Interactions of Particles with Matter

EIROFORUM School of Instrumentation

June 20th 2017

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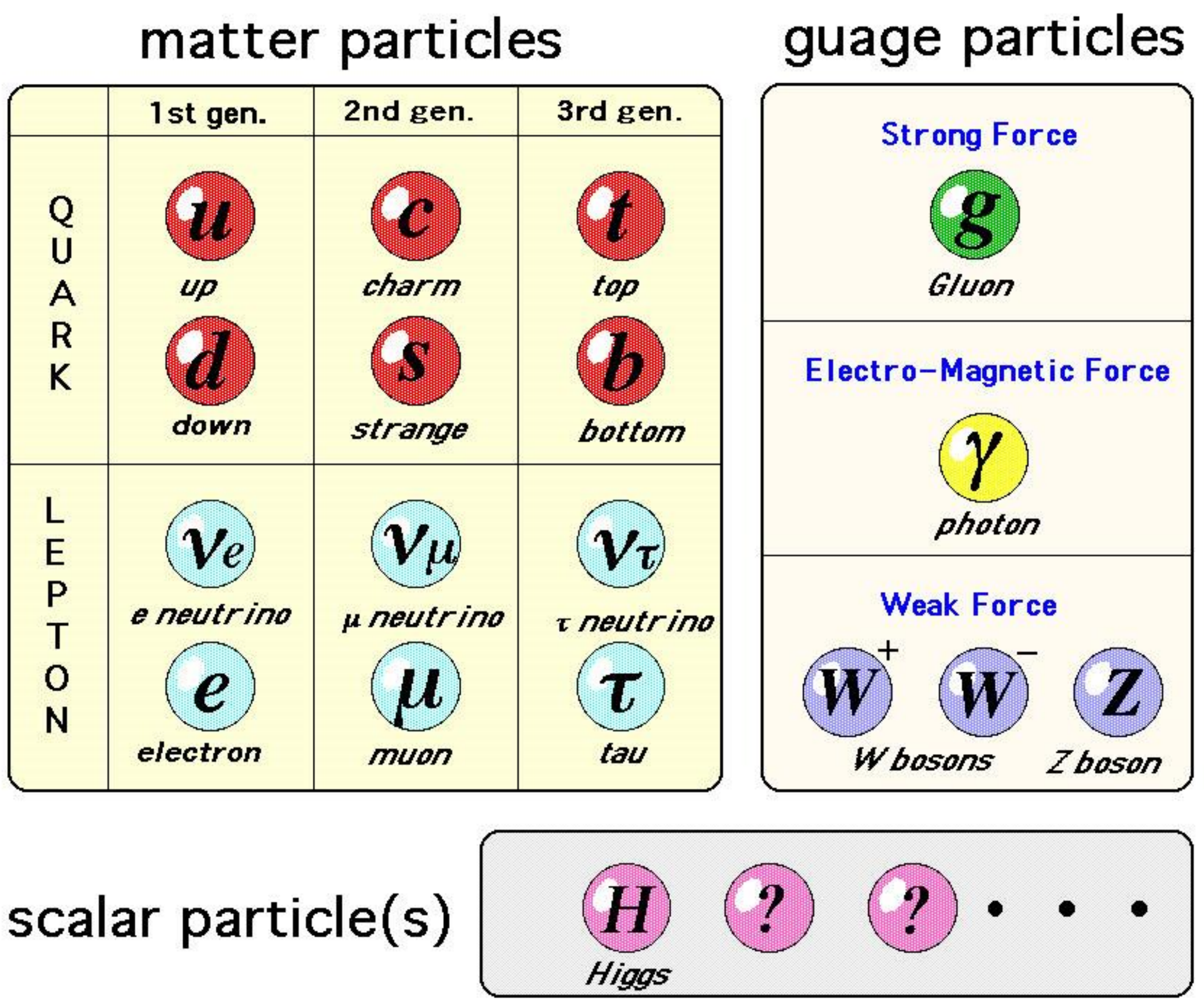
The ‘Standard Model’



The ‘Standard Model’

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

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

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

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

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

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

Over the last century

this "Standard Model" of

Fundamental Physics was discovered

by studying

Radioactivity

Cosmic Rays

Particle Collisions (Accelerators)

A large variety of Detectors and

experimental techniques have been

developed during this time.

Scales

$$E = m a^2$$

$$E = m b^2$$

$$E = m c^2 \longleftarrow \text{Energy} \mathrel{\hat=} \text{Mass}$$

$$\vdots$$

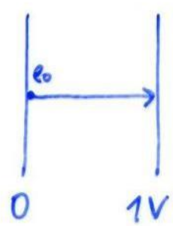
$$m(\text{electron}) = 9.1 \cdot 10^{-31}\ \text{kg}$$

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

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

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

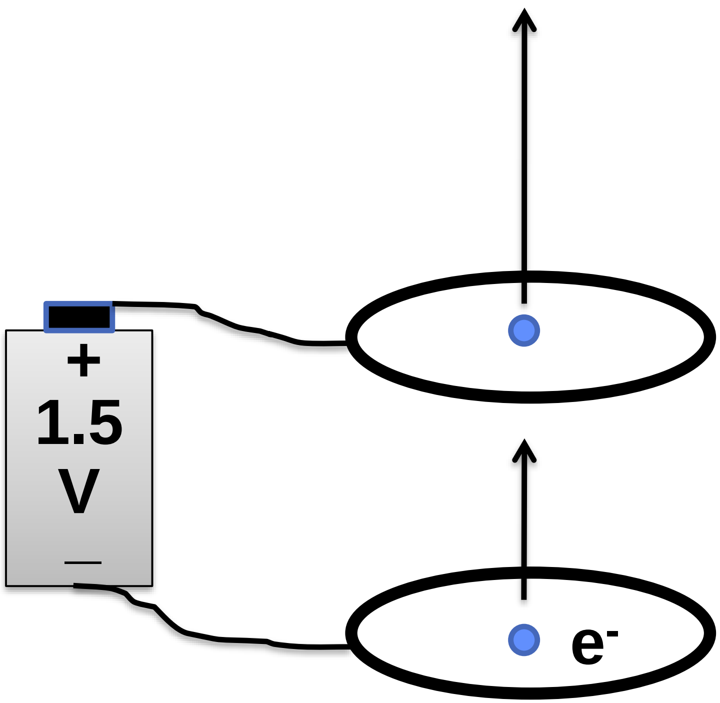
$$1\ \text{Electron Volt} = e_0 \cdot 1\text{V} = 1.603 \cdot 10^{-19}\ \text{J}$$



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

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

Build your own Accelerator



E_{kin}= 1.5eV =

2 615 596 km/h

Scales

Visible Light: $\lambda = 500\,nm$, $h\nu \sim 2.5\,eV$

Excited States in Atoms: 1 - 100 keV "X-Rays"

Nuclear Physics: 1 - 50 MeV

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

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

Basics

Lorentz Boost:

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

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

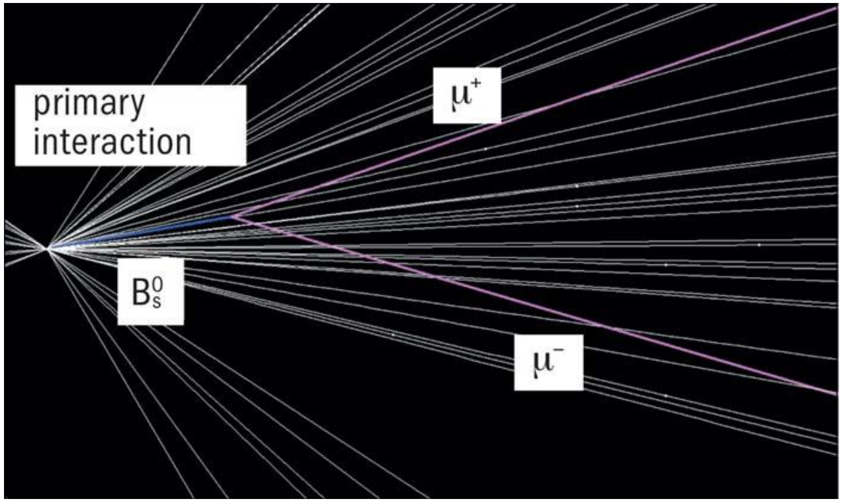
$$s = c \cdot \bar{\tau} = 12.5\, km \rightarrow \text{Earth}$$

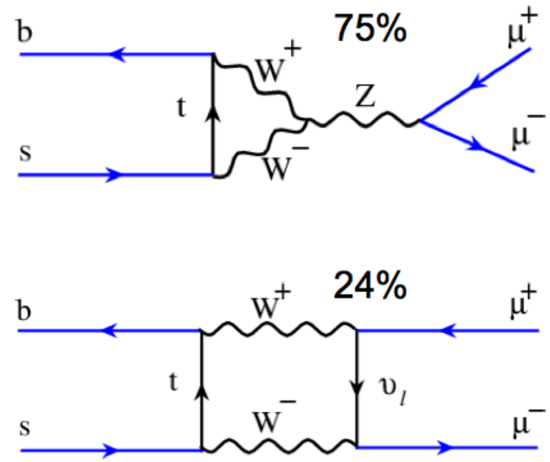
Pions: π^+, π^- $\tau \sim 2.6 \cdot 10^{-8}\, s$, $m_\pi c^2 = 135\, MeV$

