Particle detectors and large HEP experiments

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Outline

Detectors requirements for HEP experiments :

- Physics inputs
- Constraints
- Overall concept of HEP experiment detectors

Basic concepts of particle interaction in matter :

- Heavy charge particles
- Electrons/photons
- Muons
- Quarks/Gluons→ Jets

Detector technologies :

- Charge particle detectors : gaseous and solid state detectors
- Calorimeters
- Particle identification detectors

*Slides with *** will probably not be discussed*

Caution : The topic is very broad and it will be a non sense to believe to cover all detectors/technologies in ~2h so I have made (biased ?) choices

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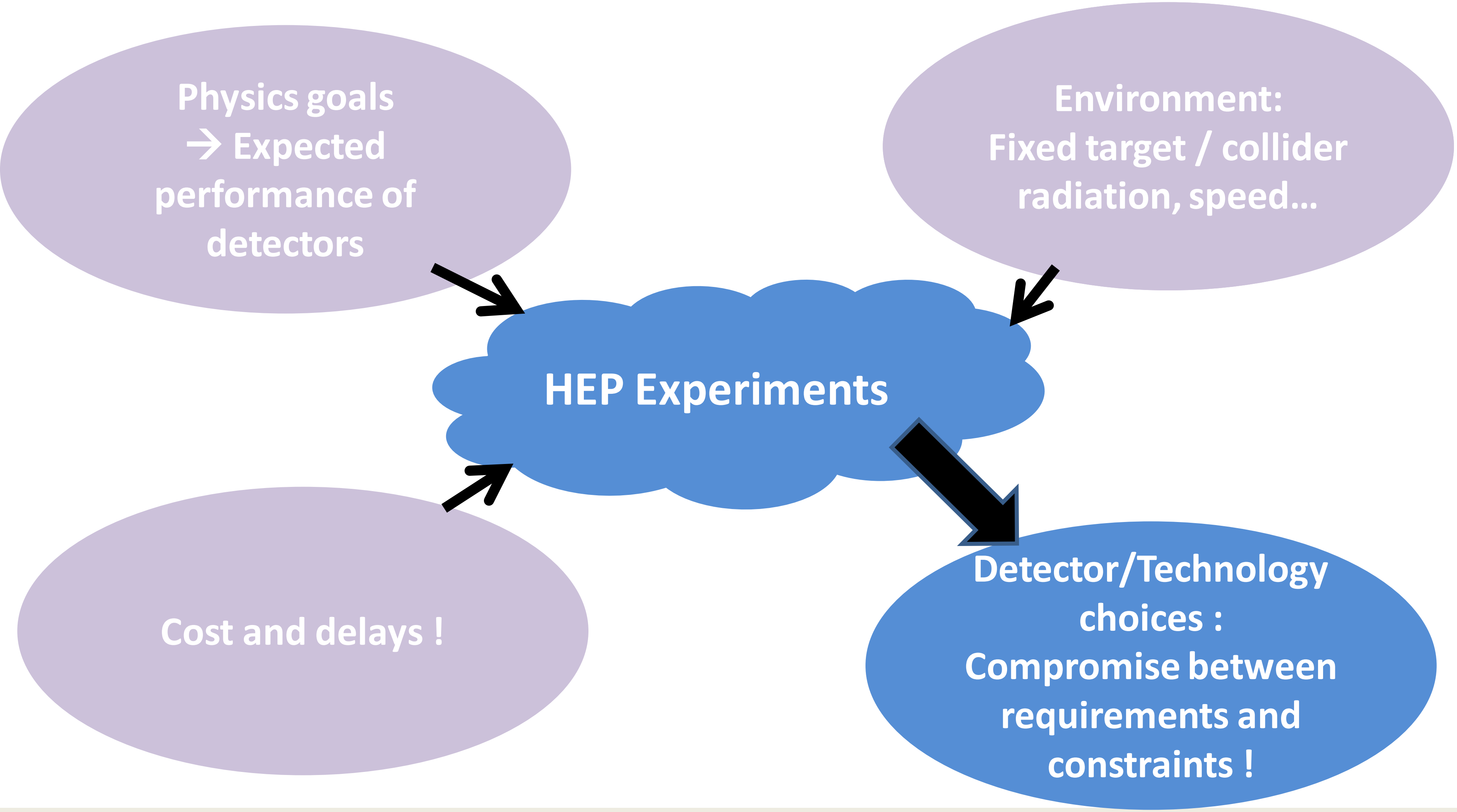
References

References books :

- Particle detectors C. Grupen+B. Shwartz Cambridge University
- Radiation detection and measurement, G. Knoll ,John Wileys & sons
- Techniques for nuclear and particles physics experiments, W. Leo, Springer
- Experimental techniques in high energy physics, T. Ferbel, World Scientific
- Semiconductor Radiation Detector G. Lutz, Springer
- ….
- Particle Data Book

+ excellent talks at CERN summer school / academic training

Constraint on HEP detectors/experiments



Physics goals
→ Expected performance of detectors

Environment:
Fixed target / collider
radiation, speed…

HEP Experiments

Cost and delays !

Detector/Technology choices :
Compromise between requirements and constraints !

Detector requirements (I)

Ideal detector should allow to measure and identify all end products of a collision :

- Charged leptons

  electron : **charged** particle **+ electromagnetic** interaction with matter

  muon : **charged** particle + **small** interaction in matter (lifetime ~10^{-6}s)

  Tau : charged particle but lifetime ~2.10^{-17} s, **reconstruct** from decay products

- Photons

  Neutral particle + (**electromagnetic**) interaction in matter

- Hadrons (quarks/gluons not directly detected → jets)

  Charged hadrons with (**electromagnetic and nuclear**) interaction in matter

  Neutral hadrons with (**nuclear**) interaction in matter

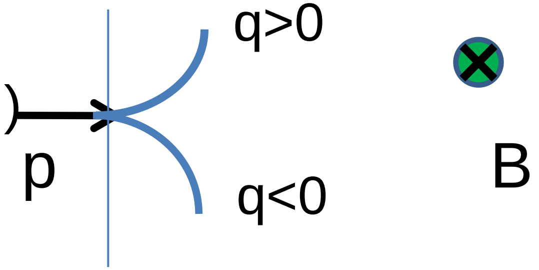
  (Special case of B hadrons with lifetime ~10^{-12}s)

Neutrinos : no interaction in matter but deduced from **energy/momentum conservation** (missing energy)

Detector requirements (II)

Charged particle : Deviation in a magnetic field, non destructive measurement of charge and momentum

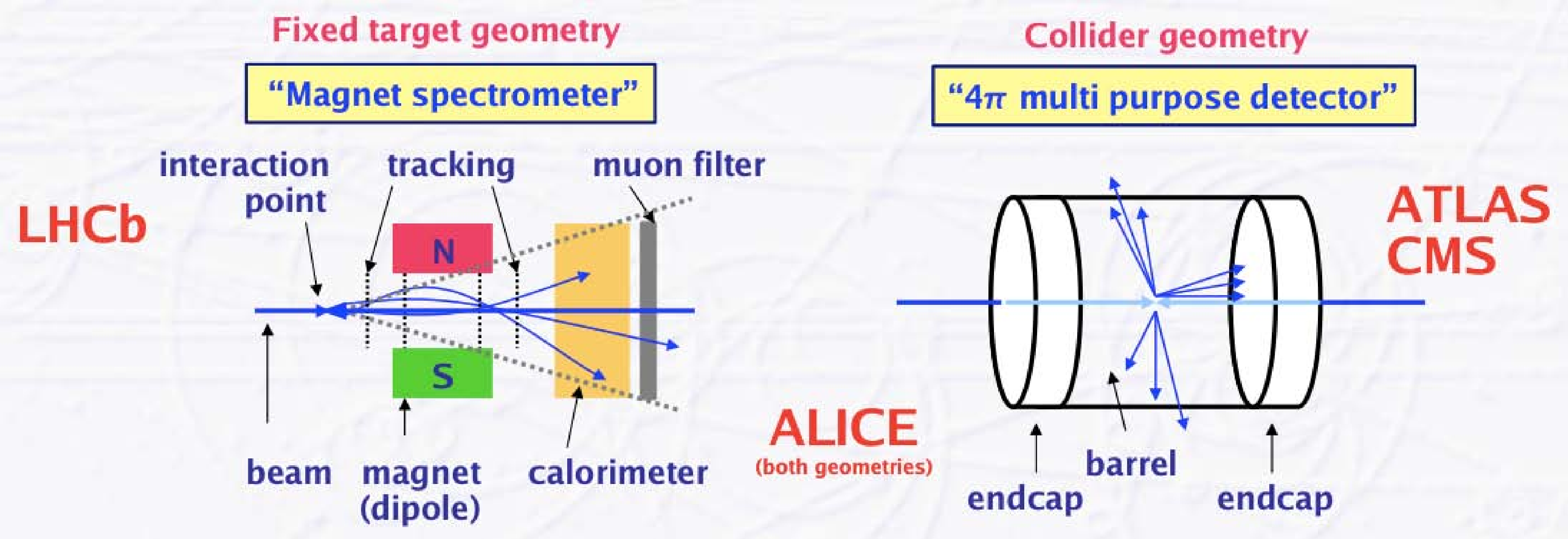
Lorentz force : $p(\mathrm{GeV})=0.3\,B(\mathrm{T})\,R(\mathrm{m})$



Energy measurement : Calorimeter techniques by stopping particle in dense materials where a signal proportional to energy is measured. Material is different for electromagnetic ($e^{\pm}$,γ) and hadronic interaction

Particle identification: Use behaviors dependent on $\gamma=E/m$ (dE/dx, transition radiation effect) or speed $\beta=v/c$ (cerenkov light, time of flight measurement)

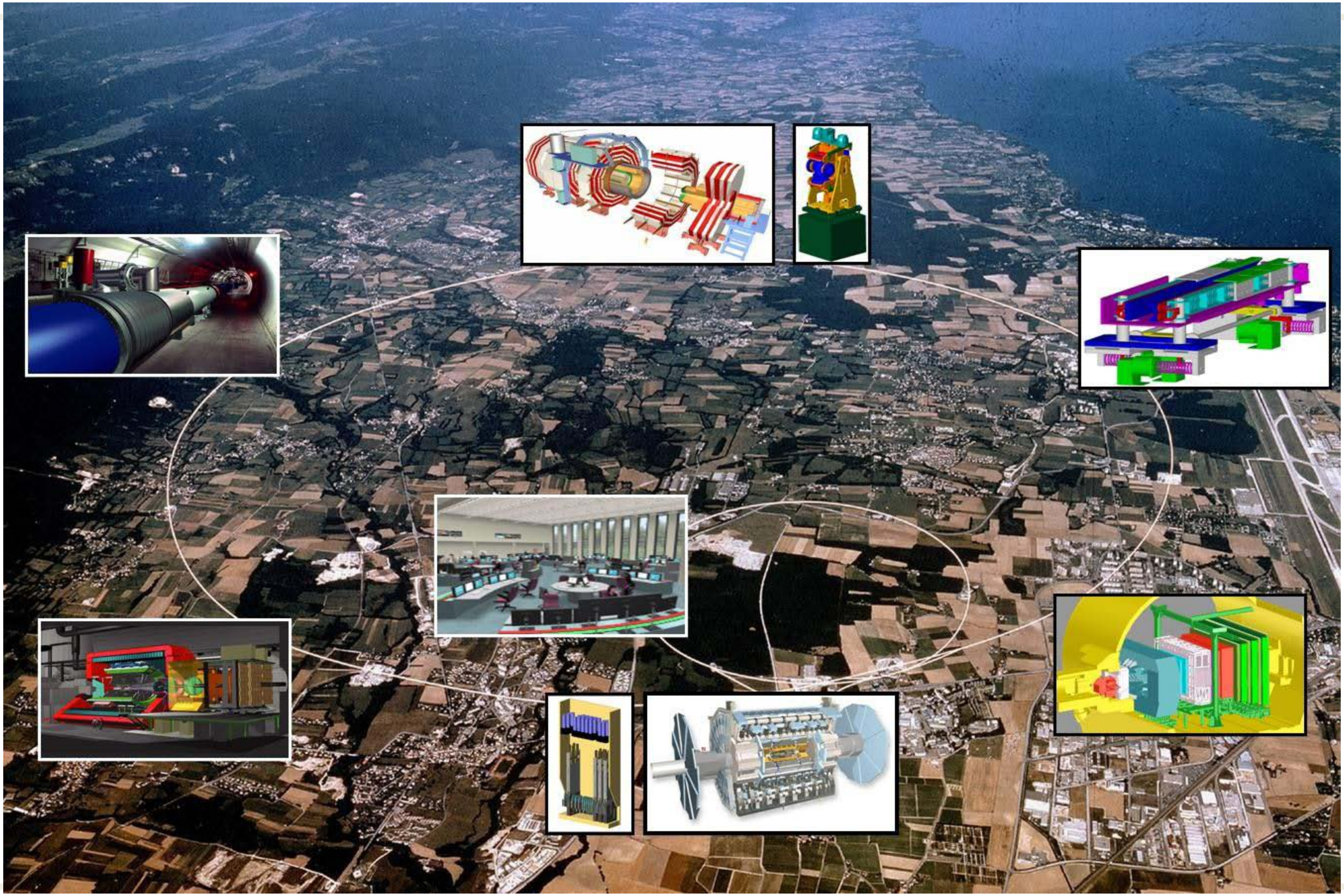
Detector geometry



Look at collision products in a small open angle along beam axis
Plane detectors perpendicular to beam

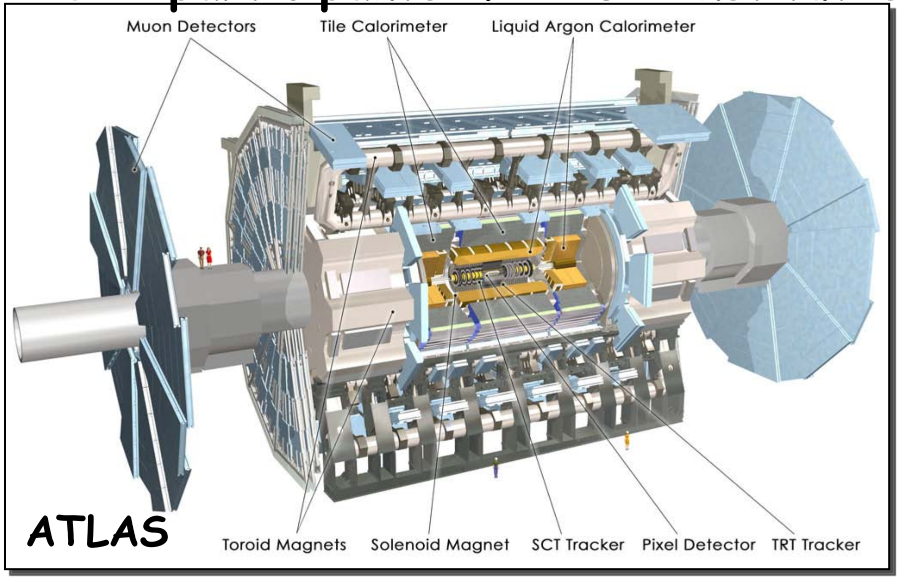
Particles to be detected over whole solid angle (4π)
Detectors arranged around beam axis with "onion structure"

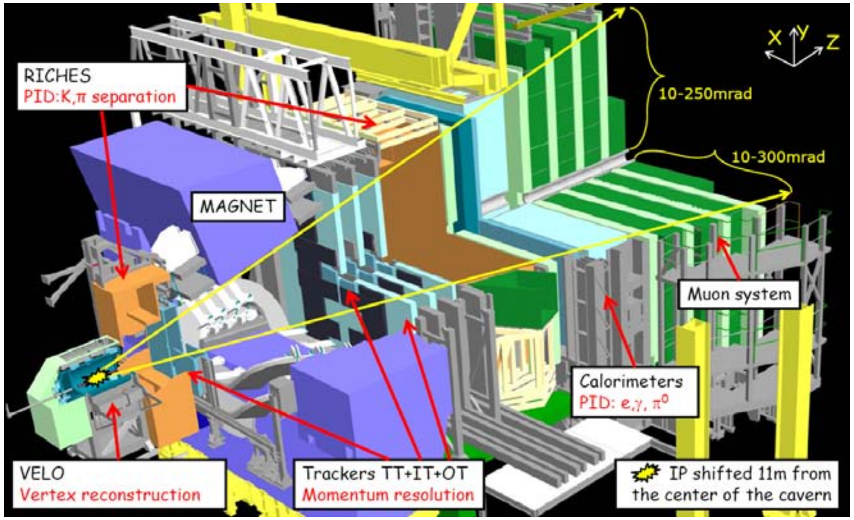
LHC experiments

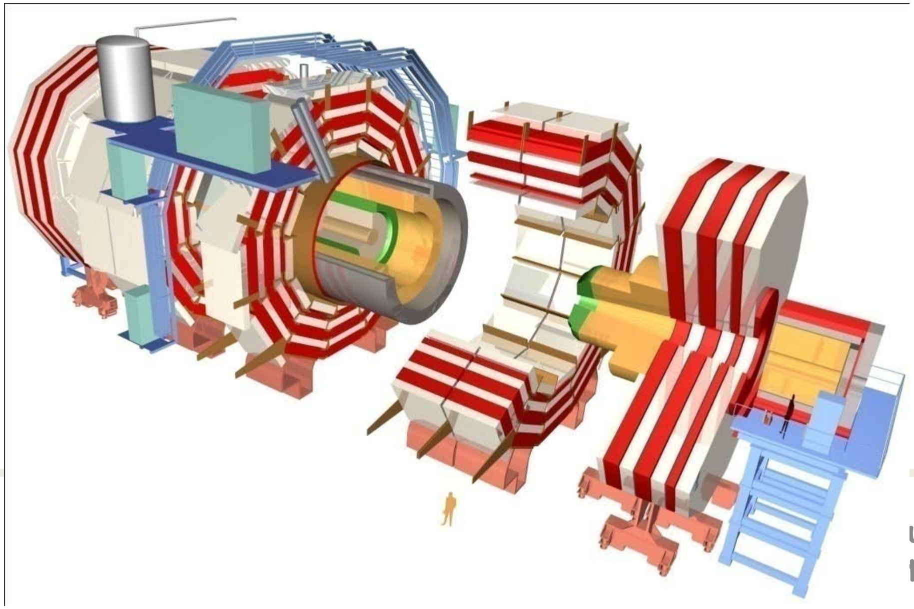


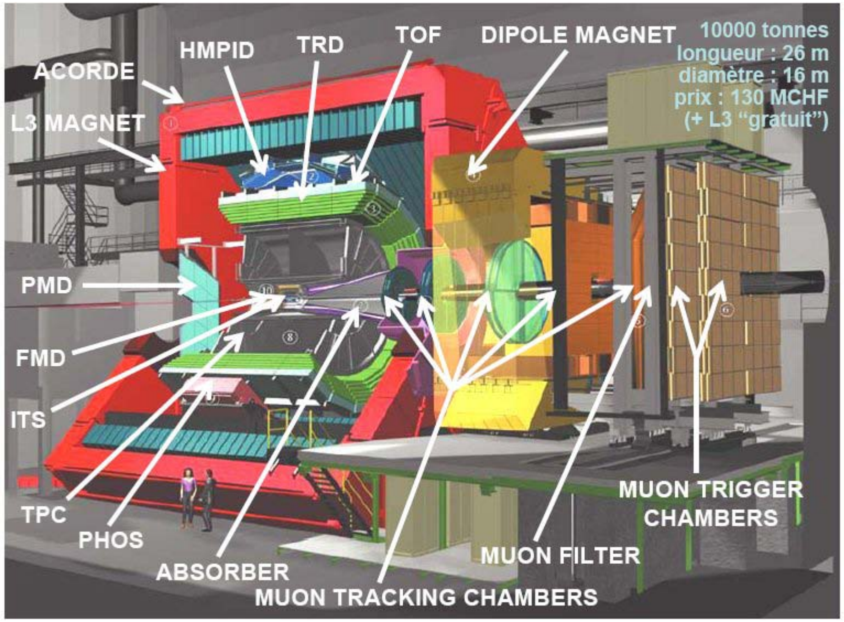
LHC detectors

2800 participants & > 150 Institutes









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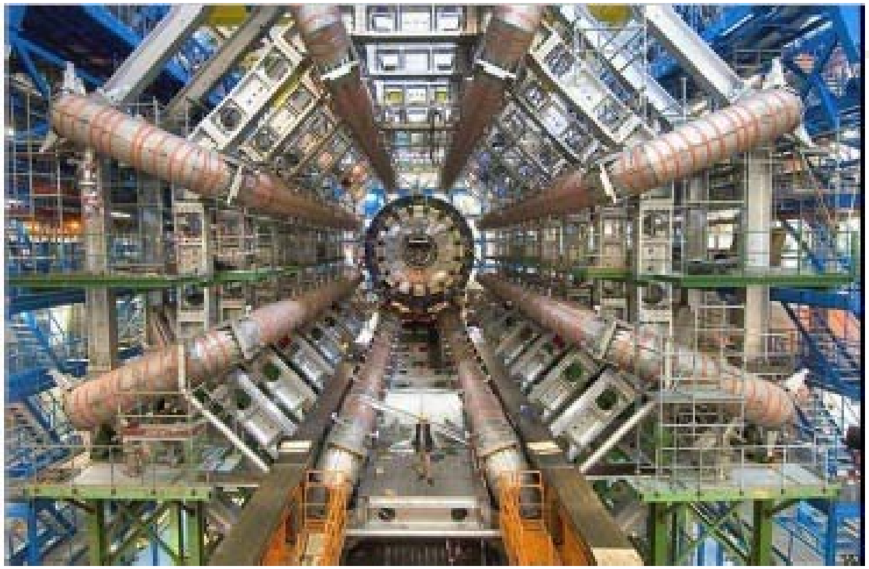
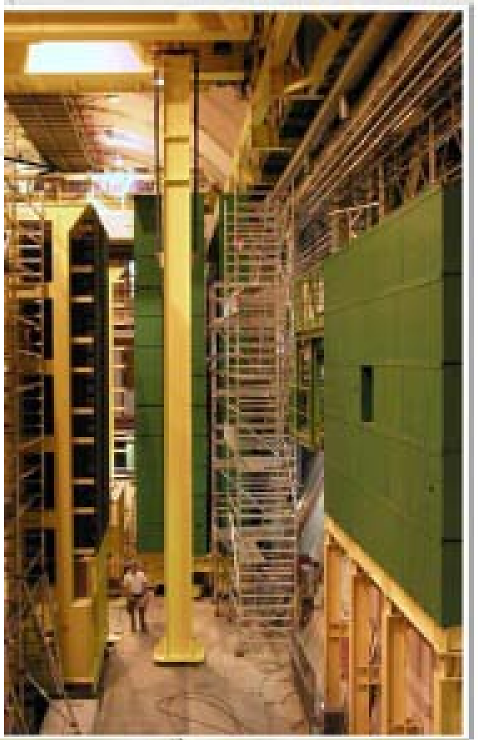
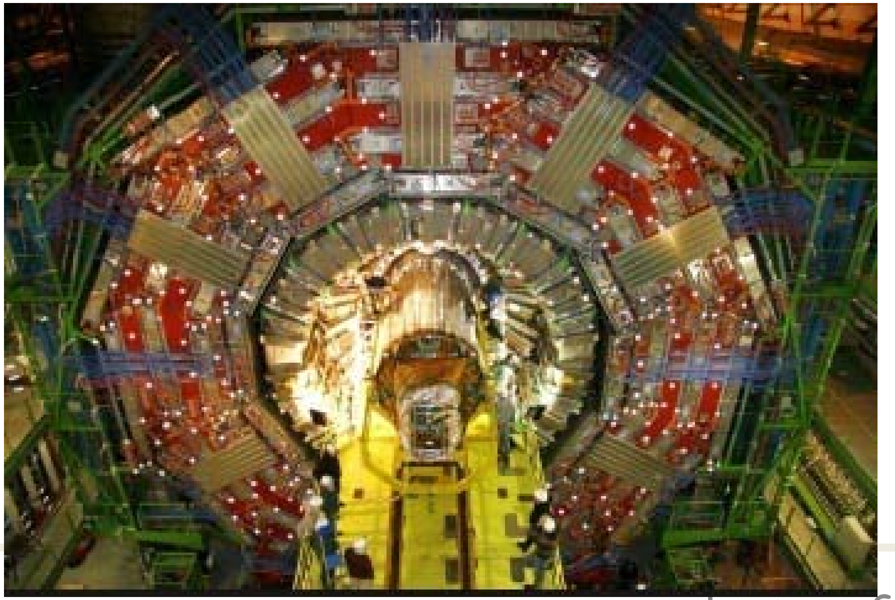
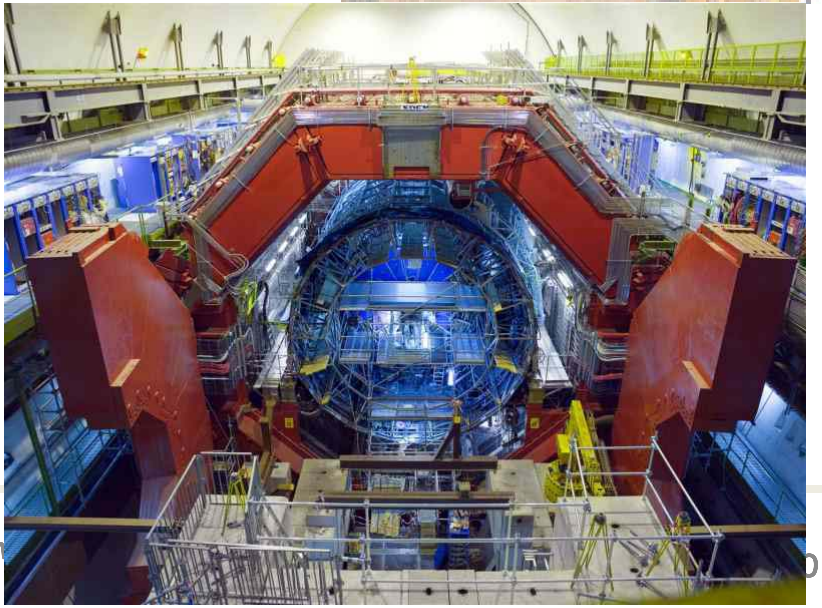
LHC detectors

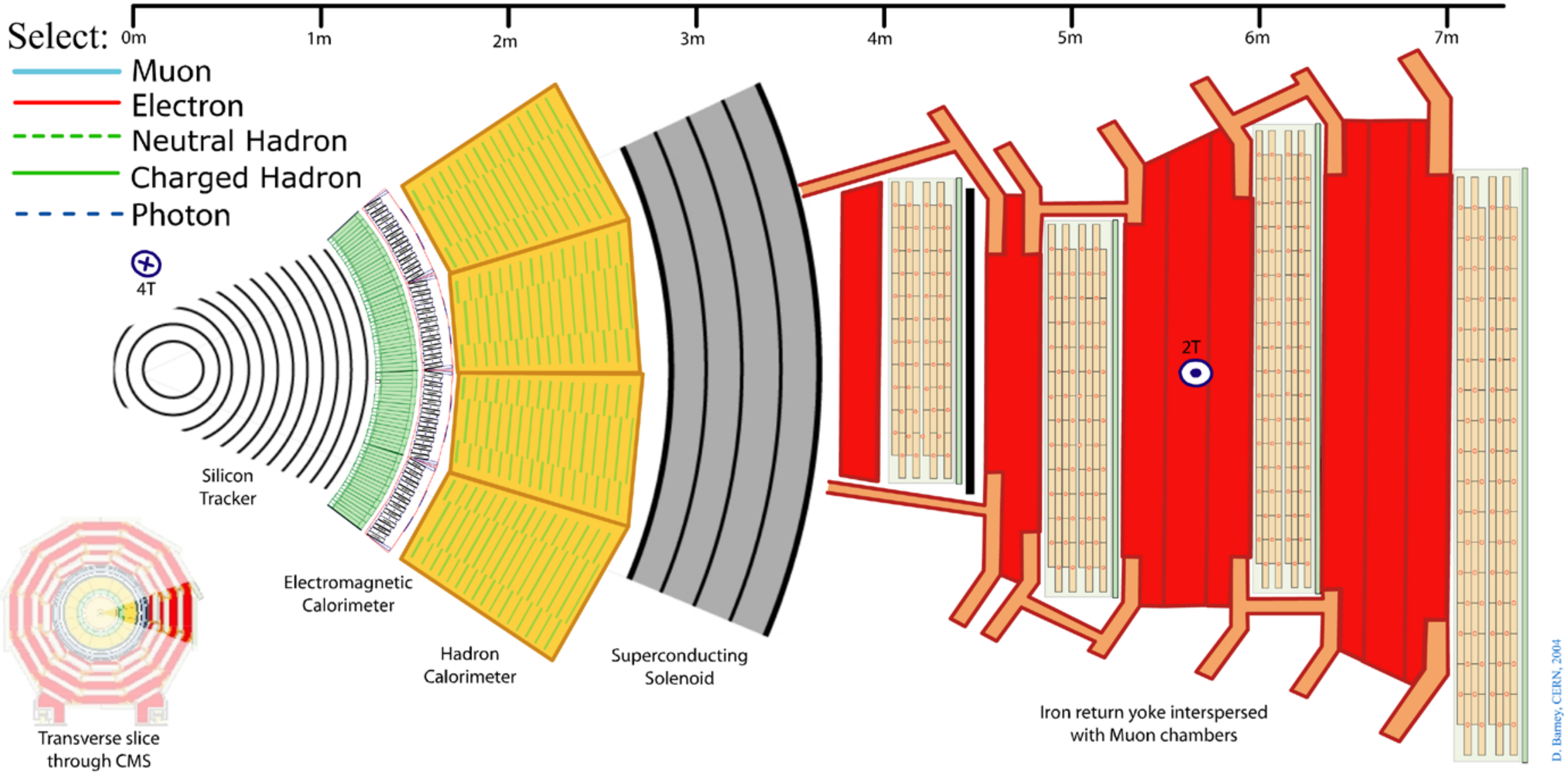








CMS detector (LHC experiment)



CMS detector (LHC experiment)

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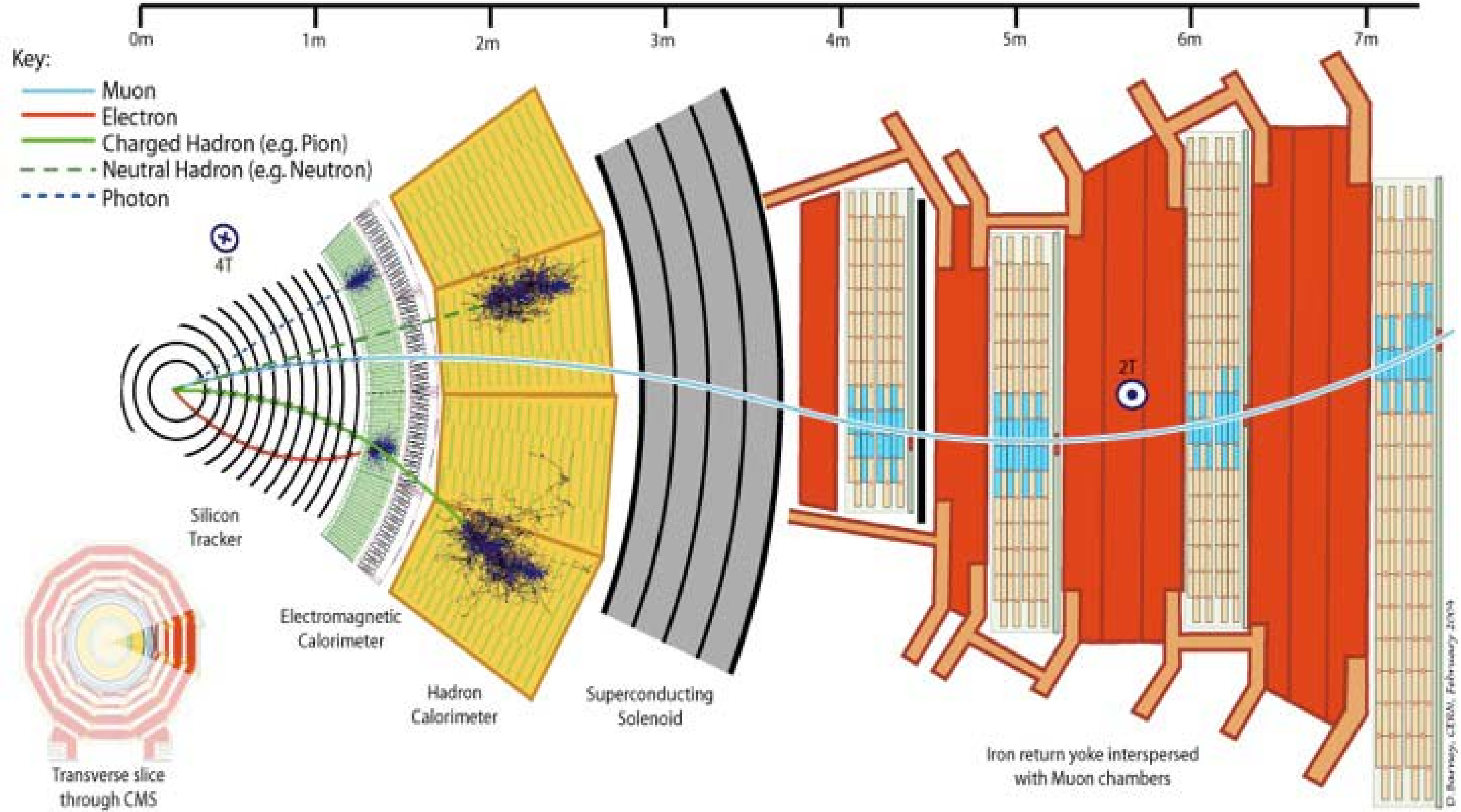

