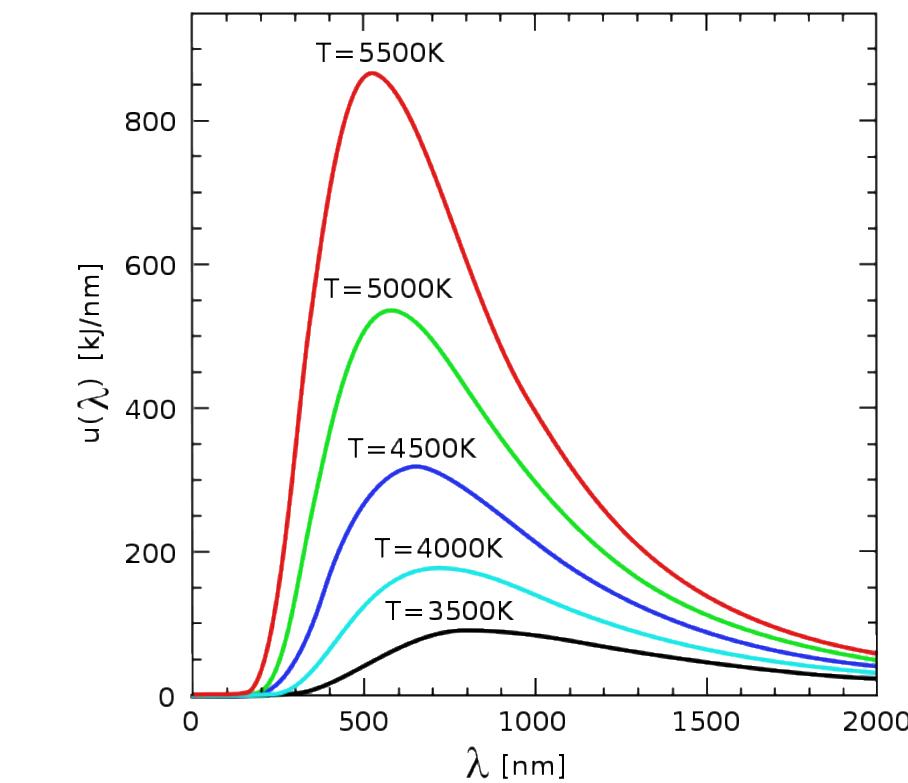
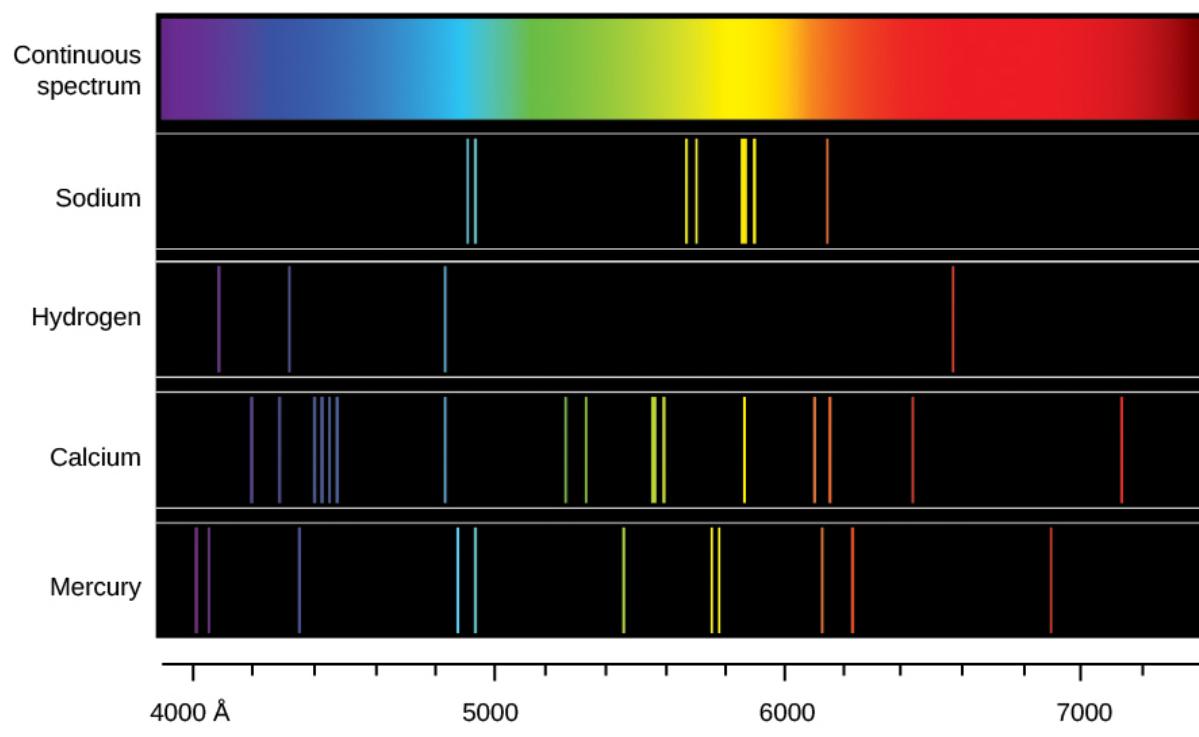
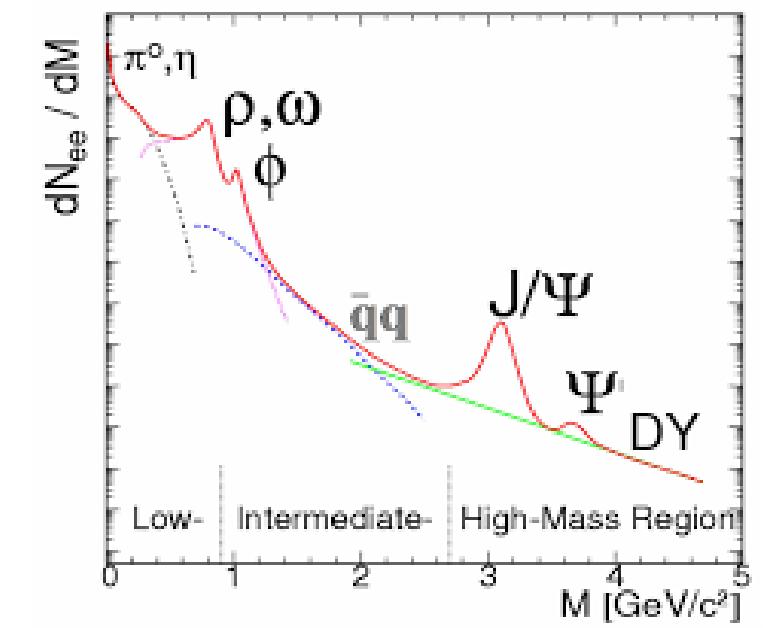
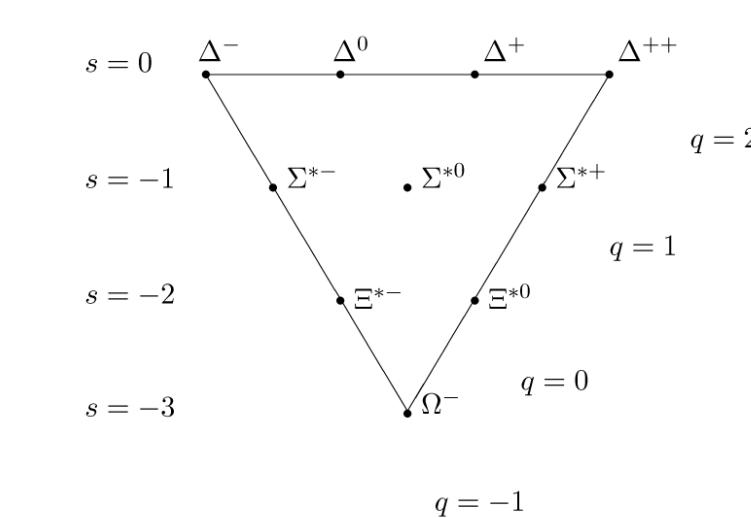
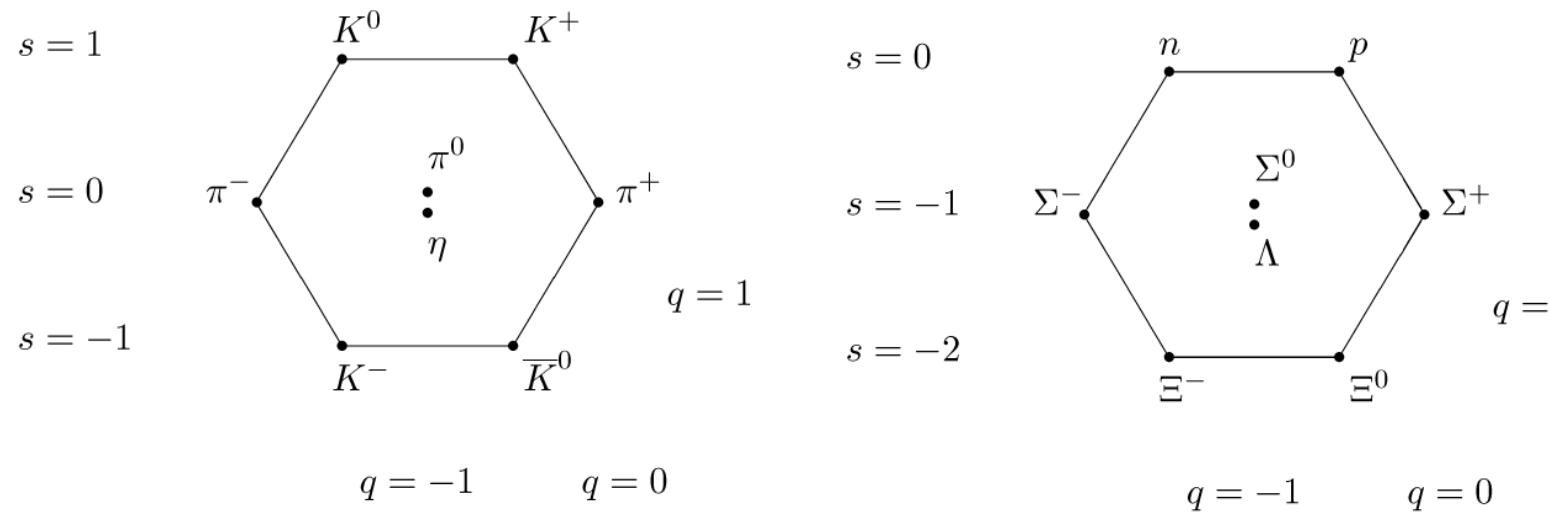


Spectral Lines, Blackbody Radiation → Quantum Mechanics



Particle Zoo, Resonances → Quarks, QCD



Particle Detectors

Summer Student Lectures 2023

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

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

and it can be shown⁴ 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'

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

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

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

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 ...

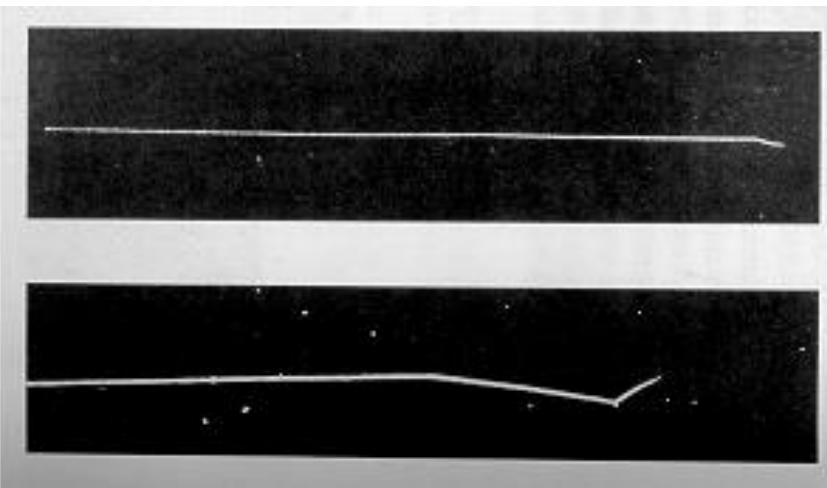
Mass ≥ 0

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 themselves are linear superpositions 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 an example with an 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:

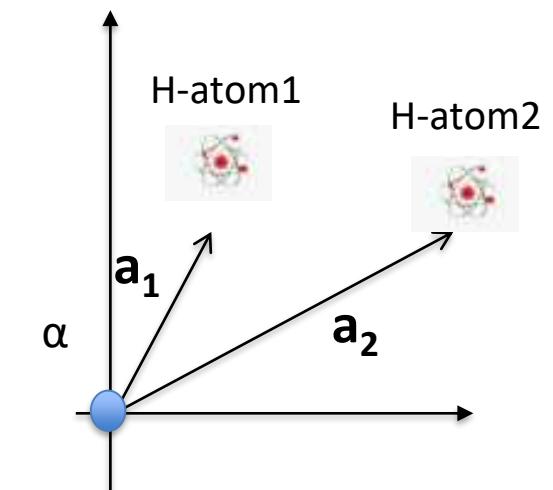
[Mo] Mott N.F., The wave mechanics of α -ray tracks. *Proc. R. Soc. Lond. A*, **126**, 79-84, 1929. Reprinted in: Wheeler J.A., Zurek W., *Quantum Theory and Measurement*, Princeton University Press, 1983.



Main objects of the investigation are periodic solutions $F(\mathbf{R}, \mathbf{r}_1, \mathbf{r}_2)e^{iEt/\hbar}$ of the Schrödinger equation for the three particle system, where \mathbf{R} , \mathbf{r}_1 , \mathbf{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

$$\begin{aligned} -\frac{\hbar^2}{2M}\Delta_{\mathbf{R}}F + \left(-\frac{\hbar^2}{2m}\Delta_{\mathbf{r}_1} - \frac{e^2}{|\mathbf{r}_1 - \mathbf{a}_1|}\right)F + \left(-\frac{\hbar^2}{2m}\Delta_{\mathbf{r}_2} - \frac{e^2}{|\mathbf{r}_2 - \mathbf{a}_2|}\right)F \\ -\left(\frac{2e^2}{|\mathbf{R} - \mathbf{r}_1|} + \frac{2e^2}{|\mathbf{R} - \mathbf{r}_2|}\right)F = E F \end{aligned} \quad (4.1)$$

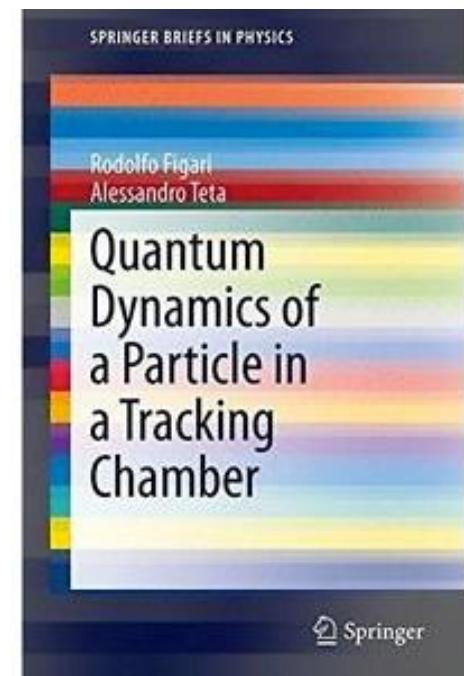
where Δ_x is the laplacian with respect to the coordinate x , M is the mass of the α -particle, m is the mass of the electron, $-e$ is the charge of the electron so that $2e$ is the charge of the α -particle.



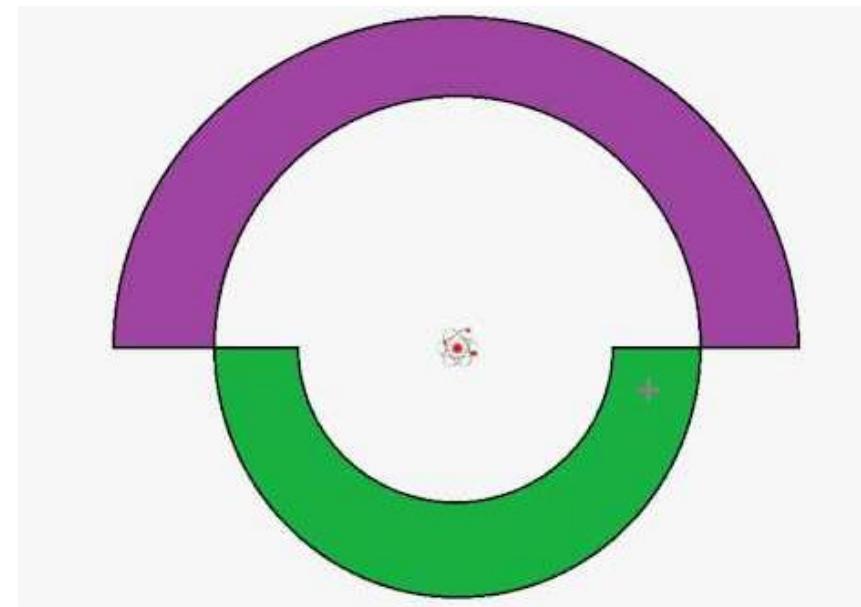
Result: The two hydrogen atoms cannot both be excited (or ionized) unless \mathbf{a}_1 , \mathbf{a}_1 and the origin lie on the same straight line.
(see Also Werner Heisenberg, Chicago lectures 1930)

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=EtyNMIXN-sw>



Renninger's negative-result experiment (1953)



A radioactive atom (emitting an 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 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

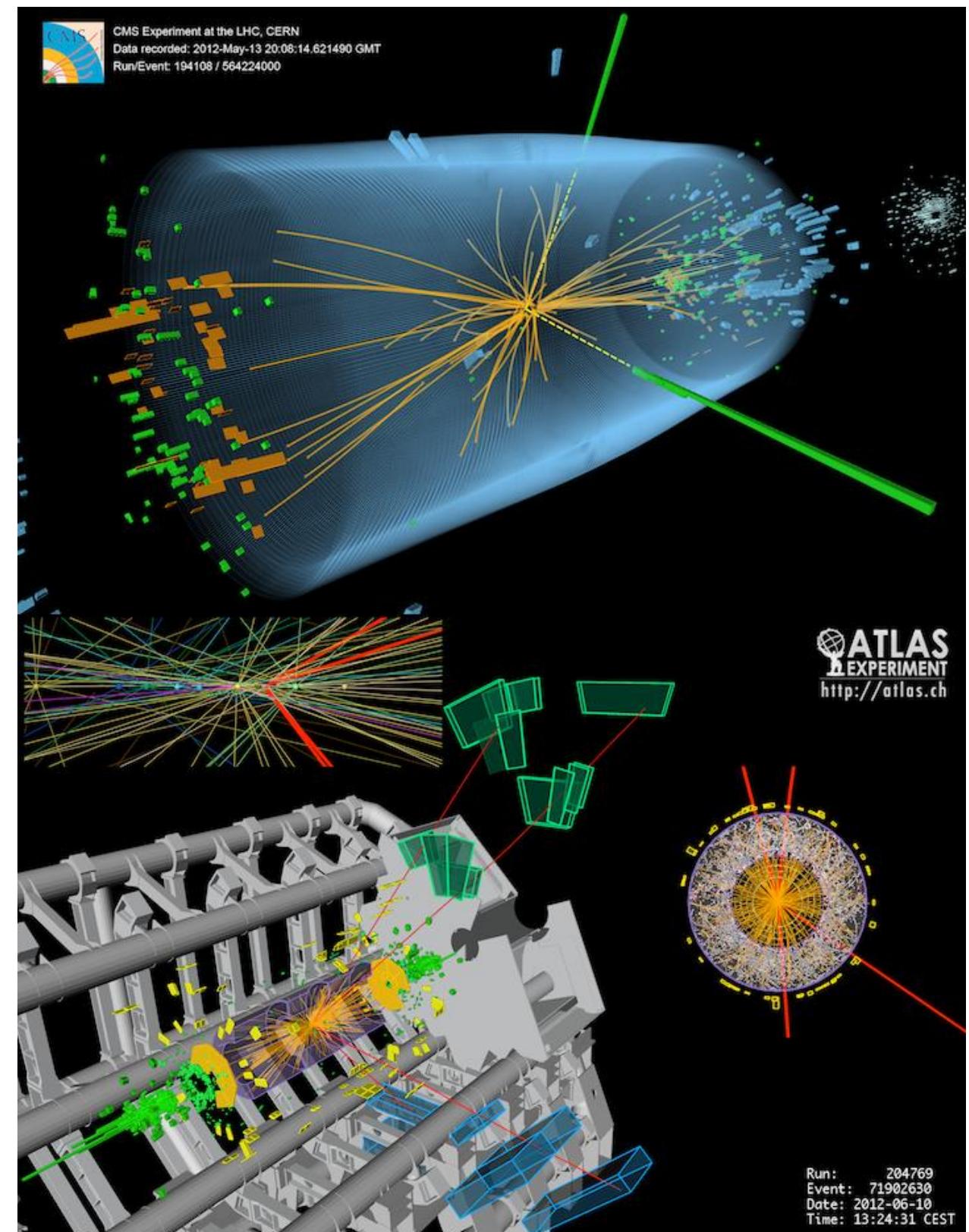
Elektro-Weak Lagrangian

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

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

Higgs Particle

	matter particles			guage particles		
	1st gen.	2nd gen.	3rd gen.			
Q U A R K	u up d down	c charm s strange	t top b bottom	Strong Force g Gluon	Electro-Magnetic Force γ photon	Weak Force W⁺ W ⁺ bosons W⁻ W ⁻ bosons Z Z boson
L E P T O N	ν_e e neutrino e electron	ν_μ μ neutrino μ muon	ν_τ τ neutrino τ tau			
scalar particle(s)	H Higgs	?	?	• • •		



