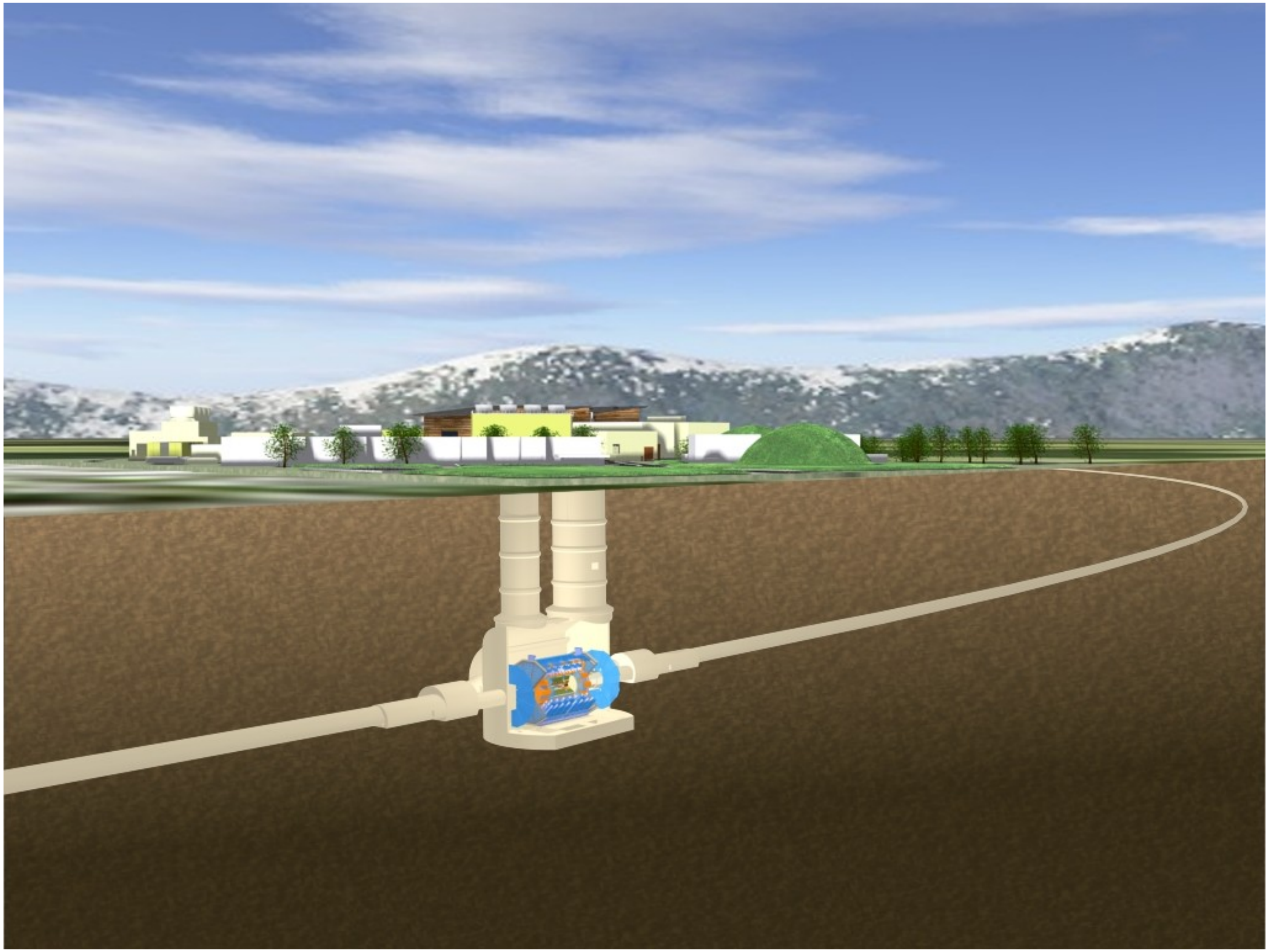
Introduction to detector physics

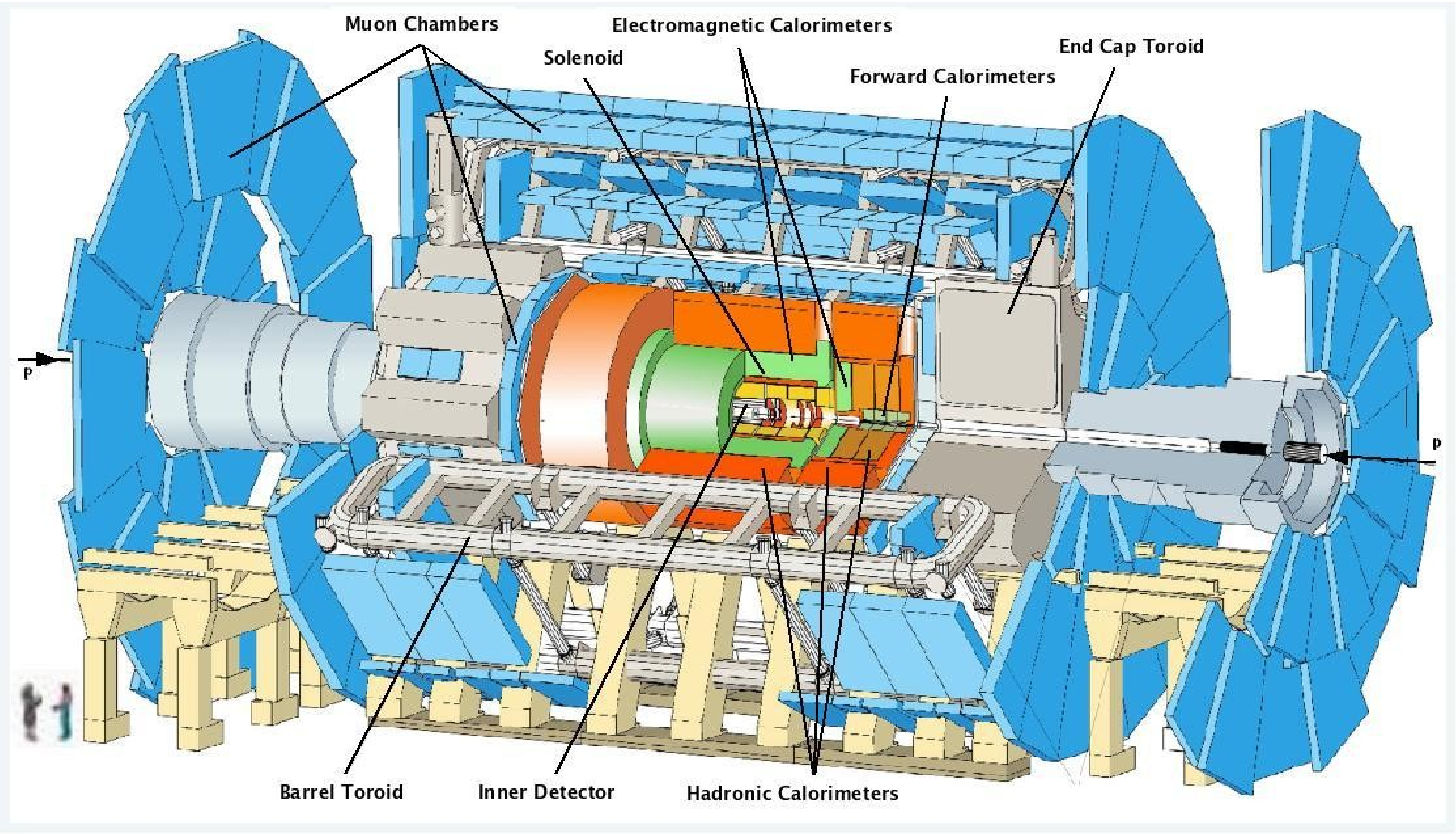
Outline

- Lecture 1 and 2: the generic general purpose high energy detector
  - The ATLAS experiment
- Lecture 3 and 4: particle identification detectors, detector simulations, and the Time Projection Chamber
  - The ALICE TPC

ATLAS detector



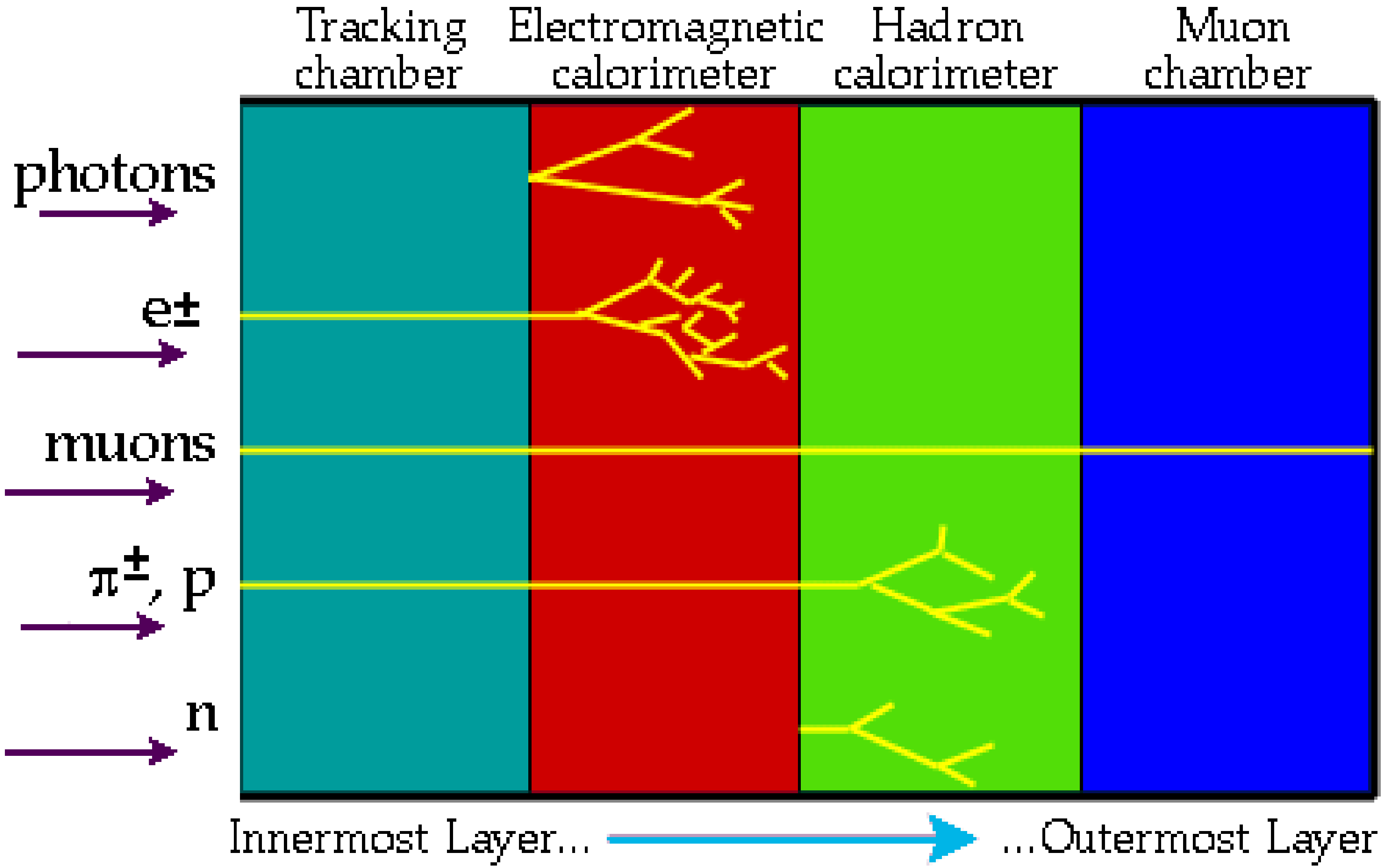
ATLAS detector



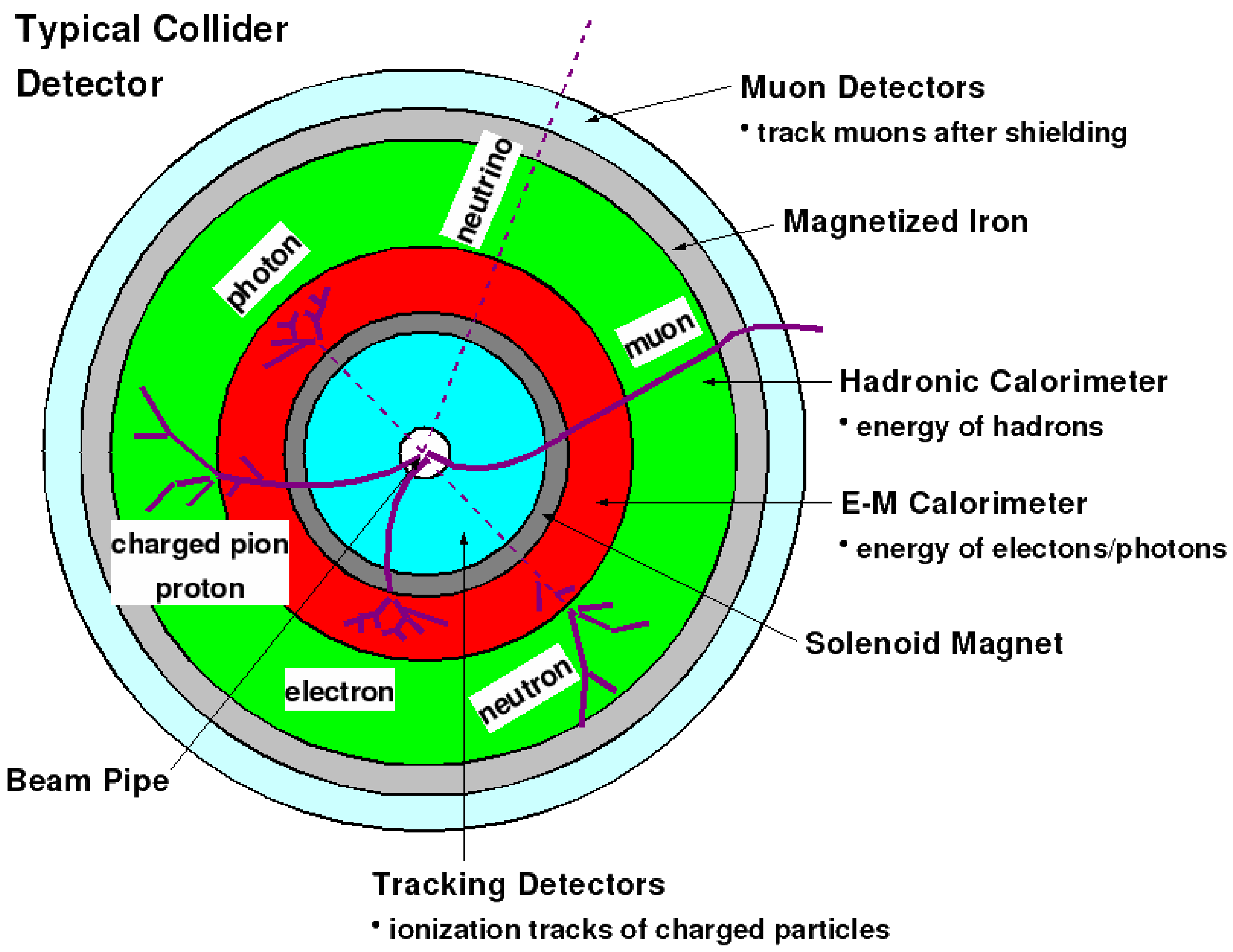
Goal of detectors

- The goal of the experiment is to provide the 4 momentum vector for (ideally) each particle produced in the collision $p = (E, \bar{p})$
- We just remind here the relativistic definitions:
  - $\beta = |\bar{p}|/E$
  - $\gamma = E/m$

