













Particle Detectors 2/2

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The 'Standard Model'

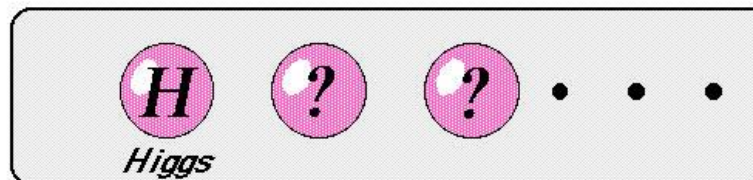
matter particles

	1st gen.	2nd gen.	3rd gen.
Q U A R K	 <i>u</i> <i>up</i>	 <i>c</i> <i>charm</i>	 <i>t</i> <i>top</i>
	 <i>d</i> <i>down</i>	 <i>s</i> <i>strange</i>	 <i>b</i> <i>bottom</i>
L E P T O N	 <i>ν_e</i> <i>e neutrino</i>	 <i>ν_μ</i> <i>μ neutrino</i>	 <i>ν_τ</i> <i>τ neutrino</i>
	 <i>e</i> <i>electron</i>	 <i>μ</i> <i>muon</i>	 <i>τ</i> <i>tau</i>

gauge particles

Strong Force  <i>g</i> <i>Gluon</i>
Electro-Magnetic Force  <i>γ</i> <i>photon</i>
Weak Force    <i>W⁺</i> <i>W⁻</i> <i>Z</i> <i>W bosons</i> <i>Z boson</i>

scalar particle(s)



The 'Standard Model'

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

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

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

$$E = ma^2$$

$$E = mb^2$$

$$E = mc^2 \leftarrow \text{Energy} \hat{=} \text{Mass}$$

⋮

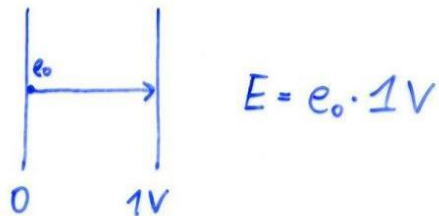
$$m(\text{electron}) = 9.1 \cdot 10^{-31} \text{ kg}$$

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

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

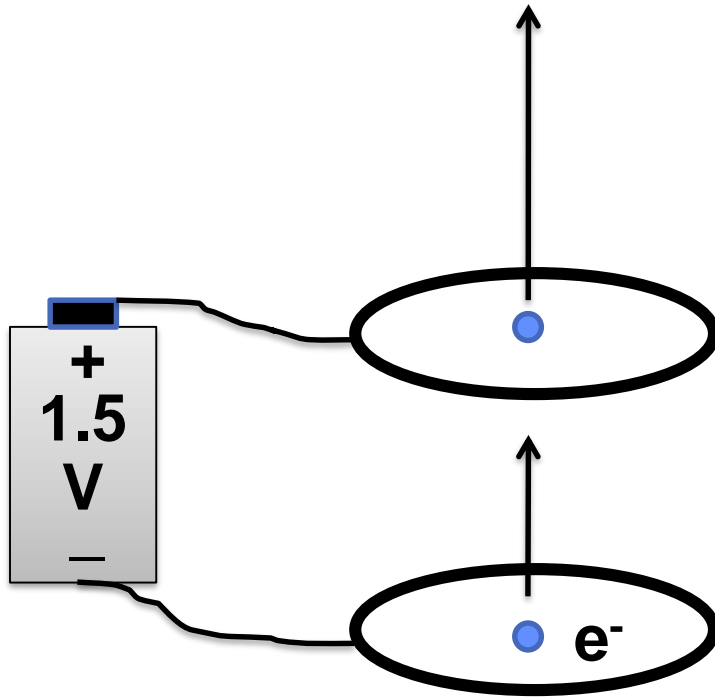
$$= 0.511 \text{ MeV}$$

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



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

Build your own Accelerator



$$E_{\text{kin}} = 1.5\text{eV} =$$

$$2\,615\,596\text{ km/h}$$

Scales

8

Visible Light:

$\lambda = 500 \text{ nm}$, $h\nu \approx 2.5 \text{ eV}$

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

9

Lorentz Boost:

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

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

$$s = v \cdot \tau \sim c \cdot \tau = 660 \text{ m}$$

But we see Muons here on Earth

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

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

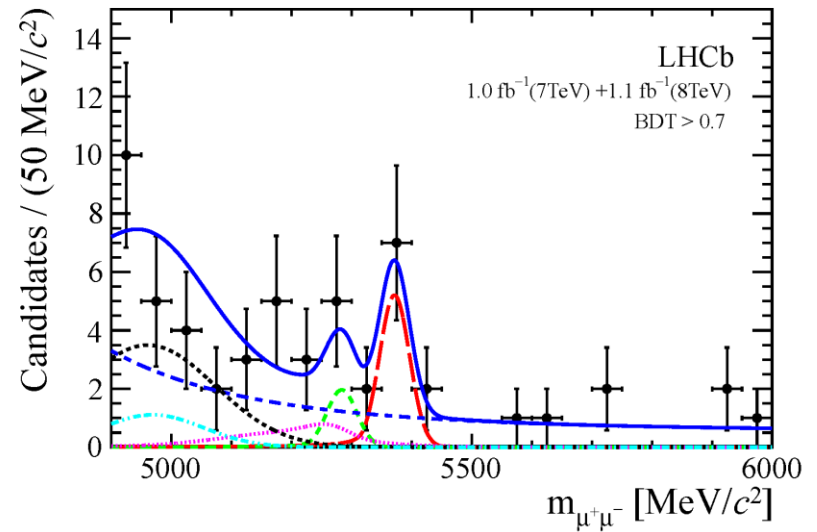
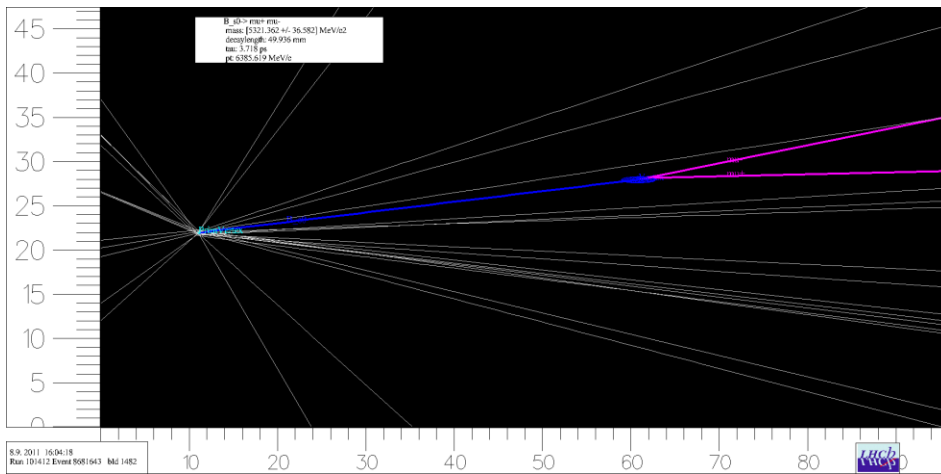
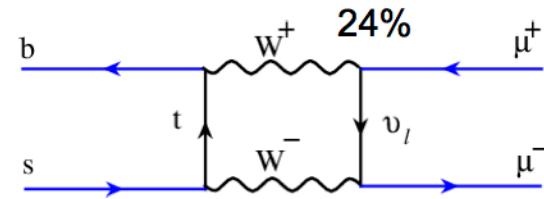
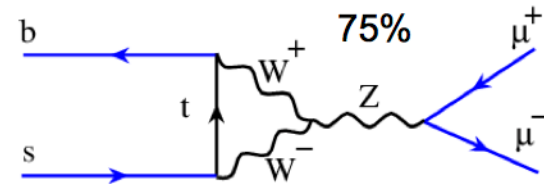
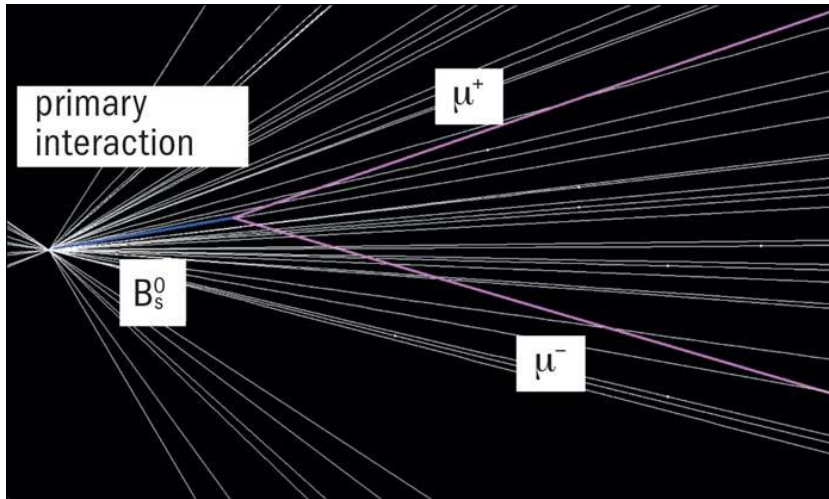
$$s = c \cdot \bar{\tau} = 12.5 \text{ km} \rightarrow \text{Earth}$$

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

$$2 \text{ GeV} \rightarrow s = 115 \text{ m}$$

Pions were discovered in Emulsions exposed
to Cosmic Rays on high mountains.

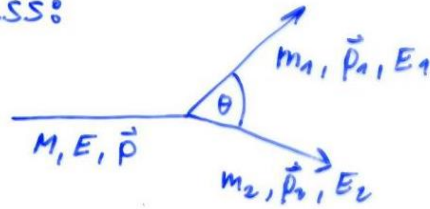
LHCb B decay, displaced Vertex



Basics

Invariant Mass:

LAB:



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

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

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

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

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

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

- Measuring Momenta and Energies OR
- Measuring Momenta and identifying Particles gives the Mass of the original Particle

$\eta, W^\pm, Z^0, g, e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau, \pi^\pm, \pi^0, \eta, f_0(660), g(770),$
 $\omega(782), \eta'(958), f_0(980), a_0(980), \phi(1020), h_1(1170), b_1(1235),$
 $a_1(1260), f_2(1270), f_1(1285), \eta(1295), \pi(1300), a_2(1320),$
 $f_0(1370), f_1(1420), \omega(1420), \eta(1440), a_0(1450), g(1450),$
 $f_0(1500), f_2'(1525), \omega(1650), \omega_2(1670), \pi_2(1670), \phi(1680),$
 $g_3(1690), g(1700), f_0(1710), \pi(1800), \phi_3(1850), f_2(2010),$
 $a_4(2040), f_4(2050), f_2(2300), f_2(2340), K^\pm, K^0, K_S^0, K_L^0, K^*(892),$
 $K_1(1270), K_1(1400), K^*(1410), K_0^*(1430), K_2^*(1430), K^*(1680),$
 $K_2(1770), K_3^*(1780), K_2(1820), K_4^*(2045), D^\pm, D^0, D^*(2007),$
 $D^*(2010)^\pm, D_1(2420)^\pm, D_2^*(2460)^\pm, D_2^*(2460)^\pm, D_s^\pm, D_s^{*\pm},$
 $D_{s1}(2536)^\pm, D_{s3}(2573)^\pm, B^\pm, B^0, B^*, B_S^0, B_c^\pm, \eta_c(1S), J/\psi(1S),$
 $\chi_{c0}(1P), \chi_{c1}(1P), \chi_{c2}(1P), \psi(2S), \psi(3770), \psi(4040), \psi(4160),$
 $\psi(4415), \Upsilon(1S), \chi_{b0}(1P), \chi_{b1}(1P), \chi_{b2}(1P), \Upsilon(2S), \chi_{b0}(2P),$
 $\chi_{b2}(2P), T(3S), T(4S), T(10860), T(11020), p, n, N(1440),$
 $N(1520), N(1535), N(1650), N(1675), N(1680), N(1700), N(1710),$
 $N(1720), N(2190), N(2220), N(2250), N(2600), \Delta(1232), \Delta(1600),$
 $\Delta(1620), \Delta(1700), \Delta(1905), \Delta(1910), \Delta(1920), \Delta(1930), \Delta(1950),$
 $\Delta(2420), \Lambda, \Lambda(1405), \Lambda(1520), \Lambda(1600), \Lambda(1670), \Lambda(1690),$
 $\Lambda(1800), \Lambda(1810), \Lambda(1820), \Lambda(1830), \Lambda(1890), \Lambda(2100),$
 $\Lambda(2110), \Lambda(2350), \Sigma^+, \Sigma^0, \Sigma^-, \Sigma(1385), \Sigma(1660), \Sigma(1670),$
 $\Sigma(1750), \Sigma(1775), \Sigma(1915), \Sigma(1940), \Sigma(2030), \Sigma(2250), \Xi^0, \Xi^-,$
 $\Xi(1530), \Xi(1690), \Xi(1820), \Xi(1950), \Xi(2030), \Omega^-, \Omega(2250)^-,$
 $\Lambda_c^+, \Lambda_c^0, \Sigma_c(2455), \Sigma_c(2520), \Xi_c^+, \Xi_c^0, \Xi_c^{*+}, \Xi_c^{*0}, \Xi(2645)$
 $\Xi_c(2780), \Xi_c(2815), \Omega_c^0, \Lambda_b^0, \Xi_b^0, \Xi_b^-, t\bar{t}$

There are many more

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
$D^0 (c\bar{u}, \bar{c}u)$	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
$B^\pm (u\bar{b}, \bar{u}b)$	5279	$1.7 \cdot 10^{-12}$	502 μm
$B^0 (b\bar{d}, \bar{b}d)$	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	$> 10^{33} \text{ y}$	∞
$n (udd)$	939.6	885.7 s	$2.655 \cdot 10^8 \text{ km}$
$\Lambda^0 (uds)$	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
$\Sigma_c^0 (ssc)$	2698	$6.0 \cdot 10^{-14}$	19 μm
$\Lambda_b (uab)$	5620	$1.2 \cdot 10^{-12}$	368 μm

"Secondary Vertices"

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

~ 13 of the 27 have $c\tau < 500\mu\text{m}$ i.e. only $\sim\text{mm}$ 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.

$$\begin{array}{l}
 e^{\pm} \quad m_e = 0.511 \text{ MeV} \\
 \mu^{\pm} \quad m_{\mu} = 105.7 \text{ MeV} \sim 200 m_e \\
 \gamma \quad m_{\gamma} = 0, \quad Q = 0
 \end{array}
 \left. \vphantom{\begin{array}{l} e^{\pm} \\ \mu^{\pm} \\ \gamma \end{array}} \right\} \text{EM}$$

$$\begin{array}{l}
 \pi^{\pm} \quad m_{\pi} = 139.6 \text{ MeV} \sim 270 m_e \\
 K^{\pm} \quad m_K = 493.7 \text{ MeV} \sim 1000 m_e \sim 3.5 m_{\pi} \\
 p^{\pm} \quad m_p = 938.3 \text{ MeV} \sim 2000 m_e
 \end{array}
 \left. \vphantom{\begin{array}{l} \pi^{\pm} \\ K^{\pm} \\ p^{\pm} \end{array}} \right\} \text{EM, Strong}$$

$$\begin{array}{l}
 K^0 \quad m_{K^0} = 497.7 \text{ MeV} \quad Q = 0 \\
 n \quad m_n = 939.6 \text{ MeV} \quad Q = 0
 \end{array}
 \left. \vphantom{\begin{array}{l} K^0 \\ n \end{array}} \right\} \text{Strong}$$

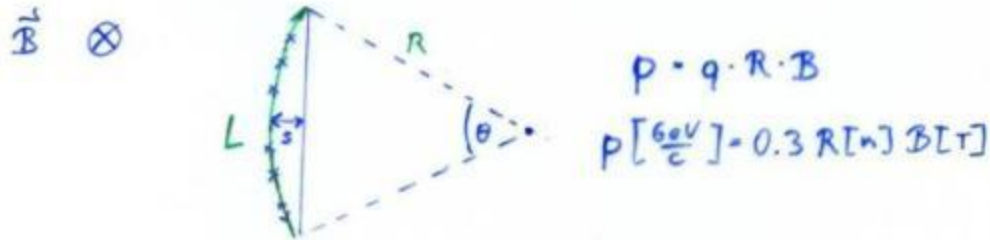
The Difference in Mass, Charge,

Mass, Charge, Interaction

is the key to the Identification

Momentum Measurement

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



$$L = R \cdot \theta$$

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

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

$$\Delta S = \frac{\sigma_x}{\sqrt{N}} \quad \sigma_x \dots \text{point resolution, } N \dots \text{Measurement Points}$$

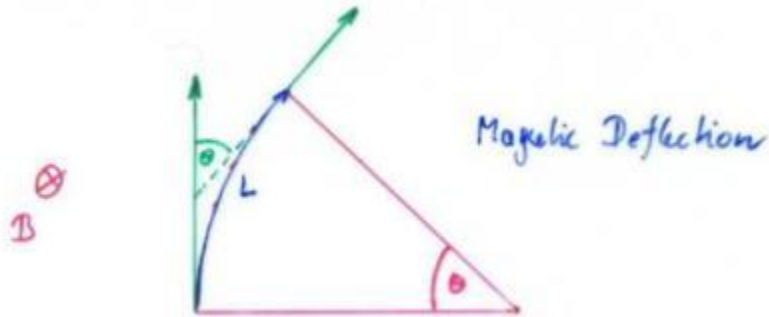
$$\frac{\Delta p}{p} = \frac{\Delta S}{S} = \frac{\sigma_x [\text{m}]}{\sqrt{N}} \cdot \frac{3.3 \cdot 8 p \left[\frac{\text{GeV}}{c} \right]}{B [\text{T}] \cdot L^2 [\text{m}^2]}$$

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

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

Limit \rightarrow Multiple Scattering

Multiple Scattering



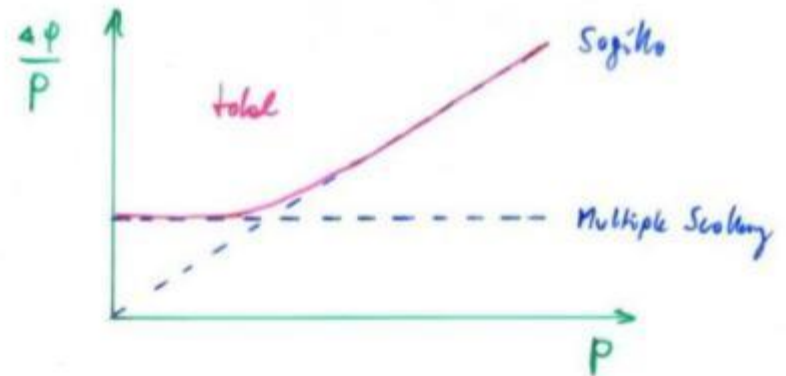
$$p \left[\frac{\text{GeV}}{c} \right] = 0.3 R [\text{m}] B [\text{T}]$$

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

$$\frac{\Delta p}{p} = \frac{\Delta \theta}{\theta} = \frac{\theta_0}{\theta} \sim \frac{0.05}{0.3 B [\text{T}] L [\text{m}]} \sqrt{\frac{L}{x_0}}$$

→ Independent of p

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



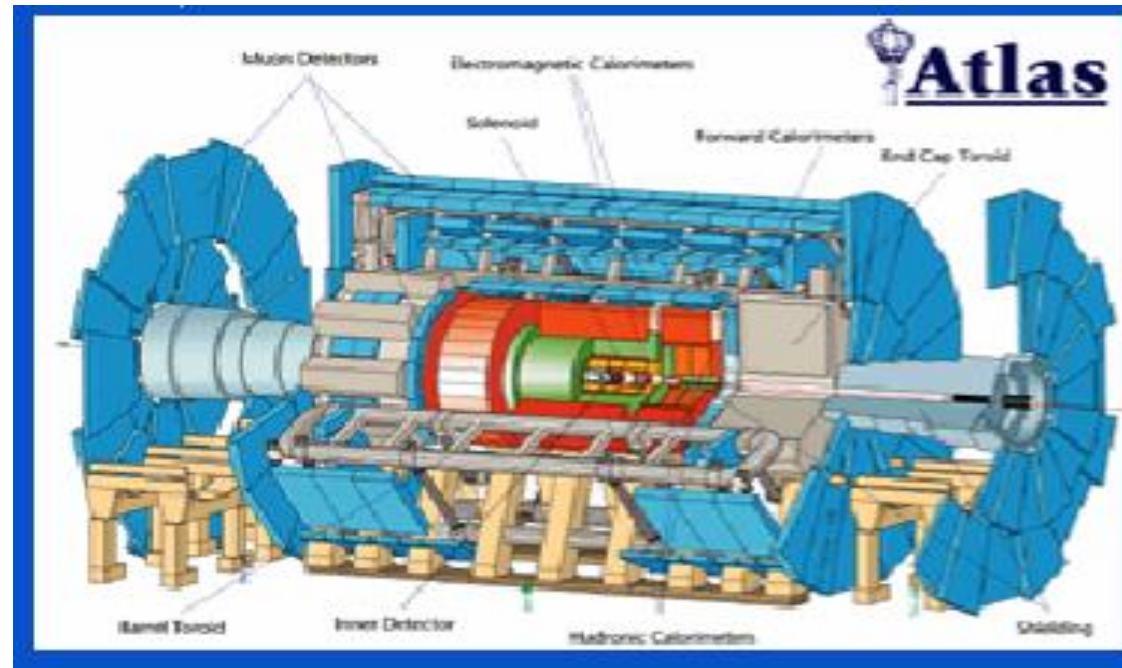
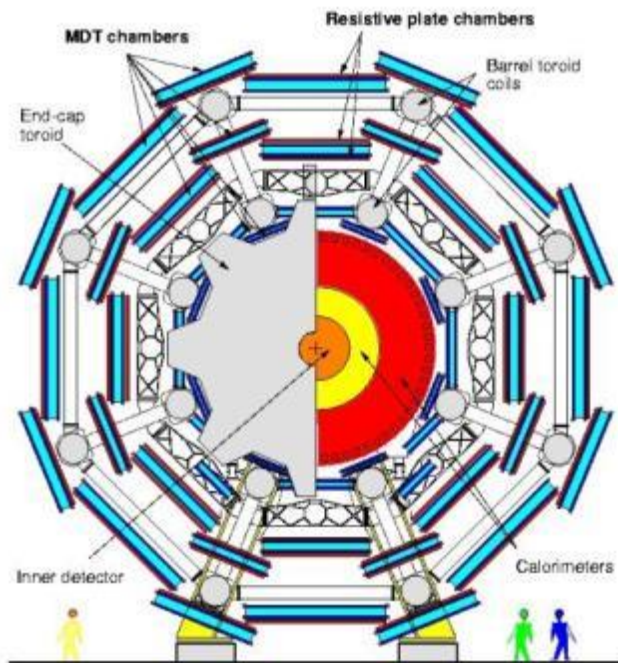
Multiple Scattering

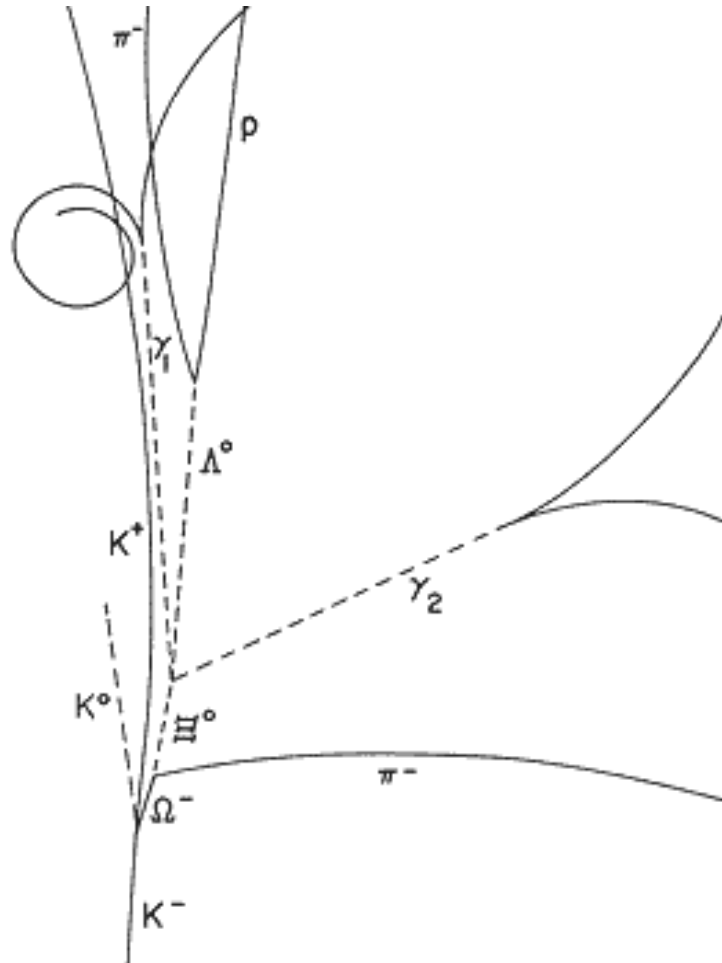
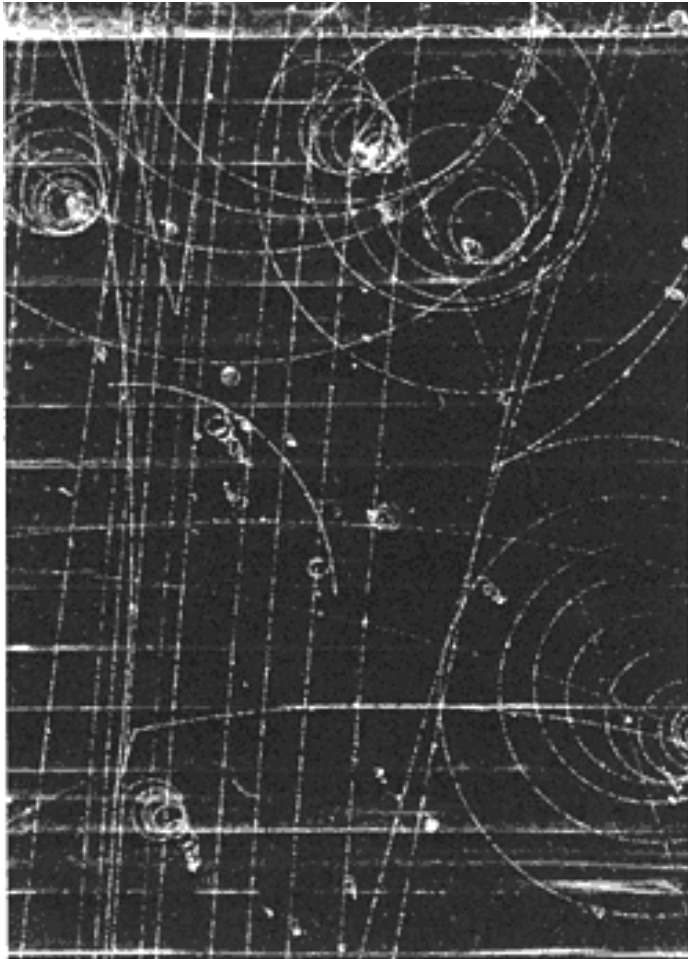
ATLAS Muon Spectrometer:

$N=3$, $\sigma=50\mu\text{m}$, $P=1\text{TeV}$,

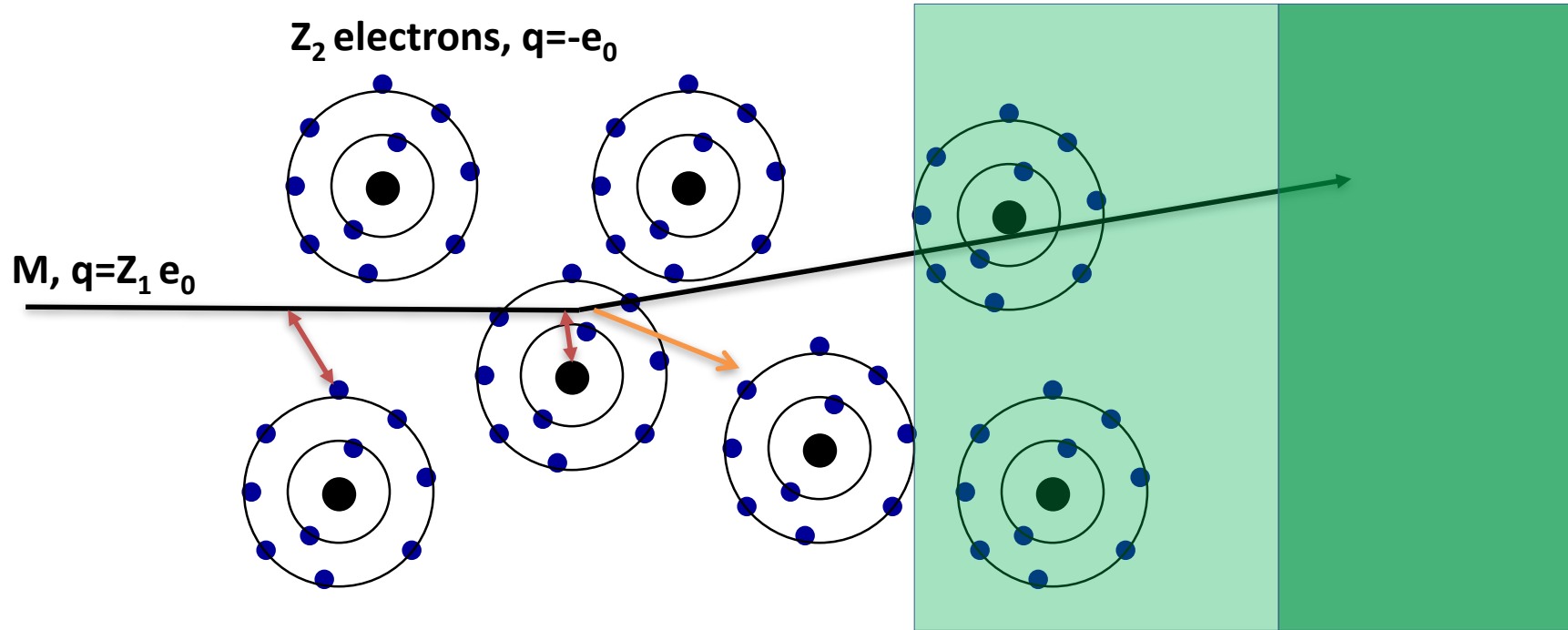
$L=5\text{m}$, $B=0.4\text{T}$

$\Delta p/p \sim 8\%$ for the most energetic muons at LHC





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 produce and X ray photon, called Transition radiation.

