Particle interaction and detectors

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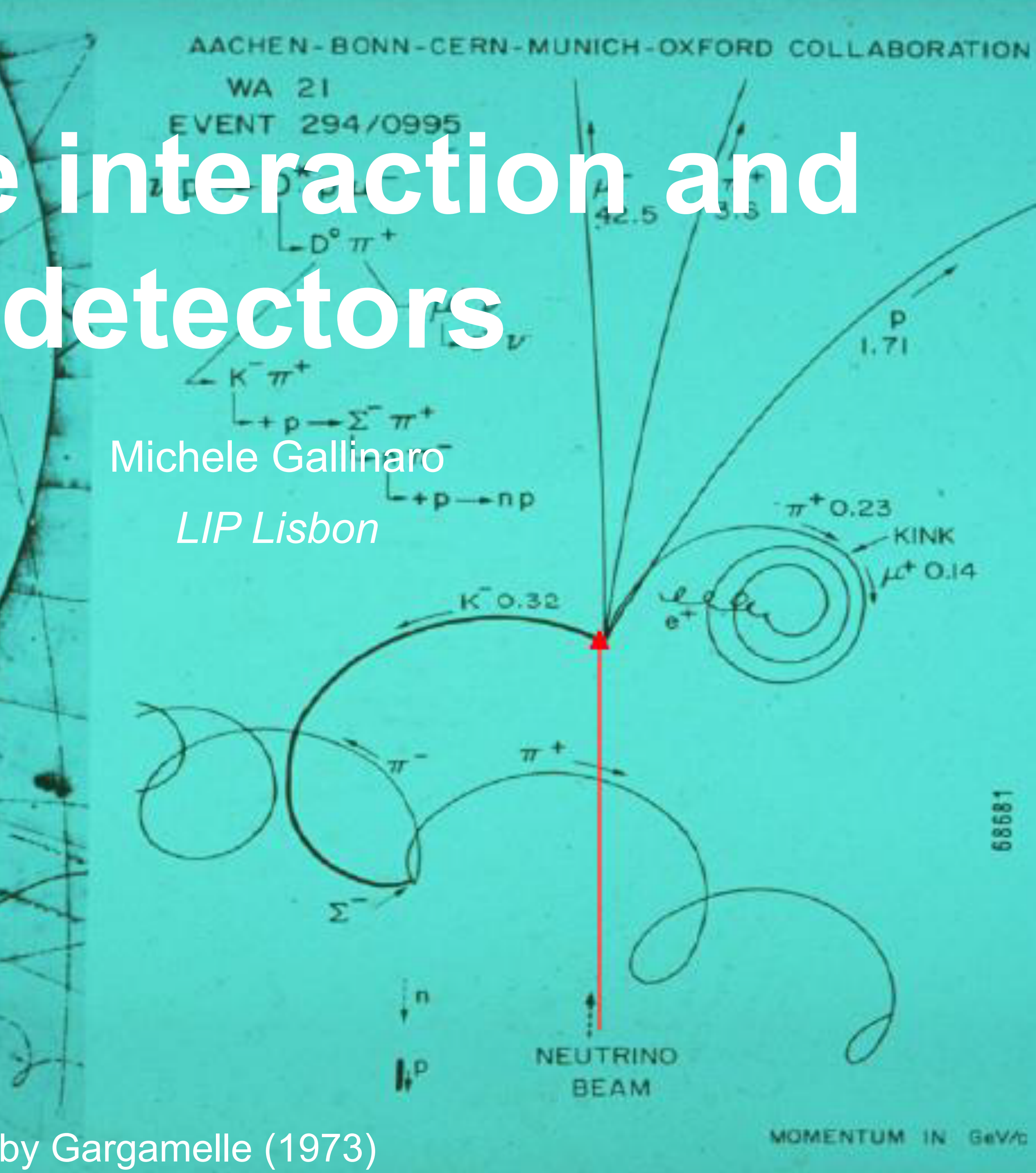
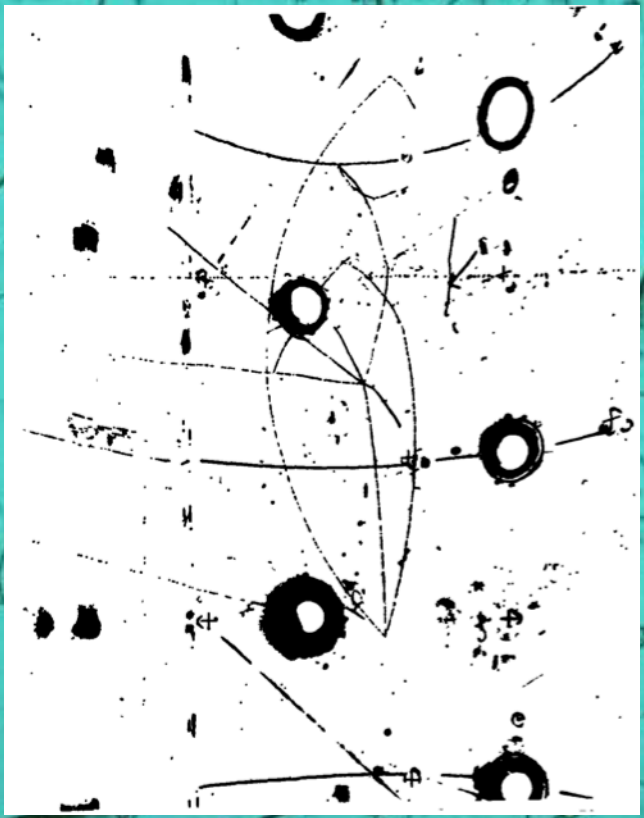




NC $\nu_\mu/\bar{\nu}_\mu + N \rightarrow \nu_\mu/\bar{\nu}_\mu + \text{hadrons},$

discovery of Neutral Currents by Gargamelle (1973)

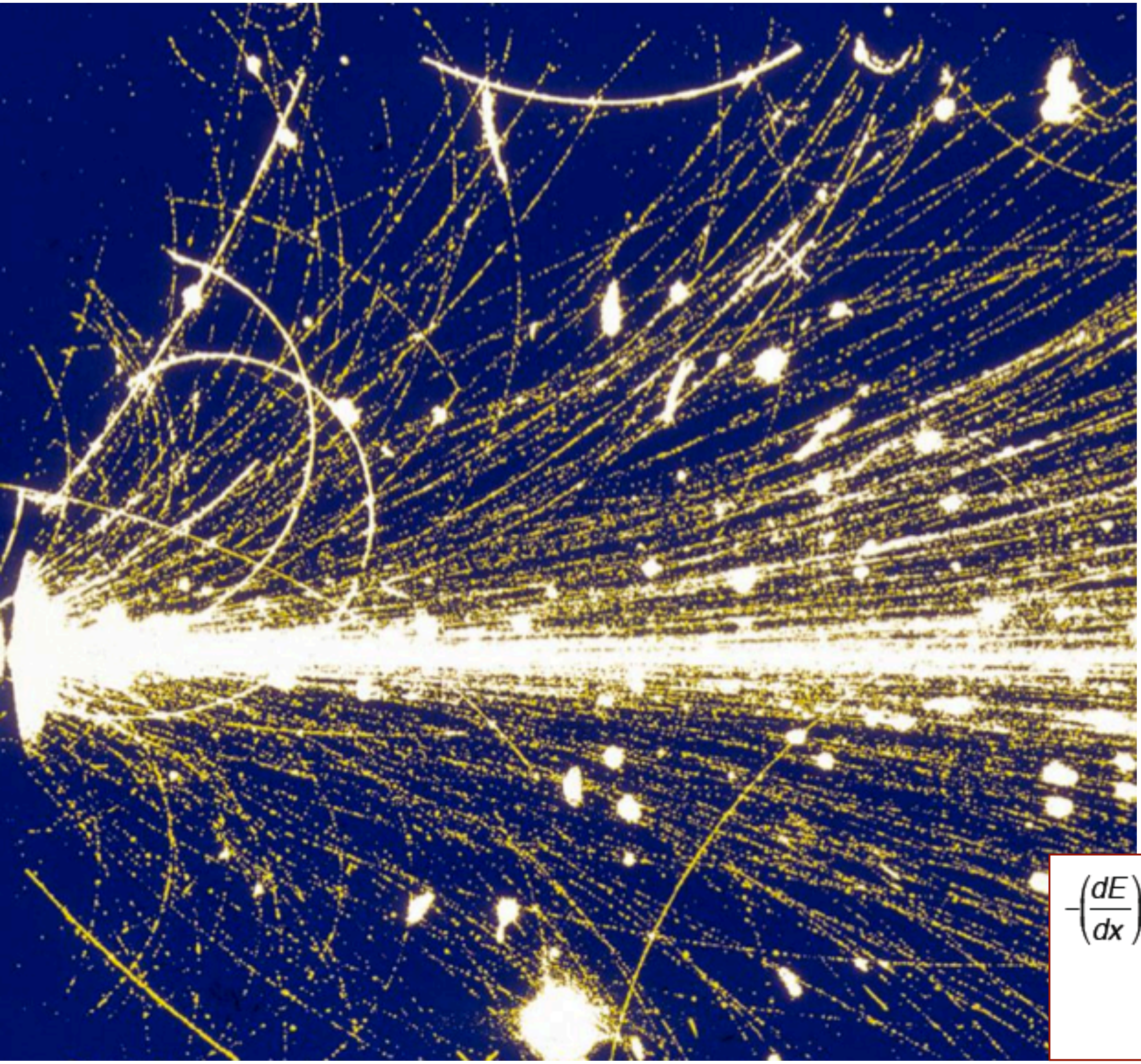
Contents

- 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)

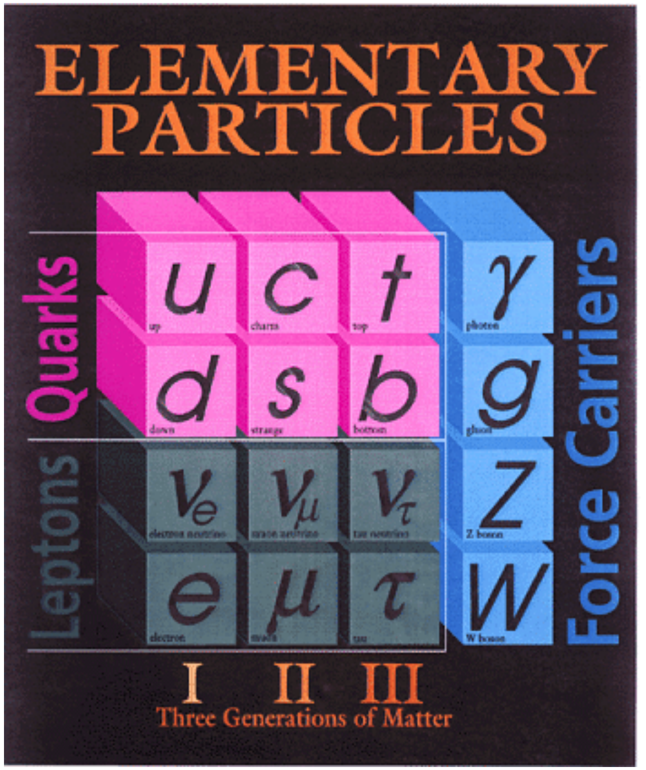
In the end, everything is converted to:

- 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.)

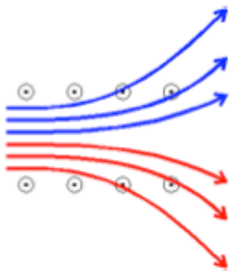
- Short-lived particles decay to long-lived ones
- We can only ‘see’ the end products of the reaction, but not the reaction itself
- In order to reconstruct the production/decay mechanism and the properties of the involved particles, we want the maximum information

Particle properties

Which properties do we want to measure?

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

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



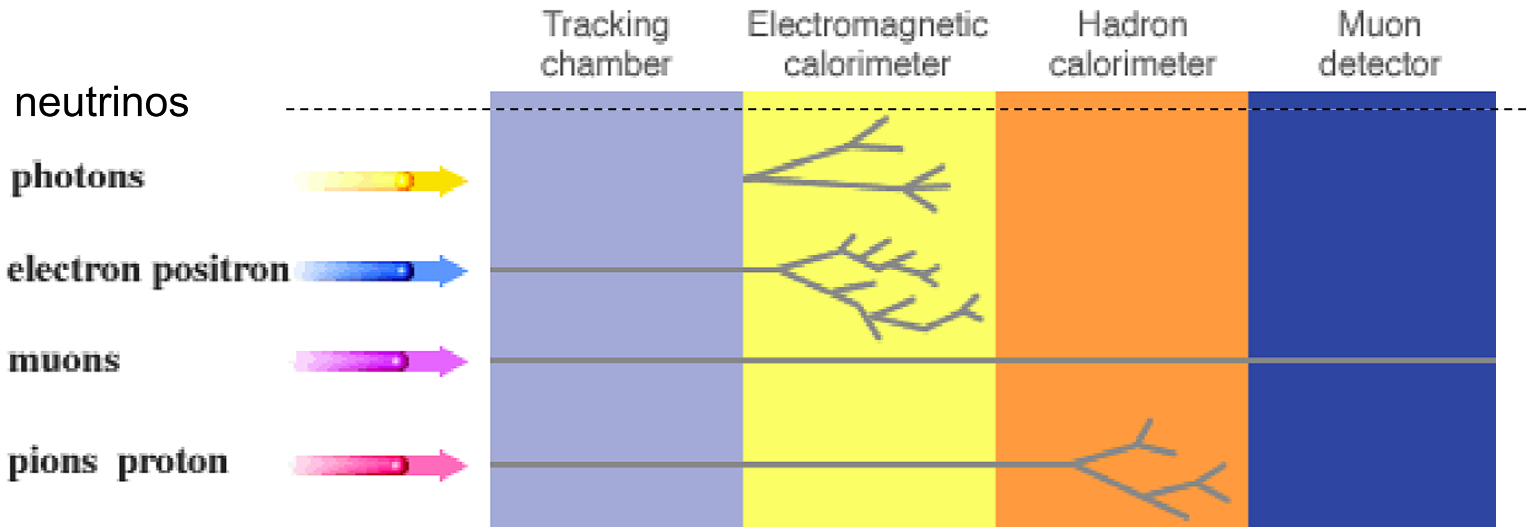
$$F = q \cdot v \cdot B = m \cdot \frac{v^2}{R}$$

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

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

Passage of particles

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



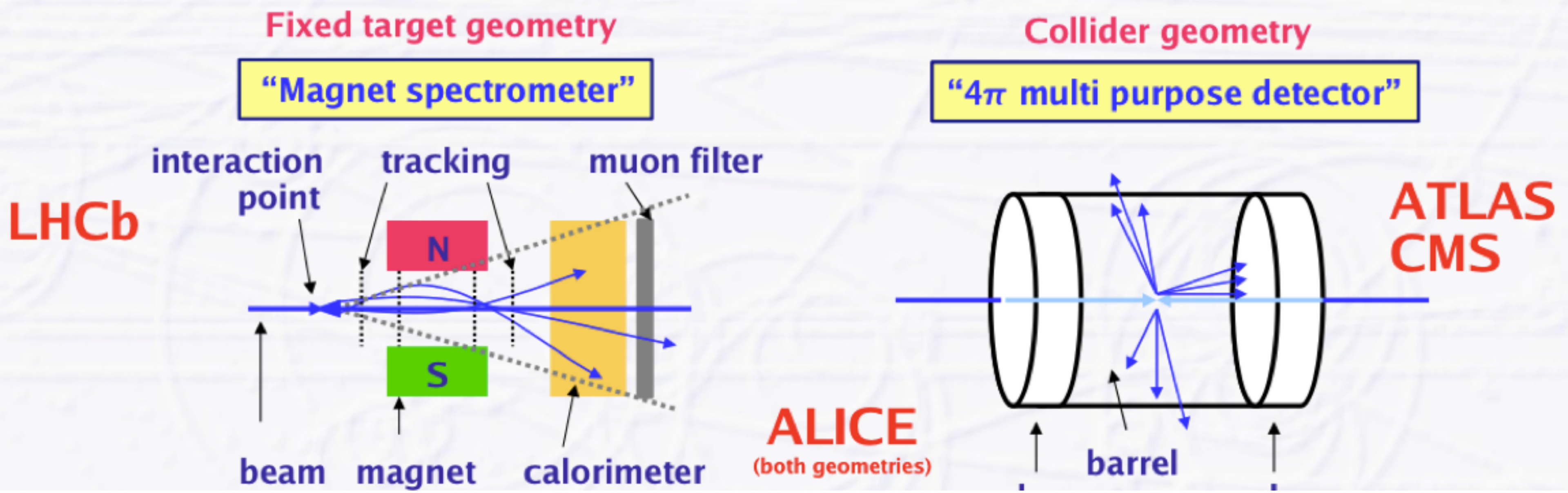
Missing ET
undetected neutrinos...

Energy measurement
total absorption of showers

momentum measurement
(curvature in magnetic field)

Muon detection
measure momentum

Fixed target vs Collider

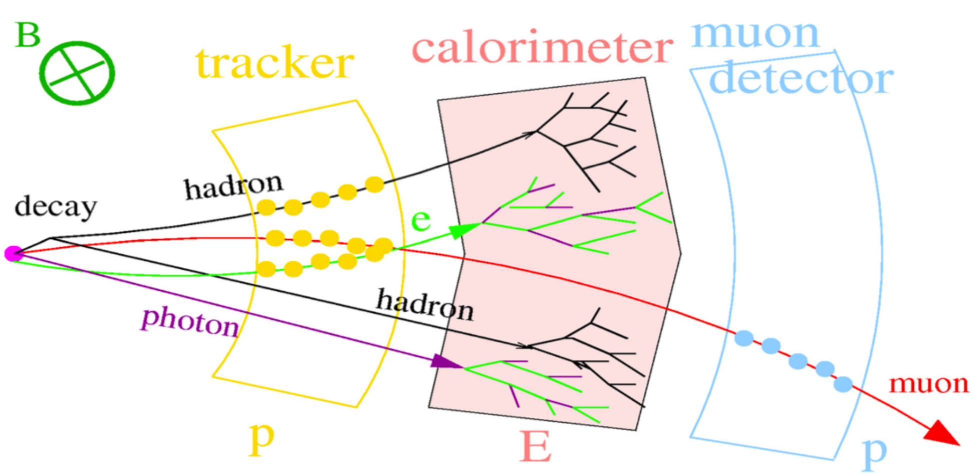


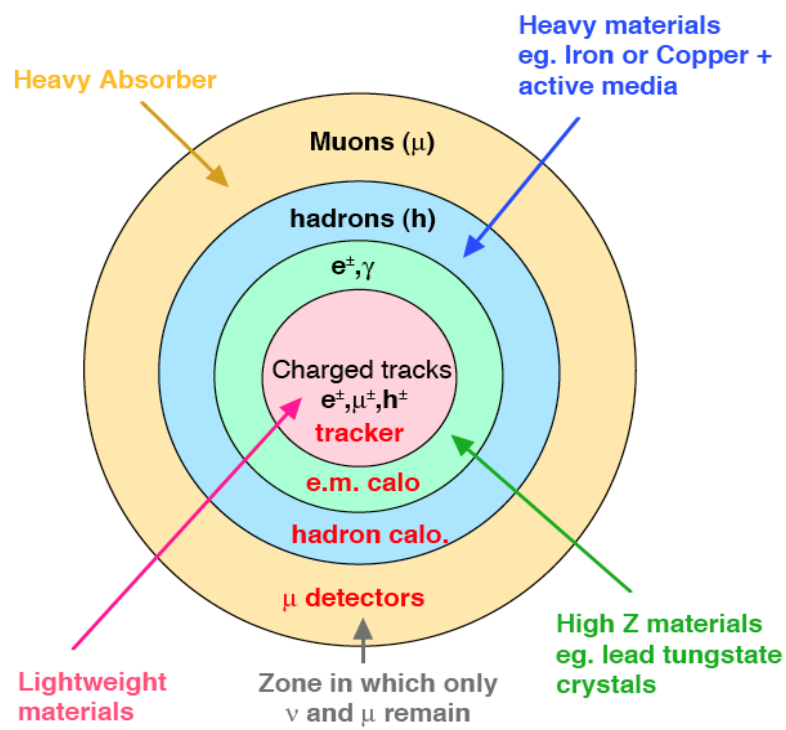
$\sqrt{s}$ = $E_{\mathrm{cm}} = \left[m_1^2 + m_2^2 + 2E_1 m_2\right]^{\frac{1}{2}}$

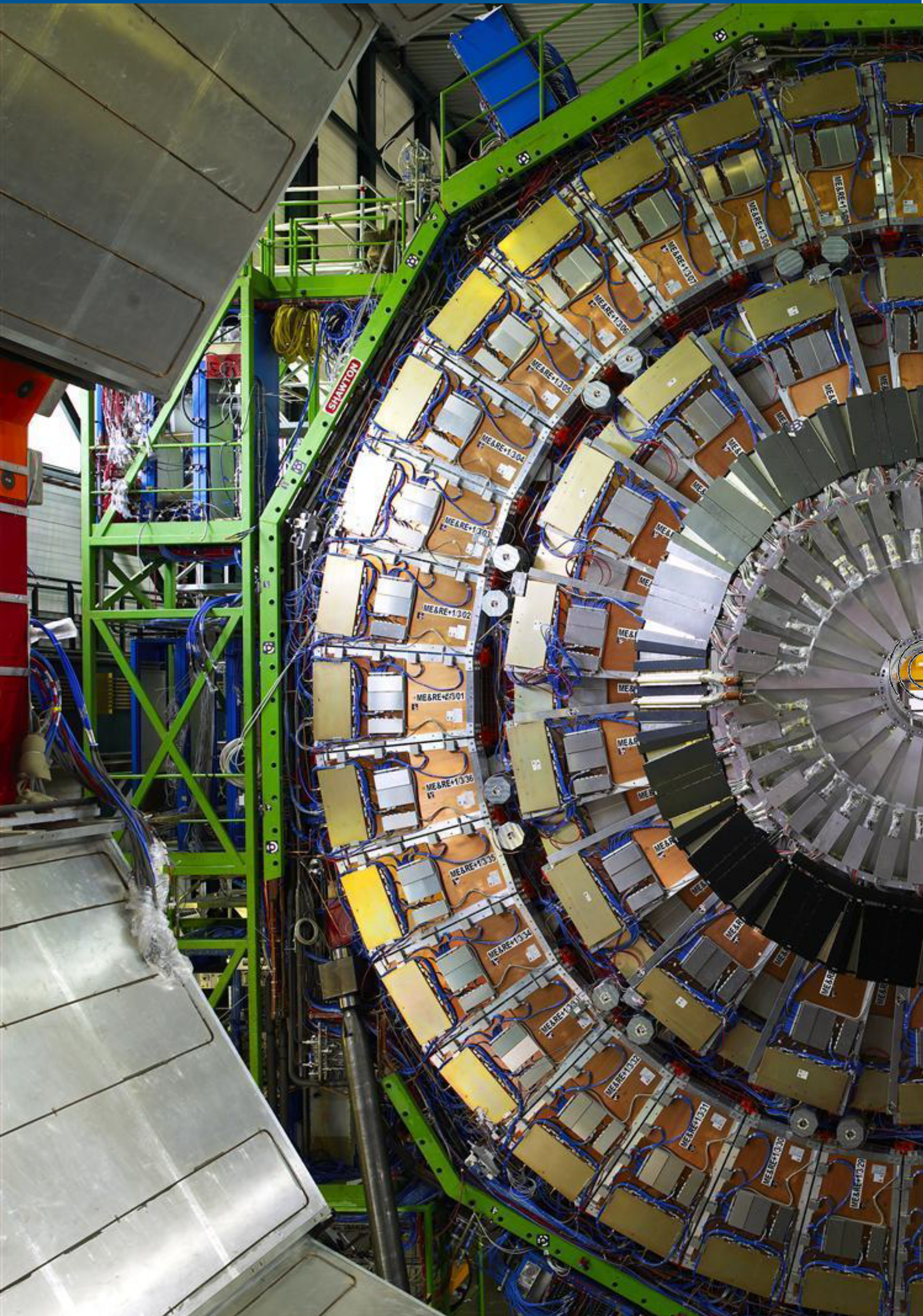
$E_{\mathrm{cm}} = 2E$

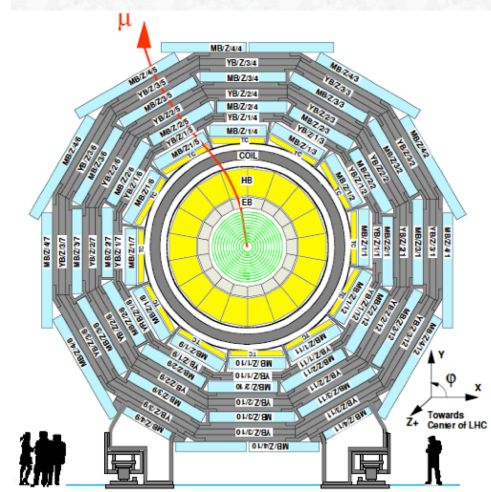
Detector layers

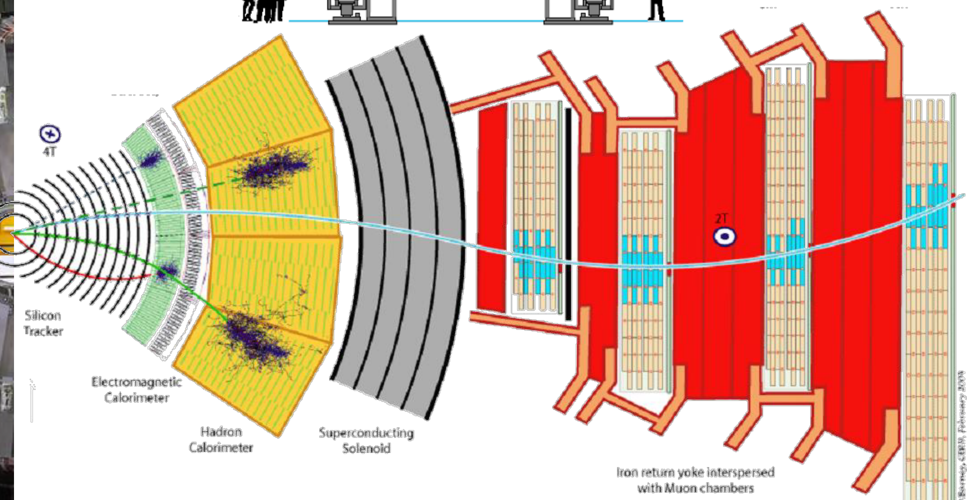
- Inner tracking
  - Measure charged particle (momentum)
- Magnetic field:
  - Measure momentum
- Calorimeters
  - Measure energy of all particles
- Outer tracking
  - Measure muons



