Particle Detectors 2/2

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Particle Detector Definition

A particle detector is a device, that is collapsing wavefunctions of quantum mechanical states, which themselves are linear superpositions of irreducible representations of the inhomogeneous Lorentz Group.

Particle Detector

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

ON UNITARY REPRESENTATIONS OF THE INHOMOGENEOUS
LORENTZ GROUP*

By E. WIGNER

(Received December 22, 1937)

of the invariance of the transition probability we have

(1) $$|(\varphi_l, \psi_l)|^2 = |(\varphi_{l'}, \psi_{l'})|^2$$

and it can be shown[4] that the aforementioned constants in the $\varphi_{l'}$ can be chosen in such a way that the $\varphi_{l'}$ are obtained from the φ_l by a linear unitary operation, depending, of course, on l and l'

(2) $$\varphi_{l'} = D(l', l)\varphi_l .$$

By going over from a first system of reference l to a second $l' = L_1 l$ and then to a third $l'' = L_2 L_1 l$ or directly to the third $l'' = (L_2 L_1)l$, one must obtain—apart from the above mentioned constant—the same set of wave functions. Hence from

$$\varphi_{l''} = D(l'', l')D(l', l)\varphi_l$$
$$\varphi_{l''} = D(l'', l)\varphi_l$$

it follows

(3) $$D(l'', l')D(l', l) = \omega D(l'', l)$$

D. Classification of unitary representations from the point of view of infinitesimal operators

→ **Scalars, spinors, vectors**
→ **m>0 and s=0, 1/2, 1, 3/2, 2**

3

The 'Standard Model'

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

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

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

matter particles

guage particles

	1st gen.	2nd gen.	3rd gen.
QUARK	u up	c charm	t top
	d down	s strange	b bottom
LEPTON	ν_e e neutrino	ν_μ μ neutrino	ν_τ τ neutrino
	e electron	μ muon	τ tau

Strong Force
g Gluon

Electro-Magnetic Force
γ photon

Weak Force
W^+ W^- Z
W bosons   Z boson

scalar particle(s)

H Higgs   ?   ?   · · ·

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

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

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

Over the last century
this "Standard Model" of
Fundamental Physics was discovered
by studying

    Radioactivity
    Cosmic Rays
    Particle Collisions (Accelerators)

A large variety of Detectors and
experimental techniques have been
developed during this time.

Scales

$$E = m a^2$$
$$E = m b^2$$
$$E = m c^2 \longleftarrow \text{Energy} \Leftrightarrow \text{Mass}$$
$$\vdots$$

$$m(\text{electron}) = 9.1 \cdot 10^{-31} \text{ kg}$$
$$m_e c^2 = 8.19 \cdot 10^{-14} \text{ J}$$
$$= 510\ 999 \text{ Electron Volt (eV)}$$
$$= 0.511 \text{ MeV}$$

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

$$E = e_0 \cdot 1V$$

0   1V
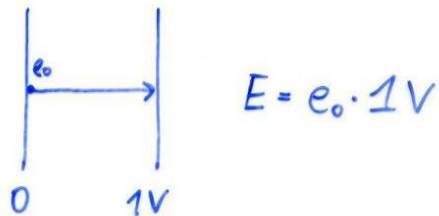
1 Electron Volt = Energy on Electron gains as
it traverses a Potential Difference of 1V

Build your own Accelerator
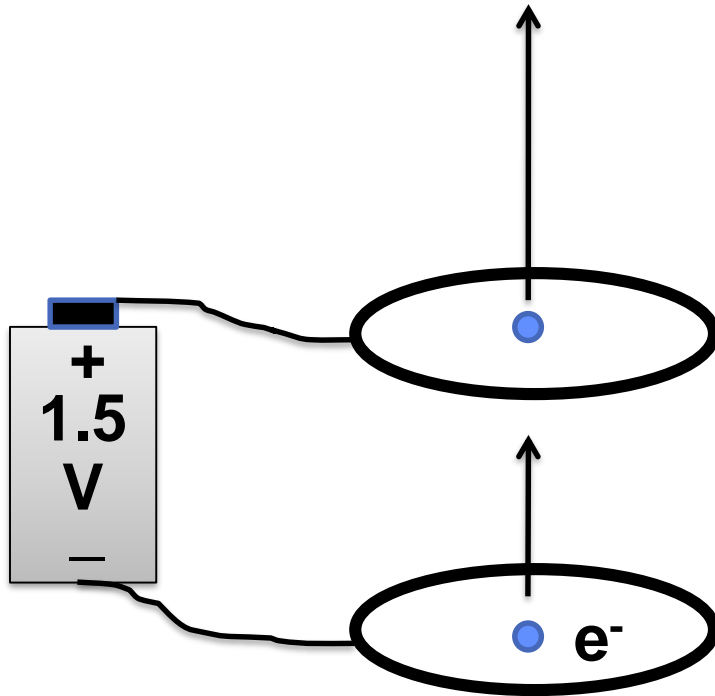
$E_{kin} = 1.5eV =$

2 615 596 km/h

+
1.5
V
–

e^-

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)

Basics

Lorentz Boost:

$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu \qquad \gamma = 2.2 \cdot 10^{-6}\, s$$

E.g. Produced by Cosmic Rays $(p, He, Li \dots)$
colliding with air in the upper Atmosphere $\sim 10\, km$

$$s = v \cdot \gamma \sim c \cdot \gamma = 660\, m$$

But we see Muons here on Earth

$$E_\mu \sim 2\, GeV, \quad m_\mu c^2 = 105\, MeV \;\to\; \gamma \sim 19$$

Relativity: $\quad \bar{\gamma} = \gamma \cdot \gamma$

$$s = c \cdot \bar{\gamma} = 12.5\, km \;\to\; Earth$$

Pions: $\pi^+, \pi^- \quad \gamma \sim 2.6 \cdot 10^{-8}\, s, \; m_\pi c^2 = 135\, MeV$

$$2\, GeV \to s = 115\, m$$

Pions where discovered in Emulsions exposed
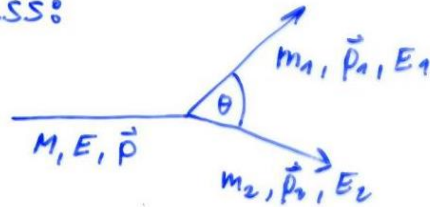to Cosmic Rays on high Mountains.

LHCb B decay
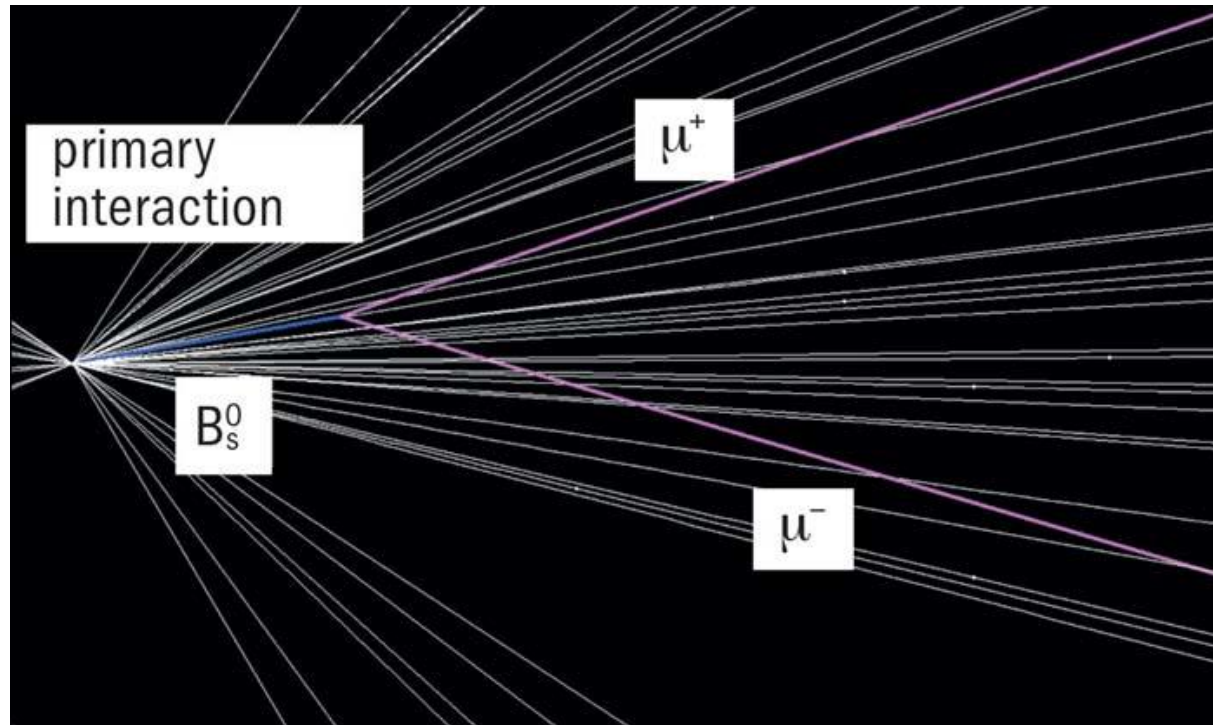
Basics

Invariant Mass:

LAB:

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

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

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

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

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

$$M^2 c^2 = m_1^2 c^2 + m_2^2 c^2 + 2\left(\frac{E_1 E_2}{c^2} - p_1 p_2 \cos\theta \right)$$

- Measuring Momenta and Energies   OR

- Measuring Momenta and identifying Particles

gives the Mass of the original Particle

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

γ, $W^{\pm}$, z^0, g, e, μ, τ, ν_e, ν_{μ}, ν_{τ}, $\pi^{\pm}$, π^0, η, $f_0(600)$, $\rho(770)$,

$\omega(782)$, $\eta'(958)$, $f_0(980)$, $a_0(980)$, $\phi(1020)$, $h_1(1170)$, $b_1(1235)$,

$a_1(1260)$, $f_2(1270)$, $f_1(1285)$, $\eta(1295)$, $\pi(1300)$, $a_2(1320)$,

$f_0(1370)$, $f_1(1420)$, $\omega(1420)$, $\eta(1440)$, $a_0(1450)$, $\rho(1450)$,

$f_0(1500)$, $f_2'(1525)$, $\omega(1650)$, $\omega_3(1670)$, $\pi_2(1670)$, $\phi(1680)$,

$\rho_3(1690)$, $\rho(1700)$, $f_0(1710)$, $\pi(1800)$, $\phi_3(1850)$, $f_2(2010)$,

$a_4(2040)$, $f_4(2050)$, $f_2(2300)$, $f_2(2340)$, $K^{\pm}$, K^0, K_S^0, K_L^0, $K^*(892)$,

$K_1(1270)$, $K_1(1400)$, $K^*(1410)$, $K_0^*(1430)$, $K_2^*(1430)$, $K^*(1680)$,

$K_2(1770)$, $K_3^*(1780)$, $K_2(1820)$, $K_4^*(2045)$, $D^{\pm}$, 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, $N(1440)$,

$N(1520)$, $N(1535)$, $N(1650)$, $N(1675)$, $N(1680)$, $N(1700)$, $N(1710)$,

$N(1720)$, $N(2190)$, $N(2220)$, $N(2250)$, $N(2600)$, $\Delta(1232)$, $\Delta(1600)$,

$\Delta(1620)$, $\Delta(1700)$, $\Delta(1905)$, $\Delta(1910)$, $\Delta(1920)$, $\Delta(1930)$, $\Delta(1950)$,

$\Delta(2420)$, Λ, $\Lambda(1405)$, $\Lambda(1520)$, $\Lambda(1600)$, $\Lambda(1670)$, $\Lambda(1690)$,

$\Lambda(1800)$, $\Lambda(1810)$, $\Lambda(1820)$, $\Lambda(1830)$, $\Lambda(1890)$, $\Lambda(2100)$,

$\Lambda(2110)$, $\Lambda(2350)$, Σ^+, Σ^0, Σ^-, $\Sigma(1385)$, $\Sigma(1660)$, $\Sigma(1670)$,

$\Sigma(1750)$, $\Sigma(1775)$, $\Sigma(1915)$, $\Sigma(1940)$, $\Sigma(2030)$, $\Sigma(2250)$, Ξ^0, Ξ^-,

$\Xi(1530)$, $\Xi(1690)$, $\Xi(1820)$, $\Xi(1950)$, $\Xi(2030)$, Ω^-, $\Omega(2250)^-$,

Λ_c^+, Λ_c^+, $\Sigma_c(2455)$, $\Sigma_c(2520)$, Ξ_c^+, Ξ_c^0, $\Xi_c'^+$, $\Xi_c'^0$, $\Xi(2645)$,

$\Xi_c(2780)$, $\Xi_c(2815)$, Ω_c^0, Λ_b^0, Ξ_b^0, Ξ_b^-, $t\bar{t}$

There are Many more

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Particle	Mass (meV)	Life time γ (s)	$c\gamma$
γ	0	∞	∞
$\pi^{\mp}$ $(u\bar{d}, d\bar{u})$	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
$B^{\mp}$ $(u\bar{b}, \bar{b}u)$	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	~$5 \cdot 10^{-13}$	150 μm
p (uud)	938.3	$> 10^{33}$ Y	∞
n (udd)	939.6	885.7 s	$2.655 \cdot 10^8$ km
Λ^0 (uds)	1115.7	$2.6 \cdot 10^{-10}$	7.89 cm
Σ^+ (uus)	1189.4	$8.0 \cdot 10^{-11}$	2.404 cm
Σ^- (dds)	1197.4	$1.5 \cdot 10^{-10}$	4.434 cm
Ξ^0 (uss)	1315	$2.9 \cdot 10^{-10}$	8.71 cm
Ξ^- (dss)	1321	$1.6 \cdot 10^{-10}$	4.91 cm
Ω^- (sss)	1672	$8.2 \cdot 10^{-11}$	2.461 cm
Λ_c^+ (udc)	2285	~$2 \cdot 10^{-13}$	60 μm
Ξ_c^+ (usc)	2466	$4.4 \cdot 10^{-13}$	132 μm
Ξ_c^0 (dcs)	2472	~$1 \cdot 10^{-13}$	29 μm
Ω_c^0 (ssc)	2698	$6.0 \cdot 10^{-14}$	19 μm
Λ_b (udb)	5620	$1.2 \cdot 10^{-12}$	368 μm

"Secondary Vertices" (bracket from $D^{\pm}$ to $B_c^{\pm}$)

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

~13 of the 27 have $c\gamma < 500\mu m$ 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.

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

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

γ $\quad m_{\gamma} = 0$, $Q = 0$

$\left.\begin{array}{}\end{array}\right\}$ EM

$\pi^{\pm}$ $\quad m_{\pi} = 139.6$ MeV $\sim 270\, m_e$ $\left.\begin{array}{}\end{array}\right\}$ EM, Strong

$K^{\pm}$ $\quad m_k = 493.7$ MeV $\sim 1000\, m_e$ $\left.\begin{array}{}\end{array}\right]$ $\sim 3.5\, m_{\pi}$

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

K^0 $\quad m_{k^0} = 497.7$ MeV $\quad Q = 0$ $\left.\begin{array}{}\end{array}\right\}$ Strong

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

The Difference in

Mass, Charge, Interaction

is the key to the Identification

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Momentum Measurement

Magnetic Spectrometer: A charged particle describes a circle in a magnetic field:

$$\vec{B} \quad \otimes$$

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

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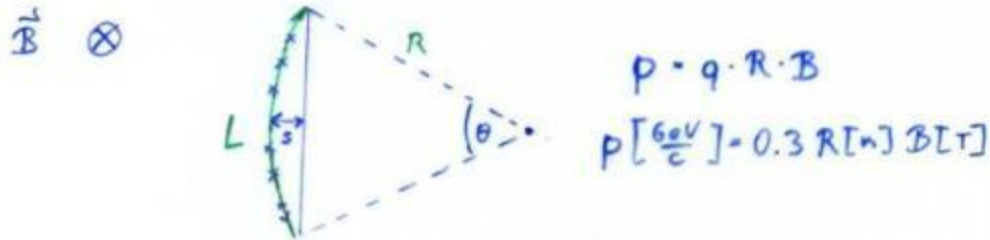
$$L = R \cdot \theta$$

$$S = R\left(1 - \cos\frac{\theta}{2}\right) \sim R\frac{\theta^2}{8} = \frac{L^2}{8R} \rightarrow R = \frac{L^2}{8S}$$

$$\Delta p = 0.3 \, B \, \Delta R = 0.3 \, B \, \frac{L^2}{8S^2} \, \Delta S$$

$$\Delta S = \frac{\sigma_x}{\sqrt{N}} \qquad \sigma_x \ldots \text{point resolution}, \quad N \ldots \text{Measured Points}$$

$$\boxed{\frac{\Delta p}{p} = \frac{\Delta S}{S} = \frac{\sigma_x [m]}{\sqrt{N}} \cdot \frac{3.3 \cdot 8 \, p\left[\frac{GeV}{c}\right]}{B[T] \cdot L^2 [m']}}$$

$$E.g: \quad p = 10 \, \frac{GeV}{c}, \quad B = 1T, \quad L = 1m, \quad \sigma = 200 \mu m, \quad N = 25$$

$$\frac{\Delta p}{p} = 0.01 \rightarrow 1\%$$

Limit → Multiple Scattering

Multiple Scattering

Magnetic Deflection
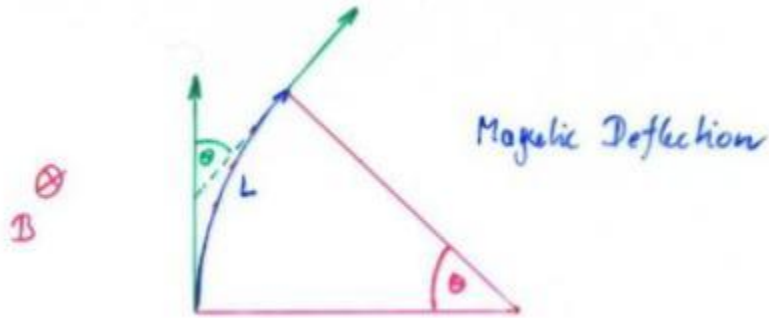
$$p\left[\frac{GeV}{c}\right] \cdot 0.3 \; R[m] \; B[T]$$

$$\theta = \frac{L}{R} = \frac{L}{p} \cdot 0.3 \, B$$

$$\frac{\Delta p}{p} = \frac{\Delta \theta}{\theta} = \frac{\theta_0}{\theta} \sim \frac{0.05}{B[T]L[m]} \cdot \sqrt{\frac{L}{X_0}}$$

→ Independent of p

$$\frac{\Delta p}{p}\bigg|_{tot} = \sqrt{\left(\frac{\Delta p}{p}\bigg|_{Sag}\right)^2 + \left(\frac{\Delta p}{p}\bigg|_{ms}\right)^2}$$

Sagitta

total

Multiple Scattering
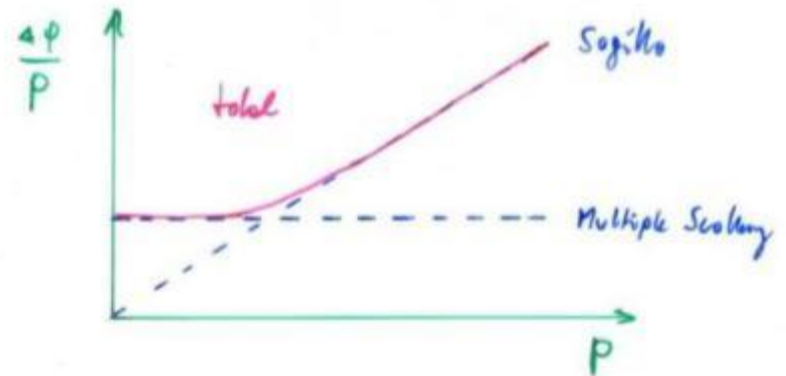
Multiple Scattering

ATLAS Muon Spectrometer:

N=3, sig=50um, P=1TeV,

L=5m, B=0.4T

Δp/p ~ 8% for the most energetic muons at LHC

π^-

p

γ_1

Λ°

K^+

γ_2

K°

π°

π^-

Ω^-

K^-

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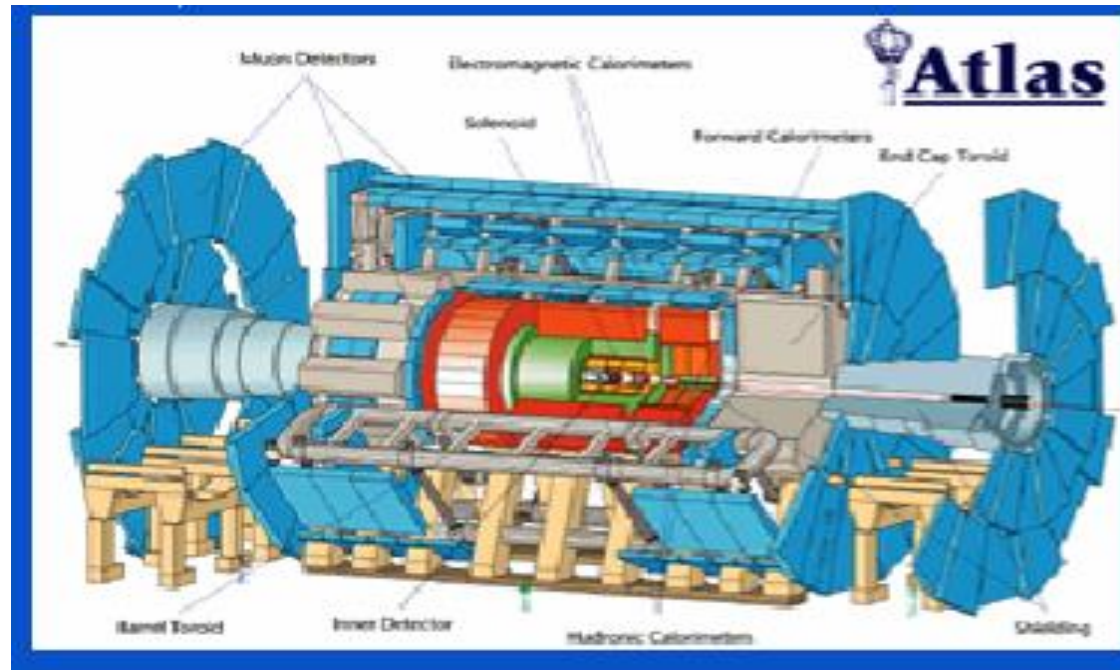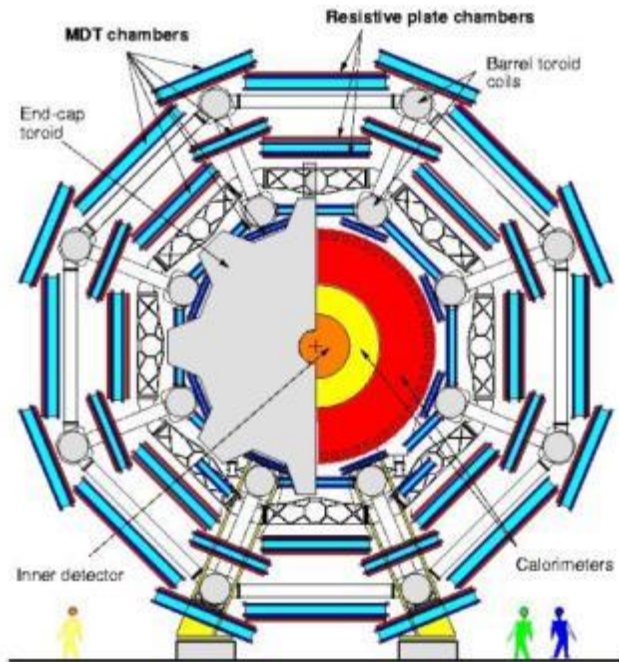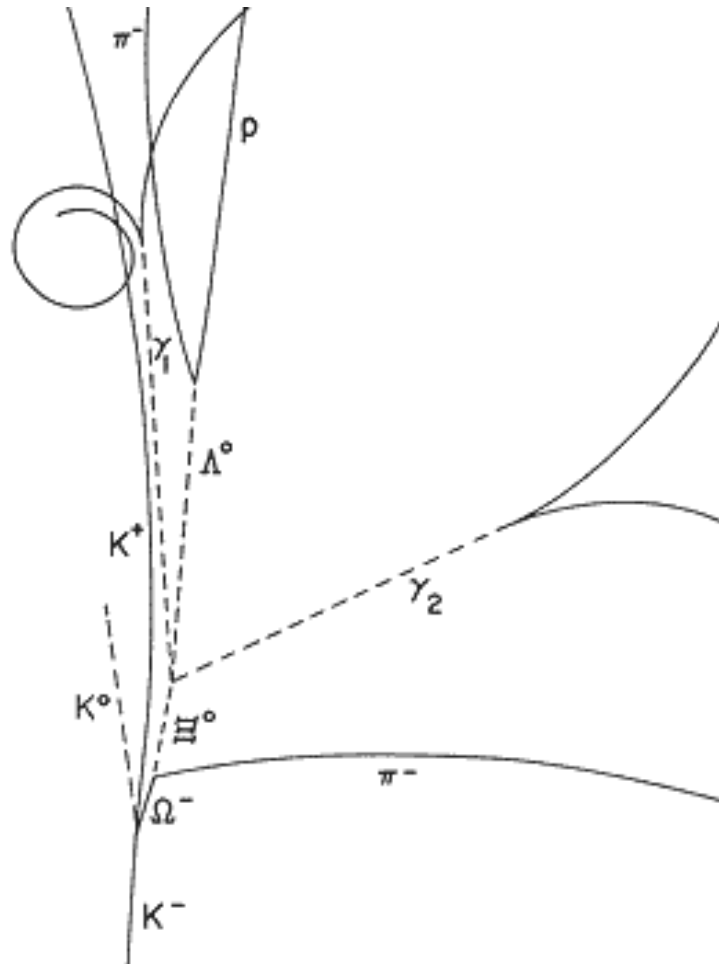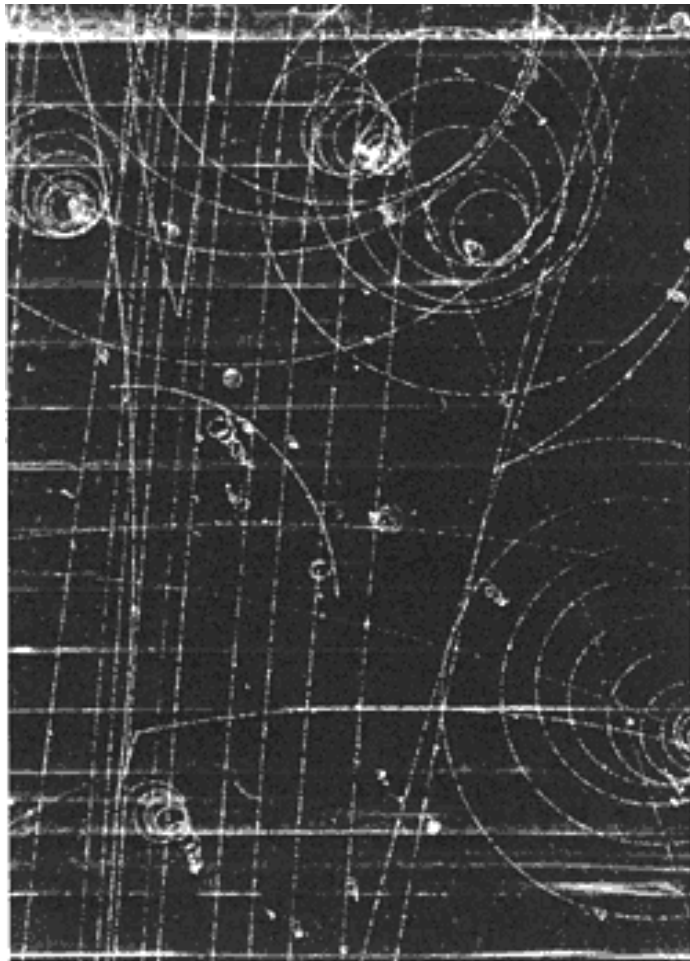
Electromagnetic Interaction of Particles with Matter

