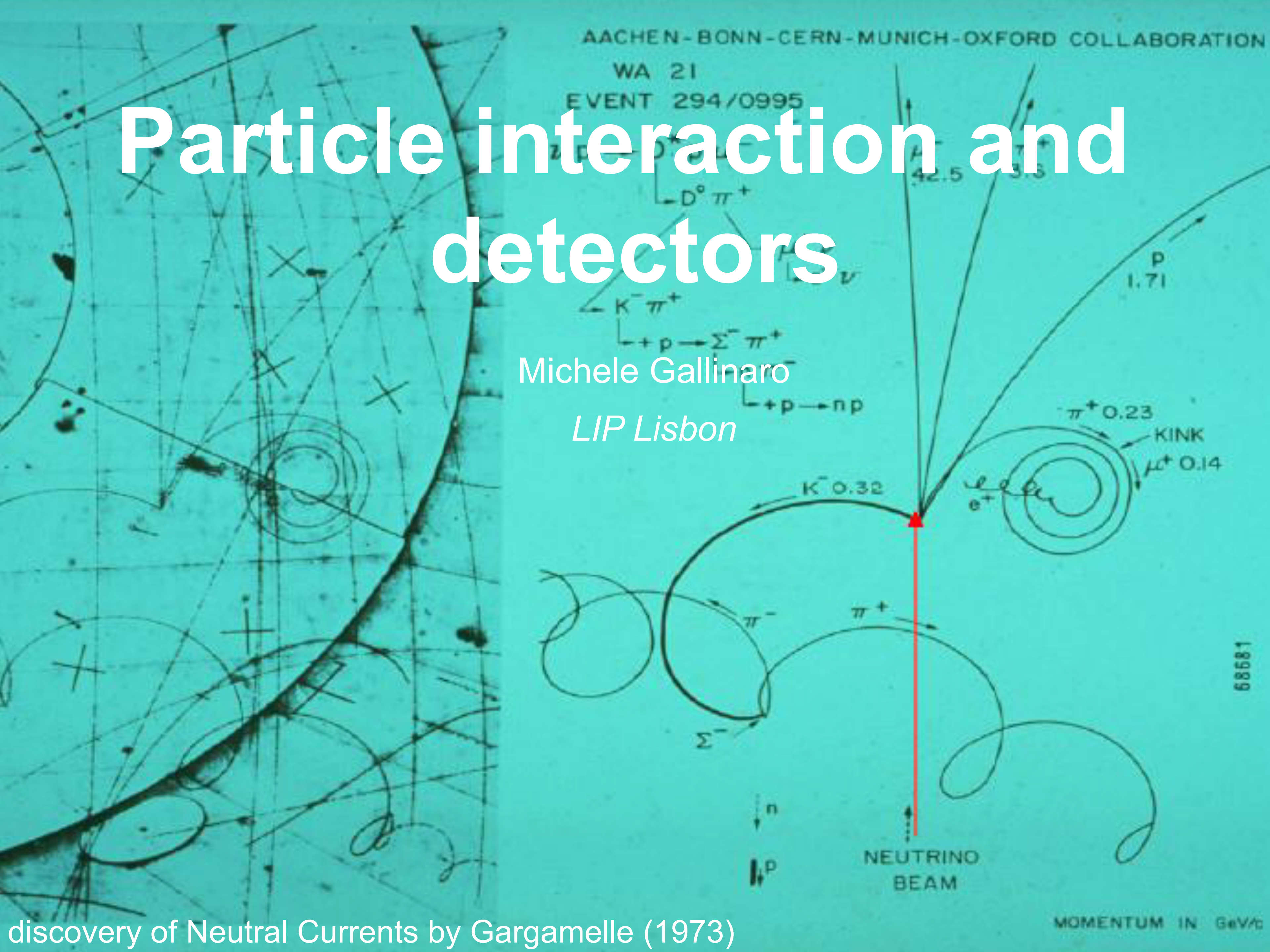


discovery of Neutral Currents by Gargamelle (1973)

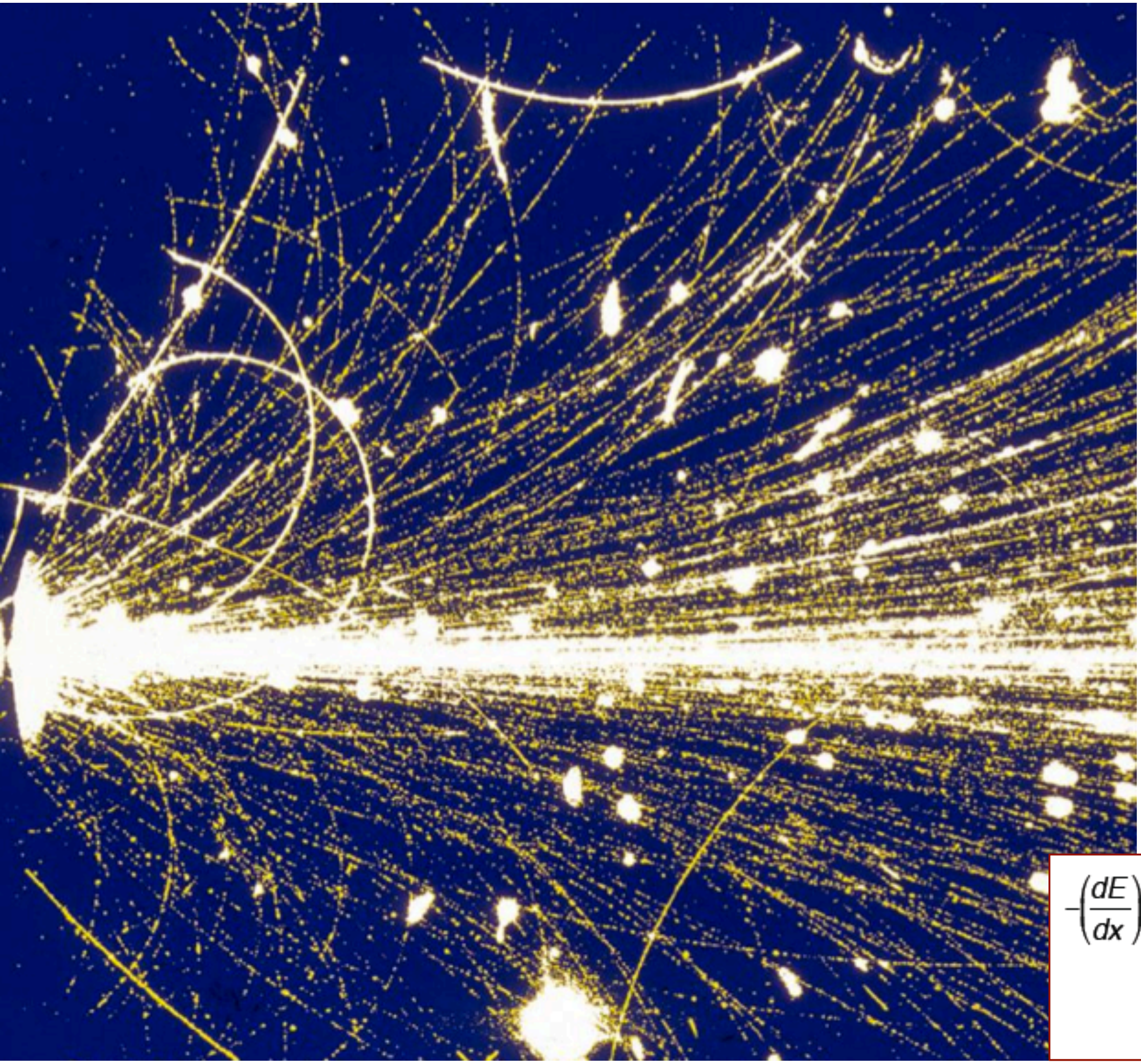
Contents

- Particle, interactions, and detectors
- Calorimetry and energy

today

- Trackers and momentum
- Trigger and data acquisition

Particle detection



Particles can be "seen" as the result of an interaction with matter (detector)

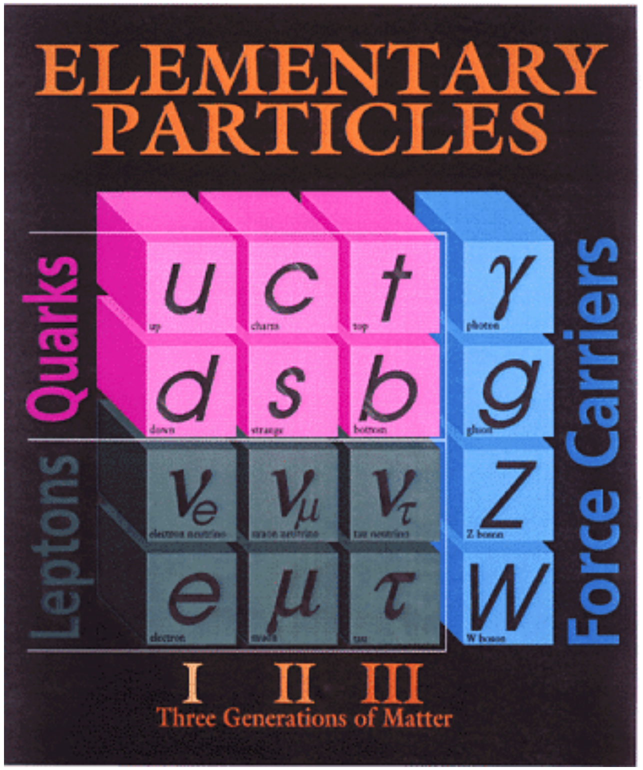
In the end, everything is converted to:

- optical pictures
- voltage/current signals

$$-\left(\frac{dE}{dx}\right)_{tot} = -\left(\frac{dE}{dx}\right)_{coll} - \left(\frac{dE}{dx}\right)_{rad} - \left(\frac{dE}{dx}\right)_{pair} - \left(\frac{dE}{dx}\right)_{photonucl} - \left(\frac{dE}{dx}\right)_{photoeff} - \left(\frac{dE}{dx}\right)_{compton} - \left(\frac{dE}{dx}\right)_{hadron}$$

What can we detect?

- Directly observable particles must:
  - Undergo strong or EM interactions
  - Be sufficiently long-lived to pass the detectors
- We can directly observe:
  - Electrons, muons, photons
  - Neutral or charged hadrons
  - Pions, protons, kaons, neutrons,...
  - analyses treat jets from quark hadronization collectively as single objects
  - Use displaced secondary vertices to identify jets originating from b-quarks
- We can indirectly observe long lived weakly interacting particles (e.g. neutrinos) through **missing transverse energy**



What can we detect? (cont.)

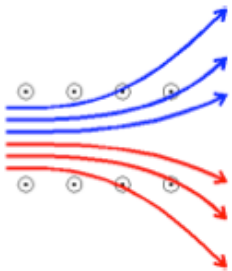
- Short-lived particles decay to long-lived ones
- We can only ‘see’ the end products of the reaction, but not the reaction itself
- In order to reconstruct the production/decay mechanism and the properties of the involved particles, we want the maximum information

Particle properties

Which properties do we want to measure?

- Energy (calorimeter)
- Momentum (tracking)
- Charge (tracking)
  - Direction, bending in magnetic field
- Life-time (tracking)
- Mass:

$$\left.\begin{matrix} E \\ \vec{p} = \begin{pmatrix} p_1 \\ p_2 \\ p_3 \end{pmatrix} \end{matrix}\right\} \begin{pmatrix} E \\ \vec{p} \end{pmatrix}$$



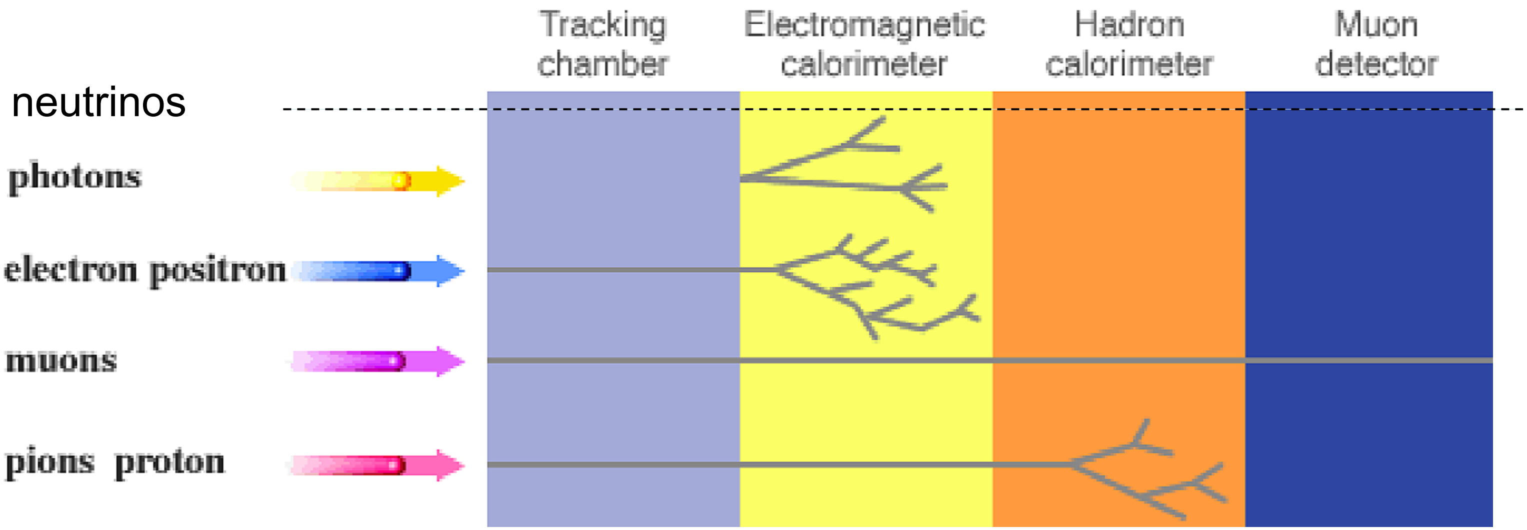
$$F = q \cdot v \cdot B = m \cdot \frac{v^2}{R}$$

$$\Rightarrow q \cdot B \cdot R = m \cdot v = |\vec{p}|$$

$$E^2 = m^2 \cdot c^4 + \vec{p}^2 c^2 \Rightarrow m = \frac{\sqrt{E^2 - \vec{p}^2 c^2}}{c^2}$$

Passage of particles

- "Onion"-like structure
- Each layer measures E and/or p of particles
- Redundancy of measurements



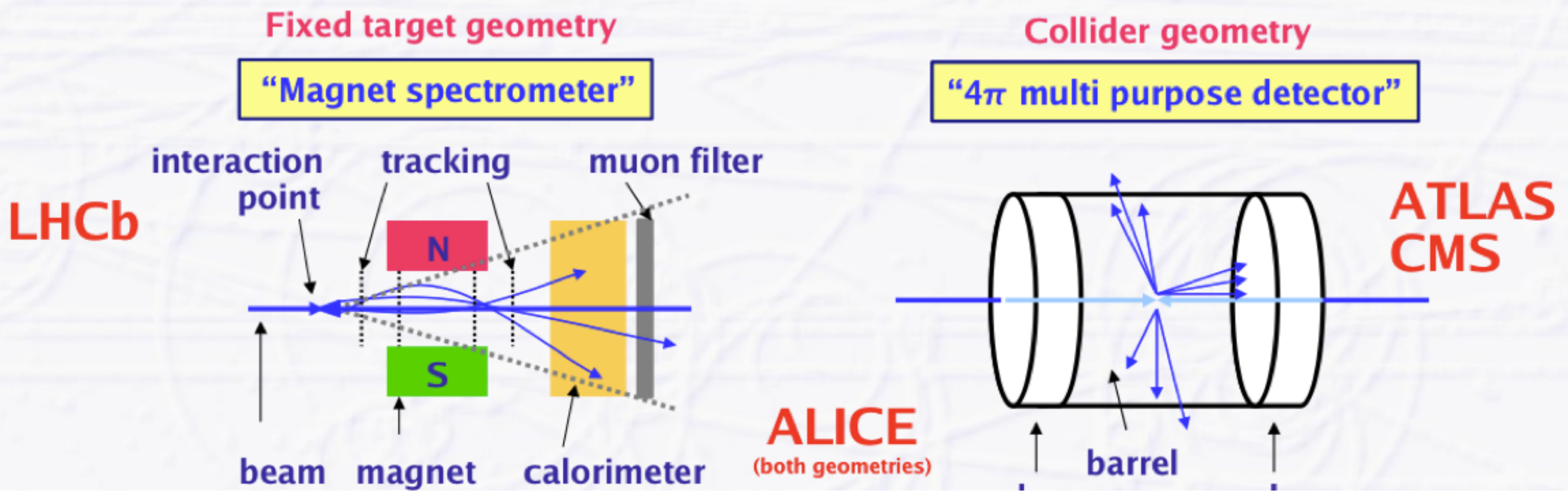
Missing ET
undetected
neutrinos...

Energy measurement
total absorption of showers

momentum measurement
(curvature in magnetic field)

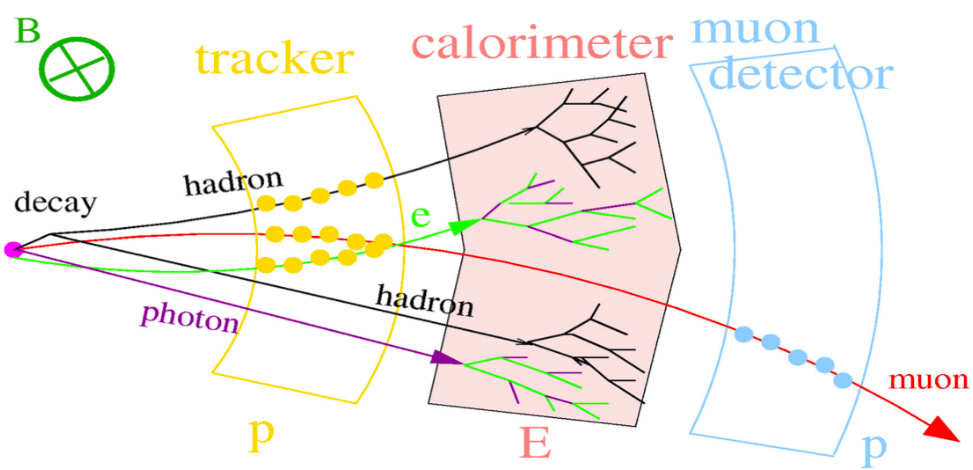
Muon detection
measure momentum

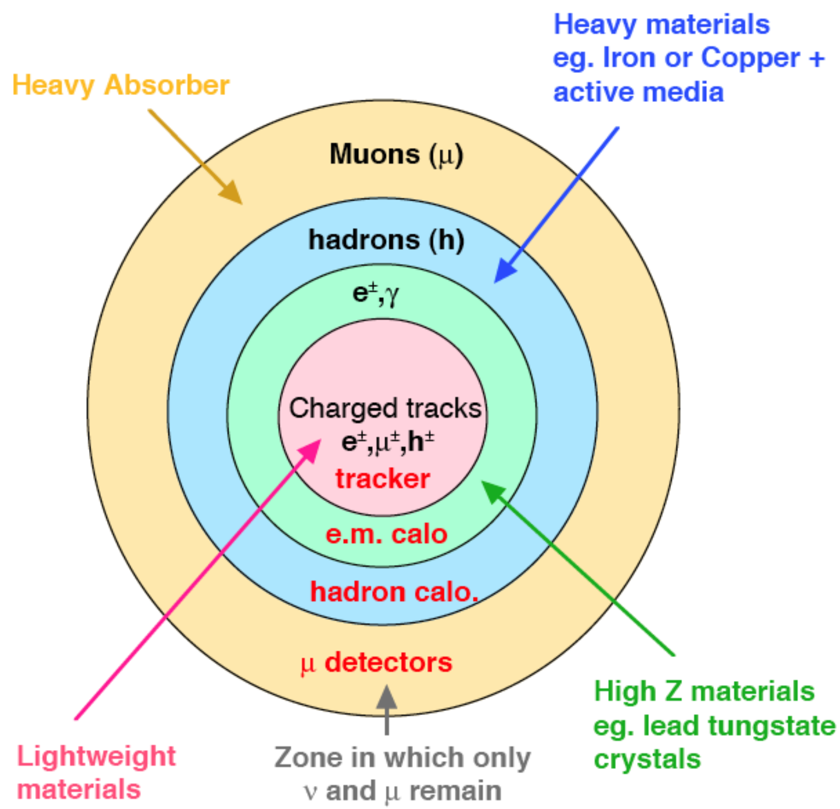
Fixed target vs Collider

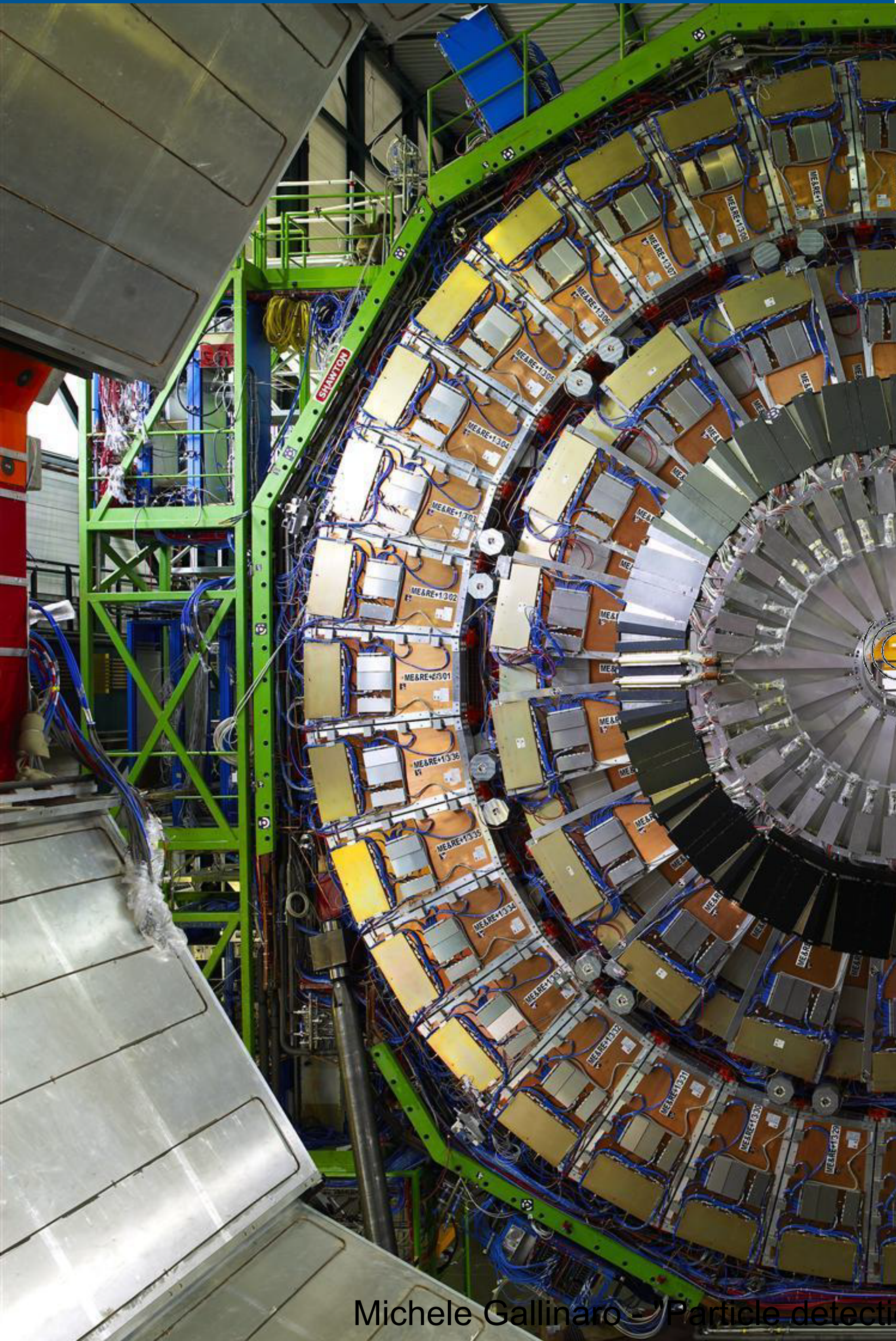


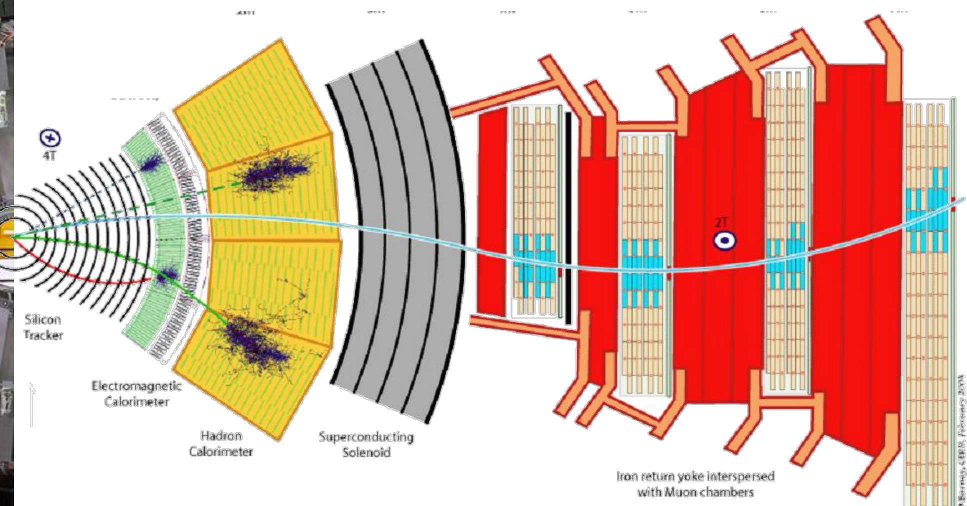
Detector layers

- Inner tracking
  - Measure charged particle (momentum)
- Magnetic field:
  - Measure momentum
- Calorimeters
  - Measure energy of all particles
- Outer tracking
  - Measure muons

