And for this physics what detector?

A detector which,
for this physics,
in the energy domain under consideration

collects a maximum of unbiased events

It is clearly
neither a LEP (e^+e^-) detector
nor an LHC detector

even though some reminiscence of LEP detectors,
some synergies with the LHC upgrades appear

Outline

The goal of such a detector — precision, efficiency, hermeticity

Physics constraints — angular distributions, energy spectra, needed performances

Charged track measurement

Neutrals measurement

Collider constraints — background, timing

The degrees of freedom — the choice of the design, is there any?

The technologies — for the different subsystems: scintillator, silicium, gas

performances?

Detector

Goal and physics constraints

The basic functions:

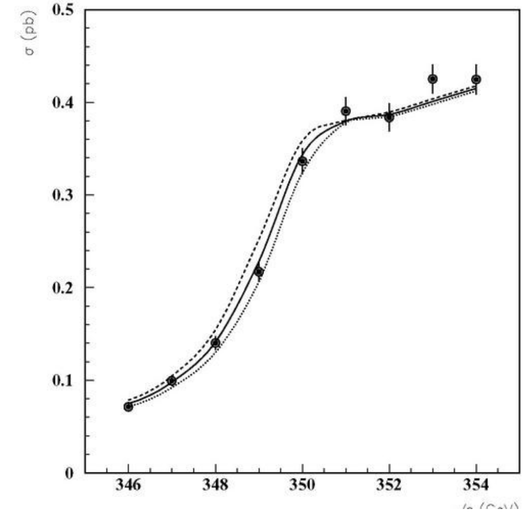
Measure
Identify

What?

Detector

Goal and physics constraints

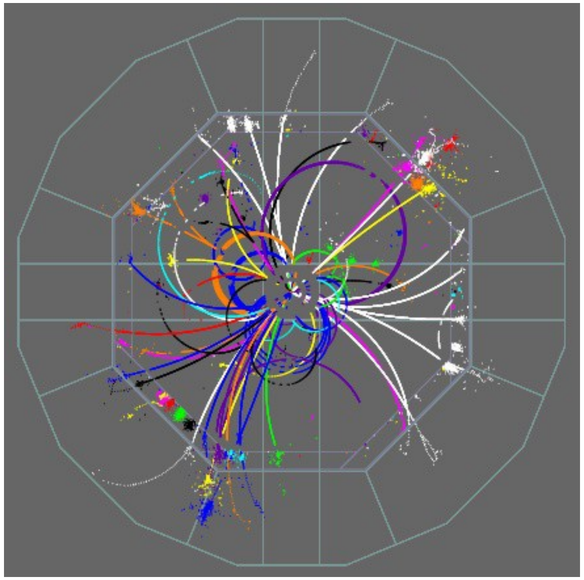
That depends!



top threshhold, measuring the $t\bar{t}$ cross section

identify the $t\bar{t}$ system
do I want to identify each t?
to measure their asymetry ??

$t\bar{t}$ to study the branching fractions of the top



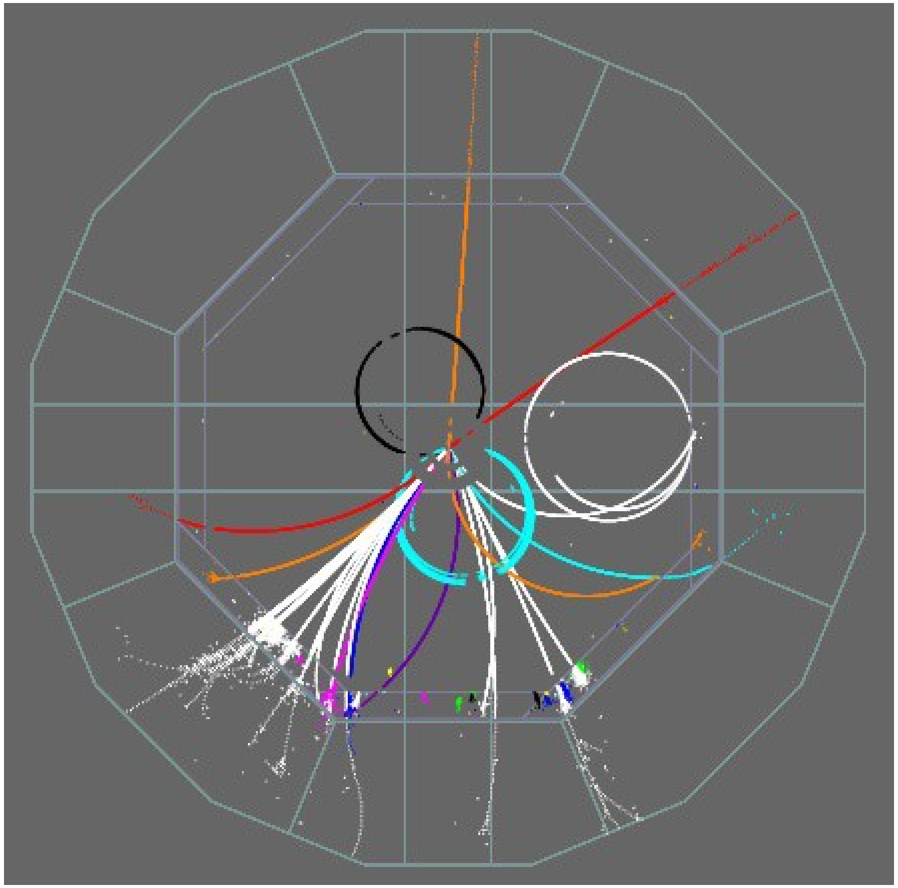
identify a top   but where is it?

study the other
in the details of its decay

Detector

Goal and physics constraints

That depends!



Higgs study

via ZH

recoil mass to the Z ?

precision on the μμ mass
⇒ precision on the momenta
precision on E_{CM}
⇒ beamstrahlung

Z identification, H signature,
branching ratios,
understanding the b's, the τ's, the W's

Detector

Goal and physics constraints

Most of the physics we consider implies seeing
W's, Z's, H's.

We do not want to see the content of the W's or Z's
(except if we want to measure more accurately their decays)
but we want to identify and measure them
in all their decay modes

But we wish to know in detail the content of the H

Detector

Goal and physics constraints

The functions of our detector are then to:

Measure momenta, energy, spin state
Identify leptons, hadrons

the leptons :
primary leptons,
leptons from decays of Z, W, H
and heavy flavours
they sign the presence of
neutral leptons

the hadrons :
primary
or coming from the Z, W, H decays
identifying those from heavy quarks b and c, or light

the photons, primary or coming from π^0.

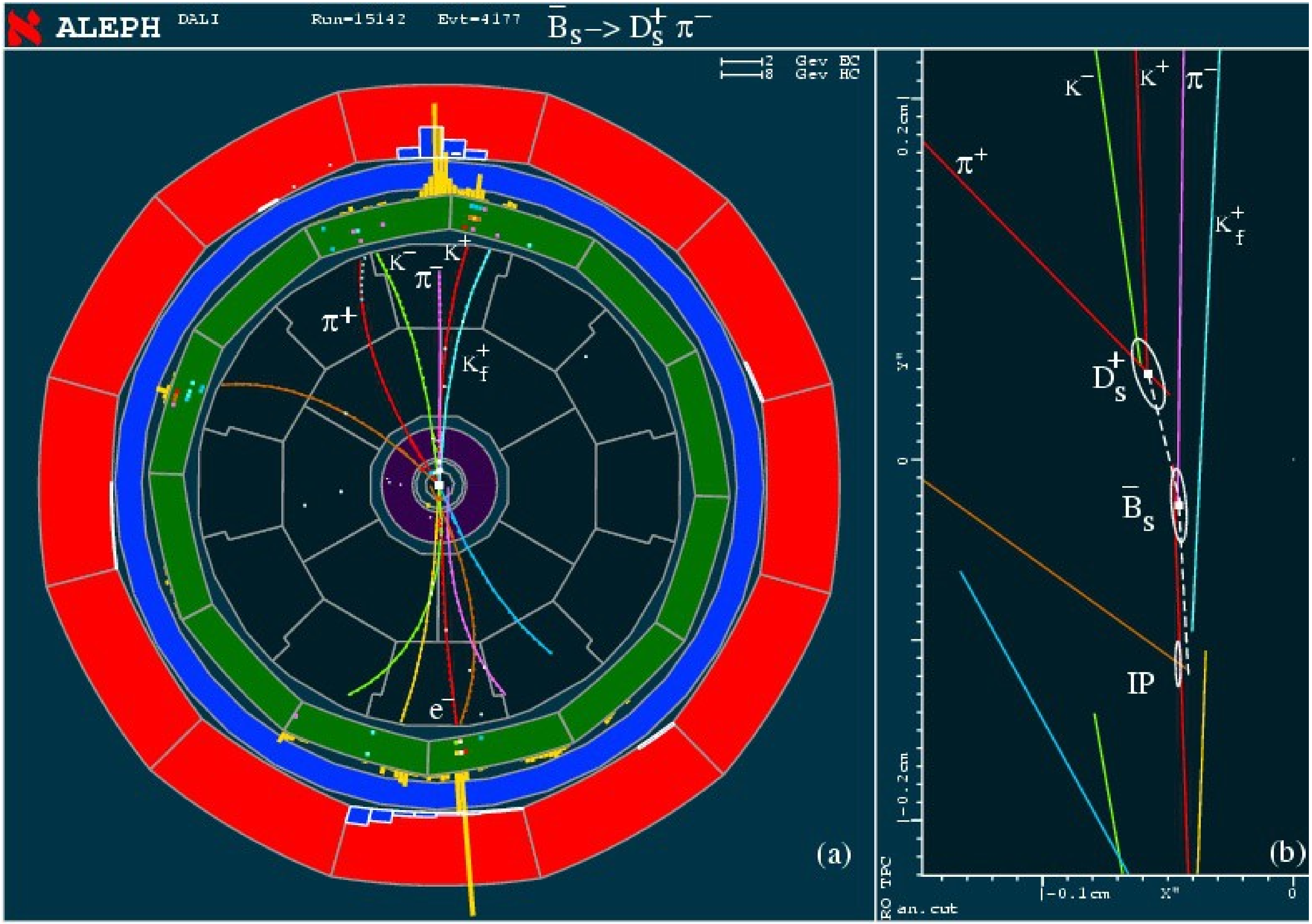
Goal and physics constraints

The hadrons of interest decay with a
lifetime different according to their content in b, c or s:
they are first identified
by their flight length, their mass, their decay content.

Do we want to know the jet of a given quark?
or simply to identify this quark
and reconstruct the 4-vector of a diquark?

Detector

Goal and physics constraints



Detector

Goal and physics constraints

The "visible" leptons are charged ⇒ measure the charged leptons

the neutral leptons never come alone

The hadron jets contain

in majority charged particles (60%)

but also photons coming from π^0 (30%)

and a certain number of neutral hadrons with a long life (K^0, n)

these fractions fluctuating stongly.

It can be envisaged to measure globally these jets,

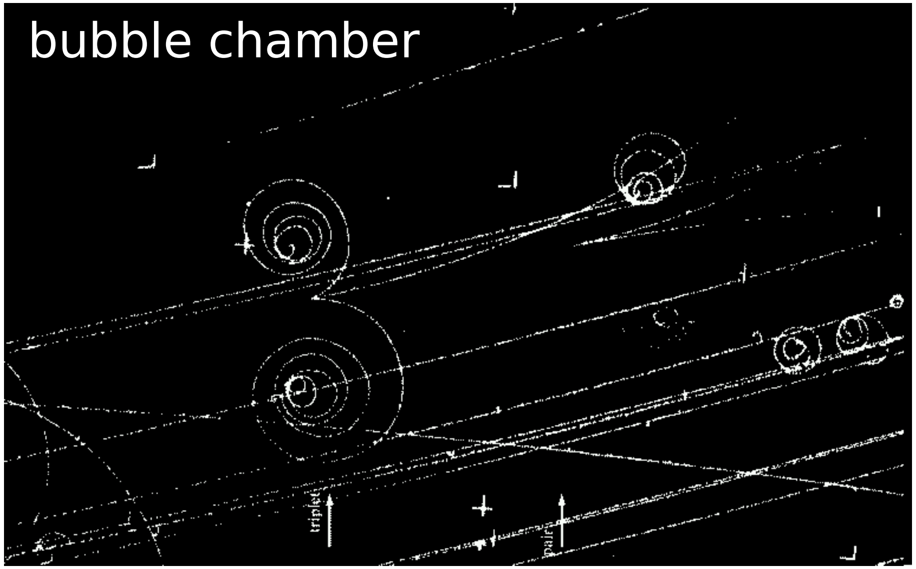
some did it,

or to measure each of them independently

But to measure a charge or even a muon
a magnetic field is mandatory

Detector

Seeing, measuring the particles
through their interaction with a surrounding medium
which takes note of their passage.



B perpendicular to page

Strong and weak interactions may provoke
interactions and decays
but what is observable directly in the detector
is linked to the electromagnetic interaction,
to the transfer of a little fluctuating
energy-momentum from a charged track to the medium.

This can be incoherent,
interaction with the atoms independently,
  excitation (light emission), ionisation (electron emission, dE/dx)
or coherent,
interaction with the medium as a whole (optical index)
  Cerenkov, transition radiation

Measurement of the charged particles

momentum measurement point precision
do not perturb trajectories, matter

impact parameter measurement

dE/dx measurement

time of flight measurement

range measurement

coherent effects

What defines the level of performance

How to measure a momentum

by a curvature in a magnetic field

Shape of the field :
C(UA1), toroid (Atlas), axial (solenoid) (many many)

Impact on the beam, on the polarisation

For electrons with longitudinal polarisation
better to have the field along the beam

Reminder

Motion of a particle in a magnetic field

$$P^{\mu} = mU^{\mu} = m\gamma(c, \vec{v}) \qquad \frac{dP^{\mu}}{d\tau} = qF^{\mu\nu}U_{\nu}$$

in the case of zero electric field the spatial part writes

$$m\gamma\frac{d\vec{v}}{d\tau} = m\gamma^2\frac{d\vec{v}}{dt} = q\gamma\ (\vec{v}\times\vec{B})$$

Writing with complex numbers the motion in the plane orthogonal to B

$\frac{dv}{dt} = -i\frac{qB}{m\gamma}v$ then writing $\omega = \frac{qB}{m\gamma}$

$$\frac{dv}{v} = -i\omega dt$$

$$v = v_0 e^{-i\omega t}$$

$$x = x_0 + i\frac{v_0}{\omega}e^{-i\omega t}$$

The trajectory is a circle of radius

$$R = \frac{v}{\omega} = \frac{m\gamma v}{qB} = \frac{p_{\perp}}{qB}$$

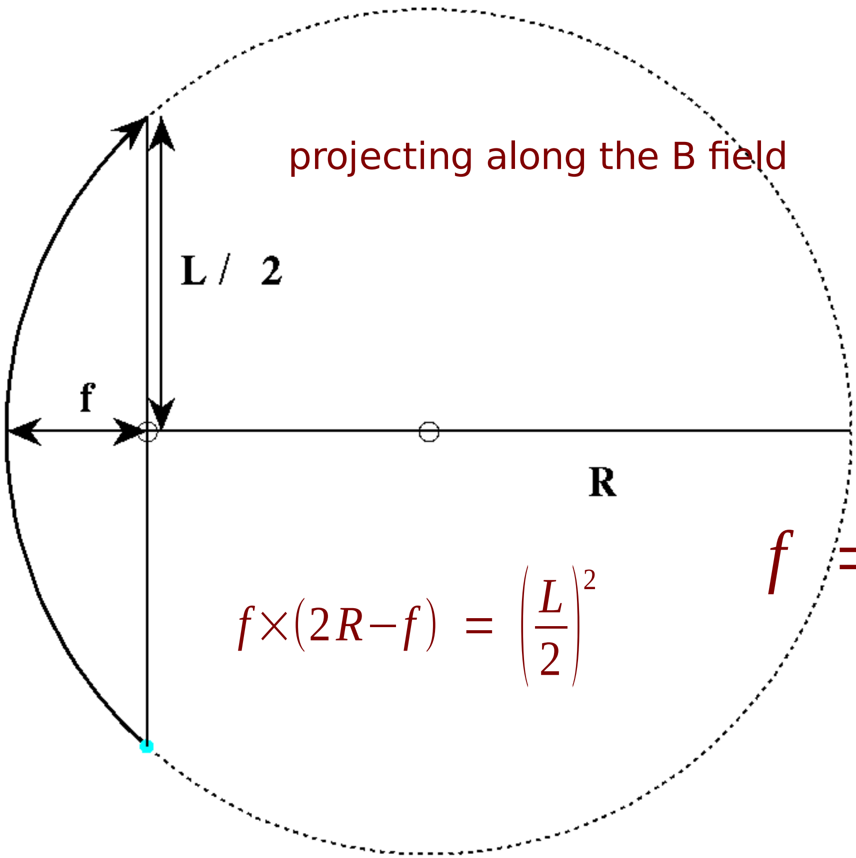
$$p_{\perp} = qRB$$

in SI, p is in VC/c, qRB in CmT
if the charge is in electrons: p (eV) = c R(m) B(T)

$$p_{\perp}(GeV) = 0.3B(T)R(m)$$

$$p = \frac{p_{\perp}}{\sin\theta}$$ θ being the angle with the B field

momentum measurement in a magnetic field by measuring the trajectory sagitta



$$f \times (2R - f) = \left(\frac{L}{2}\right)^2$$

$$f = \frac{L^2}{8R}$$

$$p_\perp \; GeV = 0.3 \, B \, R \quad T \, m$$

$$\delta\left(\frac{1}{p_\perp}\right) = \frac{\delta p_\perp}{p_\perp^2} = \delta f \frac{8}{0{,}3 \, B \, L^2}$$

at constant length,
δf for f small is constant,
number of points constant,
point precision
when L varies the number of points reduces like L and δf behaves in $L^{-1/2}$

Example: L=2m, B=4T, $\delta f = 10^{-4}$ m , $\delta p/p^2 = 0{,}4 \; 10^{-4}$
the % for 250 GeV muons

Detector

Angular dependency

a track of momentum p and polar angle θ

$$p_\perp = p\sin\theta \qquad \delta p_\perp = a\, p_\perp^2 \quad \text{with} \quad a \propto L^{-2.5} \qquad \delta p = \frac{\delta p_\perp}{\sin\theta}$$

we forget about the error on θ

putting $x = \cos\theta$

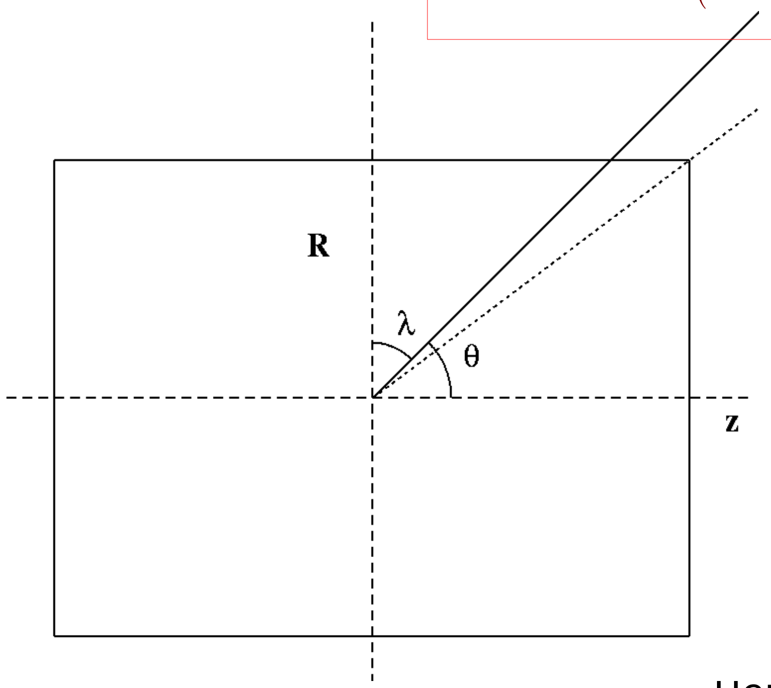
$$\delta p \propto L^{-2.5} p^2 \sin^2\theta / \sin\theta = L^{-2.5} p^2 (1-x^2)^{1/2}$$

Barrel L = R

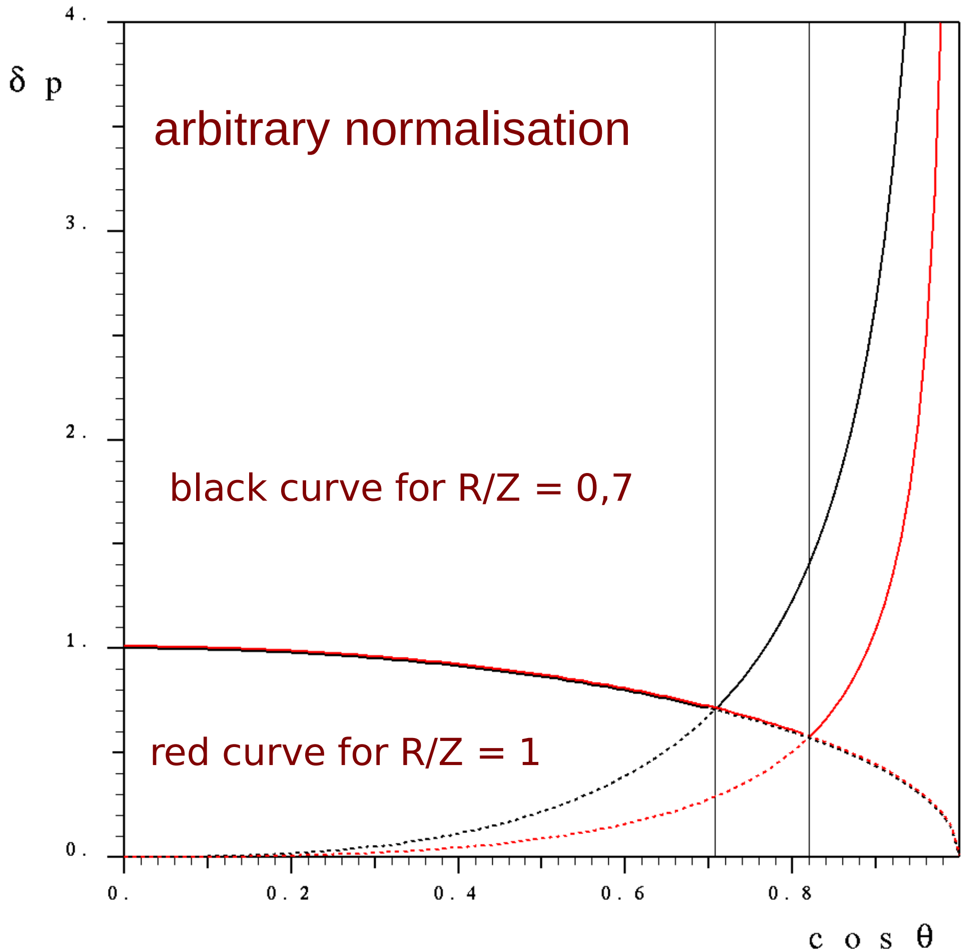
End cap L = Z tgθ

$$\delta p \propto R^{-2.5} p^2 (1-x^2)^{1/2}$$

$$\delta p \propto Z^{-2.5} p^2 \frac{x^{2.5}}{(1-x^2)^{0.75}}$$



what aspect ratio to choose for a cylindric detector ?



function 1. x q-
function 1. x q- -1.5 ** x 2.5 ** * R/Z 2.5 ** *

Detector

We could consider the following exercise:

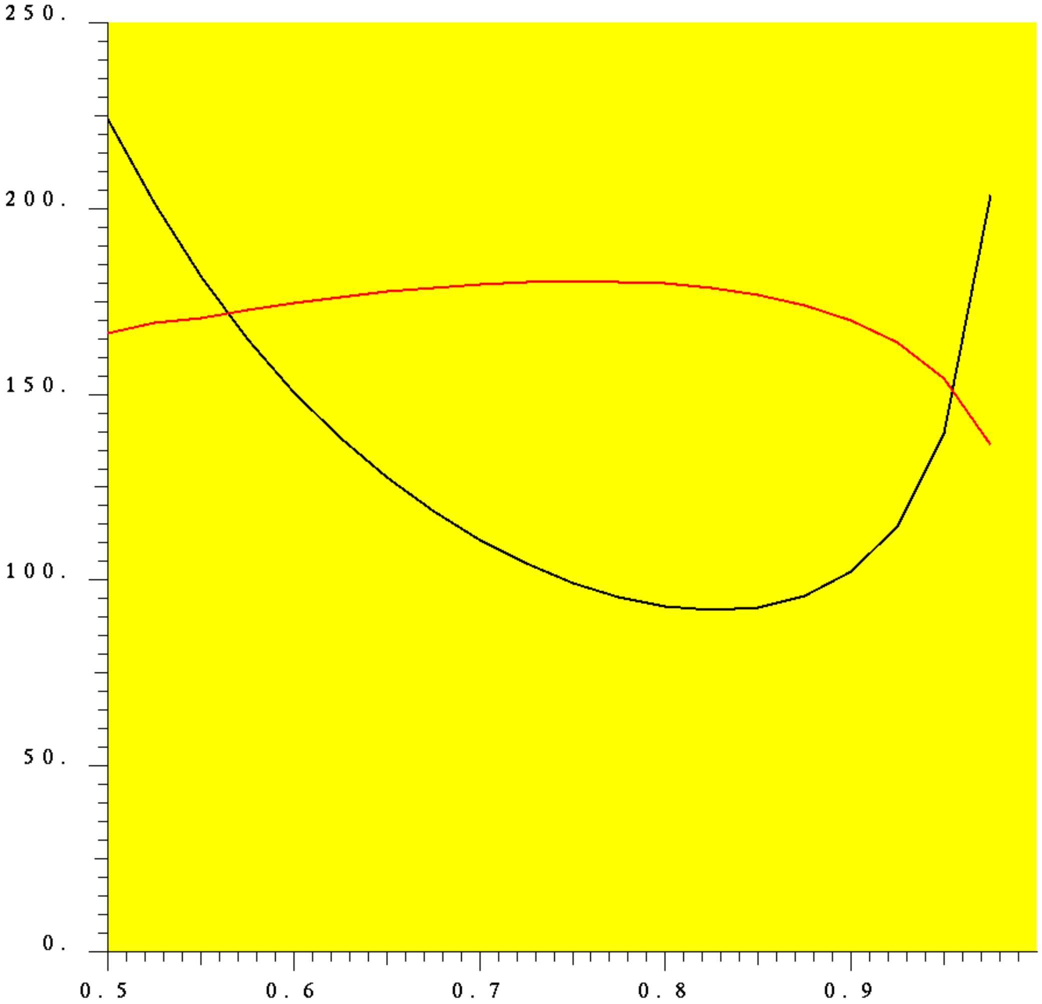
considering that the price of, say, the ECAL, is proportional to its surface, then taking the surface as a constant what is the best aspect ratio for the tracker ?
That depends on the physical angular track distribution.
Even though most of interesting physics is more picked than that we can consider a $(1 + \cos^2 \theta)$ distribution corresponding to Z or $\gamma \rightarrow 2$ fermions.

Calling R the radius and L half the length $A = 2\pi R \, 2L + 2\pi R^2$
the area A is around 60m2
the aspect ratio $\alpha = \frac{R}{L}$
the angle of the corner θ $\tan\theta = \frac{R}{L}$ $\cos\theta = \frac{L}{\sqrt{L^2+R^2}}$
take for parameters A and cos θ

$$\alpha = \sqrt{\frac{1}{\cos^2\theta} - 1}$$

$$L = \sqrt{\frac{A}{2\pi\alpha(2+\alpha)}} \qquad R = \sqrt{\frac{A\alpha}{2\pi(2+\alpha)}}$$

Detector



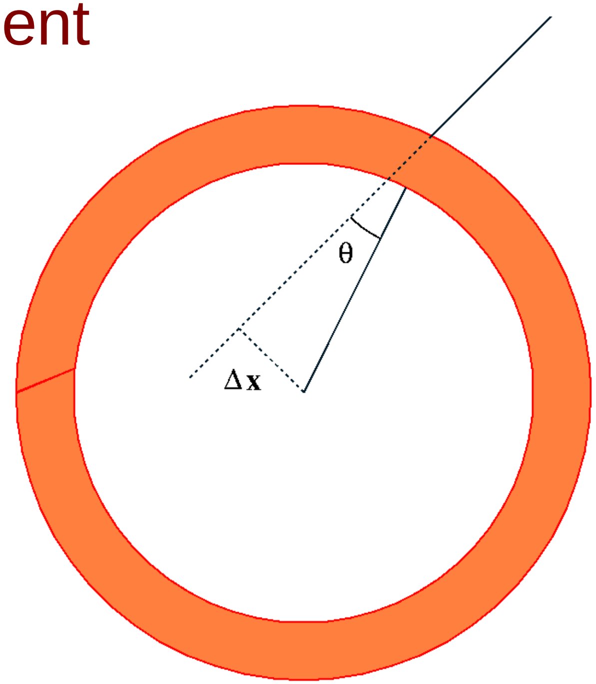
Impact parameter

Multiple scattering in the detection element

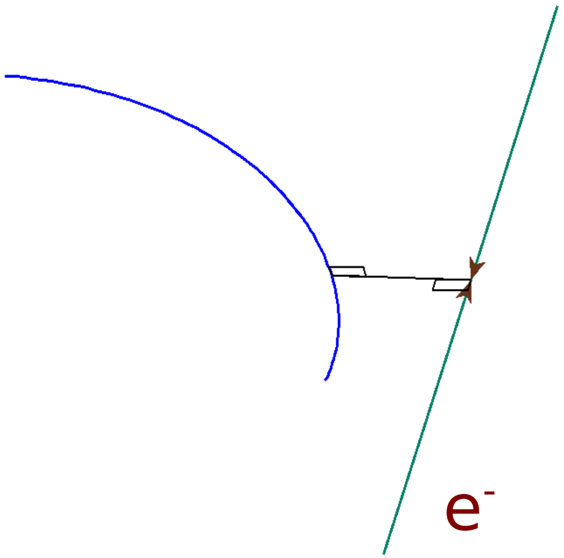
$$\theta = \frac{13.6}{p\beta}\sqrt{t}$$

where the thickness t is in radiation length and p in MeV

← induces error on →



Shortest distance from the interaction point to the track (essential for decays)



what is the origin of the particle ?
the interaction point,
a decay point ?