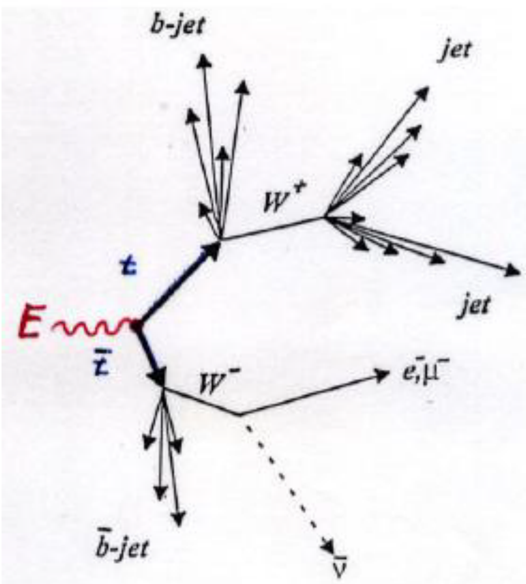


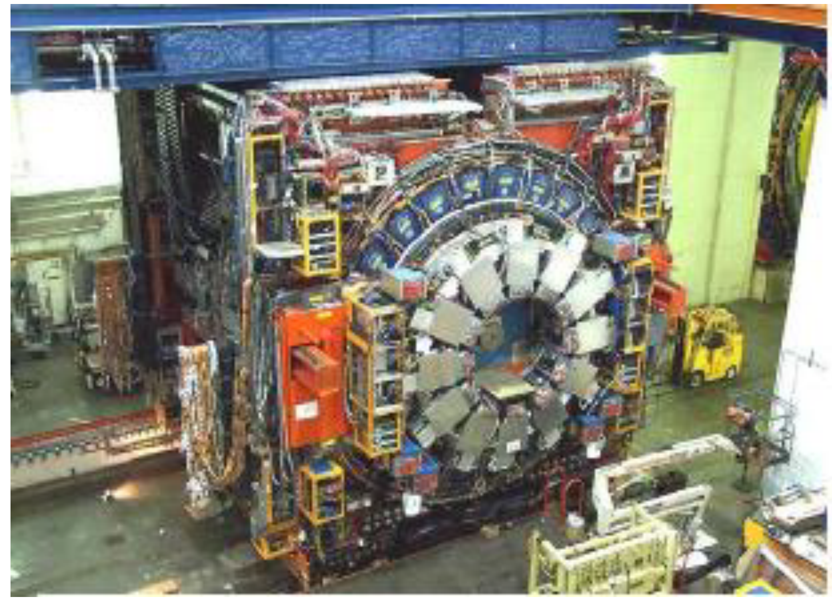


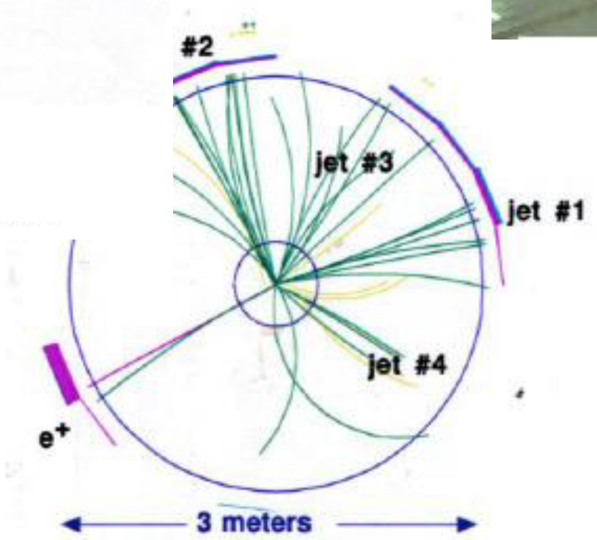

μ
COIL
HB
EB
Y
φ
x
Z+
Towards
Center of LHC


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

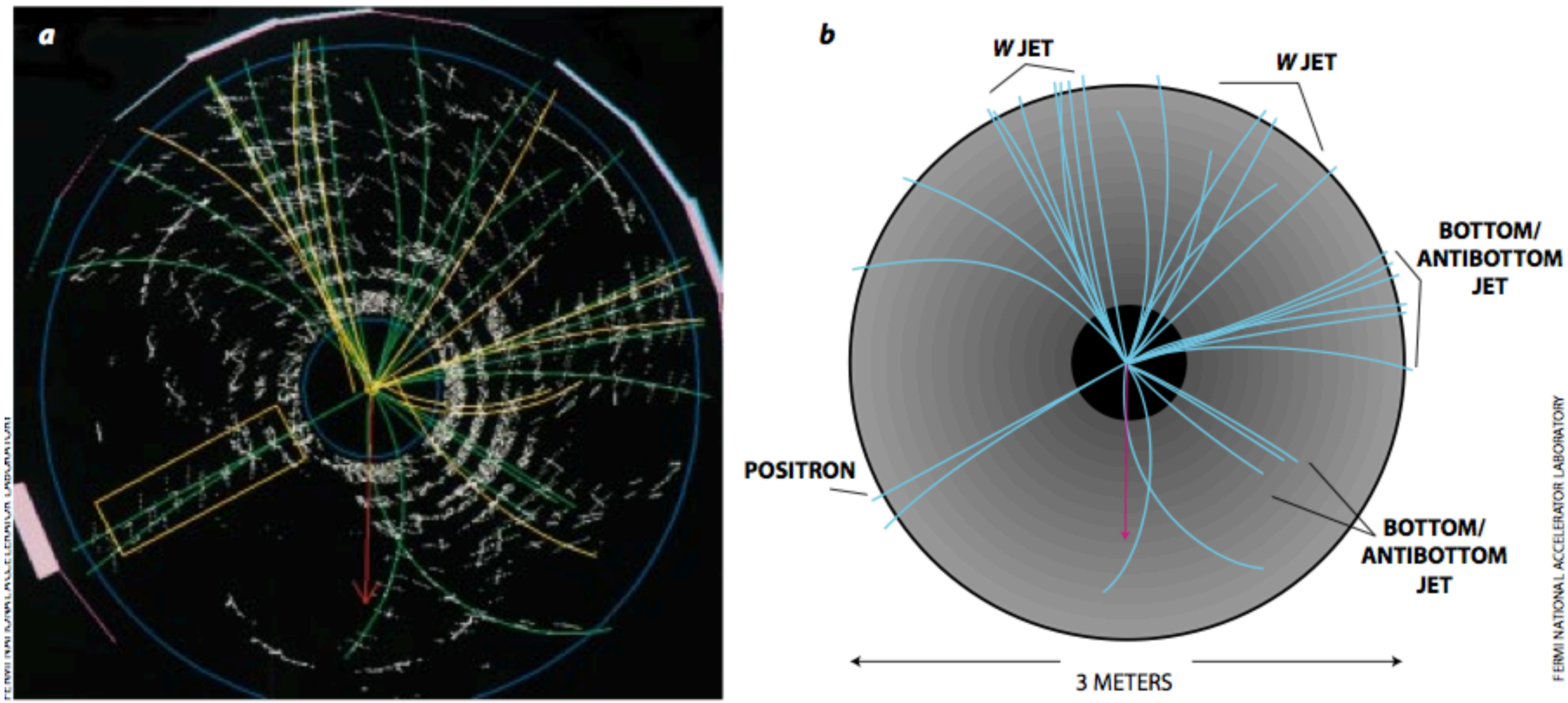
Top quarks: example



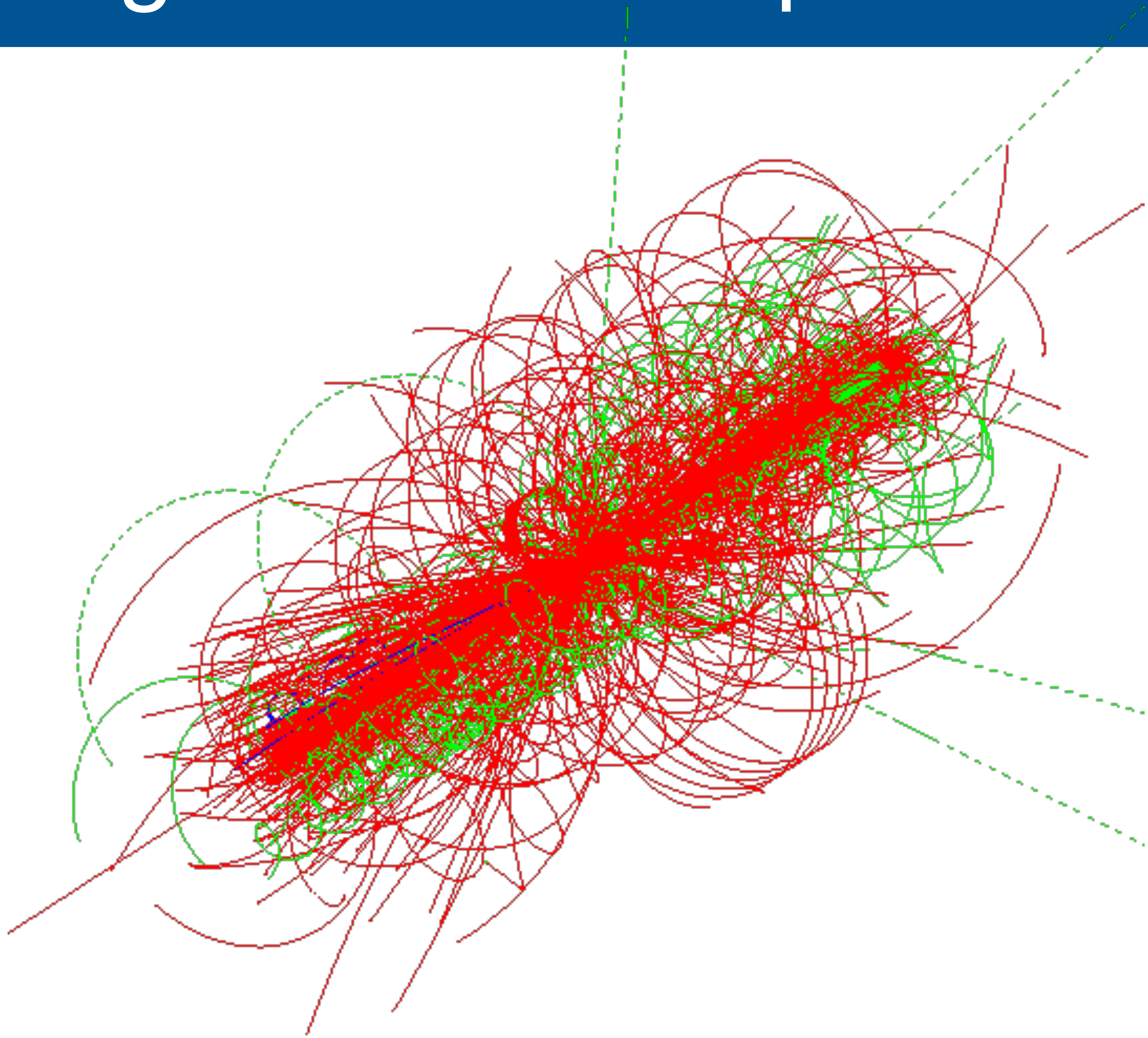




From Picture to Reconstruction



It gets more complicated



Particle detection

- In order to detect a particle
  - It must interact with the material of the detector
  - Transfer energy
- i.e. detection of particles happens through energy loss in the material it traverses

- Particle interaction:

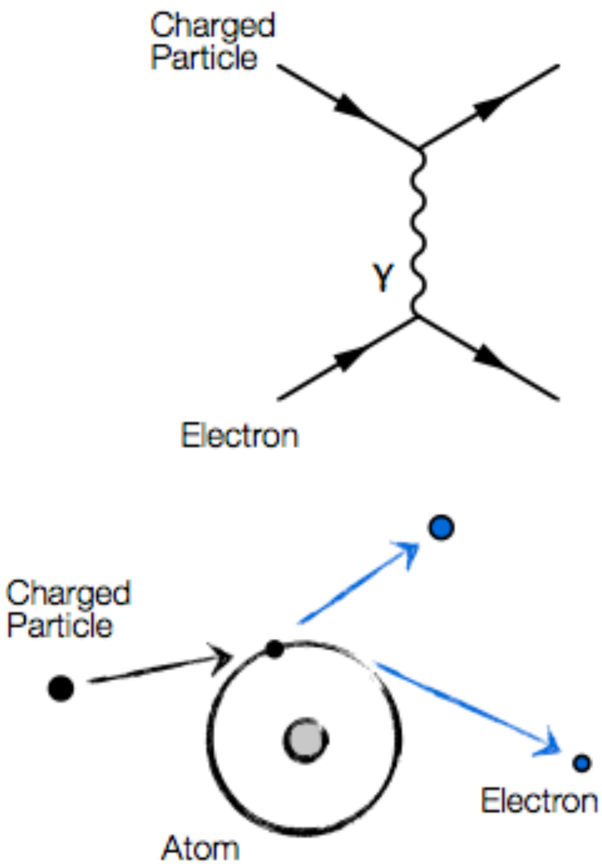
energy loss by multiple reactions

– Charged particles	Ionization, Bremsstrahlung, Cherenkov
– Hadrons	Nuclear interactions
– Photons	Photo/Compton effect, pair production
– Neutrinos	Weak interactions

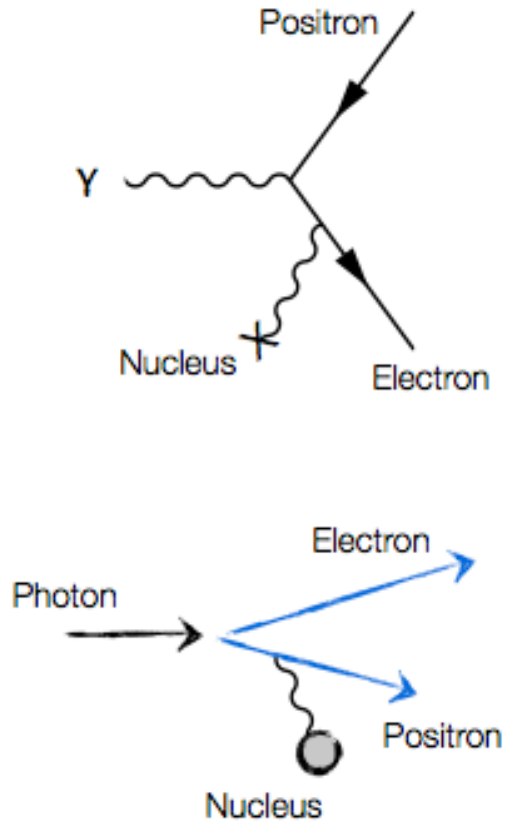
total energy loss via single interaction

Particle interaction

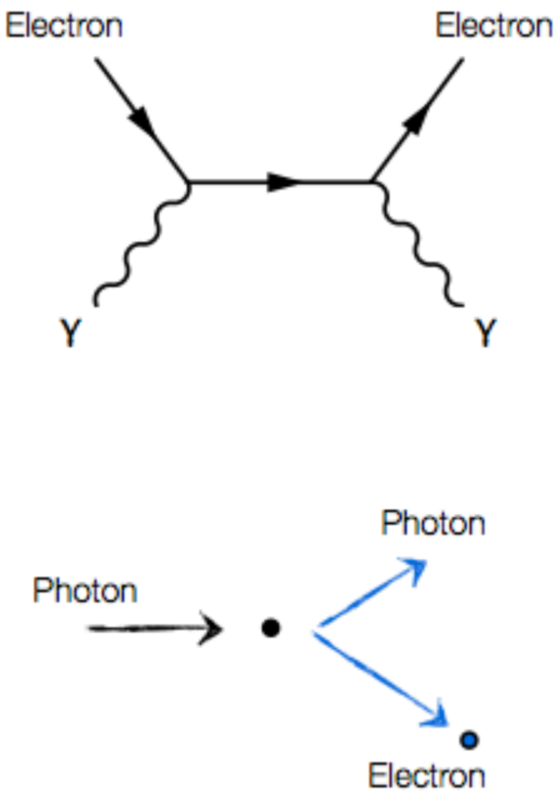
Ionization:



Pair production:

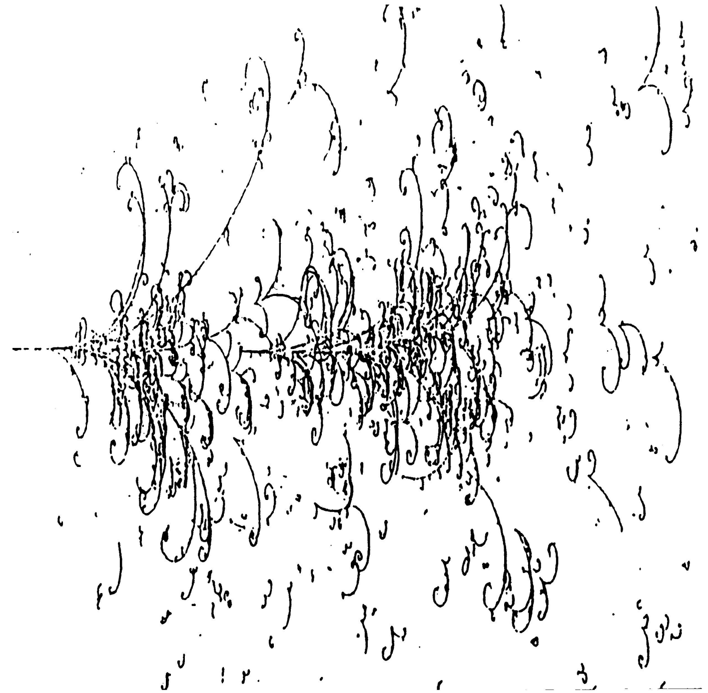


Compton scattering:



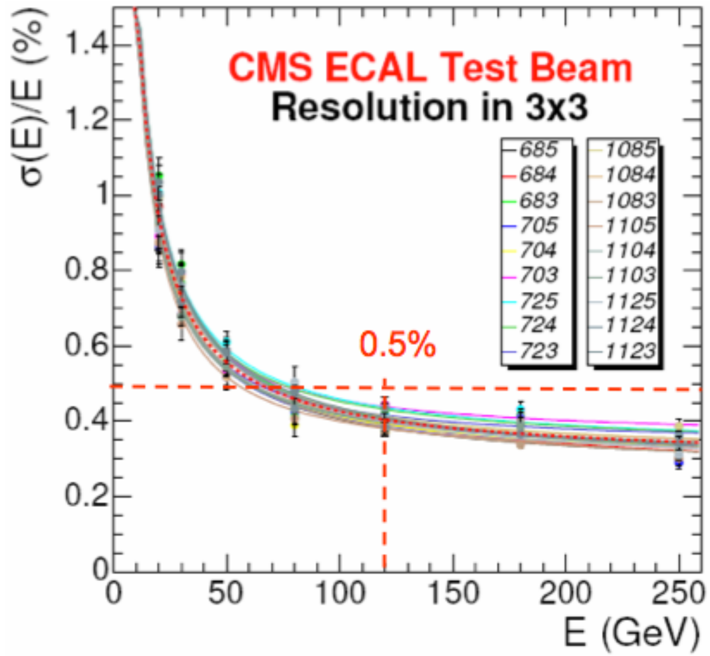
Calorimetry

- Incident particle creates a shower inside the material of detector
  - Shower can be either electromagnetic or hadronic
- Energy is deposited in material through ionization/excitation
- Measure energy deposited in material
  - Electrons, photons and hadrons (including neutral hadrons)
- Deposited energy is proportional to incident energy



Calorimetry (cont.)