Z_2 electrons, $q=-e_0$

M, $q=Z_1 e_0$
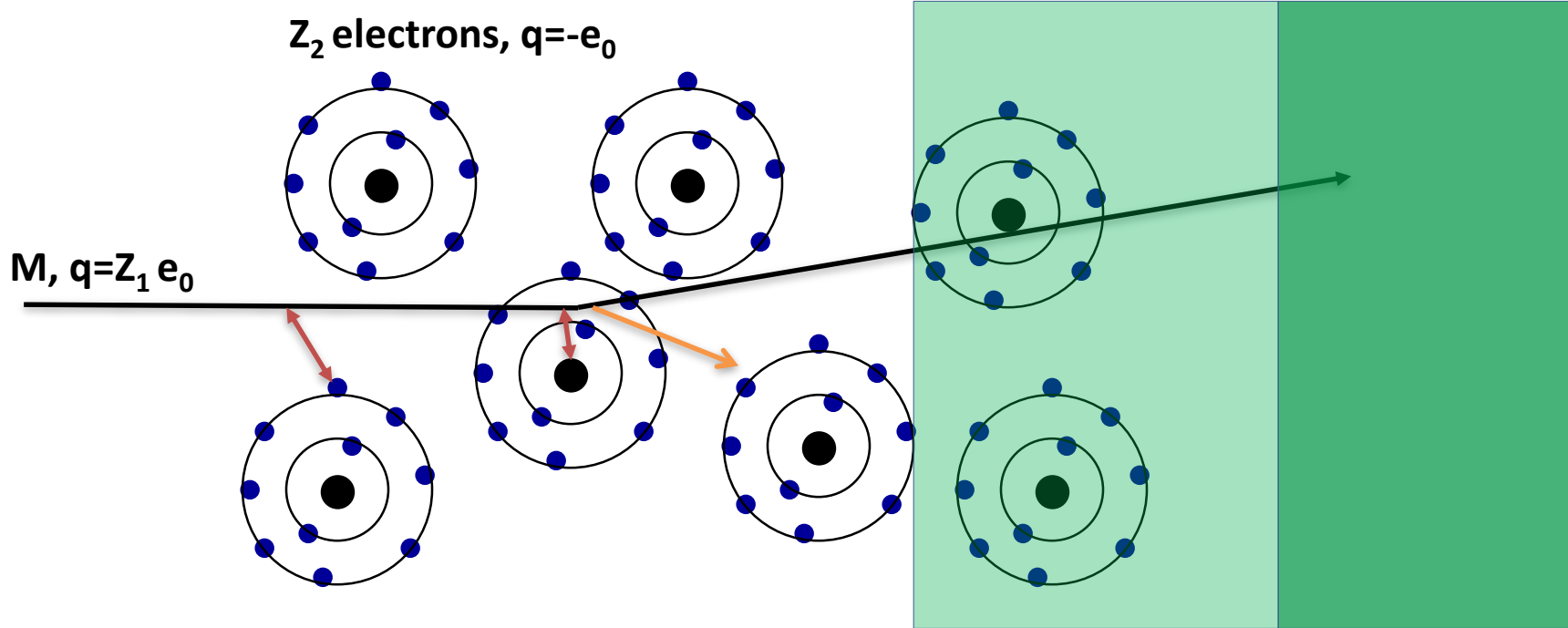
Interaction with the atomic electrons. The incoming particle loses energy and the atoms are <u>excited</u> or <u>ionized.</u>

Interaction with the atomic nucleus. The particle is deflected (scattered) causing <u>multiple scattering</u> of the particle in the material. During this scattering a <u>Bremsstrahlung</u> 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 <u>Cherenkov Radiation</u>. 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 <u>Transition radiation</u>.

Bremsstrahlung, Classical

$$\frac{d\sigma}{d\Omega} = \left(\frac{2 z_1 z_2 e^2}{4\pi\varepsilon_0 \, p\cdot v}\right)^2 \frac{1}{(2\sin\frac{\theta}{2})^4} \qquad p = M v \gamma$$

"Rutherford Scattering"

Written in Terms of Momentum Transfer $Q^2 = 2p^2(1-\cos\theta)$

$$\frac{d\sigma}{dQ} = 8\pi \left(\frac{z_1 z_2 e^2}{4\pi\varepsilon_0 \, \beta c}\right)^2 \cdot \frac{1}{Q^3}$$

$$Q = |\vec{p} - \vec{p}\,'|$$

→ From Maxwell's Eq (Jackson)

$$\lim_{\omega\to 0} \frac{dI}{d\omega} \sim \frac{2}{3\pi} \frac{z_1^2 e^2}{M^2 c^3} \frac{1}{4\pi\varepsilon_0} Q^2, \text{ Radiated Energy between } \omega, \omega+d\omega$$

$$\frac{dE}{dx} = \frac{N_A \varrho}{A} \cdot \int_0^{\omega_{max}} d\omega \int_{Q_{min}}^{Q_{max}} dQ \frac{dI}{d\omega} \cdot \frac{d\sigma}{dQ} \qquad , \ \omega_{max} = \frac{E}{\hbar}$$

$$\frac{dE}{dx} = \frac{N_A \varrho}{A} \cdot \frac{16}{3} \alpha \cdot Z^2 \cdot \left(\frac{z_1^2 e^2}{4\pi\varepsilon_0 \, M c^2}\right)^2 \cdot E \cdot \ln\frac{Q_{max}}{Q_{min}}$$

$$\alpha = \frac{e^2}{4\pi\varepsilon_0 \hbar c} \sim \frac{1}{137}$$

A charged particle of mass M and charge q=Z_1e is deflected by a nucleus of Charge Ze.

Because of the acceleration the particle radiated EM waves → energy loss.

Coulomb-Scattering (Rutherford Scattering) describes the deflection of the particle.

Maxwell's Equations describe the radiated energy for a given momentum transfer.

→ dE/dx

Proportional to Z^2/A of the Material.

Proportional to Z_1^4 of the incoming particle.

Proportional to ρ of the material.

Proportional $1/M^2$ of the incoming particle.

Proportional to the Energy of the Incoming particle →

$E(x)=Exp(-x/X_0)$ – 'Radiation Length'

$X_0 \propto M^2 A/ (\rho\ Z_1^4\ Z^2)$

X_0: Distance where the Energy E_0 of the incoming particle decreases $E_0 Exp(-1)=0.37 E_0$.

Critical Energy

such as copper to about 1% accuracy for energies between about 6 MeV and 6 GeV

For the muon, the second lightest particle after the electron, the critical energy is at 400GeV.

The EM Bremsstrahlung is therefore only relevant for electrons at energies of past and present detectors.
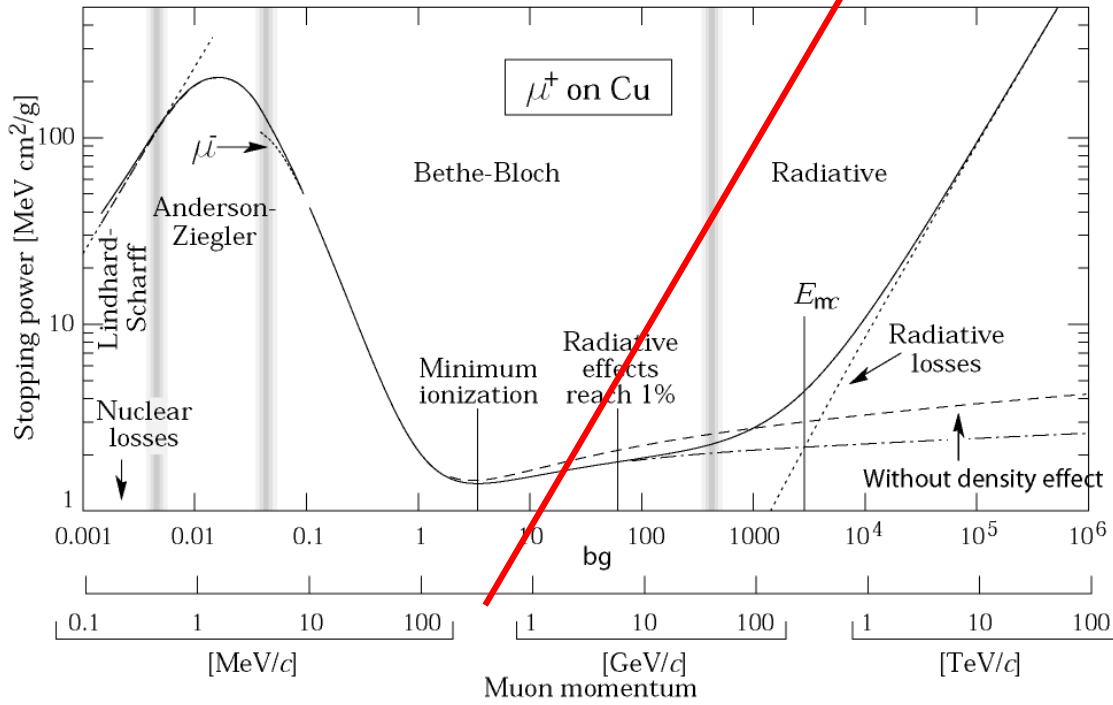
Electron Momentum   5   50   500   MeV/c

Critical Energy: If dE/dx (Ionization) = dE/dx (Bremsstrahlung)

Myon in Copper: p ≈ 400GeV
Electron in Copper: p ≈ 20MeV

Pair Production, QM
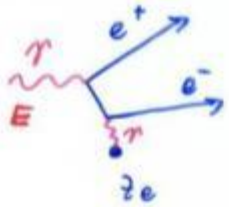
$\gamma + Nucl. \rightarrow e^+ + e^- + Nucl$

The Diagram is very similar to Bremsstrahlung
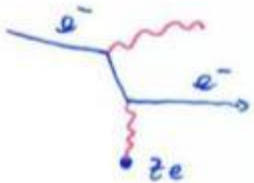
$e^- + Nucl \rightarrow \gamma + e^- + Nucl$

"Crossing Symetry: bring particle to the other side and make it the antiparticle" → 'some' correction ...

$$\frac{d\sigma'(E,E')}{dE'} = 4\alpha Z^2 r_e^2 \frac{1}{E} \cdot G(E,E') \qquad E \gg 137 m_e c^2 Z^{-\frac{1}{3}}$$

$$G(E,E') \cdot \left[\left(\frac{E'+m_ec^2}{E}\right)^2 + \left(1 - \frac{E'+m_ec^2}{E}\right)^2 + \frac{2}{3}\frac{E'+m_ec^2}{E}\left(1 - \frac{E'+m_ec^2}{E}\right) \ln Z^{-\frac{1}{3}} \right.$$
$$\left. - \frac{1}{3}\frac{E'+m_ec^2}{E}\left(1 - \frac{E'+m_ec^2}{E}\right) \right]$$

$$\sigma = \int_0^{E-2m_ec^2} \frac{d\sigma'}{dE'} dE' = 4\alpha Z^2 r_e^2 \cdot \frac{7}{3} \ln 183 Z^{-\frac{1}{3}}$$

$$P(x) = \frac{1}{\lambda} e^{-\frac{x}{\lambda}} \qquad \underline{\lambda = \frac{A}{9 N_A \sigma} = \frac{9}{7} X_0}$$

↳ Probability that Photon converts to $e^+ e^-$ after a distance x.

Average distance a high energy photon has to travel before it converts into an $e^+ e^-$ pair is equal to 9/7 of the distance that a high energy electron has to travel before reducing it's energy from E_0 to E_0*Exp(-1) by photon radiation.

Bremsstrahlung + Pair Production → EM Shower
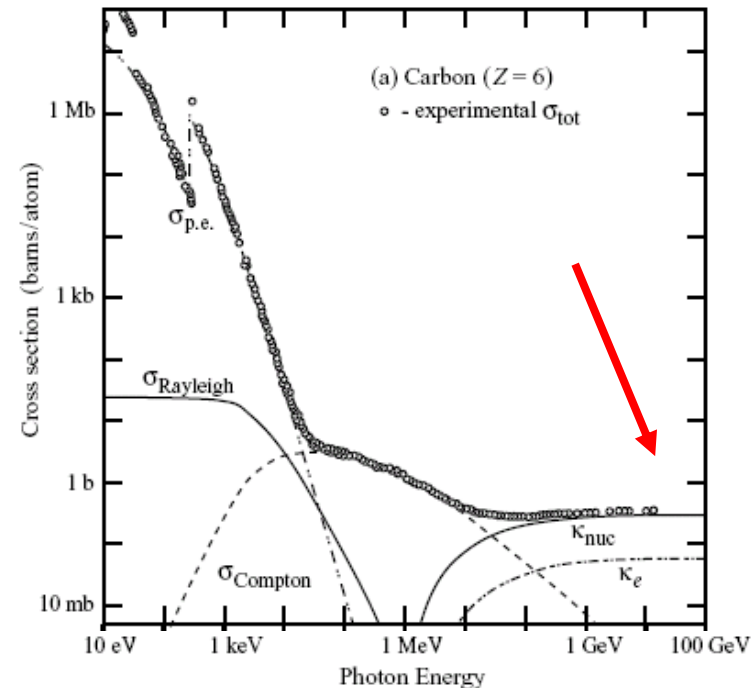
Tracking:

Momentum by bending in the B-field

Secondary vertices

Calorimeter:

Energy by absorption

Muons:

Only particles passing through calorimeters

TRACKING velocity measurement	CALORIMETERS electromagnetic	hadronic	MUONS	
ELECTRONS				$e^\pm$
PHOTONS				γ
CHARGED HADRONS				$p^\pm, k^\pm, \pi^\pm$
NEUTRAL HADRONS (e.g. neutrons)				k^0, n
MUONS				$\mu^\pm$

Typical dimensions [cm]: 100 – 200 | 50 – 100 | 200 – 400 | 200 – 400

$\vec{B}$ ⊘

Low | High | High | Tracking
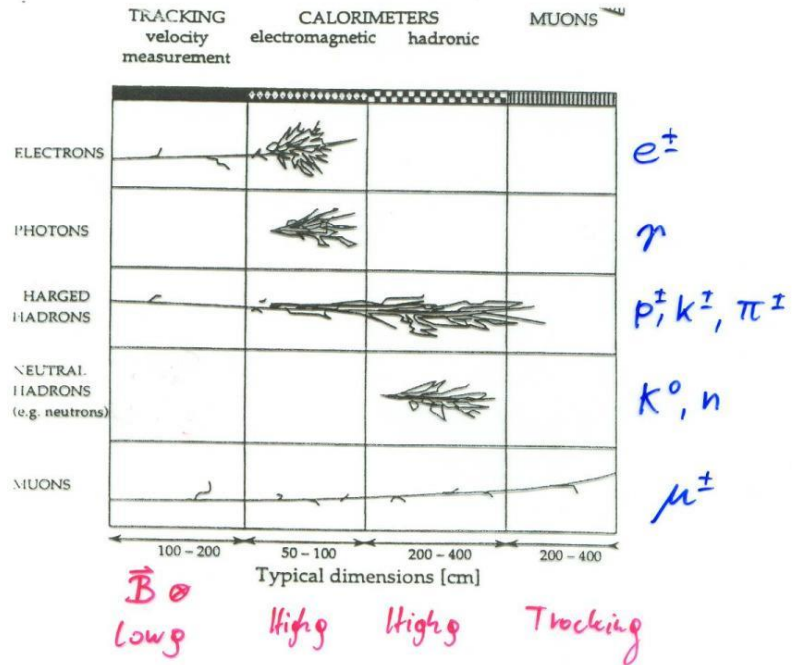
- Electrons ionize and show Bremsstrahlung due to the small mass

- 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

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

Vertex Detector
Inner Tracking Chamber
Time Projection Chamber
Electromagnetic Calorimeter
Hadron Calorimeter
Muon Detectors
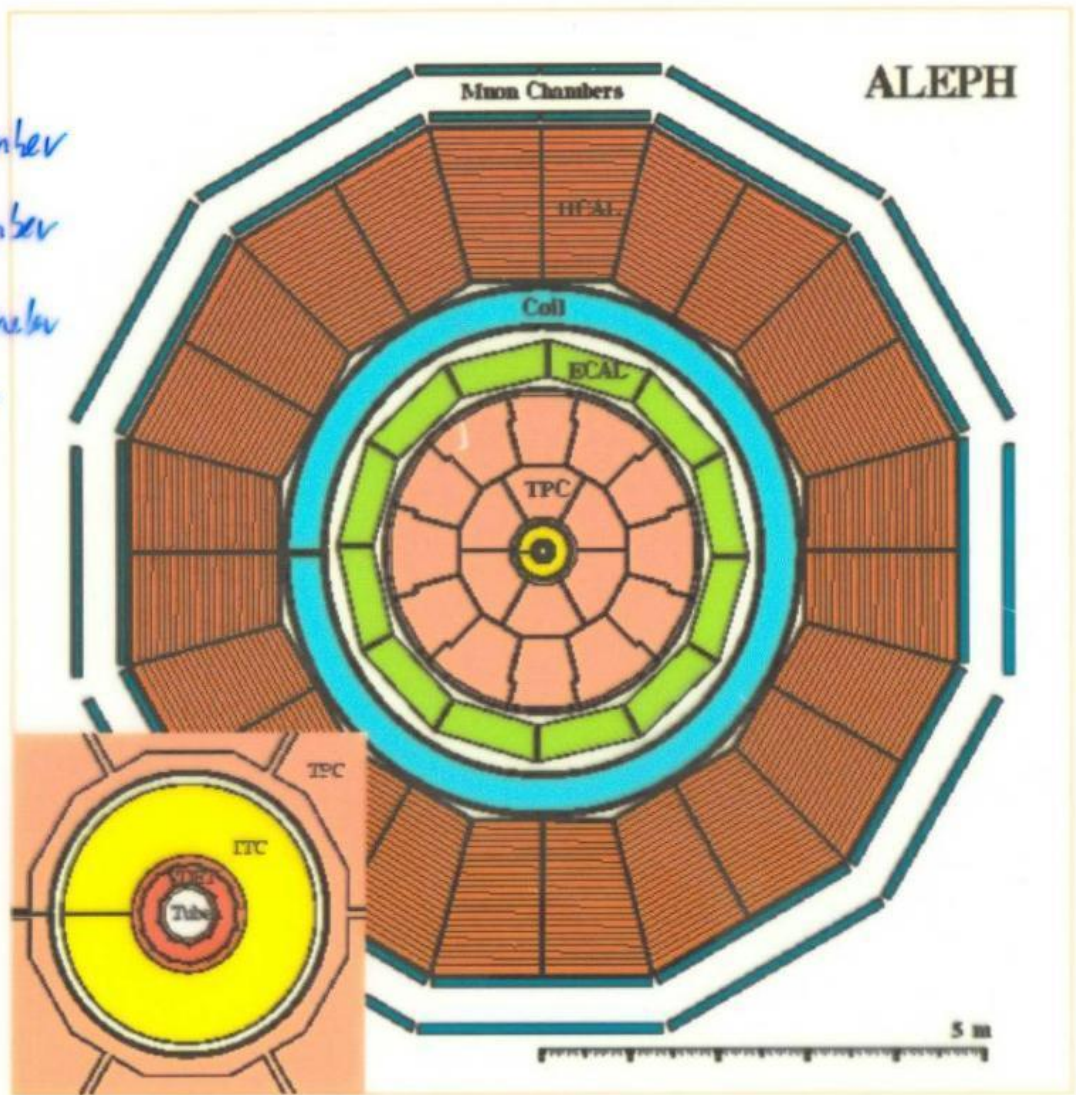
Fig. 1 - The ALEPH Detector
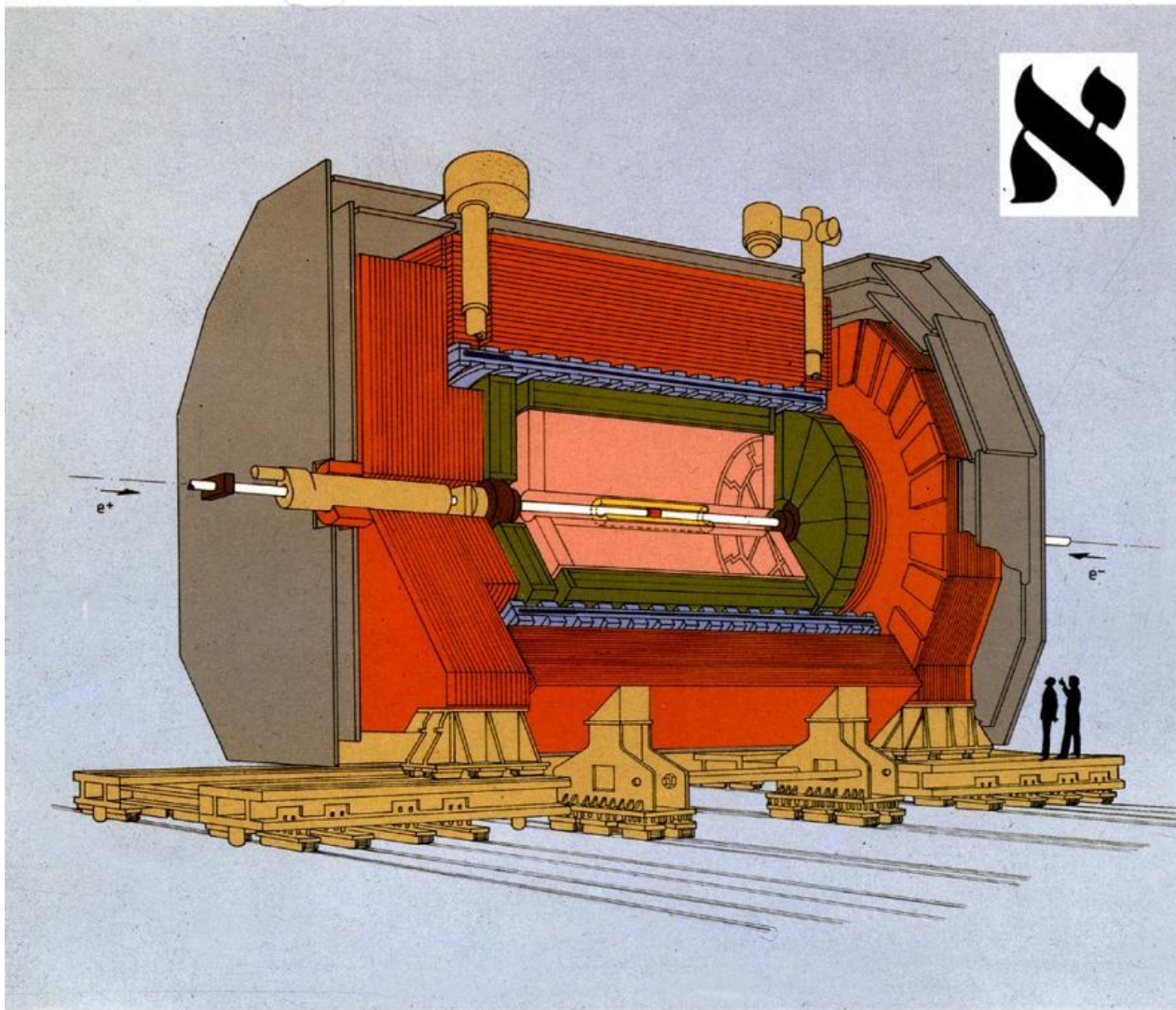
Vertex Detector