The ‘Real’ World of Particles

$\frac{1}{2}$	(e) γ_e	(μ) γ_μ	(γ) γ_γ	Electromagnetic, Weak Weak
$-\frac{1}{3}$	(u) d	(c) s	(t) b	Electromagnetic, Weak , Strong Electromagnetic, Weak, Strong
$\underbrace{\hspace{5cm}}$			$\underbrace{\hspace{5cm}}$	
Spin $\frac{1}{2}$ Particles			Spin 1 Particles	

$p \sim uvd$, 

$$n \sim 0.8$$

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

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

$$\wedge \sim vds$$

EM: γ - Photon $\xrightarrow{\text{QED}}$
 Weak: $W^\pm, Z^0 \xrightarrow{\text{Electroweak}}$
 Strong: g - Gluon $\xrightarrow{\text{QCD}}$

$$1 \begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} u \\ \nu_u \end{pmatrix} \begin{pmatrix} \bar{u} \\ \nu_{\bar{u}} \end{pmatrix} - \frac{2}{3} \begin{pmatrix} d \\ \nu_d \end{pmatrix} \begin{pmatrix} \bar{d} \\ \nu_{\bar{d}} \end{pmatrix} \begin{pmatrix} s \\ \nu_s \end{pmatrix} \begin{pmatrix} \bar{s} \\ \nu_{\bar{s}} \end{pmatrix}$$

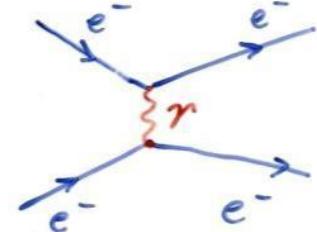
2

$$0 \begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} u \\ \nu_u \end{pmatrix} \begin{pmatrix} \bar{u} \\ \nu_{\bar{u}} \end{pmatrix} \begin{pmatrix} d \\ \nu_d \end{pmatrix} \begin{pmatrix} \bar{d} \\ \nu_{\bar{d}} \end{pmatrix} \begin{pmatrix} s \\ \nu_s \end{pmatrix} \begin{pmatrix} \bar{s} \\ \nu_{\bar{s}} \end{pmatrix} \begin{pmatrix} c \\ \nu_c \end{pmatrix} \begin{pmatrix} \bar{c} \\ \nu_{\bar{c}} \end{pmatrix} \begin{pmatrix} t \\ \nu_t \end{pmatrix} \begin{pmatrix} \bar{t} \\ \nu_{\bar{t}} \end{pmatrix}$$

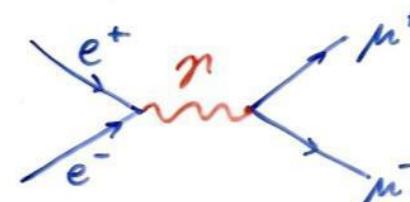
3

Electromagnetic Interaction γ -Photon

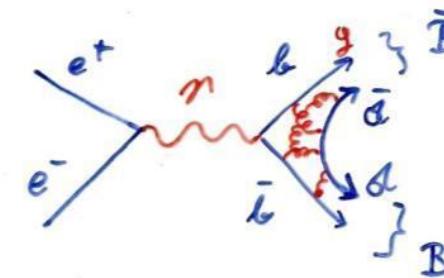
Scattering:



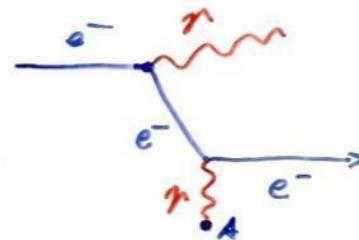
Annihilation:



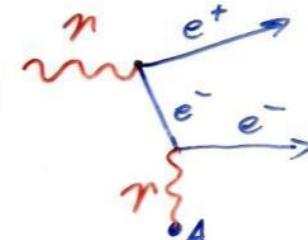
Annihilation:



Bremsstrahlung:

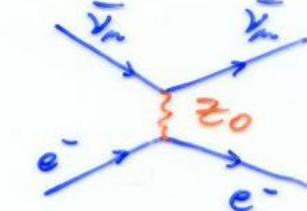


Pair Production:

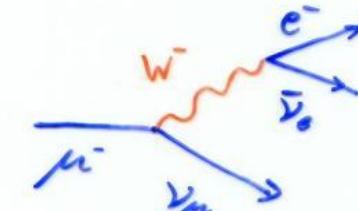


Weak Interaction W^\pm, Z^0

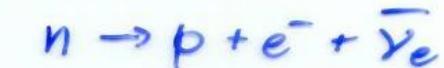
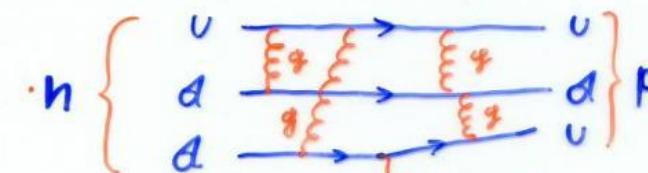
Neutral Current:



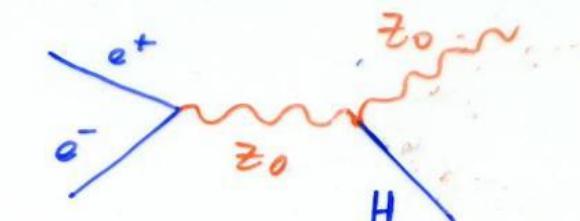
Muon Decay:



Neutron Decay:



H Production:



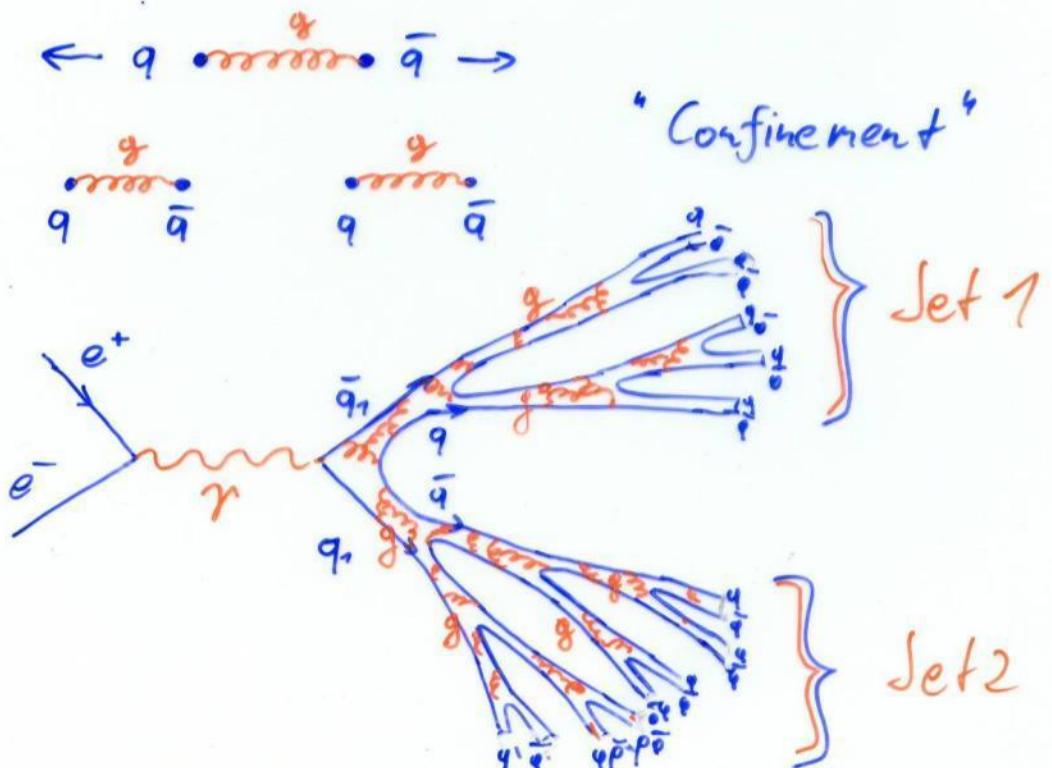
$$\begin{matrix} 1 & (e) & (\mu) & (\gamma) \\ 0 & \gamma_e & \gamma_\mu & \gamma_\gamma \end{matrix} \quad \begin{matrix} \frac{2}{3} & (u) & (c) & (t) \\ -\frac{1}{3} & (d) & (s) & (b) \end{matrix}$$

4

Strong Interaction g Gluons

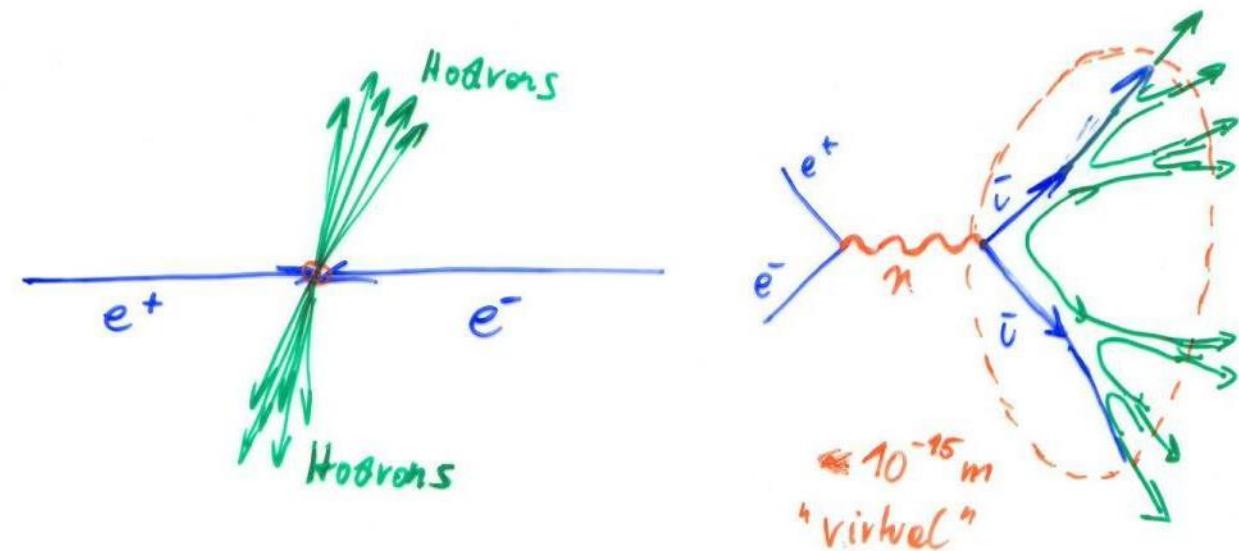


Self Interaction



.... 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

$$E = ma^2$$

$$E = mb^2$$

$$E = mc^2 \quad \text{← Energy ≈ Mass}$$

⋮

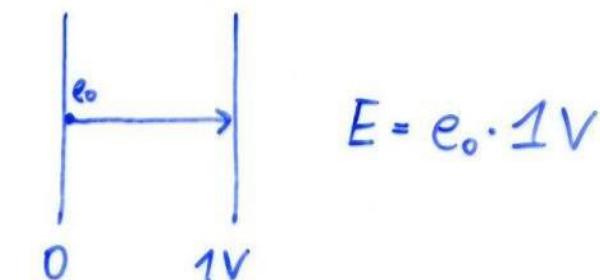
$$m(\text{electron}) = 9.1 \cdot 10^{-31} \text{ kg}$$

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

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

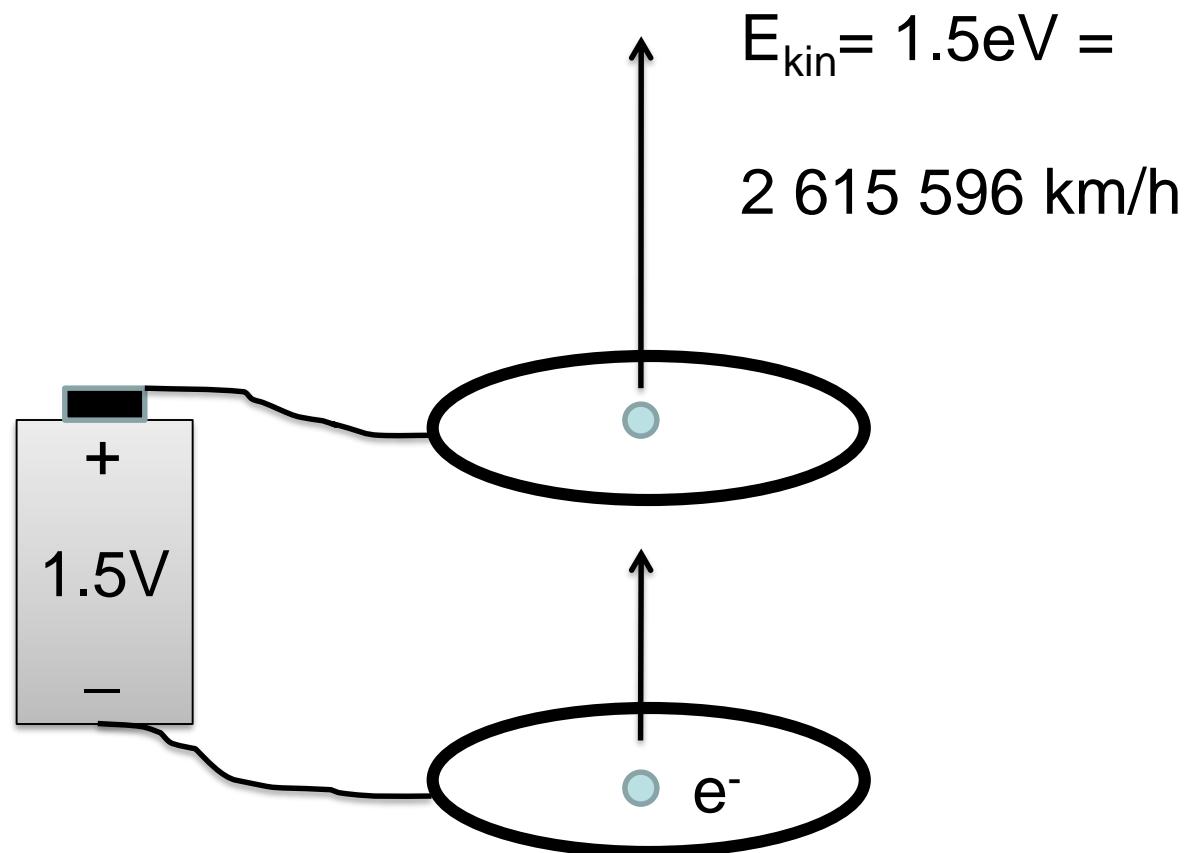
$$= 0.511 \text{ MeV}$$

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

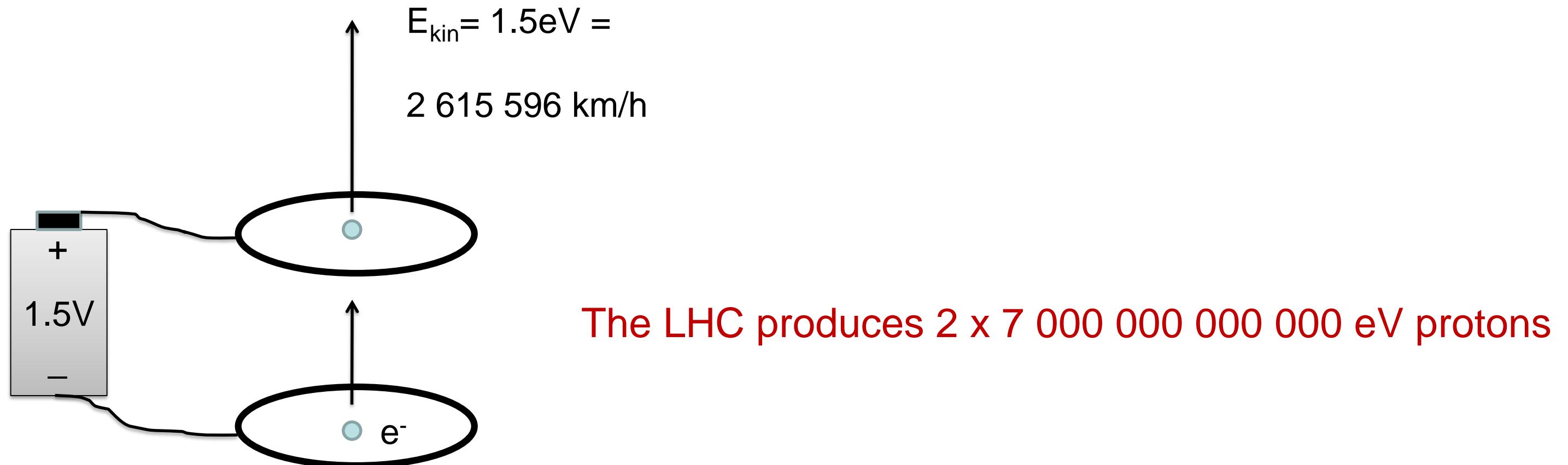


1 Electron Volt = Energy an Electron gains as
it traverses a Potential Difference of 1V

Build your own Accelerator



Build your own Accelerator



Scales

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

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

$$E_k = m_e c^2 (\gamma - 1) \quad m_e c^2 \approx 0.511 \text{ MeV}$$

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

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

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

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

$$\gamma \approx 1.0015 \quad \beta \approx 0.054 \rightarrow 16.2 \cdot 10^6 \text{ m/s}$$

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

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

Basics:

Lorentz Boost

Lorentz Boost:

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

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

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

But we see Muons here on Earth

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

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

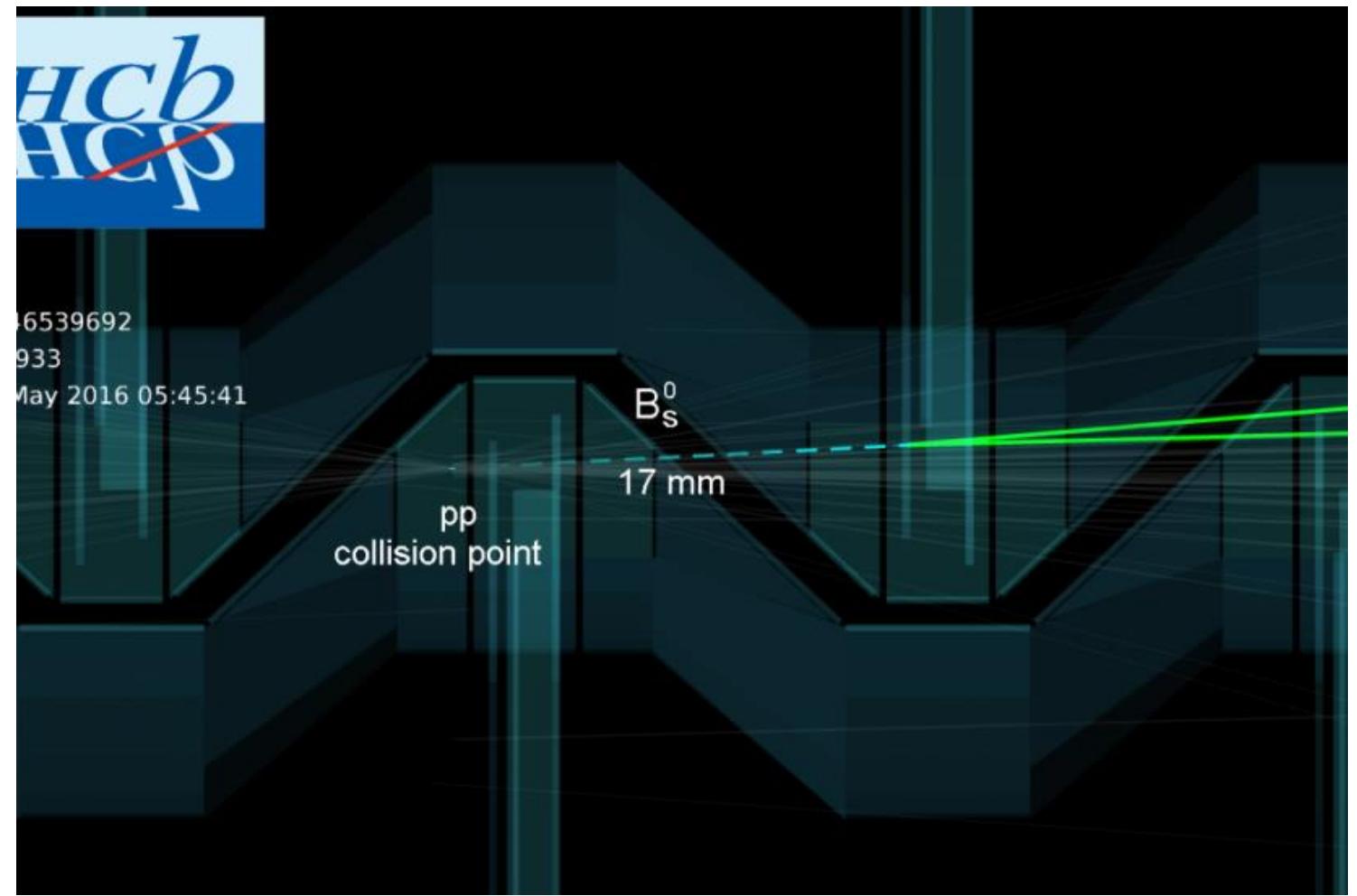
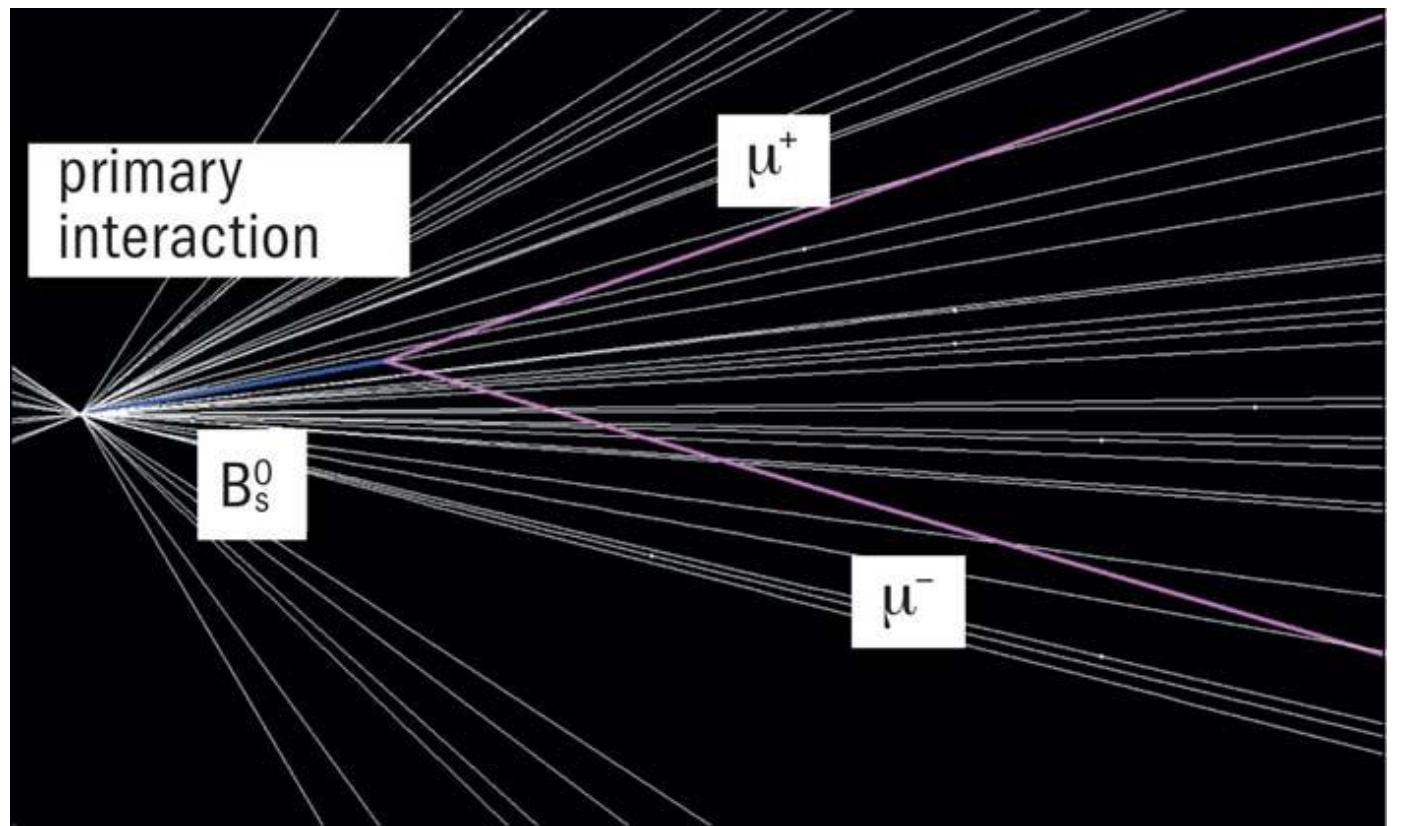
$$s = c \cdot \bar{\gamma} = 12.5\text{ km} \rightarrow \text{Earth}$$

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

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

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

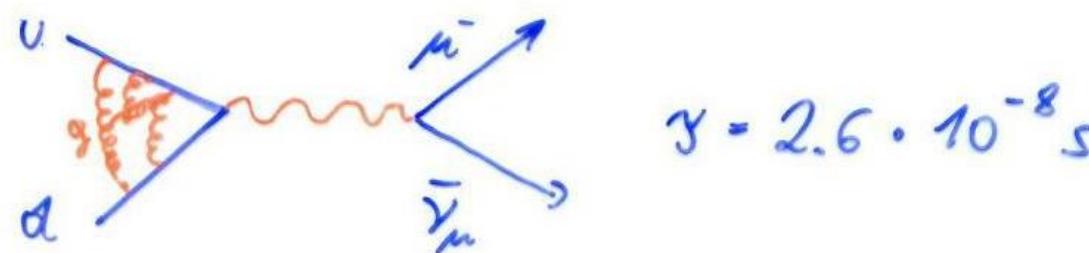
LHCb B decay



Basics:

Two Body Decay

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



$$\gamma = 2.6 \cdot 10^{-8} \text{ s}$$

$$\begin{aligned} \pi^- & \rightarrow \mu^- + \bar{\nu}_\mu \\ \vec{p} = 0, E = m_\pi c^2 & \quad \mu^- \xleftarrow{\vec{p}_1} \xrightarrow{\vec{p}_2} \bar{\nu}_\mu \\ \vec{p}_1 + \vec{p}_2 = 0, E_\mu + E_\nu & = E \end{aligned}$$

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

E_μ, E_ν are uniquely defined

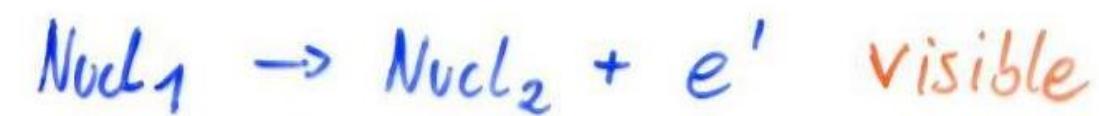
→ Two Body Decay gives "sharp"

Energies of the Decay Particles

Basics:

Three Body Decay

1920ies: β^- Radioactivity



But: e^- shows a continuous Energy Spectrum

→ W. Pauli proposed an "invisible" Particle $\rightarrow \gamma$

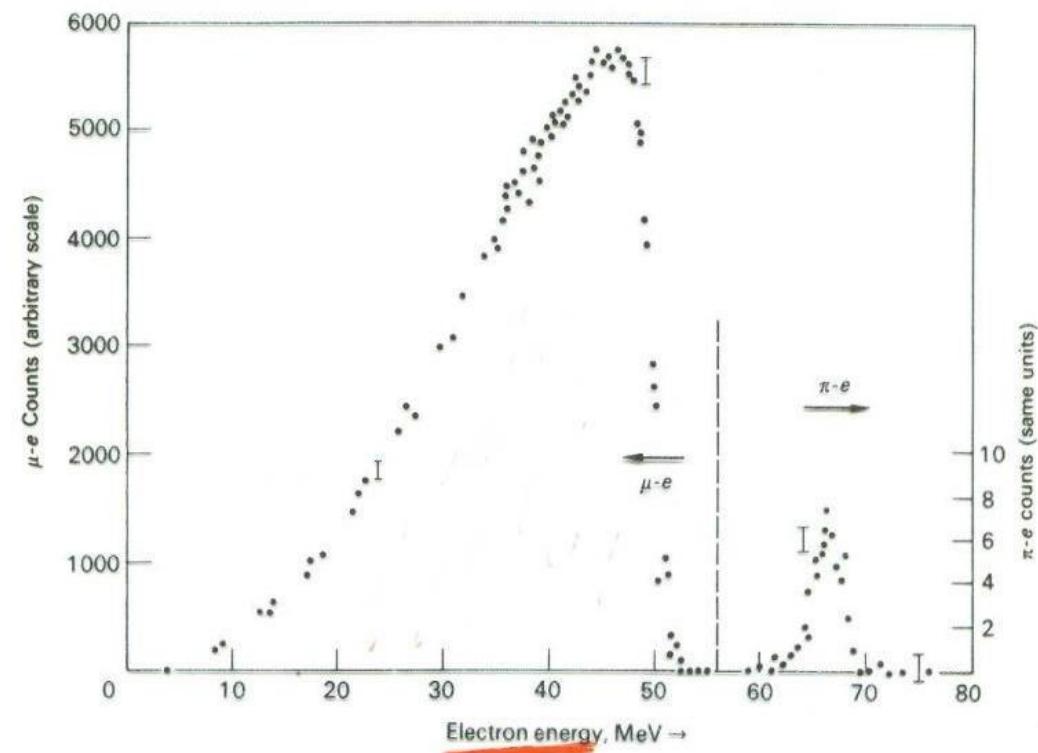


For > 2 Body decay, the Energy Spectrum of the decay particles depends on the Nature of the Interaction. Kinematics alone doesn't define the Energies.

Basics:

Two Body and Three Body Decay

Stopping Pions and measuring
the decay electron Spectrum:



$$\begin{aligned}\pi^- &\rightarrow \mu^- + \bar{\nu}_\mu \\ &\downarrow \\ &e^- + \bar{\nu}_e + \gamma_\mu \\ &\quad \searrow \text{Energy Spectrum (3 Body Decay)}\end{aligned}$$

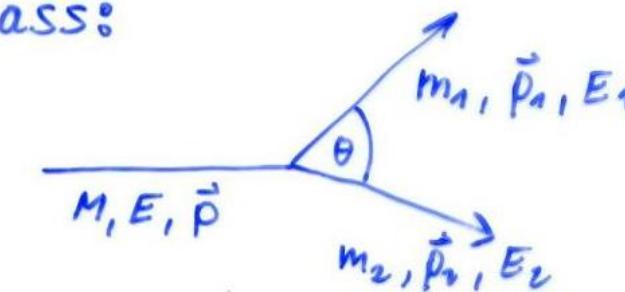
$$\begin{aligned}\pi^- &\rightarrow e^- + \bar{\nu}_e \\ &\downarrow \\ &\text{"sharp" Energy (2 Body Decay)}\end{aligned}$$

Basics:

Invariant Mass

Invariant Mass:

LAB:



Relativity: $\hat{a} = \begin{pmatrix} \alpha_0 \\ \vec{a} \end{pmatrix}$ $\hat{b} = \begin{pmatrix} b_0 \\ \vec{b} \end{pmatrix}$ $\hat{a} \cdot \hat{b} = \alpha_0 b_0 - \vec{a} \cdot \vec{b}$

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

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

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

$$\hat{\vec{p}}^2 = (\hat{\vec{p}}_1 + \hat{\vec{p}}_2)^2 \rightarrow \hat{\vec{p}} \cdot \hat{\vec{p}} = \hat{\vec{p}}_1 \cdot \hat{\vec{p}}_1 + \hat{\vec{p}}_2 \cdot \hat{\vec{p}}_2 + 2 \hat{\vec{p}}_1 \cdot \hat{\vec{p}}_2$$

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

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

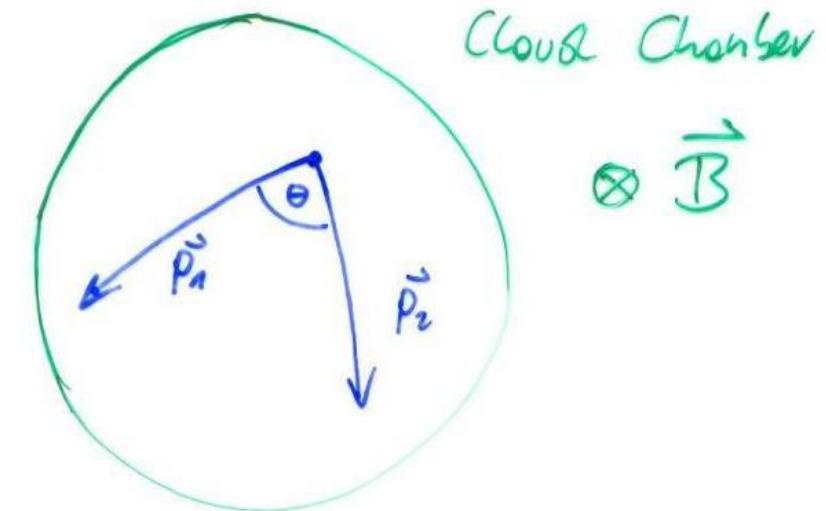
gives the Mass of the original Particle

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 is done 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 its 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 it does NOT decay in n time intervals dt but the $(n+1)^{\text{st}}$ 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 $t = n dt \rightarrow$

Probability that the particle decays between time t and $t+dt$ = $\exp(-c_1 t) c_1 dt = P(t) dt$!

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

$$\bar{x} = \int_0^{\infty} t c_1 e^{-c_1 t} dt = \frac{1}{c_1} \quad \text{Average Lifetime}$$

$$P(t) = \frac{1}{\bar{x}} e^{-\frac{t}{\bar{x}}} \quad \bar{x} = \text{"Lifetime"}$$

"A Particle has a Lifetime \bar{x} " means:

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

Known Particles

$\pi, W^\pm, Z^0, g, e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau, \pi^\pm, \pi^0, \eta, f_0(600), g(270),$
 $w(782), \eta'(858), f_0(980), a_0(980), \phi(1020), h_1(1170), b_1(1235),$
 $a_1(1260), f_2(1270), f_1(1285), \eta(1395), \pi(1300), a_2(1320),$
 $f_0(1370), f_1(1420), w(1420), \eta(1440), a_0(1450), g(1450),$
 $f_0(1500), f_2(1525), w(1650), w_3(1670), \pi_2(1670), \phi(1680),$
 $g_3(1690), g(1700), f_0(1710), \pi(1800), \phi_3(1850), f_2(2010),$
 $a_4(2040), f_4(2050), f_2(2300), f_2(2340), K^\pm, K^0, K_s^0, K_L^0, K^*(892),$
 $K_1(1270), K_1(1400), K^*(1410), K_b^*(1430), K_2^*(1430), K^*(1680),$
 $K_2(1770), K_3^*(1780), K_2(1820), K_4^*(2045), D^\pm, D^0, D^*(2007)^0,$
 $D^*(2010)^\pm, D_1(2420)^0, D_2^*(2460)^0, D_2^*(2460)^\pm, D_s^\pm, D_s^{*\pm},$
 $D_{s1}(2536)^\pm, D_{s1}(2573)^\pm, B^\pm, B^0, B^*, B_s^0, B_c^\pm, \eta_c(1S), J/\psi(1S),$
 $\chi_{c0}(1P), \chi_{c1}(1P), \chi_{c+}(1P), \psi(2S), \psi(3770), \psi(4040), \psi(4160),$
 $\psi(4415), \tau(1S), \chi_{b0}(1P), \chi_{b1}(1P), \chi_{b2}(1P), \tau(2S), \chi_{b0}(2P),$
 $\chi_{b2}(2P), \tau(3S), \tau(4S), \tau(10860), \tau(11020), p, n, N(1440),$
 $N(1520), N(1535), N(1650), N(1675), N(1680), N(1700), N(1710),$
 $N(1720), N(2190), N(2220), N(2250), N(2600), \Delta(1232), \Delta(1600),$
 $\Delta(1620), \Delta(1700), \Delta(1905), \Delta(1910), \Delta(1920), \Delta(1930), \Delta(1950),$
 $\Delta(2420), \Lambda, \Lambda(1405), \Lambda(1520), \Lambda(1600), \Lambda(1670), \Lambda(1690),$
 $\Lambda(1800), \Lambda(1810), \Lambda(1820), \Lambda(1830), \Lambda(1890), \Lambda(2100),$
 $\Lambda(2110), \Lambda(2350), \Sigma^+, \Sigma^0, \Sigma^-, \Sigma(1385), \Sigma(1660), \Sigma(1670),$
 $\Sigma(1750), \Sigma(1775), \Sigma(1915), \Sigma(1940), \Sigma(2030), \Sigma(2250), \Xi^0, \Xi^-,$
 $\Xi(1530), \Xi(1690), \Xi(1820), \Xi(1950), \Xi(2030), \Omega^-, \Omega(2250)^-,$
 $\Lambda_c^+, \Lambda_c^+, \Sigma_c(2455), \Sigma_c(2520), \Xi_c^+, \Xi_c^0, \Xi_c^{'+}, \Xi_c^{'0}, \Xi(2645)$
 $\Xi_c(2780), \Xi_c(2815), \Omega_c^0, \Lambda_b^0, \Xi_b^0, \Xi_b^-, t\bar{t}$

There are Many more

All known particles that can leave a track in the detector

All Particles with $c\tau > 1 \mu\text{m}$ @ GeV Level				19
Particle	Mass (MeV)	Lifetime τ (s)	$c\tau$	
$\pi^\pm (\bar{u}\bar{d}, \bar{d}\bar{u})$	140	\sim	\sim	
$K^\pm (\bar{u}\bar{s}, \bar{s}\bar{u})$	494	$2.6 \cdot 10^{-8}$	7.8 m	
$K^0 (\bar{d}\bar{s}, \bar{s}\bar{d})$	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	
$D^0 (c\bar{u}, \bar{u}c)$	1864	$4.1 \cdot 10^{-13}$	123 μm	
$D_s^\pm (c\bar{s}, \bar{s}c)$	1969	$4.9 \cdot 10^{-13}$	147 μm	
$B^\pm (\bar{u}\bar{b}, \bar{b}\bar{u})$	5279	$1.7 \cdot 10^{-12}$	502 μm	
$B^0 (\bar{b}\bar{d}, \bar{d}\bar{b})$	5279	$1.5 \cdot 10^{-12}$	462 μm	
$B_s^0 (\bar{s}\bar{b}, \bar{b}\bar{s})$	5370	$1.5 \cdot 10^{-12}$	438 μm	
$B_c^\pm (c\bar{s}, \bar{s}c)$	~6400	$\sim 5 \cdot 10^{-13}$	150 μm	
$\rho (\bar{u}u\bar{d})$	938.3	$> 10^{33} \text{ yr}$	∞	
$n (\bar{u}\bar{d}\bar{d})$	939.6	885.7 s	$2.655 \cdot 10^8 \text{ km}$	
$\Lambda^0 (\bar{u}\bar{d}s)$	1115.7	$2.6 \cdot 10^{-10}$	7.89 cm	
$\Sigma^+ (\bar{u}\bar{u}s)$	1189.4	$8.0 \cdot 10^{-11}$	2.404 cm	
$\Sigma^- (\bar{d}\bar{d}s)$	1197.4	$1.5 \cdot 10^{-10}$	4.434 cm	
$\Xi^0 (\bar{s}\bar{s}s)$	1315	$2.9 \cdot 10^{-10}$	8.71 cm	
$\Xi^- (\bar{d}\bar{s}s)$	1321	$1.6 \cdot 10^{-10}$	4.91 cm	
$\Omega^- (\bar{s}\bar{s}s)$	1672	$8.2 \cdot 10^{-11}$	2.461 cm	
$\Lambda_c^+ (\bar{u}\bar{d}c)$	2285	$\sim 2 \cdot 10^{-13}$	60 μm	
$\Xi_c^+ (\bar{u}\bar{s}c)$	2466	$4.4 \cdot 10^{-13}$	132 μm	
$\Xi_c^0 (\bar{d}\bar{s}c)$	2472	$\sim 1 \cdot 10^{-13}$	29 μm	
$\Sigma_c^0 (\bar{s}\bar{d}c)$	2698	$6.0 \cdot 10^{-14}$	19 μm	
$\Lambda_b (\bar{u}\bar{d}b)$	5620	$1.2 \cdot 10^{-12}$	368 μm	

"Secondary
Vertices"

