3rd WORKSHOP ON PARTICLE PHYSICS

NATIONAL CENTRE FOR PHYSICS
(QUAID-I-AZAM UNIVERSITY)

Detectors for High Energy Physics

Lecture II – General Detector Concepts

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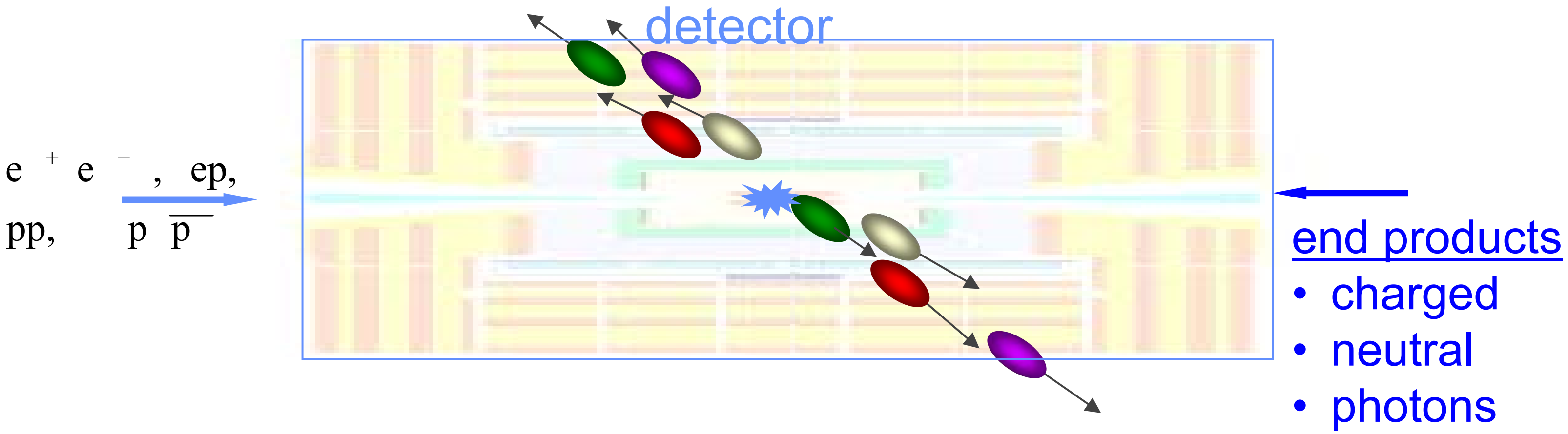
Particle Detectors



The 'ideal' particle detector should provide…

- **coverage of full solid angle (no cracks, fine segmentation)**
- **measurement of momentum and/or energy**
- **detect, track and identify all particles (mass, charge)**
- **fast response, no dead time**

Particle Detectors

practical limitations (technology, space, budget)

Particles are detected via their interaction with matter.

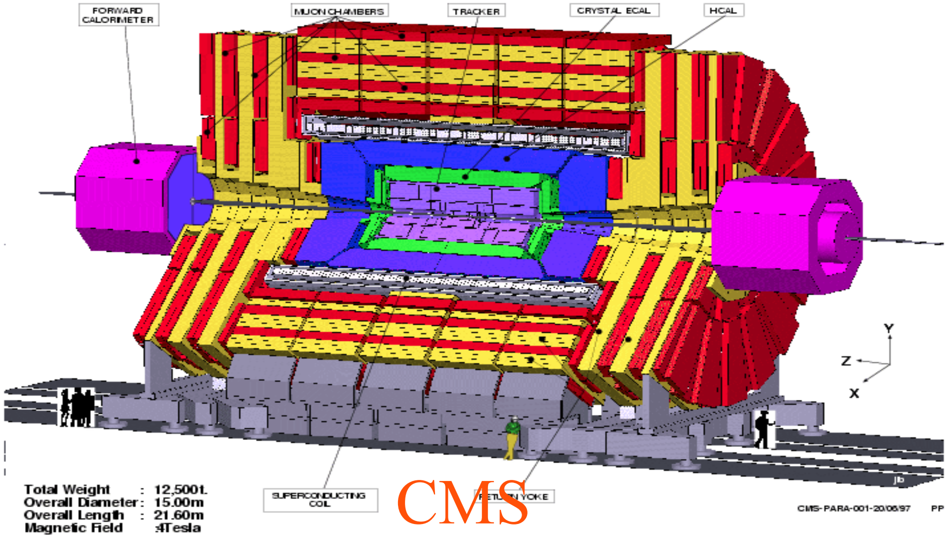
Many different physical principles are involved (mainly of electromagnetic nature).

Finally we will always observe...

onization **and** excitation **of matter.**

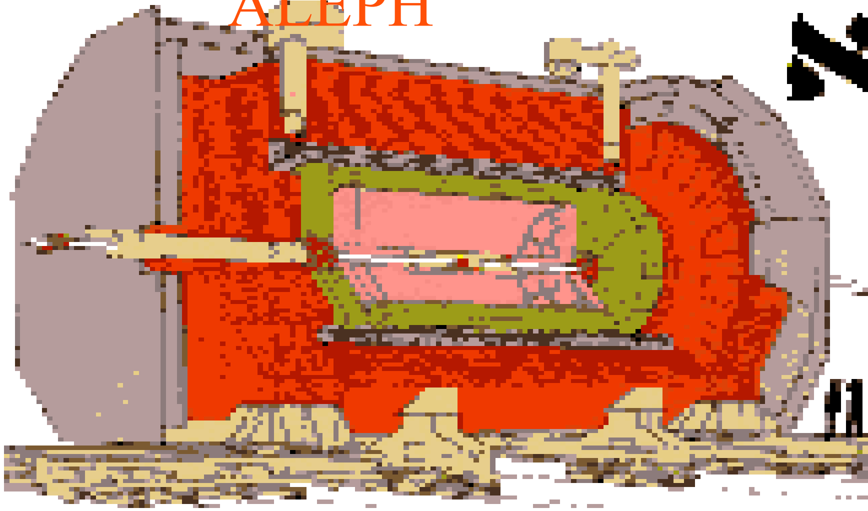
BIG DETECTORS

The concepts driving the design of a big collider experiment are very general all big collider experiments look - in first approximation - quite similar