Inner Track Chamber

Time Projection Chamber

Electromagnetic Calorimeter

Superconducting Magnet Coil

Hadron Calorimeter

Muon Detection Chambers

Luminosity Monitors

e^+

e^-

W. Riegler/CERN

$\gamma, e^{\pm}, \pi^{\pm}, k^{\pm}$

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

ALEPH

W. Riegler/CERN
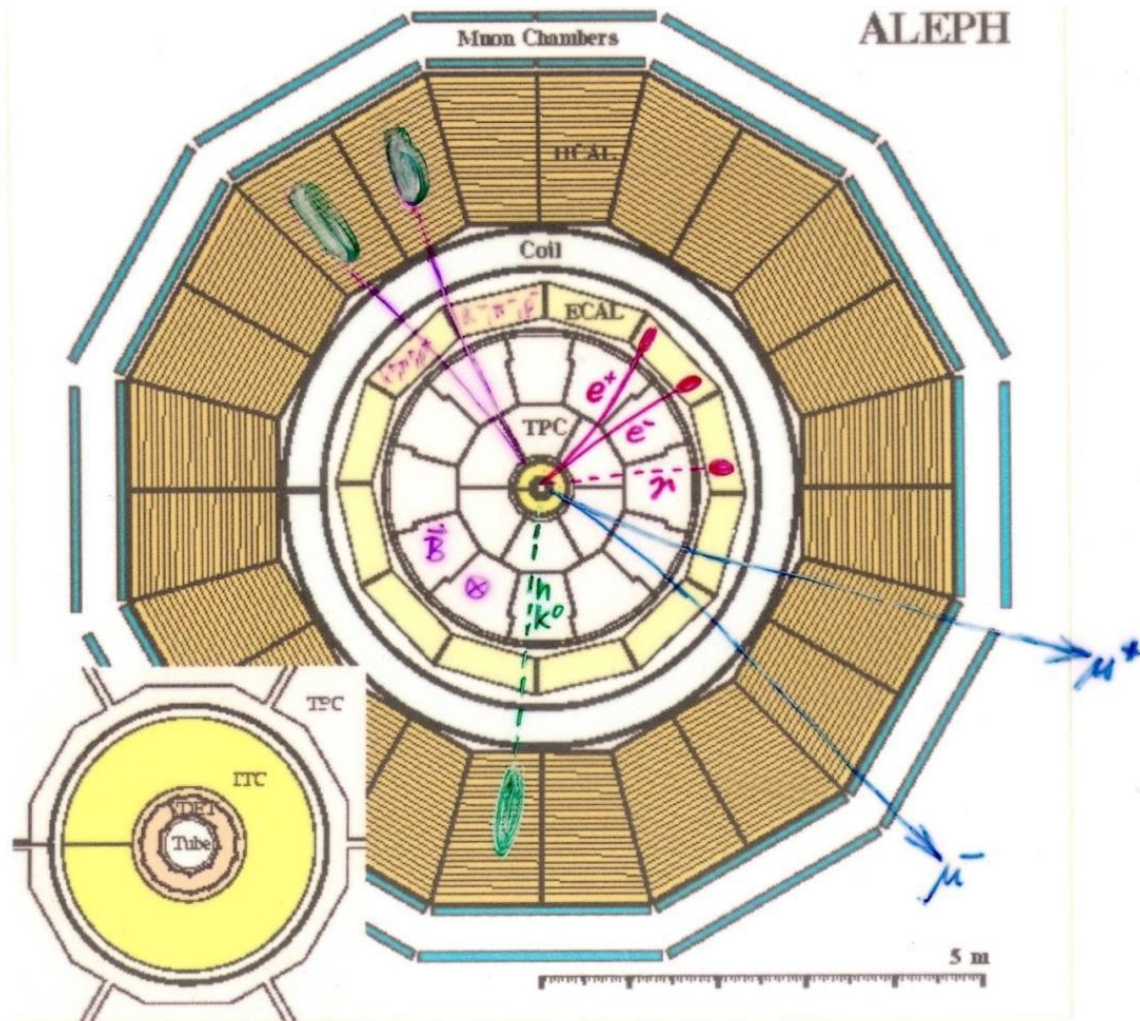
CMS

A Compact Solenoidal Detector for LHC

FORWARD CALORIMETER

MUON CHAMBERS

TRACKER

CRYSTAL ECAL

HCAL

SUPERCONDUCTING COIL

RETURN YOKE

Total weight : 12,500t.
Overall diameter : 15.00m
Overall length : 21.60m
Magnetic field : 4 Tesla

0m   1m   2m   3m   4m   5m   6m   7m

Key:
— Muon
— Electron
— Charged Hadron (e.g. Pion)
– – Neutral Hadron (e.g. Neutron)
– – Photon

4T

2T

Silicon
Tracker

Electromagnetic
Calorimeter

Hadron
Calorimeter

Superconducting
Solenoid

Iron return yoke interspersed
with Muon chambers

Transverse slice
through CMS

D. Barney, CERN, February 2004

W. Riegler/CERN

Z → e⁺ e⁻

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

W. Riegler/CERN

Z → μ⁺ μ⁻
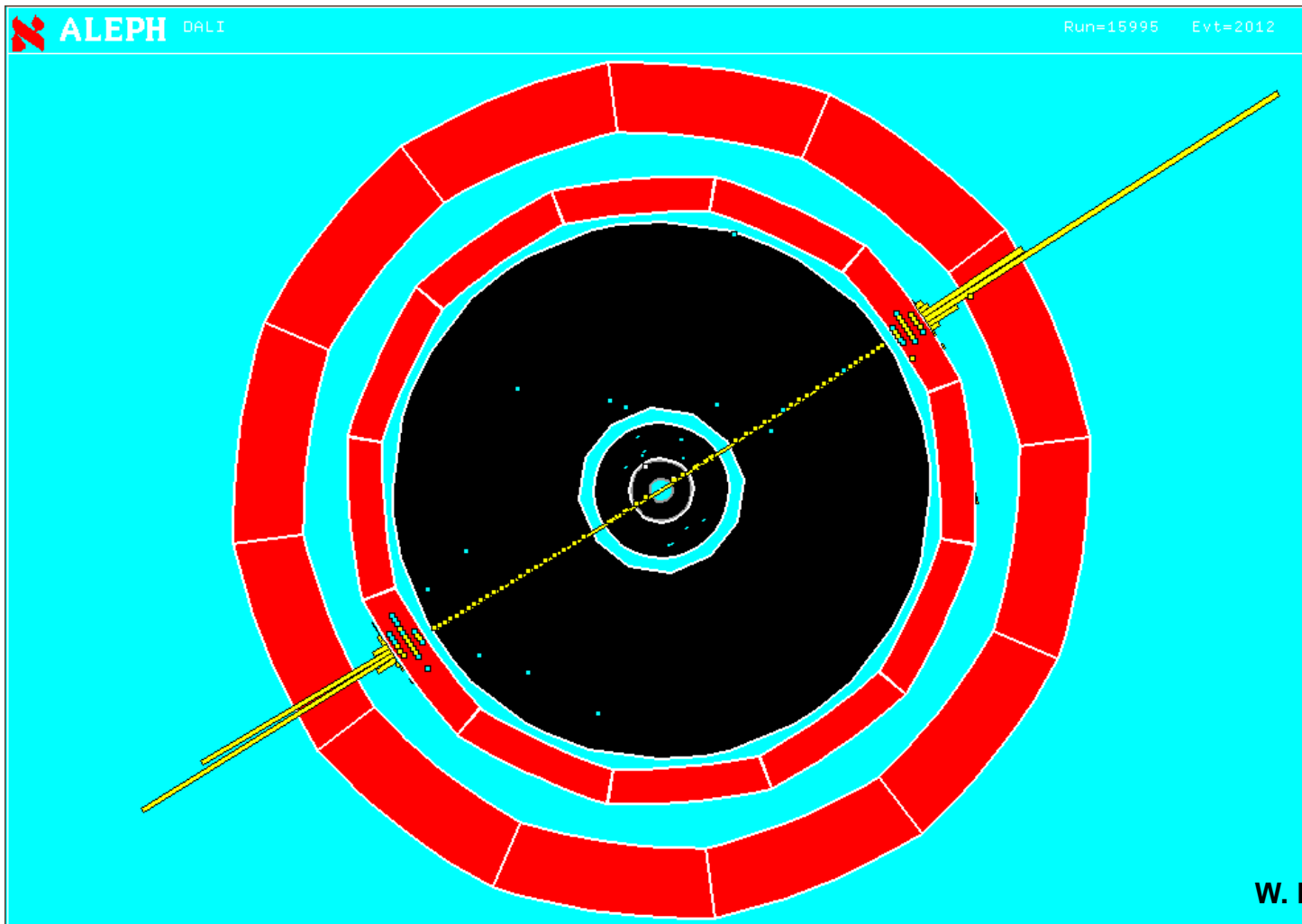
Two high momentum charged particles traversing all calorimeters and leaving a signal in the muon chambers.

W. Riegler/CERN
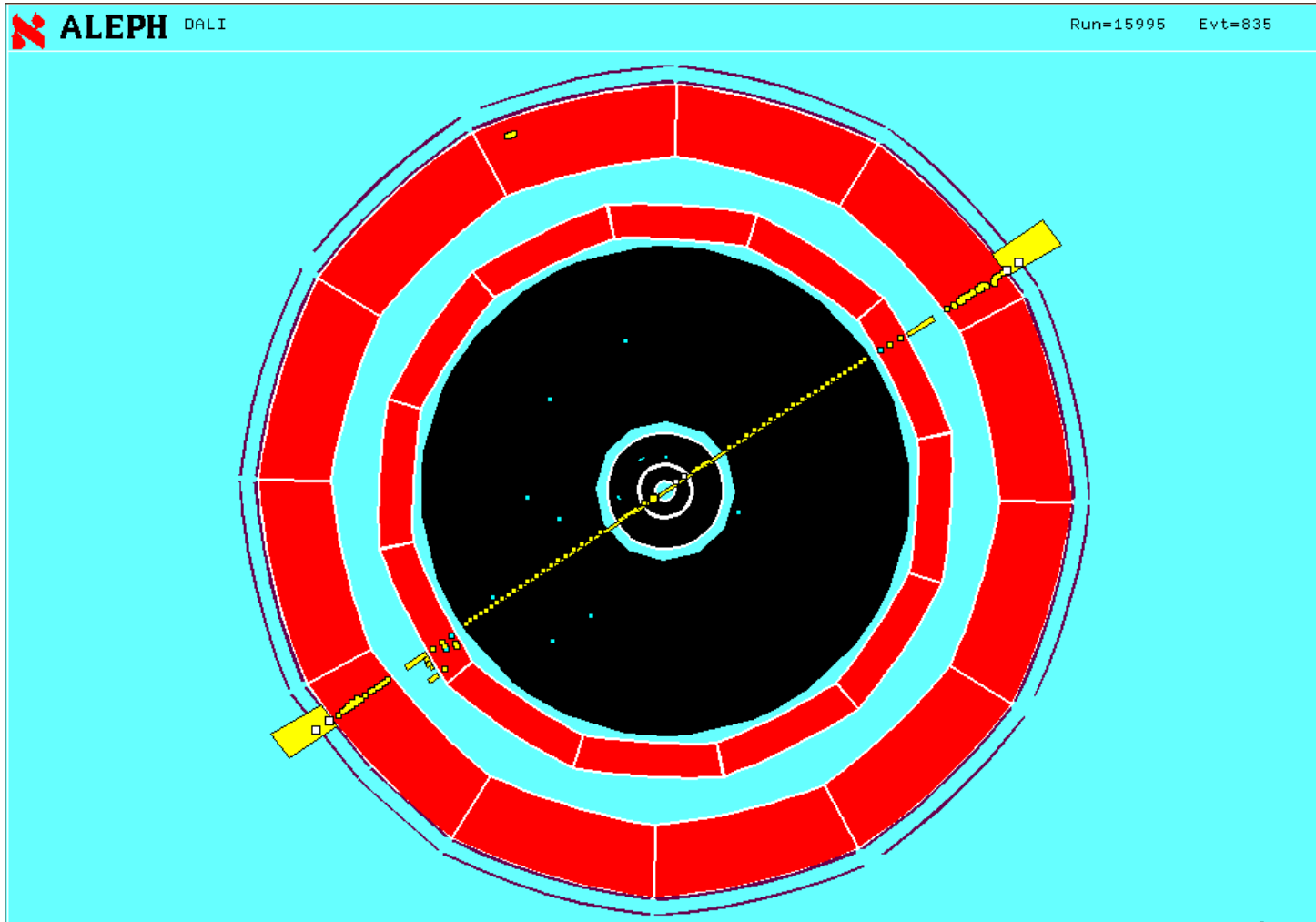
Interaction of Particles with Matter

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!"

W. Riegler/CERN

$W^+W^- \rightarrow e + \bar{\nu}_e + \nu + \mu$

Single electron, single Muon, Missing Momentum

W. Riegler/CERN
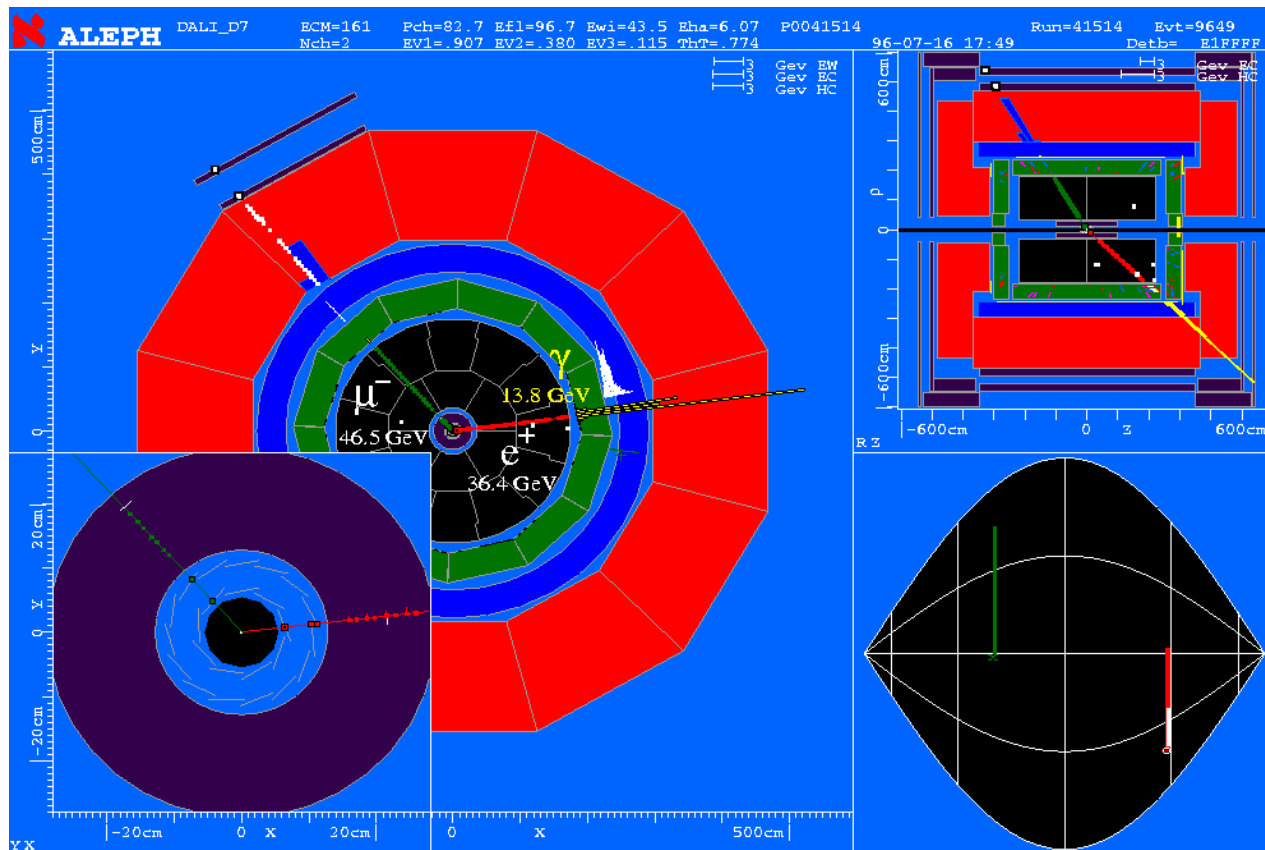
$Z \rightarrow q\, \bar{q}$

Two jets of particles

ALEPH   DALI   Run=15768   Evt=5906

W. Riegler/CERN
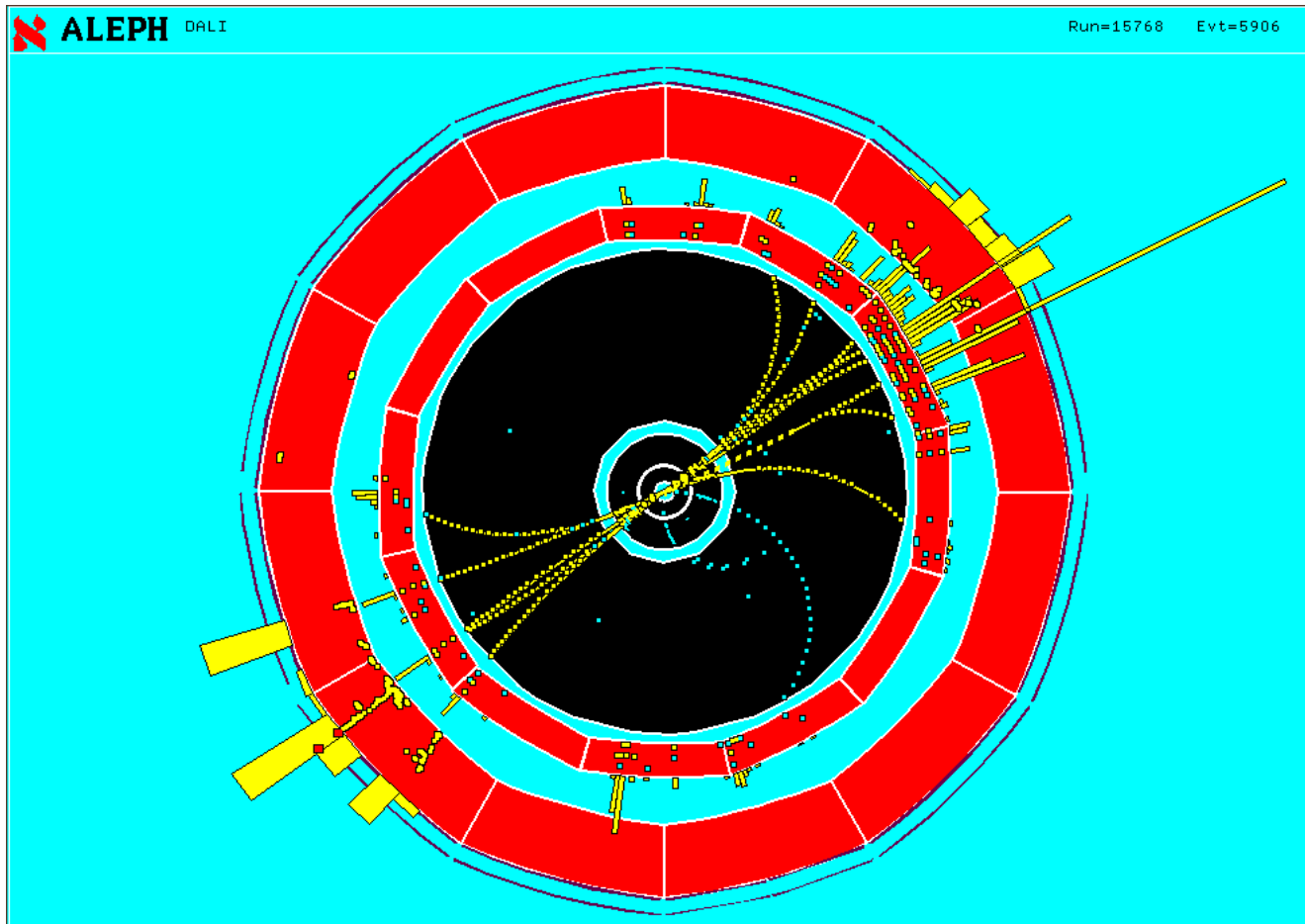
Z → q q̄ g

Three jets of particles

ALEPH DALI   Run=9063   Evt=7848
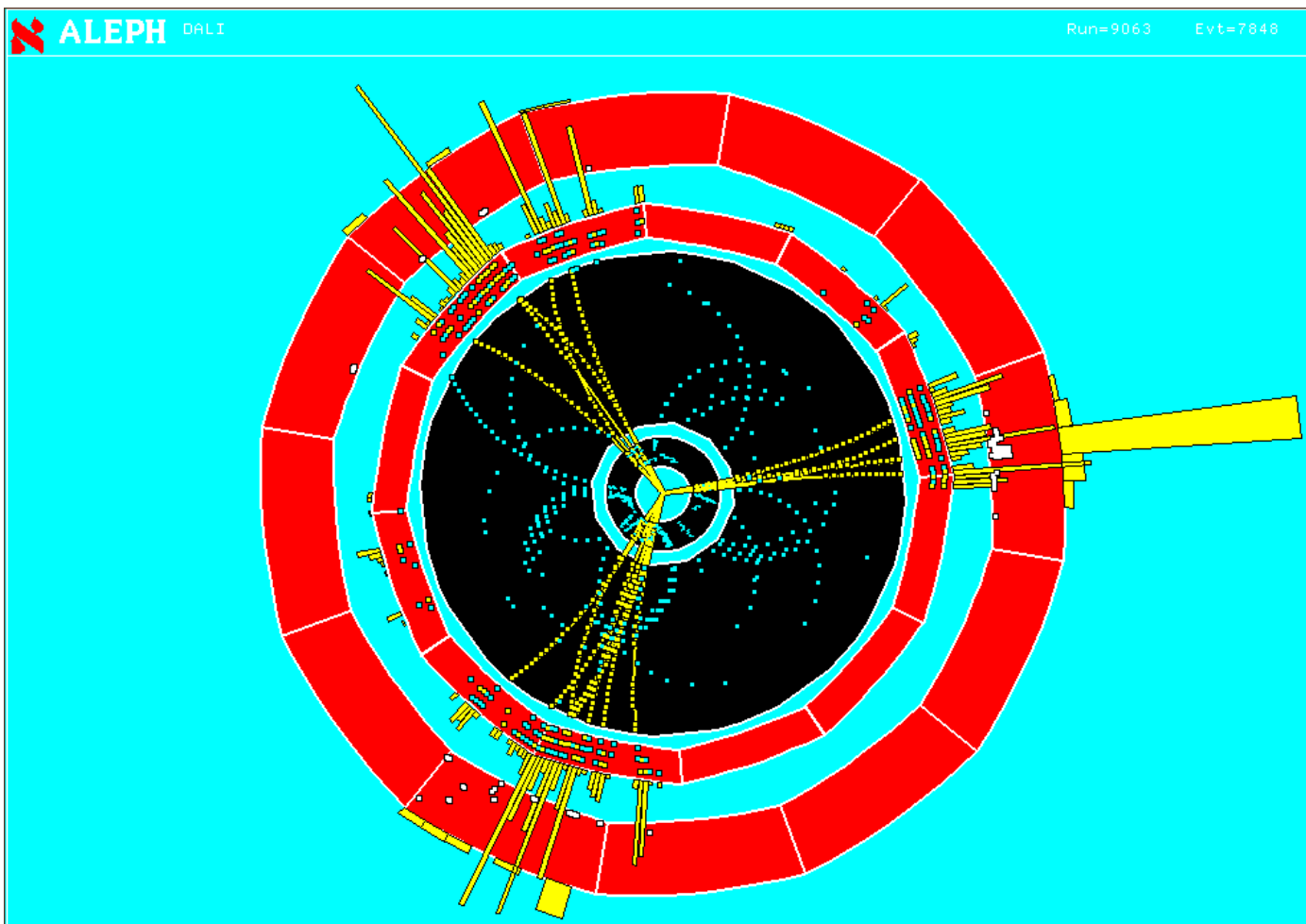
Two secondary vertices with characteristic decay particles giving invariant masses of known particles.