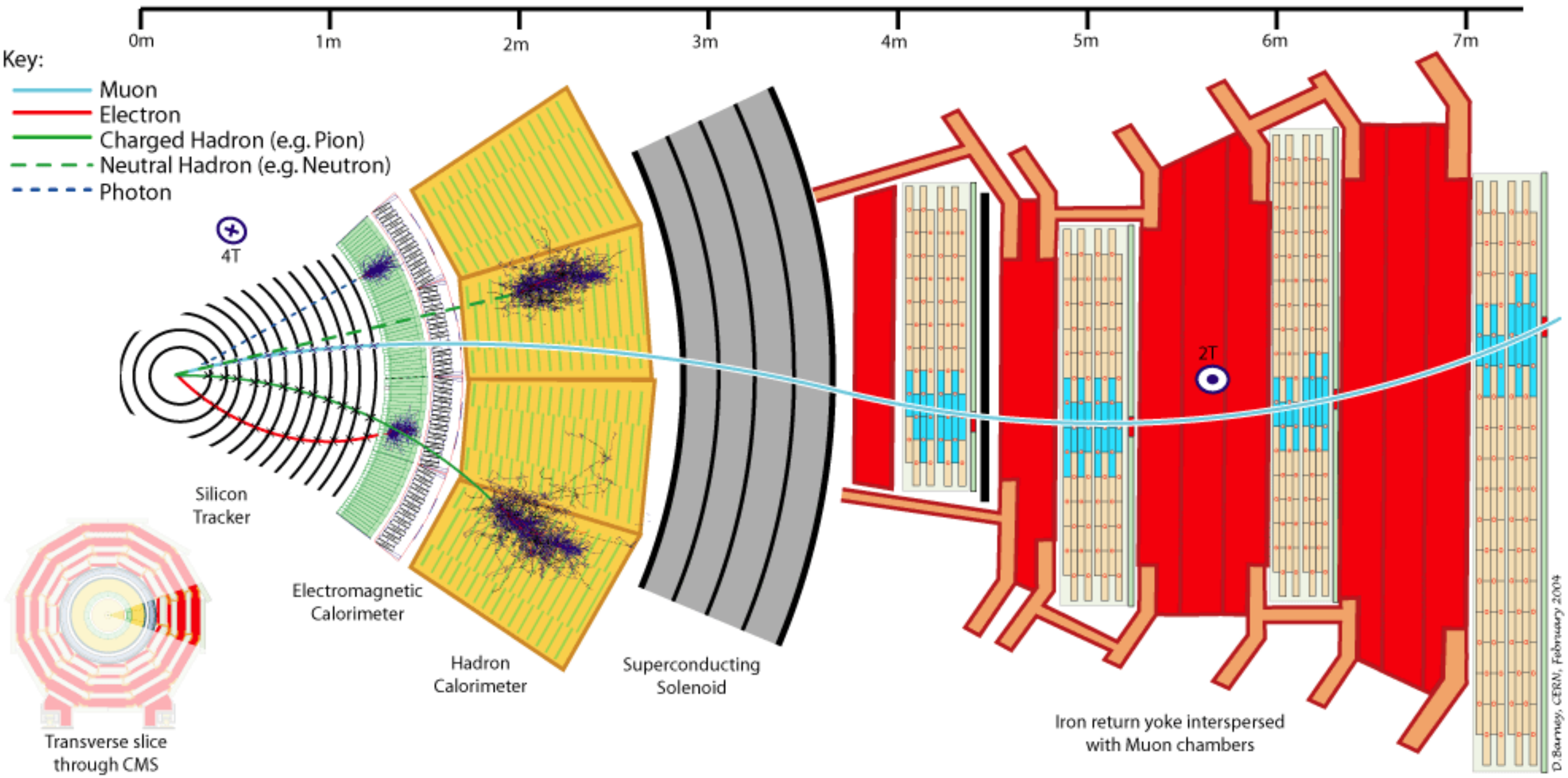




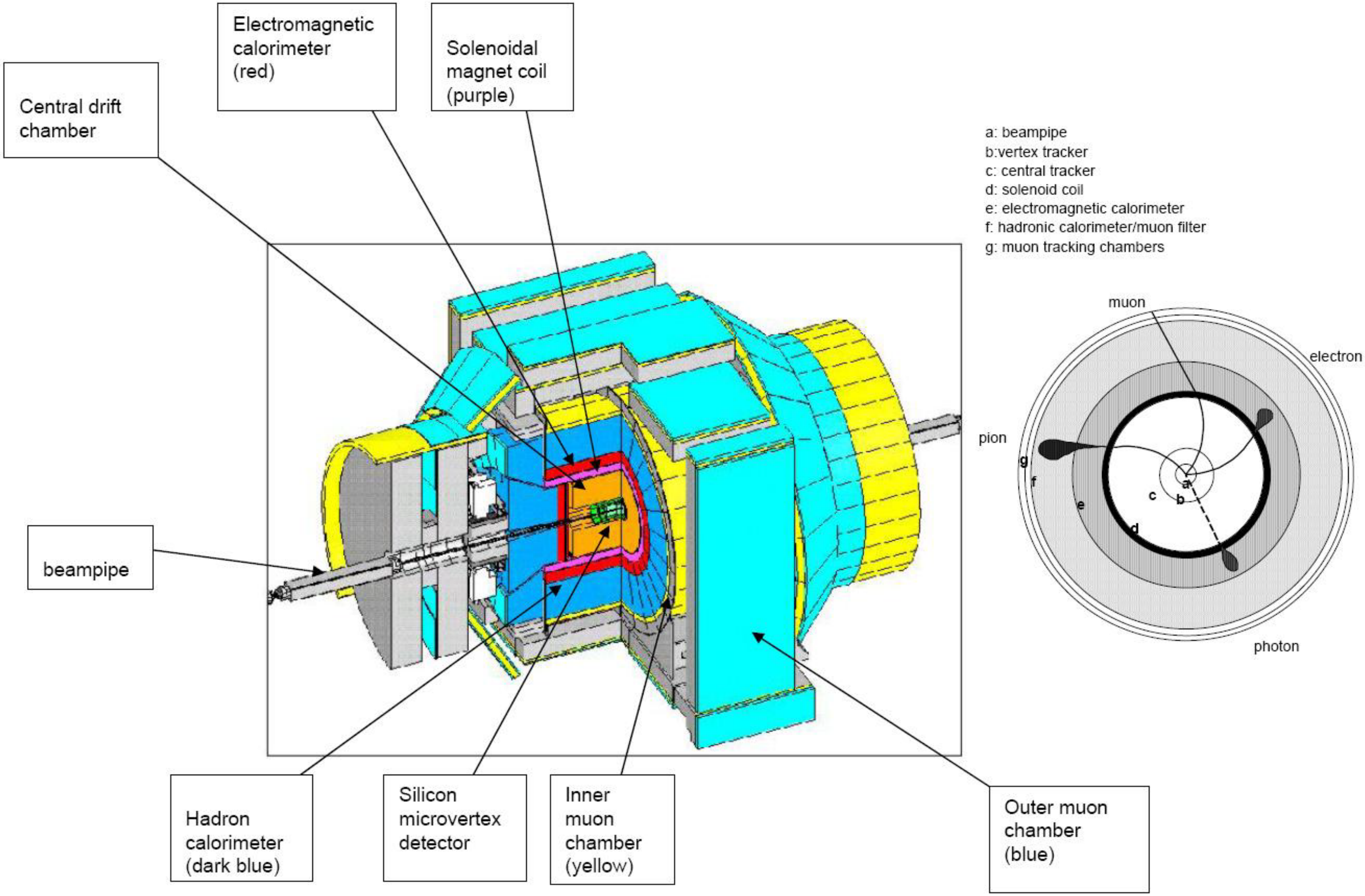



4T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
2T
Iron return yoke interspersed with Muon chambers

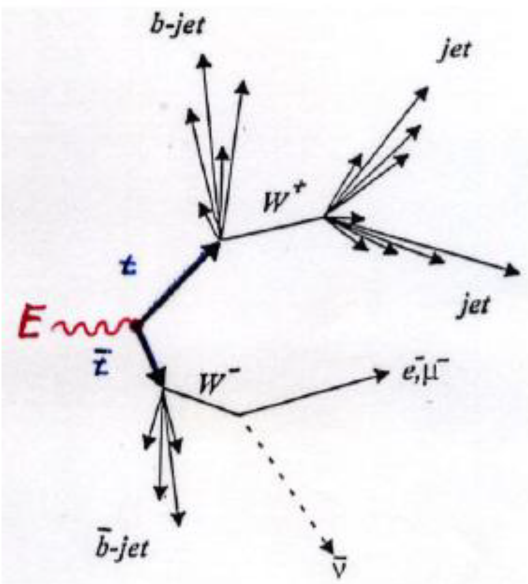
CMS experiment

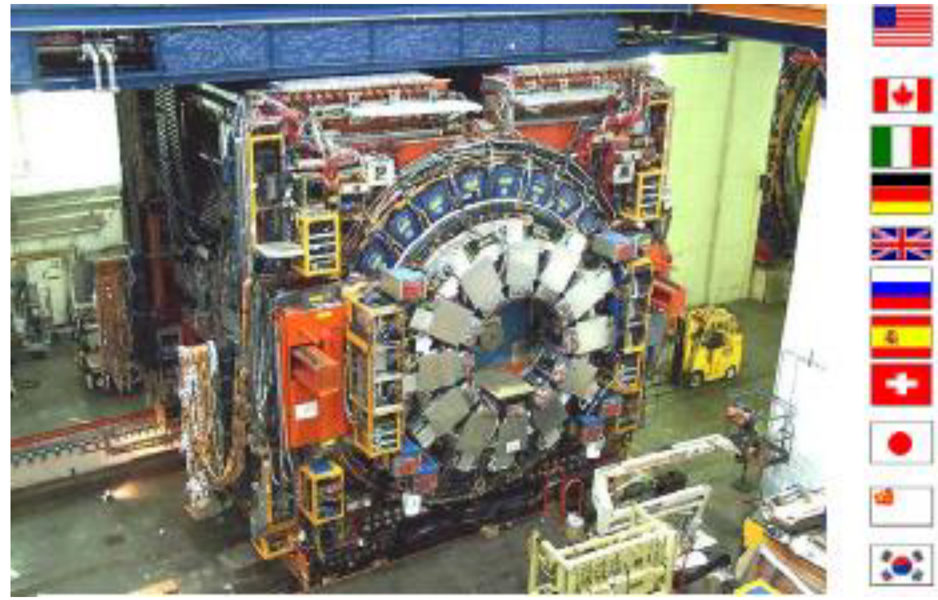


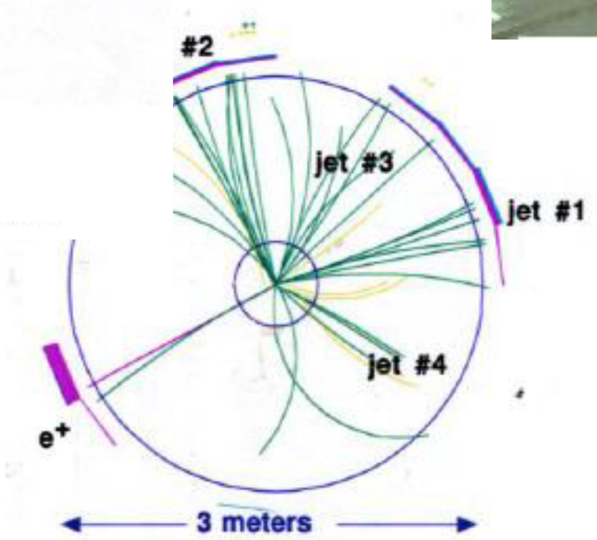
CDF experiment



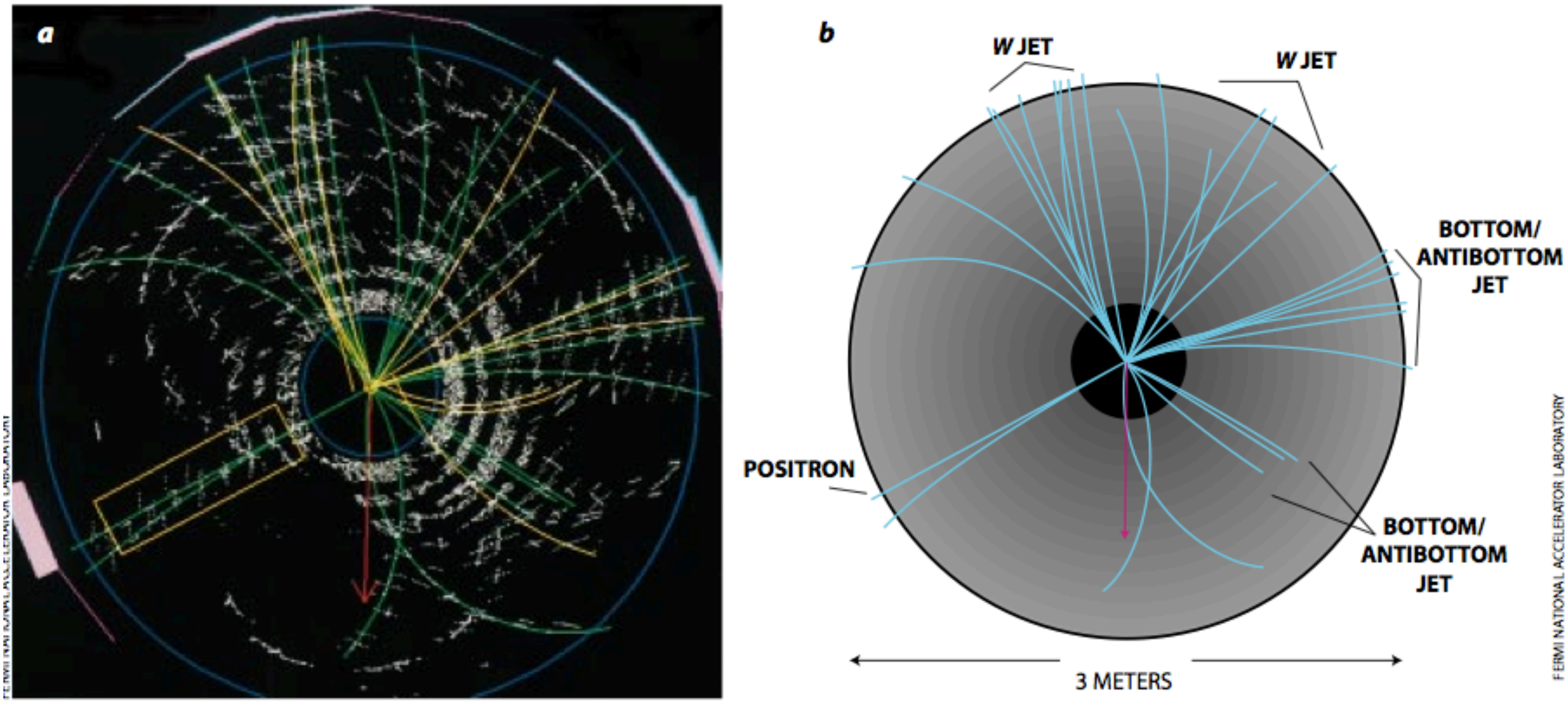
Top quarks: example



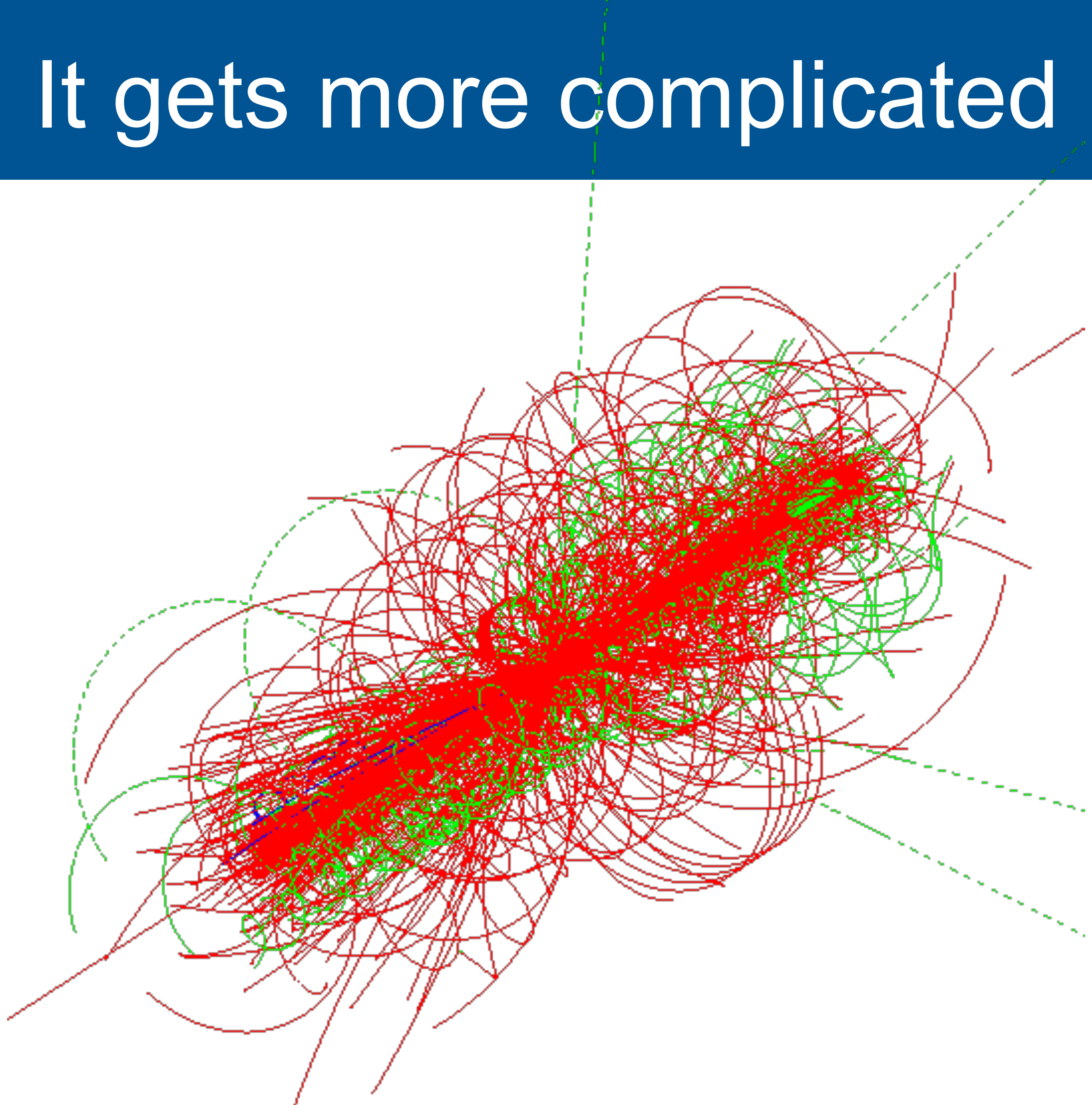




Picture to reconstruction



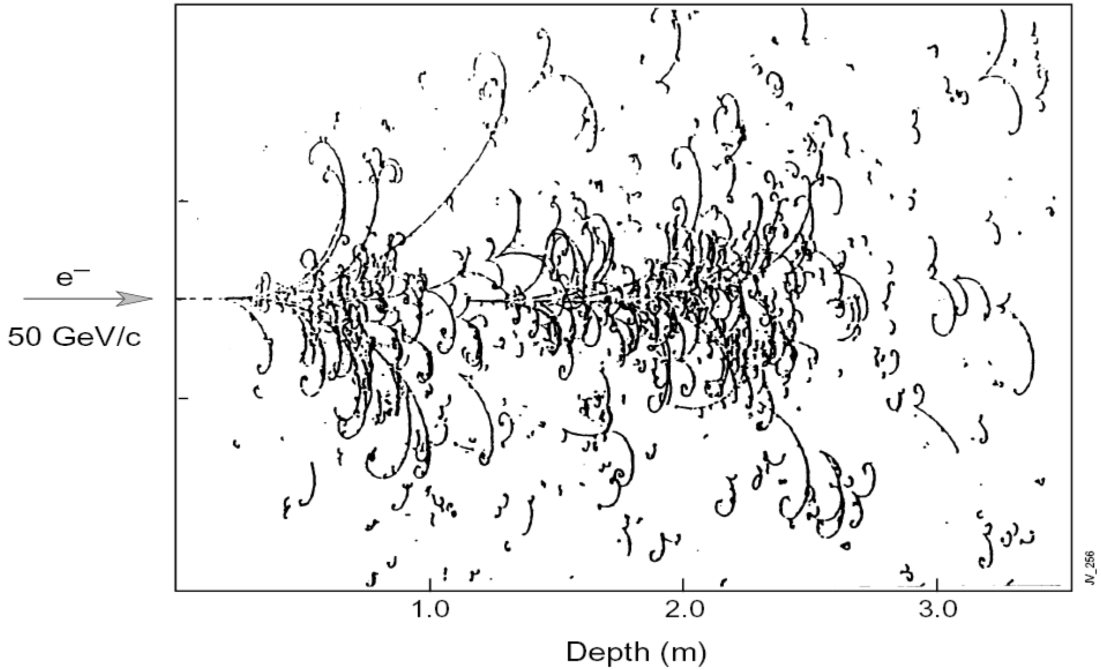
It gets more complicated



Calorimetry

Measure energy deposited in material by particles which give rise to electromagnetic or hadronic showers.
Electrons, photons and hadrons (including neutral hadrons)

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



Calorimetry (cont.)

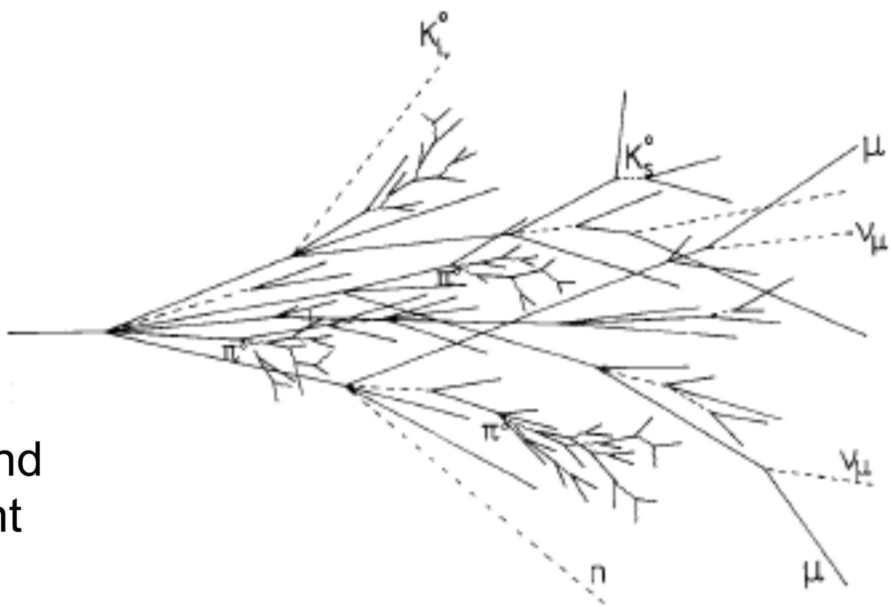
- Calorimeters are used to measure energy of neutral and charged particles
  - neutral particles cannot be momentum analyzed
  - electrons can be measured with better precision, and identified with a calorimeter
- As energy increases:
  - momentum measurements are less precise: $\sigma/p \sim p$
  - energy measurements become more precise: $\sigma_E/E \sim 1/\sqrt{E}$
- jets are often best measured by total absorption rather than measurement of individual particles

Purpose/principle of a calorimeter

- Measurement of energy via *total* absorption (destructive measurement)
- Detector response ~E for:
  - Charged particles (electrons/positrons and hadrons)
  - Neutral particles (neutrons, γ)
- Principle of measurement:
  - Electromagnetic shower
  - Hadronic shower
- Conversion due to ionization or excitation of the detector material $\Rightarrow$ current, voltage

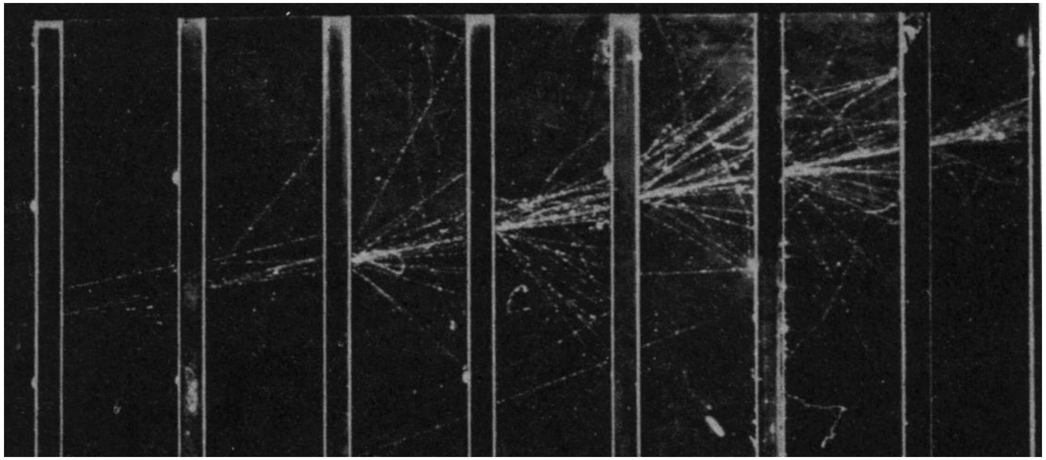
EM and hadron calorimeters

- Calorimeters are subdivided into electromagnetic and hadronic sub-detectors
- Electromagnetic interactions develop over shorter distances than hadronic interactions
- Fundamental processes of signal generation differ, calling on different optimization

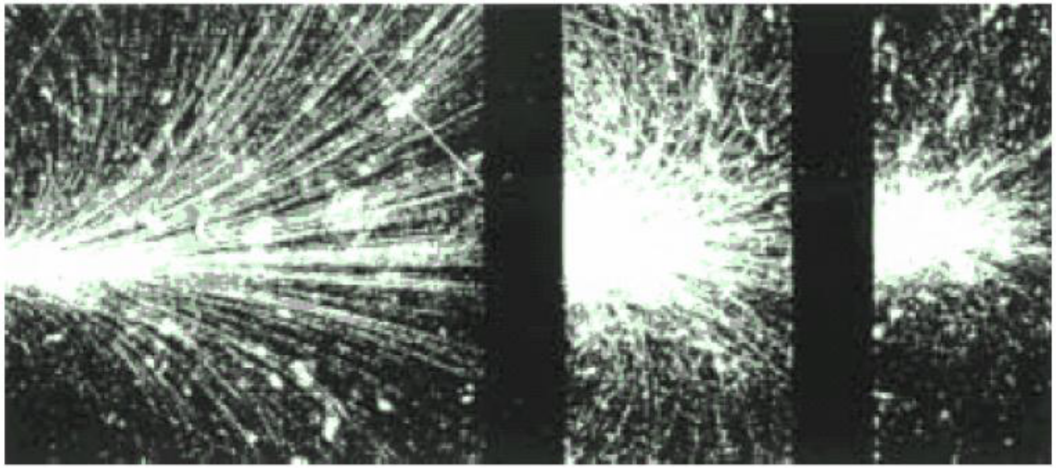


cascade with EM and hadronic component

Calorimeter and shower



Photon-induced shower in a cloud chamber; the intermediate black parts are lead blocks; in addition, there is a magnetic field perpendicular to the figure plane



How to measure the energy?

The energy is proportional to light & penetration depth of the shower

The eye is not able to quantify this; have to measure the amount of light and penetration path electronically

Evolution of calorimeters

- Nuclear Physics
  - Advances of solid state detector in the ’50s push technique of total absorption and energy measurement of nuclear radiation
- Cosmic Rays (1958)
  - construction of first sampling calorimeter
- Particle Physics
  - First electromagnetic calorimeters, eventually hadronic calorimeters become essential components
- Uranium/compensation
  - In an effort to advance energy resolution, introduce uranium calorimeters (~1975) to “compensate” for lost energy in nuclear collisions
- High precision EM calorimetry
  - Crystals continued to advance
  - Other techniques (liquid Argon, scintillating fibers, etc.)

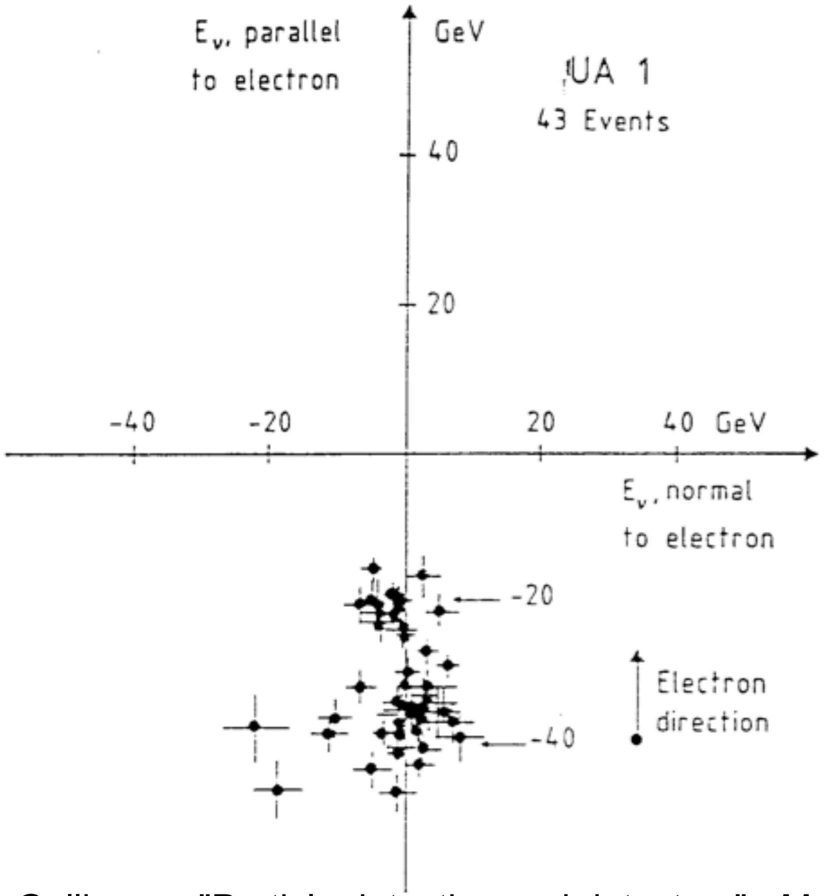
Evolution of calorimeters (cont.)

