Calorimetry by examples

1. **Motivation** for calorimetry
2. **Basics**, including electromagnetic & hadronic **showers**
3. Types of **calorimeter**
4. LHC Calorimeters
    - Example #1: **CMS ECAL**
    - Example #2: **ATLAS LAr ECAL/HCAL**
    - Example #3: **CMS Forward HCAL**
5. Increasing the information from calorimeters
    - Example #4: **DREAM**
    - Example #5: **HGCAL**

CERN Academic Training Lectures 2016, David Barney (CERN)

Acknowledgements, apologies & excuses!

I have shamelessly begged and borrowed material from a variety of sources, most notably:

CERN Academic Training Calorimetry Lecture 2011 (P. Bloch)
http://indico.cern.ch/event/115059/

EDIT 2011 Instrumentation School @ CERN (M. Diemoz, D. Fournier, R. Wigmans)
http://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=96989

Calorimetry for Particle Physics (C. Fabjan & F. Gianotti)

***Rev. Mod. Phys.* 75 (2003) 1243-1286**

DESY lectures on calorimetry (E. Garutti)
http://www.desy.de/~garutti/LECTURES/ParticleDetectorSS12/L10_Calorimetry.pdf

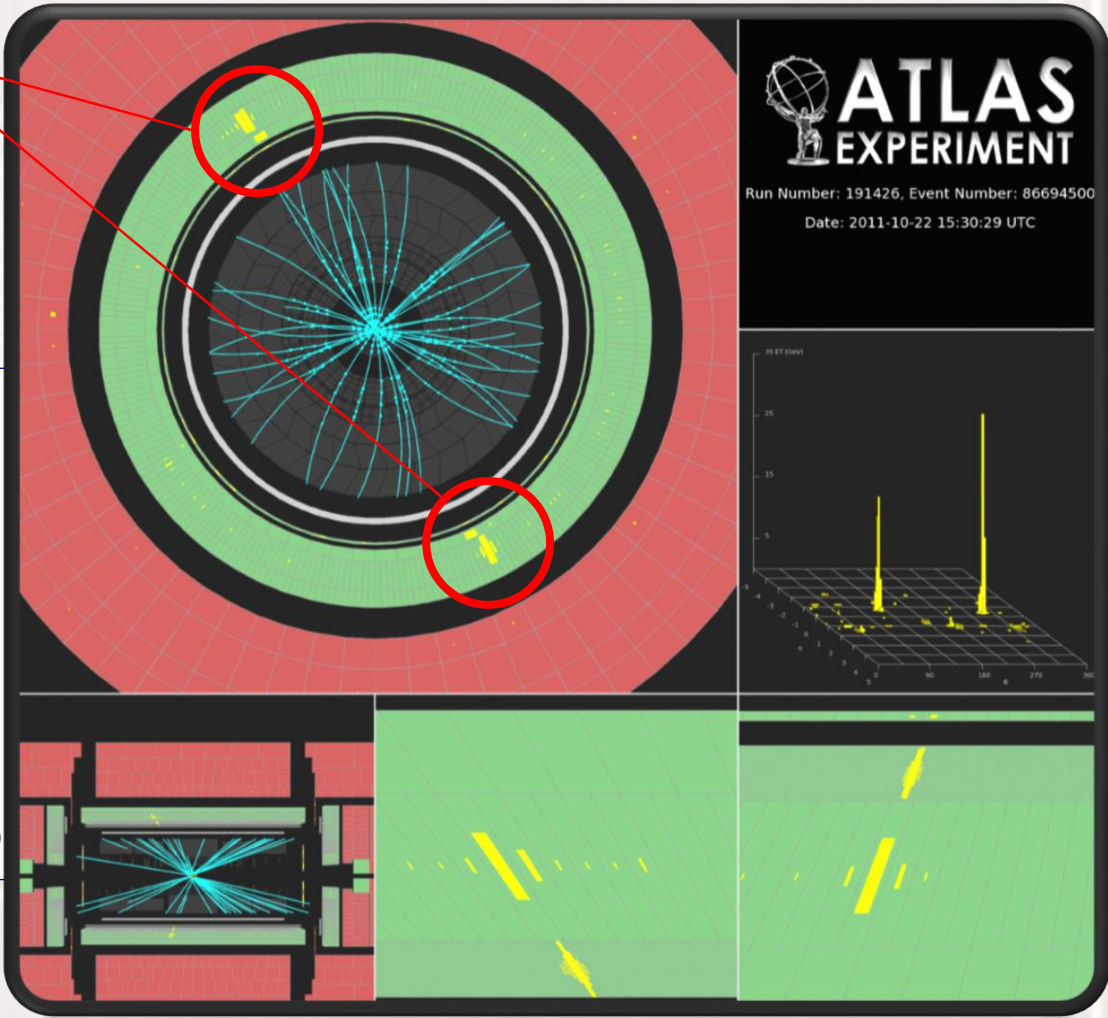
IEEE Refresher course on Calorimetry (F. Simon)
http://www.mpp.mpg.de/~fsimon/InternalFiles/CalorimetryRefresher.pdf

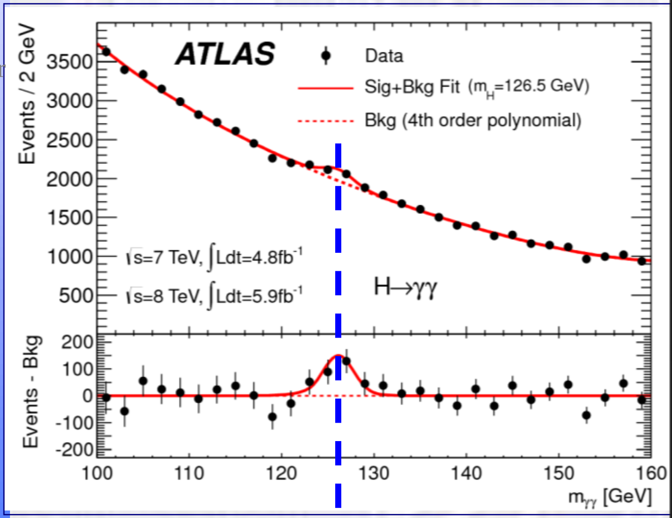
Please forgive me for not detailing your favourite calorimeter! Just a few examples are given, for a "flavour" of the variety of amazing detectors being used and designed

Calorimeters played a crucial role in the discovery of the Higgs boson in 2012

Two high-energy photons observed in the ATLAS Liquid Argon (LAr) electromagnetic calorimeter in 2012

➔ Candidate H→γγ event





Diphoton invariant mass peak at 125.6 GeV/c^2

ATLAS H→γγ

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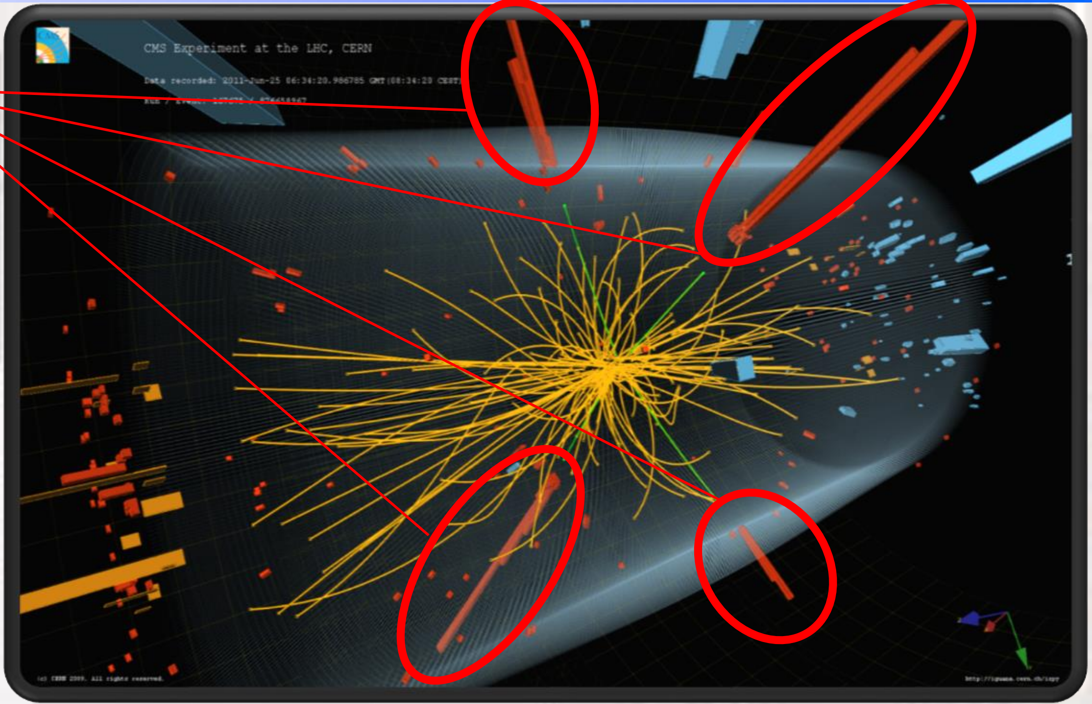
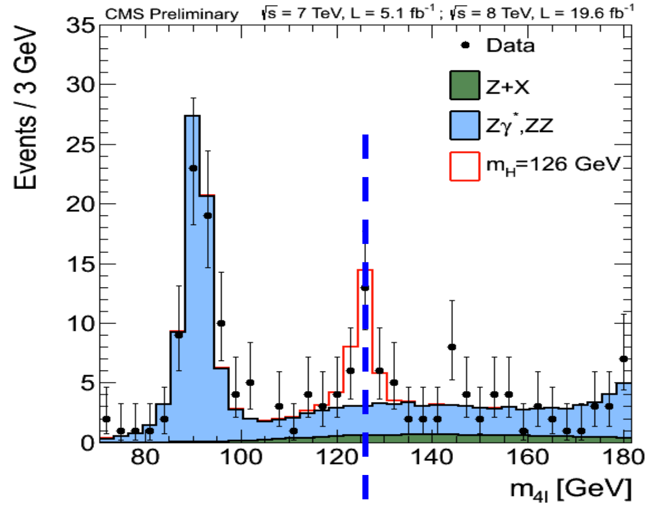
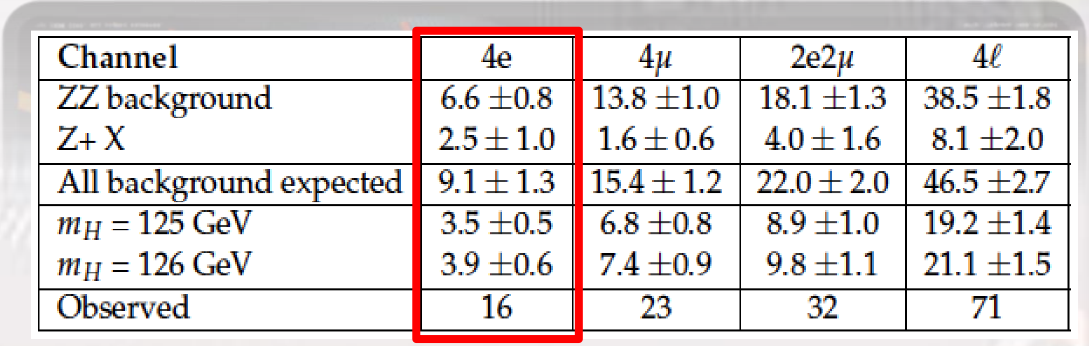
Four high-energy electrons observed in the CMS crystal electromagnetic calorimeter in 2012

➔ Candidate H→ZZ*→4e





4-lepton invariant mass peak at 126 GeV/c^2



Channel	4e	4μ	2e2μ	4ℓ
ZZ background	6.6 ±0.8	13.8 ±1.0	18.1 ±1.3	38.5 ±1.8
Z+ X	2.5 ± 1.0	1.6 ± 0.6	4.0 ± 1.6	8.1 ±2.0
All background expected	9.1 ± 1.3	15.4 ± 1.2	22.0 ± 2.0	46.5 ±2.7
m_H = 125 GeV	3.5 ±0.5	6.8 ±0.8	8.9 ±1.0	19.2 ±1.4
m_H = 126 GeV	3.9 ±0.6	7.4 ±0.9	9.8 ±1.1	21.1 ±1.5
Observed	16	23	32	71

CMS H→4 leptons

Calorimeters are perhaps the most versatile particle detectors

Primary objective is to measure the **energy** of incoming particles as **accurately as possible** – both charged and neutral (including neutrinos through missing E)

Can also measure:

- **Position**
- **Angle of incidence**
- **Arrival time**

Compact detectors: longitudinal shower spread increases only **logarithmically with E**

Unlike spectrometers, **E resolution improves with increasing E**

Calorimeter signals can be fast: **provide triggering information**

Calorimetry: energy measurement by total absorption; often with spatial information

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Latin: *calor* = heat

But: **calorimetry in particle physics ≠ ΔT***

E.g. ΔT for 1 litre of water at 20°C from energy deposition of:

- 1 GeV particle = **3.8×10^{-14} K**
- All 13 TeV from 1 LHC pp collision = **5.5×10^{-10}K**

Even if **all protons** in the LHC (~10^{14}; ~10^{8} joules) were dumped into the CMS ECAL and transferred their energy to heat, it would only **heat the CMS ECAL by about 5.5°C**

*There are some exceptions…

[$C_{water} = 4.18\ \mathrm{J\ g^{-1}\ K^{-1}}$; $m = \Delta E / (C_{water}\ \Delta T)$]

Calorimeter: slow-down incoming particle and produce signal (electrical or light)

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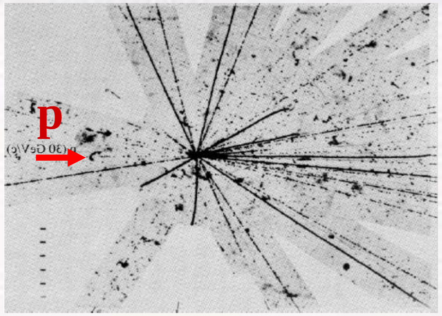
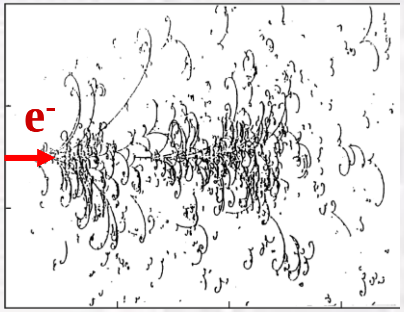
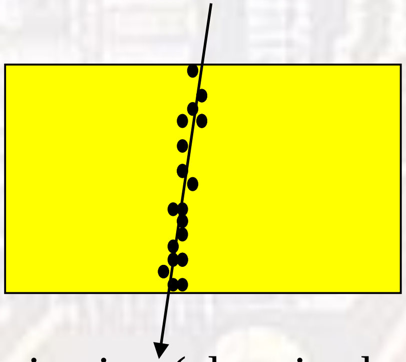
Primary (incoming) particle creates a cascade of lower-energy particles. Cascade structure depends on:

- Impinging particle type
- Material

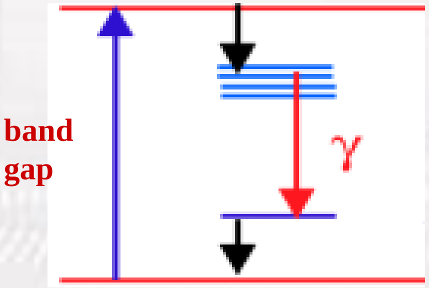




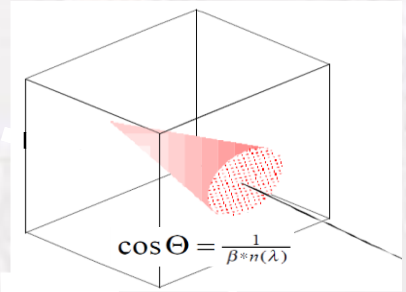
Lower-energy particles create signals in materials through:



Ionization (electric charge)



Scintillation (light)



Cerenkov (light)

Visible signal, S, is proportional to incoming particle energy, E: **S = αE**

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TO DESIGN A CALORIMETER, NEED TO UNDERSTAND SHOWER PROCESSES AND PARTICLE INTERACTIONS WITH MATTER

RATHER DIFFERENT FOR PRIMARY ELECTROMAGNETIC AND HADRONIC PARTICLES, SO CONSIDER THEM SEPARATELY

ELECTROMAGNETIC SHOWERS

Electrons and photons lose energy by interacting with nuclei & atomic electrons

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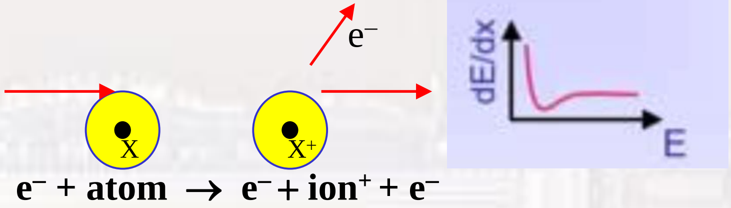
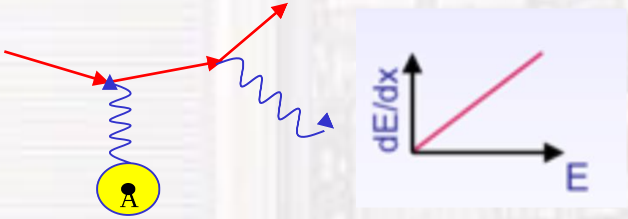
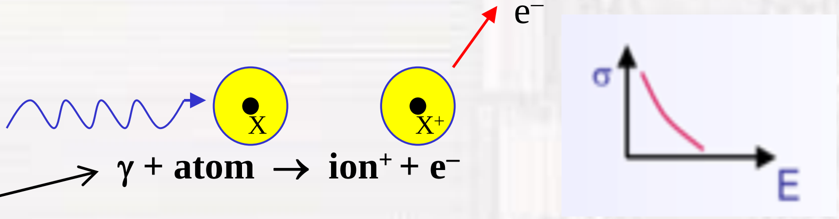
- **Electrons**
  - Ionization (atomic electrons)
  - Bremsstrahlung (nuclear)



e^{-} + atom $\rightarrow$ e^{-} + ion^{+} + e^{-}

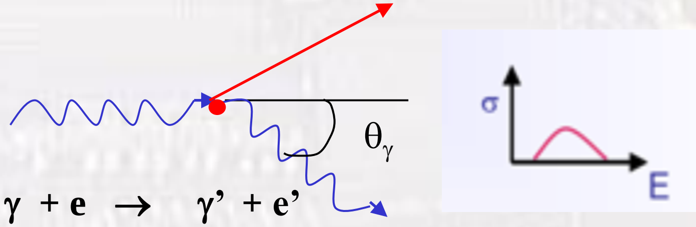


At high E, **bremsstrahlung dominates**

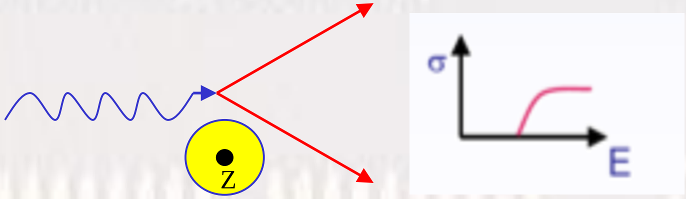


γ + atom $\rightarrow$ ion^{+} + e^{-}

- **Photons**
  - Photoelectric effect (atomic electrons)
  - Compton scattering (atomic electrons)
  - Pair-production (nucleus + electrons)



γ + e $\rightarrow$ γ’ + e’



γ + Coul. Field $\rightarrow$ e^{+} + e^{-}

At high E, **pair-production dominates**

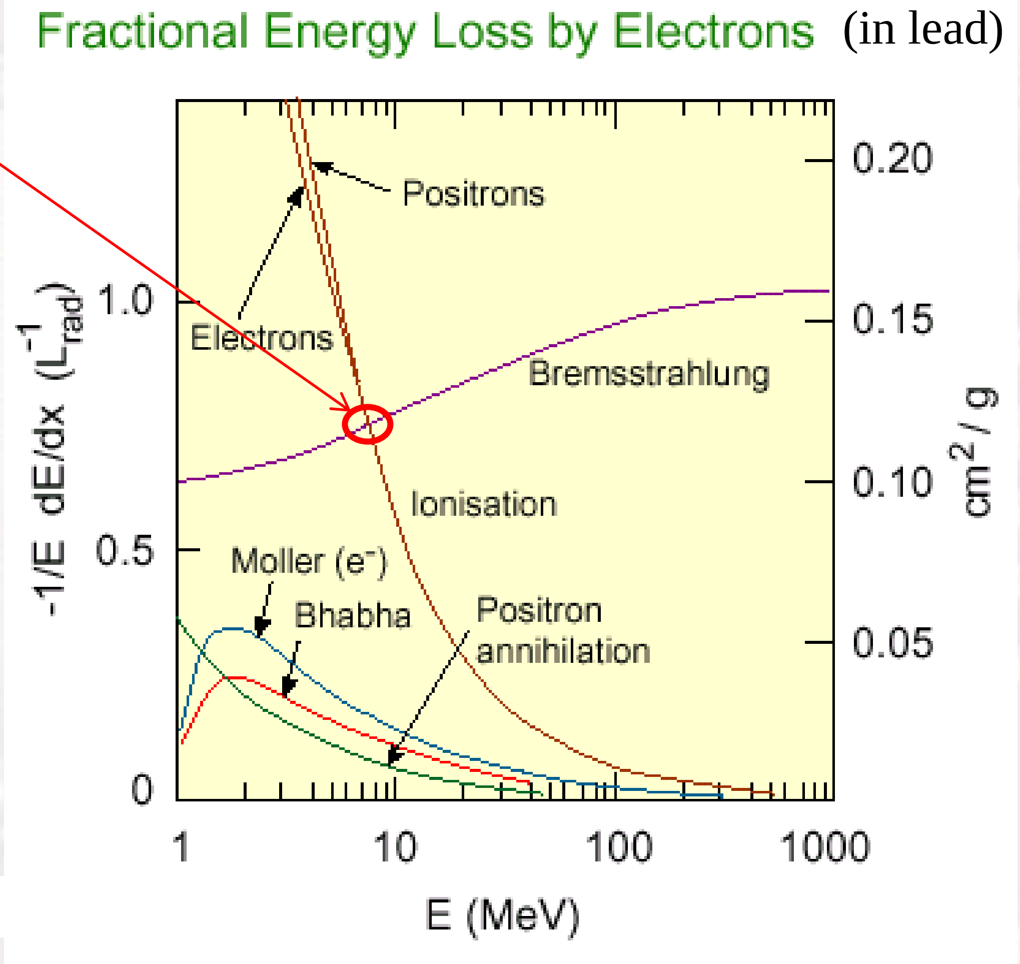
At high energy, electrons interact predominantly through bremsstrahlung

Critical Energy, $\boldsymbol{E_c}$: radiation dominates ionization

$$E_c \approx \frac{610[710]\,MeV}{Z+1.24[0.92]}$$

(solids, liquids [gas])

e.g. $E_c(e)$ = 7.4 MeV for Pb (Z=82)


Fractional Energy Loss by Electrons (in lead)

Energy loss through bremsstrahlung depends on particle, energy & material

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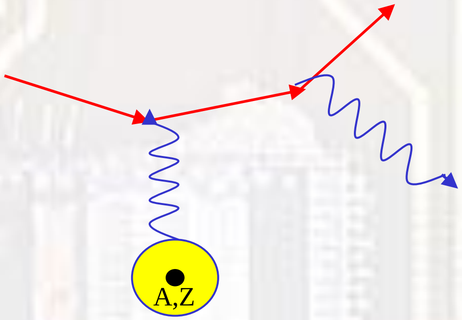

$$-\frac{dE}{dx}\Big|_{Brems} = 4\alpha N_A \left(\frac{e^2}{mc^2}\right)^2 \ln\frac{183}{Z^{1/3}}\frac{Z(Z+1)}{A} Q^2 E$$

Where: N_A, α are Avogadro's number and the fine-structure constant
m, Q are the mass and charge of the particle (e.g. electron, muon)
A, Z = mass number and atomic number of the material

For electrons:

$$-\frac{dE}{dx}\Big|_{Brems} = \frac{1}{X_0}E$$

$$E(x) = E_0 e^{-x/X_0}$$

X_0 = thickness of material that reduces the mean energy of an electron by a factor *e* (2.718)
→ **radiation length** of the material

$$\text{n.b.}: \frac{dE}{dx}\Big|_{\mu} \Big/ \frac{dE}{dx}\Big|_{e} = (m_e / m_\mu)^2 \sim 1/43000$$

Radiation length etc. for some typical materials in HEP detectors

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Material	Z	A	Density (g/cm^2)	X_0 (cm)
Carbon	6	12	2.27	18.8
Aluminium	13	27	2.7	8.9
Silicon	14	28	2.33	9.36
Iron	26	56	7.87	1.76
Copper	29	64	8.96	1.43
Tungsten	74	184	19.3	0.35
Lead	82	207	11.35	0.56
Uranium	92	238	18.95	0.32

At high energy, photons interact predominantly through pair production

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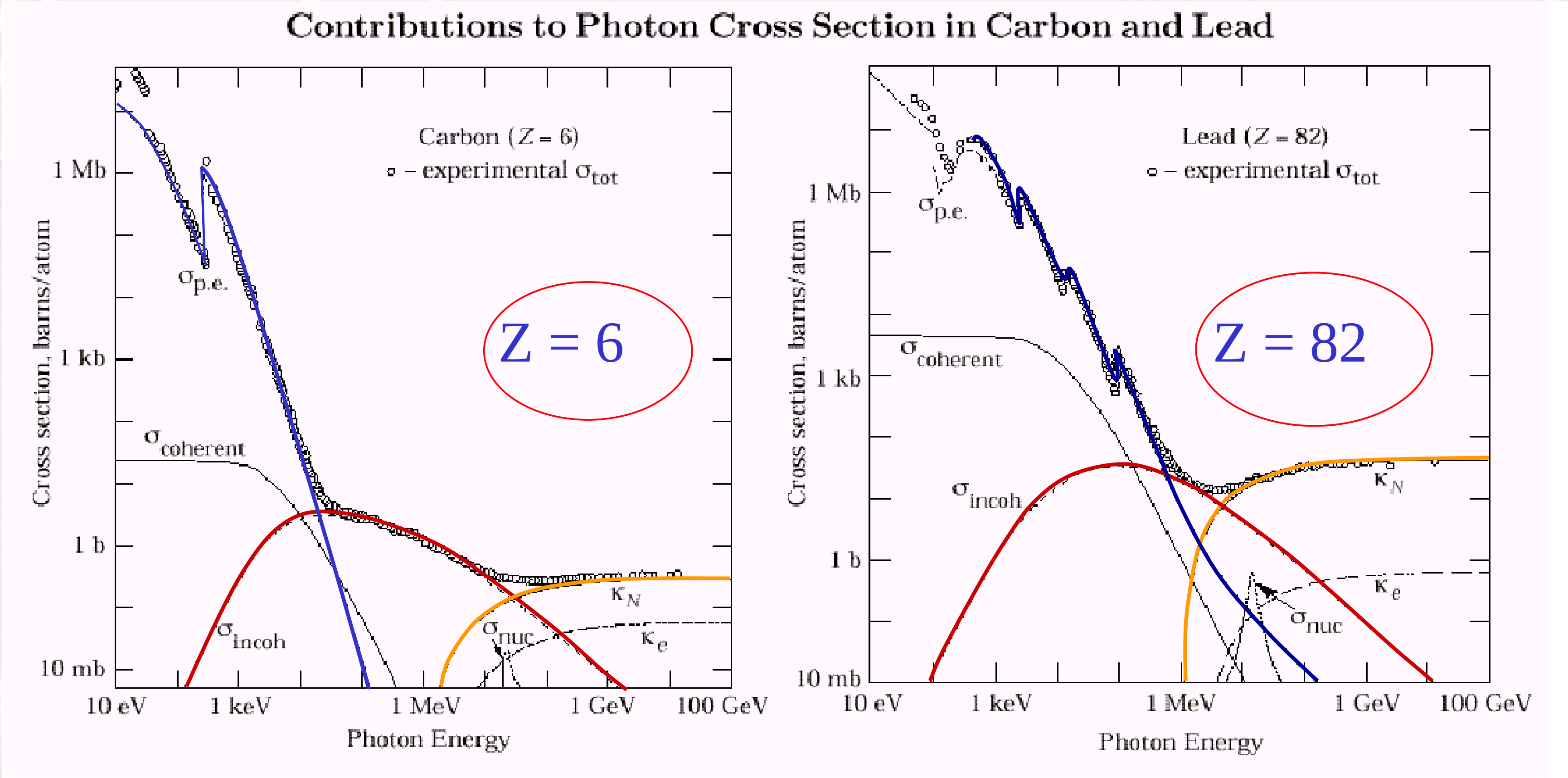