Task of a Detector

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

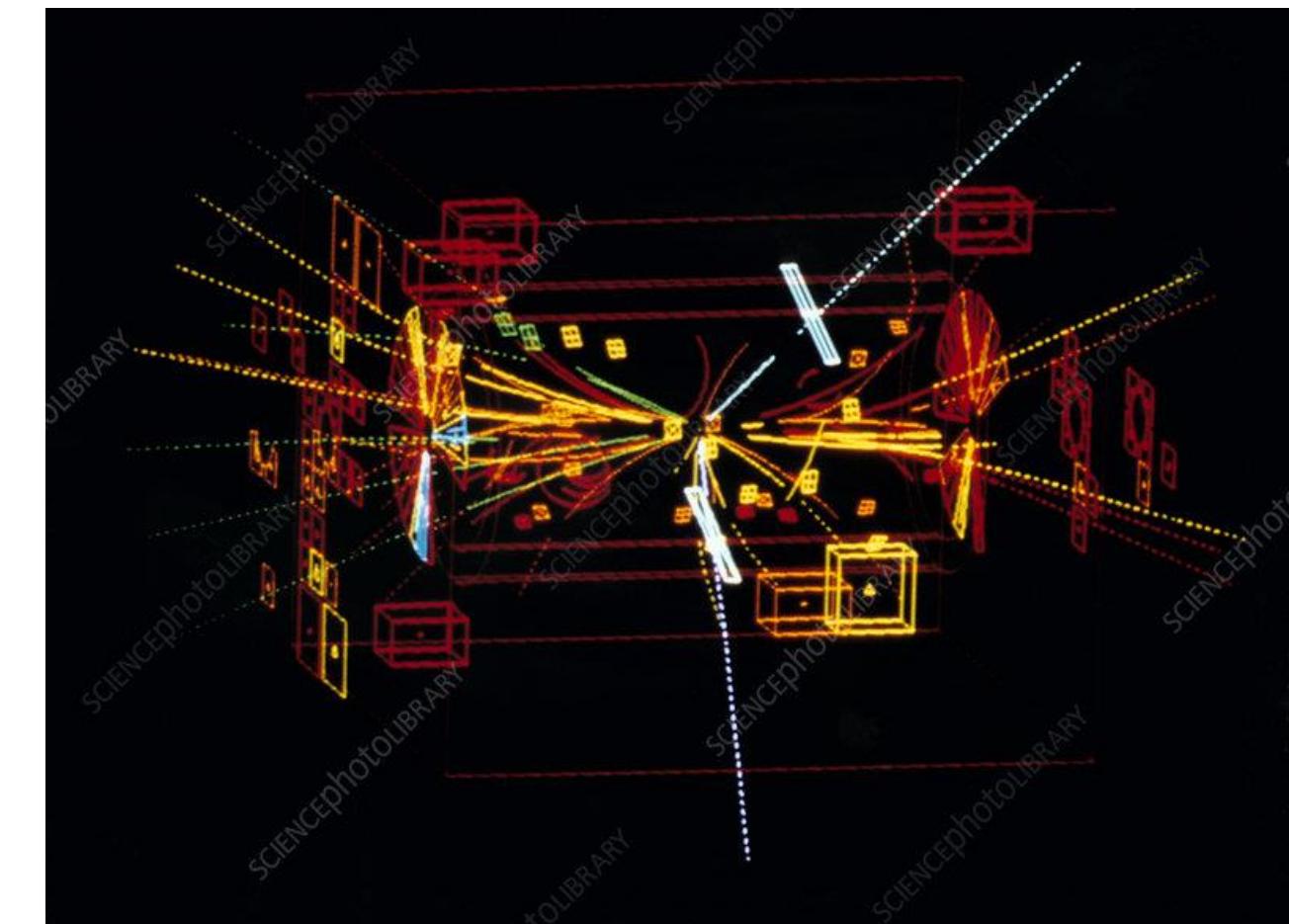
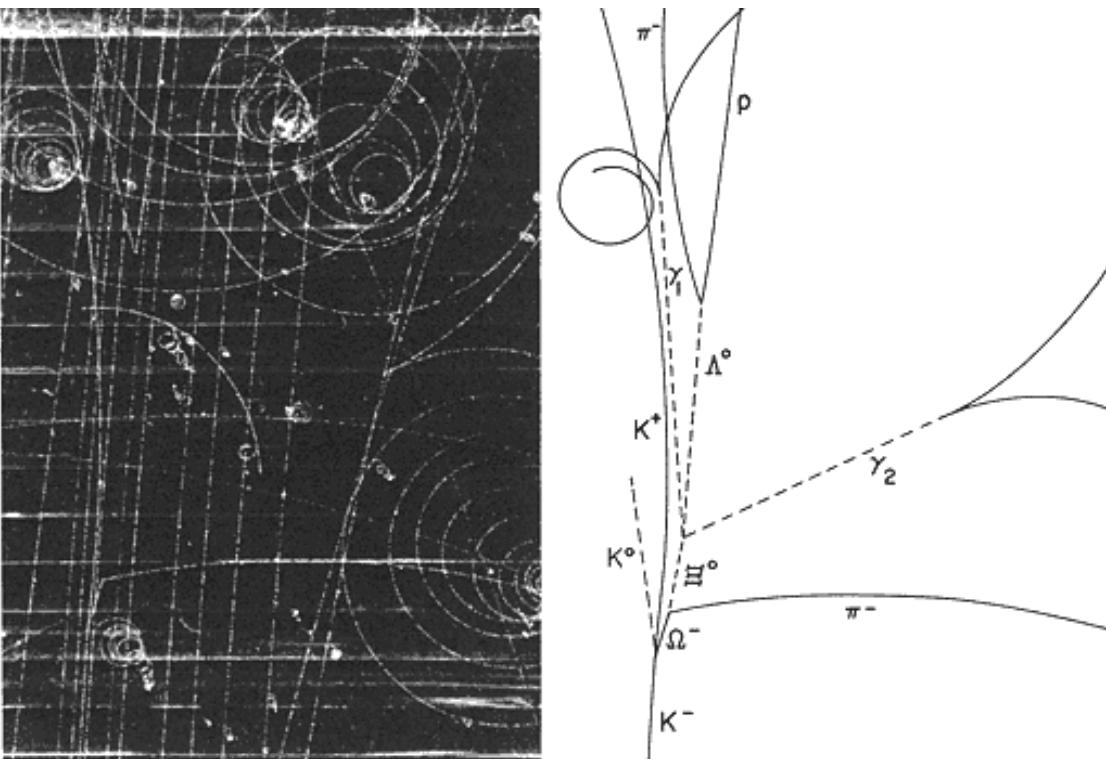
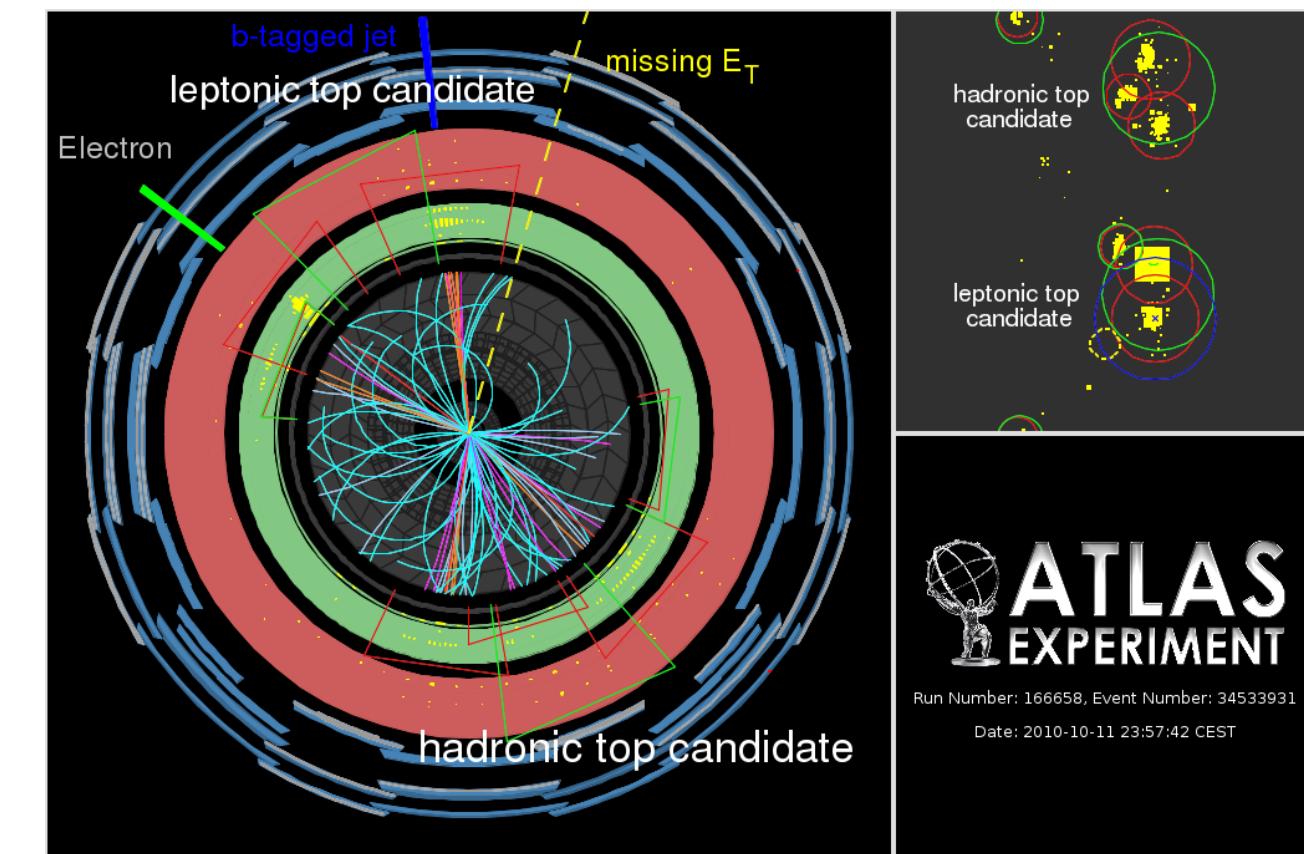
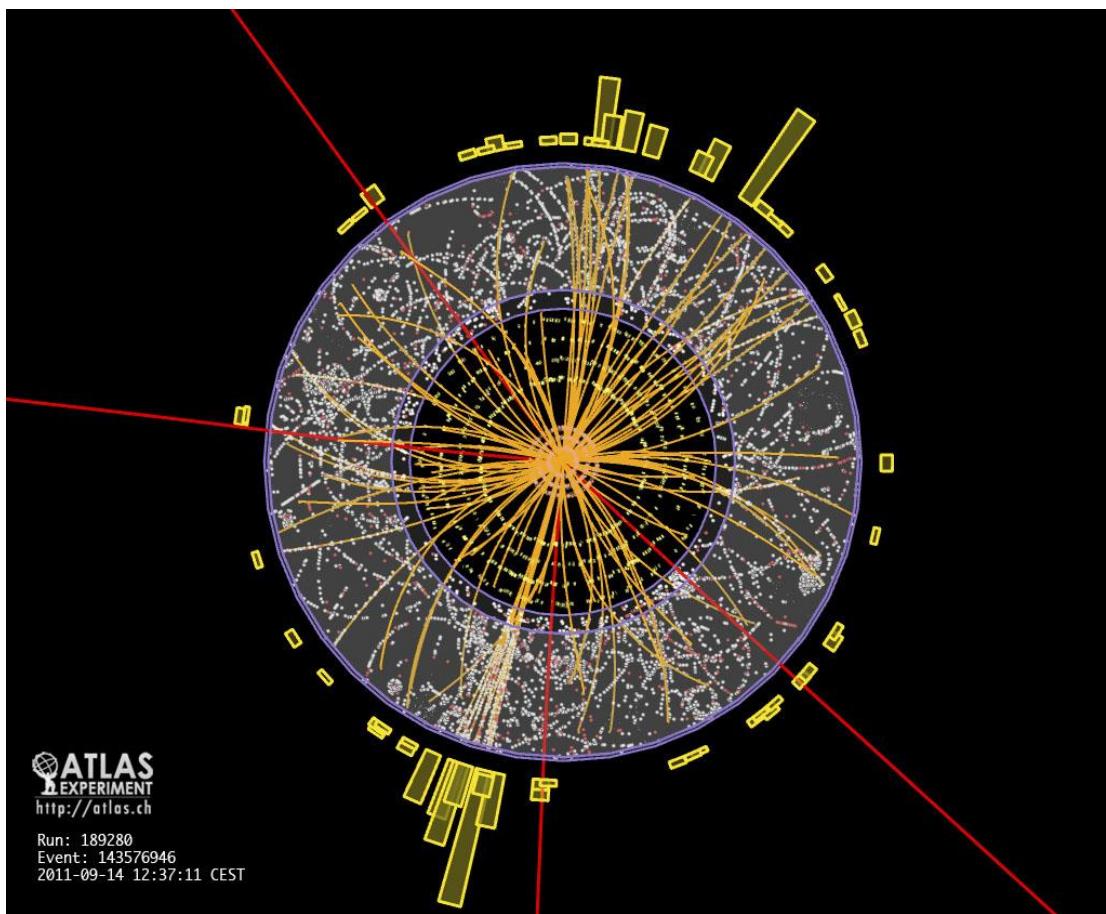
- ~13 of the 27 have $c\tau < 500\mu\text{m}$ i.e. only $\sim \text{mm}$ range at GeV Energies.
→ "short" tracks measured with Emulsions or Vertex Detectors.

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.



Interactions of the 8 particles

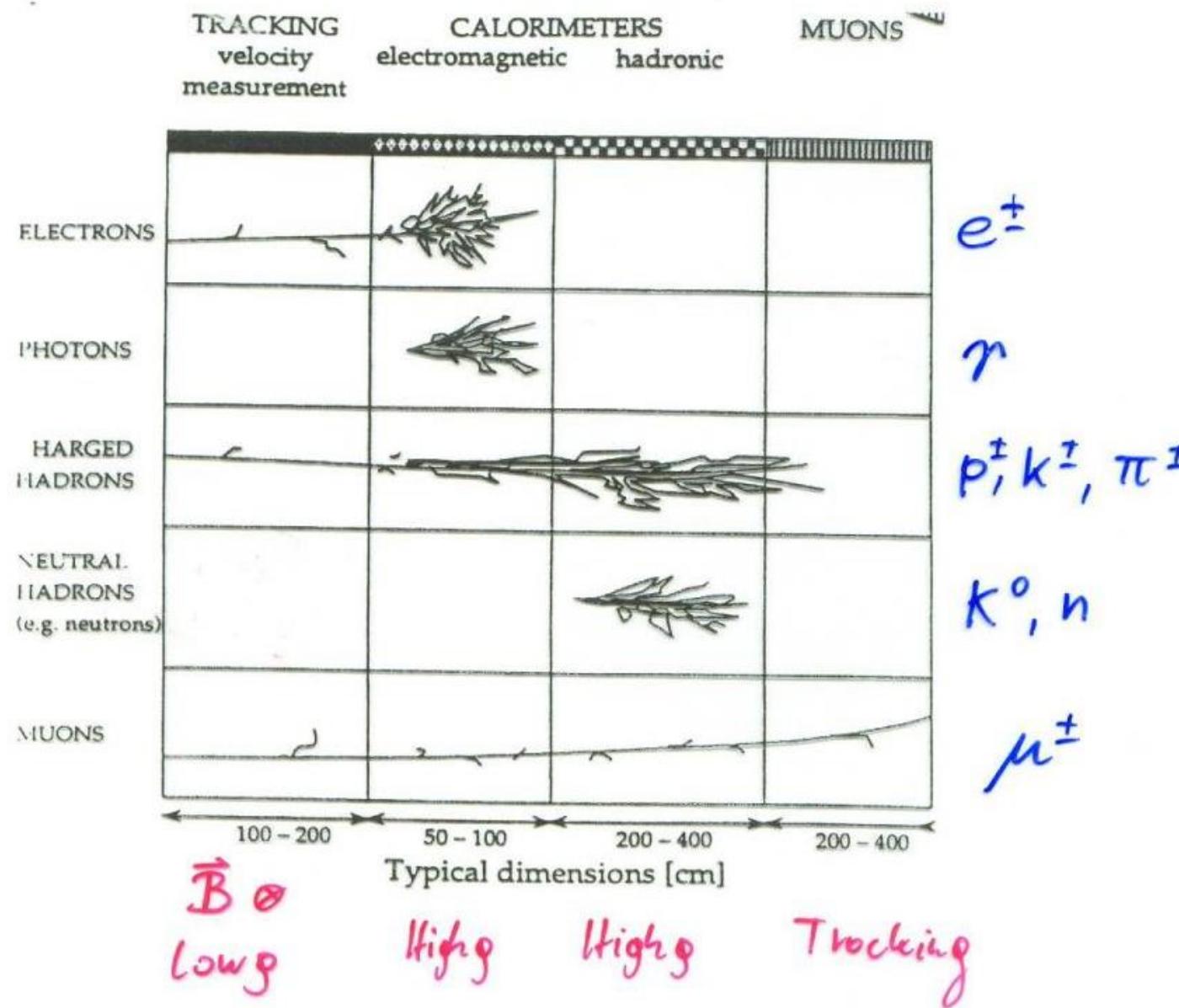
$$\left. \begin{array}{l} e^\pm \quad m_e = 0.511 \text{ MeV} \\ \mu^\pm \quad m_\mu = 105.7 \text{ MeV} \sim 200 m_e \\ \gamma \quad m_\gamma = 0, \quad Q = 0 \end{array} \right\} EM$$

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

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

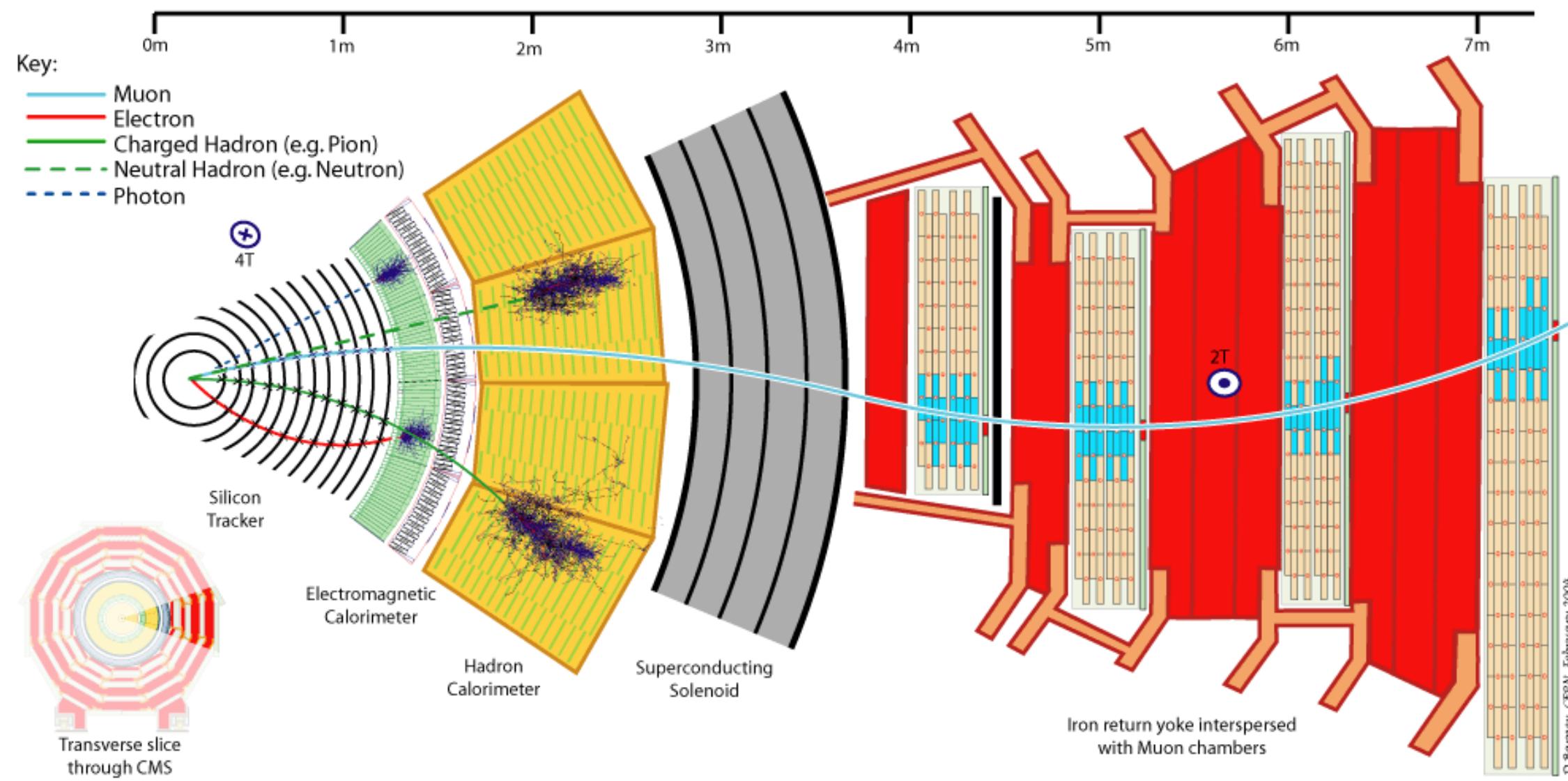
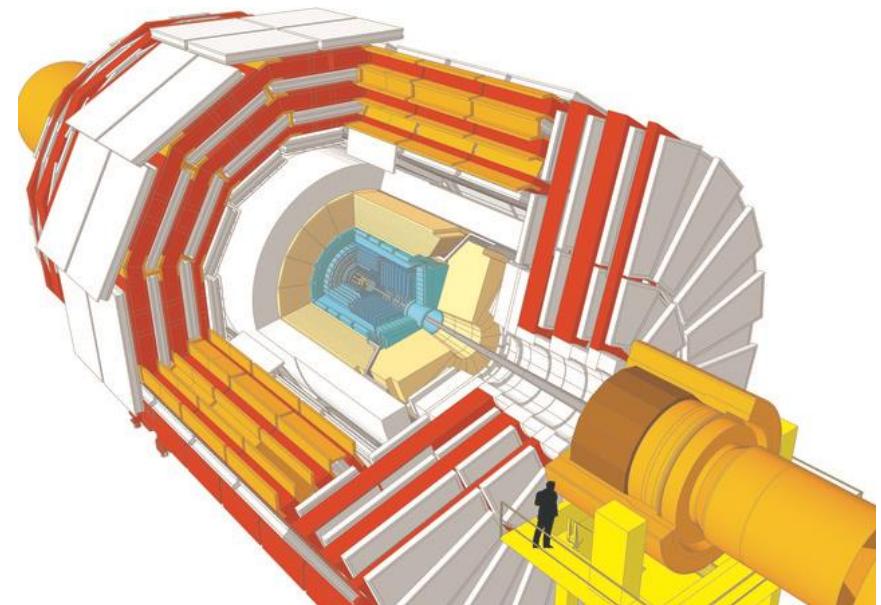
The Difference in
Mass, Charge, Interaction
is the key to the Identification