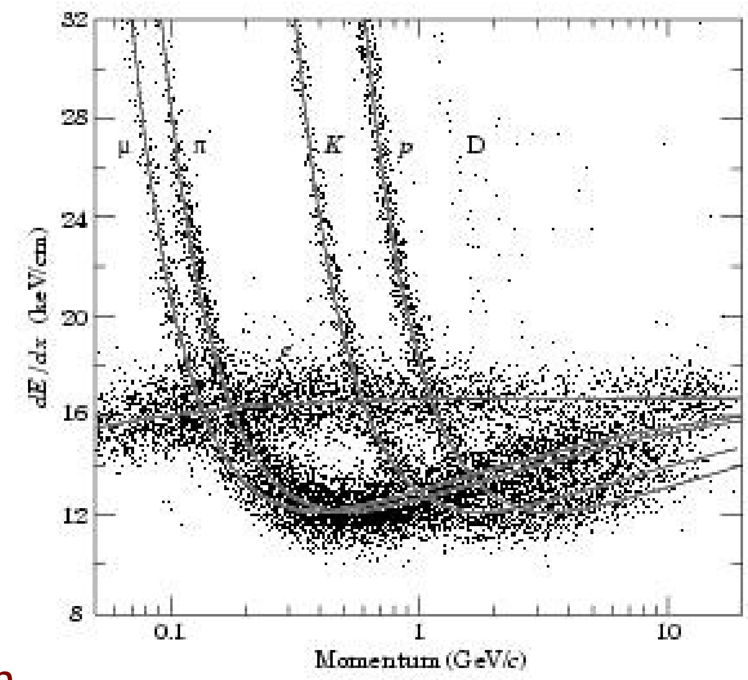
at a distance r the uncertainty on the impact parameter d is

$$\delta d = r\frac{13,6}{p\beta}\sqrt{t}$$

be as precise as possible,
as close as possible
as "transparent" as possible

Detector

dE/dx .... with the hands the global features

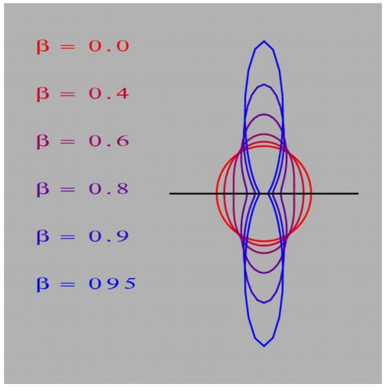


Why this first slope in $1/\beta^2$?

The momentum transfered by the incident particle to an electron of the surrounding material depends on the time during which the force induced by the electric field of the incident particle is applied : $1/\beta$

The energy lost goes like the square of the momentum

Why does it grow up when the γ of the particle grows?



The transverse field seen by the electron grows like γ
ionisation can then occur at a larger distance from the particle
The dependence with the distance to the trajectory is logarithmic

Why a plateau? (Fermi plateau)

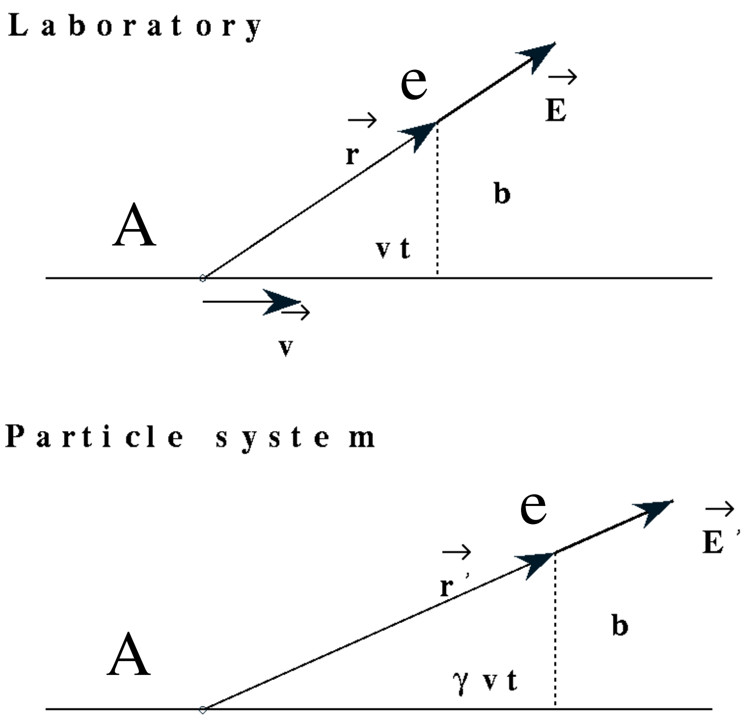
The surrounding matter gets polarised as an effect of the field which is then screened stopping the increase of the γ effect.

dE/dx

Energy lost by a particle passing through matter

Consider a charged particle A
passing at a distance b d'un from an electron

- What is the field generated by A at the place of the electron?
- What is the momentum transfered to the electron?
- What is the energy lost by A?
- What happens when a particle A goes through a material?

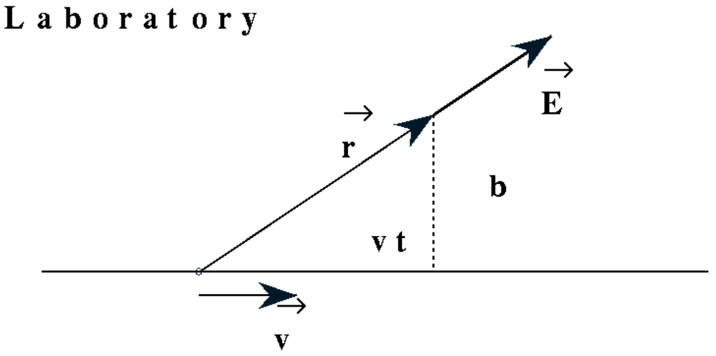


dE/dx

Energy lost by a particle passing through matter

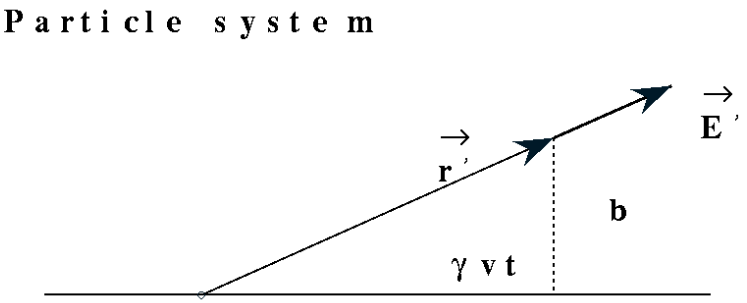
In the system of A (noted '), the electric field is

$$\vec{E}\,' = \kappa q \frac{\vec{r}\,'}{r'^3}$$



$$E'_y = \kappa q \frac{b}{r'^3} = \kappa q \frac{b}{\sqrt{b^2 + (\gamma v t)^2}^{\,3}}$$

with $\kappa = \frac{1}{4\pi\epsilon_0}$



In the laboratory:
by Lorentz transformation of the field

$$E_y = \gamma E'_y$$

$$E_y = \frac{\kappa \gamma q b}{\sqrt{b^2 + (\gamma v t)^2}^{\,3}}$$

The force applied to the electron is then $\vec{F} = e\vec{E} = \frac{d\vec{p}}{dt}$

and the transfered momentum: $\vec{p} = \int e\vec{E}\,dt$

When integrating on the time, the component along the motion of A goes to zero

Detector

Exercise

dE/dx

Energy lost by a particle passing through matter

The momentum transfered along Oy is: $p_y = e\int E_y dt = \kappa e q \frac{1}{bv}\int \frac{dx}{\sqrt{1+x^2}^3}$

where $x = \frac{\gamma v t}{b}$

writing $x = \mathrm{sh}\,\xi$

the integrand writes $\frac{d\xi}{\mathrm{ch}^2\xi} = d\,\mathrm{th}\,\xi$

The integral equal 2

$$p = 2\kappa e q \frac{1}{vb}$$

the electron being non relativistic $E \sim \frac{p^2}{2m} \sim \frac{1}{v^2 b^2}$

To get the energy loss, we have to integrate on all the electrons in the medium
i.e. integrate on *b db dφ* to get the loss by unit length:

$$\frac{dE}{dx} \propto \frac{1}{\beta^2}\int_{bmin}^{bmax}\frac{db}{b} = \frac{1}{\beta^2}[\ln b_{max} - \ln b_{min}]$$

b_{min} is linked to a maximum transfer

b_{max} is linked to a minimum transfer

Detector

Exercise

dE/dx

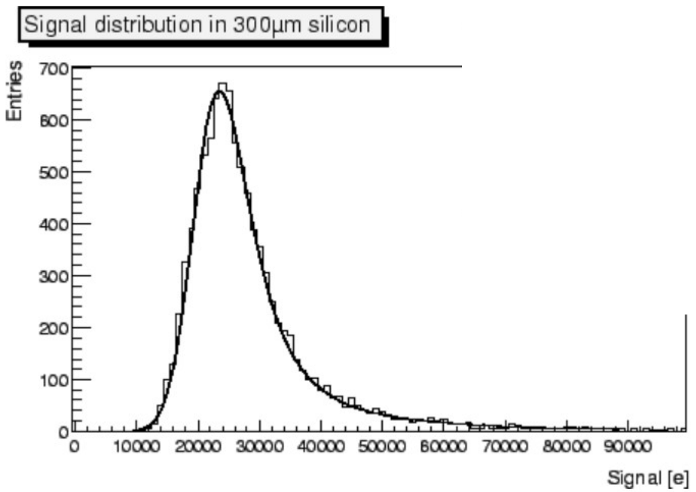
Energy lost by a particle passing through matter

$$E_{max} = 2m\gamma^2 v^2, \quad b_{min} \sim \frac{1}{\gamma m v^2}$$

$$b_{max} = \frac{\gamma v}{\omega}$$

where ω is a minimal energy transfer,
binding energy
(collision time compared to a period)
plasma energy,
screening, Fermi plateau

Energy loss fluctuation
Landau distribution
with a tail in E^{-2} ; rayons δ



MIP

Detector

Time of flight

Measuring the β of a particle hence its mass if p known

Consider a particle describing a trajectory of length L during a time t.

Its speed is $\frac{L}{t}=\beta c$ with 0<β<1. $\delta\frac{\beta}{\beta}=-\frac{\delta t}{t}$

Knowing its momentum p we deduce the mass which means identify the particle $\beta=\frac{p}{E}$ $m=|p|\sqrt{\frac{1}{\beta^2}-1}$

Distinguishing two particles of mass m and m'

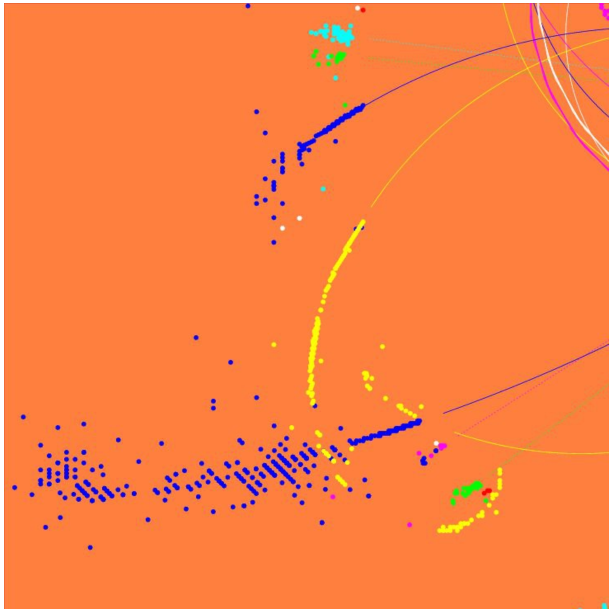
Typically L is around 1m and t around 3ns, assume a time measurement with a precision of 10ps $\delta\frac{\beta}{\beta}=-\frac{\delta t}{t}=\frac{1}{3}10^{-2}=3\,10^{-3}$ $p_{max}^2=\frac{m'^2-m^2}{2\delta\beta}$

π can be distinguished from e up to about 2 GeV
K from π up to about 6

How realistic is a δt of 10 to 20 ps? depends on design and technology

Range

If a particle does not interact strongly and does not decay weakly
before to have lost all its energy (mostly muons)
it will slow down by dE/dx then stop, the range (in calorimeters)
depends then entirely on the nature of the particle,
its mass and its momentum at the start of the range measurement.
The hypothesis that it is a muon can be then tested accurately
then its momentum measured more accurately by its range.



Detector

Coherent and macroscopic effects

A medium has a polarisability which transforms E in D

$D = E + 4\pi P$ with $P = \chi E$ where χ is the susceptibility

The dielectric constant is defined as $\epsilon = 1 + 4\pi\chi$

and the refraction index $n = \Re\sqrt{\epsilon}$

Maxwell equations

$\vec{B} = \mu \vec{H}$

$\vec{D} = \epsilon \vec{E}$

$$\nabla \cdot \vec{D} = \rho \qquad \vec{\nabla} \wedge \vec{H} - \frac{\partial \vec{D}}{\partial t} = \vec{j}$$

$$\nabla \cdot \vec{B} = 0 \qquad \vec{\nabla} \wedge \vec{E} + \frac{\partial \vec{B}}{\partial t} = \vec{0}$$

Looking for a plane wave solution

$\vec{E} = \vec{E}_0 \exp[i(\omega t - kz)]$

$$\vec{\nabla}^2 \vec{E} - \mu\epsilon \frac{\partial^2 \vec{E}}{\partial t^2} = 0$$

$$\nabla^2 \vec{E} = k^2 \vec{E} = \mu\epsilon \frac{\partial^2 \vec{E}}{\partial t^2} = \mu\epsilon\omega^2 \vec{E}$$

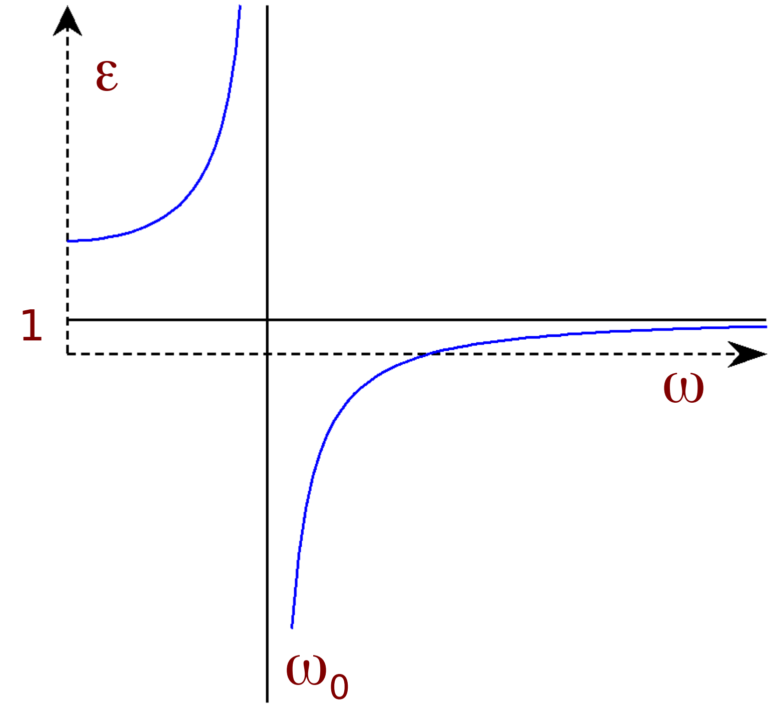
In a non magnetic medium where $\mu=1$

we get the dispersion relation $k^2=\epsilon\omega^2$ p=nE

which can be seen as a mass in terms of particles

$$m^2=\omega^2-k^2=\omega^2(1-\epsilon)$$

Shape of ε as a function of ω :



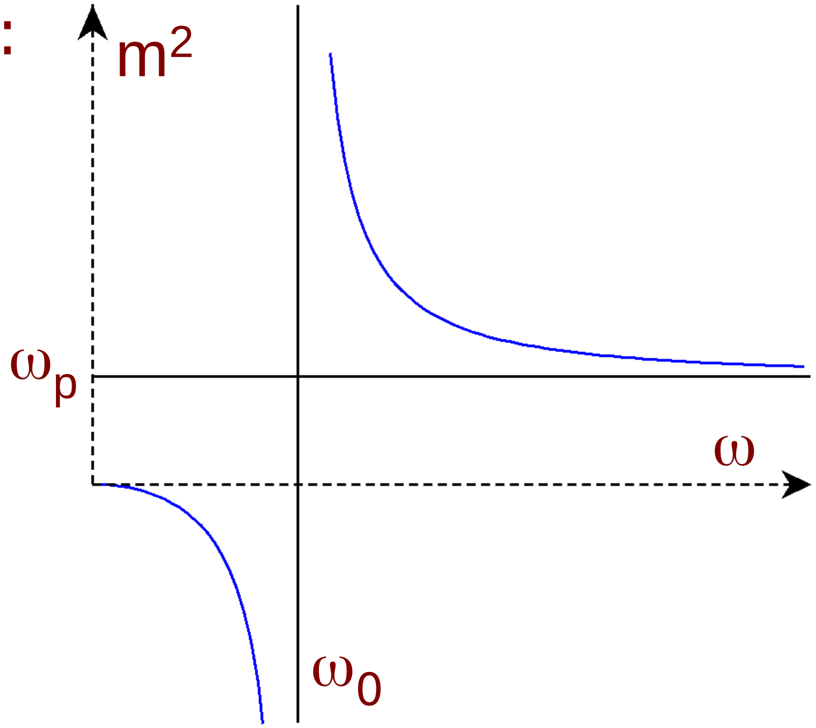
Suppose that in the medium
there is only one transition possible
with energy ω_0.

$$\epsilon=1+\frac{\omega_p^2}{\omega_0^2-\omega^2-i\omega\Gamma}$$

In term of mass $$m^2 = \frac{-\omega^2 \omega_p^2}{\omega_0^2 - \omega^2 - i\,\omega\,\Gamma}$$

In case of a weak absorption
we can neglect Γ and:

$$m^2 = \frac{\omega_p^2}{1 - \left(\frac{\omega_0}{\omega}\right)^2}$$



The square mass is negative below ω_0
then goes asymptoticaly toward ω_p

When $m^2 < 0$ spontaneous emission is possible
Cerenkov

At high energy the photon mass goes to ω_p
the emission of photons with a smaller energy is impossible: *quenching*

ω_p is called plasma frequency,
it is the collective oscillation frequency of the electrons around the ions, which corresponds to polarisation

$$\omega_p^2 = \frac{4\pi N Z e^2}{m}$$

21 MeV in water

Seen from a charged particle the electron density is x γ and the plasma frequency becomes $\gamma\ \omega_p$ (Synchrotron radiation, bremssthralung) quenching

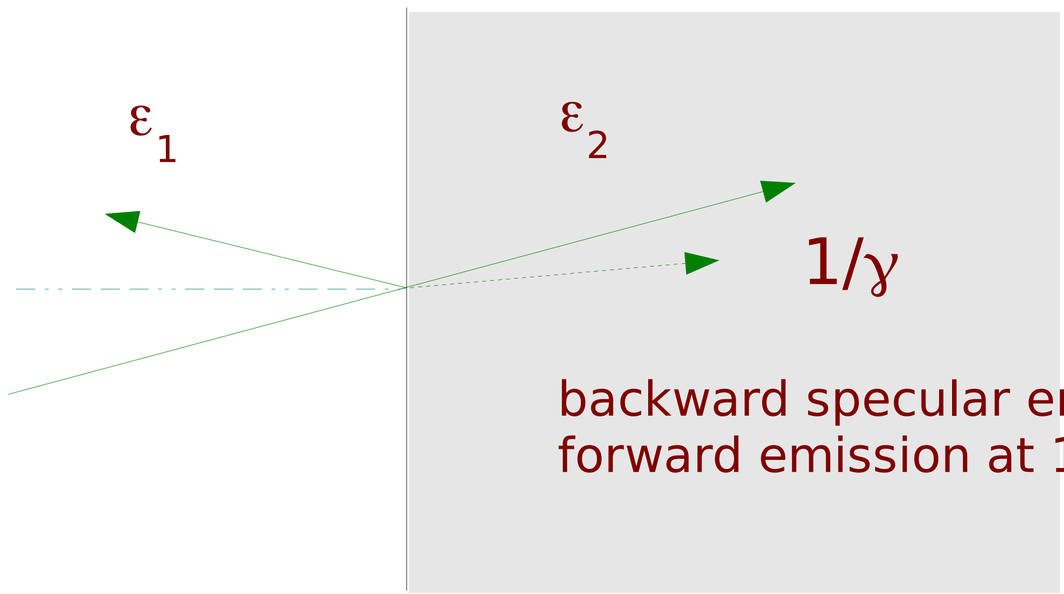
Transition radiation

radiation emitted when the particle crosses the boundary between two media with different dielectric constants

photon number ~ $\alpha\gamma$

domain: radio, optical, X

beam monitor
electron identification (Atlas)



backward specular emission
forward emission at $1/\gamma$ from the particle

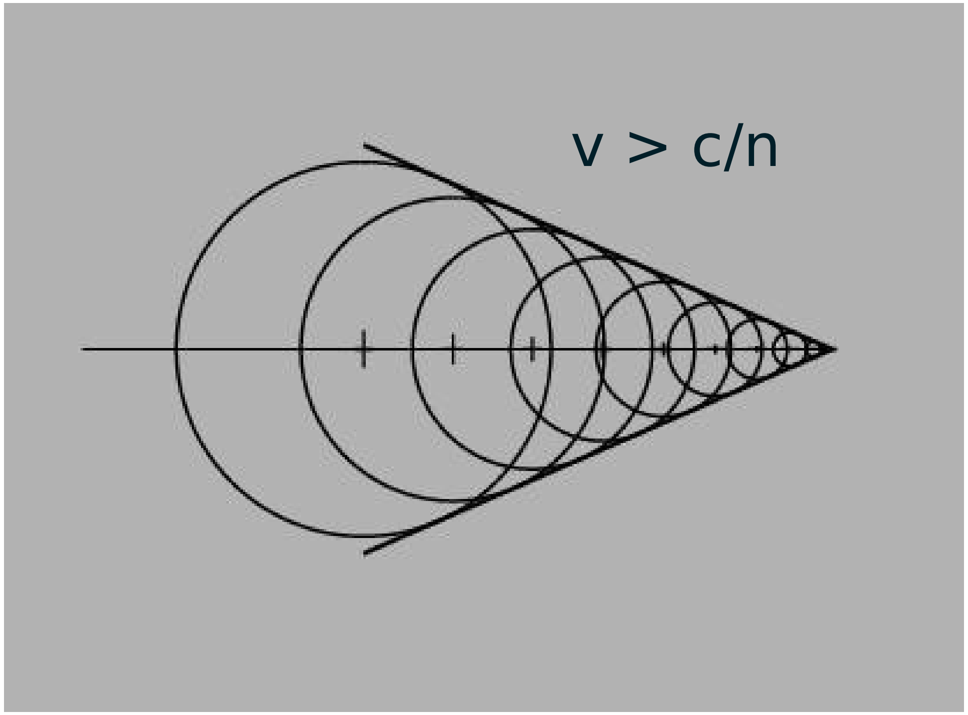
the photons with energy < $\omega\hbar$
can not penetrate

media: mylar, lithium
piles of foils
interference effects

Cerenkov

When a particle enters a medium where it propagates faster than the speed of light it radiates

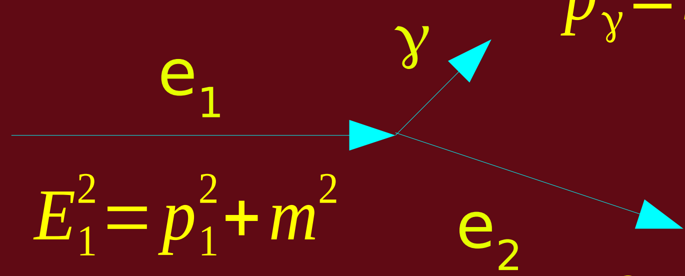
scheme derived from the Huyghens principle



Classical image: Cerenkov cone as a spherical waves envelop

Cerenkov

a particle approach



$$p_\gamma = n E_\gamma$$

$$E_1^2 = p_1^2 + m^2$$

$$p_1 = \beta E_1$$

$$E_2^2 = p_2^2 + m^2$$

$$E_1 = E_\gamma + E_2$$

$$p_1 = p_\gamma \cos\theta_\gamma + p_2 \cos\theta_2$$

$$0 = p_\gamma \sin\theta_\gamma + p_2 \sin\theta_2$$

$$(p_1 - p_\gamma \cos\theta_\gamma)^2 + (p_\gamma \sin\theta_\gamma)^2 \;=\; p_2^2 \;=\; E_2^2 - m^2$$

$$= \;(E_1 - E_\gamma)^2 - m^2 \;=\; p_1{}^2 + E_\gamma^2 - 2E_1 E_\gamma$$

rewriting the left part

$$E_\gamma{}^2 - 2E_1 E_\gamma \;=\; p_\gamma{}^2 - 2 p_1 p_\gamma \cos\theta_\gamma$$

$$(1 - n^2) E_\gamma \;=\; 2E_1 - 2n\beta E_1 \cos\theta_\gamma$$

$$\cos\theta_\gamma \;=\; \frac{1}{n\beta} + \frac{n^2 - 1}{2n\beta}\frac{E_\gamma}{E_1}$$

radiation emission if $\frac{1}{n} < \beta$

measuring θ gives β

Detector

Remark: $p_\gamma = n E_\gamma \sim \; m_\gamma^2 = (1-n^2) E_\gamma^2 < 0$ **Cerenkov**

the square mass of the photon is negative, that is why the reaction is possible

emission up to ω_0

$$\frac{d^2N}{dx \;\; dE_\gamma} = \frac{\alpha}{\hbar c} \sin^2\theta_\gamma$$

α coupling, $\hbar$c dimension, kinematics

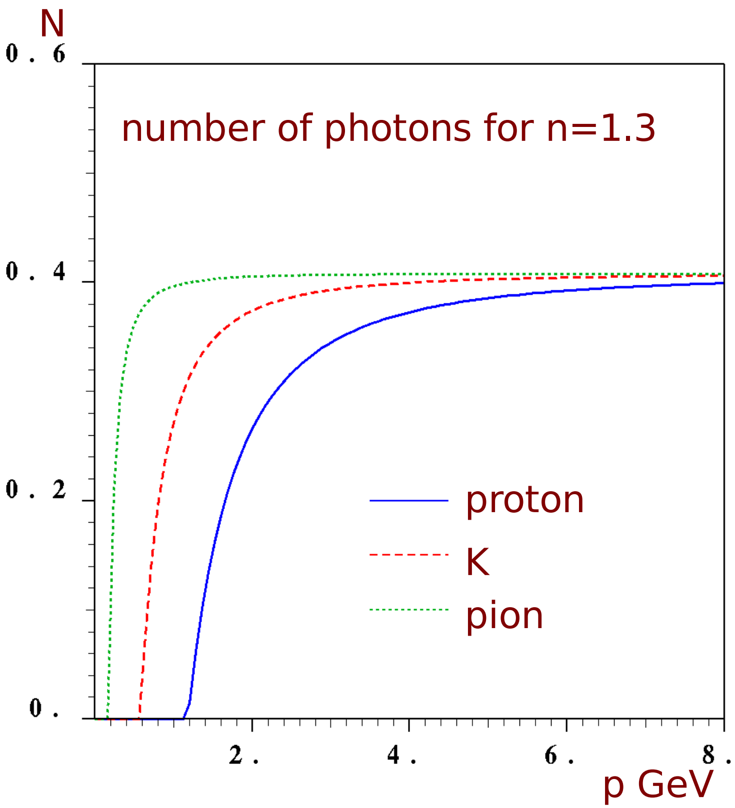
order of magnitude 1/137

if length and energy are in the same unit $\hbar$c = 1

Example : dx=1cm = 5 10^4 eV^{-1} , dE = 0,02 eV $\Rightarrow$ dN ~ 7

Additional remarks: time resolution due to the coherence,
linear polarisation due to the problem symmetry

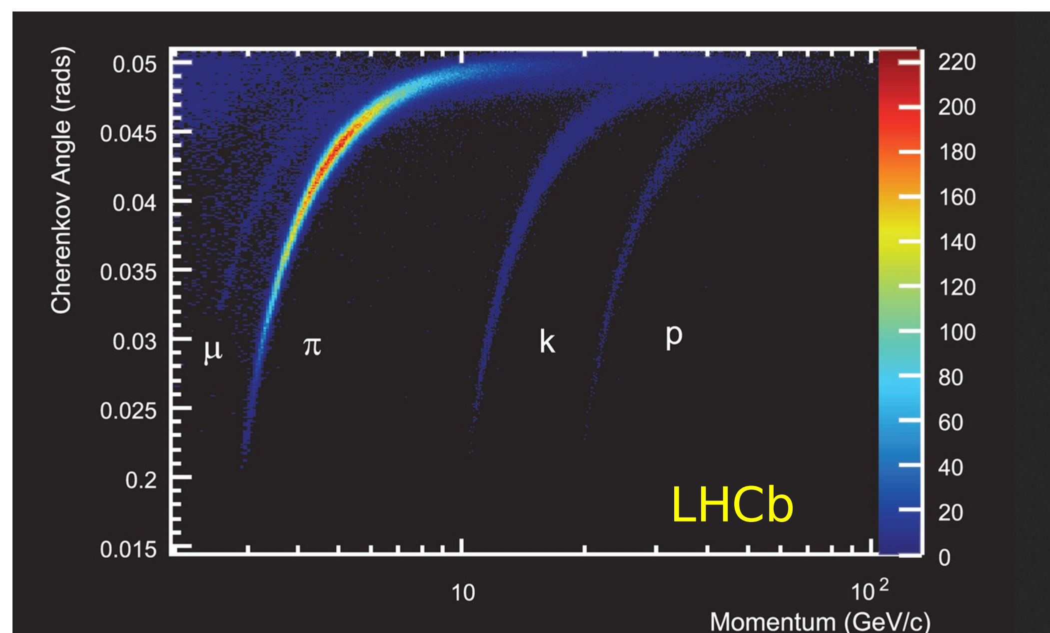
Cerenkov



Applications:
threshold Cerenkov (beams),
diaphragm Cerenkov
imaging Cerenkov

RICH, CRID, DIRC, ...
like in LHCb (LHC)
DELPHI (LEP)

difficult to integrate
in a general purpose
onion like detector



Super K

Detector

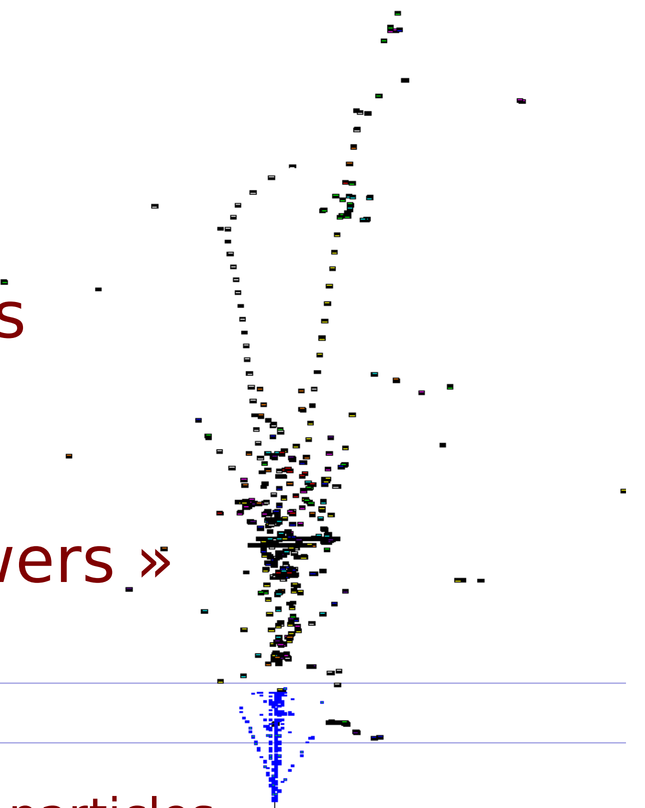
Measuring the neutrals

by converting them first into charged particles

- through electromagnetic decay or interaction : π^0's, γ's
- through weak interactions, decays (depends on lifetime) :
  D^0's, B^0's, $K^0{}_s$'s
- through strong interactions : n's, K^0L's

but decays may be in neutrals
interactions may generate neutrals

⇒ Loop on interactions : « showers »



The basis of calorimetry

calorimeter :a dense material with sensitivity to charged particles

See later

END OF THE THIRD LECTURE ?