Bubble chamber like – a single event tells what is happening. Negligible background.
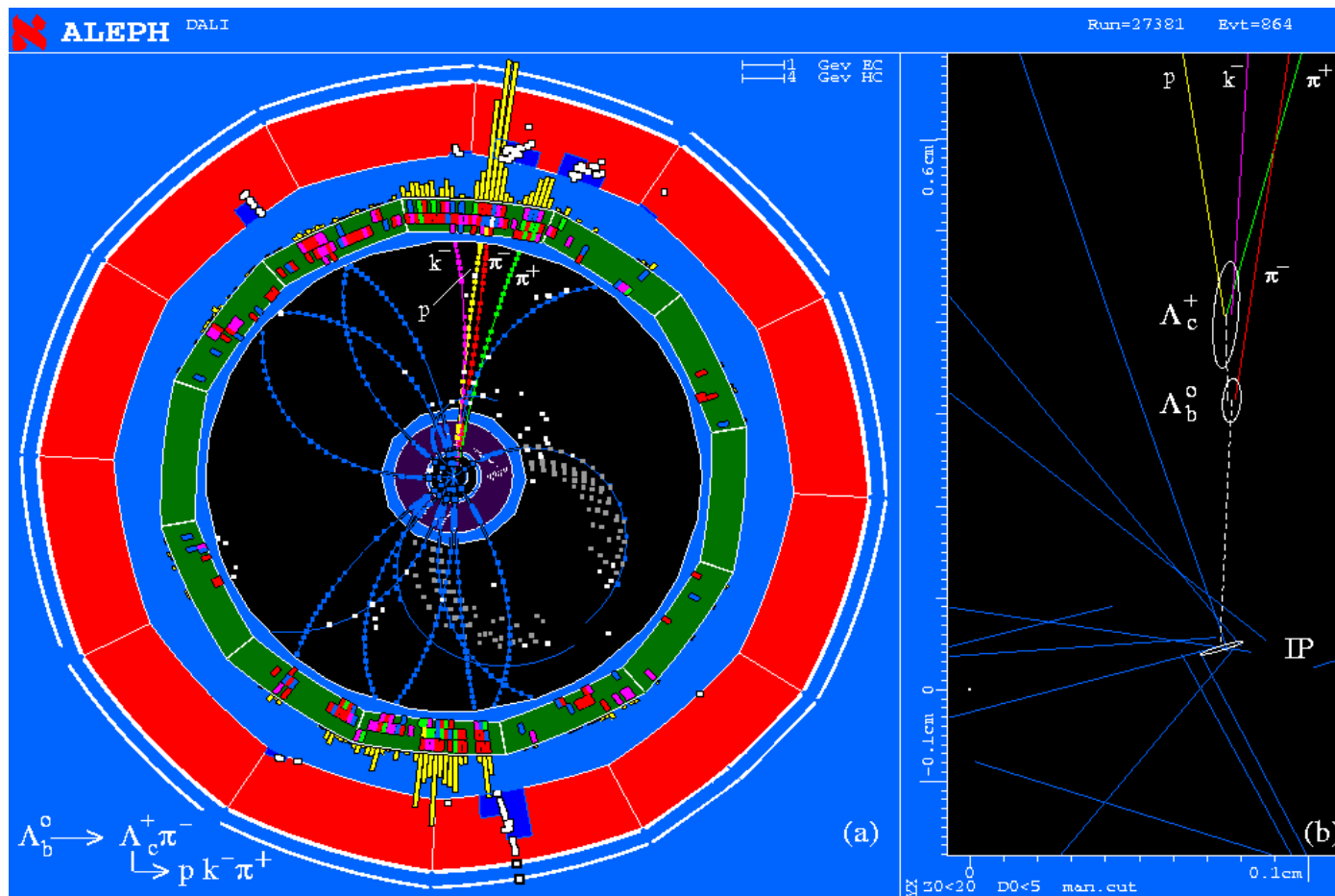
ALEPH Higgs Candidate
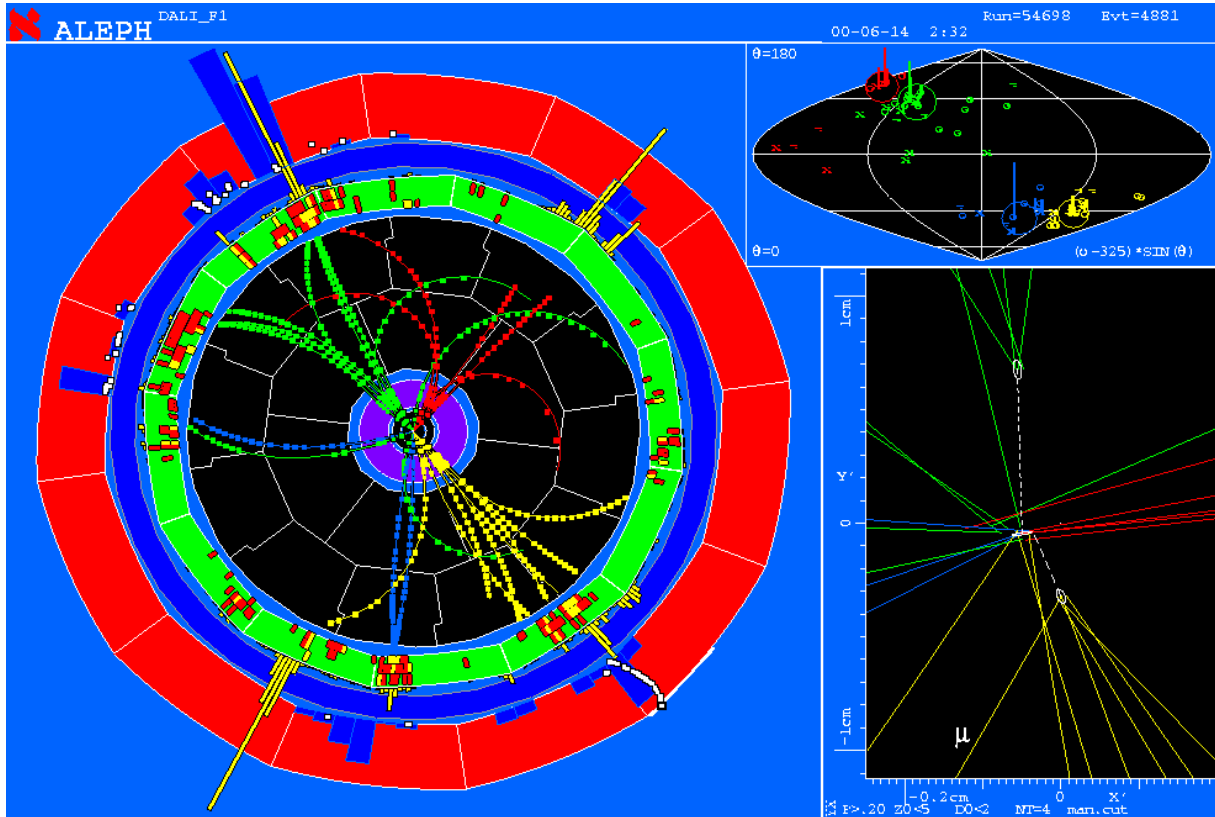
Undistinguishable background exists. Only statistical excess gives signature.

2010 ATLAS W, Z candidates

Run Number: 152409, Event Number: 5966801
Date: 2010-04-05 06:54:50 CEST

W→ev candidate in
7 TeV collisions

$p_T(e+) = 34$ GeV
$\eta(e+) = -0.42$
$E_T^{miss} = 26$ GeV
$M_T = 57$ GeV

Run Number: 154817, Event Number: 968871
Date: 2010-05-09 09:41:40 CEST

$M_{ee} = 89$ GeV

Z→ee candidate in 7 TeV collisions

$E_T(e-) = 45$ GeV $E_T(e+) = 40$ GeV
$\eta(e-) = 0.21$ $\eta(e+) = -0.38$

W. Riegler/CERN

2010 ATLAS W, Z candidates

W. Riegler/CERN
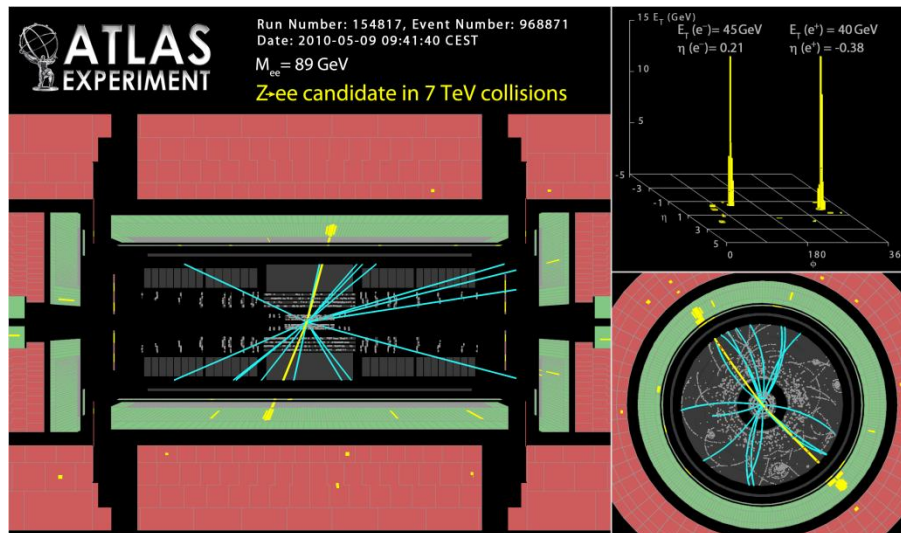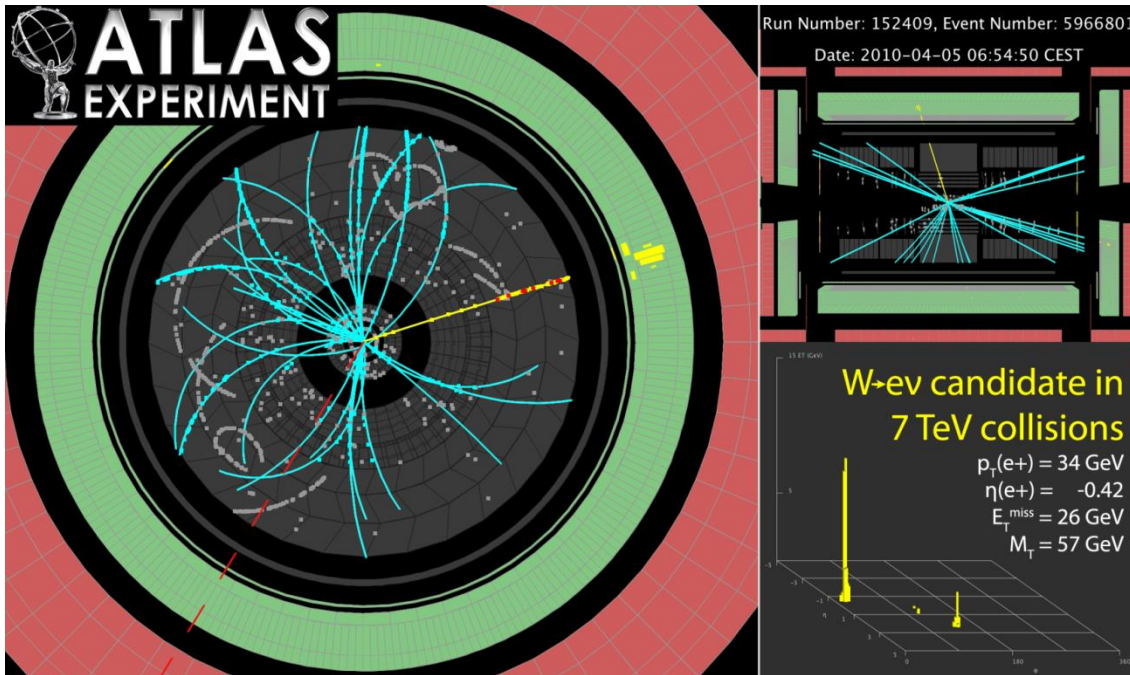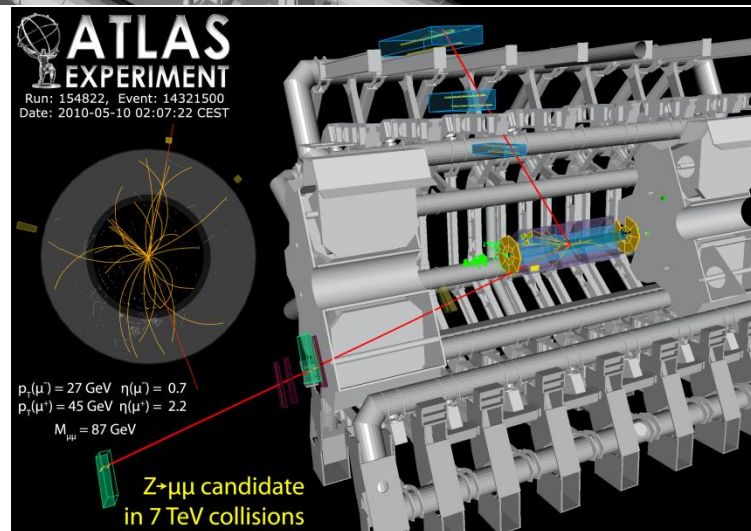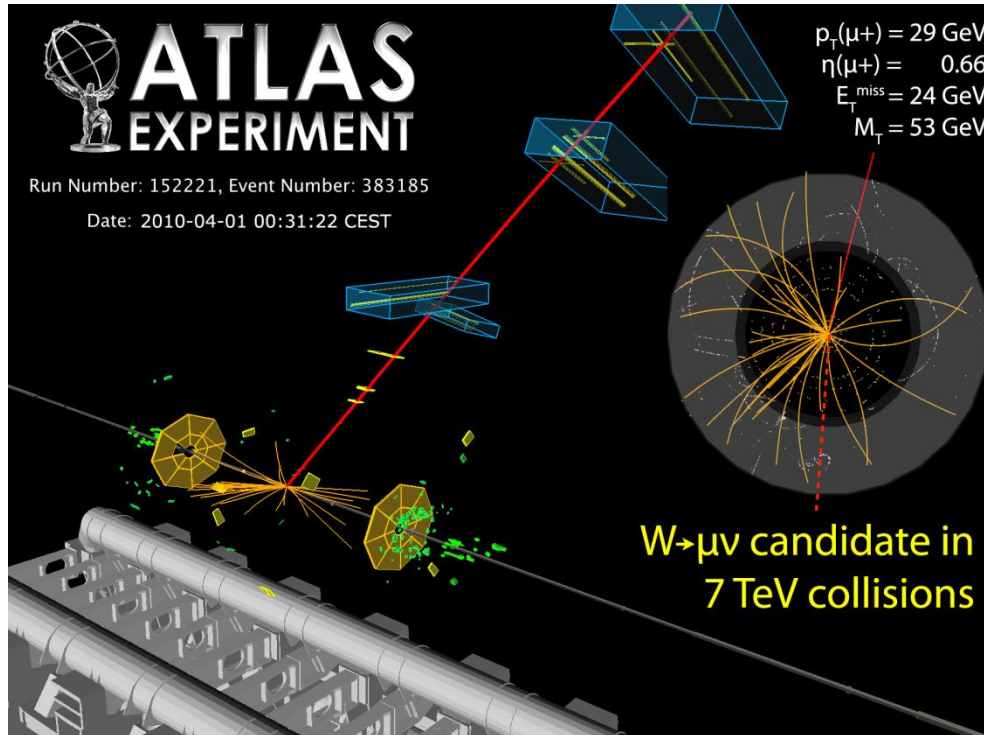
Discovery of 'New' particles
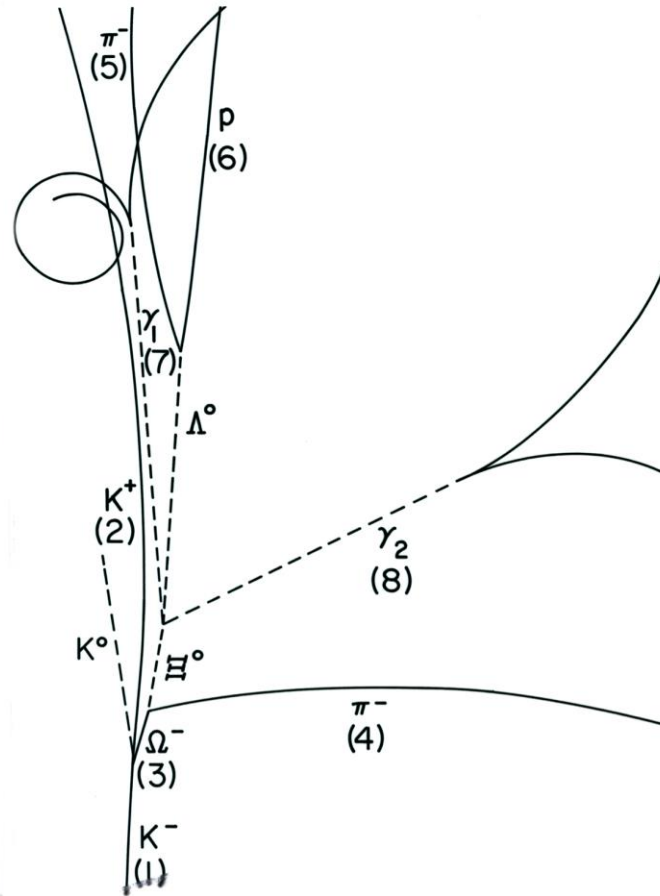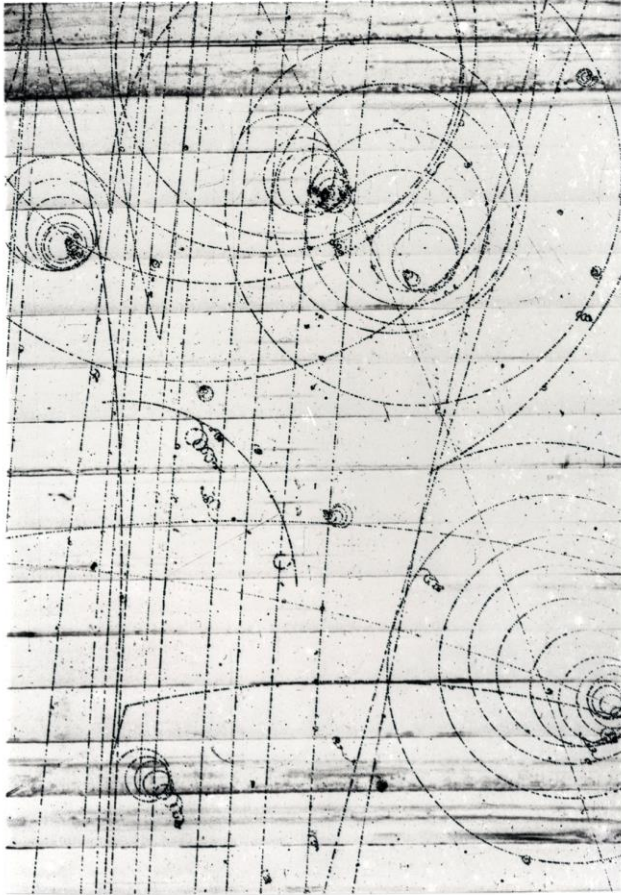
Discovery of omega minus in the Brookhaven National Laboratory 80 inch hydrogen bubble chamber in 1964. Discovery claimed by a single event – 'background free'

Simulated Higgs Boson at CMS

1. H(100 GeV) → γγ
2. H(130 GeV) → ZZ* → e⁺e⁻ e⁺e⁻
3. H(150 GeV) → ZZ* → μ⁺μ⁻μ⁺μ⁻
4. H(800 GeV) → ZZ → e⁺e⁻ jet jet
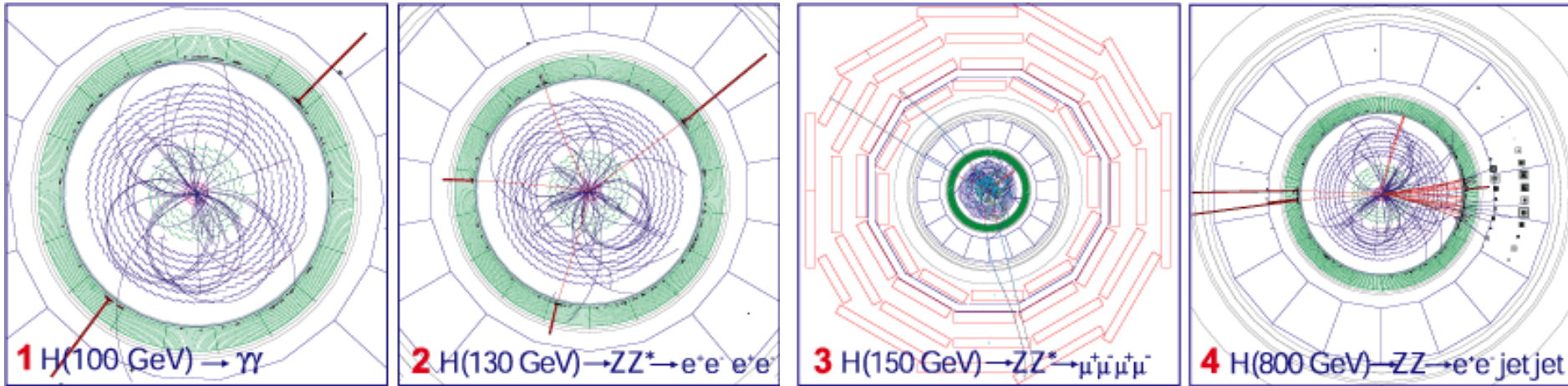
Particles are typically seen as an excess of events above an irreducible (i.e. indistinguishable) background.
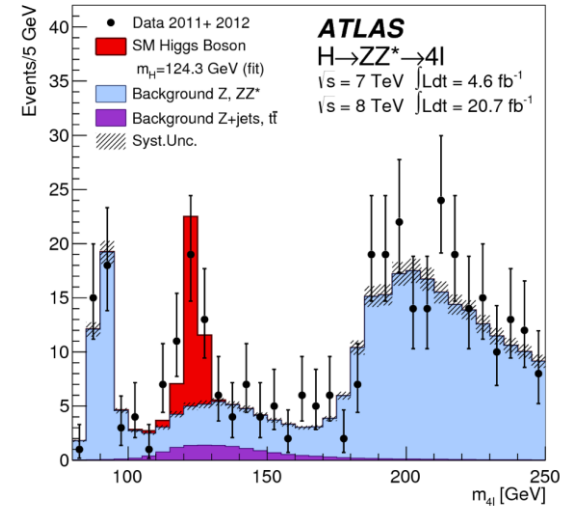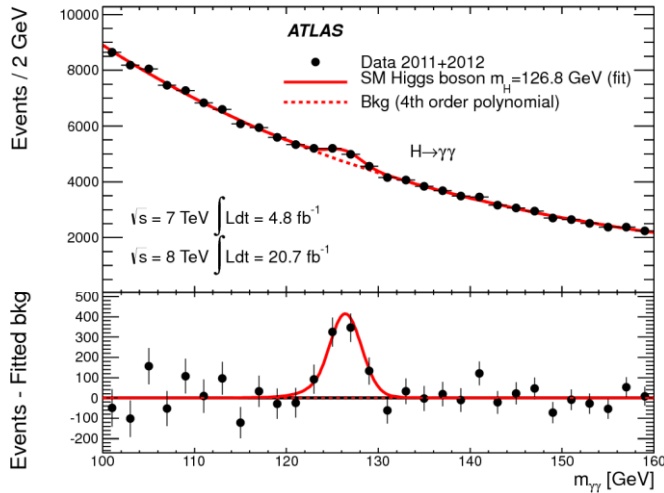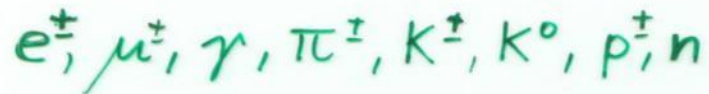
Principles:

Only a few of the numerous known particles have lifetimes that are long enough to leave tracks in a detector.

Most of the particles are measured though the decay products and their kinematic relations (invariant mass). Most particles are only seen as an excess over an irreducible background.

Some short lived particles (b,c –particles) reach lifetimes in the laboratory system that are sufficient to leave short tracks before decaying → identification by measurement of short tracks.

In addition to this, detectors are built to measure the
8 particles

$$e^{\pm}, \mu^{\pm}, \gamma, \pi^{\pm}, K^{\pm}, K^{o}, p^{\pm}, n$$

Their difference in mass, charge and interaction is the key to their identification.

Detector Technologies

Solid state detectors close to the collision point for excellent position resolution to find vertices and secondary vertices → silicon pixel detectors.

Solid state detectors (silicon strip detectors) or gas detectors at larger distances for tracking and momentum measurement.

Massive calorimeters with alternating layers of passive absorber material and active detector material for measurement of particle energies.

