LHC Detectors

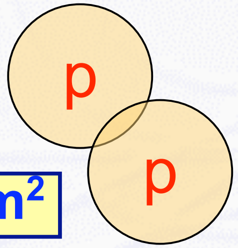
- Introduction
- Particle Interactions with Matter
- Calorimeters
  - Electromagnetic Calorimeter
  - Hadronic Calorimeter
- Tracking Detectors
  - Muon Spectrometer
  - Inner Tracker

Many thanks to:
M. Hauschild, C. Rembser, D. Froidevaux, M. Nessi, N. Ellis

LHC detectors are designed to find “needles in a haystack"

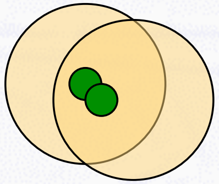
total inelastic cross section

$\sigma \sim 0.1$ barn $= 10^{-25}$ cm^2



background

point-like cross section

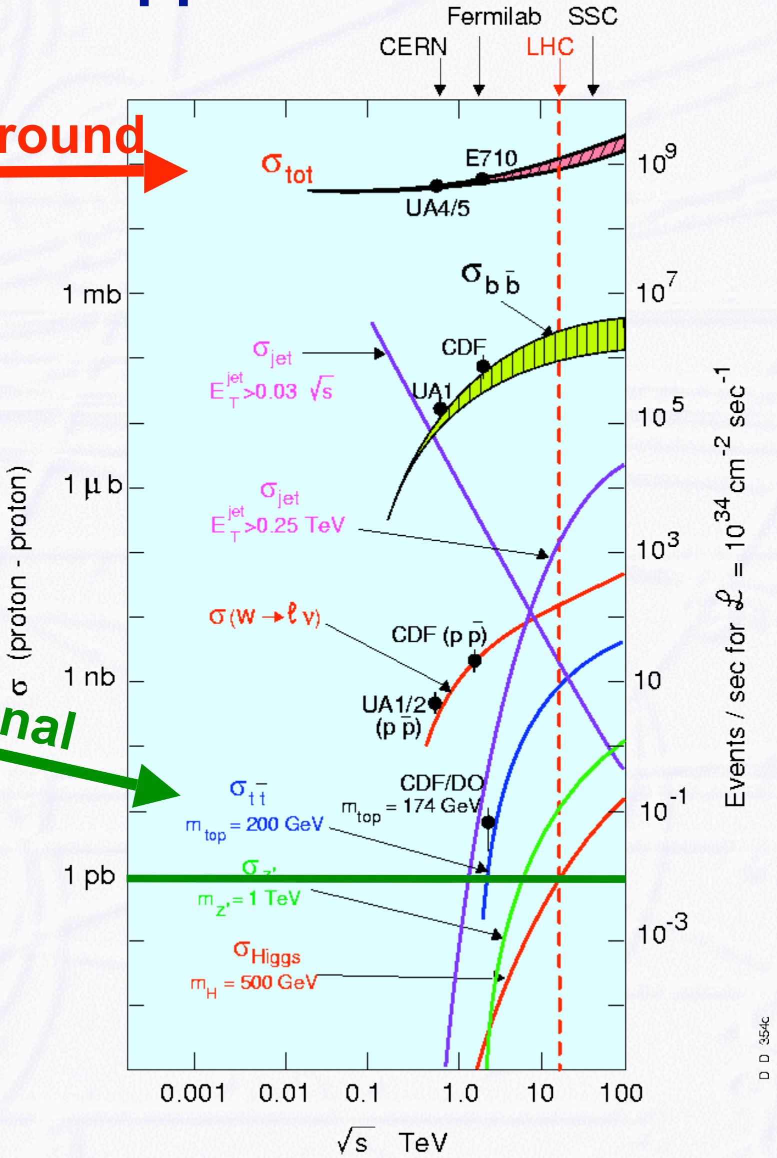


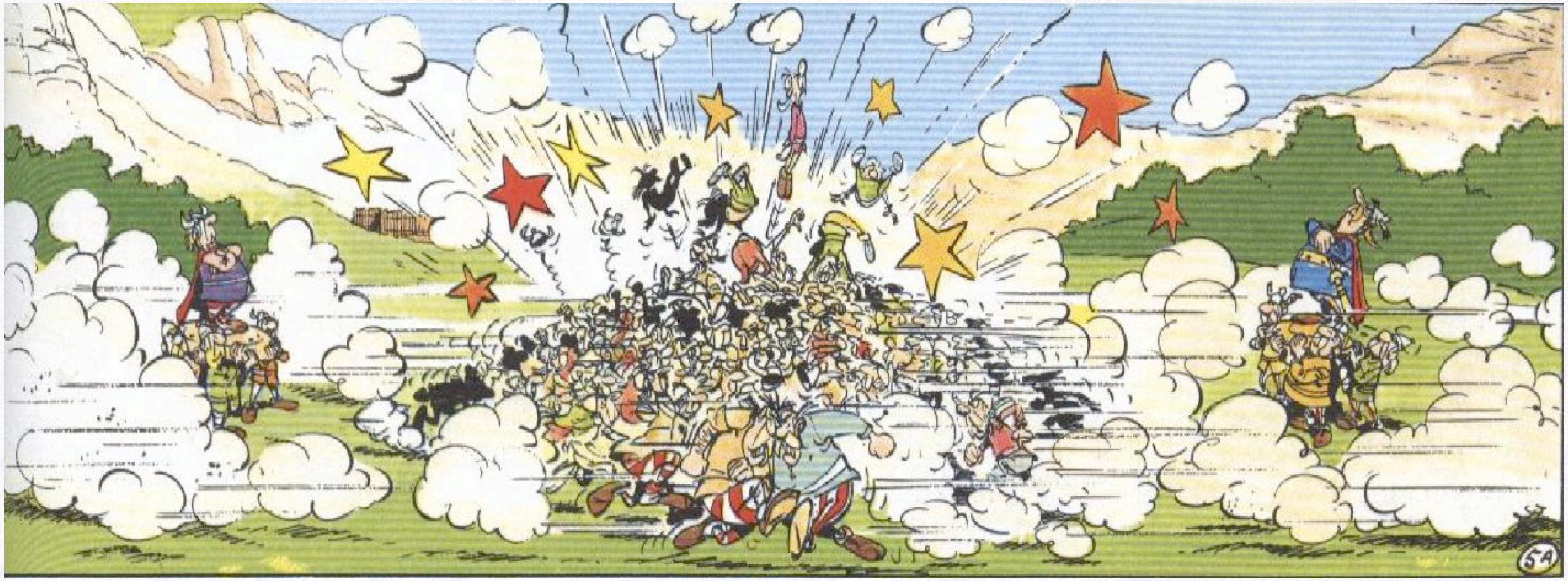
signal

$\sigma_H(m_H=500\text{ GeV}) \sim 1\text{ pb} = 10^{-36}\text{ cm}^2$

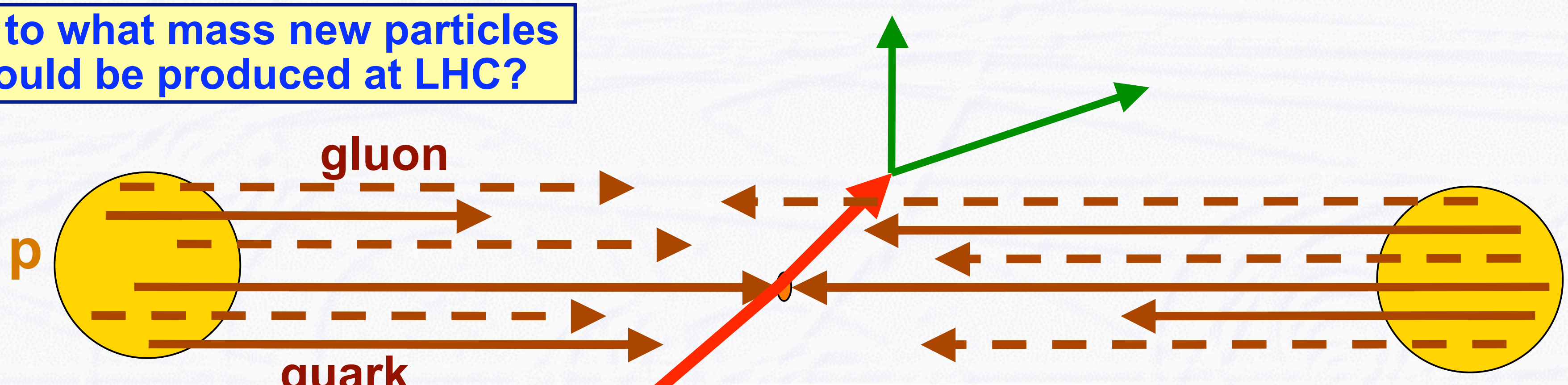
many many orders of magnitude between signal and background !

pp cross sections

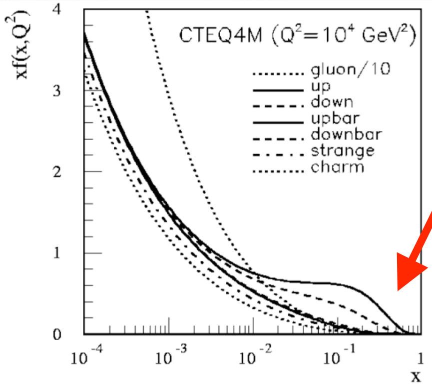




Up to what mass new particles could be produced at LHC?



fraction x of proton momentum carried by partons



spectrum ends at x ~0.35

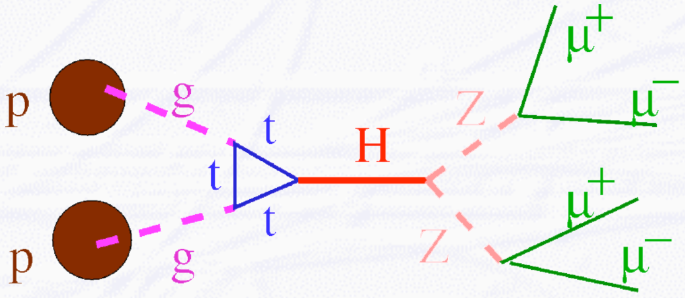
m_{max} = 0.35 x 7 TeV (p)
~ 2.5 TeV

Detector Challenges at LHC

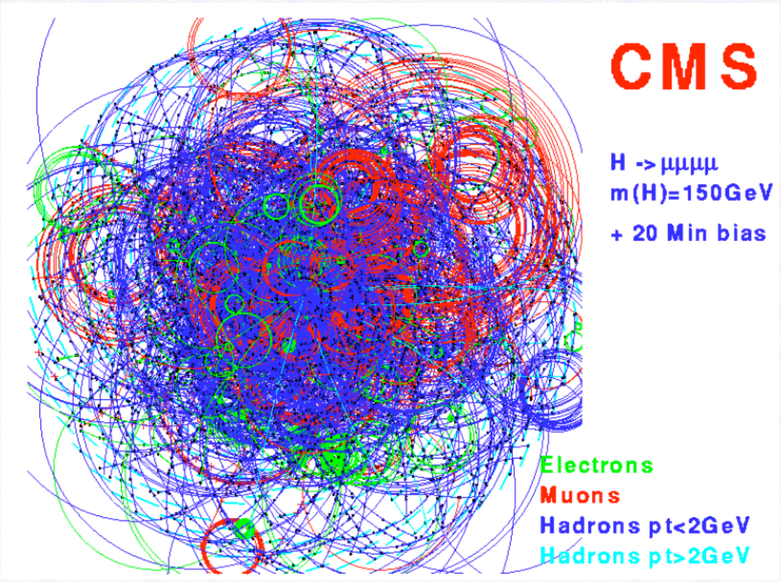
- **High energy**
  - **high momentum resolution up to TeV scale (⇒ detector size)**
- **High luminosity**
  - **design luminosity = 10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ = 10^9 interactions/sec !**
  - **LHC bunch crossing rate = 40 MHz, ~25 interactions per crossing**
  - **high rate capability, fast detectors**
- **High background, high multiplicity**
  - **multiple interactions per bunch crossing ⇒ "pile-up"**
  - **"underlying event": fragmentation of "remainder" of struck protons**
  - **high precision**
  - **high granularity, small detection units to resolve particles**
- **High radiation**
  - **radiation-hard detectors and electronics**

