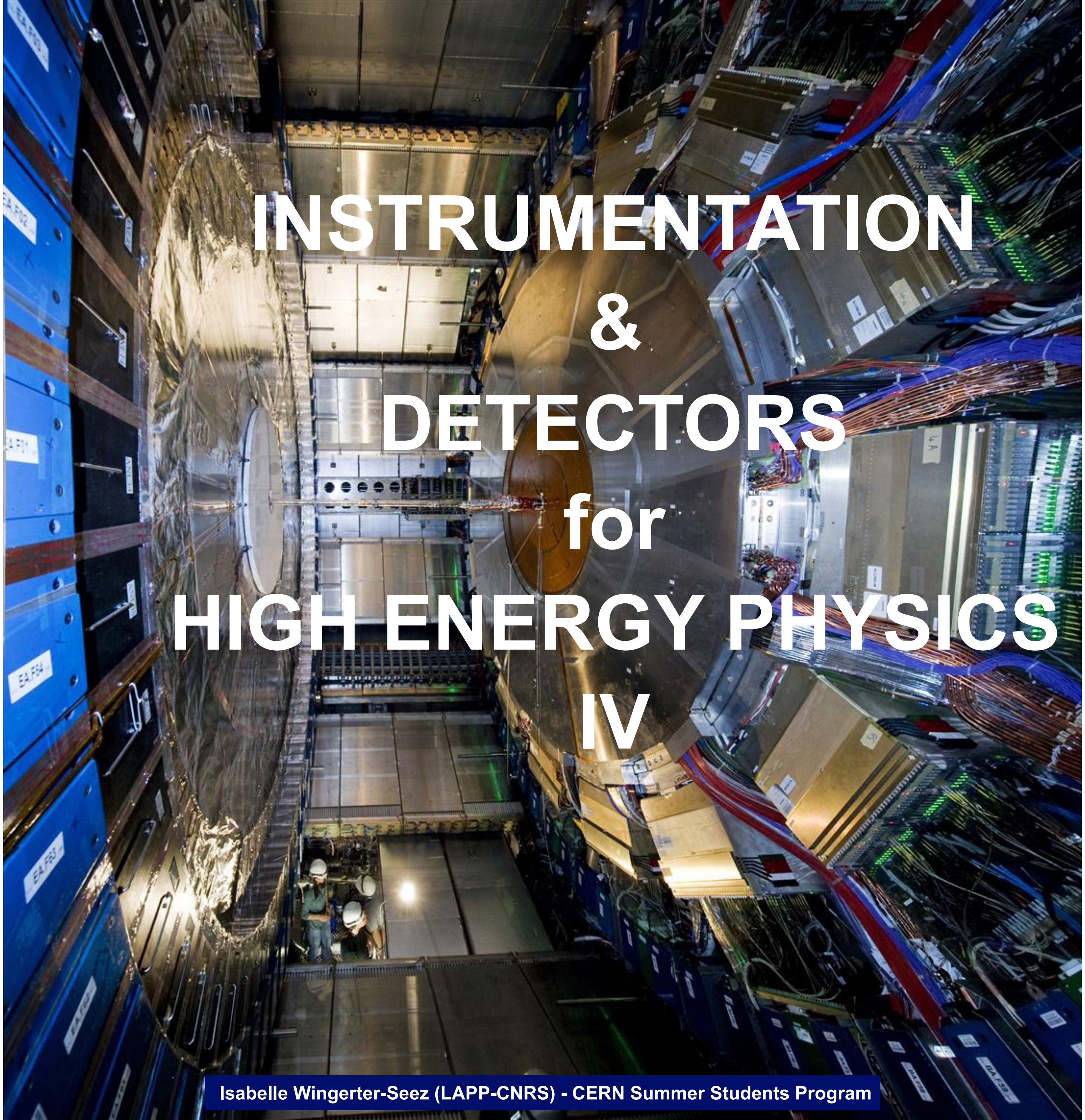
INSTRUMENTATION & DETECTORS for HIGH ENERGY PHYSICS IV



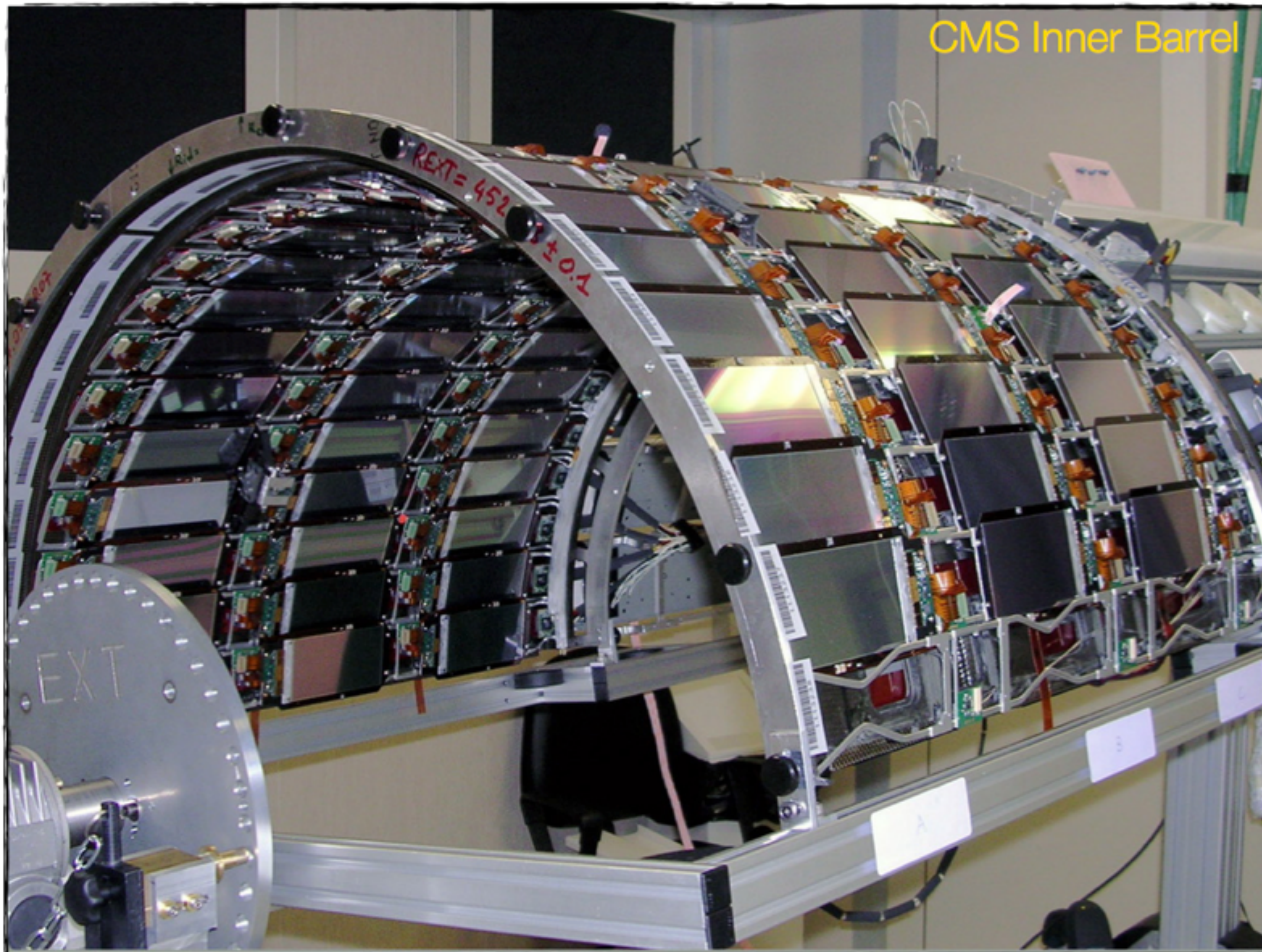
DETECTOR: LECTURE III QUIZZ

Gas vs solid state ionisation detector ?

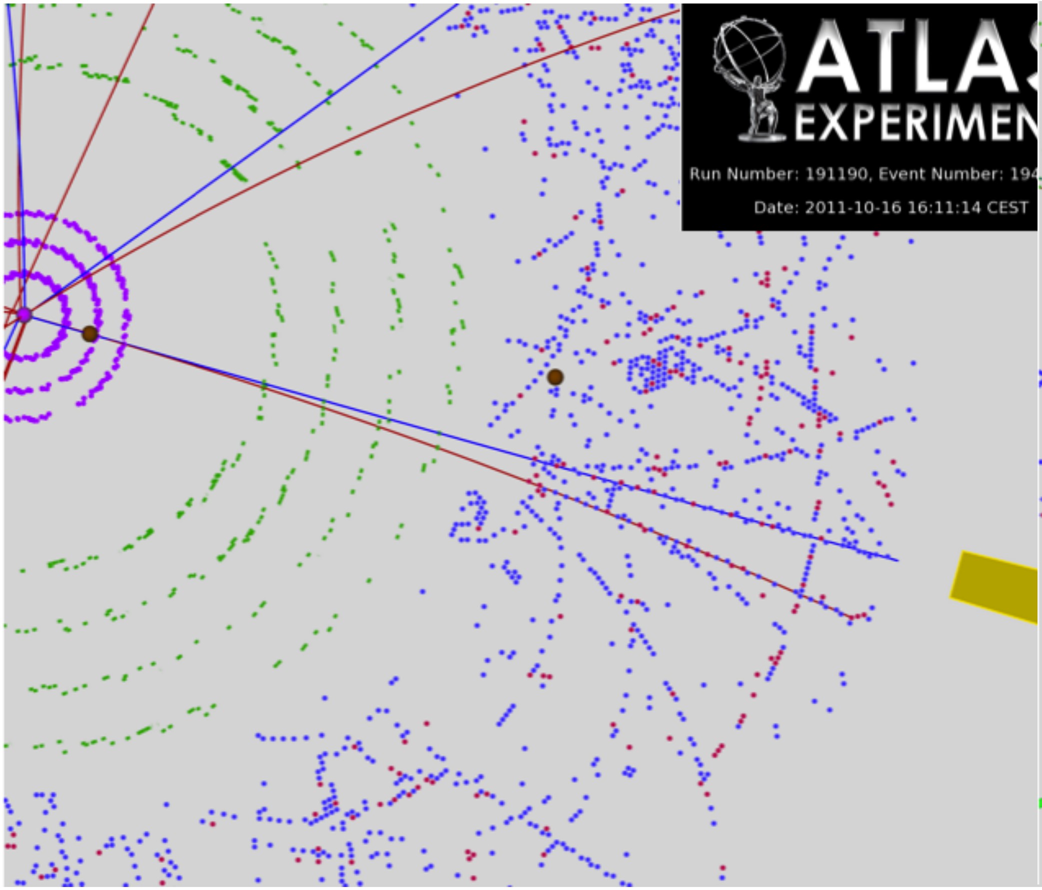
Typical size of a cell in a silicium detector

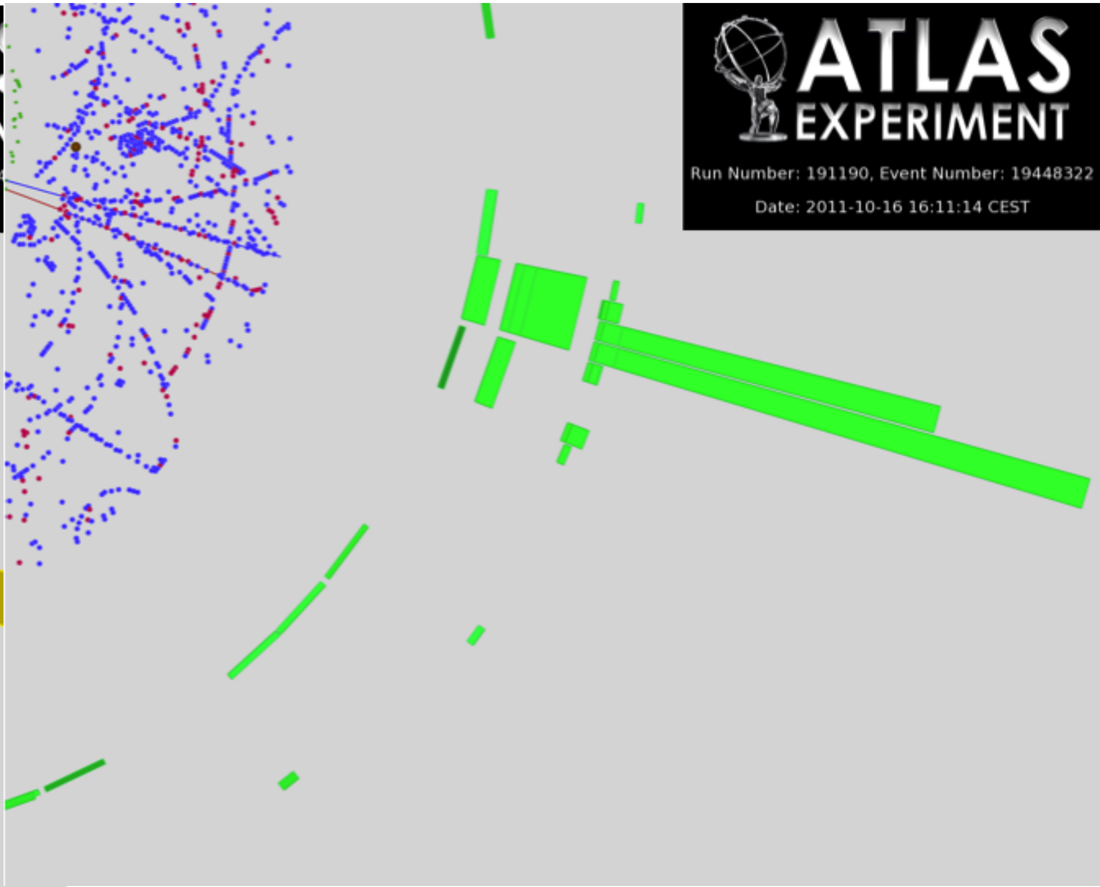
Why do experimentalists like small cell size ?

What is the consequence of small cell size ?


CMS Inner Barrel
EXT

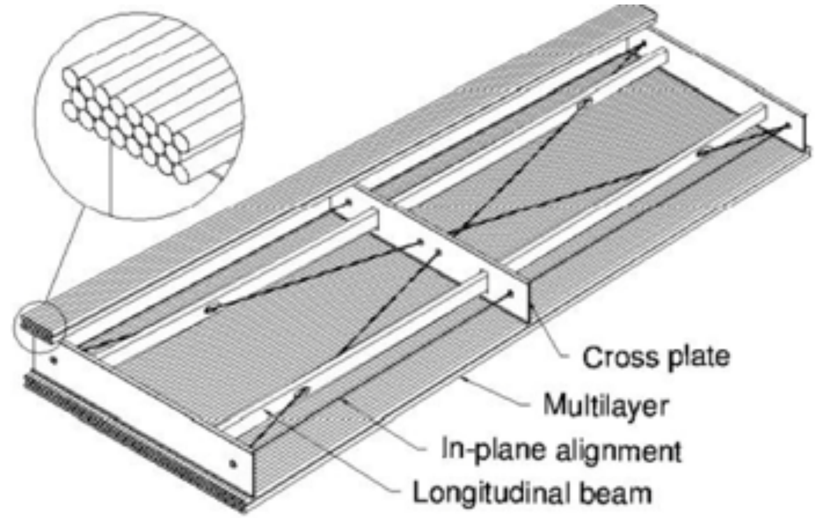
PHOTON CONVERSION

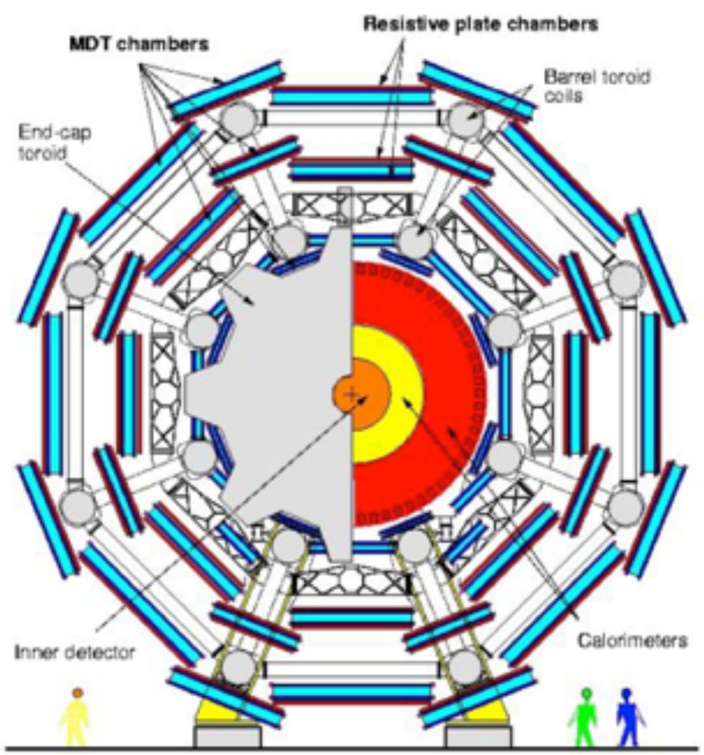


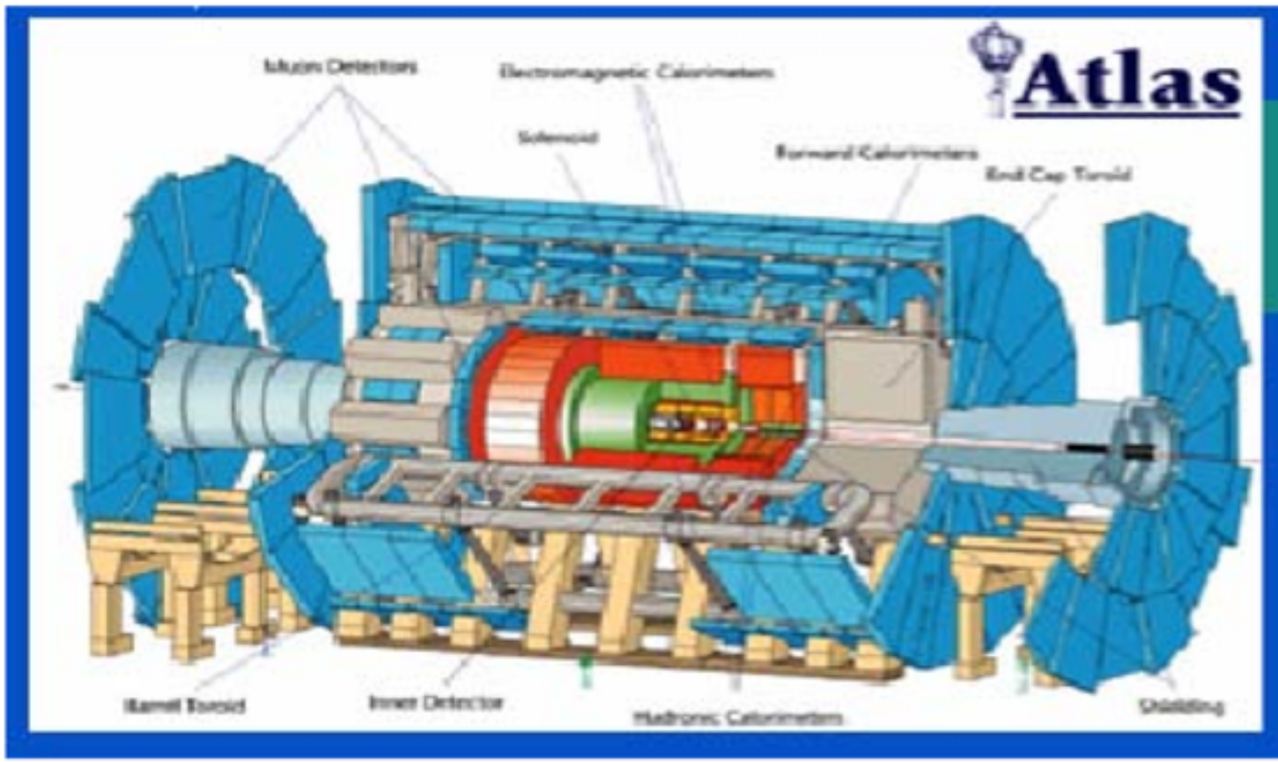


ATLAS MUON SYSTEM

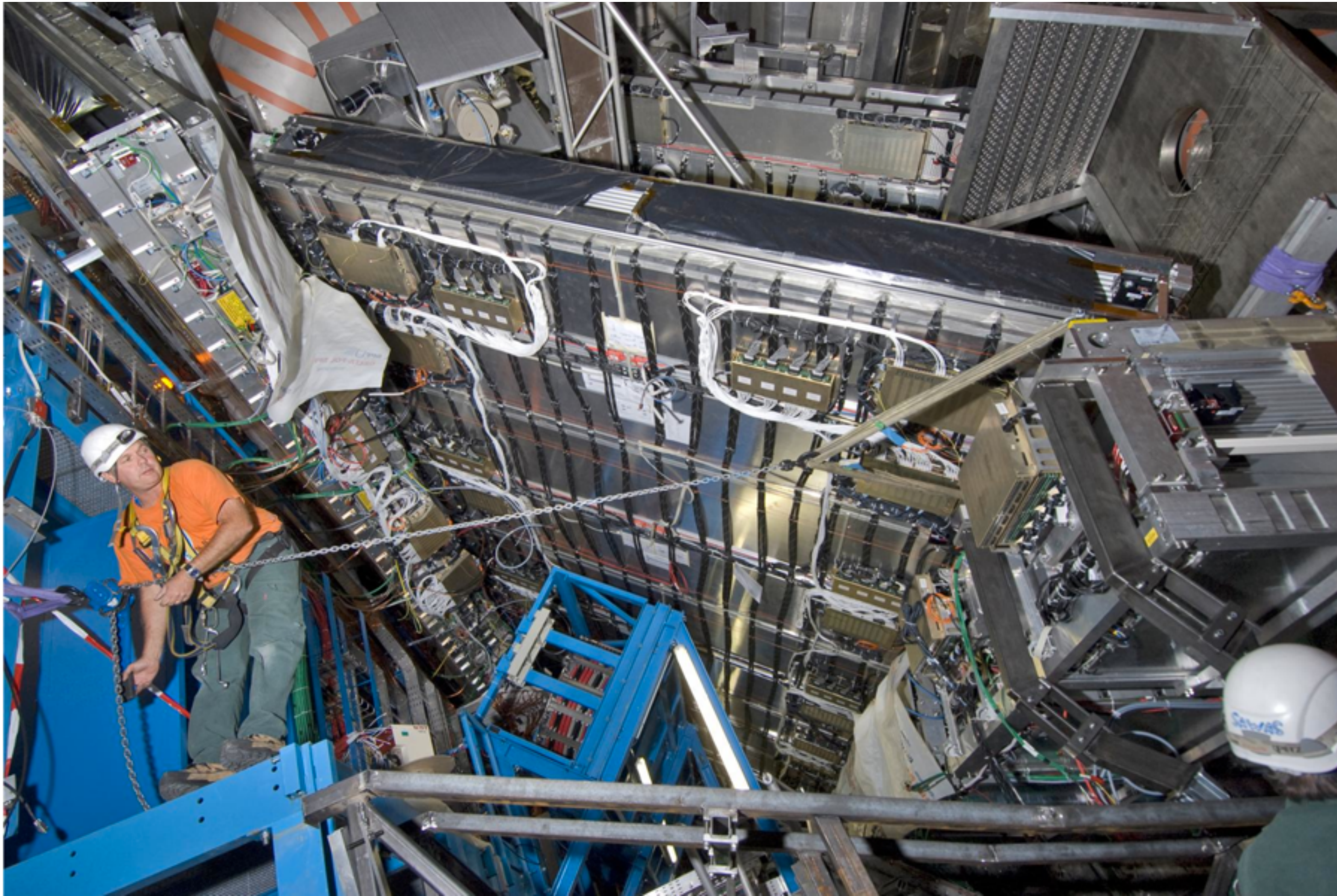
Atlas Muon Spectrometer, 44m long, from r=5 to11m.
1200 Chambers
6 layers of 3cm tubes per chamber.
Length of the chambers 1-6m !
Position resolution: 80μm/tube, <50μm/chamber (3 bar)
Maximum drift time ≈700ns
Gas Ar/CO_2 93/7





