(dis)cours / lectures on detectors for high energy physic, astro-particle physic and nuclear physic

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Lectures and evaluation

Lecture #1 (Ph.S.) : **05/09 afternoon (Orsay campus : b.100-A)**
Working aspects of a complex detector

Lecture #2 (M.C.) : **08/09 afternoon (Orsay campus : b.100-A)**
Interaction of particle with matter

Lecture #3 (M.C.) : **11/09 morning …**

Lecture #4 (M.C.) : **18/09 morning …**

Lecture #5 (Ph.S.) : **03/10 afternoon (Orsay campus : b.100-A)**
Gaseous detectors

Lecture #6 (Ph.S.) : **10/10 afternoon (Jussieu campus : tour 24-34, room 101)**
Gaseous detectors (con't), calorimeters, magnets, trigger

Lecture #7 (T.P.) : **17/10 …**

Lecture #8 (T.P.) : **24/10 … + choice of "mini-stage"**

Lecture #9 (T.P.) : **31/10 …**

Remember to look at the place + room !
(also morning or afternoon)

After these lectures : writing test + oral exam (analysis of a detector paper)
Evaluation will be discussed/presented later in September.

Warning : words…

Each human activity has its own words and *jargon*, and (unfortunately) physics detectors follow the same rule.

Thus, it will be very important for you to know as much as possible, the name to be used and the **exact meaning of the words that are used**.

The knowledge of these words are really mandatory for discussing with experts working in this field: engineers, technicians and physicians.

The difficulty of detectors field, is that there (sometimes) exists several solution for doing inventing a detector for a given problem. So it may be difficult for you to find which solution to choose…

Don’t be afraid and ask questions : there is no stupid or bad question(s) !!

Goals and limitations of these lectures

	Minimum knowledge	Understanding a paper on that	Thinking of your own experiment	Doing of your own experiment
Simple single particle detection	X	X	x (x)	(x)
Understanding an existing experiment based on a “single” particle detection *(<u>warning</u>: there is always background !)*	X	X	x (x)	
Multiple detectors experiment : satellite, ground *(<u>warning</u>: one part may induce background/bias on another part !)*	X	x (x)	(x)	
Find physics analysis bias or limitation coming from an experiment for “**single**” ->	x	x		
“**multiple**” detector types ->	(x)	(x)		
Your analysis during your PhD				

Some questions that you should be able to answer at the end of these lectures

How to measure the higgs $H \to ZZ \to 4$ *muons* (e.g. ATLAS) ?

(higgs)

How to *trigger* to detect cosmic showers (e.g. in HESS or C.T.A detectors) ?

How to built a multi-detector on an accelerator (*ID*, *calorimeter*, *muon tracker*) ?

How work this detector (sub-)element ?

Which bias may I have in my analysis using that or this detector ?

…/…

Bibliography

→ Particle Data Group (tables, figures, etc.) accessible from: http://pdg.lbl.gov

- → Claus Grupen, Particle Detectors (Cambridge University Press, 1996)
- Robert S. Gilmore, Single particle detection and measurement (Taylor & Francis, 1992)
- → Walter Blum and Luigi Rolandi, Particle detection with drift chambers (Springer-Verlag, 1994)
- Instrumentation in high energy physics (World Scientific, ed. F.Sauli, 1992)
- → Experimental techniques in high-energy nuclear and particle physics (World Scientific, ed. Th.Ferbel, 1991)
- Konrad Kleinknecht, Detectors for particle radiation (Cambridge Univ. Press, 1986)
- → W.R. Leo, Techniques for Nuclear and Particle Physics Experiments (Springer, 1994)
- Spark, streamer, proportional and drift chambers, Peter Rice-Evans (Richelieu Press, 1974)
- Review of Particle Physics (European Physical Journal, 2000)
- Revue Nuclear Instruments and Methods
- ATLAS TDR (from 1999 to 2003), ATLAS internal notes (http://www.cern.ch)
- → Resistive Gaseous Detectors, *Designs, Performance, and Perspectives*, 2018 (Wiley-VCH) Marcello Abbrescia, Vladimir Peskov, and Paulo Fonte
- Bruno Rossi, High energy particles (Prentice-Hall, 1952)

Lecture #1
Multi-detector logic

Outline

→ 0) historical remark

1) A physic analysis need a specific detector (and a specific accelerator)

2) Which particle could I see in my detector

3) Loosing energy in the detector (the minimum to be known for this lecture)

4) Layout of a multi-detector apparatus

5) Some typical detectors

6) Glossary

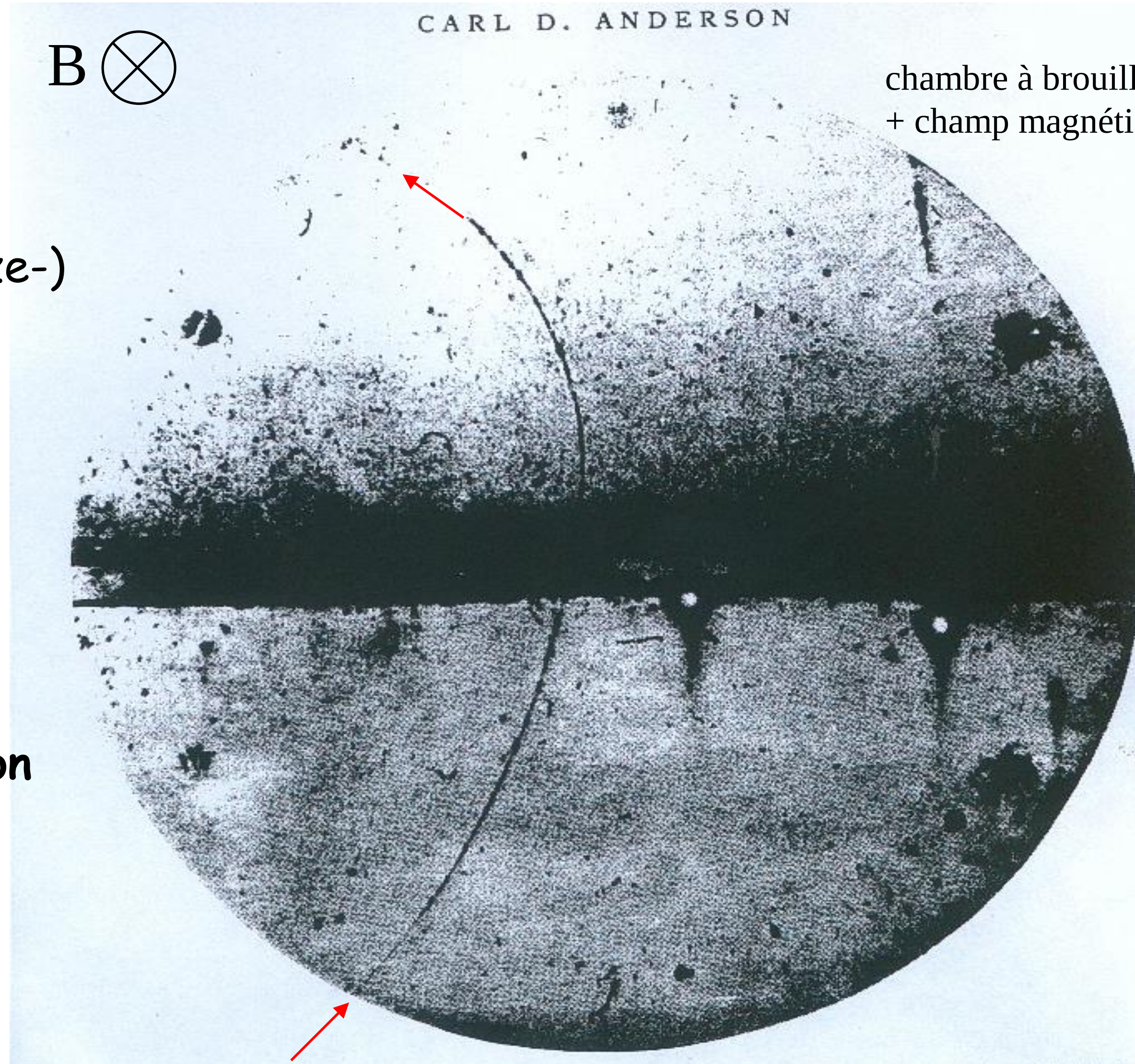
7) Event display of typical LEP events (i.e. simple examples to understand)

Discovery of positron e^+ cosmic rays

1932 C.D. Anderson :
Minimum bias particle (i.e. at the minimum of ionisation –bubbles size-) with a positive curvature

Track length incompatible with a proton in air, mass incompatible avec a proton

Energy loss in 6 mm of Lead (Pb) **compatible with electron energy loss**



chambre à brouillard
+ champ magnétique

FIG. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

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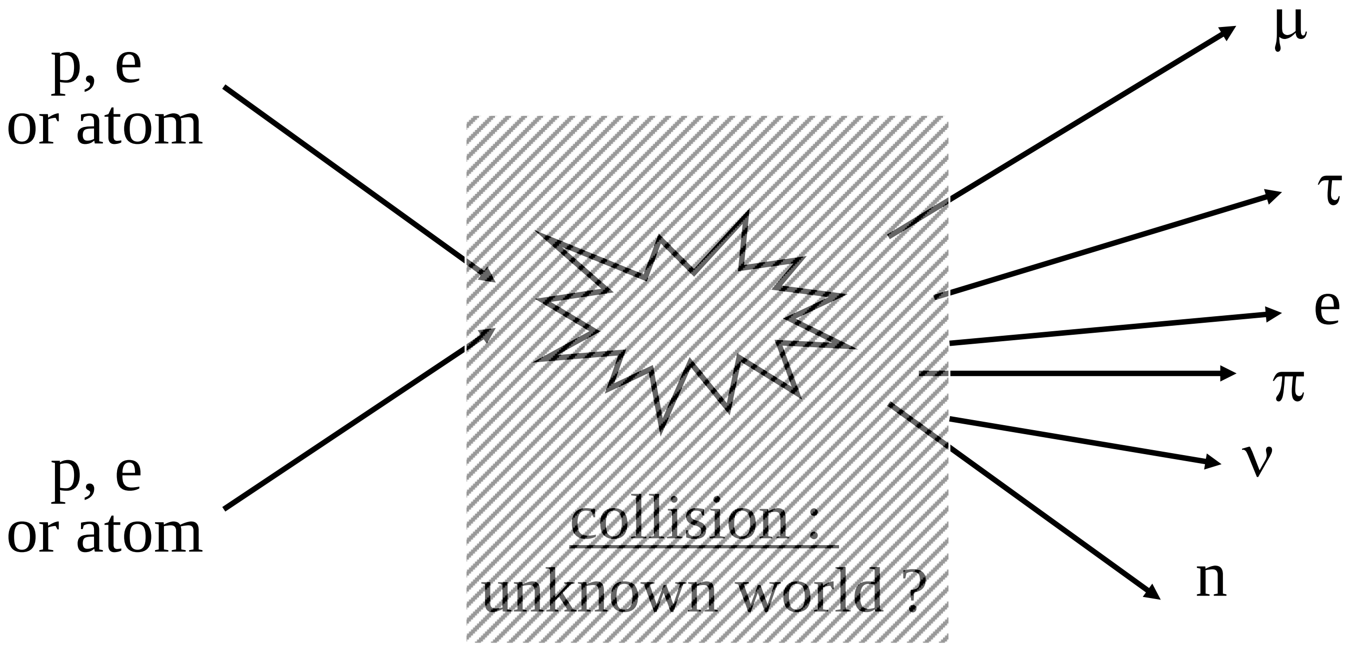
Problematic (simplified)

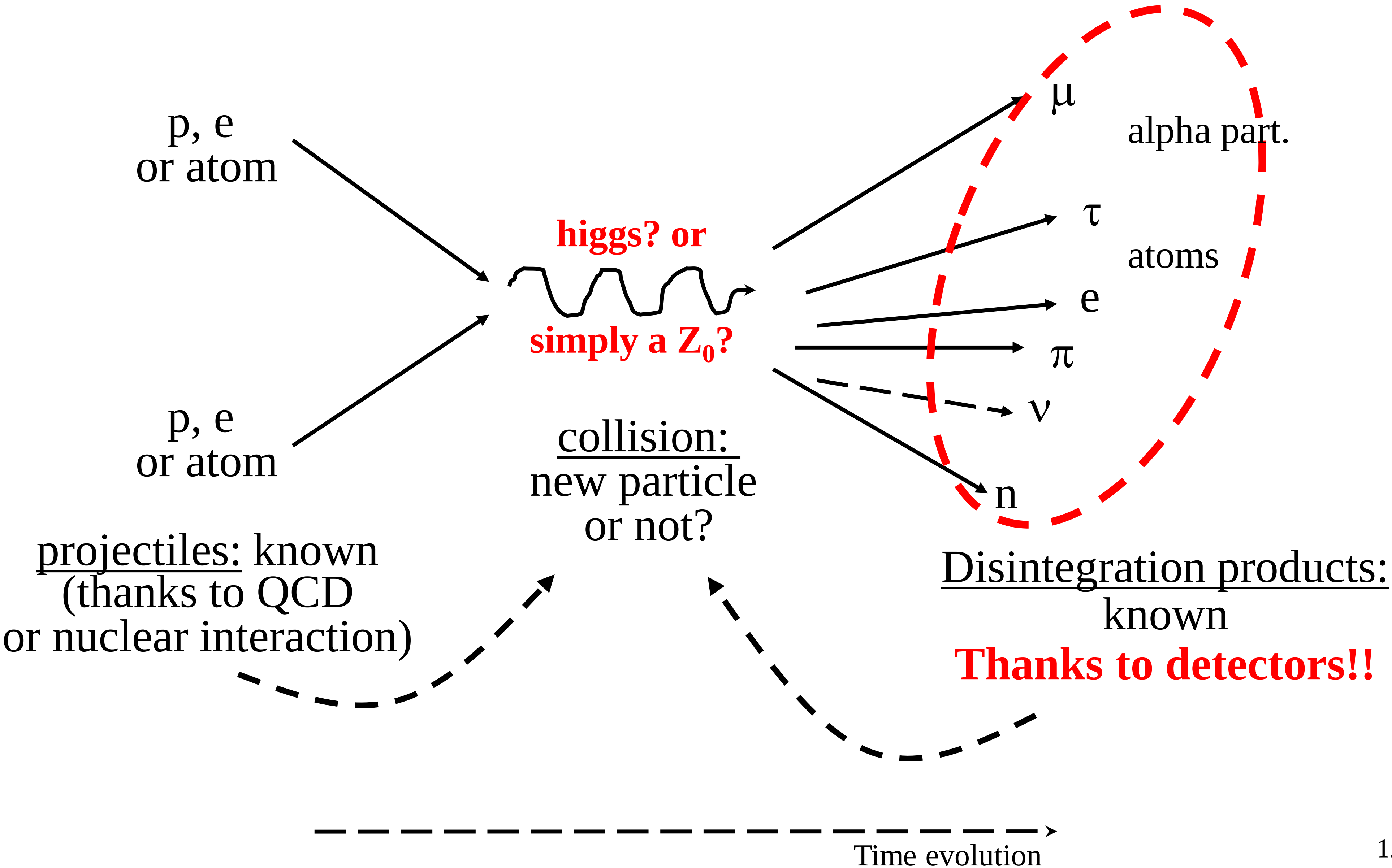


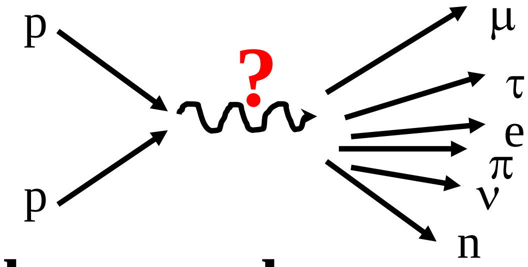
projectiles : a priori known

Disintegration products : known (with some probabilities)

Time evolution

Problematic (simplified)





Goal: test a theory.
Example of an analysis

<u>I would like to find (for example) a Higgs using its decay mode:</u>

$p + p \rightarrow H \rightarrow Z^0 Z^{0*} \rightarrow e^+ e^- \mu^+ \mu^-$ (in real life: p+p →H + … → ZZ+… →eeμμ+…)

(higgs)

I should calculate:

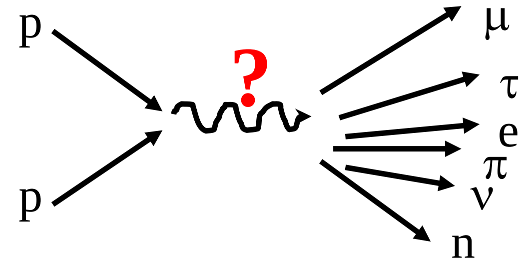
For each Z^0, I should calculate (e.g. for $Z^0 \rightarrow \mu^+ \mu^-$) :

Same thing for a Higgs decaying in two gamma's : $H \rightarrow \gamma\gamma$

In all cases, we should measure:

$E_{\mu+}$, $E_{\mu-}$, spatial momentum (i.e. tracks with their angular directions)…

Example of an analysis: consequences



<u>So I need a detector able to:</u>

In which order?

- measure energy of these particles
- measure particle position (i.e. measure tracks)
- measure direction of these particles
- identify these particles (charge and mass hyp.)

Of course it should be possible even with pile-up particles and with background. Also, we should have redundancy in the measurements and detectors should not interfere (too much). If this is the case, we should be able to understand that. Detectors should work all the whole duration of the experiment (to be defined).

All this are the « specifications » of the detector/apparatus working on an <u>accelerator</u> (the LHC in this particular example).

Needed, in order to have collisions!!

Choice of an accelerator : fixe target or collider

Up to '60, many experiments working on fixe target mode (first from Rutherford)

After start of experiment on colliders.

Fixe target

(cosmics on target like: air, detectors...)

$$(\vec{p}, E) \quad (0, m)$$

Collider

$$(\vec{p}, E) \quad (-\vec{p}, E)$$

Available centre of mass energy: $\sqrt{s}$

(centre of mass: like billiard spheres)

$s =$

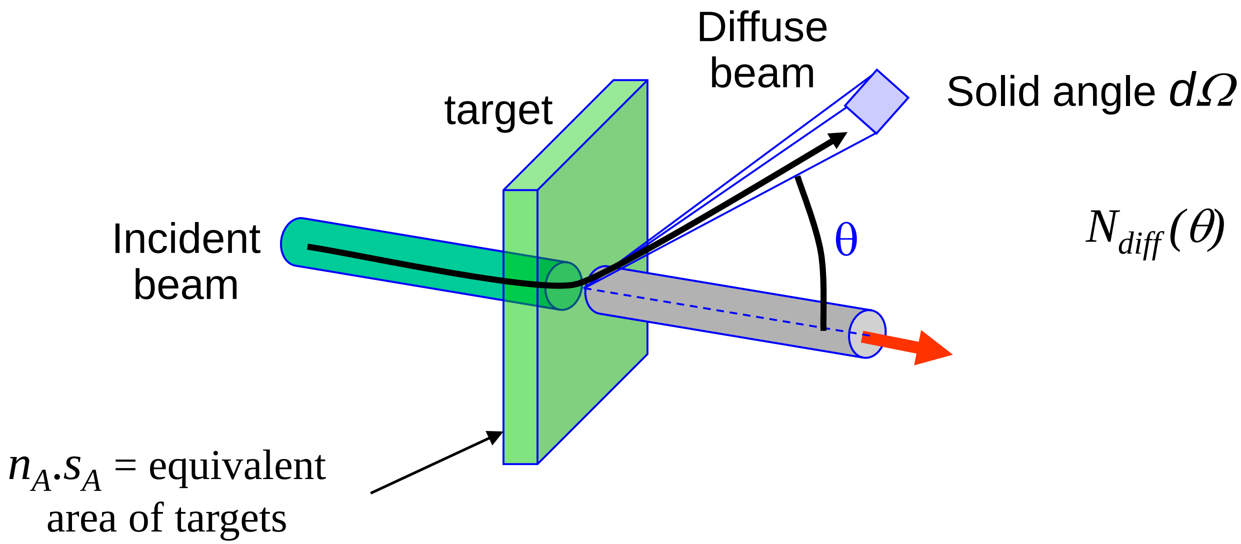
$s =$

But detectors bigger, more complex...

With the same beam energy (but with two beams) the centre of mass energy available to create new particles is much higher in collider ! (interaction of beam on fixe target may be used to produce particular secondary beams: neutrinos, muon, etc.)

Some definitions: cross section (of a particular interaction), luminosity (of an accelerator)

Cross section σ or differential cross section $d\sigma/d\Omega$ are used to calculate the interaction probability of particles:



$$N_{diff}(\theta) \propto N_{inc} \cdot n_A \cdot s_A \cdot d\Omega$$
$$= N_{inc} \cdot n_A \cdot \boldsymbol{d\sigma/d\Omega}(\theta) \cdot d\Omega$$

By definition cross section σ is an area and its unit is: barn (**1 b = 10^{-24} cm^2**)

An accelerator is characterised by its **luminosity *L*** **(cm^{-2}s^{-1})** and the interaction rate is $\sigma.L$. In colliding mode, the (theoretical) luminosity is given by: f. $n_b.n_1.n_2/(4\pi.d_x.d_y)$ where $(d_x.d_y)$ is the transverse area of beams, f the colliding frequency, n_1,n_2 the # of part. per bunch and n_b the # of bunch.

Example: the # of collisions/events p+p→X during T second is: $\sigma_{pp}^{total}.L.T$ (1 year ~ $\pi.10^7$ sec) using: σ_{pp}^{total}~110.10^{-3} barn at 14 TeV.

Example: proton-proton collision and final states at high energy

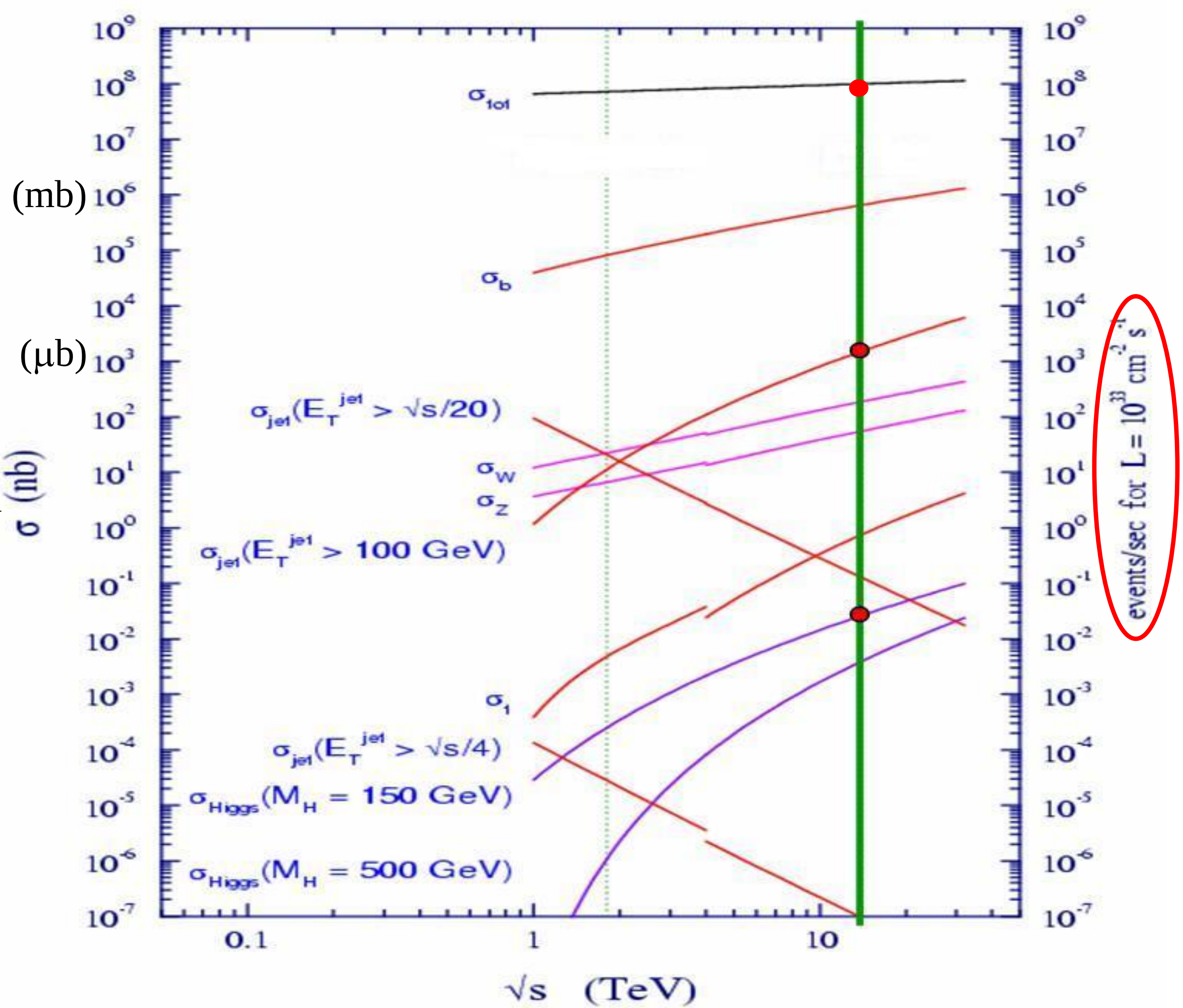
<u>Example (LHC):</u>
σ^{tot} ~ 110 mb and
$\sigma^{H\ tot}$ ~ 10^{-2} nb

$\sigma^{H\ tot}/\sigma^{tot}$ ~ few.10^{-9}

Of course, all cross sections are different for each particular decay modes!

In general, all physic channel to be studied is a rare decay mode…

=> Strong constrain in the selection process and in the event reconstruction.
=> Strong constrain on the apparatus and on all sub-detectors!