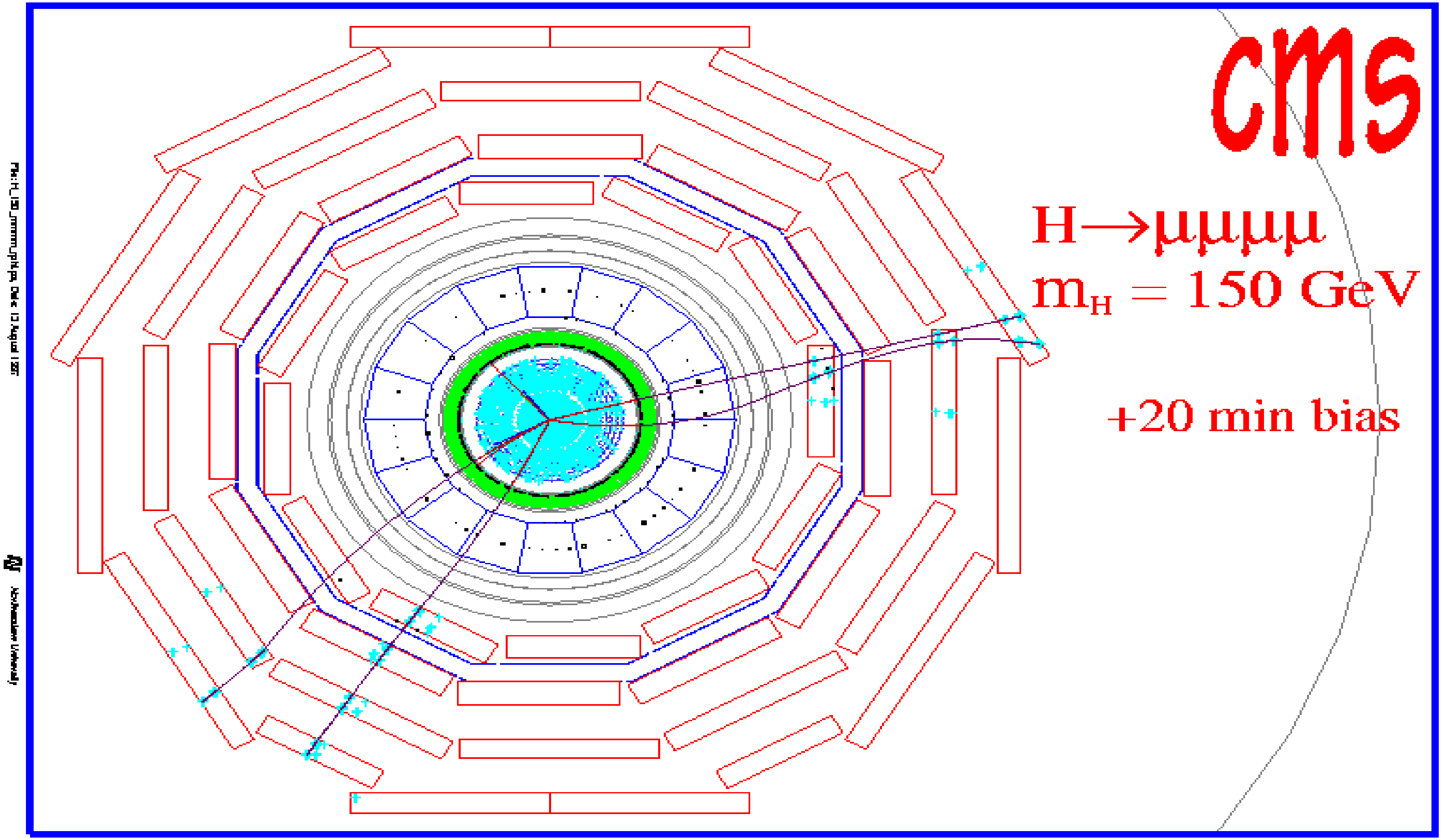


CMS

ALEPH



CMS: H in 4 muons

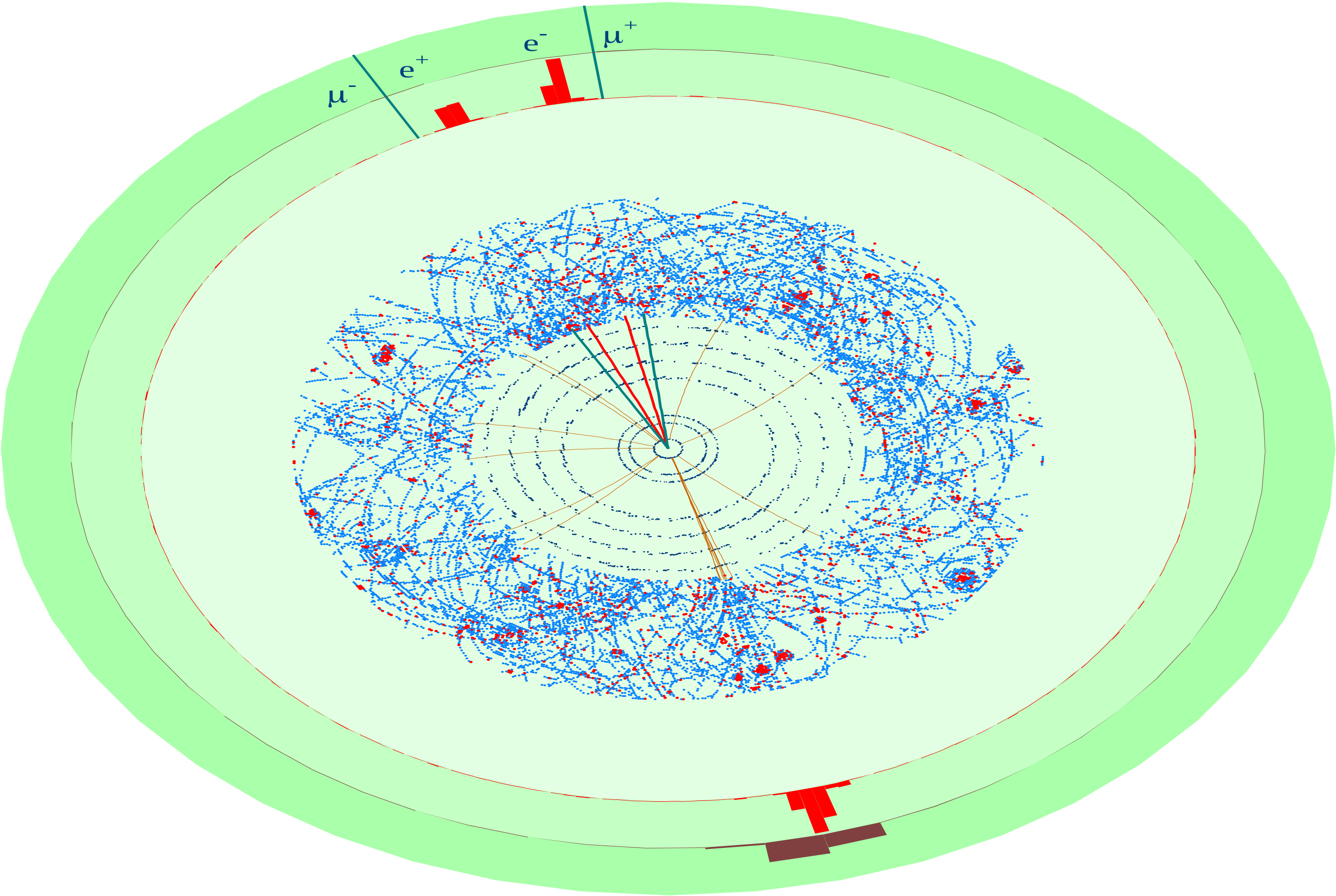


$H \rightarrow \mu\mu\mu\mu$

$m_H = 150$ GeV

+20 min bias

Atlas: H in 2e + 2mu

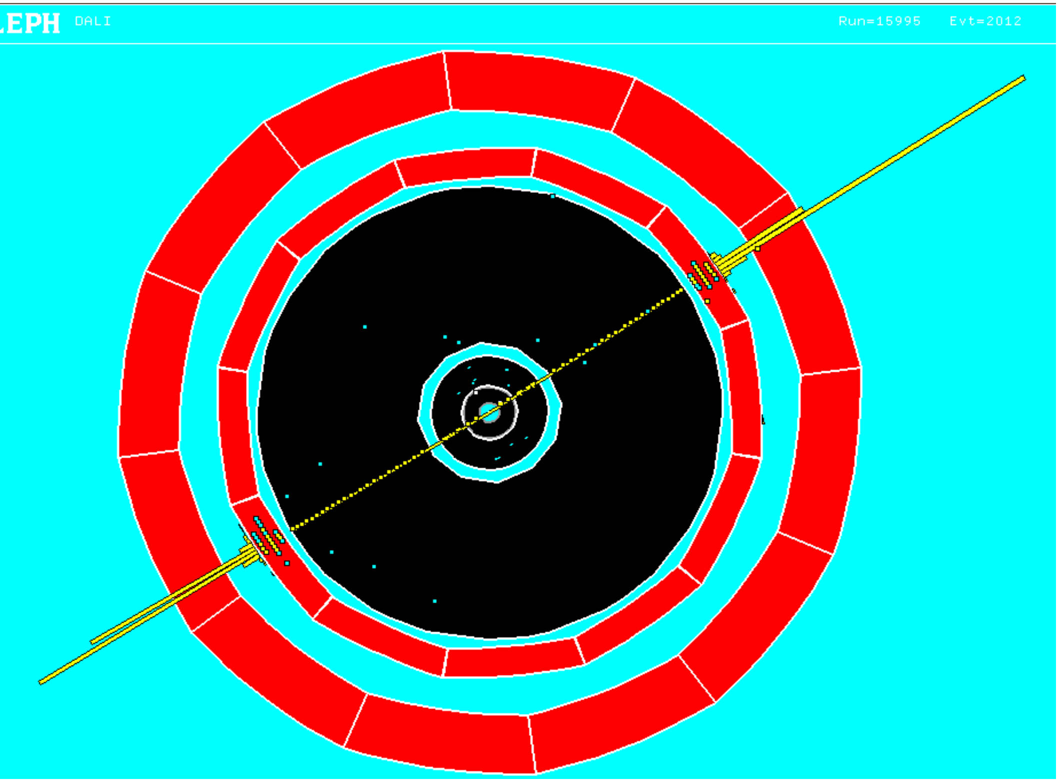


ATLAS Barrel

$H \rightarrow ZZ^{*} \rightarrow e^{+}e^{-}\mu^{+}\mu^{-}$ (m_H = 130 GeV)