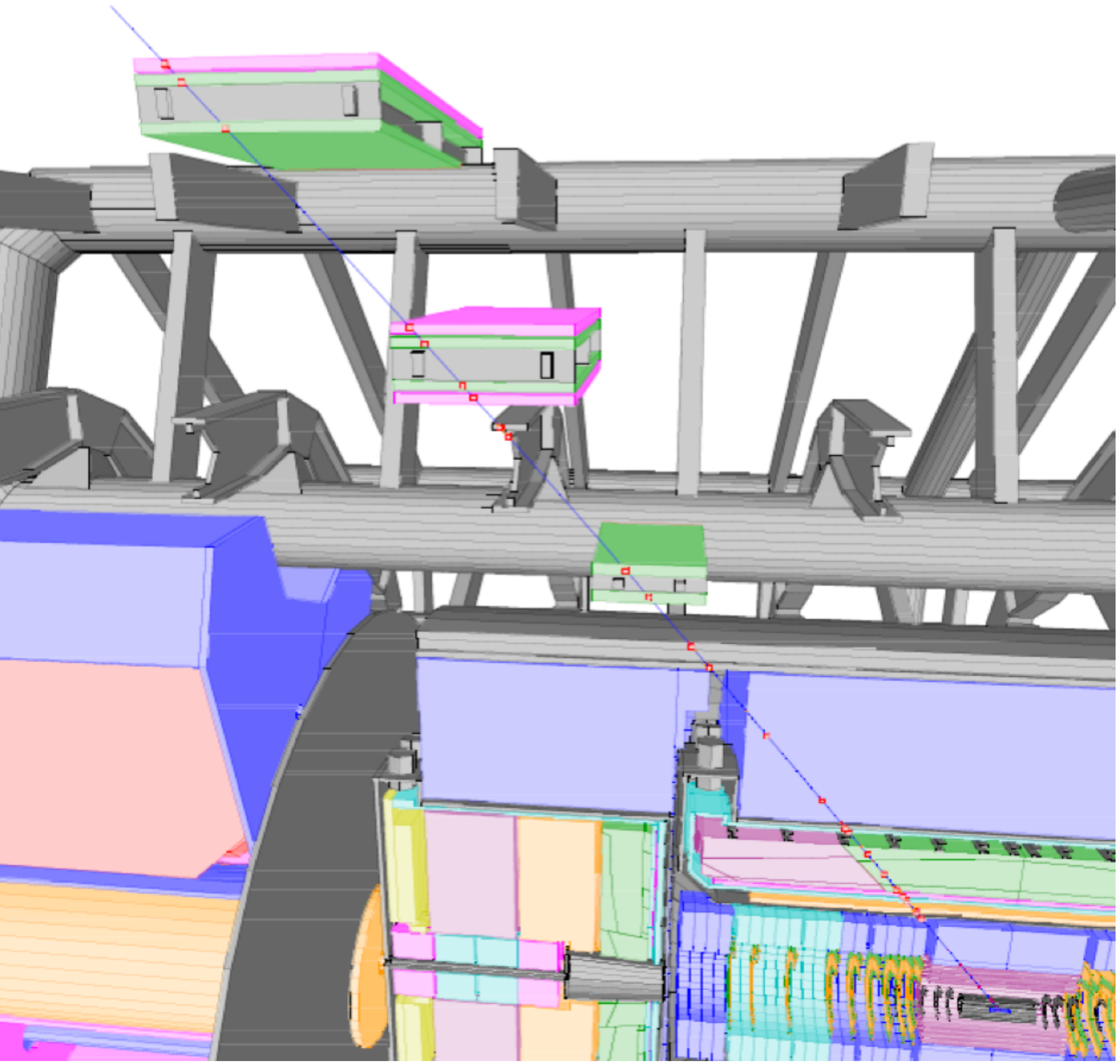


ATLAS RPC

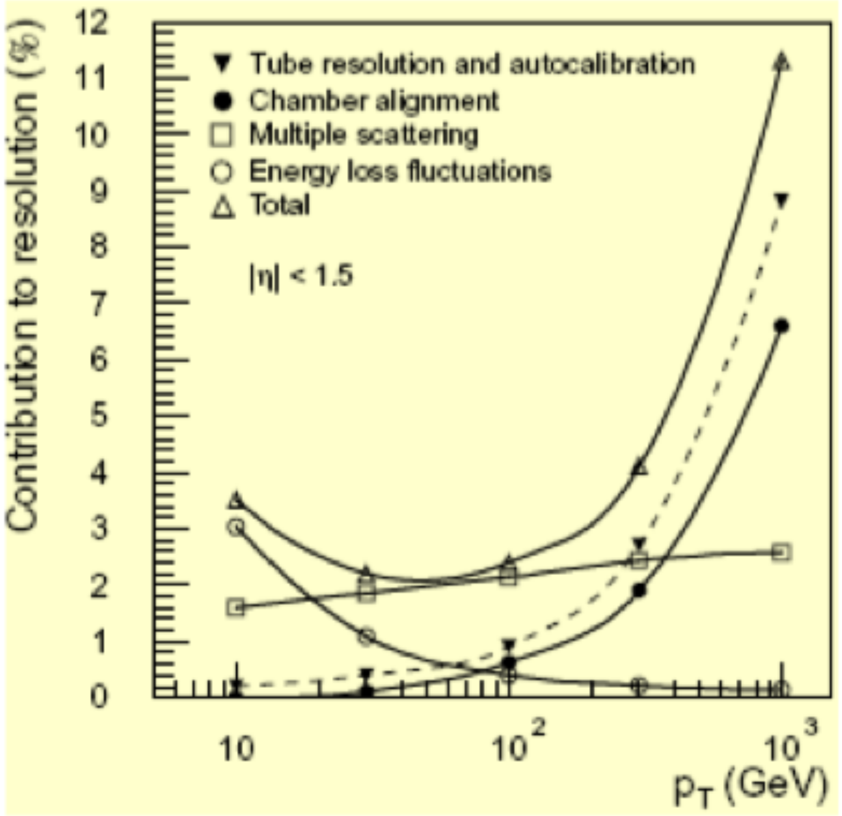


MUON MOMENTUM RESOLUTION

COMBINE Measurement from the tracker and the muon chambers



•$\delta p_T/p_T$ vs p_T



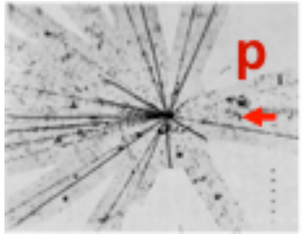
Contributions: mesure $\propto p$

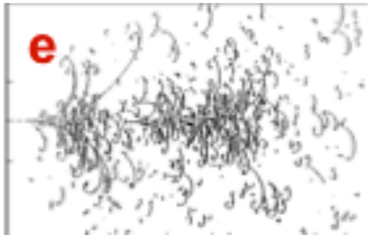
diffusion ~cte

δE*loss* $\propto 1/p$

FROM INTERACTIONS to DETECTOR

1. Particles interact with matter
   depends on particle and material

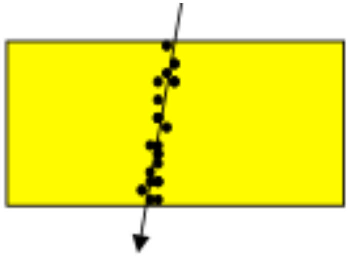




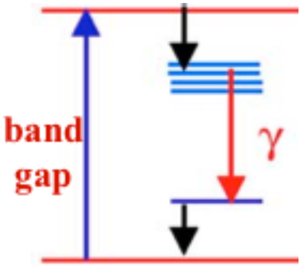
2. Energy loss transfer to detectable signal
   depends on the material

Detecting emitted light

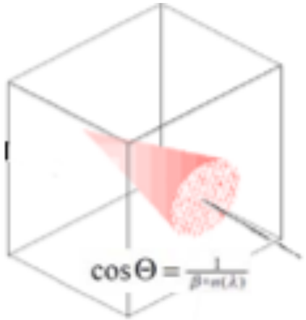
Detecting ionisation current



Ionisation

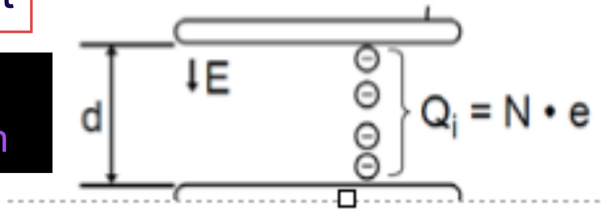


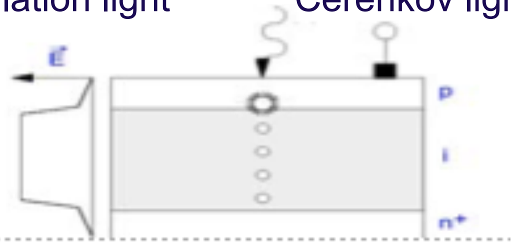
Scintillation light



Cerenkov light

3. Signal collection
   depends on signal and type of detection

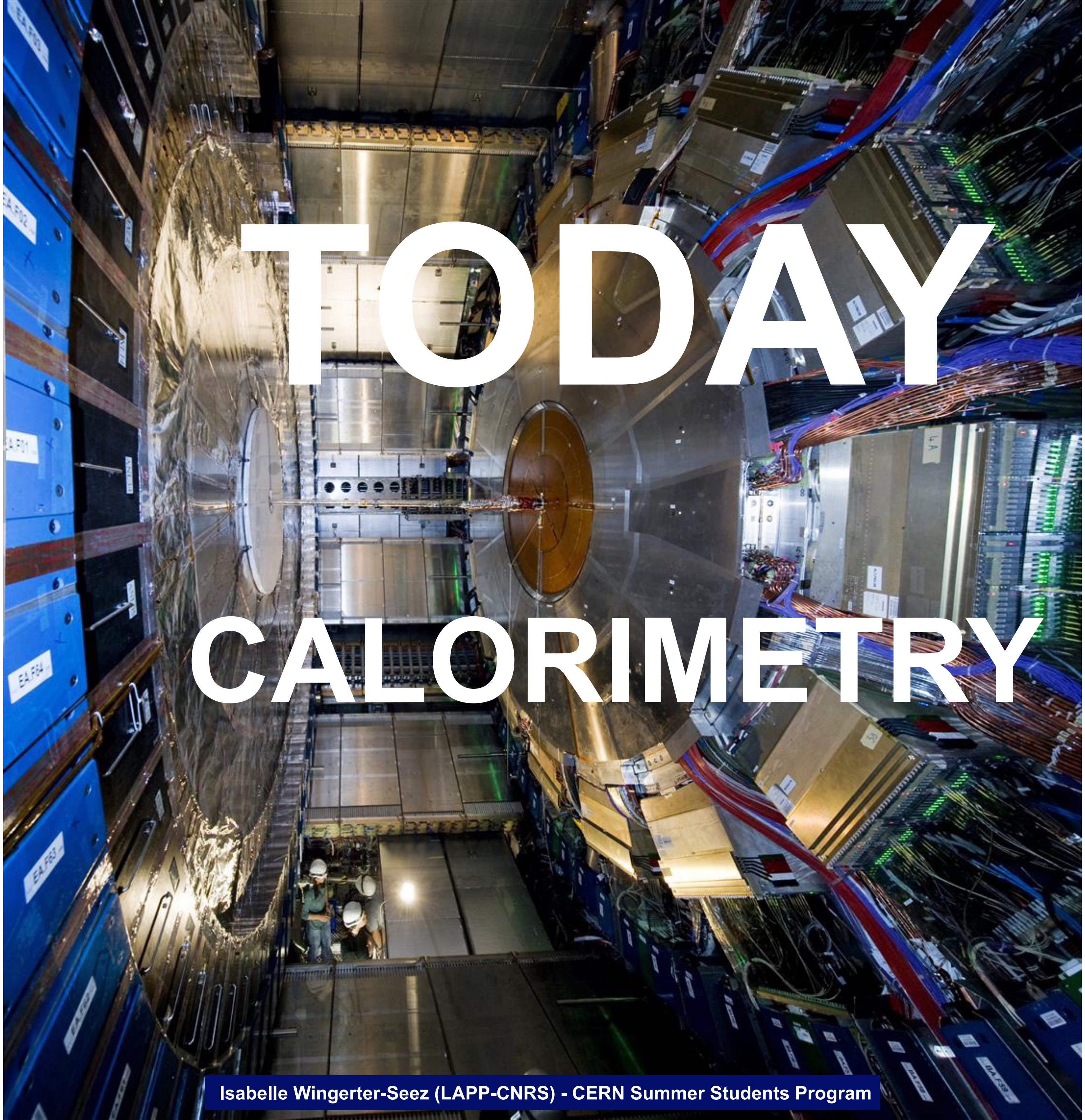




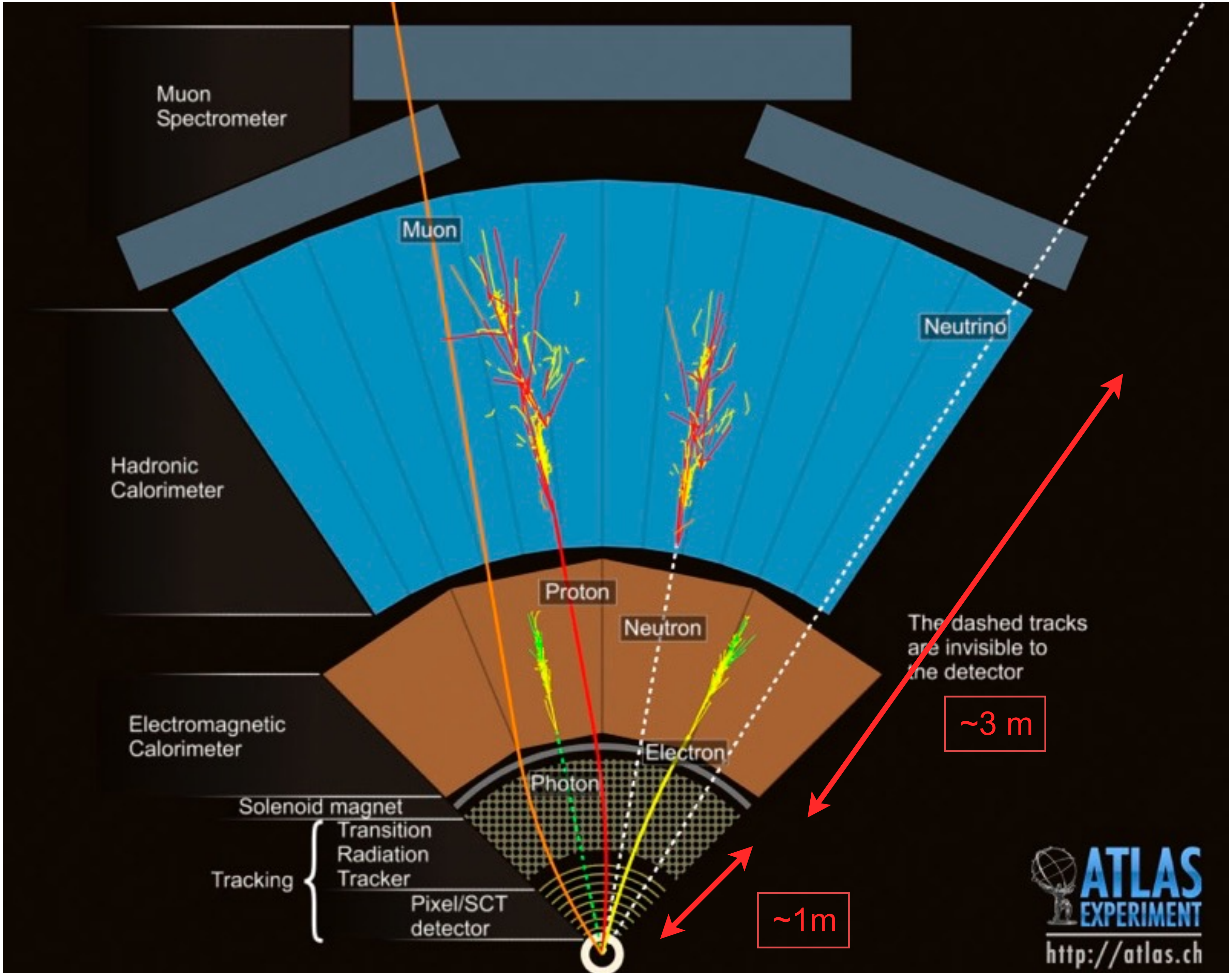
4. BUILD a SYSTEM
   depends on physics, experimental conditions,….

TODAY

CALORIMETRY



CALORIMETERS



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

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

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 ($\sim 10^{14}$; $\sim 10^{8}$ 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…

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

WHY CALORIMETERS ?

First calorimeters appeared in the 70's:

need to measure the energy of all particles, charged and neutral.

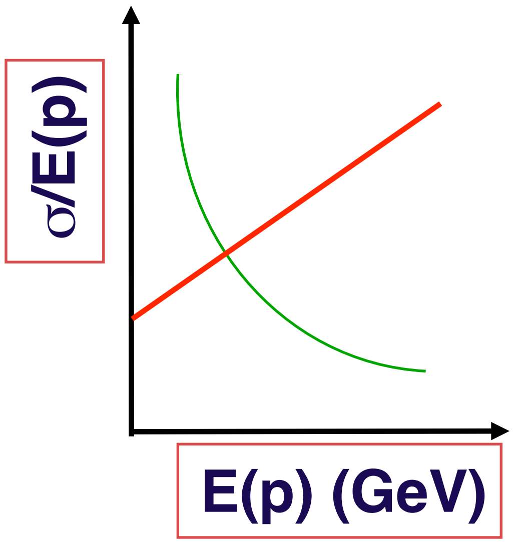
Until then, only the momentum of charged particles was measured using magnetic analysis.

The measurement with a calorimeter is destructive e.g.

$$\pi^- + p \rightarrow \pi^0 + n, \quad \pi^0 \rightarrow \gamma\,\gamma$$

Magnetic analysis

$$\frac{\sigma(p)}{p} = ap \oplus b$$



$$\frac{\sigma(E)}{E} \approx \frac{a}{\sqrt{E}}$$

Calorimetry

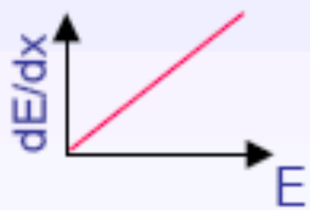
Particles (but μ and ν) do not come out alive of a calorimeter

Reminder: basic electromagnetic interactions

e^+ / e^-

- Ionisation

- Bremsstrahlung



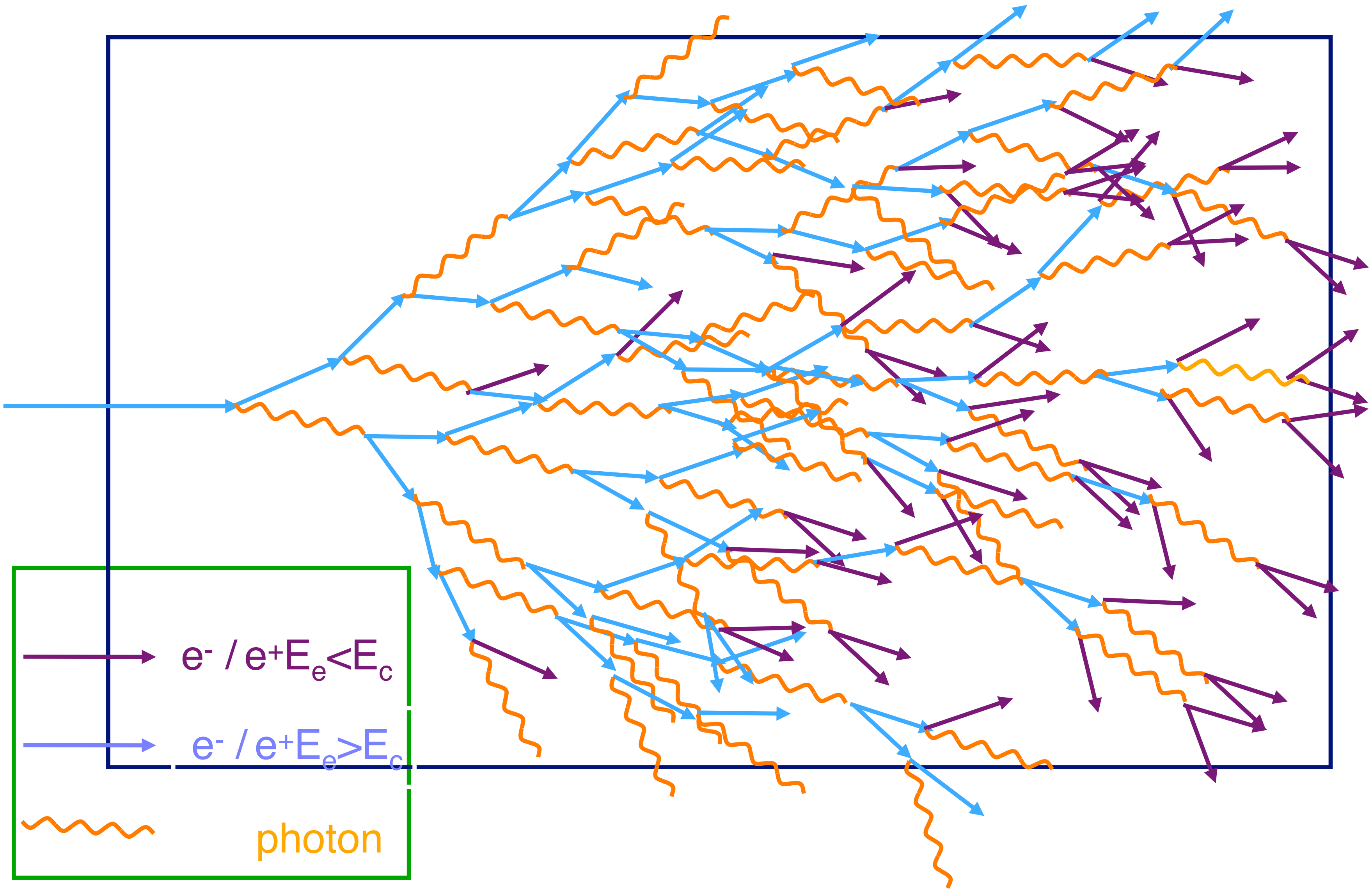
γ

- Photoelectric effect

- Compton effect

- Pair production

ELECTROMAGNETIC SHOWER



ELECTROMAGNETIC SHOWER DEVELOPMENT

The shower develops as a cascade by energy transfer from the incident particle to a multitude of particles ($e^{\pm}$ and γ).

The number of cascade particles is proportional to the energy deposited by the incident particle

The role of the calorimeter is to count these cascade particles

The relative occurrence of the various processes briefly described is a function of the material (Z)

The radiation length (X_0) allows to universally describe the shower development

CRITICAL ENERGY

Critical energy:

$$\frac{dE}{dx}(E_c)\bigg|_{\text{Brems}} = \frac{dE}{dx}(E_c)\bigg|_{\text{Ion}}$$

Approximation:

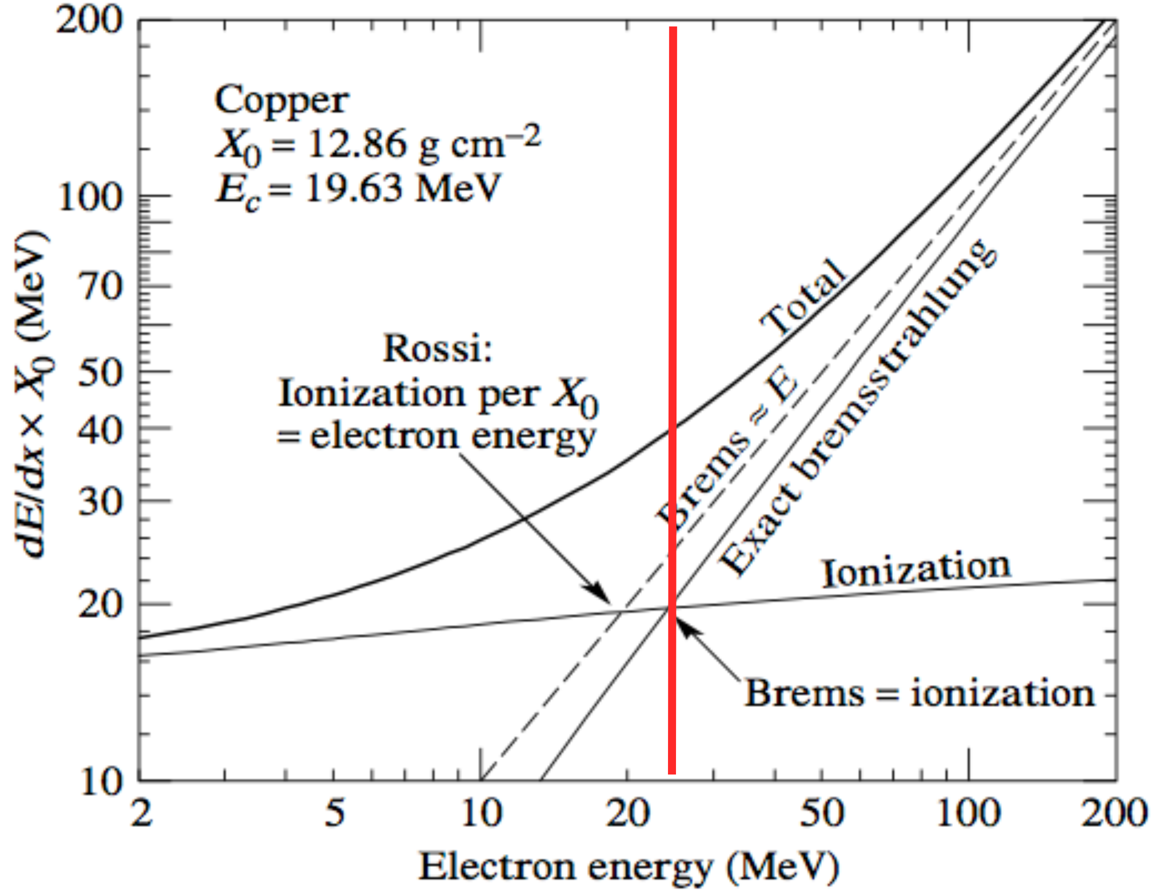
$$E_c^{\text{Gas}} = \frac{710\ \text{MeV}}{Z + 0.92}$$

$$E_c^{\text{Sol/Liq}} = \frac{610\ \text{MeV}}{Z + 1.24}$$

Example Copper:

$E_c \approx 610/30$ MeV $\approx$ 20 MeV

$$\left(\frac{dE}{dx}\right)_{\text{Tot}} = \left(\frac{dE}{dx}\right)_{\text{Ion}} + \left(\frac{dE}{dx}\right)_{\text{Brems}}$$



EM SHOWER DEVELOPMENT: SIMPLE MODEL

The multiplication of the shower continues until the energies fall below the critical energy, E_c

A simple model of the shower uses variables scaled to X_0 and E_c

$$t = \frac{x}{X_0}, y = \frac{E}{E_c}$$

Electrons loose about 2/3 of their energy in $1X_0$, and the photons have a probability of 7/9 for conversion: X_0 ~ generation length

After distance t:

number of particles, $n(t) = 2^t$

energy of particles, $E(t) \approx \frac{E}{2^t}$

When E~ E_c shower maximum:

$$n(t_{\max}) \approx \frac{E}{E_c} = y$$

$$t_{\max} \approx \ln\left(\frac{E}{E_c}\right) = \ln y$$

EM LONGITUDINAL DEVELOPMENT

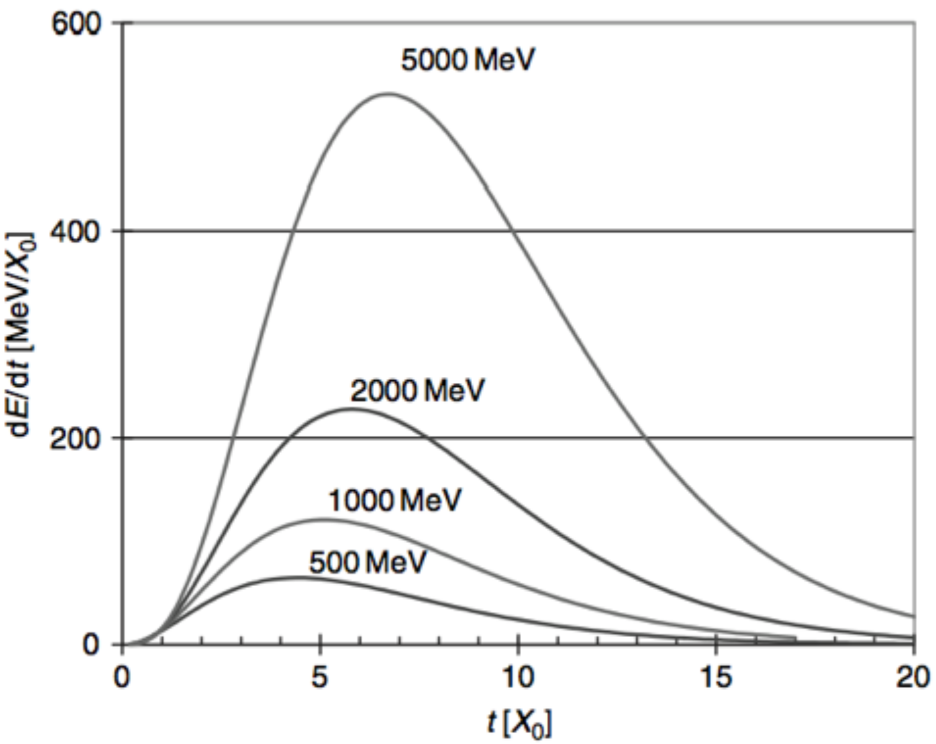
Longitudinal profile

Parametrization:
[Longo 1975]

$$\frac{dE}{dt} = E_0 \, t^{\alpha} e^{-\beta t}$$

α,β : free parameters
t^{α} : at small depth number of secondaries increases ...
$e^{-\beta t}$: at larger depth absorption dominates ...