Legend
K_n = pair on nucleus field
K_e = pair on electron field
Incoh =Compton

Pair production occurs if $E_\gamma > 2m_ec^2$ (i.e. ~1 MeV)

$$\sigma_{pair} \approx \frac{7}{9}\frac{A}{N_A}\frac{1}{X_0}$$

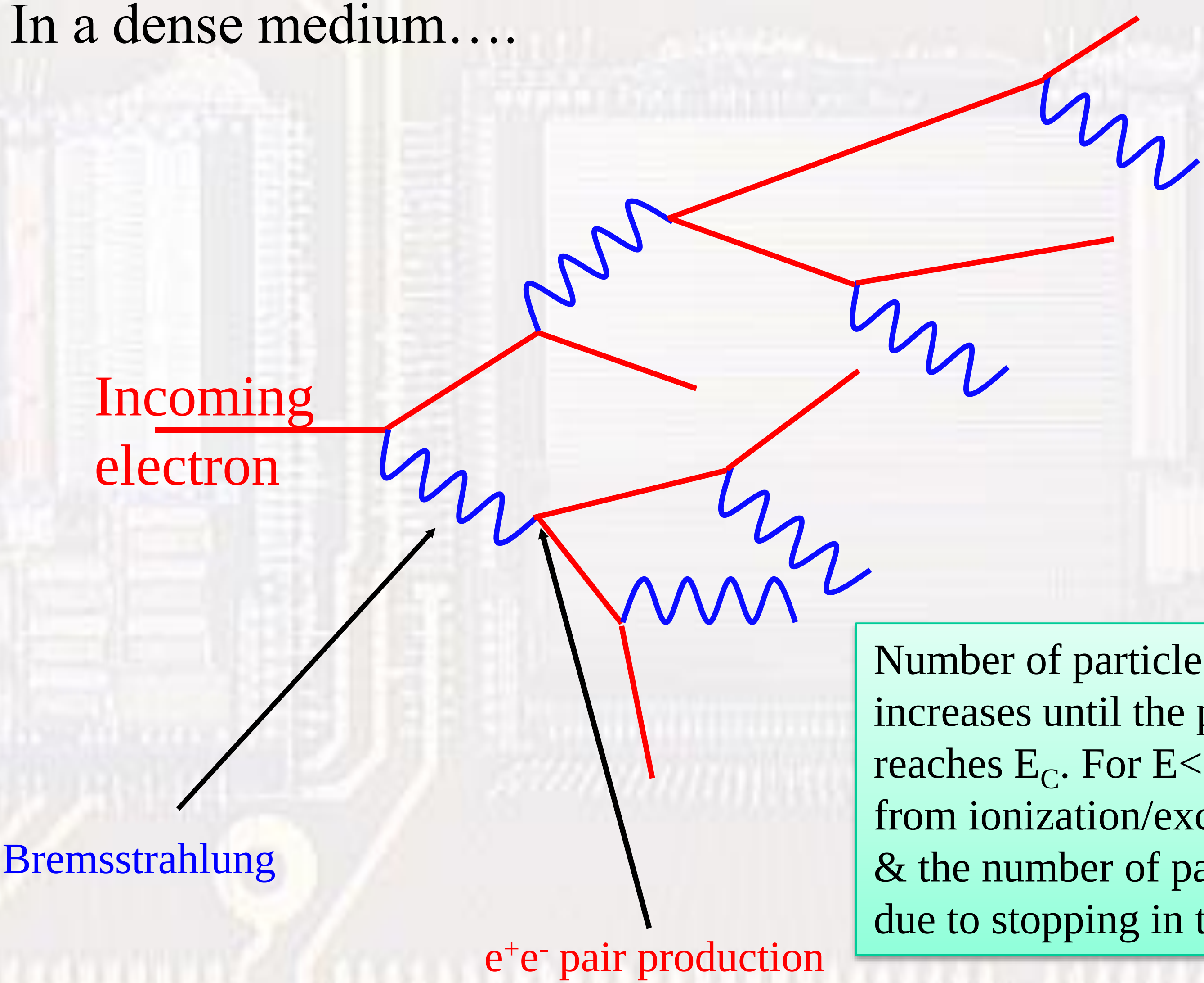
σ ~ constant when E >1 GeV

$\propto Z(Z+1)$

Probability of conversion in $1X_0$ is $e^{-7/9}$

Electromagnetic shower is mainly pair-production & bremsstrahlung

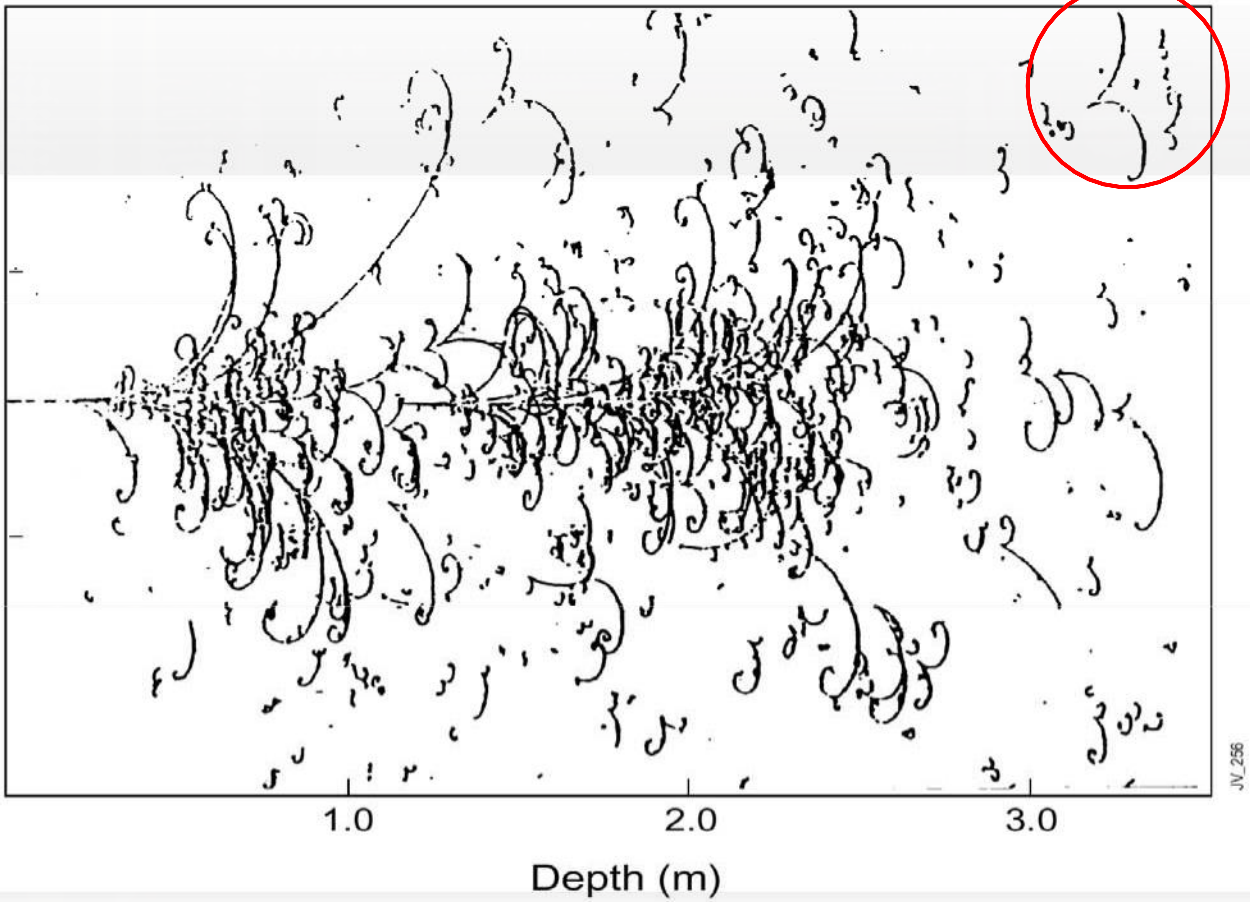
In a dense medium….



Number of particles in the shower increases until the particle energy reaches E_C. For $E<E_C$ energy loss from ionization/excitation dominates & the number of particles decreases due to stopping in the material

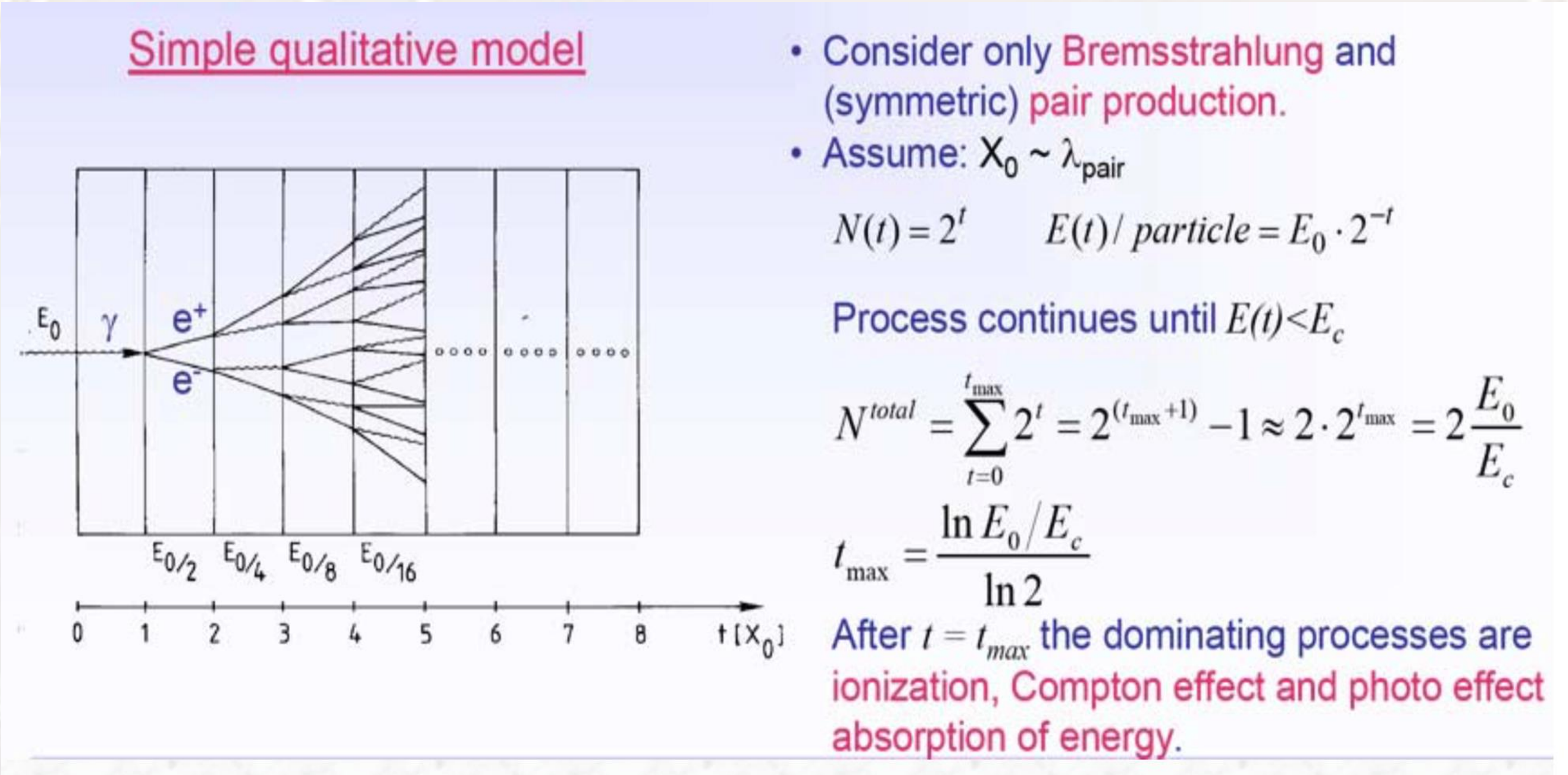
The previous generation of calorimeters could “see” showers!

γ + Coul. Field → e+ e-



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

EM showers: a simplistic qualitative model can give useful rules of thumb



Simple qualitative model

- Consider only Bremsstrahlung and (symmetric) pair production.
- Assume: $X_0 \sim \lambda_{pair}$

$$N(t) = 2^t \qquad E(t)/\,particle = E_0 \cdot 2^{-t}$$

Process continues until $E(t) < E_c$

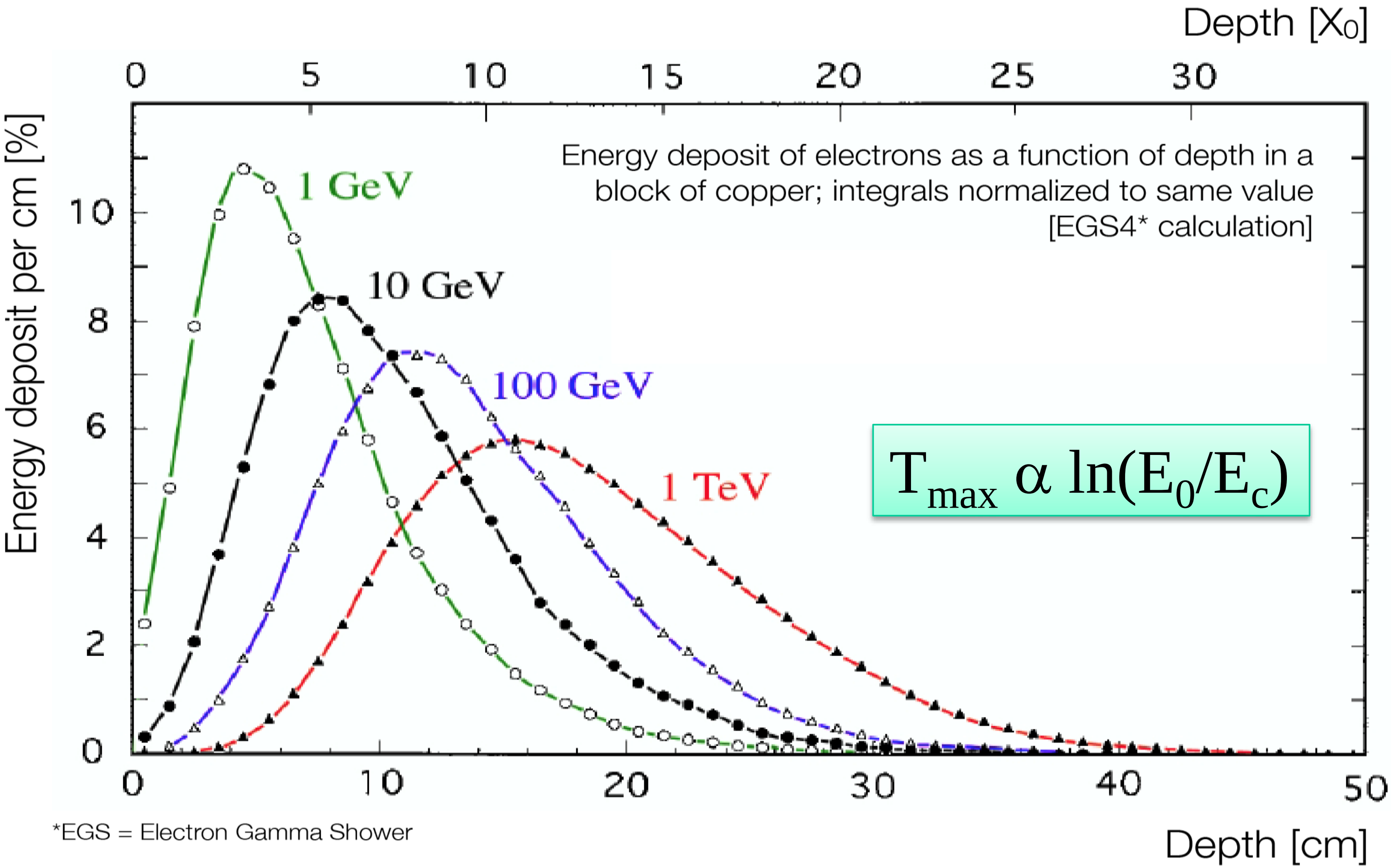
$$N^{total} = \sum_{t=0}^{t_{\max}} 2^t = 2^{(t_{\max}+1)} - 1 \approx 2 \cdot 2^{t_{\max}} = 2\frac{E_0}{E_c}$$

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

After $t = t_{max}$ the dominating processes are ionization, Compton effect and photo effect absorption of energy.

1. X_0 can be thought of as “generation length”: # of particles doubles at each generation
2. Shower maximum, t_{max}, scales only logarithmically with particle energy E_0
   → size of calorimeters did not need to increase greatly from LEP to LHC

Depth of em shower maximum increases logarithmically with energy



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

$T_{max} \propto \ln(E_0/E_c)$

*EGS = Electron Gamma Shower

For good em shower containment, need about 25 X_0 of material

Molière radius, R_M, sets the transverse shower size

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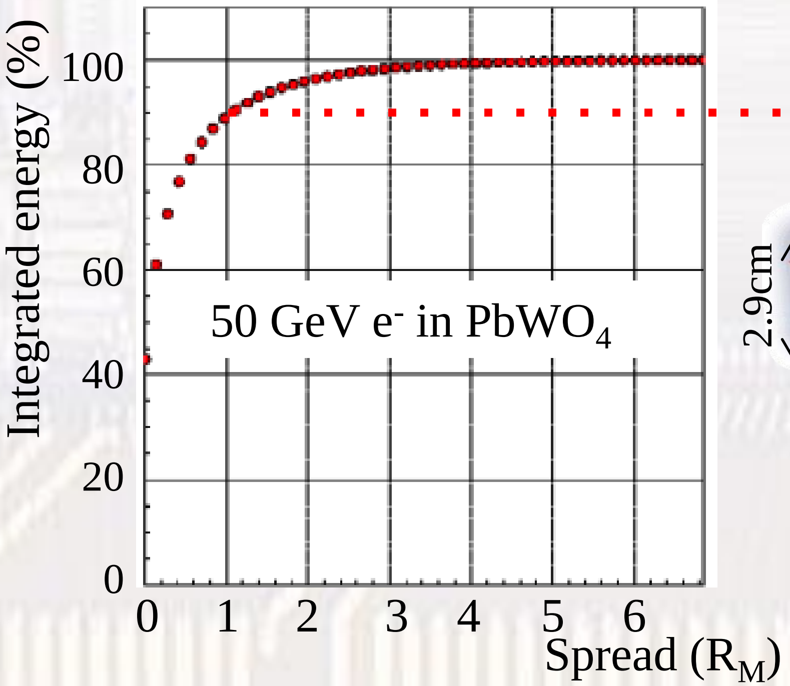
Lateral spread of an em shower is dominated by two processes:

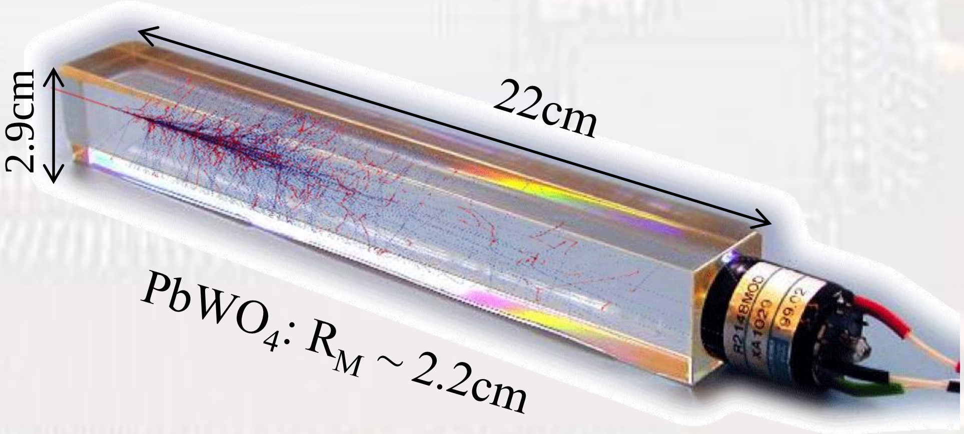
- Multiple scattering of electrons away from the shower axis
- Relatively long mean free path of photons

Molière radius: lateral spread for E_C electrons after one X_0

$$R_M = \frac{21\,MeV}{E_C} X_0 \approx 7\frac{A}{Z}$$



99% within 3.5 R_M
95% within 2 R_M
90% of shower energy within 1 R_M



HADRONIC SHOWERS (A MORE COMPLICATED STORY!)

Hadron showers contain electromagnetic and hadronic components

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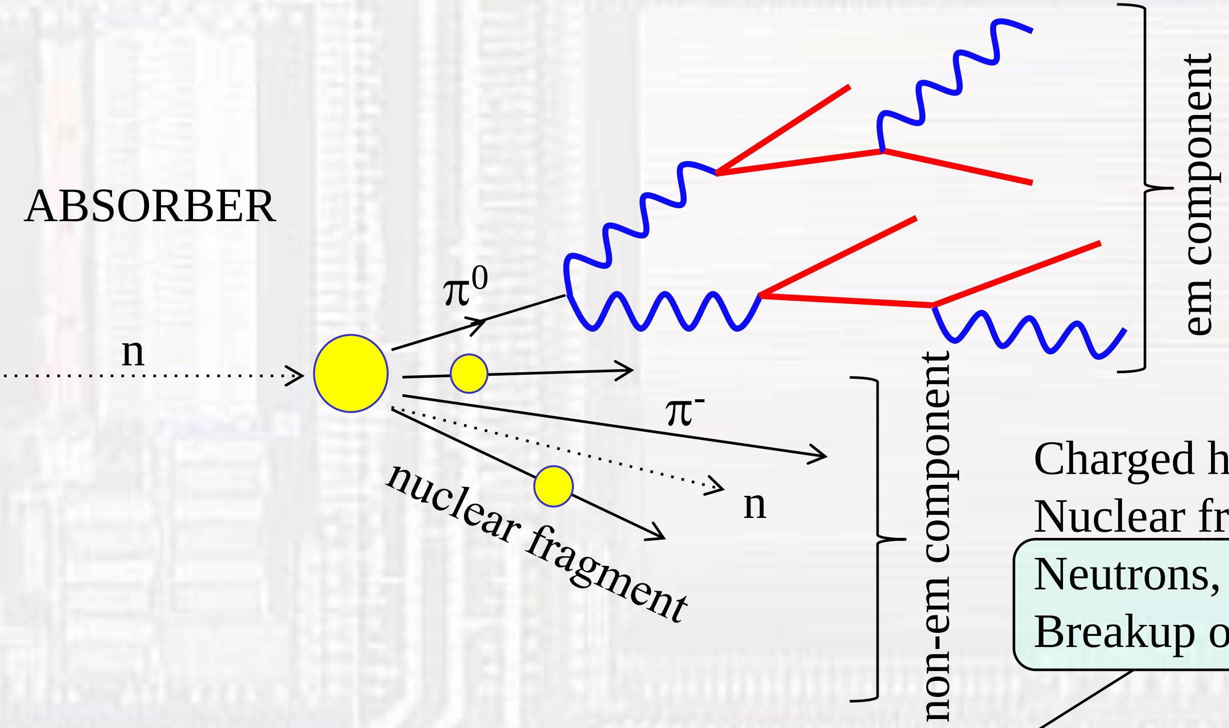

Electrons, photons
$\pi^0 \rightarrow 2\gamma$
➔ em sub-shower

Charged hadrons	(20%)
Nuclear fragments, protons	(25%)
Neutrons, soft γs	(15%)
Breakup of nuclei	(40%)

Either not detected or often too slow to be within detector time window ➔ invisible energy

Composition of hadronic showers is complex!

