Particle Detectors

Summer Student Lectures 2010

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- **History of Instrumentation $\leftrightarrow$ History of Particle Physics**
- **The 'Real' World of Particles**
- **Interaction of Particles with Matter**
- **Tracking Detectors, Calorimeters, Particle Identification**
- **Detector Systems**

The ‘Real’ World of Particles

E. Wigner:

“A particle is an irreducible representation of the inhomogeneous Lorentz group”

Spin=0,1/2,1,3/2 … Mass>0

ANNALS OF MATHEMATICS
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ON UNITARY REPRESENTATIONS OF THE INHOMOGENEOUS LORENTZ GROUP*

BY E. WIGNER

(Received December 22, 1937)

1. ORIGIN AND CHARACTERIZATION OF THE PROBLEM

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

E.g. in Steven Weinberg, The Quantum Theory of Fields, Vol1

The ‘Real’ World of Particles

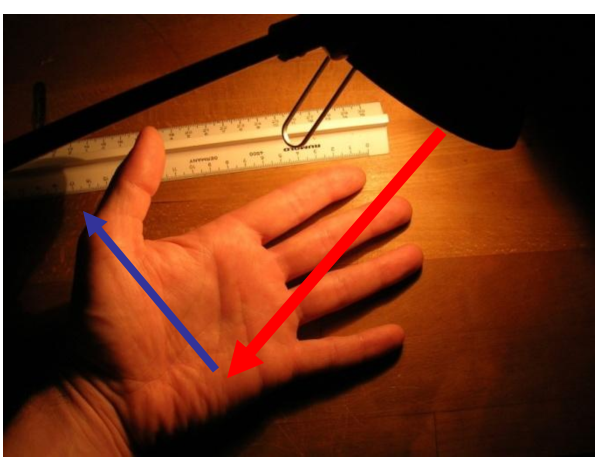
W. Riegler:

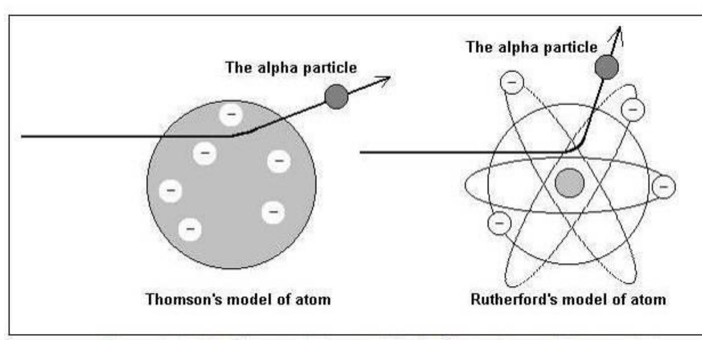
“…a particle is an object that interacts with your detector such that you can follow it’s track,

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

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

Are particles “real” ?
are they in principle “invisible” ?
…





Looking at your hand by scattering light off it is the same thing as looking at the nucleons by scattering alpha particles (or electrons) off it.

)* the content of this slide represents only the personal view of the lecturer, and must not be quoted as an official point of view of the particle physics community’

The ‘Real’ World of Particles

Elektro-Weak Lagrangian

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

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

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

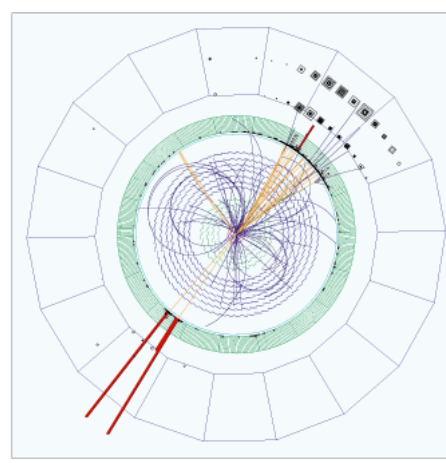
$$L_H = \frac{1}{2}(\partial_\mu H)^2 - m_H^2 H^2 - h\lambda H^3 - \frac{h}{4}H^4 +$$

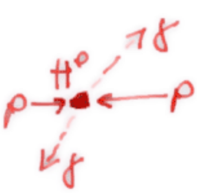
$$+ \frac{g^2}{4}\left(W_\mu^+ W^\mu + \frac{1}{2\cos^2\theta_W} Z_\mu Z^\mu \right)(\lambda^2 + 2\lambda H + H^2) +$$

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

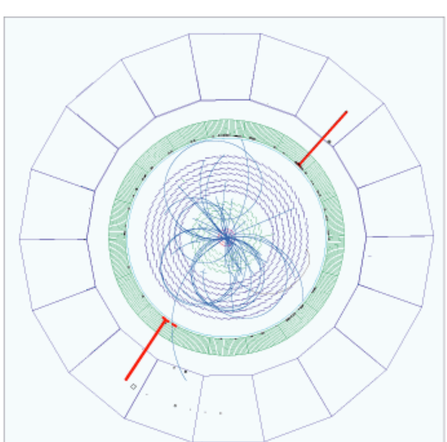
Higgs Particle

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





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



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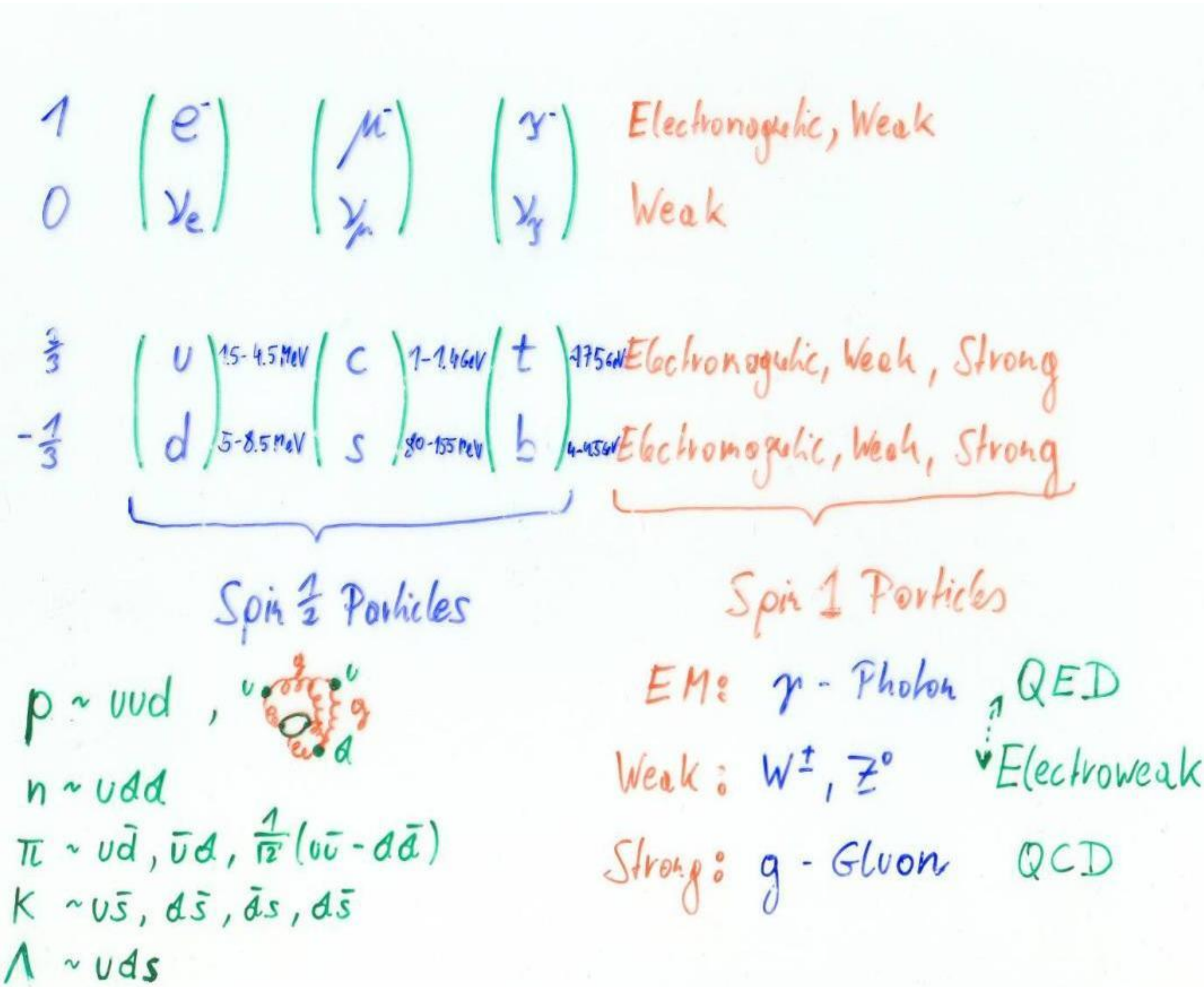
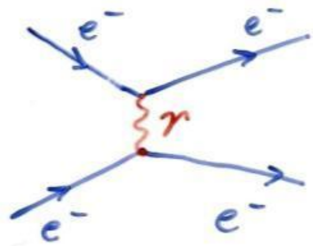
The 'Real' World of Particles



$$\begin{matrix} 1 \\ 0 \end{matrix} \begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix} \quad \begin{matrix} \frac{2}{3} \\ -\frac{1}{3} \end{matrix} \begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

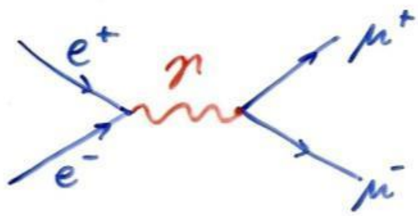
Electromagnetic Interaction γ - Photon

Scattering:



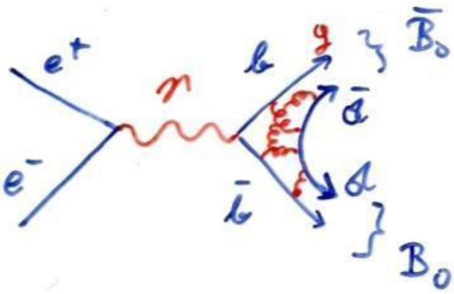
$e^- + e^- \to e^- + e^-$

Anihilation:



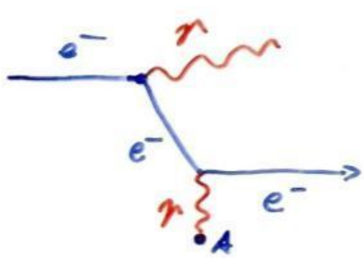
$e^+ + e^- \to \mu^+ + \mu^-$

Anihilation:



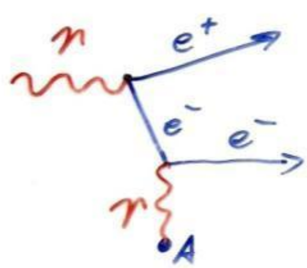
$e^+ + e^- \to B_0 + \bar{B}_0$

Bremsstrahlung:



$e + \text{Atom} \to e + \gamma + \text{Atom}$

Pair Production:

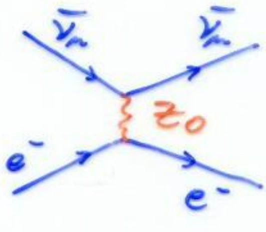


$\gamma + \text{Atom} \to e^+ + e^- + \text{Atom}$

$$\begin{matrix}1\\0\end{matrix}\begin{pmatrix}e\\ \nu_e\end{pmatrix}\begin{pmatrix}\mu\\ \nu_\mu\end{pmatrix}\begin{pmatrix}\tau\\ \nu_\tau\end{pmatrix}\quad\begin{matrix}\frac{2}{3}\\-\frac{1}{3}\end{matrix}\begin{pmatrix}u\\ d\end{pmatrix}\begin{pmatrix}c\\ s\end{pmatrix}\begin{pmatrix}t\\ b\end{pmatrix}$$

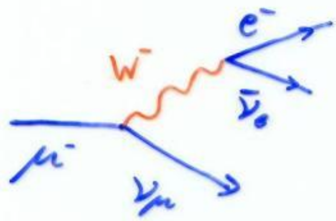
Weak Interaction $W^\pm, Z^0$

Neutral Current:



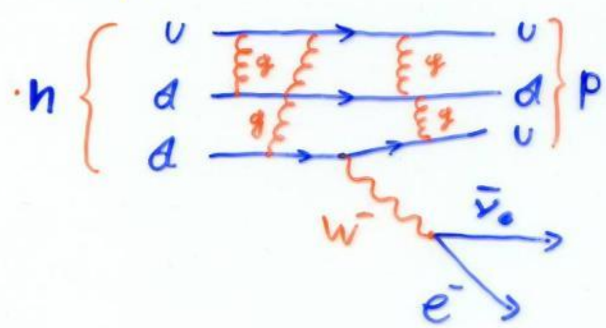
$e^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_\mu$

Muon Decay:



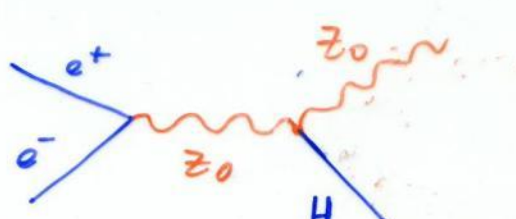
$\mu^- \rightarrow \nu_\mu + e^- + \bar{\nu}_e$

Neutron Decay:



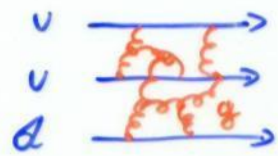
$n \rightarrow p + e^- + \bar{\nu}_e$

H Production:



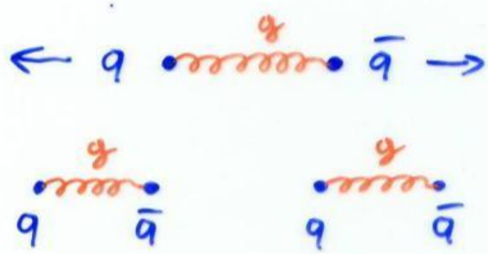
$$\begin{matrix} 1 \\ 0 \end{matrix} \begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix} \quad \begin{matrix} \frac{2}{3} \\ -\frac{1}{3} \end{matrix} \begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

Strong Interaction g Gluons

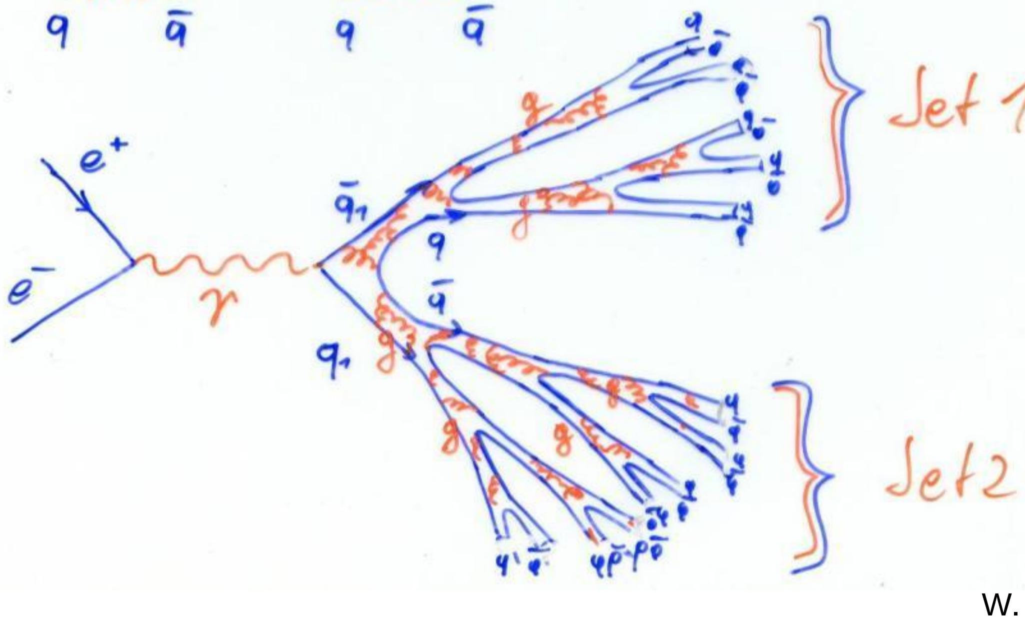


Proton

Self Interaction

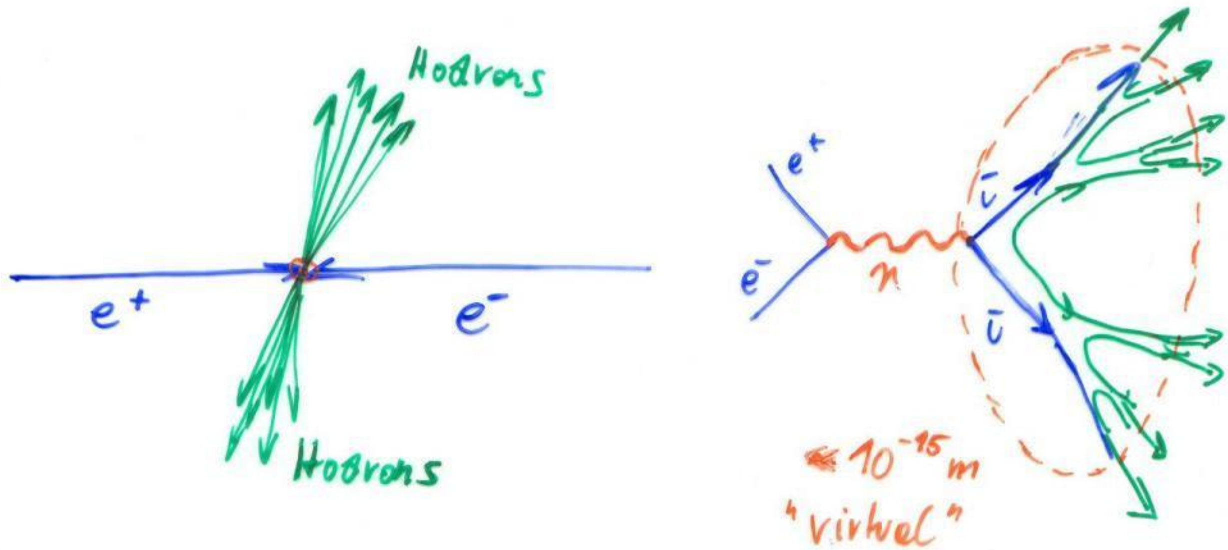


"Confinement"



.... Strong Interaction ......

$e^+ + e^- \rightarrow$ jets in Detector



e.g. Two jets of Hadrons are 'spraying' away from the Interaction Point.

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.

„Material Culture of Particle Physics"

Scales

$$E = ma^2$$

$$E = mb^2$$

$$E = mc^2$$ ← Energy ≙ Mass

⋮

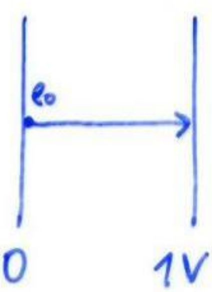
$m(\text{electron}) = 9.1 \cdot 10^{-31}$ kg

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

$= 510\,999$ Electron Volt (eV)

$= 0.511$ MeV

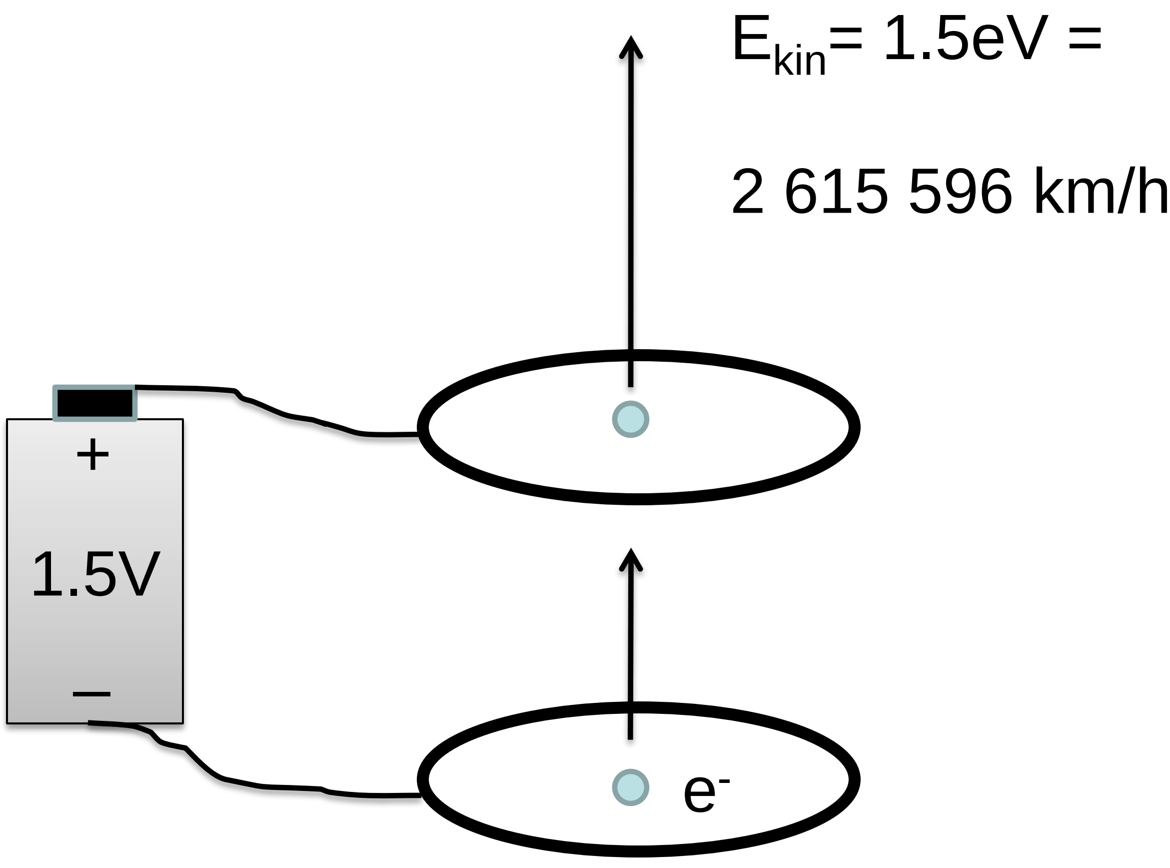
1 Electron Volt $= e_0 \cdot 1V = 1.603 \cdot 10^{-19}$ J



$$E = e_0 \cdot 1V$$

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

Build your own Accelerator



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

E.g: $^{90}_{39}Y \rightarrow \beta^- \rightarrow e^-$ with $E_{av} = 2.283\,MeV$

$$E_k = m_e c^2 (\gamma - 1) \qquad m_e c^2 \sim 0.511\,MeV$$

$$\gamma = \frac{E_k}{m_e c^2} + 1 \sim 5.5$$

$$\beta = \frac{v}{c} = \sqrt{1 - \left(\frac{m_e c^2}{E_k + m_e c^2}\right)^2} \sim 0.98 \rightarrow \text{Highly Relativistic}$$

$E_{kin} = mc^2 \rightarrow mc^2(\gamma - 1) = mc^2 \rightarrow \gamma = 2 \rightarrow \beta = 0.87$

Eg: $^{241}_{95}Am \rightarrow \alpha$ with $E_{kin} = 5.486\,MeV$, $m_\alpha c^2 = 3.75\,GeV$

$$\gamma \sim 1.0015 \qquad \beta \sim 0.054 \rightarrow 16.2 \cdot 10^6\,m/s$$

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

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

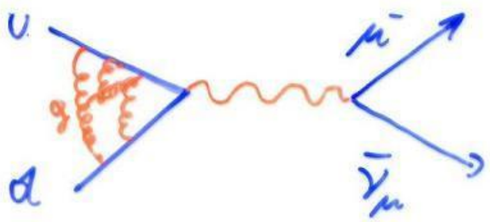
Pions: π^+, π^- $\tau \sim 2.6 \cdot 10^{-8}\, s$, $m_\pi c^2 = 135\, MeV$

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

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

Basics

E.g. $\pi^-(u\bar{d}) \rightarrow \mu^- + \bar{\nu}_\mu \quad (> 99.9\,\%)$



$\tau = 2.6 \cdot 10^{-8}\,s$

π^- • $\qquad \mu^- \xleftarrow{\vec{p}_1} \bullet \xrightarrow{\vec{p}_2} \bar{\nu}_\mu$

$\vec{p} = 0,\; E = m_\pi c^2 \qquad \vec{p}_1 + \vec{p}_2 = 0,\; E_\mu + E_\nu = E$

$$\left.\begin{aligned} 0 &= \frac{m_\mu v_1}{\sqrt{1-\frac{v_1^2}{c^2}}} + \frac{m_\nu v_2}{\sqrt{1-\frac{v_2^2}{c^2}}} \\ m_\pi c^2 &= \frac{m_\mu c^2}{\sqrt{1-\frac{v^2}{c^2}}} + \frac{m_\nu c^2}{\sqrt{1-\frac{v^2}{c^2}}} \end{aligned}\right\} v_1, v_2$$

E_μ, E_ν are uniquely defined

→ Two Body Decay gives "sharp" Energies of the Decay Particles

Basics

1920ies: β^- Radioactivity

$$Nucl_1 \rightarrow Nucl_2 + e^- \quad \text{visible}$$

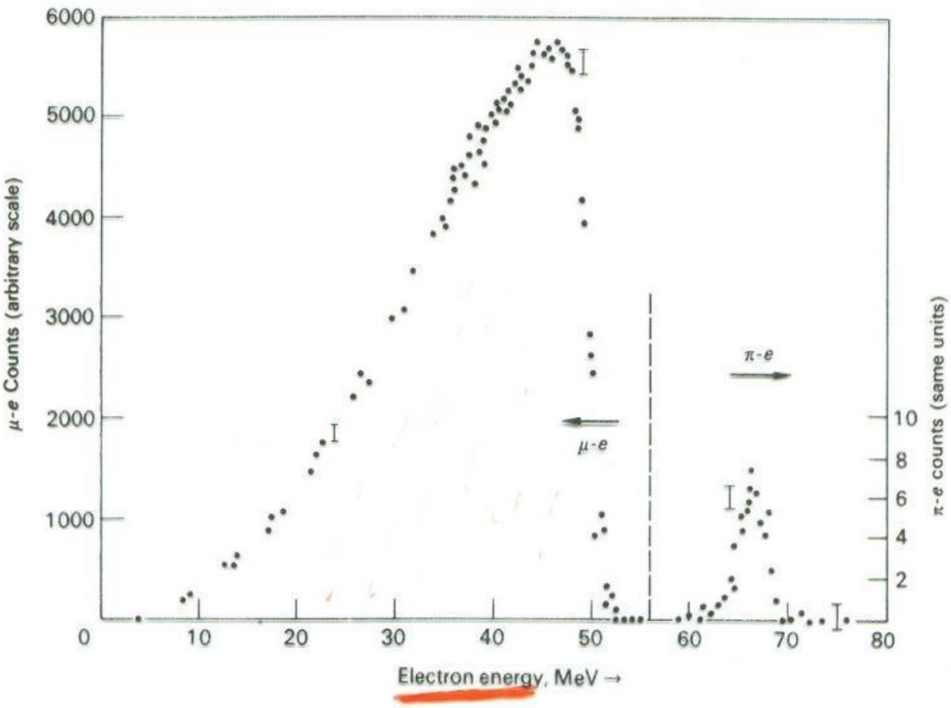
But: e^- shows a continuous Energy Spectrum

→ W. Pauli proposed an "invisible" Particle → ν

$$n \rightarrow p + e^- + \bar{\nu}_e$$

For > 2 Body decay, the Energy Spectrum of the decay particles depends on the Nature of the Interaction. Kinematics alone doesn't define the Energies.