Leptons

Z--> e+ e-

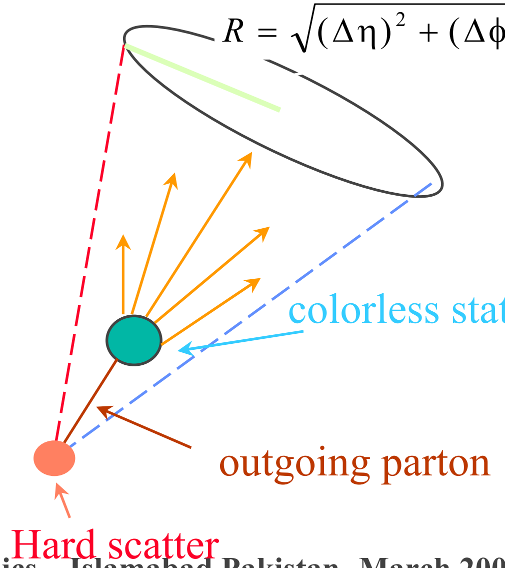


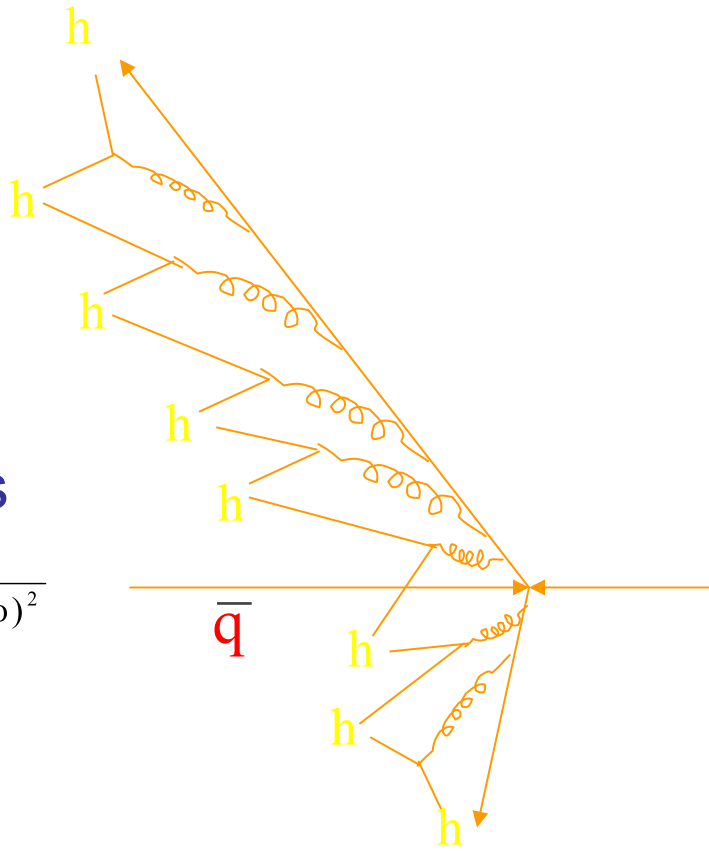
Electrons and muons are measured as single particles

Hadronization

ragmentation (hadronization):

- Final state quarks or gluons produced by the hard scattering produce lots of radiation (α_S is large!)
- Recombine to form a colorless spray of approximately collinear hadrons: a jet
- Jets are an experimental signature of quarks and gluons and are observed as localized energy deposits in the calorimeters



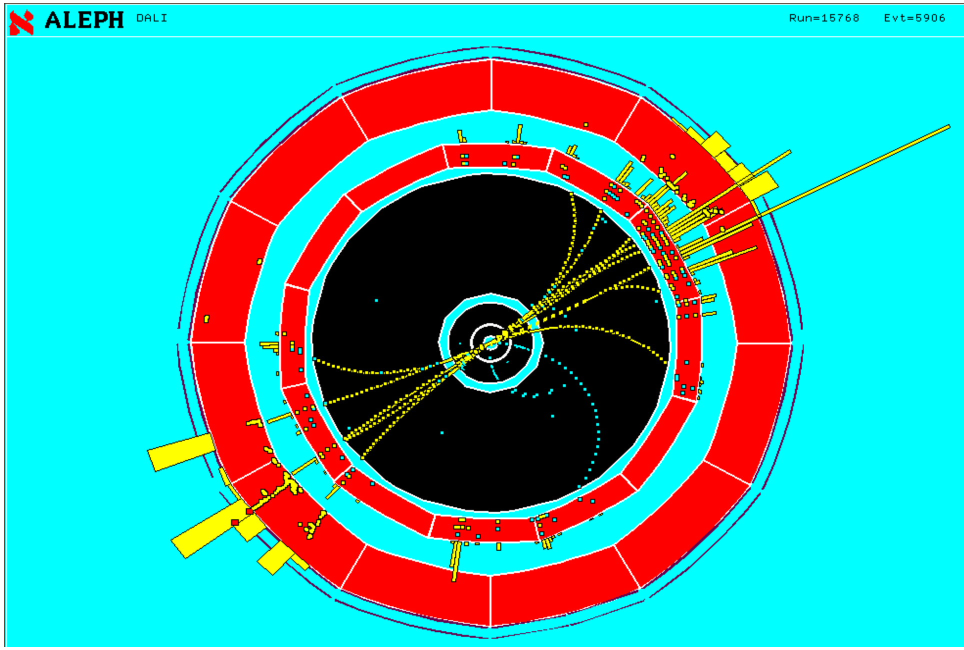


Quarks, Jets and Hadronization

Quarks and gluons
hadronize producing JETS

The jet retains the direction
and energy of the parent
parton

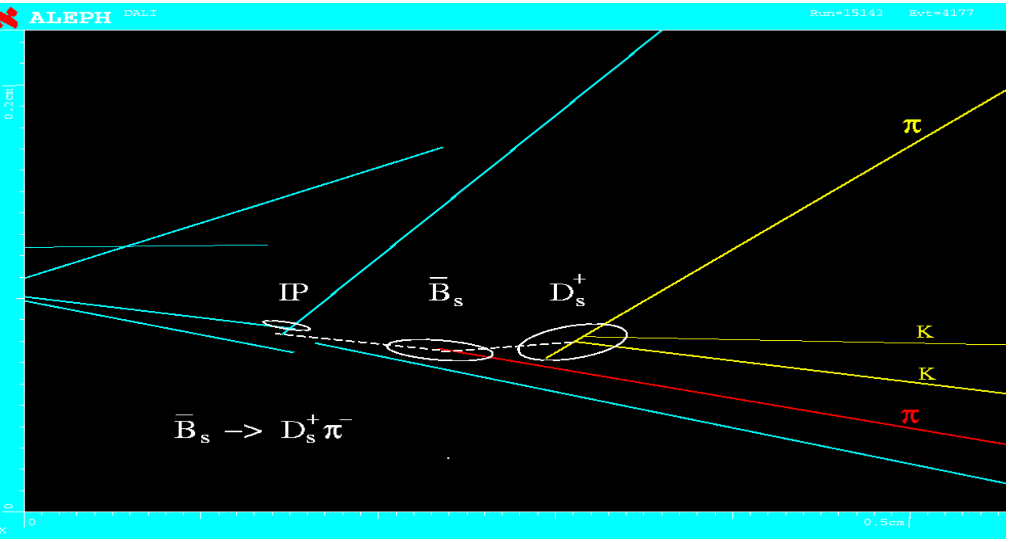
The visible final state is
constituted by *stable* hadrons (cτγ
>> meters) π+,π−, k+,k-, k0, p+ p-
,n nbar…….
π0 decays promptly into two
photons



Z--> q qbar

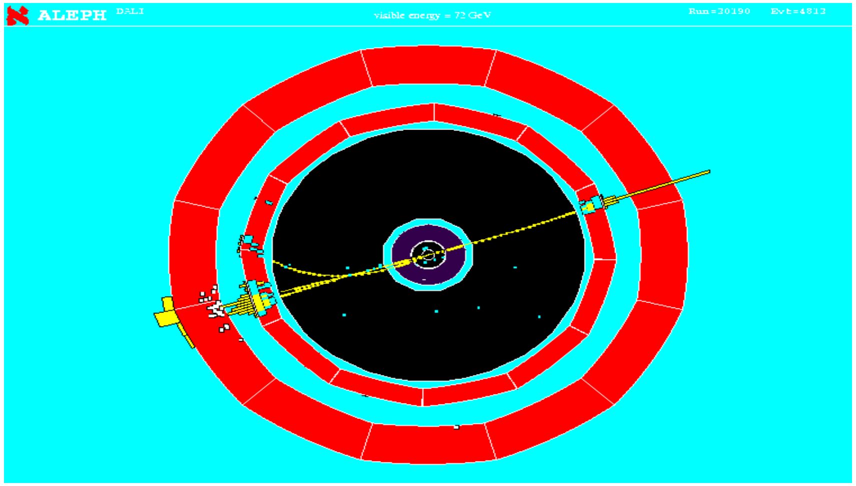
The challenge is to reconstruct
the parton parameters from the
Jet parameter

Decays



In the hadronization process (few fermi) of heavy quarks also heavy hadrons are produced. They decay weakly (few mm) and only the decay products are detected