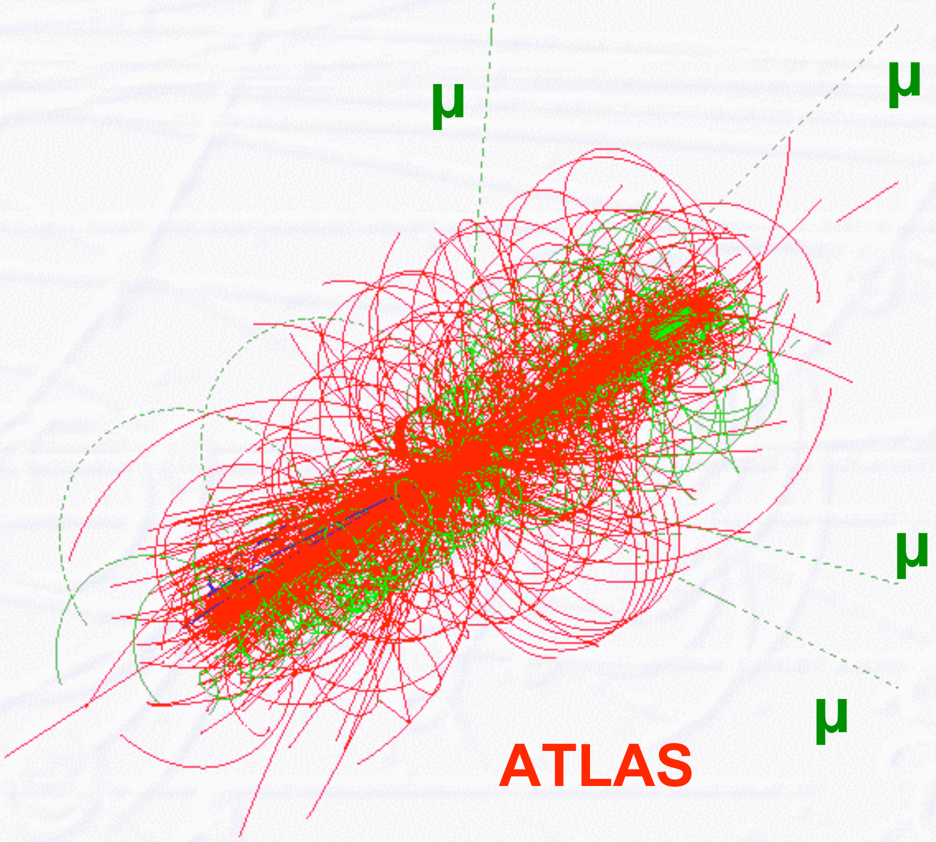
What we (have to) expect …

- **One bunch crossing every 25 ns with ~25 interactions**
  - **1000 tracks per bunch crossing = 4x10^{10} tracks per second …**
  - **… and very often you're interested in a few tracks only!**



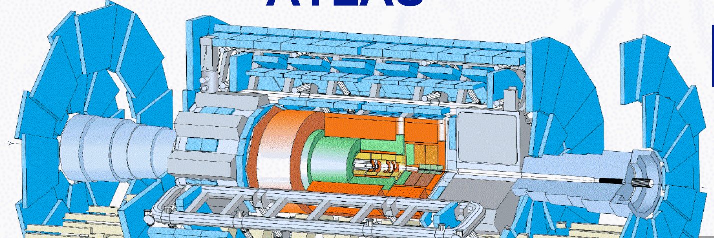
pp ⇒ H ⇒ ZZ ⇒ 4μ



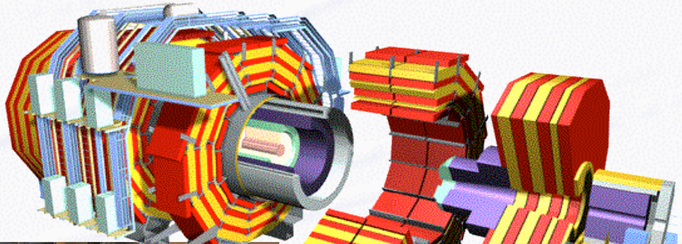


LHC Detectors

ATLAS

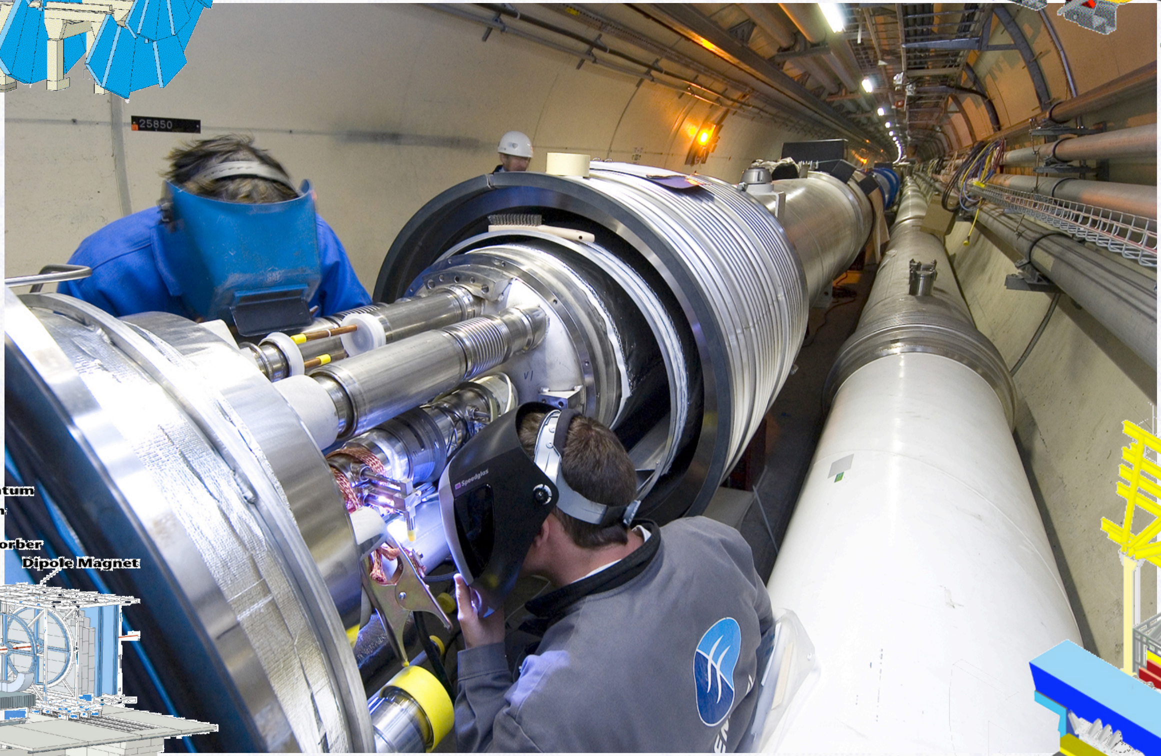


CMS

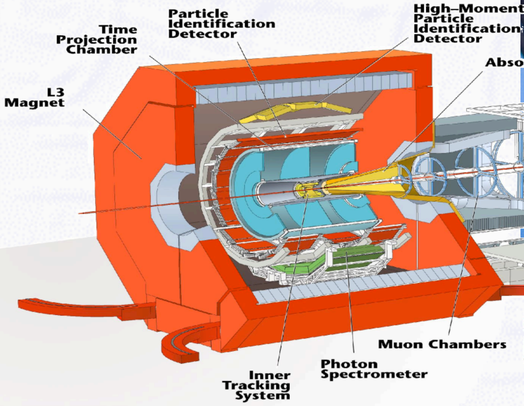


General purpose detectors

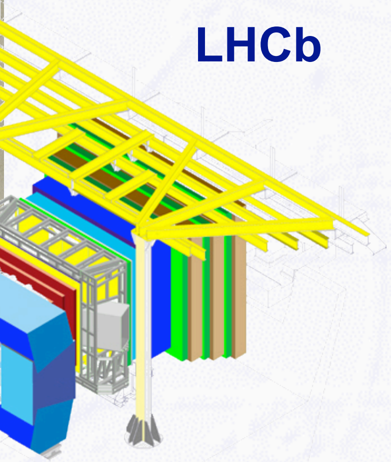
⟷



ALICE



LHCb



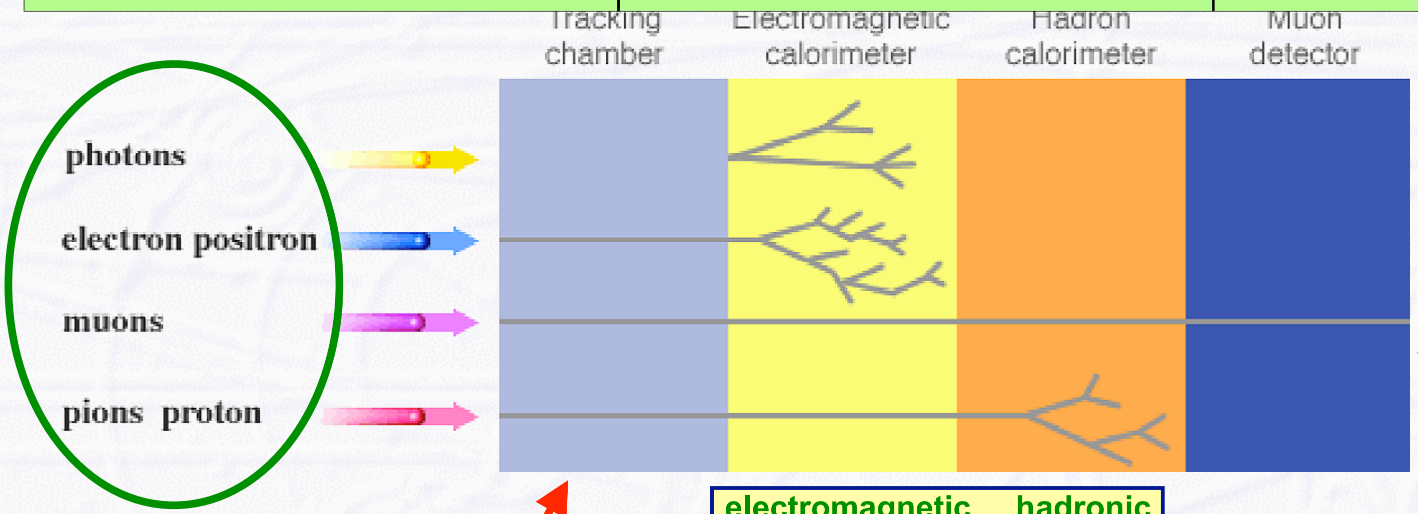
Specialized for heavy ion collisions

Specialized for b-physics

Detector principle – overview

- **Particles are "seen" indirectly through their interactions (primarily electromagnetic) with the active detector materials**