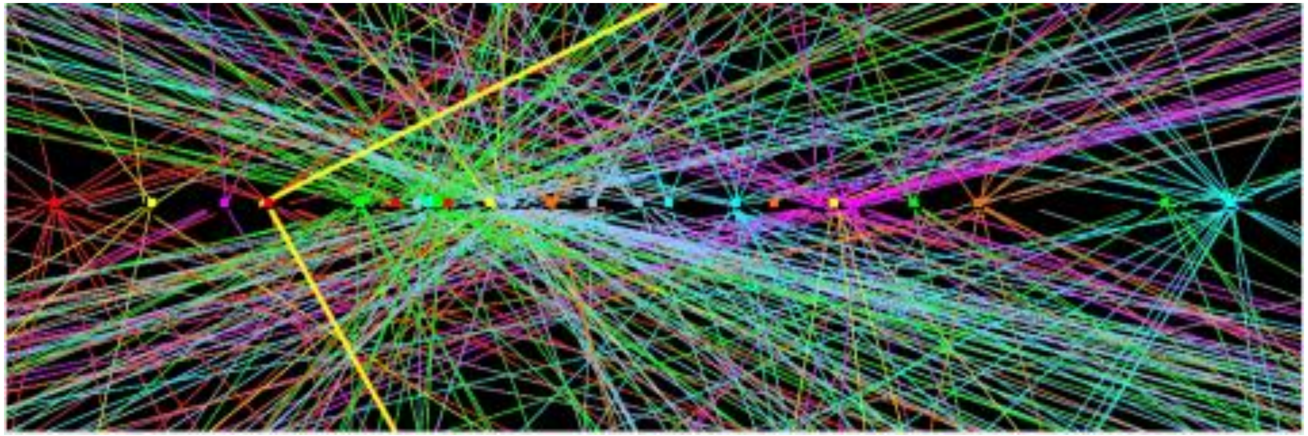
proton-proton collision and final state at high energy

The # of events p+p⟶X after some time T is : $\sigma_{pp}^{total}.\boldsymbol{L}.T$

To increase this number, one need to increase $\boldsymbol{L}$ with $\boldsymbol{L} = \mathbf{f.\ n_b.n_1.n_2/(4\pi.d_x.d_y)}$
At LHC, $n_{max} = 3808$ *(usually > 2000)*

⇒ But we will also increase the number of bad / background events…

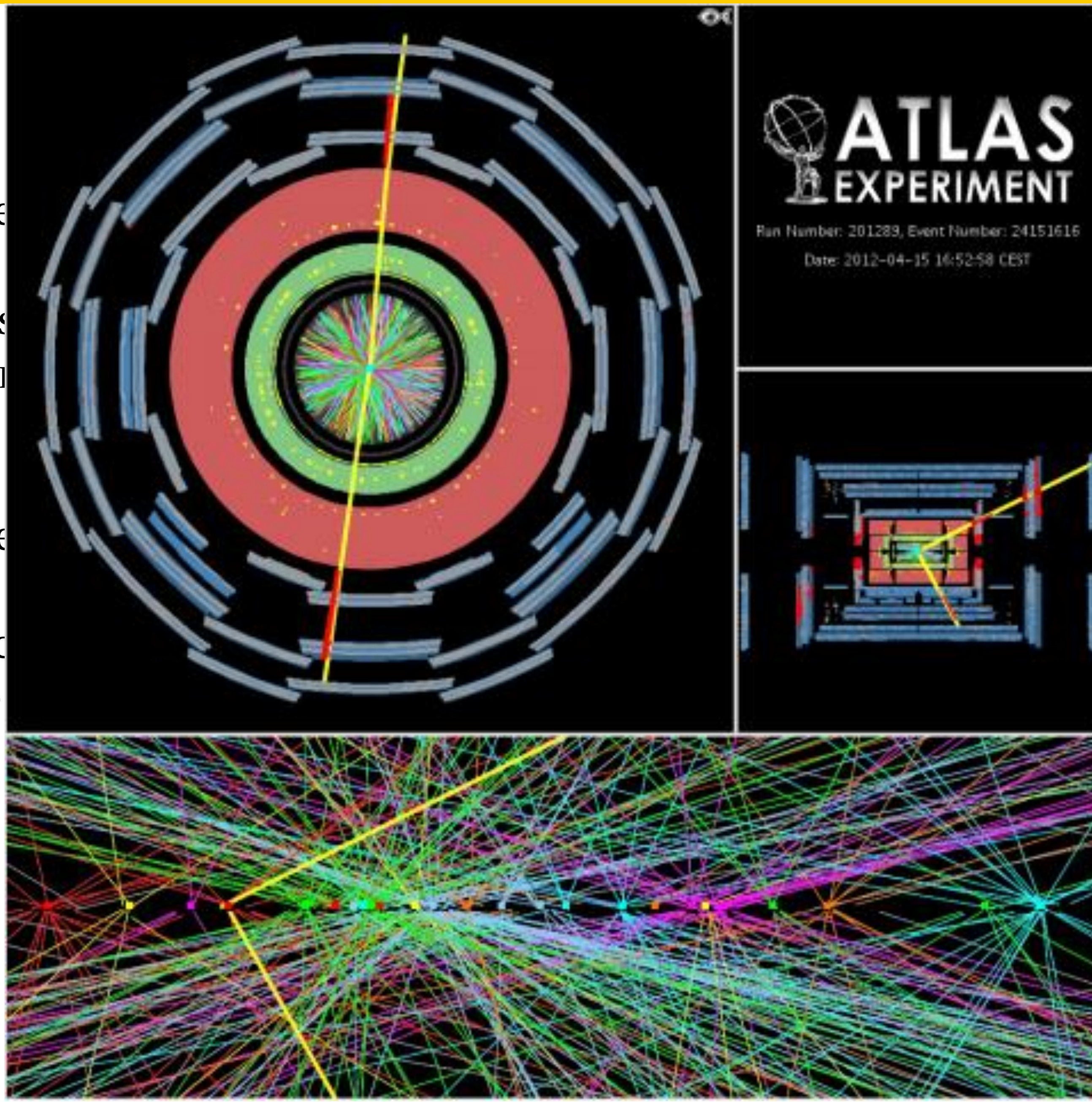
⇒ By decreasing d_x – or d_y – the number of collisions per bunch will increase : this is the so called “pile-up”.



proton-proton collision and final state at high energy

The # of e

To increas $d_x.d_y$)
At LHC, r

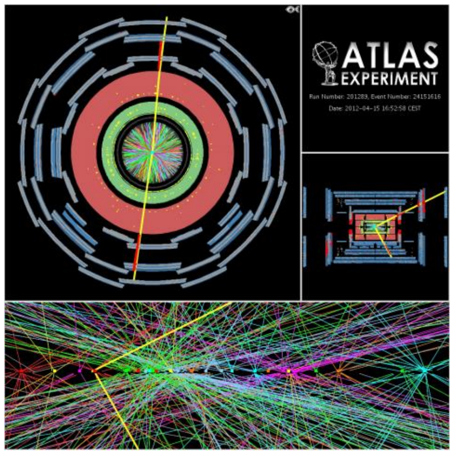


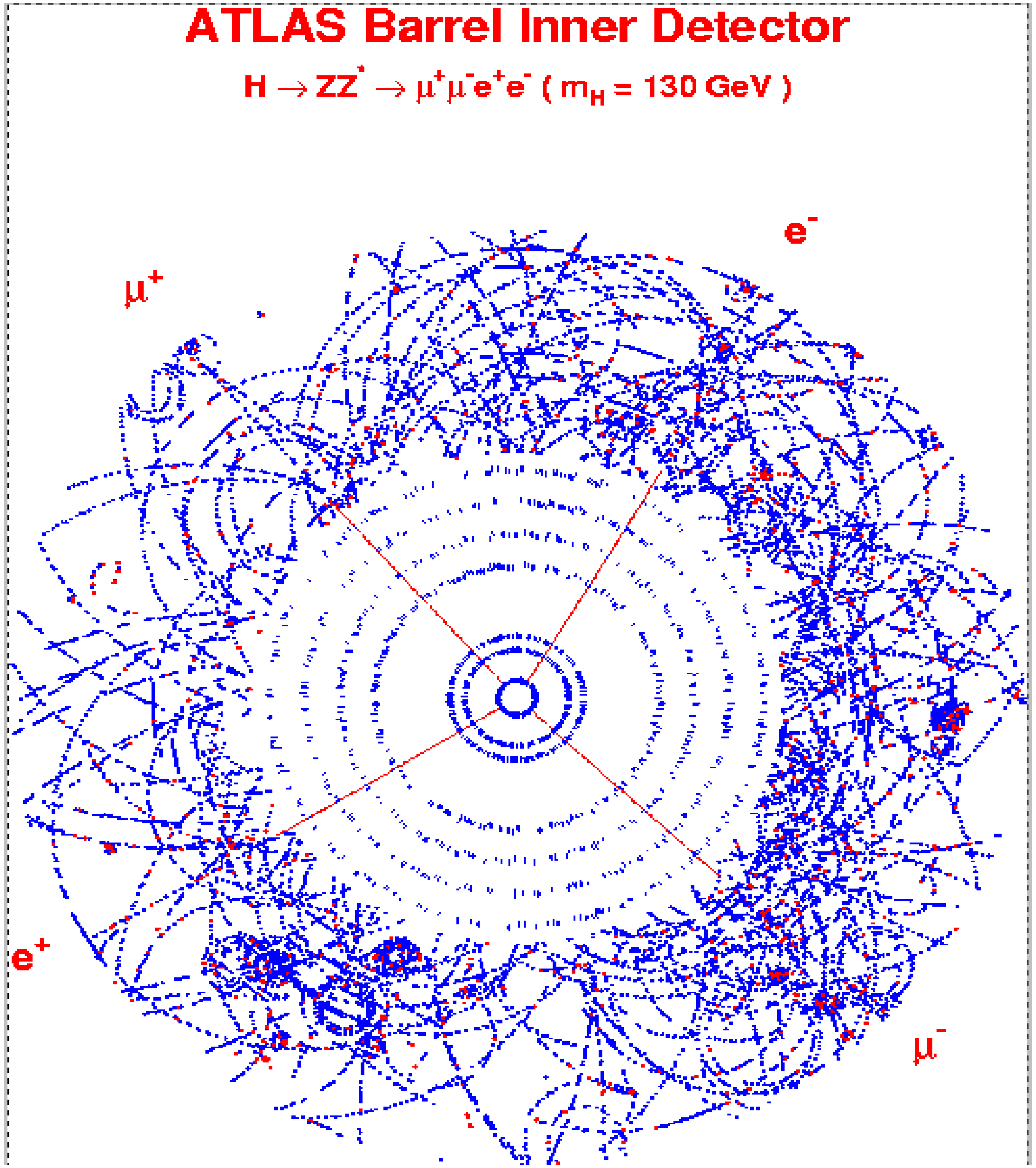
⇒ But we

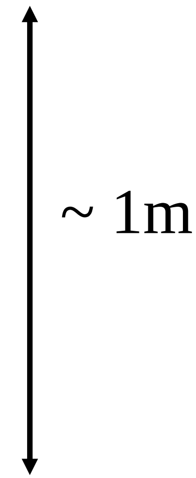
⇒ By dec ncrease :
this is the

Example: simulation of $H^0 \rightarrow Z Z^* \rightarrow e^+ e^- \mu^+ \mu^-$ in the ATLAS detector

$E_{CM} = 14$ TeV







Each point blue/red is a hit in the inner detector

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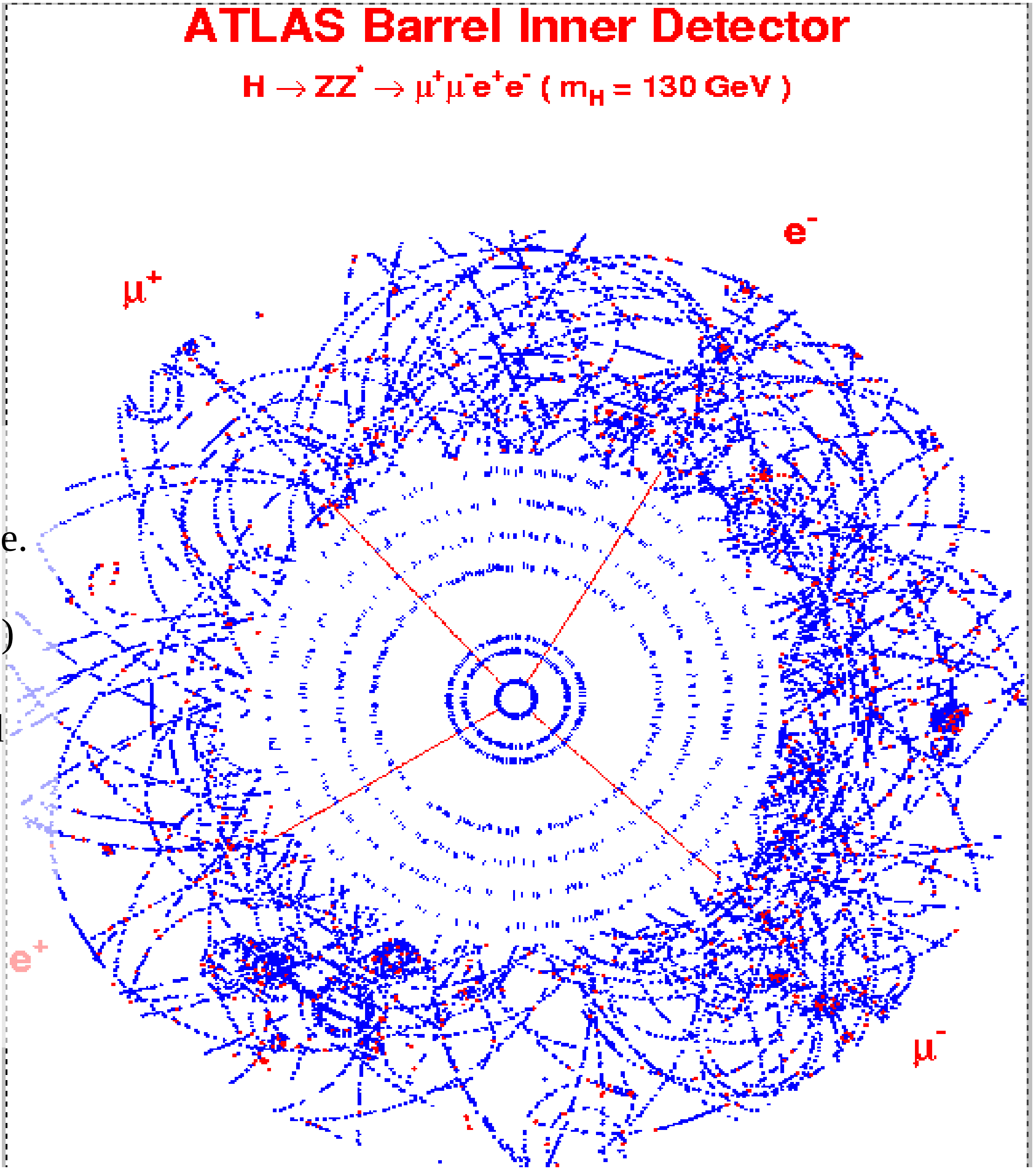

~ 1m

We see:

- several tracks (~2000), i.e. high occupancy
- curvature (mag. field ≠ 0)
- e+, e-, μ+, μ- ~straight
- several points distributed on 3 annular detectors and then 4 following, + many
- many points aligned at large radius
- some red hits(?) at large radius

Each point blue/red is a hit in the inner detector from individual particles.
(track = association of points from the same particle)

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Which particles will we detect ? (1)

Leptons spin = 1/2		
SAVEUR	masse GeV/c²	Charge électriq.
ν_e neutrino électron.	<1×10⁻⁸	0
e électron	0.000511	-1
ν_μ neutrino muon	<0.0002	0
μ muon	0.106	-1
ν_τ neutrino tau	<0.02	0
τ tau	1.7771	-1

Quarks spin = 1/2		
SAVEUR	masse GeV/c²	Charge électriq.
u up	0.003	2/3
d down	0.006	-1/3
c charm	1.3	2/3
s strange	0.1	-1/3
t top	175	2/3
b bottom	4.3	-1/3

Z^0, $W^{+/-}$, H are decaying immediately without being seen directly by the detector

Invisible : ***jets***

force électrofaible spin = 1		
Nom	Masse GeV/c²	charge électriq.
γ photon	0	0
W^-	80.4	-1
W^+	80.4	+1
Z^0	91.187	0

interaction forte spin = 1		
Nom	Masse GeV/c²	charge électriq.
g gluon	0	0

+ Higgs *(+ other Higgs ?)*

+ Super-Symetric particles ?

We detect $\nu_{e,\mu,\tau}$ only in specific detectors. Indeed, the interaction probability of ν with matter $P_{Int.}$ is extremely low: P_{Int} (ν_e of 1 MeV) ~1 in one light-year width detector!

Quarks are not visible directly in detector but ***jets*** are.

We detect quarks by 2 or 3: $q\bar{q}$ or qqq (i.e. $R\bar{R}$ or RVB)

Examples: $\pi^{+/-}$, p, n, $K^{+/-}$, etc… (as predict by QCD)

mésons baryons

hadrons

Which particles will we detect ? (2)

Finally we will measure kinematical properties for (only) the following particles:

$e+$, $e-$, γ

proton (valence quarks: uud + g +…)

neutron (udd+g+…)

$\mu+$, $\mu-$: if *Lorentz boost* ($\gamma\beta c\tau$) high enough !

$\pi+$, $\pi-$: if Lorentz boost high enough !

K+, K- : **if** Lorentz boost high enough (not the case in some *hadronic showers*)

Particular case: ν « see » using its *missing energy* $\not{E}$

(for a *colliding* experiment)

also (in nuclear physic exp.): n, $\alpha(He^{2+})$, $\beta^{+/-}(e^{+/-})$ (the 2 lasts are very ionising particles => short travelling distance)

+ heavy nuclei (on nuclei accelerator)

Why?
See T.Q.C. and Part. and Sym. lectures

And that's all…

All the other particles are detected through their decay elements:

τ, Z^0, $W^{+/-}$, Higgs, etc…

$\pi^0 \rightarrow \gamma\,\gamma$ ($\pi^0 = (u\bar{u}-d\bar{d})/\sqrt{2}$)

Baryons B, D and mesons π, K, ρ (beauty -quark b- particles, quark c, etc…)

glue ball (ggg)? penta-quarks ($qqqq\bar{q}$)?

Particular case: ***jet*** of particles (come from individual quark or gluon which hadronise)

Also (heavy) nuclei are detected through fragment decay (if unstable)

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Detailed in next detector lecture (Matthew)

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Particle interaction with matter

Particles going through detectors are seen using their interaction with matter, and in particular through their **energy loss in the detector**.

<u>Main interaction process</u> with matter are:

« ionisation » { ionisation and excitation of atoms of the detector (***Bethe-Bloch formula***)

Radiative process { radiation (*bremsstrahlung*, *pair creation)* / strong interaction (*hadrons*)

One should distinguish (detail in lecture #2) several cases depending of the particle type. The interaction with matter is function of:

the charge *z*, mass *m*, energy *E*, etc. Also at low energy, one speak of "v"

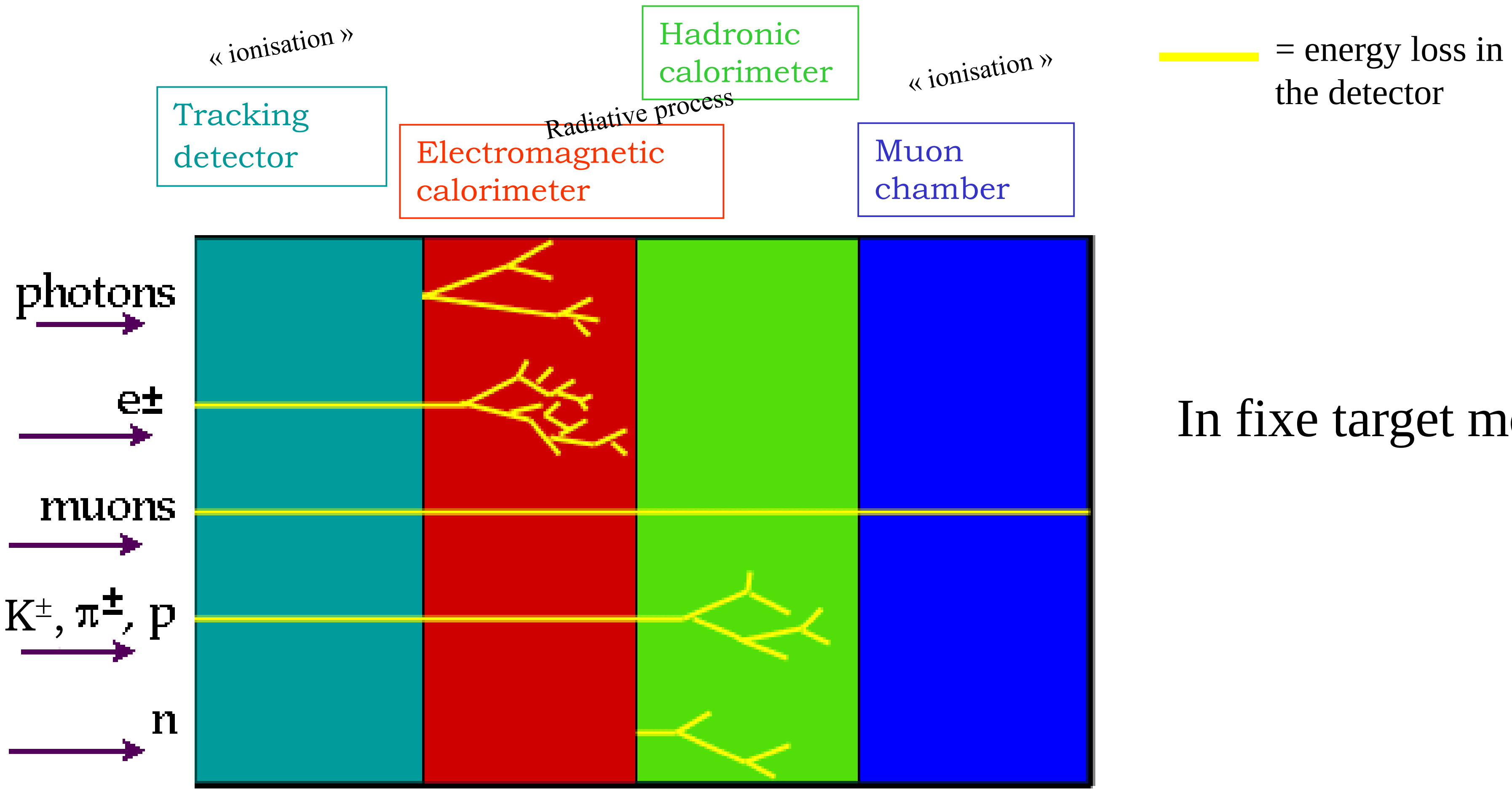
The energy loss is also depending of the medium in which the particle is propagating:

Z and *A* of the medium atoms, *critical energy* of the medium (E_c), etc…

These interactions have been calculated and/or parameterized. They are also known experimentally.

Typical output of a detector for different incident particles (1)

WHY? discussed in the following + next lecture(#2)



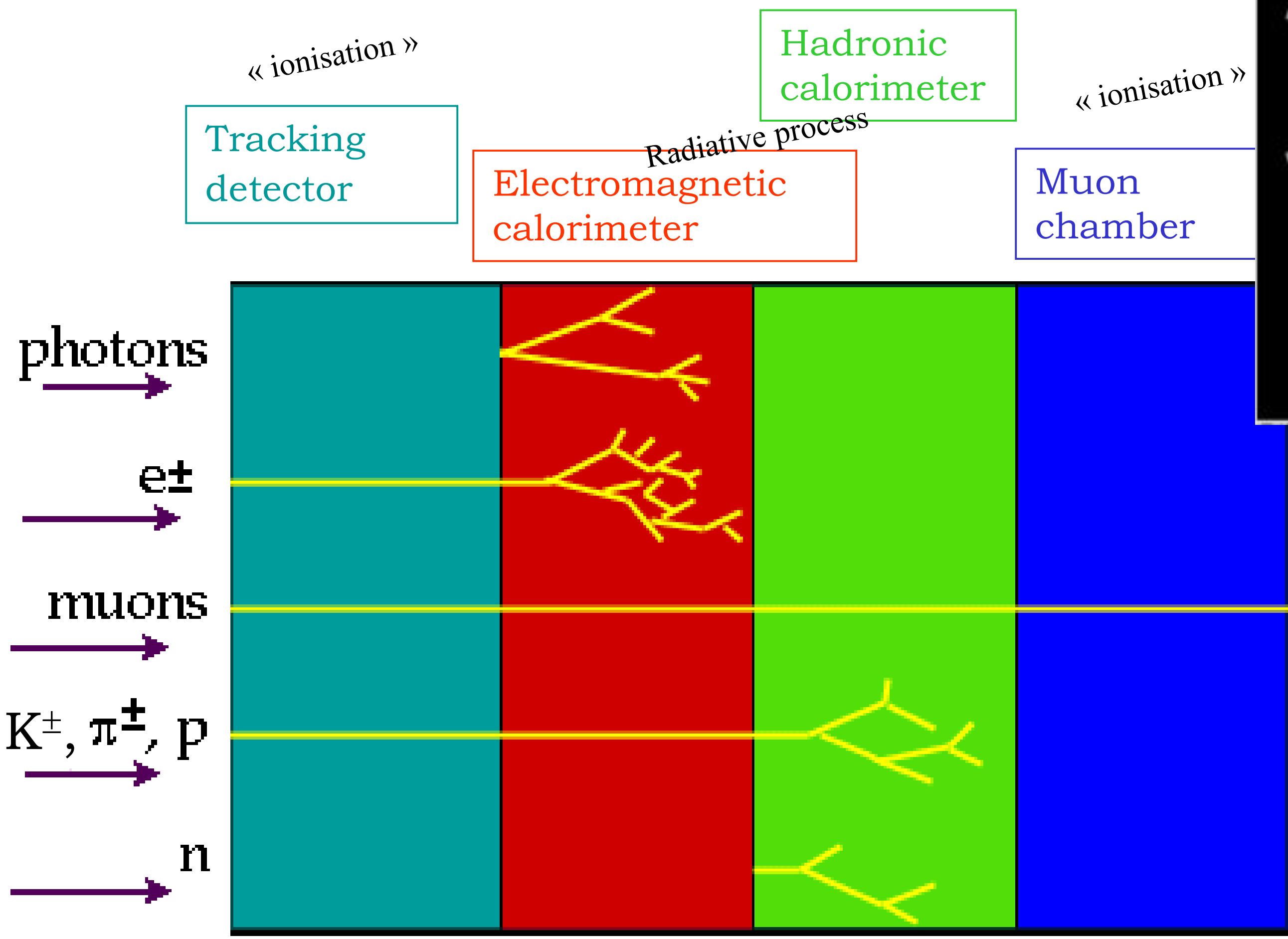
In fixe target mode

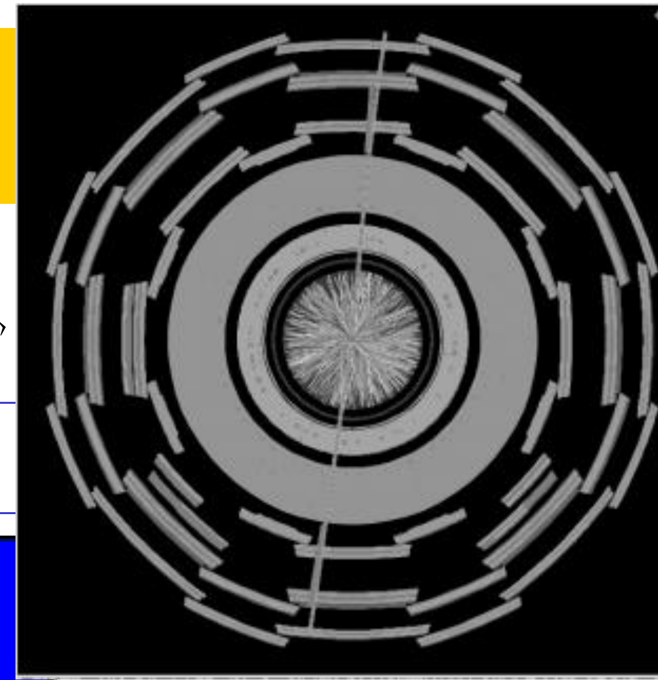
One should also consider the capability of the detector to distinguish the following particles: K/π/p, and π/e, and e/γ+π, and π^0/γ

E of particles ≳ 1 GeV

Or also to distinguish different atom types in a nuclear experiment (at lower energy)

Typical output of a detector for different incident particles (1)



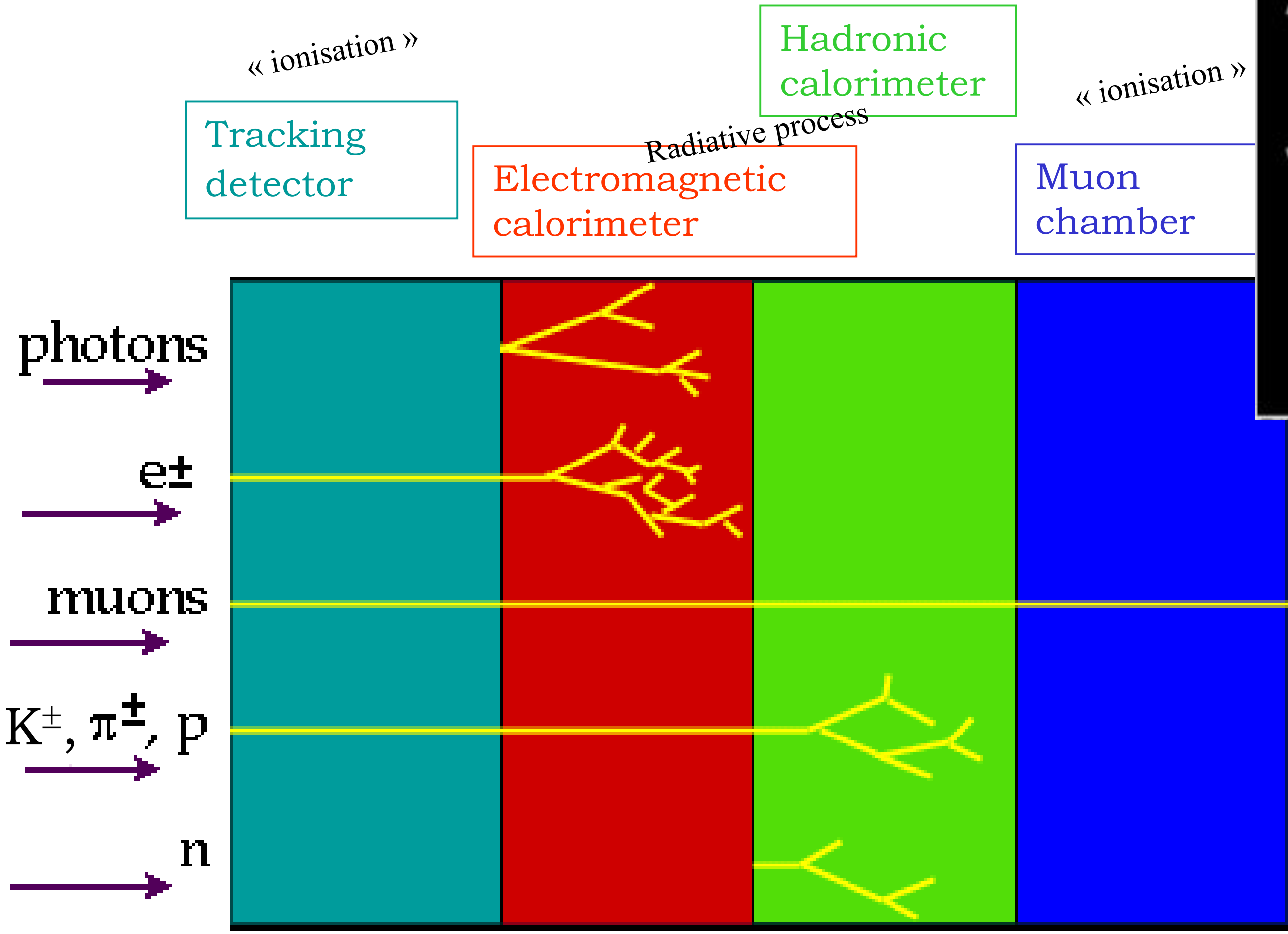


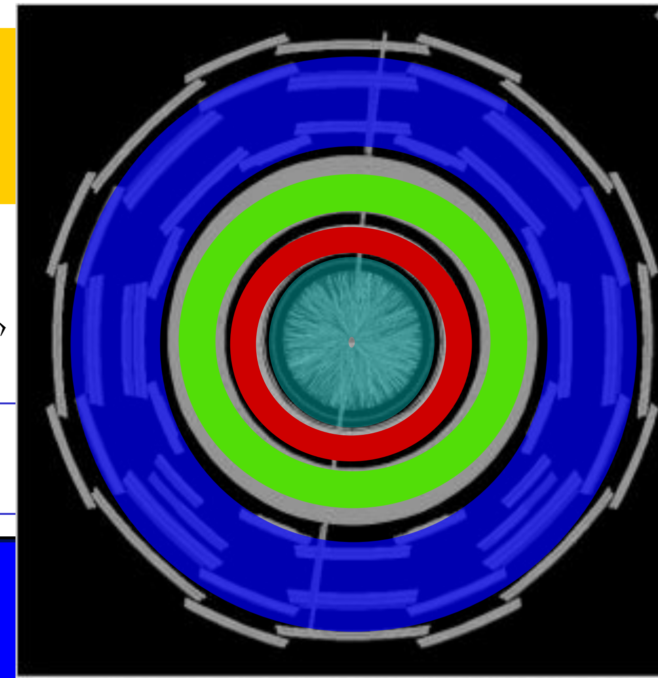
In fixe collision mode

One should also consider the capability of the detector to distinguish the following particles: $K/\pi/p$, and π/e, and $e/\gamma+\pi$, and π^0/γ