Bremsstrahlung, Classical



$$\frac{d\sigma'}{d\Omega} = \left(\frac{2Z_1Z_2e^2}{4\pi\epsilon_0 p \cdot v} \right)^2 \frac{1}{(2\sin(\frac{\theta}{2}))^4} \quad p = Mv$$

"Rutherford Scattering"

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

$$\frac{d\sigma'}{dQ} = 8\pi \left(\frac{Z_1Z_2e^2}{4\pi\epsilon_0 \beta c} \right)^2 \cdot \frac{1}{Q^3}$$



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

$\lim_{\omega \rightarrow 0} \frac{dI}{d\omega} \sim \frac{2}{3\pi} \frac{Z_1^2 e^2}{M^2 c^3} \frac{1}{4\pi\epsilon_0} Q^2$ *From Maxwell's eq (Jackson)*
Radiated Energy between $\omega, \omega + d\omega$

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

$$\frac{dE}{dx} = \frac{N_A g}{A} \cdot \frac{16}{3} d \cdot Z^2 \cdot \left(\frac{Z_1^2 e^2}{4\pi\epsilon_0 M c^2} \right)^2 \cdot E \cdot \ln \frac{Q_{max}}{Q_{min}}$$

$$d = \frac{e^2}{4\pi\epsilon_0 \hbar c} \sim \frac{1}{137}$$

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

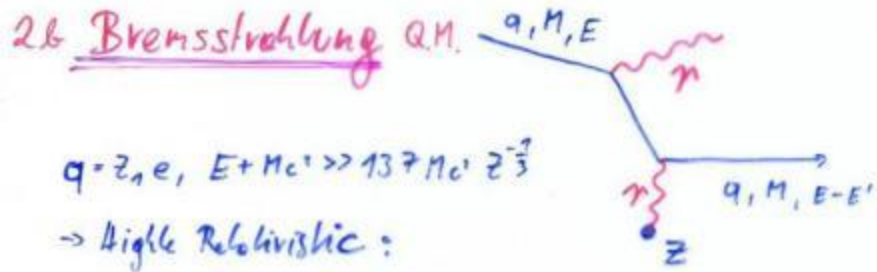
Because of the acceleration the particle radiated EM waves \rightarrow energy loss.

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

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

$\rightarrow dE/dx$

Bremsstrahlung, QM



$$\frac{d\sigma(E, E')}{dE'} = 4Z^2 Z_1^4 \left(\frac{1}{4\pi\epsilon_0} \frac{e^2}{Mc^2} \right)^2 \left(\frac{1}{E'} \right) F(E, E')$$

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

$$\frac{dE}{dx} = - \frac{N_A g}{A} \int_0^E E' \frac{d\sigma}{dE'} dE' \approx 4Z^2 Z_1^4 \left(\frac{1}{4\pi\epsilon_0} \frac{e^2}{Mc^2} \right)^2 E \left[\ln 183 Z^{-\frac{2}{3}} + \frac{1}{18} \right]$$

$$\underline{\underline{\frac{dE}{dx} = - \frac{N_A g}{A} 4Z^2 Z_1^4 \left(\frac{1}{4\pi\epsilon_0} \frac{e^2}{Mc^2} \right)^2 E \ln(183 Z^{-\frac{2}{3}})}}$$

$$E(x) = E_0 e^{-\frac{x}{X_0}} \quad X_0 = \frac{A}{4Z N_A g Z_1^4 \left(\frac{1}{4\pi\epsilon_0} \frac{e^2}{Mc^2} \right)^2 \ln 183 Z^{-\frac{2}{3}}}$$

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 →

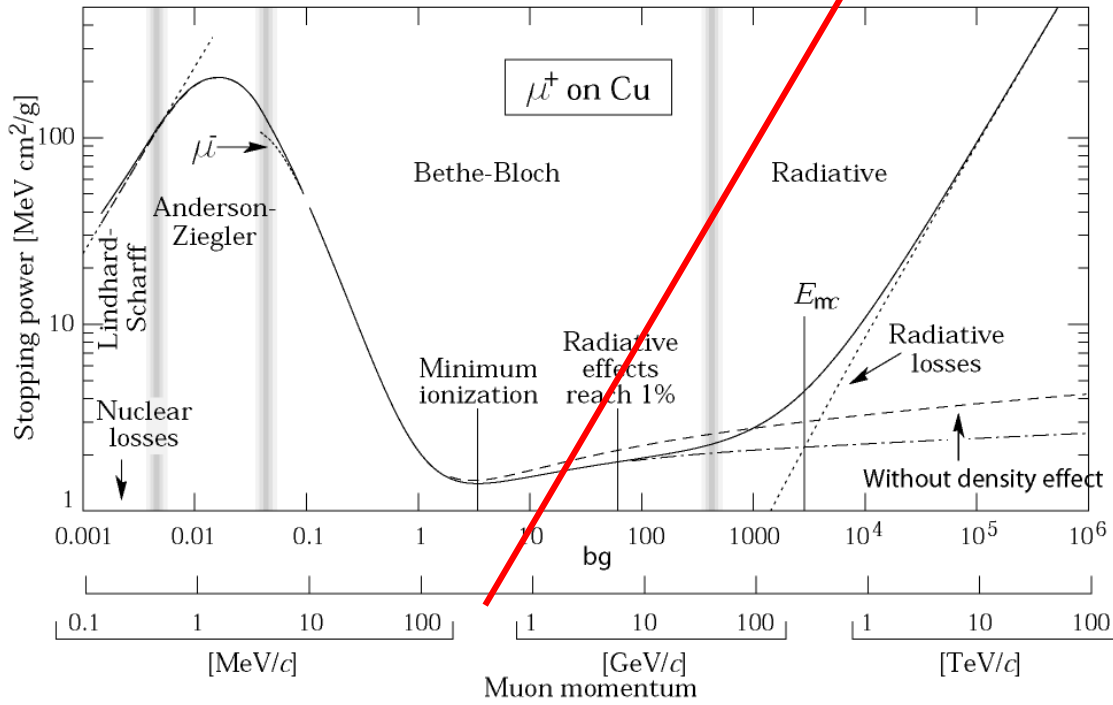
$E(x) = \text{Exp}(-x/X_0)$ – ‘Radiation Length’

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

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

Critical Energy

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



Electron Momentum 5 50 500 MeV/c

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

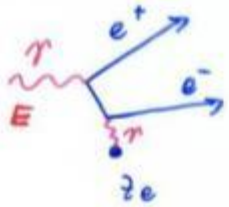
The EM Bremsstrahlung is therefore only relevant for electrons at energies of past and present detectors.

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

Myon in Copper: $p \approx 400\text{GeV}$

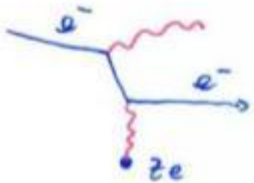
Electron in Copper: $p \approx 20\text{MeV}$

Pair Production, QM



$$\gamma + \text{Nucl.} \rightarrow e^+ + e^- + \text{Nucl.}$$

The Diagram is very similar to Bremsstrahlung



$e^- + \text{Nucl.} \rightarrow \gamma + e^- + \text{Nucl.}$
 Crossing Symmetry: bring particle to the other side and make it the anti-particle \rightarrow 'same' correction ...

$$\frac{d\sigma(E, E')}{dE'} = 4\alpha Z^2 v_0^2 \frac{1}{E} G(E, E') \quad E \gg 137 m_e c^2 Z^{-1/3}$$

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

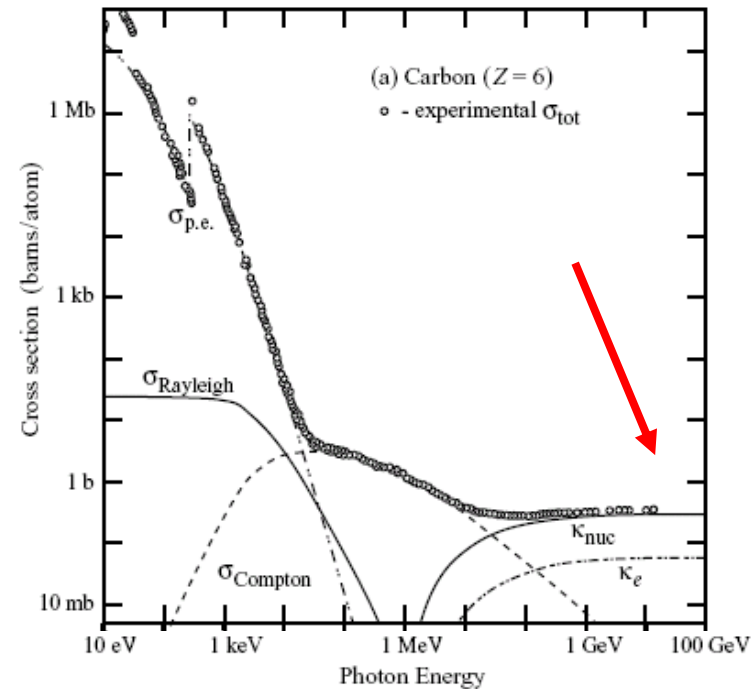
$$\sigma = \int_0^{E-2m_e c^2} \frac{d\sigma}{dE'} dE' = 4\alpha Z^2 v_0^2 \cdot \frac{7}{3} \ln 183 Z^{-1/3}$$

$$P(x) = \frac{1}{2} e^{-\frac{x}{\lambda}} \quad \lambda = \frac{A}{9 N_A \sigma} = \frac{9}{7} X_0$$

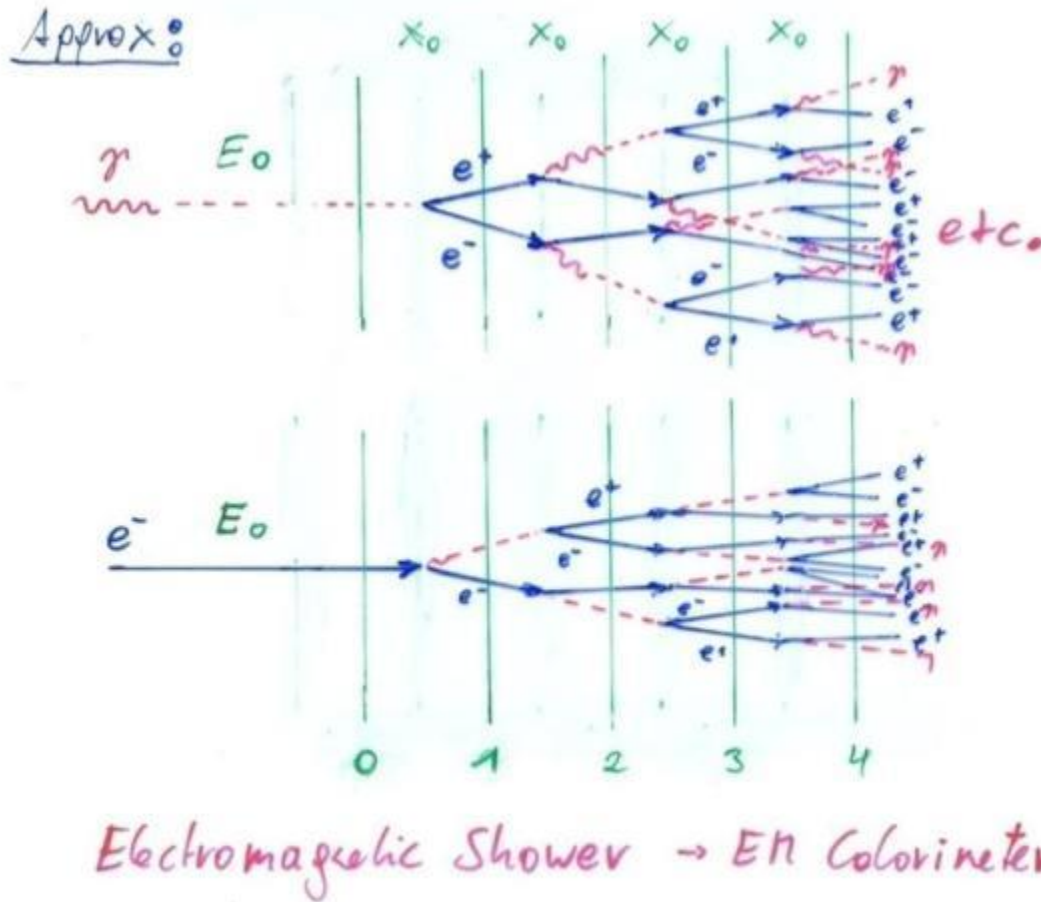
\hookrightarrow Probability that Photon converts to $e^+ e^-$ after a distance x .

For $E_\gamma \gg m_e c^2 = 0.5 \text{ MeV}$: $\lambda = 9/7 X_0$

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 $E_0 \cdot \text{Exp}(-1)$ by photon radiation.



Bremsstrahlung + Pair Production \rightarrow EM Shower



Tracking:

Momentum by bending in the B-field

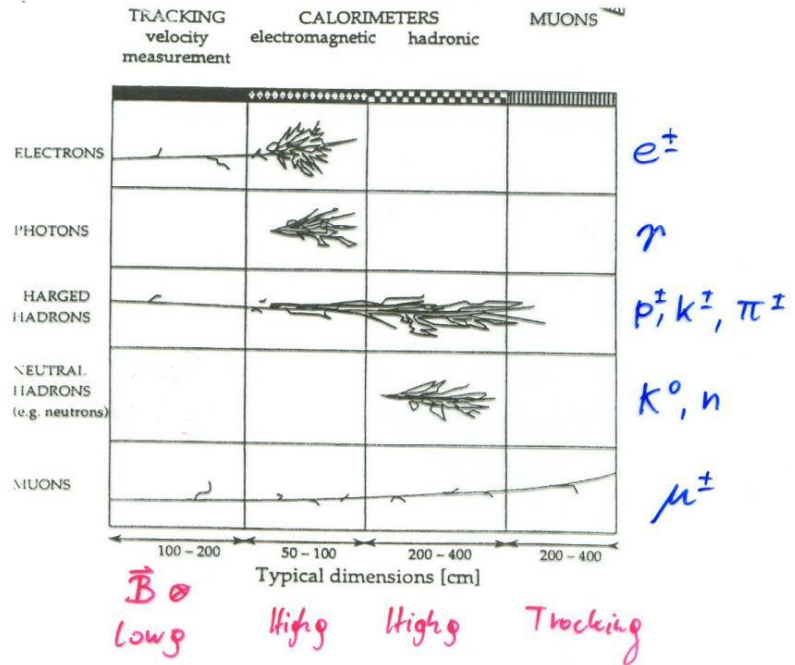
Secondary vertices

Calorimeter:

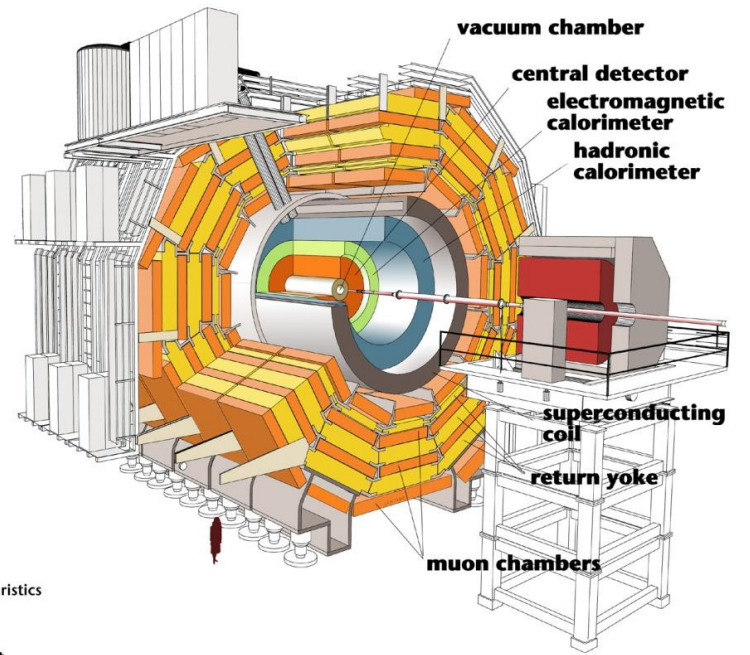
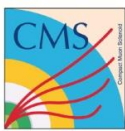
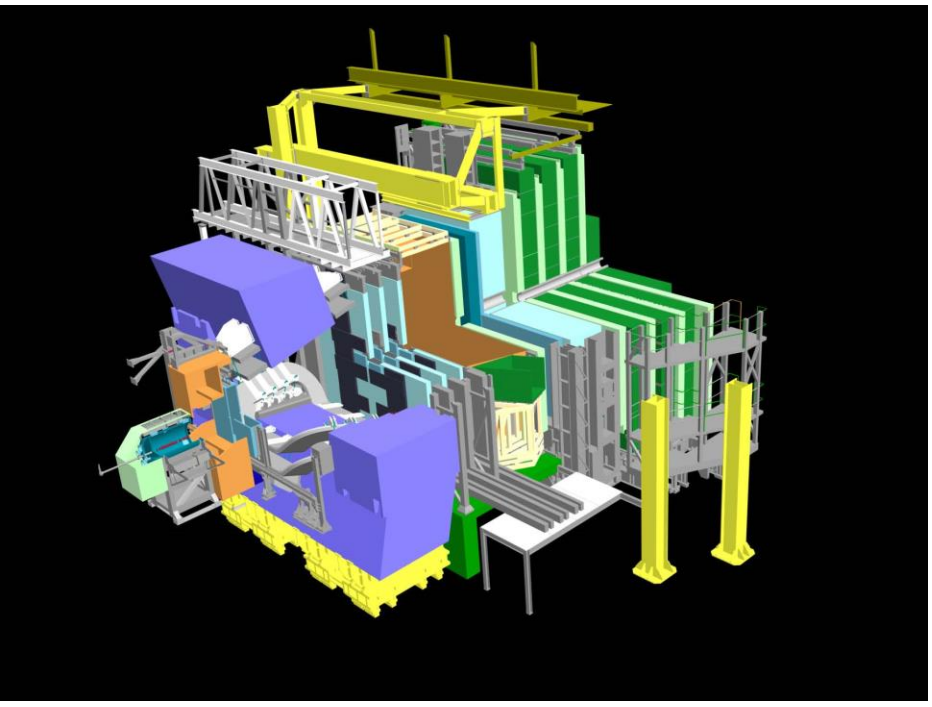
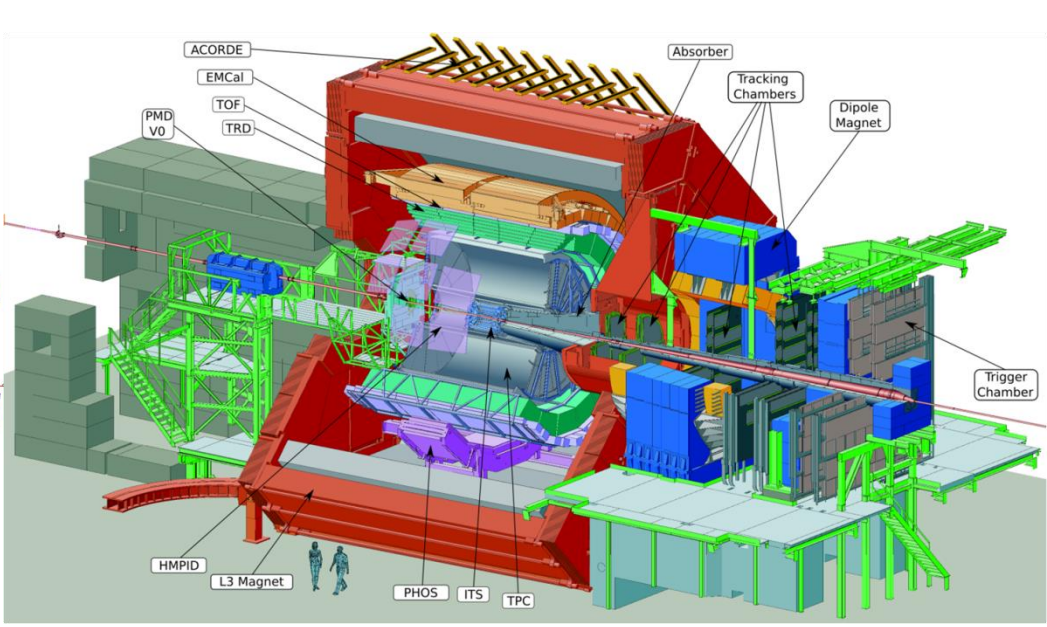
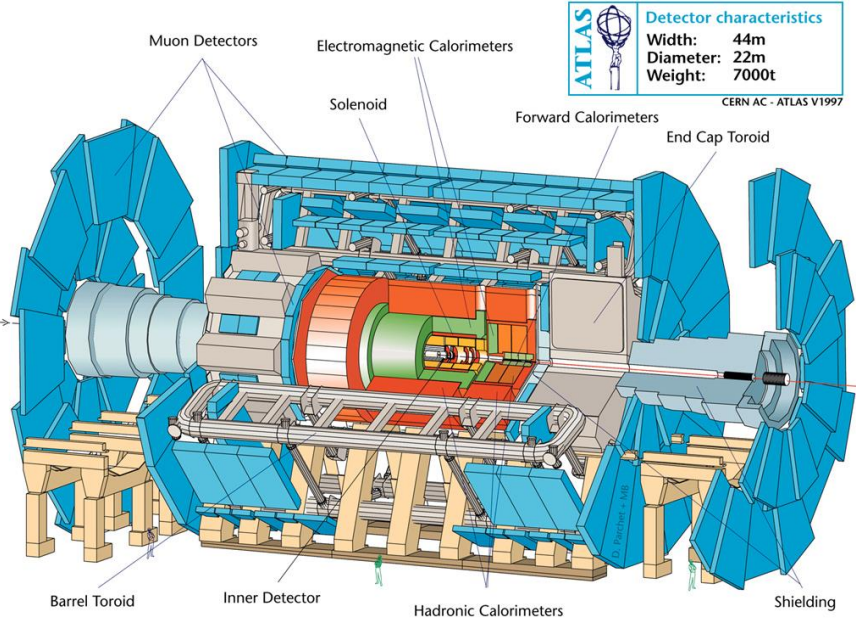
Energy by absorption

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
- Muons ionize and don't shower



