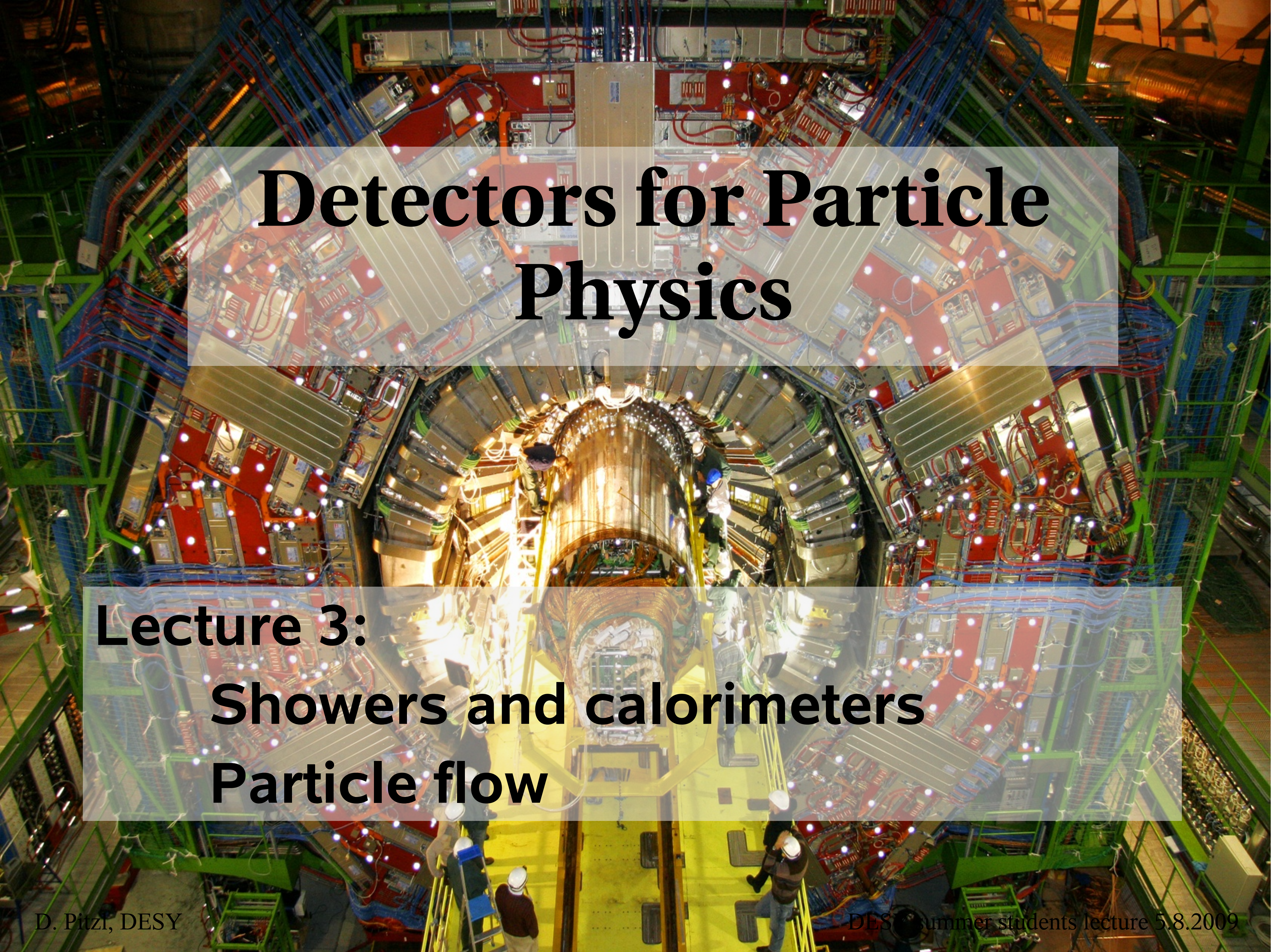


Detectors for Particle Physics

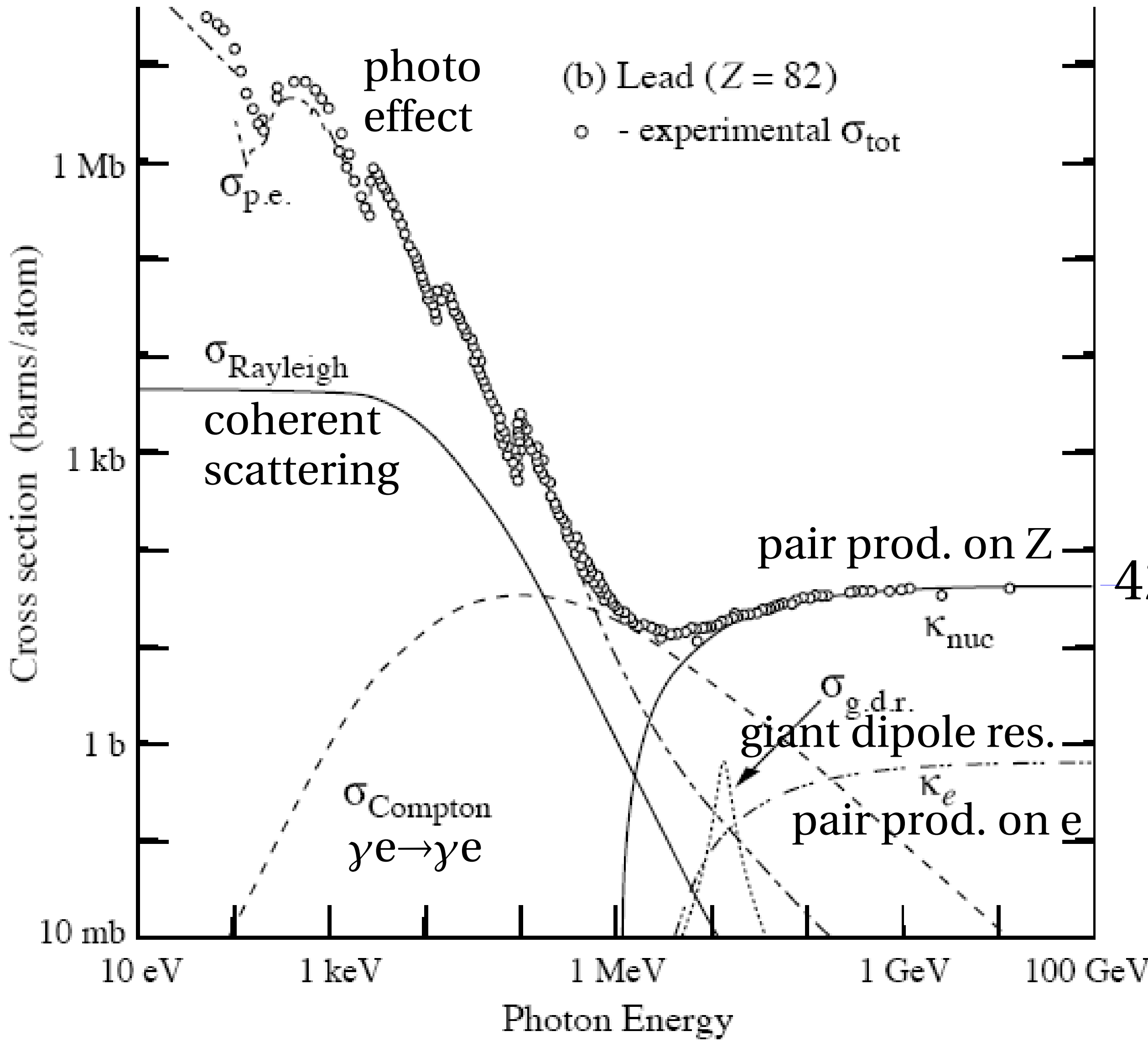
Lecture 3:

- Showers and calorimeters
- Particle flow

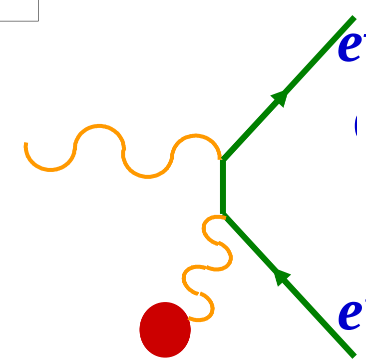
Outline

- Lecture 1:
  - Collider detectors
  - Charged particles in a magnetic field
  - Silicon detectors
- Lecture 2:
  - Drift tubes
  - Muon systems
  - MWPCs, CSCs, RPCs, TRTs, TPCs, Cherenkovs
- Lecture 3:
  - Electromagnetic showers and calorimeters
  - Photon detectors
  - Hadronics showers and calorimeters
  - Particle flow technique
- Discussion session:
  - Your questions, please

Photon interactions in matter (A, Z)



$\gamma A \rightarrow A^{*+} e^-$ $A^{*+} \rightarrow A^+ \gamma_{fluor}$	photo
$\gamma A \rightarrow A \gamma'$	Rayleigh
$\gamma e \rightarrow e \gamma'$	Compton
$\gamma Z \rightarrow Z e^+ e^-$	Pair
$\gamma e \rightarrow e e^+ e^-$	Pair



Pair production
$\gamma Z \rightarrow Z e^+ e^-$ dominates
above ~4 MeV

Radiation length

High energy photon cross section in lead: σ_γ = 42 barn/atom

Convert to photon absorption coefficient:

μ_γ [1/cm] = σ_γ [cm^2/atom] · N_A [atoms/mol] / A [g/mol] · ρ [g/cm^3]

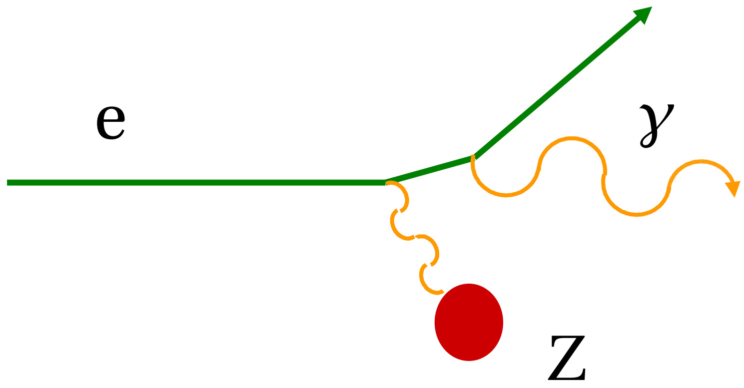
Define interaction length: $\lambda_\gamma = 1/\mu_\gamma$

Define radiation length: $X_0 = 7/9 \cdot \lambda_\gamma$

Plug in some numbers:
- 1 barn = 10^{-24} cm^2
- $N_A = 6 \cdot 10^{23}$ atoms/mol
- A = 207 for lead
- ρ = 11.35 g/cm^3 for lead

⇒ radiation length of lead: X_0 = 0.56 cm.

Radiation Loss for electrons in matter



- Bremsstrahlung: e Z → Z e γ
  electromagnetic radiation produced by the deceleration of an electron, when deflected by an atomic nucleus.

$$-\frac{dE}{dx} = \frac{E}{X_0}$$

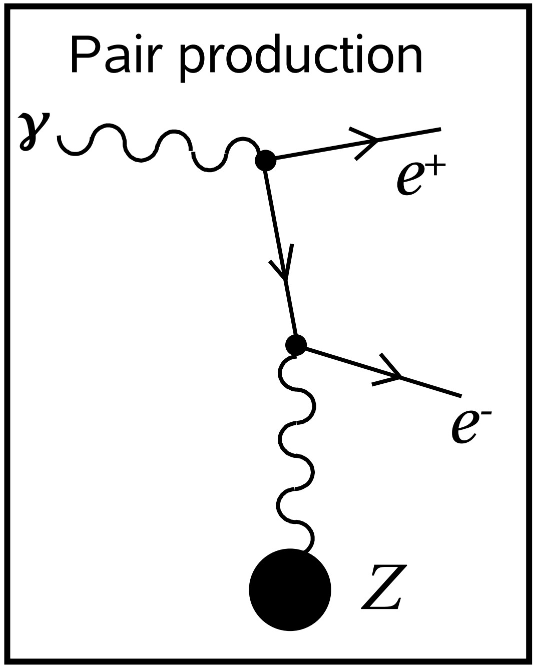
$$X_0[cm] = \frac{716}{\rho\,[g/cm^3]}\,\frac{A}{Z}\,\frac{1}{(Z+1)\ln(287/\sqrt{Z})}$$

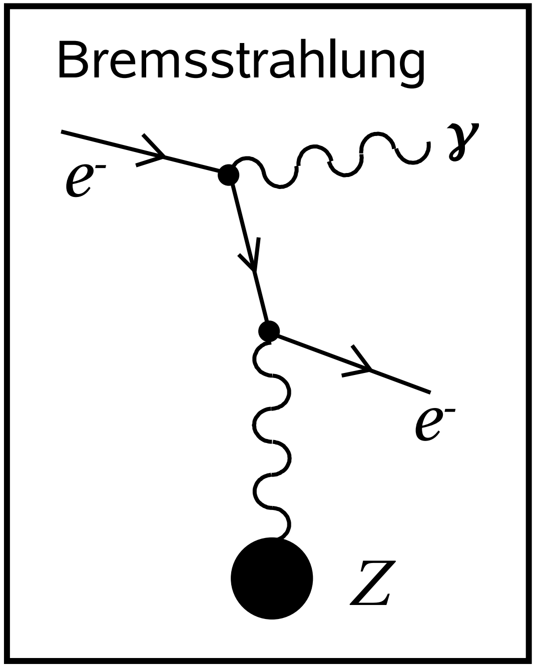
$$\Leftrightarrow E = E_0 e^{-x/X_0}$$

Pb: $X_0 = 0.56$ cm

Si: $X_0 = 8.9$ cm

Pair production and Bremsstrahlung





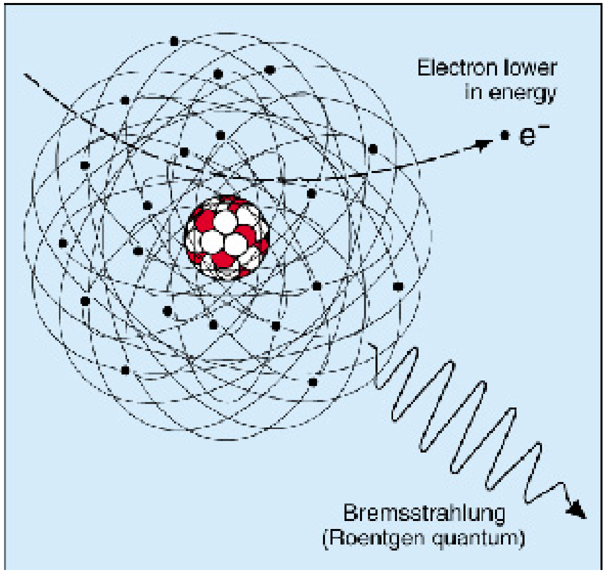
- Very similar Feynman diagrams
- Just two arms swapped.

At high energy: $\sigma_\gamma = 7/9\, \sigma_e$

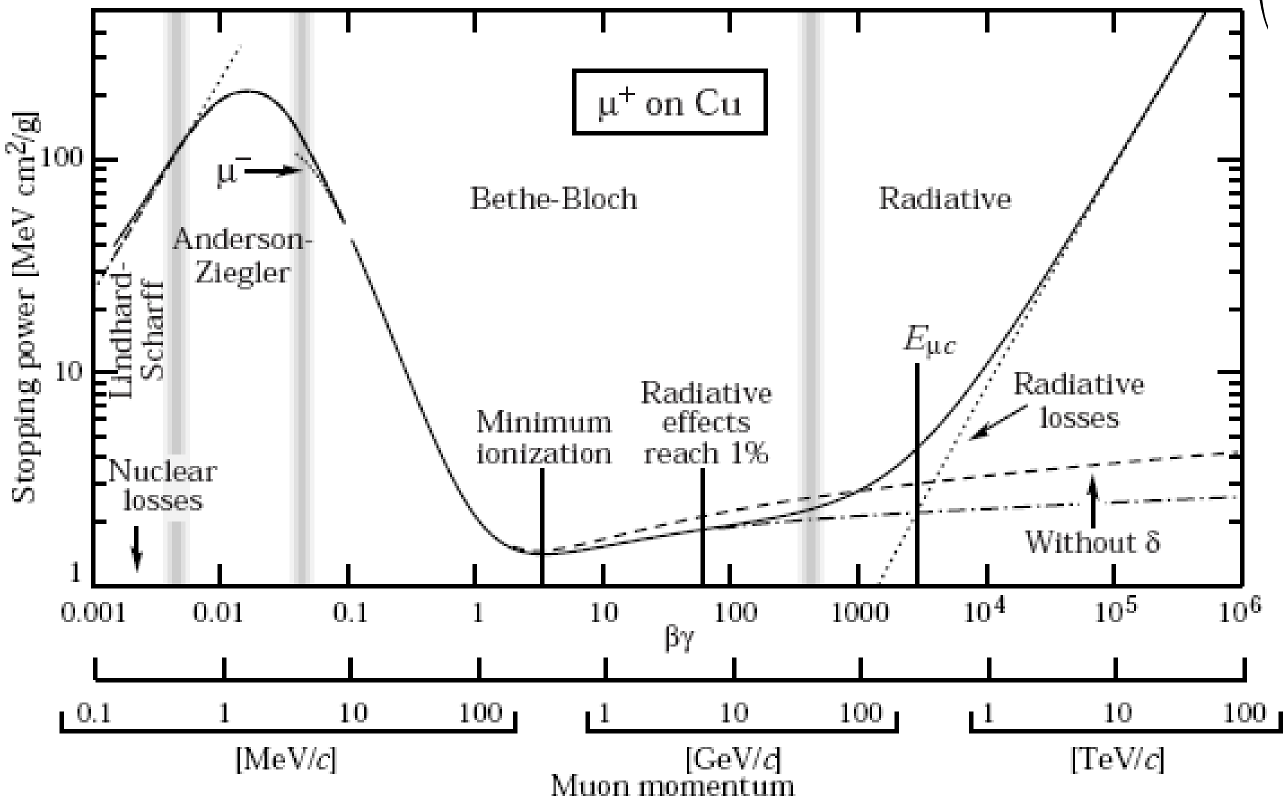
Muons radiate only at extreme energies

A particle of mass **m** may radiate a photon while being decelerated in the Coulomb field of a nucleus **Z**:

$$\frac{d\sigma}{dE} \propto \frac{Z^2}{m^2} \frac{\ln E}{E}$$



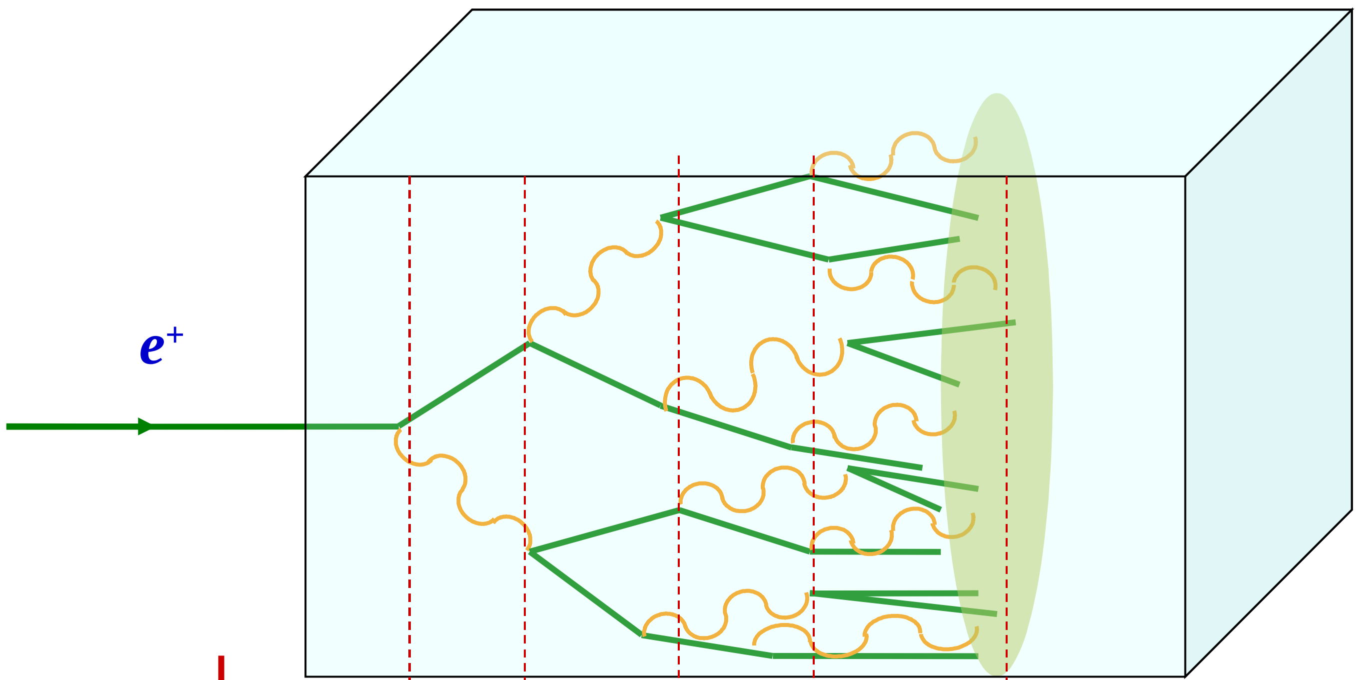
classically, radiation power $P \propto a^2 = \left(\frac{F}{m}\right)^2$



$$\frac{m_e^2}{m_\mu^2} = 2.3 \cdot 10^{-5}$$

critical energy for muons is 450 GeV in copper, 200 GeV in lead.

