Particle Detectors 2/2

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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

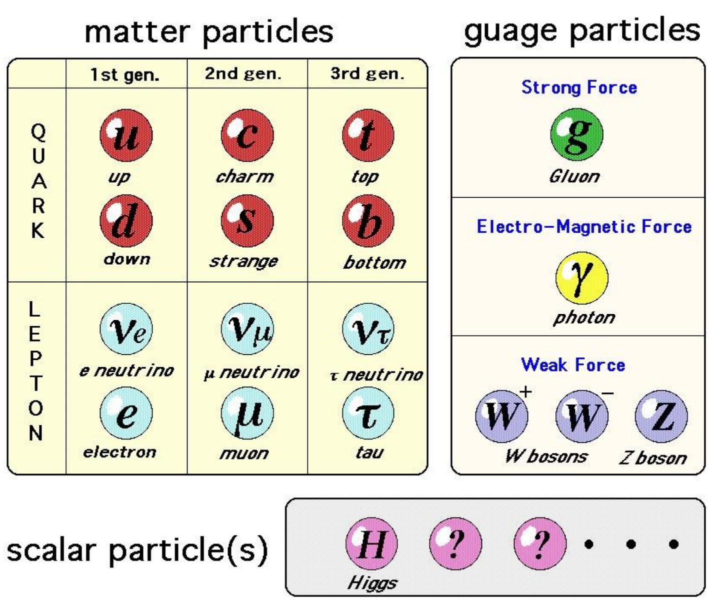
→ m>0 and s=0, 1/2, 1, 3/2, 2

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.

The ‘Standard Model’

$$L_{GSW} = L_0 + L_H + \sum_l \left\{ \frac{g}{2}\bar{L}_l\gamma_\mu\vec{\tau}L_l\vec{A}^\mu + g'\left[\bar{R}_l\gamma_\mu R_l + \frac{1}{2}\bar{L}_l\gamma_\mu L_l\right]B^\mu\right\} +$$
$$+ \frac{g}{2}\sum_q \bar{L}_q\gamma_\mu\vec{\tau}L_q\vec{A}^\mu +$$
$$+ g'\left\{\frac{1}{6}\sum_q\left[\bar{L}_q\gamma_\mu L_q + 4\bar{R}_q\gamma_\mu R_q\right] + \frac{1}{3}\sum_{q'}\bar{R}_{q'}\gamma_\mu R_{q'}\right\}B^\mu$$



$$L_H = \frac{1}{2}(\partial_\mu H)^2 - m_H^2 H^2 - h\lambda H^3 - \frac{h}{4}H^4 +$$
$$+ \frac{g^2}{4}\left(W_\mu^+ W^\mu + \frac{1}{2\cos^2\theta_W}Z_\mu Z^\mu\right)(\lambda^2 + 2\lambda H + H^2) +$$
$$+ \sum_{l,q,q'}\left(\frac{m_l}{\lambda}\bar{l}l + \frac{m_q}{\lambda}\bar{q}q + \frac{m_{q'}}{\lambda}\bar{q}'q'\right)H$$

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

$$E = ma^2$$

$$E = mb^2$$

$$E = mc^2 \longleftarrow \text{Energy} \triangleq \text{Mass}$$

$\vdots$

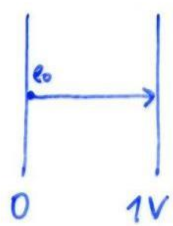
$$m(\text{electron}) = 9.1 \cdot 10^{-31}\ \text{kg}$$

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

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

$$= 0.511\ \text{MeV}$$

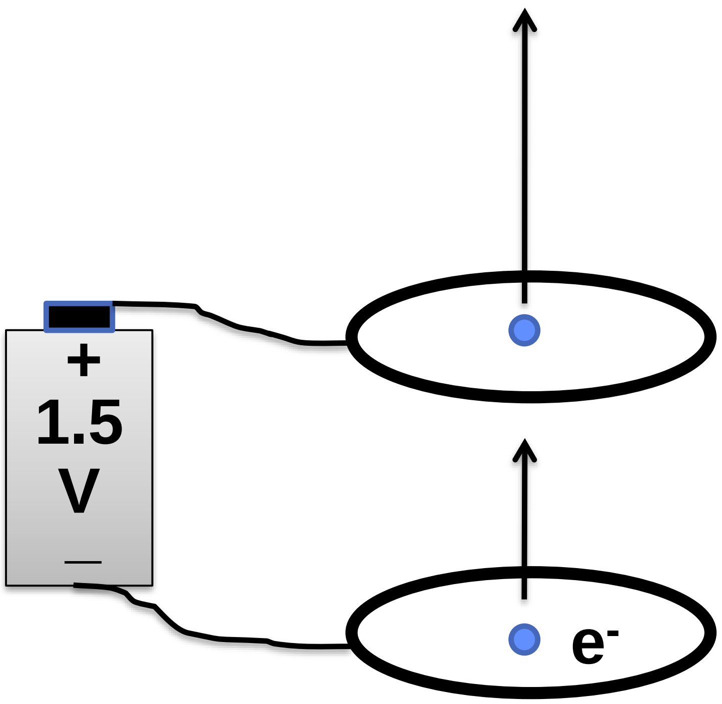
$$1\ \text{Electron Volt} = e_0 \cdot 1\text{V} = 1.603 \cdot 10^{-19}\ \text{J}$$



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

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)

Basics

Lorentz Boost:

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \quad \tau = 2.2 \cdot 10^{-6}\, s$$

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

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

But we see Muons here on Earth

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

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

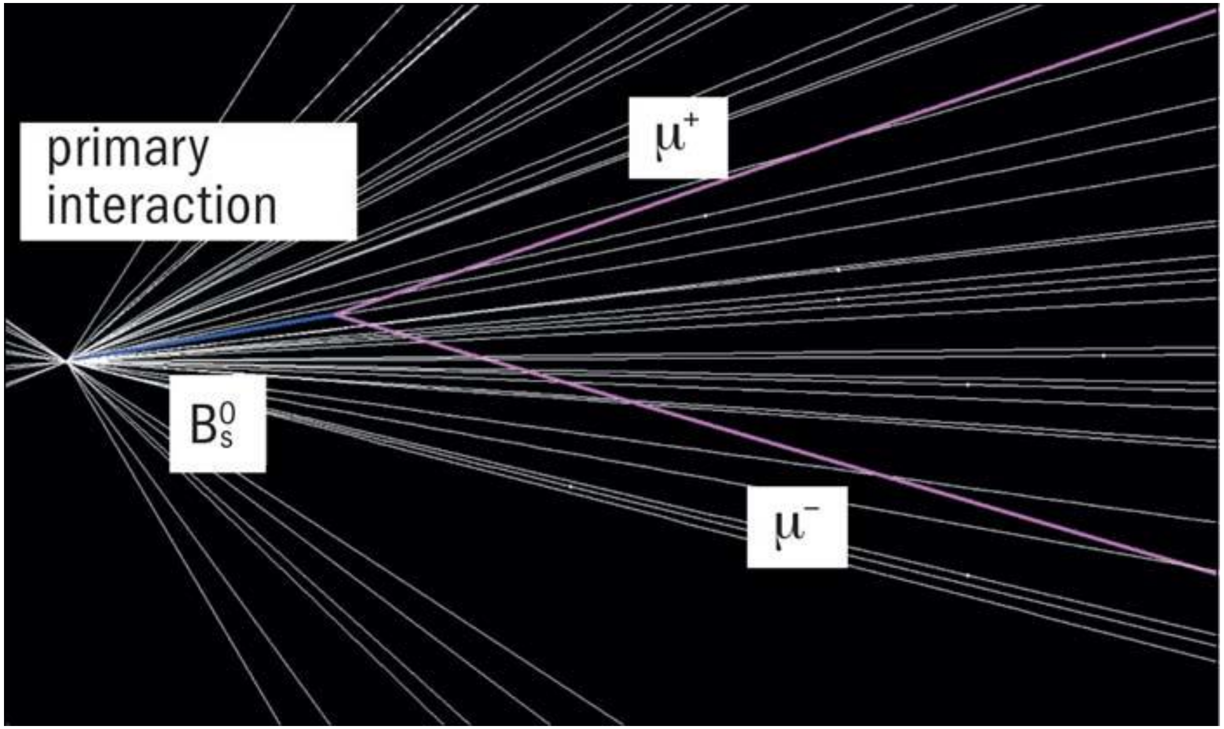
$$s = c \cdot \bar{\tau} = 12.5\, km \rightarrow \text{Earth}$$

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

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

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

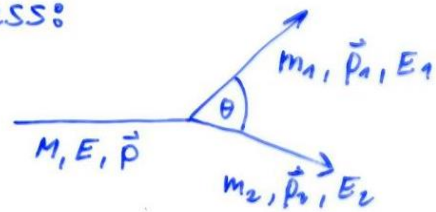
LHCb B decay



Basics

Invariant Mass:

LAB:



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

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

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

$\tilde{p} = \tilde{p}_1 + \tilde{p}_2$ 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

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

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

Particle	Mass (MeV)	Lifetime 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" (bracket spanning $D^{\pm}$ 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.

$e^\pm$ $m_e = 0.511$ 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

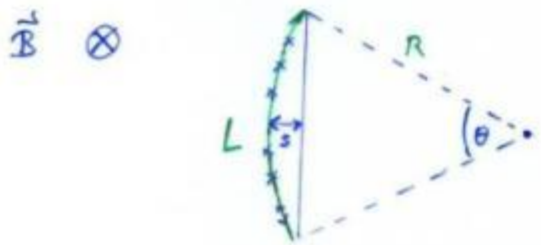
The Difference in

Mass, Charge, Interaction

is the key to the Identification

Momentum Measurement

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



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

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

$$L = R \cdot \theta$$

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

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

$$\Delta s = \frac{\sigma_x}{\sqrt{N}}$$ σ_x ... point resolution, N ... Measurement Points

$$\frac{\Delta p}{p} = \frac{\Delta s}{s} = \frac{\sigma_x[m]}{\sqrt{N}} \cdot \frac{3.3 \cdot 8\, p\left[\frac{GeV}{c}\right]}{B[T] \cdot L^2[m^2]}$$

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

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

Limit → Multiple Scattering

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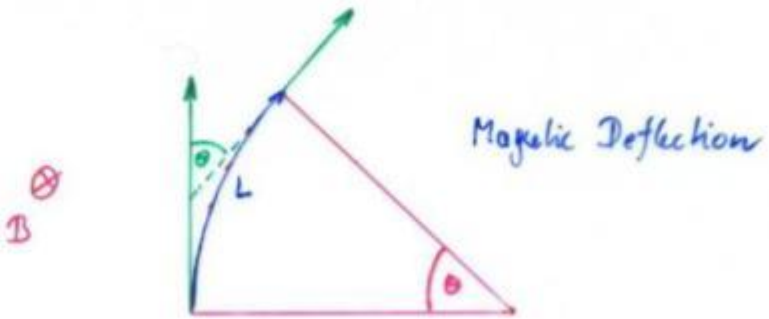
Multiple Scattering



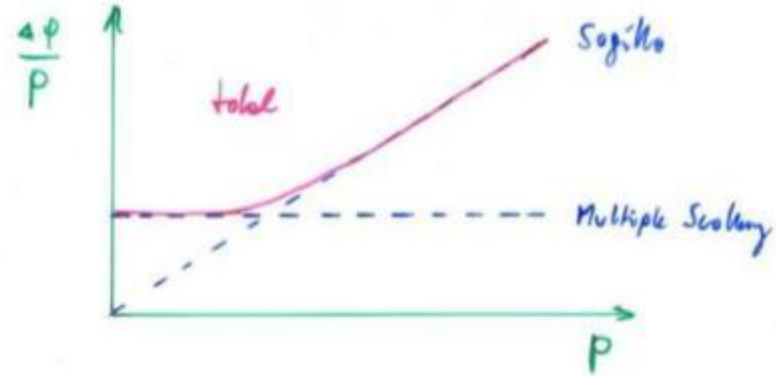
$$p\left[\frac{GeV}{c}\right] = 0.3\, R[m]\, B[T]$$

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

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

→ Independent of p

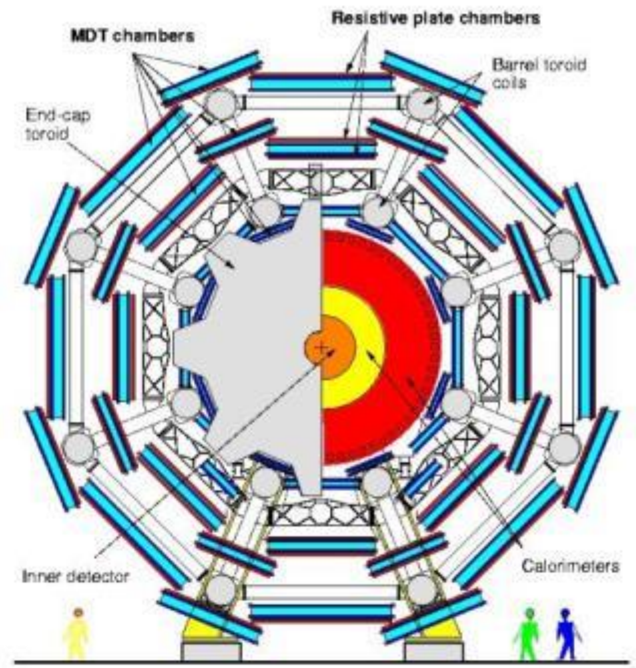
$$\left.\frac{\Delta p}{p}\right|_{tot} = \sqrt{\left(\left.\frac{\Delta p}{p}\right|_{sag}\right)^2 + \left(\left.\frac{\Delta p}{p}\right|_{ms}\right)^2}$$

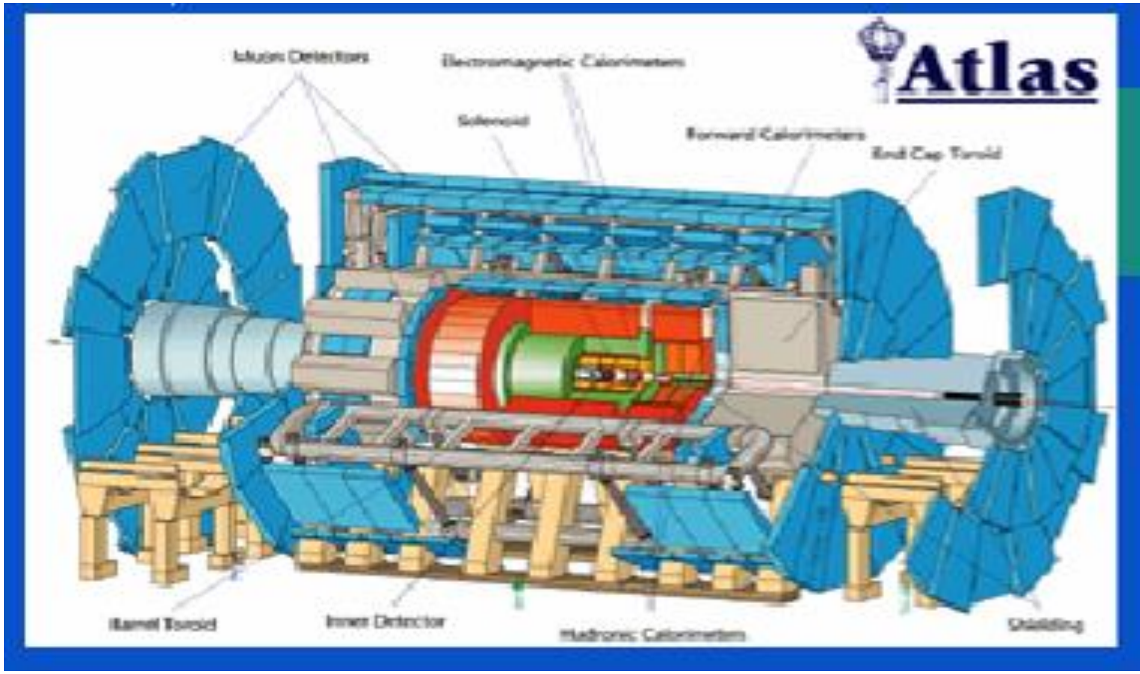


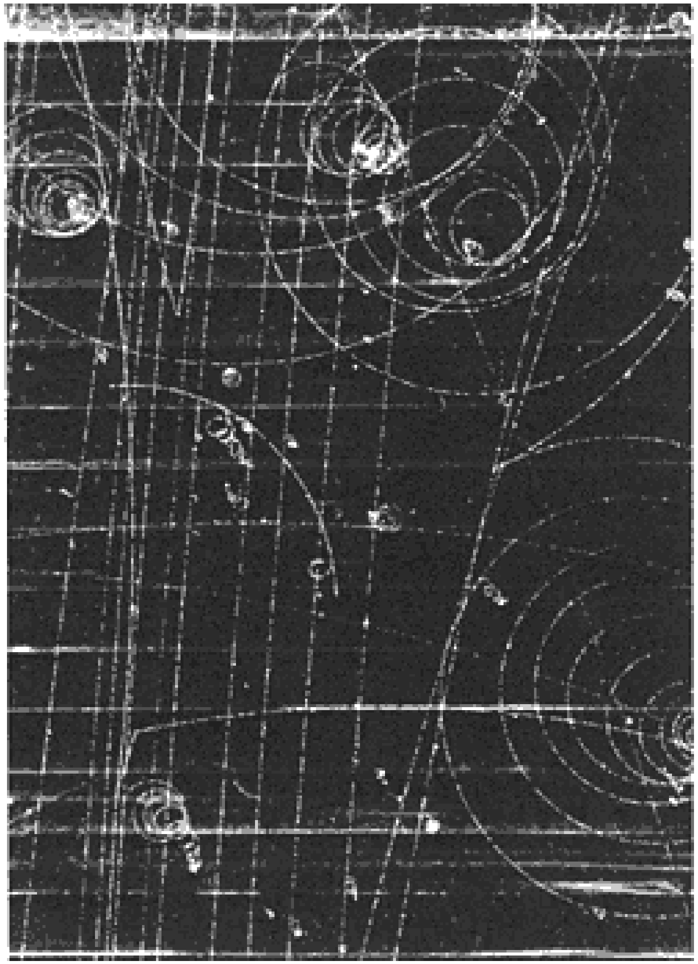
Multiple Scattering

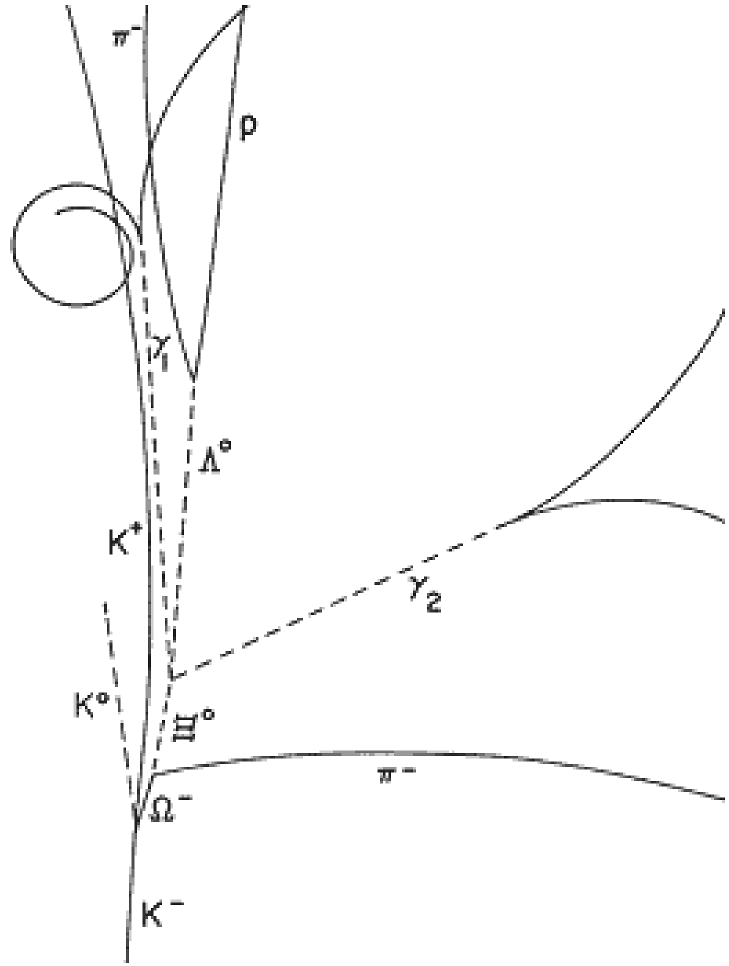
ATLAS Muon Spectrometer:
N=3, sig=50um, P=1TeV,
L=5m, B=0.4T

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









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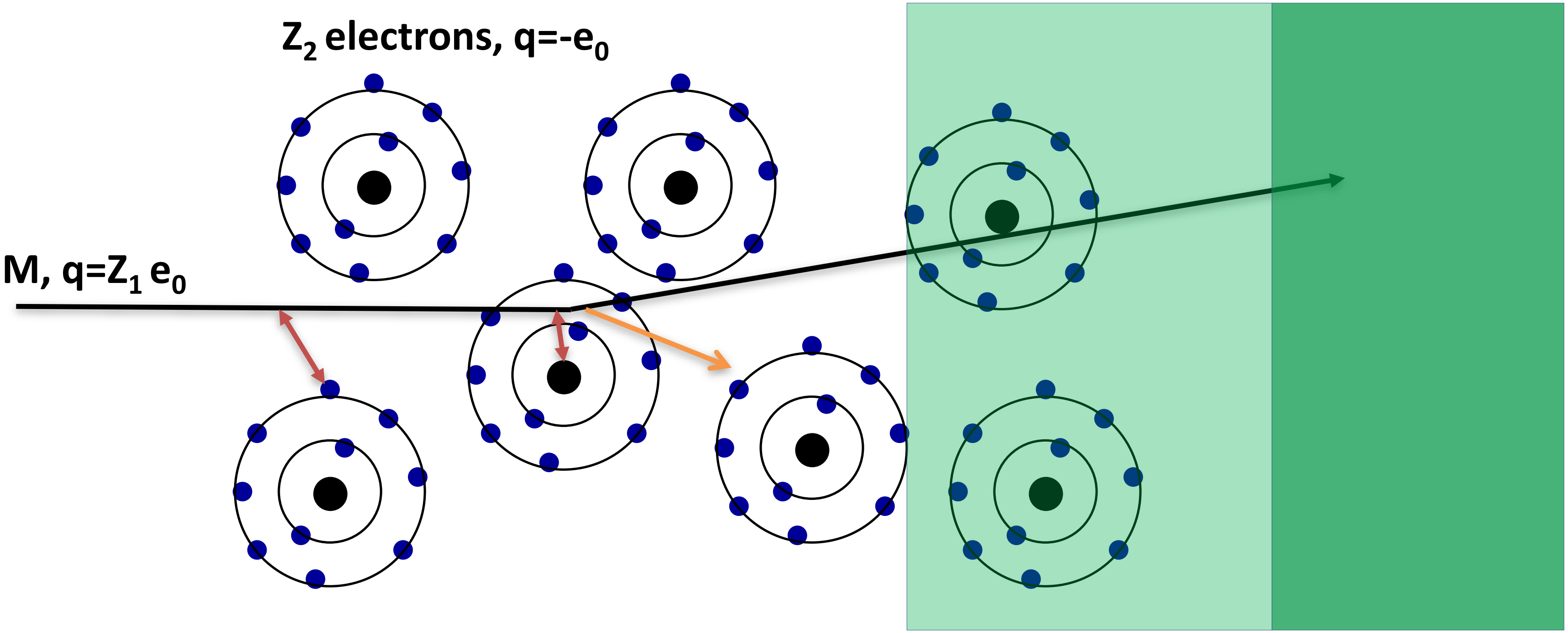
Electromagnetic Interaction of Particles with Matter

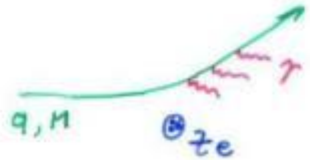


Interaction with the atomic electrons. The incoming particle loses energy and the atoms are excited or ionized.

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.

Bremsstrahlung, Classical



$q = Z_1 \cdot e$

$$\frac{d\sigma}{d\Omega} = \left(\frac{2 Z_1 Z_2 e^2}{4\pi\varepsilon_0\, p \cdot v}\right)^2 \frac{1}{(2\sin\frac{\theta}{2})^4} \qquad p = Mv\gamma$$

"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)

$$\lim_{\omega \to 0} \frac{dI}{d\omega} \sim \frac{2}{3\pi} \frac{Z_1^2 e^2}{M^2 c^3} \frac{1}{4\pi\varepsilon_0} Q^2$$ Radiated Energy between $\omega, \omega + d\omega$

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

$$\frac{dE}{dx} = \frac{N_A \rho}{A} \cdot \frac{16}{3} \alpha \cdot Z^2 \cdot \left(\frac{Z_1^2 e^2}{4\pi\varepsilon_0 M c^2}\right)^2 \cdot E \cdot \ln\frac{Q_{max}}{Q_{min}}$$

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

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.

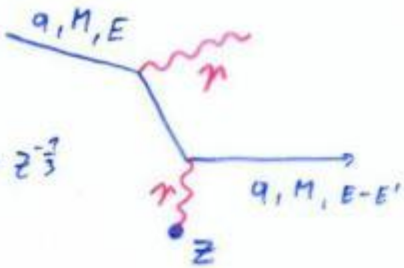
Coulomb-Scattering (Rutherford Scattering) describes the deflection of the particle.

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

→ dE/dx

Bremsstrahlung, QM

2.6 Bremsstrahlung Q.M.



$q = Z_1 e, \quad E + Mc^2 \gg 137\, Mc^2 Z^{-\frac{1}{3}}$

→ highly Relativistic:

$$\frac{d\sigma(E,E')}{dE'} = 4\alpha Z^2 Z_1^4 \left(\frac{1}{4\pi\varepsilon_0}\frac{e^2}{Mc^2}\right)^2 \frac{1}{E'} F(E,E')$$

$$F(E,E') = \left[1 + \left(1 - \frac{E'}{E+Mc^2}\right)^2 - \frac{2}{3}\left(1 - \frac{E'}{E+Mc^2}\right)\right] \ln 183 Z^{-\frac{1}{3}} + \frac{1}{9}\left(1 - \frac{E'}{E+Mc^2}\right)$$

$$\frac{dE}{dx} = -\frac{N_A \rho}{A}\int_0^E E' \frac{d\sigma}{dE'} dE' \approx 4\alpha Z^2 Z_1^4 \left(\frac{1}{4\pi\varepsilon_0}\frac{e^2}{Mc^2}\right)^2 E \left[\ln 183 Z^{-\frac{1}{3}} + \frac{1}{18}\right]$$

$$\frac{dE}{dx} = -\frac{N_A \rho}{A} 4\alpha Z^2 Z_1^4 \left(\frac{1}{4\pi\varepsilon_0}\frac{e^2}{Mc^2}\right)^2 E \ln\left(183 Z^{-\frac{1}{3}}\right)$$

$$E(x) = E_0 e^{-\frac{x}{X_0}} \qquad X_0 = \frac{A}{4\alpha N_A \rho Z^2 \left(\frac{1}{4\pi\varepsilon_0}\frac{e^2}{Mc^2}\right)^2 \ln 183 Z^{-\frac{1}{3}}}$$

X_0 ... Radiation length

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.