Detector

Means of particle identification

What are the properties specific to
leptons, electrons, muons, taus, hadrons from different quarks
which make them behave differently in the detector ?

Their type of interaction : electromagnetic, strong, weak
Their mass
Their decays, lifetime, decay mode
Their interaction products, showers

They are

Charged, then momentum measurable by its trajectory in B $\frac{\delta p}{p} = \alpha p$

electromagnetic, the energy can be measured in a calorimeter see later what is a calorimeter $\frac{\delta E}{E} = \frac{\alpha'}{\sqrt{E}}$

Typical values : $\alpha = 10^{-4}$, $\alpha' = 10^{-1}$
for momenta and energies in GeV

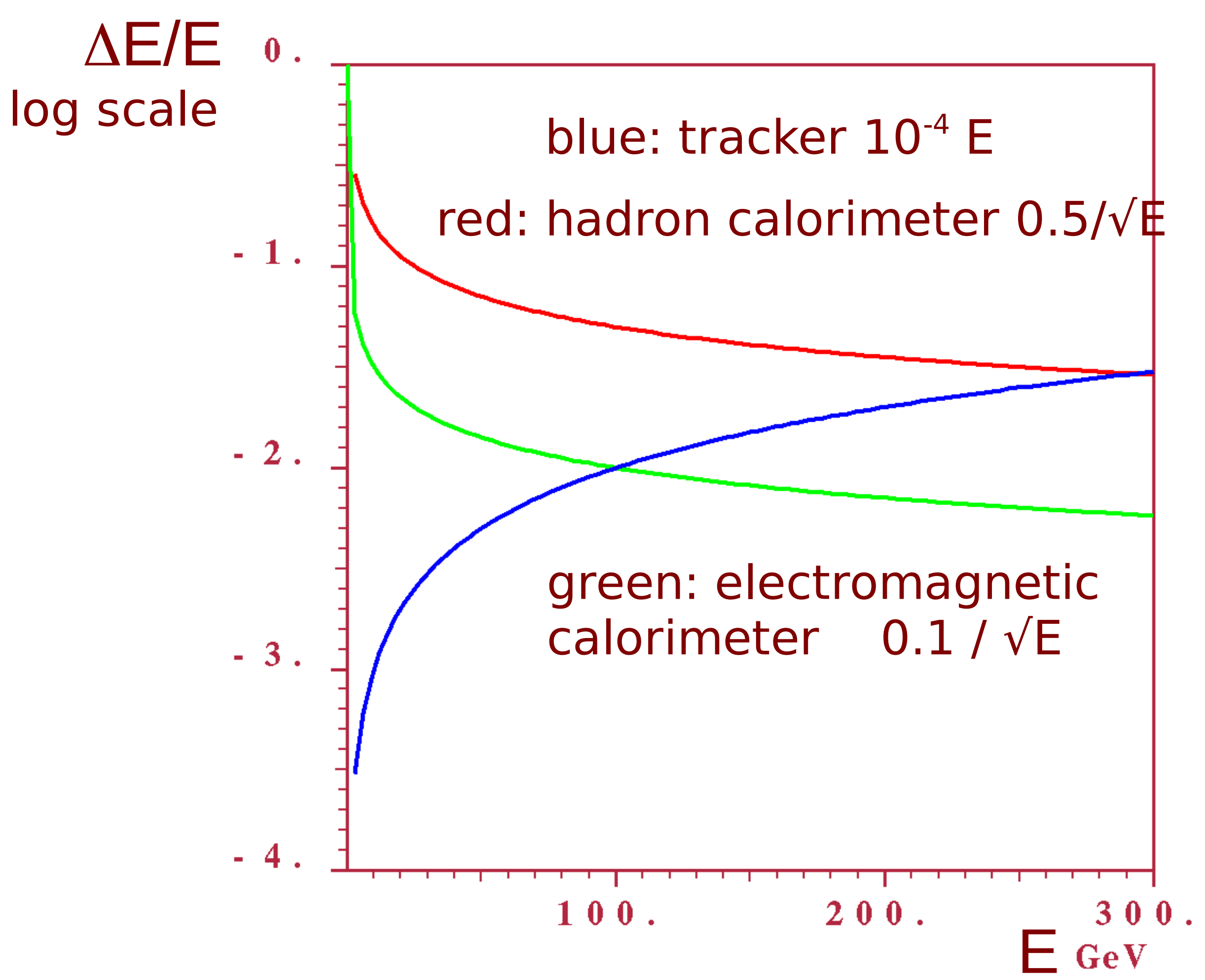
The energy is better measured than momentum above 100 GeV

But they are light:
they emit photons by bremsstrahlung (spoils the energy measurement)
and generate δ rays (spoils the trajectory measurement by biasing the points)

Detector

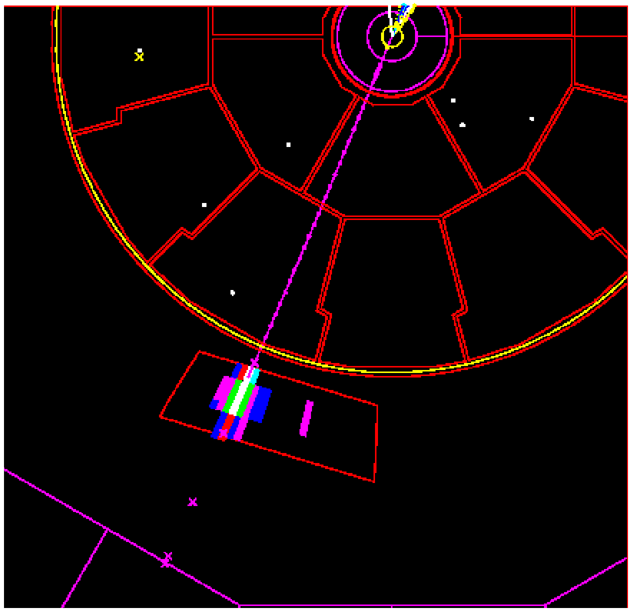
Electrons

Resolution figures



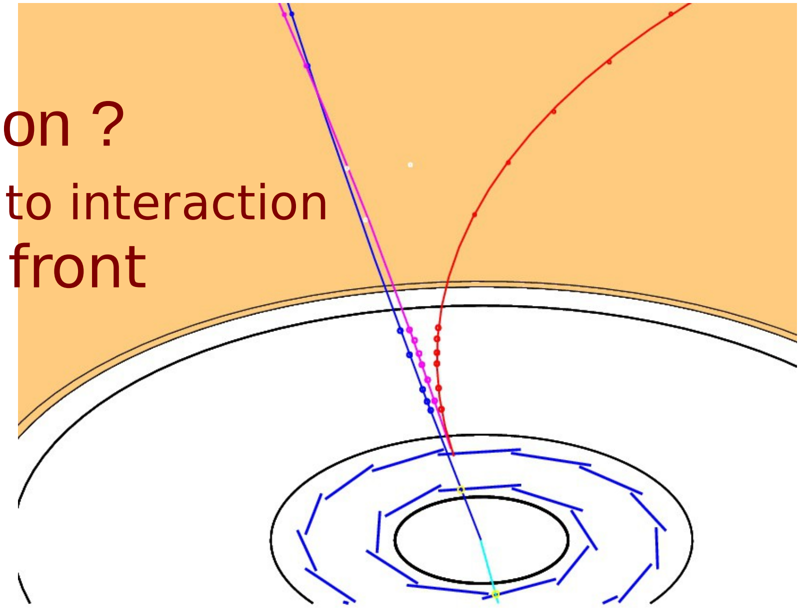
In the domain of interest the tracker is always better.

Only at very high energies does the Ecal compete for electrons measurement
but it is
needed for bremsstrahlung



Identification tools

- track to shower match
  - E(calo)/p(tracker) close to 1
  - positions at entrance of calorimeter close by
- shower shape: longitudinal
  and transverse (Moliere radius*),
- shower start
- dE/dx (even δ rays or knock-on, first K identification)
- specific detectors: Cerenkov, transition radiation



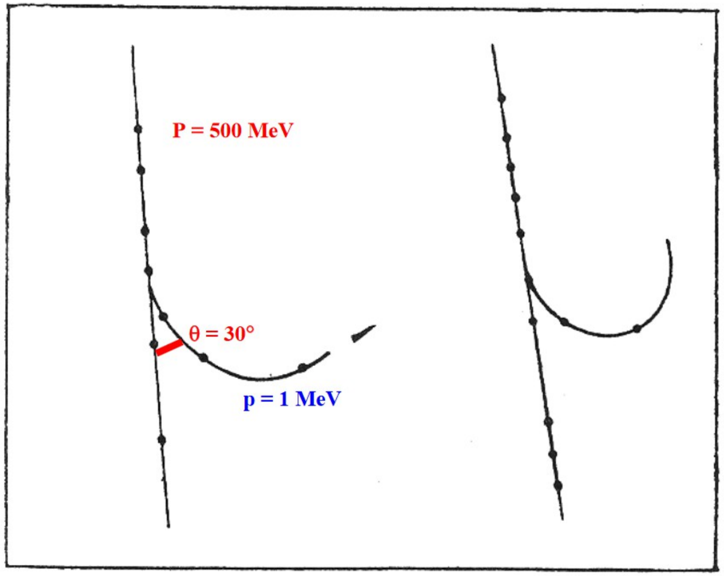
is it a "prompt" electron or a γ conversion ?

- impact parameter? difficult tangent pointing to interaction
- two tracks tangent where no point is in front
- contact point on a dense medium

Contamination: charge exchange
detector imperfections

* radius of a cylinder along the track containing 90 % of the energy

Leprince-Ringuet Lhéritier 1943



Dessin stéréoscopique de la collision.

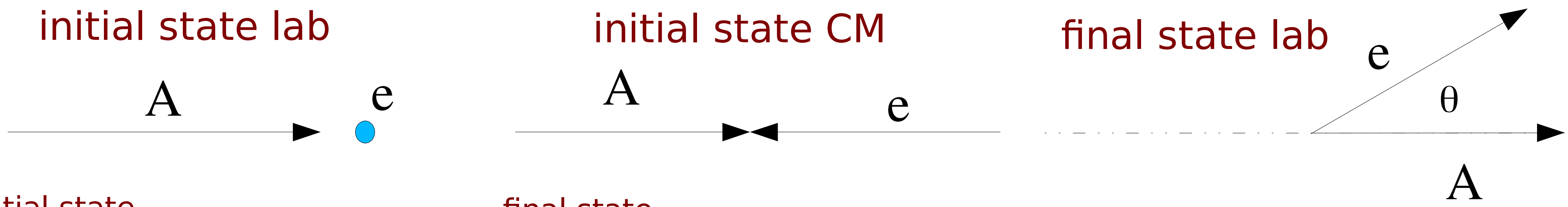
A way to sign a new particle

Exercise: A particle A with mass m_A goes through a gas and hits an electron from the medium, which momentum and angle are measured. Compute m_A from the data on the figure.

Compare to a π (140 MeV), a K (494 MeV) or a proton, is it possible, in such a case, to identify the particle by measuring the electron momentum?

m_e = 511 kEV

Exercise



initial state

$$\begin{pmatrix} E_A + m_e \\ \vec{p}_A \end{pmatrix} \qquad E_A^2 = m_A^2 + p_A^2$$

final state

$$\begin{pmatrix} E'_A + E'_e \\ \vec{p}'_A + \vec{p}'_e \end{pmatrix} \qquad E'^2_A = m_A^2 + p'^2_A \qquad E'^2_e = m_e^2 + p'^2_e$$

$$m_S^2 = (E_A + m_e)^2 - p_A^2 = m_A^2 + m_e^2 + 2 E_A m_e$$

conservation

$$E'_A + E'_e = E_A + m_e$$

$$\vec{p}'_A + \vec{p}'_e = \vec{p}_A$$

Using the conservation we write $E'^2_A = m_A^2 + p'^2_A$

$$(E_A + m_e - E'_e)^2 - (\vec{p}_A - \vec{p}'_e)^2 - m_A^2 = 0$$

$$(E_A + m_e)(m_e - E'_e) + \vec{p}_A \cdot \vec{p}'_e = 0$$

$$\vec{p}_A \cdot \vec{p}'_e = 433$$

$$m_e - E'_e = -0.612\, MeV$$

$$E_A = 708\ MeV, \quad m_A \approx 500\, MeV$$

m_e = 0.511 MeV

p_A = 500 MeV

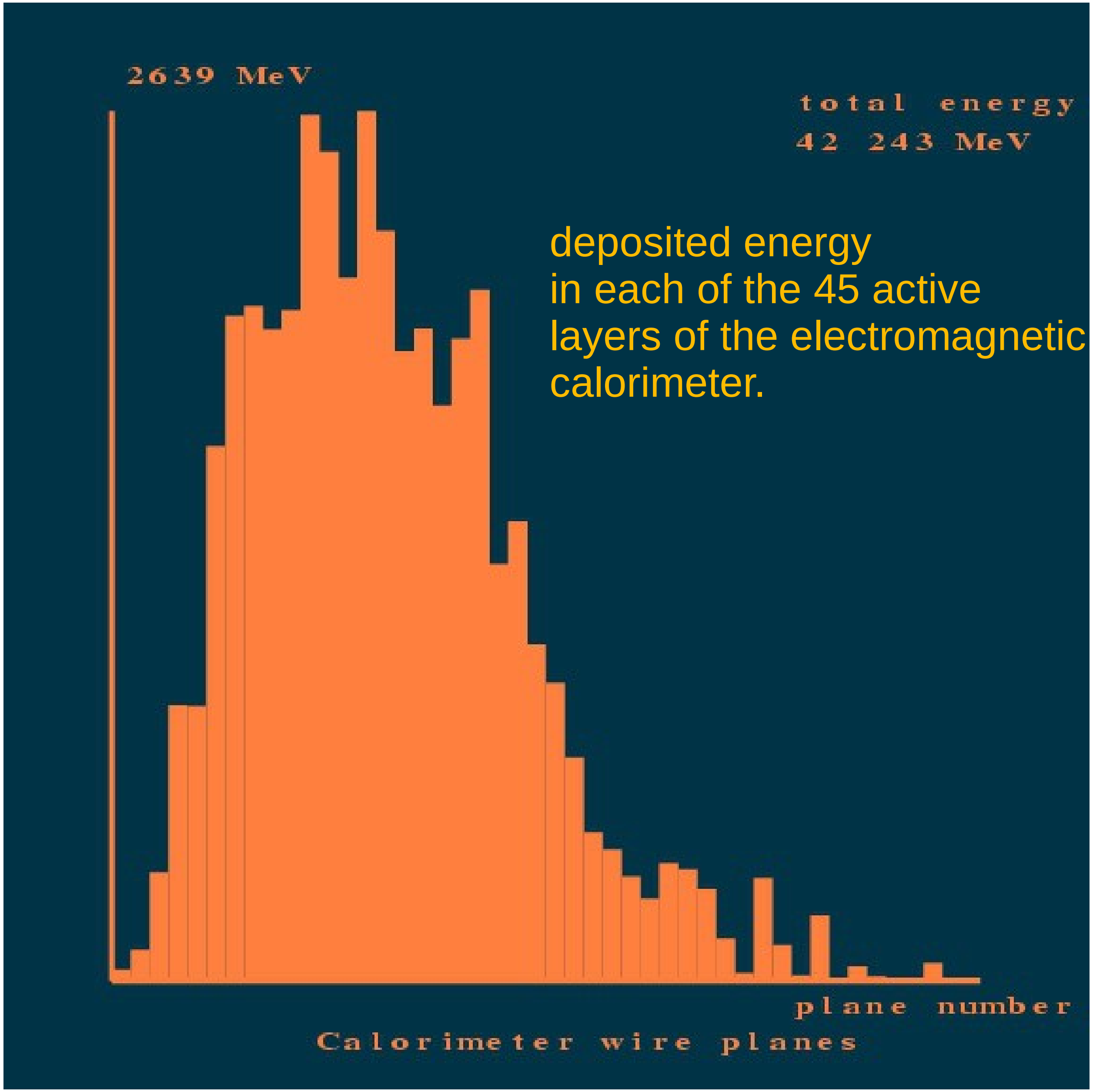
p'_e = 1 MeV

cosθ = 0.866

E'_e = 1.123 MeV

it is likely to be a K

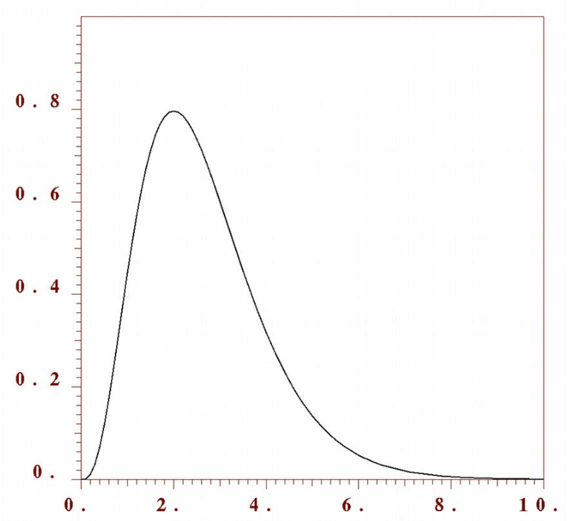
Electrons



Energy longitudinal profile of an 45 GeV electron .

ALEPH

Parametrisation: $z^{\alpha} e^{-\beta z}$



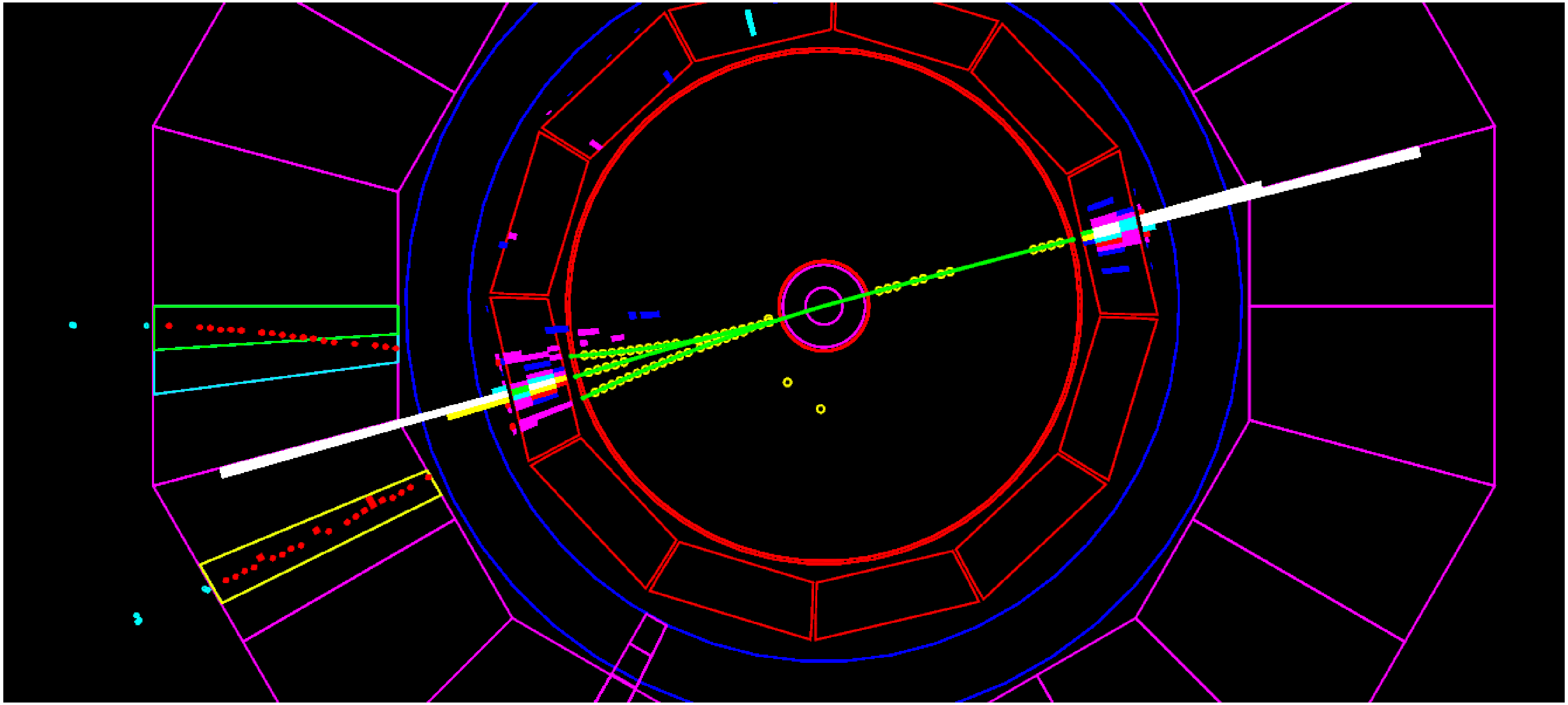
Detector

Electrons

Muons

e+ e- μ+μ-

ALEPH



Detector

Muons

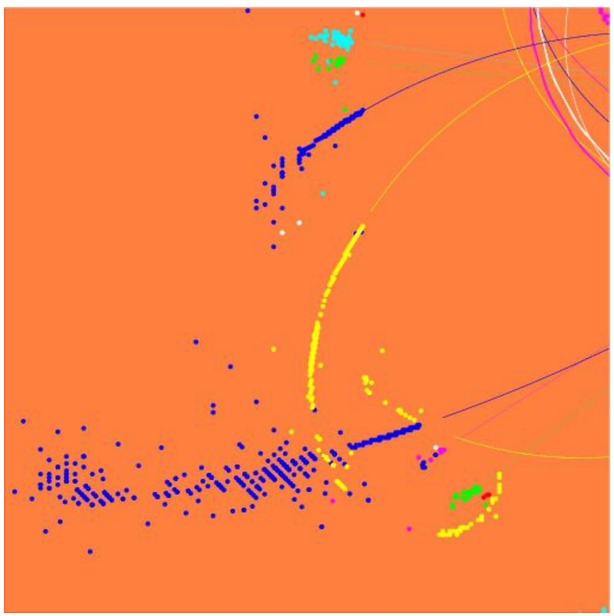
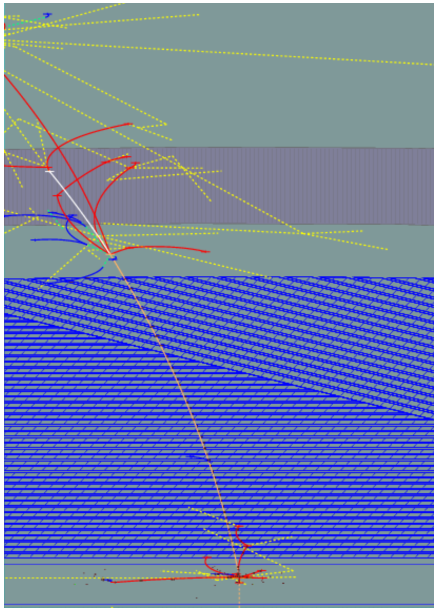
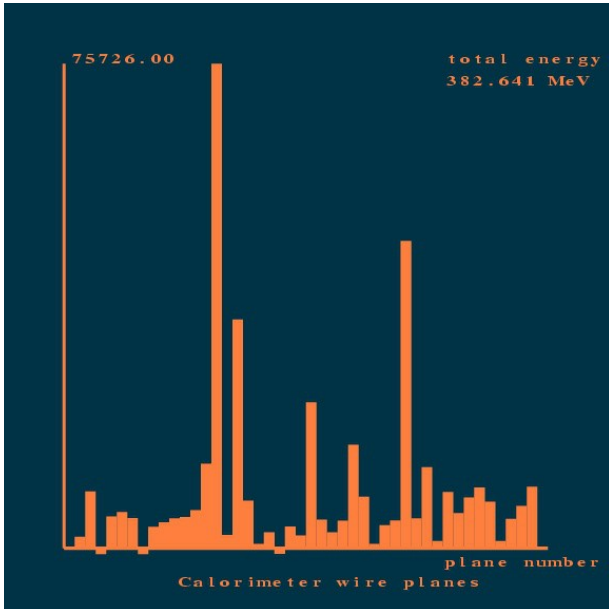
A charged particle which looses energy
~ only by dE/dx

at our energies where the mass
is not totally negligible

Muon identification

penetration, muon chambers*, range
shape of the deposit in the calorimeter,
link to the track, momentum in material

signs the presence of a neutrino

contamination: sail through or punch through, decay in flight

* detectors placed after
a lot of material

Very important for the physics

because of its lifetime 290.3 fs   cτ about 100 μ
and hadronic decay modes
which provide a measurement of its spin state

Polarimeter, correlations

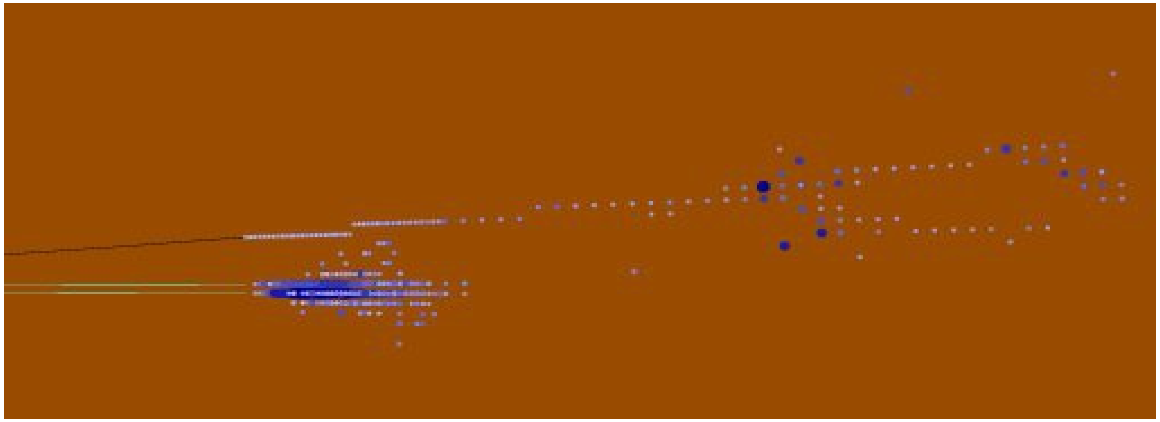
Higgs CP state by its decay in two taus
transverse/transverse polarisation correlation

main decay modes

	BR
$\tau^- \rightarrow \nu_\tau \; e^- \; \bar{\nu}_e$	17
$\tau^- \rightarrow \nu_\tau \; \mu^- \; \bar{\nu}_\mu$	17
$\tau^- \rightarrow \nu_\tau \; \pi^-$	10
$\tau^- \rightarrow \nu_\tau \; \rho^-$	23
$\tau^- \rightarrow \nu_\tau \; a_1^-$	2x9

It is essential to identify efficiently the tau,
to separate the 3 main hadronic modes

Knowing that there are essentially 0, 1 ou 2 π^0



τ direction with Vdet and
interaction point

Tau identification

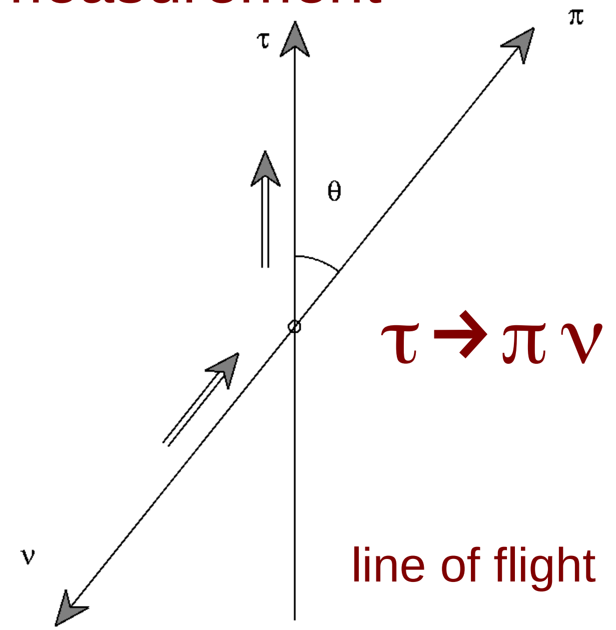
by the lifetime
by the decays

leptonic decays

hadronic decays

Tau longitudinal polarisation measurement

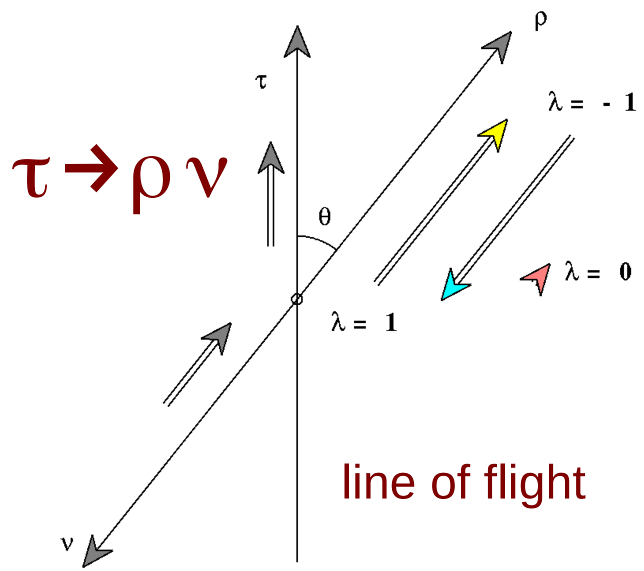
$\tau \longrightarrow \pi\nu$ decay.
Write the relation between the π energy in the laboratory and the cosine of the angle between the line of flight of the τ and the π in the τ CM.



$$m_\tau = 1{,}77 \text{ GeV} \quad m_\pi = 140 \text{ MeV} \quad m_\nu = 0$$

$$E\pi \sim E\tau/2\,(1+\cos\theta^*)$$

Polarisation and angular distribution



$$W(\cos\theta^*) = (1+P\cos\theta^*)$$

$$W(E\pi) = (1 - P + 2P\, E\pi/E\tau\,)$$

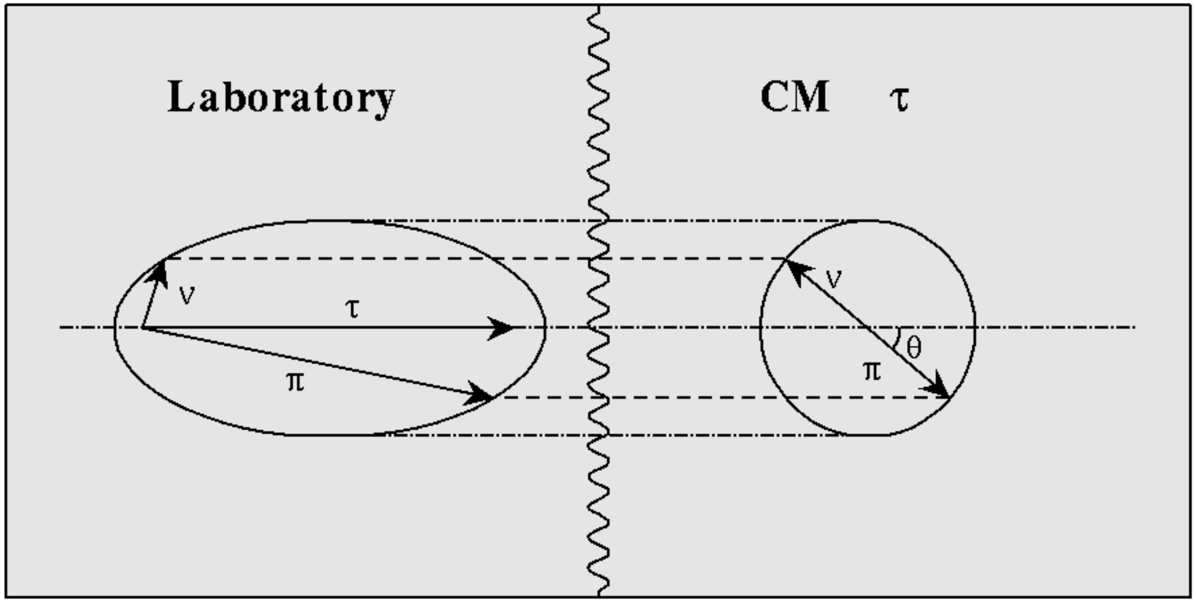
More complicated in the case of the ρ, there exist an optimal variable $\sim E_\pi - E_{\pi 0}$

