Particle Detectors Principles

Werner Riegler, CERN, werner.riegler@cern.ch

The 'Real' World of Particles

E. Wigner:

"A particle is an irreducible representation of the inhomogeneous Lorentz group"

Spin=0,1/2,1,3/2 … Mass>0

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ON UNITARY REPRESENTATIONS OF THE INHOMOGENEOUS LORENTZ GROUP*

BY E. WIGNER

(Received December 22, 1937)

1. ORIGIN AND CHARACTERIZATION OF THE PROBLEM

It is perhaps the most fundamental principle of Quantum Mechanics that the system of states forms a *linear manifold*,[1] in which a unitary *scalar product* is defined.[2] The states are generally represented by wave functions[3] in such a way that φ and constant multiples of φ represent the same physical state. It is possible, therefore, to normalize the wave function, i.e., to multiply it by a constant factor such that its scalar product with itself becomes 1. Then, only a constant factor of modulus 1, the so-called phase, will be left undetermined in the wave function. The linear character of the wave function is called the superposition principle. The square of the modulus of the unitary scalar product (ψ, φ) of two normalized wave functions ψ and φ is called the transition probability from the state ψ into φ, or conversely. This is supposed to give the probability that an experiment performed on a system in the state φ, to see whether or not the state is ψ, gives the result that it is ψ. If there are two or more different experiments to decide this (e.g., essentially the same experiment,

The ‘Real’ World of Particles

W. Riegler:

“…a particle is an object that interacts with your detector such that you can follow it’s track,

it interacts also in your readout electronics and will break it after some time,

and if you a silly enough to stand in an intense particle beam for some time you will be dead …”

The ‘Real’ World of Particles

Elektro-Weak Lagrangian

$$L_{GSW} = L_0 + L_H + \sum_l \left\{ \frac{g}{2} \bar{L}_l \gamma_\mu \vec{\tau} L_l \vec{A}^\mu + g' \left[\bar{R}_l \gamma_\mu R_l + \frac{1}{2} \bar{L}_l \gamma_\mu L_l \right] B^\mu \right\} +$$

$$+ \frac{g}{2} \sum_q \bar{L}_q \gamma_\mu \vec{\tau} L_q \vec{A}^\mu +$$

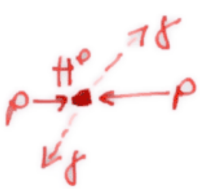
$$+ g' \left\{ \frac{1}{6} \sum_q \left[\bar{L}_q \gamma_\mu L_q + 4 \bar{R}_q \gamma_\mu R_q \right] + \frac{1}{3} \sum_{q'} \bar{R}_{q'} \gamma_\mu R_{q'} \right\} B^\mu$$

$$L_H = \frac{1}{2}(\partial_\mu H)^2 - m_H^2 H^2 - h\lambda H^3 - \frac{h}{4} H^4 +$$

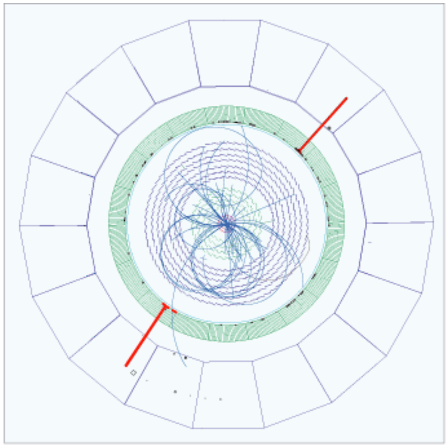
Higgs Particle

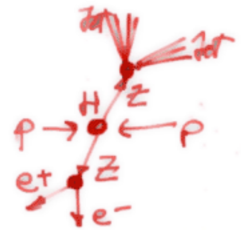
$$+ \frac{g^2}{4}\left(W_\mu^+ W^\mu + \frac{1}{2\cos^2\theta_W} Z_\mu Z^\mu\right)(\lambda^2 + 2\lambda H + H^2) +$$

$$+ \sum_{l,q,q'} \left(\frac{m_l}{\lambda} \bar{l} l + \frac{m_q}{\lambda} \bar{q} q + \frac{m_{q'}}{\lambda} \bar{q}' q' \right) H$$

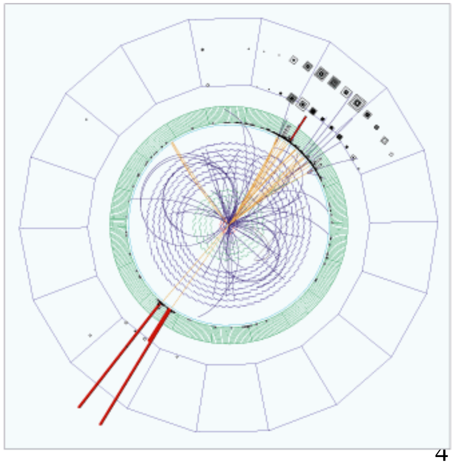


$p\,p \to H^0$
$\quad \hookrightarrow \gamma\gamma$

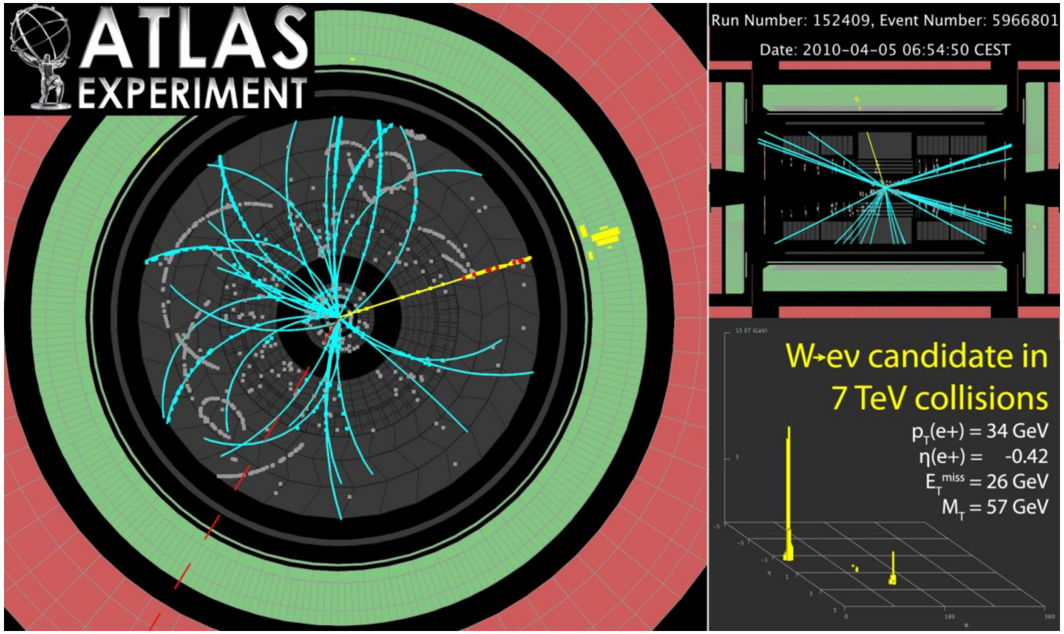


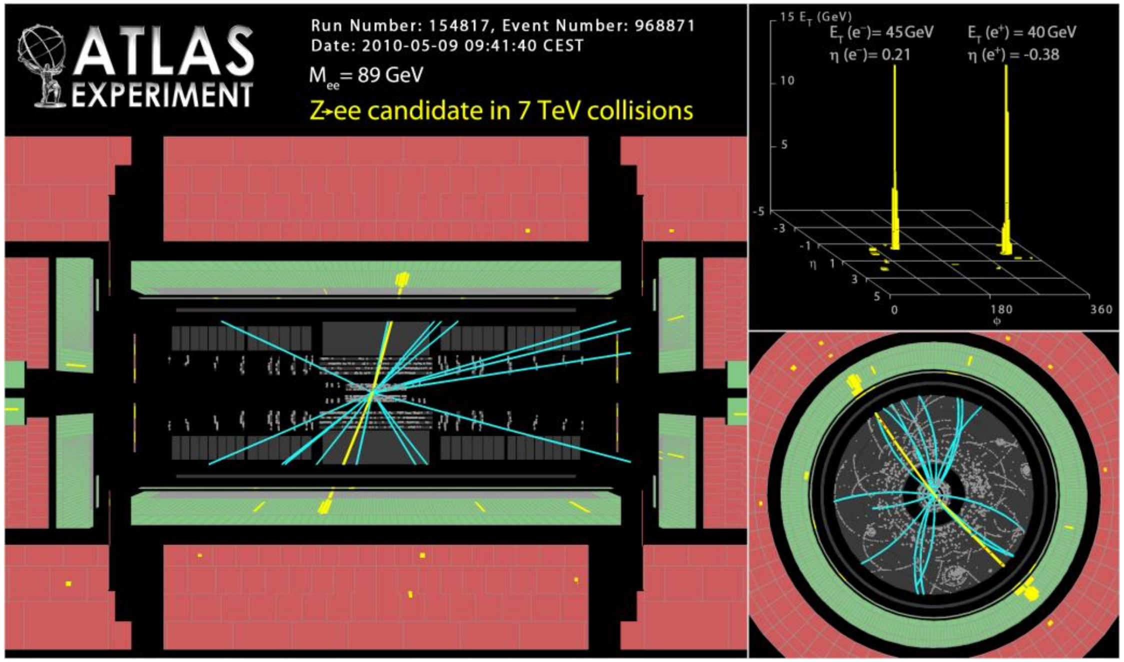


$p\,p \to H^0 \to Z\,Z$
$\quad \hookrightarrow$ jet jet
$\quad \hookrightarrow e^+ e^-$

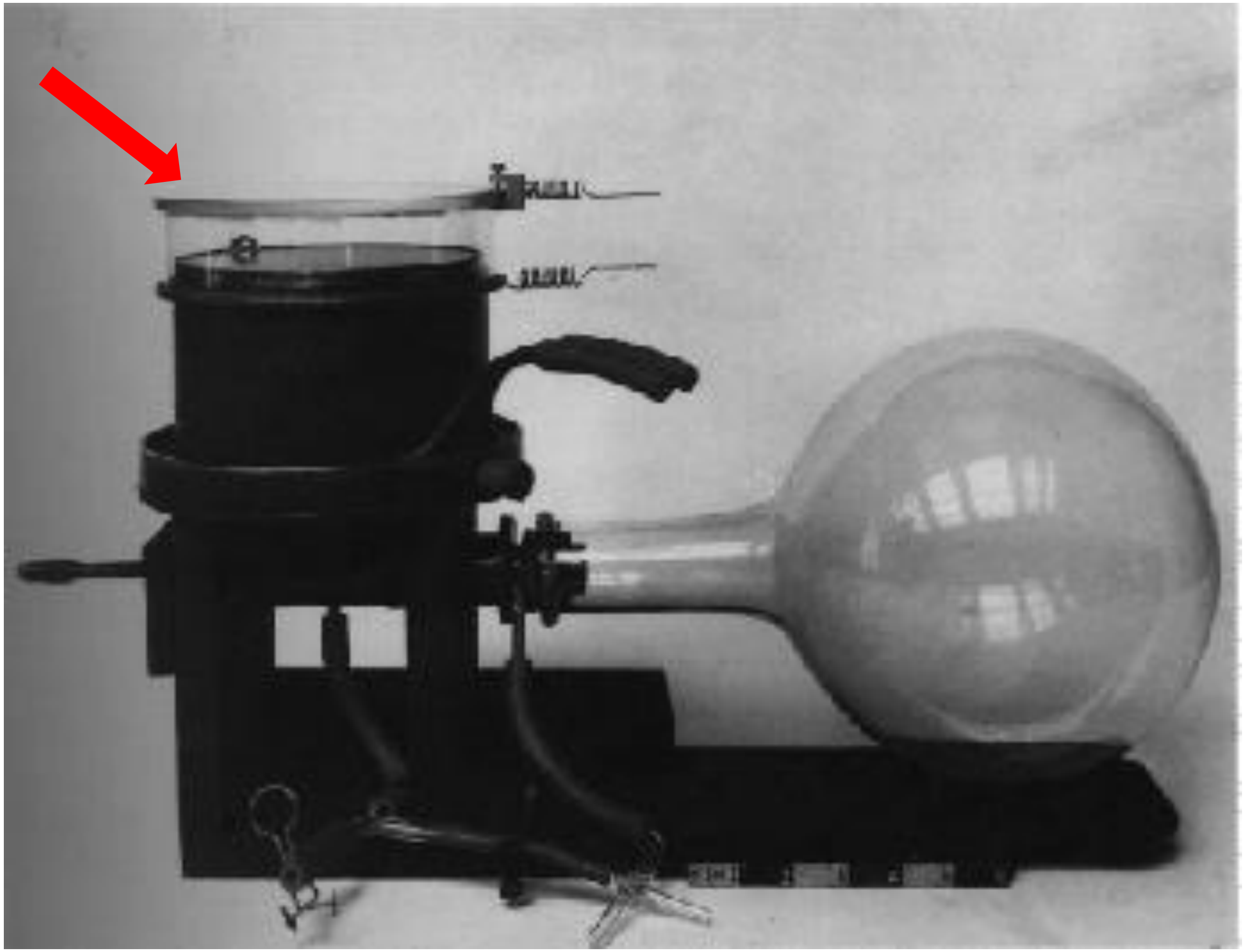


2010 ATLAS W, Z particles





Cloud Chamber 1911-1950



Wilson Cloud Chamber 1911

Cloud Chamber

Alpha Particles, Philipp 1926

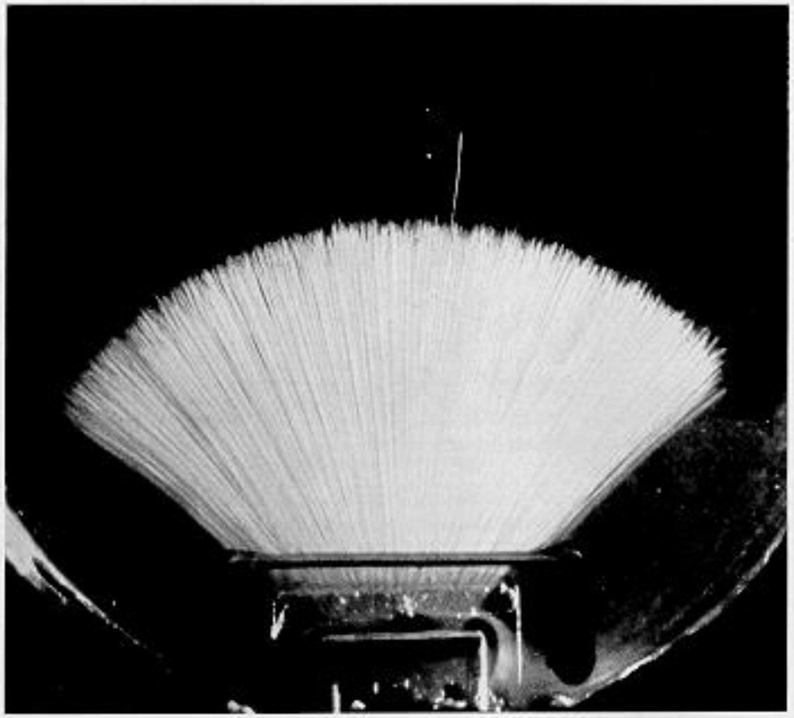


Fig. 13. K. Philipp, Naturwiss. 14, 1203 (1926).

Charges particles ionize the 'air' along their track.

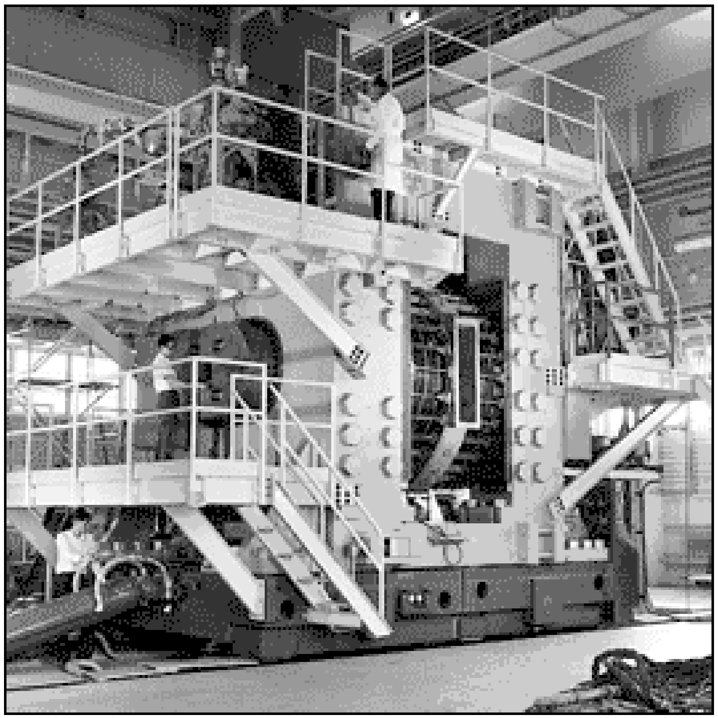
These charges will act as condensation points if the gas is supersaturated → photos of particle tracks.

The alpha particles in this picture lose energy – the fact that they all have the same range shows that all alphas have the same original energy.

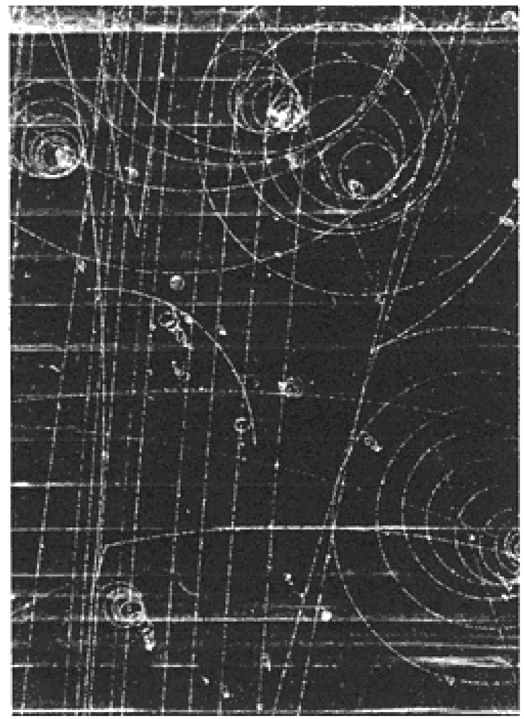
Fig. 43. Radiation Laboratory, Berkeley, Cal.

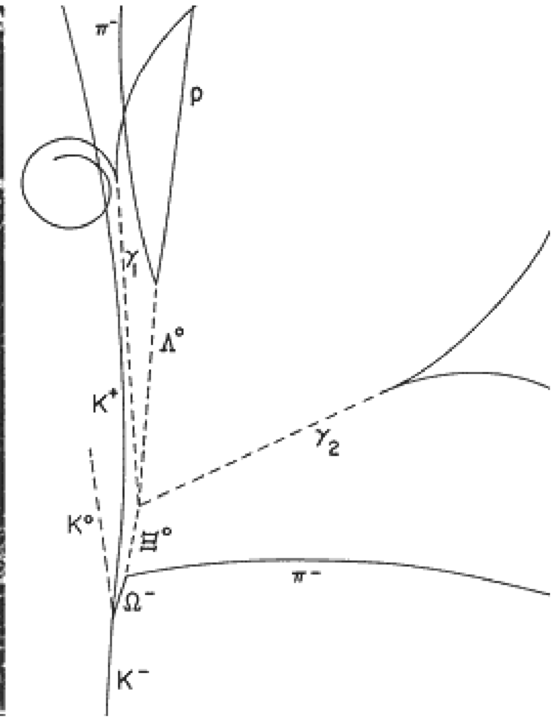
Fast electron in a magnetic field at the Bevatron, 1940

Bubble Chamber (1950-1984)

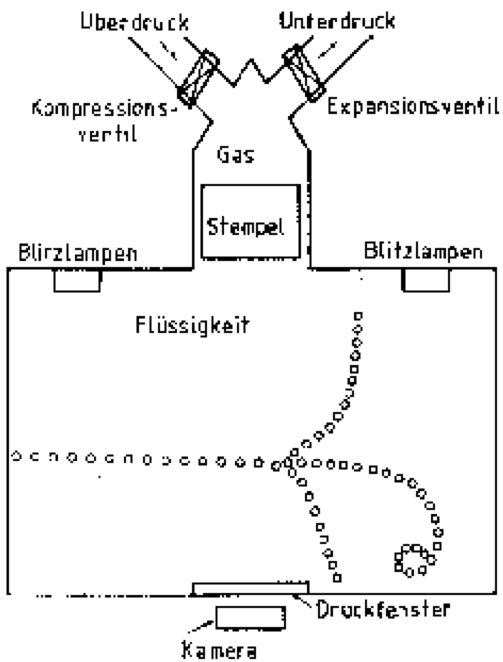


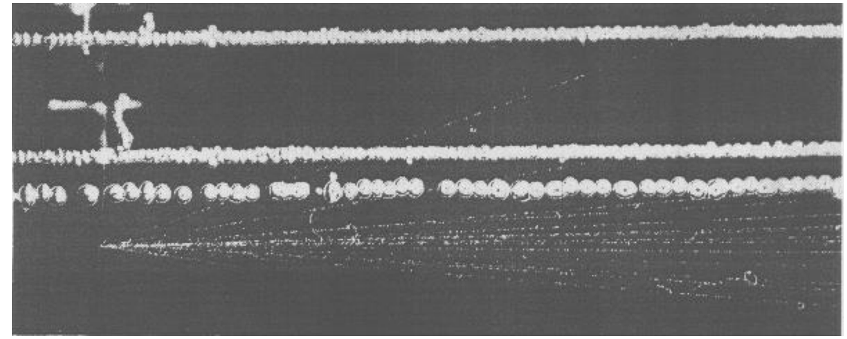
The 80-inch Bubble Chamber

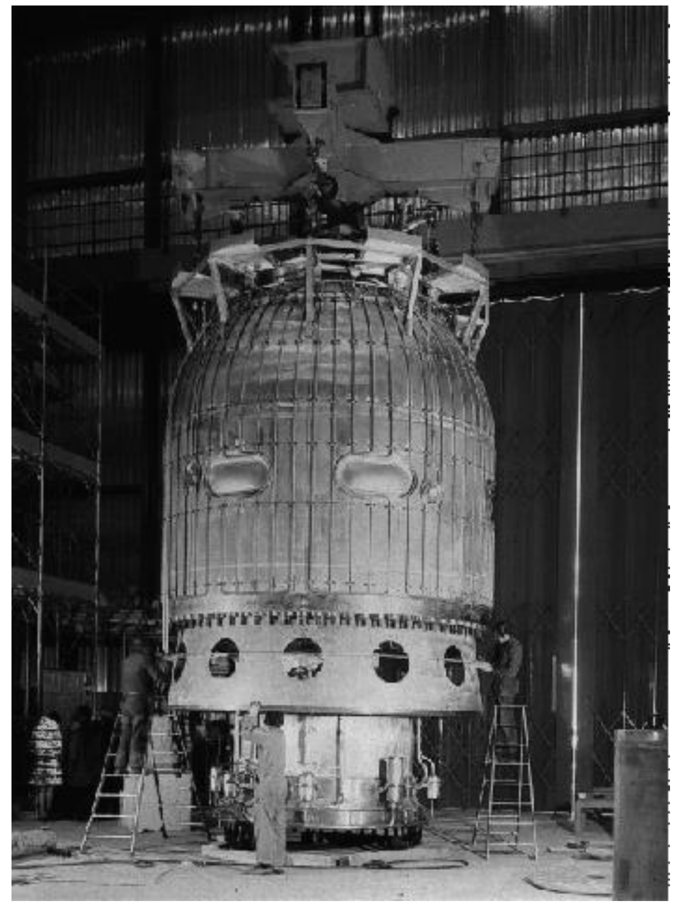




Bubble Chamber







The thermodynamic ‘counterpart’ to the cloud chamber:

A superheated liquid starts boiling when a charged particle passes the liquid and transfers energy to the atoms of the liquid.

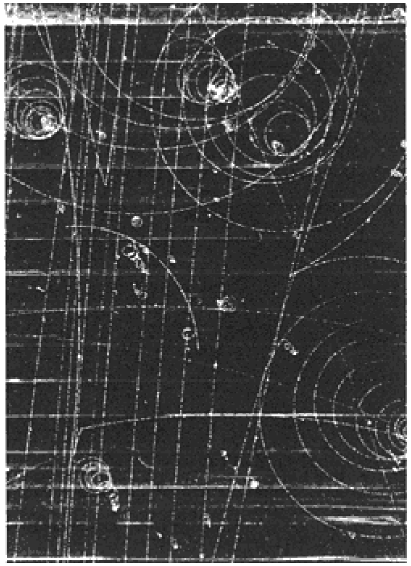
Small bubbles → photography

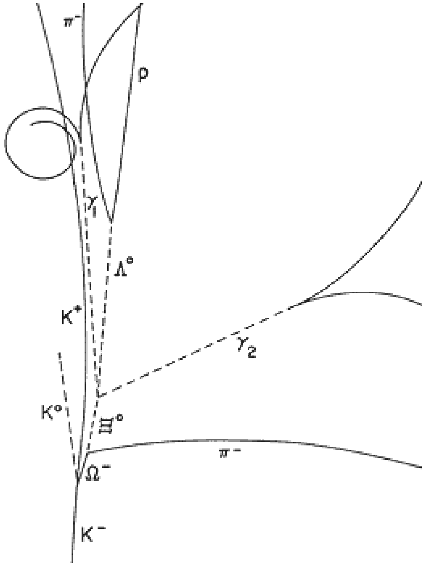
Bubble Chambers

The excellent position (5μm) resolution makes the Bubble chamber almost unbeatable for reconstruction of complex decay modes.

The drawback of the bubble chamber is the low rate capability (about 10/second). However, LHC has 10^9 collisions/second !

That's why electronics detectors took over in the 70ties.