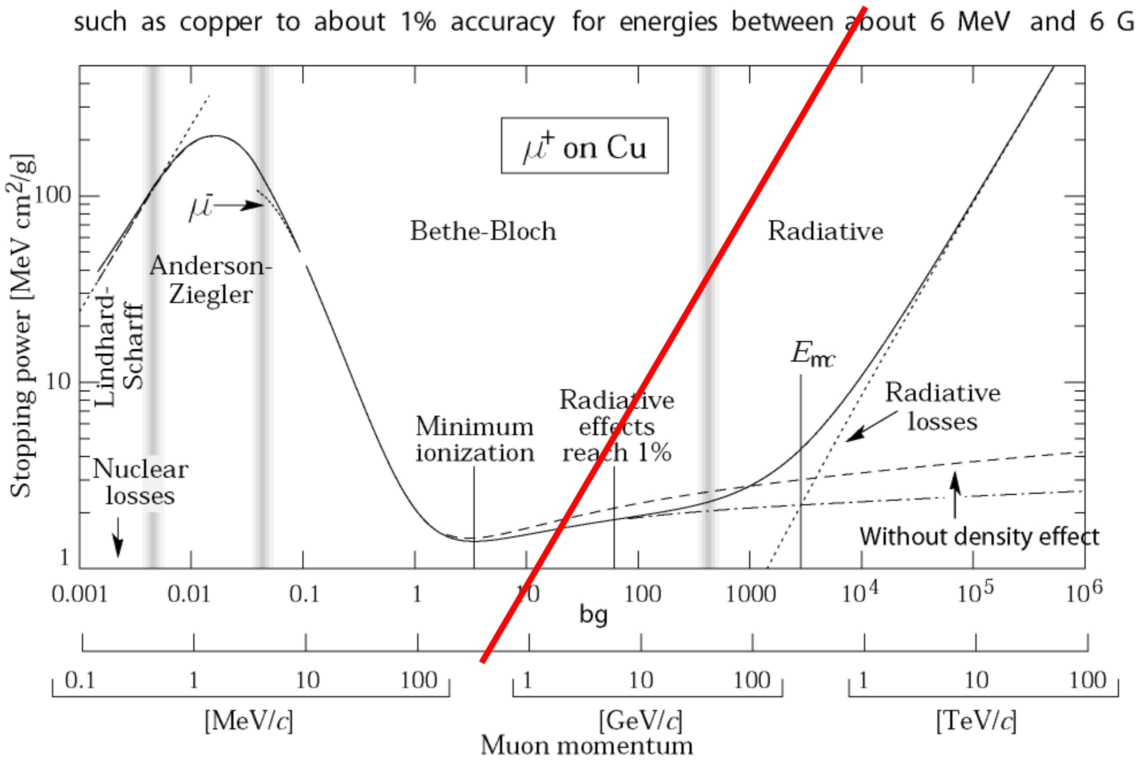
Proportional to the Energy of the Incoming particle →

$E(x)=Exp(-x/X_0)$ – '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 $E_0 Exp(-1)=0.37E_0$.

Critical Energy



Electron Momentum 5 50 500 MeV/c

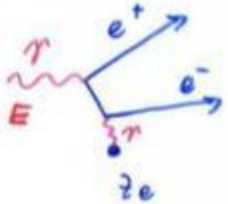
For the muon, the second lightest particle after the electron, the critical energy is at 400GeV.

The EM Bremsstrahlung is therefore only relevant for electrons at energies of past and present detectors.

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

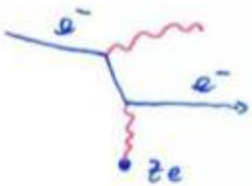
Myon in Copper: p ≈ 400GeV
Electron in Copper: p ≈ 20MeV

Pair Production, QM



γ + Nucl. → $e^+ + e^-$ + Nucl

The Diagram is very similar to Bremsstrahlung



e^- + Nucl → γ + e^- + Nucl

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

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

$$G(E,E') = \left[\left(\left(\frac{E'+m_ec^2}{E}\right)^2 + \left(1-\frac{E'+m_ec^2}{E}\right)^2 + \frac{2}{3}\frac{E'+m_ec^2}{E}\left(1-\frac{E'+m_ec^2}{E}\right)\right)\ln Z^{-\frac{1}{3}} - \frac{1}{9}\frac{E'+m_ec^2}{E}\left(1-\frac{E'+m_ec^2}{E}\right)\right]$$

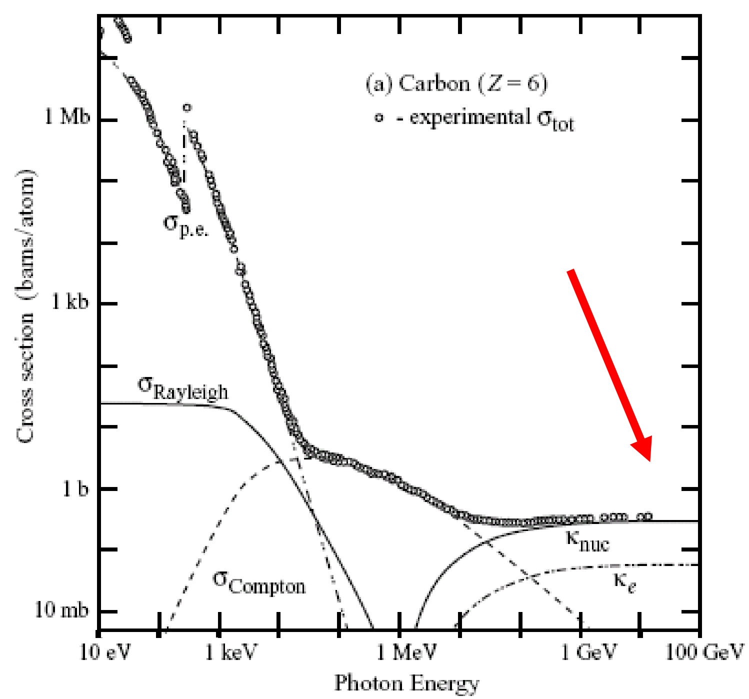
$$\sigma = \int_0^{E-2m_ec^2} \frac{d\sigma}{dE'}dE' = 4\alpha Z^2 r_e^2 \cdot \frac{7}{9} \ln 183 Z^{-\frac{1}{3}}$$

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

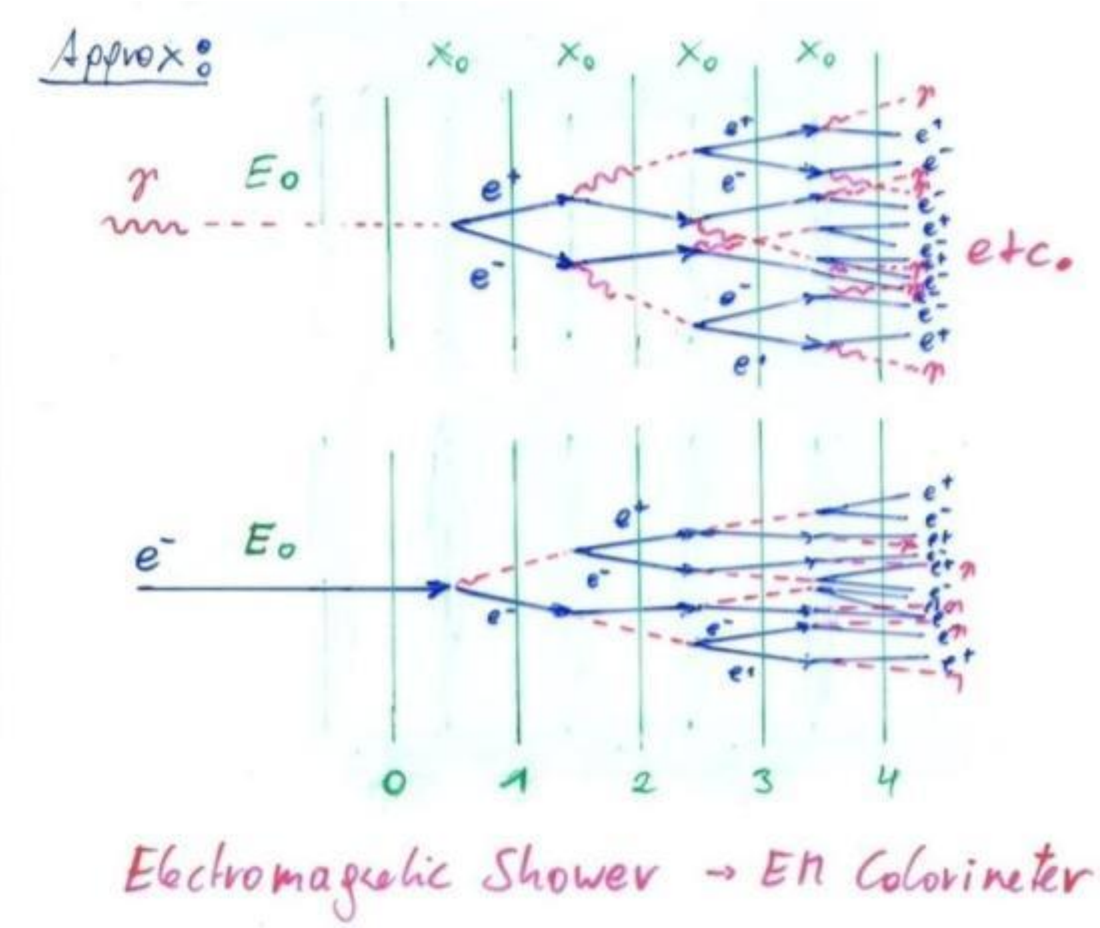
↳ Probability that Photon converts to $e^+ e^-$ after a distance x.

For $E\gamma \gg m_e c^2 = 0.5$ MeV : $\lambda = 9/7 X_0$

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



23

Tracking:

Momentum by bending in the B-field

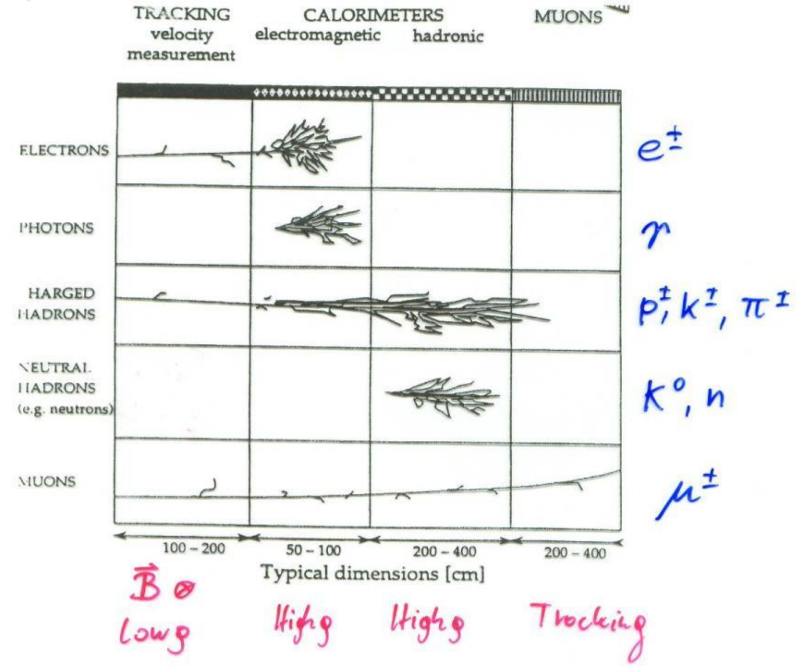
Secondary vertices

Calorimeter:

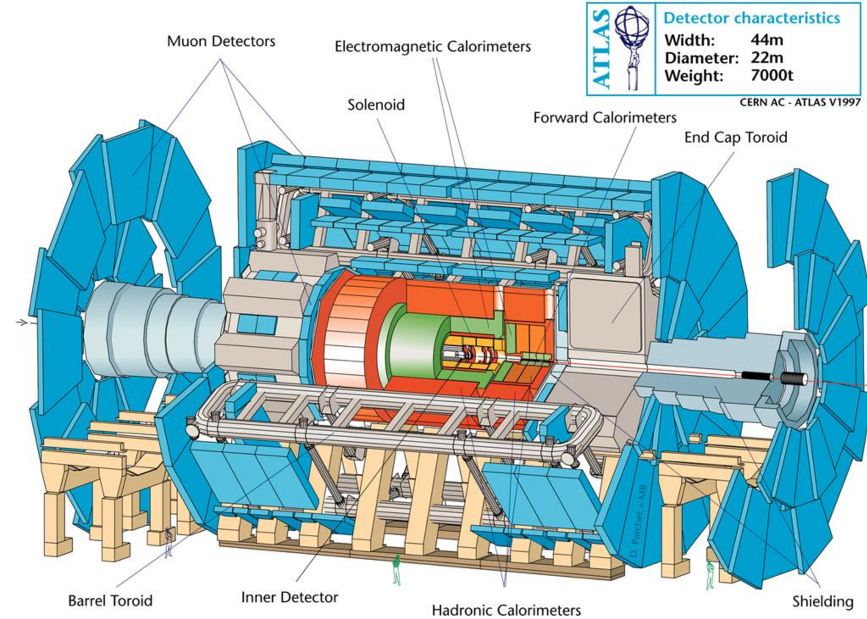
Energy by absorption

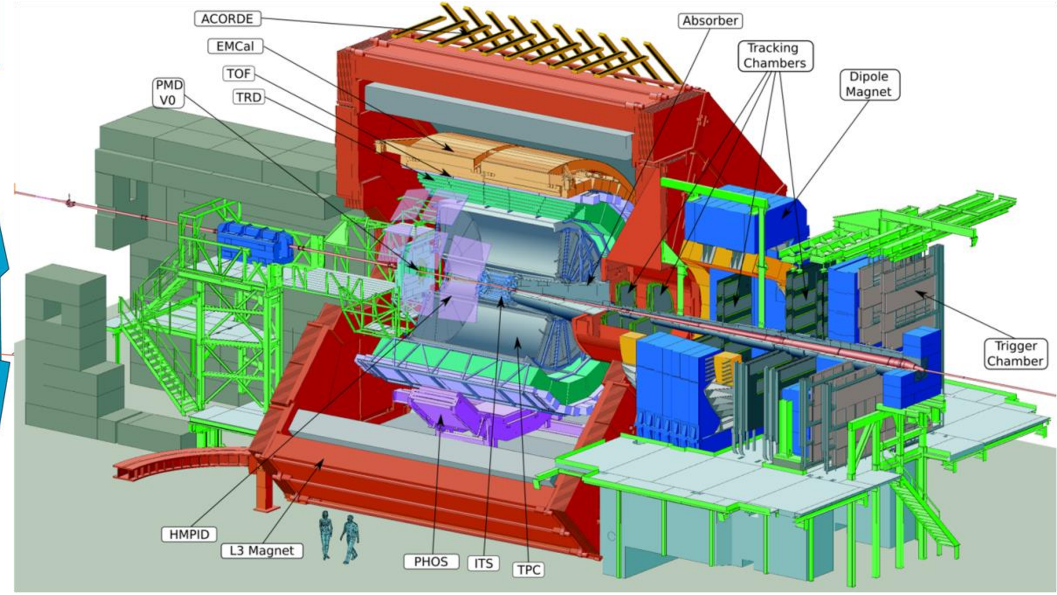
Muons:

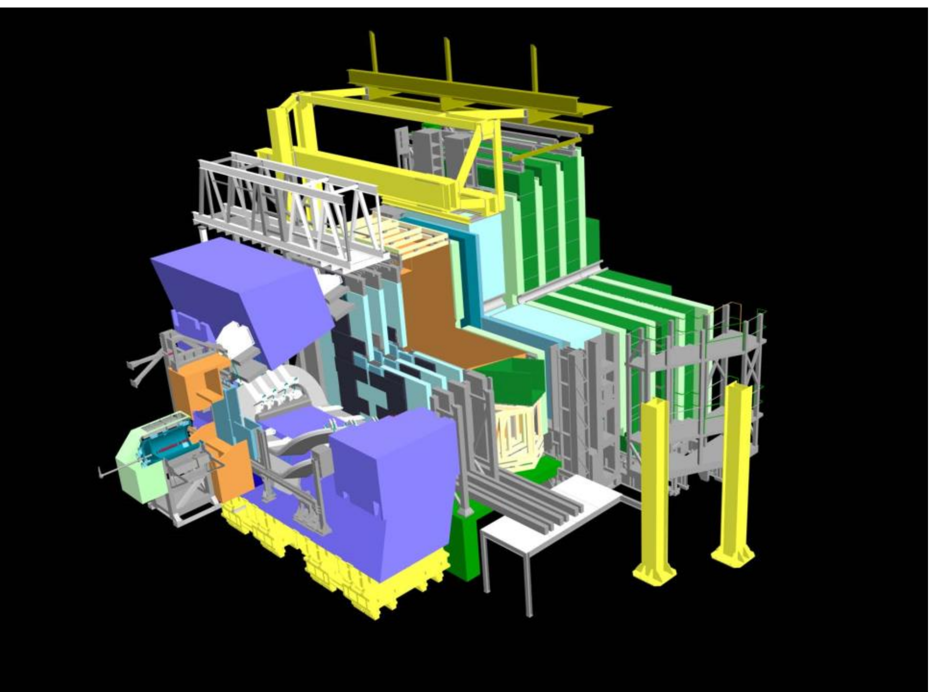
Only particles passing through calorimeters

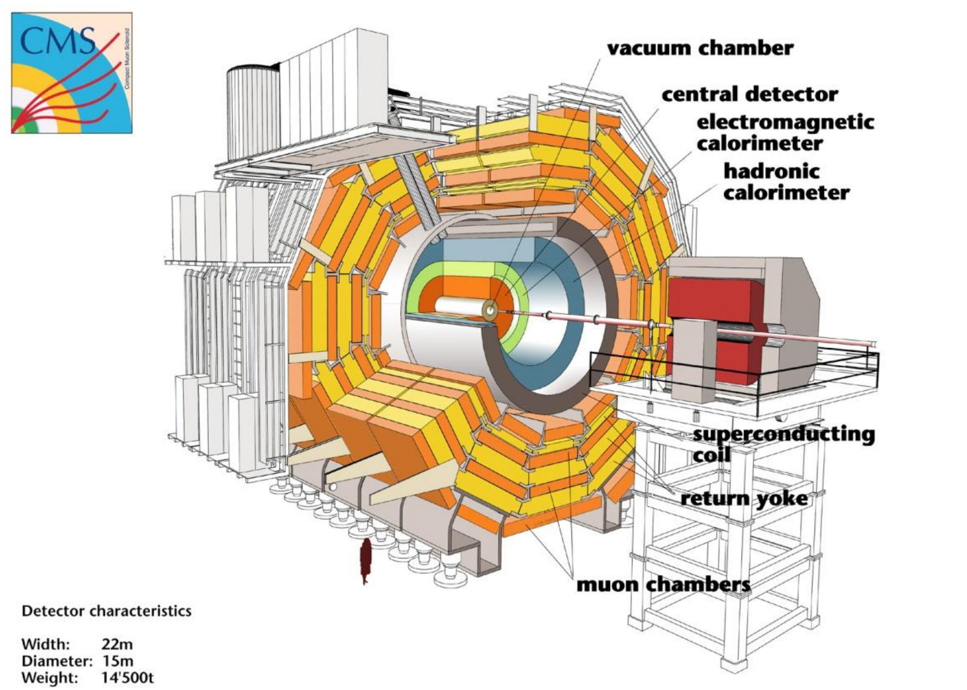


- Electrons ionize and show Bremsstrahlung due to the small mass
- Photons don't ionize but show Pair Production in high Z Material. From then on equal to $e^\pm$
- Charged Hadrons ionize and show Hadron Shower in dense material.
- Neutral Hadrons don't ionize and show Hadron Shower in dense Material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

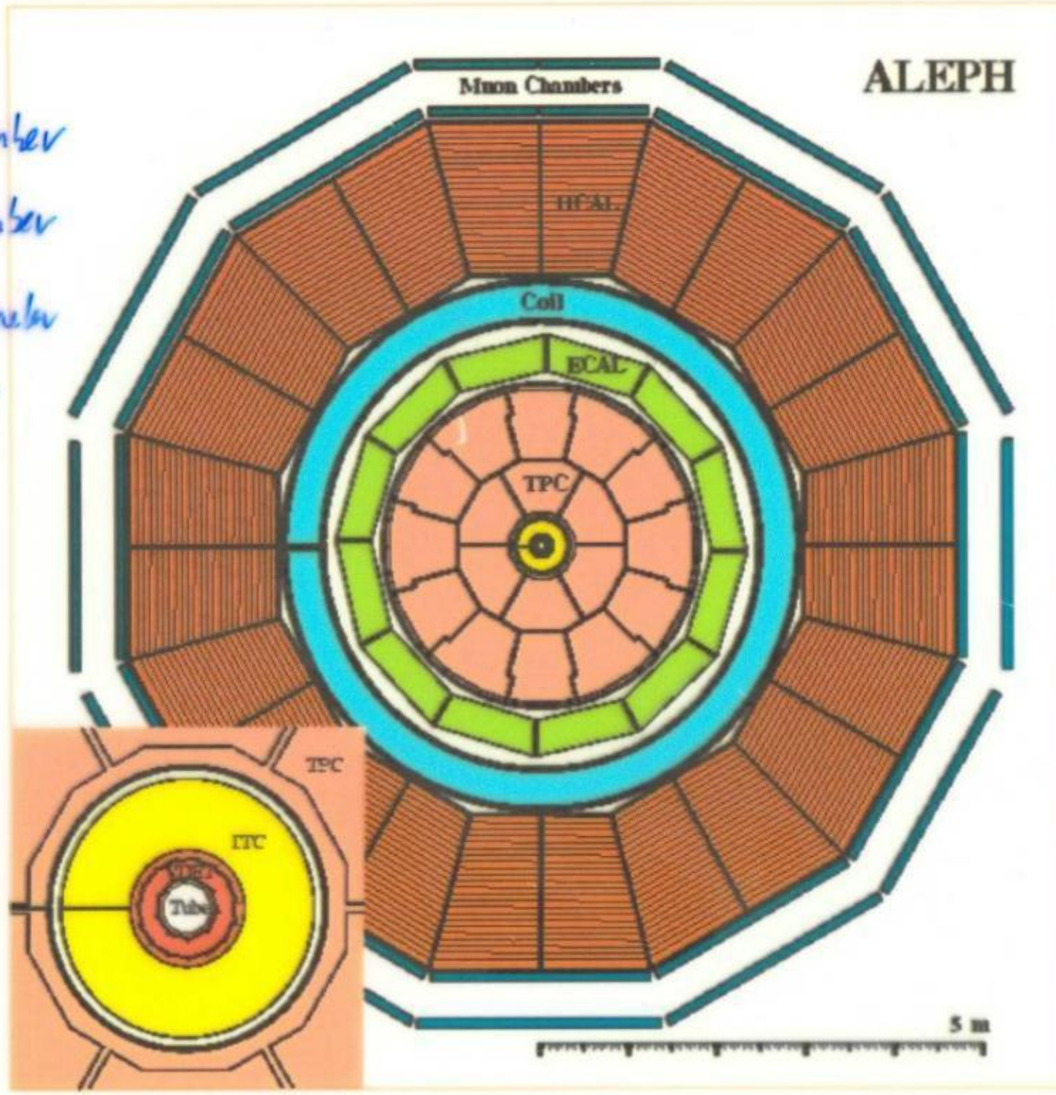

ATLAS
Detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t
CERN AC - ATLAS V1997
Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding


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



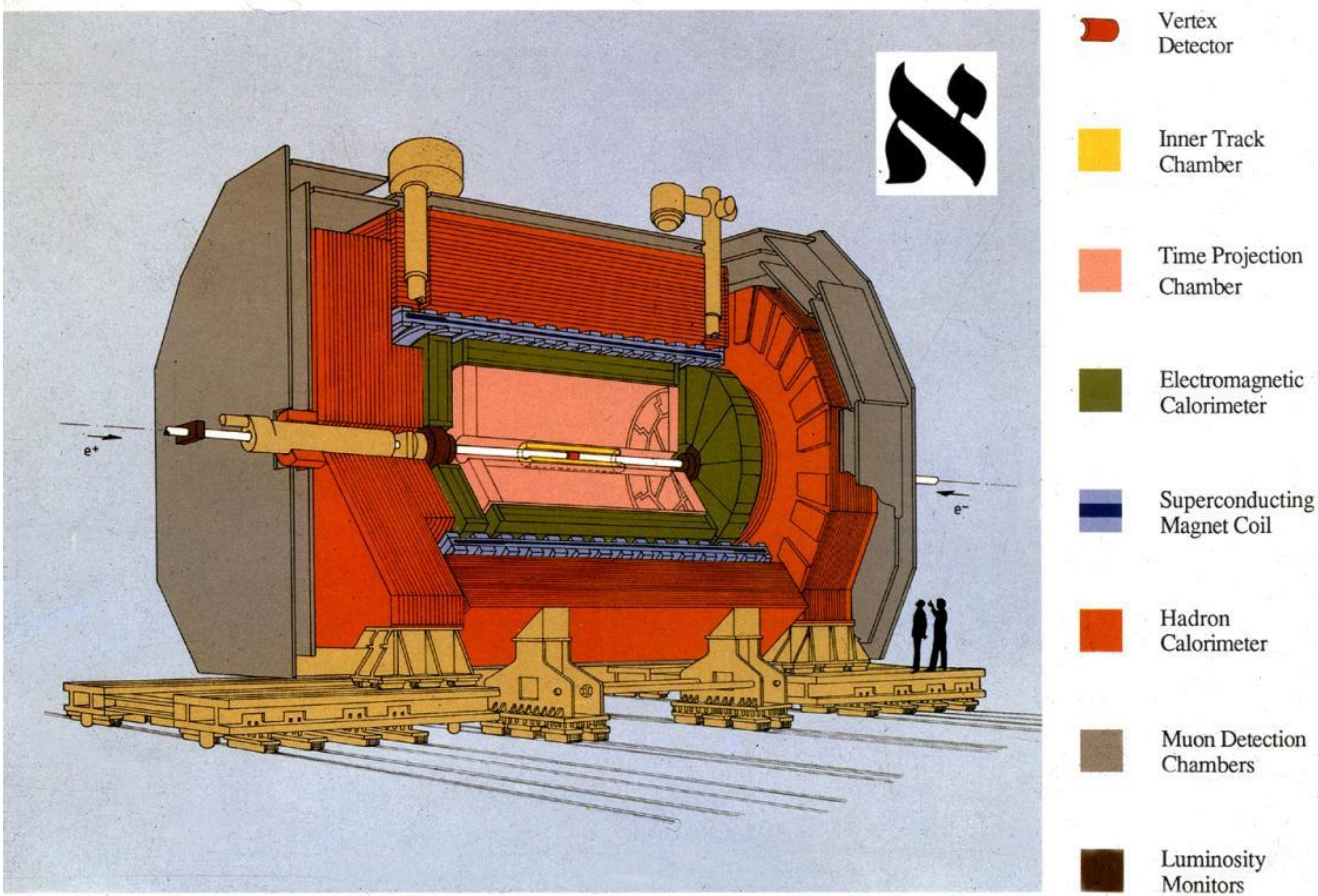
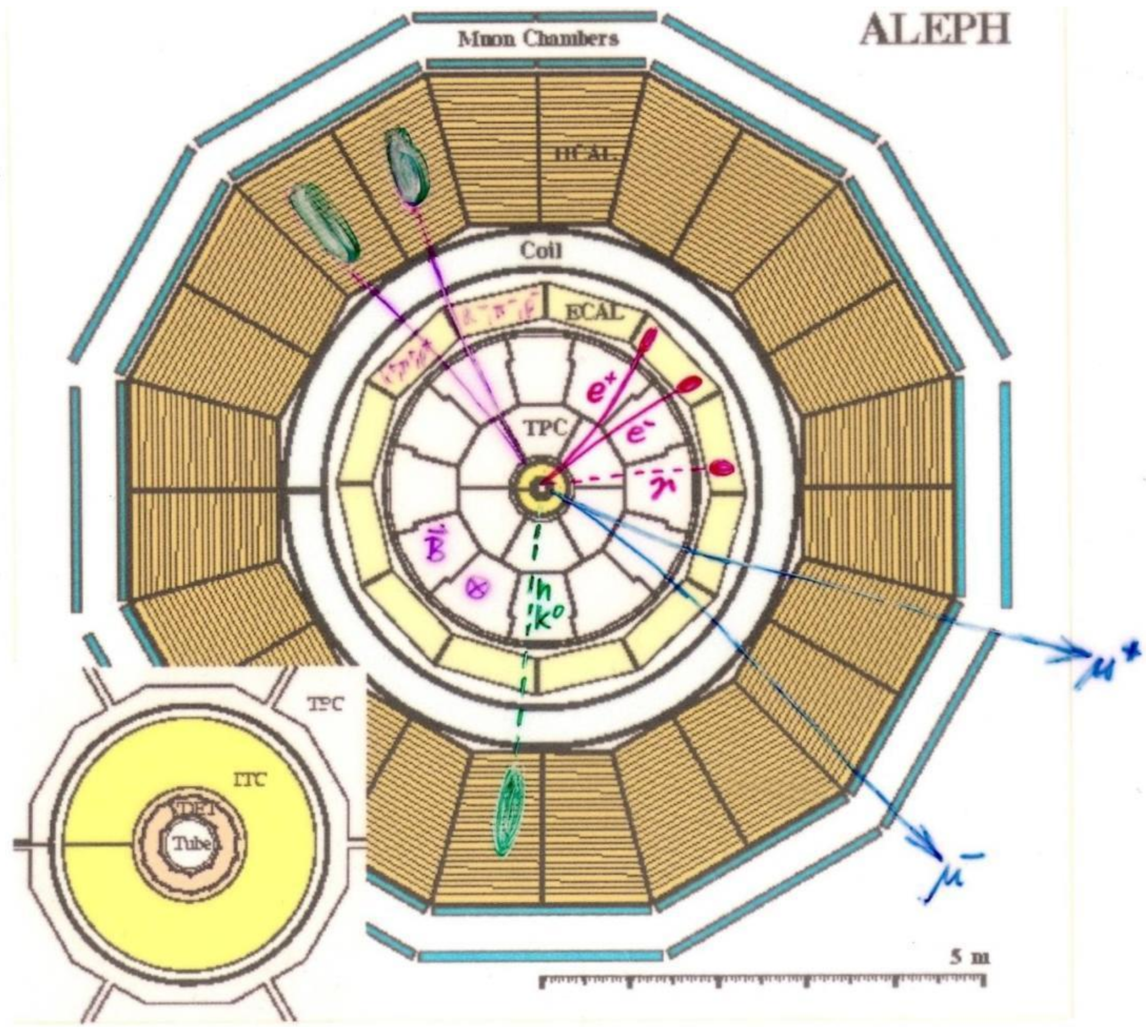


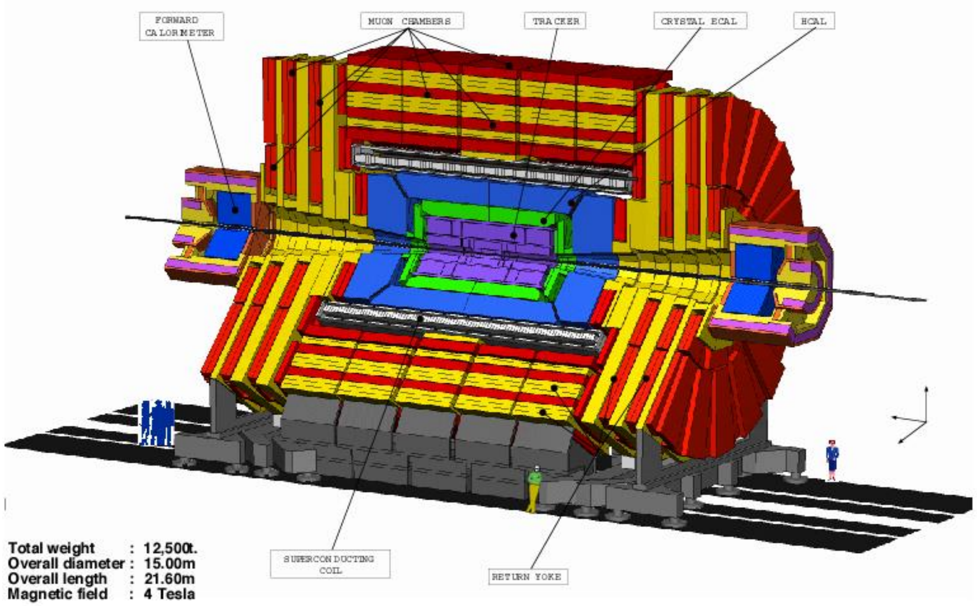
Fig. 1 - The ALEPH Detector

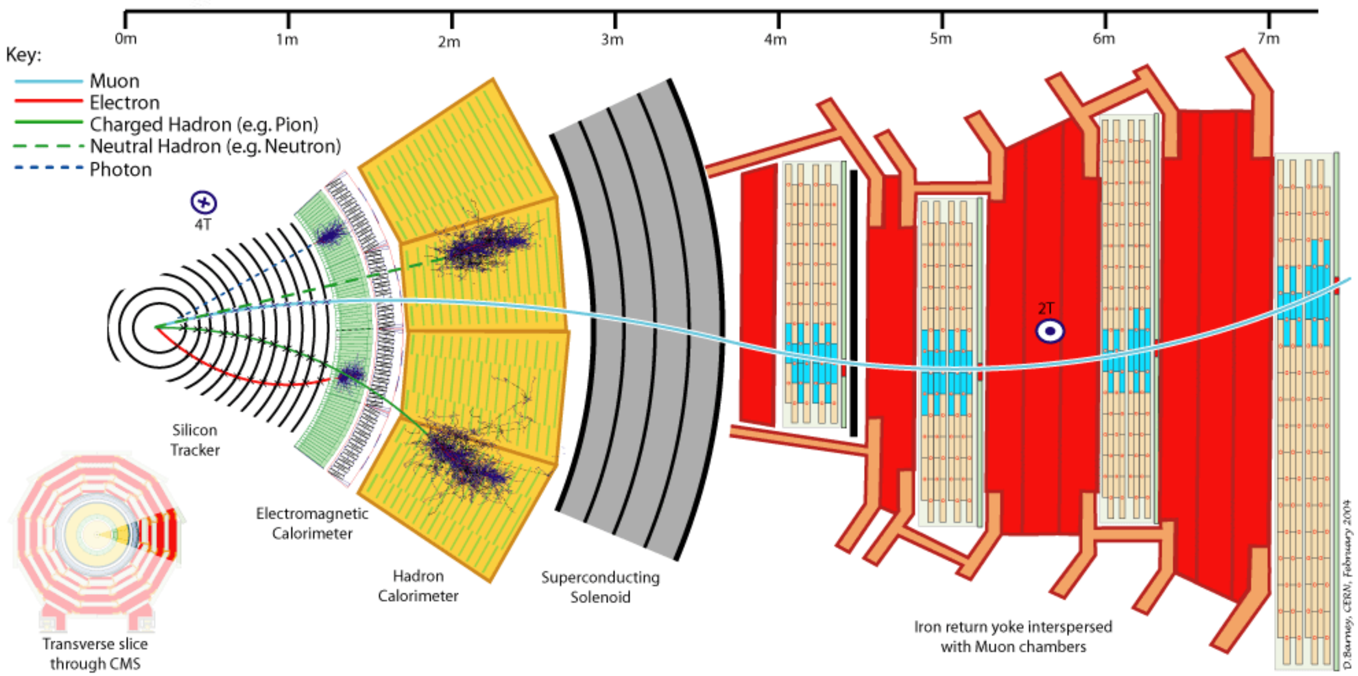
$\gamma, e^{\pm}, \pi^{\pm}, K^{\pm}$

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



CMS
A Compact Solenoidal Detector for LHC

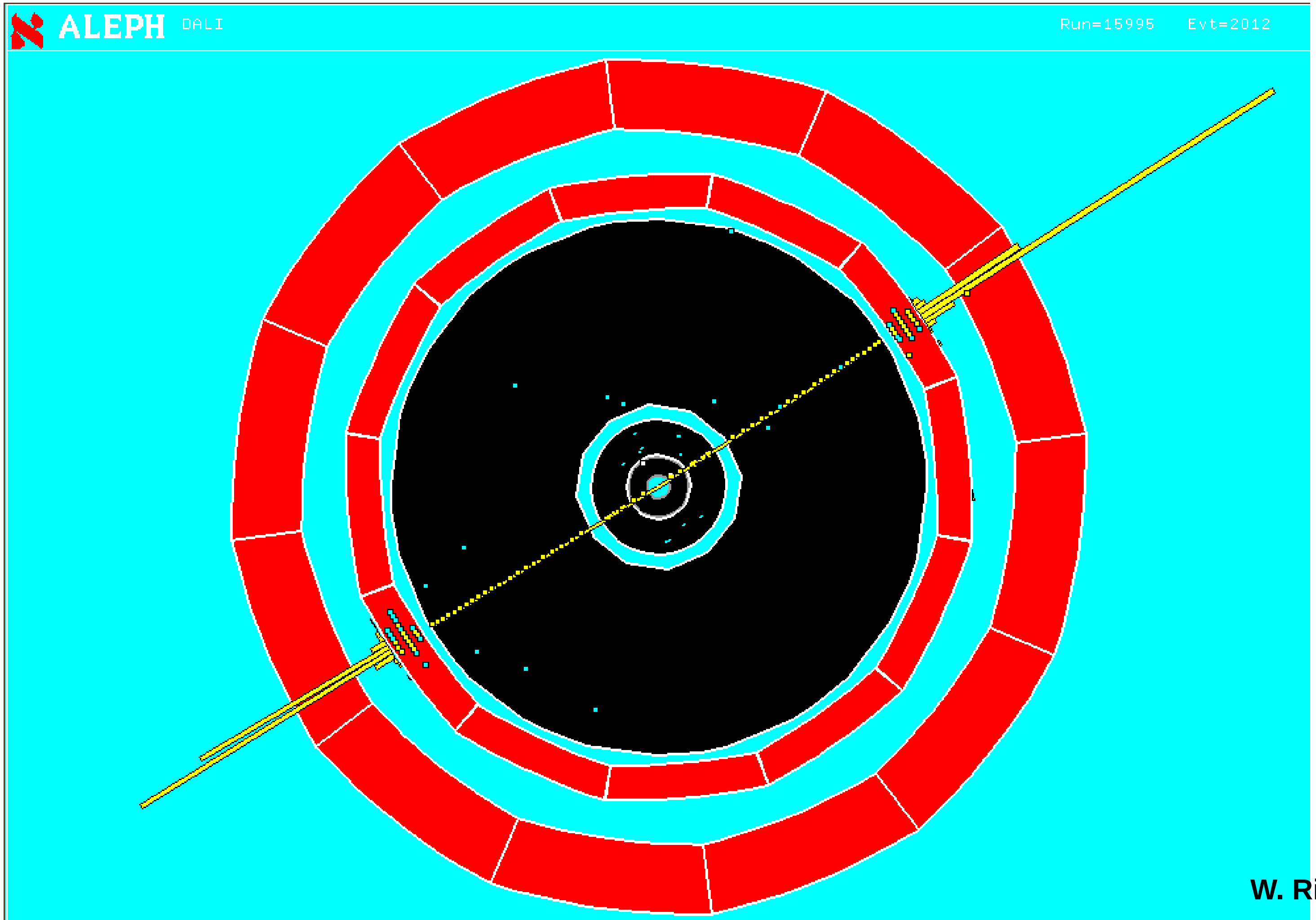




W. Riegler/CERN

$Z \rightarrow e^+ e^-$

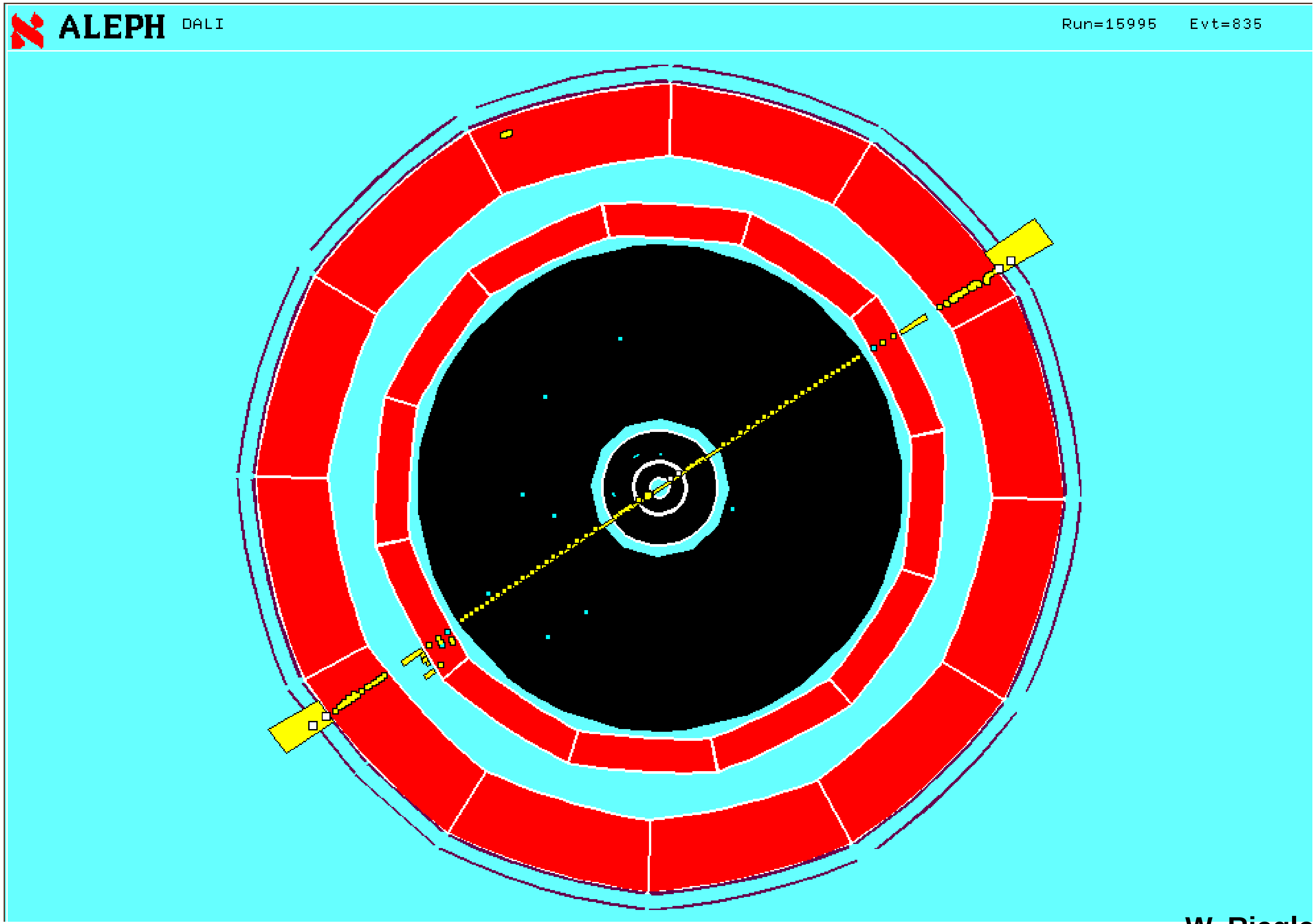
Two high momentum charged particles depositing energy in the Electro Magnetic Calorimeter



W. Riegler/CERN

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

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



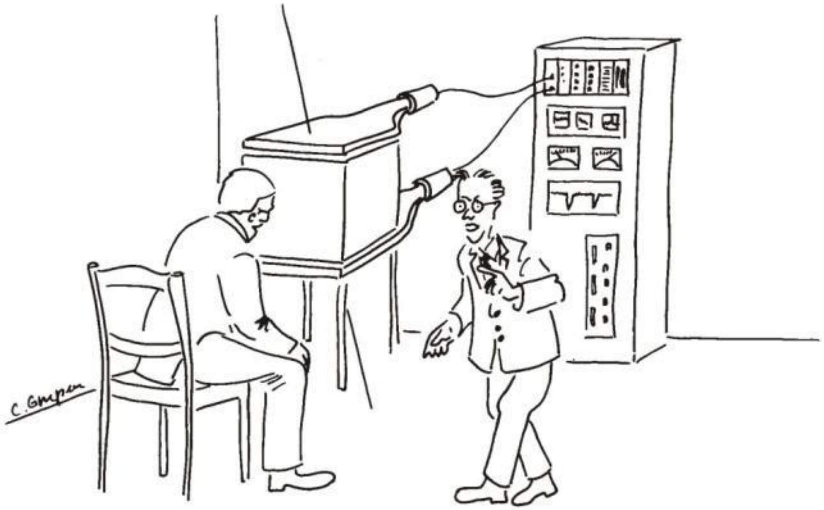
W. Riegler/CERN

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 ≠0 → neutrino escaped.

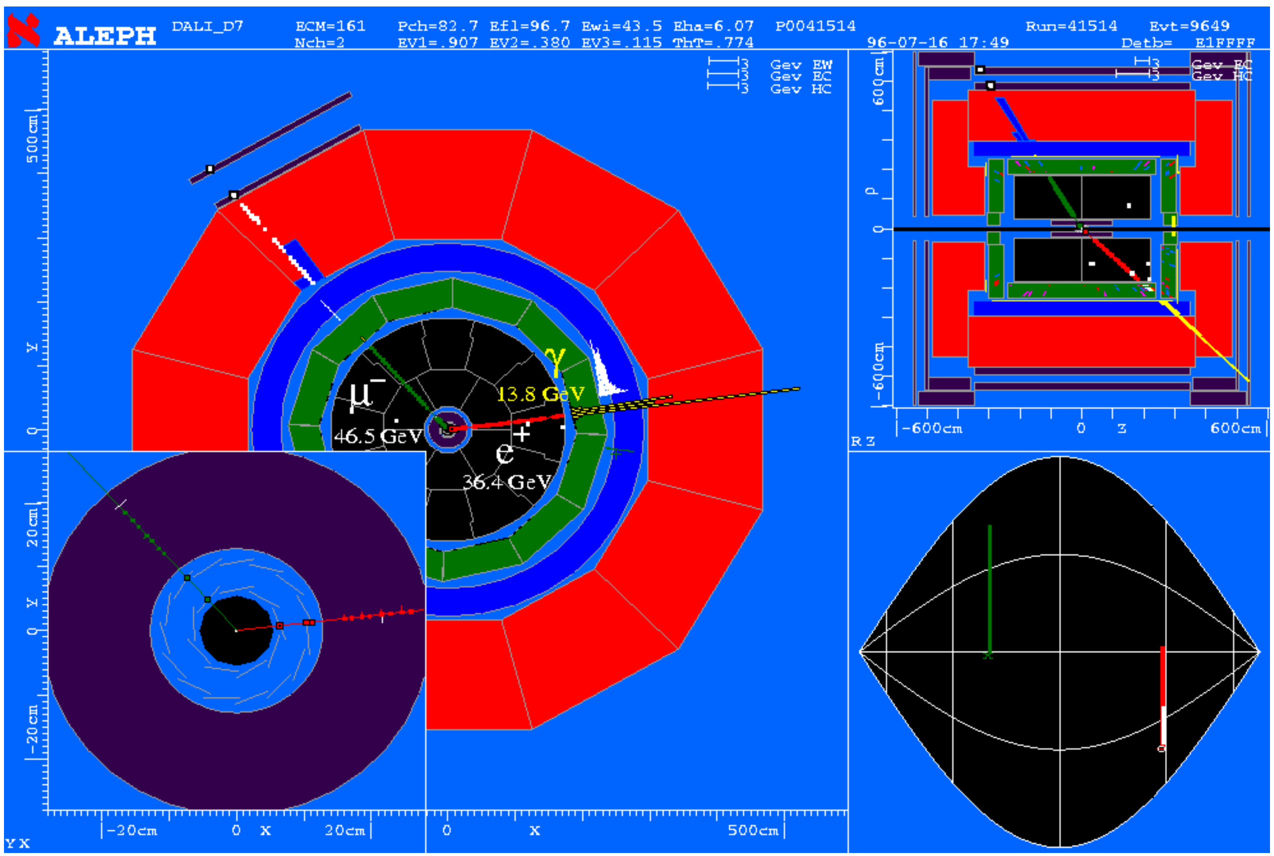


"Did you see it?"
"No nothing."
"Then it was a neutrino!"

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

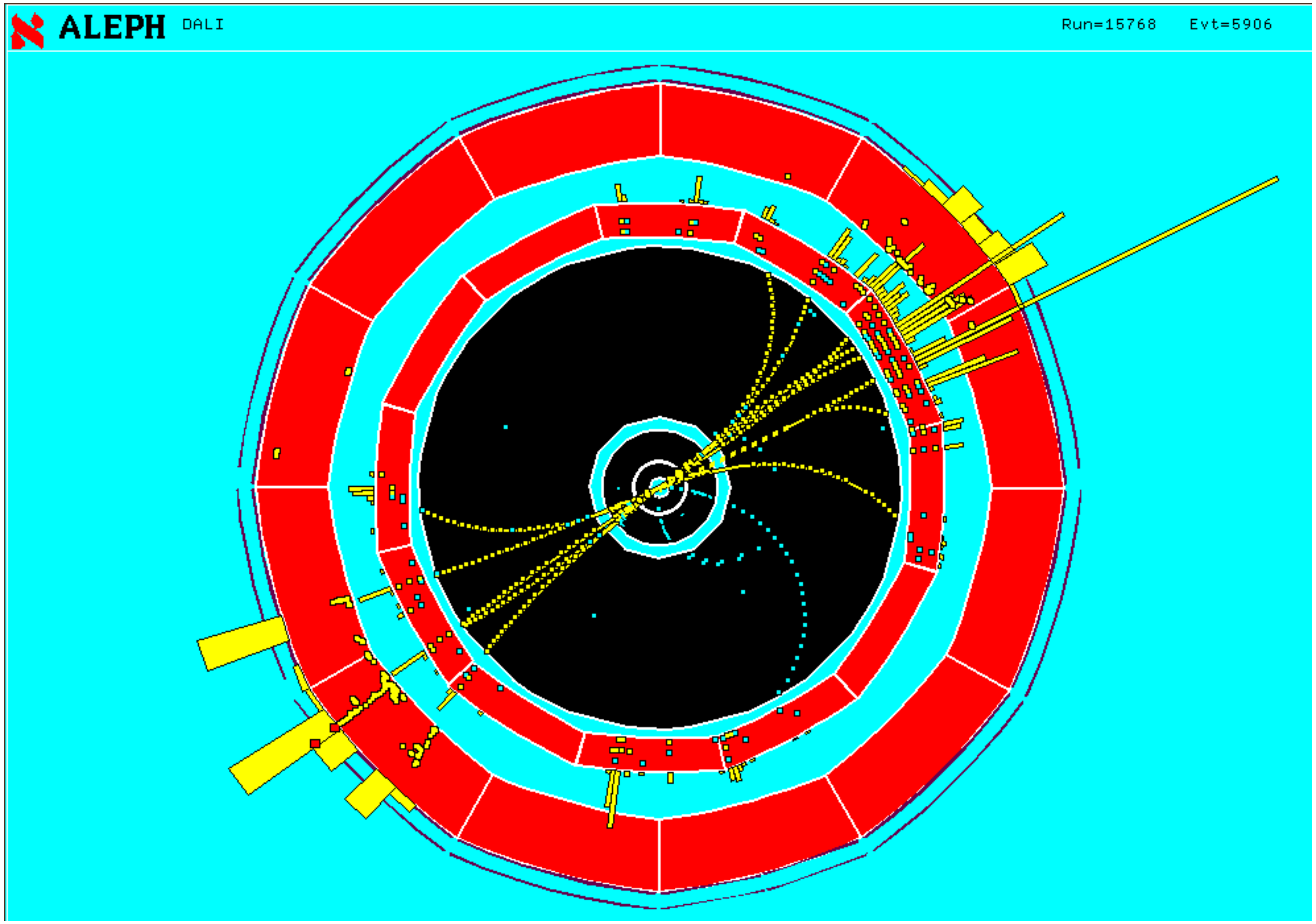
$W^+W^- \rightarrow e + \nu_e + \mu + \nu_\mu$