Today, widespread in particle physics

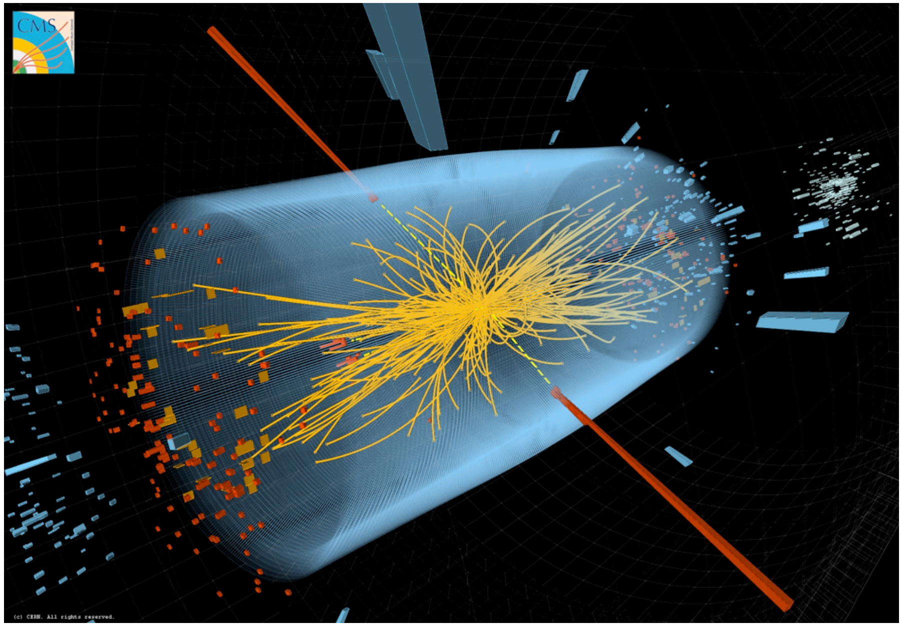
- 4π coverage at colliders
  - Energy measurements
  - Particle identification
  - Triggers
- Neutrinos detectors at accelerators
- Underground detectors
- Space-based detectors (GLAST)
- …

Discovery of the W

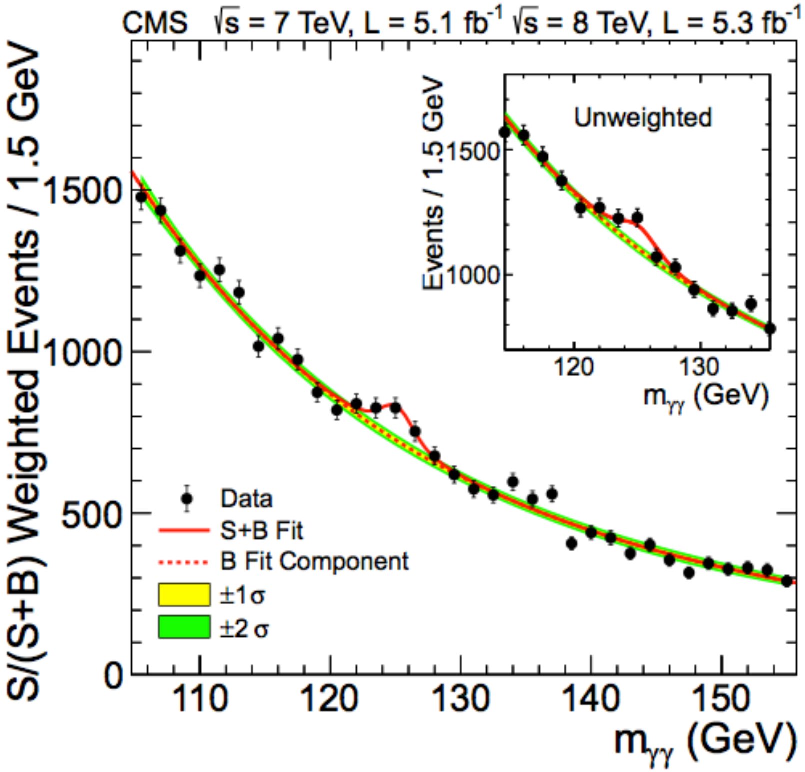
- Calorimeters are important (also for discoveries)
- High transverse energy electron measured, and recoiling neutrino deduced (to balance the electron)



Discovery of the Higgs



- di-photon invariant mass



Ideal calorimeter

- Excellent energy/position resolution
- Stable calibration
- Large dynamic range
- Excellent shower containment with multi-shower separation
- Compact
- Fast (high-rate capability)
- Operating in magnetic field
- Inexpensive
- Robust

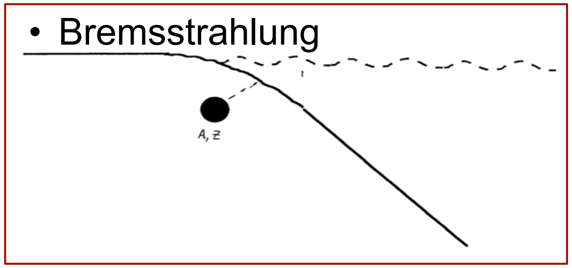
EM and hadronic showers

- Electromagnetic
  - Multiplication through pair production and bremsstrahlung
  - Mean free path
    - $9X_0/7$ for γ,
    - $X_0/\ln(E/k)$ for electrons
  - No invisible energy

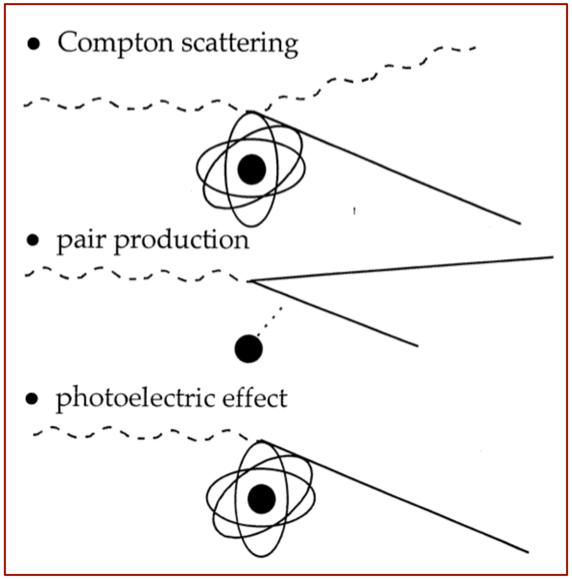
- Hadronic
  - Multiplication through multi-particle production in nuclear interactions
  - Mean free path ~λ (interaction length)
  - Nuclear binding energy, and neutrinos invisible

Electromagnetic showers

- In matter high energy electrons and photons interact primarily through EM interactions with the nucleus (and at lower energies with the atomic electrons)



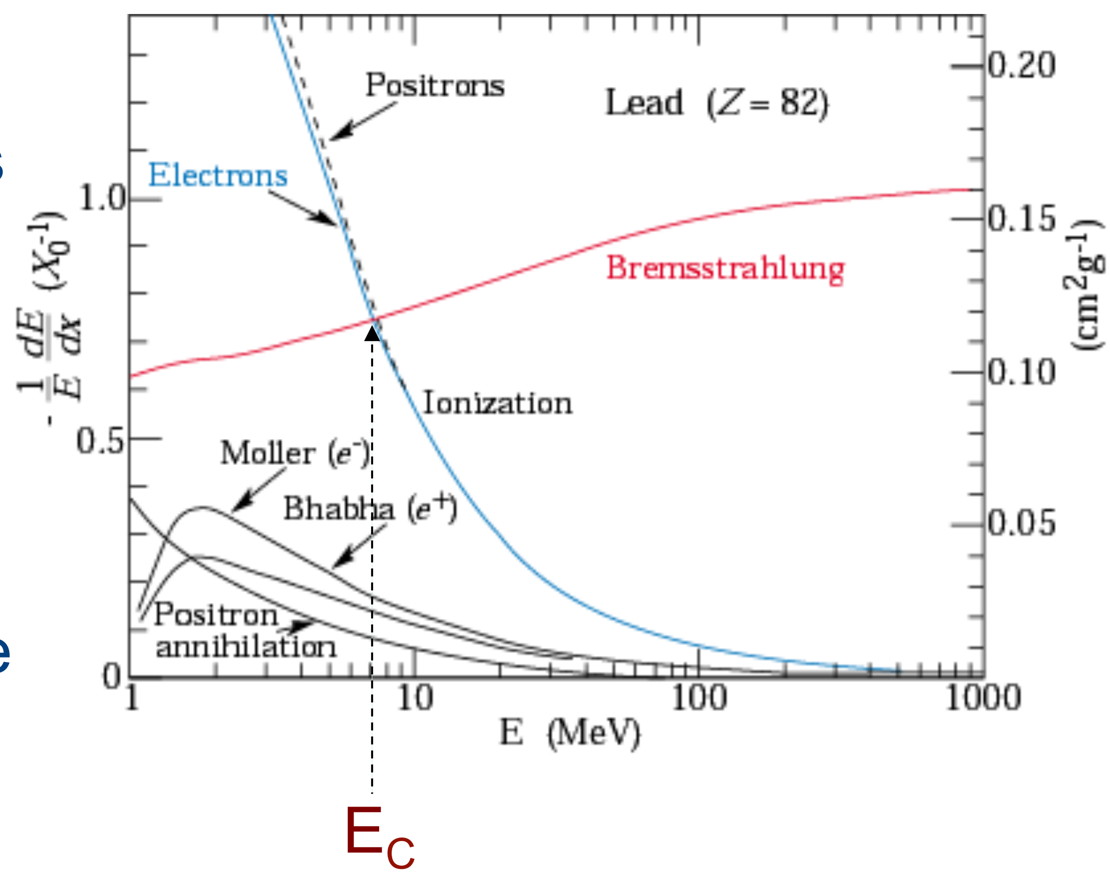
- Electrons
  – Bremsstrahlung (nuclear)



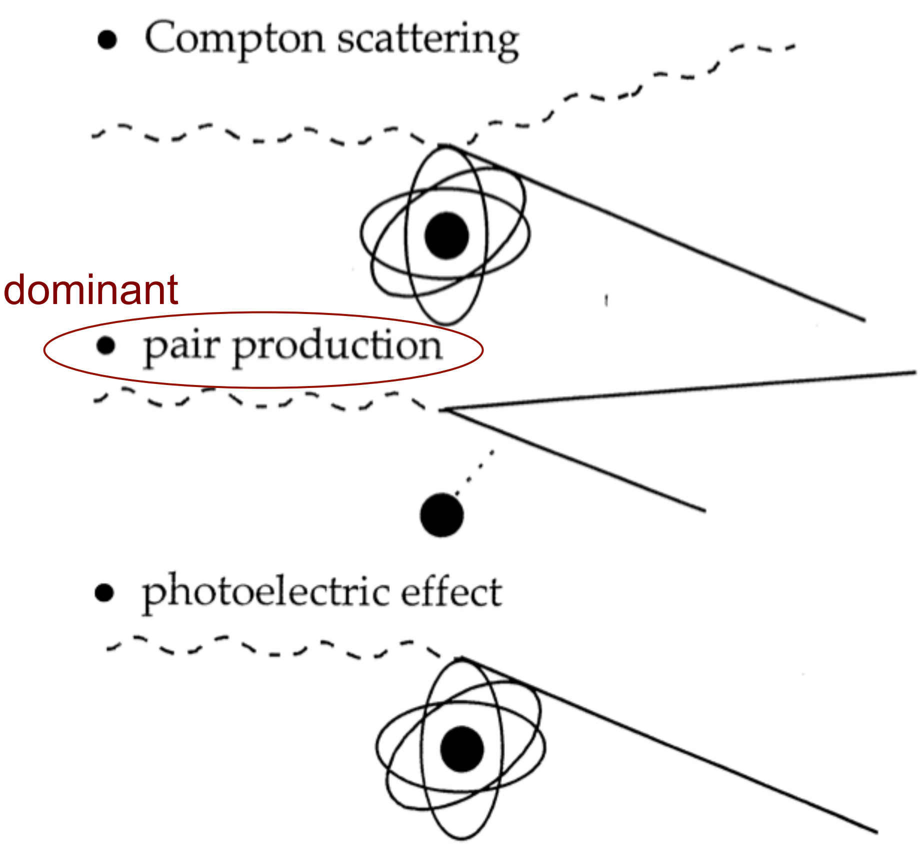
- Photons
  – Compton scattering (atomic electrons)
  – Pair production (nuclear)
  – Photoelectric effect (atomic electrons)

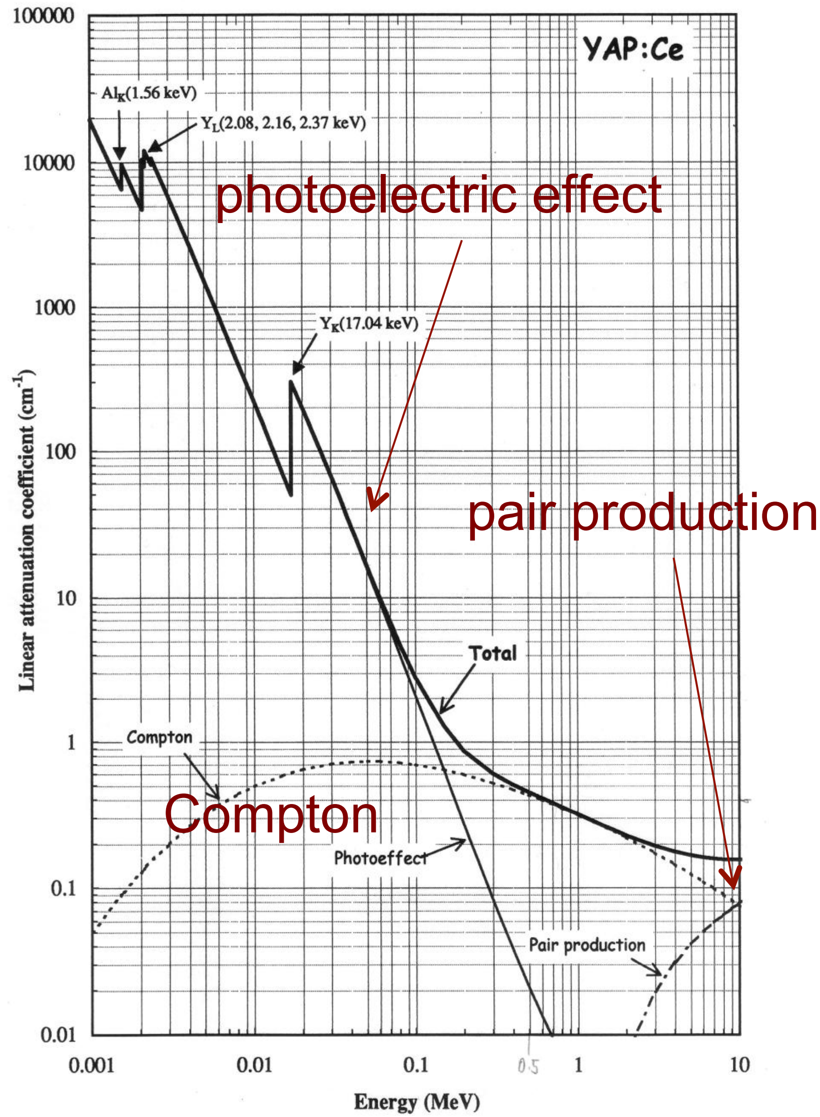
EM showers: electrons

- Electron energy loss
- At high energy, the energy loss of an electron from bremsstrahlung dominates over ionization loss
- At low energy, ionization loss becomes important
- The energy at which ionization loss equals bremsstrahlung loss, is the critical energy E_C
  - E_C~7 MeV for lead



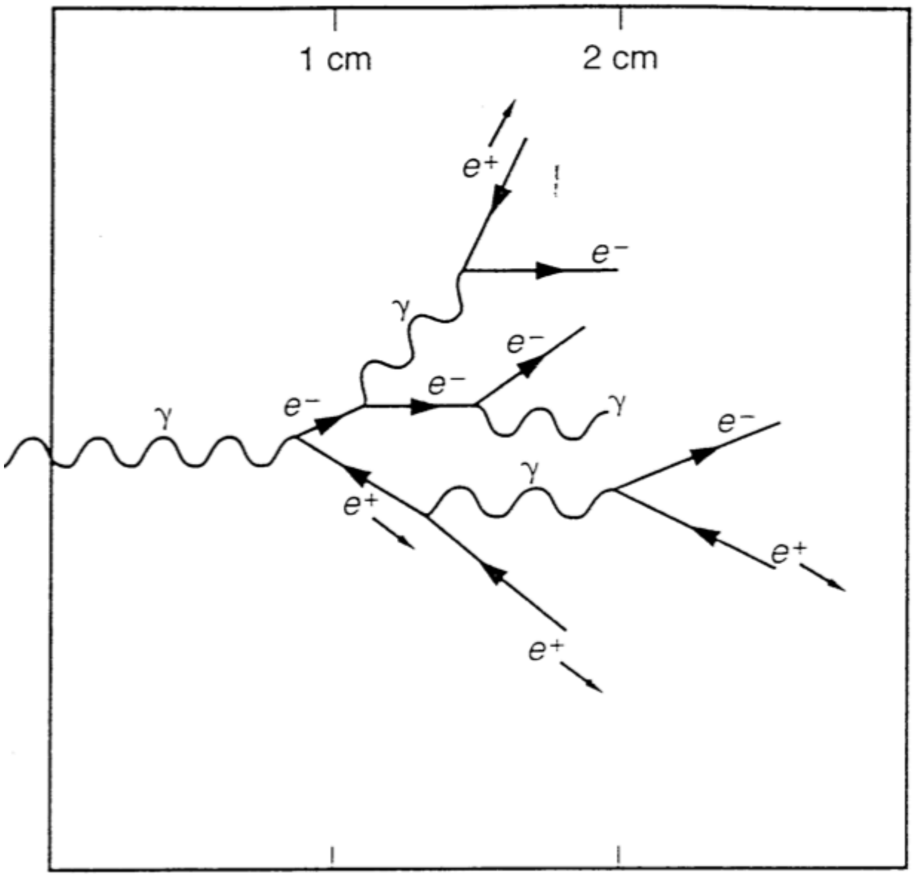
EM showers: photons





EM shower: model

- EM shower can be understood by a simple model
  - after one radiation length a photon produces an e^+e^- pair
  - the electron and positron each emit one bremsstrahlung photon after another radiation length
- It leads to a cascading number of particles: $N(t)=2^t$ (for t steps)
- each particle has an energy: $E(t)= E_0/2^t$



Electromagnetic shower: size

- Longitudinal development scales with the radiation length:
  X_0=180 A/Z^2 g/cm^2 (higher Z materials have shorter radiation lengths)

- Transverse dimension scales with the Moliere radius:
  R_M=21 MeV X_0/E_C where E_C=550 MeV/Z

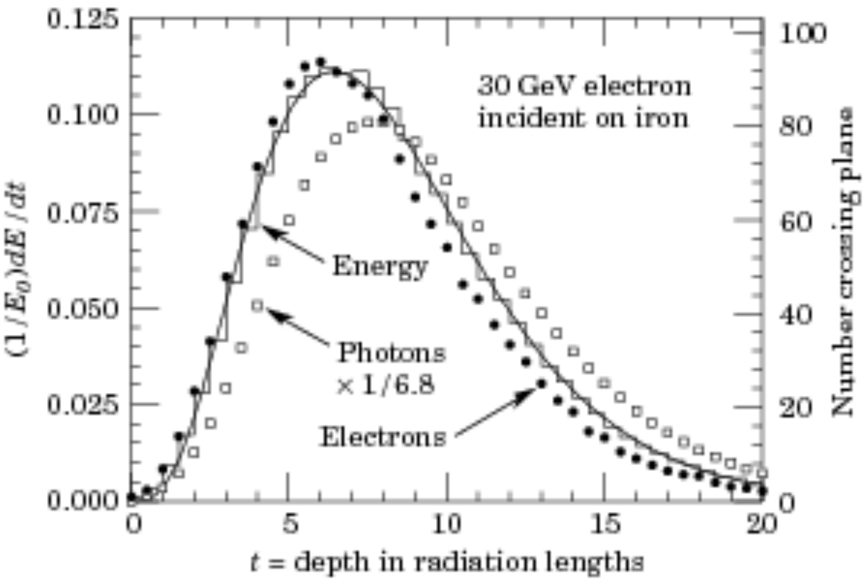
EM calorimeters: typical scales

Material	Atomic No. (Z)	Critical Energy (E_c) (MeV)	Radiation Length (X_0) (g/cm^2)	Radiation Length (X_0) (cm)	Moliere Radius (R_M) (cm)
Beryllium	_4	116._	65.19	35.28	6.4
Carbon	_6	84._	42.70	18.8_	4.7
Aluminum	13	43._	24.01	8.9_	4.4
Iron	26	22._	13.84	1.76	1.7
Copper	29	20._	12.86	1.43	1.5
Tungsten	74	8.1	6.76	0.35	0.9
Lead	82	7.3	6.37	0.56	1.6
Uranium	92	6.5	6.00	0.32	1.0

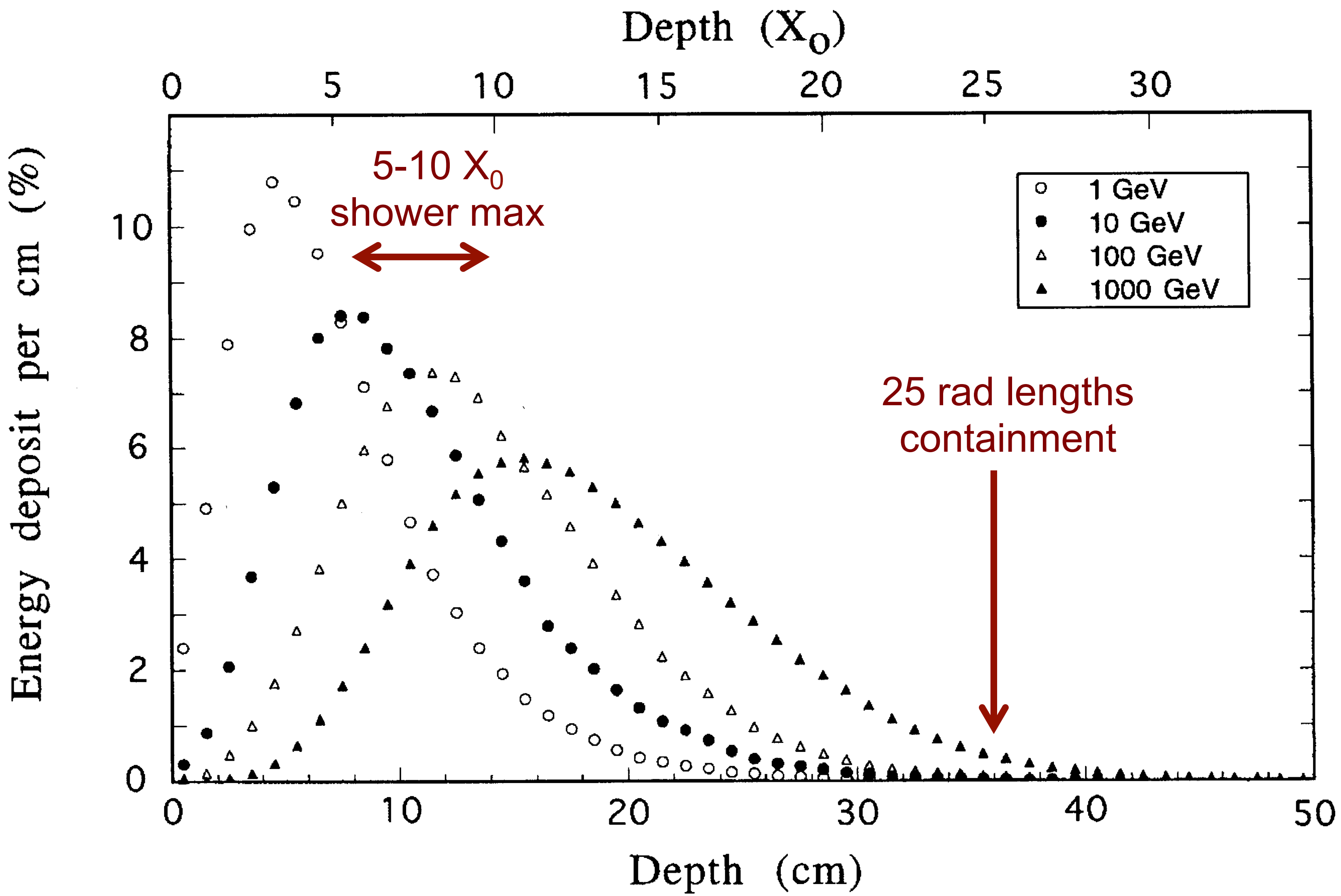
EM shower: longit. development

- Electrons generate photons through bremsstrahlung and photons produce electrons and positrons through pair production
- The observed **longitudinal development** depends on the minimum kinetic energy of an electron or a positron that can be detected (i.e. cut-off energy)
- The **shower maximum** occurs when the energy falls to:
- $E_C = E_0 / 2^{t_{max}} \Rightarrow t_{max} \sim \ln (E_0 / E_C)$

An example of longitudinal development (30 GeV electron induced shower in iron)



Longitudinal profile



EM calorimeters

- Homogeneous Calorimeter
  - shower is "observed" throughout the detector
  - Electrons and photons stop in calorimeter
  - Scintillation proportional to energy of electron
  - Advantage: excellent energy resolution
  - Limited spatial resolution
- Sampling Calorimeter
  - shower is sampled by an "active" readout medium alternated with denser radiator material
  - One material to induce showering (high Z)
  - Another to detect particles (by counting number of charged tracks)
  - Many layers sandwiched together
  - Advantages: can segmentation gives detailed shower shape information; good spatial resolution

EM showers: Fluctuations

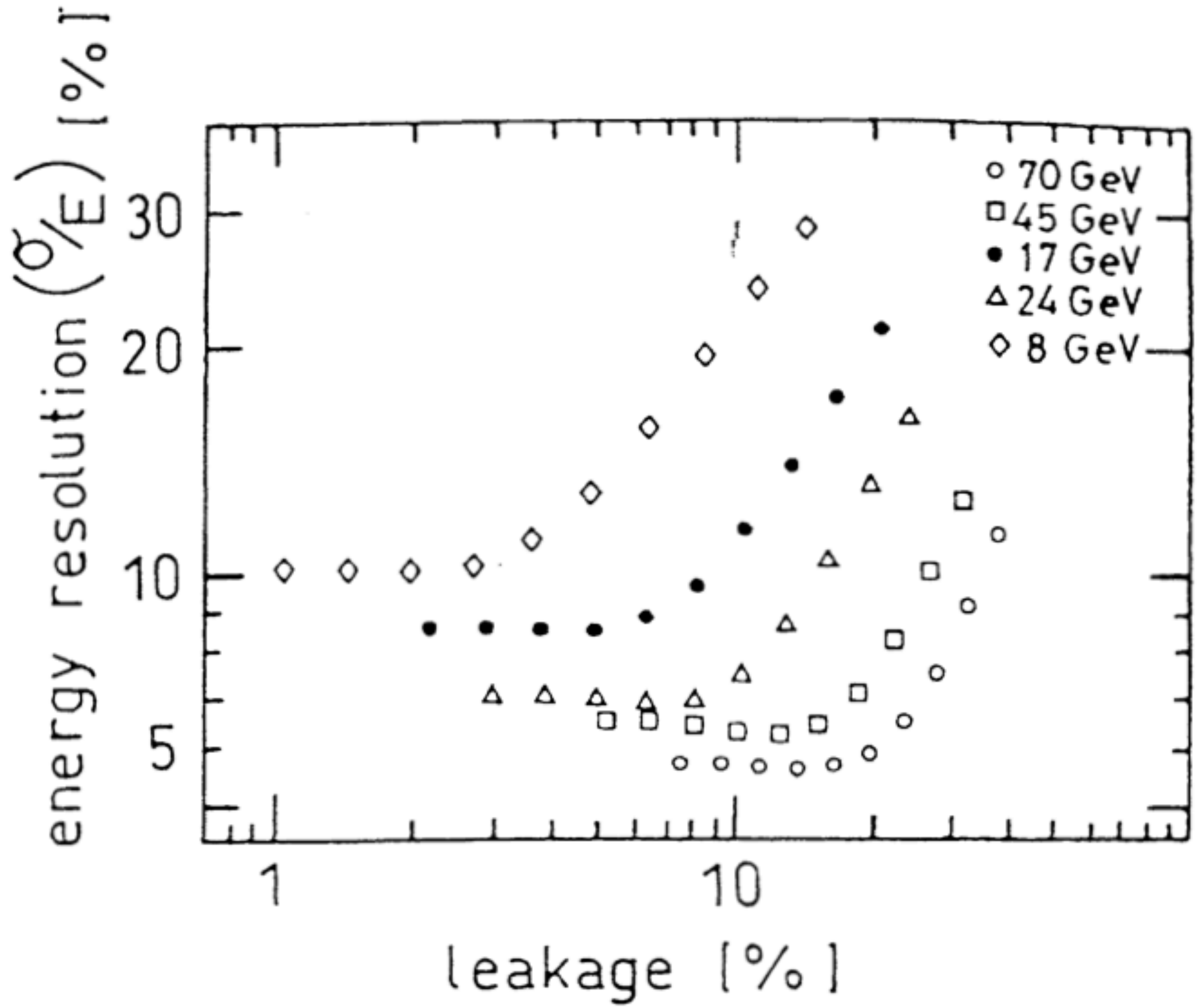
- Energy measurement is limited in precision by fluctuations in the EM shower and in the measurement process
- The shape of an EM shower fluctuates only modestly, and resolution of an EM calorimeter is usually limited by other effects (assuming full containment has been achieved)
- Dominant fluctuation in the shower is the depth of the first pair conversion.