Detector characteristics
 Width: 22m
 Diameter: 15m
 Weight: 14500t

Vertex Detector

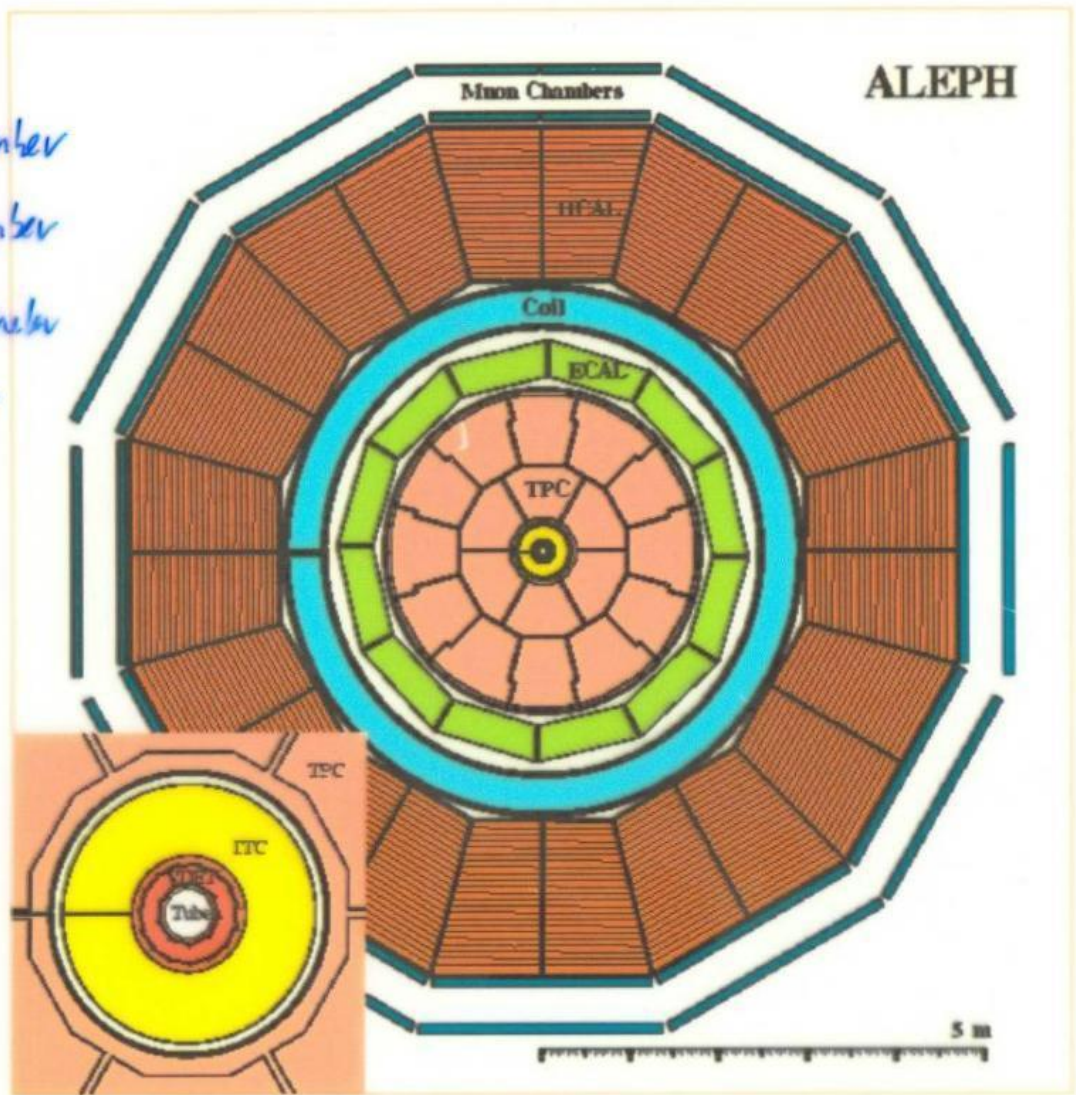
Inner Tracking Chamber

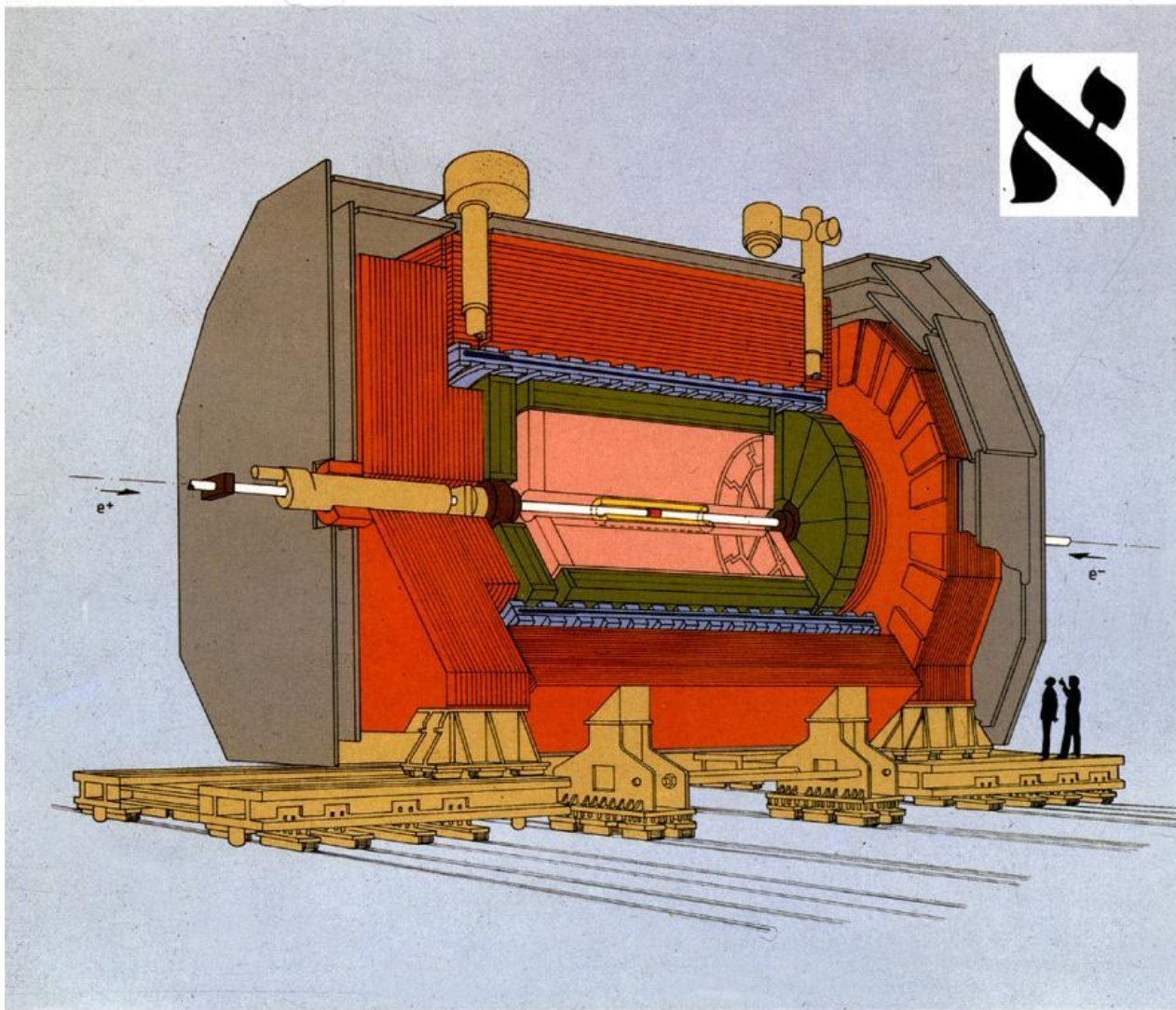
Time Projection Chamber

Electromagnetic Calorimeter

Hadron Calorimeter

Muon Detectors













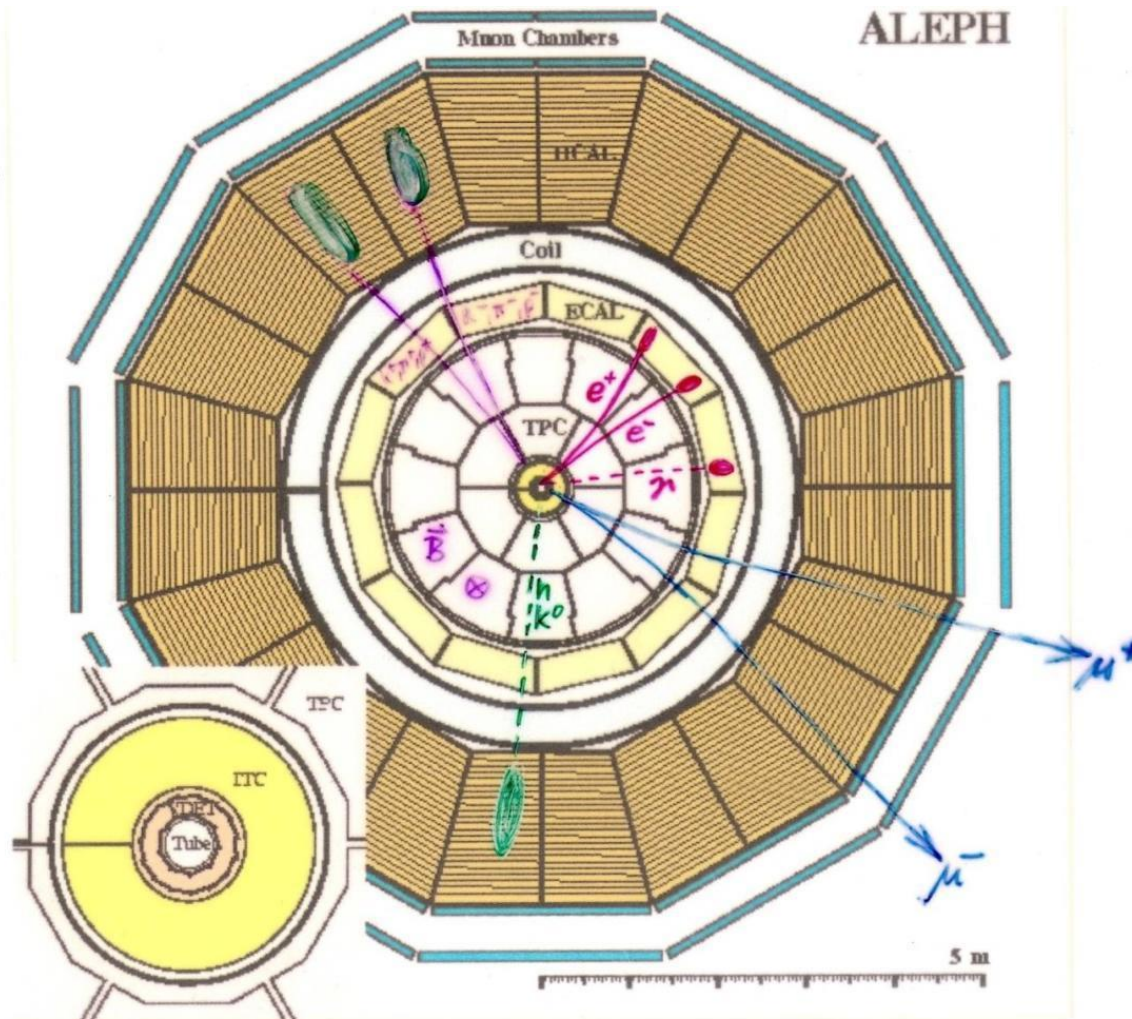
-  Vertex Detector
-  Inner Track Chamber
-  Time Projection Chamber
-  Electromagnetic Calorimeter
-  Superconducting Magnet Coil
-  Hadron Calorimeter
-  Muon Detection Chambers
-  Luminosity Monitors

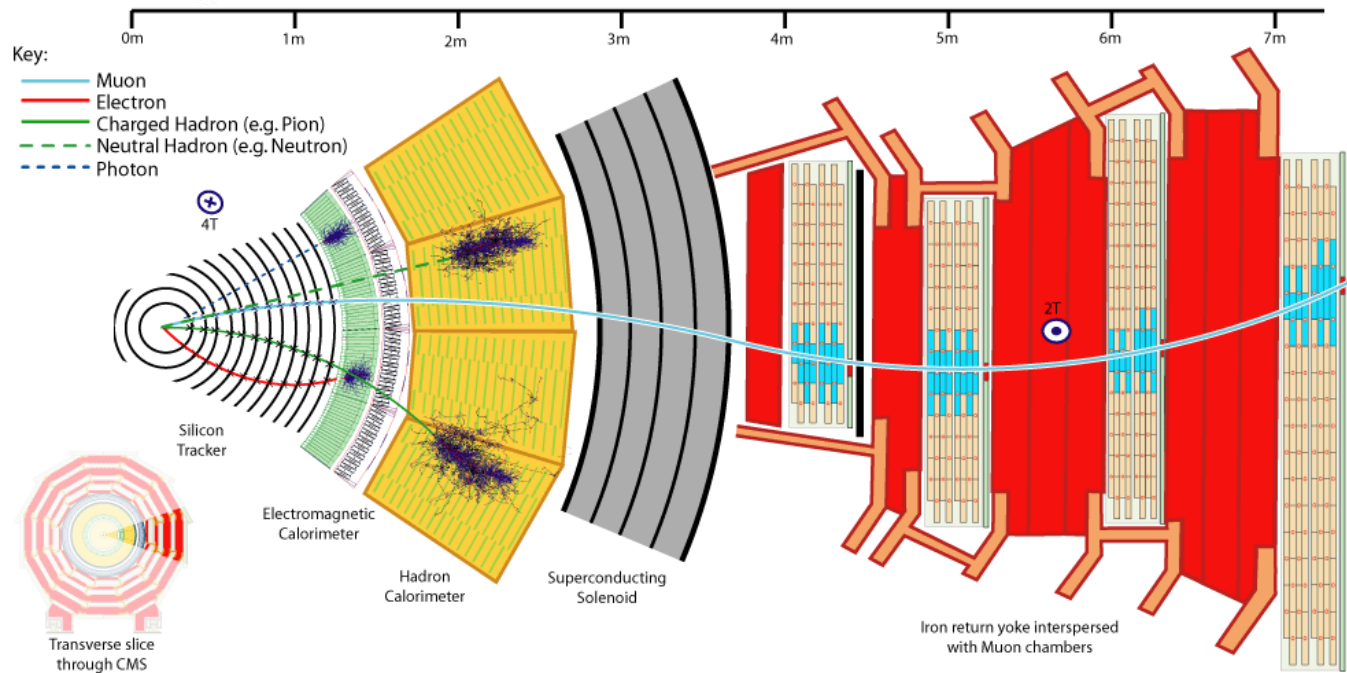
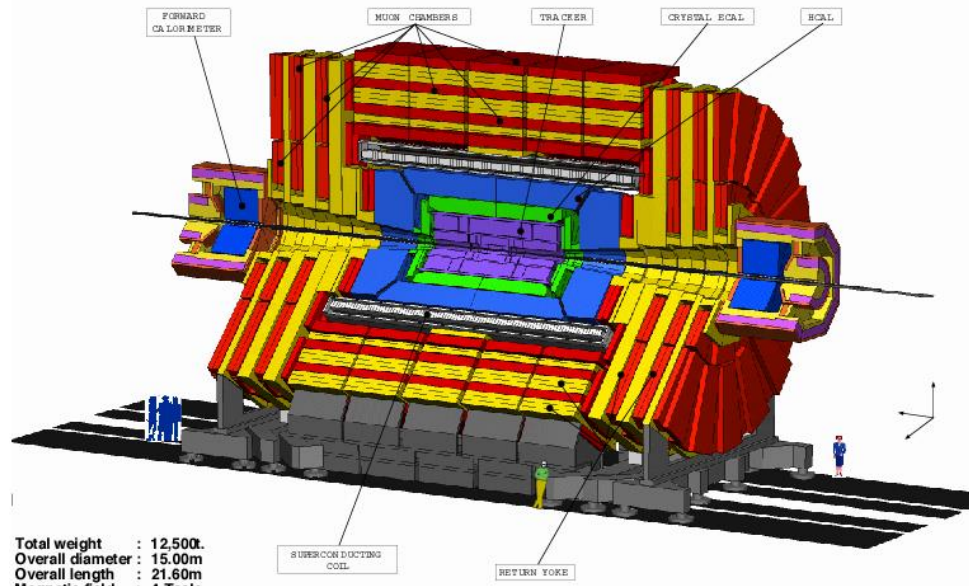
Fig. 1 - The ALEPH Detector

γ, e^+, τ^+, k^+

k^0, p, n, μ^+

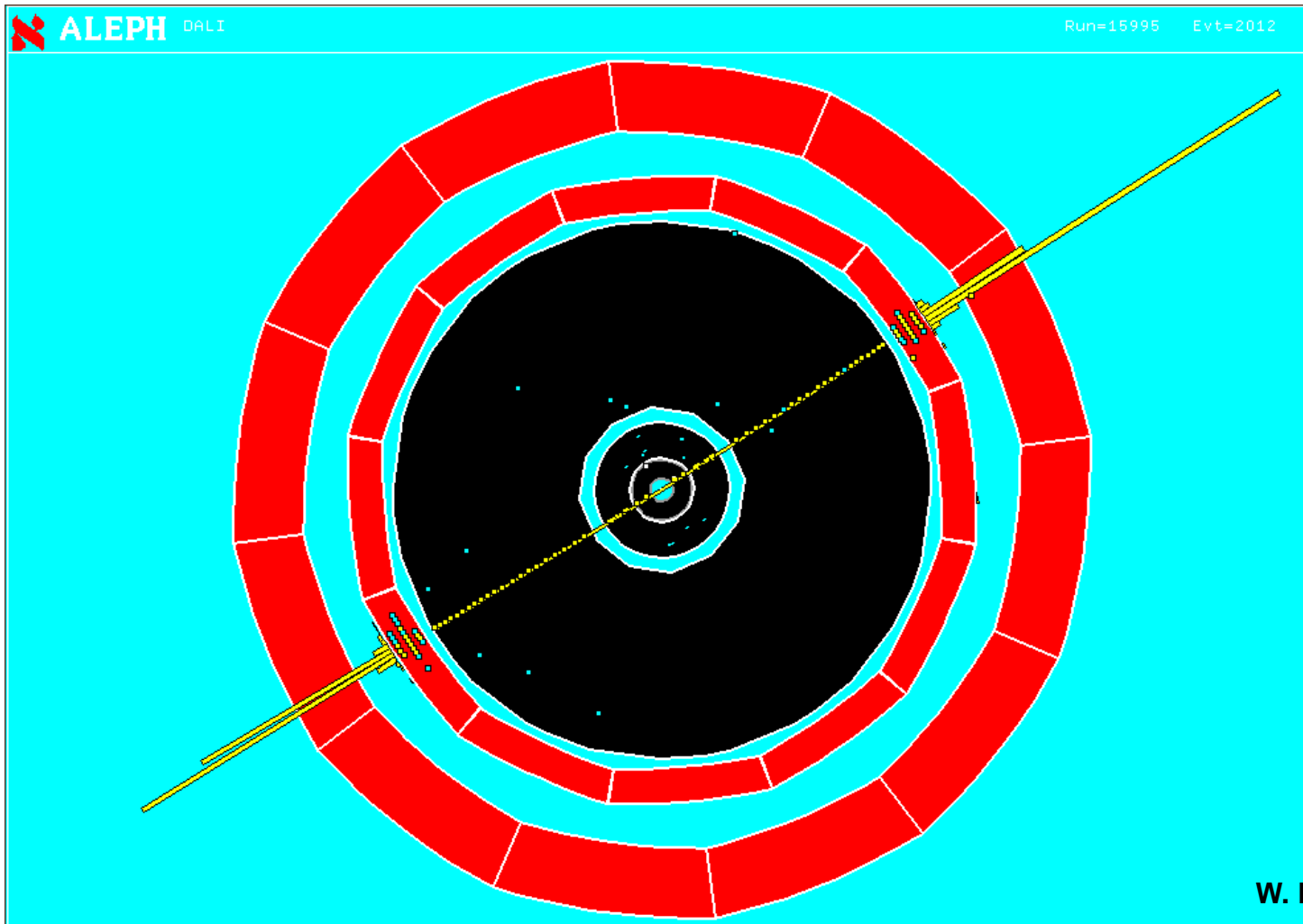


CMS A Compact Solenoidal Detector for LHC



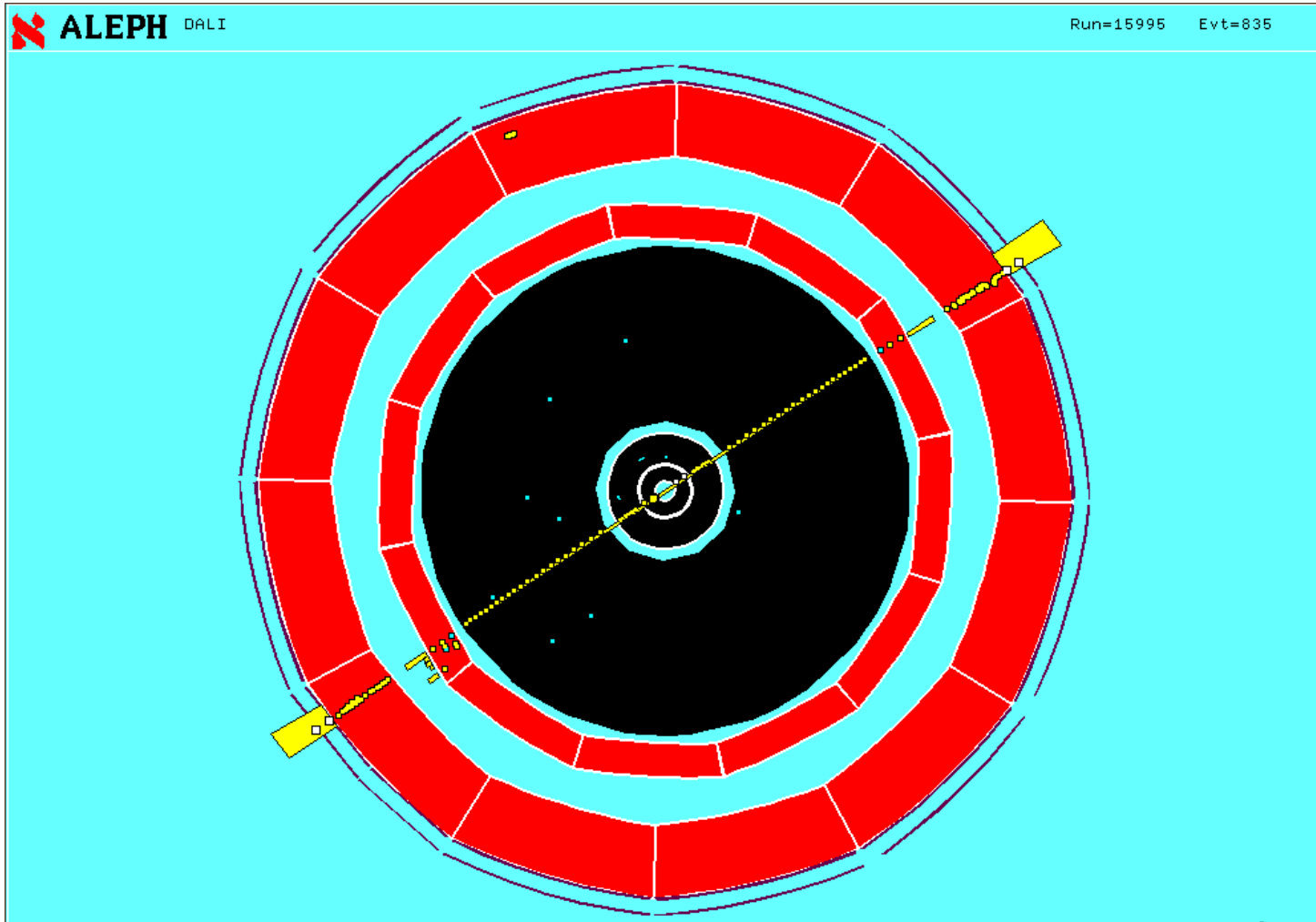
$$Z \rightarrow e^+ e^-$$

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.



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. $P_{\text{tot}}=0$,

If the Σp_i of all collision products is $\neq 0$ → neutrino escaped.



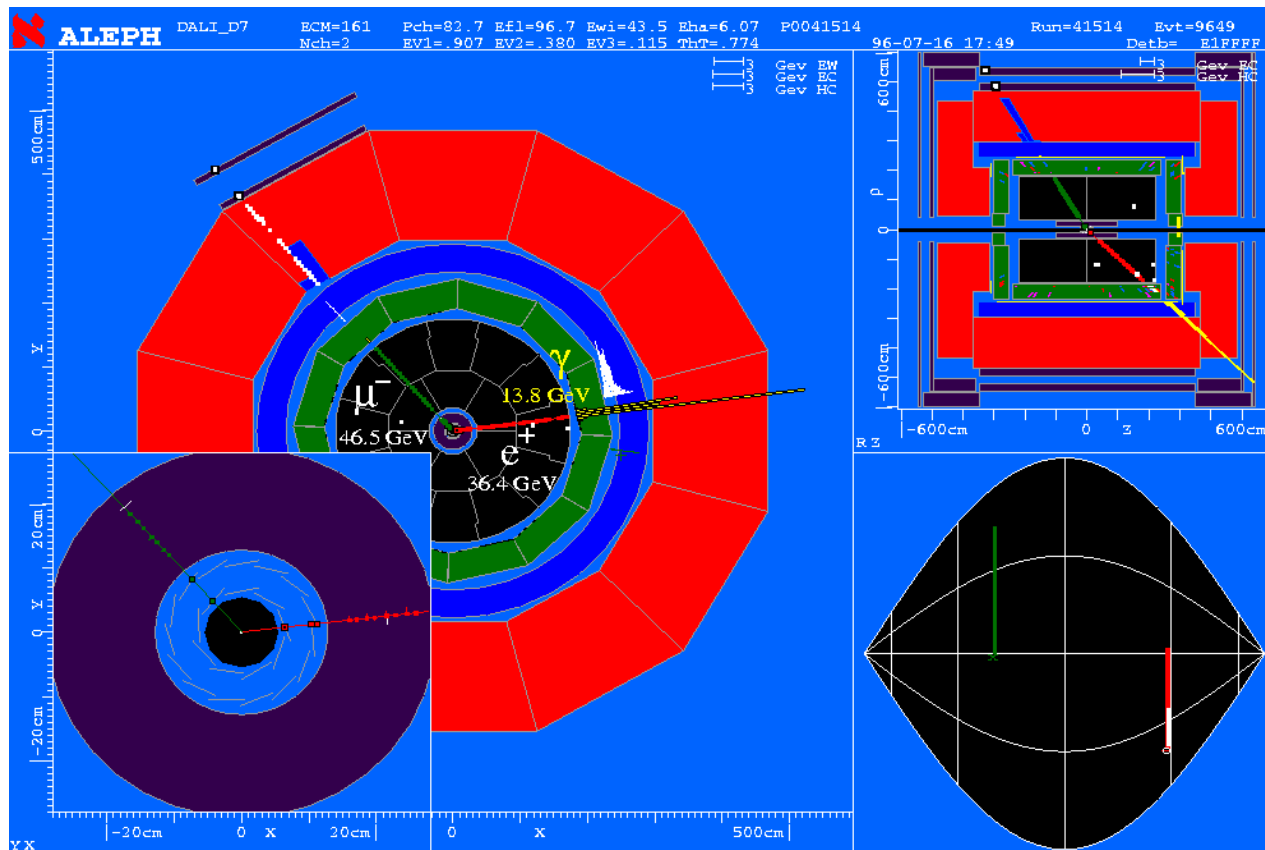
“Did you see it?”

“No nothing.”

“Then it was a neutrino!”