Charged particles	Photons	Hadrons
Excitation Ionization Bremsstrahlung Čerenkov radiation Transition radiation	Photo effect Compton scattering Pair creation	Strong interactions give rise to hadronic showers → charged particles → photons



undetected neutrinos...

electromagnetic hadronic shower

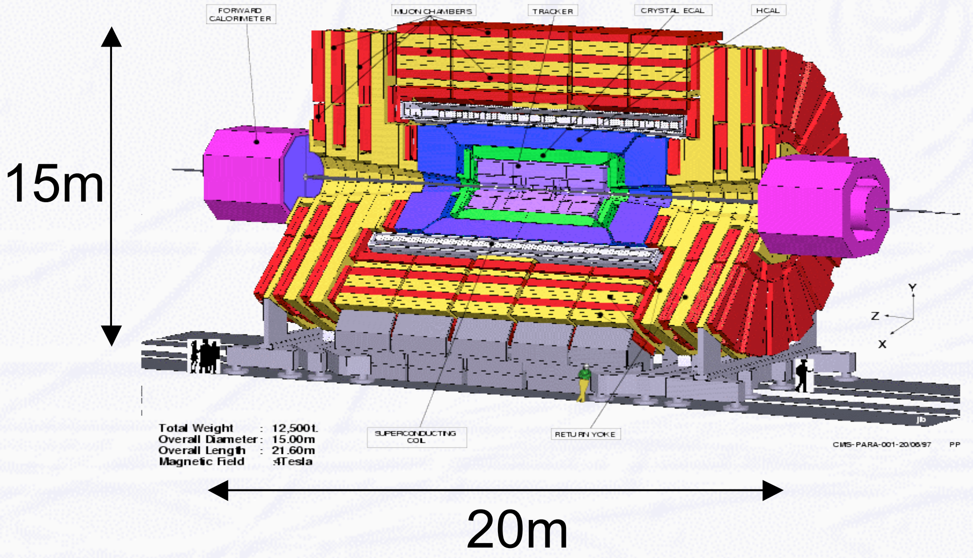
momentum measurement by curvature in magnetic field

energy measurement by creation and total absorption of showers

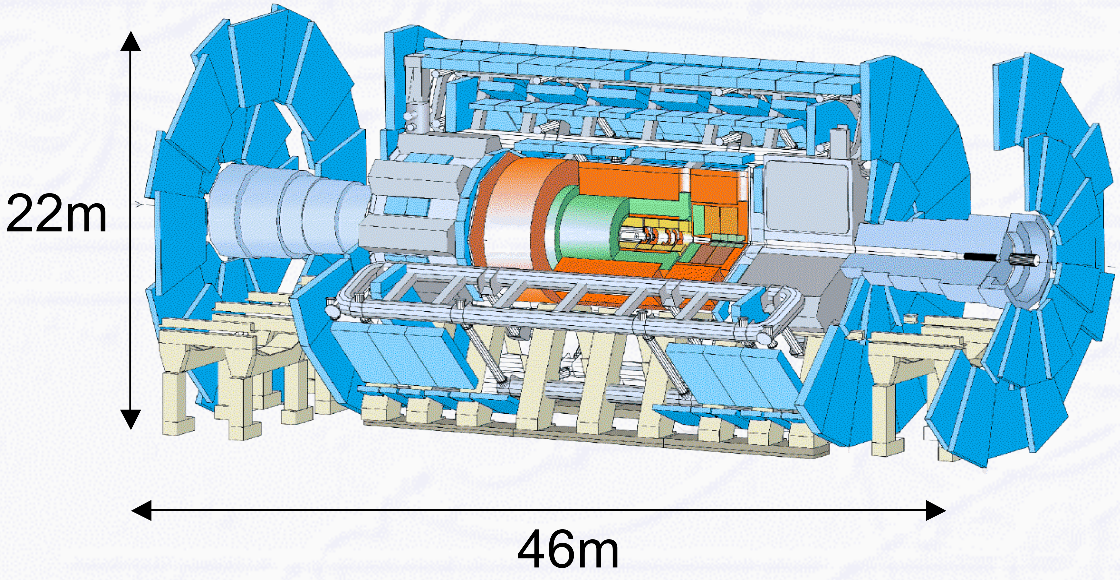
muon detection with improved momentum measurement (long lever arm)

General purpose detectors

hermetic "4π" detectors

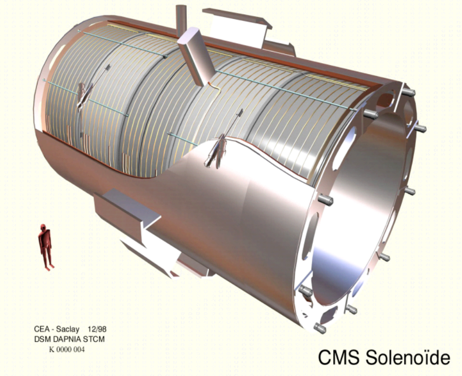


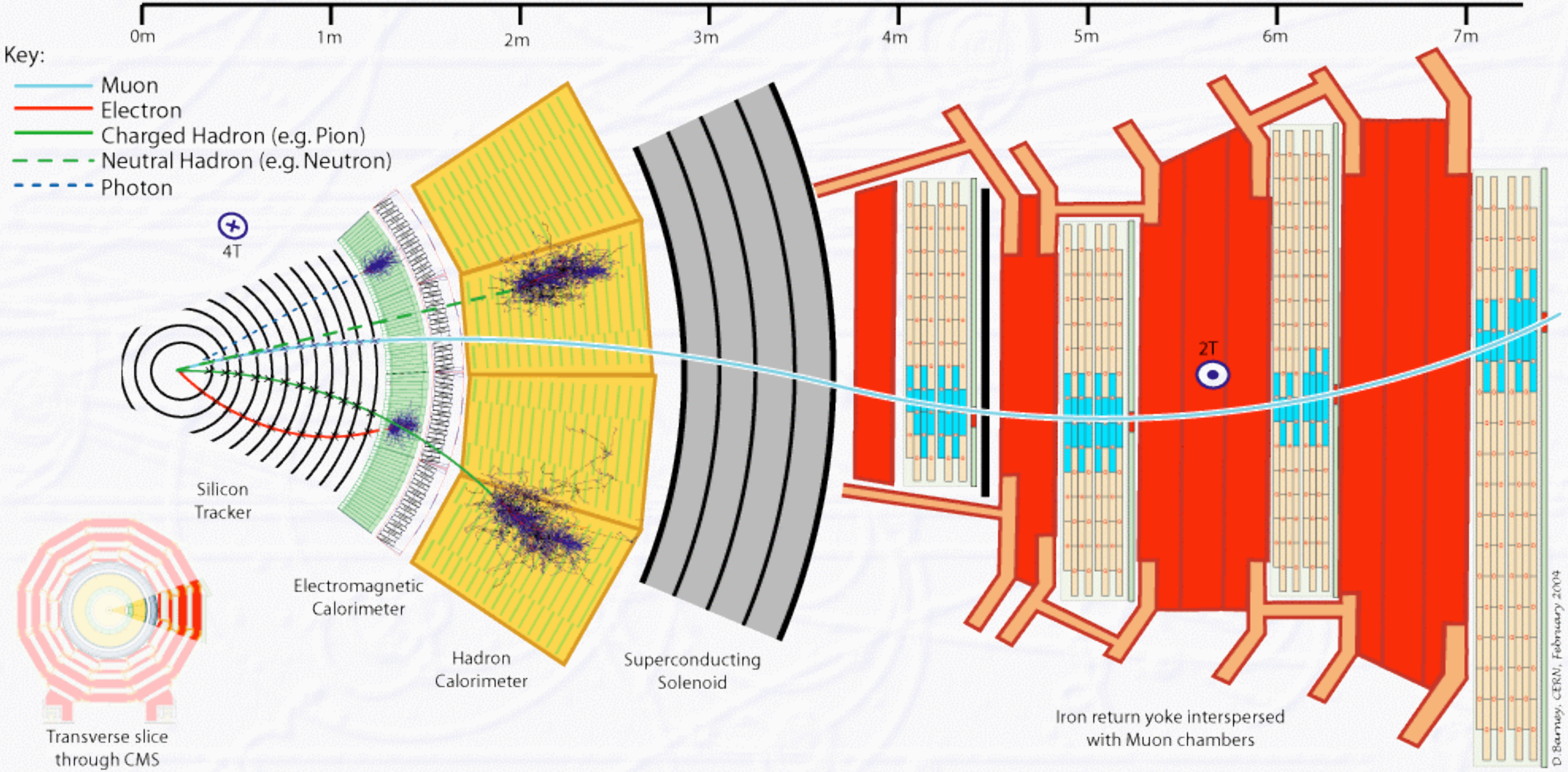
- **CMS (12,500 tons)**
  - Silicon tracker
  - EM calorimeter ($PbWO_4$ crystals)
  - Hadronic calorimeter
  - Solenoid
    - $B=4T$, $Ø_i=6.5m$, $L=12.9m \Rightarrow 2700$ MJ
  - Muon spectrometer & Magnet return yoke (iron)