Numbers for E = 2 GeV (approximate):
$\alpha = 2$, $\beta = 0.5$, $t_{max} = \alpha/\beta$



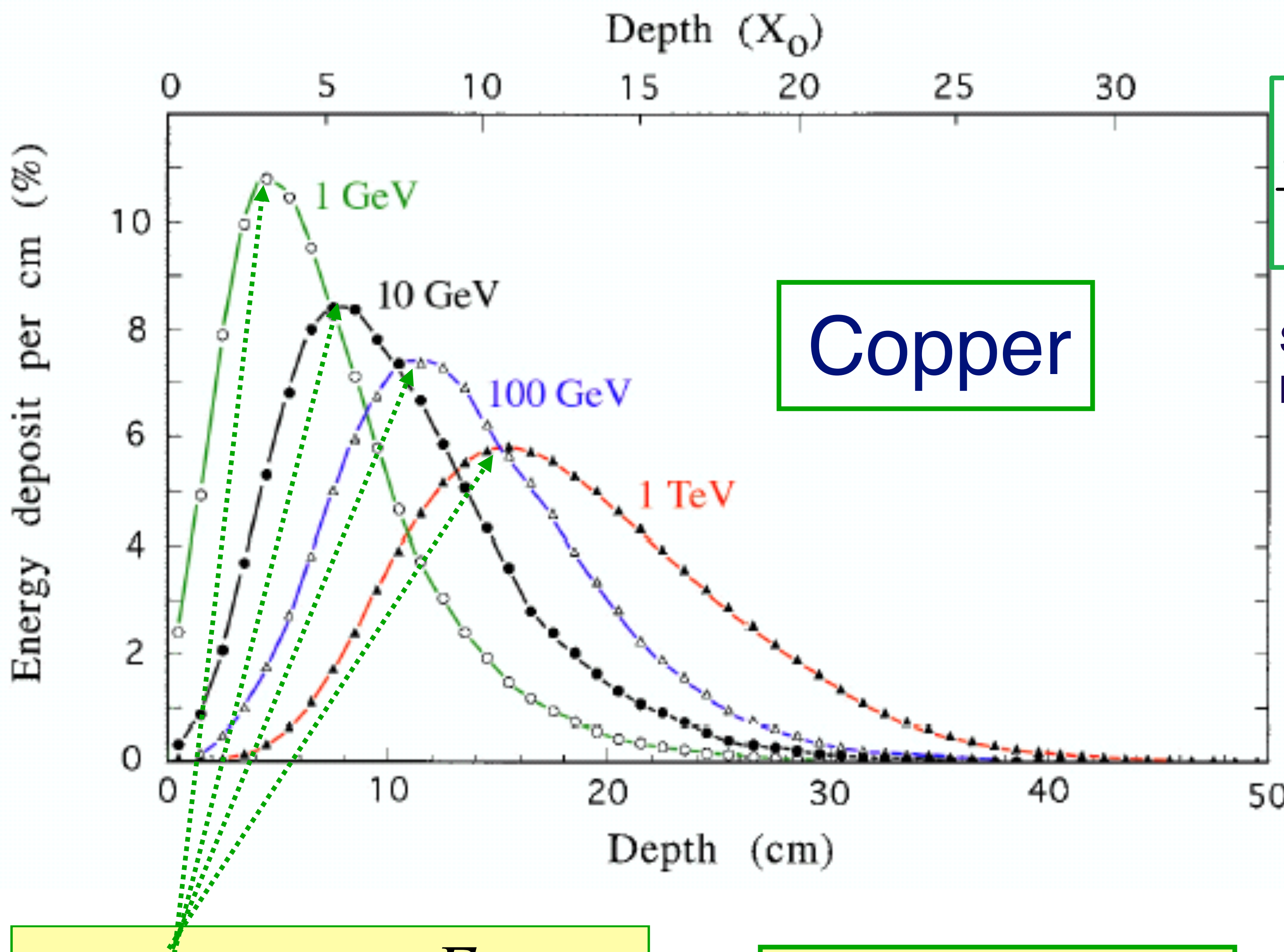
More exact
[Longo 1985]

$$\frac{dE}{dt} = E_0 \cdot \beta \cdot \frac{(\beta t)^{\alpha-1} e^{-\beta t}}{\Gamma(\alpha)} \quad \rightarrow \quad t_{\max} = \frac{\alpha - 1}{\beta} = \ln\left(\frac{E_0}{E_c}\right) + C_{e\gamma}$$

[Γ: Gamma function]

with:
$C_{e\gamma} = -0.5$ [γ-induced]
$C_{e\gamma} = -1.0$ [e-induced]

EM SHOWERS LONGITUDINAL DEVELOPMENT



$$\frac{dE}{dt} \propto E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}$$

Shower energy development parametrization

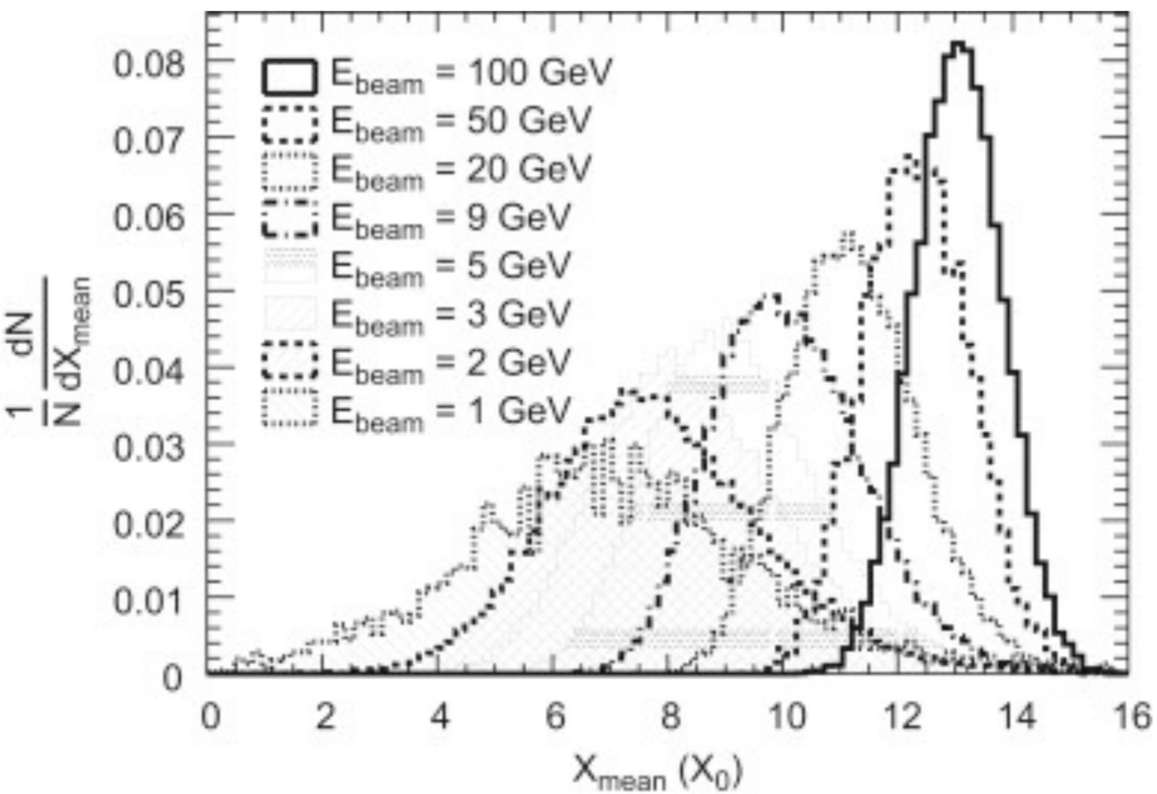
b: material

E.Longo & I.Sestili (NIM128-1975)

$$X_{\max} = X_0 \ln\left(\frac{E}{E_c} + t_0\right)$$

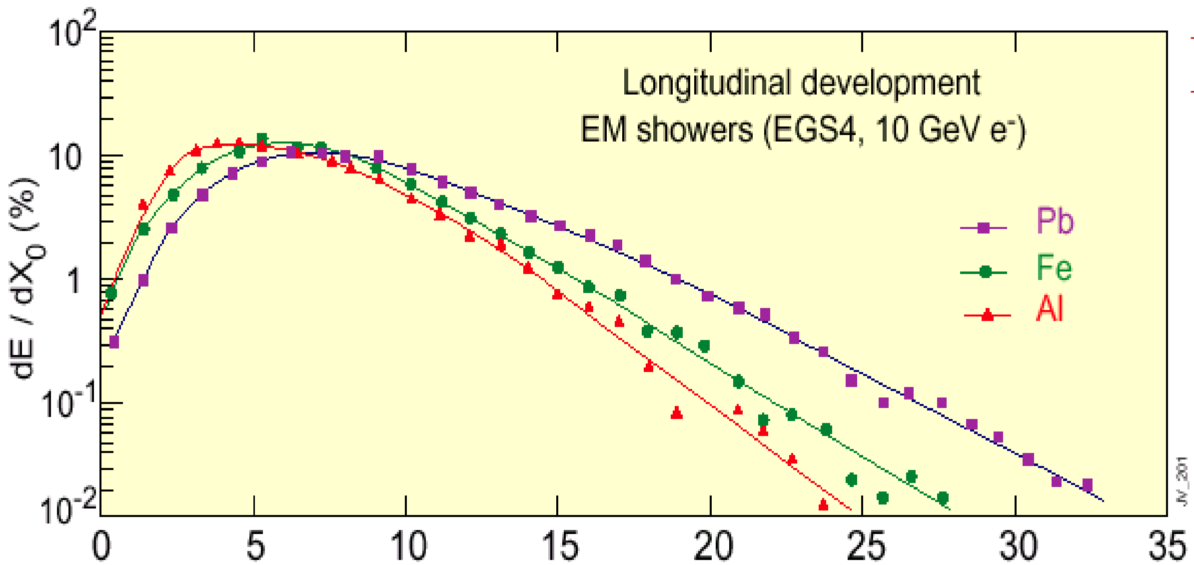
t_0= -0.5 electrons
+0.5 photons

EM SHOWERS LONGITUDINAL DEVELOPMENT



ATLAS combined testbeam 2004 setup

Electrons shower mean depth in X_0 (MC)
1,2,3,5,9,20,50, 100 GeV



$E_c \propto 1/Z$
→ Shower maximum
→ Shower tails
$t_{95\%} = t_{max} + 0.08Z + 9.6$

SEARCH FOR DECAYS OF THE Z^0 INTO A PHOTON AND A PSEUDOSCALAR MESON

ALEPH Collaboration

D. DECAMP, B. DESCHIZEAUX, C. GOY, J.-P. LEES, M.-N. MINARD

Laboratoire de Physique des Particules (LAPP), IN2P3–CNRS, F-74019 Annecy-le-Vieux Cedex, France

....

Measurement made by ALEPH

$e^+e^- \rightarrow e^+e^-$

$e^+e^- \rightarrow \gamma\gamma$

Electron/Photon longitudinal development: different

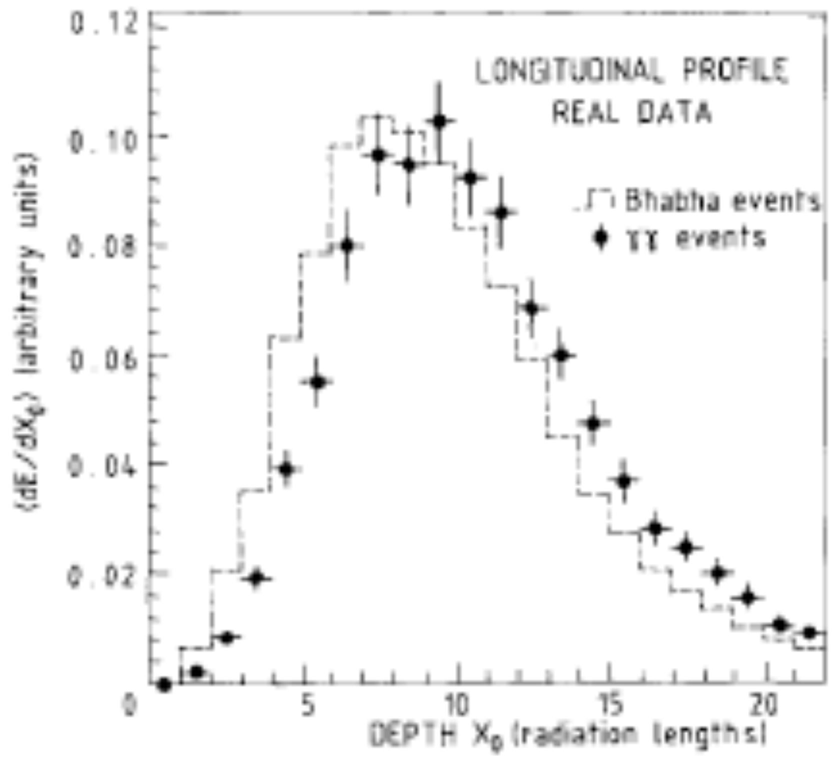


Fig. 1. Longitudinal profile of electromagnetic showers, both for electrons from $e^+e^- \rightarrow e^+e^-$ and for the $\gamma\gamma$ candidates. Both samples are real data. There is a clear shift by about 1 radiation length of the photon showers with respect to electron showers, as expected.

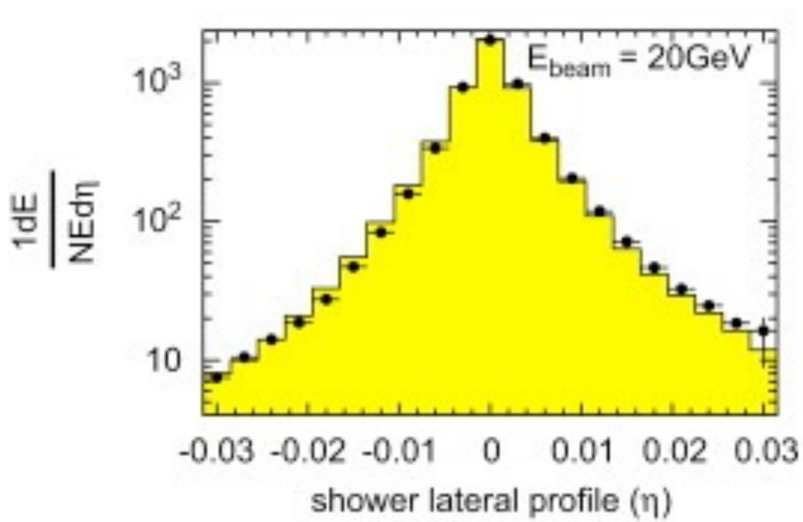
EM shower lateral development

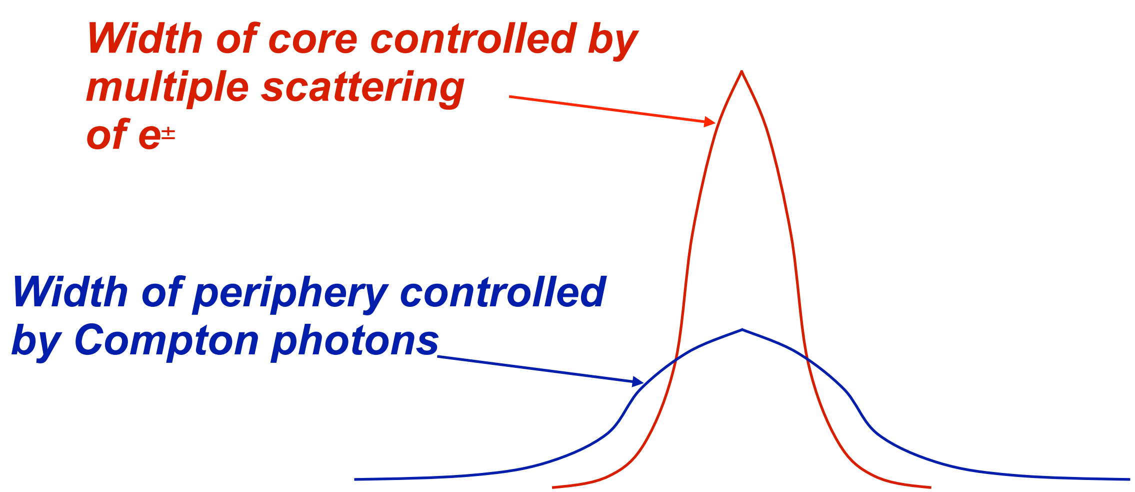
Molière radius, R_m, scaling factor for lateral extent, defined by:

$$R_M = \frac{21 MeV \times X_0}{E_c} \approx \frac{7A}{Z} g \times cm^{-2}$$

Gives the average lateral deflection of electrons of critical energy after $1X_0$

- 90% of shower energy contained in a cylinder of $1R_m$
- 95% of shower energy contained in a cylinder of $2R_m$
- 99% of shower energy contained in a cylinder of $3.5R_m$

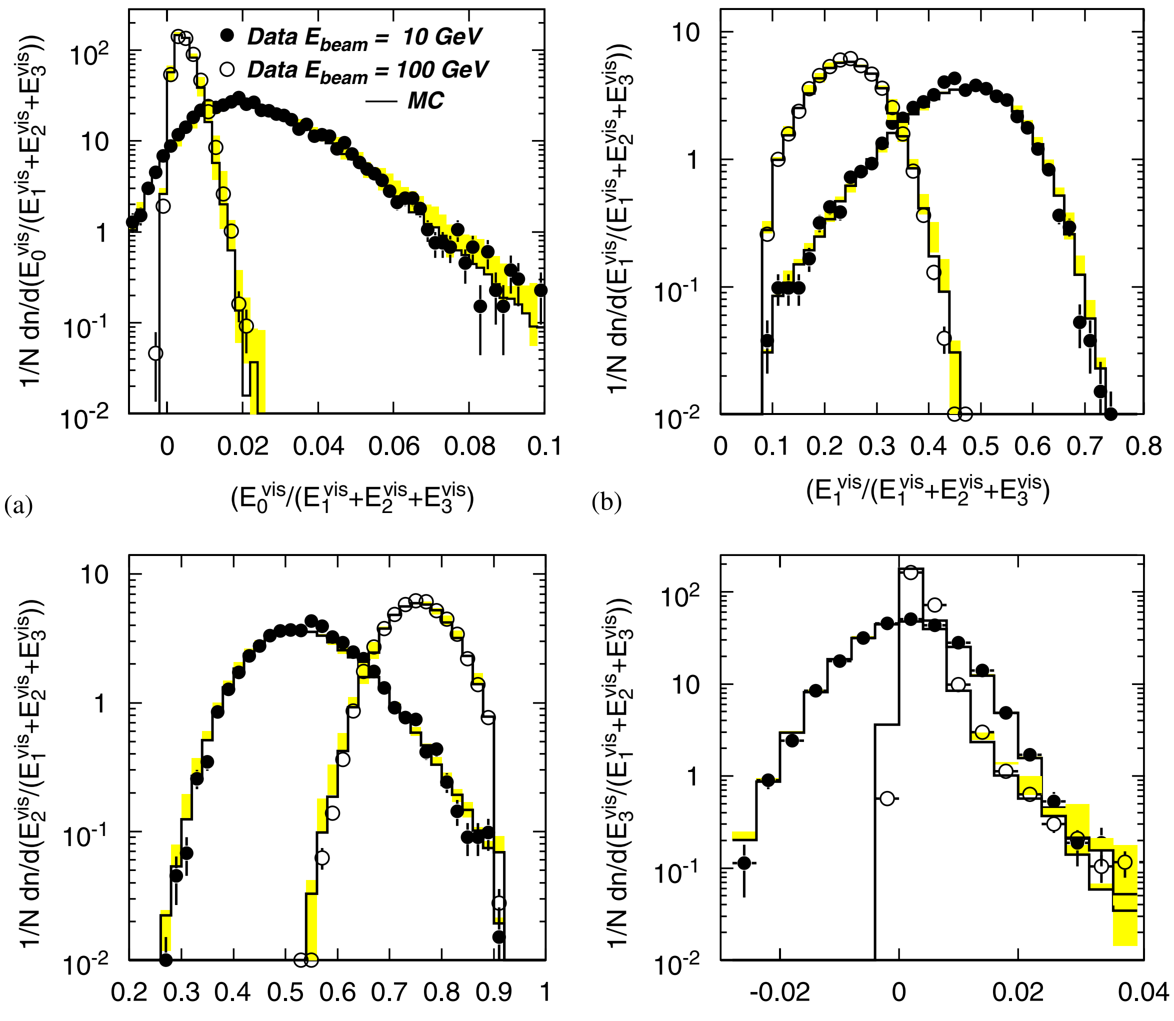




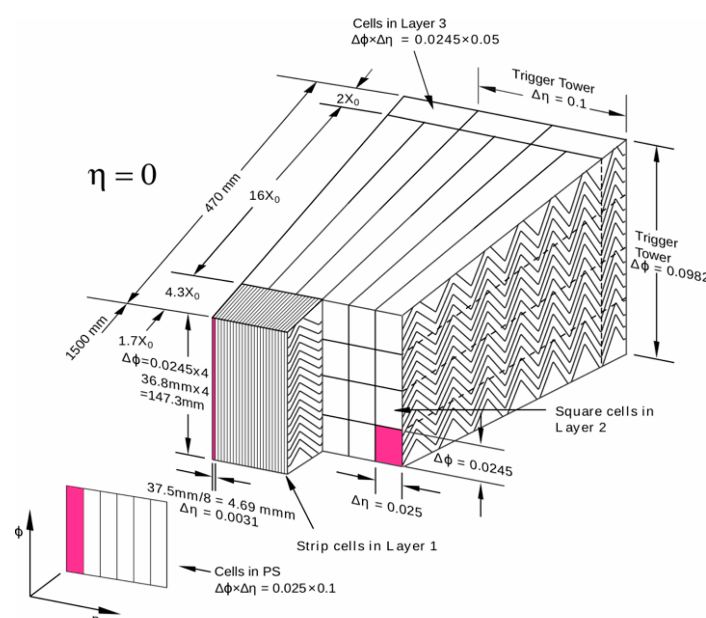
EM shower simulations

Electromagnetic processes are well understood and can be very well reproduced by MC simulation:

A key element in understanding detector performance



ATLAS EM calorimeter testbeam



PROPERTIES of ELECTROMAGNETIC CALORIMETERS

Material	Z	Density [g cm^{-3}]	E_c [MeV]	X_0 [mm]	ρ_M [mm]	λ_{int} [mm]	$(dE/dx)_{mip}$ [MeV cm^{-1}]
C	6	2.27	83	188	48	381	3.95
Al	13	2.70	43	89	44	390	4.36
Fe	26	7.87	22	17.6	16.9	168	11.4
Cu	29	8.96	20	14.3	15.2	151	12.6
Sn	50	7.31	12	12.1	21.6	223	9.24
W	74	19.3	8.0	3.5	9.3	96	22.1
Pb	82	11.3	7.4	5.6	16.0	170	12.7
^{238}U	92	18.95	6.8	3.2	10.0	105	20.5
Concrete	-	2.5	55	107	41	400	4.28
Glass	-	2.23	51	127	53	438	3.78
Marble	-	2.93	56	96	36	362	4.77
Si	14	2.33	41	93.6	48	455	3.88
Ge	32	5.32	17	23	29	264	7.29
Ar (liquid)	18	1.40	37	140	80	837	2.13
Kr (liquid)	36	2.41	18	47	55	607	3.23
Polystyrene	-	1.032	94	424	96	795	2.00
Plexiglas	-	1.18	86	344	85	708	2.28
Quartz	-	2.32	51	117	49	428	3.94
Lead-glass	-	4.06	15	25.1	35	330	5.45
Air 20°, 1 atm	-	0.0012	87	304 m	74 m	747 m	0.0022
Water	-	1.00	83	361	92	849	1.99

TOWARDS ELECTROMAGNETIC CALORIMETERS

Detectable signal is proportional to the number of potentially detectable particles in the shower $N_{tot} \propto E_0/E_c$

Total track length $T_0 = N_{tot} \,.\, X_0 \sim E_0/E_c \,.\, X_0$

$$\frac{\sigma(E)}{E} \propto \frac{1}{\sqrt{T_0}} \propto \frac{1}{\sqrt{E}}$$

Detectable track length $T_r = f_s \,.\, T_0$ where f_s is the fraction of N_{tot} which can be detected by the involved detection process (Cerenkov light, scintillation light, ionization) $E_{kin} > E_{th}$