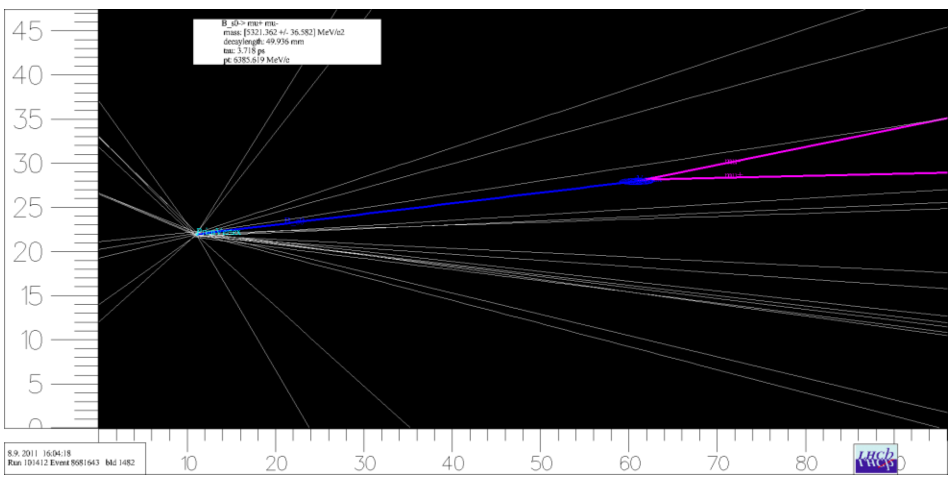
$$2\, GeV \rightarrow s = 115\, m$$

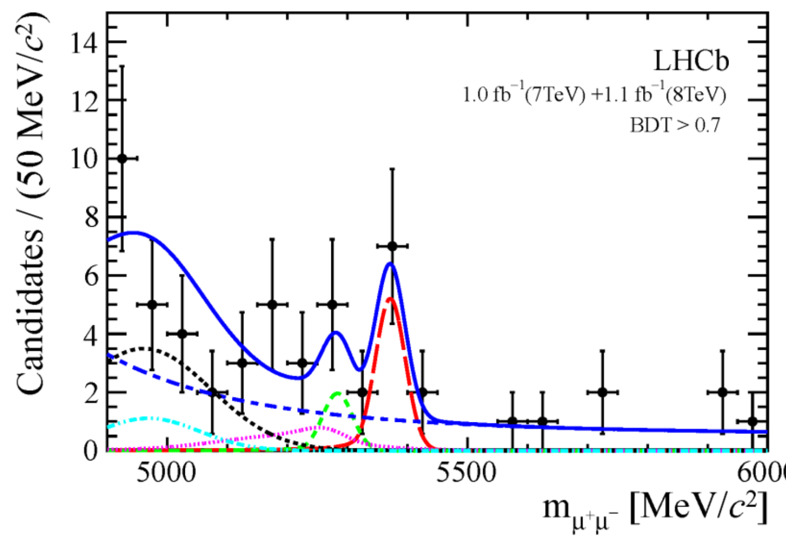
Pions where discovered in Emulsions exposed
to Cosmic Rays on high Mountains.

LHCb B decay, displaced Vertex





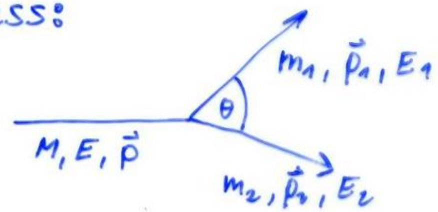




Basics

Invariant Mass:

LAB:



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

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

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

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

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

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

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

gives the Mass of the original Particle

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

γ, $W^\pm$, Z^0, g, e, μ, τ, ν_e, ν_μ, ν_τ, $\pi^\pm$, π^0, η, $f_0(600)$, $\rho(770)$,
$\omega(782)$, $\eta'(958)$, $f_0(980)$, $a_0(980)$, $\phi(1020)$, $h_1(1170)$, $b_1(1235)$,
$a_1(1260)$, $f_2(1270)$, $f_1(1285)$, $\eta(1295)$, $\pi(1300)$, $a_2(1320)$,
$f_0(1370)$, $f_1(1420)$, $\omega(1420)$, $\eta(1440)$, $a_0(1450)$, $\rho(1450)$,
$f_0(1500)$, $f_2'(1525)$, $\omega(1650)$, $\omega_3(1670)$, $\pi_2(1670)$, $\phi(1680)$,
$\rho_3(1690)$, $\rho(1700)$, $f_0(1710)$, $\pi(1800)$, $\phi_3(1850)$, $f_2(2010)$,
$a_4(2040)$, $f_4(2050)$, $f_2(2300)$, $f_2(2340)$, $K^\pm$, K^0, K^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_s^0, $B_c^\pm$, $\eta_c(1S)$, $J/\psi(1S)$,
$\chi_{c0}(1P)$, $\chi_{c1}(1P)$, $\chi_{c2}(1P)$, $\psi(2S)$, $\psi(3770)$, $\psi(4040)$, $\psi(4160)$,
$\psi(4415)$, $\Upsilon(1S)$, $\chi_{b0}(1P)$, $\chi_{b1}(1P)$, $\chi_{b2}(1P)$, $\Upsilon(2S)$, $\chi_{b0}(2P)$,
$\chi_{b2}(2P)$, $\Upsilon(3S)$, $\Upsilon(4S)$, $\Upsilon(10860)$, $\Upsilon(11020)$, p, n, $N(1440)$,
$N(1520)$, $N(1535)$, $N(1650)$, $N(1675)$, $N(1680)$, $N(1700)$, $N(1710)$,
$N(1720)$, $N(2190)$, $N(2220)$, $N(2250)$, $N(2600)$, $\Delta(1232)$, $\Delta(1600)$,
$\Delta(1620)$, $\Delta(1700)$, $\Delta(1905)$, $\Delta(1910)$, $\Delta(1920)$, $\Delta(1930)$, $\Delta(1950)$,
$\Delta(2420)$, Λ, $\Lambda(1405)$, $\Lambda(1520)$, $\Lambda(1600)$, $\Lambda(1670)$, $\Lambda(1690)$,
$\Lambda(1800)$, $\Lambda(1810)$, $\Lambda(1820)$, $\Lambda(1830)$, $\Lambda(1890)$, $\Lambda(2100)$,
$\Lambda(2110)$, $\Lambda(2350)$, Σ^+, Σ^0, Σ^-, $\Sigma(1385)$, $\Sigma(1660)$, $\Sigma(1670)$,
$\Sigma(1750)$, $\Sigma(1775)$, $\Sigma(1915)$, $\Sigma(1940)$, $\Sigma(2030)$, $\Sigma(2250)$, Ξ^0, Ξ^-,
$\Xi(1530)$, $\Xi(1690)$, $\Xi(1820)$, $\Xi(1950)$, $\Xi(2030)$, Ω^-, $\Omega(2250)^-$,
Λ_c^+, Λ_c^+, $\Sigma_c(2455)$, $\Sigma_c(2520)$, Ξ_c^+, Ξ_c^0, $\Xi_c'^+$, $\Xi_c'^0$, $\Xi(2645)$
$\Xi_c(2780)$, $\Xi_c(2815)$, Ω_c^0, Λ_b^0, Ξ_b^0, Ξ_b^-, $t\bar{t}$

There are many more

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

Particle	Mass (MeV)	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	"Secondary Vertices"
$B^0 (b\bar{d}, d\bar{b})$	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	