Z-->b bbar

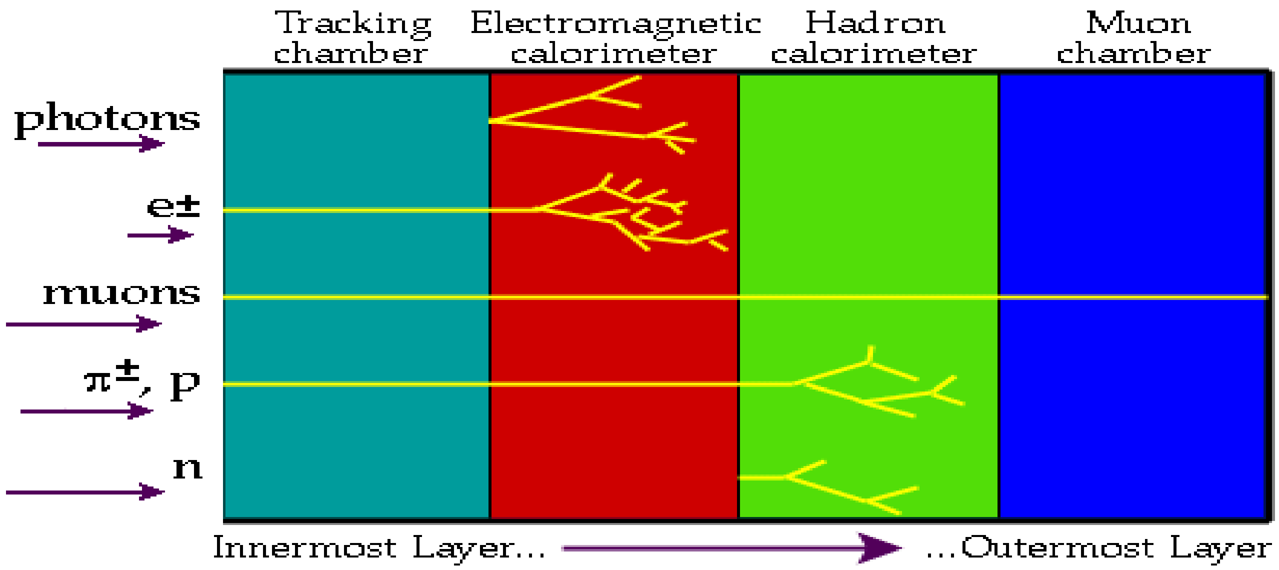


Also τ leptons decay with $c\tau\gamma$ few mm

Z--> τ+τ−

General Principle

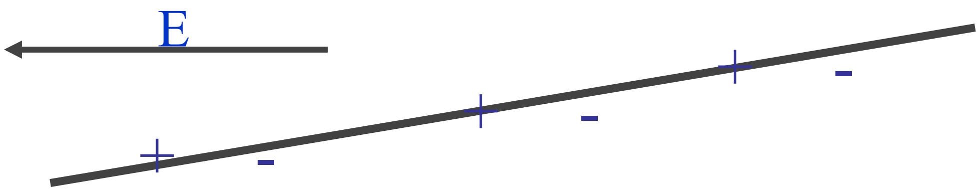
Visible particles are measured by the various subdetectors and identified from their characteristic pattern .



The parameters of the quarks are reconstructed from the hadronic jets.

The flavor of the quark is determined reconstructing the hadronic decays of heavy mesons or detecting their detached decay vertex

Charged particle trajectories



Charged particles ionize and their trajectories can be reconstructed detecting the ionization electrons on charge sensitive detectors.

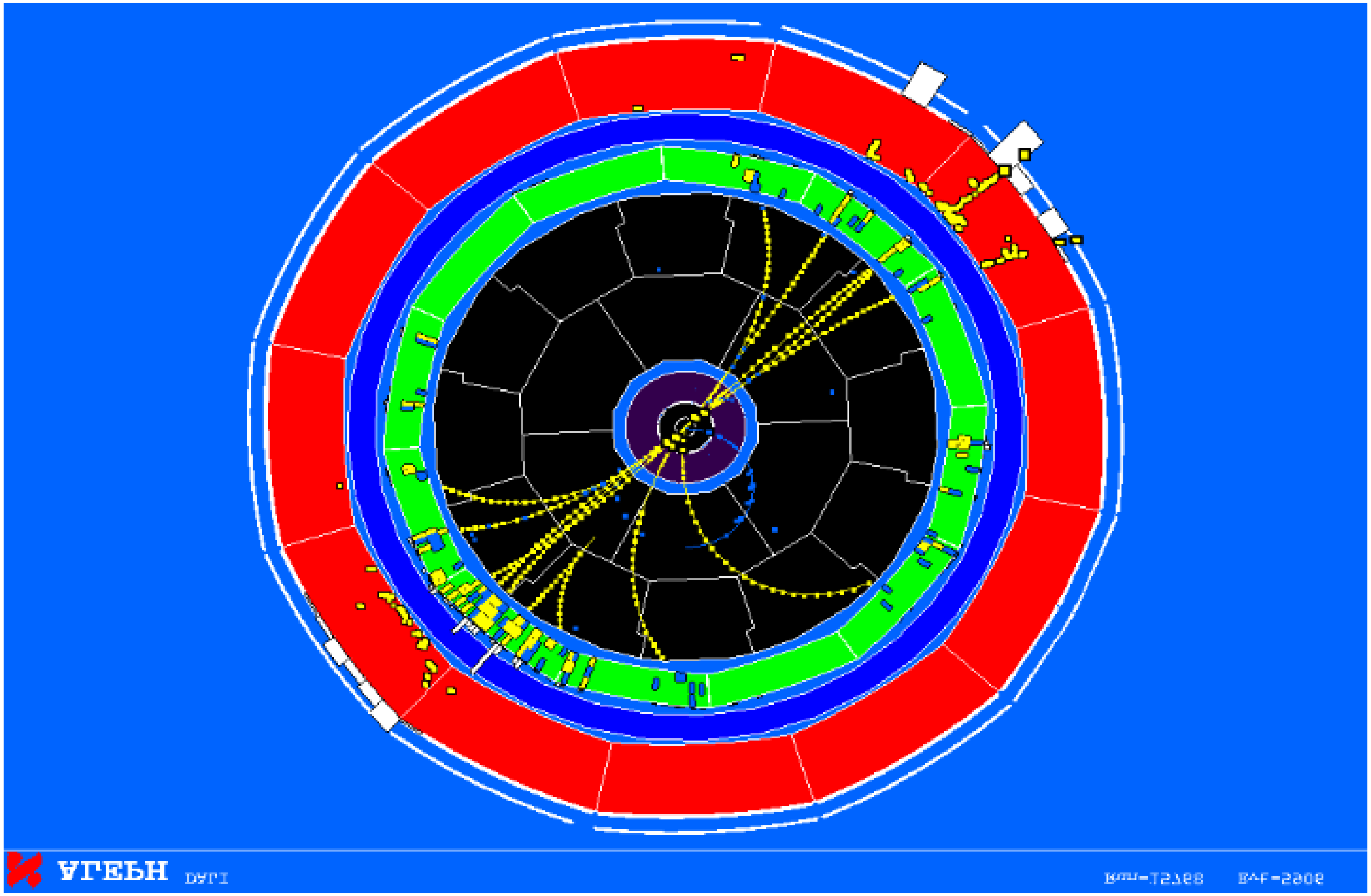
The measurement of the trajectory in a magnetic field gives