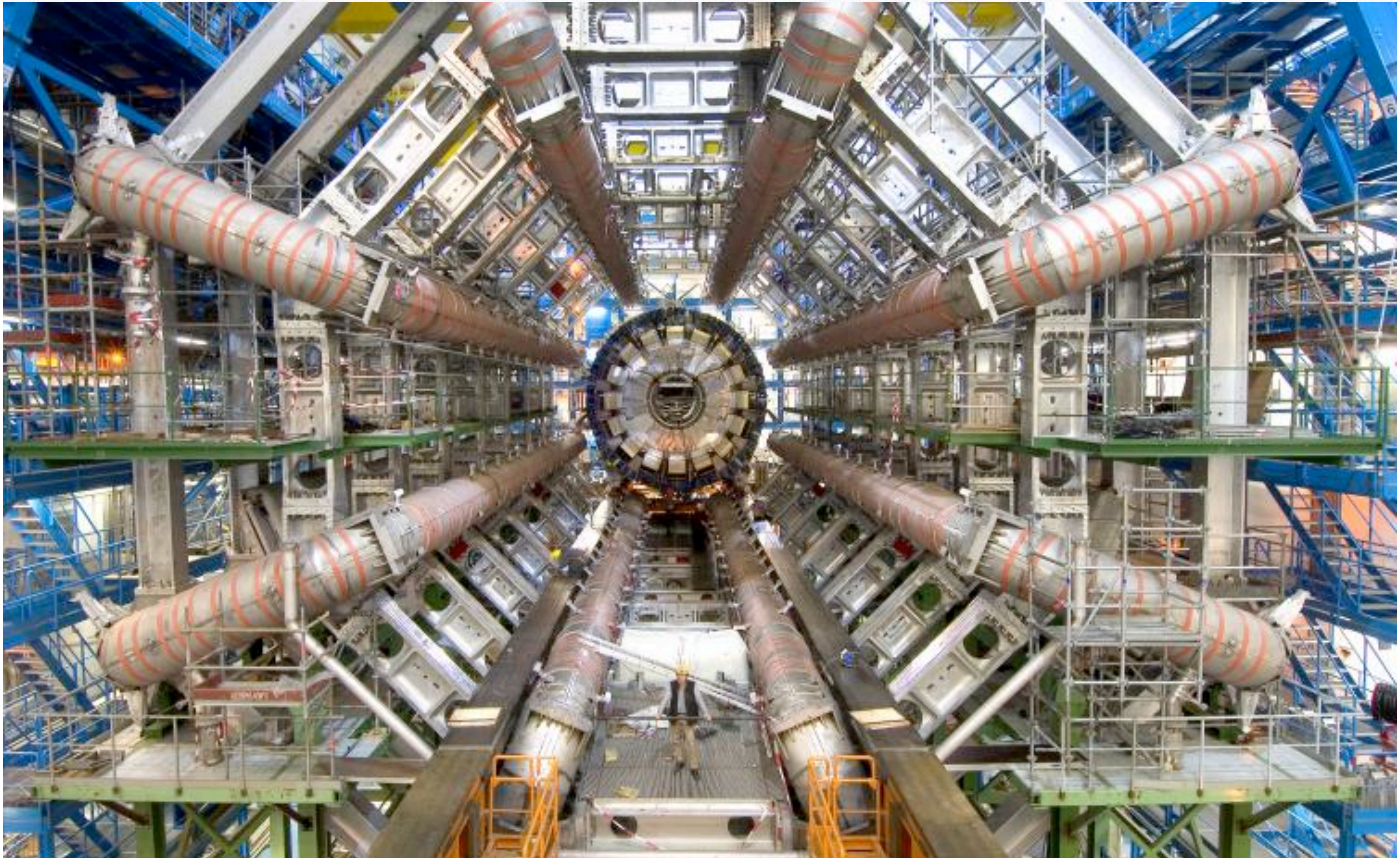
- **ATLAS (7000 tons)**
  - Silicon & gaseous tracker
  - Solenoid
    - $B=2T$, $Ø_i=2.4m$, $L=5.3m \Rightarrow 38$ MJ
  - EM calorimeter (Liquid Argon)
  - Hadronic calorimeter
  - Muon Spectrometer & Toroidal magnets (air-core)
    - Barrel toroid: $3\ T \cdot m$, 1080 MJ
    - End-cap toroids: $6\ T \cdot m$, 206 MJ

CMS


CEA - Saclay 12/98
DSM DAPNIA STCM
K 0000 004
CMS Solenoïde


0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D. Barney, CERN, February 2004

ATLAS

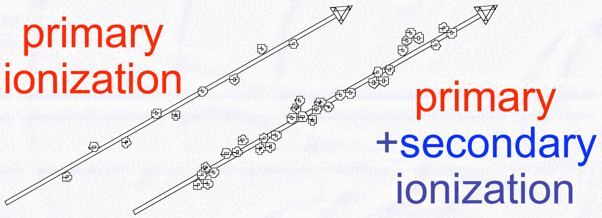


Particle Interactions with Matter

Charged particles	Photons	Hadrons
Excitation Ionization Bremsstrahlung Čerenkov radiation Transition radiation	Photo effect Compton scattering Pair creation	Strong interactions give rise to hadronic showers → charged particles → photons

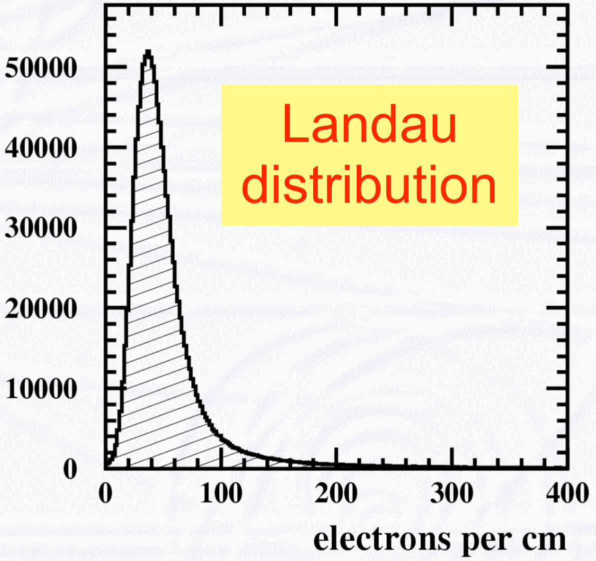
Charged particle interactions
Energy loss by ionization

- Primary number of ionizations per unit length is Poisson-distributed
  - typically ~30 primary interactions (ionization clusters) / cm in gas at 1 bar
- However, primary electrons sometimes get large energies
  - secondary ionization
  - δ-electrons
  - large energy loss fluctuations



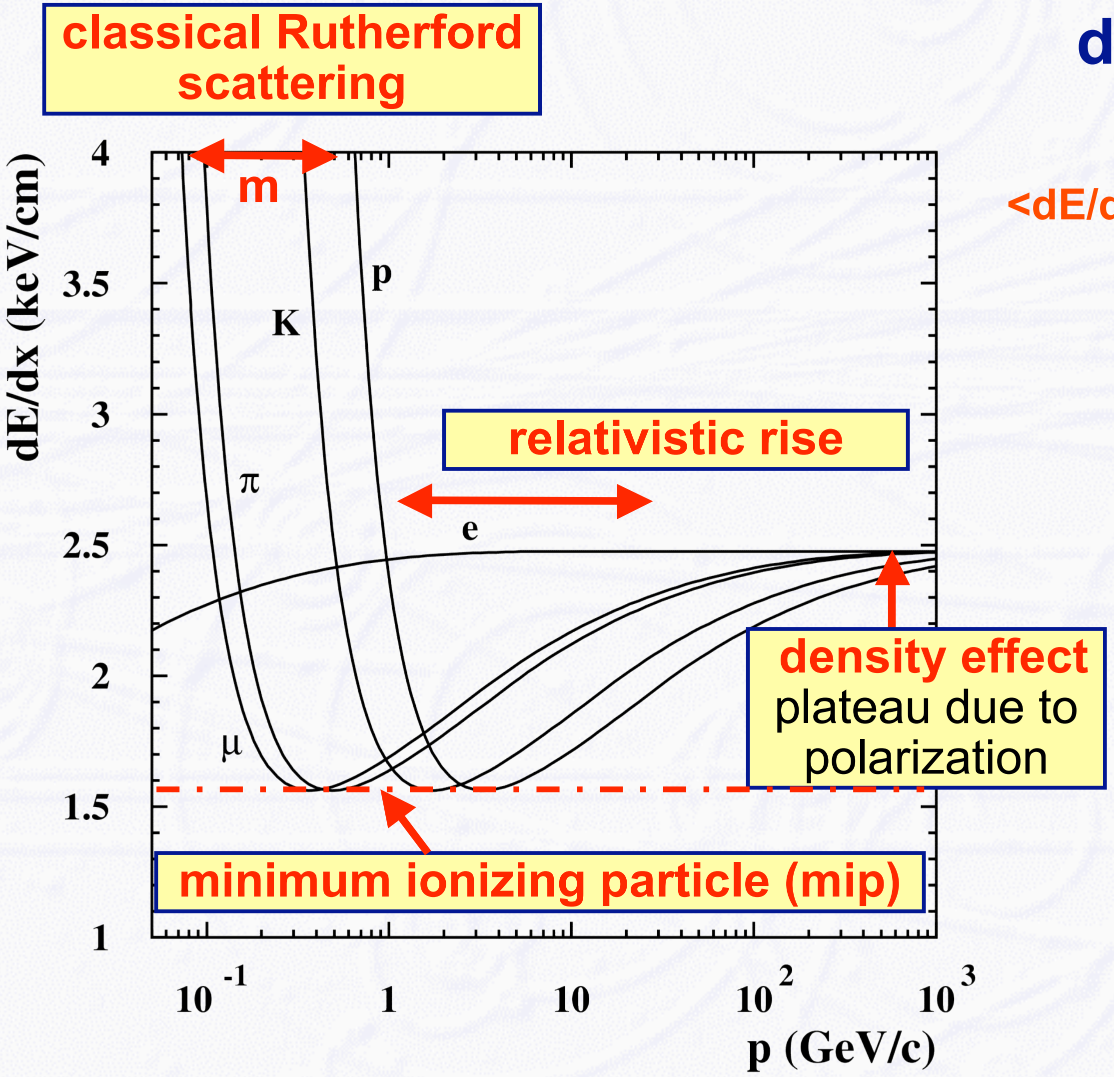
  - Typically:
    total ionization = 3 x primary ionization
    i.e. ~ 90 electrons/cm in gas at 1 bar

- Cluster size fluctuations cause large variations of energy loss from track to track



- dE/dx = mean energy loss
  - Ionization chamber
  - Proportional counter
  - Calorimetry (see later)

Charged particle interactions
Energy loss by ionization



classical Rutherford scattering

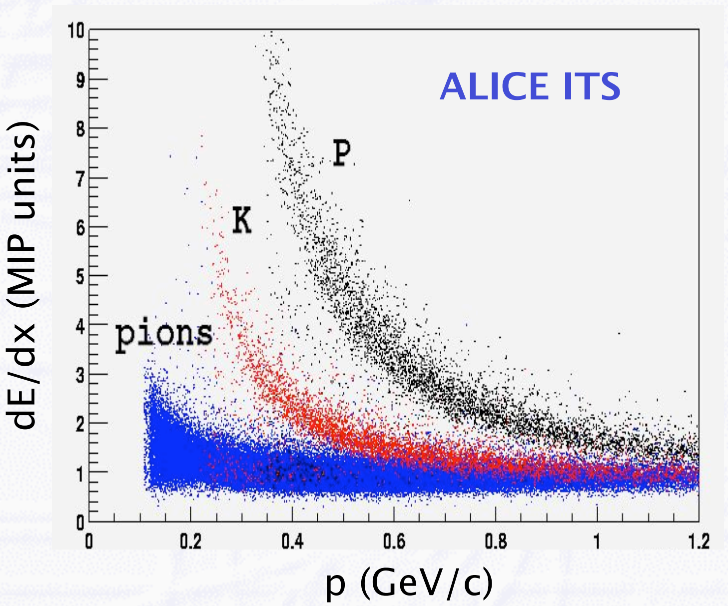
relativistic rise

density effect plateau due to polarization

minimum ionizing particle (mip)