Detector environment :e^+ e^- collision

e^+e^- collision : small interaction rate (electromagnetic and weak interaction process)
electron are point-like particles :
- Center of mass energy / momentum well defined
- Clean final state

Example of LEP Experiments (e+e- collisions at CERN in LHC tunnel) :

- At 91 GeV (Z mass) (1989-1995)

LEP I

- Up to 209 GeV for Higgs search and new particles + W mass measurement (1996-2000)

LEP II

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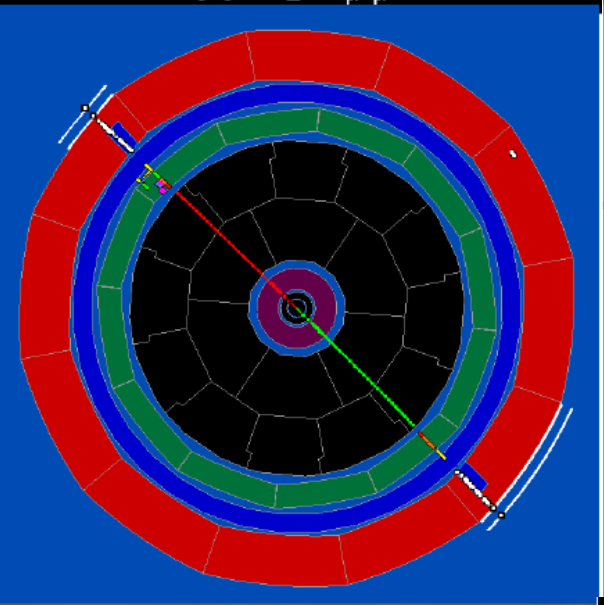
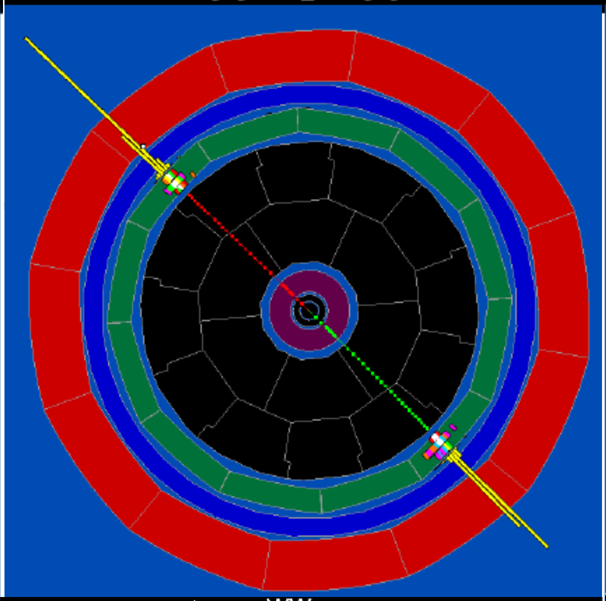
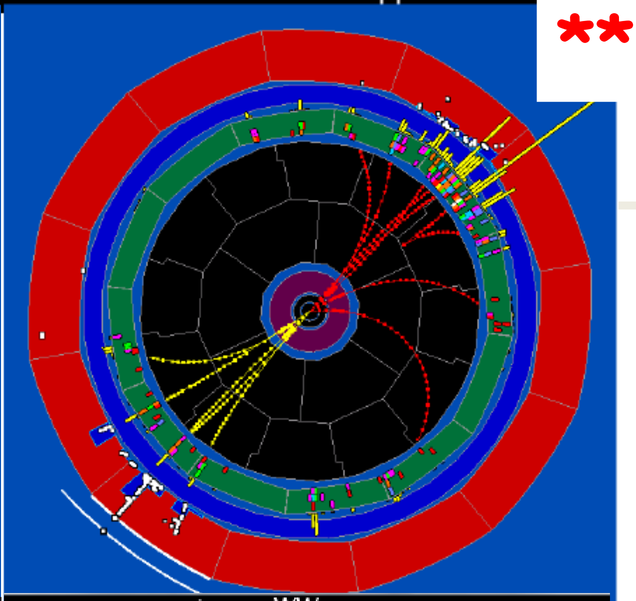
$e^+e^- \rightarrow Z \rightarrow \mu^+\mu^-$



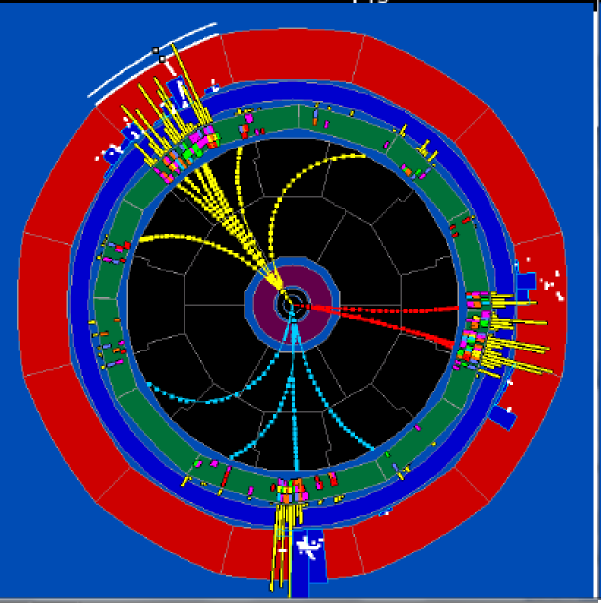
$e^+e^- \rightarrow Z \rightarrow e^+e^-$



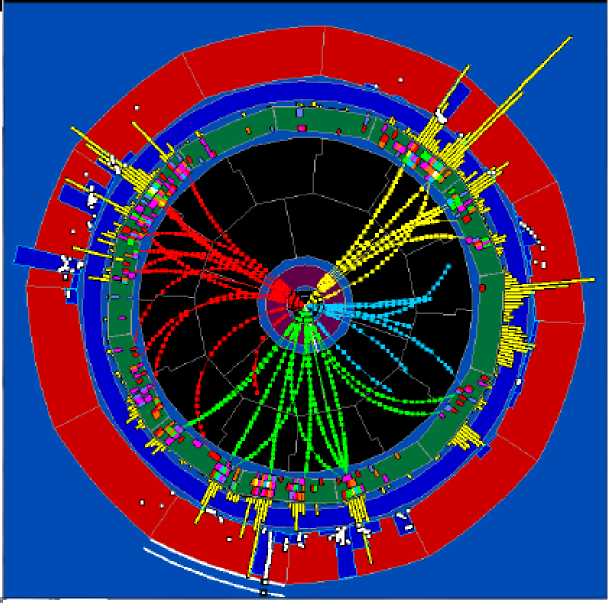
$e^+e^- \rightarrow Z \rightarrow qq$



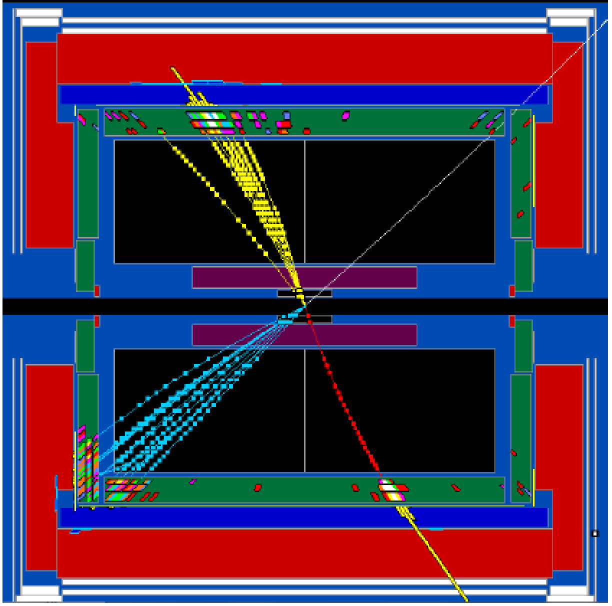
$e^+e^- \rightarrow Z \rightarrow qqg$



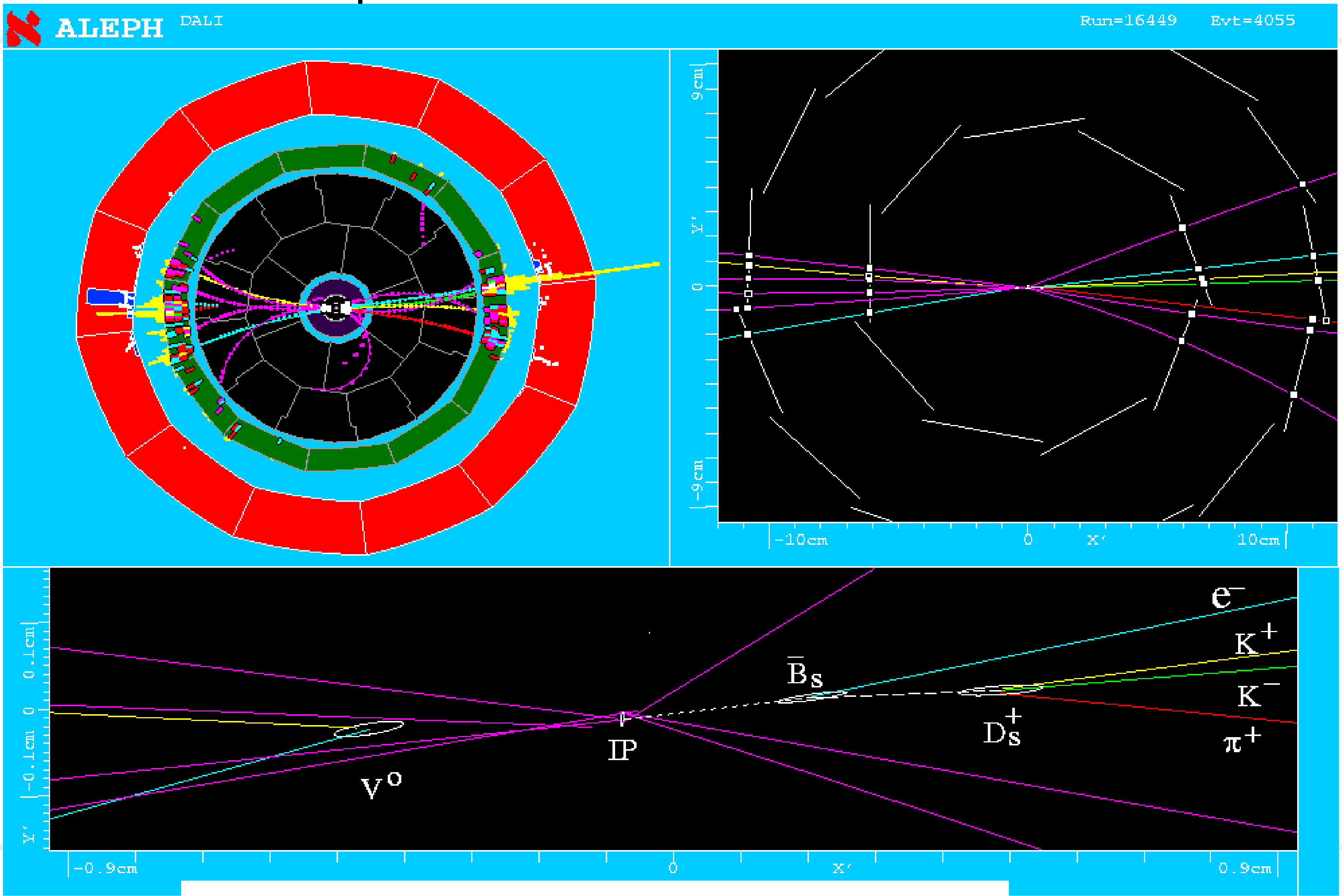
$e^+e^- \rightarrow WW \rightarrow qq\ qq$



$e^+e^- \rightarrow WW \rightarrow e\nu\ qq$



vertex position measurement → B hadrons

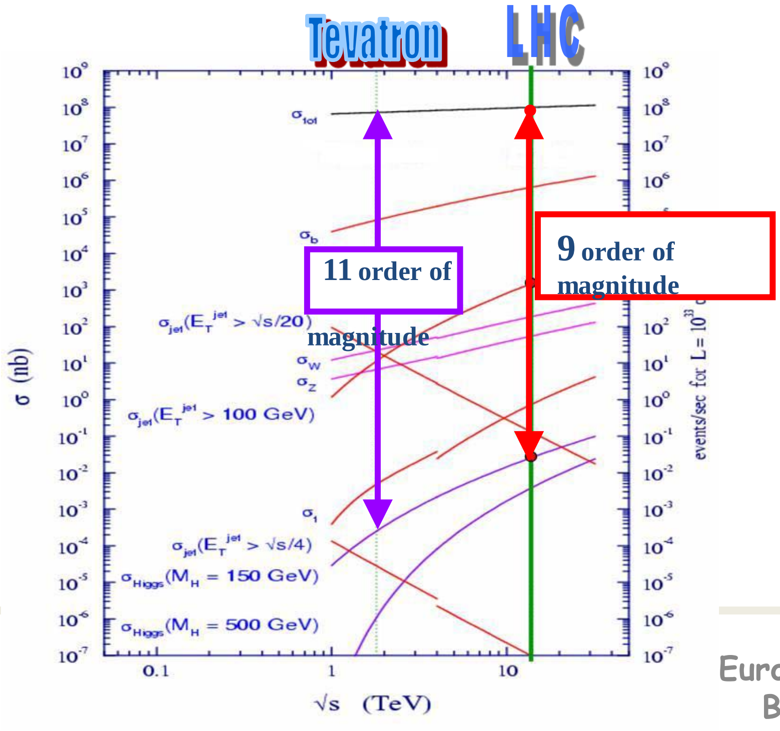


Need detectors near interaction point

Detector environment :pp collision LHC

pp collision : large cross section (strong interaction) and high luminosity :

- 8 interactions in average per bunch crossing now at LHC
- Bunch crossing ultimately every 25 ns (now 50ns) :
  - → high radiation environment (dedicated materials)
  - → detector speed (fast electronics) and fine detector segmentation to reduce pile-up collision
  - → need to have efficient trigger to reduce data flow



$\sqrt{s} = \sqrt{(x_1x_2)}\,(2E_{beam})$: different from one event to another depending on fraction taken by quark and gluon

Initial energy/momentum not known but constraint in transverse plane : quark/gluon have no p_T

Radiation levels at LHC in ATLAS

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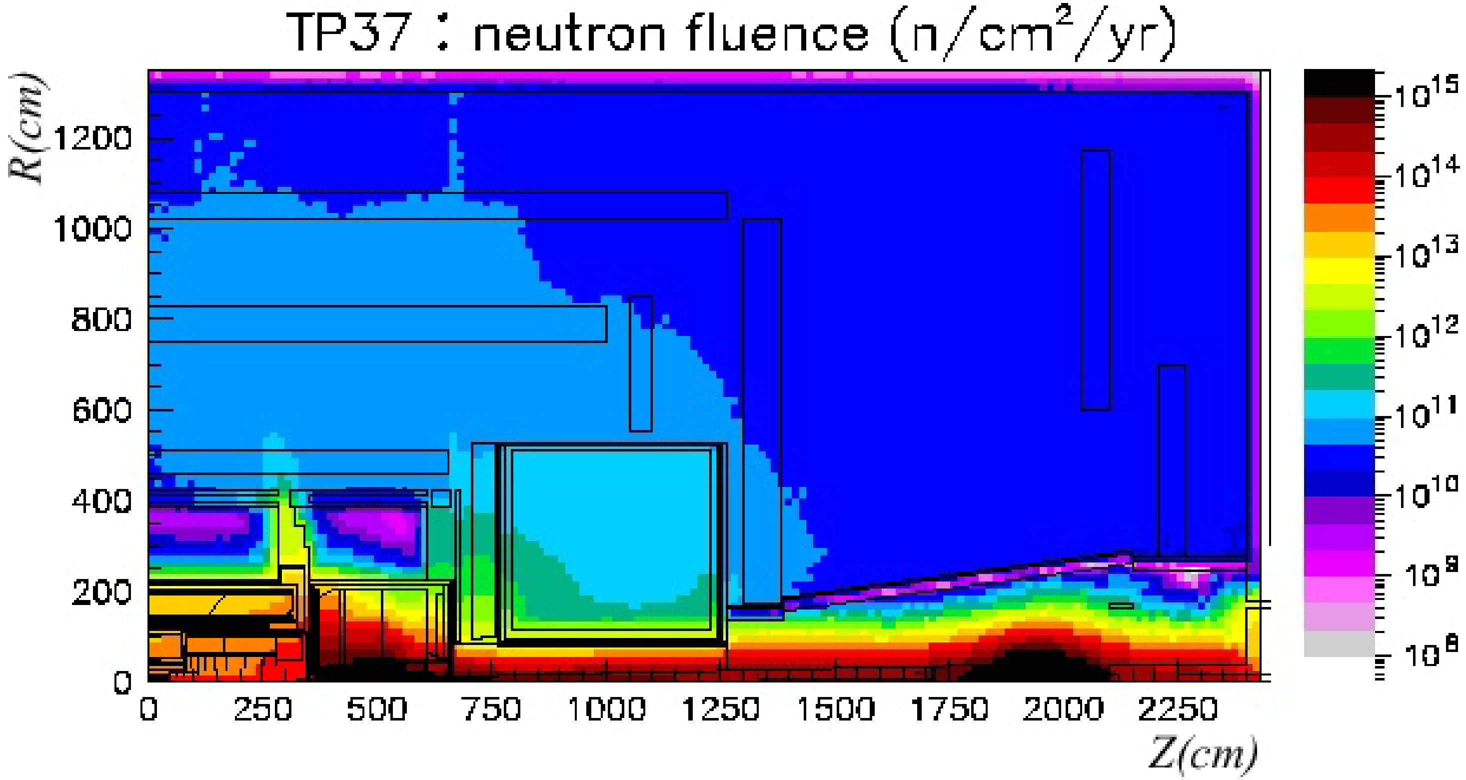
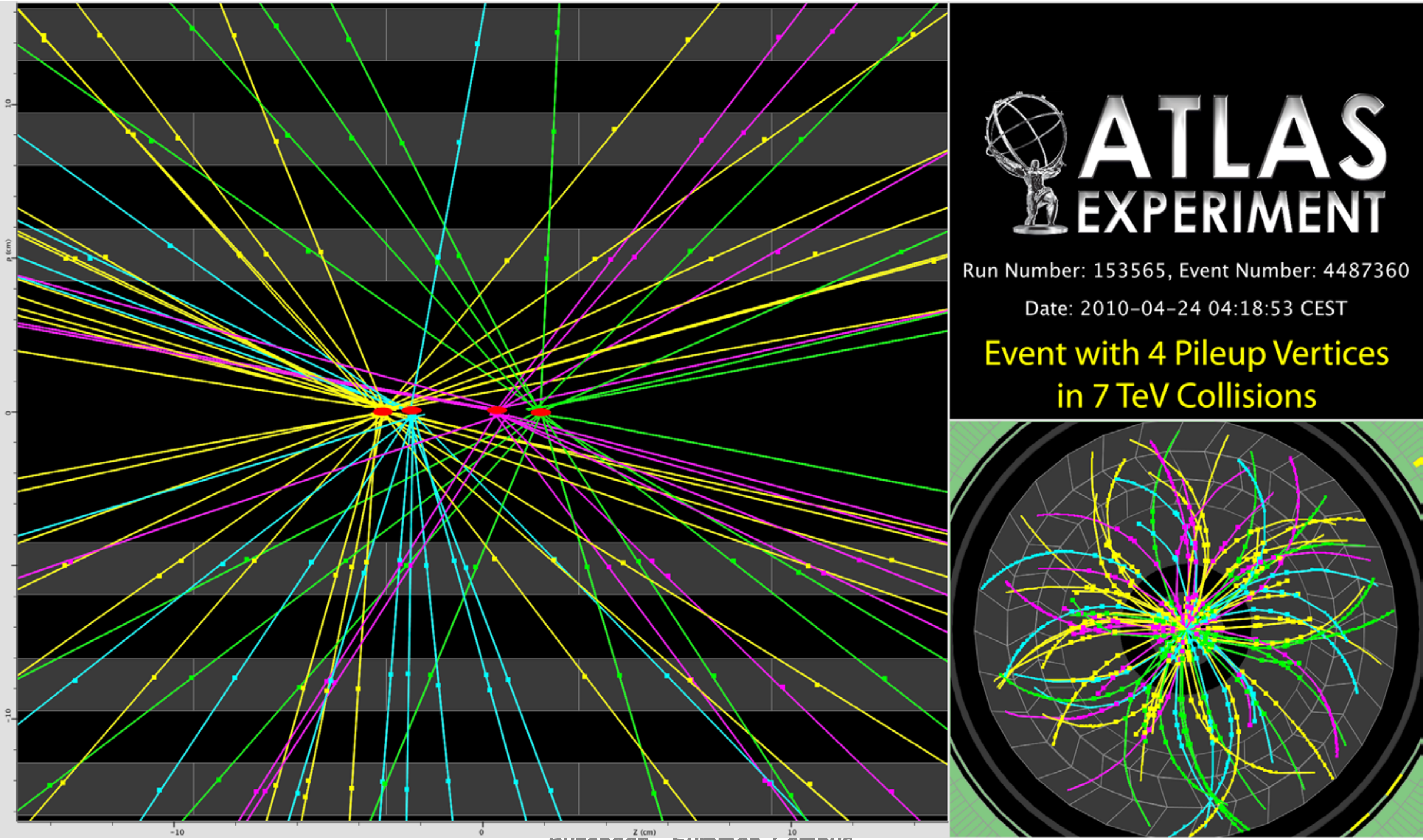


At r=11 cm, photons flux of 30 MRad !
100 Rad ~ 6.2410^{12} MeV/kg deposited energy (1J/kg)

Strong constraint on detector technology and electronics : ageing in gaseous detectors , pollution in liquids detectors, light loss (transparency) in scintillators/cerenkov, atom displacement in solid detectors

Primary vertex in LHC collisions

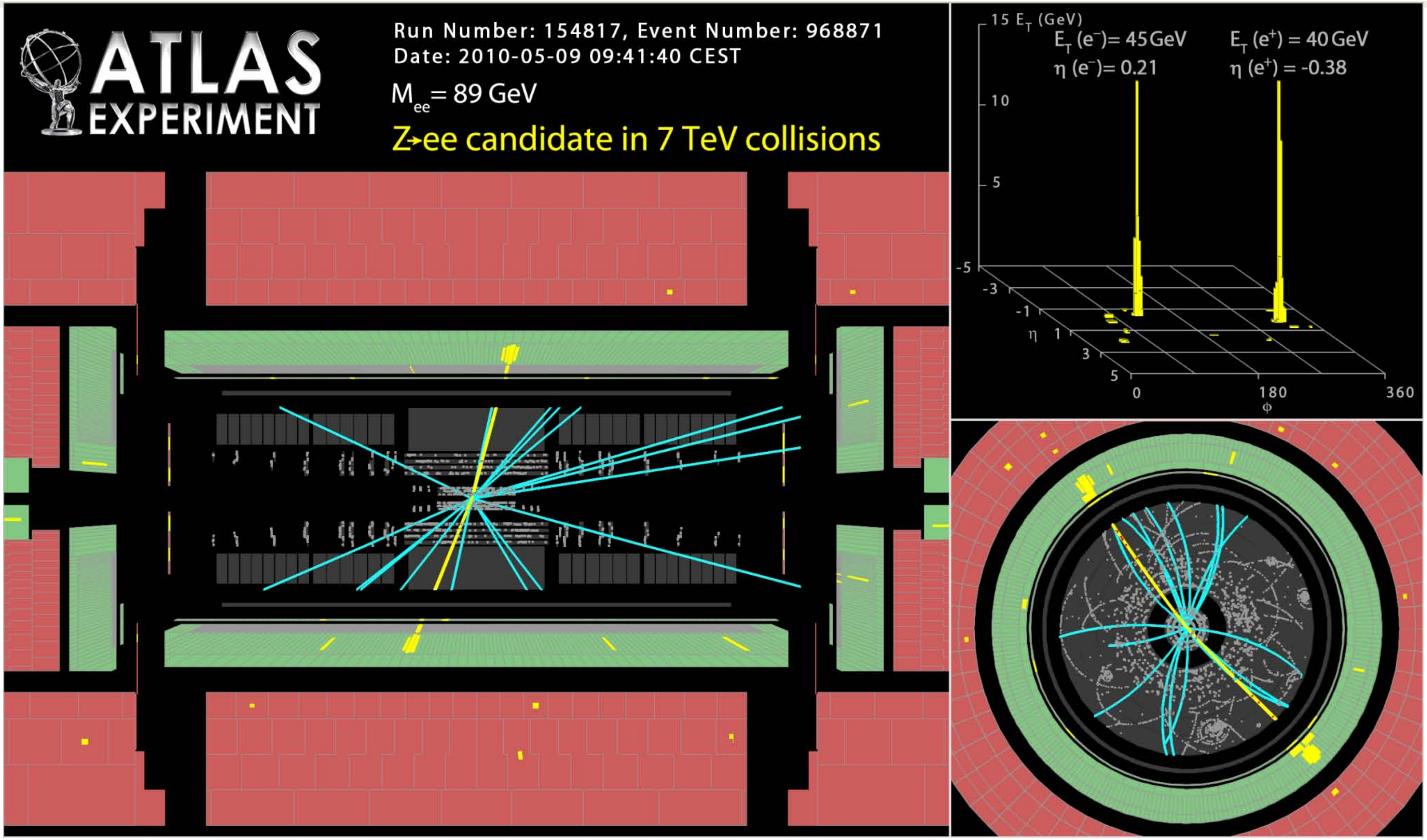


Run Number: 153565, Event Number: 4487360

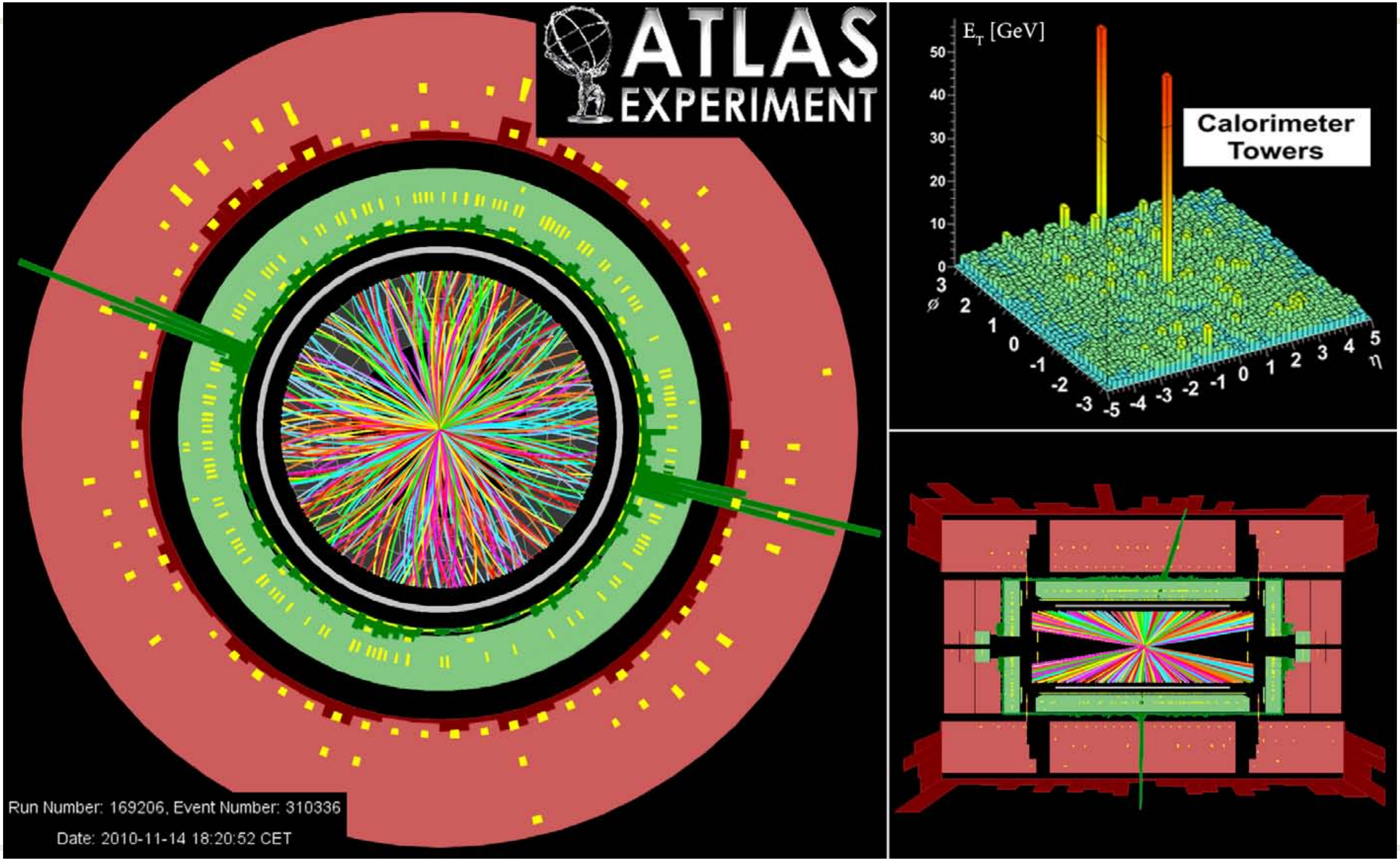
Date: 2010-04-24 04:18:53 CEST

Event with 4 Pileup Vertices in 7 TeV Collisions

Z→ e+e- in pp collisions with ATLAS



Z→ e+e- in PbPb collisions with ATLAS



Run Number: 169206, Event Number: 310336

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Another nice candidate

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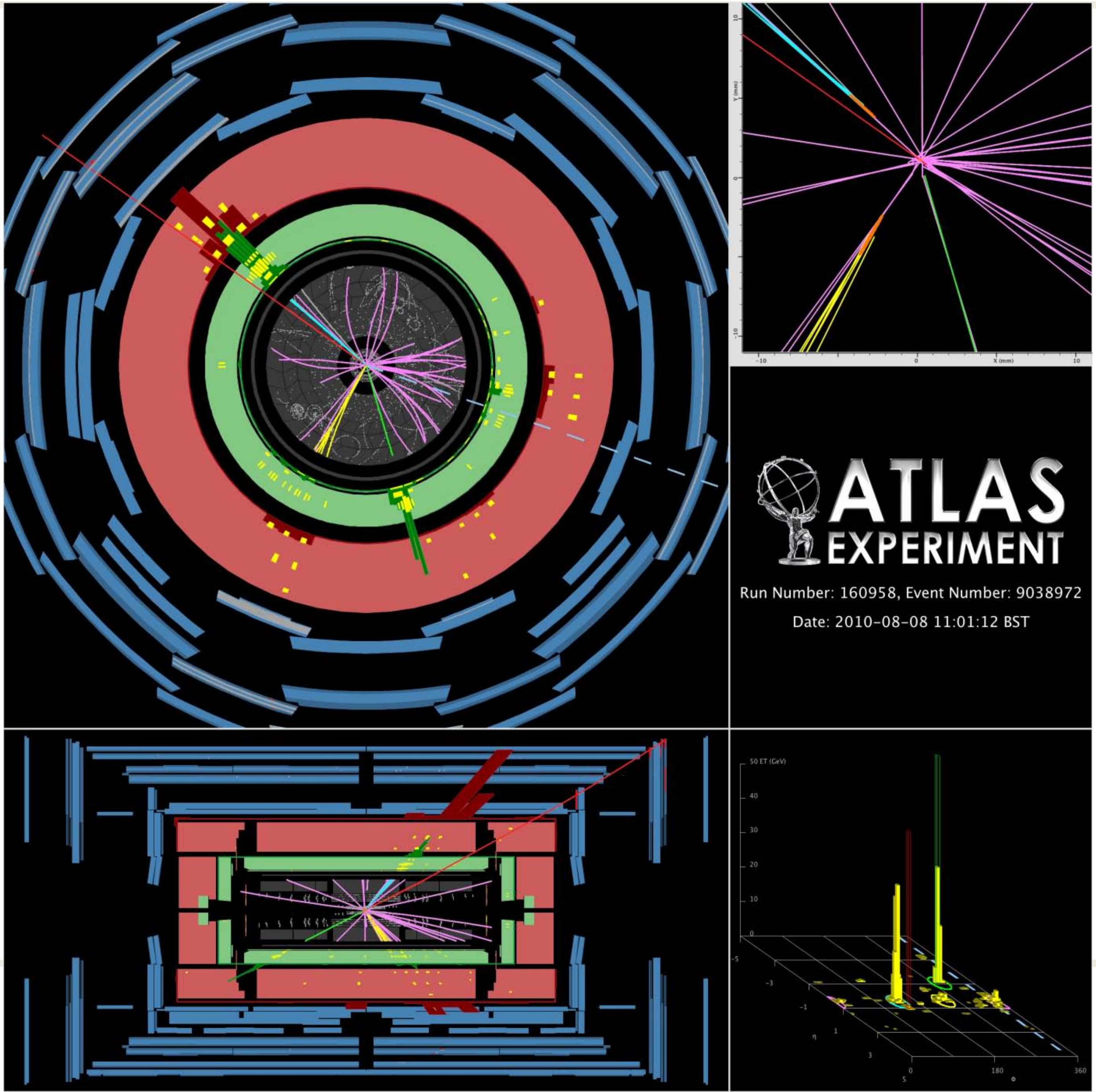
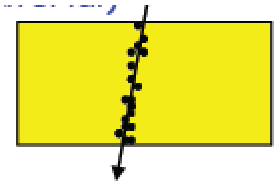
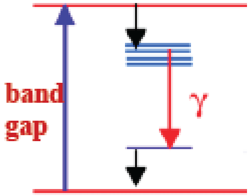


From basic ideas to complex detectors

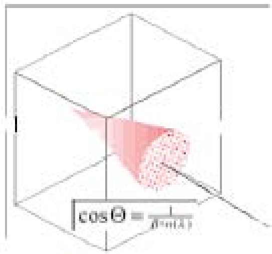
Large majority of the physics detection processes are well known and studied since long time and based mainly on electromagnetic interaction : ionization, excitation, photo-electric effect, pair creation / bremsstrahlung, cerenkov effect, transition radiation….