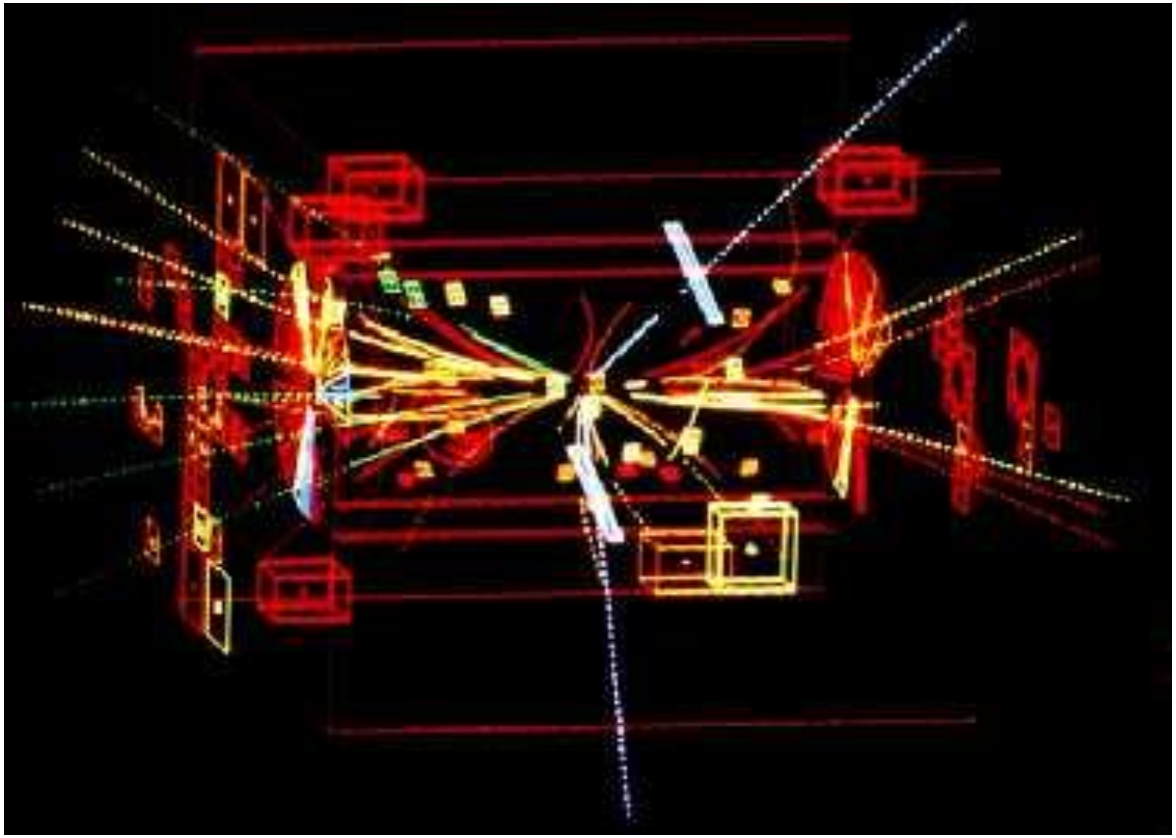




W, Z-Discovery 1983/84

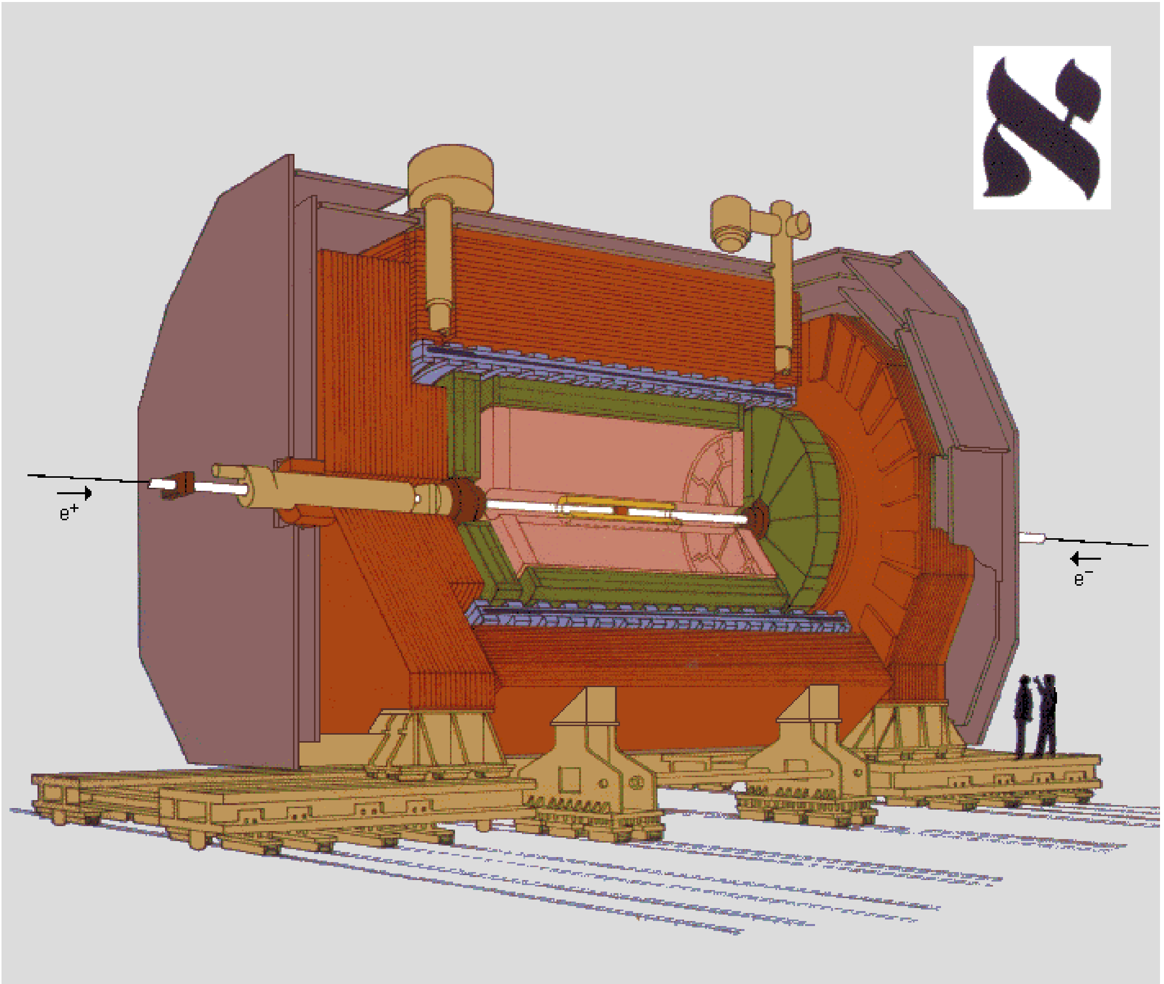
UA1 used a very large wire chamber.

Can now be seen in the CERN Microcosm Exhibition



This computer reconstruction shows the tracks of charged particles from the proton-antiproton collision. The two white tracks reveal the Z's decay. They are the tracks of a high-energy electron and positron.

LEP 1988-2000



- Vertex Detector
- Inner Tracking Chamber
- Time Projection Chamber
- Electromagnetic Calorimeter
- Superconducting Magnet Coil
- Hadron Calorimeter
- Muon Chambers
- Luminosity Monitors

The ALEPH Detector

All Gas Detectors

Increasing Multiplicities in Heavy Ion Collisions

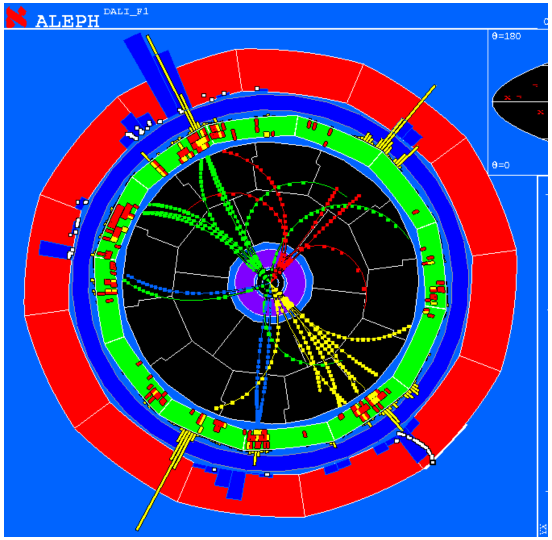
e+ e- collision in the ALEPH Experiment/LEP.

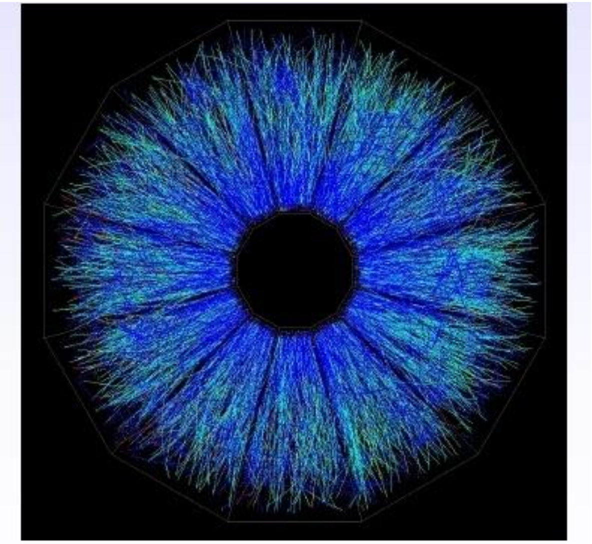
Au+ Au+ collision in the STAR Experiment/RHIC

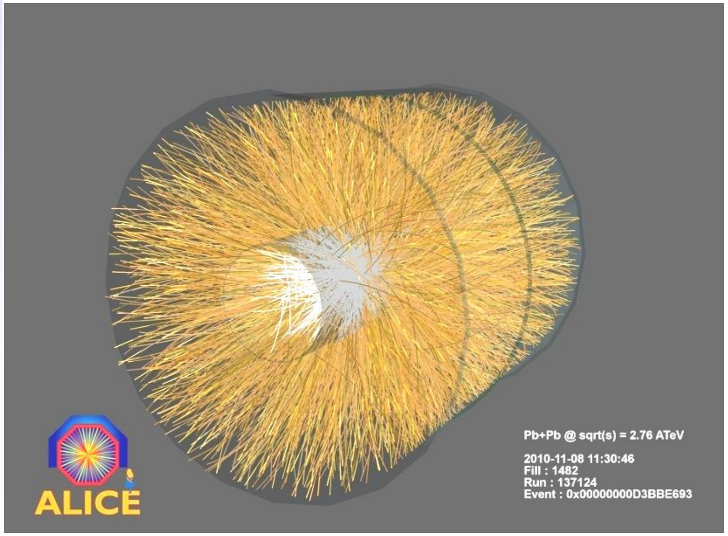
Up to 2000 tracks

Pb+ Pb+ collision in the ALICE Experiment/LHC

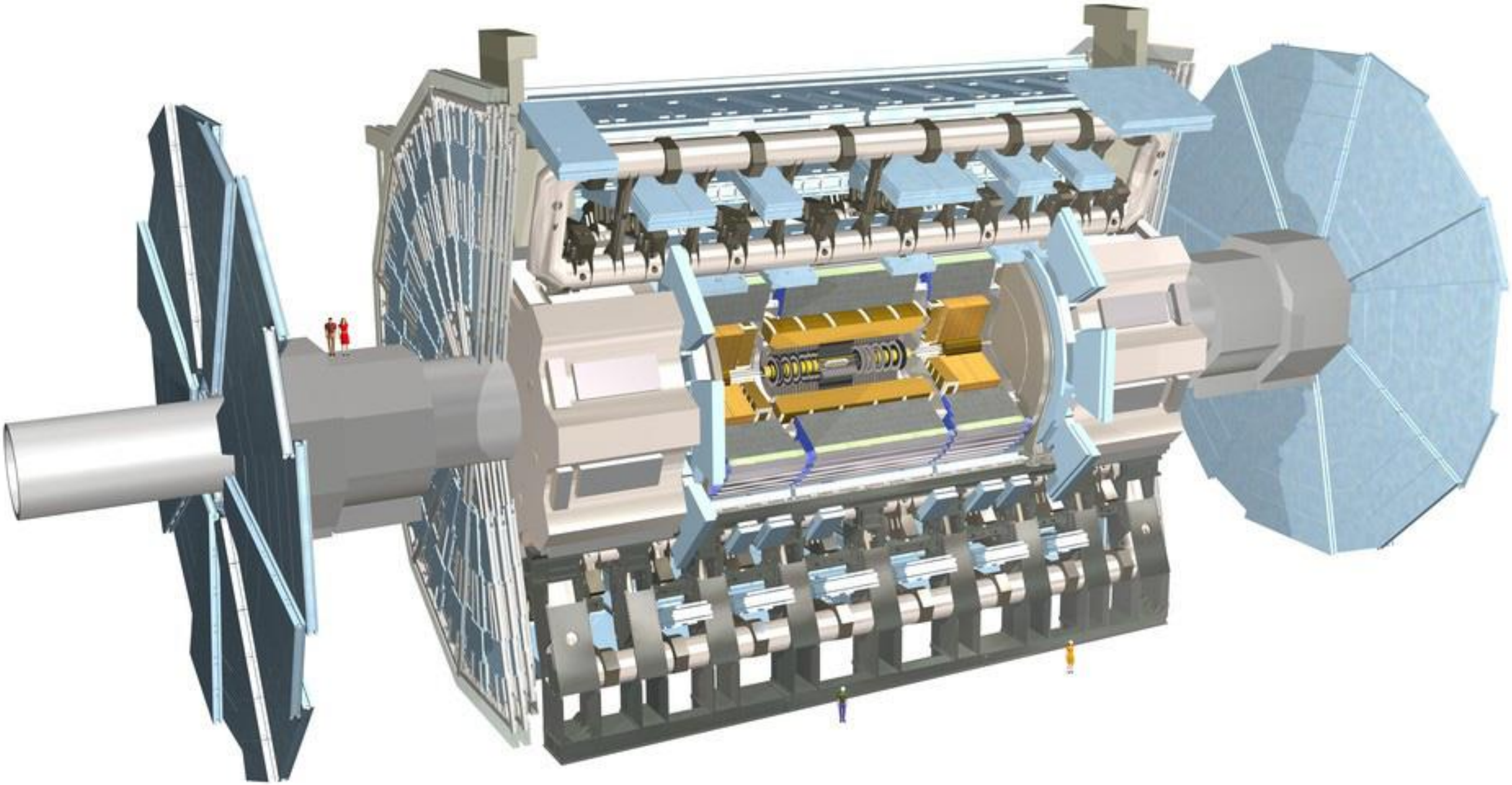
Up to 10 000 tracks/collision







ATLAS at LHC



The ATLAS detector uses more than 100 million detector channels.

Measuring 1 billion collisions per second.

Scales

$$E = m a^2$$

$$E = m b^2$$

$$E = m c^2 \longleftarrow \text{Energy} \hat{=} \text{Mass}$$

$$\vdots$$

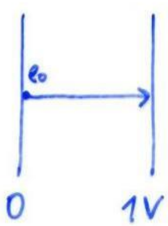
$$m(\text{electron}) = 9.1 \cdot 10^{-31}\ \text{kg}$$

$$m_e c^2 = 8.19 \cdot 10^{-14}\ \text{J}$$

$$= 510\,999 \text{ Electron Volt (eV)}$$

$$= 0.511 \text{ MeV}$$

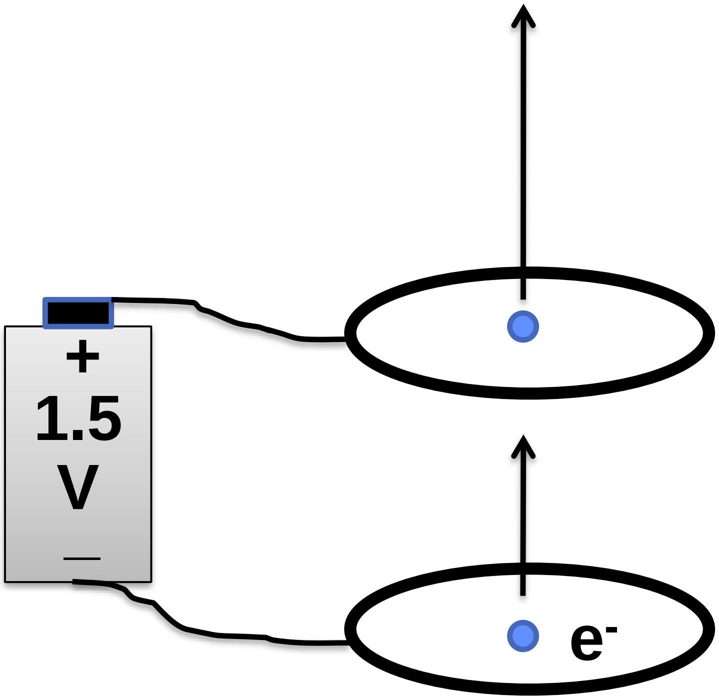
$$1 \text{ Electron Volt} = e_0 \cdot 1\text{V} = 1.603 \cdot 10^{-19}\ \text{J}$$



$$E = e_0 \cdot 1\text{V}$$

1 Electron Volt = Energy an Electron gains as it traverses a Potential Difference of 1V

Build your own Accelerator



E_{kin}= 1.5eV =

2 615 596 km/h

Scales

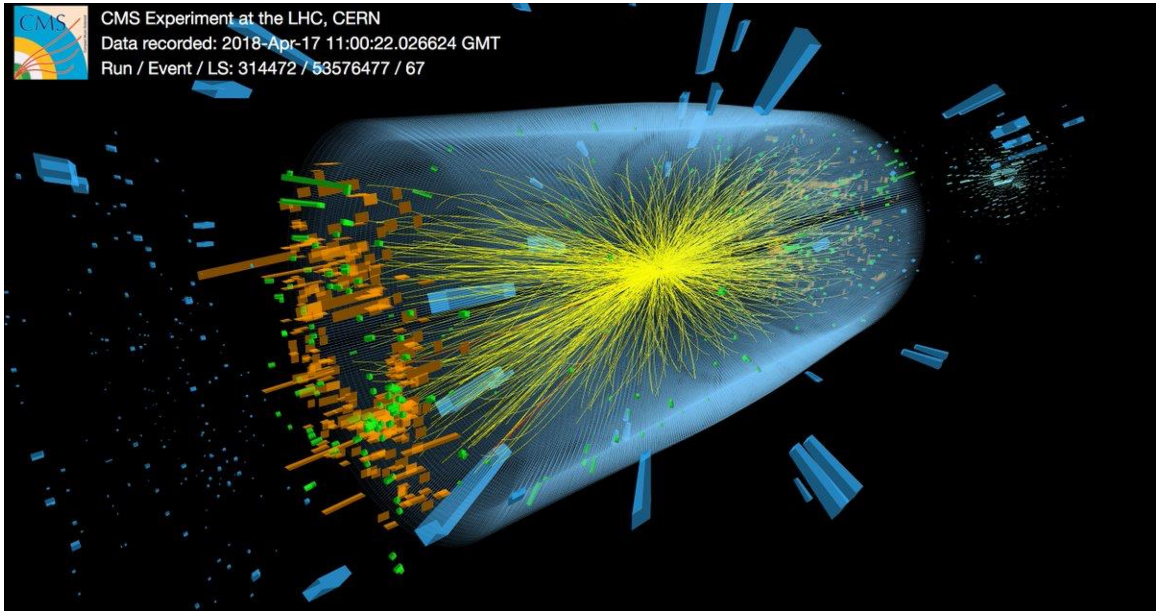
Visible Light: $\lambda = 500\,nm$, $h\nu \sim 2.5\,eV$

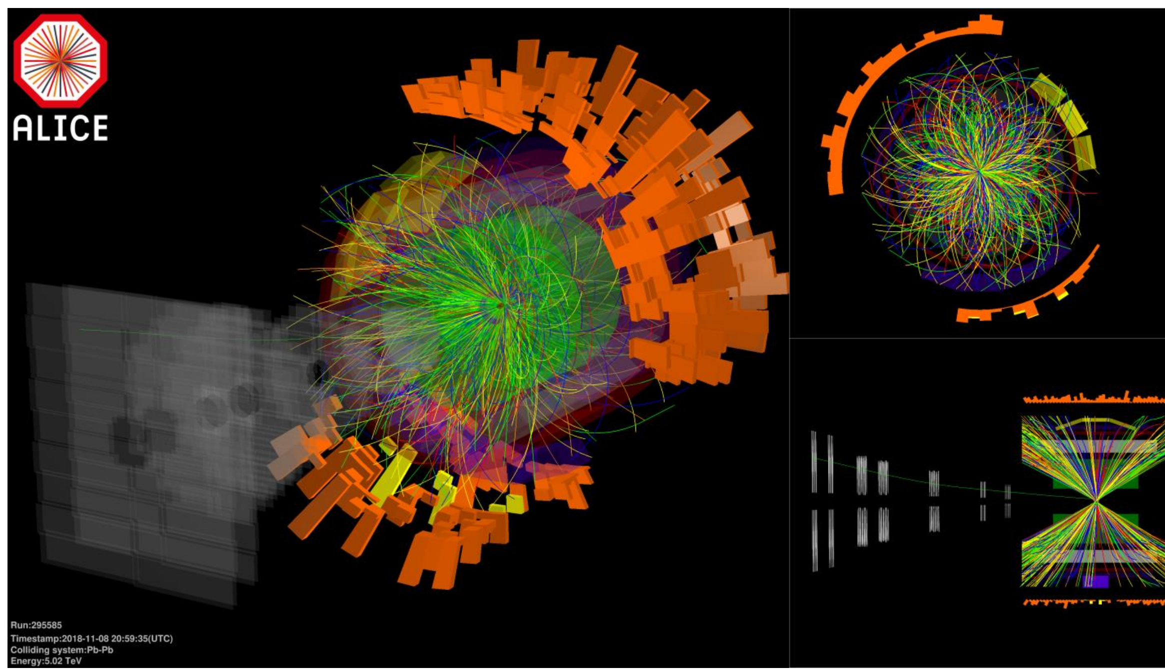
Excited States in Atoms: 1 - 100 keV "X-Rays"

Nuclear Physics: 1 - 50 MeV

Particle Physics: 1 - 1000 GeV (LHC 14 TeV)

Highest Measured Energy: 10^{20} eV (Cosmic Rays)


CMS Experiment at the LHC, CERN
Data recorded: 2018-Apr-17 11:00:22.026624 GMT
Run / Event / LS: 314472 / 53576477 / 67


ALICE
Run:295585
Timestamp:2018-11-08 20:59:35(UTC)
Colliding system:Pb-Pb
Energy:5.02 TeV

http://pdg.lbl.gov ~ **180 Selected Particles**

$\gamma, W^{\pm}, Z^{0}, g, e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau, \pi^{\pm}, \pi^{0}, \eta, f_0(600), \rho(770),$
$\omega(782), \eta'(958), f_0(980), a_0(980), \phi(1020), h_1(1170), b_1(1235),$
$a_1(1260), f_2(1270), f_1(1285), \eta(1295), \pi(1300), a_2(1320),$
$f_0(1370), f_1(1420), \omega(1420), \eta(1440), a_0(1450), \rho(1450),$
$f_0(1500), f_2'(1525), \omega(1650), \omega_3(1670), \pi_2(1670), \phi(1680),$
$\rho_3(1690), \rho(1700), f_0(1710), \pi(1800), \phi_3(1850), f_2(2010),$
$a_4(2040), f_4(2050), f_2(2300), f_2(2340), K^{\pm}, K^{0}, K^{0}_{S}, K^{0}_{L}, K^{*}(892),$
$K_1(1270), K_1(1400), K^{*}(1410), K_0^{*}(1430), K_2^{*}(1430), K^{*}(1680),$
$K_2(1770), K_3^{*}(1780), K_2(1820), K_4^{*}(2045), D^{\pm}, D^{0}, D^{*}(2007)^{0},$
$D^{*}(2010)^{\pm}, D_1(2420)^{0}, D_2^{*}(2460)^{0}, D_2^{*}(2460)^{\pm}, D_s^{\pm}, D_s^{*\pm},$
$D_{s1}(2536)^{\pm}, D_{sJ}(2573)^{\pm}, B^{\pm}, B^{0}, B^{*}, B_s^{0}, B_c^{\pm}, \eta_c(1S), J/\psi(1S),$
$\chi_{c0}(1P), \chi_{c1}(1P), \chi_{c2}(1P), \psi(2S), \psi(3770), \psi(4040), \psi(4160),$
$\psi(4415), \Upsilon(1S), \chi_{b0}(1P), \chi_{b1}(1P), \chi_{b2}(1P), \Upsilon(2S), \chi_{b0}(2P),$
$\chi_{b2}(2P), \Upsilon(3S), \Upsilon(4S), \Upsilon(10860), \Upsilon(11020), p, n, N(1440),$
$N(1520), N(1535), N(1650), N(1675), N(1680), N(1700), N(1710),$
$N(1720), N(2190), N(2220), N(2250), N(2600), \Delta(1232), \Delta(1600),$
$\Delta(1620), \Delta(1700), \Delta(1905), \Delta(1910), \Delta(1920), \Delta(1930), \Delta(1950),$
$\Delta(2420), \Lambda, \Lambda(1405), \Lambda(1520), \Lambda(1600), \Lambda(1670), \Lambda(1690),$
$\Lambda(1800), \Lambda(1810), \Lambda(1820), \Lambda(1830), \Lambda(1890), \Lambda(2100),$
$\Lambda(2110), \Lambda(2350), \Sigma^{+}, \Sigma^{0}, \Sigma^{-}, \Sigma(1385), \Sigma(1660), \Sigma(1670),$
$\Sigma(1750), \Sigma(1775), \Sigma(1915), \Sigma(1940), \Sigma(2030), \Sigma(2250), \Xi^{0}, \Xi^{-},$
$\Xi(1530), \Xi(1690), \Xi(1820), \Xi(1950), \Xi(2030), \Omega^{-}, \Omega(2250)^{-},$
$\Lambda_c^{+}, \Lambda_c^{+}, \Sigma_c(2455), \Sigma_c(2520), \Xi_c^{+}, \Xi_c^{0}, \Xi_c'^{+}, \Xi_c'^{0}, \Xi(2645)$
$\Xi_c(2780), \Xi_c(2815), \Omega_c^{0}, \Lambda_b^{0}, \Xi_b^{0}, \Xi_b^{-}, t\bar{t}$

There are many more

All particles that can possibly leave a track in the detector:

All Particles with $c\tau > 1\mu m$ @ GeV Level

Particle	Mass (MeV)	Life time τ (s)	$c\tau$
γ	0	∞	∞
$\pi^\pm (u\bar{d}, d\bar{u})$	140	$2.6 \cdot 10^{-8}$	7.8 m
$K^\pm (u\bar{s}, \bar{u}s)$	494	$1.2 \cdot 10^{-8}$	3.7 m
$K^0 (d\bar{s}, \bar{d}s)$	497	$5.1 \cdot 10^{-8}$ $8.9 \cdot 10^{-11}$	15.5 m 2.7 cm
$D^\pm (c\bar{d}, \bar{c}d)$	1869	$1.0 \cdot 10^{-12}$	315 μm
$D^0 (c\bar{u}, u\bar{c})$	1864	$4.1 \cdot 10^{-13}$	123 μm
$D_s^\pm (c\bar{s}, \bar{c}s)$	1969	$4.9 \cdot 10^{-13}$	147 μm
$B^\pm (u\bar{b}, \bar{b}u)$	5279	$1.7 \cdot 10^{-12}$	502 μm
$B^0 (b\bar{d}, d\bar{b})$	5279	$1.5 \cdot 10^{-12}$	462 μm
$B_s^0 (s\bar{b}, \bar{s}b)$	5370	$1.5 \cdot 10^{-12}$	438 μm
$B_c^\pm (c\bar{b}, \bar{c}b)$	~6400	$\sim 5 \cdot 10^{-13}$	150 μm
$p (uud)$	938.3	$> 10^{33}$ y	∞
$n (udd)$	939.6	885.7 s	$2.655 \cdot 10^8$ km
$\Lambda^0 (uds)$	1115.7	$2.6 \cdot 10^{-10}$	7.89 cm
$\Sigma^+ (uus)$	1189.4	$8.0 \cdot 10^{-11}$	2.404 cm
$\Sigma^- (dds)$	1197.4	$1.5 \cdot 10^{-10}$	4.434 cm
$\Xi^0 (uss)$	1315	$2.9 \cdot 10^{-10}$	8.71 cm
$\Xi^- (dss)$	1321	$1.6 \cdot 10^{-10}$	4.91 cm
$\Omega^- (sss)$	1672	$8.2 \cdot 10^{-11}$	2.461 cm
$\Lambda_c^+ (udc)$	2285	$\sim 2 \cdot 10^{-13}$	60 μm
$\Xi_c^+ (usc)$	2466	$4.4 \cdot 10^{-13}$	132 μm
$\Xi_c^0 (dcs)$	2472	$\sim 1 \cdot 10^{-13}$	29 μm
$\Omega_c^0 (ssc)$	2698	$6.0 \cdot 10^{-14}$	19 μm
$\Lambda_b (udb)$	5620	$1.2 \cdot 10^{-12}$	368 μm

"Secondary Vertices" ($D^\pm$ through $B_c^\pm$)

From the 'hundreds' of Particles listed by the PDG there are only ~27 with a life time $c\tau >\sim 1\mu m$ i.e. they can be seen as 'tracks' in a Detector.

~13 of the 27 have $c\tau < 500\mu m$ i.e. only ~mm range at GeV Energies.
→ "short" tracks measured with Emulsions or Vertex Detectors.

