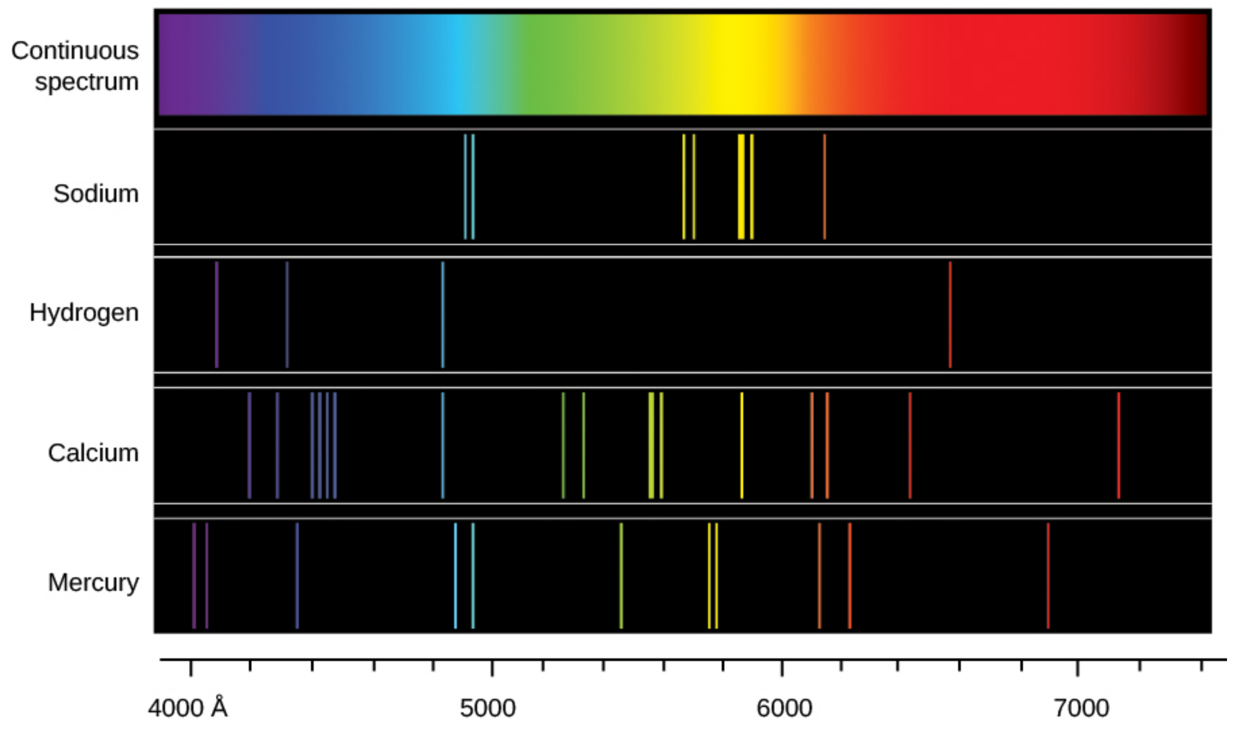
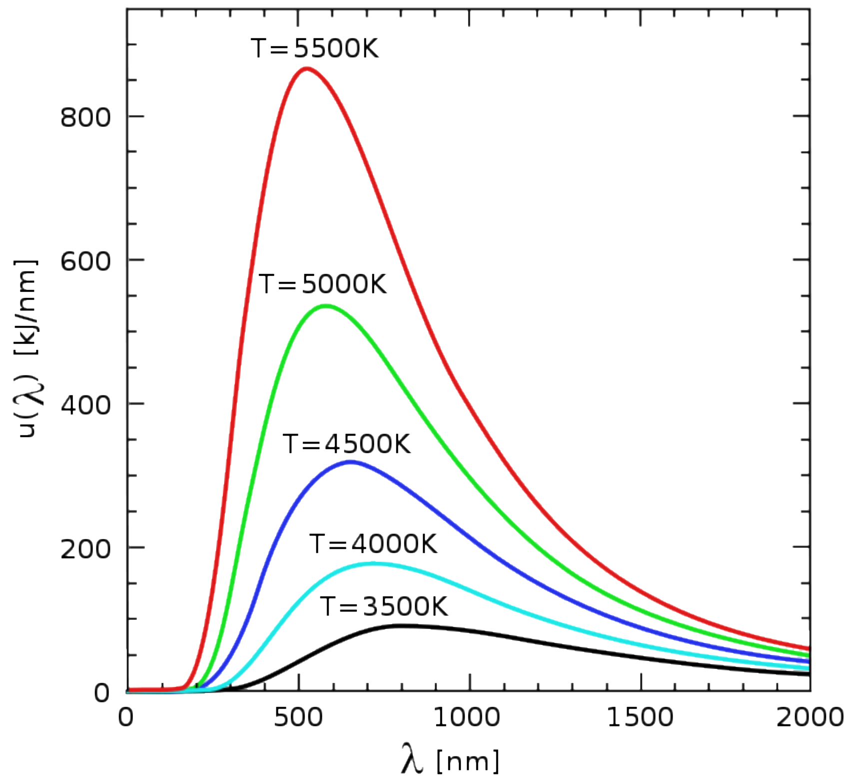
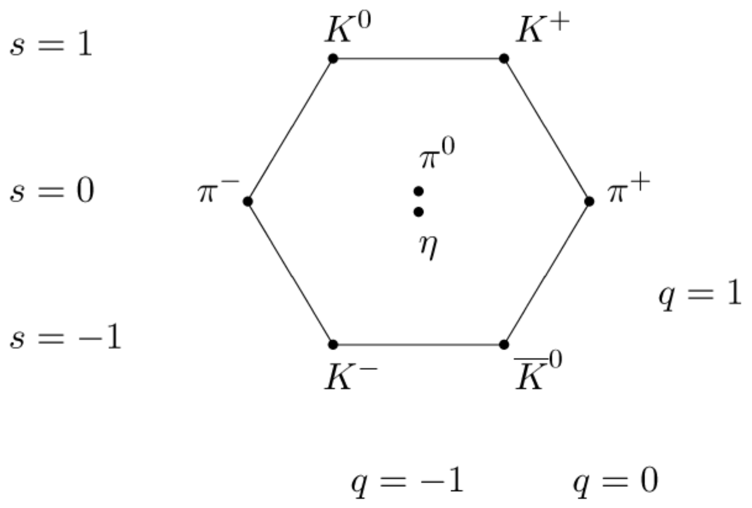
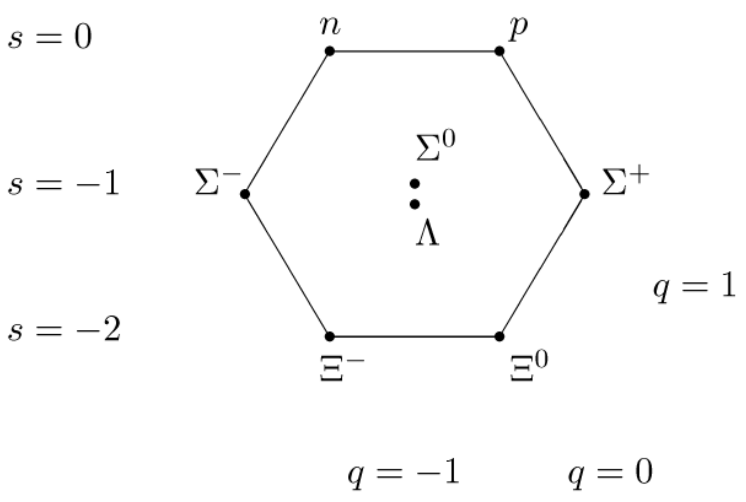
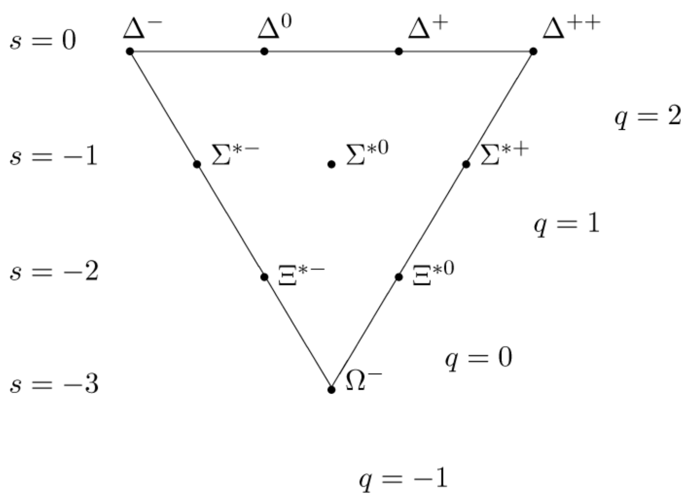
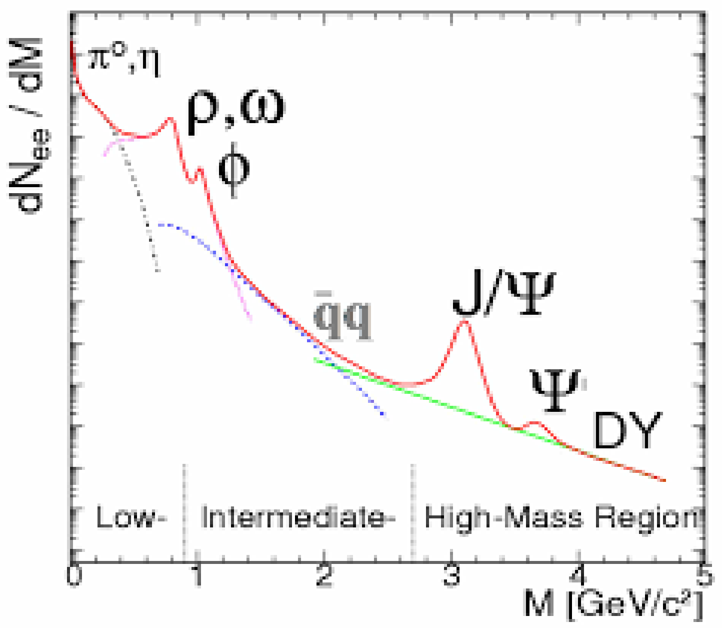

Continuous spectrum
Sodium
Hydrogen
Calcium
Mercury
4000 Å
5000
6000
7000


T=5500K
T=5000K
T=4500K
T=4000K
T=3500K
u(λ) [kJ/nm]
λ [nm]
0
200
400
600
800
0
500
1000
1500
2000


s = 1
s = 0
s = −1
K^0
K^+
π^−
π^0
η
π^+
K^−
K̄^0
q = 1
q = −1
q = 0


s = 0
s = −1
s = −2
n
p
Σ^−
Σ^0
Λ
Σ^+
Ξ^−
Ξ^0
q = 1
q = −1
q = 0


s = 0
s = −1
s = −2
s = −3
Δ^−
Δ^0
Δ^+
Δ^++
Σ*−
Σ*0
Σ*+
Ξ*−
Ξ*0
Ω^−
q = 2
q = 1
q = 0
q = −1


dN_ee / dM
π°,η
ρ,ω
φ
q̄q
J/Ψ
Ψ'
DY
Low-
Intermediate-
High-Mass Region
0
1
2
3
4
5
M [GeV/c²]

Theorists React to the CERN 750 GeV Diphoton Data

Last December, the ATLAS and CMS Collaborations at the Large Hadron Collider reported preliminary data with a small excess of diphoton events at an invariant mass of about 750 GeV [1,2], which, if verified, would require unexpected new elementary particles. The collaborations have recently reanalyzed their data [3,4], and the signal has become slightly stronger. Though the results are extremely intriguing, more data are required to establish if the excess is real, or a statistical fluctuation.

Over 250 theory papers have appeared following the December announcement, and a number of them were submitted to us. We found it appropriate to publish a small sample of them. To maximize the coherence and fairness of our choices, we obtained informal advice from several experts.

Four such Letters appear in this issue [5–8]. Others may follow, but we think that this set gives readers a sense of the kind of new physics that would be required to explain the data, if confirmed.

Robert Garisto
Editor

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[3] M. Delmastro, Diphoton searches in ATLAS, 51st Rencontres de Moriond EW 2016.
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[5] Y. Nakai, R. Sato, and K. Tobioka, Footprints of New Strong Dynamics via Anomaly and the 750 GeV Diphoton, Phys. Rev. Lett. 116, 151802 (2016).
[6] G. Li, Y.-n. Mao, Y.-L. Tang, C. Zhang, Y. Zhou, and S.-h. Zhu, Pseudoscalar Decaying Only via Loops as an Explanation for the 750 GeV Diphoton Excess, Phys. Rev. Lett. 116, 151803 (2016).
[7] C. Petersson and R. Torre, 750 GeV Diphoton Excess from the Goldstino Superpartner, Phys. Rev. Lett. 116, 151804 (2016).
[8] W.S. Cho, D. Kim, K. Kong, S.H. Lim, K.T. Matchev, J.-C. Park, and M. Park, 750 GeV Diphoton Excess May Not Imply a 750 GeV Resonance, Phys. Rev. Lett. 116, 151805 (2016).

Published 12 April 2016
DOI: 10.1103/PhysRevLett.116.150001

Particle Detectors

Summer Student Lectures 2022

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

History of Instrumentation ↔ 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

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

E. Wigner:

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

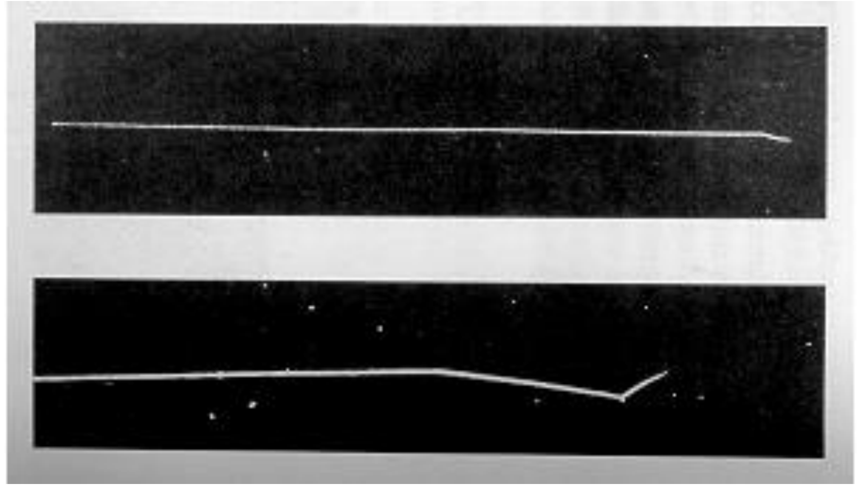
Spin=0,1/2,1,3/2 …
Mass ≥ 0

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

Particle Detector

W. Riegler:

A particle detector is a classical device, that is collapsing wave functions of quantum mechanical states, which are linear super positions of irreducible representations of the inhomogeneous Lorentz group (Poincare group).



Solvay Conference 1927, Einstein:

"A radioactive sample emits alpha particles in all directions; these are made visible by the method of the Wilson Cloud Chamber. Now, if one associates a spherical wave with each emission process, how can one understand that the track of each alpha particle appears as a (very nearly) straight line …. "

Born, Heisenberg:

"As soon as such an ionization is shown by the appearance of cloud droplets, in order to describe what happens afterwards one must reduce the wave packet in the immediate vicinity of the drops. One thus obtains a wave packet in the form of a ray, which corresponds to the corpuscular character of the phenomenon."

According to this reasoning the whole process is described in terms of the interaction of a quantum system (the alpha particle) with a classical measurement apparatus (the atoms of the vapour).

Nevill Mott (1929):

Assuming the atoms of the vapour also to be part of the quantum mechanical system, " … it is a little difficult to picture how it is that an outgoing spherical wave can produce a straight track; we think intuitively that it should ionise atoms at random throughout space."

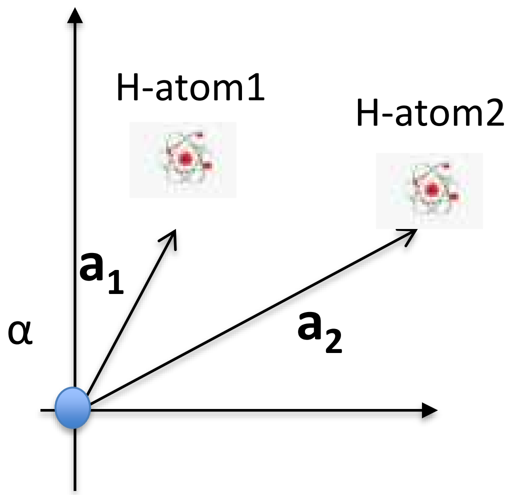
Mott considers and example with and alpha particle at the origin, one hydrogen atom at position $\mathbf{a_1}$ and another hydrogen atom at $\mathbf{a_2}$, and the two hydrogen atoms only having EM interaction with the alpha particle:

[Mo] Mott N.F., The wave mechanics of α-ray tracks. *Proc. R. Soc. Lond. A*, **126**, 79-84, 1929. Reprinted in: Wheeler J.A., Zurek W., *Quantum Theory and Measurement*, Princeton University Press, 1983.

Main objects of the investigation are periodic solutions $F(\boldsymbol{R}, \boldsymbol{r_1}, \boldsymbol{r_2})e^{iEt/\hbar}$ of the Schrödinger equation for the three particle system, where $\boldsymbol{R}$, $\boldsymbol{r_1}$, $\boldsymbol{r_2}$ denote the coordinates of the α-particle and of the two hydrogen atom electrons respectively. The function F (depending parametrically on E) is solution of the stationary Schrödinger equation

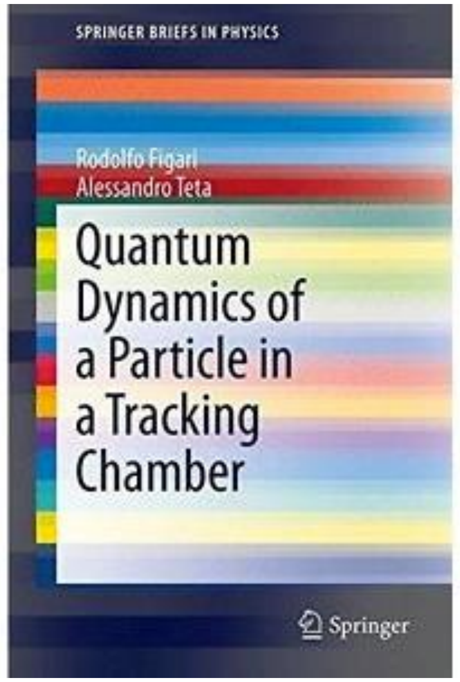
$$-\frac{\hbar^2}{2M}\Delta_R F + \left(-\frac{\hbar^2}{2m}\Delta_{r_1} - \frac{e^2}{|\boldsymbol{r_1} - \boldsymbol{a_1}|}\right)F + \left(-\frac{\hbar^2}{2m}\Delta_{r_2} - \frac{e^2}{|\boldsymbol{r_2} - \boldsymbol{a_2}|}\right)F$$
$$-\left(\frac{2e^2}{|\boldsymbol{R} - \boldsymbol{r_1}|} + \frac{2e^2}{|\boldsymbol{R} - \boldsymbol{r_2}|}\right)F = E\,F \tag{4.1}$$

where Δ_x is the laplacian with respect to the coordinate x, M is the mass of the α-particle, m is the mass of the electron, $-e$ is the charge of the electron so that $2e$ is the charge of the α-particle.

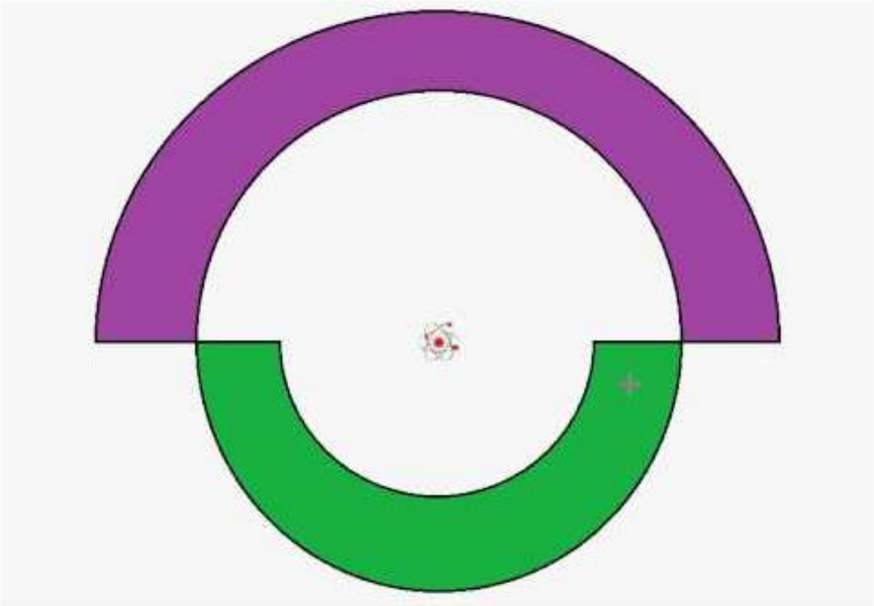


Result: The two hydrogen atoms cannot both be excited (or ionized) unless $\mathbf{a_1}$, $\mathbf{a_1}$ and the origin lie on the same straight line.
(see Also Werner Heisenberg, Chicago lectures 1930)

This example (i.e. moving the boundary between the quantum system and classical measurements device) is also used by S. Coleman in the lecture
Quantum Mechanics in Your Face [1994] https://www.youtube.com/watch?v=EtyNMlXN-sw
to show how the collapse of the wave function and other 'interpretations of QM' become unnecessary if one removes this boundary and simply considers the entire world (including us) as QM systems.