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

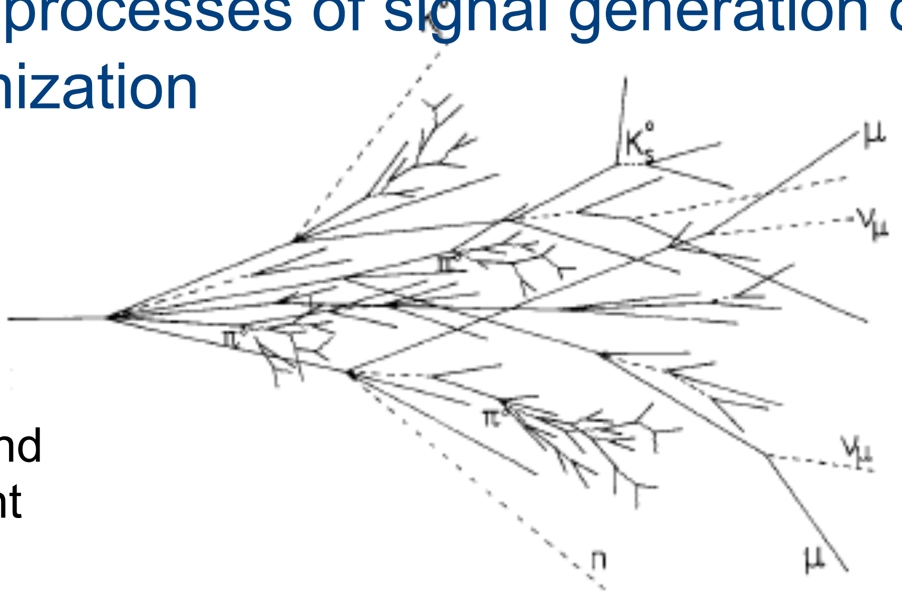


Purpose/principle of a calorimeter

- 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

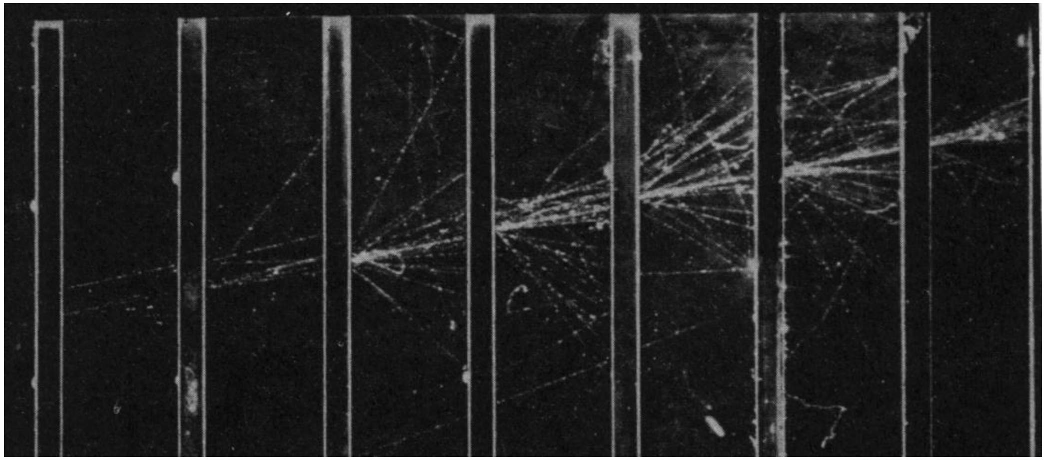
EM and hadron calorimeters

- Calorimeters are subdivided into electromagnetic and hadronic sub-detectors
  - EM: electrons and photons
  - Had: hadrons
- 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

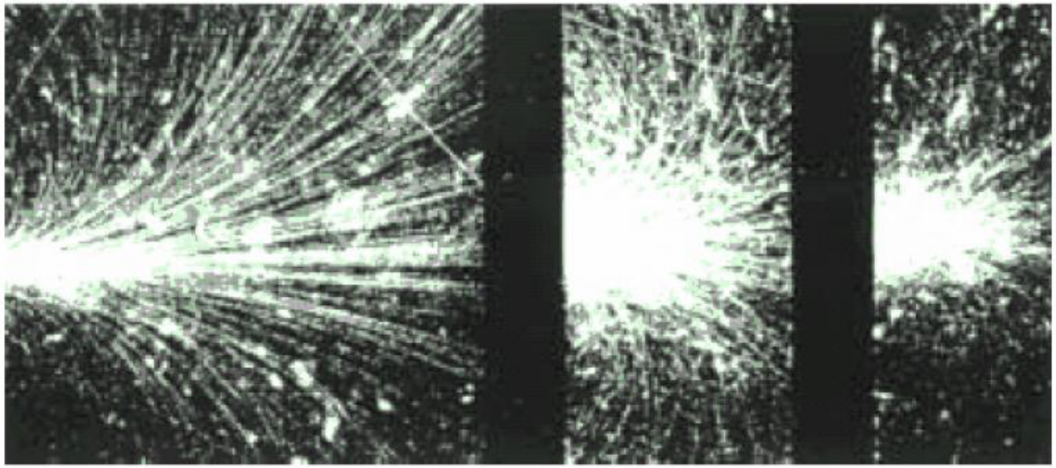
Calorimeter and shower



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.)

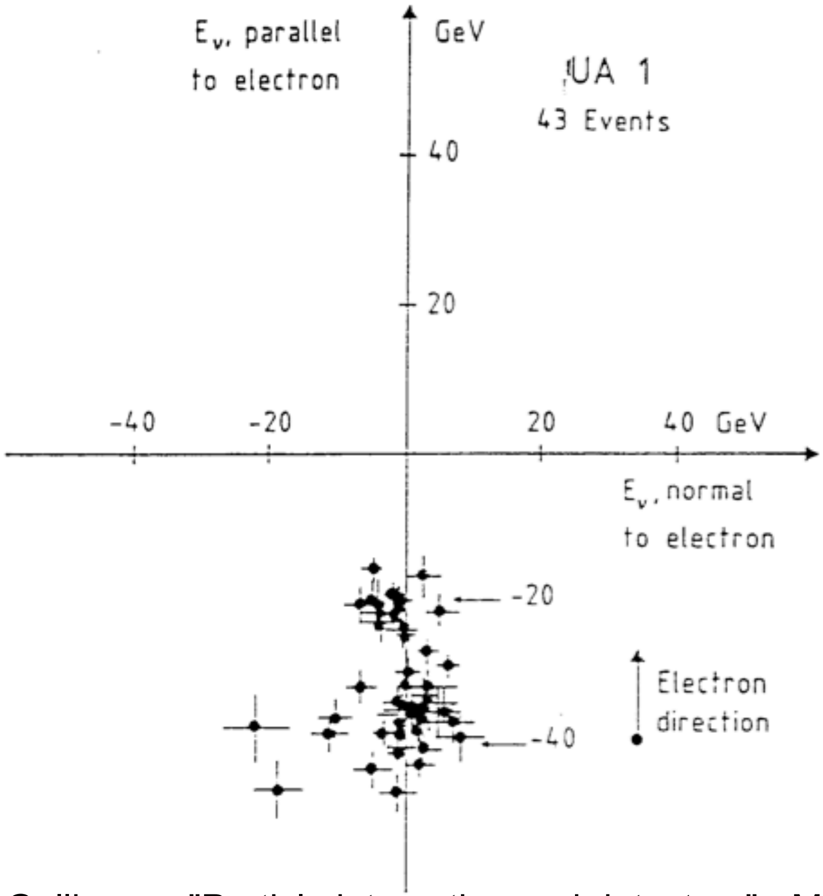
Evolution of calorimeters (cont.)

Today, widespread in particle physics

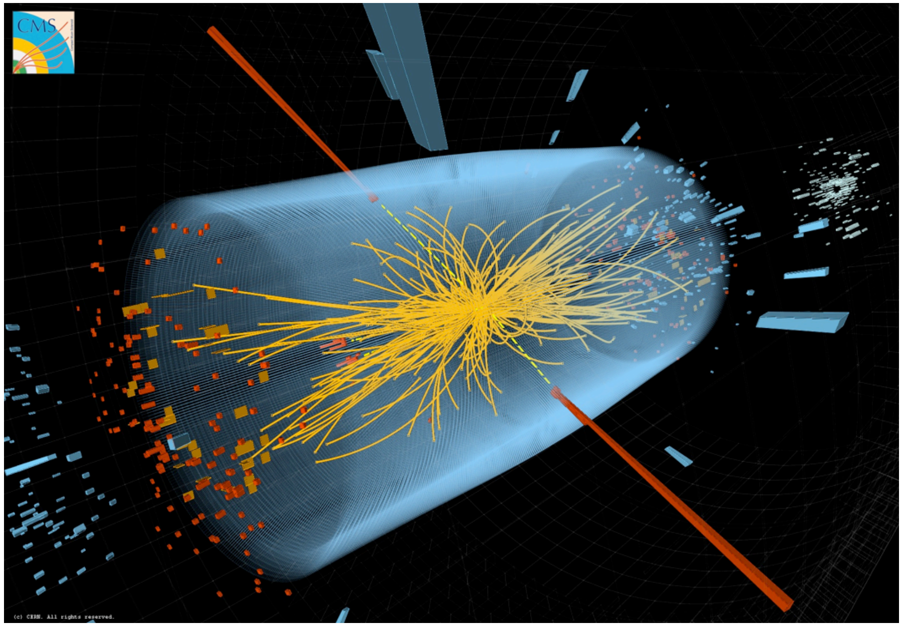
- 4π coverage at colliders
  - Energy measurements
  - Particle identification
  - Triggers
- Neutrinos detectors at accelerators
- Underground detectors
- Space-based detectors (GLAST, AMS)
- …

Discovery of the W

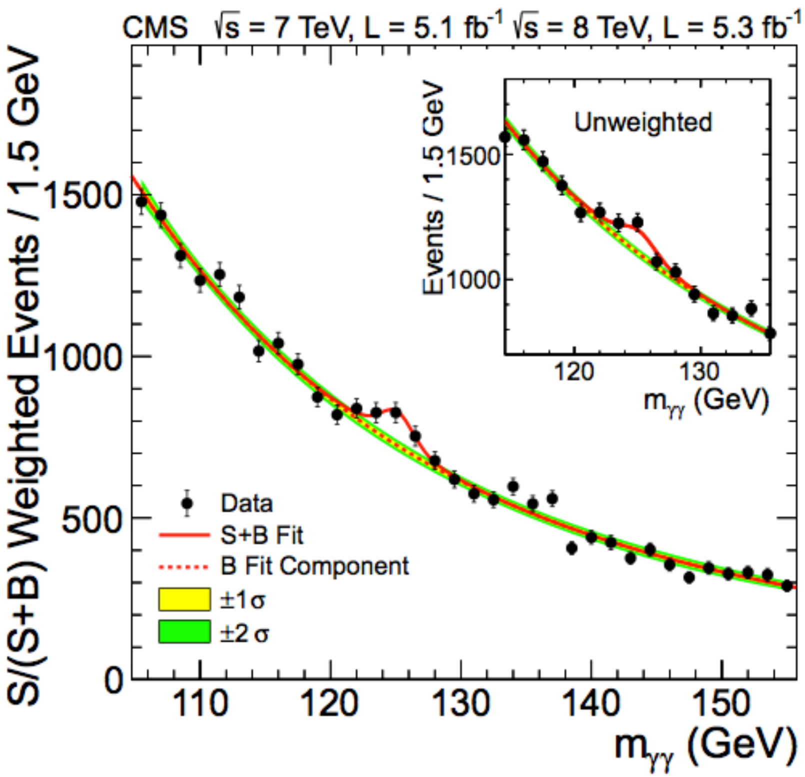
- Calorimeters are important in the discoveries
- High transverse energy electron measured, and recoiling neutrino deduced (to balance the electron)



Discovery of the Higgs



- di-photon invariant mass

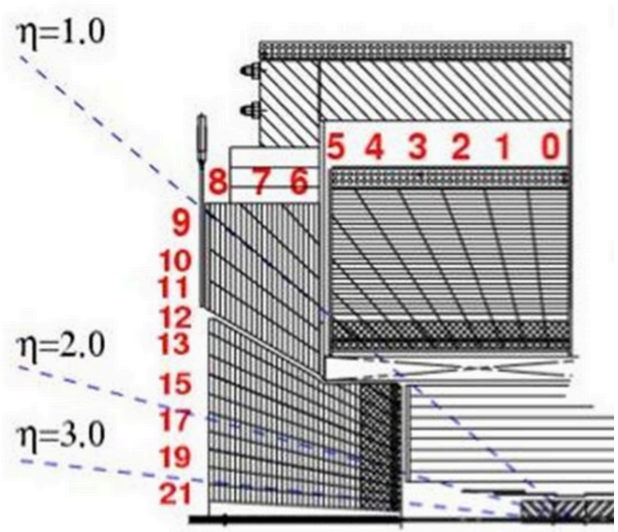


Ideal calorimeter

- 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 (radiation, etc)

Calorimeter detectors

- Favor shower development
- Collect deposited energy
- Alternate passive and active material
  – Lead (iron) interspersed with scintillator
- Sampling (vs. homogeneous)
  – Scintillator (sensitive material) emits light with passage of ionizing particle
  – Collect light deposited in sensitive material
  – WLS, PMTs convert light into electric signal
- “Projective” tower geometry
  – Each tower has EM followed by Had calorimeter
- (almost) “full” coverage
  – central, forward, etc



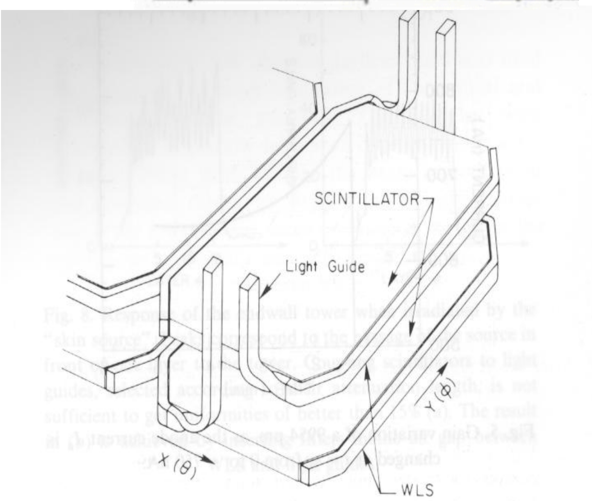
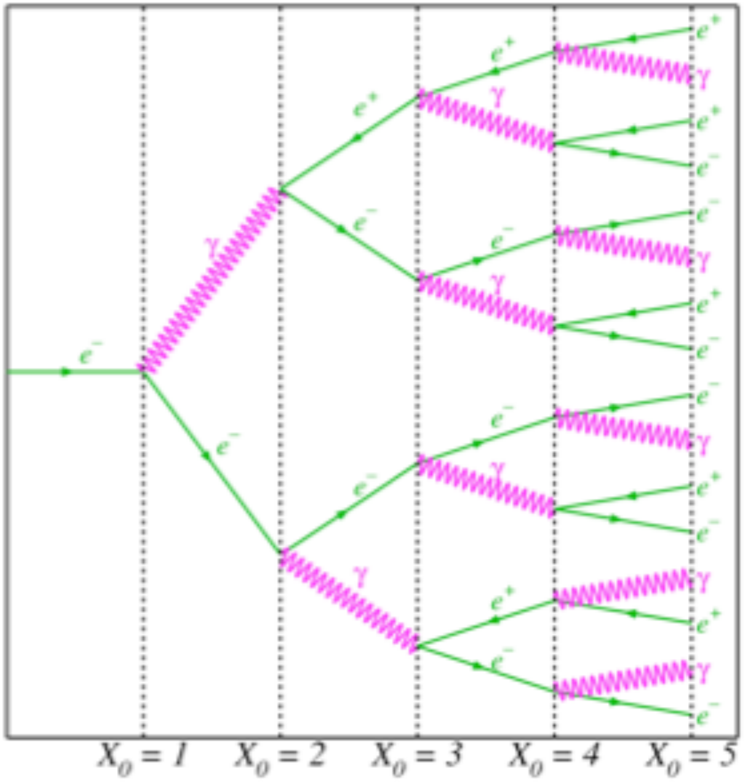


Fig. 4. Two WLS strips collect light from each scintillator layer. In the air gap between WLS and light guide, filters are inserted to ensure light output equalization for different layers of the same tower.

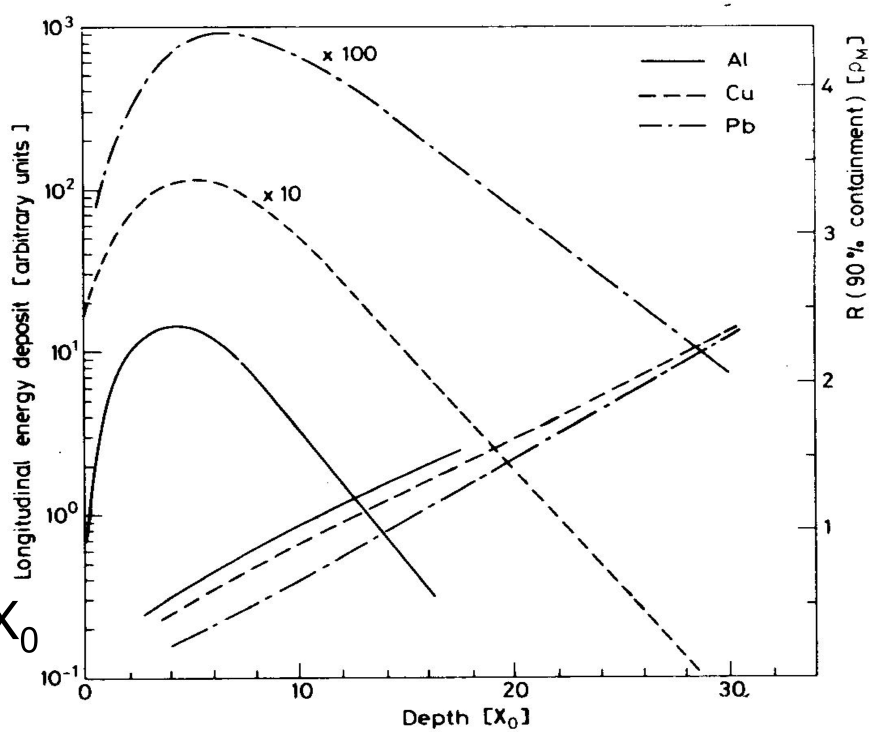
EM and HADronic showers

- Electromagnetic
  - Multiplication through pair production and bremsstrahlung
  - Mean free path X_0 (radiation length)
  - No invisible energy
- Hadronic
  - Multiplication through multi-particle production in nuclear interactions
  - Mean free path ~λ (interaction length)
  - Nuclear binding energy, and neutrinos invisible

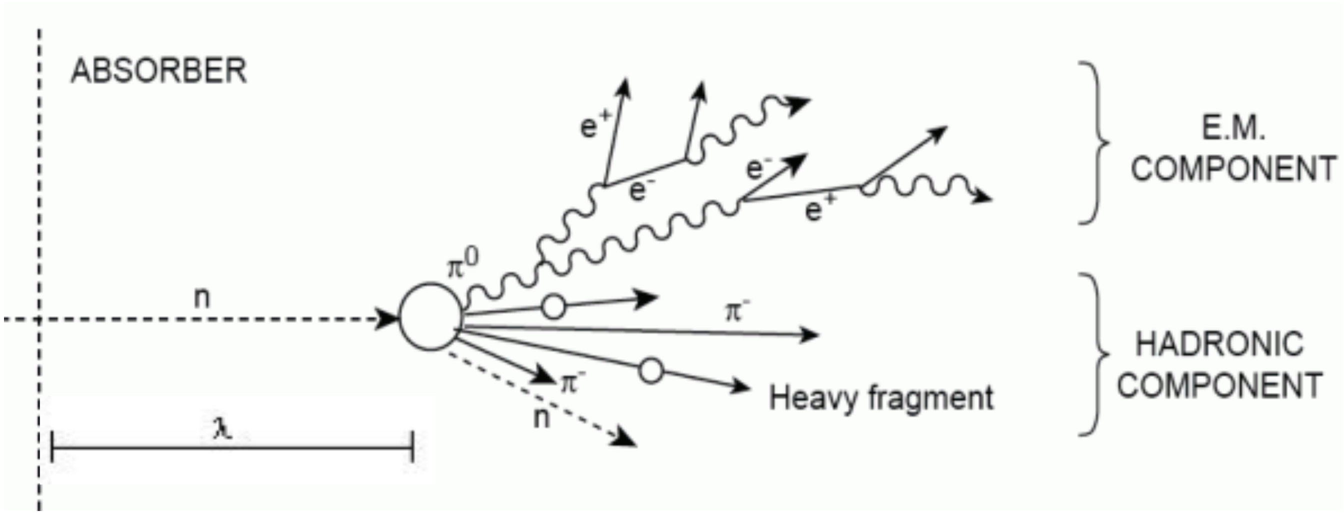


EM showers

- Created by incident electron or photon
  - Electrons emit bremsstrahlung
  - Photons undergo pair production
- Length of shower expressed in terms of X_0 (radiation length)
  - X_0 depends on material
  - 95% containment requires typically 20 X_0



Hadronic shower

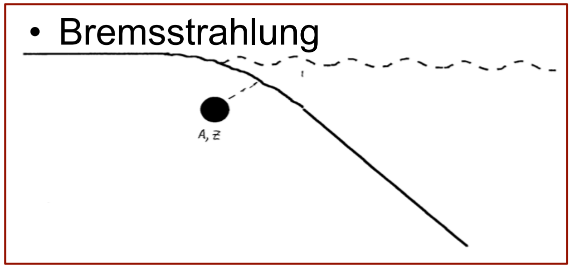


- Created by incident charged pion, kaon, proton, etc.
- Typical composition
  - 50% EM (e.g. $\pi^0 \rightarrow \gamma\gamma$)
  - 25% visible non EM-energy
  - 25% invisible energy (nuclear breakups)
- Requires longer containment (expressed in λ, interaction length)

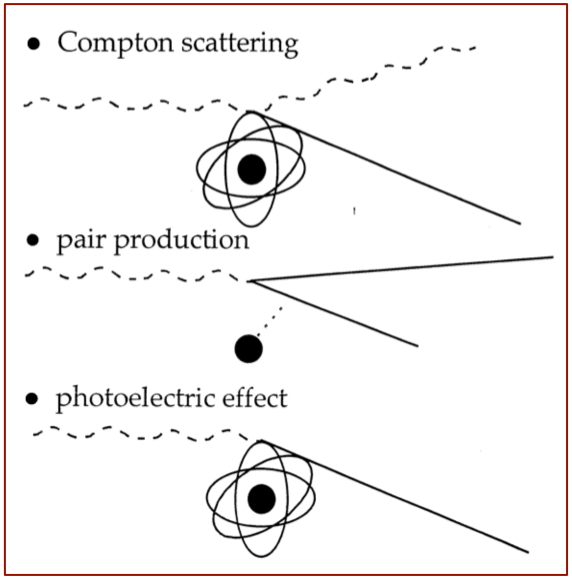
Electromagnetic showers

- 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)

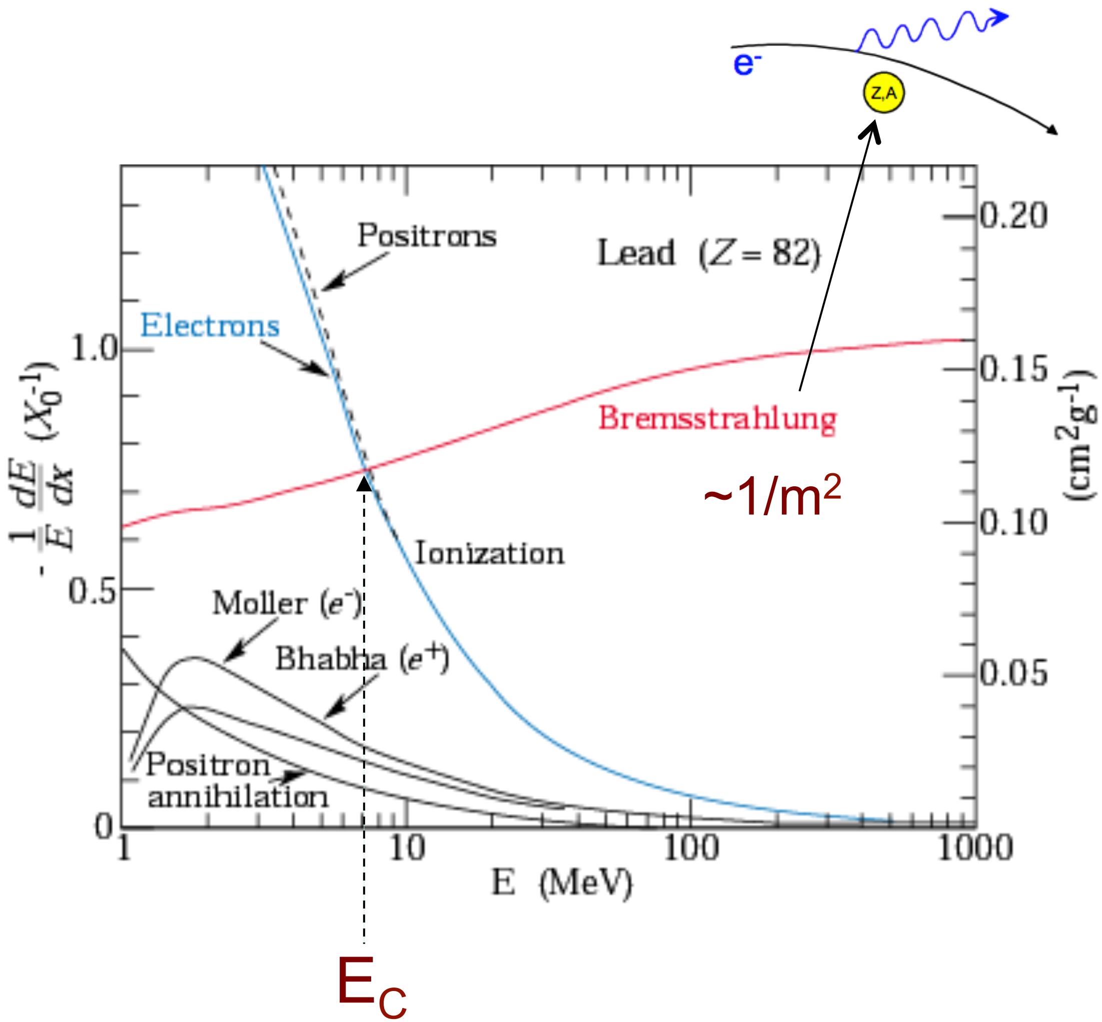


- Photons
  - Compton scattering (atomic electrons)
  - Pair production (nuclear)
  - Photoelectric effect (atomic electrons)