E of particles $\gtrsim$ 1 GeV

Typical output of a detector for different incident particles (1)



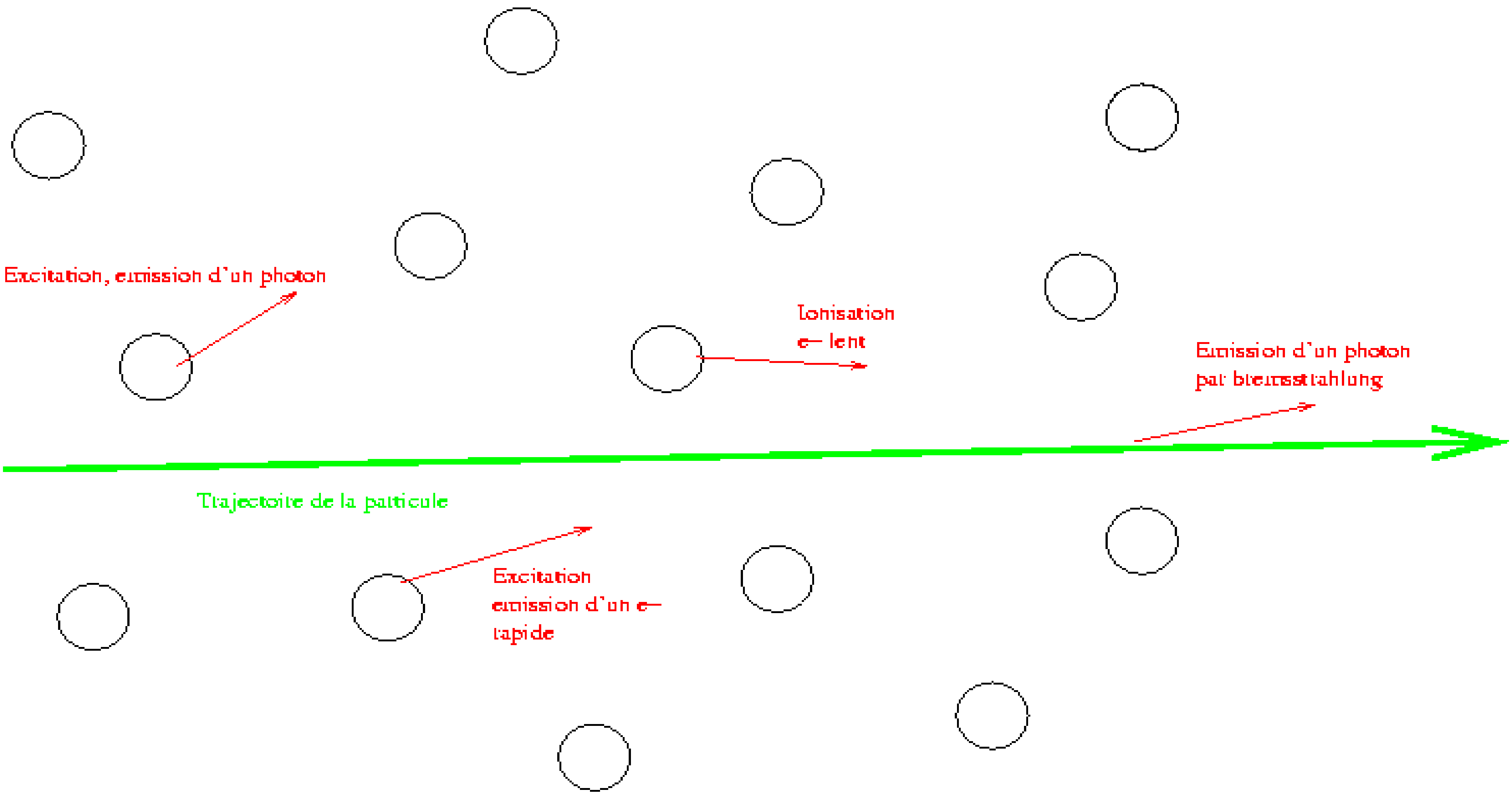


In fixe collision mode

One should also consider the capability of the detector to distinguish the following particles: $K/\pi/p$, and π/e, and $e/\gamma+\pi$, and π^0/γ

E of particles ≳ 1 GeV

What happens for a (charge) particle going through matter?



Some order of magnitude for energy loss of electron/positrons

- Excitation : $e^- X \rightarrow e^- X^*$

- Ionisation : $e^- X \rightarrow e^- X^* + e^- \text{ lent}$
  - Ionisation : ΔE ≈ about atomic energy of electron

- Excitation : $e^- X \rightarrow e^- X^* + e^- \text{ rapide}$
  - Excitation : ΔE >> atomic energy of electron

- Bremsstrahlung

$$e^- X \rightarrow e^- \gamma X$$

(each process will be studied in more details in the following lectures)

Some order of magnitude for energy loss of electron/positrons

- Excitation : $e^- X \rightarrow e^- X^*$ ΔE: few eV up to few keV
- Ionisation : $e^- X \rightarrow e^- X^* + e^- \ \mathrm{lent}$ ΔE: ~10 eV up to ~100 keV
  - Ionisation : ΔE ≈ about atomic energy of electron
- Excitation : $e^- X \rightarrow e^- X^* + e^- \ \mathrm{rapide}$ ΔE > 100 keV
  - Excitation : ΔE >> atomic energy of electron
- Bremsstrahlung

$$e^- X \rightarrow e^- \gamma X$$

ΔE > 0.1 MeV

(each process will be studied in more details in the following lectures)

Remark on units

We do not "use" h and c: $h = c = 1$ (p in GeV/c → GeV…)

So the energy E will be in eV, keV, MeV, GeV

Cross section:

σ in barn with 1 barn = 10^{-24} cm^2

Radiation length (typical length describing energy loss by radiations):

(it helps to compare the effect of a given material w.r.t. others)

X_0 in cm or

X_0 in g/cm^2 ⇔ $\rho.X_0$

Energy loss in matter:

dE/dx in MeV/cm

dE/dx in MeV/(g/cm^2) ⇔ $1/\rho$.(dE/dx)

(1/E)dE/dx in $(g/cm^2)^{-1}$ or in $1/X_0$

Example: if we have (1/E)dE/dx = 1 = $1(X_0)^{-1}$ for an e^- of 6 MeV, it means that the electron loose 6 MeV per X_0, i.e. 6 MeV per radiation length (for the considered material –for which we know X_0–). Remark: this electron loose a lot of energy… Before loosing its total energy, this electron will go from the "radiative" regime, to the "ionizing" regime

Energy loss by **ionisation/collision**: Bethe-Bloch formula

- Bethe-Bloch formula (see lecture #2) for heavy particles:

$$-\frac{dE}{dx} = 4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\ln\frac{2m_e c^2\gamma^2\beta^2}{I} - \beta^2 - \frac{\delta}{2}\right]$$

$$\beta = \frac{v}{c} \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

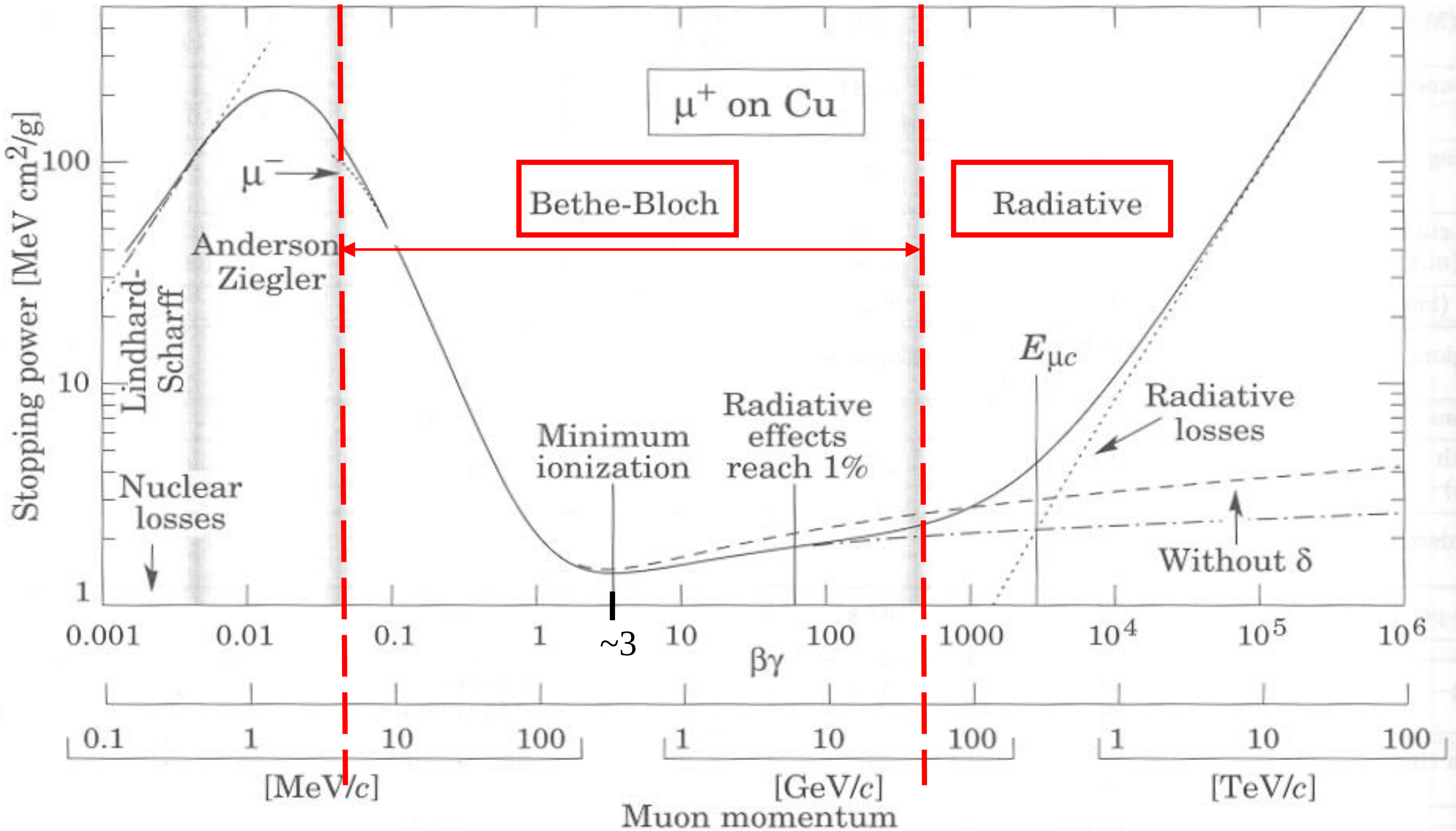
  - z charge of the incoming particle
  - Z,A charge and atomic number of the considered material
  - m_e electron mass
  - r_e classical radius of the electron $\quad r_e = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{m_e c^2} \sim 3$ fm
  - N_A Avogadro number
  - I ionisation constant ($I = 16\ Z^{0.9}$ eV $Z>1$)
  - δ : screening parameter due to the electric field of the incoming particle (depend on atomic e-)

(for e-: term in [ ] is different)

Many possible parameterizations, all ~equivalents

Interaction of particle with matter (example of the muon)

dE/dx



Energy loss by ionisation (**Bethe-Bloch**) dominate at low energy and at higher energy radiation interaction play an important role (at very high energy for muon: E > 100 GeV).

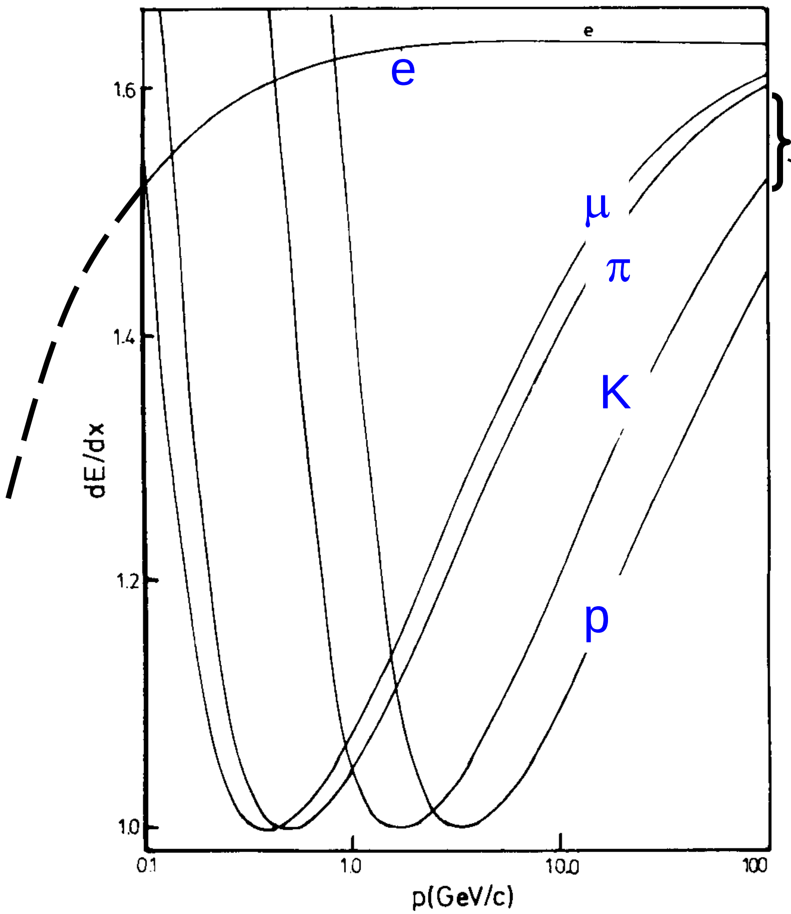
For μ, when $E^{\mu} = E_c^{\mu} \sim \frac{8000}{(Z+2)^{0.88}} GeV$ then energy loss $\Delta E(ionisation, excitation) \simeq \Delta E(brem)$

Comparison of dE/dx for different charge particles

$$p = m_0 \beta \gamma c$$

$$\frac{dE}{dx} \propto \frac{1}{\beta^2} \ln\left(\beta^2 \gamma^2\right)$$

Simultaneous measurement of p and dE/dx defines mass m, hence the particle identity



π/K separation (2σ) requires a dE/dx resolution of < 5%

Average energy loss for e,μ,π,K,p in 80/20 Ar/CH_4 (NTP)
(J.N. Marx, Physics today, Oct.78)

But: Large fluctuations + Landau tails (i.e. not only gaussian fluctuations…) !

dE/dx in real life…

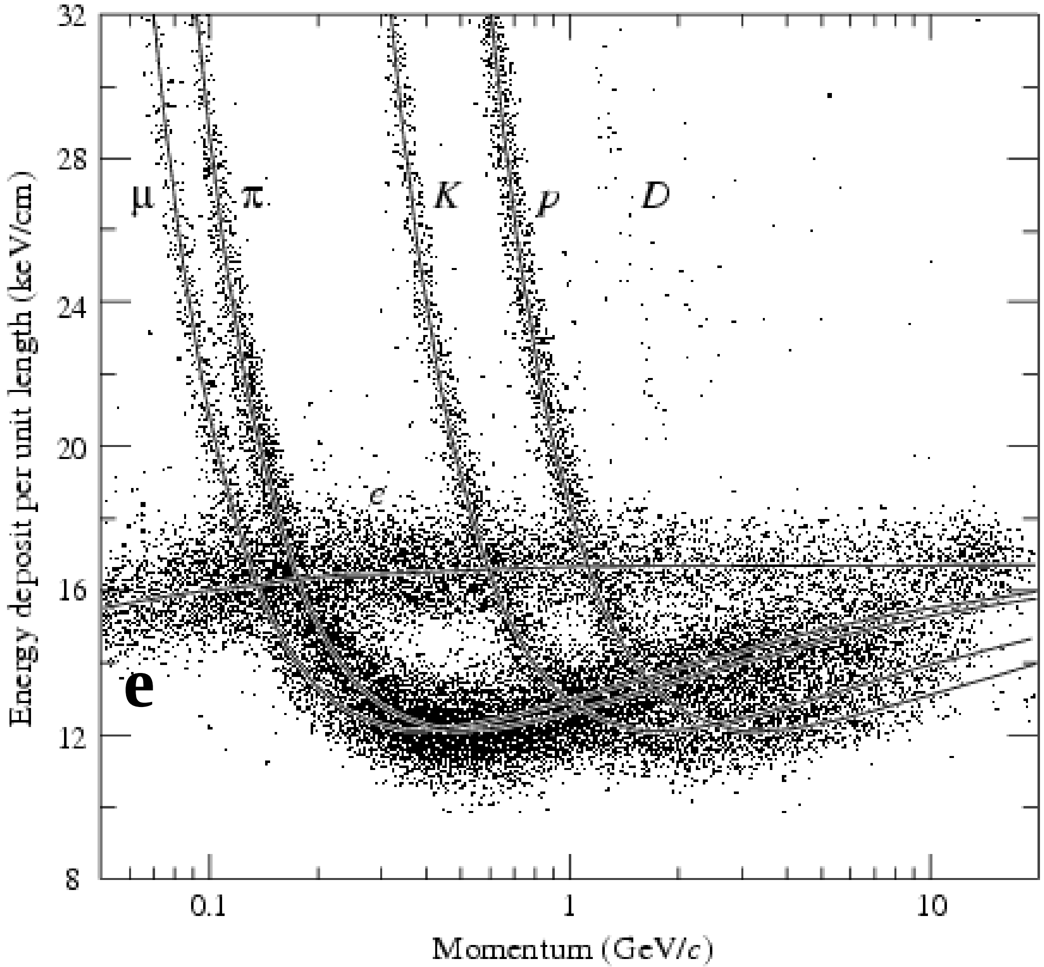


Figure 28.5: PEP4/9-TPC energy-deposit measurements (185 samples @8.5 atm Ar-CH_4 80–20%) in multihadron events. The electrons reach a Fermi plateau value of 1.4 times the most probably energy deposit at minimum ionization. Muons from pion decays are separated from pions at low momentum; π/K are separated over all momenta except in the cross-over region. (Low-momentum protons and deuterons originate from hadron-nucleus collisions in inner materials such as the beam pipe.)

Radiation length X_0 for μ or for electron

$$-\left.\frac{dE}{dx}\right|_{Brem} = \frac{E}{X_0} \quad \text{avec} \quad 1/X_0 = \frac{4\alpha N_A z^2 Z^2 r_e^2 \ln\left(183 Z^{-1/3}\right)}{A}$$

Radiation length = characterisation of the material

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

Describe the attenuation by radiation

X_0 [g/cm^{-2}]

X_0/ρ [cm]

$$r_e = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{m_e c^2}$$

E_c is the (critical) energy at which a particle loose almost the same energy by ionisation or by Bemsstrahlung :

$$E_c^e \approx \frac{710 \text{ MeV}}{Z + 0.92} \quad \text{(gaz)}$$

$$E_c^\mu \approx E_c^e \left(\frac{m_\mu}{m_e}\right)^2 \approx 43000 E_c^e$$

At high energy, to stop a muon is about 43000 times « more difficult » than to stop an electron or a photon !

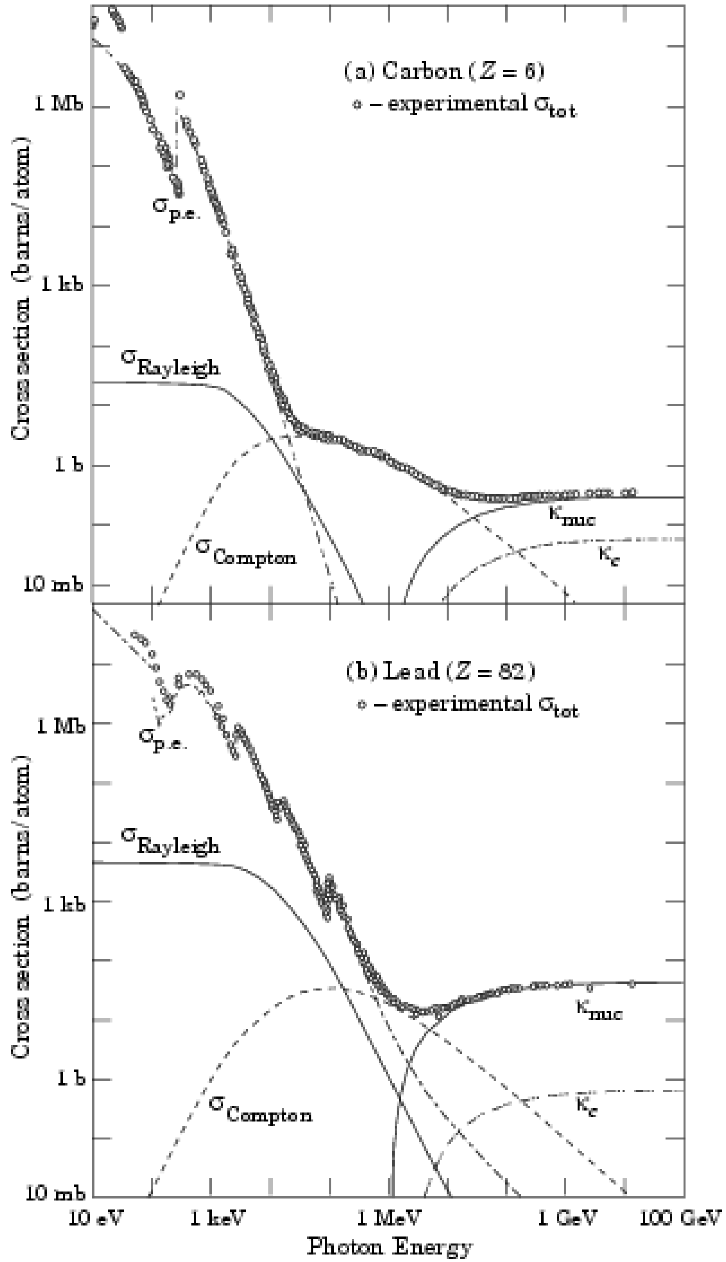
Interaction of particle with matter (example of γ)

$\sigma(p.e.) \sim Z^5$

Remark: for photons the energy is not degraded but the intensity of the beam: i.e. photons are absorb or deviated (by Compton diffusion) :

$$I(x) = I_0 \exp(-\mu x)$$

With μ = absorption coefficient

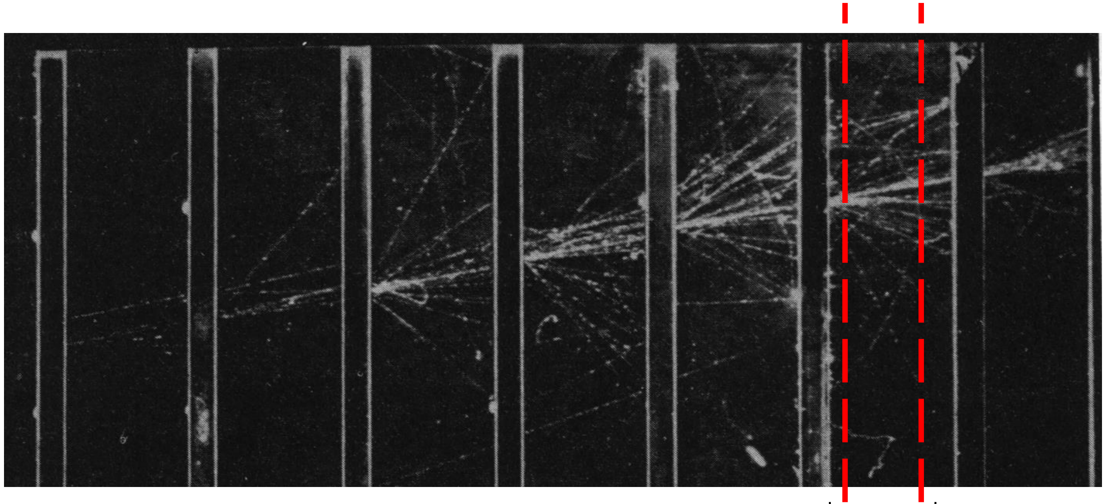


Paire production is proportional to. Z^2

$\sigma(pp) = 7/9.\sigma$ (brem)

(X_0 also characterized pair production)

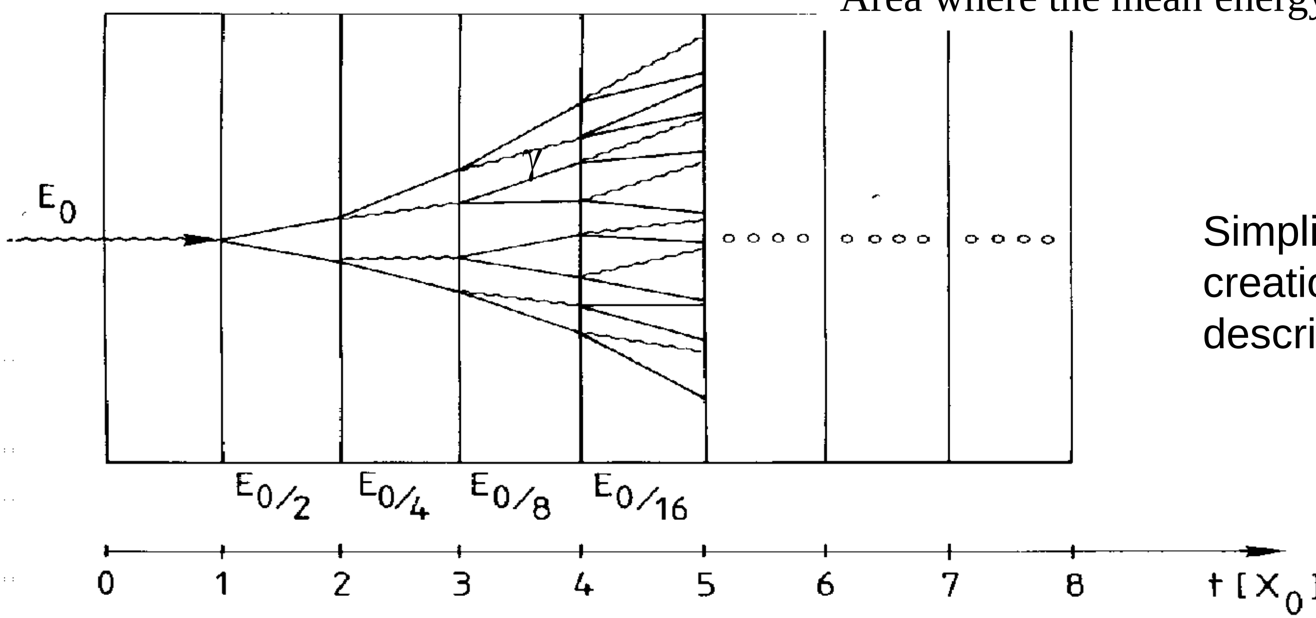
Some illustrations of these effect: electromagnetic shower



Area where the mean energy of particles is about ~ E_c

Picture of an electron shower in a spark chamber (with Lead absorber)
$E_{initial}$ = 20 GeV

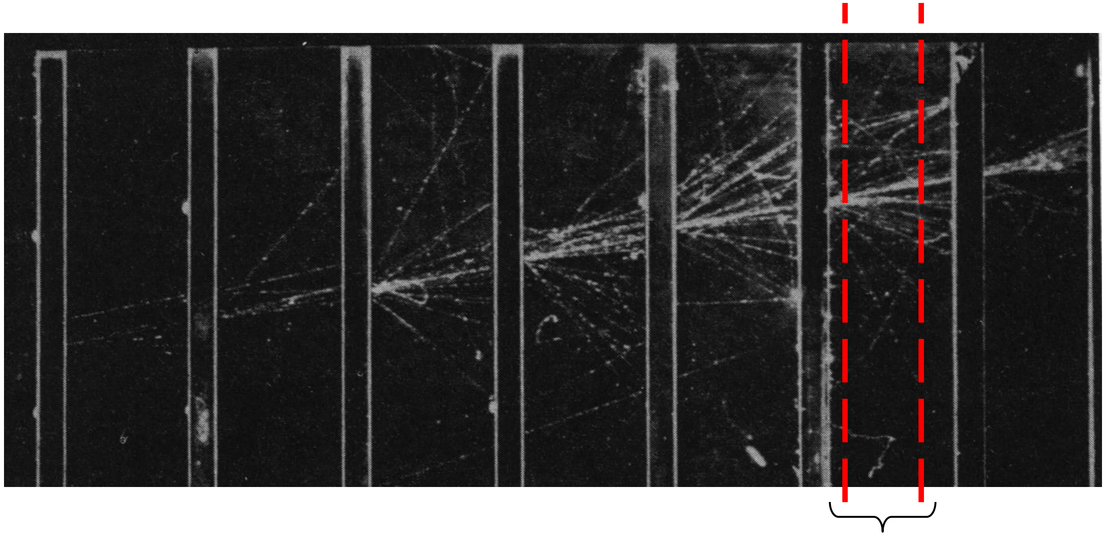
Same processes for a cosmic ray in atmosphere!!!