Ionisation



scintillation



Cerenkov

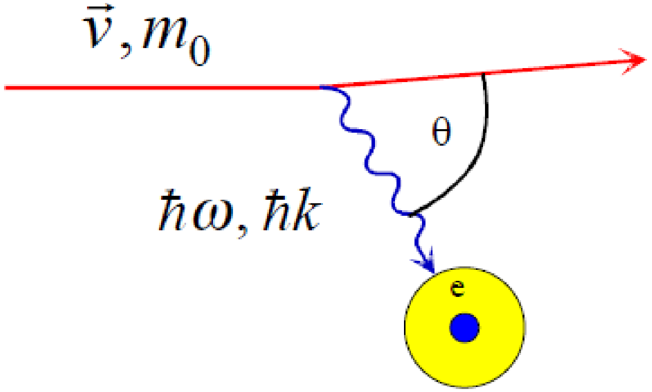
All the cleverness lies in the best way to use these processes to build a detector and to measure a signal :

- Electric signal : charge collection (drift in an electrical field)
- Optic signal : Light collection

(- Thermal : temperature , bolometer, not discussed in these lessons)

Most of the progress in detection has been allowed by the impressive progress in electronics/computing (speed, low noise, complex logic online…)

Charged particle interaction in matter (I)



Incident particle is slowing down, loosing kinetic energy through collisions mainly with atomic electrons (Coulomb interaction)

-The energy exchanged is large enough to eject an electron, ionization and electron charge collection : $X \rightarrow X^+ + e^-$

-The atom or molecule is excited to a higher energy level and produced some light through de-excitation (light collection) : $X^* \rightarrow X + \gamma$

- Under some conditions real photon can be produced : Emission of Cerenkov (if $v > c/n$) or transition (discontinuous refractive index) radiation These two processes contribute very little to the energy loss (< 5%) and will be neglected to describe charged particle energy loss

Energy loss for charged heavy particles : $m>>m_e$ (II)

Average energy loss per unit length dE/dx of a particle of charge z in a material of atomic number A/Z, in low energy approximation (Bethe Bloch formulae)

$$-\frac{1}{\rho}\frac{dE}{dx} = 4\pi N_A r_e^2 m_e c^2 \boxed{z^2}\,\boxed{\frac{Z}{A}}\,\frac{1}{\beta^2}\left(\ln\frac{2m_e c^2\gamma^2\beta^2}{I} - \beta^2 - \frac{\delta}{2} - 2\frac{C}{Z}\right)$$

N_A : Avogadro number
r_e : classical electron radius
ρ : density
I : atom ionization constant

$\beta = v/c$
$\gamma = E/m$

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

Formulae need to be modified for electron/positron (incident electron can be deflected. Moreover at high energy other interaction process for electron in matter)

Energy loss for charged heavy particles : m>>m_e (III)

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

- Independent of incoming particle mass

- proportional to Z/A of the absorber material, to density (ρ) and z^2

- in low energy domain, decreases as $1/\beta^2$ ($\beta^{-5/3}$) "slower particle loose more energy "

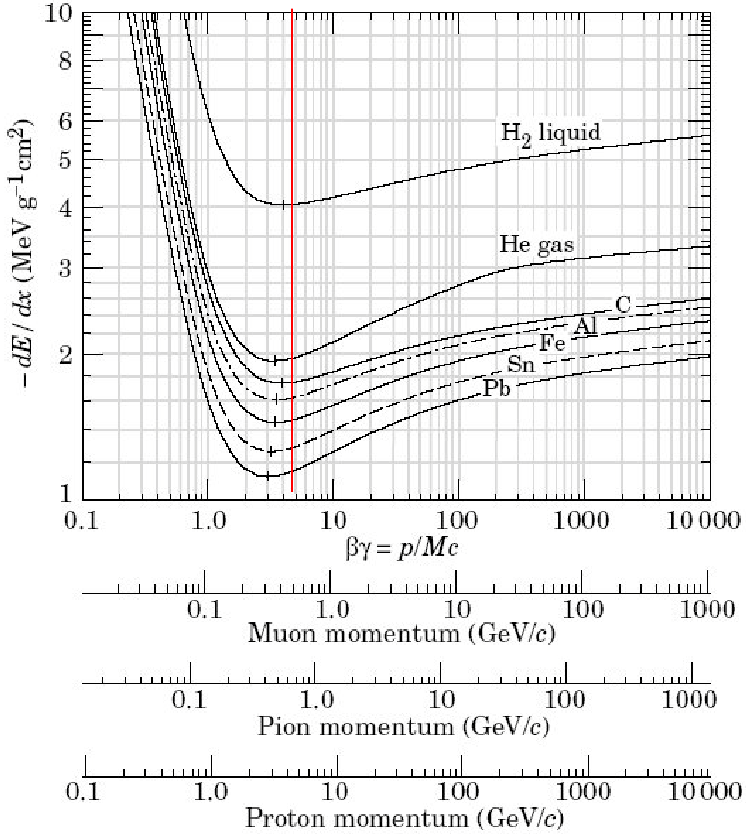
- reach a minimum around $\gamma\beta = 3\text{-}4$, called Minimum Ionizing Particles or mips quite similar for all elements ~2 MeV/(g/cm^2)

- Above minimum, relativistic rise as 2ln(γ)

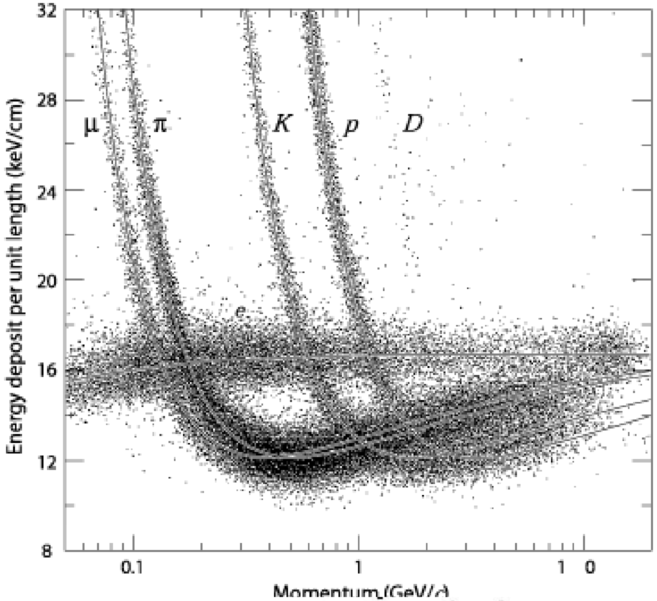
- δ term important at high energy : comes from polarization of the atoms along incoming particle →screening effect of the field, decreases loss at high energy

- C term important at low energy to take into account effects which appear when β of the particle ~ β of bound electrons.

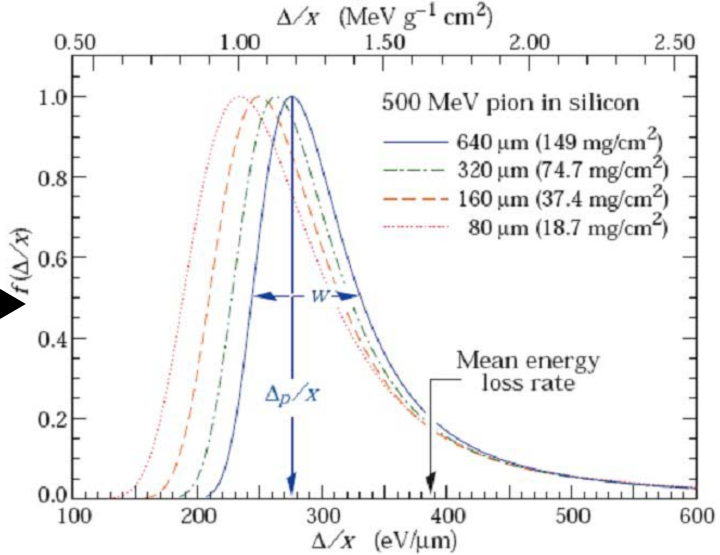
Charged particle interaction in matter (IV)



dE/dx + p : particle identification



Large fluctuation on energy loss described by Landau distribution



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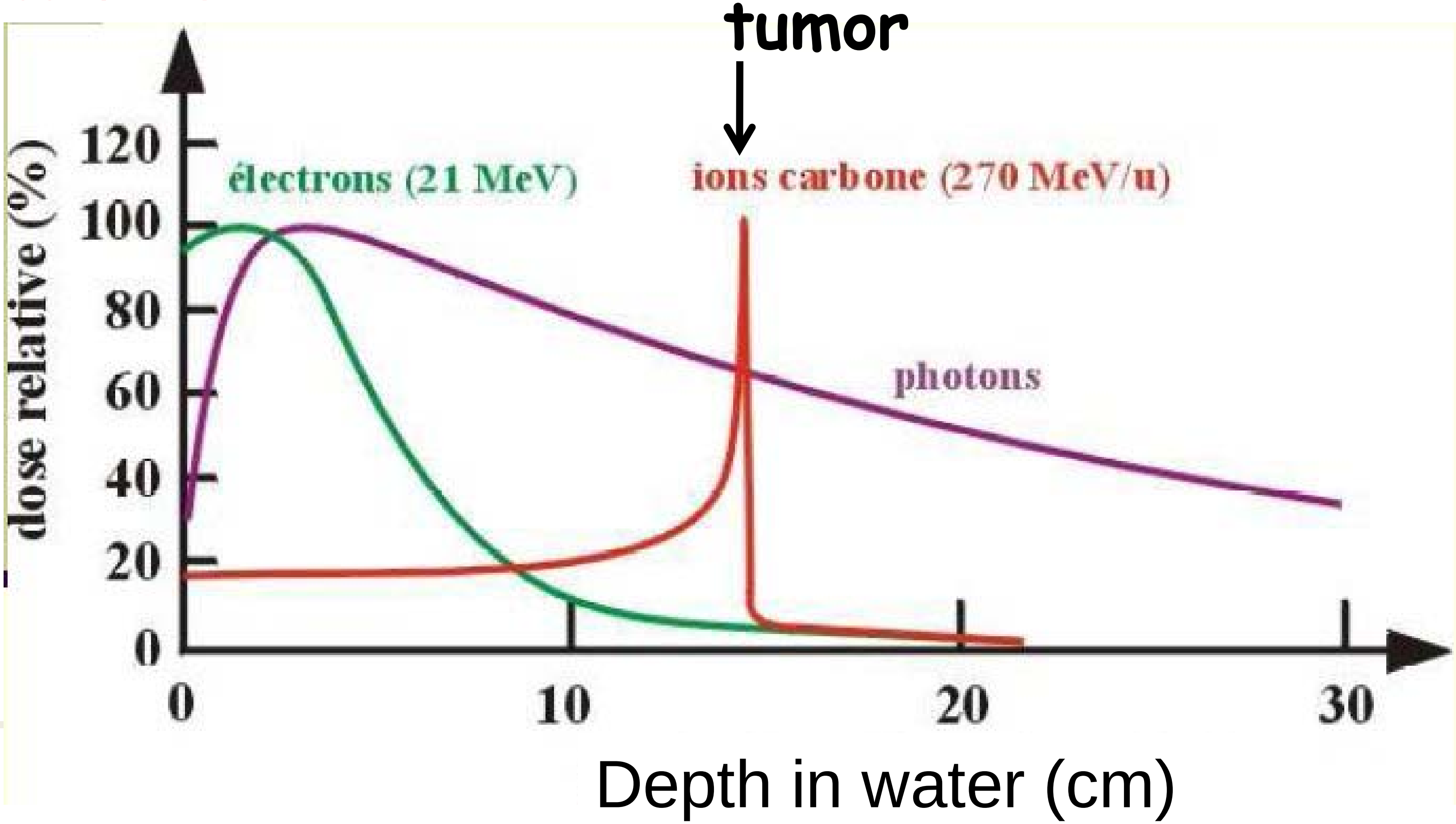
Interlude Hadrontherapy

Electron : most of the energy released in first cm

Photon : Large energy loss all over the path (X rays therapy)

C ions : heavy charged particle : most of the energy lost at the end of path (Braggs peak)



Comparison X rays vs proton beam

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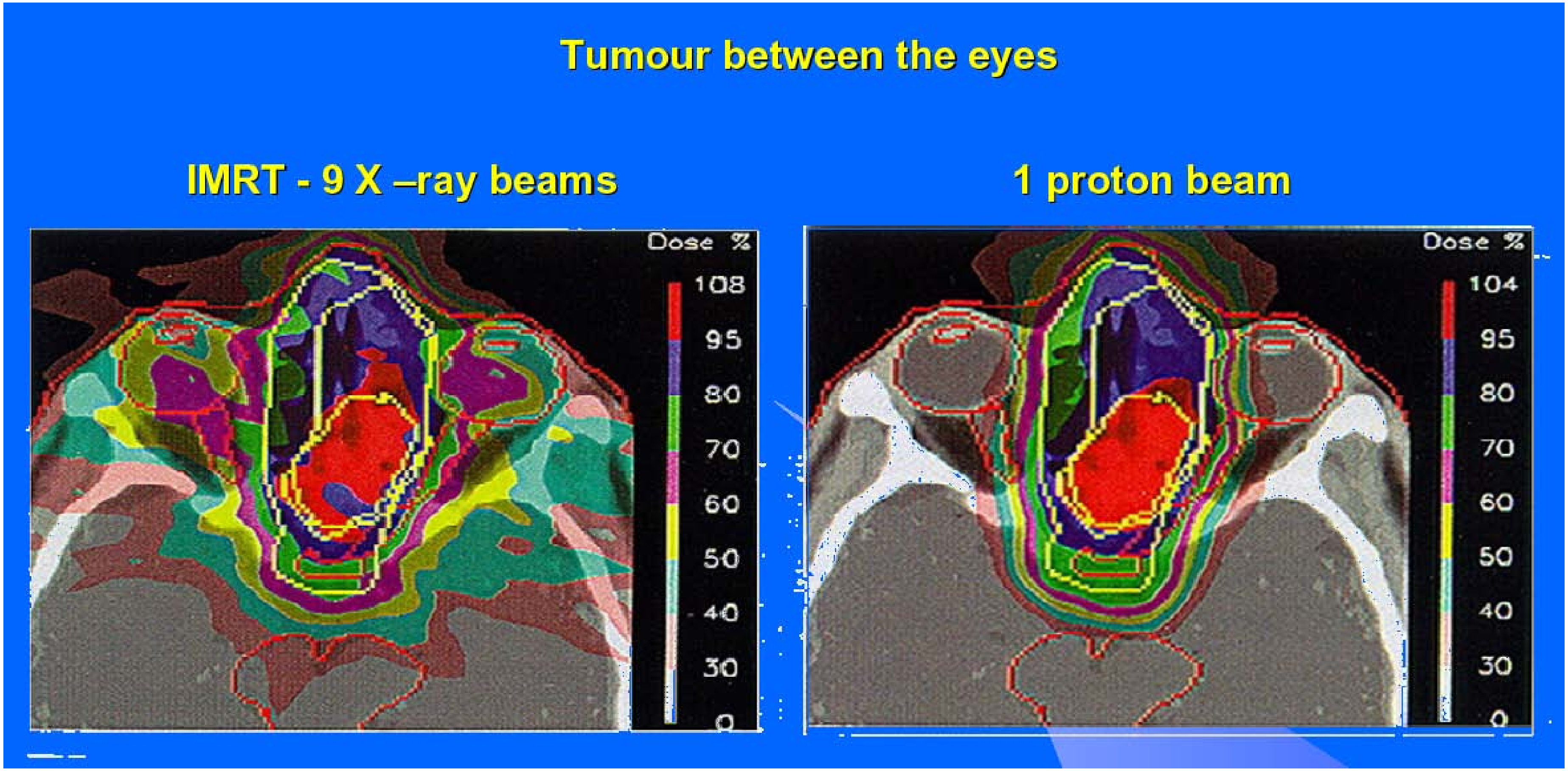

Tumour between the eyes

IMRT - 9 X –ray beams

1 proton beam

A few illustrative numbers…

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Energy loss of a 10 GeV muon in 1cm of plastic scintillator (ρ =1) or a gas chamber (ρ =0.001) ?

Muons can be considered as a mip with 2 MeV/(g/cm^2)
→2 MeV in 1 cm scintillator
→2 keV in 1 cm of gas
To stop a 450 GeV muon beam, will need 900 m of concrete (density 2.5) !
Easy to understand why they exit from detector…

How many meters of air to stop an α particle of 2 MeV ?

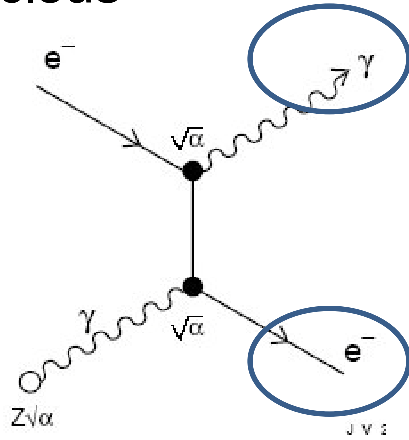
Particle with very low β (below the minimum ionization)
dE/dx around 700 MeV /(g/cm^2) and ρ =1g/l → 0.7 MeV/cm
Can stop a α in 2-3 cm of air

Interaction of electron/positron in matter

Energy loss for electrons/positrons involve mainly two different physics mechanisms:

-Excitation/ionization as for heavy charged particle but with revisited formulae

-Bremsstrahlung : emission of photon by scattering with the nucleus electrical field



$$-\frac{dE}{dx}(brem) = (4N_A\frac{\boxed{Z^2\alpha^3}(\hbar c)^2}{\boxed{m_e^2c^4}}\ln\frac{183}{Z^{1/3}})\boxed{E}$$

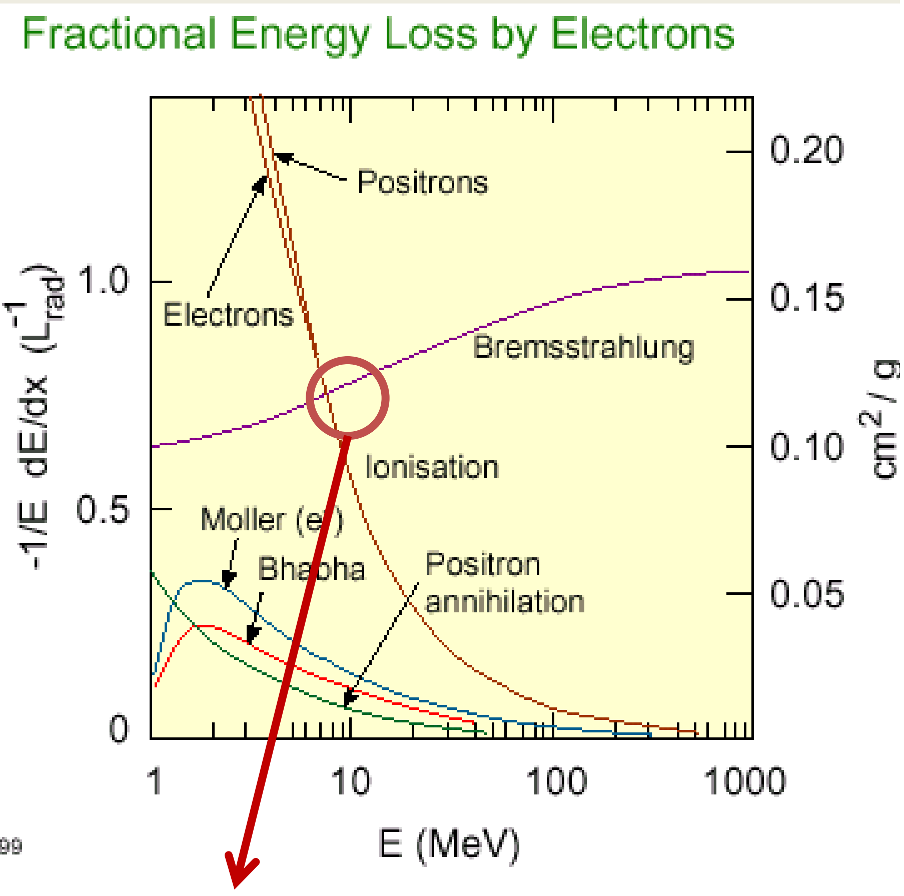
Proportional to E and $1/m^2$

Dominant process for electrons E > 1 GeV (and ultra relativistic muons)

High Z material to stop electrons (Pb)

$$(\frac{dE}{dx})_{tot} = (\frac{dE}{dx})_{Brem} + (\frac{dE}{dx})_{ion}$$

Interaction of electron/positron in matter



Critical energy E_c

Above E_c mainly brem energy loss

The radiation length X_0 (L_{rad}) is defined as the distance over which the mean energy of an incident electron is reduced by a factor e

$$E = E_0 \exp(-x / X_0)$$

Some examples of X_0 :

H_2 gas : 866 cm

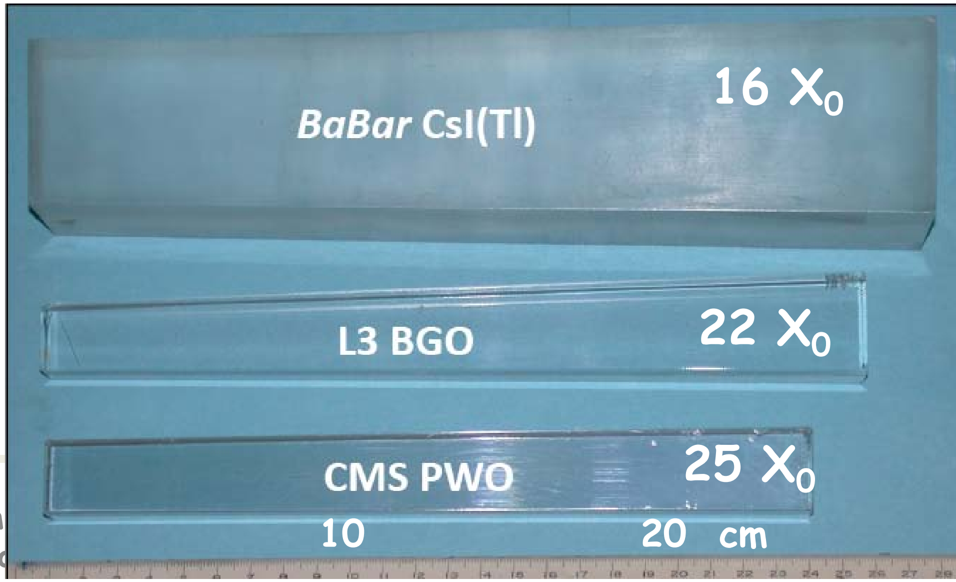
C : 18.8 cm

Ar liq : 14 cm

Fe : 1.76 cm

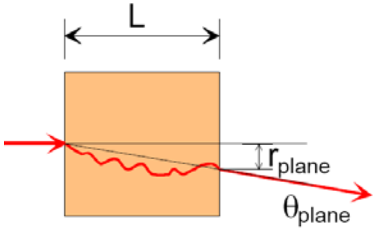
Pb : 0.56 cm

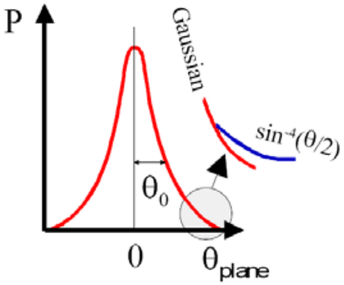
W : 0.35 cm



Multiple scattering

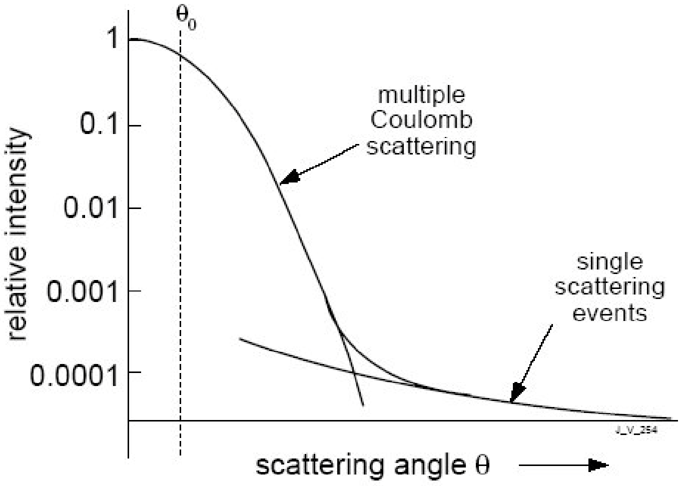
Momentum transfer → change in direction (Rutherford scattering)
If the material is thick enough → multiple scattering, effect on average null for many particles but seen as a fluctuation (important for position resolution)





rms of scattering angle is given by :

$$\theta_0 = \frac{13.6\ MeV}{\beta c p} z \sqrt{\frac{L}{X_0}} \left\{ 1 + 0.038 \ln\left(\frac{L}{X_0} \right) \right\}$$



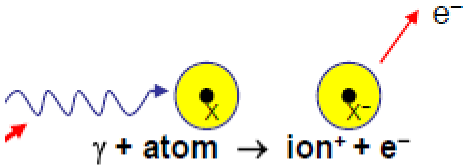
Smaller for high energy, small material thickness and large radiation length

Crucial for position measurement in tracking detectors

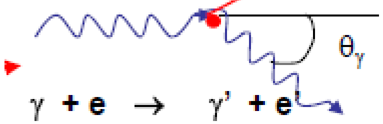
Photon interaction in matter

Three main processes depending on energy :

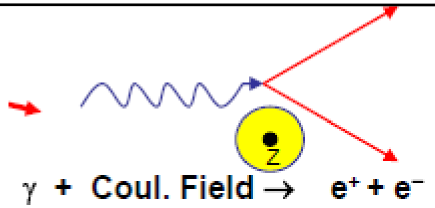
- photoelectric effect (atomic electron)



- Compton effect (atomic electron)



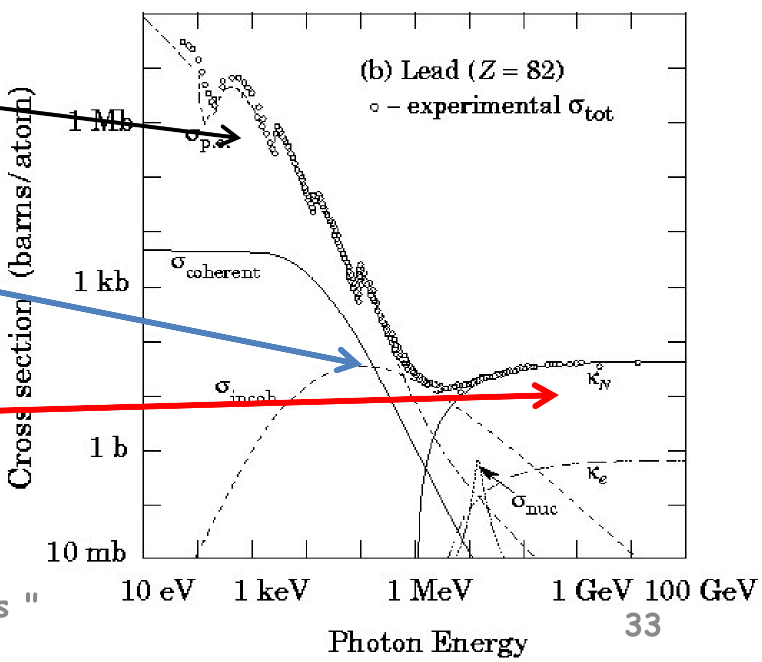
- e^+e^- pair creation (nucleus and electron)



-Low energy : photoelectric dominant (varies as $1/E^{7/2}$ and Z^5)

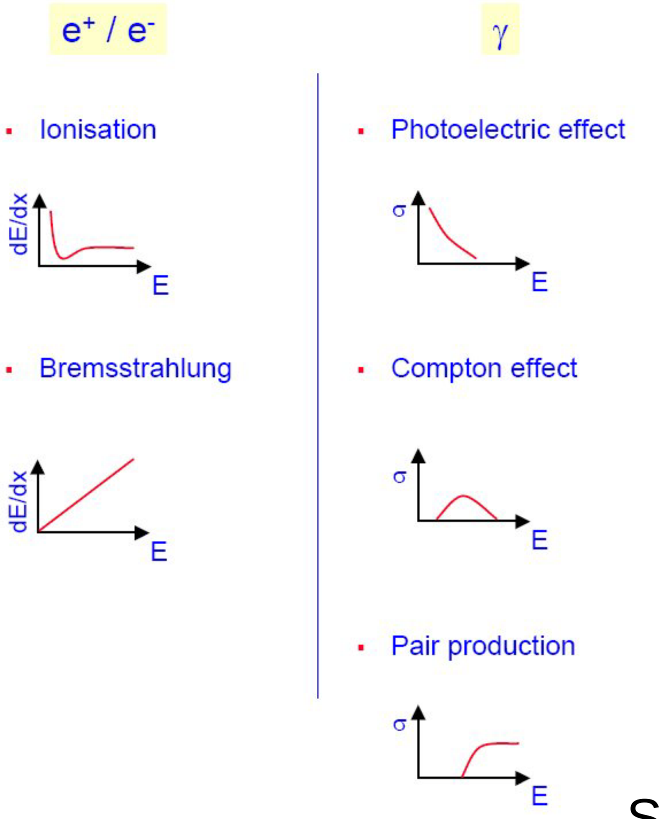
- Intermediate regime : Compton ($\propto Z$ and $1/E$)

- E > 1 MeV : pair creation is dominant, energy independent ($\propto A$), proba of conversion in 1 X_0 is $e^{-7/9}$