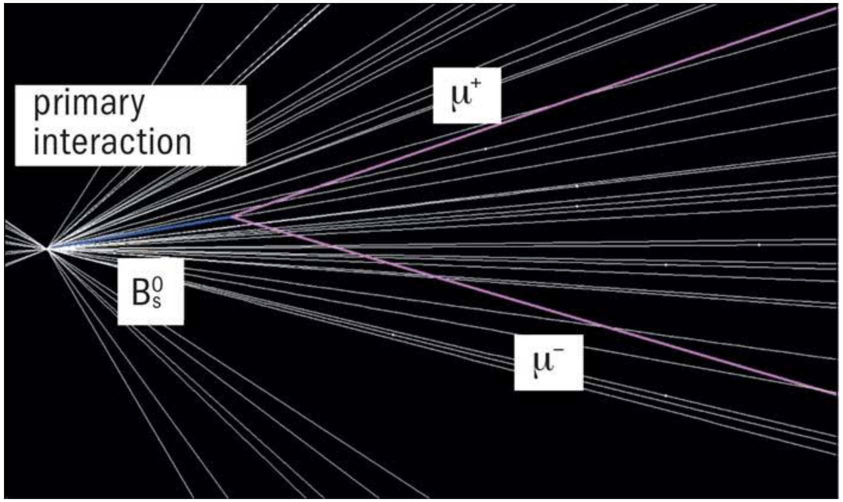
From the ~14 remaining particles

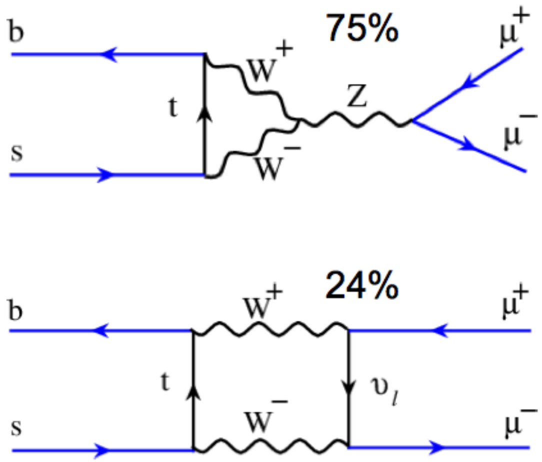
$e^\pm, \mu^\pm, \gamma, \pi^\pm, K^\pm, K^0, p^\pm, n$

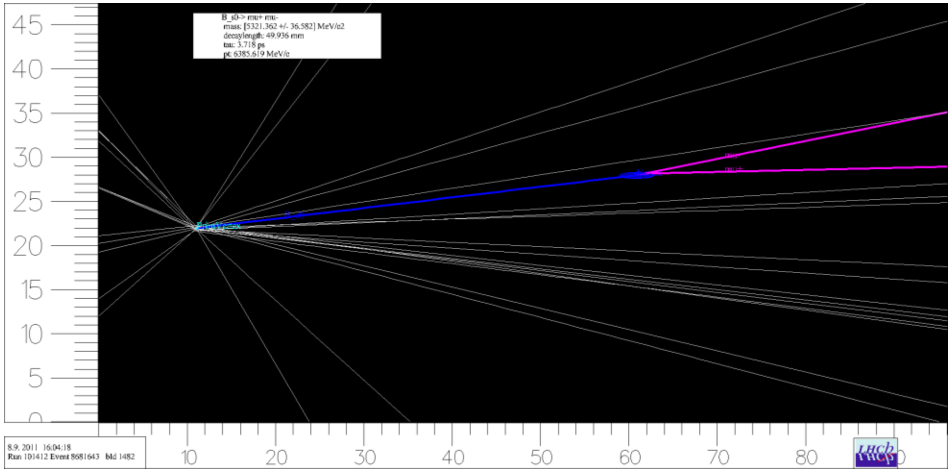
are by far the most frequent ones

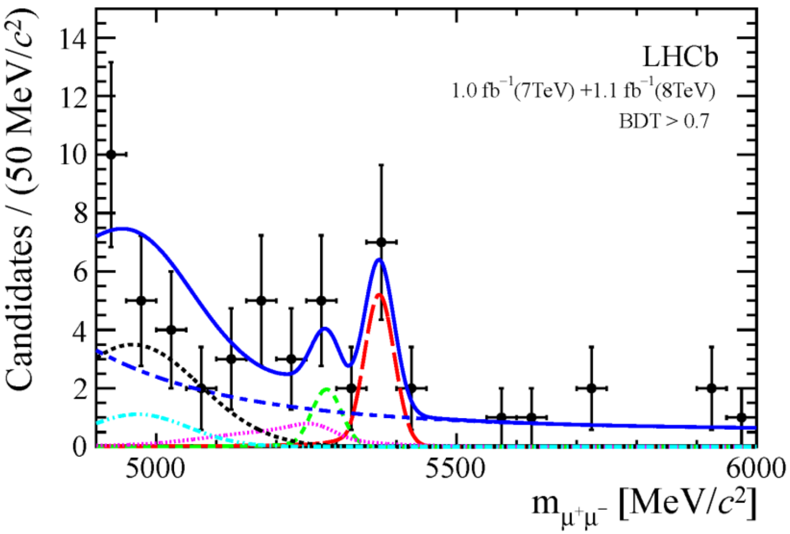
A particle Detector must be able to identify and measure Energy and Momenta of these 8 particles.

LHCb B decay, displaced Vertex









$e^{\pm}$ $m_e = 0.511$ MeV

$\mu^{\pm}$ $m_\mu = 105.7$ MeV $\sim 200\, m_e$

γ $m_\gamma = 0$, $Q = 0$

} EM

$\pi^{\pm}$ $m_\pi = 139.6$ MeV $\sim 270\, m_e$

$K^{\pm}$ $m_K = 493.7$ MeV $\sim 1000\, m_e$ $\sim 3.5\, m_\pi$

$p^{\pm}$ $m_p = 938.3$ MeV $\sim 2000\, m_e$

} EM, Strong

K^0 $m_{K^0} = 497.7$ MeV $Q = 0$

n $m_n = 939.6$ MeV $Q = 0$

} Strong

The Difference in

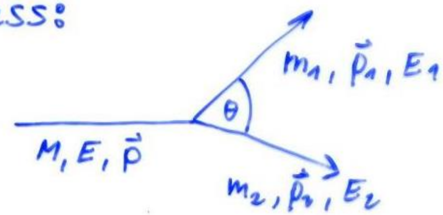
Mass, Charge, Interaction

is the key to the Identification

Basics

Invariant Mass:

LAB:



Relativity: $\tilde{a} = \begin{pmatrix} a_0 \\ \vec{a} \end{pmatrix}$ $\tilde{b} = \begin{pmatrix} b_0 \\ \vec{b} \end{pmatrix}$ $\tilde{a}\tilde{b} = a_0 b_0 - \vec{a}\vec{b}$

$$E = mc^2\gamma \ , \quad \vec{p} = m\vec{v}\gamma$$

$$\tilde{p} = \begin{pmatrix} \frac{E}{c} \\ \vec{p} \end{pmatrix} \ , \quad \tilde{p}_1 = \begin{pmatrix} \frac{E_1}{c} \\ \vec{p}_1 \end{pmatrix} \ , \quad \tilde{p}_2 = \begin{pmatrix} \frac{E_2}{c} \\ \vec{p}_2 \end{pmatrix}$$

$\tilde{p} = \tilde{p}_1 + \tilde{p}_2$ Energy + Momentum Conservation

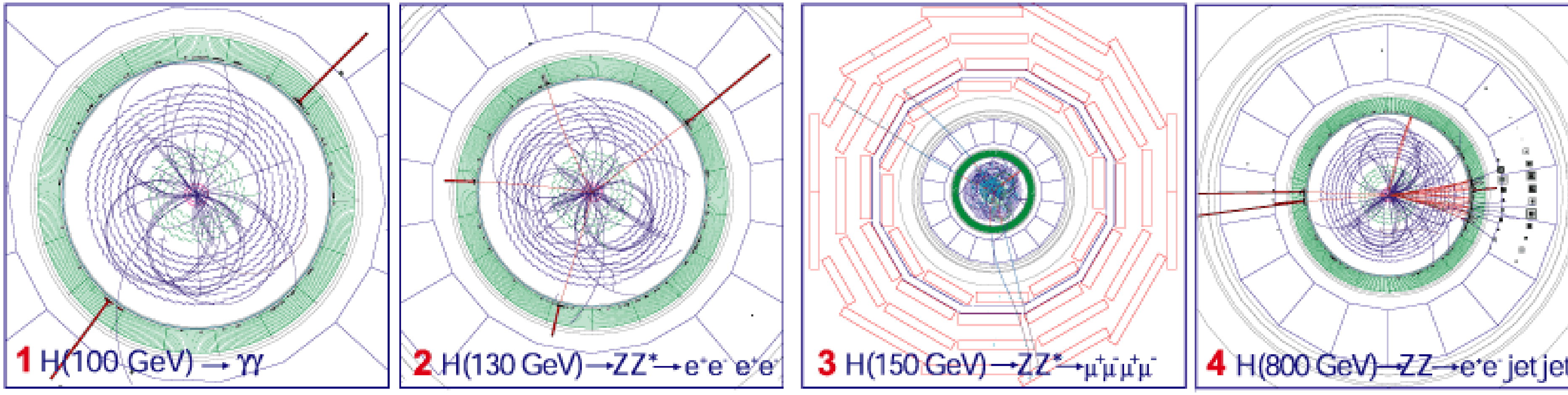
$$\tilde{p}^2 = (\tilde{p}_1 + \tilde{p}_2)^2 \rightarrow \tilde{p}\tilde{p} = \tilde{p}_1\tilde{p}_1 + \tilde{p}_2\tilde{p}_2 + 2\tilde{p}_1\tilde{p}_2$$

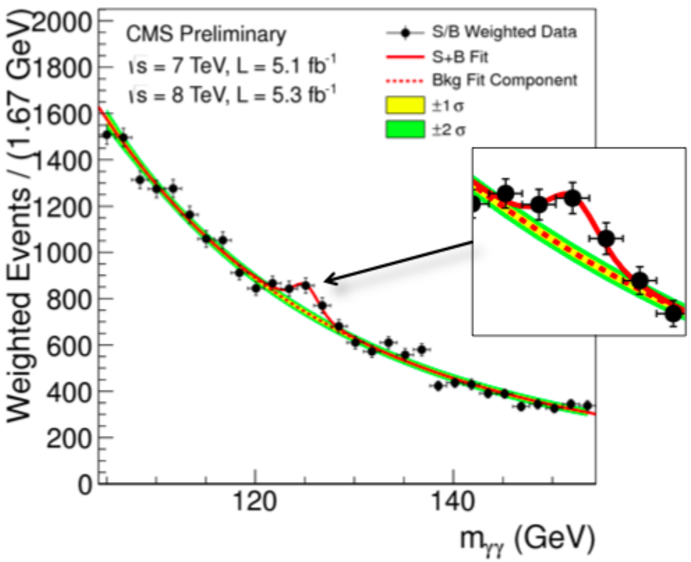
$$M^2c^2 = m_1^2c^2 + m_2^2c^2 + 2\left(\frac{E_1E_2}{c^2} - p_1p_2\cos\theta\right)$$

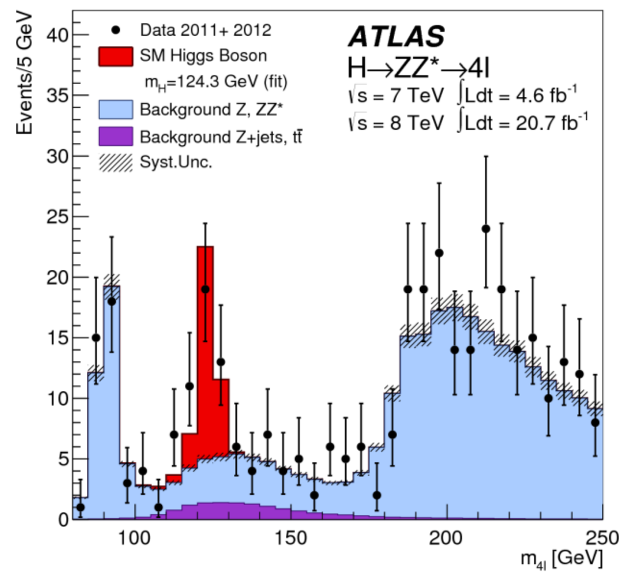
- Measuring Momenta and Energies OR
- Measuring Momenta and identifying Particles

gives the Mass of the original Particle

Simulated Higgs Boson at CMS



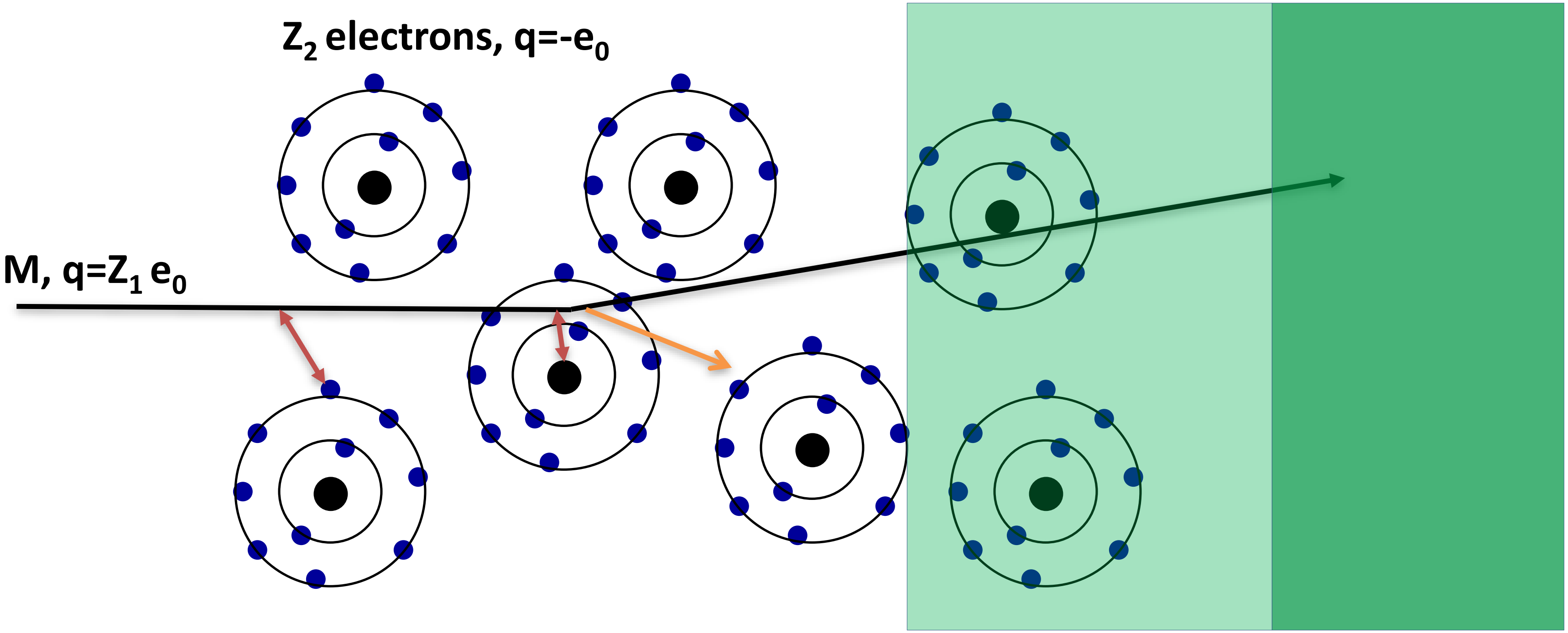




Particle seen as an excess of two photon events above the irreducible background.

W. Riegler/CE

Electromagnetic Interaction of Particles with Matter

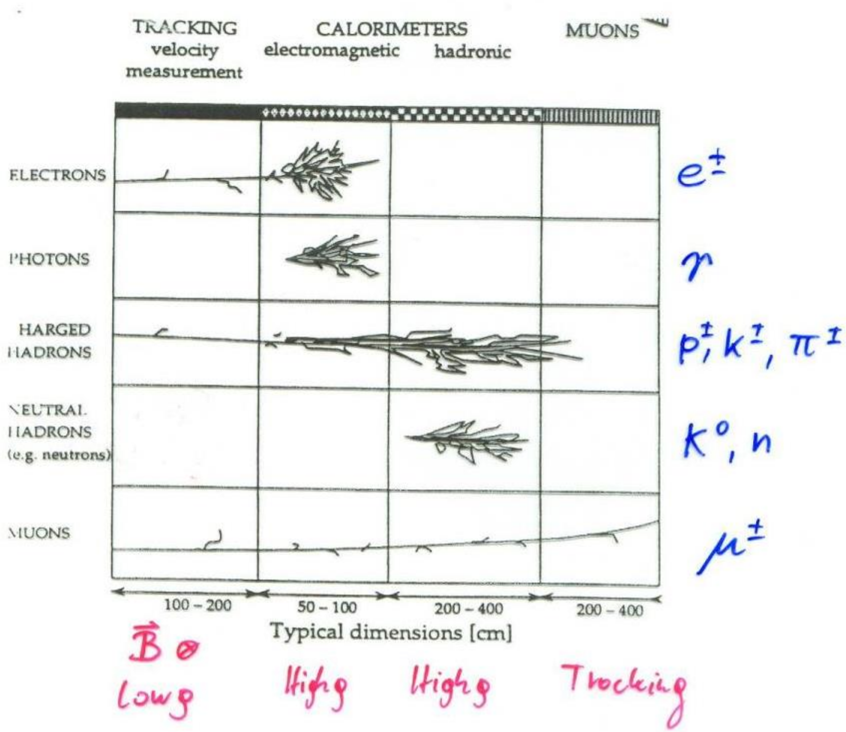


Interaction with the atomic electrons. The incoming particle loses energy and the atoms are excited or ionized.

Interaction with the atomic nucleus. The particle is deflected (scattered) causing multiple scattering of the particle in the material. During this scattering a Bremsstrahlung photon can be emitted.

In case the particle's velocity is larger than the velocity of light in the medium, the resulting EM shockwave manifests itself as Cherenkov Radiation. When the particle crosses the boundary between two media, there is a probability of the order of 1% to produced and X ray photon, called Transition radiation.

Task of a Particle Detector

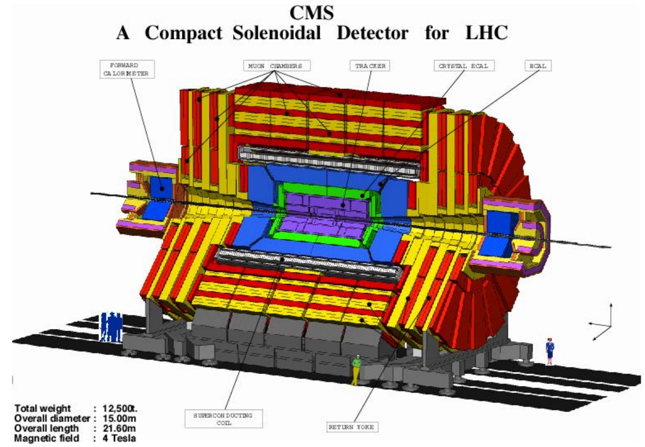


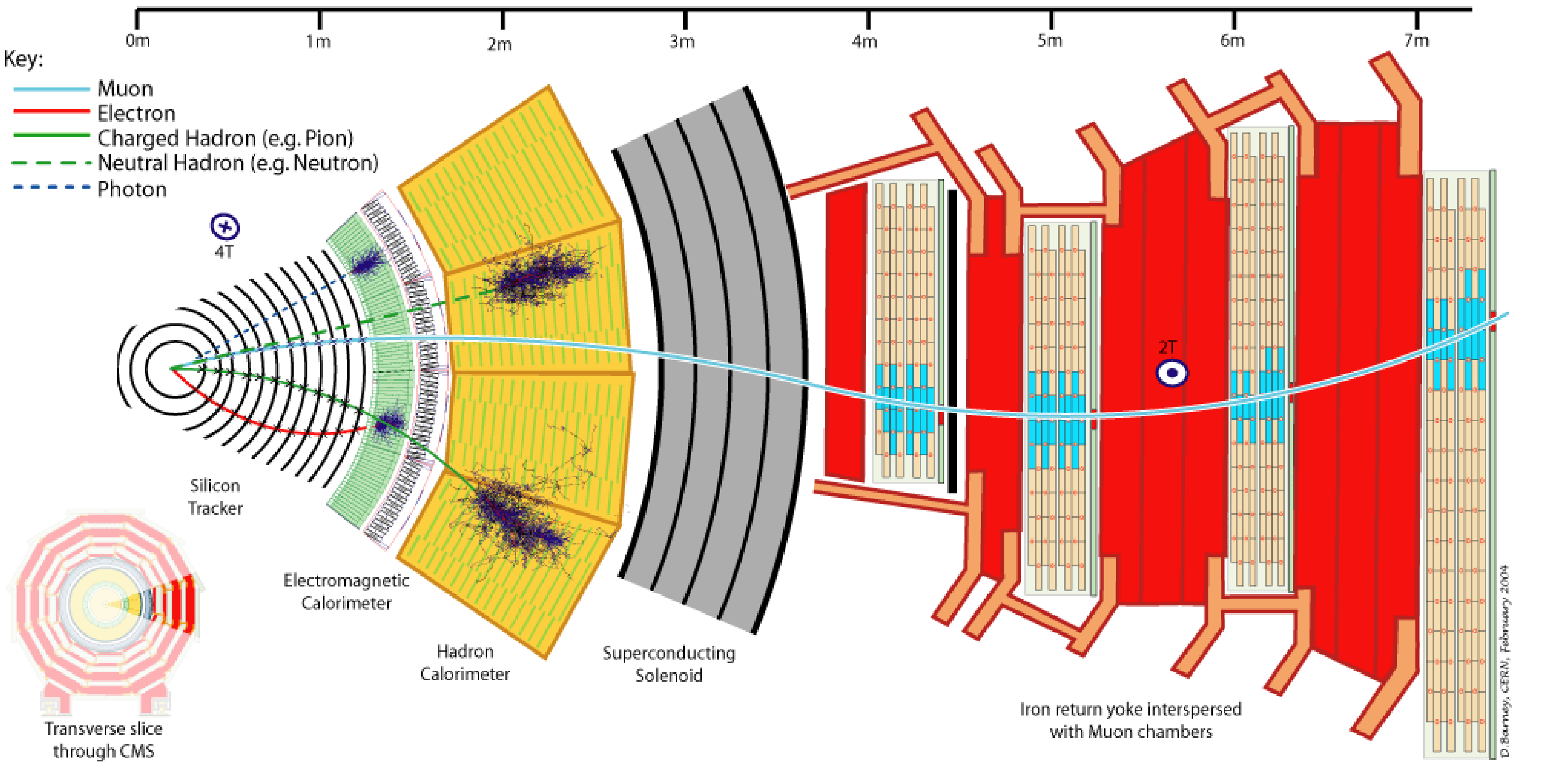
- Electrons ionize and show Bremsstrahlung due to the small mass
- Photons don't ionize but show Pair Production in high Z Material. From then on equal to $e^\pm$
- Charged Hadrons ionize and show Hadron Shower in dense material.
- Neutral Hadrons don't ionize and show Hadron Shower in dense Material
- Muons ionize and don't shower

Electron, Muon, Photon

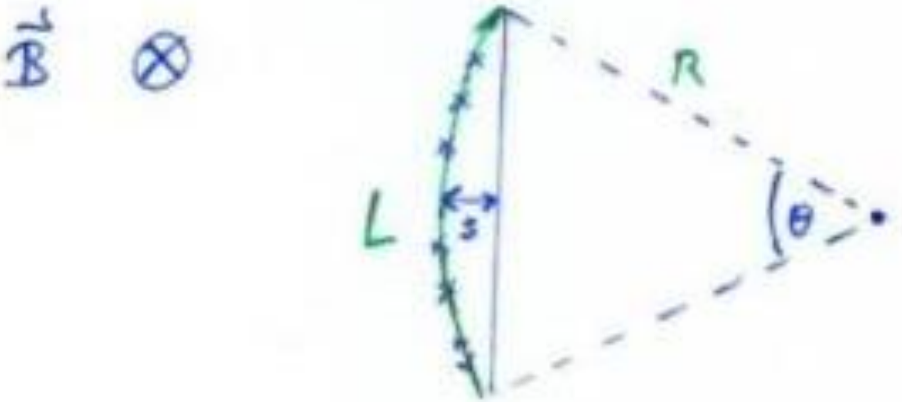
Pion, Charged Kaon, Proton

Neutral Kaon, Neutron





W. Riegler/CERN



$$p = q \cdot R \cdot B$$

$$p\left[\frac{GeV}{c}\right] = 0.3\, R[m]\, B[T]$$

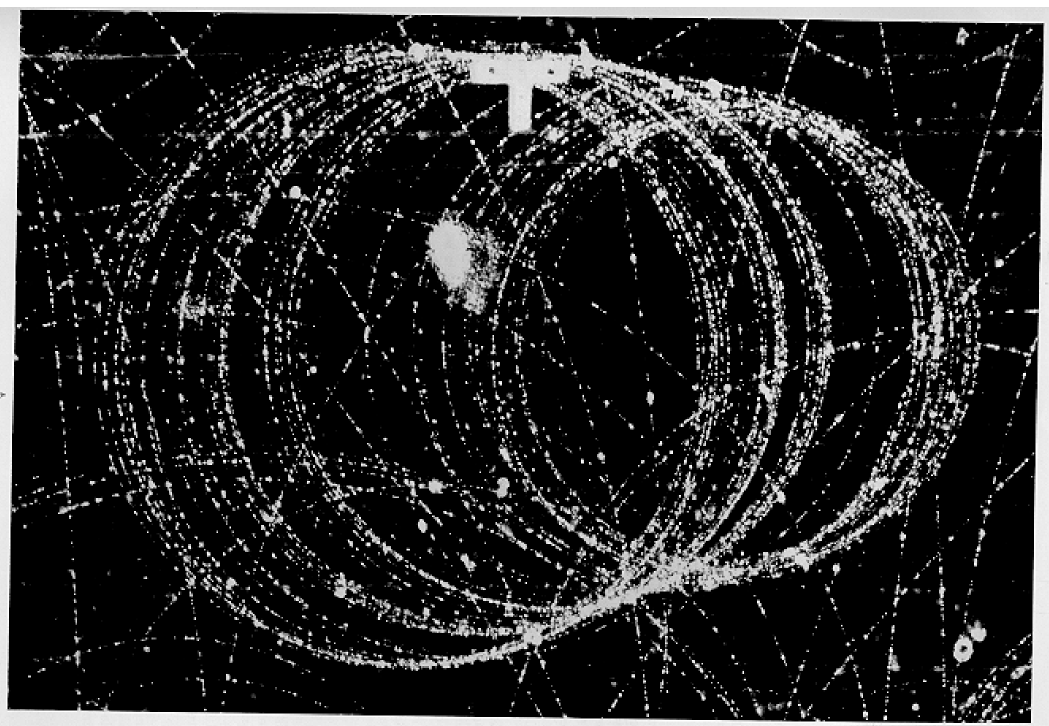


Fig. 43. Radiation Laboratory, Berkeley, Cal.