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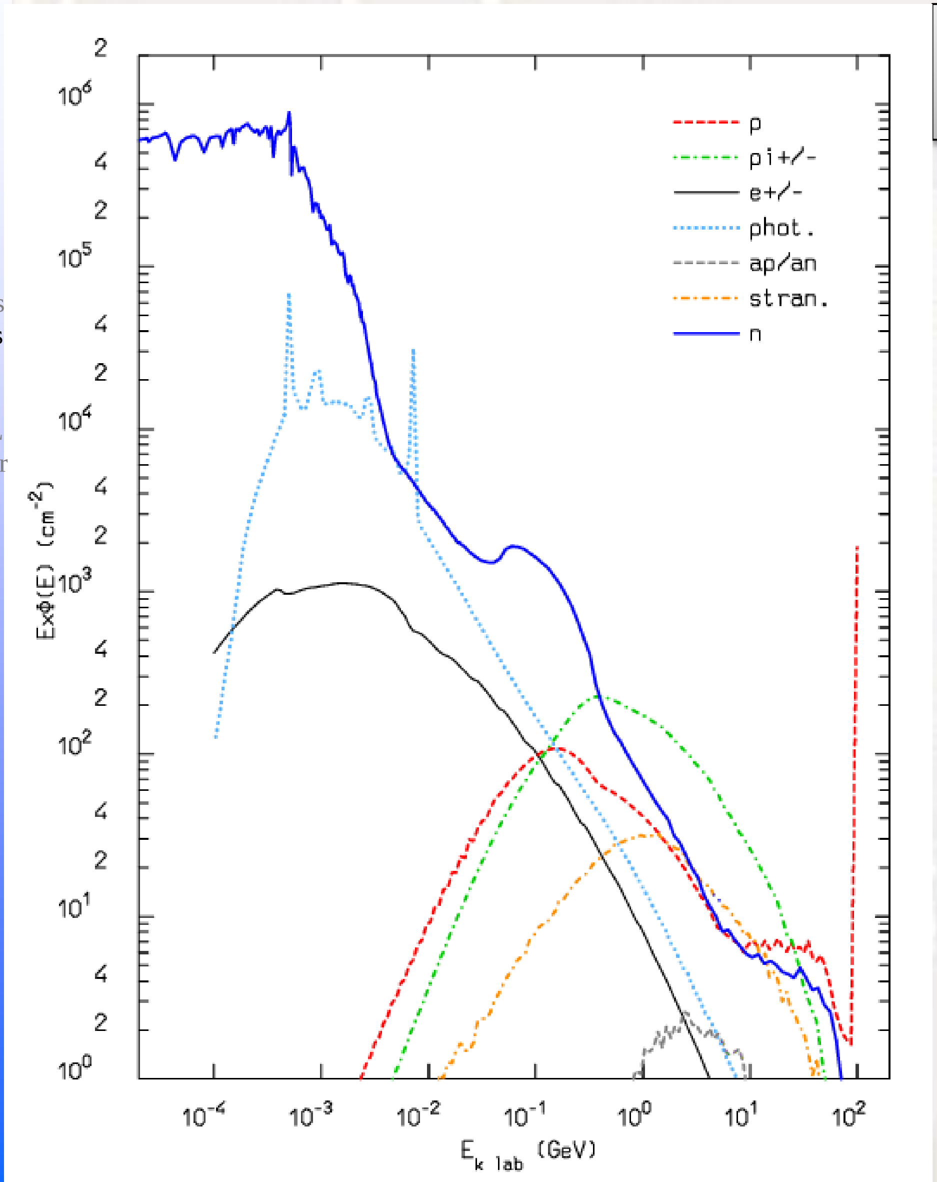


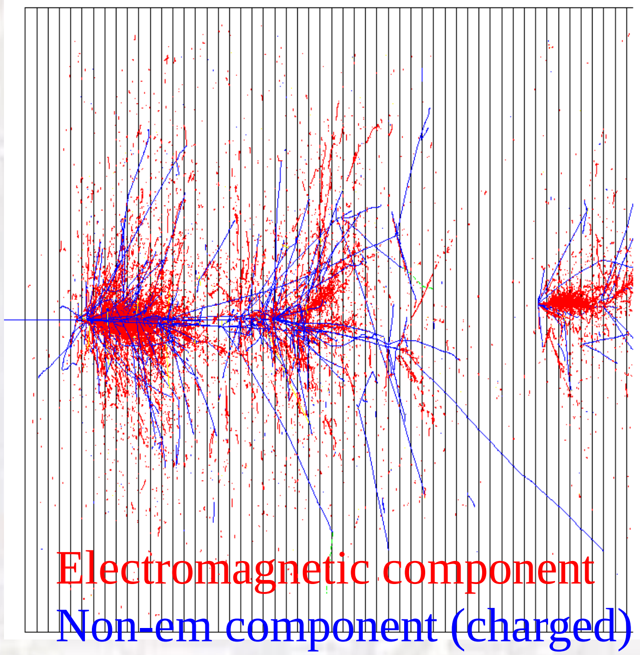
Hadron shower induced by a 100 GeV proton in Pb: energy spectra of the major shower components, weighted by their track length in the shower (*Ferrari, 2001*)

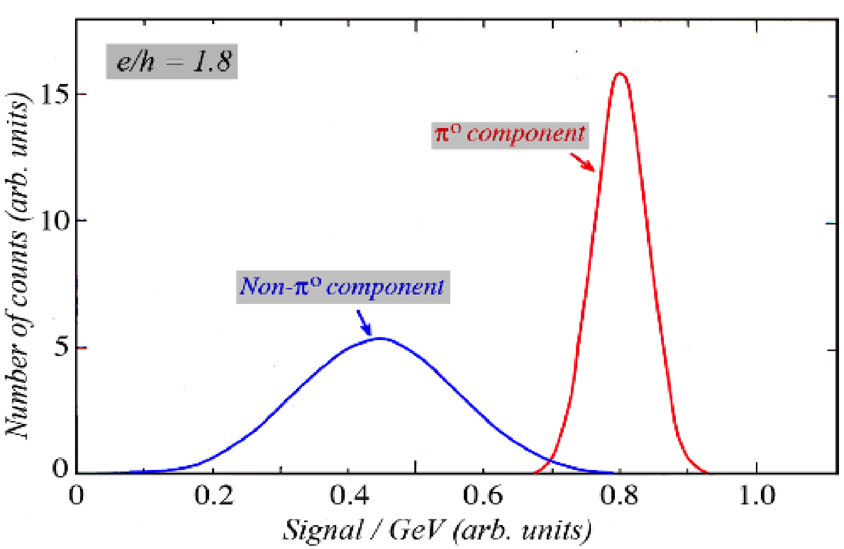
Fractions of particle types:

- Fluctuate in a non-Gaussian way
- Are energy dependent
- Depend on initial particle (p,π,n)

Simulation is very difficult as the number of physical processes and their fluctuations are large & span a large energy range: GeV → <MeV

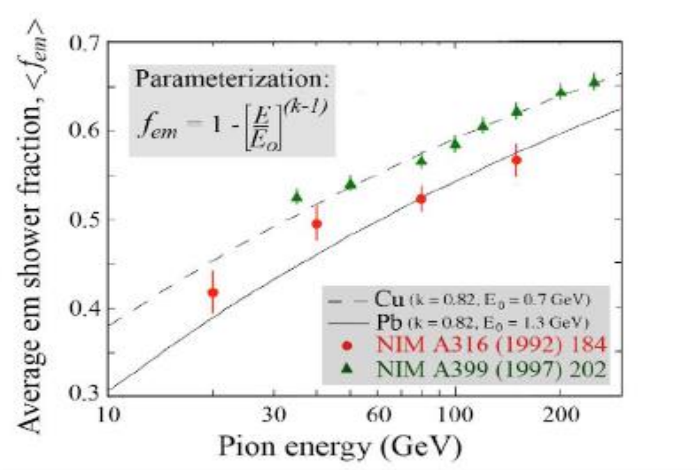
Efficiency of detecting hadronic & em components differs from unity: non-compensation





Fraction of non-em component ("h") detected is far lower than for the em-component ("e"): e/h > 1 for most detectors. This leads to:

- Non-linearities
- Non-Gaussian response
- Relatively poor energy resolution



em fraction is large & varies with energy & fluctuates with non-Gaussian tails

Several approaches to deal with non-compensation in hadron calorimeters

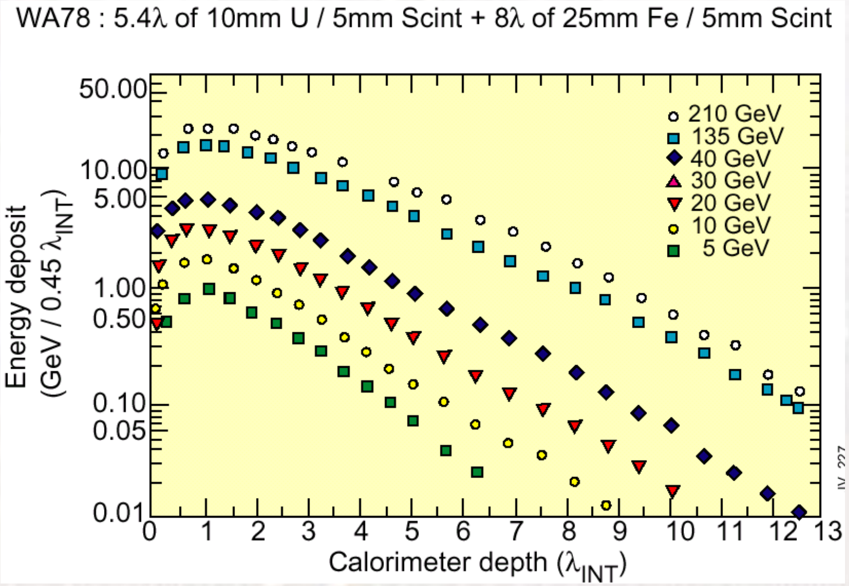
- **Compensation**
  - Hardware: bring the response of hadrons and electrons/photons to the same level (e/h=1) by e.g. including materials more sensitive to neutrons, e.g. Zeus detector @ HERA
  - Software: identify em hot-spots and down-weight them. Requires high segmentation in 3D, e.g. H1 @ HERA, ATLAS
- **Dual (or triple) readout**
  - Evaluate the two components separately, e.g. DREAM
- **Particle flow**
  - Use the hadron calorimeter predominantly for the neutral hadron component, e.g. CMS

Hadron shower shapes are characterized by the nuclear interaction length, λ_{INT}

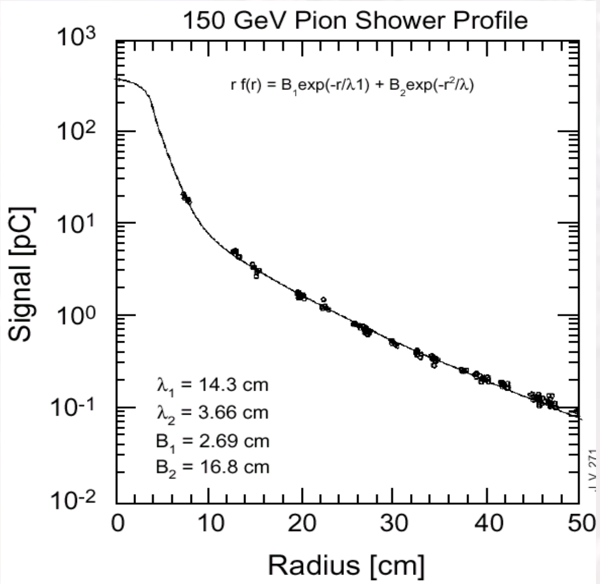
- **Strong interaction → hadron shower development**
- **Multiplication continues until the hadron energy is below the pion production threshold**

Typical scale: interaction length $\lambda_{INT} = 35\ A^{1/3}\ \mathrm{gcm}^{-2}$

Good containment requires ~10λ_{INT} thickness and ~1λ_{INT} width



Longitudinal development



Transverse development

Interaction length etc. for some typical materials in HEP detectors

Material	Z	A	Density (g/cm^2)	X_0 (cm)	λ_{INT} (cm)
Carbon	6	12	2.27	18.8	38
Aluminium	13	27	2.7	8.9	39.4
Silicon	14	28	2.33	9.36	45.5
Iron	26	56	7.87	1.76	16.8
Copper	29	64	8.96	1.43	15.1
Tungsten	74	184	19.3	0.35	9.6
Lead	82	207	11.35	0.56	17.1
Uranium	92	238	18.95	0.32	10.5

As X_0 is lower than λ_{INT}, electromagnetic calorimeters are placed in front of hadron calorimeters

Energy resolution of calorimeters

Ideally, if all shower particles were counted: E~N, σ~√N~√E

In practice: other effects, such that, for em calorimeters:

$$\frac{s(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

a: stochastic term

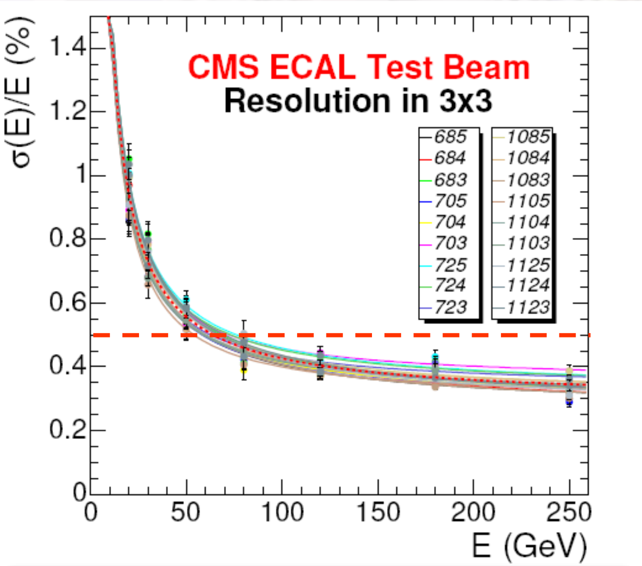
- intrinsic statistical shower fluctuations
- sampling fluctuations
- signal quantum fluctuations (e.g. photo-statistics)

b: noise term

- readout electronics noise
- radioactivity, pileup fluctuations

c: constant term

- inhomogeneities (hardware or calibration)
- imperfections in calorimeter construction (gaps, dimensions variations etc.)
- non-linearity of readout electronics
- fluctuations in longitudinal energy containment
- fluctuations in energy lost in material upstream (or within) the calorimeter



For 9 $PbWO_4$ crystals tested @ CERN

This is also a ***reasonable*** approximation for hadron calorimeters

Summary of electromagnetic & hadronic showering processes

Electromagnetic showering process is:

- Well understood
- Very linear
- Good energy resolution
- Reproduced well in simulation (e.g. GEANT4 contains EGS); may need optimization by tuning low-level cuts

Hadronic showers:

- Are less well understood
- Fluctuate with energy, incoming particle type etc.
- Lead to non-compensation (e/h≠1) → poor energy resolution

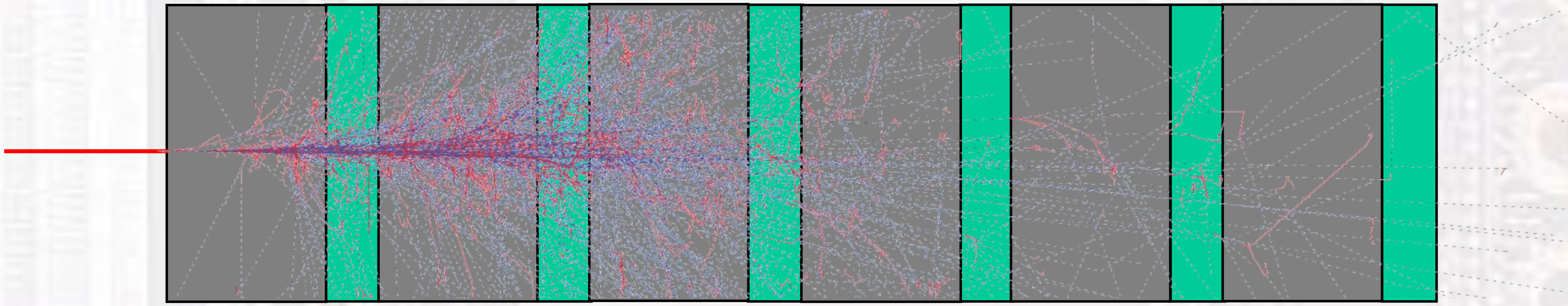
HOMOGENEOUS VS SAMPLING CALORIMETERS

Two main types of calorimeter: Sampling and Homogeneous

Sampling Calorimeter

$\sigma/E \sim (10\text{-}30)\%/\sqrt{E}$

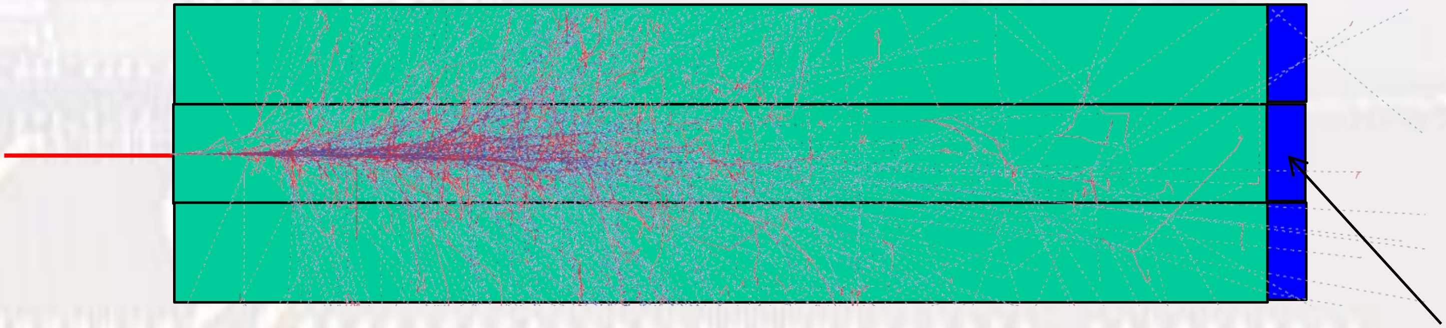
Layers of passive 'absorber' (e.g. Pb, Cu, W) alternate with active layers, such as Si, scintillator, liquid Argon (LAr)



Homogeneous Calorimeter

$\sigma/E \sim (1\text{-}3)\%/\sqrt{E}$

Single dense medium serves as both absorber and signal producer, e.g. liquid Xe or Kr (ionization), crystals such as BGO, $PbWO_4$ (scintillation)



Light detector, e.g. PMT, APD, VPT

Choice of homogeneous vs sampling calorimeter depends on application

Homogeneous

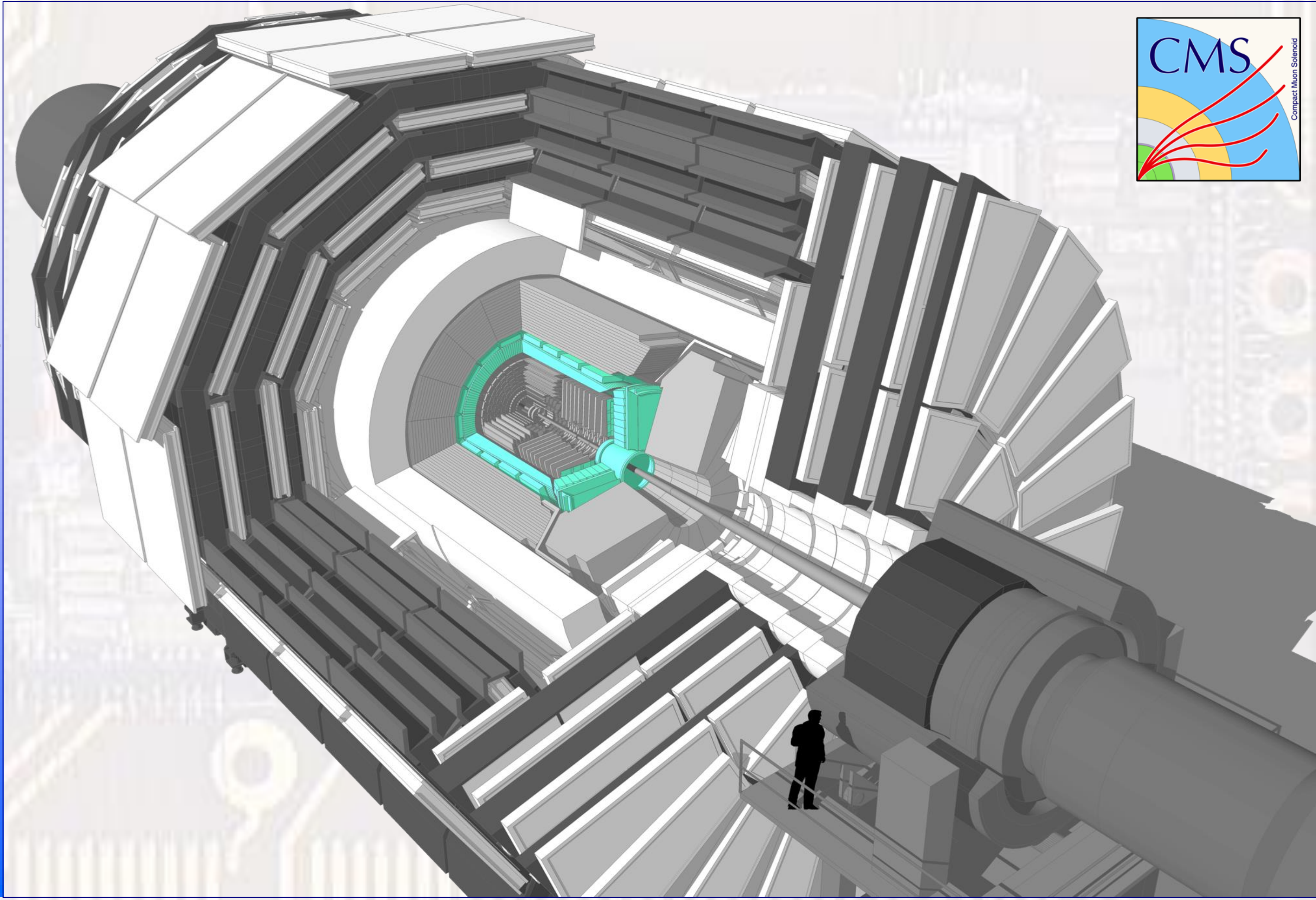
- Advantages
  - See all charged particles in the shower → best statistical precision (**lowest stochastic term**) → minimizes detector contribution to measured particle widths
  - Same response from everywhere → **good linearity** (in principle)
- Disadvantages
  - Limited segmentation
  - Relatively high cost
- Examples
  - B-factories (small γ energies)
  - OPAL, Delphi, L3 (LEP)
  - ALICE PHOS & CMS ECAL

Sampling

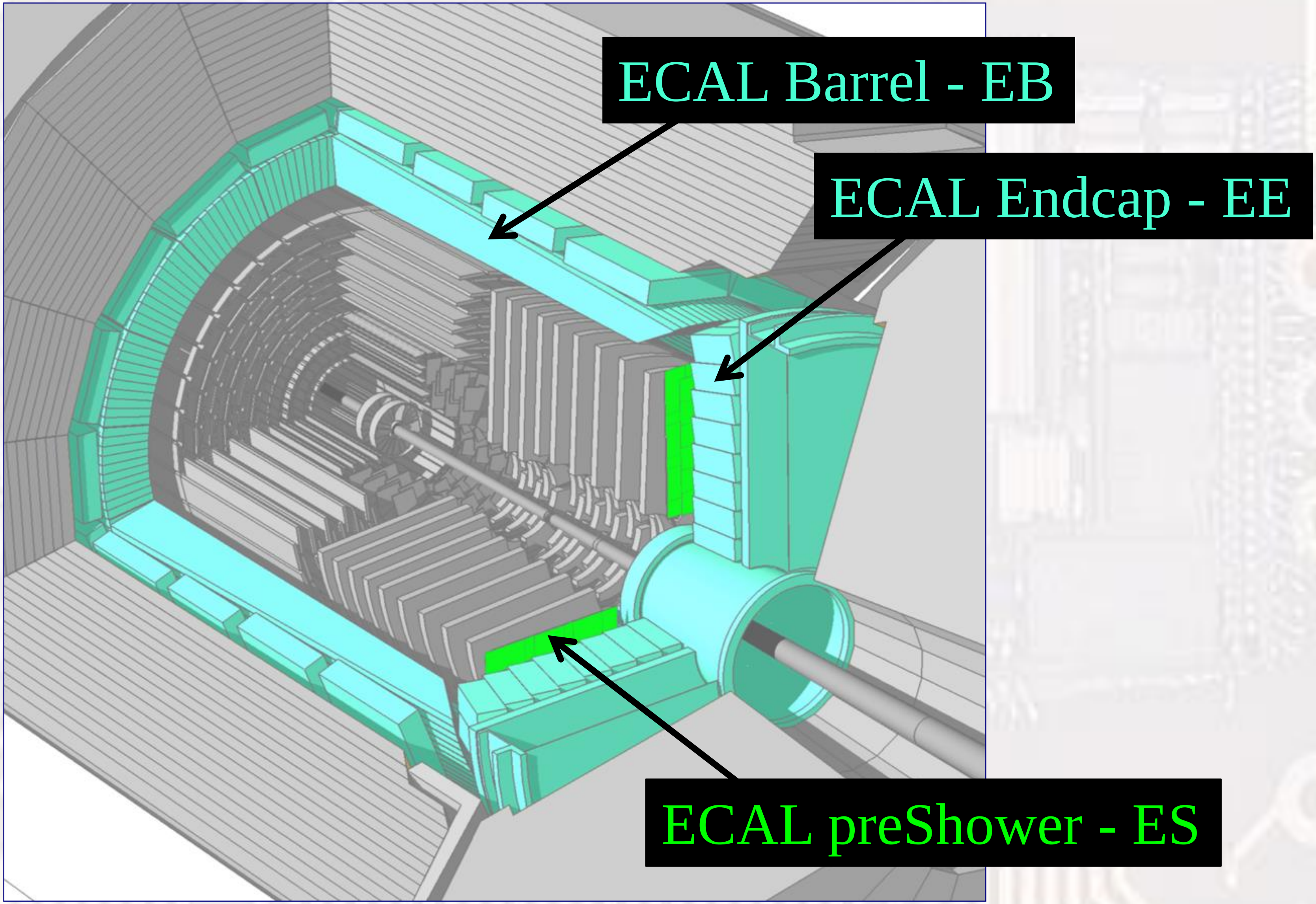
- Advantages
  - Relatively **low cost**
  - **Transverse & longitudinal segmentation** possibilities → can significantly help to suppress background
- Disadvantages
  - Only part of the shower is seen → higher stochastic (sampling) term
- Examples
  - Aleph ECAL (LEP)
  - LHCb & ATLAS ECALs
  - All HCALs (that I am aware of)

CALORIMETRY BY EXAMPLES: CMS ELECTROMAGNETIC CALORIMETER - ECAL

CMS ECAL is just outside of the Tracker, and inside the HCAL and solenoid



All three parts of CMS ECAL are located within the solenoid



ECAL Barrel - EB

ECAL Endcap - EE

ECAL preShower - ES

CMS ECAL: homogeneous calorimeter based on $PbWO_4$ scintillating crystals

Motivation
Basics
EM showers
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HGCAL

- **Criteria for design of ECAL in CMS**
  - Hermetic, compact and granular, with **excellent energy resolution to $|\eta|<2.5$**
    ➔ **homogeneous** calorimeter (minimizes sampling fluctuations)
  - **Large dynamic range**, coupled with excellent linearity, to > 1 TeV
  - Provide **triggering** info. e.g. particle ID, energy, isolation
  - **Radiation tolerant** to expected dose rates and cumulative doses/fluences
- **Several options in the early days (early 1990s) of CMS, including:**

	Sampling	**Homogeneous scintillators**		
Property	Pb/plastic Shashlik	Liquid Xenon	CeF_3 crystals	**$PbWO_4$ crystals**
Density ($g\ cm^{-3}$)	4.5	3.06	6.16	**8.28**
Radiation length X_0 (cm)	1.7	2.77	1.68	**0.85**
Molière radius R_M (cm)	3.4	4.1	3.39	**2.19**
Wavelength peak (nm)	500	175	300	**440**
Fast decay constant (ns)	<10	2.2	5	**<10**
Light yield (γ per MeV)	13	$\sim 5 \times 10^4$	4000	**100**

Selected by CMS in 1994

The CMS ECAL: ~75000 $PbWO_4$ scintillating crystals with APD/VPT light detection