Electron + photon interaction in matter :
Electromagnetic shower

Electromagnetic shower

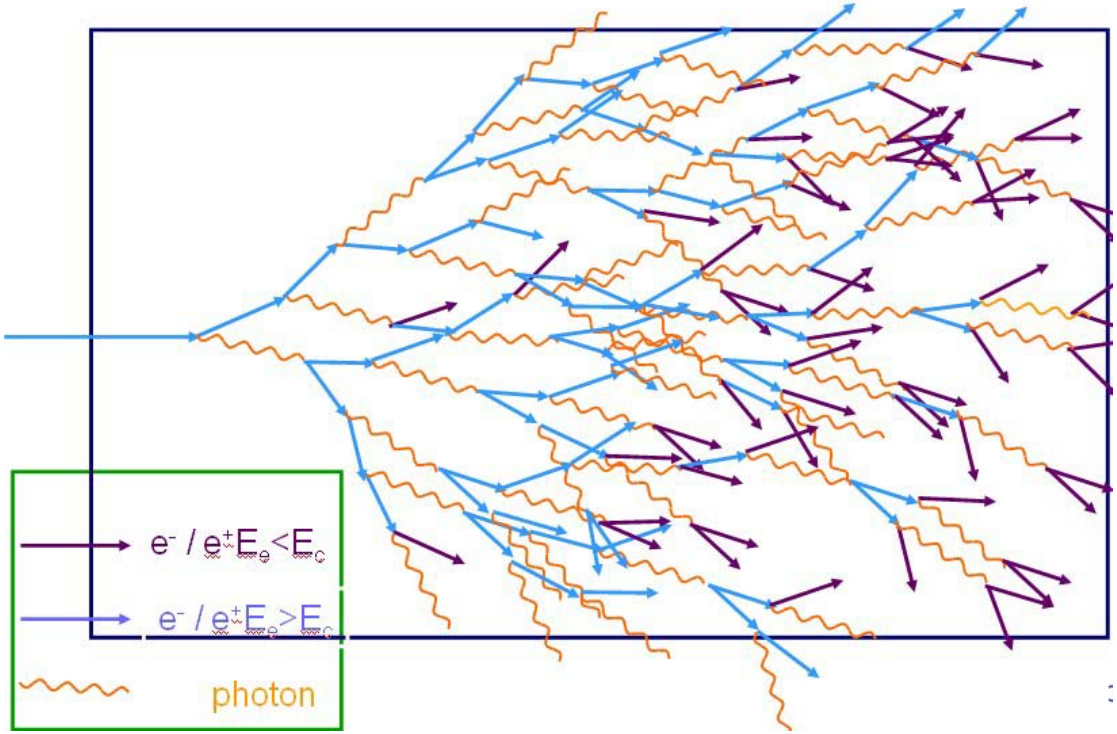


e^+ / e^-

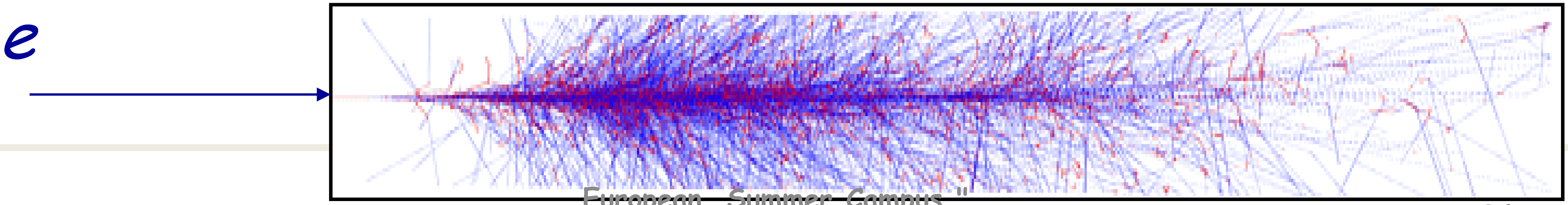
- Ionisation
- Bremsstrahlung

γ

- Photoelectric effect
- Compton effect
- Pair production



Simulation of electron interaction in a crystal



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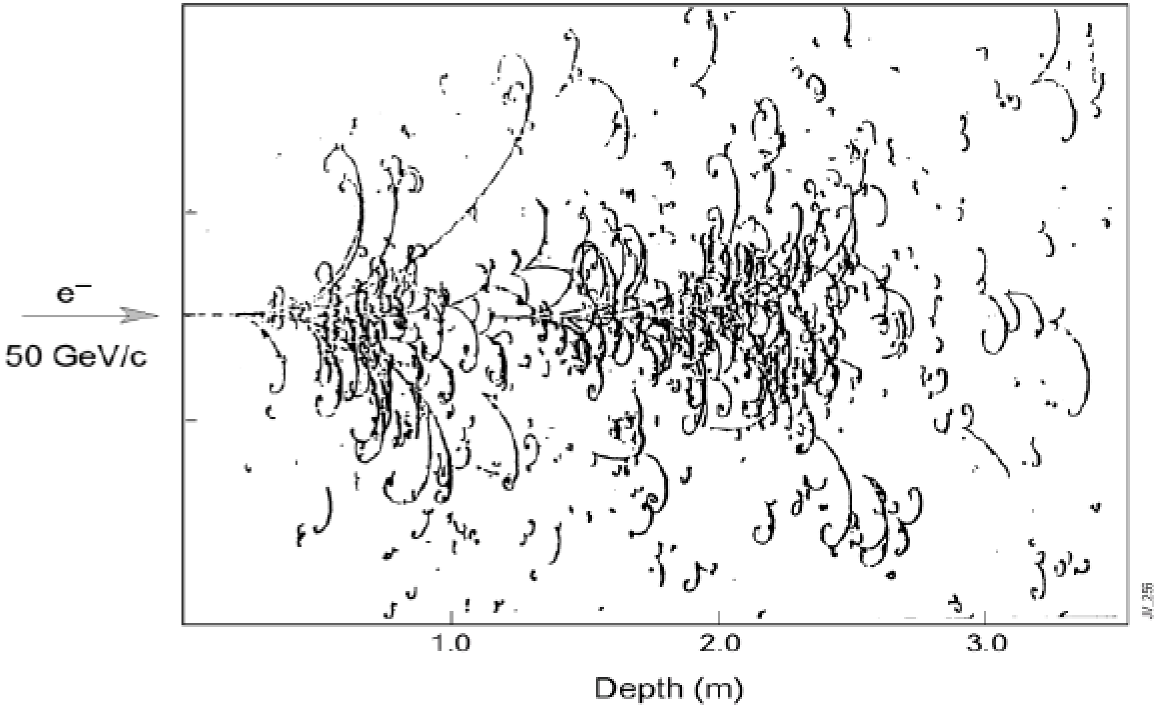
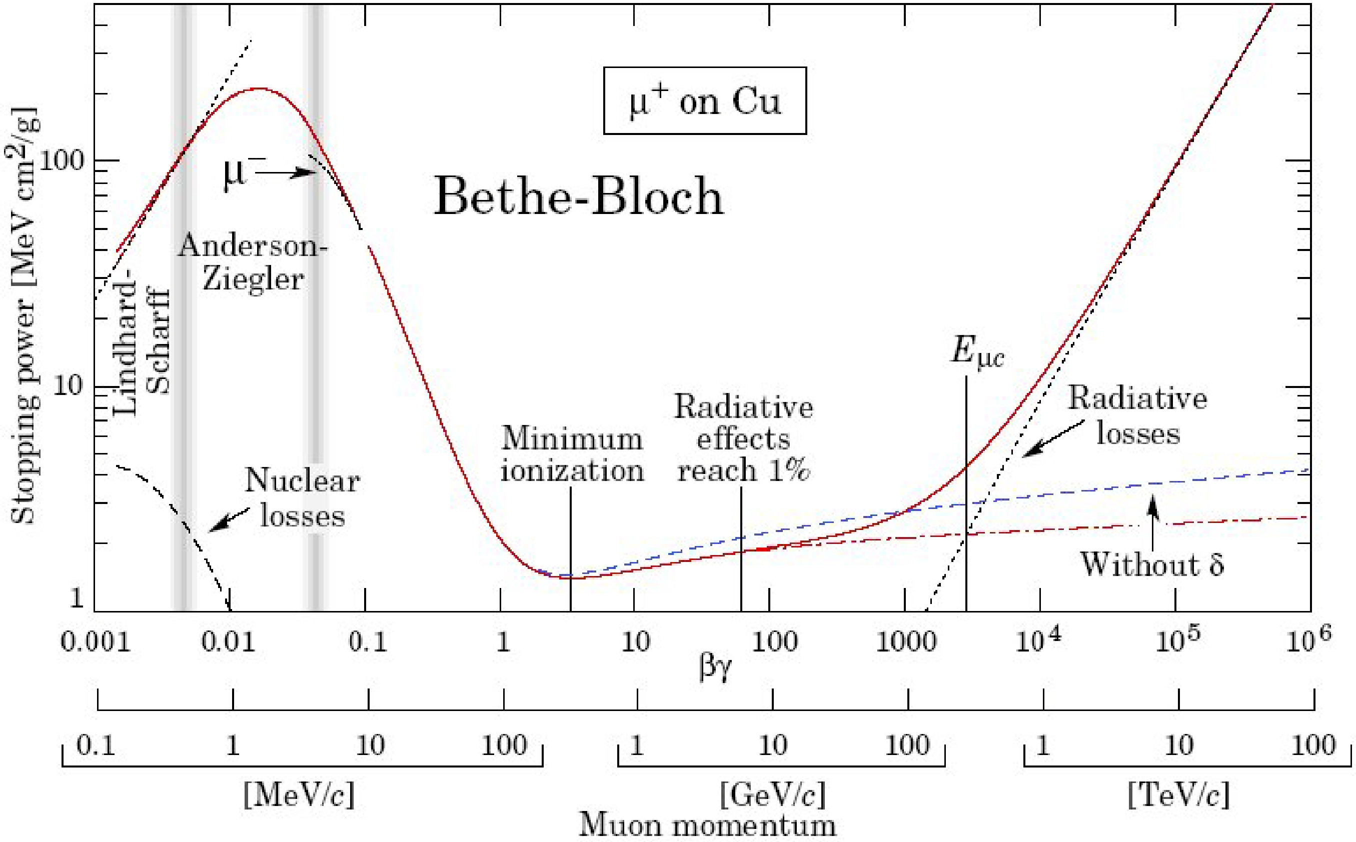
Electromagnetic shower

In a dense material, cascade of pair production + Bremsstrahlung until the energy of charged secondaries has been degraded to an energy dominated by ionization loss (below E_c)



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

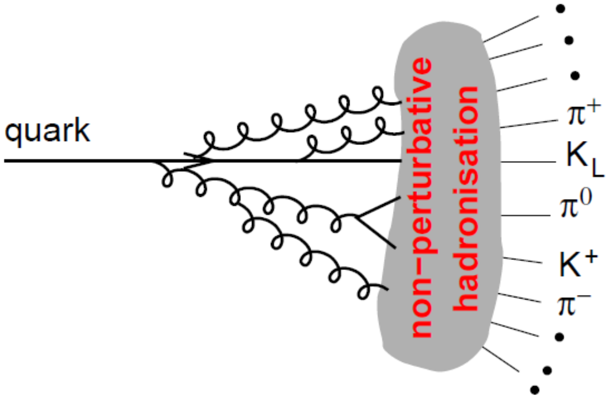
Muon interaction in matter



m_μ ~200 m_e → Bremsstrahlung only at high energy (~TeV)
Muons are the only charged particles escaping detectors.

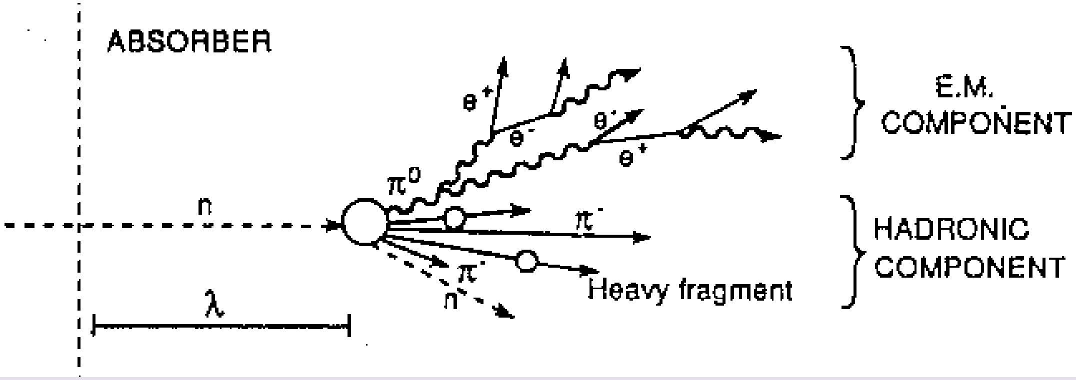
Hadron (quark/gluon) interaction in matter (I)

Quark & gluon can not be directly observed (fragmentation and hadronisation) : production of neutral and charged hadrons →



Particle flow along the quark/gluon direction : jet

Interaction of charged/neutral hadrons involves mainly nuclear interaction : excitation and nucleus break-up, production of secondary particles + fragment



$N_{sec} \propto \ln E$ with p_T ~0.35 GeV

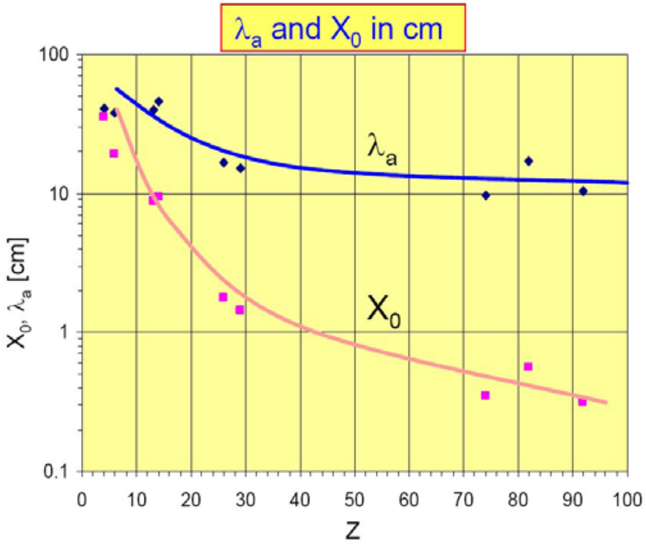
For E > 1 GeV : $\sigma \sim \sigma_0 A^{0.7}$, with σ_0 = 35 mb and independent of particle type (π, p,K..)

Hadronic shower : typically 10 times wider and deeper than EM showers

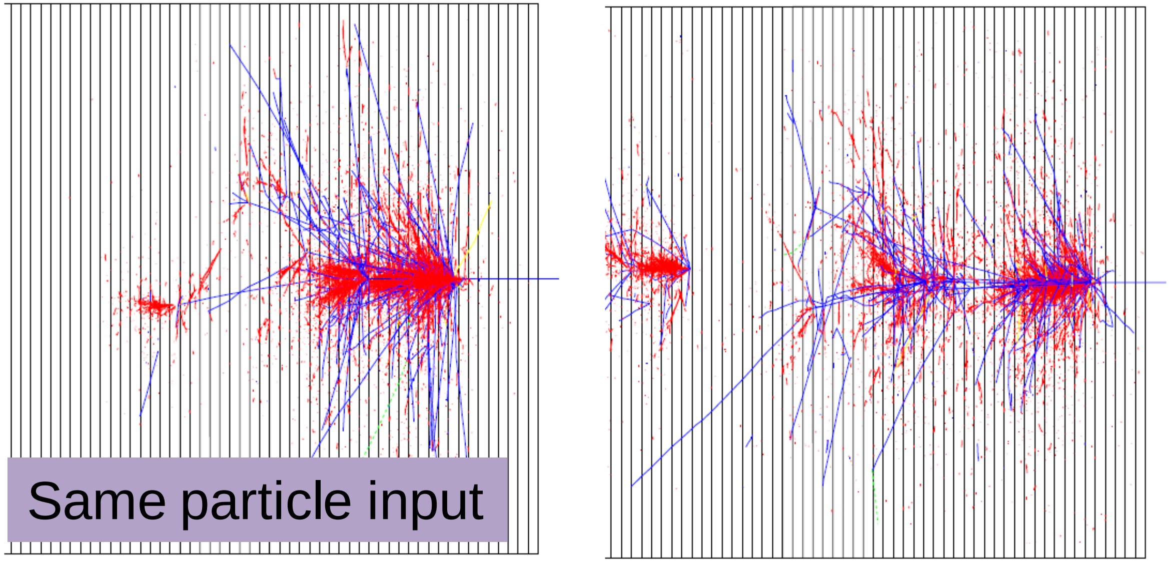
Hadronic shower

Convenient to introduce the (hadronic) absorption length :

$$\lambda_{I(a)} = \frac{A}{N_A \sigma_{total(inel)}} \propto A^{1/3}, N = N_0 e^{-\frac{x}{\lambda_a}}$$



Absorber depth to stop hadron much larger than for electron/photon showers.



Same particle input

red - e.m. component
blue - charged hadrons

Large fluctuation of the shower development

Energy resolution will be worse than for EM shower
Non linear and tails…

Now ready to design detectors !!!

- Charged particle measurement
  - Momentum measurement magnetic field
  - Magnetic field configuration
  - position detectors : gaseous detectors and solid state detectors

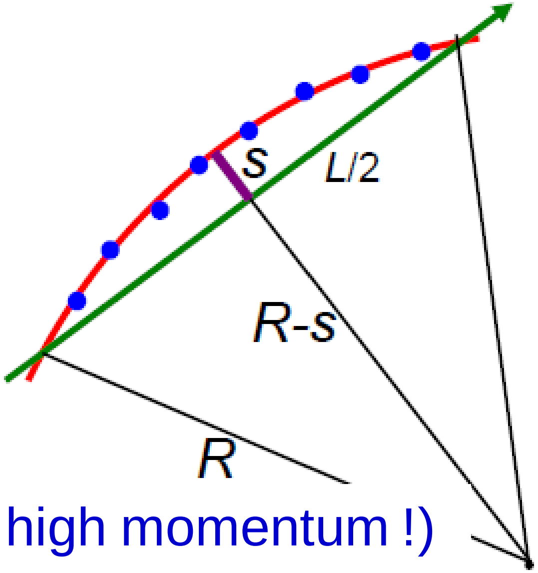
-Energy measurement
  - Electromagnetic calorimeters
  - Hadronic calorimeters

- Particle identification detectors (if time left)
  - Time of flight measurement
  - Cerenkov detectors
  - Radiation transition detectors

Momentum measurement in a magnetic field (I)

Charged particle in B field : p(GeV)=0.3 B(T) R(m)

Measure sagitta s from track arc R



$$s \approx \frac{0.3}{8}\frac{L^2 B}{p_T} \longrightarrow \frac{\sigma(p_T)}{p_T} = \frac{\sigma_s .8\, p_T}{0.3.BL^2}$$

Relative uncertainty proportional to p_T (not optimal for high momentum !)
and sagitta uncertainty (detector performance)
Better to have strong B field and long path length L

Sagitta uncertainty from N (detectors) points linearly spaced :

$$\sigma_s = \sqrt{\frac{720}{N+4}}\,\frac{\sigma_x}{8}$$

Should also include deterioration of resolution due to multiple scattering

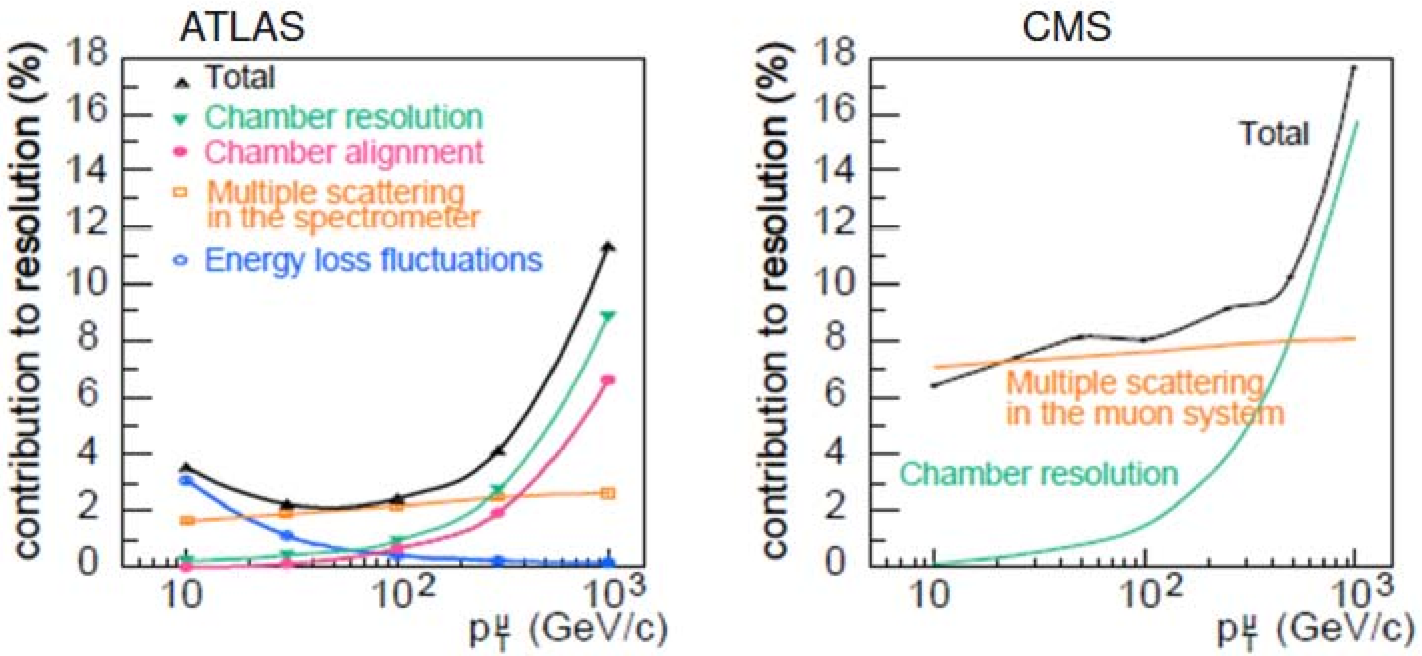
$$\sigma_s \propto \frac{L}{p_T \sin^{1/2}\theta}\sqrt{\frac{L}{X_0}}$$

Knowing accurately the position of the detectors is crucial → alignment , will not be discussed at all in these lessons…..

Expected momentum resolution

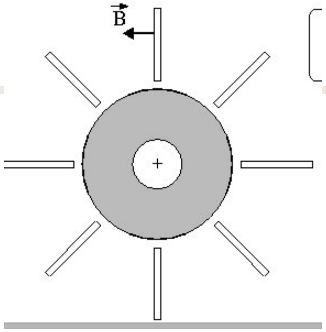
Typical parameterization for resolution

$$\frac{\sigma(p_T)}{p_T} = a.p_T \oplus \frac{b}{\sin^{1/2}\theta}$$



Spectrometer resolution different due to different magnetic field configurations (see later). When spectrometer measurement combined with inner detector measurements, similar performances in ATLAS & CMS

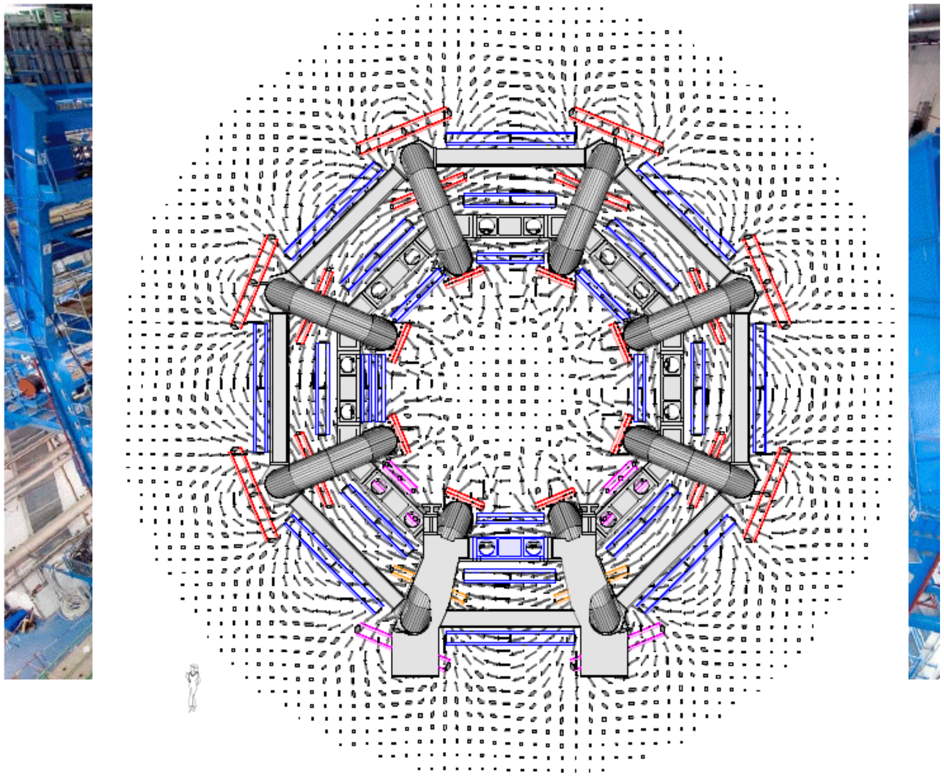
Which magnetic field ?



Two main categories in magnets : solenoid (most frequent) or toroid

CMS solenoid, 12.9m long
with 5.9 m inner diameter
→ 4 T , 2.7 GJ !

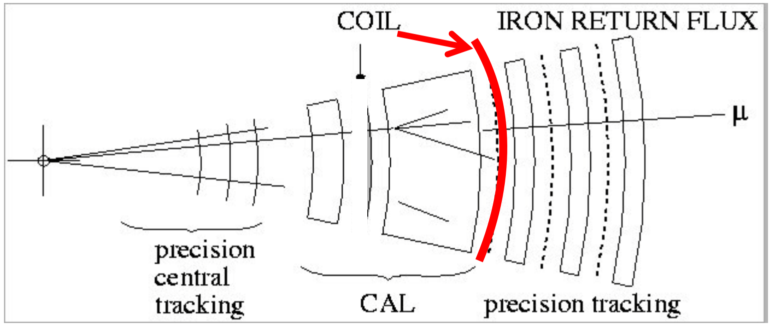
ATLAS barrel toroid for μ



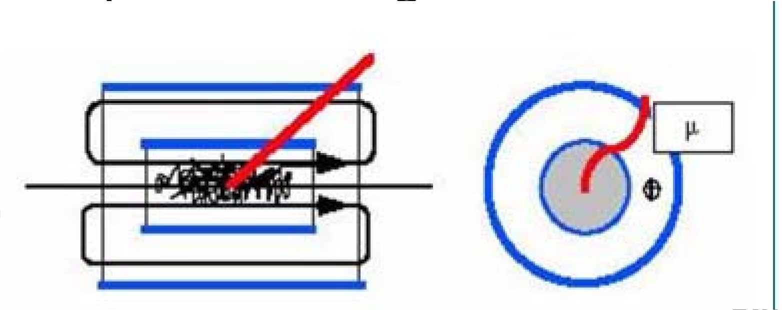
B field much more complex → field map measurement

Magnetic field configuration

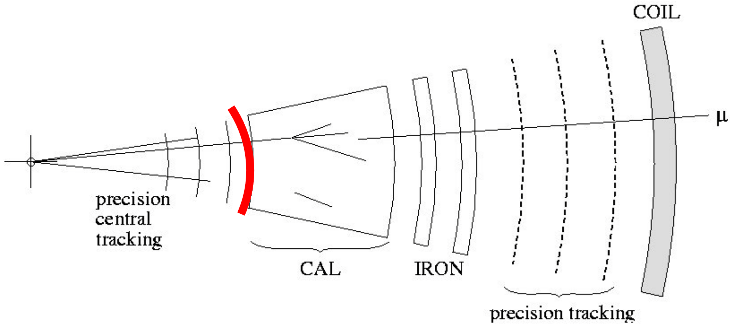
~ CMS



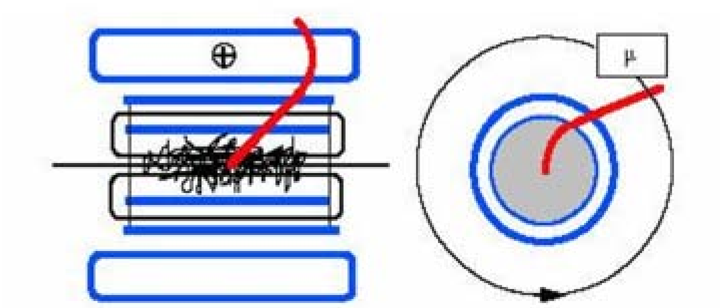
Measurement using the iron solenoid return flux (not very homogeneous)
Only one magnetic solenoid with a large field (4 T)
Muons see large material (Fe) so resolution is strongly limited by multiple scattering at ~10 %



ATLAS



Chambers are inside coil.
Less material/multiple scattering so
Robust standalone measurement
Huge and complex magnet system
In ATLAS need also a solenoid (2T) for inner detector.



Tracking detectors

They should detect the passage of a charged track.
Two main classes of detectors :

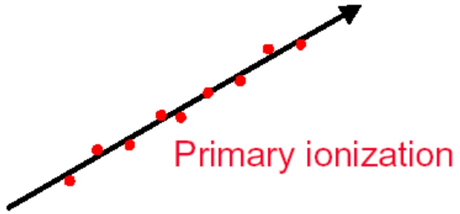
- Gaseous detectors :
  well adapted as low density material (small amount of x_0) and small multiple scattering and quite cheap
  Not always suited for high rate environment (pp collider) as quite slow but a lot of progress in this direction with Micro-gazeous detectors
  Continuous improvement since 60’

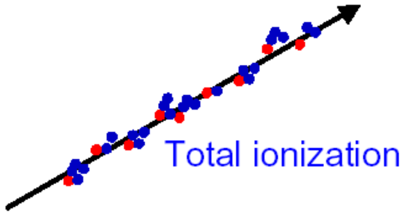
-Solid state detectors :
 Used for energy measurement (Si, Ge, Ge(Li)) since long time at low energy (nuclear physics, $E/\Delta E$ measurement).
 Use as precision device in High Energy physics (due to advance in micro-electronic techniques) since LEP : very high granularity (precision) and small devices but no charge multiplication mechanism and quite dense

Gas detectors : principle

1) Ionization of gas : $N_T = N_{primary} + N_{secondary}$ $N_{secondary}$ ~2-3 N_{prim}

Example : dE/dx in Ar = 1.519 MeV/(g.cm^2)
density : 1.396g/l w =26 eV
$N_T = \Delta E/w = 1.519\ 10^6 * 1.396\ 10^{-3} / 26$
= 80 pairs /cm





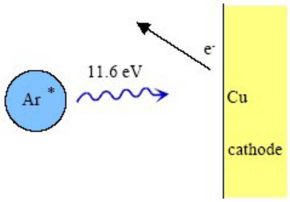
About 10 times smaller than electronics noise in charge preamp ! → Needs amplification of signal

2) Amplification : add an electrical field E, primary/secondary electrons from ionization can get enough energy to induce new ionization

→ amplification/avalanche : current or charge large enough / noise

→ various regime depending on Voltage with amplification up to 10^8

NB : Choice of the gas could be a key point
Need quenching element to prevent permanent discharge ! but ageing….
Should find the best compromise



→ new avalanches → permanent discharges !