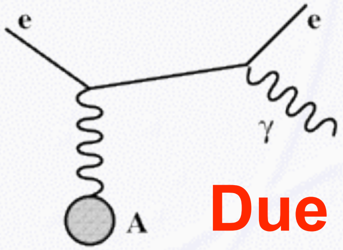
described by the well-known Bethe-Bloch formula:

$$\langle dE/dx \rangle = \xi * 1/\beta^2 * Q^2 * [K + \ln Q^2 + \ln\gamma^2 - \beta^2 - \delta(\beta)]$$

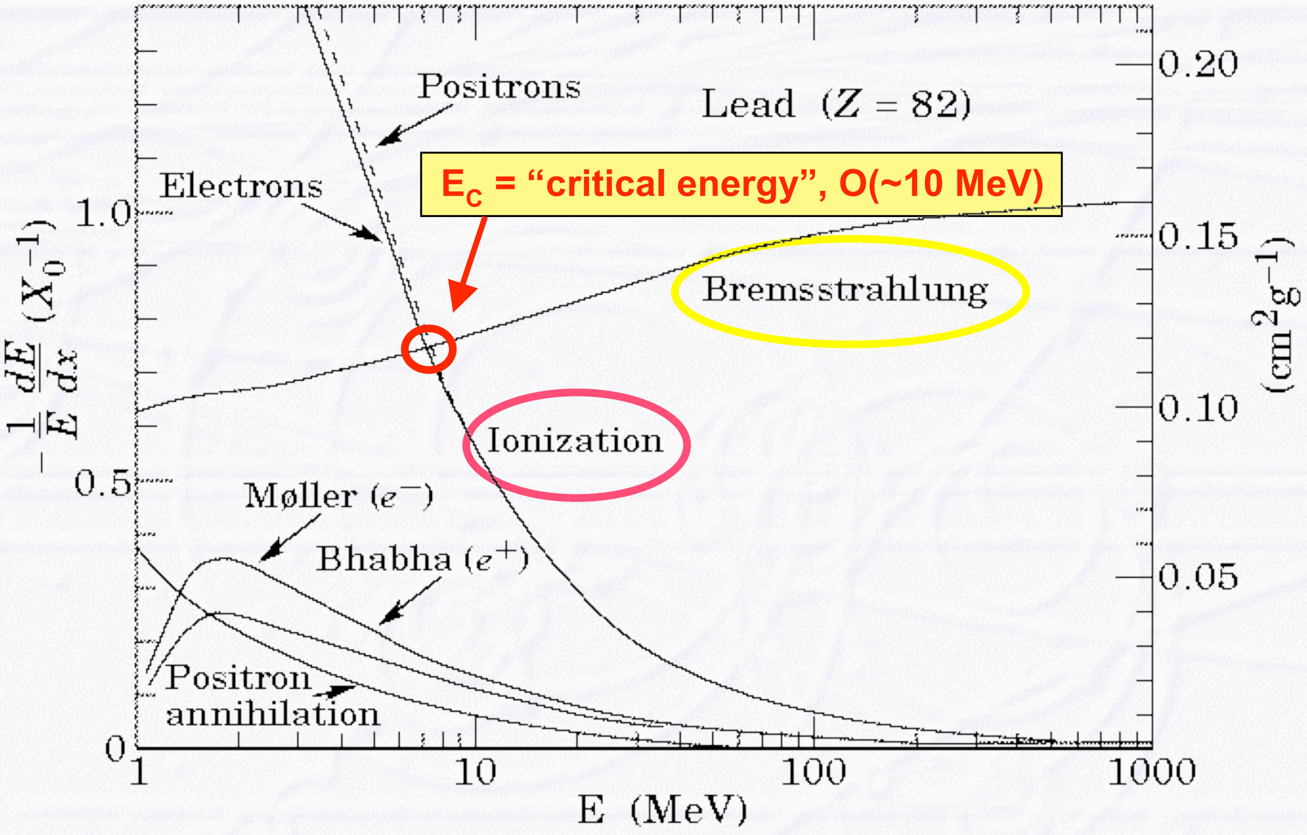


The other LHC detectors focus on high momenta and are optimised for fast response, not for good dE/dx resolution

Charged particle interactions
Bremsstrahlung

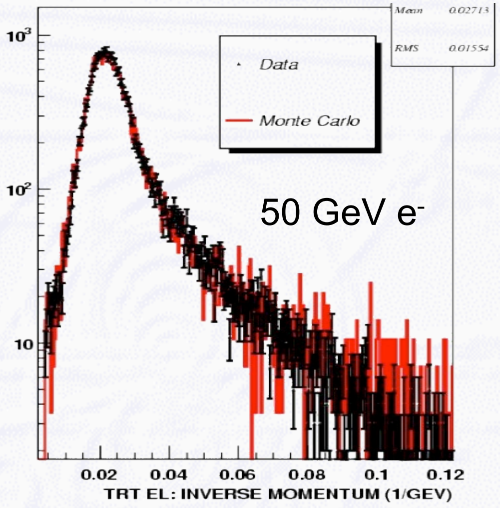


Due to interaction with the Coulomb field of a nucleus



E_C = "critical energy", O(~10 MeV)

- **Dominant energy loss mechanism for electrons down to very low momenta**
- **Leads to tail in $1/p_t$ - distribution measured by tracking detectors**



50 GeV e^-

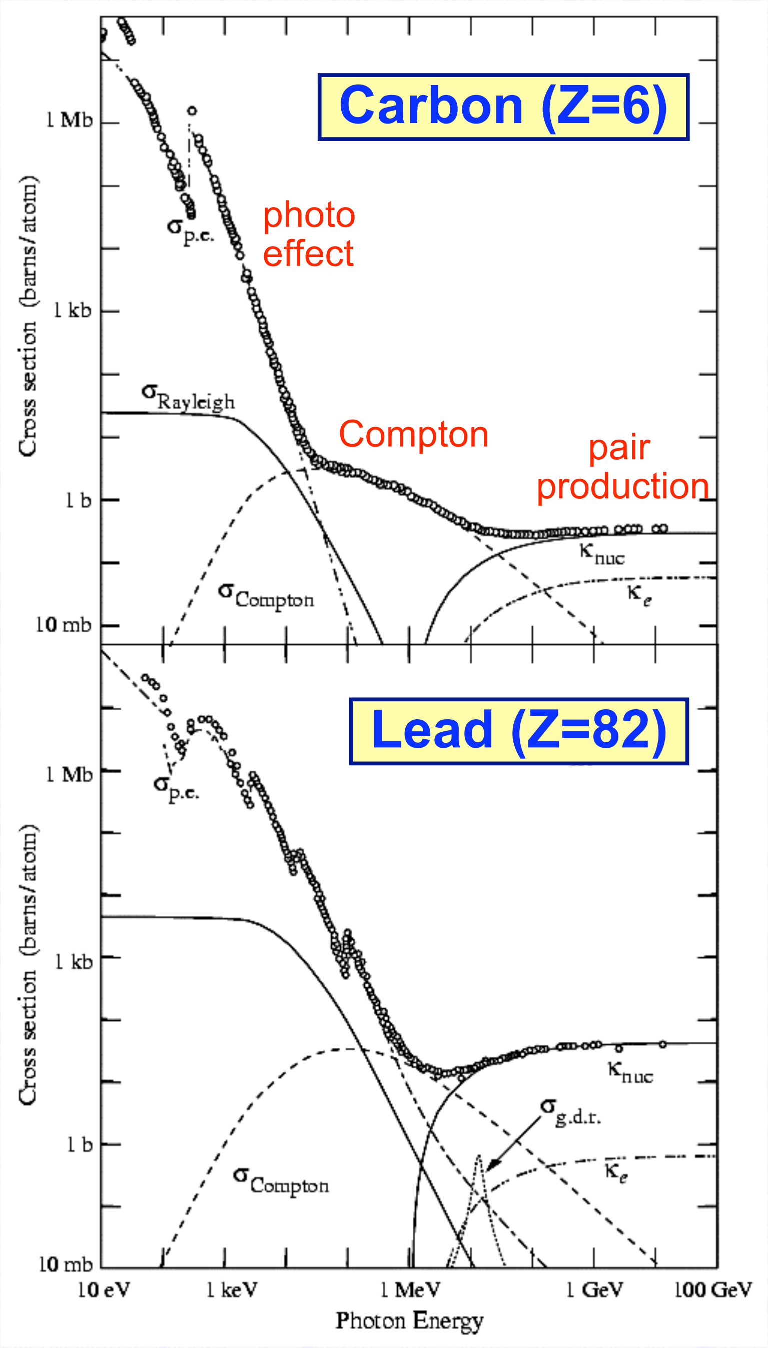
- **Initiates electromagnetic cascades (showers)**

Multiple Scattering

- **Charged particles traversing a medium are deflected by many successive small-angle scatters**
  - **after passing a layer of thickness L, the particle leaves with some displacement *r* and a deflection angle θ**
  - **the angular distribution is roughly Gaussian for small angles**
    - **large-angle tails behave like Rutherford scattering:** $\propto \sin^{-4}(\theta/2)$
  - **width of the Gaussian:** $\theta_0 \propto (1/p)\sqrt{L/X_0}$ X_0 = radiation length (see later)

- **Consequences**
  - **Limits precision of momentum measurements**
  - **Complicates performance analysis of tracking detectors, and the relative alignment of track segments in large detectors**

Photon Interactions



- **Photo effect dominating at low γ energies (< some 100 keV)**
  - **Photo Multiplier Tubes (PMT)**
  - **photo diodes**
- **Compton scattering regime ~some 100 keV up to ~10 MeV**
  - **not used for particle detection**
    - **but was/is used for polarization measurement of beams in e^+e^- machines**
- **Pair production dominating at high energies (> ~10 MeV)**
  - **initiates electromagnetic showers in calorimeters, unwanted in tracking detectors**

Radiation Length

- Expresses material thickness on the basis of
  - bremsstrahlung for $e^{\pm}$ (dominant energy loss for high energy electrons)
  - pair production for γ (dominant energy loss for high energy photons)

- Definition

X_0 = length of a given material over which an electron looses all but 1/e of its energy by bremsstrahlung
= 7/9 of mean free path length of photon before pair production