Stopping Pions and measuring the decay electron Spectrum:



$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

$\quad \hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$

→ Energy Spectrum (3 Body Decay)

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

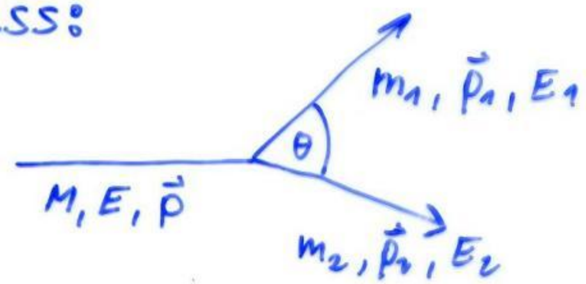
↓

"sharp" Energy (2 Body Decay)

Basics

Invariant Mass:

LAB:



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

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

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

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

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

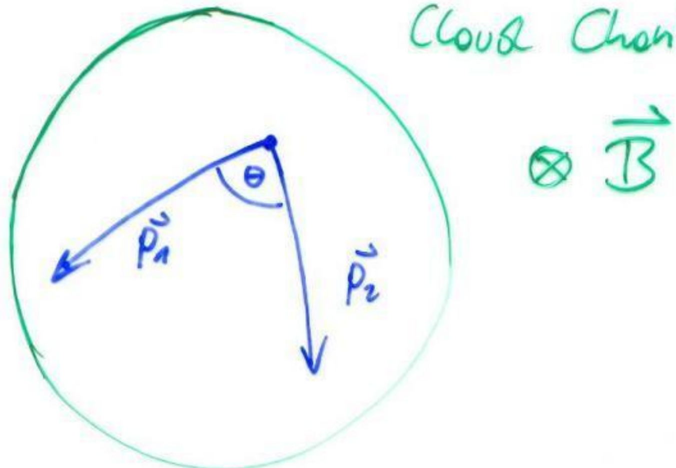
$$M^2c^2 = m_1^2c^2 + m_2^2c^2 + 2\left(\frac{E_1E_2}{c^2} - p_1p_2\cos\theta\right)$$

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

gives the Mass of the original Particle

Basics

E.g: Discovery of V_0 Particles



$$\Lambda^0 \rightarrow p^+ + \pi^-$$

"If 1 is a Proton and 2 is a Pion the Mass of the V^0 particle is ...."

Identification in the Experiment by looking at the specific Ionization .....

(see later)

μ - Lifetime

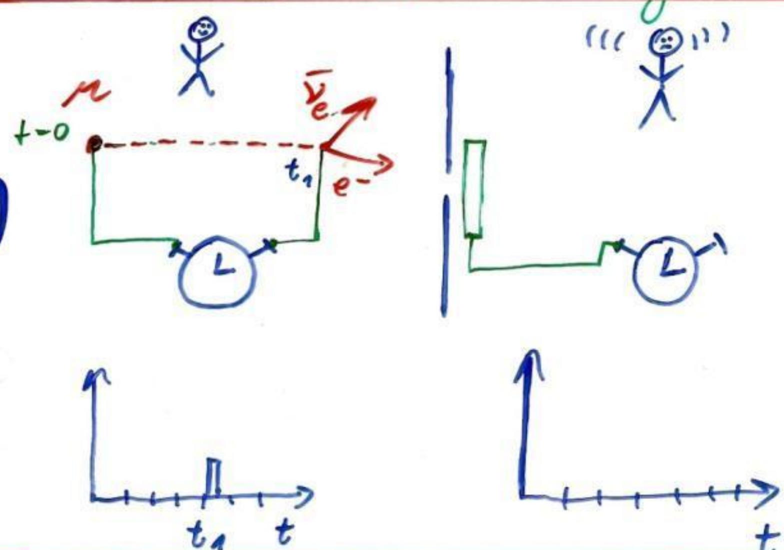
The muon (any unstable Particle) doesn't have an inner 'clock', i.e. nothing that tells it' age.

Probability that it decays in the time interval Δt = p

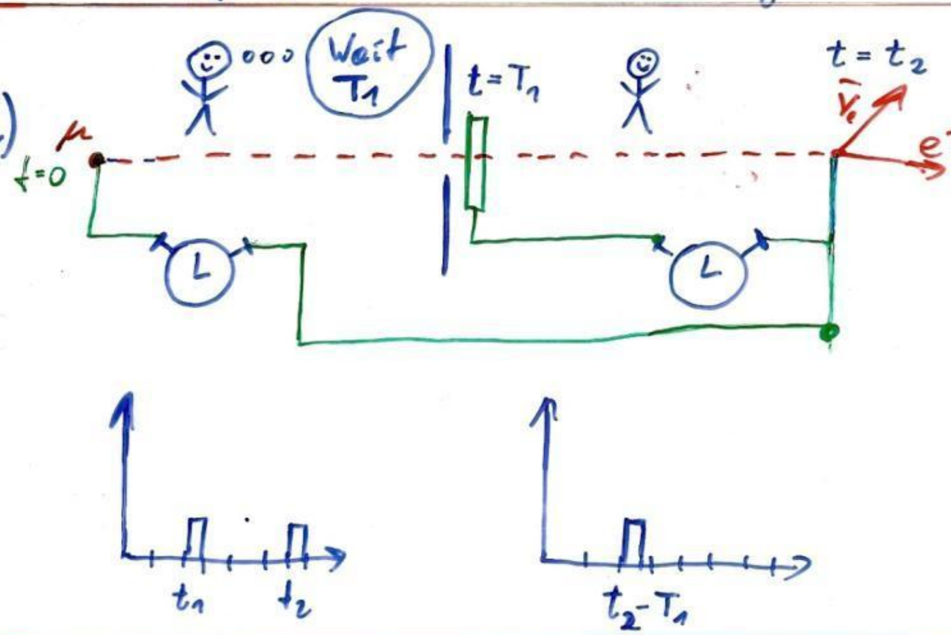
μ - Lifetime

The muon (any unstable Particle) doesn't have an inner "clock", i.e. nothing that tells it's age.

1)



2)



3)

$$P_2(t) := C_1 \cdot P_1(t)$$

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We look for a Distribution P(t) where drawing a time t from P(t) and subtracting a random Number T gives again the same Distribution P(t) for t > 0

p(T): Arbitrary Distribution

$$P_2(t) = \int_0^\infty p(T)\, P_1(t-T)\, dt$$

$$P_2(t) := c_1 P_1(t)$$

only if $P_1(t-T) = P_1(t) \cdot P_1(-T)$

$\rightarrow$ $P(t) = c_1 e^{-c_1 t}$ $\rightarrow$ Exponential Distribution

$\tau = \int_0^\infty t\, c_1 e^{-c_1 t} = \frac{1}{c_1}$ Average Lifetime

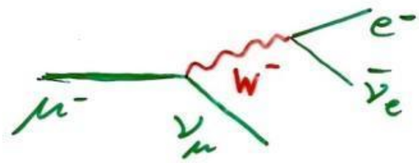
$$P(t) = \frac{1}{\tau} e^{-\frac{t}{\tau}}$$ τ = "Life time"

"A Particle has a Lifetime τ" means:

The Probability that it Decays at time t after starting to measure it (independent of what happened before) is $P(t) = \frac{1}{\tau} e^{-\frac{t}{\tau}}$

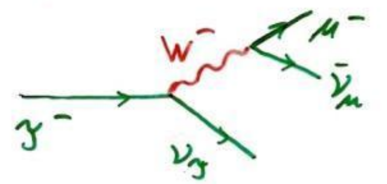
Electron e $m_e = 0.511\ MeV$ $\tau = \infty$,

Myon μ $m_\mu = 105.7\ MeV$ $\tau = 2.2 \cdot 10^{-6}\ s$, $c\tau = 659\ m$

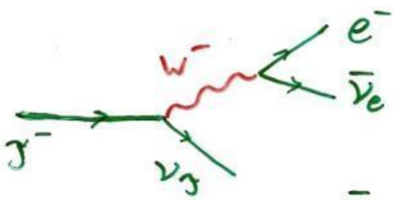


$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$ ($> 99.9\%$)

Tauon τ $m_\tau = 1777\ MeV$ $\tau = 2.9 \cdot 10^{-13}\ s$, $c\tau = 87\ \mu m$



$\tau^- \to \mu^- + \bar{\nu}_\mu + \nu_\tau$ ($\sim 17\%$)



$\tau^- \to e^- + \bar{\nu}_e + \nu_\tau$ ($\sim 17\%$)

$\tau^- \to \pi^- + \nu_\tau$ ($\sim 11\%$)

$\tau^- \to \pi^0 + \pi^- + \nu_\tau$ ($\sim 25\%$)

⋮

Due to the larger Mass, more Decay Possibilities are open to the τ

→ the Lifetime is smaller ....

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, $f_0(660)$, $\rho(770)$,
$\omega(782)$, $\eta'(958)$, $f_0(980)$, $a_0(980)$, $\phi(1020)$, $h_1(1170)$, $b_1(1235)$,
$a_1(1260)$, $f_2(1270)$, $f_1(1285)$, $\eta(1295)$, $\pi(1300)$, $a_2(1320)$,
$f_0(1370)$, $f_1(1420)$, $\omega(1420)$, $\eta(1440)$, $a_0(1450)$, $\rho(1450)$,
$f_0(1500)$, $f_2'(1525)$, $\omega(1650)$, $\omega_3(1670)$, $\pi_2(1670)$, $\phi(1680)$,
$\rho_3(1690)$, $\rho(1700)$, $f_0(1710)$, $\pi(1800)$, $\phi_3(1850)$, $f_2(2010)$,
$a_4(2040)$, $f_4(2050)$, $f_2(2300)$, $f_2(2340)$, $K^\pm$, K^0, K^0_S, K^0_L, $K^*(892)$,
$K_1(1270)$, $K_1(1400)$, $K^*(1410)$, $K_0^*(1430)$, $K_2^*(1430)$, $K^*(1680)$,
$K_2(1770)$, $K_3^*(1780)$, $K_2(1820)$, $K_4^*(2045)$, $D^\pm$, D^0, $D^*(2007)^0$,
$D^*(2010)^\pm$, $D_1(2420)^0$, $D_2^*(2460)^0$, $D_2^*(2460)^\pm$, $D_s^\pm$, $D_s^{*\pm}$,
$D_{s1}(2536)^\pm$, $D_{sJ}(2573)^\pm$, $B^\pm$, B^0, B^*, B^0_s, $B^\pm_c$, $\eta_c(1S)$, $J/\psi(1S)$,
$\chi_{c0}(1P)$, $\chi_{c1}(1P)$, $\chi_{c2}(1P)$, $\psi(2S)$, $\psi(3770)$, $\psi(4040)$, $\psi(4160)$,
$\psi(4415)$, $\Upsilon(1S)$, $\chi_{b0}(1P)$, $\chi_{b1}(1P)$, $\chi_{b2}(1P)$, $\Upsilon(2S)$, $\chi_{b0}(2P)$,
$\chi_{b2}(2P)$, $\Upsilon(3S)$, $\Upsilon(4S)$, $\Upsilon(10860)$, $\Upsilon(11020)$, 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, $\Xi_c'^+$, $\Xi_c'^0$, $\Xi(2645)$
$\Xi_c(2790)$, $\Xi_c(2815)$, Ω_c^0, Λ_b^0, Ξ_b^0, Ξ_b^-, $t\bar{t}$

There are many more

W. Riegler/CERN

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" ($D^\pm$ 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.