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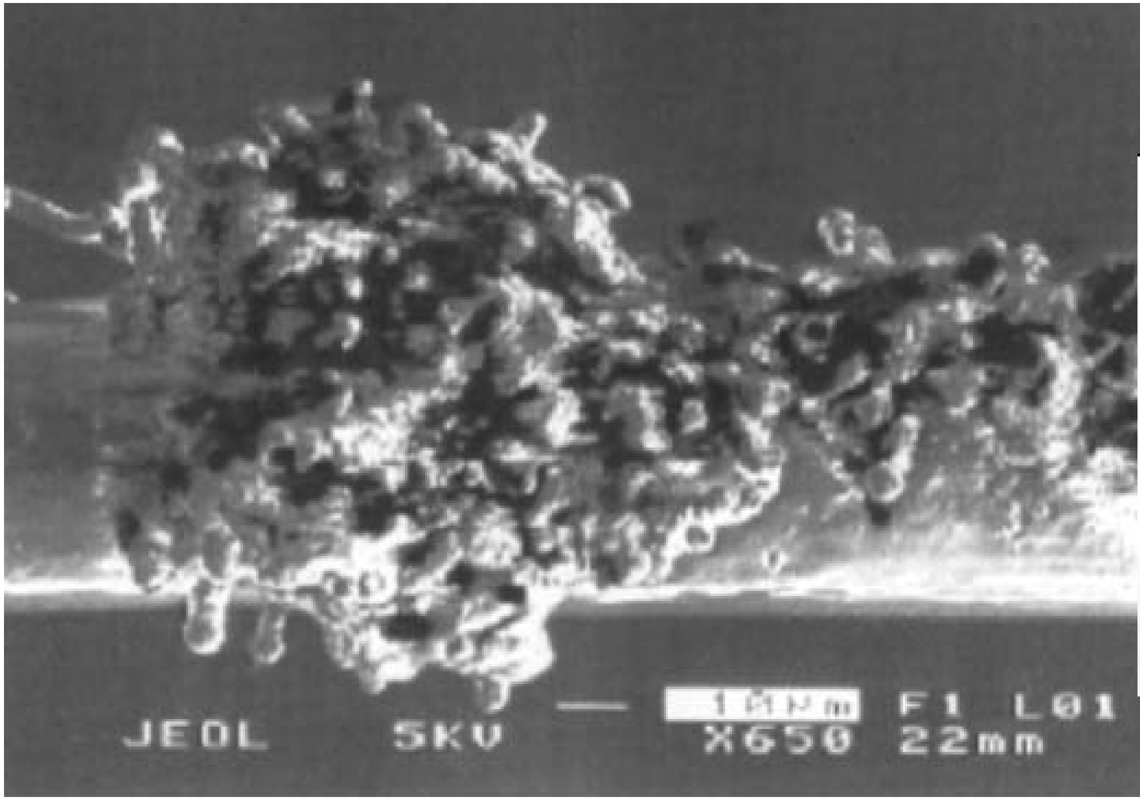
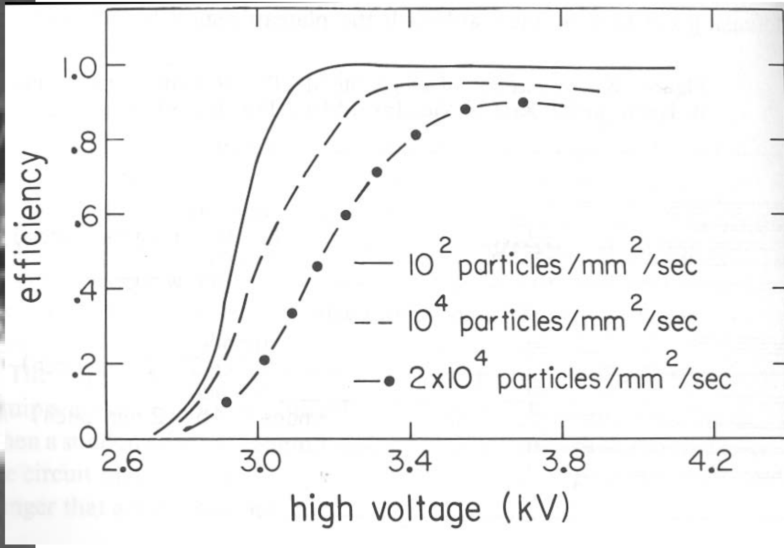
Anode after detector use

The quenching molecules dissociate in smaller molecules which are deposited on the anode and acts as an insulating : Loss of efficiency with time and/or high flux…





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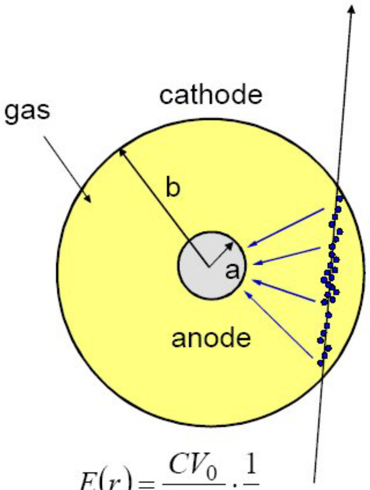
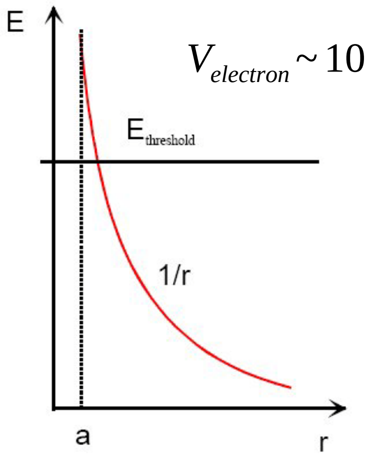
Historical tracking detectors : cylindrical proportional counter



$$E(r) = \frac{CV_0}{2\pi\varepsilon_0} \cdot \frac{1}{r}$$

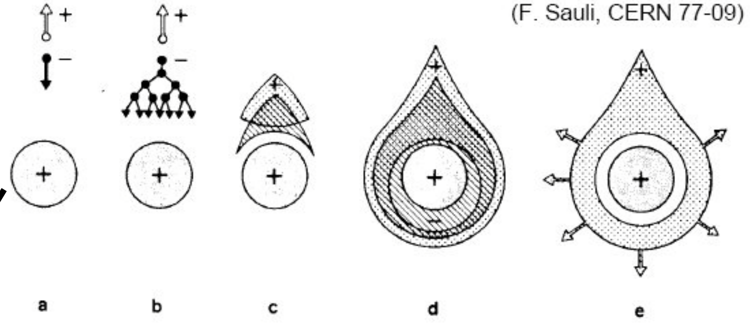
$$V(r) = \frac{CV_0}{2\pi\varepsilon_0} \cdot \ln\frac{r}{a}$$

C = capacitance / unit length



$$V_{electron} \sim 100 - 1000\ V_{ion}$$

Charge development versus time



(F. Sauli, CERN 77-09)

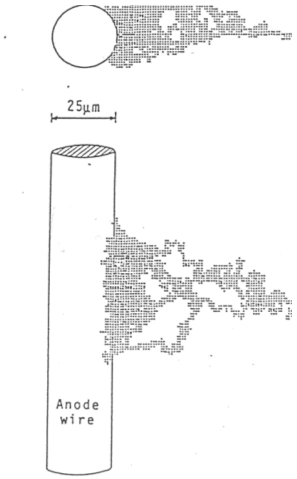
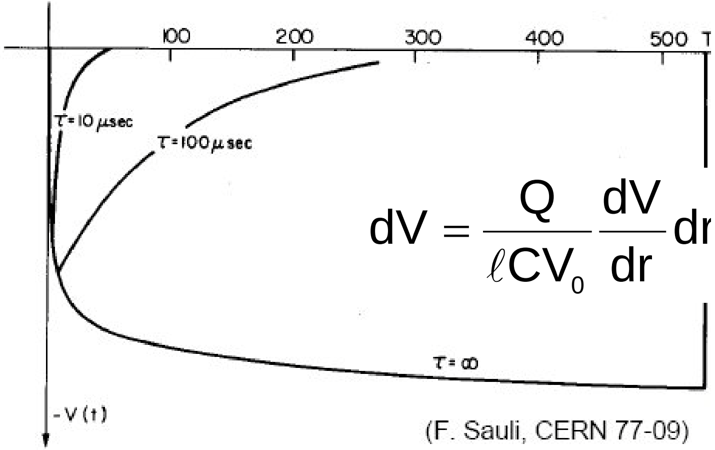


Fig. 7 Two dimensional displays of a simulated electron avalanche. Shading shows the density of electrons in the avalanche.



$$dV = \frac{Q}{\ell C V_0}\frac{dV}{dr}dr$$

(F. Sauli, CERN 77-09)

Movement of electrons and ions induce negative (positive) signal on anode (cathode) .Very fast electrons signal (multiplication near anode) while ions have to go through whole gap to cathode :

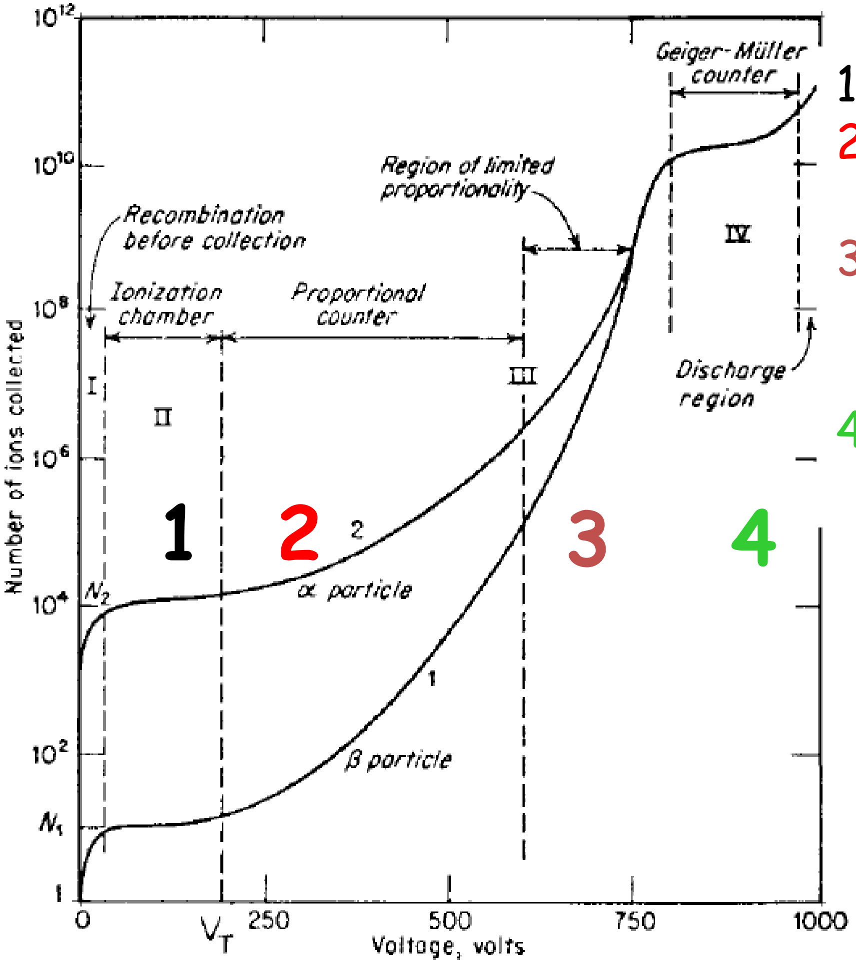
Electrons give small contribution to total signal only at early time (dr small)

Most of the signal given by ion and gives the signal duration

Needs differentiation (τ) to have fast Signal and low electronics noise preamp

***

Proportional counter : voltage operation mode



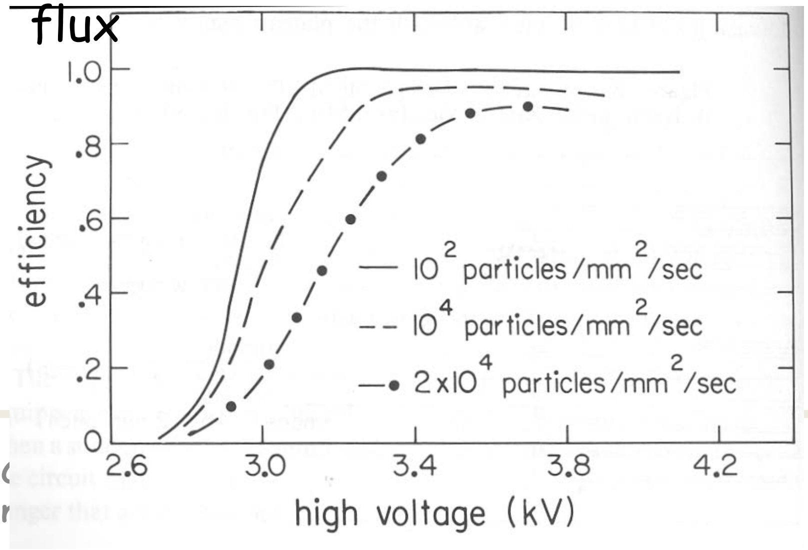
1) Ionization mode, M=1, Qtot

2) Proportional above $V_{Treshold,}$, needs quenching
signal ∝ original ionization (dE/dx), $M\sim10^4$-10^5

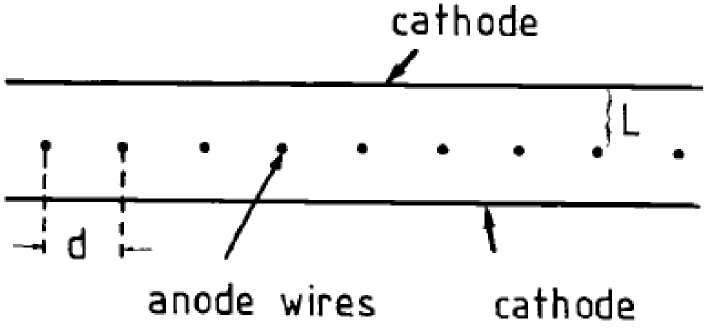
3) Limited proportional → saturated → streamer
$M\sim10^8$, large signals so easier electronics
but needs efficient quenching or pulsed HV

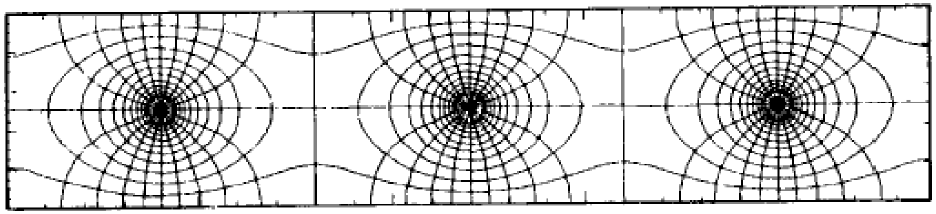
4) Geiger mode : massive photo emission
Stop avalanche by HV down

Efficiency vs voltage at different flux

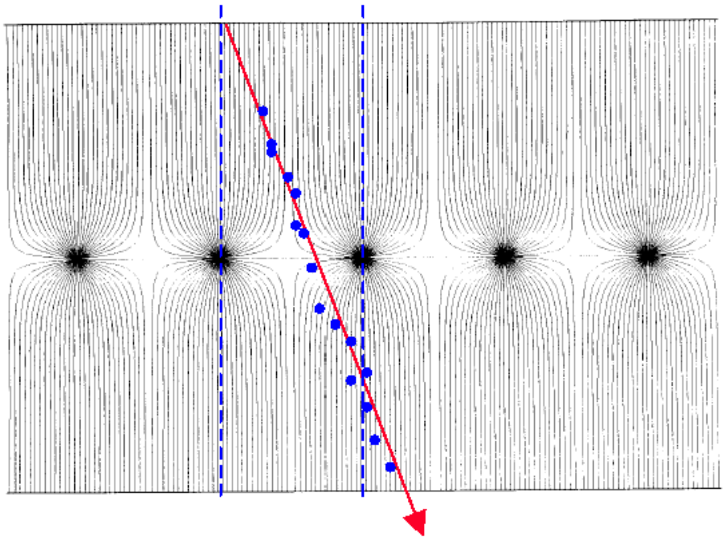


Wire chambers (Charpak)





field lines and equipotentials around anode wires



Typical parameters
L=8 mm, d=2 mm,
Wire diameter (W gold plated) : 20-30 μ
Optimum for L/d≈3-4
If digital readout (fired wires above a threshold) ,
$\sigma \sim d/\sqrt{12} \sim 600\mu m$
- Smaller d will give better resolution but limited by electrostatic force between wires
-Mechanical tolerance :
$d/L >= 1.5*10^{-3} V(kV)\sqrt{(20g/T(\text{in gr}))}$

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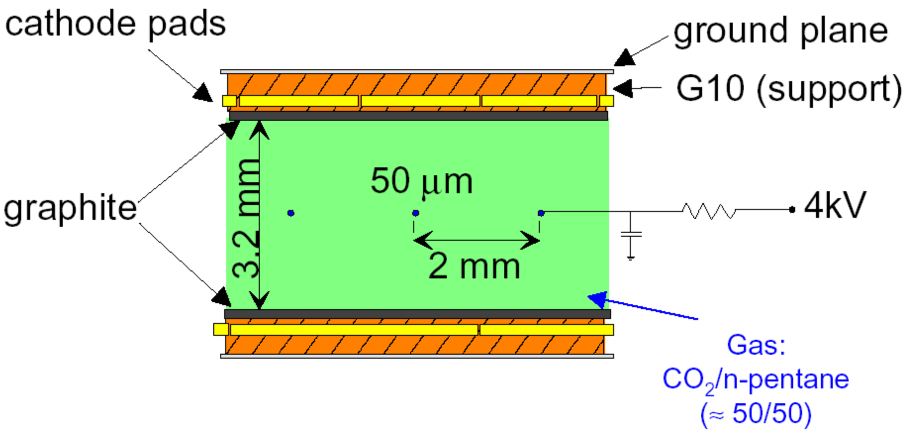
Modern MWPC

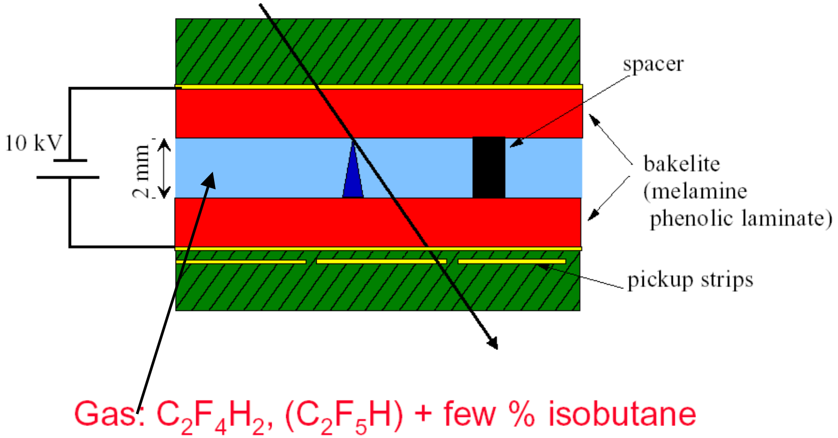
ATLAS TGC : endcap μ measurement



Use in saturated mode
M ~10^6
Fast signal (risetime in ~2ns)
Quite robust

Babar, Belle, ATLAS/CMS μ trigger

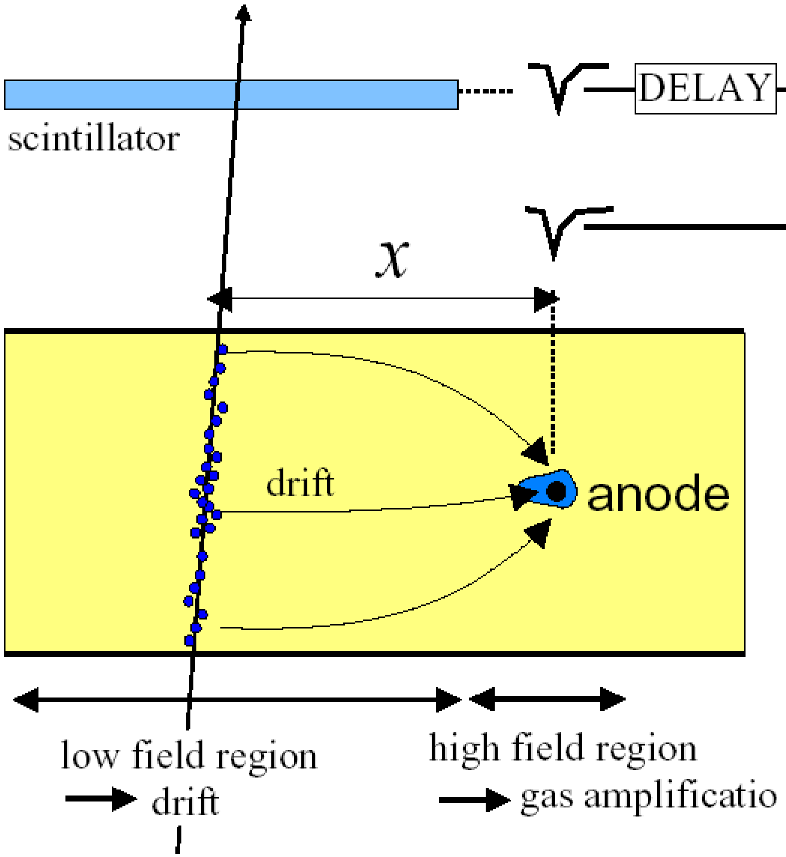
Resistive Plate chamber : No wires !



Use near streamer mode
M ~10^8
Fast signal (risetime in ~2ns)
Efficiency improve with multi layers
Operation not always so easy but
widely used for trigger

***

Drift chamber : measure arrival time of signal



Measurement of time arrival with respect to external trigger.

Needs to know :

- Drift velocity
- Diffusion over long distance

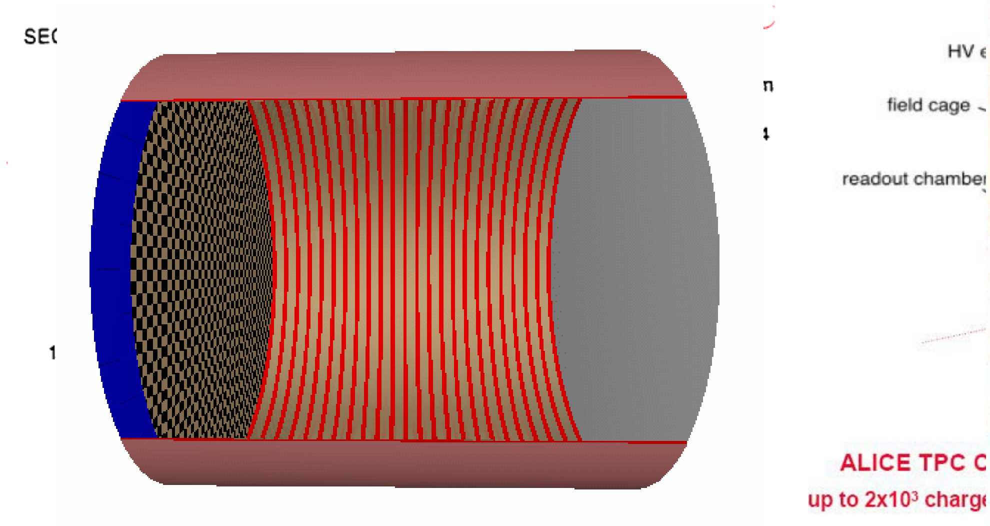
Mainly used for low environment (but also in ALICE) with Time Projection Chamber

Advantages : less wires and large volume (cost), mechanical structure with less constraint
but slow signal and needs external trigger

***

Time Projection Chambers

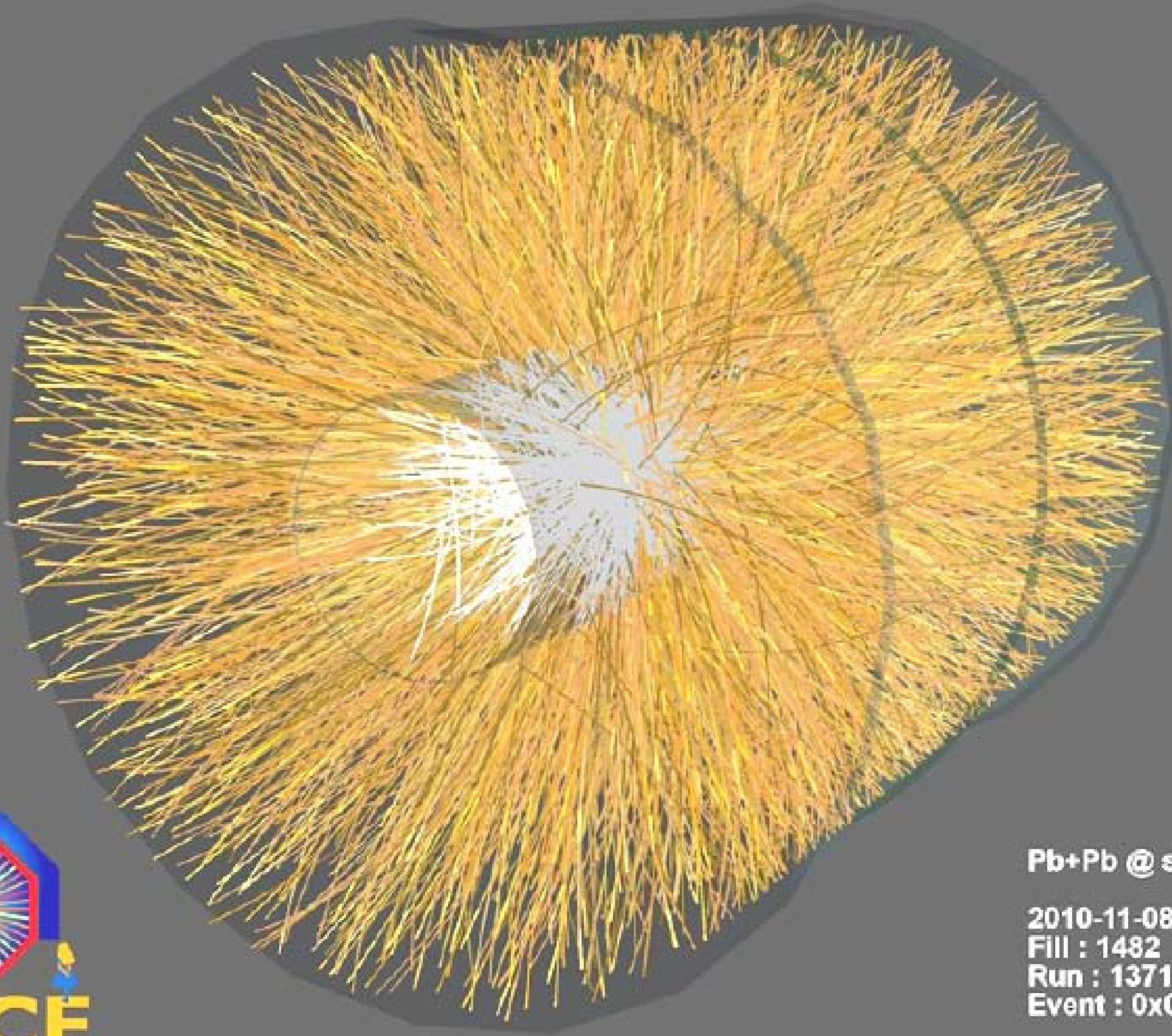
Can combine drift along z + end-planes x&y measurement : 3D measurement
Use of electrical and magnetic field (solenoid) along z .B help to reduction multiple diffusion along z



For endplates, can use any position sensitive detectors

***

ALICE heavy ion event display

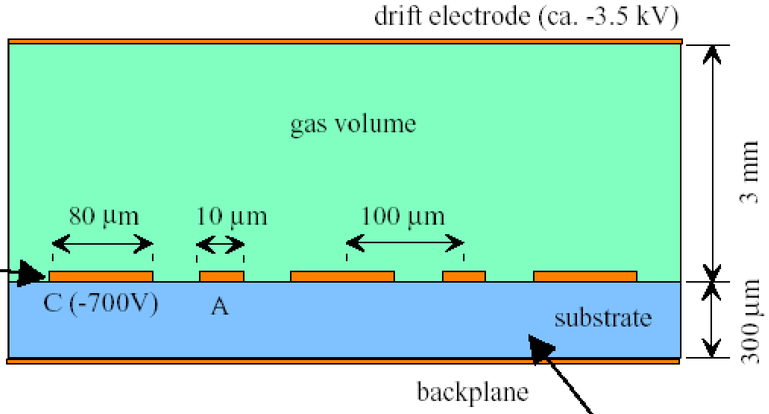


Pb+Pb @ sqrt(s) = 2.76 ATeV

2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE693

Faster and better precision : Micro pattern gaseous detectors

geometry and typical dimensions
(former CMS standard)



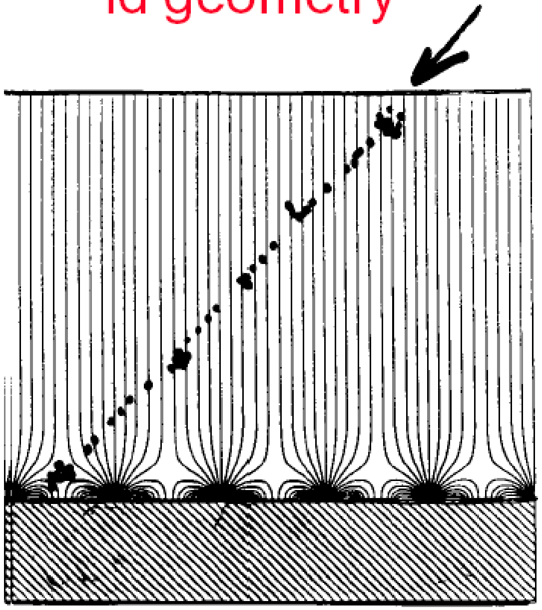
Gold strips
+ Cr underlayer

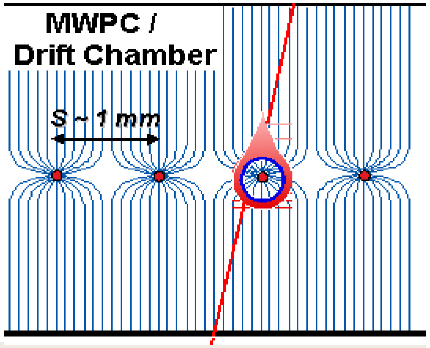
Glass DESAG AF45 + S8900
semiconducting glass coating,
$\rho=10^{16}\ \Omega/\square$

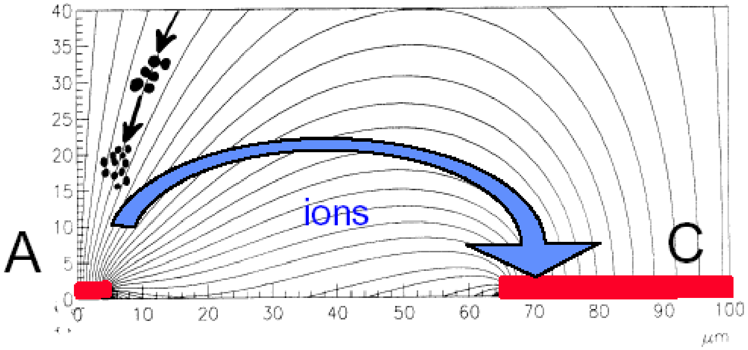
200 μm between anode
→Good resolution
Fast ion evacuation
→High flux capability

Gain ~10^4

Id geometry

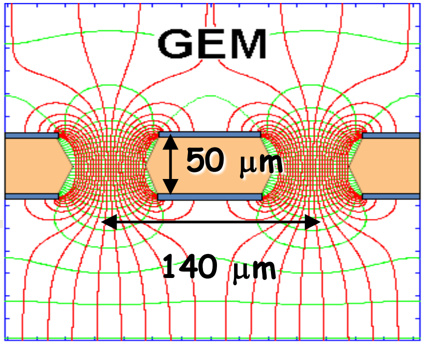






Fast ion evacuation → high rate capability
≈ 10^6 /($mm^2 \cdot s$)

Discharge should be avoided : damage and/or dead time + ageing…..



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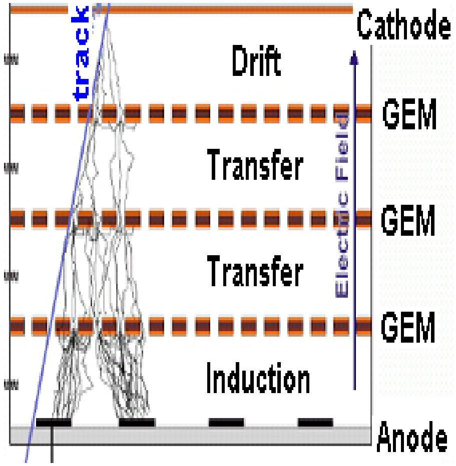
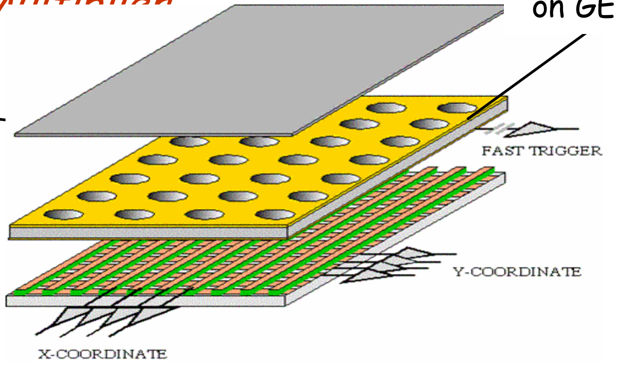
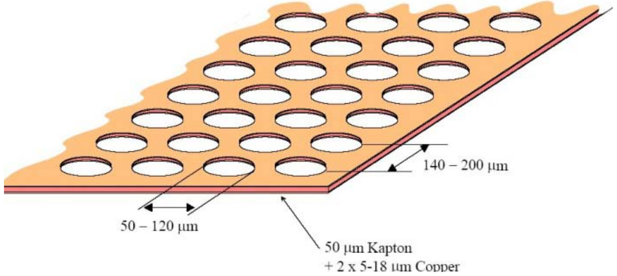
Gas Electron Multiplier

GEM : Gas Electron Multiplier

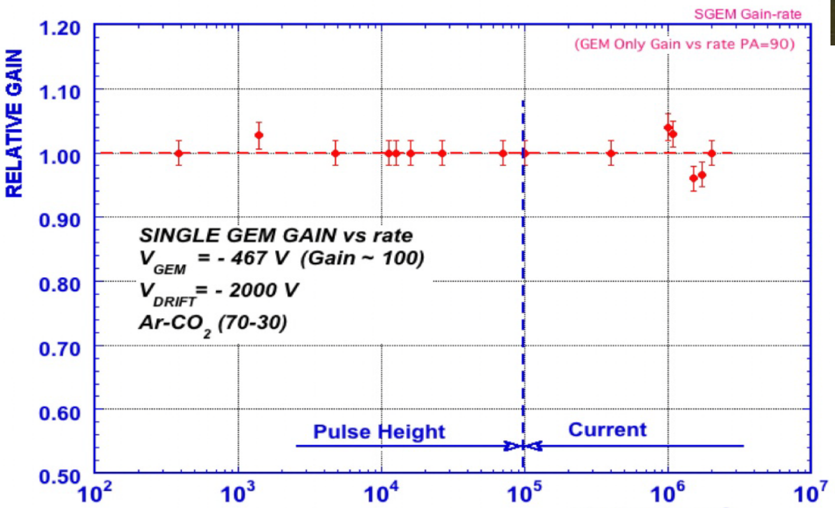
Ions produced near cathode collected on GEM electrodes



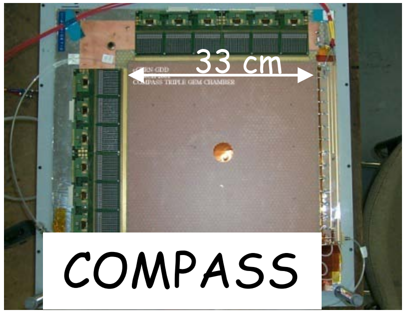


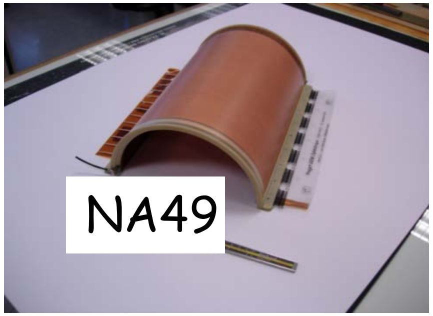


High-rate capability > 10^5 Hz/mm^2



J. Benlloch et al, IEEE NS-45(1998)234





Hadronic interaction→ a lot of primary electrons (>10000), multiplication, creation of a plasma → short
Dead time and protection to electronics