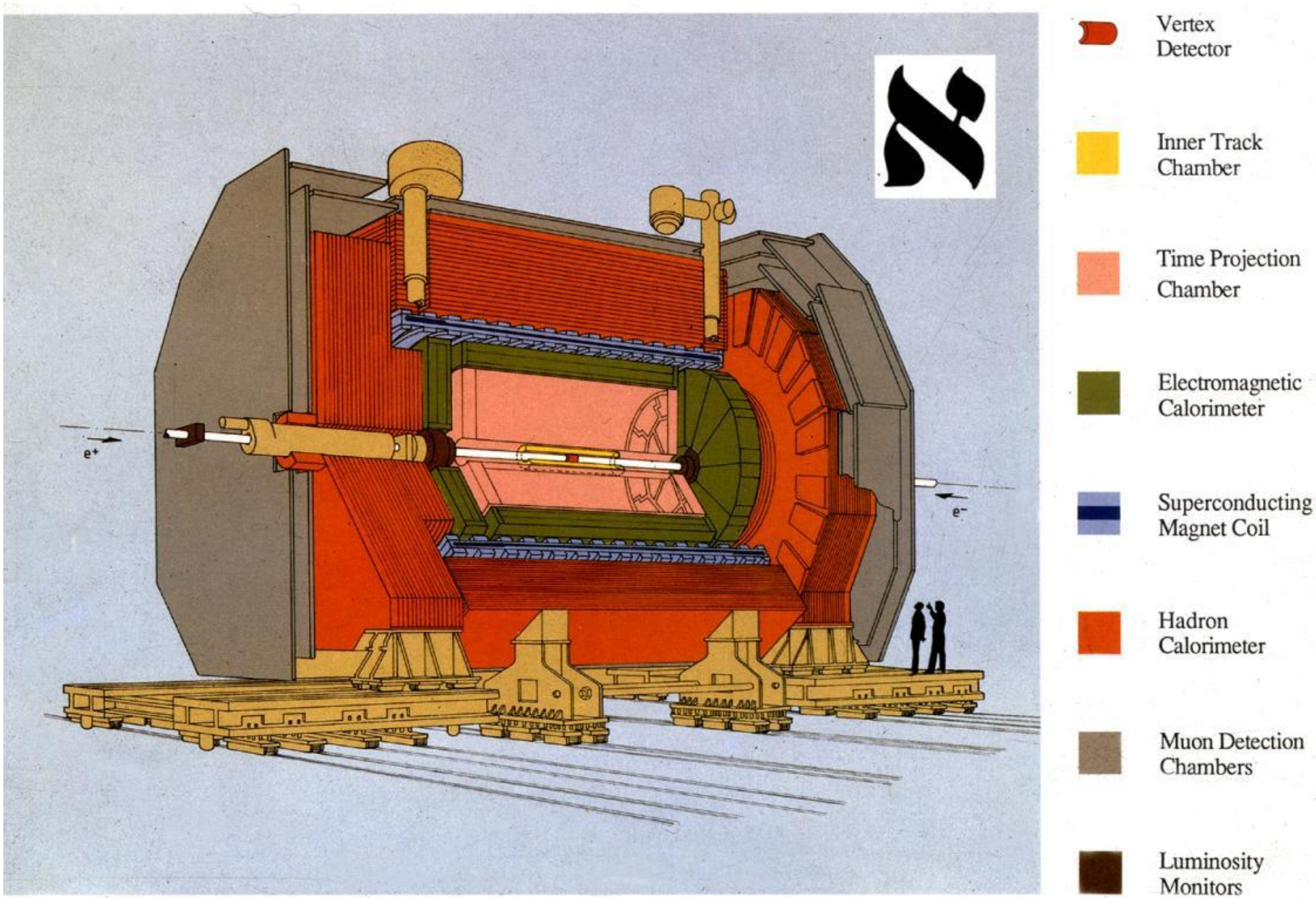
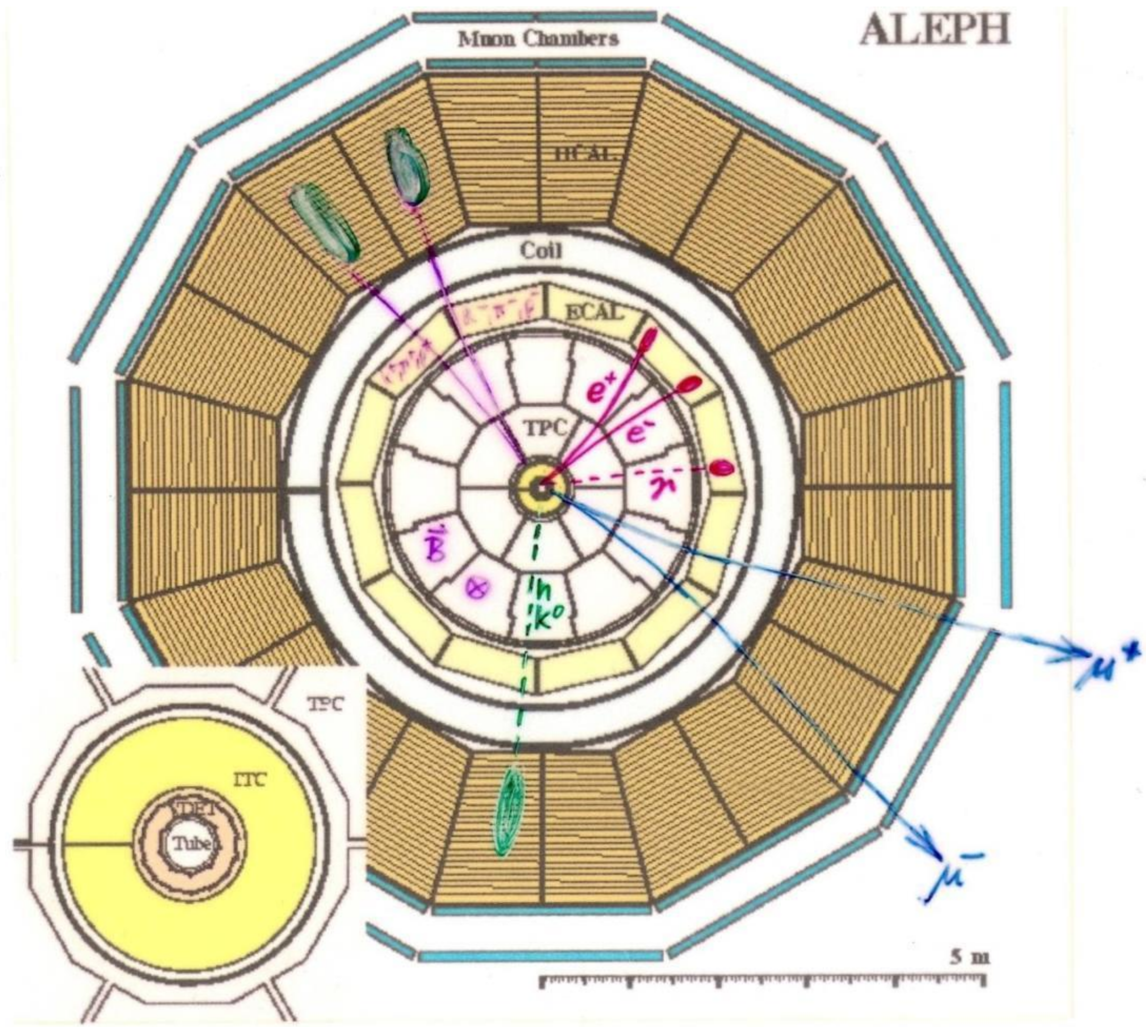


Fig. 1 - The ALEPH Detector

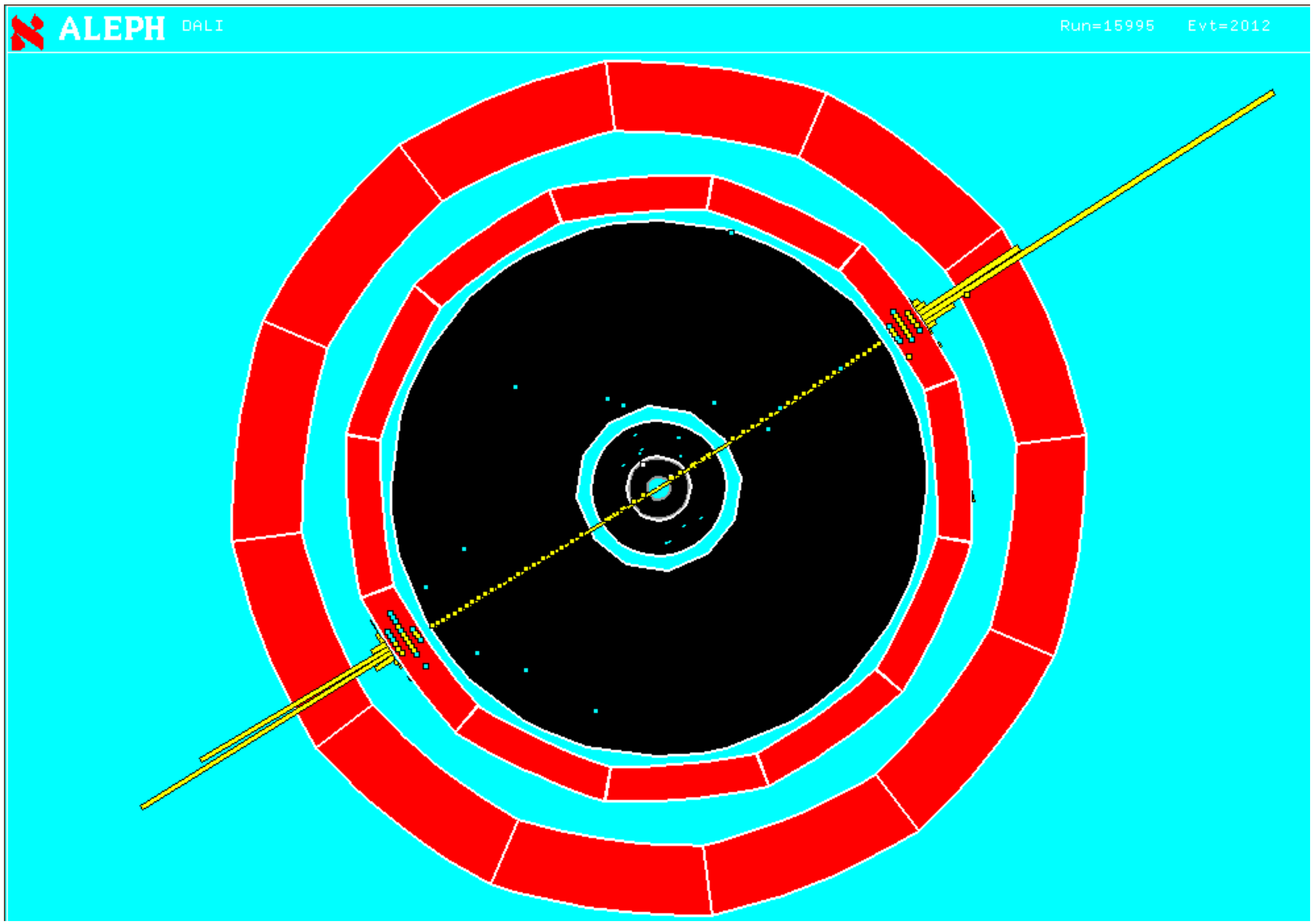
γ, $e^{\pm}$, $\pi^{\pm}$, $K^{\pm}$

K^0, p, n, $\mu^{\pm}$



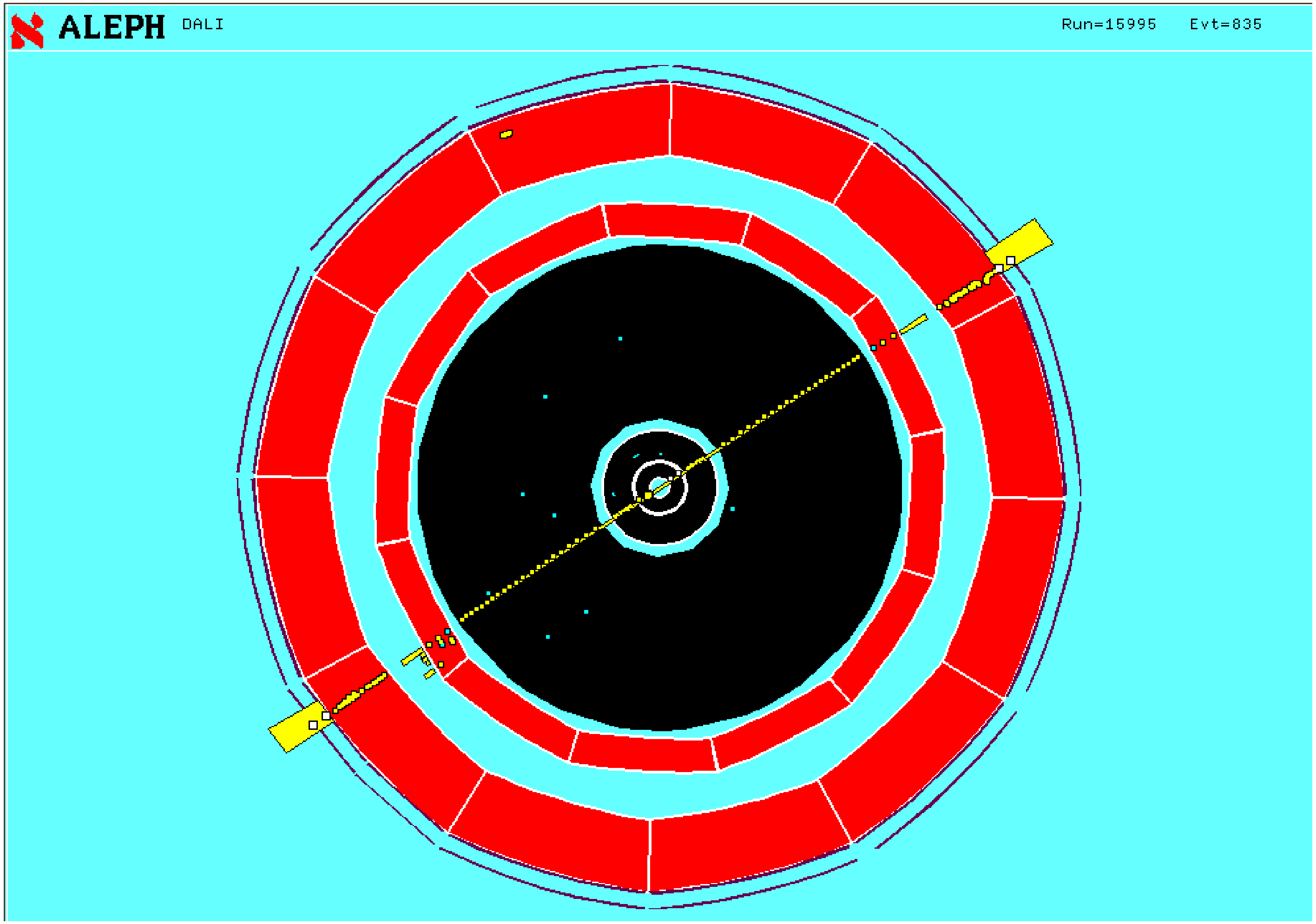
$Z \rightarrow e^+ e^-$

Two high momentum charged particles depositing energy in the Electro Magnetic Calorimeter



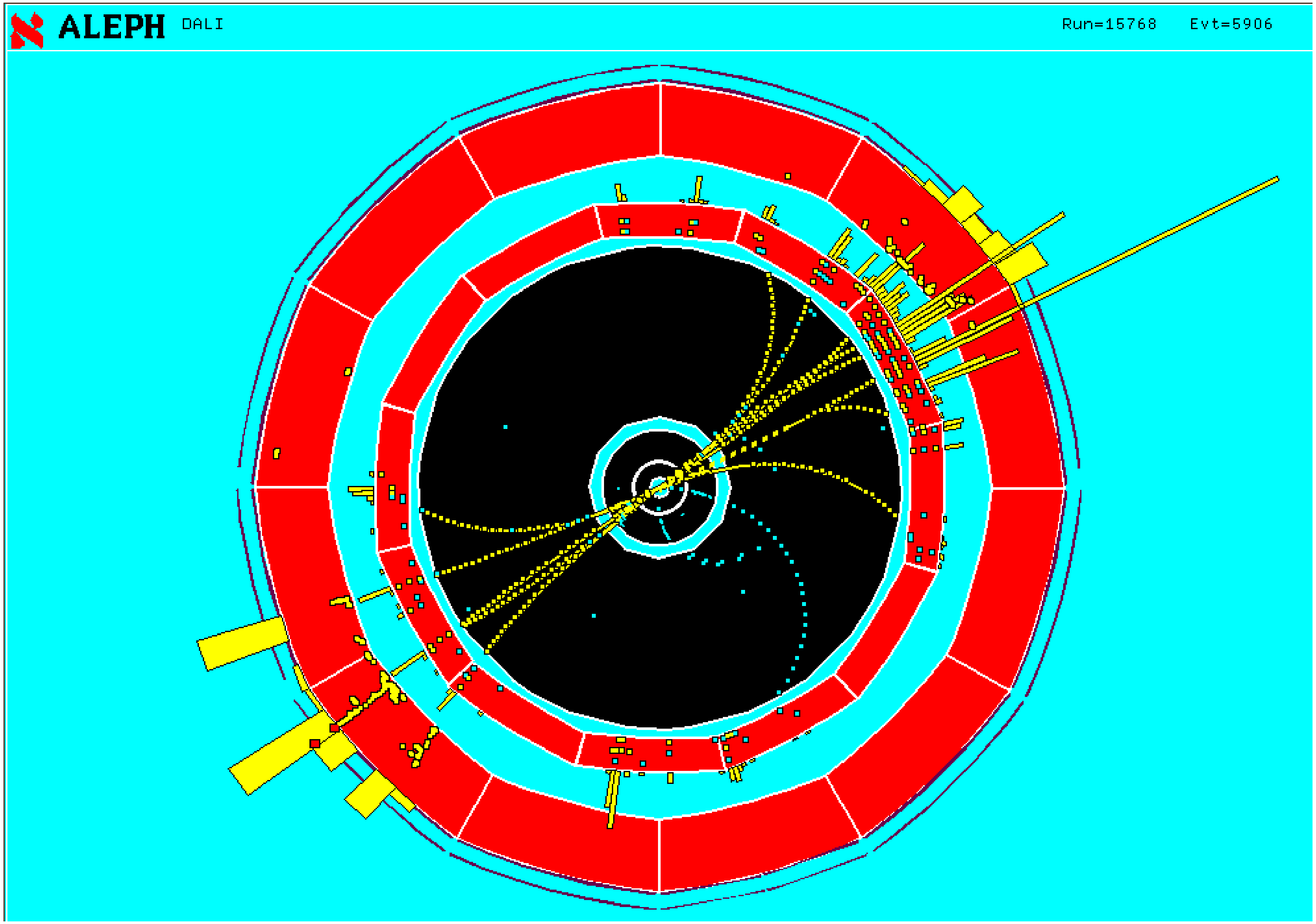
$Z \rightarrow \mu^+ \mu^-$

Two high momentum charged particles traversing all calorimeters and leaving a signal in the muon chambers.



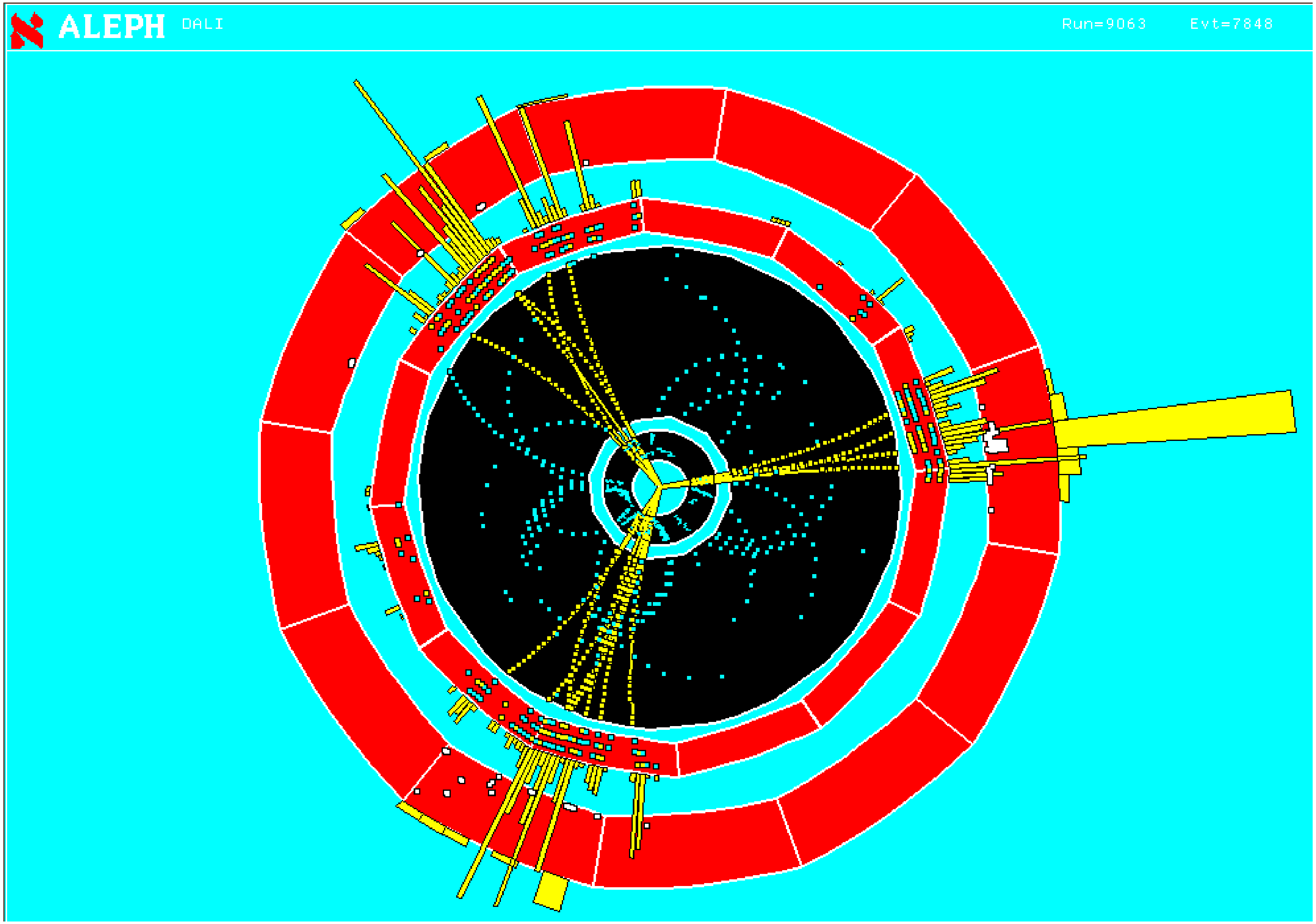
$Z \rightarrow q\bar{q}$

Two jets of particles



$Z \rightarrow q\bar{q}g$

Three jets of particles



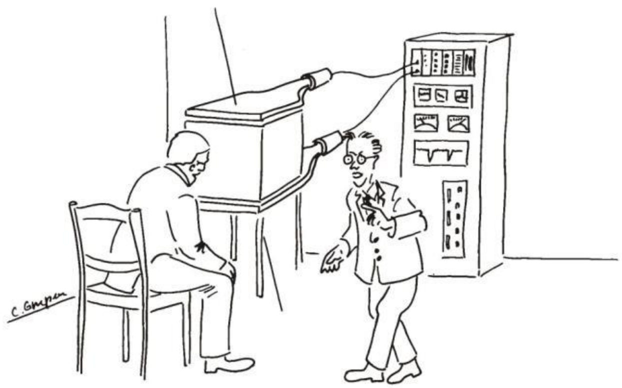
Interaction of Particles with Matter

Any device that is to detect a particle must interact with it in some way → almost …

In many experiments neutrinos are measured by missing transverse momentum.

E.g. e^+e^- collider. $P_{tot}=0$,

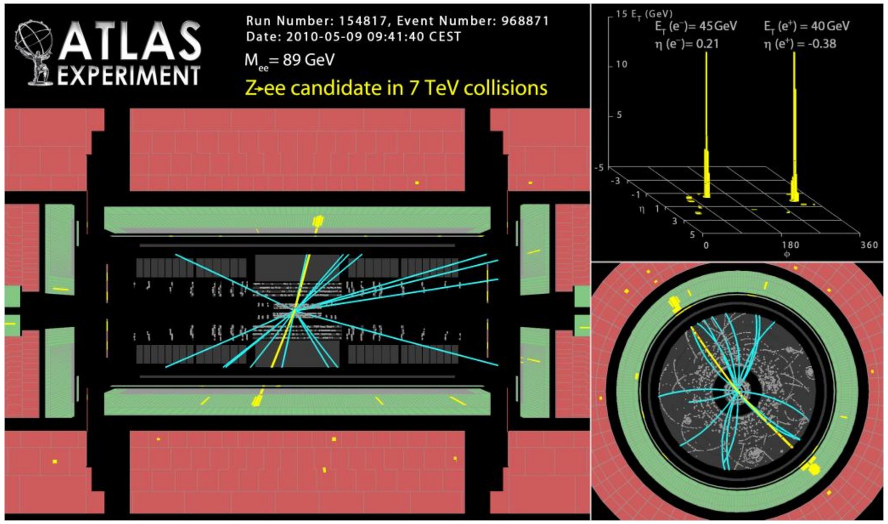
If the $\Sigma\, p_i$ of all collision products is $\neq 0$ → neutrino escaped.

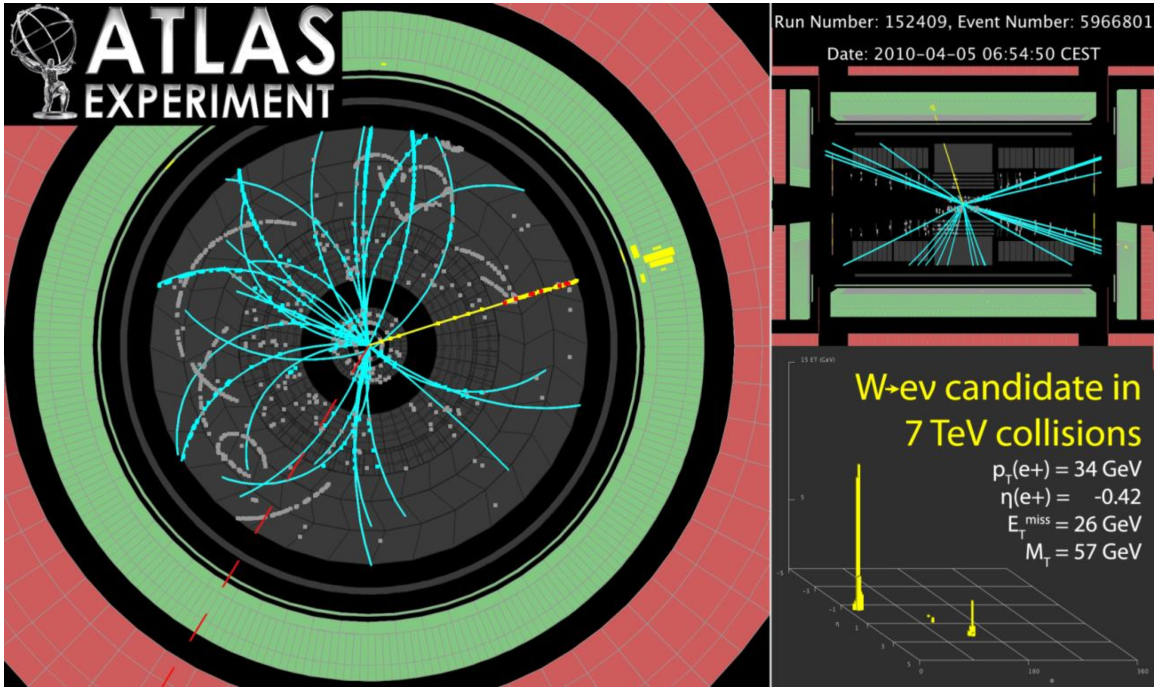


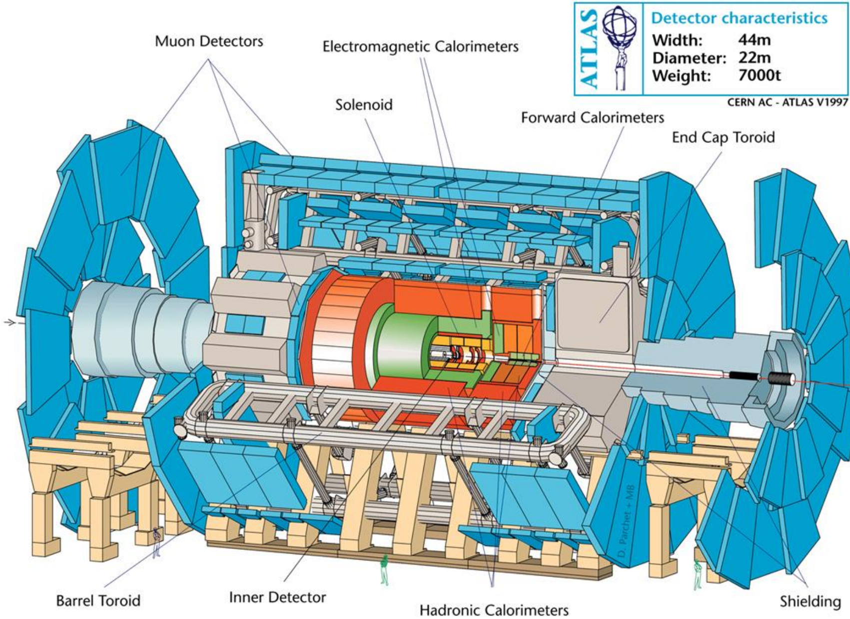
"Did you see it?"
"No nothing."
"Then it was a neutrino!"

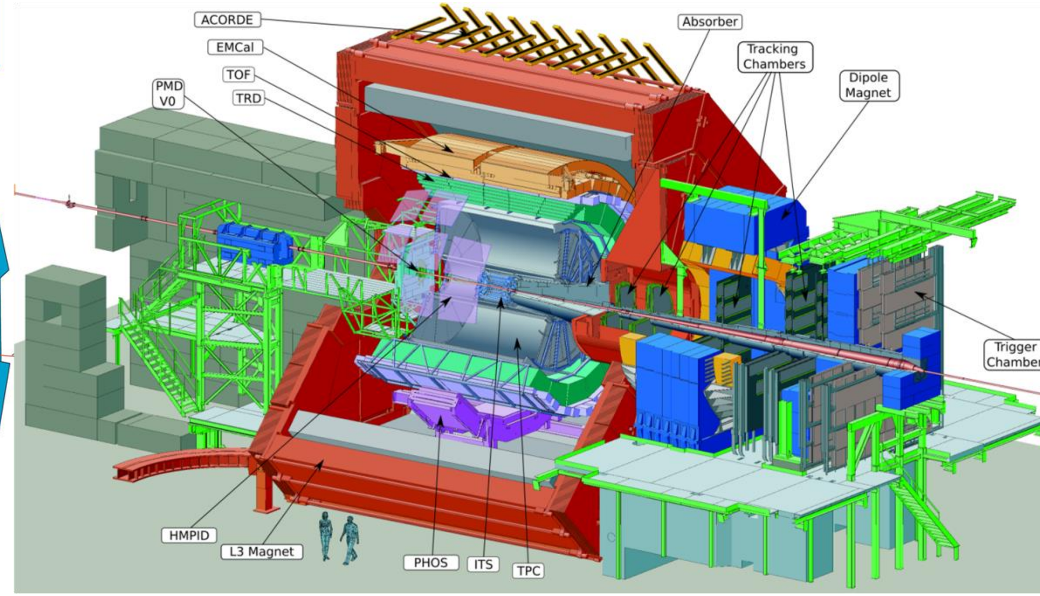
Claus Grupen, Particle Detectors, Cambridge University Press, Cambridge 1996 (455 pp. ISBN 0-521-55216-8)

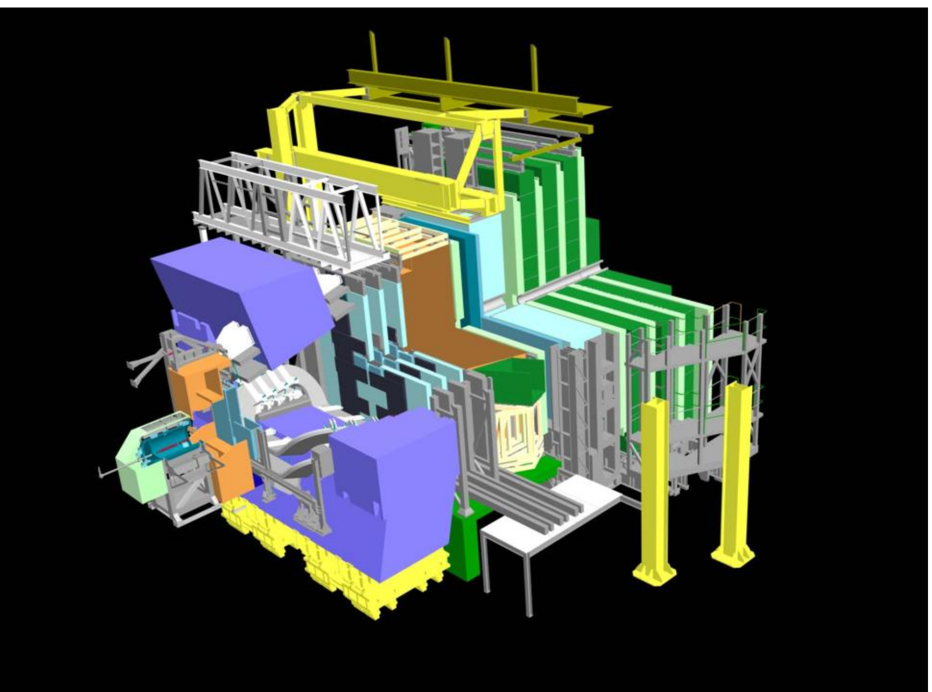
ATLAS W, Z particles !