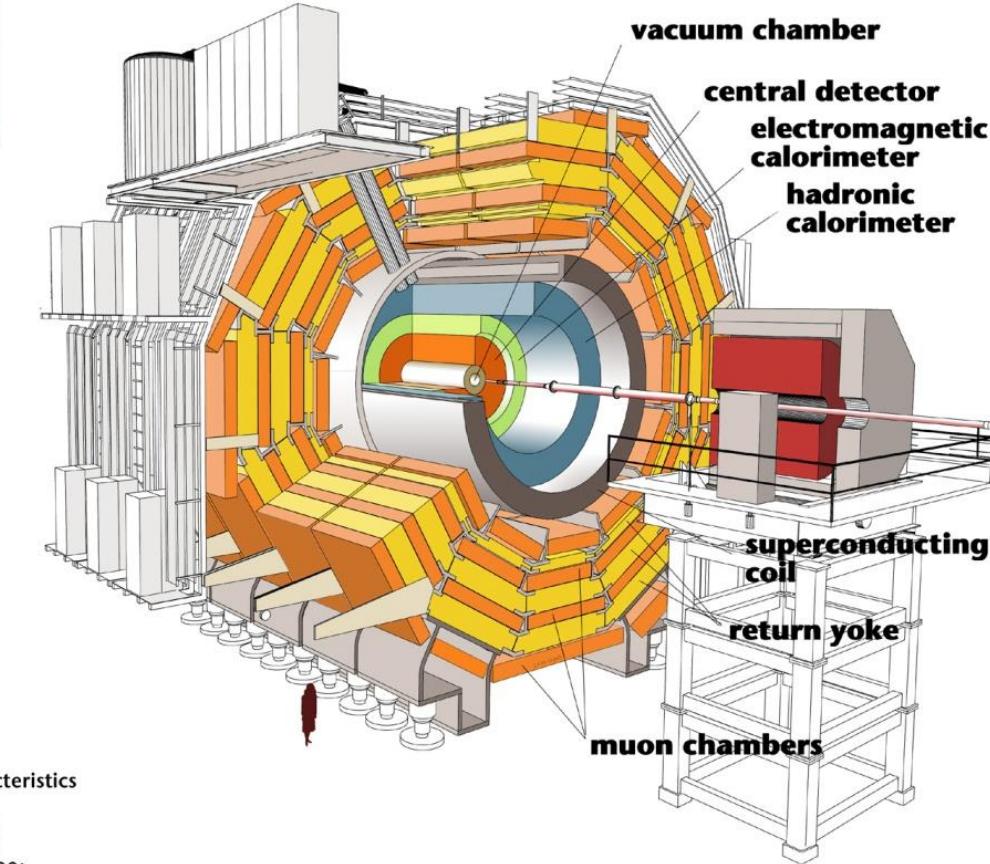
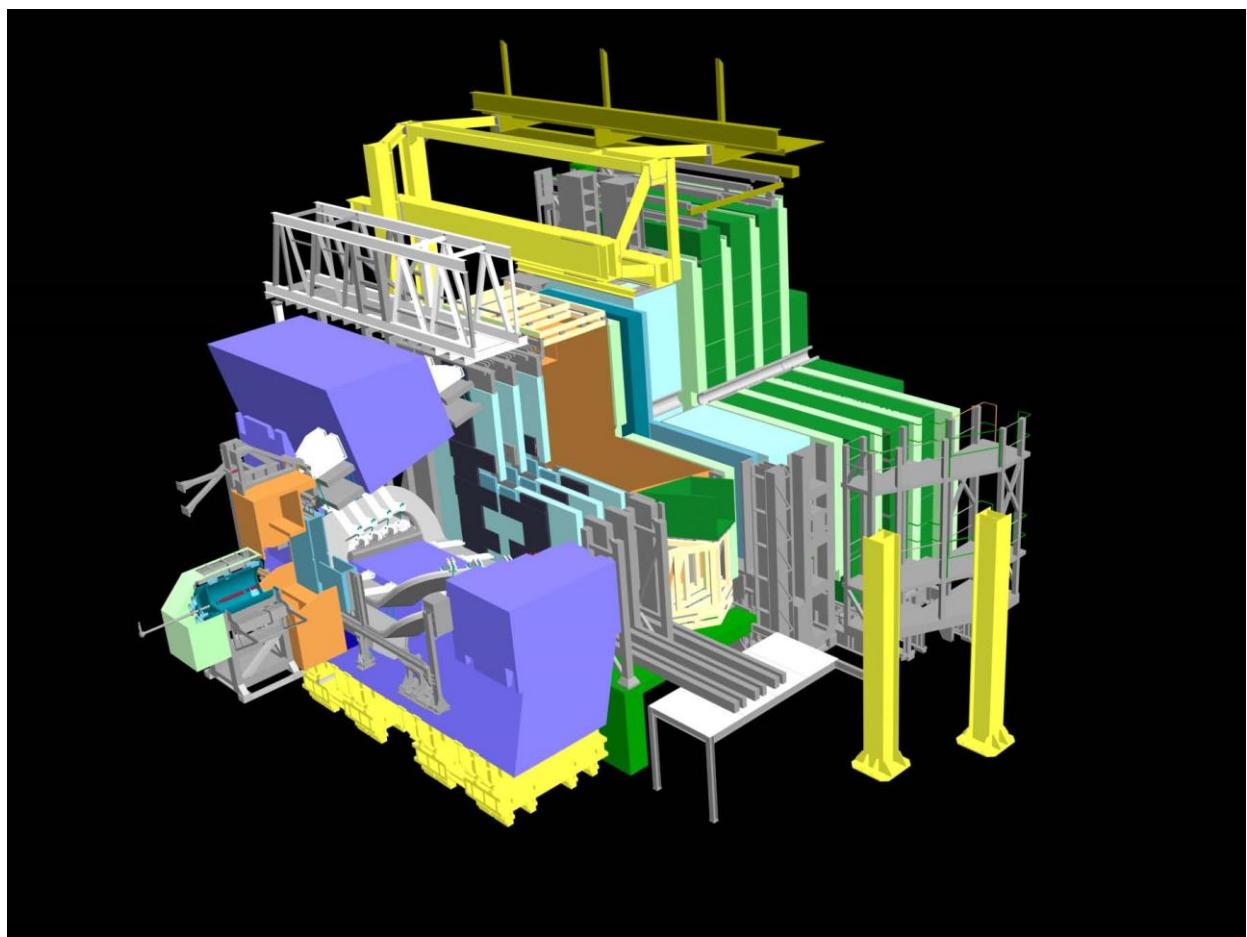
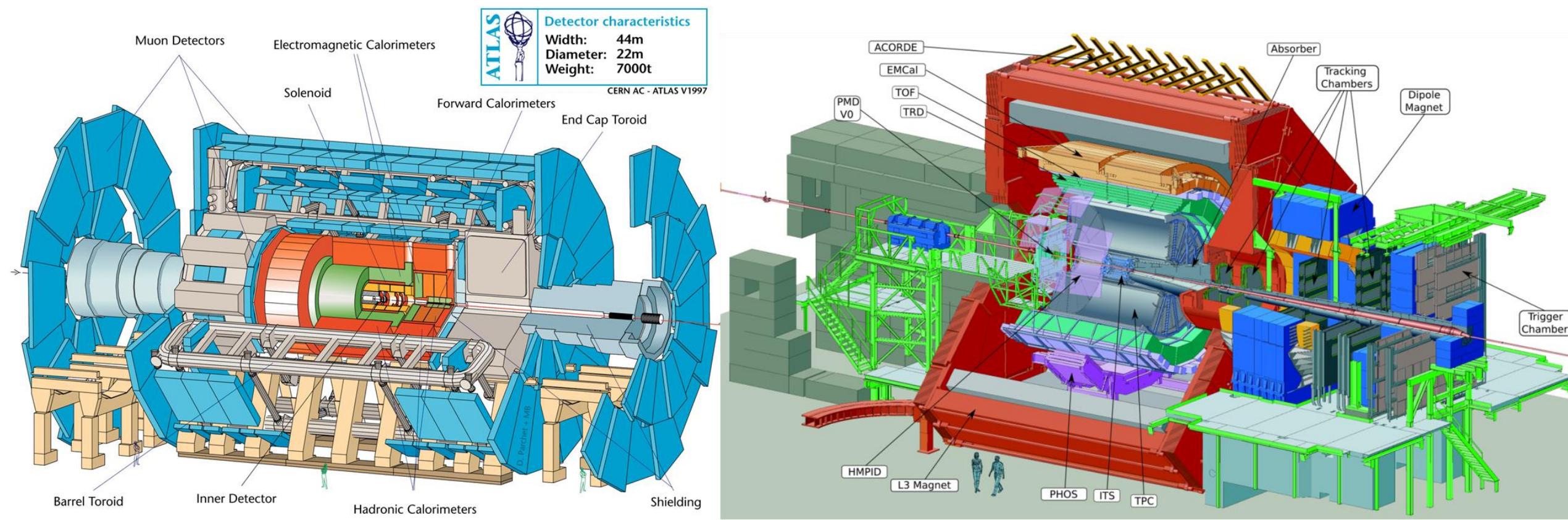
Task of a Particle Detector



- Electrons ionize and show Bremsstrahlung due to the small mass.
- Photons don't ionize but show Pair Production in high τ Material. From here 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

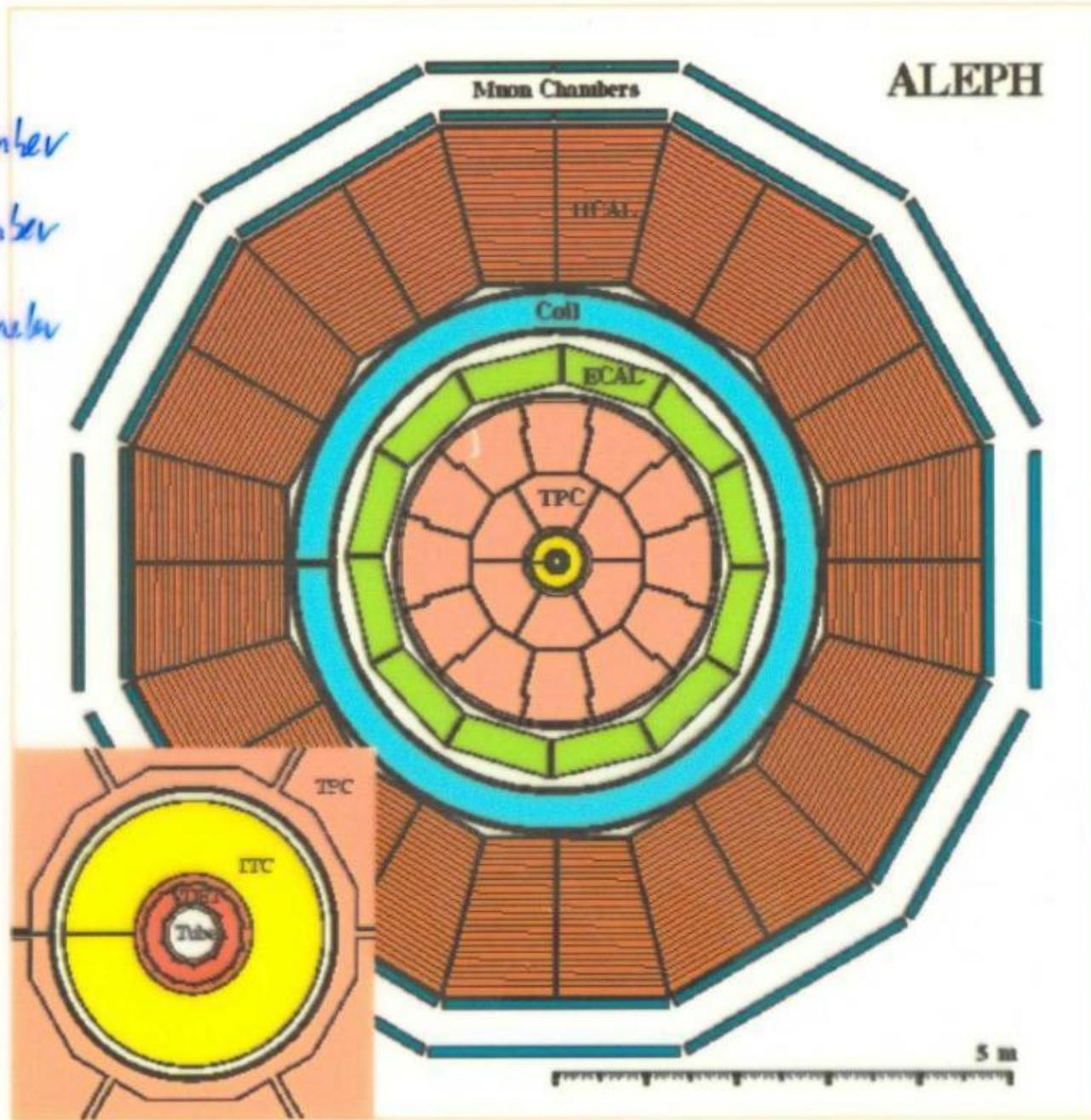
CMS Detector





ALEPH detector (LEP 1988 - 2000)

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



ALEPH detector (LEP 1988 - 2000)

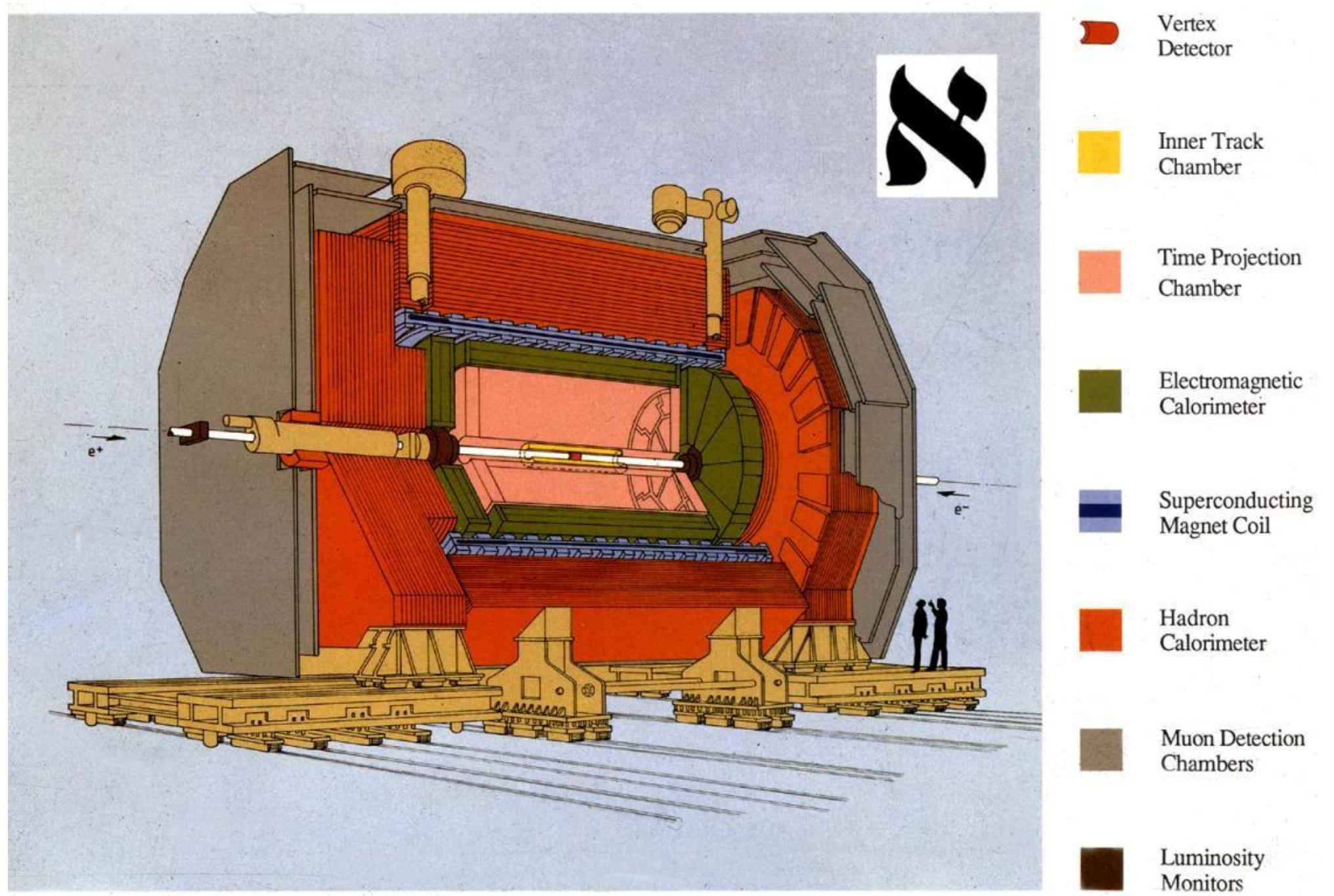
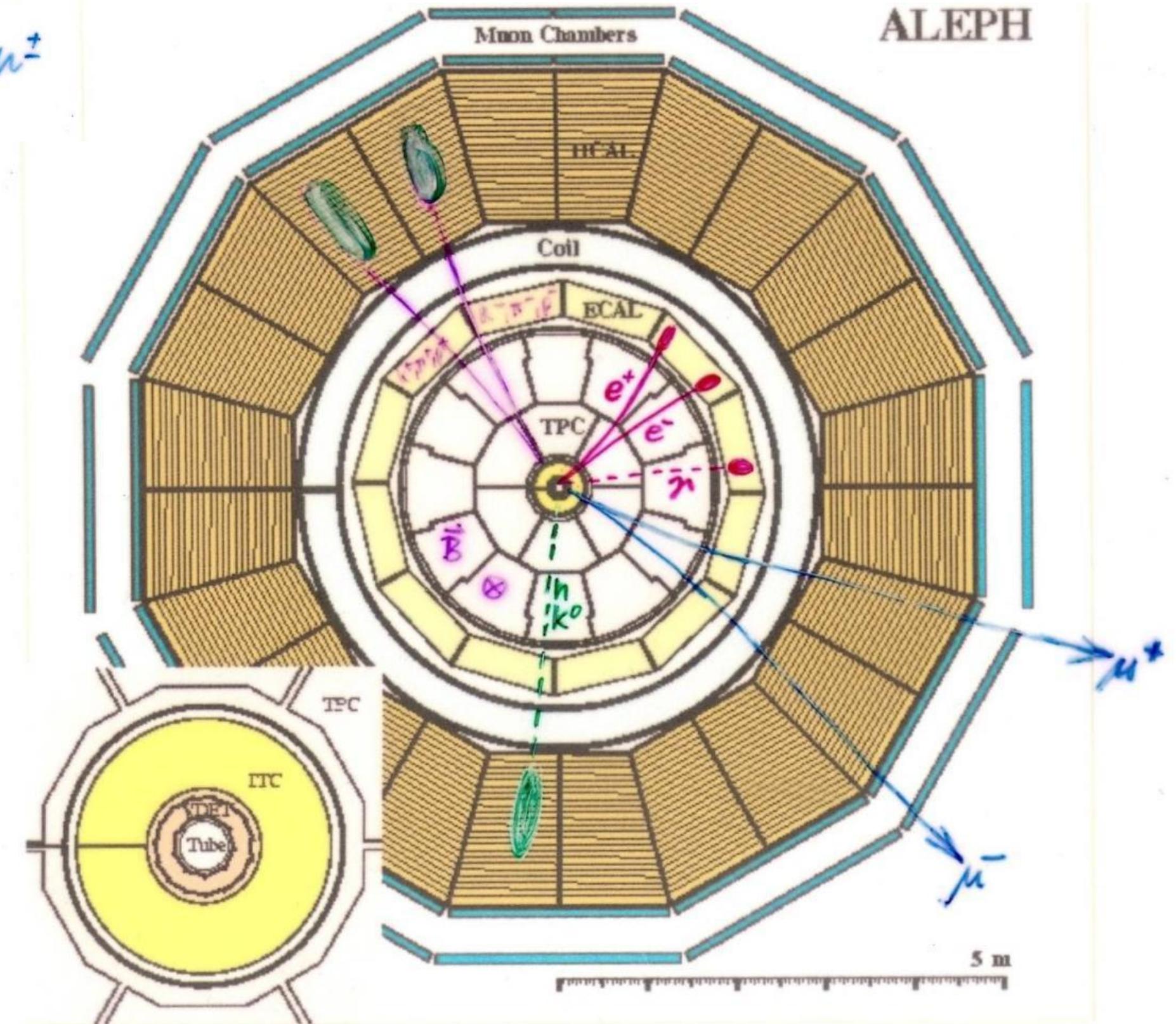