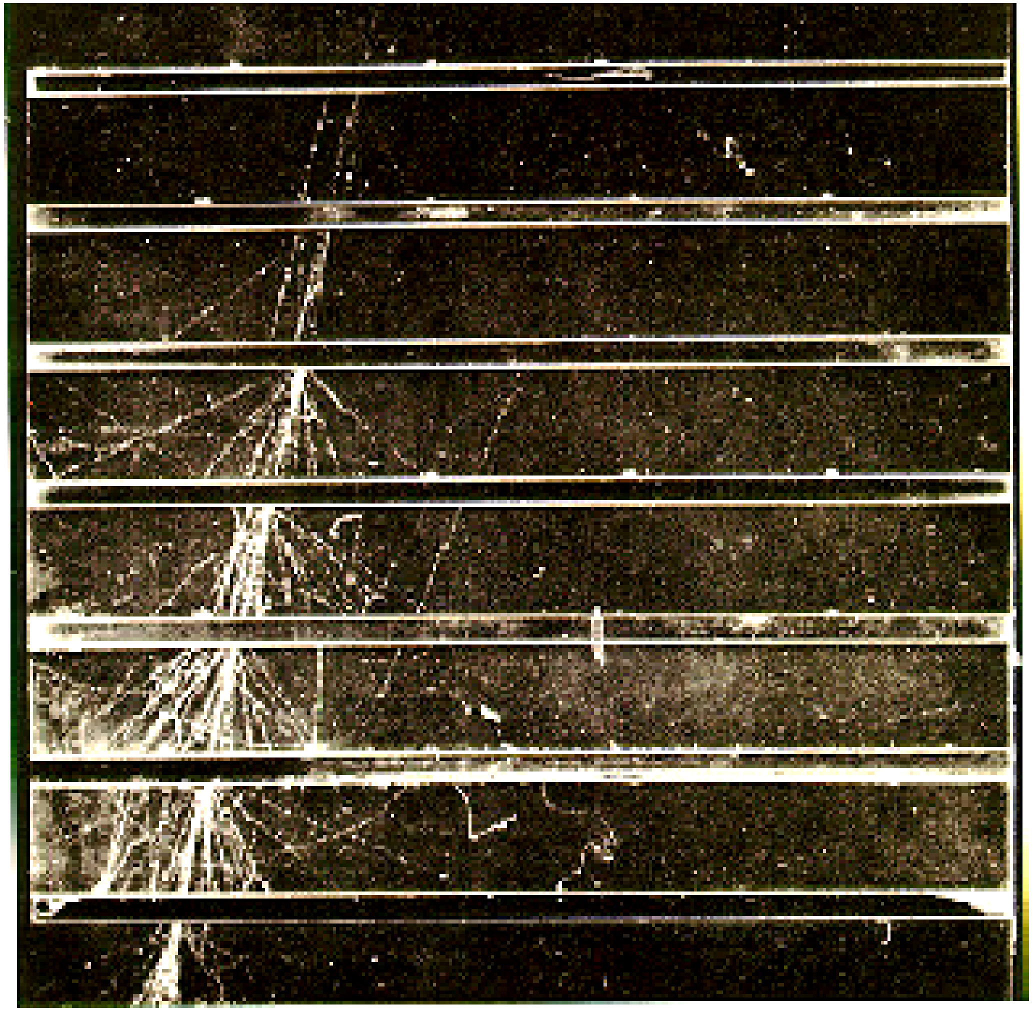
Electromagnetic Showers



x	0	X_0	$2X_0$	$3X_0$	$4X_0$	
N	1	2	4	8	16	0
$\langle E \rangle$	E_0	$E_0/2$	$E_0/4$	$E_0/8$	$E_0/16$	$< E_c$

Shower in a cloud chamber

- Cloud chamber image of a shower between lead plates.



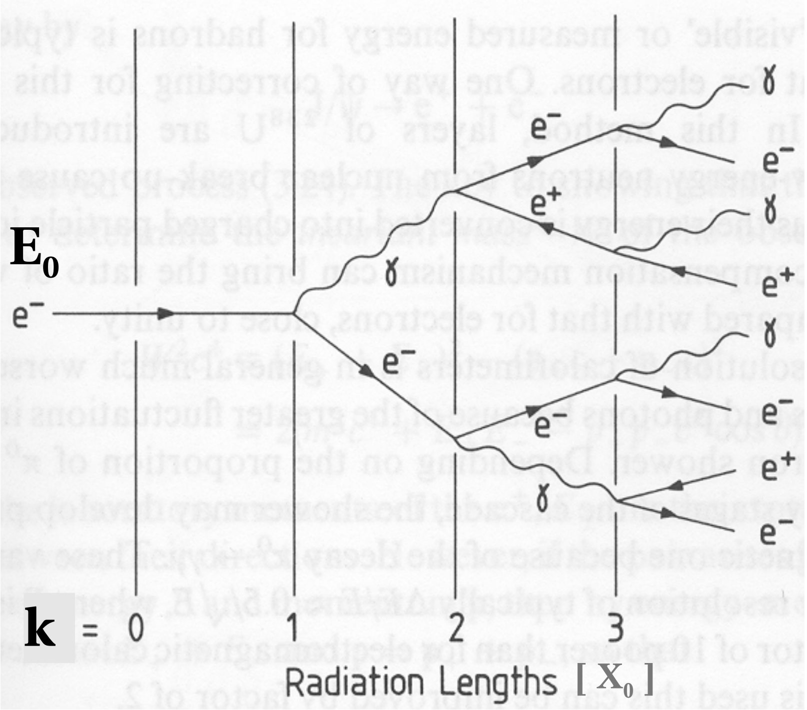
A simple shower model

Start with a high energy electron: $\mathbf{E_0}$

$\Rightarrow$ After $\mathbf{1X_0}$: $\mathbf{1\ e^-}$ and $\mathbf{1\gamma}$, each with $\mathbf{E_0/2}$

$\Rightarrow$ After $\mathbf{2X_0}$: $\mathbf{2\ e^-}$, $\mathbf{1\ e^+}$ and $\mathbf{1\ \gamma}$, each with $\mathbf{E_0/4}$

$\Rightarrow$ After $\mathbf{kX_0}$: total $\mathbf{N = 2^k}$, each with $\mathbf{\langle E\rangle = E_0/2^k}$



At $\mathbf{\langle E\rangle = E_c}$ pair production and bremsstrahlung stop.

Compton- or photoeffect and ionization take over. The shower ranges out.

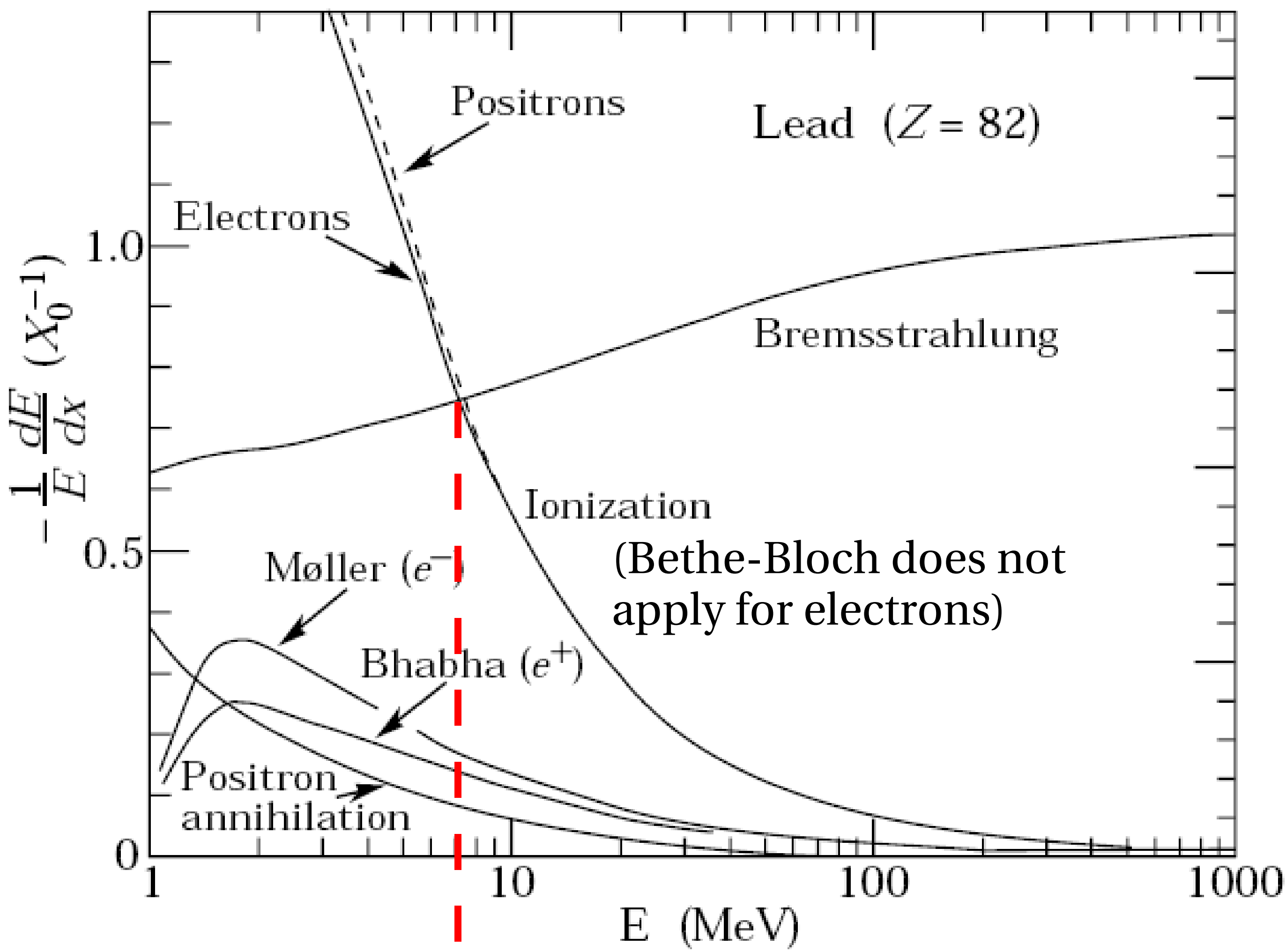
$E_c = 0.6$ GeV / (Z+1.24) = 7 MeV for lead. (empirical fit by the PDG)

$\Rightarrow$ $\mathbf{k_{max} = lg_2(E_0/E_c)}$. **Shower depth grows logarithmically with E_0.**

$\Rightarrow$ $\mathbf{N_{max} = 2^{kmax} = E_0/E_c}$. **Number of shower particles grows linearly with E_0.**

Electron energy loss and critical energy

relative energy loss for electrons:



(Bethe-Bloch does not apply for electrons)

7 MeV in Pb.

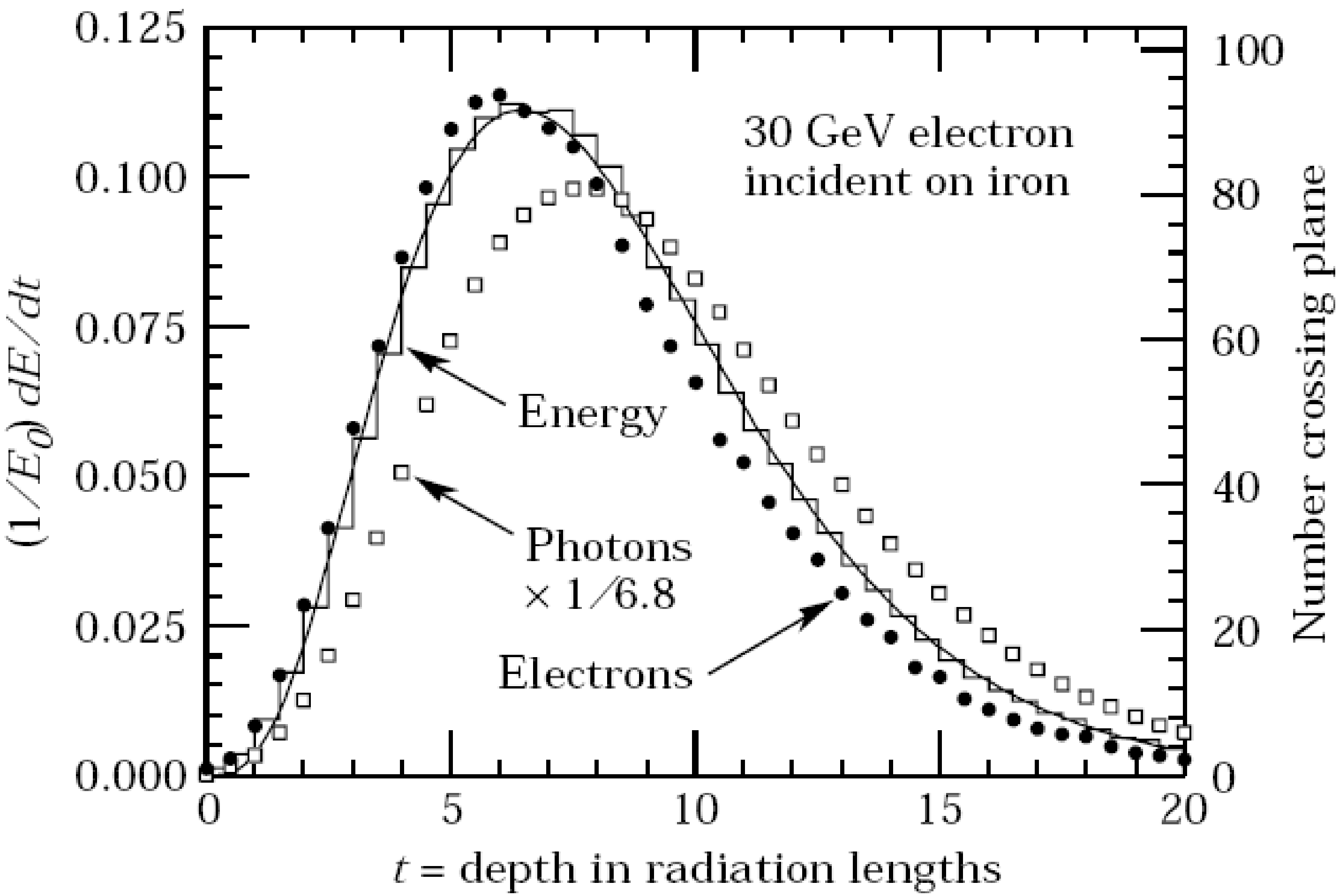
Critical energy: energy loss due to Bremstrahlung and ionization are equal:

$$E_c \approx \frac{610\ MeV}{Z + 1.24}$$

High Z material gives more signal: shower stops later

A sophisticated shower simulation

Energy profile

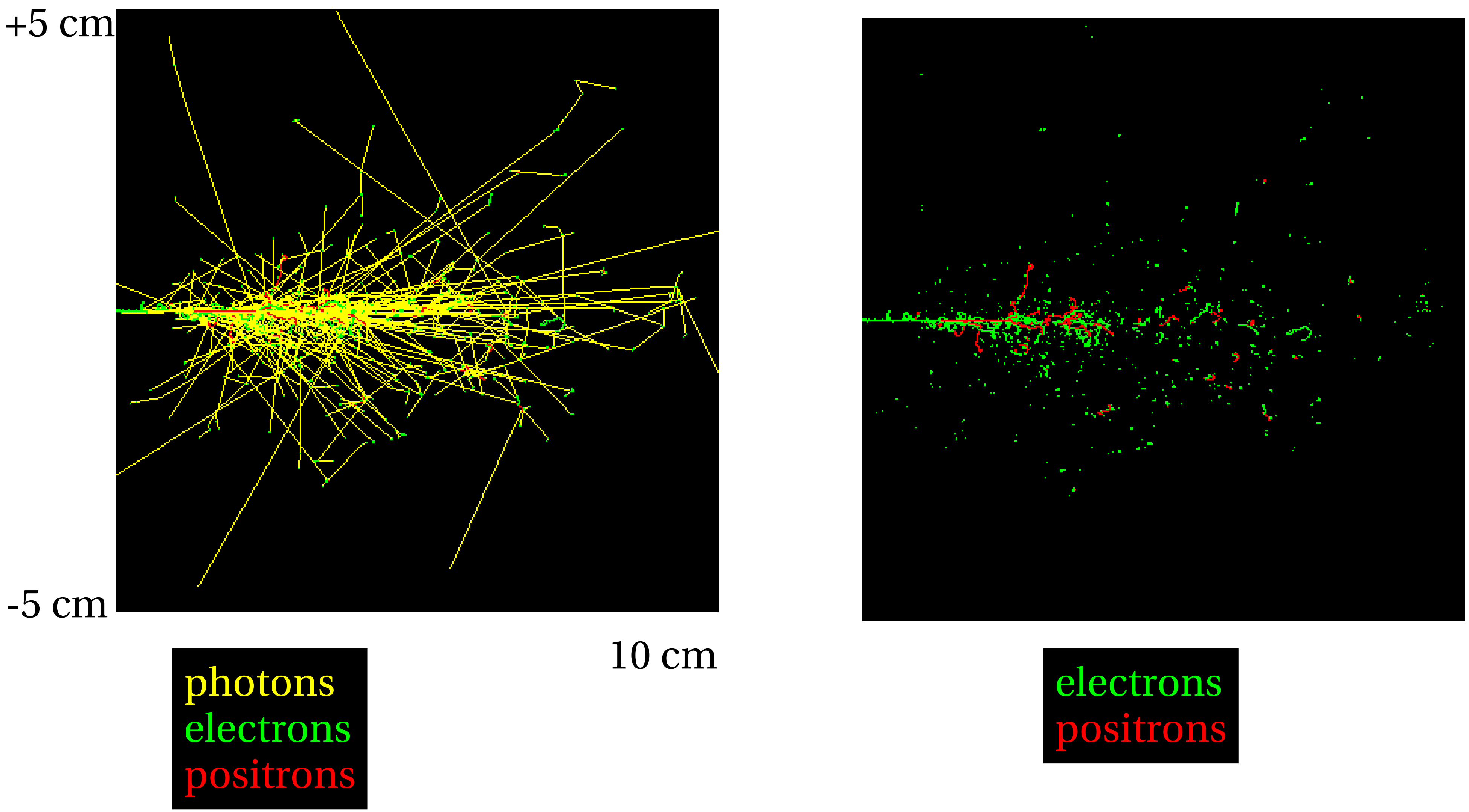


particle flow

$$\frac{dE}{dt} \triangleq E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}, \quad t \quad \frac{x}{X_0}$$

Shower simulation

1 GeV e^- in lead



interactive at http://www2.slac.stanford.edu/vvc/egs/basicsimtool.html

Energy measurement

Total number of particles in the shower in the simple model:

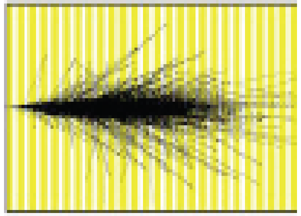
$\mathbf{N_{tot} = \Sigma_k 2^k = 2\, k_{max} - 1 \approx 2\, E_0 / E_c}$

2/3 of N_{tot} are charged ($e^+ + e^-$).

$\Rightarrow$ $\mathbf{N_{ch} \approx 4/3\, E_0 / E_c}$

Each *e* travels 1 X0 between interactions.

$\Rightarrow$ **total path length:** $\mathbf{L_{ch} \approx 4/3\, X_0\, E_0 / E_c}$



Electrons and positrons also **ionize** the medium.

collect charge or fluorescent light signal: $\mathbf{S \sim X_0\, E_0 / E_c}$

After calibration, S is an energy measurement!

Shower fluctuations: particle production is a Poisson process.

$\Rightarrow$ $\boldsymbol{\sigma(N) = \sqrt{N}}$

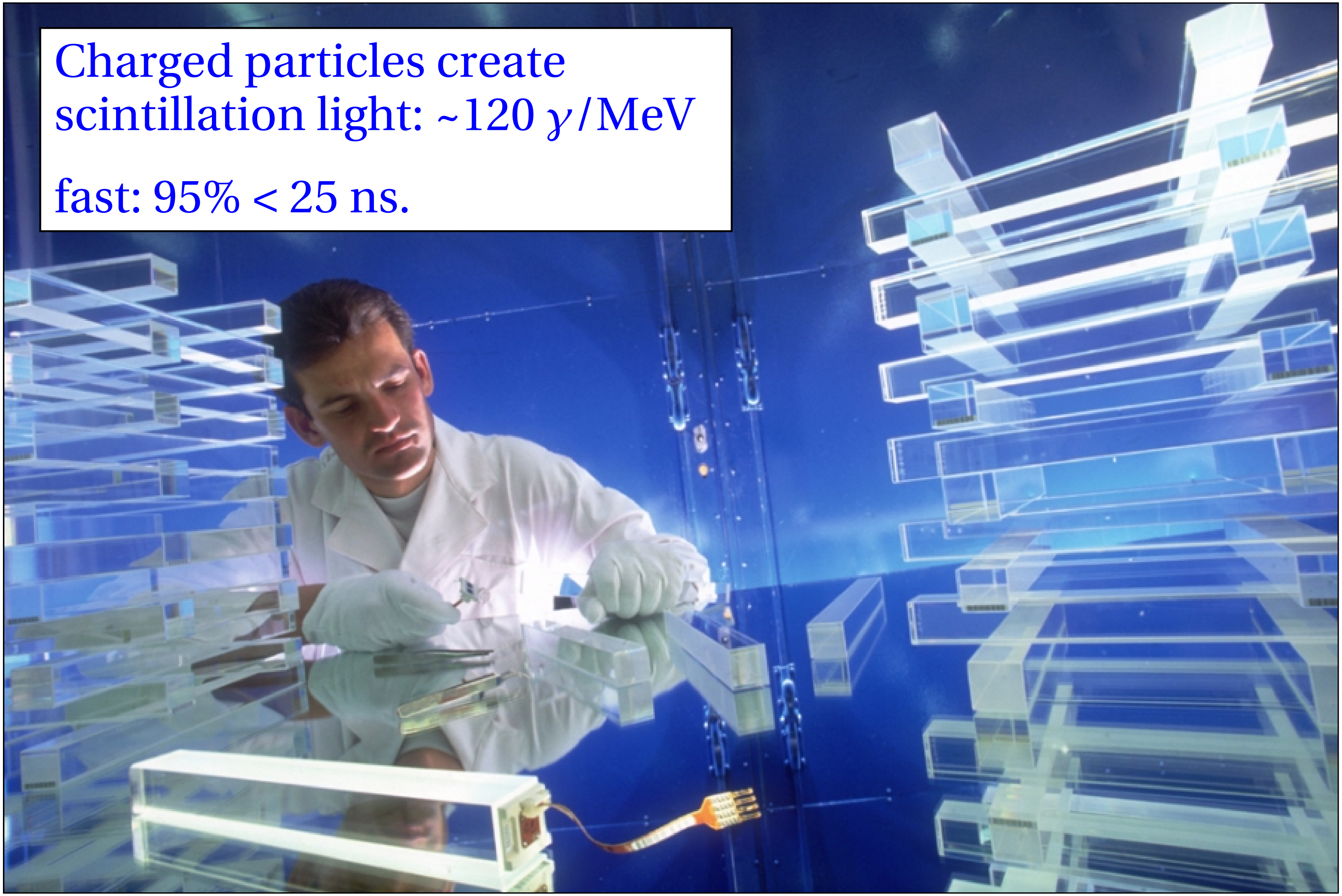
$\Rightarrow$ $\boldsymbol{\sigma(S) / S = 1 / \sqrt{S}}$

The relative energy resolution improves with $\mathbf{E_0}$!