EM showers: Energy resolution

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

- Stochastic (or “sampling”) term
  - Accounts for statistical fluctuations of the number of primaries
- Noise term:
  - Electronic noise, pedestal fluctuations, etc.
  - Pileup (other energy entering the measurement region)
- Constant term
  - Non-uniformities, calibration uncertainties
  - Incomplete shower containment (leakage), other fluctuations proportional to energy

EM showers: longit. leakage



Examples of EM calorimeters

• NaI(Tl)	$2.7\%/E^{1/4}$
• Lead Glass	$5\%/E^{1/2}$
• Lead-liq. argon	$7.5\%/E^{1/2}$
• Lead-scin. sand.	$9\%/E^{1/2}$
• Lead-scin. spaghetti	$13\%/E^{1/2}$
• Prop. wire chamber	$23\%/E^{1/2}$

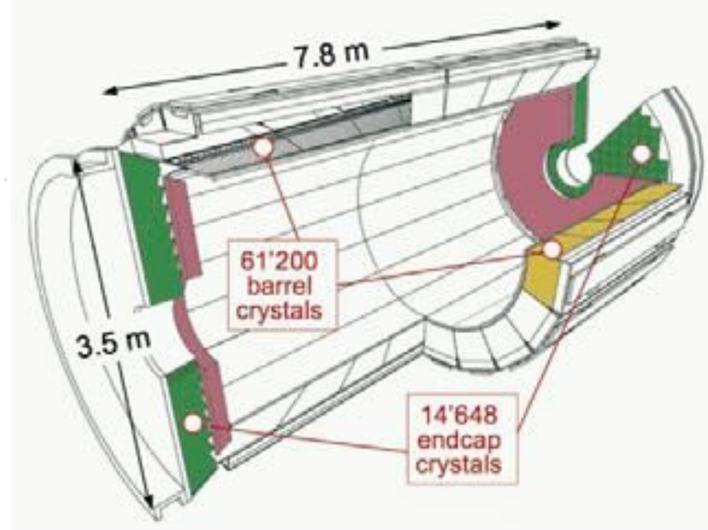
- These resolutions must be added in quadrature with the appropriate constant term (~1%)

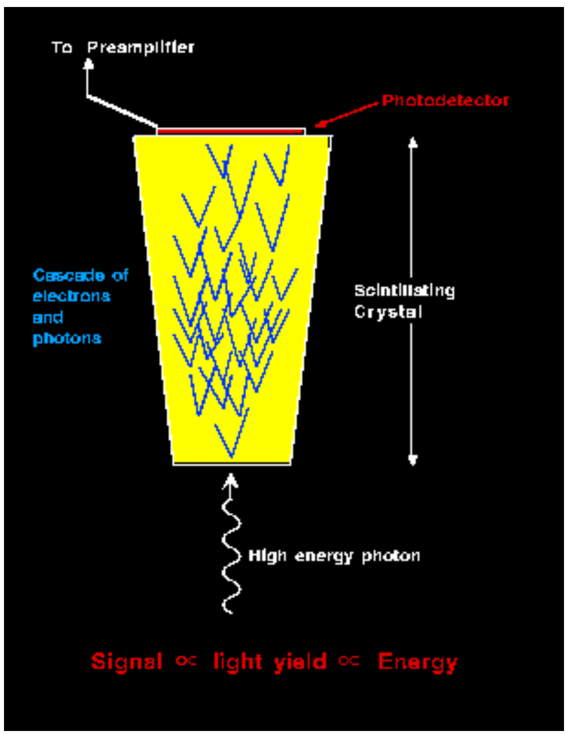
Position and pointing resolution

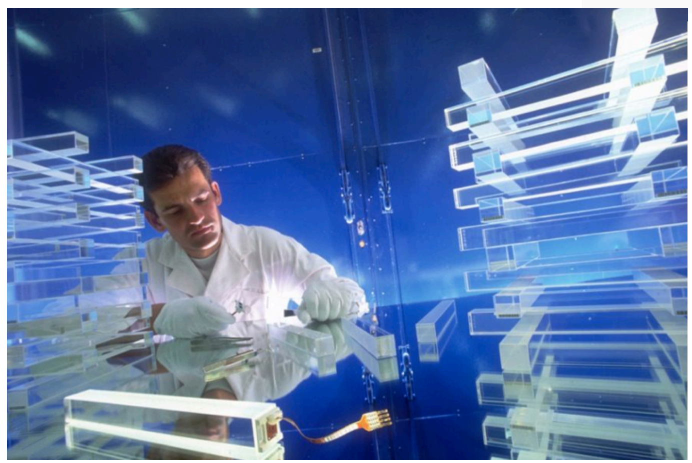
- Measurement of the impact point of a photon entering an EM calorimeter is limited by the transverse fluctuations in the shower, and the measurement errors
  - This measurement involves determining the centroid of the shower as a function of depth in the calorimeter
  - Typically, achievable resolution is: *few mm* / $\sqrt{E}$
- Measurement of the direction of the incident particle is more challenging
- Position resolution often reflects on the electron identification performance

Crystal calorimeter example

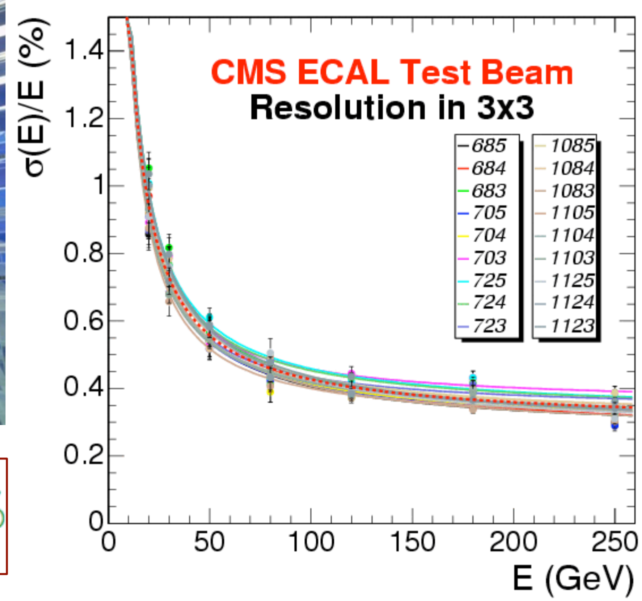
- CMS EM Calorimeter:
  - 83,000 crystals ($PbWO_4$, lead tungstate)
  - Very dense, fast, radiation hard
  - Scintillation light yield not significantly damaged by radiation
  - 1% resolution at 30 GeV







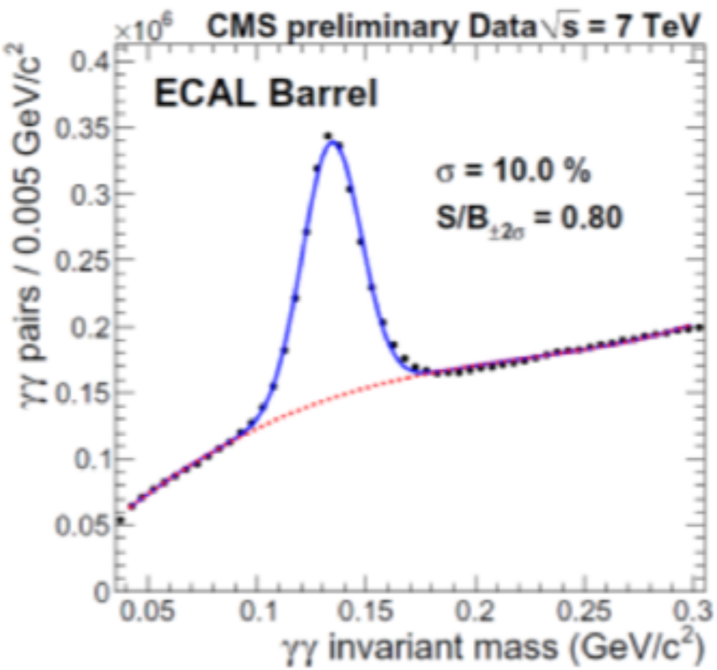
$$\frac{\sigma}{E} = \frac{2.8\%}{\sqrt{E(\mathrm{GeV})}} \oplus \frac{125}{E(\mathrm{MeV})} \oplus 0.3\%$$

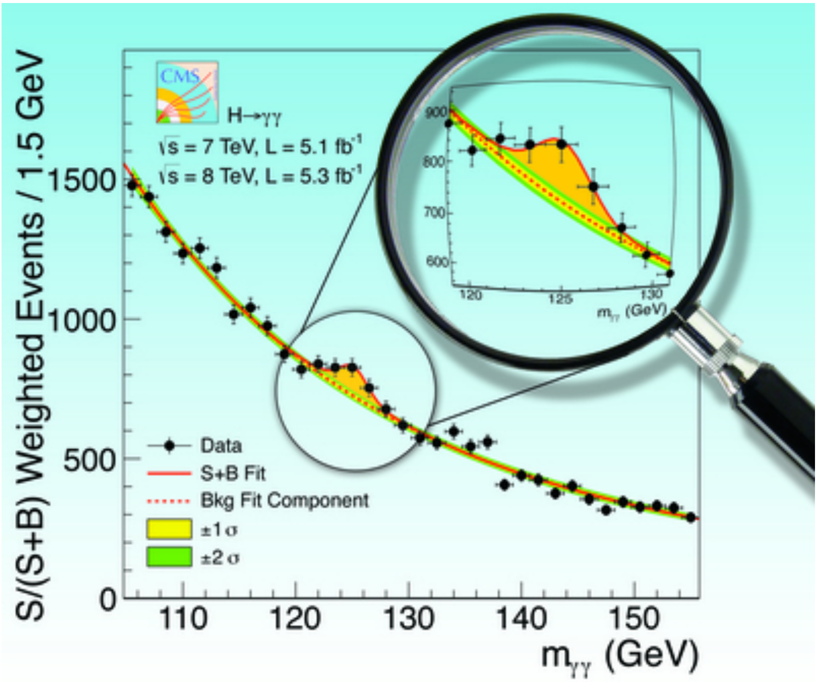


Energy resolution

Inter-calibration:

- Several steps before, during, after data-taking
  - test beam pre-calibration
  - monitoring during data-taking
  - inter-calibration by physics with specialized data streams



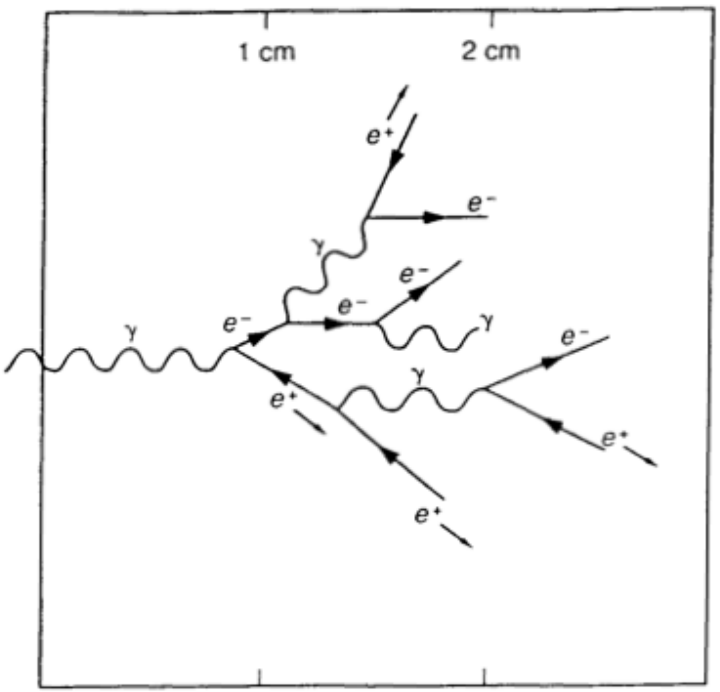


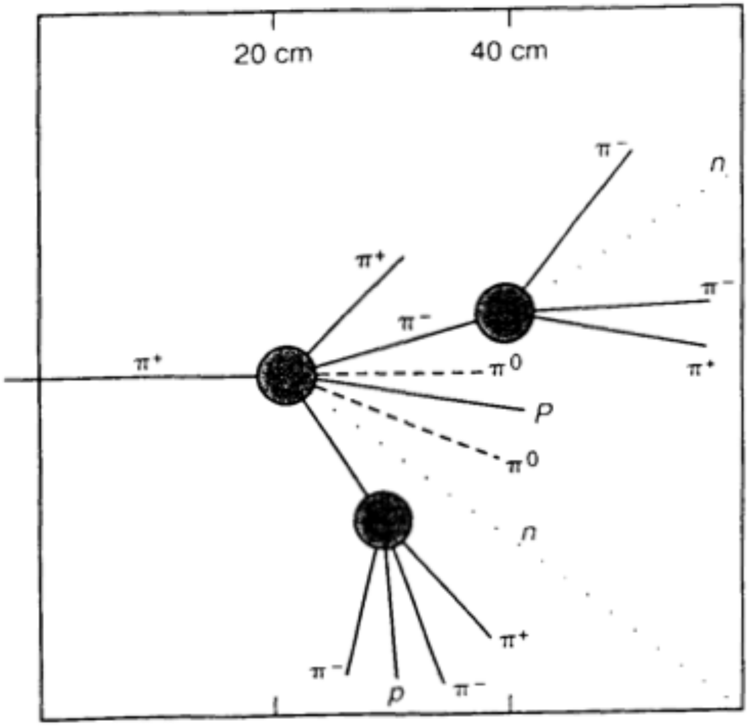
Hadron calorimetry

- Hadron Calorimeters, as EM calorimeters, measure the energy of the incident particle(s) by fully absorbing the energy of the particle(s) and providing a measurement of the absorbed energy
- Hadronic Showers are more complicated than EM showers, significantly reducing the optimal precision

Had and EM showers

- Had shower: the longitudinal development is characterized by the nuclear interaction length





Hadronic showers

- The impinging particles strongly interact (inelastically) with a nucleus according to the nuclear cross section
- Nuclear interaction length: mean free path before interaction

$$\lambda_{int} \approx 35\ A^{1/3} \cdot g \cdot cm^{-2}$$

- Nuclear interaction length is longer than radiation length

Material	Atomic No. (Z)	Radiation Length (X_0) (g/cm²)	Radiation Length (X_0) (cm)	Interaction Length (λ) (g/cm²)	Interaction Length (λ) (cm)	X_0/λ
Beryllium	_4	65.19	35.28	75.2	40.7	1.2
Carbon	_6	42.70	18.8_	86.3	38.1	2.0
Aluminum	13	24.01	8.9_	106.4	39.4	4.4
Iron	26	13.84	1.76	131.9	16.8	9.5
Copper	29	12.86	1.43	134.9	15.1	15.1
Tungsten	74	6.76	0.35	185._	9.6	27.4
Lead	82	6.37	0.56	194._	17.1	30.5
Uranium	92	6.00	0.32	199._	10.5	33.2

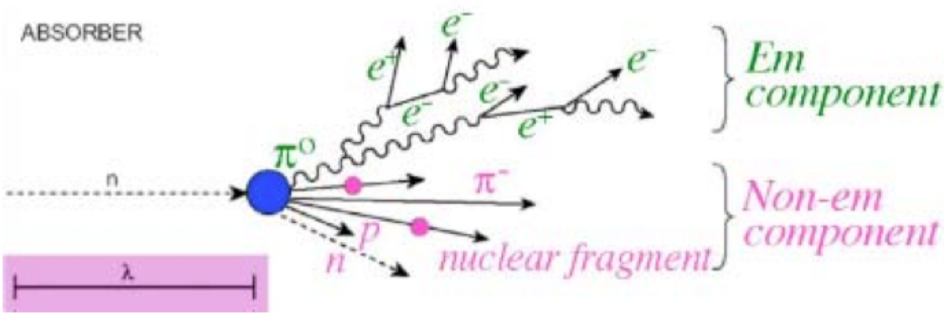
higher *Z* materials separate hadronic/EM interactions better

Hadronic showers

- Hadronic cascades develop analogously to EM showers
  - Strong interaction controls overall development
- As a strongly interacting particle (hadron) passes through matter, it initiates a nuclear interaction, and starts a nuclear shower
- Energy deposited by:
  - Electromagnetic component (i.e. as for EM showers)
  - Charged pions or protons
  - Low energy neutrons
  - Energy lost in breaking nuclei (nuclear binding energy ~8 MeV/nucleon)

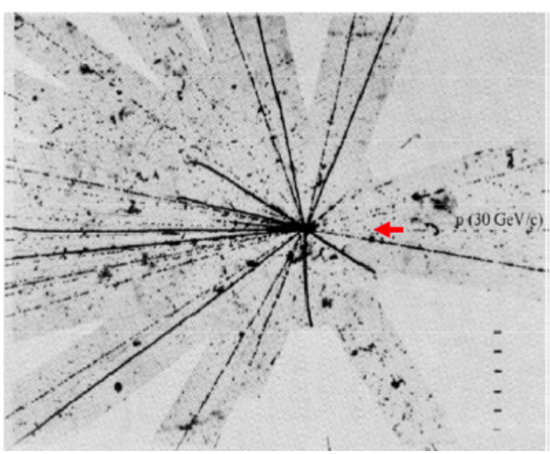
Hadronic showers

- Hadronic showers are:
  - broader and more penetrating
  - subject to larger fluctuations

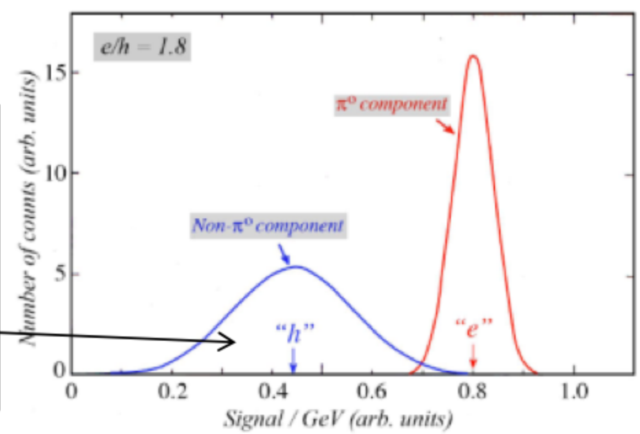


Electrons, photons
$\pi^0 \to 2\gamma$

Charged hadrons	(20%)
Nuclear fragments , p	(25%)
Neutrons, soft γ's	(15%)
Breakup of nuclei	(40%)

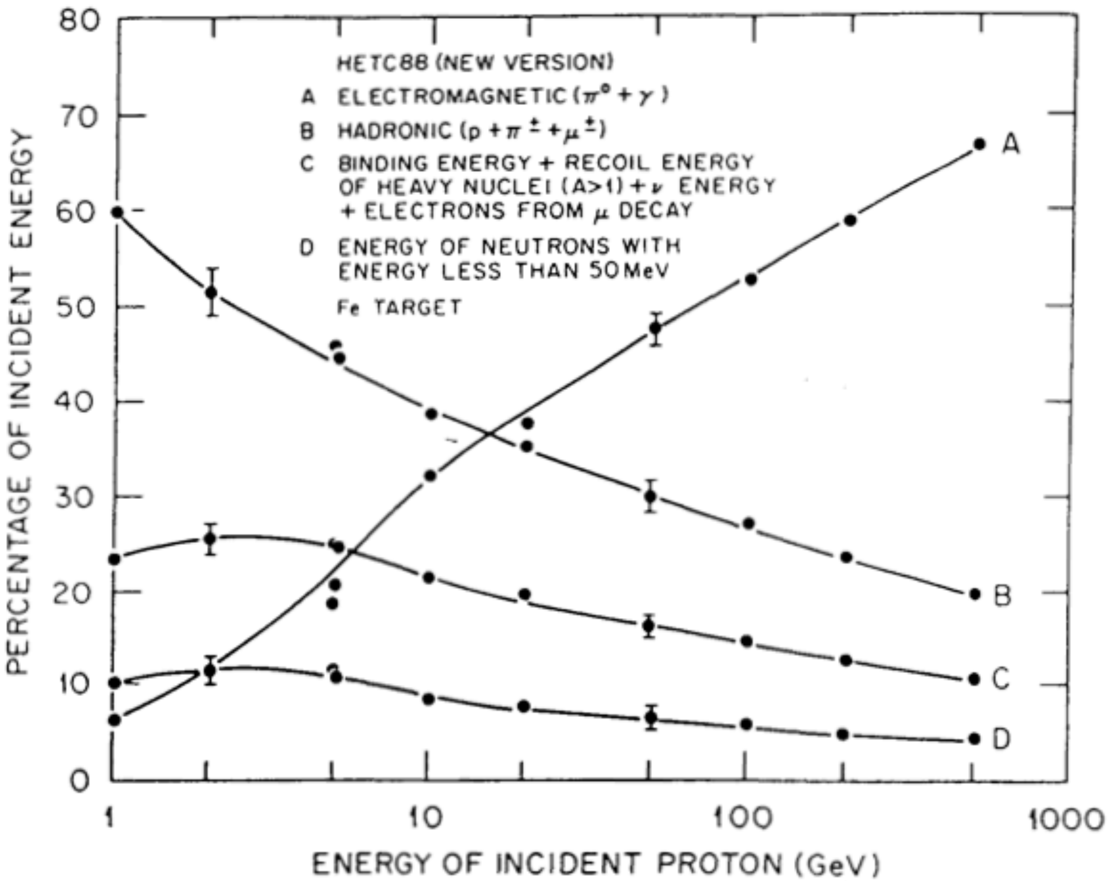


Either not detected or often to slow to be within detector time window
= Invisible energy
e/h > 1



