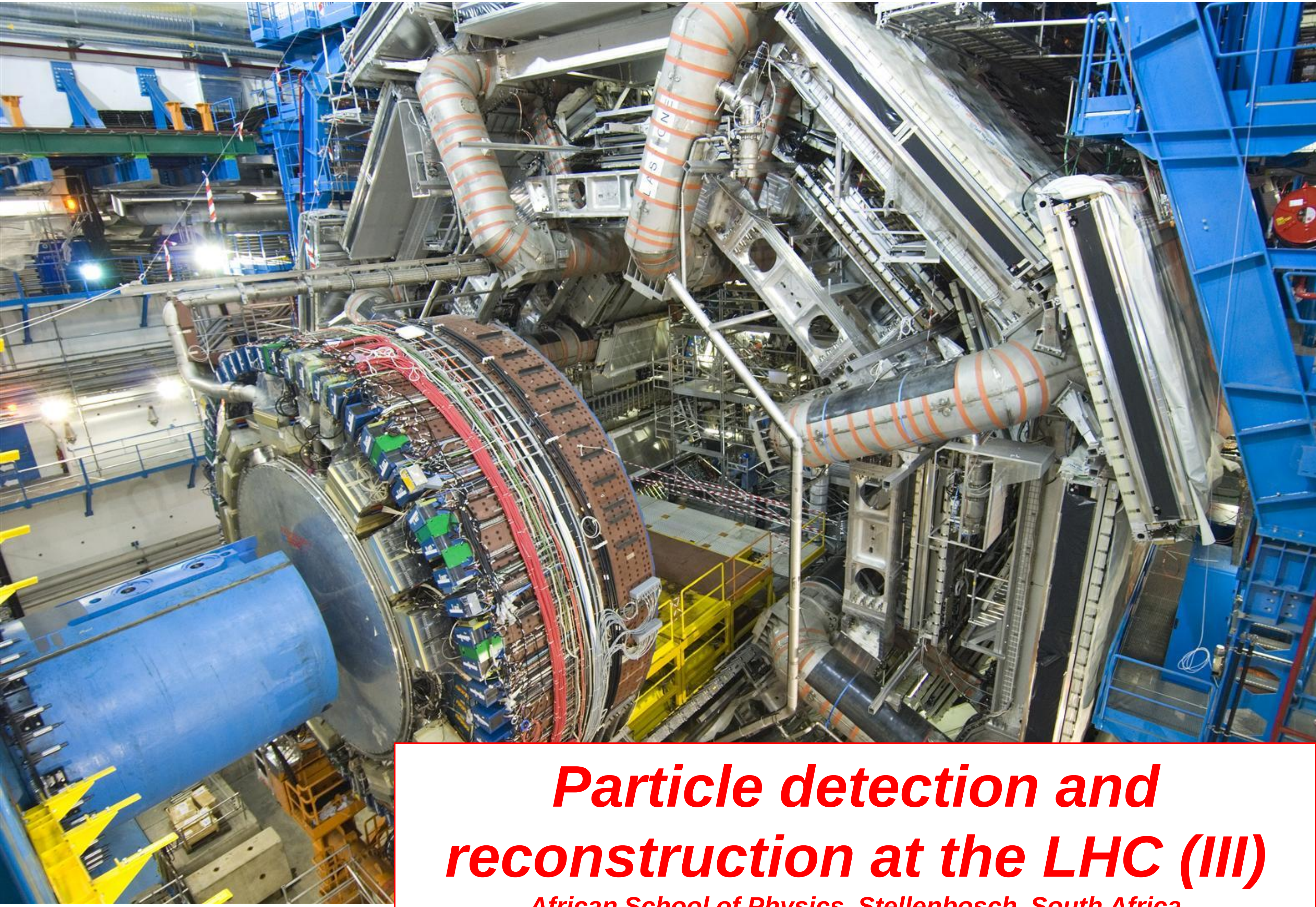


Particle detection and reconstruction at the LHC (III)

African School of Physics, Stellenbosch, South Africa
August 2010 (D. Froidevaux, CERN)

Particle detection and reconstruction at the LHC (and Tevatron)

Lecture 1

- Introduction to ATLAS/CMS experiments at the LHC
- Experimental environment and main design choices

Lecture 2

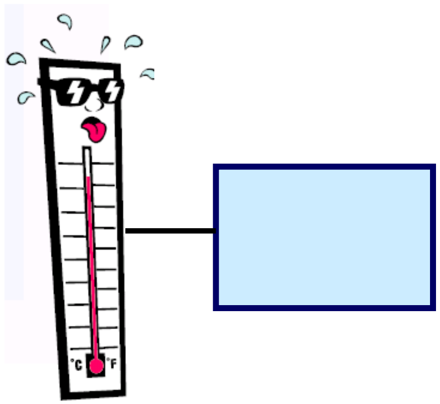
- Detector techniques: tracking

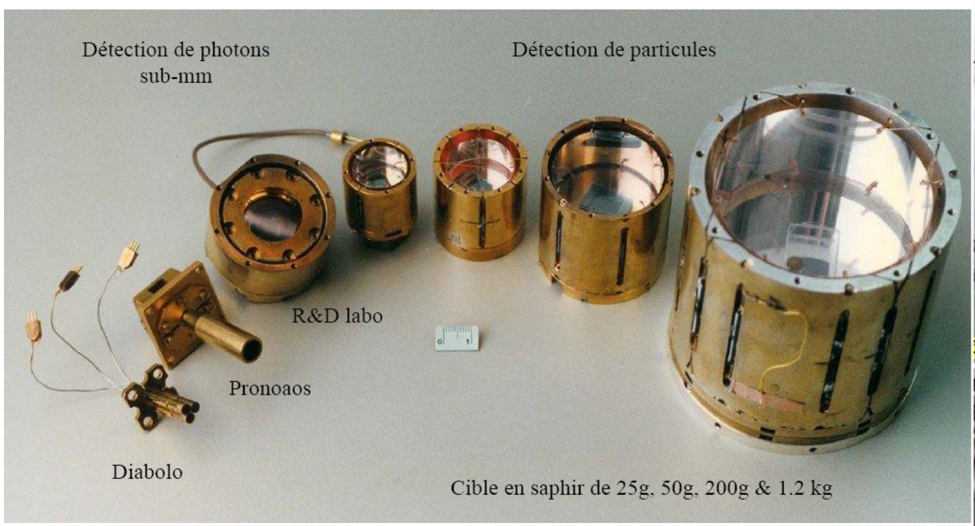
Lecture 3

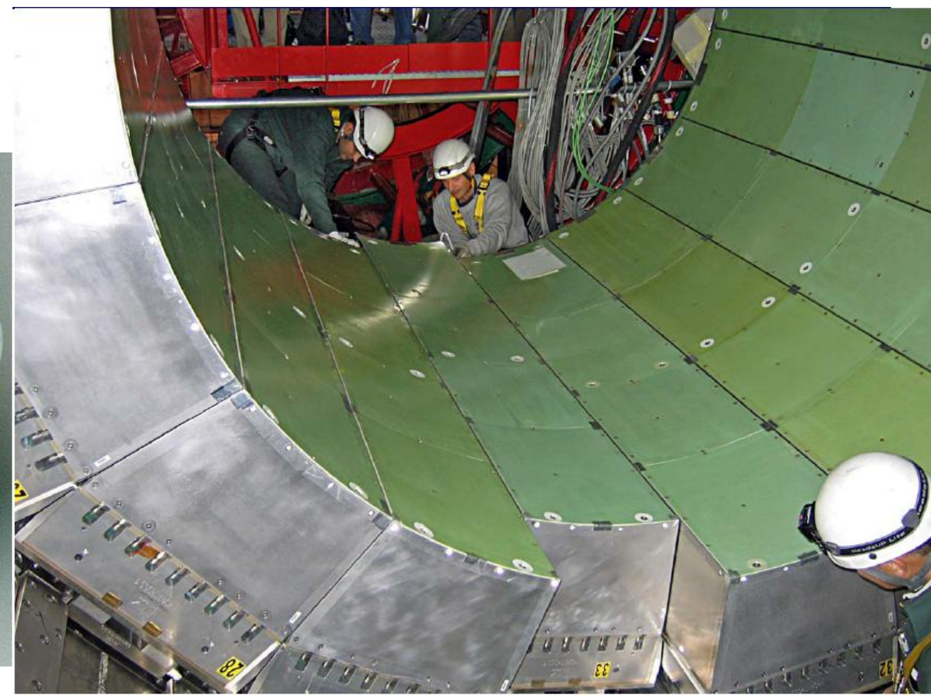
- Detector techniques: calorimetry
- Detector techniques: trigger overview

Calorimetry : not a well chosen terminology

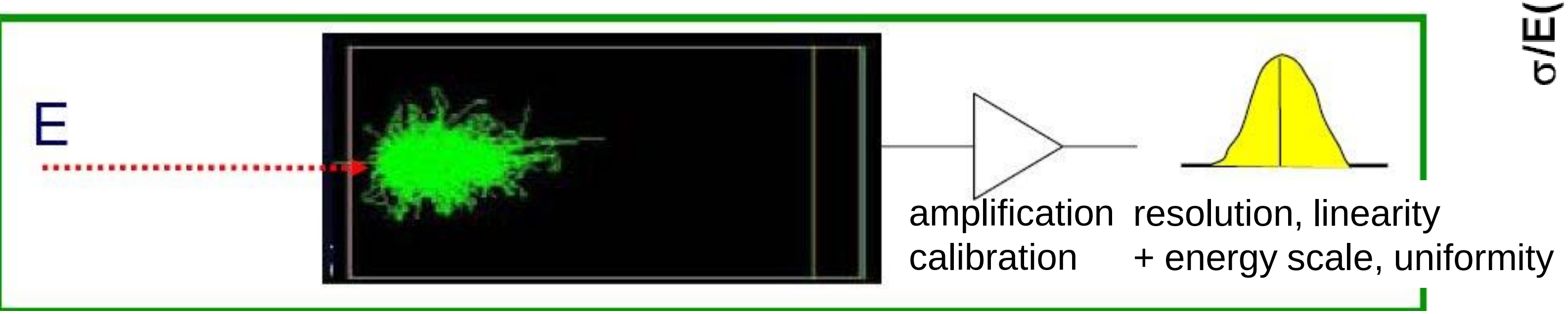
This is what we should call calorimetry !! but is called bolometry.
Small detectors but as complex as high energy detectors

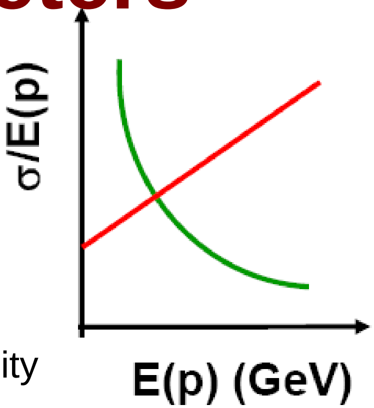






Energy measurement → calorimeters





"Destructive method" with formation of electromagnetic or hadronic showers measurement by total absorption with signal ∝ E

Calorimeters are key detectors in many experiments because:
- They measure energies of charged particles (electrons + hadrons) and neutral particles (photons, neutrons …)
- The large multiplicity of cascading particles provides a resolution ∝ $1/\sqrt{E}$ so improving with energy (as opposed to momentum measurement $\Delta p/p \propto p$)
- The depth of a calorimeter goes as ln(E) while for a spectrometer at constant resolution it goes like $\sqrt{p}$.
- Calorimeters can measure jets energy stand-alone
- They also provide position/angular measurements (for photons) and contribute to particle identification when segmented laterally and longitudinally
- They can be very fast : trigger interesting events and reject out-of-time events
- With sufficient coverage, they allow to measure the missing (transverse) energy

Electromagnetic calorimetry: radiation length

- Particles are detected through their interaction with the active detector materials
  - Energy loss by ionisation
  - Bremsstrahlung
  - Multiple scattering
  - **Radiation length**

Material thickness in detector is measured in terms of dominant energy loss reactions at high energies:

- Bremsstrahlung for electrons
- Pair production for photons

Definition:

X_0 = Length over which an electron loses all but **1/*e*** of its energy by bremsstrahlung

= 7/9 of mean free path length of photon before pair production

➡ Describe material thickness in units of X_0

Material	X_0 [cm]
Be	35.3
Carbon-fibre	~ 25
Si	9.4
Fe	1.8
$PbWO_4$	0.9
Pb	0.6

Pb: ATLAS LAr absorber

$PbWO_4$: CMS ECAL crystals

Electromagnetic calorimetry: radiation length

6. ATOMIC AND NUCLEAR PROPERTIES OF MATERIALS

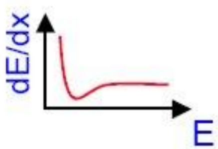
Table 6.1. Revised May 2002 by D.E. Groom (LBNL). Gases are evaluated at 20°C and 1 atm (in parentheses) or at STP [square brackets]. Densities and refractive indices without parentheses or brackets are for solids or liquids, or are for cryogenic liquids at the indicated boiling point (BP) at 1 atm. Refractive indices are evaluated at the sodium D line. Data for compounds and mixtures are from Refs. 1 and 2. Futher materials and properties are given in Ref. 3 and at `http://pdg.lbl.gov/AtomicNuclearProperties`.