CMS PbWO Crystals

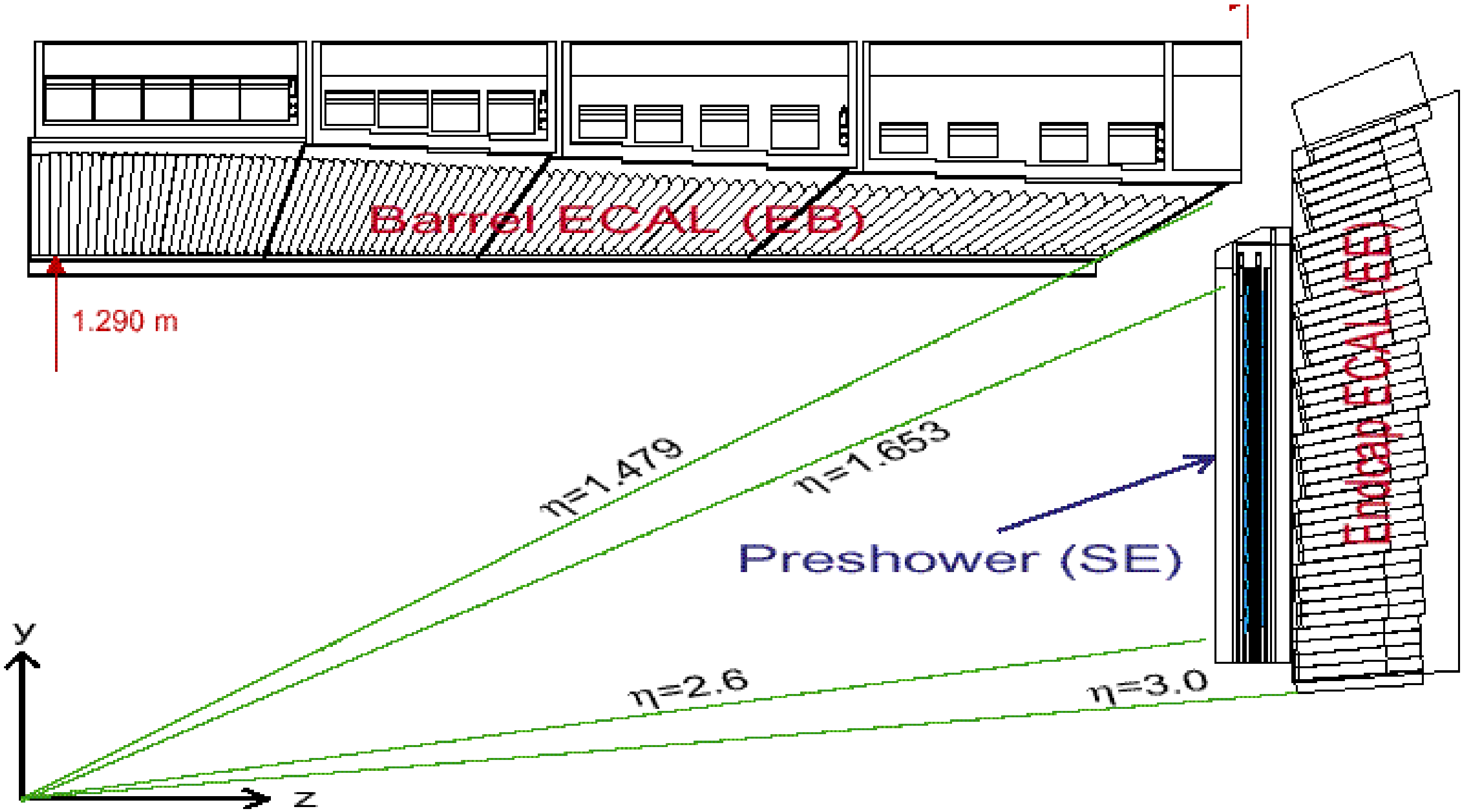
Charged particles create scintillation light: ~120 γ/MeV

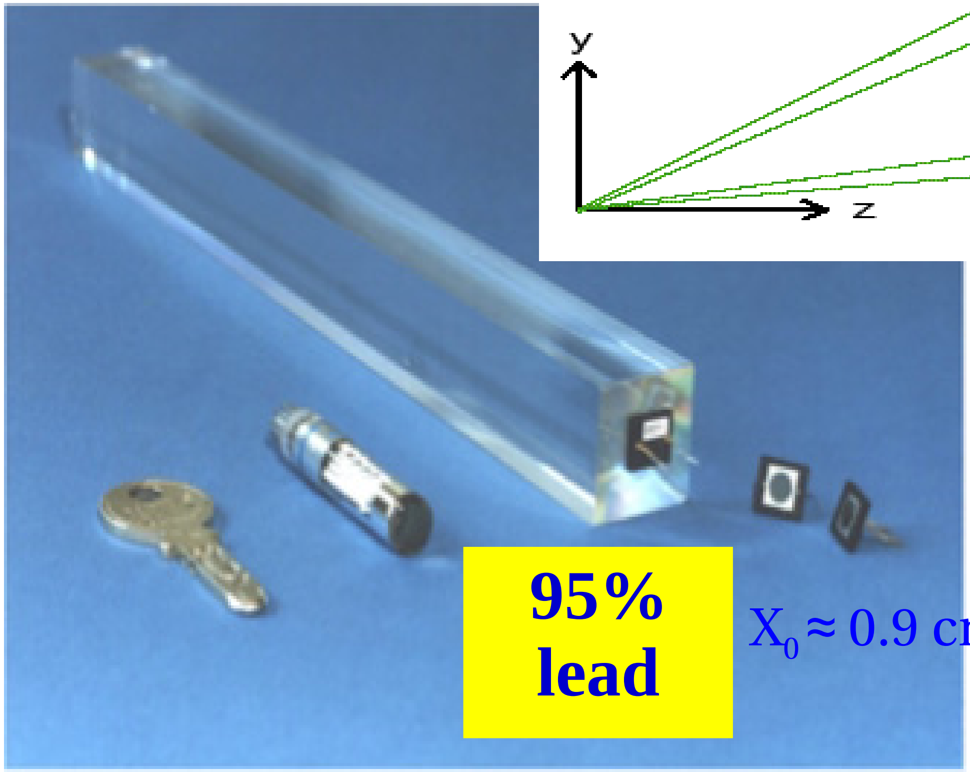
fast: 95% < 25 ns.



CMS ECAL

CMS $PbWO_4$ crystal calorimeter



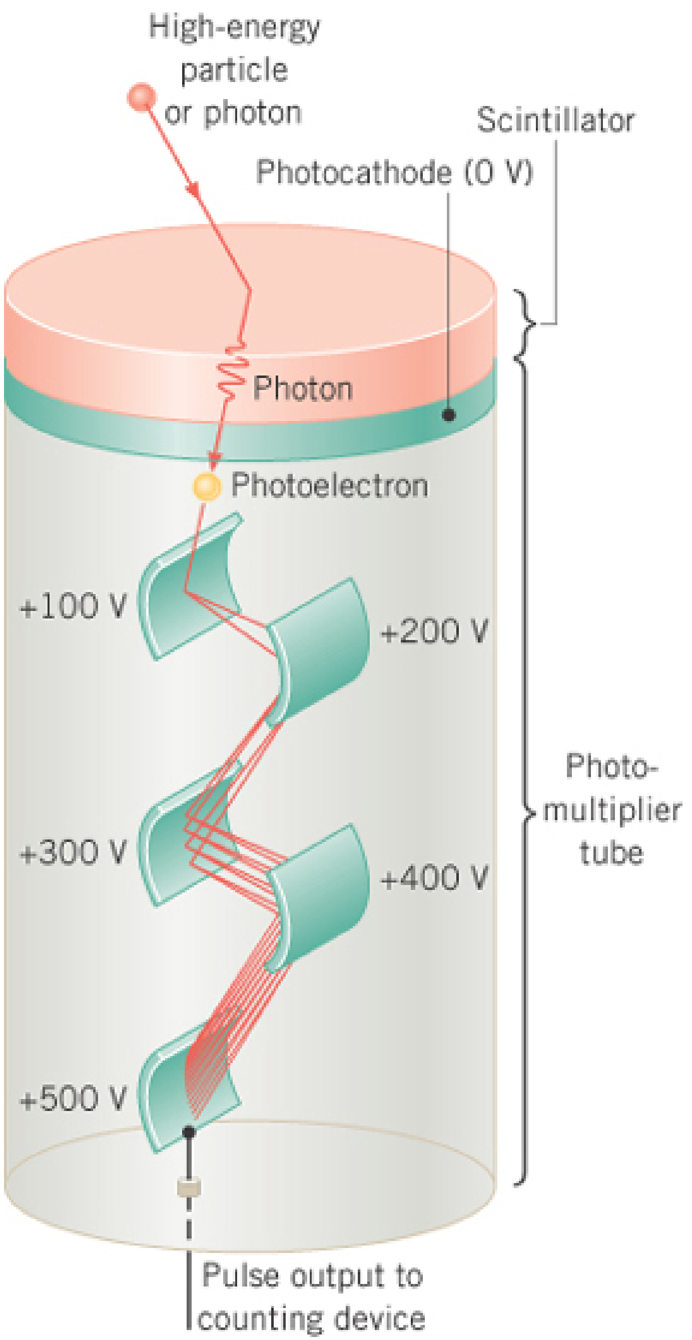


$X_0 \approx 0.9$ cm

- **Barrel: 62k crystals 2.2 × 2.2 × 23 cm**
- **End-caps: 15k crystals 3 × 3 × 22 cm**

Photomultiplier Tube

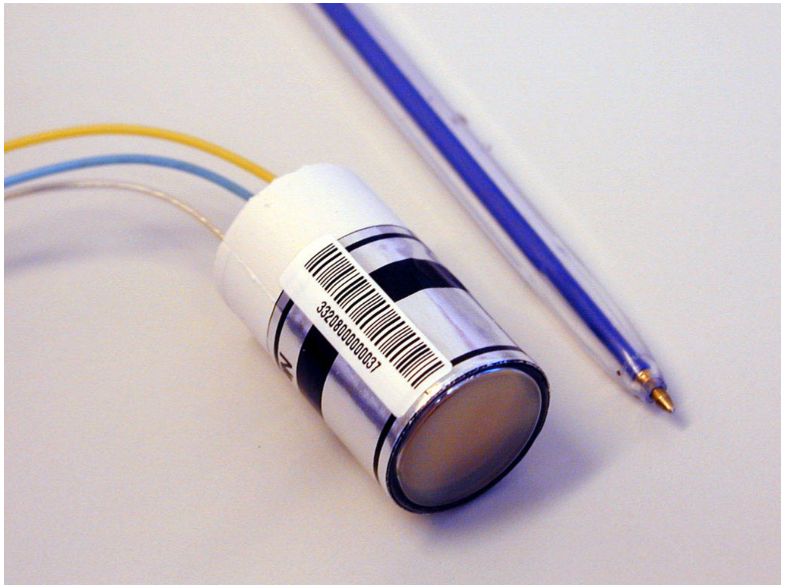
- Light falls on a photocathode and a photoelectron is emitted (photo effect)
  - **Quantum Efficiency** depends on cathode material and wavelength (QE ~ 25%)
- Photoelectron focused and accelerated towards the first **dynode** by electric field.
- Photoelectron strikes dynode and several electrons are emitted (on average n ~ 5)
- Several dynodes (~ 10-15) give high gain (10^7)
- High speed: few ns transit time.
- Gain can be much lower in magnetic fields, depending on orientation.



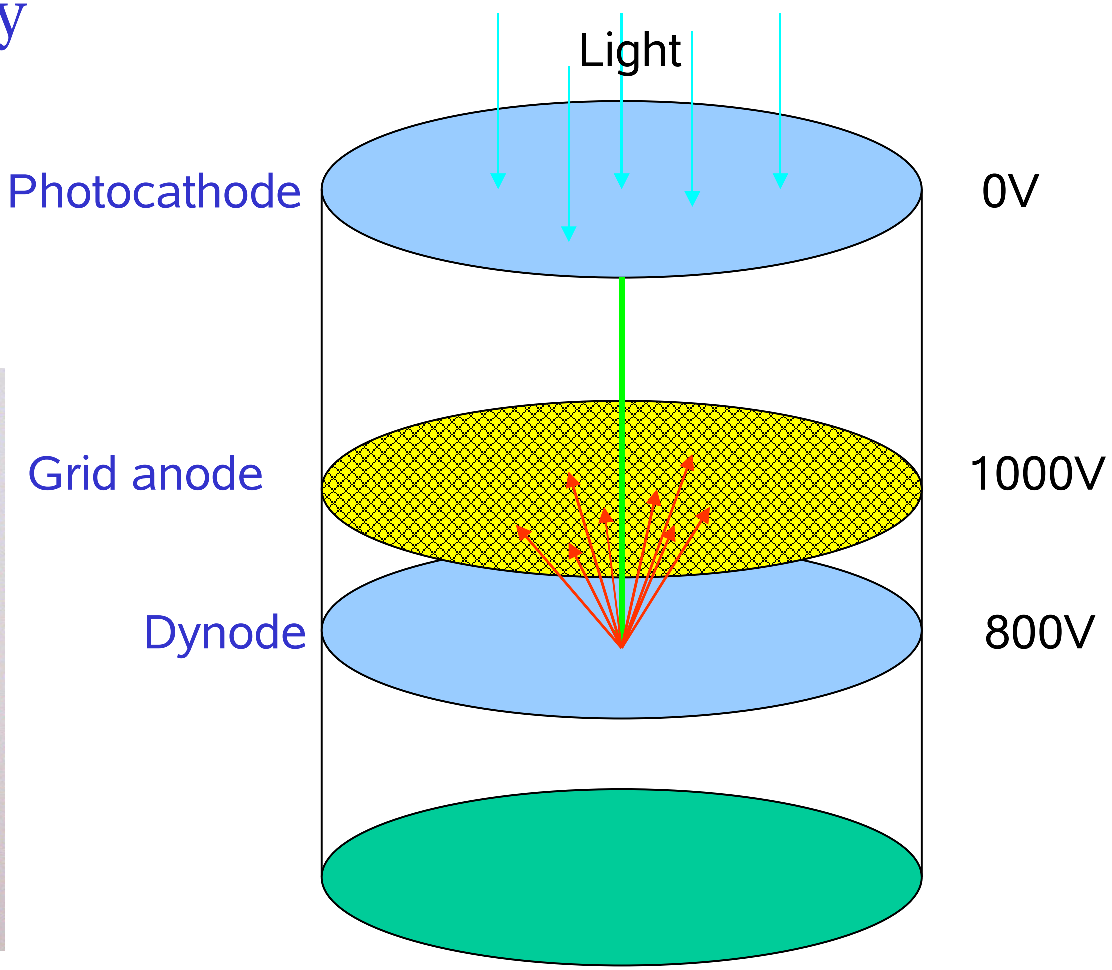
Source: Cutnell and Johnson, 7th edition image gallery

Vacuum photo-triodes

- ~20% quantum efficiency
- Single-stage photomultiplier
- Gain ~ 10 at B = 4 T



radiation-resistant UV glass window
used in the CMS endcap ECAL.



Avalanche Photodiode

85% quantum efficiency

300-400 V reverse bias:

photoelectrons create cascade of electron-hole pairs in the bulk.

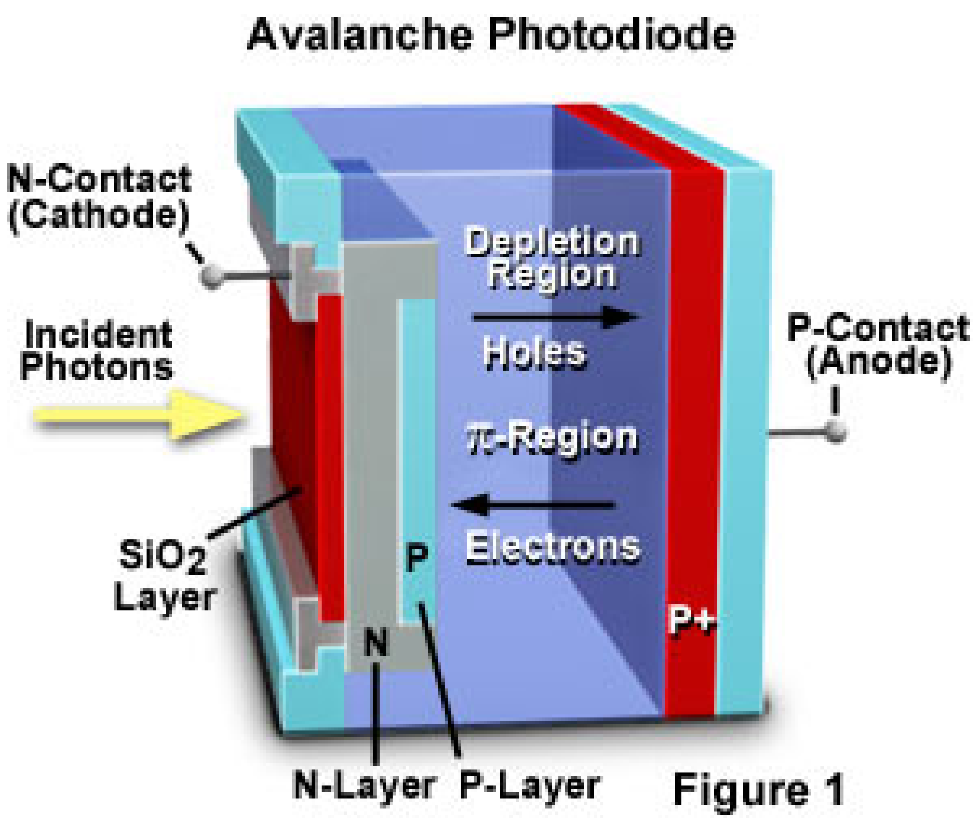
Gain ~100 in linear mode.

Low sensitivity to magnetic field.

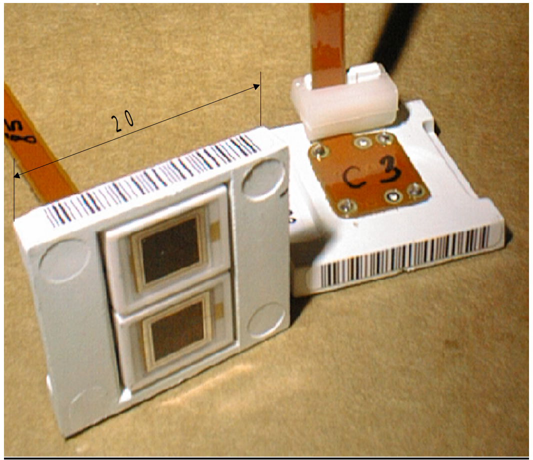
APD gain decreases by 2.3%/^{O}C.

Crystal light yield decreases by 2.2%/^{O}C

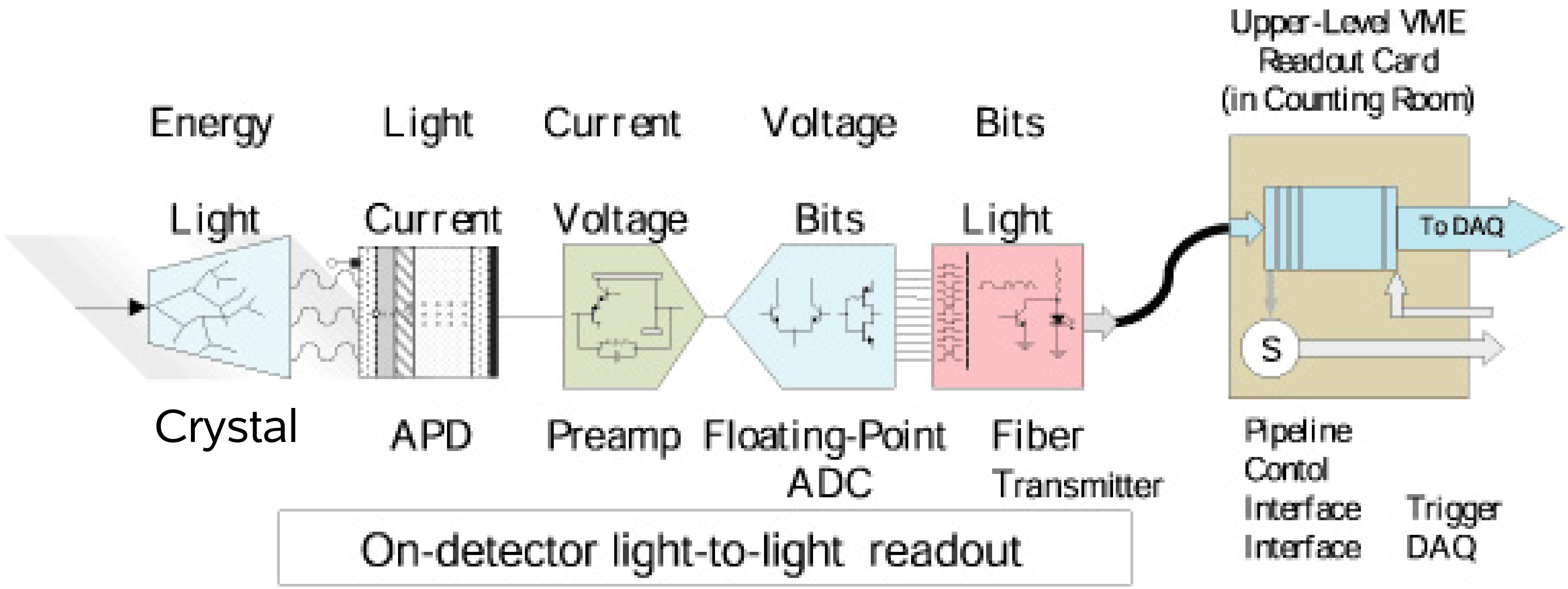
Need temperature stabilization within 0.1^{O}C in the ECAL!