W. Riegler/CERN
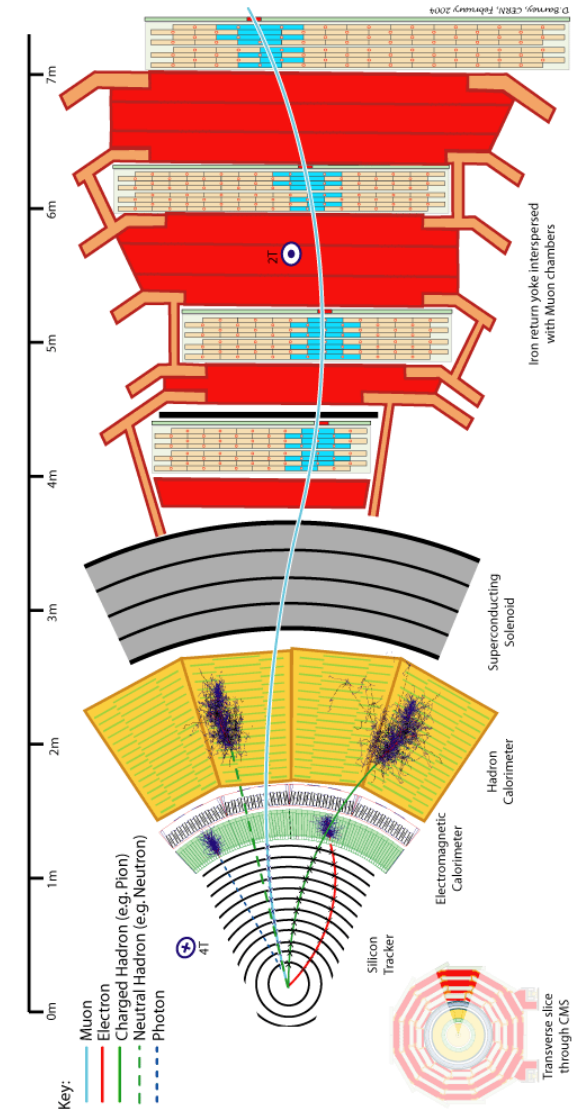
Silicon Pixel Detectors
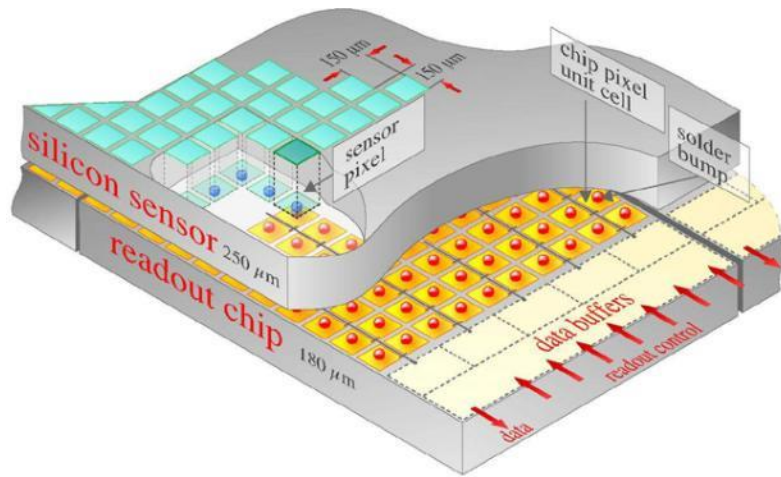
ATLAS: 1.4x10⁸ pixels

40 000 000 'images' per second.
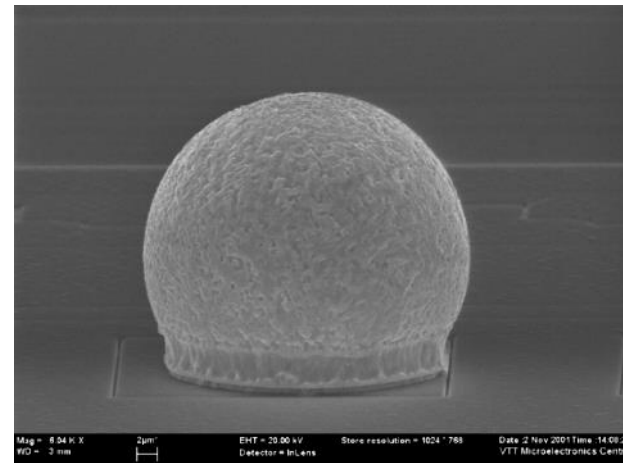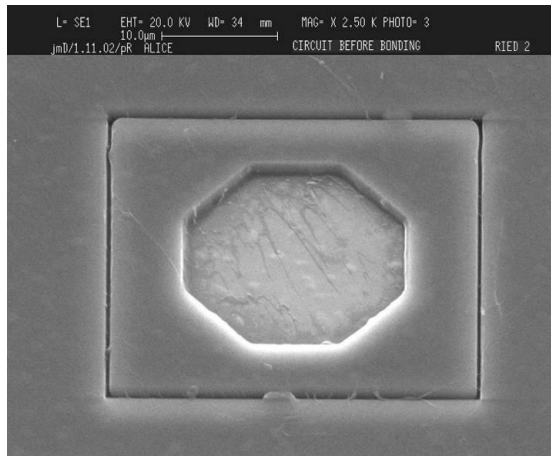
ATLAS Silicon Pixel Detector
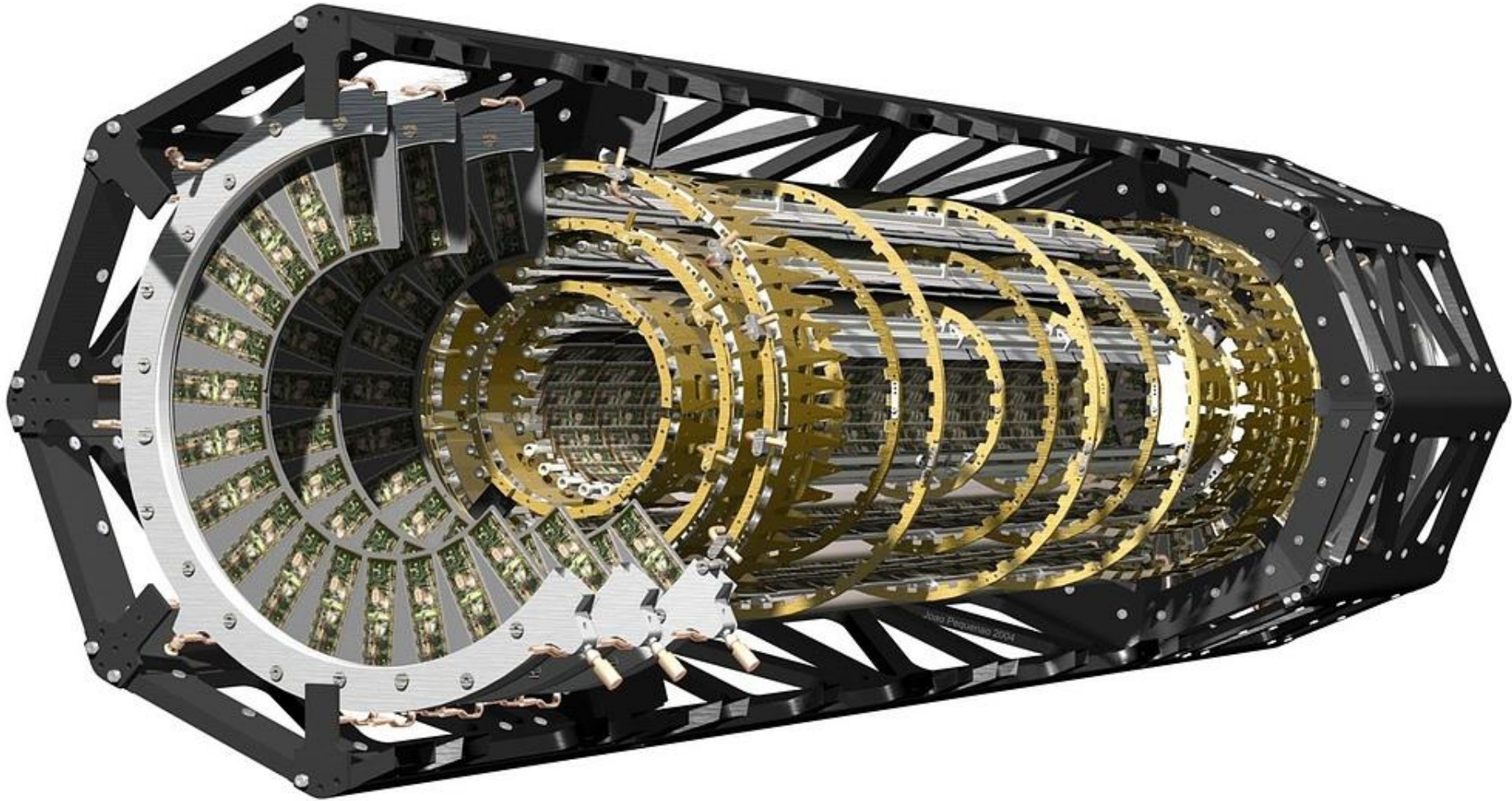
Silicon Strip Detectors

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

Two dimensional readout is possible.
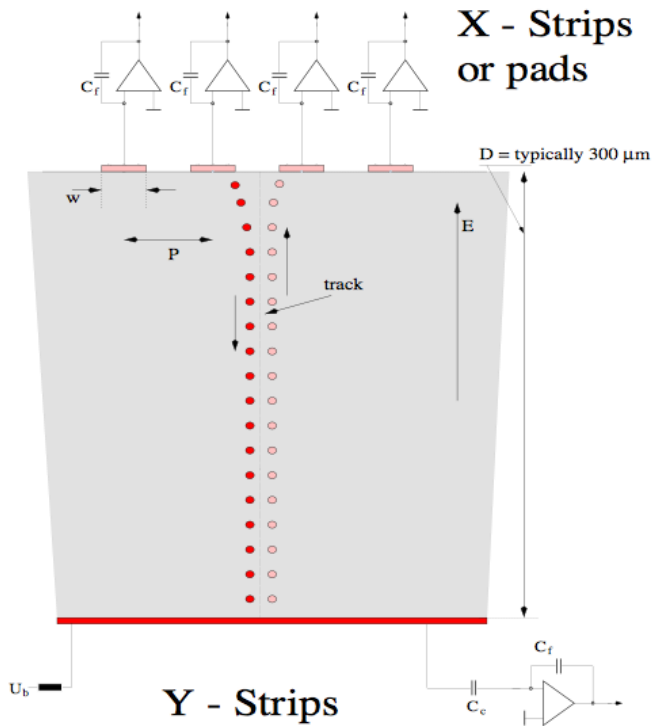
CMS Outer Barrel Module

Solid State Detectors
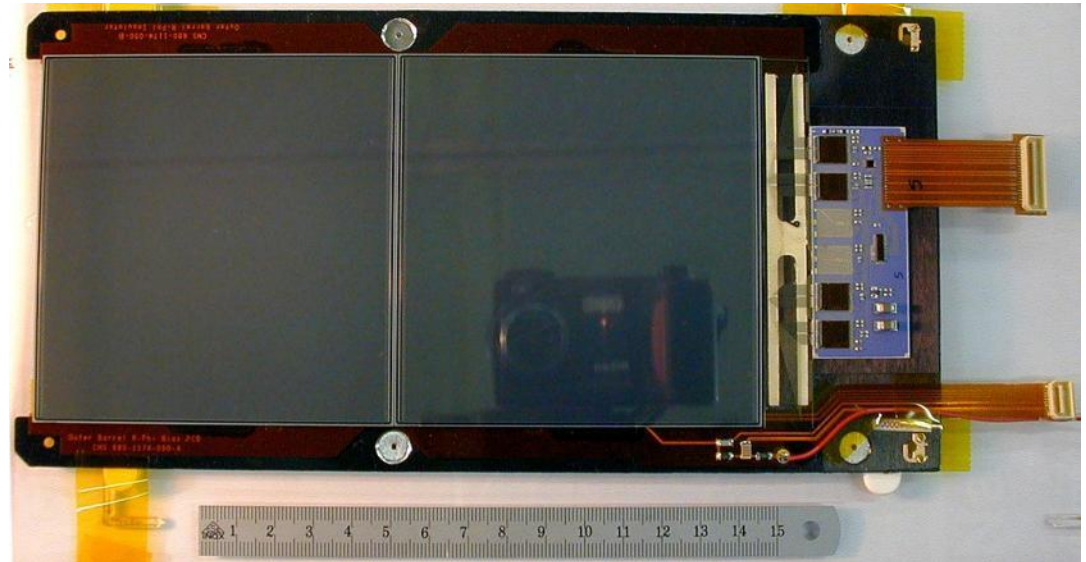
Silicon Strip Detectors
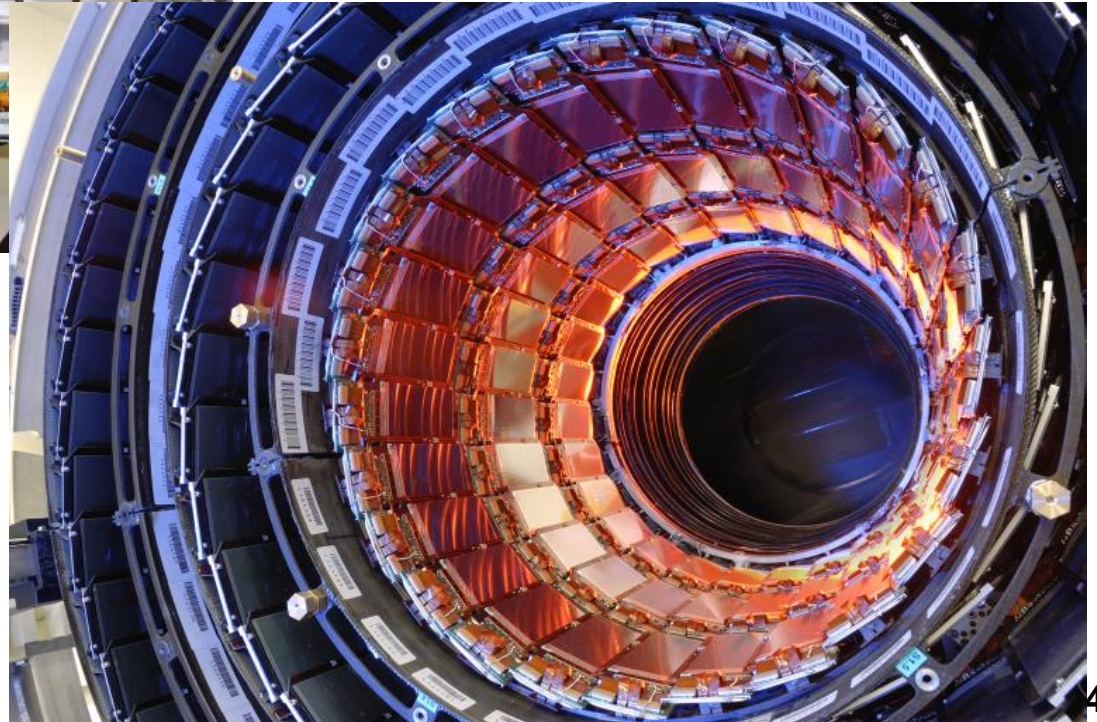
Time Projection Chamber (TPC):

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 !

gas volume

B

drift

E

y

x

z

charged track

Wire Chamber to detect the tracks

ALEPH DALI

Run=15768   Evt=5906

O.Ullaland CERN 2005
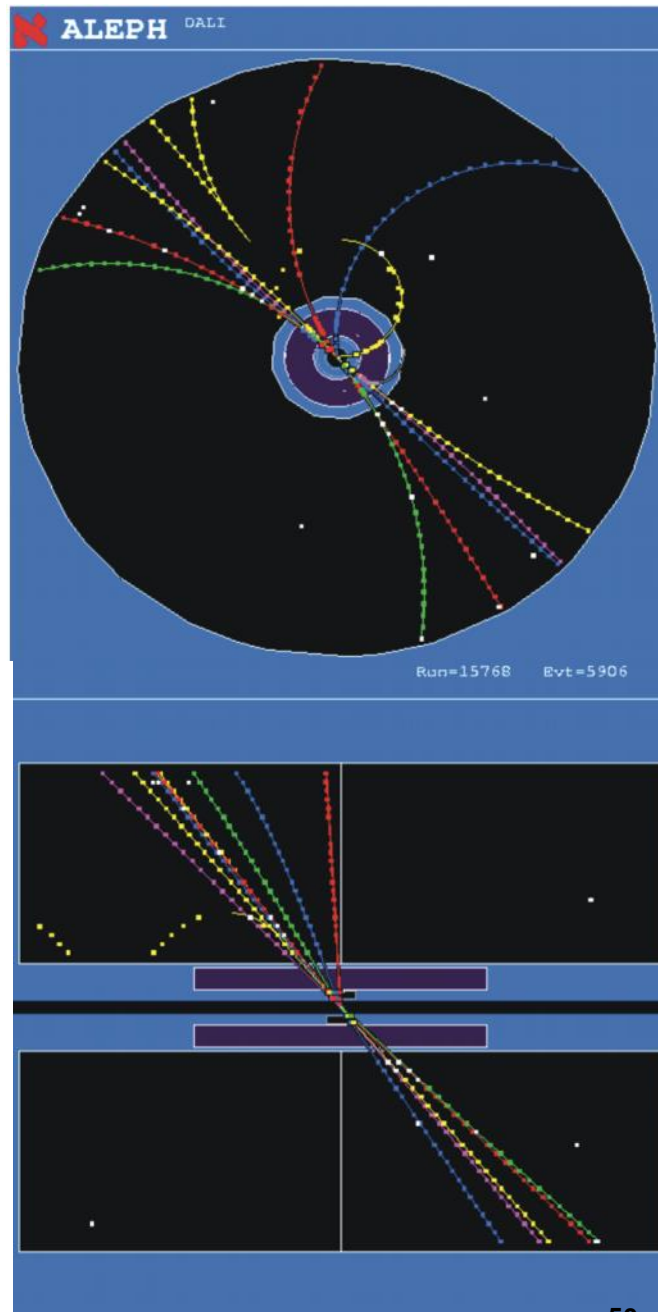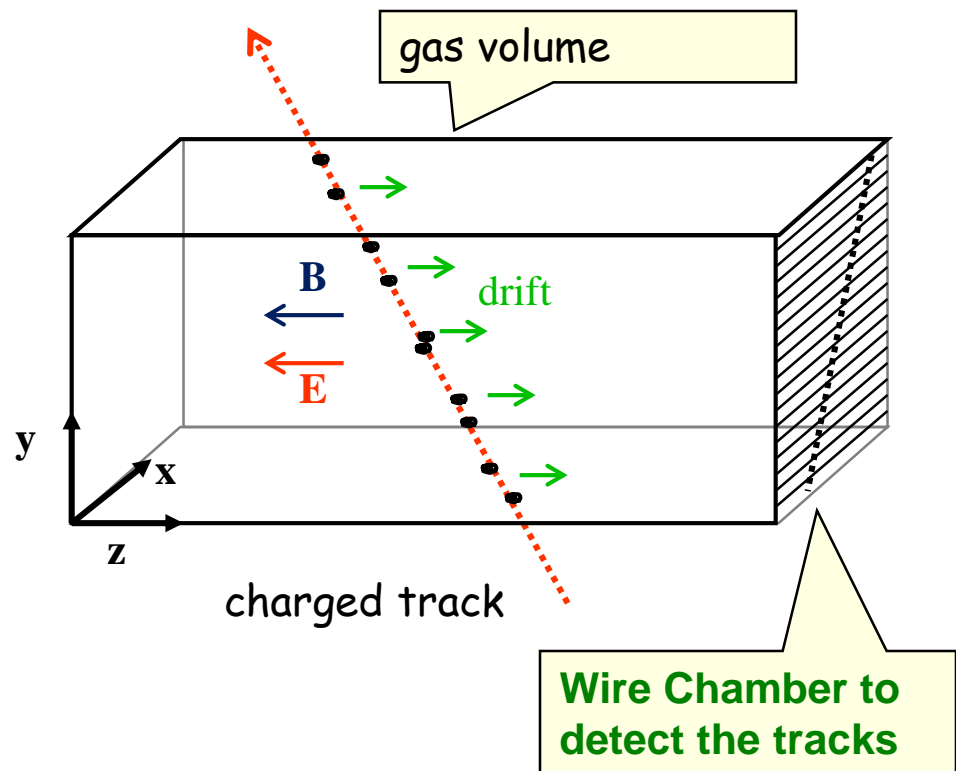
ALICE TPC: Construction Parameters

- **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%)**
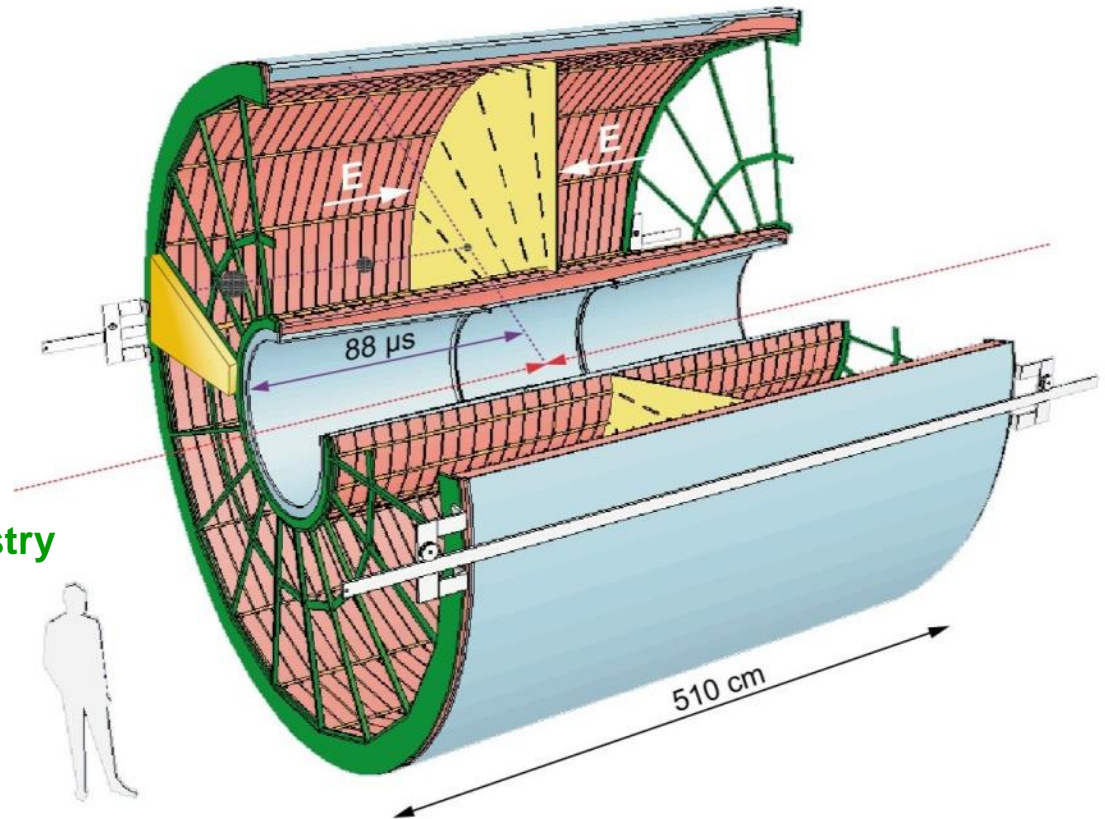
ALICE TPC: Pictures of the Construction

Precision in z: 250μm

End plates 250μm

Wire chamber: 40μm
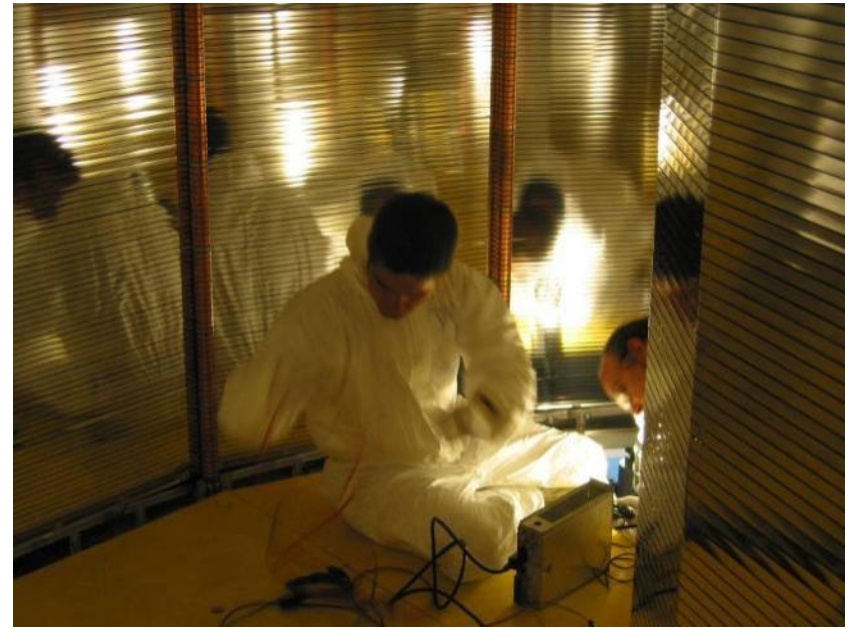
ALICE TPC Construction

My personal contribution:

A visit inside the TPC.