Material	Z	A	$\langle Z/A \rangle$	Nuclear [a] collision length λ_T {g/cm^2}	Nuclear [a] interaction length λ_I {g/cm^2}	$dE/dx\vert_{min}$ [b] $\left\{\frac{\text{MeV}}{\text{g/cm}^2}\right\}$	Radiation length [c] X_0 {g/cm^2}	Radiation length X_0 {cm}	Density {g/cm^3} ({g/ℓ} for gas)	Liquid boiling point at 1 atm(K)	Refractive index n ($(n-1)\times10^6$ for gas)
H_2 gas	1	1.00794	0.99212	43.3	50.8	(4.103)	61.28 [d]	(731000)	(0.0838)[0.0899]		[139.2]
H_2 liquid	1	1.00794	0.99212	43.3	50.8	4.034	61.28 [d]	866	0.0708	20.39	1.112
D_2	1	2.0140	0.49652	45.7	54.7	(2.052)	122.4	724	0.169[0.179]	23.65	1.128 [138]
He	2	4.002602	0.49968	49.9	65.1	(1.937)	94.32	756	0.1249[0.1786]	4.224	1.024 [34.9]
Li	3	6.941	0.43221	54.6	73.4	1.639	82.76	155	0.534		—
Be	4	9.012182	0.44384	55.8	75.2	1.594	65.19	35.28	1.848		—
C	6	12.011	0.49954	60.2	86.3	1.745	42.70	18.8	2.265 [e]		—
N_2	7	14.00674	0.49976	61.4	87.8	(1.825)	37.99	47.1	0.8073[1.250]	77.36	1.205 [298]
O_2	8	15.9994	0.50002	63.2	91.0	(1.801)	34.24	30.0	1.141[1.428]	90.18	1.22 [296]
F_2	9	18.9984032	0.47372	65.5	95.3	(1.675)	32.93	21.85	1.507[1.696]	85.24	[195]
Ne	10	20.1797	0.49555	66.1	96.6	(1.724)	28.94	24.0	1.204[0.9005]	27.09	1.092 [67.1]
Al	13	26.981539	0.48181	70.6	106.4	1.615	24.01	8.9	2.70		—
Si	14	28.0855	0.49848	70.6	106.0	1.664	21.82	9.36	2.33		3.95
Ar	18	39.948	0.45059	76.4	117.2	(1.519)	19.55	14.0	1.396[1.782]	87.28	1.233 [283]
Ti	22	47.867	0.45948	79.9	124.9	1.476	16.17	3.56	4.54		—
Fe	26	55.845	0.46556	82.8	131.9	1.451	13.84	1.76	7.87		—
Cu	29	63.546	0.45636	85.6	134.9	1.403	12.86	1.43	8.96		—
Ge	32	72.61	0.44071	88.3	140.5	1.371	12.25	2.30	5.323		—
Sn	50	118.710	0.42120	100.2	163	1.264	8.82	1.21	7.31		—
Xe	54	131.29	0.41130	102.8	169	(1.255)	8.48	2.87	2.953[5.858]	165.1	[701]
W	74	183.84	0.40250	110.3	185	1.145	6.76	0.35	19.3		—
Pt	78	195.08	0.39984	113.3	189.7	1.129	6.54	0.305	21.45		—
Pb	82	207.2	0.39575	116.2	194	1.123	6.37	0.56	11.35		—
U	92	238.0289	0.38651	117.0	199	1.082	6.00	≈0.32	≈18.95		—

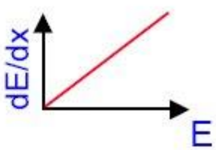
Electromagnetic showers

e^+ / e^-

- Ionisation

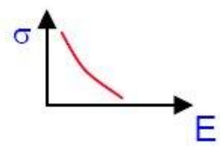


- Bremsstrahlung

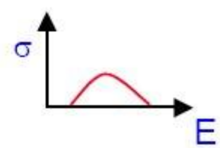


γ

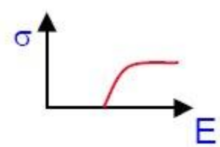
- Photoelectric effect

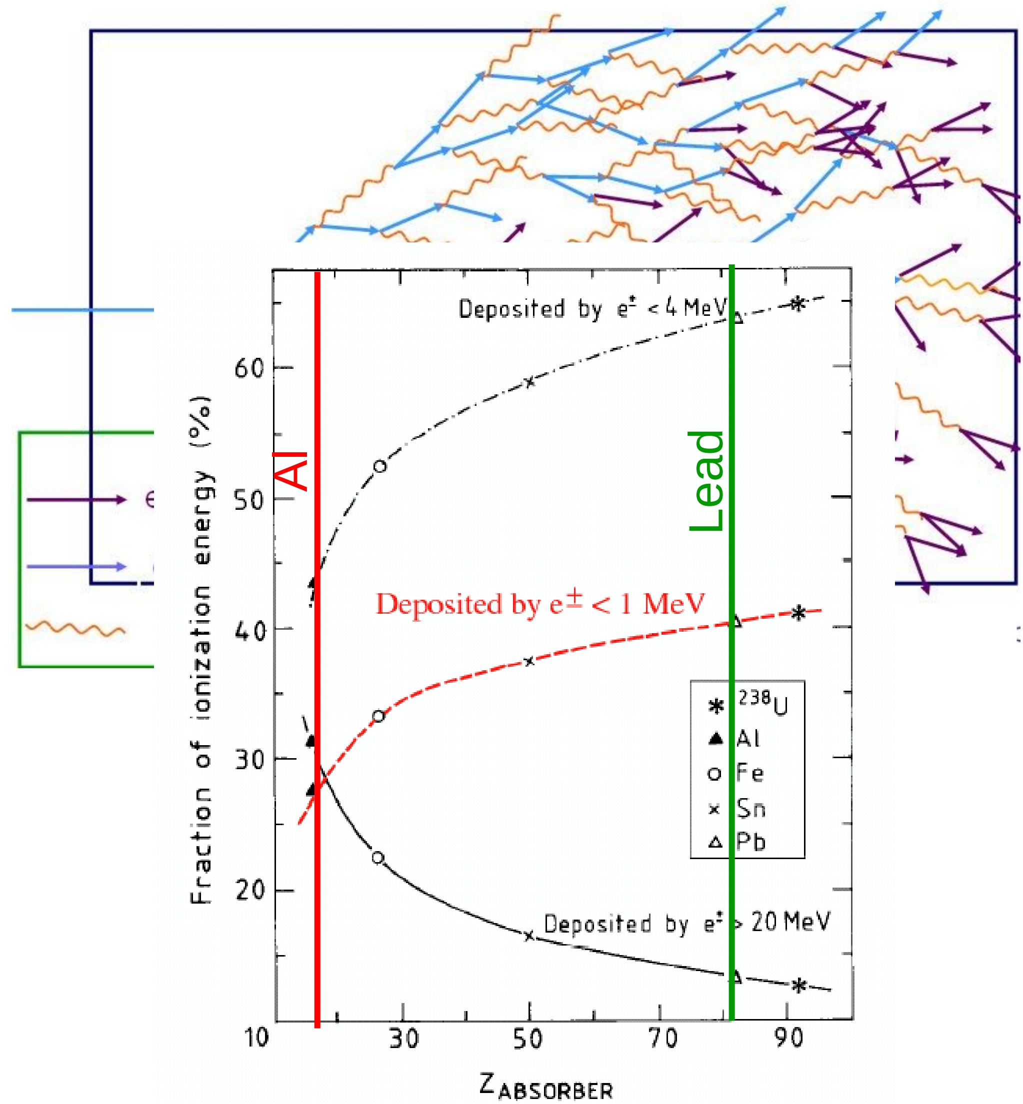


- Compton effect



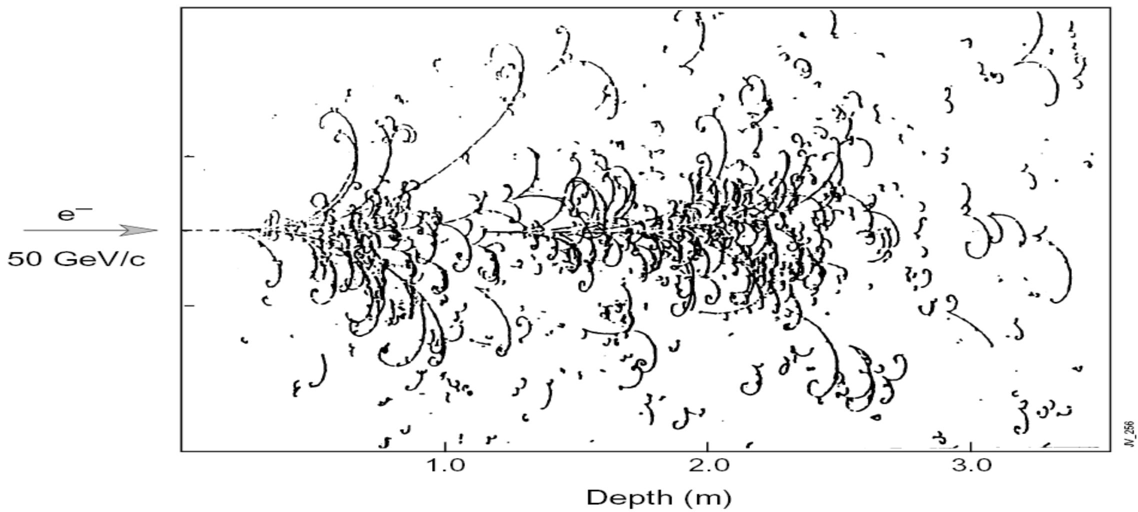
- Pair production



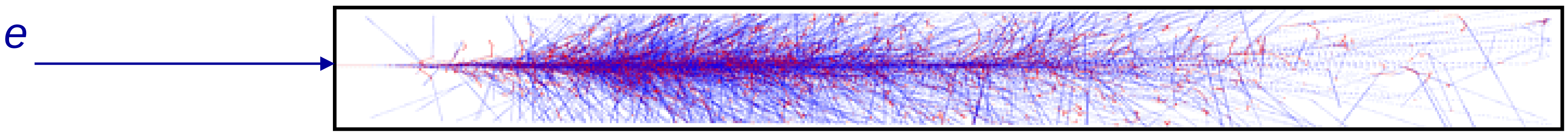


Electromagnetic showers

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



$PbW0_4$ CMS, X_0=0.89 cm



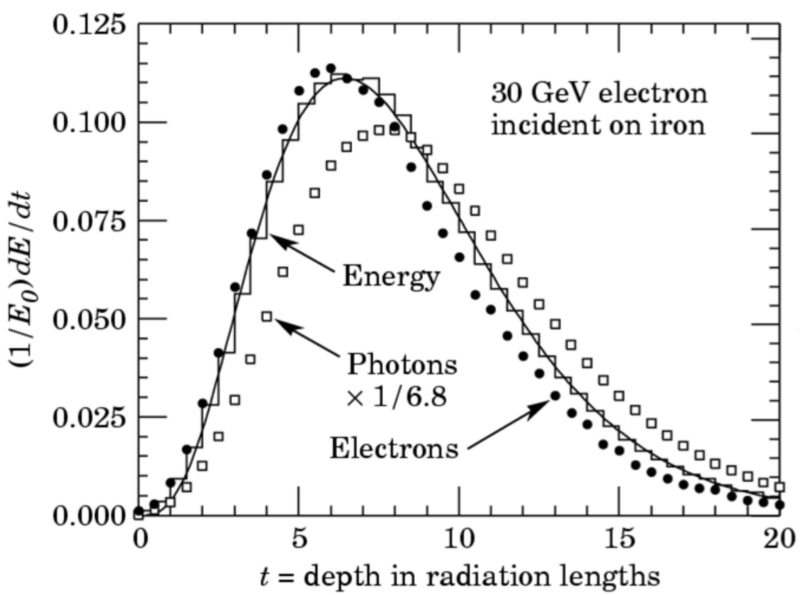
Electromagnetic Cascades

- A high-energy electron or photon incident on absorber initiates EM cascade
  - Bremsstrahlung and pair production generate lower energy electrons and photons
  - Shower profile strongly depends on the absorber's X_0

Longitudinal shower profile

Governed by high-energy part of cascade

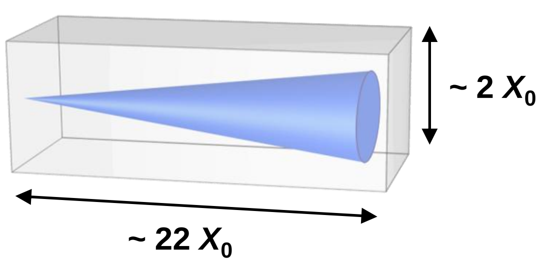
[for $E<E_c$ cascade exhausts by ionisation, Compton, …]



Transverse shower profile

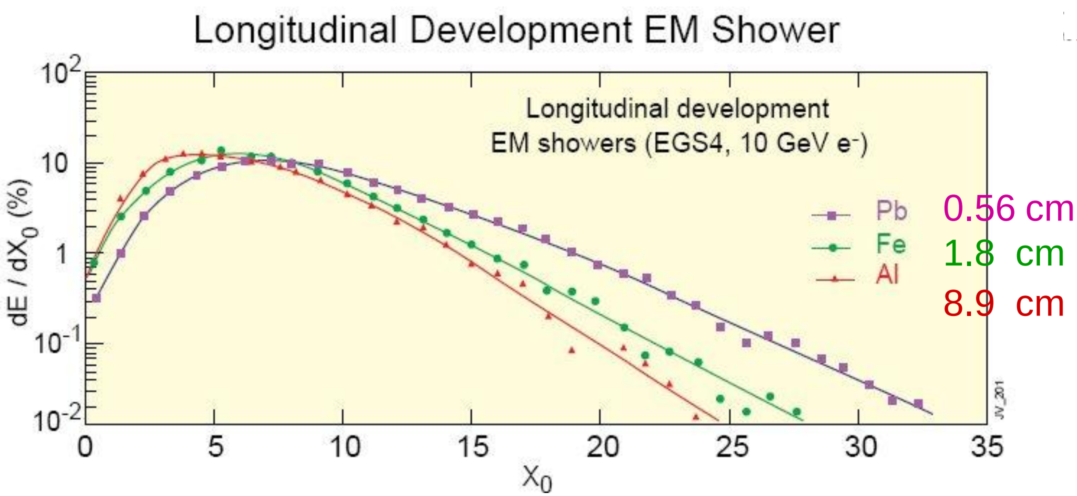
Width given by *Molière radius :*

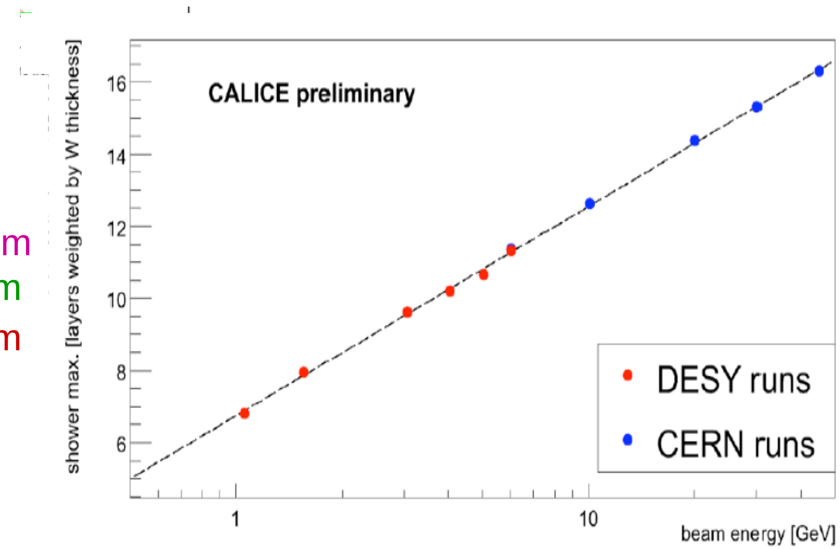
$$R_M = \frac{21\,\text{MeV}}{E_c} X_0, \quad E_c \approx \frac{600}{Z+1.2} \approx 7_{\text{Pb}}$$