- Direction at the origin

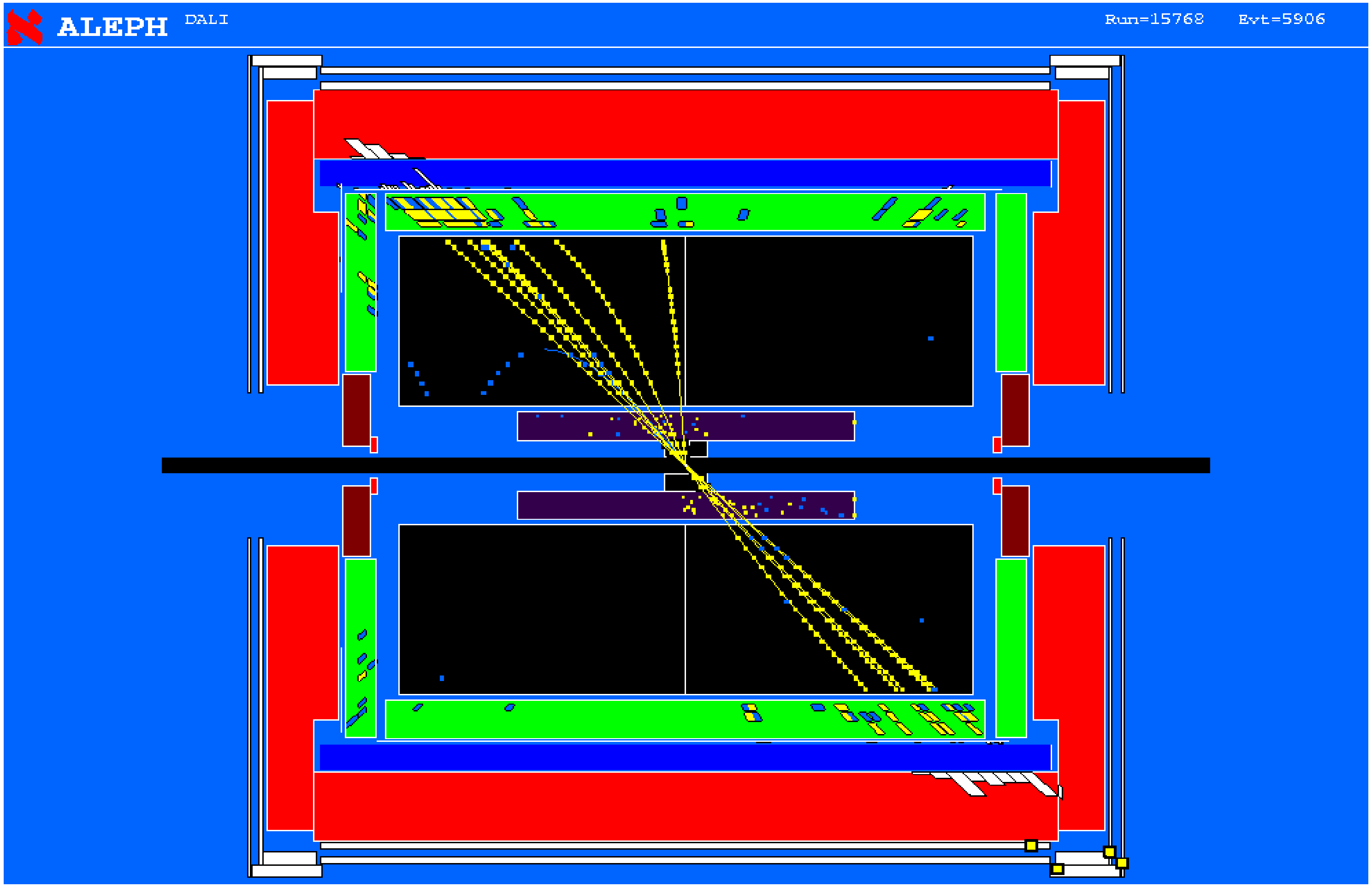
- Sign of the charge Q of the particle

- Pt/abs(Q) Pt= component of the momentum perpendicular to the magnetic field

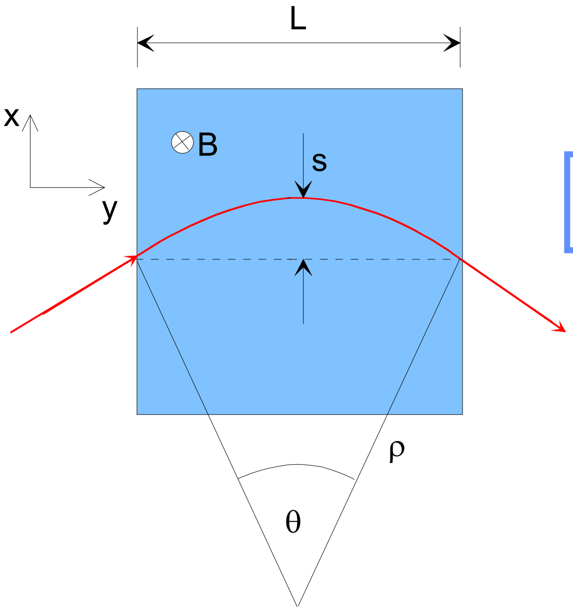
Magnetic field is along the beam axis



Magnetic field is along the beam axis



Momentum Measurement



$$\frac{mv^2}{\rho} = q(v\times B) \quad\rightarrow\quad p_T = qB\rho$$

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

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

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

$$s = x_2 - \tfrac{1}{2}(x_1+x_3)$$

$$\boxed{\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} = \frac{\sigma(s)}{s} = \frac{\sqrt{\frac{3}{2}}\sigma(x)}{s} = \frac{\sqrt{\frac{3}{2}}\sigma(x)\cdot 8p_T}{0.3\cdot BL^2}}$$

The sagitta s is determined by three measurements with errors σ(x)

Momentum measurement

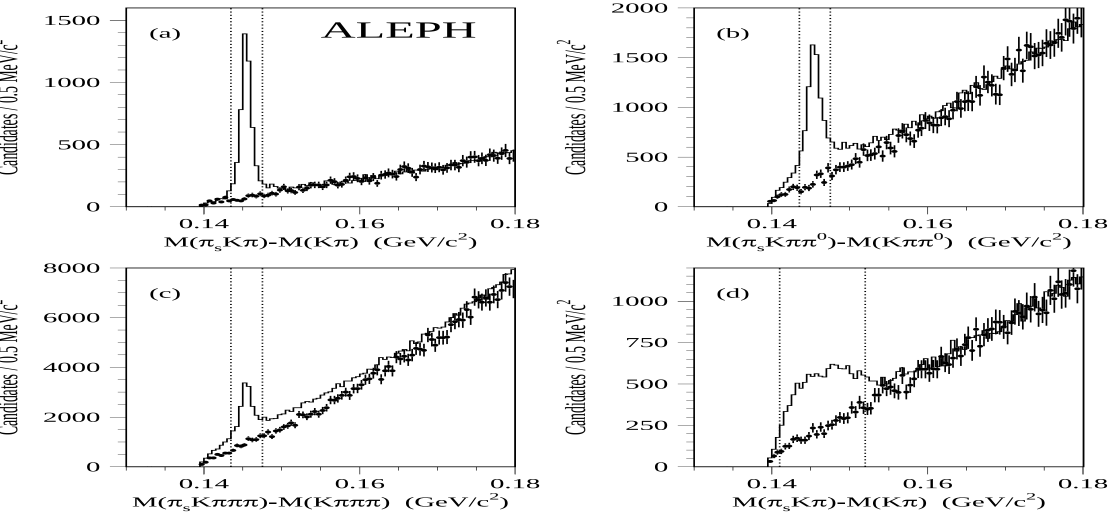
for N equidistant measurements, one obtains
(R.L. Gluckstern, NIM 24 (1963) 381)

$$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} = \frac{\sigma(x)\cdot p_T}{0.3\cdot BL^2}\sqrt{720/(N+4)}$$ (for N ≥ ≈10)

$$\frac{(p)}{p} \approx 0.25\left(\frac{\sigma(s)}{100\ \mu m}\right)^{1}\left(\frac{1\ m}{L}\right)^{2}\left(\frac{1\ T}{B}\right)^{1}\left(\frac{p}{100\ GeV}\right)$$

Momentum resolution increases with the square of the lever arm L and only linearly with B
Momentum resolution increases with momentum 100% error means that charge cannot be measured

Momentum resolution (2)



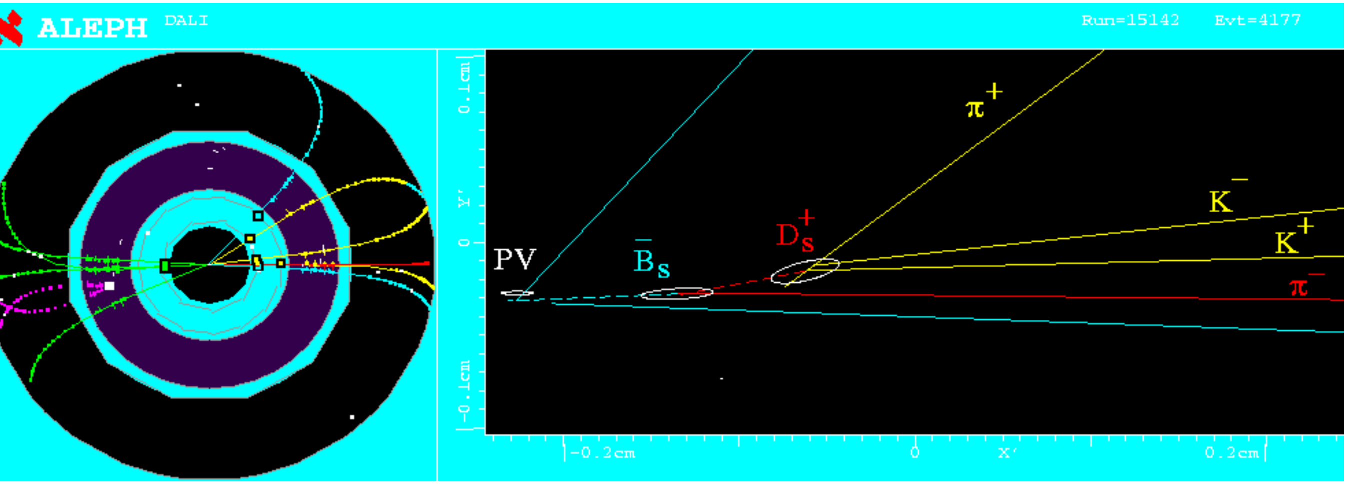
Mass resolution is proportional to momentum resolution

Good momentum resolution implies narrow peaks and better signal to background ratio

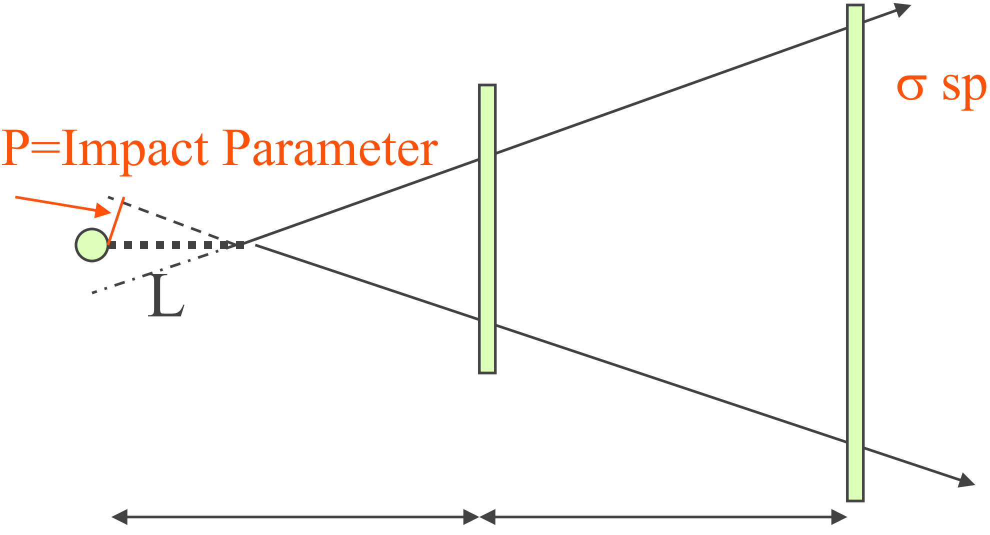
Flavor can be identified reconstructing known resonances from their decay products.