Single electron, single Muon, Missing Momentum



$Z \rightarrow q\bar{q}$

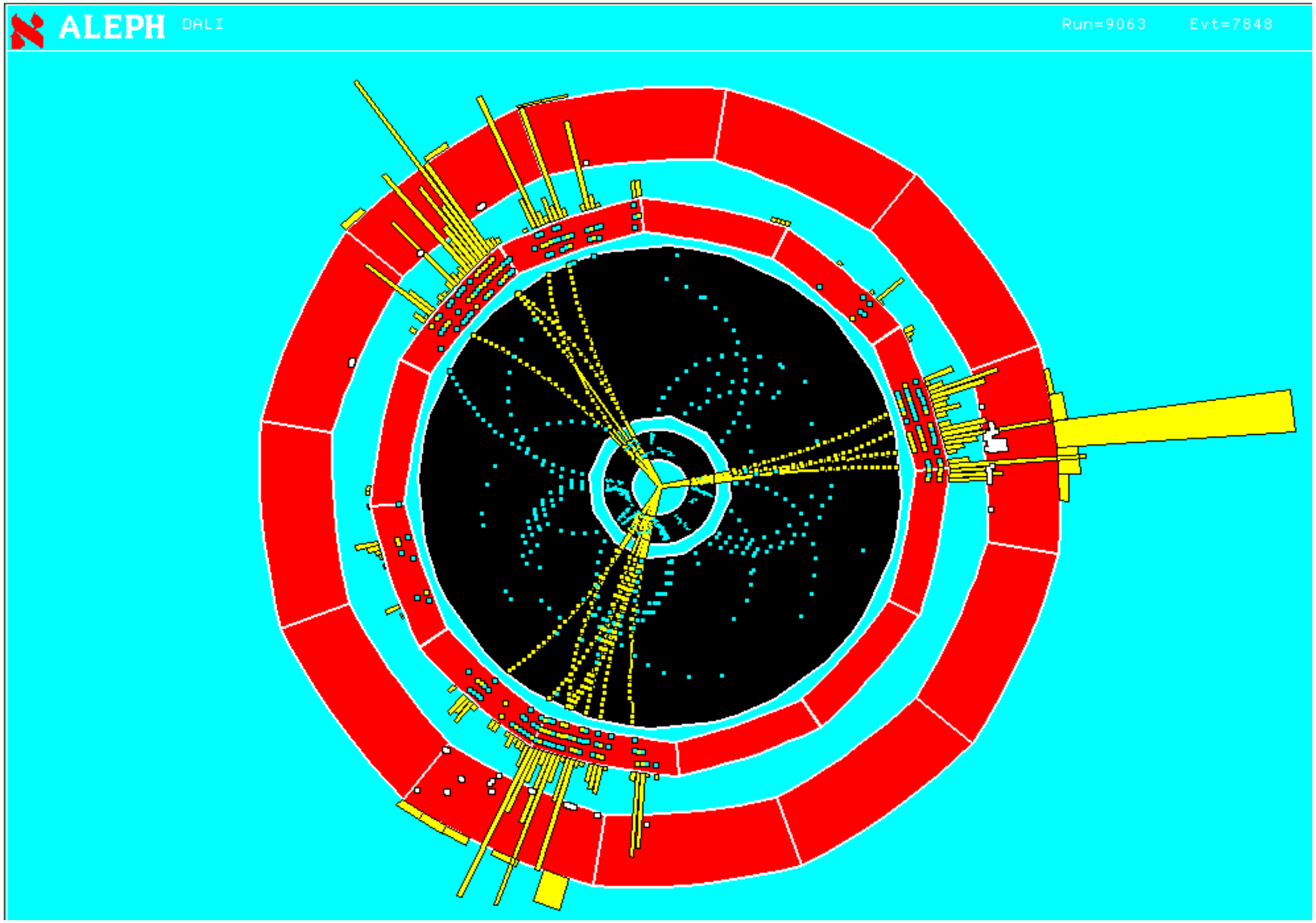
Two jets of particles



W. Riegler/CERN

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

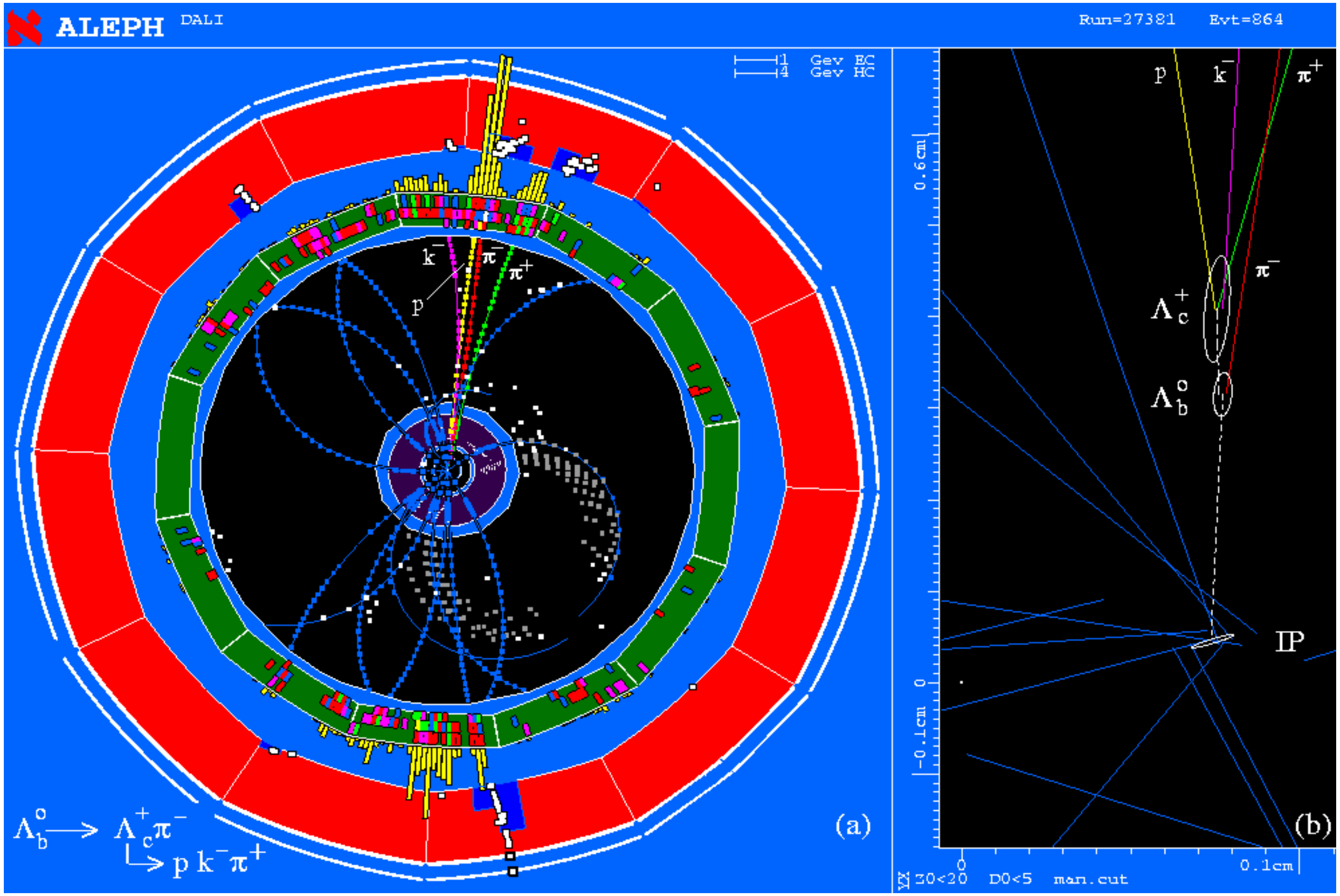
Three jets of particles



W. Riegler/CERN

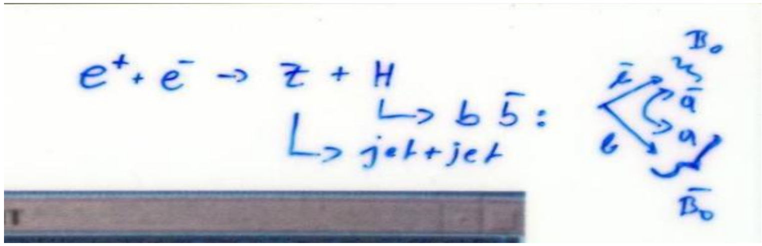
Two secondary vertices with characteristic decay particles giving invariant masses of known particles.

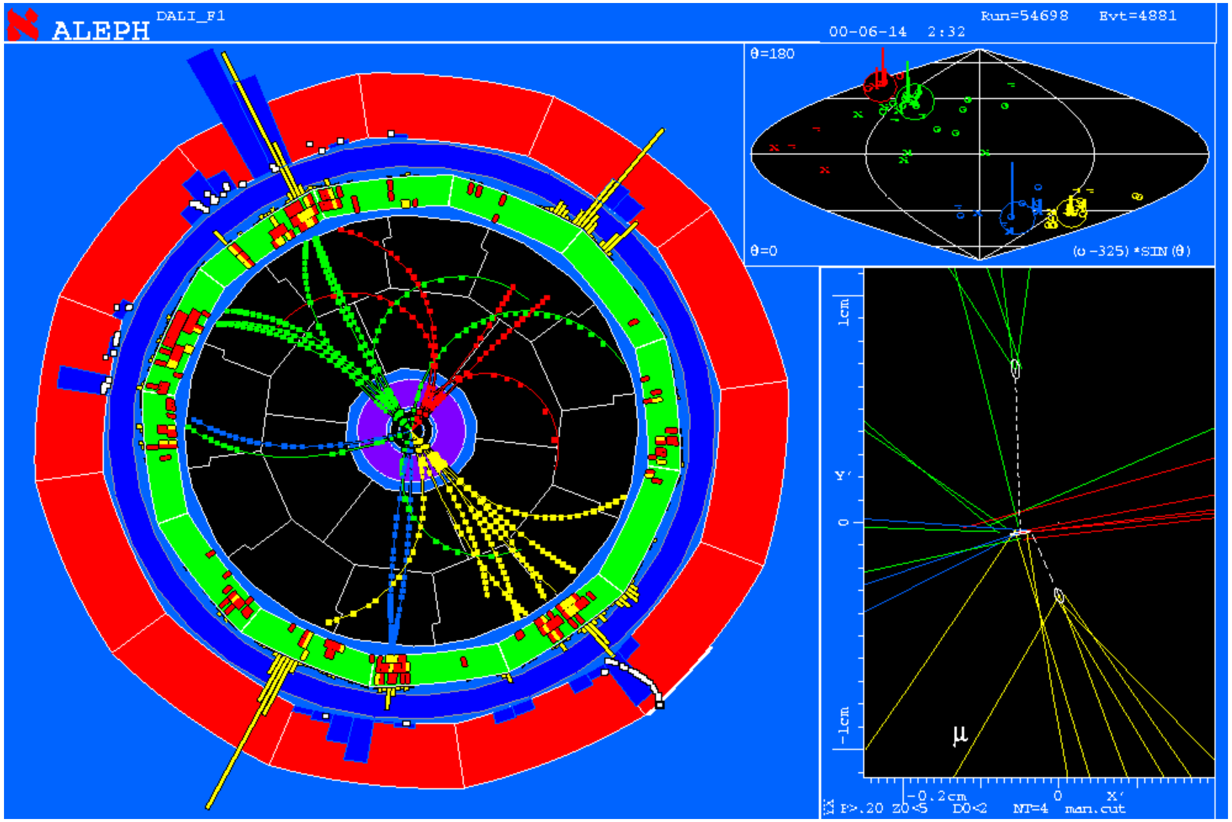
Bubble chamber like – a single event tells what is happening. Negligible background.



W. Riegler/CERN

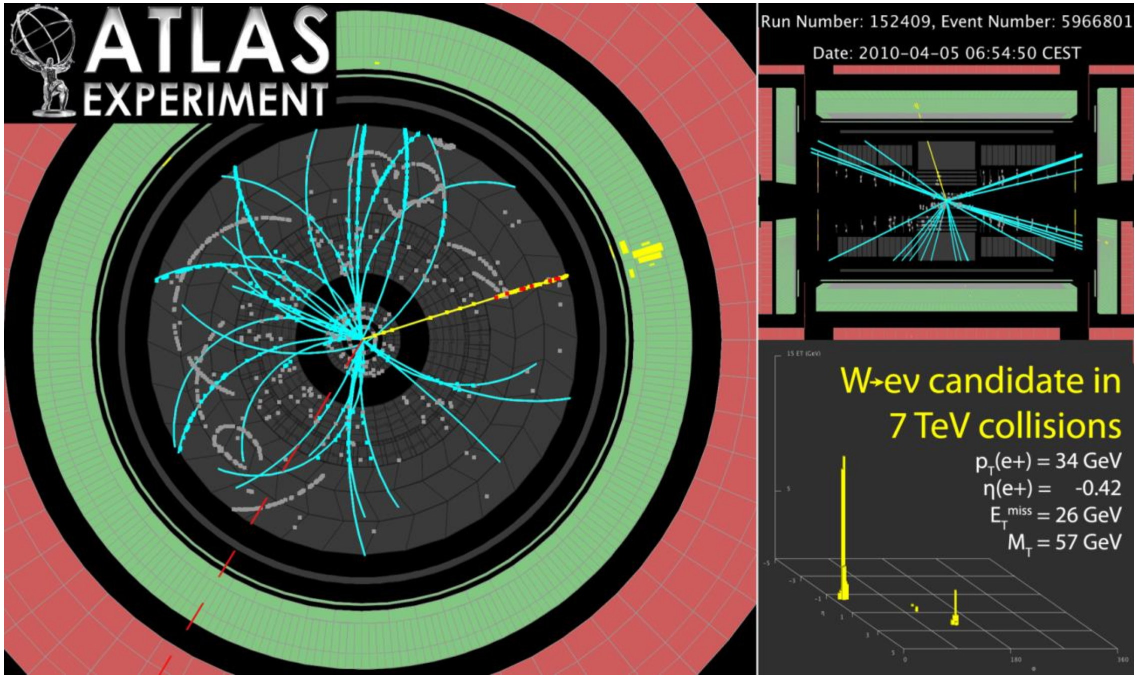
ALEPH Higgs Candidate

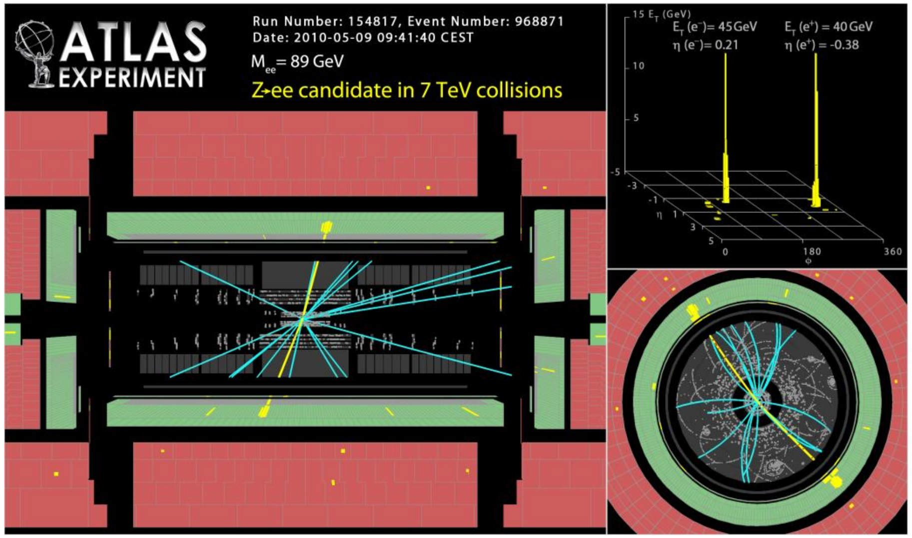




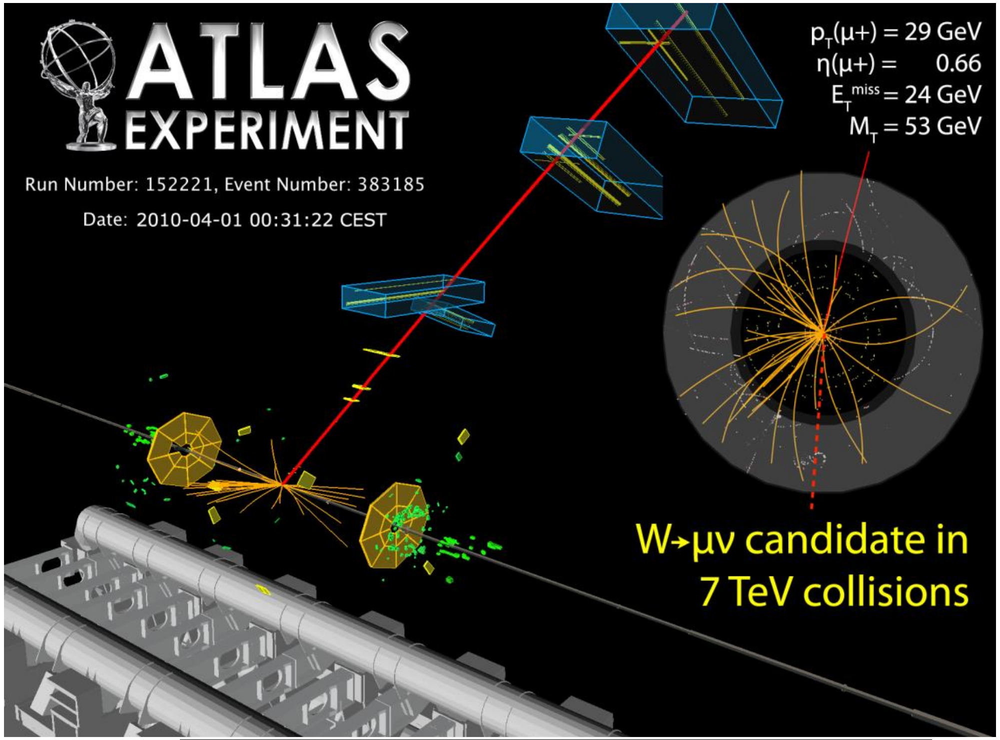
Undistinguishable background exists. Only statistical excess gives signature.

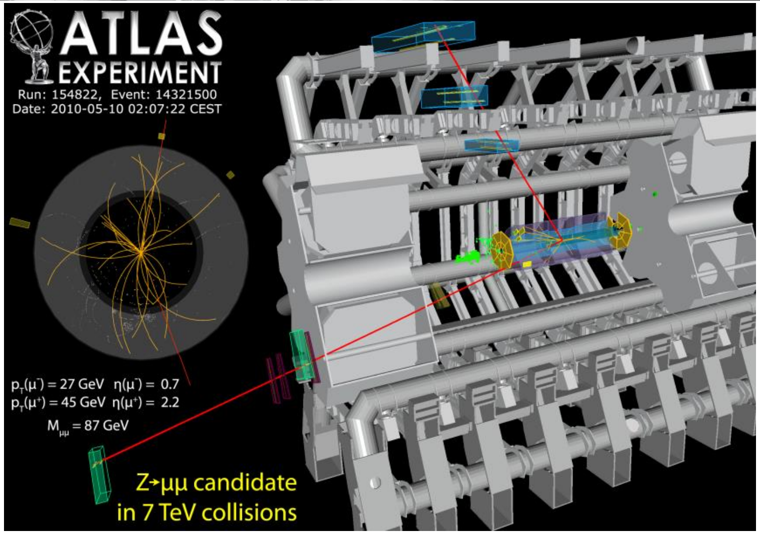
2010 ATLAS W, Z candidates



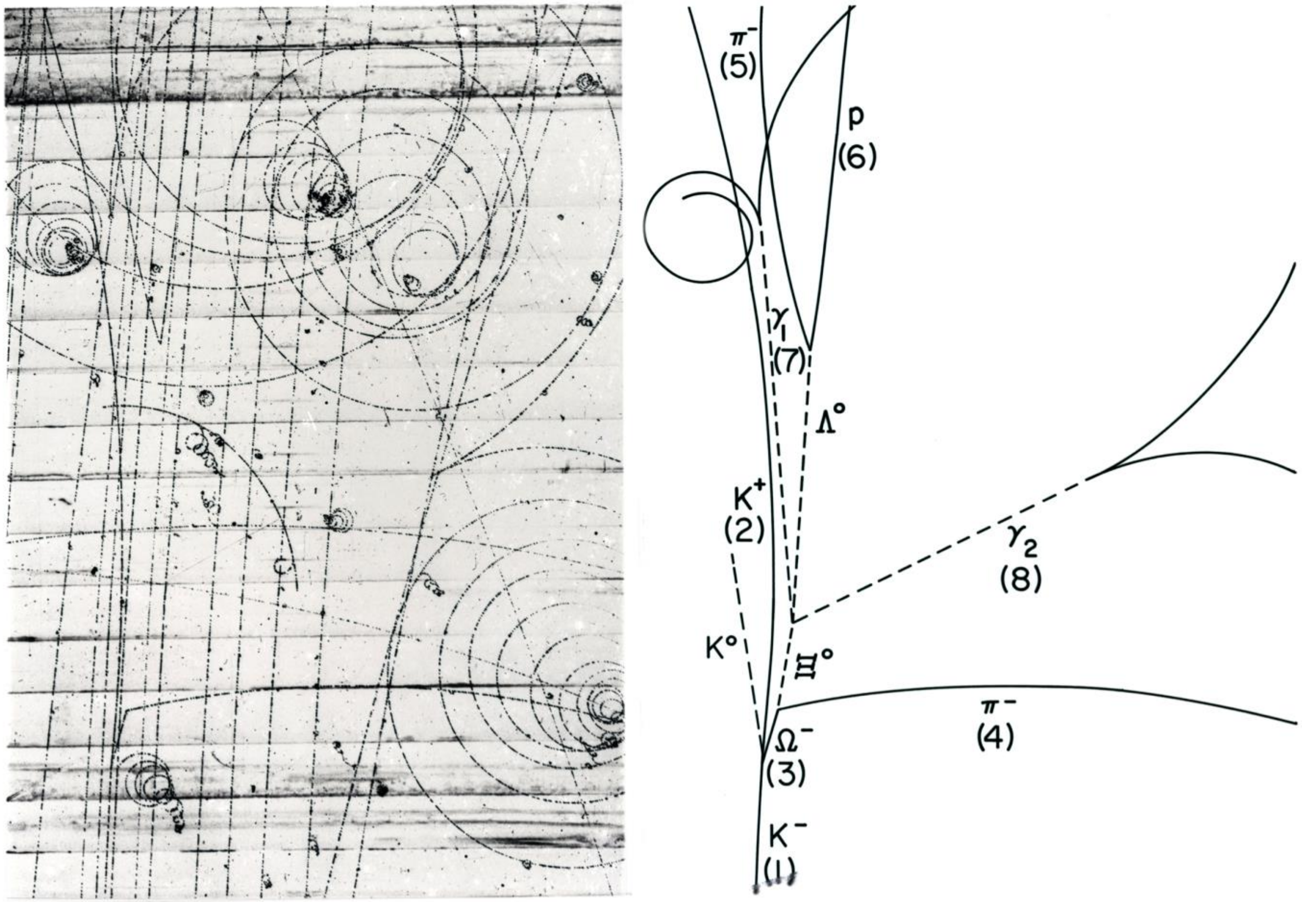


2010 ATLAS W, Z candidates





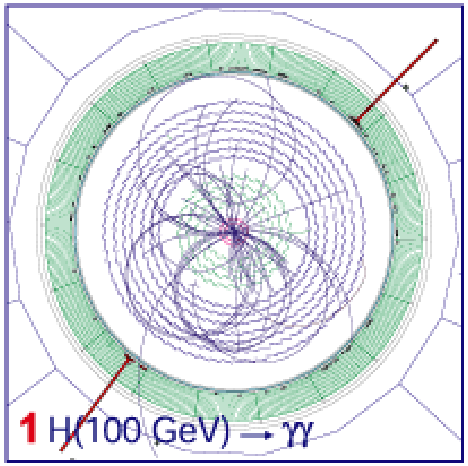
Discovery of 'New' particles

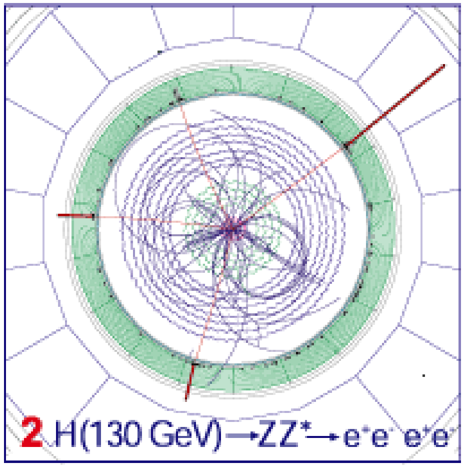


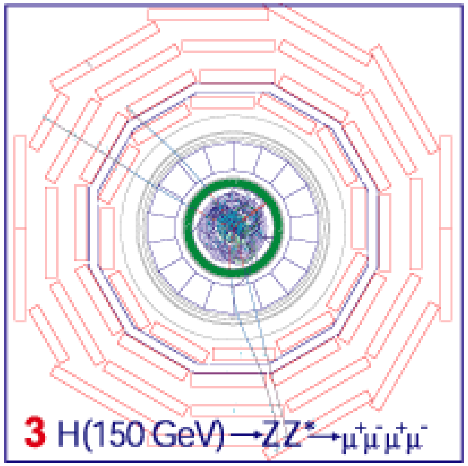
Discovery of omega minus in the Brookhaven National Laboratory 80 inch hydrogen bubble chamber in 1964. Discovery claimed by a single event – 'background free'

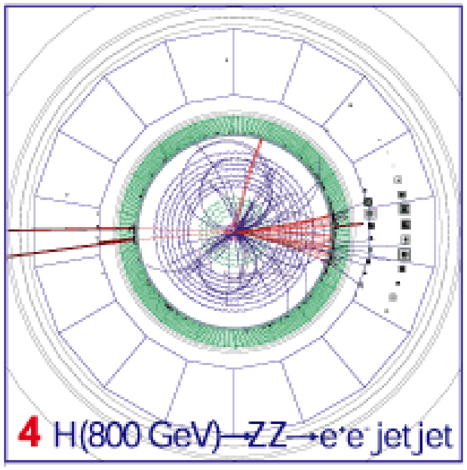
Finding the Higgs Boson

Simulated Higgs evens in CMS

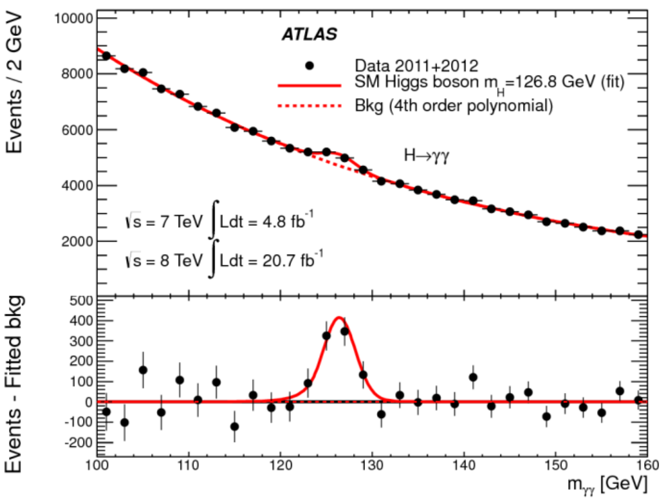


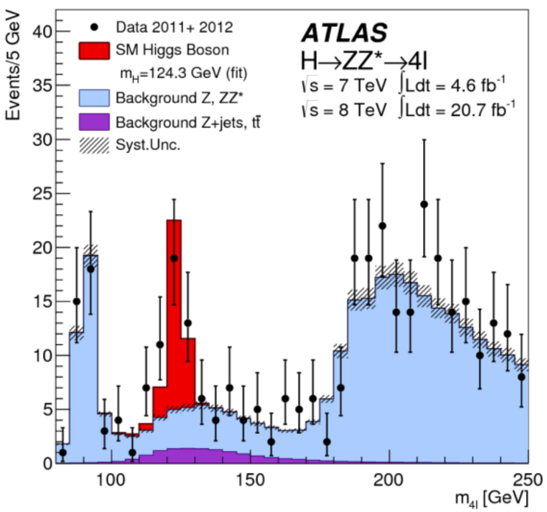






Measurements of di-photon and 4-lepton invariant mass spectrum





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

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

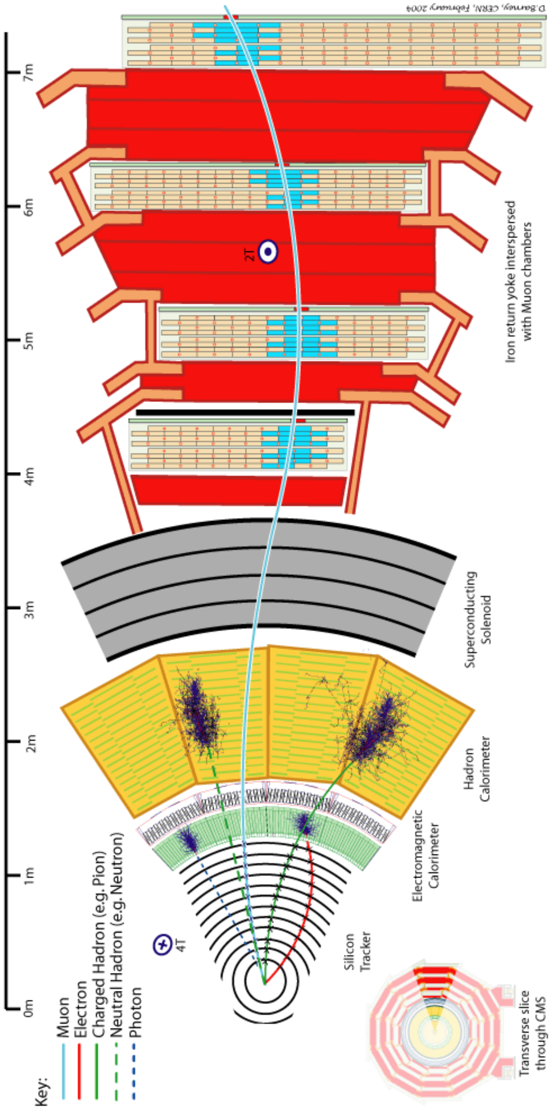
Their difference in mass, charge and interaction is the key to their identification.