- Calorimeters aim at large X/X_0 (20 – 30)
- And prefer transparent material in front
- Presampler corrects E for early showers

Longitudinal profiles





- multiplication of electrons up to max shower depth where majority reach E_c
- Exponential fall off of the shower after maximum given by photon attenuation
- Quasi universal behavior wrt X_0 but :

- Shower maximum deeper at high Z
- Slower decay at high Z as lower energy photon

→ Critical energy $\propto$ 1/Z

$$X_{max} = X_0 \ln(E/E_c + a)$$

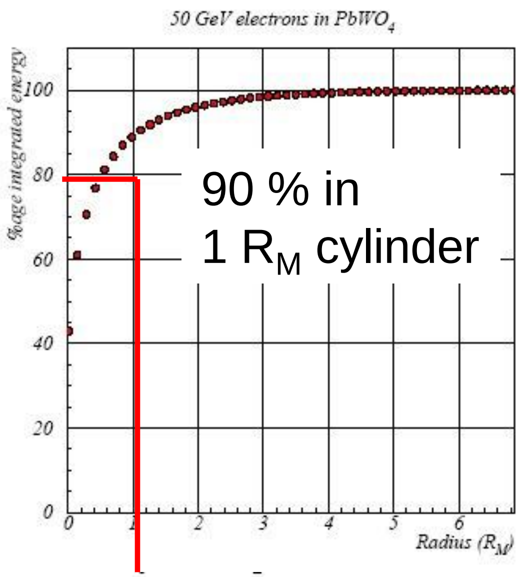
with $a = -0.5$ for $e^{\pm}$ and $+0.5$ for γ

Comes from $9/7 X_0$ length for pair conversion of photons

Lateral profiles

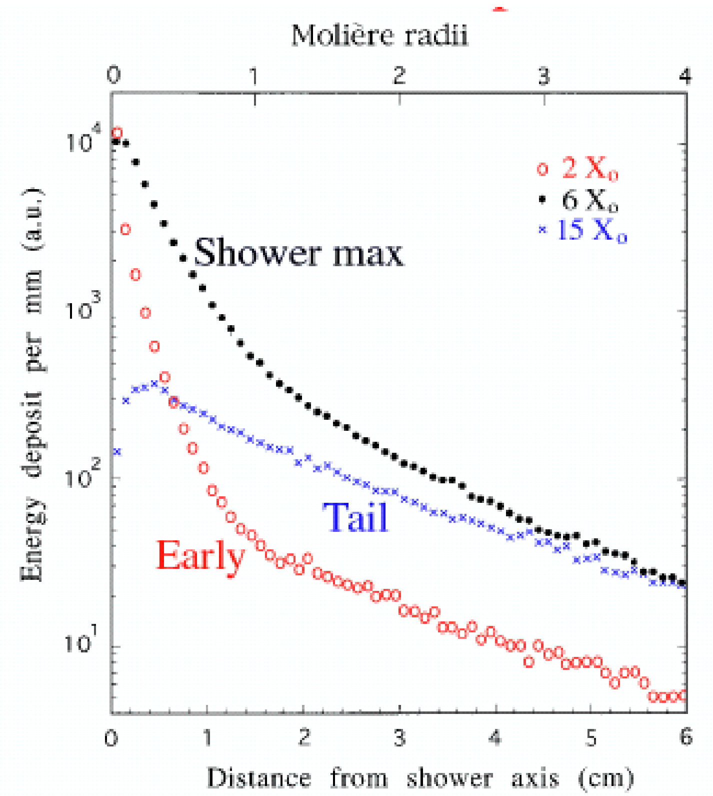
Lateral profile given by multiple scattering of electron + low energy photons which travel far away for shower axis

Moliere Radius (R_M): average lateral deflection of electron with E_c after 1 X_0



90 % in
1 R_M cylinder

$$R_M = \frac{21_{MeV} X_0}{\varepsilon} \approx \frac{7A}{Z} \quad g.cm^{-2}$$

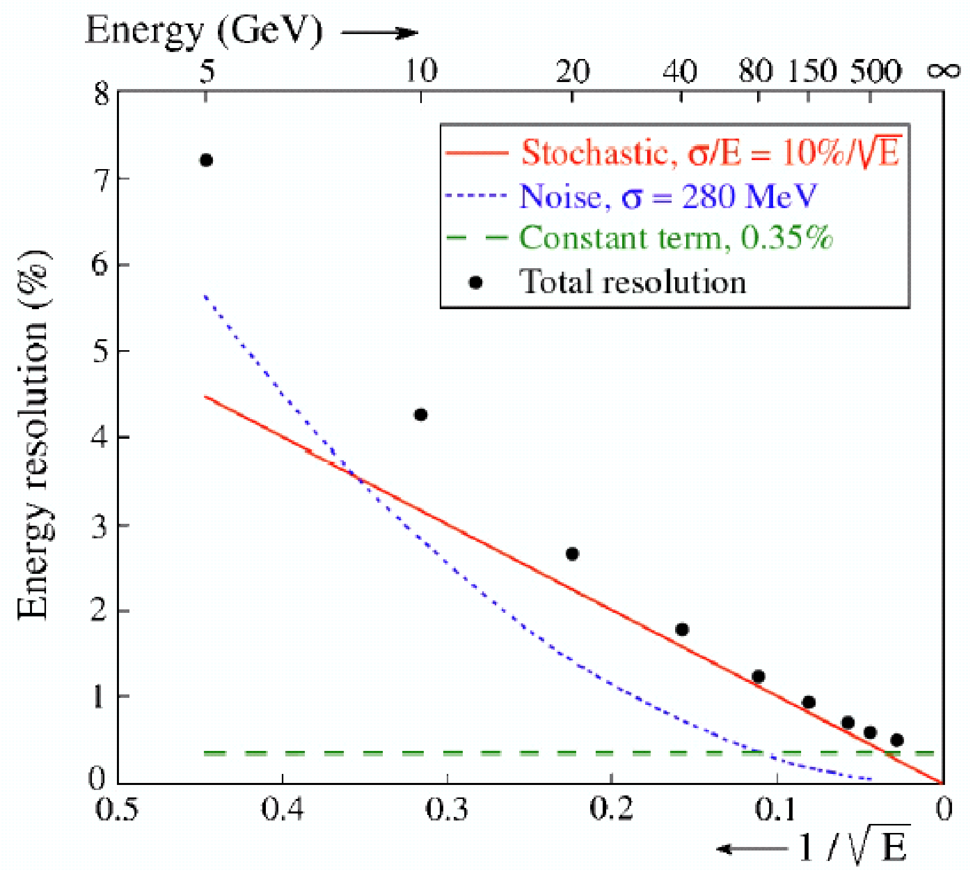


Important parameter for shower separation

Calorimeter energy resolution

Usually parametrised by
(stands also for hadron calorimeter) :

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



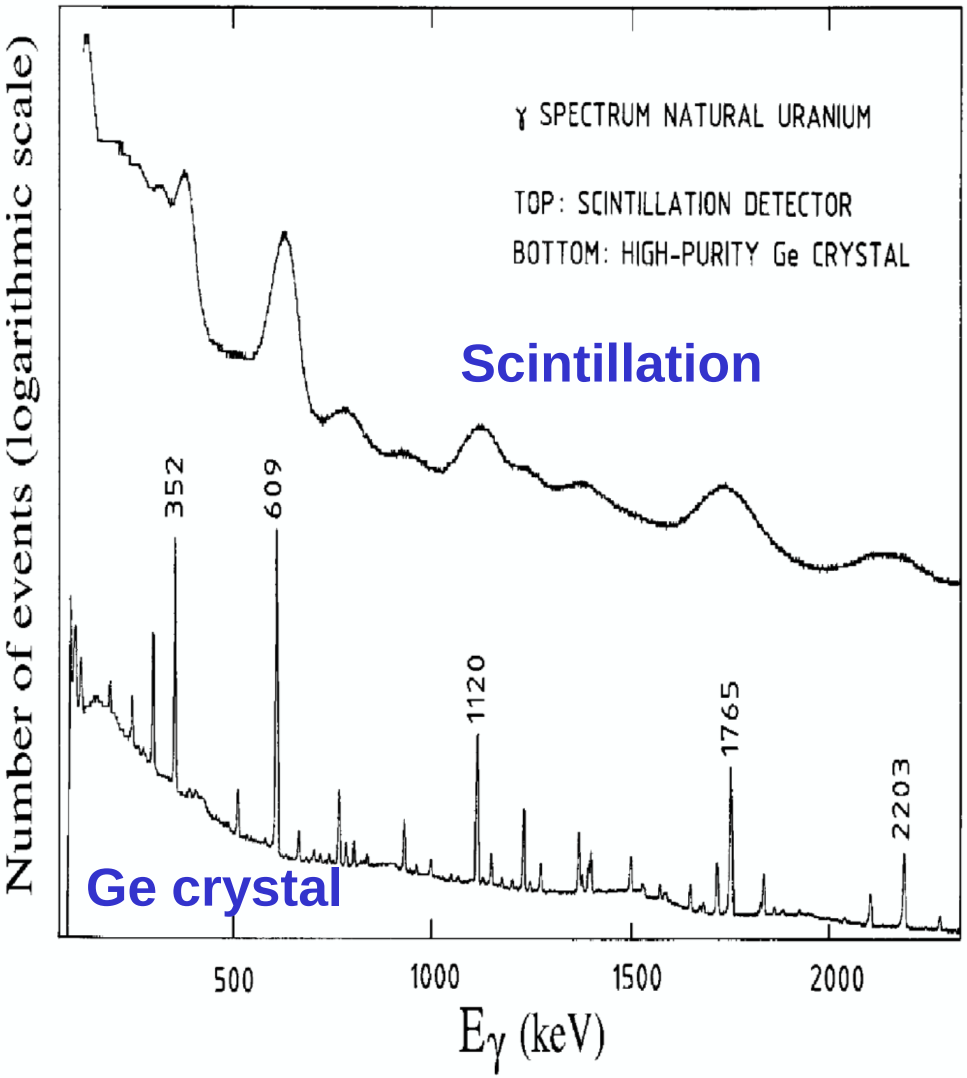
a : intrinsic resolution or stochastic term
→ given by technology choice

c : contribution of electronics noise
+ at LHC pile up noise…
→ given by electronics design

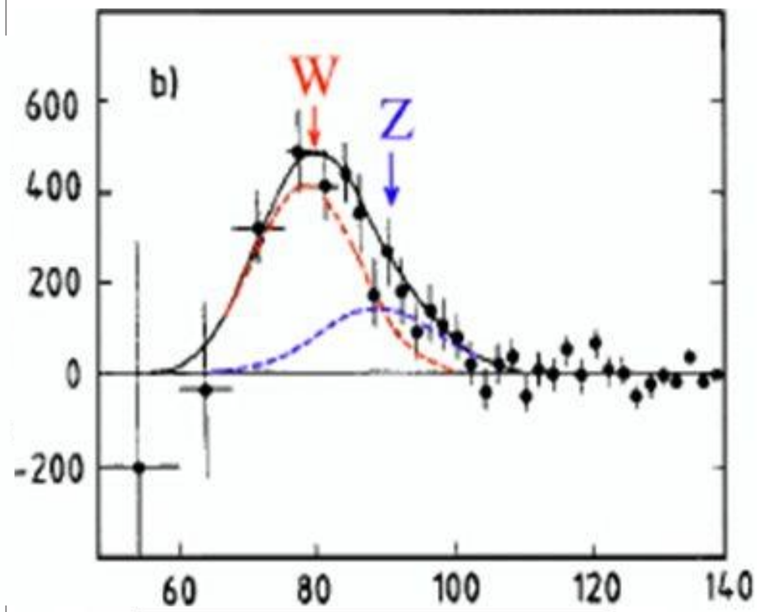
b : constant term, it contains all the imperfection
response variation versus position (uniformity), time (stability), temperature….
→ Constraints on all aspects : mechanics, electronics….

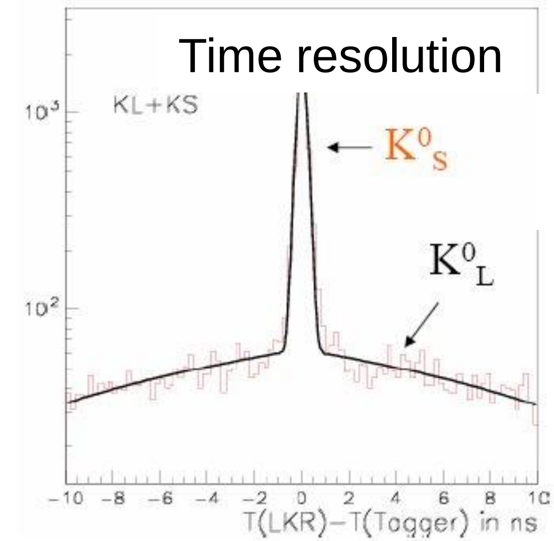
Calorimeter energy resolution

EM calorimeters



Hadron calorimeters





NA48
220 ps !