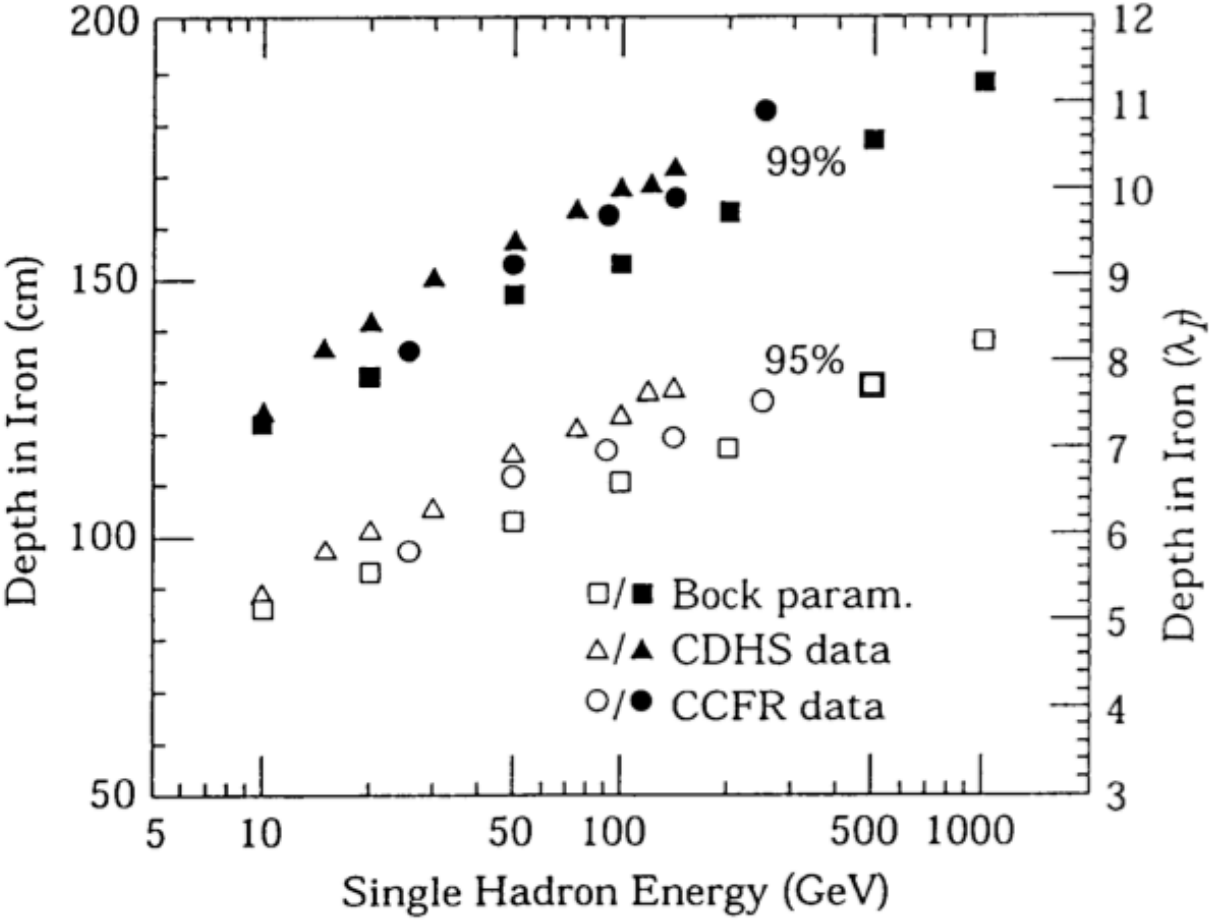
Hadronic showers: energy fractions

The EM energy fraction of the shower increases with energy



Longitudinal development

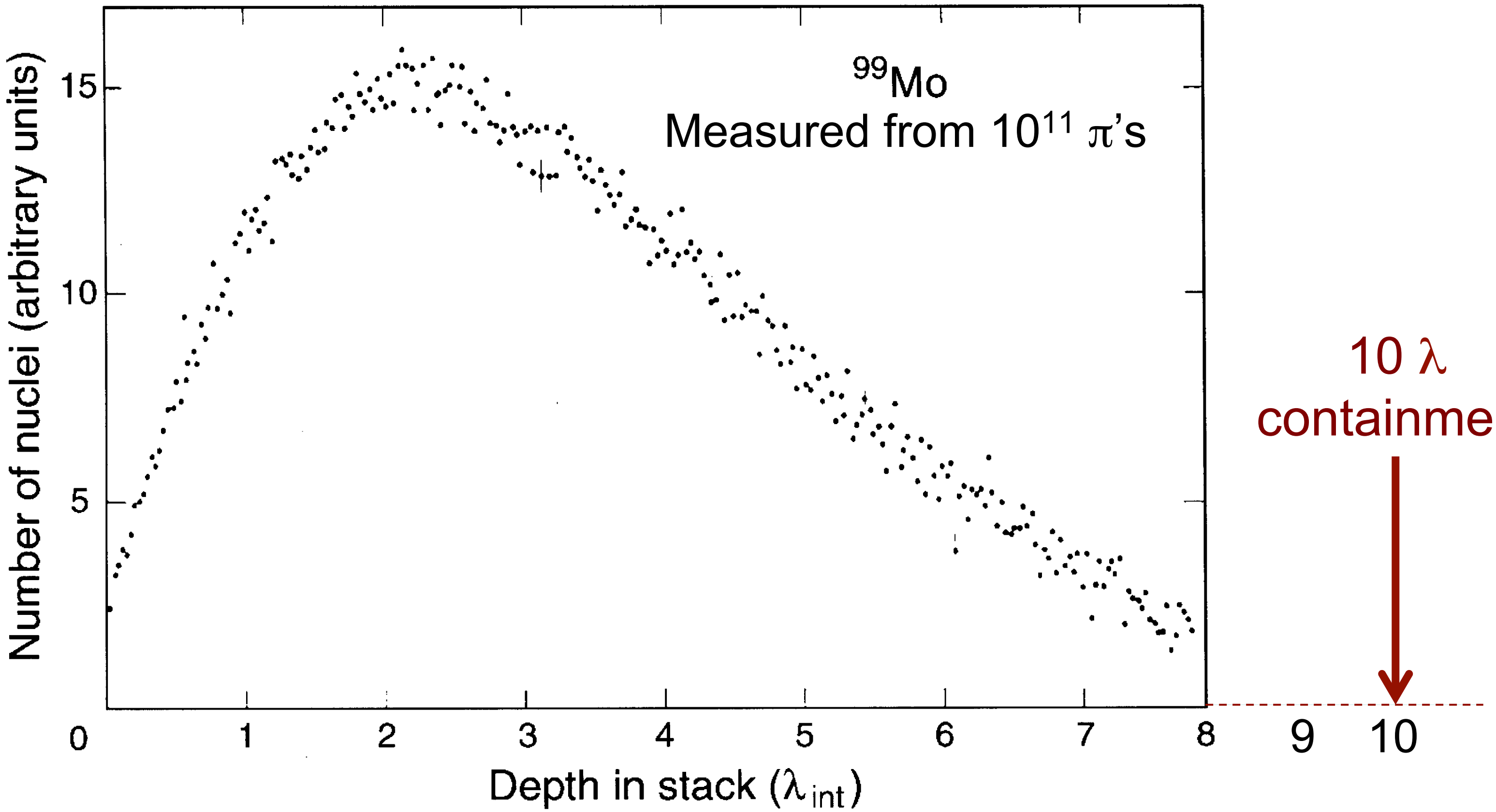
- Fit parametrization by Bock et al. NIM 186 (1981) 533



As with EM showers: depth to contain a shower increases with log(E)

Had shower profile and containment

- 300 GeV π^- in U



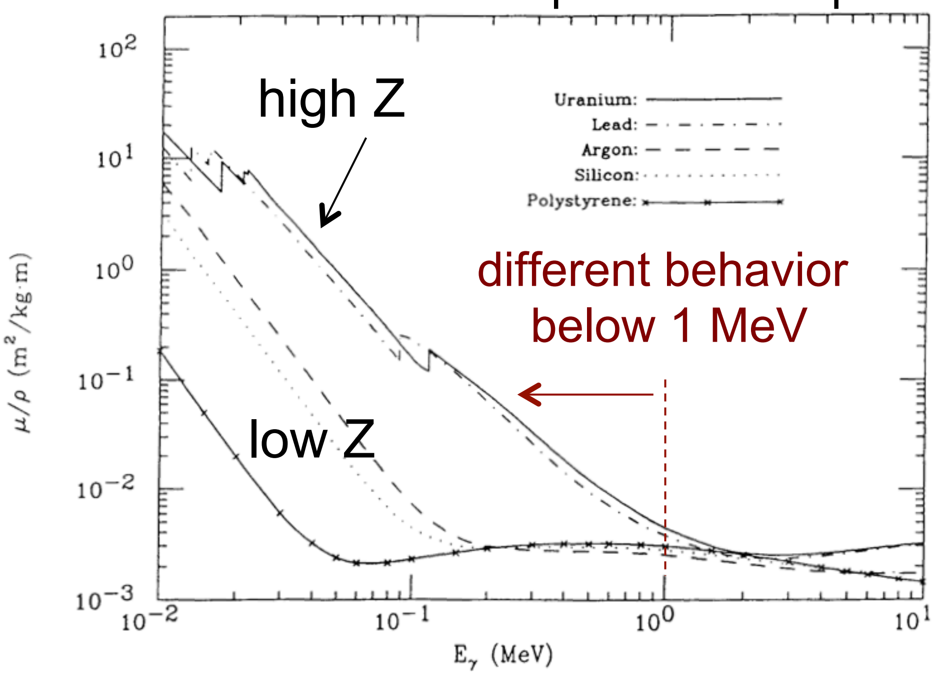
EM shower component

- Calibrate energy using muons
- Interaction of low energy γs differs for different materials
- An EM cascade does not deposit its energy in the same proportion between the high-Z radiator material and the low-Z material of the sensitive layers

- Typical examples:
  - Fe or Cu radiator: e/μ ~ 0.9-1.0
  - Pb radiator: e/μ ~ 0.7-0.8
  - U radiator: e/μ ~ 0.6-0.7

- EM sampling inefficiency results from the rise in low energy photon absorption in high *Z* materials below 1 MeV

photon absorption



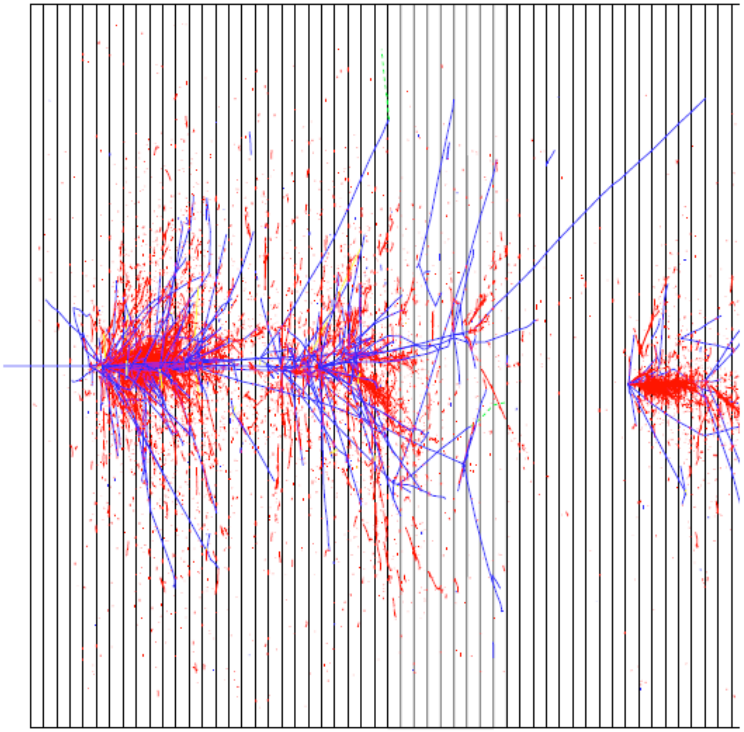
Hadronic showers: fluctuations

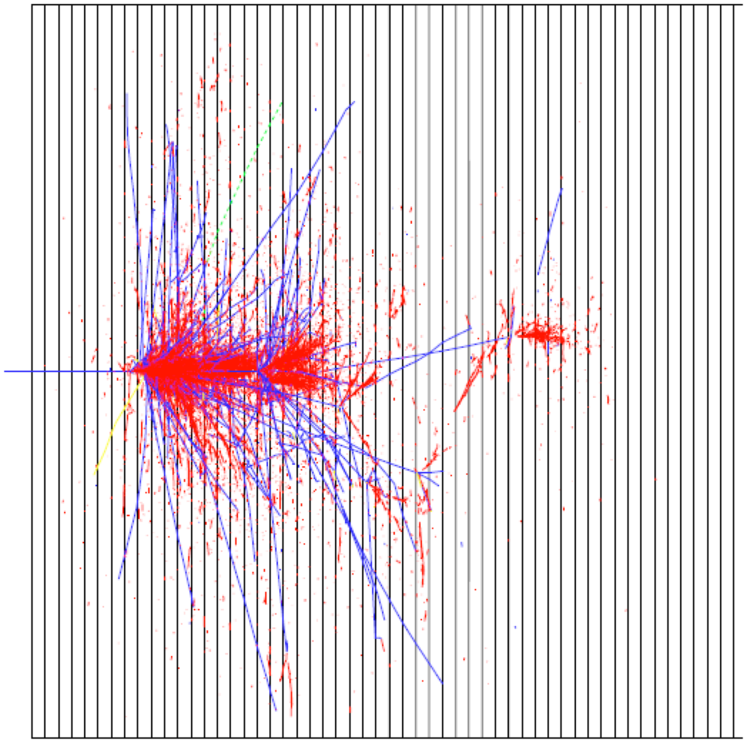
Sources of fluctuations:

- EM vs. non-EM components
- nuclear binding energy losses
- sampling
- leakage of ionizing particles
- leakage of non-ionizing particles
- detector response: saturation or non-linear
- noise
- non-uniformities of the detector
- time dependence of various components

Hadronic showers

- Individual hadronic showers are quite dissimilar

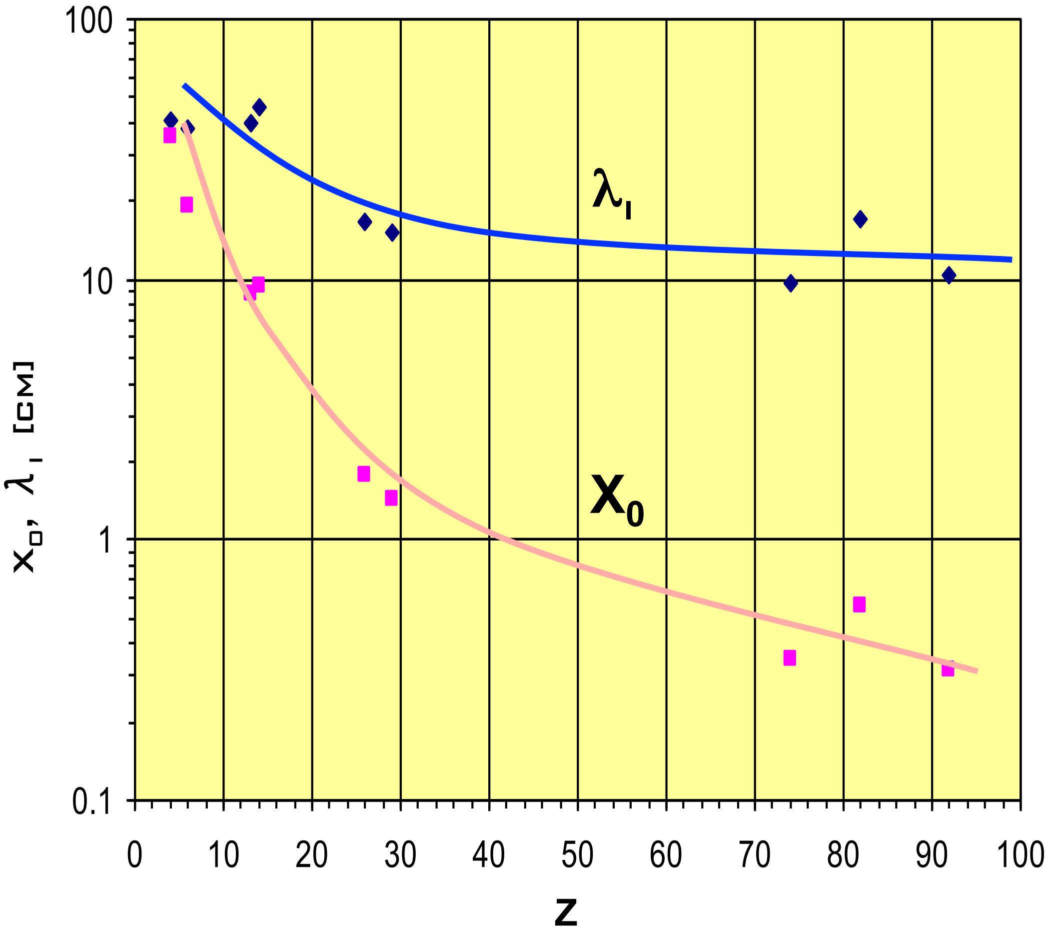




red – EM component

blue – charged hadrons

Two scales of shower development



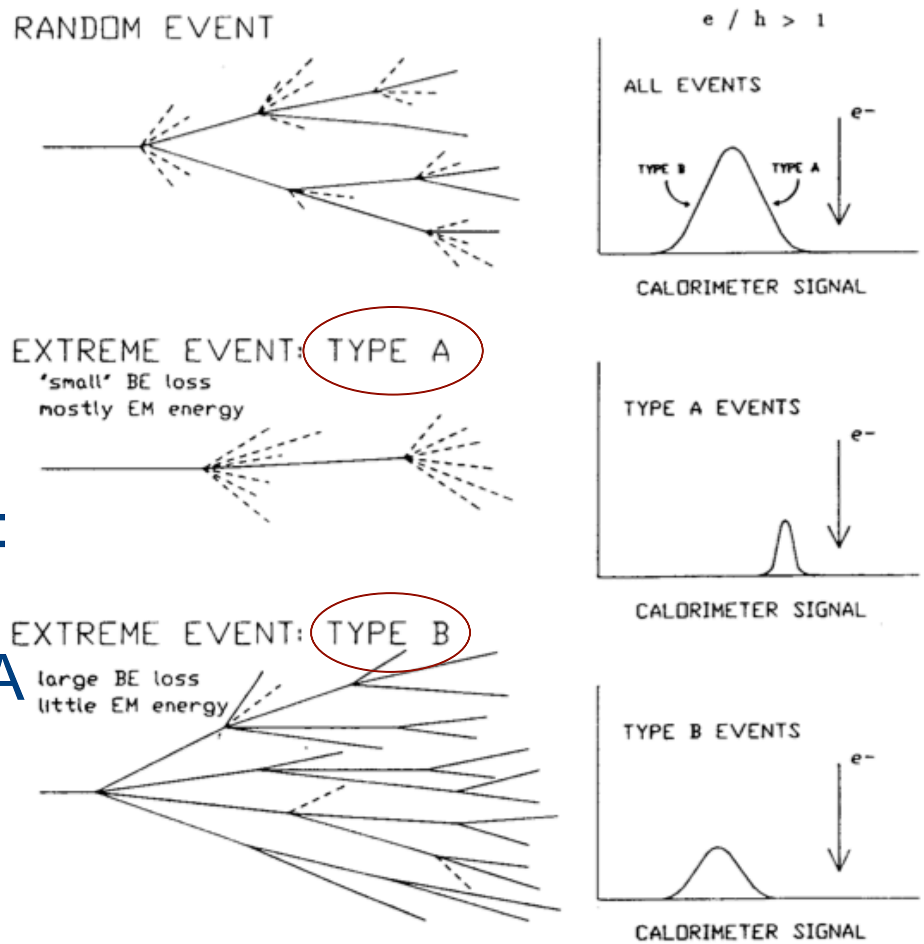
Hadronic vs. EM response

- Not all hadronic energy is "visible"
  - Lost nuclear binding energy
  - Neutrino energy
  - Slow neutrons, …

For instance in lead (Pb):
- Nuclear break-up (invisible) energy: 42%
- Ionization energy: 43%
- Slow neutrons ($E \sim 1$ MeV): 12%
- Low energy g's ($E_\gamma \sim 1$ MeV): 3%

Hadronic shower: resolution

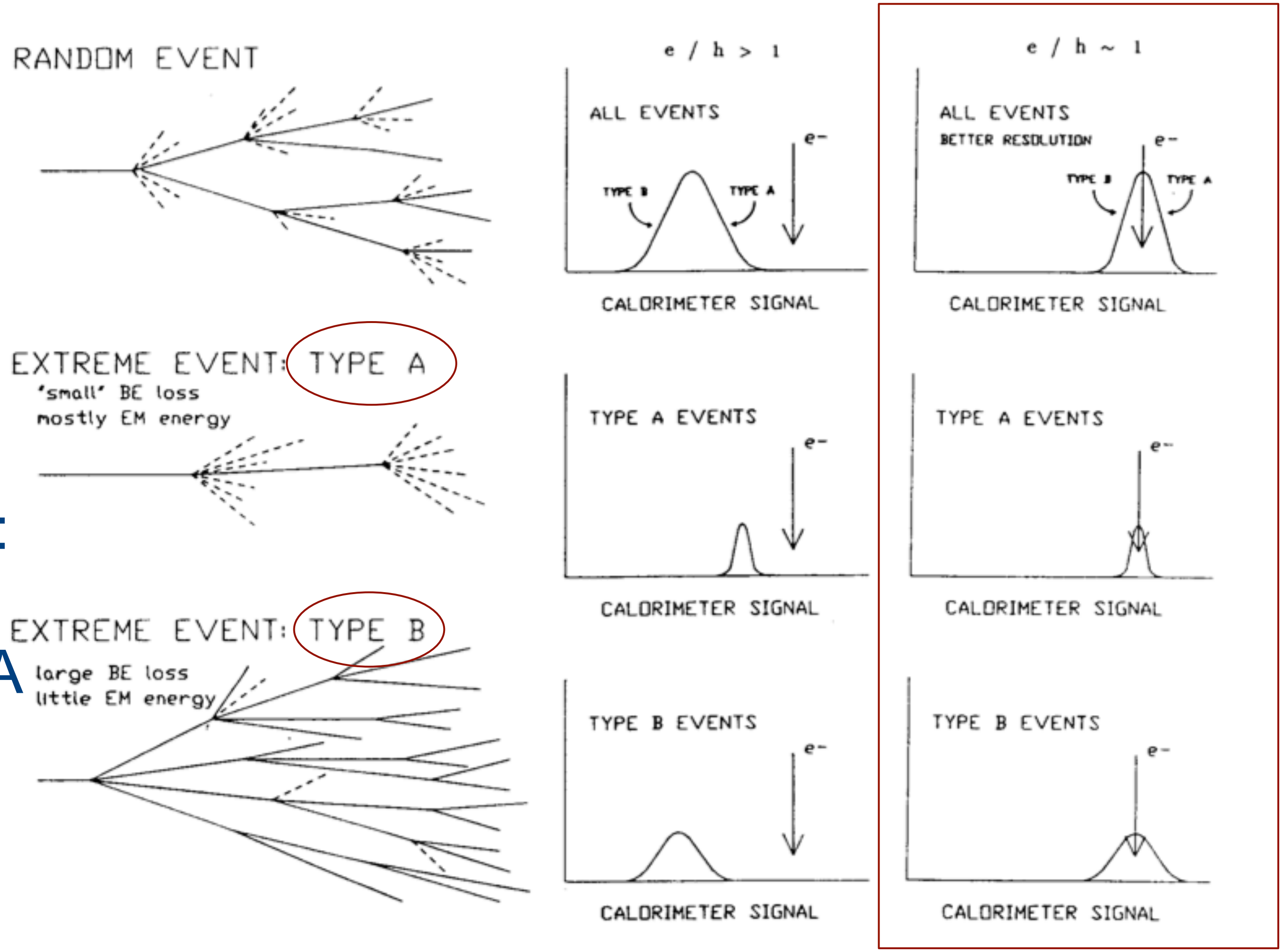
- fluctuations of en. measurement
  - the most important fluctuation: binding energy (BE) losses
  - correlated with EM shower energy fraction
- optimal resolution: need to equalize response of type A vs. type B



Hadronic shower: resolution

- fluctuations of en. measurement
  - the most important fluctuation: binding energy (BE) losses
  - correlated with EM shower energy fraction
- optimal resolution: need to equalize response of type A vs. type B

compensation: e/h~1



Hadronic showers: compensation

- A dominant factor in the resolution of a hadron calorimeter is the unequal response to EM energy deposition and hadronic energy deposition
- Recover part of the “invisible energy”
- one can reduce this fluctuation by equalizing the EM and hadronic response: e/h=1
  - Amplify the nuclear signal (amplify the nuclear energy itself or favor the nuclear signal in sampling)
  - Attenuate the EM signal
  - Measure the hadronic/EM ratio in each event and correct
- Offline compensation:
  - Weighting methods
  - Multiple shower measurements (2+ active media, select EM, etc.)

EM calorimeters: summary

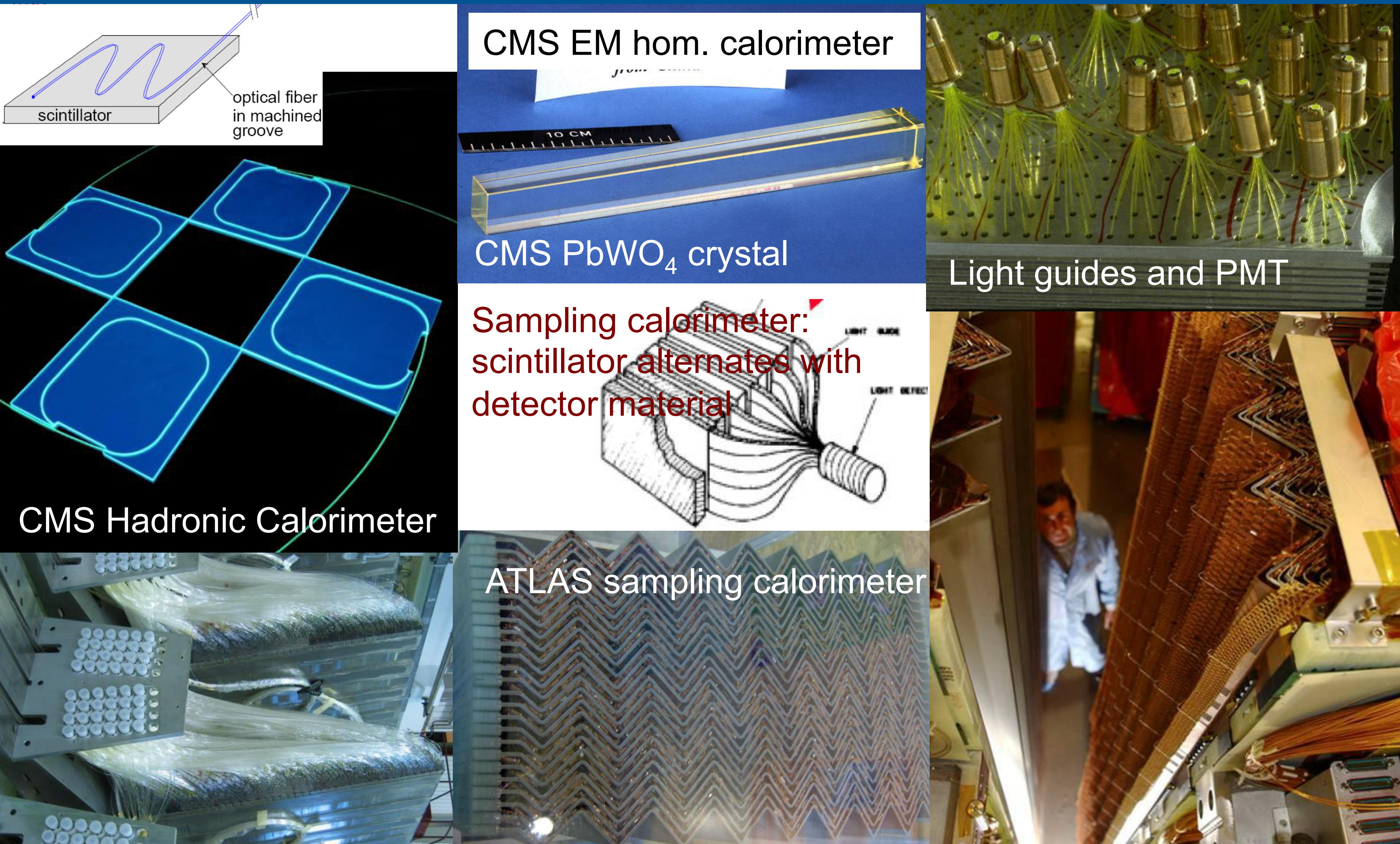
- EM showers are very well understood theoretically
- Electromagnetic calorimeters are continuing to advance
- Optimization is always a trade-off between competing constraints
- EM calorimeters have good energy resolution (typically 2-10%/$E^{1/2}$)
- EM showers develop through brems and pair production
- Characteristic length is radiation length X_0

Hadronic shower: summary

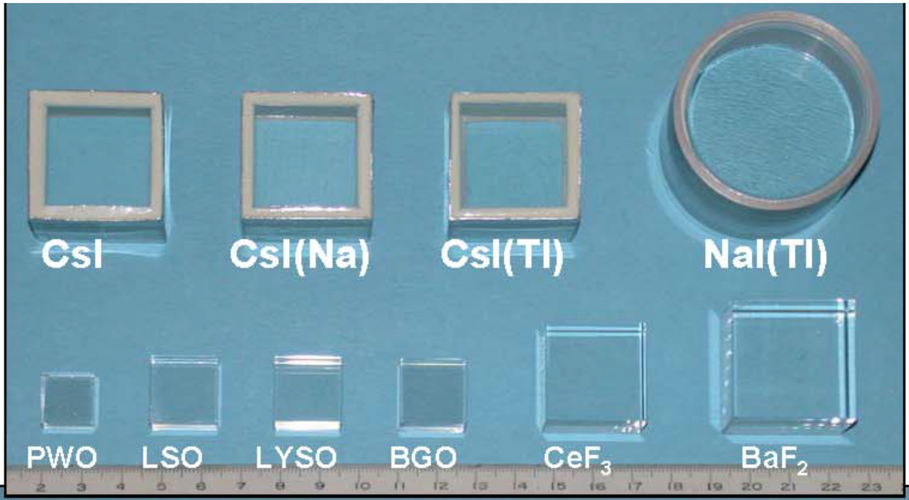
- Hadronic showers are more complex than EM showers
- Hadronic calorimeters have worse energy resolution than EM cal. (typically $40\%/E^{1/2}$ to $100\%/E^{1/2}$)

- Hadrons also loose energy through a showering process
- However, instead of brems, the fundamental process is nuclear interaction
- Characteristic length is called the hadronic interaction length λ ($\lambda \approx 35$ gm/cm^2 $A^{1/3}$)