Detector Technologies

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

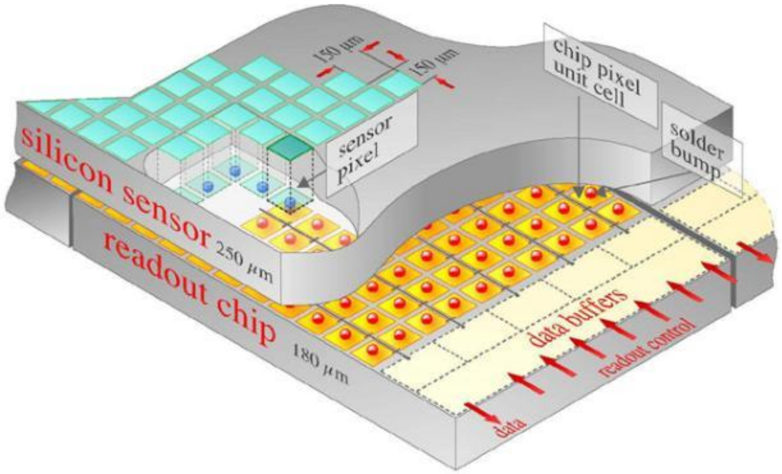
Solid state detectors (silicon strip detectors) or gas detectors at larger distances for tracking and momentum measurement.

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



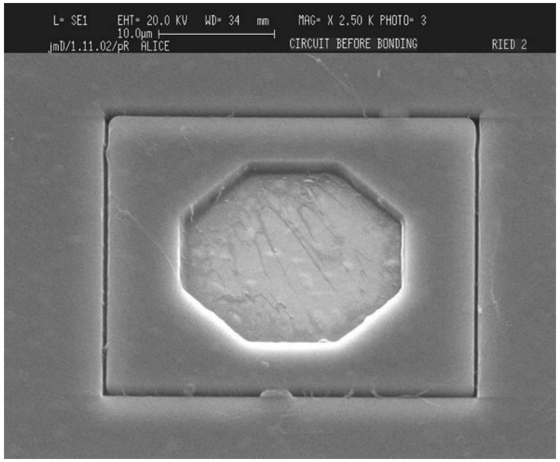
W. Riegler/CERN

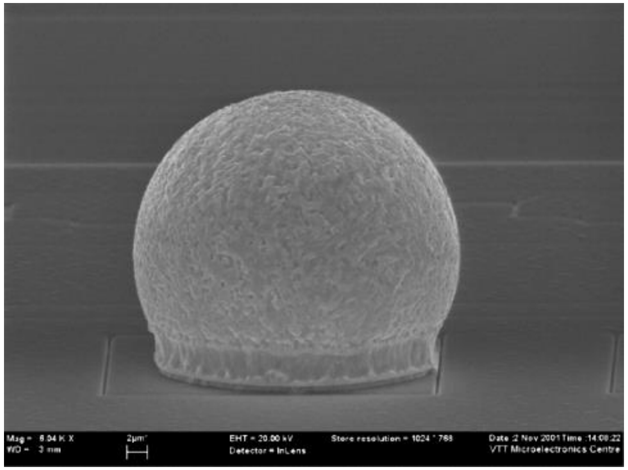
Silicon Pixel Detectors



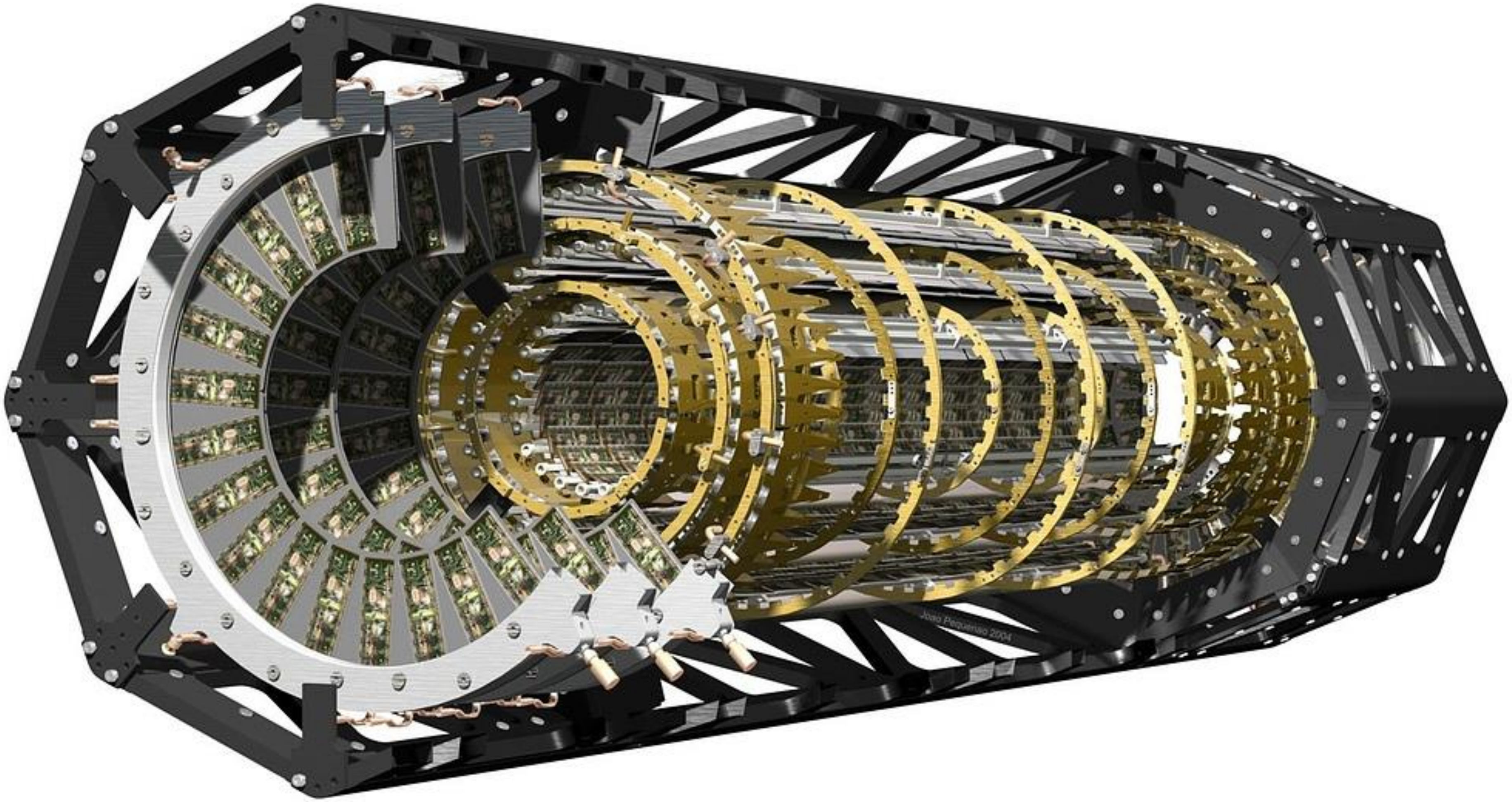
ATLAS: $1.4x10^8$ pixels

40 000 000 'images' per second.





ATLAS Silicon Pixel Detector

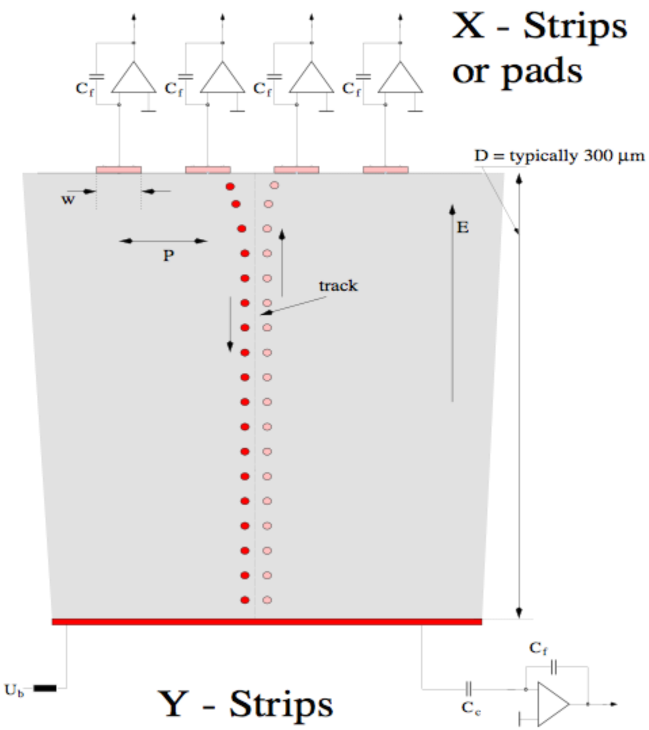


W. Riegler/CERN

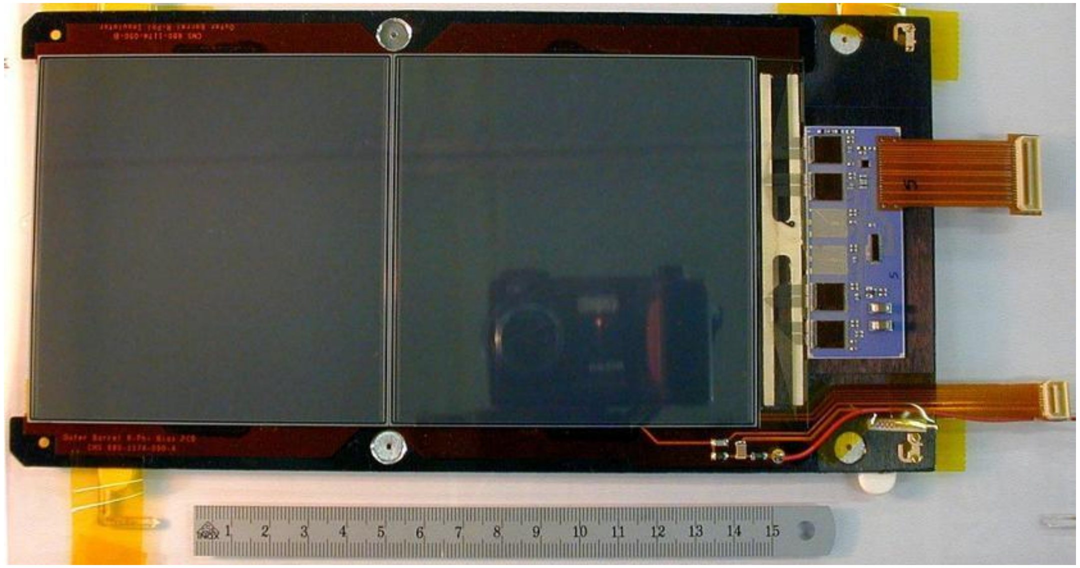
Silicon Strip Detectors

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

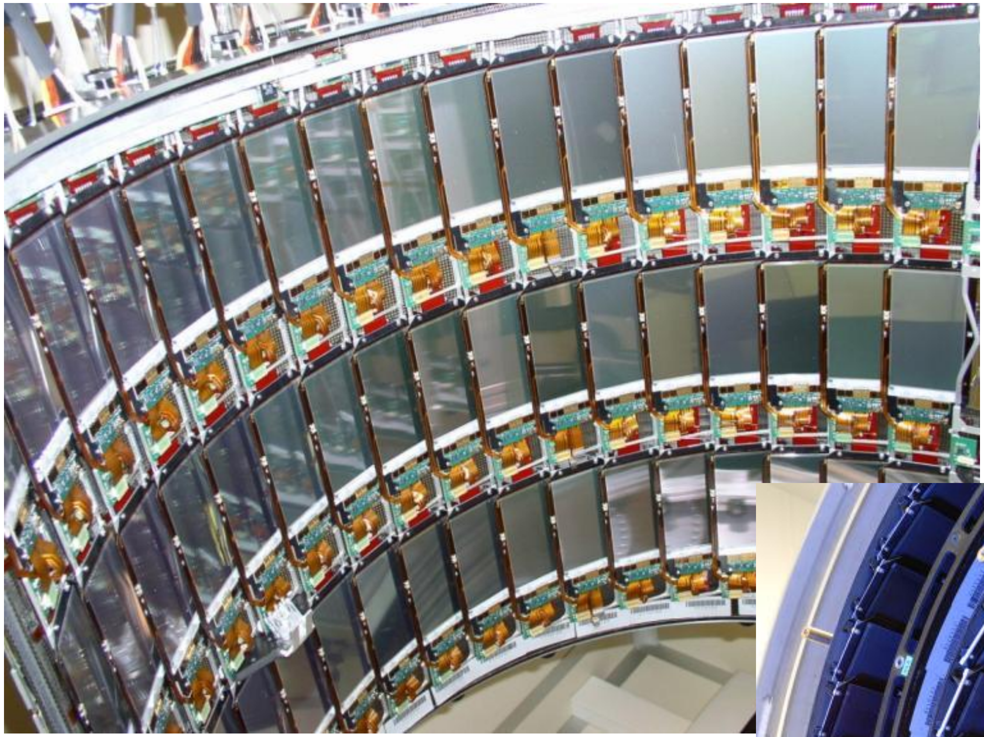
Two dimensional readout is possible.

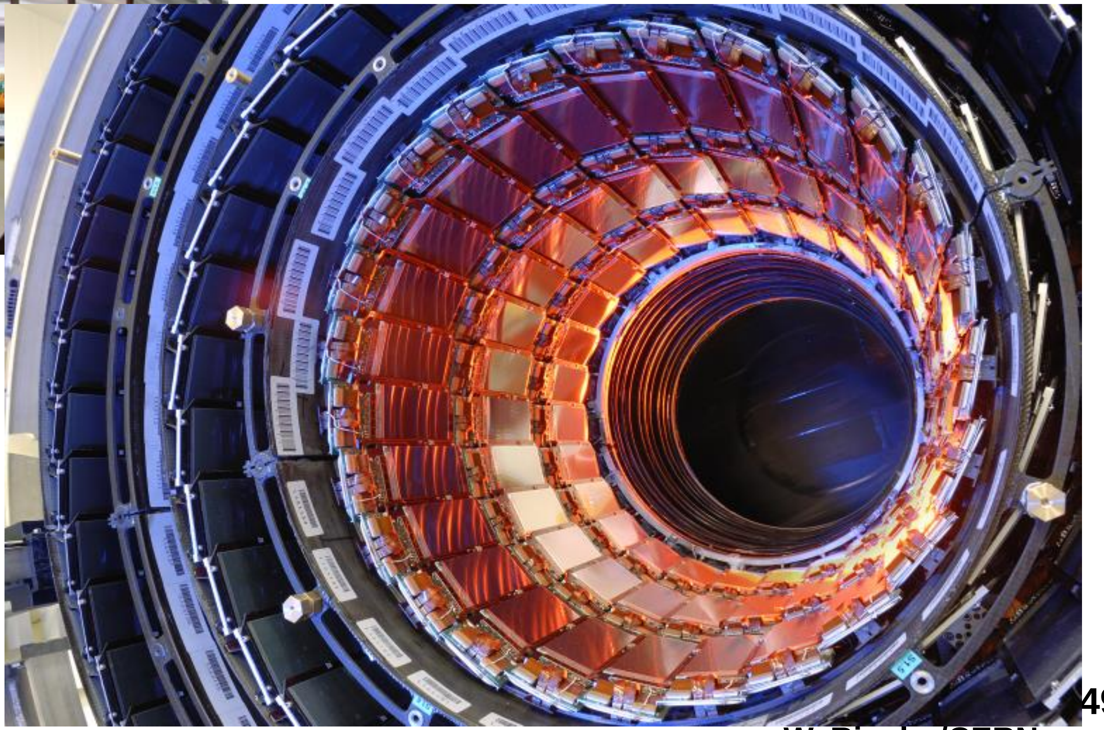


CMS Outer Barrel Module



Silicon Strip Detectors



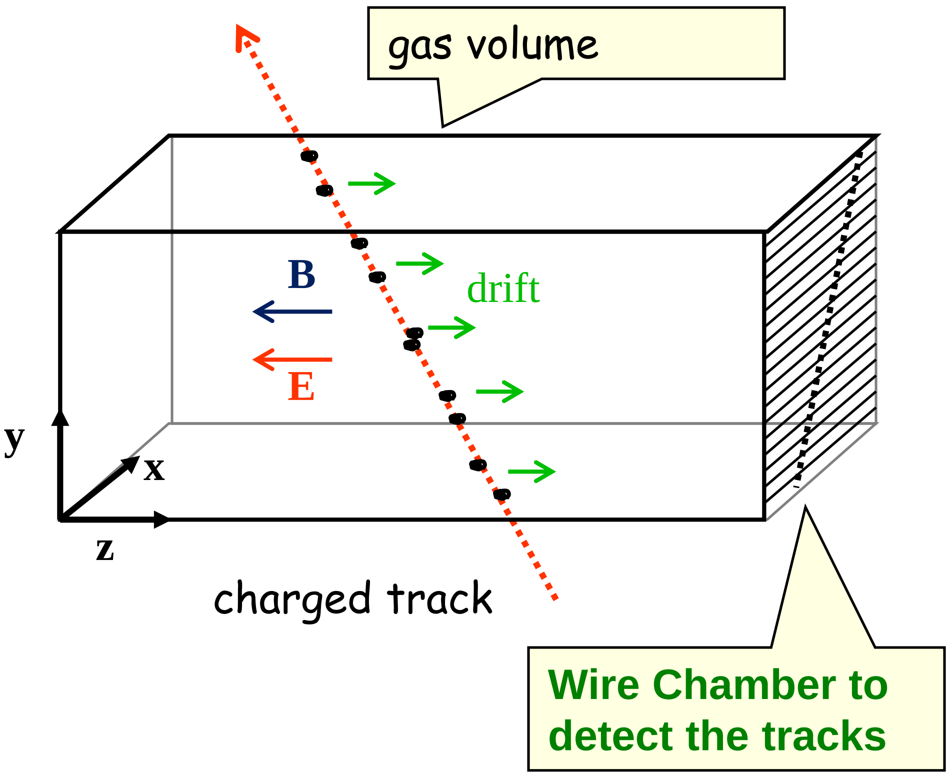


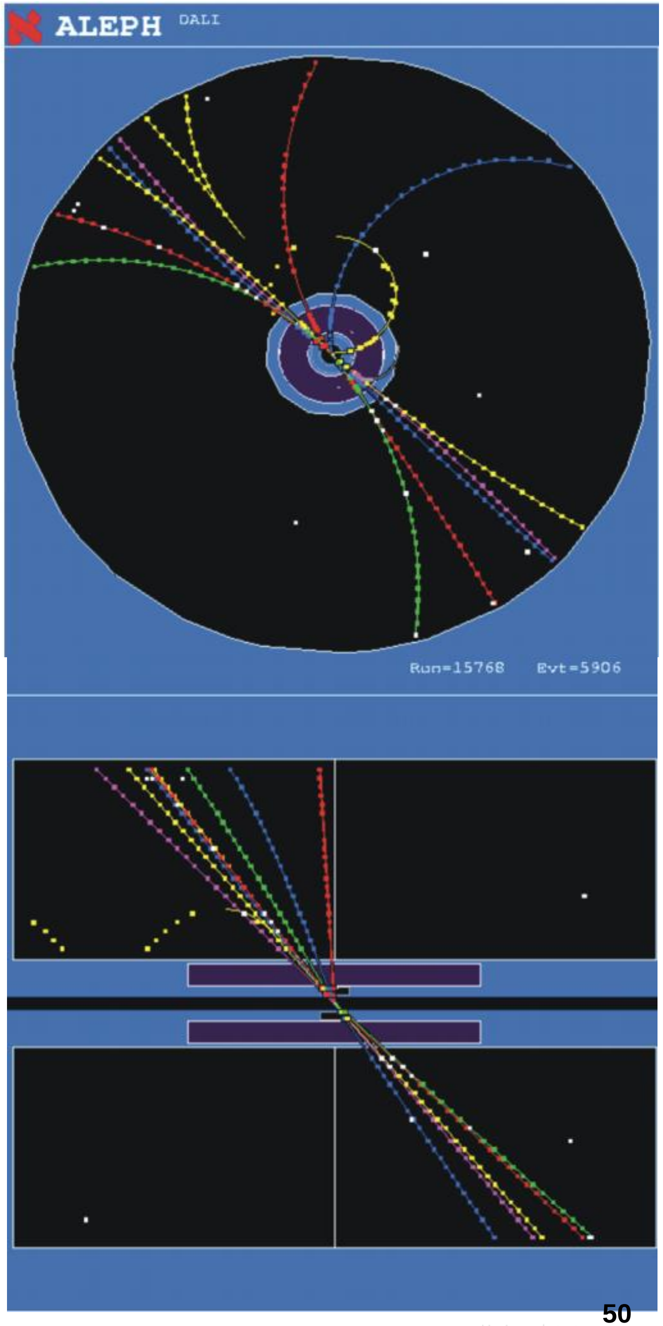
W. Riegler/CERN

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 !