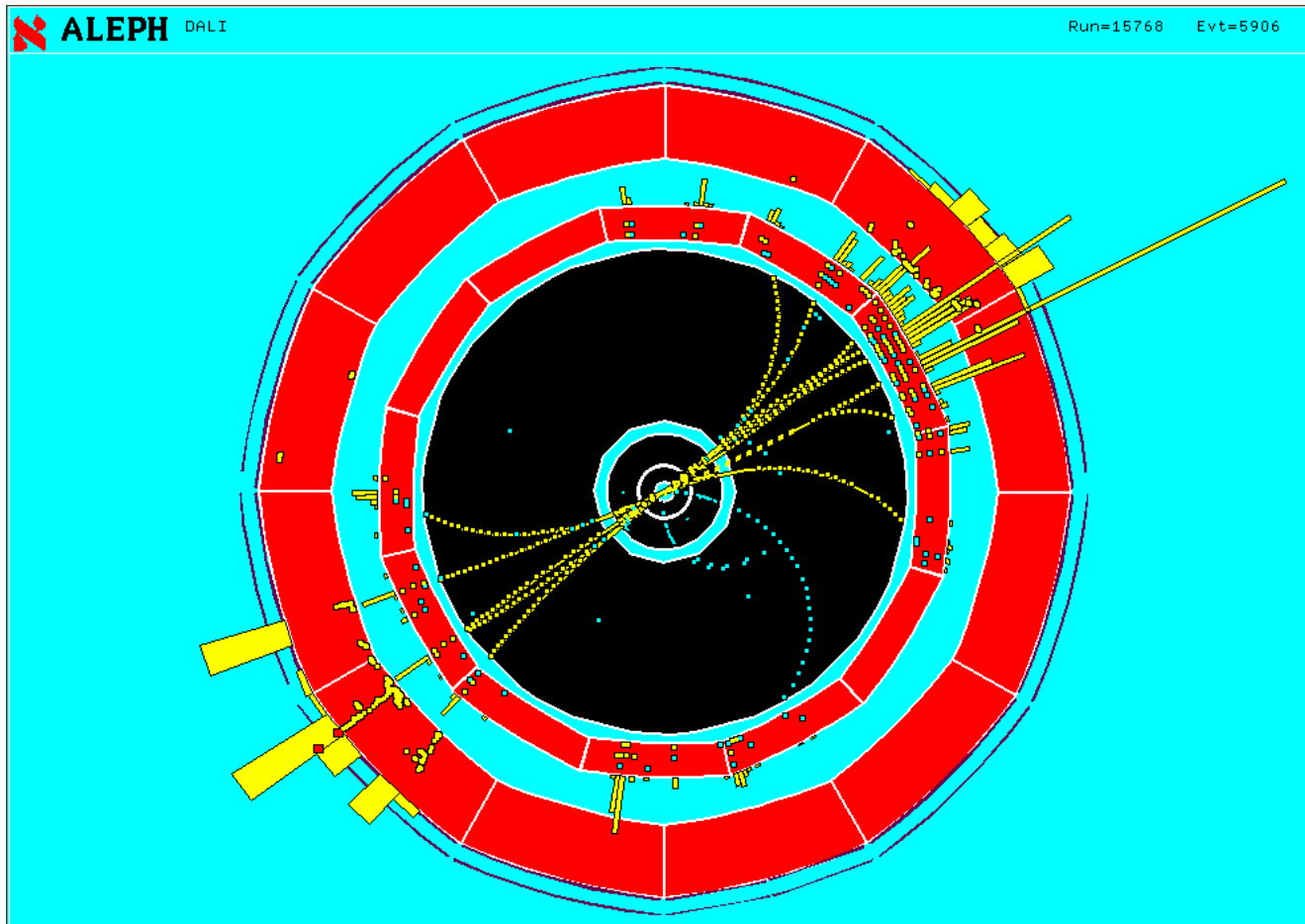
$$W^+W^- \rightarrow e + \mu + \gamma$$

Single electron, single Muon, Missing Momentum



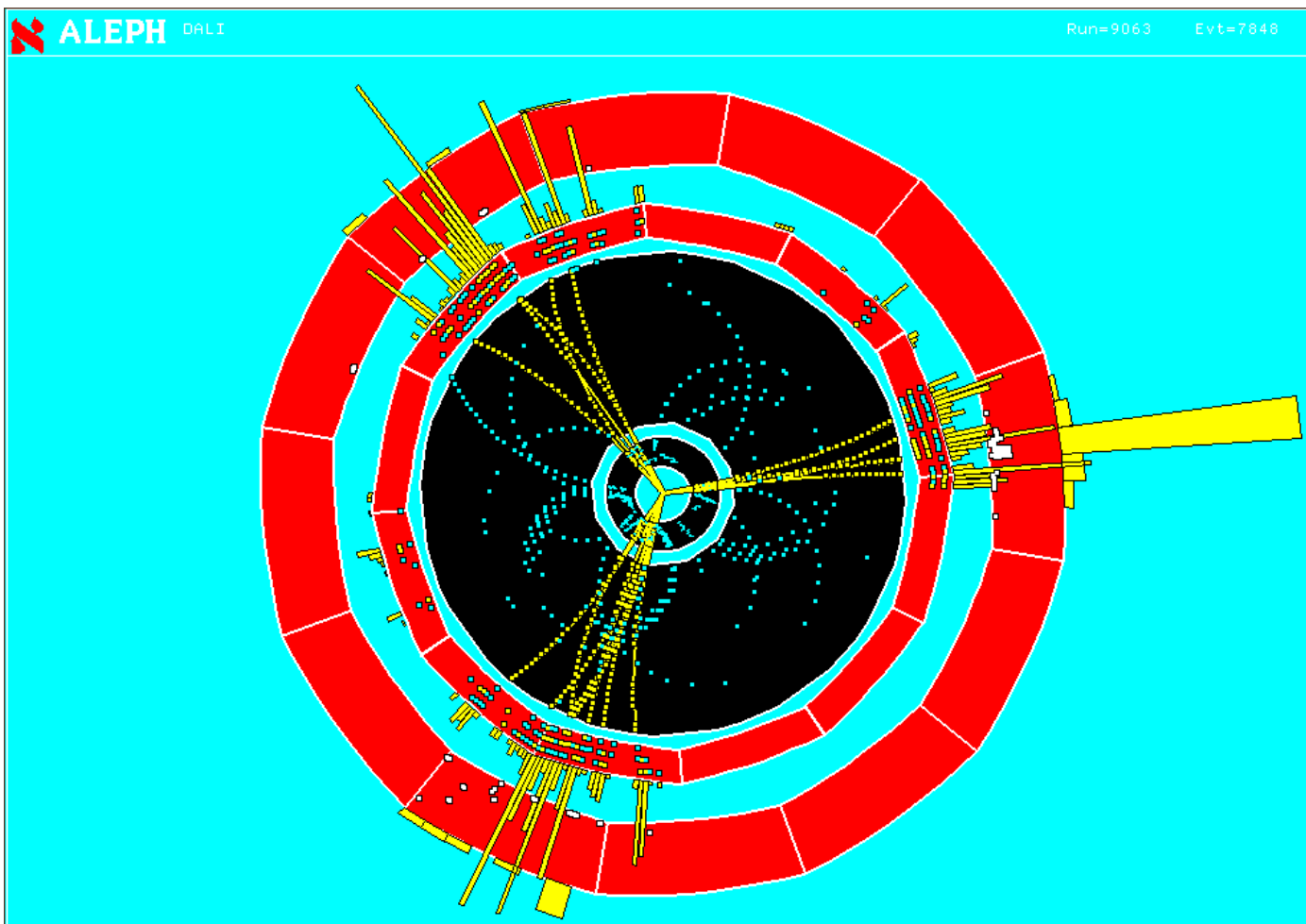
$$Z \rightarrow q \bar{q}$$

Two jets of particles



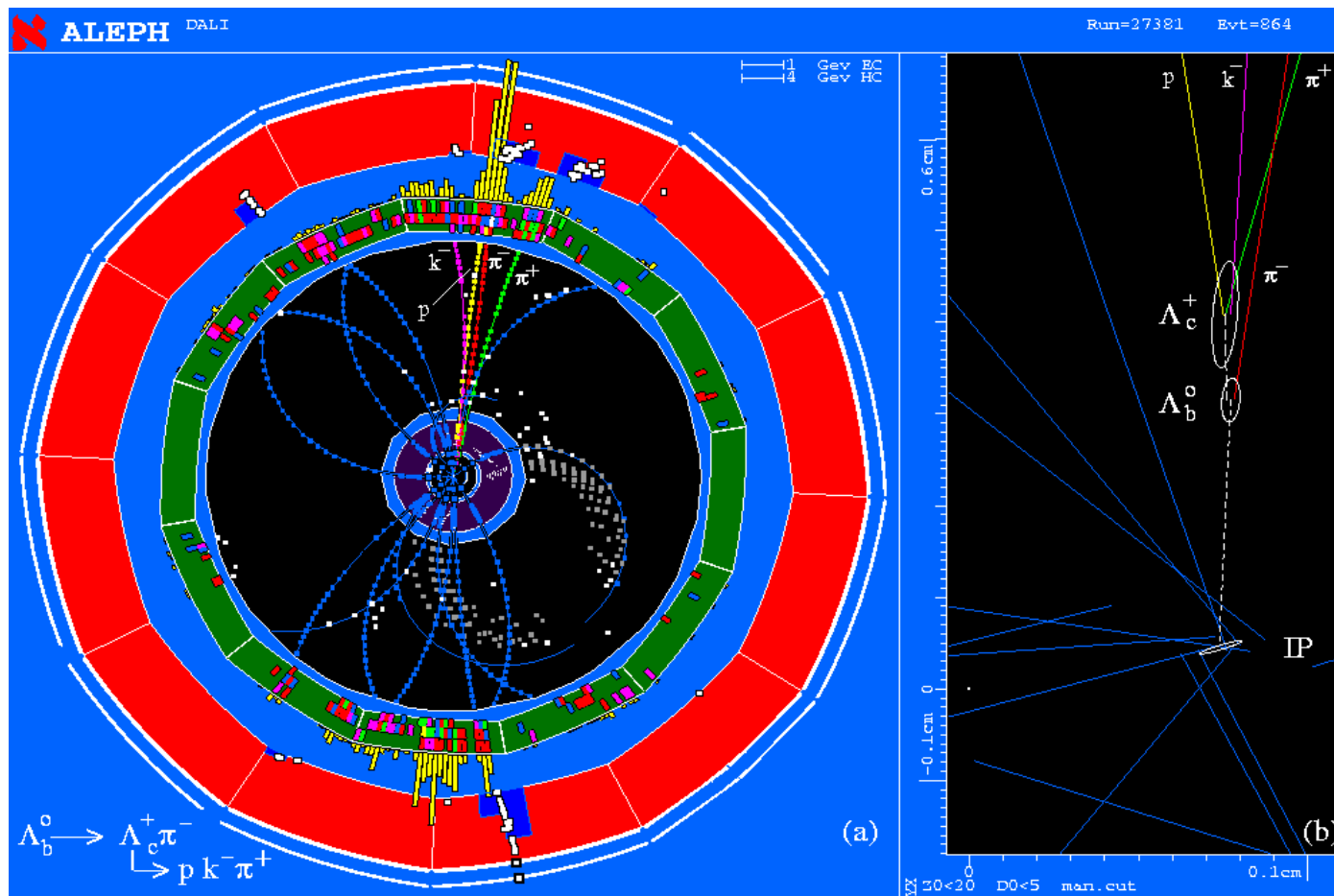
$$Z \rightarrow q \bar{q} g$$

Three jets of particles




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.

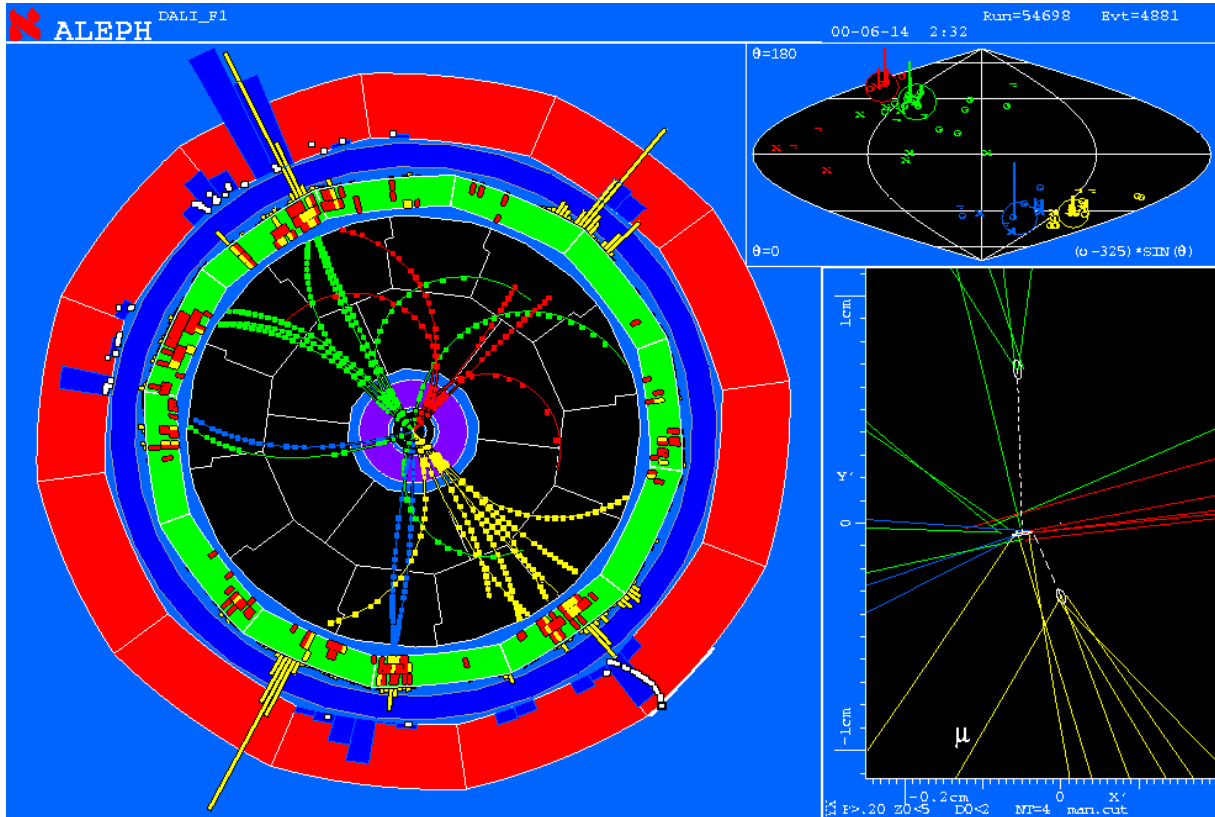


ALEPH Higgs Candidate

$e^+e^- \rightarrow Z + H$
 $L \rightarrow b\bar{b}$
 $L \rightarrow \text{jet} + \text{jet}$

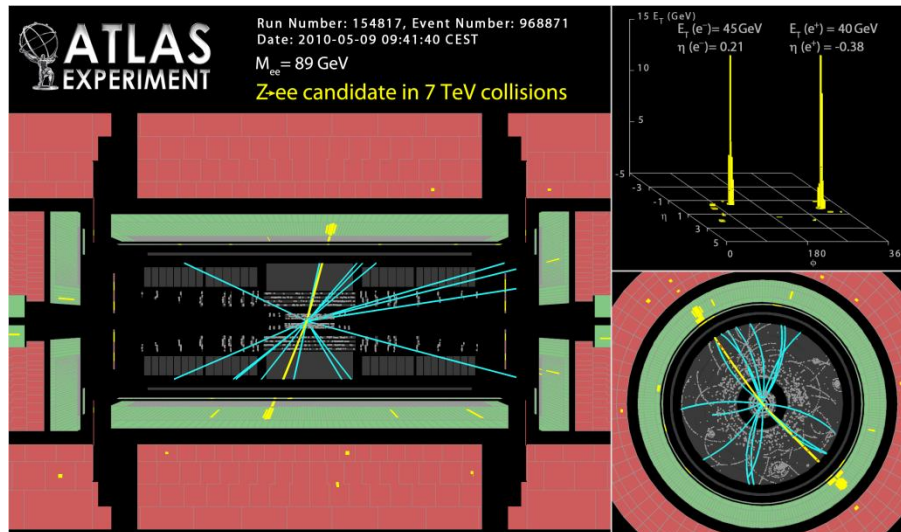
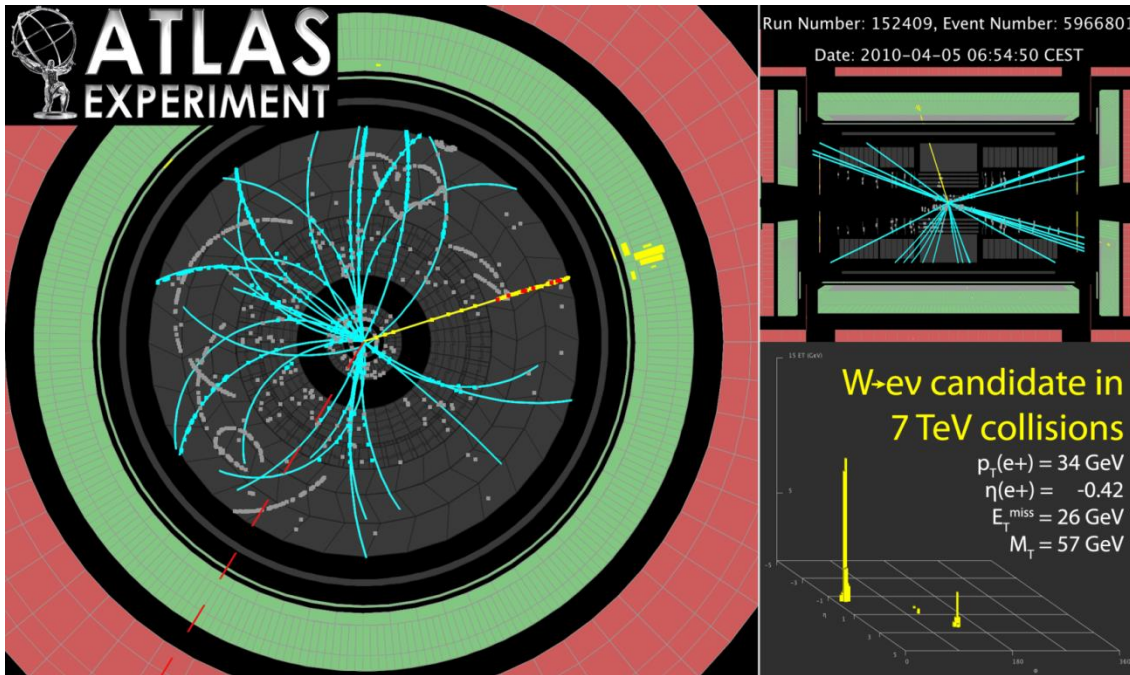


The diagram shows a Z boson decaying into two b quarks (b and b-bar) and a Higgs boson decaying into two jets (jet and anti-jet).

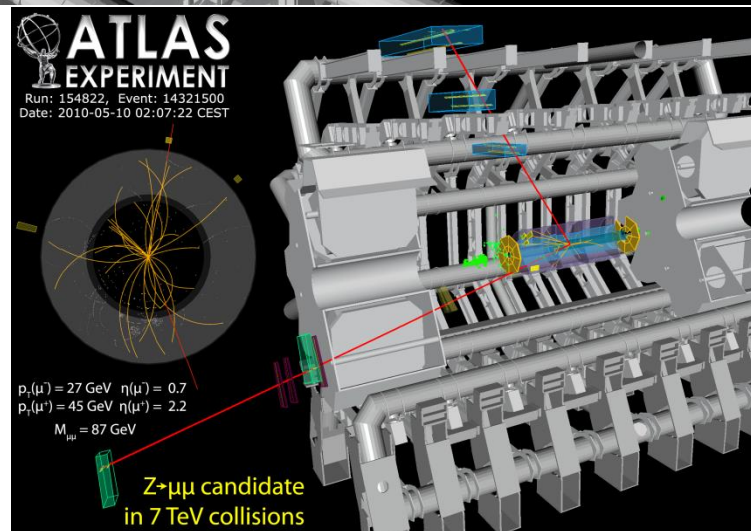
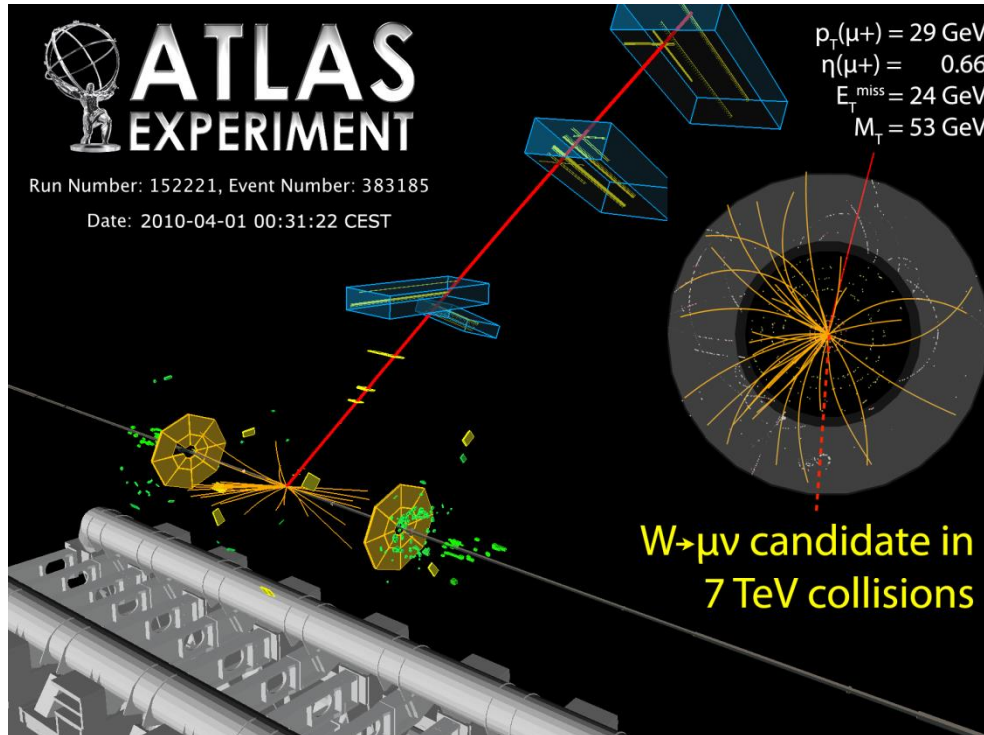


Undistinguishable background exists. Only statistical excess gives signature.

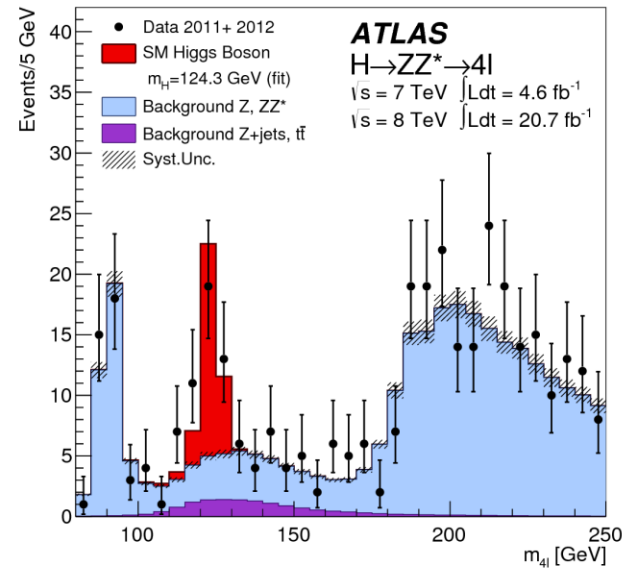
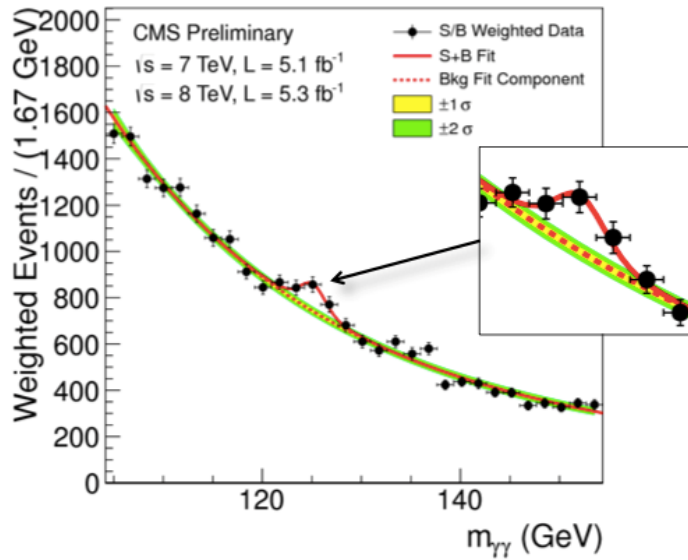
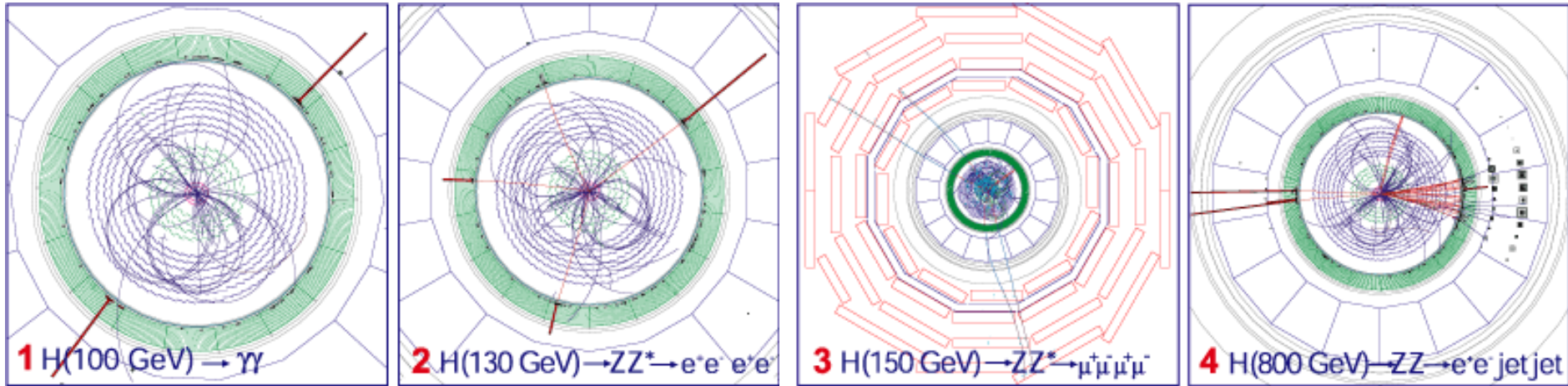
2010 ATLAS W, Z candidates



2010 ATLAS W, Z candidates



Simulated Higgs Boson at CMS



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



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

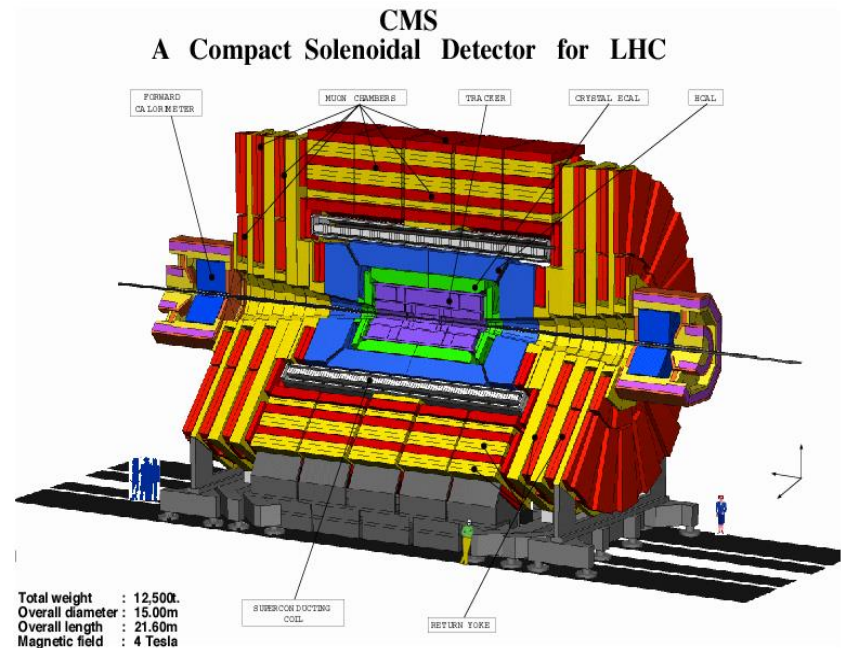
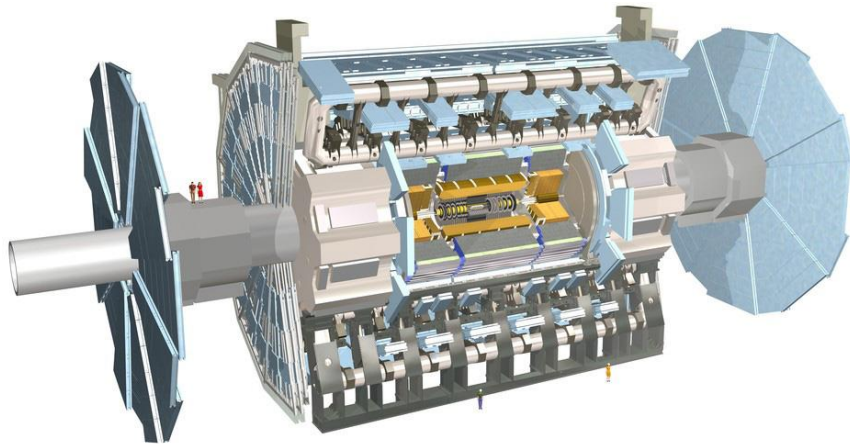
Their difference in mass, charge and interaction is the key to their identification.