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

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

From the ~14 remaining particles

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

are by far the most frequent ones

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

$e^{\pm}$ $m_e = 0.511$ MeV

$\mu^{\pm}$ $m_\mu = 105.7$ MeV $\sim 200\, m_e$

γ $m_\gamma = 0$, $Q = 0$

} EM

$\pi^{\pm}$ $m_\pi = 139.6$ MeV $\sim 270\, m_e$

$K^{\pm}$ $m_K = 493.7$ MeV $\sim 1000\, m_e$ $\sim 3.5\, m_\pi$

$p^{\pm}$ $m_p = 938.3$ MeV $\sim 2000\, m_e$

} EM, Strong

K^0 $m_{K^0} = 497.7$ MeV $Q = 0$

n $m_n = 939.6$ MeV $Q = 0$

} Strong

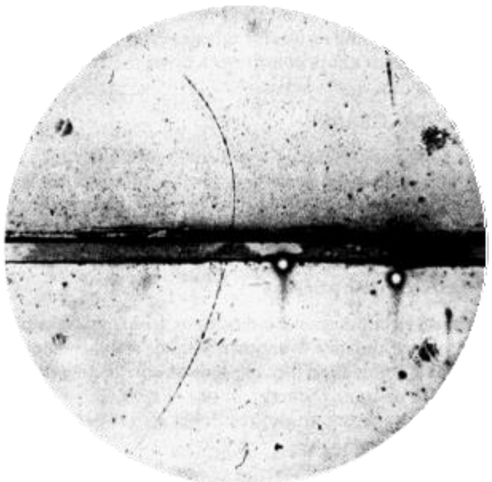
The Difference in

Mass, Charge, Interaction

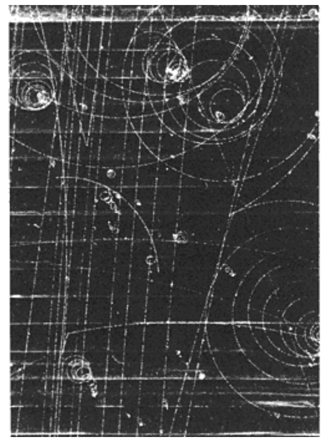
is the key to the Identification

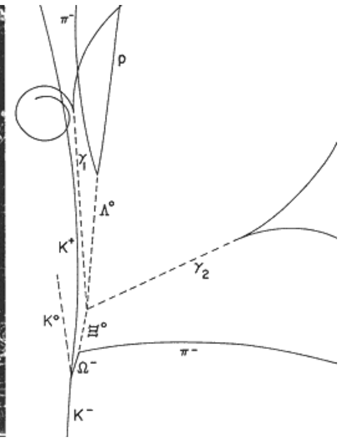
Interactions of Particles with Matter

Cloud chambers
1911-1950ies

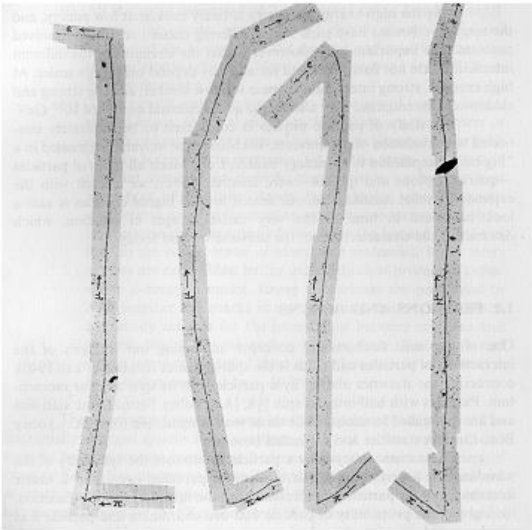


Bubble chambers
1950ies-1980ies

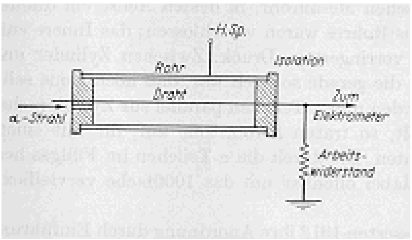




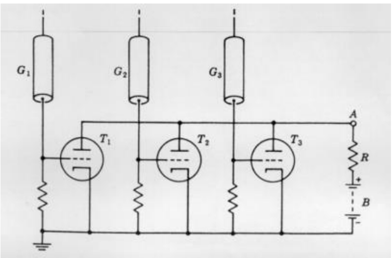
Photographic Emulsions
1930ies to present



Geiger Counter
since 1906

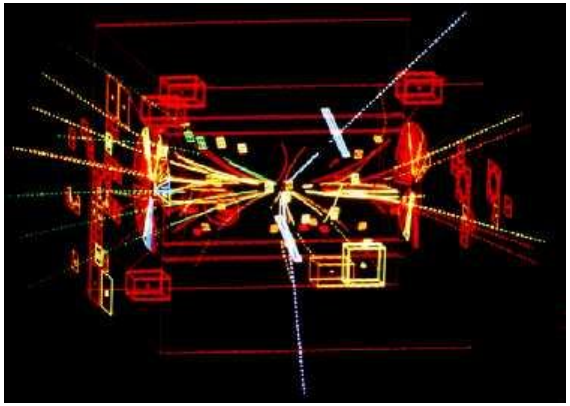


Geiger Counter
Electronics 1930ies



….

Today: Large variety of
electronic detectors



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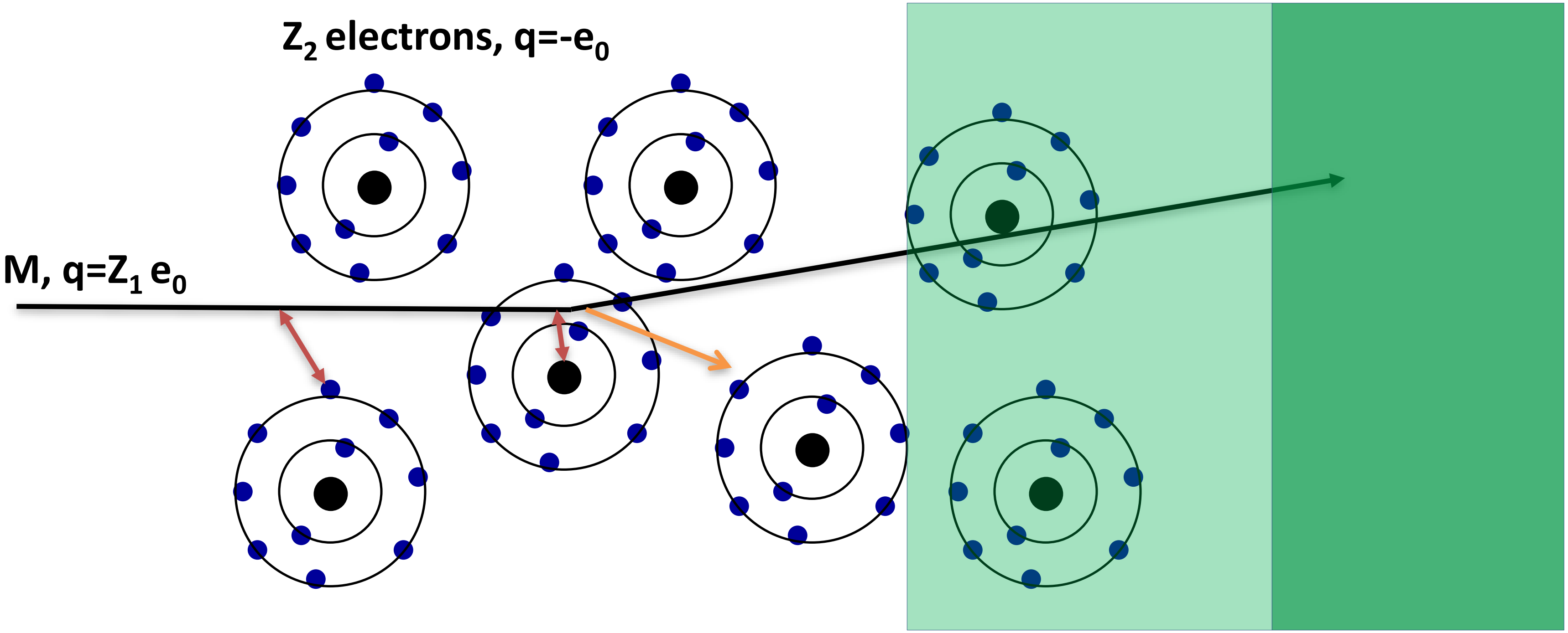
Electromagnetic Interaction of Particles with Matter

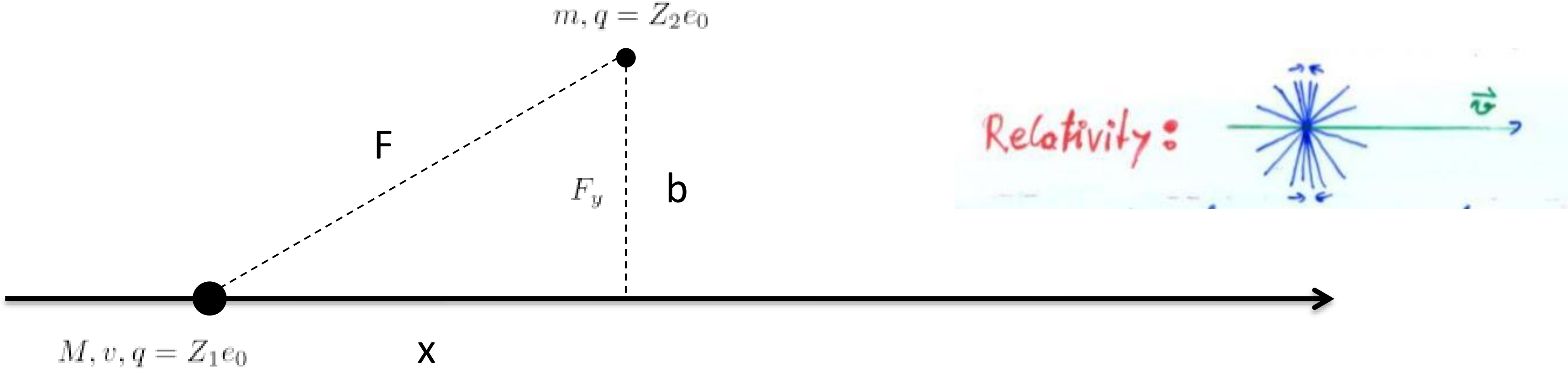


Interaction with the atomic electrons. The incoming particle loses energy and the atoms are excited or ionized.