Executive summary (1/3)

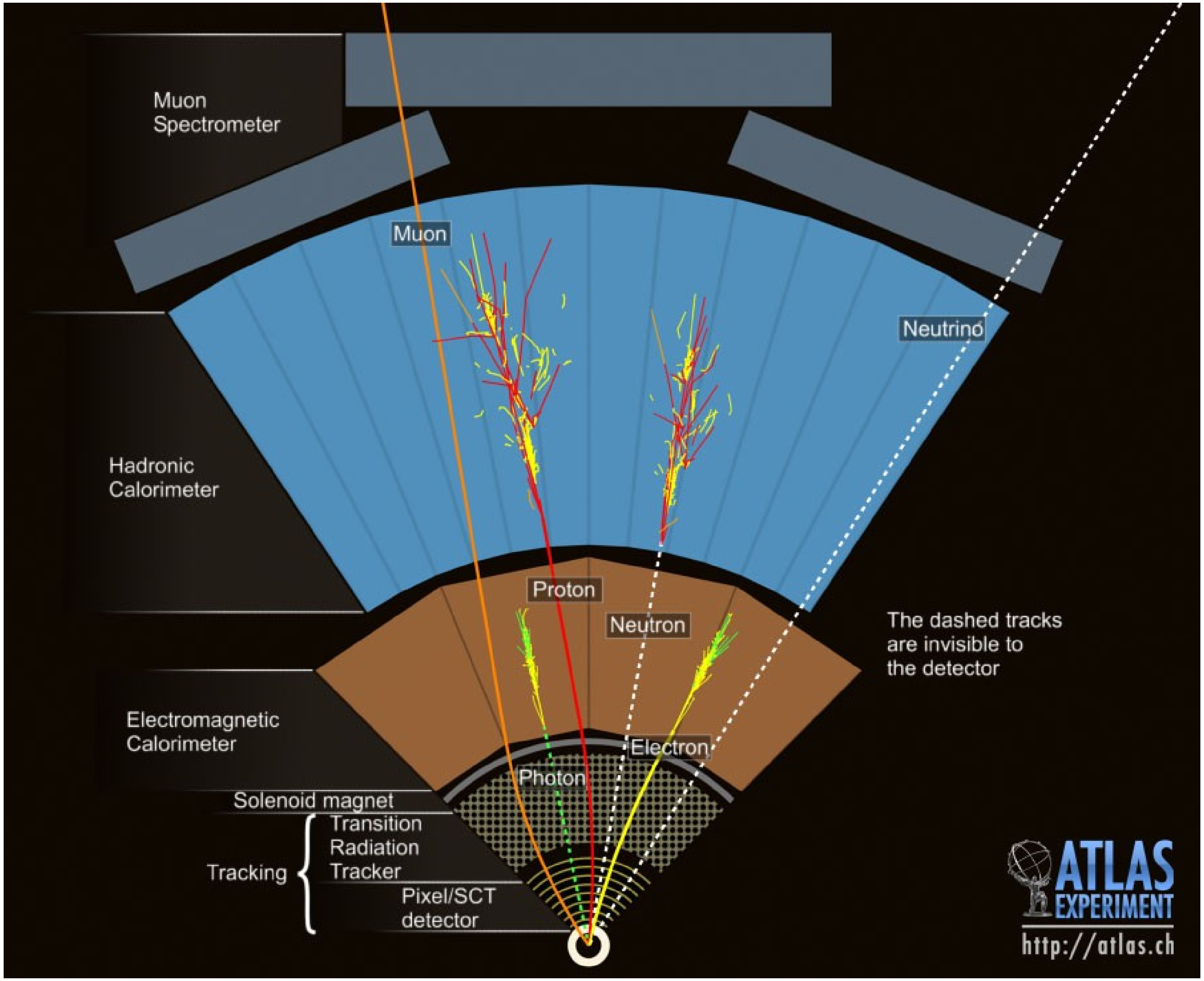


Executive summary (2/3)

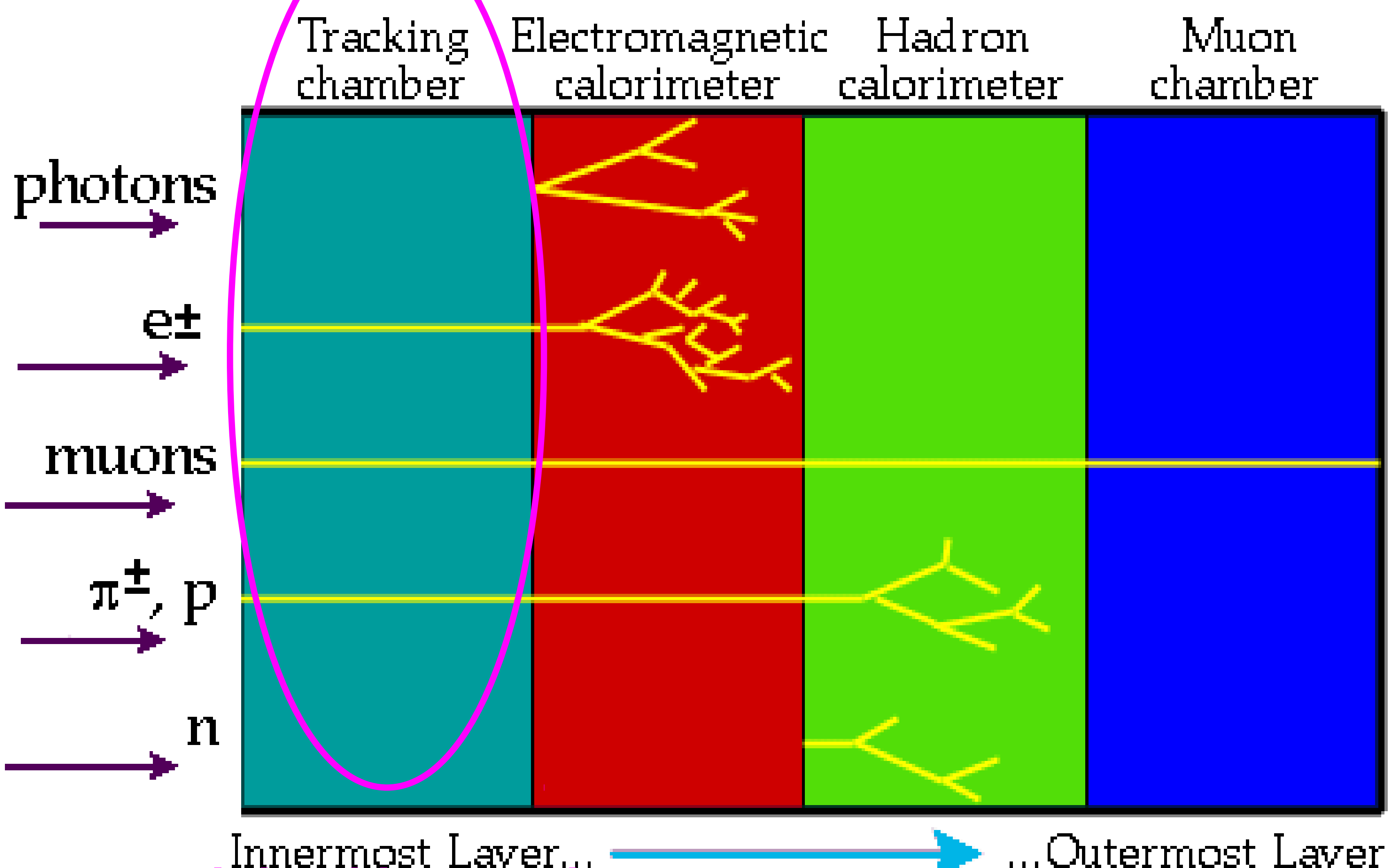


Layers, like an onion
(even everybody loves cake)

Executive summary (3/3)



Tracking chambers



Minimal interaction
Low material

Energy loss in matter: the Bethe-Bloch equation

$$-\frac{\mathrm{d}E}{\mathrm{d}x} = \frac{D q^2 n_e}{\beta^2}\left[\ln\left(\frac{2m_e c^2\beta^2\gamma^2}{I}\right) - \beta^2 - \frac{\delta(\gamma)}{2}\right], \quad (4.9a)$$

where x is the distance travelled through the medium,

$$D = \frac{4\pi\,\alpha^2 h^2}{m_e} = 5.1 \times 10^{-25}\,\mathrm{MeV\,cm^2}, \quad (4.9b)$$

m_e is the electron mass, $\beta = \upsilon/c$ and $\gamma = (1-\beta^2)^{-1/2}$. The other constants refer to the properties of the medium: n_e is the electron density, I is the mean ionization potential of the atoms averaged over all electrons, which is given approximately by $I = 10Z\,\mathrm{eV}$ for Z greater than 20, and δ is a dielectric screening correction that is important only for highly relativistic particles. The corresponding formula for spin-$\frac{1}{2}$ particles

- Depends only on βγ (but γ also only depends on β)
- It is useful to remember that βγ = p/m, since β= p/E and γ=E/m

Examples of dE/dx

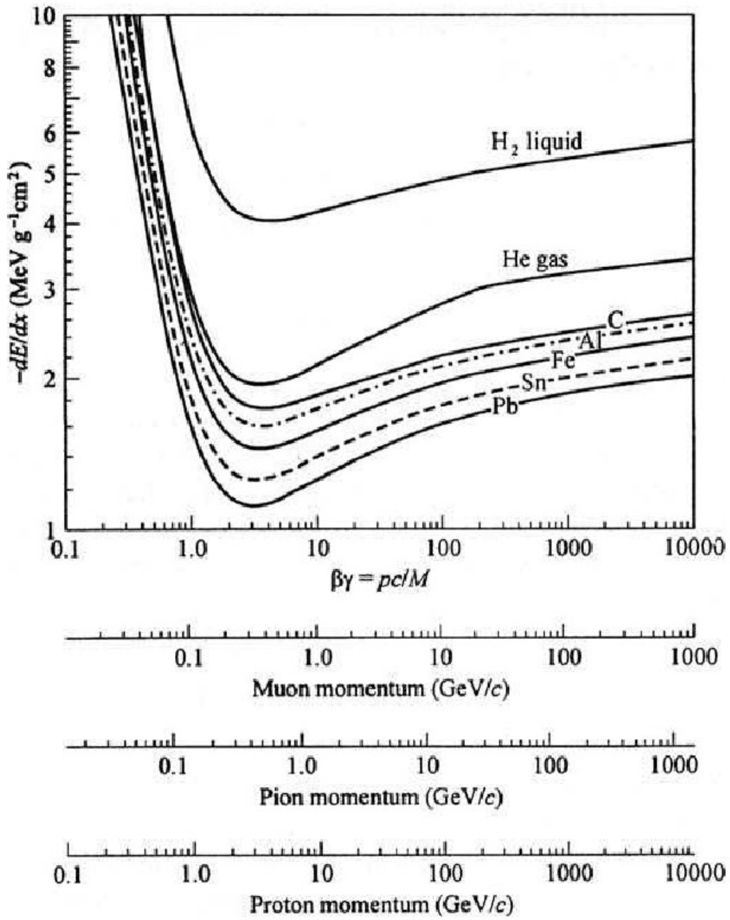


Figure 4.6 Ionization energy loss for muons, pions and protons on a variety of materials. The units of dE/dx are explained in the text. (Reprinted by permission of Institute of Physics (IOP), Fig. 27.7, W.-M. Yao *et al.*, *Journal of Physics*, **G33**, 1, 2006.)

Can we understand parts of the Bethe-Bloch formula?

$$-\frac{\mathrm{d}E}{\mathrm{d}x} = \frac{Dq^2 n_e}{\beta^2}\left[\ln\left(\frac{2m_e c^2\beta^2\gamma^2}{I}\right) - \beta^2 - \frac{\delta(\gamma)}{2}\right], \tag{4.9a}$$

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What materials to use

TABLE 4.2 The minimum ionization energy losses $(-\mathrm{d}E/\mathrm{d}x)_{min}$ for various materials and their dependence on the density ρ in $\mathrm{g\,cm^{-3}}$.

Element	Z	ρ	$\left(-\frac{\mathrm{d}E}{\mathrm{d}x}\right)_{min}$ $(\mathrm{MeV cm^{-1}})$	$-\frac{1}{\rho}\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_{min}$ $(\mathrm{MeV g^{-1} cm^2})$
H*	1	0.063	0.26	4.12
C	6	2.26	4.02	1.78
Al	13	2.70	4.37	1.62
Fe	26	7.87	11.6	1.48
Pb	82	11.35	12.8	1.13

* Liquid hydrogen at 26 K. The other materials are solids.