Renninger's negative-result experiment (1953)



A radioactive atom (emitting and alpha particle) is placed in the center of a detector that consists of two hemispheres and that are 100% efficient to alpha particles.

Considering the second (purple) hemisphere to be very large, the absence of the a signal on the green detector after a given time will indicate that the alpha particle will hit the purple detector.

The QM analysis will come out right, with a given probability for the red or the green part to fire and zero probability that both fire.

The semi-classical analysis is however confusing:
The wave-function has collapsed although there was no measurement performed with the green detector ?
A non measurement collapses a wave-function ?

The ‘Real’ World of Particles

W. Riegler:

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

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

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

The ‘Real’ World of Particles

Elektro-Weak Lagrangian

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

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

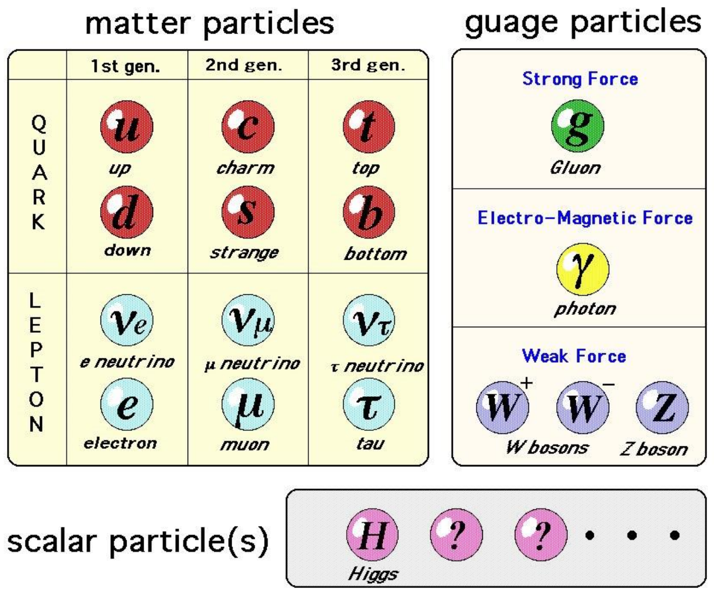
$$+ g' \left\{ \frac{1}{6} \sum_q \left[\bar{L}_q \gamma_\mu L_q + 4 \bar{R}_q \gamma_\mu R_q \right] + \frac{1}{3} \sum_{q'} \bar{R}_{q'} \gamma_\mu R_{q'} \right\} B^\mu$$

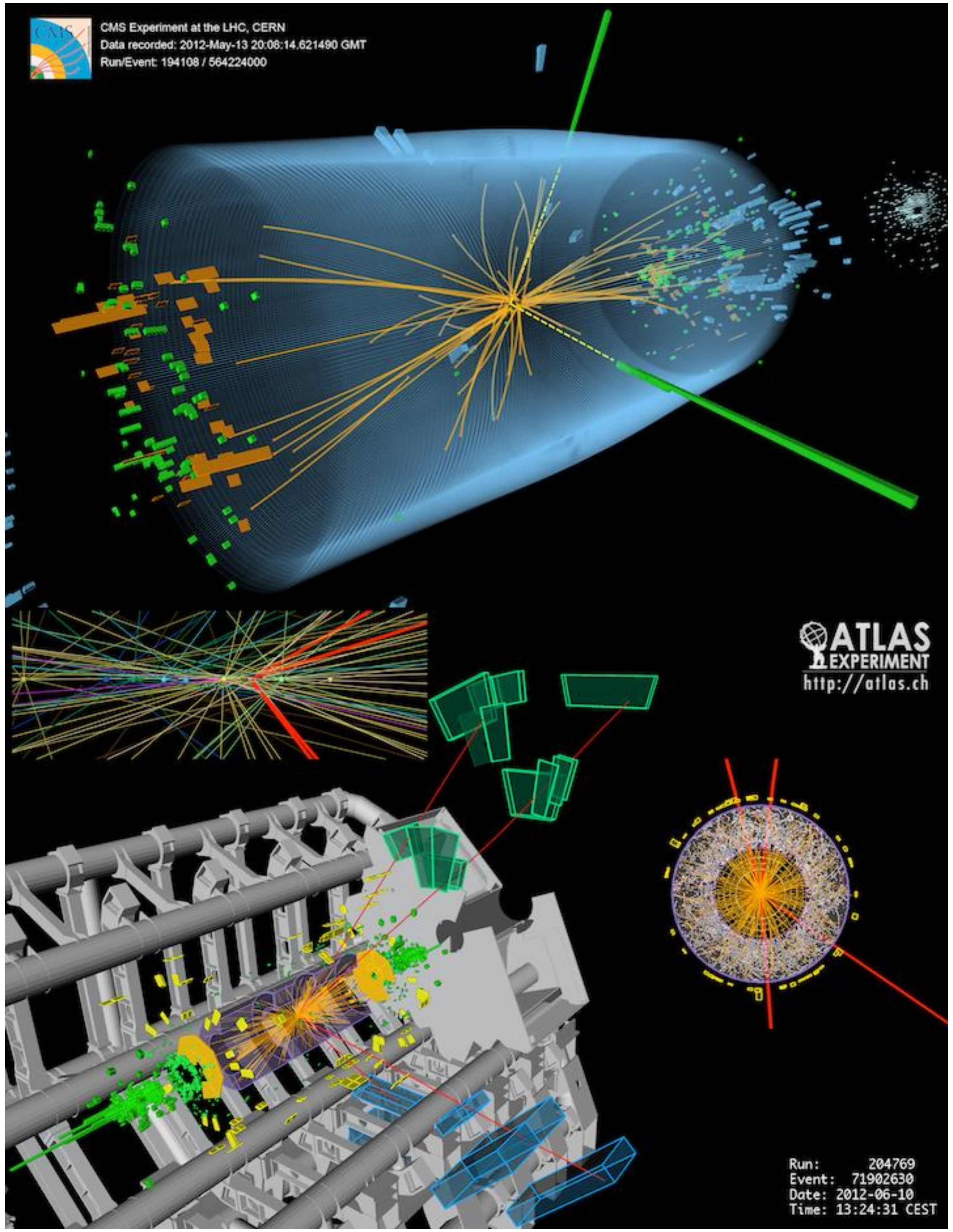
$$L_H = \frac{1}{2} (\partial_\mu H)^2 - m_H^2 H^2 - h\lambda H^3 - \frac{h}{4} H^4 +$$

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

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

Higgs Particle





The 'Real' World of Particles

1	e^-	μ^-	τ^-	Electromagnetic, Weak
0	ν_e	ν_μ	ν_τ	Weak
$\frac{2}{3}$	u	c	t	Electromagnetic, Weak, Strong
$-\frac{1}{3}$	d	s	b	Electromagnetic, Weak, Strong

Spin $\frac{1}{2}$ Particles

Spin 1 Particles

$p \sim uud$, 

$n \sim udd$

$\pi \sim u\bar{d}, \bar{u}d, \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$

$K \sim u\bar{s}, d\bar{s}, \bar{d}s, d\bar{s}$

$\Lambda \sim uds$

EM: γ - Photon QED

Weak: $W^\pm, Z^0$ Electroweak

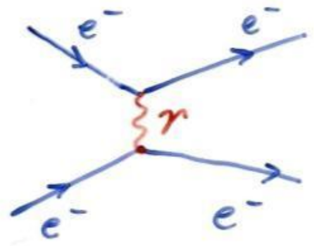
Strong: g - Gluon QCD

2

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

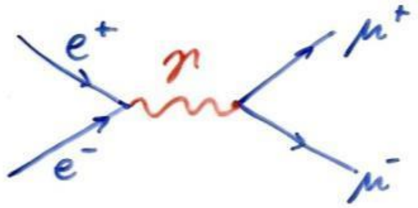
Electromagnetic Interaction γ - Photon

Scattering:



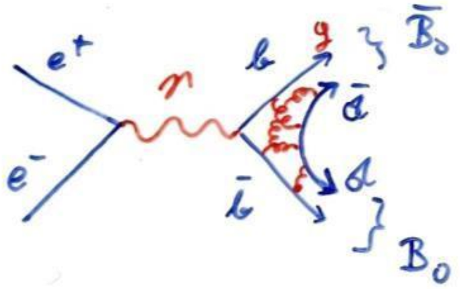
$e^- + e^- \to e^- + e^-$

Anihilation:



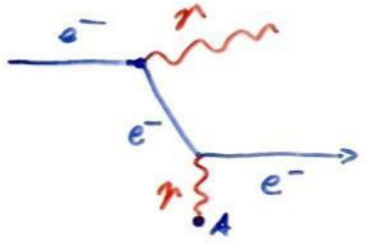
$e^+ + e^- \to \mu^+ + \mu^-$

Anihilation:



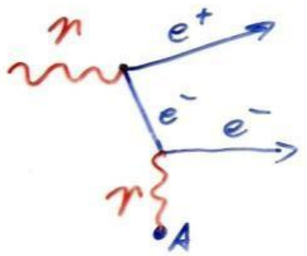
$e^+ + e^- \to B_0 + \bar{B}_0$

Bremsstrahlung:



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

Pair Production:



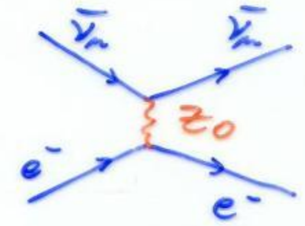
$\gamma + \text{Atom} \to e^+ + e^- + \text{Atom}$

3

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

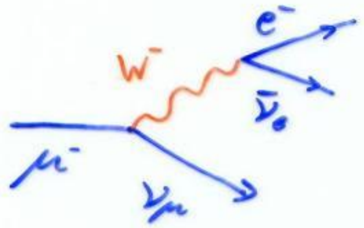
Weak Interaction $W^\pm, Z^0$

Neutral Current:



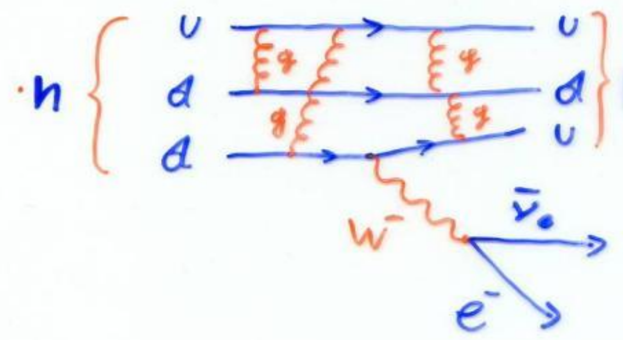
$e^- + \bar{\nu}_\mu \to e^- + \bar{\nu}_\mu$

Muon Decay:



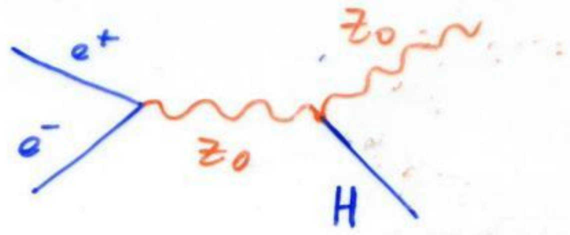
$\mu^- \to \nu_\mu + e^- + \bar{\nu}_e$

Neutron Decay:



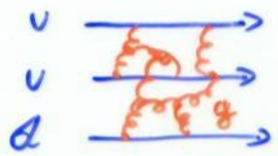
$n \to p + e^- + \bar{\nu}_e$

H Production:



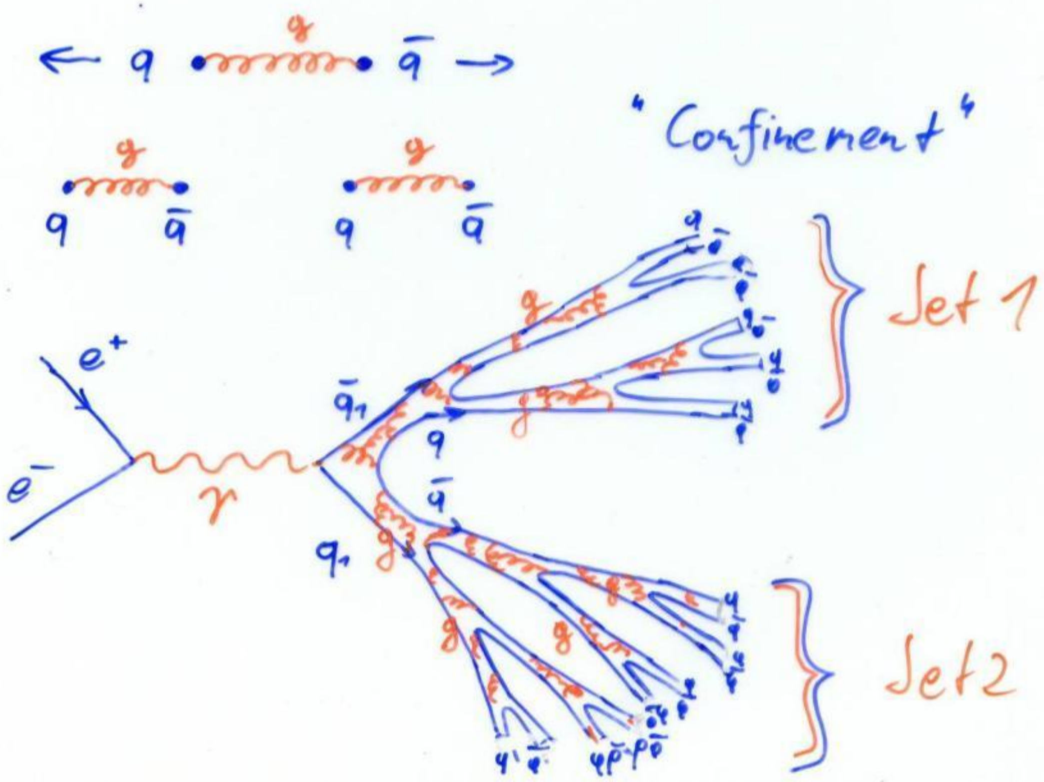
$$\begin{matrix} 1 \\ 0 \end{matrix} \begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix} \quad \begin{matrix} \frac{2}{3} \\ -\frac{1}{3} \end{matrix} \begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix}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

Strong Interaction   g   Gluons



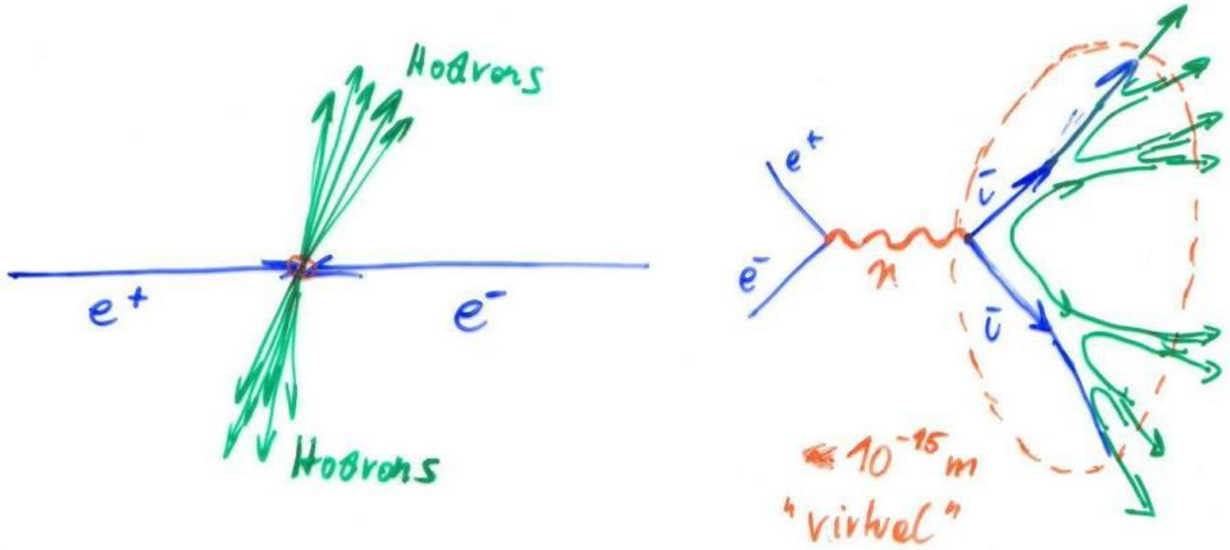
Proton

Self Interaction



.... 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

⋮

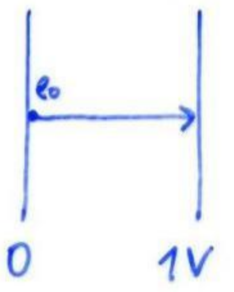
$m(\text{electron}) = 9.1 \cdot 10^{-31}\ \text{kg}$

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

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

$= 0.511$ MeV

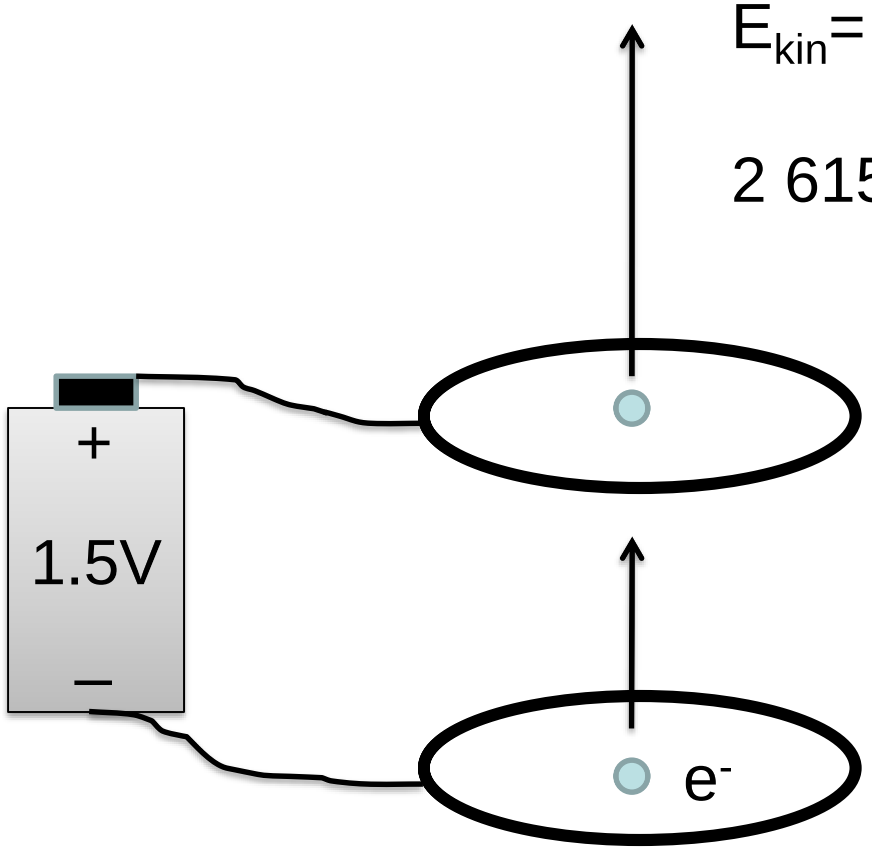
1 Electron Volt $= e_0 \cdot 1\text{V} = 1.603 \cdot 10^{-19}$ J



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

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

Build your own Accelerator



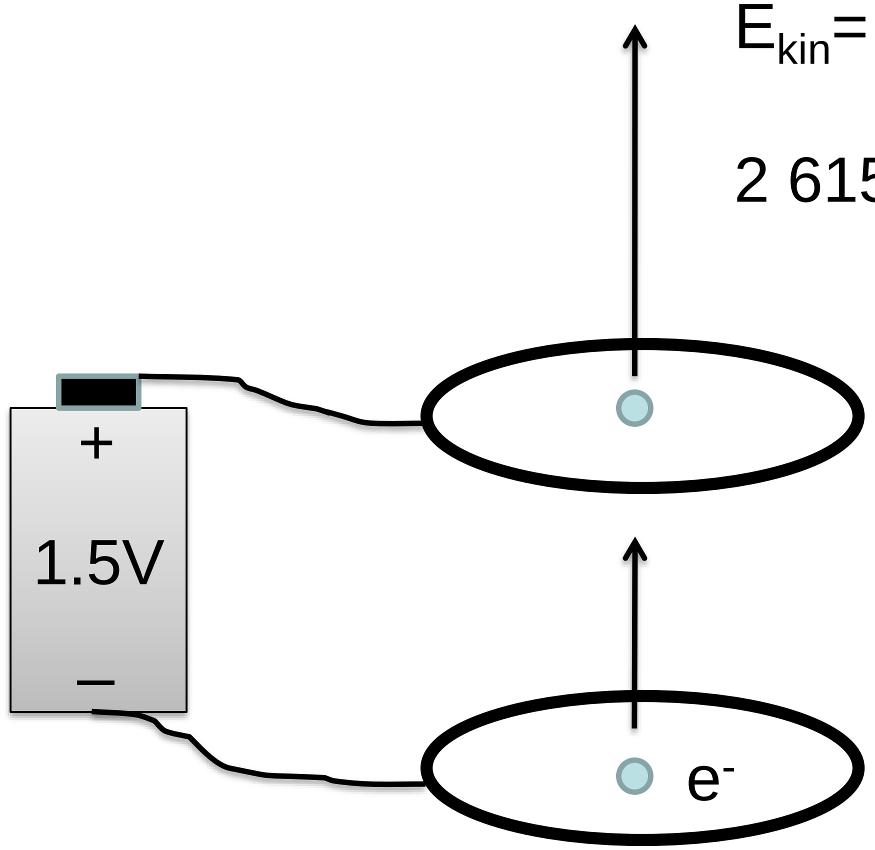
E_{kin}= 1.5eV =

2 615 596 km/h

Build your own Accelerator

E_{kin}= 1.5eV =

2 615 596 km/h



The LHC produces 2 x 7 000 000 000 000 eV protons

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

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

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

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

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

E.g.: $^{241}_{95}Am \to \alpha$ with $E_{kin} = 5.486\,MeV$, $m_\alpha c^2 = 3.75\,GeV$