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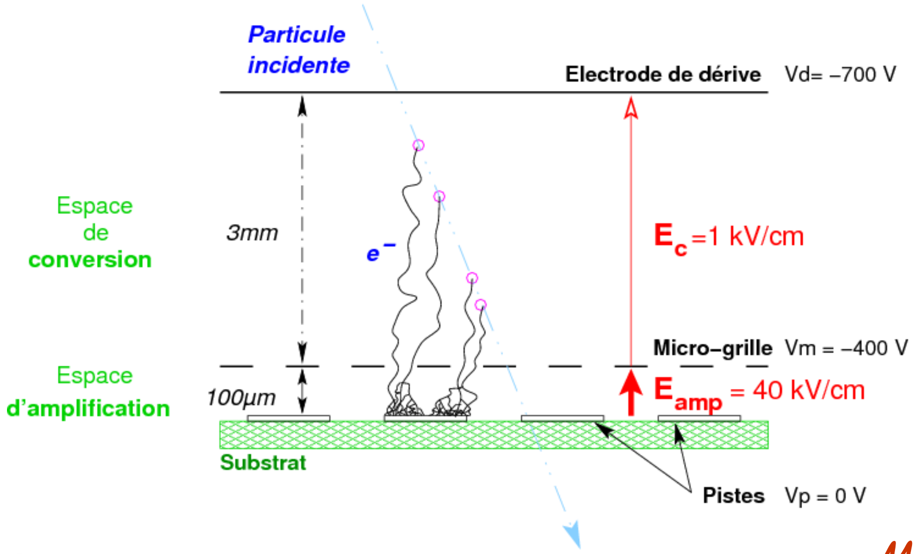
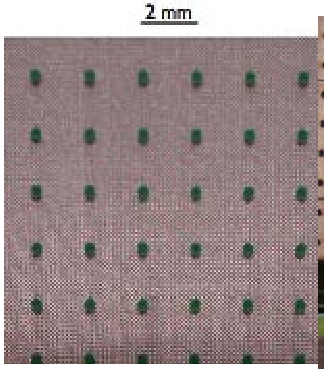
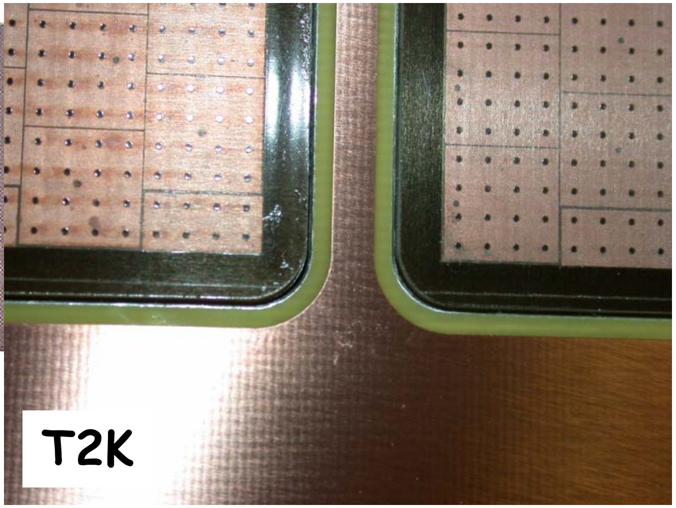
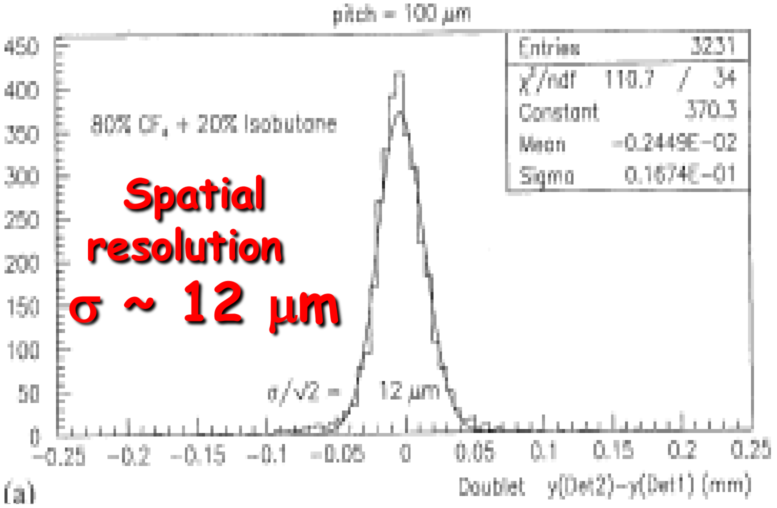
Micro Megas



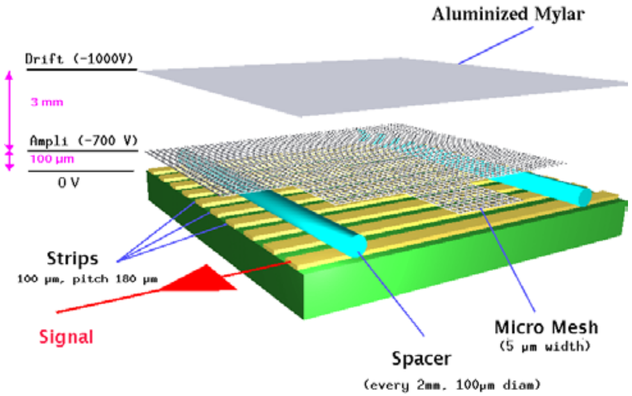




Micromegas : Micro Mesh Gaseous Detector



Spatial resolution σ ~ 12 µm



Both GEM and Micro Megas in operation in COMPASS since 2002 and no aging problem observed in a 25 kHz/mm² environment. Could be used for µ at SLHC

Solid state detectors

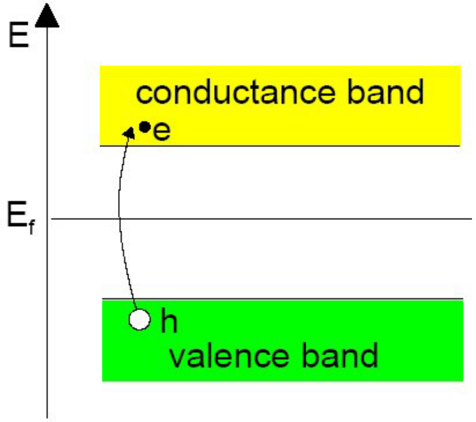
Advantages : (example of Si)

- High radiation hardness
- Can accept very large flux and have very small segmentation
- Rigid detectors so self “supporting structures”
- Energy to create e-/hole pair is very low 3.6 eV (1/10 of gas)
- High density 2.33 g/cm^2 . dE/dx per track is 390 eV/μm → 108 e/h pairs and High mobility : 1450 cm^2/Vs for electron and 450 for holes
  → small size and fast signal

-Very good single point accuracy (a few μm)

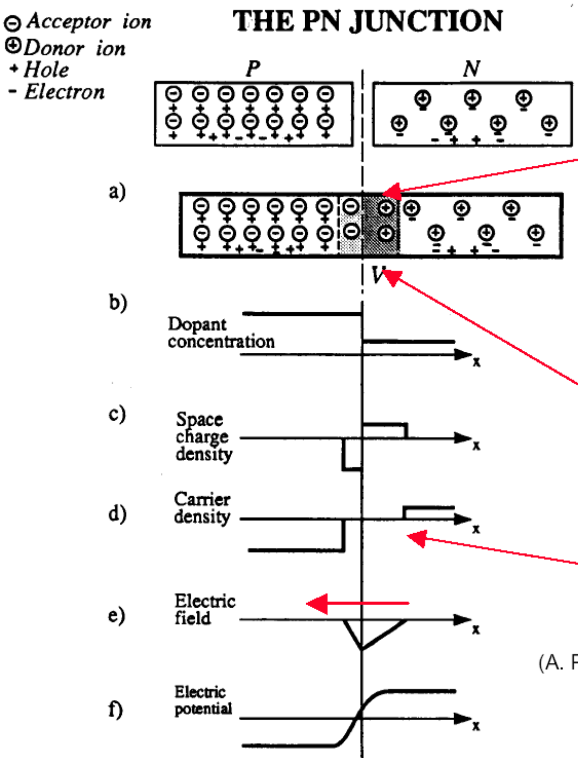
Disadvantages : No charge multiplication , no continuous tracking (layer structure)
Needs cooling system to operate at low temperature (less radiation)
High density : radiation length before calorimeter
Cost (in general more expensive than gas detectors)

Reminder of solid state physics !



At T=0 Semi Conductor is an insulator but when T electron density (n) = Hole density (p) = n_i
→ $1.45.10^{10}/cm^3$ for silicon (given by exp(-Eg/kT)

In a 1cm x 1cm x 300μm detector already $4.5.10^8$ free charges against $3.2.10^4$ e/h produced for a mip particle
→ S/√N =1 no chance to see signal



diffusion of e^- into p-zone, h^+ into n-zone
→ potential difference stopping diffusion

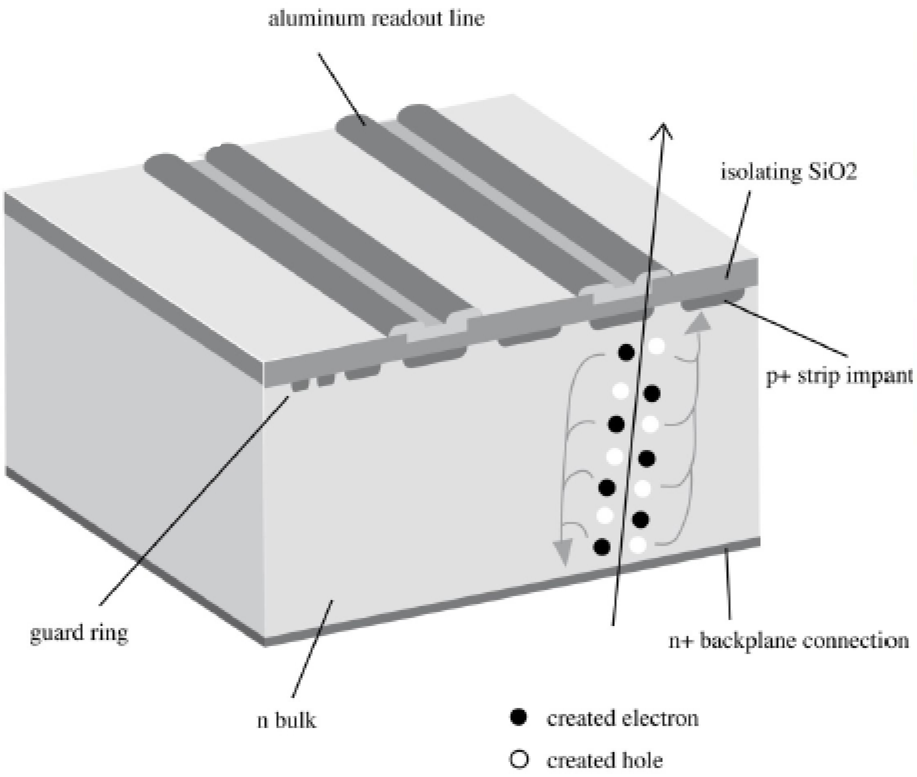
thin depletion zone

no free charge carriers in depletion zone

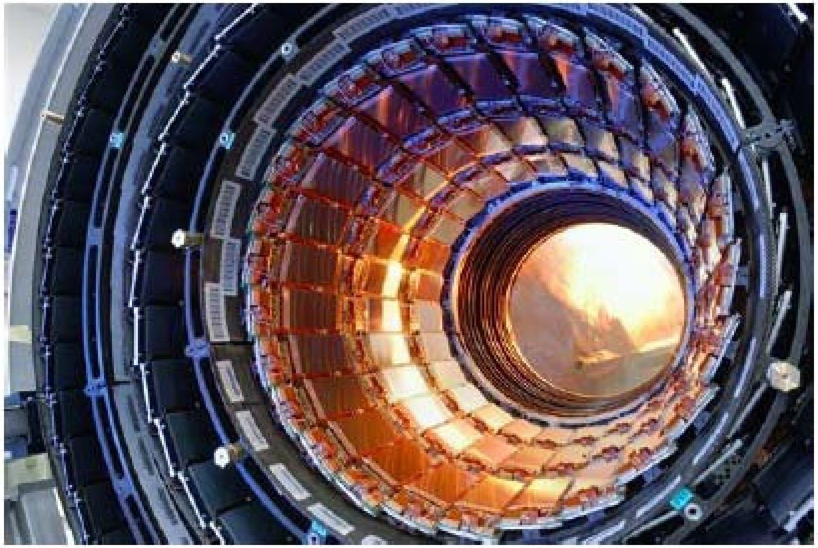
(A. Peisert, Instrumentation In High Energy Physics, World Scientific)

Need to create a region with no free charge carriers
Add doping attracting hole & electron in semiconductor
→ When in contact, produce a region with no free electron/hole and a potential difference.
→Add a V across the junction can be fully depleted.
→ Now can hope to see mip particle across The detector !

Some examples of detectors : micro strips sensors



~50 μm strip pitch

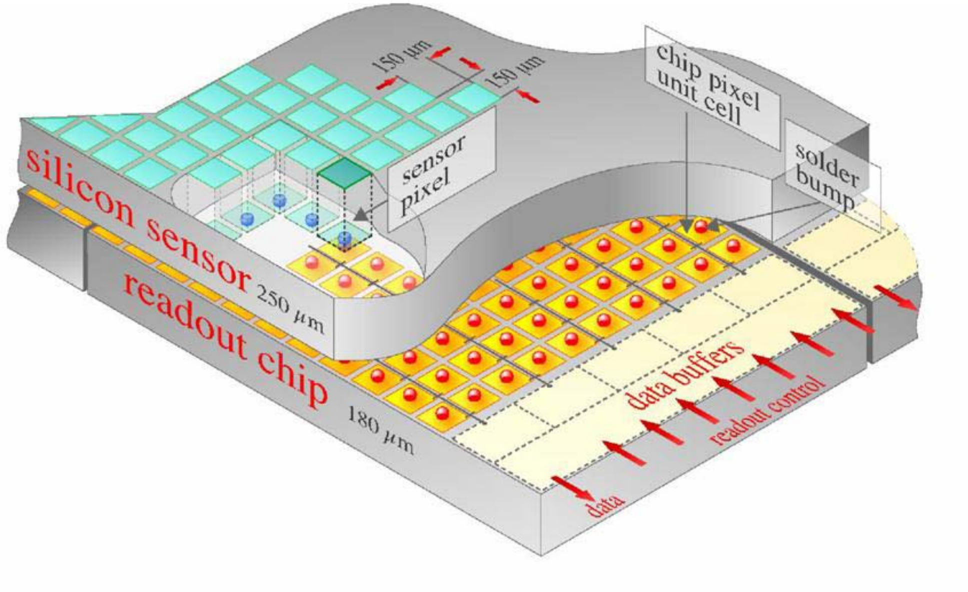


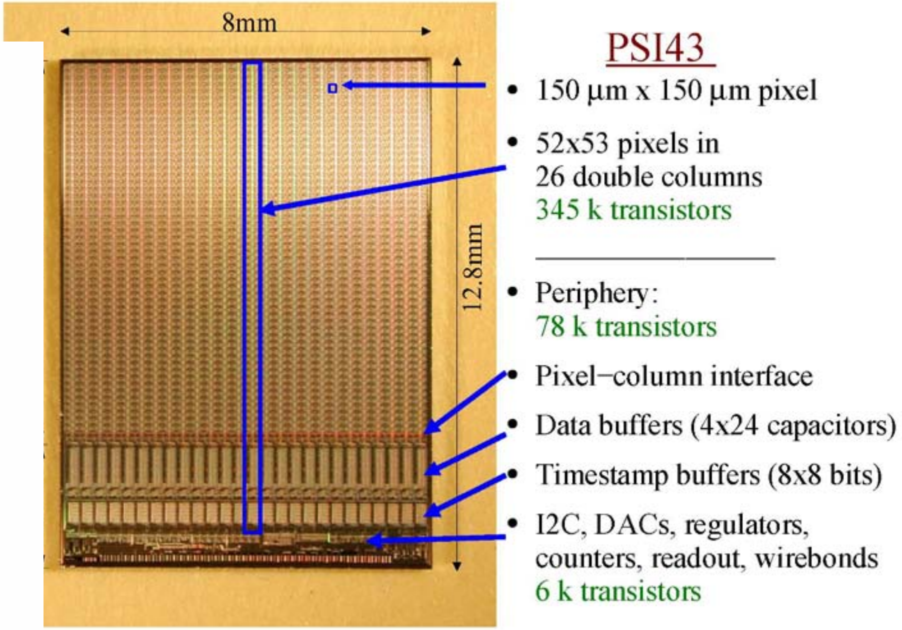
CMS tracker

- full silicon tracker
- 210 m^2 of silicon
- 10.7 M channels

Some examples of detectors : pixel sensors

2d information (pixel size ~150μm 150 μm). Allow to resolve strip ambiguity in very high multiplicity environment

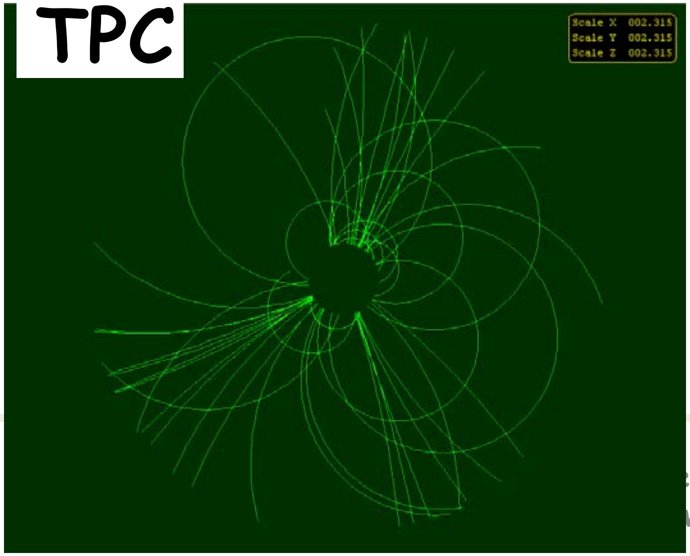




Can use same substrate for sensor and electronics : CMOS detectors with IPHC as one of the world’s expert lab.

Summary track detectors

- Charged track detectors have taken full benefit of progress in magnets (supra) with high field and dimensions, and electronics developments. Whatever technologies B field knowledge + alignment of detectors is needed (can use real events)
- Gaseous are used since 60' but have really a new revival with the micro strips gas chambers
  high flux no more a problem. Good resolution can be really good with pixel readout
  Many many applications, not only in HEP
  New TPC will probably use these readout devices in future LC experiments project
- Solid state detectors : considerable progress in // with electronics readout.
  one order of magnitude in their use with the LHC experiment
  (200 m^2 in CMS detector of Si strips !)
  Many R&D to improve radiation hardness, readout speed, material budget…..



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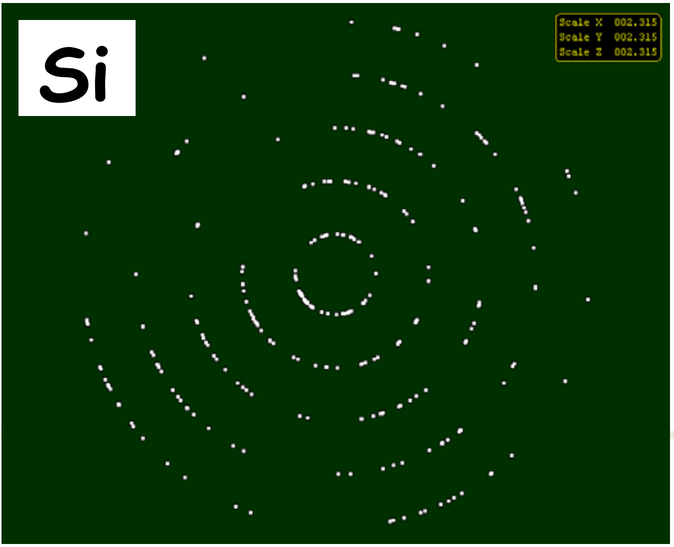
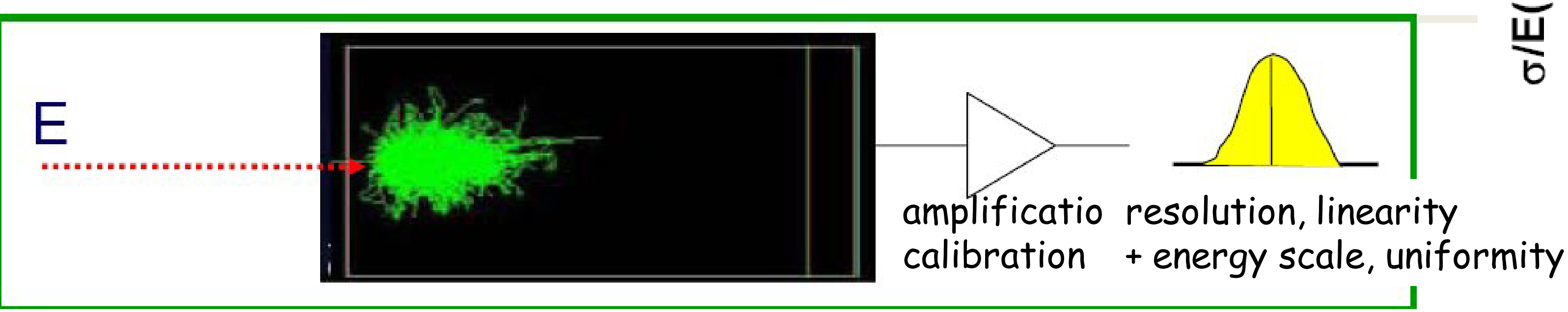
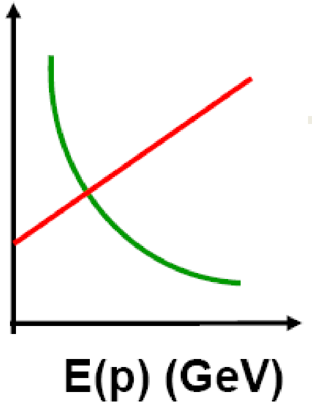


Energy measurement → calorimeters





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

Calorimeters are key detectors in experiment as :

-Work for charged particles (electrons + hadrons) and neutral particles (photon, neutron…)

-The resolution through cascade provides a resolution ∝ 1/√E so improving with energy (dp/p ∝p)

-The depth of a calorimeter goes as ln(E) while for a spectrometer at constant resolution it goes like √p.

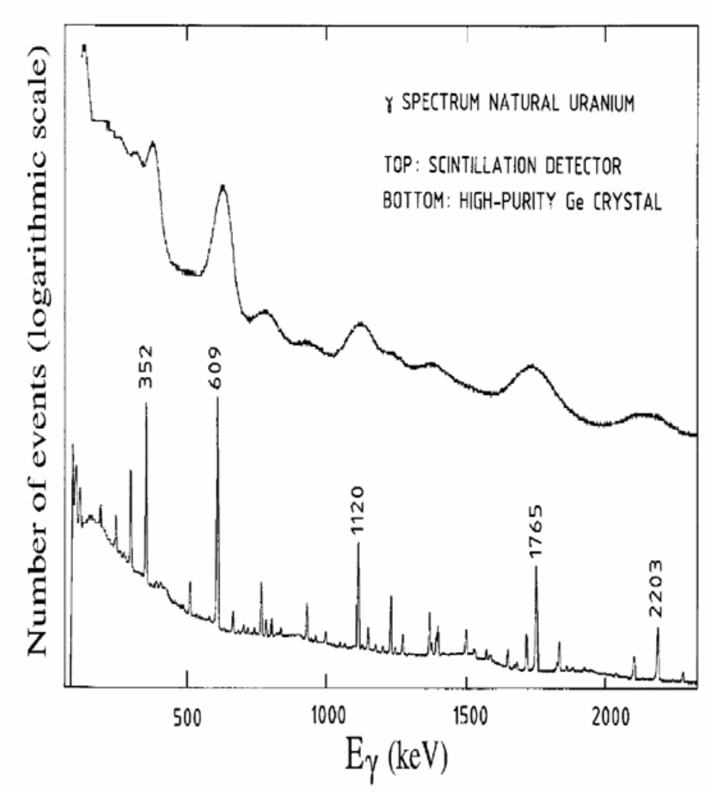
- Able to measure jets energy alone

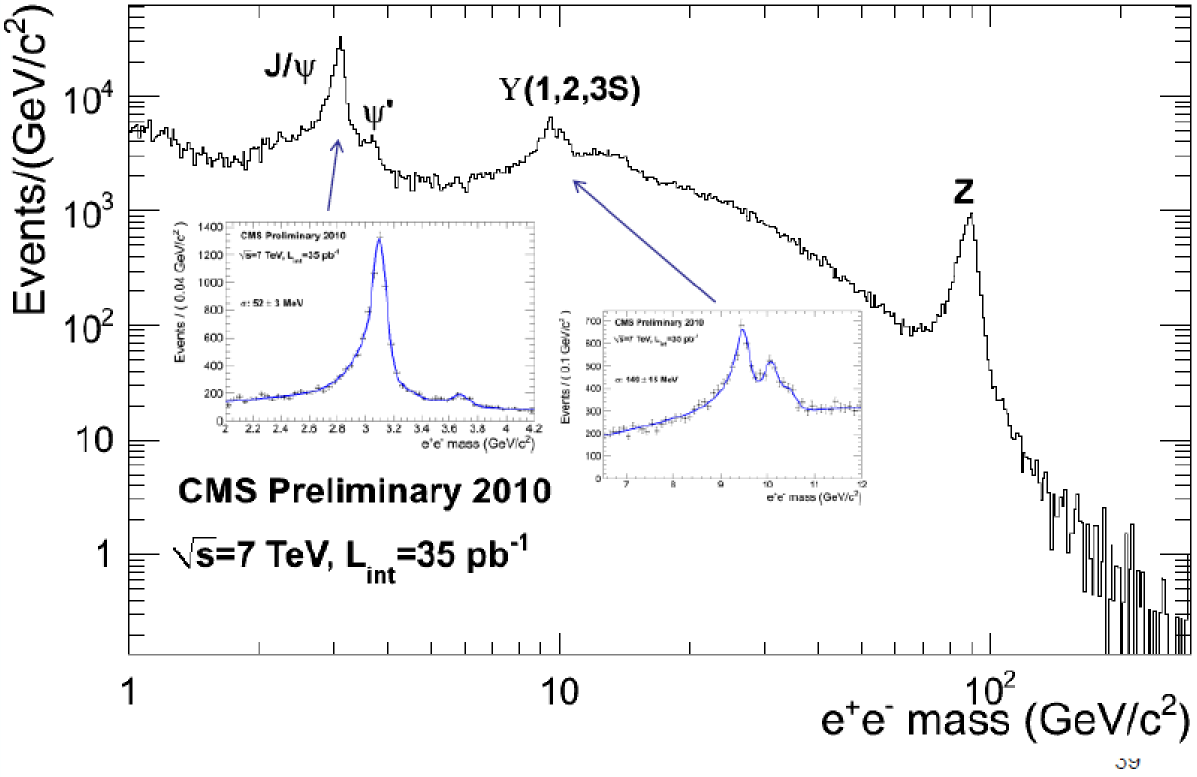
- Provide position/angular measurements (for photons) and contribute to particle identification when segmented laterally and longitudinally

- Can be fast : trigger and time measurement

- Full coverage allow to measure missing energy

Energy resolution

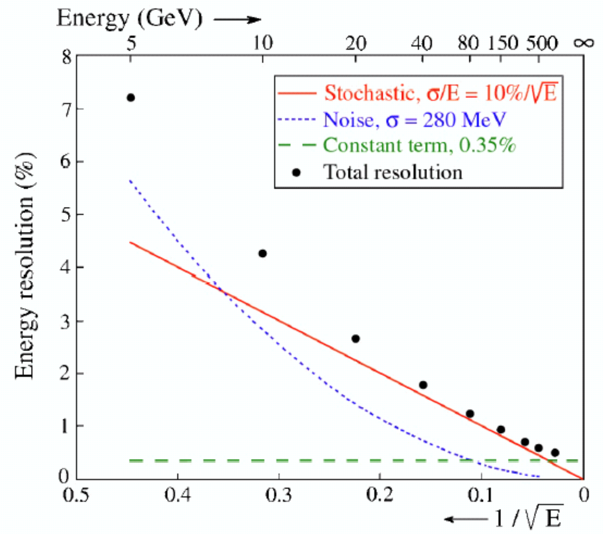




Energy resolution

Usually parameterized by
(stands also for hadron calorimeter) :

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



a : intrinsic resolution or stochastic term

→ given by technology choice

c : contribution of electronics noise

+ at LHC pile up noise…

→ given by electronics design

b : constant term, it contains all the imperfection, response variation versus position (uniformity), time (stability), temperature….

→ Constraints on all aspects : mechanics, electronics….

Linearity is also important : signal ∝ E over large dynamics with material upstream, lateral and longitudinal leakage

Calorimeters technologies

Homogeneous calorimeters

Material used to develop shower (dense) is also producing the signal proportional to E (only EM calorimeter) :

-Cristal calorimeters : NaI, CsI, PbW0$_4$ (X$_0$=2.2 cm)

→ Light signal

- Noble liquids: Ar, Kr (4.7), Xe(2.8)

→ ionization signal (+light)

+ Large fraction of the energy released is measured → good intrinsic energy resolution (3% /√E)

- Usually expensive as rare material. No longitudinal segmentation

Sampling calorimeters

Only solution for hadronic calorimeters to be compact. Alternate dense material (absorber, Pb, W) to develop shower and active layer to measure signal (noble liquid/gas, Si layer, scintillator….)

+ can have longitudinal segmentation, in principle cheaper detector

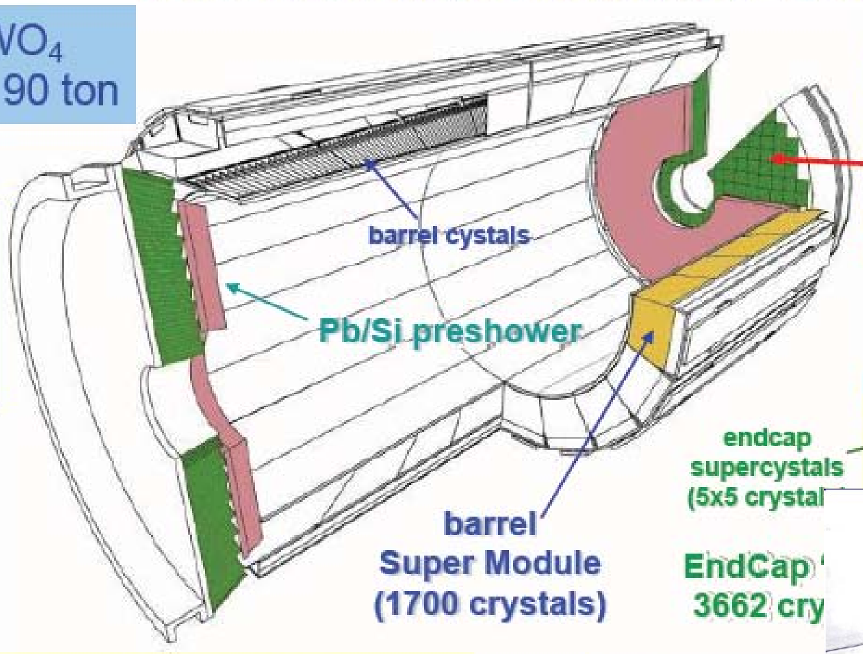
- Some energy released in absorber thus large fluctuation : worse intrinsic energy resolution ~10%/√E for EM, 50% for had

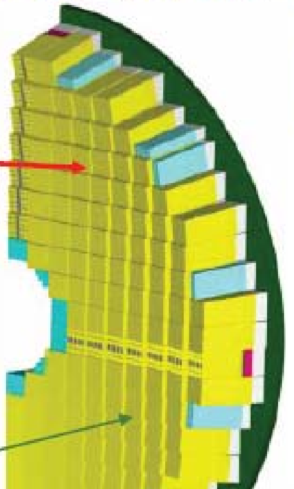
Example of homogeneous calorimeter : CMS

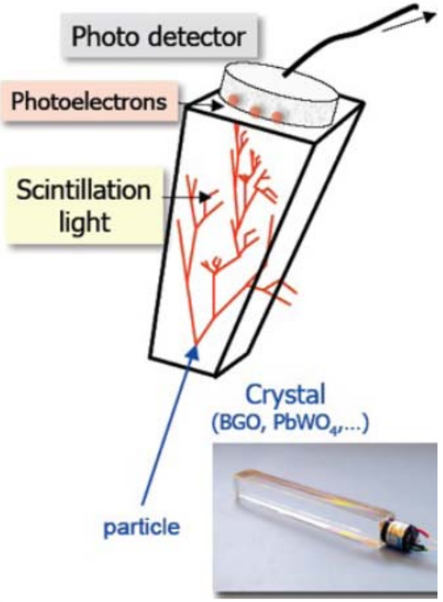
Precision electromagnetic calorimetry: 75848 PWO crystals

PWO: $PbWO_4$
about 10 m³, 90 ton

Previous
Crystal
calorimeters:
max 1m³

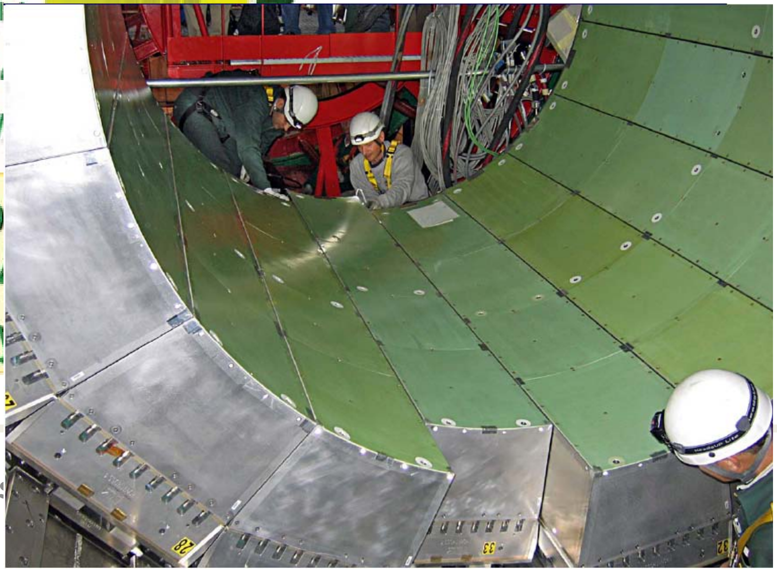






Barrel: $|\eta| < 1.48$
36 Super Modules
61200 crystals (2x2x23cm³)