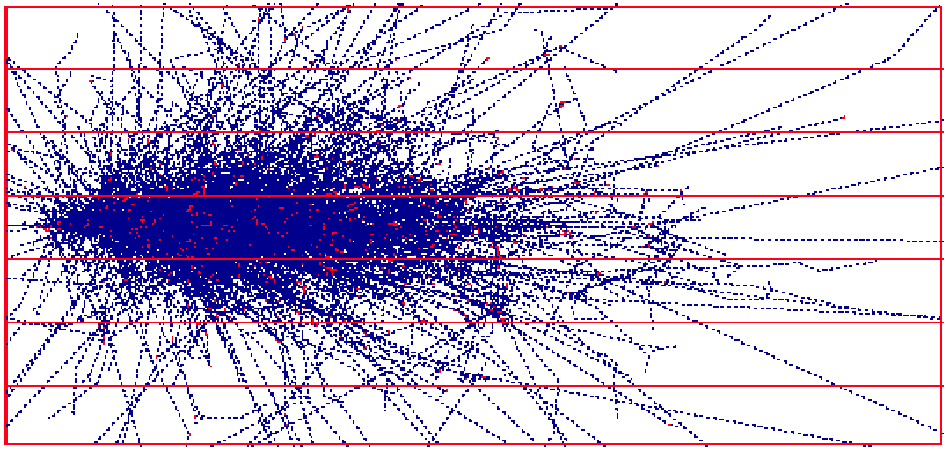
$$\frac{\sigma(E)}{E} \propto \frac{1}{\sqrt{E}} \frac{1}{\sqrt{f_S}}$$

Converting back to materials ($X_0 \propto A/Z^2$, $E_c \propto 1/Z$) and fixing E

- Maximize detection f_s
- Minimize Z/A

$$\frac{\sigma(E)}{E} \propto \frac{1}{\sqrt{f_s}} \sqrt{\frac{E_C}{X_0}} \propto \frac{1}{\sqrt{f_s}} \sqrt{\frac{Z}{A}}$$

HOMOGENOUS CALORIMETERS



All the energy is deposited in the active medium

- Excellent energy resolution
- No longitudinal segmentation

All $e^{\pm}$ with $E_{kin} > E_{th}$ produce a signal

Scintillating crystals

$E_{th} \approx \beta . E_{gap} \sim$ eV

$\rightarrow 10^2 \div 10^4\ \gamma$/MeV

$\sigma/E \sim (1 \div 3)\%/\sqrt{E}$ (GeV)

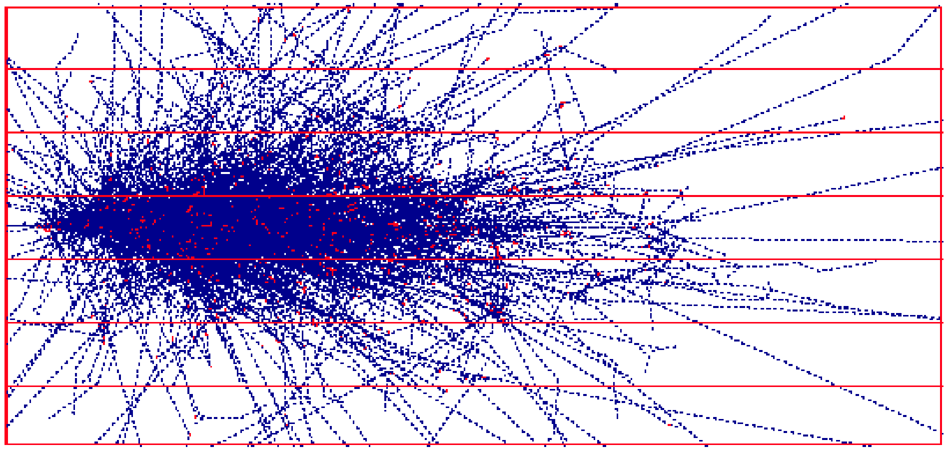
Cerenkov radiators

$\beta > 1/n \rightarrow E_{th} \approx 0.7$ MeV

$\rightarrow 10 \div 30\ \gamma$/MeV

$\sigma/E \sim (5 \div 10)\%/\sqrt{E}$ (GeV)

HOMOGENOUS CALORIMETERS



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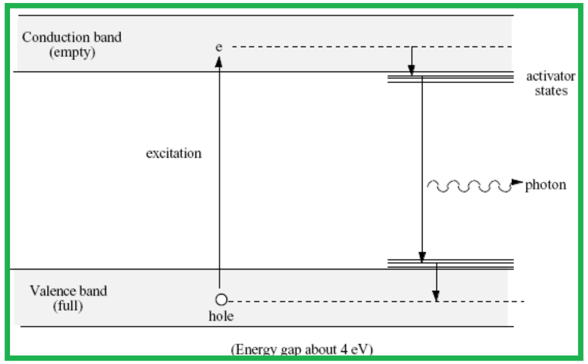

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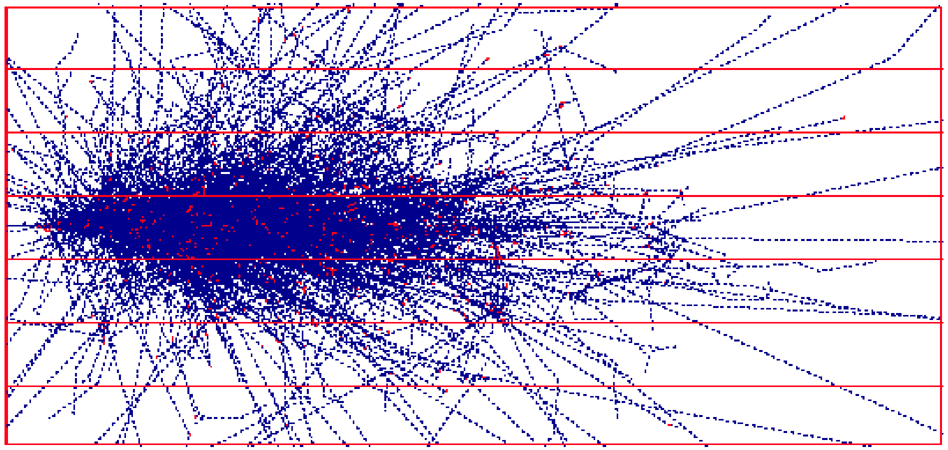

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All $e^{\pm}$ with $E_{kin} > E_{th}$ produce a signal

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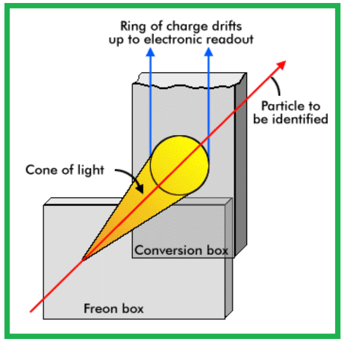

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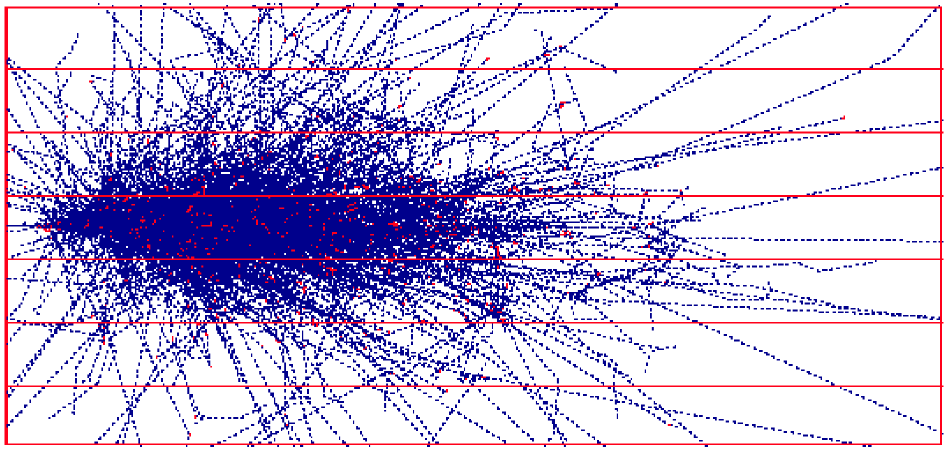

All the energy is deposited in the active medium

- Excellent energy resolution
- No longitudinal segmentation

All $e^{\pm}$ with $E_{kin} > E_{th}$ produce a signal

Scintillating crystals
$E_{th} \approx \beta . E_{gap} \sim$ eV
$\rightarrow 10^2 \div 10^4$ γ/MeV
$\sigma/E \sim (1 \div 3)\%/\sqrt{E}$ (GeV)

Cerenkov radiators
$\beta > 1/n \rightarrow E_{th} \approx 0.7$ MeV
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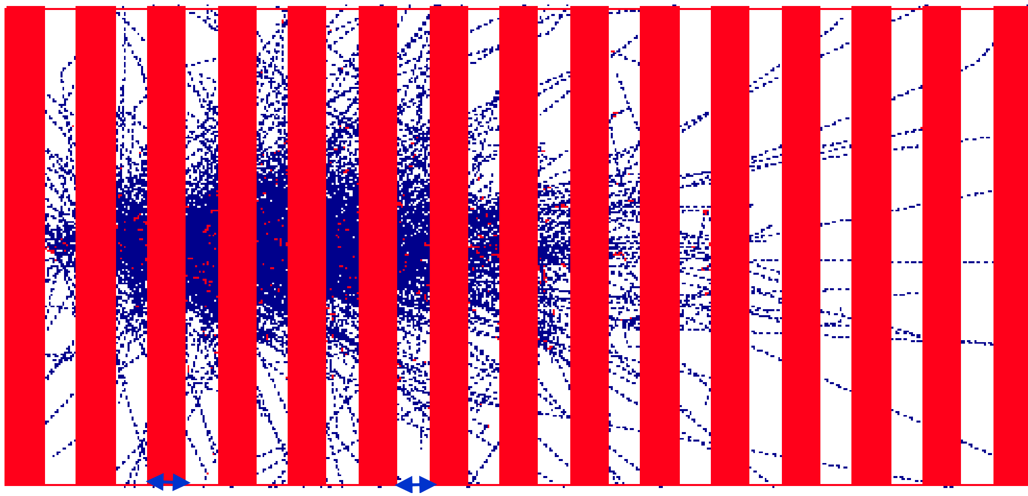
SAMPLING CALORIMETERS



Shower is sampled by layers of an active medium and dense radiator

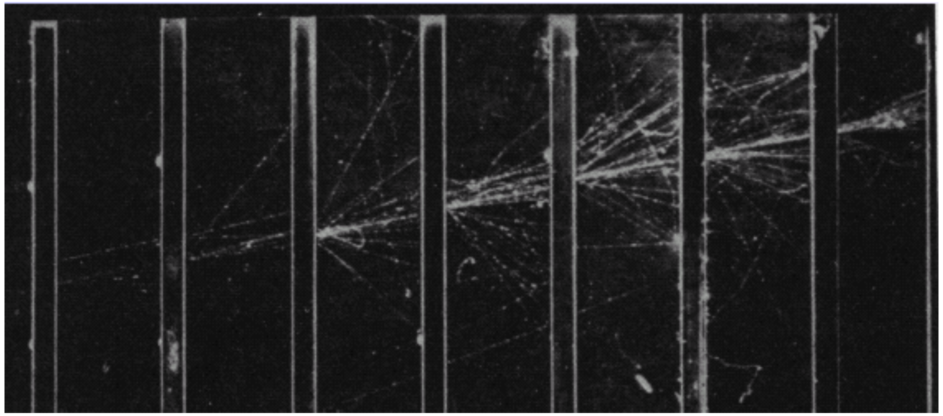
- Limited energy resolution
- Longitudinal segmentation

Only $e^{\pm}$ with $E_{kin} > E_{th}$ of the active layer produce a signal

Absorber (high Z): typically Lead, Uranium

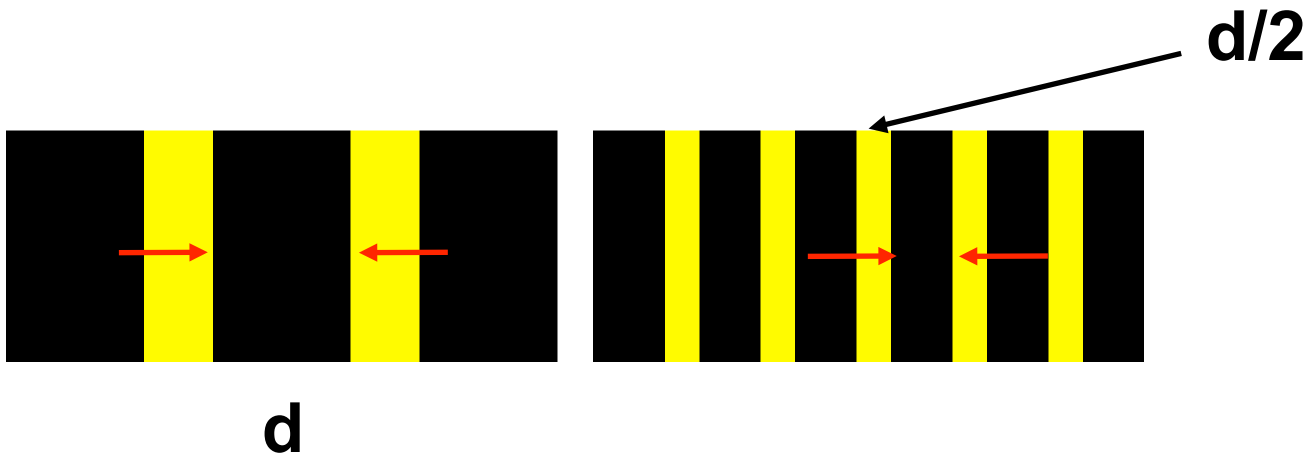
Active medium (low Z): typically Scinillators, Liquid Argon, Wire chamber

Energy resolution of sampling calorimeter dominated by fluctuations in energy deposited in the active layers



$$\sigma(E)/E \sim (10 \div 20)\%/\sqrt{E}\ (\mathrm{GeV})$$

SAMPLING FLUCTUATIONS



Most of detectable particles are produced in the absorber layers

Need to enter the active material to be counted/measured

Using the model of the track length

$T_r = f_s T_0 \sim f_s \,.\, E/E_c^{abs} \,.\, X_0^{abs}$

f_s: sampling fraction

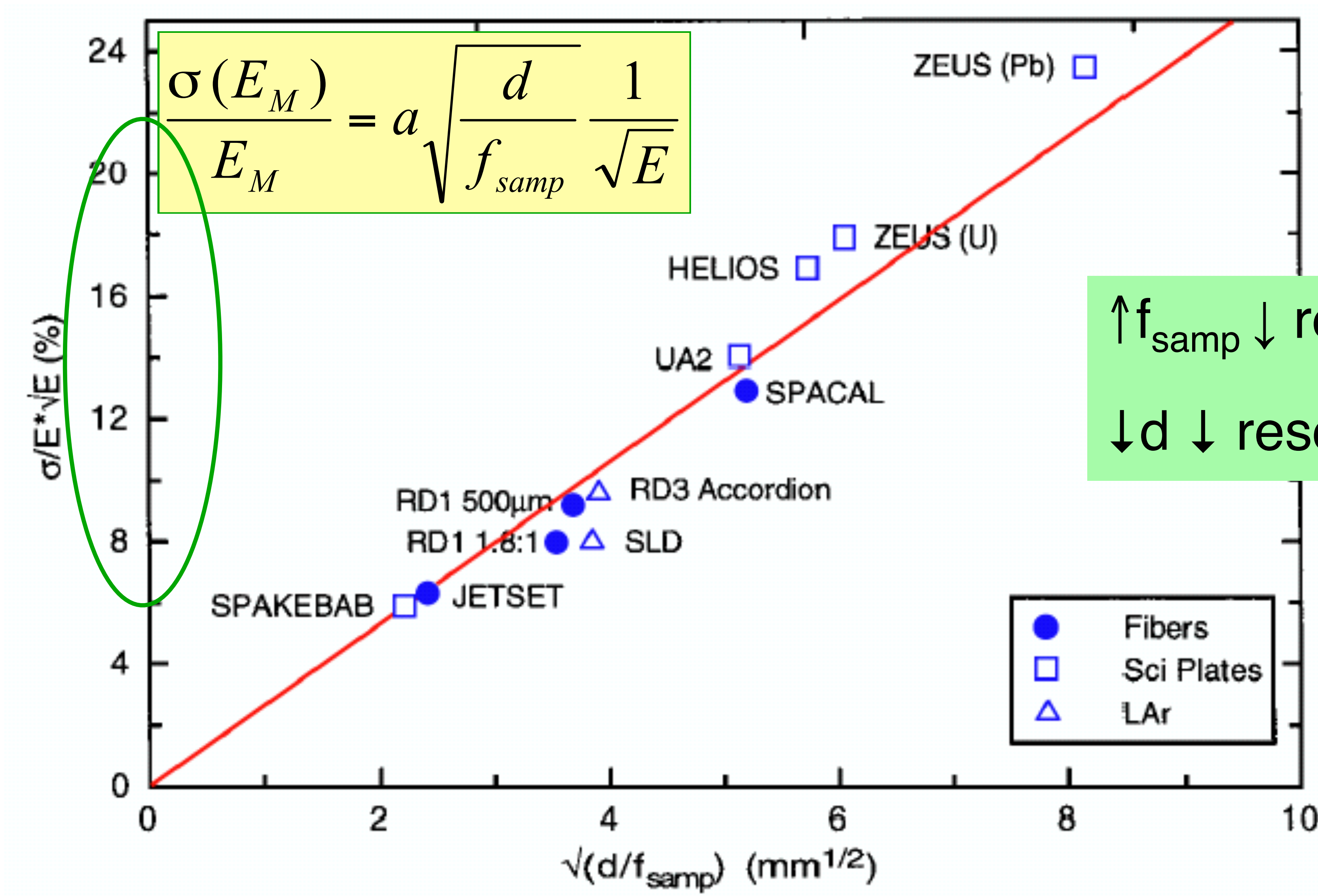
Number of detectable particles in active layer

$N_r = T_r/d = f_s \,.\, E/E_c^{abs} \,.\, X_0^{abs}/d$

Resolution scales like

$$\frac{\sigma(E_M)}{E_M} = a\sqrt{\frac{d}{f_{samp}}}\frac{1}{\sqrt{E}}$$

RESOLUTION FOR SAMPLING CALORIMETERS



$$\frac{\sigma(E_M)}{E_M} = a\sqrt{\frac{d}{f_{samp}}}\frac{1}{\sqrt{E}}$$

$\uparrow f_{samp} \downarrow$ resolution

$\downarrow d \downarrow$ resolution

ENERGY RESOLUTION

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

a the stochastic term accounts for Poisson-like fluctuations

- naturally small for homogeneous calorimeters
- takes into account sampling fluctuations for sampling calorimeters

b the noise term (hits at low energy)

- mainly the energy equivalent of the electronics noise
- at LHC in particular: includes fluctuation from non primary interaction (pile-up noise)

c the constant term (hits at high energy)

- Essentially detector non homogeneities like intrinsic geometry, calibration but also energy leakage

EXAMPLE

Take a Lead Glass crystal

E_c = 15 MeV

produces Cerenkov light

Cerenkov radiation is produced par $e^{\pm}$ with $\beta > 1/n$, i.e $E > 0.7$MeV

Take a 1 GeV electron

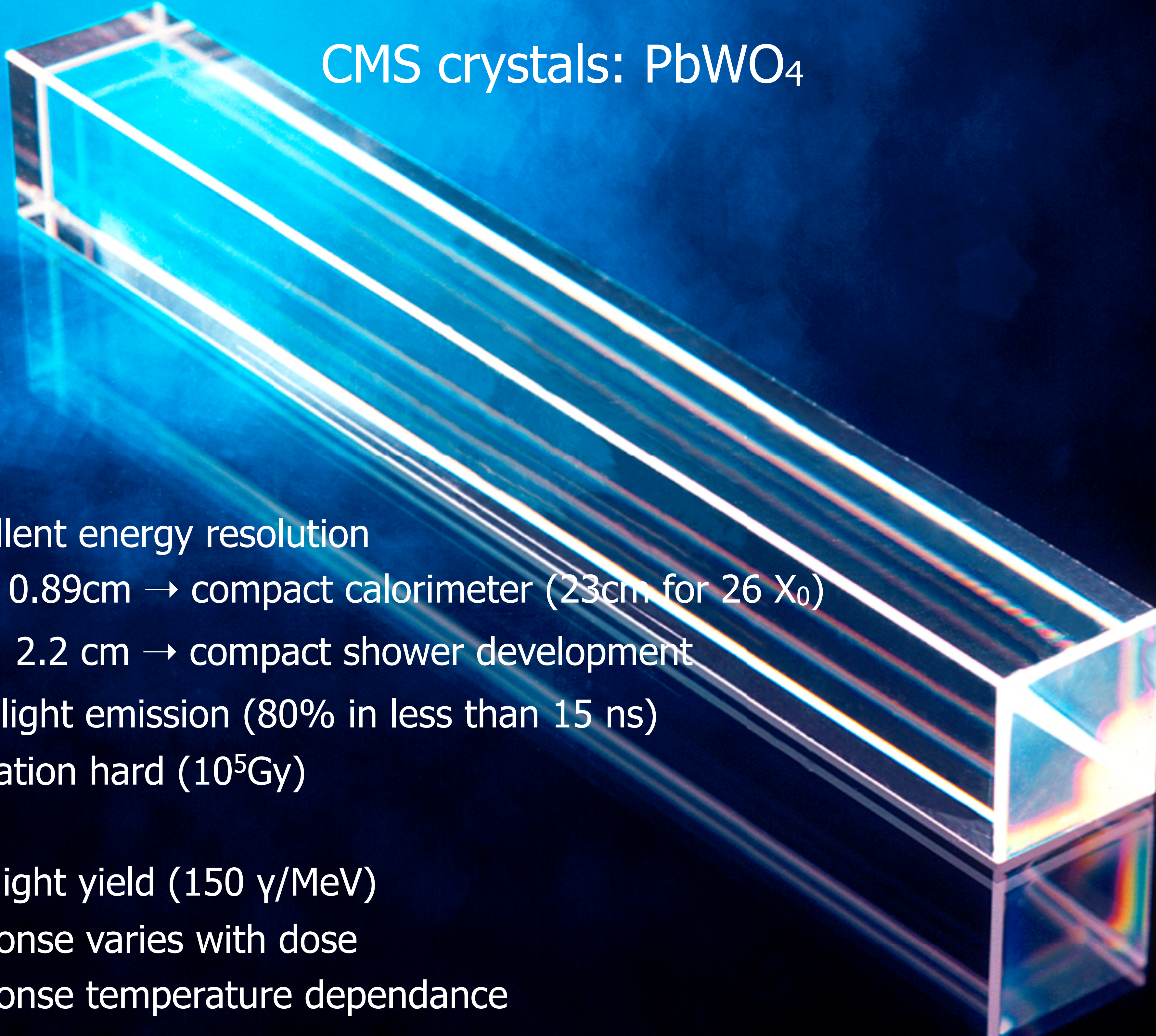
At maximum 1000 MeV/0.7 MeV $e^{\pm}$ will produce light

Fluctuation $1/\sqrt{1400} = 3\%$

One then has to take into account the photon detection efficiency which is typically 1000 photo-electrons/GeV: $1/\sqrt{1000} \sim 3\%$

Final resolution $\sigma/E \sim 5\%/\sqrt{E}$

CMS crystals: $PbWO_4$



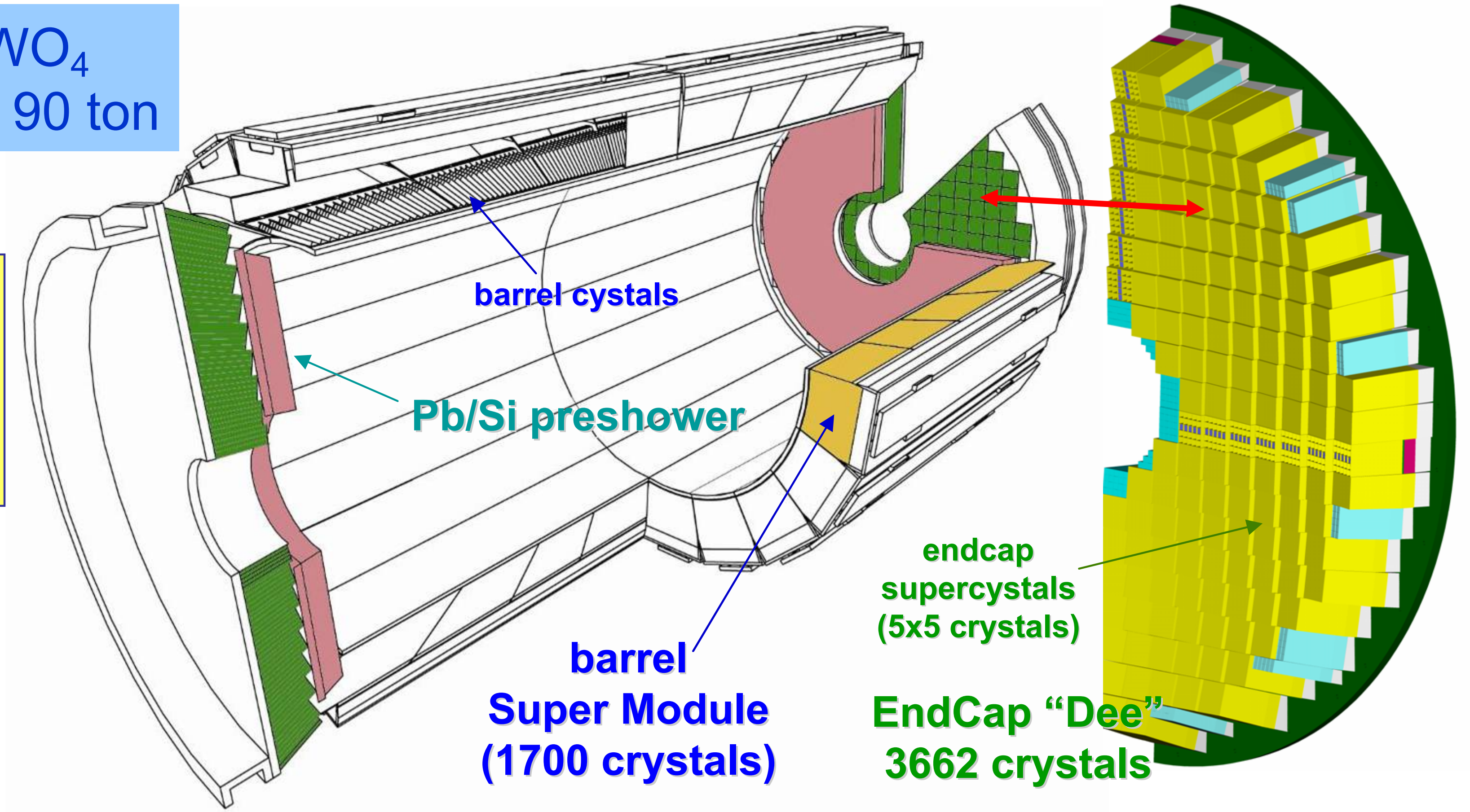
- Excellent energy resolution
  - X_0 = 0.89cm → compact calorimeter (23cm for 26 X_0)
  - R_M = 2.2 cm → compact shower development
  - Fast light emission (80% in less than 15 ns)
  - Radiation hard (10^5Gy)
- But
  - Low light yield (150 γ/MeV)
  - Response varies with dose
  - Response temperature dependance