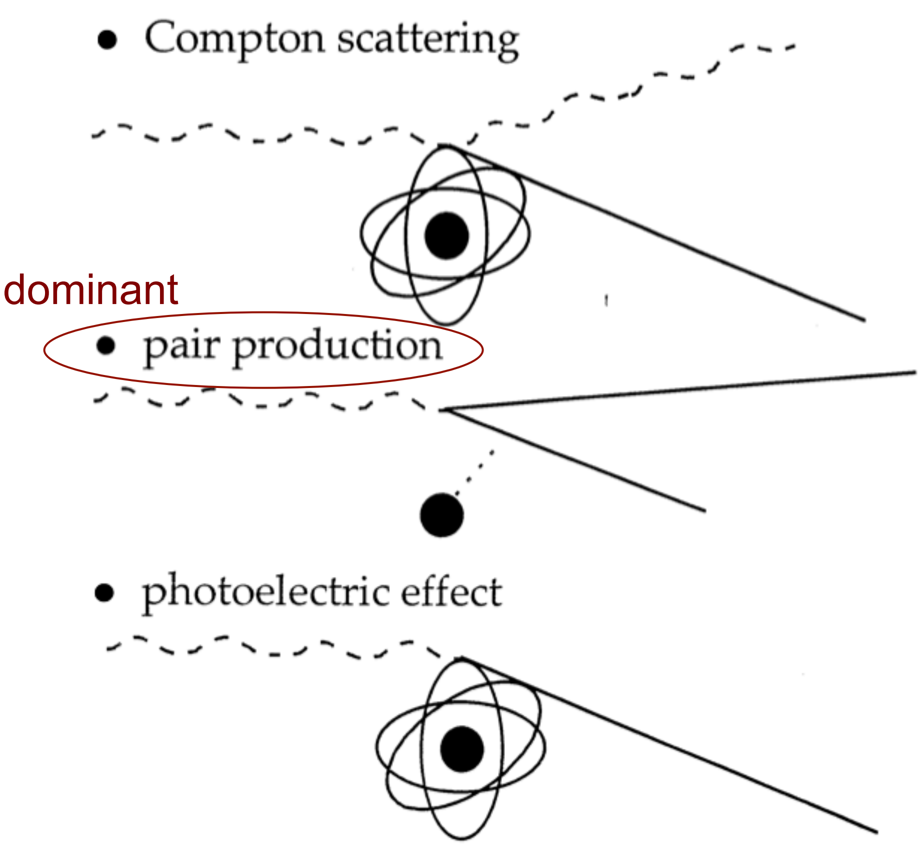


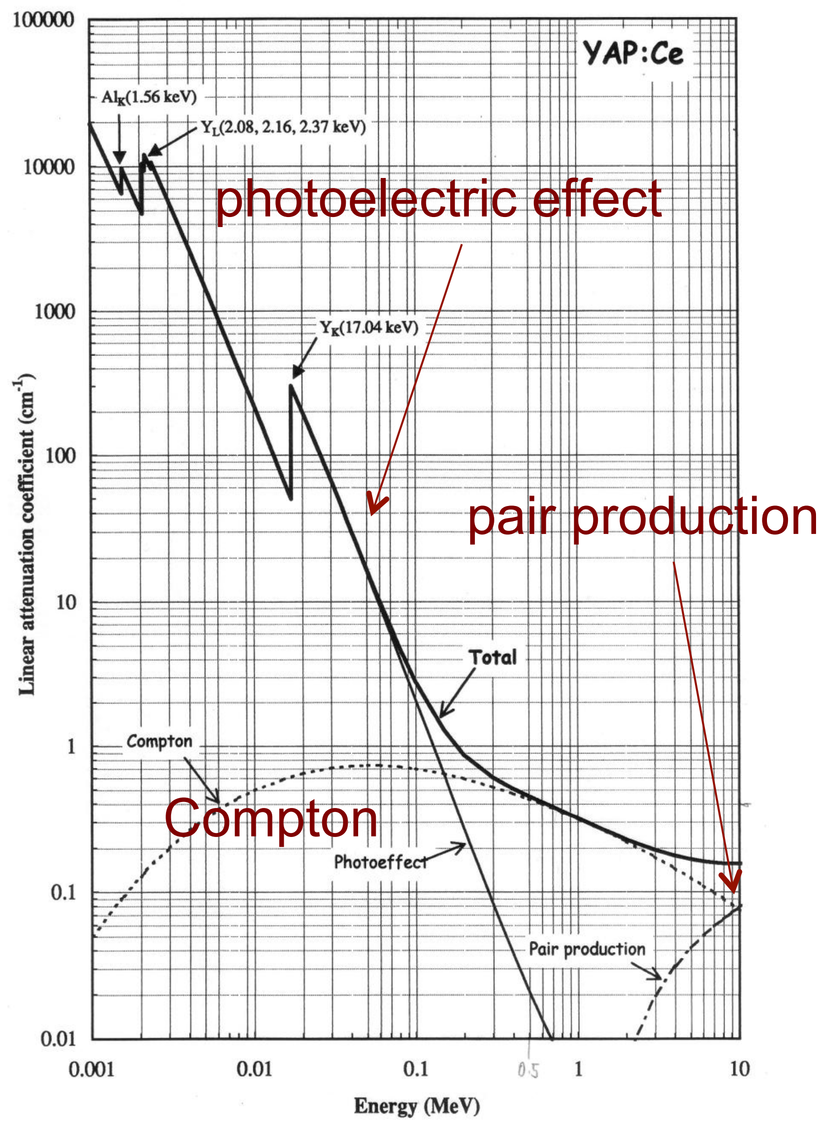
EM showers: electrons

- 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



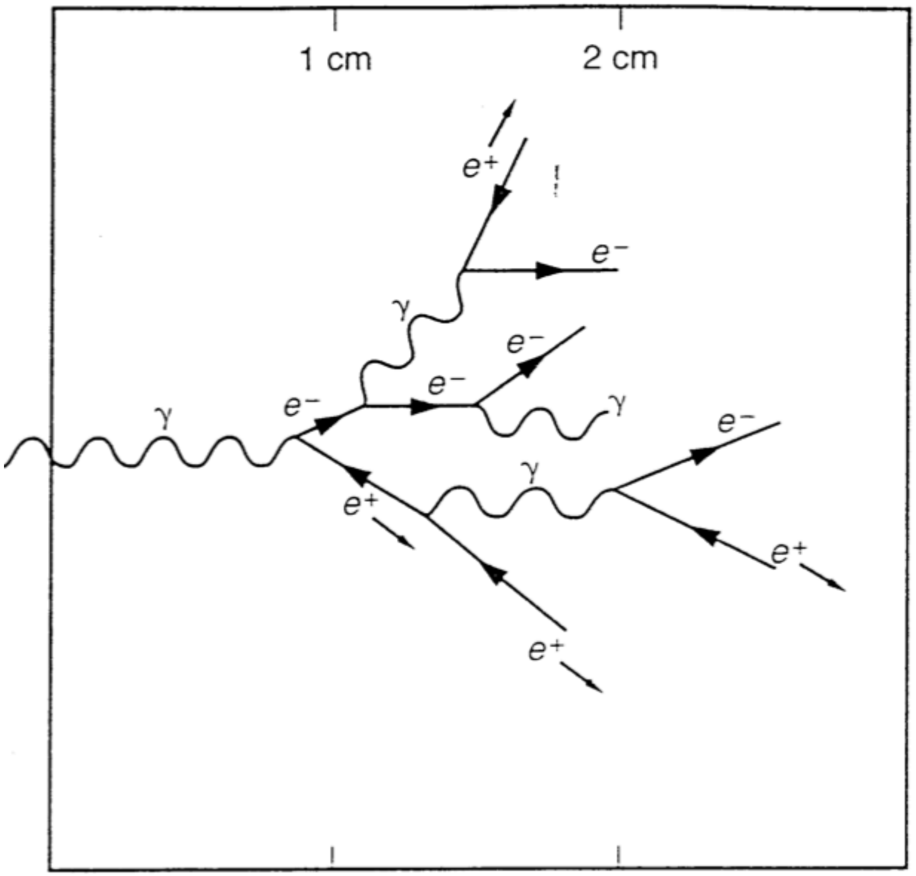
EM showers: photons





EM shower: model

- EM shower can be understood by a simple model
  - after one radiation length X_0 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

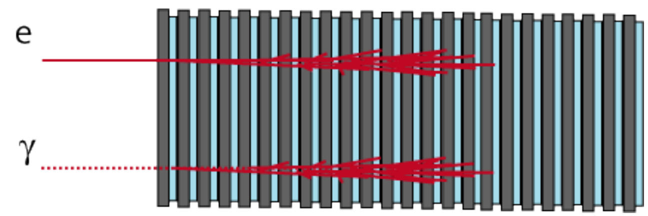
- Longitudinal development depends on material thickness:
  $X_0=180\ A/Z^2\ g/cm^2$ (higher Z materials have shorter radiation lengths)

Z is the atomic number

- Transverse dimension scales with the Moliere radius:
  $R_M=21\ MeV\ X_0/E_C$ where $E_C=580\ MeV/Z$

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: segmentation gives detailed shower shape information; good spatial resolution

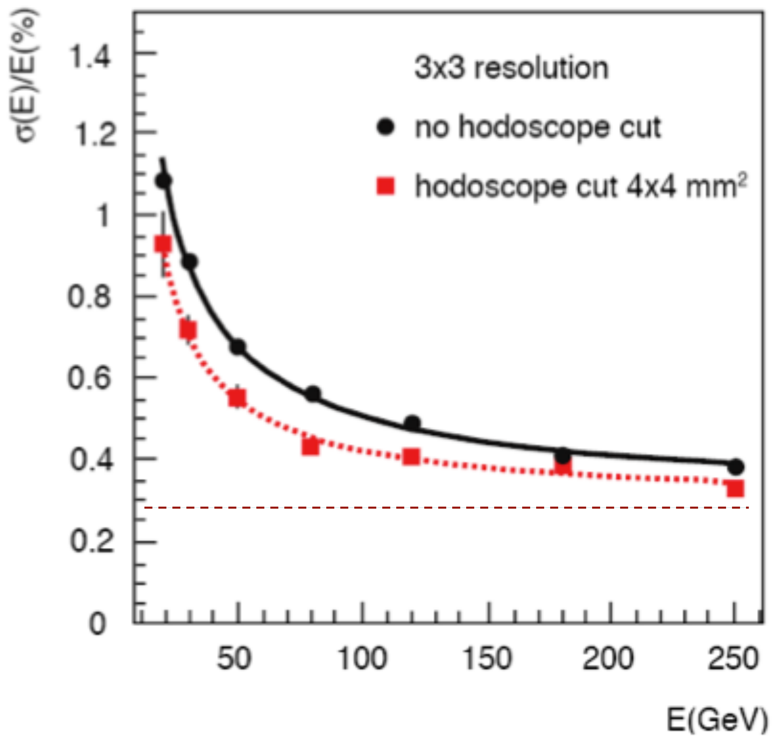
EM showers: Fluctuations

- 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

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

- 1st: Stochastic (or "sampling") term
  - Accounts for statistical fluctuations of the number of primaries
- 2nd: Noise term:
  - Electronic noise, pedestal fluctuations, etc.
  - Pileup (other energy entering the measurement region)
- 3rd: Constant term
  - Non-uniformities, calibration uncertainties
  - Incomplete shower containment (leakage), other fluctuations proportional to energy



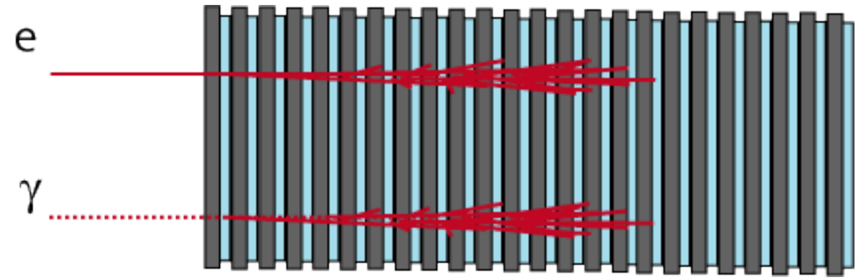
$$\frac{\sigma_E}{E} = \frac{2.8\%}{\sqrt{E(\mathrm{GeV})}} \oplus \frac{12\%}{E(\mathrm{GeV})} \oplus 0.3\%$$

Constant term dominated by longitudinal non uniformity of light collection

EM calorimeter types

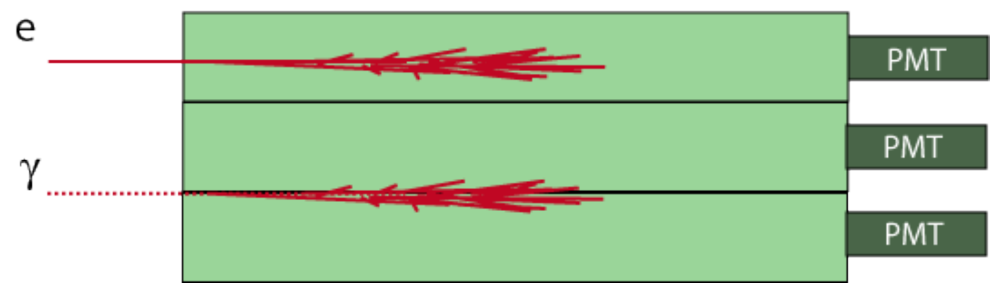
- "Lead-scintillator" calorimeter

Energy resolutions:



$\Delta E/E \sim 20\%/\sqrt{E}$

- Exotic crystals (BGO, PbW, ..)



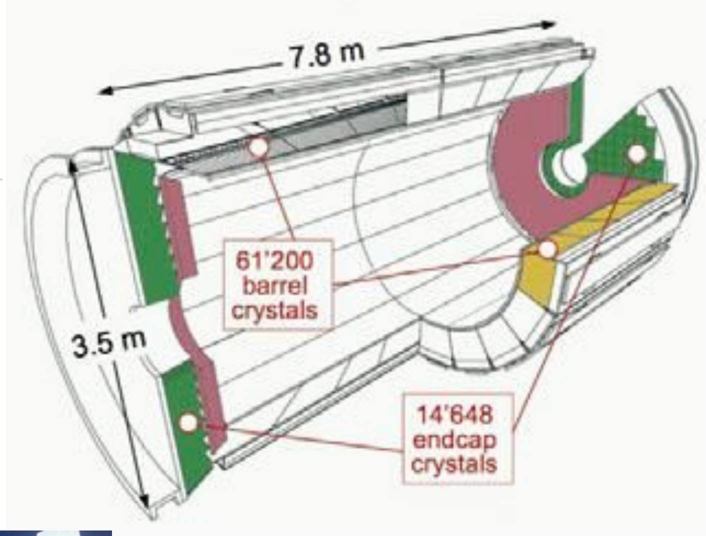
$\Delta E/E \sim 1\%/\sqrt{E}$

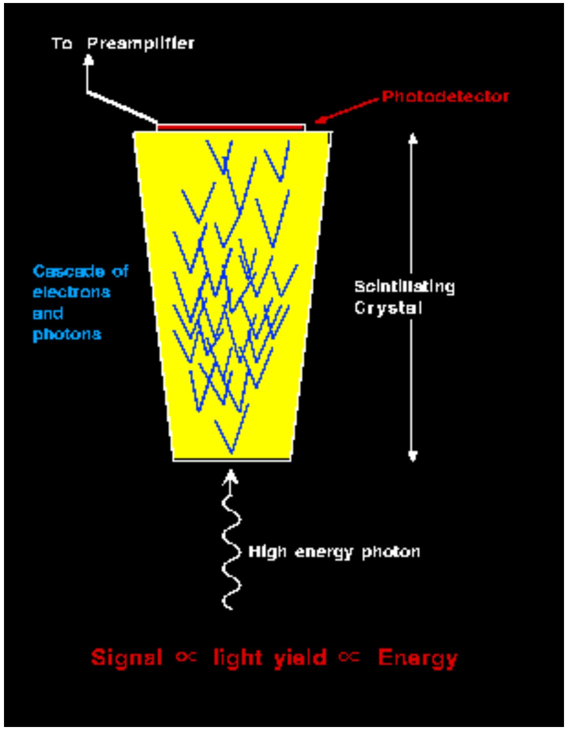
- Liquid argon calorimeter
  - Slow collection time (~1μsec)

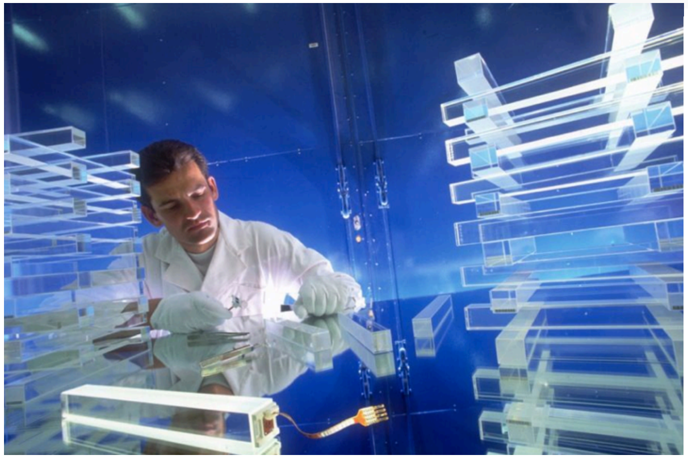
$\Delta E/E \sim 18\%/\sqrt{E}$

Crystal calorimeter example

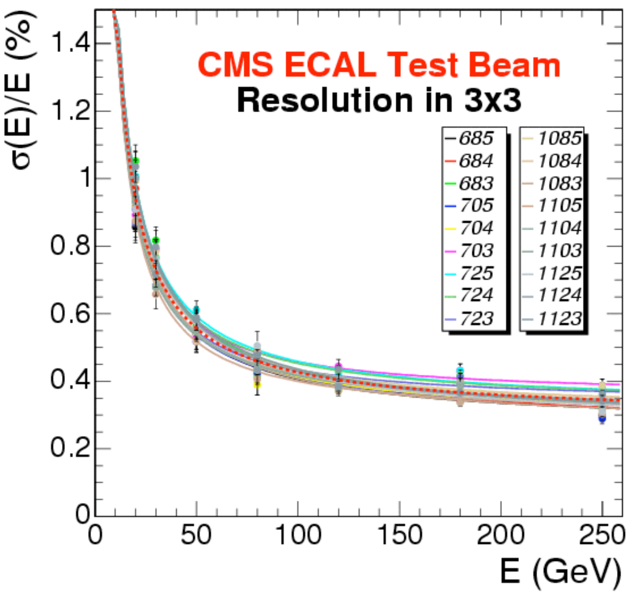
- CMS EM Calorimeter:
  - 83,000 crystals ($PbWO_4$, lead tungstate)
  - Very dense, fast, radiation hard
  - Scintillation light yield not significantly damaged by radiation
  - 1% resolution at 30 GeV







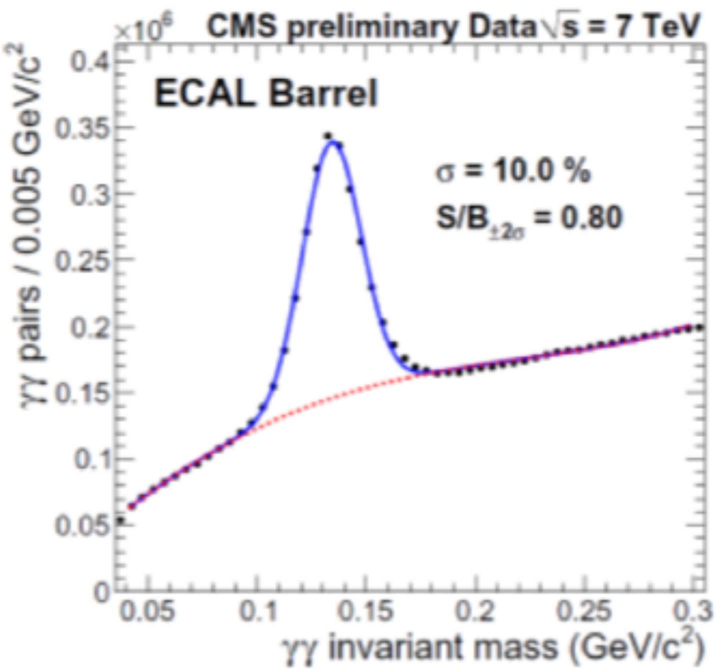
$$\frac{\sigma}{E} = \frac{2.8\%}{\sqrt{E(\mathrm{GeV})}} \oplus \frac{125}{E(\mathrm{MeV})} \oplus 0.3\%$$

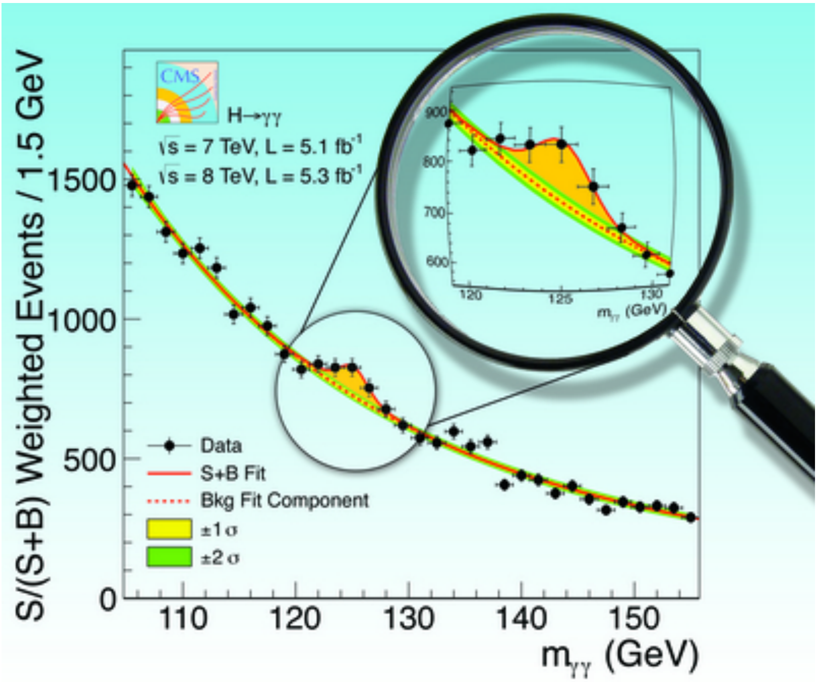


Energy resolution

Relative and *absolute* energy calibration:

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





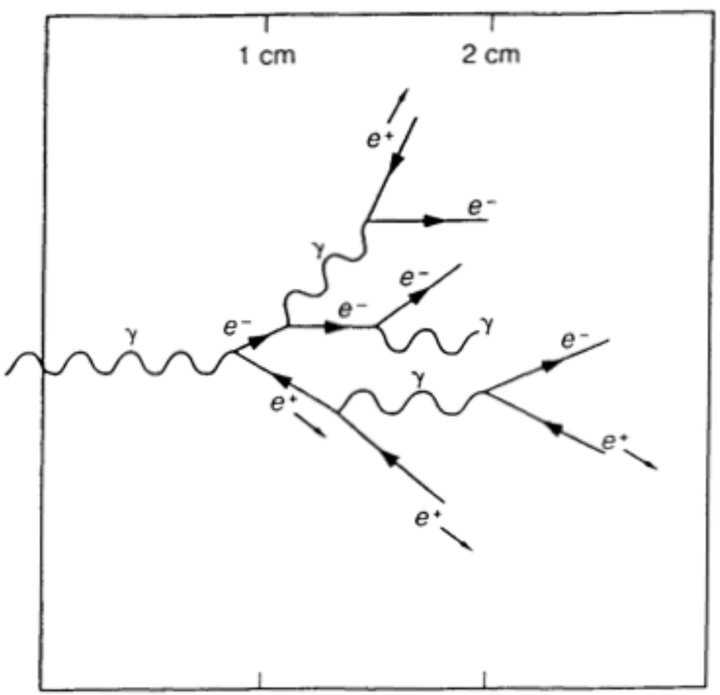
Hadron calorimetry

- 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

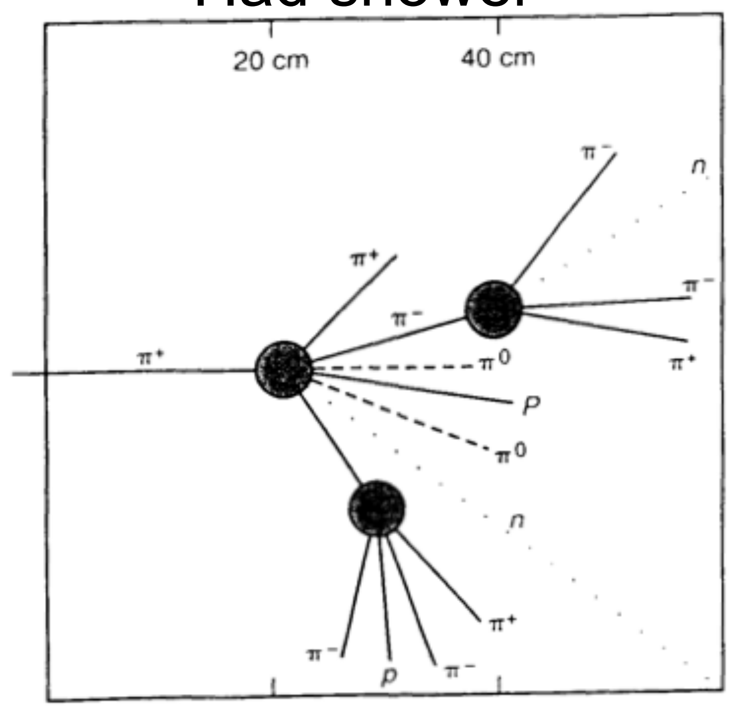
Had and EM showers

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

EM shower



Had shower

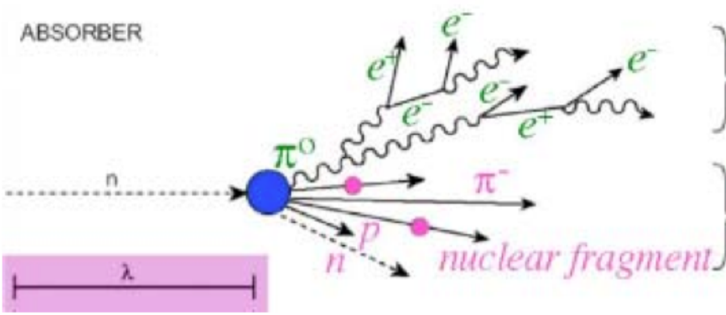


Hadronic showers

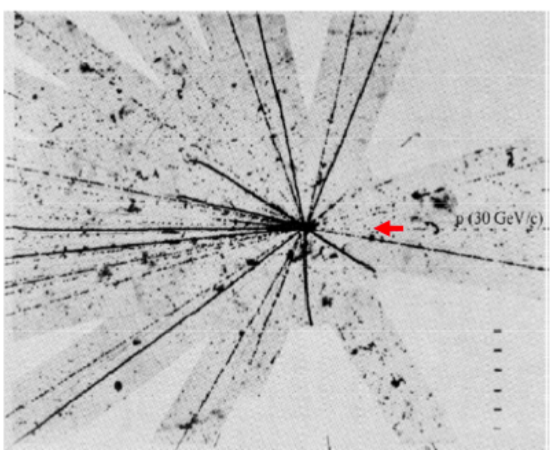
- Hadronic cascades develop analogously to EM showers
  - Strong interaction controls overall development
- As a strongly interacting particle (hadron) passes through matter, it initiates a nuclear interaction, and starts a nuclear shower
- Energy deposited by:
  - Electromagnetic component (i.e. as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

Hadronic showers

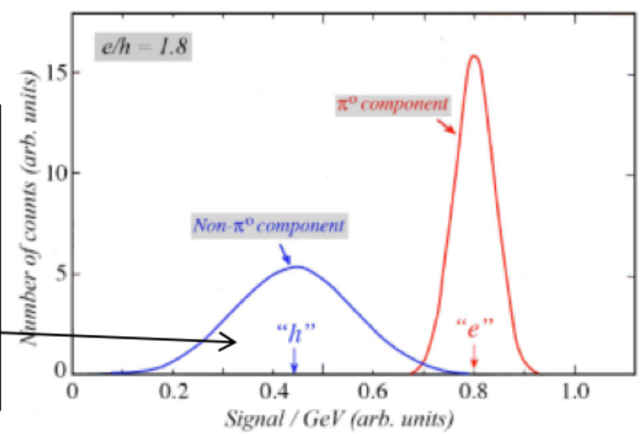
- Hadronic showers are:
  - broader and more penetrating
  - subject to larger fluctuations



Em component	Electrons, photons $\pi^0 \rightarrow 2\gamma$	~50%
Non-em component	Charged hadrons (20%) Nuclear fragments , p (25%) Neutrons, soft γ's (15%) Breakup of nuclei (40%)	~50%



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



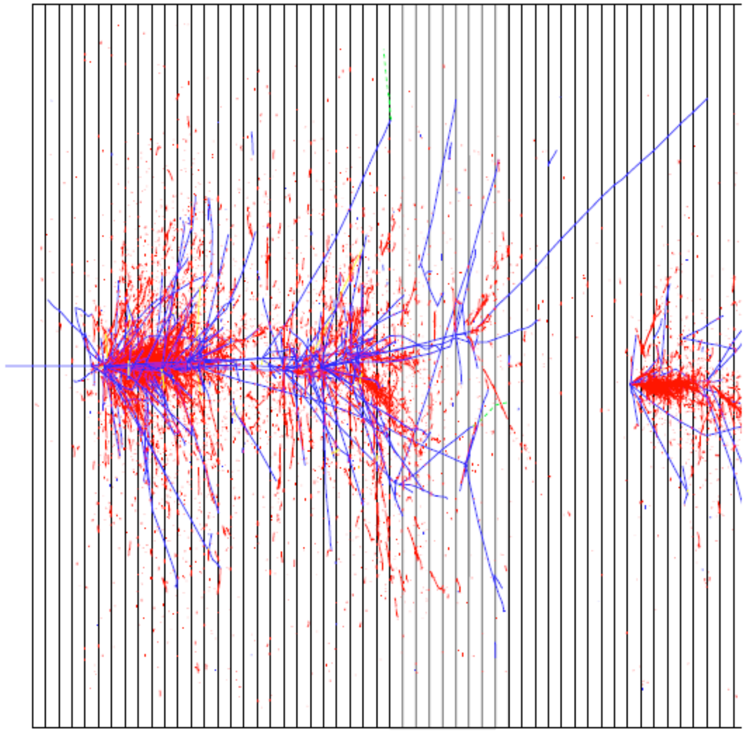
Hadronic showers: fluctuations

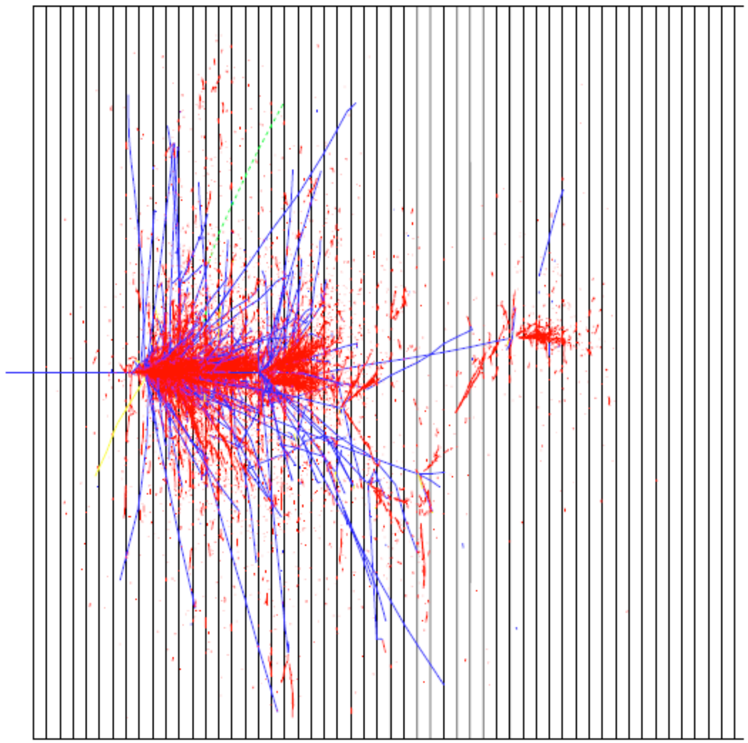
Sources of fluctuations:

- 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

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

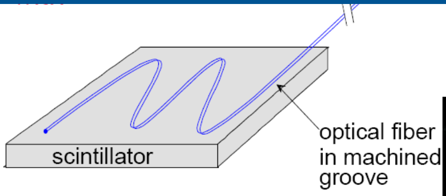
- EM showers are well understood theoretically
- Electromagnetic calorimeters are continuing to advance
- Optimization is trade-off between competing constraints
- EM calorimeters have good energy resolution (typically 2-10%/$E^{1/2}$)
- EM showers develop through brems and pair production
- Characteristic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

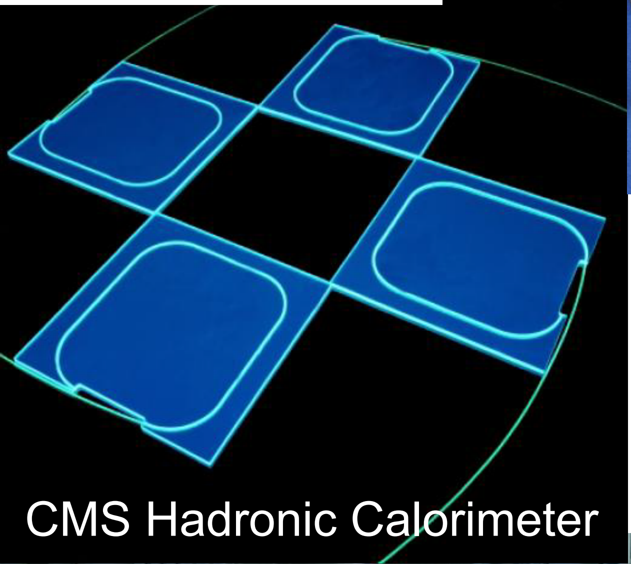
Hadronic shower: summary

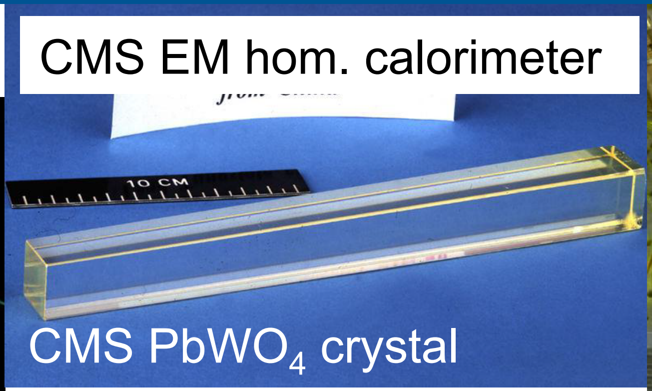
- Hadronic showers are more complex than EM showers
- Hadronic calorimeters have worse energy resolution than EM cal. (typically $40\%/E^{1/2}$ to $100\%/E^{1/2}$)

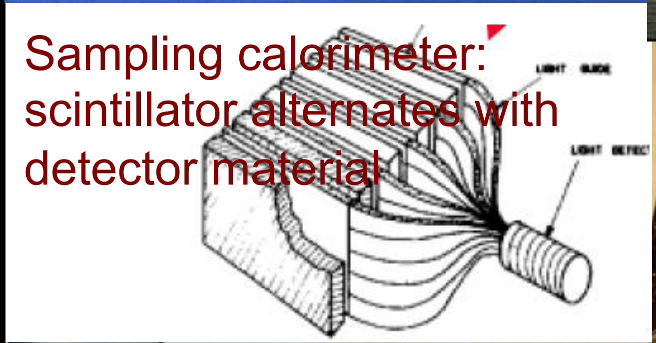
- Hadrons also loose energy through a showering process
- However, instead of brems, the fundamental process is nuclear interaction
- Characteristic length is called the hadronic interaction length λ ($\lambda \approx 35$ gm/cm^2 $A^{1/3}$)

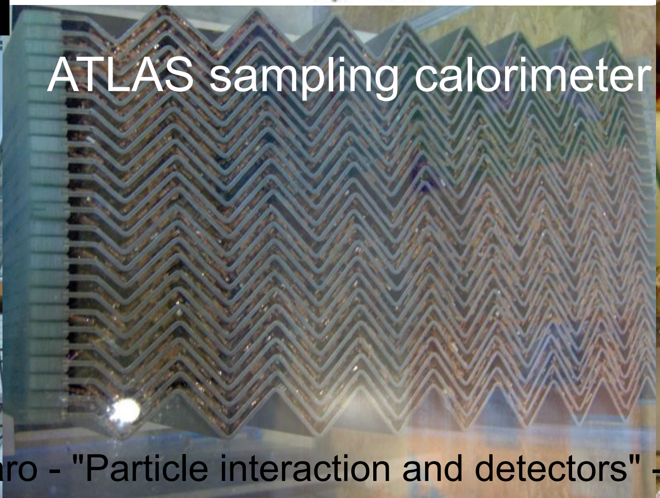
Calorimeters









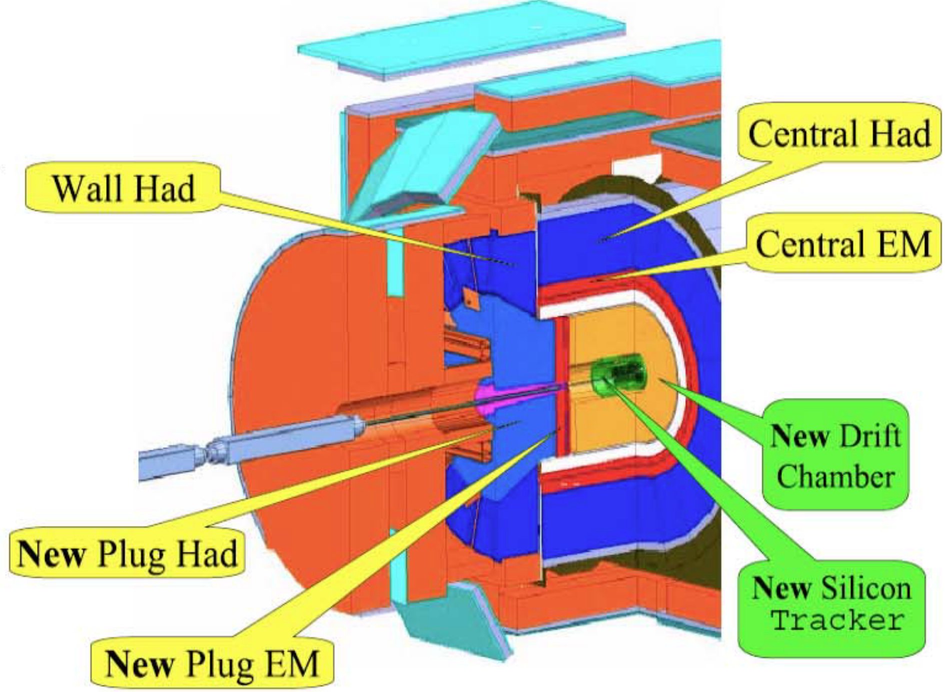


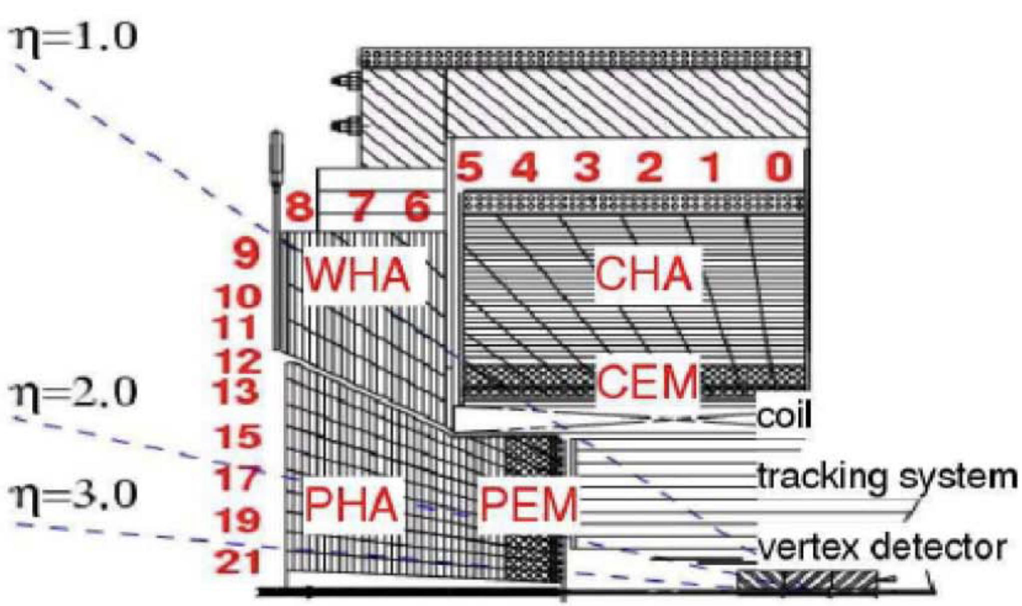
The CDF Calorimeters

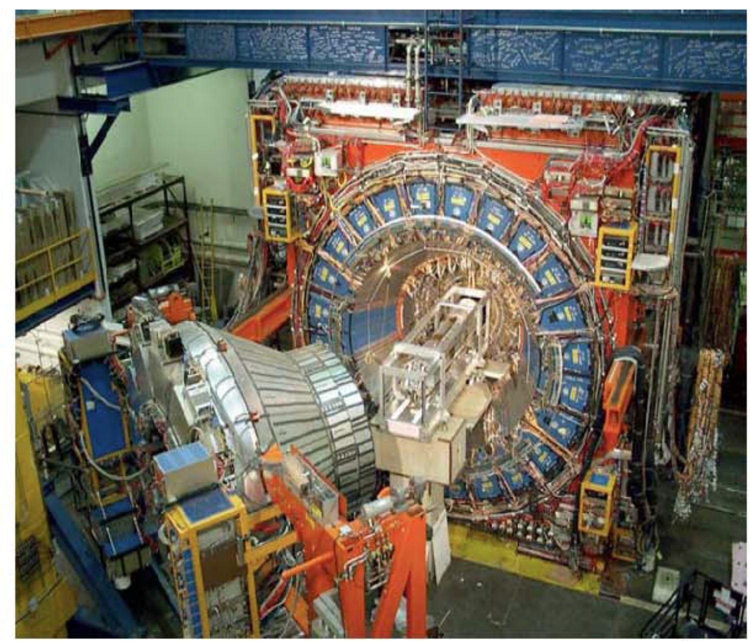
All scintillator-based sampling calorimeters