2 avalanche photodiodes per crystal in the barrel:

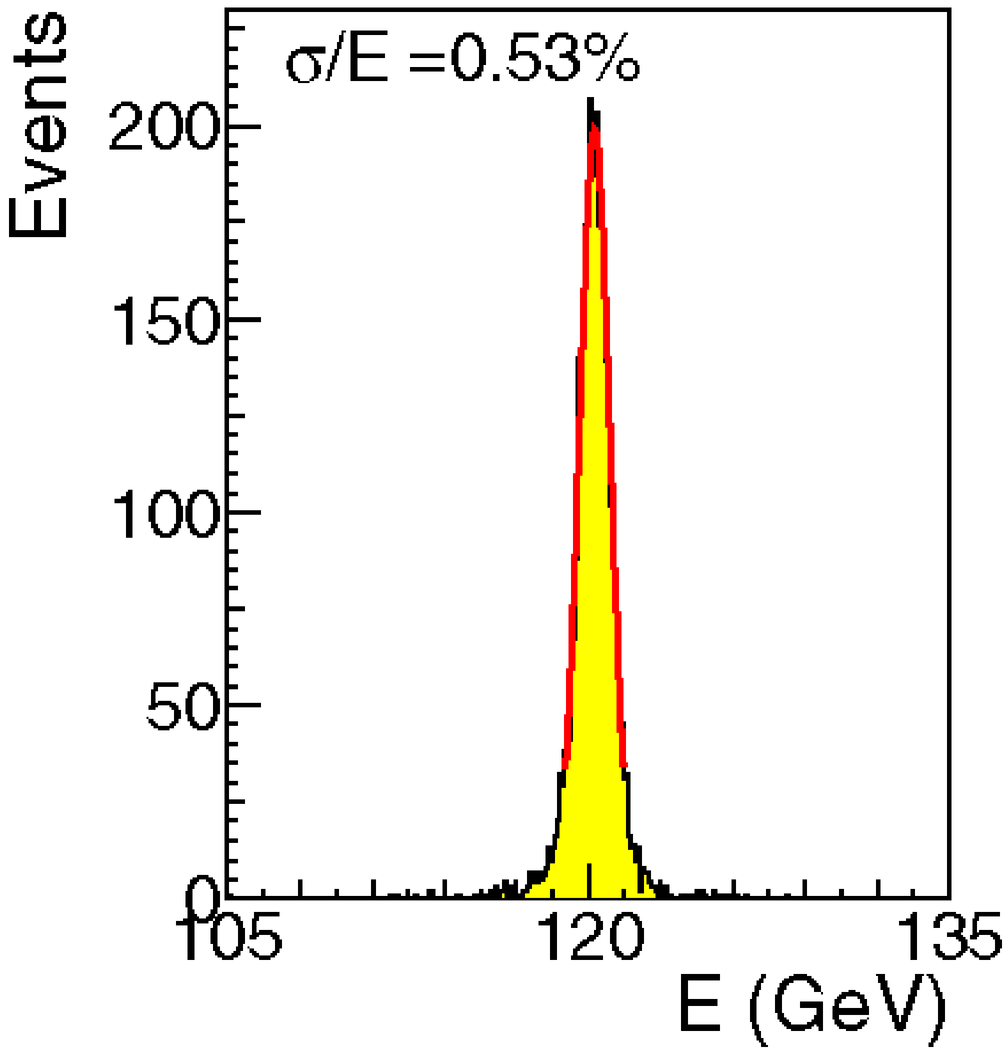


CMS EM Calorimeter Readout



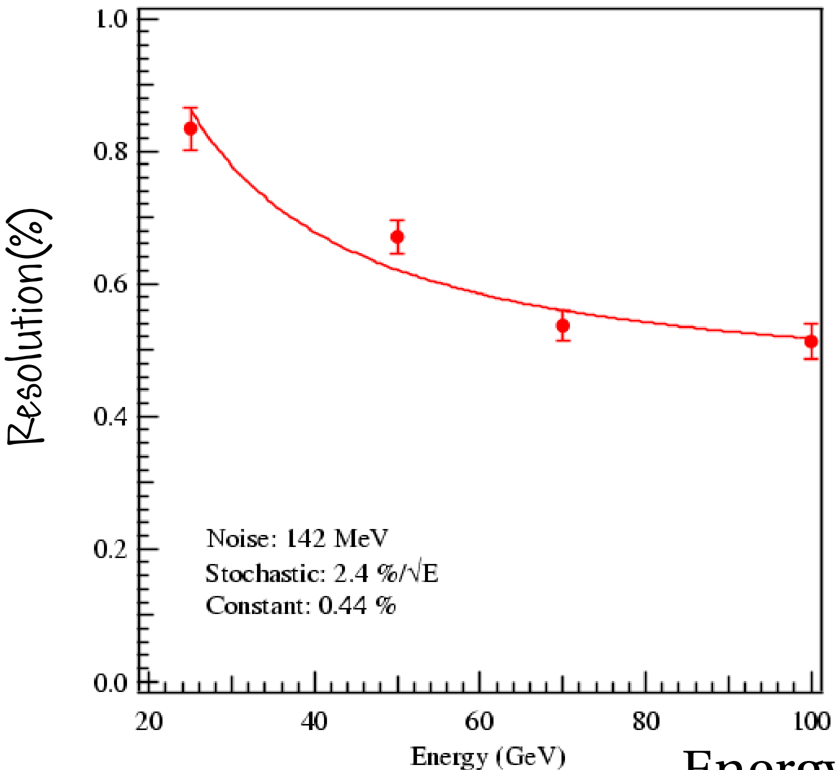
Test beam calibration

Response of a $PbWO_4$ calo to a 120 GeV e^- test beam:



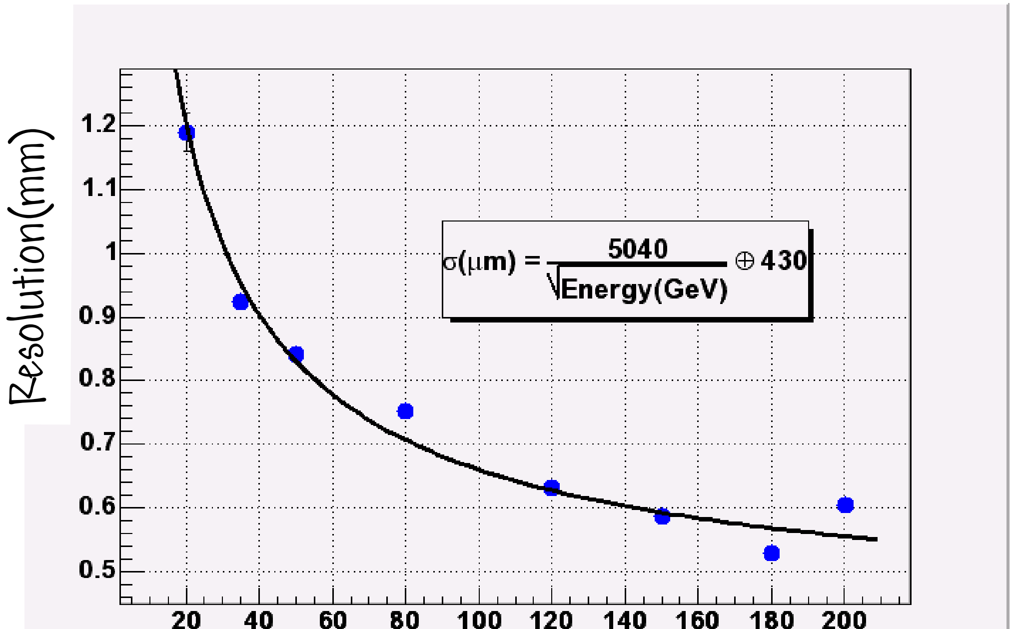
CMS ECAL Test beam with final electronics.

Energy



Energy (GeV)

Position



Energy (GeV)

$$\frac{\sigma(E)}{E} = \frac{2.4\,\%}{\sqrt{E}} \oplus \frac{142\,\text{MeV}}{E} \oplus 0.44\ \%$$

0.6% at 50 GeV.

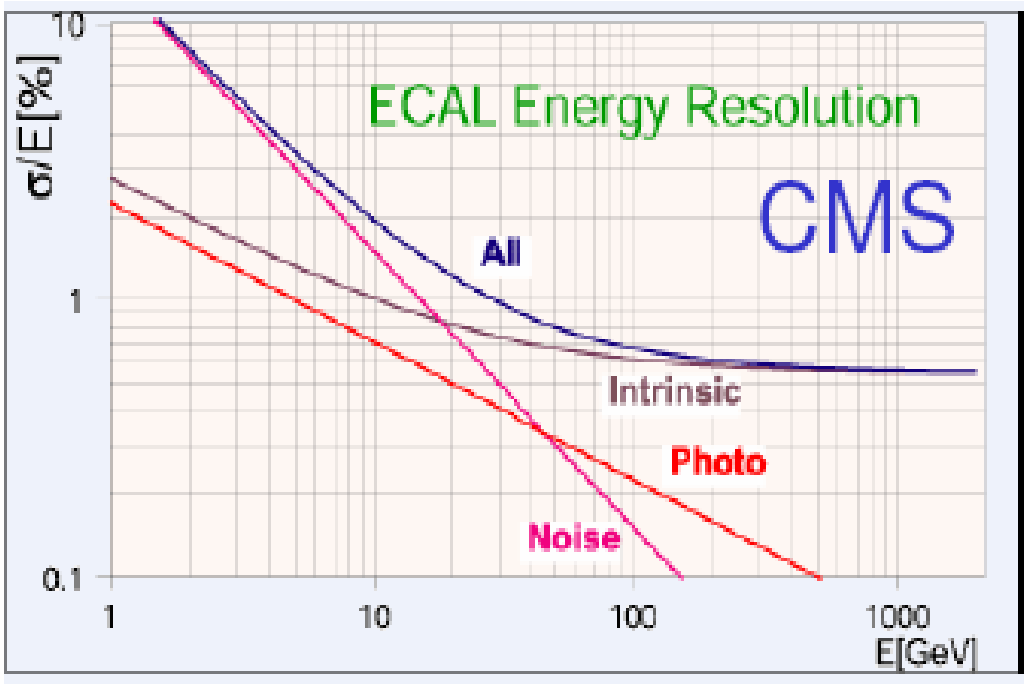
$$\sigma_Y\ (\mu m) = \frac{5040}{\sqrt{E}} \oplus 430$$

0.85 mm at 50 GeV.

Energy resolution terms

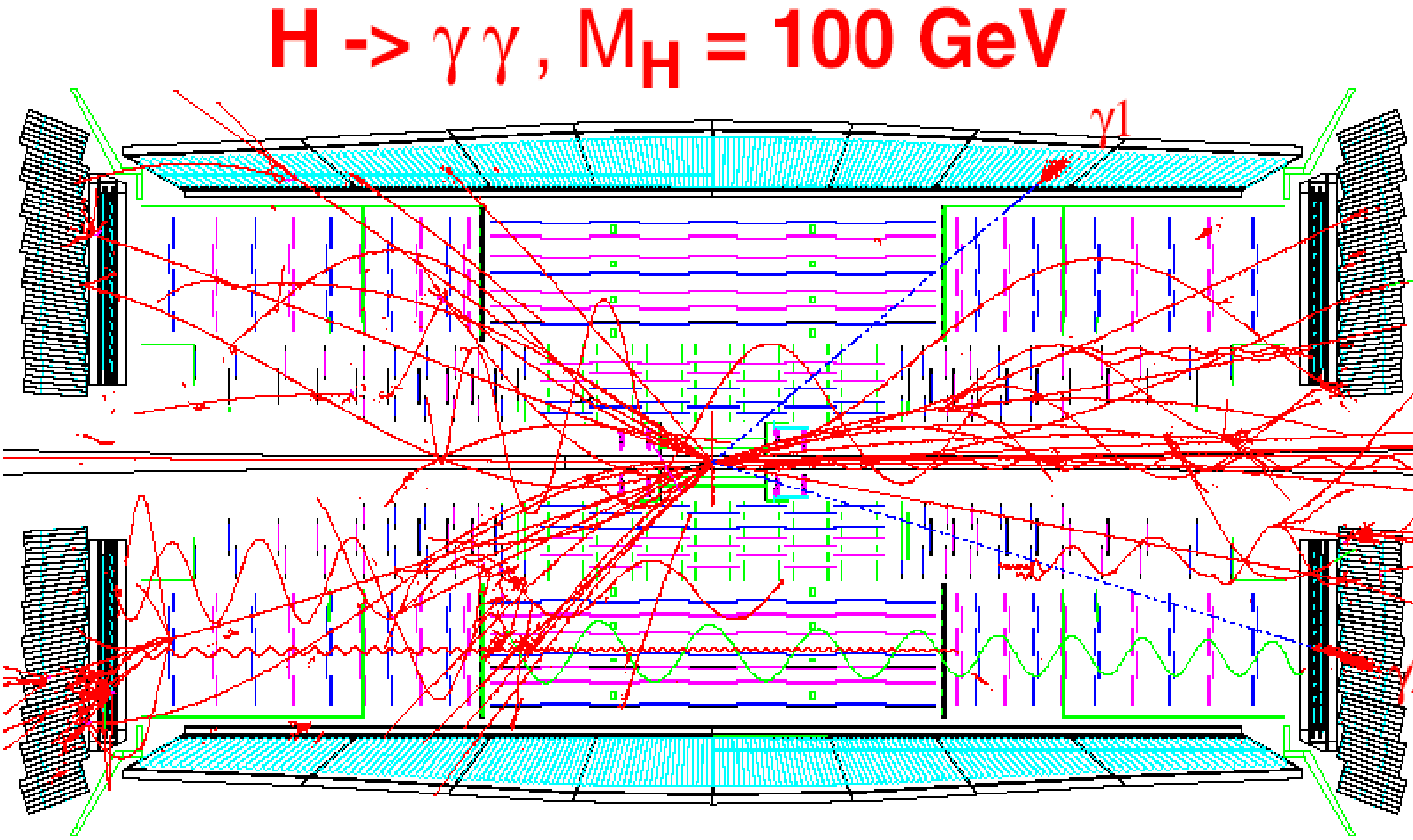
- The intrinsic shower fluctuations give σ(E) ~ √E
- Fluctuations in the photo-electron yield also give σ(E) ~ √E
- Noise (electronics, radiation) gives a constant term: σ(E) = c
- Inhomogeneities and leakage give σ(E) ~ E

σ(E) / E [%]



$$\frac{\sigma(E)}{E} = \frac{2.4\,\%}{\sqrt{E}} \oplus \frac{142\,\mathrm{MeV}}{E} \oplus 0.44\ \%$$

Higgs decay into two Photons



Sampling calorimeter

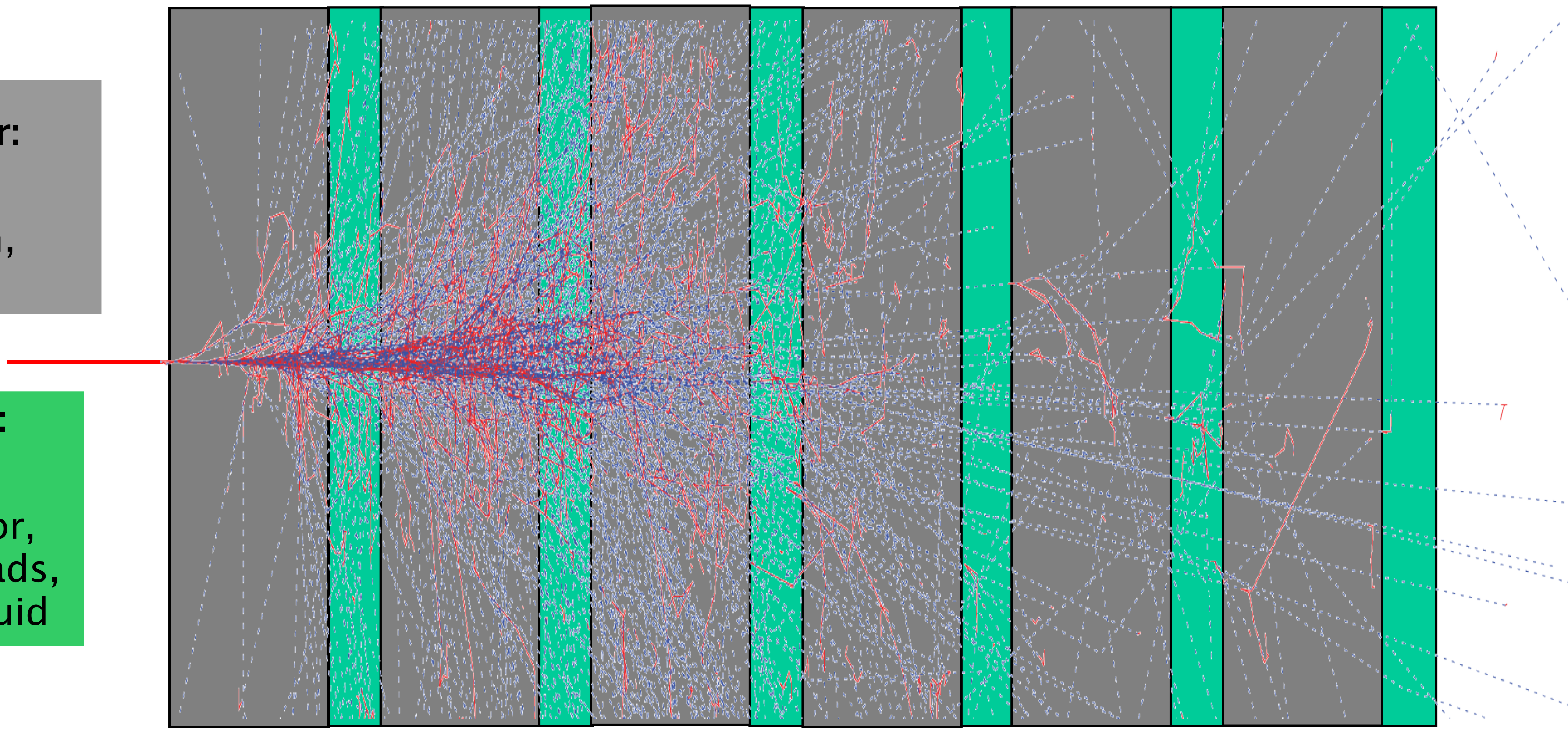
Absorber and detector are separated as passive and active layers.

Absorber:

Lead,
Tungsten,
Uranium

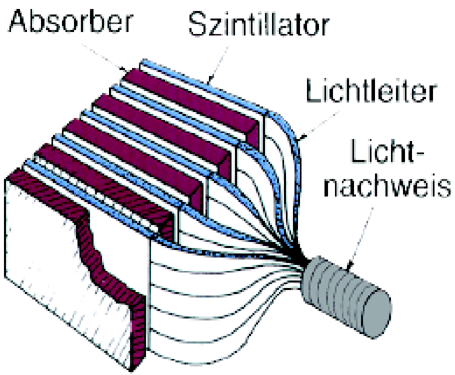
Detector:

MWPC,
scintillator,
silicon pads,
noble liquid

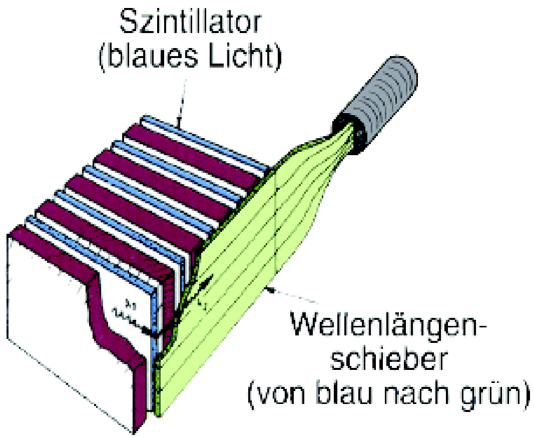


The active detector material **samples** a fraction F of the shower.
The detector signal is still proportional to the incident energy.
Allows longitudinal segmentation, good for hadrons.
Energy resolution is degraded ~$1/\sqrt{F}$ ('sampling fluctuations').
Less expensive.

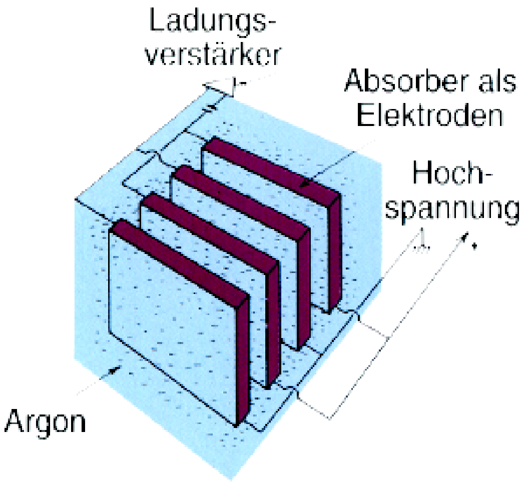
varieties of sampling calorimeters



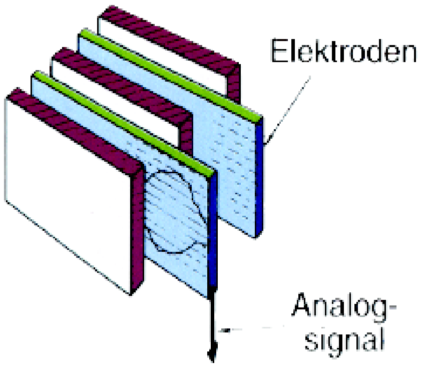
Absorber + scintillor
with photomultiplier readout
Fixed target experiments



Absorber + scintillator
with light guide to PMT
ZEUS at HERA
CDF at Tevatron

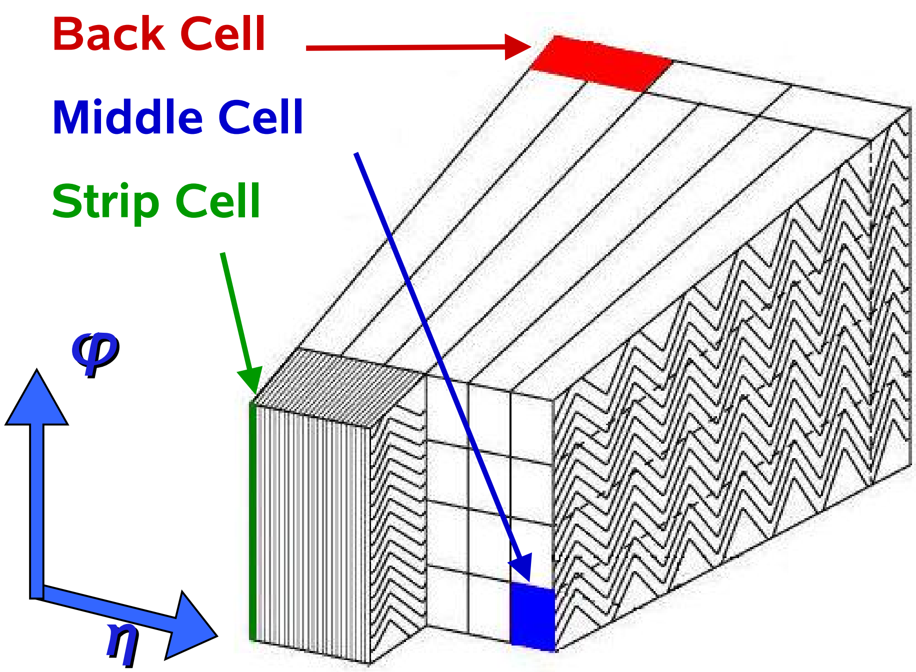


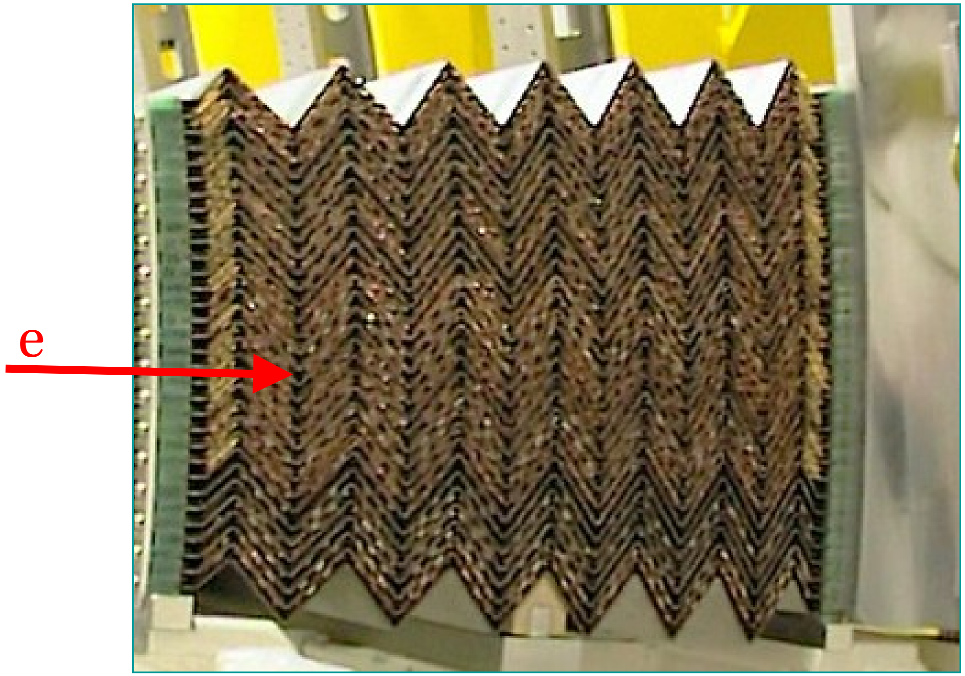
Absorber and liquid argon
electronic readout of ionization signal
H1 at HERA, D0 at Tevatron, ATLAS