In the centre of mass frame *

$$m_\tau = E_\pi{}^* + E_\nu{}^* \quad \vec{0} = \vec{p}_\pi{}^* + \vec{p}_\nu{}^* \quad \Rightarrow \quad p_\nu{}^* = p_\pi{}^* = p^*$$

$$E_\nu{}^{*2} = p^{*2} \qquad E_\pi{}^{*2} = p^{*2} + m_\pi^2 \qquad E_\pi{}^{*2} - E_\nu{}^{*2} = m_\pi^2$$

$$E_\pi{}^* - E_\nu{}^* = \frac{m_\pi^2}{m_\tau} \qquad E_\pi{}^* = \frac{1}{2}\frac{m_\tau^2 + m_\pi^2}{m_\tau} \qquad E_\nu{}^* = \frac{1}{2}\frac{m_\tau^2 - m_\pi^2}{m_\tau} = p^*$$



Going to the lab frame

$$\gamma = \frac{E_\tau}{m_\tau}$$

$$E_\pi = \gamma E_\pi{}^* + \beta\gamma p^* \cos\theta_\pi{}^*$$

At very high energy

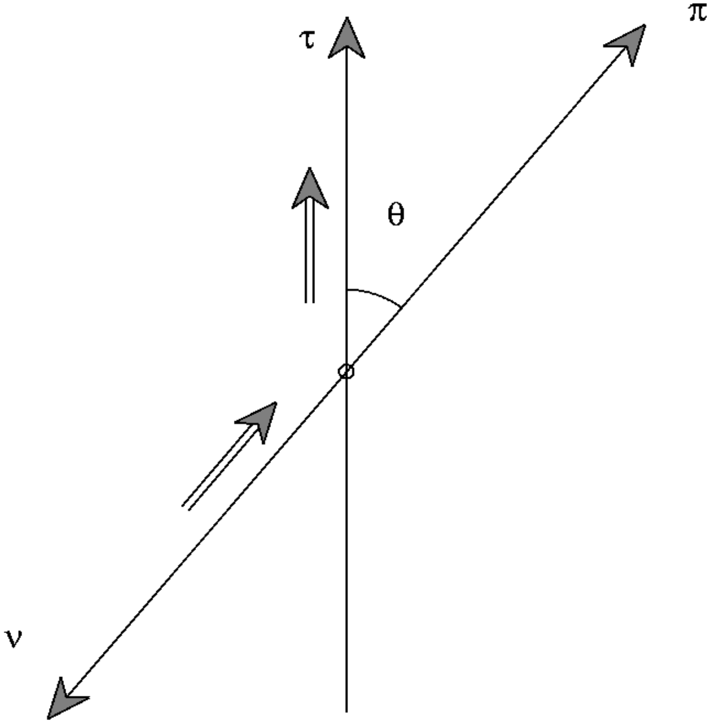
$$E_\pi = \gamma E_\pi{}^* \left(1 + \cos\theta_\pi{}^*\right)$$

Tau polarisation and decay products angular distribution

Spin ½ rotation matrix $D_y(\theta) = \begin{pmatrix} \cos\frac{\theta}{2} & -\sin\frac{\theta}{2} \\ \sin\frac{\theta}{2} & +\cos\frac{\theta}{2} \end{pmatrix}$

Taking a tau (spin 1/2) of a given helicity $\hbar/2$
we move to its rest frame,
the spin is aligned with the tau line of flight.
After decay in π ν,
the spin of the π is 0, the helicity of the ν is ξ (-1/2)
the probability to measure $\hbar/2$
along a direction at an angle θ*
is given by the rotation matrix to be $\cos^2\theta^*/2$

$$\langle 1/2, 1/2 | \theta^*, -1/2 \rangle = \langle 1/2, 1/2 | R_y(\theta^*) | 0, -1/2 \rangle$$



The angular distribution is then in $\frac{(1+\cos\theta^*)}{2}$

for the other tau helicity $\frac{(1-\cos\theta^*)}{2}$

Detector

Exercise

Tau polarisation and decay products angular distribution

P^+ (P^-) being the probability for the τ to be in the ℏ/2 (-ℏ/2) state
the probability to observe ℏ/2 along the π direction is

$$P^+ \frac{(1+\cos\theta^*)}{2} + P^- \frac{(1-\cos\theta^*)}{2} \propto 1+P\cos\theta^* \quad with \quad P=\frac{P^+ - P^-}{P^+ + P^-}$$

P being the tau polarisation

The angular distribution in the CM writes then

$$W(\theta,\varphi)=\frac{1}{4\pi}(1+P\cos\theta^*)\,d\cos\theta\,d\varphi$$

To measure the tau polarisation we use the pion energy in the laboratory

$$E_\pi=\gamma_\tau E_\pi{}^* + \beta_\tau \gamma_\tau p_\pi{}^* \cos\theta_\pi{}^*$$

neglecting the pion mass squared
in front of the tau mass squared

$$E_\pi = E_\tau \frac{1+\cos\theta^*}{2}$$

the pion energy spectrum is then

$$W(E_\pi)=1-P + 2P\frac{E_\pi}{E_\tau}$$

The slope of the pion energy spectrum provides P

Detector

The hadrons and the study of the energy flows.

Except when they come from taus, hadrons appear in jets issued from quarks

hadrons are a problem of jets

The charged hadrons:
they are measured in the trajectometer
they are seen in the calorimeter also

they are identified as not being leptons
Knowing where they come from : what vertex, V0's, decays

The neutral hadrons are seen only in the calorimeter

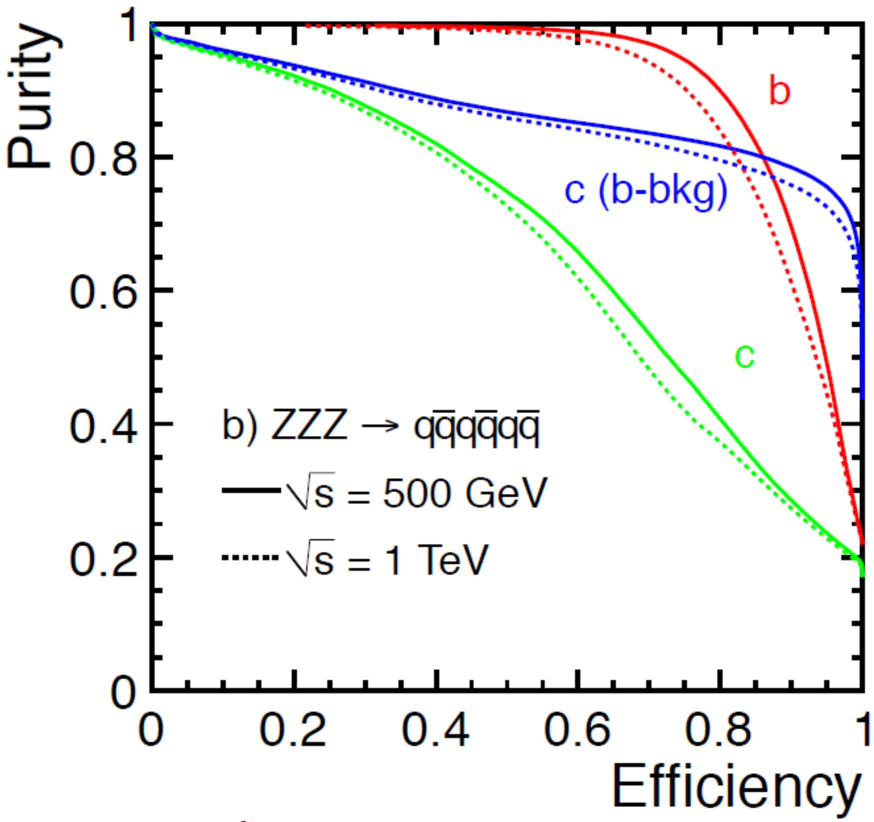
Typical energy fractions at ILC in jets:

charged tracks	60%
neutral hadrons	12%
photons	28%

These are only mean numbers,
they fluctuate a lot depending of the event type and on the specific event

Identify the jet nature by identifying the jet vertex :
b with a lifetime of B0 1520fs
but also c D0 410fs

It is a strong advantage to have a good vertex detector precise, stable close to the interaction point

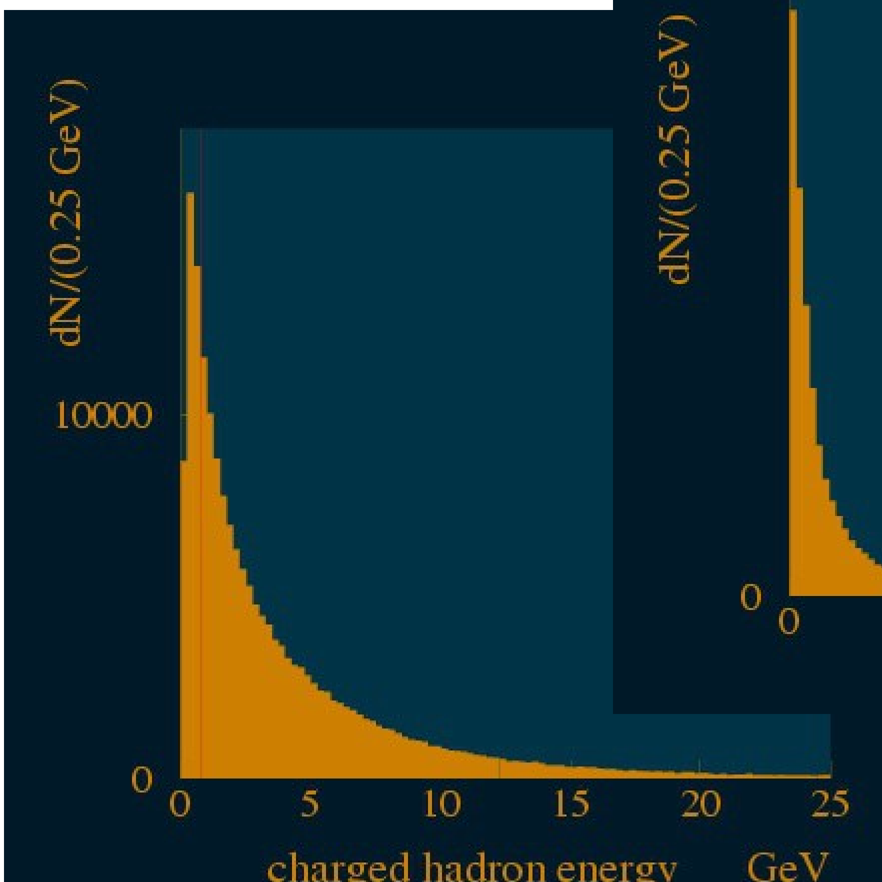


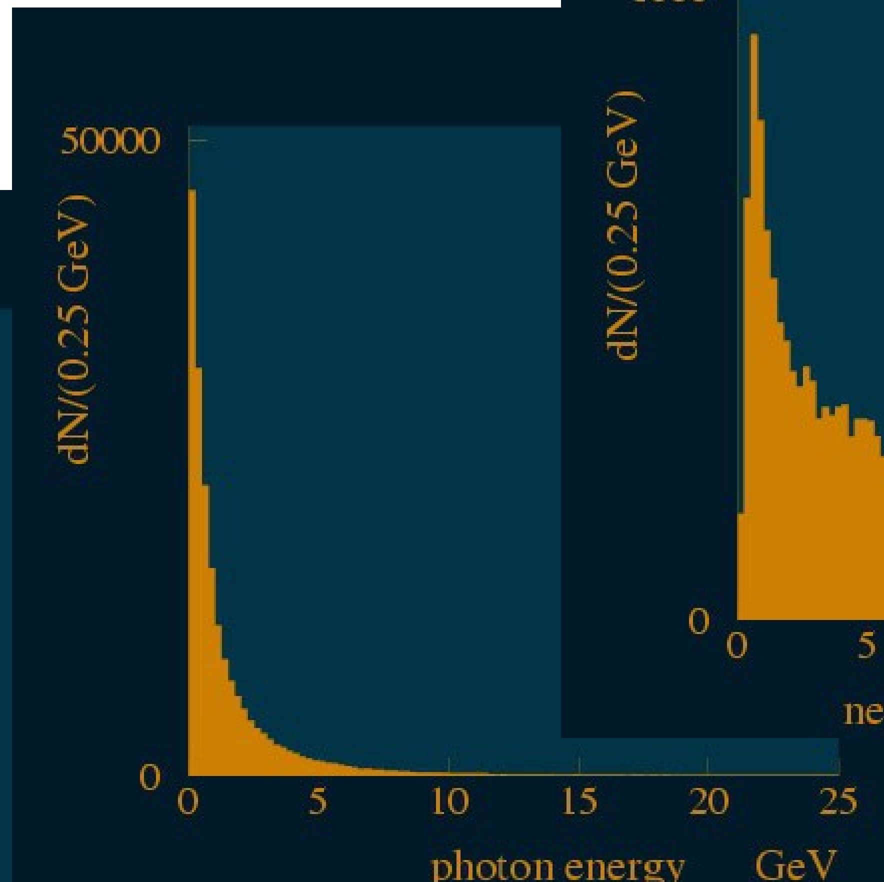
ILD in ILC TDR

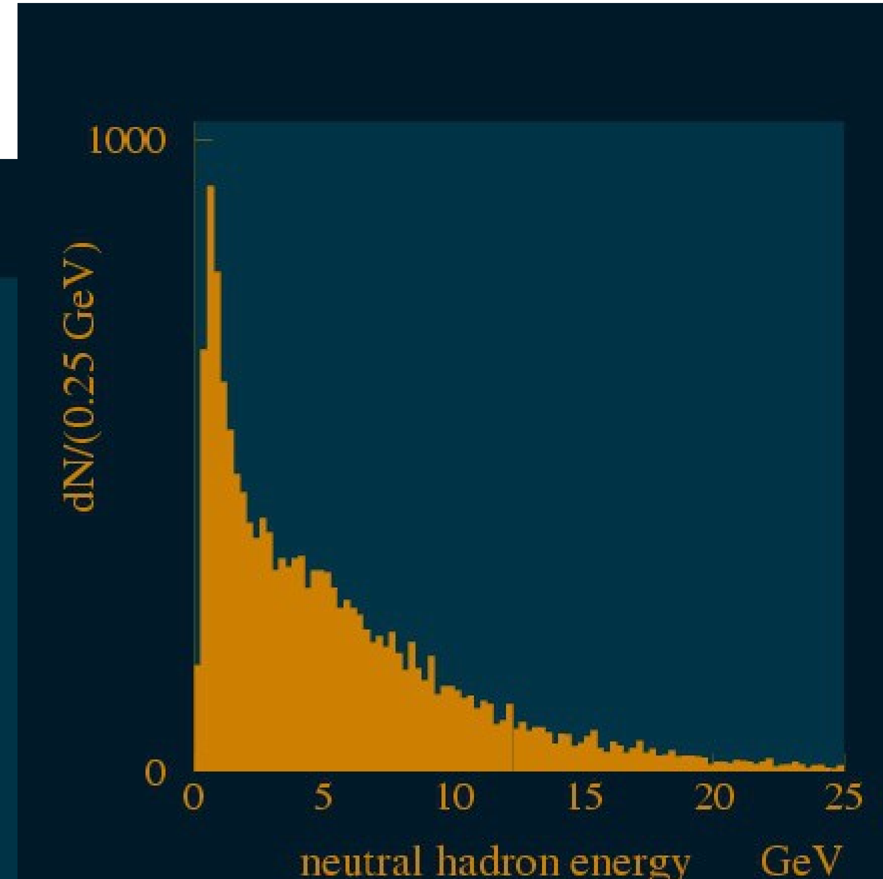
The hadrons and the study of the energy flows.

What CM energy ? 250 GeV

multiplicity rises







$E_\gamma = 1/2\ E_{ch}$

all this is of rather low energy

Detector

The hadrons and the study of the energy flows.

To measure the particle jets, it is possible to globally sum the energy of the particles as measured in a calorimeter

doing your best for equalising the response to hadronic and electromagnetic particles.

simply compensation or getting the low energy neutron contribution

It is also possible to try a more analytic approach by separating all the particles making the jet, and measuring each of them in the best suited detector :

the charged ones in the trajectometer,
the photons with the electromagnetic calorimetre,
the neutral hadrons with the calorimetre.

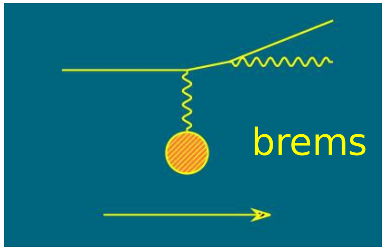
This technique appears in two flavours according to the fact that it is possible or not to isolate the showers topologically:
when this is possible and the energy, we try to measure, does not contribute to the particle shower recognition
the technique is referred to as « Particle Flow Analysis »
when, due to a less adequate detector, the energy has to be invoked,
the technique is referred to as « Energy Flow »

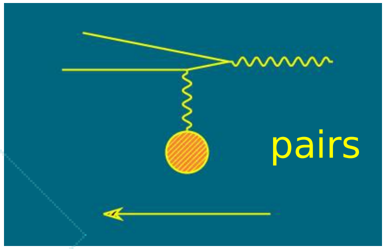
Examples

Detector

Before to go deeper on the PFA, a brief recall on calorimetry

electromagnetic: the photon or electron develop a shower of electrons and positrons through Bremsstrahlung/pair creation (above 2MeV)





The incident energy is estimated by measuring the energy deposited by the shower charged tracks.

hadronic:

the hadrons interact in the matter
creating hadrons and π^0's +n +K0 ..
those develop electromagnetic showers
when the charged hadron deposit by dE/dx,
but there are nuclear effects, creation of slow neutrons

Recall on the radiation/interaction length

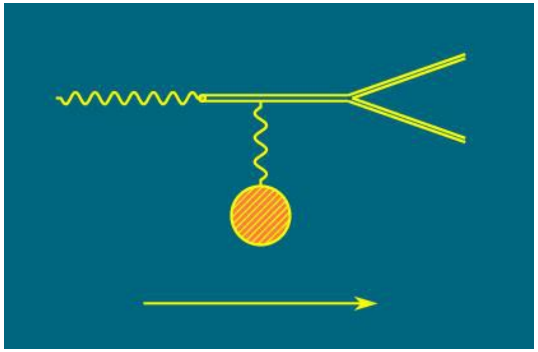
The radiator is characterised by the cross sections of the incoming particles

For electromagnetic processes (pair conversions, Bremsstrahlung)
the cross sections are essentially flat above 100 MeV
concept of radiation length (X_0) :
length of material after which electrons have lost 1/e of their energy.
It is expressed in units of length (cm) but often in g/cm^2 by dividing by the density.

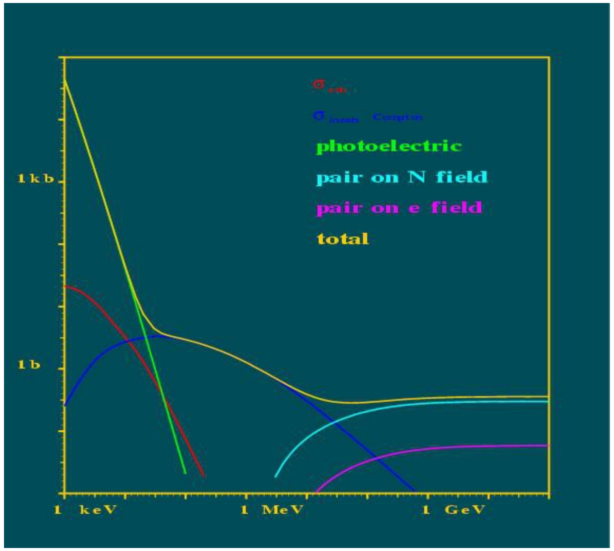
Approximately $$X_0 = 180 \frac{A}{Z^2} \quad g\,cm^{-2}$$

Critical energy, comparing the radiation loss with the dE/dx

At low energies (< 2 GeV)
- Compton
- Photoelectric effect



At high energy
at the level of 10^{-4}
muon pair creation
pions



Detector

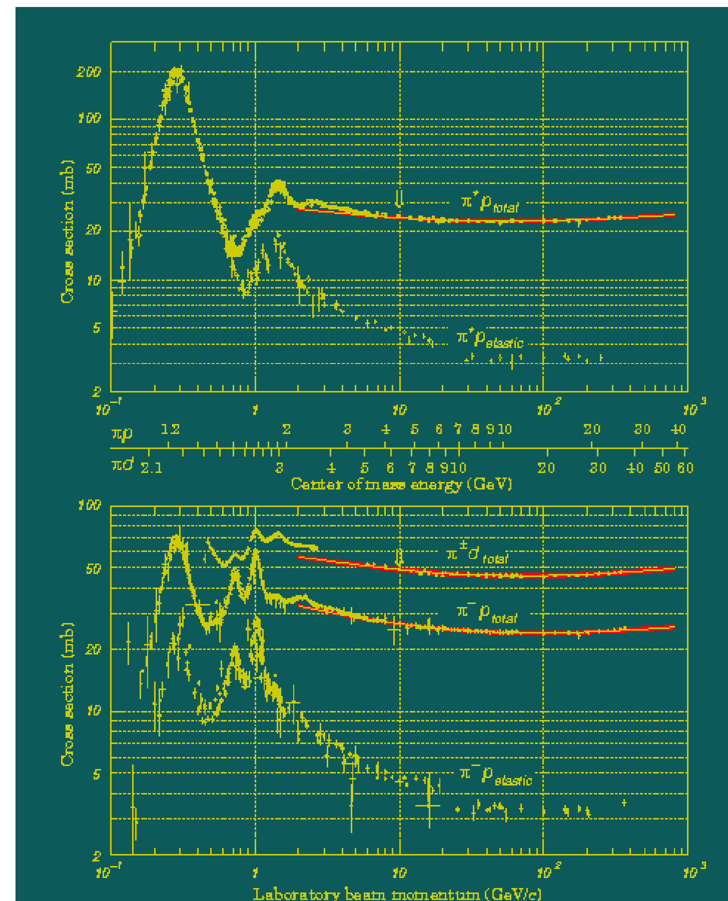
Recall on the radiation/interaction length

Above few GeV the cross sections are flat
and not too different,
concept of interaction length
Below, huge differences due to resonances.

About one third
of the products of a strong interaction are π^0's

The non interacting charged hadrons
loose energy by dE/dx and
nuclear collisions with nuclei (40%)

π^+ p and π^- p cross sections
from PDG



10 mbarn = 1 fm^{-2}

The importance of the calorimeter grain in space and time.

It could seem that the point is on measuring the energy
but we measure the 4-momentum and the position of
the shower which provides, for neutrals, the momentum direction
is at least as essential.
The identification of the shower which rests on its shape needs
a grain < shower size longitudinal and transverse.
The separation between close by showers needs the same type of grain.

Recently, linked to technological progress and to the cell size,
the precise measurement of the time has revealed as a powerful tool.

Detector

Calorimetric devices

- The homogeneous calorimeters
  getting a medium where a large fraction
  of the deposited energy can be seen

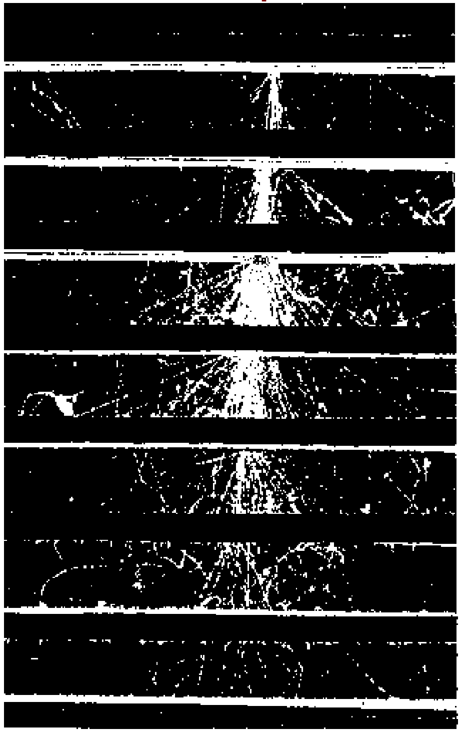
  Examples : Cerenkov calorimeters lead glass, (superK)
  scintillation.
  crystals NaI, CsI, BGO, PbW04 (CMS)

  The energy resolution is excellent,
  but a fine granularity is difficult to realise

- The sampling calorimeters
  the functions of radiator to develop the shower
  and of detector to see the charged tracks are separated
  the sampling determines the energy resolution
  since the energy deposited in the radiator is lost.
  This makes it much easier for the grain.

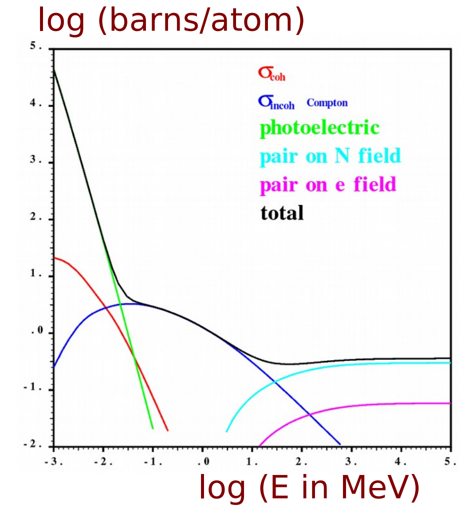
  Today the grain is determined by a detecting cell size

cloud chamber
with Pb plates

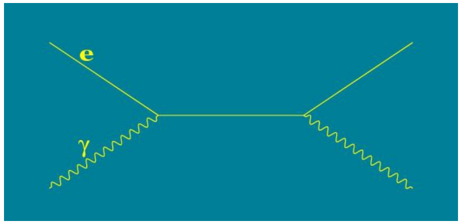


Detector

Losses and fluctuations



Electromagnetic
Aside what is lost due to sampling (see previous slide)
photons below certain energy
electrons stopping in the detecting medium



Hadronic
the hadrons passing through the calorimeter medium
break nuclei, emitting nuclei fragments which may
generate huge energy deposit in the detecting medium
but also numerous low energy neutrons which wander
slowly till they eject a free proton.
Not measuring the neutronic energy creates an imbalance
between electromagnetic and hadronic deposits (e/h ratio often around 1.3)
introducing in the energy measurement the fluctuations
of the electromagnetic fraction

Time problem : the signals from the wandering neutrons is always delayed
but may be by times large compared to the electronic integration time or
the time between crossing.

Detector

The problem of hadronic shower resolution is mostly related to the different response of the calorimeter to the hadronic component, where neutrons are lost, and to the electromagnetic one, i.e. π^0

There are two solutions:
one is to adjust the medium to obtain equal response, (next slide)
the other to identify the two components and weight them adequately

This last solution can be obtained by hardware (dual read-out) or by some recognition, this was already the case in H1 with a liquid argon calorimeter...

and that is what we recommend

These methods to optimise the hadronic resolution are often referred to as "energy flow" techniques as well and indeed the ideas behind are similar.

Also example from ILD AHCAL

Detector

Dual read-out

if you can have access to two informations,
one more sensitive to electrons like Cerenkov
one less,
for the same volume
you can combine the two results to correct e/h.

Adjusting e/h

adapt the medium sensitivity to neutrons
by adjusting the amount of hydrogen (Uranium, scintillator)

tune the response by playing with
the interaction/radiation length ratio, (10 for Fe, 30 for W).

play with the integration time or using time measurement
play with the cell size or FD for digital read out.

Radiator physical properties

Material		Z	λ_I / X_0	dE/dx × X_0 MeV	$X_{\square}$ cm
Iron	Fe	26	9.5	20.1	1.76
Tungsten	W	74	27.4	7.7	0.35
Lead	Pb	82	30.5	7.1	0.56
Uranium	U	92	32.8	6.7	0.32
Argon (liq)	A	18	6.0	29.8	14.
Air			2.5	66.7	30300

Detector

much remains to be done on the subject

As a result of these corrections depending on
the energy density and the overall energy of the cluster

less tails,
more Gaussian distribution
better resolution (by 15% in H1)

An approach by neural net on LC simulation gives
an improvement of 30%.

This means that we have to design the capability to distinguish electromagnetic and hadronic components.

This may rely on
energy density measurement if the cell size is adequate,
in case of a read-out by cells small enough fractal dimension .
Notice that in the case of digital read-out the cell size
modifies the e/h as measured by counting the hits
time measurement

The digital read-out

If you measure globally a shower the only information you have
is one number meant to be the shower energy
your read-out needs to be analogue
you may use a dual read-out and have two numbers.

if your detector has been split in pieces,
you have a measurement in each piece
plus the topology of the fired pieces.
and you may have that way tools to reduce the fluctuations.

The simplest way is to count the number of fired cells,
you loose the information on the deposited energy in the cell
but you get rid of its fluctuations. It is a trade.
The cell size has to be adjusted for the energy range and
for the measurement accuracy.
As the typical size for an electromagnetic shower differs from
a hadronic shower, the cell size plays on compensation.