Very compact:
- X_0 ~0.85cm, R_M ~ 2.2cm

Excellent energy resolution

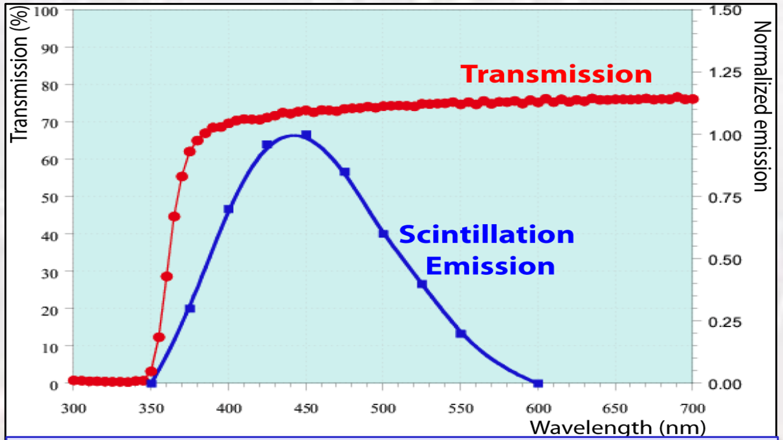
Fast << 100ns signals

High transverse granularity

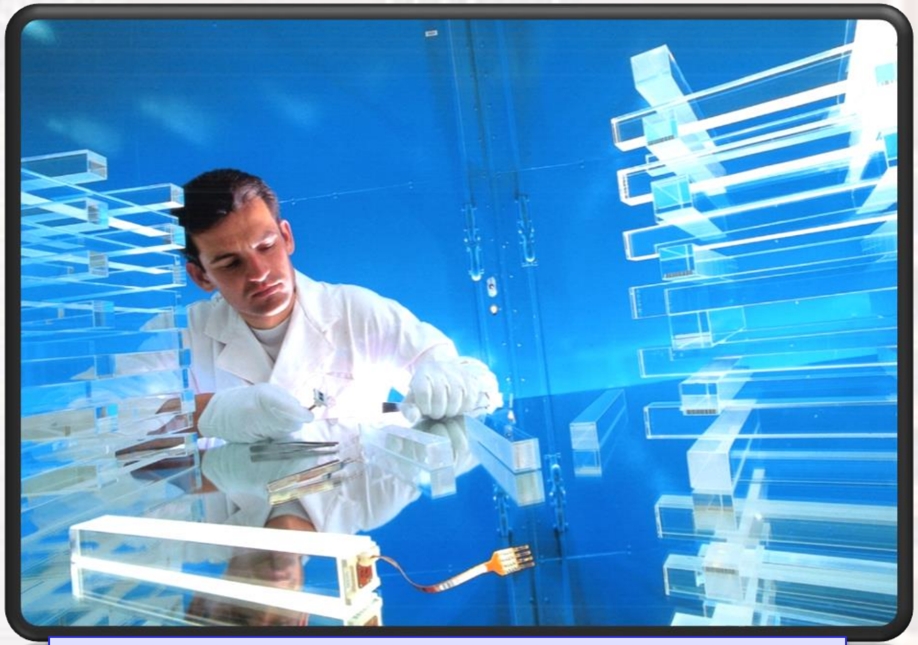
No longitudinal segmentation

→ No angular measurement

Time-dependent variations, due to:
- Temperature dependence
- Radiation damage



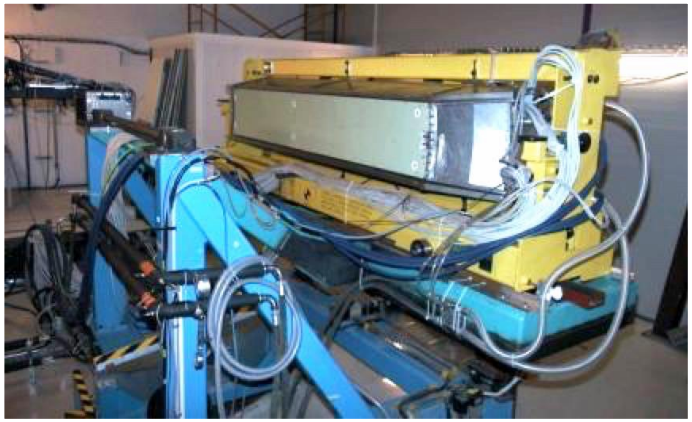
$PbWO_4$ crystals are transparent to the entire scintillation emission spectrum – before irradiation (see later)



Avalanche PhotoDiodes (APDs, gain ~50) or Vacuum PhotoTriodes (VPTs, gain ~10) are glued to the lead tungstate ($PbWO_4$) crystals to detect the scintillation light in the barrel and endcaps of the CMS ECAL respectively

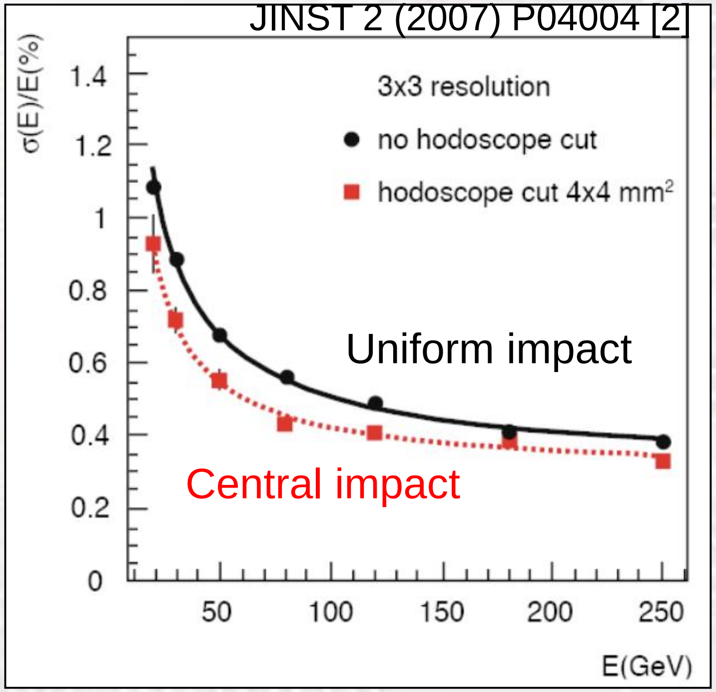
Beam tests of ECAL supermodules (1700 crystals each): excellent performance

- **ECAL "standalone" performance thoroughly studied at test beams**
  - No magnetic field, **no material upstream** of ECAL
  - Negligible systematic term from channel response variations ("**perfect calibration**")



- **Energy resolution for central impact on 3x3 arrays of barrel crystals [2]:**

$$\frac{\sigma_E}{E} = \frac{2.8\%}{\sqrt{E\,(\mathrm{GeV})}} \oplus \frac{0.128}{E\,(\mathrm{GeV})} \oplus 0.3\%$$

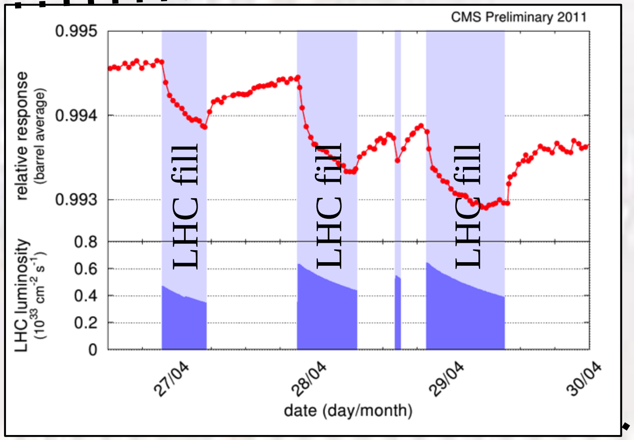


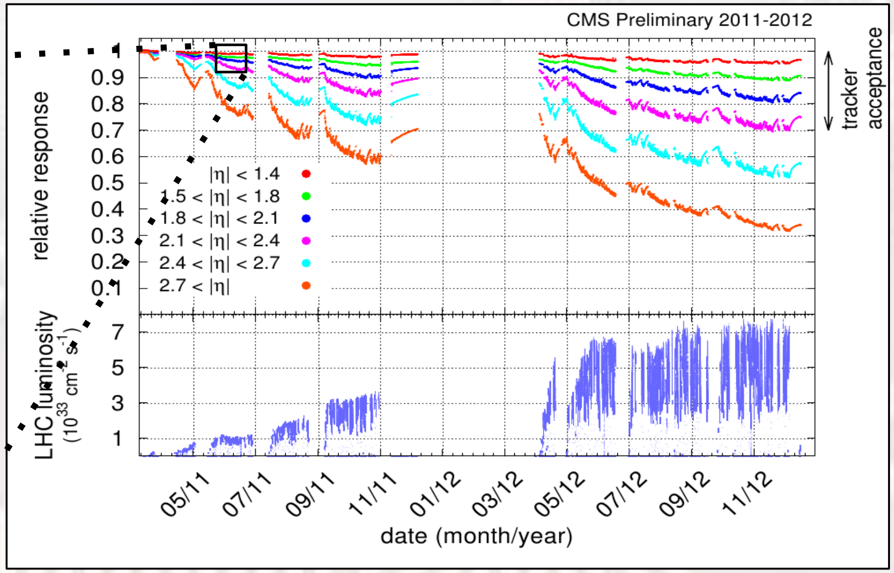
JINST 2 (2007) P04004 [2]

  - **Constant** term dominated by **longitudinal non-uniformity** of light collection : limited to less than 0.3% at construction

Time-dependent instabilities can (mostly) be controlled

- **Minimize environmental instabilities**
  - Achieved $\Delta T < 0.02^{o}$C, $\Delta V_{APD} < 20$ mV (well within spec.)
- **Monitor the radiation-induced effects – heavily η dependent**
  - **Crystal transparency changes**
    - Colour-centre formation, but **no damage to scintillation** mechanism
    - Electromagnetic damage is **spontaneously recovered** at room temperature
      - Fast damage and recovery on **the order of hours**
    - Hadronic damage causes **permanent** (at room temp.) and **cumulative** defects
  - VPT photocathode conditioning with accumulated charge*
  - APD leakage current increases





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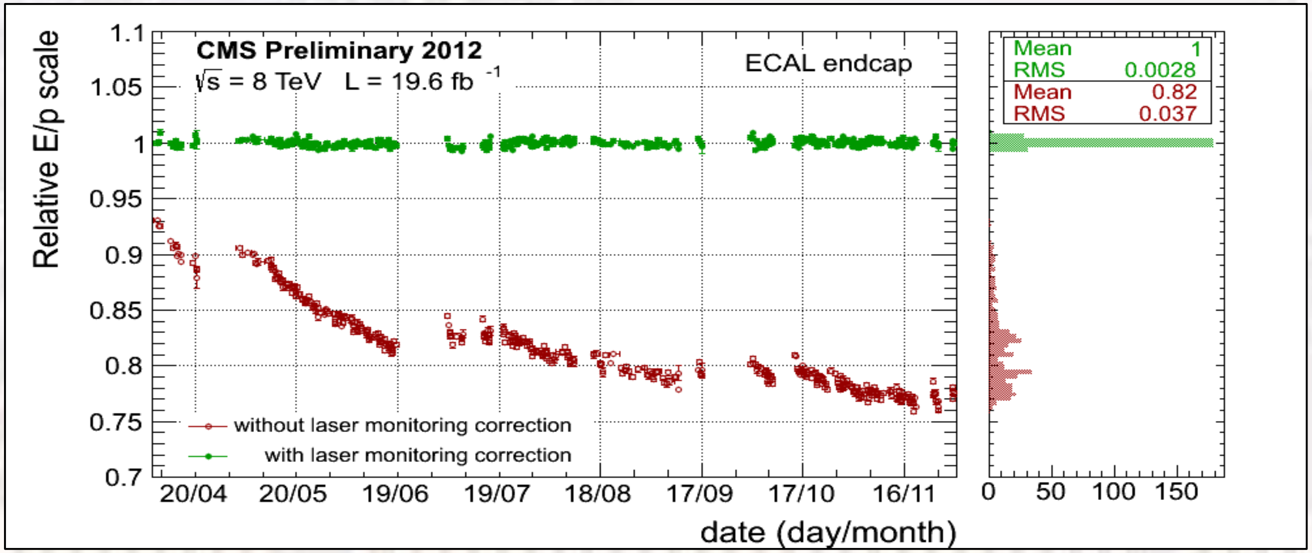
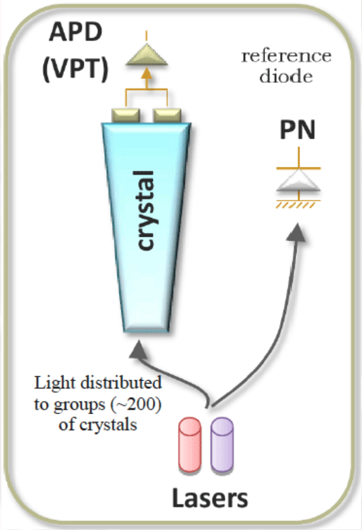
*Not disentangled from transparency changes

Crystal response stability is monitored and corrected through a laser system

Light from laser (447nm, ~peak emission) injected into each crystal

- One (averaged) measurement of the crystal transparency **every 40 minutes**
- Corrections ready for prompt reconstruction in **less than 48 hours**!
  - Validity checked using electrons from W decays





(Inter)Calibrating the CMS ECAL is driven by physics processes: $\sigma<0.8\%$ in barrel

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Basics
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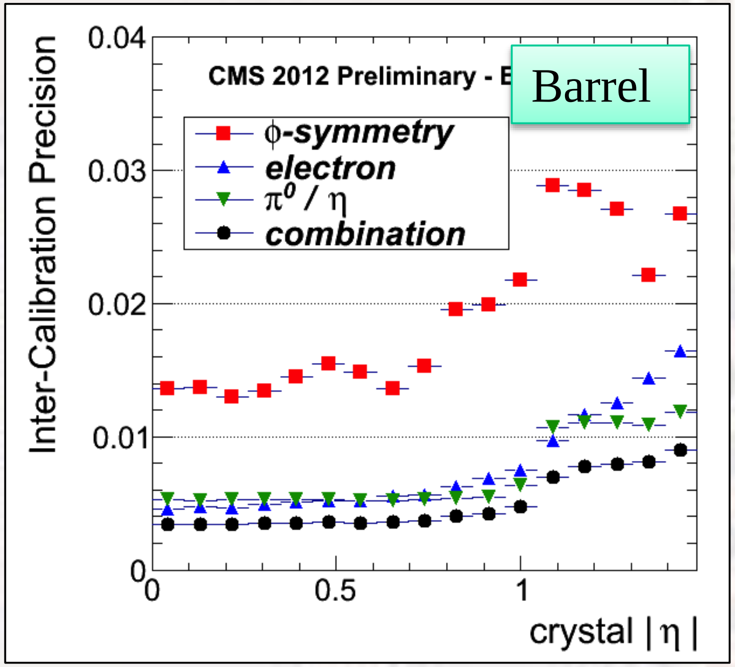
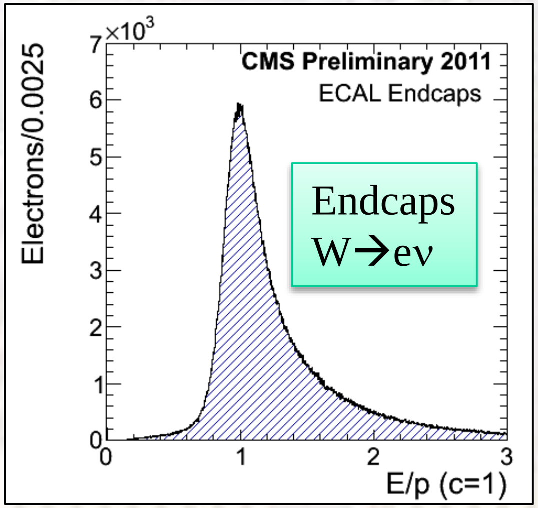
- ϕ- and time-invariance of energy flow in crystals at given η
  - Short calibration periods ~ 2 days
  - Excellent for checking ECAL stability
- $\pi^0/\eta \rightarrow \gamma\gamma$ invariant mass
  - Average calibration periods ~weeks

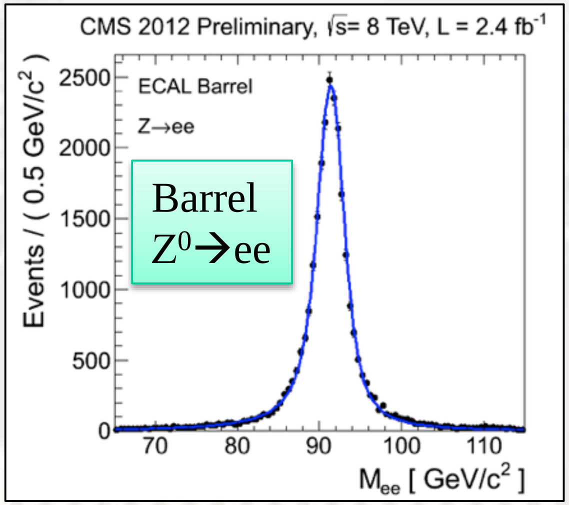
Dedicated high-rate (~10 kHz) trigger streams

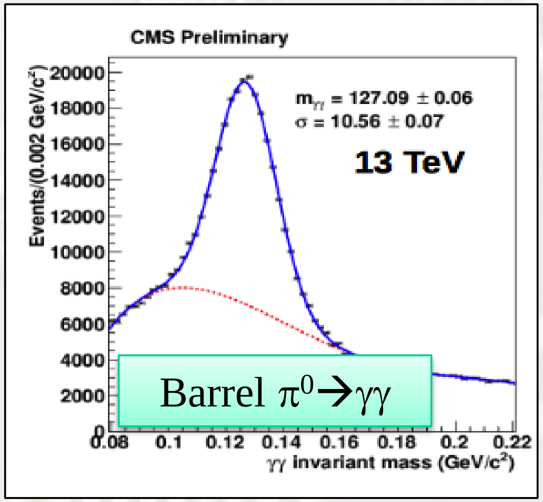
- $Z \rightarrow e^+e^-$ invariant mass and E/p with electrons from $W \rightarrow e\nu$
  - Long calibration periods ~months
  - Z peak also → absolute energy scale

Non pre-scaled analysis triggers

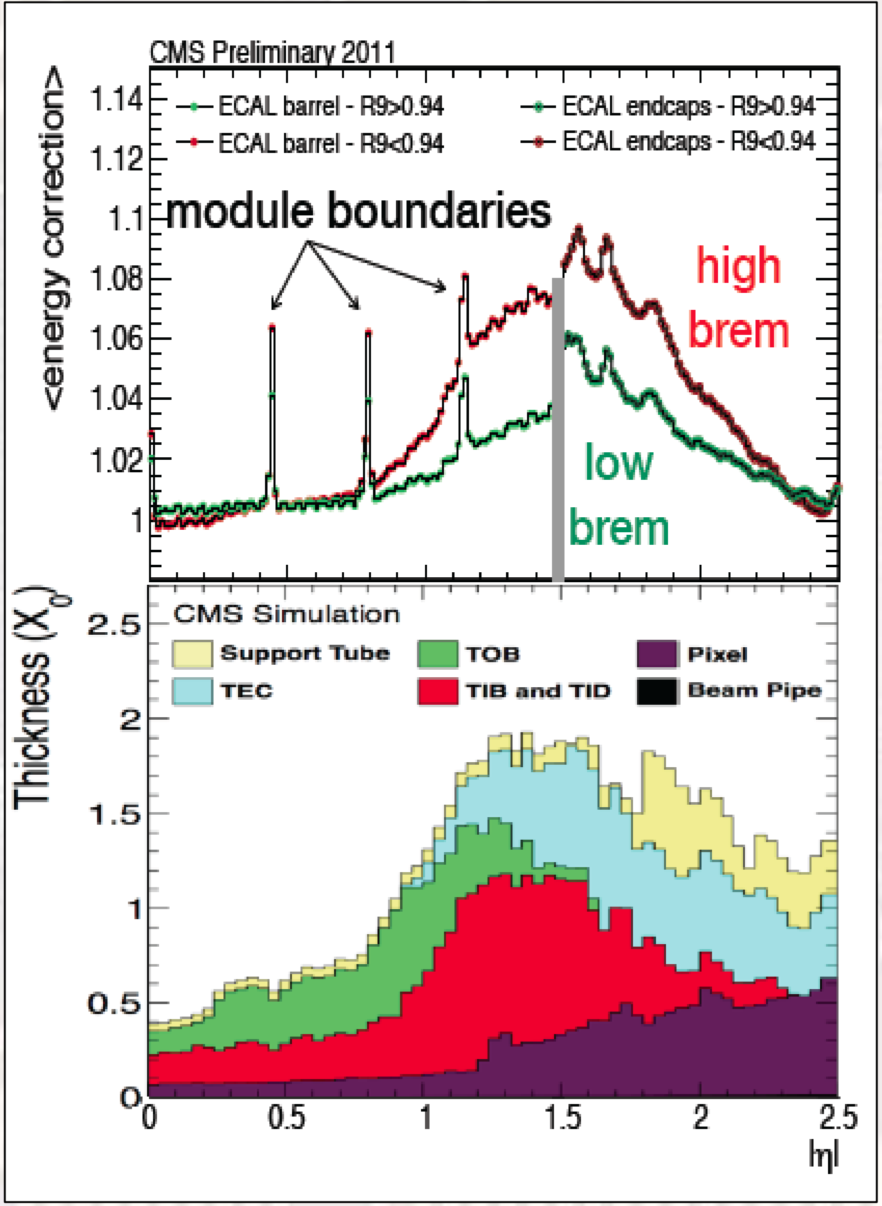








The bitter reality of a real HEP calorimeter: upstream material can diminish performance



- **Correct energy clusters for:**
  - Energy loss in **material upstream** of ECAL
    - e^+e^- bremsstrahlung and γ conversions
  - Local shower containment
  - Crystal geometry
- **Corrections currently derived with an MC-driven multivariate (MVA) technique**
  - Using shower location, shape and global event variables

CMS ECAL energy resolution is good and stable with time

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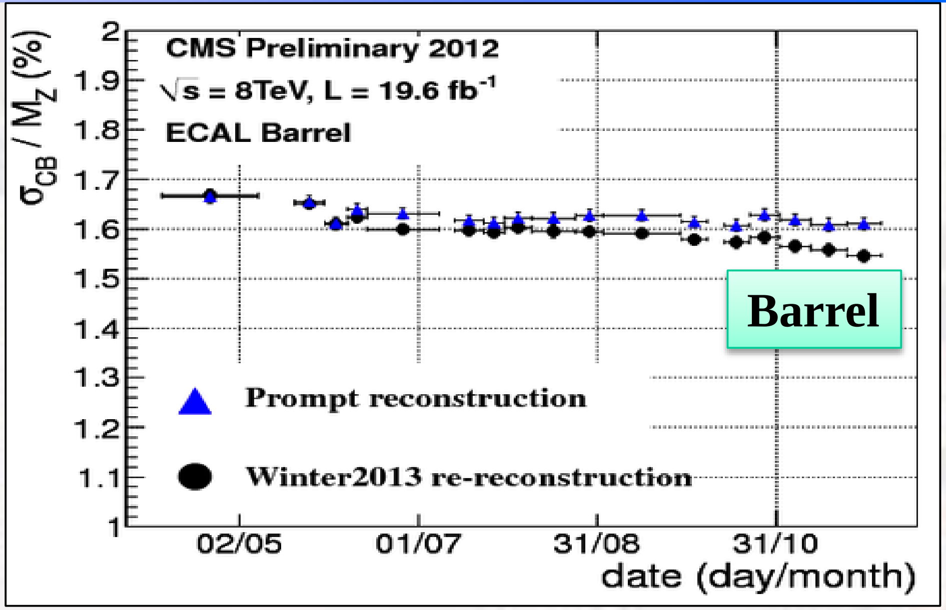
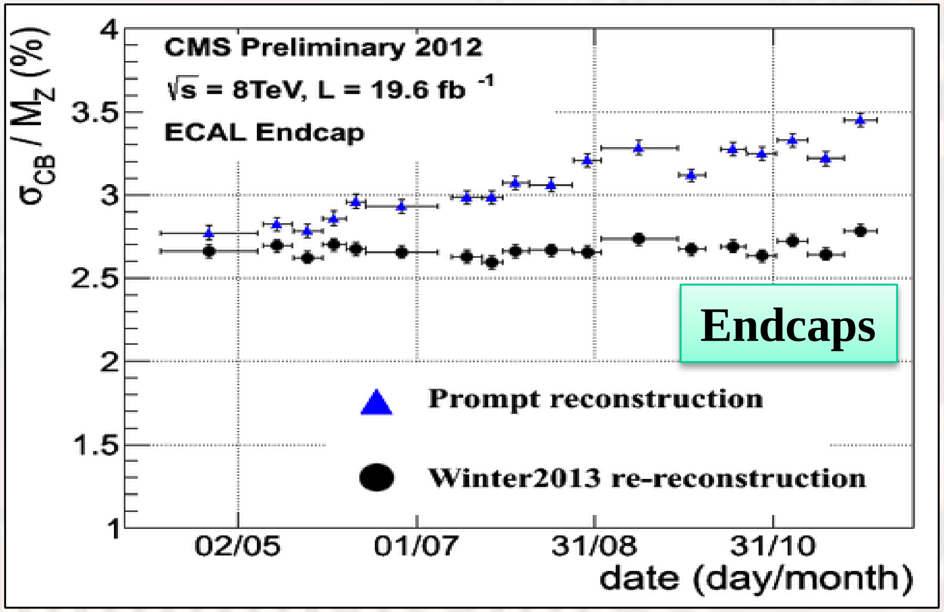
- Width of the **Z→e$^+$e$^-$ peak** fitted with a Crystal Ball (CB) function convoluted with a Gaussian
  - Use CB width as a measure of the **mass resolution**
- "Prompt" reconstruction (<48 hours after data taken) already excellent
- Absolute resolution and stability improved further once final inter-crystal calibration applied for a "re-reconstruction", especially in the endcaps (where radiation damage is significant)



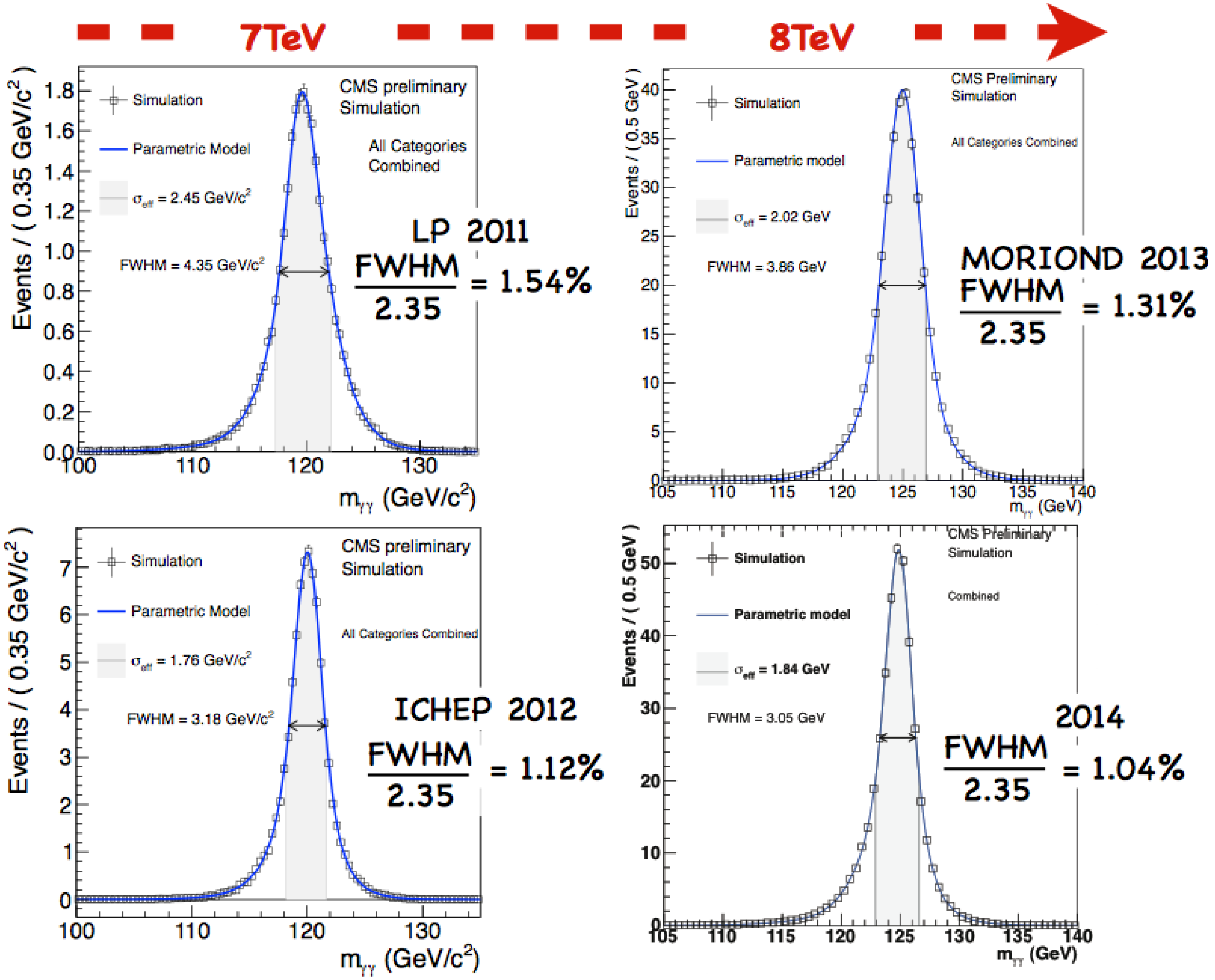


The CMS ECAL Benchmark: H→γγ

- The energy resolution measured in data with $Z \rightarrow ee$ is used to model the expected $H \rightarrow \gamma\gamma$ signal in the simulation
- **Steady progress and excellent results**