$\|\eta\|$ 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

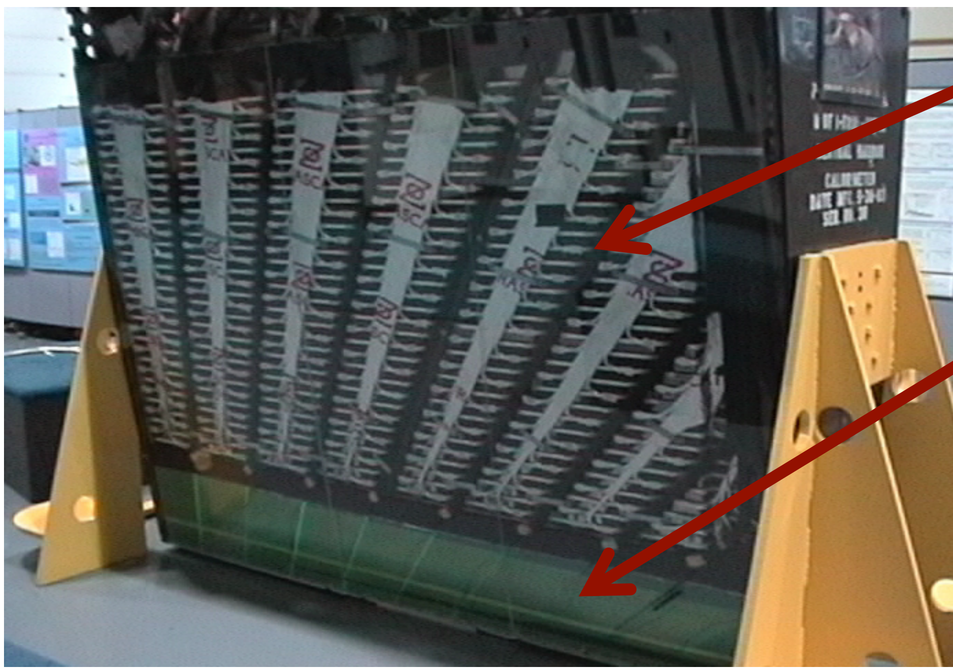






CDF calorimeters at the Tevatron

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



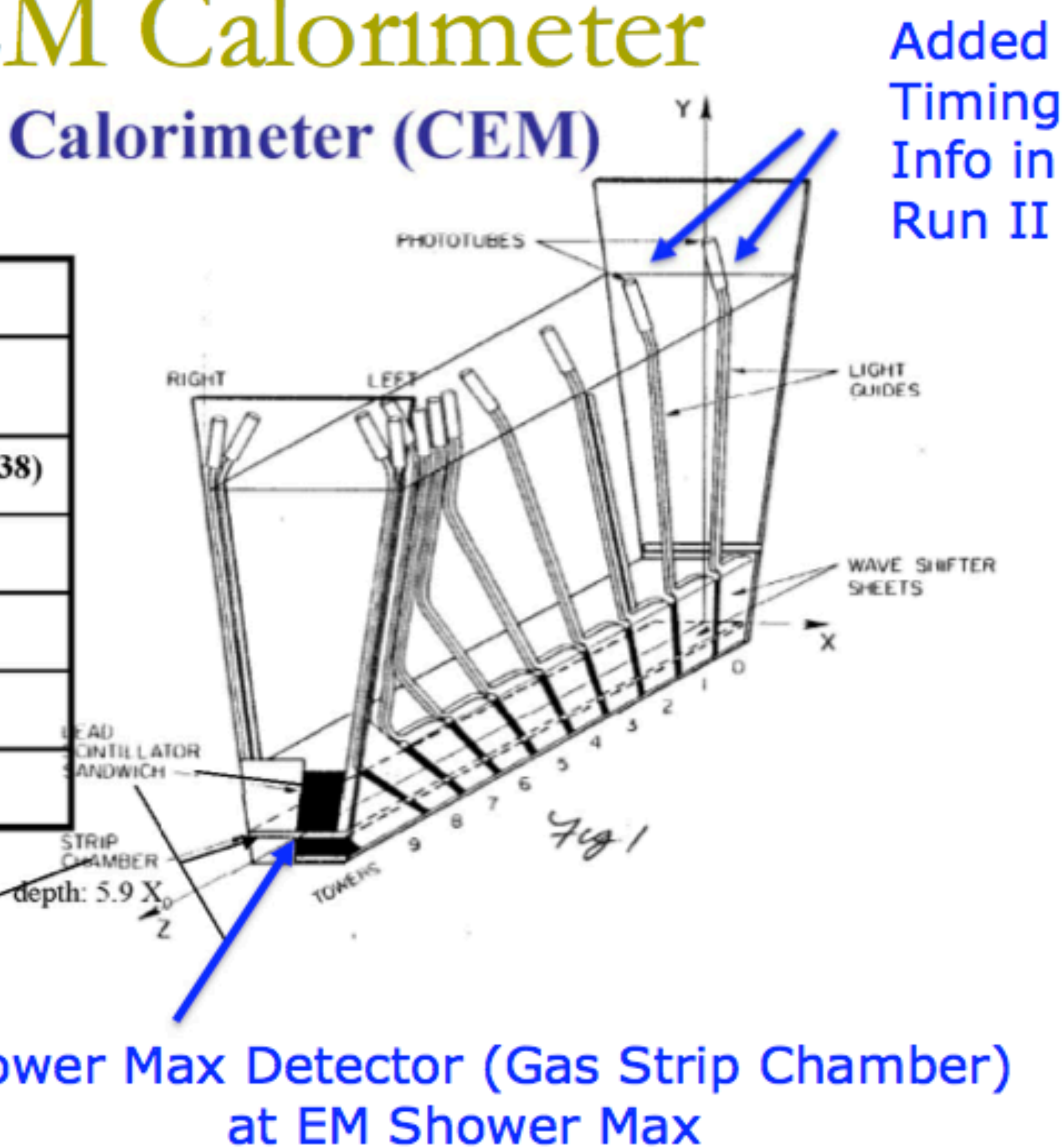
Hadron calorimeter

EM calorimeter

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	$13.5/\sqrt{E_T}$



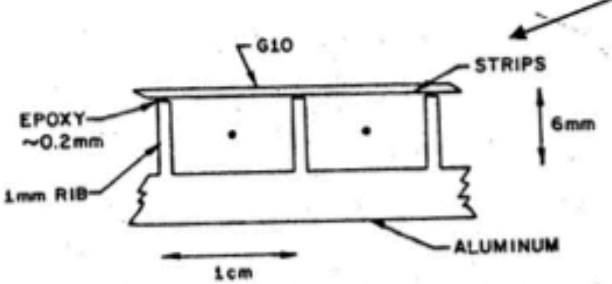
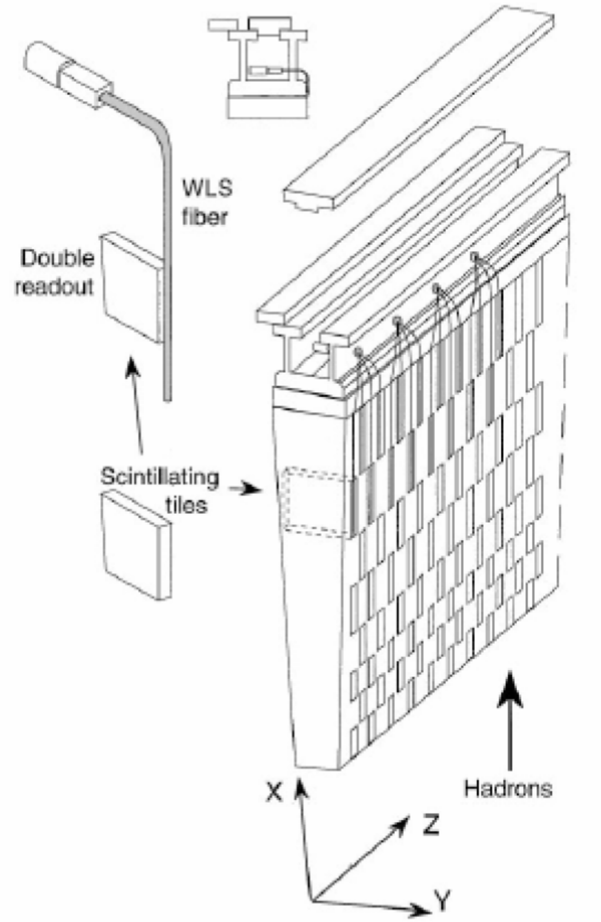
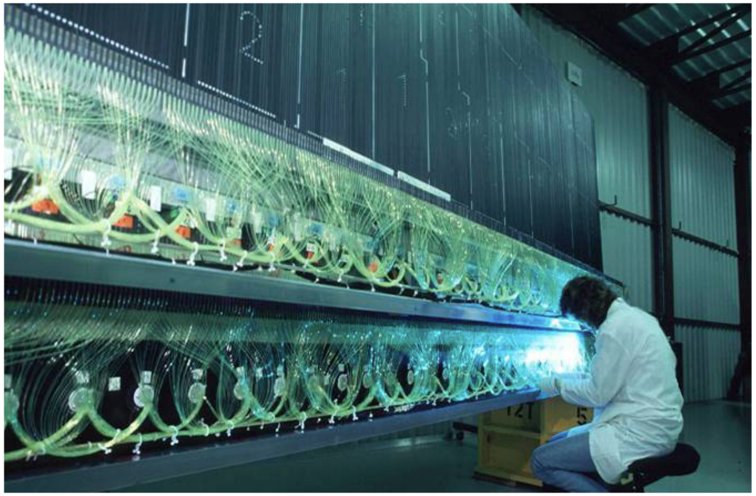


Fig. 3. Prototype strip chamber cross section.

HCAL: ATLAS tile calorimeter





Fe/Scint with WLS fiber Readout via PMT

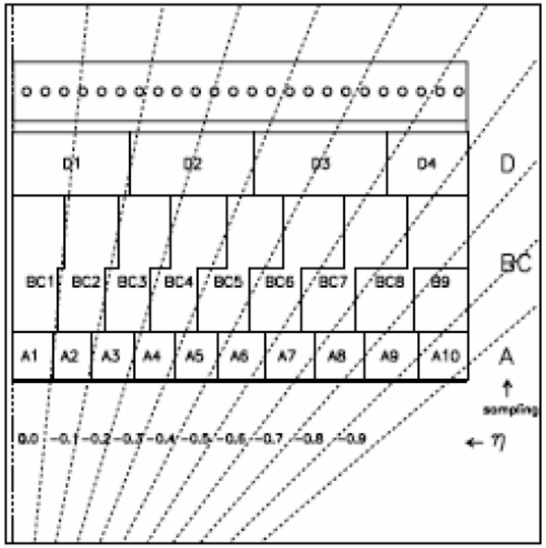


Figure 5-15 Cell geometry of half of a barrel module. The fibres of each cell are routed to one PMT.

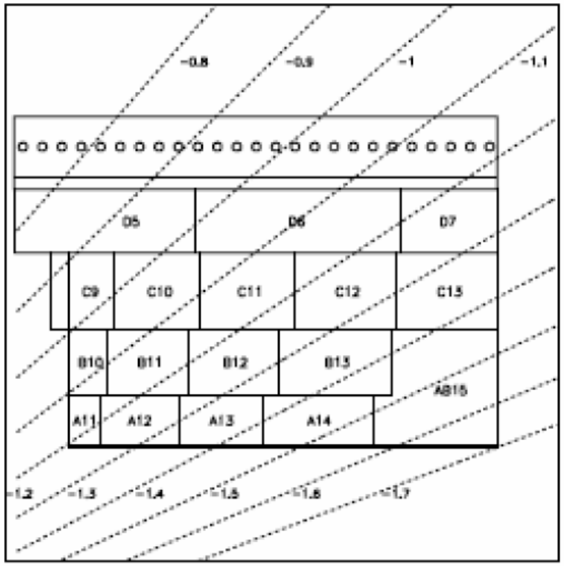
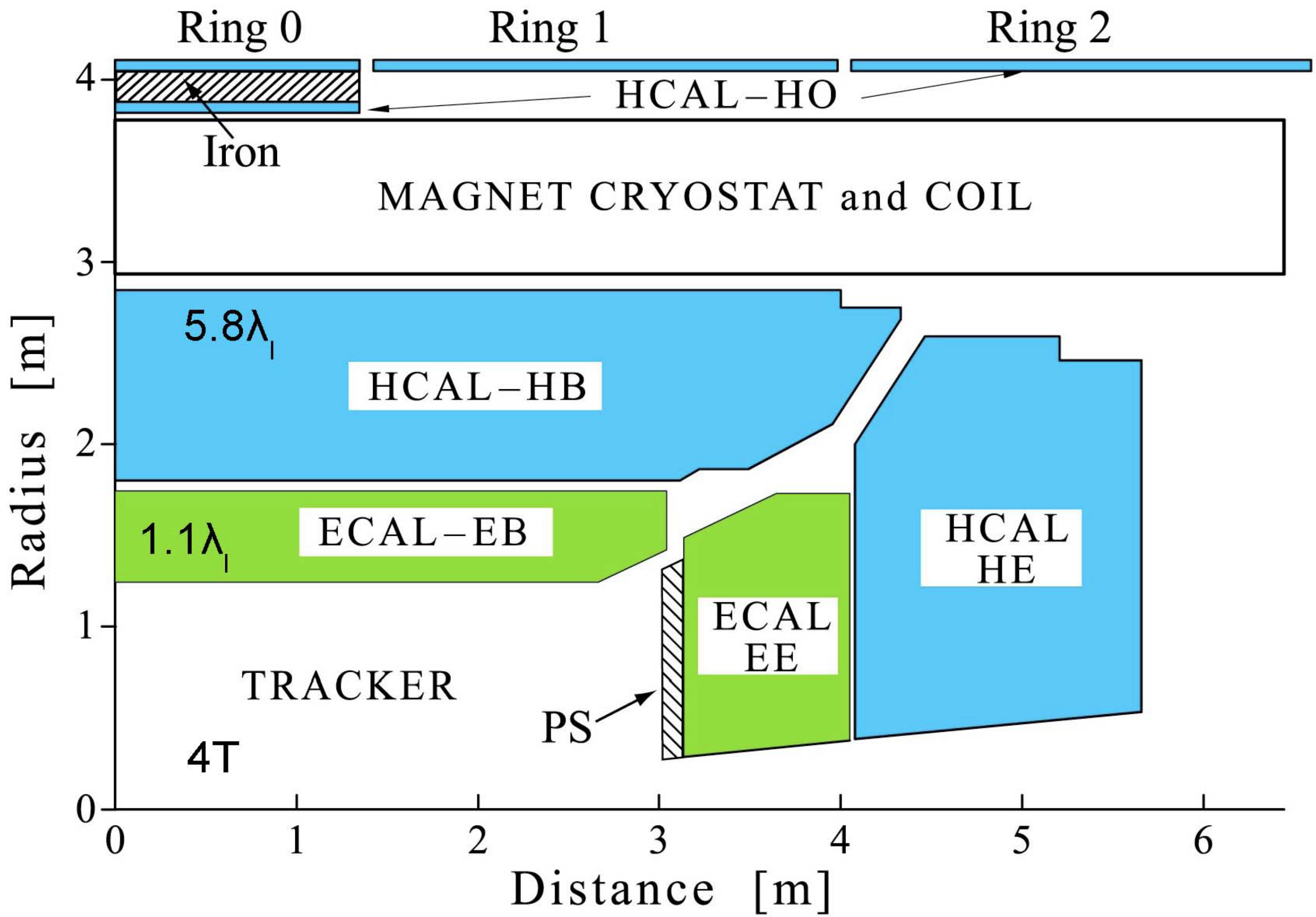
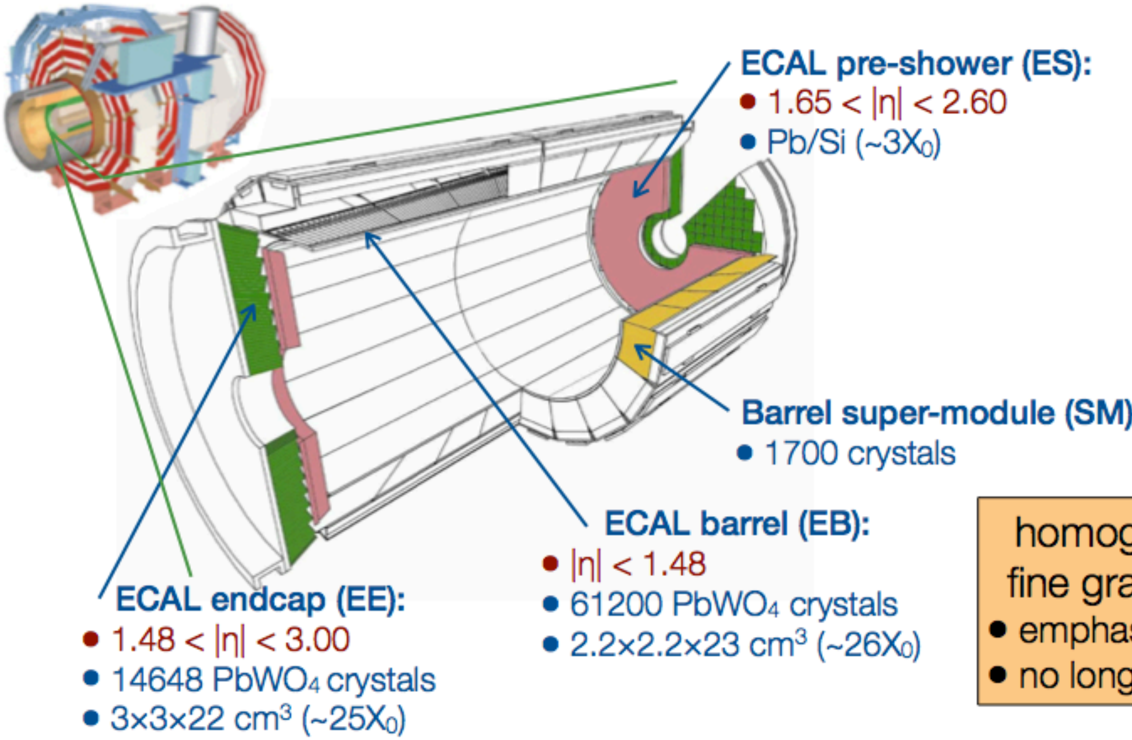


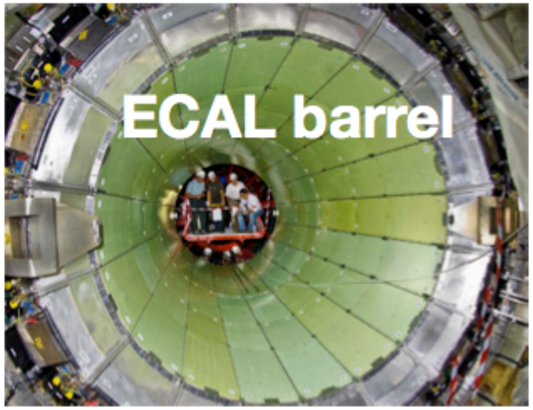
Figure 5-16 Proposed cell geometry for the extended barrel modules (version "a la barrel").

CMS calorimeters



CMS ECAL calorimeter





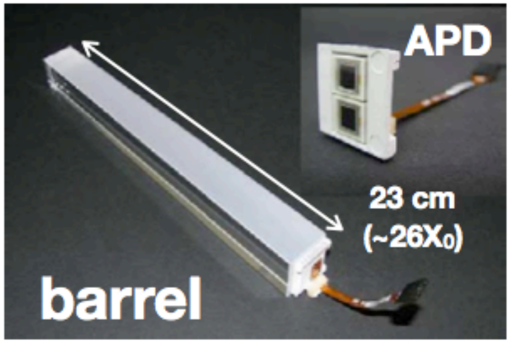
ECAL

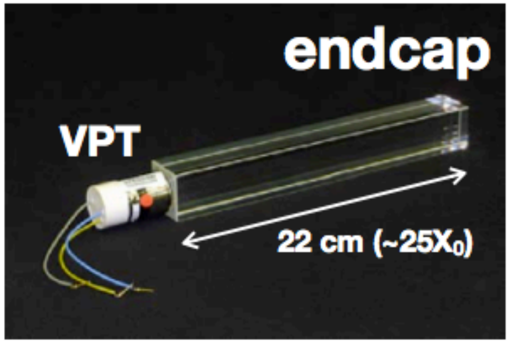
homogeneous, compact, hermetic, fine grain $PbWO_4$ crystal calorimeter

- emphasis on e/γ energy resolution
- no longitudinal segmentation

$PbWO_4$

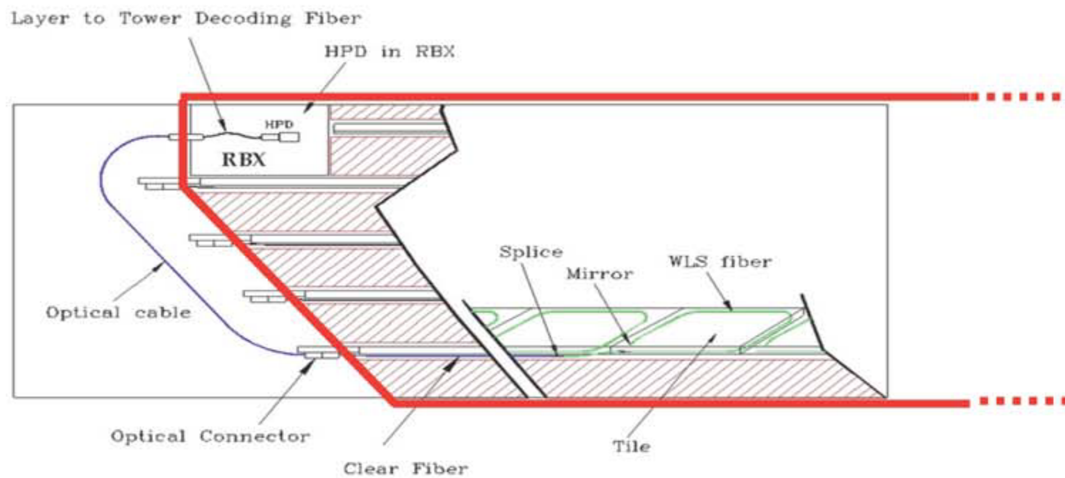
high density (8.3 g/cm^3)
small Molière radius (2.2 cm)
short rad. length (0.89 cm)
fast (80% of scintillation in 25 ns)
radiation hard





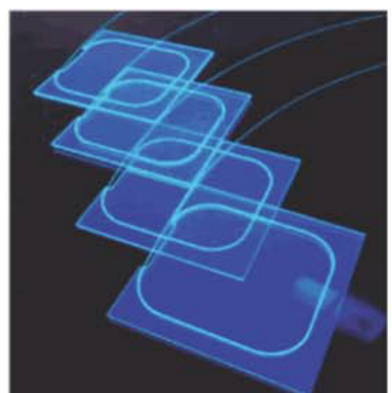
HCAL: CMS sampling calorimeter

CMS HCAL barrel



2593 towers

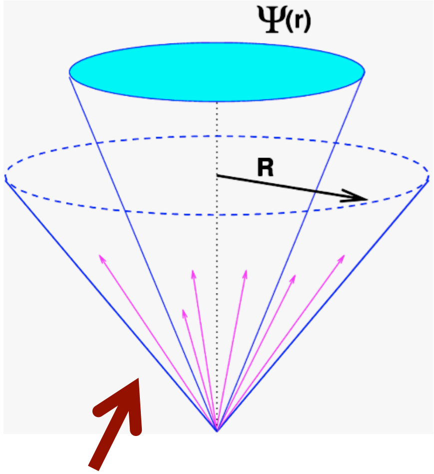
$\Delta\eta \times \Delta\phi = 0.017 \times 0.017$

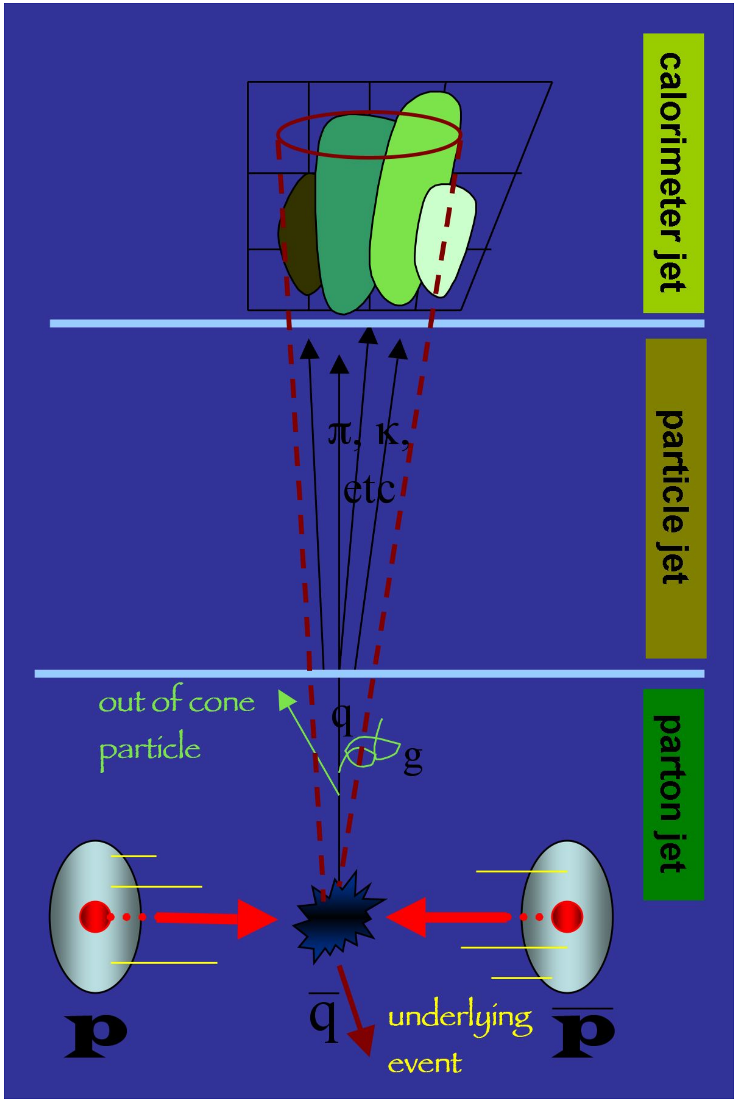


pixel HybridPhotoDiode

Jets

- A "jet" is a narrow cone of hadrons and other particles produced by the **hadronization** of a quark or gluon
- Processes creating jets are complicated
  - parton fragmentation, with EM or Had showering
- Jet reconstruction is difficult
- Jet energy scale and reconstruction is large source of uncertainty