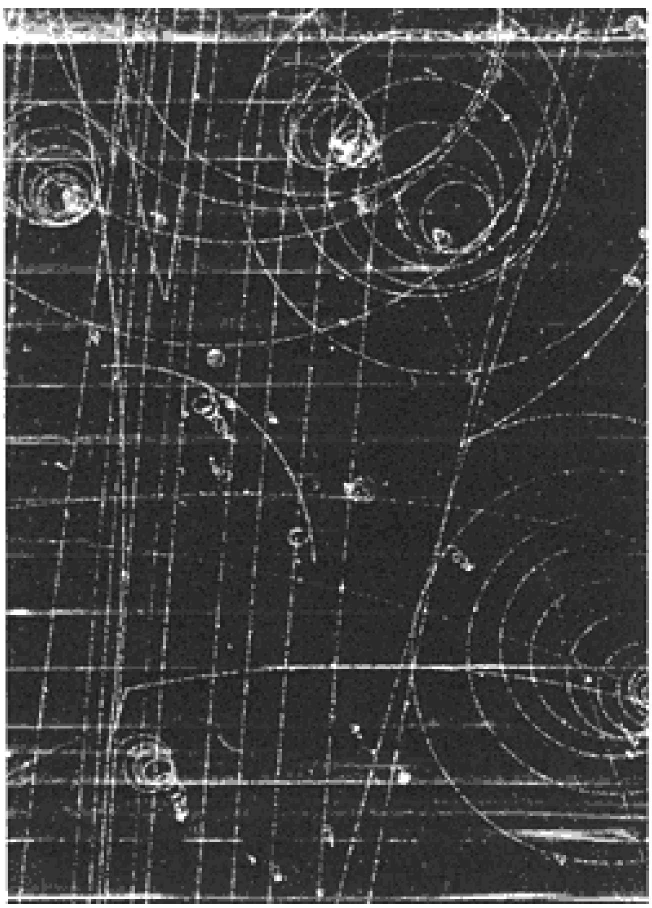
~13 of the 27 have $c\tau < 500\mu m$ i.e. only ~mm range at GeV Energies.
→ "short" tracks measured with Emulsions or Vertex Detectors.

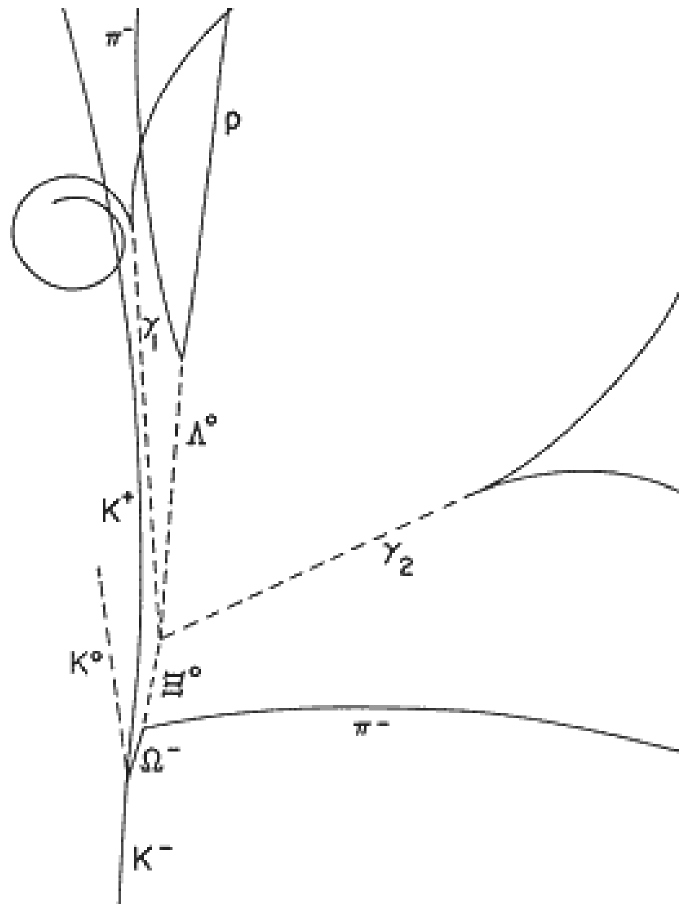
From the ~14 remaining particles

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

are by far the most frequent ones

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



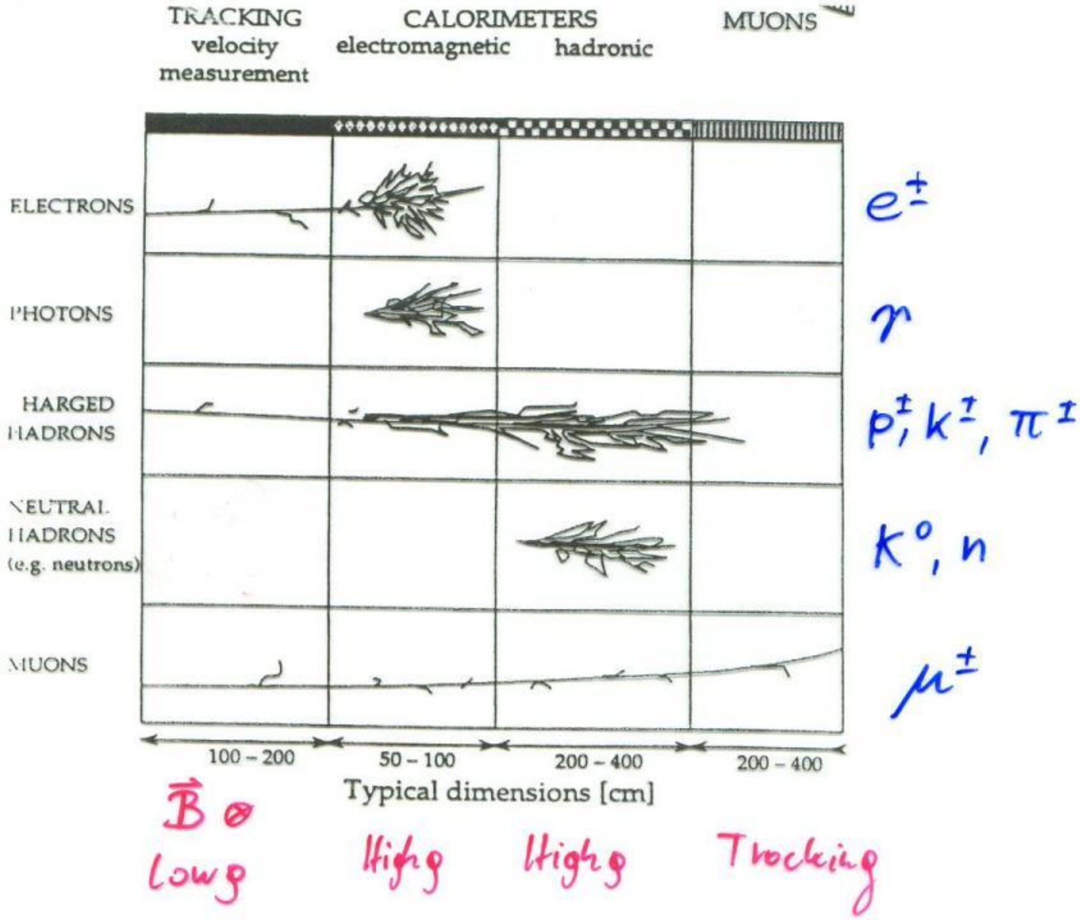

π⁻
p
γ1
Λ°
K⁺
γ2
K°
Ξ°
π⁻
Ω⁻
K⁻

Particle	Mass		Interaction
$e^\pm$	$m_e = 0.511$ MeV		EM
$\mu^\pm$	$m_\mu = 105.7$ MeV	$\sim 200\, m_e$	EM
γ	$m_\gamma = 0$, $Q = 0$		EM
$\pi^\pm$	$m_\pi = 139.6$ MeV	$\sim 270\, m_e$	EM, Strong
$K^\pm$	$m_K = 493.7$ MeV	$\sim 1000\, m_e$	EM, Strong ($\sim 3.5\, m_\pi$)
$p^\pm$	$m_p = 938.3$ MeV	$\sim 2000\, m_e$	EM, Strong
K^0	$m_{K^0} = 497.7$ MeV	$Q = 0$	Strong
n	$m_n = 939.6$ MeV	$Q = 0$	Strong

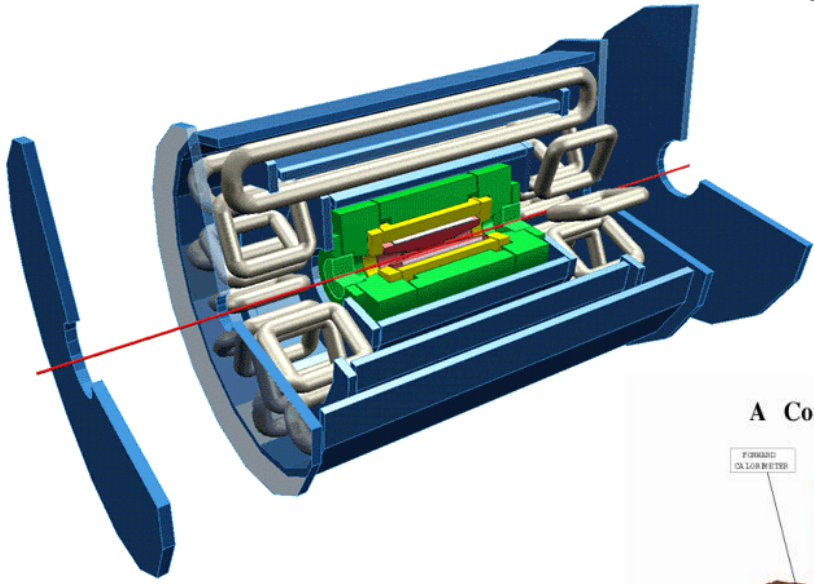
The Difference in

Mass, Charge, Interaction

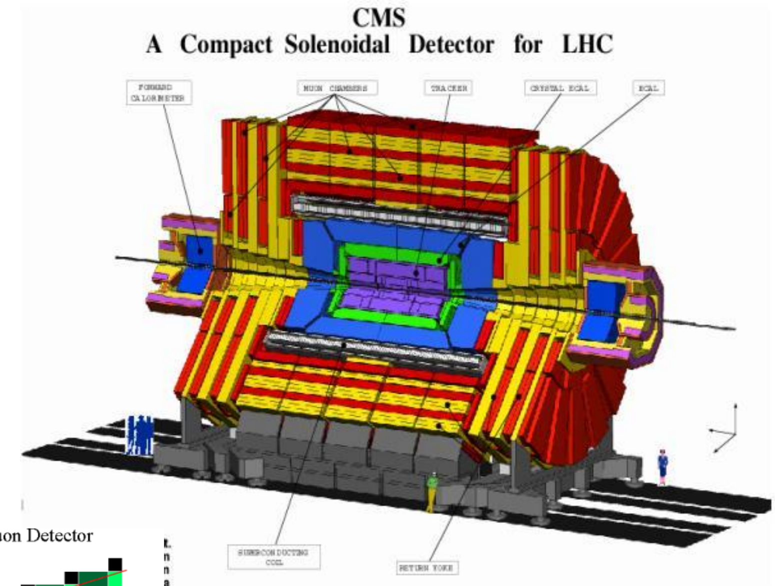
is the key to the Identification



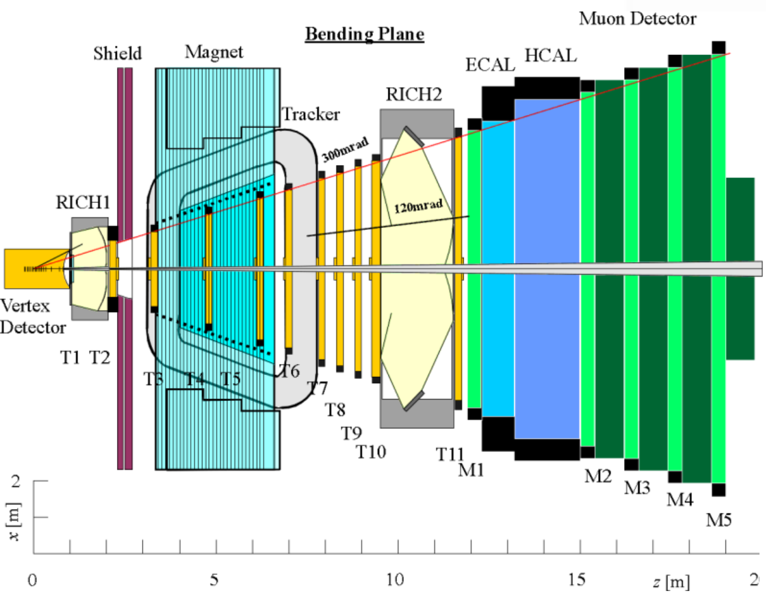
- Electrons ionize and show Bremsstrahlung due to the small mass
- Photons don't ionize but show Pair Production in high Z Material. From then on equal to $e^\pm$
- Charged Hadrons ionize and show Hadron Shower in dense material.
- Neutral Hadrons don't ionize and show Hadron Shower in dense Material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