Interaction with the atomic nucleus. The particle is deflected (scattered) causing multiple scattering of the particle in the material. During this scattering a Bremsstrahlung photon can be emitted.

In case the particle's velocity is larger than the velocity of light in the medium, the resulting EM shockwave manifests itself as Cherenkov Radiation. When the particle crosses the boundary between two media, there is a probability of the order of 1% to produced and X ray photon, called Transition radiation.

Ionization and Excitation



While the charged particle is passing another charged particle, the Coulomb Force is acting, resulting in momentum transfer

$$F_y = \frac{Z_1 Z_2 e_0^2}{4\pi\varepsilon_0 (b^2 + v^2 t^2)} \frac{b}{\sqrt{b^2 + v^2 t^2}} \qquad \Delta p = \int_{-\infty}^{\infty} F_y(t) dt = \frac{2 Z_1 Z_2 e_0^2}{4\pi\varepsilon_0 v b}$$

The relativistic form of the transverse electric field doesn't change the momentum transfer. The transverse field is stronger, but the time of action is shorter

$$F_y = \frac{\gamma Z_1 Z_2 e_0^2 b}{4\pi\varepsilon_0 (b^2 + \gamma^2 v^2 t^2)^{3/2}} \qquad \Delta p = \int_{-\infty}^{\infty} F_y(t) dt = \frac{2 Z_1 Z_2 e_0^2}{4\pi\varepsilon_0 v b}$$

The transferred energy is then

$$\Delta E = \frac{(\Delta p)^2}{2m} = \frac{Z_2^2}{m} \frac{2 Z_1^2 e_0^4}{(4\pi\varepsilon_0)^2 v^2 b^2}$$

$$\Delta E(electrons) = Z_2 \frac{1}{m_e} \frac{2 Z_1^2 e_0^4}{(4\pi\varepsilon_0)^2 v^2 b^2} \qquad \Delta E(nucleus) = \frac{Z_2^2}{2 Z_2 m_p} \frac{2 Z_1^2 e_0^4}{(4\pi\varepsilon_0)^2 v^2 b^2} \qquad \frac{\Delta E(electrons)}{\Delta E(nucleus)} = \frac{2 m_p}{m_e} \approx 4000$$

→ The incoming particle transfer energy only (mostly) to the atomic electrons !

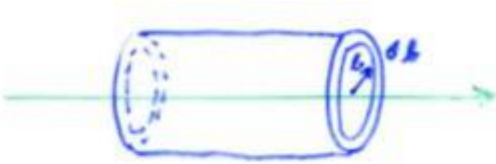
Ionization and Excitation

Target material: mass A, Z_2, density ρ [g/cm^3], Avogadro number N_A

A gramm → N_A Atoms: Number of atoms/cm^3 $n_a = N_A \rho/A$ [1/cm^3]

Number of electrons/cm^3 $n_e = N_A \rho Z_2/A$ [1/cm^3]

$$\Delta E(electrons) = \frac{2Z_2 Z_1^2 m_e c^2}{\beta^2 b^2} \frac{e_0^4}{(4\pi\varepsilon_0 m_e c^2)^2} = \frac{2Z_2 Z_1^2 m_e c^2}{\beta^2 b^2} r_e^2$$



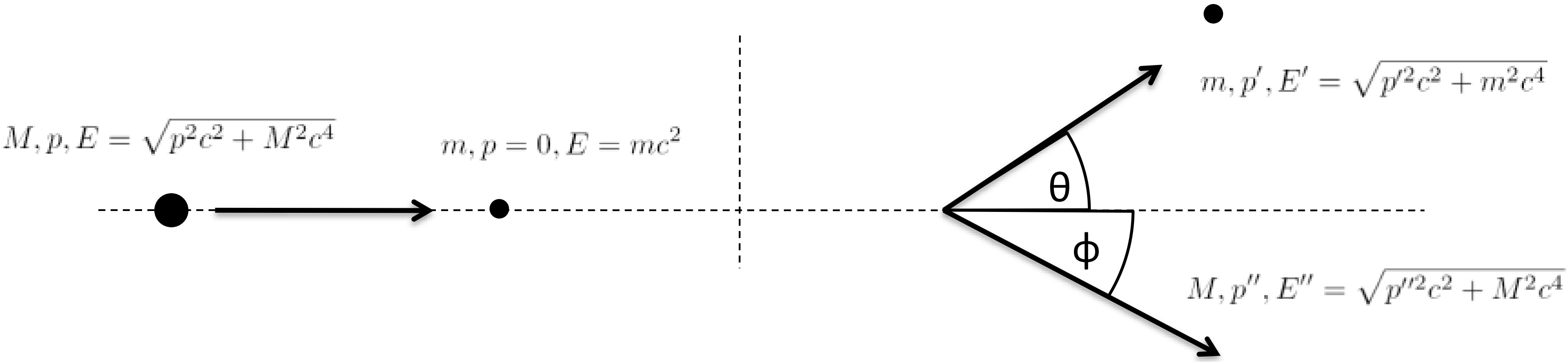
$$dE = -\int_{b_{min}}^{b_{max}} n_e \Delta E dx 2b\pi db = -\frac{4\pi Z_2 Z_1^2 m_e c^2 r_e^2}{\beta^2} \frac{N_A \rho}{A} \int_{b_{min}}^{b_{max}} \frac{db}{b}$$

With $\Delta E(b)$ → $db/b = -1/2\, dE/E$ → $E_{max} = \Delta E(b_{min})$ $E_{min} = \Delta E(b_{max})$

$$\frac{dE}{dx} = -2\pi r_e^2 m_e^2 c^2 \frac{Z_1^2}{\beta^2} \frac{N_A Z_2 \rho}{A} \int_{E_{min}}^{E_{max}} \frac{dE}{E} \qquad = \qquad -2\pi r_e^2 m_e^2 c^2 \frac{Z_1^2}{\beta^2} \frac{N_A Z_2 \rho}{A} \ln \frac{E_{max}}{E_{min}}$$

$E_{min} \approx I$ (Ionization Energy)

Relativistic Collision Kinematics, E_{max}



1) $\sqrt{p^2c^2 + M^2c^4} + mc^2 = \sqrt{p'^2c^2 + m^2c^4} + \sqrt{p''^2c^2 + M^2c^4}$

2) $$p = p' \cos\theta + p'' \cos\phi \qquad p''^2 = p'^2 + p^2 - 2pp' \cos\theta$$
$$0 = p' \sin\theta + p'' \sin\phi$$

1+2) $$E^{k'} = \sqrt{p'^2c^2 + m^2c^4} - mc^2 = \frac{2mc^2\, p^2c^2 \cos^2\theta}{\left[mc^2 + \sqrt{p^2c^2 + M^2c^4}\right]^2 - p^2c^2\cos^2\theta}$$

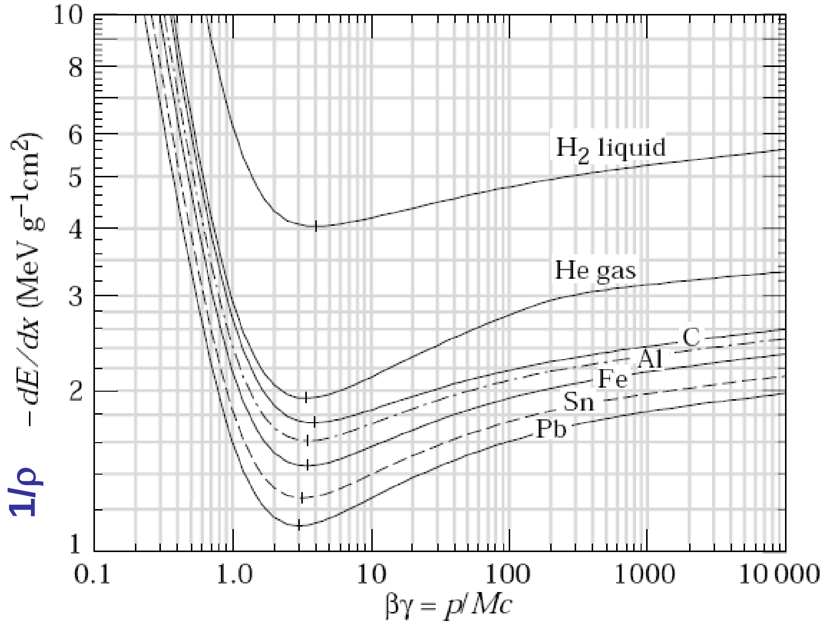
$$E^{k'}{}_{max} = \frac{2mc^2p^2c^2}{(m^2 + M^2)c^4 + 2m\sqrt{p^2c^2 + M^2c^4}} = 2mc^2\beta^2\gamma^2 F \qquad F = \left(1 + \frac{2m}{M}\sqrt{1 + \beta^2\gamma^2} + \frac{m^2}{M^2}\right)^{-1}$$

Classical Scattering on Free Electrons

$$\frac{1}{\rho}\frac{dE}{dx} = -2\pi r_e^2\, m_e c^2\, \frac{Z_1^2}{\beta^2}\, N_A \frac{Z}{A} \ln\frac{2m_e c^2\beta^2\gamma^2 F}{I}$$

This formula is up to a factor 2 and the density effect identical to the precise QM derivation →

Bethe Bloch Formula



$$\frac{1}{\rho}\frac{dE}{dx} = -4\pi r_e^2\, m_e c^2\, \frac{Z_1^2}{\beta^2}\, N_A \frac{Z}{A}\left[\ln\frac{2m_e c^2\beta^2\gamma^2 F}{I} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

Electron Spin

$$\delta(\beta\gamma) = \ln h\omega_p/I + \ln\beta\gamma - \frac{1}{2}$$

Density effect. Medium is polarized Which reduces the log. rise.