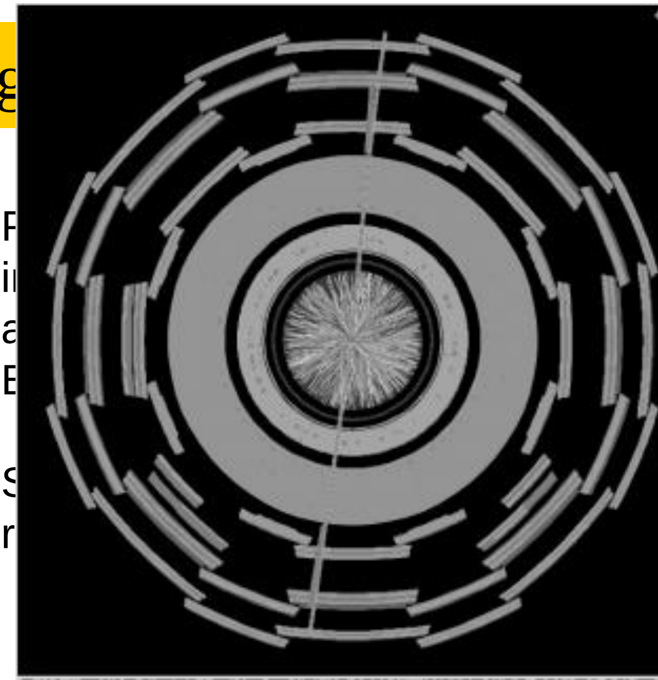
Simplify model assuming only pair creation and bremsstrahlung (both describe by X_0)

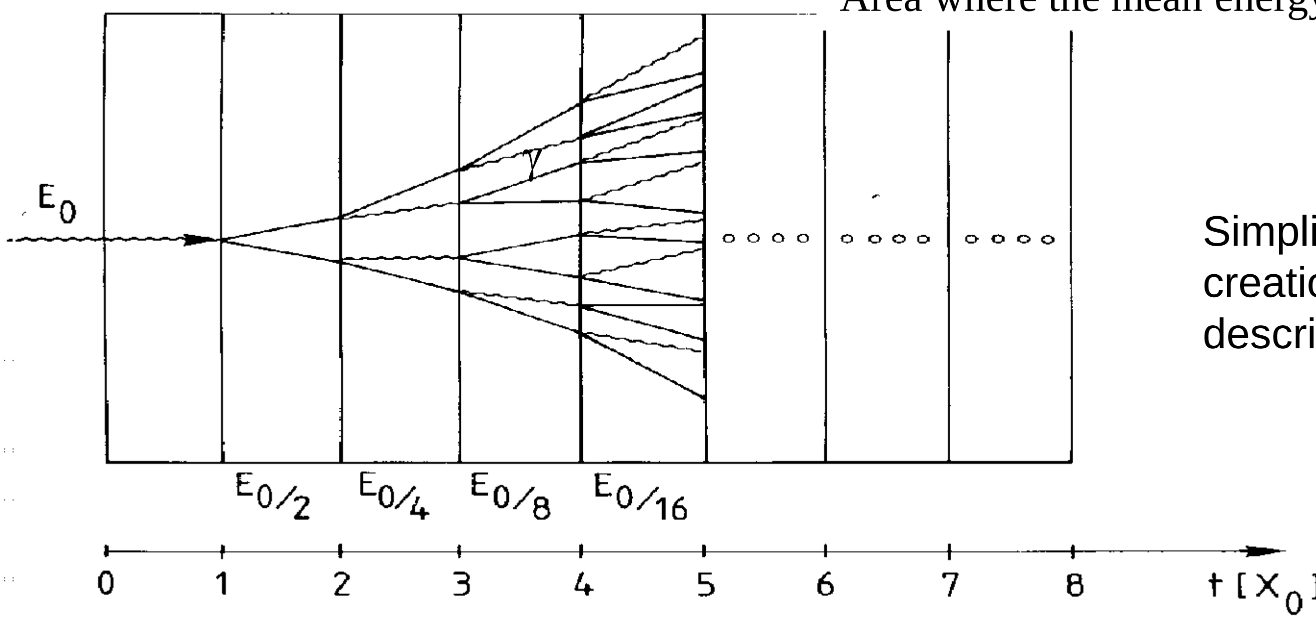
$$N(t) = 2^t \qquad E(t)/\,particle = E_0 \cdot 2^{-t}$$

Some illustrations of these effect: electromag



Area where the mean energy of particles is about ~ E_c





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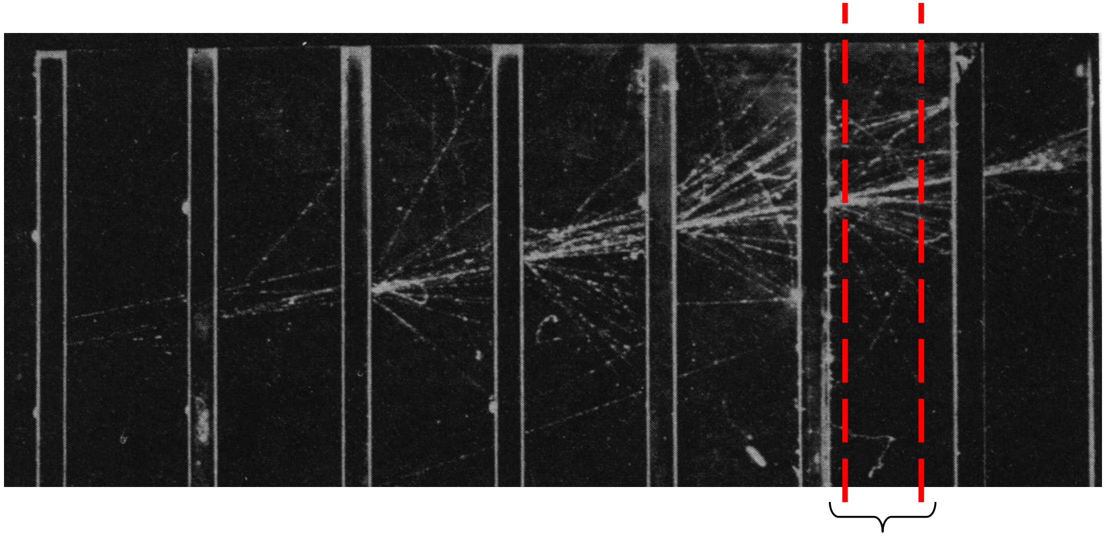
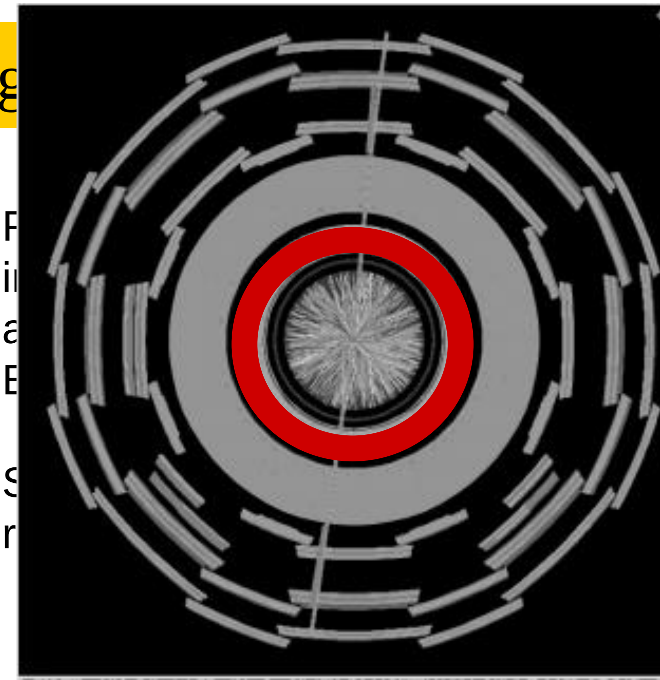
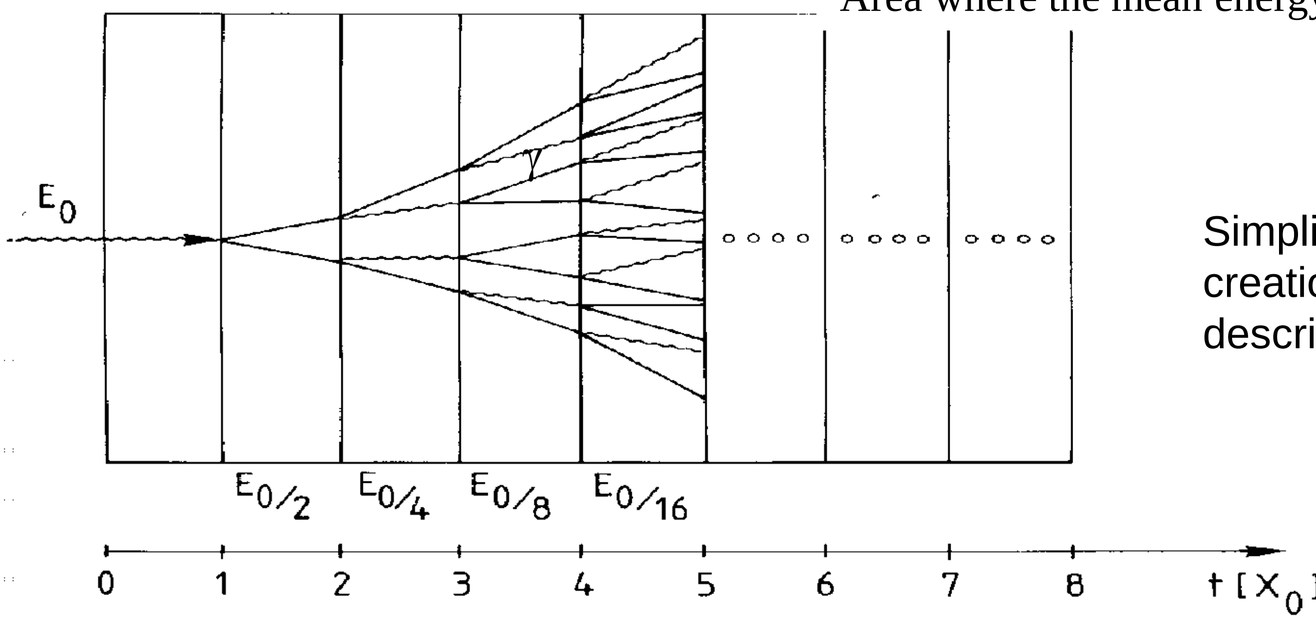




Area where the mean energy of particles is about ~ E_c

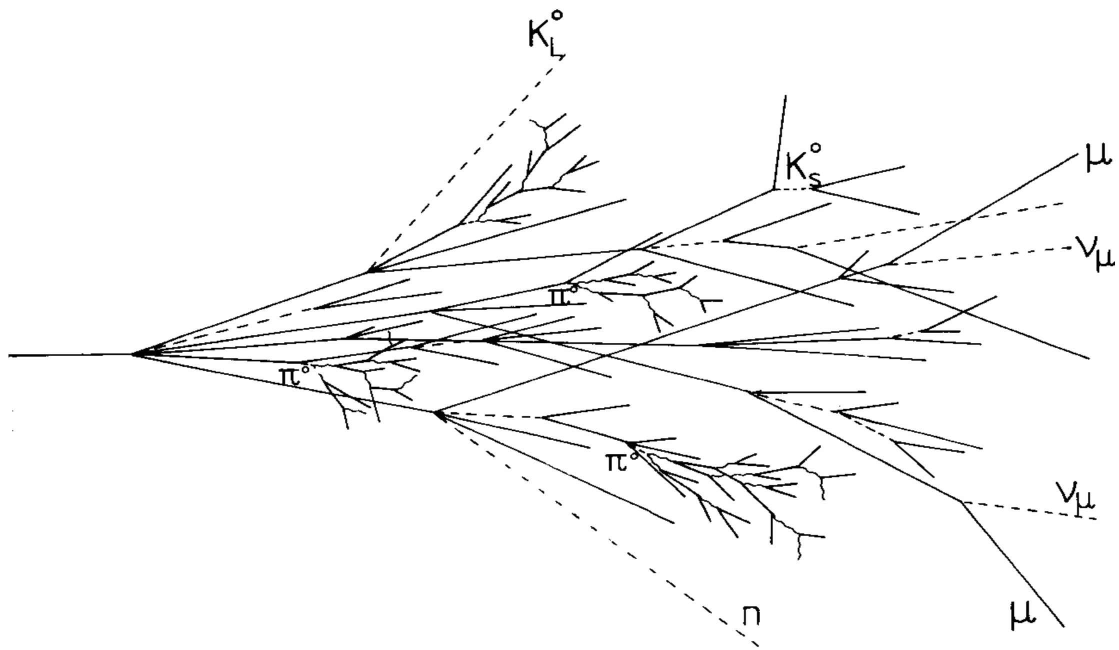


Simplify model assuming only pair creation and bremsstrahlung (both describe by X_0)

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

Some illustrations of these effect: hadronic shower

In a hadronic shower, there will be production of many π, K and **neutrons**. π^0 will give an EM component, and some low energy π and K will decay in μ and ν. Neutrons are difficult to detect (neutral particle) and may escape the detector.

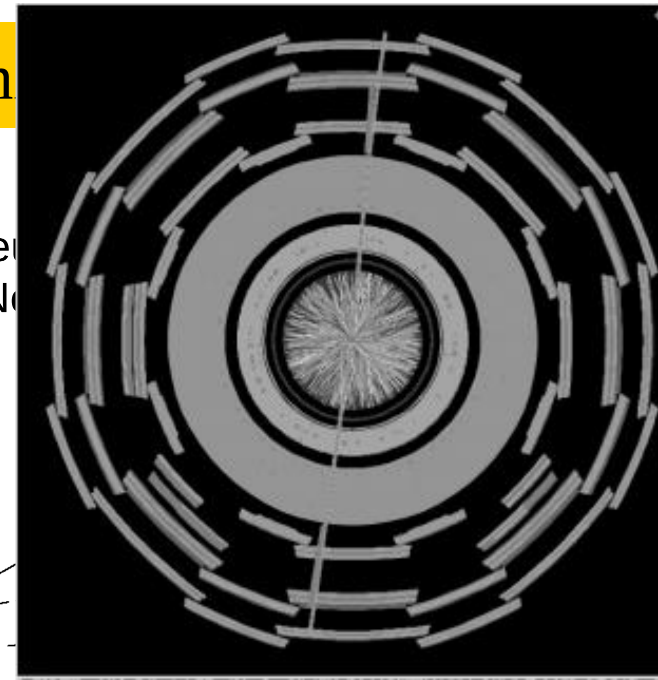


$$n(\pi^0) \approx \ln E(GeV) - 4.6$$

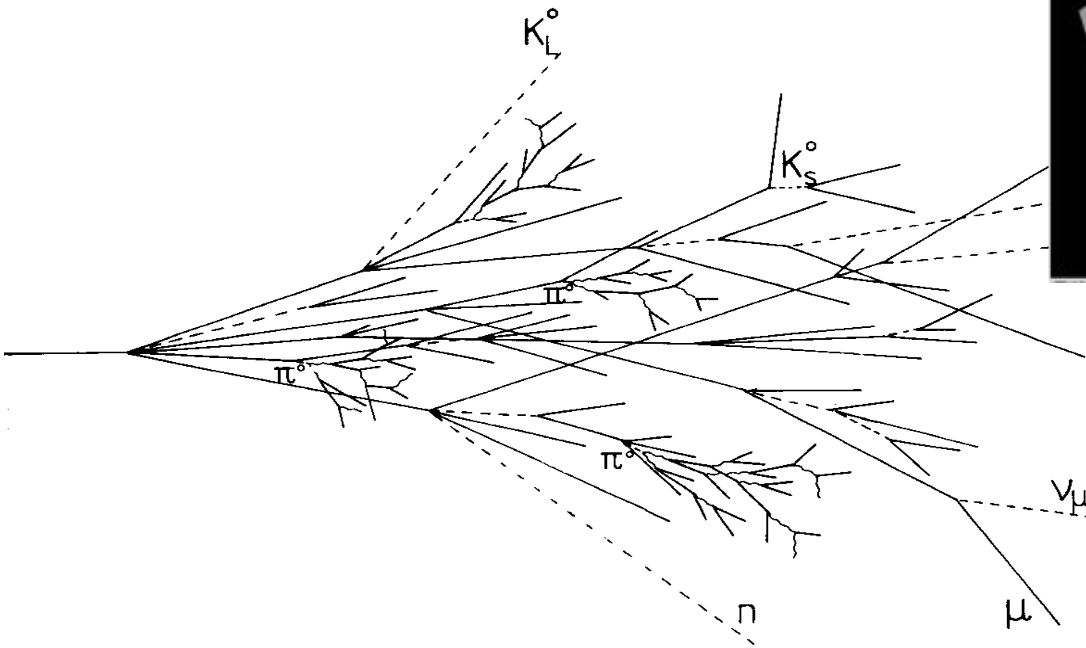
example 100 GeV: $n(\pi^0) \approx 18$

Remark: energy profile of deposit energy are different for EM and Hadronic showers: the particle multiplicity of Had. shower is higher at the beginning of the shower (lecture #2).

Some illustrations of these effect: hadron



In a hadronic shower, there will be production of many π, K and ne
component, and some low energy π and K will decay in μ and ν. N
detect (neutral particle) and may escape the detector.



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<u>Remark:</u> energy profile of deposit energy are different for EM and Hadronic showers: the particle multiplicity of Had. shower is higher at the beginning of the shower (lecture #2).

Quelques illustration de ces effets : gerbes h

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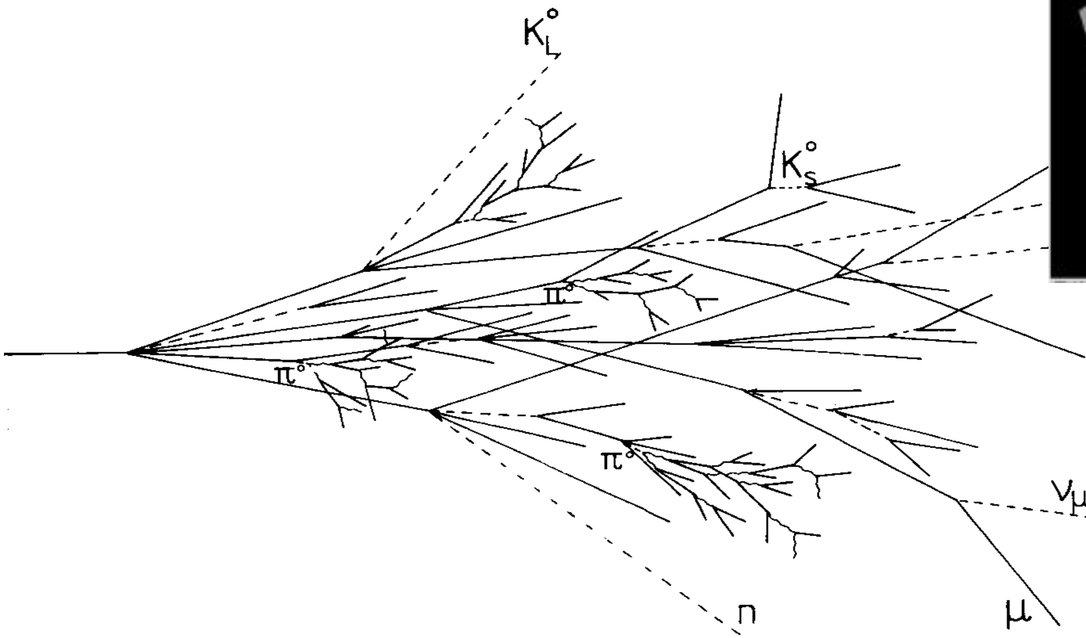

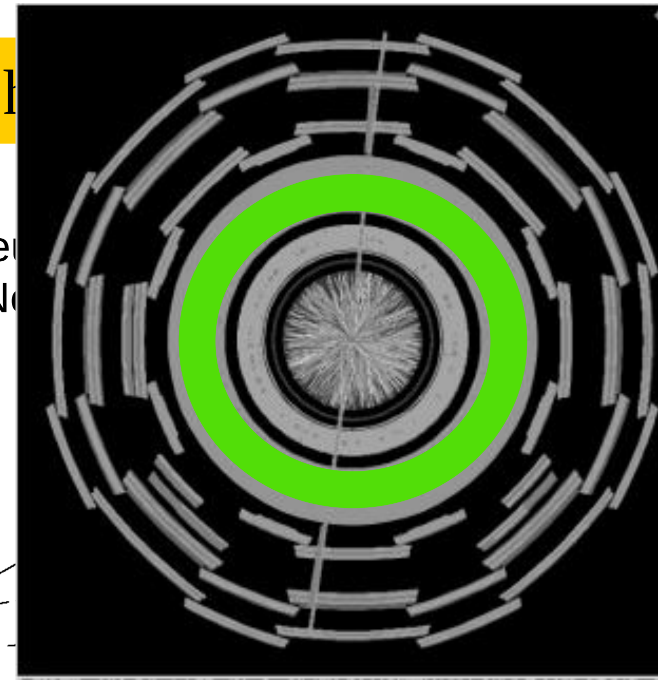

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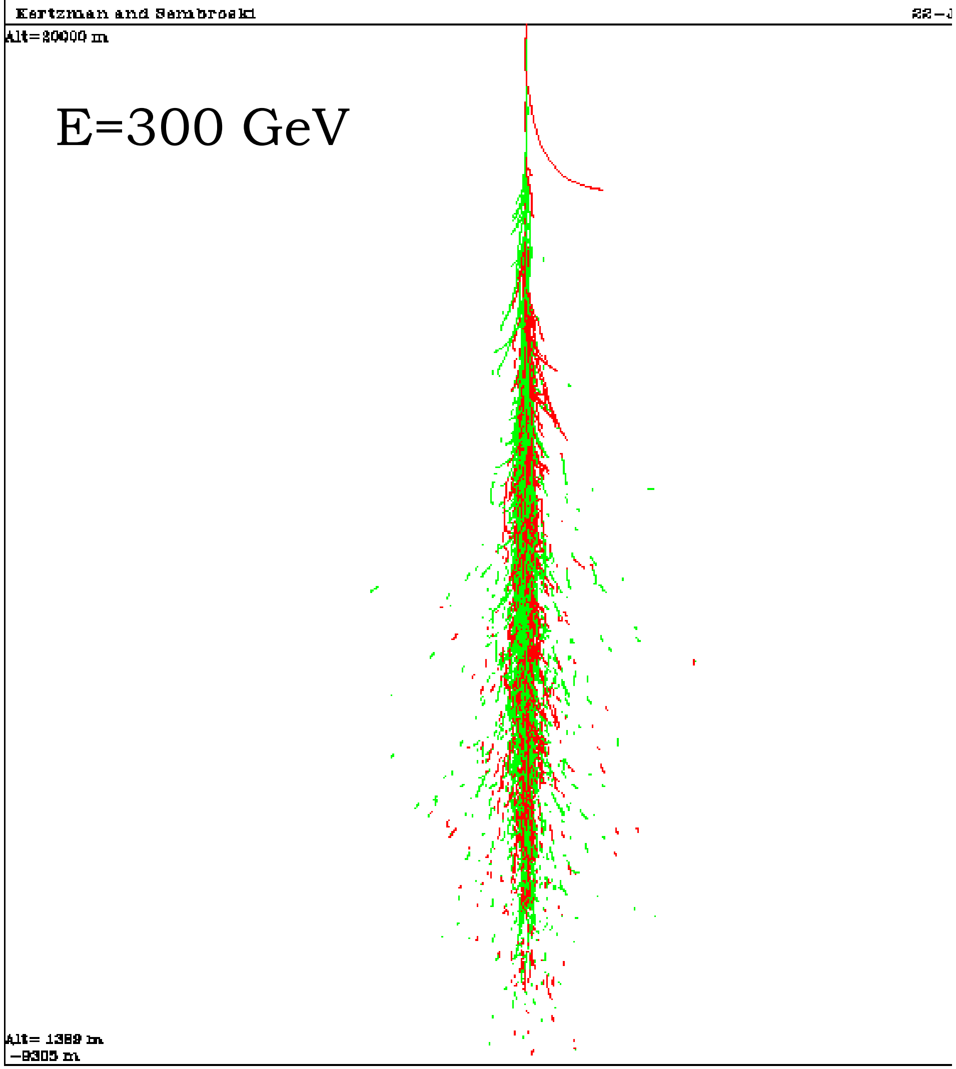
example 100 GeV: $n(\pi^0) \approx 18$

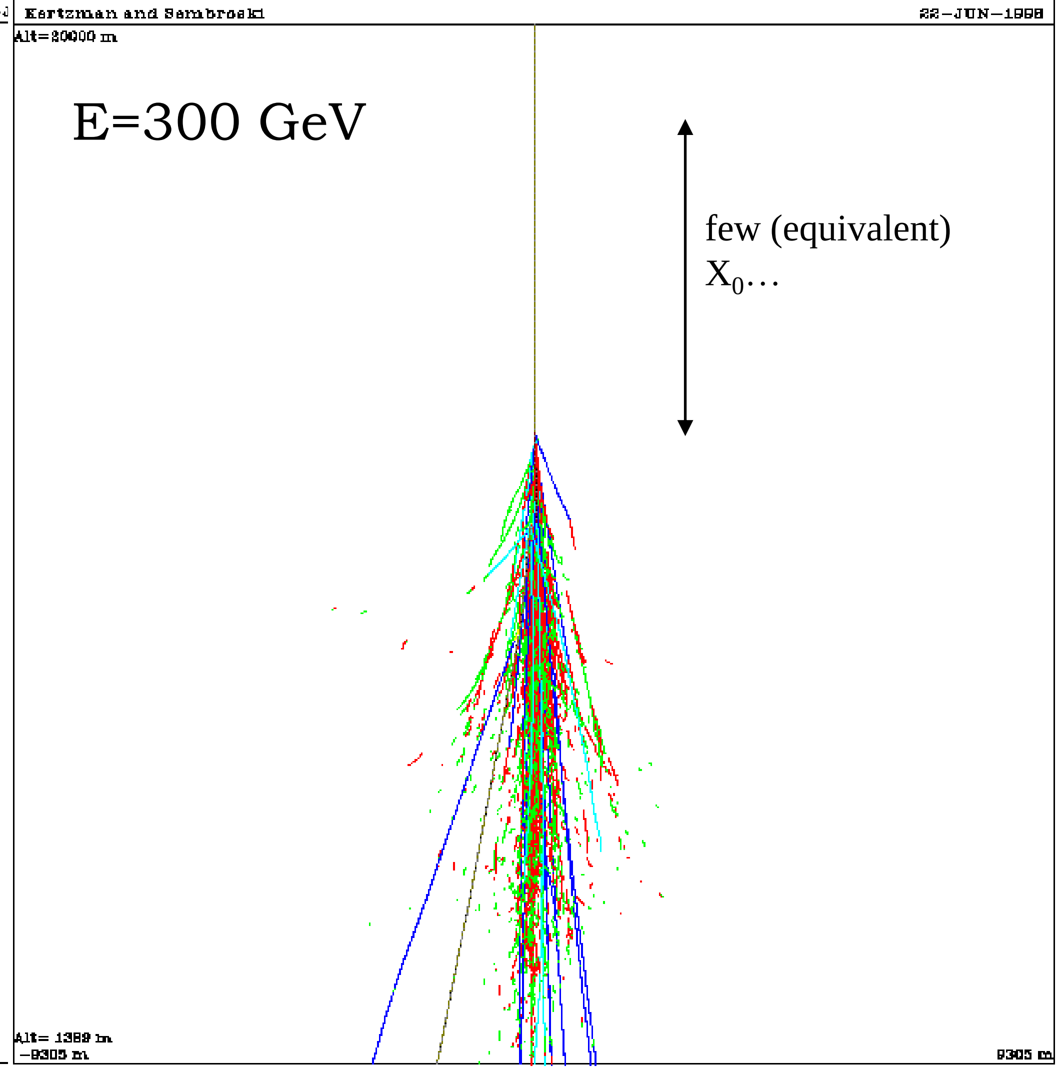
<u>Remark:</u> energy profile of deposit energy are different for EM and Hadronic showers: the particle multiplicity of Had. shower is higher at the beginning of the shower (lecture #2).