Gas ionisation chamber:
DELPHI and ALEPH at LEP

ATLAS LAr ECAL

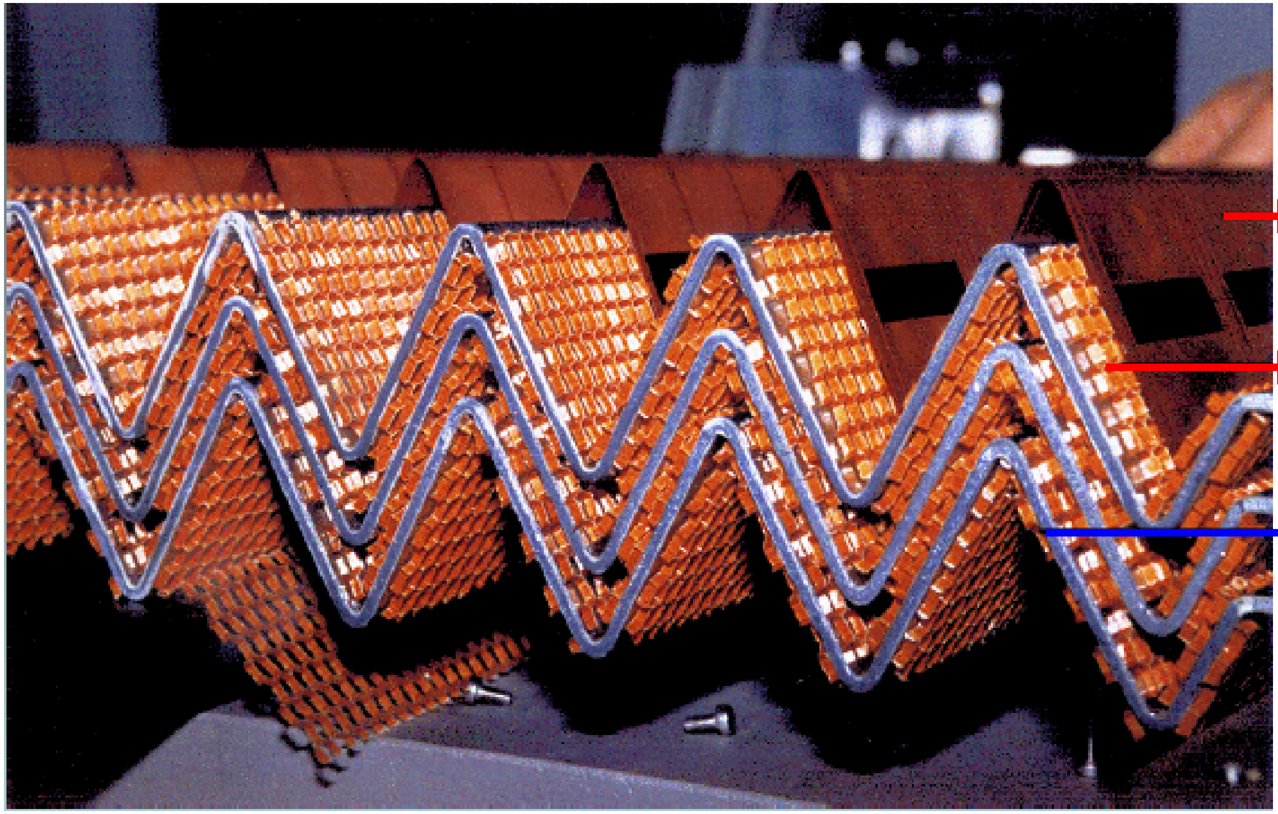




3 sections:
- strips for position resolution
- middle for energy measurement
- back for leakage control

- Pb absorber in LAr
- Accordion geometry for routing of readout signals to the back
- Allows dense packing and fine granularity.

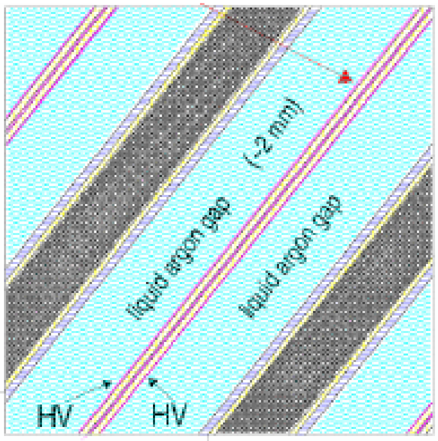
ATLAS LAr ECAL



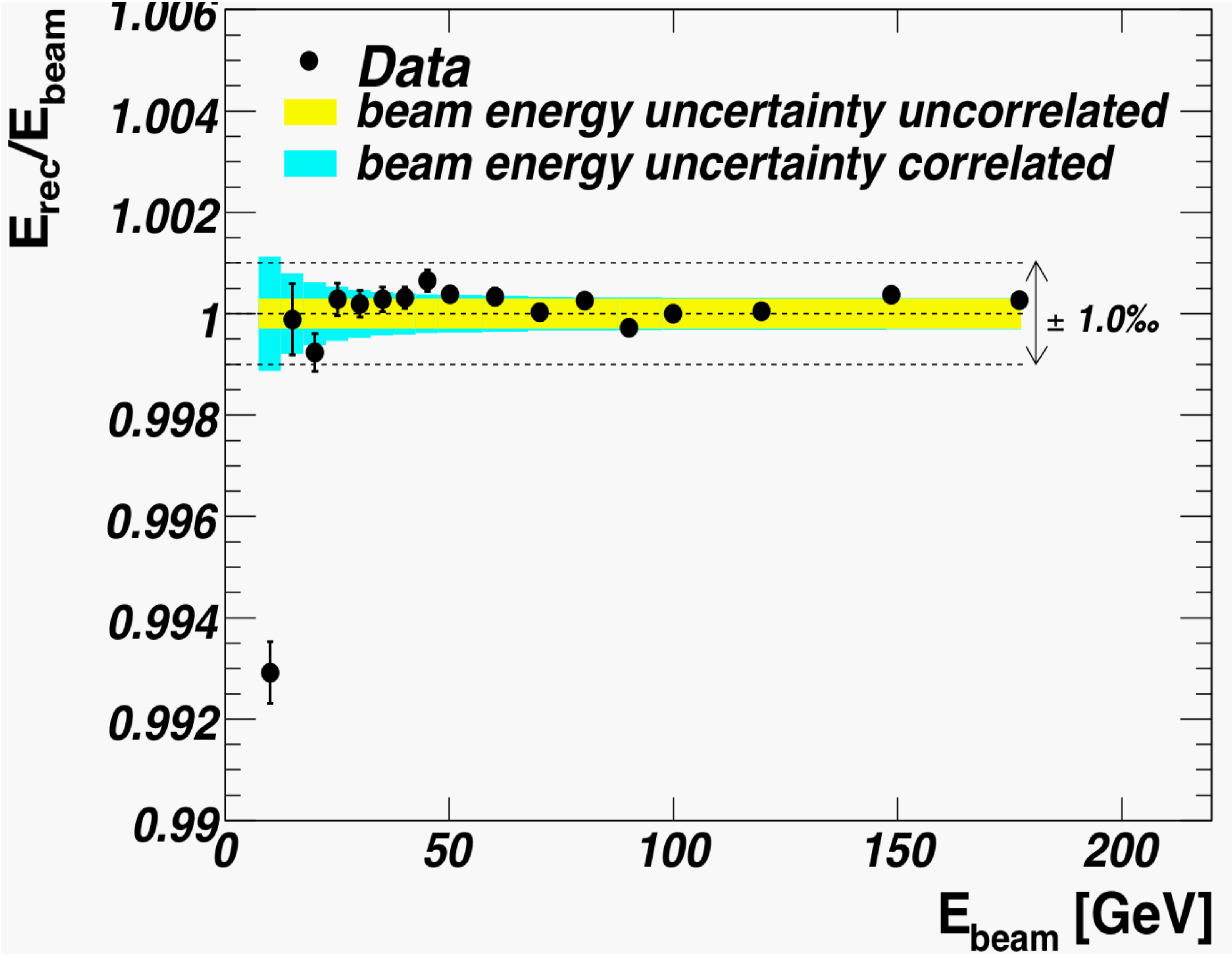
Cu electrodes at +HV

Spacers define LAr gap
2×2 mm

2 mm Pb absorber
clad in stainless steel.

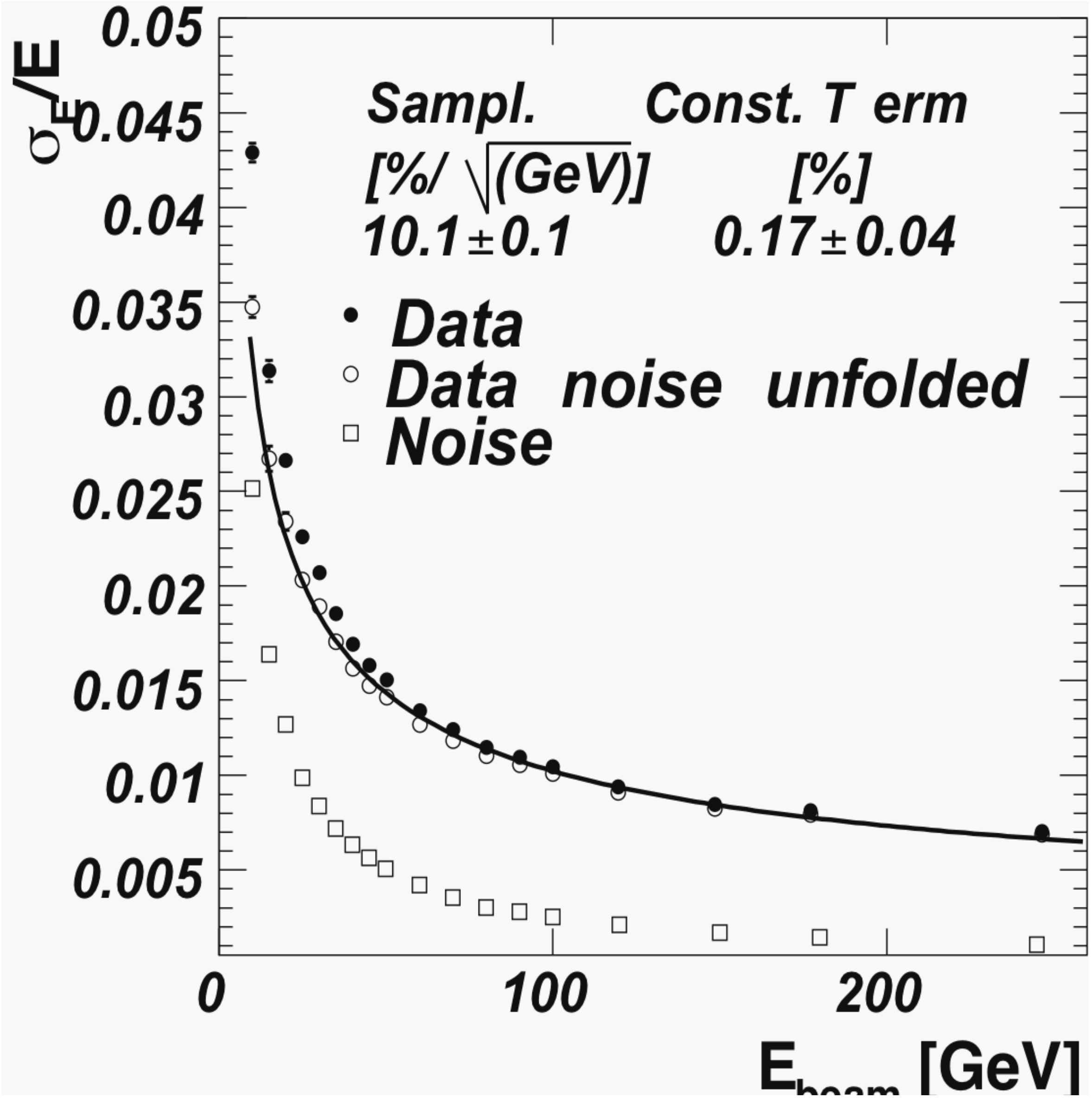


ATLAS LAr Barrel ECAL Linearity



within 0.1% for 15-180 GeV, E=10 GeV 4 per mil too low, reason unclear&

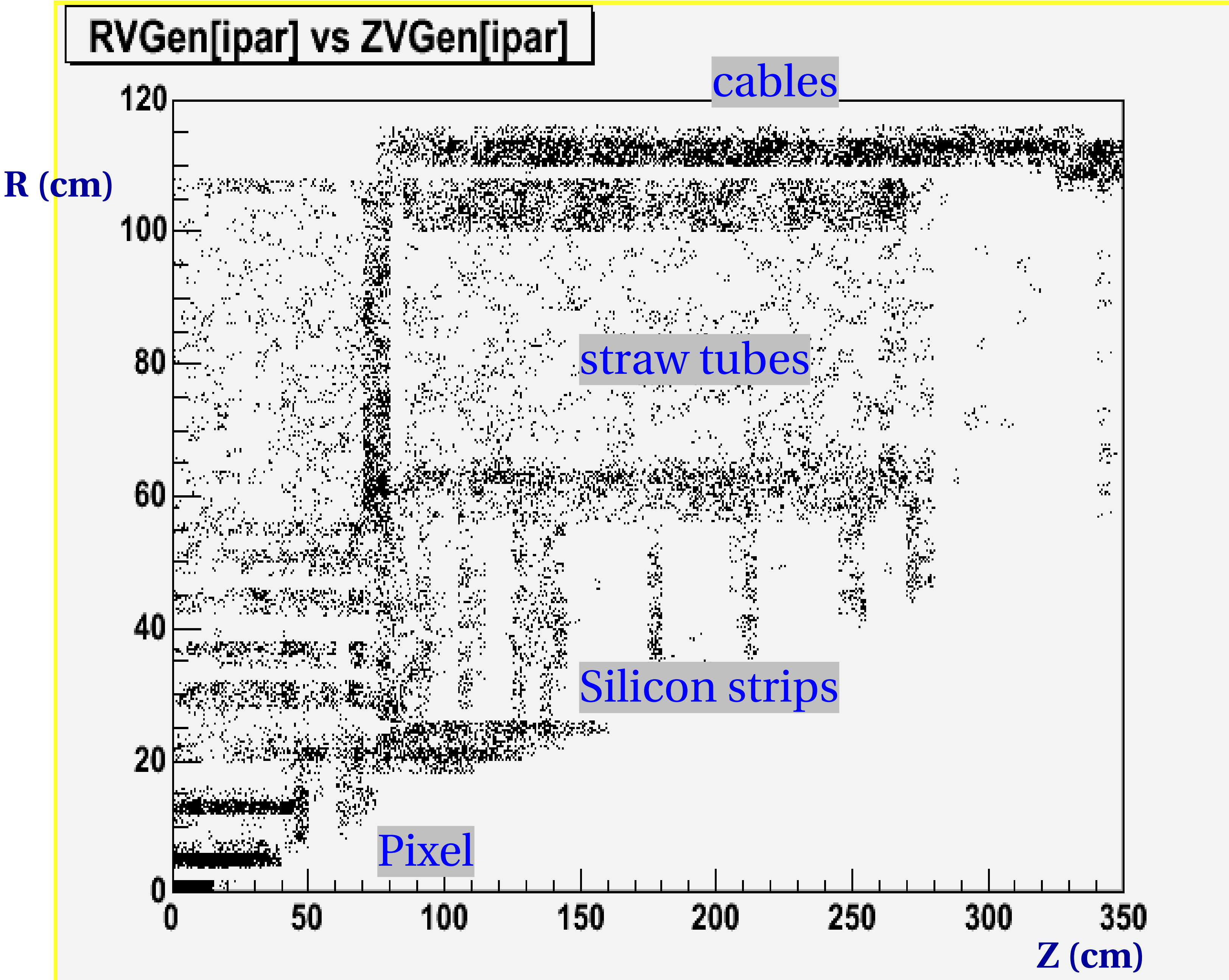
ATLAS LAr Barrel ECAL resolution



2002 test beam data

Photon conversions in the ATLAS tracker

simulation



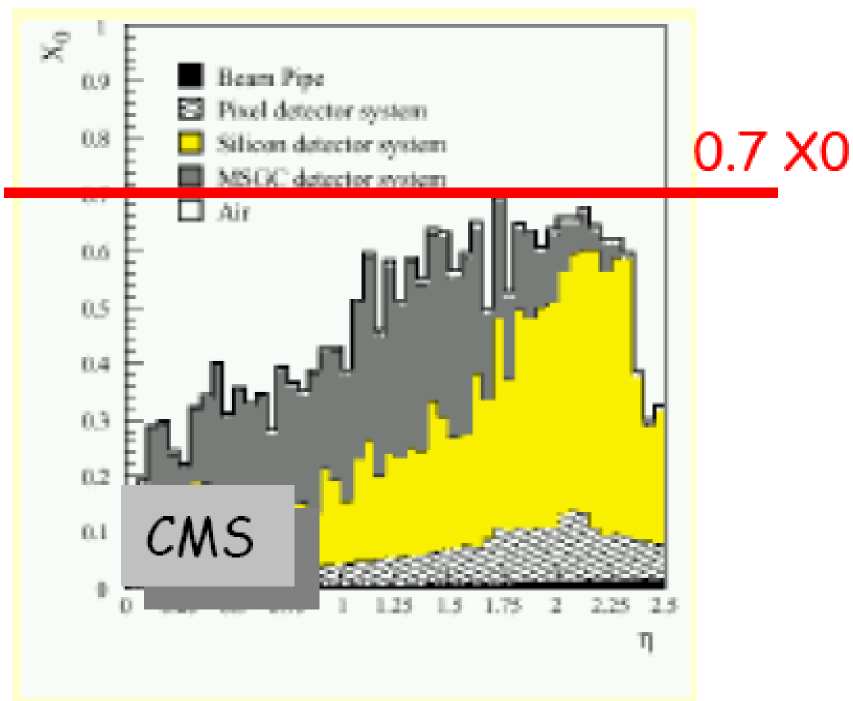
$\gamma Z \rightarrow Z\, e^{+}\, e^{-}$

30% - 50% of all photons convert in front of the calorimeter!

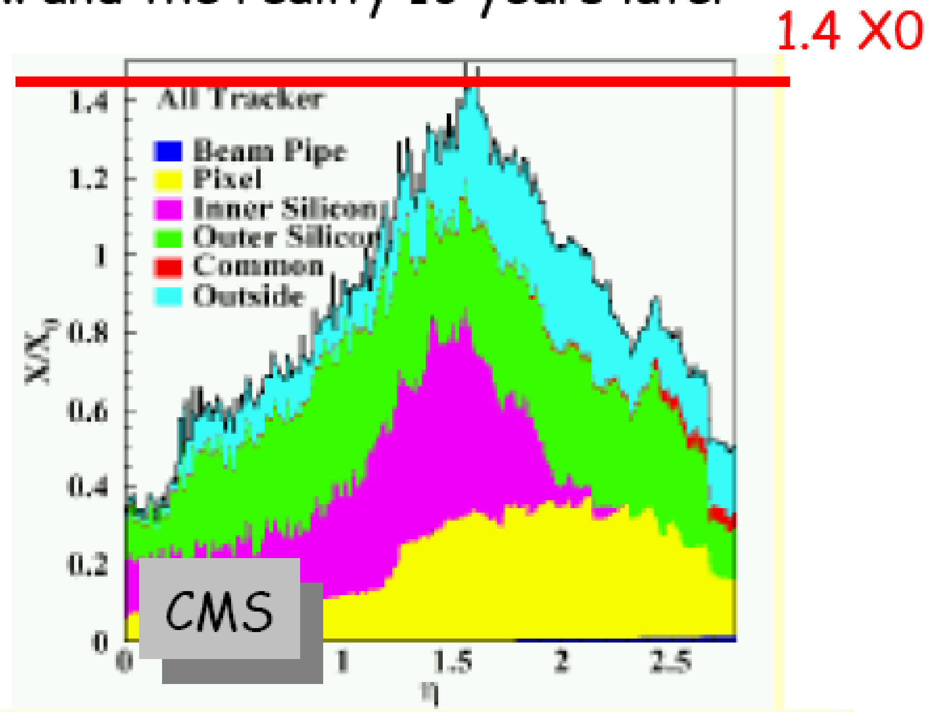
LHC tracker material budget

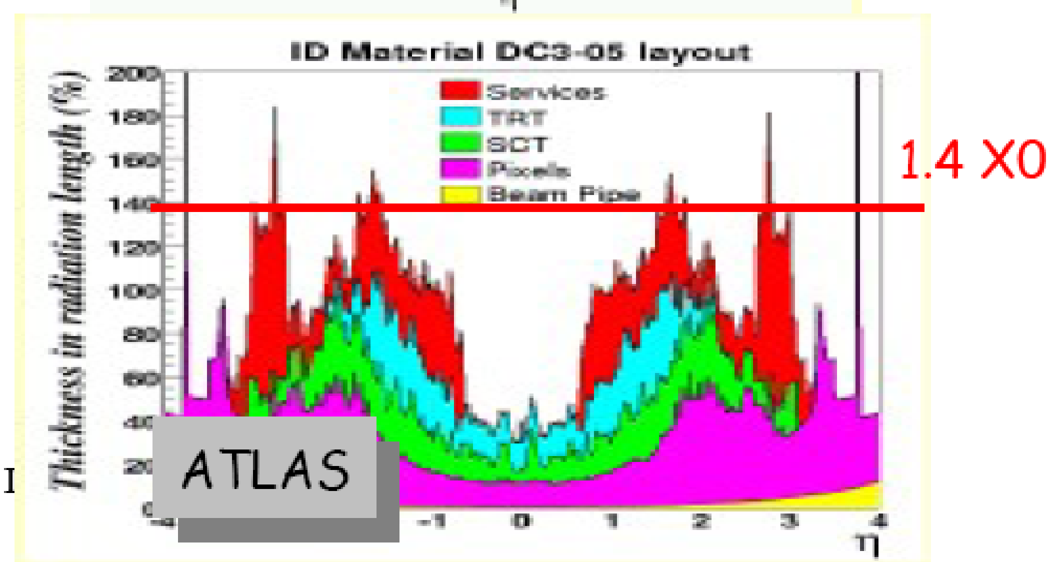
Major difference / advance to LHC detectors is needed:

The detector TDR 1996

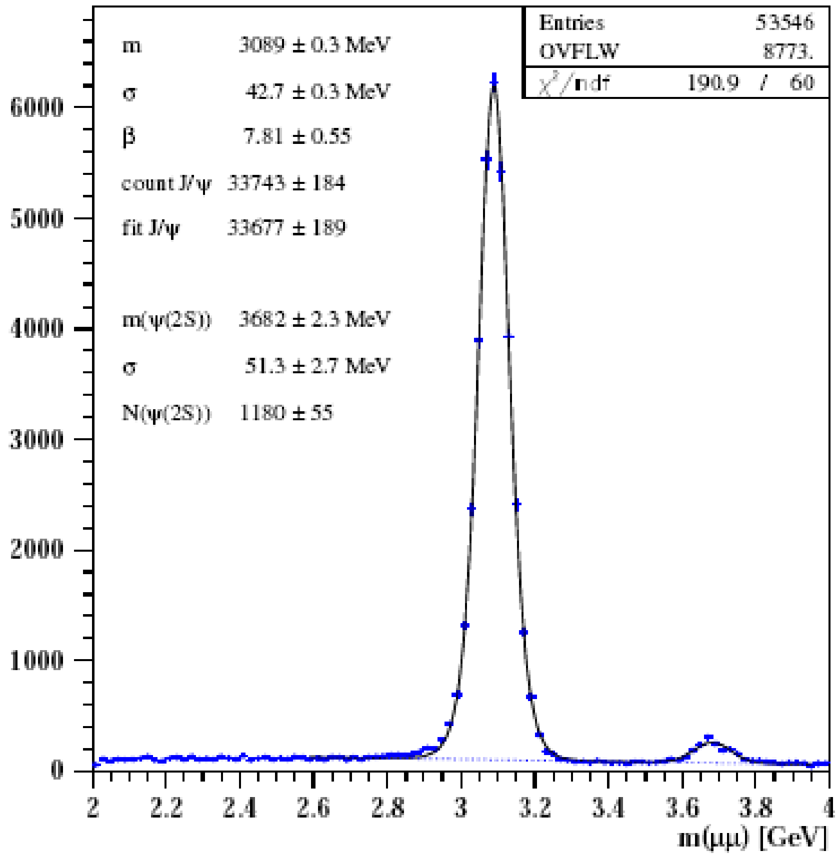


... and the reality 10 years later

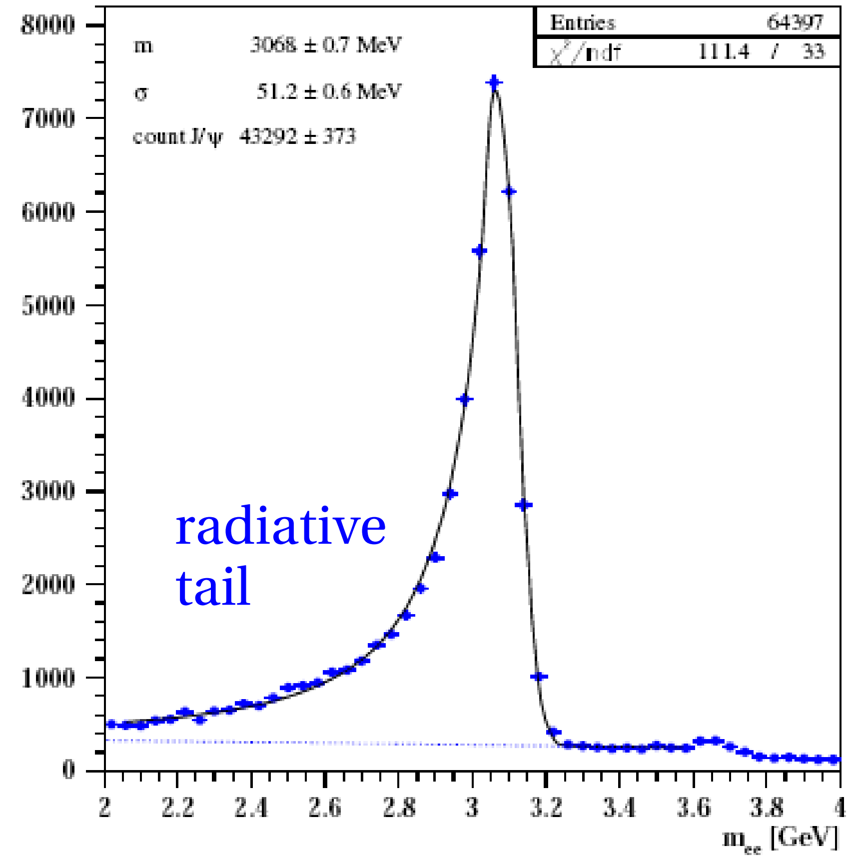




Electron tracks radiate



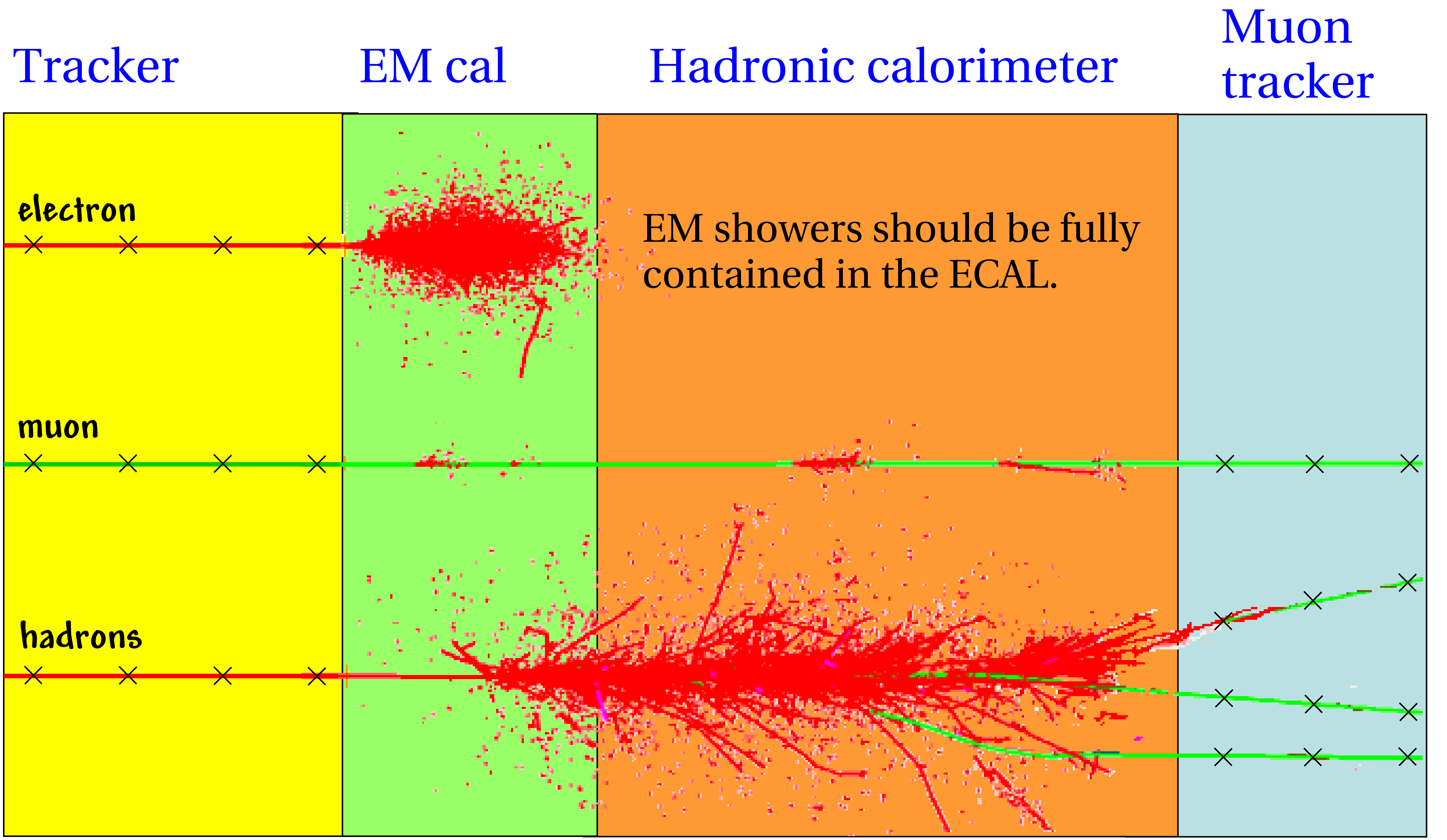
$J/\psi \rightarrow \mu\mu$



$J/\psi \rightarrow ee$

$e \rightarrow e\,\gamma$ in front of the tracker,
e track has lower momentum.

Hadronic showers



Hadronic showers may already start in the ECAL and extend into the HCAL.

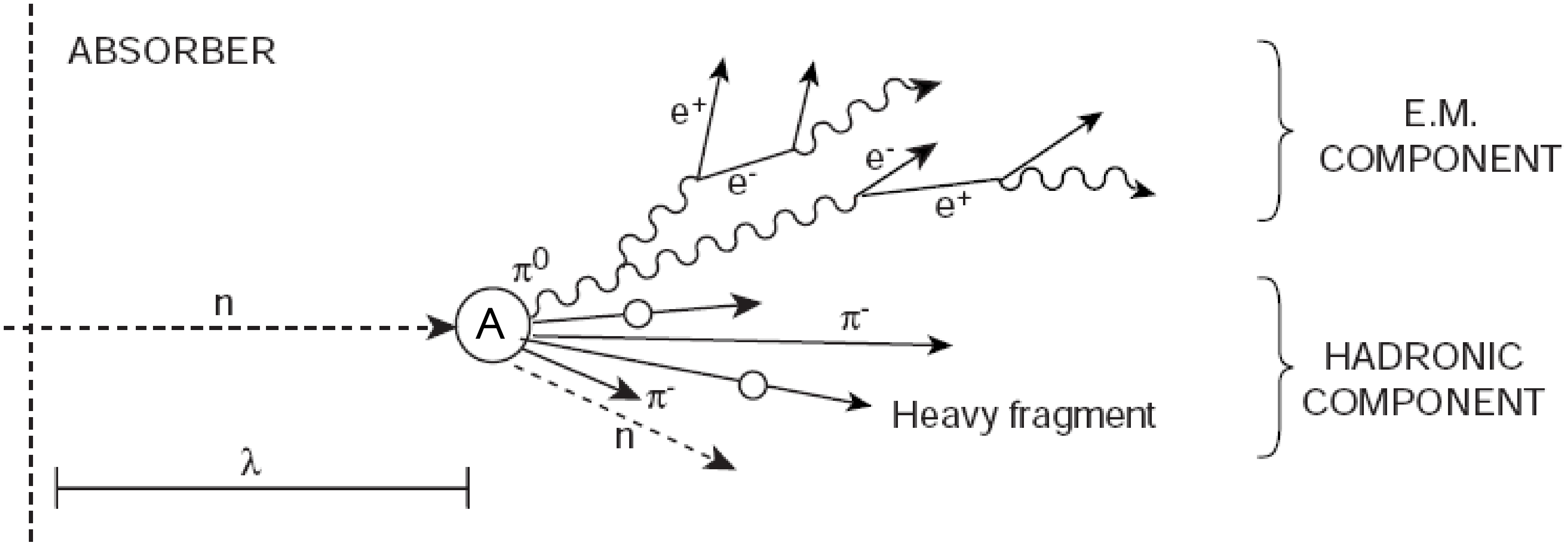
Hadronic interaction length

- Pion-proton cross section $\sigma(\pi p) \approx$ 25 mbarn above a few GeV.
- $\sigma(\pi A) \approx \sigma(\pi p)\, A^{2/3}$ (black disk limit).
- $\Rightarrow$ hadronic interaction length:

$$\lambda_I = \frac{A}{\sigma\, N_A\, \rho} = \frac{35\ cm}{\rho}\ A^{1/3}$$

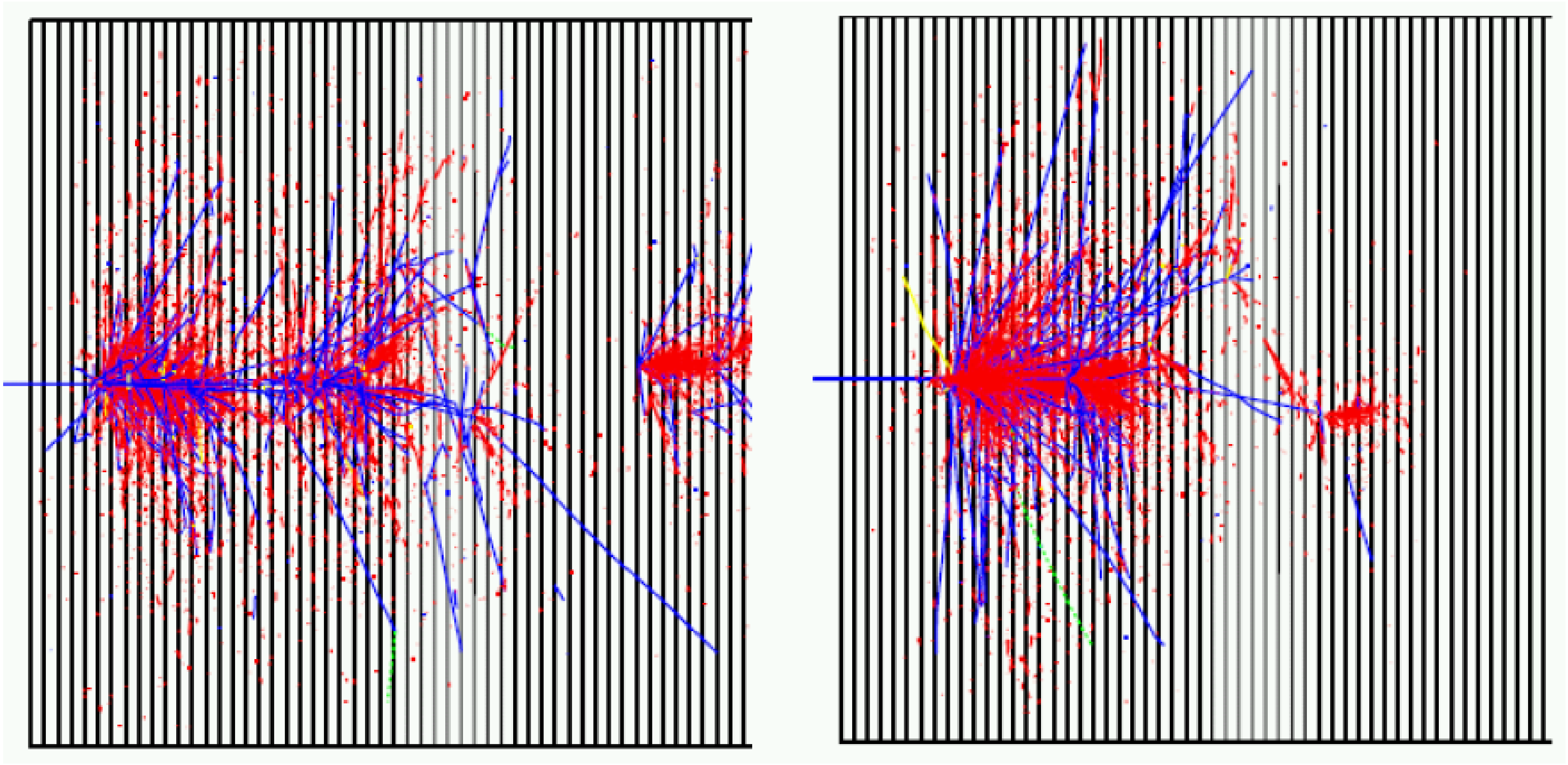
- λ_I = 17 cm in Fe or Pb.
- Much larger than X_0.

Hadronic showers



- Hadronic interaction have high multiplicity:
  - Shower is to 95% contained in ~7λ at 50 GeV (1.2m of iron).
- Hadronic interactions produce π^0:
  - $\pi^0 \rightarrow \gamma\gamma$, leading to local EM showers ('hot spots', ~30%)
- Some energy lost in nuclear breakup and neutrons ('invisible energy', 15-35%).
- Stronger fluctuations in a hadronic shower:
  - Worse energy resolution.

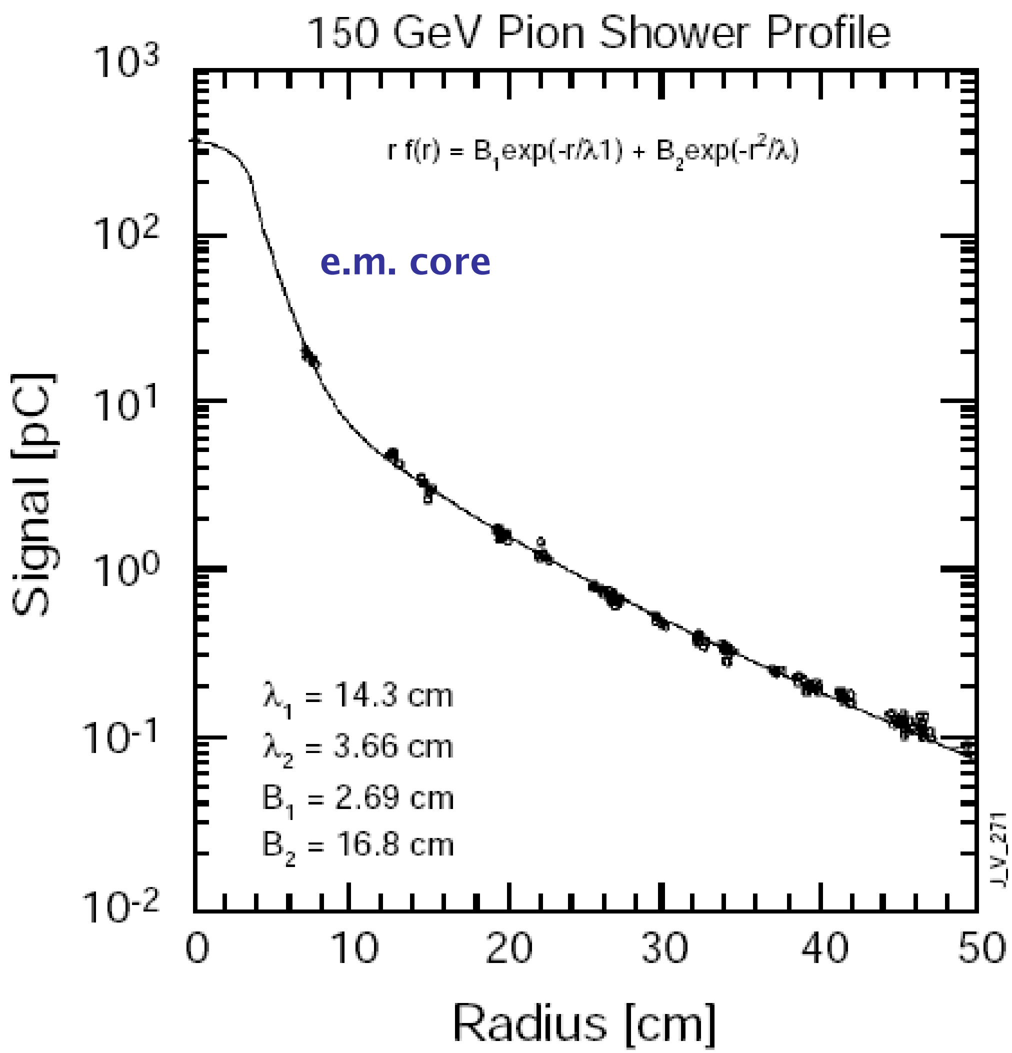
2 hadronic showers



blue = hadronic component   red = electromagnetic component

A good hadron calorimeter should have
equal response to hadrons and electrons ('hardware compensation')
or high granularity to isolate the hot spots ('software compensation')

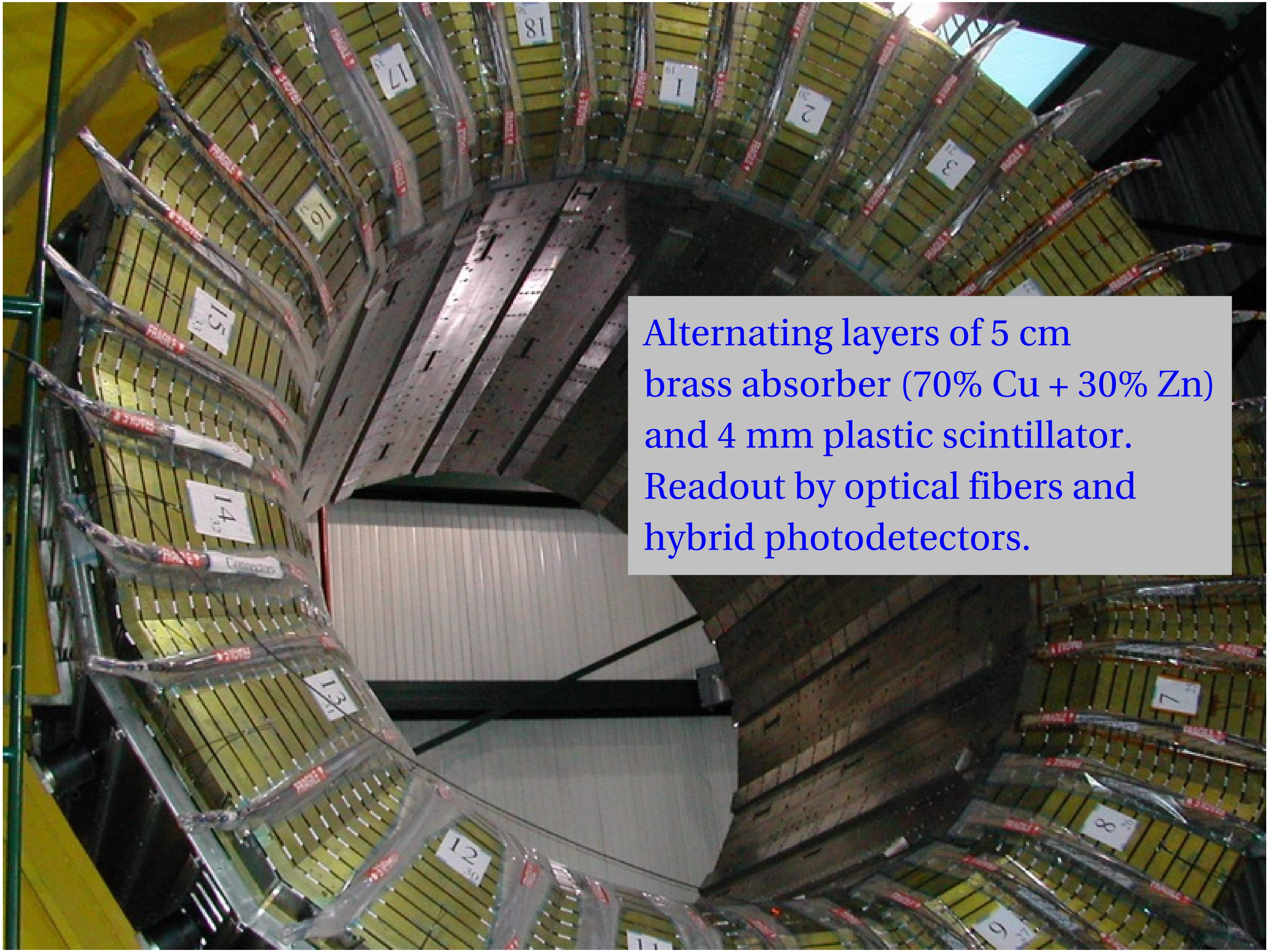
Hadron shower transverse size



T.S.Virdee, Proc. of the 1998 European School of High-Energy Physics, CERN 99-04

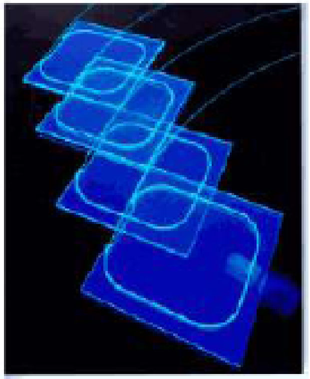
- Transverse shower development:
  - The secondaries have significant transverse momenta and produce a wide shower (compared with EM showers)
  - Part of the shower gets an electromagnetic nature (i.e. The decay of the π^0 produced in the interaction) and does remain inside a narrow cylinder (two times the Moliere radius)

CMS Hadron calorimeter



Alternating layers of 5 cm brass absorber (70% Cu + 30% Zn) and 4 mm plastic scintillator.
Readout by optical fibers and hybrid photodetectors.