- To minimize material (that causes distortions) one often uses gas detectors for tracking (and often nowadays silicon detectors)

Example of gas detectors

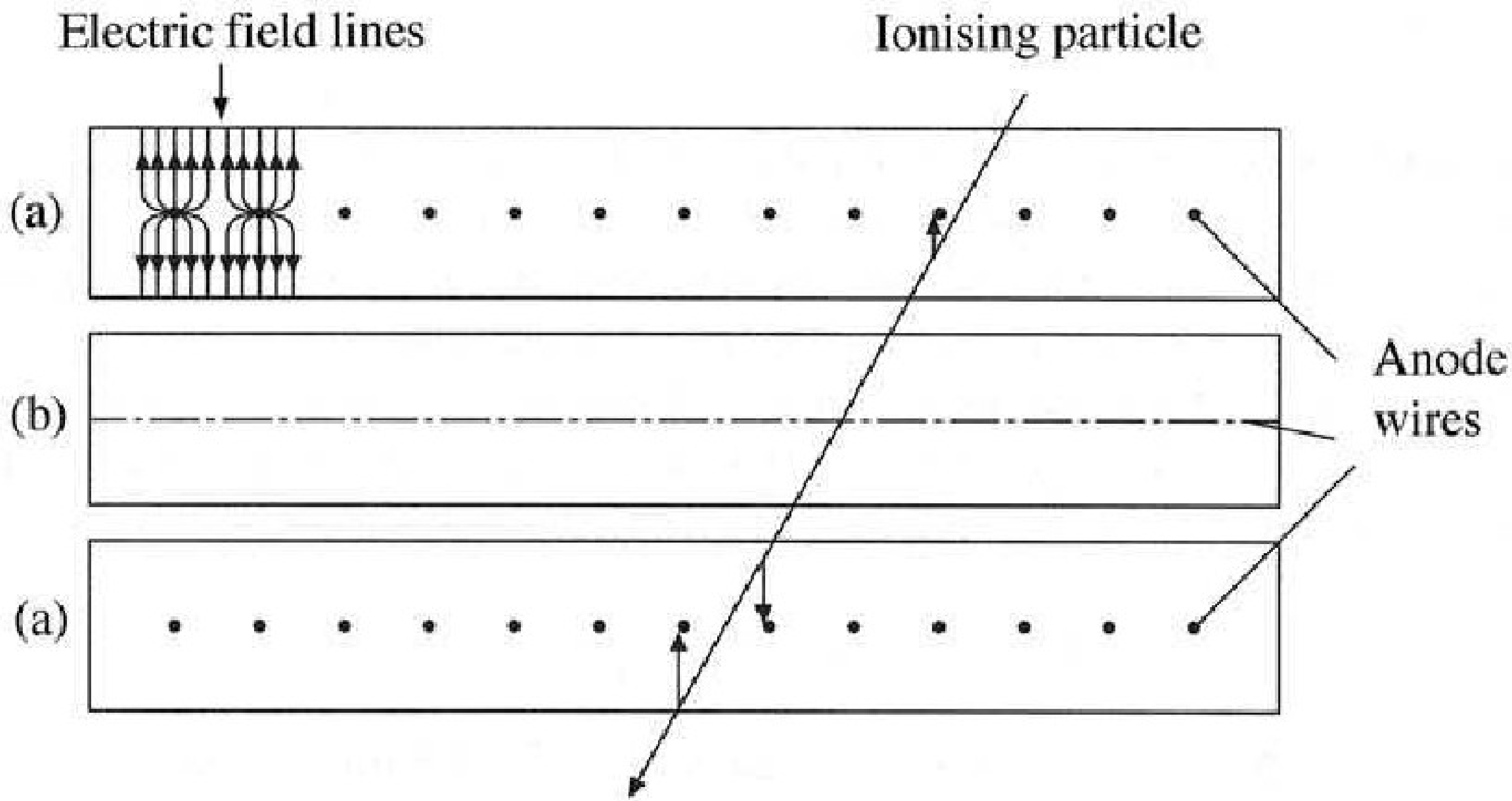


Figure 4.11 A group of three planes of a MWPC (see text for details). (From *Particles and Nuclei*, Povh, Rith, Scholz and Zetsche, Fig. A7, 1999. With kind permission of Springer Science and Business Media.)

Amplification to get a signal out

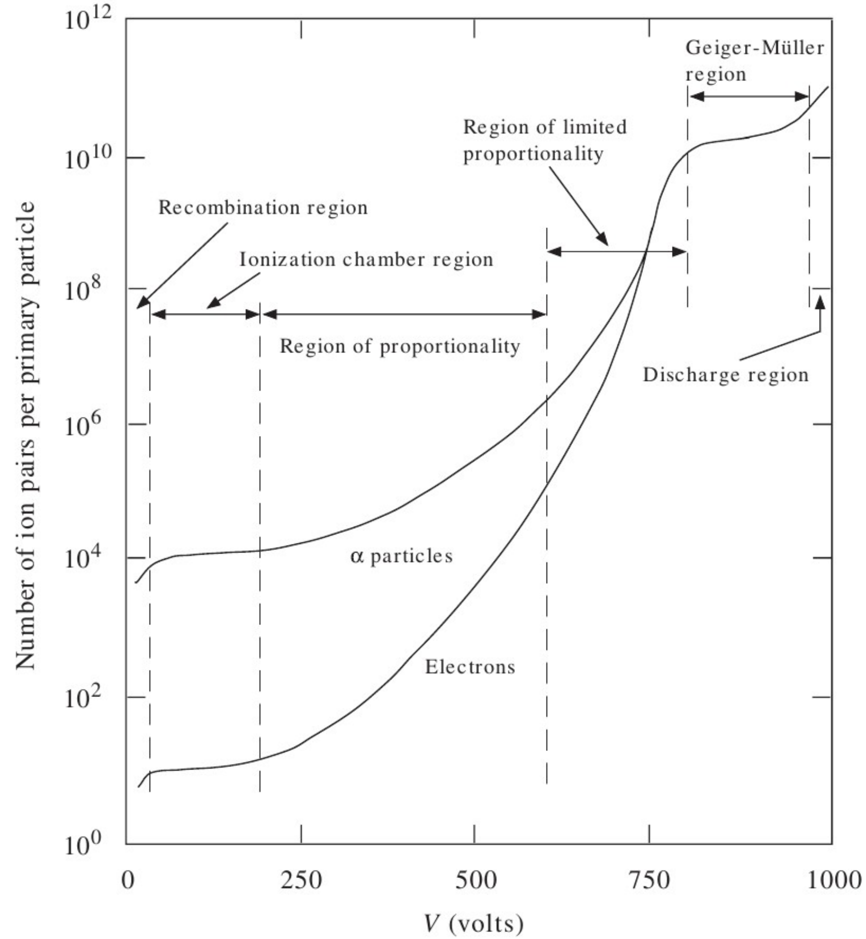
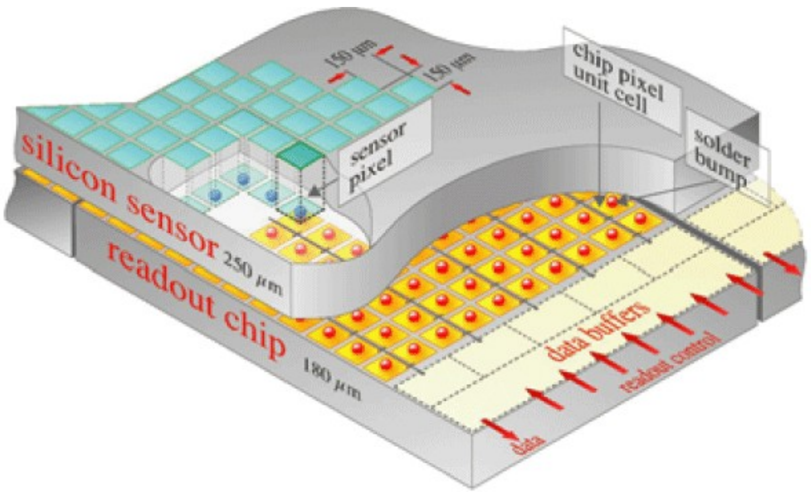
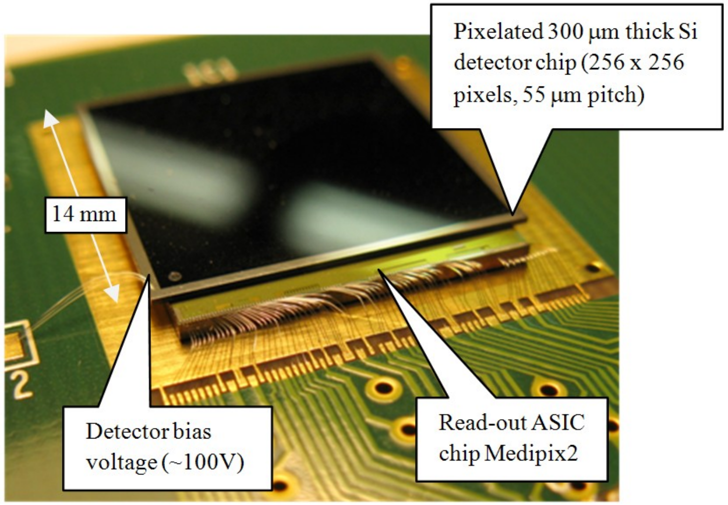


Figure 4.10 Gas amplification factor as a function of voltage V applied in a single-wire gas detector, with a wire radius typically $20\,\mu$m, for a strongly ionizing particle (α) and a weakly ionizing particle (electron).

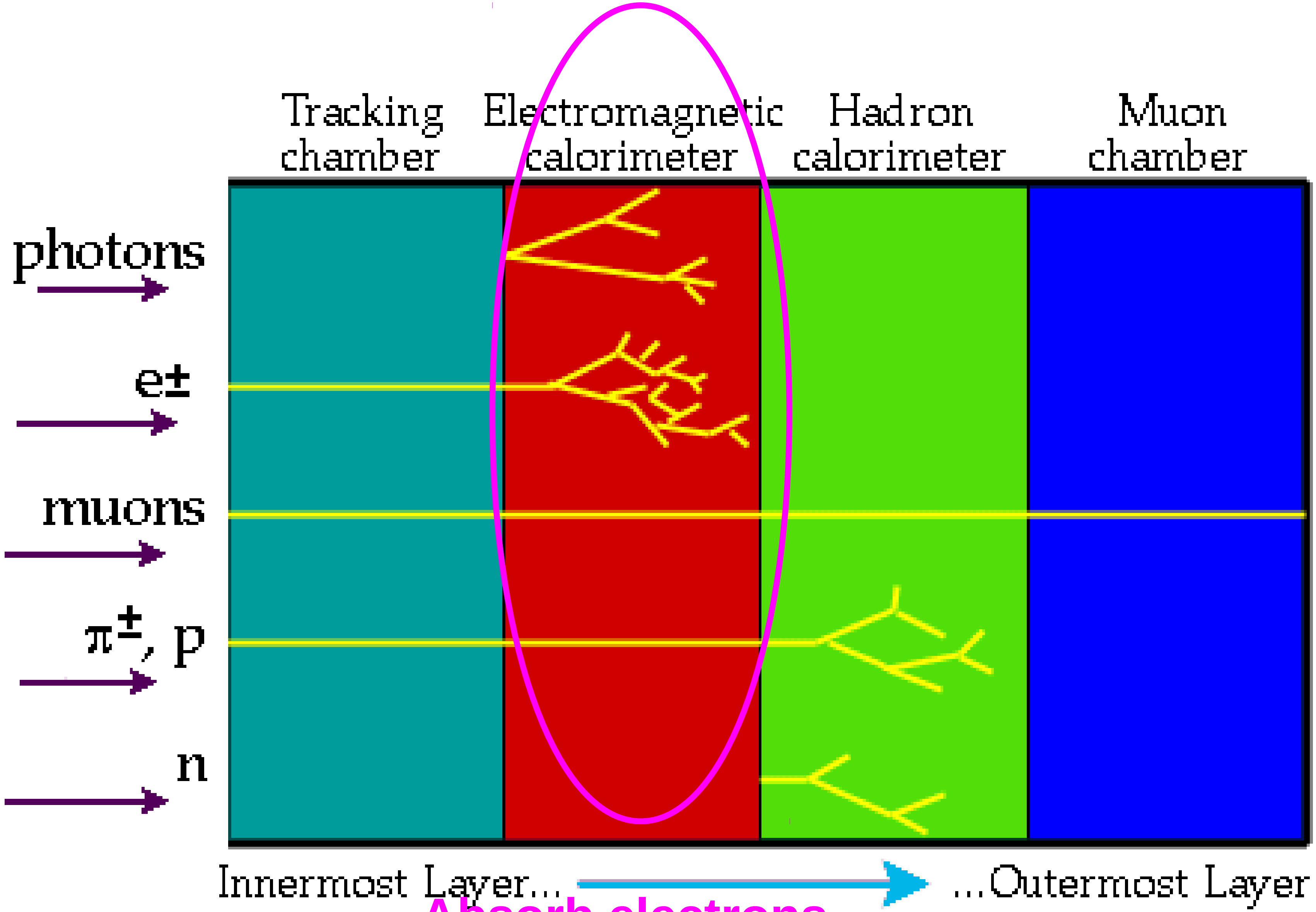
Silicon semi-conductor detectors





- Extremely good resolution and segmentation especially for pixel detectors as shown here
- Semi-conductor: low ionization potential and easy to read out

Electromagnetic calorimeter



Absorb electrons and photons

Energyloss of electrons

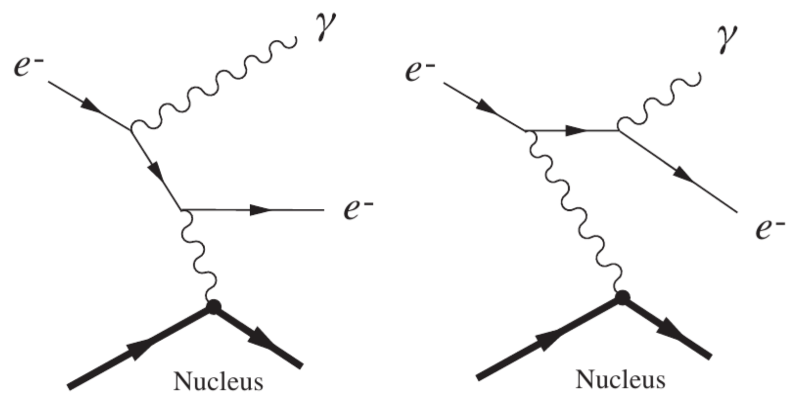


Figure 4.7 Dominant Feynman diagrams for the bremsstrahlung process $e^- + (Z, A) \to e^- + \gamma + (Z, A)$.