In this example charm jets are identified through the presence of a charmed meson

mpact parameter resolution



$$IP \approx L \cdot \frac{1}{\gamma} \approx c\tau\gamma \cdot \frac{1}{\gamma} = c\tau$$



IP=Impact Parameter

σ spatial resolution

$$\Delta IP \approx \sqrt{5}\sigma$$

$$\Delta IP << IP \Rightarrow \sigma << c\tau / \sqrt{5}$$

cτ B ~ 500 μm

cτ τ ~ 100 μm

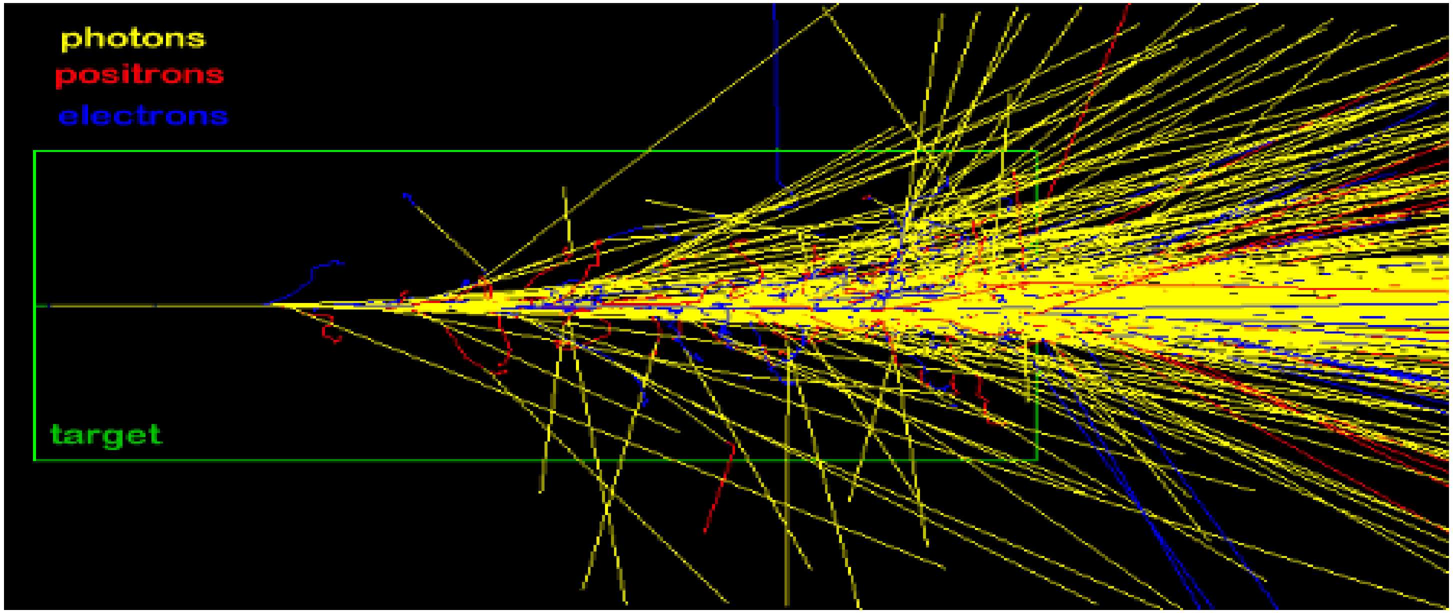
Requirements on Tracking

In order to precisely measure momenta of the order of 100 GeV the Tracking System must have a resolution of few hundred microns, a lever arm of few meters and a magnetic field of few Tesla.

In order to efficiently identify B mesons and tau leptons through their finite impact parameter, the tracking near the vertex must have few points measured with spatial resolution better than 50 micron.

Photon Detection

Massive shower in a tungsten cylinder (outlined in green) produced by a single 10 GeV incident electron.

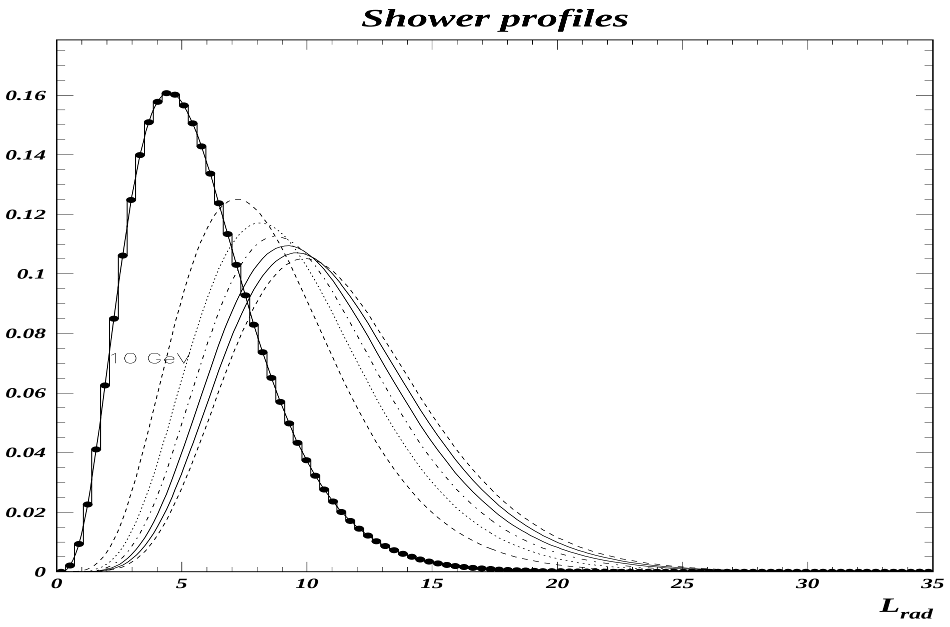


Photons and electrons interact in matter producing showers of neutral and charged particles.

The number of secondary particles is proportional to the energy.

Radiation length

The physical size of the shower is described by the Radiation Length Xo
Dense material have Xo ~ 1 cm



Shower profiles for

10, 100, 200, 300… GeV

electrons

The length of the shower increases with the log of the energy

The lateral size does not depend on the energy (90% in 2-3 cm)

Energy resolution

In order to absorb high-energy photon/electron the calorimeter must integrate 15-25 Xo.

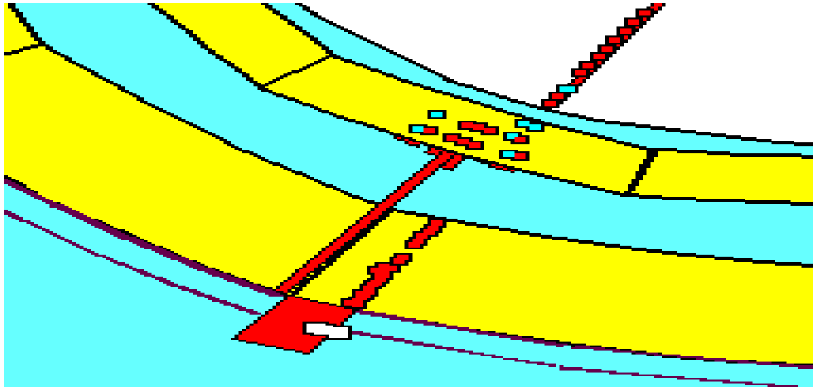
The energy resolution has a statistical term that depends on the number of secondary charged particles, which in turn is proportional to the energy

$$\frac{\Delta E}{E} \approx \frac{(3-30)\%}{\sqrt{E(GeV)}} \oplus O(1\%)$$

The size of the statistical term depends on the technique used in the calorimeter