Fig. 1 - The ALEPH Detector

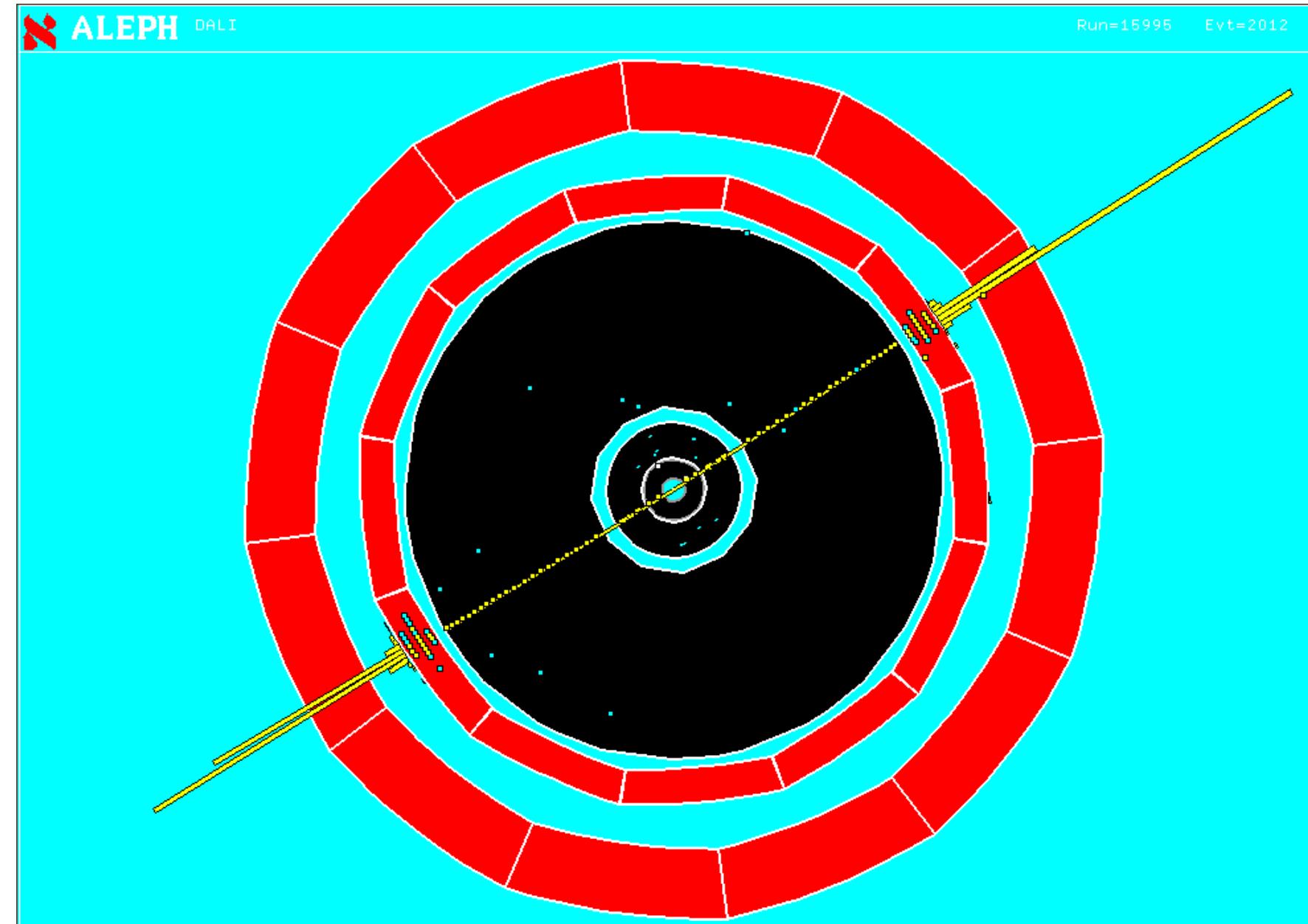
ALEPH detector (LEP 1988 - 2000)

$\gamma, e^\pm, \pi^\pm, k^\pm$
 K^0, p, n, μ^\pm



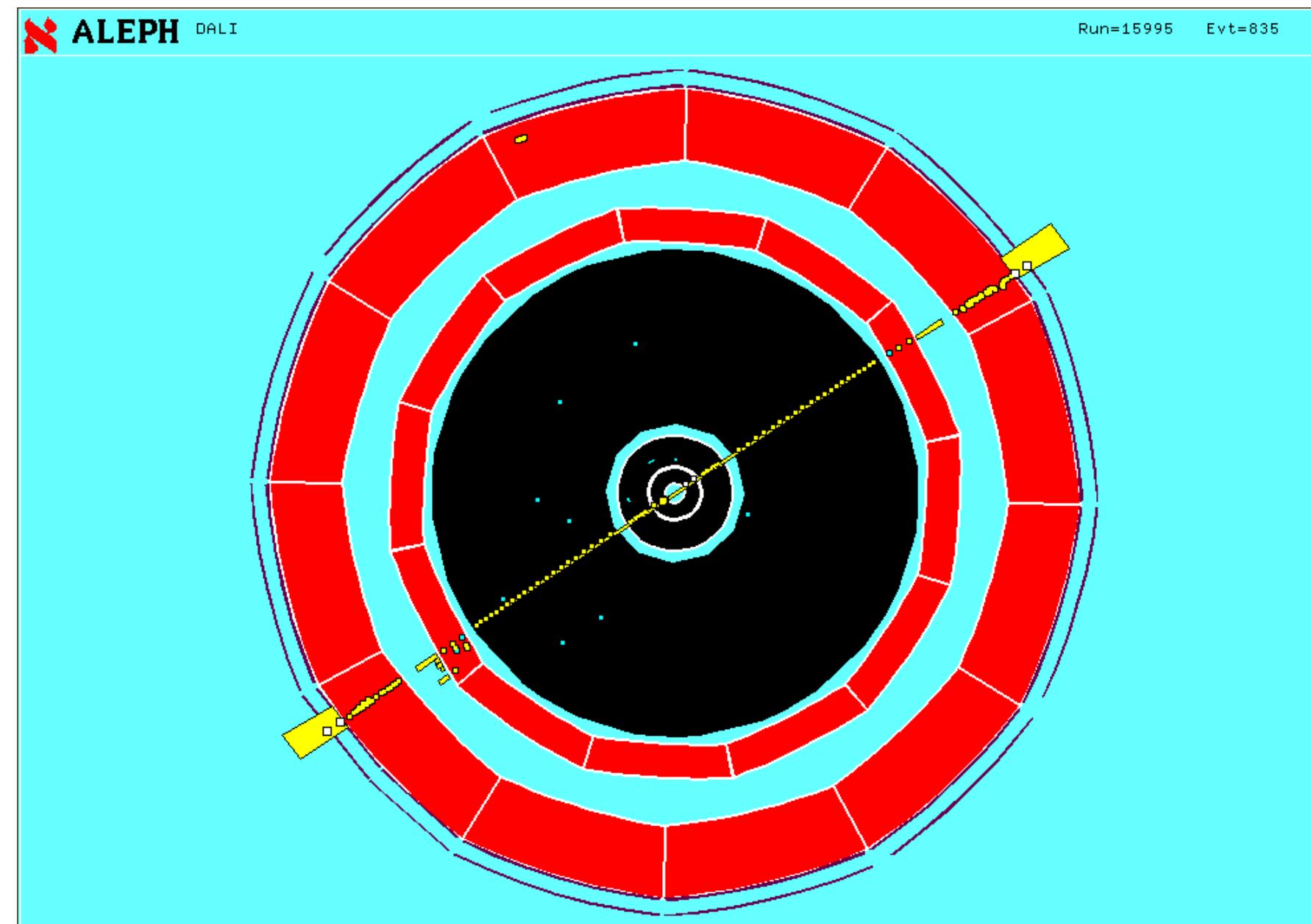
$$Z \rightarrow e^+ e^-$$

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



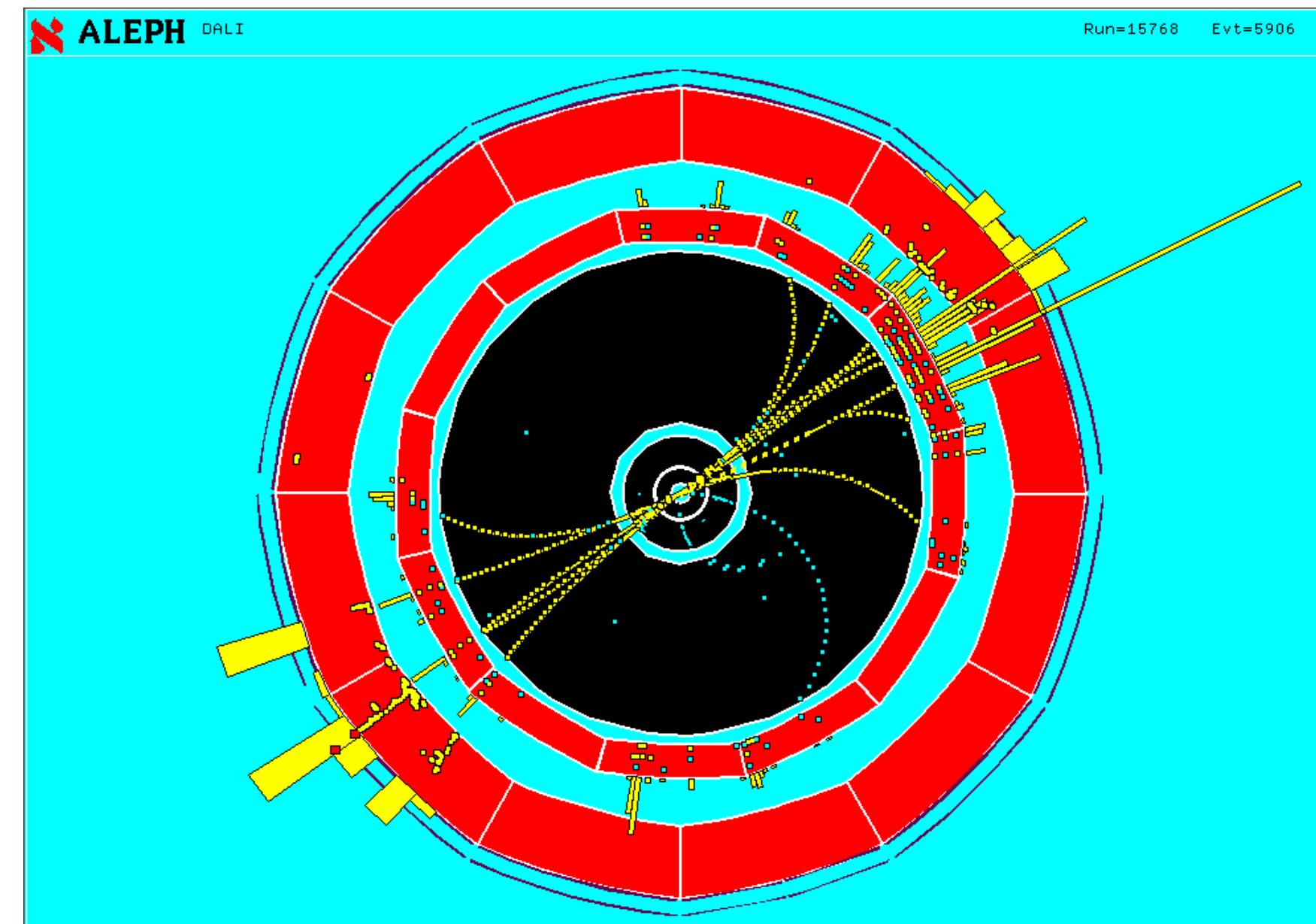
$$Z \rightarrow \mu^+ \mu^-$$

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



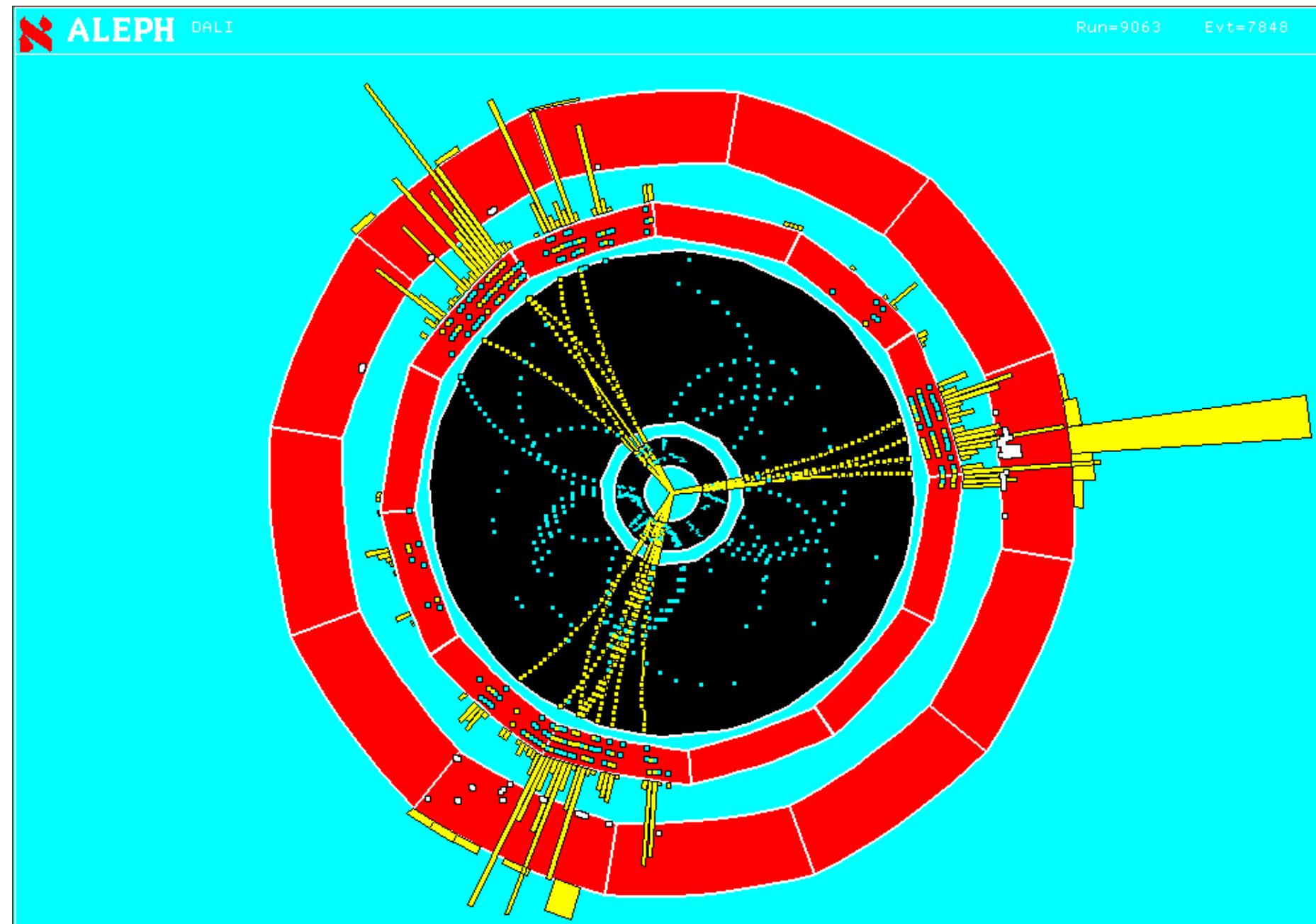
$$Z \rightarrow q\bar{q}$$

Two jets of particles



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

Three jets of particles



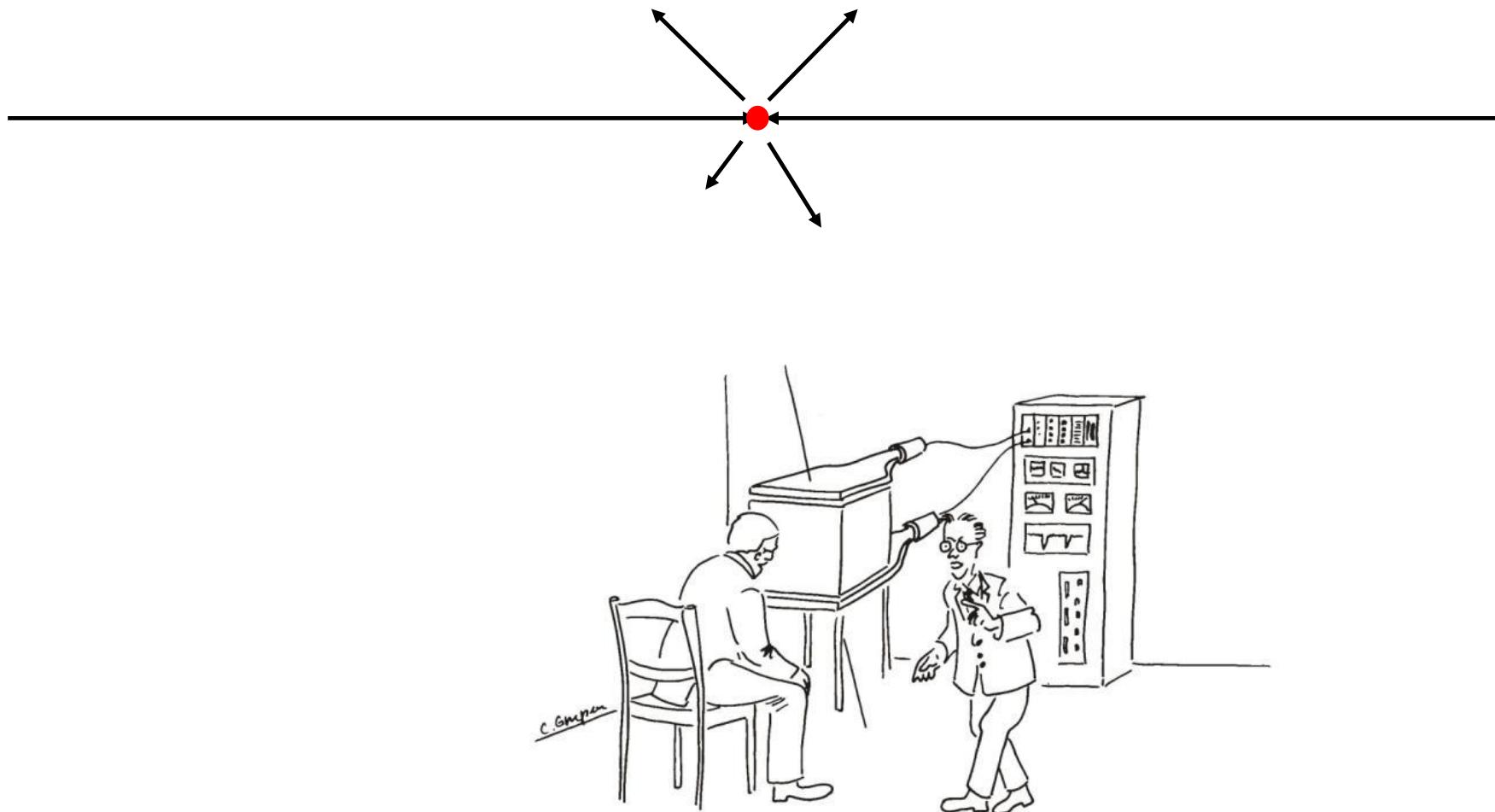
Interaction of Particles with Matter

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.