$$-\mathrm{d}E/\mathrm{d}x = E/L_R. \tag{4.14}$$

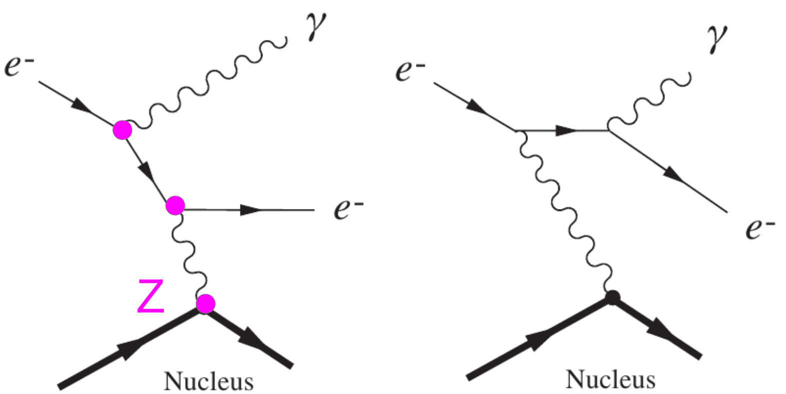
The constant L_R is called the *radiation length* and is given by

$$\frac{1}{L_R} = 4\left(\frac{\hbar}{mc}\right)^2 Z(Z+1)\alpha^3 n_a \ln\left(\frac{183}{Z^{1/3}}\right), \tag{4.15}$$

where n_a is the number density of atoms/cm^3 in the medium. Integrating (4.14) gives

$$E = E_0 \exp(-x/L_R), \tag{4.16}$$

Energyloss of photons



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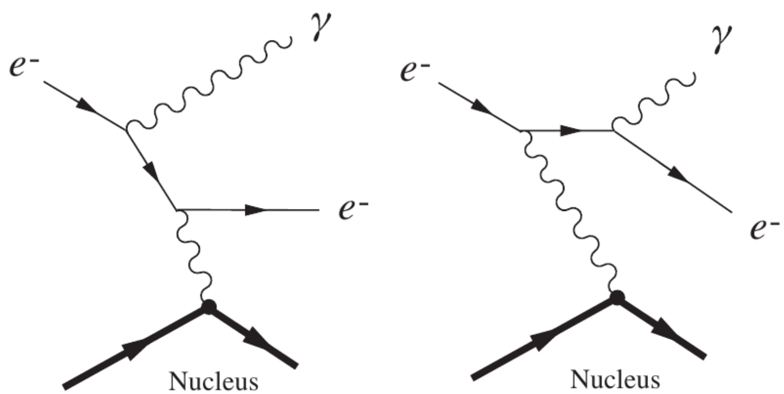
$$E = E_0 \exp\left(-x/L_R\right), \tag{4.16}$$

Scales wit 1/mass^2
→ only relevant for electrons



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where n_a is the number density of atoms/cm^3 in the medium. Integrating (4.14) gives

$$E = E_0 \exp\left(-x/L_R\right), \tag{4.16}$$

And photons:

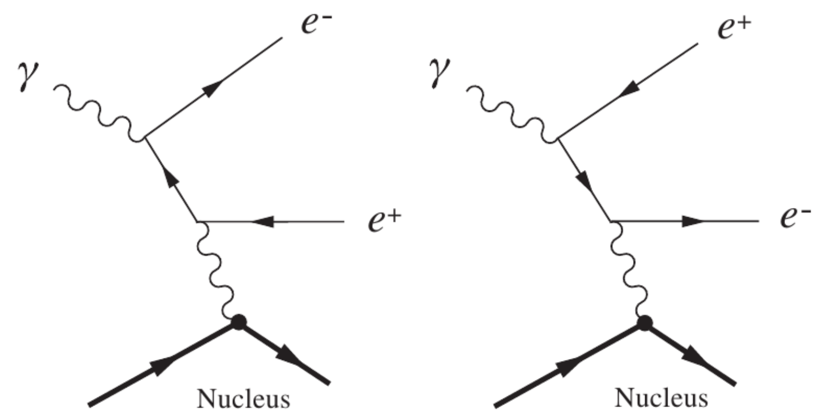


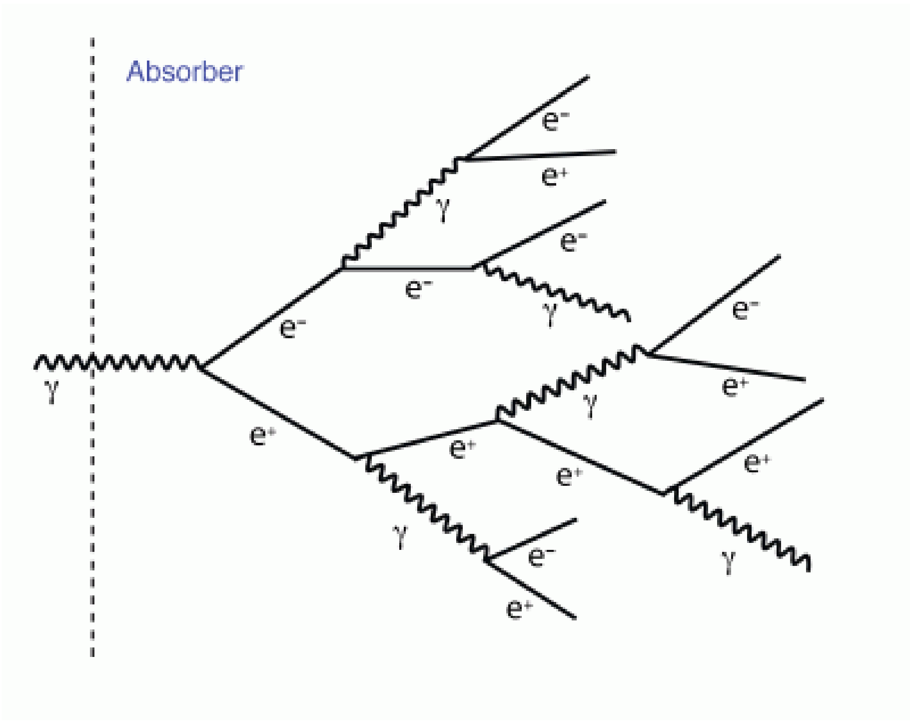
Figure 4.9 The pair production process $\gamma + (Z, A) \to e^- + e^+ + (Z, A)$.

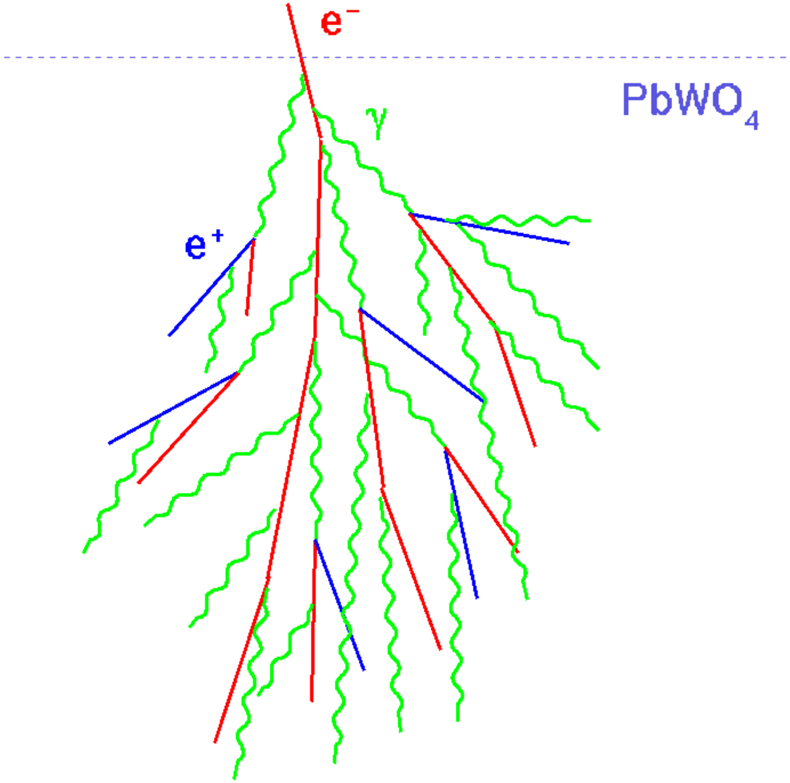
$$\sigma_{pair} = \frac{7}{9}\frac{1}{n_a L_R} \tag{4.20}$$

for $E_\gamma \gg mc^2/\alpha Z^{1/3}$, where L_R is the radiation length. Substituting these results into (4.19) gives

$$I(x) = I_0 \exp(-7x/9L_R), \tag{4.21}$$

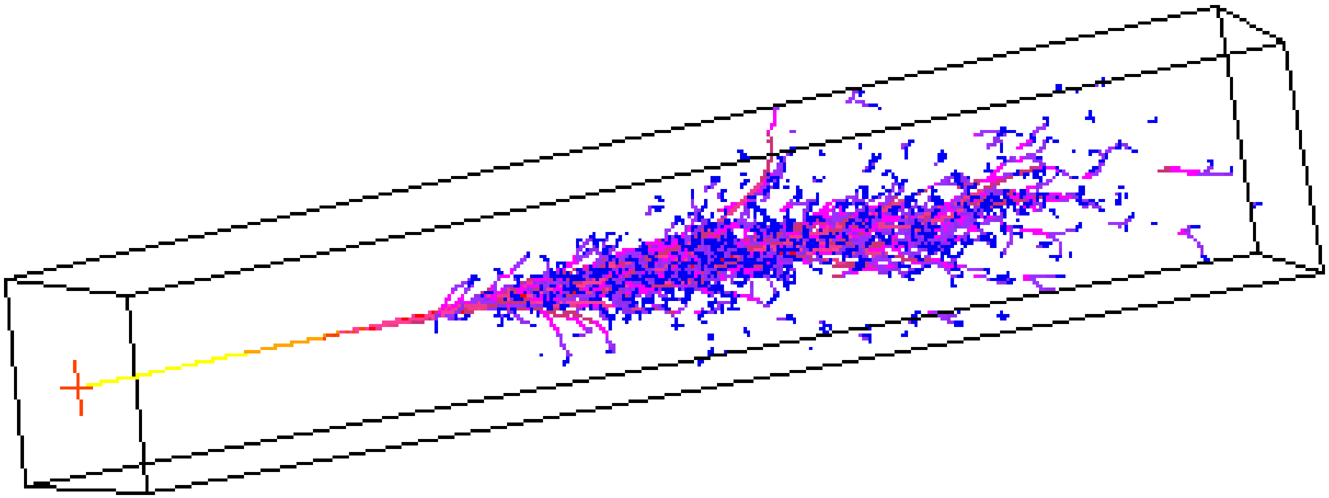
How the EMCAL works

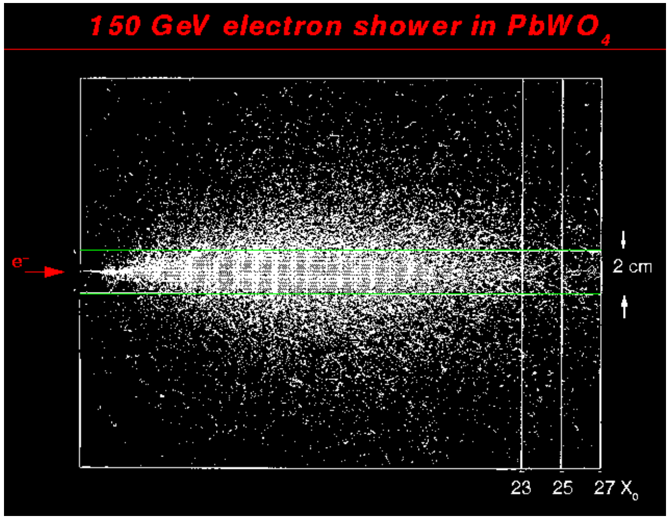




Choice of material: large Z e.g. Pb crystals!

Showers in the crystal





Organize crystals in detectors Light output is proportional to energy deposit

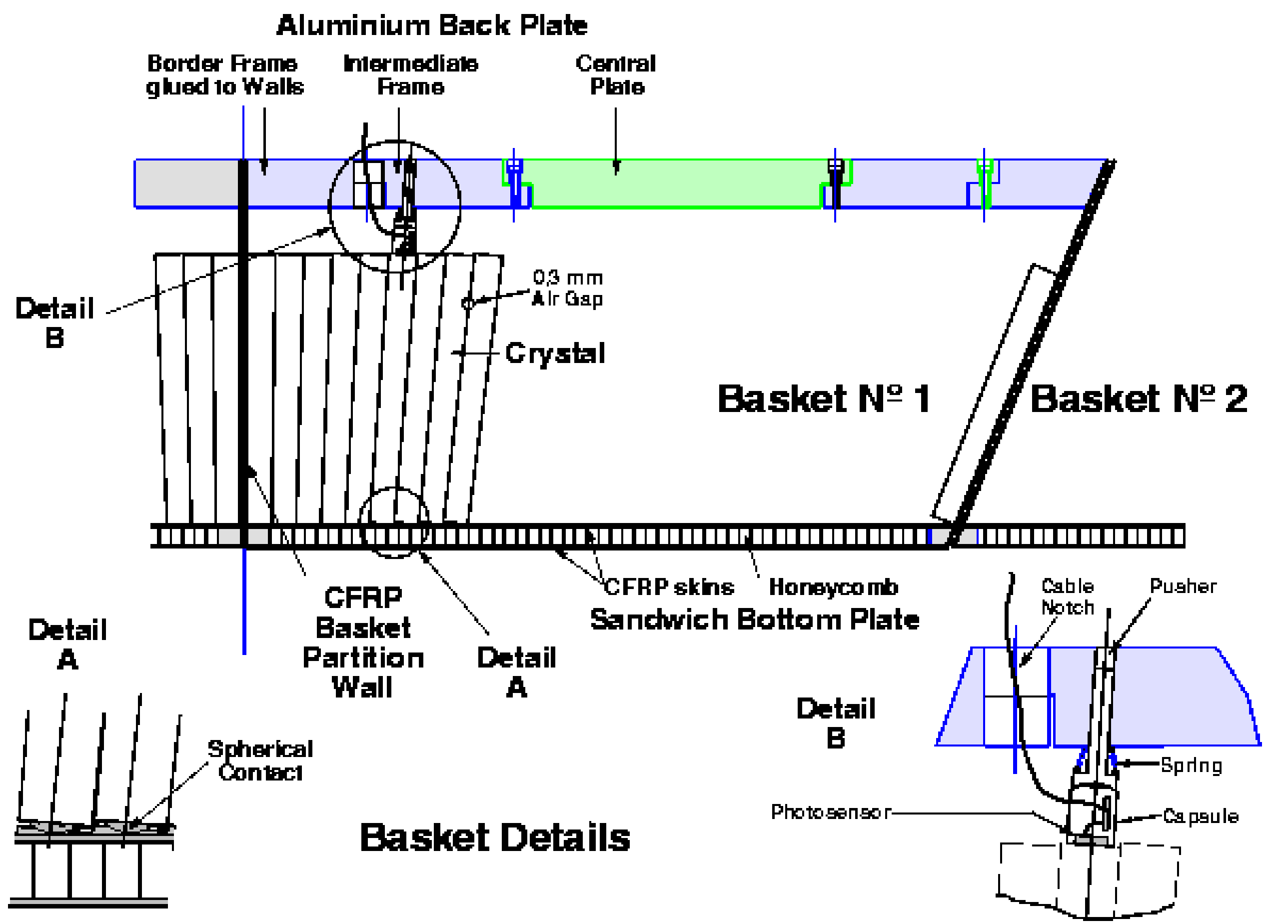


Fig. 6.1. The longitudinal cut of a basket showing how the crystals are held by the pressing mechanism.