- Thickness/density of materials are conveniently expressed in units of X_0

Material	X_0 [cm]
Si	9.36
Fe	1.76
$PbWO_4$	0.89
Pb	0.56

CMS ECAL → $PbWO_4$

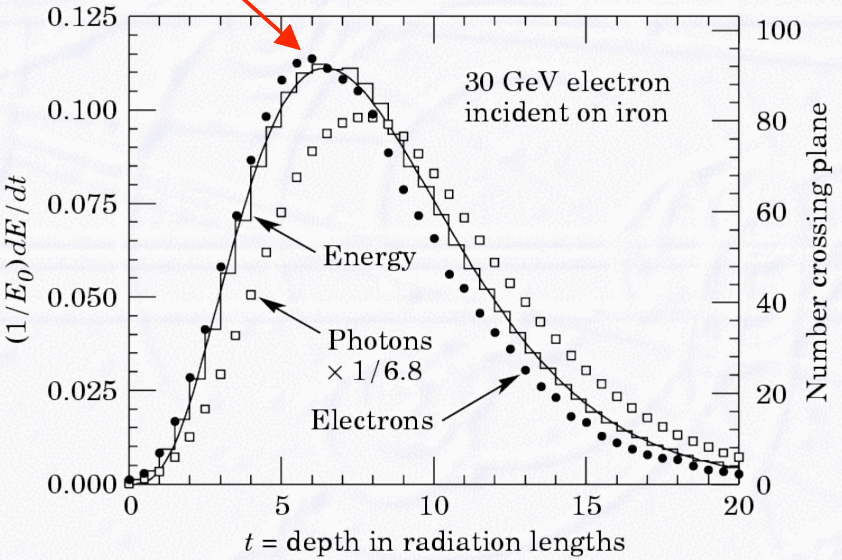
ATLAS LAr absorber → Pb

Electromagnetic Cascades

- **A high-energy electron or photon incident on an absorber initiates an electromagnetic cascade, as bremsstrahlung and pair production generate more and more electrons and photons of lower energy**

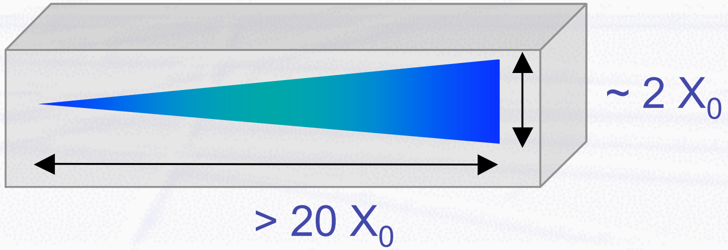
Longitudinal shower profile

$$t_{max}[X_0] = \ln\frac{E_0}{E_c}\frac{1}{\ln 2}$$



Transverse shower width given by Moliere radius

$$R_M = \frac{21\,MeV}{E_c}X_0$$



- **Electromagnetic calorimeters should have X_0 as high as possible (typically 20...30 X_0)**
- **Tracking detectors should have X_0 as low as possible (<< 1 X_0)**

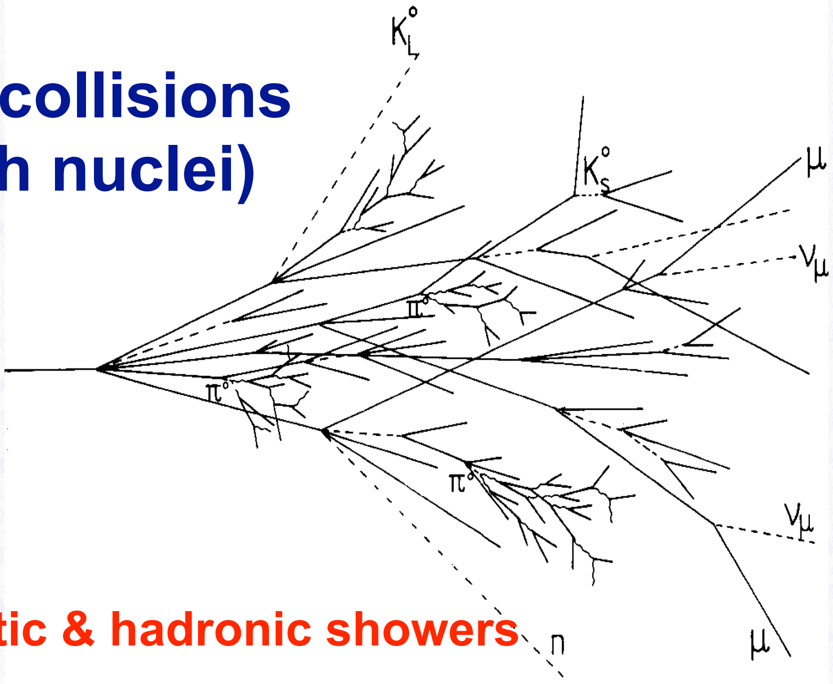
ATLAS and CMS trackers are not really "transparent" ⇒ high probability to initiate electromagnetic showers before e/γ reach calos

Pre-shower **detectors in front of calorimeter help to correct the measured ECAL energy for such early showers**

Nuclear Interaction Length

- **Mean free path of hadrons between collisions (i.e. between strong interactions with nuclei)**

Material	λ_I [cm]
Si	45.5
Fe	16.75
Pb	17.1



C. Grupen

  - **note: $\lambda_I > X_0 \Rightarrow$ separation of electromagnetic & hadronic showers**
  - **Development of hadronic cascades (showers)**

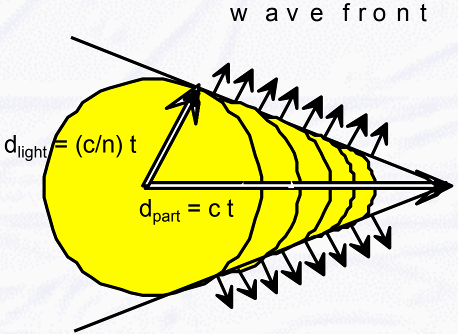
multiplicity ∝ ln*(E)*

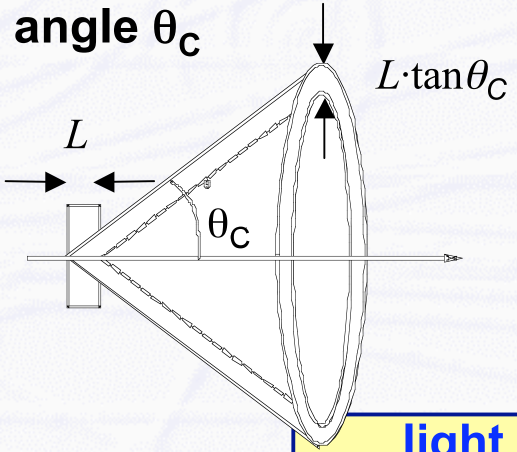
- **Hadronic showers have 2 main components**
  - **hadronic**
    - **charged hadrons, breaking up of nuclei (binding energy) nuclear fragments, neutrons**
  - **electromagnetic**
    - **decay of neutral pions: $\pi^0 \rightarrow 2\gamma$**

“invisible” energy ⇒ large energy fluctuations

Charged particle interactions
Čerenkov Radiation

- **Čerenkov radiation is emitted when a charged particle passes though a dielectric medium with refractive index n at velocity $\beta c > c/n = \beta_{threshold}$**
  - **wave front = cone under Čerenkov angle θ_C**





$$\cos\theta_C = \frac{1}{n\beta}$$

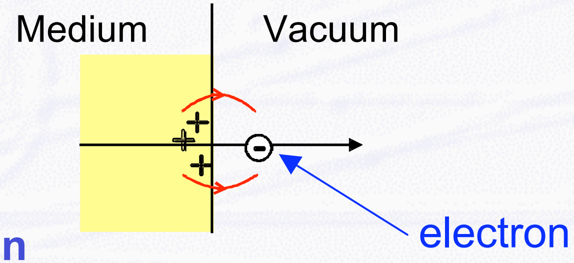
continuous wave front emission from track

light cone emission when passing thin medium

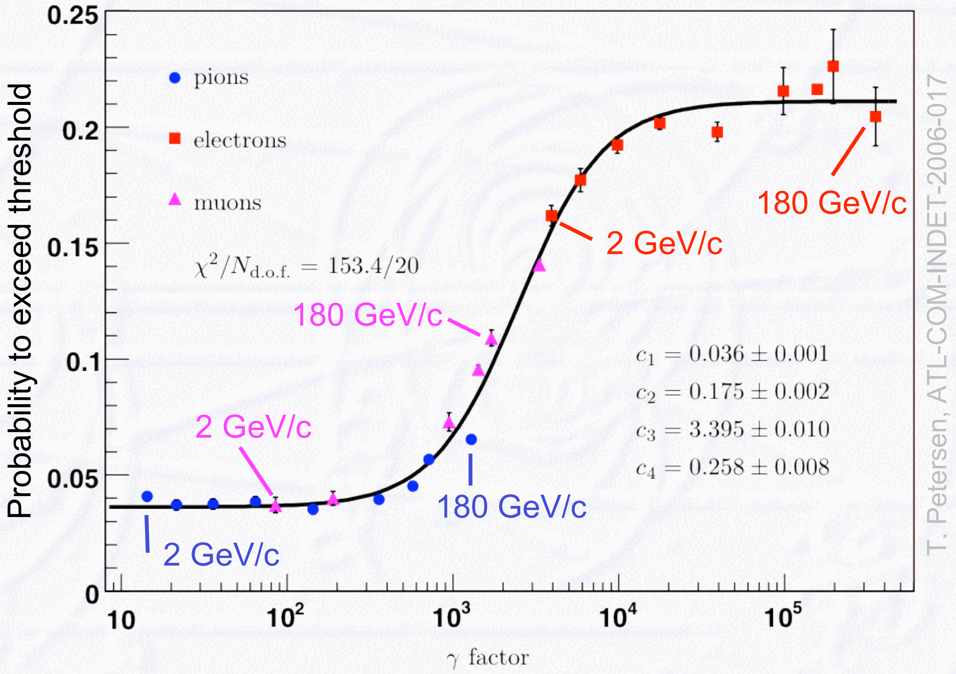
- **Threshold Č counters are used for particle separation in beam lines**
  - **For a given beam momentum $p = \beta\gamma mc$, the radiating medium is chosen such that (e.g.)** $\beta_{muon} \leq 1/n = \beta_{threshold} < \beta_{electron}$
- **Ring Imaging Č (RICH) counters measure θ_C**
  ⇒ particle tracking & identification (used in LHCb)

Transition Radiation

- **Photon radiation when charged particles traverse the boundary of two media with different refractive index (Ginzburg and Franck, 1946)**
  - **(very) simple picture**
    - **charged particle is polarizing medium**
    - **polarized medium is left behind when particle leaves media and enters unpolarized vacuum**
    - **oscillating electrical dipol emits (transition) radiation**