Calorimeters



Inorganic scintillating crystals



1.5 X_0 Samples:

Hygroscopic Halides

Non-hygroscopic

Full Size Crystals:

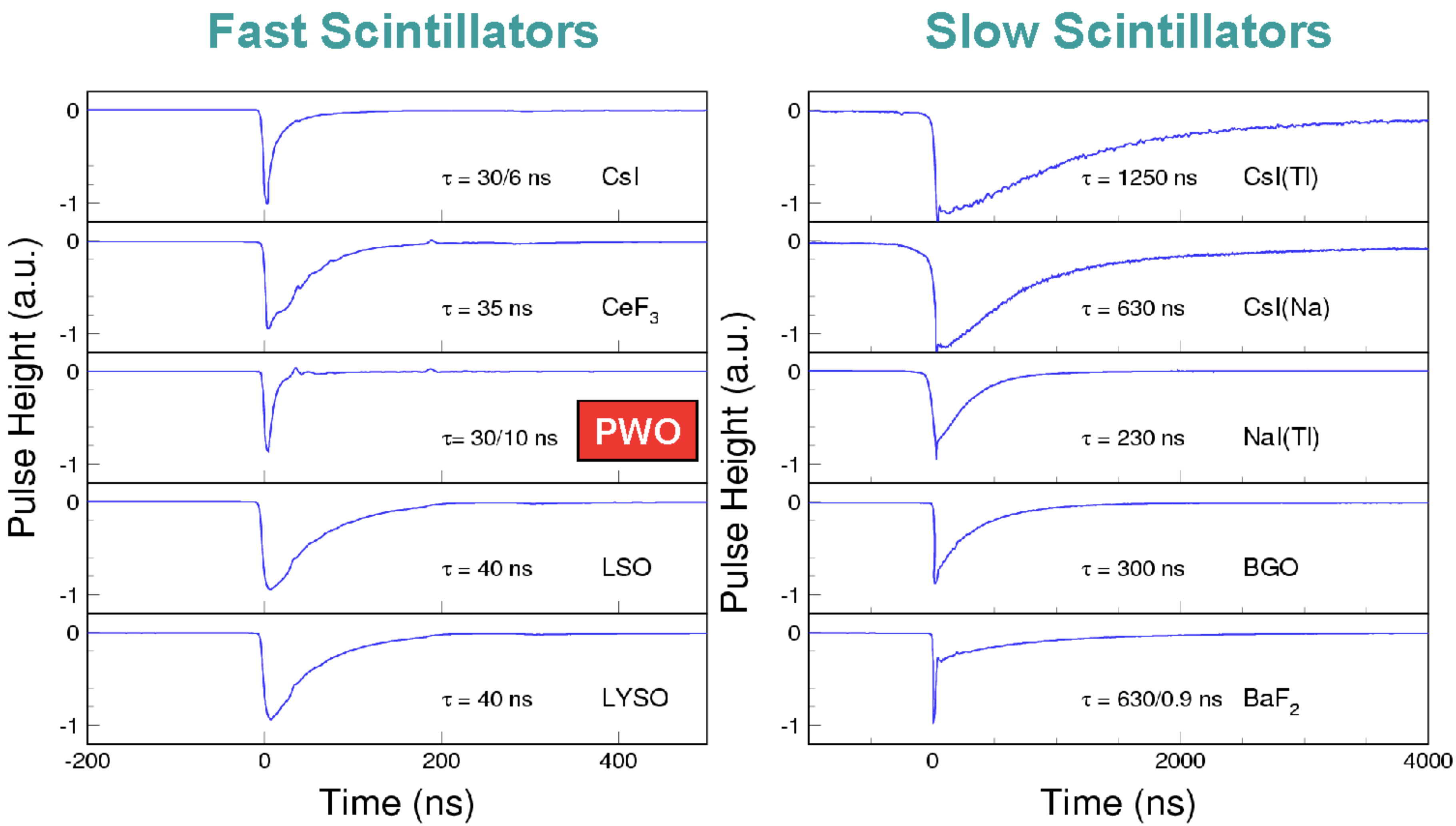
BaBar CsI(Tl): 16 X_0

L3 BGO: 22 X_0

CMS PWO(Y): 26 X_0

Decay time constant for crystals

Recorded with Agilent 6052A digital scope

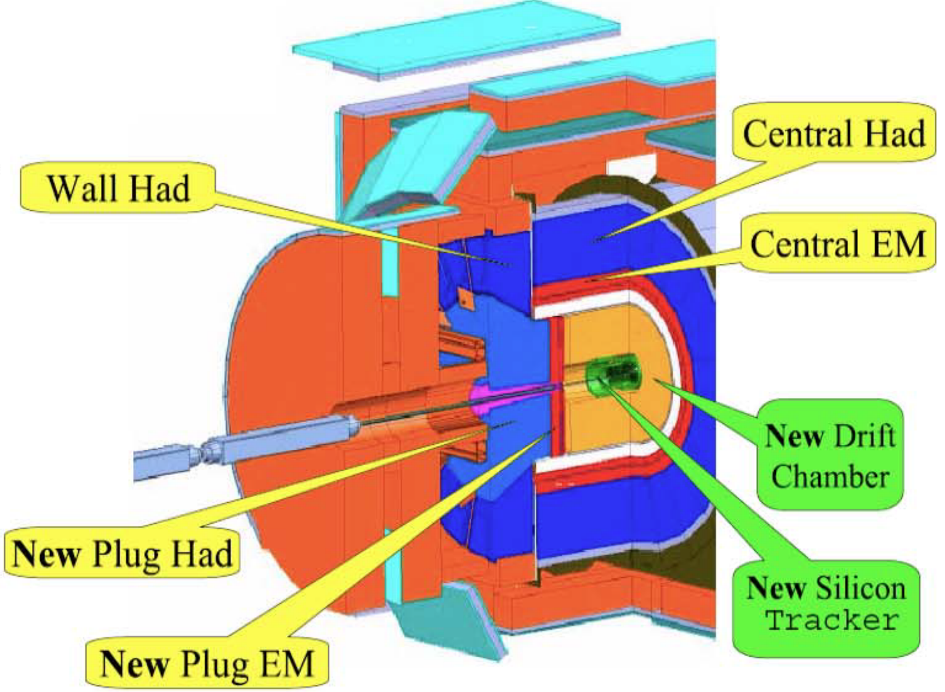


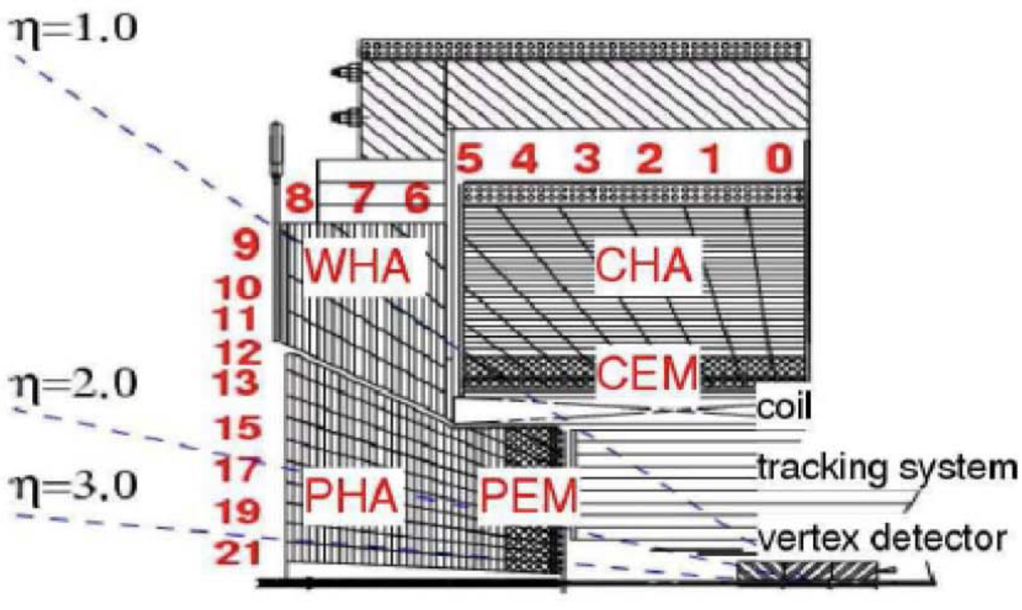
The CDF Calorimeters

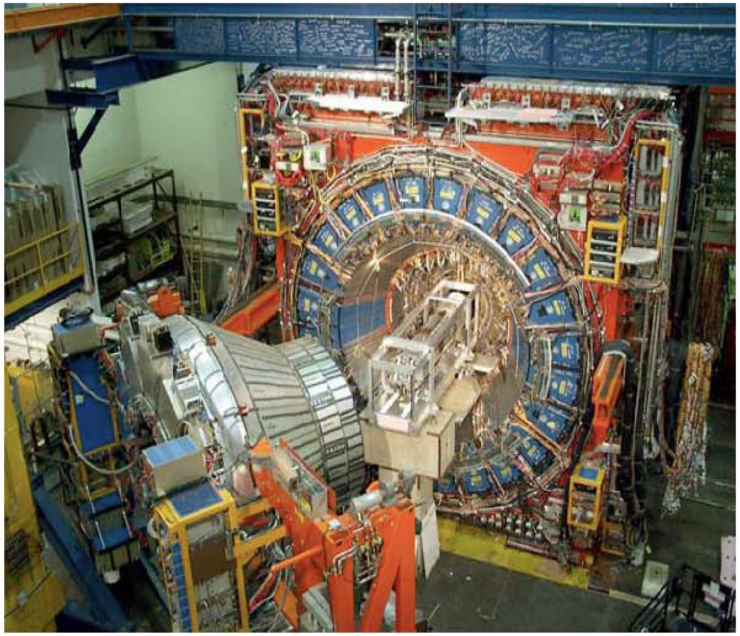
All scintillator-based sampling calorimeters

$\|\eta\|$ Range	$\Delta\phi$	$\Delta\eta$
0. - 1.1 (1.2 h)	15°	~ 0.1
1.1 (1.2 h) - 1.8	7.5°	~ 0.1
1.8 - 2.1	7.5°	~ 0.16
2.1 - 3.64	15°	0.2 - 0.6

Table 1.2: CDF II Calorimeter Segmentation

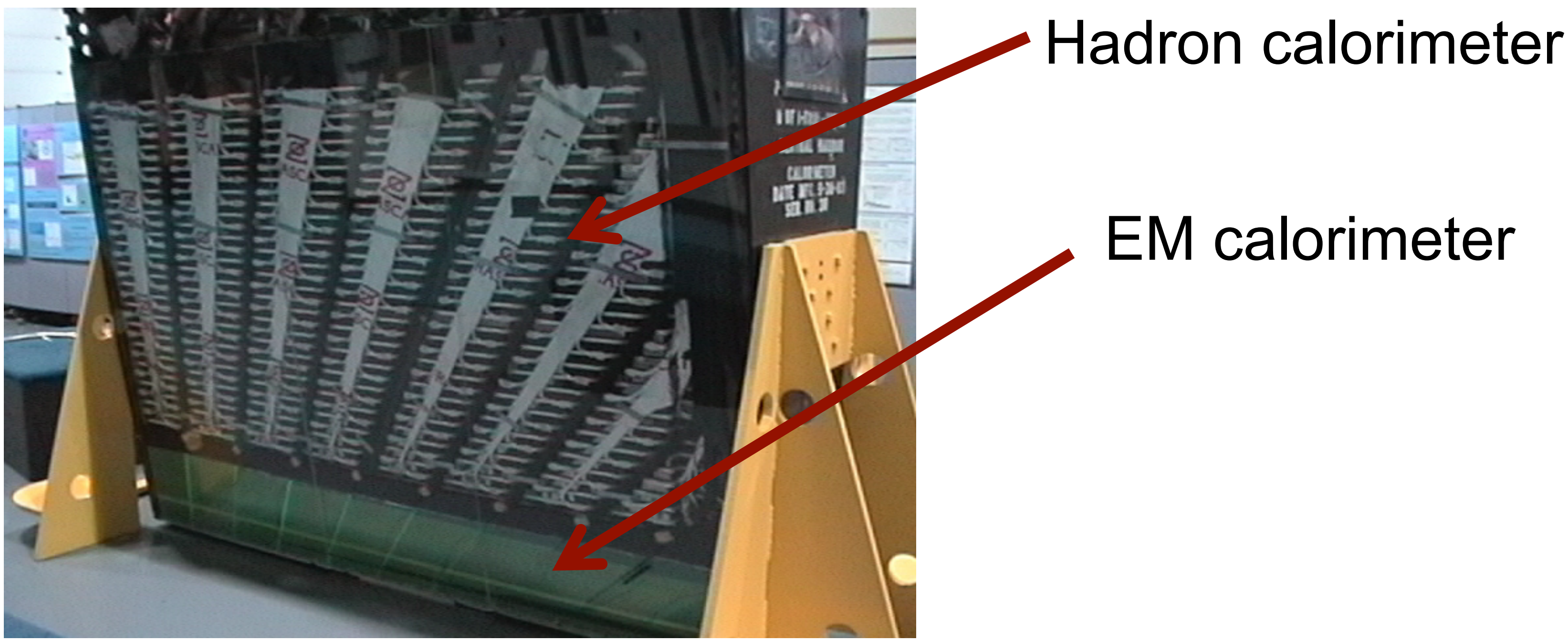






CDF calorimeters at the Tevatron

- EM calorimeter in front; Hadron in the back
- Lead for EM; steel for hadron in sandwich
- Scintillator to detector shower

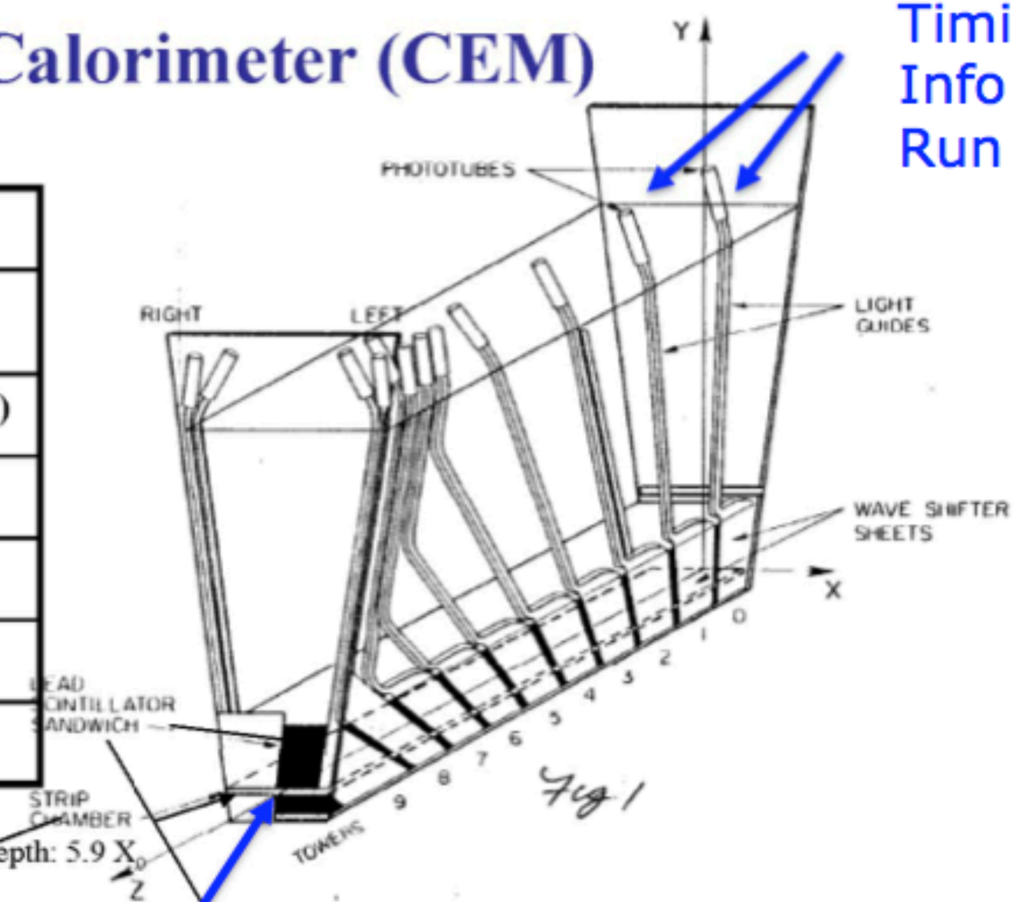


CDF EM Calorimeter

Central Electromagnetic Calorimeter (CEM)

Thickness	**$18X_0$, 1l**
Abs. (pb) layer	**1/8” (4.2 mm,0.6 X_0)**
Scint. layer	**5 mm , polystyrene (SCSN-38)**
w.l.s.	**3mm Y7 acrylic sheet**
PMT	**Ham. R580 (1.5”)**
light yield	**>100 p.e./GeV/pmt**
resolution	$13.5/\sqrt{E_T}$

Added Timing Info in Run II



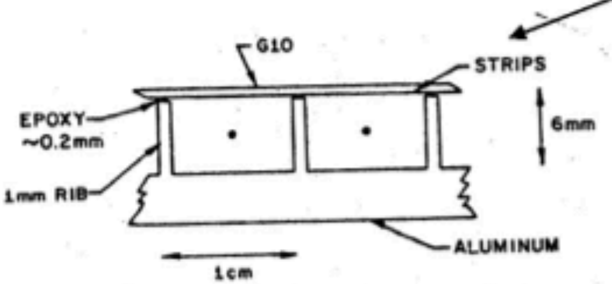


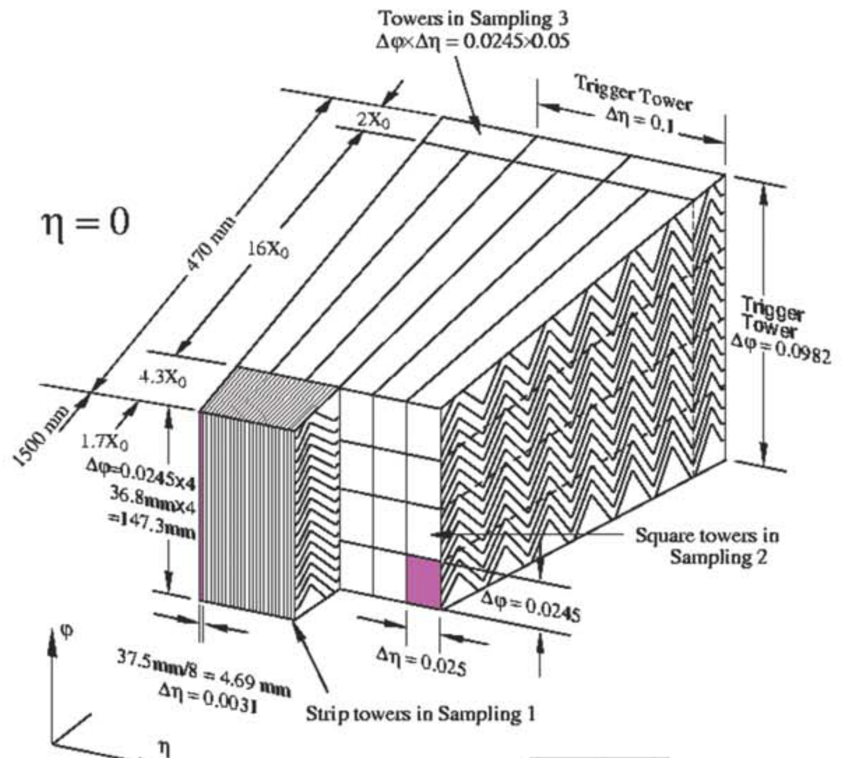
Fig. 3. Prototype strip chamber cross section.

Shower Max Detector (Gas Strip Chamber) at EM Shower Max

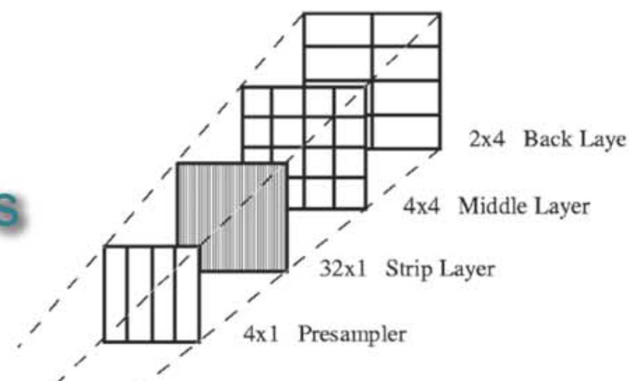
ECAL: ATLAS sampling calorimeter

ATLAS Pb/LAr EM

- Length: at least 22 X_0 (47 cm)
- 3 longitudinal layers (+presampler)
- 4 X_0 rejection of π^0 in two photons
- 16 X_0 for shower core
- 2 X_0 evaluation of late showers

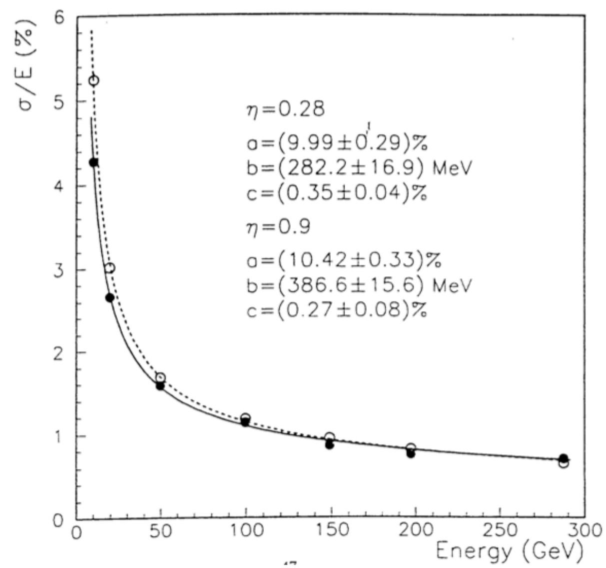


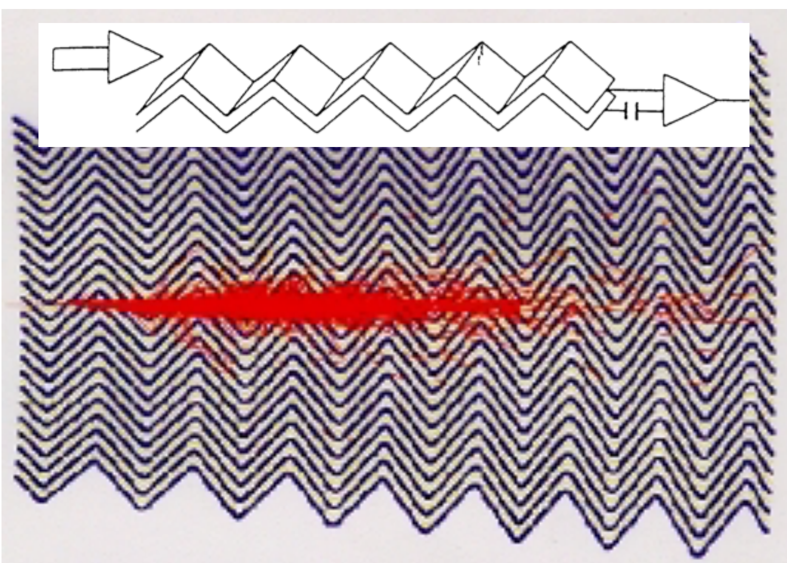
170000 channels

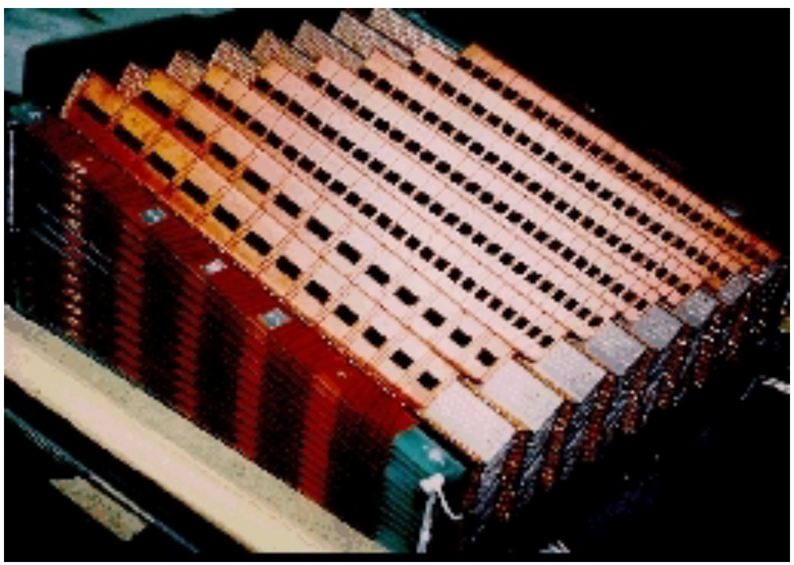


ECAL: ATLAS sampling calorimeter

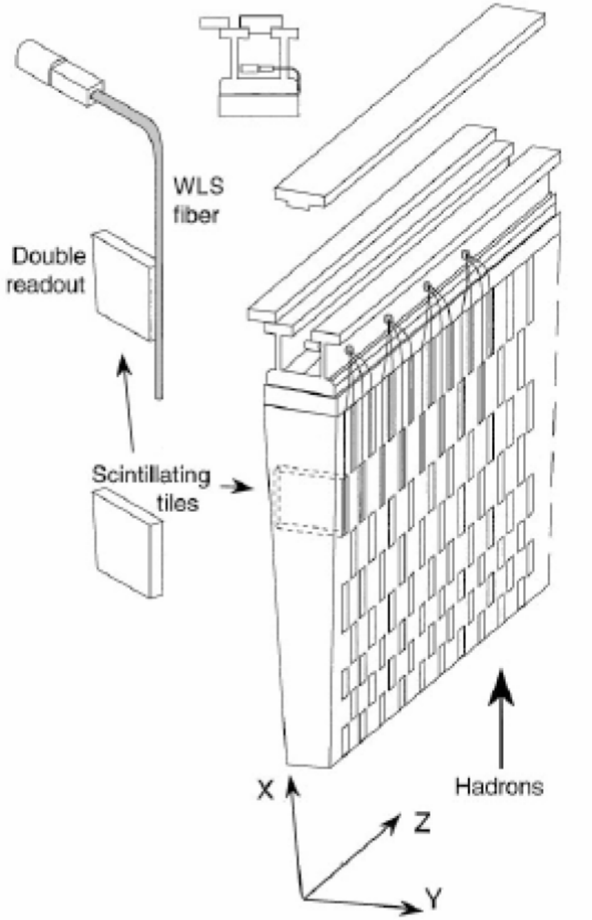
- ATLAS EM Calorimeter: accordion design, lead plates to initiate showering
- Ionization occurs in liquid Argon: drifts to sensors (electrodes on Cu/kapton sheets)
- Fine segmentation transversely; 3 depths
- Resolution: ~10%/$E^{1/2}$

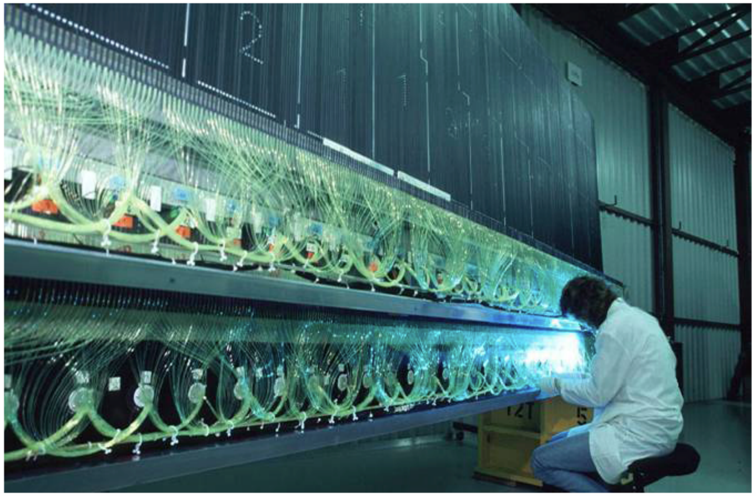






HCAL: ATLAS Tile calorimeter





Fe/Scint with WLS fiber Readout via PMT

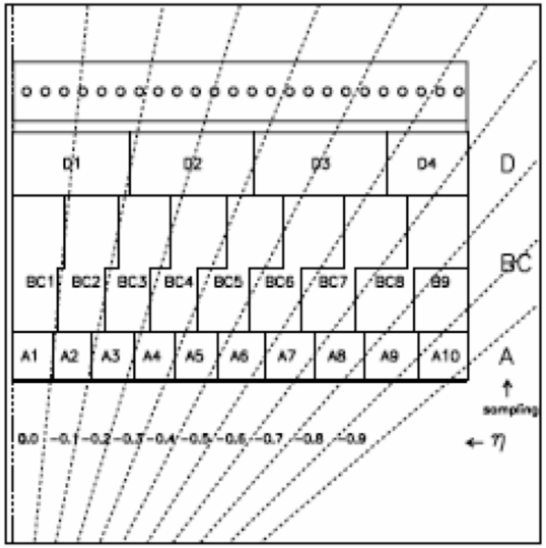


Figure 5-15 Cell geometry of half of a barrel module. The fibres of each cell are routed to one PMT.