ECAL @ CMS

Precision electromagnetic calorimetry: 75848 PWO crystals

PWO: $PbWO_4$
about 10 m^3, 90 ton

Previous Crystal calorimeters: max $1m^3$



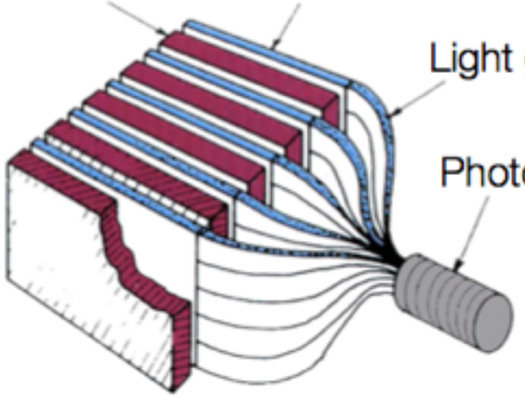
Barrel: $|\eta| < 1.48$
36 Super Modules
61200 crystals ($2x2x23cm^3$)

EndCaps: $1.48 < |\eta| < 3.0$
4 Dees
14648 crystals ($3x3x22cm^3$)

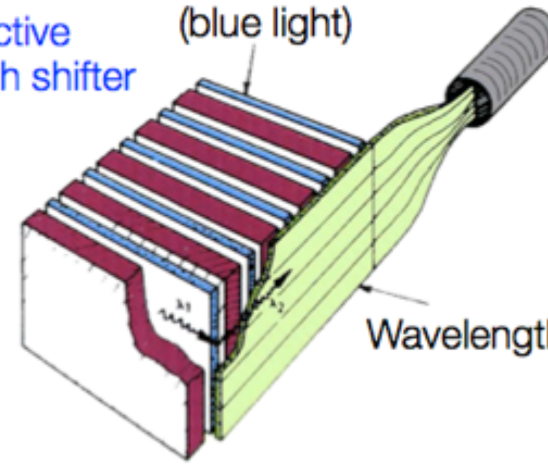
SAMPLING CALORIMETER

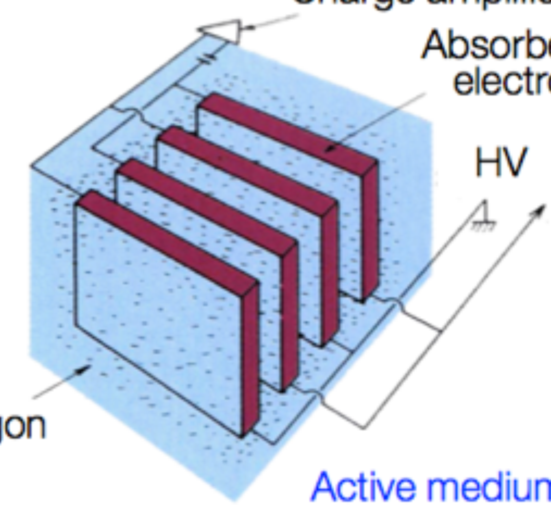
Possible setups

Scintillators as active layer;
signal readout via photo multipliers



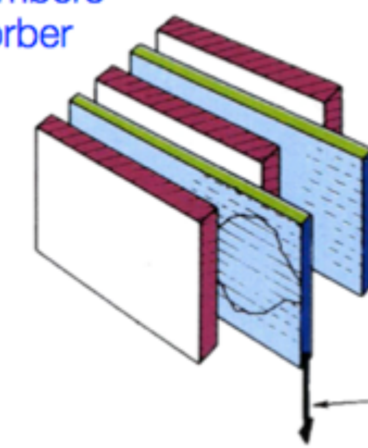
Scintillators as active
layer; wave length shifter
to convert light



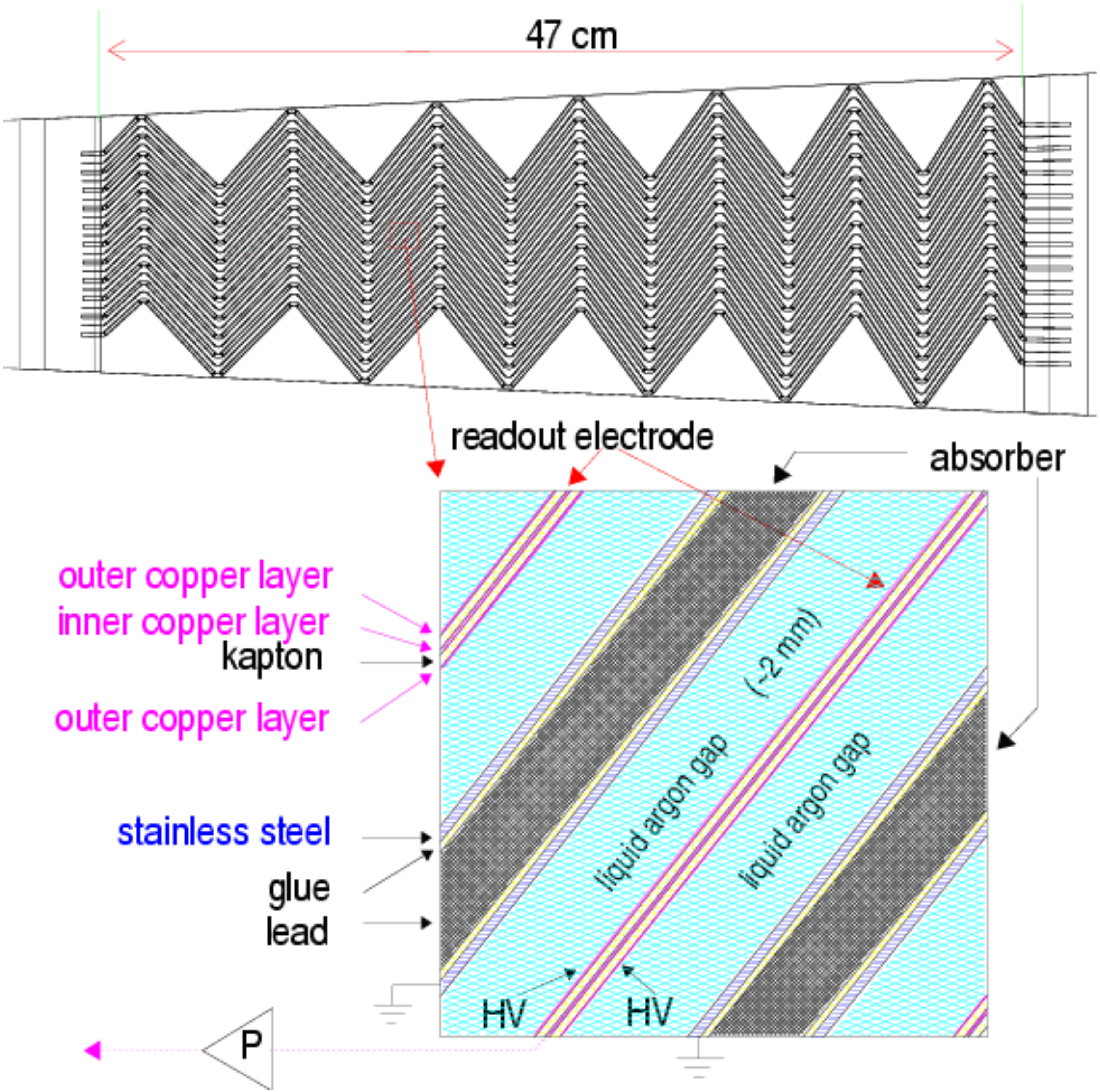


Active medium: LAr; absorber
embedded in liquid serve as electrods

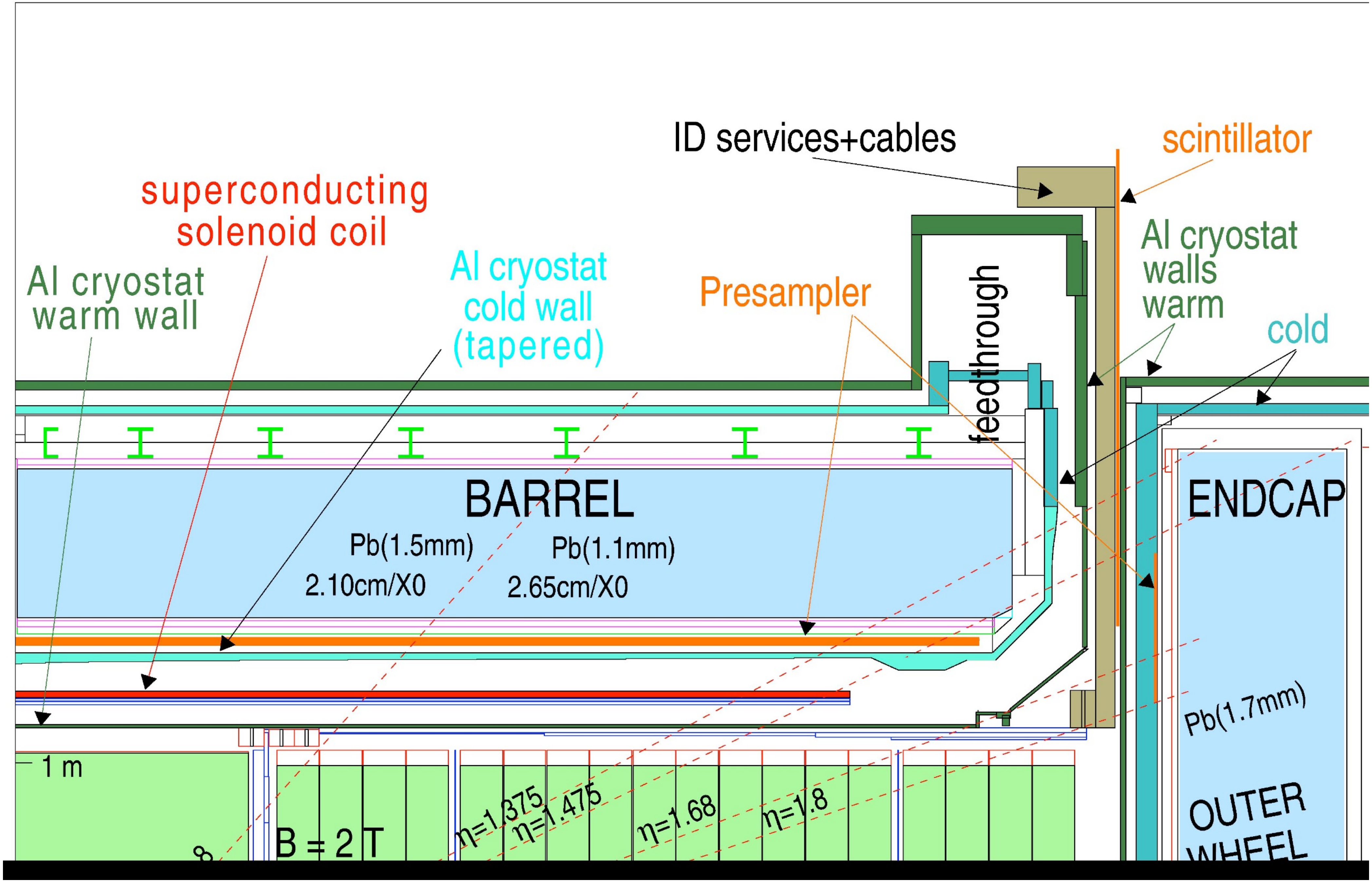
Ionization chambers
between absorber
plates



ATLAS LIQUID ARGON EM CALORIMETER



THE ATLAS CALORIMETER STRUCTURE



ATLAS ELECTROMAGNETIC CALORIMETER

Accordion Pb/LAr |η|<3.2 ~170k channels

Precision measurement |η|<2.5

3 layers up to |η|=2.5 + presampler |η|<1.8

2 layers 2.5<|η|<3.2

Layer 1 (γ/π^0 rej. + angular meas.)

$\Delta\eta.\Delta\varphi = 0.003 \times 0.1$

Layer 2 (shower max)

$\Delta\eta.\Delta\varphi$ = 0.025 x 0.0.25

Layer 3 (Hadronic leakage)

$\Delta\eta.\Delta\varphi$ = 0.05 x 0.0.025

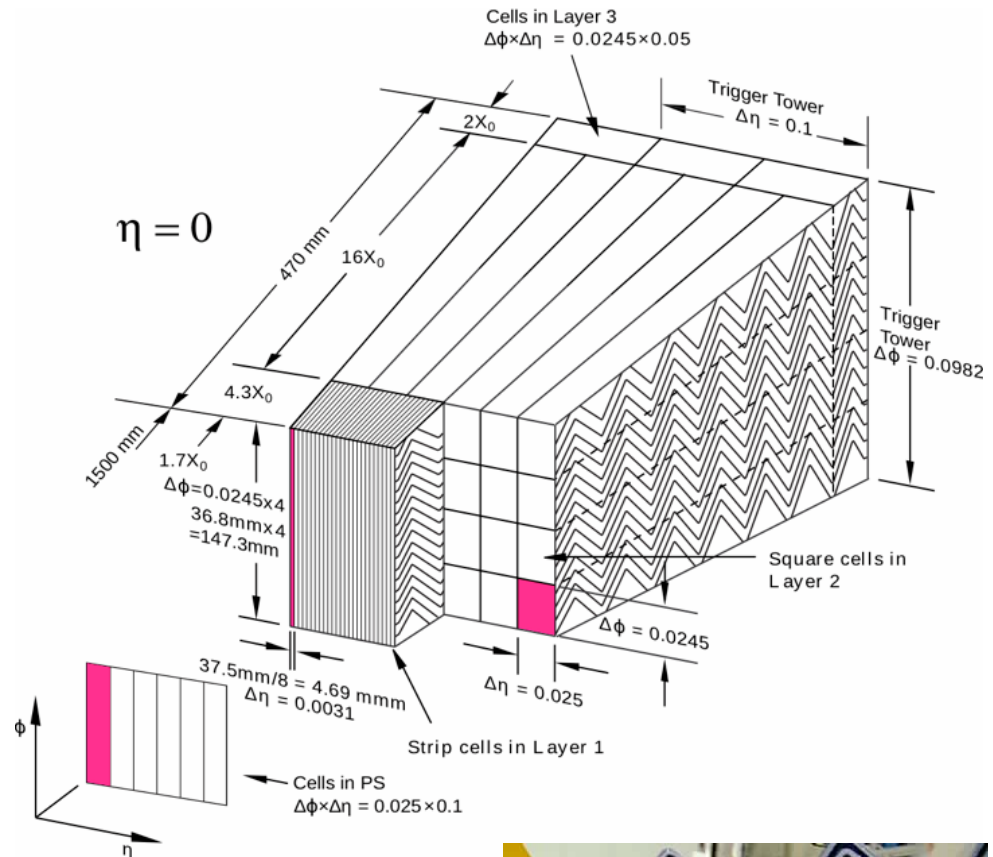
Energy Resolution: design for η~0

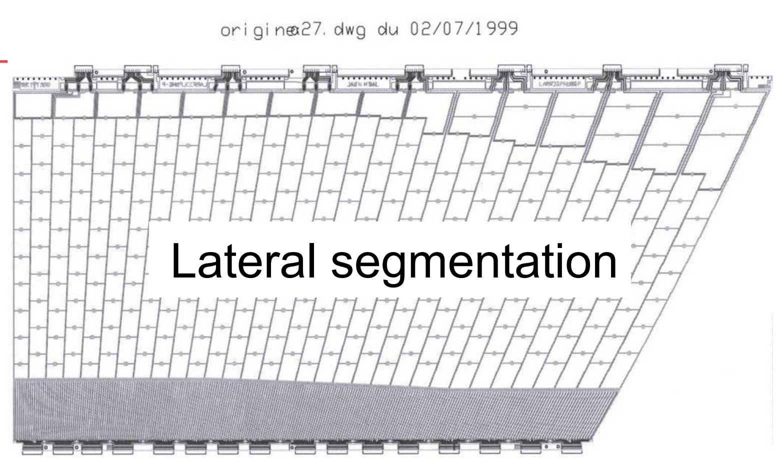
$\Delta E/E \sim 10\%/\sqrt{E} \oplus 150\ \text{MeV}/E \oplus 0.7\%$

Angular Resolution

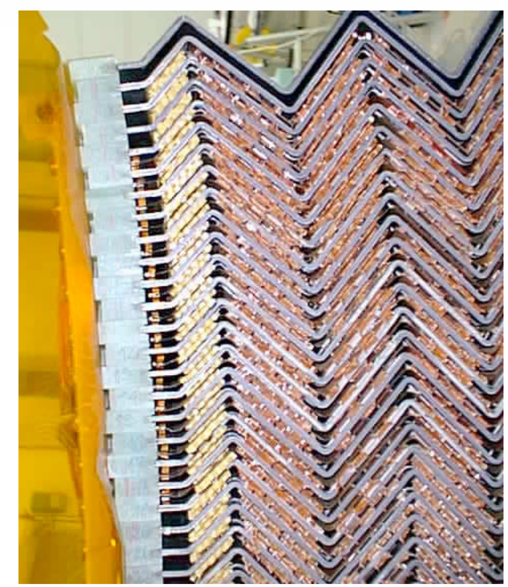
$50\text{mrad}/\sqrt{E(\text{GeV})}$

170k channels





Lateral segmentation

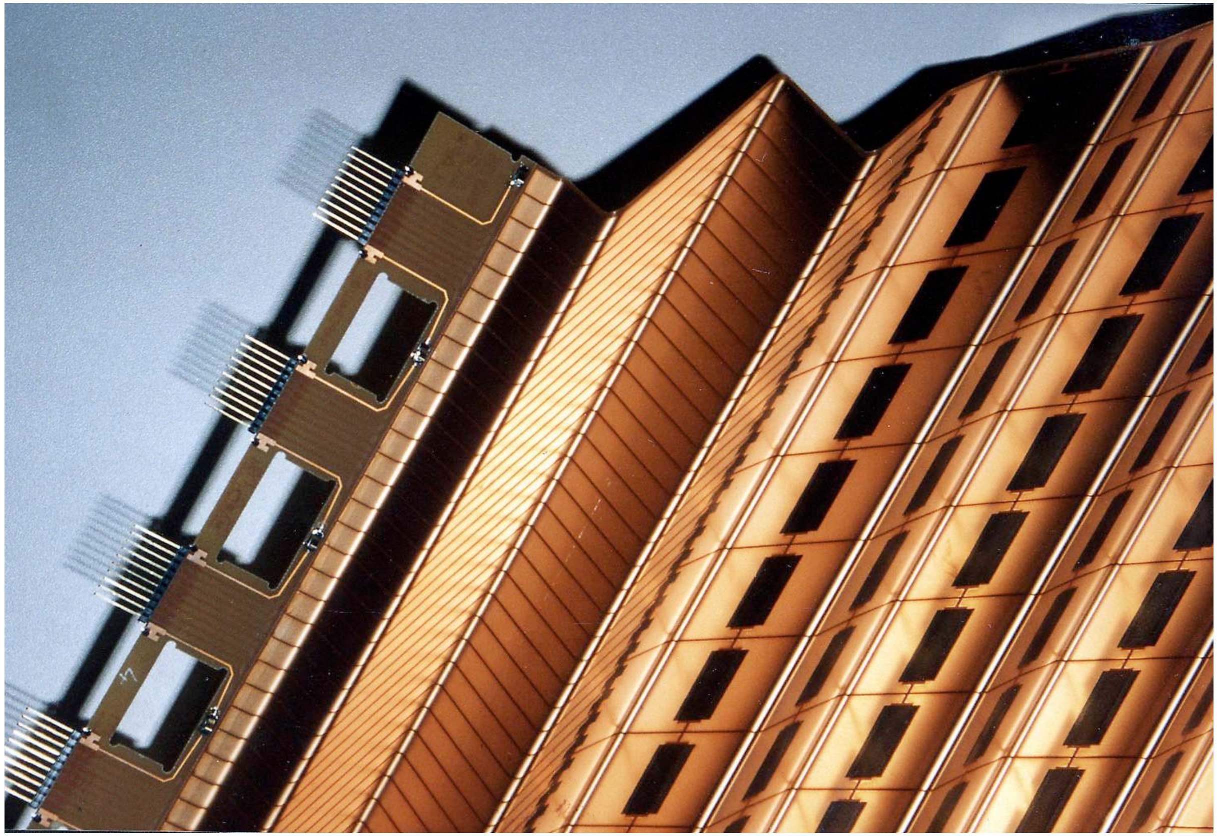


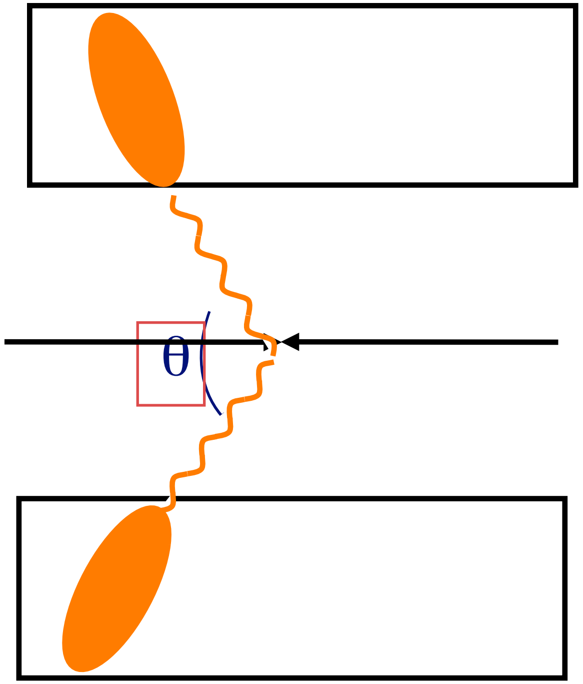
POSITION-ANGULAR RESOLUTION

Higgs Boson in ATLAS

For $M_H \sim 120$ GeV, in the channel $H \rightarrow \gamma\gamma$

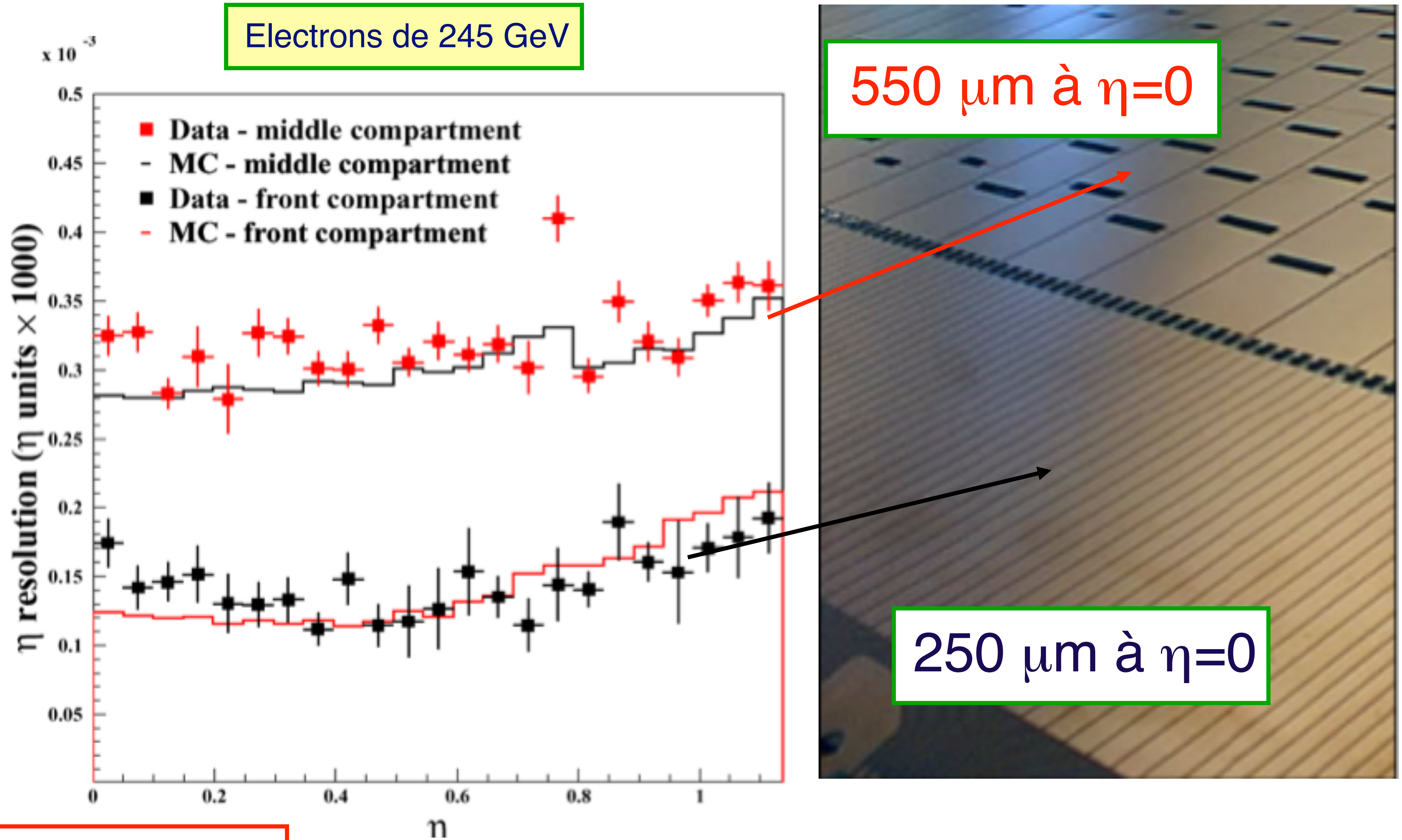
$\sigma(M_H) / M_H = \frac{1}{2} [\sigma(E_{\gamma 1})/E_{\gamma 1} \oplus \sigma(E_{\gamma 2})/E_{\gamma 2} \oplus \cot(\theta/2)\, \sigma(\theta)]$