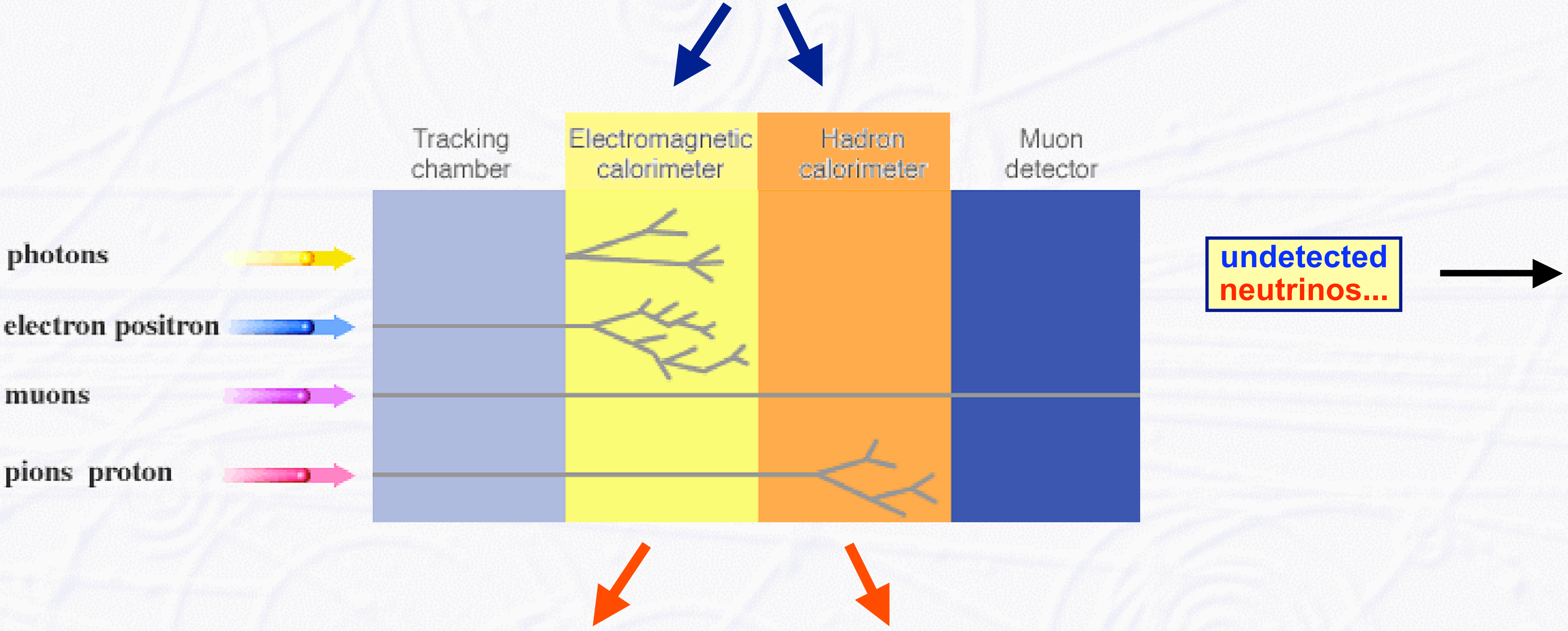


  - **only highly relativistic particles** $\gamma > 1000$ **radiate significant energy**
    - **in direction of charged particle (**$\theta \sim 1/\gamma$**)**
  - **useful photon energy** 2…20 keV
    - **peaking at ~8 keV**
  - **need many** (> ~100) **boundaries to get just a few photons**
    - **Radiator (medium) = foam, fibres, foils**



- **Used for electron identification**
  - **ALICE TRD, ATLAS TRT**

Calorimeters



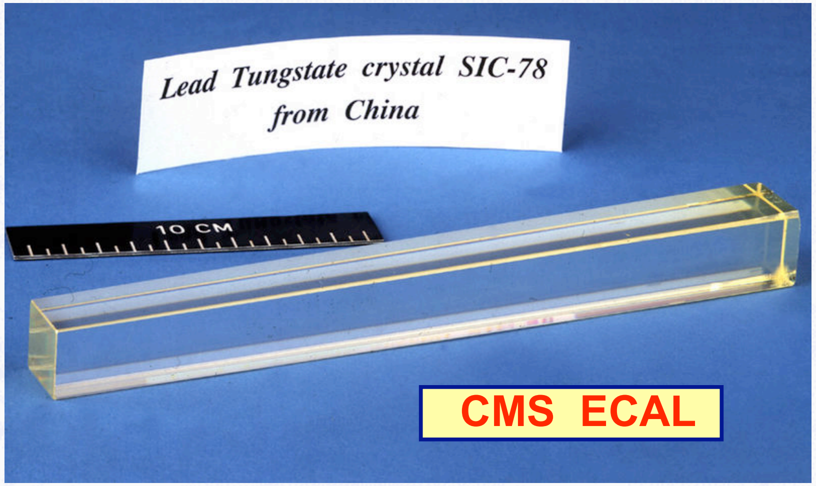
undetected neutrinos...

homogeneous calorimeter (CMS)
sampling calorimeter (ATLAS)

sampling calorimeter
(CMS & ATLAS)

Calorimeter Concepts

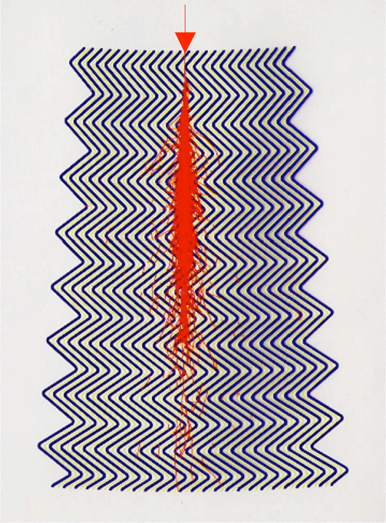
- Homogeneous Calorimeter
  - entire shower is kept in active detector material
    - high density (small X_0)
    - transparent, high light yield
    - no particles lost in passive absorber
    - high resolution
  - limited granularity
    - longitudinal shower shape unmeasured



CMS ECAL

- Sampling Calorimeter
  - passive, heavy absorber interleaved with active detector material
  - absorbers
    - Fe, Cu, Pb, W, U
  - active detector materials
    - gas detectors (MWPCs)
    - plastic scintillators
    - liquid noble gases (LAr, LKr)
  - granular read-out

ATLAS LAr Calorimeter



Energy Resolution

- **Number of particles in shower is proportional to energy of initial particle**

$$N_{track} = \frac{E}{E_c}$$

  - **error of energy measurement due to statistical fluctuations of N_{track}**

$$\sigma(N_{track}) = \sqrt{N_{track}} \quad \Rightarrow \quad \frac{\sigma(E)}{E} \propto \frac{1}{\sqrt{E}}$$

- **Generic formula**
  - **includes contributions from detector inhomogeneities and noise**
  - **used both for homogeneous & sampling calorimeters, and for electromagnetic & hadronic calorimeters**

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

stochastic term

number of shower particles

constant term

inhomogeneities
non-linearities

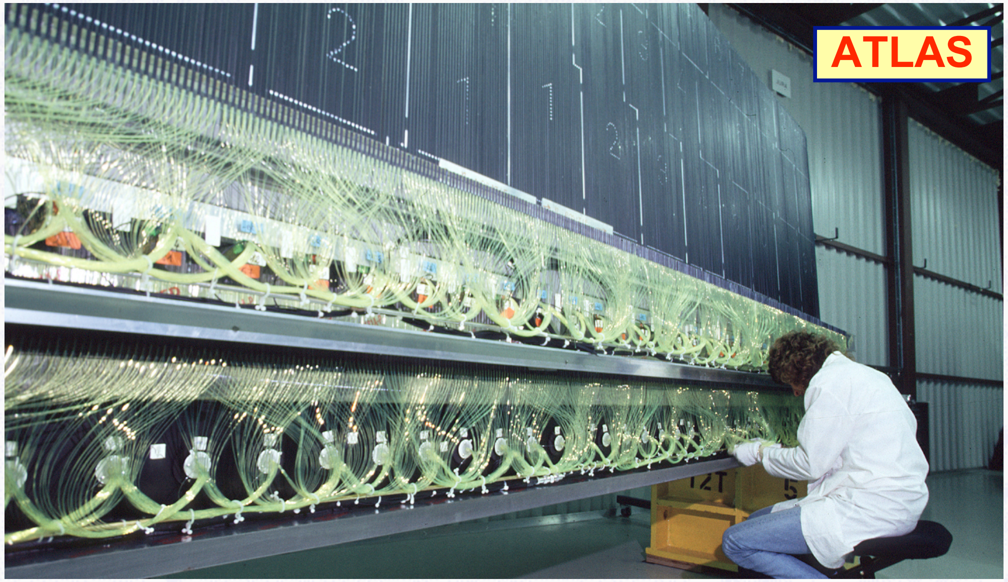
noise term

electronics noise

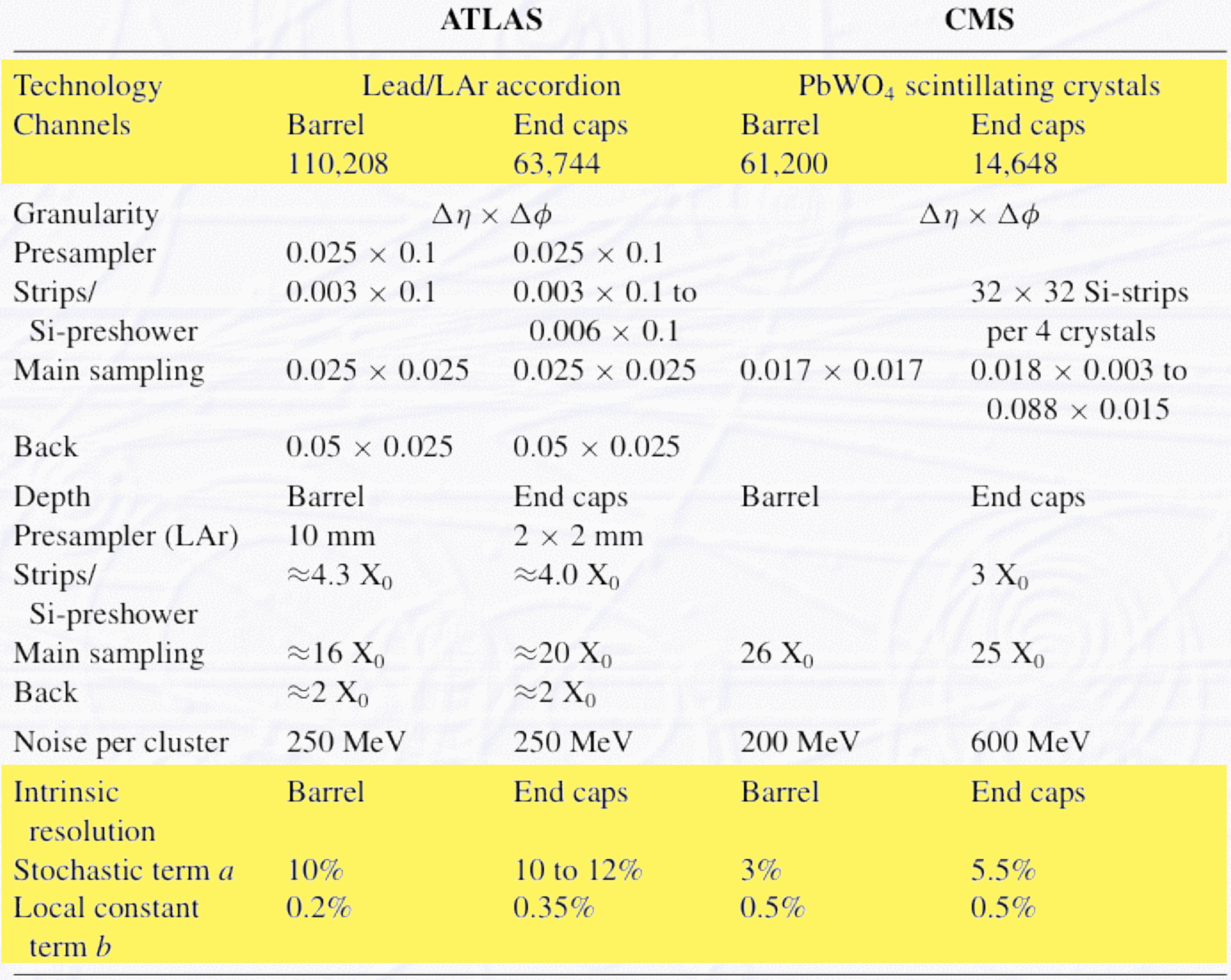
Hadron Calorimeters

- **Usually sampling type**
- **Energy resolution worse than for electromagnetic calorimeters**
    - larger fluctuations in hadronic shower
    - different response for electromagnetic and hadronic shower component, e/h > 1
    - typical depth ~10 nuclear interaction lengths λ_I $\Rightarrow$ > 95% containment up to 1 TeV
- **ATLAS and CMS use scintillators as active detector material**