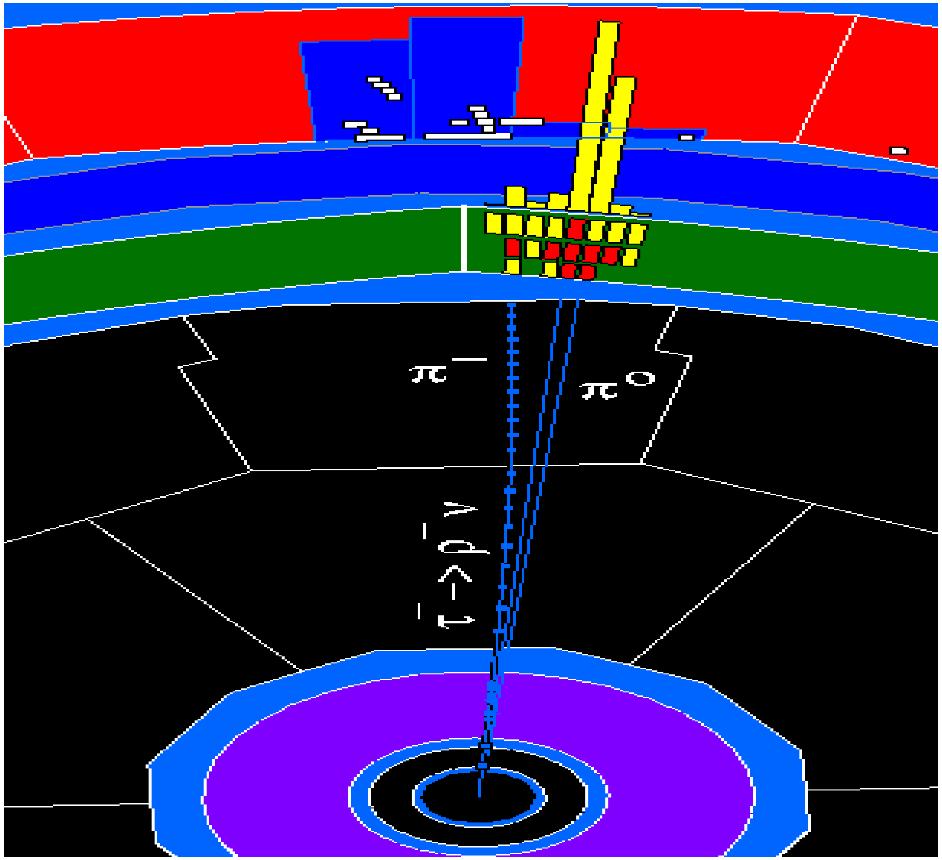
At high momentum Energy resolution for an electron in the calorimeter is better than momentum resolution in the tracker

Granularity



High granularity is needed to separate showers induced by nearby particles.

The angular separation is limited by the lateral size of the shower and by the distance of the calorimeter from the interaction point

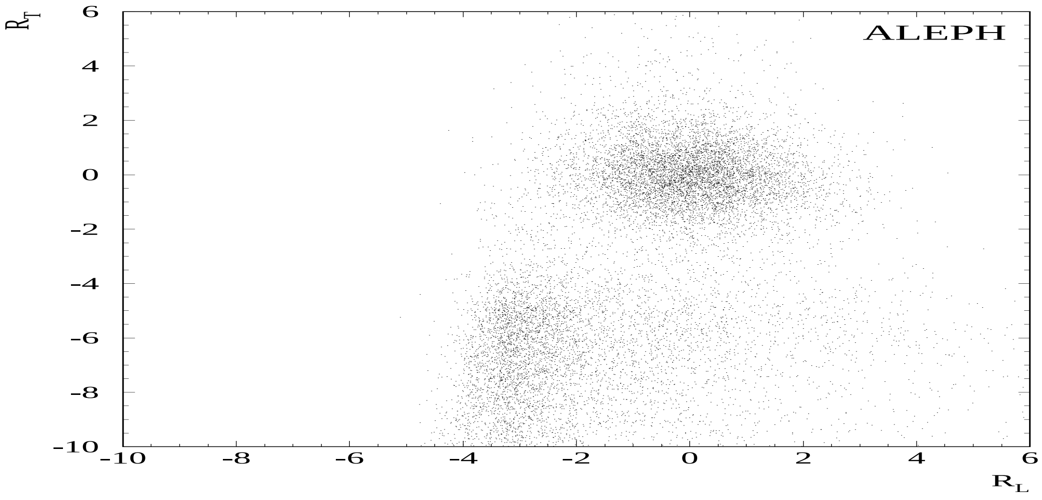


Photons are identified as compact showers not associated to charged particles

Electron identification

Electrons can be identified (wrt to charged hadrons) comparing the momentum measured in the tracker and the energy measured in the calorimeter.

Extra separation is obtained by exploiting the longitudinal shower profile



Match energy and momentum

Longitudinal shape of the shower

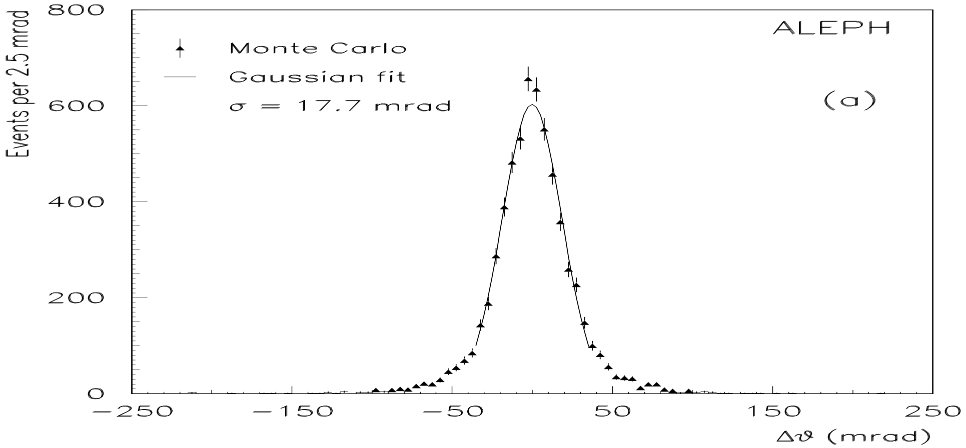
Hadronic energy

Hadrons interact in the Electromagnetic calorimeter producing hadronic showers that are not absorbed since the hadronic interaction length is much larger than a radiation length (11 cm vs 0.5 cm in lead).

The hadronic shower is absorbed in the Hadron calorimeter: typically 1-2 meters of heavy material (iron, copper) interleaved with detecting elements.

Jet parameters

Careful analysis of the charged particles trajectories and their match with clusters measured in the calorimeters allows a good definition of the jet energy and direction.