EM shower versus Had. shower in air

Electromagnetic shower



Hadronic shower

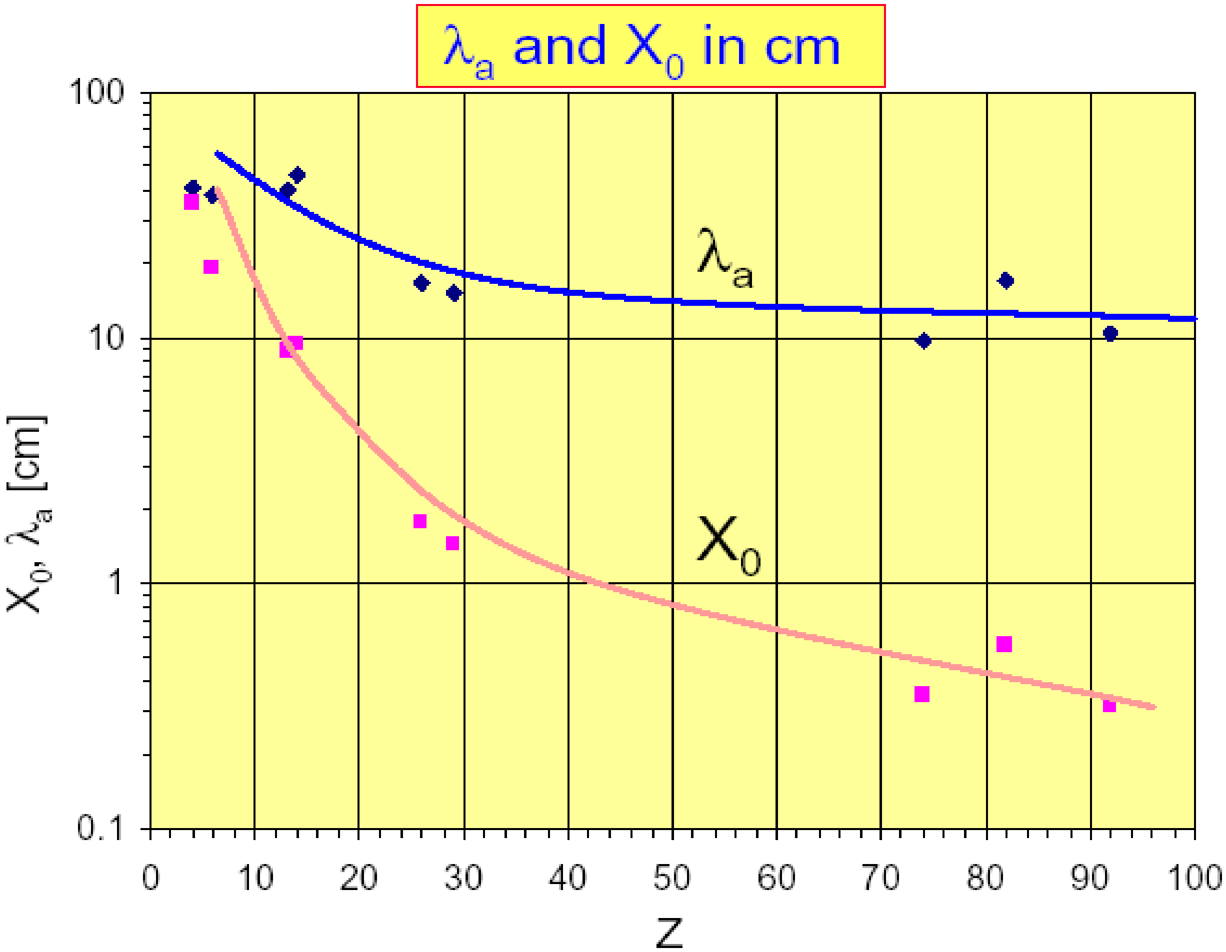


At see level, we have: ~ .. X_0

Radiation length vs interaction length

At high energy ($E>E_c$), radiation interaction could be describe by an "absorption" constant: after travelling through x (depth) of material, there is only $e^{-x/L}$ initial particles. L will be written X_0 for EM interaction and written λ_I for hadronic interaction. Unit: cm or g/cm^2.

Remark: we always have: $\lambda_I > X_0$ for Z > 6.



$$\lambda_I \approx 35(\text{g.cm}^{-2})A^{1/3}$$

For material above Z=50:

$\lambda_I > 10 \times X_0$

$$X_0 = \frac{716.4(\text{g.cm}^{-2})A}{Z(Z+1)\ln(287/\sqrt{Z})}$$

Summary of interaction of particle with matter (1)

(what should be remembered for next lectures)

1) There is a critical energy (critique E_c), different for each particle type (e, μ, γ) and different for each material:
E_c^e from ~10 MeV to 300 MeV, $E_c^\mu > 100$ GeV and $E_c^\gamma \sim 1$ MeV

2) Below E_c energy loss of charged particles (e, μ) are from ionisation -Bethe-Bloch formula- and from photo-electric or Compton interaction for photon. Incoming particle "still continue" (except for ph.-el. int.).

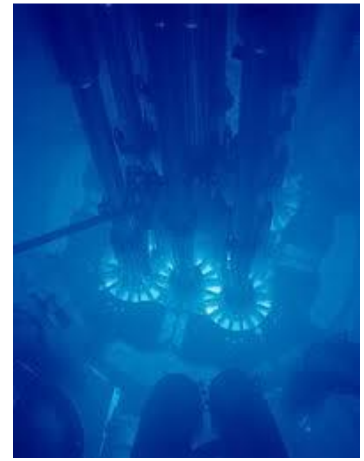
3) Above E_c, energy loss are due to radiation interactions: $\gamma \rightarrow e^+e^-$, $e^{+/-} \rightarrow e^{+/-}\gamma$. These interactions are characterized by a radiation length: X_0.

4) Hadrons loose their energy by Bethe-Bloch formula (elastic diffusion) but also by strong interactions. For the last, with a characterized length: λ_I the interaction length (> than X_0 if Z>6).

Summary of interaction of particle with matter (2)

(what should be remembered for next lectures)

5) At m.i.p. minimum of ionisation dE/dx ~ 2 MeV/(g/cm^2)



For some particular conditions, charged particles can emit:

6) Cerenkov radiation with a typical angle: θ_c (visible photons and UV, i.e. eV) function of $1/\beta$ of the incoming particle

7) « transition radiation » (X-ray)

Those two radiations do not contribute too much to the total energy loss of the incoming particle (<5%).

8) When crossing material, charged particle will have **multiple scattering** (Coulomb diffusion$^{(*)}$): θ_{MS} or θ_0 with $\vartheta_0 \sim \frac{14\,\text{MeV}}{\beta p} z \sqrt{x/X_0}$
(this effect may disturb the track reconstruction)

(*) on atoms

Outline

0) historical remark

1) A physic analysis need a specific detector (and a specific accelerator)

2) Which particle could I see in my detector

3) Loosing energy in the detector (the minimum to be known for this lecture)

→ 4) Layout of a multi-detector apparatus

5) Some typical detectors

6) Glossary

7) Event display of typical LEP events

Where to install sub-detectors (layout)

Knowing the energy loss in matter we could measure all interested parameters (E, $p_{x,y,z}$, z, id.=m) from the vertex in the following (logical) order :

1) Detector "light" or gaseous at the beginning :
   - ⇒ measure vertex position
   - ⇒ measure track parameters momentum (if B magnetic field)
   - ⇒ identify particles through small dE/dx or TRD rad. or Cerenkov light or through time of light (if enough variation from one particle to the other)

few energy loss if thin total thickness in unit of rad. length, i.e. < $1X_0$

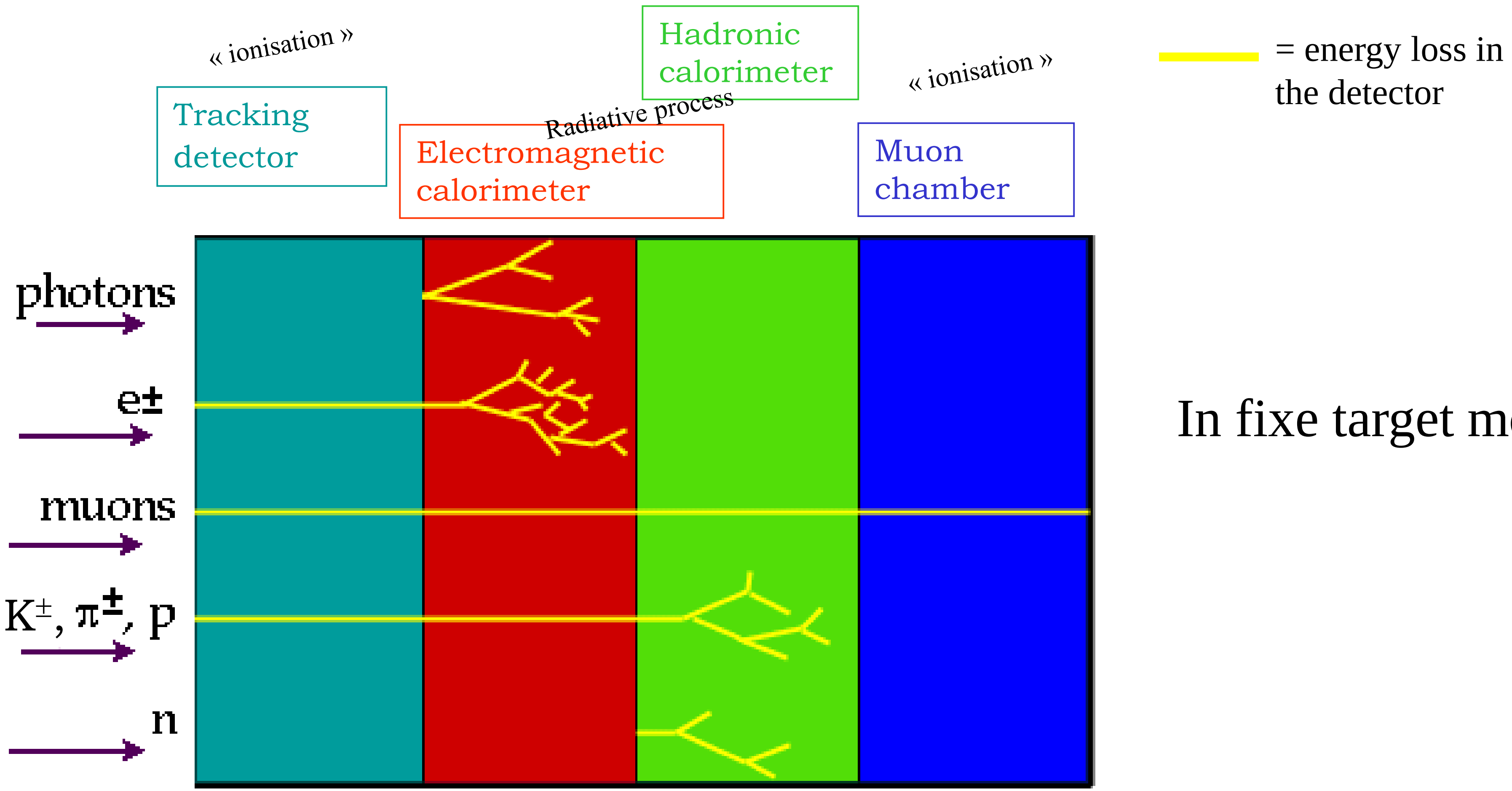
2) Calorimeters (massive detectors) : measure total energy of particles (+ identification). **Remark: you always measure a part. of the total energy !**

3) measure momentum of muons if magnetic field (=> give also particle type !)

4) Sign non equilibrium of energy deposit in the detector => sign of a ν

Typical/simplify output of a detector for different incident particles (1)

WHY? discussed in the following + next lecture(#2)



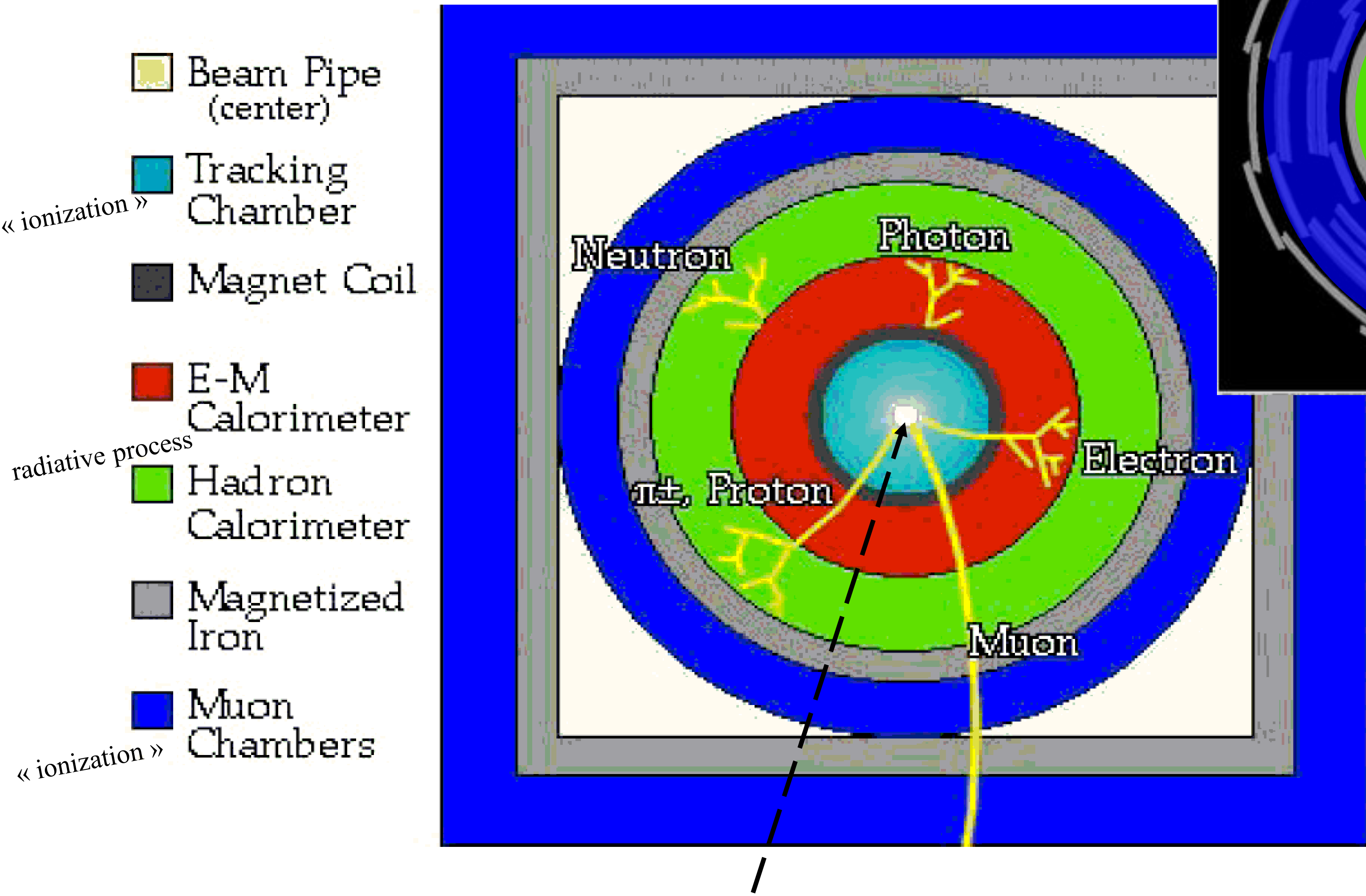
In fixe target mode

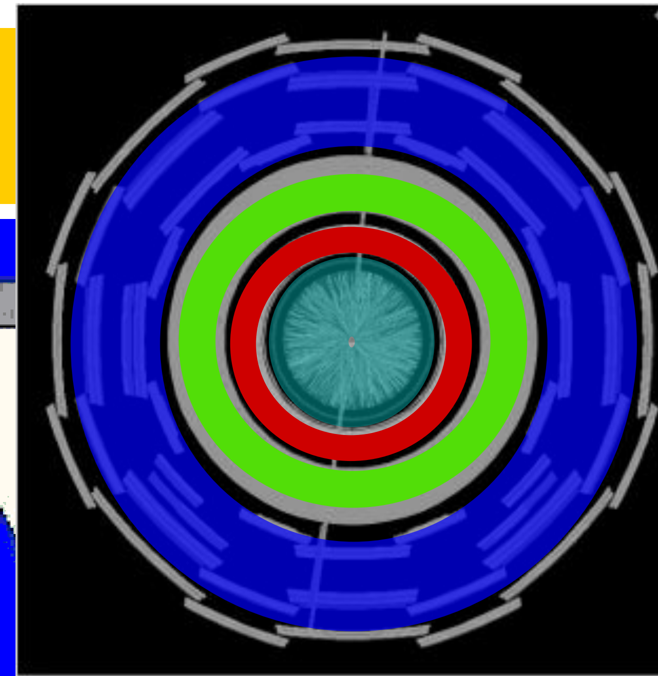
One should also consider the capability of the detector to distinguish the following particles: K/π/p, and π/e, and e/γ+π, and π^0/γ

Or also to distinguish different atom types in a nuclear experiment (at lower energy)

E of particles ≳ 1 GeV

Typical/simplify output of a detector for different incident particles (2)





« collisionneur »

Interaction vertex. Particles to be detected are coming from this area (not a fixe area from one collision to the other at the few ten's/hundred microns)

E of particles ≳ 1 GeV

Few expected numbers of a "typical" multi-detector experiment

(on a collider or not)

- Good resolution σ on : E, $p_{x,y,z}$, etc…

- Good efficiency : ε. Typically >90 to 95% depending on sub-detectors.

- Good acceptance : $A_{detector}$. If $A_{detector}$=95% thus for H decaying in 4 muons A_{total}(H, 4μ)~80%

- No unknown dead area (1-*A)* excluding feet, intermediate area. Needed to sign ν's missing E.

- **Functioning stability : a detector should work on its « plateau » area of its own important/critical parameters : HV, % of gas, temperature, etc…**

- Adapted granularity : to avoid event or tracks superposition

- Less material before calorimeters / energy measurement det. (< or ~ 0.5X_0, i.e. 4cm of Al. or 0.7cm of Cu). Origin = services : cables, mechanical structure, cooling, feet…

- Small "fake track" (ghost) in the trackers. This is also related to efficiency of sub-detectors. Typically around % or less.

- Dead time as low as possible or negligeable.

- No detection bias between particle/anti-particle or between different particles. Important for symmetry studies.

- Good trigger system (*déclenchement*). Example at LHC : beam crossing each 25ns i.e. 40MHz (×1Mo/evt !!). After trigger : "only" ~400Hz = 36To/day.

- support ageing, i.e. support radiations (exp. on accelerator or in space)

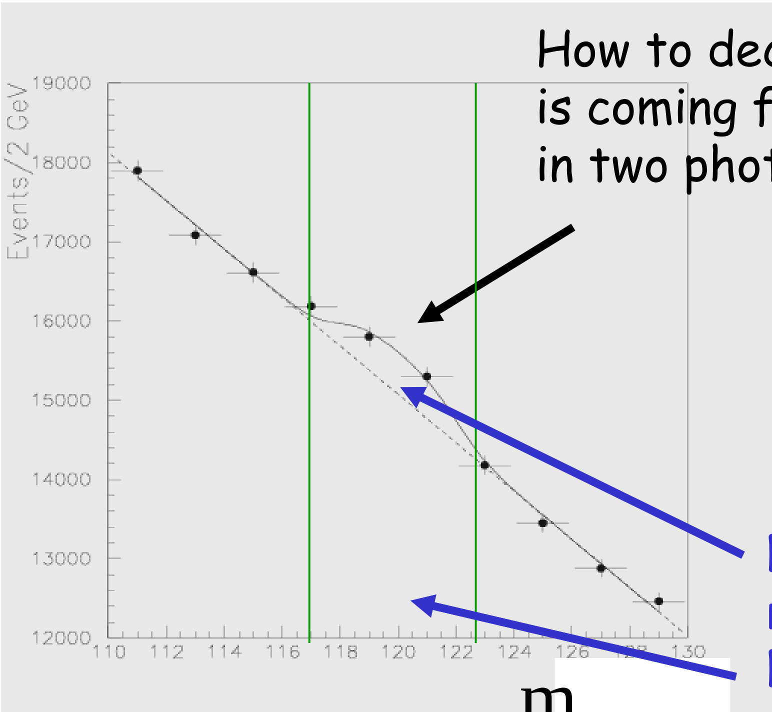
(some of these numbers will be illustrated in following lectures)

How to improve performances ? (1)

Degrading previous numbers => degrade / lower global performances !

How to improve performances ? (1)

Example : **H -> γγ**



$m_{\gamma\gamma}$

How to decide that this excess is coming from a (new) particle in two photons ?

Statistical significance : $S = N_S / \sqrt{N_B}$

N_S : Nombre of events of estimated signal in the peak region

N_B : Nombre of events of estimated background in the peak region : error on this number goes like $\sqrt{N_B}$

$p + p \rightarrow Z^0 + \ldots \rightarrow \gamma\gamma$

S > 5 → the signal is higher than 5 times fluctuation on the number of events of (still) background after cuts of the analysis : probability that background fluctuate by more than 5 σ is : 10^{-7}

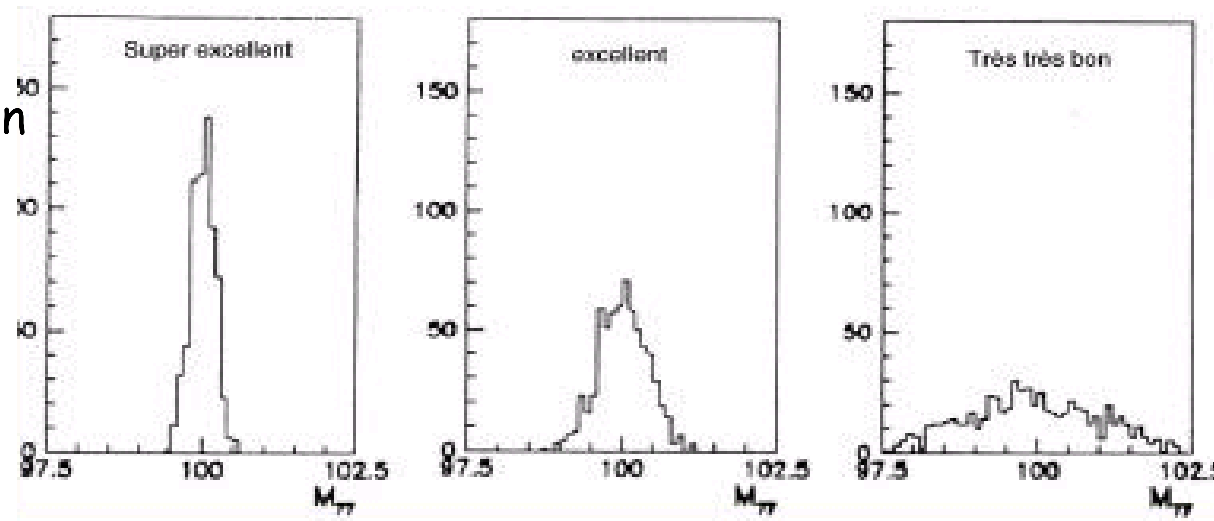
→ discovery !

How to improve performances ? (2)

To maximise signal one should play on :

Detector resolution :
If $\sigma \times 2$, it means that we use a region 2 times larger, but N_S is unchanged but $N_B \times 2$ => degradation by $\sqrt{2}$

→ $S \sim 1/\sqrt{\sigma}$



Increase the luminosity :
$N_S \sim L$, $N_B \sim L$ → $S \sim \sqrt{L}$

Of course have the best **efficiency** for signal rejecting as much as possible background → $S \sim \varepsilon$

$$S \approx \varepsilon \sqrt{\frac{L}{\sigma}}$$

Another solution is to use different final states : 2γ, $2e2\mu$, $4e$, 4μ, etc…

Outline

0) historical remark

1) A physic analysis need a specific detector (and a specific accelerator)

2) Which particle could I see in my detector

3) Loosing energy in the detector (the minimum to be known for this lecture)

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→ 5) Some typical detectors

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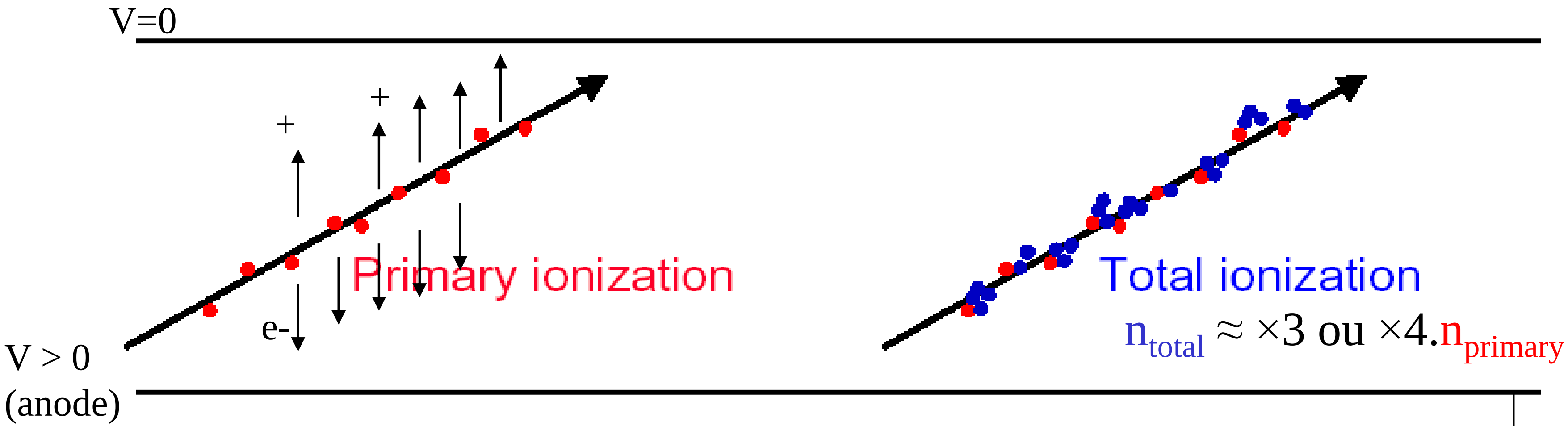
7) Event display of typical LEP events

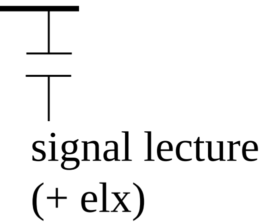
Typical sub-detectors

Existing (sub)detectors :

- vertex : solid (p-i-n)
- Transition radiation
- Track measurement + dE/dx : gas (TPC)
- Some possible magnetic structures
- Calorimeter
- PM signal

Ionization : signal collection





In gas, electrons/ions created pairs by « ionisation » of the inciming charged particule may have enough energy (from 10 to 100 eV) to create also others électrons/ions. They are called secondary electrons. They then distribute their energy.

Minimum energy to create a ion/e- primary pair is ~30 eV in gas and only ~3 eV in a semi-conductor (e^-/hole). In that last case there is only primary ionisation. Signal is collected thanks to a potentiel difference between electrodes : // plane areas, tube and internal wire, electrods and multi-wires, etc.

We will see that in gas one can amplify the signal thus increasing the total number of paires. Thus the signal could be detected more easely (E field close to the anode).

Signal collection : typical characteristics of some detectors

Table 28.1: Typical spatial and temporal resolutions of common detectors. Revised September 2003 by R. Kadel (LBNL).