Calorimeter energy resolution

Simplified model :
Number of produced ions/e $^-$ pairs (or photon) N=E/w
Detectable signal (→E) is $\propto$ N (N being quite large)

$$\frac{\sigma}{E} = \frac{\sigma_N}{N} = \frac{1}{\sqrt{N}} \approx \frac{a}{\sqrt{E}}$$

Rem :

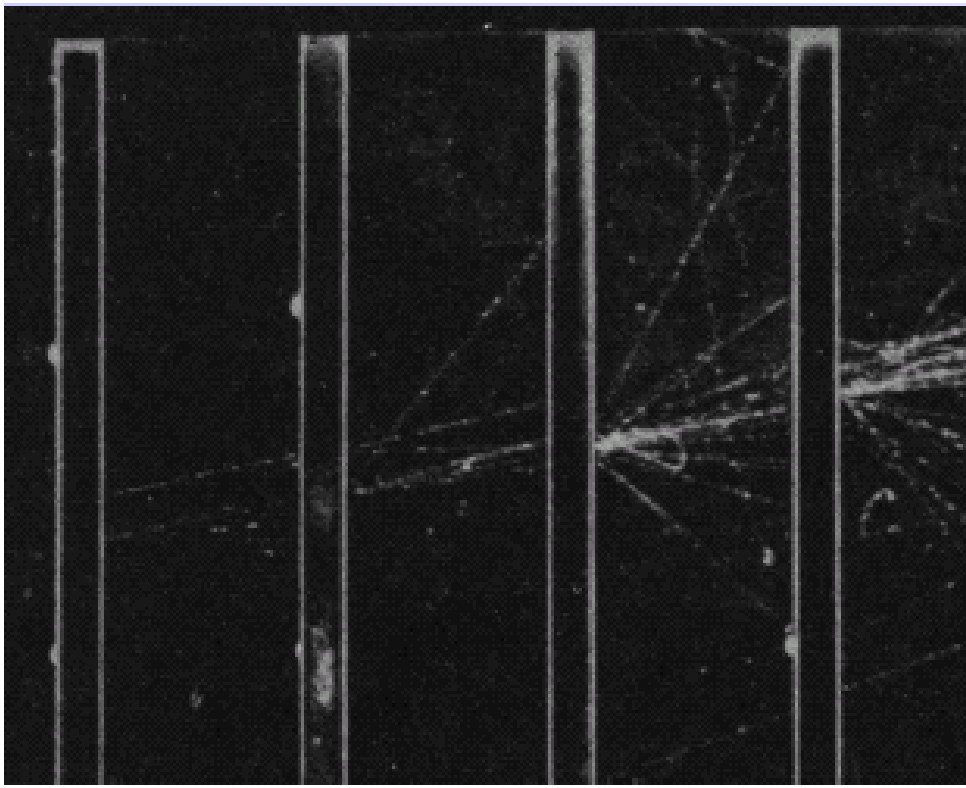
1) In homogeneous calorimeters where all the energy is detected, resolution better than 1/√N by a factor √F because total energy does not fluctuate.
   (F : fano factor)
   Ge : 100 keV, w=2.96 eV → 475 eV while measured 180 eV F=0.13

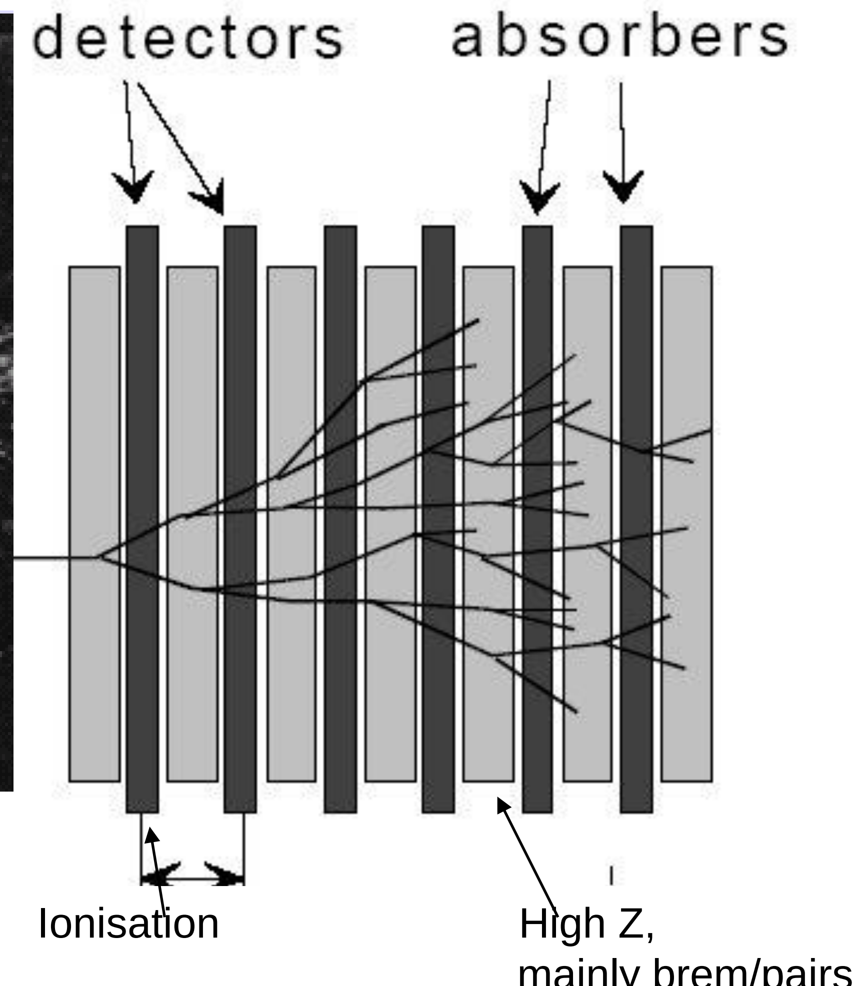
2) Most of the time not all the released energy is measured (ionization or light, or dead material), only a fraction f_s measured (lateral/long loss…)

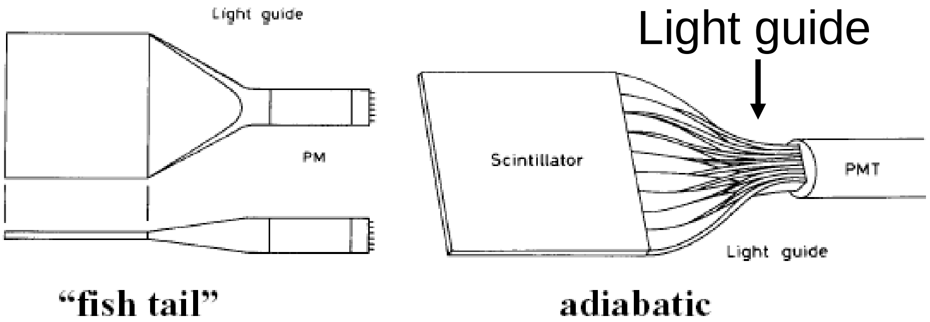
$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \frac{1}{\sqrt{f_s}}$$

Intrinsic resolution can go from 1-3 % for crystal or homogeneous noble liquids to 8-12% for sampling calorimeters

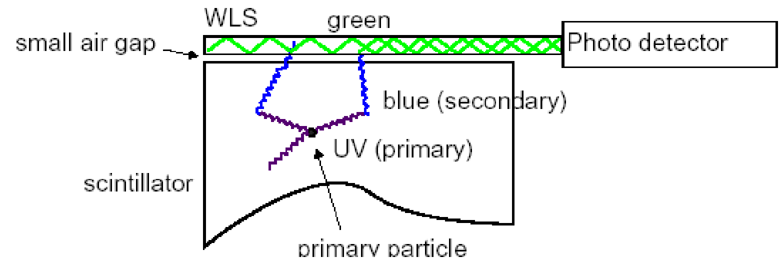
Use a different medium to generate the shower and to detect signal : Only a fraction of signal measured (f_S) → larger stochastic term



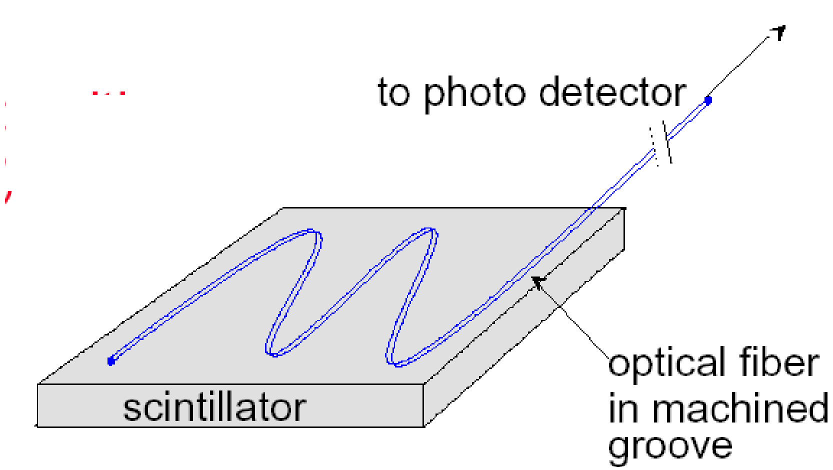


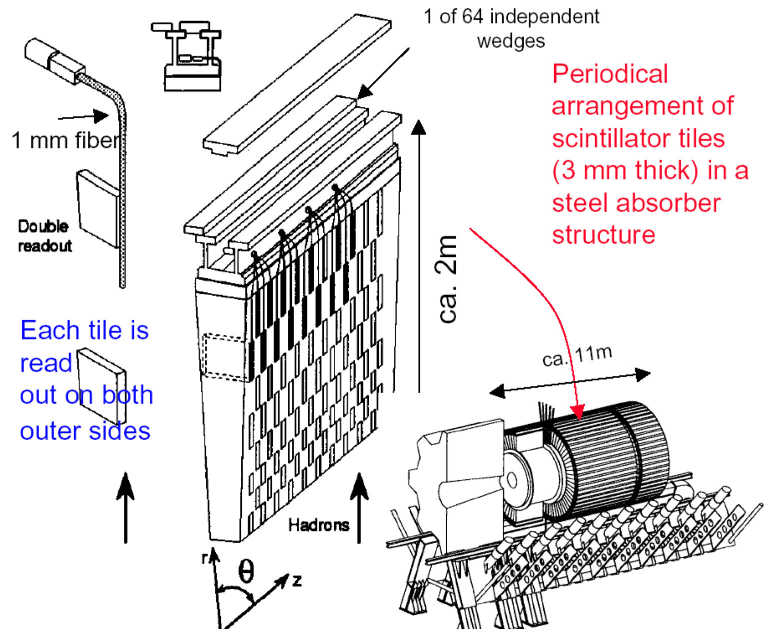


Shift wave length in a material where one can get total reflection



ATLAS hadron calorimeter Fe/scintillators

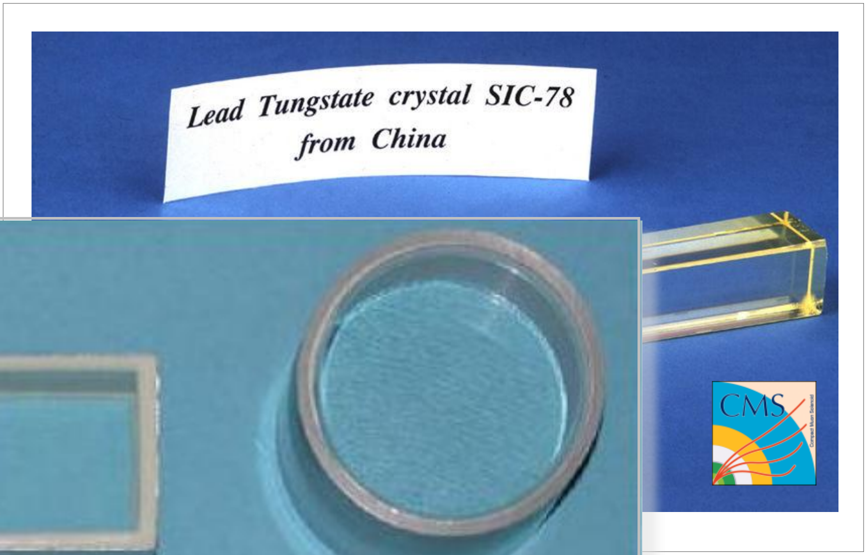


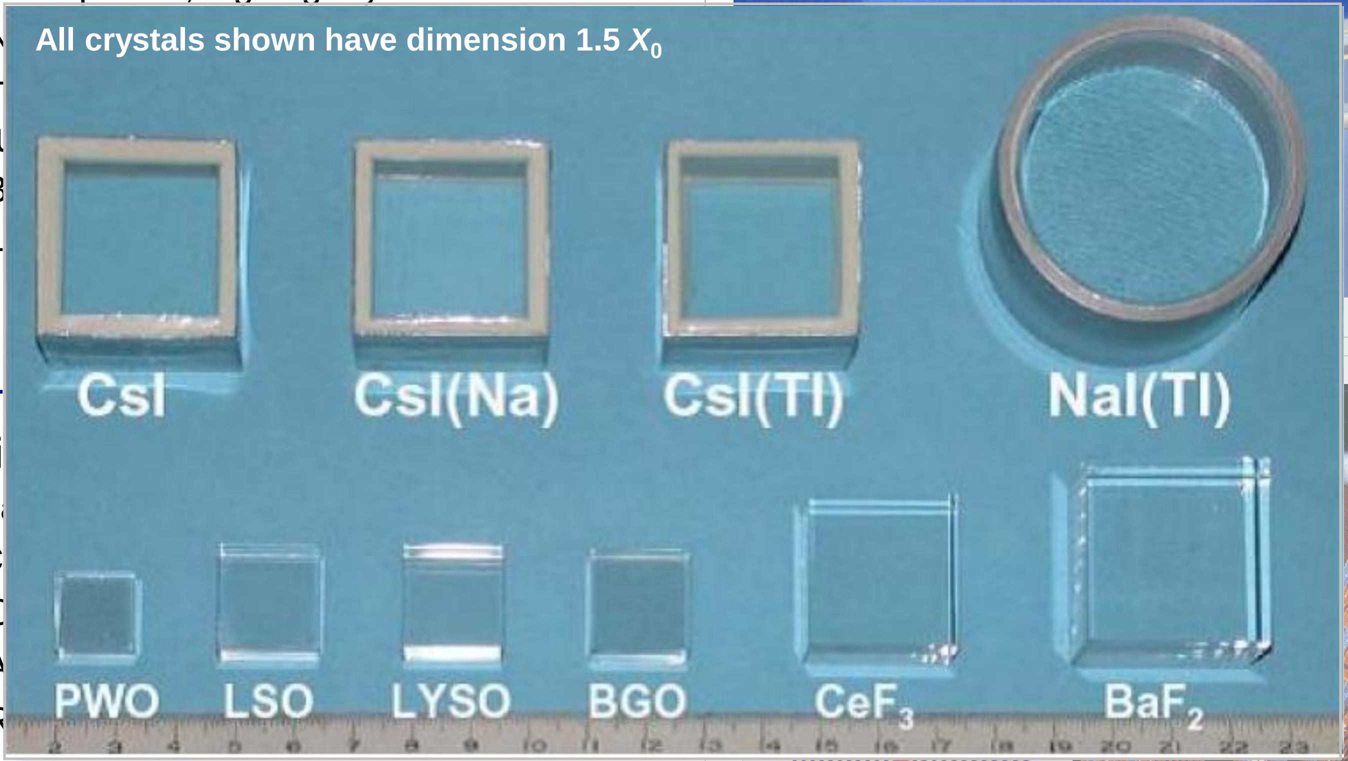


Under irradiation, transmission of scintillators decreases → loss of signal !