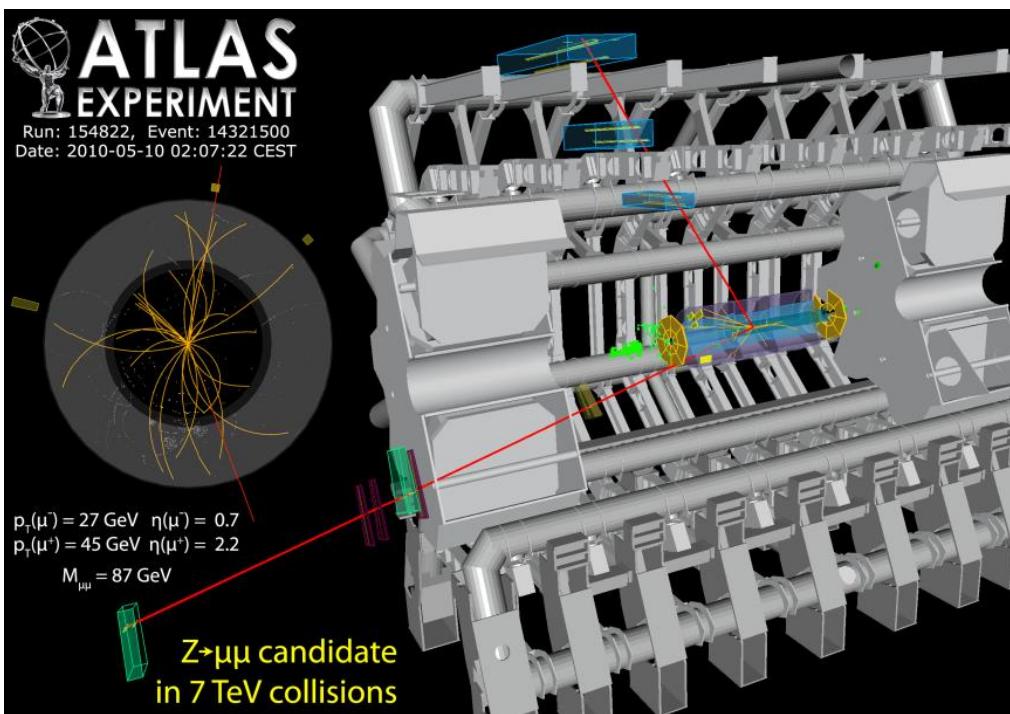
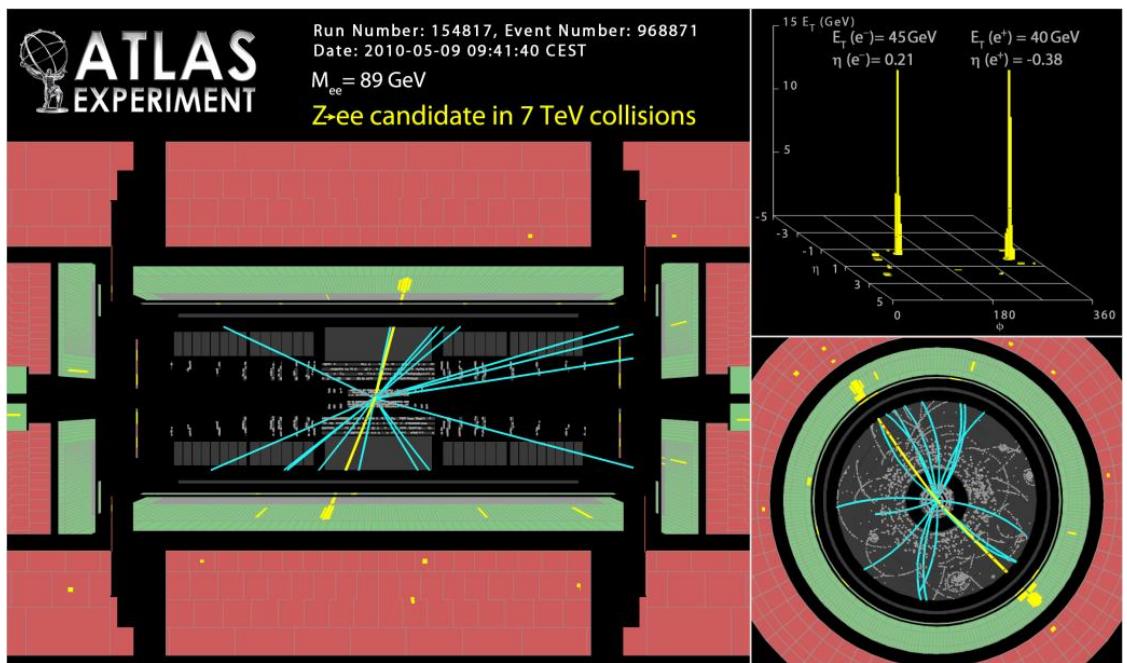
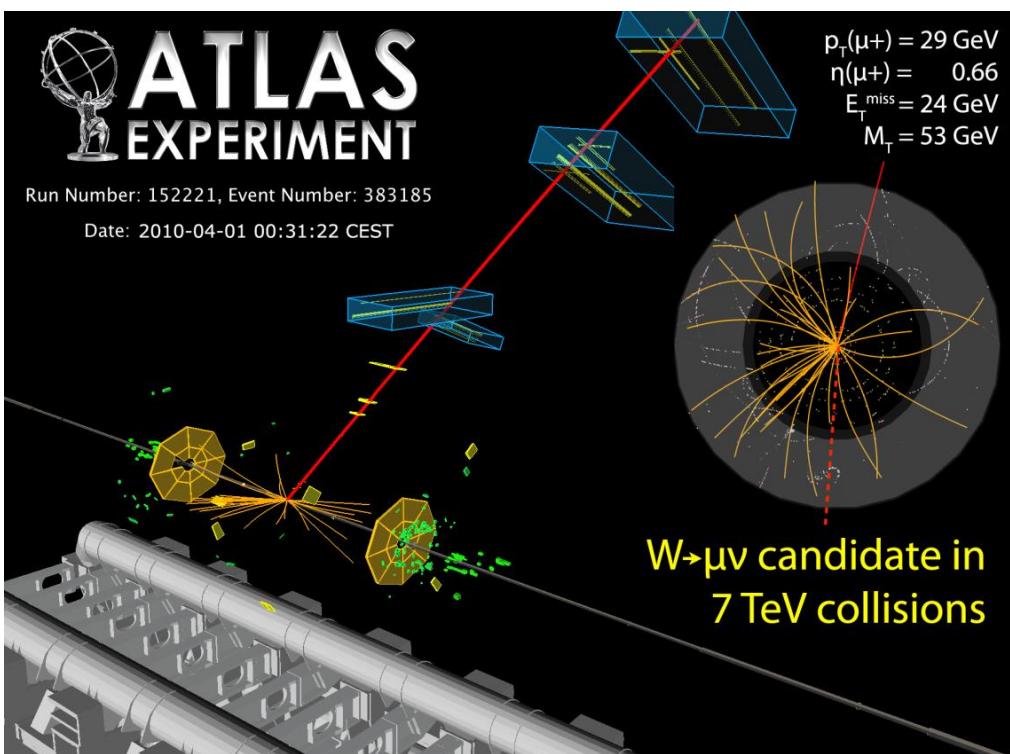
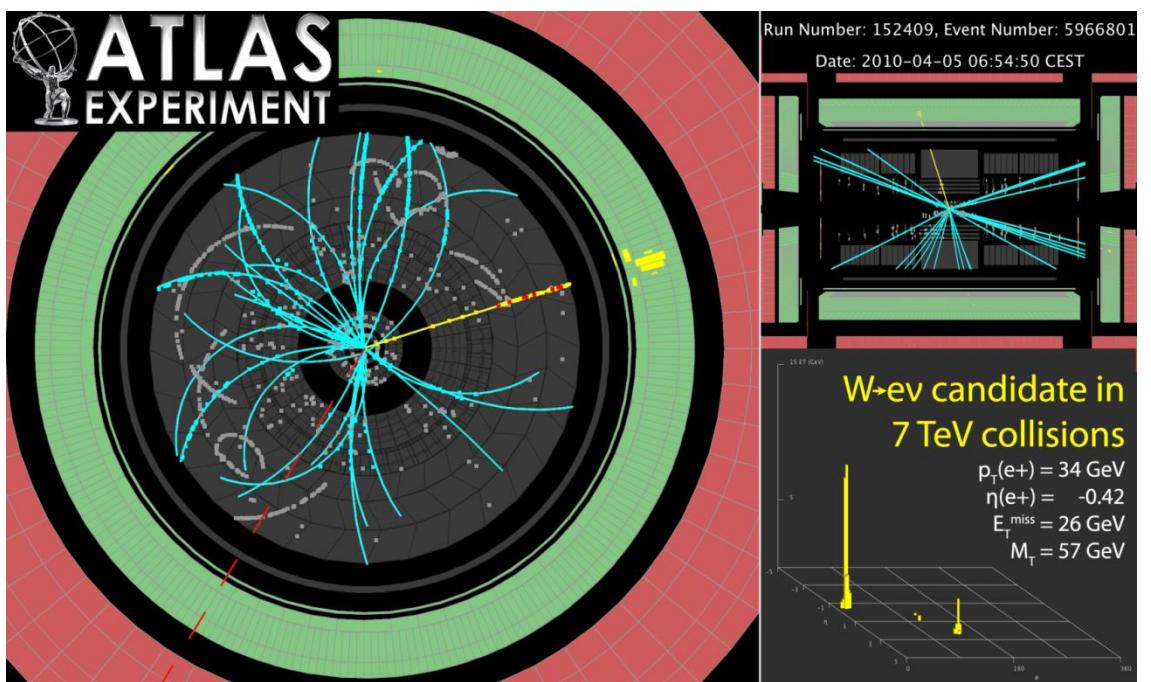
E.g. e^+e^- collider. $P_{\text{tot}}=0$,

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



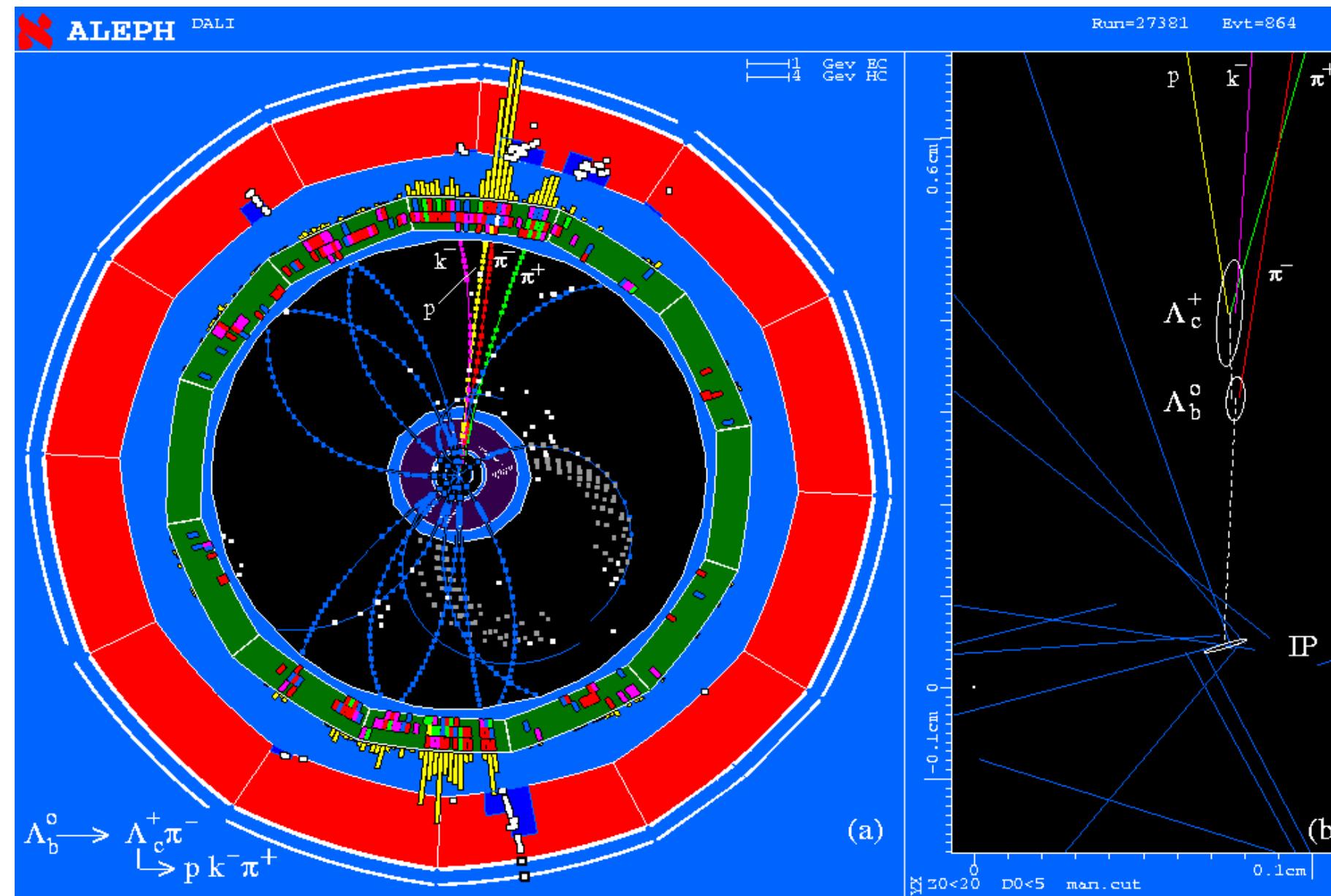
“Did you see it?”
“No nothing.”
“Then it was a neutrino!”

2010 ATLAS W, Z candidates !

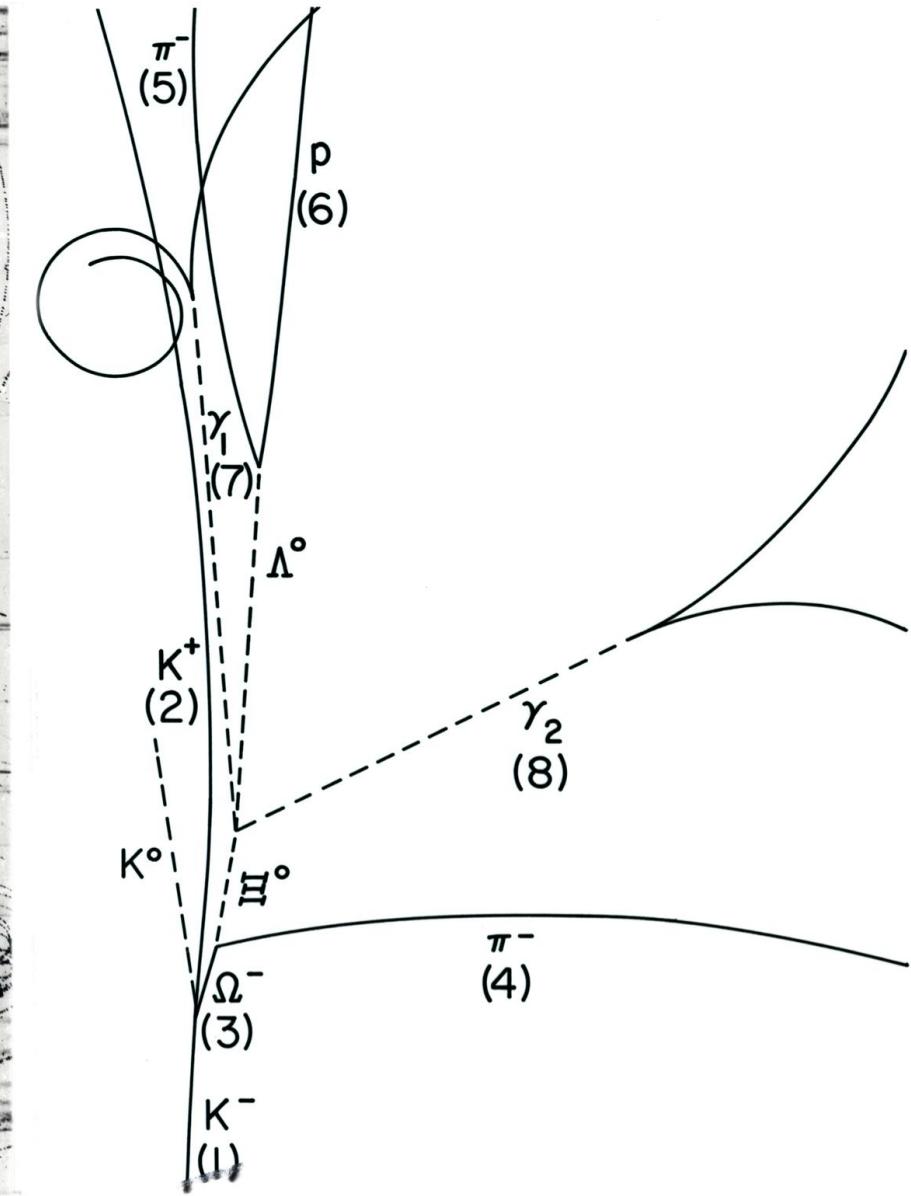
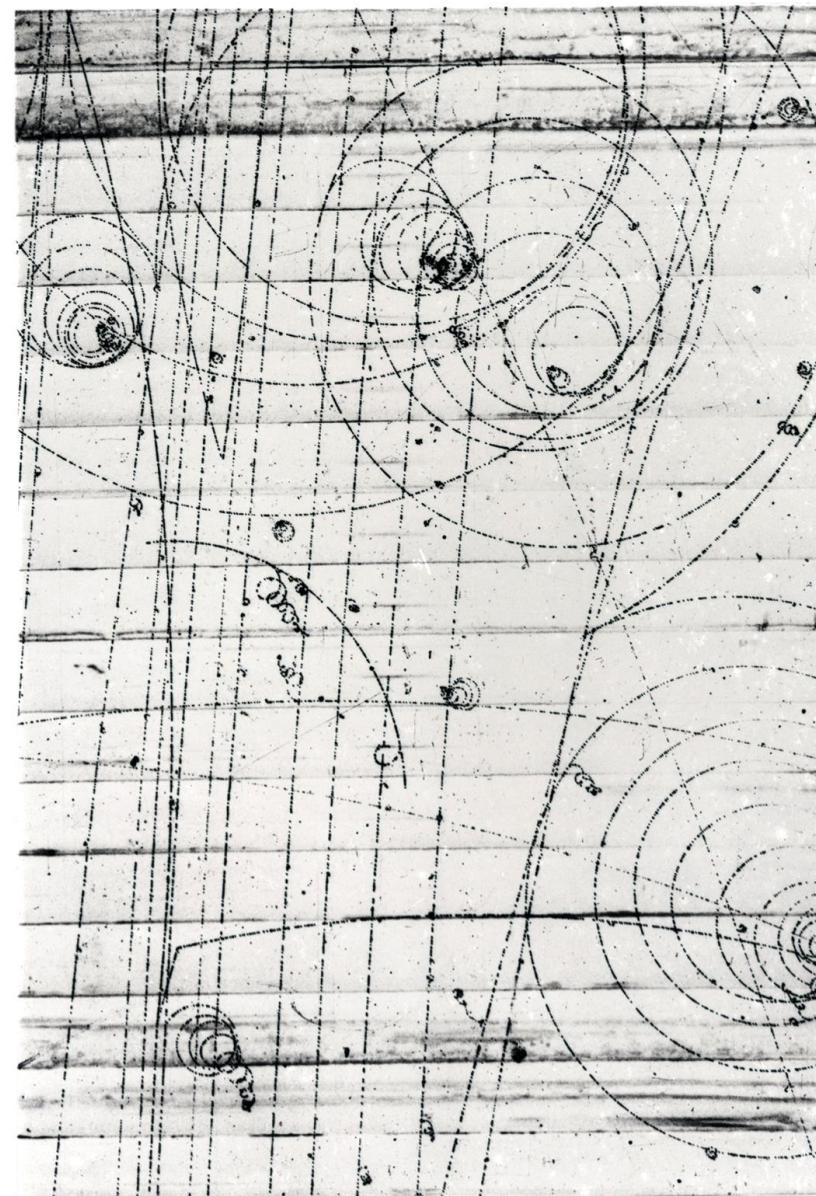


Two secondary vertices with characteristic decay particles giving invariant masses of known particles.