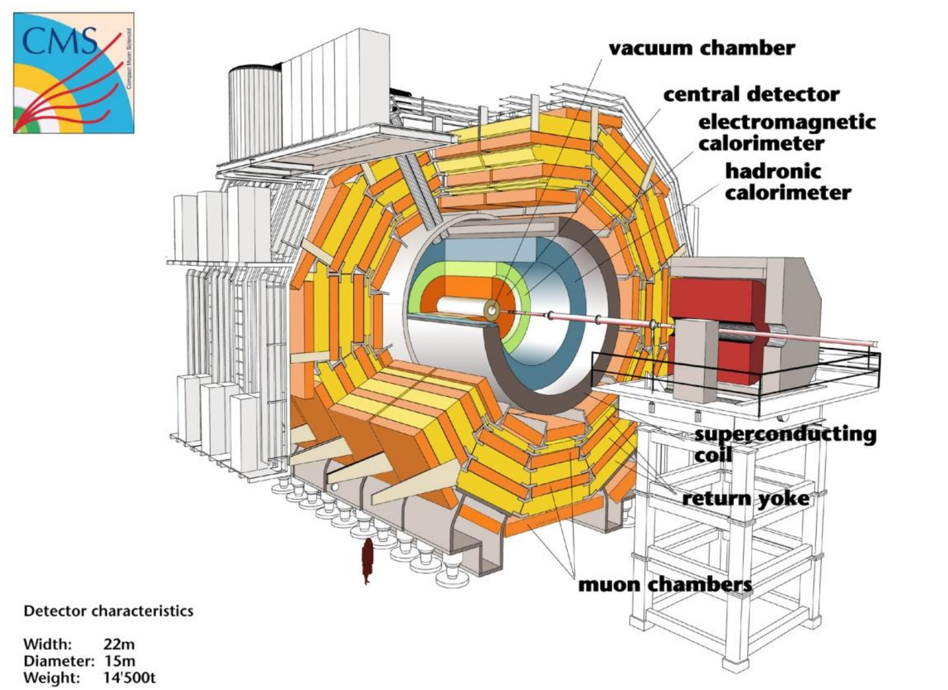





ATLAS
Detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t
CERN AC - ATLAS V1997
Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding


ACORDE
EMCal
TOF
TRD
PMD
V0
Absorber
Tracking Chambers
Dipole Magnet
Trigger Chamber
HMPID
L3 Magnet
PHOS
ITS
TPC




CMS
vacuum chamber
central detector
electromagnetic calorimeter
hadronic calorimeter
superconducting coil
return yoke
muon chambers
Detector characteristics
Width: 22m
Diameter: 15m
Weight: 14'500t

Tracker:

Charged particles are bent in the magnetic field.

Positive and negative particles are bent in opposite directions.

The bending radius measures the particle's momentum.

The task of the tracker is to measure the curved particle track.

When particles traverse material they are deflected, which reduces the accuracy of the momentum measurement.

The beampipe and the tracker must be built with as little (thin) material as possible !!

Neutral particles are not bent in the magnetic field and do not leave a trace in the tracker.

Calorimeter:

The calorimeter fully absorbs a particle and measures it's energy.

Calorimeters are built from very heavy materials in order to absorb the particles in the shortest possible distance.

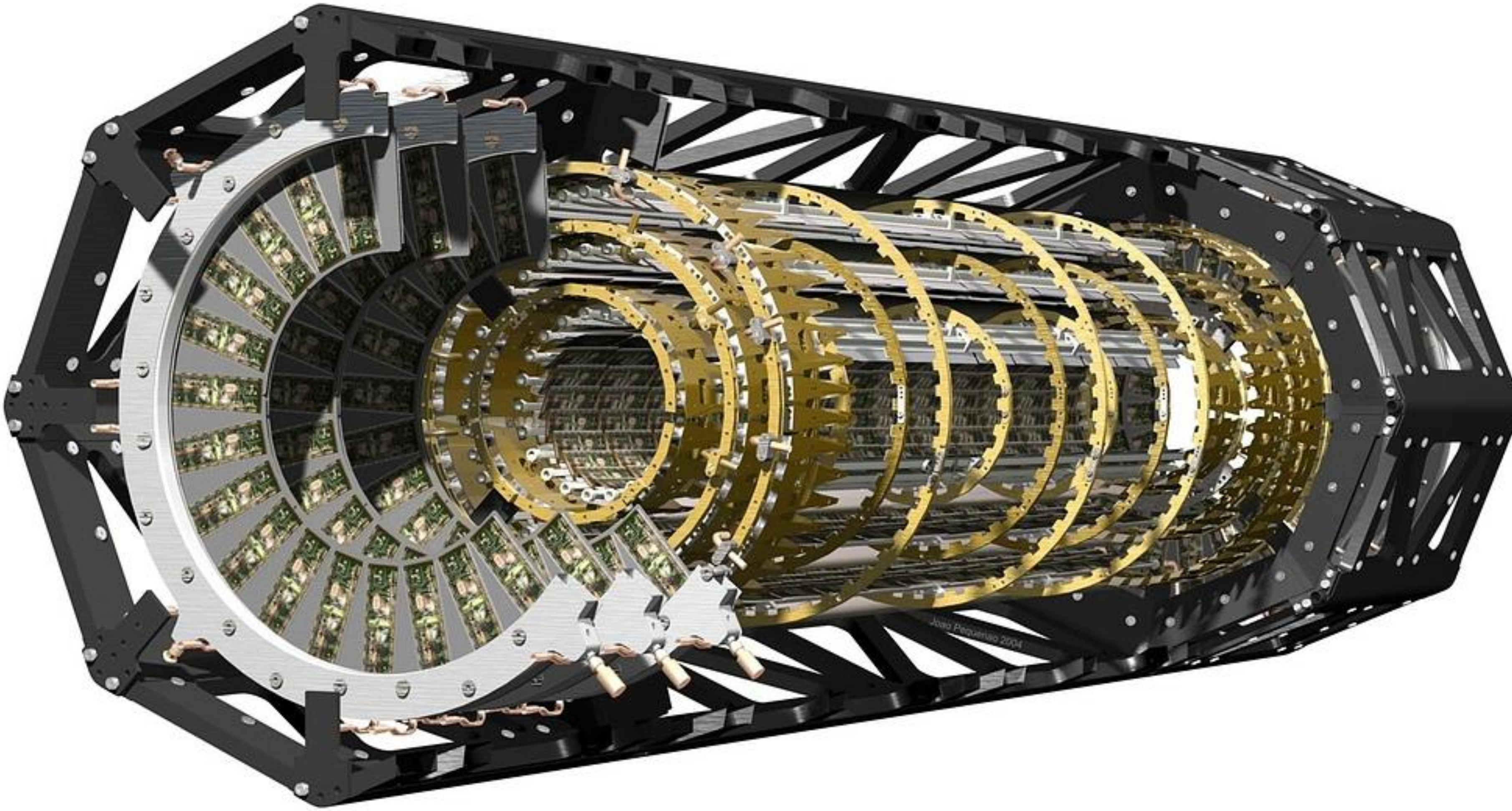
Electrons and photons are absorbed over very short distances due to there small mass → Electromagnetic Calorimeter.

The hadrons need much more material thickness to be absorbed → Hadron Calorimeter.

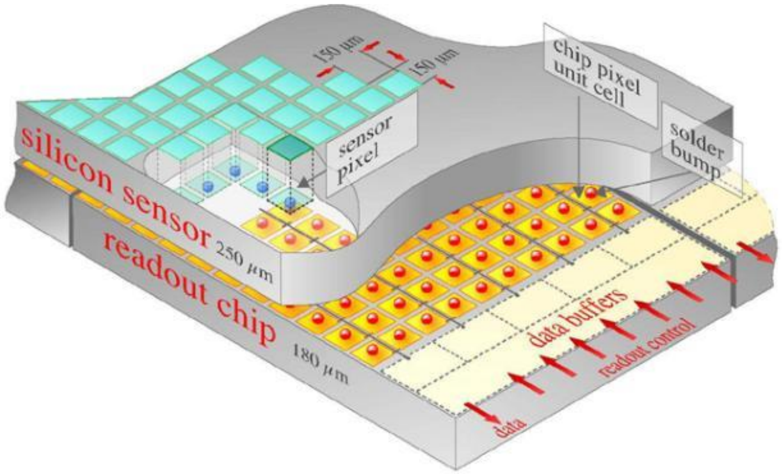
Muon system

Muons are the only particles that manage to go through the hadron calorimeter.

ATLAS Silicon Pixel Detector

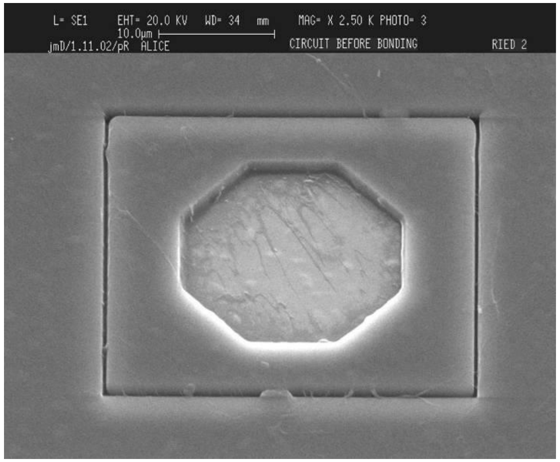


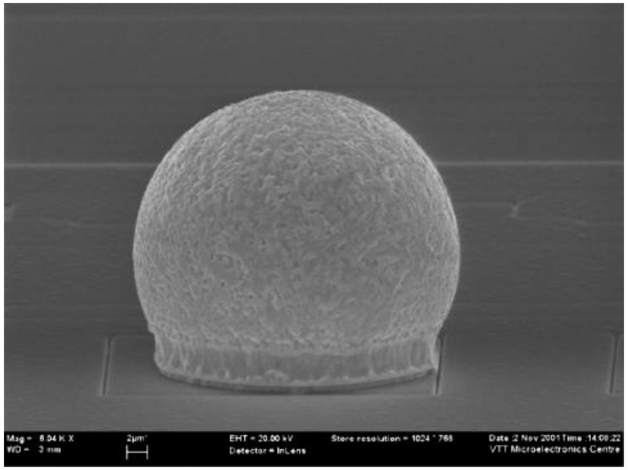
Silicon Pixel Detectors



ATLAS: 1.4x10^{8} pixels

40 000 000 'images' per second.

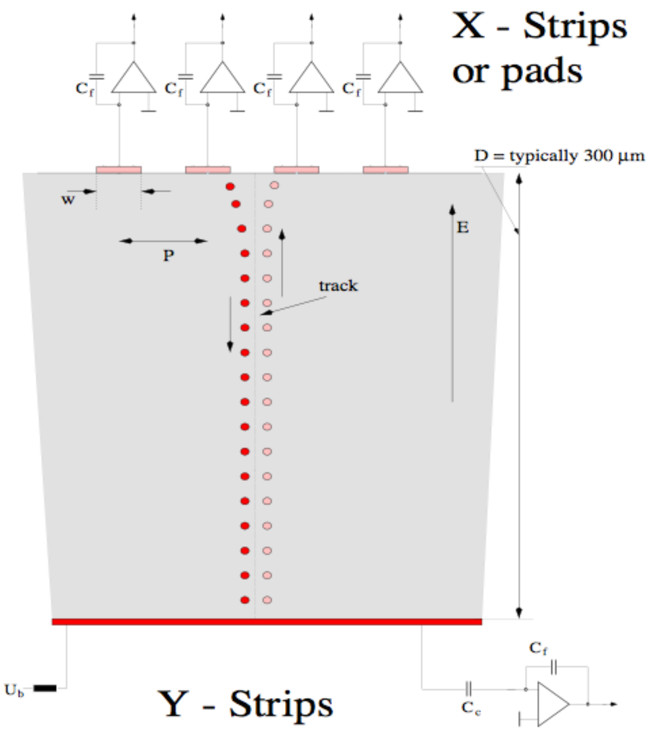




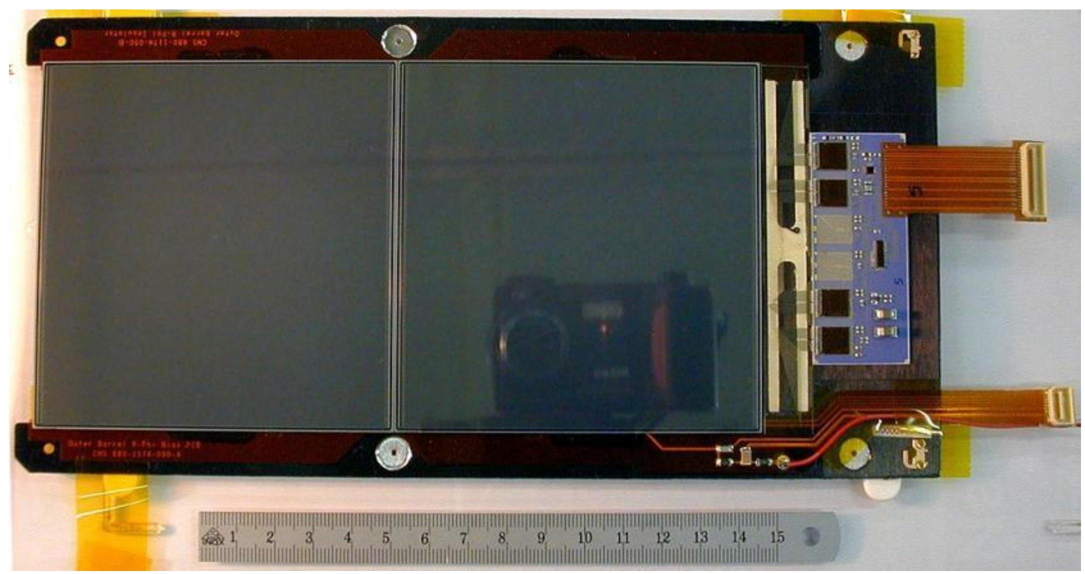
Silicon Strip Detectors

Every electrode is connected to an amplifier →
Highly integrated readout electronics.

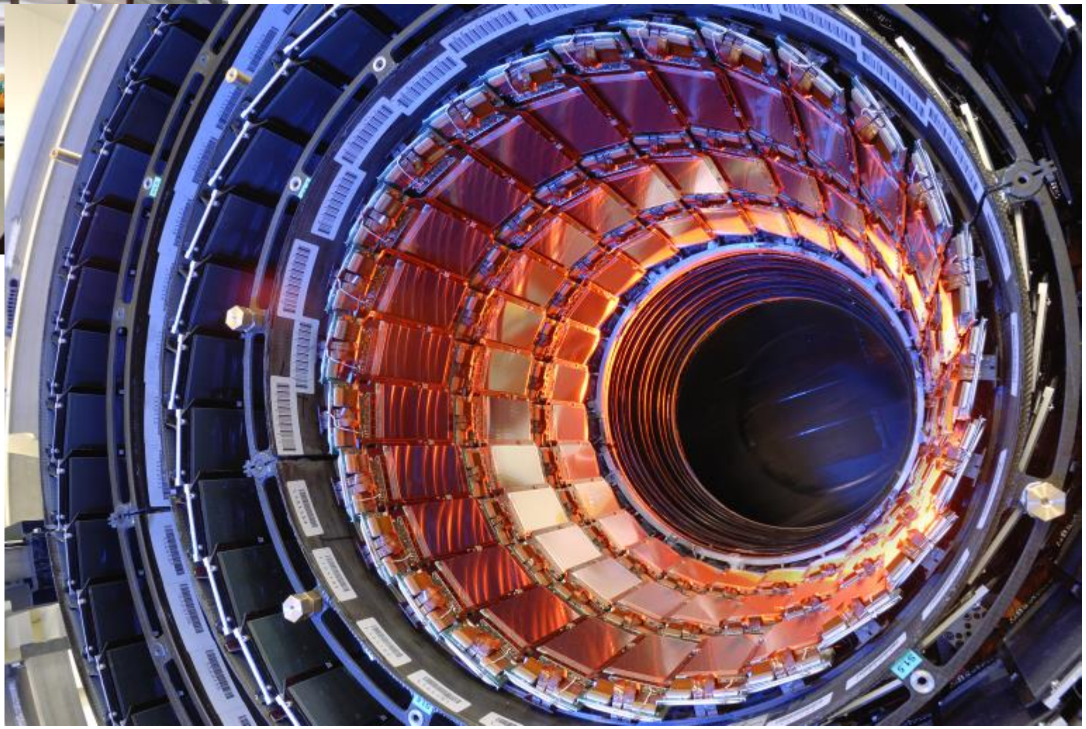
Two dimensional readout is possible.



CMS Outer Barrel Module



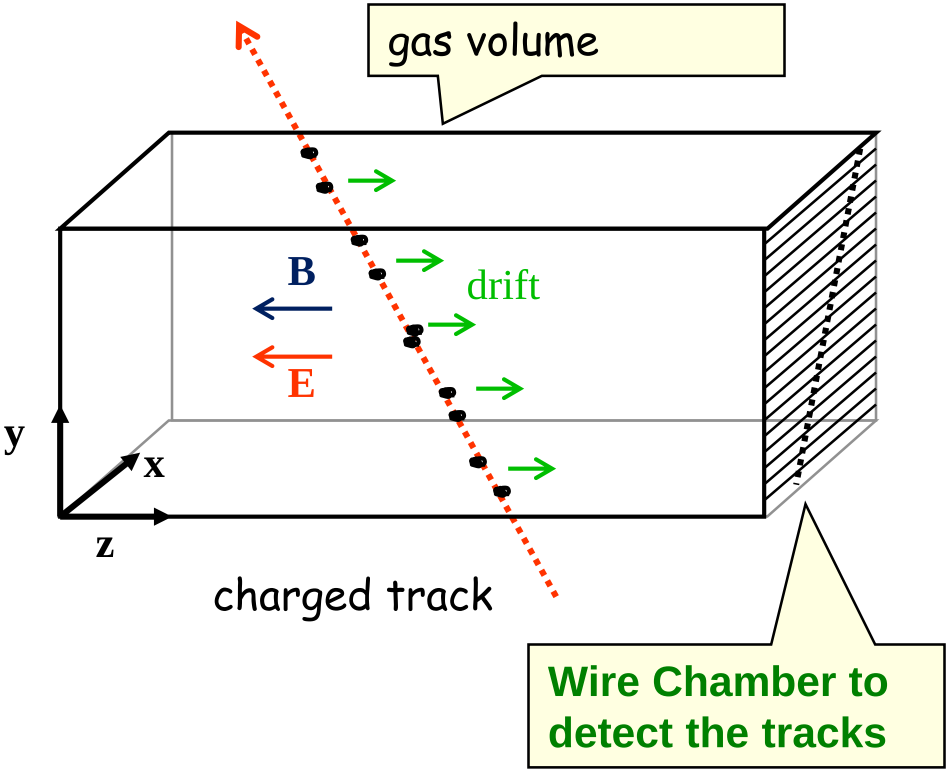
Silicon Strip Detectors

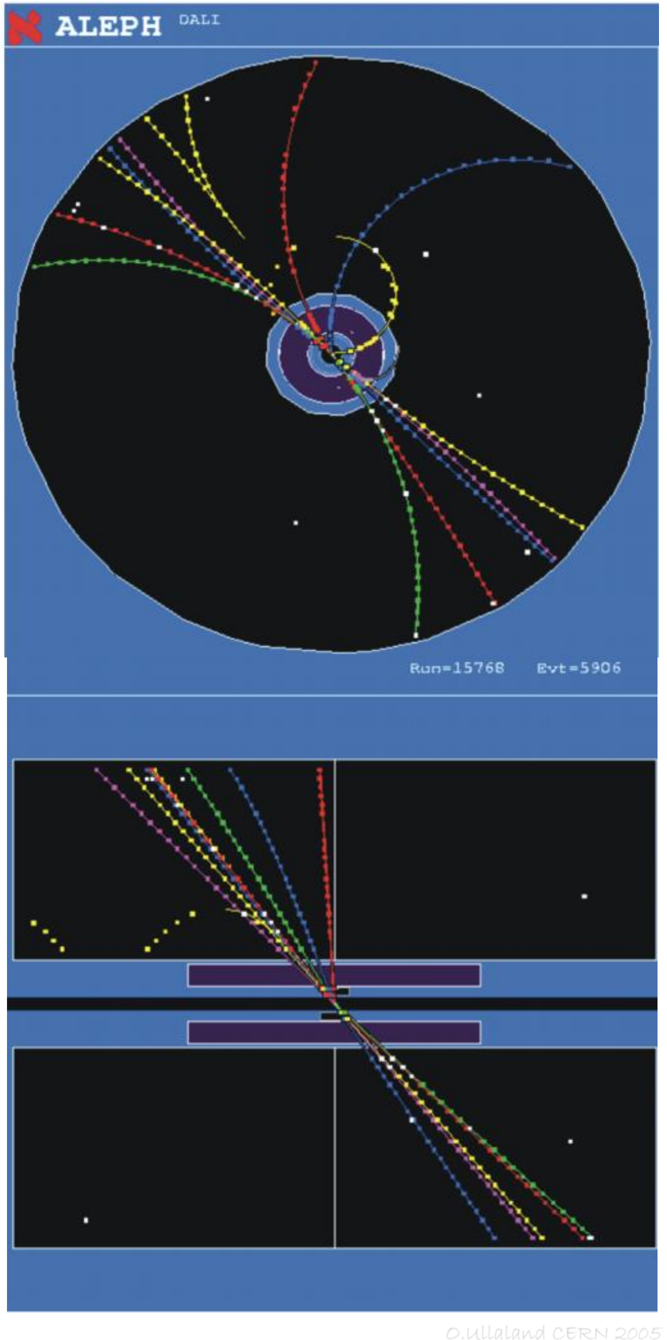


Time Projection Chamber (TPC):

Gas volume with parallel E and B Field.
B for momentum measurement. Positive effect: Diffusion is strongly reduced by E//B (up to a factor 5).

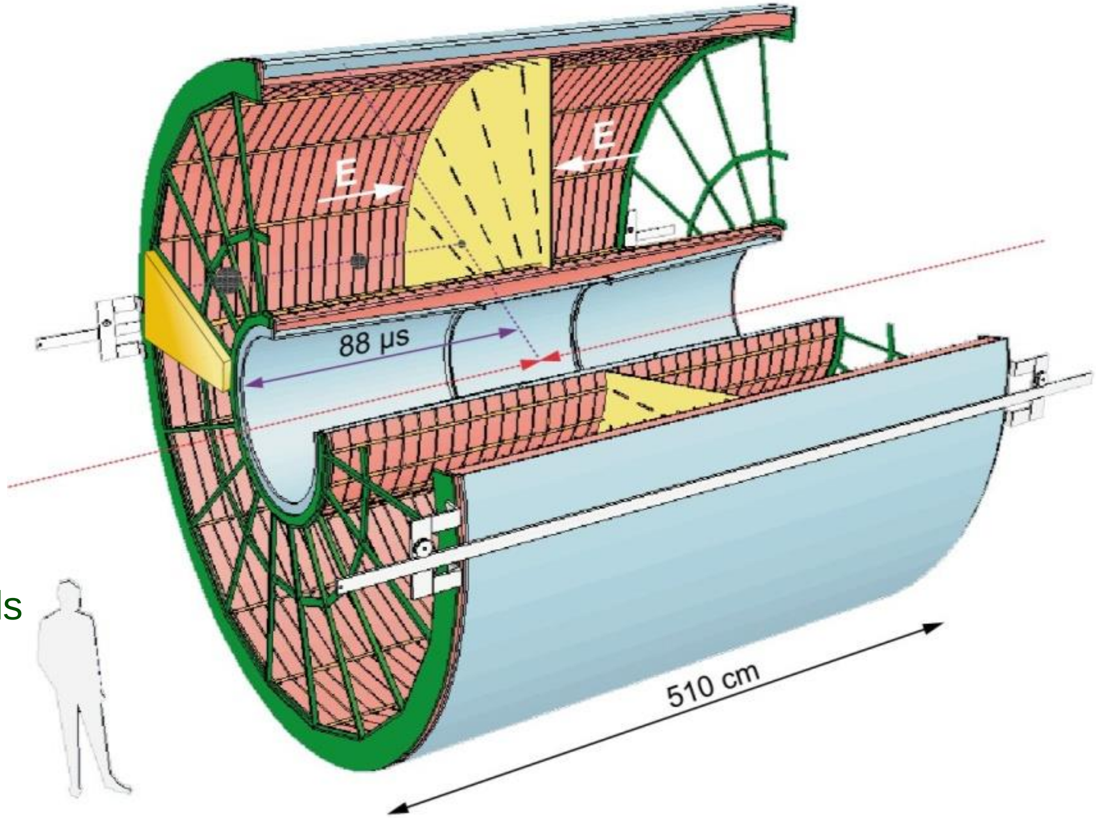
Drift Fields 100-400V/cm. Drift times 10-100 μs.
Distance up to 2.5m !