ATLAS and CMS EM Calorimeters

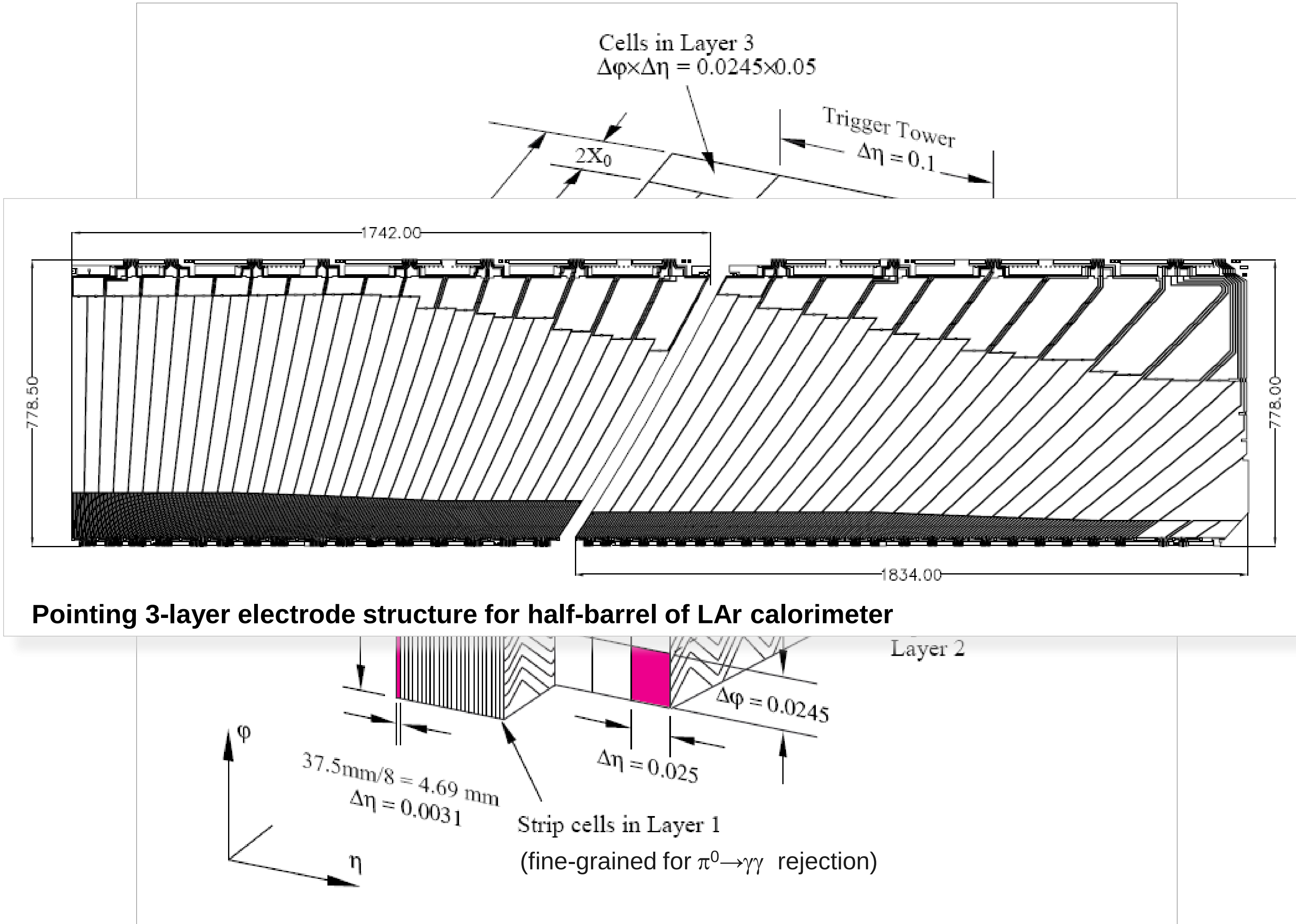
- CMS: $PbWO_4$ Scint. Crystal Calorimeter
  - Entire shower in active detector material
    - High density crystals (28 X_0)
    - Transparent, high light yield
    - N
    - H
  - Granu
    - B
    - L





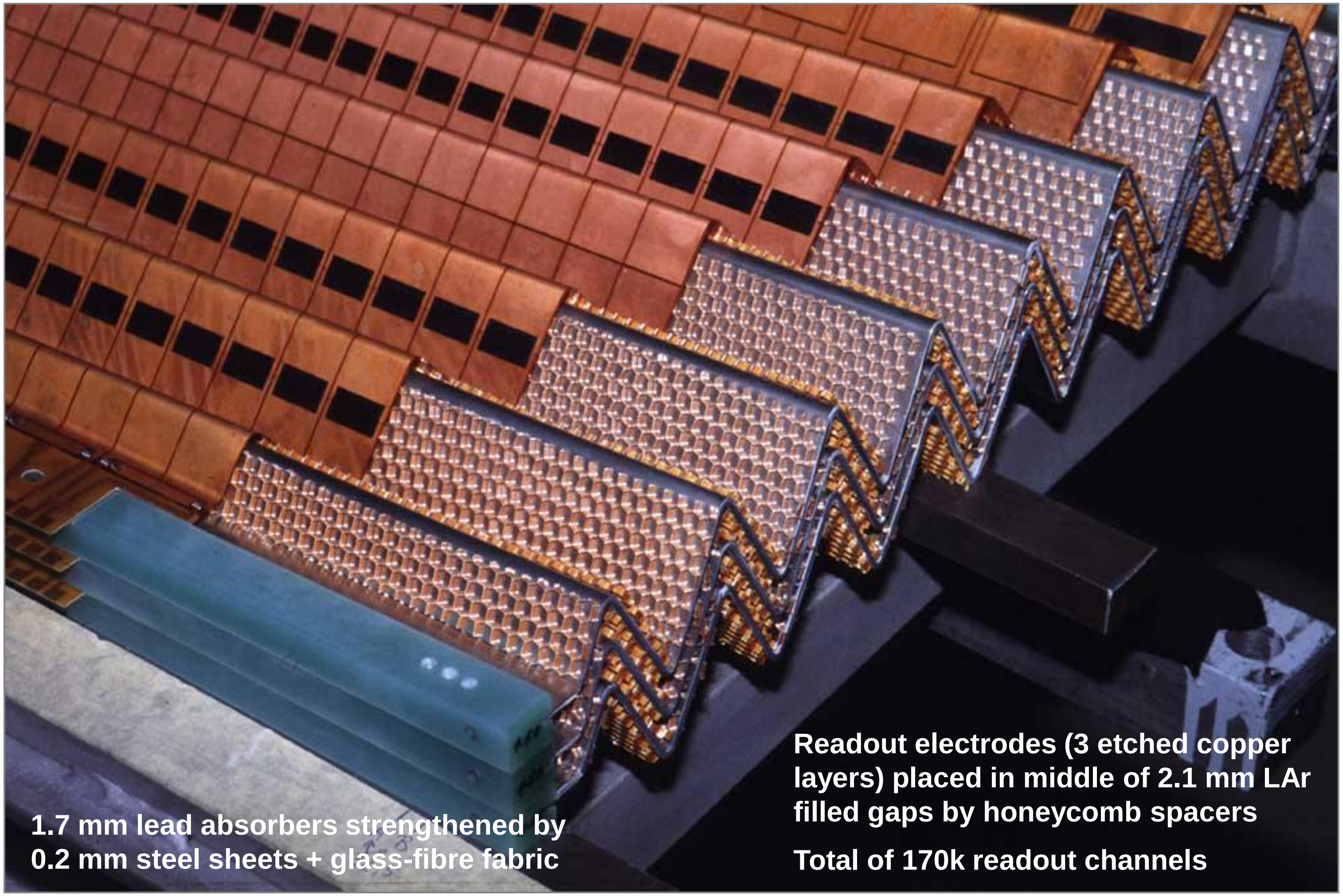
- ATLAS: L
  - Passi
    thick [b
    detec
    - C
    - A
    - R
  - Granularity
    - Barrel: $\Delta\eta \times \Delta\phi = 0.025^2$ rad (main layer)
    - Longitudinal segmentation (3 layers)

ATLAS Liquid Argon EM Calorimeter



Pointing 3-layer electrode structure for half-barrel of LAr calorimeter

ATLAS Liquid Argon EM Calorimeter



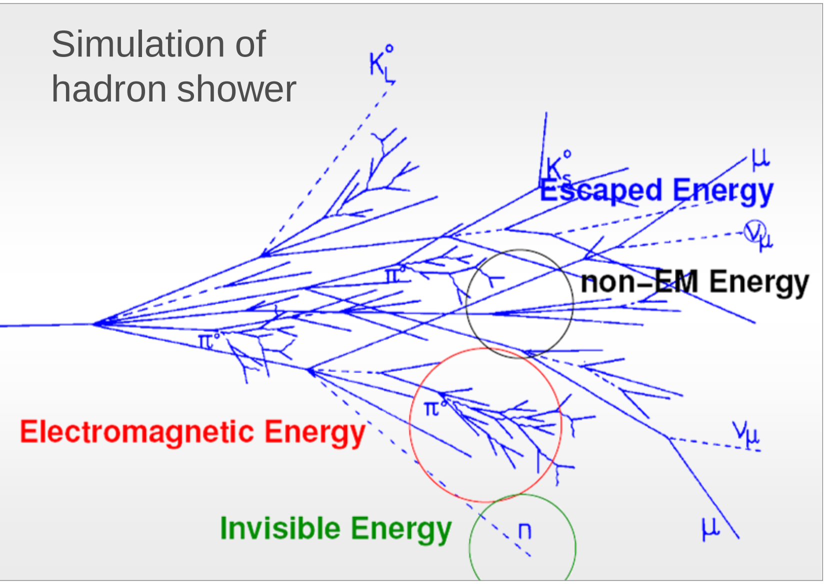
Hadronic Showers

- Nuclear interaction length λ: *mean free path of hadrons between strong collisions*

Material	λ [cm]
Si	45.5
Fe	16.8
Pb	17.1

Interactions with nuclei lead to hadronic (HAD) showers

- Since $\lambda > X[X_0]$ one can separate EM (close) from HAD (far) showers



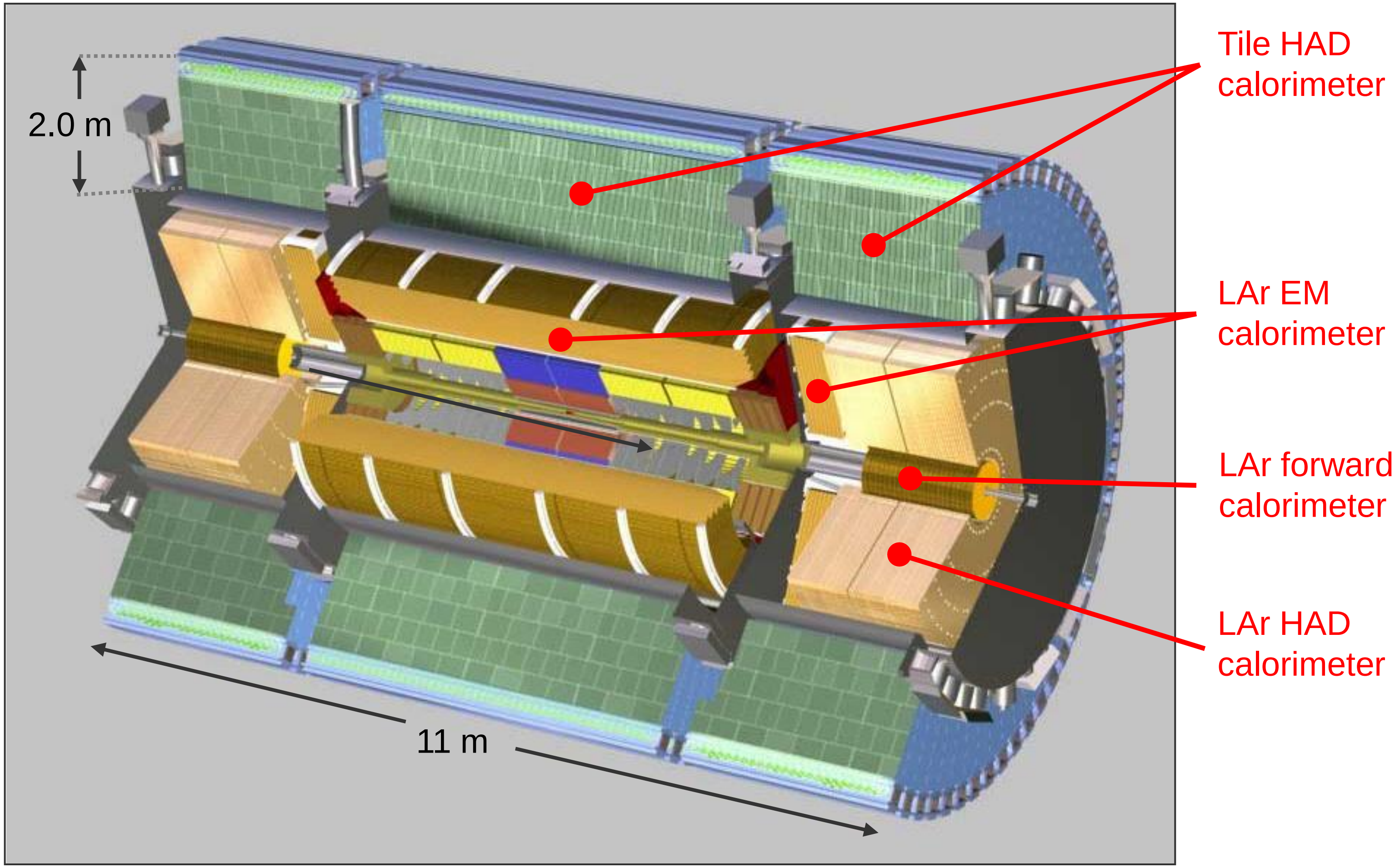
A hadronic shower consists of:

- EM energy (e.g., $\pi^0 \to \gamma\gamma$) O(50%)
- Non-EM energy (*e.g.*, dE/dx from $\pi^\pm$,$\mu^\pm$,$K^\pm$) O(25%)
- Invisible energy
  (nuclear fission/excitation, neutrons) O(25%)
- Escaped energy (*e.g.* neutrinos) O(2%)

Invisible energy is the main source of worse energy resolution for hadronic showers