Alternative EMCAL

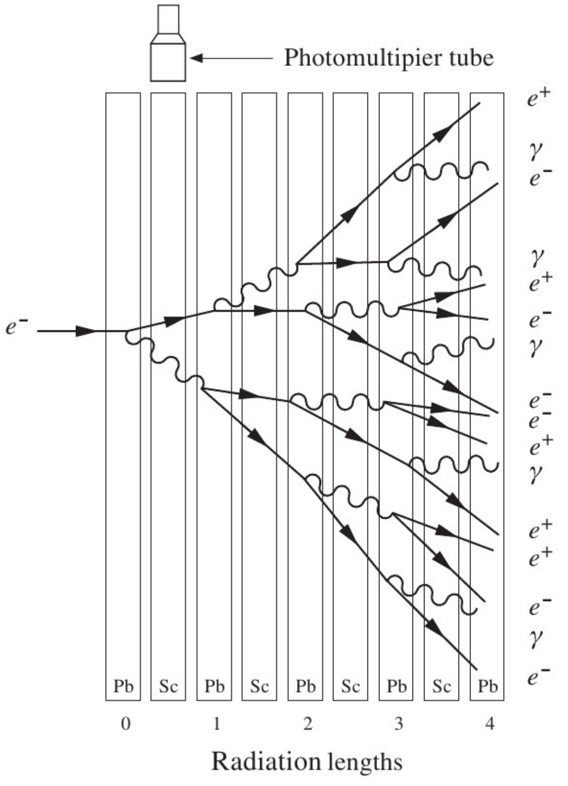
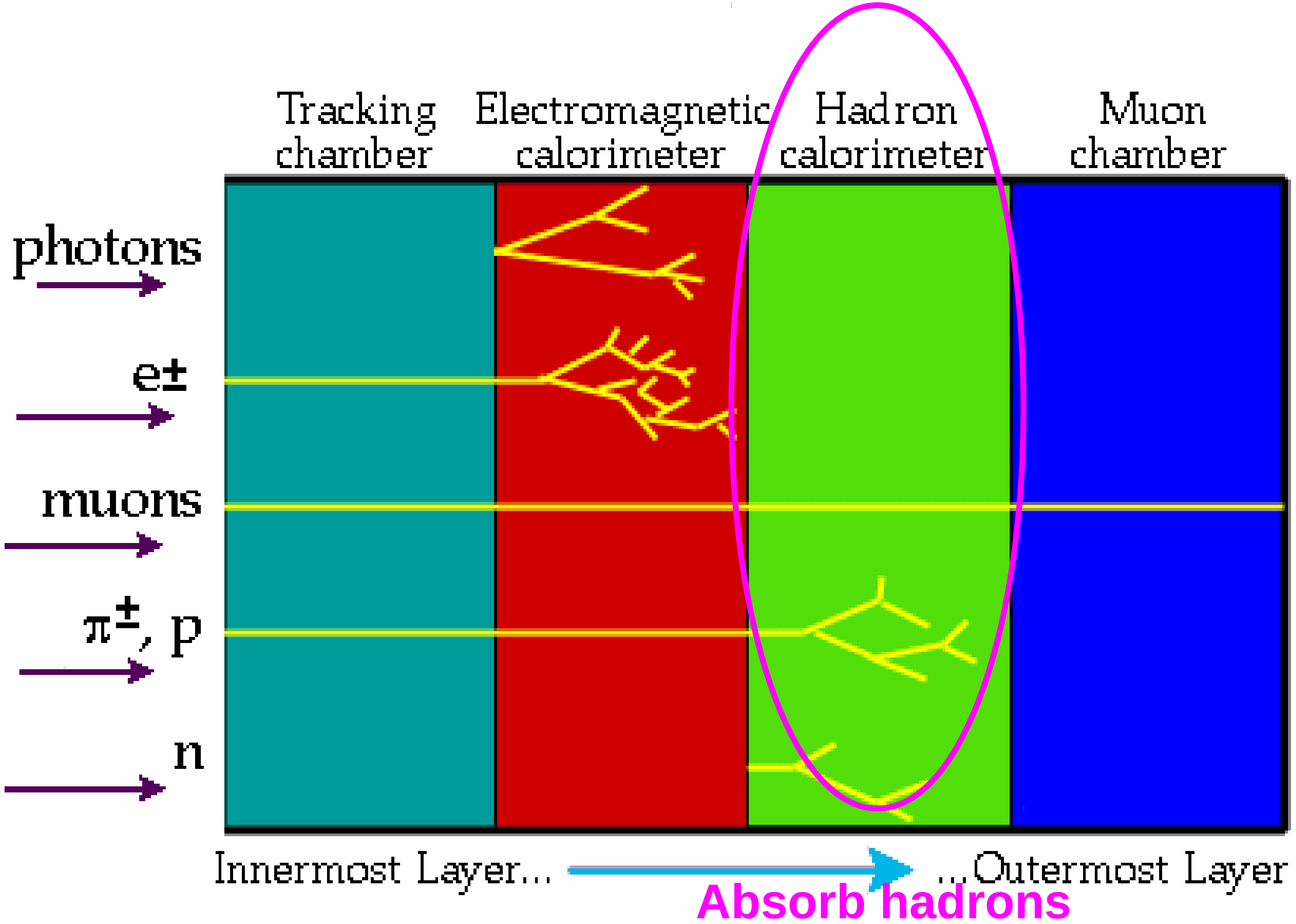


Figure 4.17 Approximate development of an electromagnetic shower in a sampling calorimeter assuming the simple model of the text. The calorimeter consists of alternate layers of lead (Pb) and a scintillator (Sc), the latter attached to photomultipliers (one only shown).

Hadron calorimeter



We need to absorb the hadrons

- We use the strong interactions so it means that the particle interacts inelastically with nucleons in the detector material

Hadronic reactions with nuclei

4.3.1 Short-range interactions with nuclei

For hadrons, the most important short-range interactions with nuclei are due to the strong nuclear force, which unlike the electromagnetic interaction is as important for neutral particles as for charged ones. For the simplest nucleus, the proton, the resulting reactions are of two types: *elastic scattering* such as

$$\pi^- + p \to \pi^- + p, \tag{4.4a}$$

where for illustration we have taken the incident particle to be a π^-; and *inelastic reactions* such as

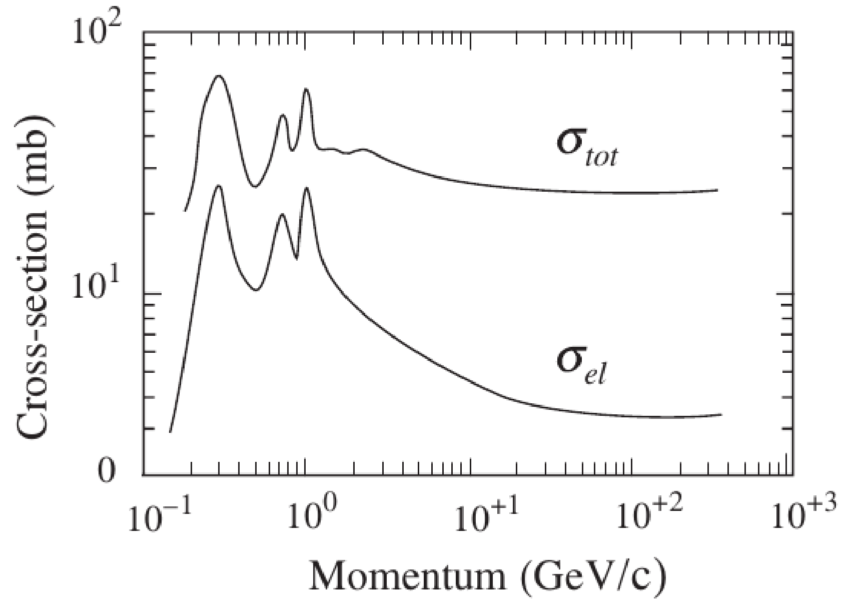
$$\pi^- + p \to \pi^+ + \pi^- + \pi^0 + n \tag{4.4b}$$

and

$$\pi^- + p \to K^0 + \Lambda, \tag{4.4c}$$

in which the final state particles differ from those in the initial state. At high energies, many inelastic reactions are possible, most of them involving the production of several particles in the final state. The total cross-section

$$\sigma_{tot} = \sigma_{el} + \sigma_{inel} \tag{4.5}$$



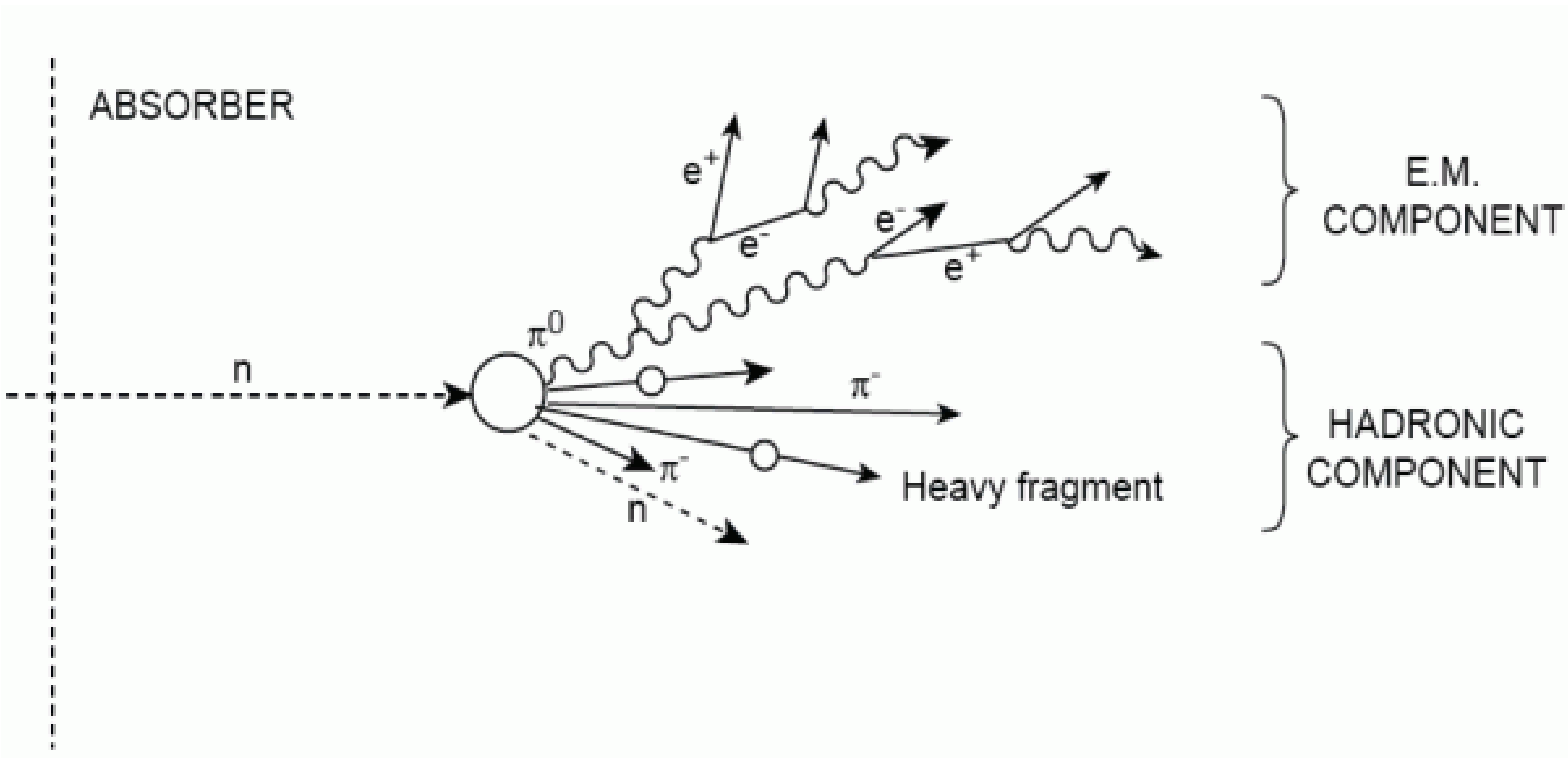
Hadronic interactions with nuclei

TABLE 4.1 Nuclear cross-sections and the associated collision lengths l_c and absorption lengths l_a for incident neutrons with energies in the range 80–300 GeV. The values for protons are approximately the same.