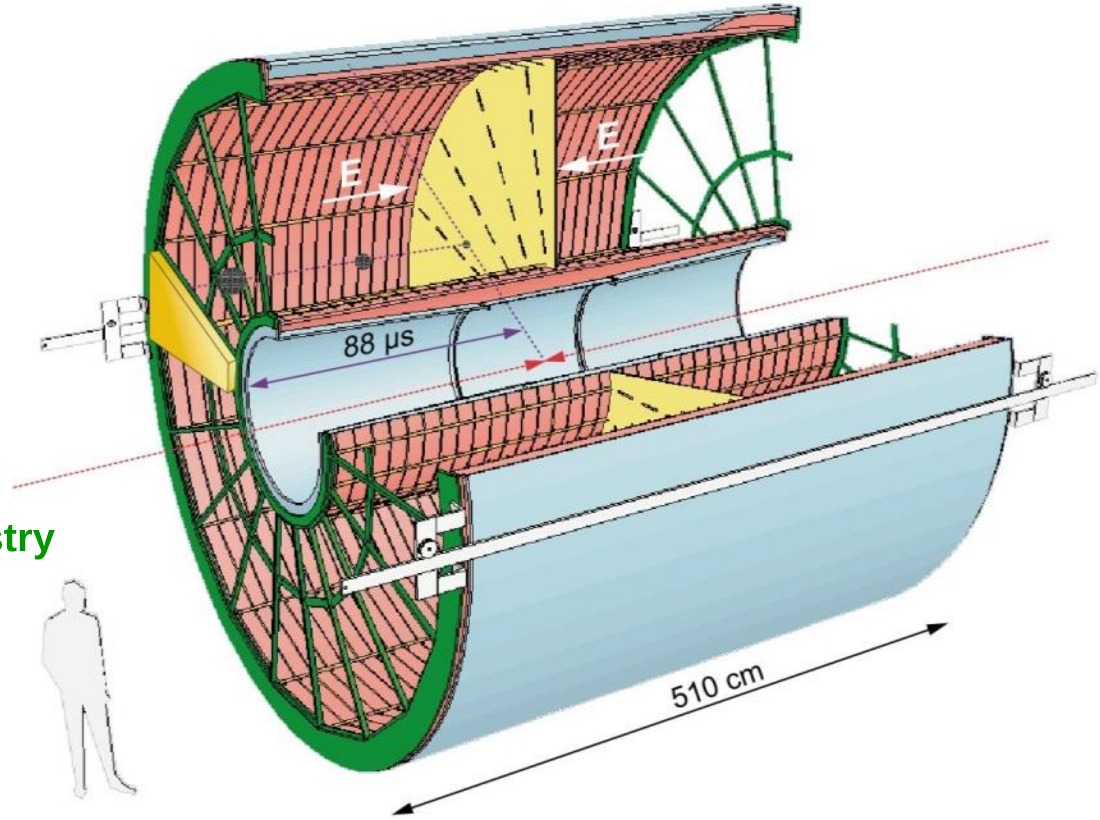


ALICE TPC: Construction Parameters

- **Largest TPC:**
  - **Length 5m**
  - **Diameter 5m**
  - **Volume 88m^3**
  - **Detector area 32m^2**
  - **Channels ~570 000**

- **High Voltage:**
  - **Cathode -100kV**

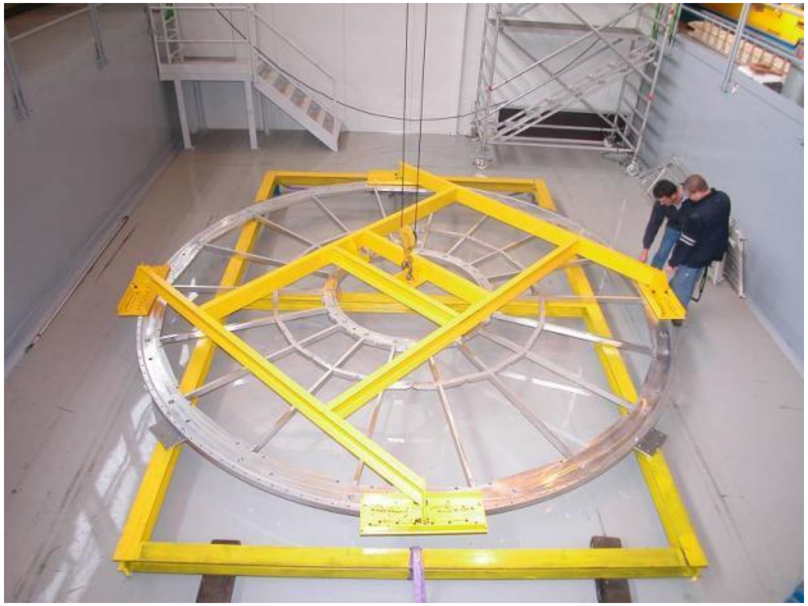
- **Material X_0**
  - **Cylinder from composite materials from airplane industry (X_0= ~3%)**

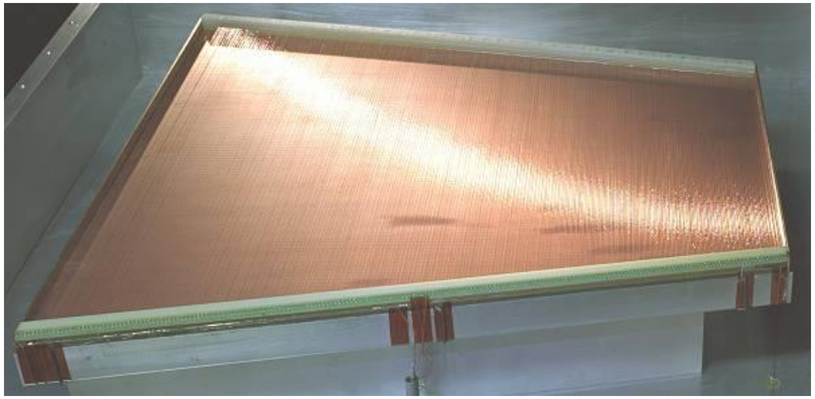


ALICE TPC: Pictures of the Construction

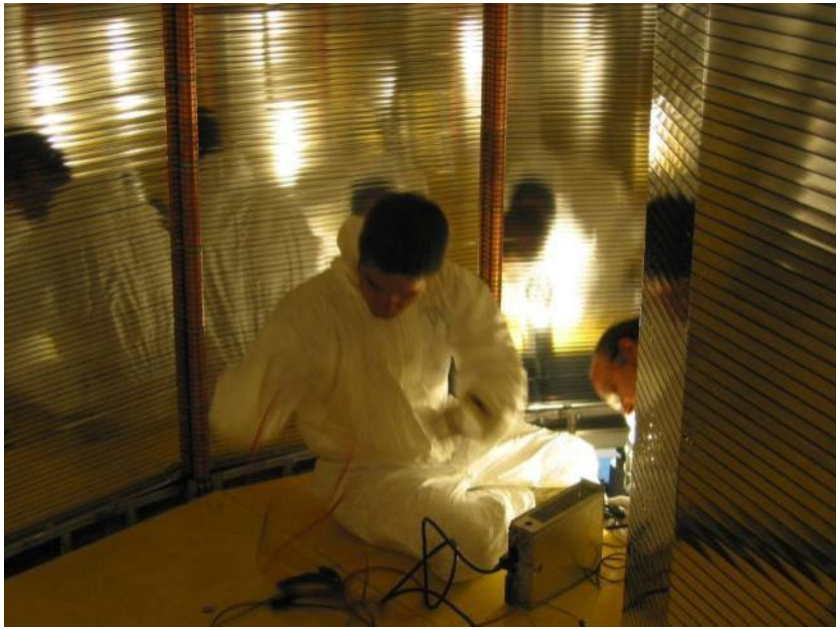
Precision in z: 250μm

End plates 250μm





Wire chamber: 40μm

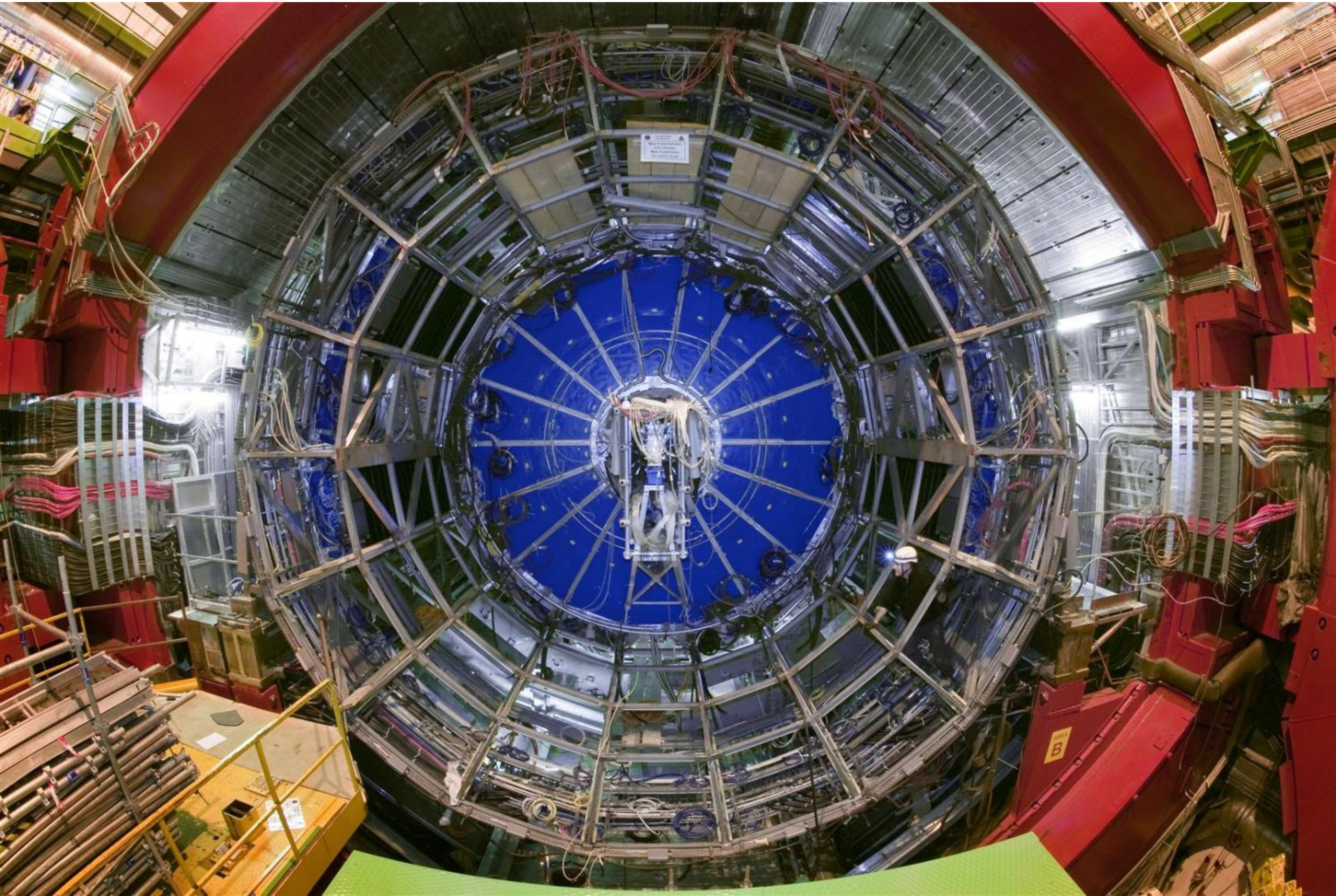


ALICE TPC Construction

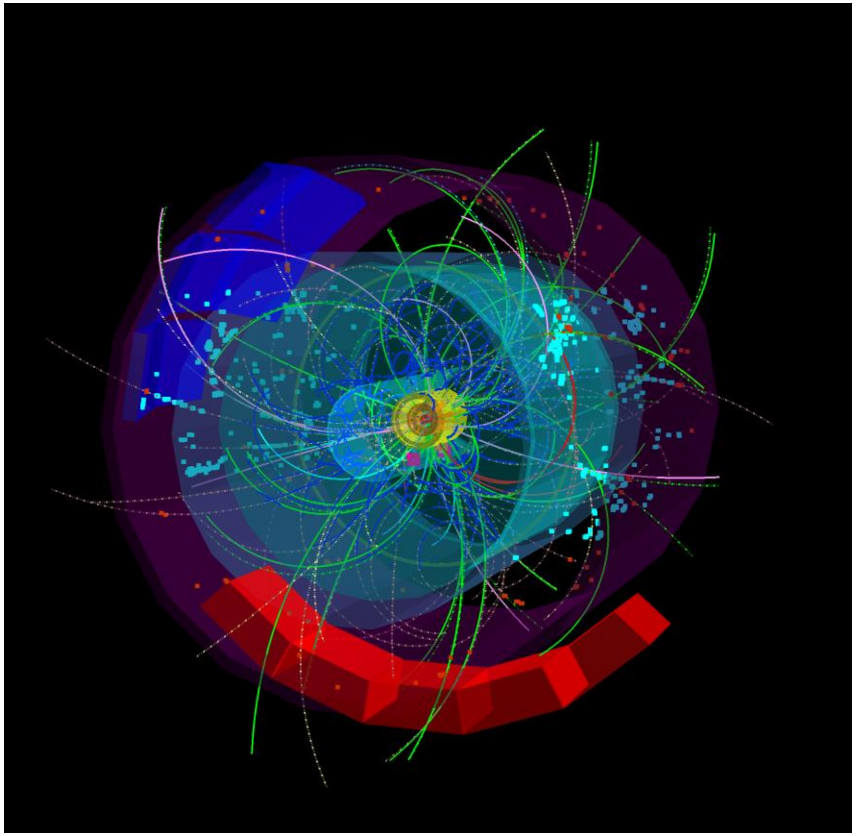
My personal contribution:

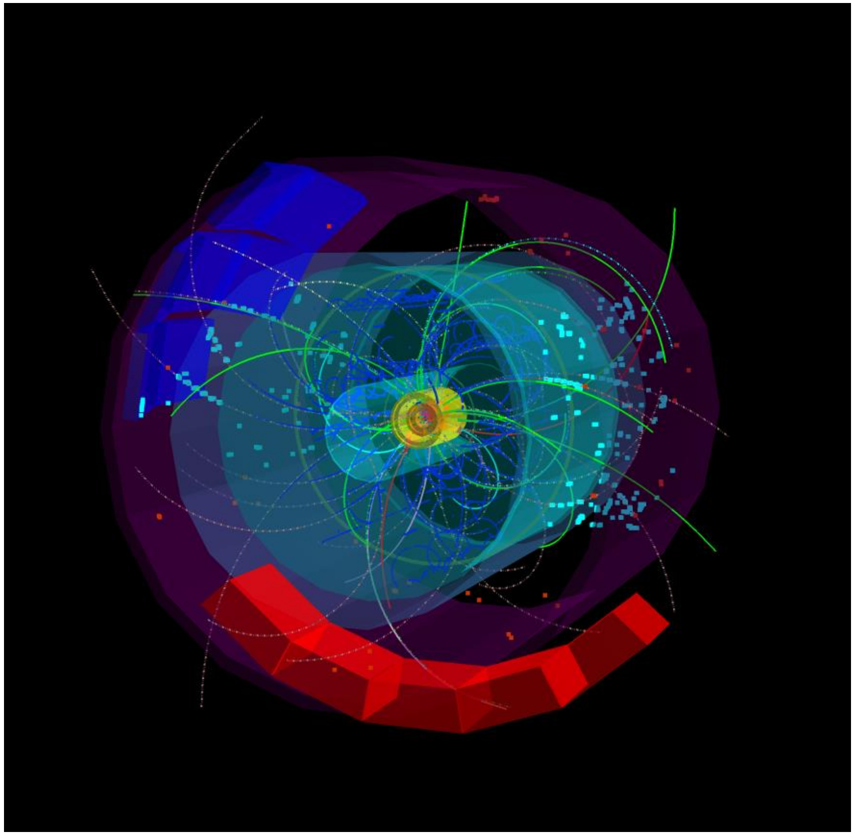
A visit inside the TPC.

TPC installed in the ALICE Experiment

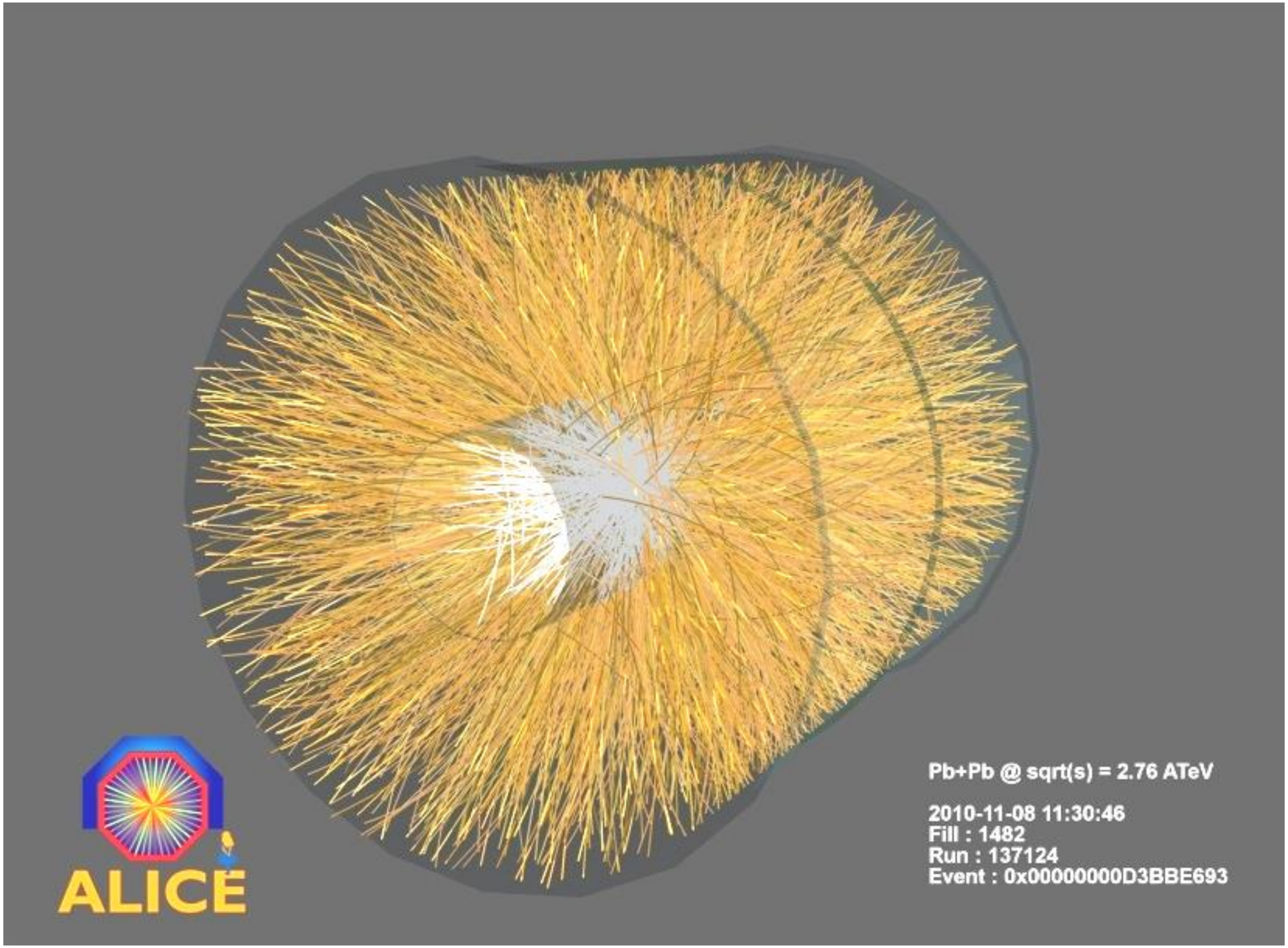


First 7 TeV p-p Collisions in the ALICE TPC in March 2010 !



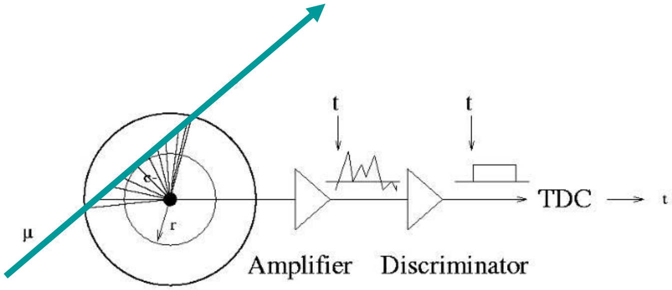


First Pb Pb Collisions in the ALICE TPC in Nov 2010 !

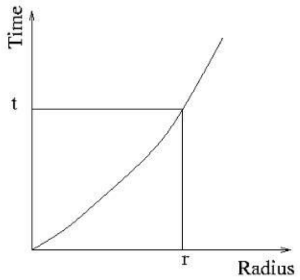


The Geiger Counter reloaded: Drift Tube

ATLAS MDT R(tube) =15mm



Calibrated Radius-Time correlation



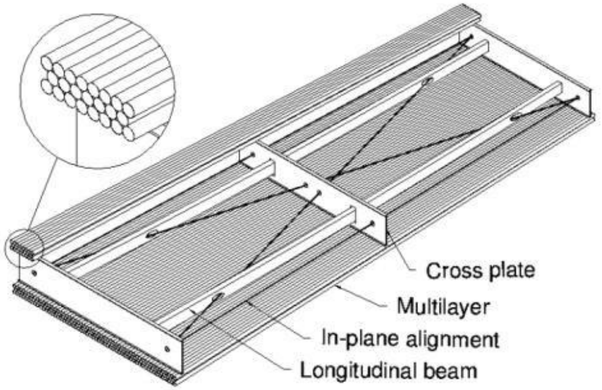
Primary electrons are drifting to the wire.

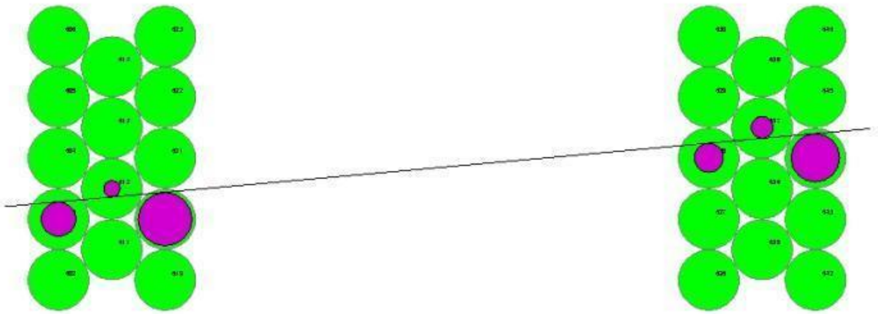
Electron avalanche at the wire.

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





ATLAS MDTs, 80μm per tube

The Geiger counter reloaded: Drift Tube

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

1200 Chambers

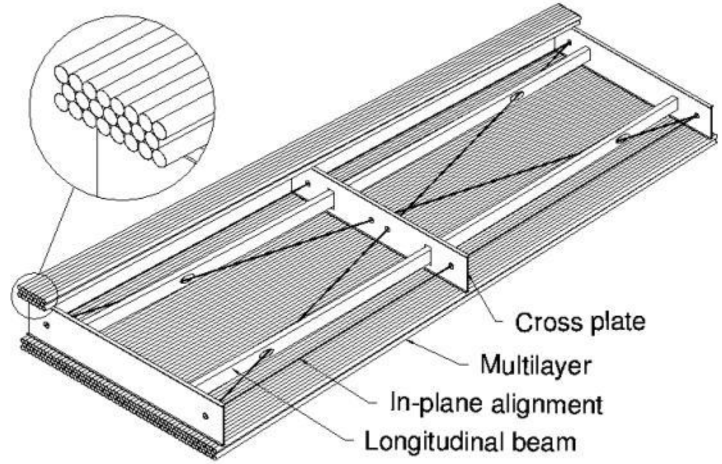
6 layers of 3cm tubes per chamber.

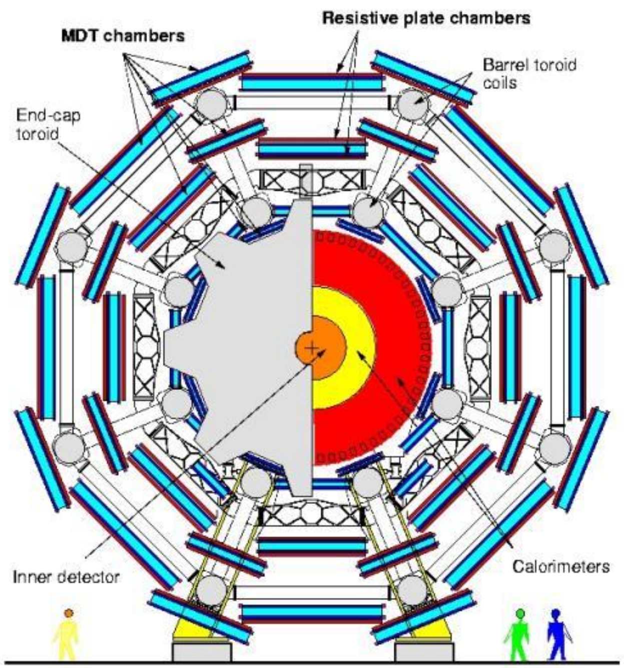
Length of the chambers 1-6m !

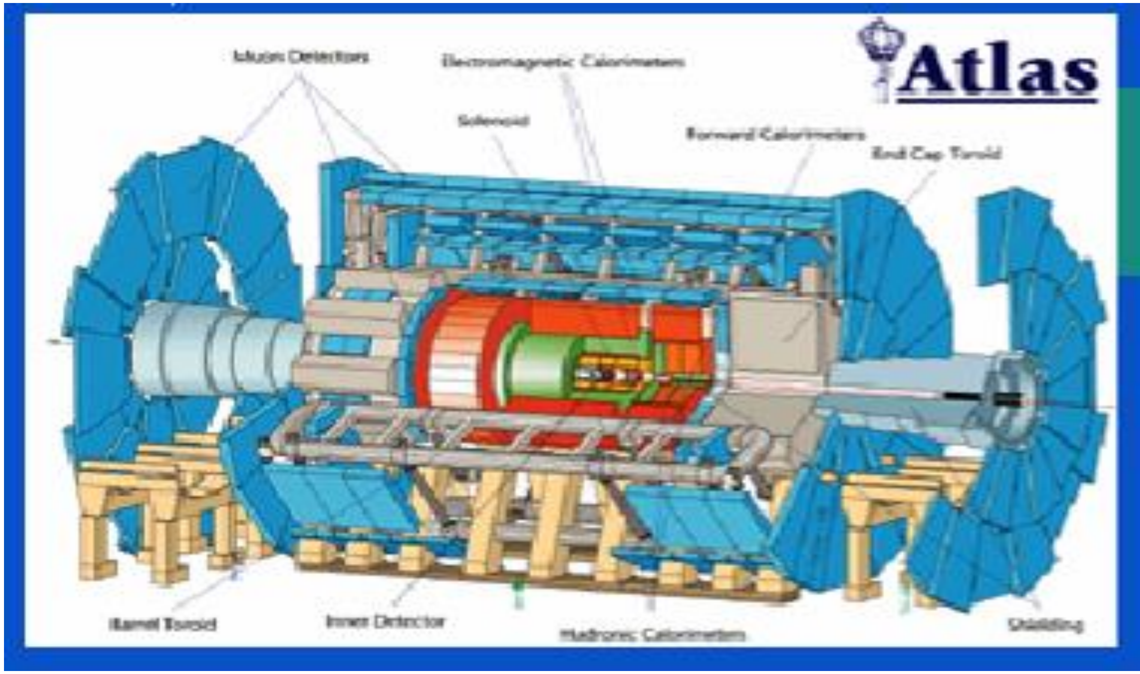
Position resolution: 80μm/tube, <50μm/chamber (3 bar)