TPC installed in the ALICE Experiment
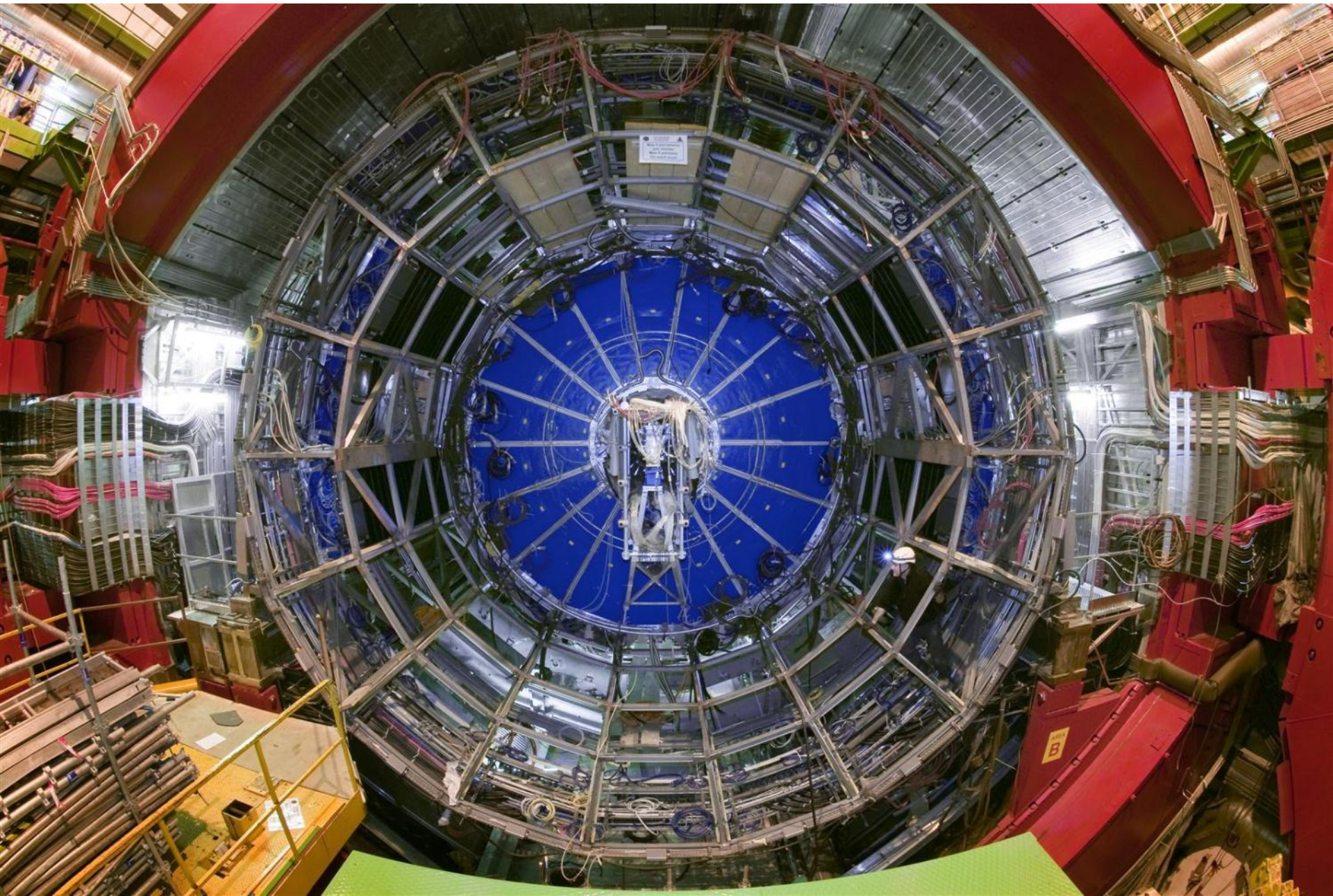
First 7 TeV p-p Collisions in the ALICE TPC in March 2010 !
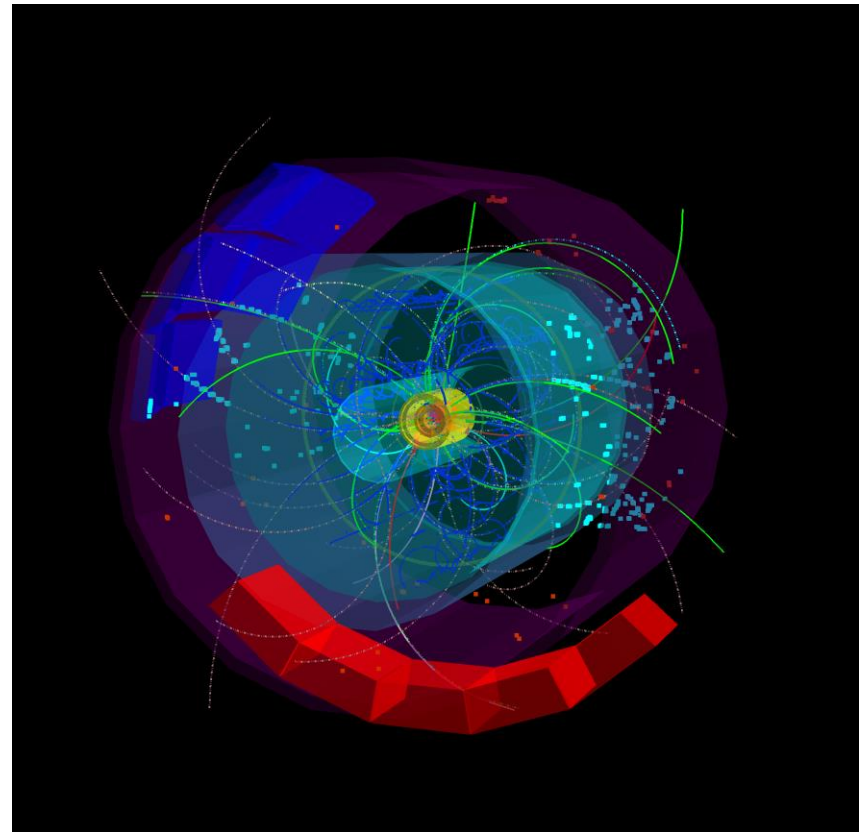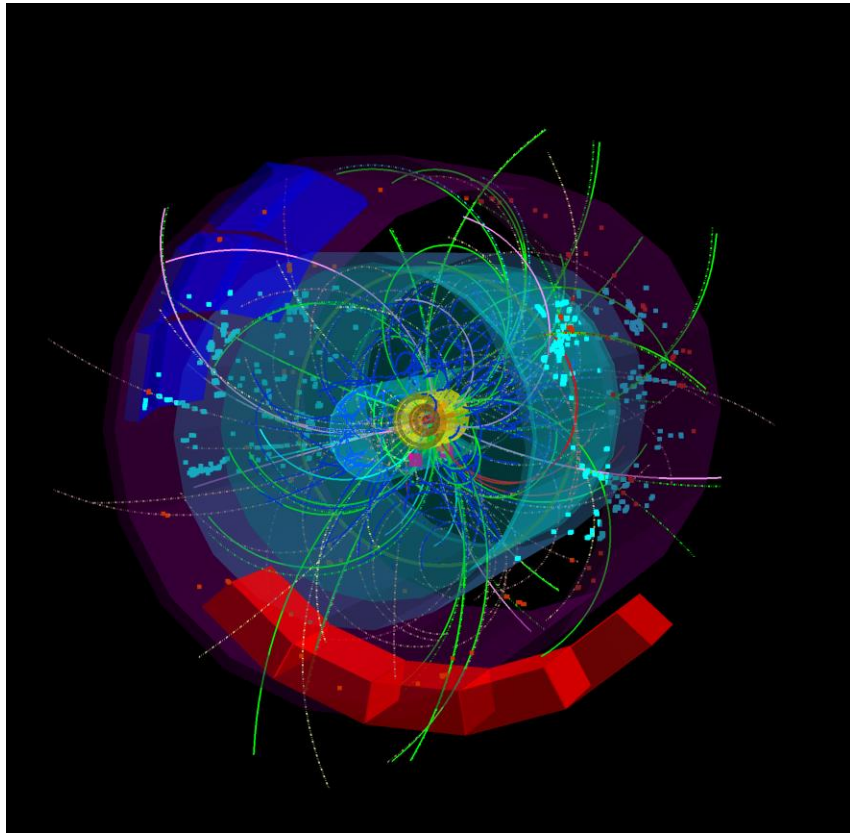
11/23/2018

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

Pb+Pb @ sqrt(s) = 2.76 ATeV

2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE693
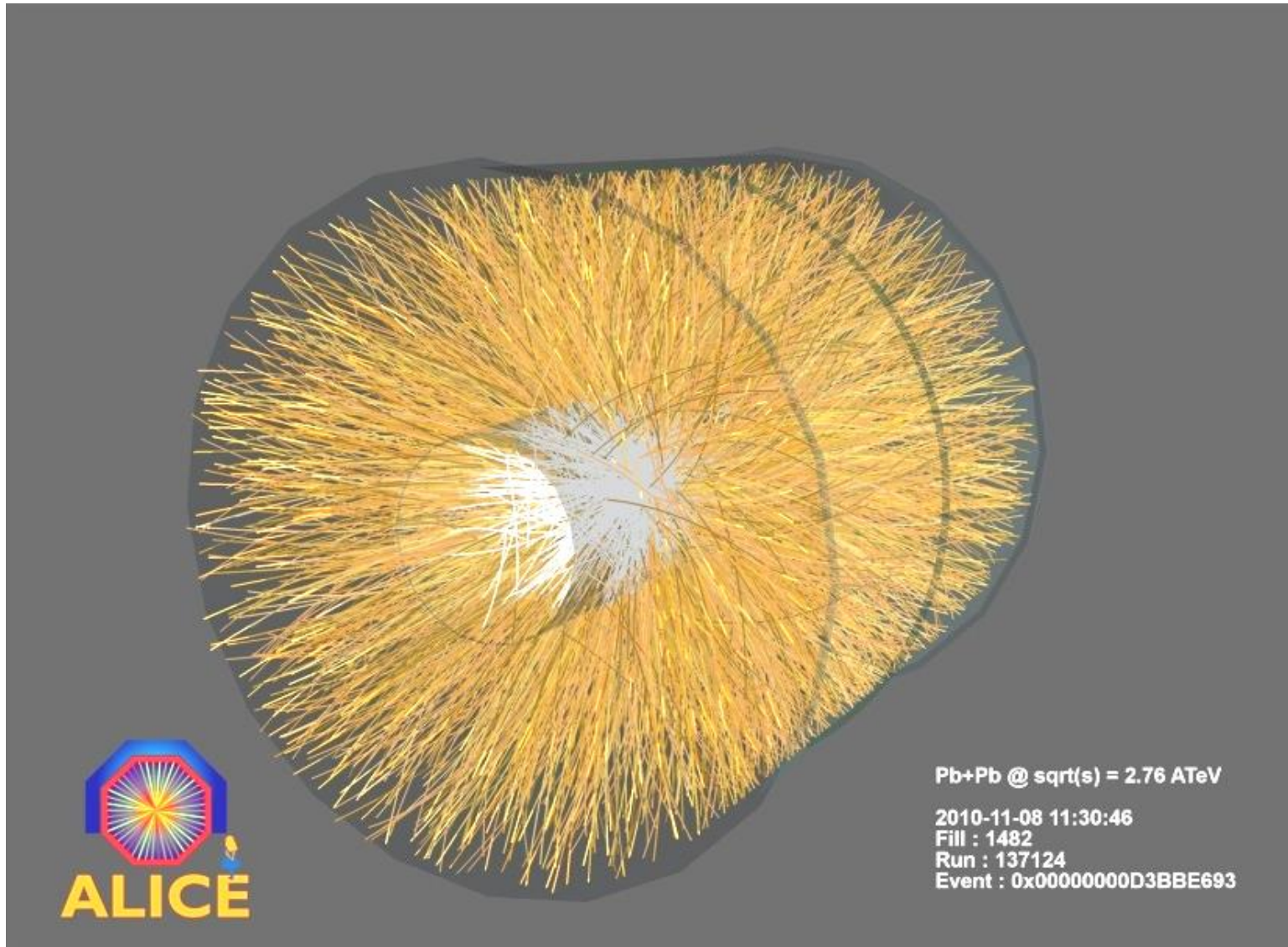
11/23/2018

The Geiger Counter reloaded: Drift Tube

ATLAS MDT R(tube) =15mm

Calibrated Radius-Time correlation

Primary electrons are drifting to the wire.
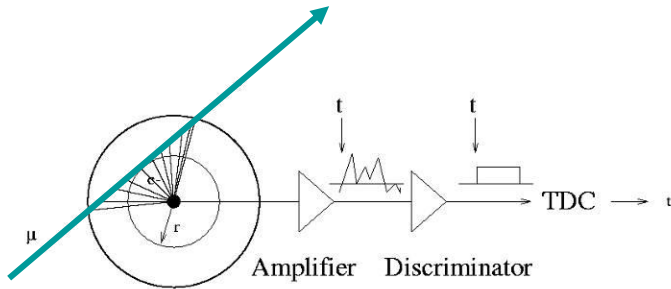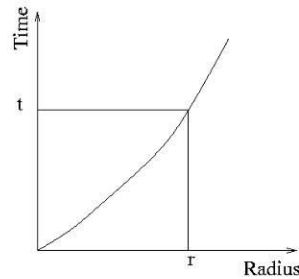
Electron avalanche at the wire.

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

- Cross plate
- Multilayer
- In-plane alignment
- Longitudinal beam
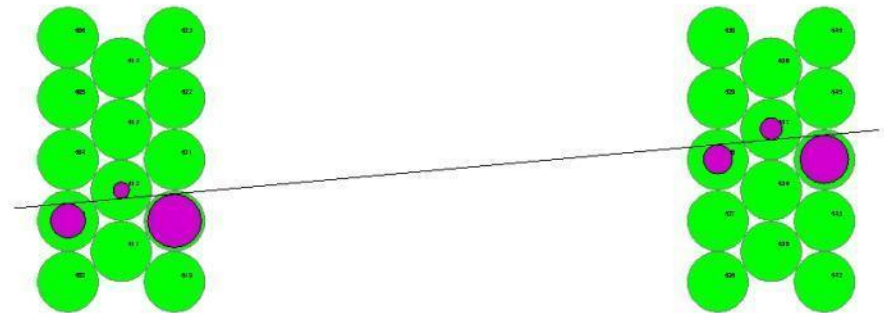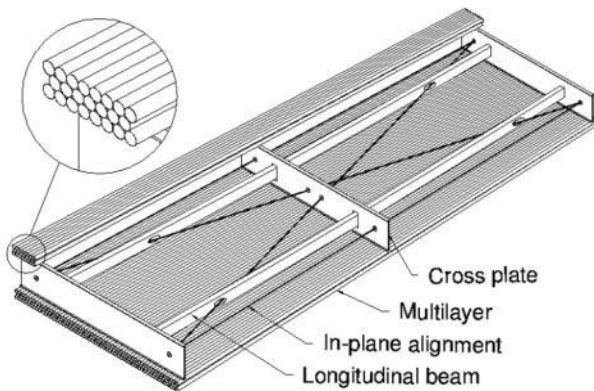
ATLAS MDTs, 80μm per tube

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

Cross plate
Multilayer
In-plane alignment
Longitudinal beam

MDT chambers
Resistive plate chambers
Barrel toroid coils
End-cap toroid
Inner detector
Calorimeters

Atlas

Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding
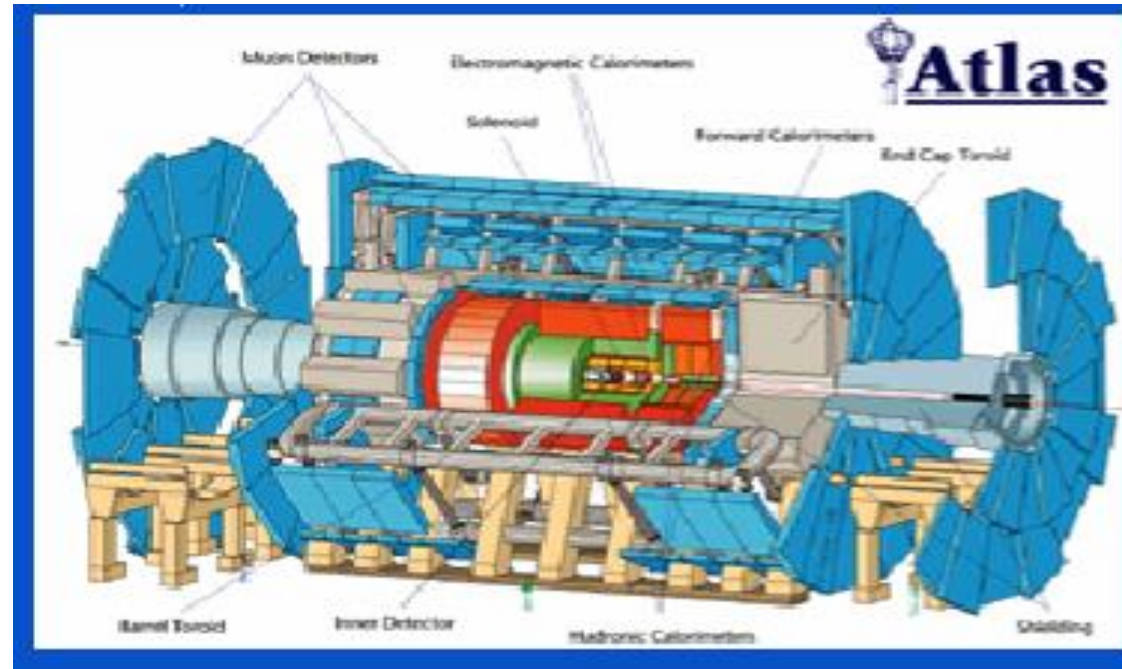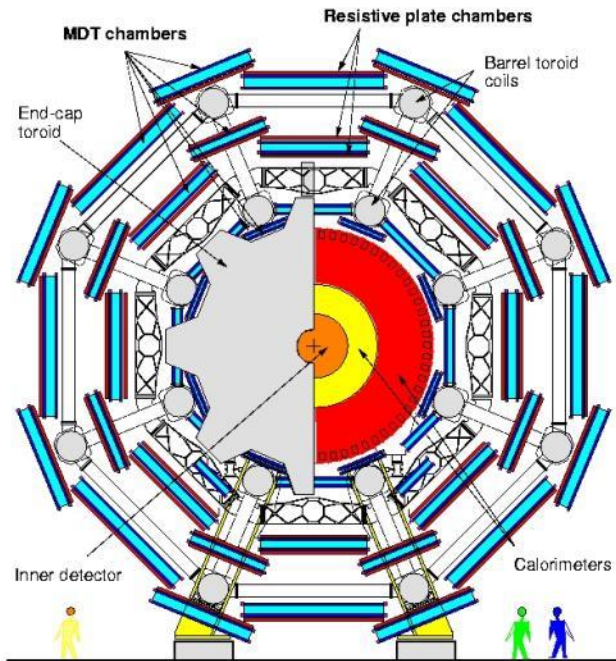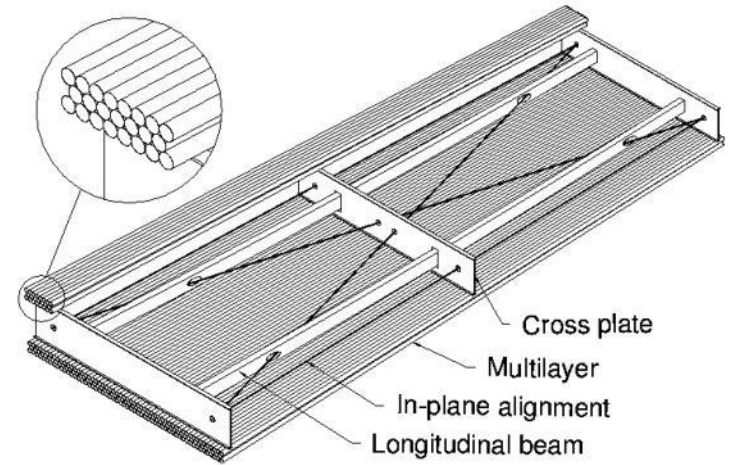
Detector Systems

CERN Neutrino Gran Sasso

(CNGS)

CNGS

If neutrinos have mass:

$$\nu_e$$

$$\nu_\mu \longleftrightarrow \nu_\tau$$
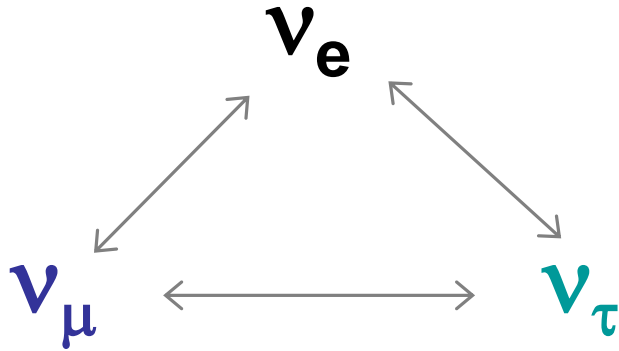
Muon neutrinos produced at CERN.
See if tau neutrinos arrive in Italy.

CERN

$\nu_\mu \longrightarrow \nu_\tau \longrightarrow \nu_\mu \longrightarrow \nu_\tau$