PROMPT reconstruction within 48h from data taking

RECONSTRUCTION with improved conditions



LP 2011 $\frac{FWHM}{2.35} = 1.54\%$

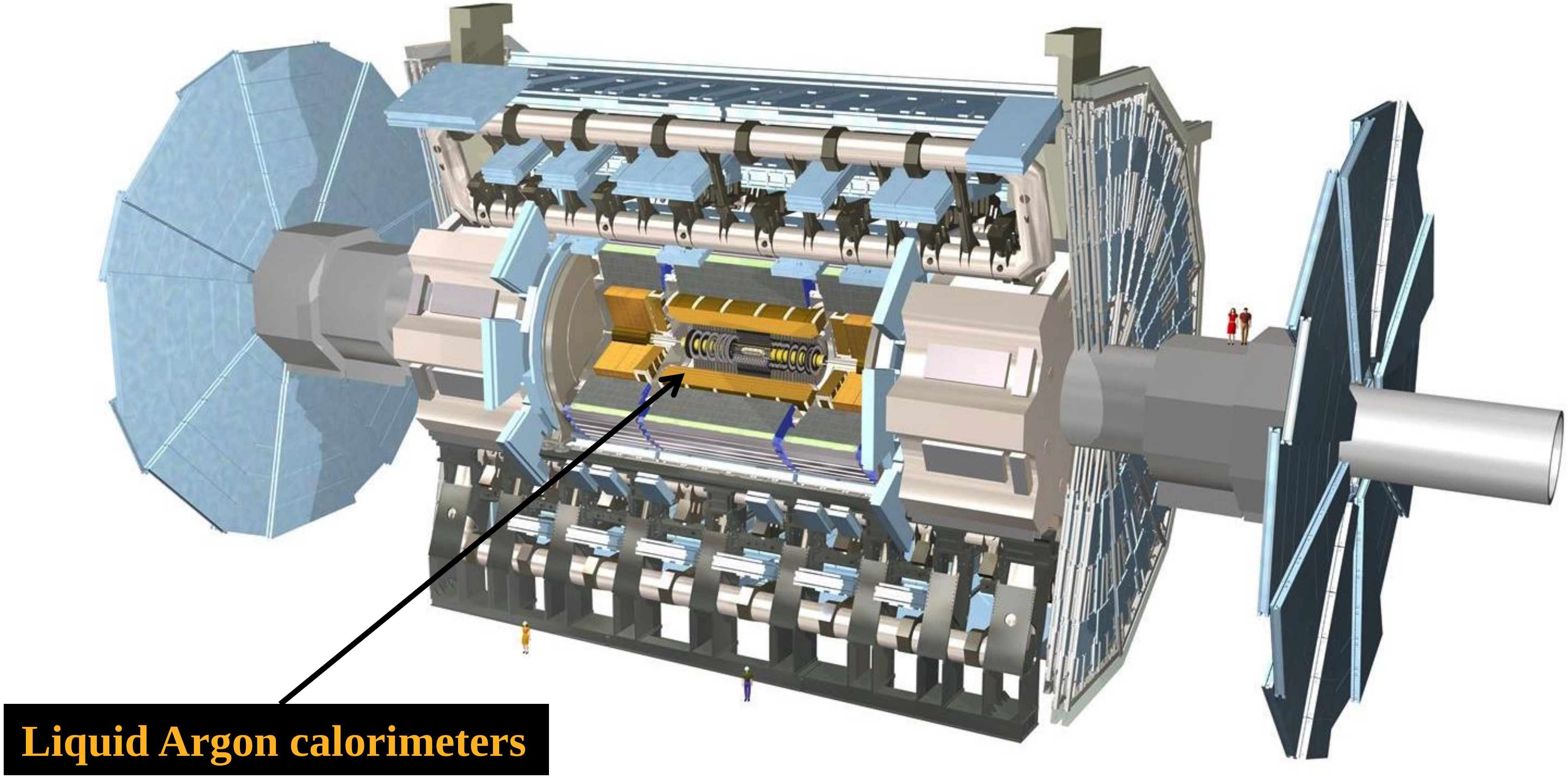
MORIOND 2013 $\frac{FWHM}{2.35} = 1.31\%$

ICHEP 2012 $\frac{FWHM}{2.35} = 1.12\%$

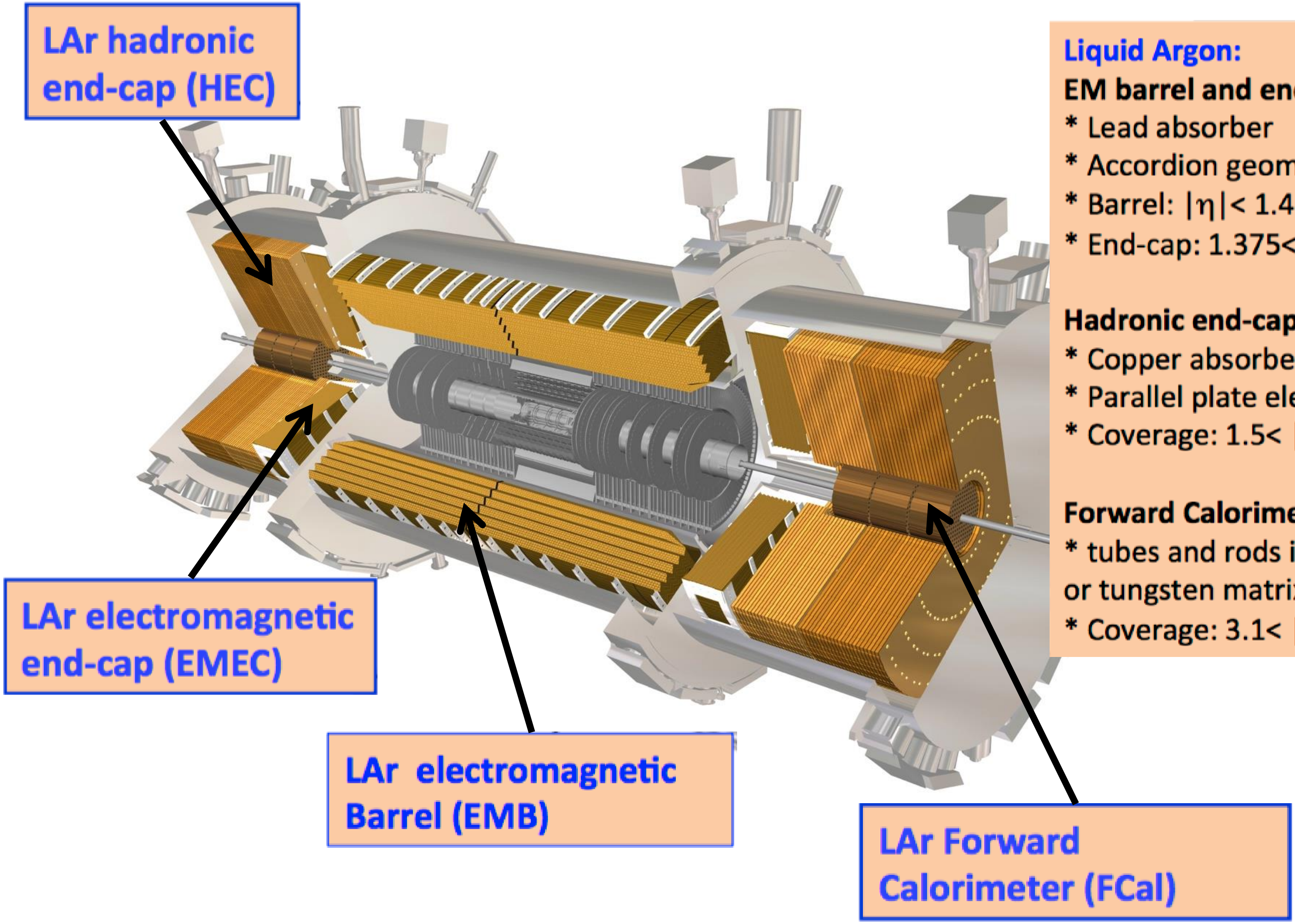
2014 $\frac{FWHM}{2.35} = 1.04\%$

CALORIMETRY BY EXAMPLES: ATLAS LIQUID ARGON CALORIMETERS

ATLAS Liquid Argon Sampling Calorimeters



ATLAS Liquid Argon electromagnetic and endcap/forward hadronic calorimeters



LAr hadronic end-cap (HEC)

LAr electromagnetic end-cap (EMEC)

LAr electromagnetic Barrel (EMB)

LAr Forward Calorimeter (FCal)

Liquid Argon:

EM barrel and end-cap
- Lead absorber
- Accordion geometry
- Barrel: $|\eta| < 1.475$
- End-cap: $1.375 < |\eta| < 3.2$

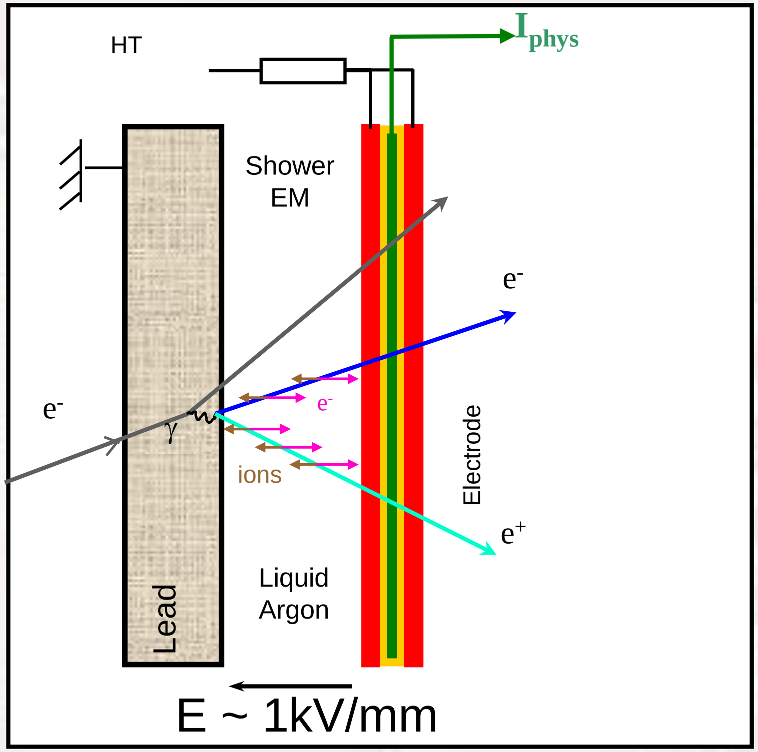
Hadronic end-cap
- Copper absorber
- Parallel plate electrodes
- Coverage: $1.5 < |\eta| < 3.2$

Forward Calorimeter
- tubes and rods in copper or tungsten matrix
- Coverage: $3.1 < |\eta| < 4.9$

ATLAS Liquid Argon calorimeter system

Sampling calorimeters using liquid argon as signal producer → ionization

- High # electron-ion pairs / MeV deposited → **no amplification needed, low fluctuations**
- **Good energy resolution**
- High **granularity** (110000 channels)
- Longitudinally **segmented** → angle measurement; background suppression
- Intrinsically **uniform** & **radiation hard**
- Argon = liquid @ -183°C
  → cryogenic system
- Not so fast (~450ns)
- Temperature **sensitive** ~2%/°K
- Not too compact: 25 X_0 = 47cm



Signal is given from collection of released electrons

Drift velocity depends on electron mobility and applied field. In ATLAS :

LAr gap 2 mm, ΔV = 2kV

ATLAS LAr calorimeter uses a novel "accordion" geometry to optimize performance

Motivation
Basics
EM showers
HD showers
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CMS HF
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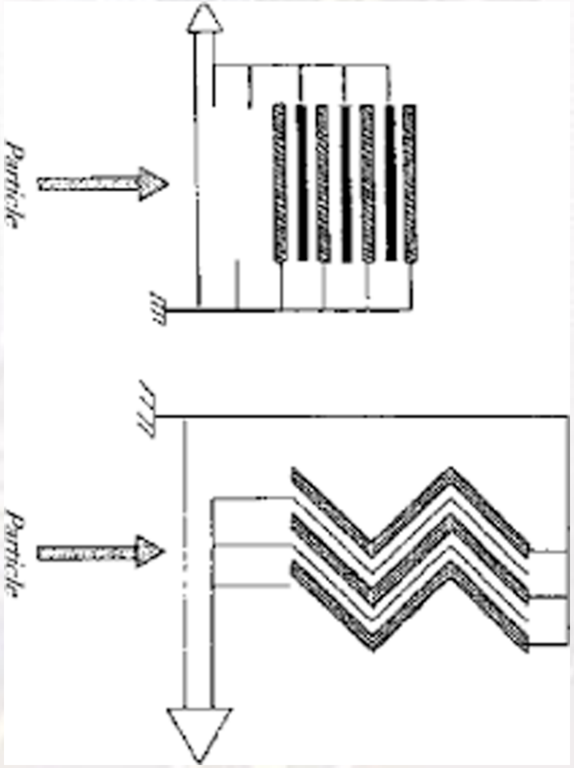
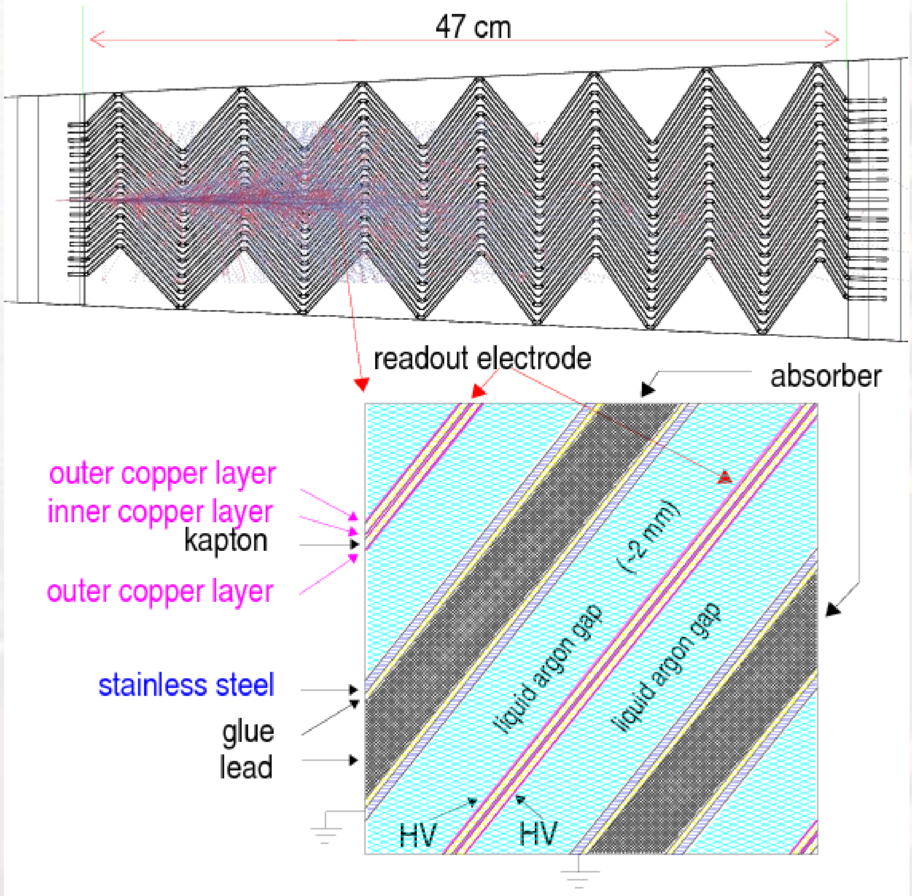
Absorber and gap layers in sampling calorimeters are normally perpendicular to the incoming particle direction → **gaps/cracks at boundaries**; long signal cables
Largely **avoided** in ATLAS by using novel "**accordion**" **geometry**



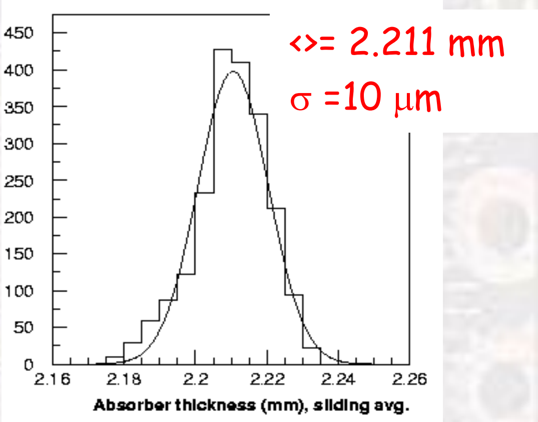
Traditional sampling calorimeter (top) and ATLAS accordion geometry (bottom)

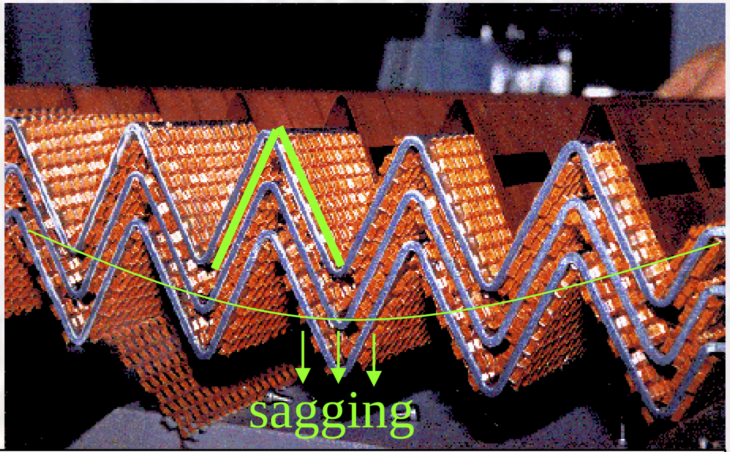


Keeping the constant term low was a major challenge for the ATLAS LAr

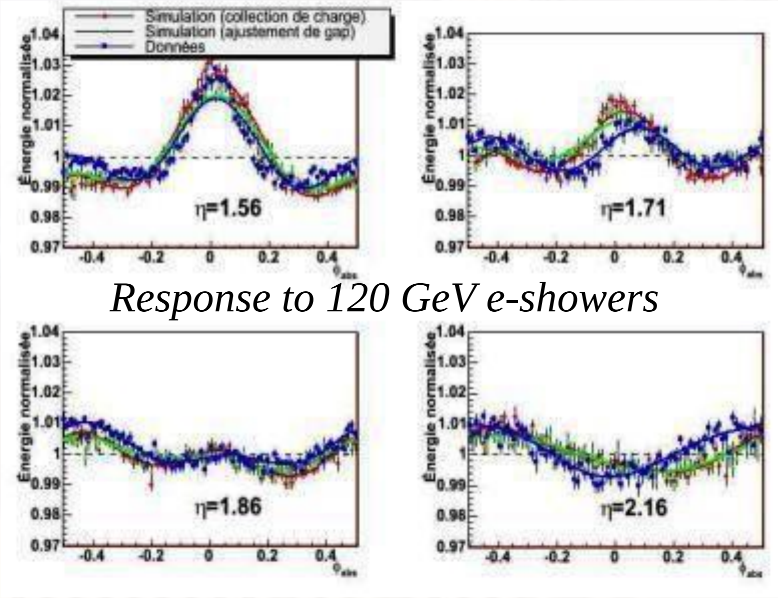
Mechanical non-uniformities can modify the electric field and detector response. Great care needed during construction; try to reproduce effects and apply corrections

1% variation in Pb (~200μm)
→ 0.6% change in response
Measured dispersion
 σ = 10μm
Translates to
 < 2‰ on constant term





ϕ-modulations measured & simulated, and corrections applied



Response to 120 GeV e-showers

Beam-test performance of LAr prototypes showed excellent potential

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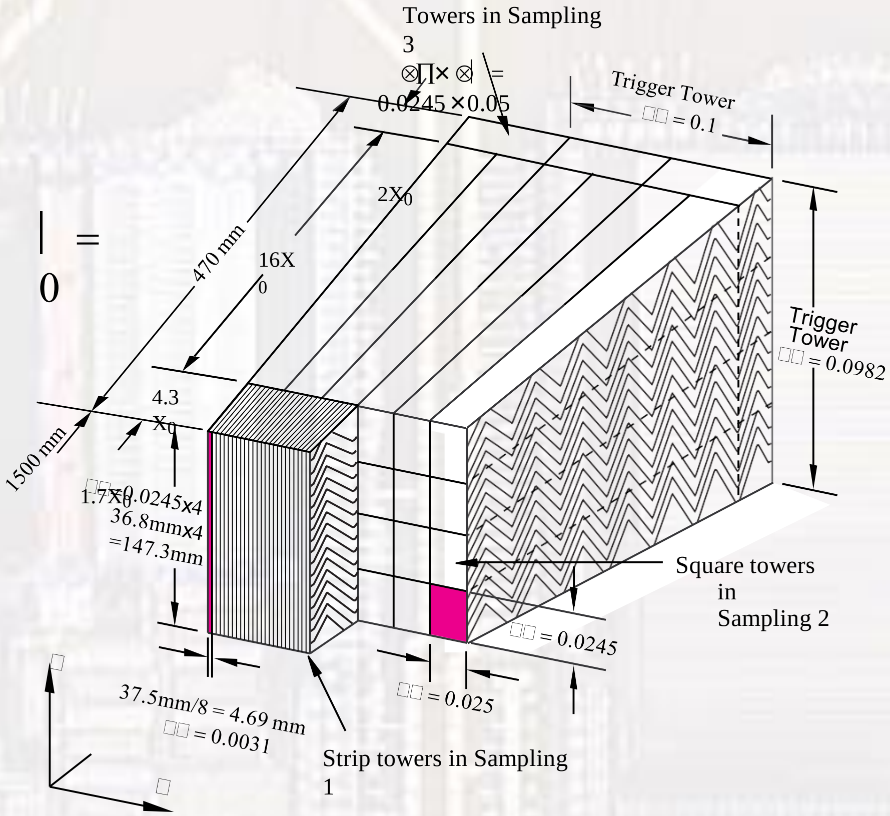
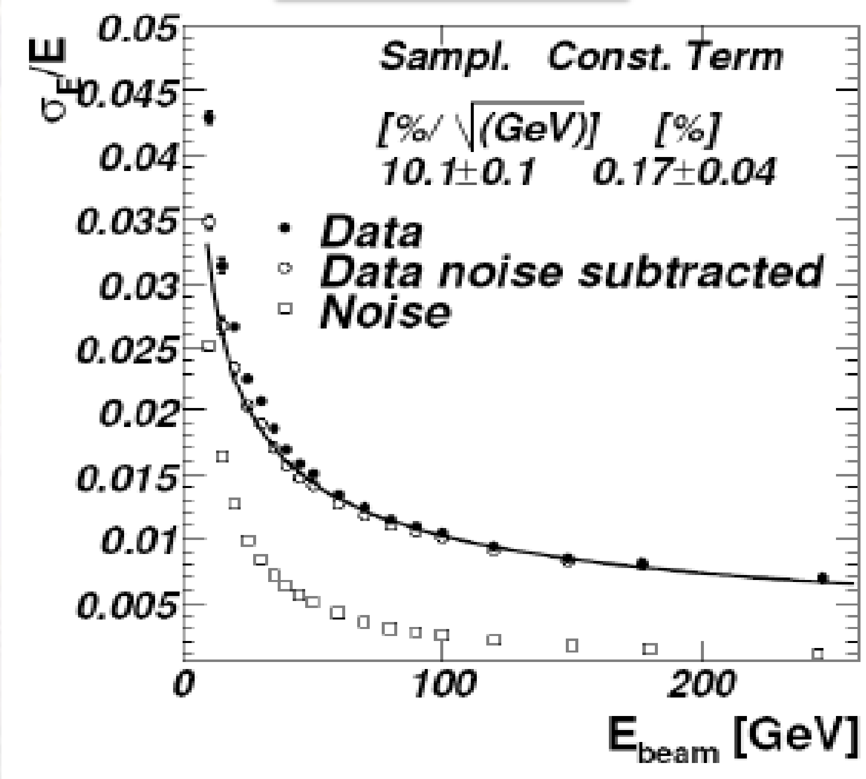


2002 Beam test

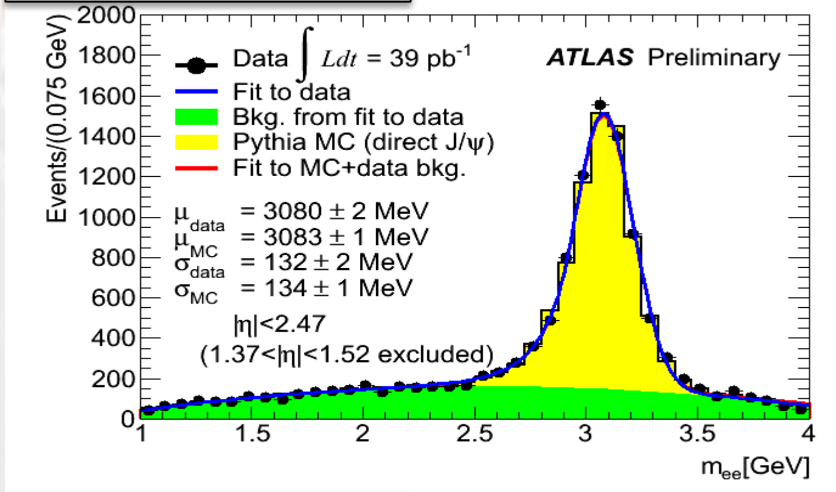


Constant term is dominated by:

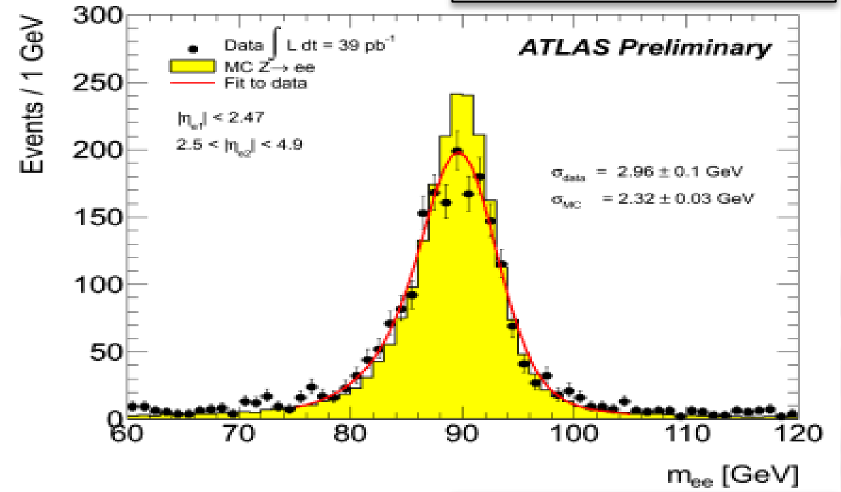
- **Equalization** of the electronic readout (=**calibration**)
- **Non-uniformity** of electric field & **sampling fraction** from the accordion structure

ATLAS LAr performed excellently from day 1 of LHC operation – and improved!