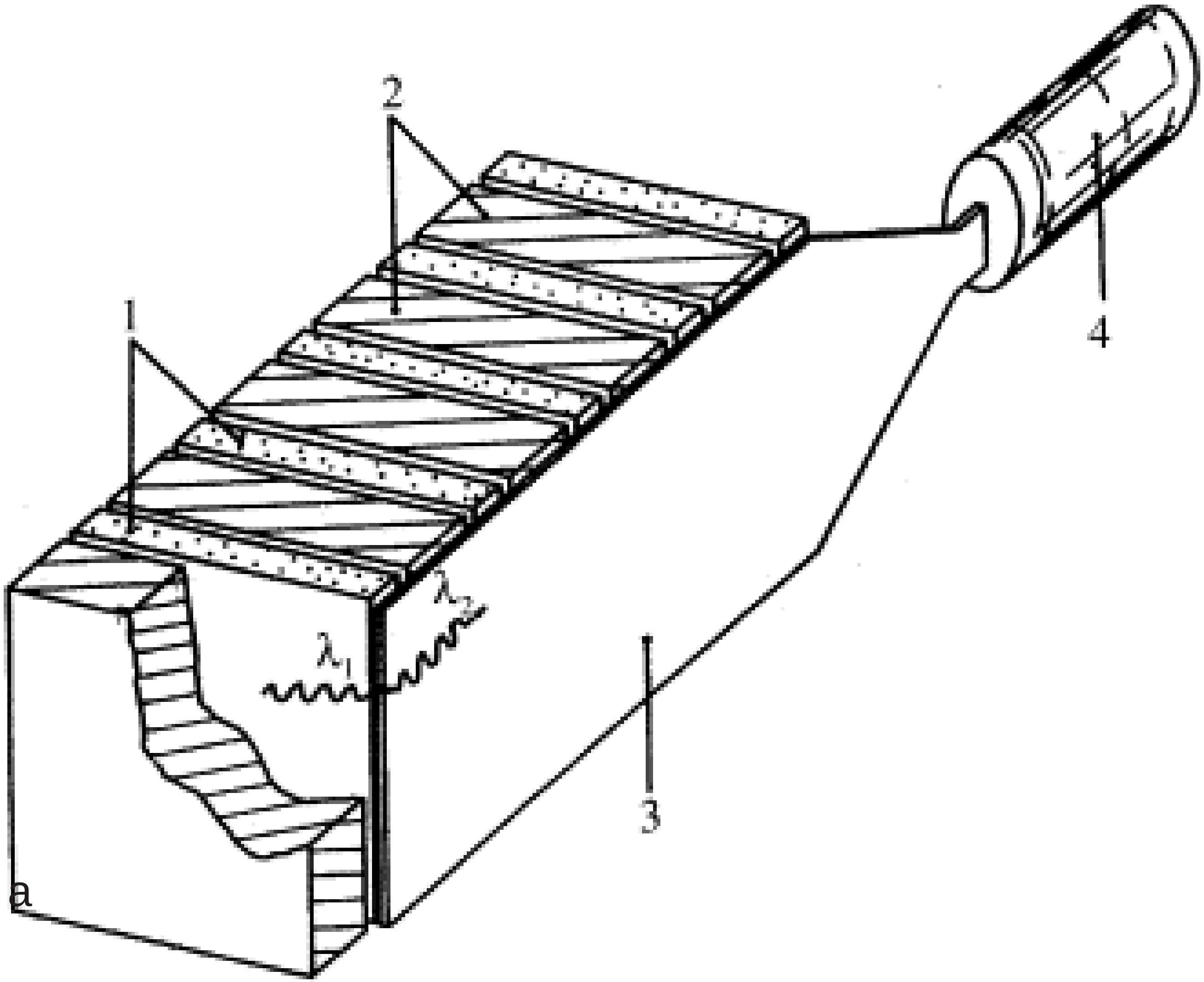
Element	Z	Nuclear cross-section (b)		Interaction length (cm)	
		σ_{tot}	σ_{inel}	l_c	l_a
H*	1	0.039	0.033	687	806
C	6	0.331	0.231	26.6	38.1
Al	13	0.634	0.421	26.1	39.4
Fe	26	1.120	0.703	10.5	16.8
Pb	82	2.960	1.770	10.2	17.1

* Liquid hydrogen at 26 K. The other materials are solids.

Hadronic shower

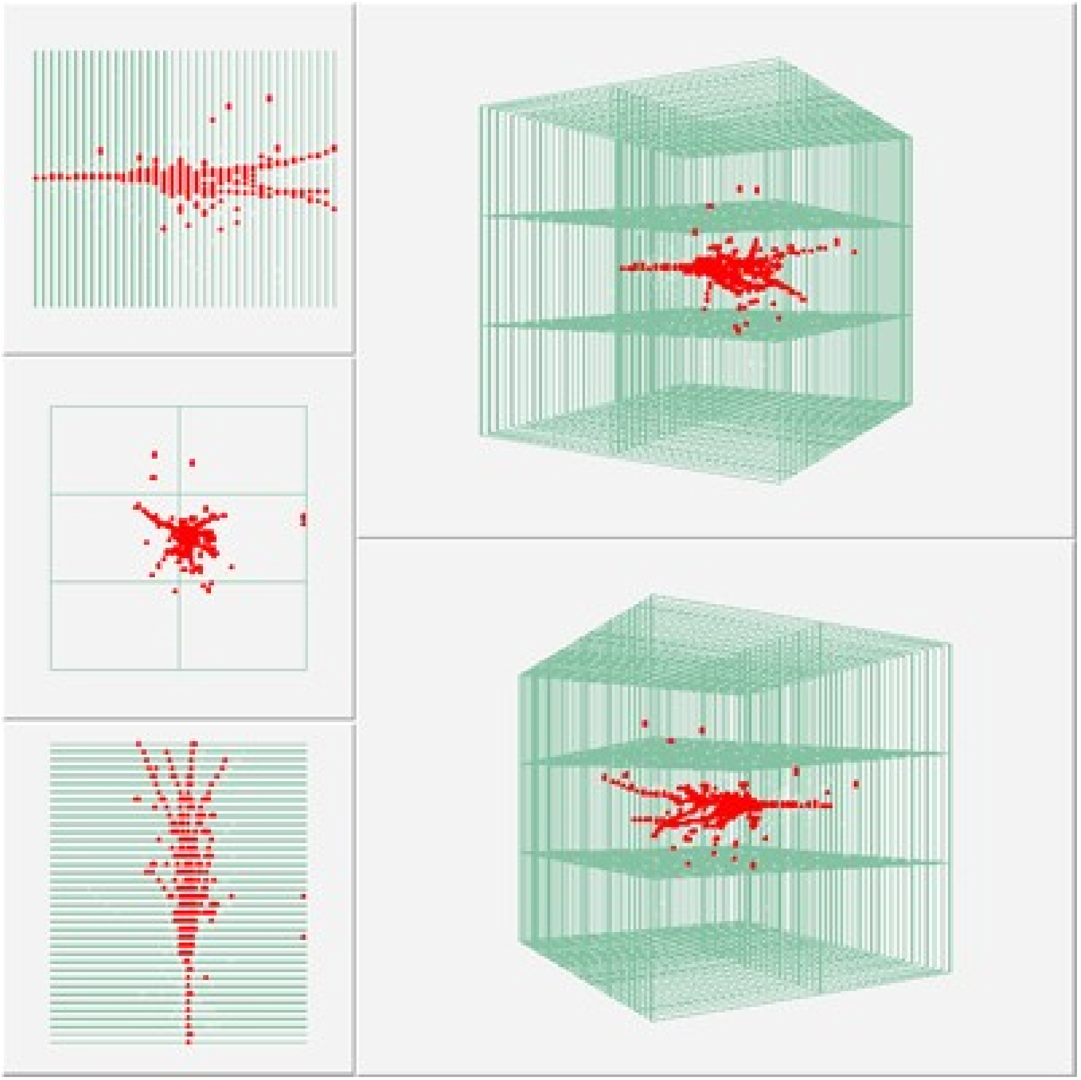


Basic calorimeter
1. scintillating plates, 2. lead absorber

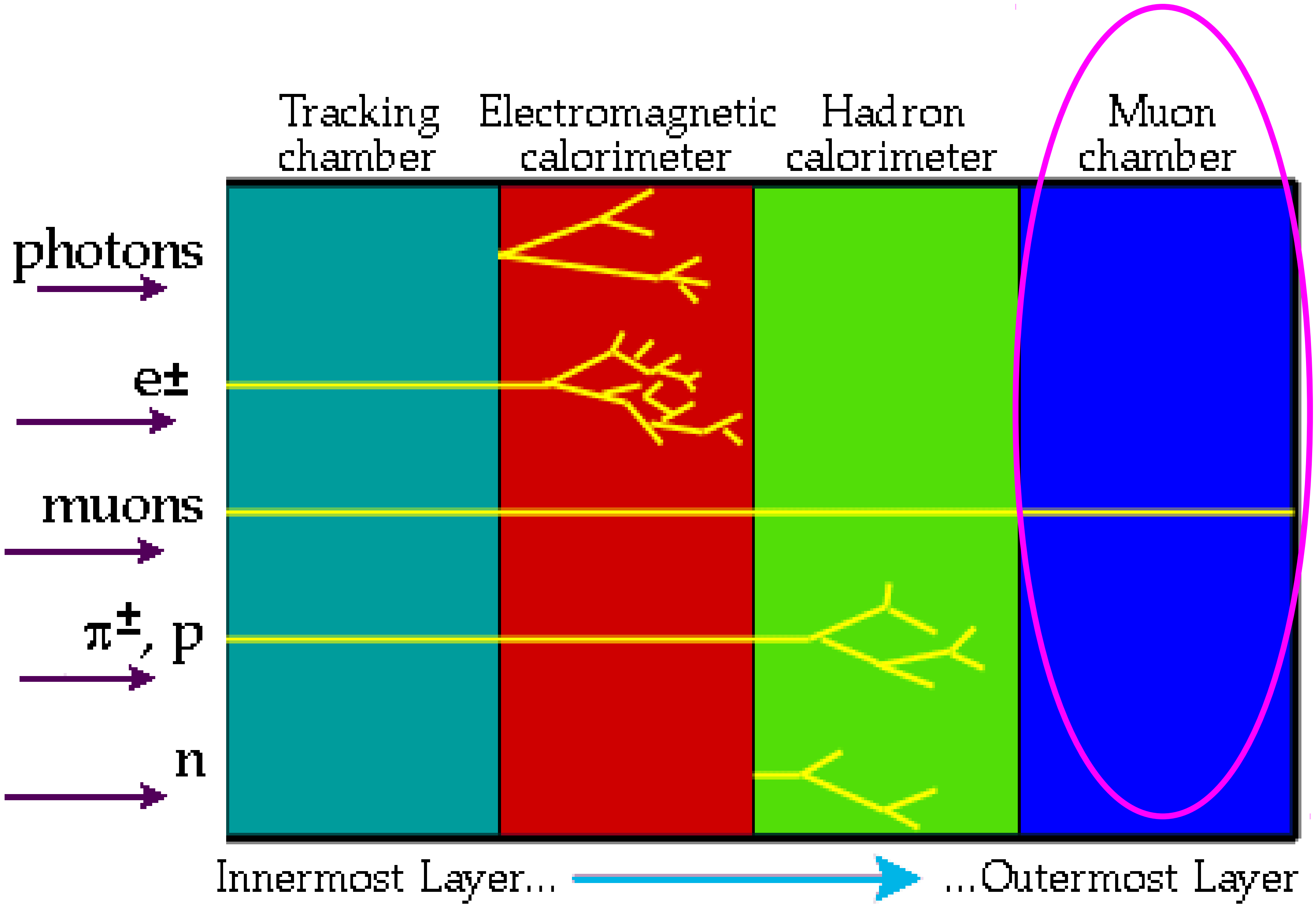


Measure a

32 GeV pion in Digital Hadronic calorimeter (CALICE collaboration)



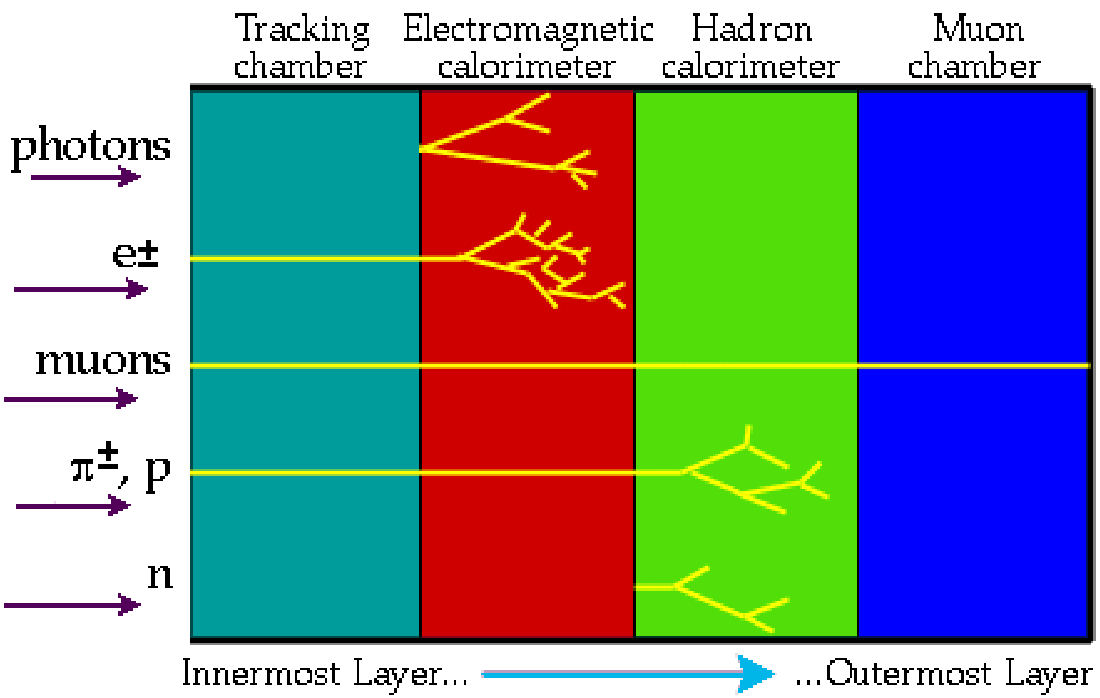
Muon chamber



The muon chamber is easy!