ALICE TPC: Construction Parameters

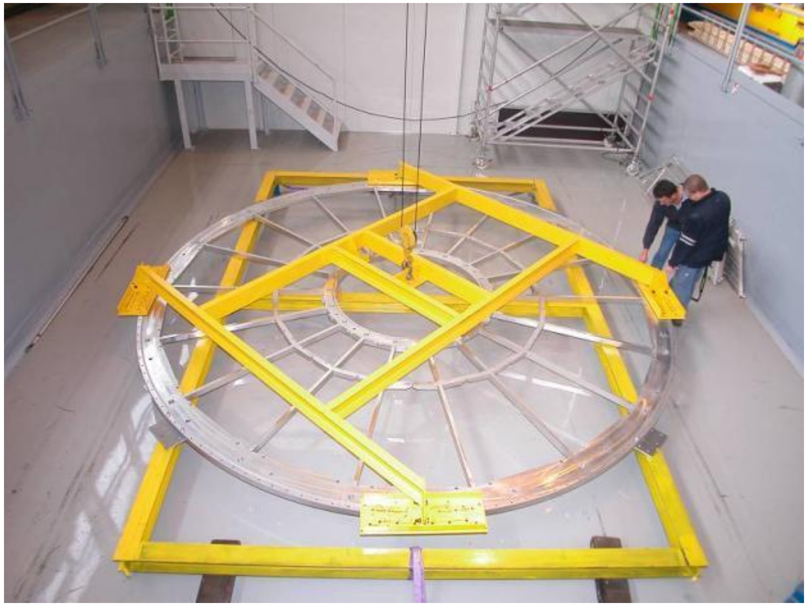
- Largest TPC:
  - Length 5m
  - Diameter 5m
  - Volume 88m^3
  - Detector area 32m^2
  - Channels ~570 000
- High Voltage:
  - Cathode -100kV
- Material X_0
  - Cylinder from composite materials from airplane industry (X_0= ~3%)

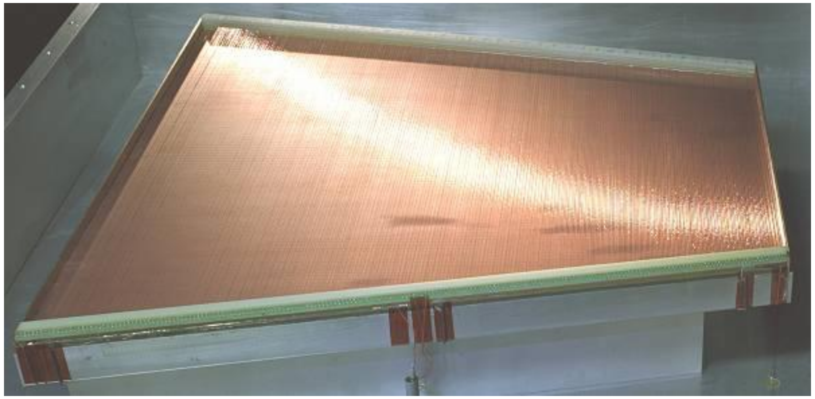


ALICE TPC: Pictures of the Construction

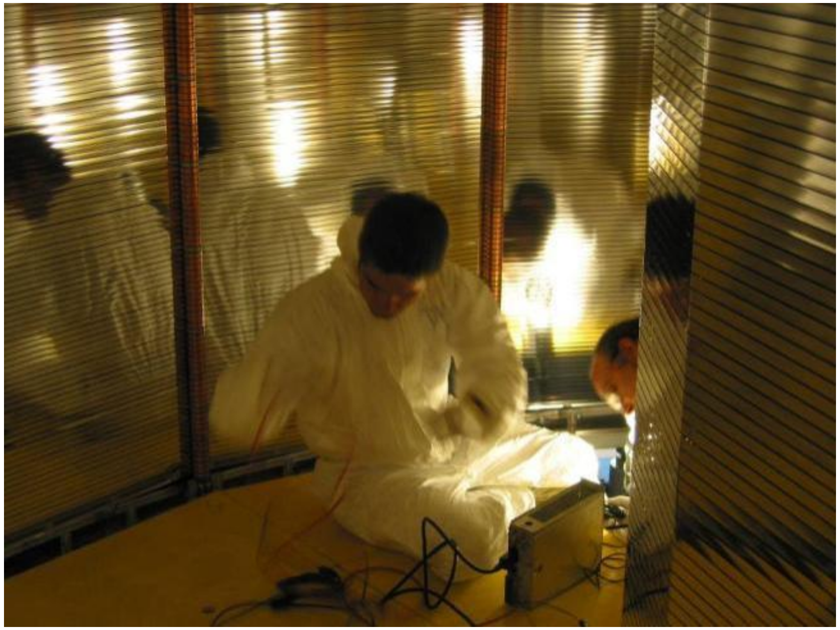
Precision in z: 250μm

End plates 250μm





Wire chamber: 40μm

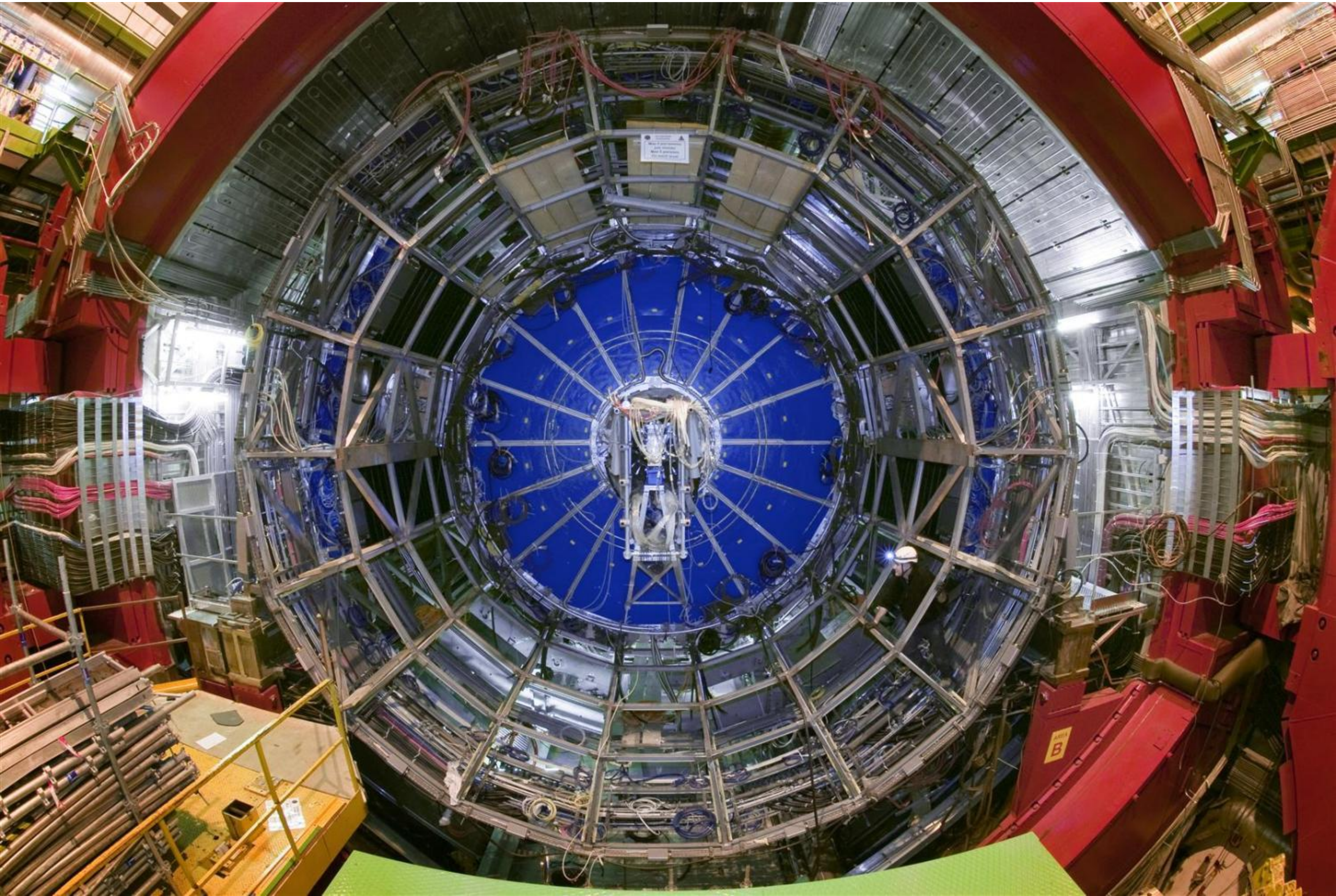


ALICE TPC Construction

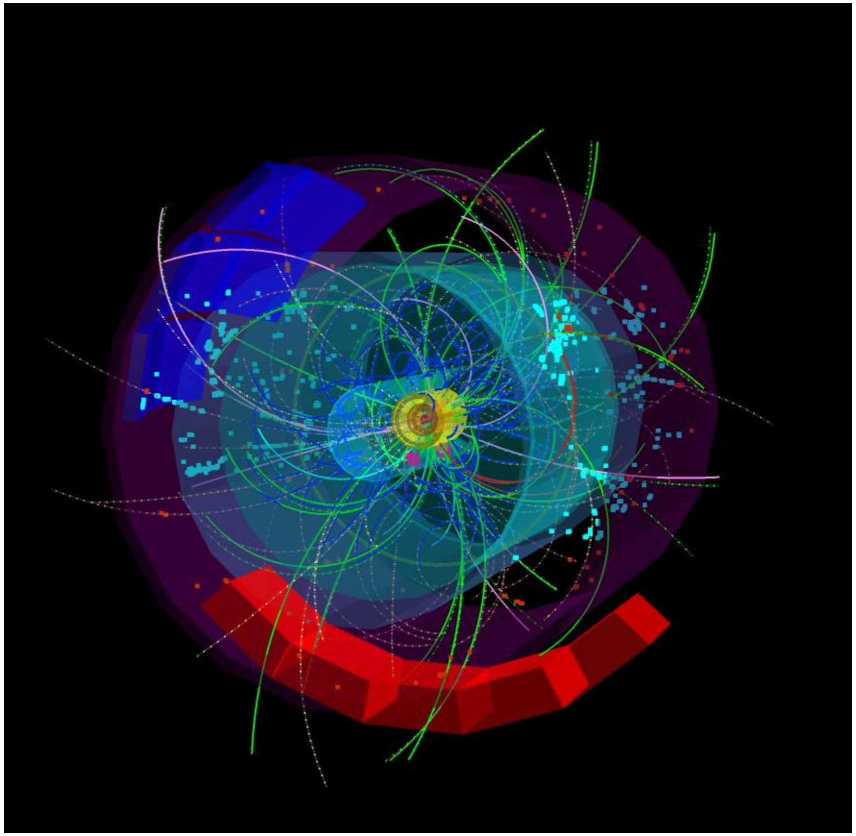
My personal contribution:

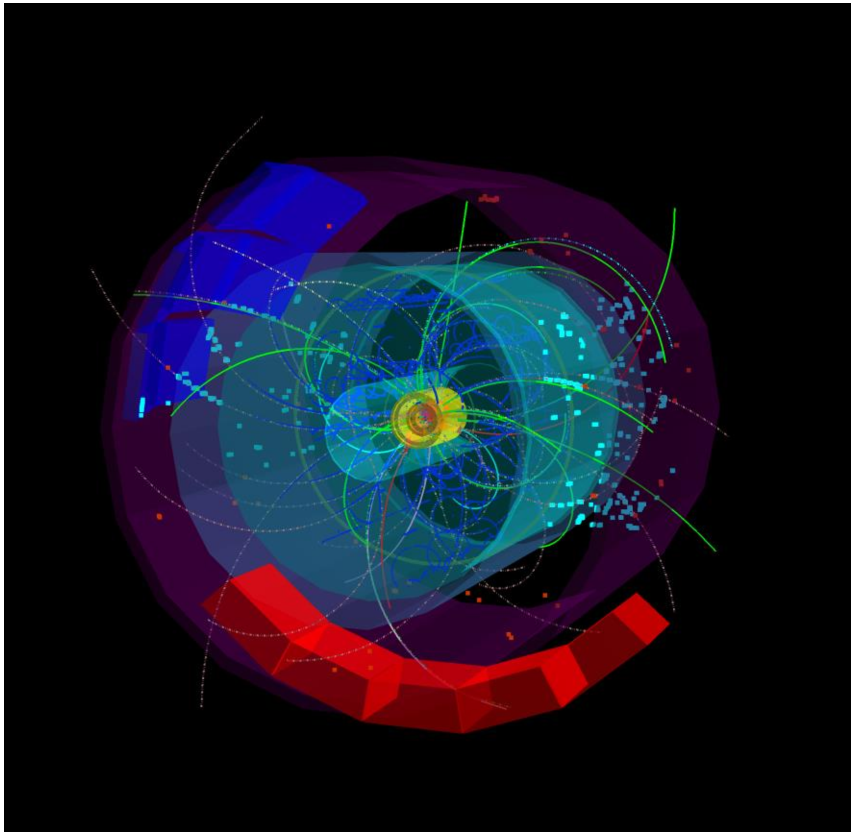
A visit inside the TPC.

TPC installed in the ALICE Experiment

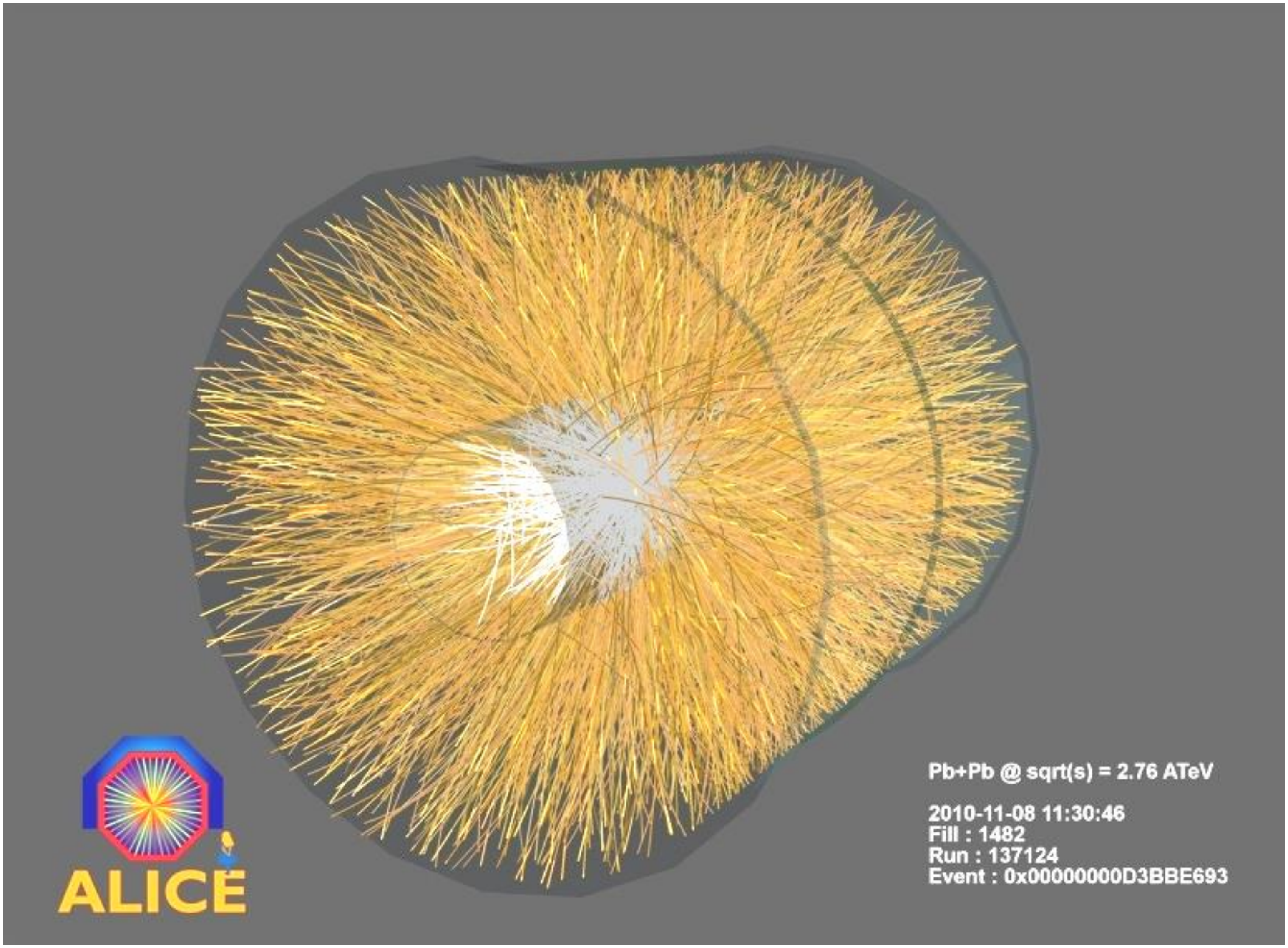


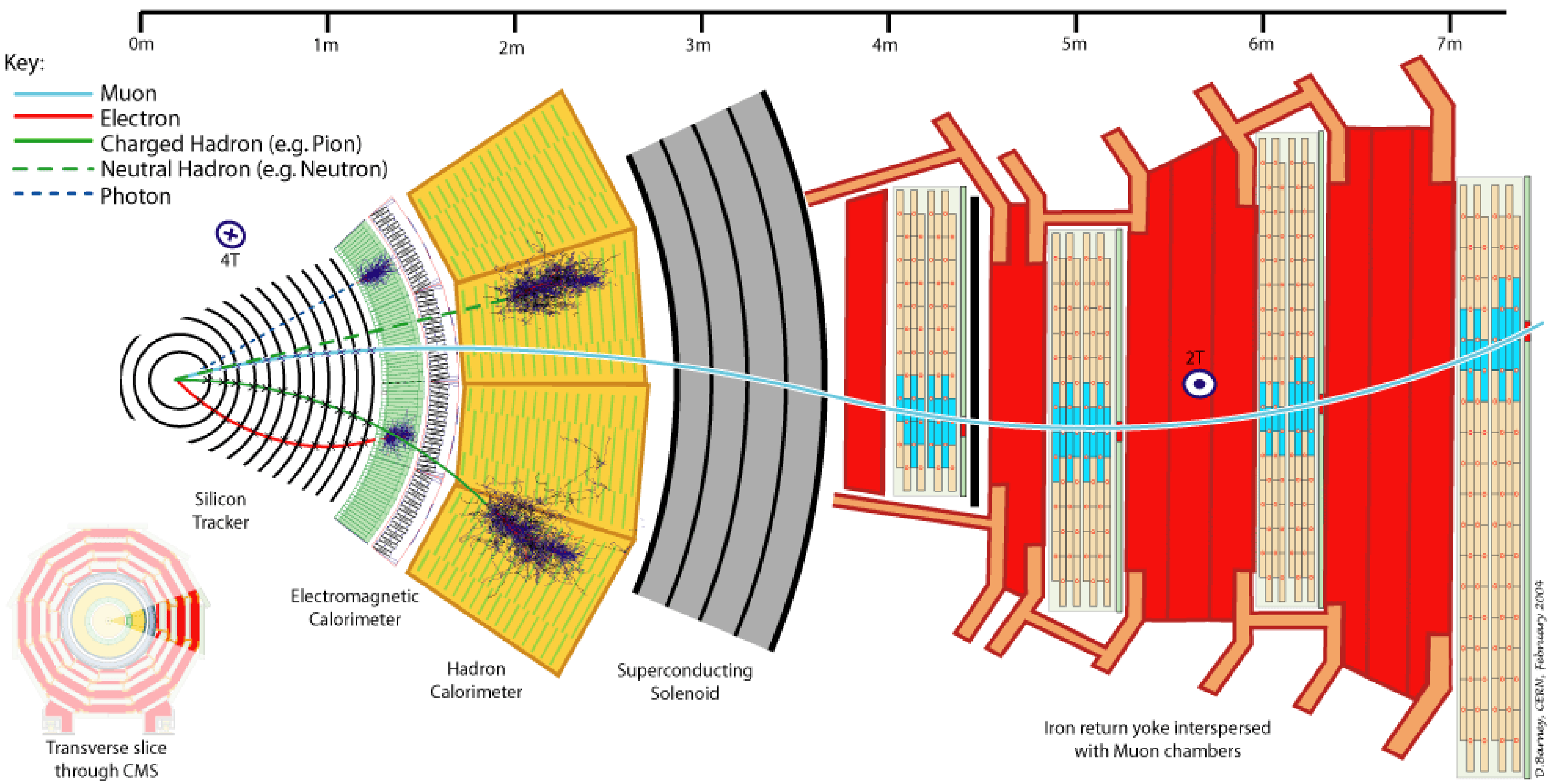
First 7 TeV p-p Collisions in the ALICE TPC in March 2010 !





First Pb Pb Collisions in the ALICE TPC in Nov 2010 !





W. Riegler/CERN

Calorimeter

Homogeneous

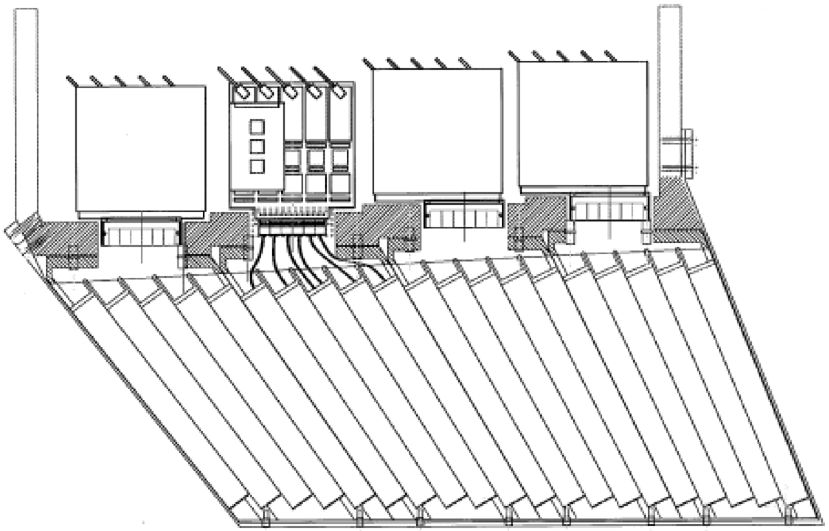
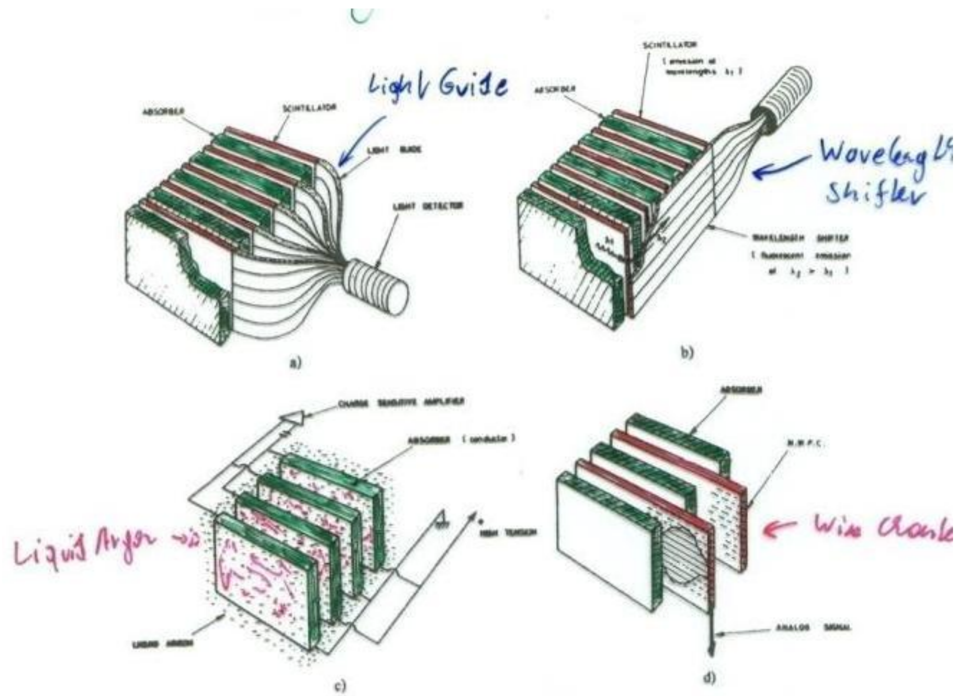


Fig. 2. Longitudinal drawing of module 2, showing the structure and the front-end electronics layout.

Sampling



The Geiger counter reloaded: Drift Tube

Atlas Muon Spectrometer, 44m long, from r=5 to11m.

1200 Chambers

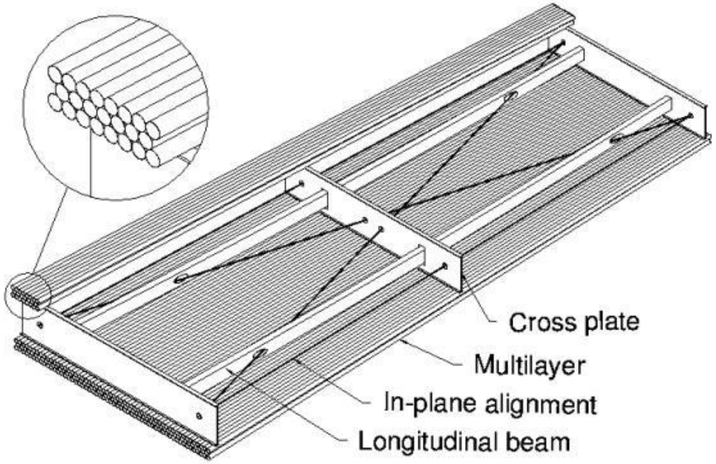
6 layers of 3cm tubes per chamber.

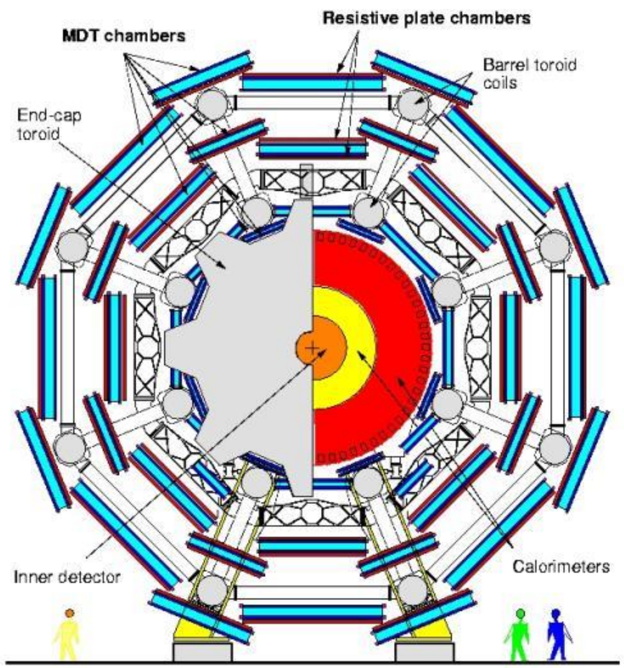
Length of the chambers 1-6m !

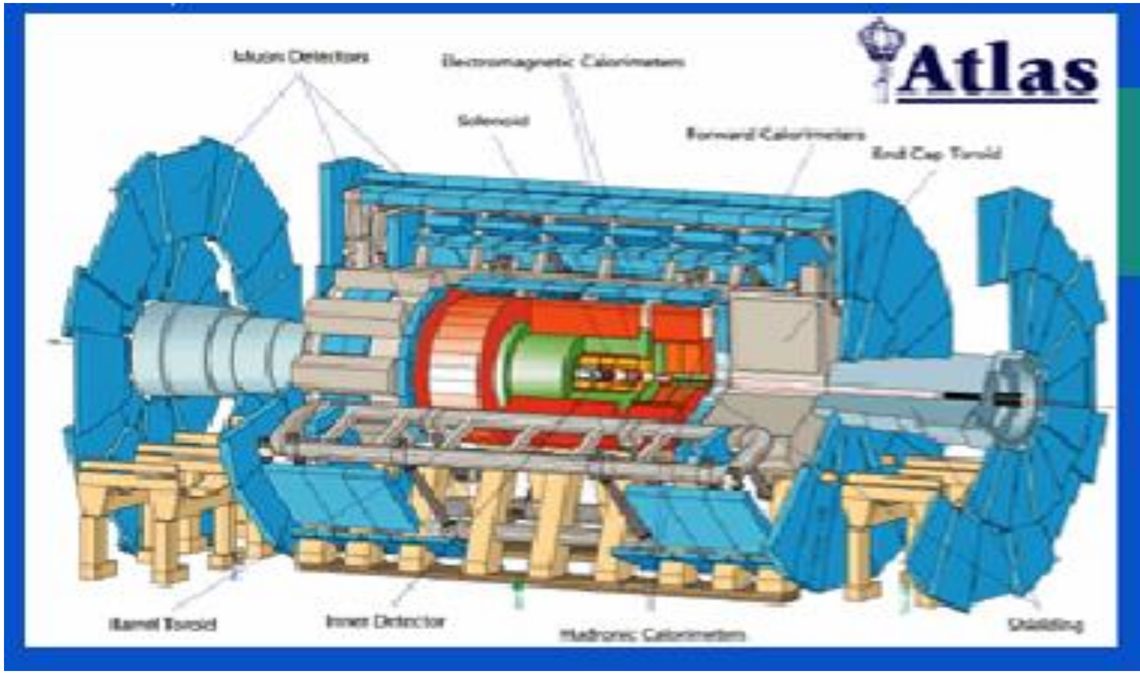
Position resolution: 80μm/tube, <50μm/chamber (3 bar)

Maximum drift time ≈700ns

Gas Ar/CO_2 93/7

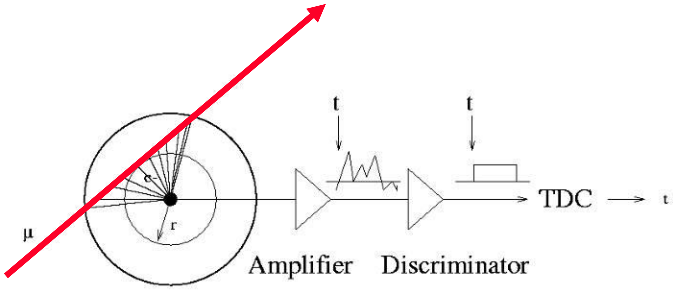




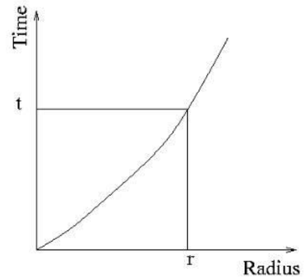


Drift Tube

ATLAS MDT R(tube) =15mm



Calibrated Radius-Time correlation



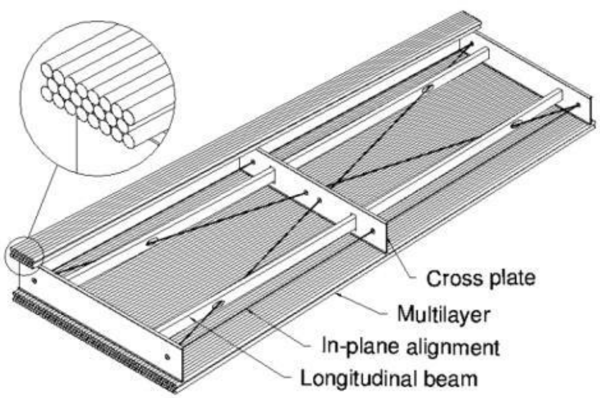
Primary electrons are drifting to the wire.