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

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

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

Basics:

Lorentz Boost

Lorentz Boost:

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

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

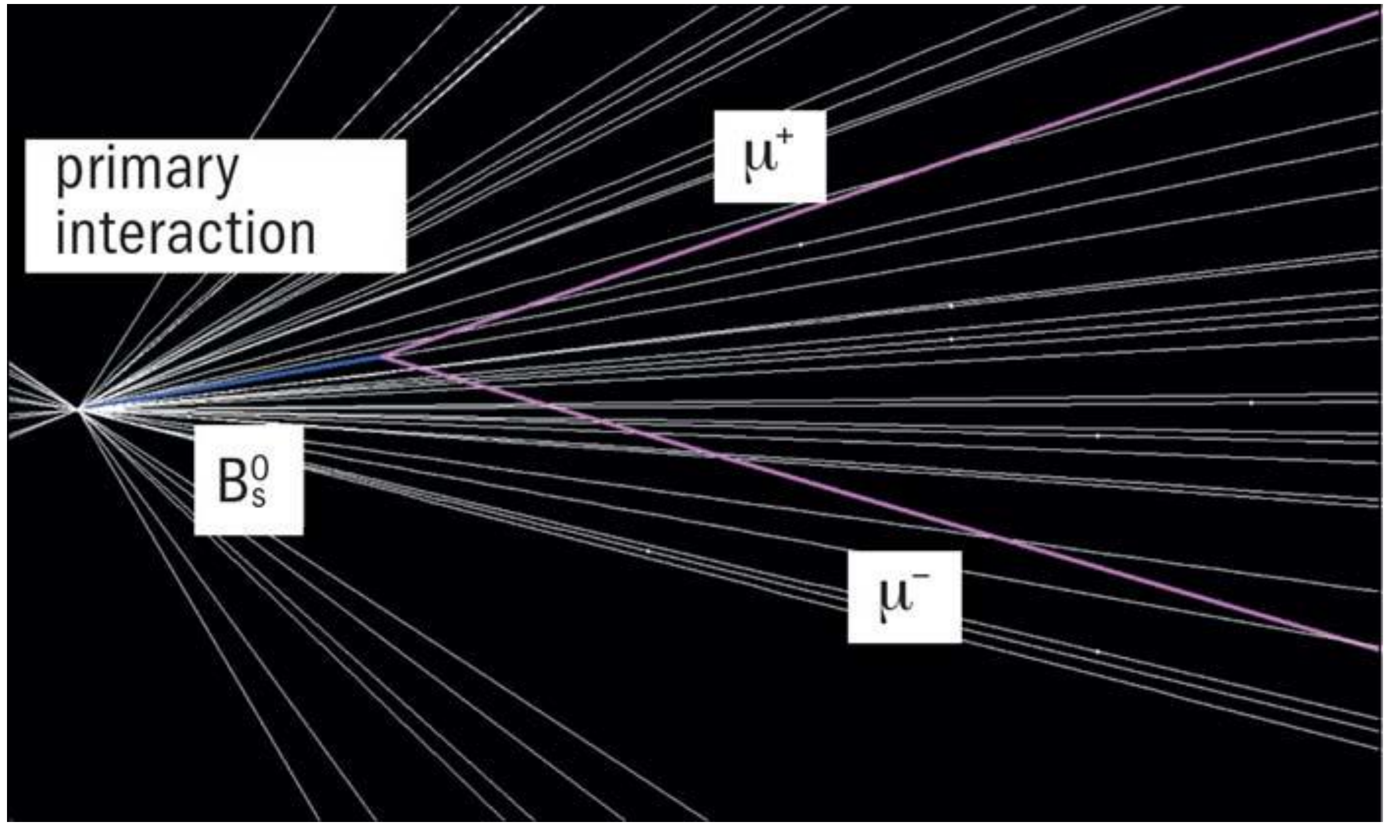
$$s = c \cdot \bar{\tau} = 12.5\, km \rightarrow \text{Earth}$$

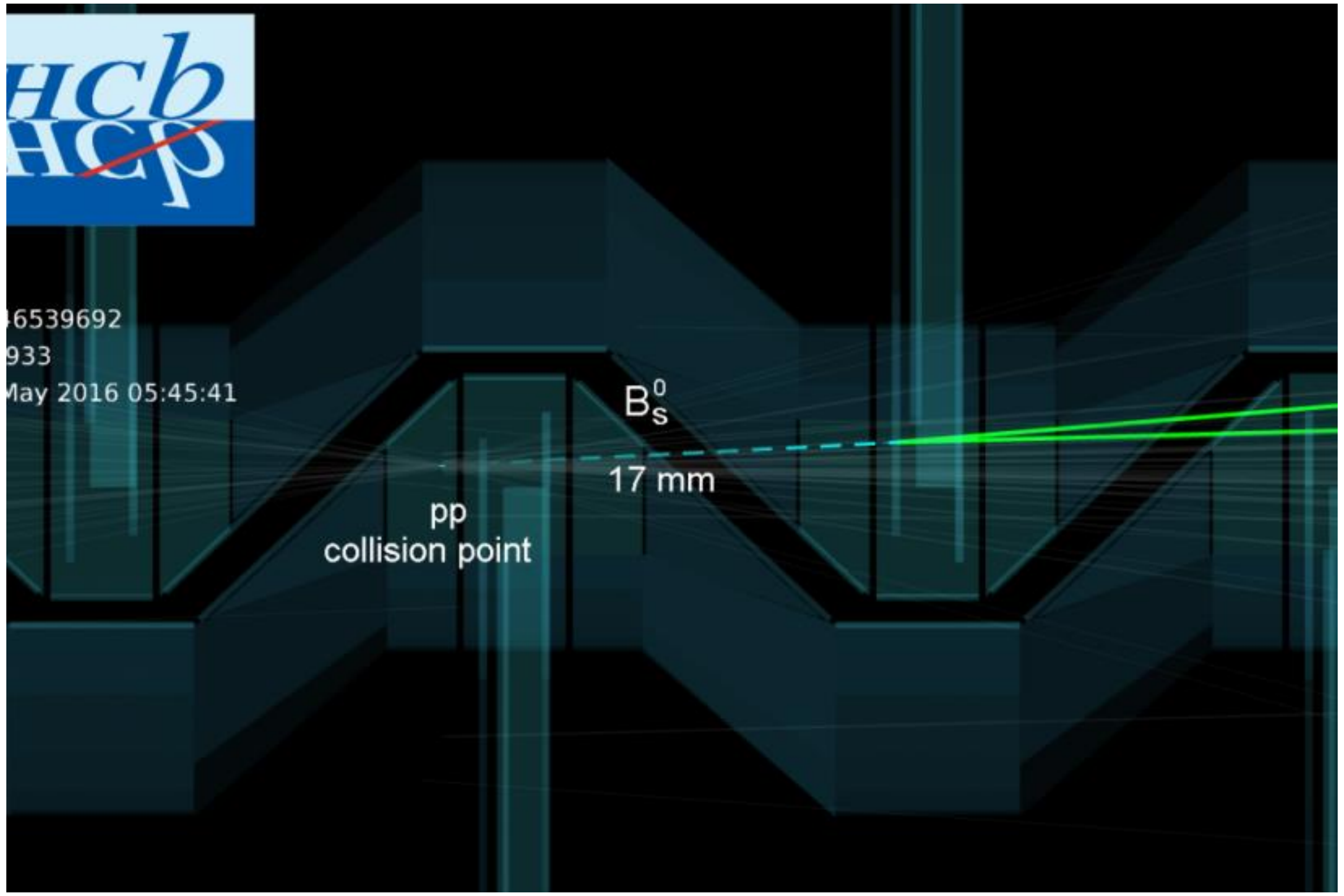
Pions: $\pi^+, \pi^- \quad \tau \sim 2.6 \cdot 10^{-8}\, s,\; m_\pi c^2 = 135\, MeV$

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

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

LHCb B decay

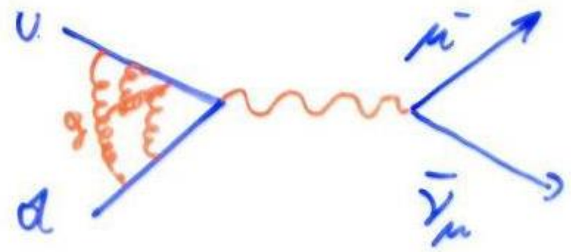




Basics:

Two Body Decay

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



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

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

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

$$0 = \frac{m_\mu v_1}{\sqrt{1-\frac{v_1^2}{c^2}}} + \frac{m_\nu v_2}{\sqrt{1-\frac{v_2^2}{c^2}}}$$

$$m_\pi c^2 = \frac{m_\mu c^2}{\sqrt{1-\frac{v_1^2}{c^2}}} + \frac{m_\nu c^2}{\sqrt{1-\frac{v_2^2}{c^2}}}$$

$\Big\}\ v_1, v_2$

E_μ, E_ν are uniquely defined

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

Basics:

Three Body Decay

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

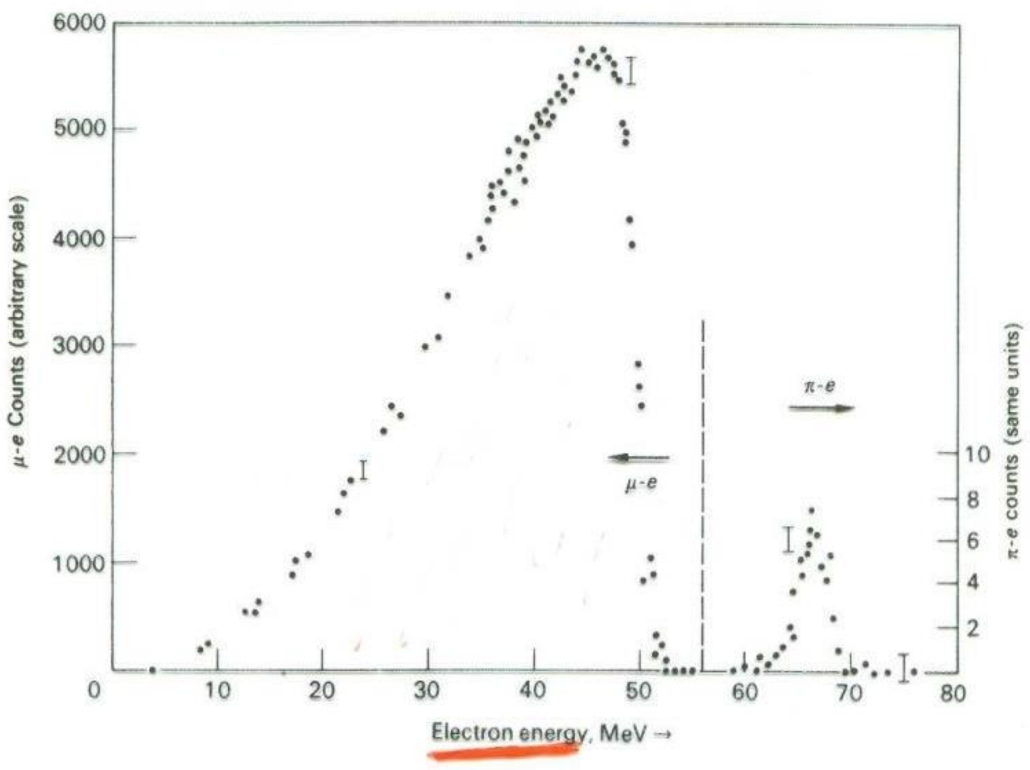
$$n \rightarrow p + e^- + \bar{\nu}_e$$

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.

Basics:

Two Body and
Three Body Decay

Stopping Pions and measuring the decay electron Spectrum:



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

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

$\quad\quad \hookrightarrow$ Energy Spectrum (3 Body Decay)

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

$\downarrow$

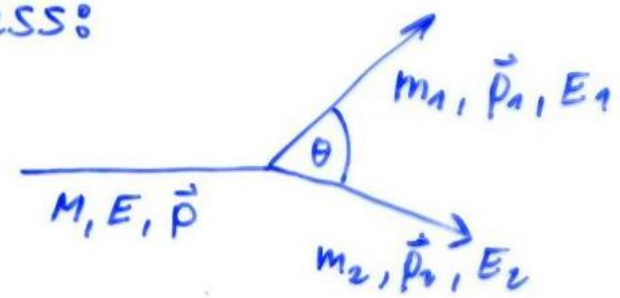
"sharp" Energy (2 Body Decay)

Basics:

Invariant Mass

Invariant Mass:

LAB:



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

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

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

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

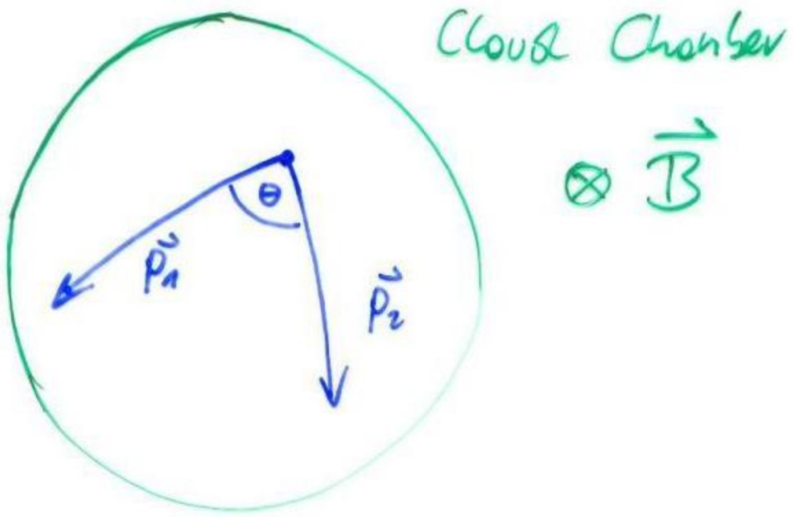
gives the Mass of the original Particle

Basics:

Invariant Mass

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)

Lifetime of a Particle → Exponential distribution

μ - Lifetime 15

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

What is the probability P(t)dt that the muon will decay between time t and t+dt after starting to measure it – independently of how long it lived before ?

Probability p that it decays within the time interval dt after starting to measure = p=P(0) dt = c_1 dt.

Probability that is does NOT decay in n time intervals dt but the (n+1)st time interval
= $(1- p)^n\, p \approx \exp(-n\, p)\, p$ with $p = c_1\, dt$.

n time intervals of dt means a time of t = n dt →

Probability that the particle decays between time t and t+dt = $\text{Exp}(-c_1 t)\, c_1\, dt = P(t)\, dt$!

→ $P(t) = c_1 e^{-c_1 t}$ → 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 $P(t) = \frac{1}{\tau} e^{-\frac{t}{\tau}}$

Known Particles

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

$\gamma, W^\pm, Z^0, g, e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau, \pi^\pm, \pi^0, \eta, f_0(600), \rho(770),$
$\omega(782), \eta'(958), f_0(980), a_0(980), \phi(1020), h_1(1170), b_1(1235),$
$a_1(1260), f_2(1270), f_1(1285), \eta(1295), \pi(1300), a_2(1320),$
$f_0(1370), f_1(1420), \omega(1420), \eta(1440), a_0(1450), \rho(1450),$
$f_0(1500), f_2'(1525), \omega(1650), \omega_3(1670), \pi_2(1670), \phi(1680),$
$\rho_3(1690), \rho(1700), f_0(1710), \pi(1800), \phi_3(1850), f_2(2010),$
$a_4(2040), f_4(2050), f_2(2300), f_2(2340), K^\pm, K^0, K^0_S, K^0_L, K^*(892),$
$K_1(1270), K_1(1400), K^*(1410), K_0^*(1430), K_2^*(1430), K^*(1680),$
$K_2(1770), K_3^*(1780), K_2(1820), K_4^*(2045), D^\pm, D^0, D^*(2007)^0,$
$D^*(2010)^\pm, D_1(2420)^0, D_2^*(2460)^0, D_2^*(2460)^\pm, D_s^\pm, D_s^{*\pm},$
$D_{s1}(2536)^\pm, D_{sJ}(2573)^\pm, B^\pm, B^0, B^*, B^0_s, B^\pm_c, \eta_c(1S), J/\psi(1S),$
$\chi_{c0}(1P), \chi_{c1}(1P), \chi_{c2}(1P), \psi(2S), \psi(3770), \psi(4040), \psi(4160),$
$\psi(4415), \Upsilon(1S), \chi_{b0}(1P), \chi_{b1}(1P), \chi_{b2}(1P), \Upsilon(2S), \chi_{b0}(2P),$
$\chi_{b2}(2P), \Upsilon(3S), \Upsilon(4S), \Upsilon(10860), \Upsilon(11020), p, n, N(1440),$
$N(1520), N(1535), N(1650), N(1675), N(1680), N(1700), N(1710),$
$N(1720), N(2190), N(2220), N(2250), N(2600), \Delta(1232), \Delta(1600),$
$\Delta(1620), \Delta(1700), \Delta(1905), \Delta(1910), \Delta(1920), \Delta(1930), \Delta(1950),$
$\Delta(2420), \Lambda, \Lambda(1405), \Lambda(1520), \Lambda(1600), \Lambda(1670), \Lambda(1690),$
$\Lambda(1800), \Lambda(1810), \Lambda(1820), \Lambda(1830), \Lambda(1890), \Lambda(2100),$
$\Lambda(2110), \Lambda(2350), \Sigma^+, \Sigma^0, \Sigma^-, \Sigma(1385), \Sigma(1660), \Sigma(1670),$
$\Sigma(1750), \Sigma(1775), \Sigma(1915), \Sigma(1940), \Sigma(2030), \Sigma(2250), \Xi^0, \Xi^-,$
$\Xi(1530), \Xi(1690), \Xi(1820), \Xi(1950), \Xi(2030), \Omega^-, \Omega(2250)^-,$
$\Lambda_c^+, \Lambda_c^+, \Sigma_c(2455), \Sigma_c(2520), \Xi_c^+, \Xi_c^0, \Xi_c'^+, \Xi_c'^0, \Xi(2645)$
$\Xi_c(2790), \Xi_c(2815), \Omega_c^0, \Lambda_b^0, \Xi_b^0, \Xi_b^-, t\bar{t}$

There are many more

All known particles that can leave a track in the detector

All Particles with $c\tau > 1\mu m$ @ GeV Level 19

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

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

Task of a Detector

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.

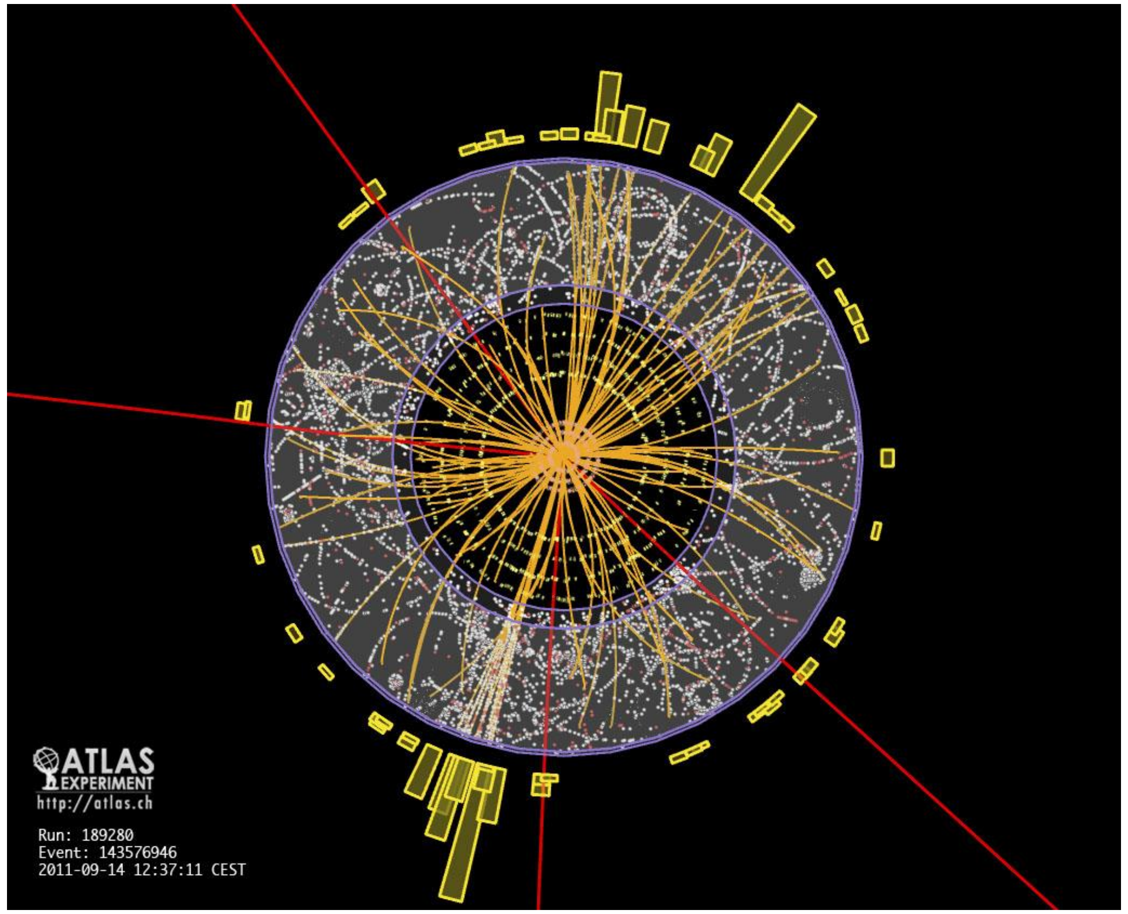
~13 of the 27 have $c\tau < 500\mu m$ i.e. only ~mm range at GeV Energies.
→ "short" tracks measured with Emulsions or Vertex Detectors.