Maximum drift time ≈700ns

Gas Ar/CO_2 93/7







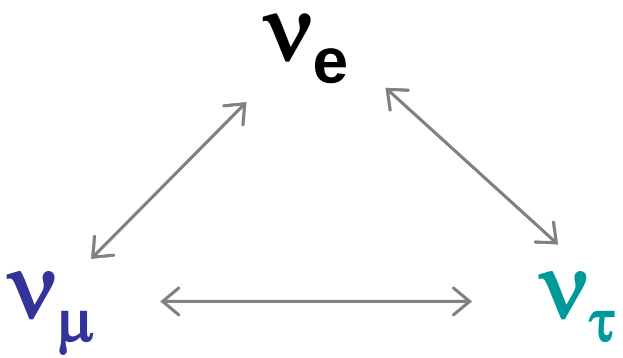
Detector Systems

CERN Neutrino Gran Sasso

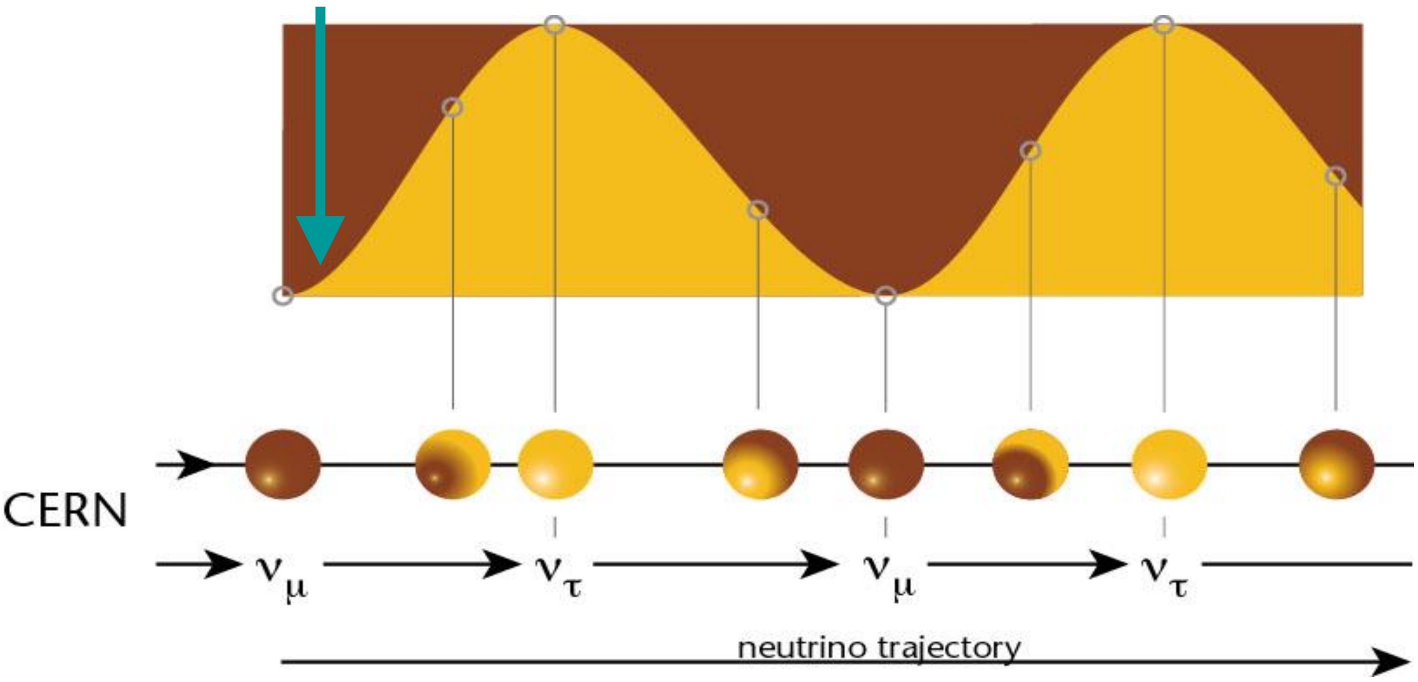
(CNGS)

CNGS

If neutrinos have mass:



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



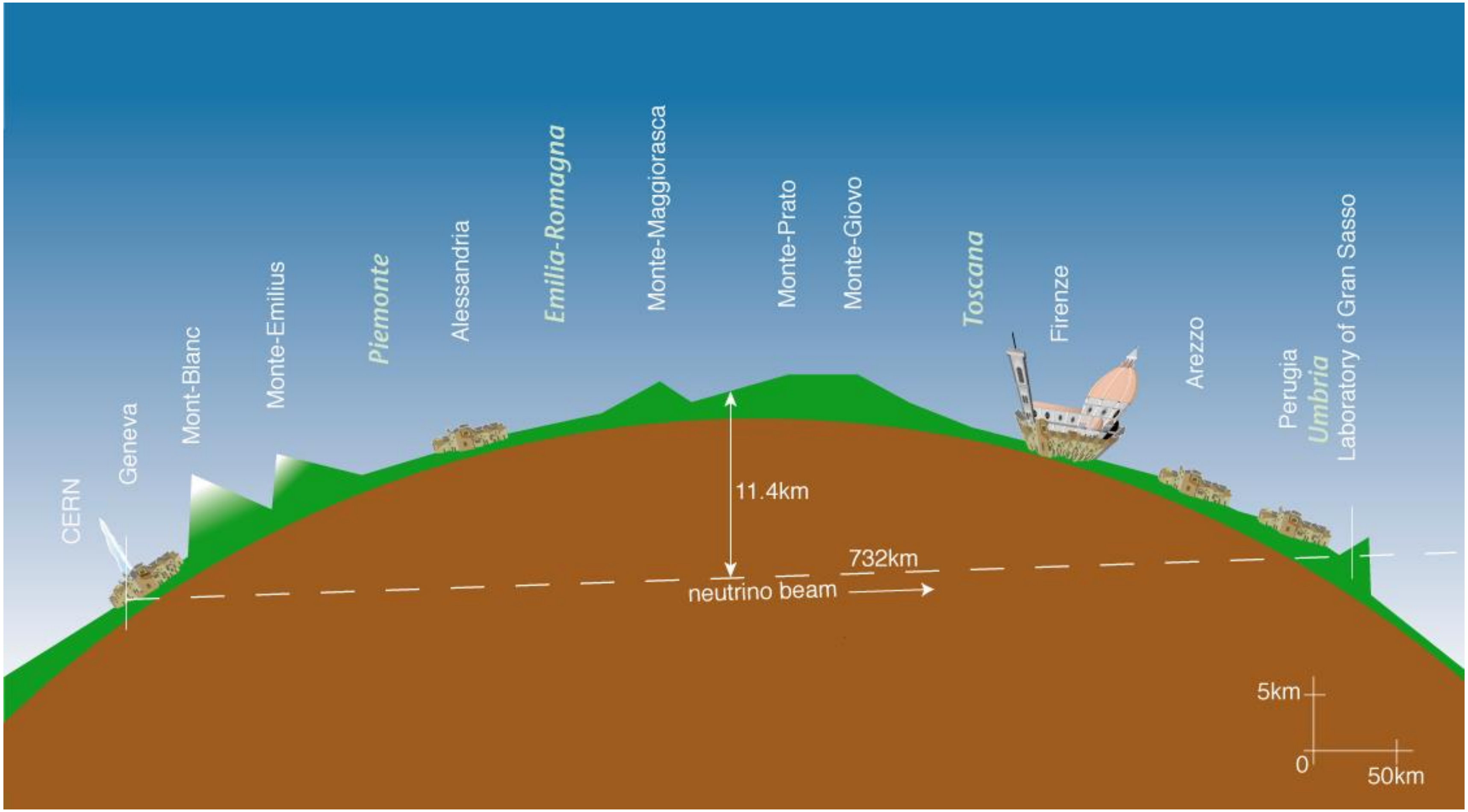
CNGS Project

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

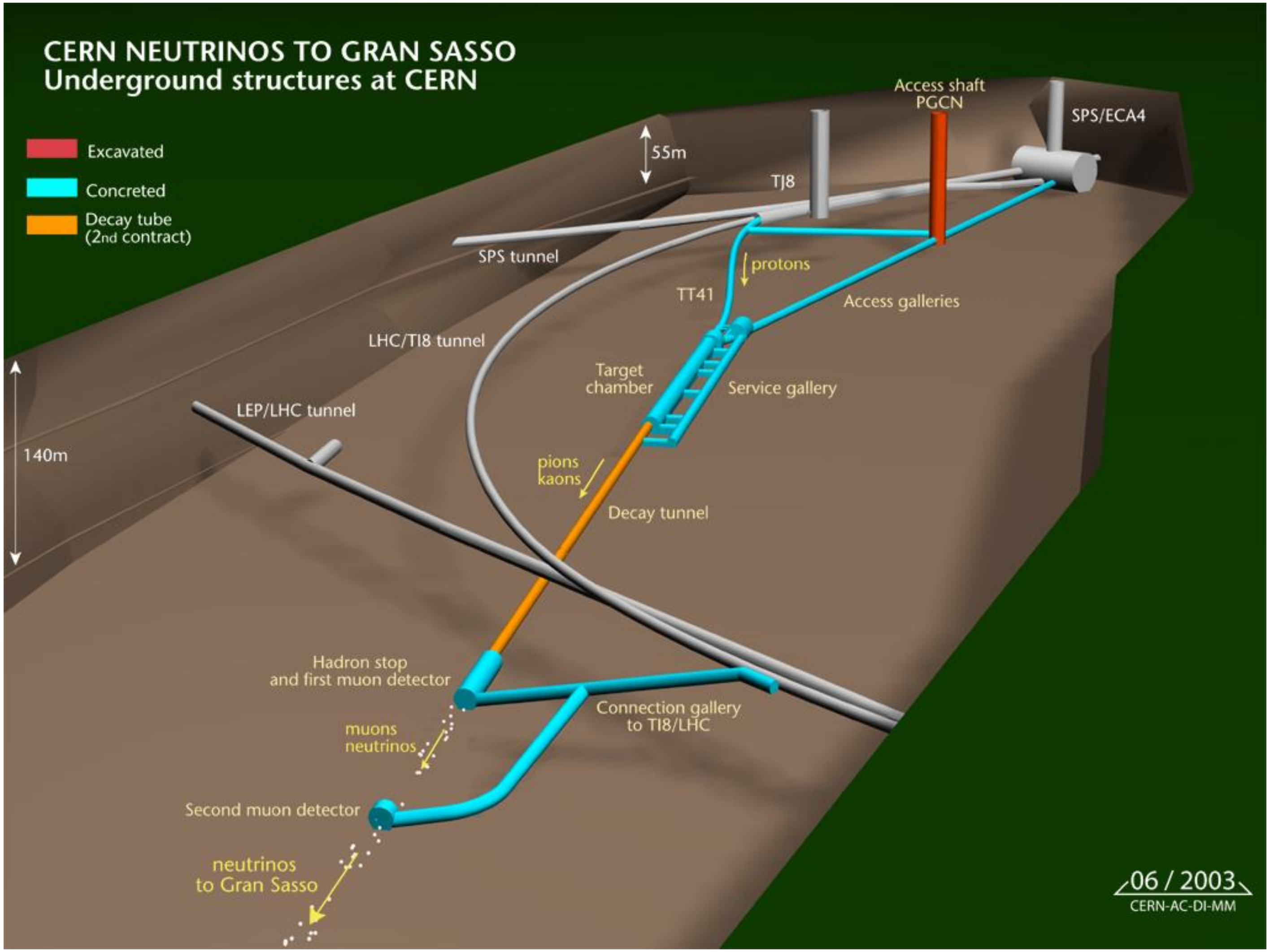
➔ **direct proof of ν_μ - ν_τ oscillation (appearance experiment)**

CNGS



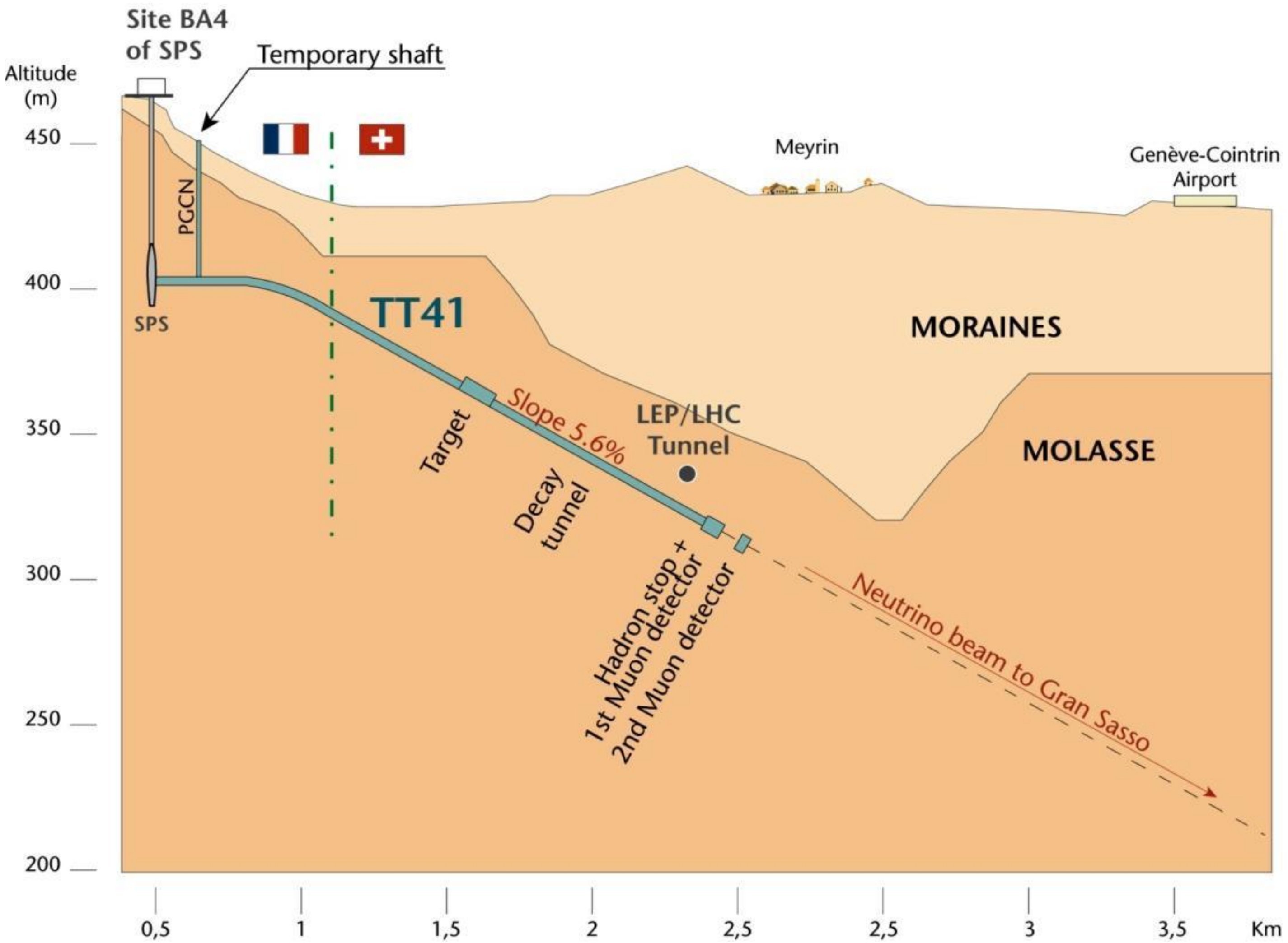
CERN
Geneva
Mont-Blanc
Monte-Emilius
Piemonte
Alessandria
Emilia-Romagna
Monte-Maggiorasca
Monte-Prato
Monte-Giovo
Toscana
Firenze
Arezzo
Perugia
Umbria
Laboratory of Gran Sasso
11.4km
732km
neutrino beam
5km
0
50km

CNGS



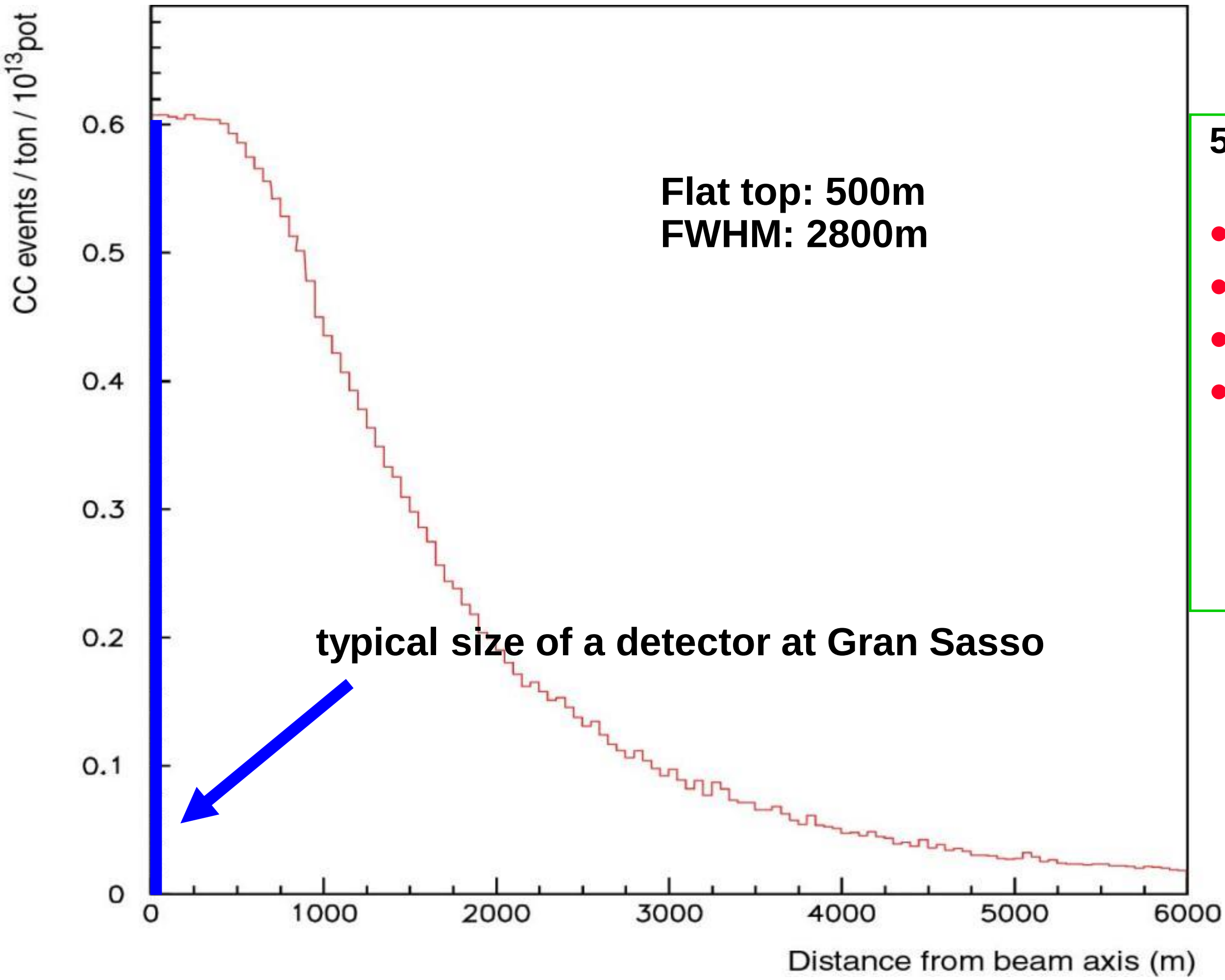
CERN NEUTRINOS TO GRAN SASSO
Underground structures at CERN
Excavated
Concreted
Decay tube
(2nd contract)
55m
TJ8
Access shaft
PGCN
SPS/ECA4
SPS tunnel
protons
TT41
Access galleries
LHC/TI8 tunnel
Target
chamber
Service gallery
LEP/LHC tunnel
140m
pions
kaons
Decay tunnel
Hadron stop
and first muon detector
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

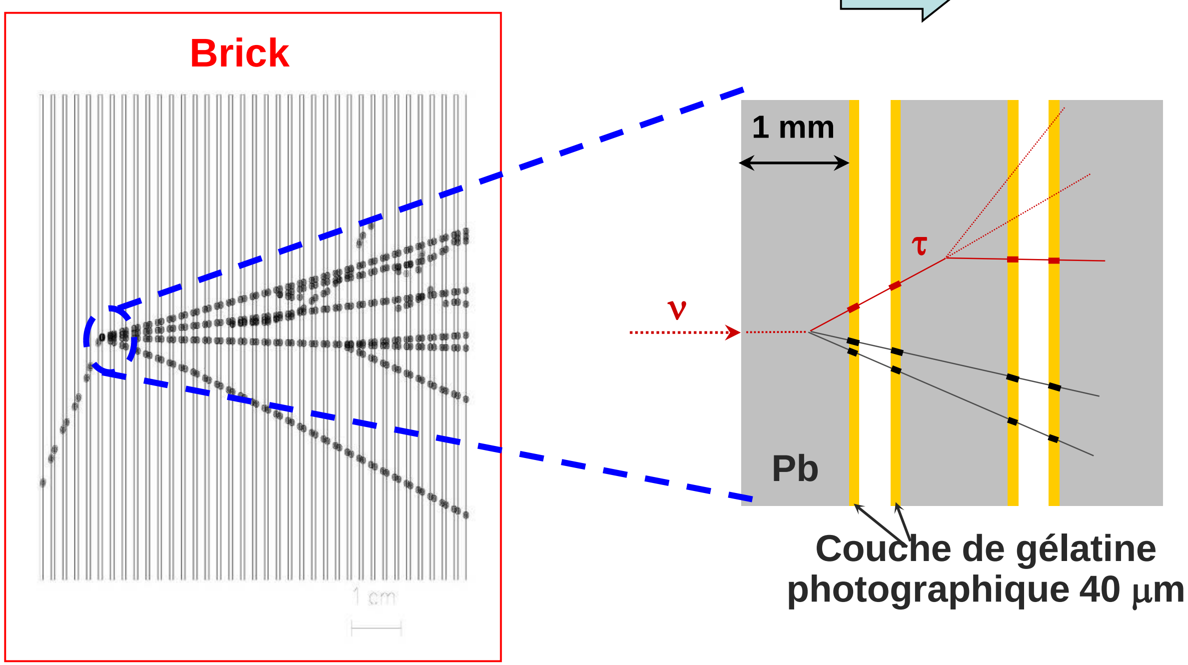
Opera Experiment at Gran Sasso

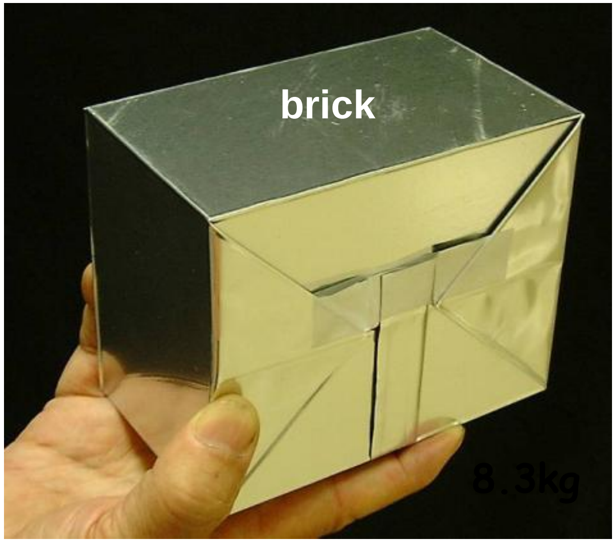
Basic unit: brick

56 Pb sheets + 56 photographic films (emulsion sheets)

Lead plates: massive target

Emulsions: micrometric precision

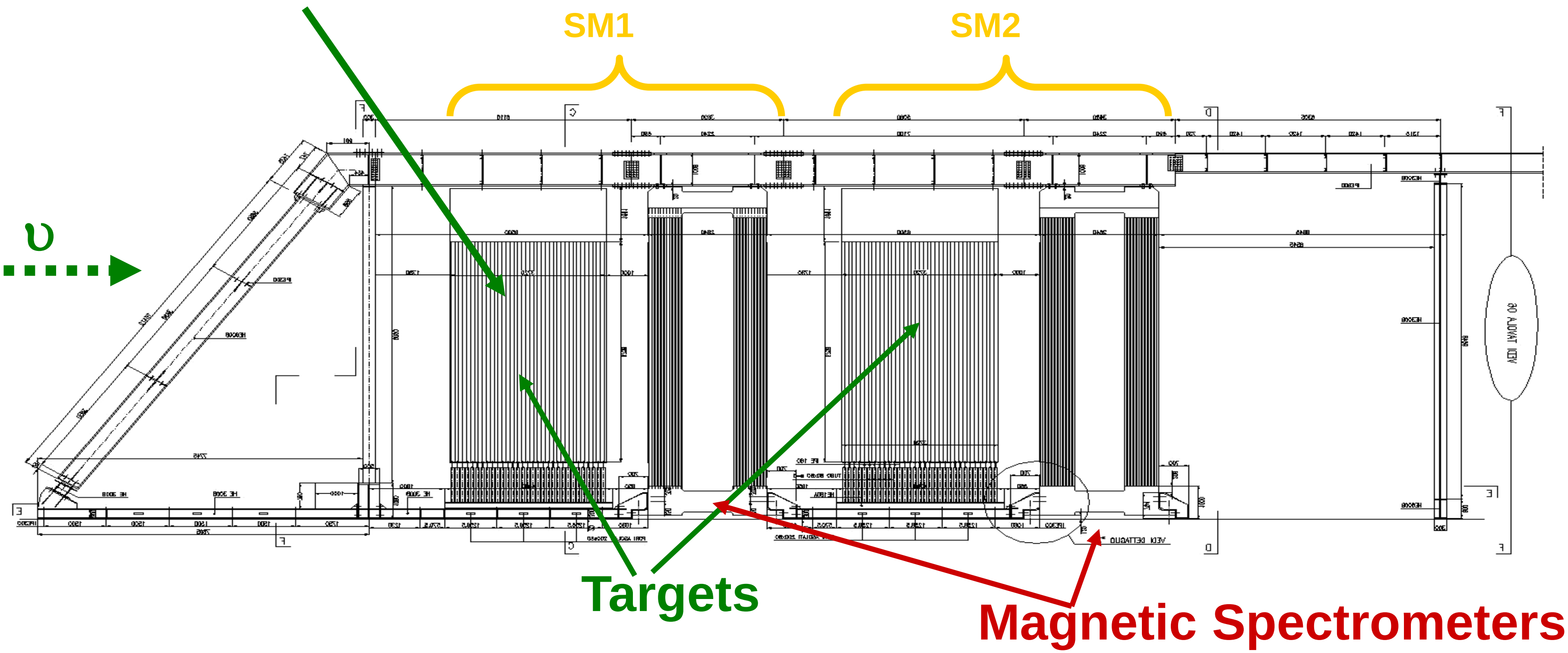




10.2 x 12.7 x 7.5 cm^3

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

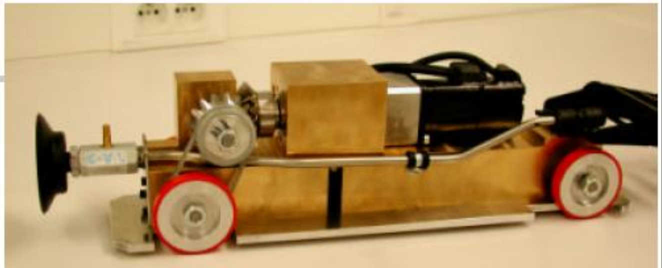
3050 m^2 Resistive Plate Counters

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 !