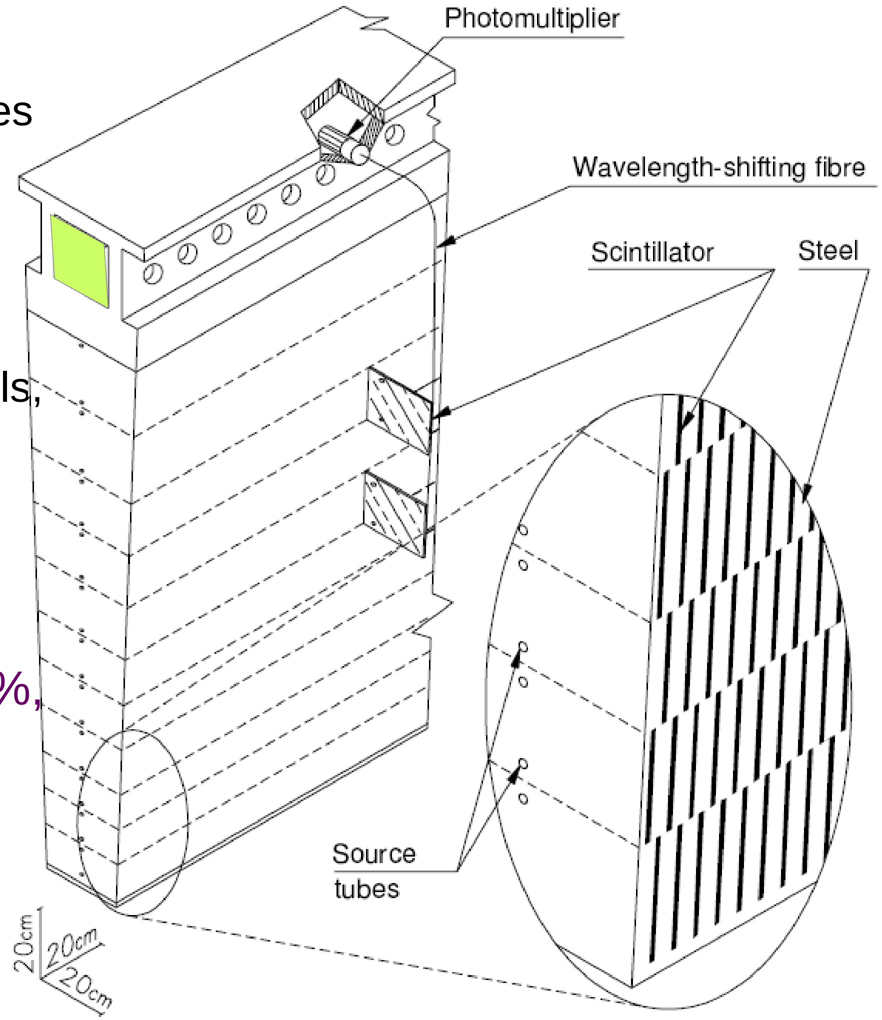
Hadronic Calorimeters

- EM calorimeter absorbs EM showers but only parts of showers initiated by hadrons
  - Following calorimeter layers (usually sampling calorimeters) fully absorb HAD showers



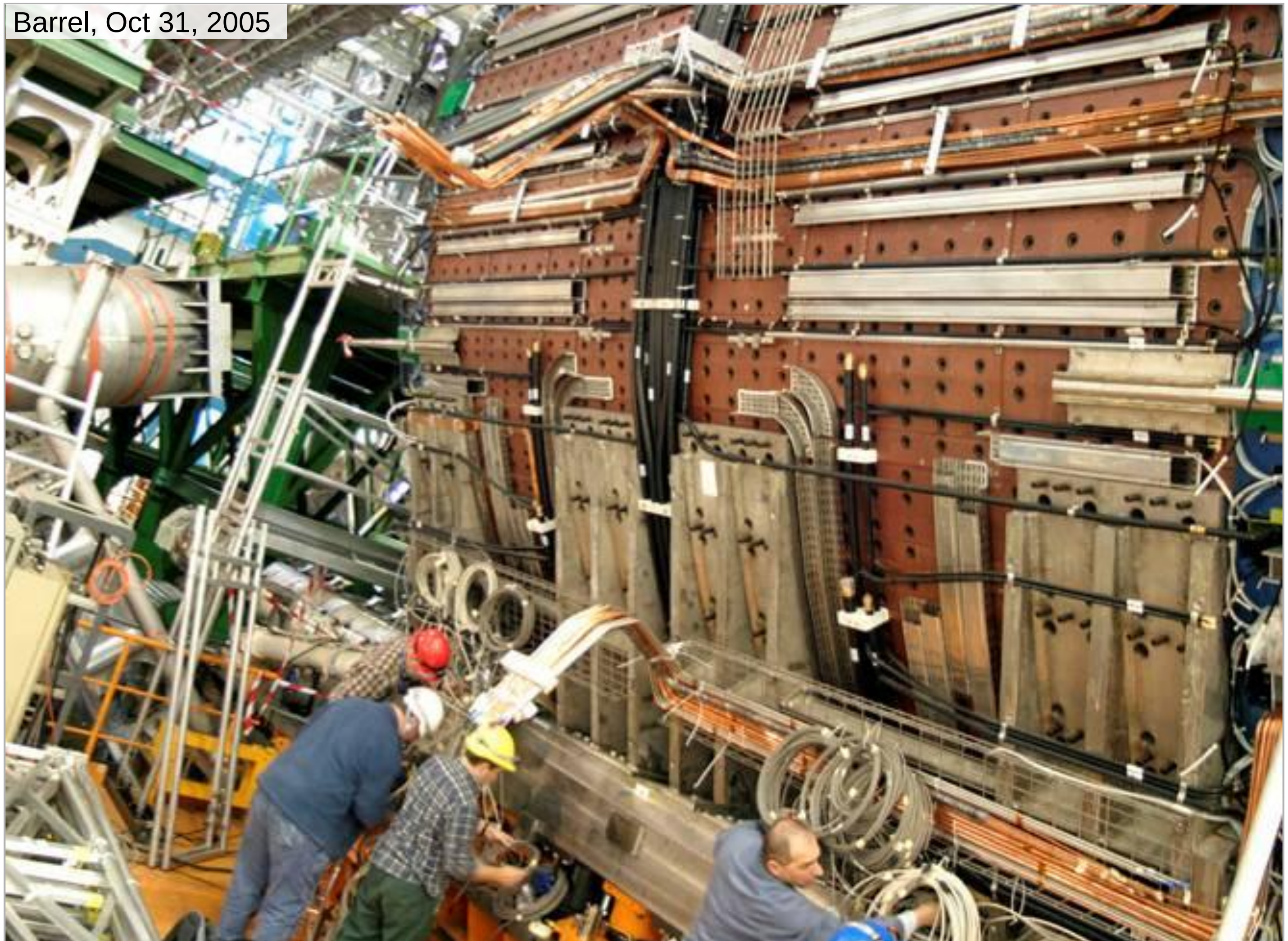
The ATLAS Tile Hadronic Calorimeter

- Three Tile layers (9.7 λ, CMS 7.2 λ at $|\eta| = 0$) cover extended barrel region ($|\eta| < 1.7$)
  - Alternating samplings of iron absorber plates (14 mm) and scintillating tiles (3 mm)
  - Tile edges read out by optical fibers transporting light to 2 photomultipliers
  - Projective PMT grouping with ~10k channels, granularity $\Delta\eta \times \Delta\phi = 0.1^2$ rad

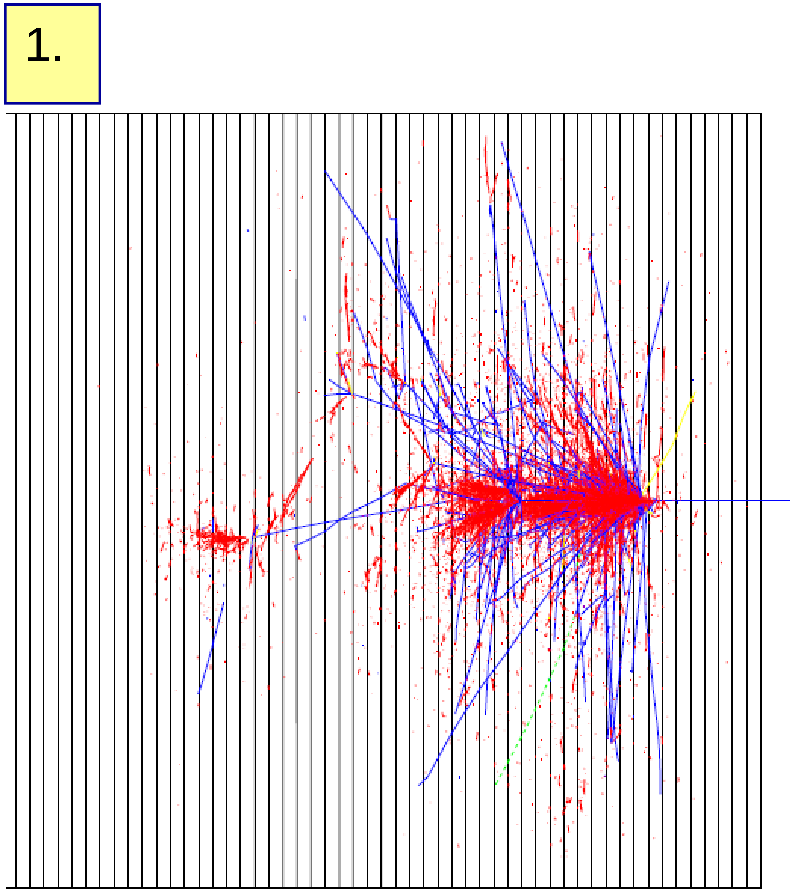


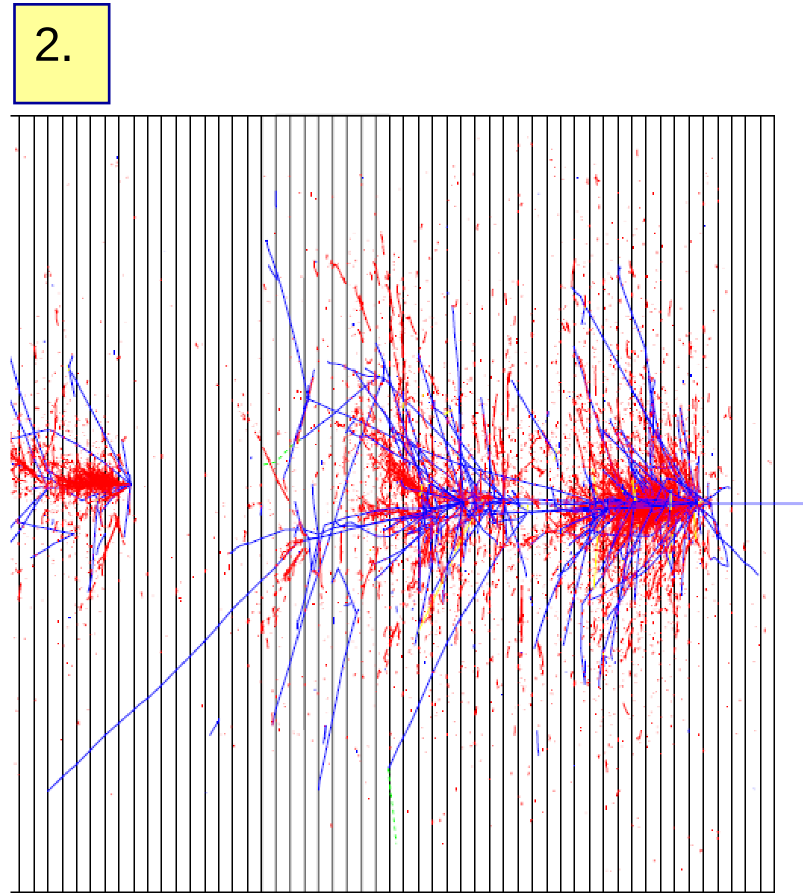
- Resolution (EM & HAD calorimeters)
  At high E_T, ~60 % of jet energy released in EM calo
  - Hadrons (test beam): stochastic: ~52 %, constant: ~3 %, noise: ~0.5 GeV
  - Jets (central, MC): stochastic: ~60 %, constant: ~3 %, noise: ~0.5 GeV
  - Missing transverse energy: $\sigma(E_T^{miss}) \approx 0.5 \sqrt{\Sigma E_T}$

The ATLAS Tile Hadronic Calorimeter



Two hadronic showers in a sampling calorimeter





Red: electromagnetic component
Blue: charged hadron component

Very large fluctuations from one event to another
→ energy resolution worse than for electromagnetic showers

ATLAS/CMS: from design to reality

One word about neutrinos in hadron colliders:

✓ since most of the energy of the colliding protons escapes down the beam pipe, one can only use

the energy-momentum balance in the transverse plane

→ concepts such as E_T^{miss}, missing transverse momentum and mass are often used (only missing component is E_z^{miss})

→ reconstruct "fully" certain topologies with neutrinos, e.g. $W \to l\nu$ and even better $H \to \tau\tau \to l\nu_l\nu_\tau\ h\nu_\tau$

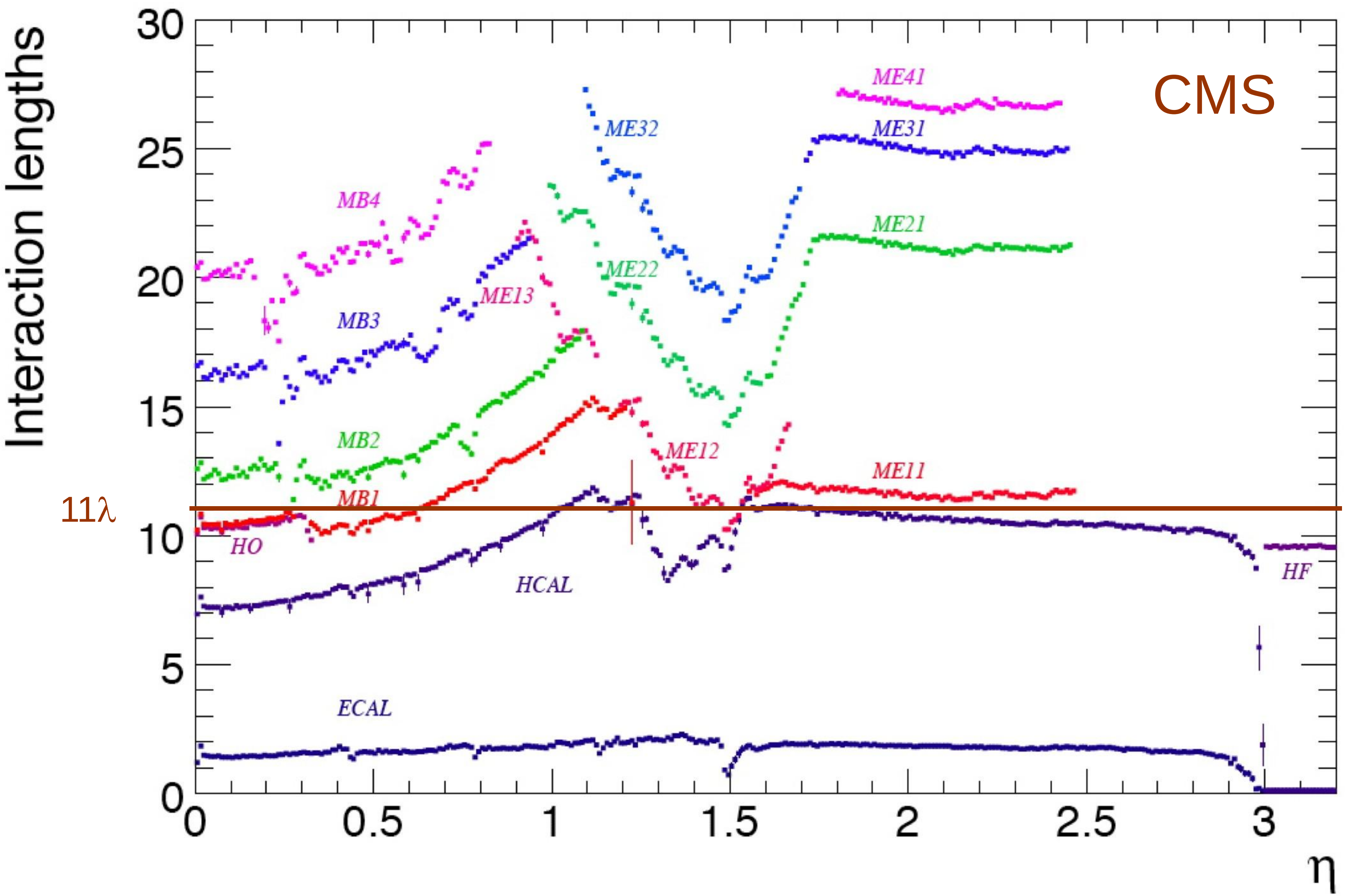
✓ the detector must therefore be quite hermetic