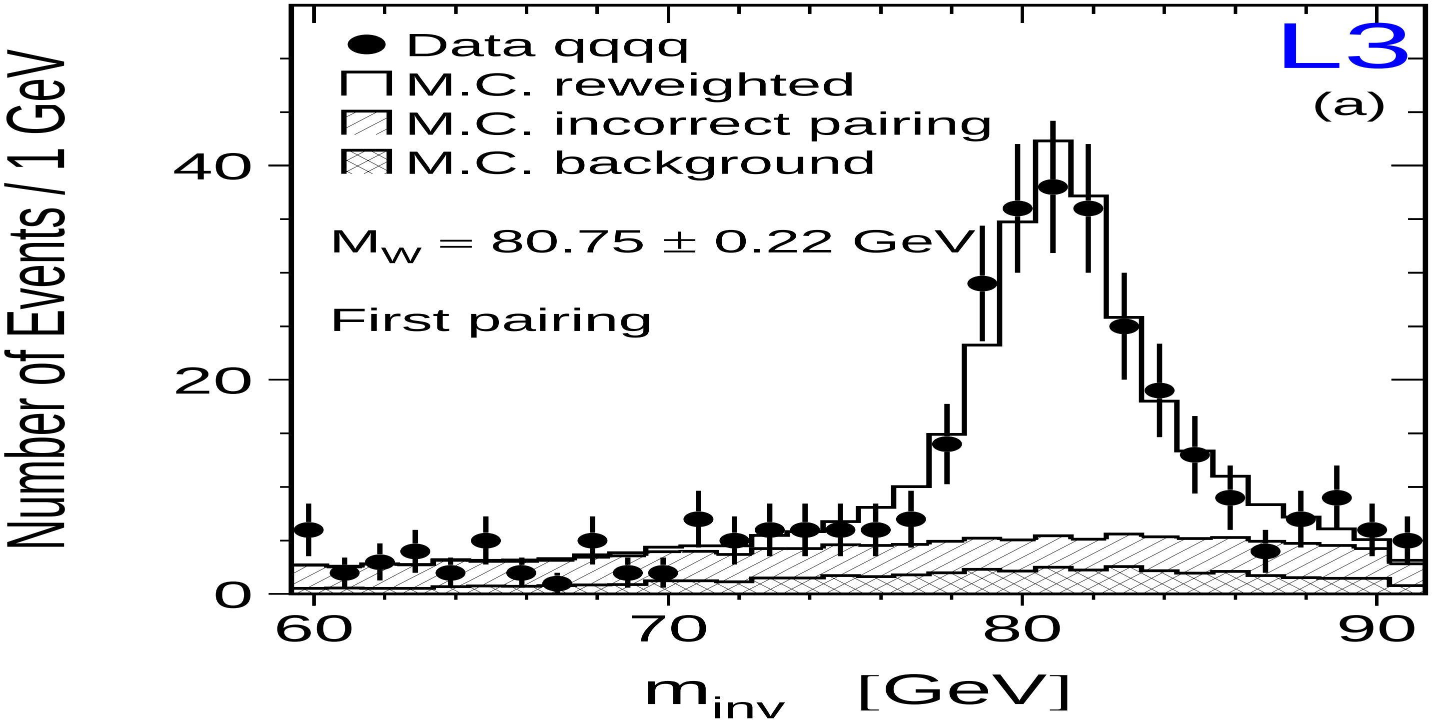


Jet direction is reconstructed in ALEPH with a resolution of about 20 mrad

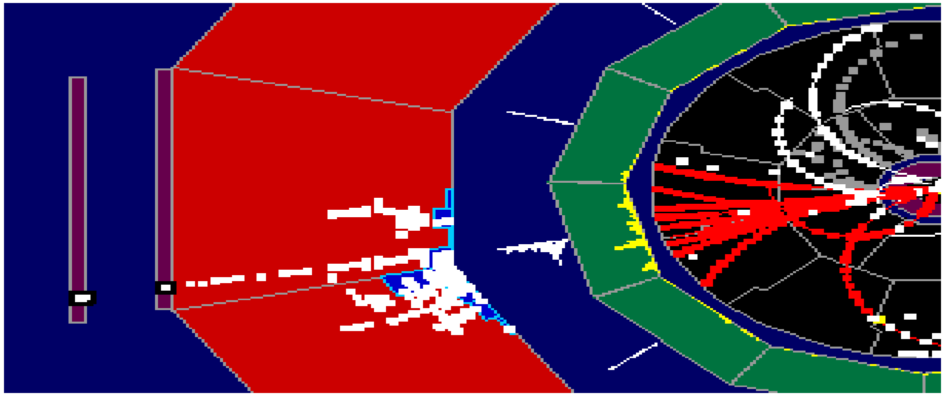
Energy resolution is $0.6/\sqrt{E\ (Gev)}$ A naïve method (summing all the energy measured in the calorimetric cells) gives a factor two larger energy resolution.

W--> q q'bar peak

The W mass peak is reconstructed from the jet-jet invariant mass in e+e - --> WW events at LEP.



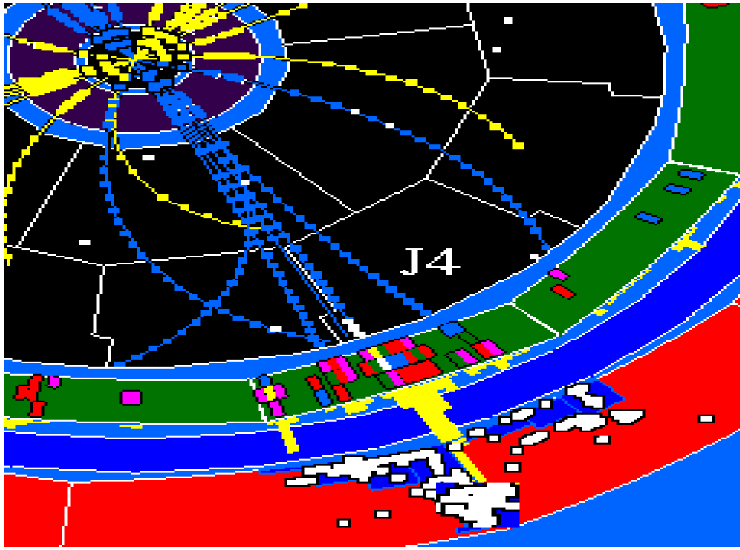
Muon identification



Muons have no hadronic interaction and very long electromagnetic interaction length.

They cross the detector almost undisturbed and are identified by their penetration through the calorimeters

With small probability hadronic showers PUNCH THROUGH the hadron calorimeter and fake a muon



Summary

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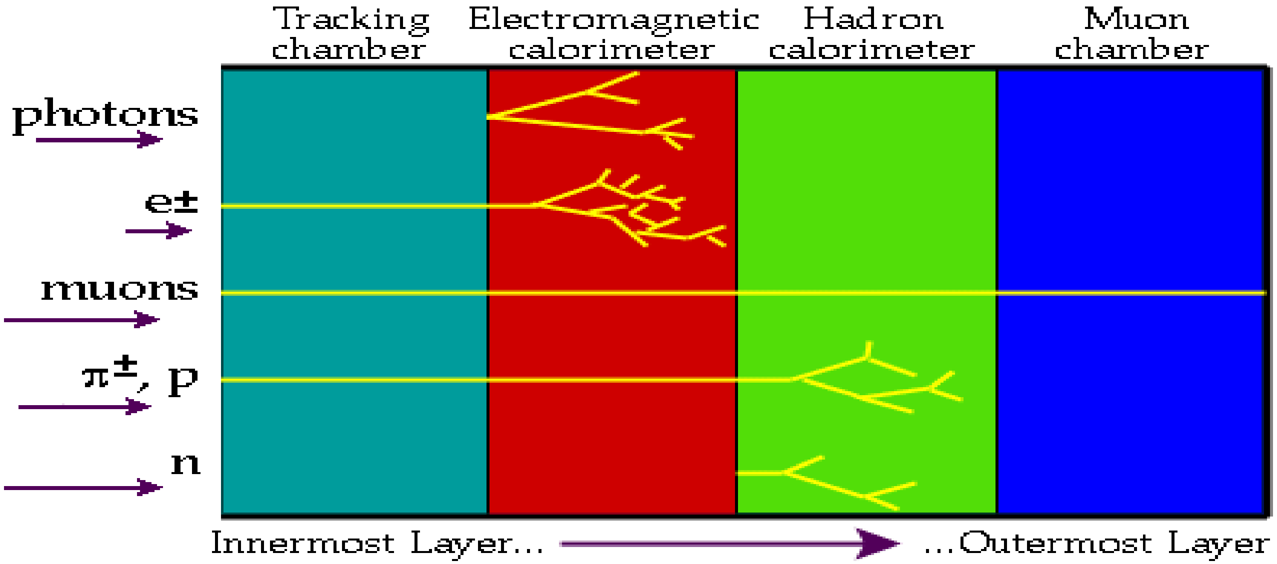

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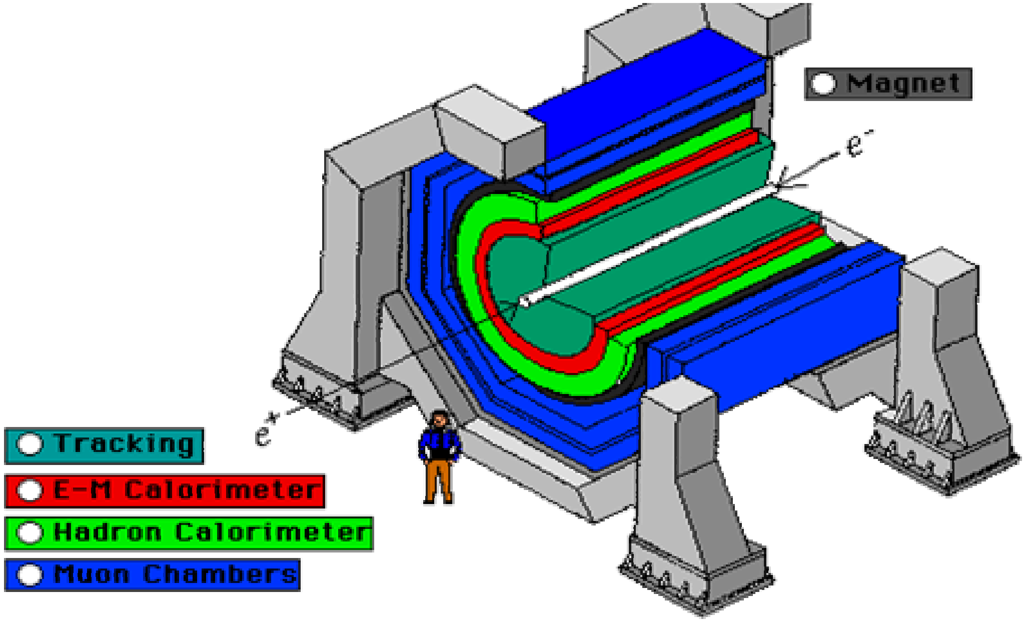
Conclusions



Collider detectors look all similar since they must perform in sequence the same basic measurements.

The dimension of the detector are driven by the required resolution . The calorimeter thickness change only with the logarithm of the energy: for this reason the dimension of the detectors change only slightly with the energy.