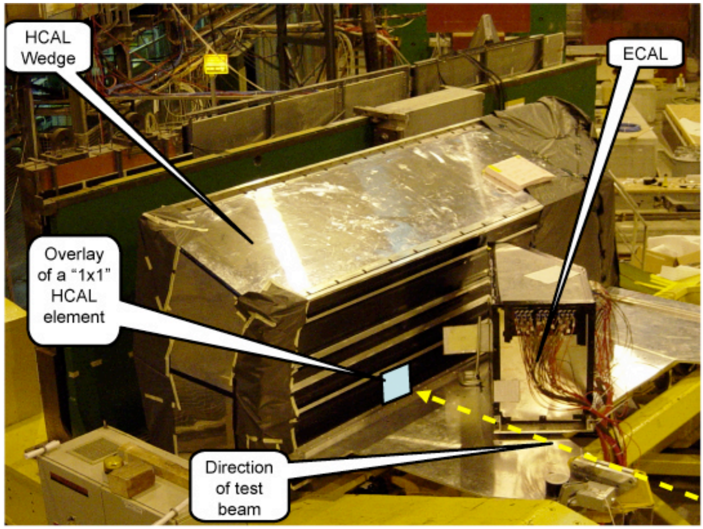


- Measure energy in a "cone"

Jets: calibration

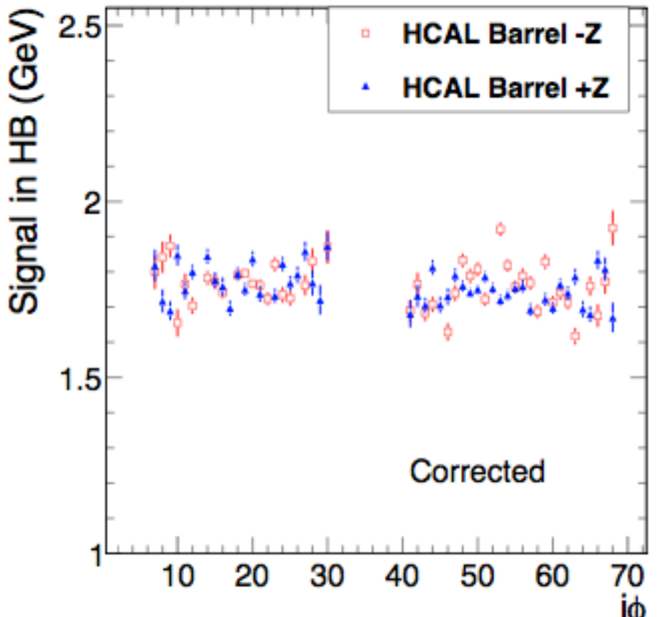
Before experiment starts

- Test beam
  - take one calorimeter "wedge", send beam of particles with known energy
  - obtain correspondence "detector response → energy" in GeV



When the experiment is built/running

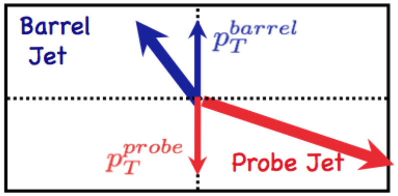
- Hardware calibration
  - Use radioactive sources with well defined decay energy (between runs)
  - Sources can move and "illuminate" all towers
  - Check uniformity
  - Laser calibration (connected to individual PMTs)
  - Measure uniform response over time
  - Cosmic rays (muons)

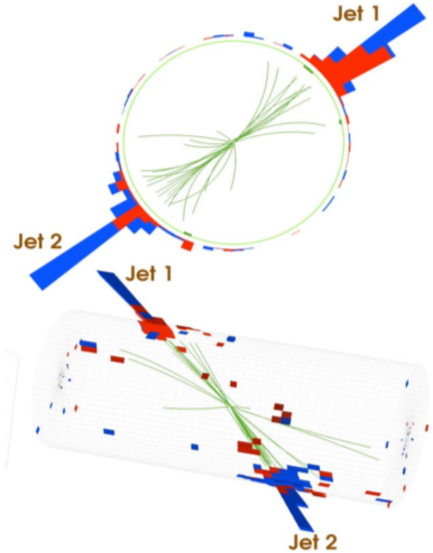


Jets: calibration (cont.)

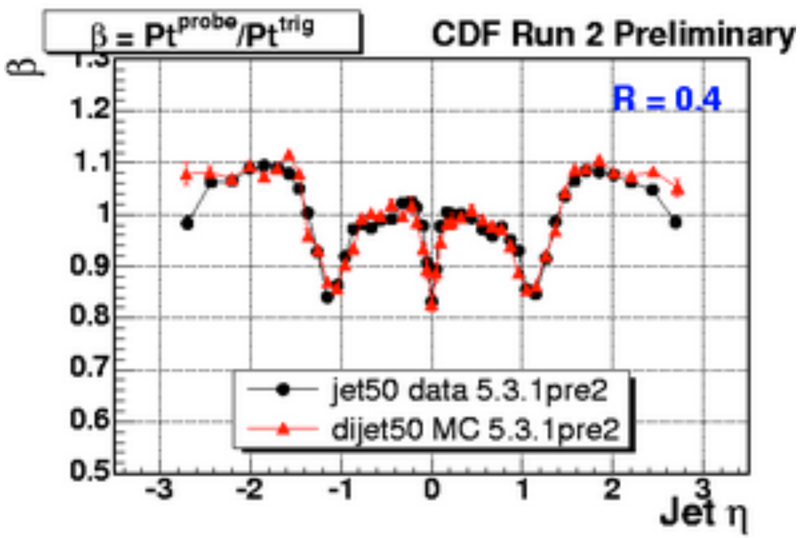
When the experiment is running

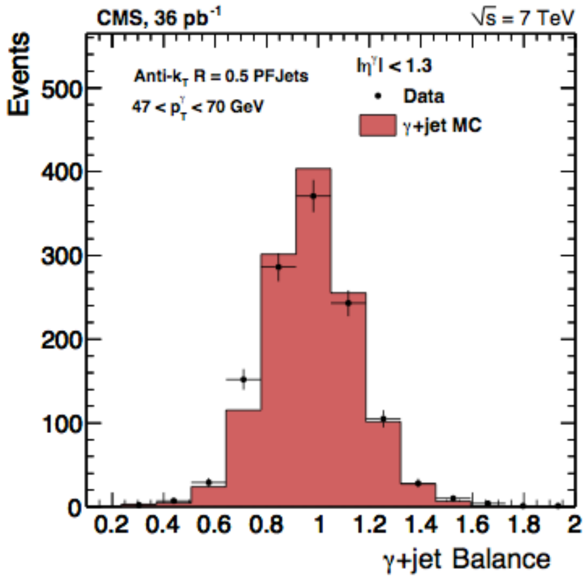
- *Relative* and *absolute* en. calibration
- Collider data
  - Measure of known physics process (i.e. Z+jets, γ-jet, jet-jet balancing)
  - Energy measured in tracker (redundancy)





- Measure jets at high energy colliders



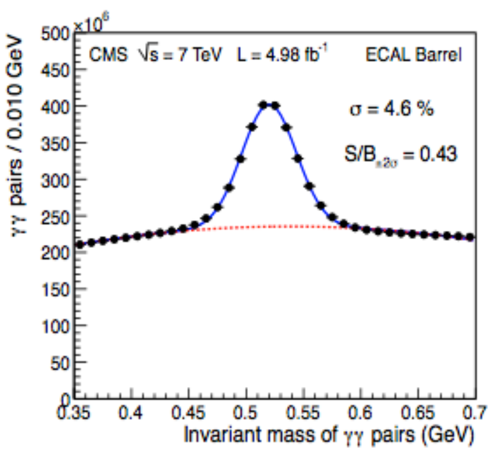


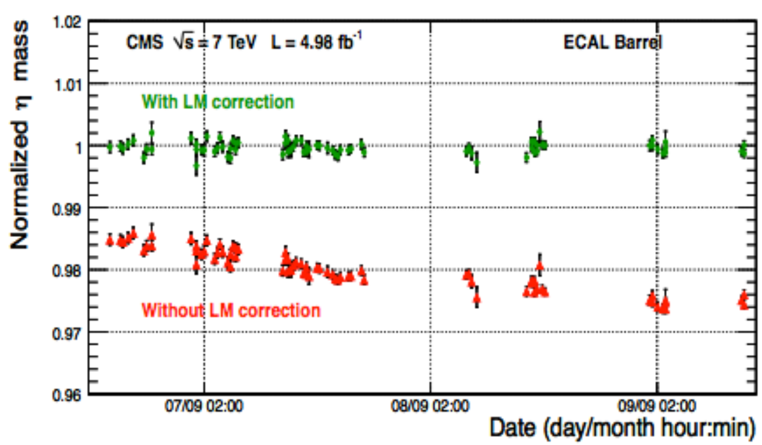
Jets: calibration (cont.)

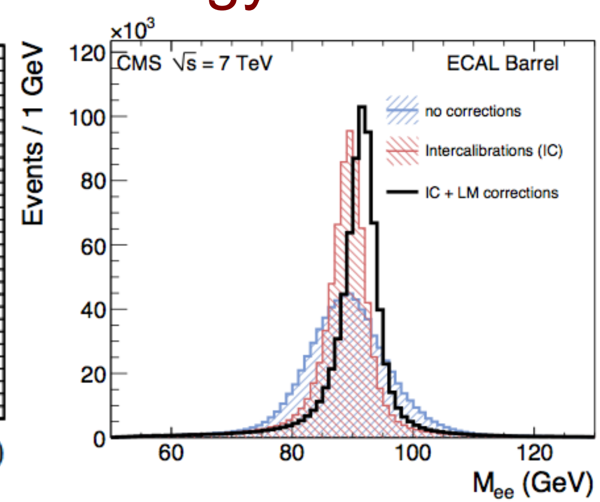
When the experiment is running

- *Relative* and *absolute* en. calibration
- Collider data
  - Measure of known physics process (i.e. Z+jets, γ-jet, jet-jet balancing)
  - Energy measured in tracker (redundancy)
- Measure jets at high energy colliders

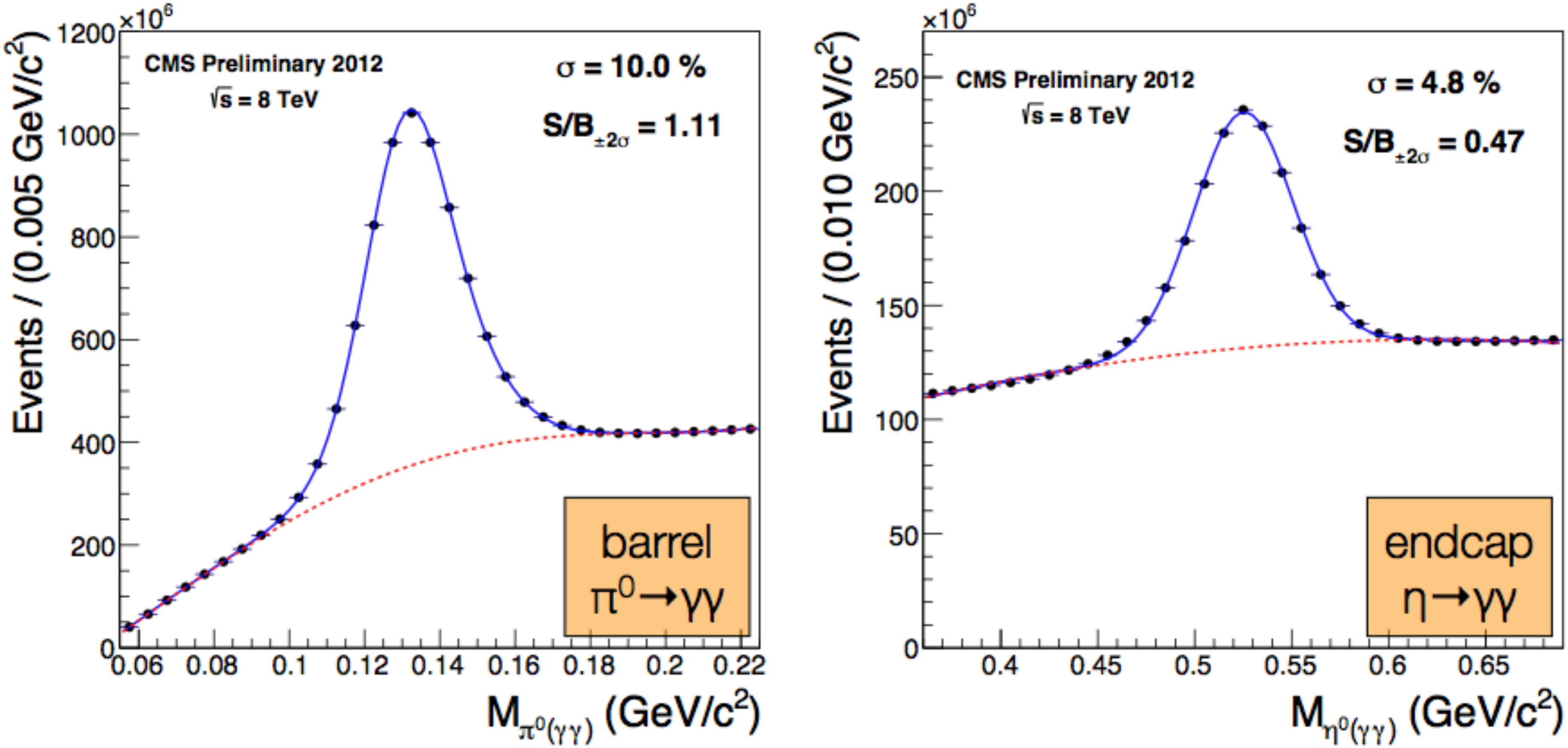
EM shower energy calibration



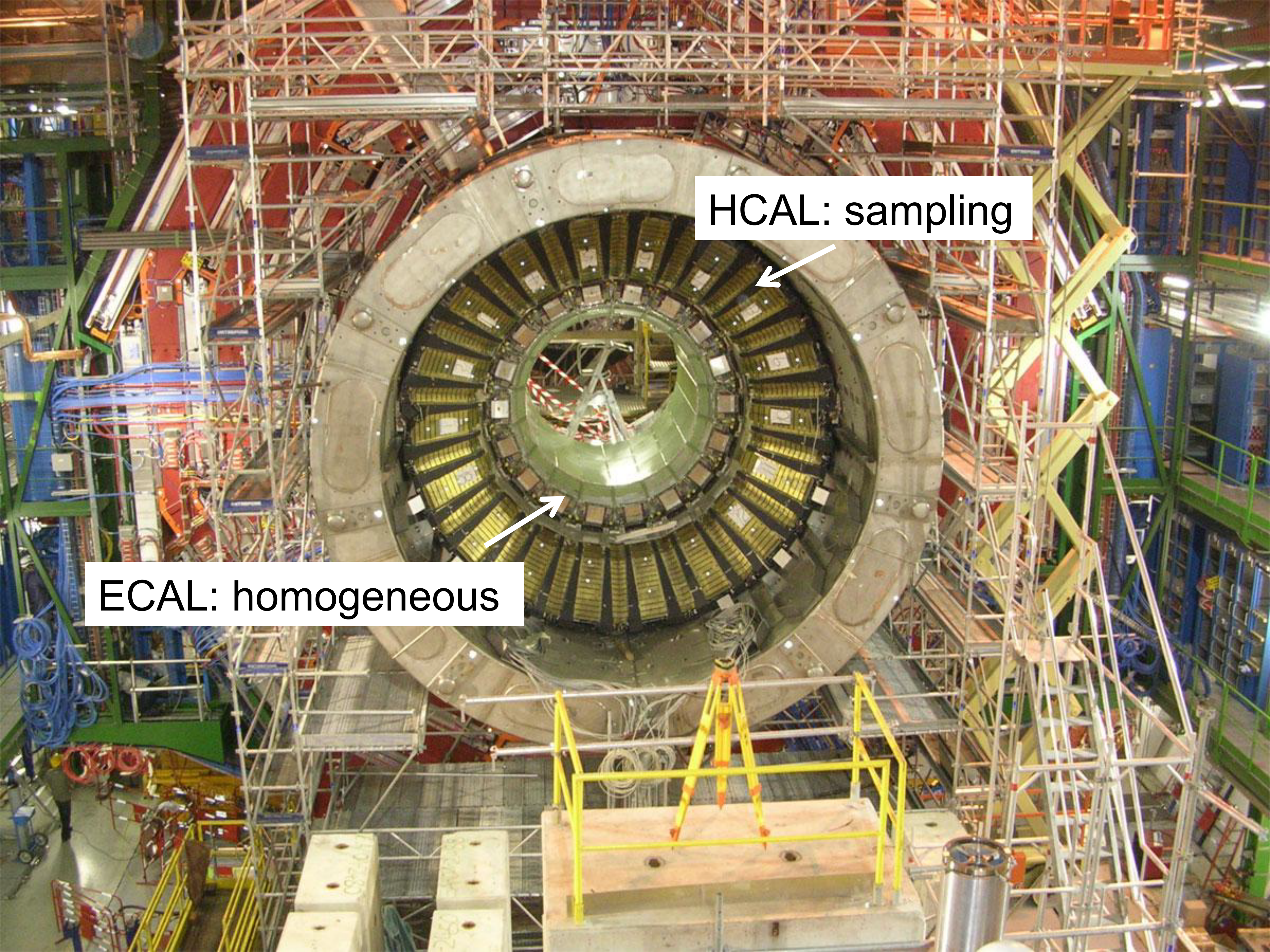




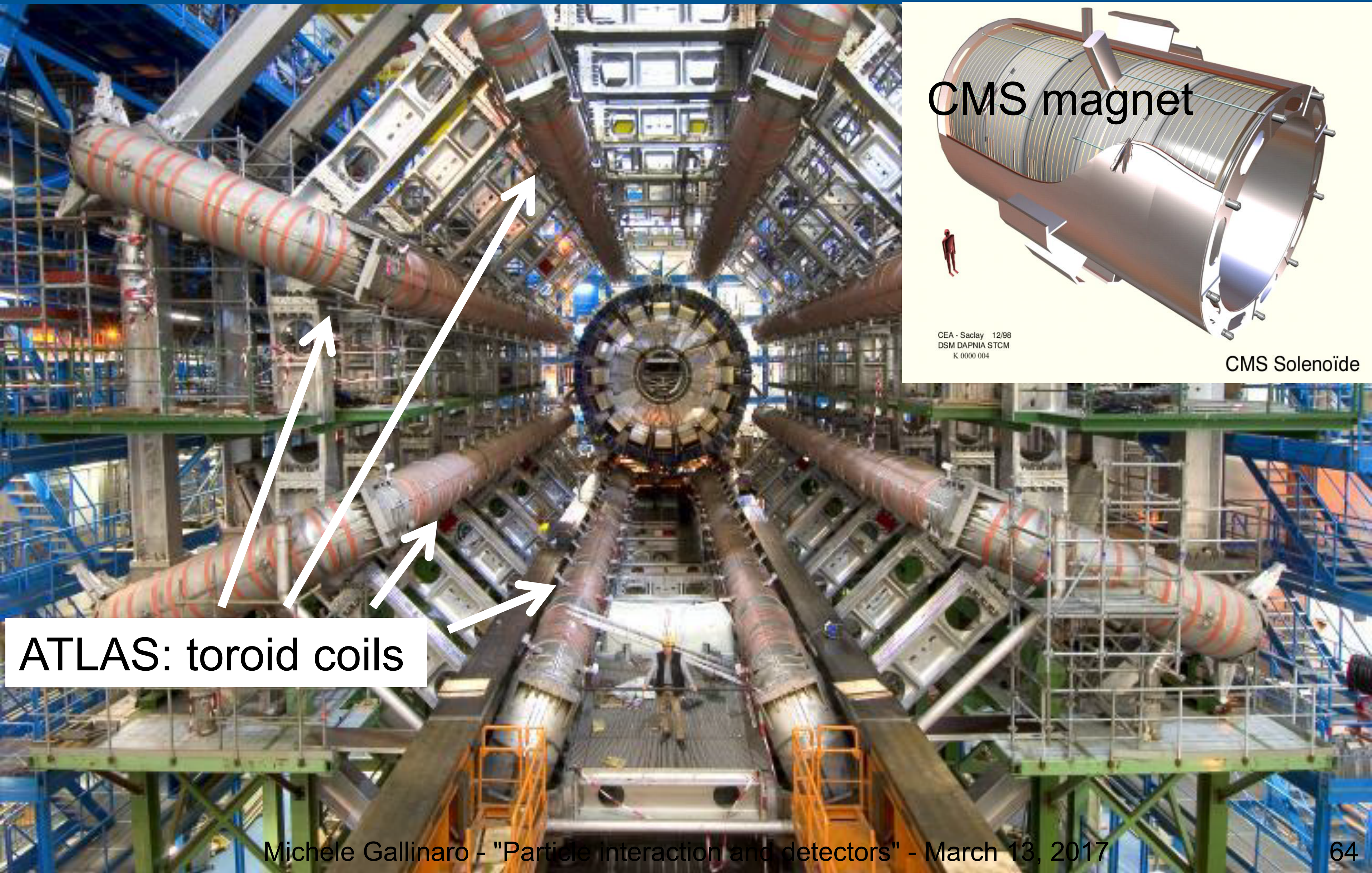
Invariant mass of neutral mesons



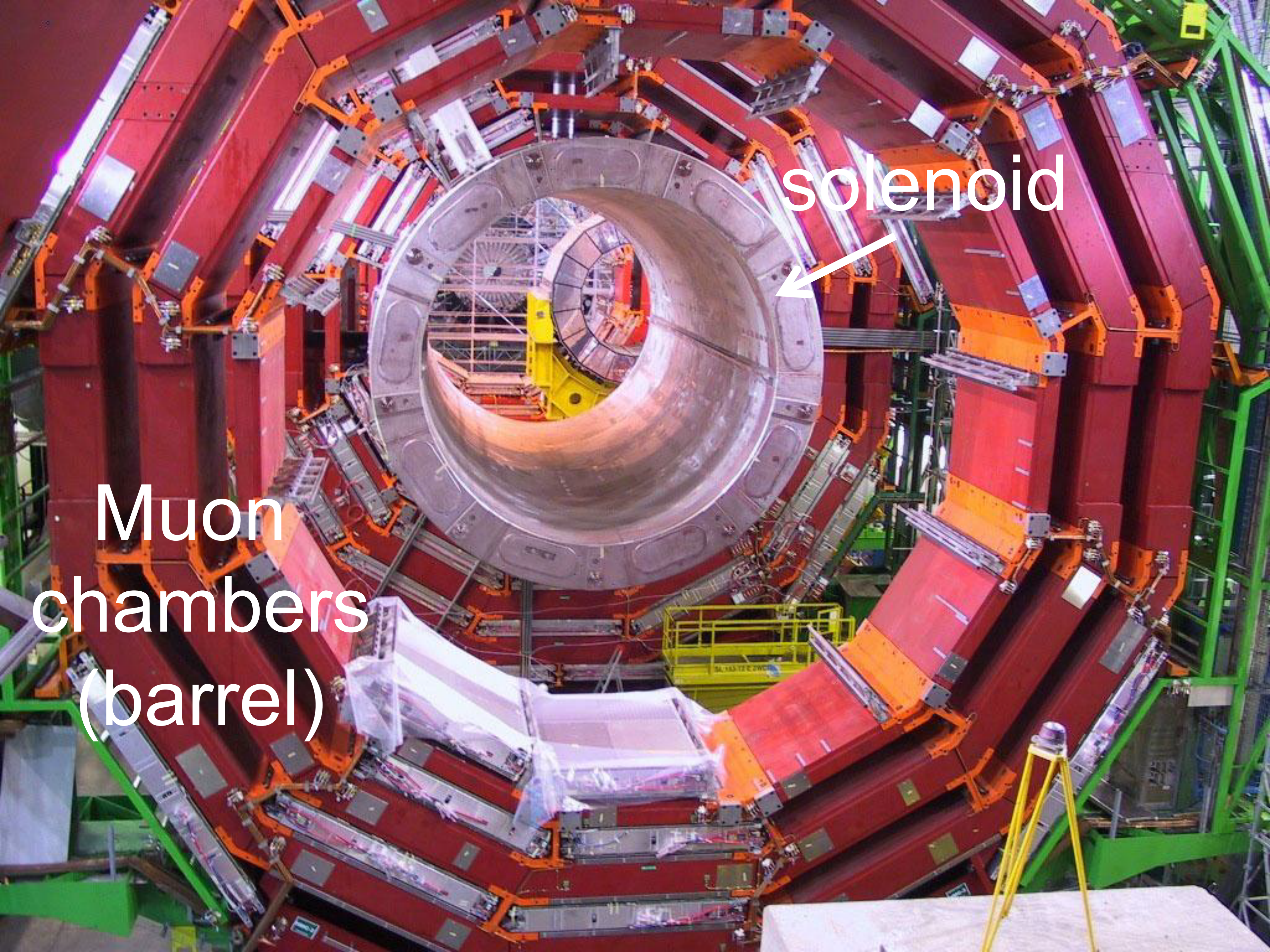
Remarkable performance at few hundreds of MeV