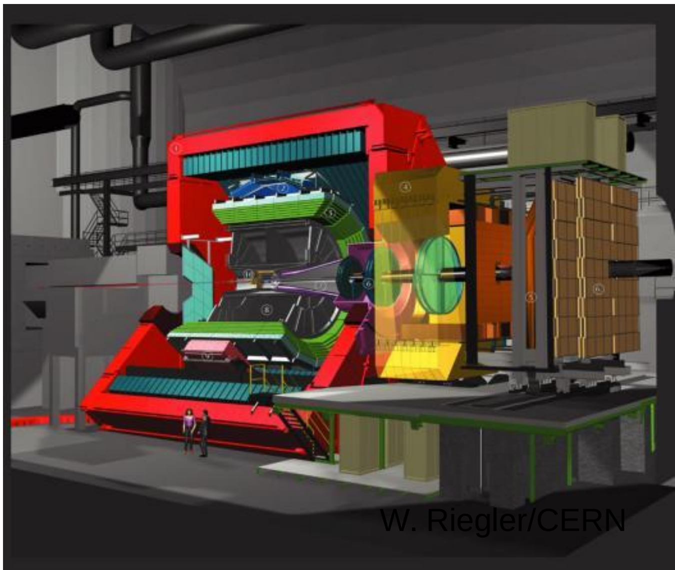
ATLAS



CMS



LHCb



ALICE

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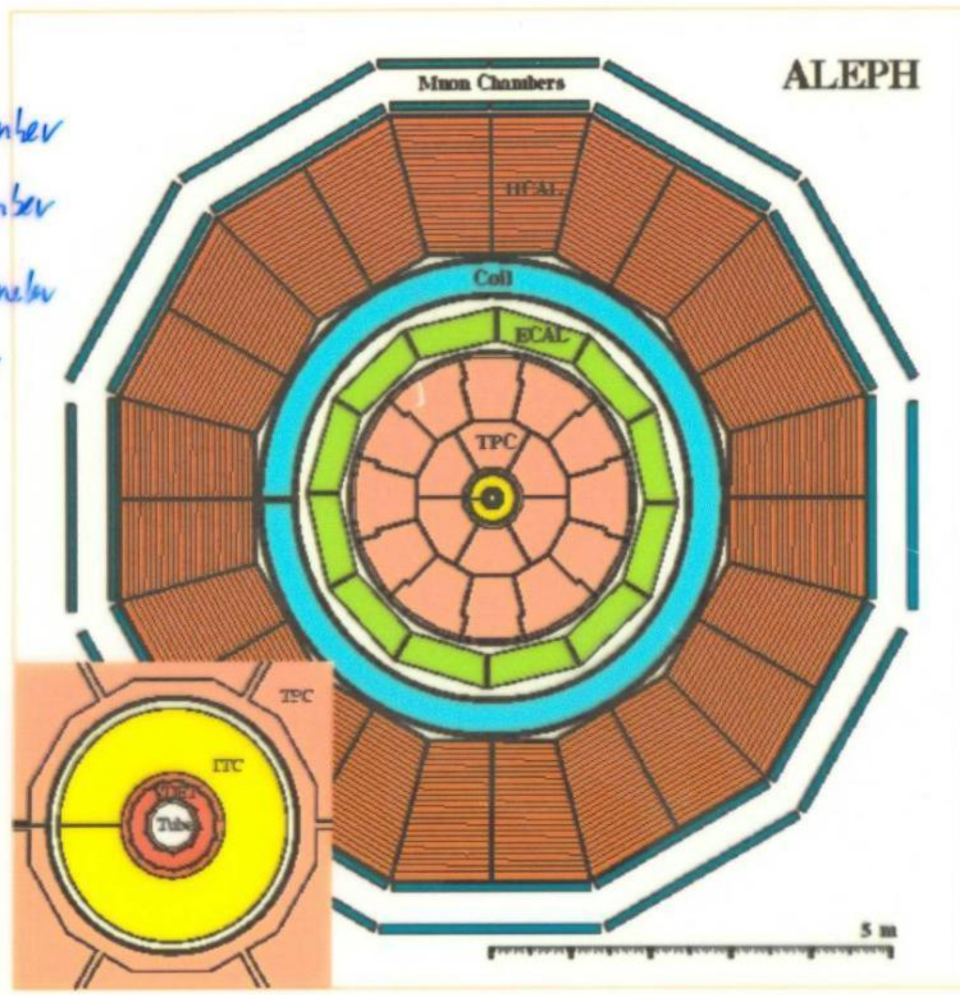
Vertex Detector
Inner Tracking Chamber
Time Projection Chamber
Electromagnetic Calorimeter
Hadron Calorimeter
Muon Detectors



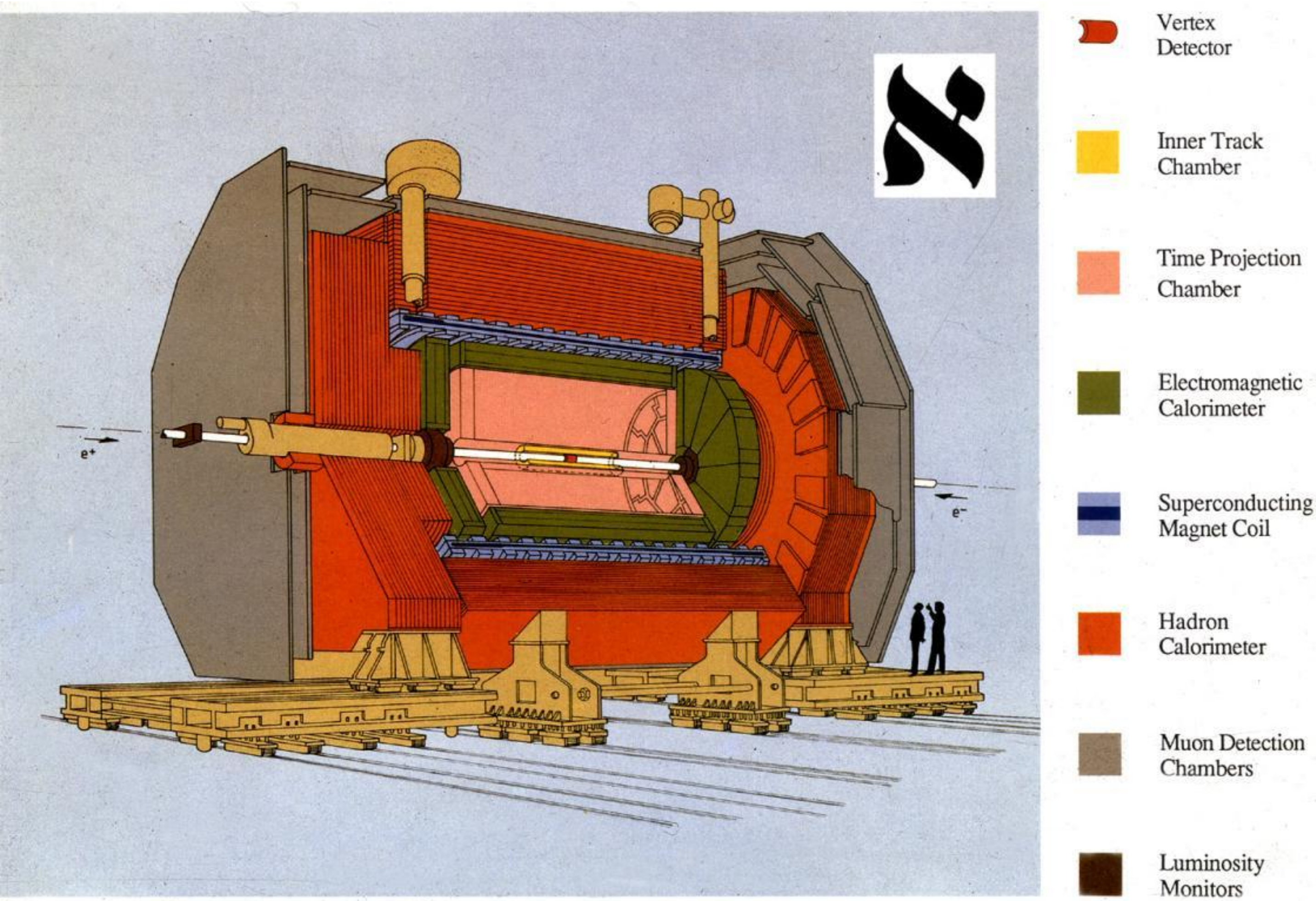
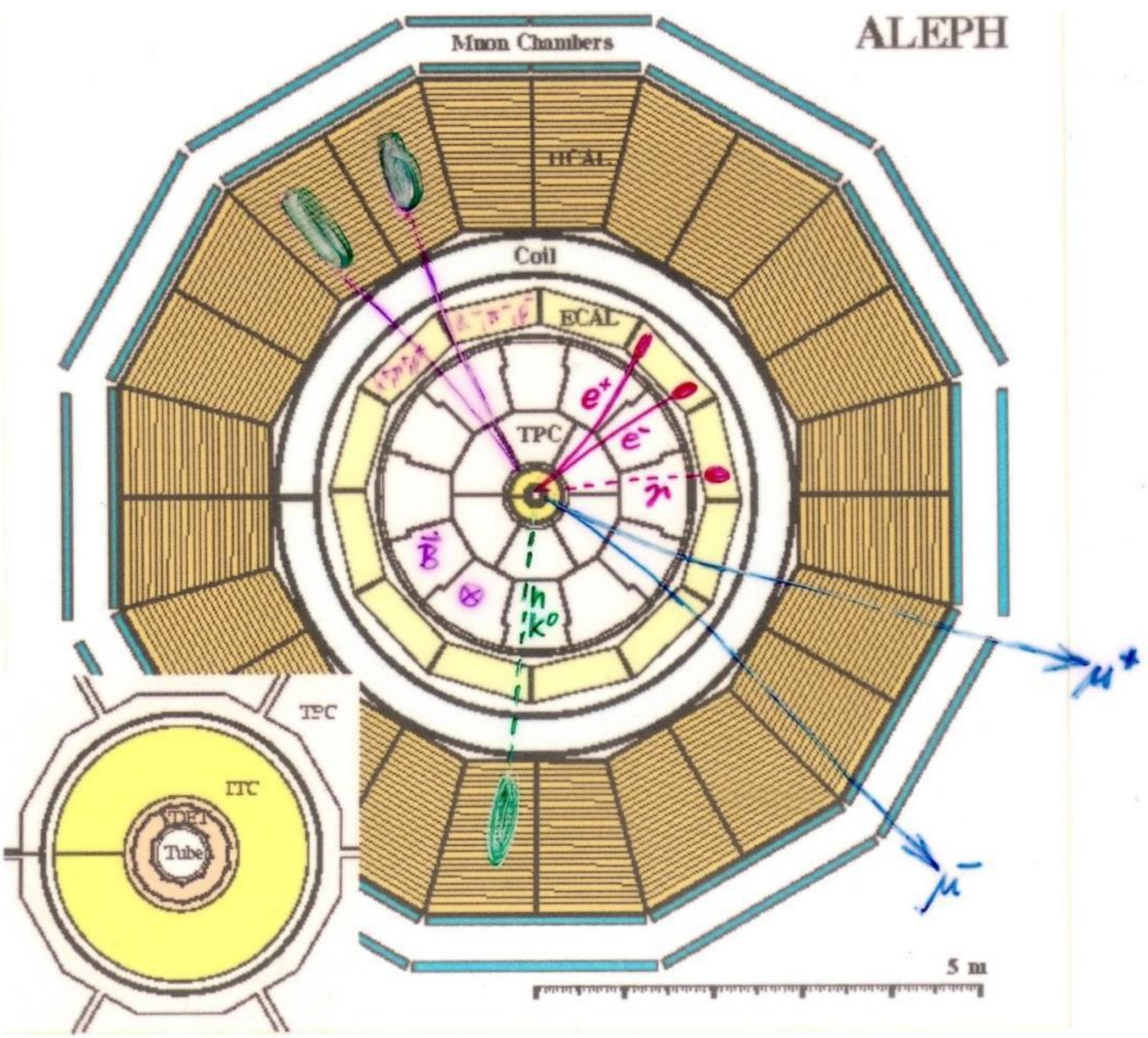
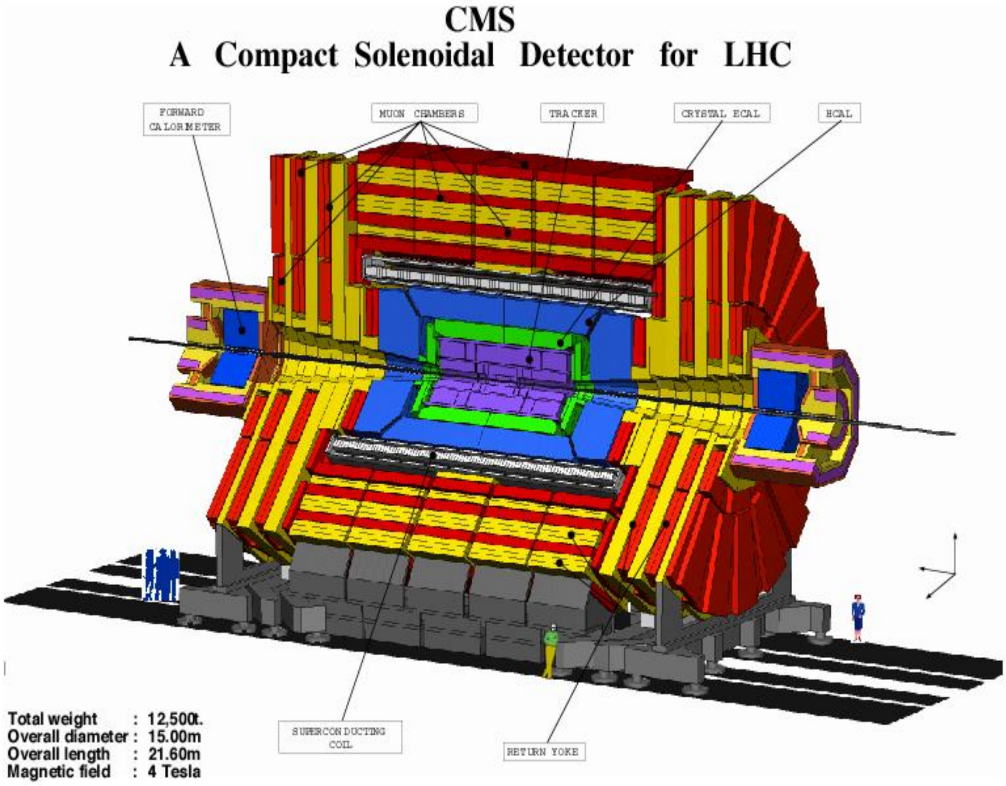