→ transverse energy flow fully measured with reasonable accuracy

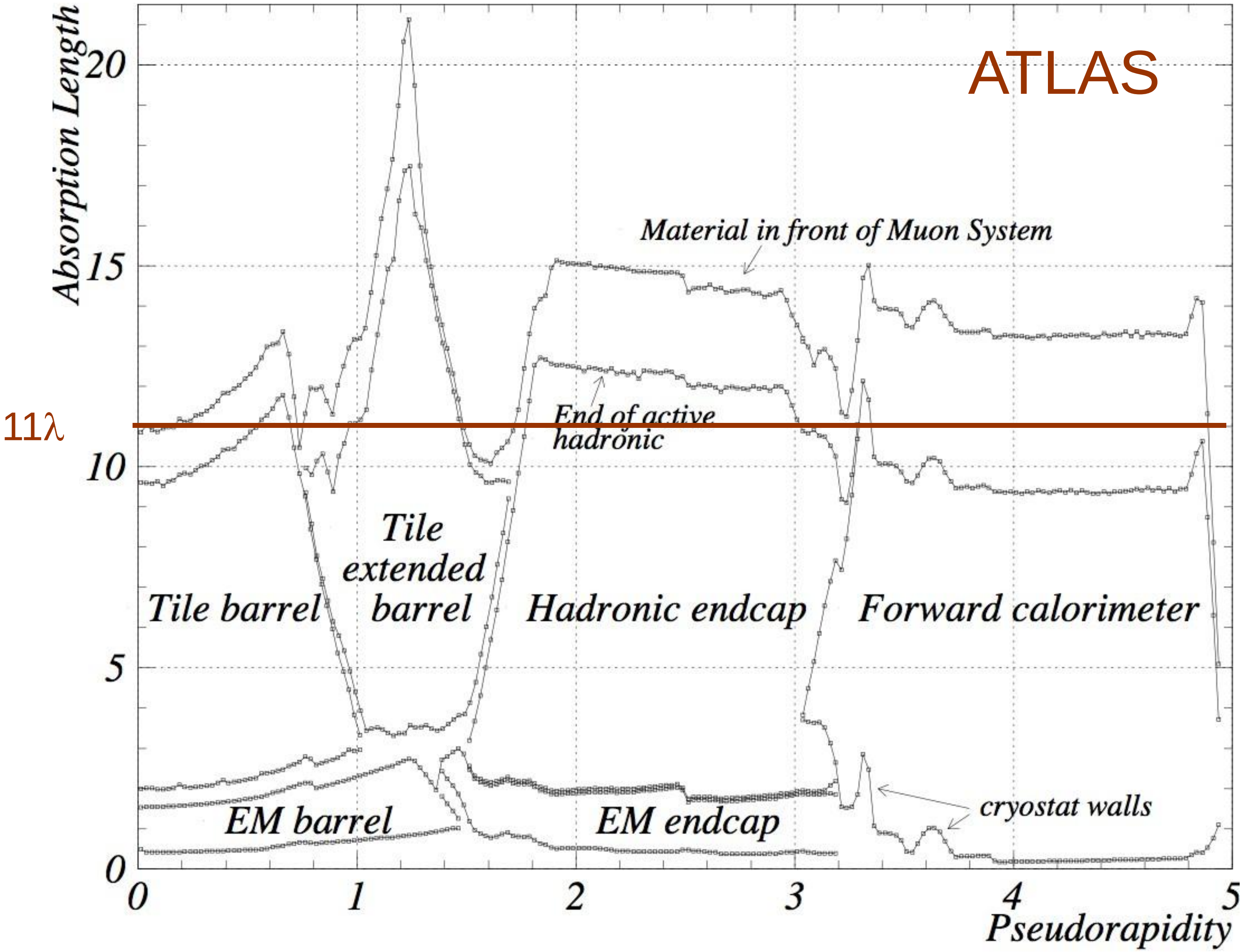
→ no neutrino escapes undetected

→ no human enters without major effort (fast access to some parts of ATLAS/CMS quite difficult)

ATLAS/CMS: from design to reality

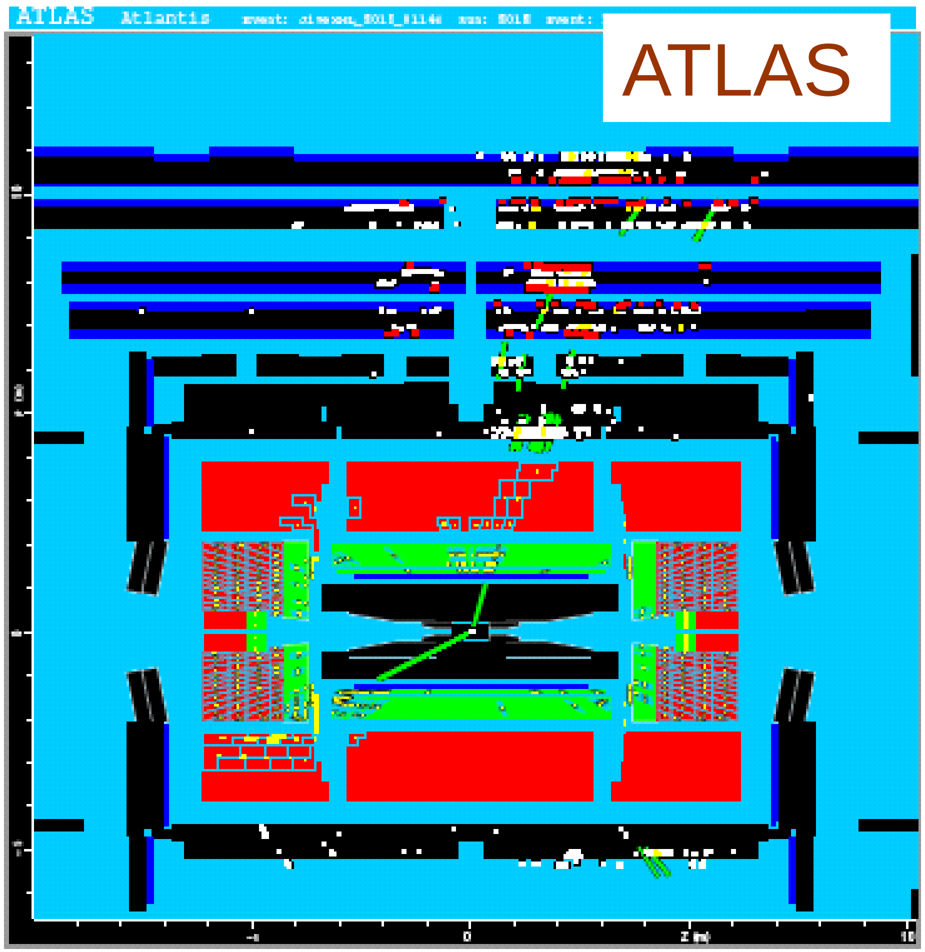


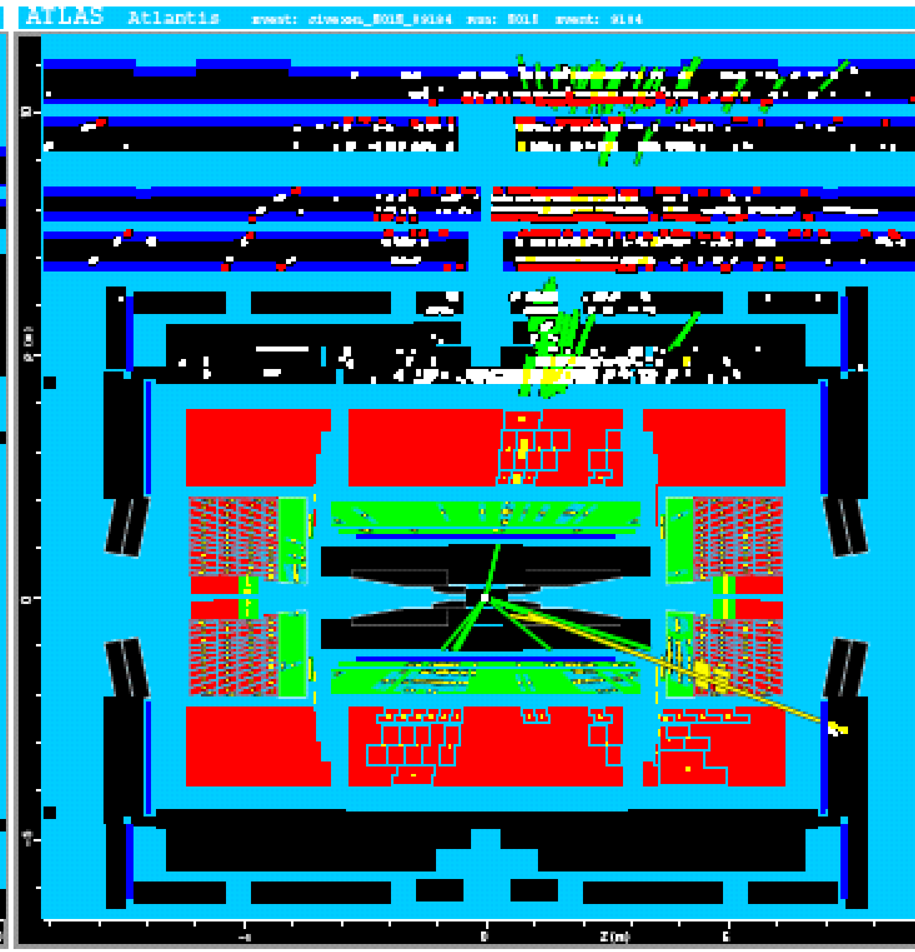
ATLAS/CMS: from design to reality



ATLAS/CMS: from design to reality

For an integrated luminosity of ~ 100 pb^{-1}, expect a few events like this? This is apparent E_T^{miss} occurring in fiducial region of detector!





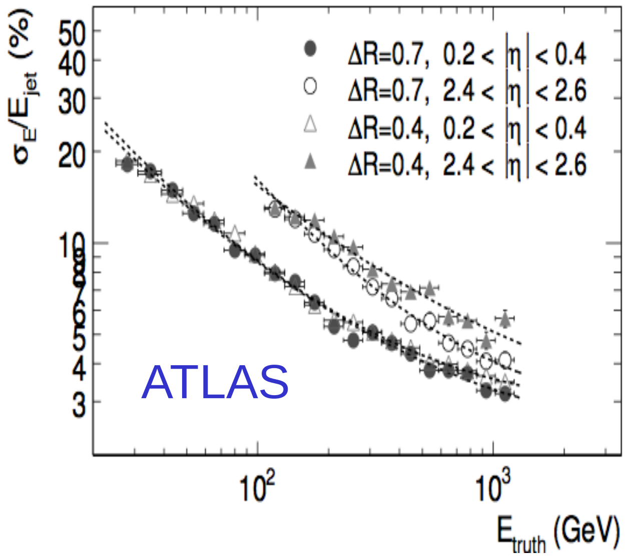
ATLAS/CMS: from design to reality

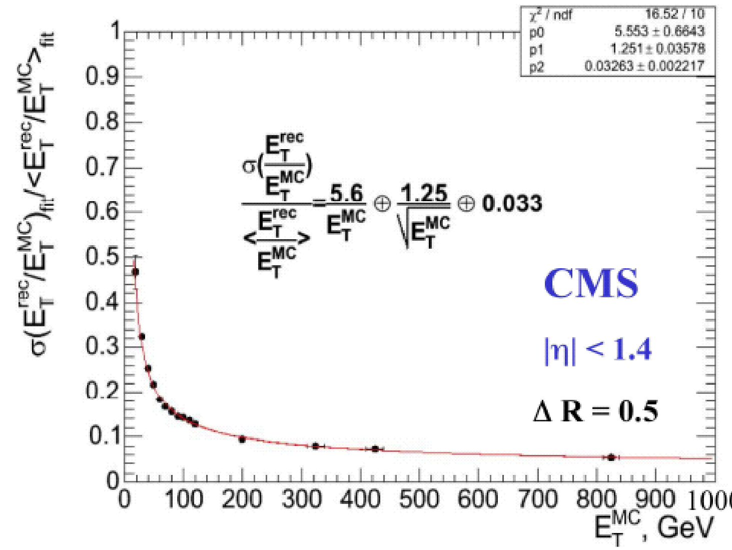
Biggest difference in performance perhaps for hadronic calo

Jets at 1000 GeV

ATLAS ~ 3% energy resolution

CMS ~ 5% energy resolution, (but expect sizable improvement using tracks at lower energies)