neutrino trajectory
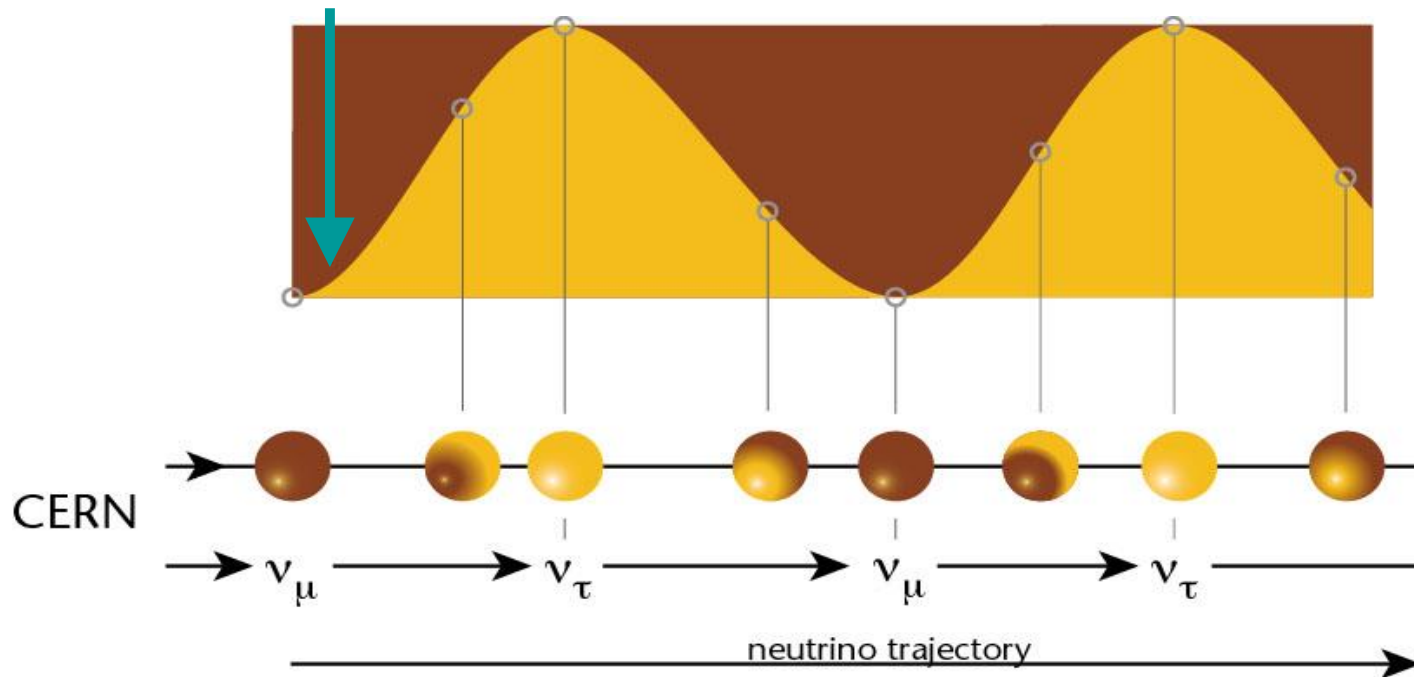
CNGS Project

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

CNGS

CERN NEUTRINOS TO GRAN SASSO
Underground structures at CERN
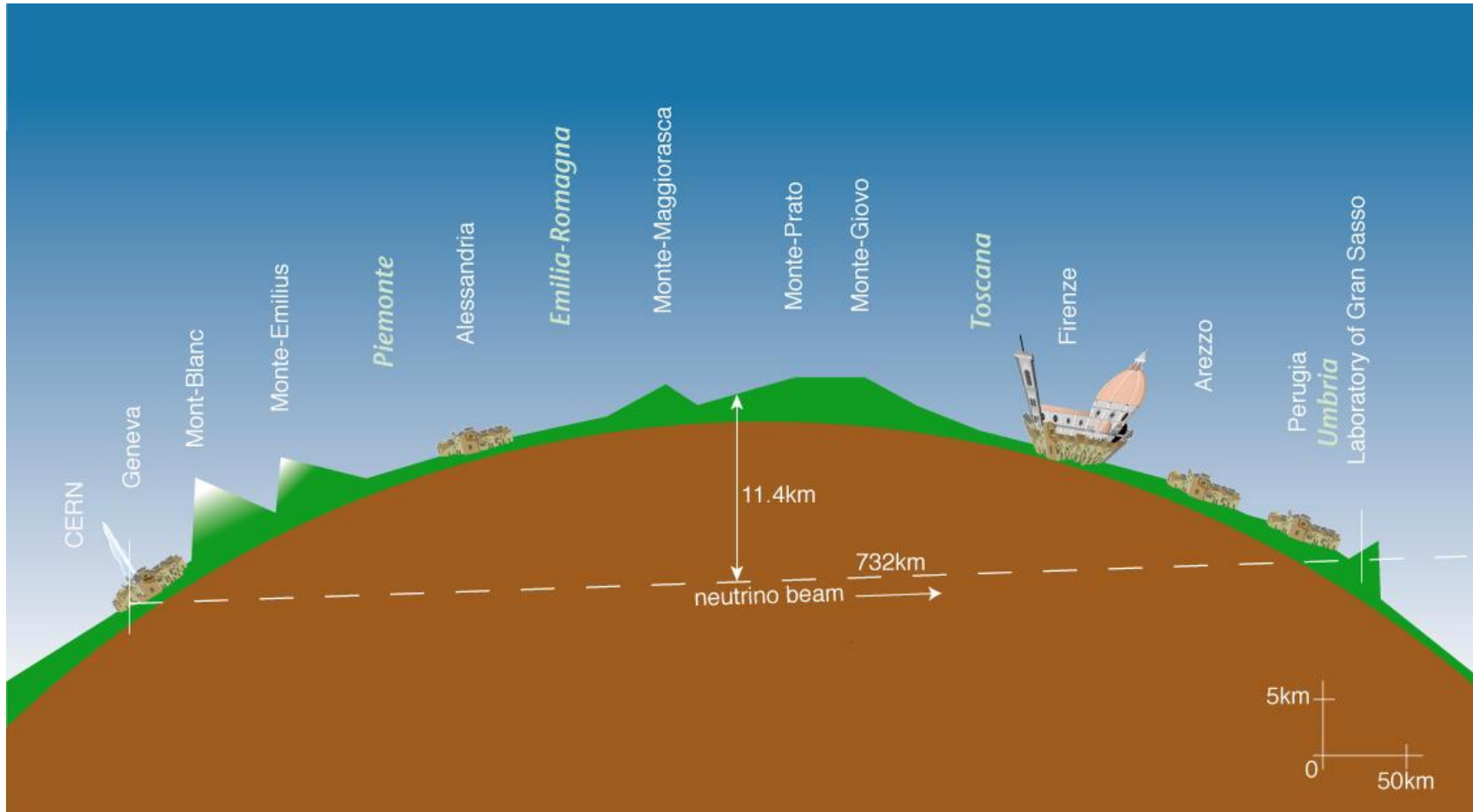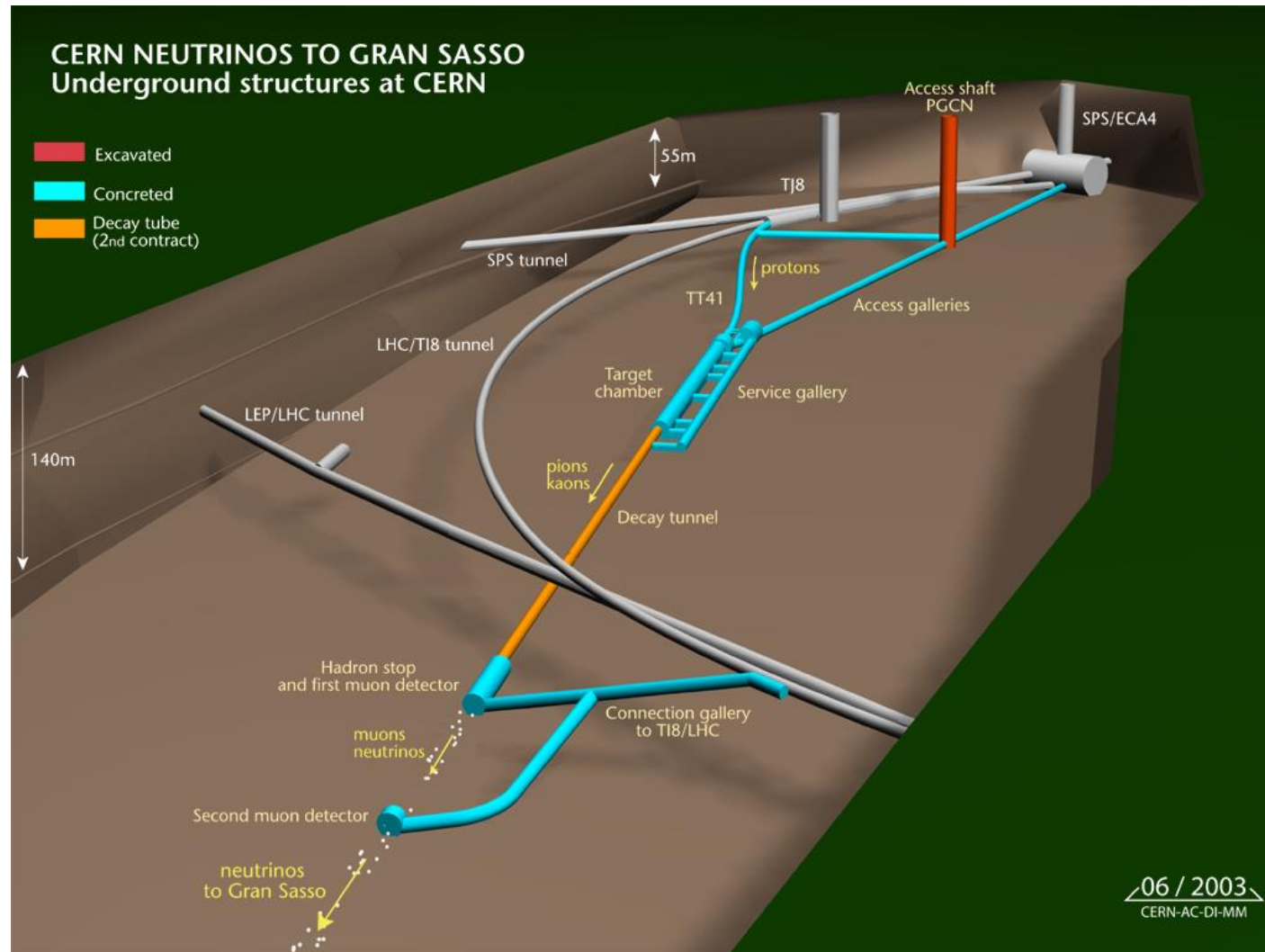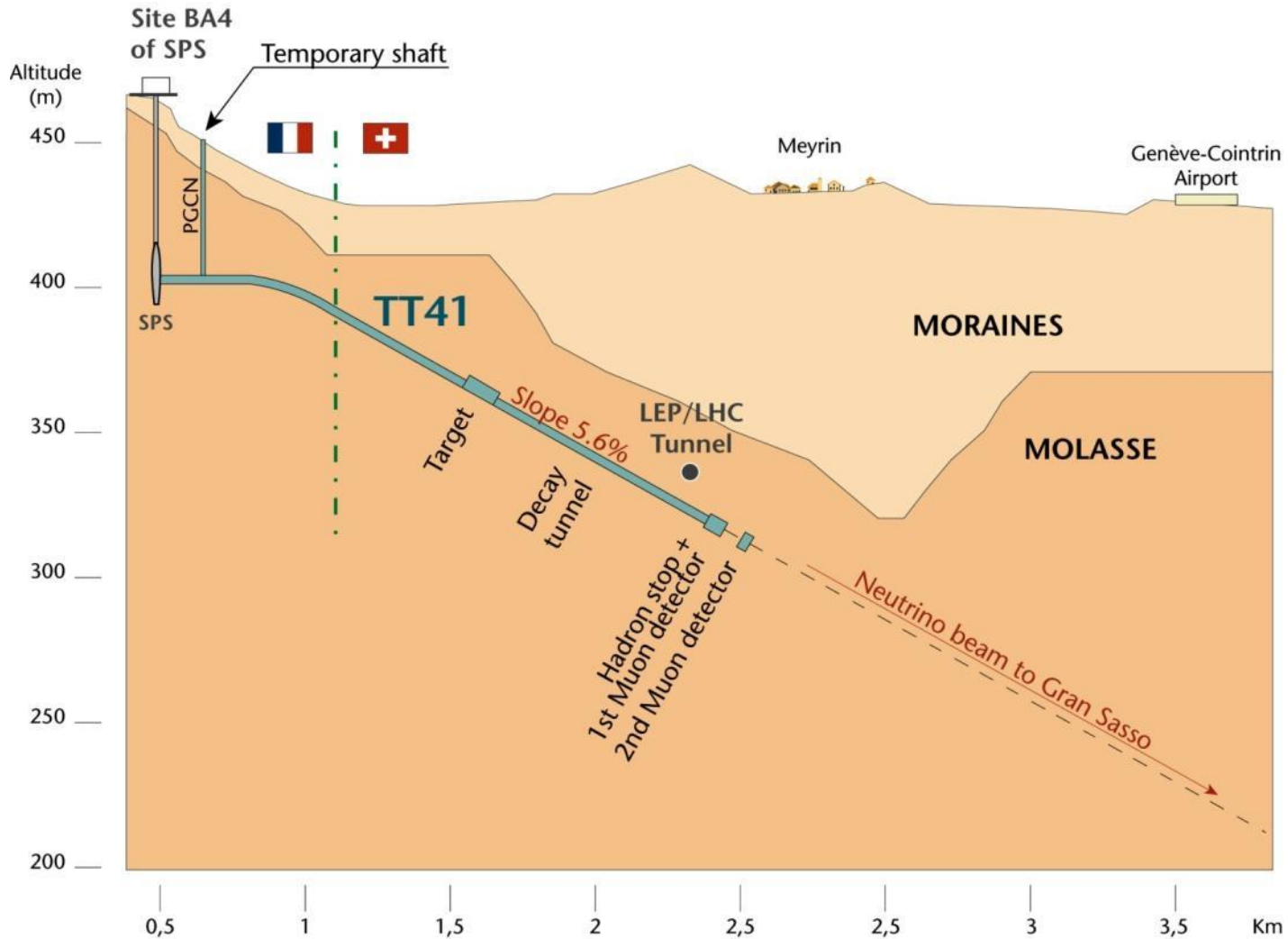
CNGS

Radial Distribution of the ν_μ-Beam at GS

Flat top: 500m
FWHM: 2800m

typical size of a detector at Gran Sasso
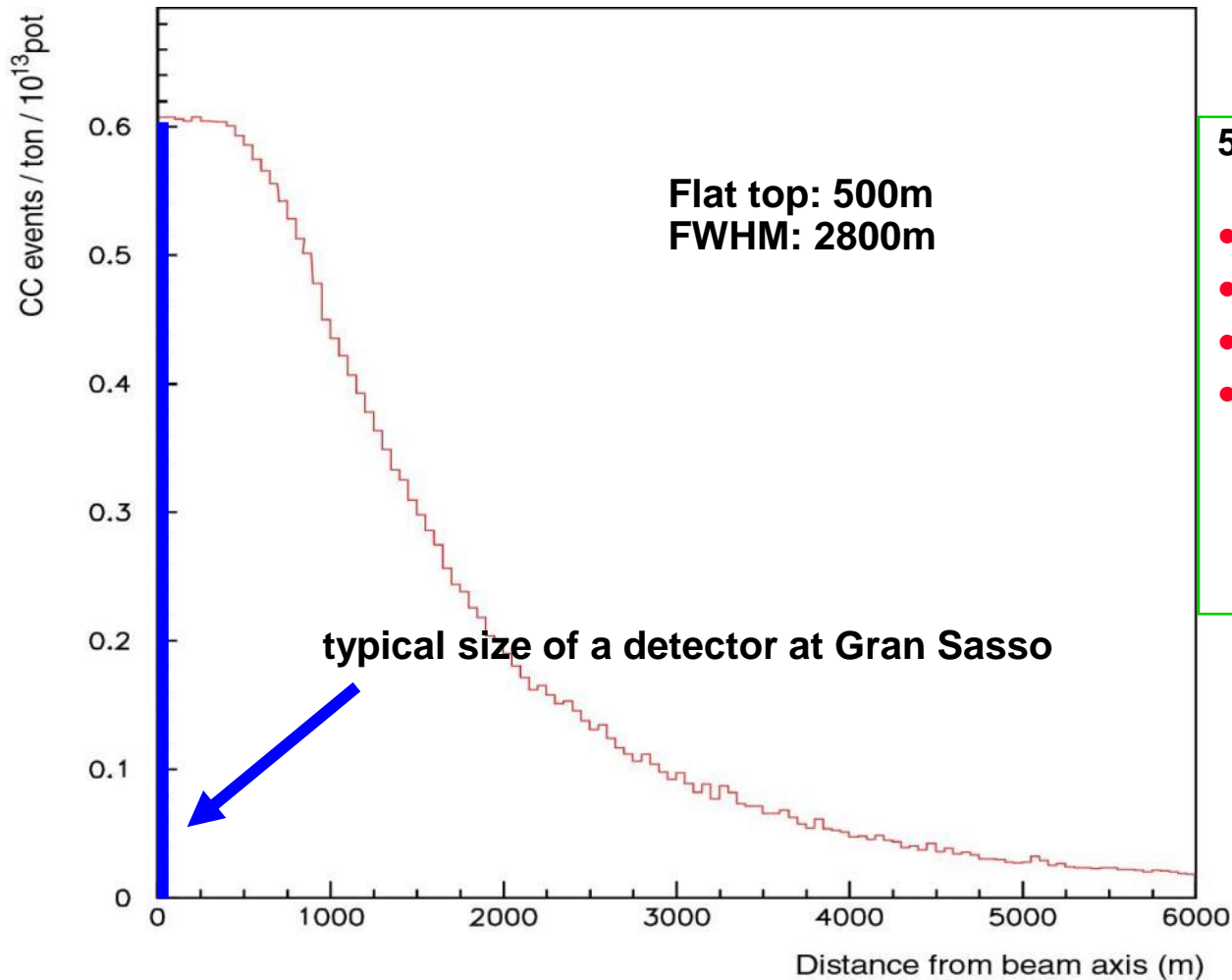
5 years CNGS operation, 1800 tons target:

- **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

Brick

1 mm

τ

ν

Pb

Couche de gélatine photographique 40 μm

brick

8.3kg
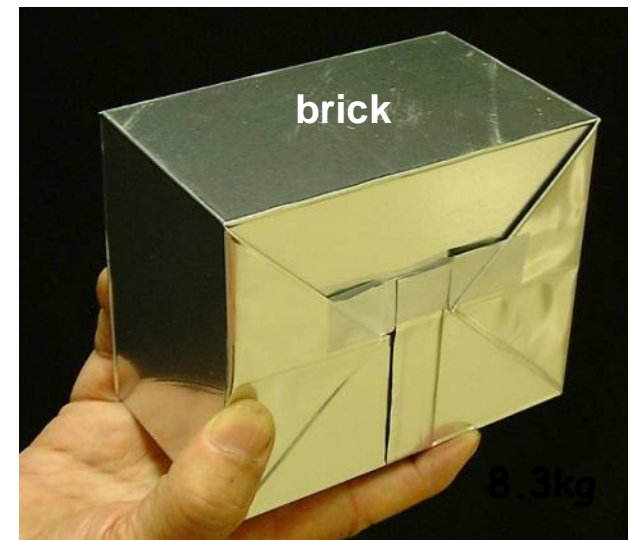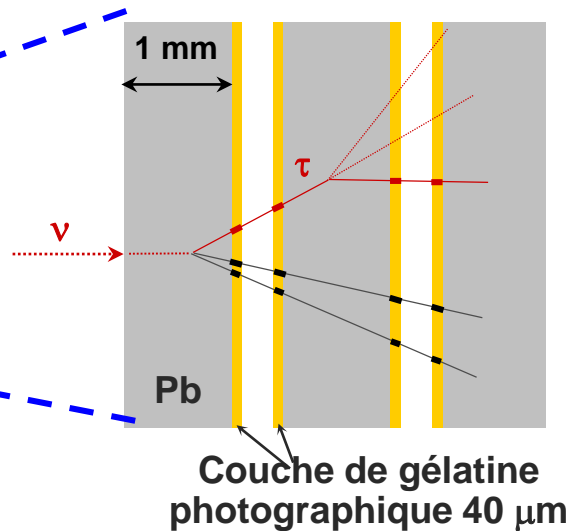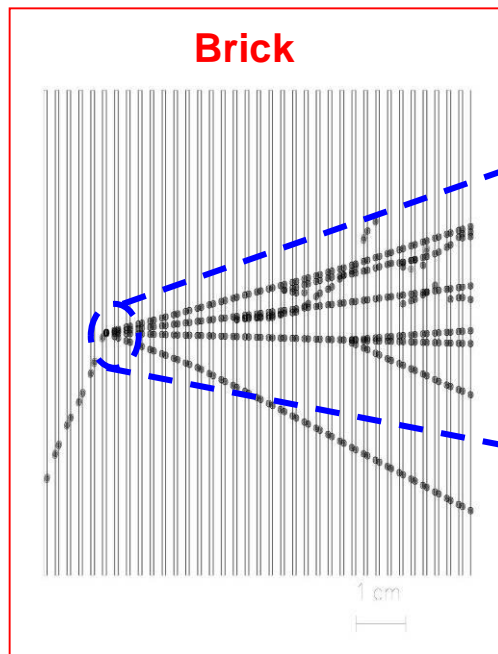
10.2 x 12.7 x 7.5 cm³

Opera Experiment at Gran Sasso

31 target planes / supermodule   **In total: 206336 bricks, 1766 ton**

SM1   SM2

ν

Targets

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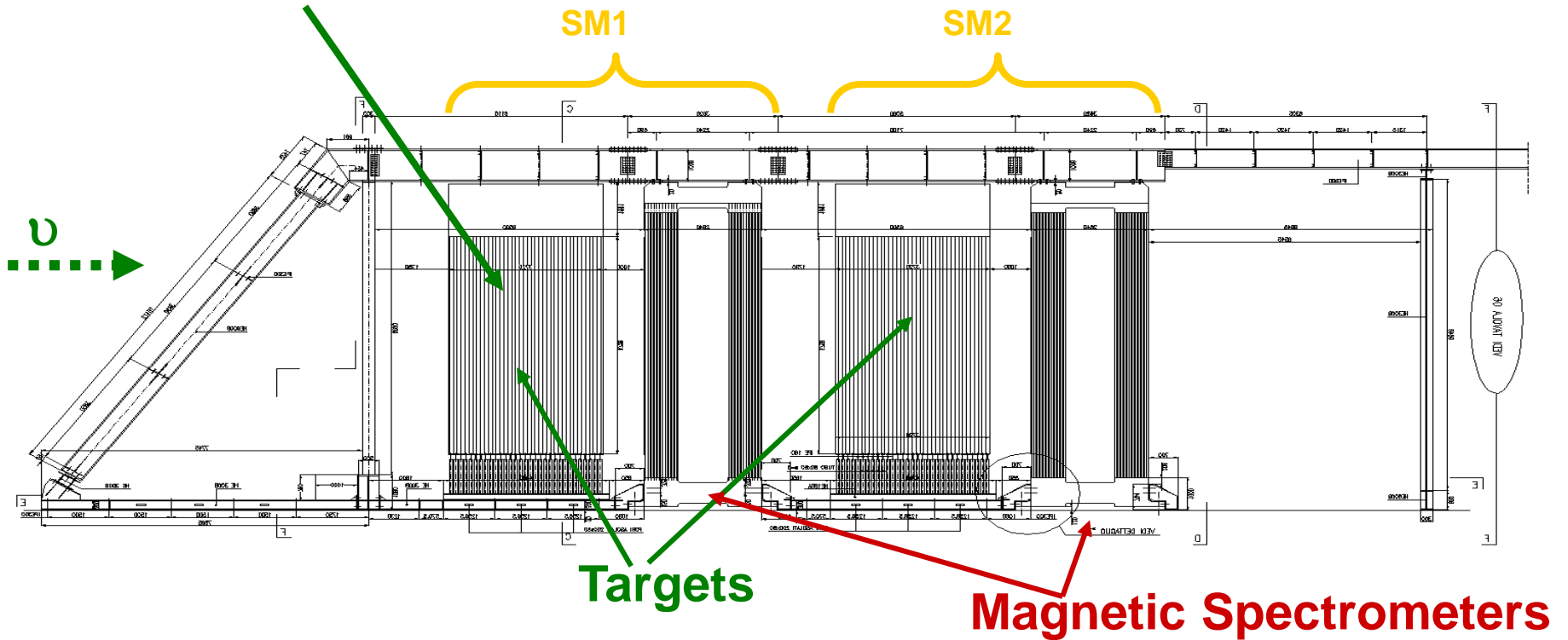
First observation of CNGS beam neutrinos : August 18th, 2006

Opera Experiment at Gran Sasso

Second Super-module

Details of the first spectrometer
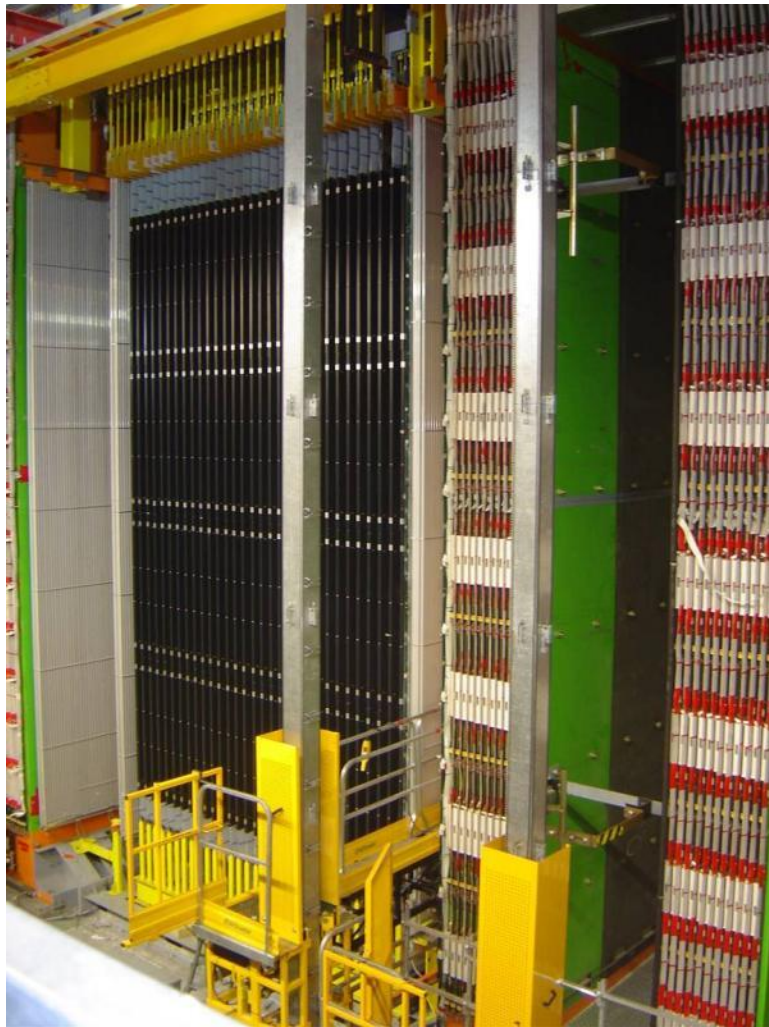
Scintillator planes 5900 m^2

8064 7m long drift tubes
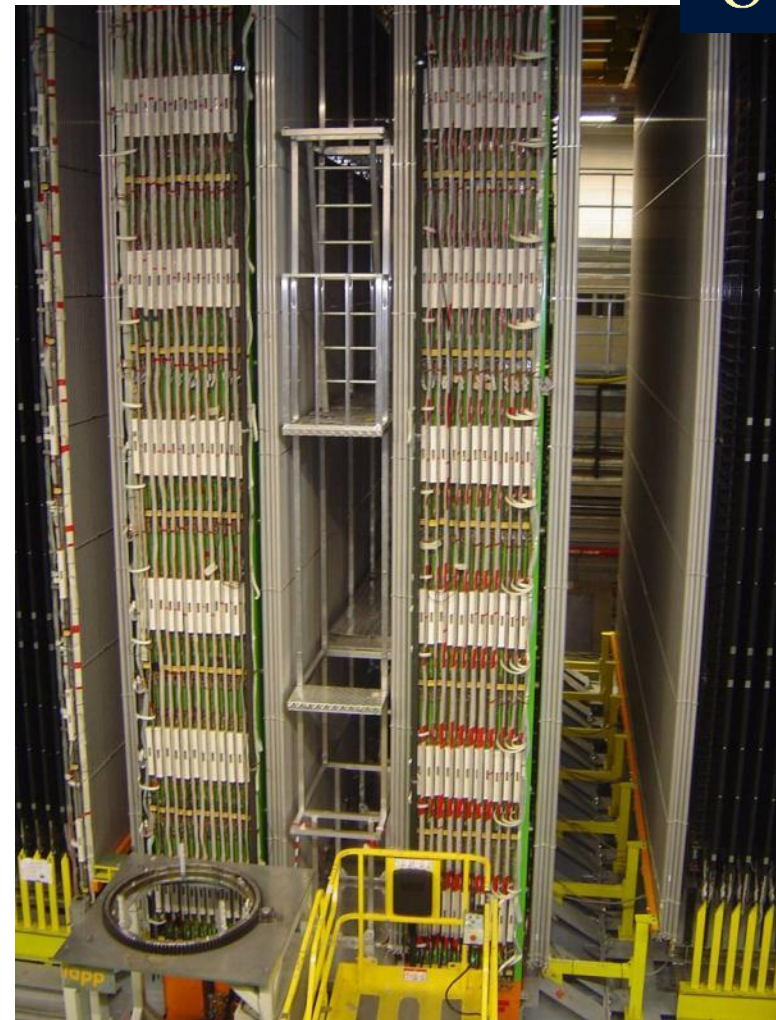
3050 m^2 Resistive Plate Counters