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

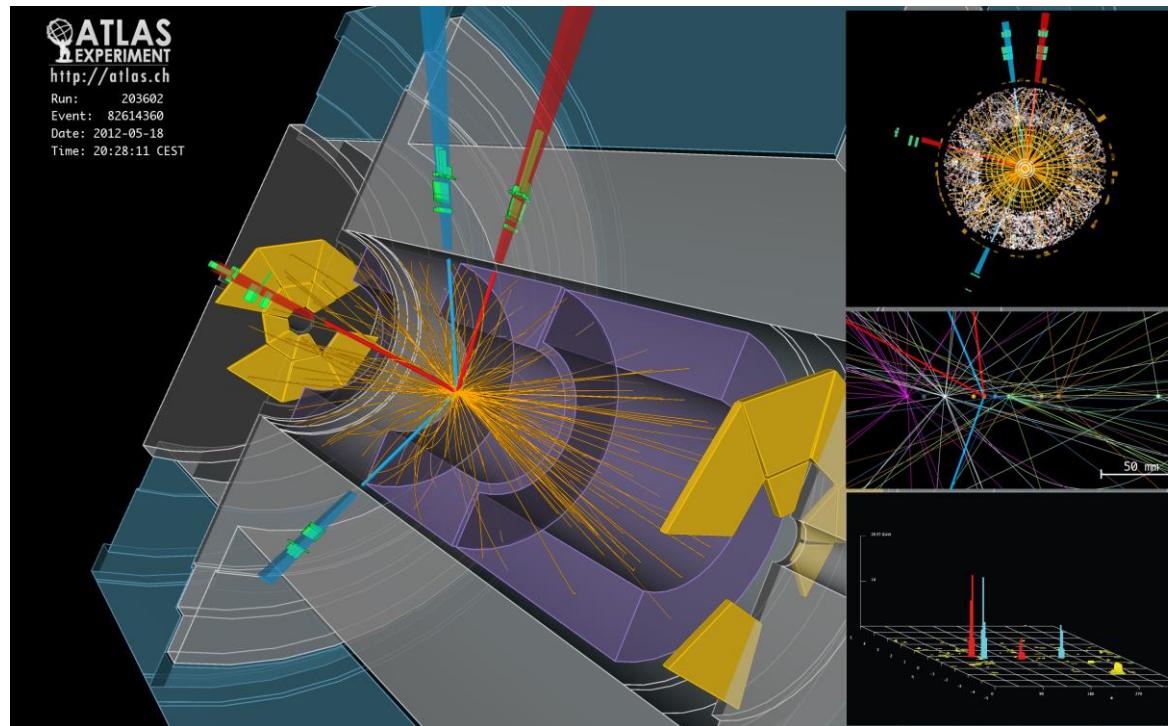


Discovery of ‘new’ Particles

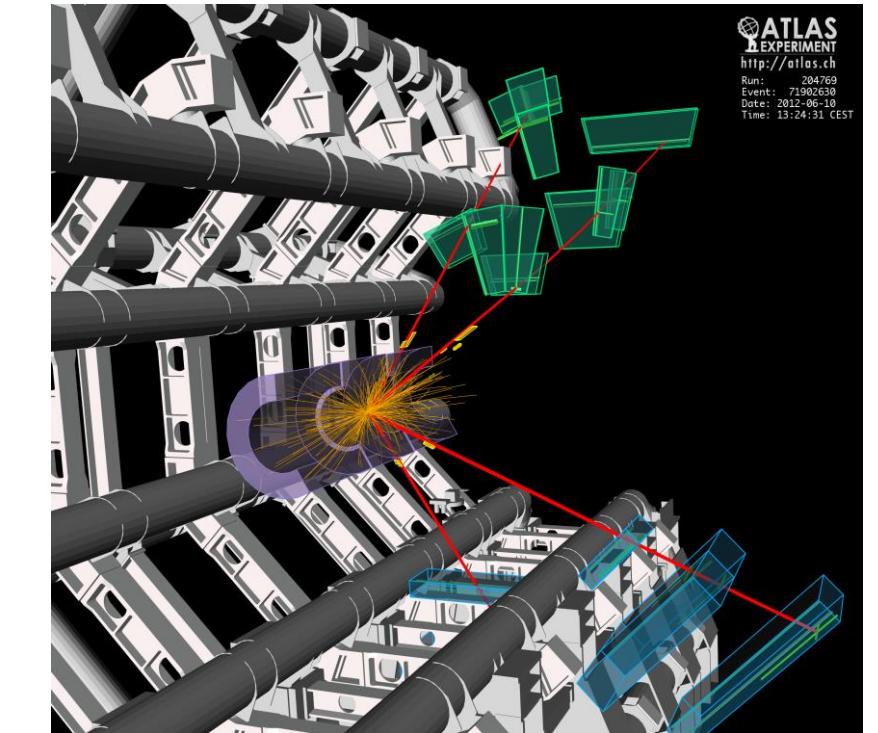


Discovery of Ω^- at the Brookhaven National Laboratory 80 inch hydrogen bubble chamber in 1964.
Discovery claimed by a single event – ‘background free’

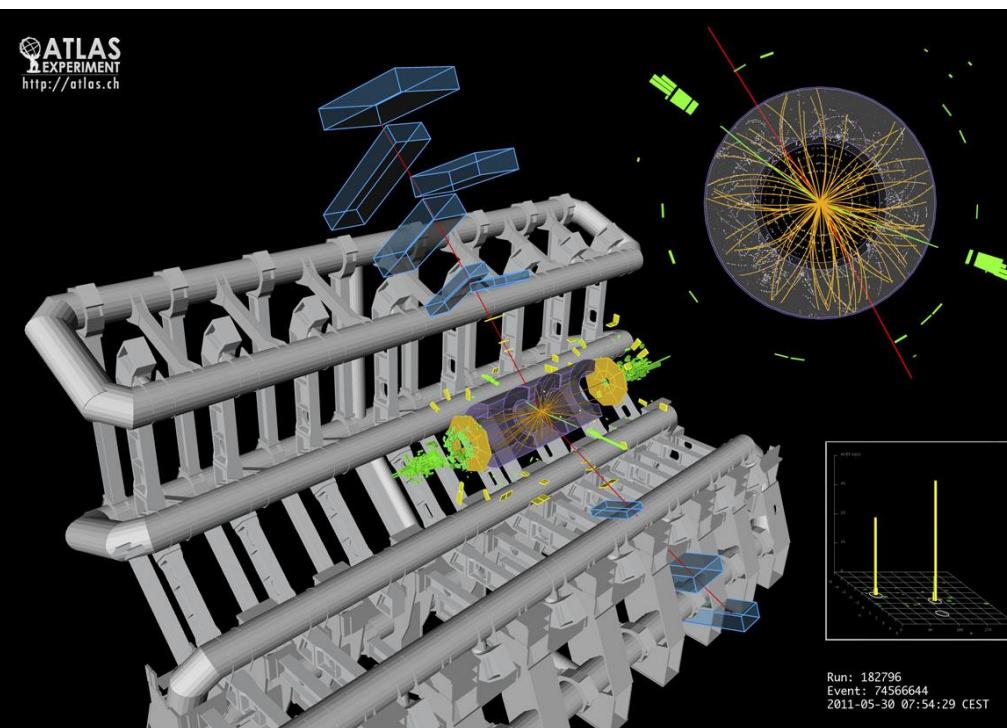
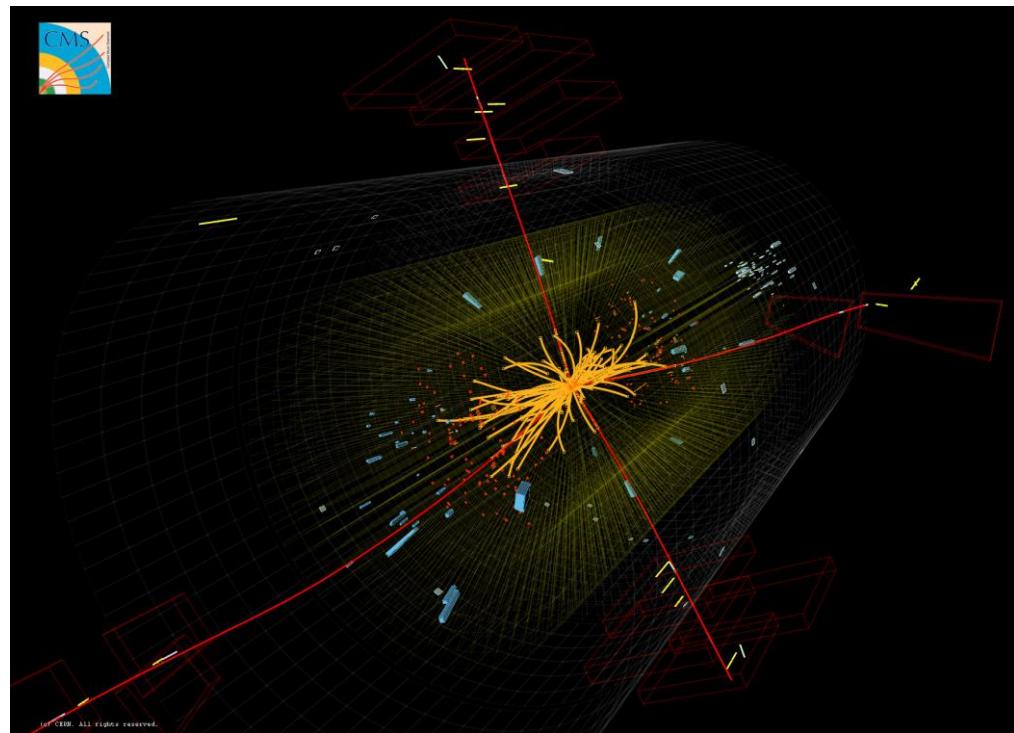
Candidate Higgs Events



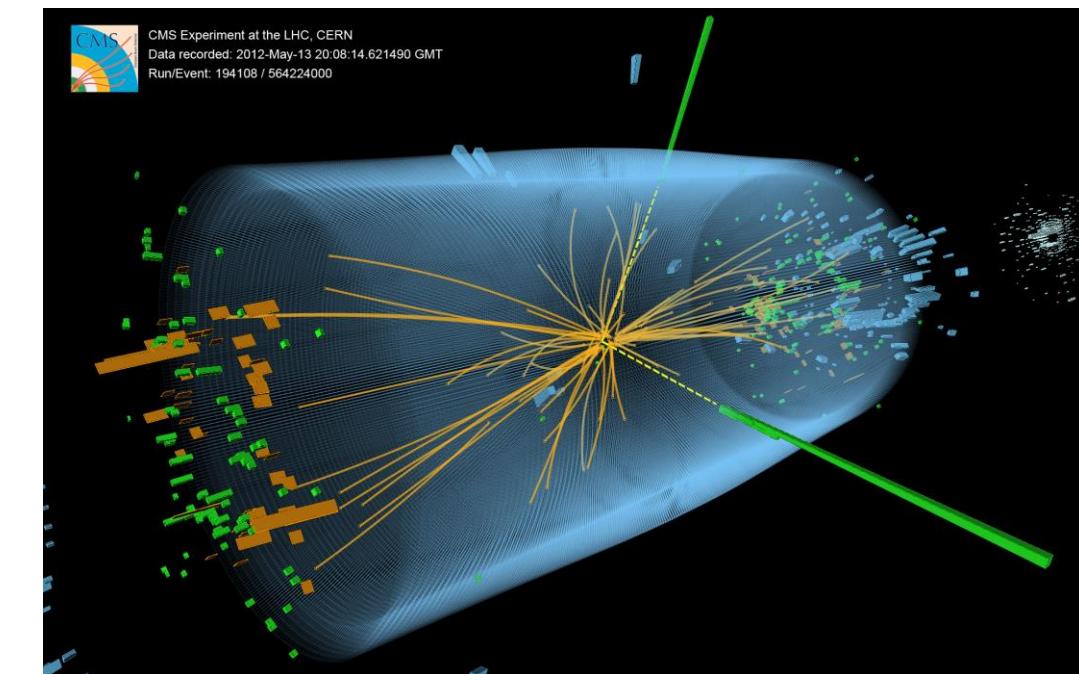
Candidate Higgs $\rightarrow 4e$



Candidate Higgs $\rightarrow 4\mu$

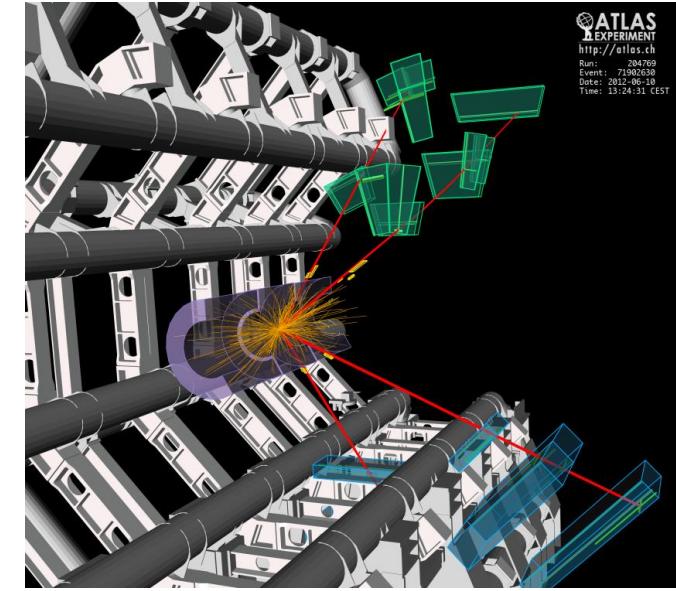
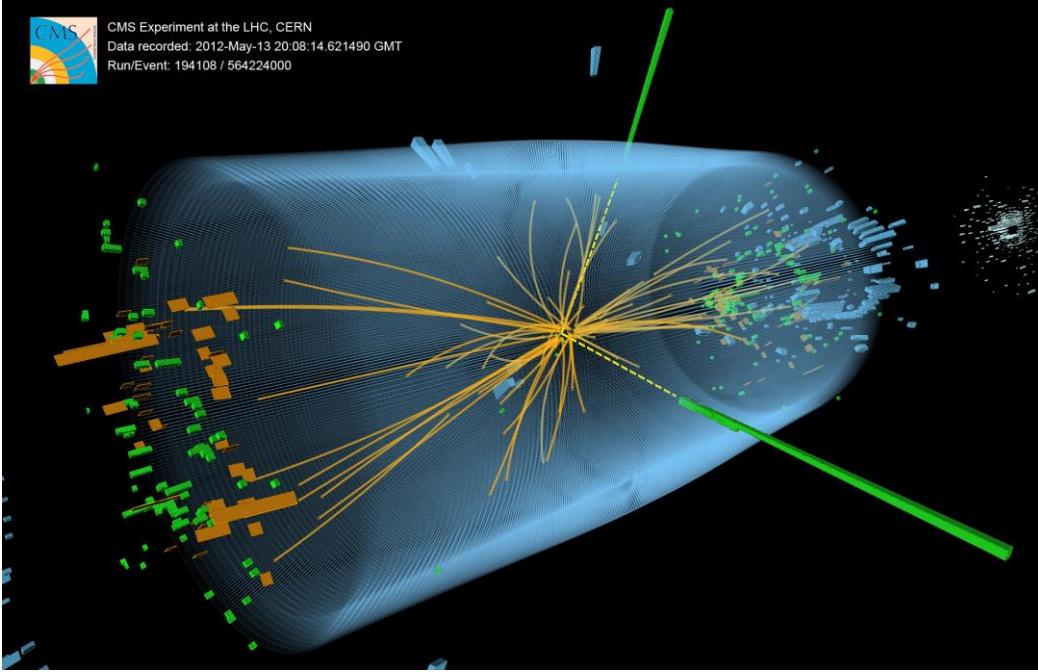


Candidate Higgs $\rightarrow 2\mu 2e$

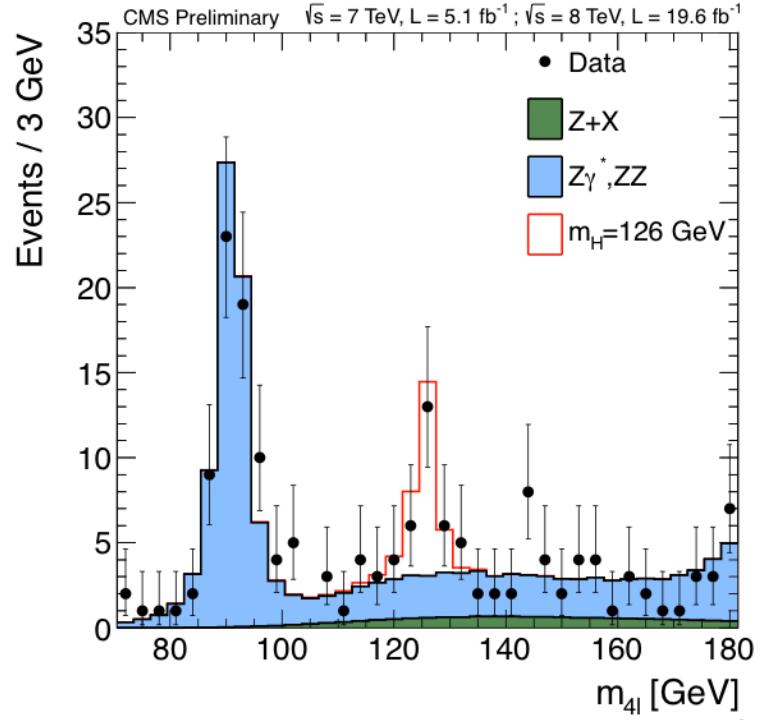
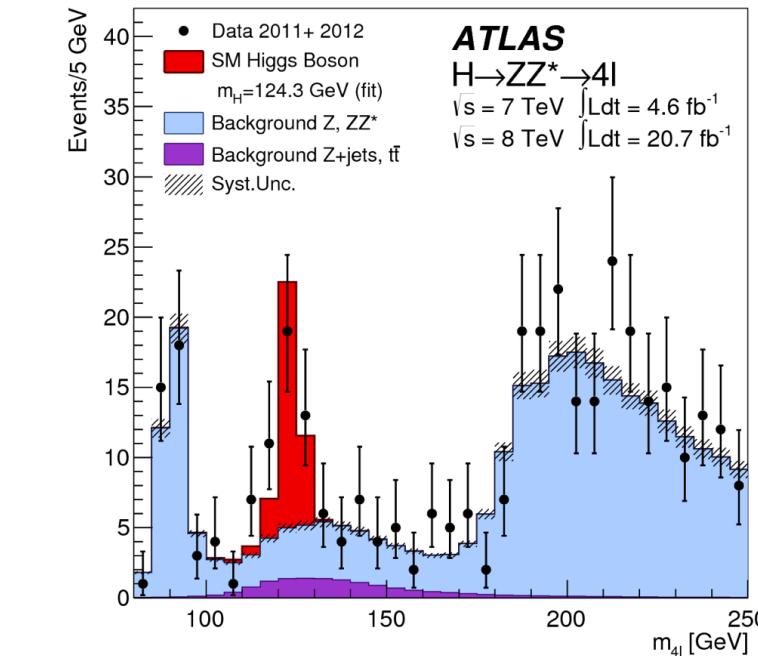
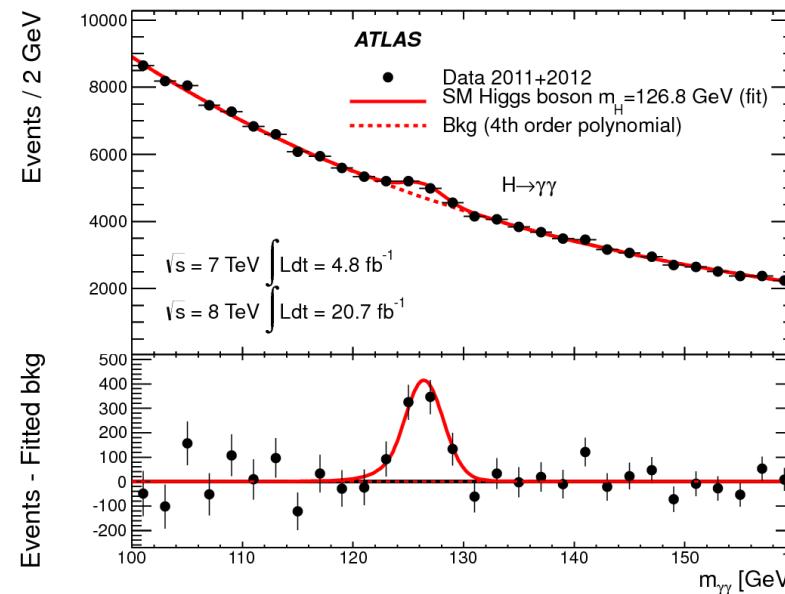
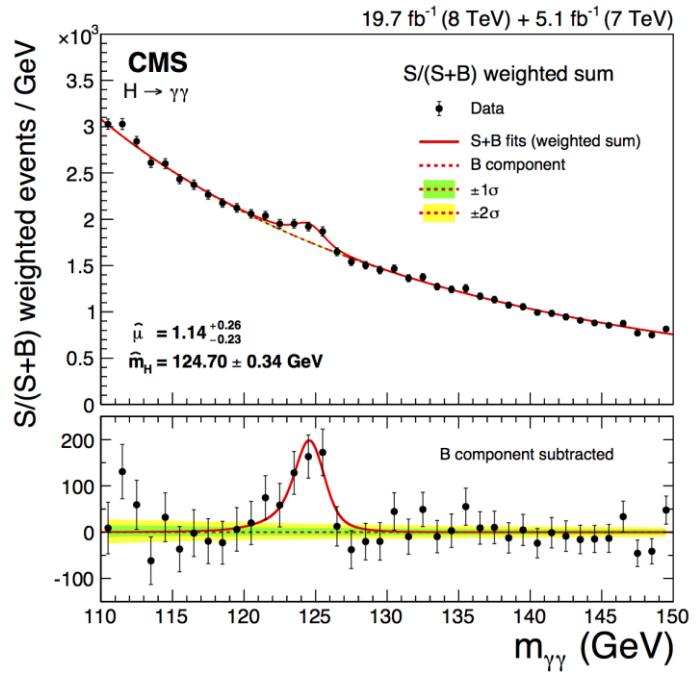


Candidate Higgs $\rightarrow 2 \text{ photons}$

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 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.

Conclusion

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

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