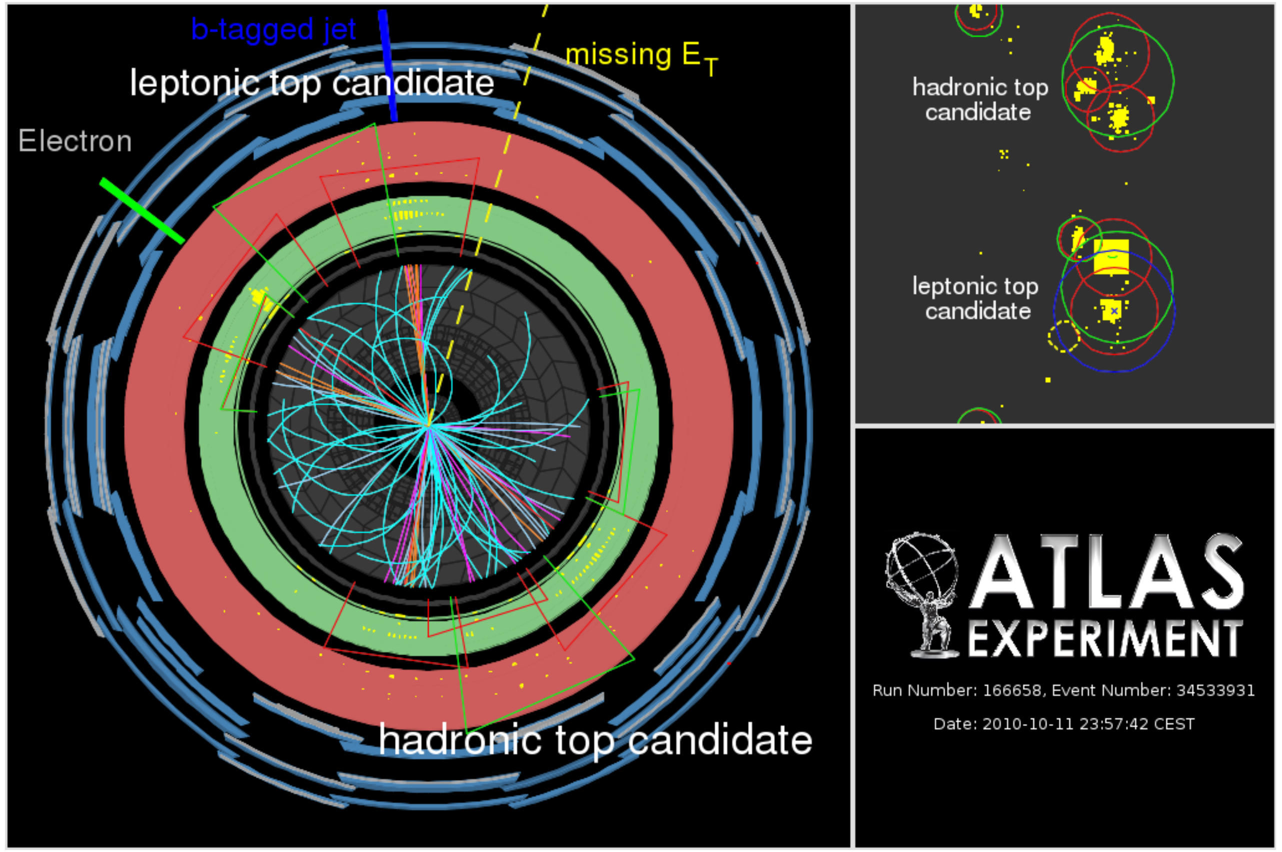
From the ~14 remaining particles

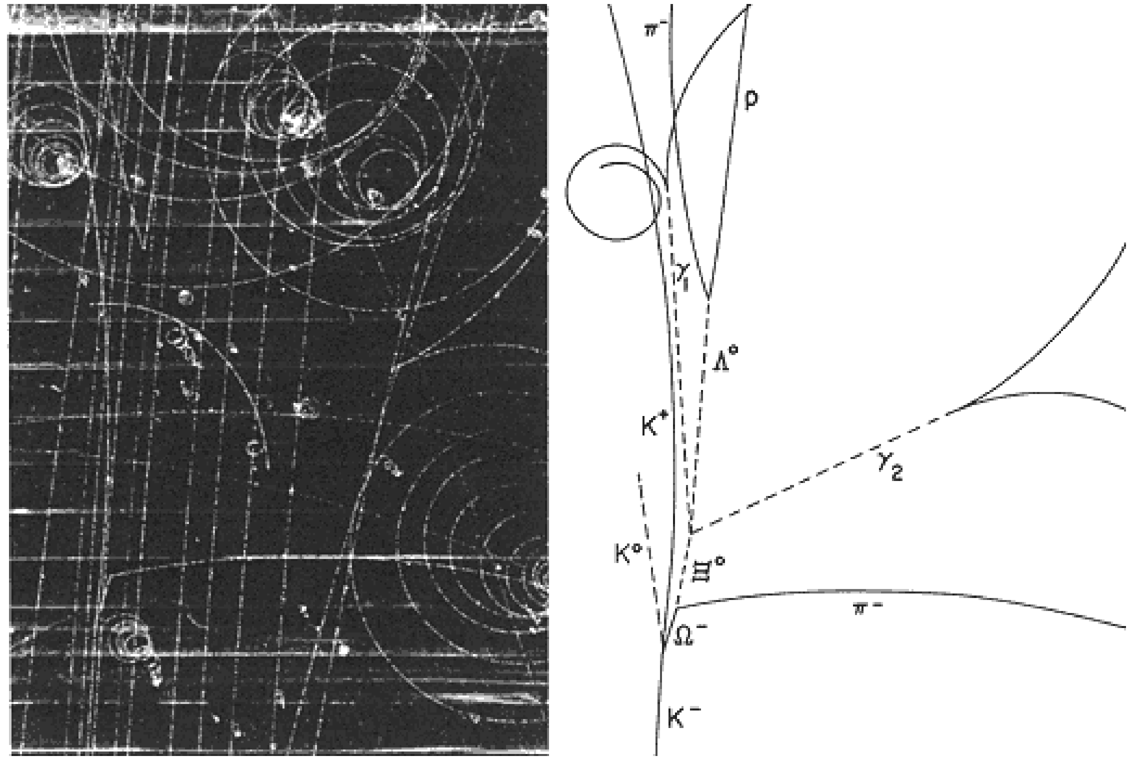
$$e^{\pm}, \mu^{\pm}, \gamma, \pi^{\pm}, K^{\pm}, K^{0}, p^{\pm}, n$$

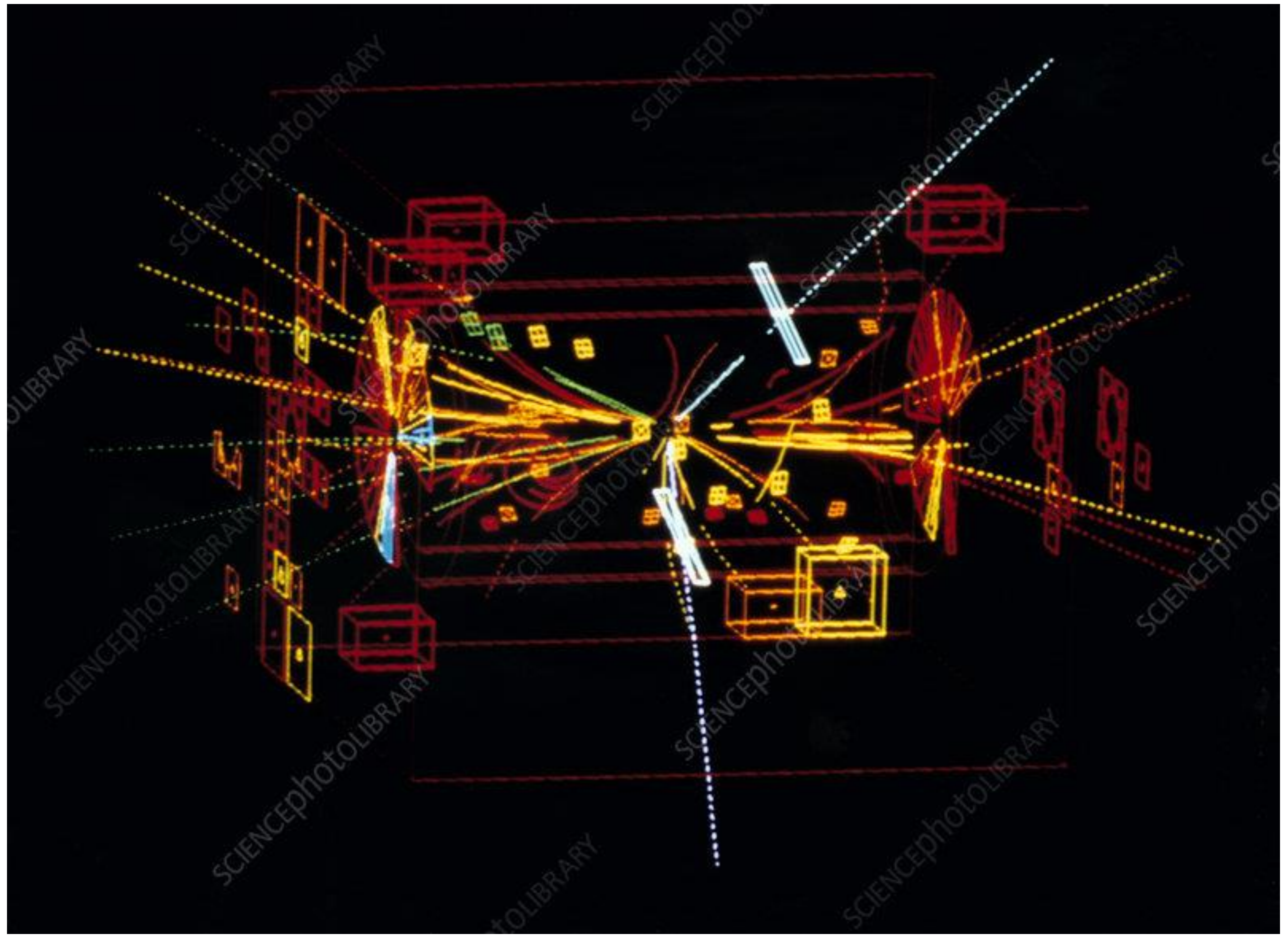
are <u>by far</u> the most frequent ones

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


ATLAS
EXPERIMENT
http://atlas.ch
Run: 189280
Event: 143576946
2011-09-14 12:37:11 CEST


b-tagged jet
missing E_T
leptonic top candidate
Electron
hadronic top candidate
hadronic top candidate
leptonic top candidate
ATLAS
EXPERIMENT
Run Number: 166658, Event Number: 34533931
Date: 2010-10-11 23:57:42 CEST


π^-
p
γ_1
Λ^0
K^+
γ_2
K^0
Ξ^0
Ω^-
π^-
K^-



Interactions of the 8 particles

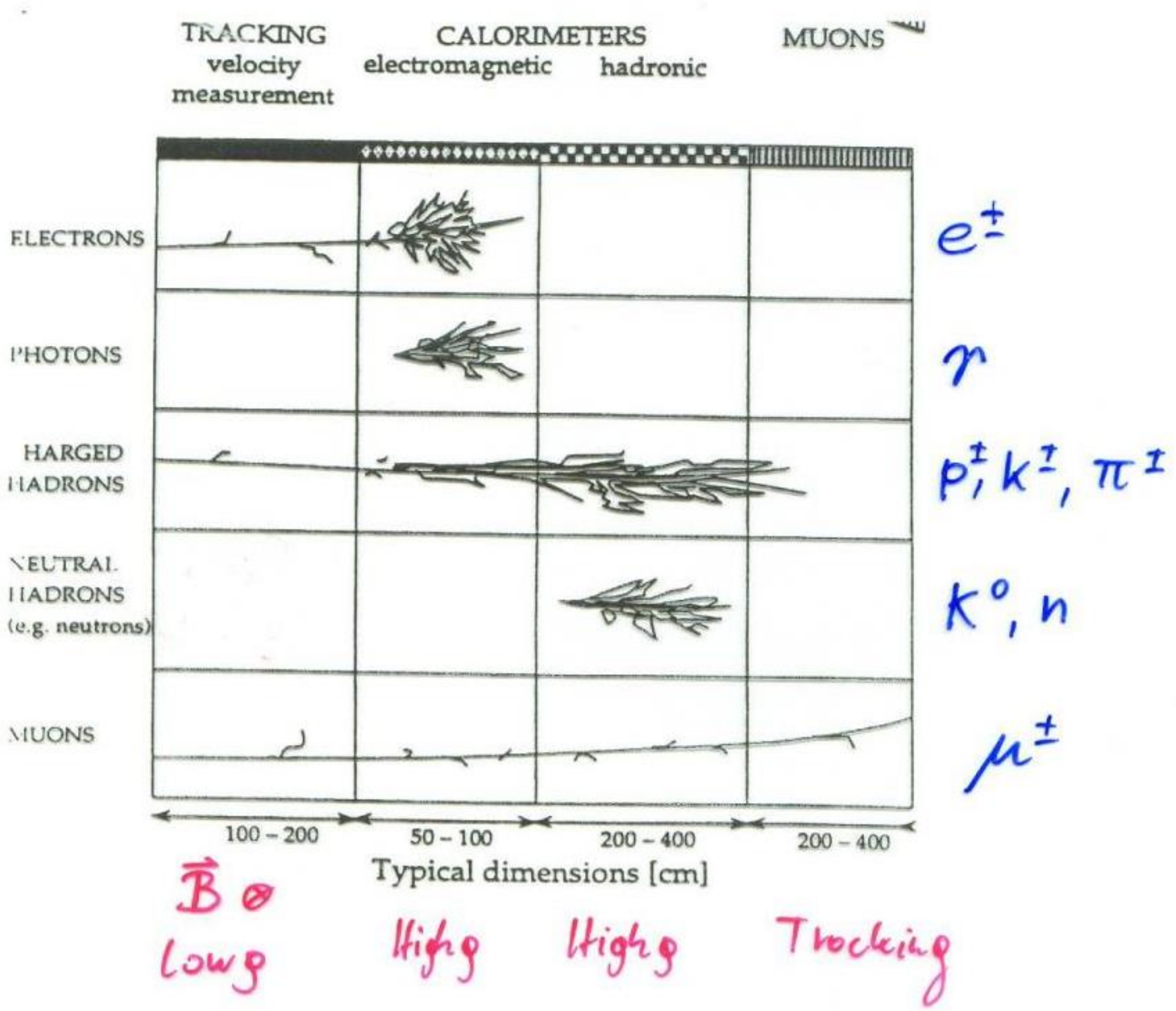
Particle	Mass			Interaction
$e^{\pm}$	$m_e = 0.511$ MeV			EM
$\mu^{\pm}$	$m_\mu = 105.7$ MeV	$\sim 200\, m_e$		EM
γ	$m_\gamma = 0$, $Q = 0$			EM
$\pi^{\pm}$	$m_\pi = 139.6$ MeV	$\sim 270\, m_e$		EM, Strong
$K^{\pm}$	$m_K = 493.7$ MeV	$\sim 1000\, m_e$	$\sim 3.5\, m_\pi$	EM, Strong
$p^{\pm}$	$m_p = 938.3$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