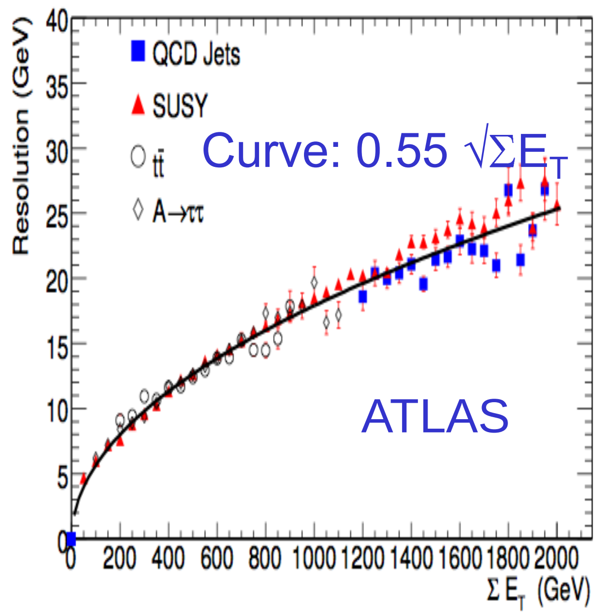


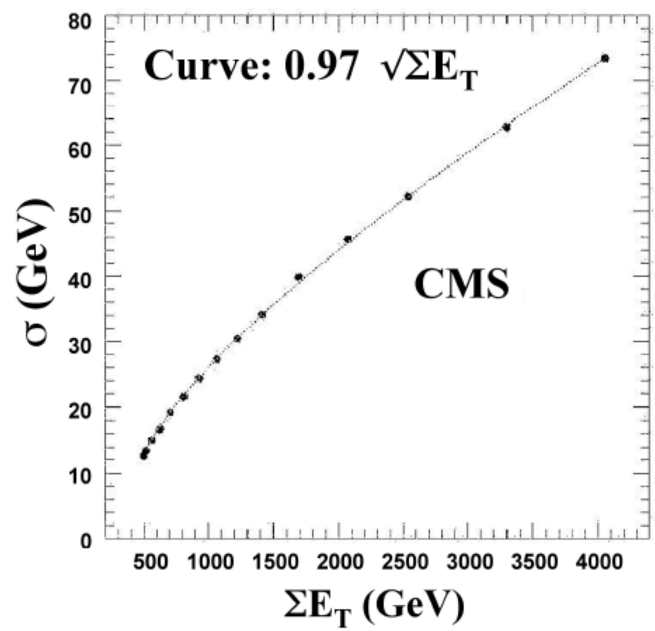
E_T^{miss} at ΣE_T = 2000 GeV

ATLAS: σ ~ 25 GeV

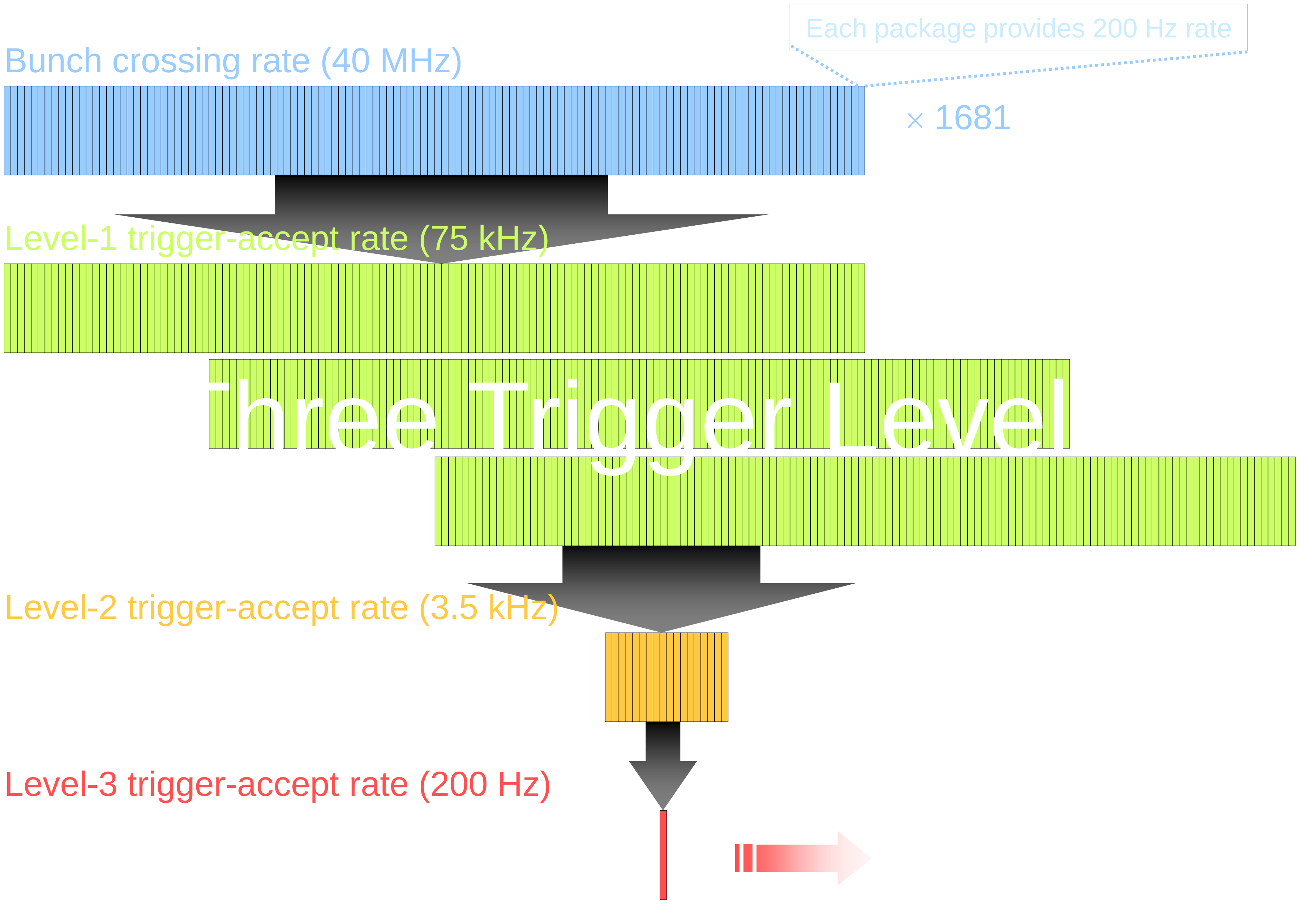
CMS: σ ~ 40 GeV

This may be important for high mass H/A to ττ





Trigger & Data Acquisition

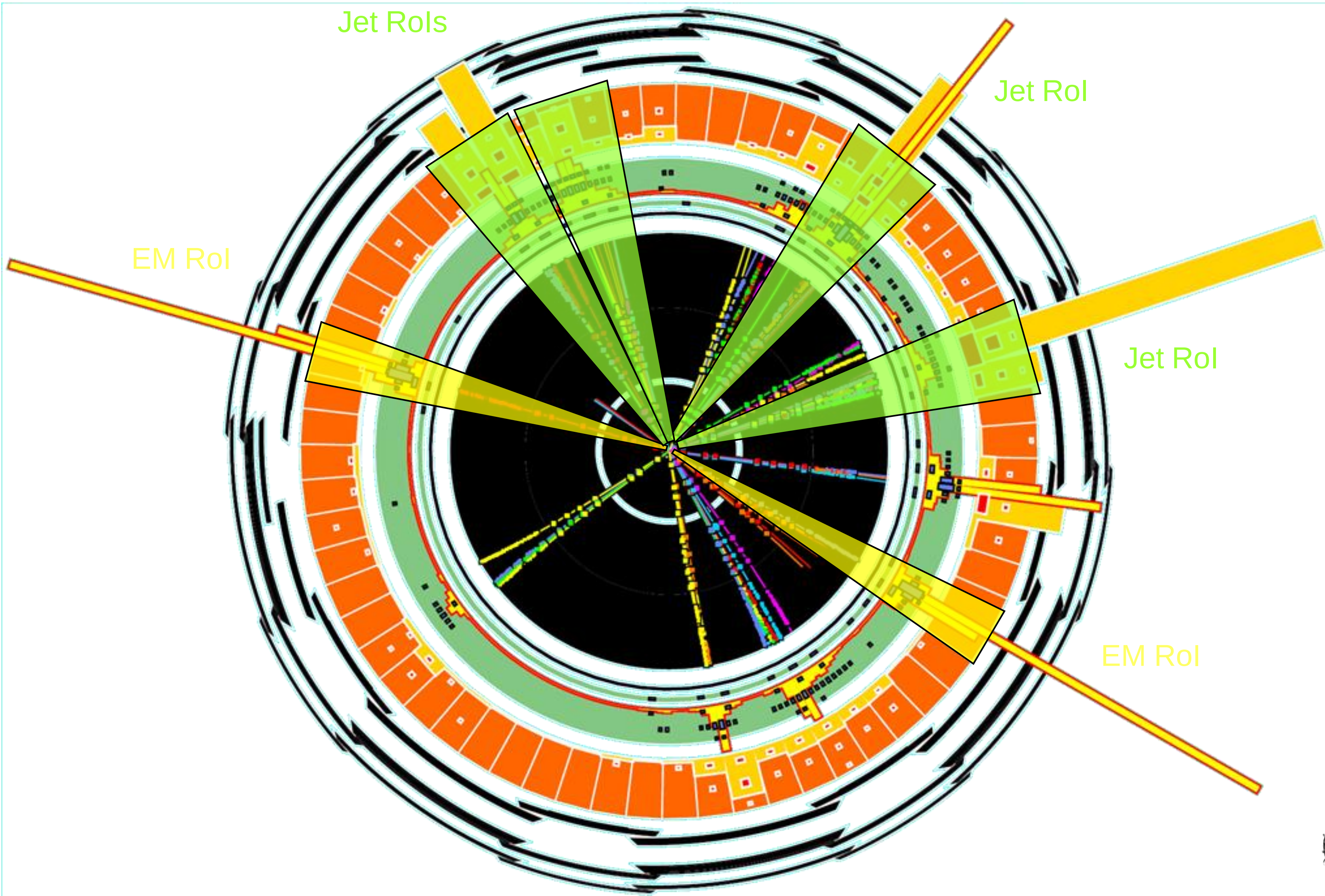

Each package provides 200 Hz rate
Bunch crossing rate (40 MHz)
× 1681
Level-1 trigger-accept rate (75 kHz)
Three Trigger Level
Level-2 trigger-accept rate (3.5 kHz)
Level-3 trigger-accept rate (200 Hz)

The ATLAS Trigger System

- Characteristics of ATLAS trigger system
  - 3 physically distinct trigger levels: Level-1 is hardware, Level-2 and 3 are software
  - Input to Level-1 trigger from EM+HAD calorimeter and muon systems (not inner tracker!)
  - Regions-of-Interest (RoI in $\Delta\eta \times \Delta\phi$) from Level-1, requested and analysed by Level-2
  - Full event building after Level-2 accept
  - Event is stored to file after Level-3 accept (write to *streams* based on trigger decision)
  - Overall rejection factor $\sim 2\times 10^5$ → trigger selection needs to be highly efficient

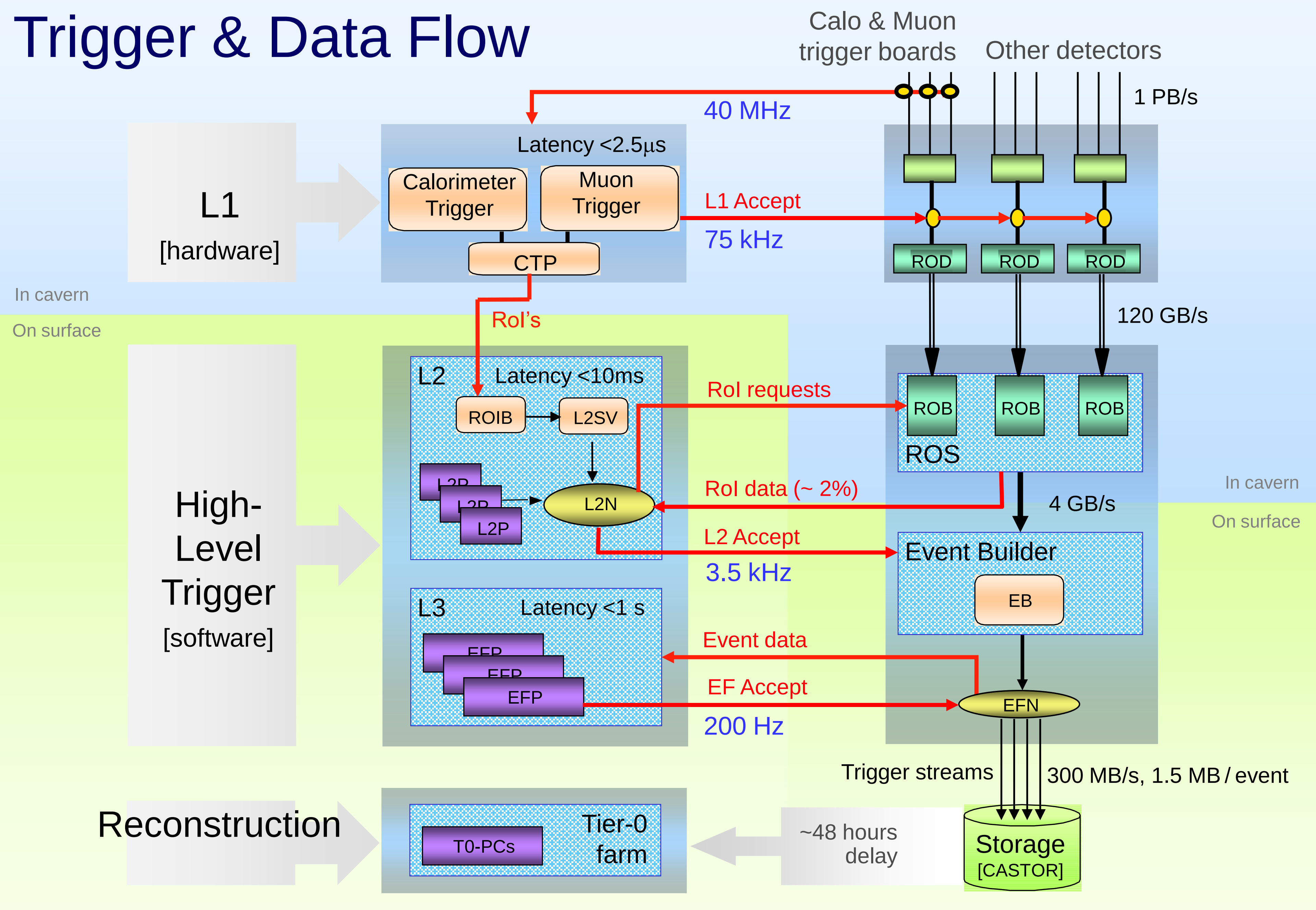
- Trigger restrictions are mainly due to affordability rather than technical
  - Detector occupancy and signal speed
  - Available front-end pipeline memory (128 bunch crossings = 3.2 μs)
  - Speed of readout links from detectors to Level-2 and event building computer farms
  - Size of Level-2 and Level-3 computer farms (500 and 1800 nodes, respectively)
  - Size of event-building and event-writing computer farm (100 and 5 nodes, respectively)
  - Bandwidth for event building and event storage

Regions of Interest (RoI)



Simulation of a Black Hole event in ATLAS

Trigger & Data Flow



The ATLAS Trigger System

Because computers become ever more powerful,
it’s always too early to buy them…