Detector Type	Accuracy (rms)	Resolution Time	Dead Time
Bubble chamber	10–150 μm	1 ms	50 ms[a]
Streamer chamber	300 μm	2 μs	100 ms
Proportional chamber	50–300 μm[b,c,d]	2 ns	200 ns
Drift chamber	50–300 μm	2 ns[e]	100 ns
Scintillator	—	100 ps/n[f]	10 ns
Emulsion	1 μm	—	—
Liquid Argon Drift [Ref. 6]	~175–450 μm	~ 200 ns	~ 2 μs
Gas Micro Strip [Ref. 7]	30–40 μm	< 10 ns	—
Resistive Plate chamber [Ref. 8]	$\lesssim 10$ μm	1–2 ns	—
Silicon strip	pitch/(3 to 7)[g]	h	h
Silicon pixel	2 μm[i]	h	h

[a] Multiple pulsing time.

[b] 300 μm is for 1 mm pitch.

[c] Delay line cathode readout can give ±150 μm parallel to anode wire.

[d] wirespacing/$\sqrt{12}$.

[e] For two chambers.

[f] n = index of refraction.

[g] The highest resolution ("7") is obtained for small-pitch detectors ($\lesssim 25$ μm) with pulse-height-weighted center finding.

[h] Limited by the readout electronics [9]. (Time resolution of ≤ 25 ns is planned for the ATLAS SCT.)

[i] Analog readout of 34 μm pitch, monolithic pixel detectors.

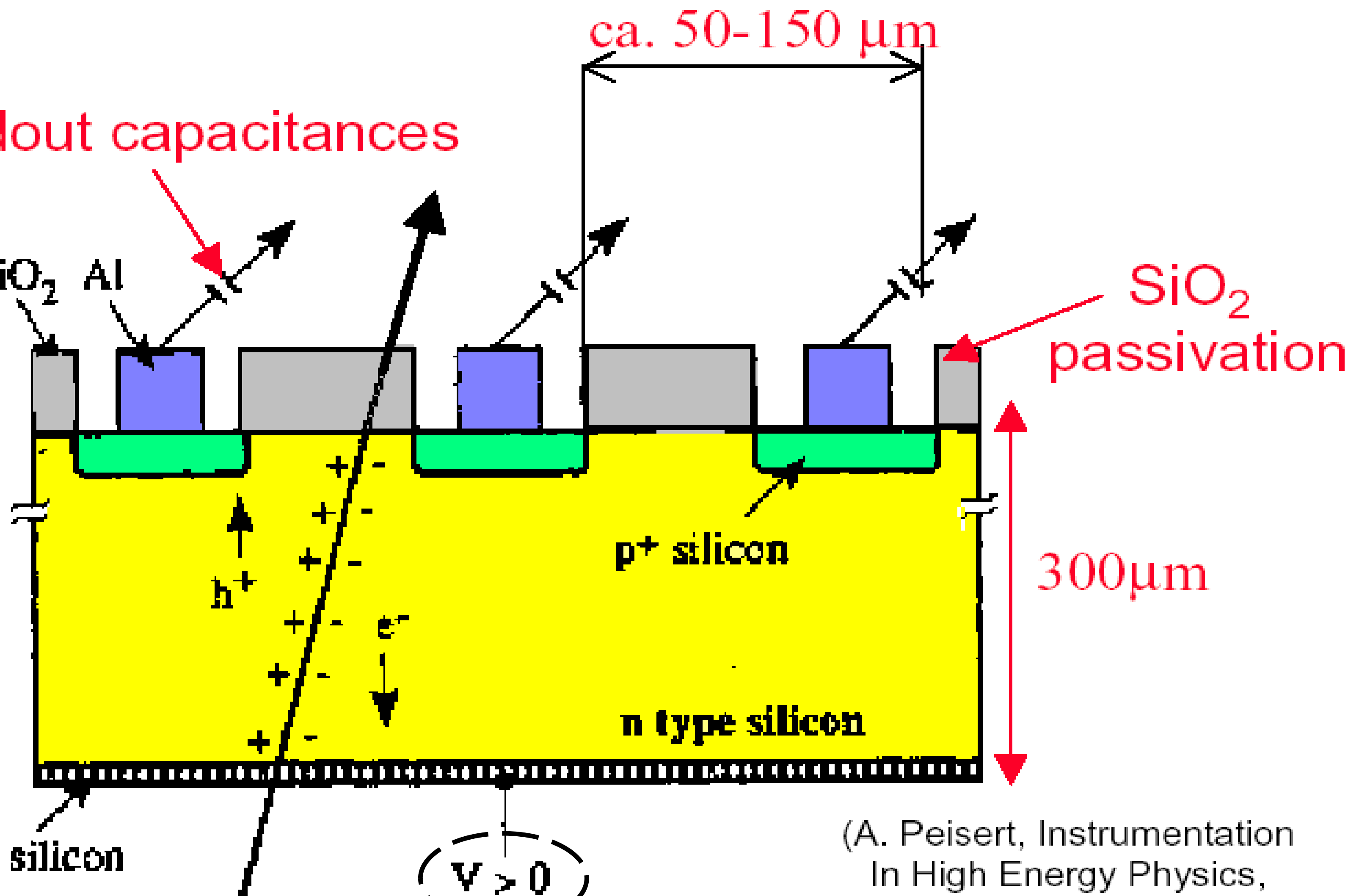
PDG extraction:

Remark: collection time of signal is related to time of drift (energy deposit is ~ instantaneous : ps in liquid/ solid, ns in gas) but not only: the choice of the electronic determine also recorded time.

Structure of Silicium detector

3,6 eV / e-h pair
<< gas !
But no amplification.

i.e. 22000 e-

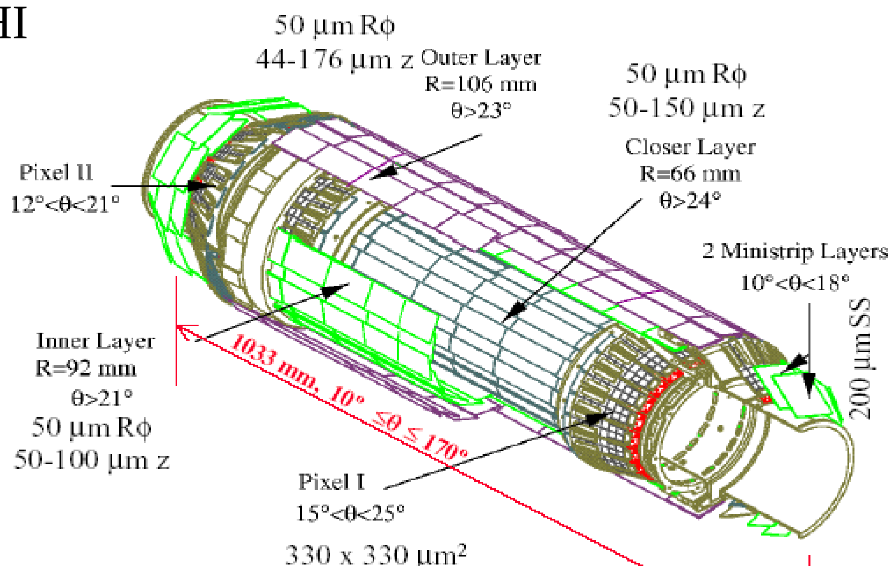


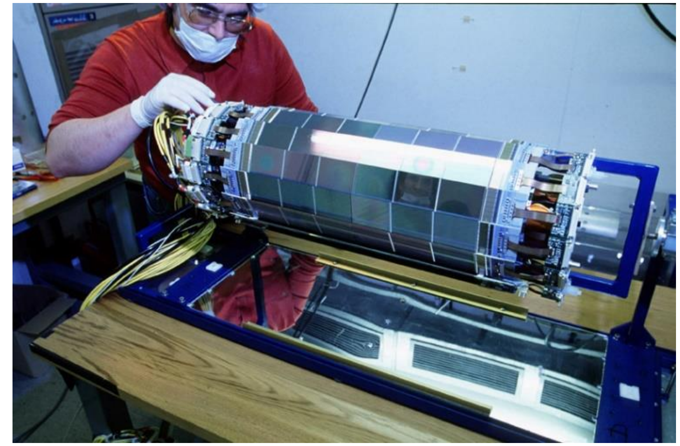
defines end of depletion zone
+ good ohmic contact

(A. Peisert, Instrumentation In High Energy Physics, World Scientific)

Vertex or micro-vertex detector

DELPHI





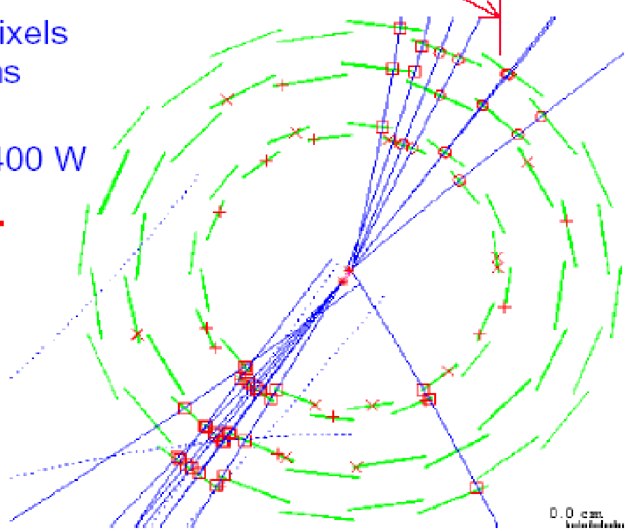
Détecteur de vertex au silicium d'ALEPH

readout channels
ca. 174 k strips, 1.2 M pixels
total readout time: 1.6 ms

Total dissipated power 400 W
→ water cooling system

Hit resolution in barrel part ≈ 10 µm
Impact parameter resolution (rϕ)

$$28\mu m \oplus 71/\left(p\sin^{\frac{3}{2}}\theta\right)$$



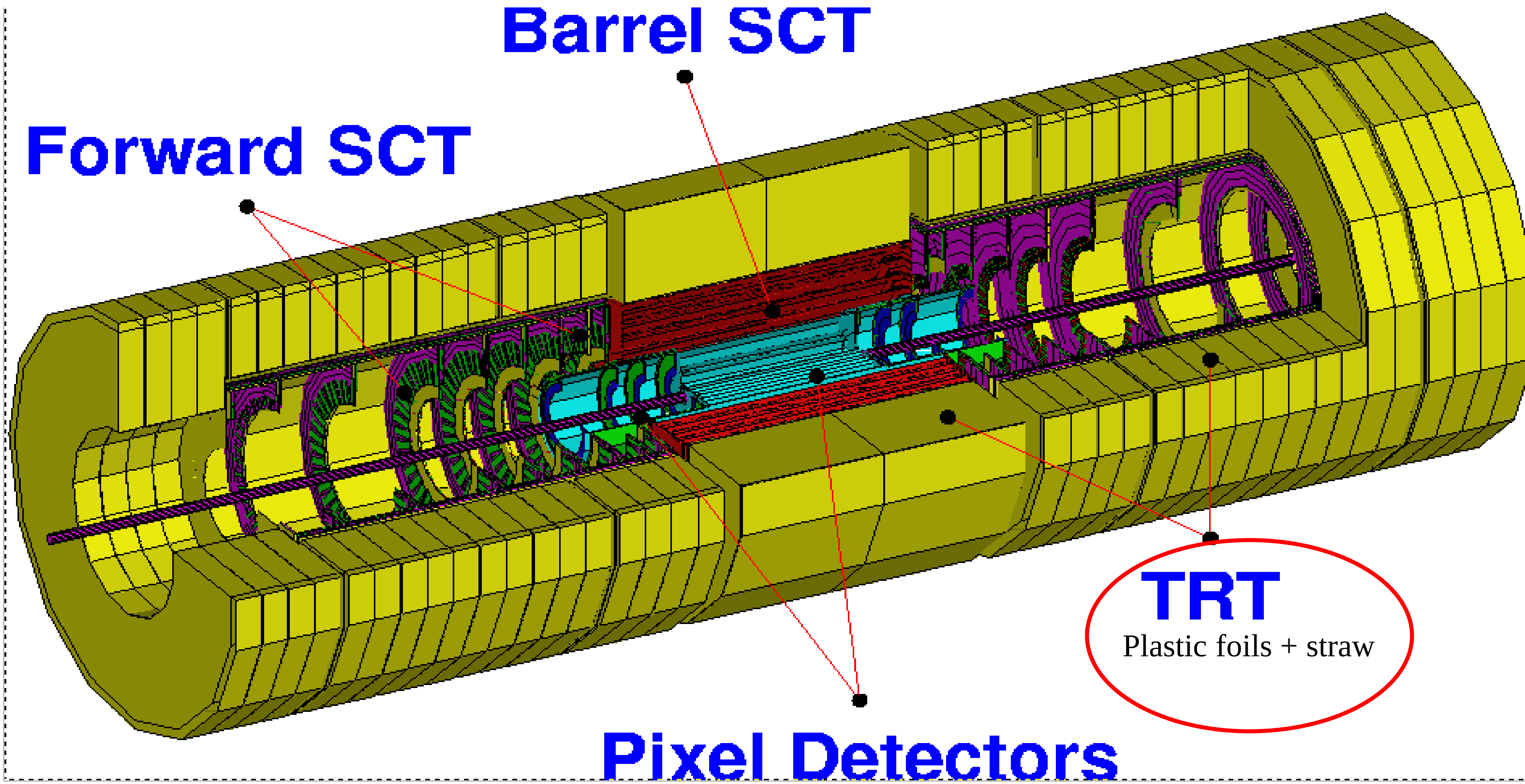
Alignment extremely important : we need to know each plate position at few µm :

- structure deformation ?
- thermal effects ?
- redundancy

(there could be also weak modes in the deformation reconstruction parameters)

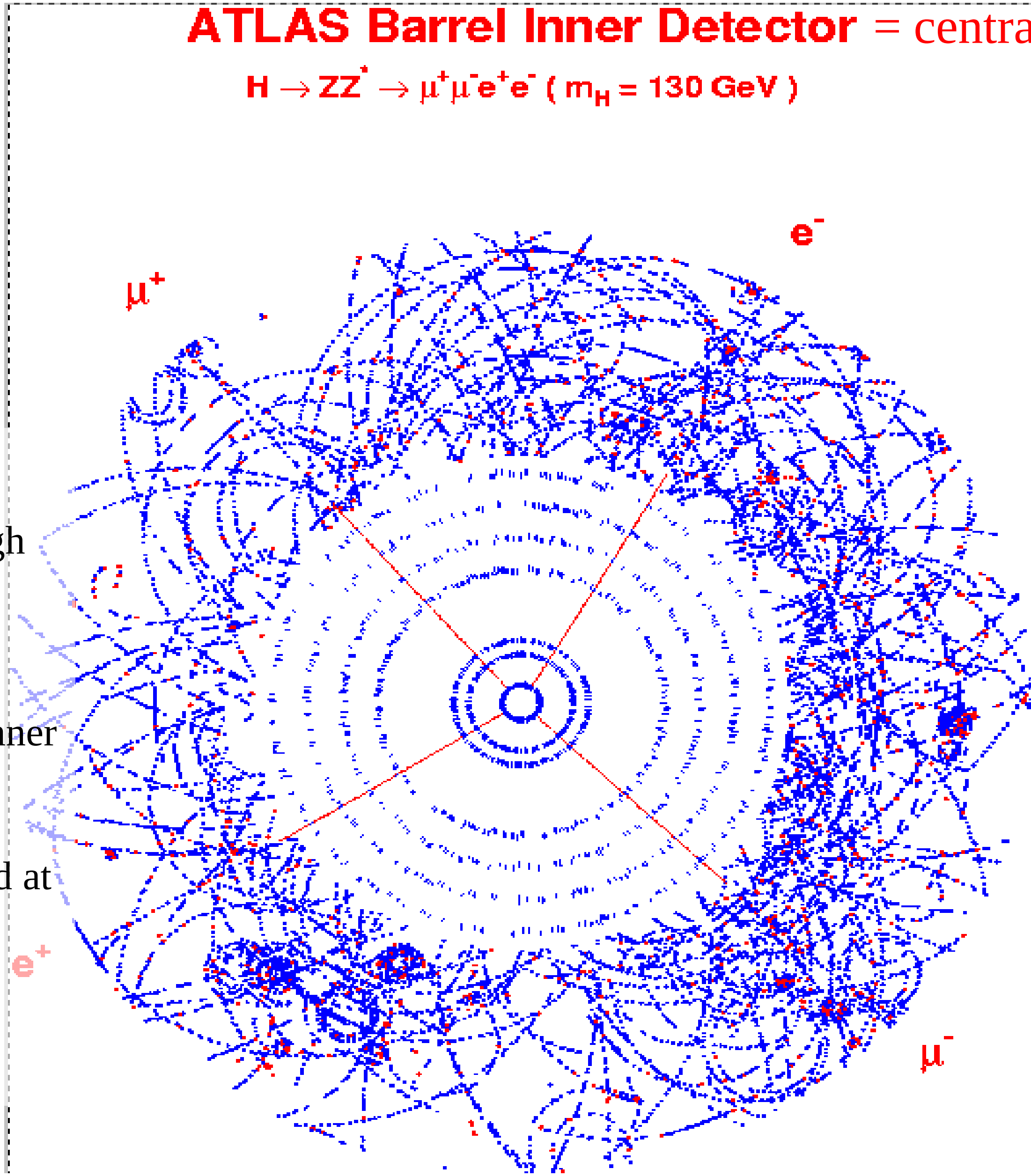
ATLAS inner detector

SCT & Pixel = Si detectors
TRT = Transition Radiation Tracker



Transition de radiation + Si (inner tracker)

$E_{CM} = 14$ TeV



= central inner detector

~ 1m

Remark :

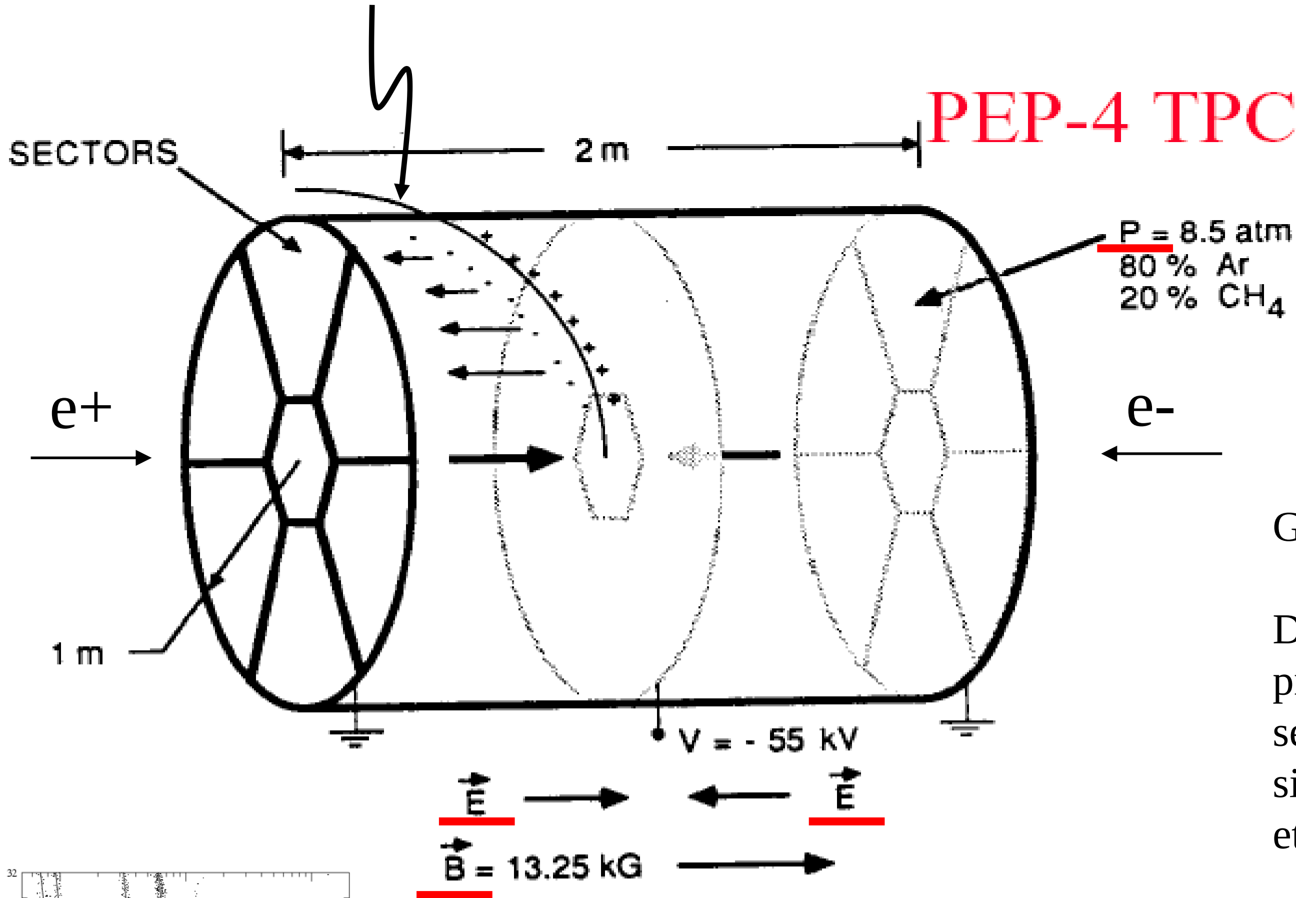
- lot of tracks (~2000), high occupancy
- curvature (mag. $B \neq 0$)
- e+, e-, μ+, μ- ~ straight
- a lot of points on the 3 inner zone and less in the 4 following
- a lot of points are aligned at high radius
- some small red points at high radius

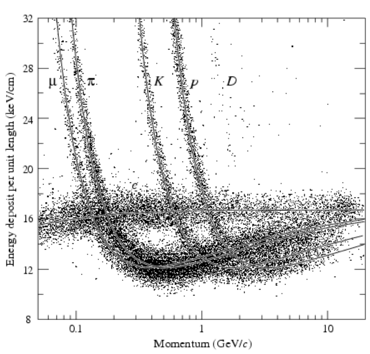
= dE/dx + low E X-ray

Each point blue/red represent a *hit* in one of the detector (inner det.)

Temporal Projection Chamber (TPC)

Particule chargée issue de la collision centrale





X and Y are measured at the end by MWPC (wires) or by MPGD detectors.
Z obtained by drift time.

Gas diffusion is reduced by magnetic field.

Difficulty : one need to know drift velocity precisely V_D (~at few cm/μs) of secondary/drift electrons. Obtain by simulation or through a laser measurement, etc.

Long drift distance : control of gas purity.

To avoid/clean ions back flow : mesh/grid in the TPC end-plate areas.

dE/dx in practice…

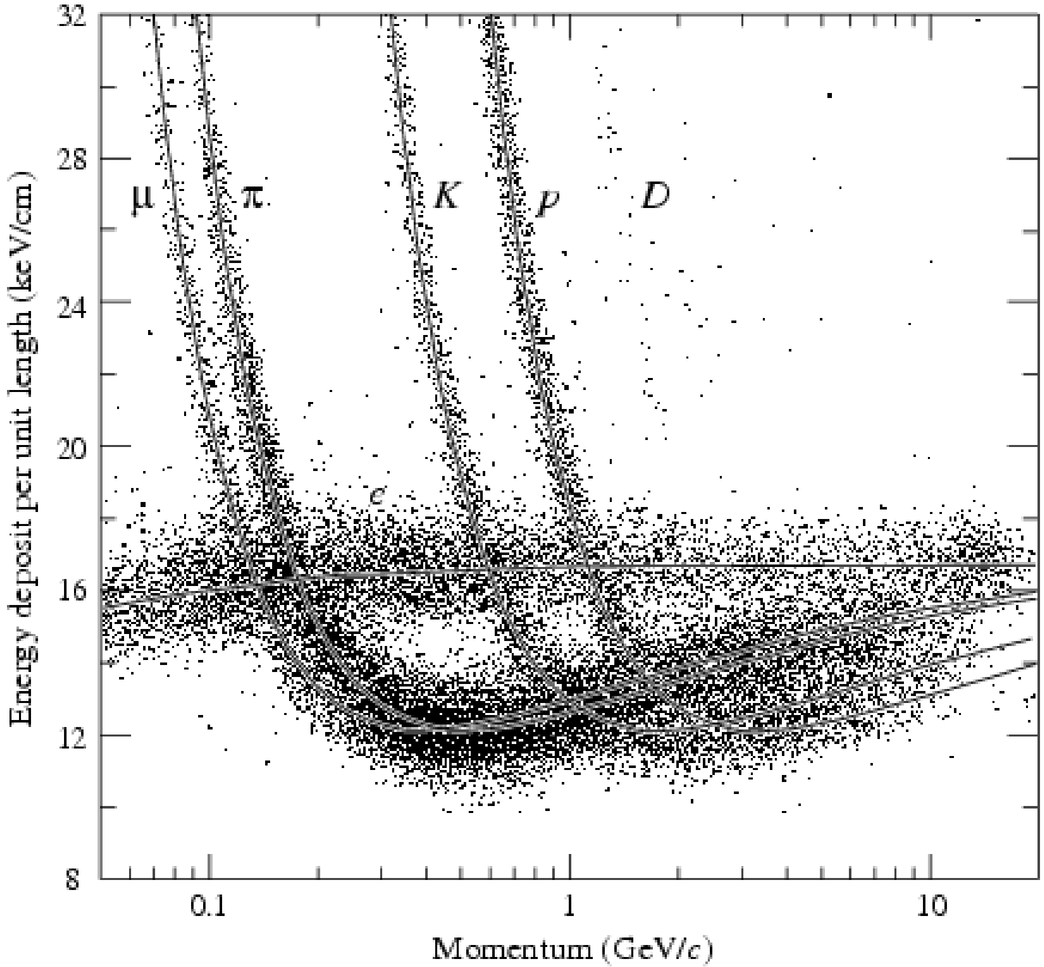
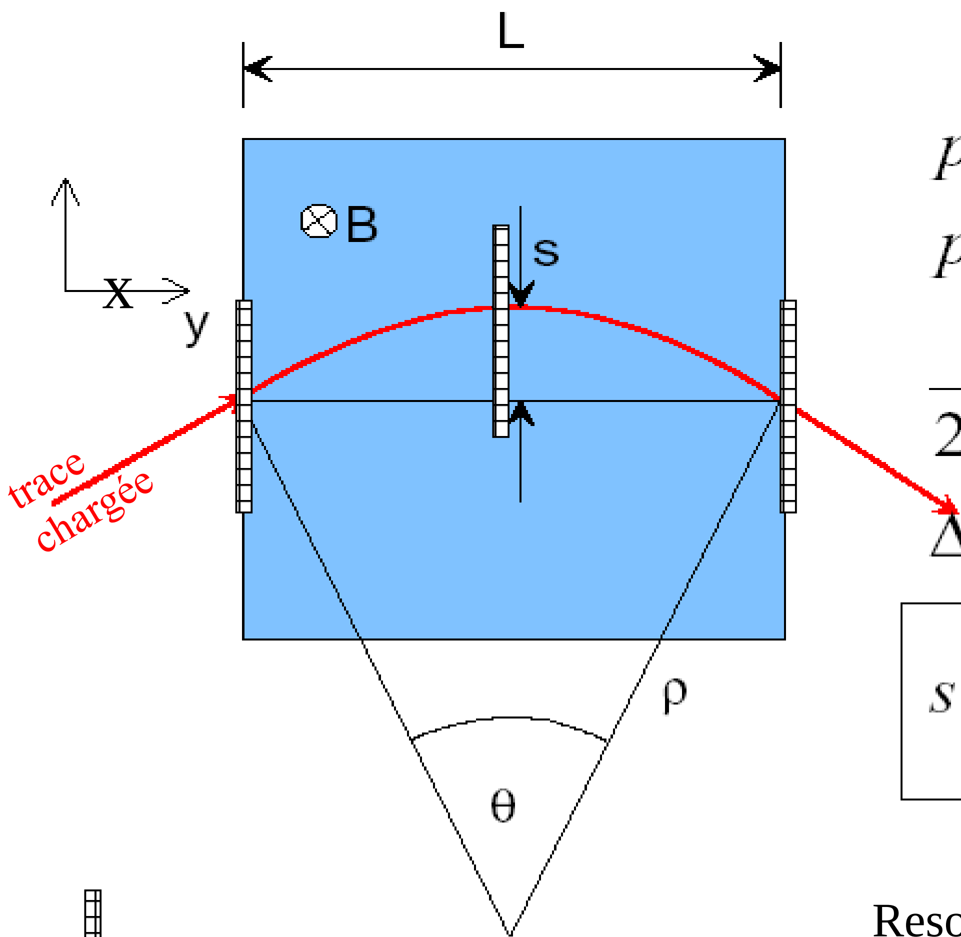


Figure 28.5: PEP4/9-TPC energy-deposit measurements (185 samples @8.5 atm Ar-CH_4 80–20%) in multihadron events. The electrons reach a Fermi plateau value of 1.4 times the most probably energy deposit at minimum ionization. Muons from pion decays are separated from pions at low momentum; π/K are separated over all momenta except in the cross-over region. (Low-momentum protons and deuterons originate from hadron-nucleus collisions in inner materials such as the beam pipe.)