Detector Technologies

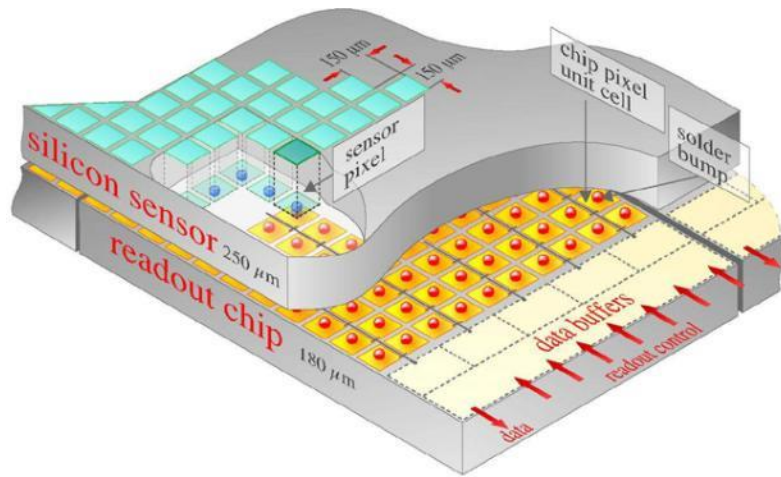
Solid state detectors close to the collision point for excellent position resolution to find vertices and secondary vertices → **silicon pixel detectors**.

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.

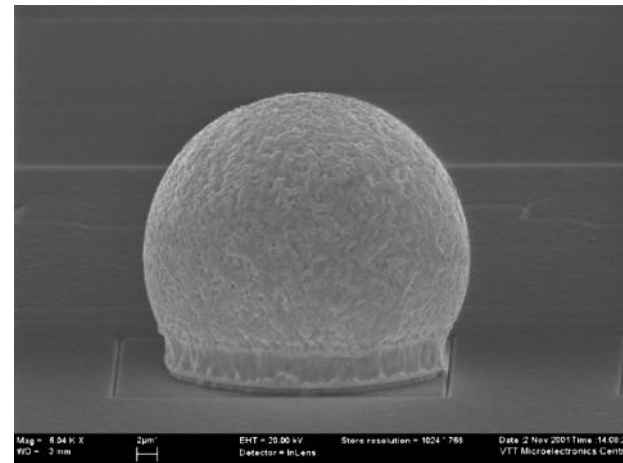
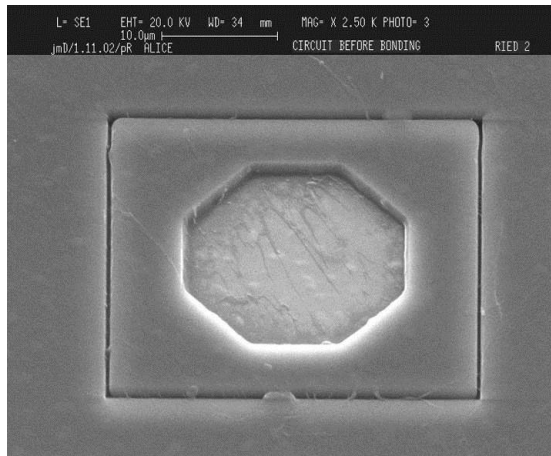


Silicon Pixel Detectors

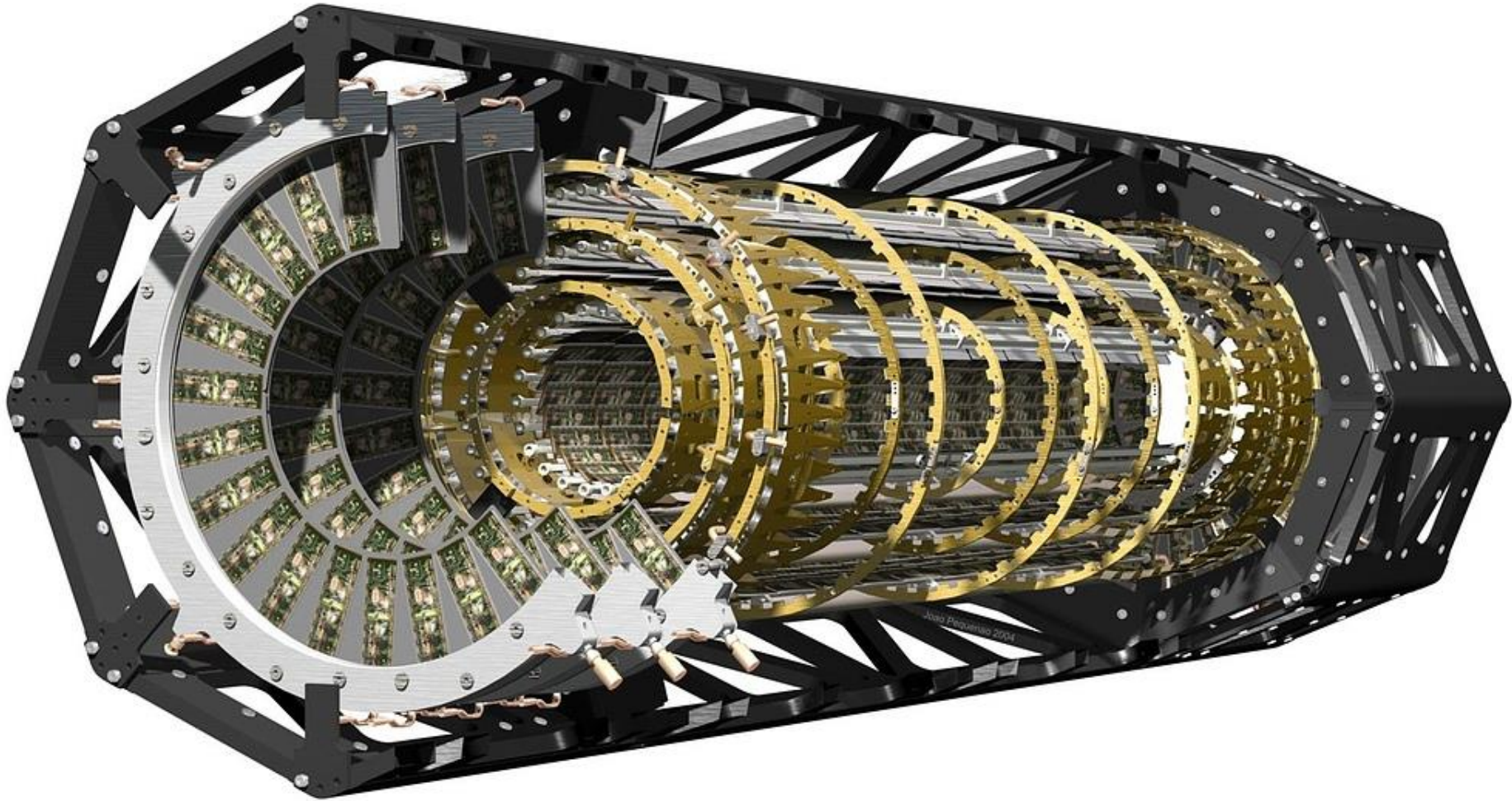


ATLAS: 1.4×10^8 pixels

40 000 000 'images' per second.



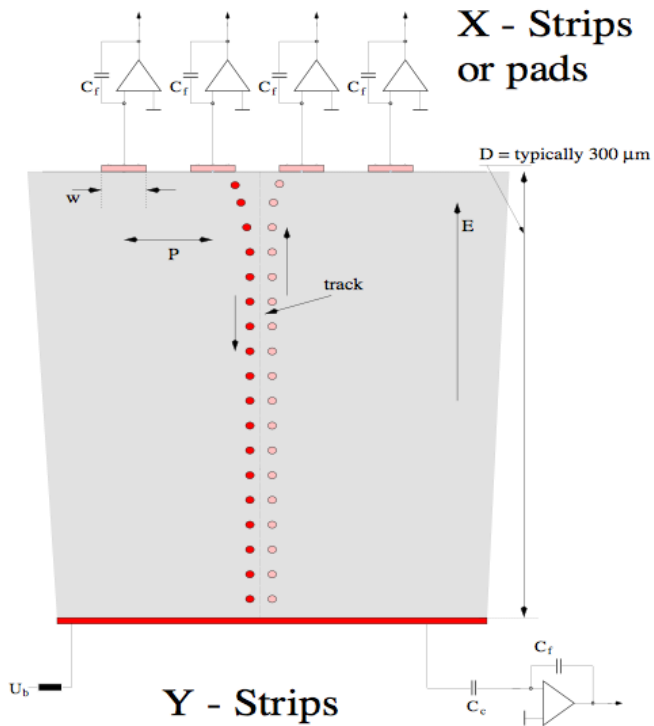
ATLAS Silicon Pixel Detector



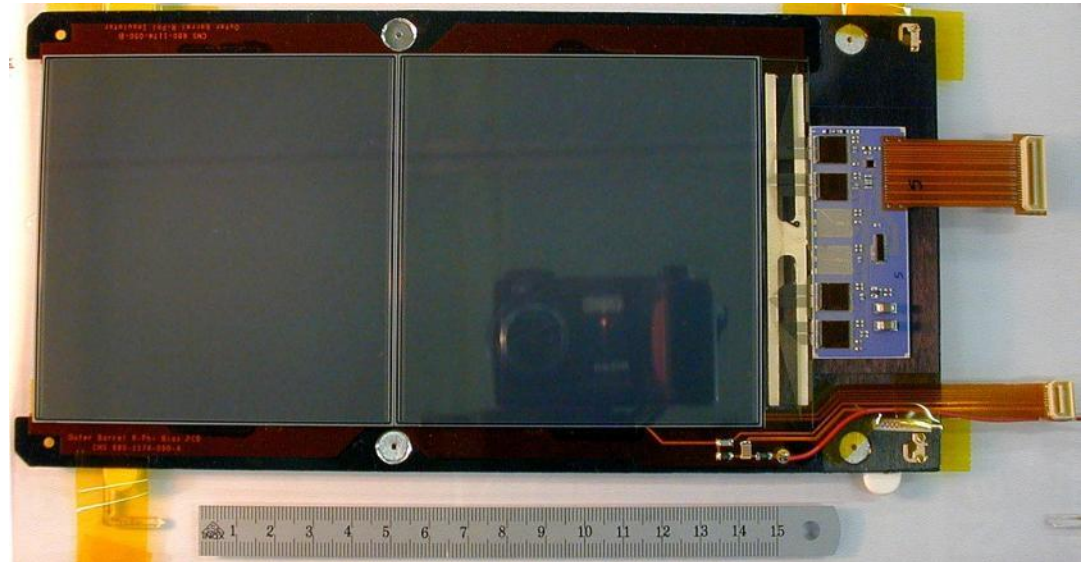
Silicon Strip Detectors

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

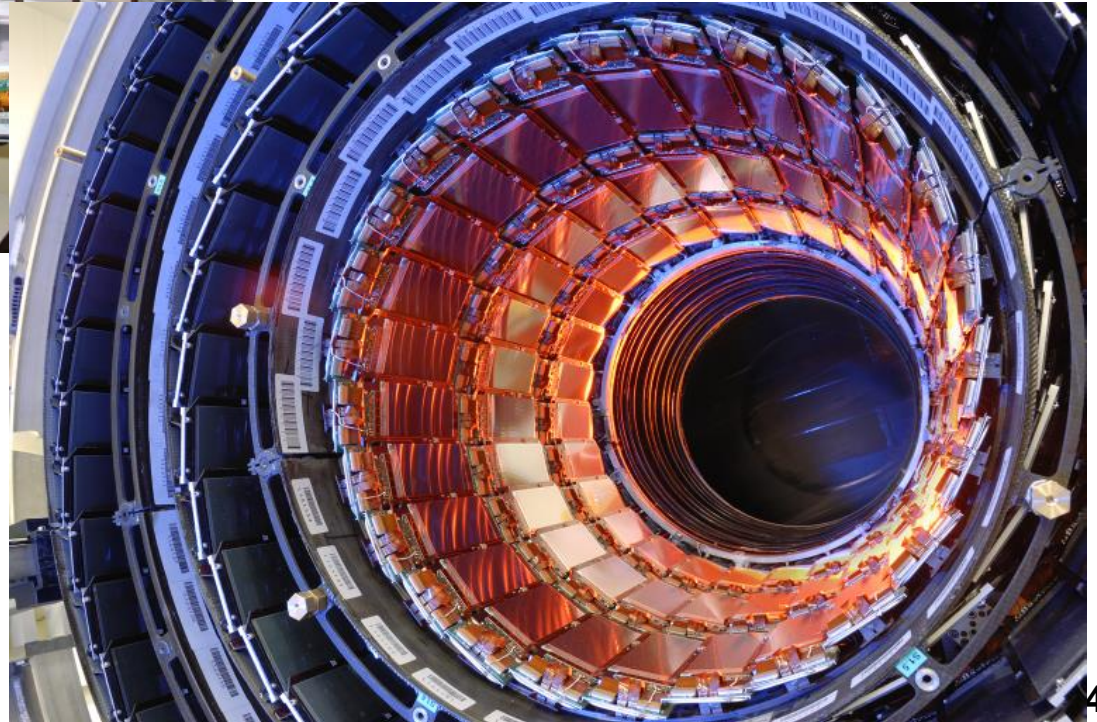
Two dimensional readout is possible.



CMS Outer Barrel Module



Silicon Strip Detectors



Time Projection Chamber (TPC):

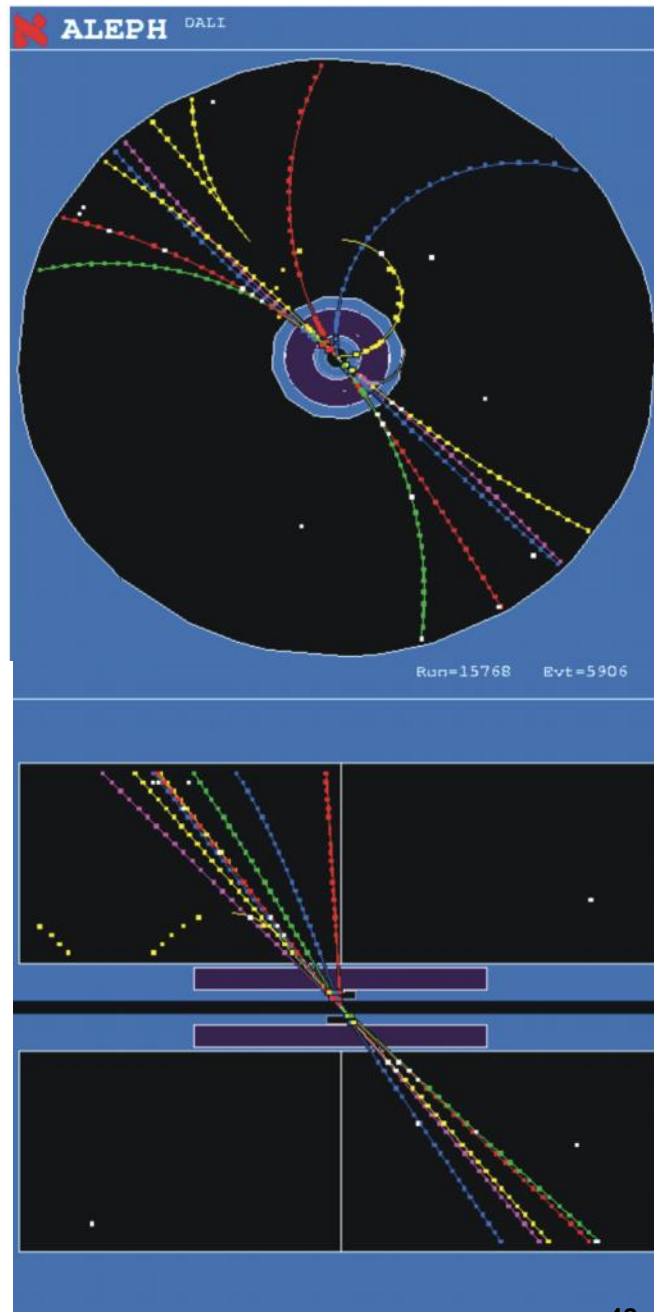
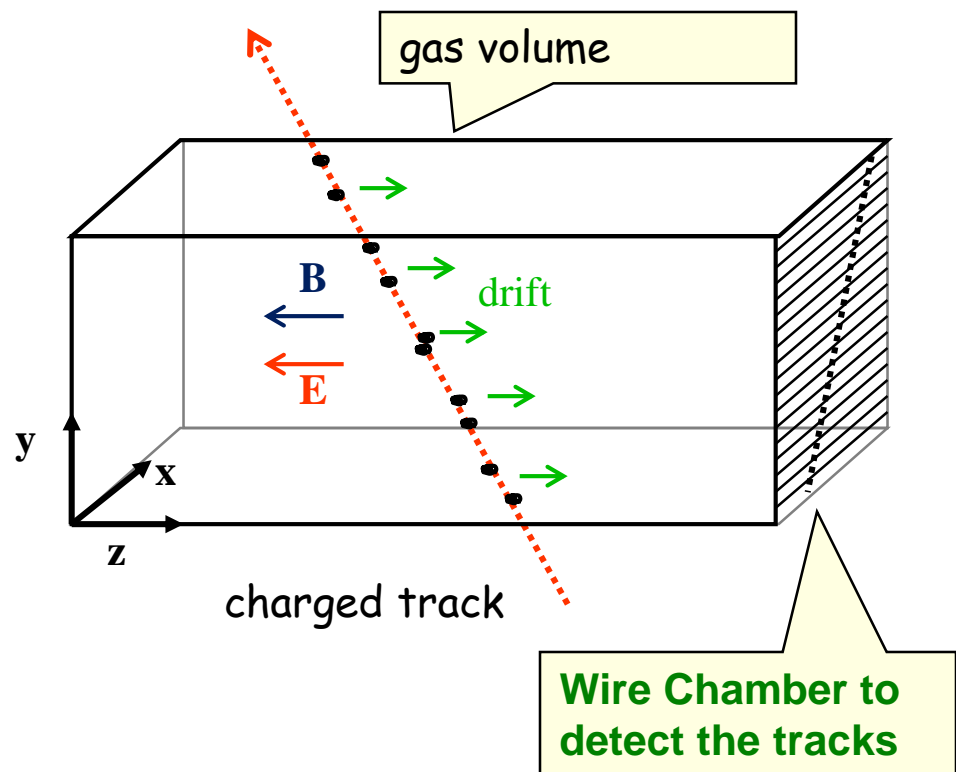
Gas volume with parallel E and B Field.

B for momentum measurement. Positive effect:

Diffusion is strongly reduced by E/B (up to a factor 5).

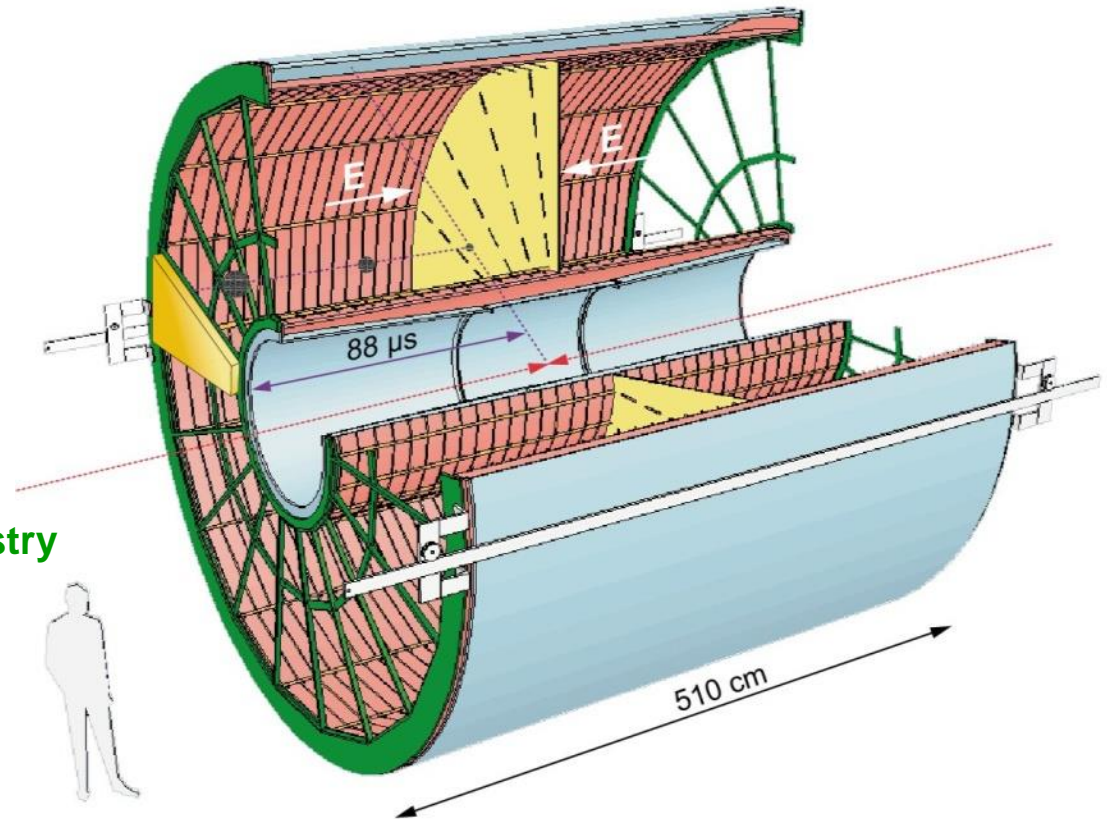
Drift Fields 100-400V/cm. Drift times 10-100 μ s.

Distance up to 2.5m !



ALICE TPC: Construction Parameters

- **Largest TPC:**
 - Length 5m
 - Diameter 5m
 - Volume 88m³
 - Detector area 32m²
 - Channels ~570 000
- **High Voltage:**
 - Cathode -100kV
- **Material X_0**
 - Cylinder from composite materials from airplane industry ($X_0 = \sim 3\%$)



ALICE TPC: Pictures of the Construction

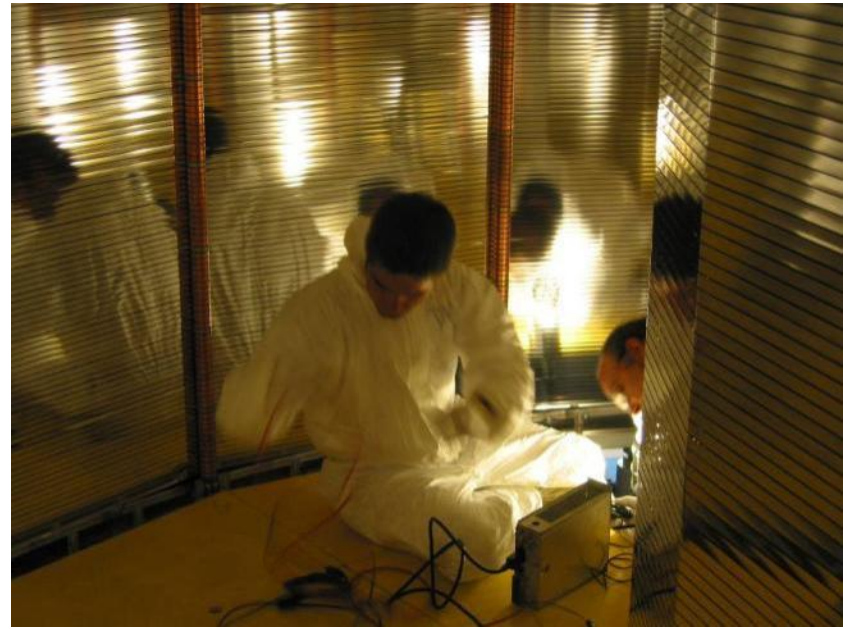
Precision in z: 250 μ m



End plates 250 μ m



Wire chamber: 40 μ m



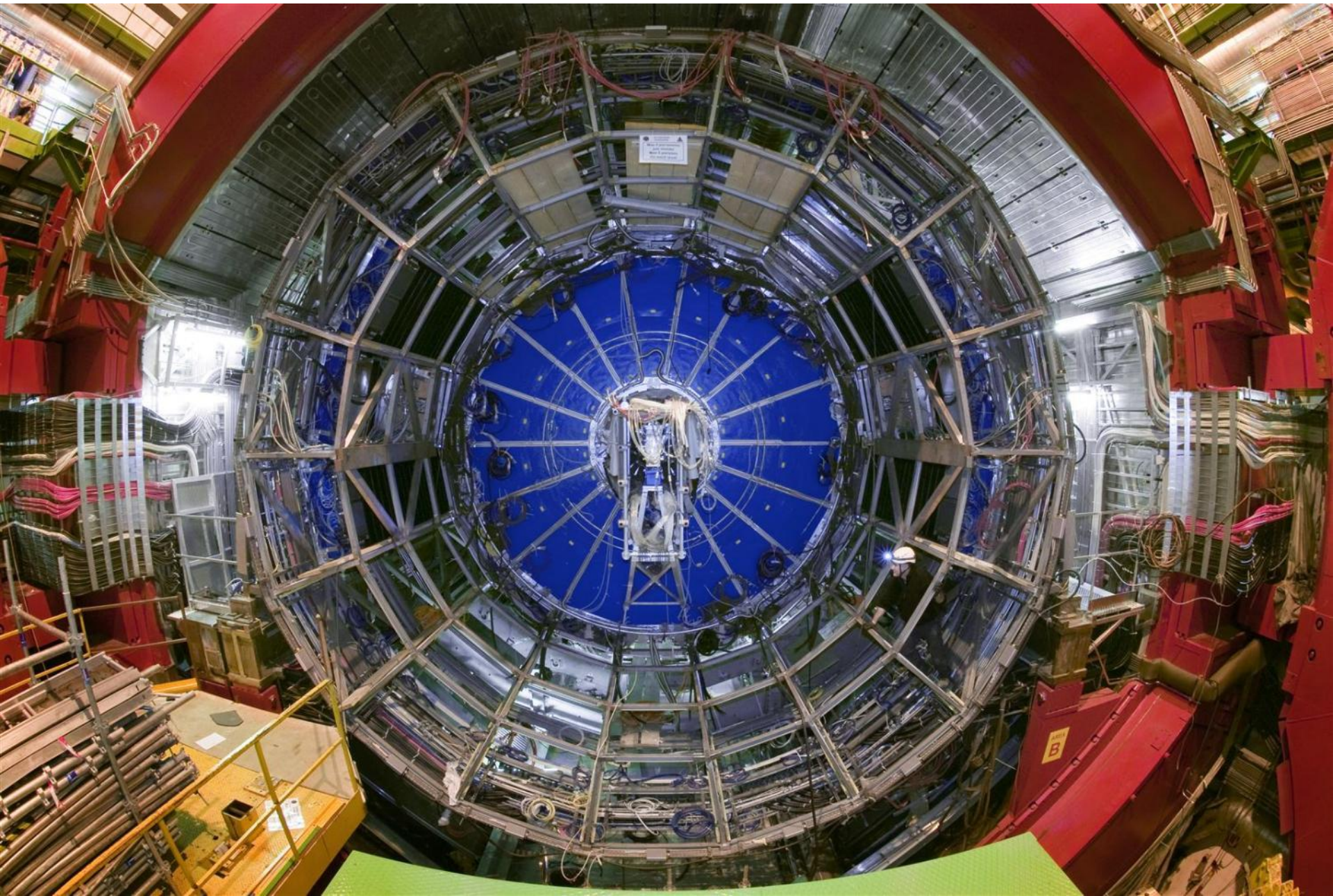
ALICE TPC Construction

My personal contribution:

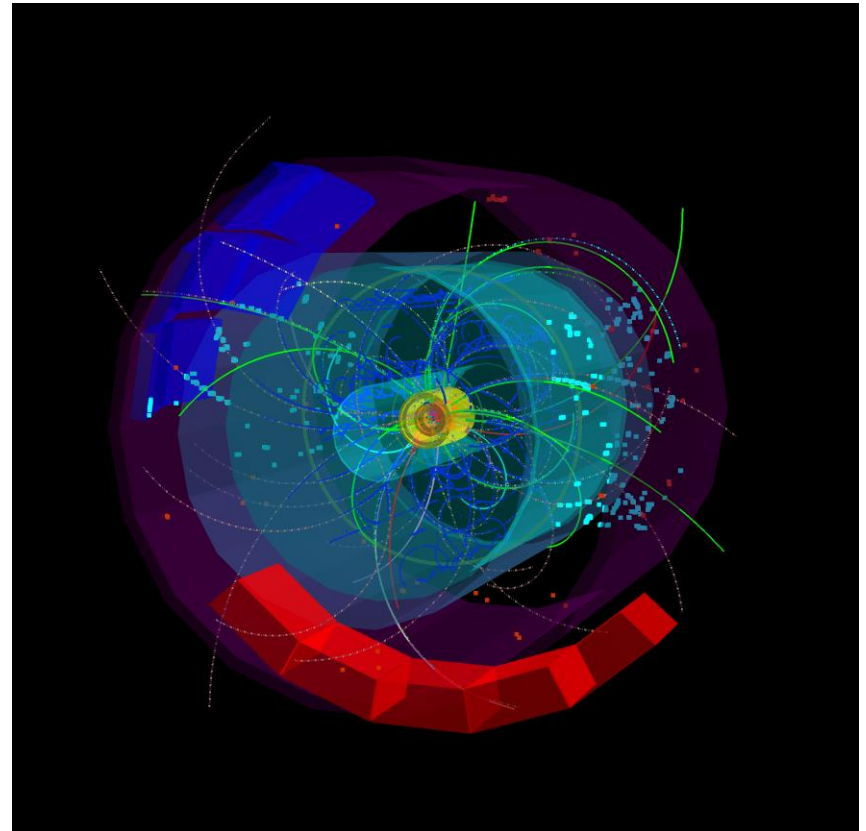
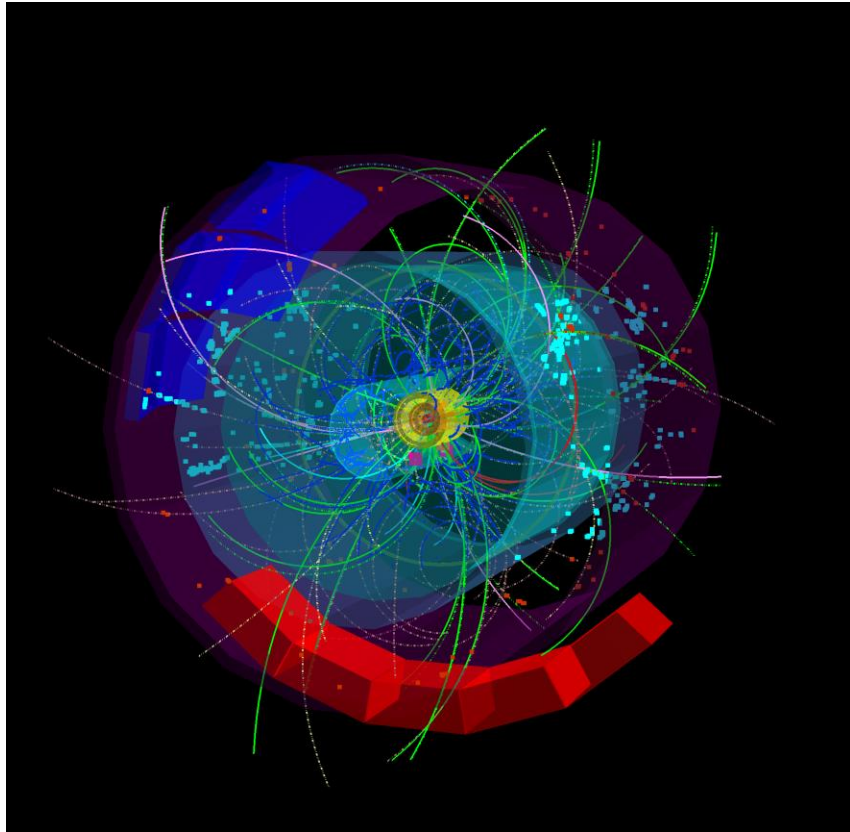
A visit inside the TPC.



TPC installed in the ALICE Experiment

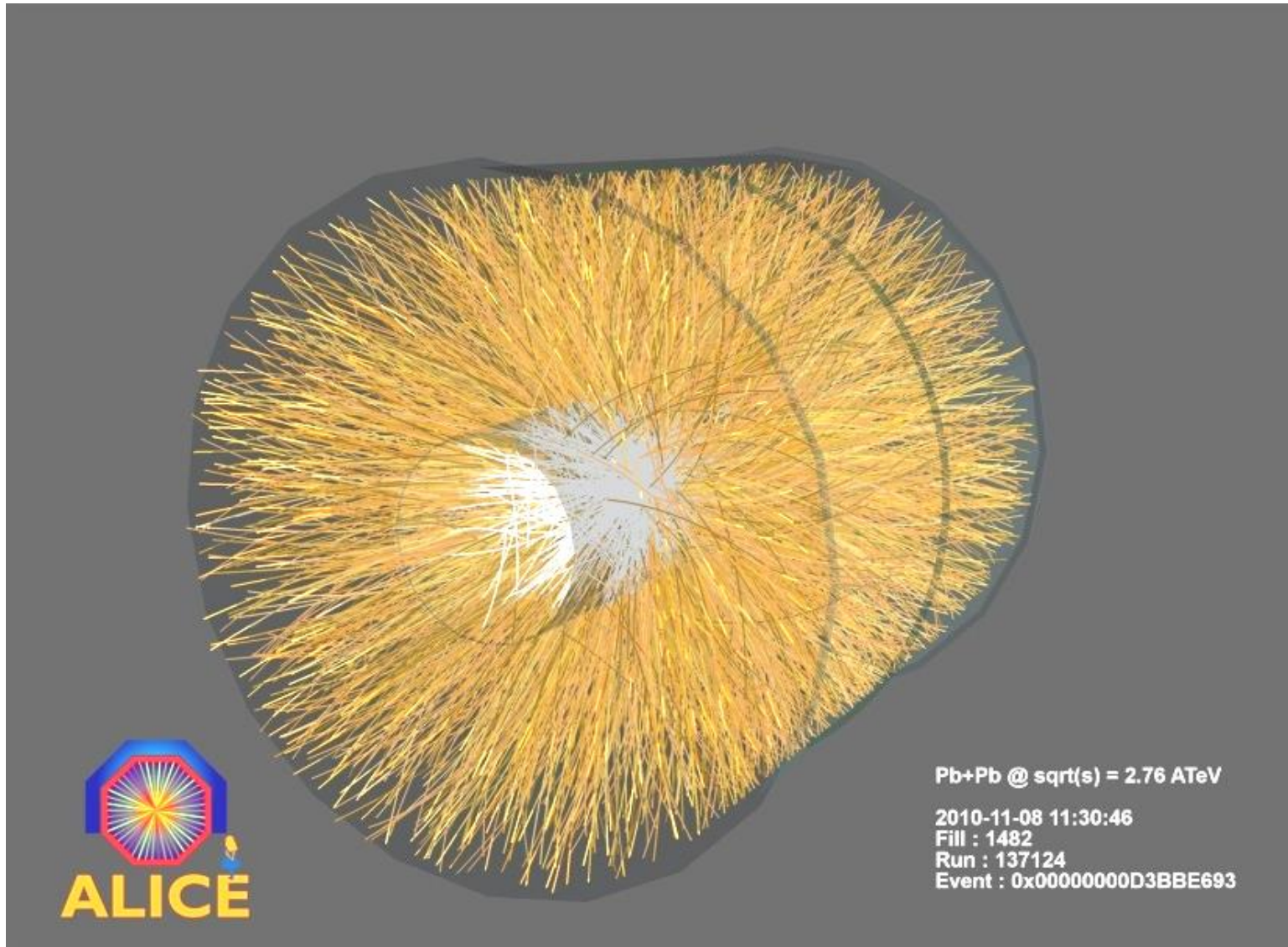


First 7 TeV p-p Collisions in the ALICE TPC in March 2010 !



8/14/2017

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

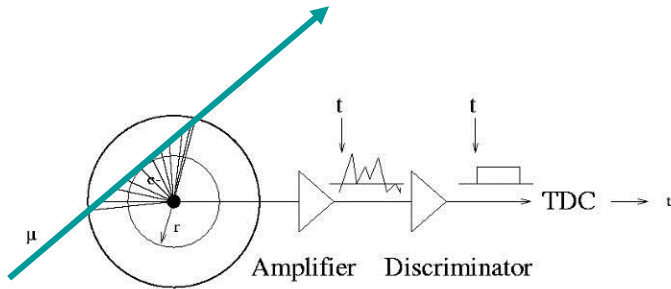


8/14/2017

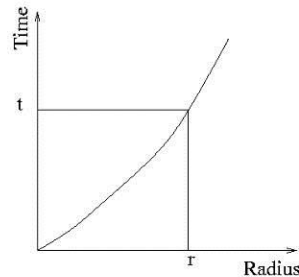
The Geiger Counter reloaded: Drift Tube

Primary electrons are drifting to the wire.

ATLAS MDT R(tube) = 15mm



Calibrated Radius-Time correlation

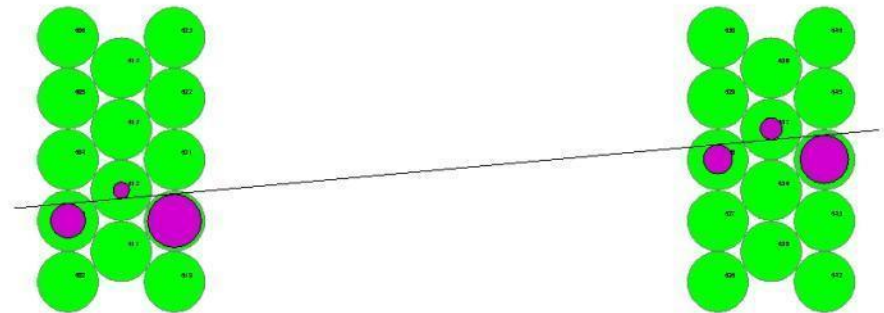
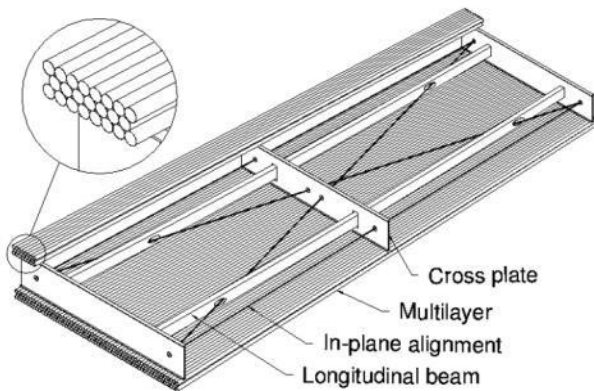


Electron avalanche at the wire.

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, 80 μ m per tube

The Geiger counter reloaded: Drift Tube

Atlas Muon Spectrometer, 44m long, from $r=5$ to 11m.

1200 Chambers

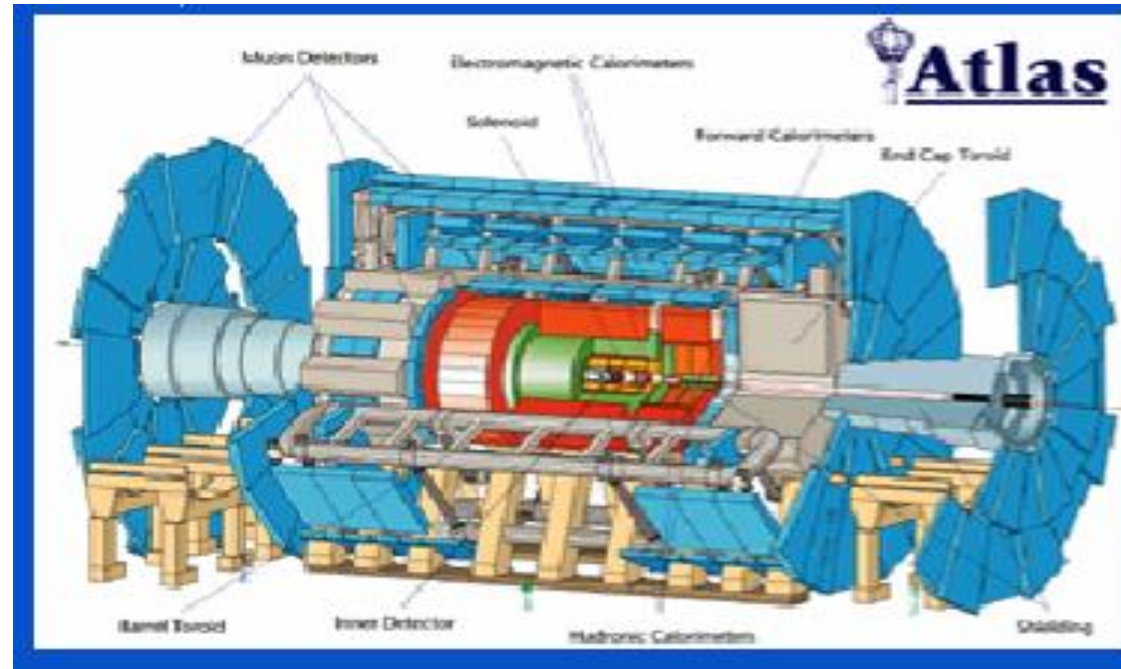
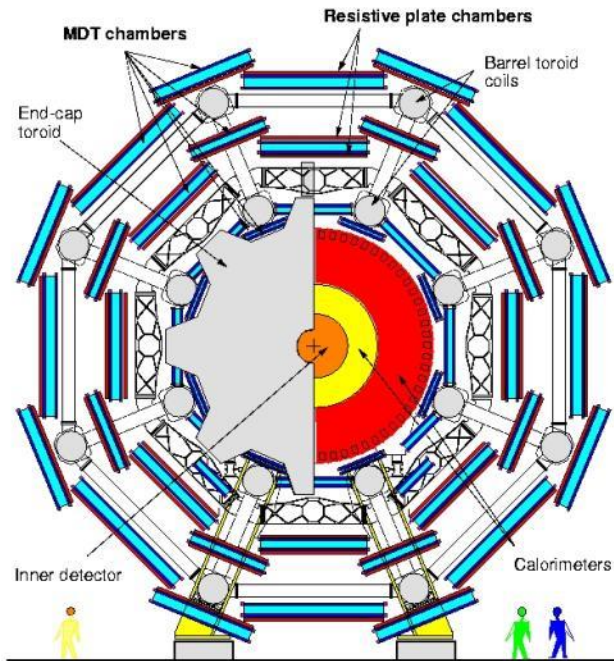
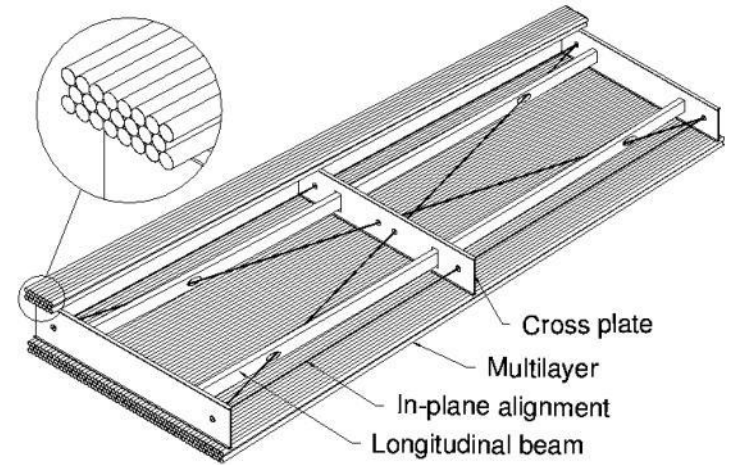
6 layers of 3cm tubes per chamber.

Length of the chambers 1-6m !

Position resolution: $80\mu\text{m}/\text{tube}$, $<50\mu\text{m}/\text{chamber}$ (3 bar)

Maximum drift time $\approx 700\text{ns}$

Gas Ar/CO₂ 93/7



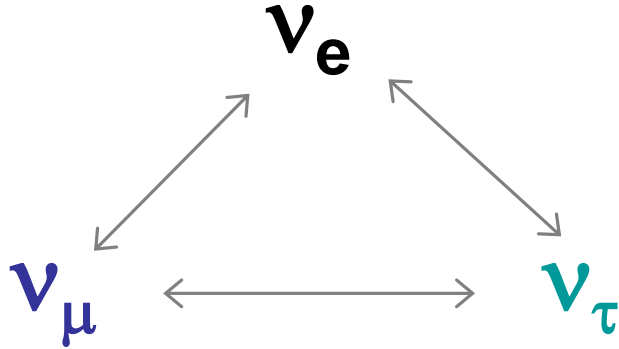
Detector Systems

CERN Neutrino Gran Sasso

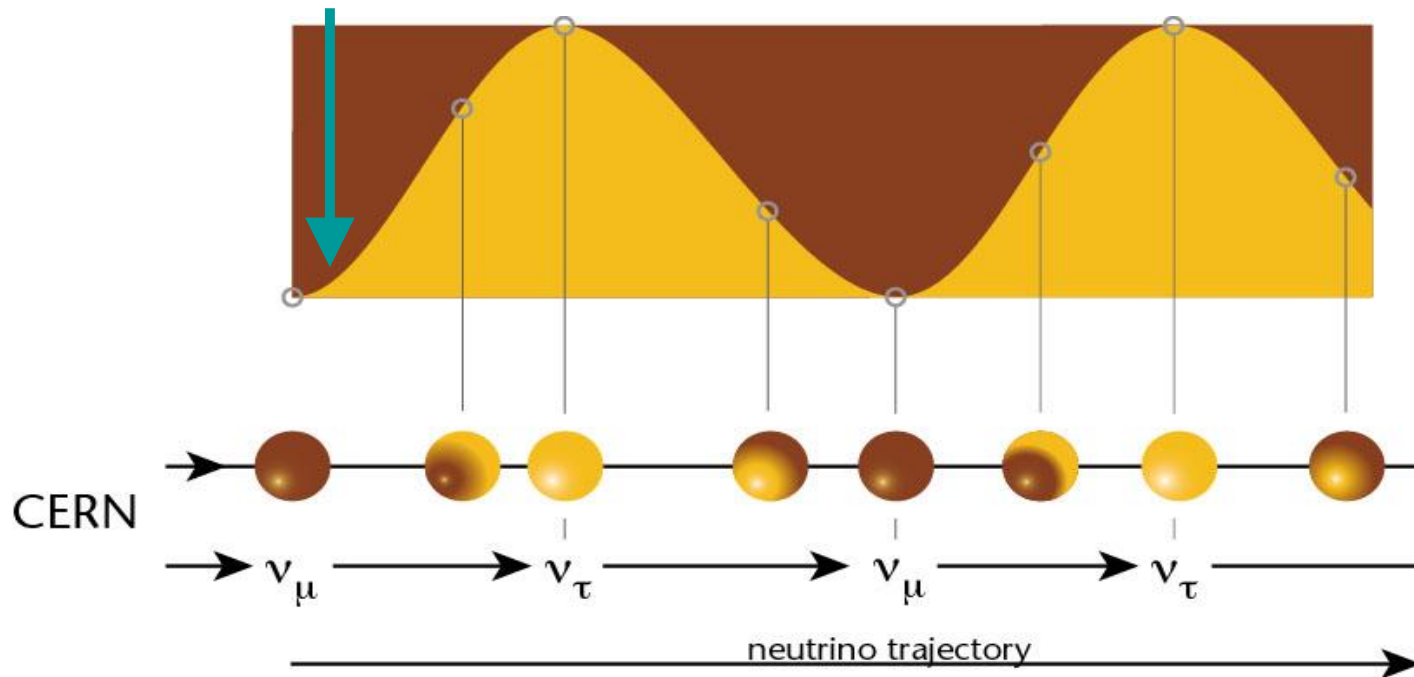
(CNGS)

CNGS

If neutrinos have mass:



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



CNGS Project

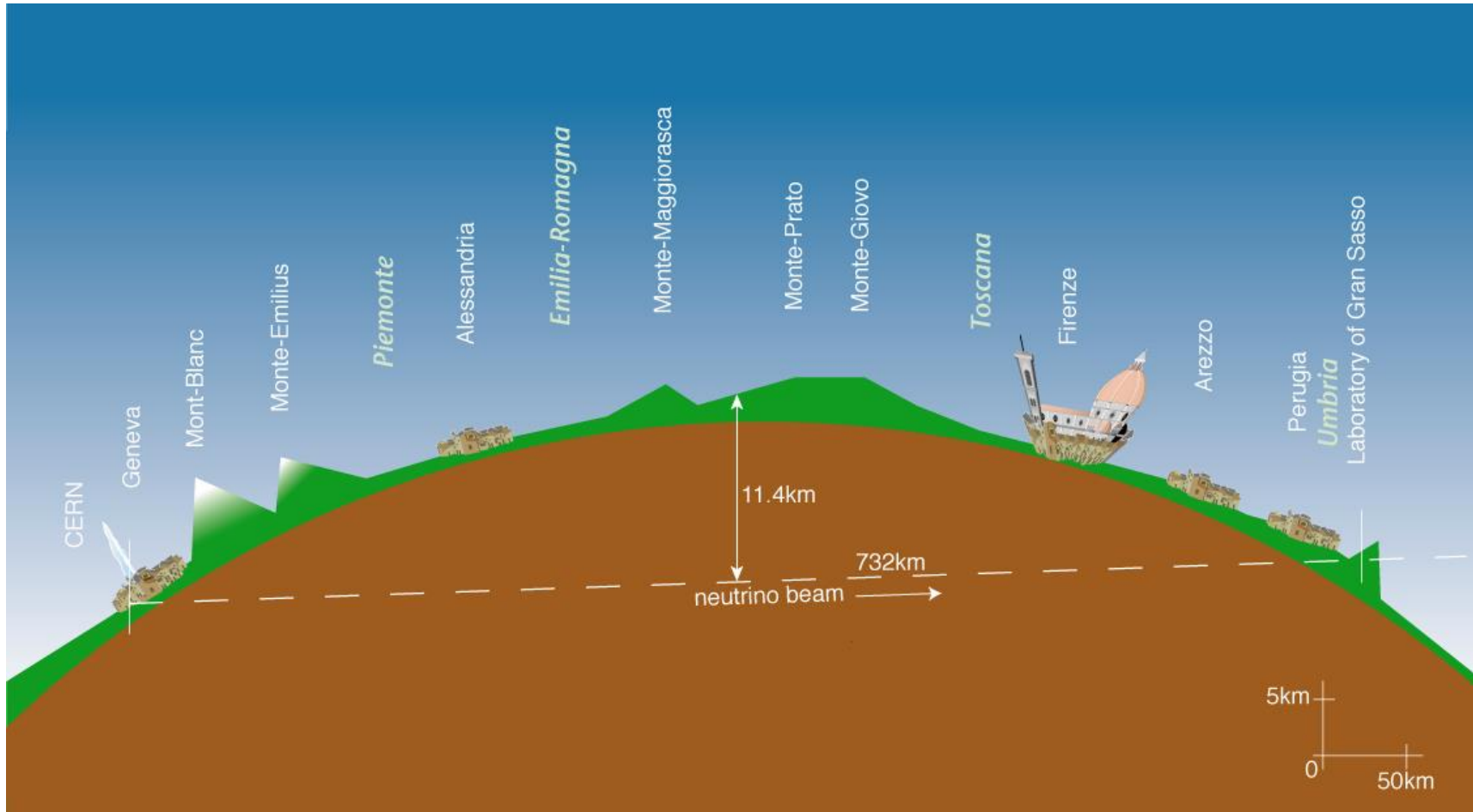
CNGS (CERN Neutrino Gran Sasso)

- 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

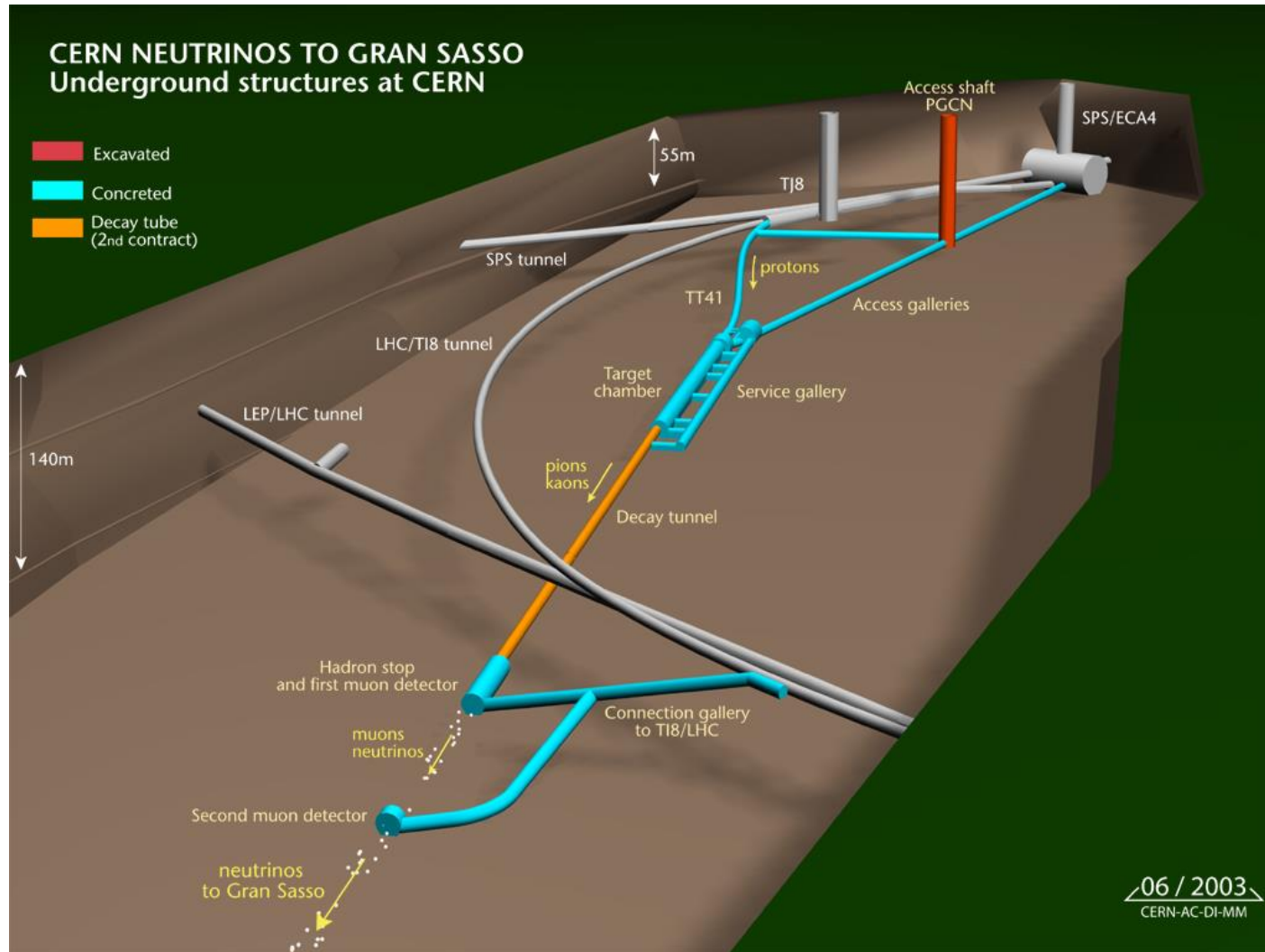


➔ direct proof of ν_{μ} - ν_{τ} oscillation (appearance experiment)