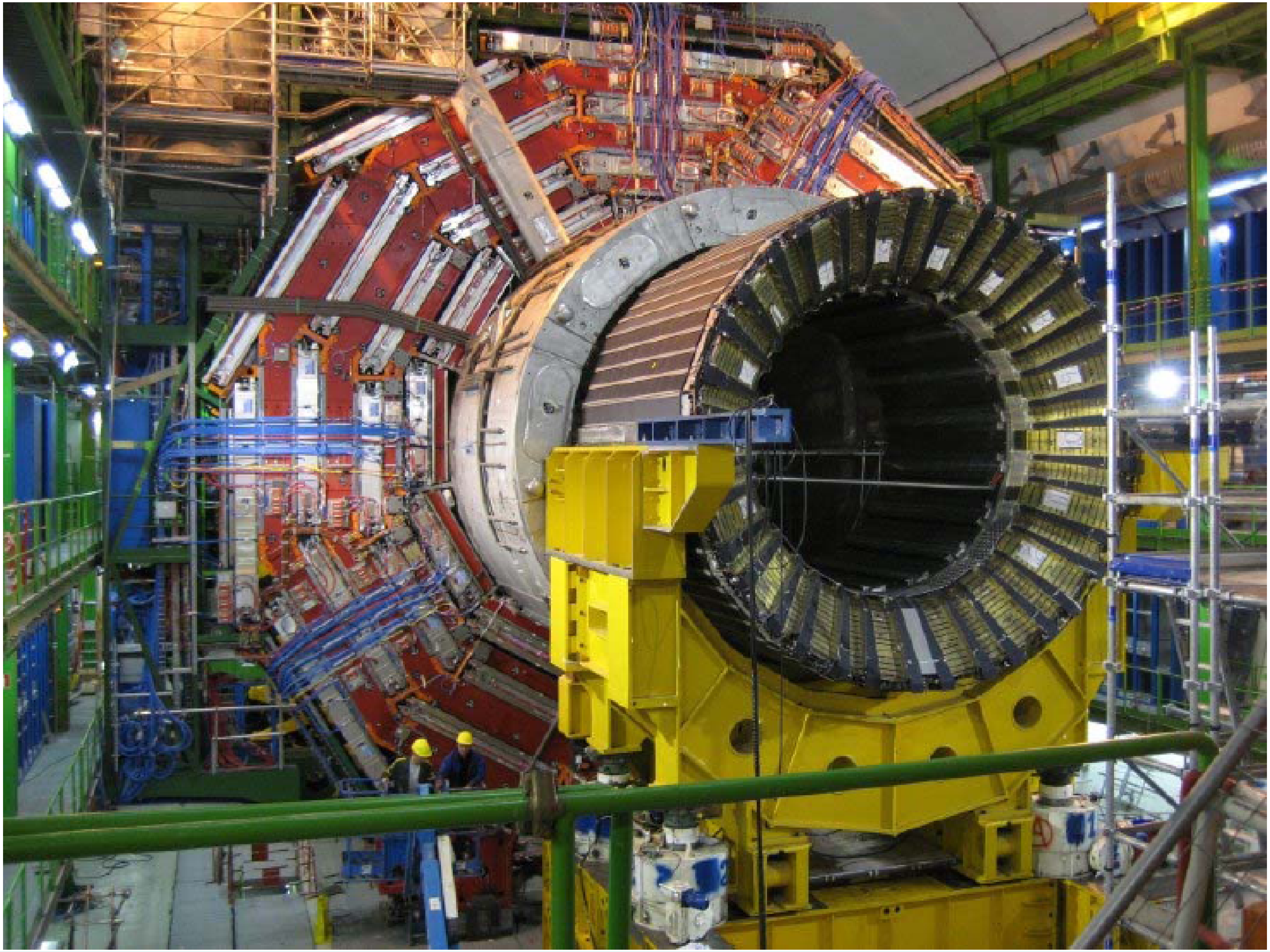
CMS HCAL readout



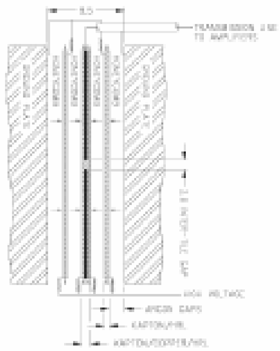
- Scintillators coupled to readout fibers.
- Bundles of fibers coupled to an avalanche photodiode
- ECAL+HCAL energy resolution for pions:

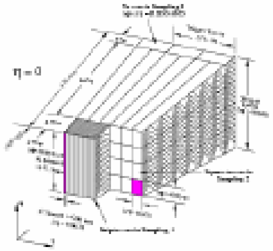
$$\frac{\sigma(E)}{E} = \frac{127\ \%}{\sqrt{E}} \oplus 6.5\ \%$$

Inserting the CMS Hadron Calorimeter

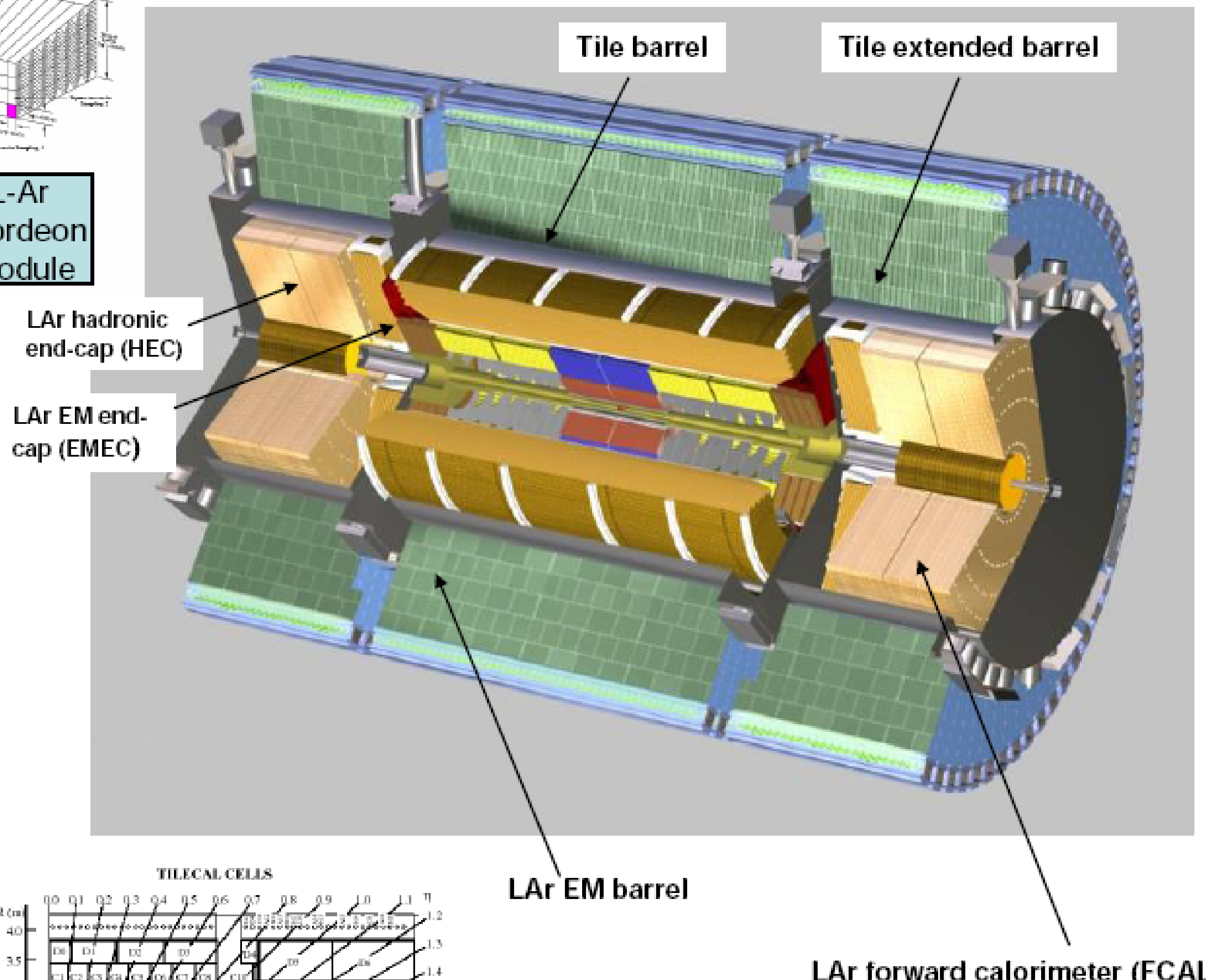


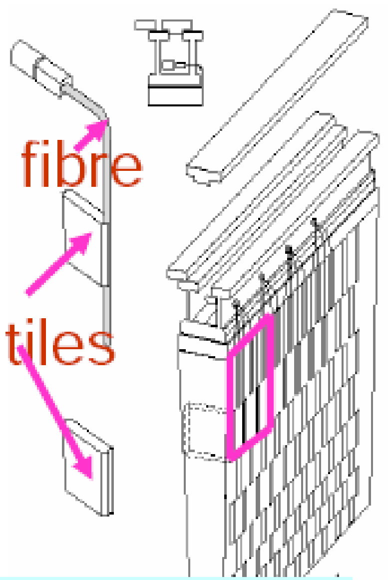
LAr and Tile Calorimeters



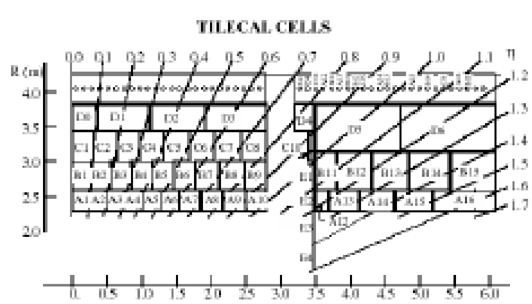


L-Ar Acordeon module





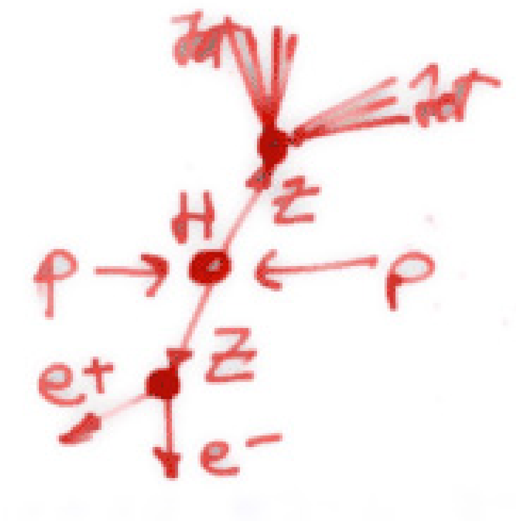
A TileCal Module
64 Barrel
2x64 Ext. Barrel



ATLAS tile calorimeter

ATLAS LAr + Tile for pions: $\frac{\sigma(E)}{E} = \frac{42\ \%}{\sqrt{E}} \oplus 2\ \%$

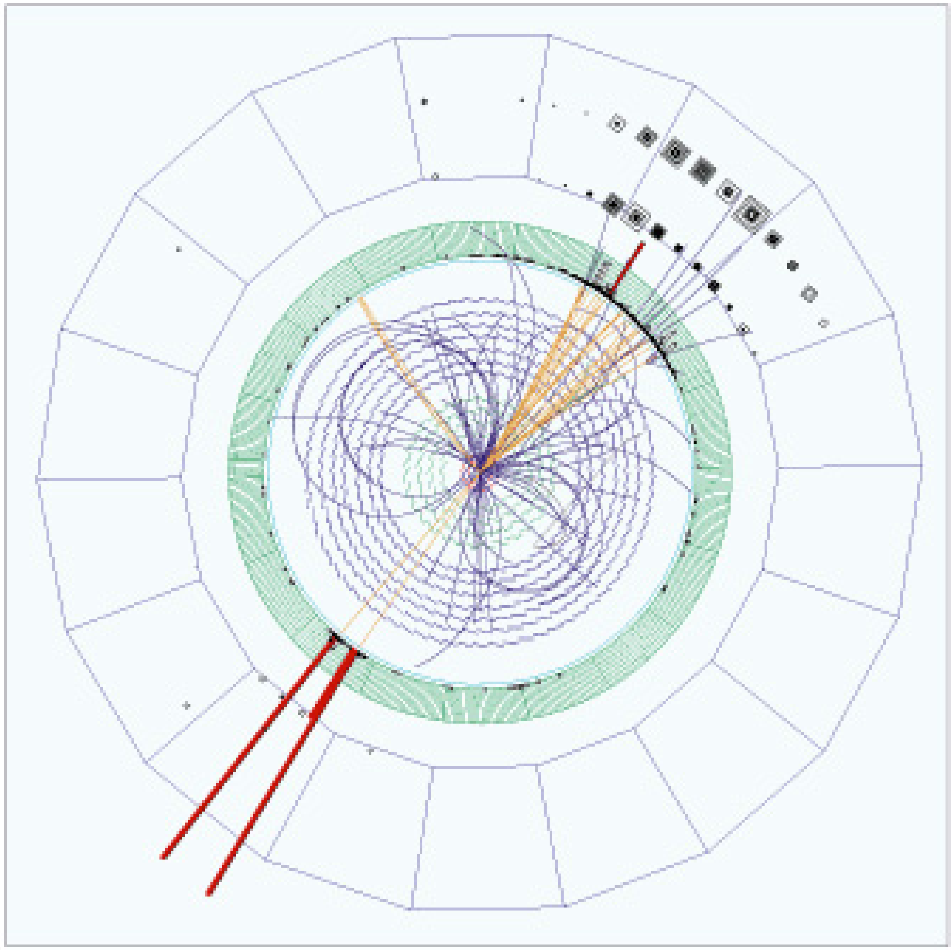
Jets in the CMS hadron Calorimeter



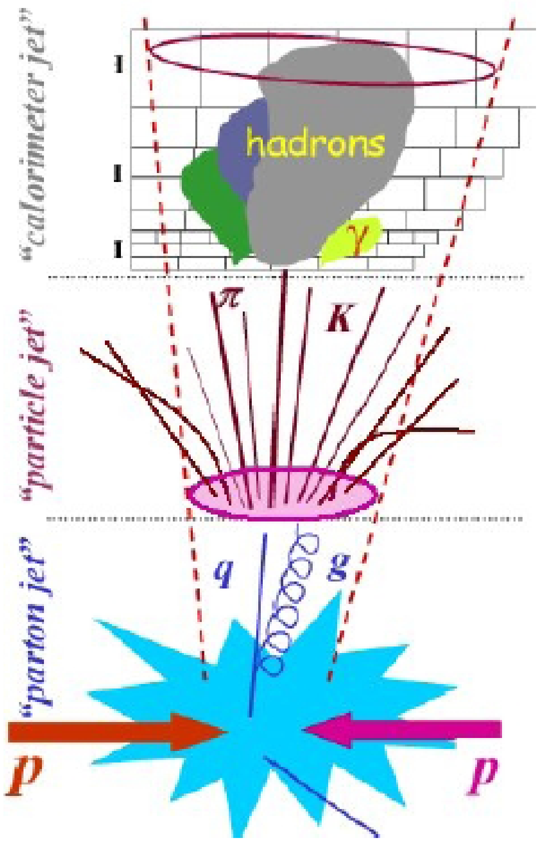
$p\,p \to H^0 \to Z\,Z$

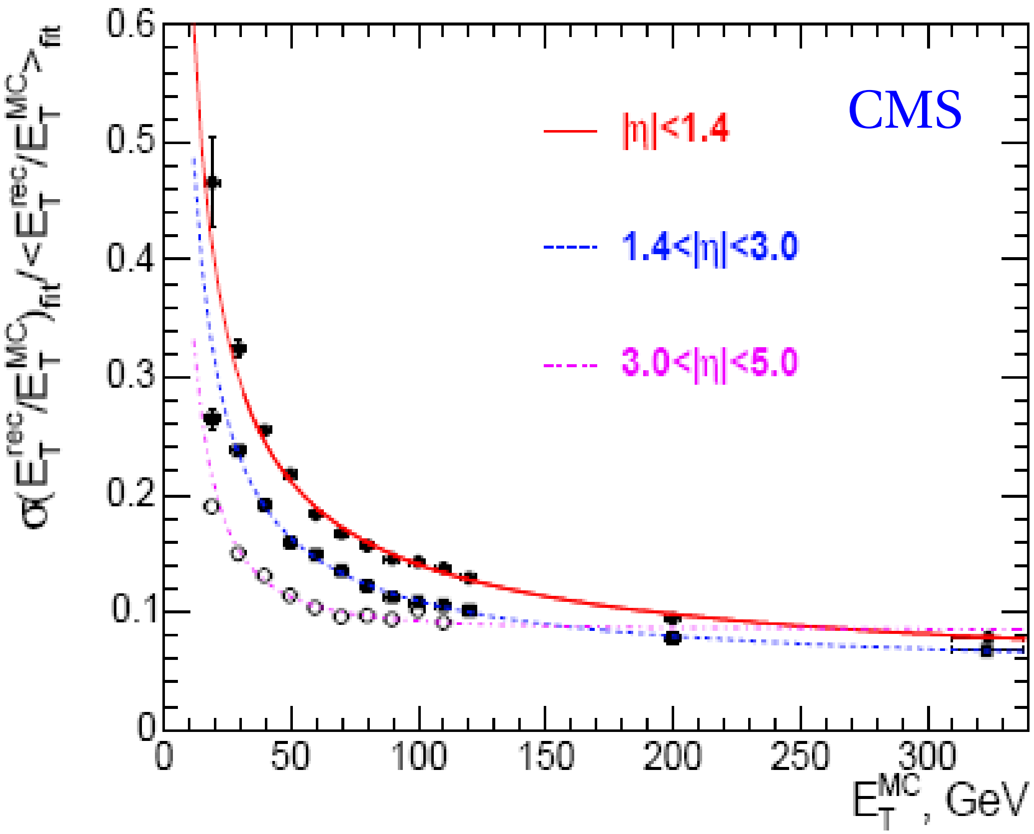
$\hookrightarrow$ jet jet

$\hookrightarrow$ $e^+ e^-$



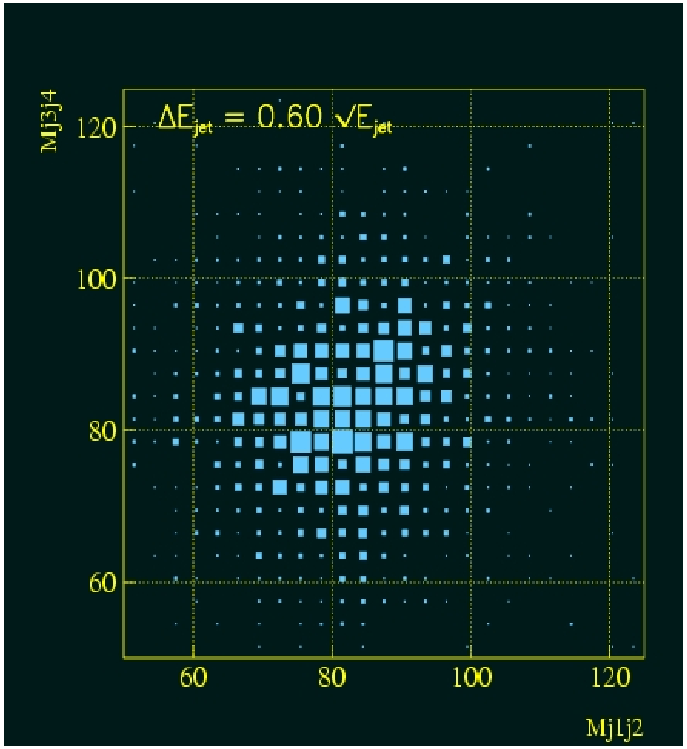
Jet energy resolution

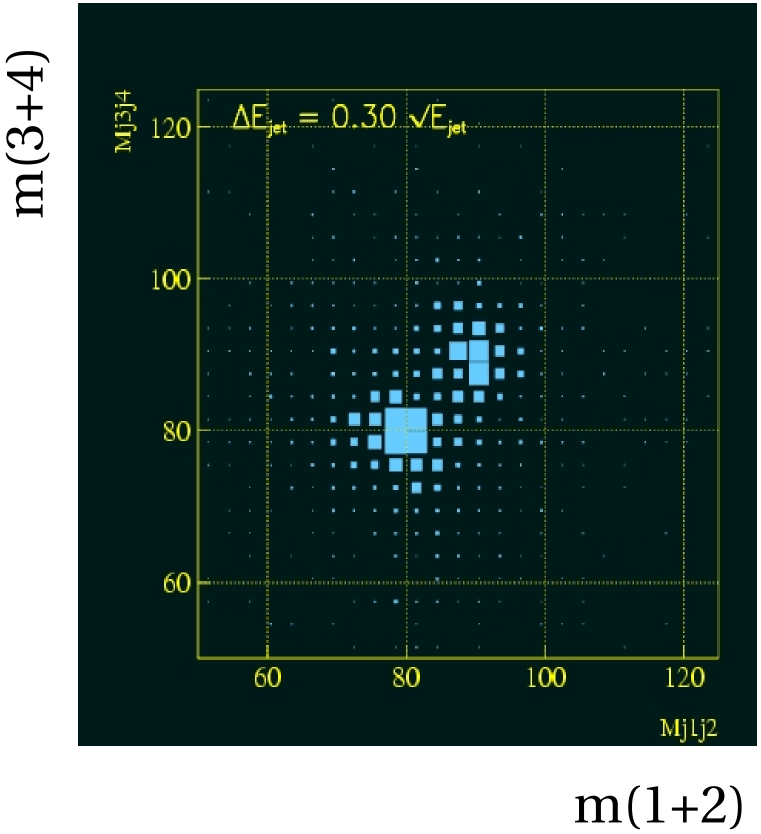




A new concept: Particle Flow

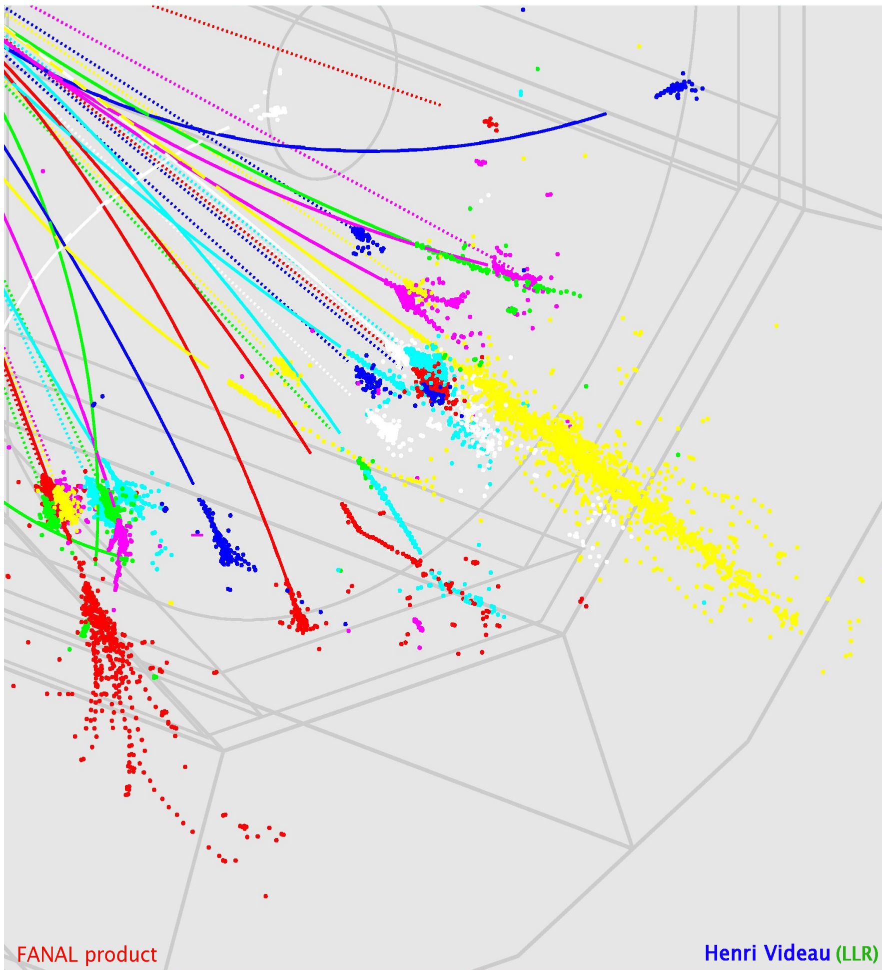
- Goal: measure jets with 30% / √E
  - Resolve W → jet jet (80.4 GeV)
  - from Z → jet jet (91.2 GeV)
  - in events with 4 jets:

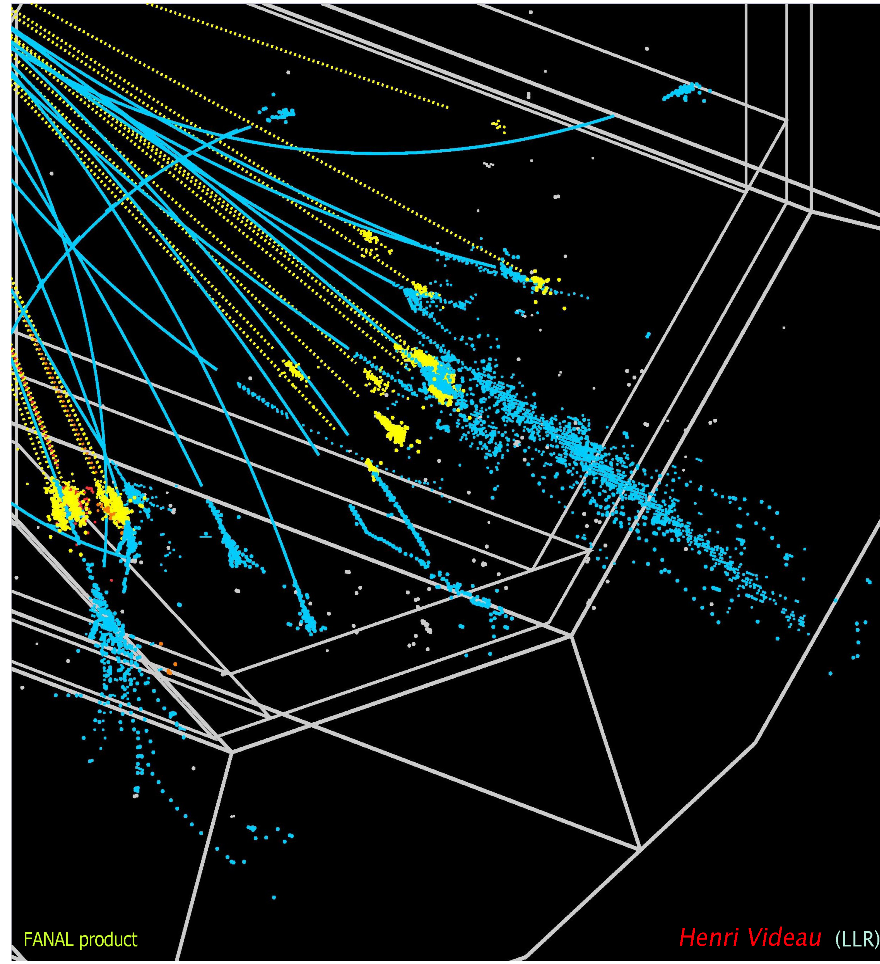




Particle flow simulation

idea: reconstruct each particle separately: tracks, γ, n, K^0_L, μ





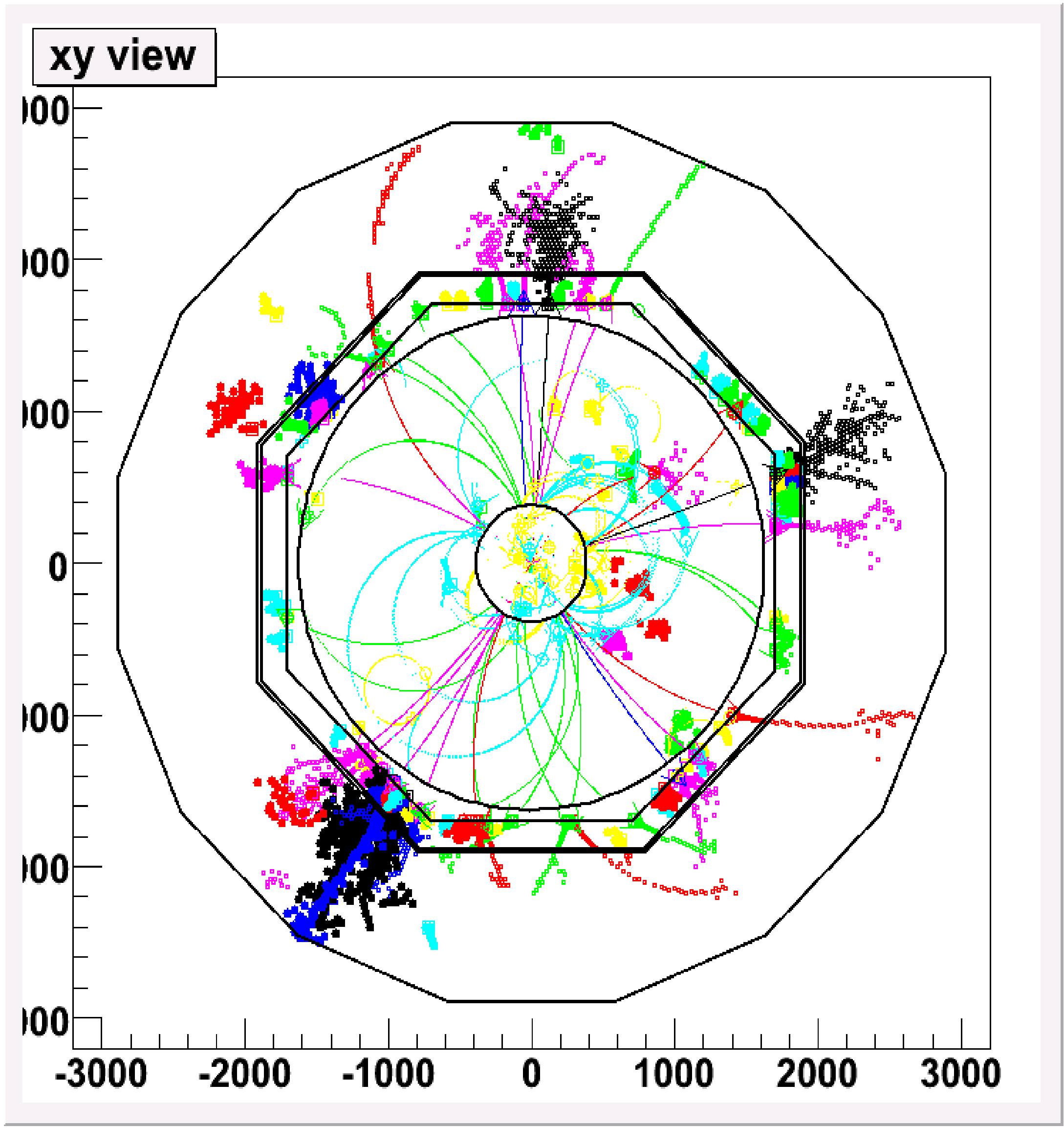
generated

reconstructed

from: http://llr.in2p3.fr/activites/physique/flc/justif/justif-granul.html

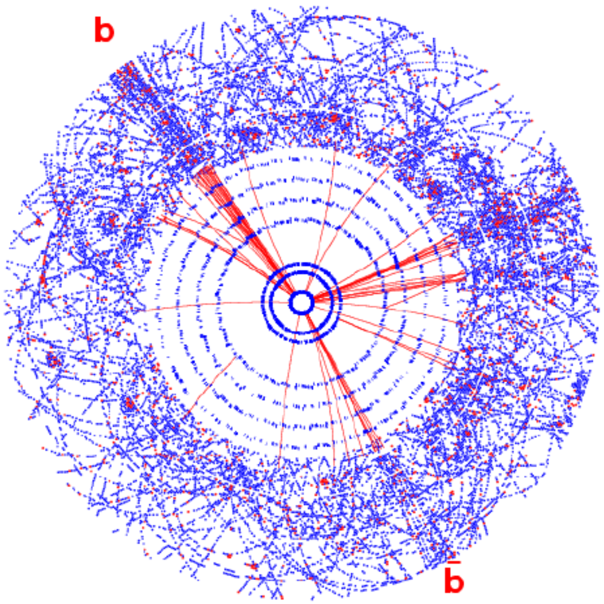
Detector for a 500 GeV linear e^+e^- collider

- Strong solenoid field
- Thin silicon pixel vertex detector
- Large TPC drift chamber
- High granularity Si-W EM calorimeter
- High granularity hadron calorimeter
- Muon detector
- Design studies in progress
- Prototypes in test beams.

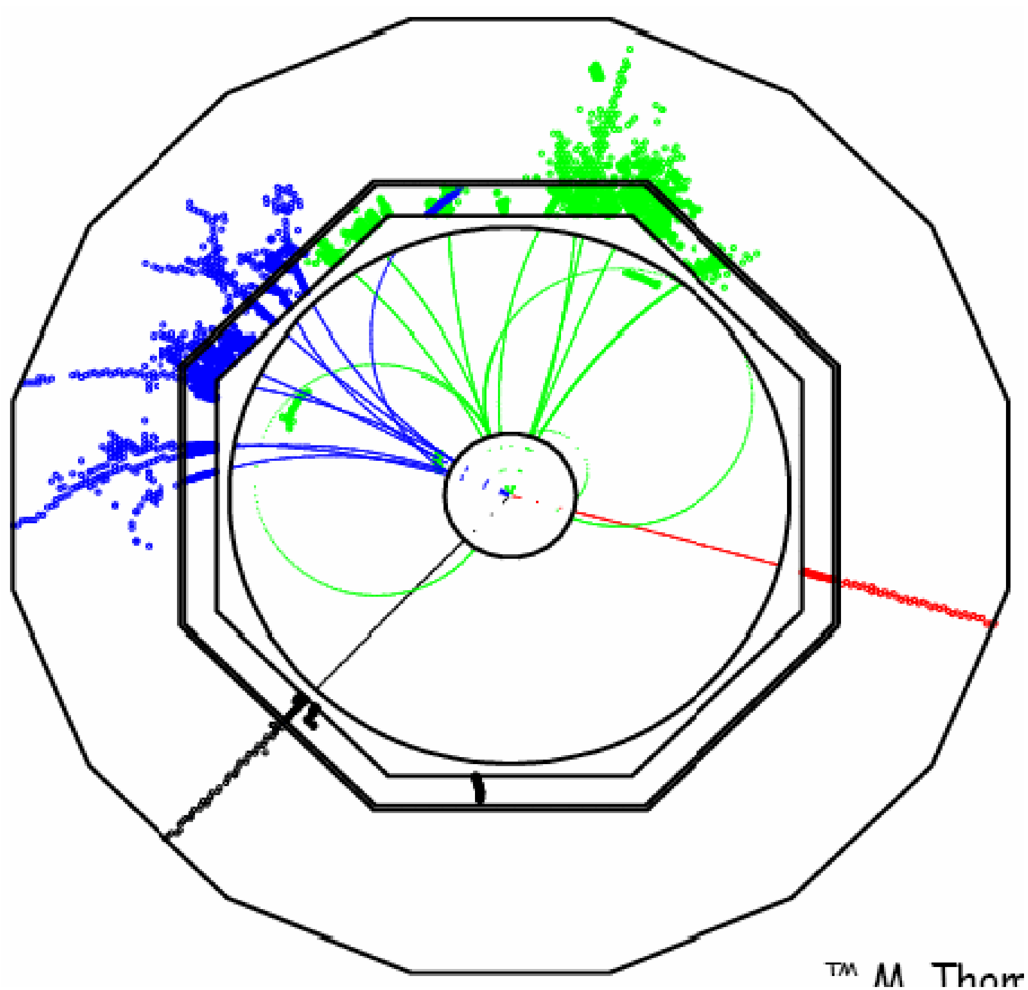


ILC vs LHC

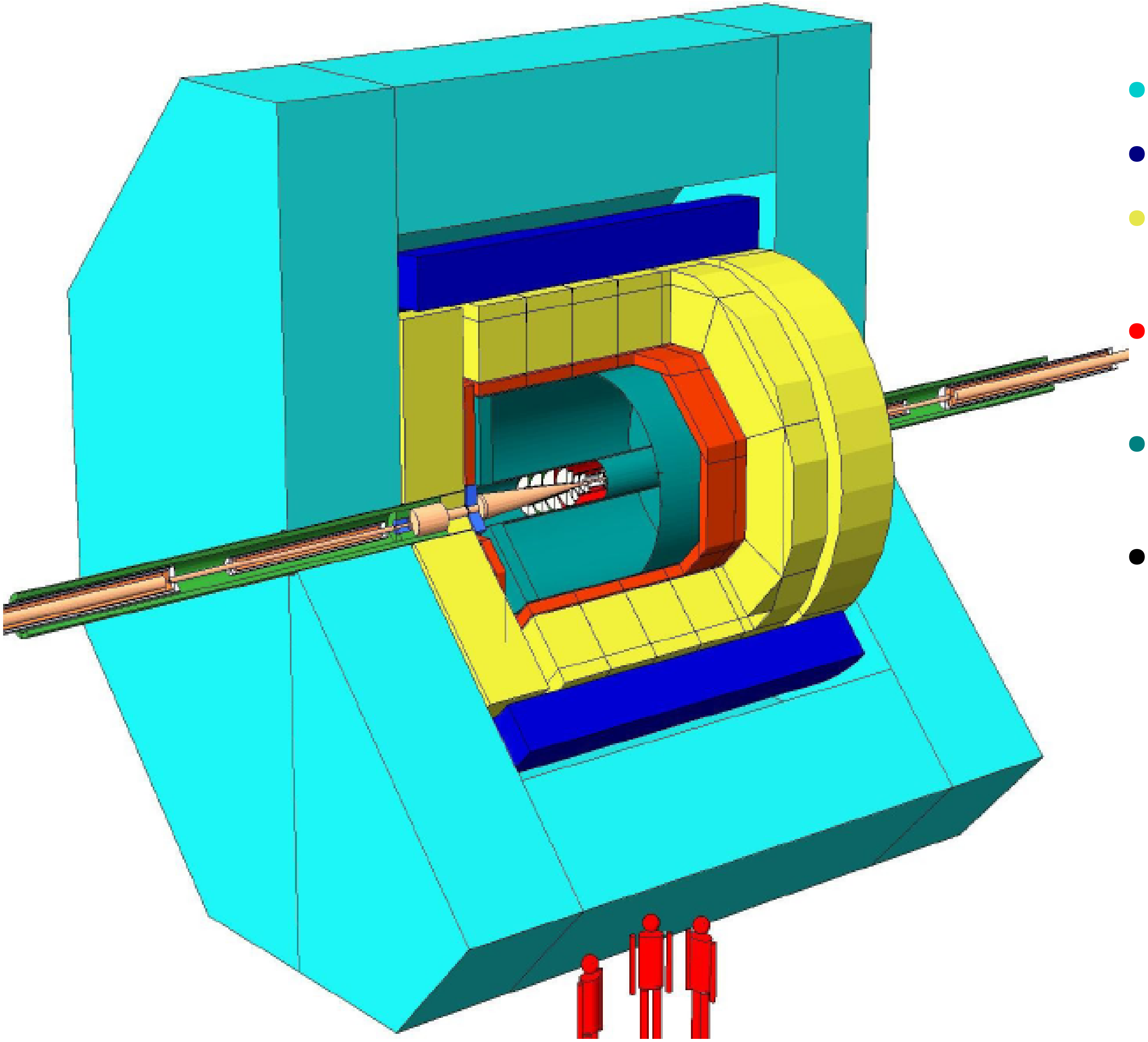
ATLAS, LHC
tracking in a tt event



ILC tracking and
calorimetry in a tt event



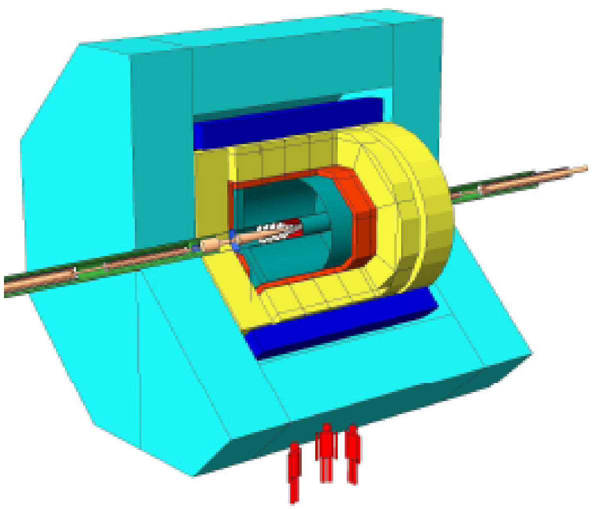
Detector for a 500 GeV linear e^+e^- collider



- Muon detector
- Strong solenoid field
- High granularity hadron calorimeter
- High granularity Si-W EM calorimeter
- Large TPC drift chamber
- Thin silicon pixel vertex detector

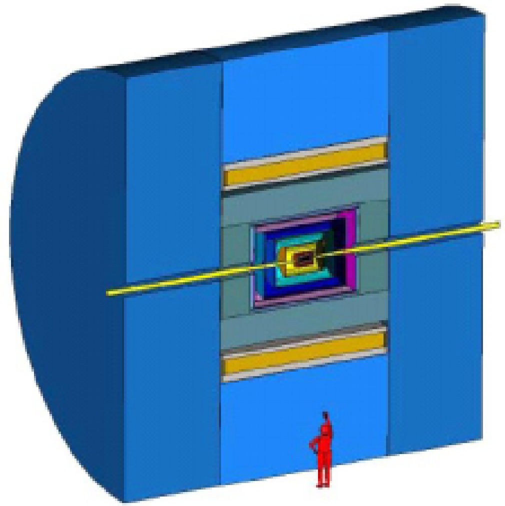
Detectors for a 500 GeV linear e^+e^- collider

ILD



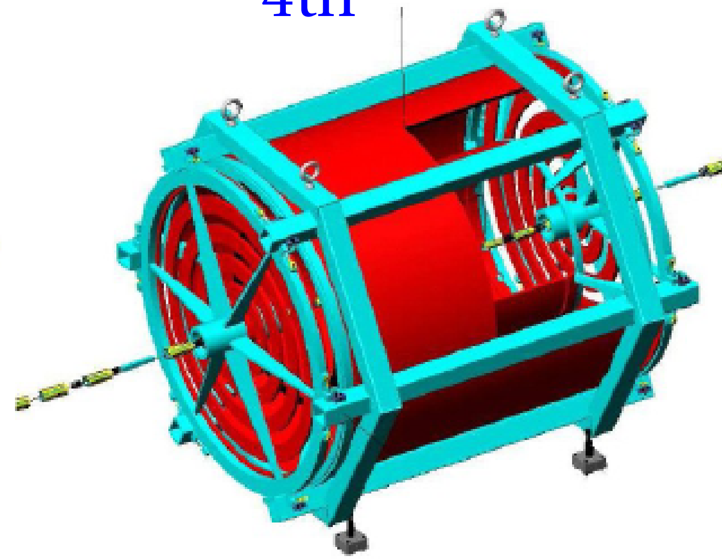
silicon pixel
large TPC
SiW EM calo
Fe-scint pad HCAL
4T solenoid
iron yoke
696 physicists

SiD



silicon pixel
Si strip tracker
SiW EM calo
Fe-gas pad HCAL
5T solenoid
iron yoke
234 physicists

4th



silicon pixel
drift tracker
crystal EM calo
dual fiber HCAL
4T solenoid
anti-solenoid
140 physicists

3/2009: Letters of intent. 2012: Design reports, 201?: start construction

Summary

- Lecture 1:
  - Collider detectors
  - Charged particles in a magnetic field
  - Silicon detectors
- Lecture 2:
  - Drift tubes
  - Muon systems
  - MWPCs, CSCs, RPCs, TRTs, TPCs, Cherenkovs
- Lecture 3:
  - Electromagnetic showers and calorimeters
  - Photon detectors
  - Hadronic showers and calorimeters
  - Particle flow technique
- Discussion session:
  - Your questions, please