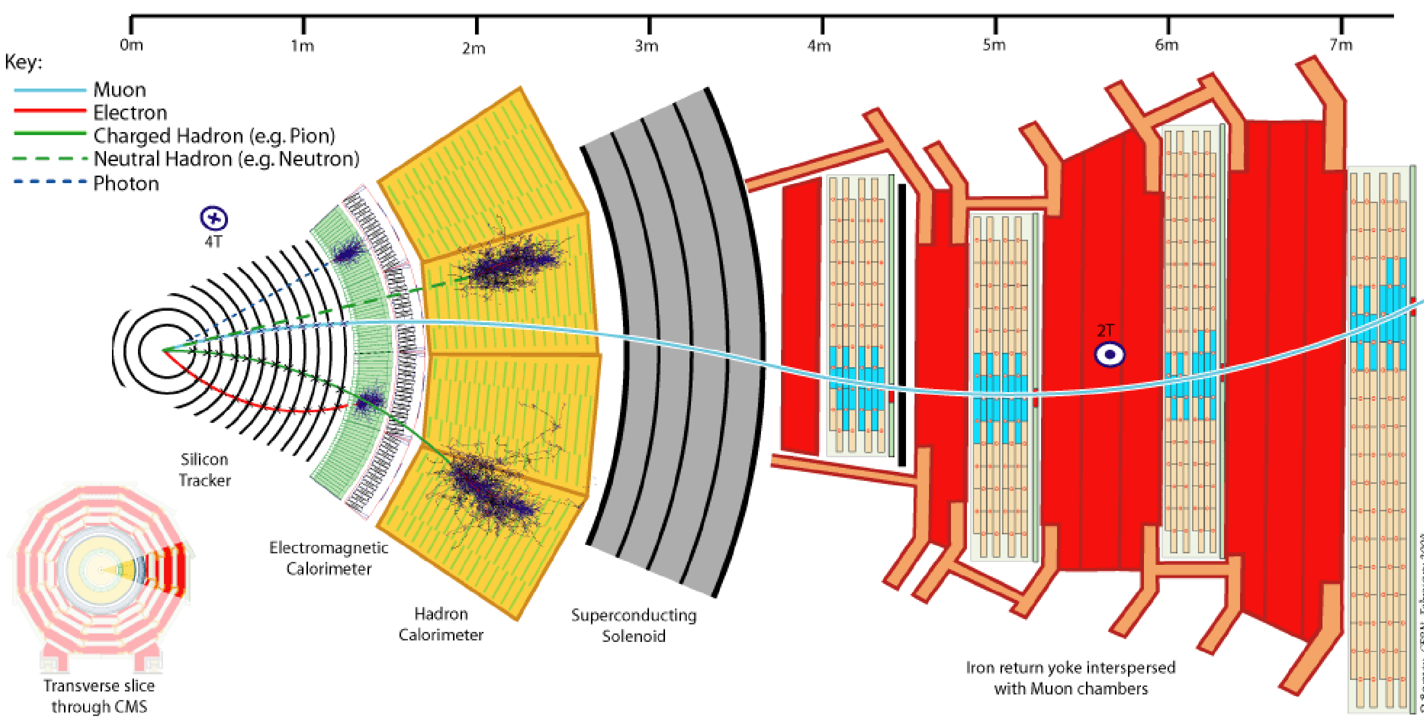
Fig. 1 - The ALEPH Detector

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

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







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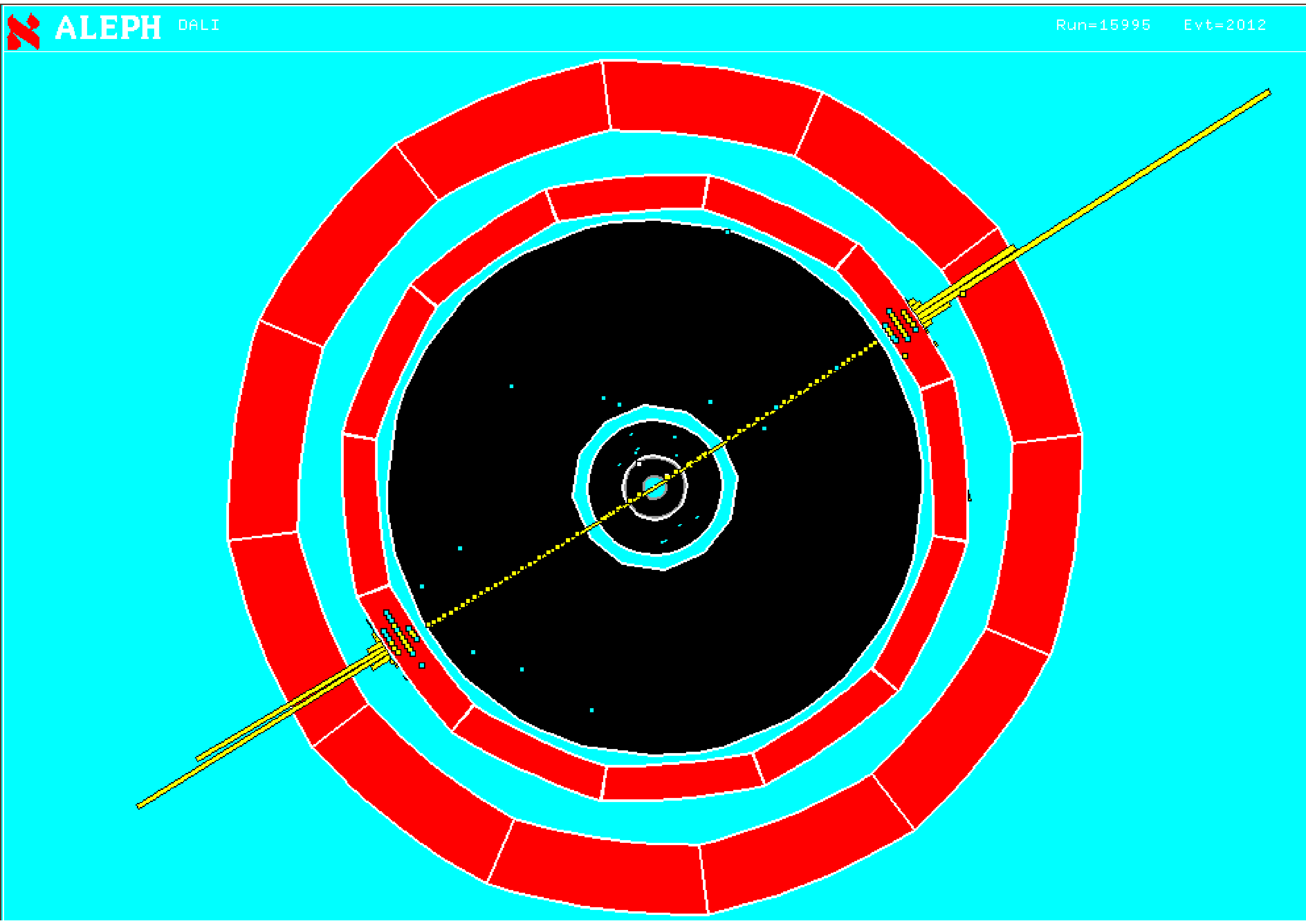
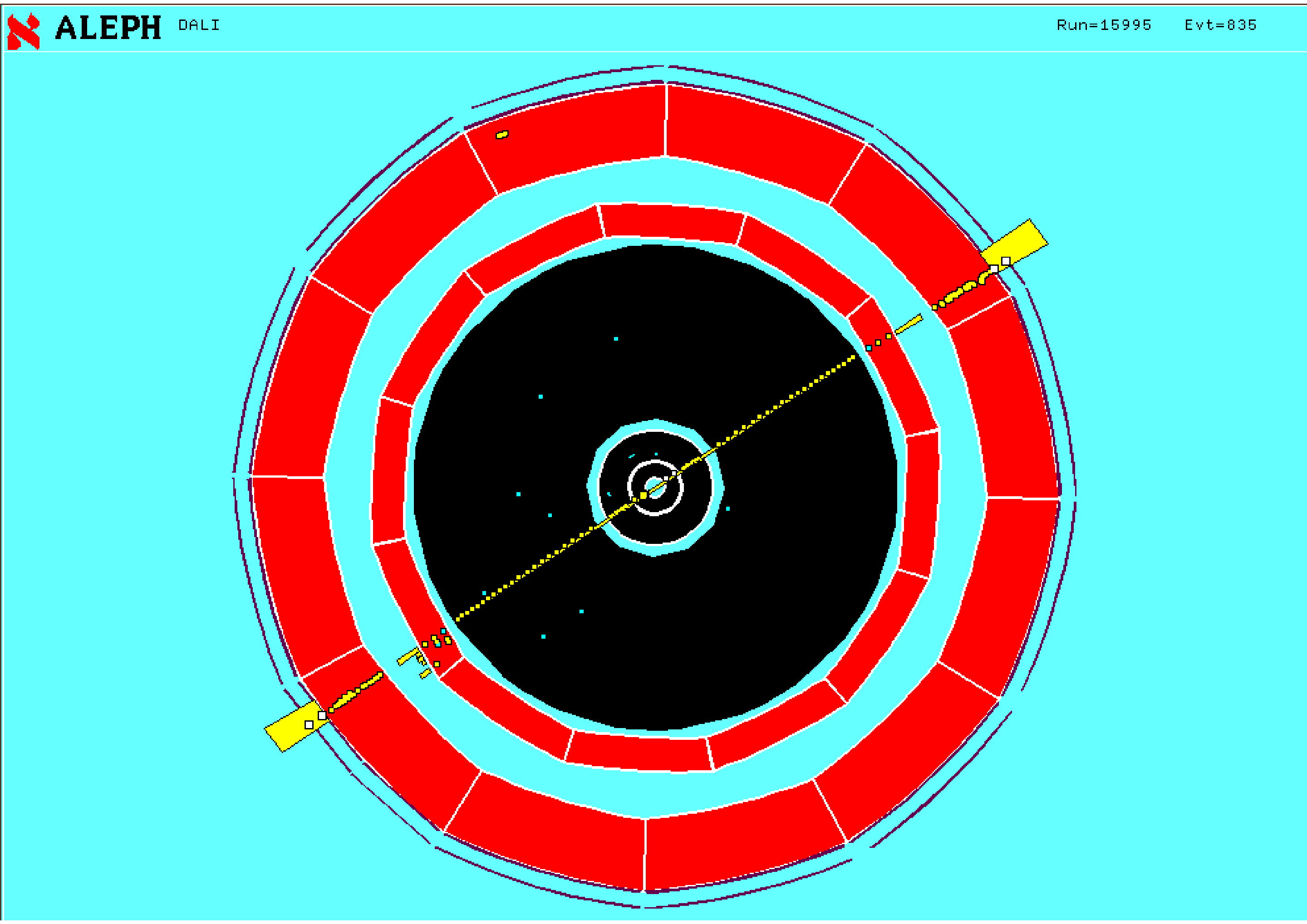
$Z \rightarrow e^+ e^-$