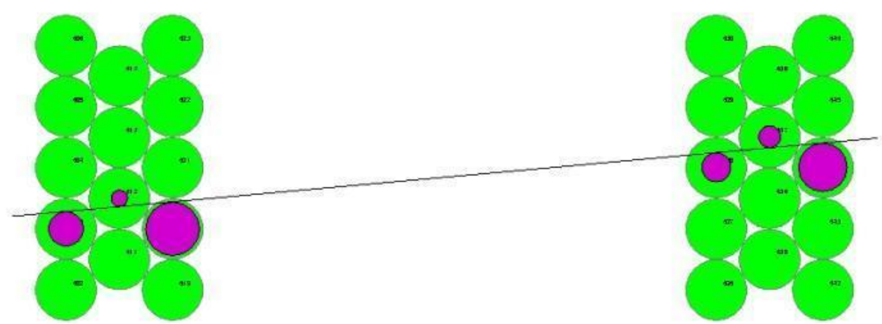
Electron avalanche at the wire.

The measured drift time is converted to a radius by a (calibrated) radius-time correlation.

Many of these circles define the particle track.

ATLAS Muon Chambers





ATLAS MDTs, 80μm per tube

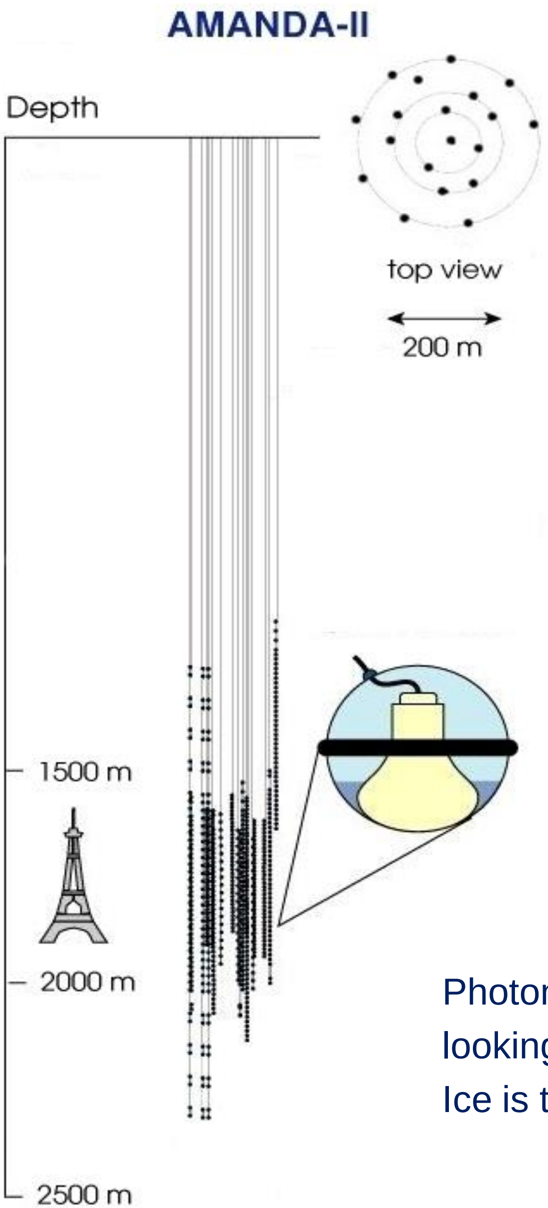
AMANDA

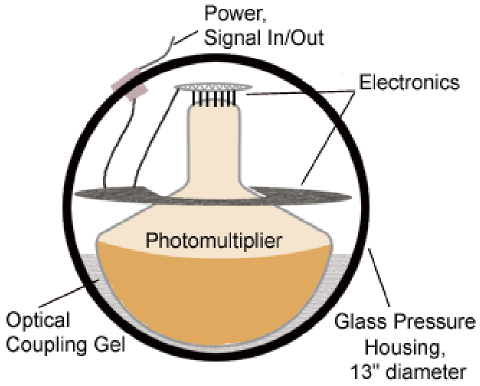
Antarctic Muon And Neutrino Detector Array

AMANDA & ICE Cube

South Pole

AMANDA



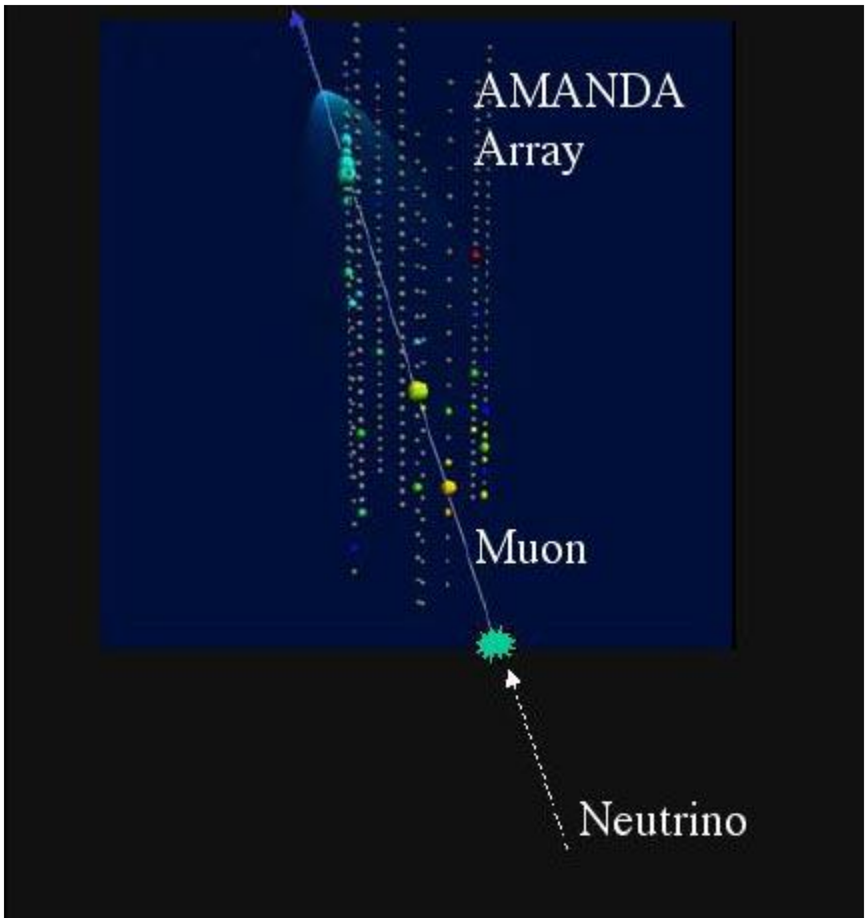


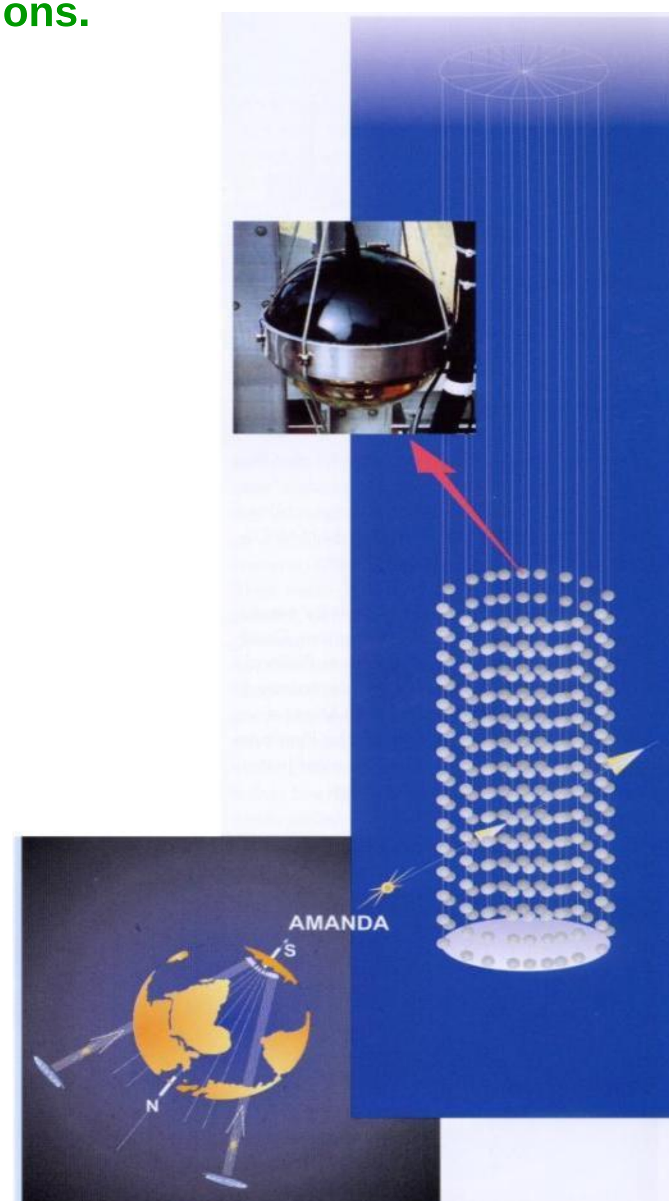
Photomultipliers in the Ice,
looking downwards.
Ice is the detecting medium.

AMANDA

Look for upwards going Muons from Neutrino Interactions.
Cherekov Light propagating through the ice.

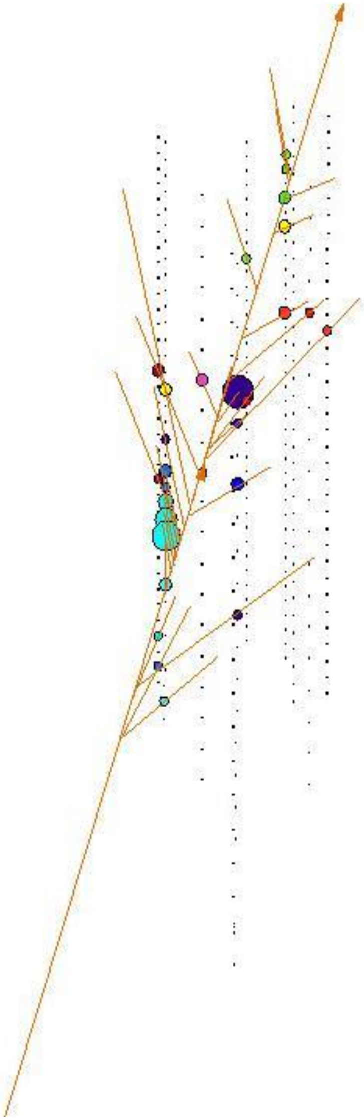
→ **Find neutrino point sources in the universe !**

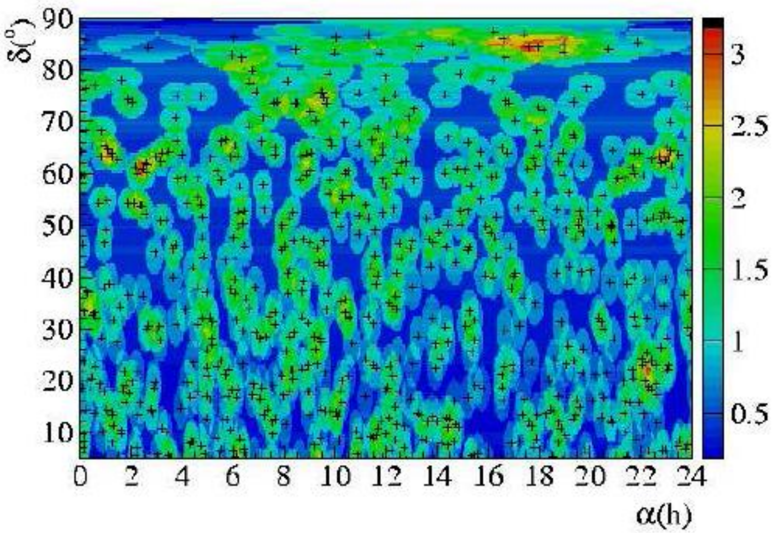


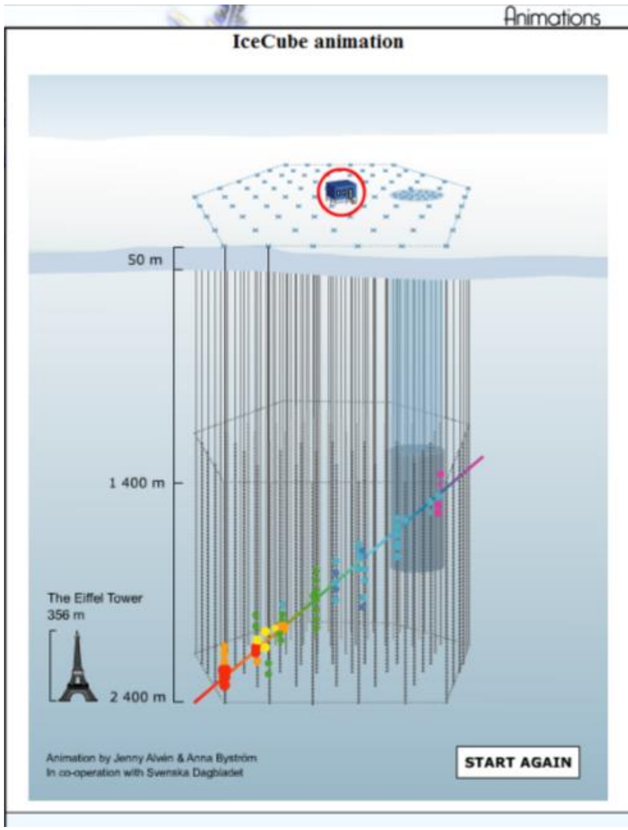


AMANDA

Event Display







Up to now: No significant point sources but just neutrinos from cosmic ray interactions in the atmosphere were found .

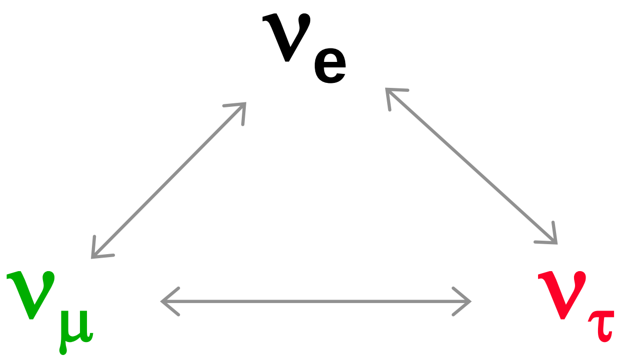
→ Ice Cube for more statistics !

CERN Neutrino Gran Sasso

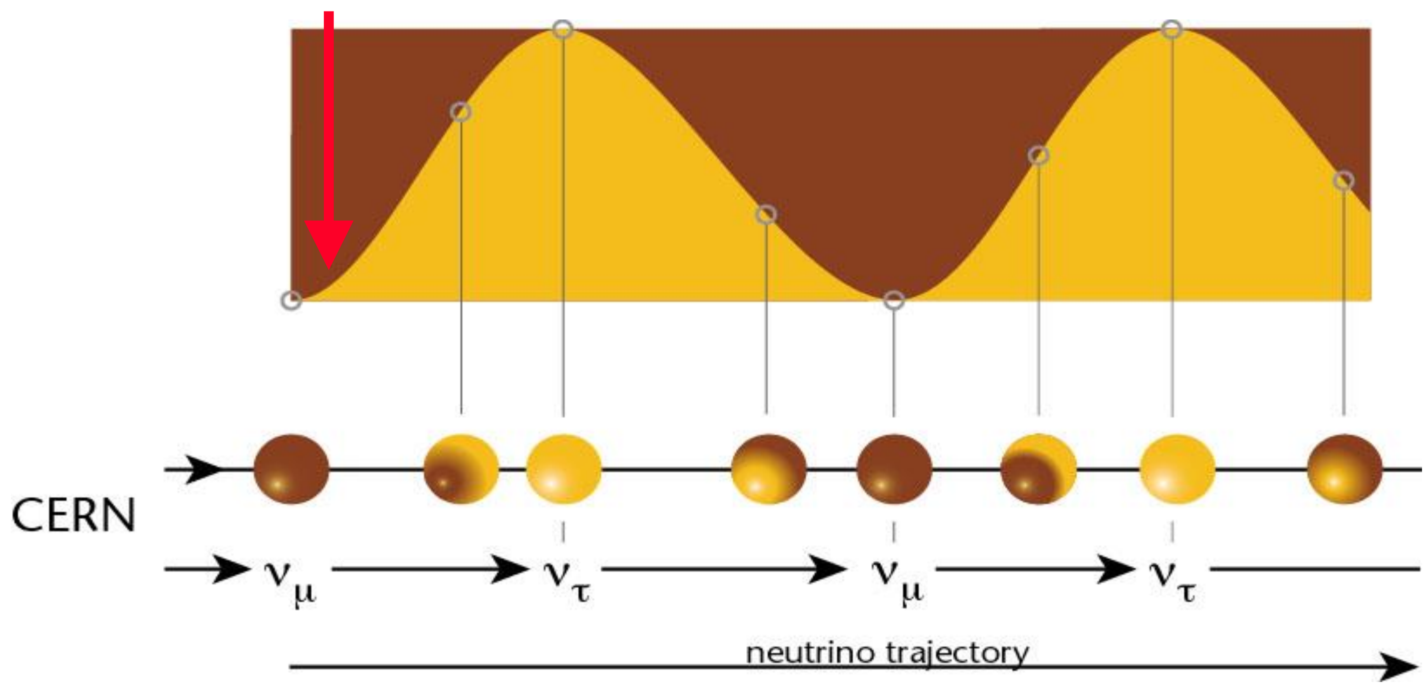
(CNGS)

CNGS

If neutrinos have mass:



Muon neutrinos produced at CERN.
See if tau neutrinos arrive in Italy.



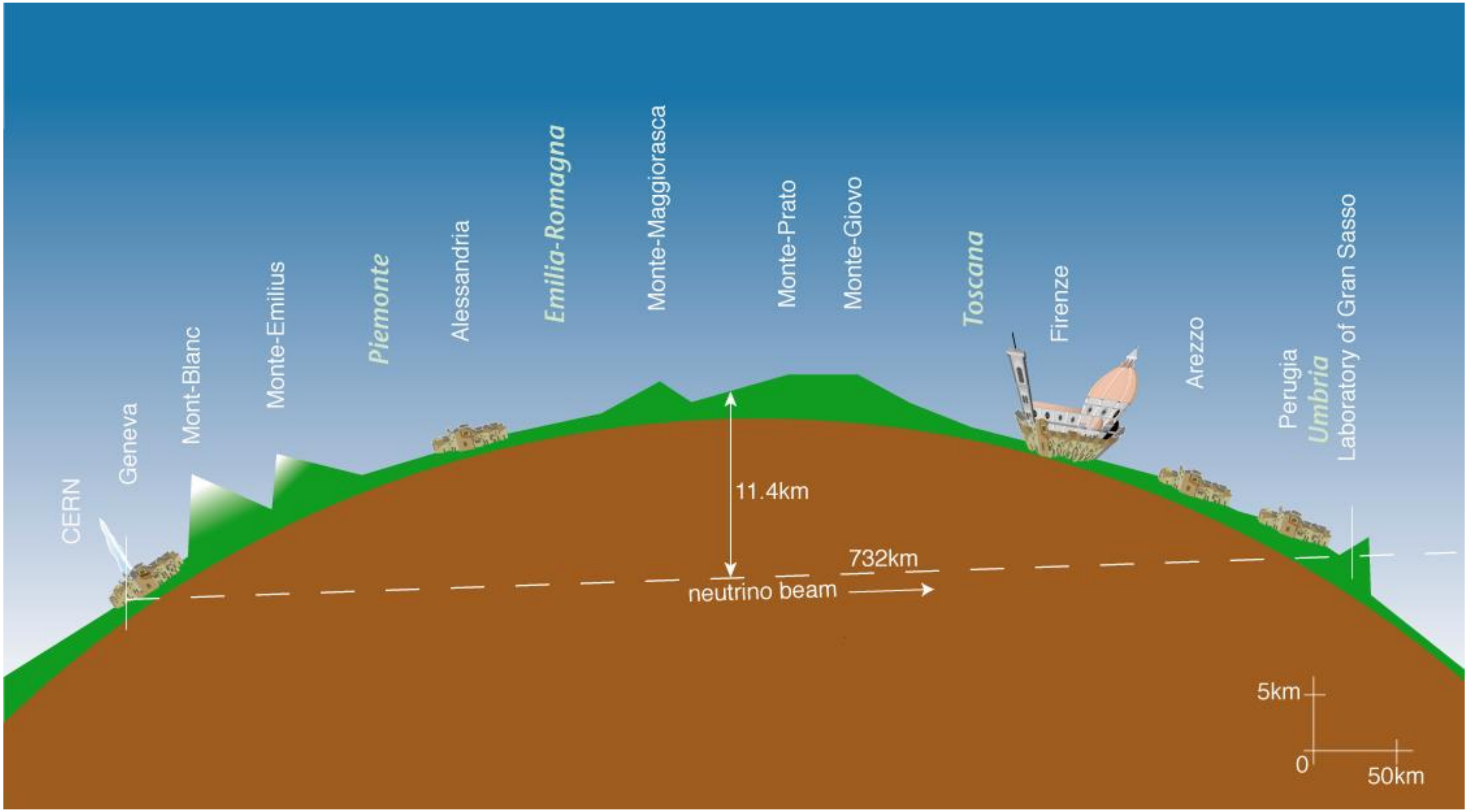
CNGS Project

CNGS (CERN Neutrino Gran Sasso)

- **A long base-line neutrino beam facility (732km)**
- **send ν_μ beam produced at CERN**
- **detect ν_τ appearance in OPERA experiment at Gran Sasso**

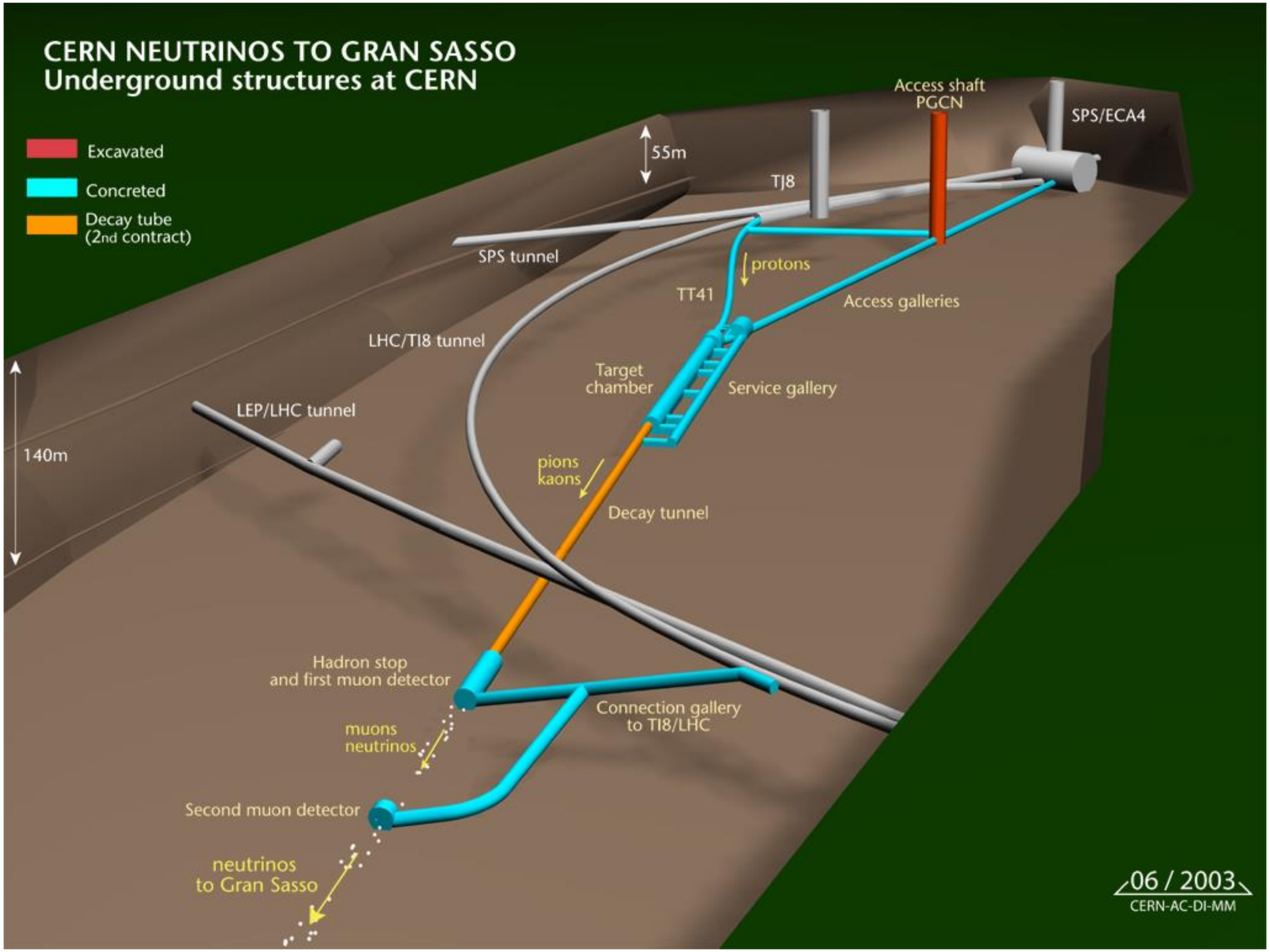
➔ **direct proof of ν_μ - ν_τ oscillation (appearance experiment)**

CNGS



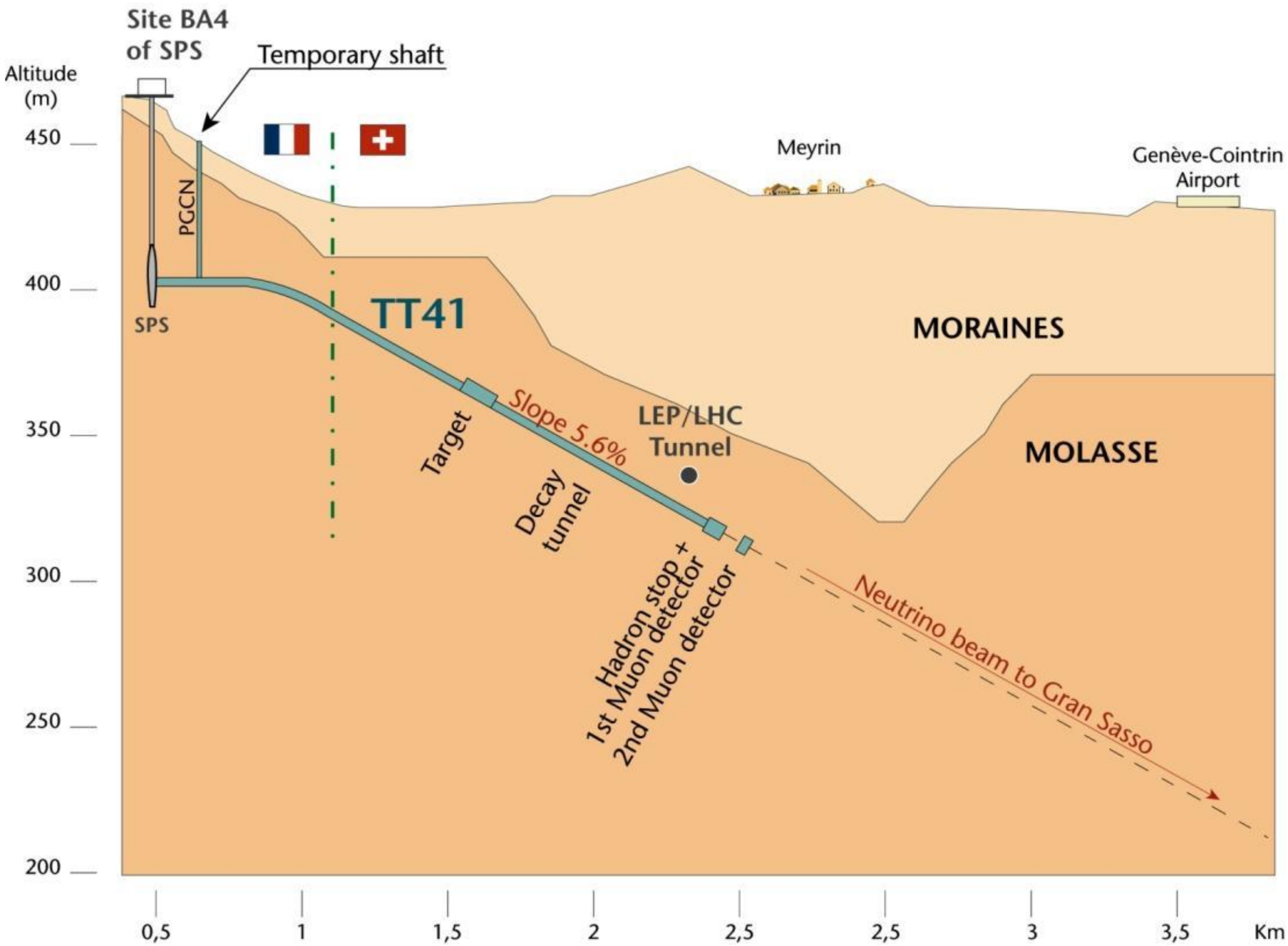
CERN
Geneva
Mont-Blanc
Monte-Emilius
Piemonte
Alessandria
Emilia-Romagna
Monte-Maggiorasca
Monte-Prato
Monte-Giovo
Toscana
Firenze
Arezzo
Perugia
Umbria
Laboratory of Gran Sasso
11.4km
732km
neutrino beam
5km
0
50km