Charge track momentum measurement in a magnetic field



$$p_T = qB\rho$$

$$p_T\ (\mathrm{GeV/c}) = 0.3B\rho \quad (\mathrm{T\cdot m})$$

$$\frac{L}{2\rho} = \sin\theta/2 \approx \theta/2 \quad \rightarrow \quad \theta \approx \frac{0.3L\cdot B}{p_T}$$

$$\Delta p_T = p_T \sin\theta \approx 0.3L\cdot B$$

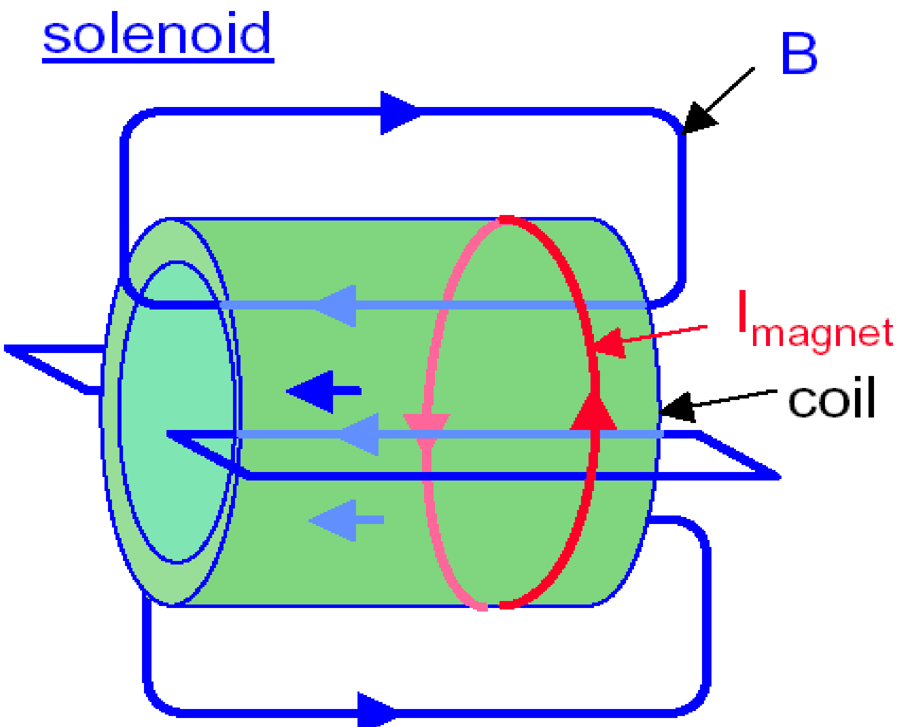
$$\boxed{s = \rho(1-\cos\theta/2) \approx \rho\frac{\theta^2}{8} \approx \frac{0.3}{8}\frac{L^2 B}{p_T}}$$

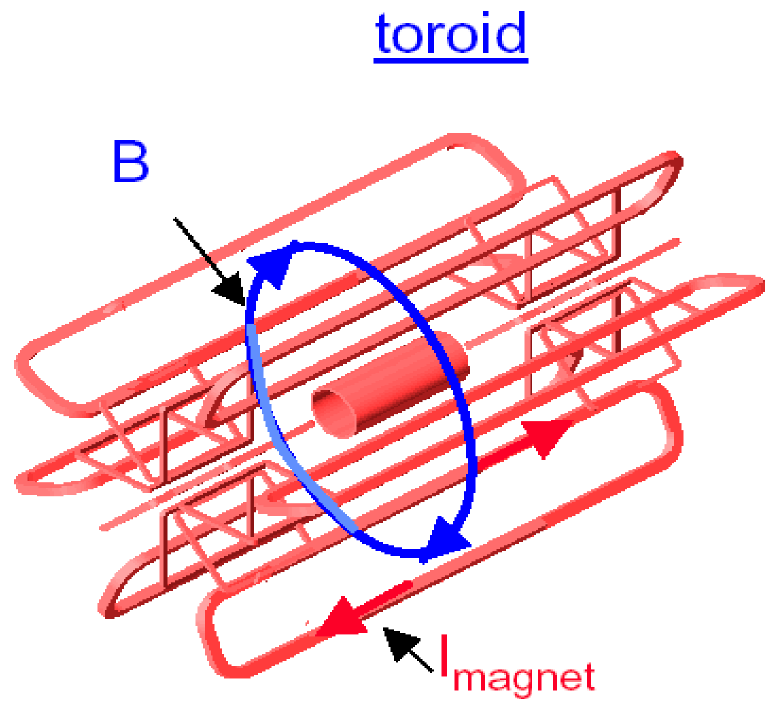

= détecteur de traces
(ex. : TPC, ch. à dérives)

Resolution is deteriorated by :

- multiple scattering (in the middle area)
- if there is misalignment

Examples of magnetic field configuration

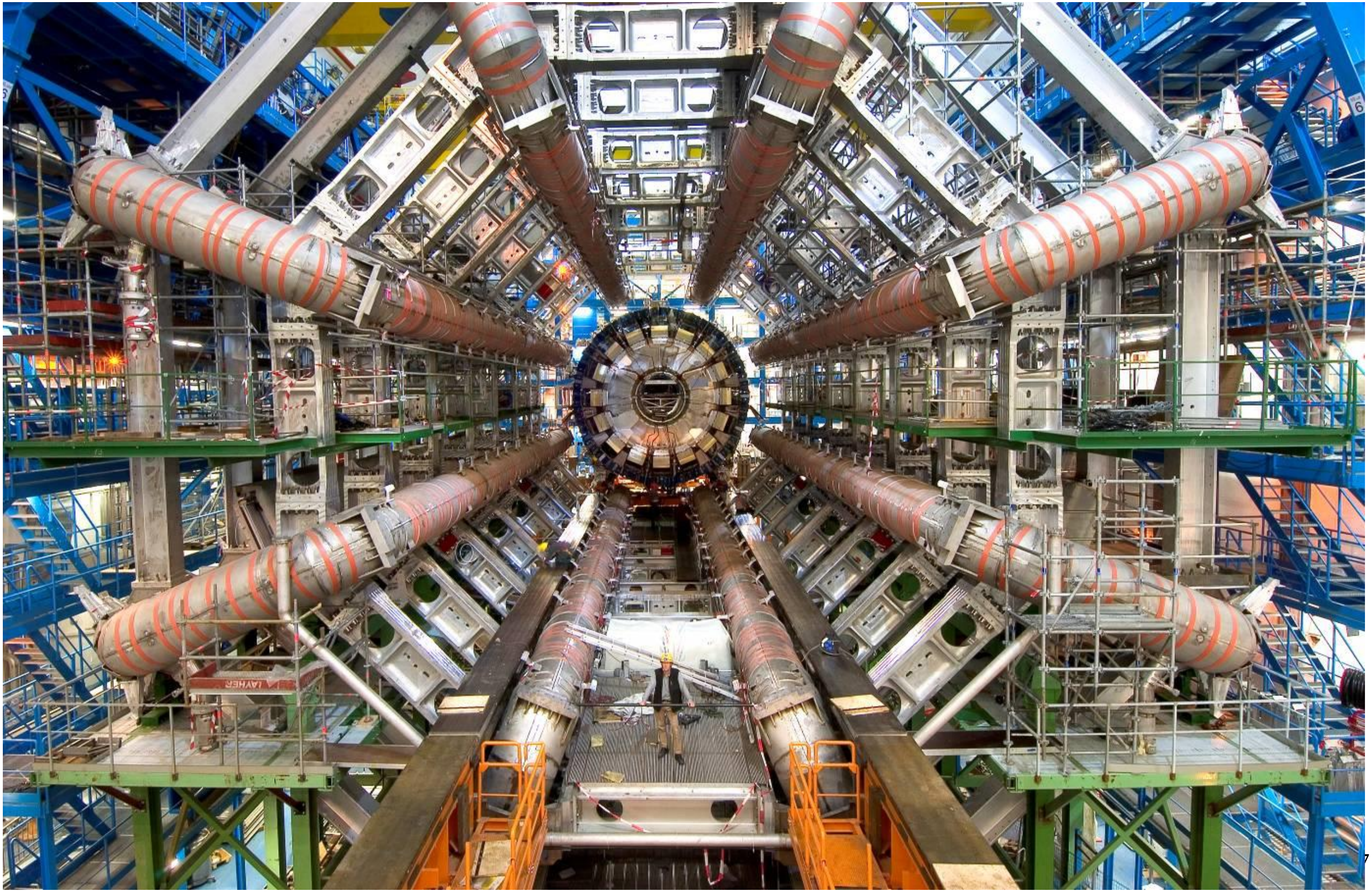


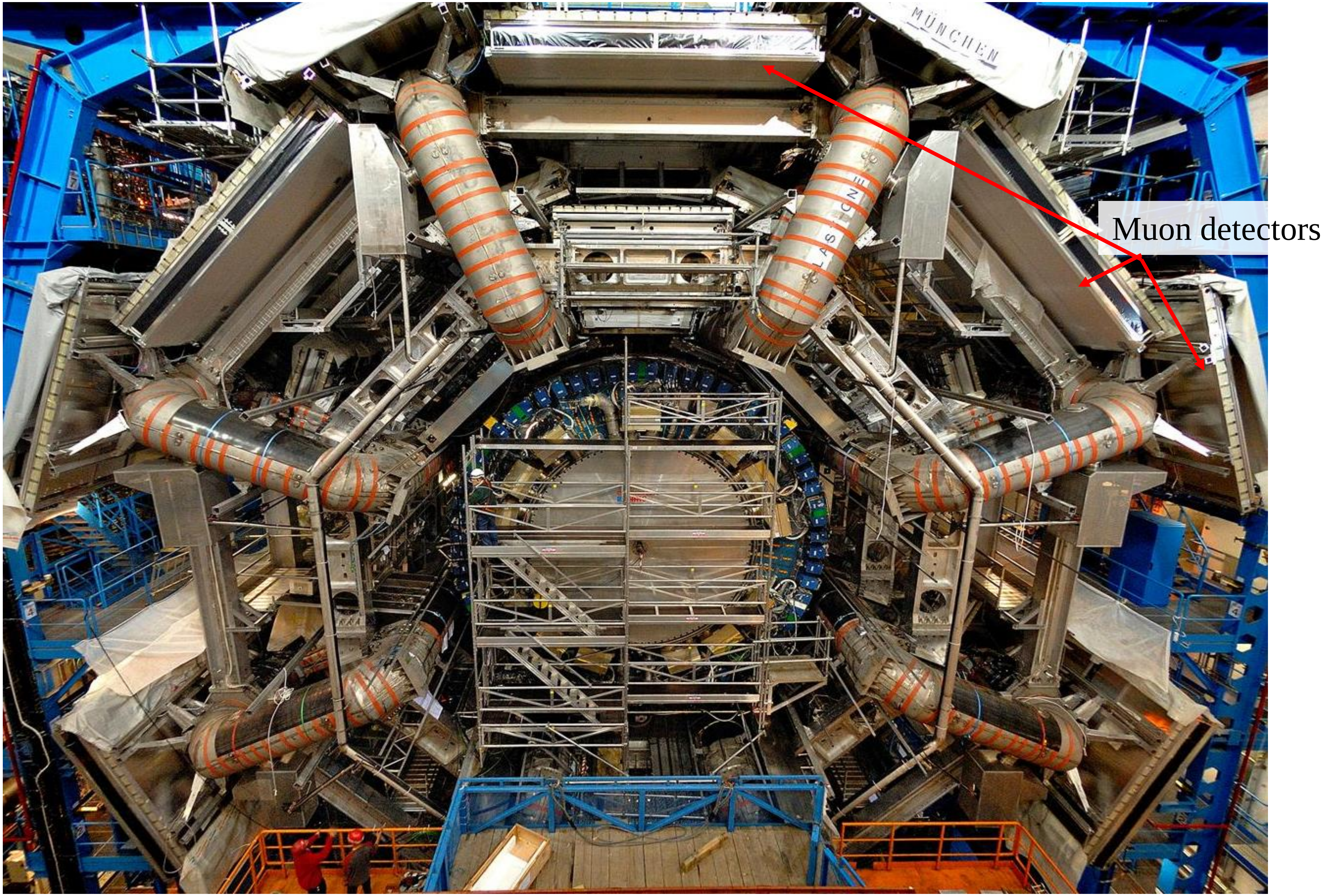


- \+ Vertex information usefull
- \+ Large homogenous field inside coil
- \- weak opposite field in return yoke
- \- Size limited (cost)
- \- rel. high material budget

- \+ independant muon system (redondancy)
- \+ Rel. large fields over large volume
- \+ Rel. low material budget
- \- non-uniform field
- \- complex structure
- \- Vertex non-usable

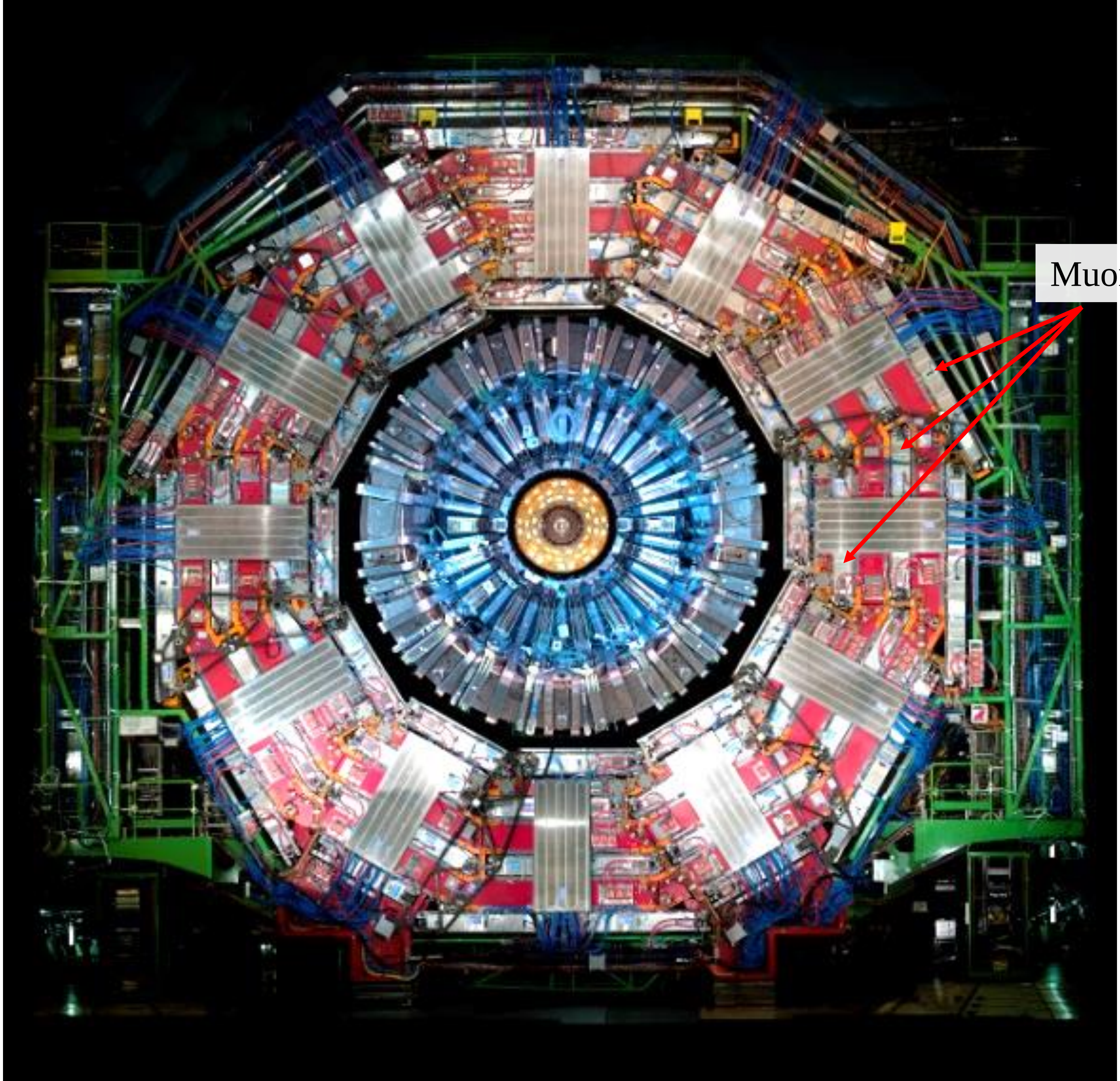
Magnetic fields : supraconducting magnets of ATLAS




Muon detectors
MÜNCHEN

Several magnetic field configuration possible :
CMS solenoid magnet (depends of the conductiong wires position)

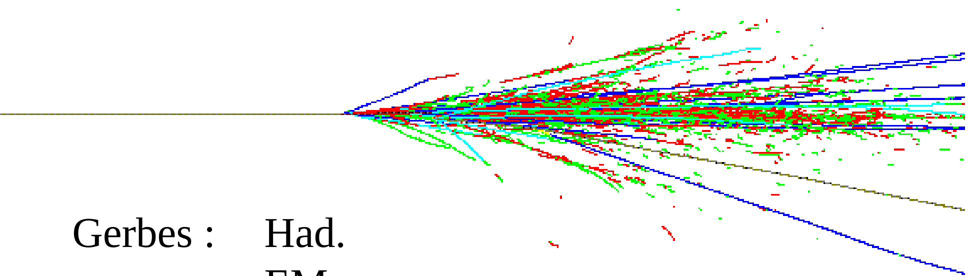
Muon detectors



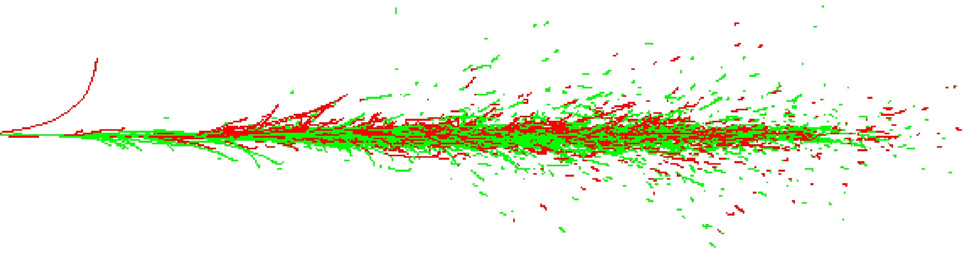
Muon detectors

Calorimetry

PbW_4 crystals readout by photo-detectors (APD)

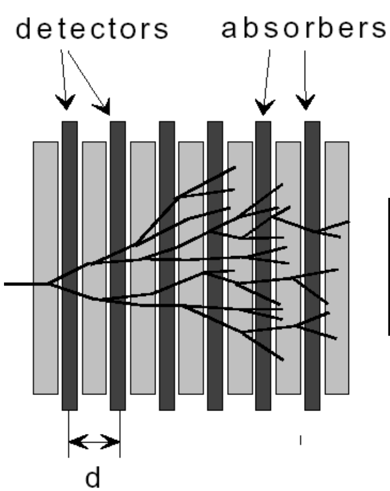


Gerbes : Had.
EM



- Homogenous : <u>detector and absorber are the same !</u>
  - Good resolution in energy
  - Longitudinal segmentation difficult (identification of particles)
  - Spatial resolution limited
  - Used for electromagnetic calorimeter

- Sampling calo. :
  - Absorber and detectors are separated (<u>sandwich</u>)
  - Lower energy resolution and less homogenous
  - Best spatial resolution
  - Used in electromagnetic or hadronic calorimeter



$$N = \frac{T_{det}}{d}$$ Detectable track segments

$$= F(\xi)\frac{E}{E_c}X_0\frac{1}{d}$$

$$\frac{\sigma(E)}{E} \propto \frac{\sqrt{N}}{N} \propto \sqrt{\frac{1}{E}} \cdot \sqrt{\frac{d}{X_0}}$$

Outline

0) historical remark

1) A physic analysis need a specific detector (and a specific accelerator)

2) Which particle could I see in my detector

3) Loosing energy in the detector (the minimum to be known for this lecture)

4) Layout of a multi-detector apparatus

5) Some typical detectors

→ 6) Glossary

7) Event display of typical LEP events

GLOSSARY

Some words and expressions frequently used :

X_0, λ_I, R_M, π/e separation at nσ, multiple scattering, dE/dx, bremsstrahlung, vertex, pair creation, ionisation, mip, quencher, cerenkov effet , δ_{ray}, E_c, fractional -constant- threshold, Lorentz boost, EM or Had. shower, cascade, PM, dynode, HT (HV), drift chamber, calorimeter, pre-shower, tracker, TRD, ageing, attenuation length, ID, vertex, rising time/edge, trailing edge, trigger, cyclotron frequency, Landau fluctuation, W_I, Bragg peak, range, cross section, afterglow signal, dead time, efficiency, plateau, magnet return yoke, instrumented iron, punchthrough, CCD, missing E, transverse energy/momentum (E_t, p_t), photo-electron, strip, pad/pixel, MWPC, pedestal, jitter, slewing, photodiode, quartz window, photocathode, WLS, TPC, Bethe-Bloch formula, ADC, TDC, analogic/numeric, bit/octet/byte, n-bits converter, twisted pair (cable), linearity, Lorentz angle, anode, gap, pitch, Compton diffusion, Geïger-Müller mode, streamer mode, FWHM, Monte-Carlo, rapidity/eta, r-t relation, T_0, calibration, cross section, hit, barrel/end-cap, signal shaper, granularity, jets, front-end electronic, fack/ghost tracks, on-line, off-line, etc…

GLOSSAIRE

Quelques mots et expressions fréquemment employés (à connaître par cœur !!) :

X_0, λ_I, R_M, séparation π/e à nσ, diffusion multiple (multiple scattering), dE/dx, bremsstrahlung, vertex, création de paire, ionisation, mip, quencheur, effet cerenkov, δ_{ray}, E_c, seuil -à fraction constante- (-constant- threshold), boost de Lorentz, gerbe EM ou Had., cascade, PM, dynode, HT (HV), chambre à dérive, calorimètre, pré-shower, tracker, TRD, vieillissement (aging), longueur d'atténuation, ID, vertex, temps de montée (rising time/edge), signal de fin (trailing edge), déclenchement (trigger), fréquence cyclotron, fluctuation de Landau, W_I, pic de Bragg, range, section efficace (cross section), fin/retour de signal (afterglow), temps mort (dead time), efficacité (efficiency), plateau, retour d'aimant (return yoke), fer instrumenté, punchthrough, CCD, énergie manquante (missing E), énergie/impulsion transverse (E_t, p_t), photoélectron, strip, pad/pixel, MWPC, pedestal, jitter, slewing, photodiode, fenêtre en quartz, photocathode, WLS, TPC, formule de Bethe-Bloch, ADC, TDC, analogique/numérique, bit/octet/byte, échantillonneur n-bits (n-bits converter), paire twistée, linéarité, angle de Lorentz, anode, gap, pitch, diffusion Compton, mode Geïger-Müller, mode streamer, FWHM, Monte-Carlo, rapidité/eta, relation r-t, T_0, étalonnage (calibration), section efficace, coup (hit), barrel/end-cap, mise en forme (shaper), granularité, jets, électronique front-end, traces fantômes (fack/ghost tracks), on-line, off-line, etc…

Outline

0) historical remark

1) A physic analysis need a specific detector (and a specific accelerator)

2) Which particle could I see in my detector

3) Loosing energy in the detector (the minimum to be known for this lecture)

4) Layout of a multi-detector apparatus

5) Some typical detectors

6) Glossary

→ 7) Event display of typical LEP or LHC events

Does all this is true or not ?
Event display of "typical" events (ALPEH, ATLAS)

Event display of "typical" events from ALEPH experiment at CERN on LEP accelerator :

$e^+e^- \rightarrow Z \rightarrow$ something @ $\sqrt{s} \sim 91$ GeV

This experiment has detector for :

- vertex
- TPC i.e. gaseous det. (dE/dx)
- EM calorimeter
- solenoide magnet

} +B field

- Had calorimeter
- return flux "instrumented" (μ)

} -B

Does all this is true or not ?
Event display of "typical" events (ALPEH, ATLAS)

Event display of "typical" events from ATLAS experiment at CERN on LHC accelerator :

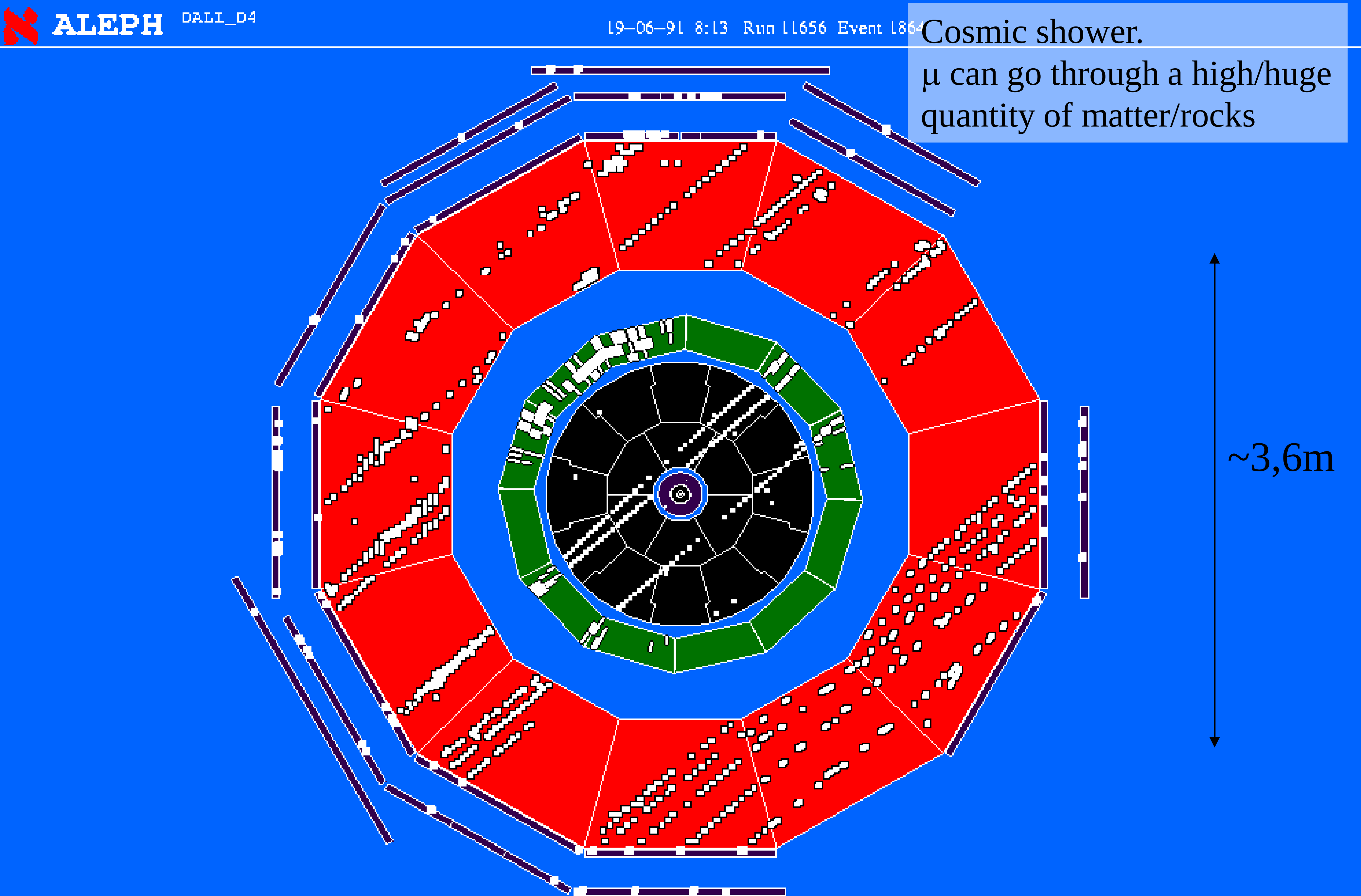
pp → (many)something @ $\sqrt{s}$ ~ 7 to 13 TeV