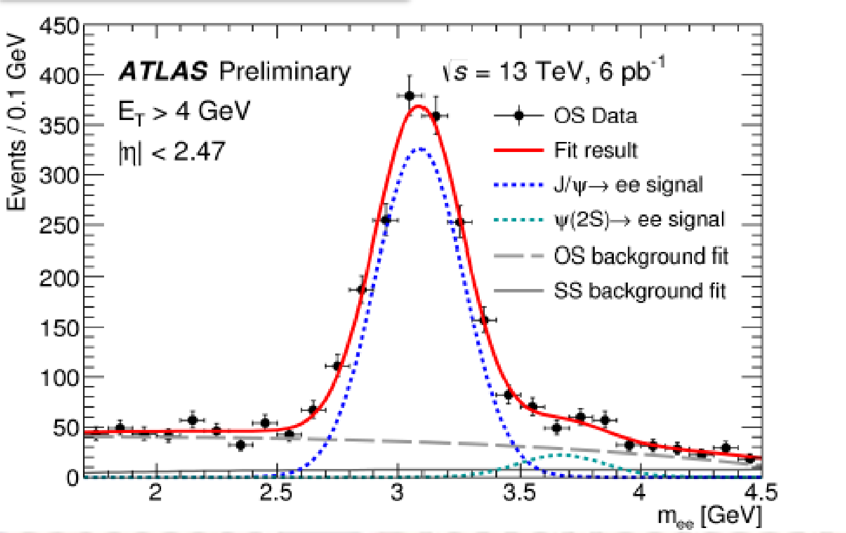
2011: J/ψ → e^+e^-



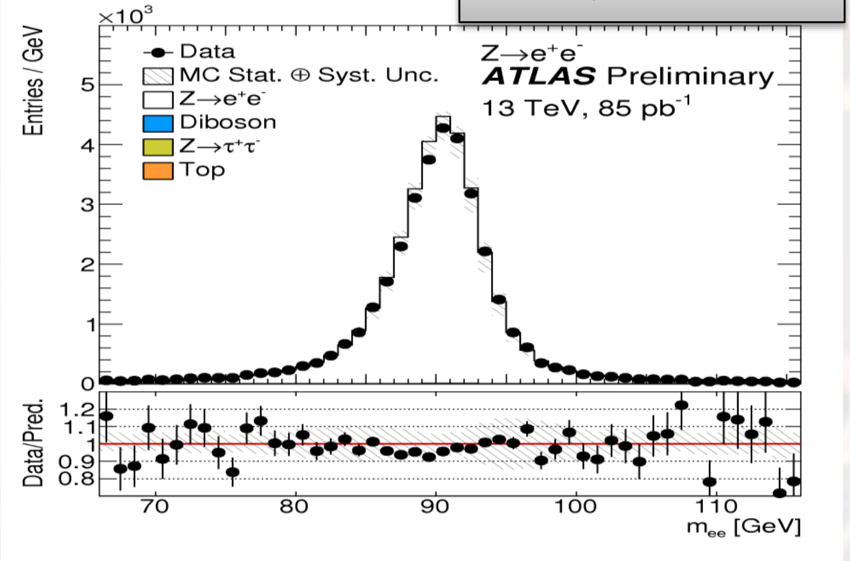
2011: Z^0 → e^+e^-



2015: J/ψ → e^+e^-

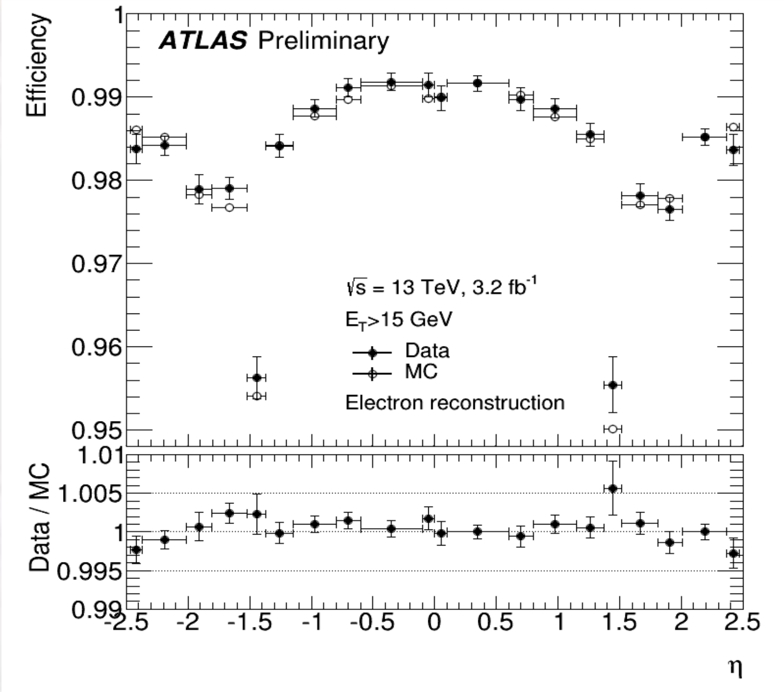


2015: Z^0 → e^+e^-



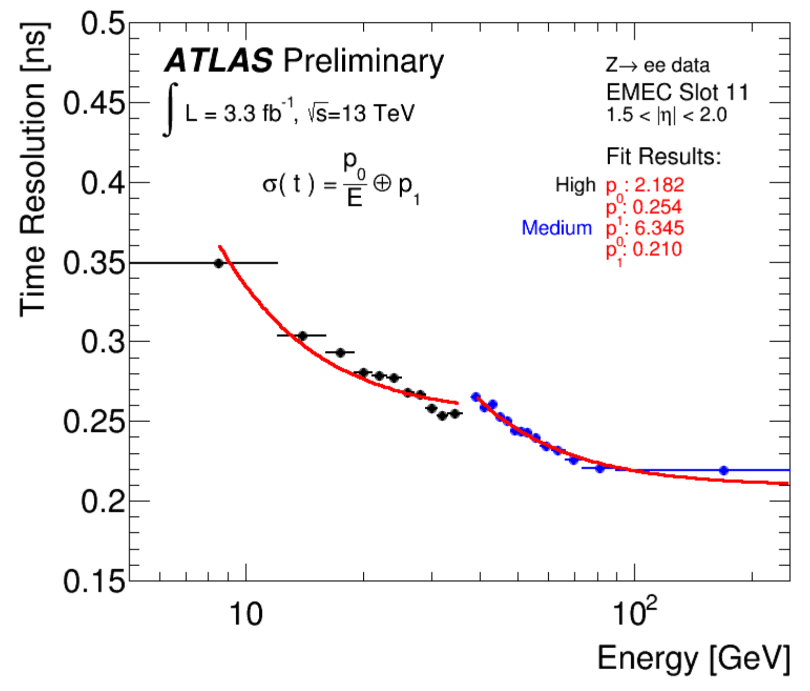
Calorimeters are not only for energy measurements!

Particle identification in ATLAS LAr



Electron identification efficiency as a function of η for the ATLAS LAr calorimeters. **Above 97%** except for barrel/endcap transition region

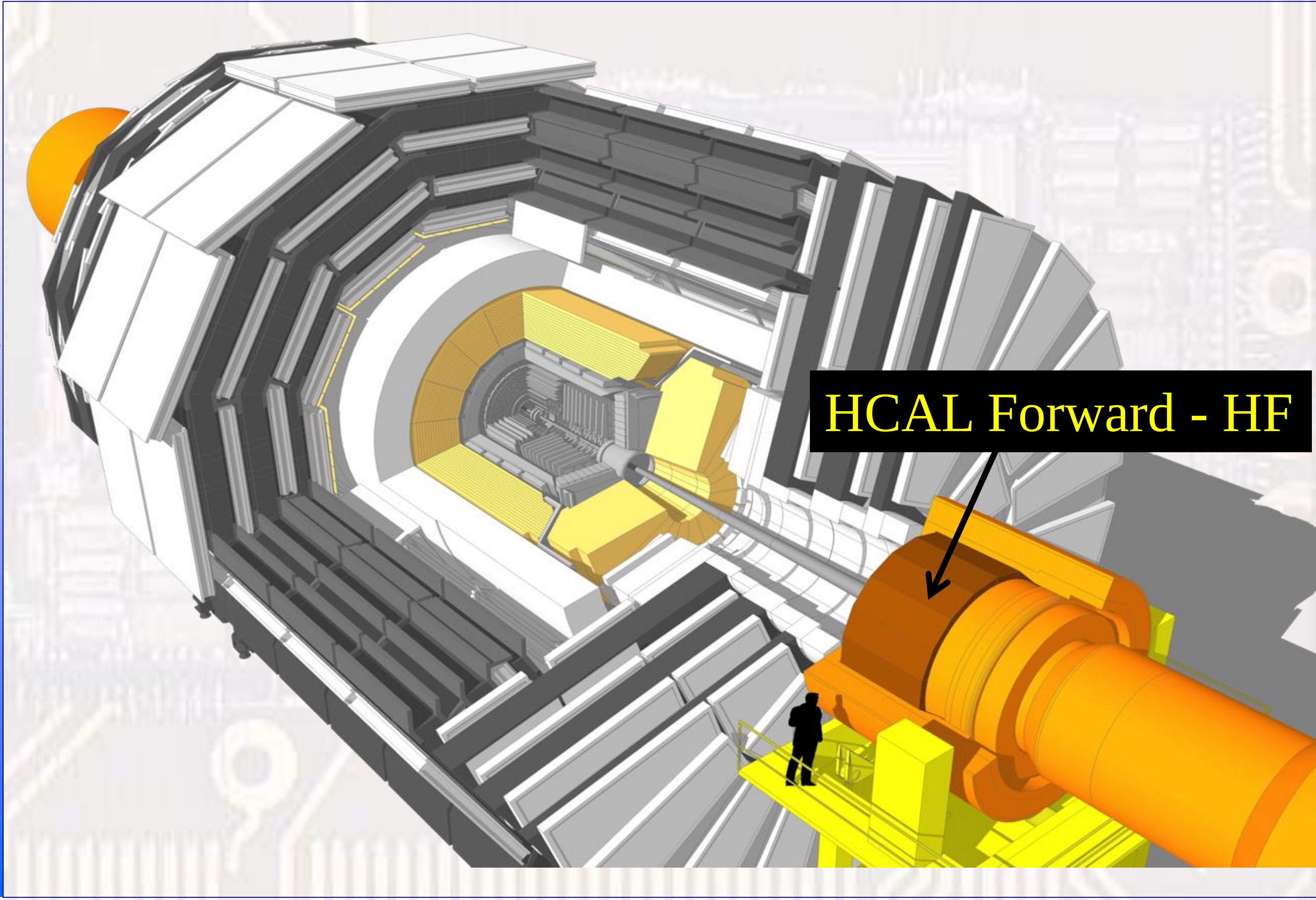
Timing performance in LAr endcaps



Timing measurements can help with pileup rejection. The above plot includes a contribution of ~200ps from the beamspread → intrinsic timing **precision approaches 65ps**! (about the **same as in CMS ECAL**)

CALORIMETRY BY EXAMPLES: CMS FORWARD HCAL

CMS Forward HCAL covers the highest η region → exposed to the highest radiation


HCAL Forward - HF

Forward HCAL measures Cerenkov light produced in quartz fibres

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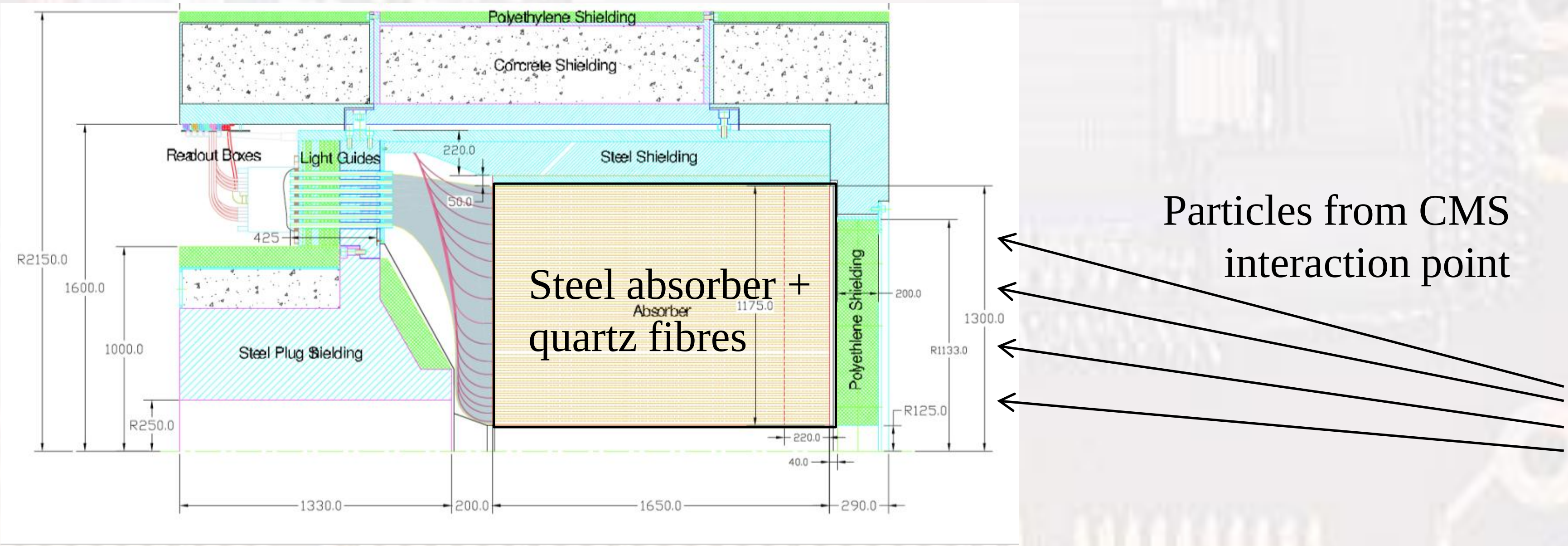
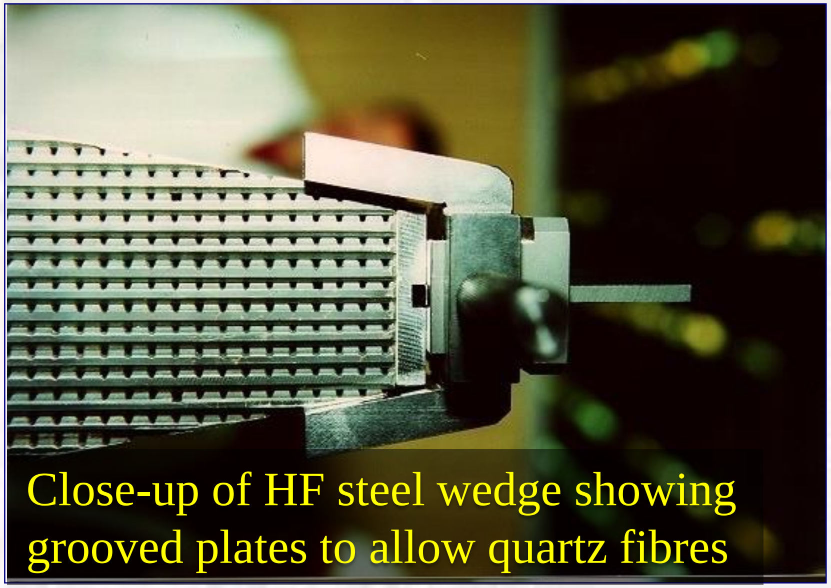
- **Forward (HF): 3.0<|η|<5.0, 18 wedges per end**
  - **Grooved steel plates**, 5mm thick, 165cm long → ~10 λ
  - ~square grid of holes spaced 5mm apart
  - 1mm diameter **fibres** (600μm **quartz core** + cladding + buffer) → highly resistant to radiation
  - **2 fibre lengths** (read out separately) to **distinguish e/γ from hadron showers**:
    - Half are **165cm long**
    - Other half start **after a depth of 22cm**



Steel absorber + quartz fibres

Particles from CMS interaction point

Assembly of the 350-tonne HFs



Close-up of HF steel wedge showing grooved plates to allow quartz fibres

Inserting quartz fibres into a steel wedge

Wedges being assembled into Dees

Completed HF ready for installation

The main task of the CMS Forward HCAL: Luminosity Measurement

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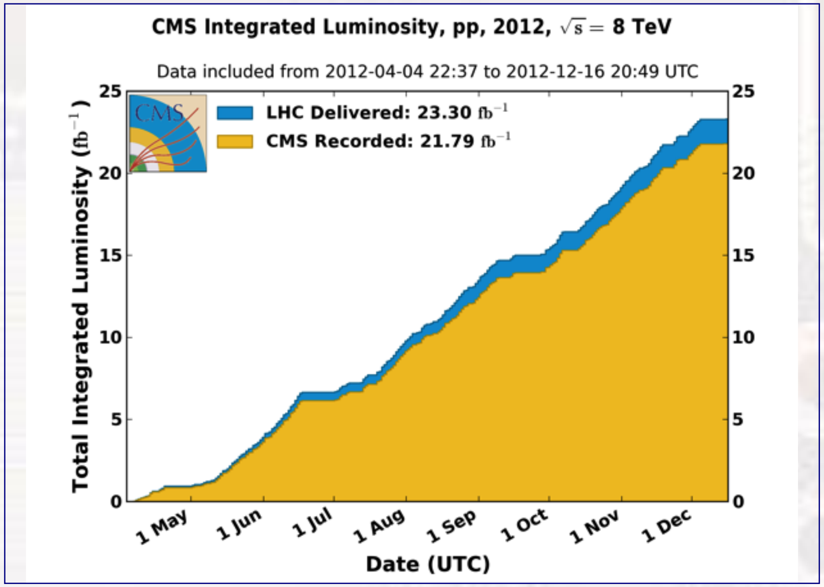
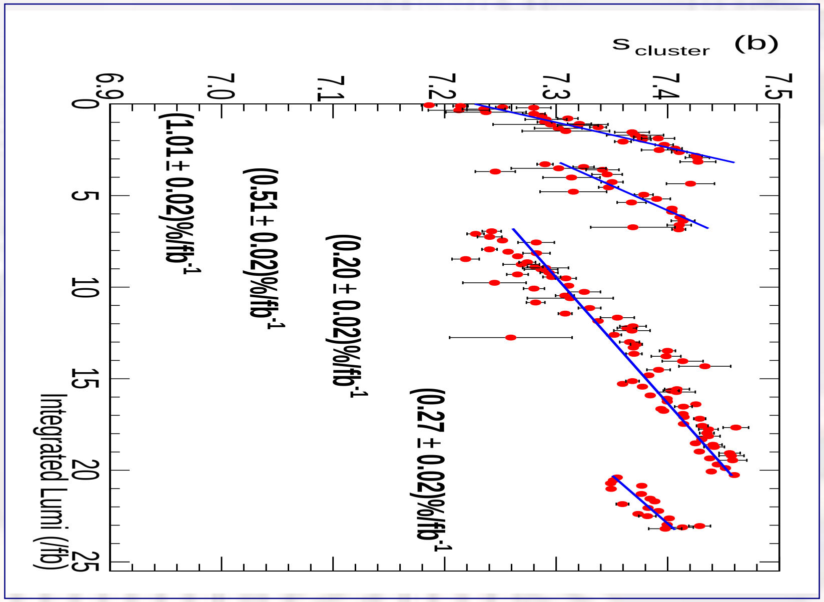
- CMS provides real-time monitoring of the **LHC luminosity** to determine an overall normalization for use in physics analyses
  - The **online luminosity measurement** is based on the forward hadronic calorimeter (HF) – "**HF lumi**"
- The HF Lumi is subject to calibration drift as a result of gain changes in the HF PMTs and possible other effects. Such drifts typically occur over a long period of time
  - These **drifts are calibrated-out**



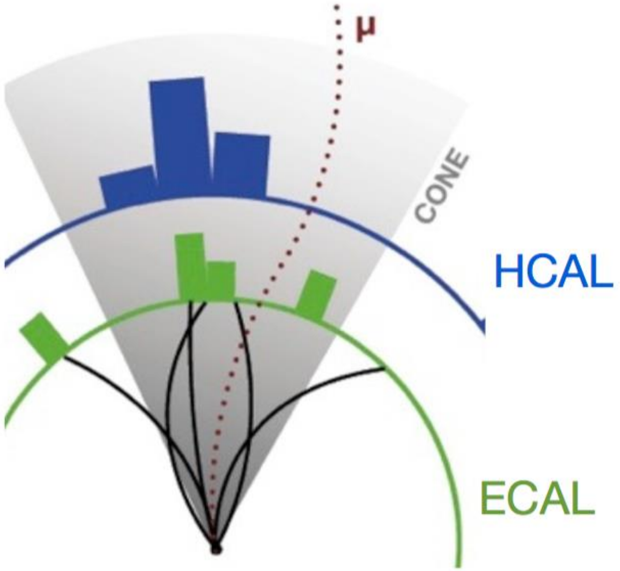


ASIDE: CURRENT FRONTIER IN HEP CALORIMETRY → IMPROVE JET MEASUREMENTS!

Real need to improve jet energy resolution for the next generation of calorimeters

- At high energies the measurement of jets is crucial
  - Multi-jet final states (outgoing quarks, gluons)
  - Missing energy reconstruction - Invisible particles

The principle of jet reconstruction: Sum energy in a cone (geometry etc given by jet finding algorithm) to determine energy of original parton



The limitations:
Neutral hadrons, photons from neutral pion decay: Cannot just sum charged tracks - The calorimeter with the worst energy resolution (the HCAL) drives the performance for jets!

Two main approaches for improving jet energy resolution

The goal for the next generation of calorimeters: a significant leap in jet energy resolution

- Motivated by the requirement to **separate heavy bosons** (W, Z, H) in hadronic decays

Two main approaches:

- Substantial improvement of the energy resolution of hadronic calorimeters for single hadrons: **dual (or triple!) readout**
- Precise reconstruction of each particle within the jet → reduction of HCAL resolution impact: **particle flow algorithms and imaging calorimeters**

CALORIMETRY BY EXAMPLES: DREAM

DREAM is a generic detector R&D project, not linked to any particular experiment

Goal: investigate & eliminate the factors that prevent the measurement of hadrons and jets with the same precision as electrons/photons

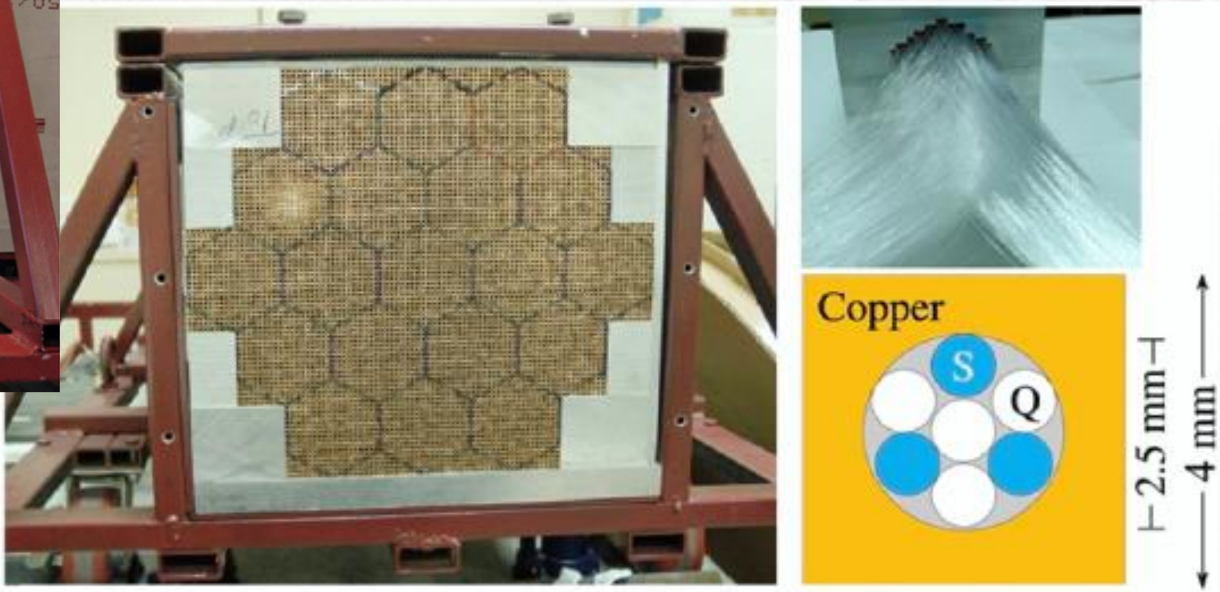
DREAM: Dual READout Method – CERN RD52 project

Simultaneous measurement of **scintillation light** (dE/dx) and **Cerenkov** light produced in showers:

- ***Cerenkov*** light only produced by relativistic particles: em component
- ***Scintillation*** light produced by relativistic and non-relativistic: em + hadronic component

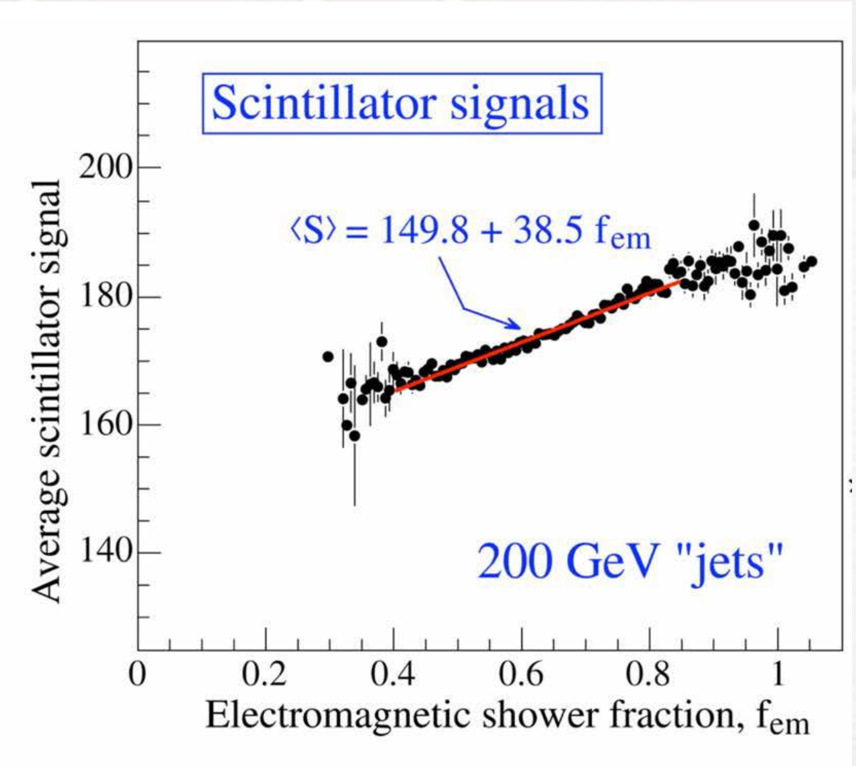
→ can measure the **em fraction** event by event, eliminating the effects of em shower fluctuations