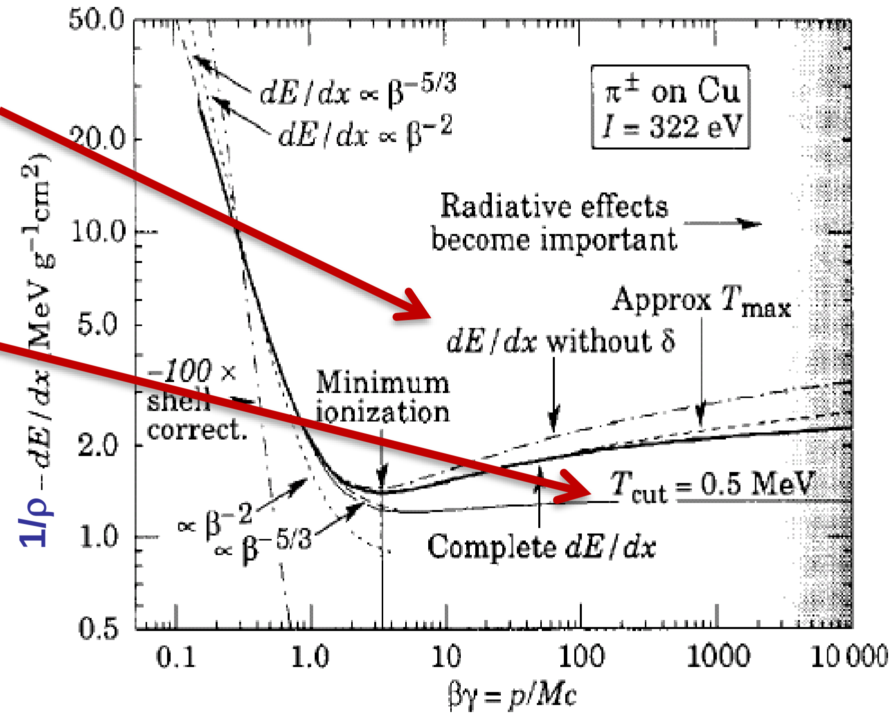
Bethe Bloch Formula

$$\frac{1}{\rho}\frac{dE}{dx} = -4\pi r_e^2\, m_e c^2\, \frac{Z_1^2}{\beta^2}\, N_A \frac{Z}{A}\left[\ln\frac{2m_e c^2\beta^2\gamma^2 F}{I} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

Für Z>1, $I \approx 16Z^{0.9}$ eV

For Large βγ the medium is being polarized by the strong transverse fields, which reduces the rise of the energy loss → density effect

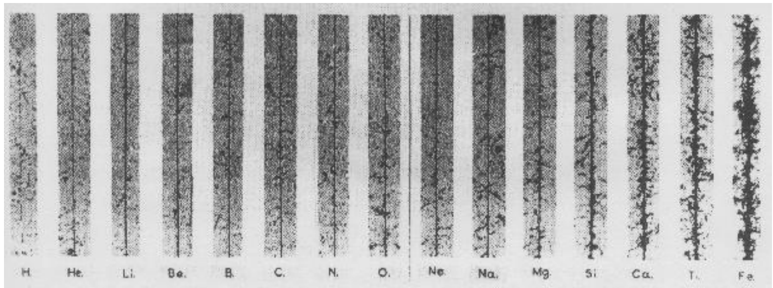
At large Energy Transfers (delta electrons) the liberated electrons can leave the material.
In reality, E_{max} must be replaced by E_{cut} and the energy loss reaches a plateau (Fermi plateau).



Characteristics of the energy loss as a function of the particle velocity (βγ)

The specific Energy Loss 1/ρ dE/dx

- **first decreases as $1/\beta^2$**
- **increases with ln γ for β =1**
- **is ≈ independent of M ($M \gg m_e$)**
- **is proportional to Z_1^2 of the incoming particle.**
- **is ≈ independent of the material (Z/A ≈ const)**
- **shows a plateau at large βγ (>>100)**
- **dE/dx ≈ 1-2 x ρ [g/cm³] MeV/cm**



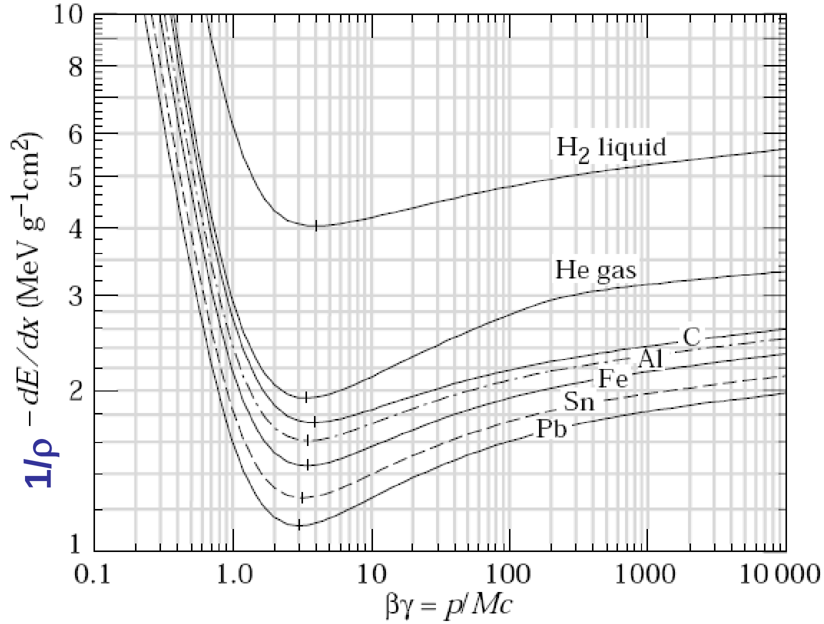
Bethe Bloch Formula

Bethe Bloch Formula, a few Numbers:

For $Z \approx 0.5 A$
$1/\rho \; dE/dx \approx 1.4$ MeV cm ^{2}/g for $\beta\gamma \approx 3$

Example :
Iron: Thickness = 100 cm; $\rho = 7.87$ g/cm^3
$dE \approx 1.4 * 100 * 7.87 = 1102$ MeV

→ A 1 GeV Muon can traverse 1m of Iron



This number must be multiplied with ρ [g/cm^3] of the Material → dE/dx [MeV/cm]

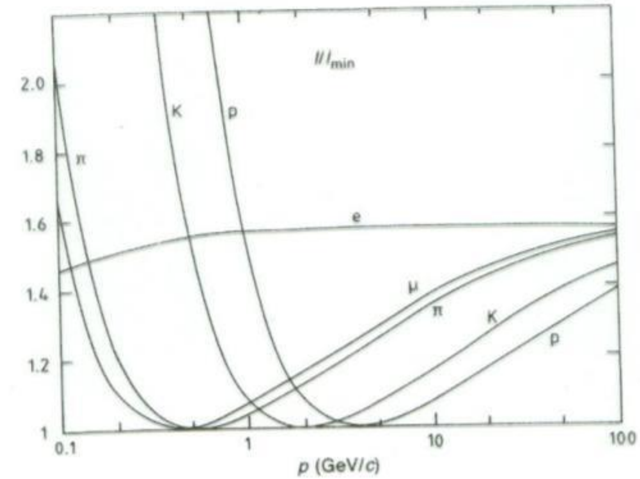
Energy Loss as a Function of the Momentum

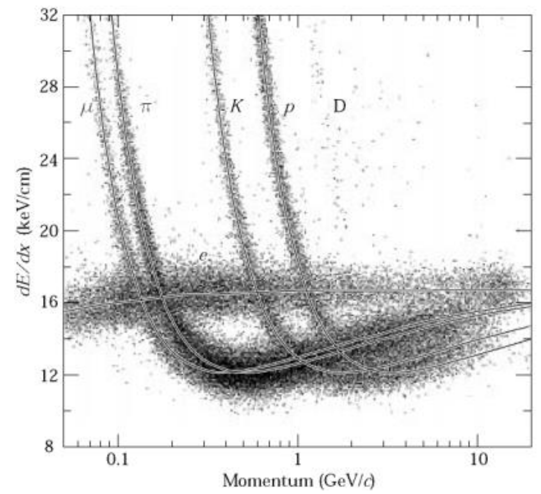
Energy loss depends on the particle velocity and is ≈ independent of the particle's mass M.