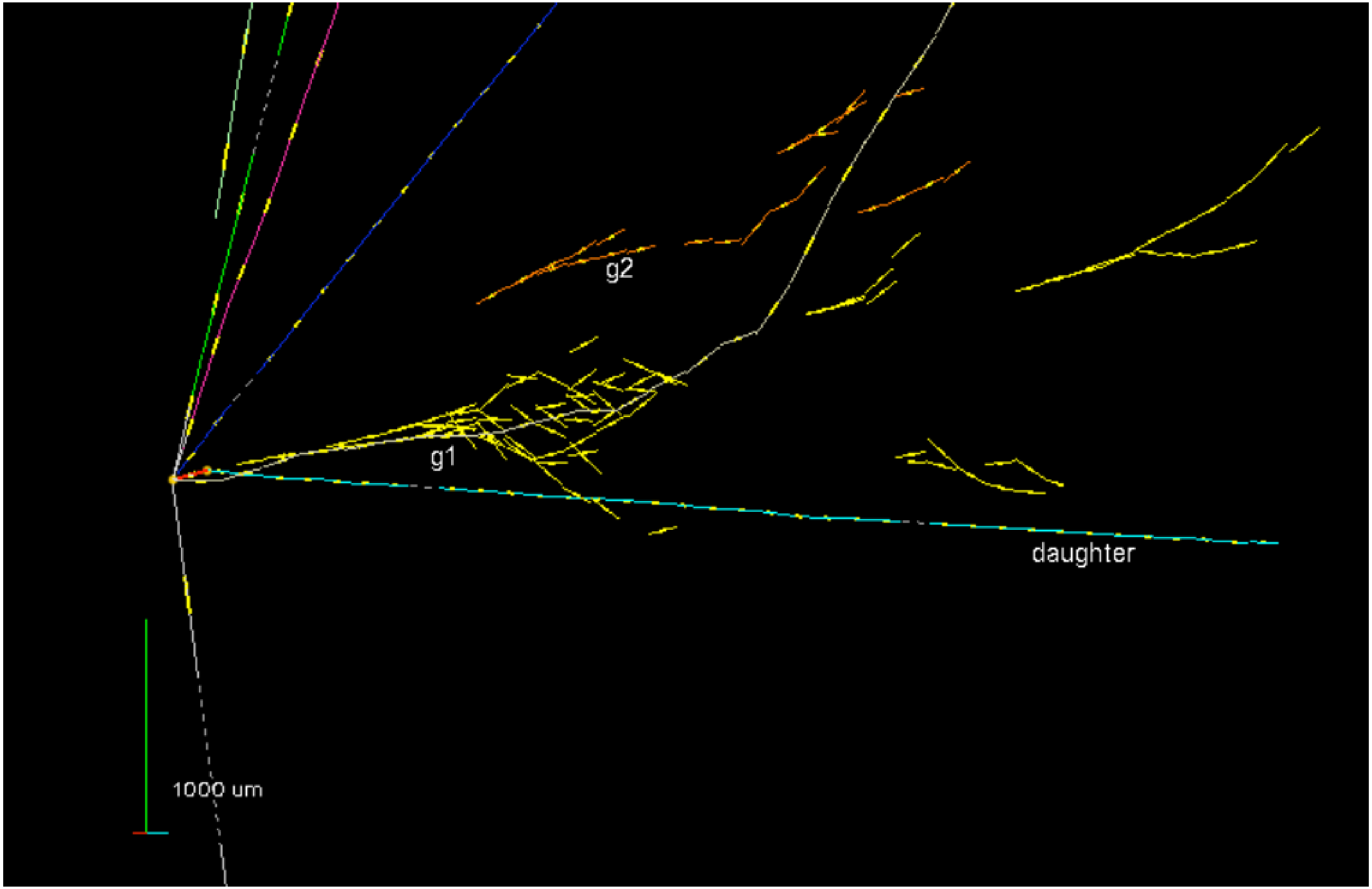
Tests with the prototype wall



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

"Carousel" brick dispensing and storage system

First Tau Candidate seen a few weeks ago !



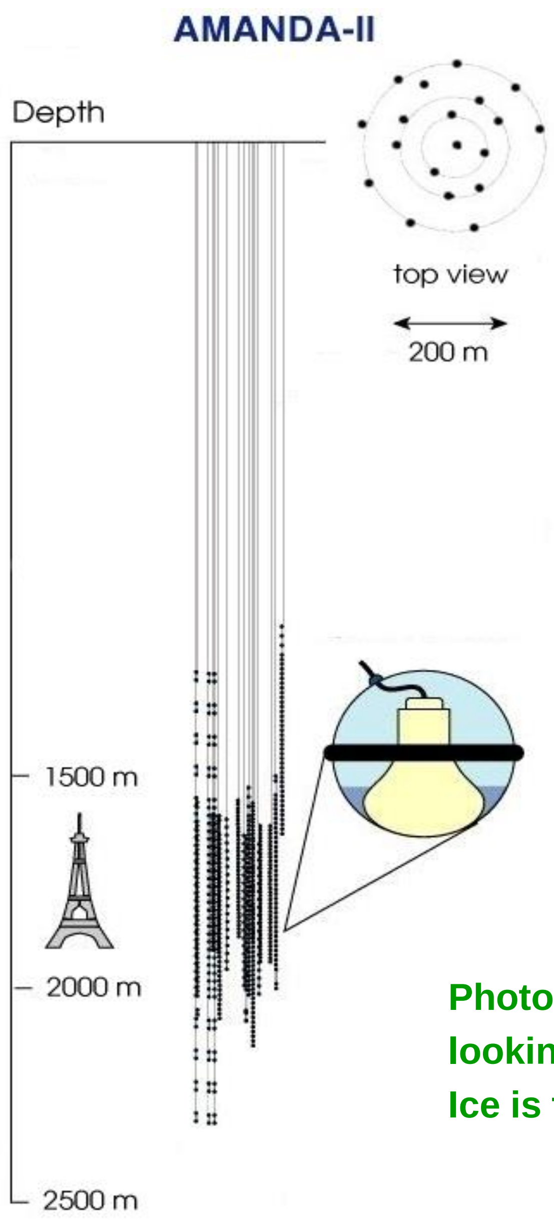
AMANDA

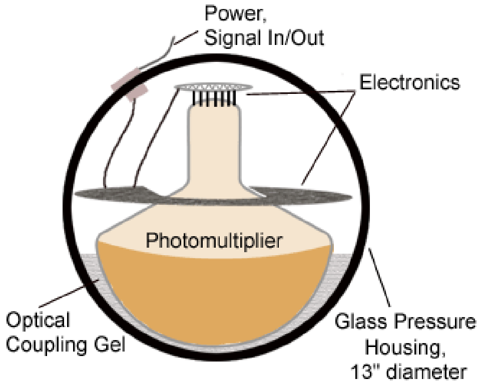
Antarctic Muon And Neutrino Detector Array

AMANDA

South Pole

AMANDA



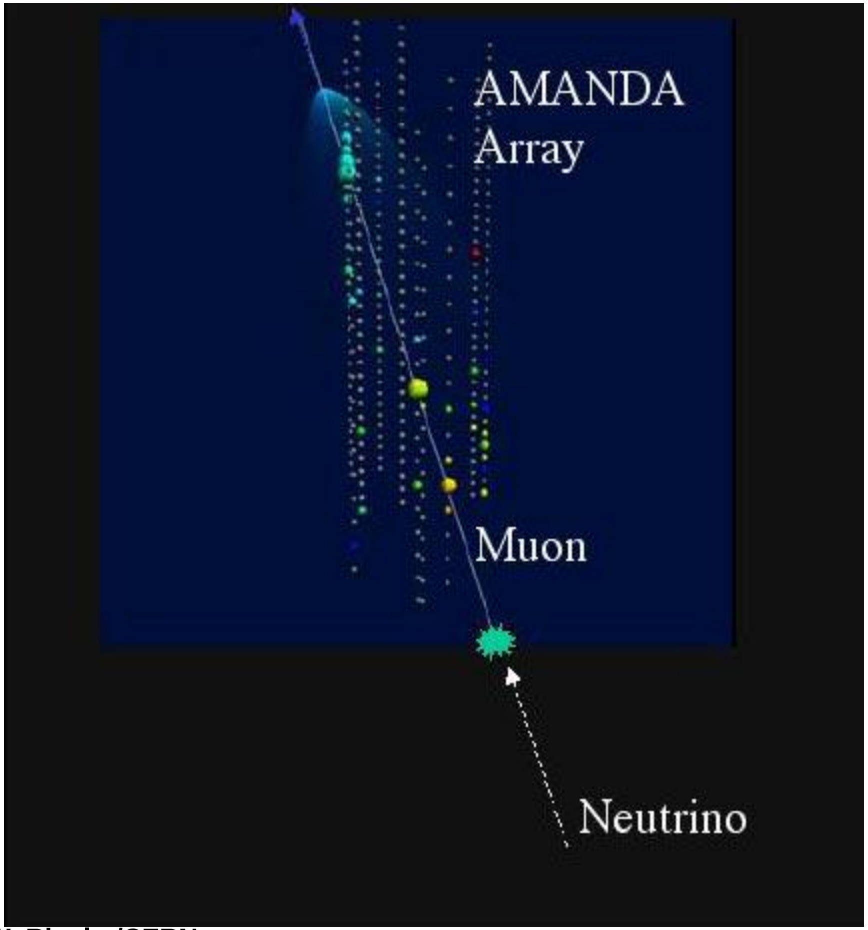


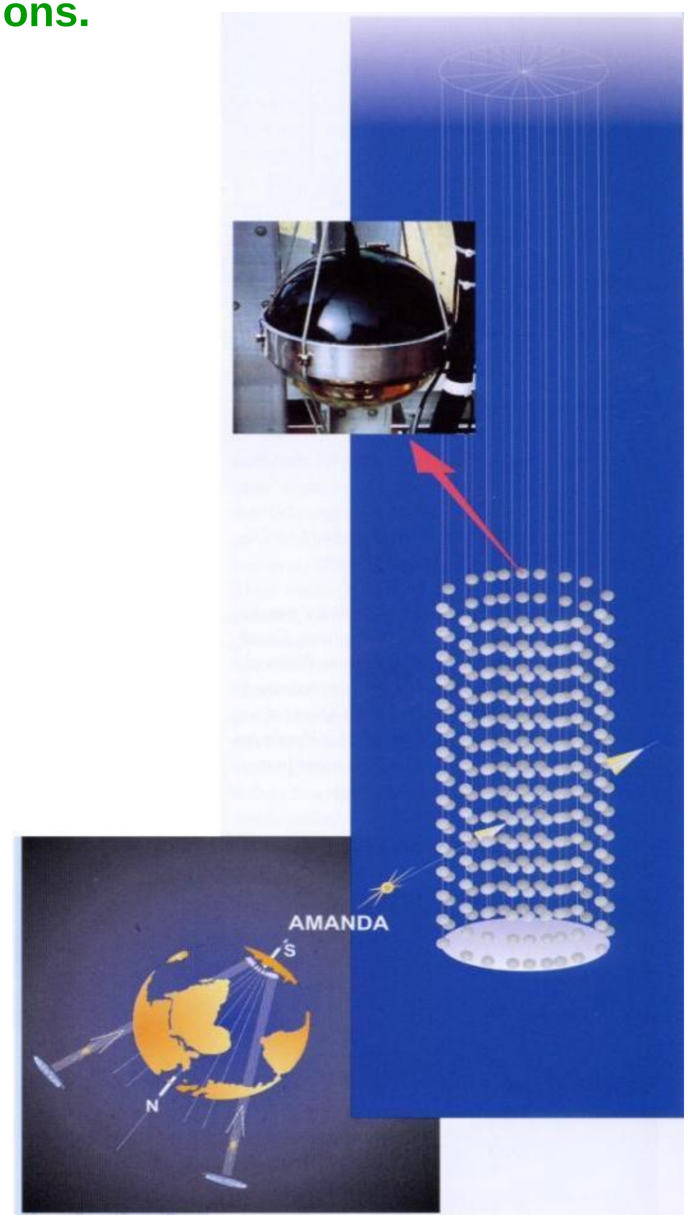
Photomultipliers in the Ice,
looking downwards.
Ice is the detecting medium.

AMANDA

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

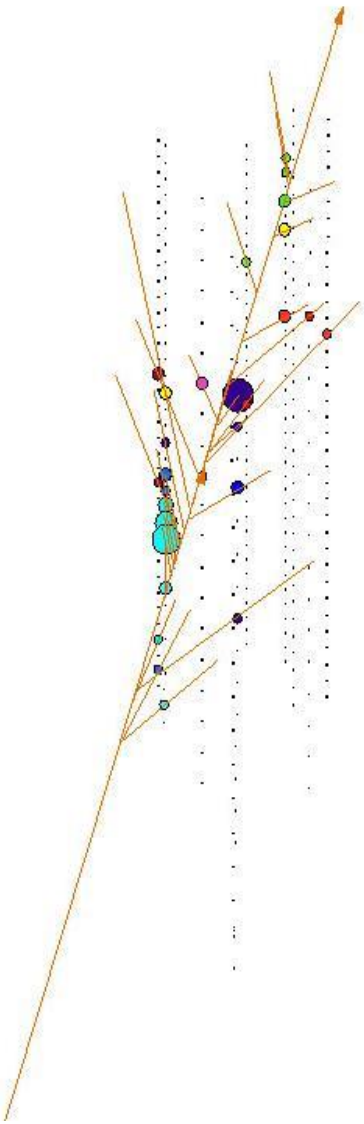
→ **Find neutrino point sources in the universe !**

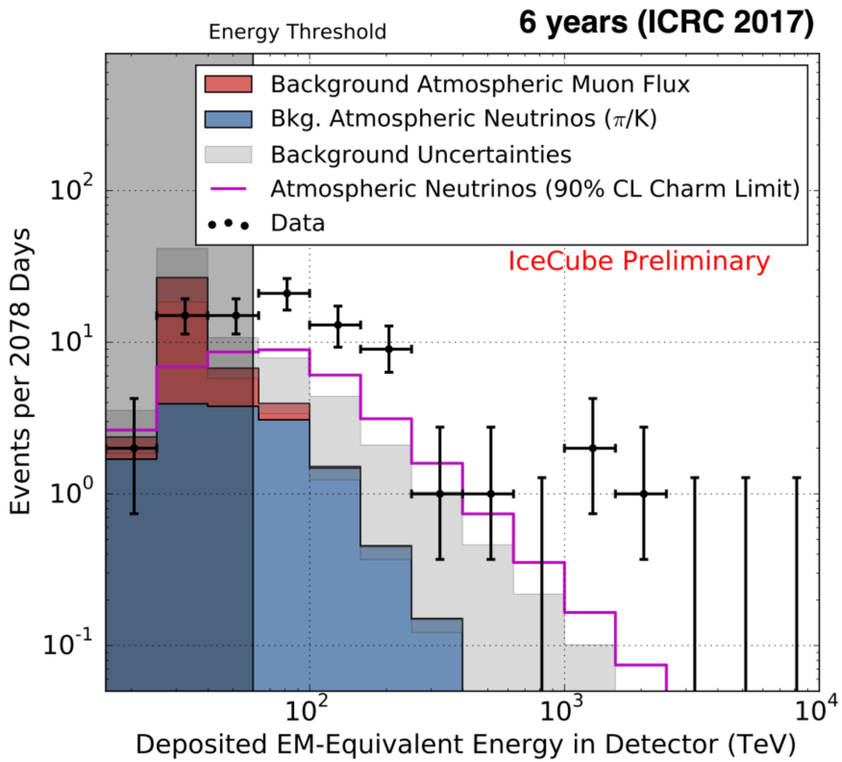


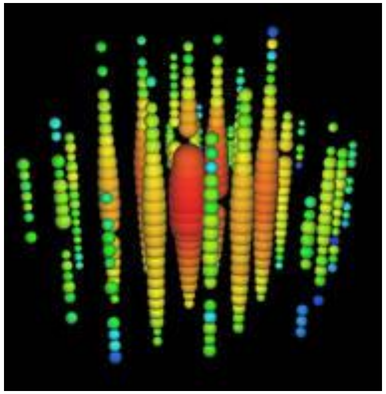


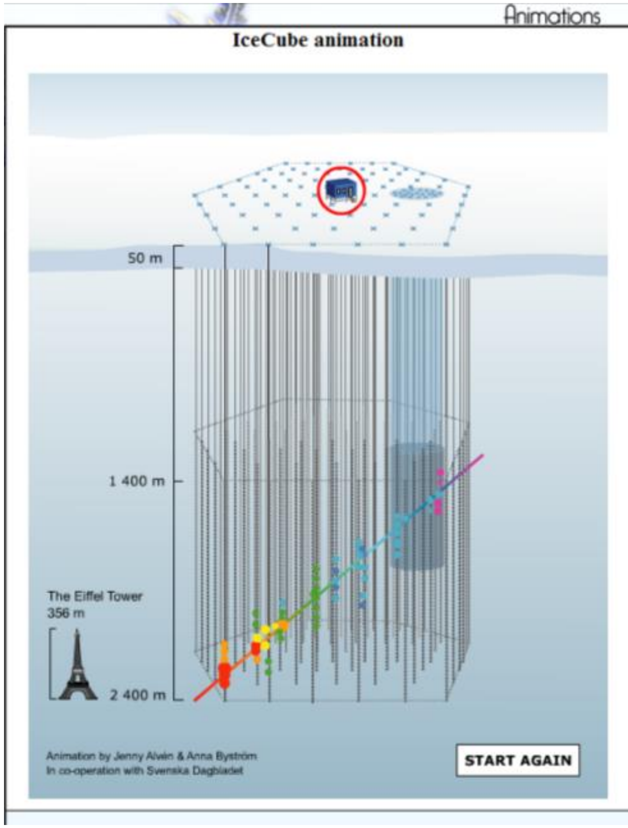
Ice Cube

Event Display









→ Ice Cube for more statistics !

AMS

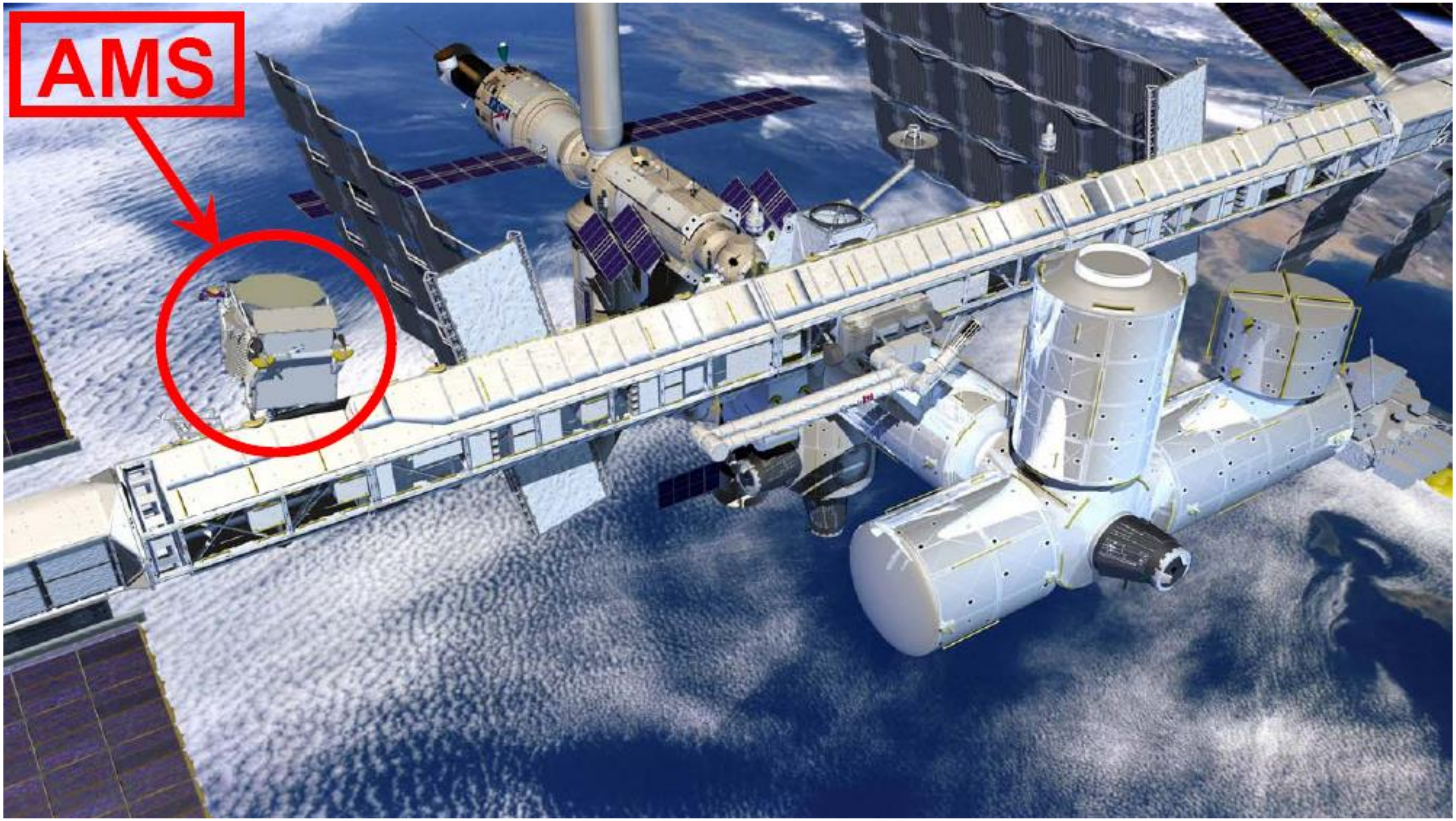
Alpha **M**agnetic **S**pectrometer

Try to find Antimatter in the primary cosmic rays.

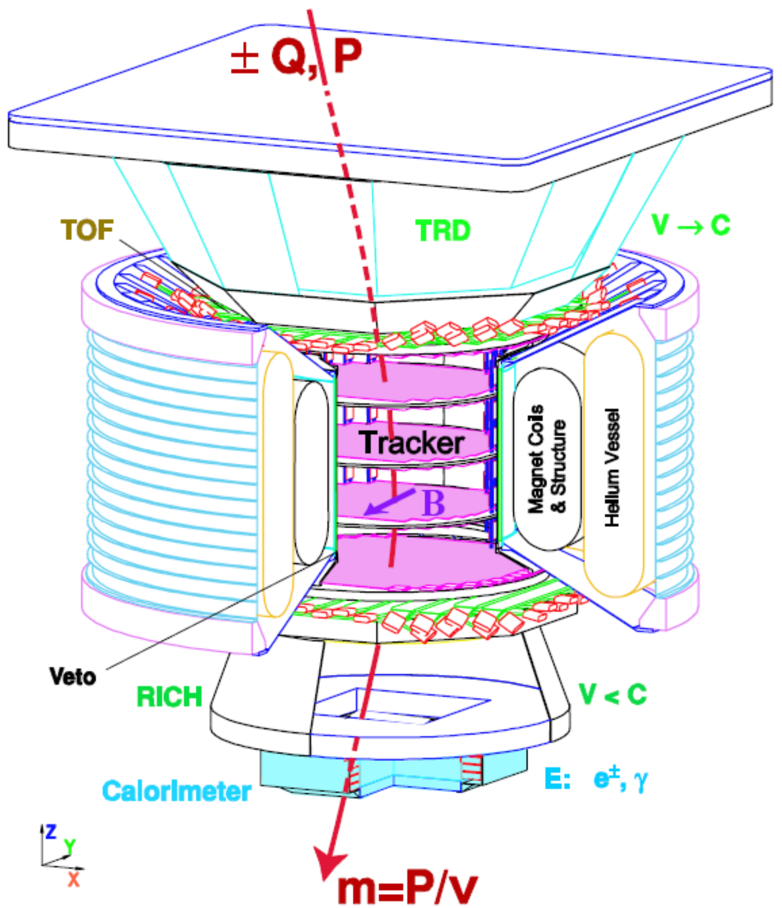
Study cosmic ray composition etc. etc.

AMS

Is installed on the international space station.

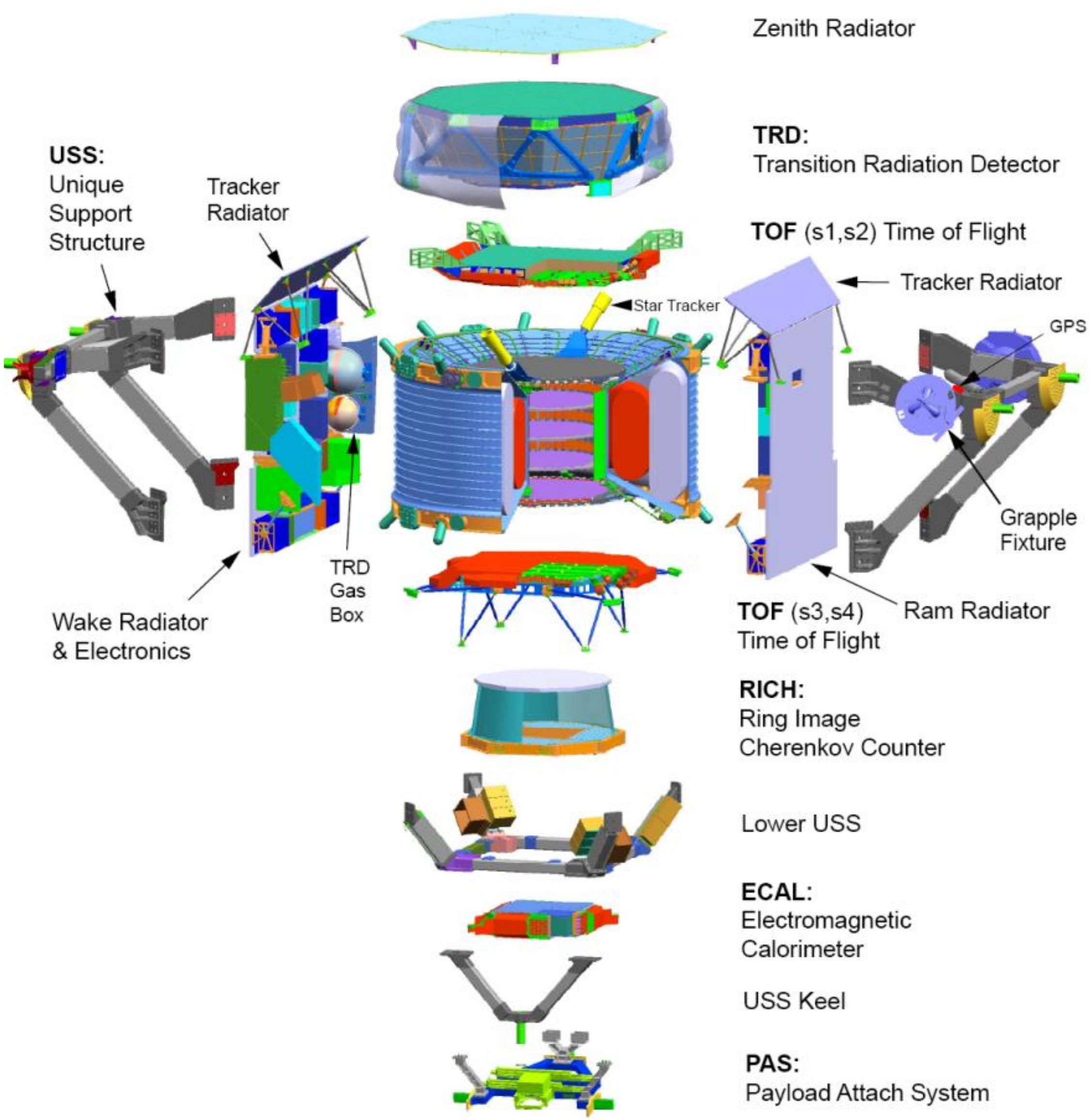


AMS



± 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