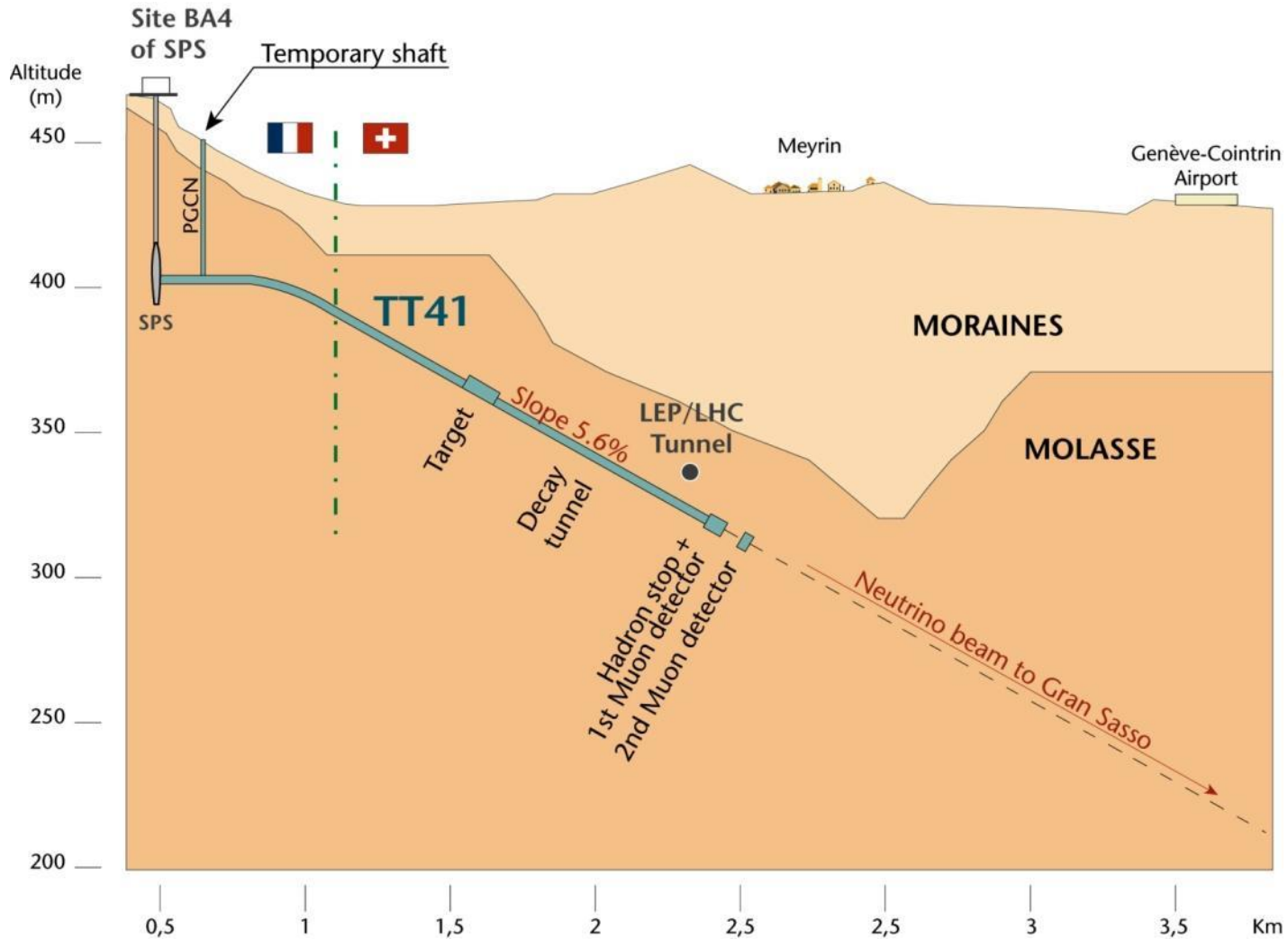
CNGS



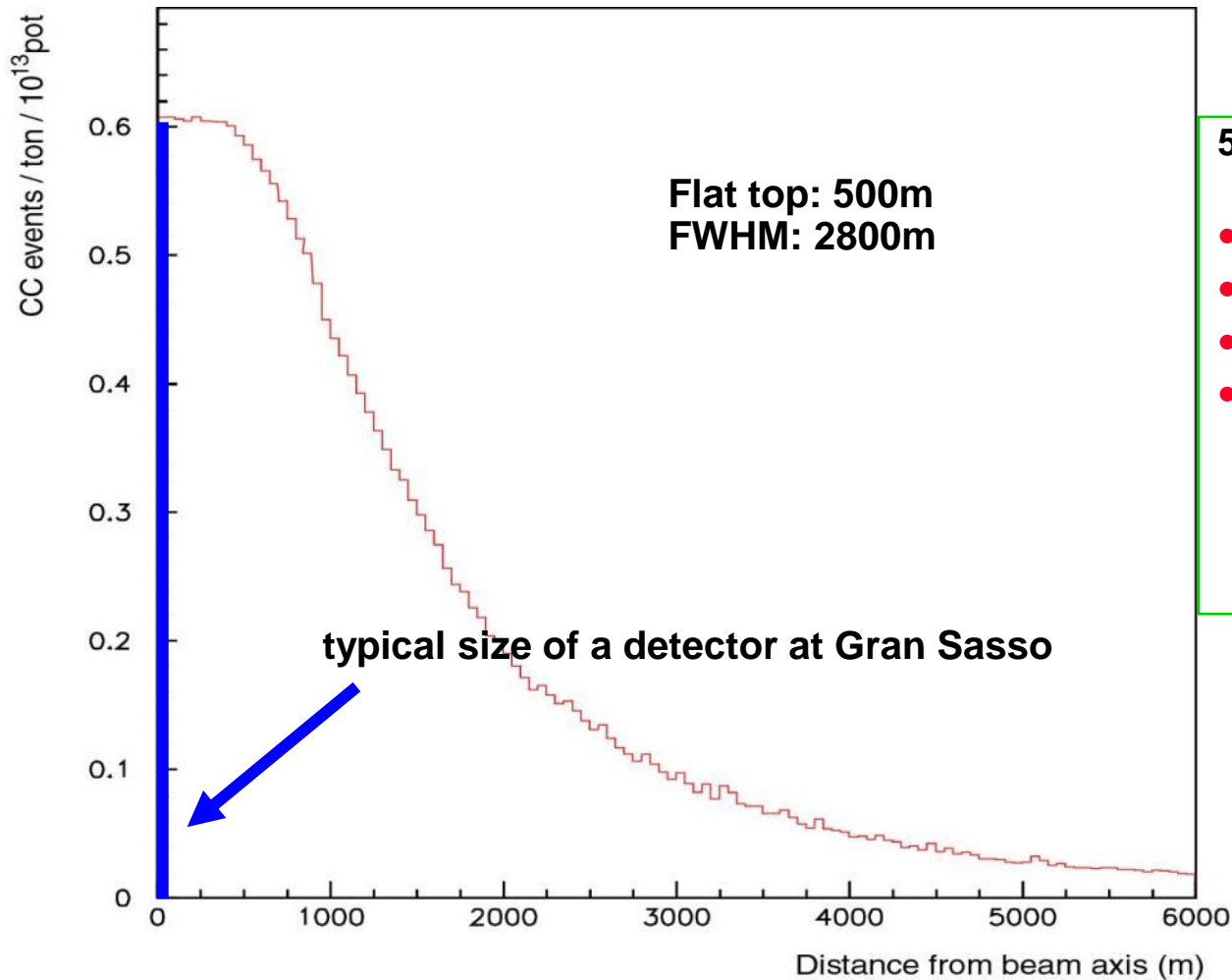
CNGS



CNGS



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}	
N_{μ} events per day in OPERA	≈ 2500	
N_{τ} events (from oscillation)	≈ 2	

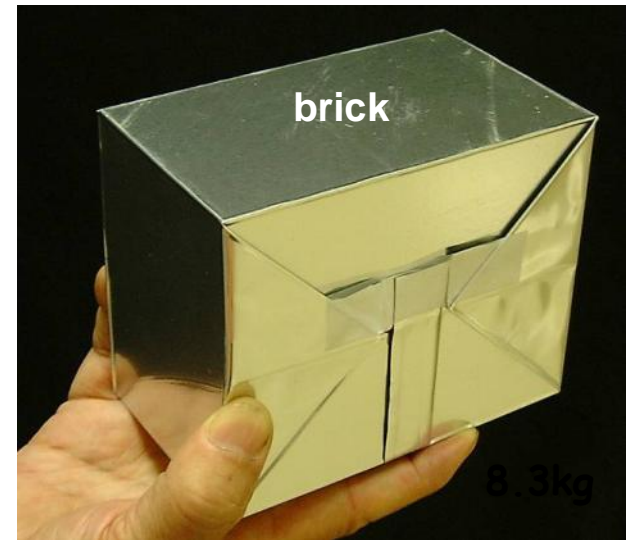
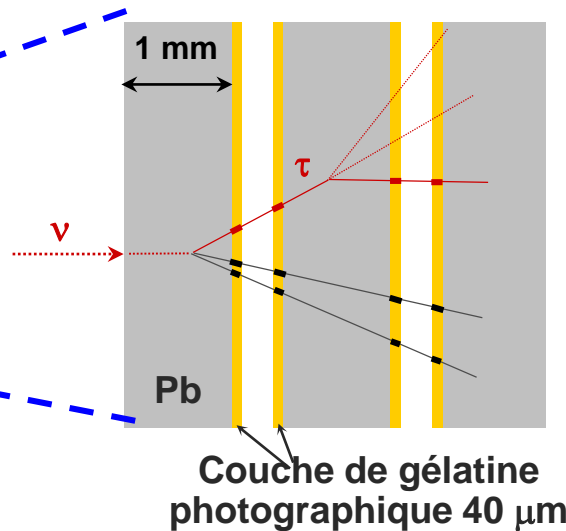
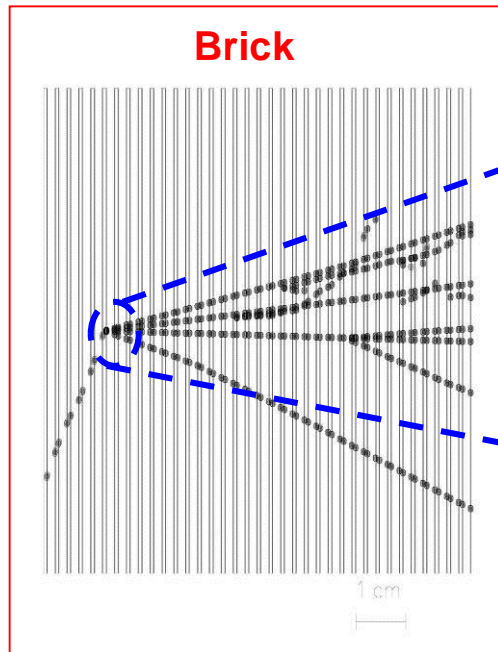
Opera Experiment at Gran Sasso

Basic unit: brick

56 Pb sheets + 56 photographic films (emulsion sheets)

Lead plates: massive target

Emulsions: micrometric precision

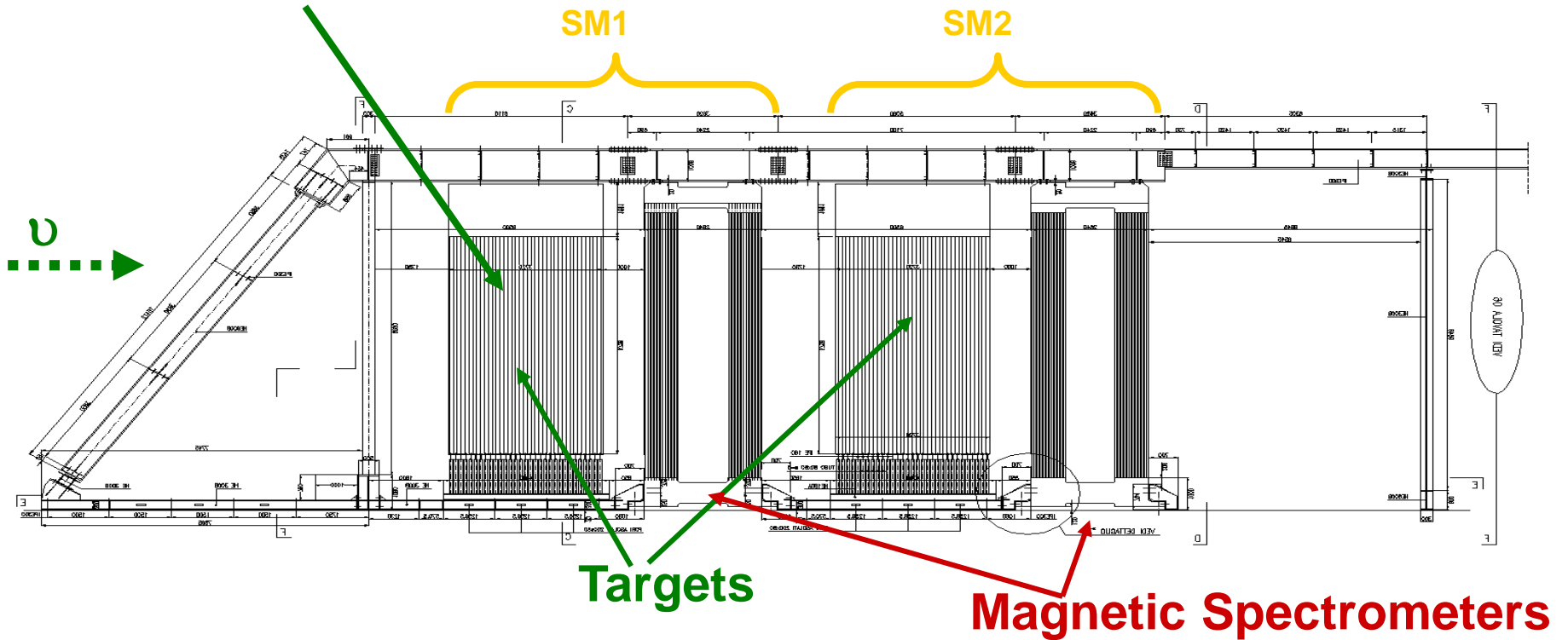


10.2 x 12.7 x 7.5 cm³

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

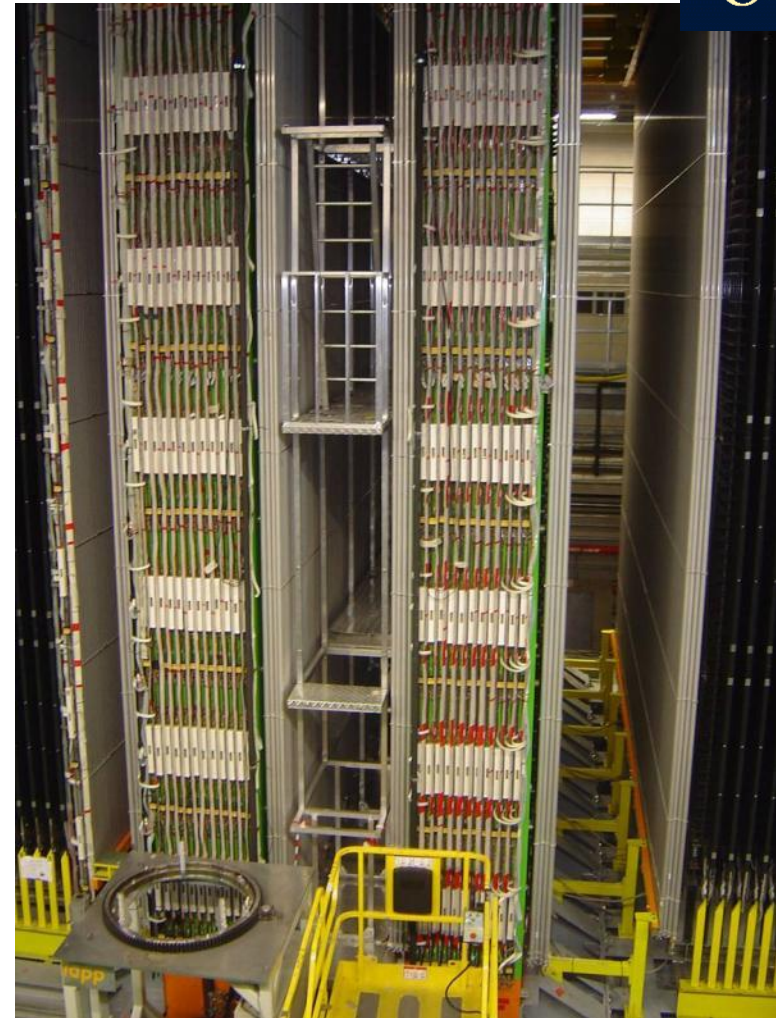


Second Super-module



Scintillator planes 5900 m²
8064 7m long drift tubes

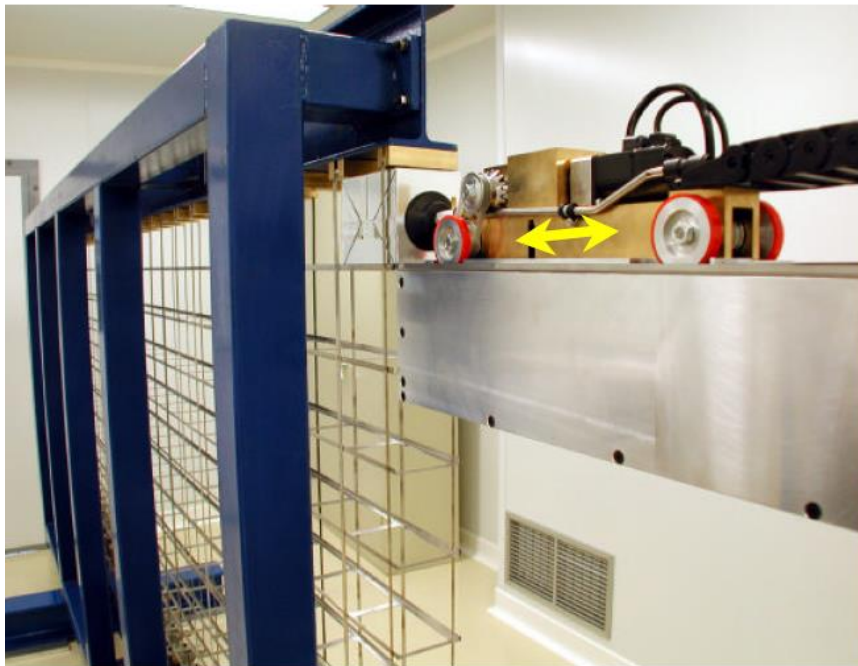
Details of the first spectrometer



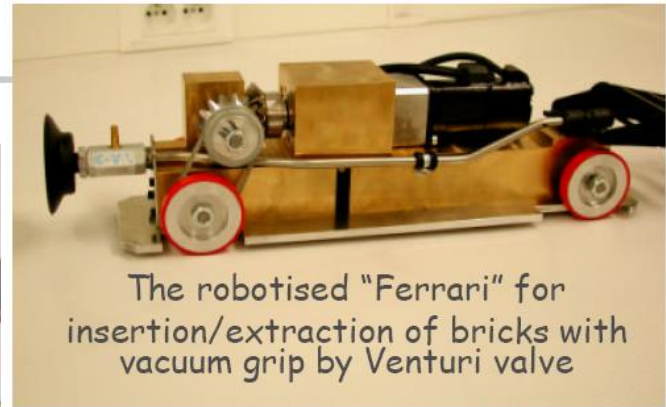
3050 m² Resistive Plate Counters
2000 tons of iron for the two magnets

Opera Experiment at Gran Sasso

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



Tests with the prototype wall

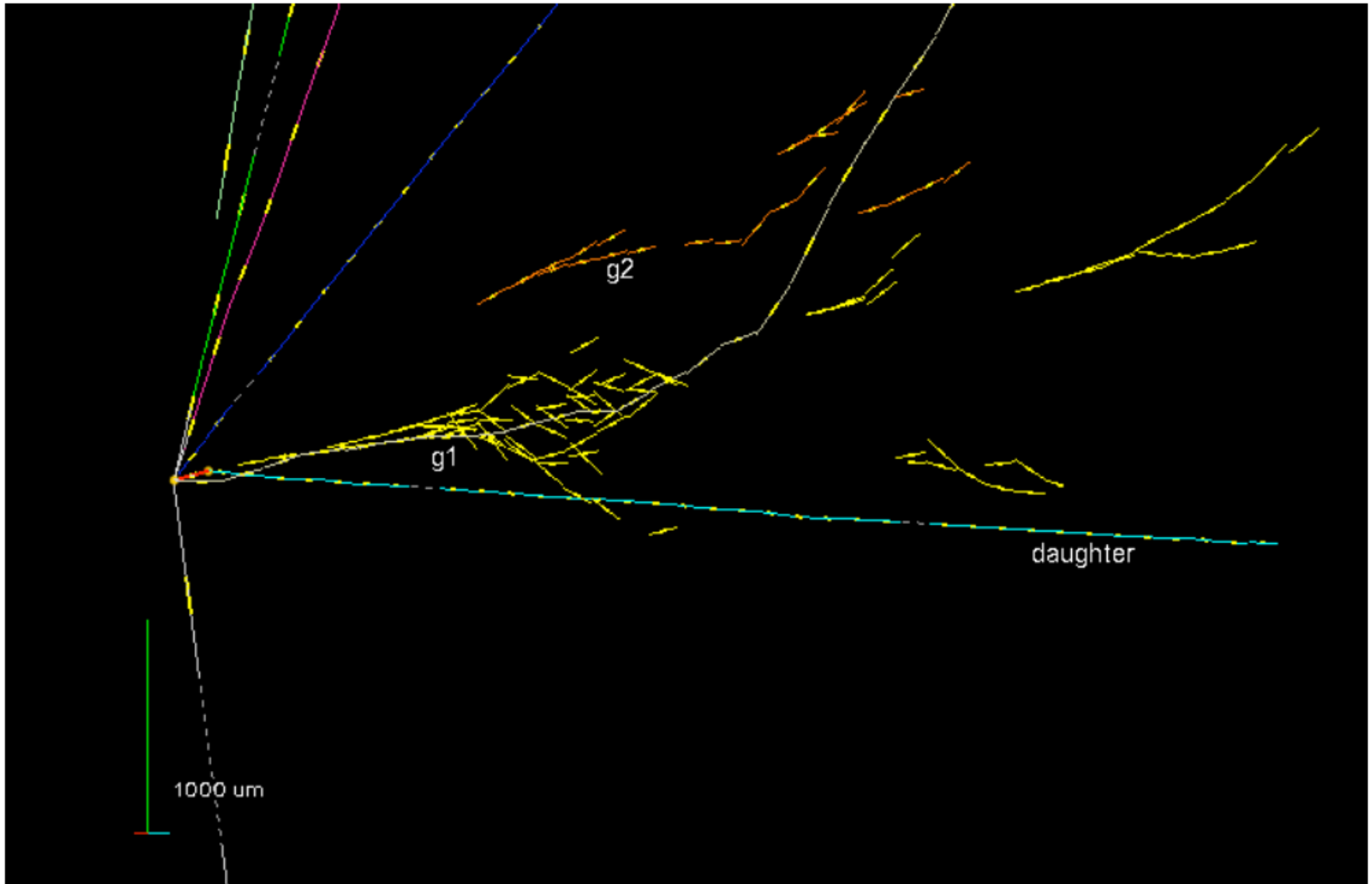


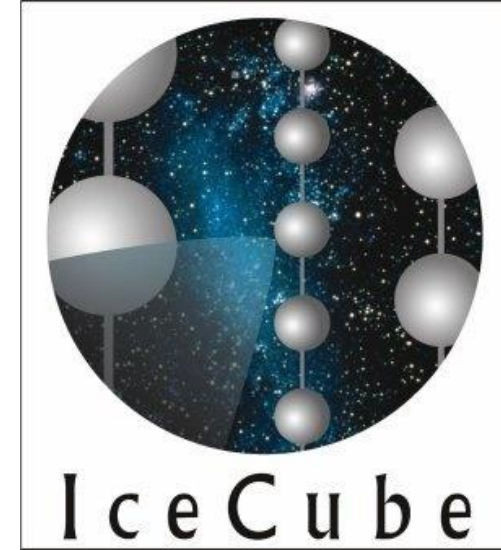
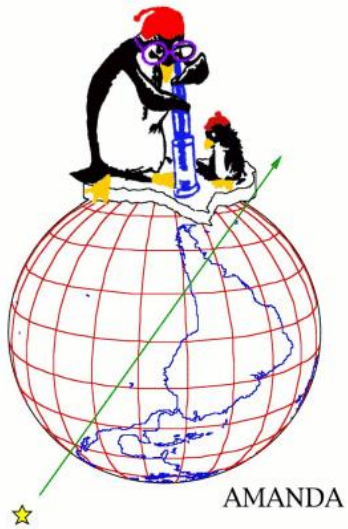
The robotised "Ferrari" for
insertion/extraction of bricks with
vacuum grip by Venturi valve