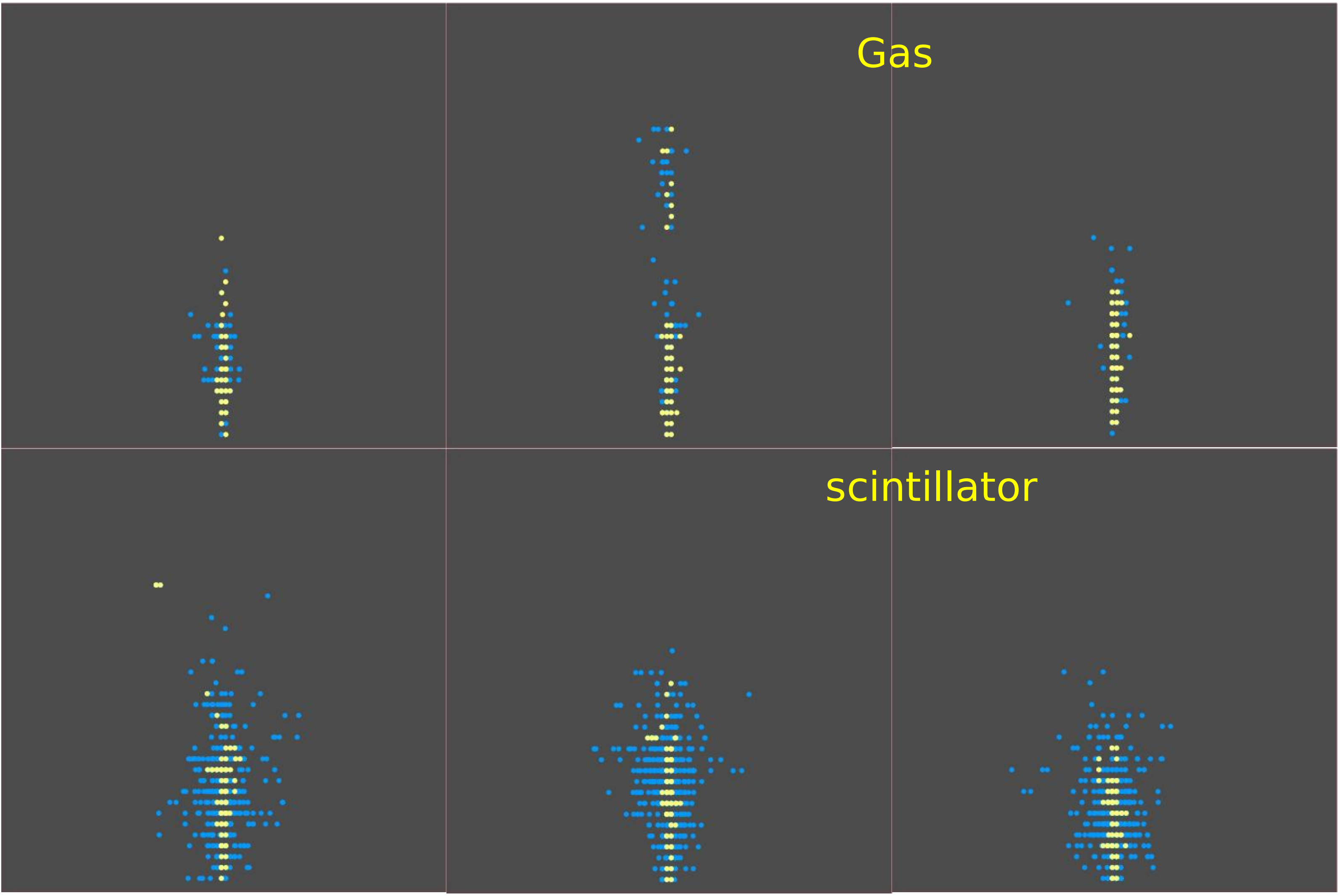
An adequate compromise may be the semi-digital read-out
where we record the cells according to different threshold.

The digital mode is less sensitive to the deposits.

Gas / scintillator as detecting medium

Geant4 simulation

10 GeV electrons   electron hit cells   positron hit cells



Gas advantage
slimmer showers,
drawback :
energy lost

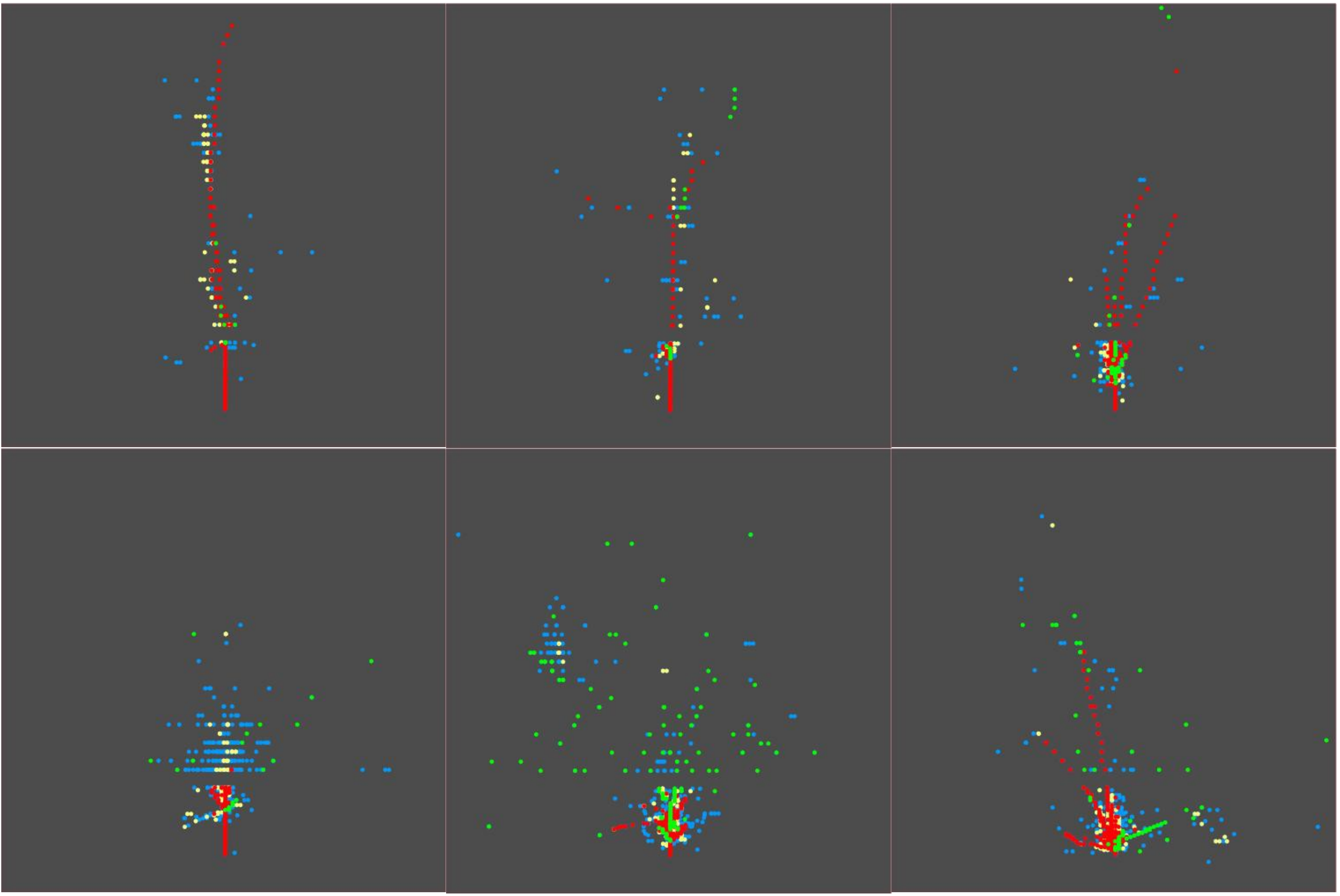
the halo blue hits
come from Compton
induced in Sc by
photons

Detector

electron hit cells
positron hit cells

20 GeV pions

proton hit cells
pion +. hit cells



an effect of density
gas /sc

the halo green dots
are protons kicked
out by neutrons

Can you collect,
eliminate,
the neutrons?
What's best?

Detector

Particle flow algorithm

An approach to jet energy measurement
by separating the different particles of the jet and estimating at best the energy of each of them.

The charged particles are measured in the tracker
but the calorimeter has to be cleaned from their deposit
The electrons are measured by both combined.
The photons rely on the electromagnetic calorimeter only
The neutral hadrons are what remains if proper.

The challenge is 1) to effectively separate
and not create fakes
identify the decays
2) to optimise the resolutions
and particularly the hadronic one

It may imply some level of particle identification

Detector

Once the decays (secondary vertices) have been properly found we can write the 4-momentum of a set of particles as

$$\vec{P} = \sum \vec{P}_{charged\ particles} + \vec{P}_{\gamma} + \vec{P}_{neutral\ hadrons}$$

and $$\sigma^2 = \sigma^2_{chp} + \sigma^2_{\gamma} + \sigma^2_{nh}$$

10^{-4} tracker
0.1 elmgn
0.5 hadronic

In this ideal case with the quoted values $$\frac{\Delta E}{E} \approx \frac{0.18}{\sqrt{E}}$$

The photon resolution plays little role and the effort has to be on the hadronic resolution: going to 0.3 would achieve 0.12 on the jet

Detector

But for a real detector two effects play a role

The existence of an effective threshold on
- charged particles due to the high magnetic field needed for background, precision and separation
- photons due to cell threshold and physical background

The probability of confusion
- efficiency of track reconstruction
- vertex misidentification
- wrong associations between tracks and calorimeter cells

$$\sigma^2=\sigma^2_{chp}+\sigma^2_{\gamma}+\sigma^2_{nh}+\sigma^2_{conf}+\sigma^2_{thresh}$$

The main enemy is confusion, far more than resolution and the design of the detector has to address this point first

Detector

possible algorithm for such a flow analysis

goes by descending order of clarity

tracks with vertices, V^0's and γ's

electron identification

photons from the Ecal knowing the tracks

muon identification

charged hadrons in the calorimeter

neutral hadrons, by topology with energy balance check

then build masses, energies, momenta for any set

And now

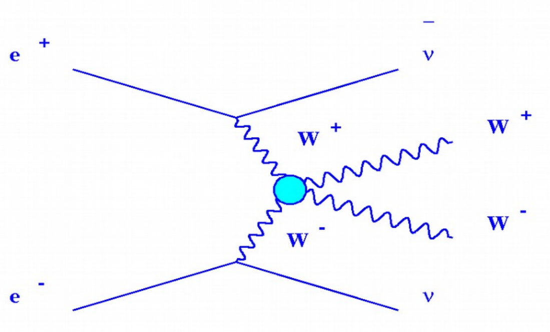
Trying to figure out
a real detector
on a real collider.

Advantages and problems linked to the IL collider

Advantages

Clean events
no pile-up

The laboratory frame is almost the centre of mass



We could naively expect
almost isotropic angular distributions
(for example à la $1+\cos^2\theta$ like in $e+e- \rightarrow f\bar{f}$),
but ..,
a large part of the physics is forward !!

Good precision of the vertex
It is possible to measure the tracks very close to the interaction point, 1.6 cm
in fact it is limited by the pairs

precise interaction point but for the crossing angle

For a superconducting machine good time separation between events

But

The energy-momentum constraint is partially lost due to the beamstrahlung.

Pair background due to beamstrahlung.
imposes a minimum size to the beam tube/ vertex detector
generates background in the forward detectors

Measurement of beam energy, luminosity, polarisation

Timing is difficult for a warm machine. (CLIC)

Crossing angle

The evacuation of the spent beams imposes an angle of 14mrad between the two beams, breaking the symmetry.

What is then the detector axis, the field axis?

up to now the detector and field axes are the same
they make an angle of 7 mrad with beams, impact on:
- forward detectors, they have two holes
- beam polarisation for incoming beam
- pair background ending on the forward calorimeters

The low energy pairs due to beamstrahlung
are captured by the field along the axis
and not along the spent beam.

anti Dipole Integrated Device

L* and cavern size

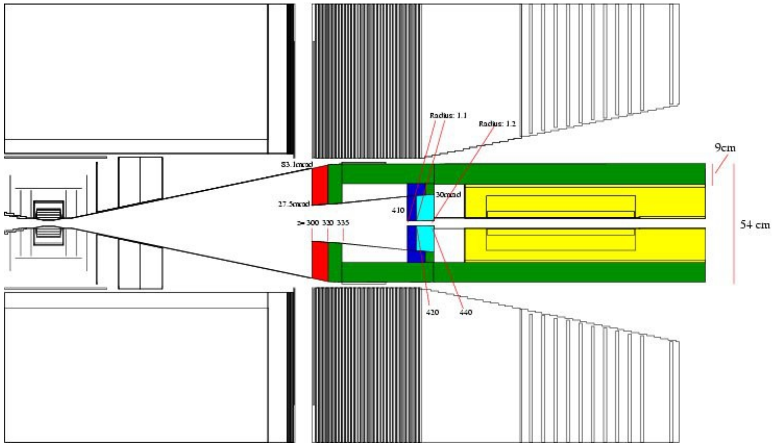
in today's ILC concept there are two detectors able to occupy the interaction point one after the other, the push-pull scheme

Each of them has to
have an assembly / garage place
be able to move to the interaction point
not to generate fringe fields detrimental to the other

In view of its cost the cavern has to be as small as reasonable

The accelerator has to focus the beam to the point of interaction with a quadrupole which front is at a distance called L* about 4m.

It is much shorter in CEPC which makes things difficult



This L* dictates more or less the length of the detector

The detector design

Basically I will describe here a detector à la ILD.
ILD is not a formal collaboration, there exist no TDR
and the design is still in evolution.

driven by the technological developments
and the weight of the software

How to ensure:

the hermeticity up to very low angles (Susy)
where an axial field becomes inefficient
the charged tracks and neutrals measurement
the lepton identification ;

but should we forget the hadrons ? (jet charge)

The degrees of freedom

An affair of symmetries

(read Flatland)

Physicists have an obsession with symmetry.
quasi a religion which does not need to be followed

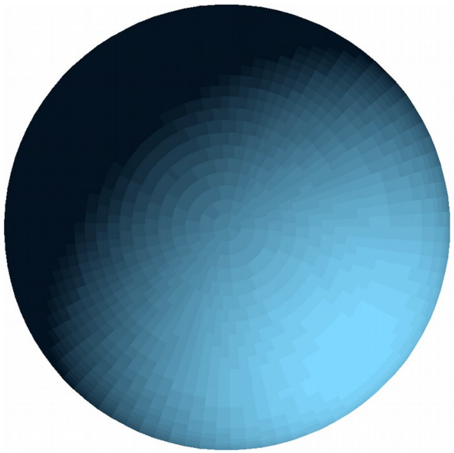
There is one “point” of interaction
would we go for a sphere? paving a sphere?
not easy for mechanics!

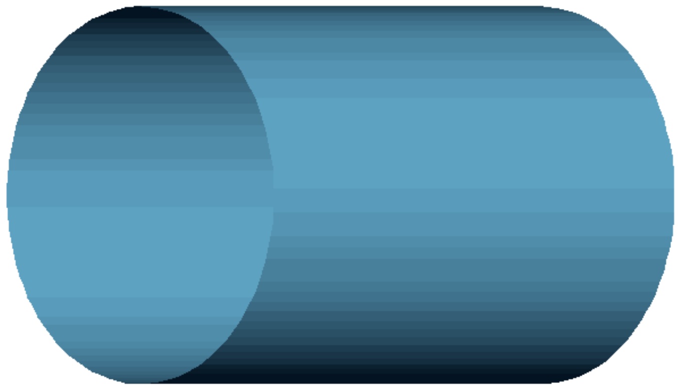
Neglecting the crossing angle, there is an axis
that speaks for a cylindrical symmetry
which is convenient for the coil of a solenoid
not an infinite cylinder though   (good for rapidity)
end caps for a limit which re-establish roughly the spherical symmetry

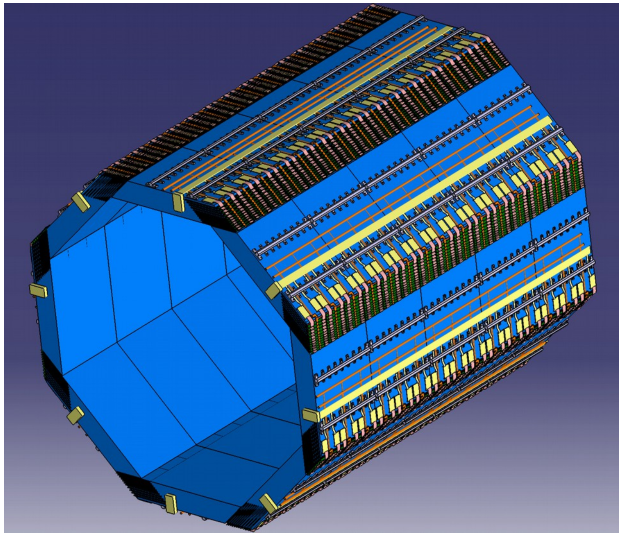
But again a cylindrical symmetry is not mechanically trivial
and the 2π symmetry gets broken to a regular polygon
the more sides, the closer to a circle
the choice depends on other considerations like holes, feed through ..

but be carefull not to ruin the asymmetries you measure

Detector

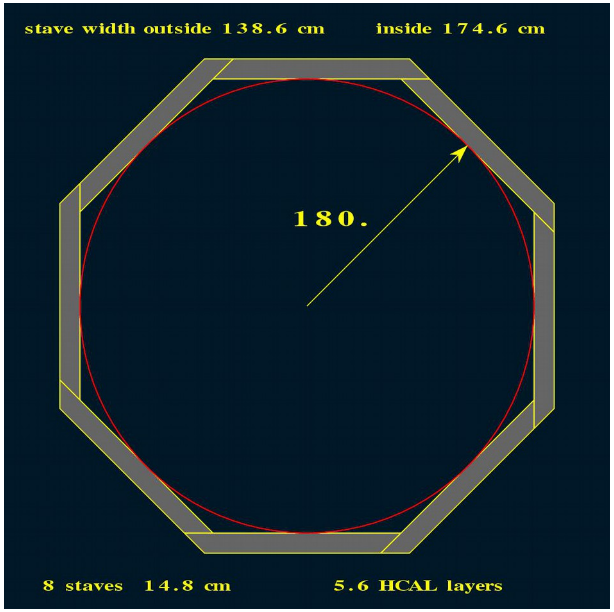


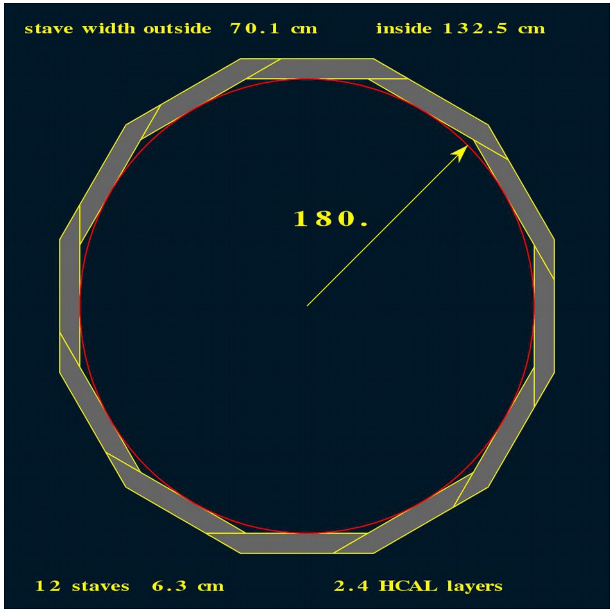


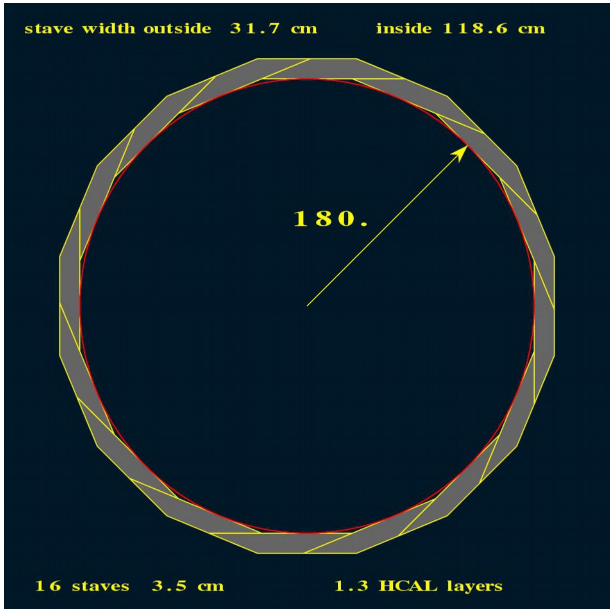


From sphere to real

the eightfold way







Detector

You may feel free to construct your design from nice principles
BUT
It depends first on the amount you consider possible to spend!

which here boils down to what was CMS or Atlas price
(at the time of TDR or real?).

And the coil??

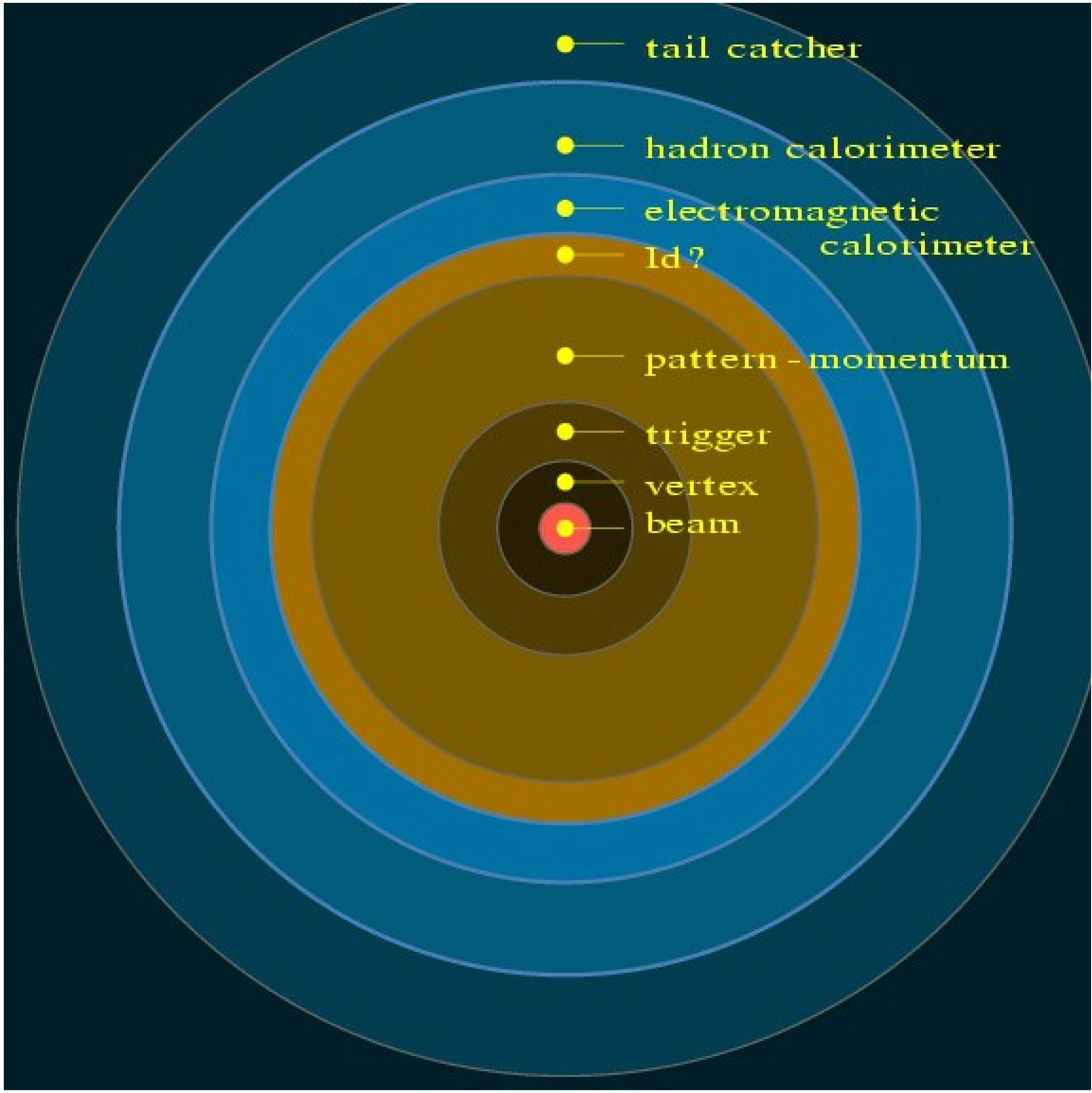
An onion with
the tracker at the centre
surrounded by the calorimeter

High precision close to the IP
with high transparency

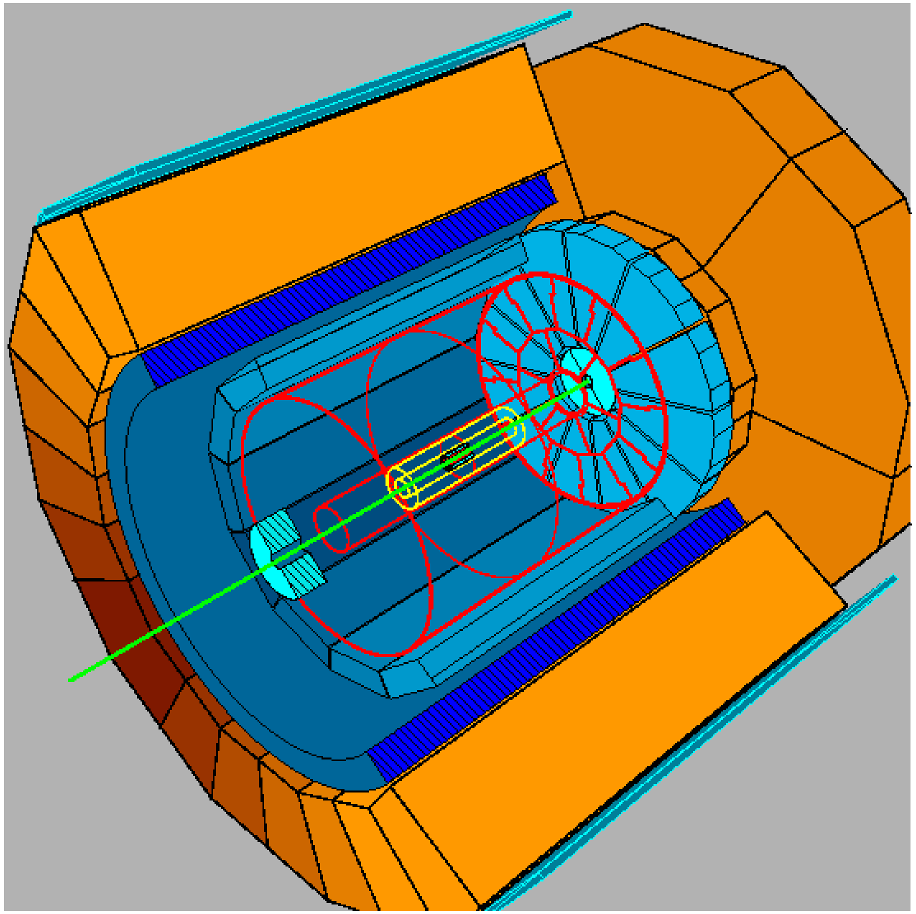
then reveal the event pattern
and measure the momenta

and very close tothe calorimetry
which tries to separate at best
photons and hadrons

Provide an information on particles
redundant and
as continuous as possible
no crack in depth.



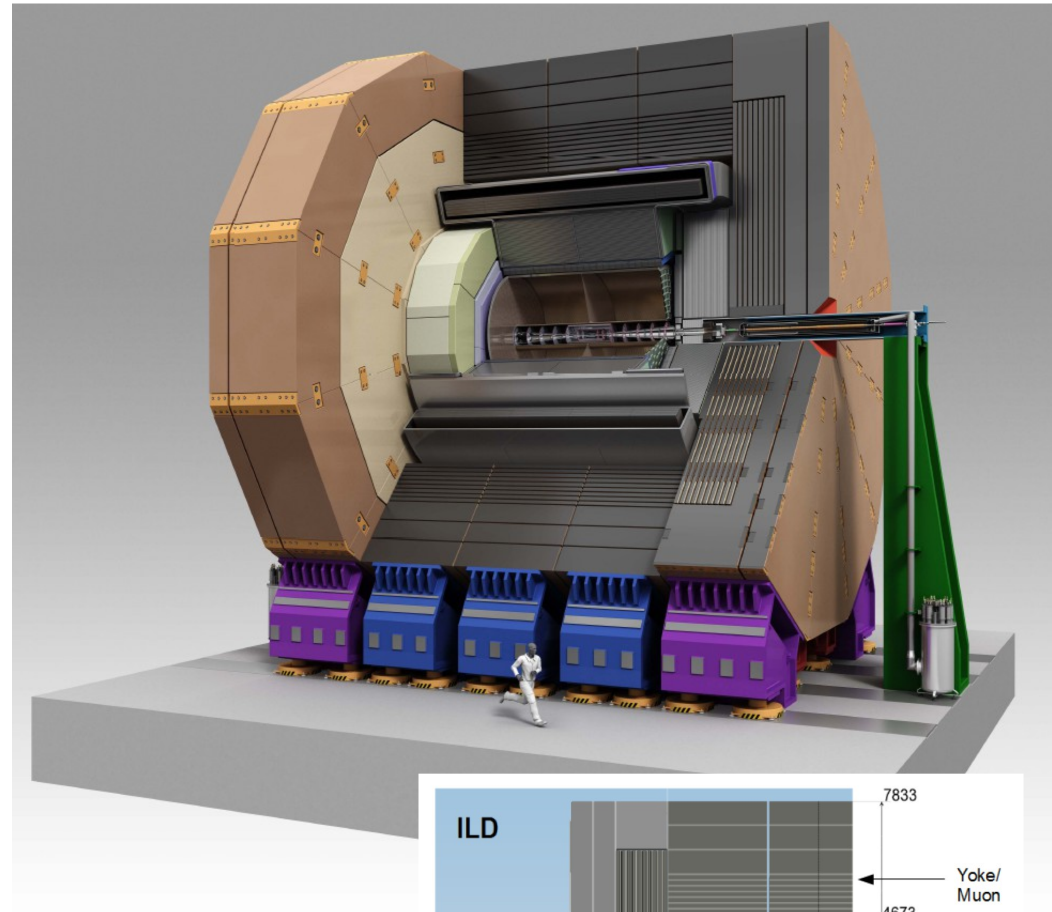
Detector



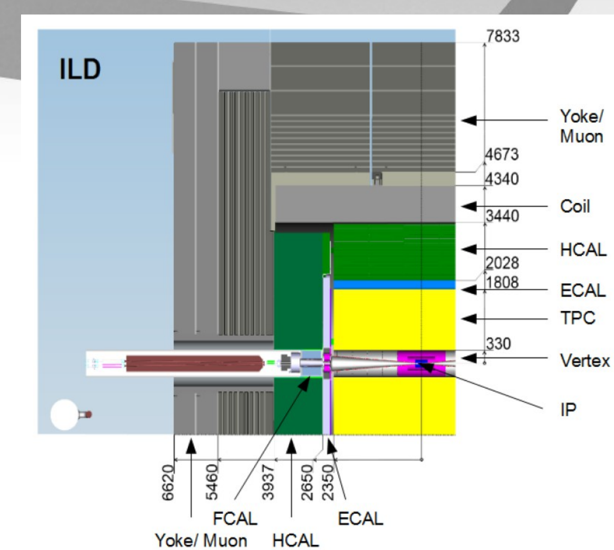
ALEPH a detector for LEP

place of the coil:
an historical evolution
first after the tracker UA1, PEP4
then after the electromagnetic
 calorimeter   ALEPH for example

now after the hadron calorimeter



ILD



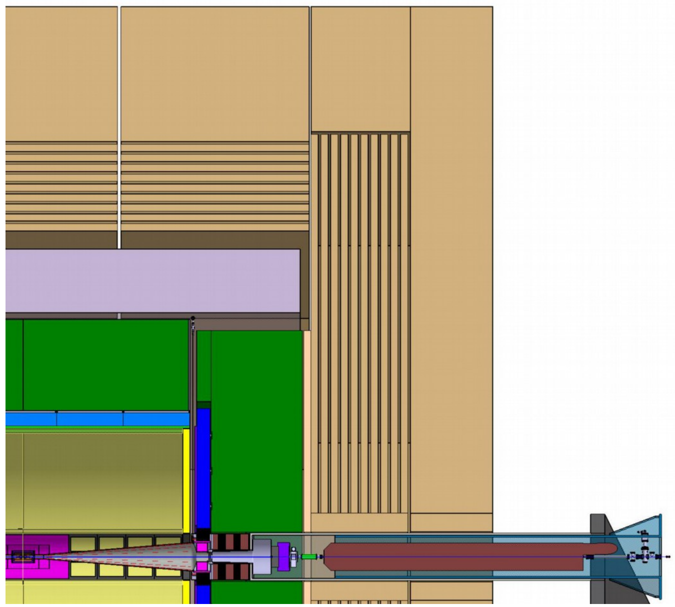
Detector

The typical longitudinal design

In a cylindrical scheme
we have to close the cylinder, or the different cylinders

We try to follow the onion scheme but

the beam needs a hole
the field needs to be returned, by iron or coils
generating strong mechanical constraints
the accelerator has constraints like L*



The nightmare of the beam vicinity
in particular if you choose a TPC

How to close the vertex, pixel disks
how do you close the tracker down to ?