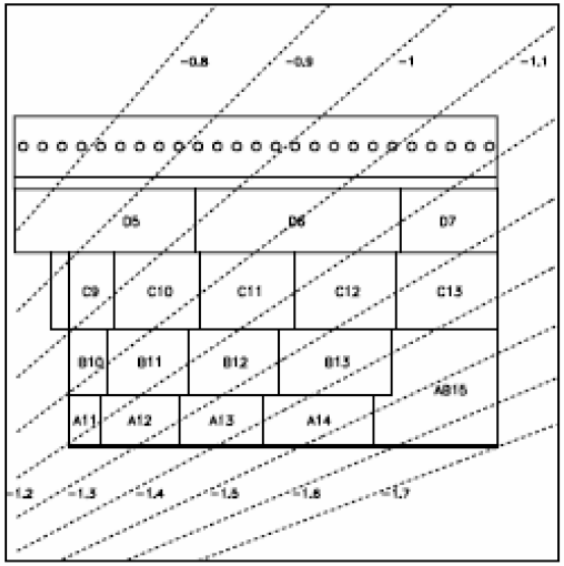
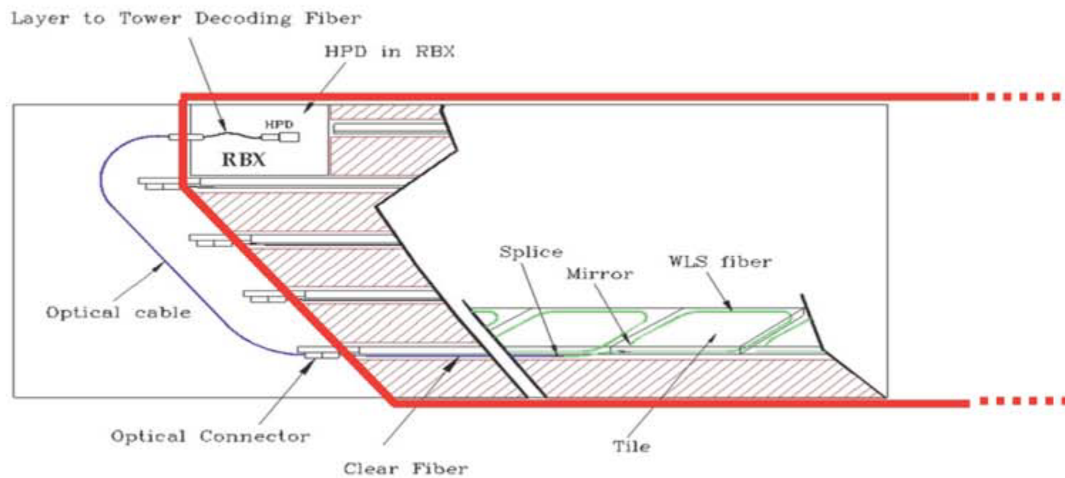


Figure 5-16 Proposed cell geometry for the extended barrel modules (version "a la barrel").

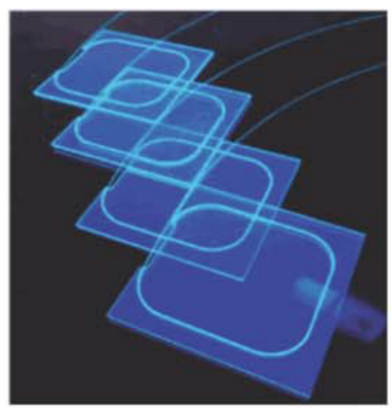
HCAL: CMS sampling calorimeter

CMS HCAL barrel



2593 towers

$\Delta\eta \times \Delta\phi = 0.017 \times 0.017$

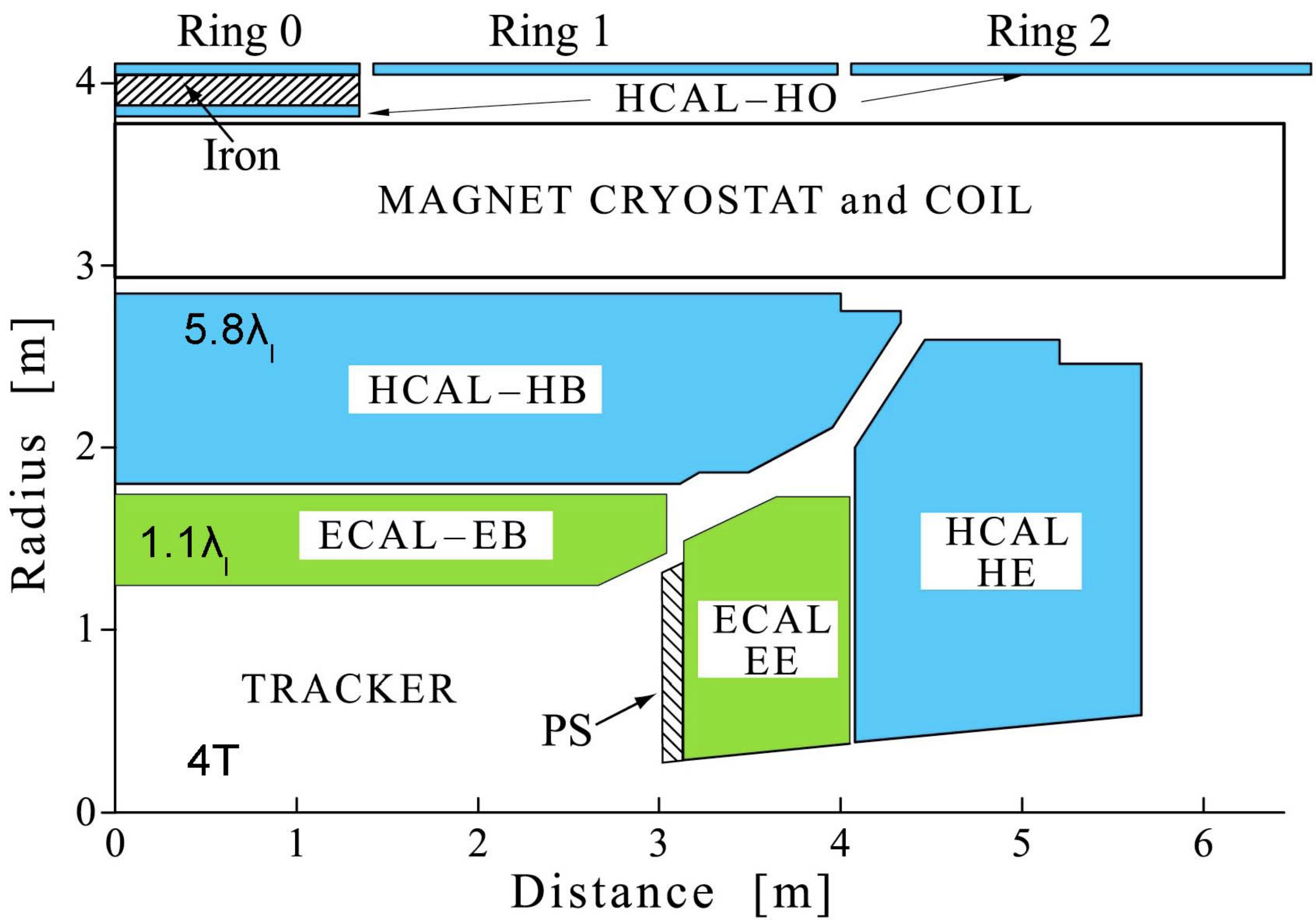


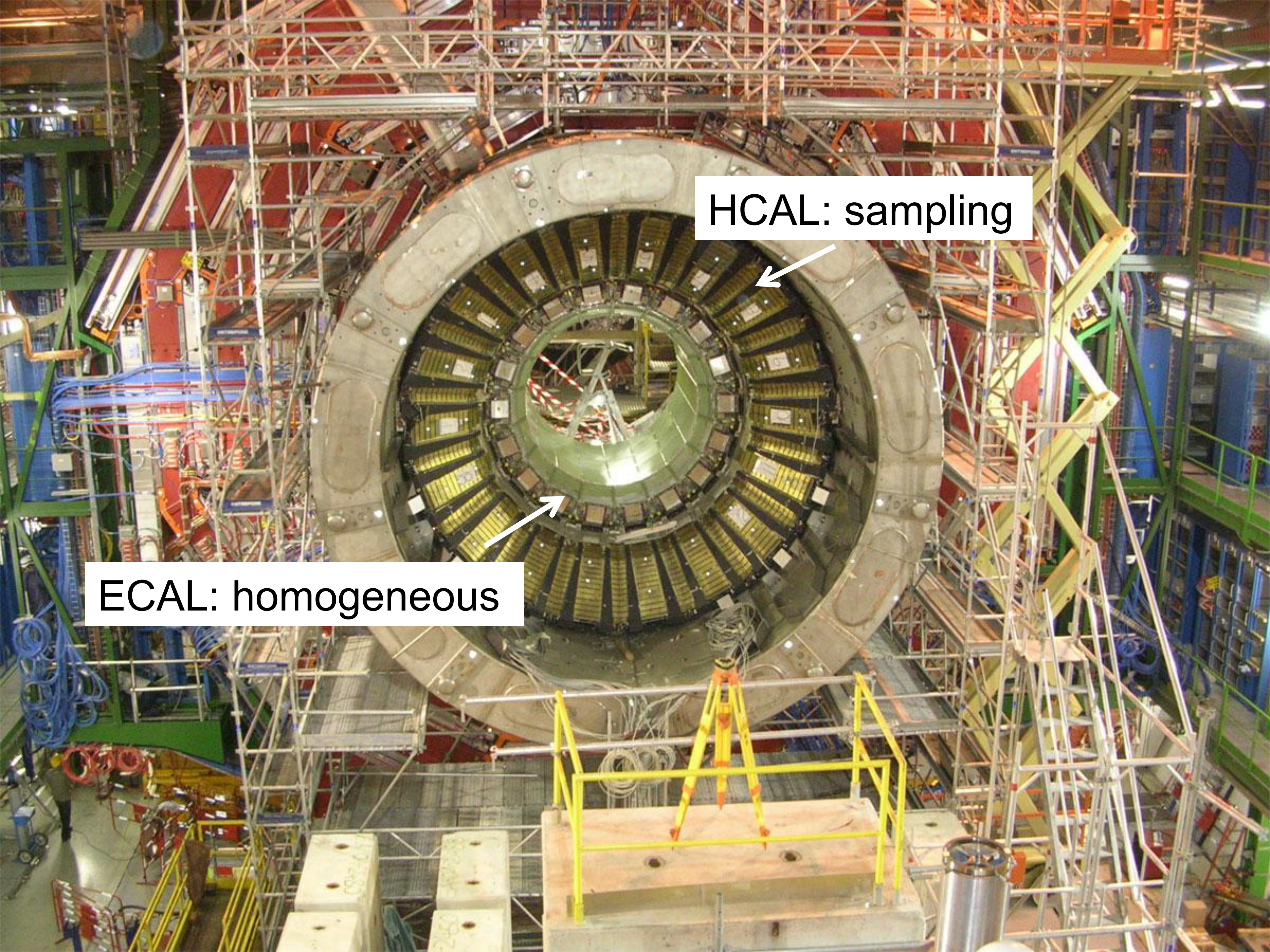
pixel HybridPhotoDiode

HCAL: ATLAS vs CMS

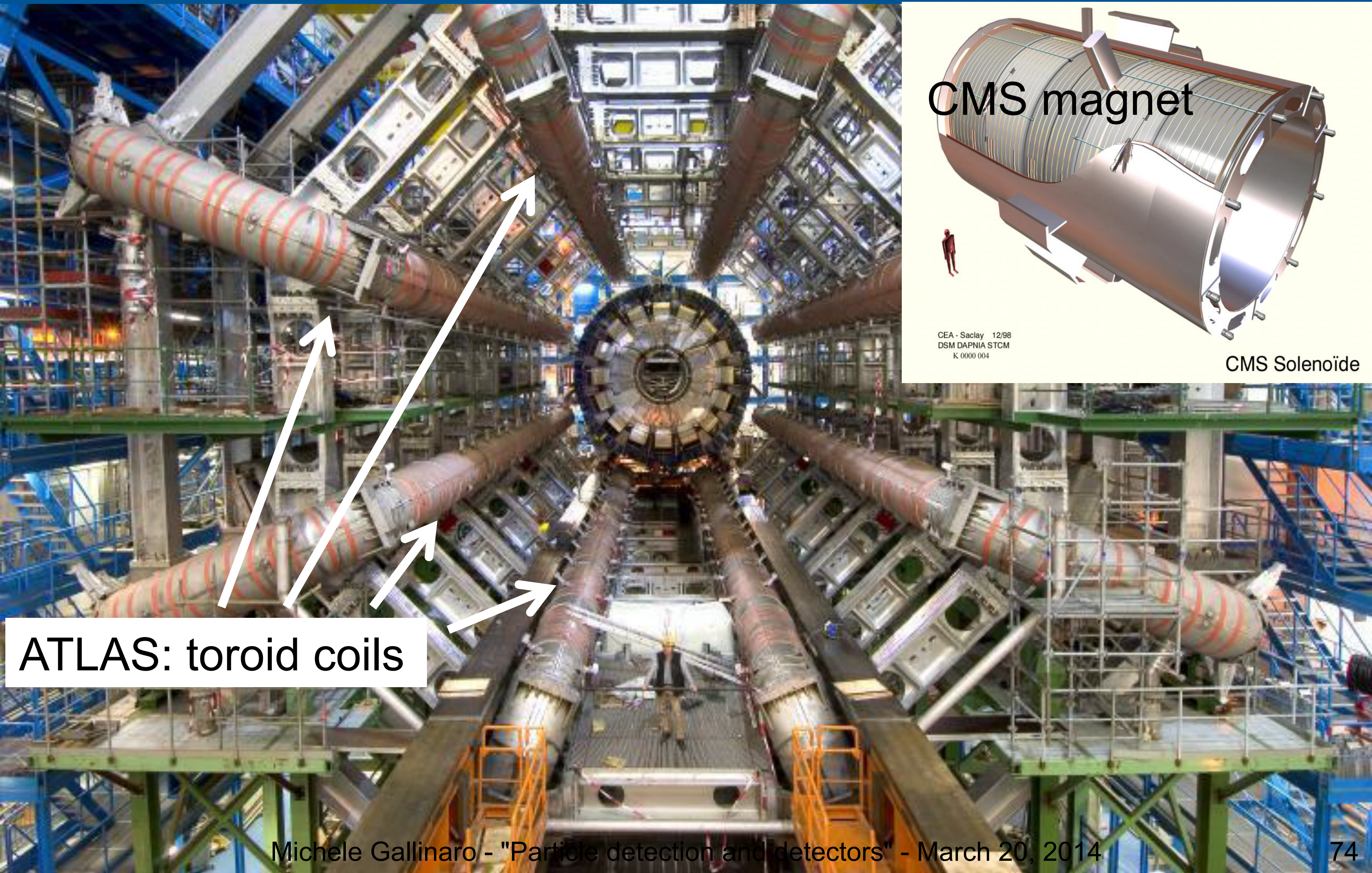
	ATLAS	CMS
Technology		
Barrel / Ext. Barrel	14 mm iron / 3 mm scint.	50 mm brass / 4 mm scint.
End-caps	25 mm (front) - 50 mm (back) copper / 8.5 mm LAr	80 mm brass / 4 mm scint.
Forward	Copper (front) - Tungsten (back) 0.25 - 0.50 mm LAr	4.4 mm steel / 0.6 mm quartz
# Channels		
Barrel / Ext. Barrel	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

CMS calorimeters

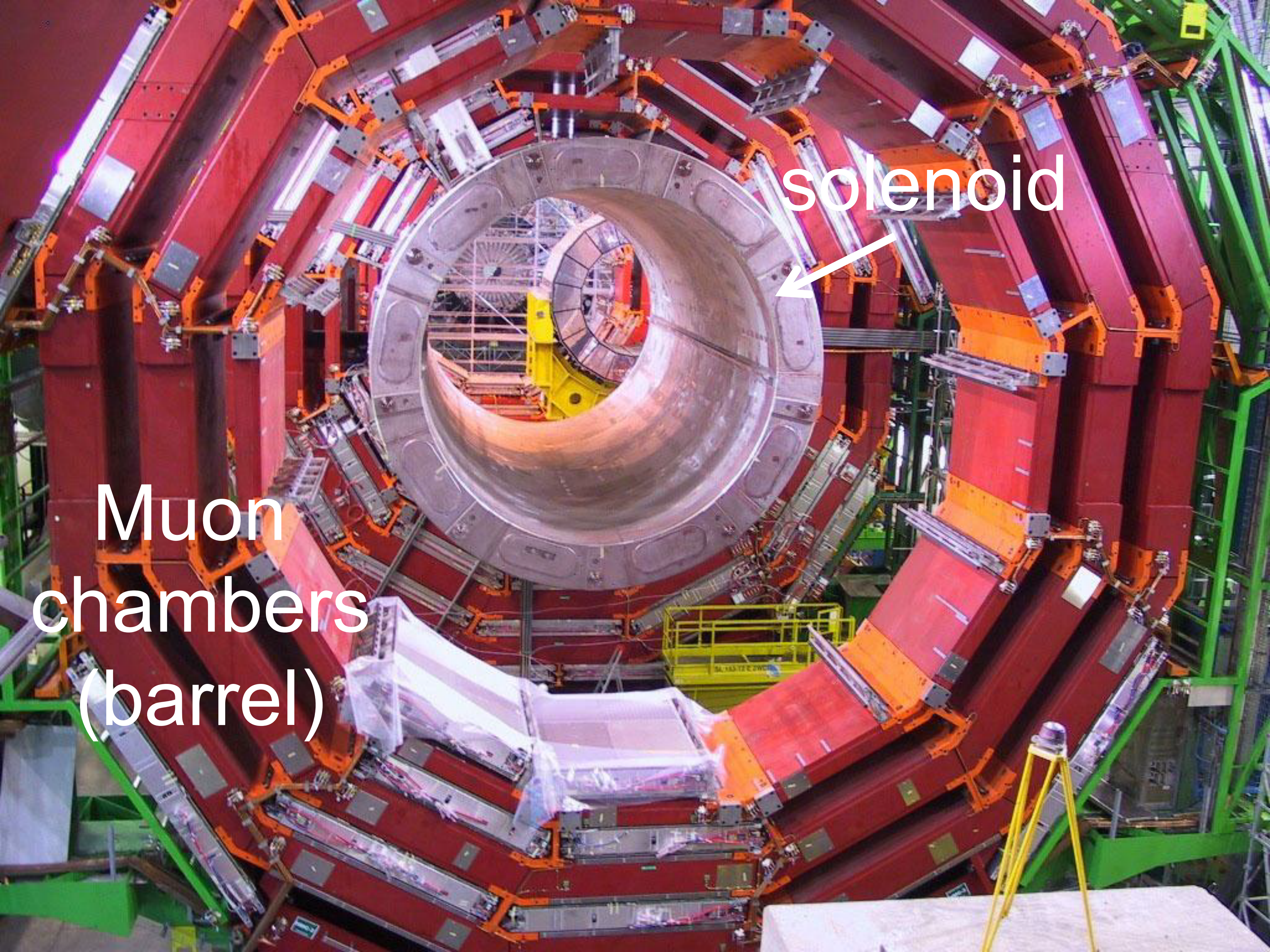



HCAL: sampling
ECAL: homogeneous

Magnetic coil



Assembly of iron yoke


solenoid
Muon
chambers
(barrel)