→ **optical fibers to transport light from scintillators to photo detectors**



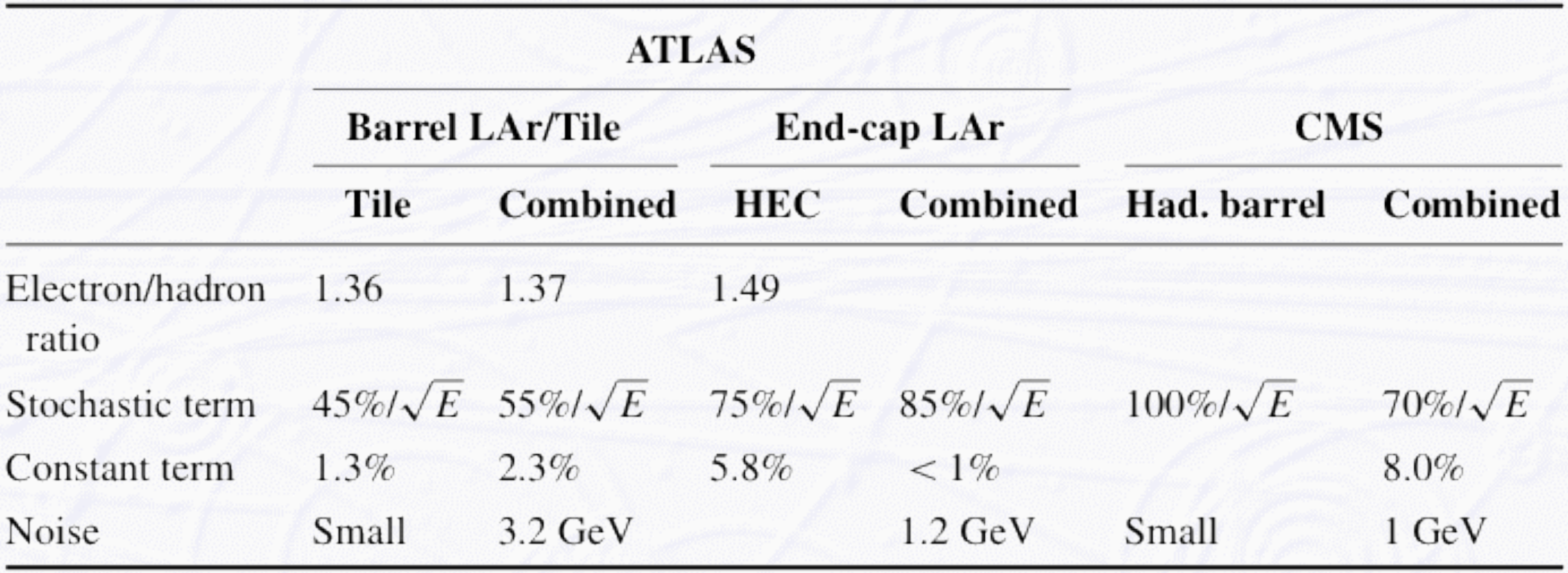
Main parameters of ATLAS and CMS electromagnetic calorimeters



	ATLAS		CMS	
Technology	Lead/LAr accordion		$PbWO_4$ scintillating crystals	
Channels	Barrel	End caps	Barrel	End caps
	110,208	63,744	61,200	14,648
Granularity	$\Delta\eta \times \Delta\phi$		$\Delta\eta \times \Delta\phi$	
Presampler	0.025 × 0.1	0.025 × 0.1		
Strips/ Si-preshower	0.003 × 0.1	0.003 × 0.1 to 0.006 × 0.1		32 × 32 Si-strips per 4 crystals
Main sampling	0.025 × 0.025	0.025 × 0.025	0.017 × 0.017	0.018 × 0.003 to 0.088 × 0.015
Back	0.05 × 0.025	0.05 × 0.025		
Depth	Barrel	End caps	Barrel	End caps
Presampler (LAr)	10 mm	2 × 2 mm		
Strips/ Si-preshower	≈4.3 X_0	≈4.0 X_0		3 X_0
Main sampling	≈16 X_0	≈20 X_0	26 X_0	25 X_0
Back	≈2 X_0	≈2 X_0		
Noise per cluster	250 MeV	250 MeV	200 MeV	600 MeV
Intrinsic resolution	Barrel	End caps	Barrel	End caps
Stochastic term *a*	10%	10 to 12%	3%	5.5%
Local constant term *b*	0.2%	0.35%	0.5%	0.5%

D. Froidevaux and P. Sphicas, Annual Review of Nuclear and Particle Science, Vol. 56: 375-440

Main parameters of ATLAS and CMS hadronic calorimeters

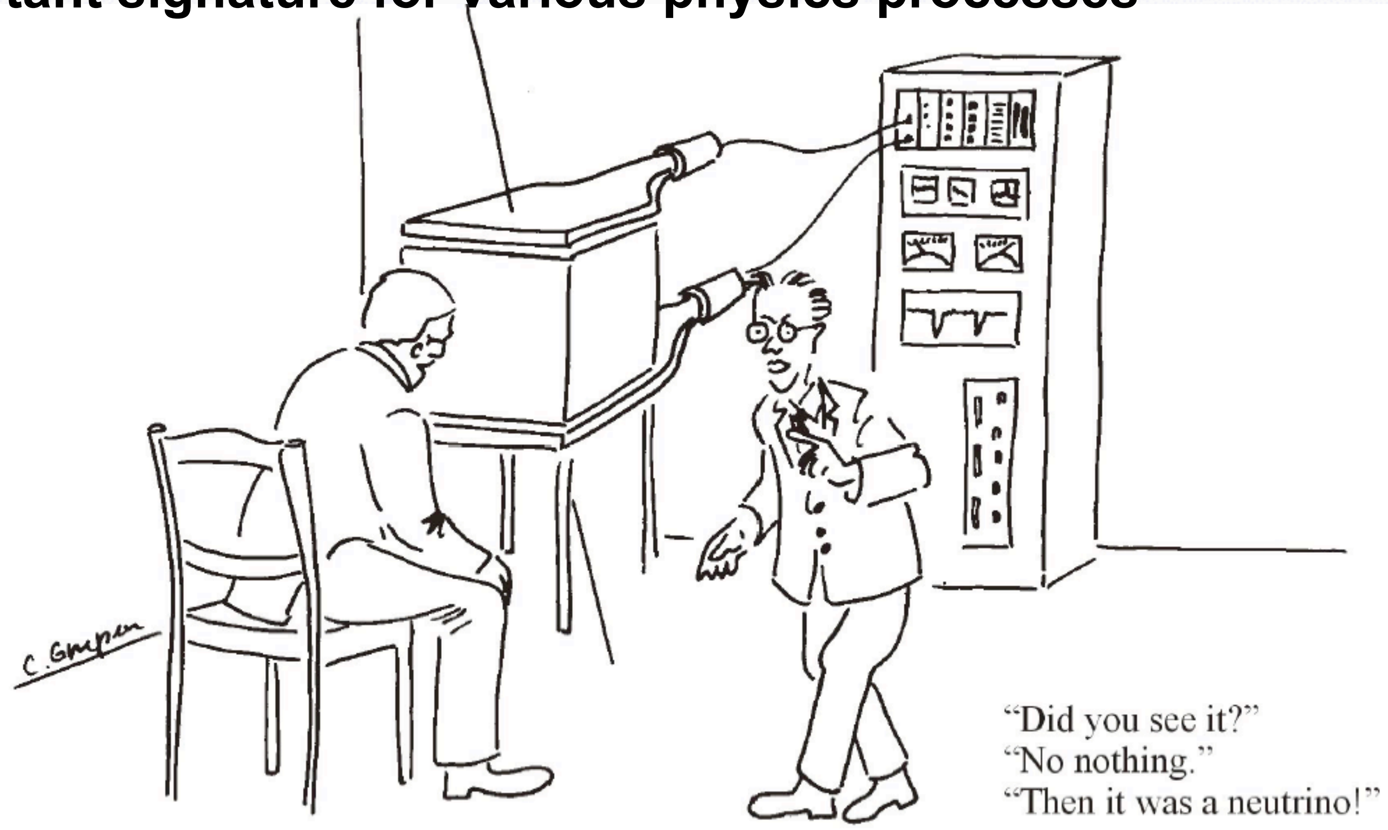


	ATLAS					
	Barrel LAr/Tile		**End-cap LAr**		**CMS**	
	Tile	**Combined**	**HEC**	**Combined**	**Had. barrel**	**Combined**
Electron/hadron ratio	1.36	1.37	1.49			
Stochastic term	$45\%/\sqrt{E}$	$55\%/\sqrt{E}$	$75\%/\sqrt{E}$	$85\%/\sqrt{E}$	$100\%/\sqrt{E}$	$70\%/\sqrt{E}$
Constant term	1.3%	2.3%	5.8%	$< 1\%$		8.0%
Noise	Small	3.2 GeV		1.2 GeV	Small	1 GeV

D. Froidevaux and P. Sphicas, Annual Review of Nuclear and Particle Science, Vol. 56: 375-440

Missing E_T

- Calorimeters are also used to measure missing energy
  - only in hermetic (“4π”) detectors like ATLAS & CMS
- $E_{Tmiss} > 0$ ⇔ momentum imbalance in the transverse plane
  - e.g. due to a neutrino escaping with high transverse momentum
  - important signature for various physics processes



“Did you see it?”
“No nothing.”
“Then it was a neutrino!”