CNGS

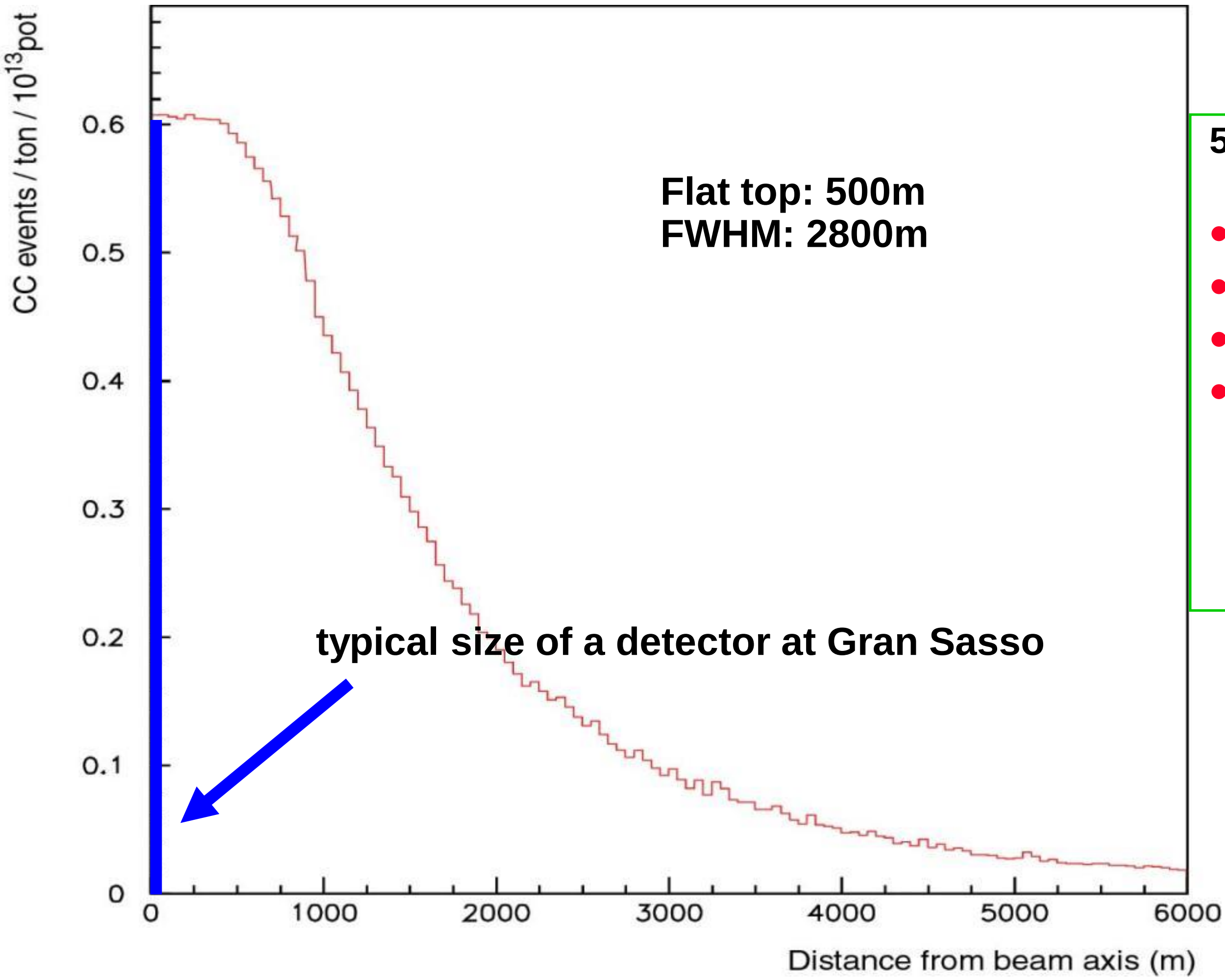


CERN NEUTRINOS TO GRAN SASSO
Underground structures at CERN
Excavated
Concreted
Decay tube
(2nd contract)
55m
TJ8
Access shaft
PGCN
SPS/ECA4
SPS tunnel
protons
TT41
Access galleries
LHC/TI8 tunnel
Target
chamber
Service gallery
LEP/LHC tunnel
140m
pions
kaons
Decay tunnel
Hadron stop
and first muon detector
Connection gallery
to TI8/LHC
muons
neutrinos
Second muon detector
neutrinos
to Gran Sasso
06 / 2003
CERN-AC-DI-MM

CNGS


Site BA4
of SPS
Temporary shaft
Altitude
(m)
450
400
350
300
250
200
PGCN
SPS
TT41
Meyrin
Genève-Cointrin
Airport
MORAINES
MOLASSE
LEP/LHC
Tunnel
Slope 5.6%
Target
Decay
tunnel
Hadron stop +
1st Muon detector
2nd Muon detector
Neutrino beam to Gran Sasso
0,5
1
1,5
2
2,5
2,5
3
3,5
Km

Radial Distribution of the ν_μ-Beam at GS



5 years CNGS operation, 1800 tons target:

- **30000 neutrino interactions**
- **~150 ν_τ interactions**
- **~15 ν_τ identified**
- **< 1 event of background**

Neutrinos at CNGS: Some Numbers

For 1 year of CNGS operation, we expect:

protons on target 2×10^{19}

pions / kaons at entrance to decay tunnel 3×10^{19}

ν_μ in direction of Gran Sasso 10^{19}

ν_μ in 100 m^2 at Gran Sasso 3×10^{14}

ν_μ events per day in OPERA ≈ 2500

ν_τ events (from oscillation) ≈ 2

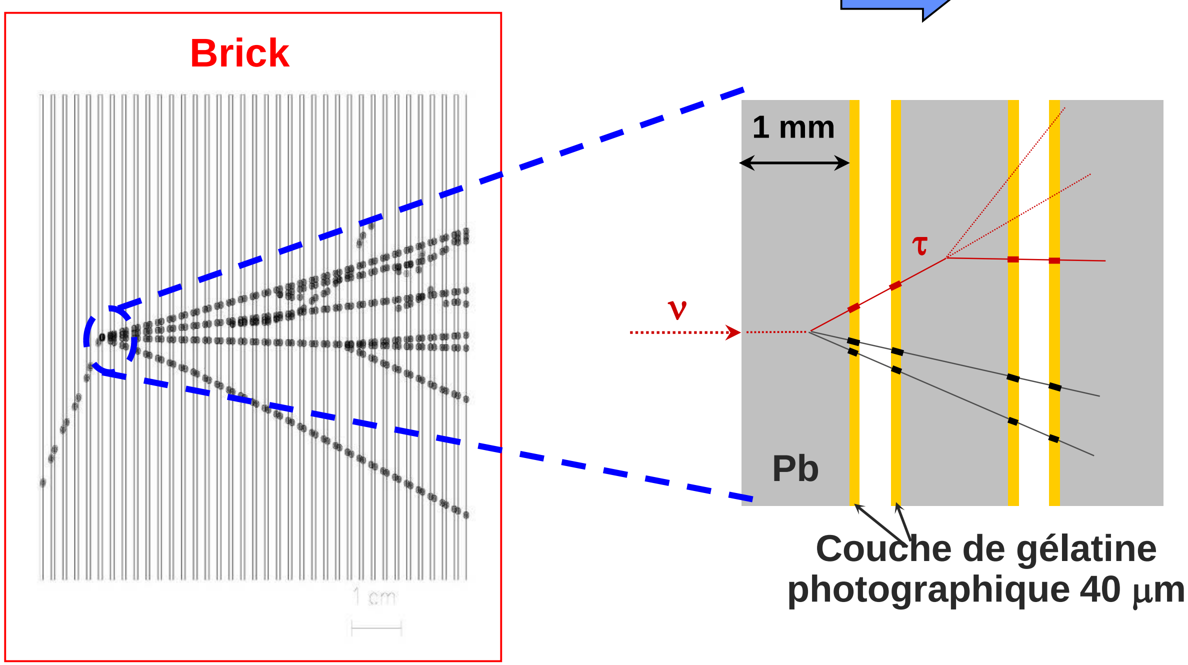
Opera Experiment at Gran Sasso

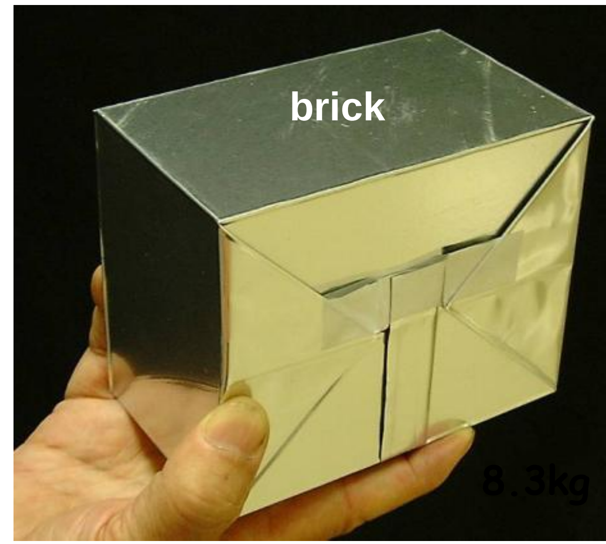
Basic unit: brick

56 Pb sheets + 56 photographic films (emulsion sheets)

Lead plates: massive target

Emulsions: micrometric precision





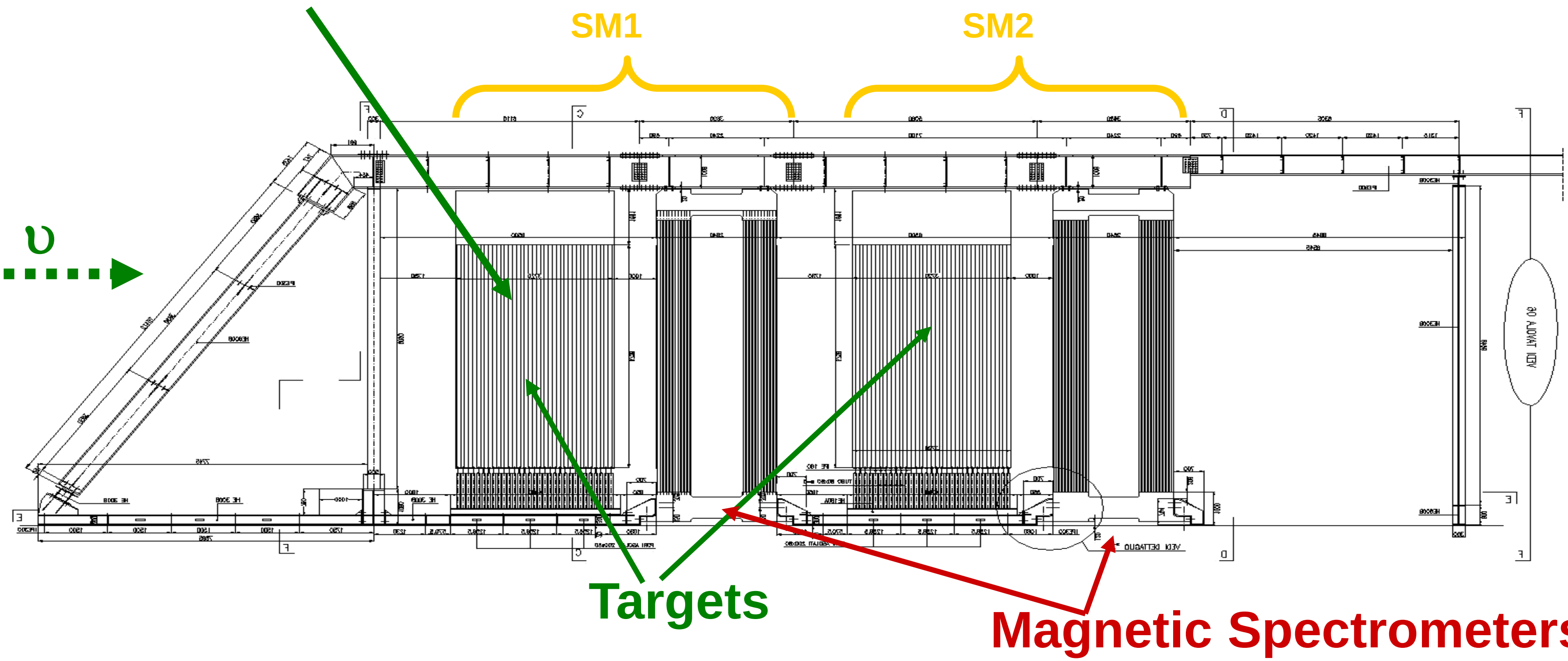
10.2 x 12.7 x 7.5 cm^3

W. Riegler/CERN

Opera Experiment at Gran Sasso

31 target planes / supermodule

In total: 206336 bricks, 1766 ton



First observation of CNGS beam neutrinos : August 18th, 2006

Opera Experiment at Gran Sasso

Second Super-module

Scintillator planes 5900 m^2

8064 7m long drift tubes

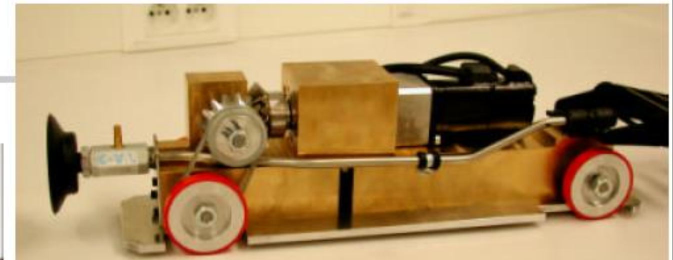
Details of the first spectrometer

3050 m^2 Resistive Plate Counters

2000 tons of iron for the two magnets

Opera Experiment at Gran Sasso

The Brick Manipulator System (BMS) prototype:
a lot of fun for children and adults !

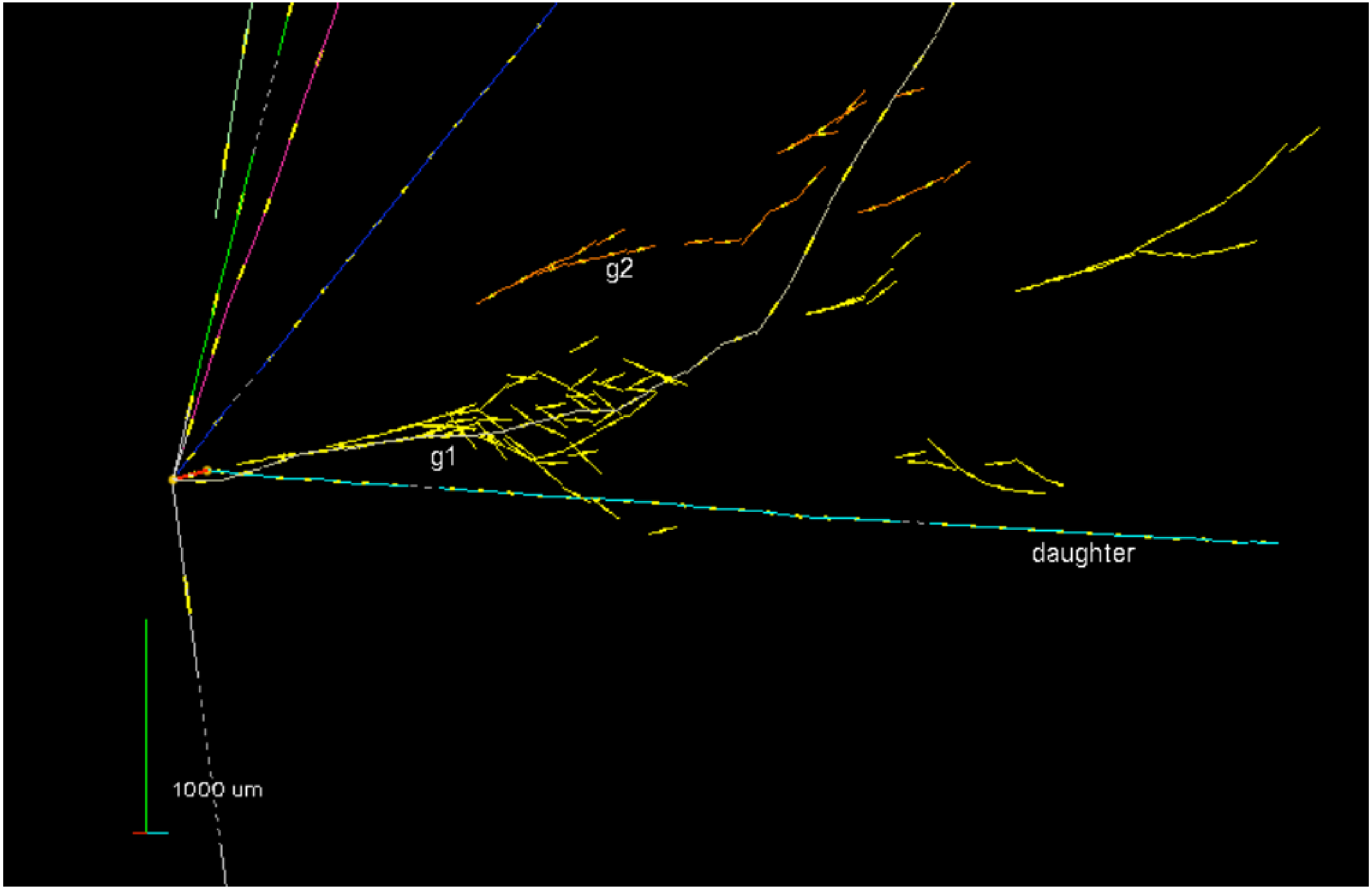


The robotised "Ferrari" for insertion/extraction of bricks with vacuum grip by Venturi valve

Tests with the prototype wall

"Carousel" brick dispensing and storage system

First Tau Candidate seen a few weeks ago !



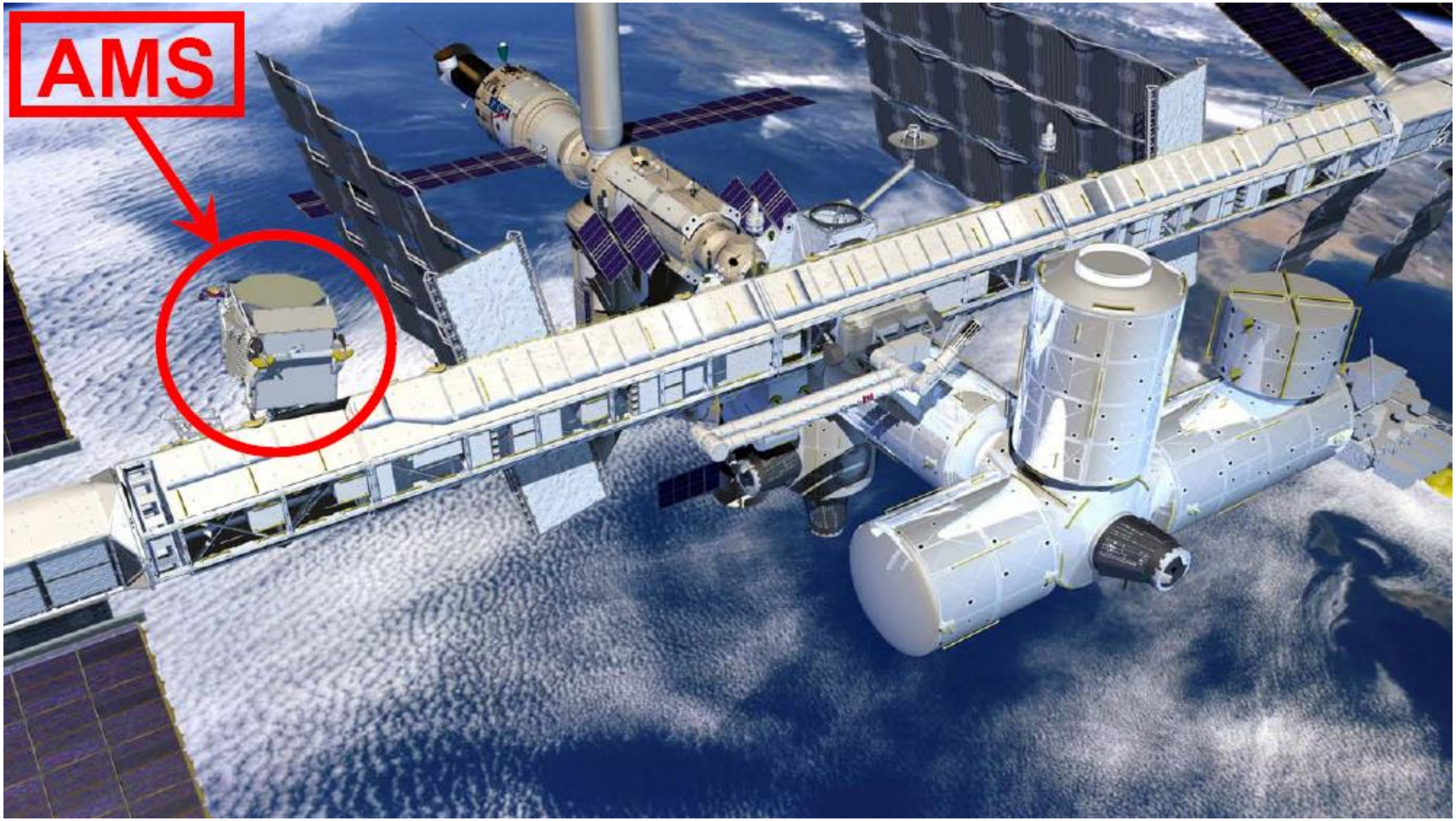
AMS

Alpha Magnetic Spectrometer

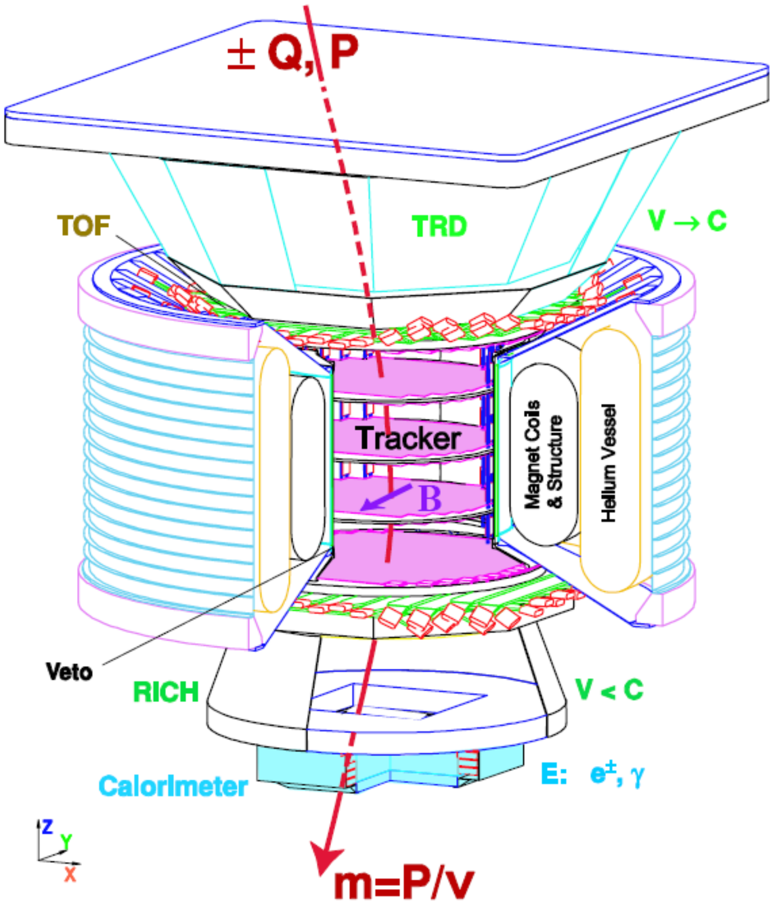
Try to find Antimatter in the primary cosmic rays.
Study cosmic ray composition etc. etc.

AMS

Installed on the space station.

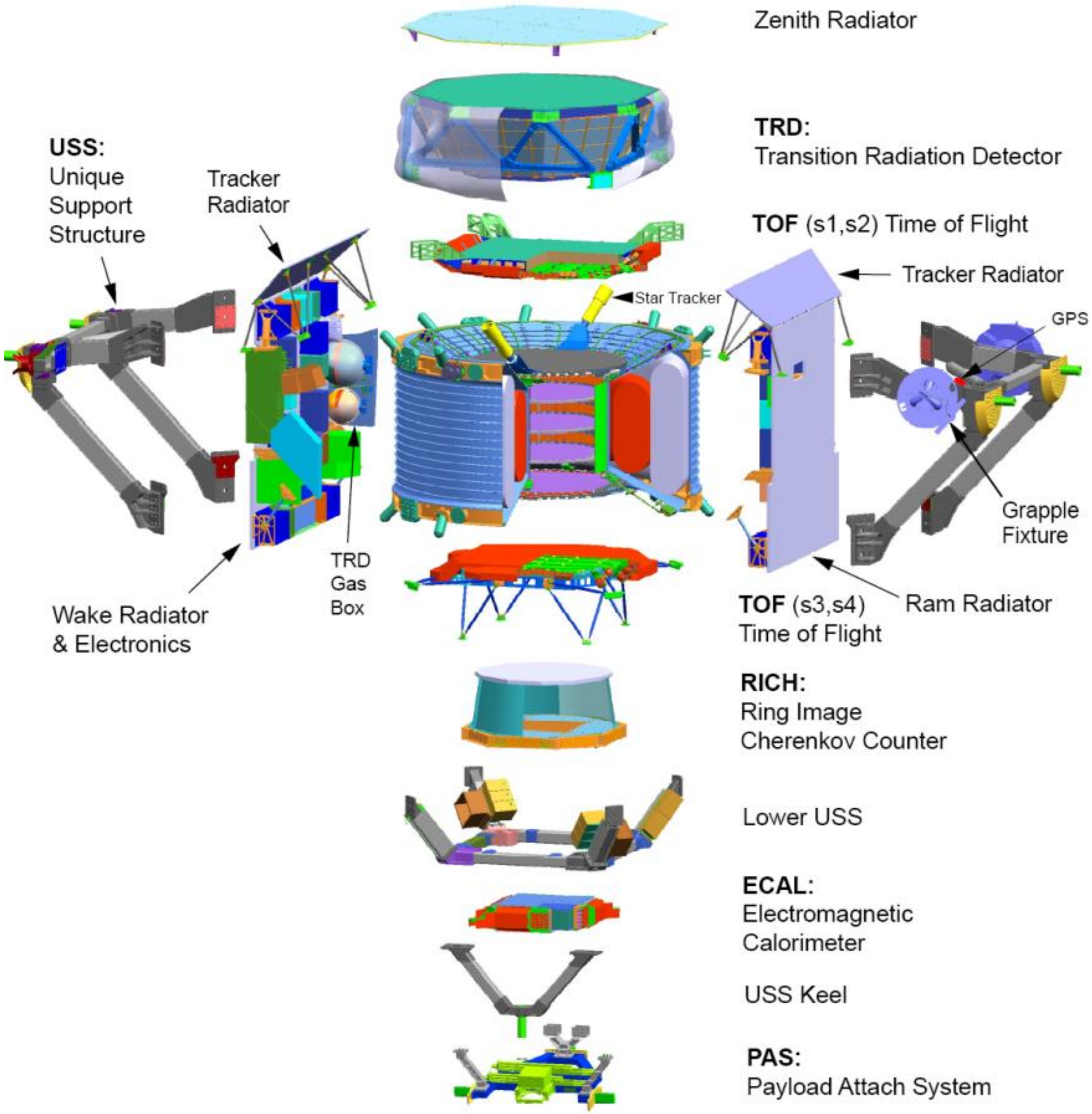


AMS



± Q, P
TOF
TRD
V → C
Tracker
B
Magnet Coils & Structure
Helium Vessel
Veto
RICH
V < C
Calorimeter
E: e±, γ
Z
Y
X
m=P/v

AMS



Zenith Radiator
TRD:
Transition Radiation Detector
USS:
Unique
Support
Structure
Tracker
Radiator
TOF (s1,s2) Time of Flight
Tracker Radiator
Star Tracker
GPS
Grapple
Fixture
TRD
Gas
Box
Wake Radiator
& Electronics
TOF (s3,s4)
Time of Flight
Ram Radiator
RICH:
Ring Image
Cherenkov Counter
Lower USS
ECAL:
Electromagnetic
Calorimeter
USS Keel
PAS:
Payload Attach System

Summary

There are just a few basic principles for particle detection …

… but there is an infinite number if ingenious ways to use these principles in order to force nature to reveal it’s secrets !