$pp \rightarrow H + x \rightarrow \gamma\gamma + x$

SPATIAL RESOLUTION

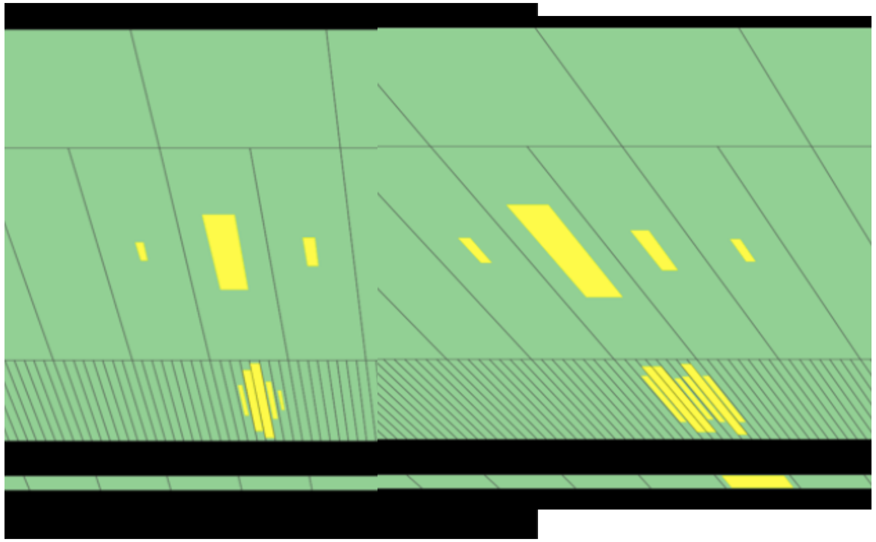


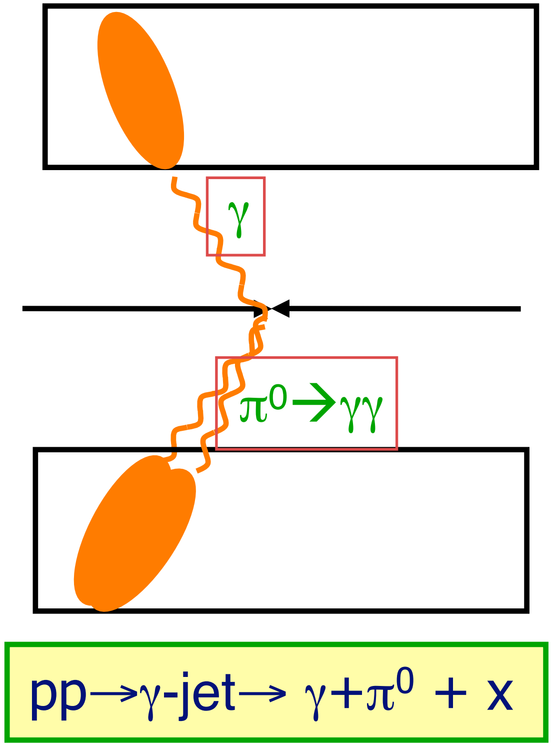
NIM A550 96-115 (2005)

PIONS REJECTION

Higgs boson in ATLAS

- With $M_H \sim 125$ GeV in the channel $H \rightarrow \gamma\gamma$
- Background: π^0 looking like a γ





HOMOGENEOUS vs SAMPLING CALORIMETERS

Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/E^{1/4}$	1983
$Bi_4Ge_3O_{12}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	16–$18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl) (BELLE)	$16X_0$	1.7% for $E_\gamma > 3.5$ GeV	1998
$PbWO_4$ (PWO) (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997
Lead glass (OPAL)	$20.5X_0$	$5\%/\sqrt{E}$	1990
Liquid Kr (NA48)	$27X_0$	$3.2\%/\sqrt{E} \oplus 0.42\% \oplus 0.09/E$	1998
Scintillator/depleted U (ZEUS)	20–$30X_0$	$18\%/\sqrt{E}$	1988
Scintillator/Pb (CDF)	$18X_0$	$13.5\%/\sqrt{E}$	1988
Scintillator fiber/Pb spaghetti (KLOE)	$15X_0$	$5.7\%/\sqrt{E} \oplus 0.6\%$	1995
Liquid Ar/Pb (NA31)	$27X_0$	$7.5\%/\sqrt{E} \oplus 0.5\% \oplus 0.1/E$	1988
Liquid Ar/Pb (SLD)	$21X_0$	$8\%/\sqrt{E}$	1993
Liquid Ar/Pb (H1)	20–$30X_0$	$12\%/\sqrt{E} \oplus 1\%$	1998
Liquid Ar/depl. U (DØ)	$20.5X_0$	$16\%/\sqrt{E} \oplus 0.3\% \oplus 0.3/E$	1993
Liquid Ar/Pb accordion (ATLAS)	$25X_0$	$10\%/\sqrt{E} \oplus 0.4\% \oplus 0.3/E$	1996

Homogeneous

Sampling

Resolution of typical electromagnetic calorimeter
[E is in GeV]

HADRONIC SHOWERS

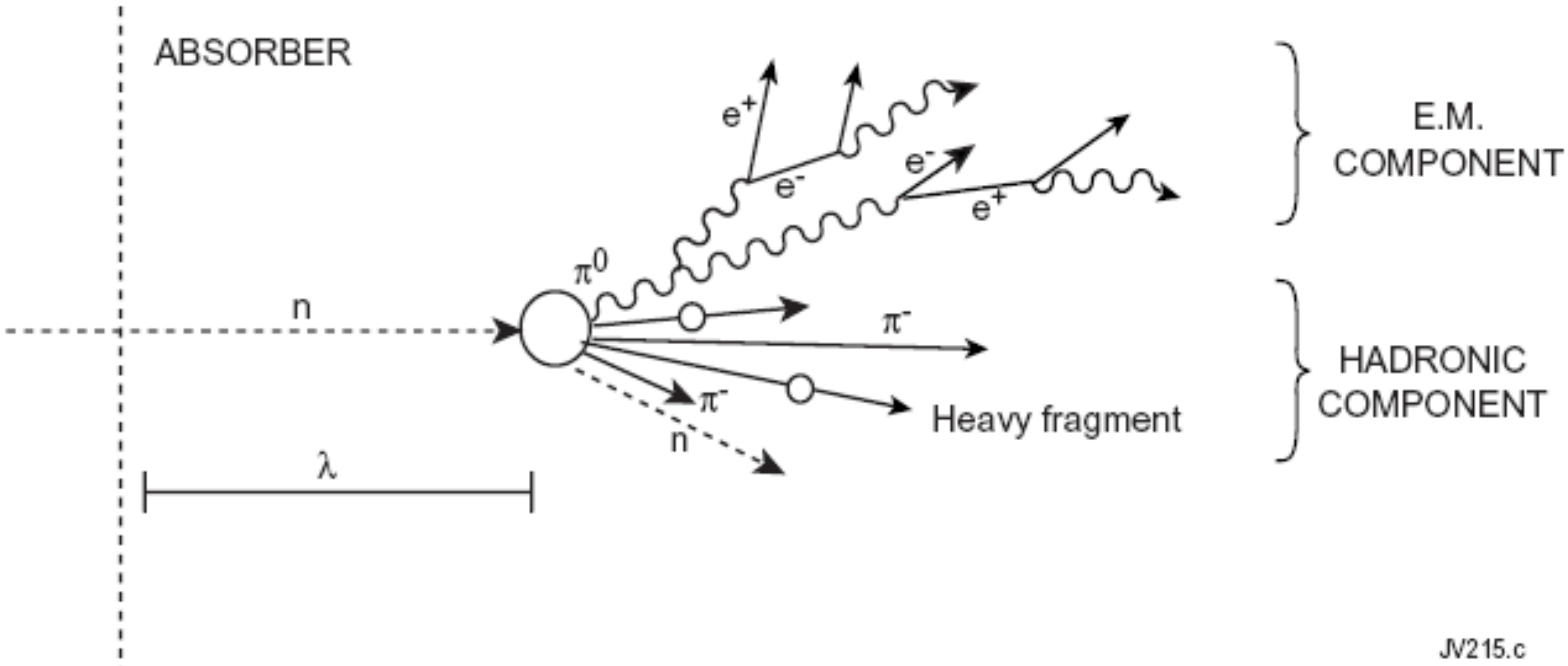
Hadronic cascades develop in an analogous way to e.m. showers

- Strong interaction controls overall development
- High energy hadron interacts with material, leading to multi-particle production of more hadrons
- These in turn interact with further nuclei
- Nuclear breakup and spallation neutrons
- Multiplication continues down to the pion production threshold
  - $E \sim 2m_\pi = 0.28\ \mathrm{GeV}/c^2$
- Neutral pions result in an electromagnetic component (immediate decay: $\pi^0 \rightarrow \gamma\gamma$) (also: $\eta \rightarrow \gamma\gamma$)

Energy deposited by:

- Electromagnetic component (i.e. as for e.m. showers)
- Charged pions or protons
- Low energy neutrons
- Energy lost in breaking nuclei (nuclear binding energy)

HADRONIC CASCADE



As compared to electromagnetic showers, hadron showers are:

- Larger/more penetrating
- Subject to larger fluctuations – more erratic and varied

HADRONIC SHOWERS: WHERE DOES THE ENERGY GO ?

	Lead	*Iron*
Ionization by pions	19%	21%
Ionization by protons	37%	53%
Total ionization	56%	74%
Nuclear binding energy loss	32%	16%
Target recoil	2%	5%
Total invisible energy	34%	21%
Kinetic energy evaporation neutrons	10%	5%
Number of charged pions	0.77	1.4
Number of protons	3.5	8
Number of cascade neutrons	5.4	5
Number of evaporation neutrons	31.5	5
Total number of neutrons	36.9	10
Neutrons/protons	10.5/1	1.3/1

HADRONIC INTERACTION

Simple model of interaction on a disk of radius R: $\sigma_{int} = \pi R^2 \propto A^{2/3}$

$\sigma_{inel} \approx \sigma_0 A^{0.7}$, σ_0 = 35 mb

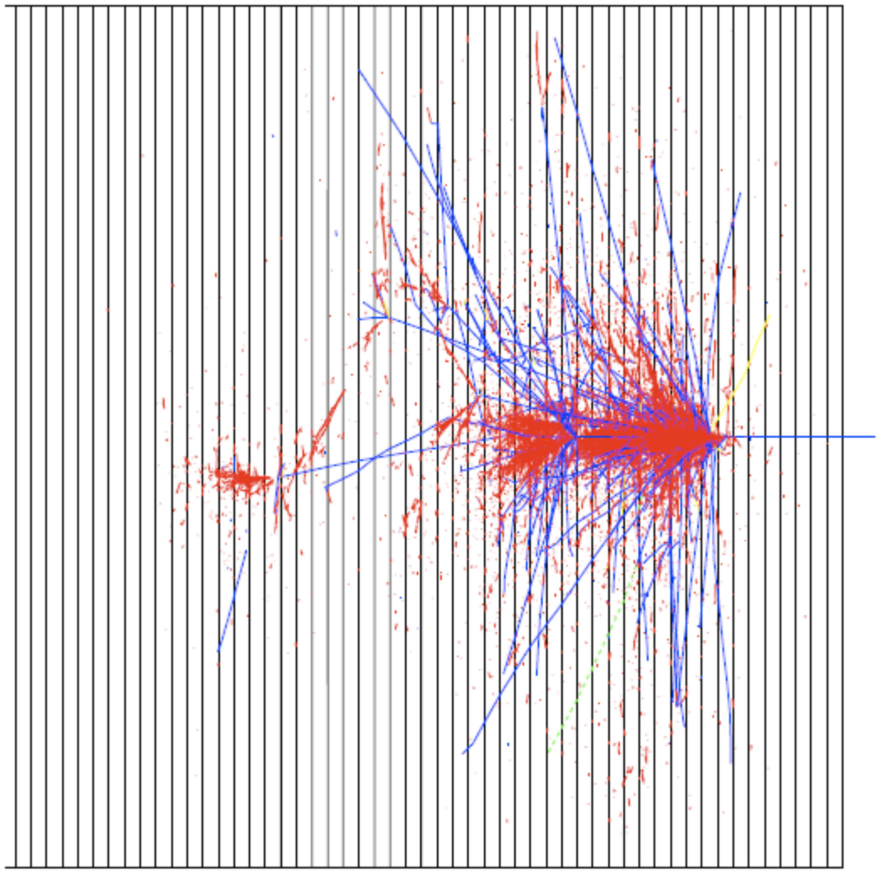
Nuclear interaction length: mean free path before inelastic interaction

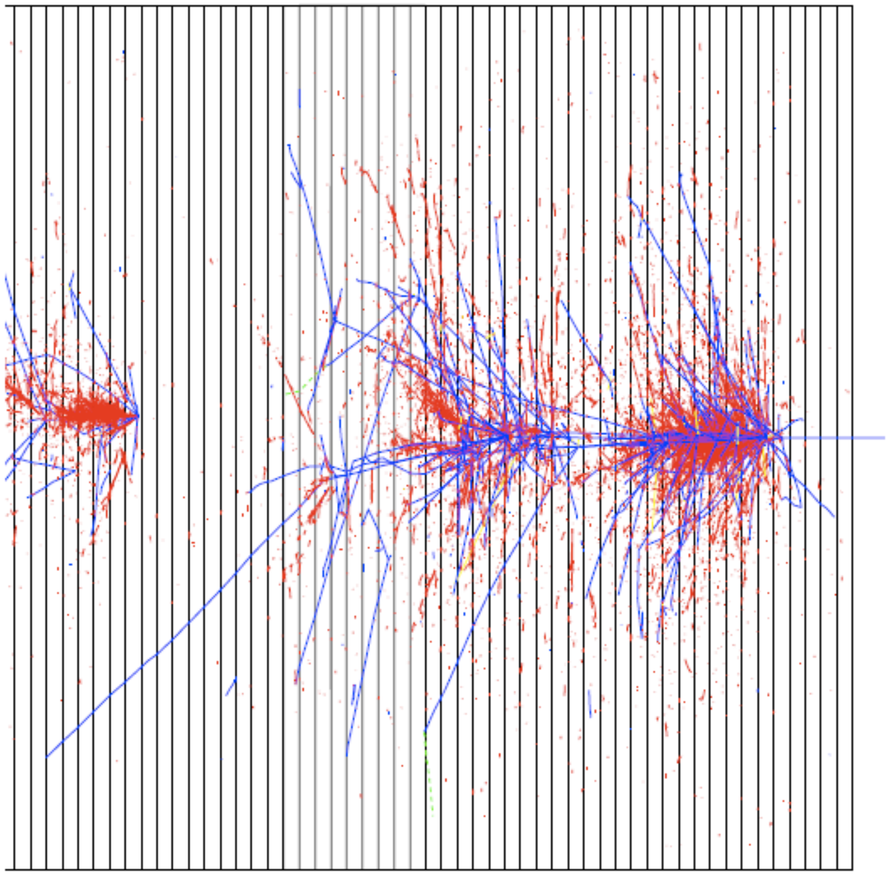
$$\lambda_{int} \approx \frac{A}{N_A \sigma_{int}} \approx 35 A^{1/3} g \times cm^{-2}$$

	Z	ρ (g.cm^{-3})	E_c (MeV)	X_0 (cm)	λ_{int} (cm)
Air				30 420	~70 000
Water				36	84
$PbWO_4$		8.28		0.89	22.4
C	6	2.3	103	18.8	38.1
Al	13	2.7	47	8.9	39.4
L Ar	18	1.4		14	84
Fe	26	7.9	24	1.76	16.8
Cu	29	9	20	1.43	15.1
W	74	19.3	8.1	0.35	9.6
Pb	82	11.3	6.9	0.56	17.1
U	92	19	6.2	0.32	10.5

HADRONIC SHOWERS

1. Individual hadron showers are quite 2. similar





red - e.m. component
blue - charged hadrons

HADRONIC SHOWERS and NON-COMPENSATION

$$R_h = \varepsilon_e E_e \quad + \quad \varepsilon_h E_h$$

- R_h: Response to hadrons
- ε_e: fract. of detected EM energy
- E_e: shower EM energy
- ε_h: fract. of detected HAD energy
- E_h: shower HAD enerrgy

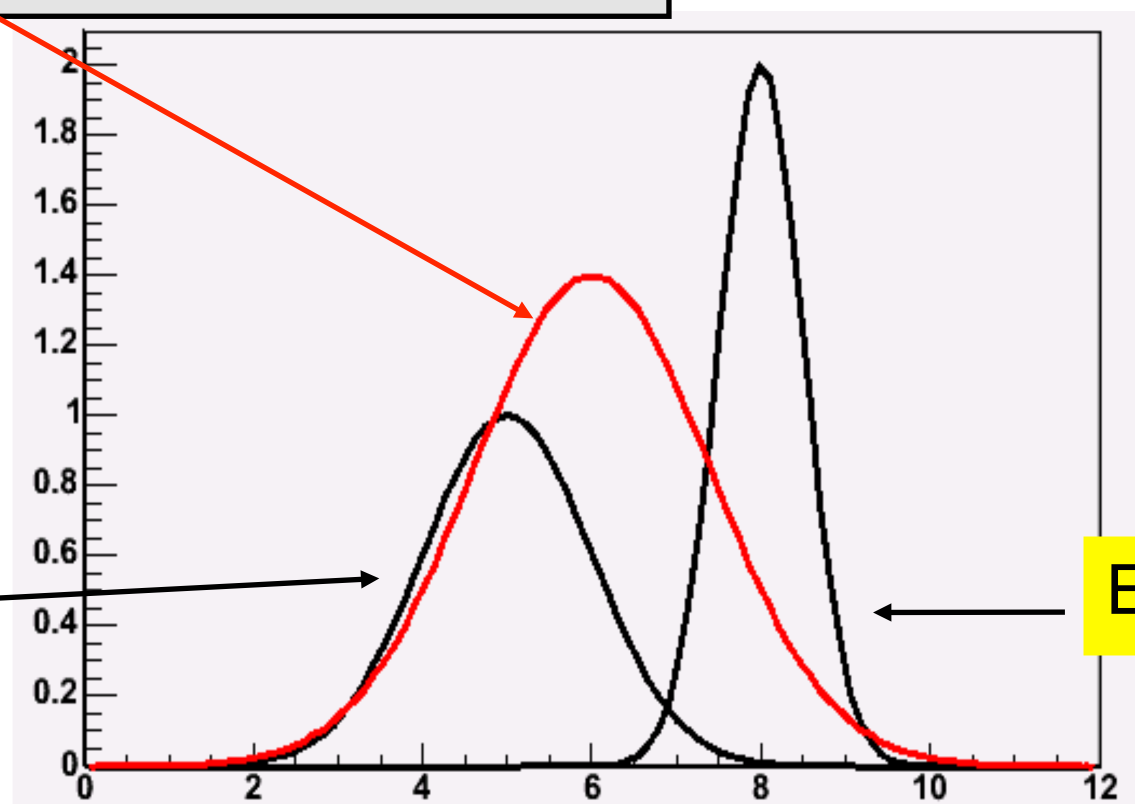
$$\frac{e}{h} = \frac{\varepsilon_e}{\varepsilon_h}$$

- ≈ 1 : compensating calorimeter
- > 1 : non compensating calorimter

HADRONIC SHOWERS and NON-COMPENSATION

$$R_h = \varepsilon_e E_e \quad + \quad \varepsilon_h E_h$$

$$\varepsilon_e > \varepsilon_h$$



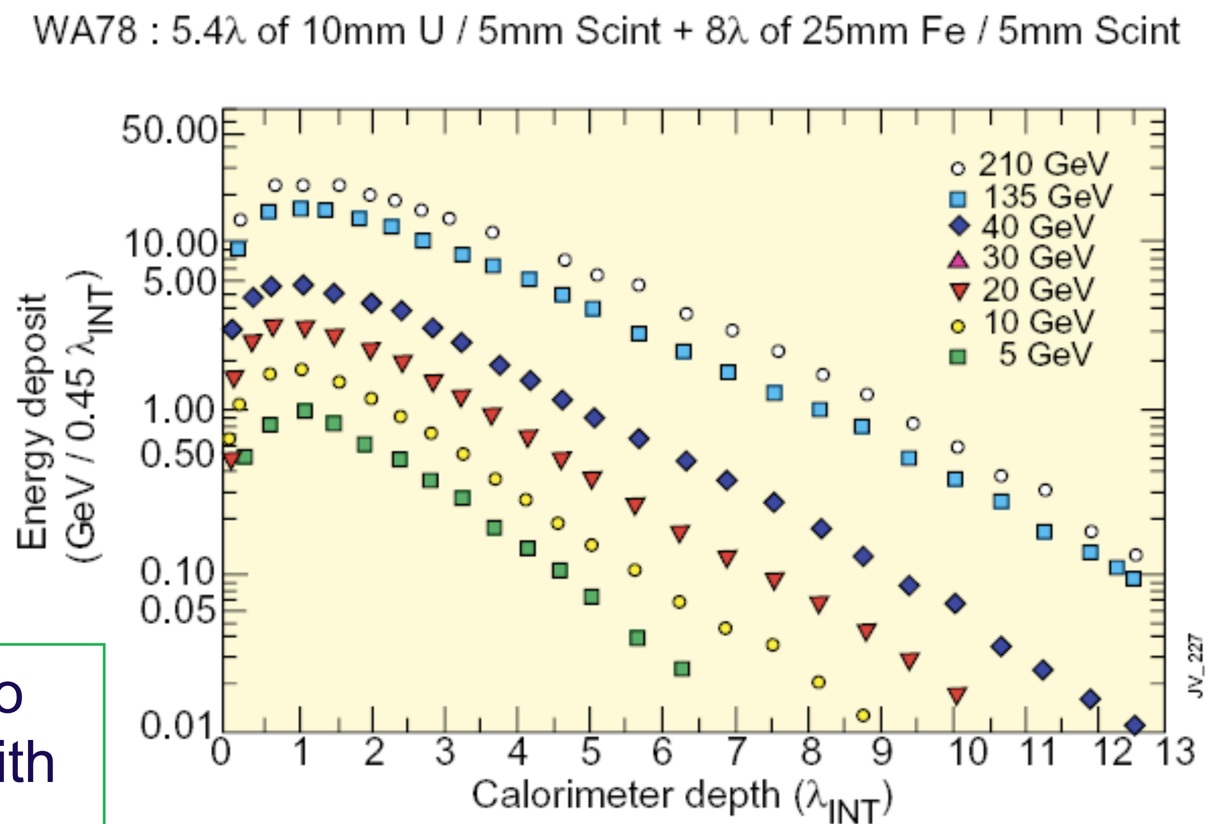
$E_e \ll E_h$

$E_e \gg E_h$

HADRONIC SHOWER LONGITUDINAL DEVELOPMENT

Longitudinal profile

- Initial peak from π^0s produced in the first interaction length
- Gradual falloff characterised by the nuclear interaction length, λ_{int}



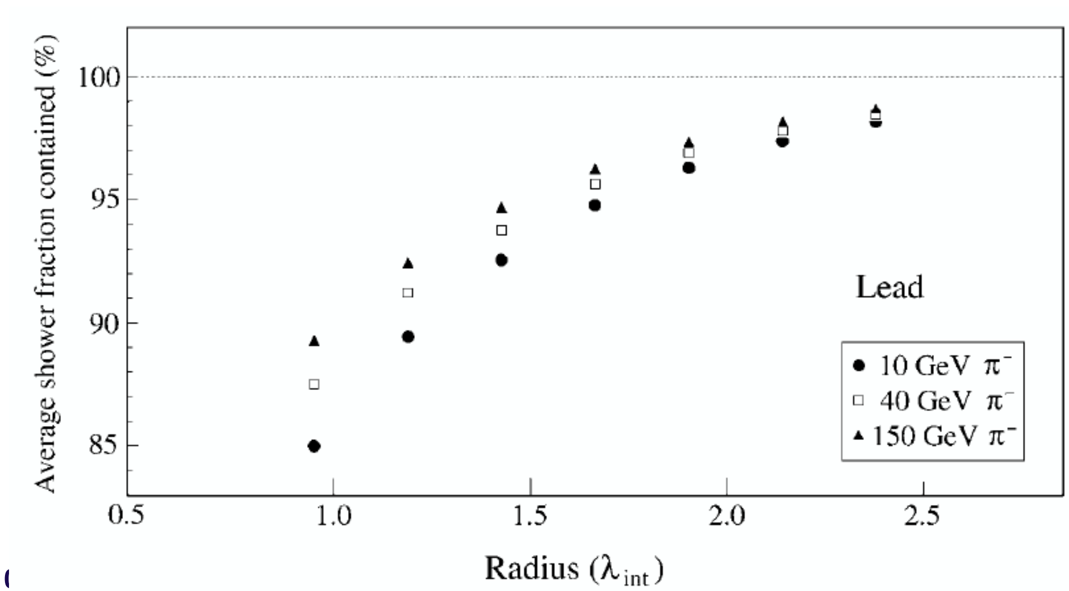
As with e.m. showers: depth to contain a shower increases with log(E)