EndCap
4
14648 cr



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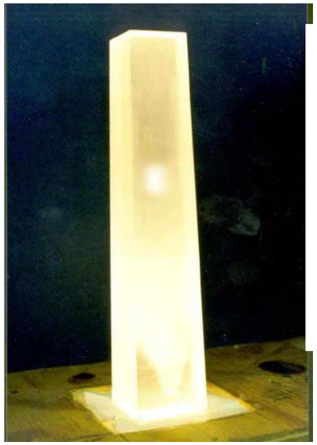
Examples of homogeneous calorimeter with crystals : Babar

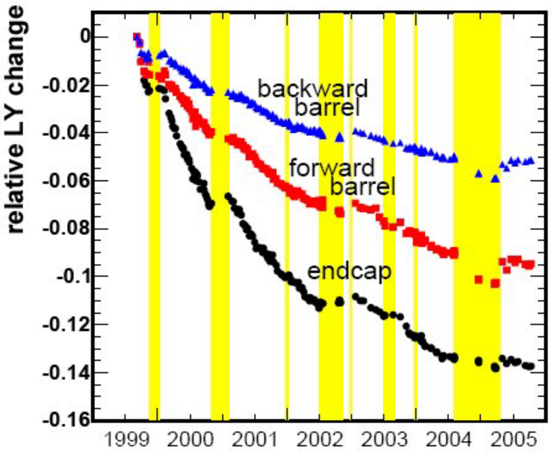


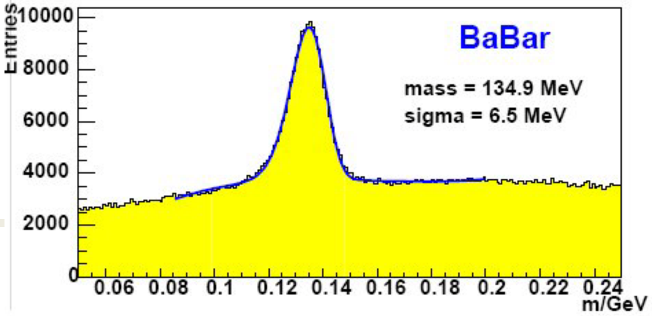
6580 crystals of CSI(Tl
about 17 X_0

Photon energy between
20 MeV and 8 GeV

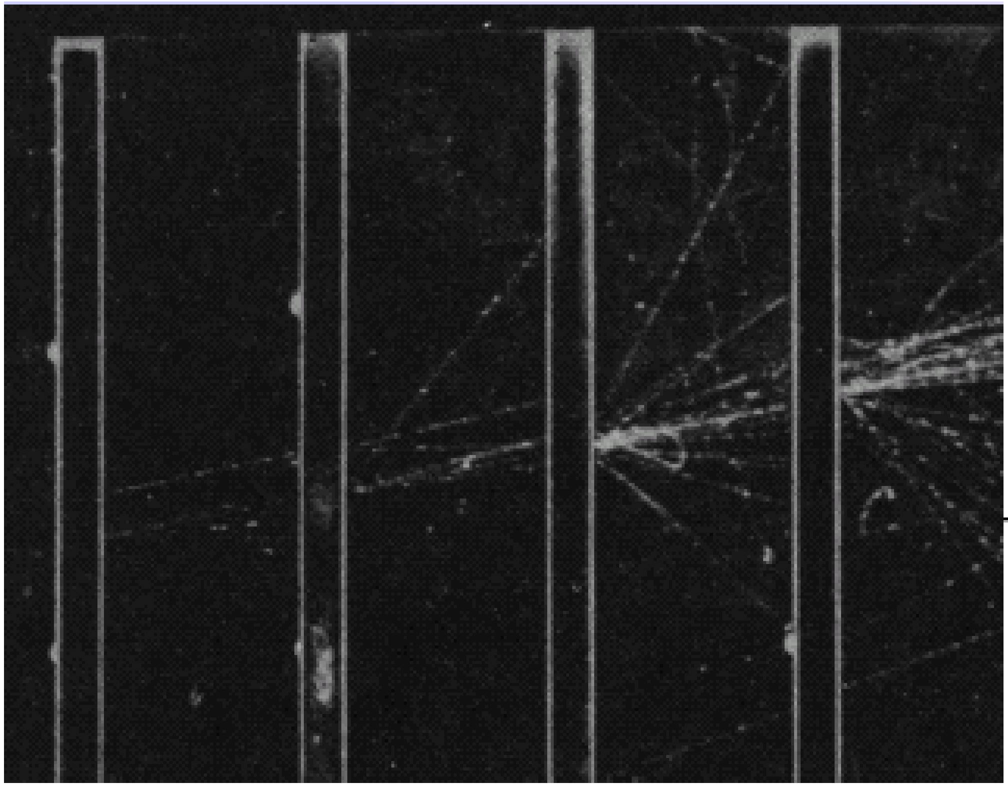
$$\frac{\sigma_E}{E} = \frac{(2.30 \pm 0.03 \pm 0.3)\%}{\sqrt[4]{E(\mathrm{GeV})}} \oplus (1.35 \pm 0.08 \pm 0.2)\%$$

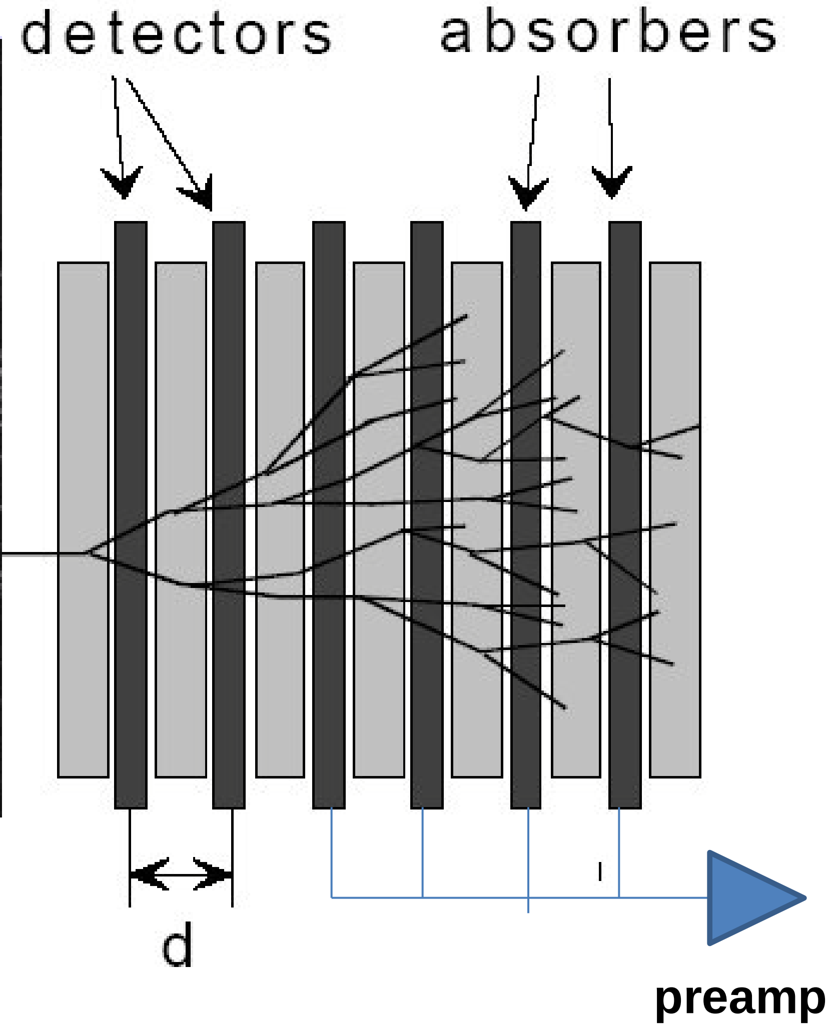
$$\sigma_\theta = \sigma_\phi = \frac{(4.16 \pm 0.04)\ \mathrm{mrad}}{\sqrt{E(\mathrm{GeV})}}$$



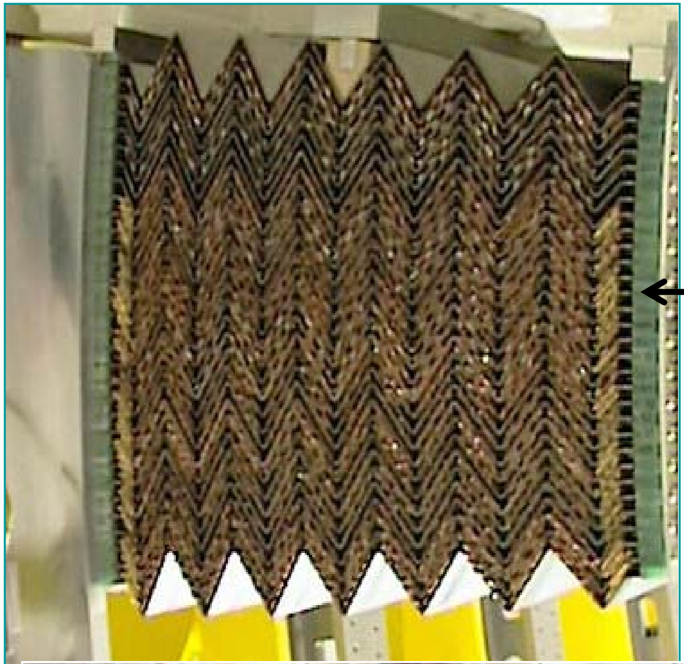


Sampling calorimeters





Example of sampling calorimeter : ATLAS



ATLAS EM calorimeter :

Sandwich of lead (1.1->1.8 mm) absorbers and liquid argon active layer (2x 2mm gap)

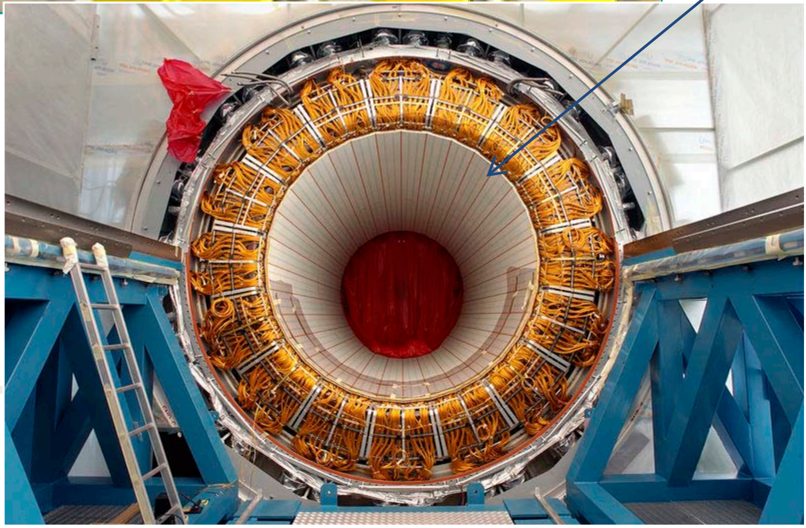
Collect ionization signal in Ar with electrical field

Accordion shape to ensure φ homogeneity

longitudinal segmentation

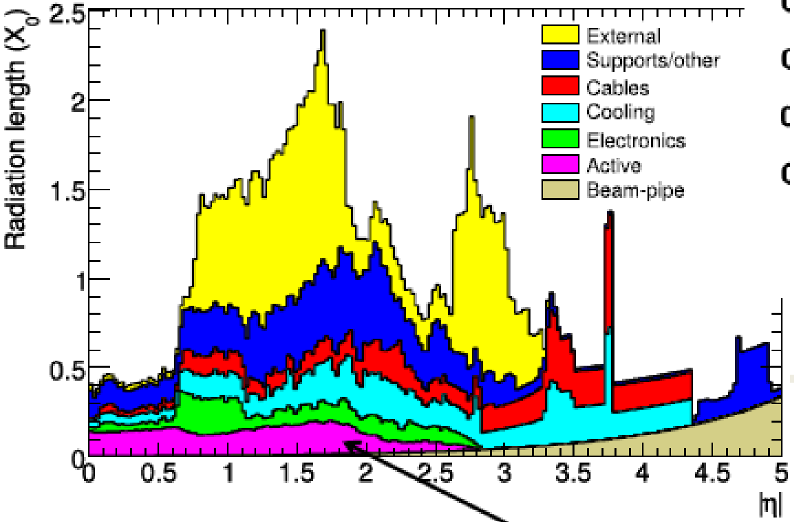
→Angular measurement for photon.

→ Presampler

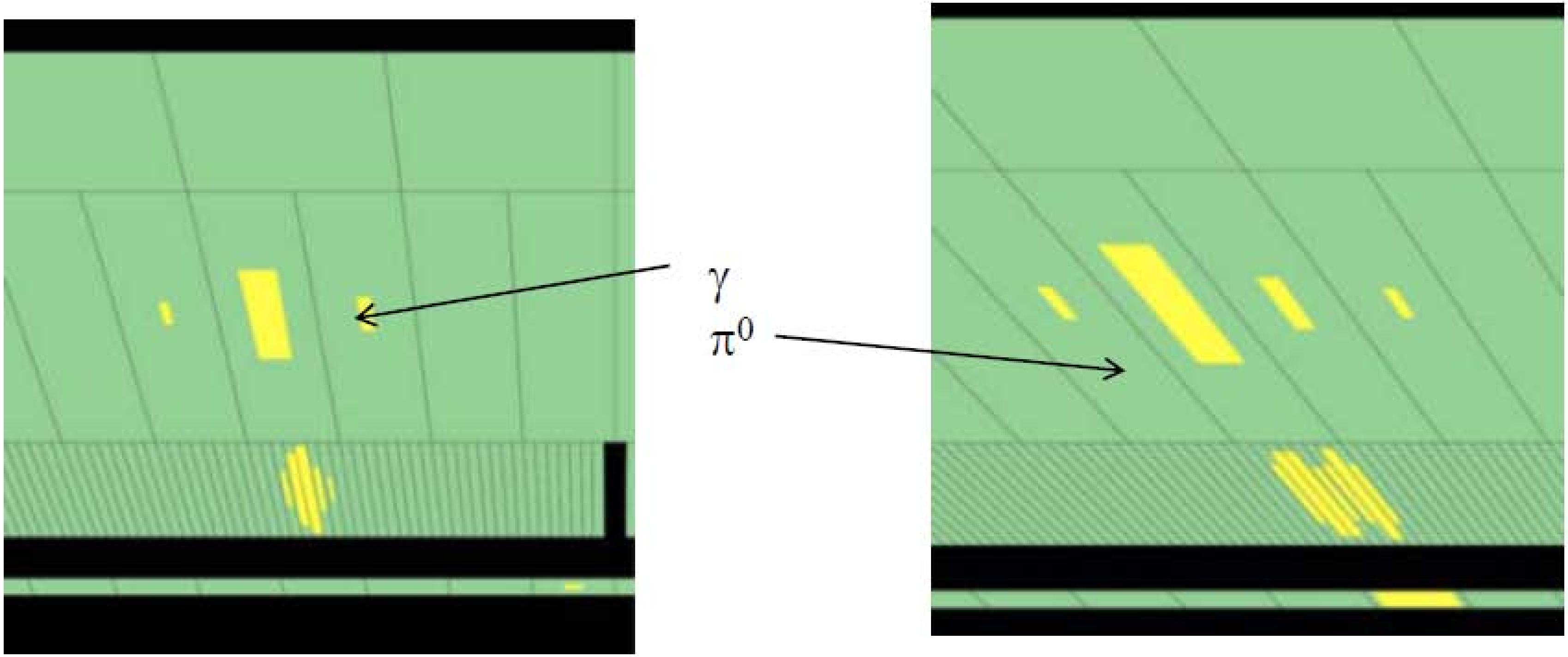


Calorimeter enemy :

Upstream material from tracker !



Lateral segmentation



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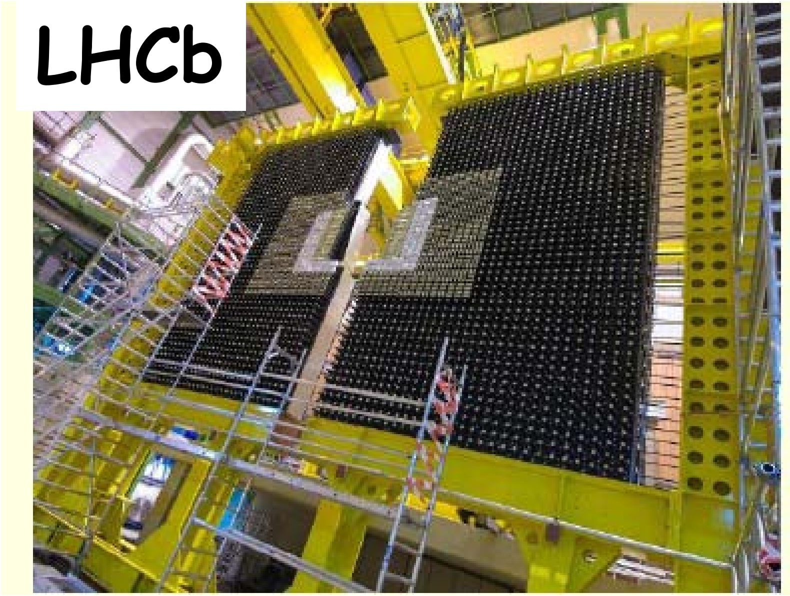
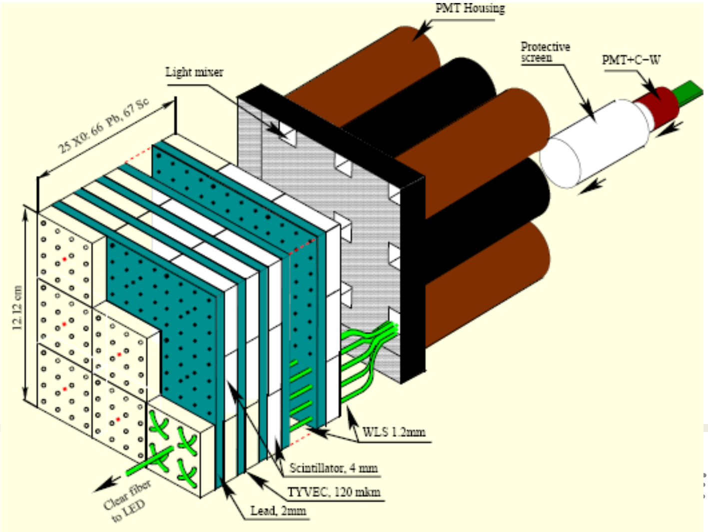
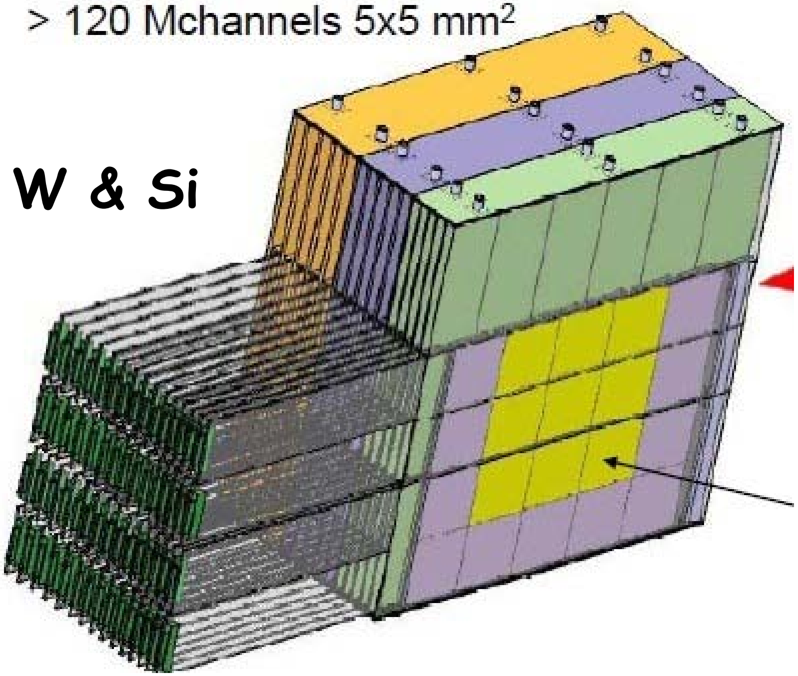
Example of sampling calorimeters : LHCb & CALICE





CALICE : imaging calorimeter for LC collider

> 120 Mchannels 5x5 mm^2



W & Si

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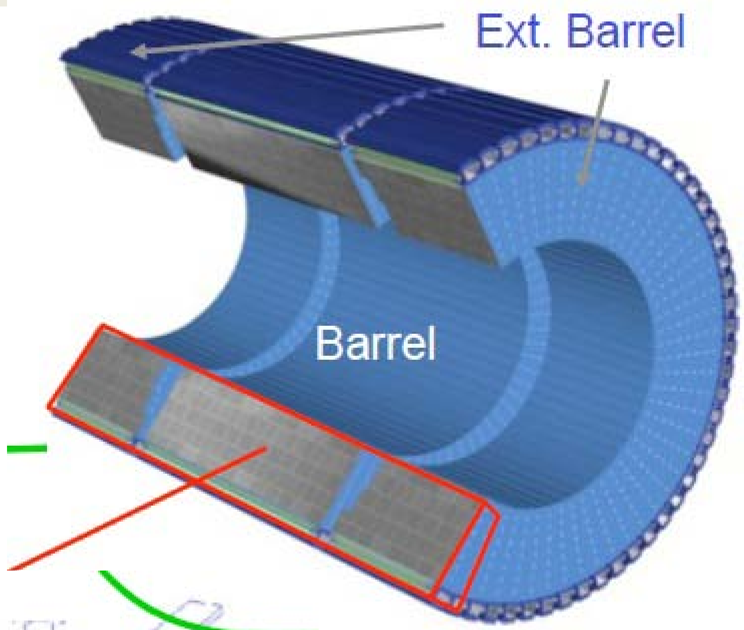
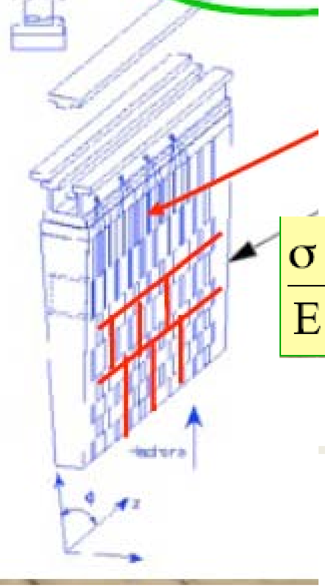
Example of Hadron calorimeters





ATLAS
Fe/scintillator

$$\frac{\sigma}{E} = \left(\frac{41.9\%}{\sqrt{E}} + 1.8\%\right) \oplus \frac{1.8}{E}$$

- CMS Hadron calorimter

Cu absorber + scintillators
↓
2 x 18 wedges (barrel)
+ 2 x 18 wedges (endcap) ≈ 1500 T absorber

$65\%/\sqrt{E} \oplus 5\%$

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Summary calorimeters

1) Electromagnetic calorimeter, only approach to measure high energy photon. Better also for electron energy measurement, as resolution improves as $1/\sqrt{E}$.

→ Best sampling term given by homogeneous calorimeters (crystal/noble liquid).

→ Constant term is dominant at high energy: importance of uniformity/stability response.

→ In real experiment, material upstream +B field are a main concern : photon conversion, electron bremsstrahlung

- New crystals on the market (LSO,LYSO) similar density as PWO, 200 more light, no temperature sensitivity…. mass production ?

2) Hadronic calorimeter (sampling calorimeters) and jet reconstruction :

- classical sampling calorimeters used at hadrons colliders, limited at 50-60 $\%/\sqrt{E}$ for jets. Small improvement with the energy weighting of the cells.

-Two new approaches :

PFA approach with combination of all detectors and fine calorimeter granularity to track any particle (particle multiplicy should not be too high, easier in e+e-)

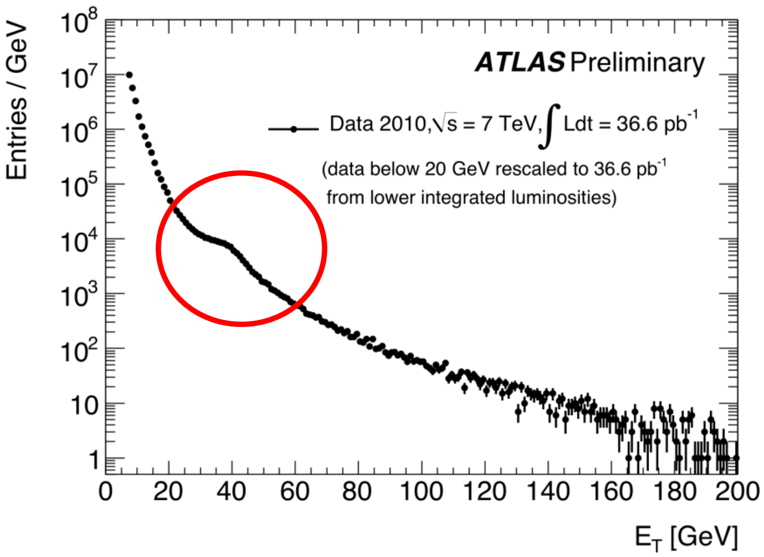
- Use of different techniques to detect independently each contribution to the energy deposit (all, em fraction, neutron….).

Why particle identification (I)

ATLAS/CMS@LHC

Jet cross-section ~10^5 larger than electron from W/Z

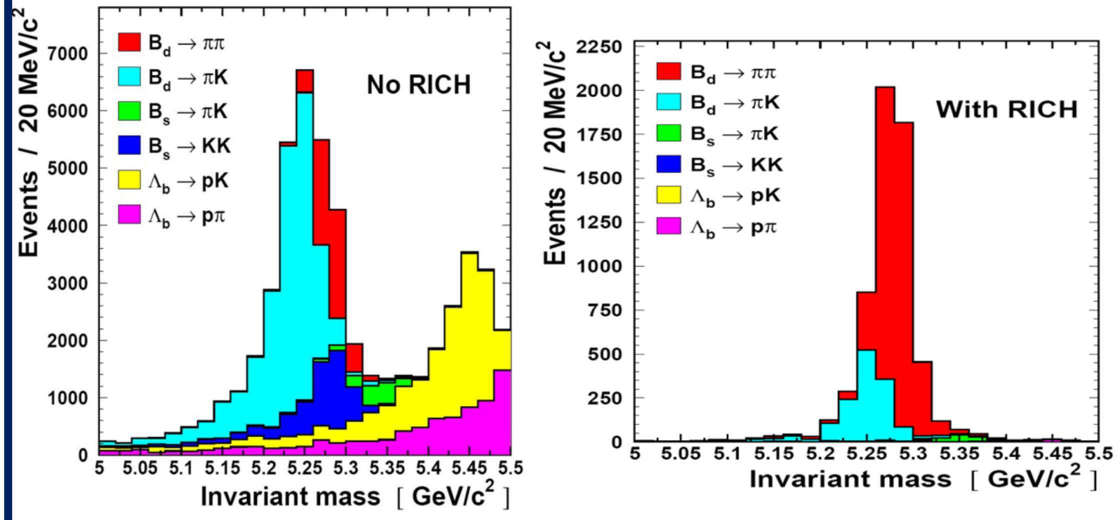
Jet can also mimic photon



With 10^5 rejection factor, can see Z/W in inclusive spectrum

LHCb@LHC

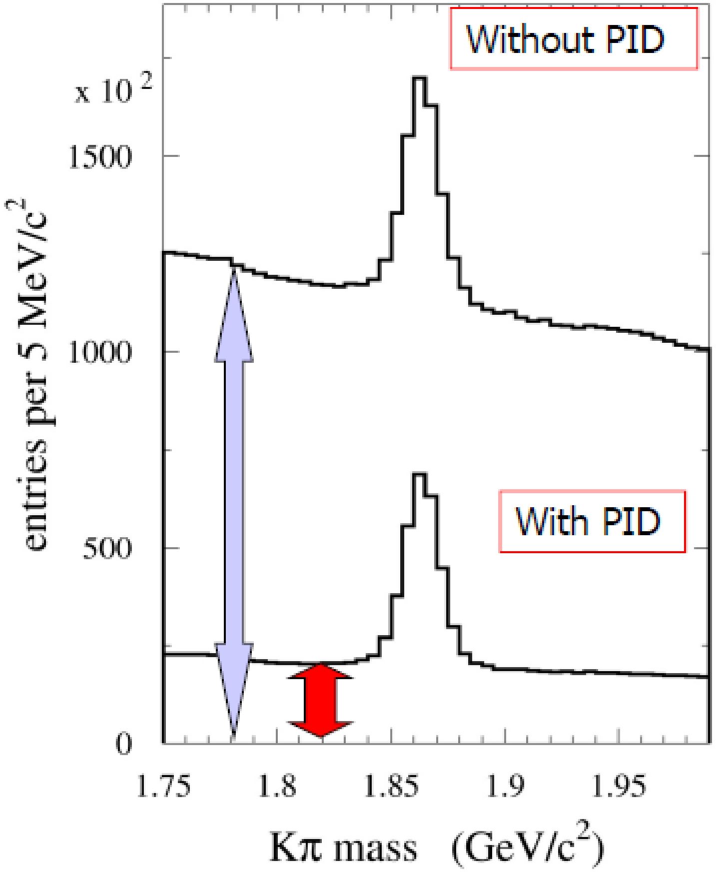
Need to separate B decays in p, K, π to extract B→$\pi\pi$



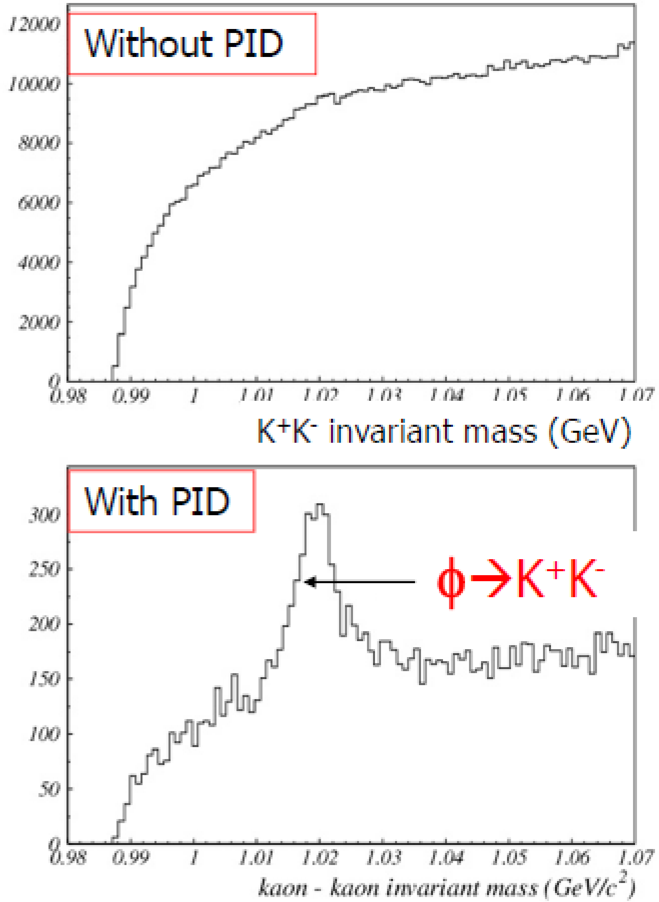
Dedicated cerenkov detectors

Why particle identification (2)

B factory



HeraB



PID with calorimeters : example ATLAS

Use EM showers characteristics

—— electron

---- Jet

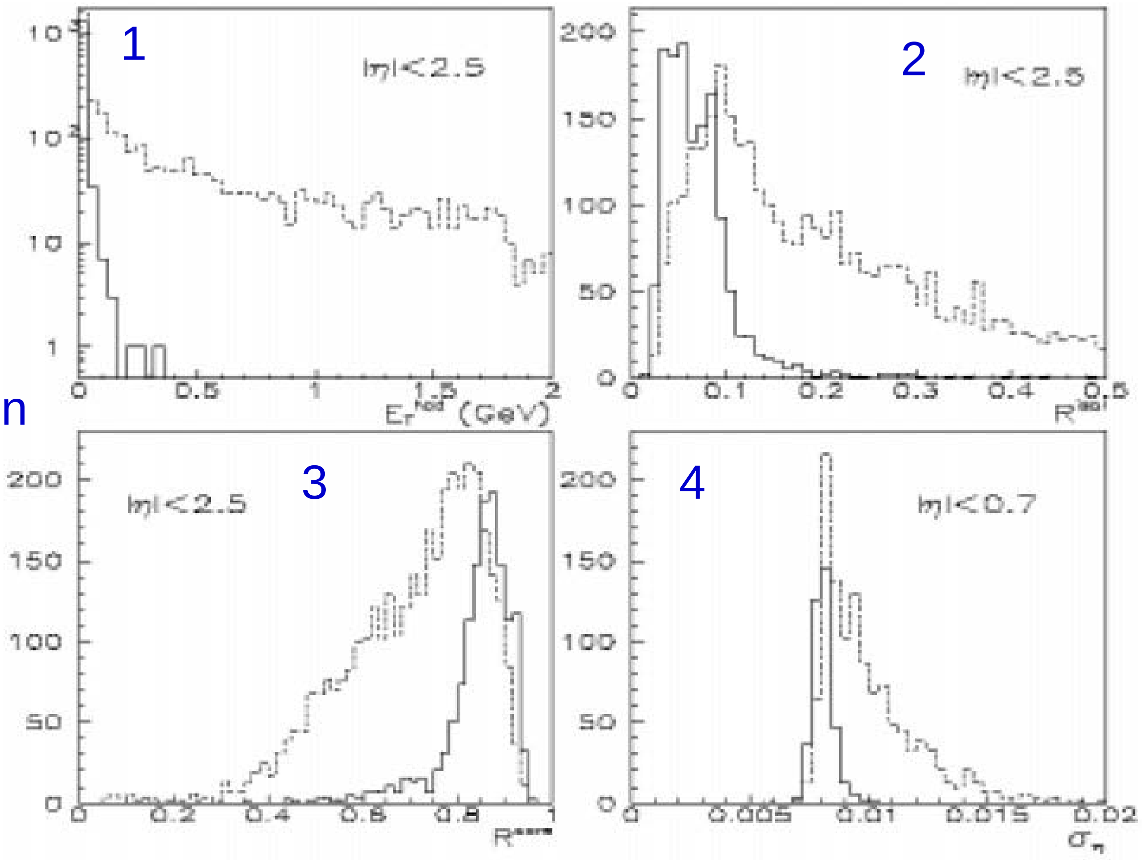
1) Most of energy release in EM Calorimeter, hadronic signal small