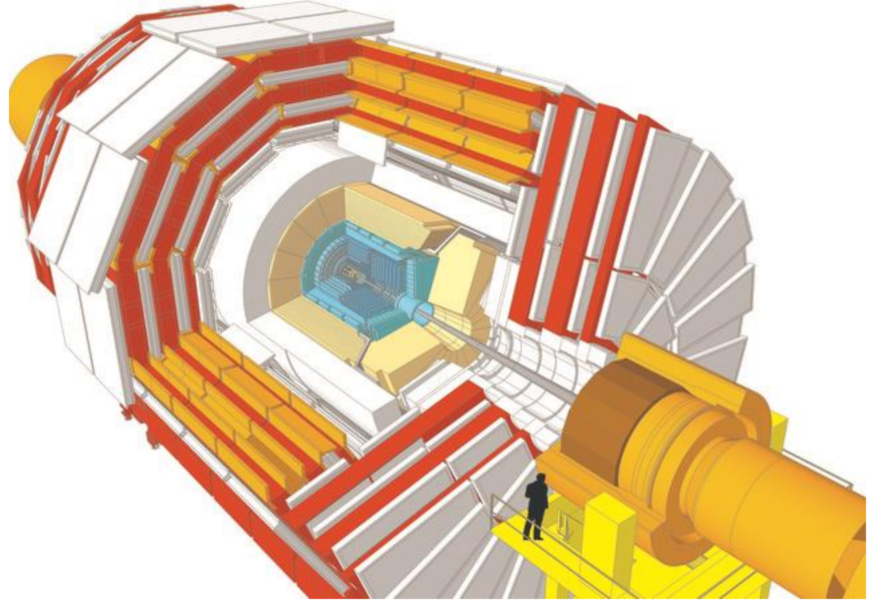
is the key to the Identification

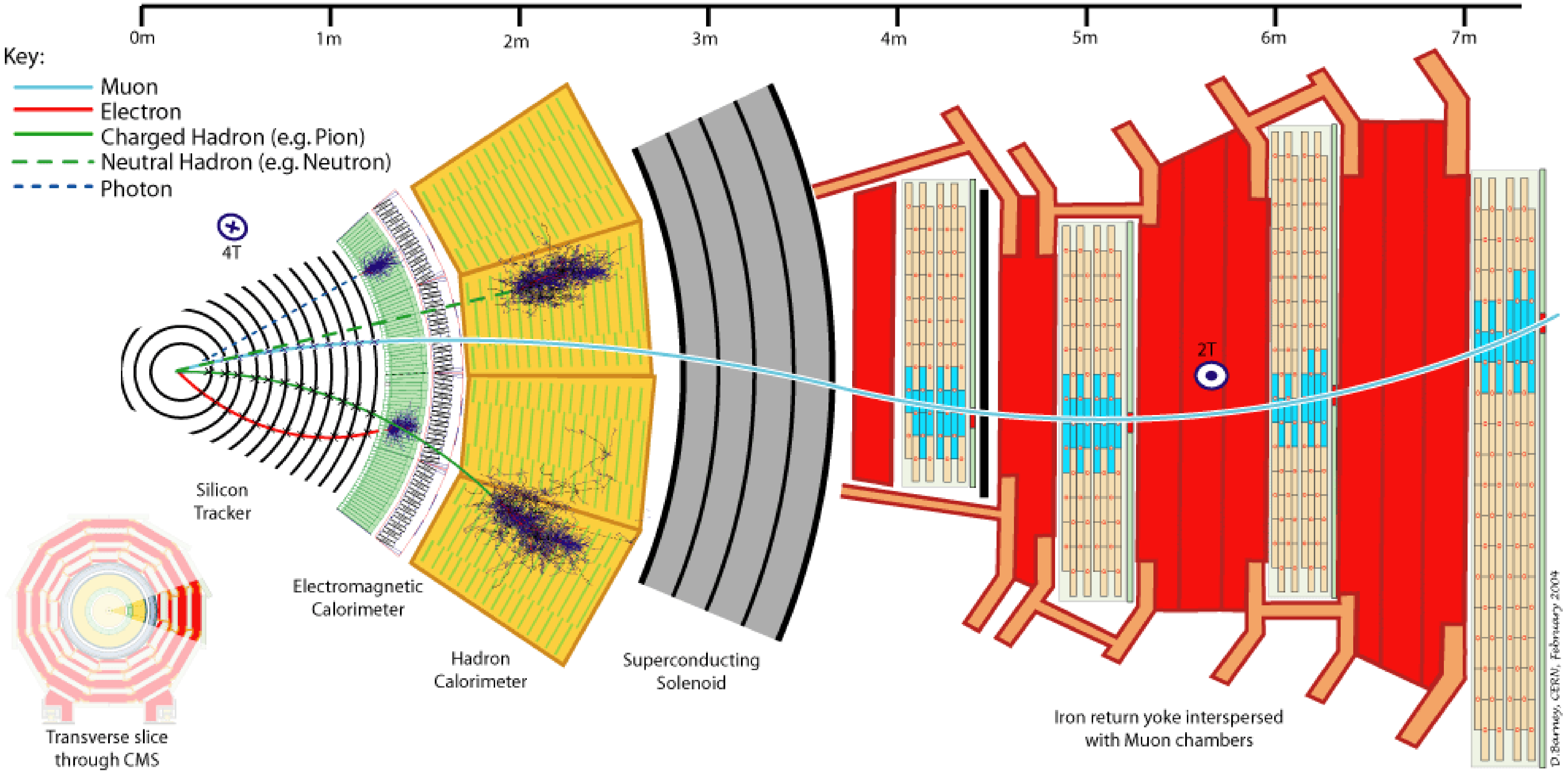
Task of a Particle Detector

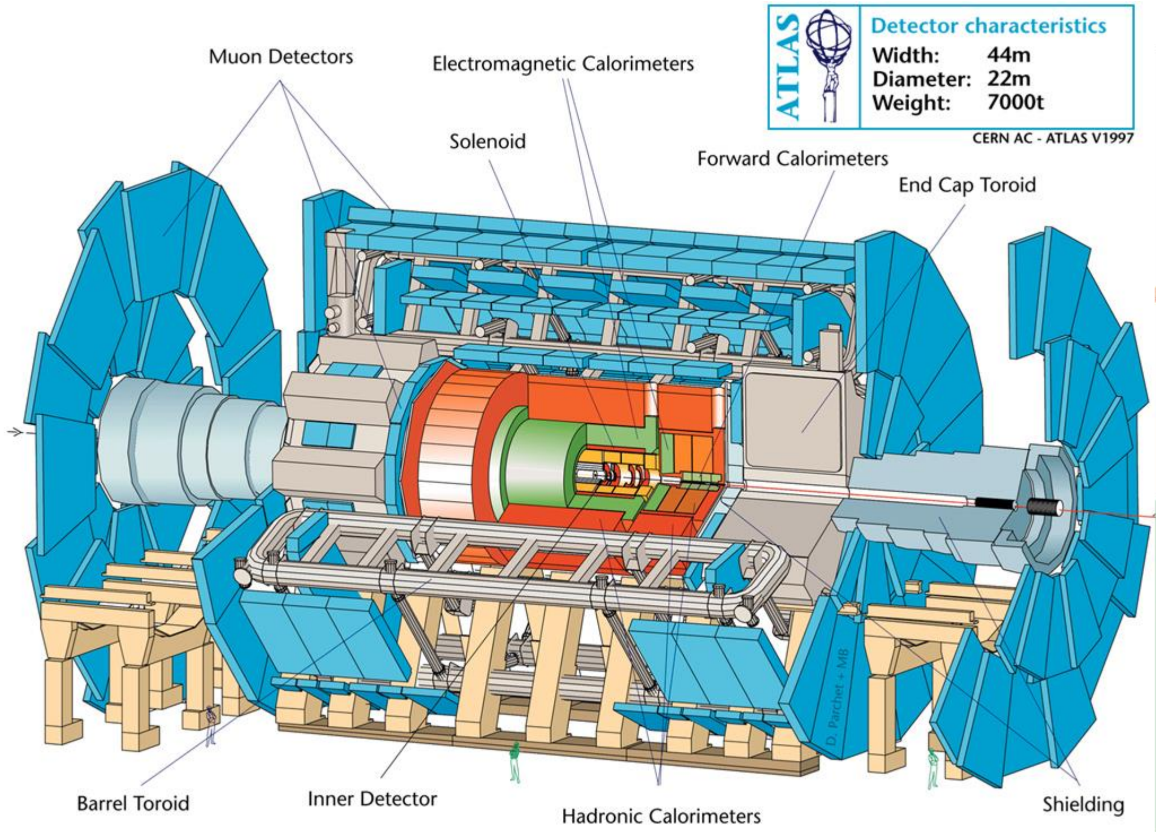


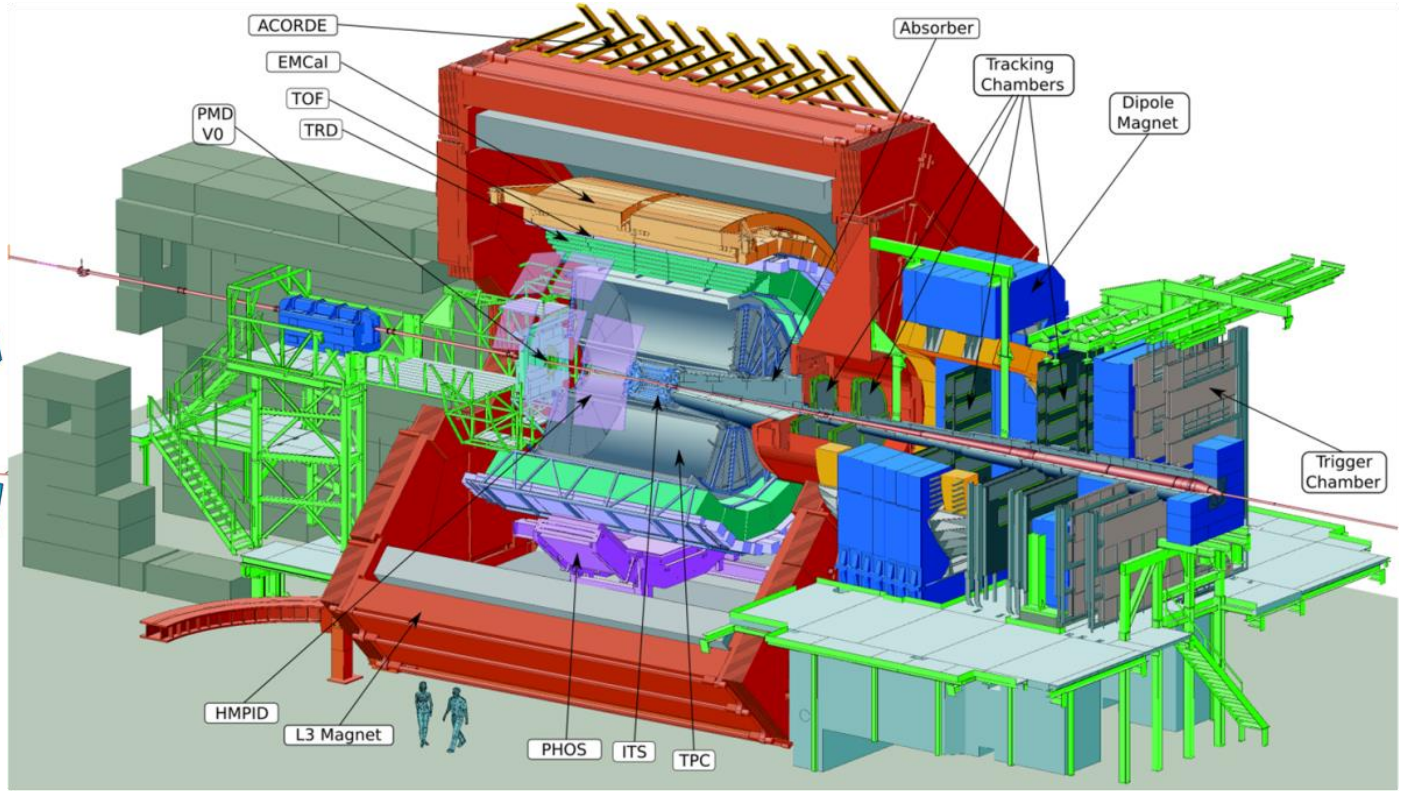
- Electrons ionize and show Bremsstrahlung due to the small mass
- Photons don't ionize but show Pair Production in high Z Material. From then on equal to $e^\pm$
- Charged Hadrons ionize and show Hadron Shower in dense material.
- Neutral Hadrons don't ionize and show Hadron Shower in dense Material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

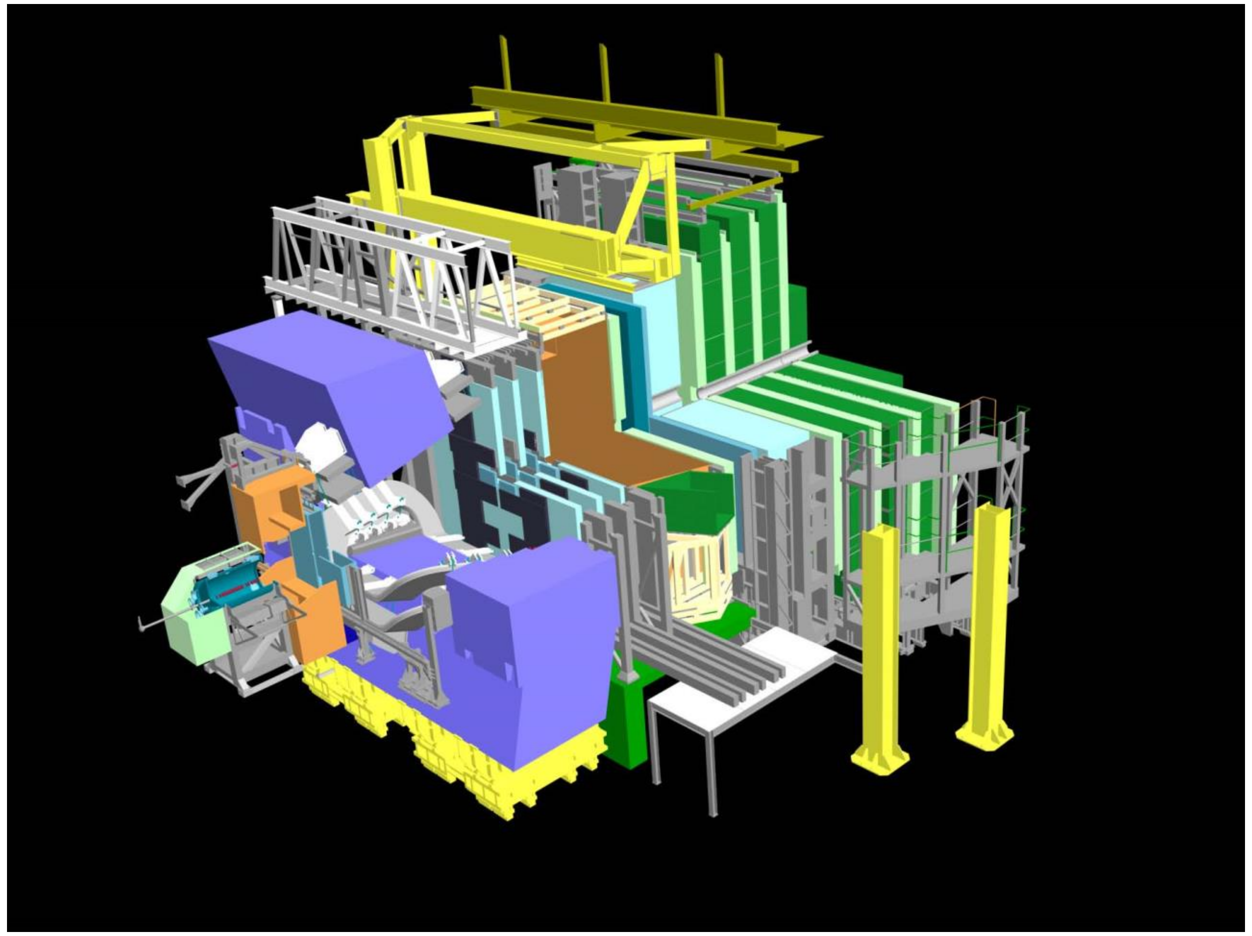
CMS Detector

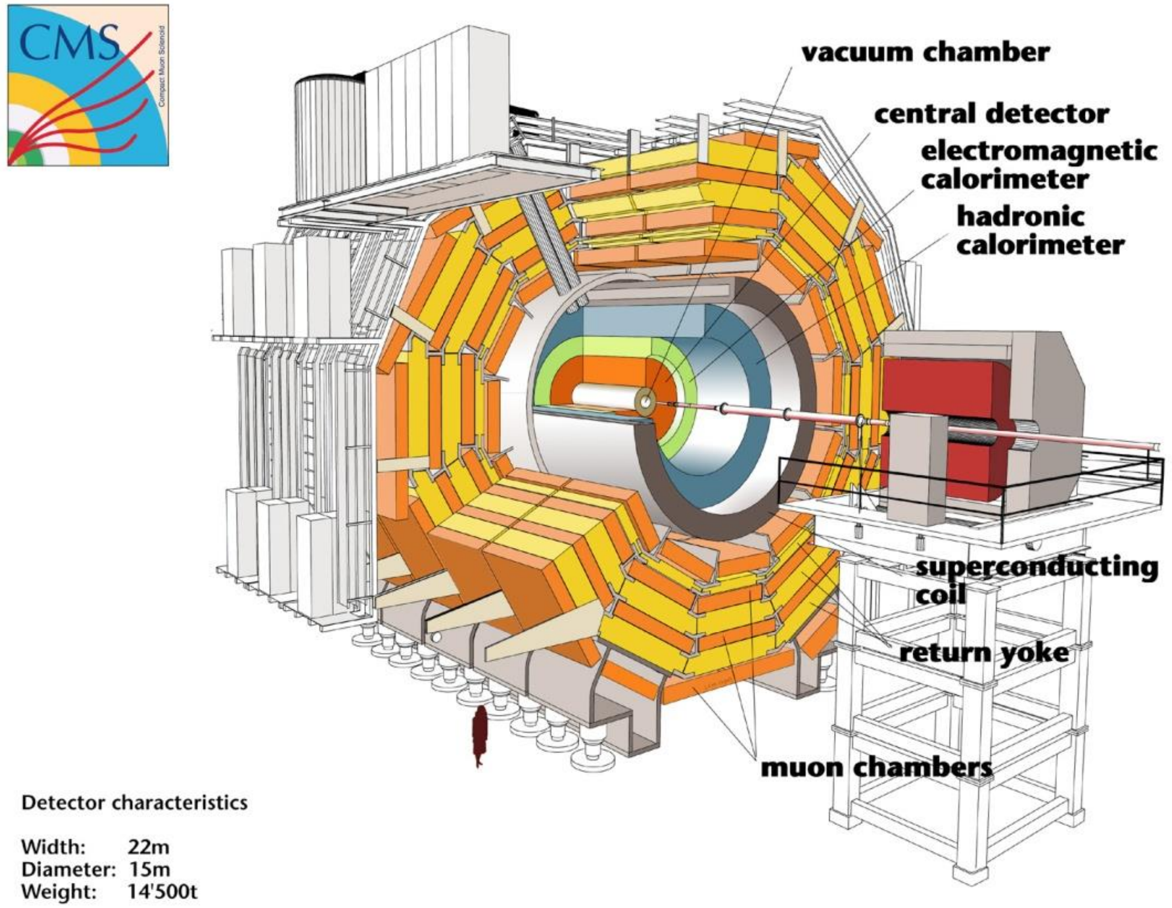




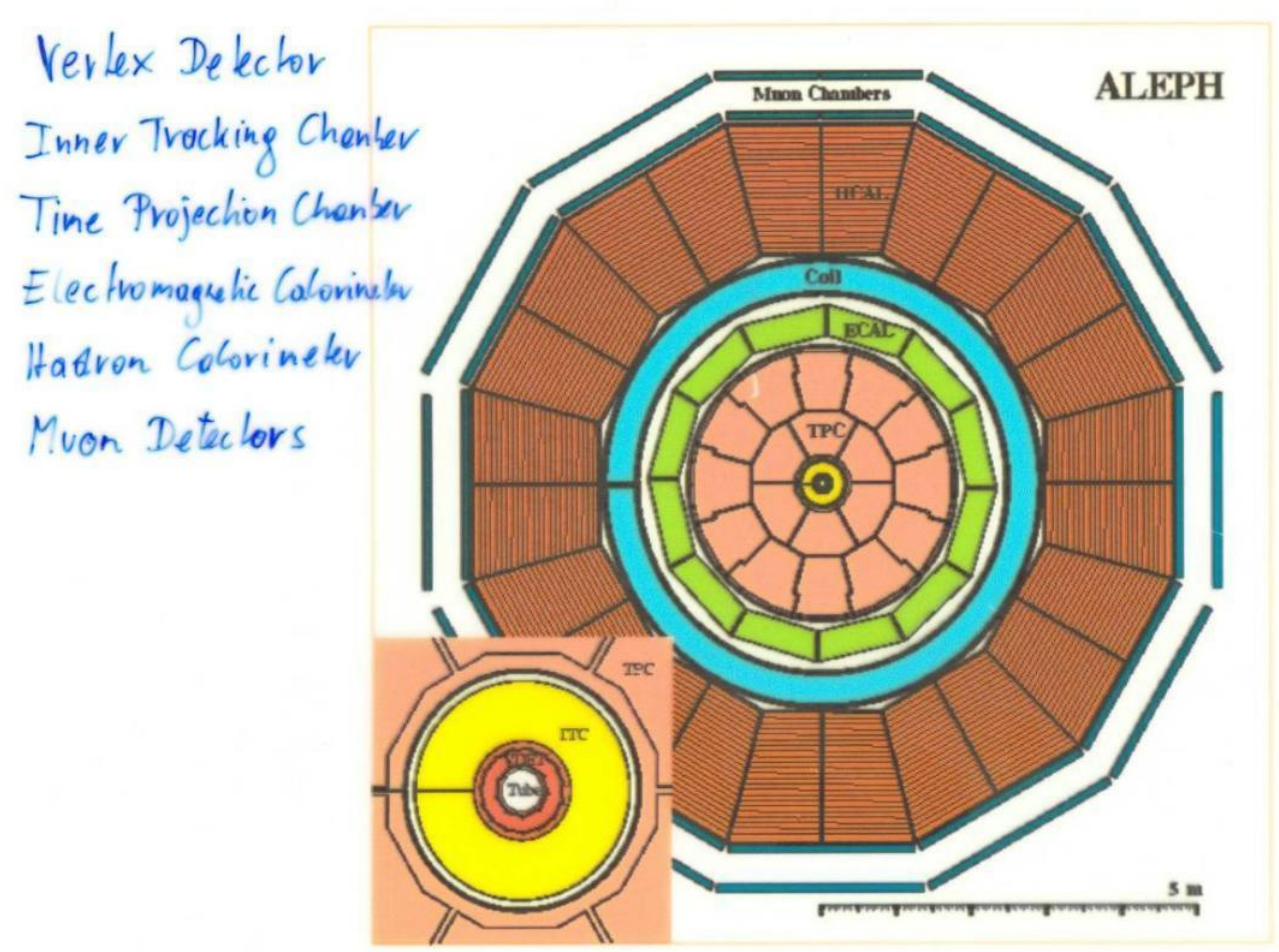

Detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t
ATLAS
CERN AC - ATLAS V1997
Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding


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

ALEPH detector
(LEP 1988 - 2000)



ALEPH detector
(LEP 1988 - 2000)