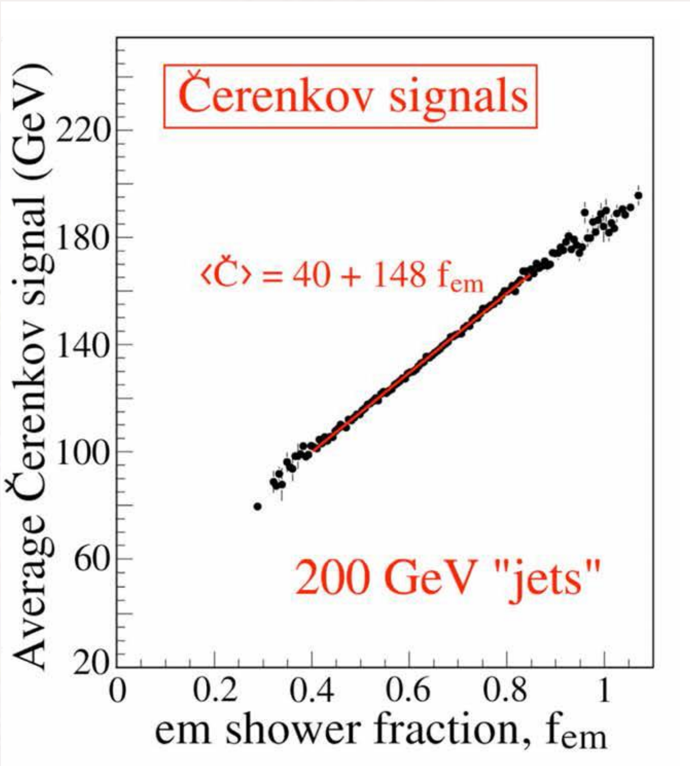
DREAM prototypes use arrays of fibres producing scintillation & Cerenkov light



- *Some characteristics of the DREAM detector*
  - Depth 200 cm (10.0 λ_{int})
  - Effective radius 16.2 cm (0.81 λ_{int}, 8.0 ρ_M)
  - Mass instrumented volume 1030 kg
  - Number of fibers 35910, diameter 0.8 mm, total length $\approx$ 90 km
  - Hexagonal towers (19), each read out by 2 PMTs

DREAM: Energy measurement comes from the combination of signals

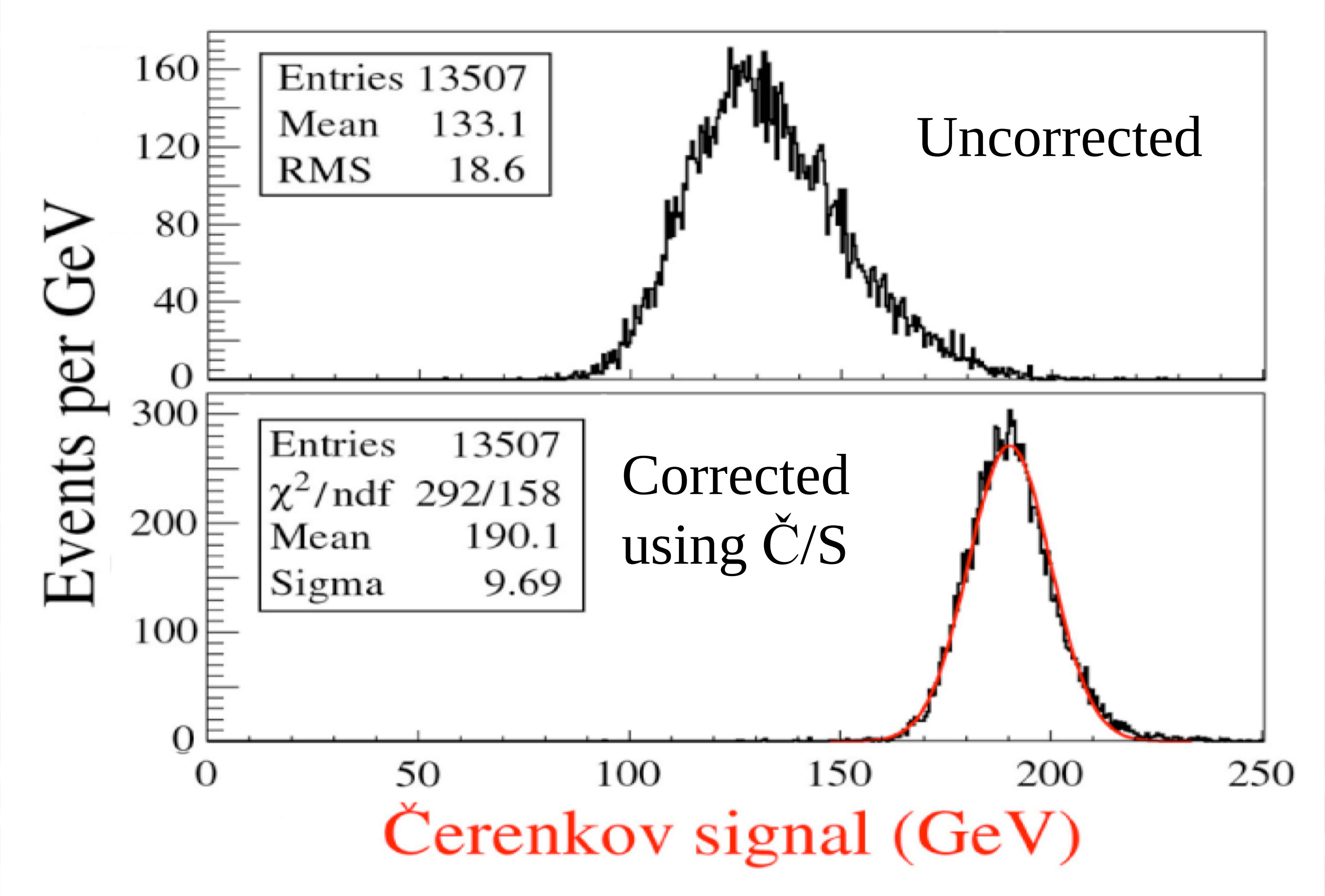




In practice the two systems respond differently to hadrons: $(e/h)_S$ =1.3; $(e/h)_C$ =4.7

$$\left.\begin{aligned} C &= E\quad [f_{em} + \frac{1}{(e/h)_C} \times (1 - f_{em})] \\ S &= E\quad [f_{em} + \frac{1}{(e/h)_S} \times (1 - f_{em})] \end{aligned}\right\} \quad E = \frac{S - \chi C}{1 - \chi} \quad \text{where} \quad \chi = \frac{1 - 1/(e/h)_S}{1 - 1/(e/h)_C}$$

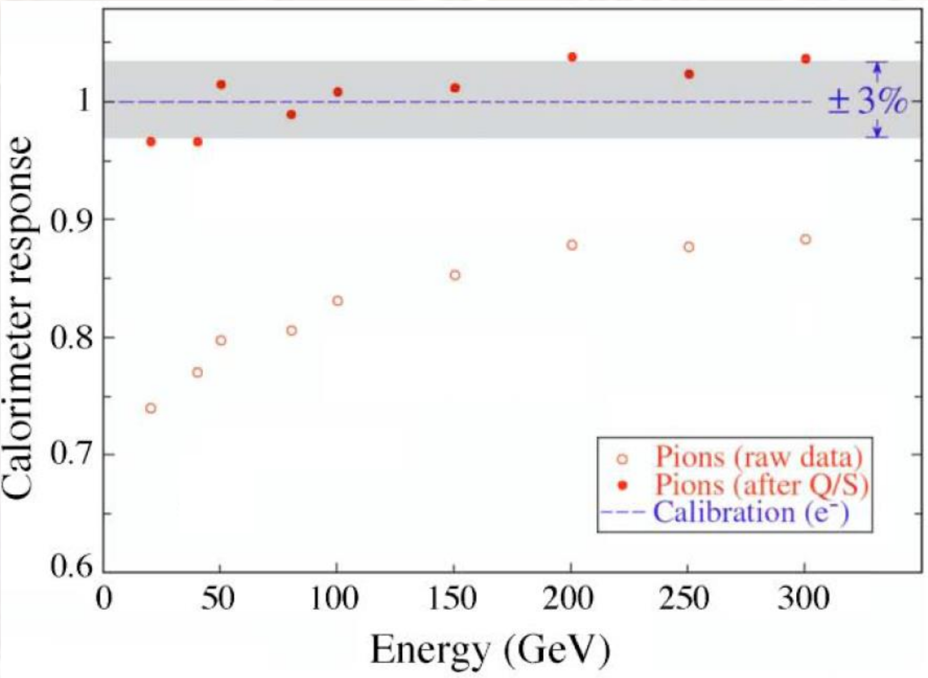
For 200 GeV jets, C/S correction gives a significant improvement to σ(E)/E

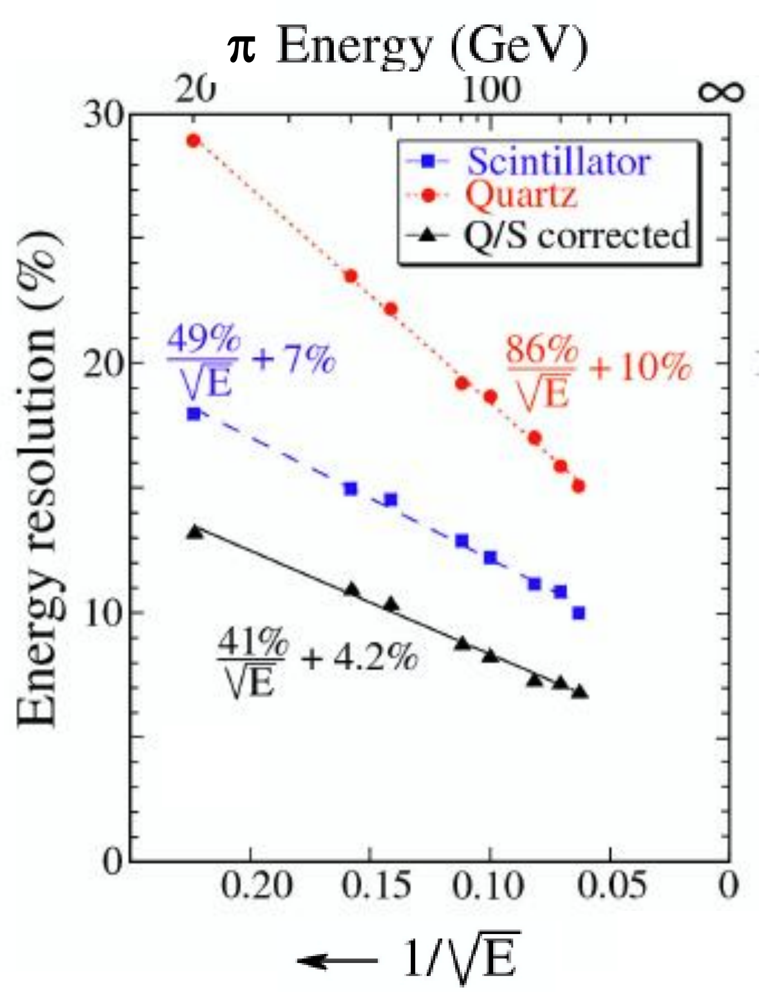


Energy resolution of prototype DREAM shows excellent potential

Motivation
Basics
 EM showers
 HD showers
Calo types
LHC Calos
 CMS ECAL
 ATLAS LAr
 CMS HF
Future
 DREAM
 HGCAL

Hadron response after Č/S correction





- **Gaussian response**
- Much **improved linearity**
- Correct **energy scale**
- Still room for improvement

Latest DREAM modules use Pb or Cu absorbers: tested in November 2015

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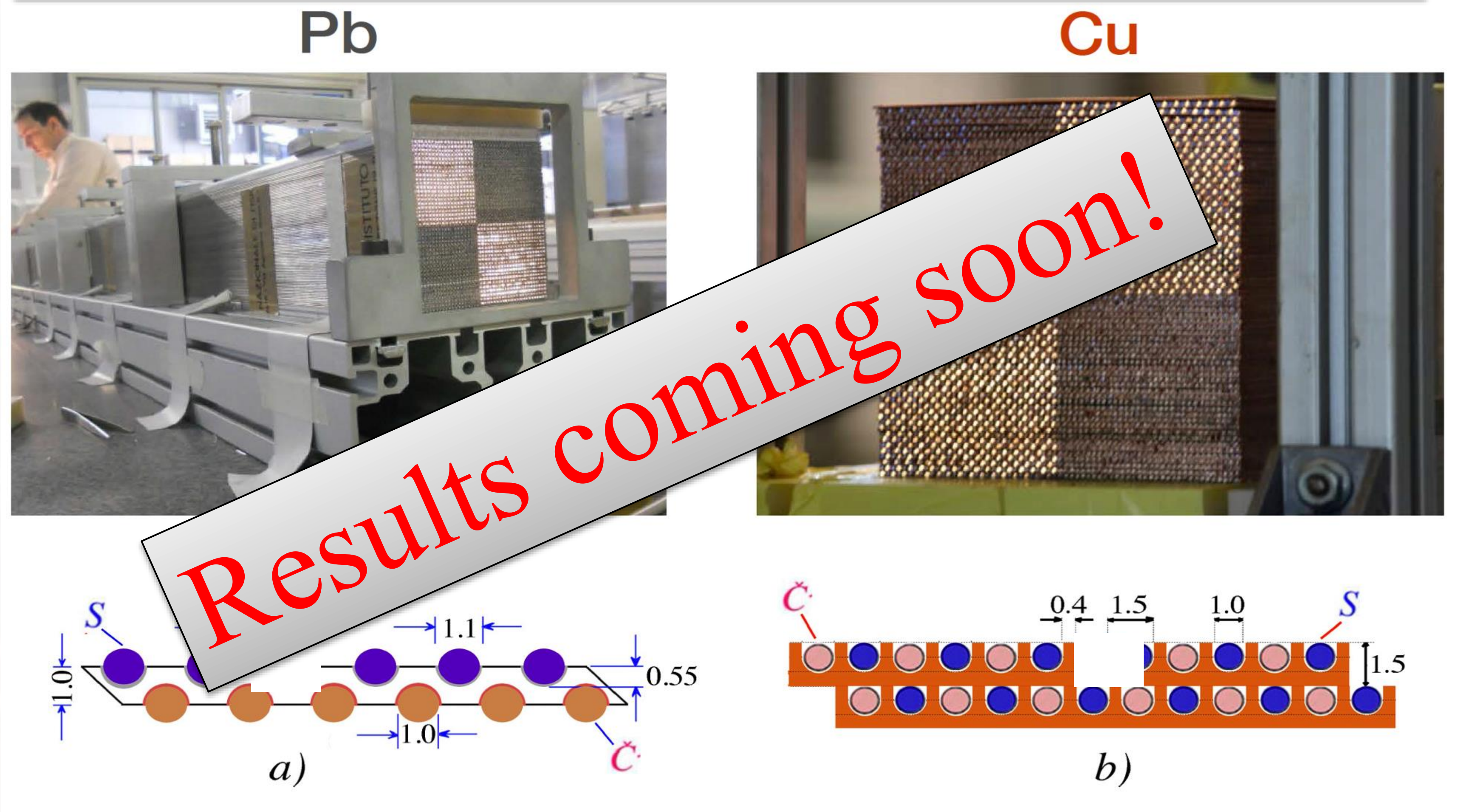
Following first beam tests more than a decade ago, further prototypes developed to:

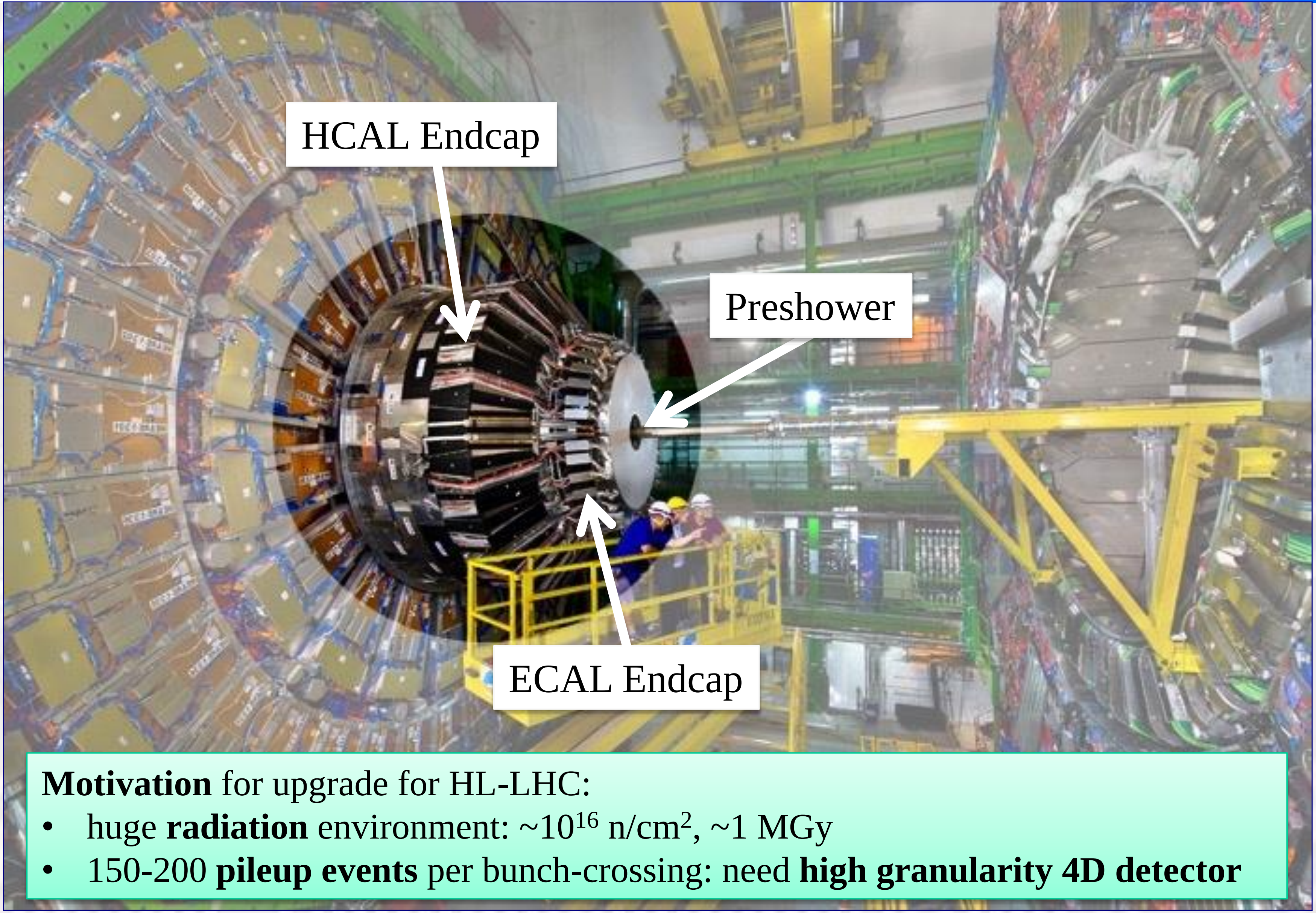
- Reduce shower leakage → build **larger detector**
- Increase **Cerenkov light yield**
- Reduce sampling fluctuations → increase **fraction of fibres**



Results coming soon!

CALORIMETRY BY EXAMPLES: CMS HGCAL (AND CALICE)

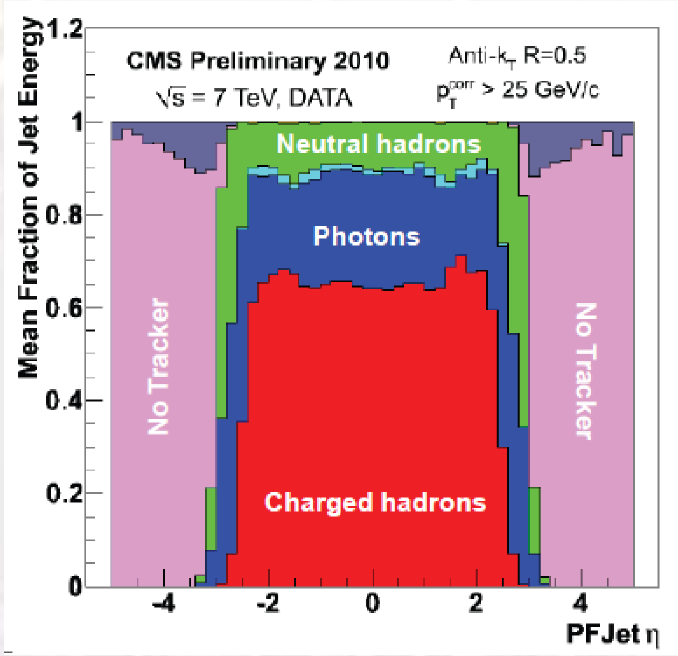
CMS High Granularity Calorimeter will replace all endcap calorimeters in ~2025



Motivation for upgrade for HL-LHC:

- huge **radiation** environment: ~10^{16} n/cm^2, ~1 MGy
- 150-200 **pileup events** per bunch-crossing: need **high granularity 4D detector**

Particle flow technique: make best use of all detectors to measure jet energies

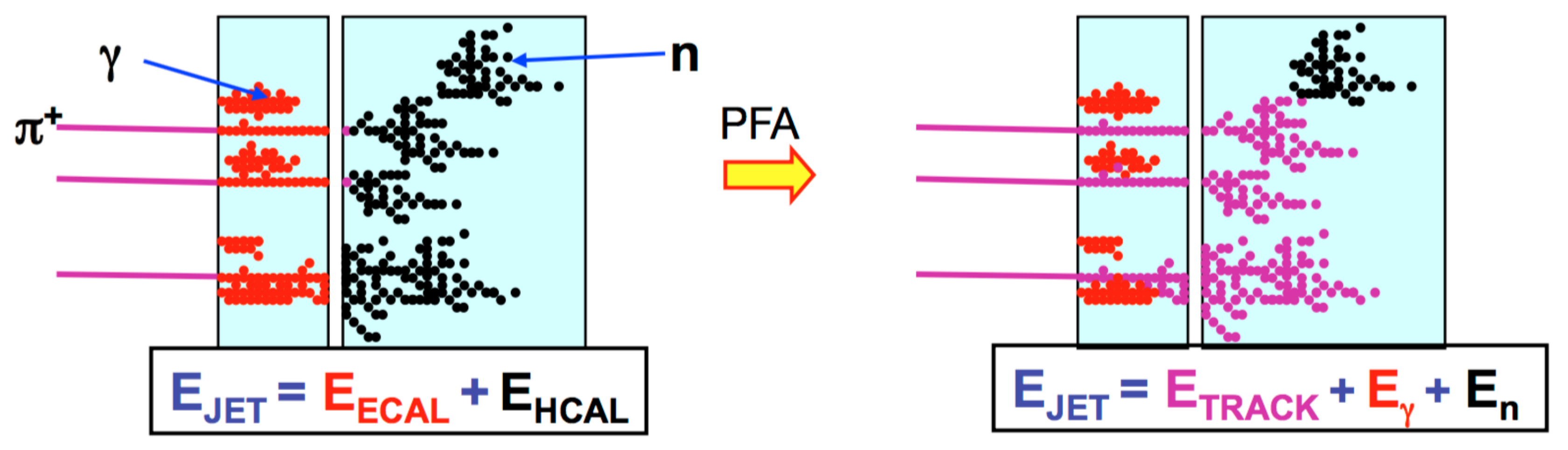


A majority of particles within jets can be measured by Trackers and ECALs

Charged tracks = Tracker

e/photons = ECAL

Neutral hadrons (only 10%) = HCAL



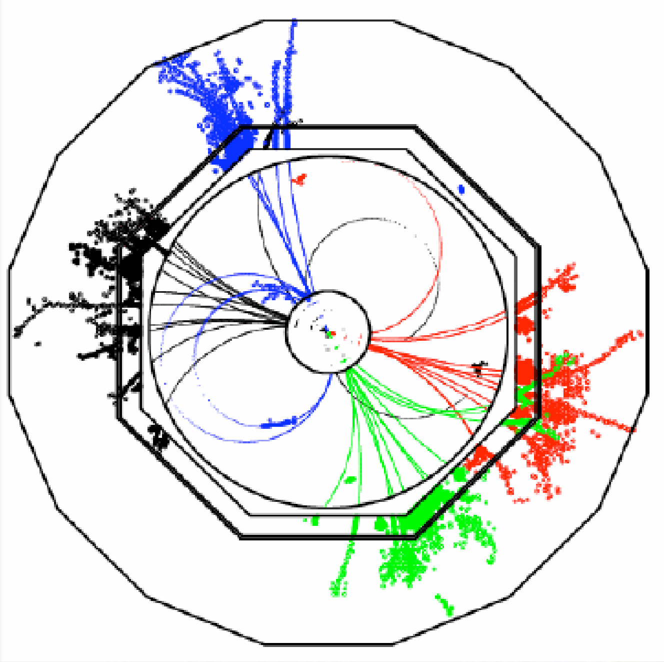
$E_{JET} = E_{ECAL} + E_{HCAL}$

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

For best results: high granularity in 3D – separation of individual particle showers

For a Particle-Flow Calorimeter:

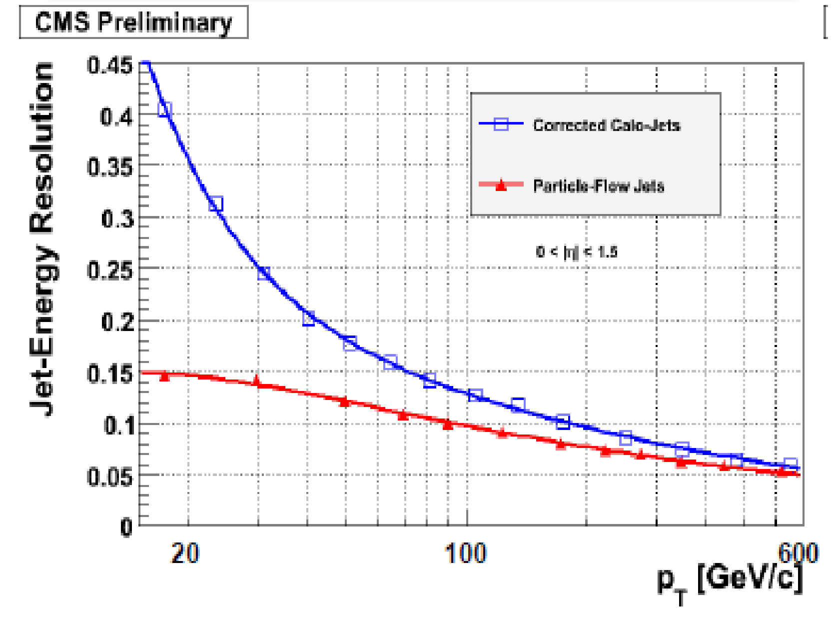
- **Granularity** is more important than energy resolution!
- Lateral granularity should be **below Molière radius** in ECAL and HCAL
- In particular in the ECAL: small Molière radius to provide **good two-shower separation** (particularly in high pileup environment)
  - → **tungsten** absorbers (lowest X_0)
  - → **Silicon** active elements (highest sampling density)
- **Sophisticated software** needed!