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 !
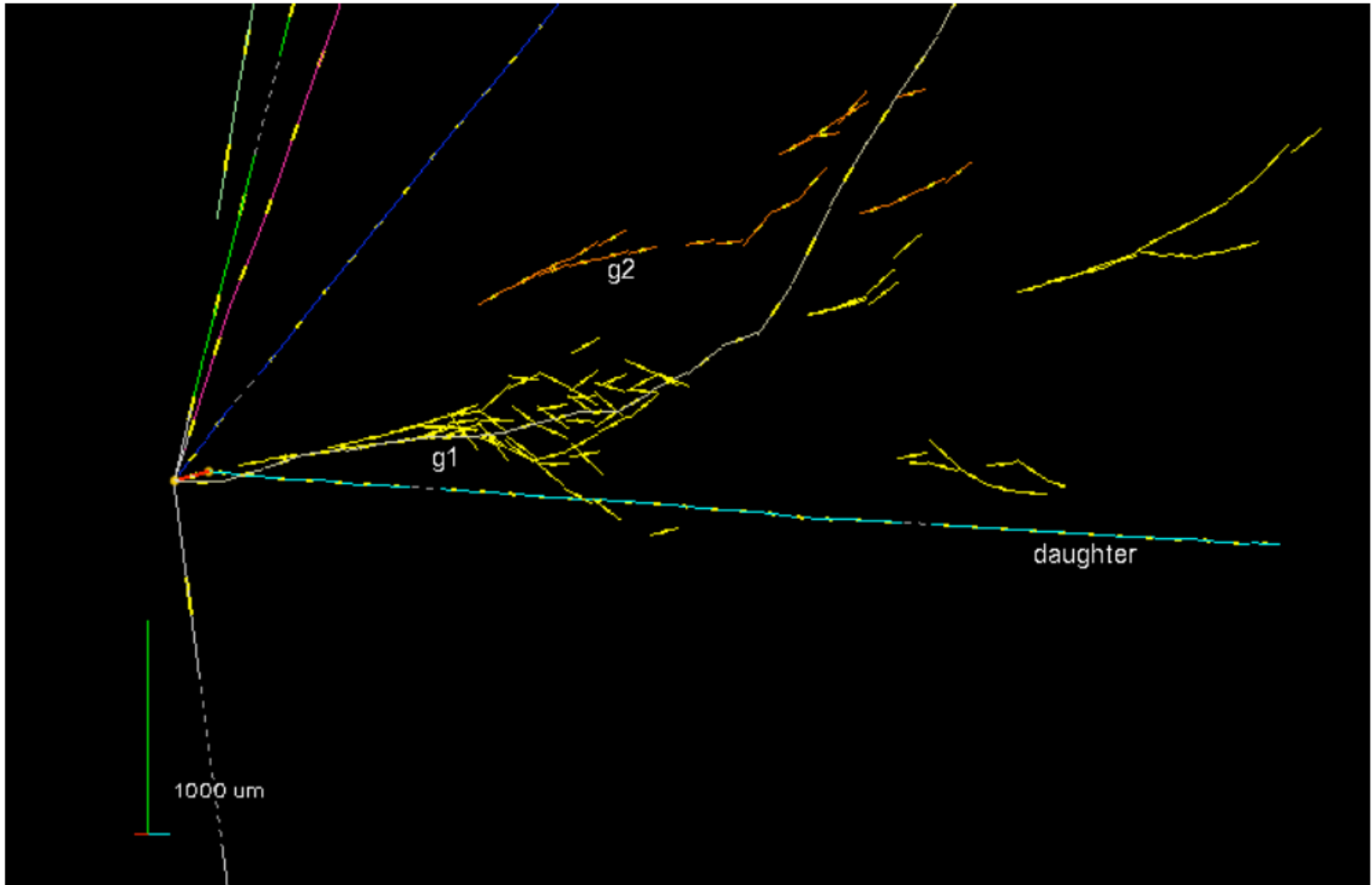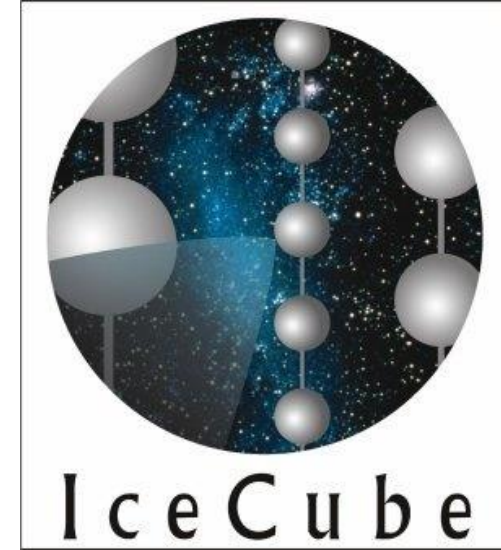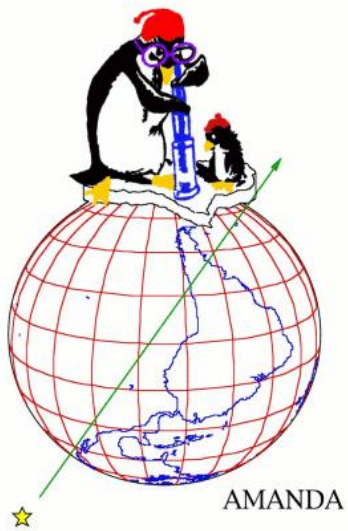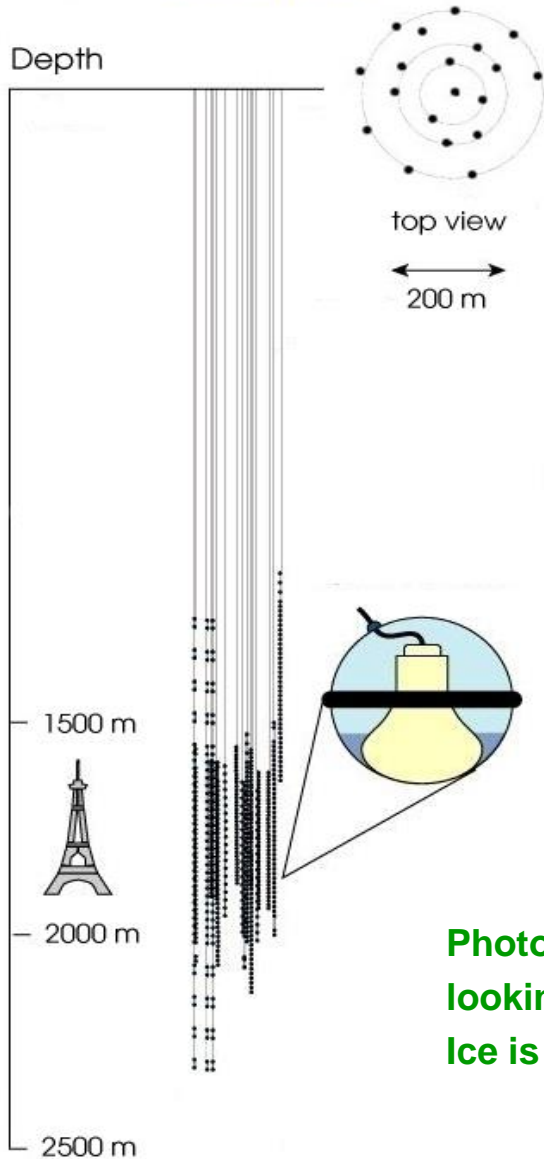
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**Antarctic Muon And Neutrino Detector Array**

AMANDA

South Pole

AMANDA

AMANDA-II

Depth

top view

200 m

1500 m

2000 m

2500 m

Power, Signal In/Out

Electronics

Photomultiplier

Optical Coupling Gel
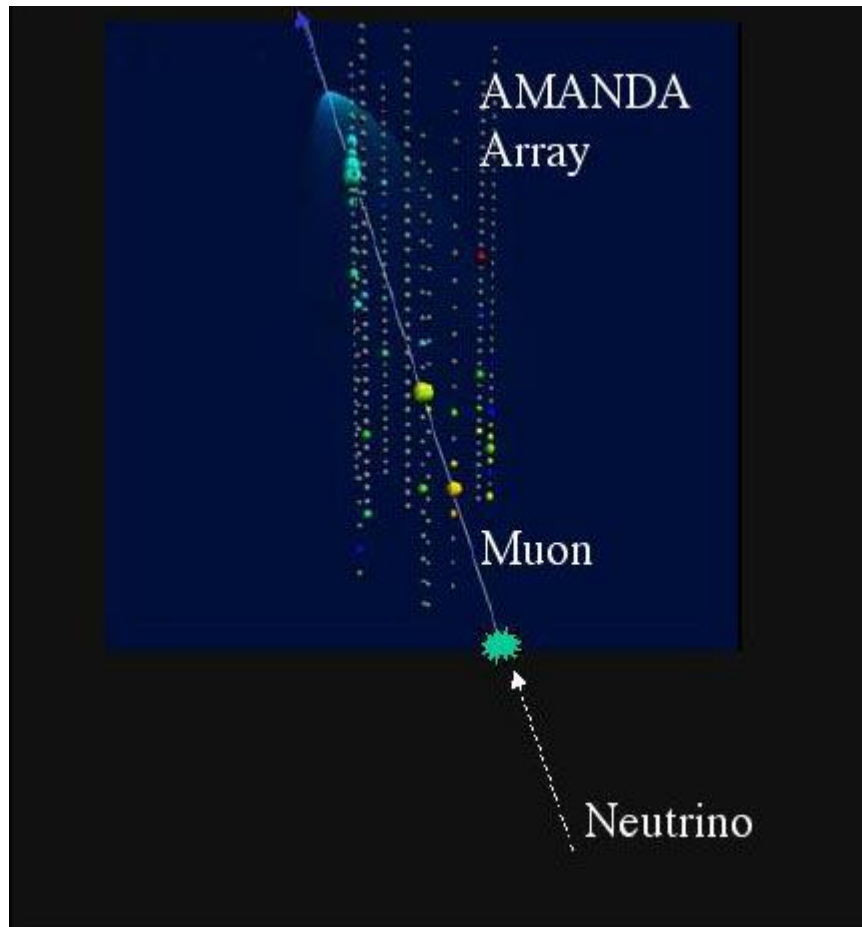
Glass Pressure Housing, 13" diameter
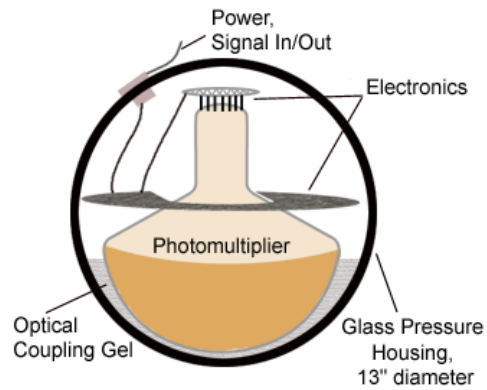
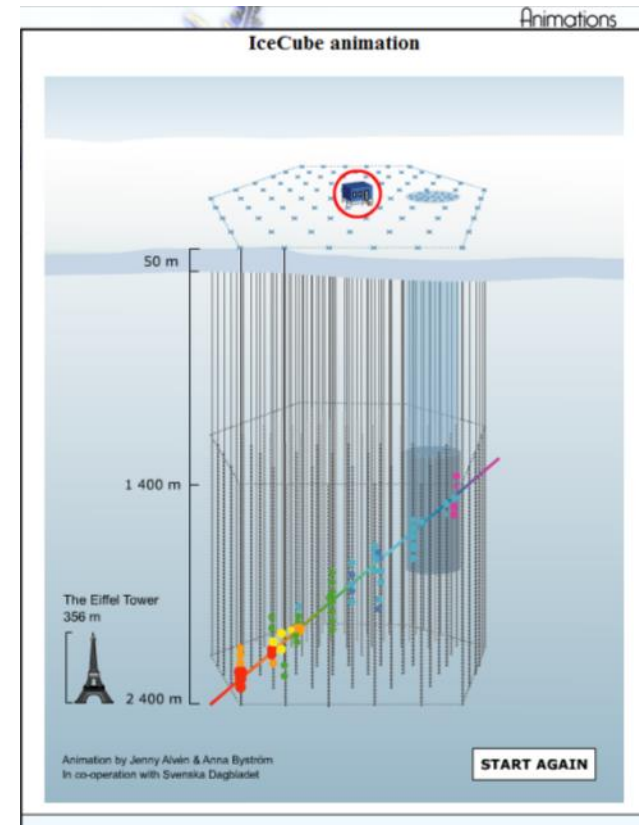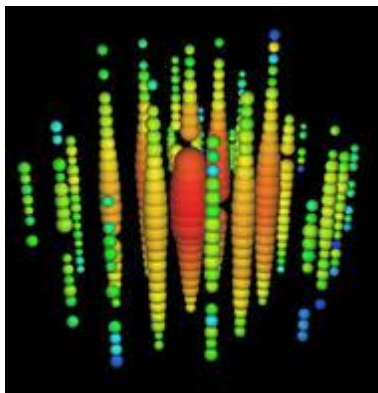**Photomultipliers in the Ice, looking downwards. Ice is the detecting medium.**
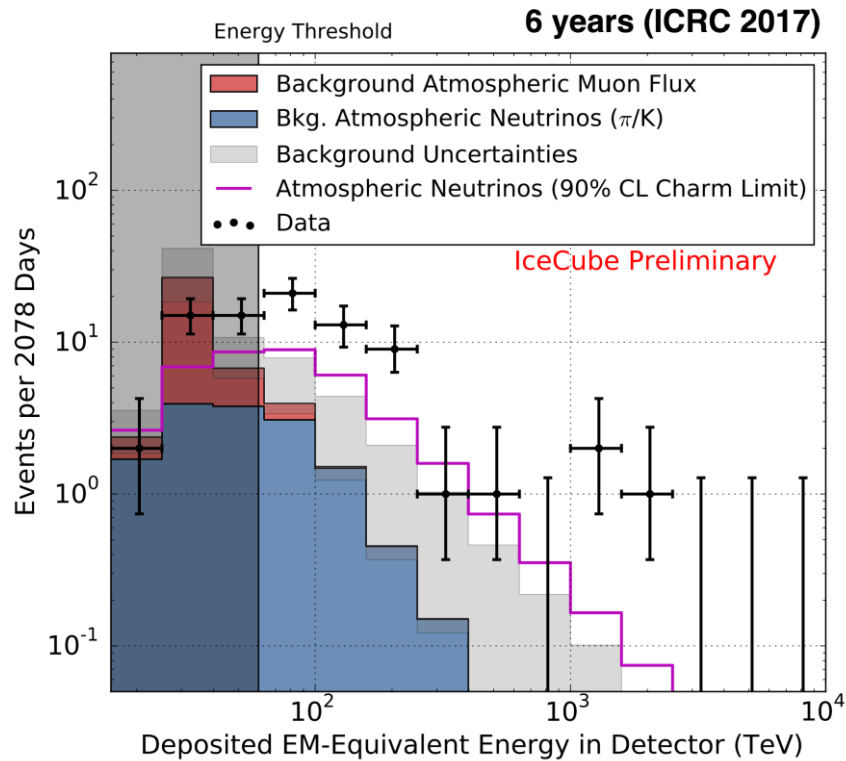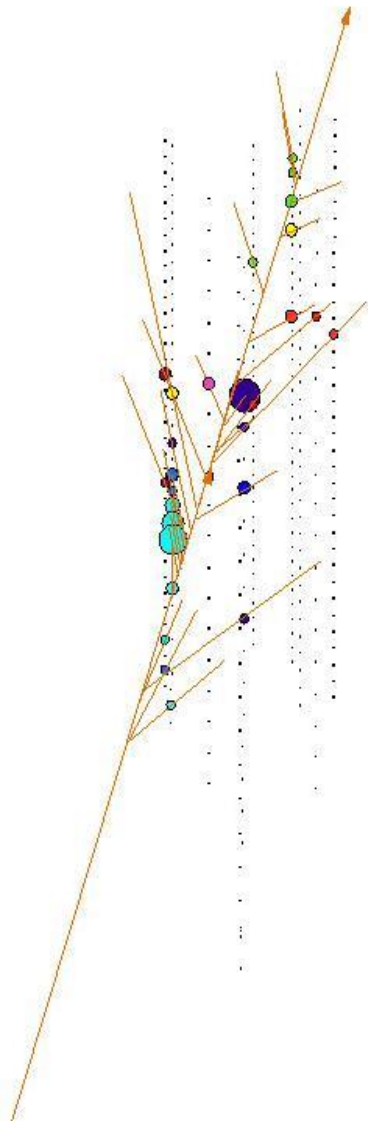
AMANDA

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

$\rightarrow$ **Find neutrino point sources in the universe !**

Ice Cube

Event Display

6 years (ICRC 2017)
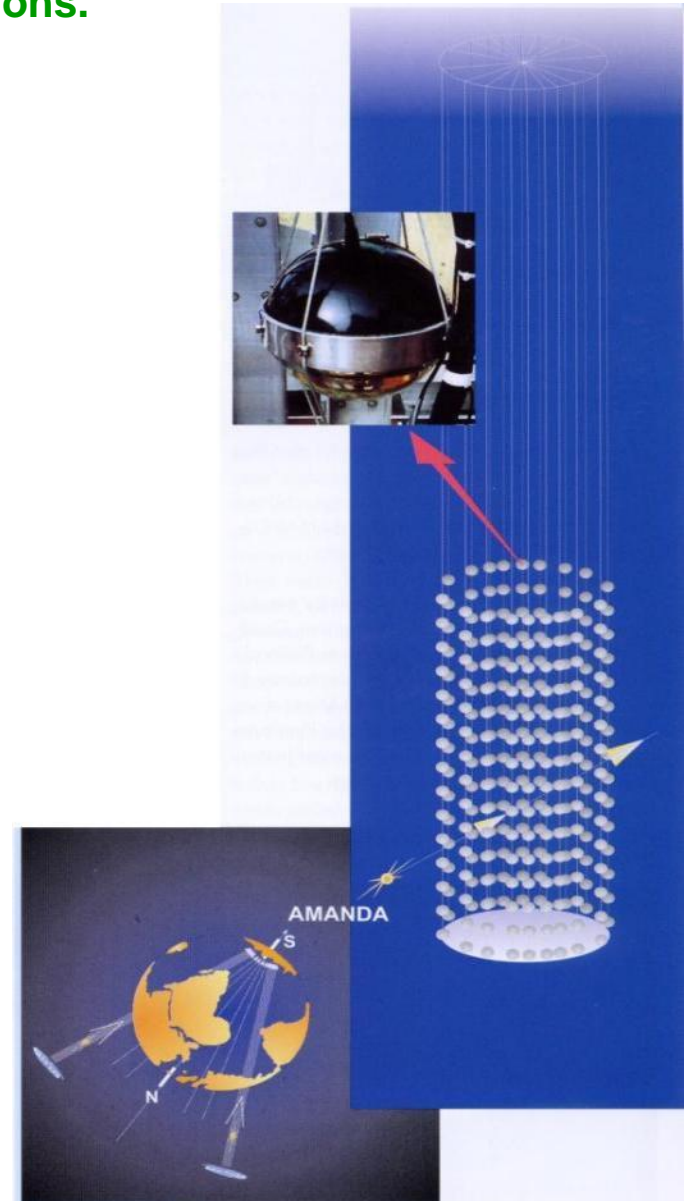
IceCube Preliminary

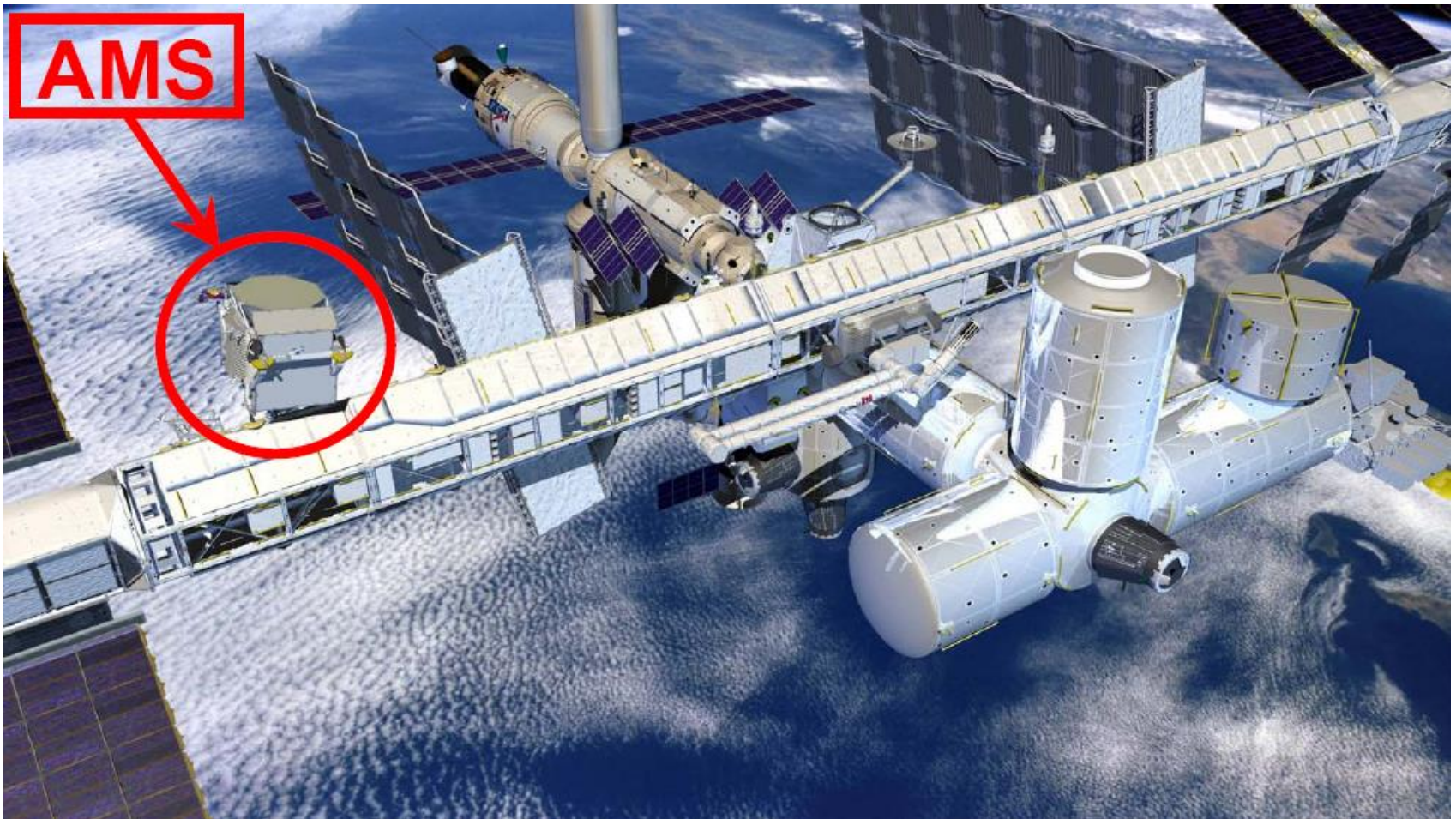→ Ice Cube for more statistics !

AMS

Alpha Magnetic Spectrometer

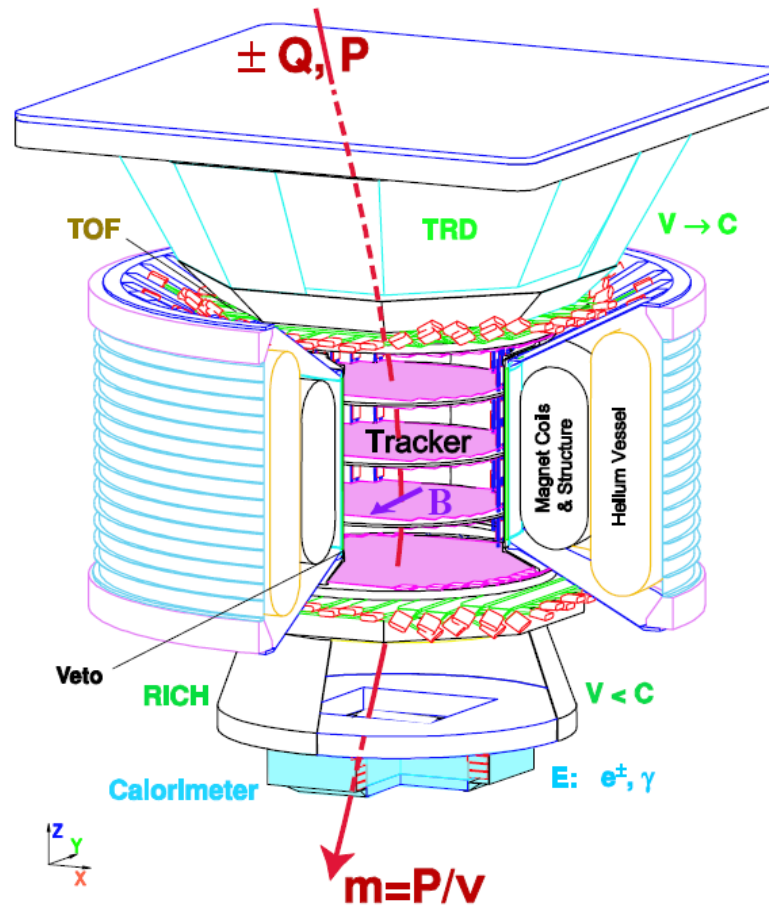**Try to find Antimatter in the primary cosmic rays.**

Study cosmic ray composition etc. etc.

AMS

Is installed on the international space station.

AMS

AMS