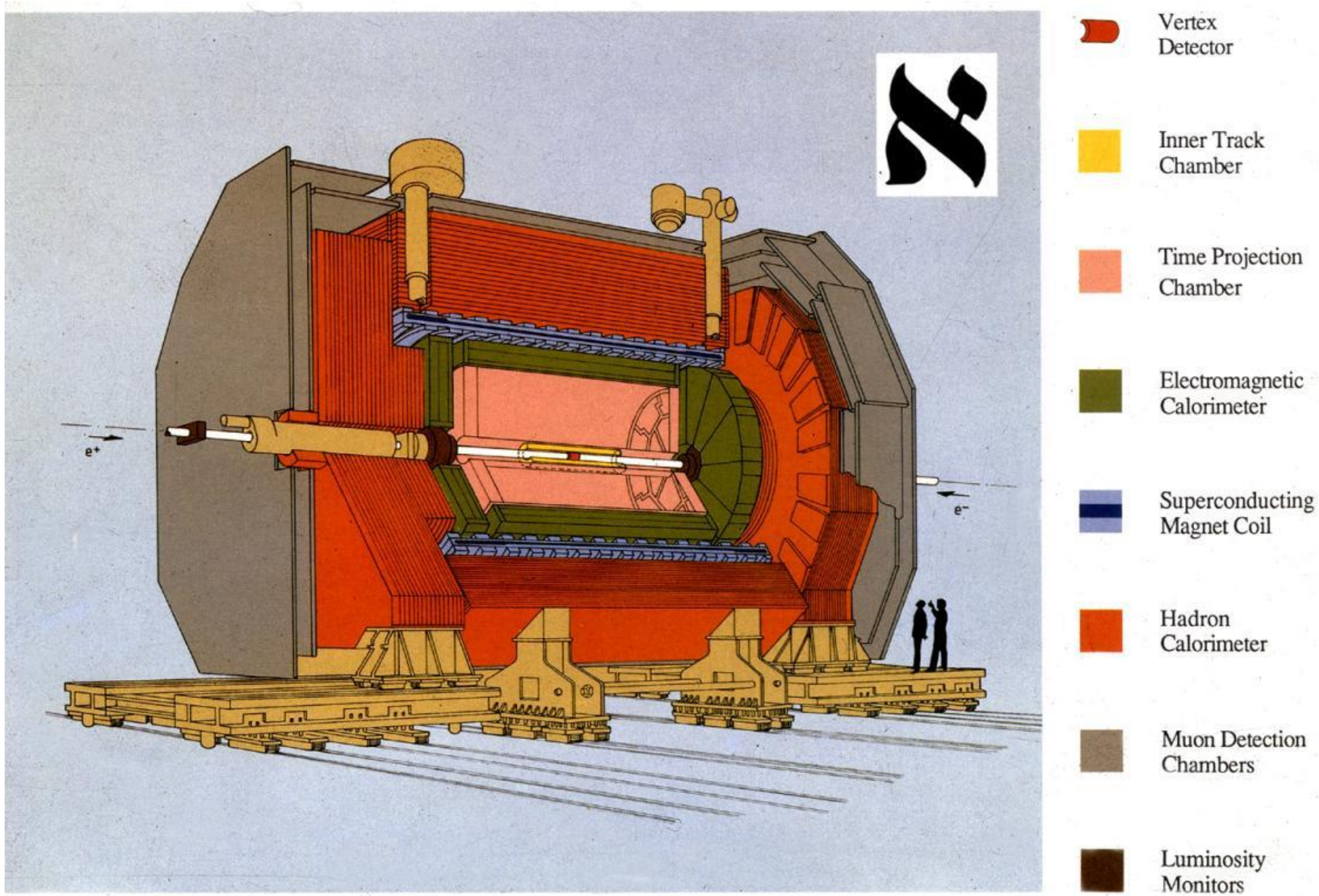
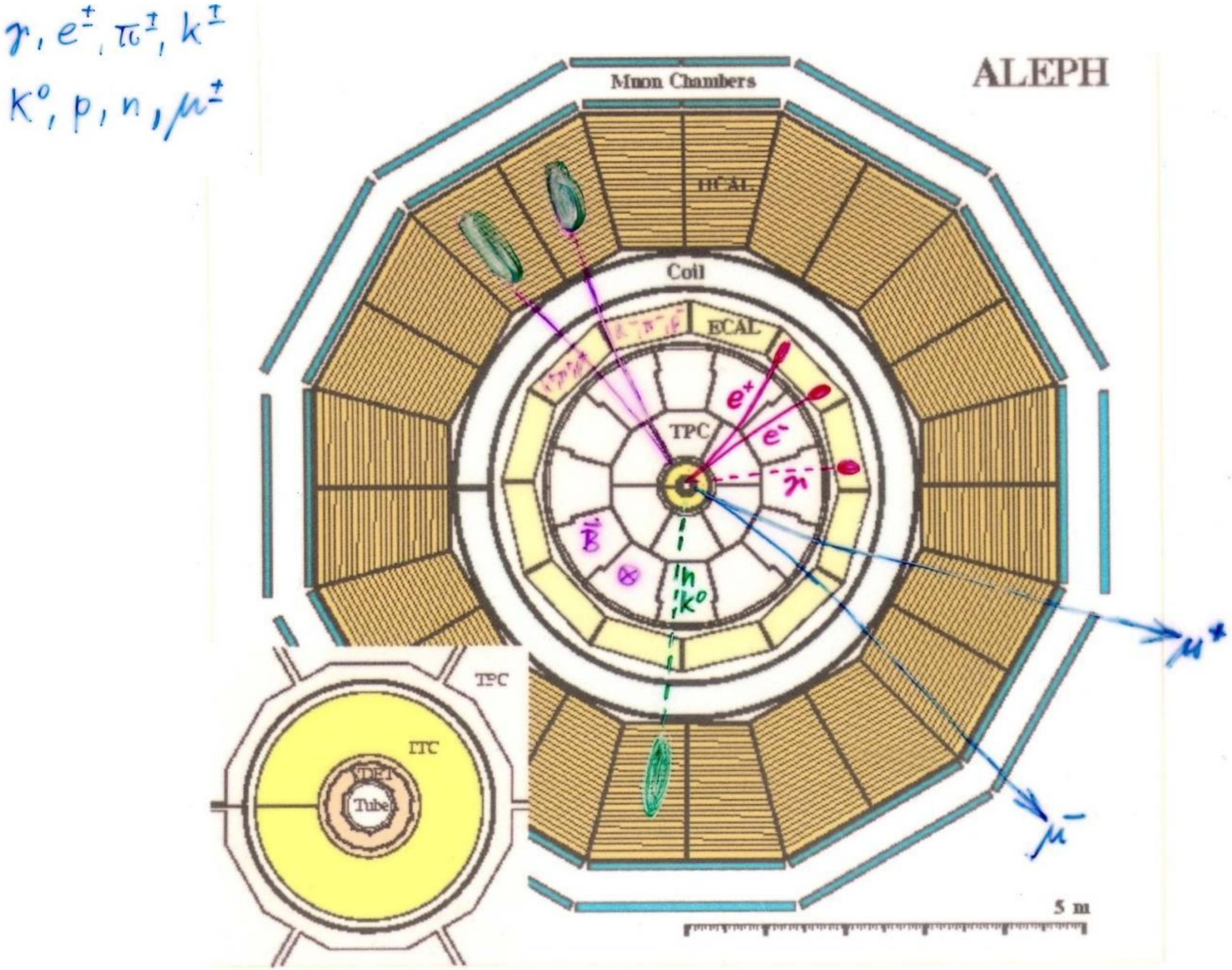


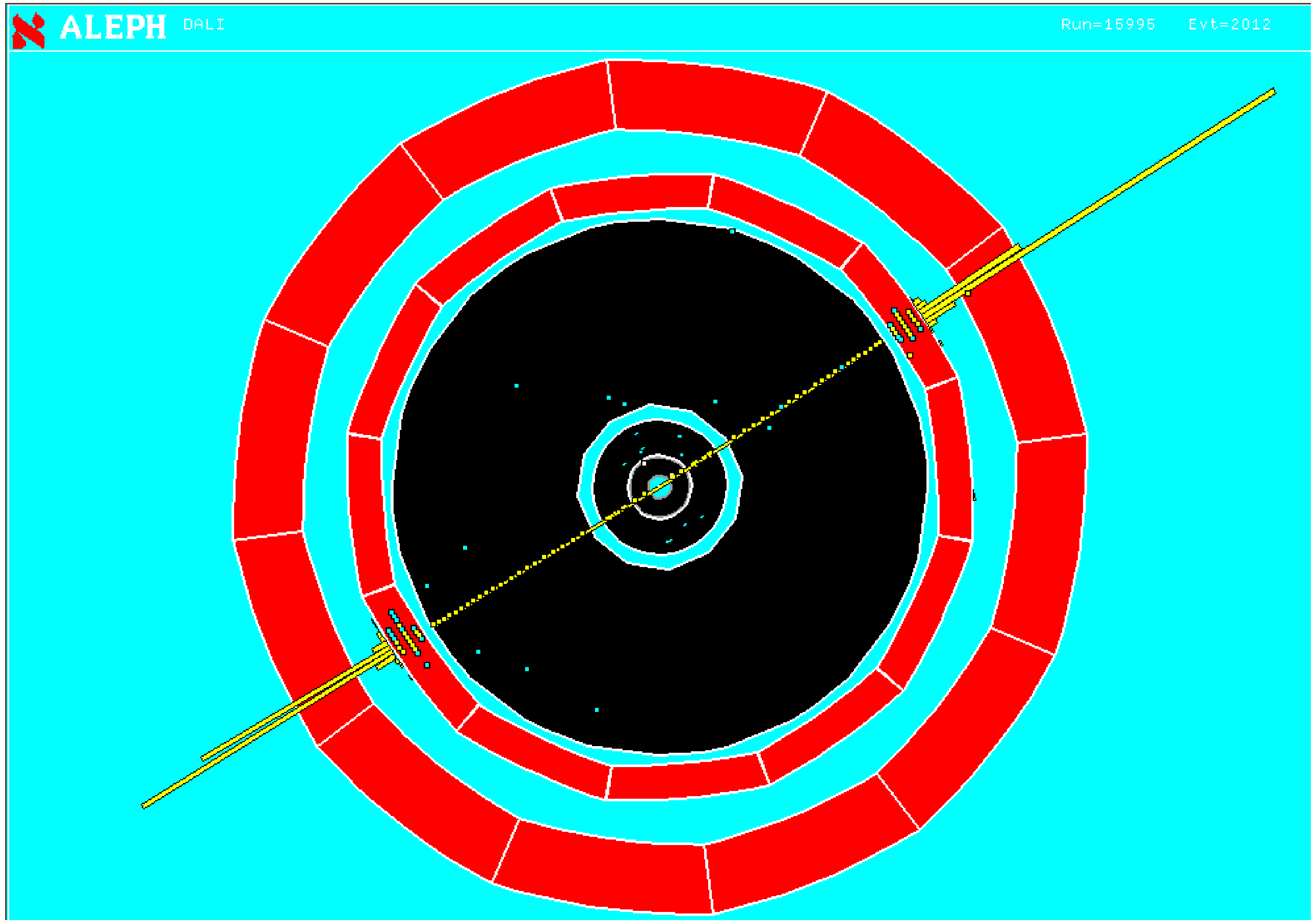
Fig. 1 - The ALEPH Detector

ALEPH detector
(LEP 1988 - 2000)



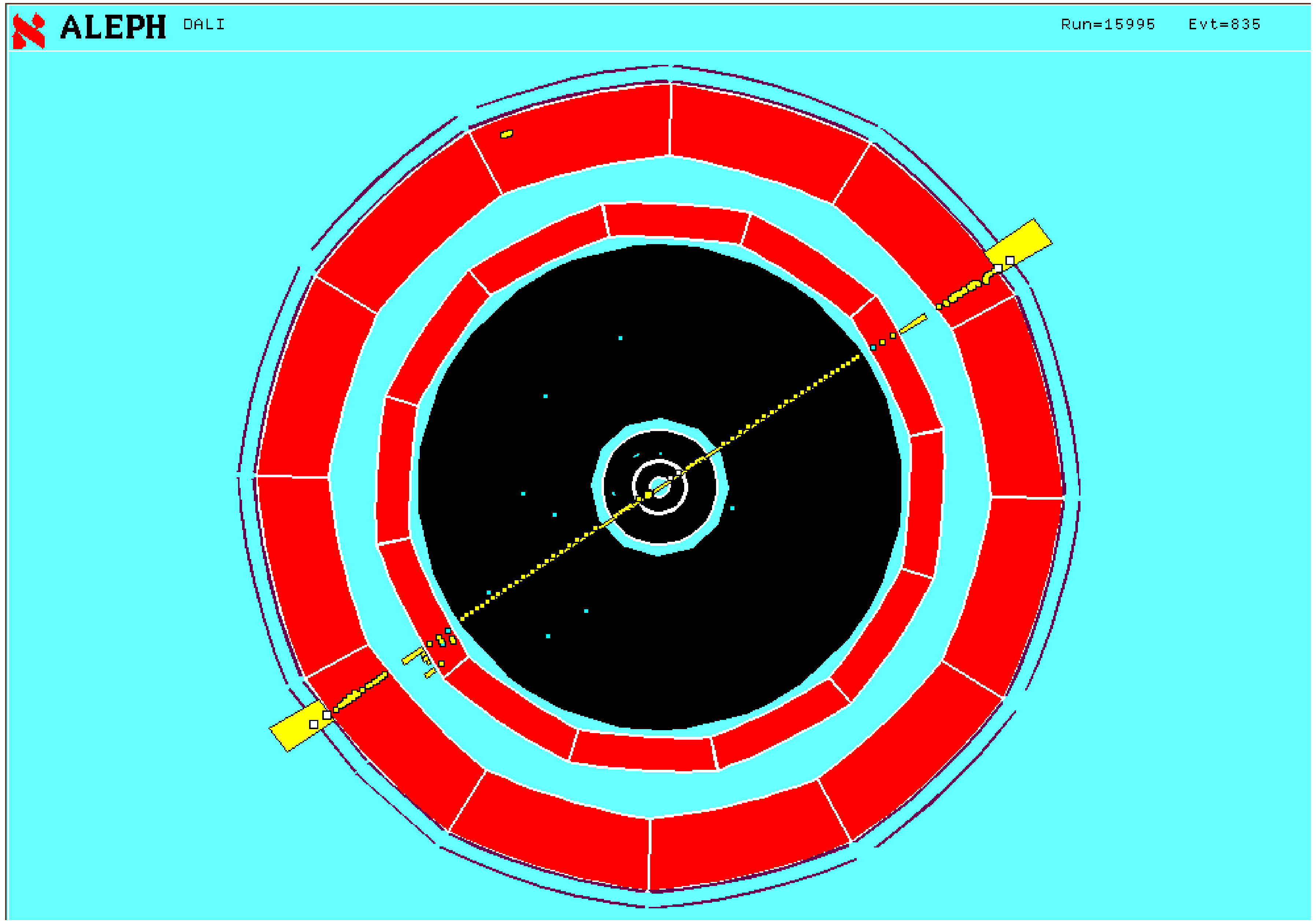
$Z \rightarrow e^+ e^-$

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



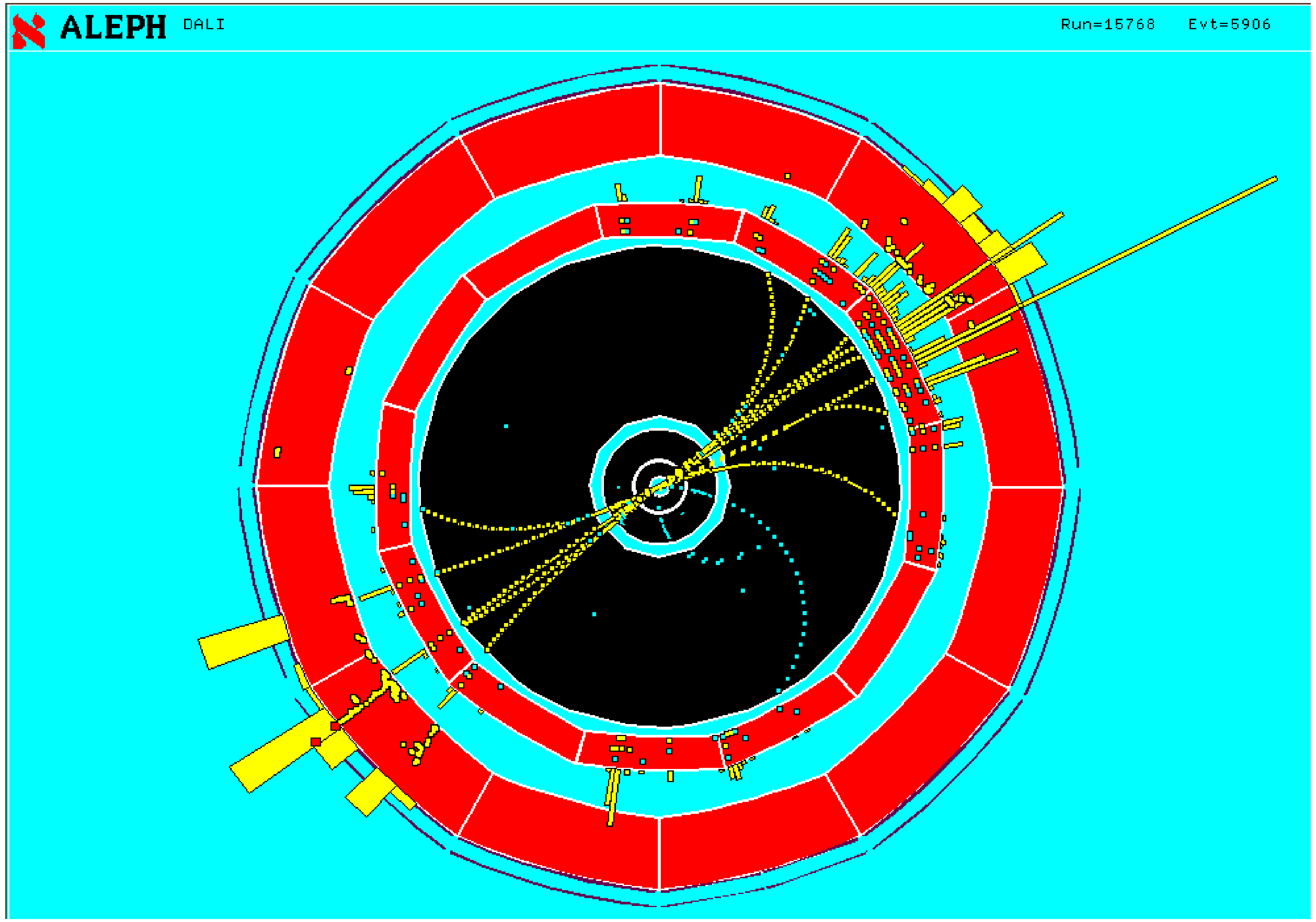
$Z \rightarrow \mu^+ \mu^-$

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



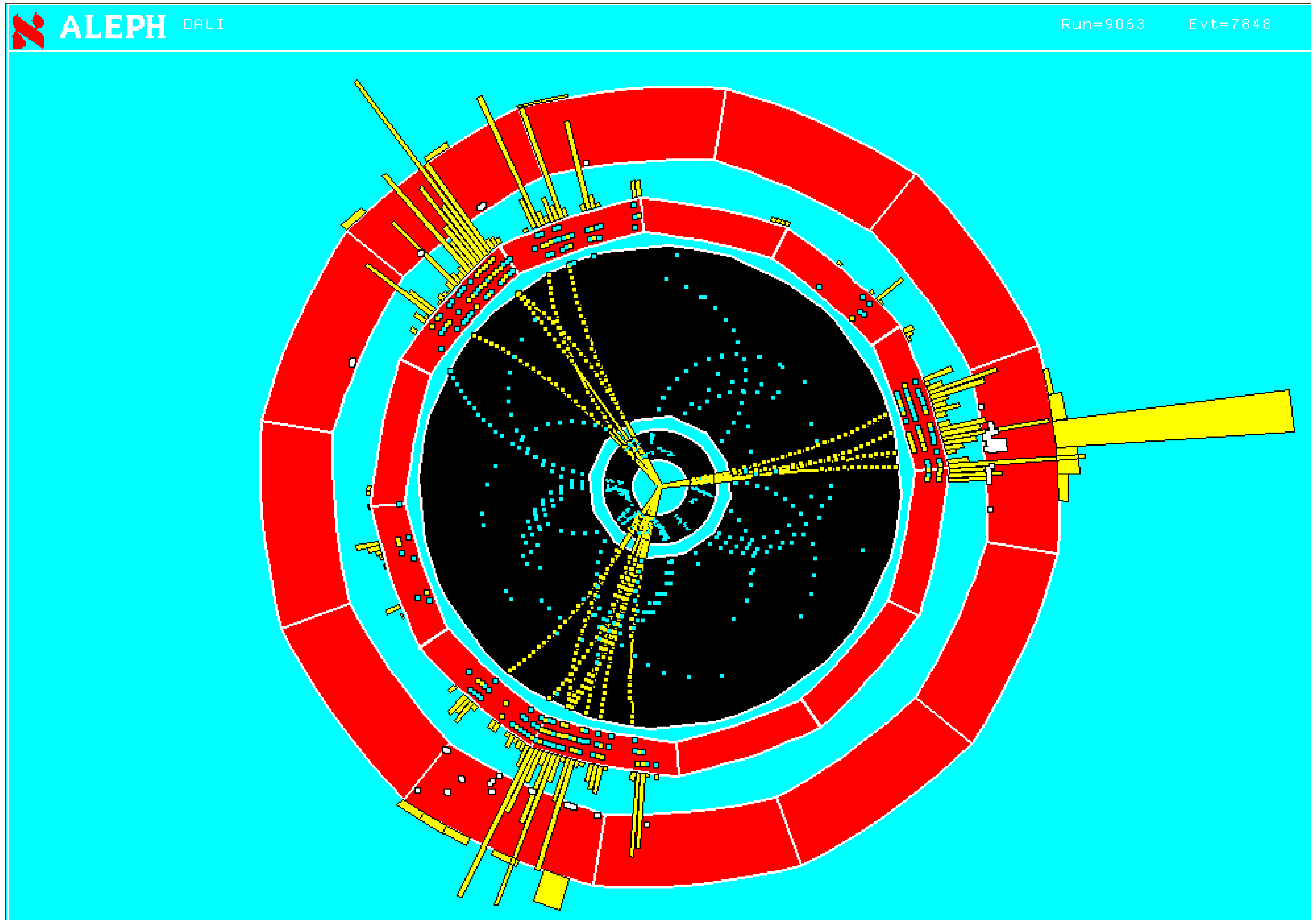
$Z \rightarrow q\bar{q}$

Two jets of particles



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

Three jets of particles

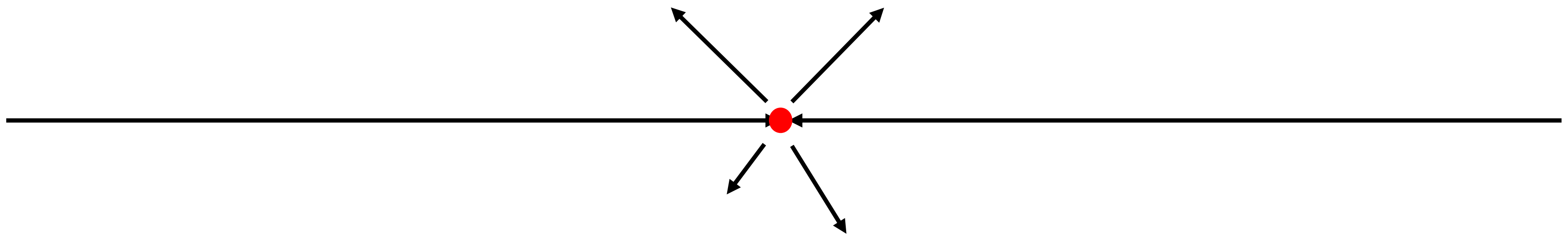


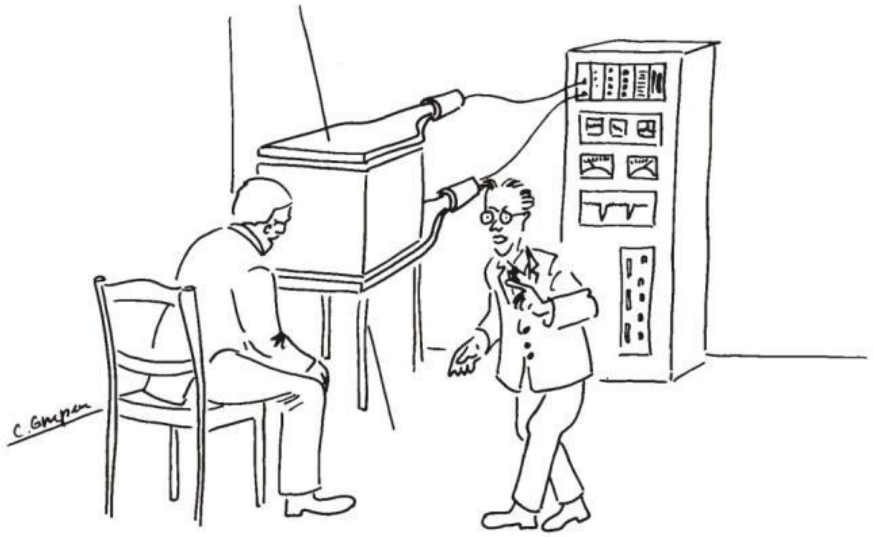
Interaction of Particles with Matter

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

In many experiments neutrinos are measured by missing transverse momentum.