"Carousel" brick dispensing
and storage system

First Tau Candidate





AMANDA

Antarctic Muon And Neutrino Detector Array

AMANDA

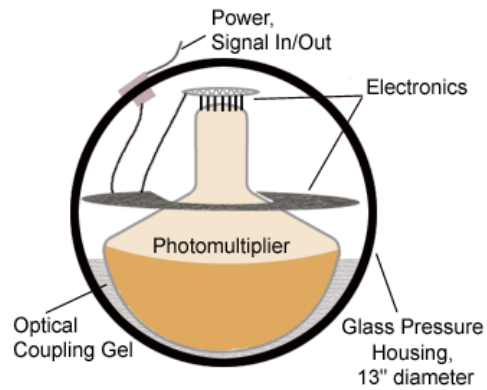
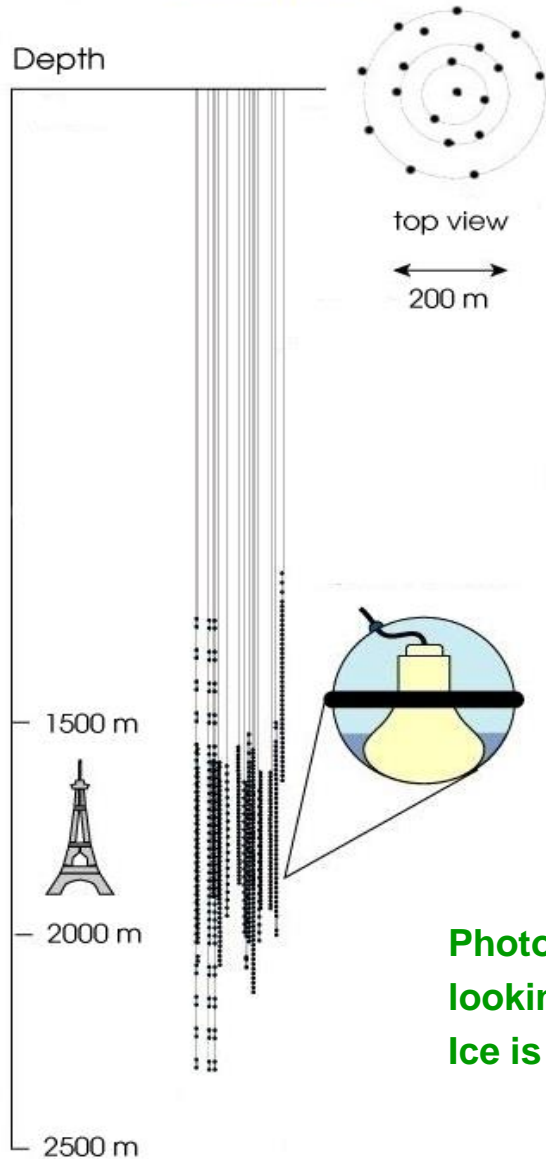


South Pole



AMANDA

AMANDA-II



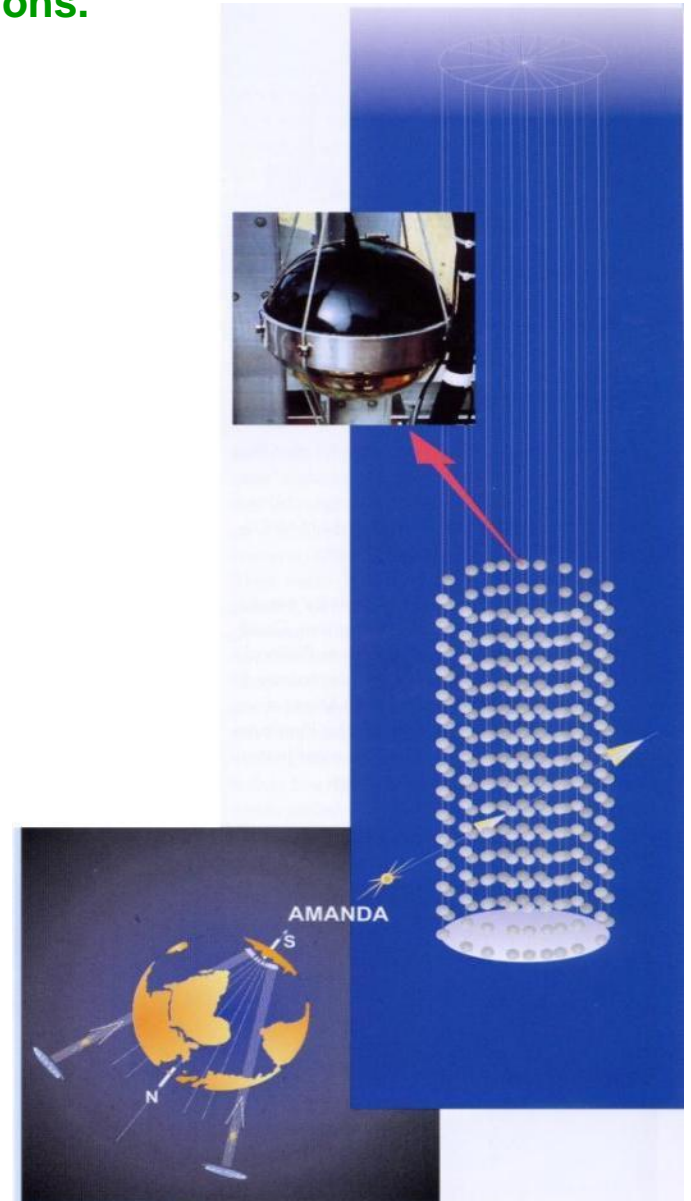
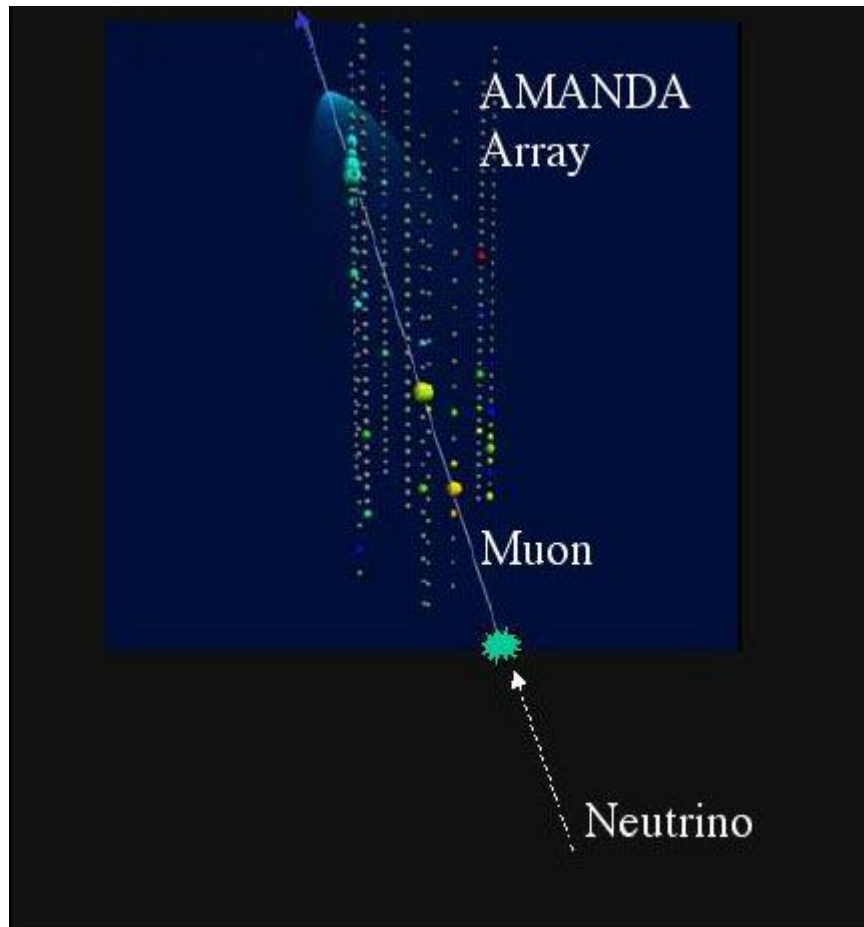
**Photomultipliers in the Ice,
looking downwards.
Ice is the detecting medium.**



AMANDA

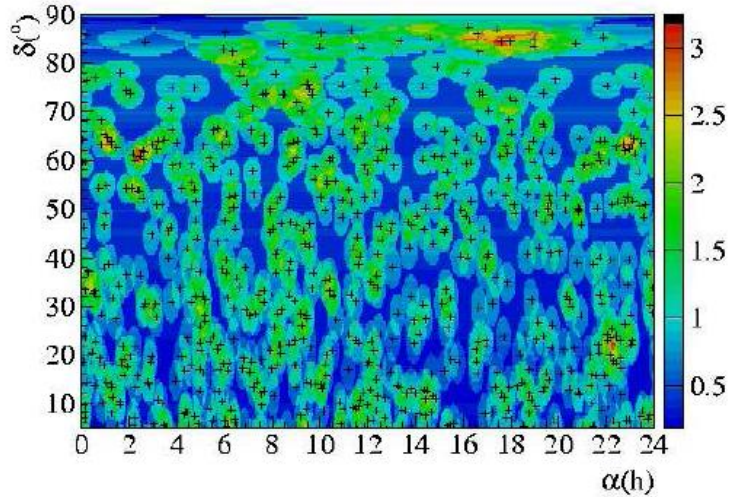
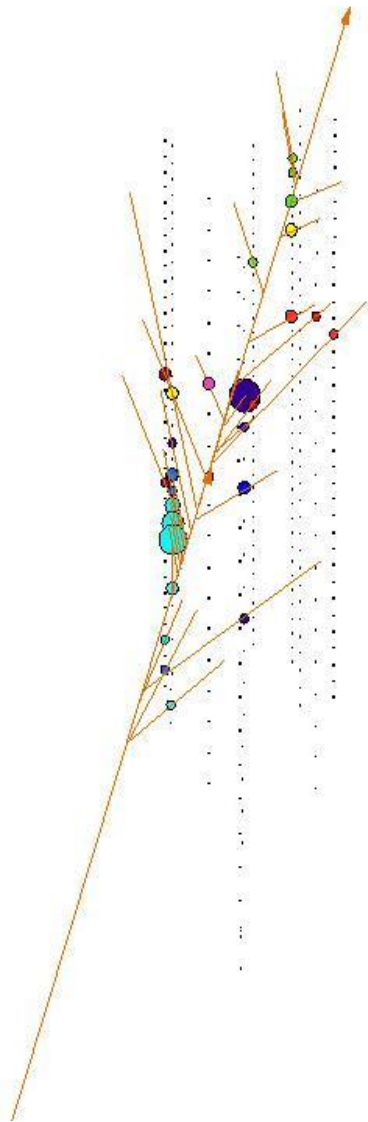
Look for upwards going Muons from Neutrino Interactions.
Cherckov Light propagating through the ice.

→ Find neutrino point sources in the universe !



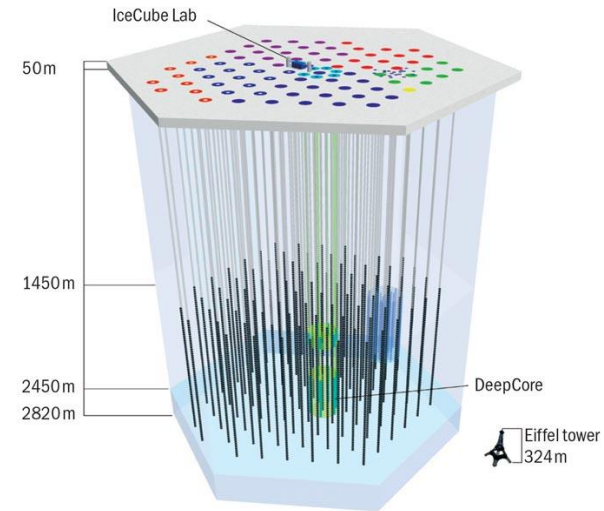
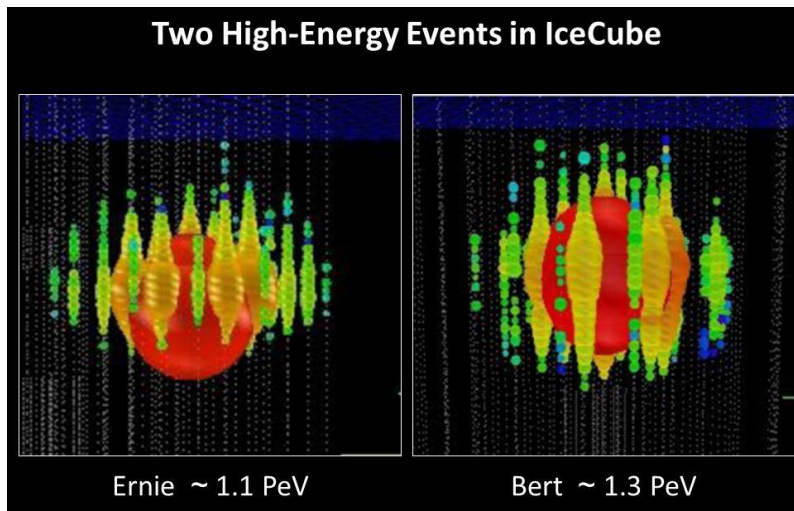
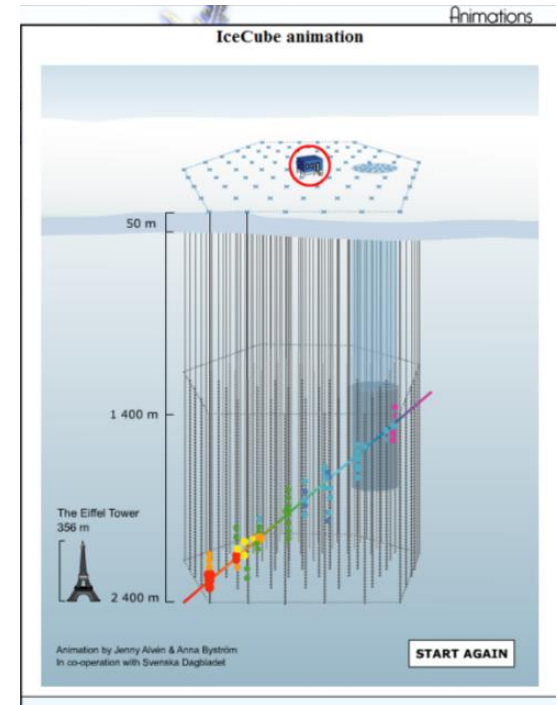
AMANDA

Event Display



Neutrinos from cosmic ray interactions in the atmosphere found with AMANDA

Ice Cube for more statistics !





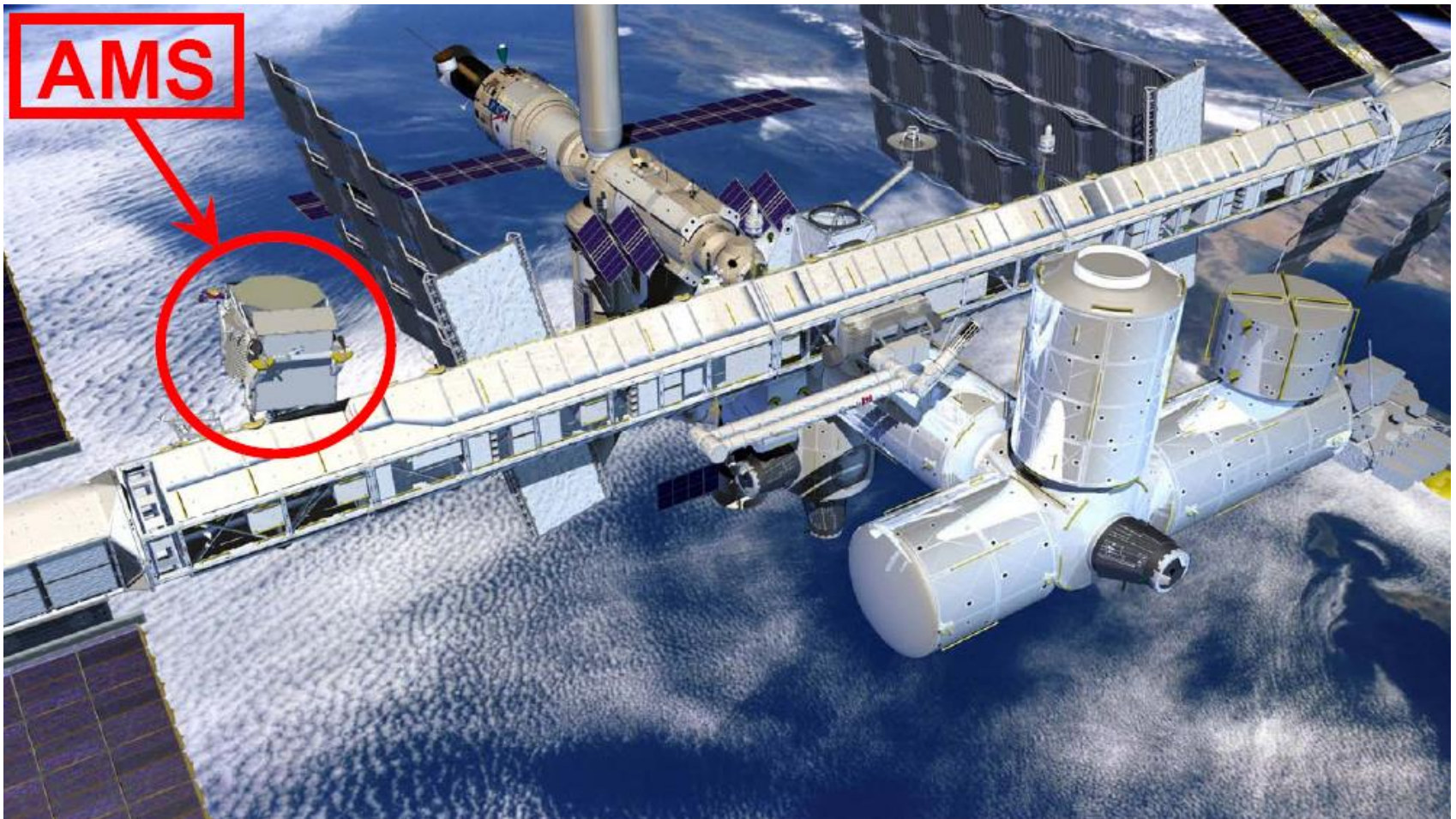
AMS

Alpha Magnetic Spectrometer

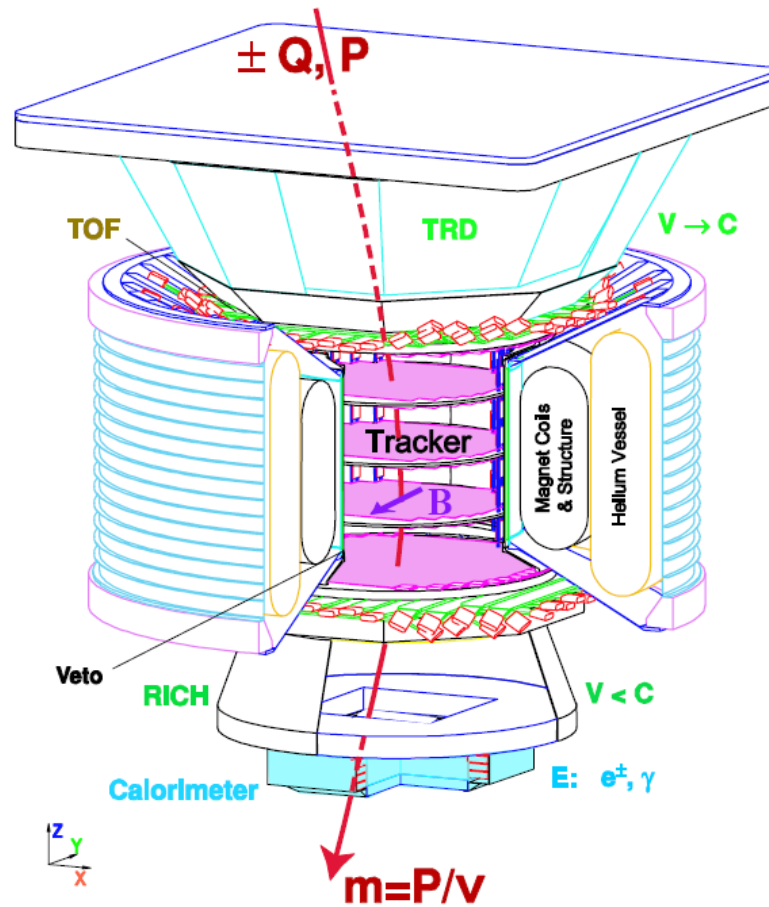
Try to find Antimatter in the primary cosmic rays.
Study cosmic ray composition etc. etc.

AMS

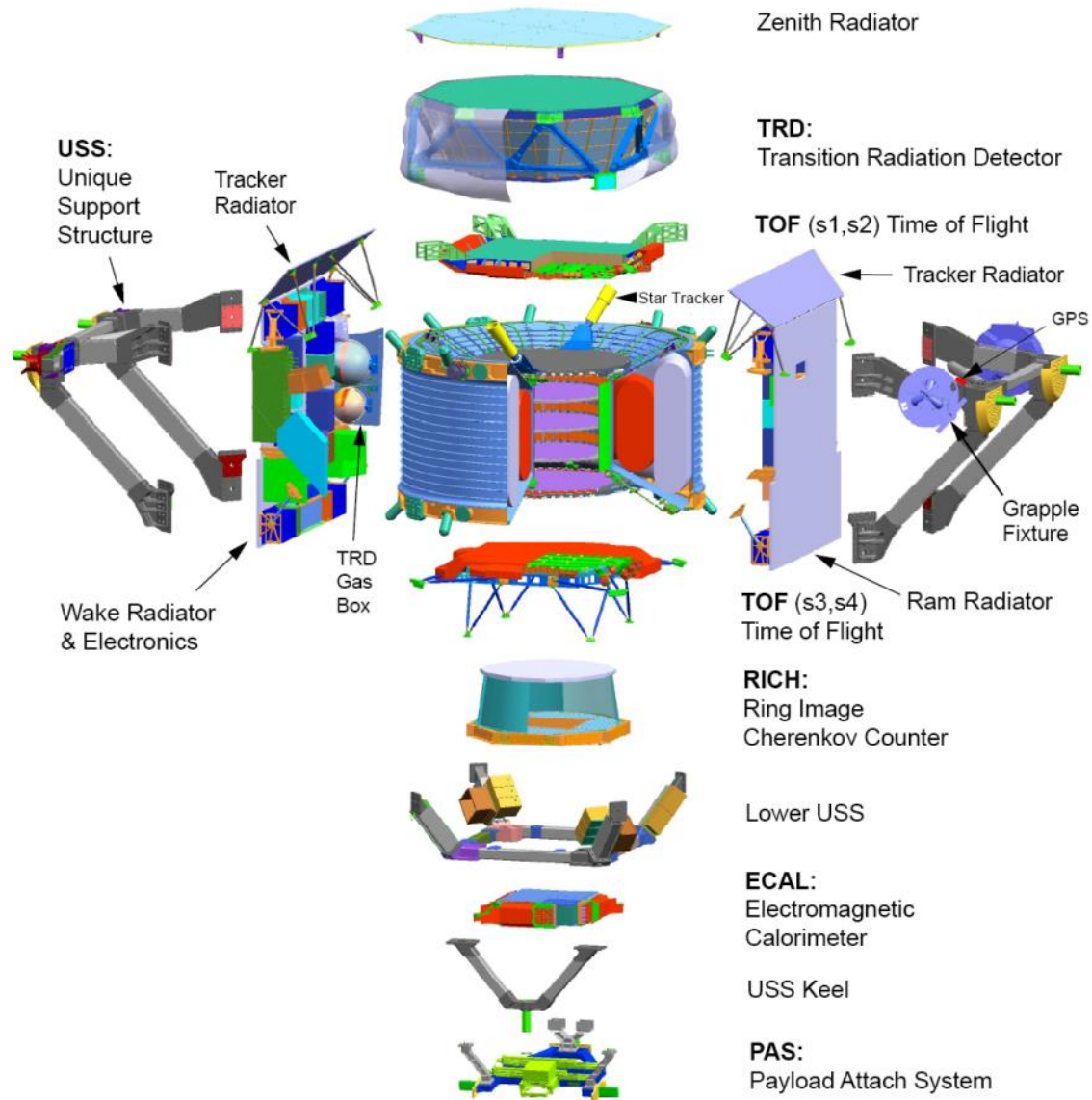
Is installed on the international space station.



AMS

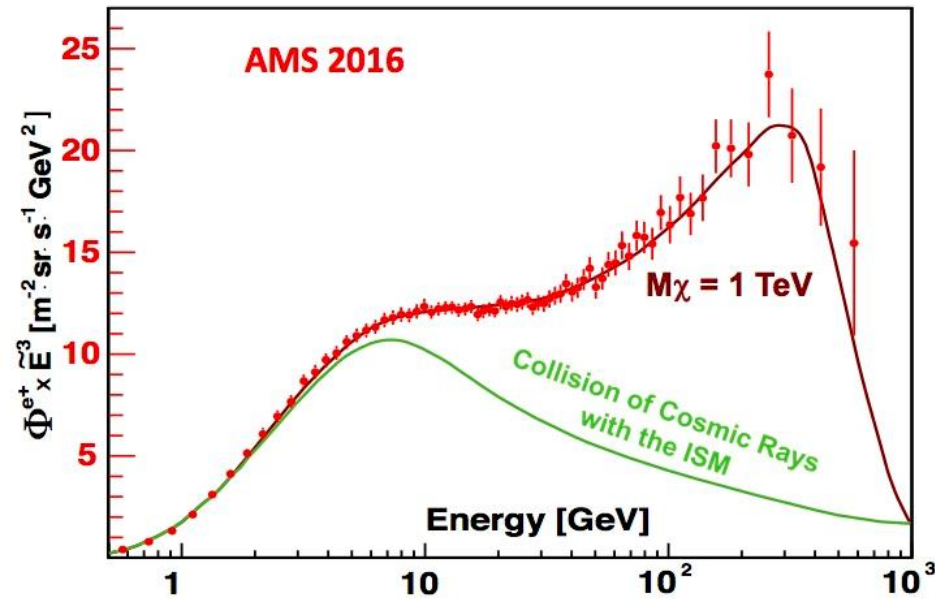


AMS

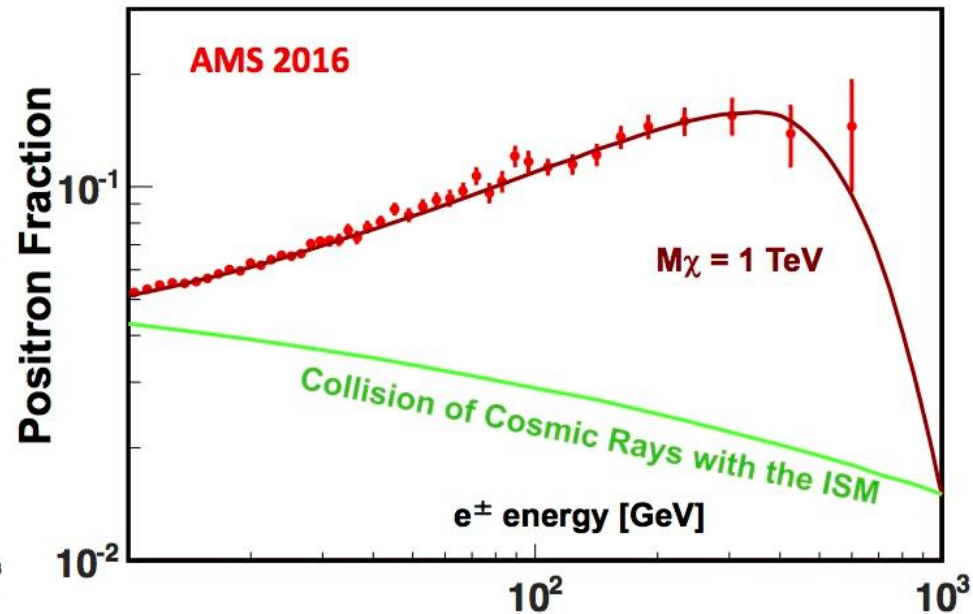


Recent Results on Positrons

Positron Spectrum



Positron Fraction



... interpretations to be seen ...

Summary

Very large scale particle detector systems are in operation at present

- **At large accelerators**
- **At laboratories burried deep inside mountains**
- **At the southpole**
- **In space**
- **...**

Stay tuned !