2) Electron is isolated, no energy Outside cluster

3) Shower is compact : large fraction of energy released In a few cells

4) Small lateral profile

Can also used E(calo)/P(tracker)



PID at low momentum : e/π/K/p

Use physics process sensitive to particle mass or speed :

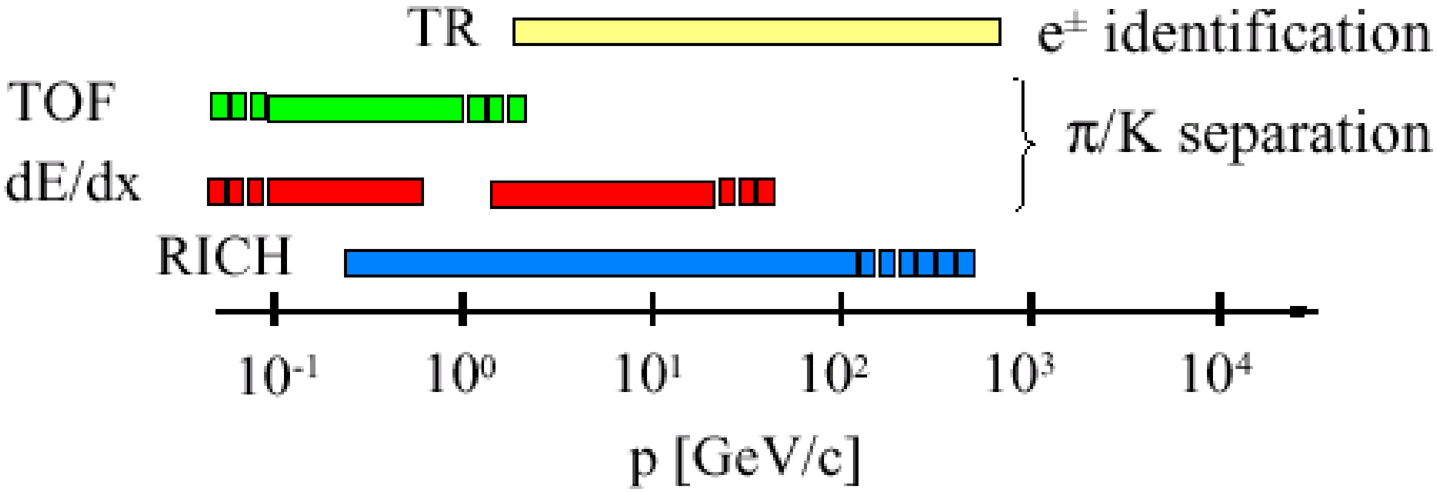
-Transition radiation (sensitive to $\gamma=E/m$): distinguish electron from heavy charged particles

- TOF : measure particle speed : two particles of same energy have different speed if different mass

- dE/dx : dependence on γ and β

- Rich detectors : linked to particle speed in the medium

Most of the time need to combine two techniques and/or with p momentum



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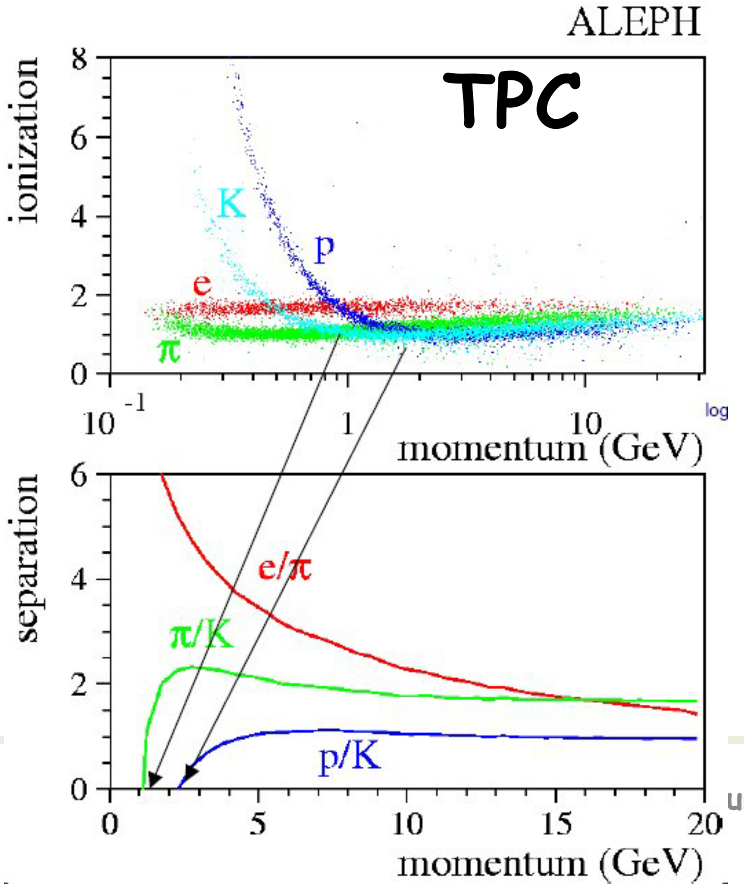
dE/dx measurements

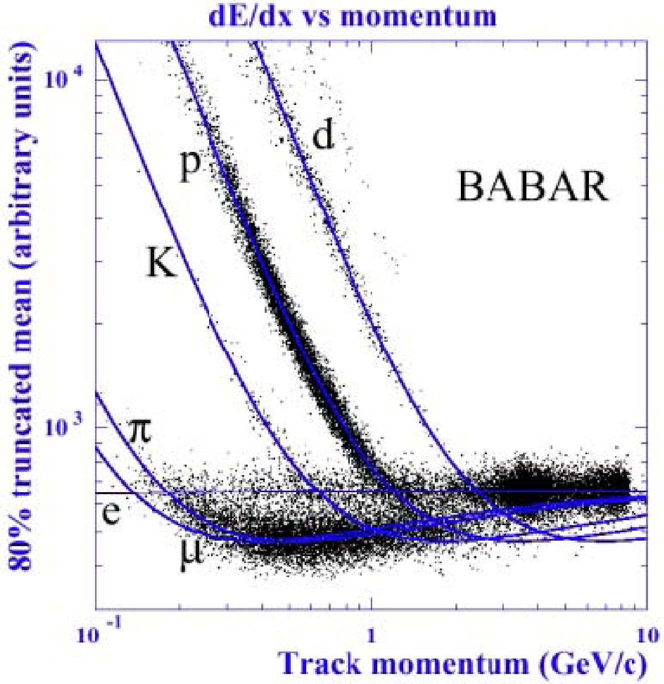
$$p = m_0 \beta\gamma$$

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

Simultaneous measurement of p and dE/dx gives access to mass

DCH +SVT dE/dx

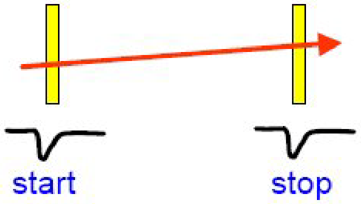




Time of flight measurement

Particle ID using Time Of Flight (TOF)

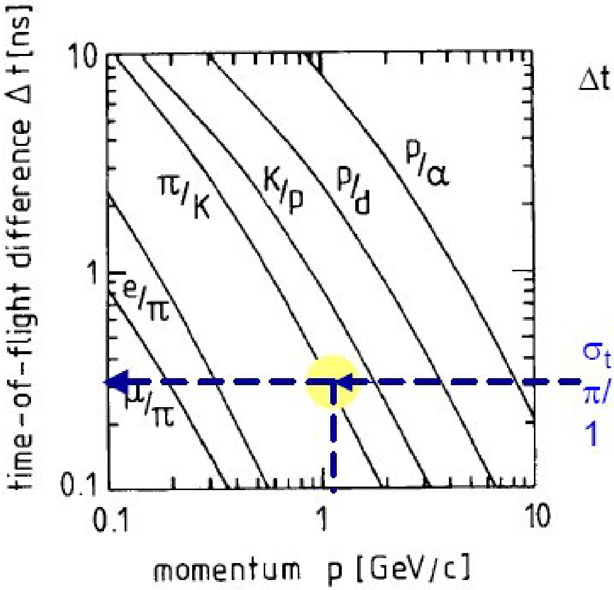
$$t = \frac{L}{\beta c}$$



Combine TOF with momentum measurement $(p = m_0 \beta\gamma)$

$$m = p\sqrt{\frac{c^2t^2}{L^2} - 1}$$

Mass resolution $$\frac{dm}{m} = \frac{dp}{p} + \gamma^2\left(\frac{dt}{t} + \frac{dL}{L}\right)$$



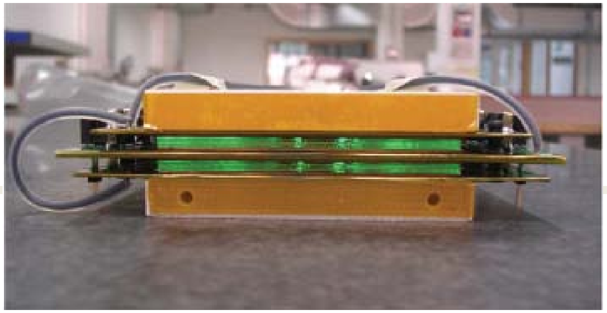
Δt for L = 1 m path length

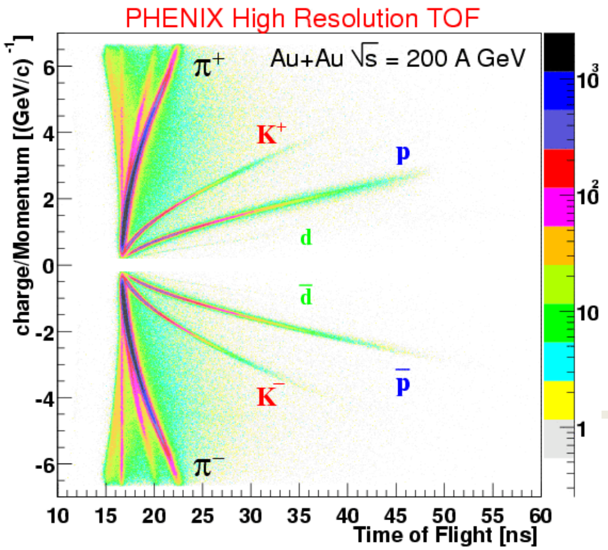
σ_t = 300 ps
π/K separation up to
1 GeV/c

TOF difference of 2 particles at a given momentum

$$\Delta t = \frac{L}{c}\left(\frac{1}{\beta_1} - \frac{1}{\beta_2}\right) = \frac{L}{c}\left(\sqrt{1 + m_1^2c^2/p^2} - \sqrt{1 + m_2^2c^2/p^2}\right) \approx \frac{Lc}{2p^2}\left(m_1^2 - m_2^2\right)$$

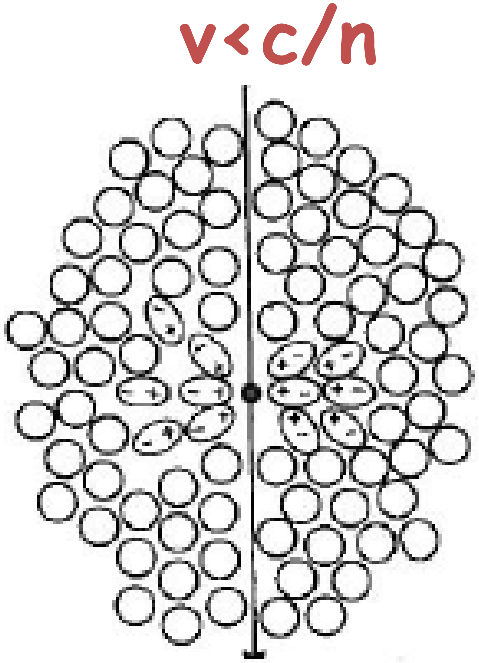
Used in ALICE with time resolution about 100 ps with multigaps RPC

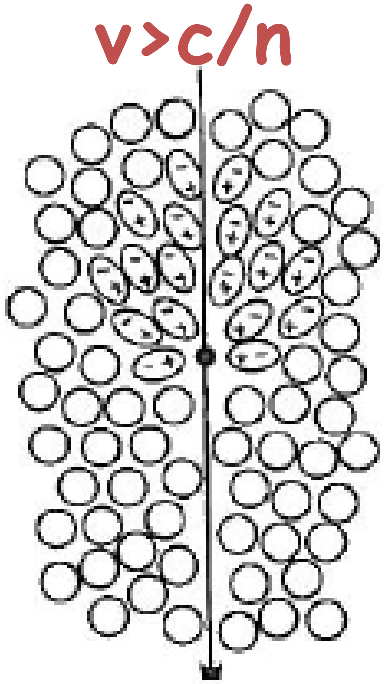




Cerenkov effect

Cerenkov radiation is emitted when a charged particle passes through a dielectric medium with a velocity > threshold speed (speed of light in the medium)





Measure θ_c

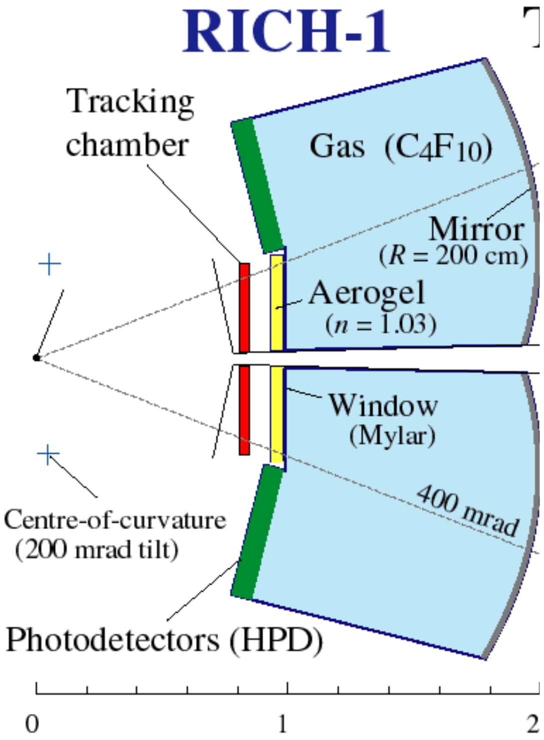
Use a few detectors with different refractive index and threshold technique (only counter)

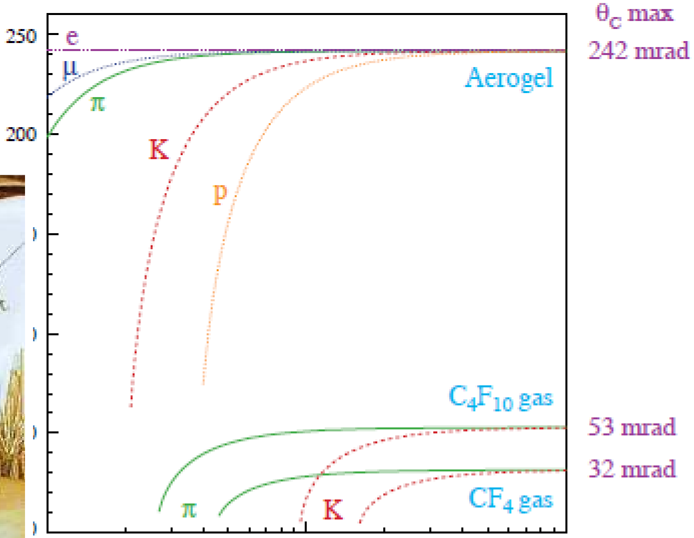
isobutane	1.00127	2.89	0.941
water	1.33	41.2	160.8
quartz	1.46	46.7	196.4

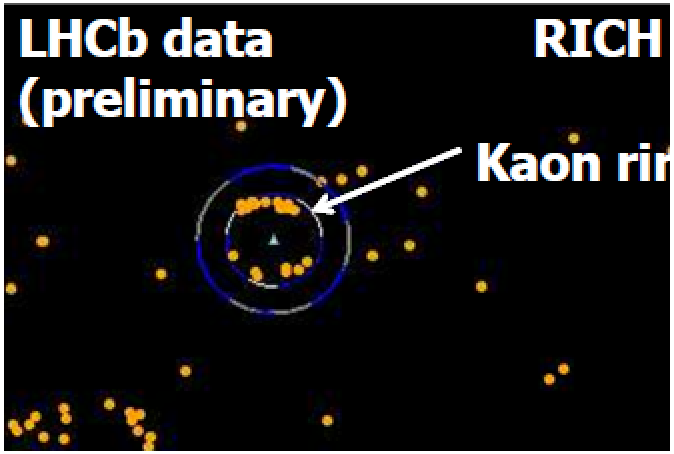
~50 less photons than with a scintillator

Example of Cerenkov detectors : LHCb

Two detectors (HPD) and three radiators :
aerogel (2-10 GeV), C_4F_{10} (10-60),CF_4(16-100)







Radiation transition effect

Electromagnetic radiation is emitted when a charged particle traverses a Medium with discontinuous refractive index (at the transition)

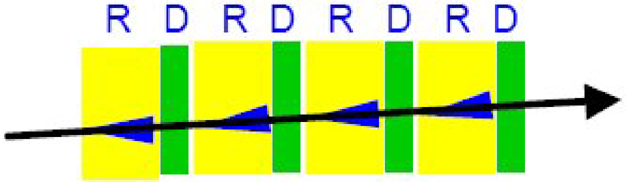
Radiated energy $W = \frac{1}{3}\alpha\hbar\omega_p\gamma$

$$\omega_p = \sqrt{\frac{N_e e^2}{\varepsilon_0 m_e}} \quad \left(\begin{array}{c}\text{plasma}\\ \text{frequency}\end{array}\right) \quad \hbar\omega_p \approx 20\text{eV} \ \text{(plastic radiators)}$$

Only high energy electrons will give some signal

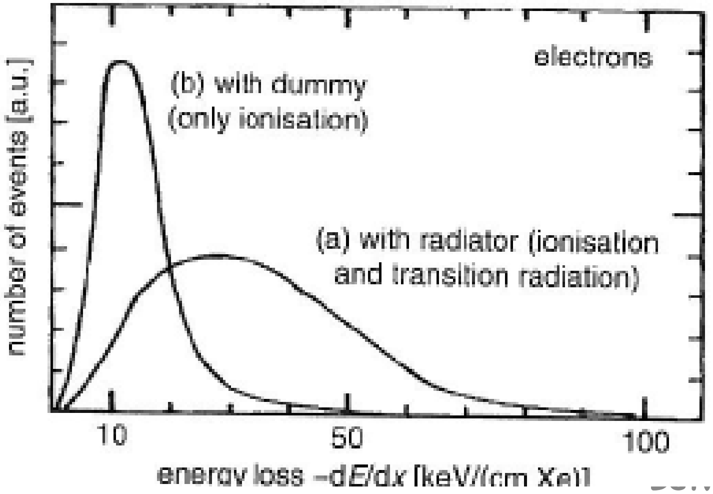
Number of photon / transition about α=1/137 !

→ Need a lot of transitions



Photons emitted with max angle $\theta=1/\gamma$

Typical spectrum in CH2 foil

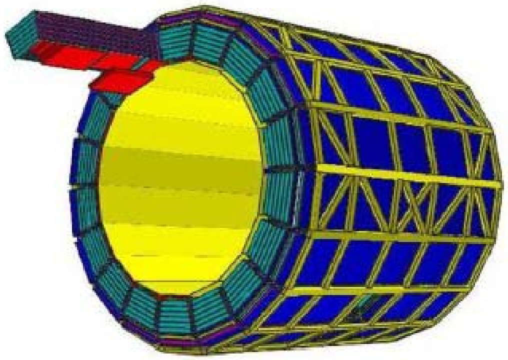


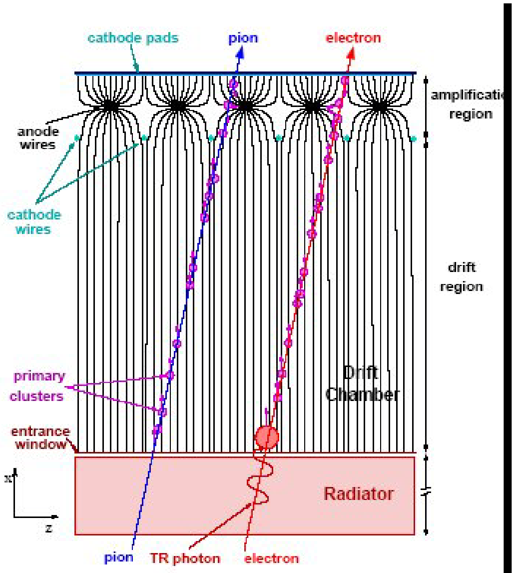
Radiator should be low Z (not re absorb the photons by photo electric effect !)

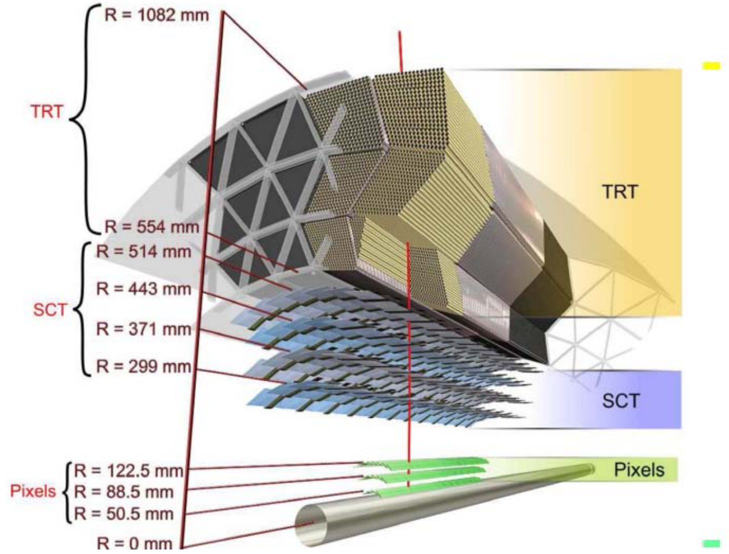
Xray detectors : gaseous detectors (drift chamber, MWPC, straw tubes…)

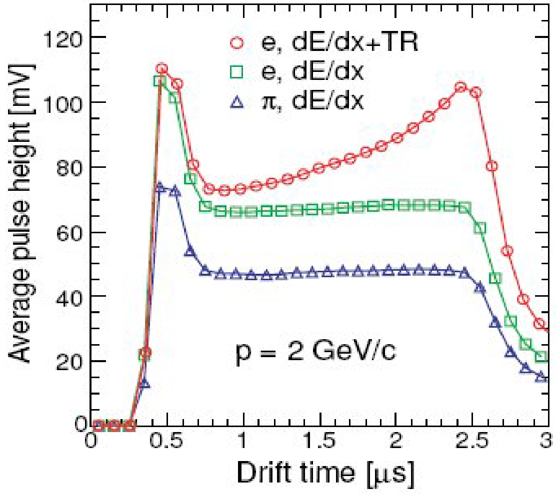
Signal should be larger than dE/dx to be detected by threshold !

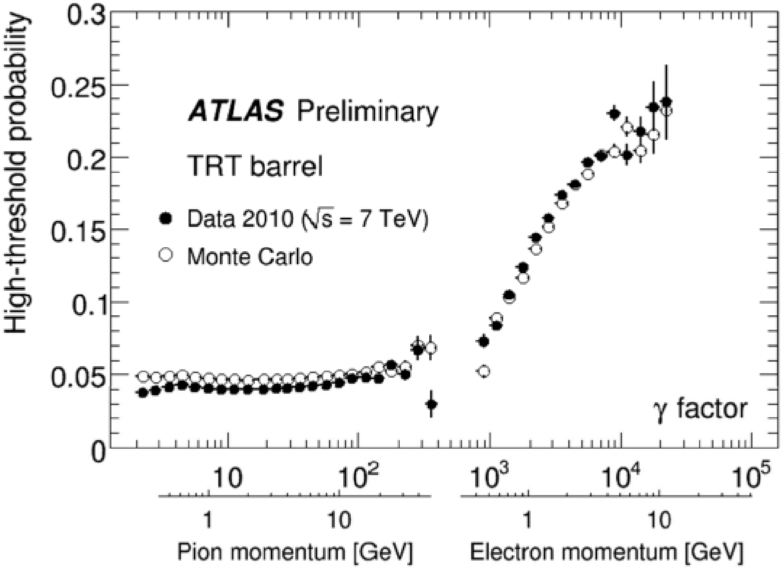
Example of TR detectors : ALICE & ATLAS











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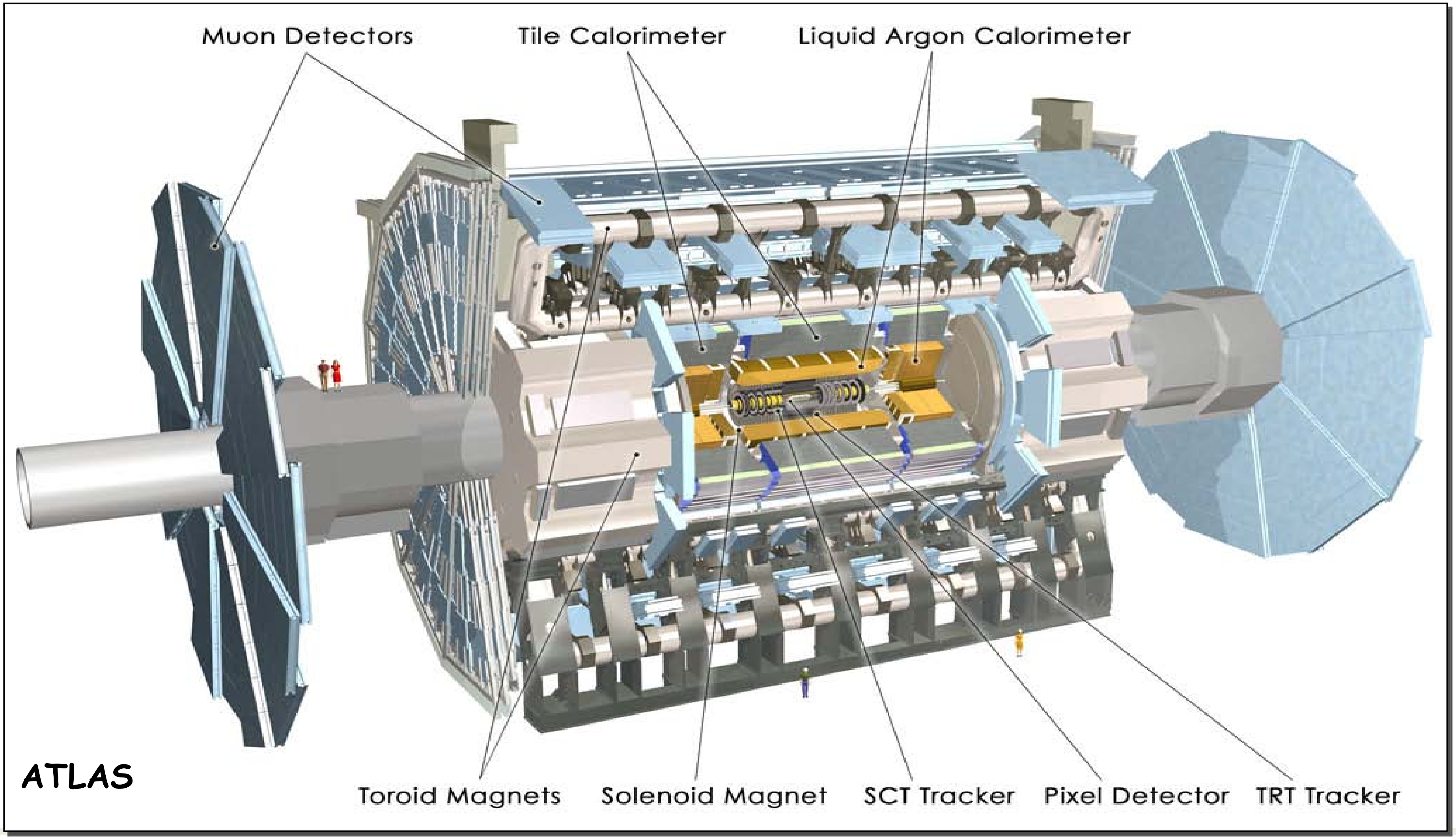
ATLAS


Muon Detectors
Tile Calorimeter
Liquid Argon Calorimeter
ATLAS
Toroid Magnets
Solenoid Magnet
SCT Tracker
Pixel Detector
TRT Tracker

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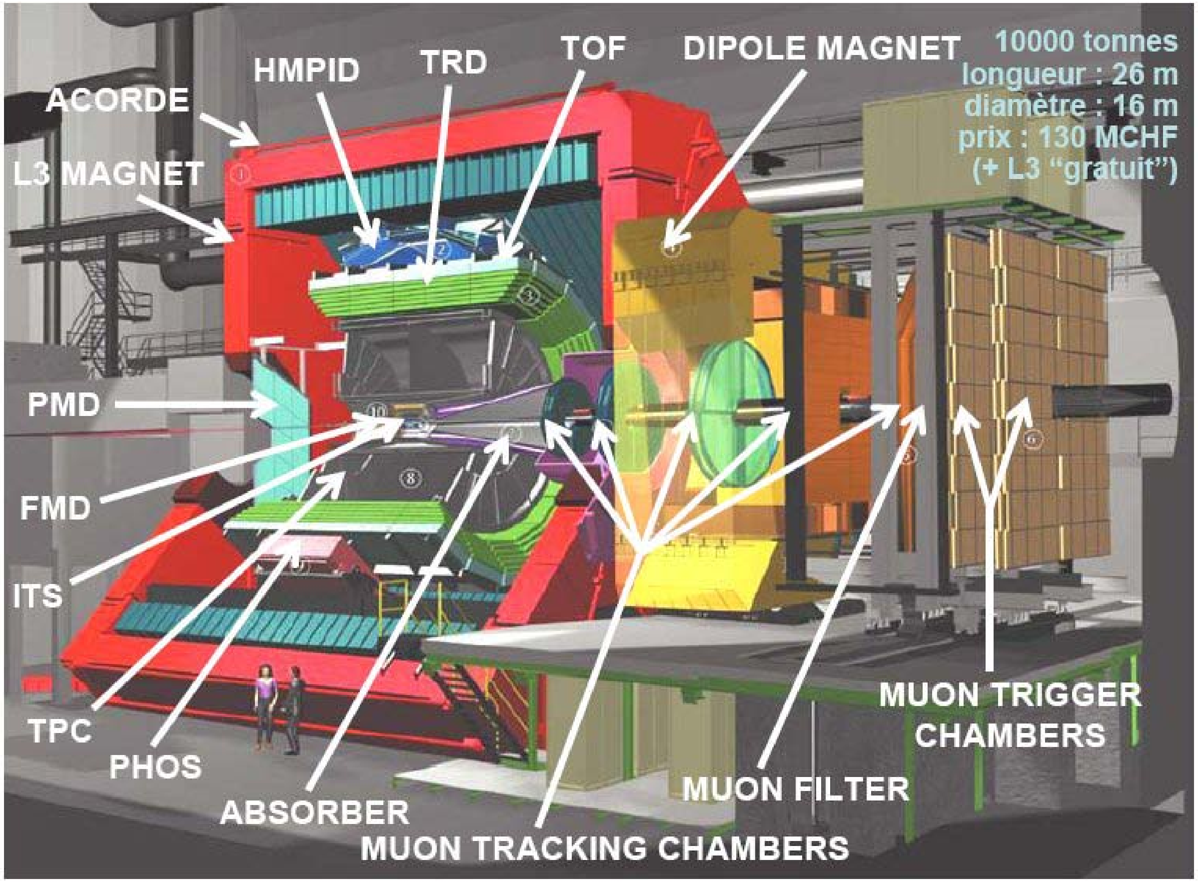
ALICE

RICH TRD detector TOF μ spectrometer

TPC : dE/dx

EM calo (PHOS EMcal)



Conclusion

- Detection of particle based on quite simple physics mechanisms, most of them very well known and simulated

- Detectors development (R&D) is a very rich domain in continuous evolution with a lot of new clever ideas (ILC, SLHC, Super B….) and using high technology

- Conception of an experiment is always a difficult enterprise : the best technology can be spoiled by the environment where it is used. Should define it with respect to the physics goals.

- A good experiment is not only good detectors but efficient trigger (for hadron collider) and easy/efficient software

- Understanding the detector response correctly is an absolutely needed step before claiming any discovery/physics results