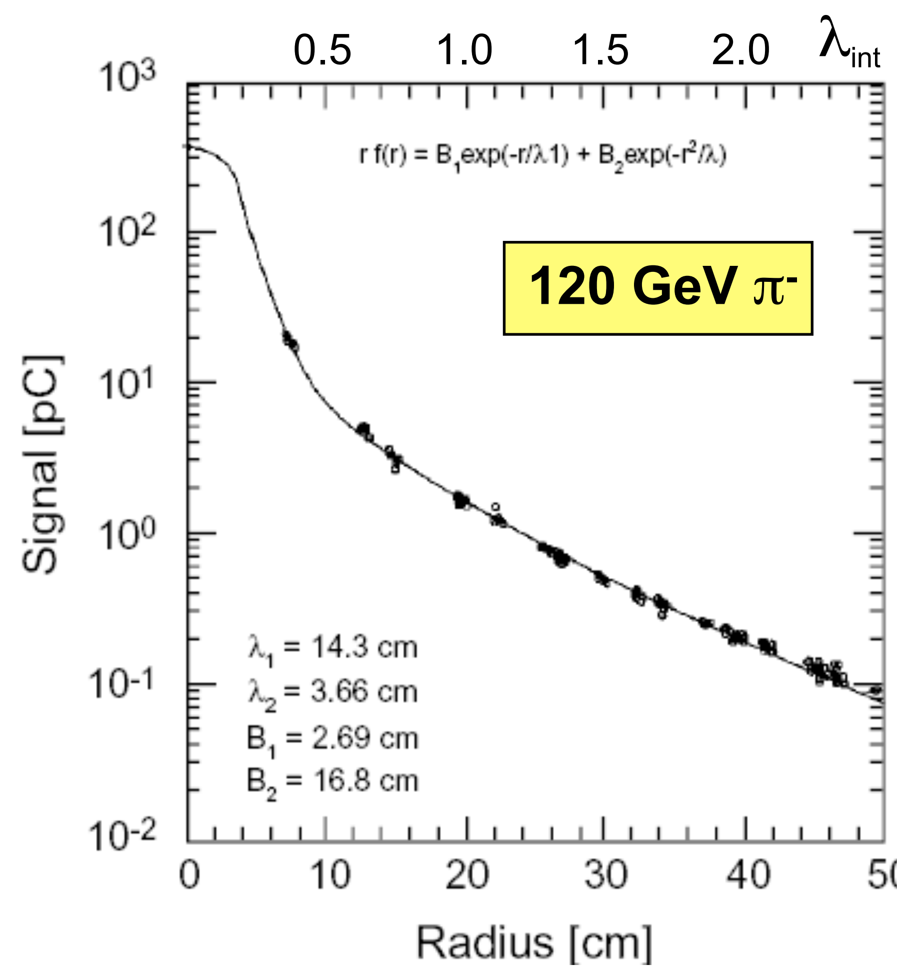
HADRONIC SHOWERS TRANSVERSE PROFILE

Mean transverse momentum from interactions, $\langle p_T \rangle \sim 300$ MeV, is about the same magnitude as the energy lost traversing 1λ for many materials

So radial extent of the cascade is well characterized by λ

The π^0 component of the cascade results in an electromagnetic core





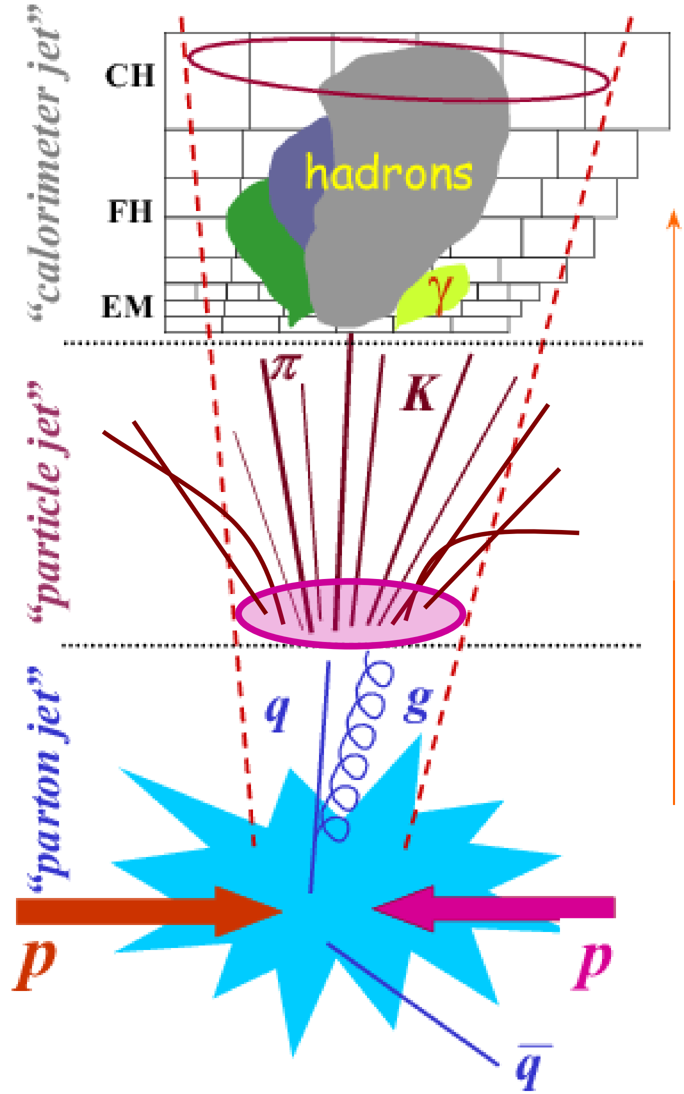
Lateral containment increases with energy

JETS at HIGH ENERGY COLLIDERS

At Hadronic Colliders, quarks & gluons produced, evolves (parton shower, hadronisation) to become jets

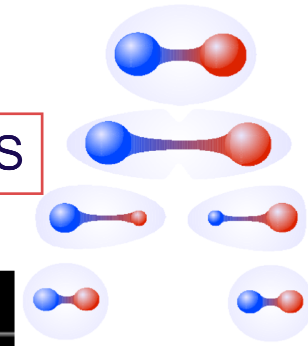
- In a cone around the initial parton: high density of hadrons
- LHC calorimeters cannot separate all the incoming hadrons
  - Use dedicated calibration schemes (based on simulation in ATLAS)
  - Use tracking system to identify charged hadrons (Particle Flow in CMS)

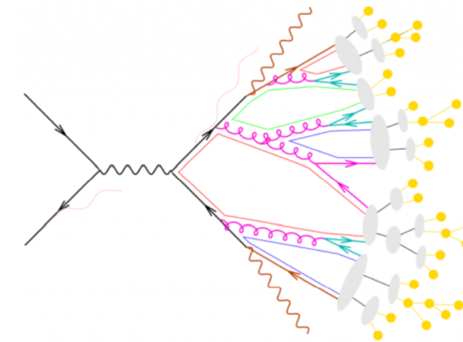
  - In the future, very highly segmented calorimeters

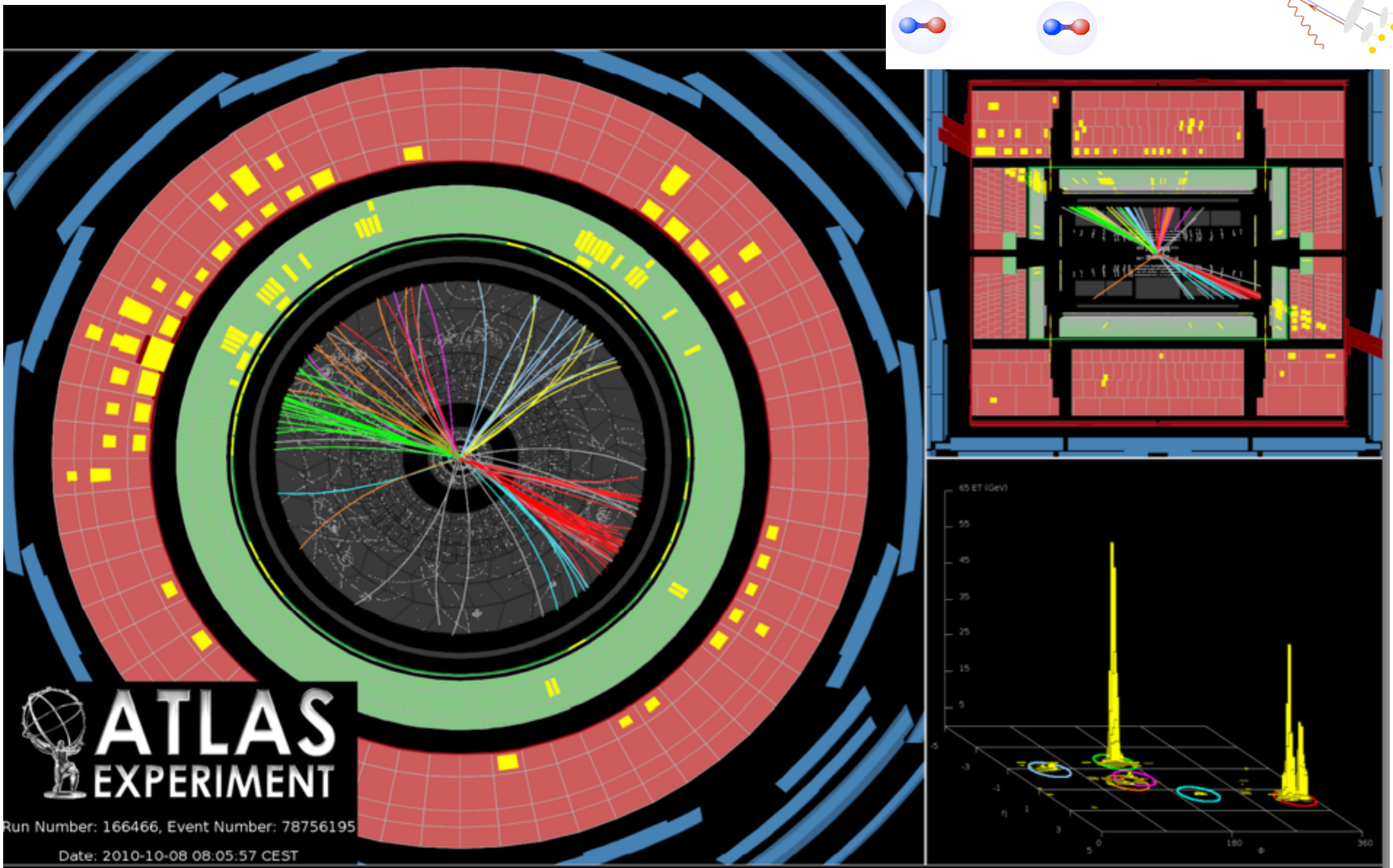


JETS

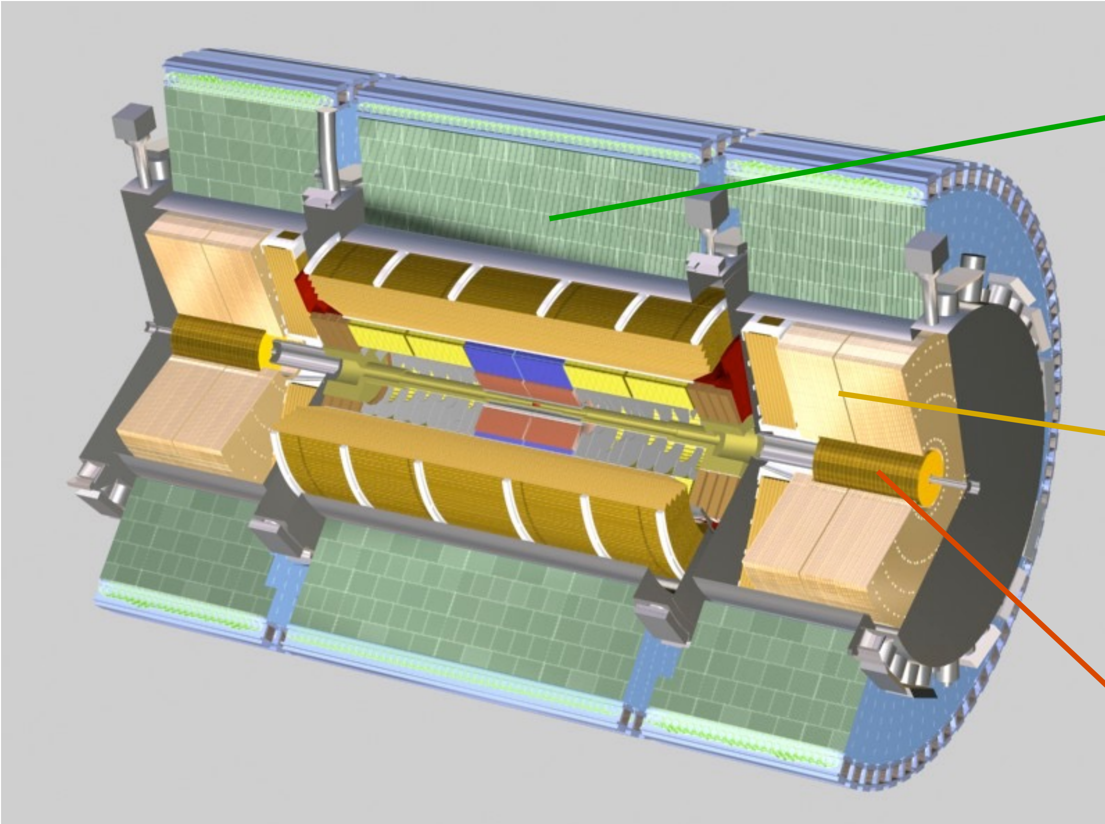
NEED a REFINED CALIBRATION PROCEDURE FOR JETS







ATLAS HADRON CALORIMETER



Tiles Calorimeter $|\eta| < 1.7$

Fe / Scintillator

3 layers in depth

LAr/Cu $1.7 < |\eta| < 3.2$

4 layers in depth

Forward: 1 layer EM, 2 HAD

LAr/Cu or W $3.2 < |\eta| < 4.9$

Total thickness: ~ 8 -10 λ

Use of different technics: cope with radiations in forward region

Scintillator tile calorimeter

	Barrel	Extended barrel
$\|\eta\|$ coverage	$\|\eta\| < 1.0$	$0.8 < \|\eta\| < 1.7$
Number of layers	3	3
Granularity $\Delta\eta \times \Delta\phi$	0.1×0.1	0.1×0.1
Last layer	0.2×0.1	0.2×0.1
Readout channels	5760	4092 (both sides)

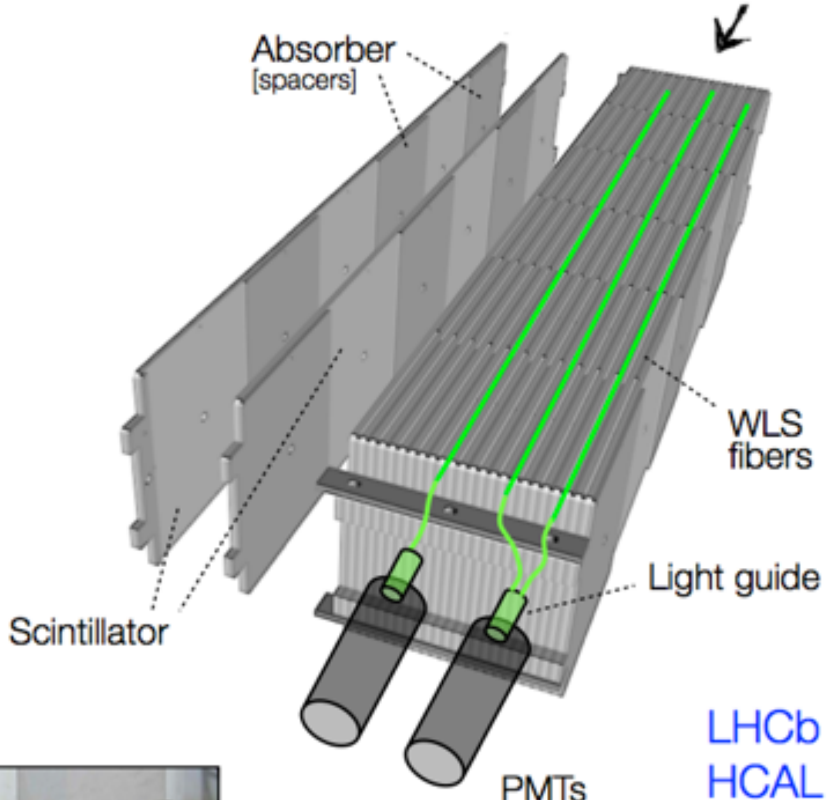
HADRONIC CALORIMETER

Most common realization: Sampling Calorimeter

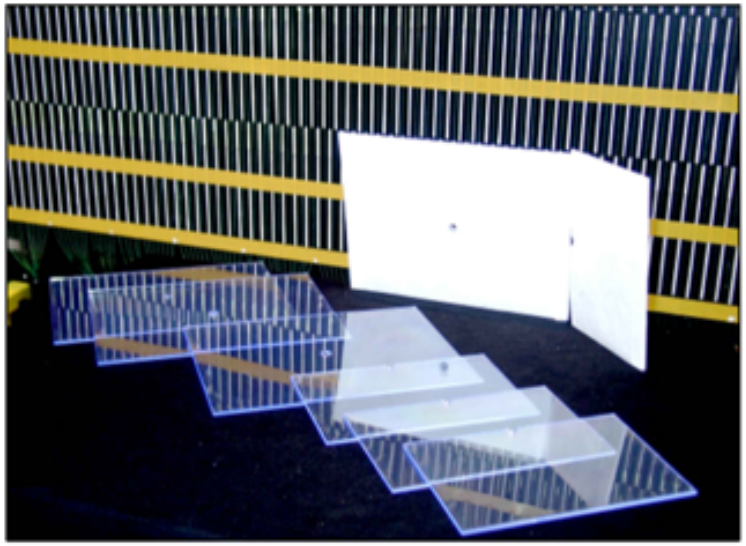
Utilization of homogenous calorimeters unnecessary (and thus too expensive) due to fluctuations of invisible shower components ...

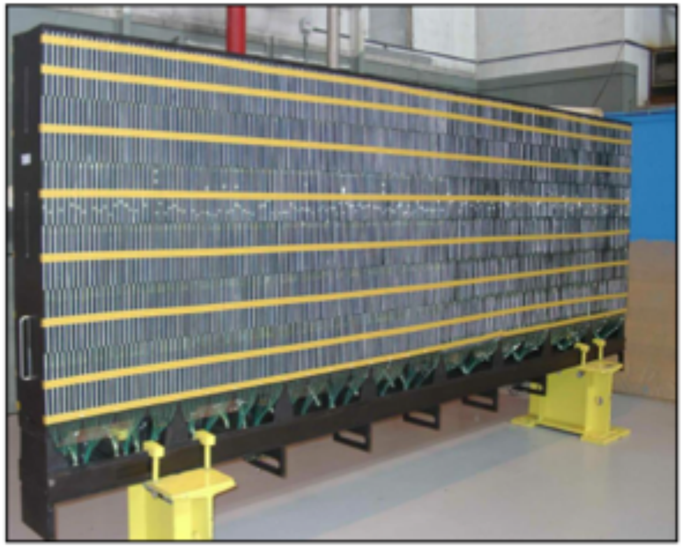
Typical absorbers : Fe, Pb, U ...
Sampling elements : Scintillators, LAr, MWPCs ...

Typical setup:
Alternating layers of active and passive material
[also: 'spaghetti' or 'shashlik' calorimeter]



LHCb
HCAL

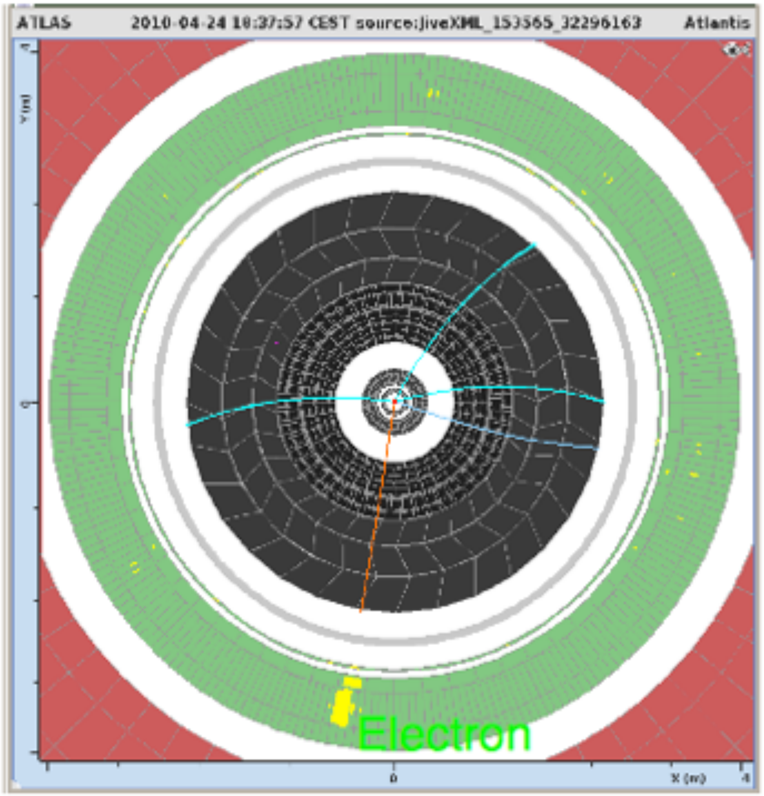


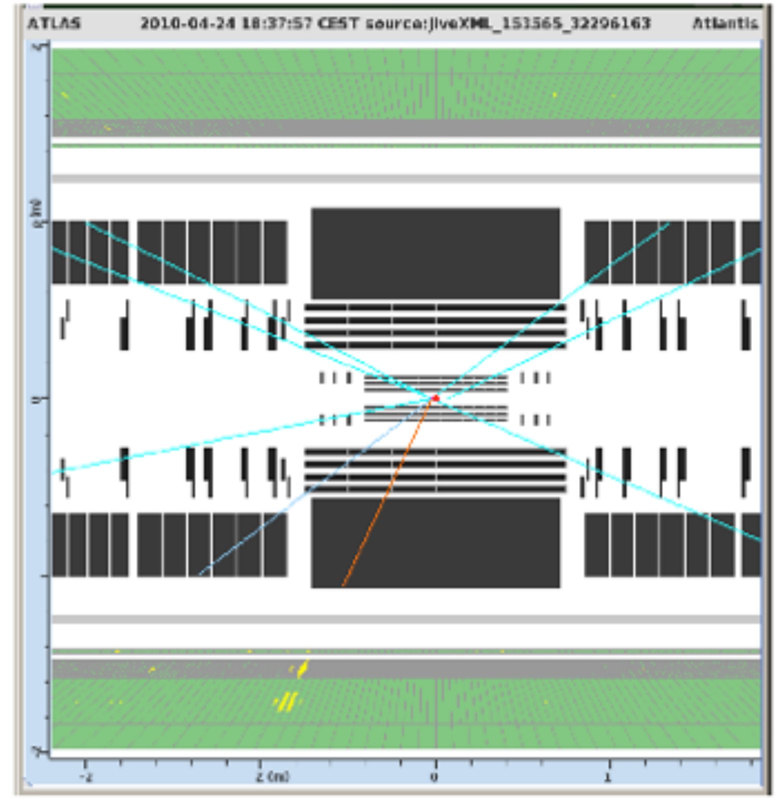


Example:
LHCb Hadron Calorimeter

MISSING TRANSVERSE ENERGY

Missing transverse energy : W $\rightarrow e\,\nu$ candidate





For a pp collision, for instance, and in the absence of escaping particles (neutrinos, neutralinos, DM,..) the transverse energy is ~balanced.