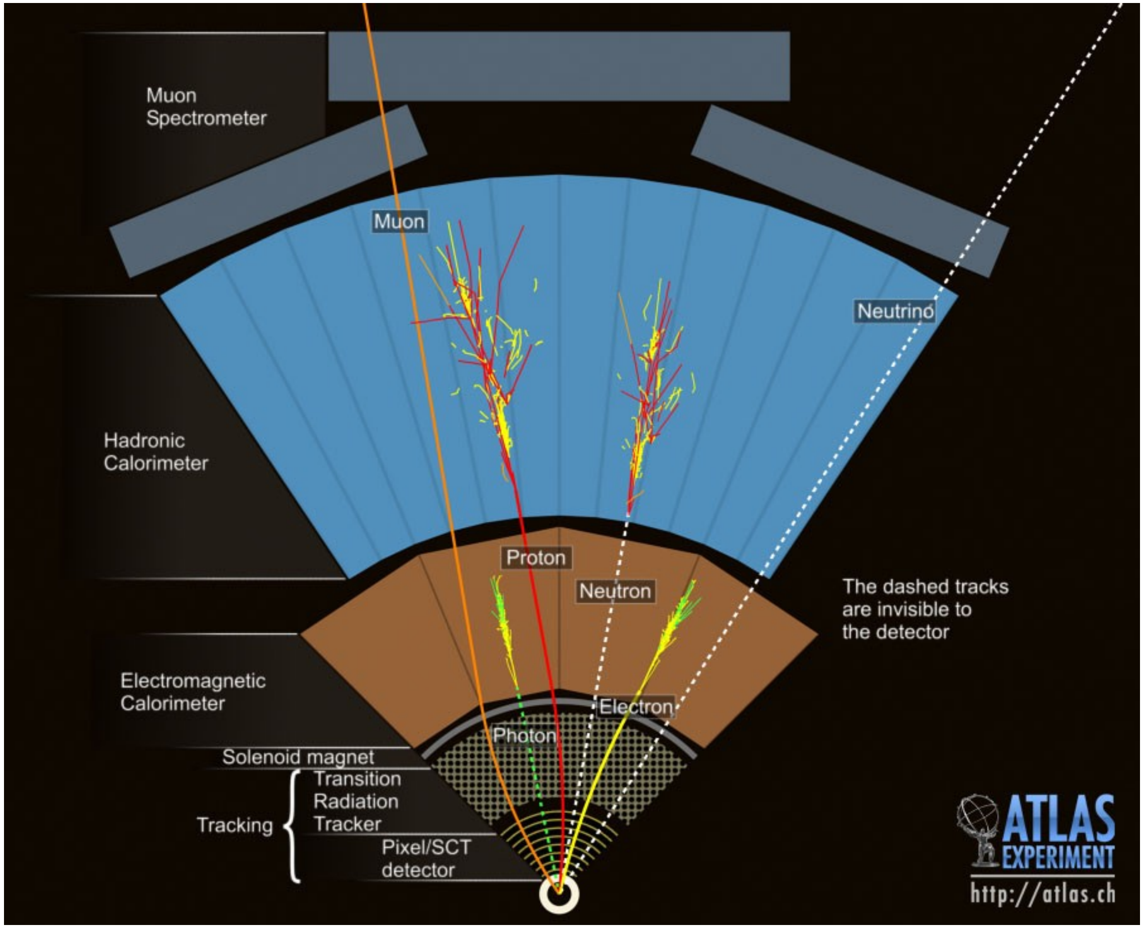
- The muons are basicly tracks that goes through all the material
- Too large mass for EM cal
- Not interacting strongly so it also passes hadron caorimeter
- Lifetime is so long that it does not decay (this τ does because of its large mass)
- <u>So the muon chamber is a normal tracking chamber</u>

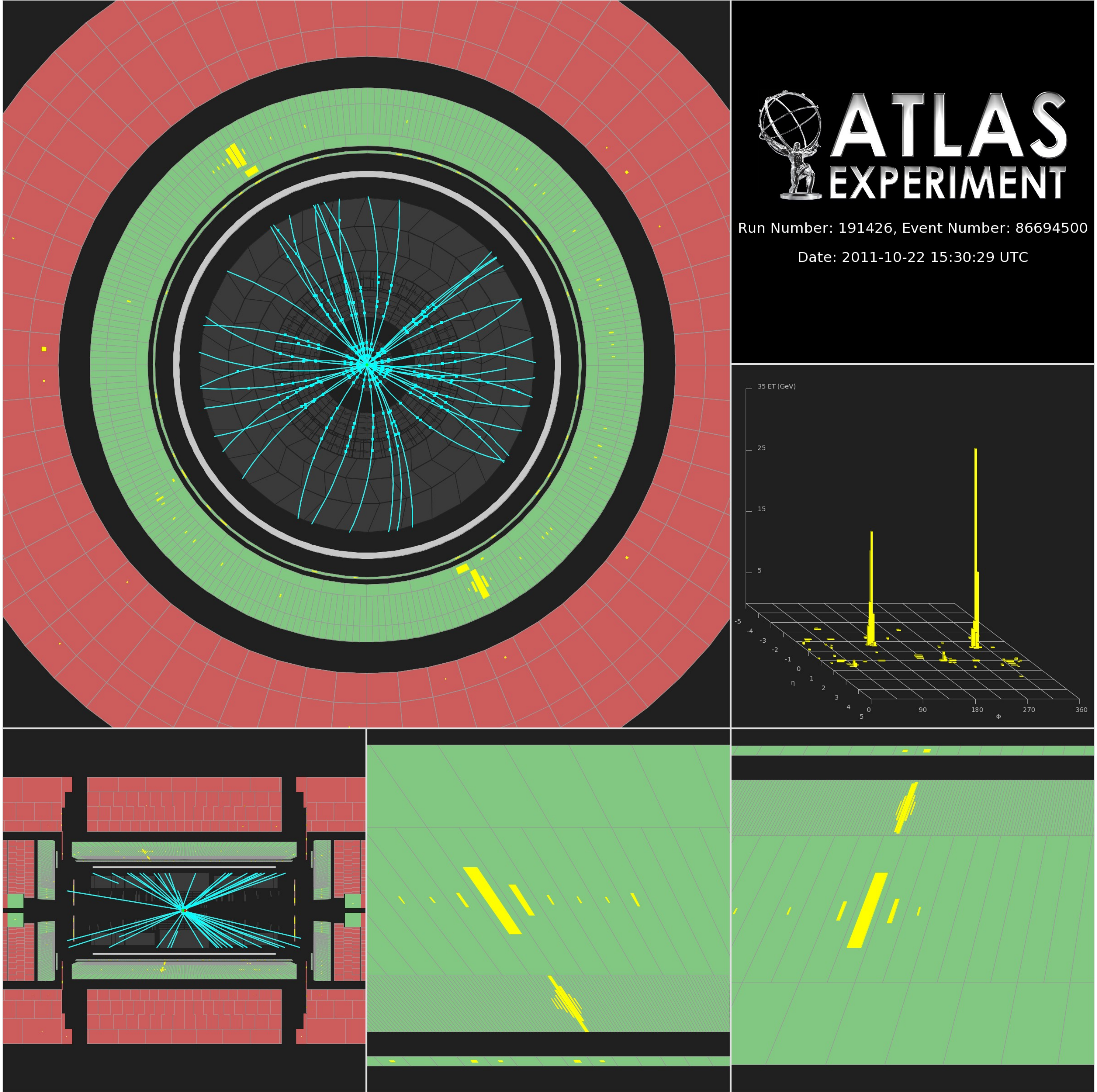
Summary

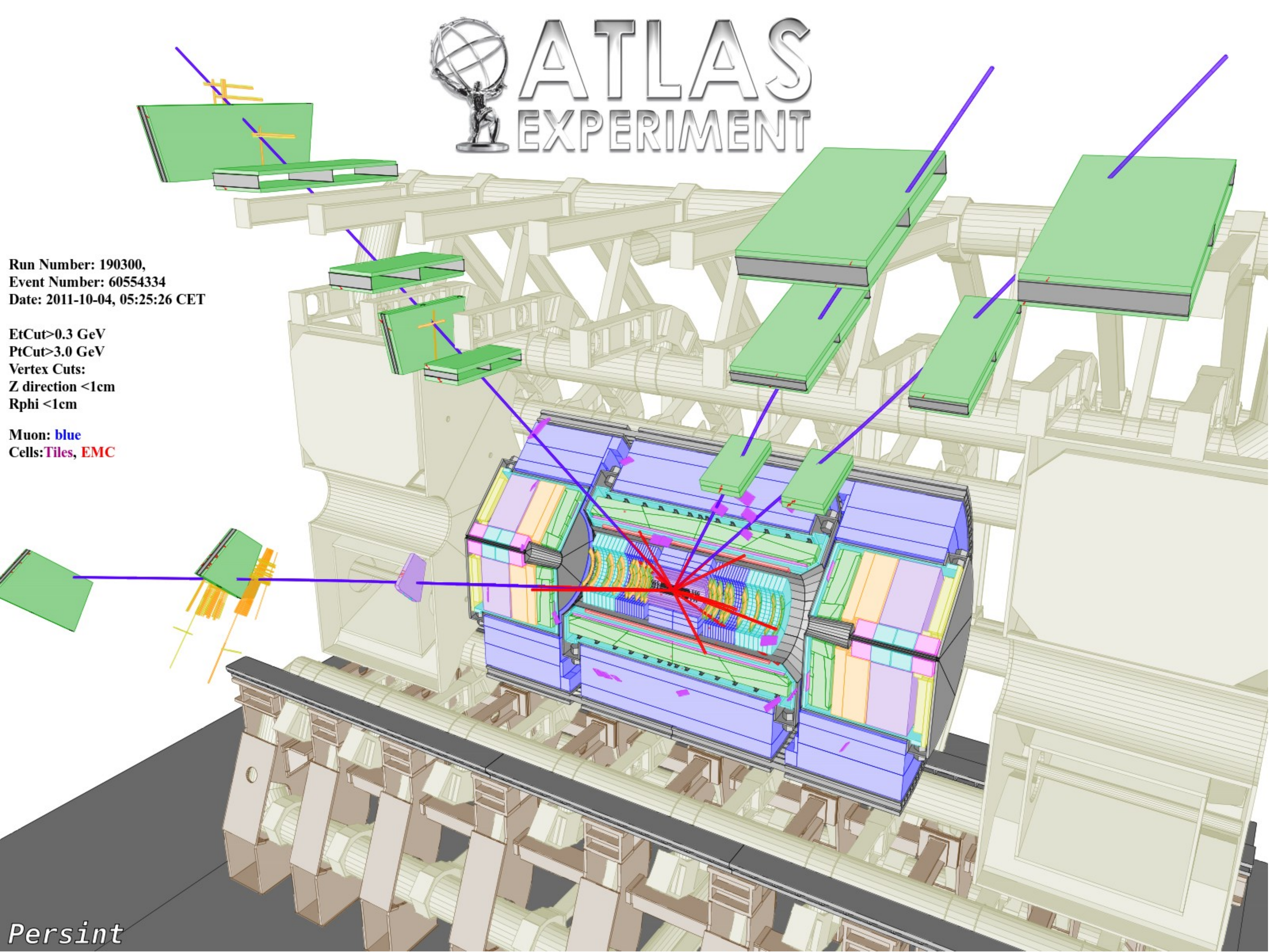


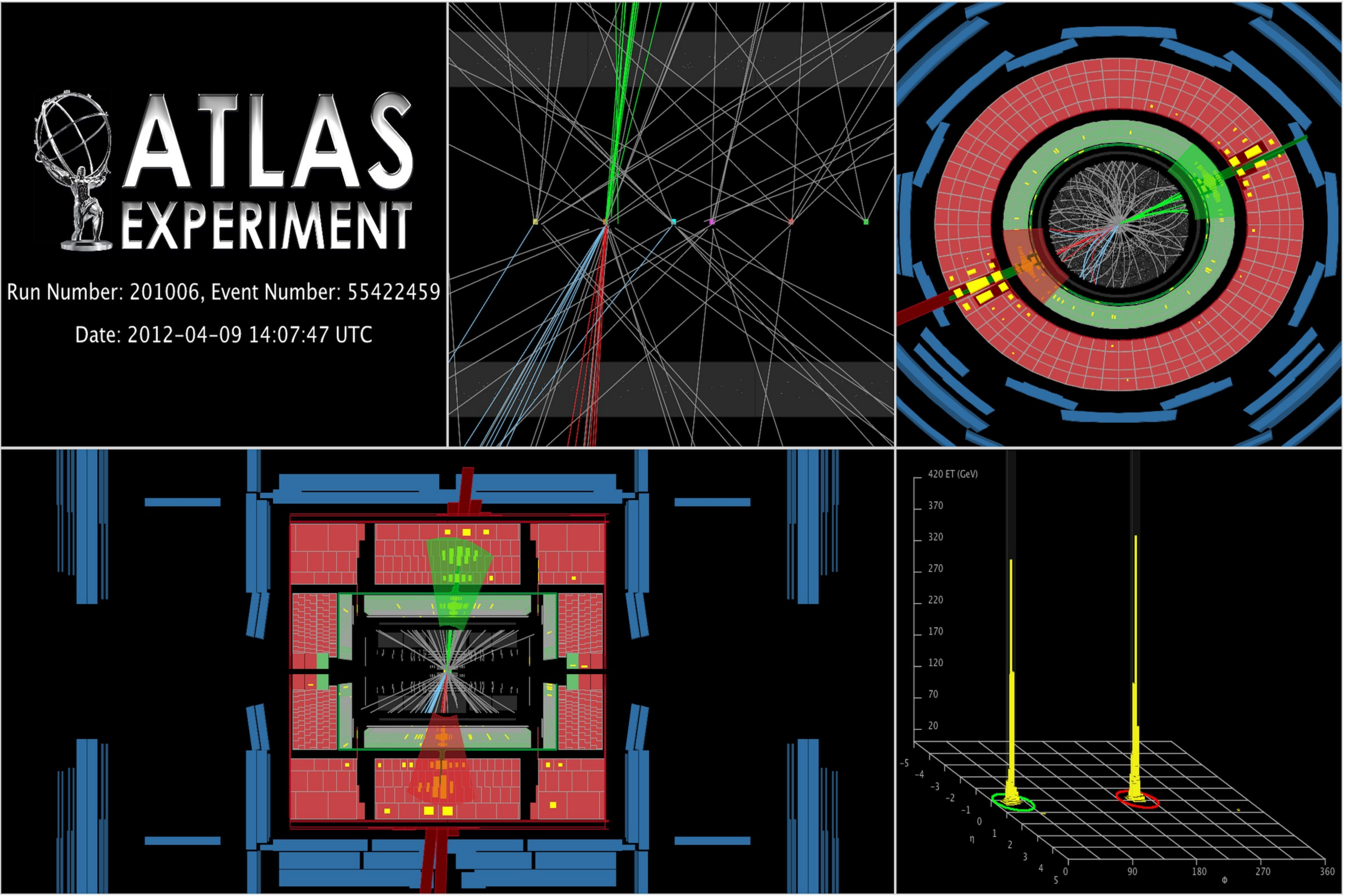
- Tracking: energloss due to EM interaction with electrons in matter
- EMCAL: dE/dx due to EM interaction with nuclei
- HCAL: dE/dx due to STRONG interaction with nuclei