HCAL: sampling
ECAL: homogeneous

Magnetic coil



Assembly of iron yoke


solenoid
Muon
chambers
(barrel)

Experimental cavern

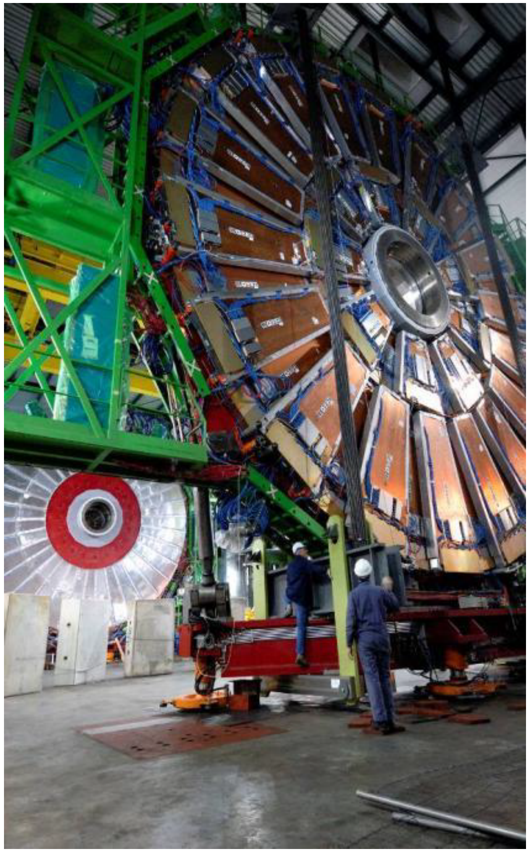
2004


Lowering of the detectors
2006

Lowering: Endcap disks

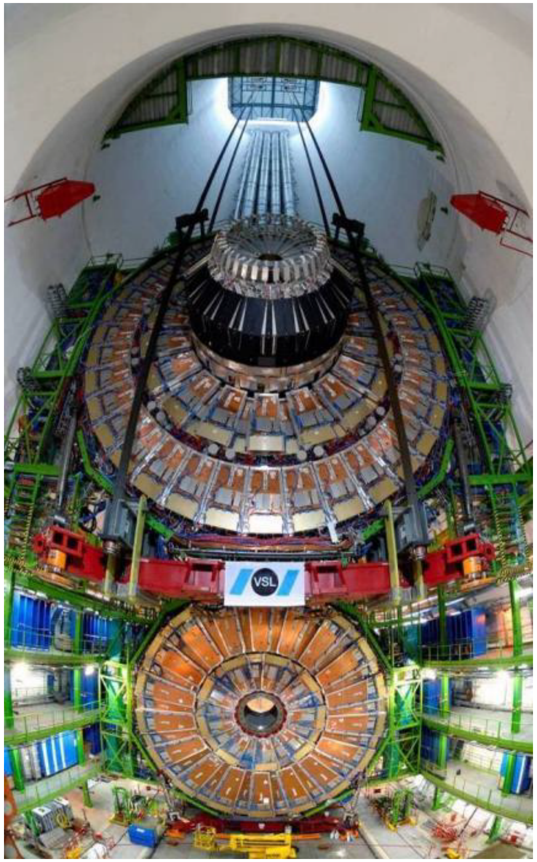
YE+3

30.11.2006



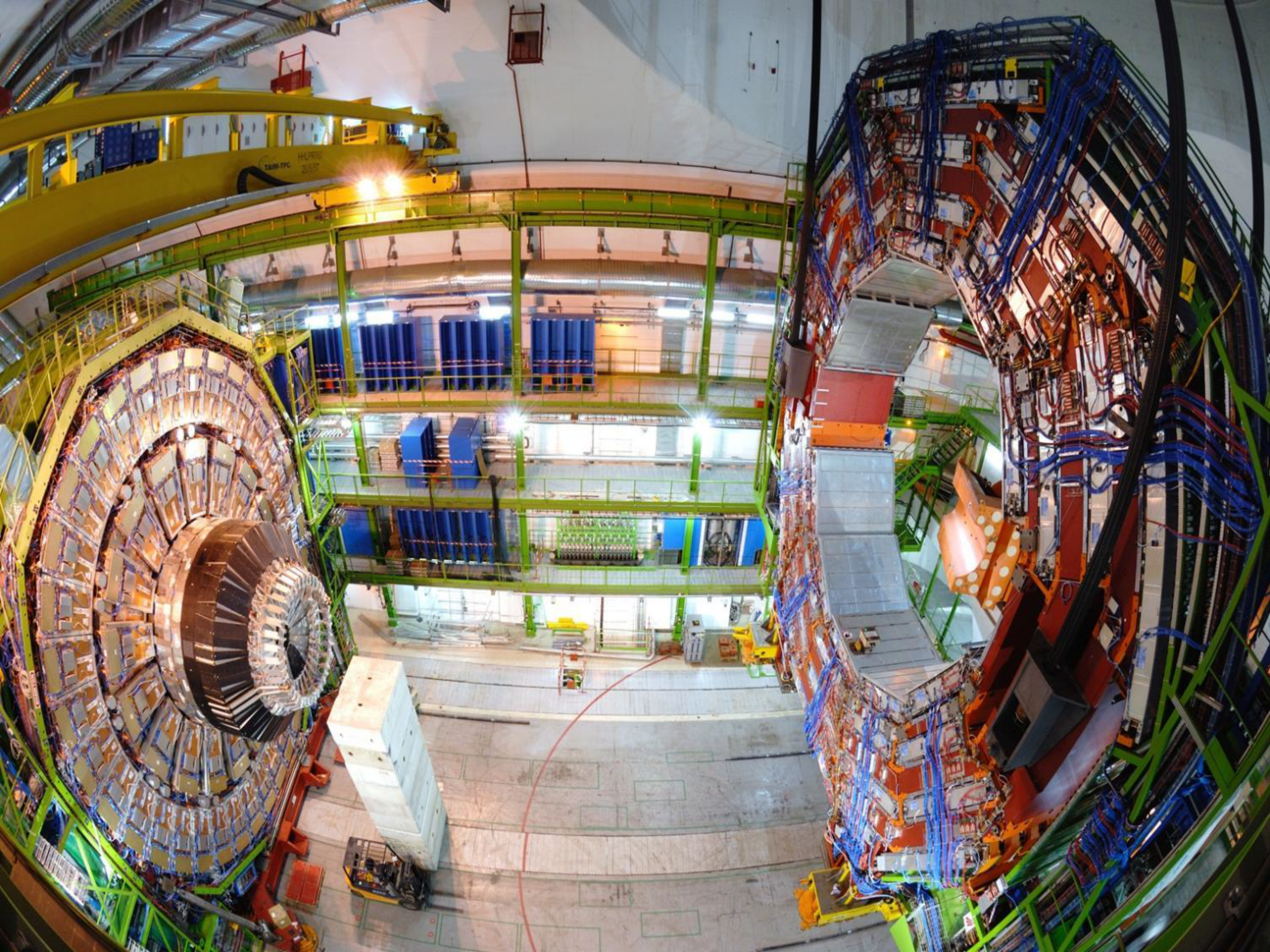
YE+2

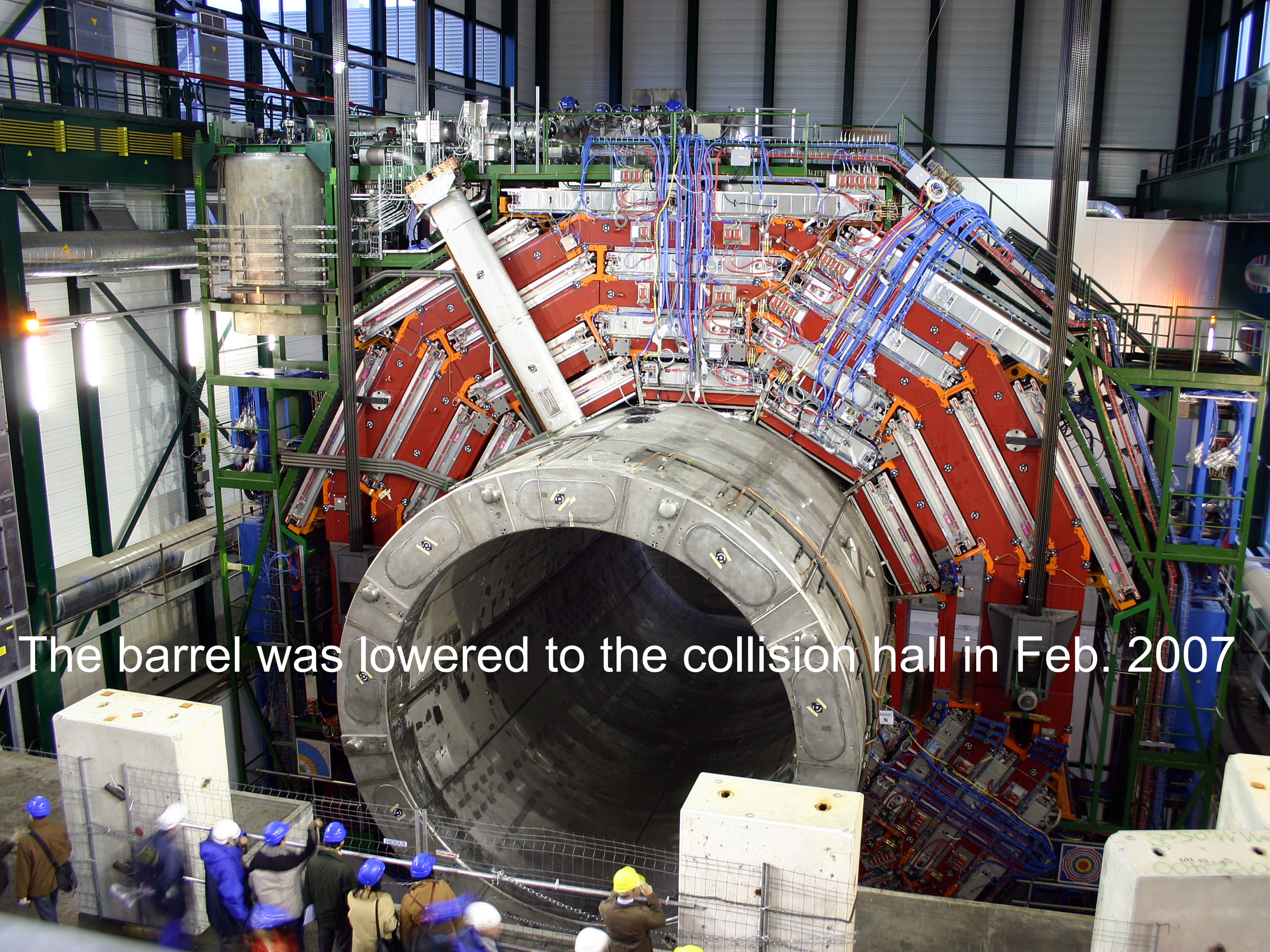
12.12.2006



YE+1

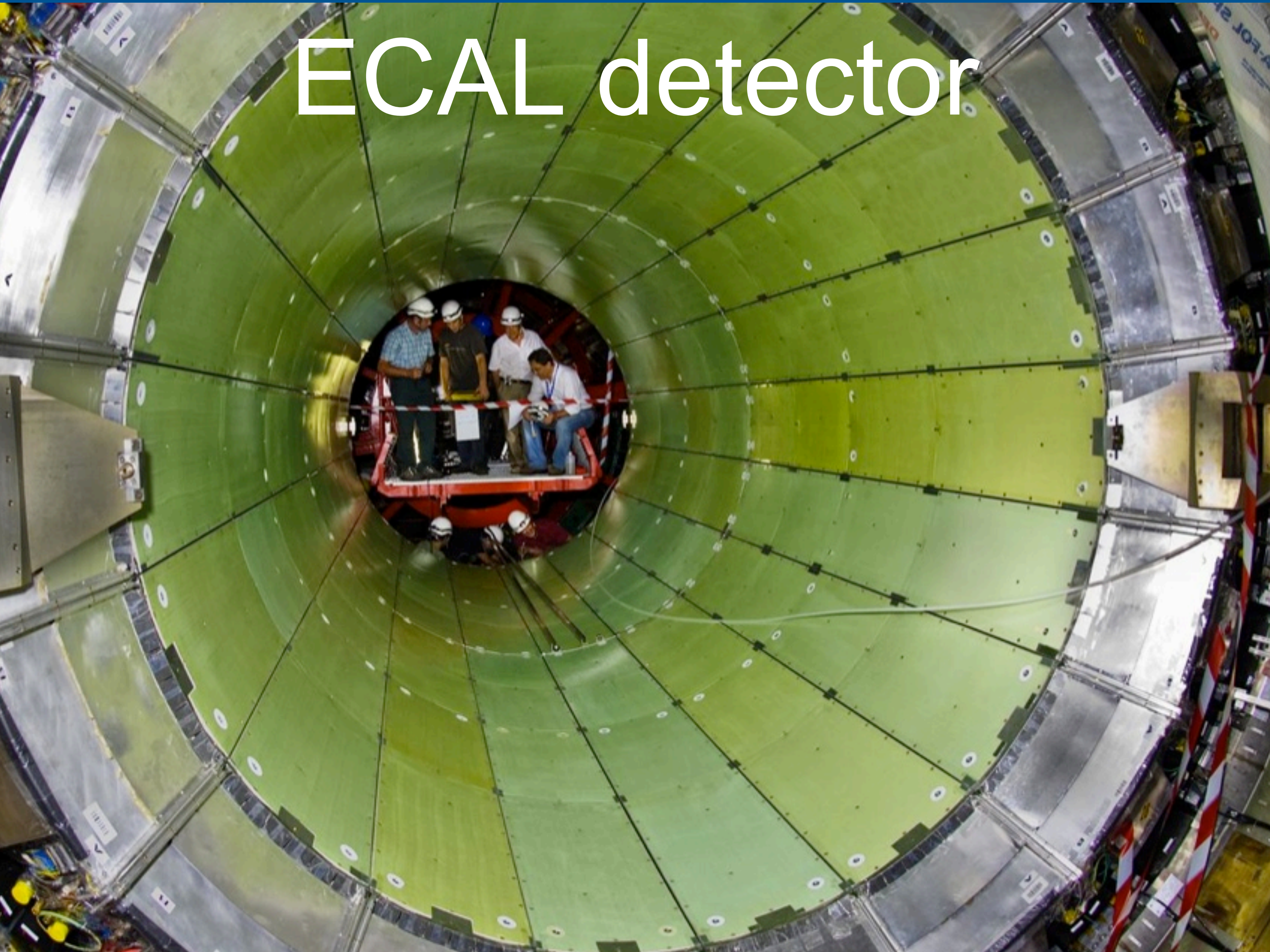
9.1.2007



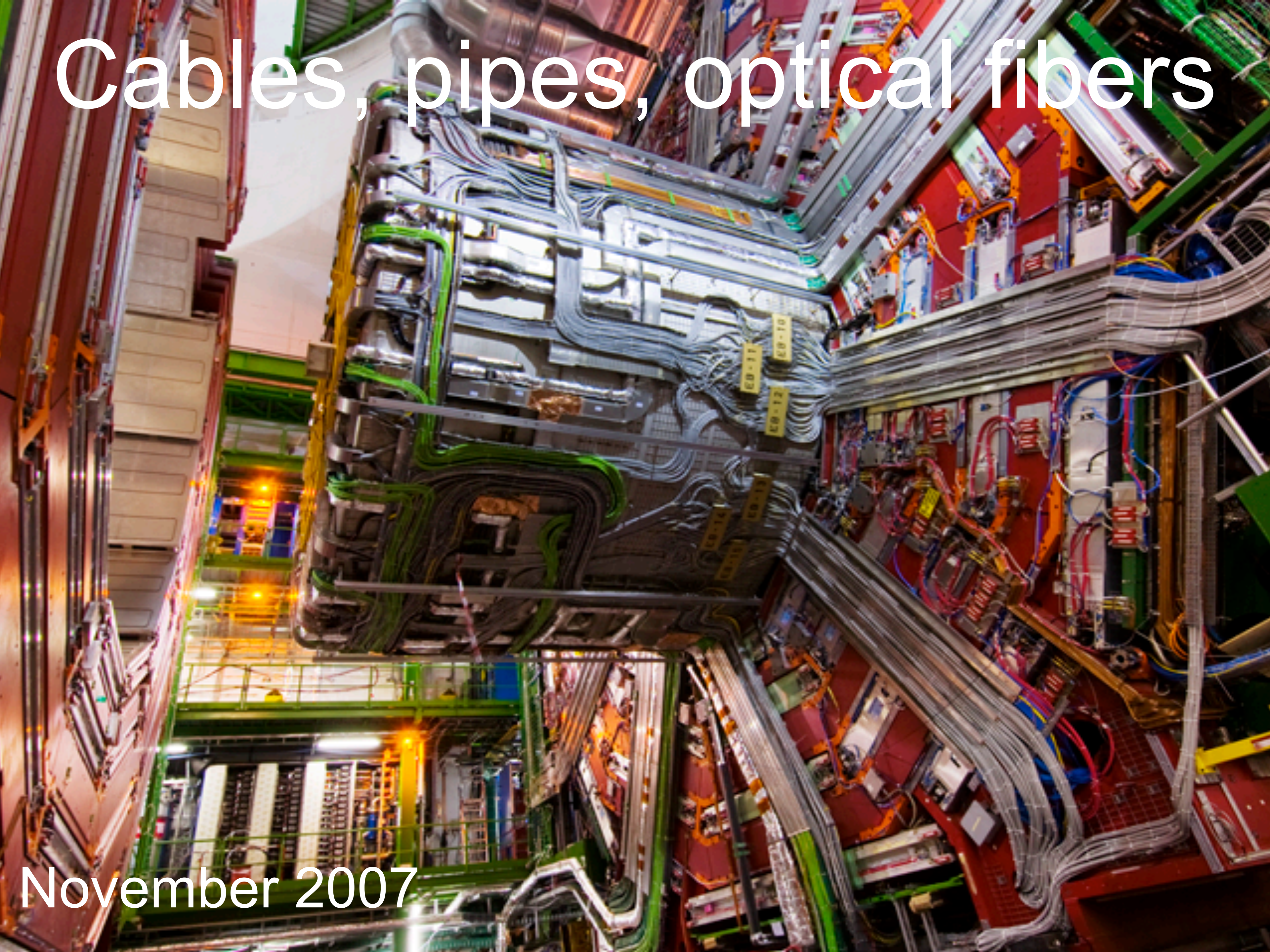


The barrel was lowered to the collision hall in Feb. 2007

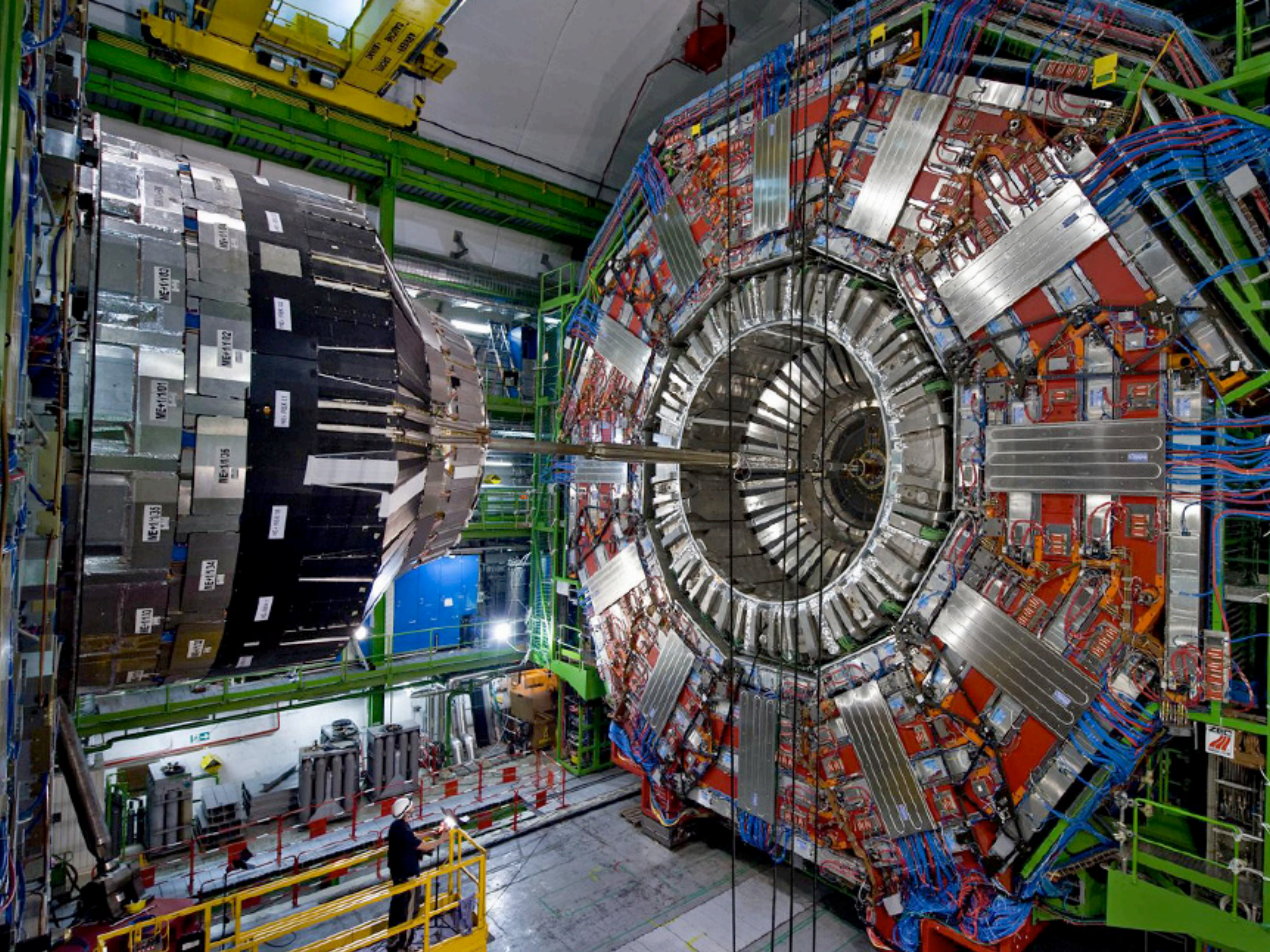
ECAL detector



Cables, pipes, optical fibers



November 2007




CMS tracker
next lecture, only this picture today