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



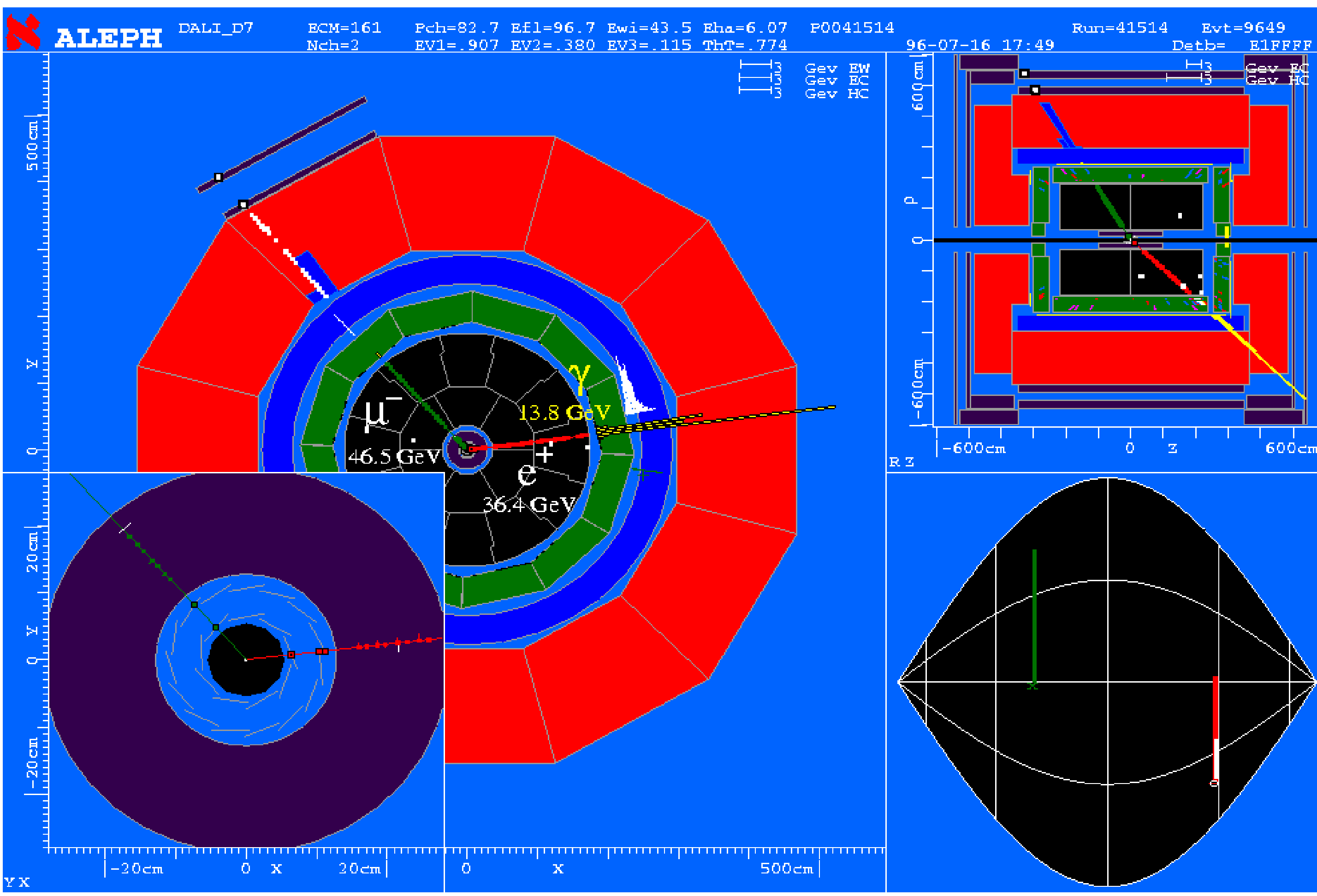
$Z \rightarrow \mu^{+} \mu^{-}$

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



$W^+W^- \rightarrow$ e+ ○ + ■$_e$+■$_○$

Single electron, single Muon, Missing Momentum



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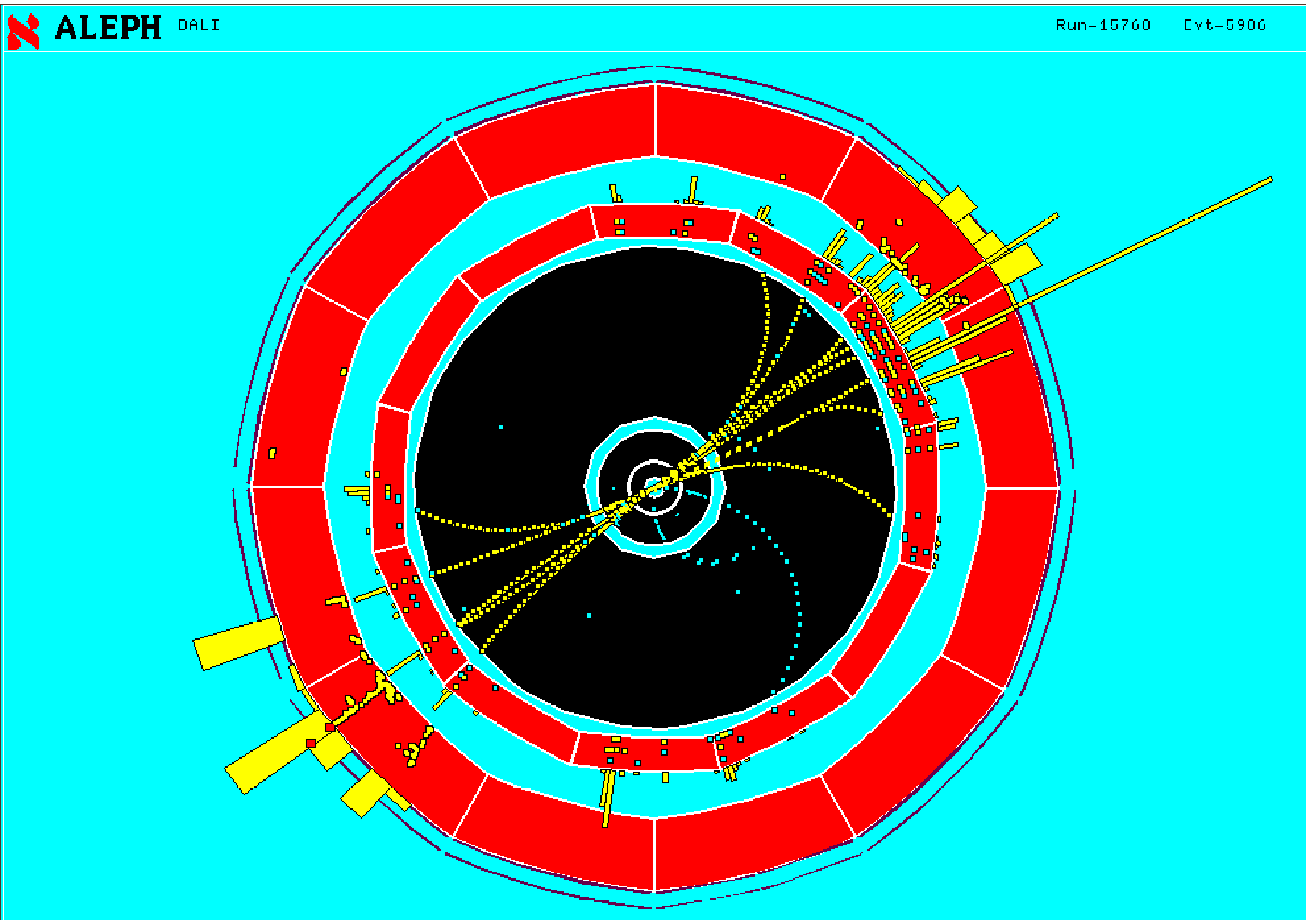
$Z \rightarrow q\bar{q}$

Two jets of particles



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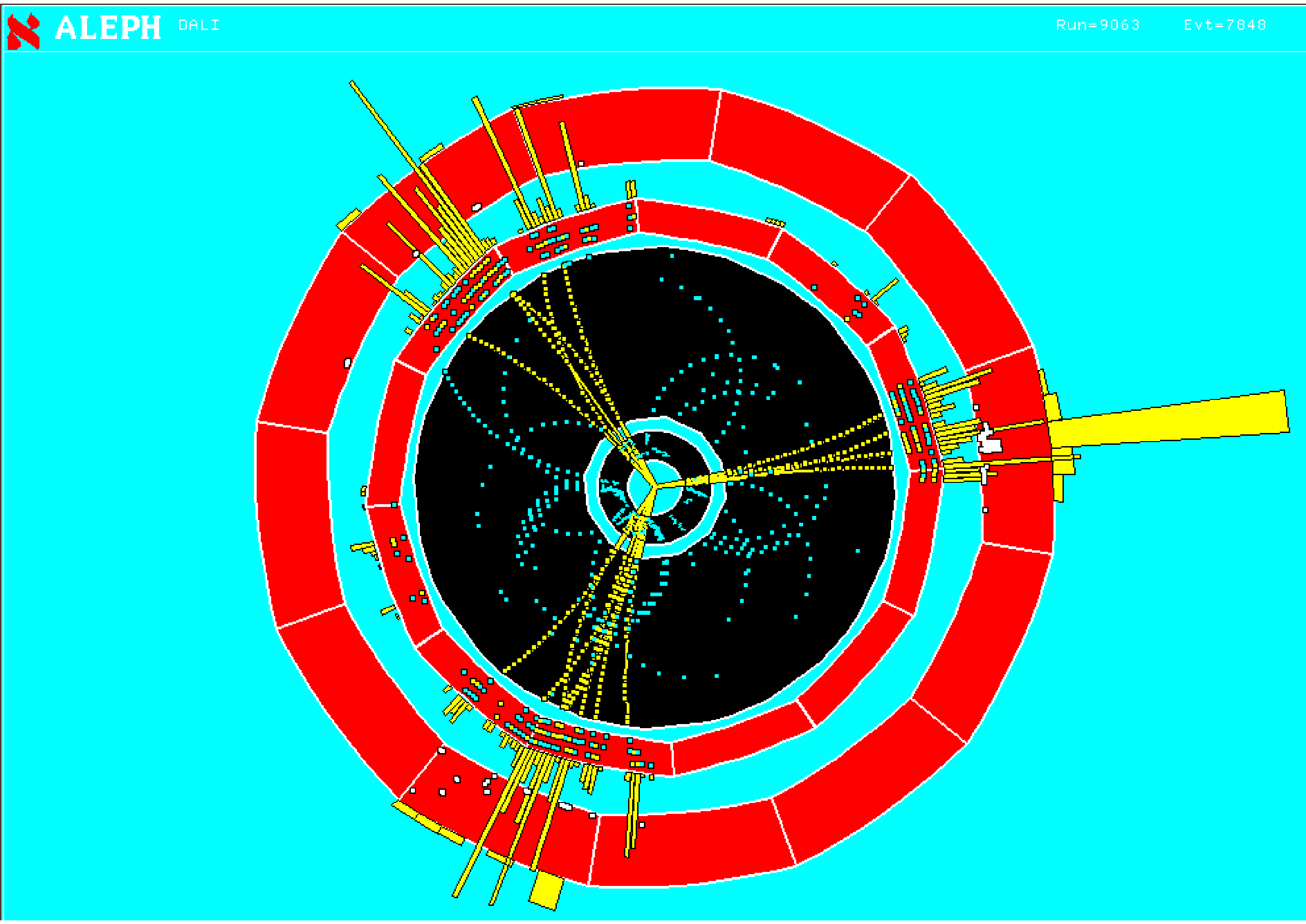
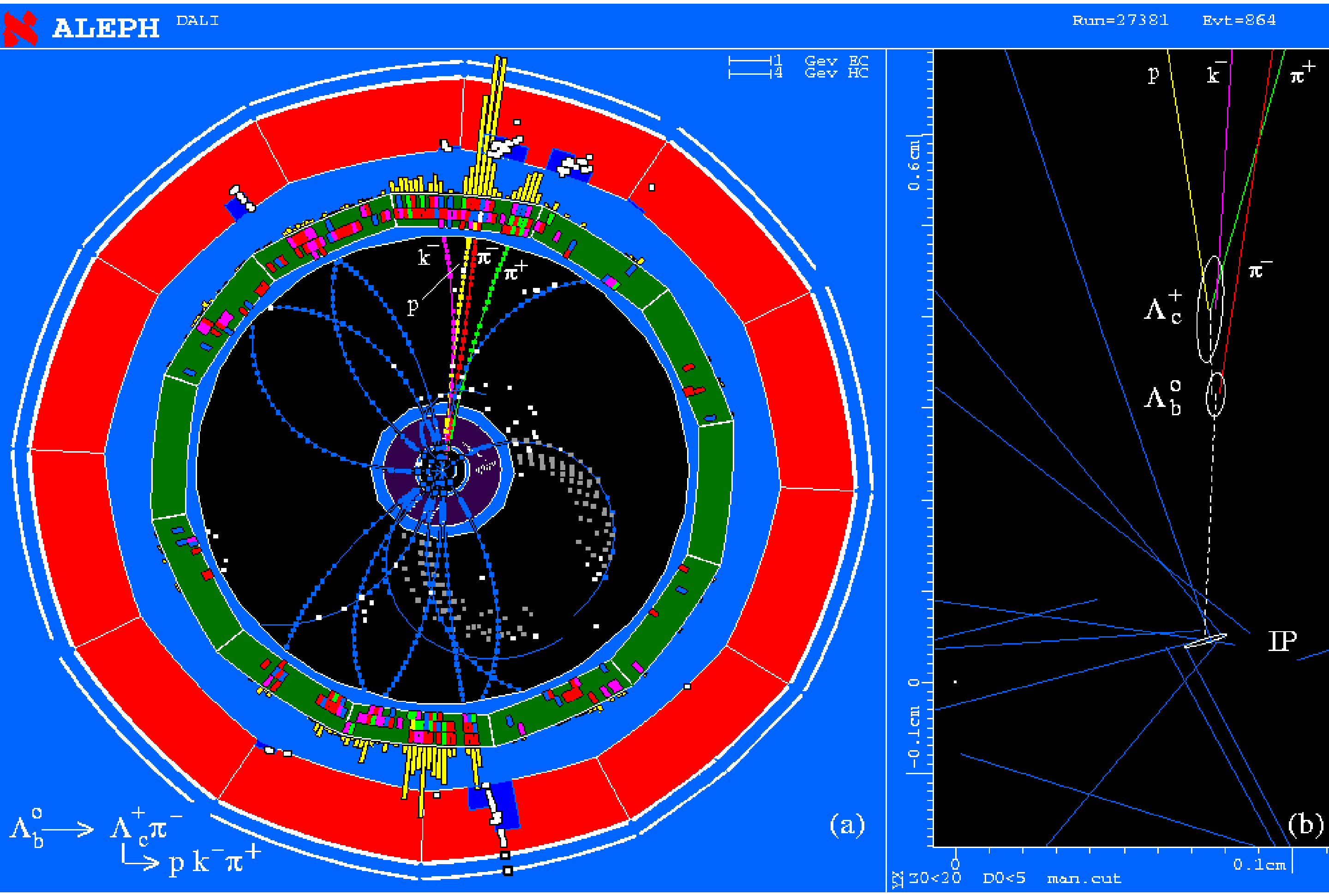
$Z \rightarrow q \bar{q} g$