E.g. e^+e^- collider. $P_{tot}=0$,
If the $\Sigma\ p_i$ of all collision products is $\neq 0$ → neutrino escaped.

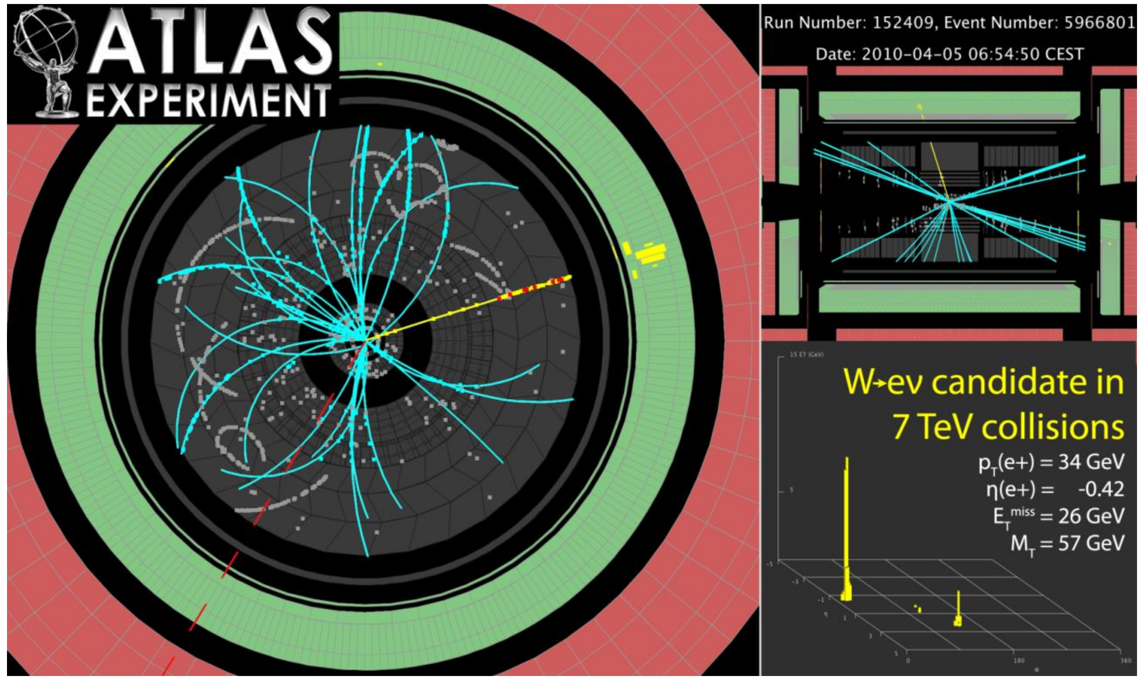


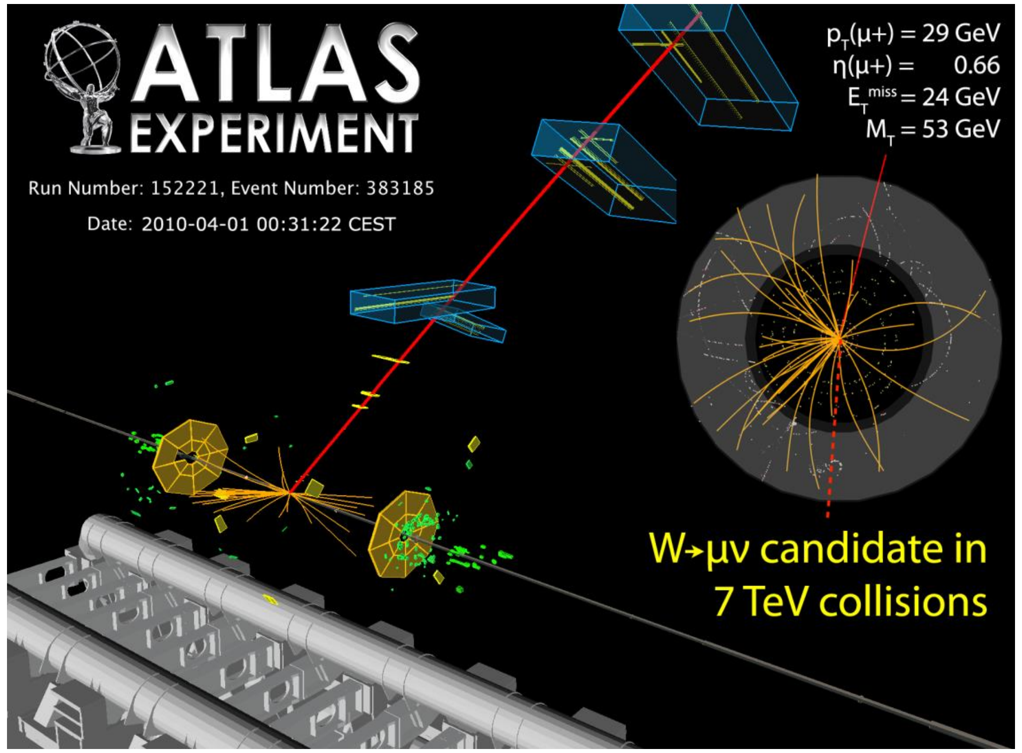


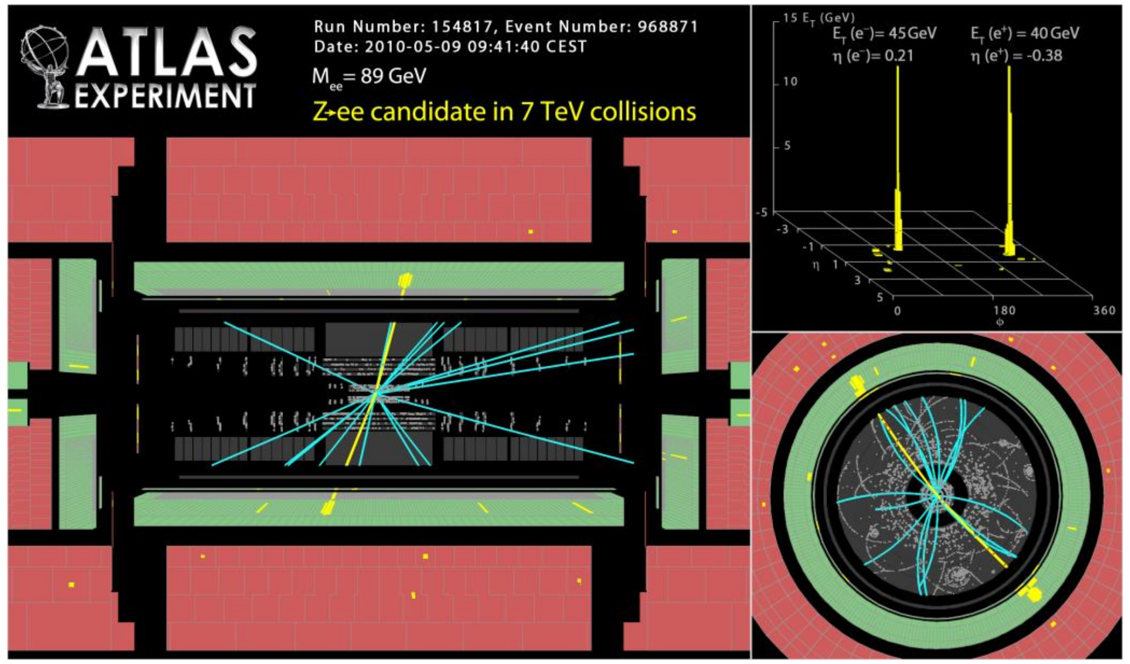
"Did you see it?"
"No nothing."
"Then it was a neutrino!"

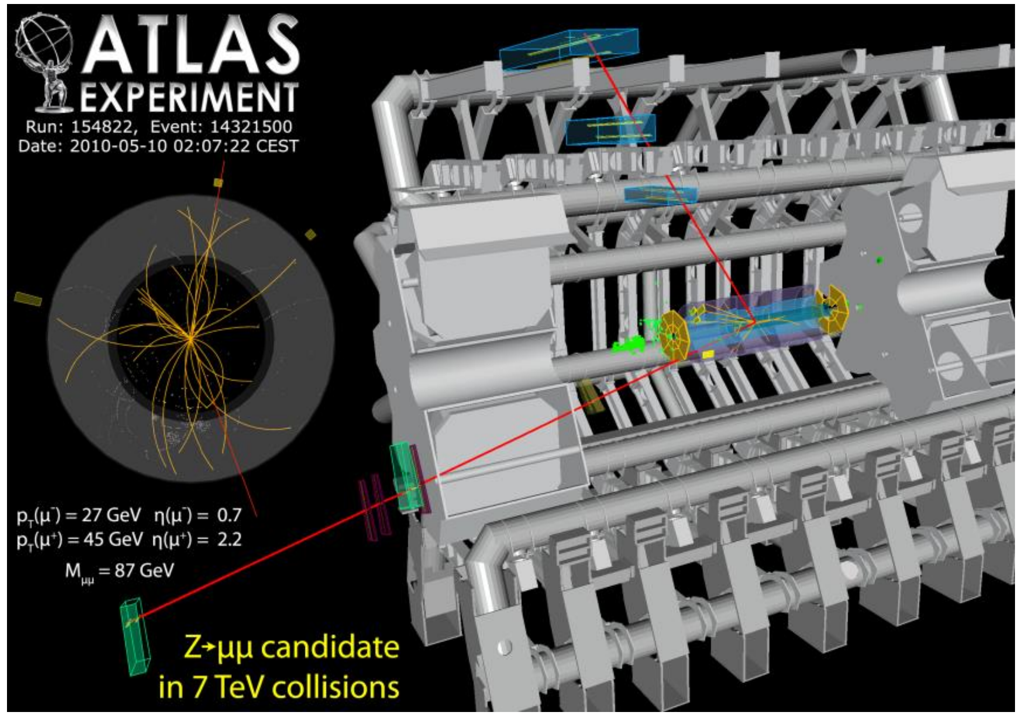
Claus Grupen, Particle Detectors, Cambridge University Press, Cambridge 1996 (455 pp. ISBN 0-521-55216-8)

2010 ATLAS W, Z candidates !



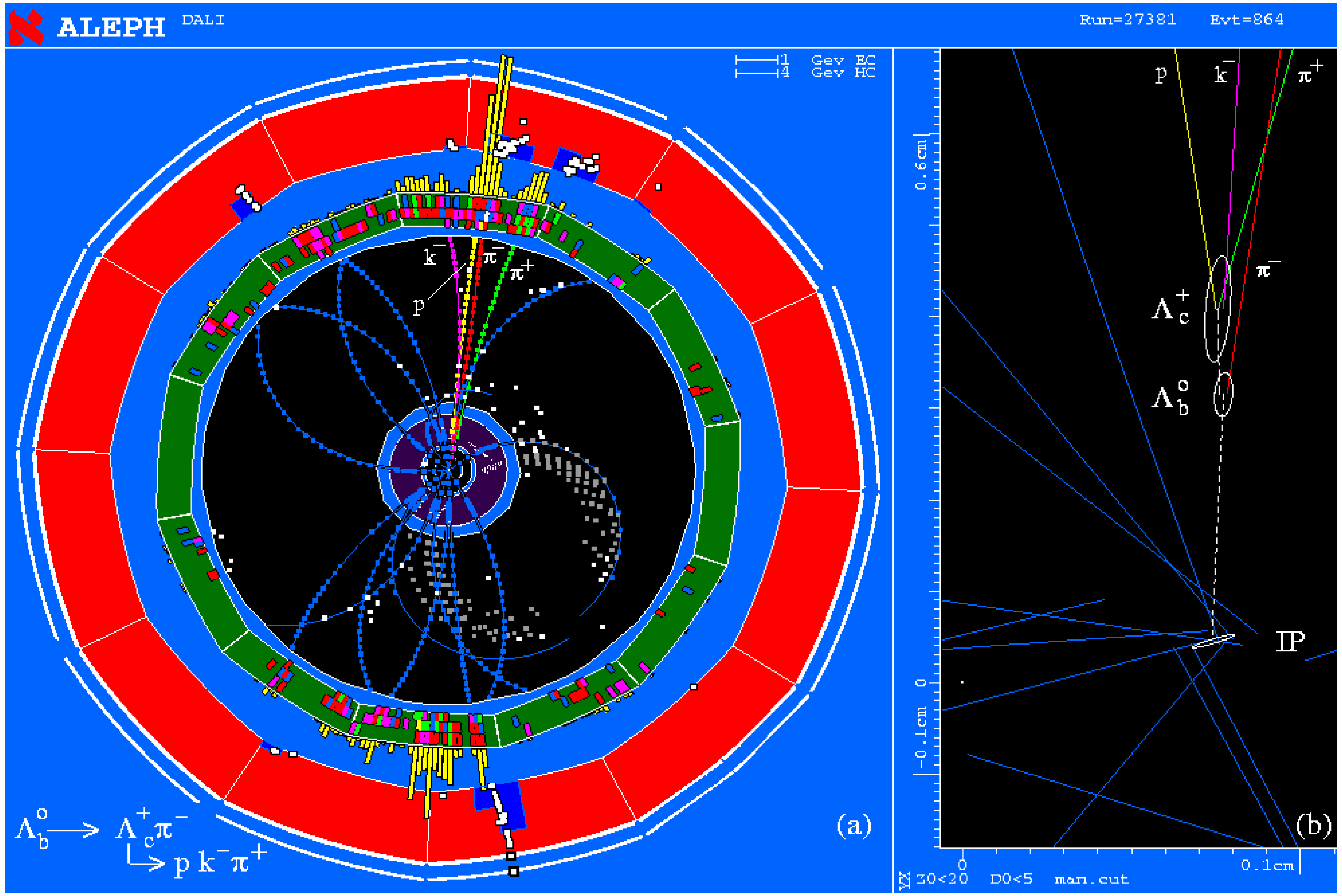




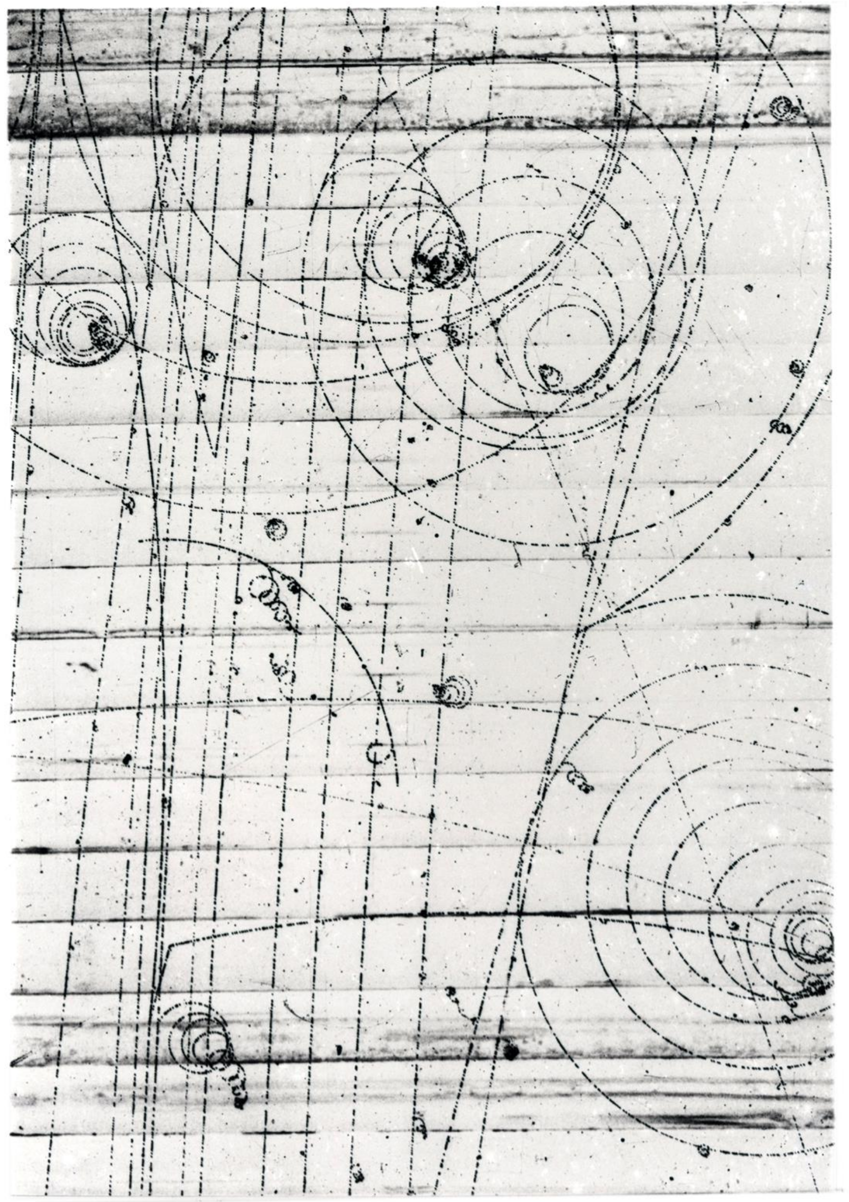


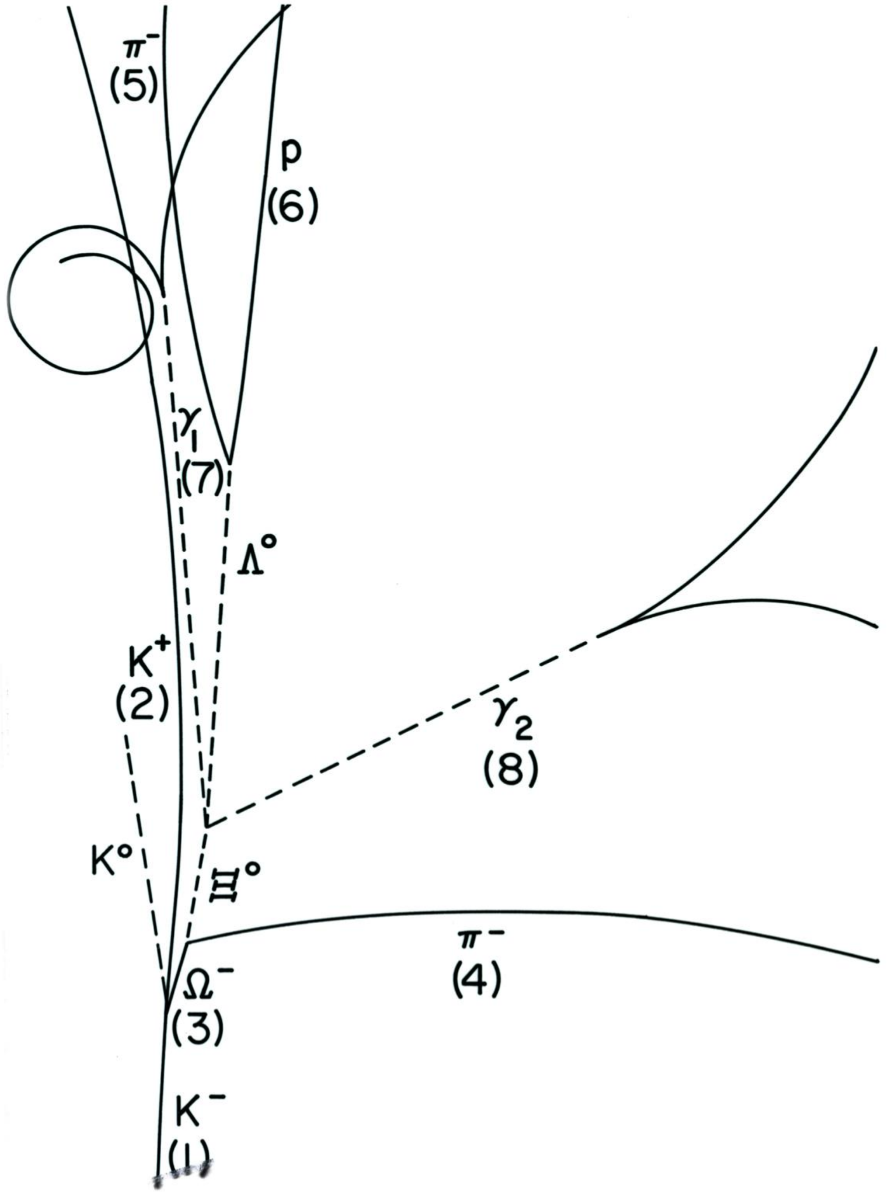
Two secondary vertices with characteristic decay particles giving invariant masses of known particles.