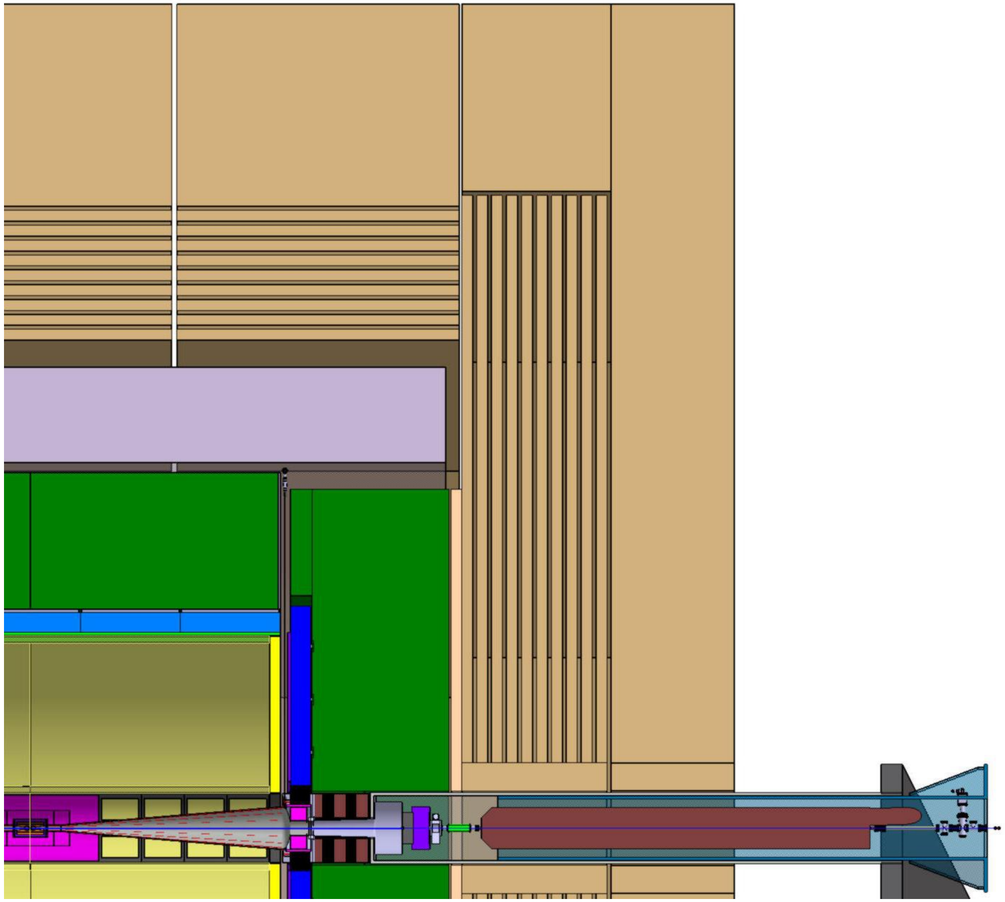
The trouble of a Luminosity calorimeter with its constraints, physical/technical

In a cylinder the delicate corners

Not speaking about
how power gets in and signal out

The choices of ILD

ILD follows the recipe with:
- a composite central tracker,
  - gaseous TPC in the middle
  - a silicon tracker
    - vertex
    - inner Si tracker
    - outer Si tracker
- a forward system,
  - lumical
  - ⇒ conical beam tube
  - tracking disks
  - LHCAL, fills transverse and depth holes
  - beamCal
- a calorimetric system inside the coil
  - ECal
  - HCal
- the coil in its cryostat
- the return yoke instrumented



The specific id detector with coherent effects
Cerenkov
TR detector

There are none in ILD

Detector

the field system

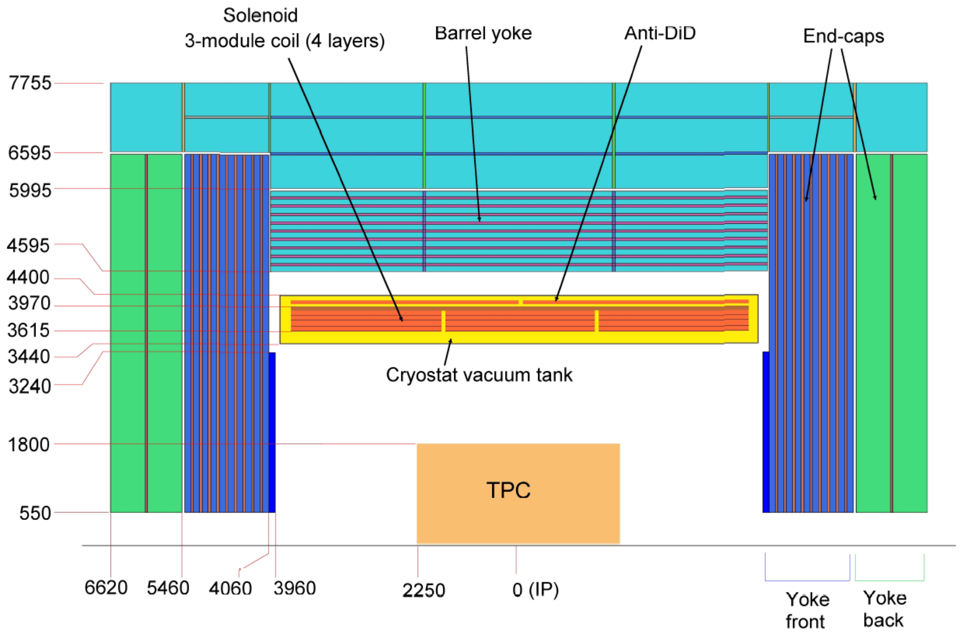
need of a 3.5-4 T field to
- provide the momentum precision
- squeeze the background in the beam tube

To be rather homogeneous in TPC
at least well mapped
even though we may add a dipole field
to focus the background (anti-DID)

well returned by an instrumented yoke
fringe field

Precision in BR^2 or rather in $BR^{2.5}$
but R very forward??

What field? 3, 4, 5, 6 T?
mechanical stability in B^2R



Little exercise

Consider a coil with R=3m, B=4T
with a tracker R=1.7m

as the calorimeter is inside 1.3 m

$BR^2 = 11.56$ et $B^2R = 36$

To reduce size and cost, we cut the tracking zone at R=1,2m
et preserve le calorimeter hence R=2.5

We obtain the same resolution with B=8T !!! $B^2R = 160$!!!!

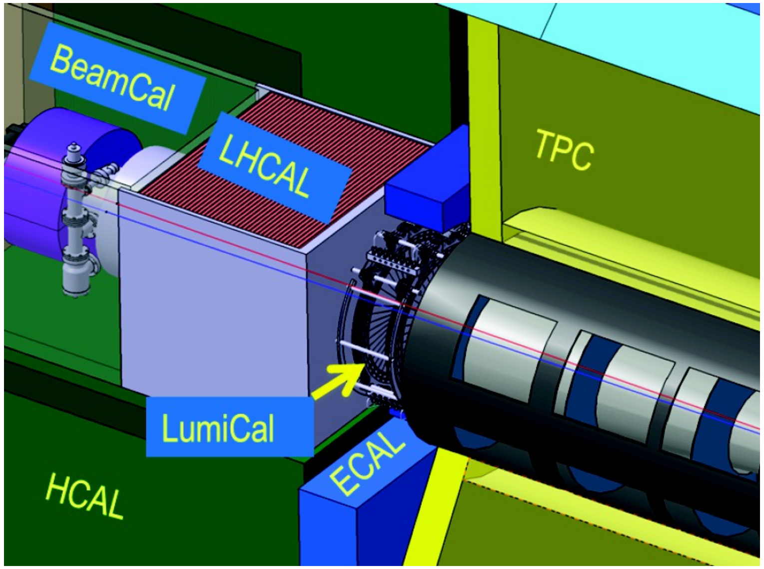
It is clear that we must first improve the measurement precision:
by a factor $(1.2/1.7)^2$ i.E. ~2 hard !

and we should keep the tracker transparent,
little material in front of the calorimeter

Detector

the forward system

The luminosity calorimeter Lumical
to measure the luminosity with Bhabhas
no material in front
⇒ conical beam tube
centred around the outgoing beam,
not the detector axis

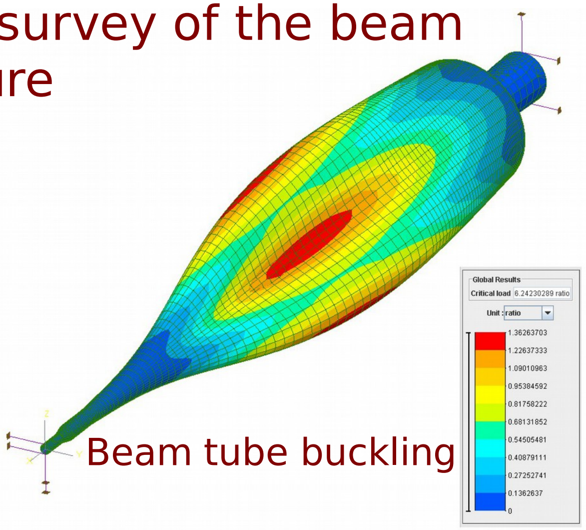


conical beam tube
lumical for the luminosity
LHCAL to sign low angle hadrons
beamcal survey of the beam
and closure

The beam tube
transparent : Beryllium in its centre
but loaded with cables

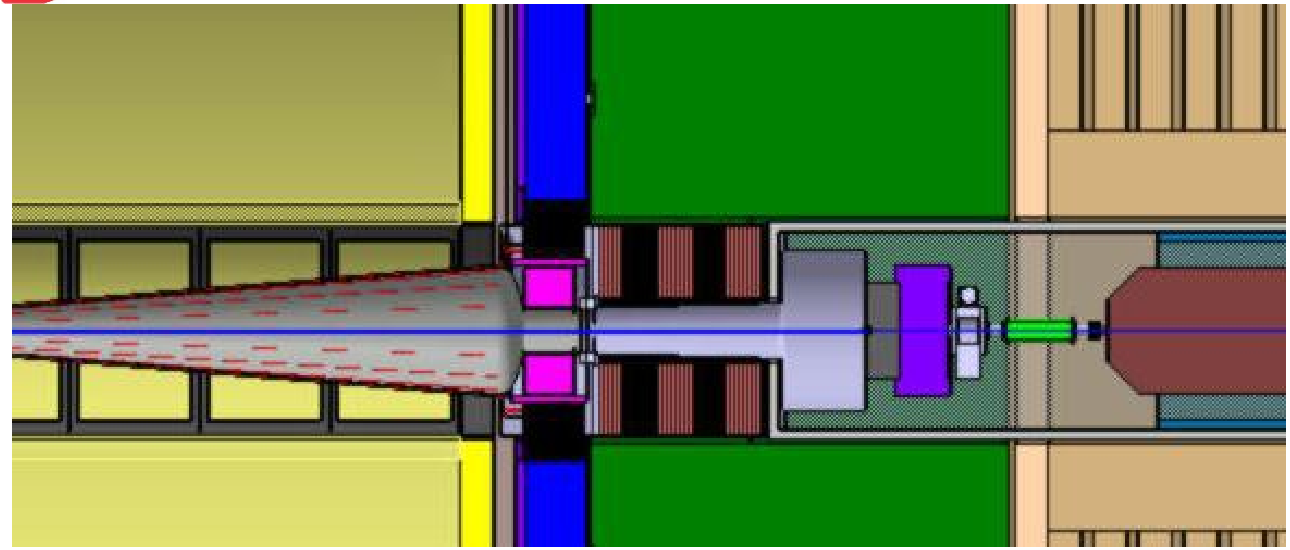
LHCAL
a hadron calorimeter which helps hermeticity
and provides pion/muon separation forward
SUSY

BeamCal
a small calorimeter which receives and backscatters
a lot of background, identifies electrons
and monitors the beam

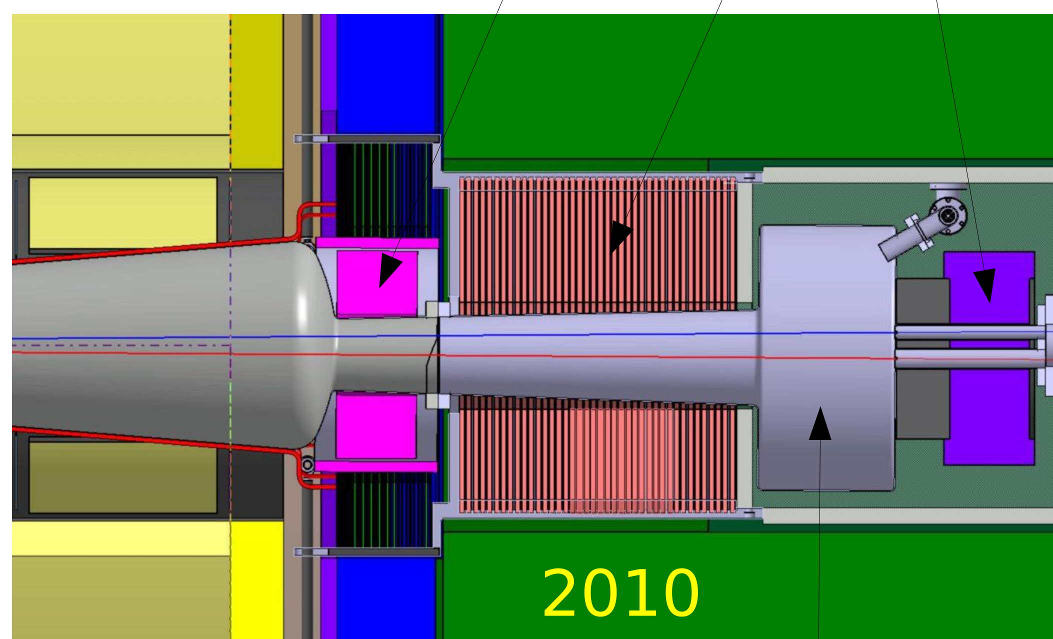


Beam tube buckling

Detector



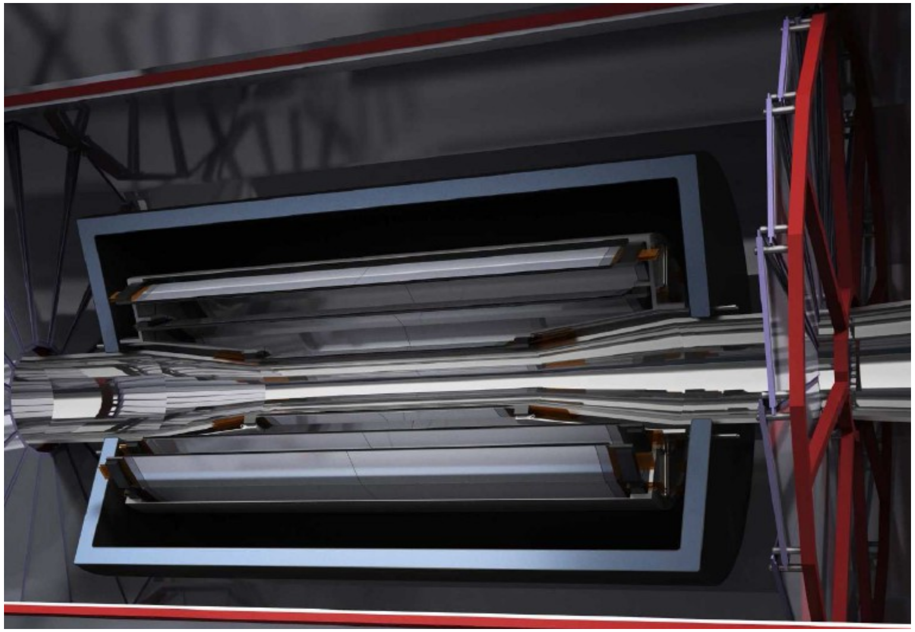
LumiCal LHCal BCal



Pump to be removed L*

Recipe for the vertex detector

Very precise,
close to the interaction vertex,
very transparent,
but with enough layers to be able
to do an autonomous track reconstruction
(low momenta)



precision: intrinsic (pixels),
alignment a priori, using data

close to IP,
but the price is a strong background,
radiation hardness, occupation level ⇒ pixels
read-out speed

transparent then thin with a minimum of mechanical structure
and electronics but stability. Cabling more power than data.

number of layers, cost ? amount of material at the start of the tracker

Recipe or a central tracker

A TPC surrounded by silicon:
a gaseous TPC for transparency (except end plates)
redundancy 200 points
then easy pattern
dE/dx
a silicon envelope for ultimate precision (factor 2)
safety
alignment

Forward the field does not help
we can only count on
kinematical opening:
do it large and mostly long!!

but stability, alignment, distortions, cost!!
and it does not help to make it large if you can not ensure
an adequate separation.

Dilemma: small precise (for good separation) / lousy large?

Recipe or a central tracker

2 solutions: silicon à la CMS hopefully lighter!
gaseous detector TPC
a mix

Silicon

beyond a certain radius, the occupation level is such that strips are enough, pixels are not needed but may become competitive

make it thin, though preserving the positioning precision stability at a level of few microns!

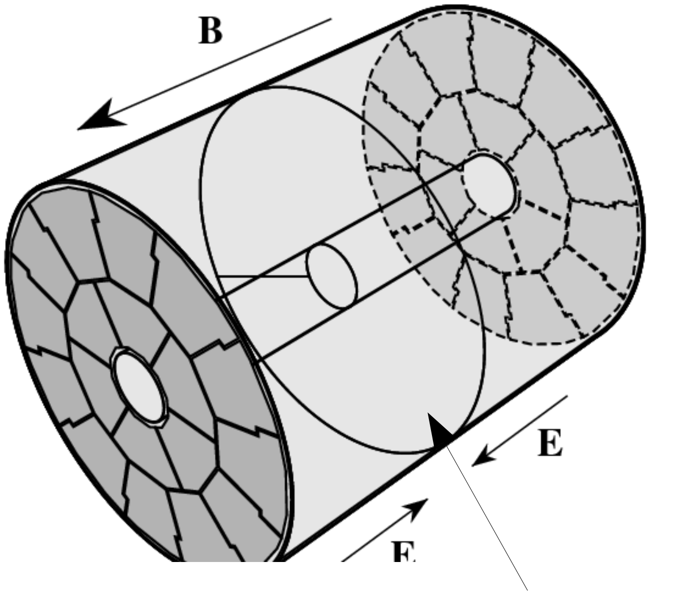
problem of mechanical support and electronic volume and power supplies

Recipe or a central tracker

TPC the principle

In a volume of gas there are a magnetic field and an electric field more or less parallel.
The particle passing through excite some atoms luminescence and ionize others.
The freed electrons start to drift under the joint effect of the fields.

The TPC is a cylindrical field cage defining properly E between a central electrode and two end plates.
The electrons drift toward the end plate their time of arrival provides the z coordinate, pads on the end plates provide X and y



Drift under the action of electric and magnetic fields

$$\frac{d\vec{P}}{dt} = \vec{F} - \kappa\vec{v}$$

Where kv is a braking force

the form can be inferred from a microscopic model where the electrons collide with the atoms.

$$\left(\frac{d}{dt} + \frac{1}{\tau}\right)\vec{v} = \frac{e}{m}(\vec{E} + \vec{v}\wedge\vec{B})$$

In the absence of field $\frac{d}{dt}\vec{v} = -\frac{1}{\tau}\vec{v}$ $\quad \vec{v} = \vec{v}_0 e^{\frac{-t}{\tau}}$

In stationary regime (!) $\tau\frac{e}{m}\vec{E} = \vec{v} - \tau\frac{e}{m}\vec{v}\wedge\vec{B}$

writing $\vec{\omega} = \frac{e}{m}\vec{B}$ $\quad \tau\frac{e}{m}\vec{E} = \boldsymbol{M}\vec{v}$ where $\boldsymbol{M} = \begin{pmatrix} 1 & -\omega_z\tau & \omega_y\tau \\ \omega_z\tau & 1 & -\omega_x\tau \\ -\omega_y\tau & \omega_x\tau & 1 \end{pmatrix}$

$$\vec{v} = \tau\frac{e}{m}\boldsymbol{M}^{-1}\vec{E}$$

To simplify the writing without loosing anything we take B along Oz and E in the zOx plane.

$$\boldsymbol{M}^{-1} = \frac{1}{1+\omega^2\tau^2}\begin{pmatrix} 1 & -\omega\tau & 0 \\ \omega\tau & 1 & 0 \\ 0 & 0 & 1+\omega^2\tau^2 \end{pmatrix}$$

Detector

Exercise

$$v_x = \tau \frac{e}{m} \frac{1}{1+\omega^2\tau^2} E_x$$

$$v_y = \tau \frac{e}{m} \frac{1}{1+\omega^2\tau^2} \omega\tau E_x$$

$$v_z = \tau \frac{e}{m} E_z$$

The locus of v as a function of ωτ in the plane xOy is a half-circle centred in (1/2, 0)

Two extreme regimes :

$\omega\tau \gg 1 \qquad v_x = v_y = 0 \qquad v_z = \tau \frac{e}{m} E_z$

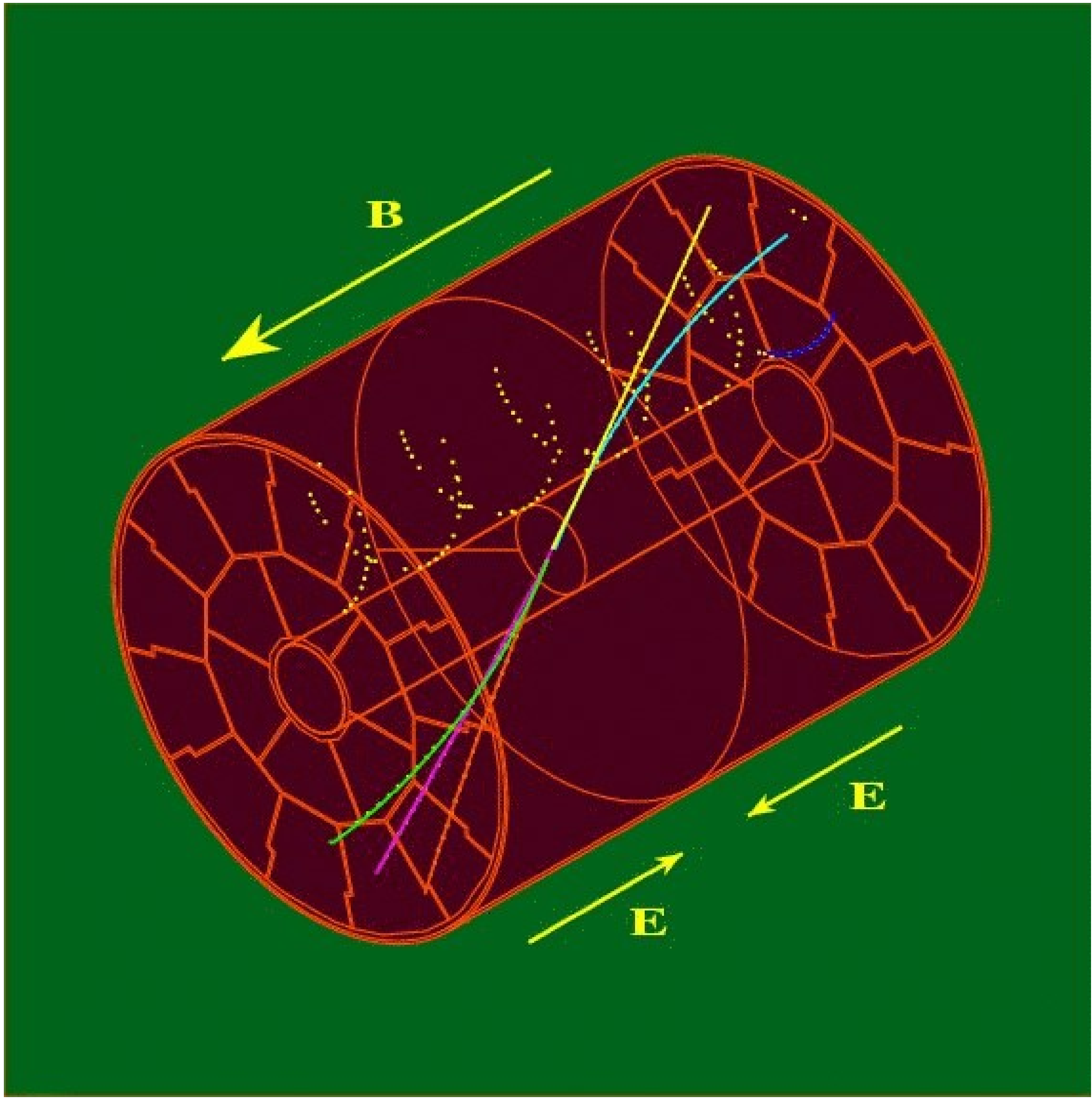
The mean time between collisions is much larger than the circling time, the electron follows B

$\omega\tau \ll 1 \qquad v_y = 0 \qquad v_x = \tau \frac{e}{m} E_x \qquad v_z = \tau \frac{e}{m} E_z$

The mean time between collisions is much smaller than the circling time, the electron follows E

Recipe or a central tracker

TPC drift



Detector

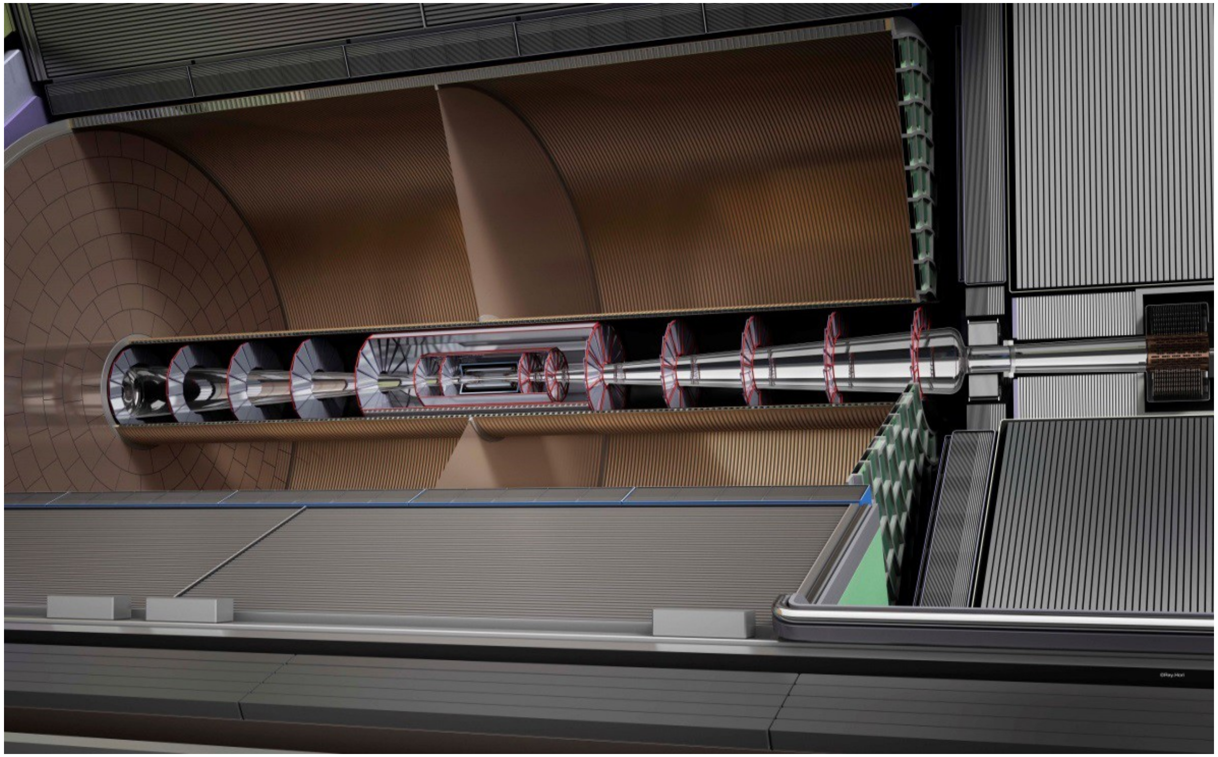
Recipe or a central tracker

TPC is gas then transparent

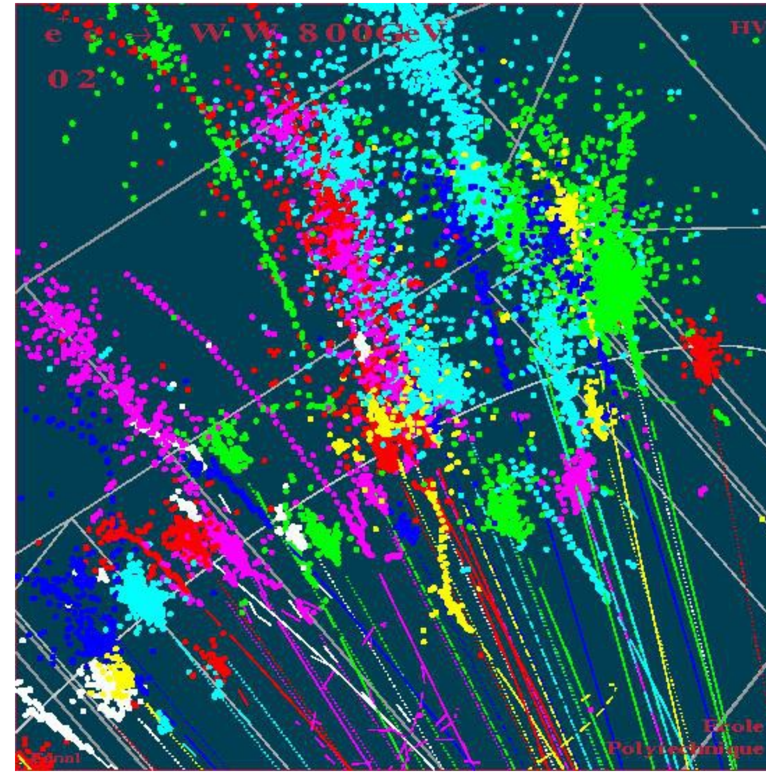
but the end plates have a structure and a lot of electronics