The energy loss as a function of particle Momentum P= Mcβγ IS however depending on the particle's mass

By measuring the particle momentum (deflection in the magnetic field) and measurement of the energy loss on can measure the particle mass

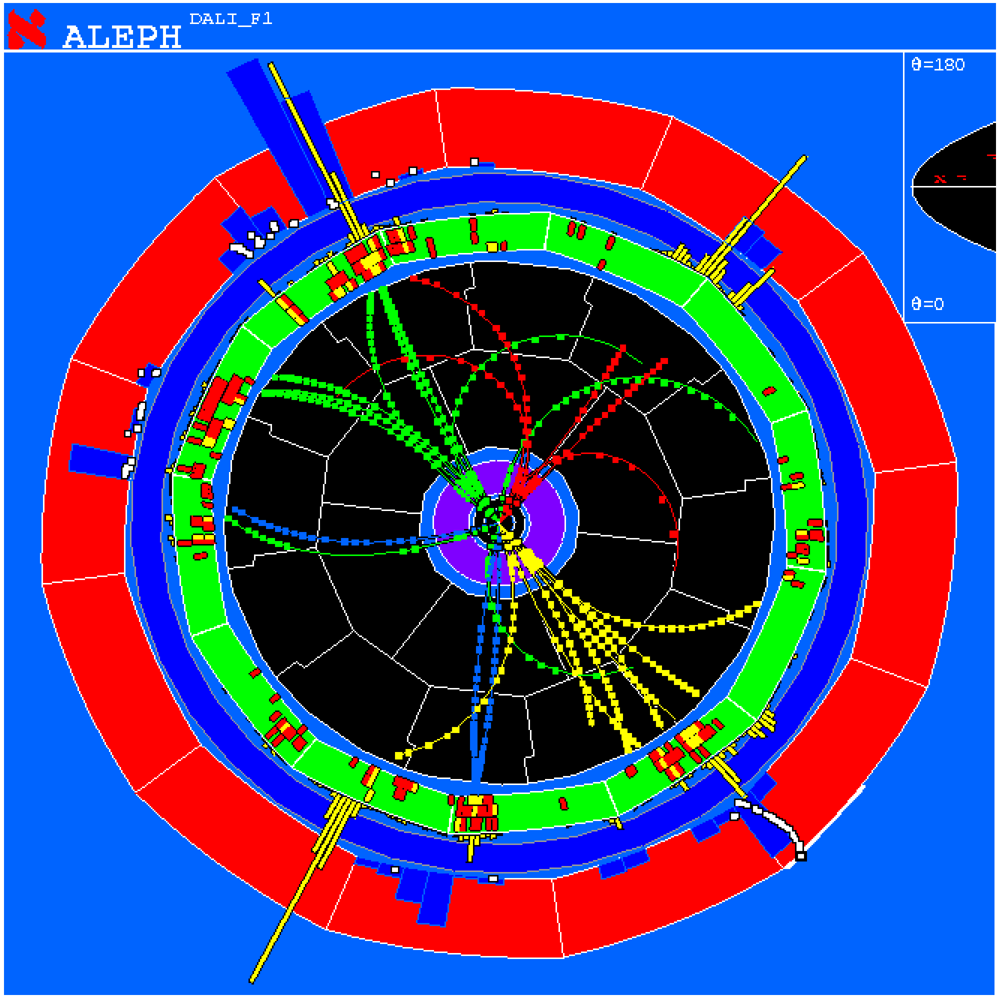
→ Particle Identification !





$$\frac{1}{\rho}\frac{dE}{dx} = -4\pi r_e^2\, m_e c^2\, Z_1^2 \frac{p^2 + M^2c^2}{p^2}\, N_A \frac{Z}{A}\left[\ln\frac{2m_ec^2F}{I}\frac{p^2}{M^2c^2} - \frac{p^2}{p^2+M^2c^2}\right]$$

Energy Loss as a Function of the Momentum



Measure momentum by curvature of the particle track.

Find dE/dx by measuring the deposited charge along the track.

→Particle ID

Range of Particles in Matter

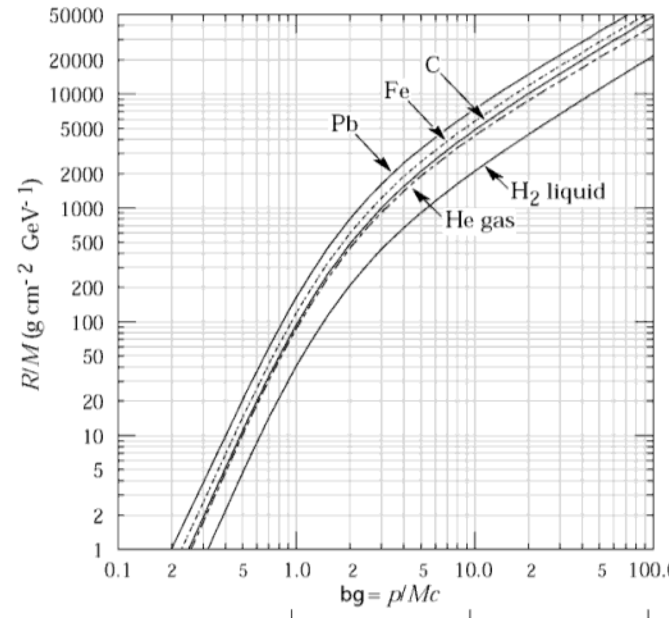
Particle of mass M and kinetic Energy E_0 enters matter and looses energy until it comes to rest at distance R.

$$R(E_0) = \int_{E_0}^{0} \frac{-1}{dE/dx} dE$$

$$R(\beta_0\gamma_0) = \frac{Mc^2}{\rho} \frac{1}{Z_1^2} \frac{A}{Z} f(\beta_0\gamma_0)$$

$$\frac{\rho}{Mc^2} R(\beta_0\gamma_0) = \frac{1}{Z_1^2} \frac{A}{Z} f(\beta_0\gamma_0)$$

≈Independent of the material

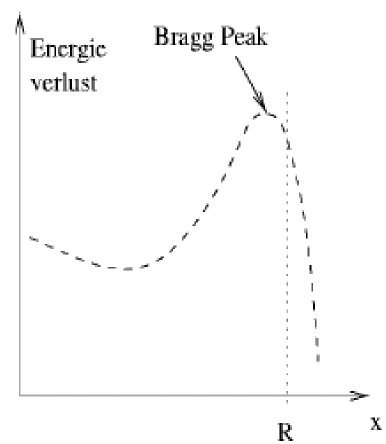


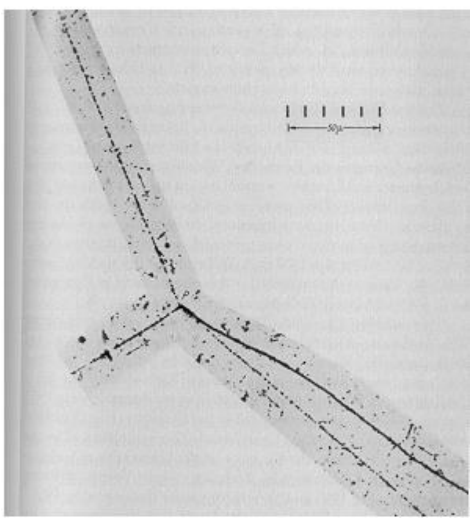
Bragg Peak:

For βγ>3 the energy loss is ≈ constant (Fermi Plateau)

If the energy of the particle falls below βγ=3 the energy loss rises as $1/\beta^2$