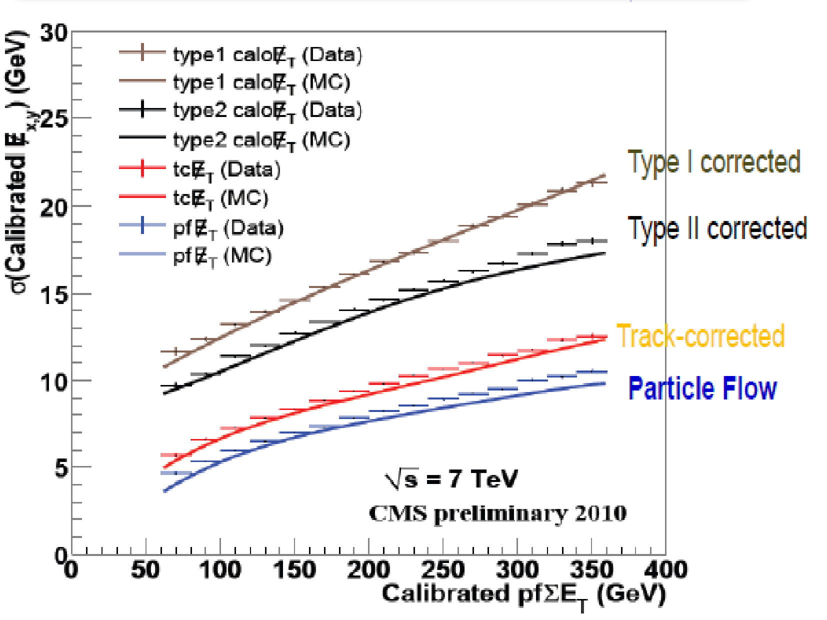
Extensively developed and studied in past decade for Linear Collider detectors (e.g. **CALICE**): jet energy resolution goals (3%-4% for energies from 45 GeV to 500 GeV) can be met

Particle flow already used in Aleph & CMS (both have relatively low resolution HCALs)

Simulation: jet energy resolution

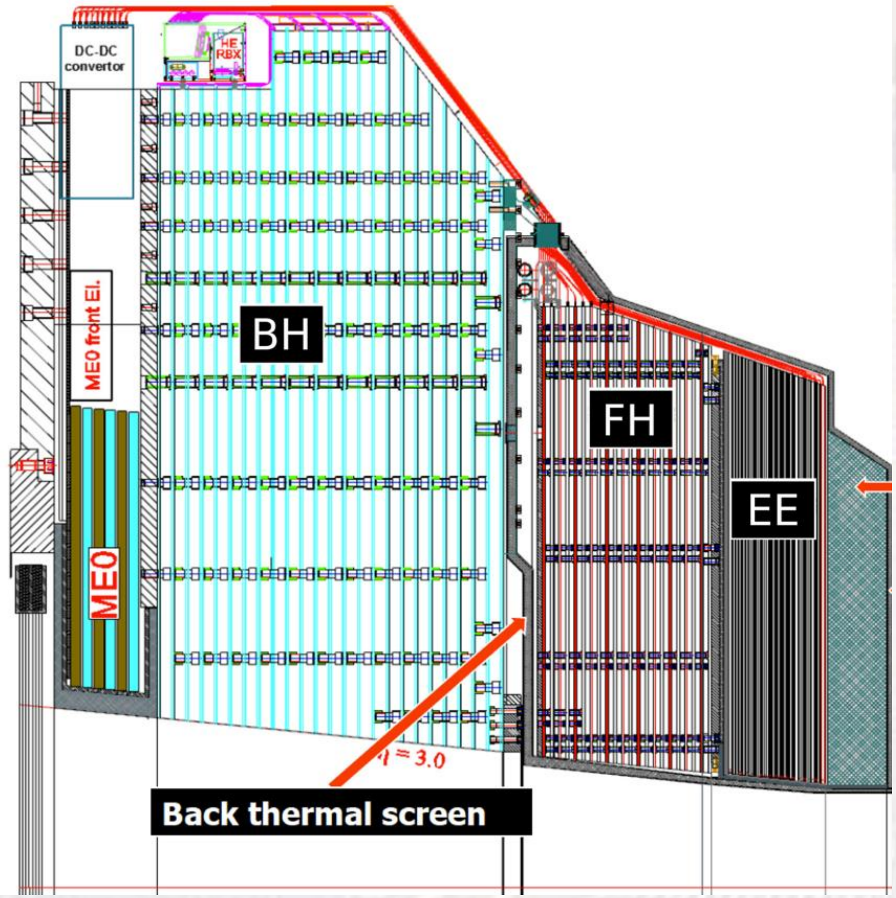


Data: Missing energy resolution



Measurement of jets in **CMS** is **enhanced greatly** by the use of particle flow techniques

CMS HGCAL: a sampling calorimeter with unprecedented number of readout channels



Essentially combines tracking and calorimetry to make a particle-flow calorimeter (like CALICE)

Key parameters:

- **593 m^2 of silicon (3x CMS TK!)**
- 6M ch, 0.5 or 1 cm^2 cell-size
- 21,660 modules (8” or 2x6” sensors)
- 92,000 front-end ASICS.
- Power at end of life 115 kW
- ~230 tonnes per endcap

System Divided into three separate parts:

EE – **Silicon** with **tungsten** absorber – 28 sampling layers – 25 X_o + ~1.3 λ
FH – **Silicon** with **steel** absorber – 12 sampling layers – 3.5 λ
BH – **Scintillator** with **steel** absorber – 11 layers – 5.5 λ

HGCAL has the potential to visualize individual components of showers

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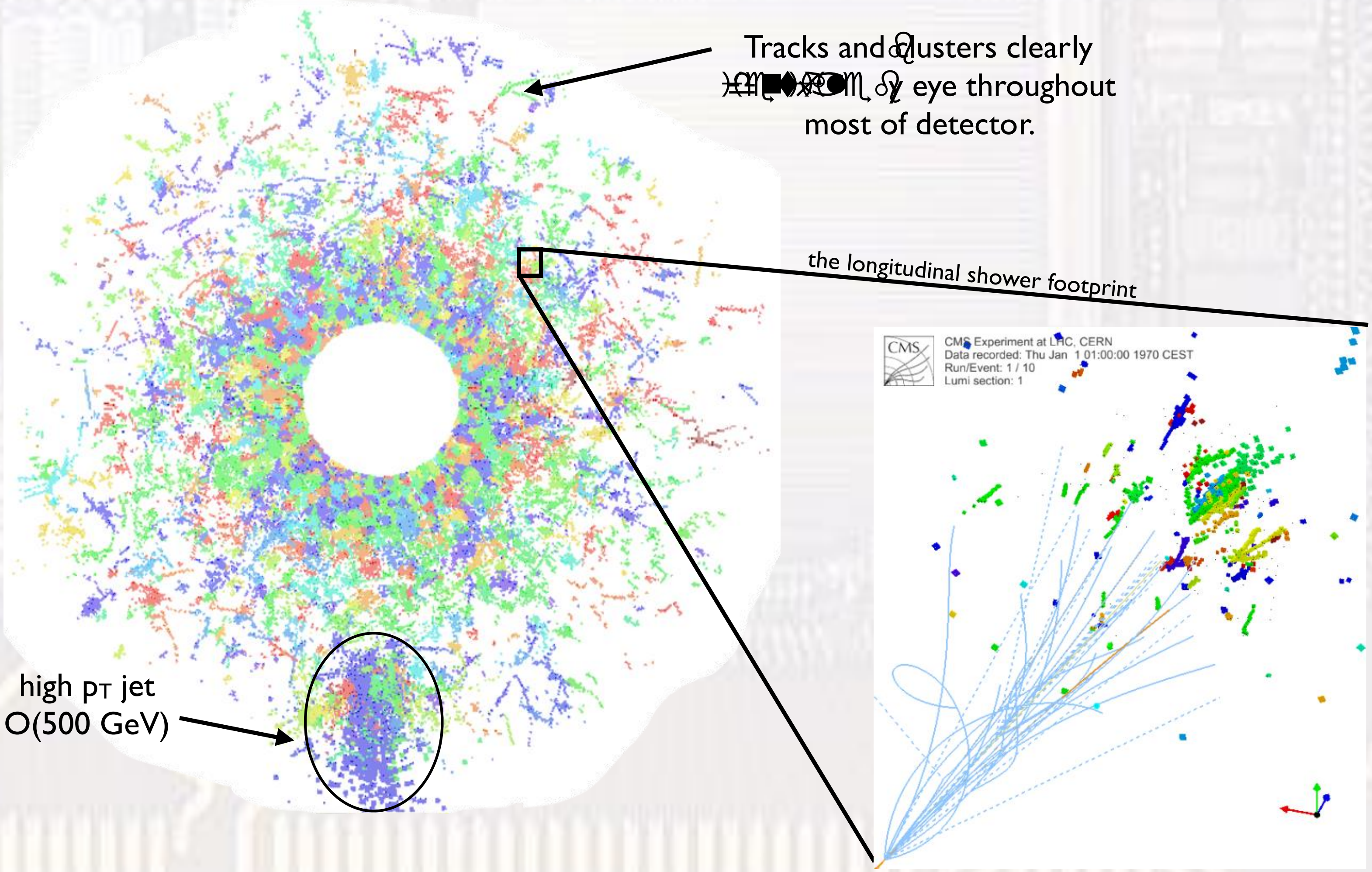
Simulation of 140 pileup events in CMS



Tracks and clusters clearly [illegible] eye throughout most of detector.

the longitudinal shower footprint

high p_T jet
O(500 GeV)

Silicon/Tungsten part of HGCAL baseline: based on CALICE (Calorimeter for ILC)

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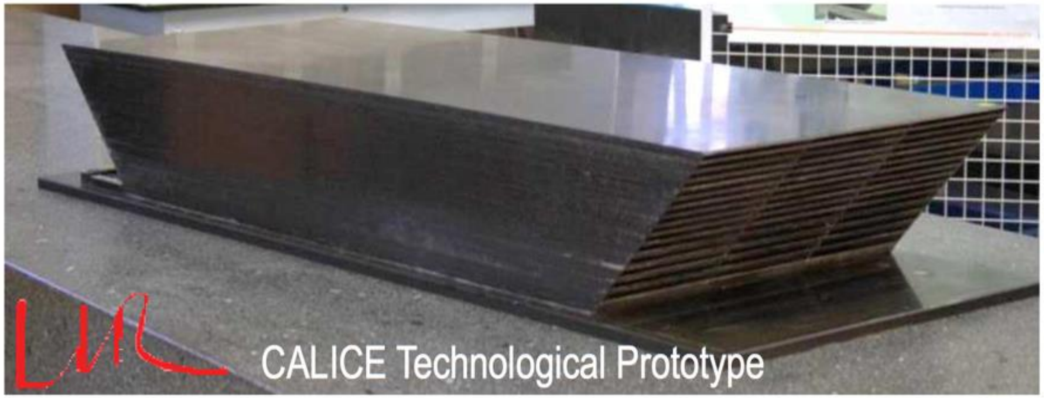
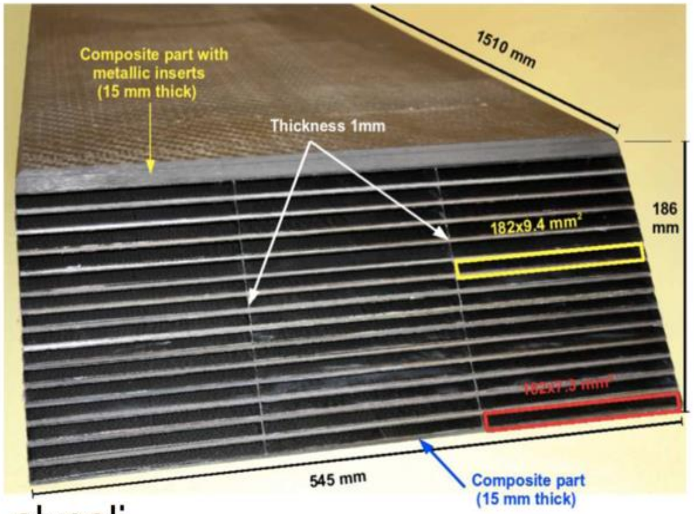
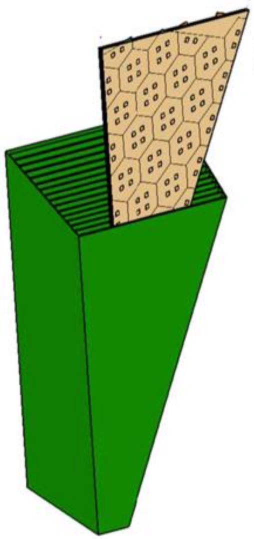
Carbon-fibre composite **alveolar structure** with embedded **W** absorber







Cassettes (with active element) inserted in alveoli.

The design is modular and can be adapted.
(absorber thickness, number of layers, geometry, etc…)

- Profit from 10 years of R&D.
- All problems (extraction of signal, heat, …)
  can be studied/resolved at the level of a single cassette !
- Structure can go in test beam & fully tested.
- Allows developments & construction in parallel (in different sites)

HGCAL silicon modules are hexagonal, divided into hexagonal pads ~0.5-1.0cm^2

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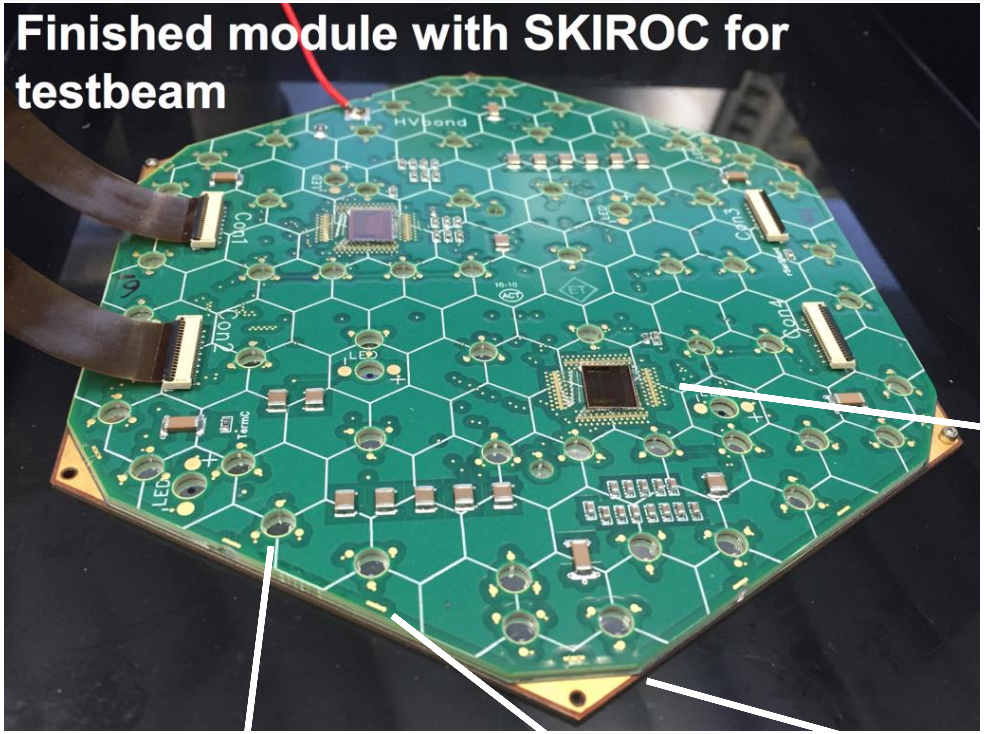
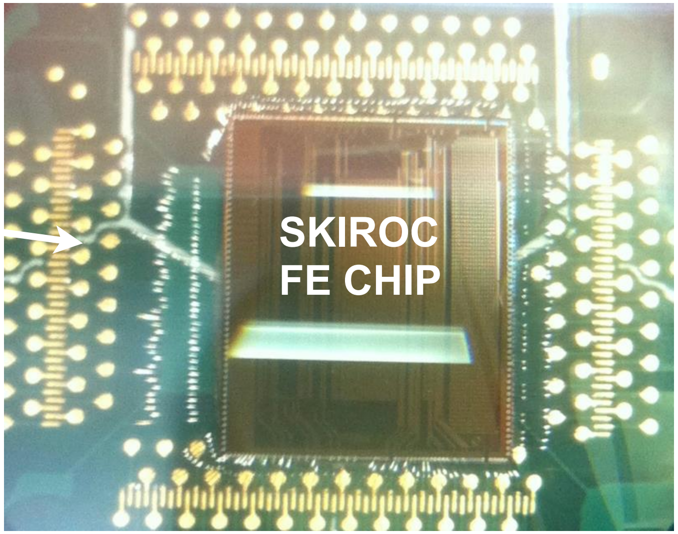
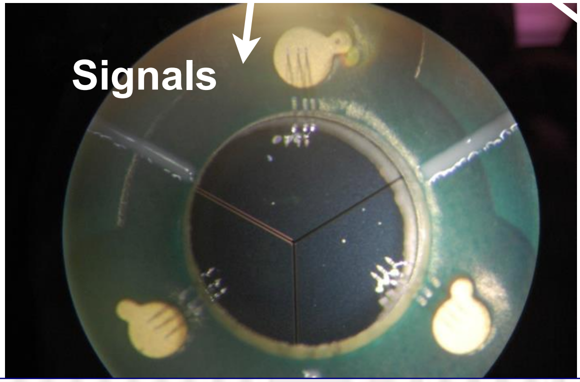
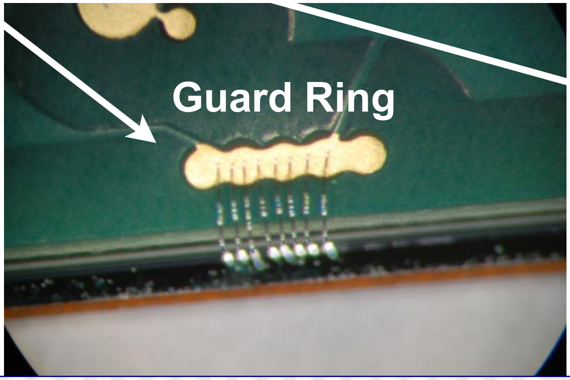
First prototype (March 2016) used Skiroc front-end chip (developed for CALICE)

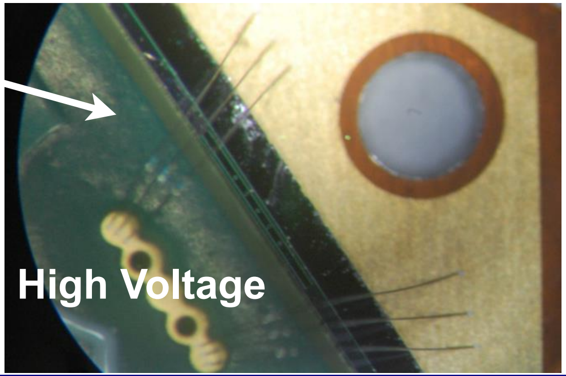


~ 700 wire bonds on a single module!



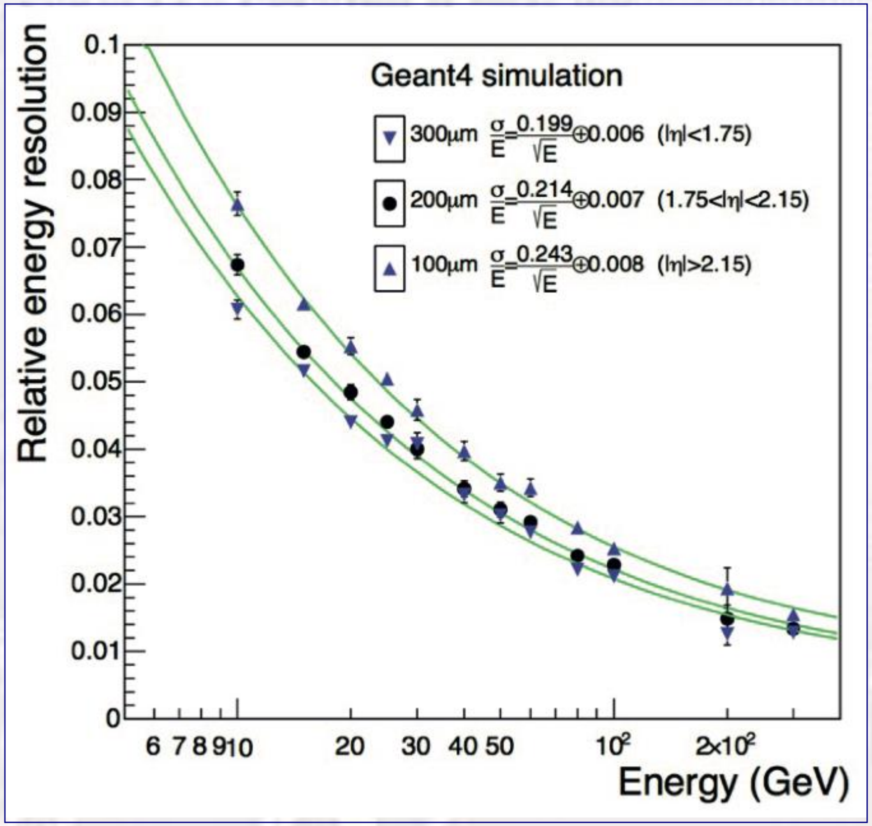




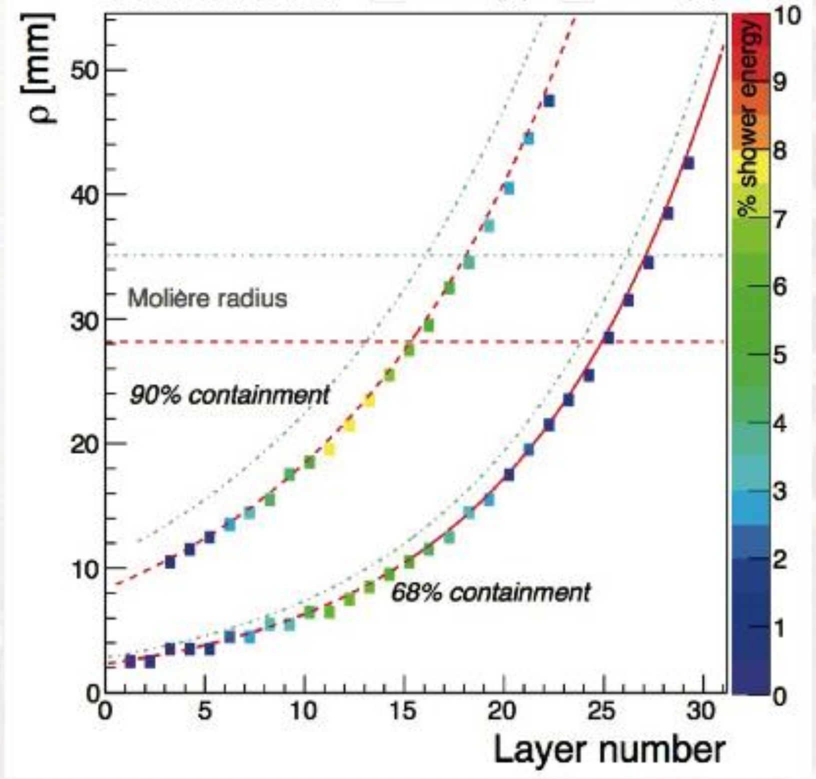


HGCAL energy resolution: stochastic term rather modest, but constant term low

Energy resolution: stochastic term rather modest, but **constant term low**



Shower radius is quite small in first layers: can **use longitudinal granularity** for pileup rejection etc.



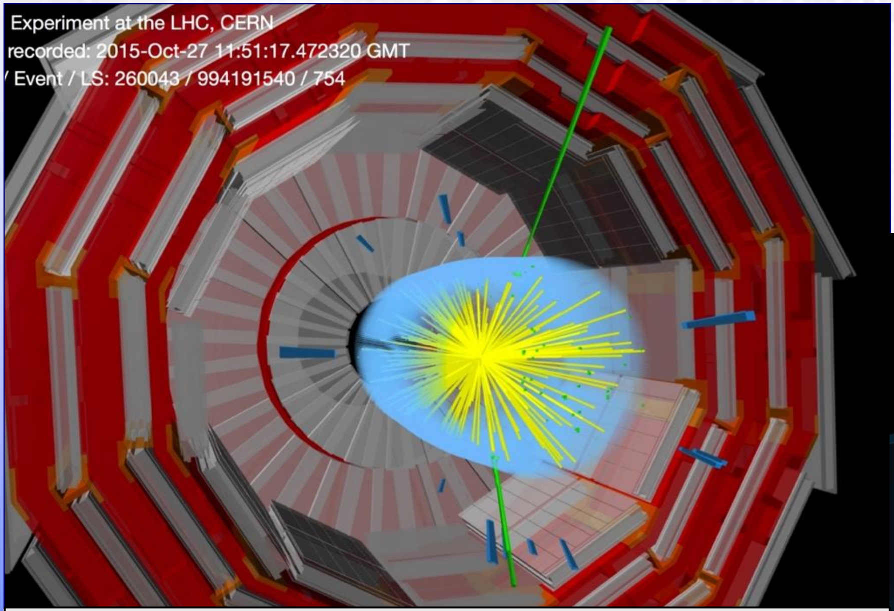
Achieving the potential of the HGCAL is a **major engineering challenge** for the next decade!

THE FUTURE IS CALORIMETRY!

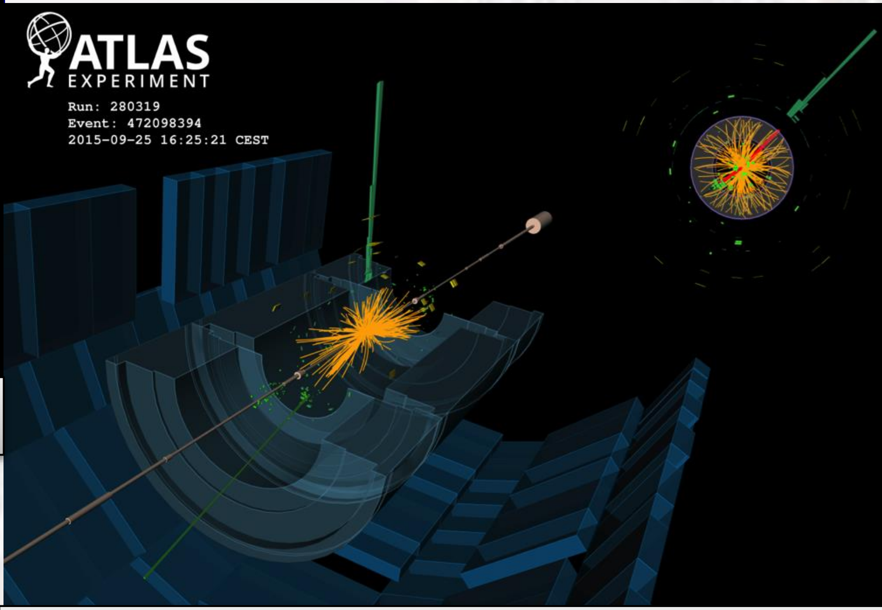
I have only scratched the surface!

- Capabilities of calorimeters are **growing every year**
  - Fortunate, as so are the **challenges**!
- I focused on **energy resolution**
  - But they also perform **triggering**, **timing** measurements, measure **position/angle**…
- Wide **variety** of calorimeter **designs**, depending on particular **application**
  - I only discussed **HEP**, but the fields of astro-particle physics, dark matter searches, medical physics etc. also make use of advanced calorimeters (some inspired by HEP)

What will calorimeters help reveal in 2016?



? → $\gamma\gamma$ in CMS, 2015; $m_{\gamma\gamma}$ ~ 750 GeV



? → e^+e^- in ATLAS, 2015; m_{ee} ~ 1775 GeV