but the field cages are thick

in front of the ECAL
and not that close



Recipe for a calorimeter



The neutrals get separated only with distance

put the calorimeter as far as possible

electromagnetic part: large ratio λ_I/X^0

good depth about $24X_0$ at our energies

very dense, reduced Molière radius

very granular

$\sim 1/4R_M$

no hole toward

hadronic part: dense, where the showers stay narrow

with a good ratio λ_I/X^0 may enter e/h

very granular, as much as you dare

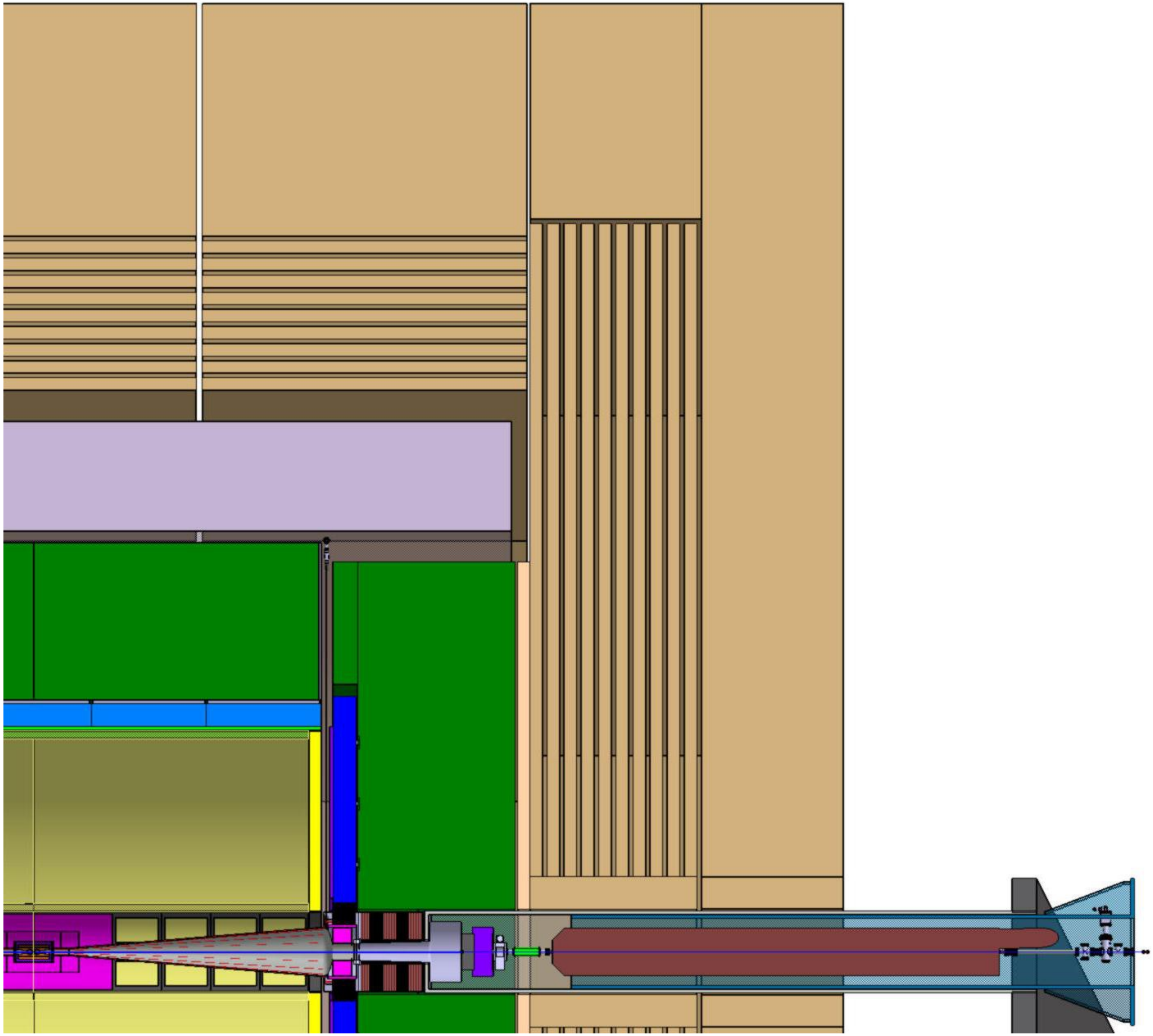
Detector

Cut of the quadrant for ILD

a weight which may reach 14000t.
2 times the Eiffel tower

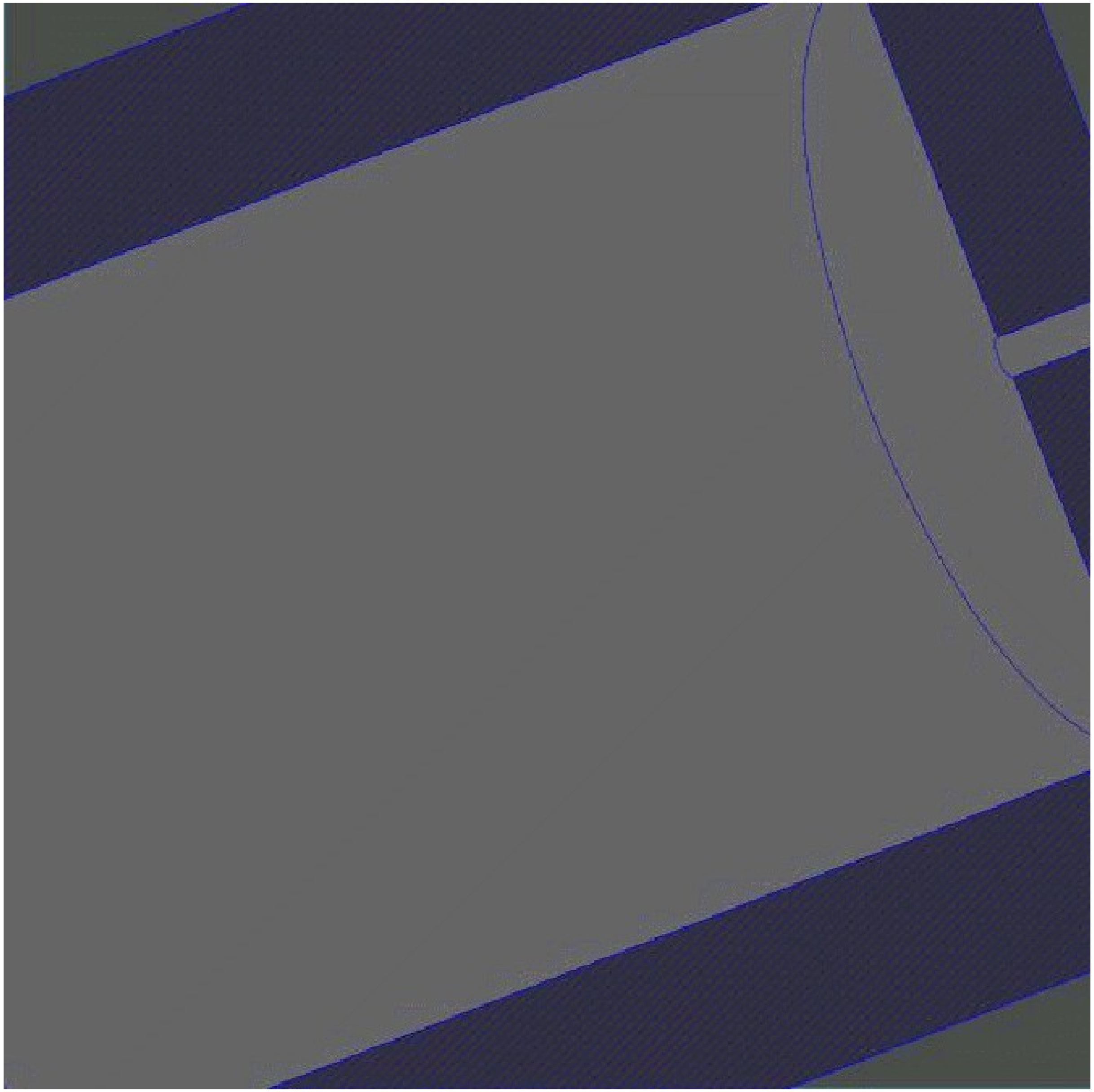
1) the magnet
2) around the beam

The impact of earthquakes



Putting in place the calorimeter shell

Field return
muon detector
Coil 4T
Field plate
Hcal end cap
Hcal barrel
Ecal end cap
Ecal barrel

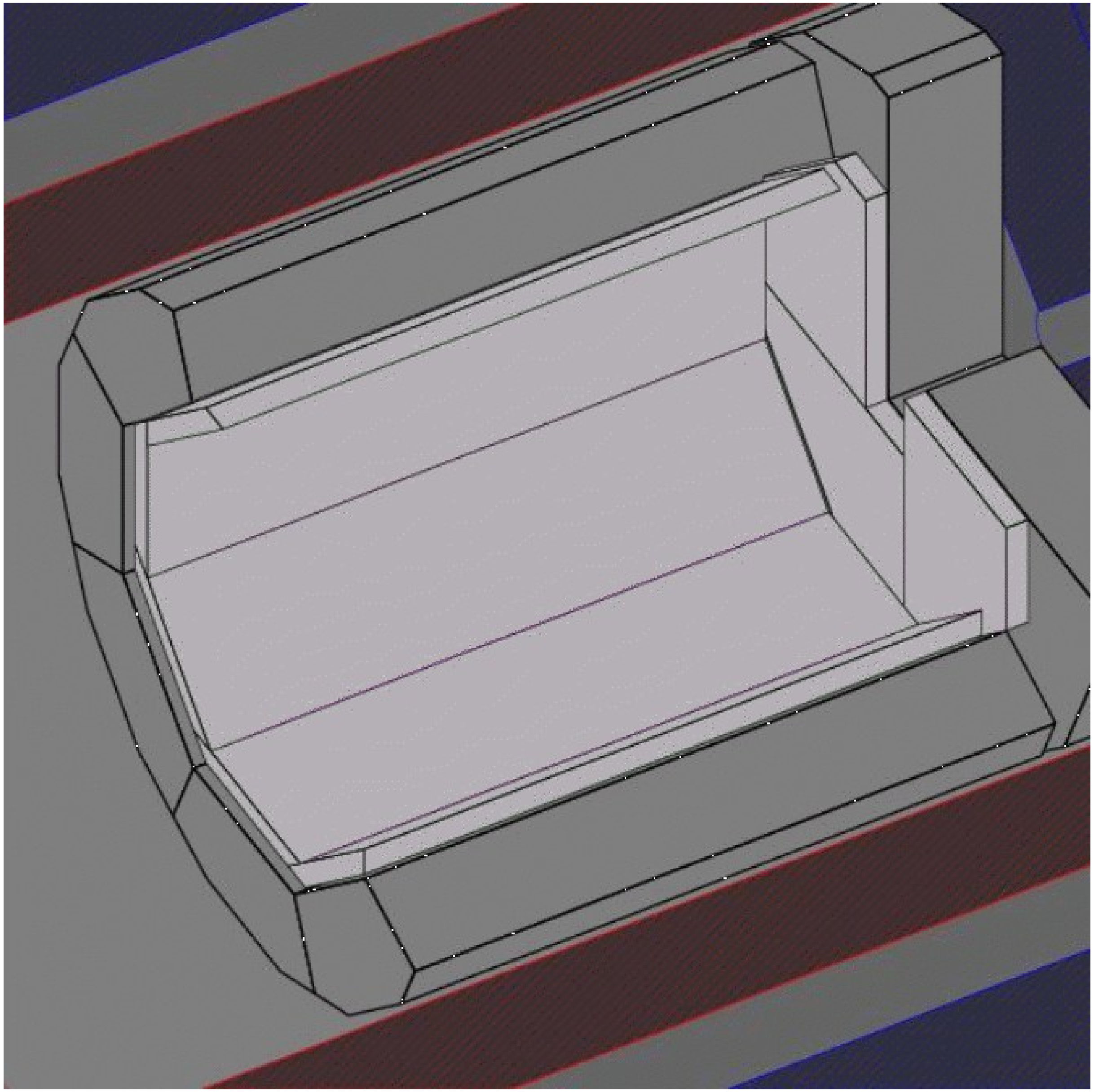


Detector

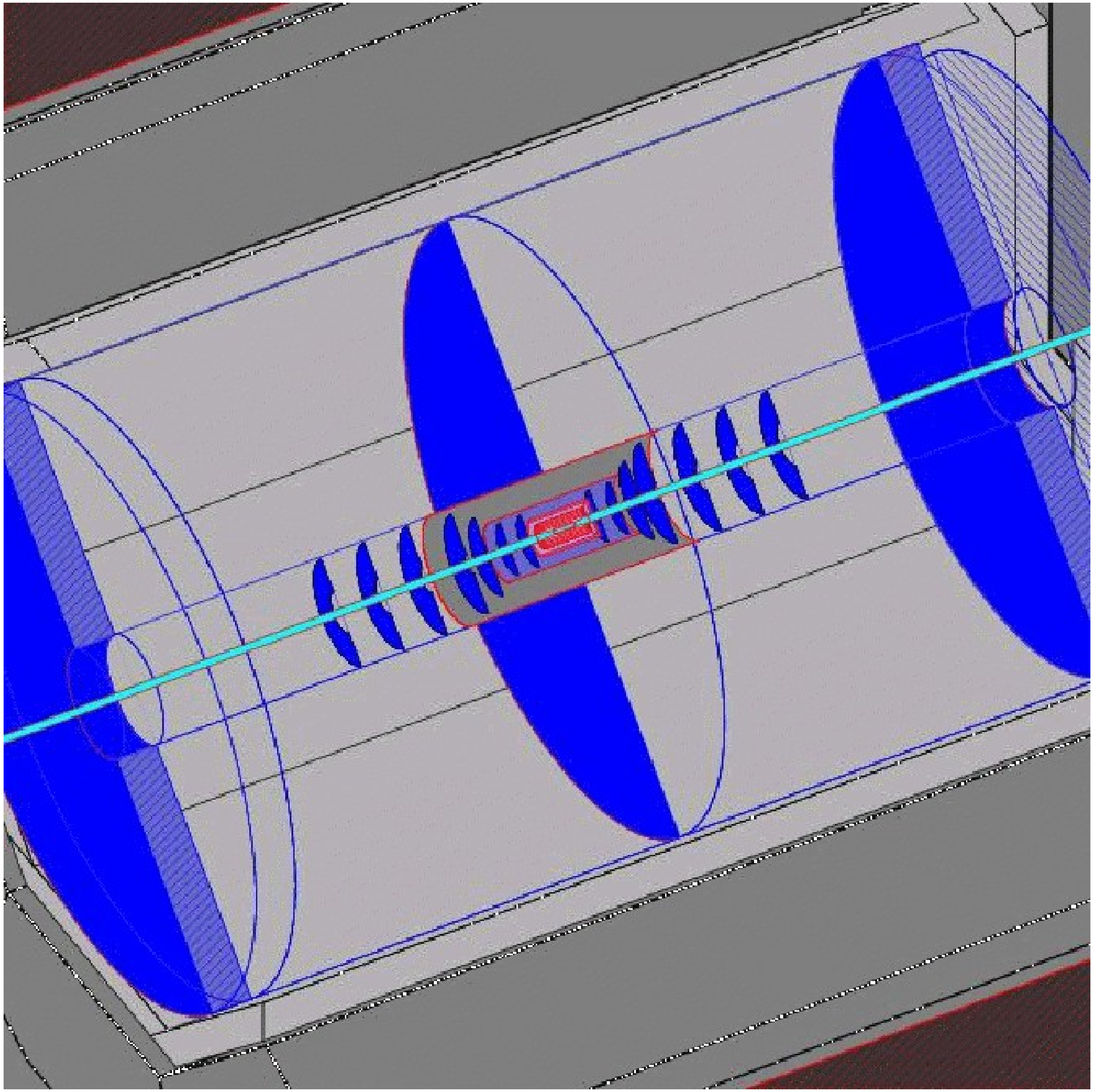
Tracking detectors

Forward chambers
Time Projection Chamber
Silicon Inner Tracker
Forward disks
Vertex detector
Vacuum tube

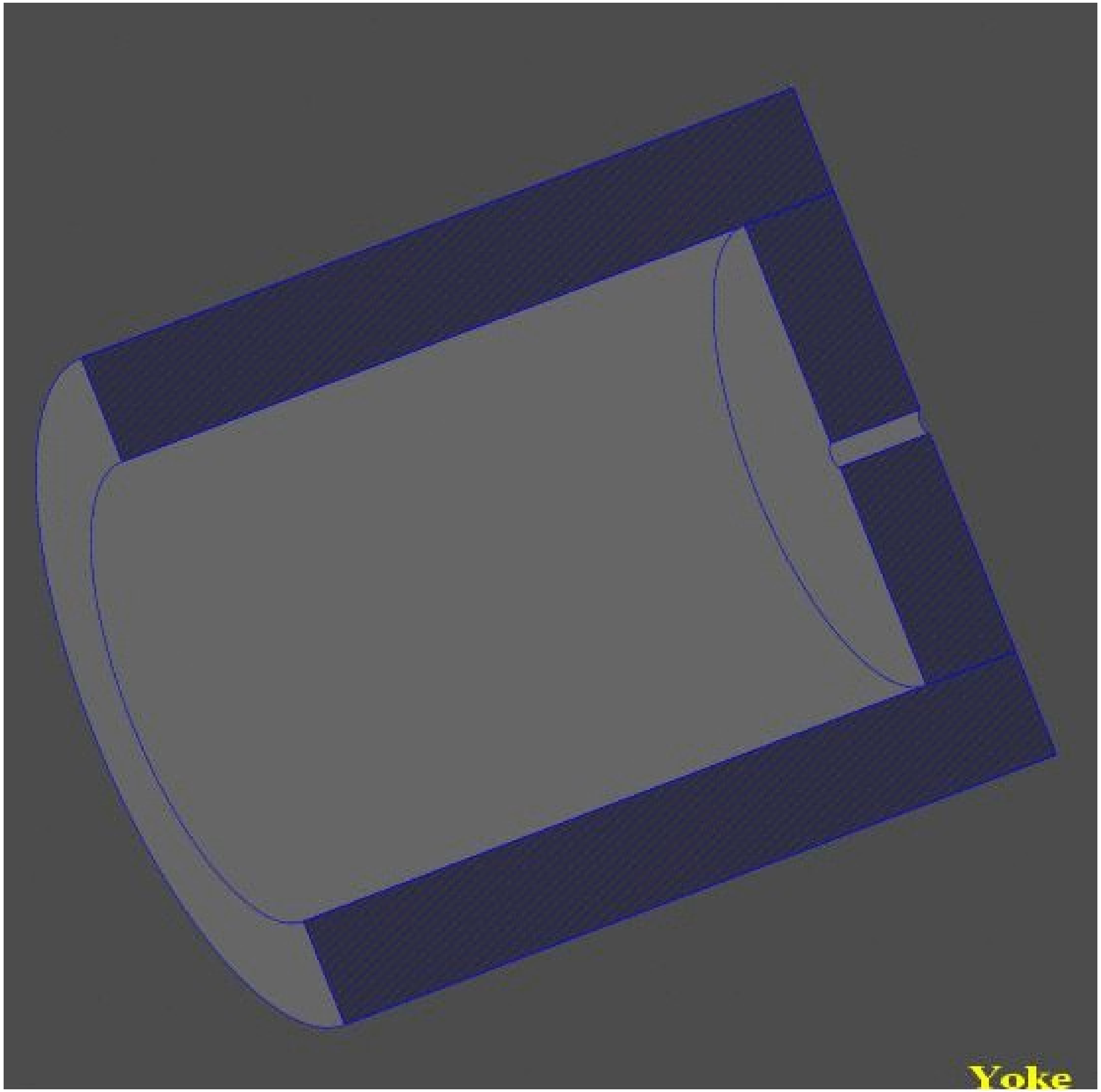
SET ?



Detector



Detector mounting



Trigger and acquisition

Due to the low backgrounds, to the rarity of events,
to the will of not loosing anything,

GMSB

and because it is possible

NO TRIGGER,
or rather a self-trigger of the measuring cells

electromagnetic calo cut at 1/3 mip

Identification of the crossing number for the interaction

The acquisition may suffer from long trains

The depth underground the detector should be built (Kitakami)
precludes any impact of cosmics
the muon halo from accelerator should not harm.

Services

power supplies, cooling

A front-end electronics entirely embedded in the detector means bringing in a lot of low voltage power and some heat.

Use of the time structure in ILC / CEPC

power pulsing to gain a factor 100 on the heat.

A partial review of technologies studied for
not a full review of ILD:

vertex detector	silicon pixels ..
central tracker	silicon strips, gas TPC
electromagnetic calorimeter	silicon, scintillator
hadron calorimeter	scintillator, gas
tail catcher / muon detector	
detection at low angle	

Notice that the question is not of the best technology
but of the best group of people
to make sure that at any price they will make it work

Speaking of technologies

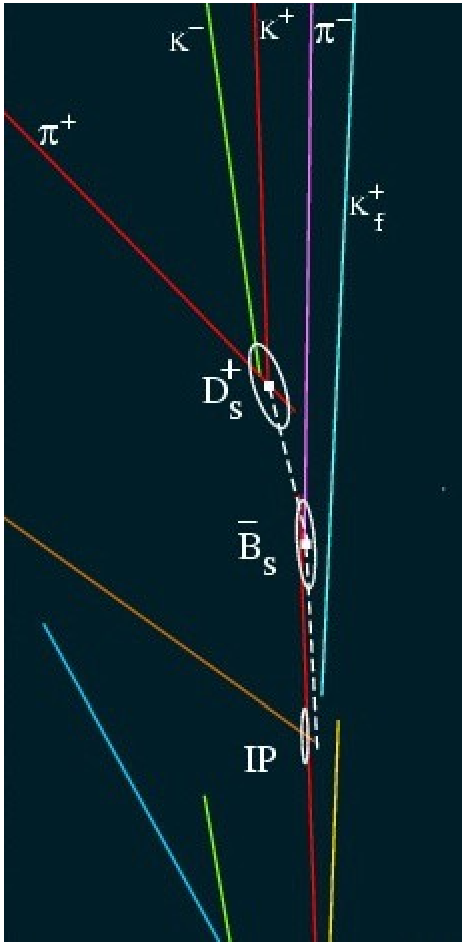
vertex detector

first goal : measure as precisely as possible the track impact parameter to identify displaced vertices.
this implies point resolution, low multiple scattering, occupancy

second
it is a part of the tracker
and contributes
to the momentum measurement precision
and
to the track pattern recognition in particular
for low energy tracks

it can also contribute to the alignment/calibration of a TPC

quality criteria: spatial resolution
read-out time
material budget



Speaking of technologies

vertex detector

As it comes at the end and is of reduced size
it does not need a long construction, can come late
and the R&D can be pursued.

Different choices with different strategies
not linked solely to ILC but to many developments for other experiments
or even out of our discipline.

Largely imported from A. Besson at Santander 016

Technological solutions under consideration

- SOI:
  - SOFIST 1: first prototype delivered end 2015
    - Analog read-out + col. ADC circuit
  - SOFIST 2: time stamp (lay-out in 2016)

KEK, Osaka University,
University of Tsukuba, Tohoku University

- FPCCD
  - Large FPCCD prototype (6µm, 50µm thick)
  - Neutron irradiation studies
    - Dark current, hot pixels, CTI
  - Double sided ladder concept
  - Next steps: Beam test, ladders, read-out speed, etc.

[1]Tohoku University
[2]KEK
[3]Shinshu University
[4]JAXA

- DEPFET
  - Development driven by Belle-II PXD
  - PXD DEPFET modules ready for series production
  - Micro-channel cooling under devpt
  - Interests in Pixelated FTD
  - Next steps: r.o. speed, integration

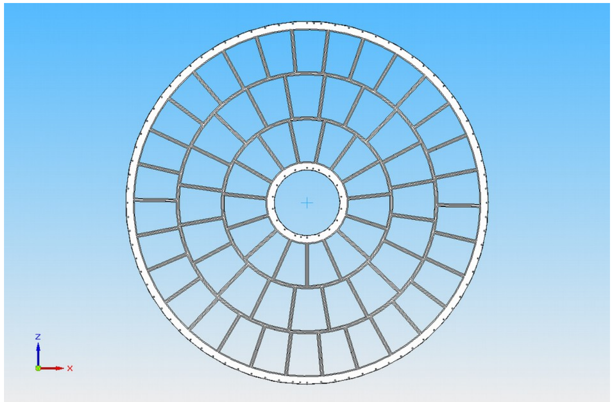
DEPFET Collaboration

- CPS : already used in STAR (3 years of physics data taking)
  - Development driven by ALICE-ITS and CBM-MVD
  - Focus on increased read-out speed : O(few µs) ⇛ Bunch tagging
    - to comply with beam backgd uncertainties
  - Extend CPS to trackers (large surfaces)
    - Large pixels det. eff. demonstrated

IPHC, CERN

Detector Speaking of technologies

central tracker



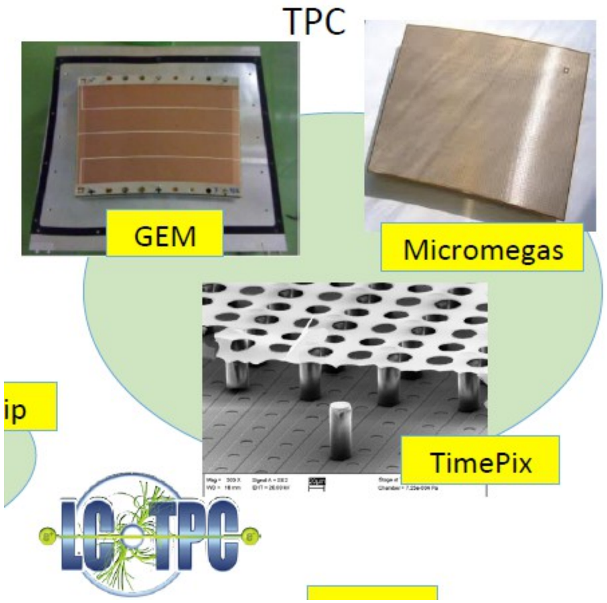
TPC D. Nygren 1975

a well known detector:
PEP4, ALEPH, DELPHI, ALICE, ...

limit the impact of positive ions
from the chamber or back from
the amplification

to be transparent,
the technology of the end plate
structure and electronics

numerous points (200)
hence high pattern capability
high precision,
if the distortions are mastered
electric and magnetic field very well mapped.



electron detection:
GEM, MicroMegas, or silicon (Timepix)
providing a very high granularity

central tracker

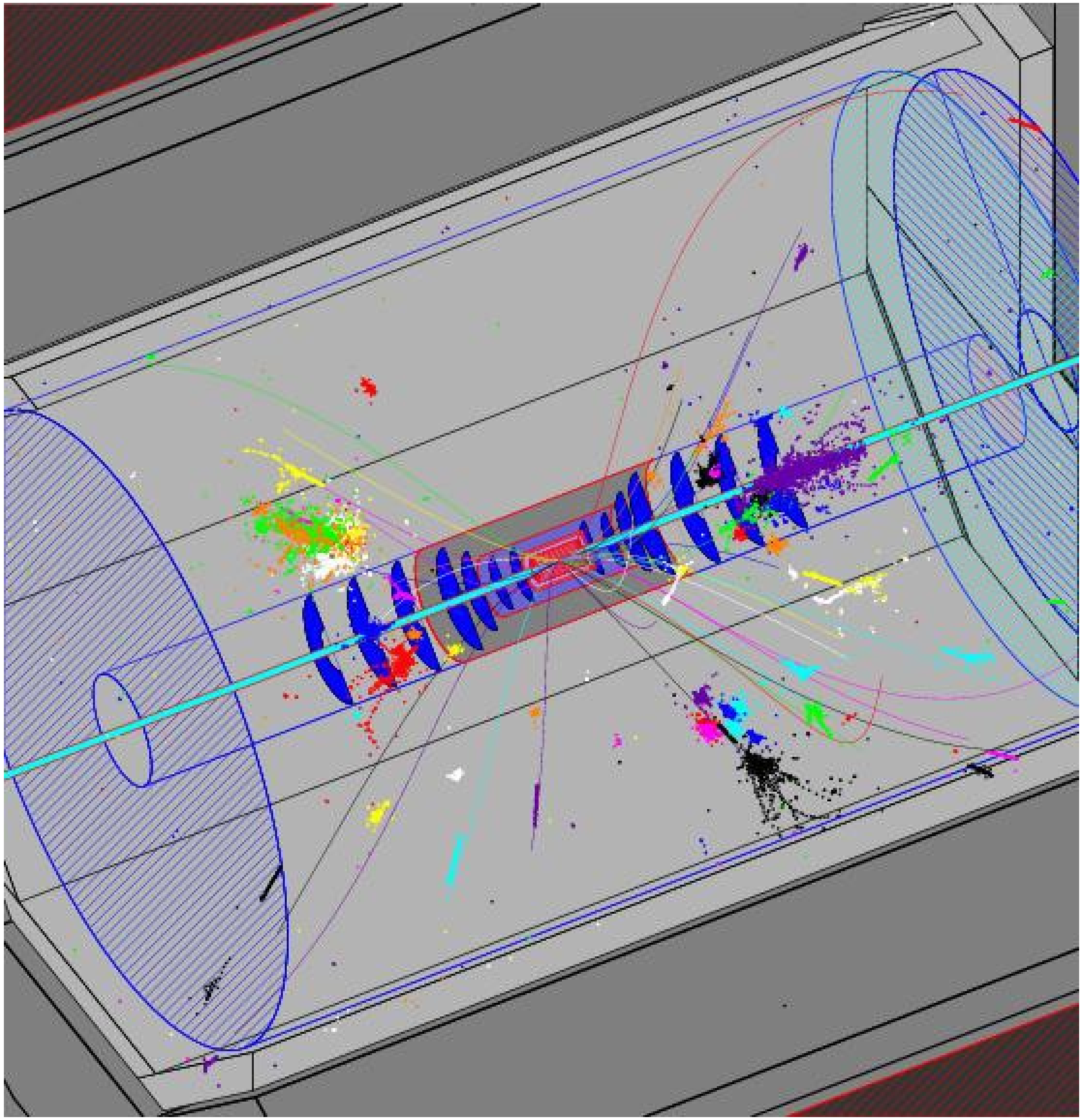
A mix

Due to the distortions induced by
the positive ions
close to the interaction,
the TPC can not start at a small radius
ILD 33 cm

The pixel vertex detector
ends at about 10 cm

The TPC offers a poor precision
at low angle

The zone between vertex and TPC
is then equipped with few silicon
cylinders or disks
read out by strips or pixels
the last one becoming more fashionable
with the technological evolution



Detector

Speaking of technologies

central tracker

It is considered to install a silicon layer just outside the TPC
to improve the resolution (~ by 2), be less sensitive to distortions
align and calibrate the TPC.