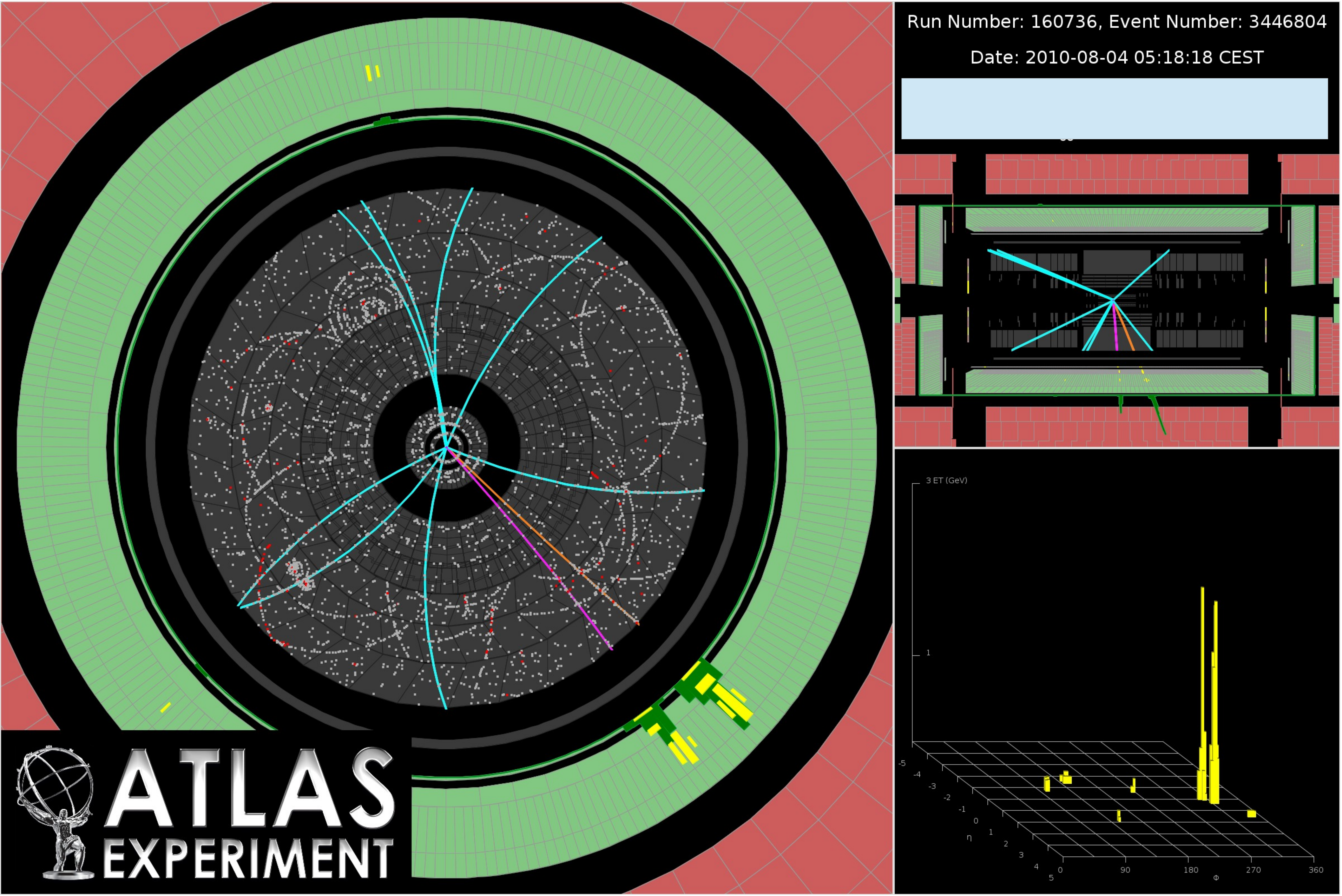
The what is this quiz!

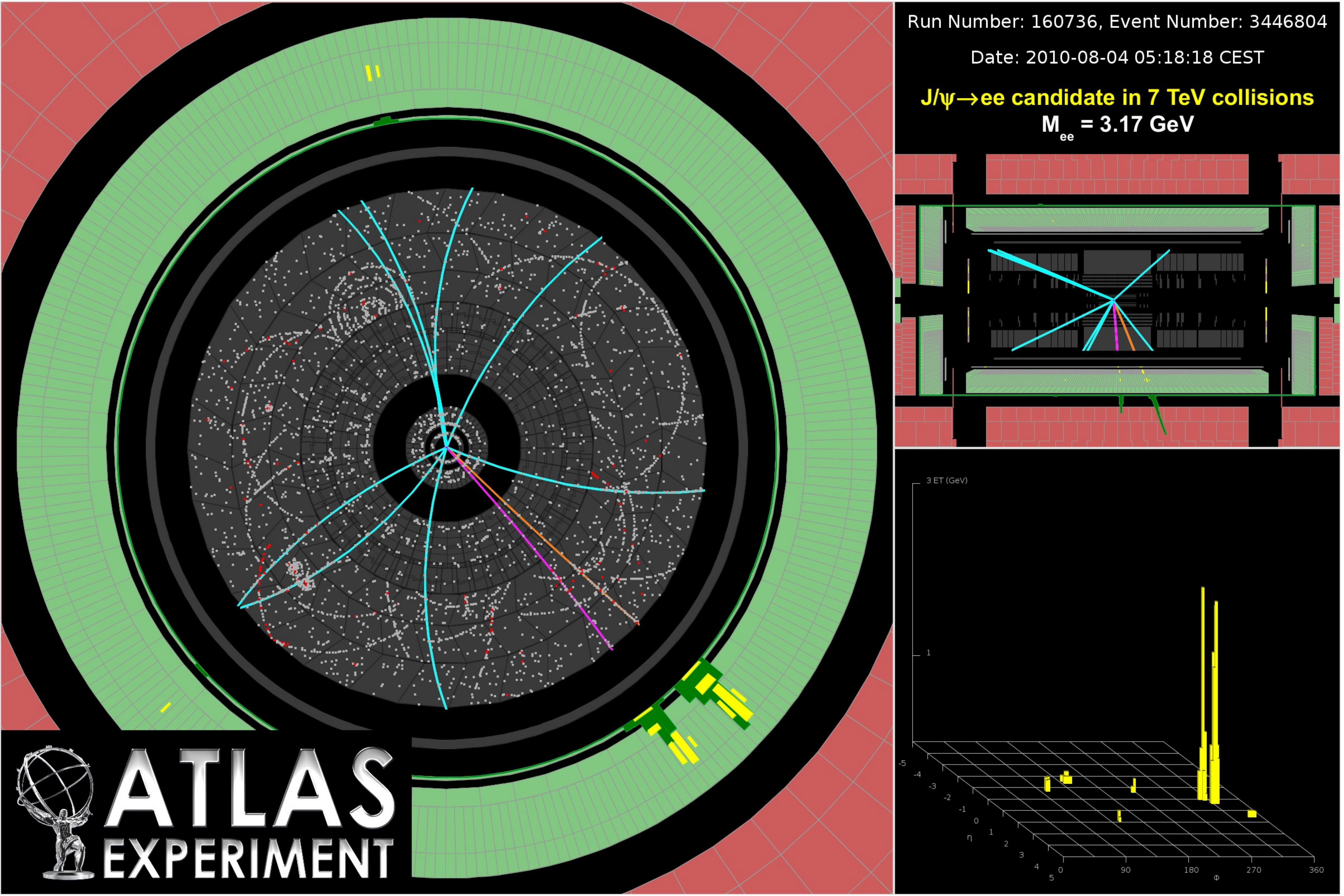



ATLAS EXPERIMENT
Run Number: 191426, Event Number: 86694500
Date: 2011-10-22 15:30:29 UTC
35 ET (GeV)
25
15
5
-5 -4 -3 -2 -1 0 1 2 3 4 5
η
0 90 180 270 360
Φ


ATLAS
EXPERIMENT
Run Number: 190300,
Event Number: 60554334
Date: 2011-10-04, 05:25:26 CET
EtCut>0.3 GeV
PtCut>3.0 GeV
Vertex Cuts:
Z direction <1cm
Rphi <1cm
Muon: blue
Cells:Tiles, EMC
Persint


ATLAS
EXPERIMENT
Run Number: 201006, Event Number: 55422459
Date: 2012-04-09 14:07:47 UTC
420 ET (GeV)
370
320
270
220
170
120
70
20
-5
-4
-3
-2
-1
0
1
2
3
4
5
η
0
90
180
270
360
ϕ

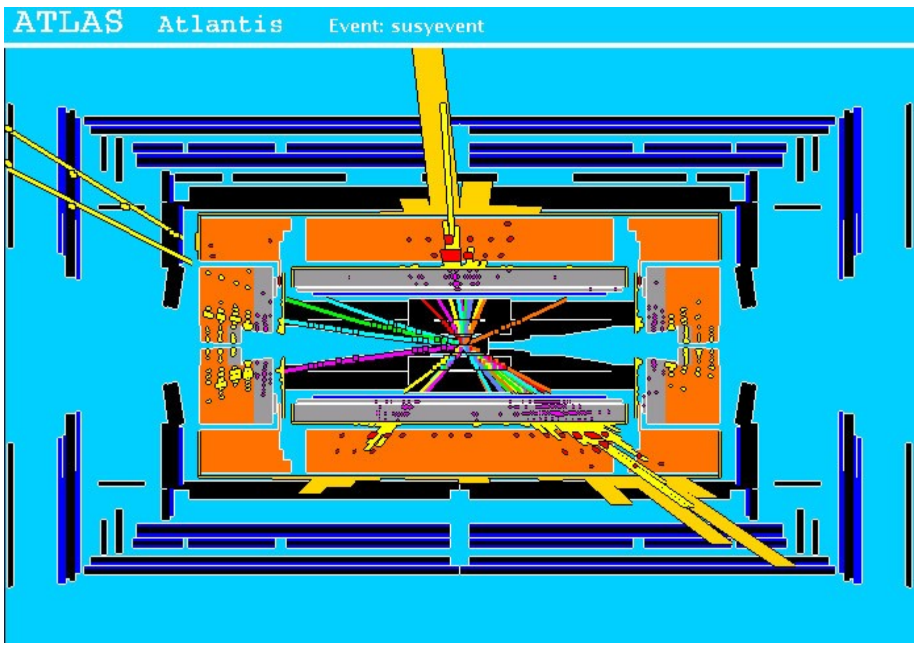

Run Number: 160736, Event Number: 3446804
Date: 2010-08-04 05:18:18 CEST
ATLAS
EXPERIMENT
3 ET (GeV)
1
η
-5
-4
-3
-2
-1
0
1
2
3
4
5
Φ
0
90
180
270
360

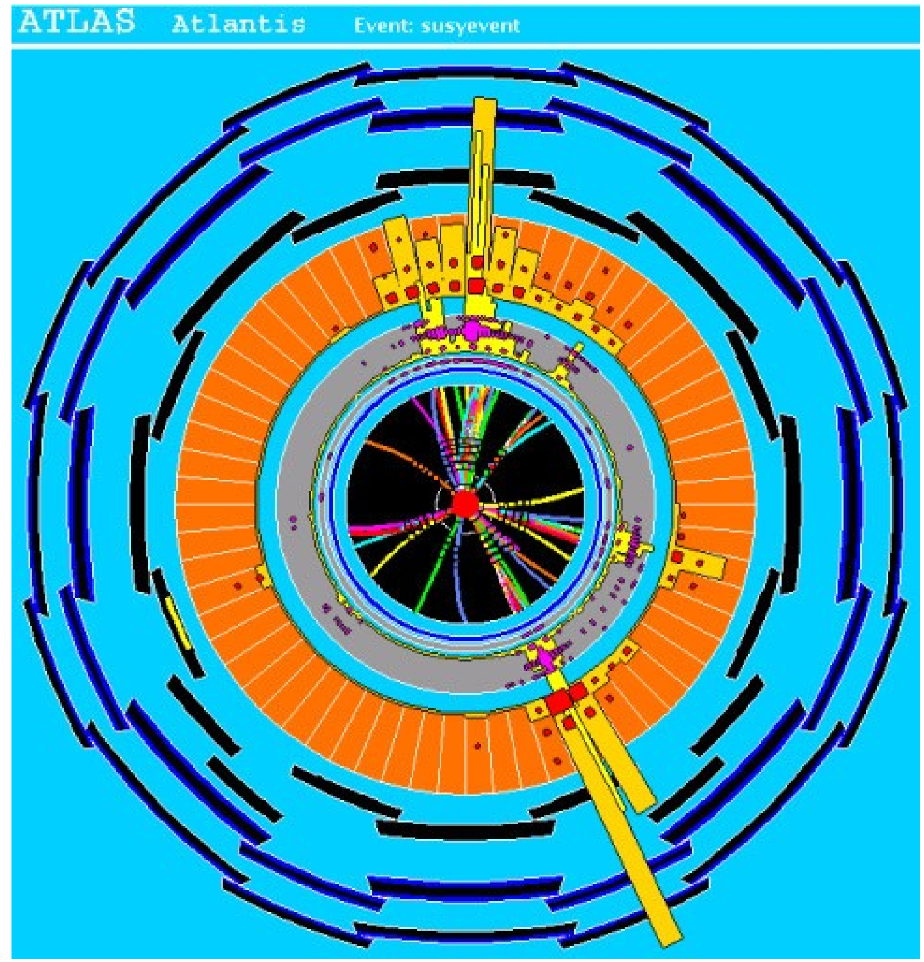

Run Number: 160736, Event Number: 3446804
Date: 2010-08-04 05:18:18 CEST
J/ψ→ee candidate in 7 TeV collisions
M_{ee} = 3.17 GeV
ATLAS
EXPERIMENT
3 ET (GeV)
1
η
Φ
0
90
180
270
360

What about particles that do not interact?

- What if we created a completely new heavy particle that doe not interact?
- How would we observe that?

The reason for the 4π design (Simulated event)





Simulated SUSY Missing Transverse Energy (MET) event