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



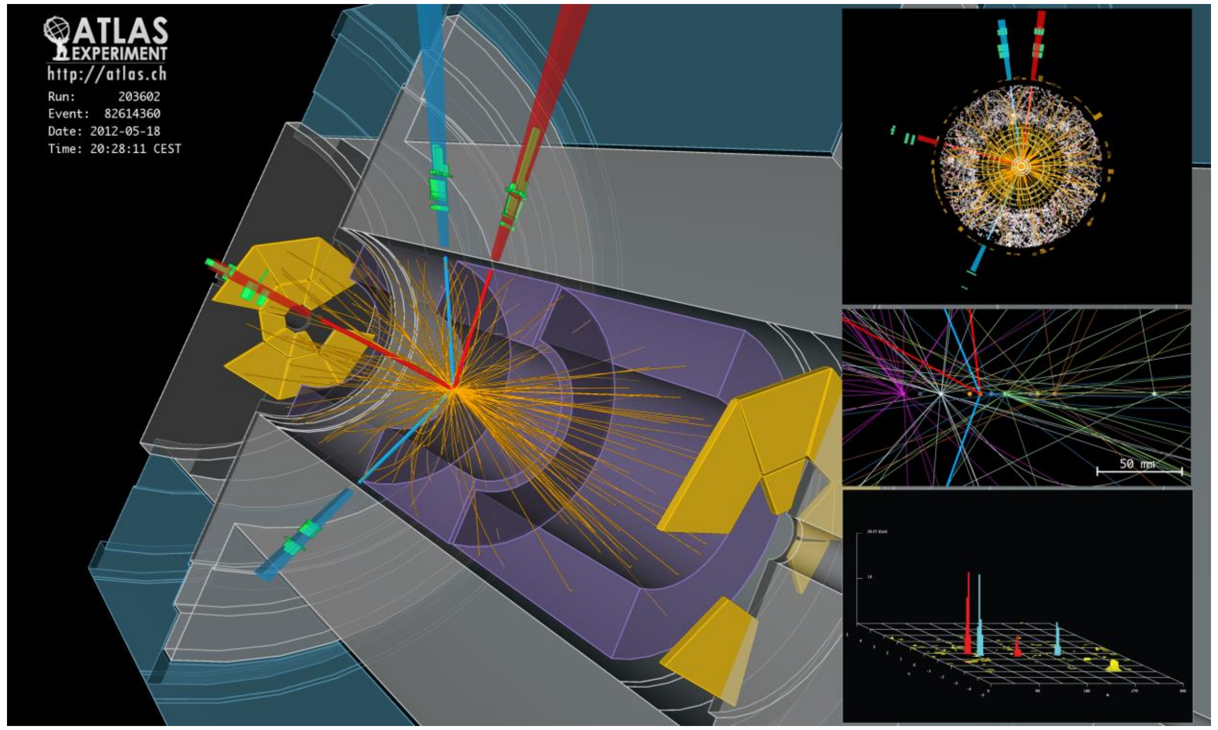
Discovery of ‘new’ Particles



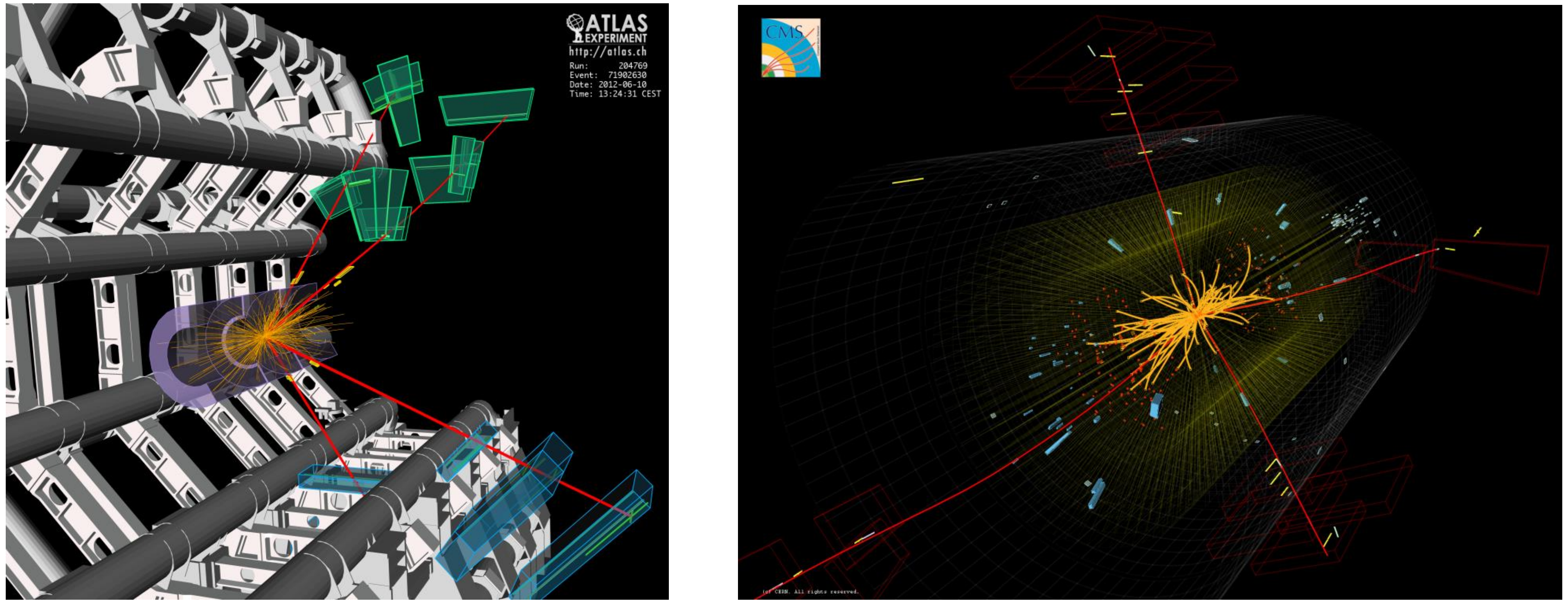


Discovery of Ω^- at the Brookhaven National Laboratory 80 inch hydrogen bubble chamber in 1964.
Discovery claimed by a single event – ‘background free’

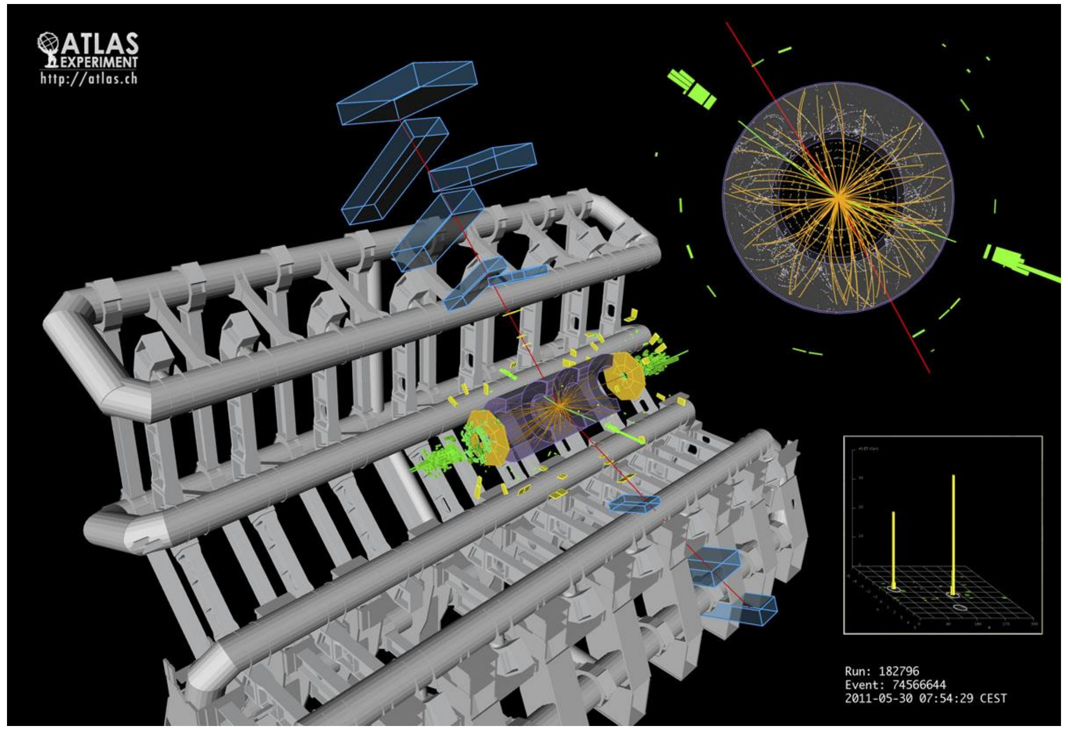
Candidate Higgs Events



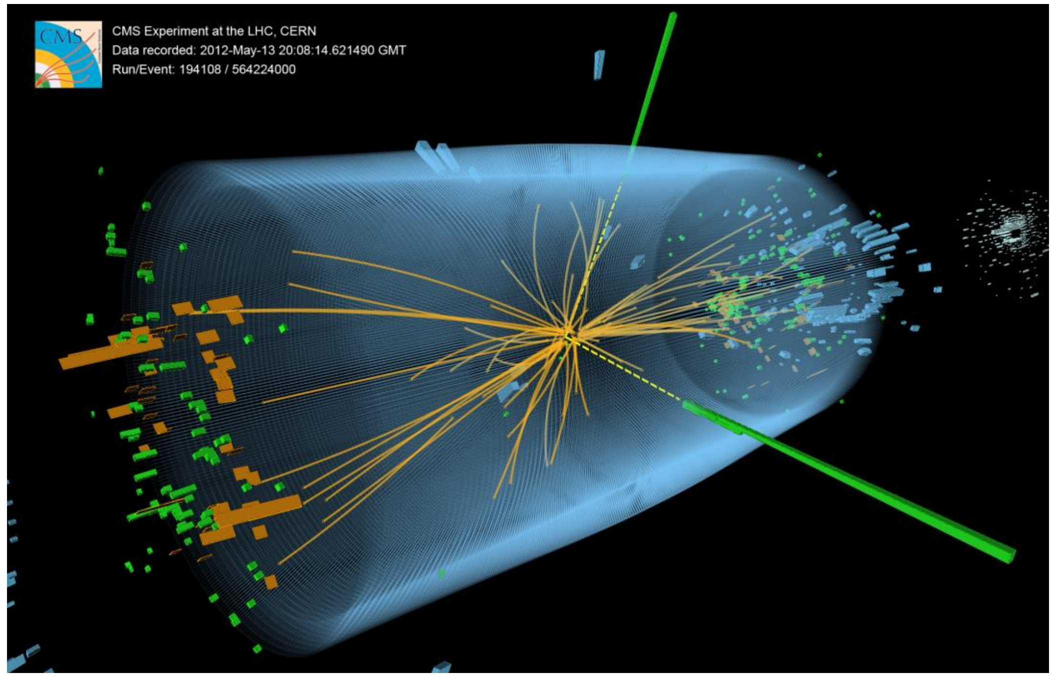
Candidate Higgs → 4e



Candidate Higgs → 4μ

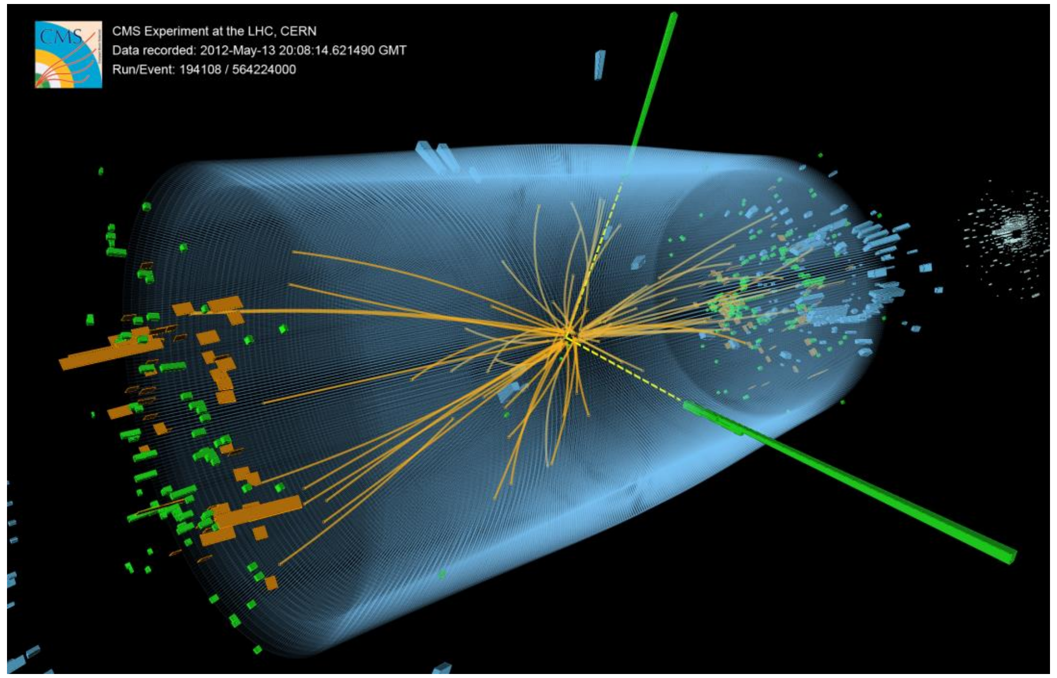


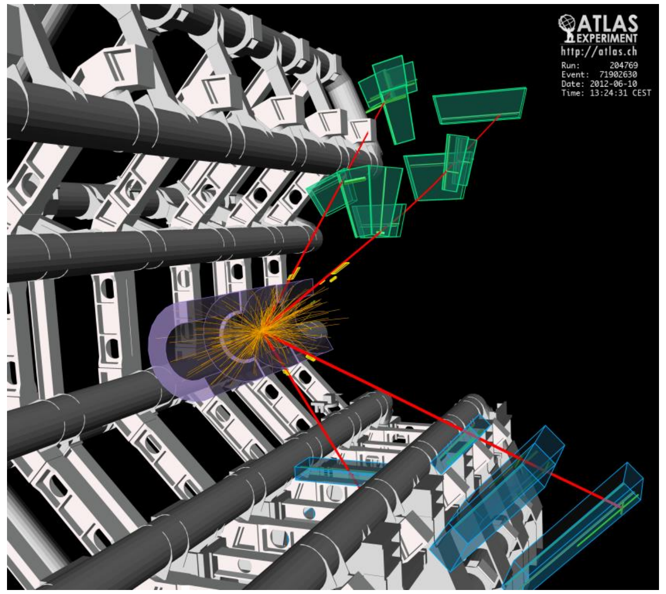
Candidate Higgs → 2μ2e



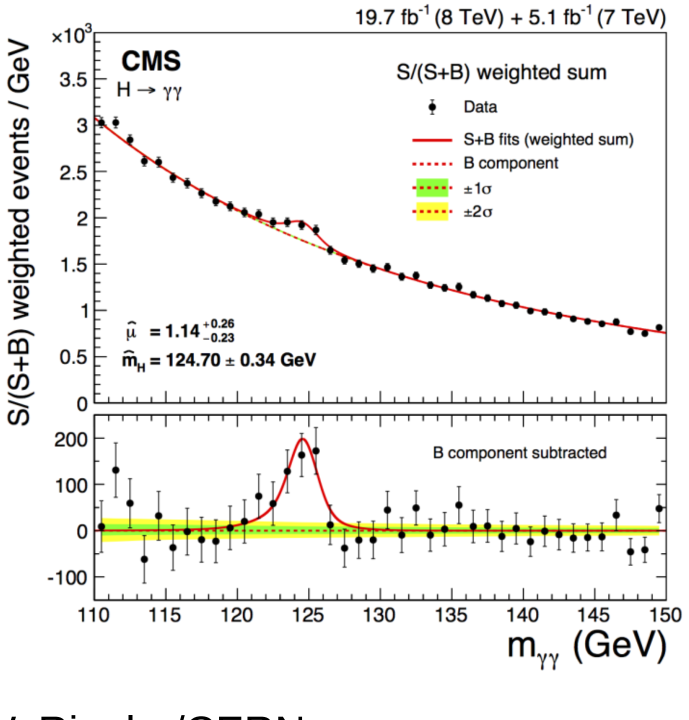
Candidate Higgs → 2 photons

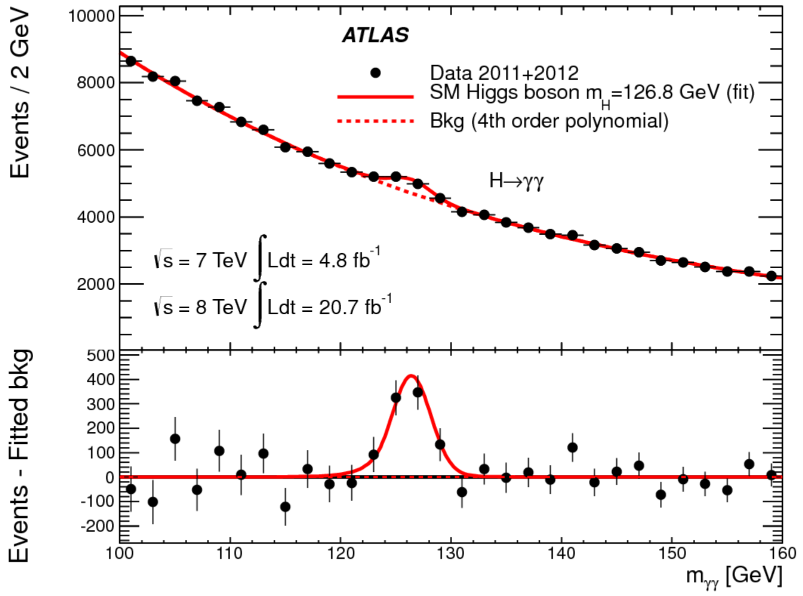
Signal and Background

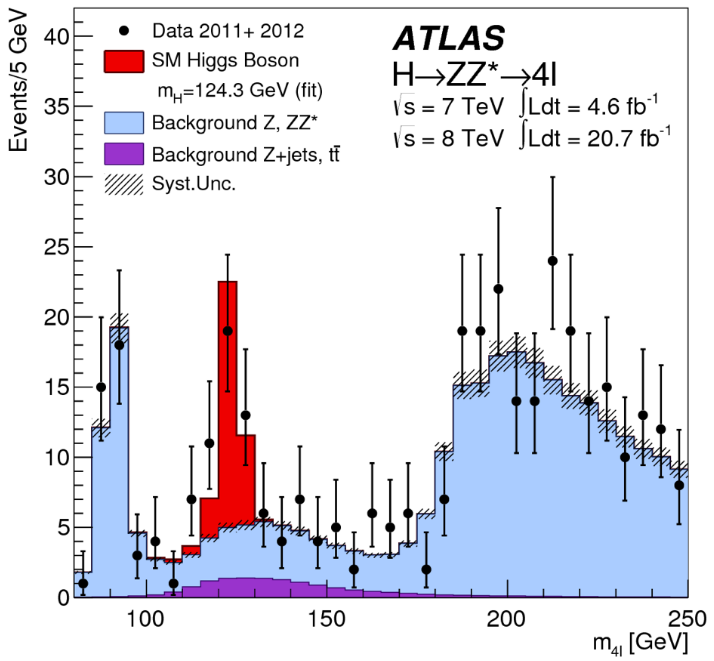


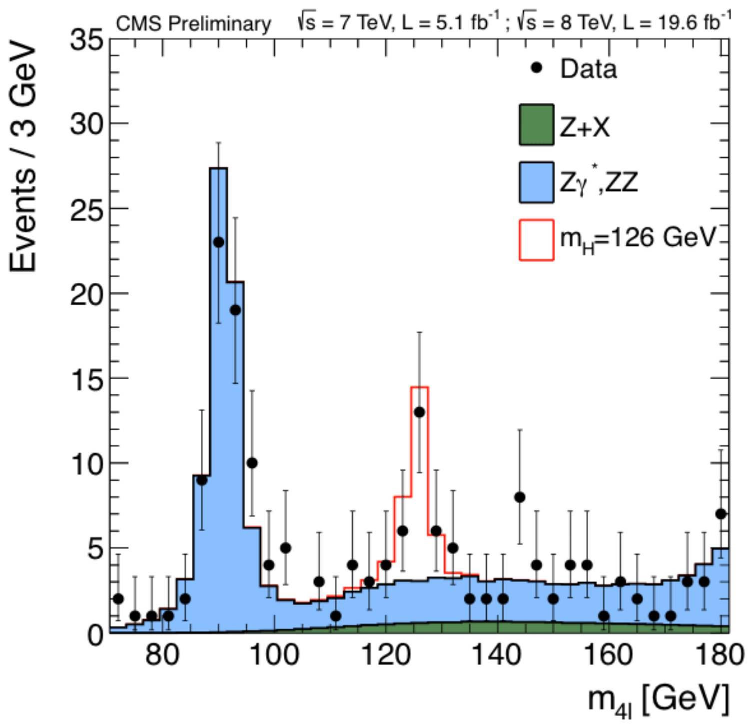


Particles are typically seen as an excess of events above an irreducible (i.e. indistinguishable) background.









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.

Conclusion

A particle detector is an (almost) irreducible representation of the properties of these 8 particles

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