Experimental cavern

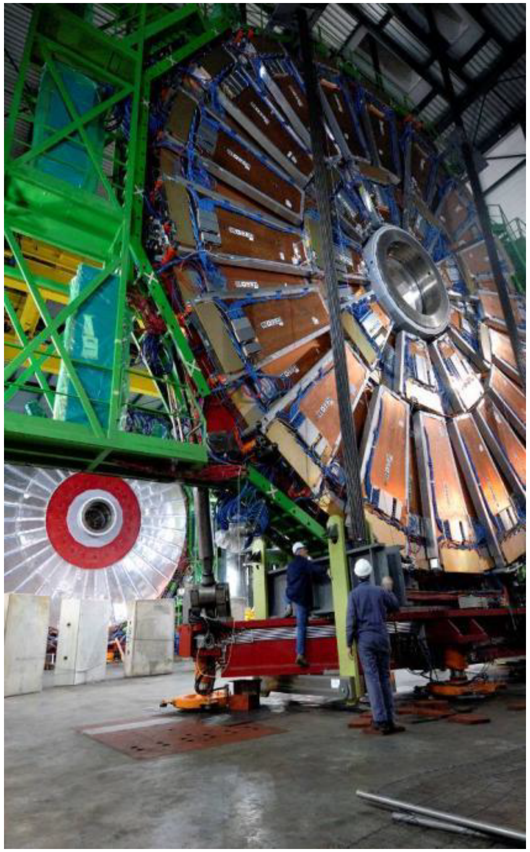
2003

2004

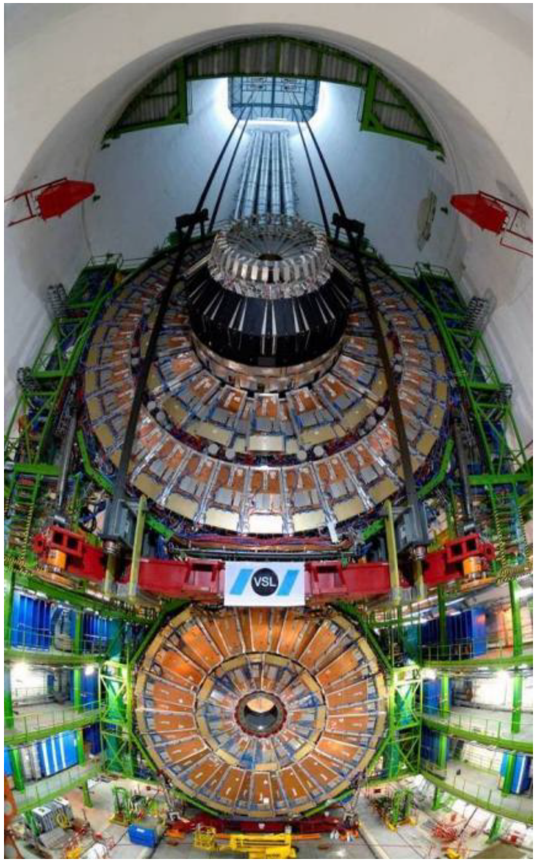

Lowering of the detectors
2006

Lowering: Endcap disks

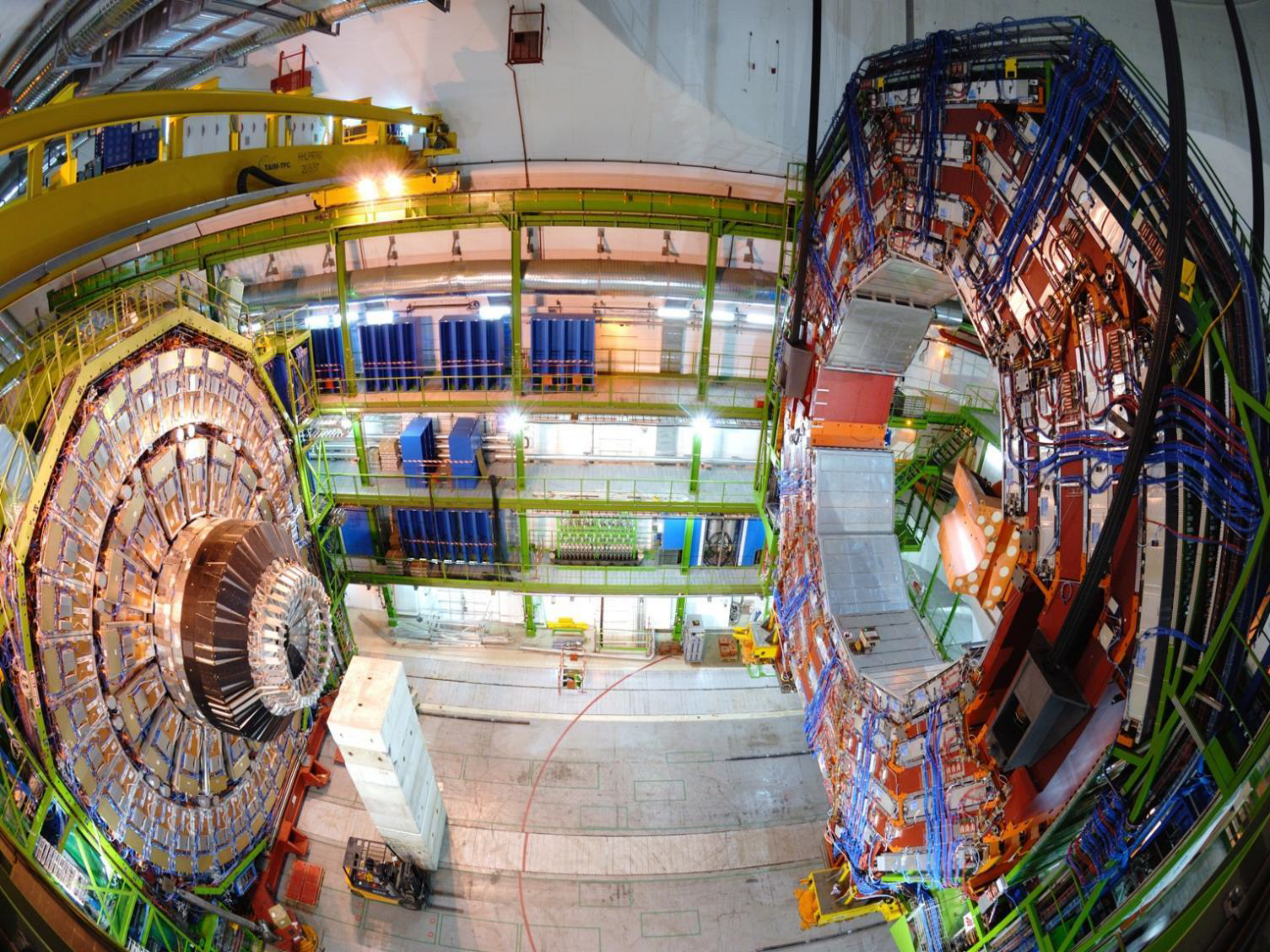
YE+3
30.11.2006

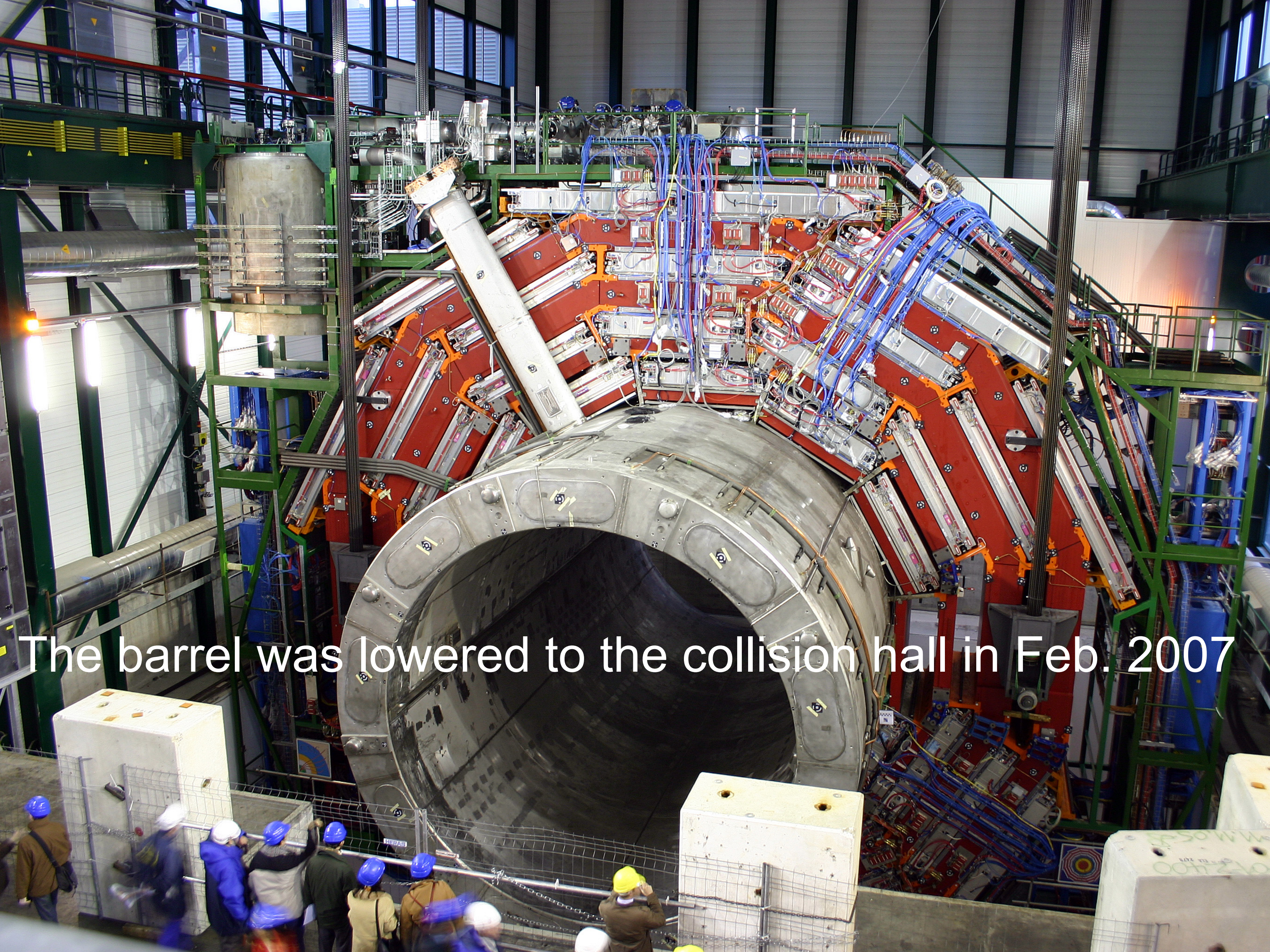


YE+2
12.12.2006



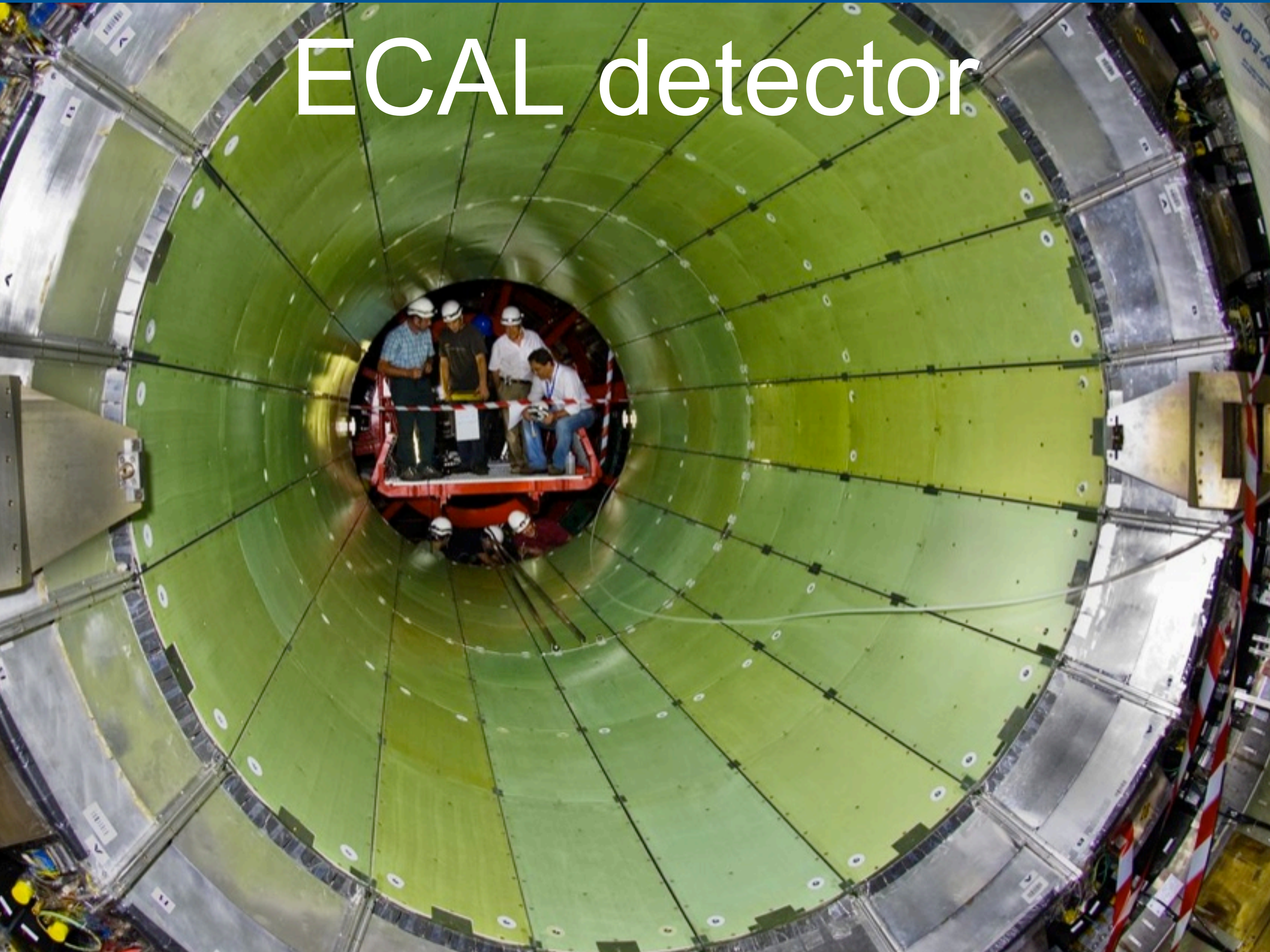
YE+1
9.1.2007



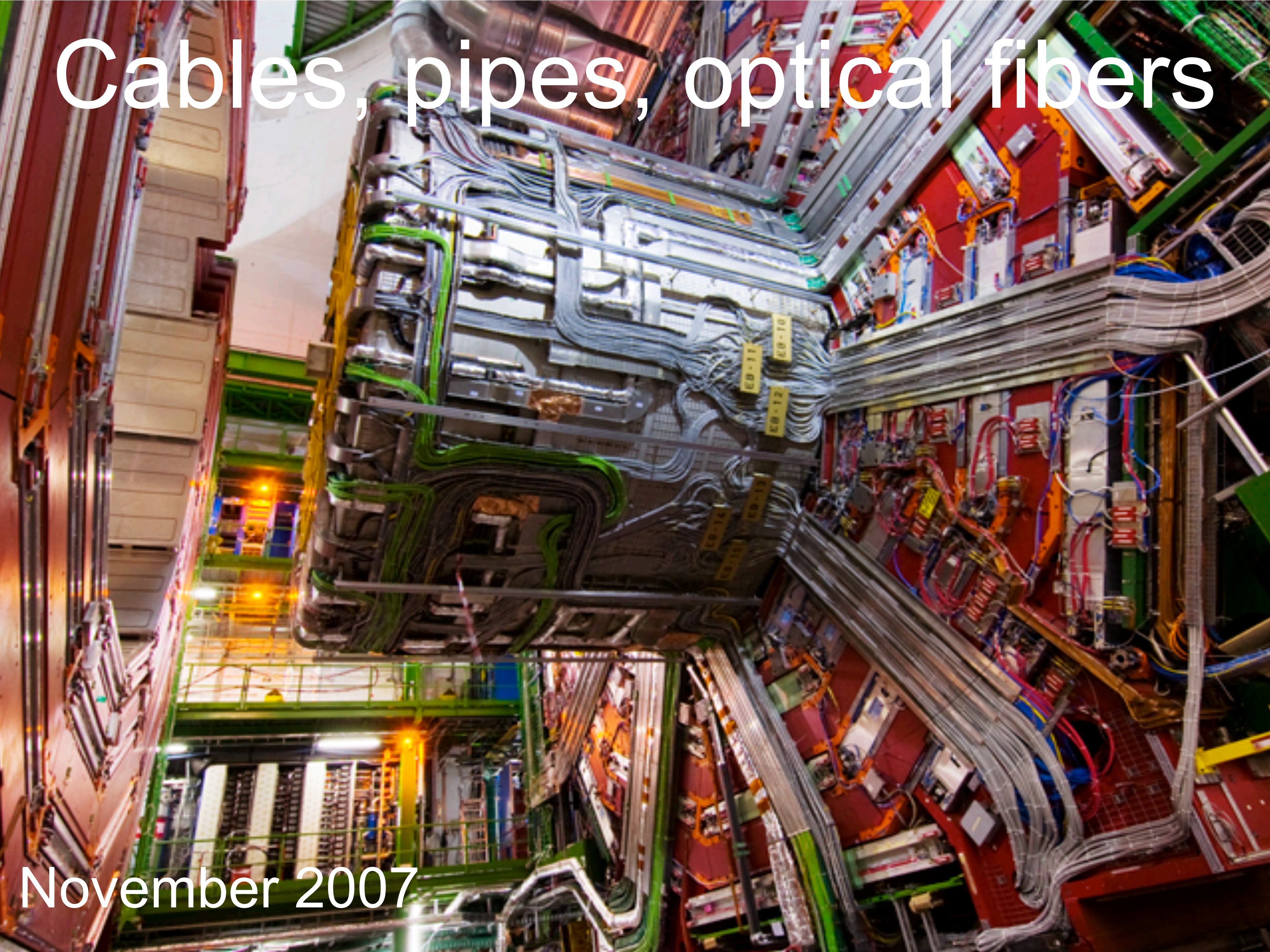


The barrel was lowered to the collision hall in Feb. 2007

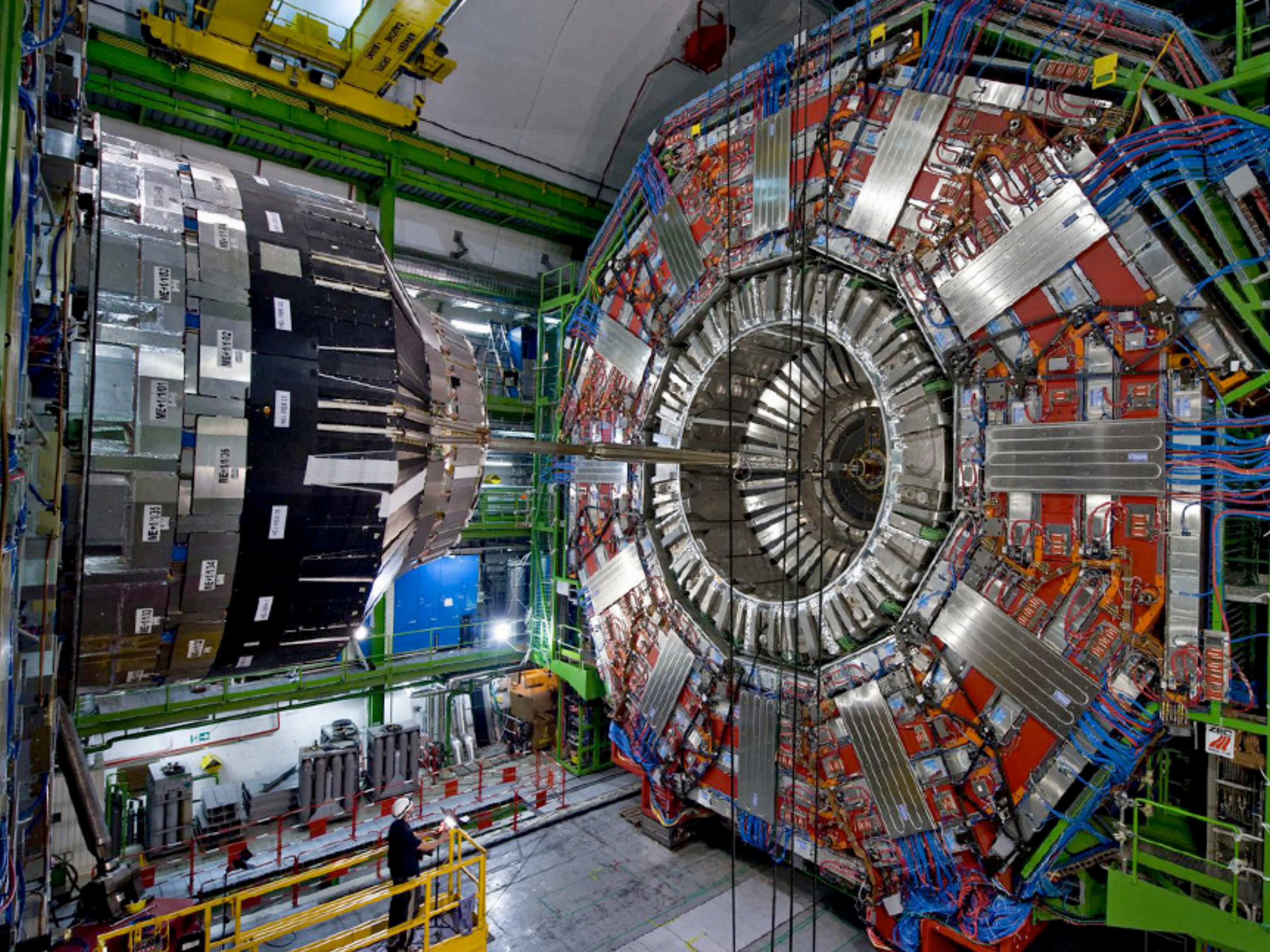
ECAL detector



Cables, pipes, optical fibers

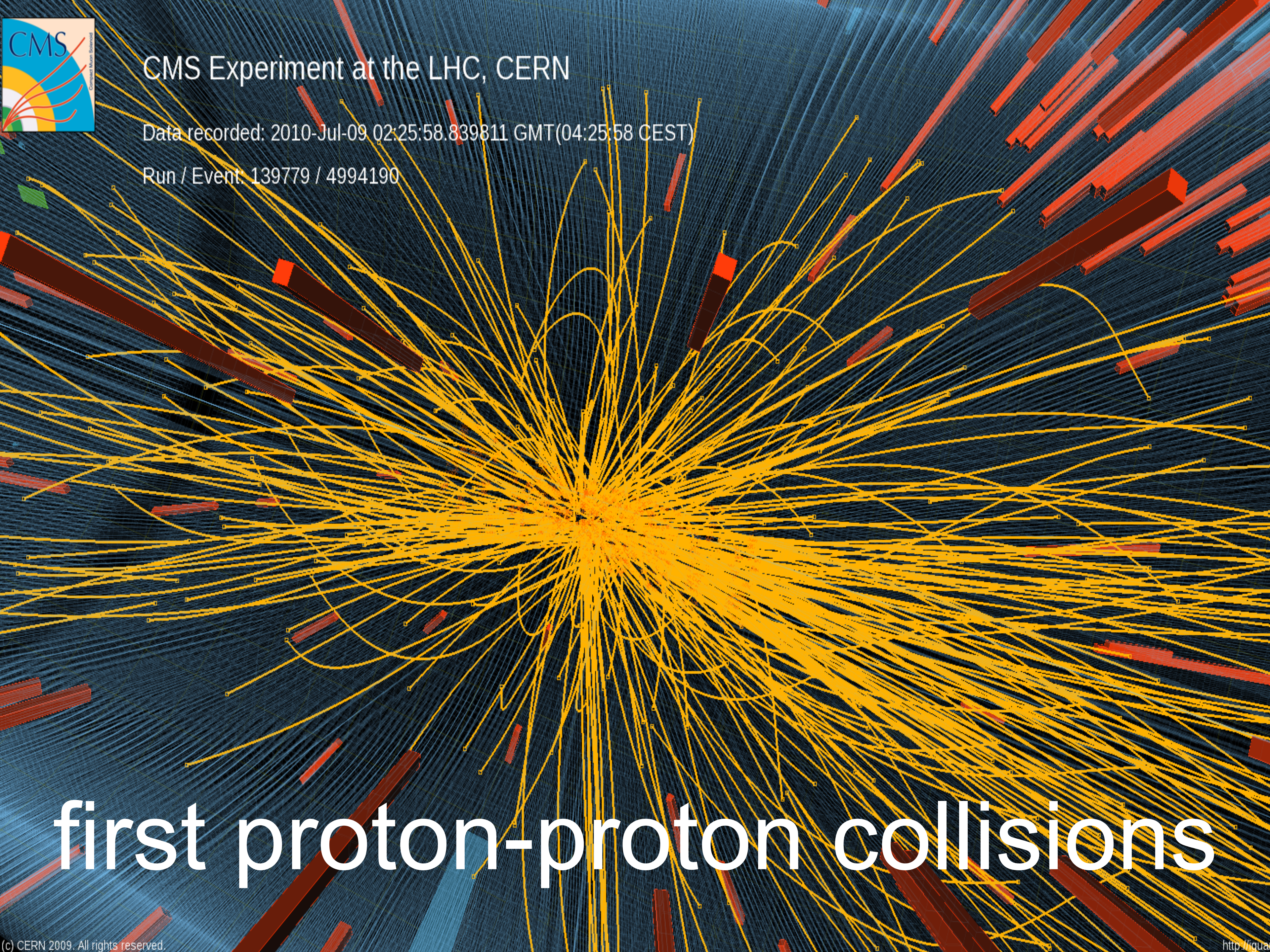


November 2007



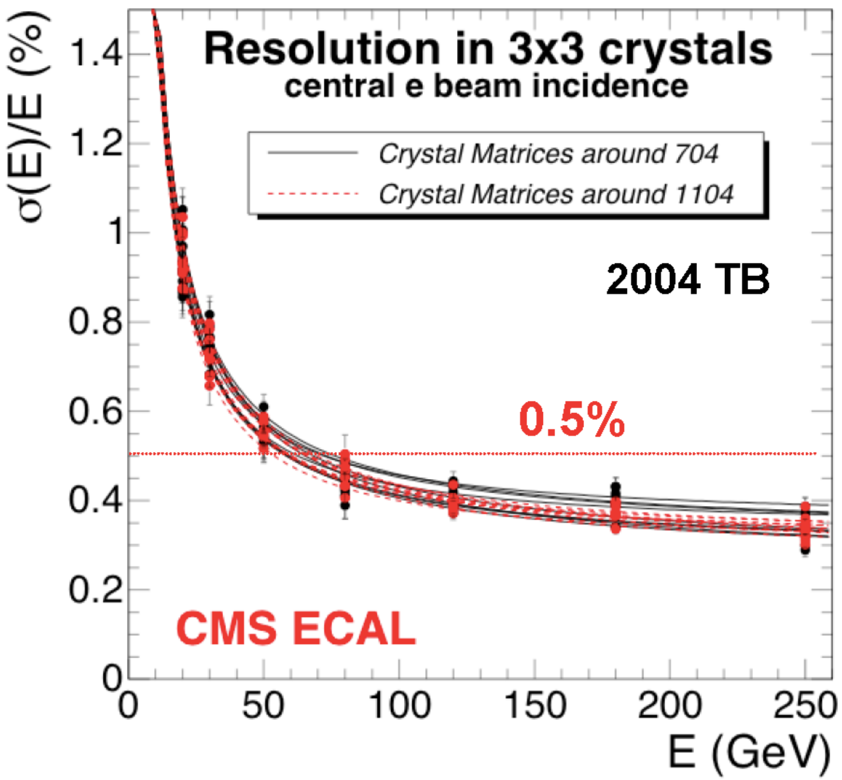
CMS tracker

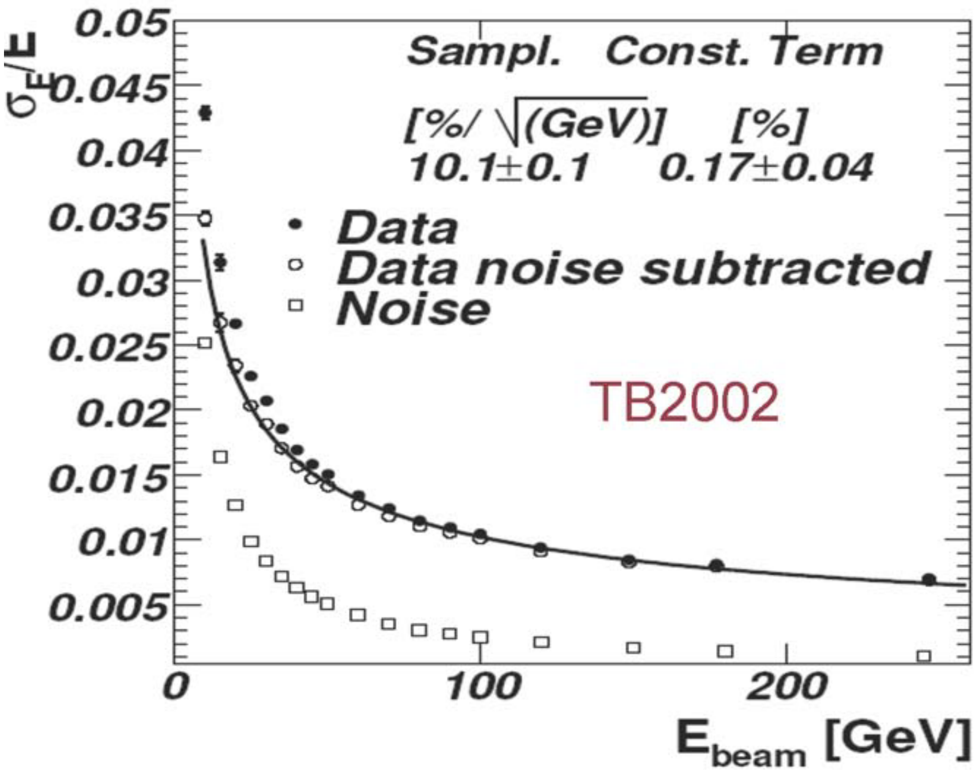
next lecture, only this picture today


CMS
CMS Experiment at the LHC, CERN
Data recorded: 2010-Jul-09 02:25:58.839811 GMT(04:25:58 CEST)
Run / Event: 139779 / 4994190
first proton-proton collisions
(c) CERN 2009. All rights reserved.

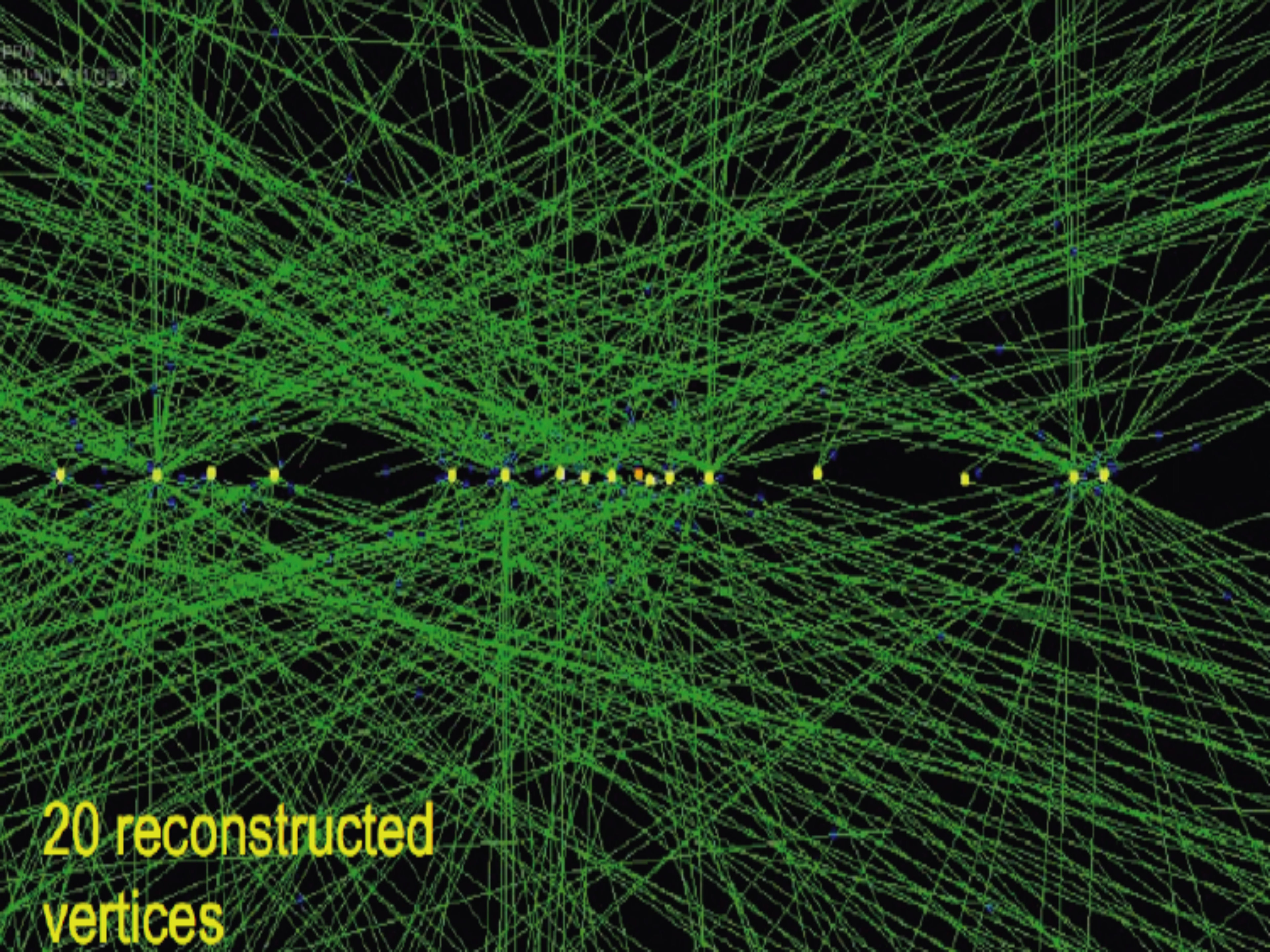
backup

ATLAS vs CMS ECAL





$$\frac{\sigma}{E} = \frac{2.8\%}{\sqrt{E(\mathrm{GeV})}} \oplus \frac{125}{E(\mathrm{MeV})} \oplus 0.3\%$$


20 reconstructed
vertices