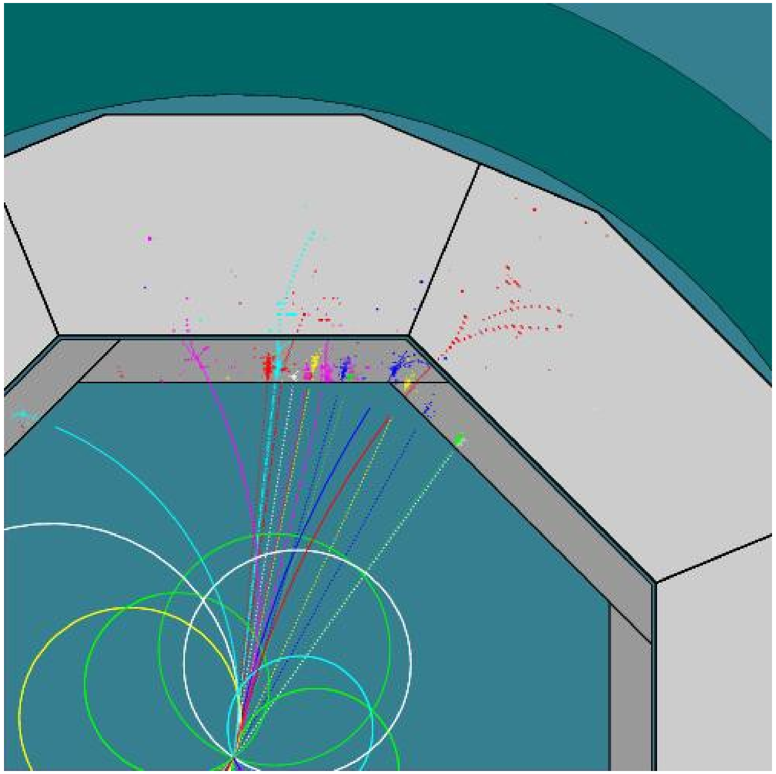
Two arguments for a TPC:
- the redundancy is large (> 100 points par trace)
  $\Rightarrow$ easy pattern, in particular for V^0's or kinks (K+-).
- the dE/dx in the gas presents a relativistic rise which enables electron identification up to 10-20 GeV as well as π/K separation

Two questions:
what will be the point precision, 100 μ?
a constant term ~ 50μ (plate) plus diffusion, depends on the square root of the drift length
and the distortions in a field possibly quite inhomogeneous $\overline{\text{DID}}$?

how much material, how much space in front of ECAL?

Speaking of technologies

electromagnetic calorimeter



goal: very compact, hermetic,
good separation
hence high transverse granularity
high longitudinal granularity (≠ CMS)
the energy resolution
is NOT a decisive criterion

Notice the structure of the modules
to avoid cracks

All the technical aspects of calorimetry for ILD
are developed in the collaboration CALICE

Speaking of technologies
electromagnetic calorimeter

Today, but for the cost,
the preference (mine) goes to tungsten-silicon sandwiches

The silicon is stable in temperature, voltage,
good resolution depending on sampling, Si thickness,
the granularity may be excellent.

Typically 24 X_0 in about 20 cm, a Moliere radius around 1.5 cm
a resolution between 15 and 20% .
Read-out by pads (~5x5mm^2) on 6 to 8 inch wafers
the size of these pads has been proven essential for jet resolution

Huge number of read-out channels (tens of millions)
but silicon area, cost

The front-end electronics is embedded
power supply, heat, cooling, read-out

Si 2 to 3 $ du cm^2
to be more studied
but CMS

Silicon detectors

Using thin wafers of high resistivity silicon, from 100μ to 725μ

When a charged particle crosses the wafer diode it creates a number of pairs electron-hole, more than 10000 per mm, no need of local amplification.
The diode has an electric field large enough to be completely depleted.
Then the number of collected charges depends only on the Si thickness (stability, calibration)
The electrons (faster) are collected and their signal recorded.

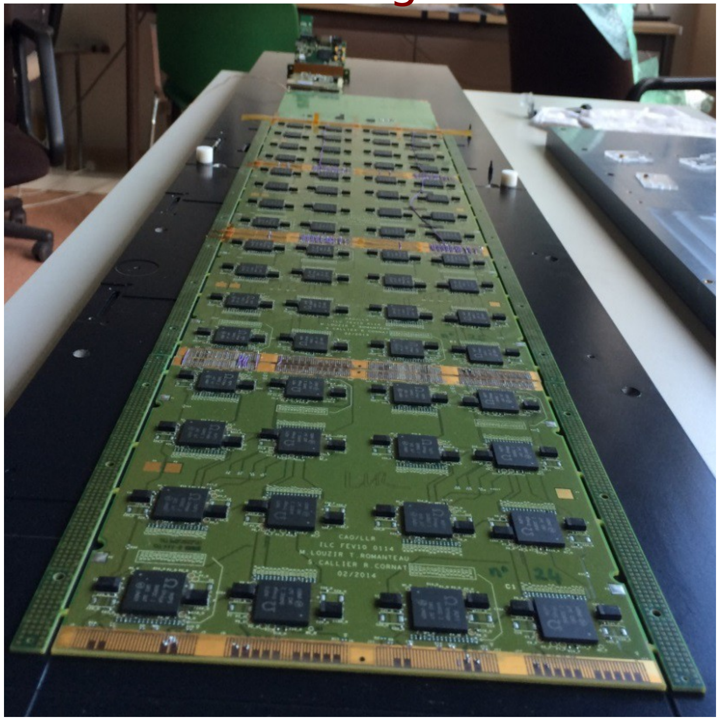
The same technology is to serve for the end cap calorimeter upgrade of CMS

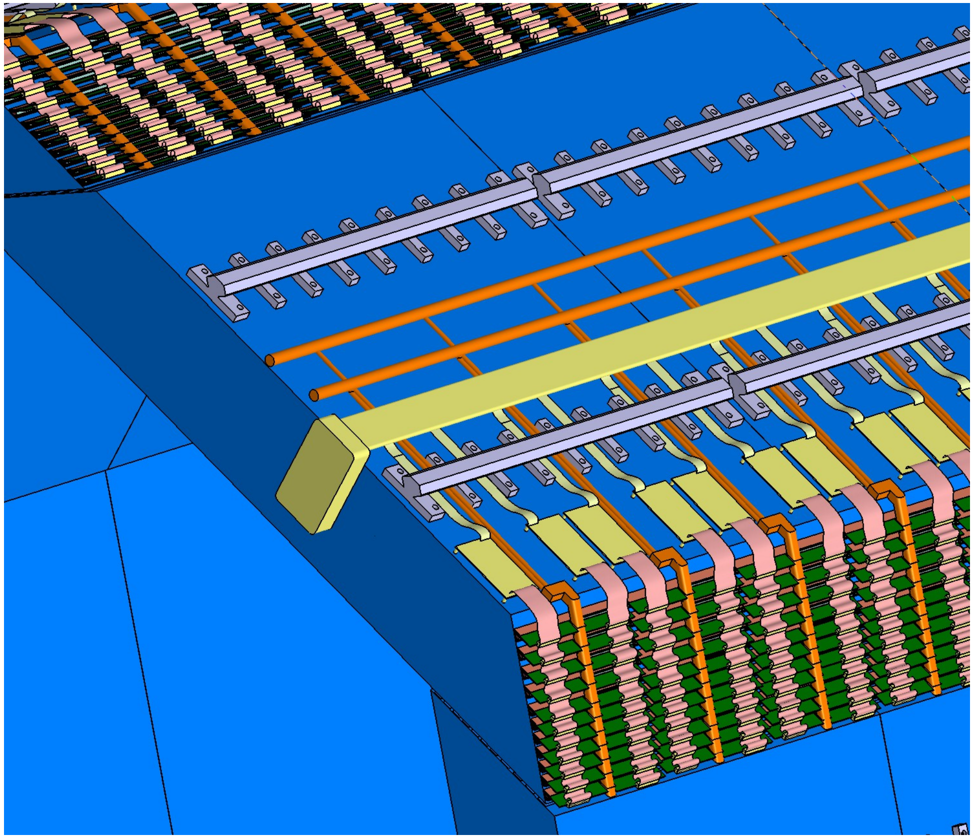
Detector

electromagnetic calorimeter

A structure in carbon fibres
embedding half of the W radiator

Detecting slabs





Once you have chosen a sampling calorimeter inside the coil what are the main parameters ?

- the radiator material, amagnetic and not too good a conductor,
  - brass (CMS), stainless steel (ILD), tungsten (tried for CLIC)?
- the number of interaction lengths (5-6) knowing that the ECal has 1
  - the coil behind has 2 and a tail catcher can be built beyond
- the sampling, intrinsic resolution + longitudinal granularity
- the detecting medium, gas scintillator
- the size of the detecting cells.

ILD studies two solutions

hadron calorimeter

analogue calorimeter

A classical solution: scintillator
cells as small as technology permits about 3x3 cm^2
read in situ using a non classical SiPM (MPPC).
The energy deposited in the cells is collected
with a good dynamics 12 bits

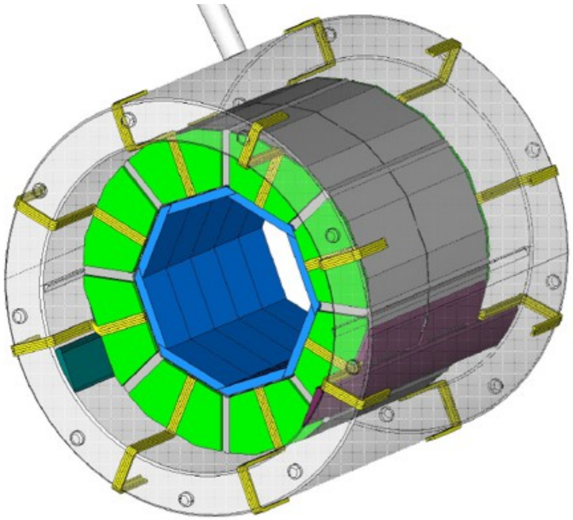
Or

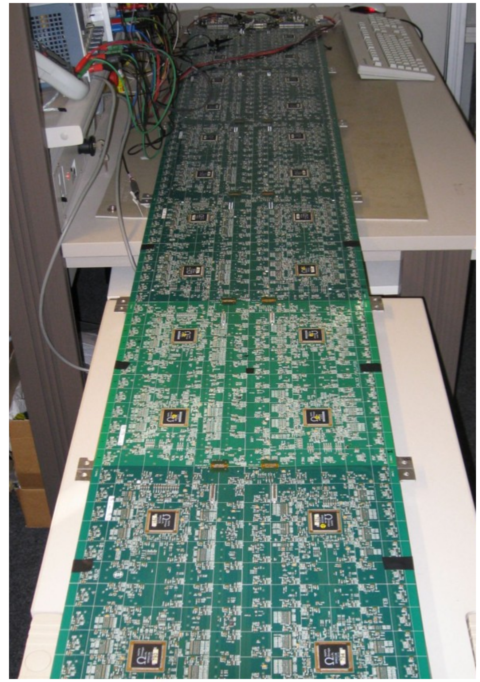
digital (semi) calorimeter

In view of the fluctuations of the energy deposited by cell
it has been shown that
the resolution may be better (up to a certain energy)
using a single read out threshold or up to three
in cells adapted in size:
gas cells $1cm^2$, RPC , but scintillator cells (3x3) also
read out in situ

It can be noticed that is has been shown that the analogue treated as semi-digital exhibits better resolution

Detector



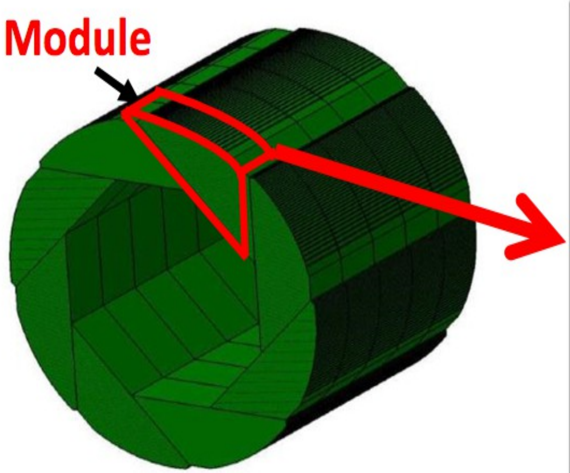


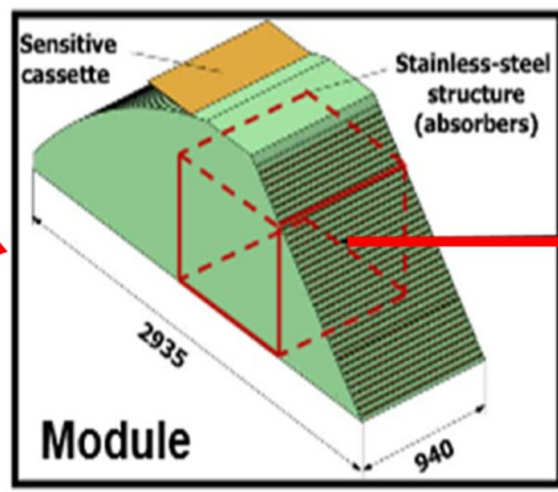
A choice of structure
to be made soon

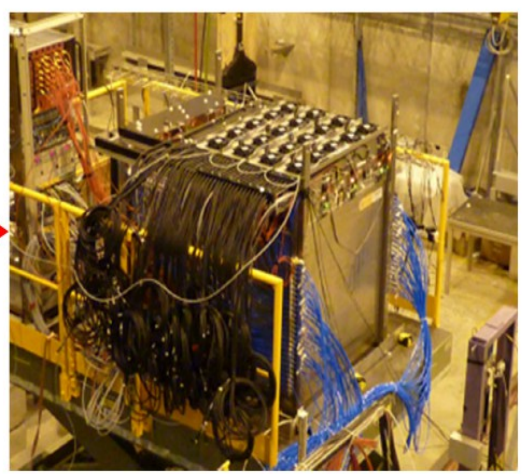
SDHCAL ILD barrel

SDHCAL ILD module

SDHCAL 1.3m3 prototype

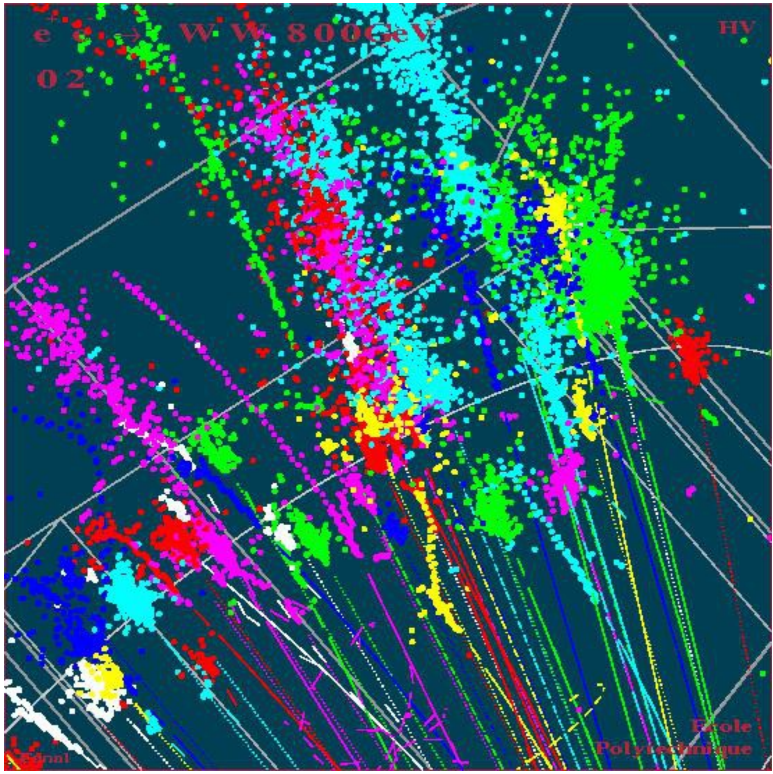






An interesting software development ,

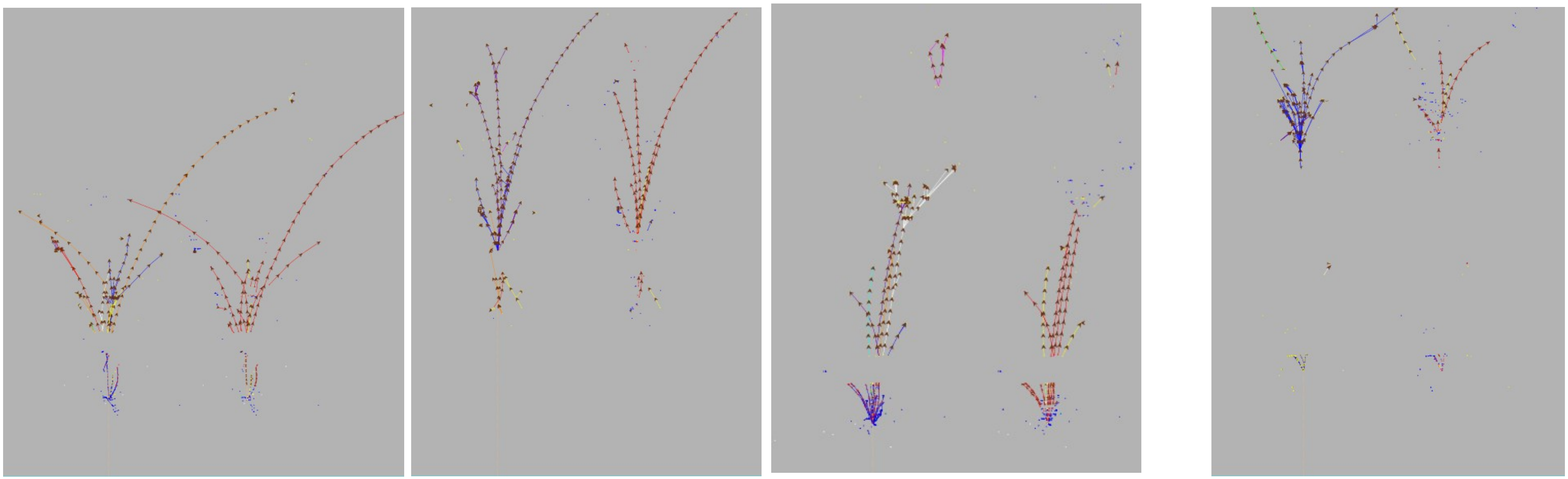
finding the showers
with their associated tracks
in a highly granular calorimeter,
where the MIPs are well seen
but some discontinuities linked to neutrals
the resolution optimisation (compensation)
by an adequate weighting.



the particle flow!

with time

Detector



How do we know all of these pieces belong to the same shower ?

Can we link the tracks in the Hcal and Ecal ?

How to estimate at best the energy
How to estimate the leakage

Few 10 GeV pions starting in the Ecal
the reconstruction is done with Arbor

Tail catcher and muon detector

Rather ordinary techniques
scintillators, RPC or tubes,
the low occupation rates and the high multiple scattering
make the requested qualities rather easy.

Detector

Speaking of technologies

low angle detectors

Avoid any hole, veto at least!

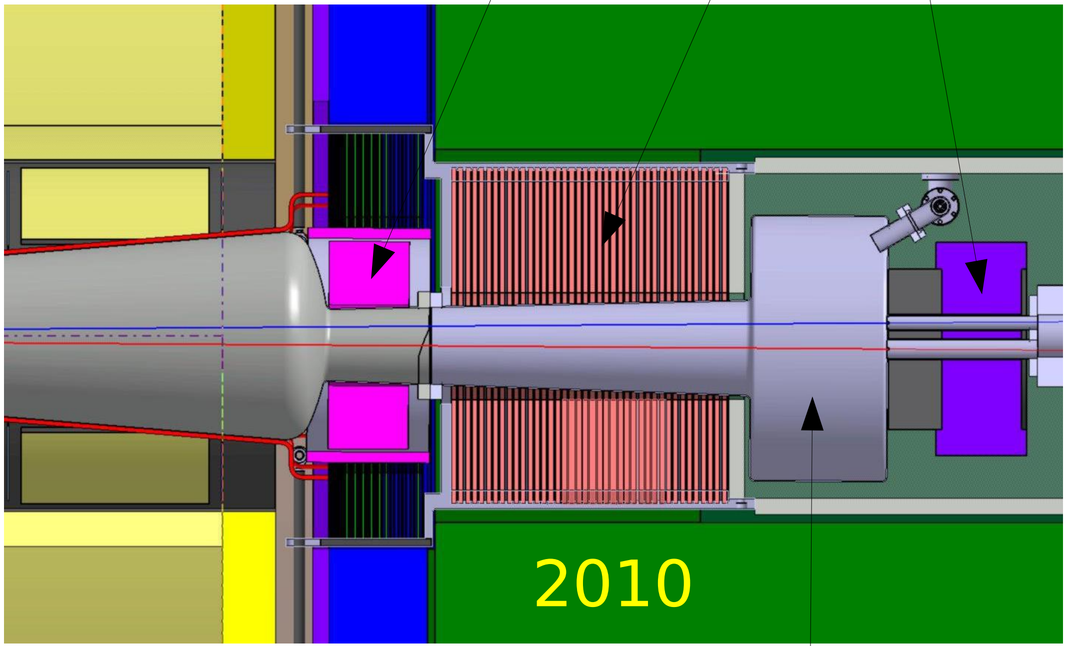
Sign the forward particles : electrons, muons, hadrons

Huge flux of pairs

radiation hard calorimeter.

Tungsten-diamond?

Keep the backscattering of particles low



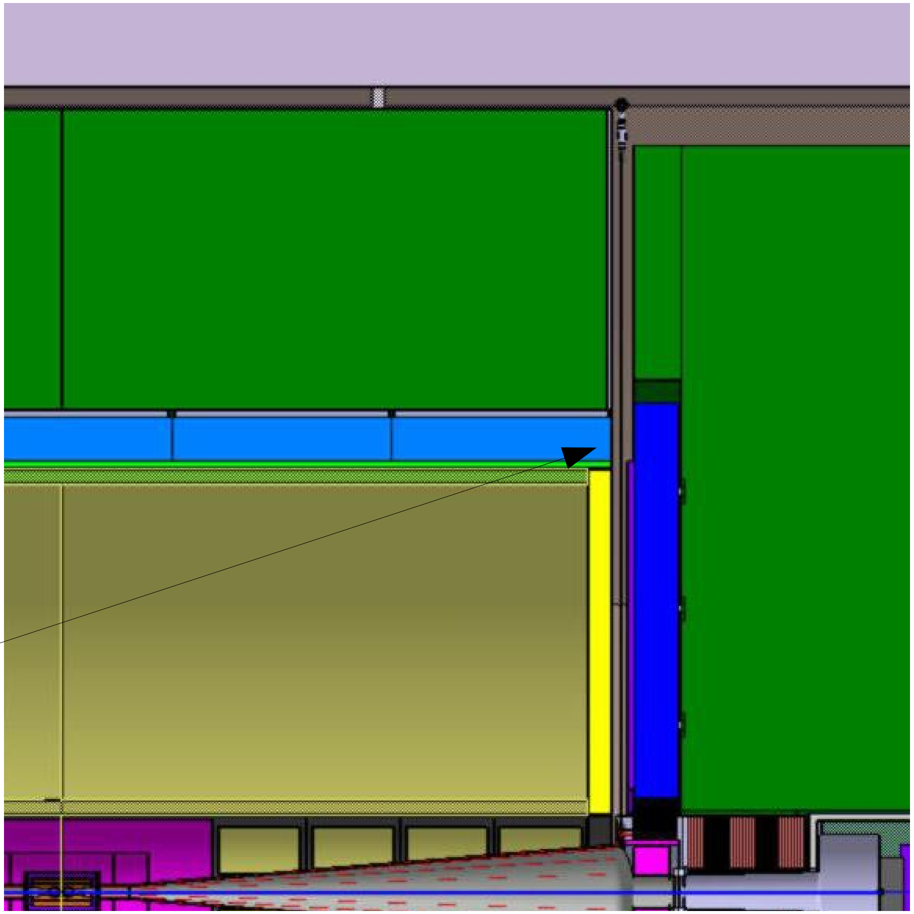
Detector

A word on the corners, often called overlap region

The place where particles enter
in the barrel and continue in the end caps

Again the problem of connection

Try to close it but :
- safety margin for the closure
of the detector
- space for services



compared to LEP detectors (the preceding e+e- collider):
10 times better in momentum,
100 times more granular
2 times better in jet energy
no trigger
time measurement.

A detector full of innovations
fun to conceive

by its grain, its resolution, the absence of trigger
should offer an optimal collection of all the physics
reachable between 0.25 and 1.5 TeV.

The end of our visit through detectors

I hope to have helped you to realise that we have here a project

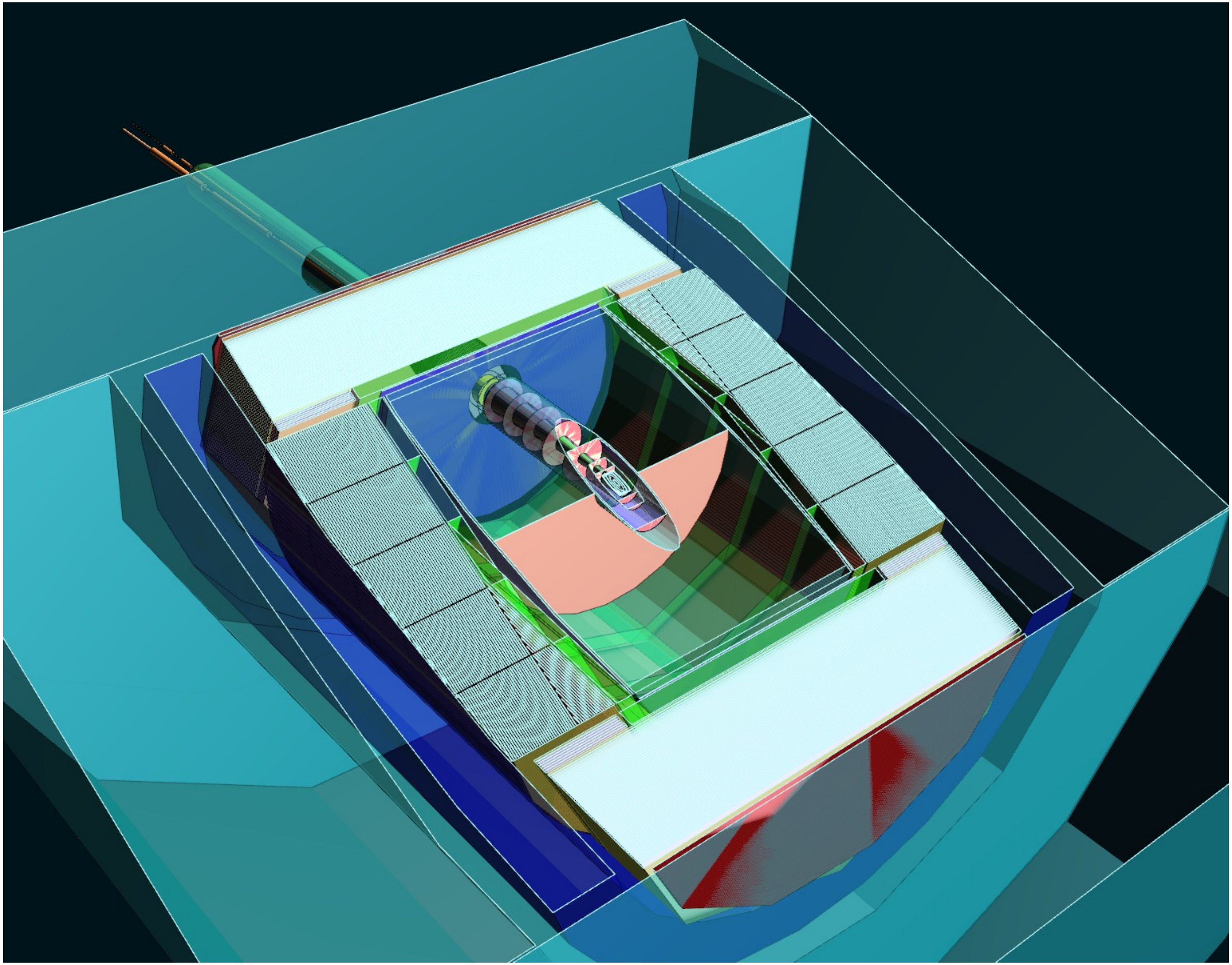
capable of bringing a new essential understanding, even
after what LHC has discovered and still will discover.

The machine is a challenge shown to be realistic (TDR)

and excellent detectors can be built with a lot more
funny developments to come like time.

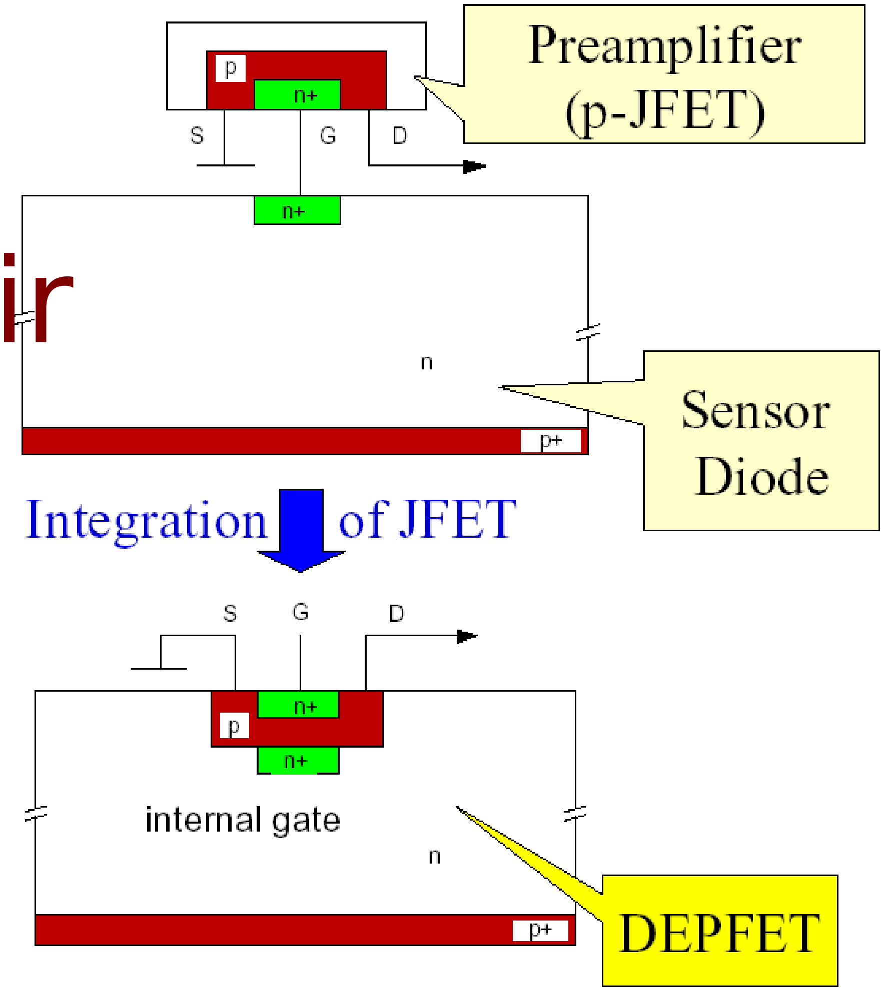
Now it is up to you!

The ILD boat
fluctuat, mergitur ?



Autres solutions DEpFET

DEPFET - principle idea



A revoir

Kemmer, Lutz (1987):

- integrate preamplifier into Sensor Si- Substrate

Advantage:

- Small input capacitance
- no stray capacitance

=> Large Signal to Noise Ratio

Detector

ALEPH
a detector
for LEP