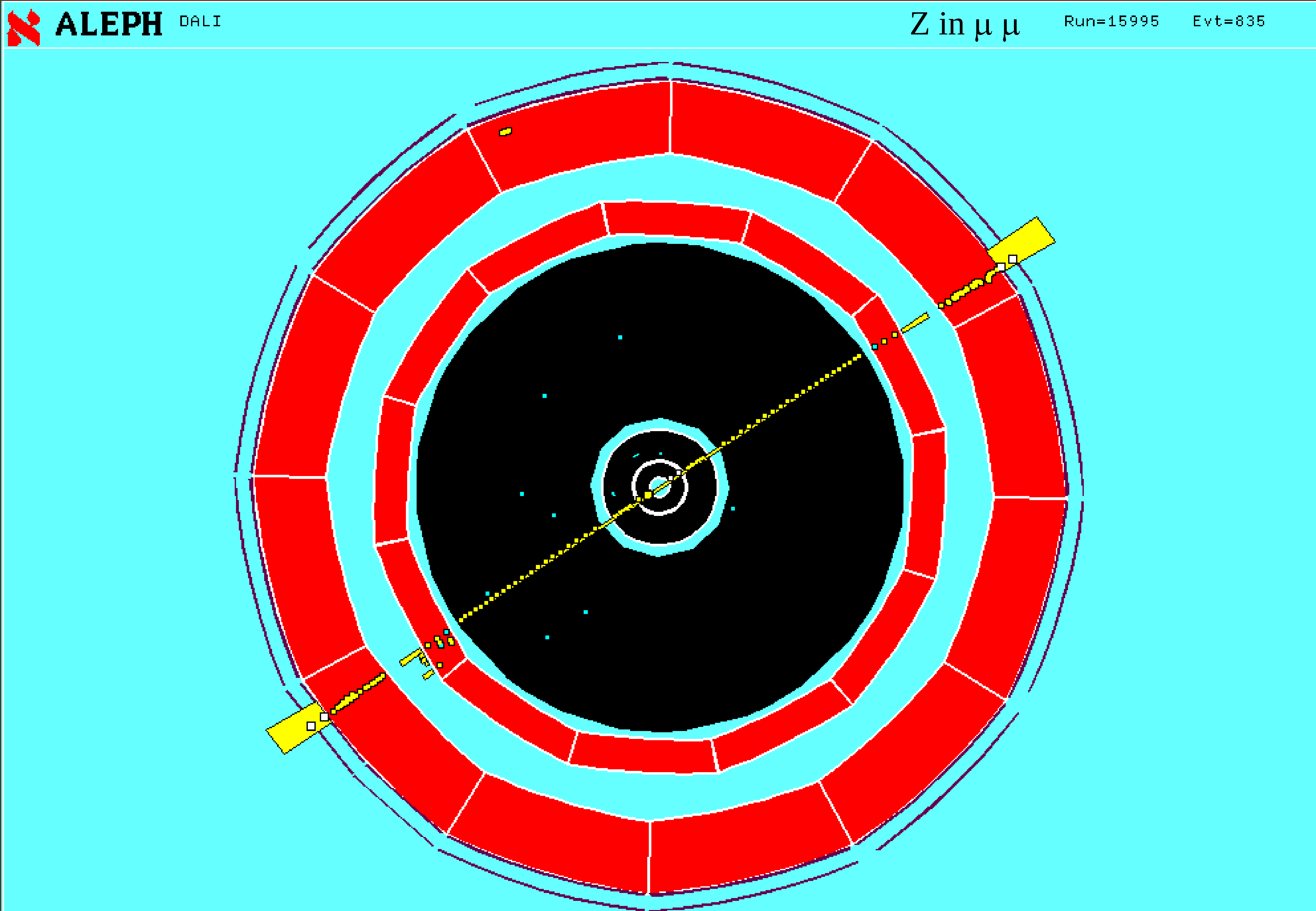
This experiment has detector for :

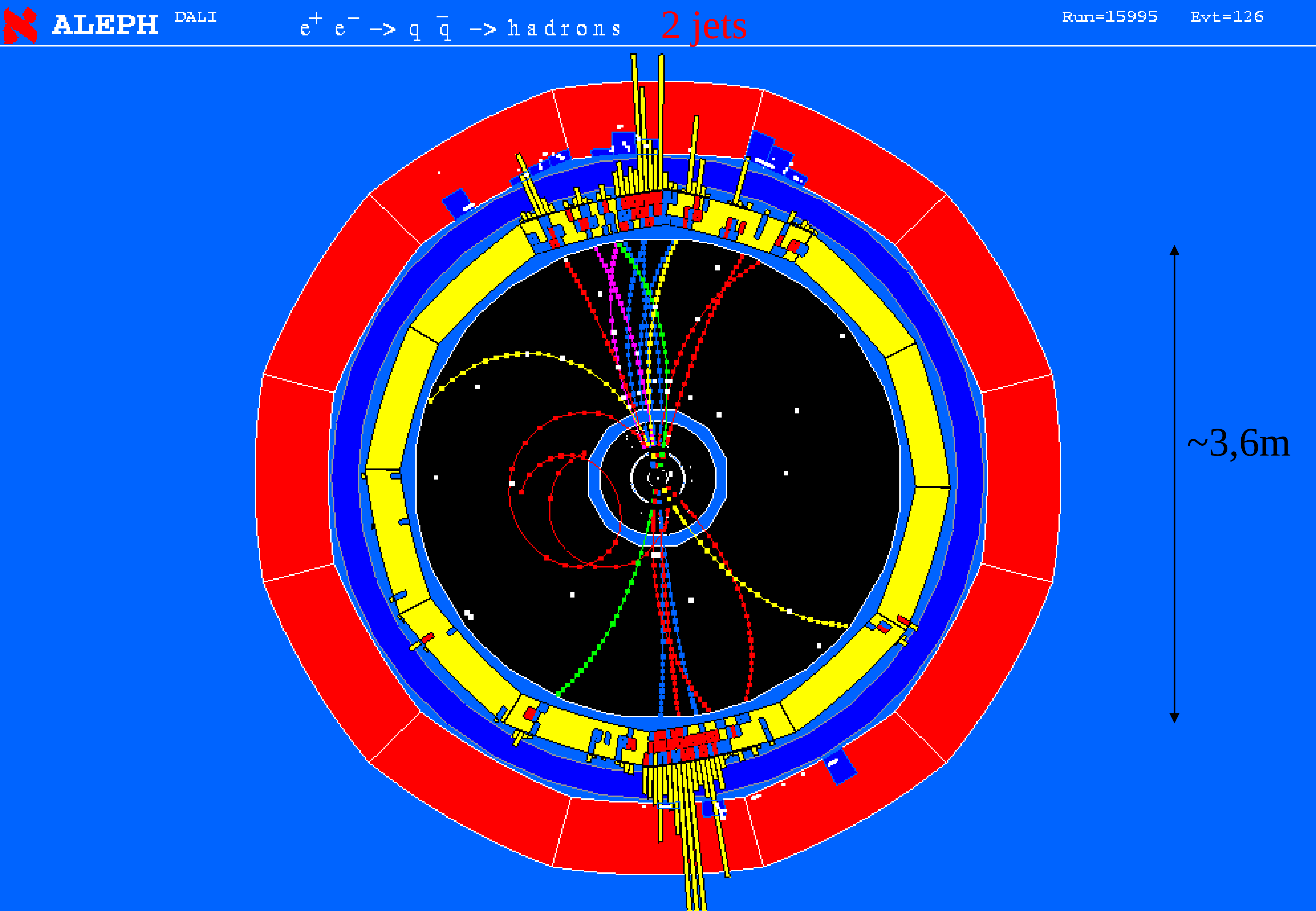
vertex Si + gaseous det. solenoid magnet	} B field
EM calorimeter	
Had calorimeter	
toroid magnet muon chambers (μ)	} B field Tor.

Cosmic shower.

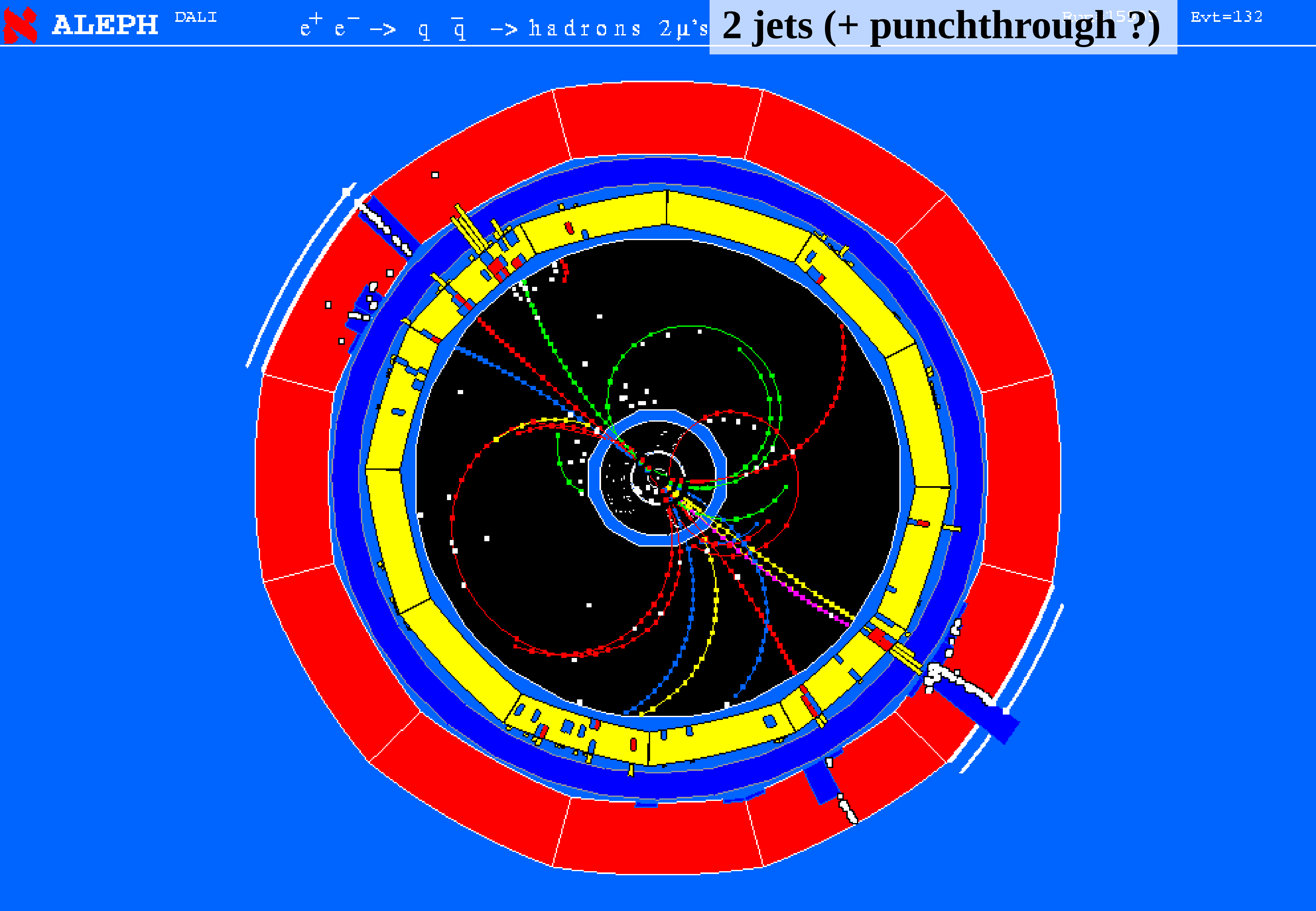
μ can go through a high/huge quantity of matter/rocks

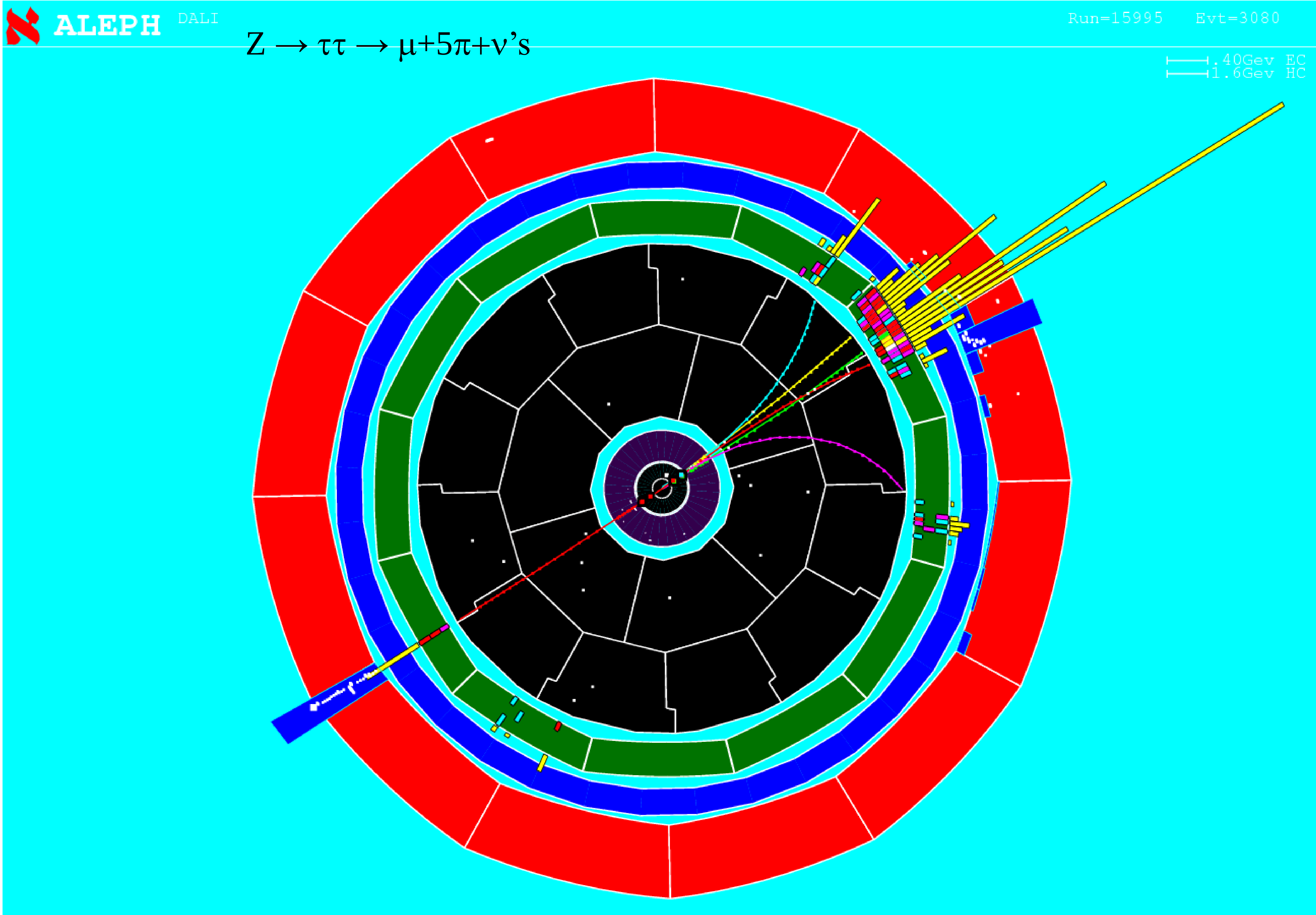


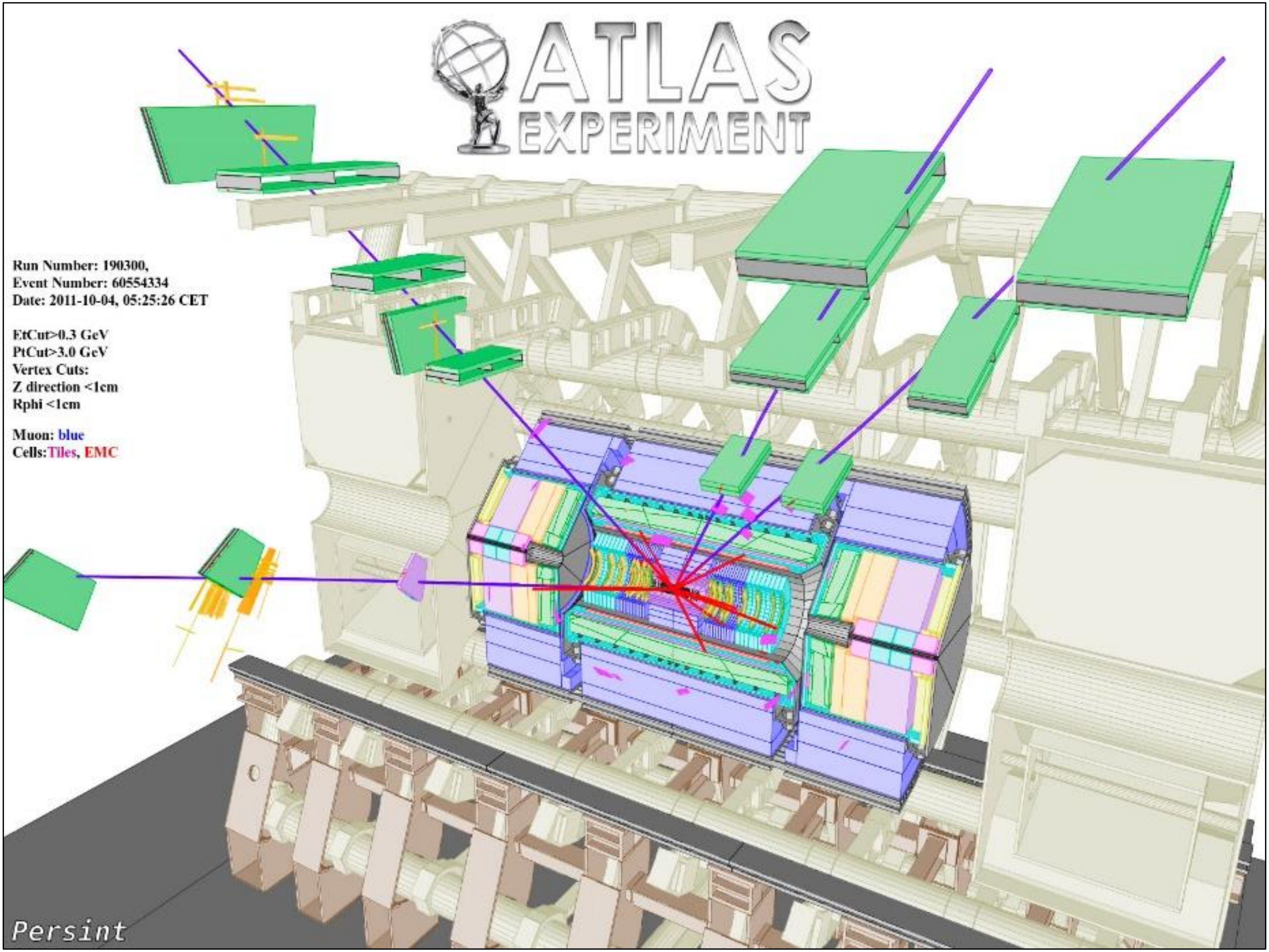

ALEPH
DALI
Z in μ μ
Run=15995
Evt=835


ALEPH DALI
e+ e− −> q q̄ −> hadrons
2 jets
Run=15995 Evt=126
~3,6m

2 jets (+ punchthrough ?)



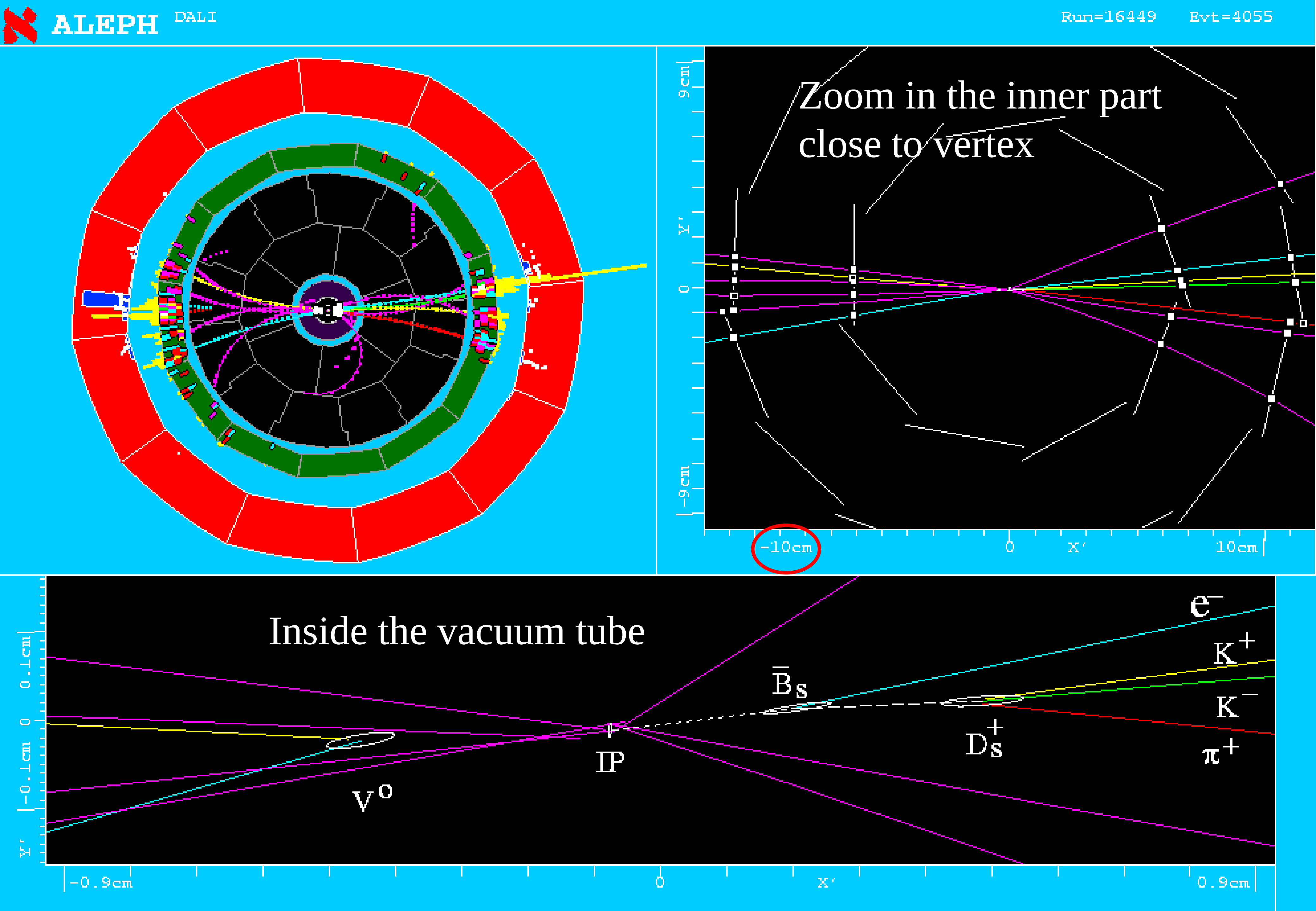

ALEPH
DALI
$Z \rightarrow \tau\tau \rightarrow \mu+5\pi+\nu$'s
Run=15995
Evt=3080
.40Gev EC
1.6Gev HC


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

Closer to the vertex

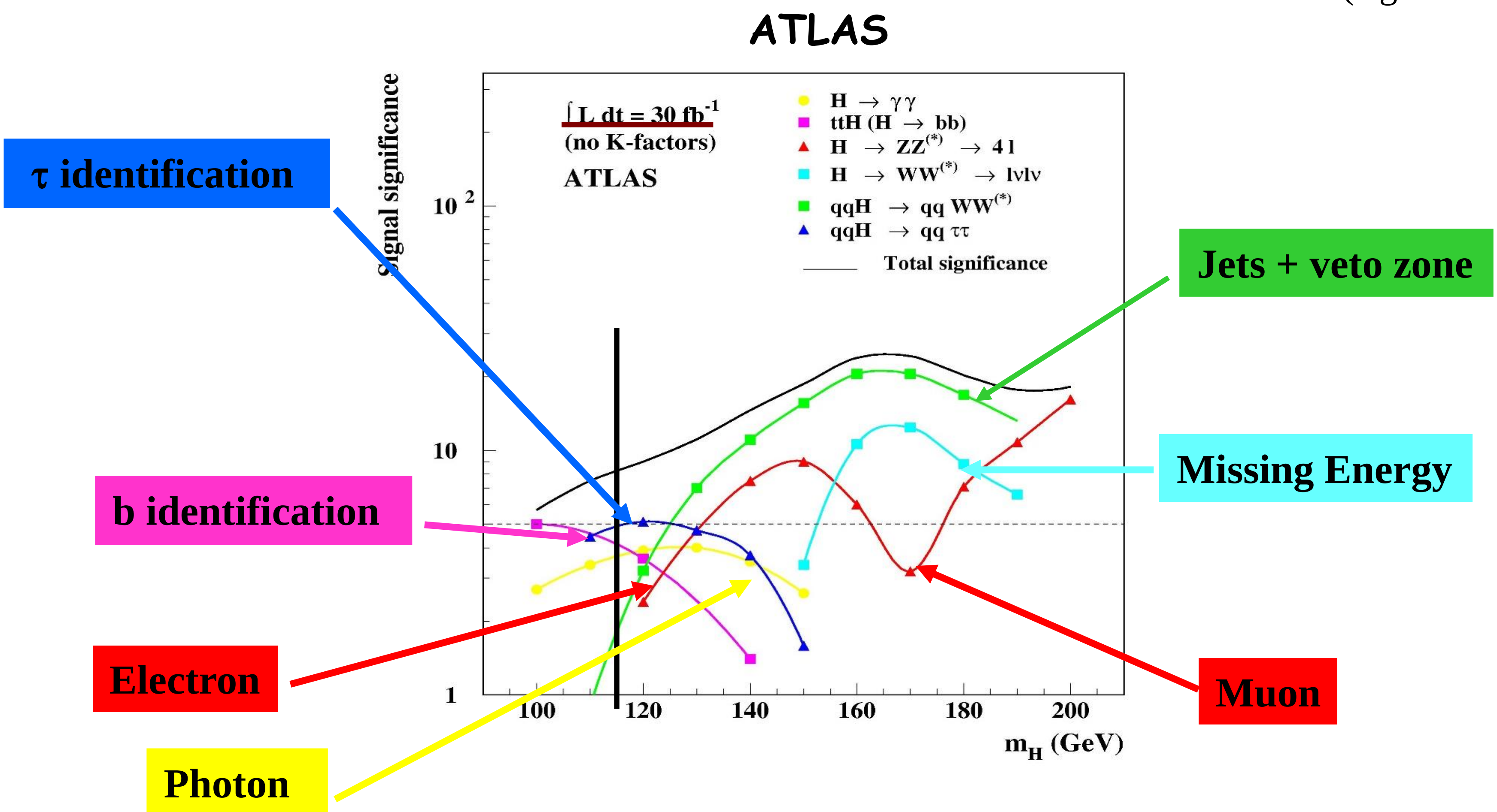
Some B mesons have a lifetime long enough to "flight", thanks to Lorentz boost, over measurable distances : few 100 microns.

If we succeed to measure a secondary vertex, shifted from the initial one, one thus sign the existence of such a particular particle.
The exact flavour may/could be determine by decay products of this (secondary) particle.


ALEPH
DALI
Run=16449
Evt=4055
Zoom in the inner part close to vertex
9cm
Y'
0
-9cm
-10cm
0
X'
10cm
Inside the vacuum tube
e^-
K^+
$\bar{B}_s$
K^-
D_s^+
π^+
IP
V^0
0.1cm
0
-0.1cm
Y'
-0.9cm
0
X'
0.9cm

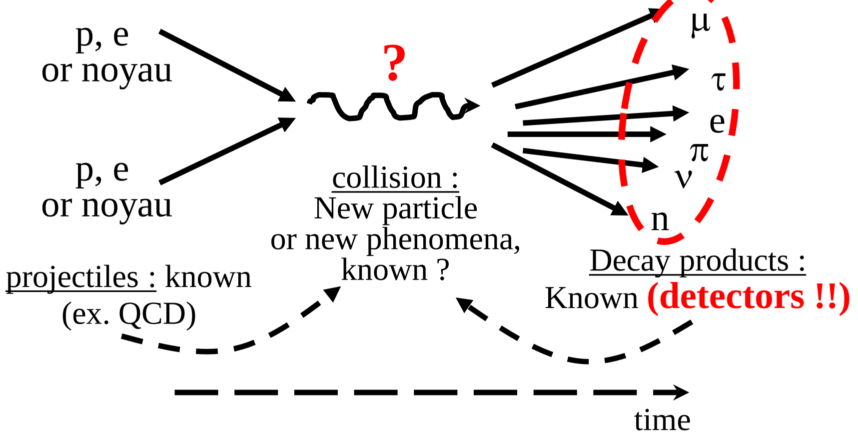
Example : Higgs search at LHC
or how detectors are usefull

(e.g. neutral H° of SM)



All mass spectrum is covered, by several possible decay channels (redondancy). Detector performances are crucials

Conclusions for the first lecture



What we have (briefly seen) :

• process to be studied are characterised by a cross section (allowing us to calculate the number of expected events on an accelerator, using its luminosity and its – useful - working time)

• We would like/need that our detectors can :

Measure : E, p, x, y, z, dE/dx, id. (mass), charge, time,…

=> important of these measurements for our analyses (with high efficiency, etc. !)

• Which particles will we "see"/detect in our detectors : e, μ, γ, π, K, proton, n, jets, (ν),

also α, $\beta^{+/-}$ and atoms

Depends of the experiment goal

• a very brief looking of energy loosing of (visible) particles in matter, so in our detector and out to detect a signal.

• How to measure interested parameters through few example of detectors

We still need to look in more details to :

interactions of particles with matter (mandatory…)

<u>different type detectors (!!)</u> : gaseous, solids, light detectors, etc…

(with how to use it - theoretically, with some bias…)