Three jets of particles

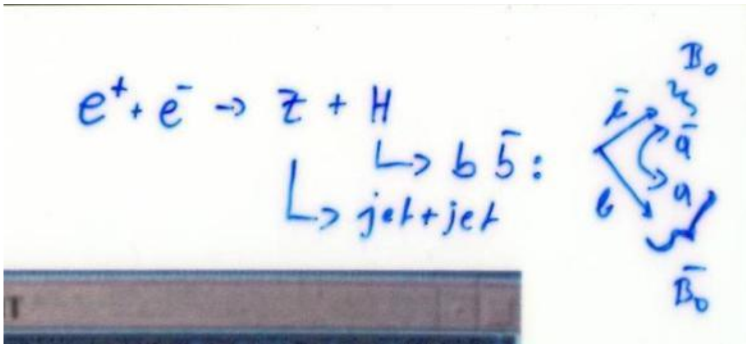


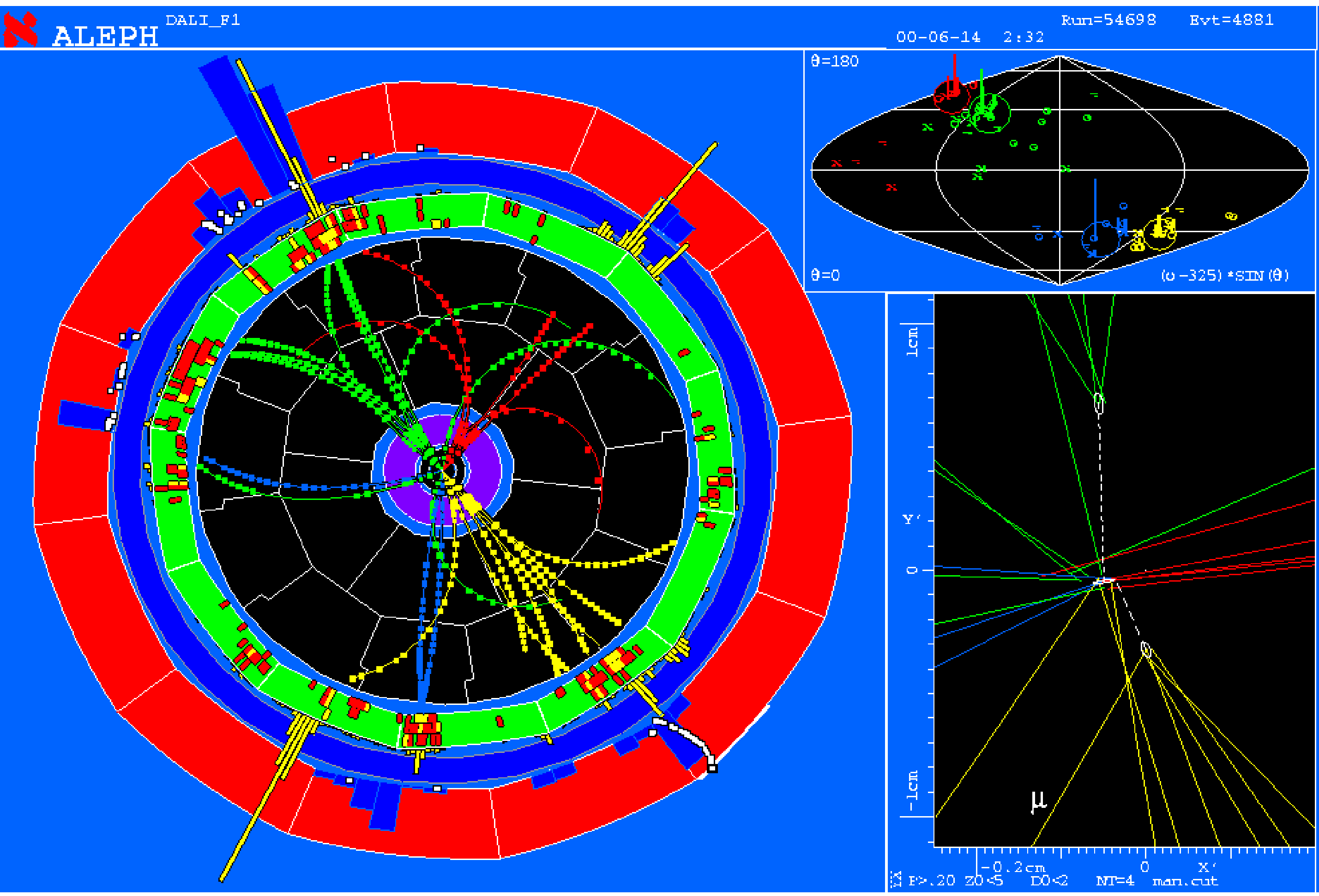
Two secondary vertices with characteristic decay particles giving invariant masses of known particles.

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



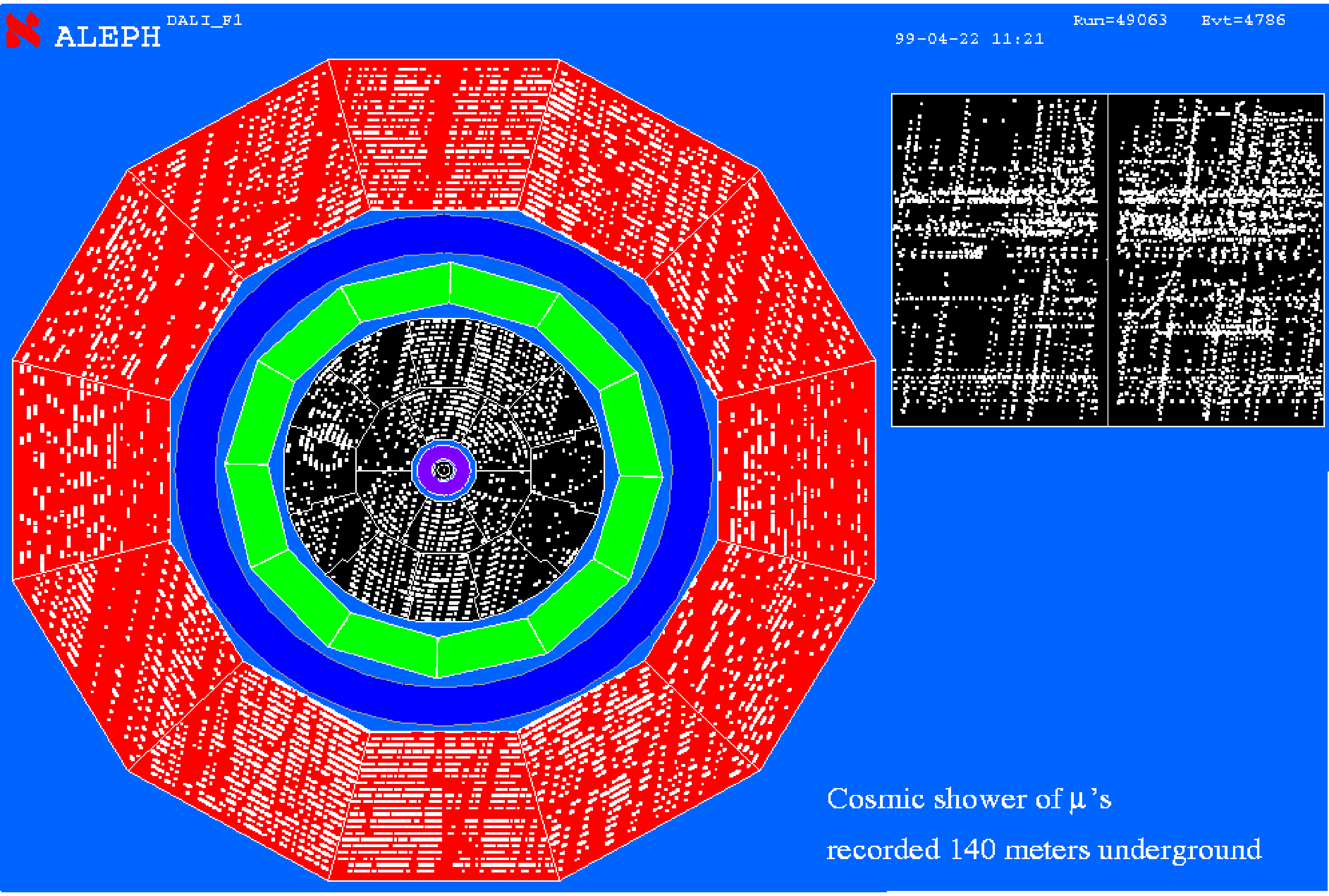
ALEPH Higgs Candidate



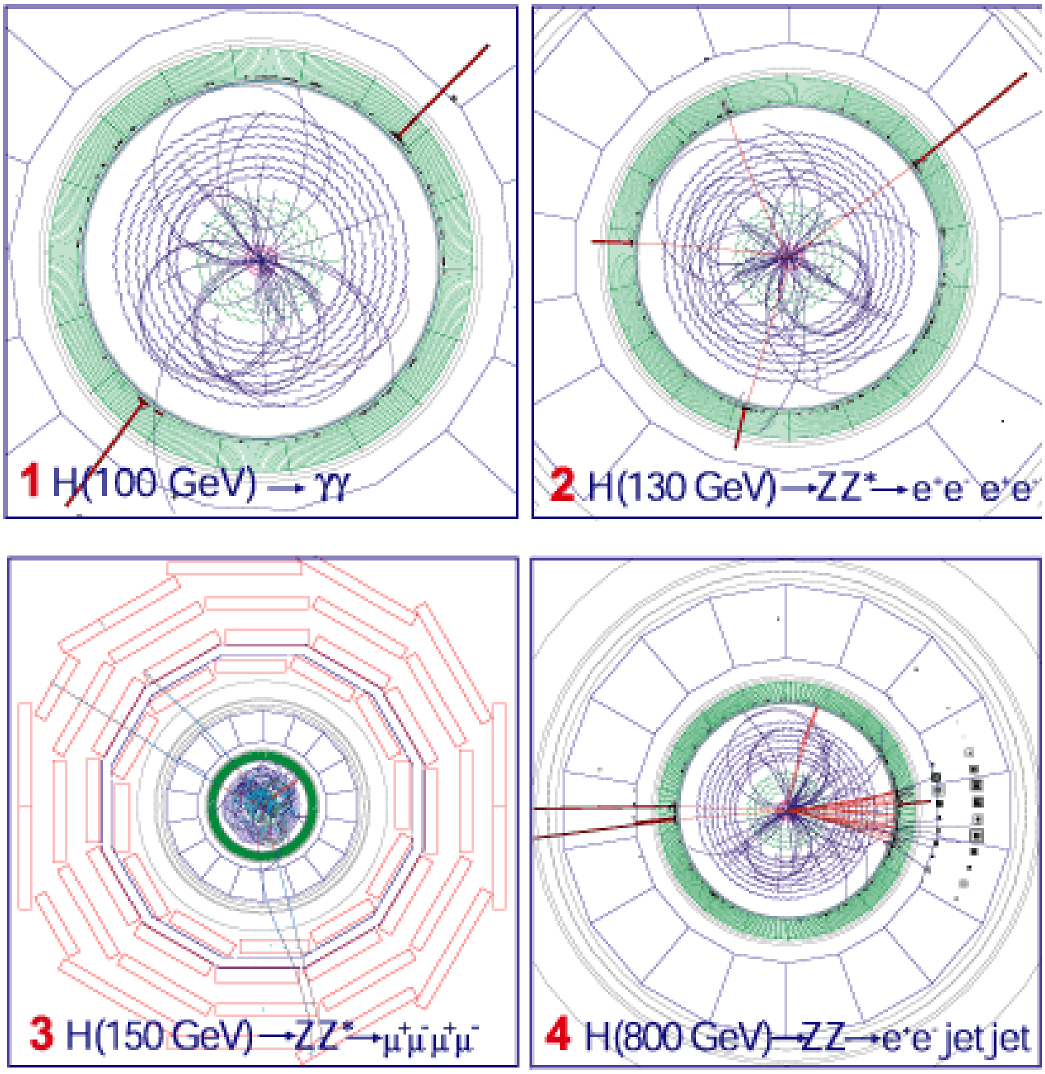


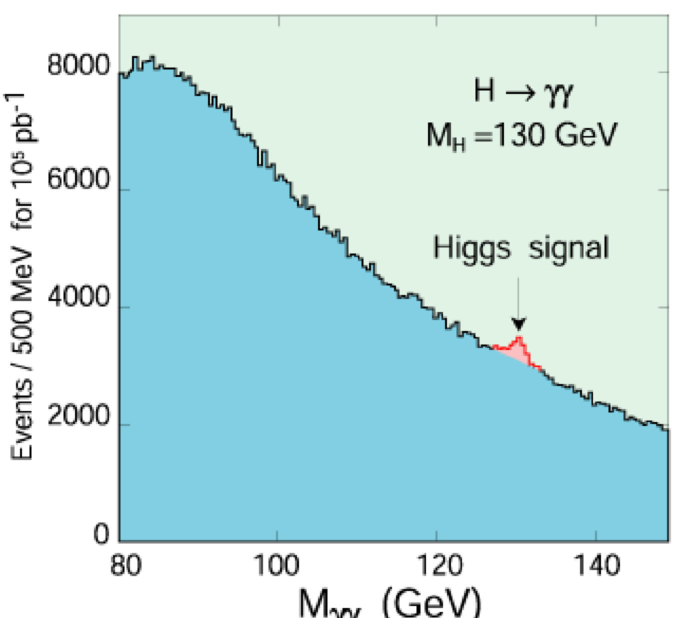
Undistinguishable background exists. Only statistical excess gives signature.

Cosmic Shower of Muons



Higgs Boson at CMS





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

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Conclusion:

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.