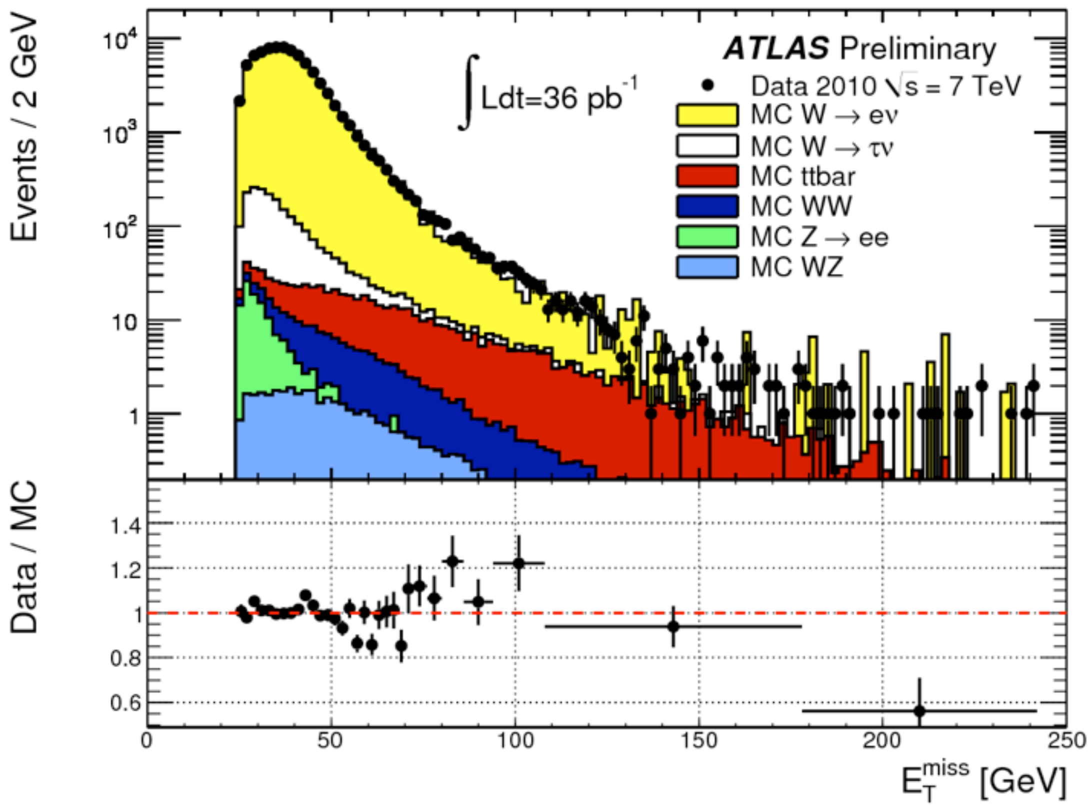
Missing transverse energy is interpreted as the presence of a neutrino.

$$\vec{E}_T^{miss} = -\sum_i^{cells} \vec{E}_T$$

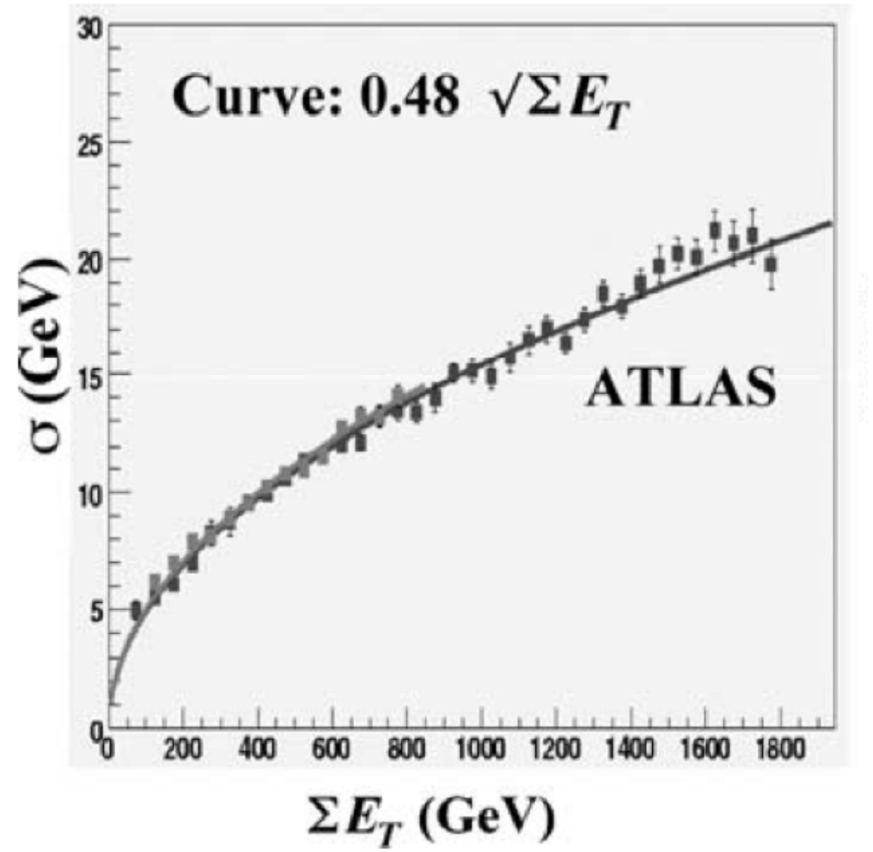
E_T^{miss} is the modulus of the vectorial sum of energy deposited in each calorimeter cell

MISSING TRANSVERSE ENERGY: CALIBRATION

Missing transverse energy in ATLAS for W→eν events



Missing transverse energy expected resolution in ATLAS



A FEW SUMMARY WORDS on CALORIMETERS

Calorimeters are attractive in our field for various reasons:

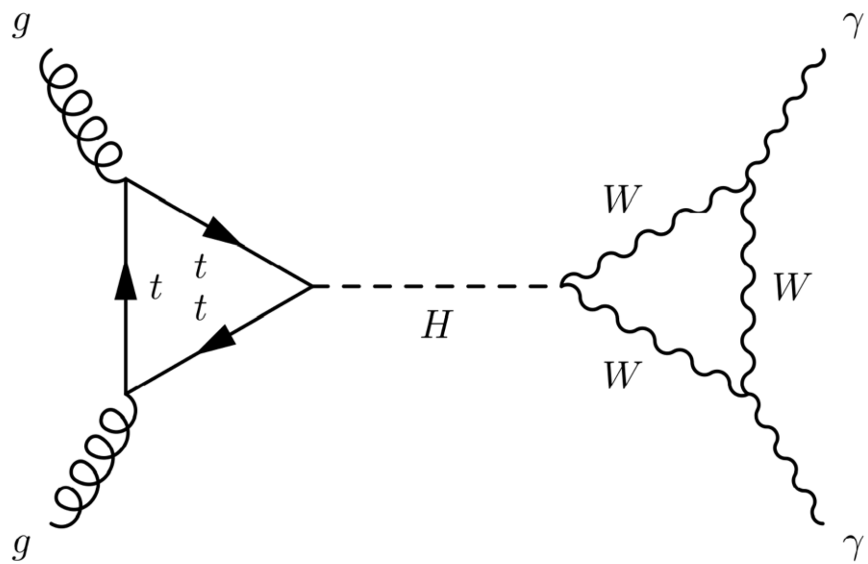
In contrast with magnet spectrometers, in which the momentum resolution deteriorates linearly with the particle momentum, on most cases the calorimeter energy resolution improves as 1/Sqrt(E), where E is the energy of the incident particle. Therefore calorimeters are very well suited for high-energy physics experiments.

In contrast to magnet spectrometers, calorimeters are sensitive to all types of particles, charged and neutral. They can even provide indirect detection of neutrinos and their energy through a measurement of the event missing energy.

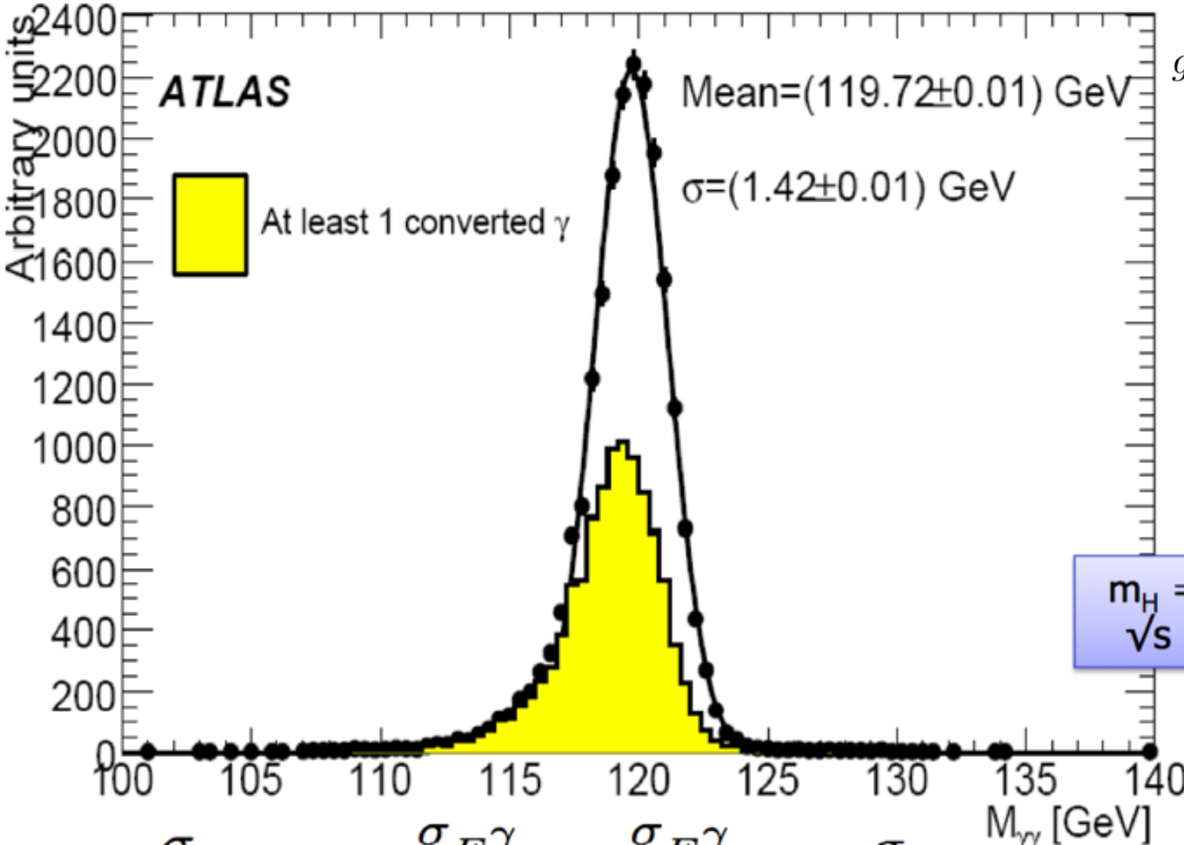
Calorimeters are commonly used for trigger purposes since they can provide fast signals that are easy to process and interpret.

They are space and therefore cost effective. Because the shower length increases only logarithmically with energy, the detector thickness needs to increase only logarithmically with the energy of the particles. In contrast for a fixed momentum resolution, the bending power BL^2 of a magnetic spectrometer must increase linearly with the particle momentum.

HIGGS MASS RESOLUTION



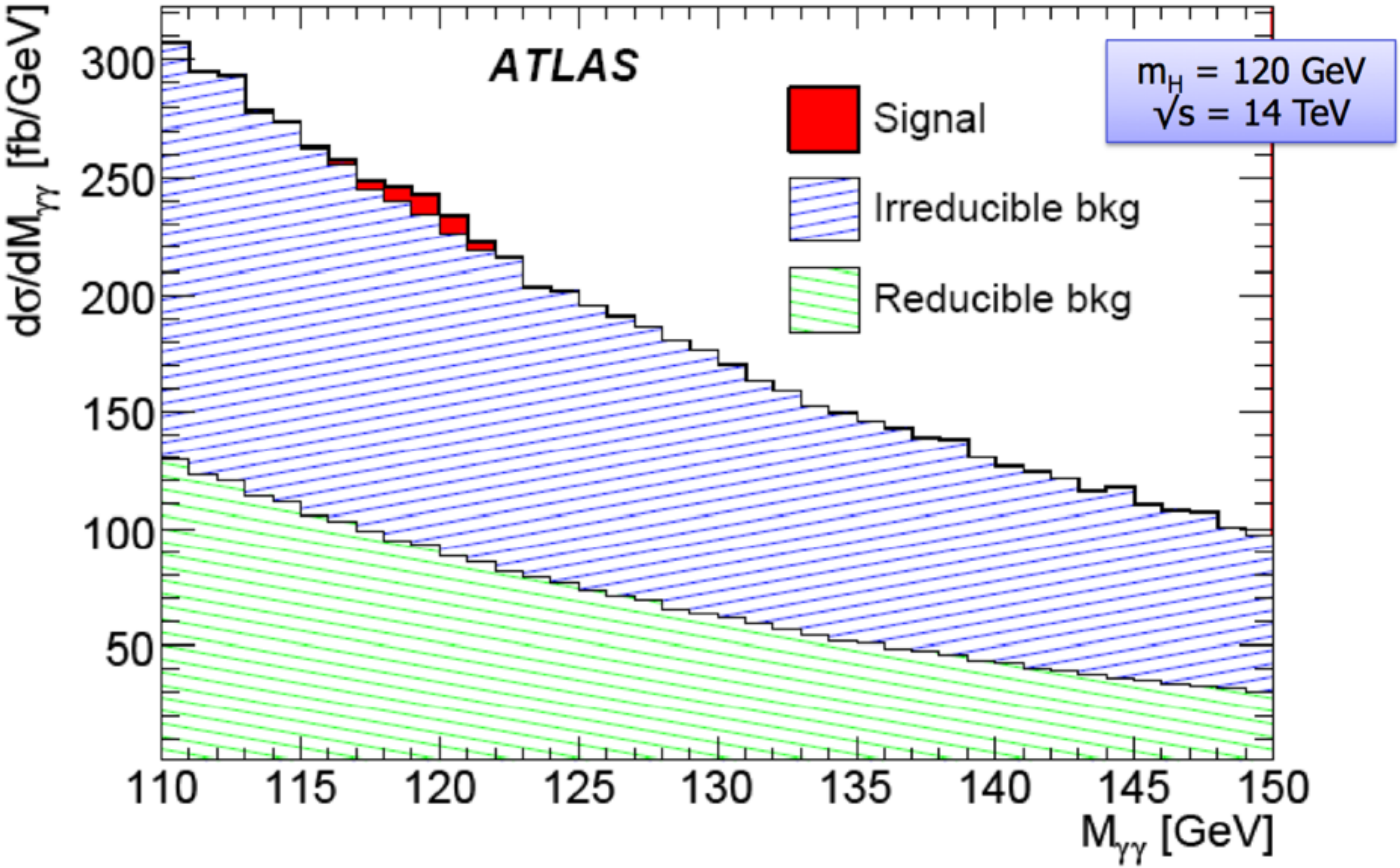
$$m_{\gamma\gamma} = \sqrt{E_1^\gamma E_2^\gamma (1 - \cos\alpha_{12})}$$



m_H = 120 GeV
$\sqrt{s}$ = 14 TeV

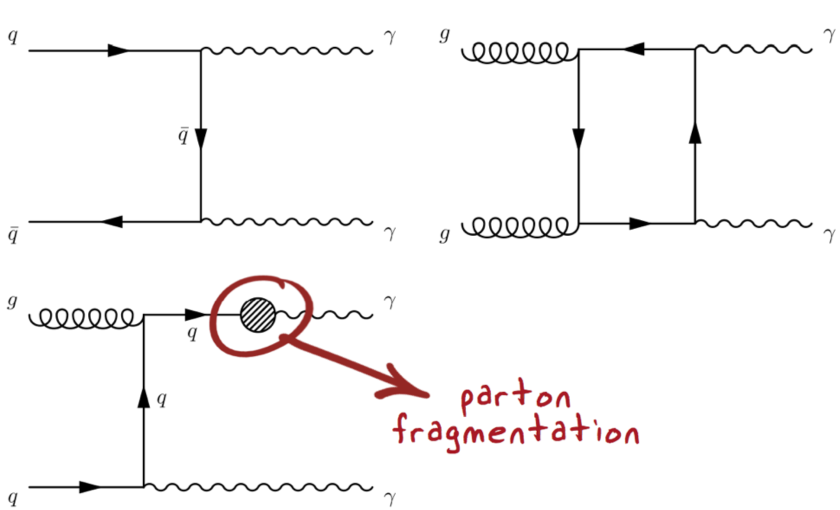
$$\frac{\sigma_{m_{\gamma\gamma}}}{m_{\gamma\gamma}} = \frac{\sigma_{E_1^\gamma}}{E_1^\gamma} \oplus \frac{\sigma_{E_2^\gamma}}{E_2^\gamma} \oplus \frac{\sigma_{\alpha_{12}}}{\tan\alpha_{12}}$$

SIGNAL on a LARGE BACKGROUND

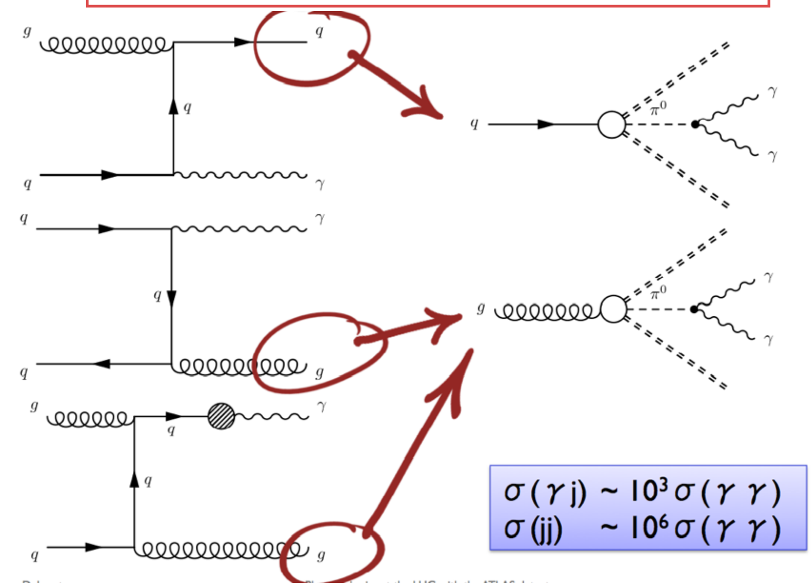


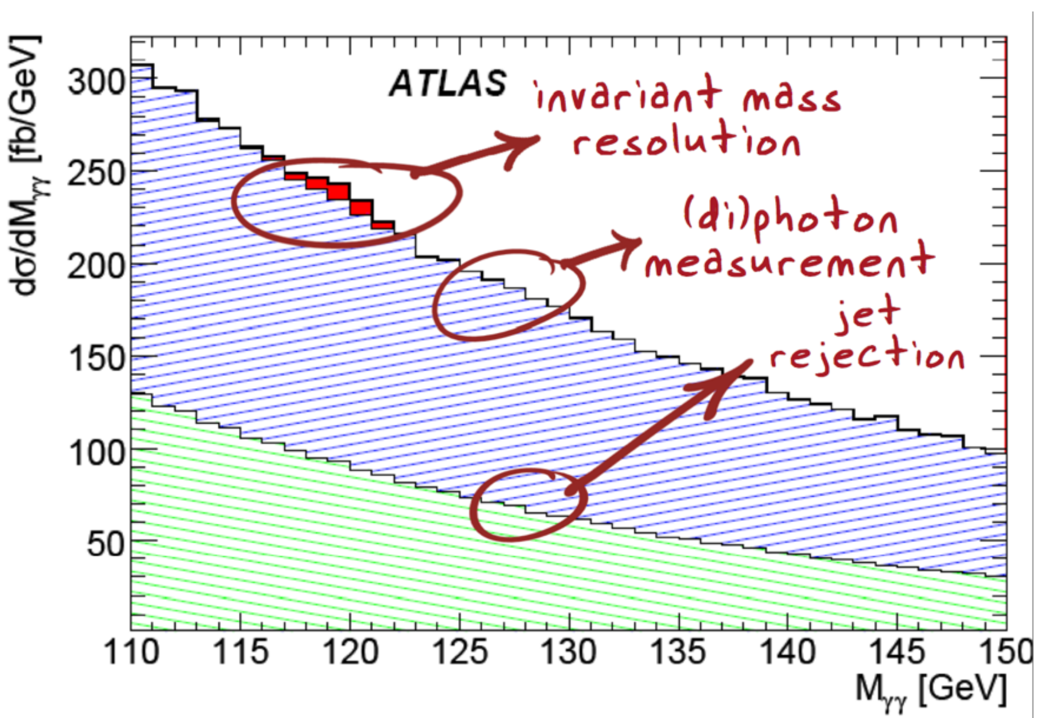
SIGNAL on a LARGE BACKGROUND

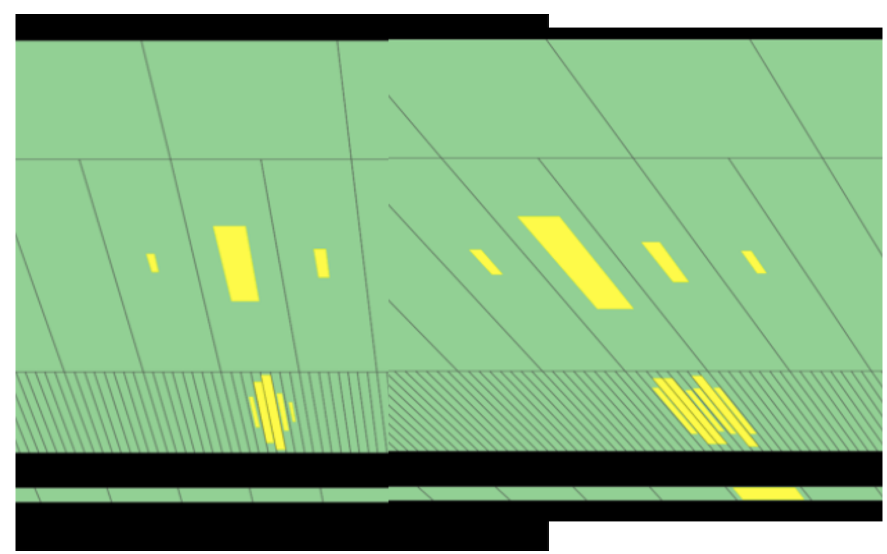
IRREDUCIBLE BACKGROUND
γ in the FINAL STATE



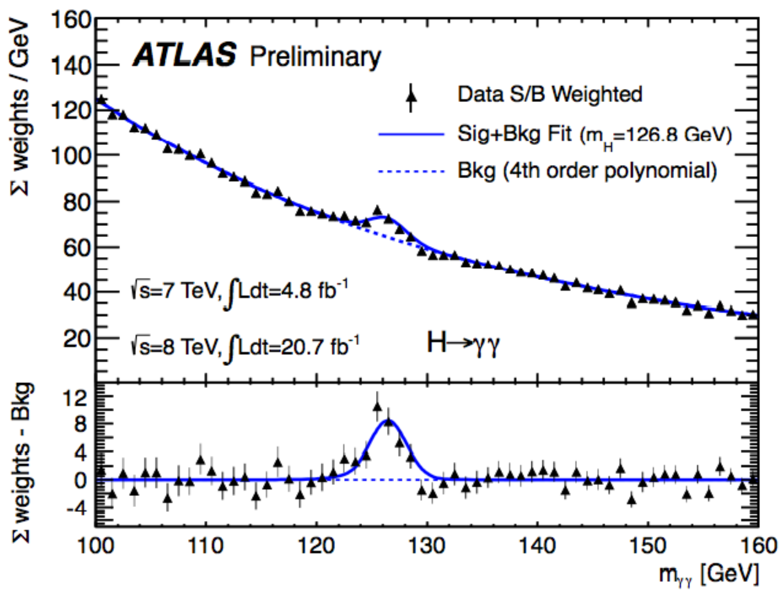
REDUCIBLE BACKGROUND
π^0 in the FINAL STATE

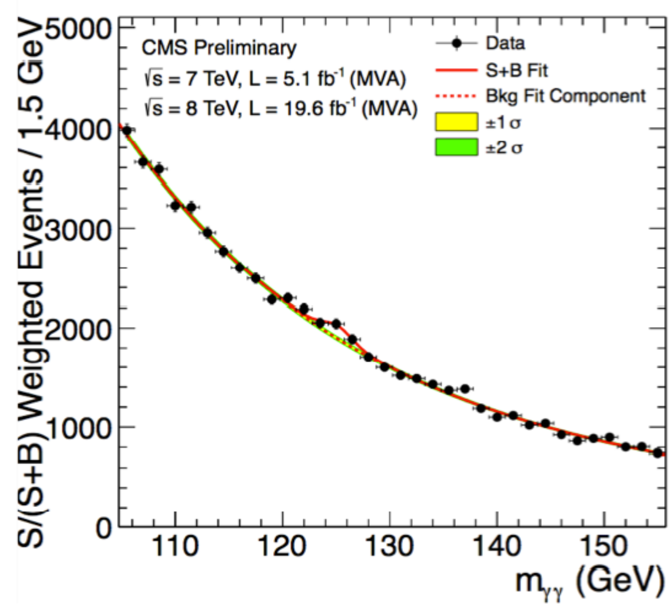


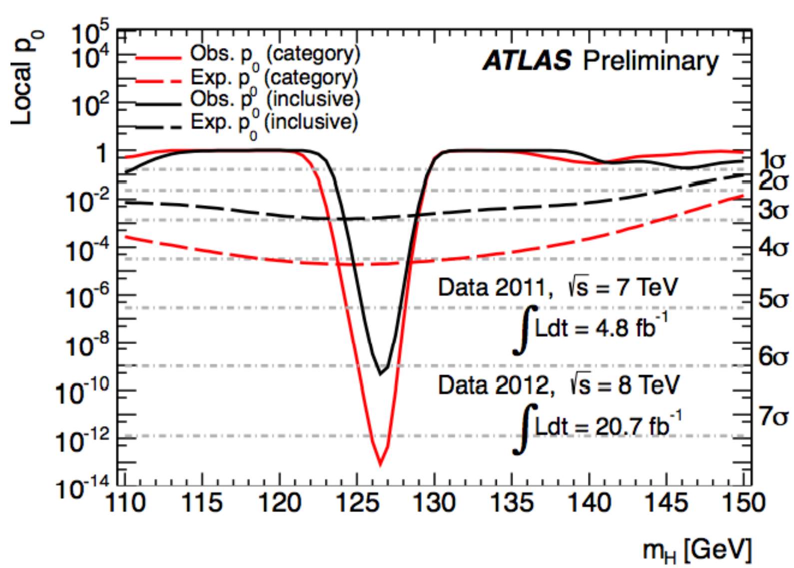


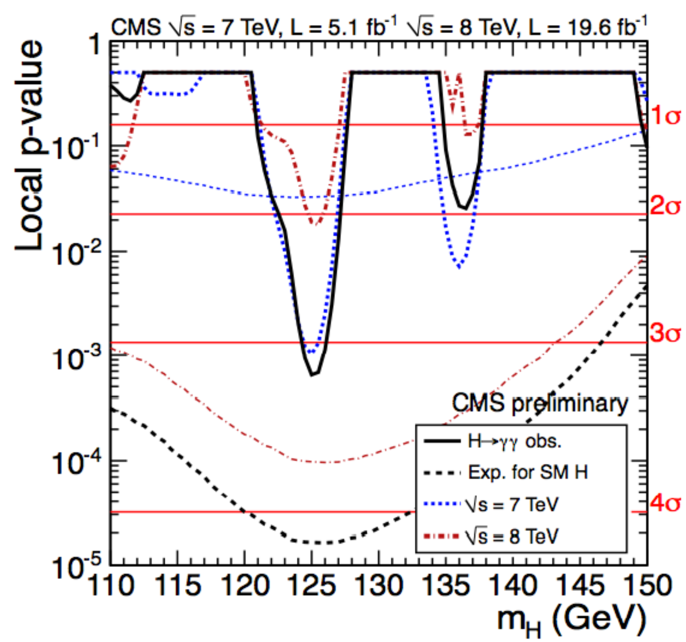


H→γγ MASS SPECTRA & SIGNAL OBSERVATION









CONSTANT TERM

The constant term describes the level of uniformity of response of the calorimeter as a function of position, time, temperature and which are not corrected for.

- Geometry non uniformity
- Non uniformity in electronics response
- Signal reconstruction
- Energy leakage

Dominant term at high energy

ATLAS LAr EMB testbeam

Correlated contributions	Impact on uniformity	
Calibration	0.23%	
Readout electronics	0.10%	
Signal reconstruction	0.25%	
Monte Carlo	0.08%	
Energy scheme	0.09%	
Overall (**data**)	0.38% (**0.34%**)	
Uncorrelated contribution	P13	P15
Lead thickness	0.09%	0.14%
Gap dispersion	0.18%	0.12%
Energy modulation	0.14%	0.10%
Time stability	0.09%	0.15%
Overall (**data**)	0.26% (**0.26%**)	0.25% (**0.23%**)