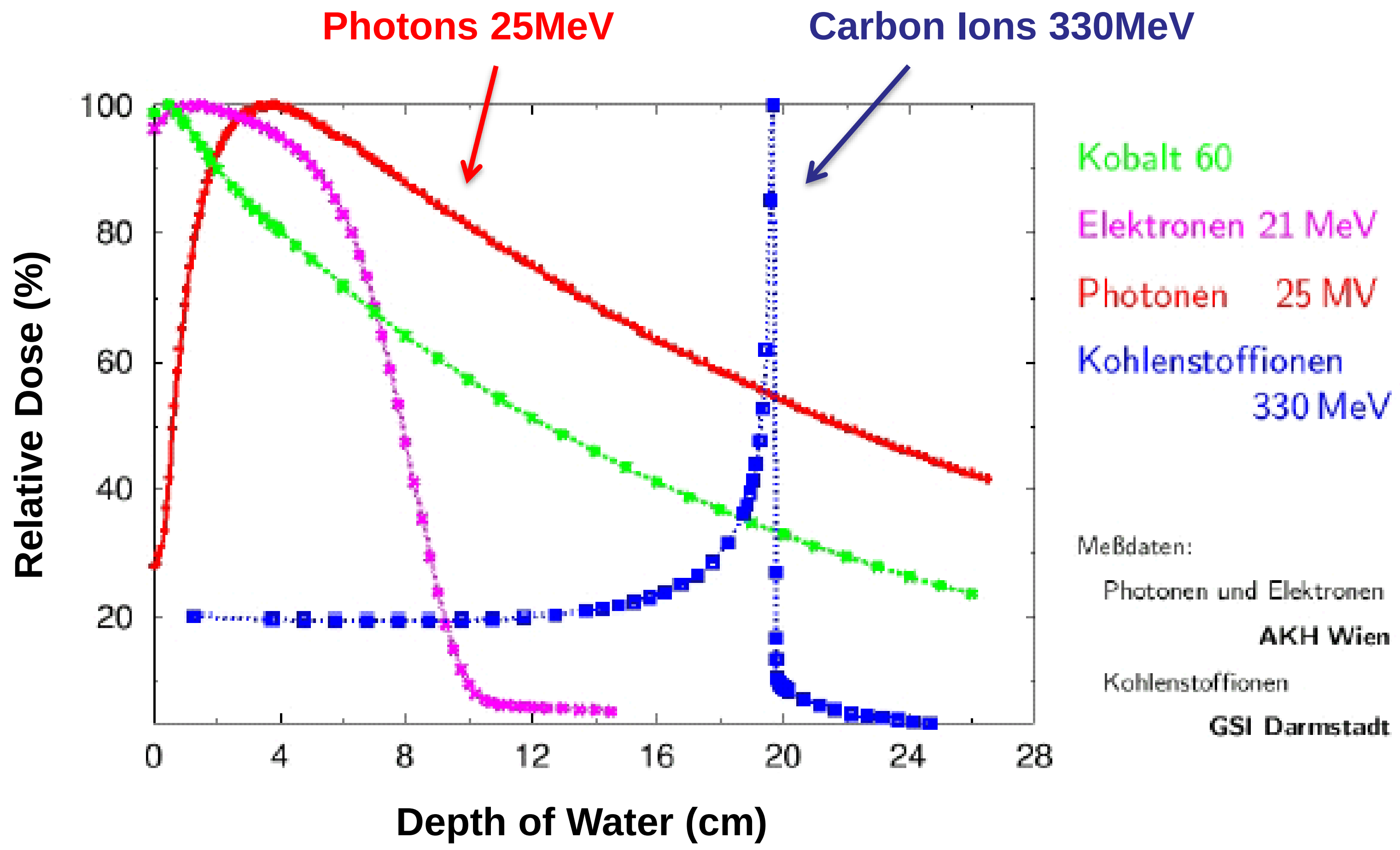
Towards the end of the track the energy loss is largest → Cancer Therapy.





Range of Particles in Matter

Average Range:
Towards the end of the track the energy loss is largest → Bragg Peak → Cancer Therapy



Fluctuation of the energy Loss: Landau Distribution

Landau Distribution

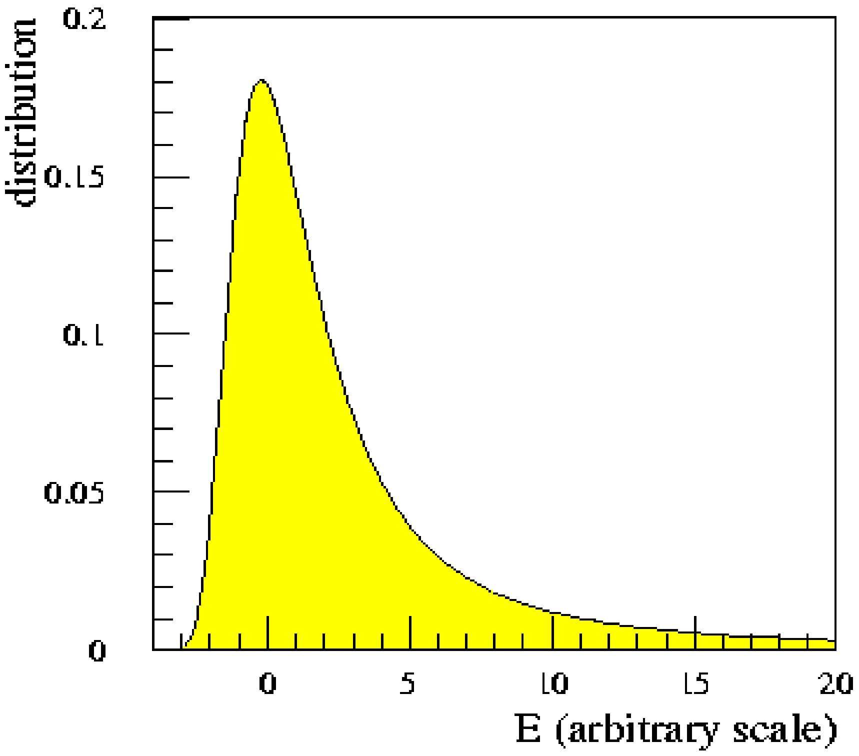
P(Δ): Probability for energy loss Δ in matter of thickness D.

Landau distribution is very asymmetric.

Average and most probable energy loss must be distinguished !

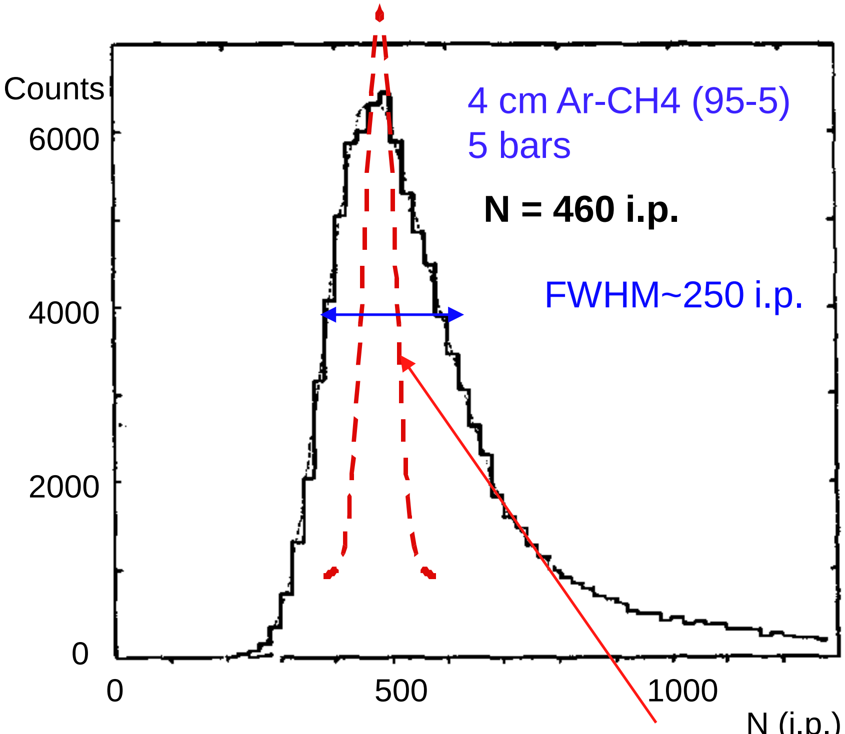
Measured Energy Loss is usually smaller that the real energy loss:

3 GeV Pion: E'_{max} = 450MeV → A 450 MeV Electron usually leaves the detector.



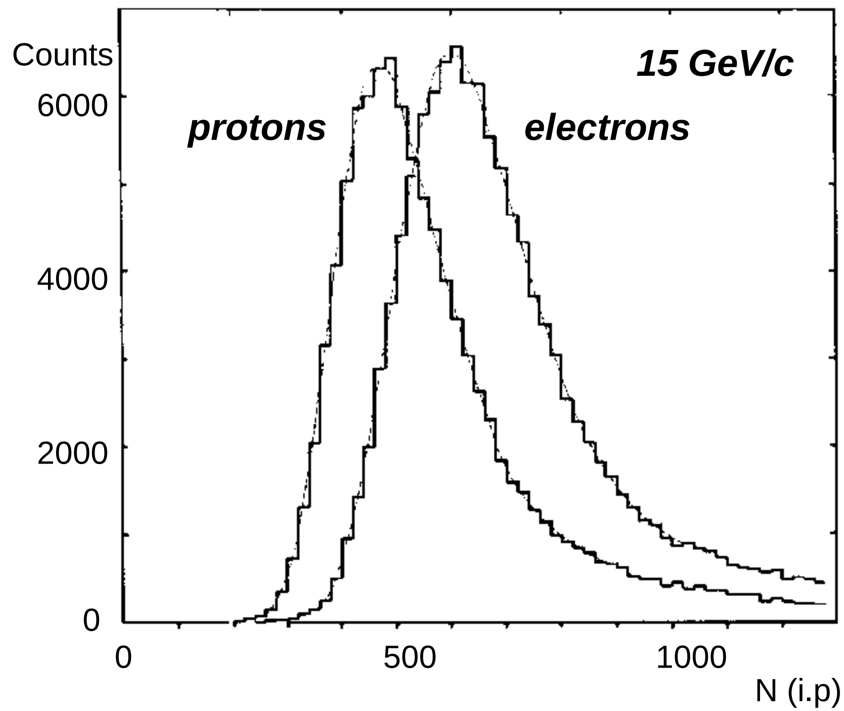
Landau Distribution

LANDAU DISTRIBUTION OF ENERGY LOSS:



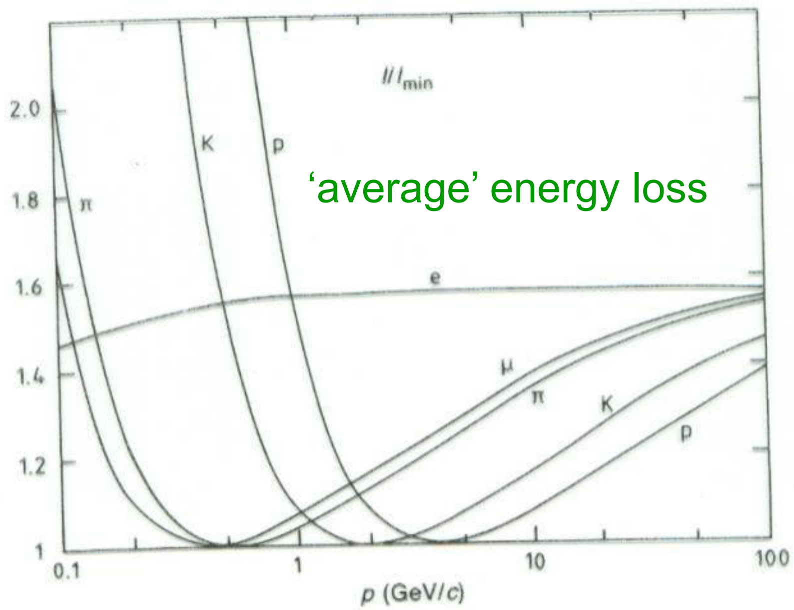
For a Gaussian distribution: **σ_N ~ 21 i.p.**
FWHM ~ 50 i.p.

PARTICLE IDENTIFICATION
Requires statistical analysis of hundreds of samples

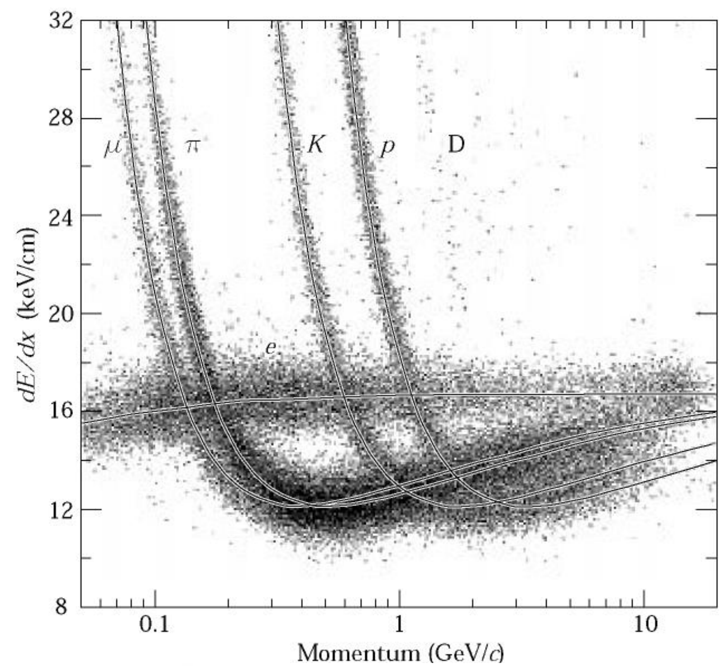


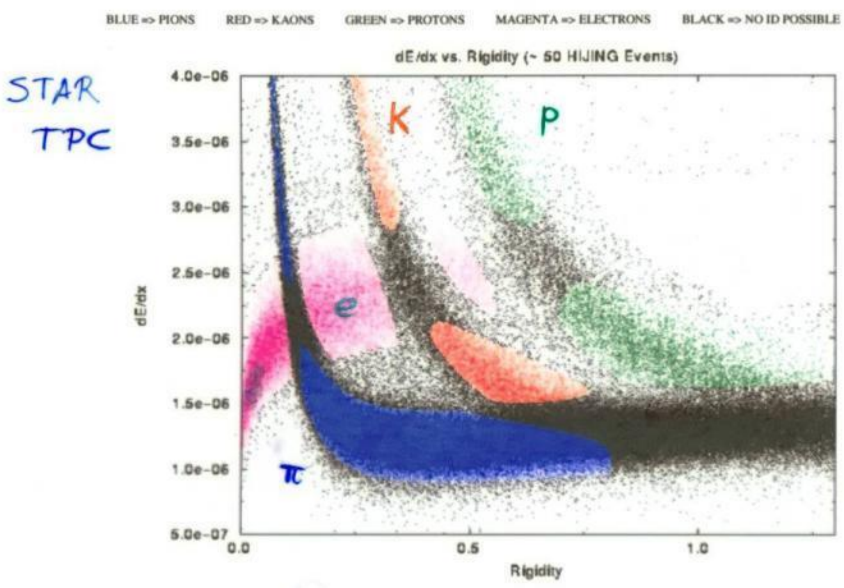
I. Lehraus et al, Phys. Scripta 23(1981)727

Particle Identification



Measured energy loss

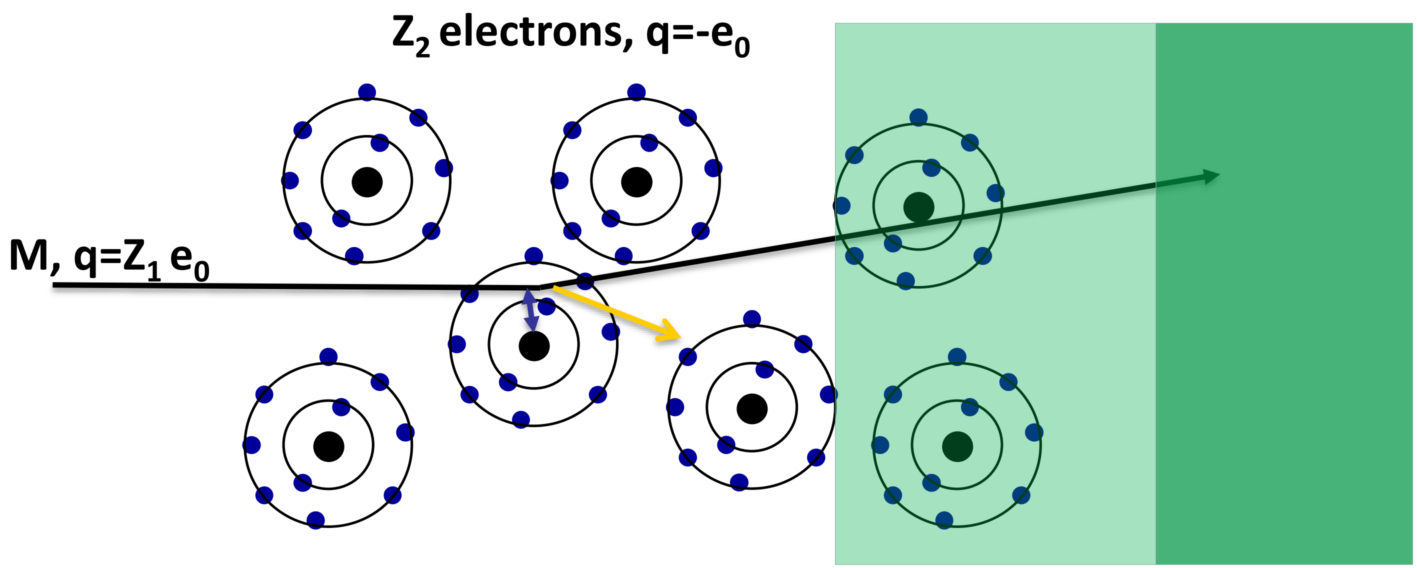




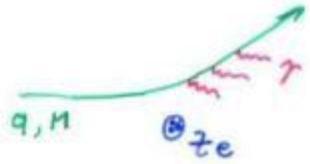
In certain momentum ranges, particles can be identified by measuring the energy loss.

Bremsstrahlung

A charged particle of mass M and charge $q=Z_1e$ is deflected by a nucleus of charge Ze which is partially 'shielded' by the electrons. During this deflection the charge is 'accelerated' and it therefore radiated → Bremsstrahlung.



Bremsstrahlung, Classical



$q = Z_1 \cdot e$

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

"Rutherford Scattering"

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

$$\frac{d\sigma}{dQ} = 8\pi\left(\frac{Z_1 Z_2 e^2}{4\pi\varepsilon_0 \beta c}\right)^2 \cdot \frac{1}{Q^3}$$

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

→ From Maxwell's Eq (Jackson)

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

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

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

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

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

Because of the acceleration the particle radiated EM waves → energy loss.

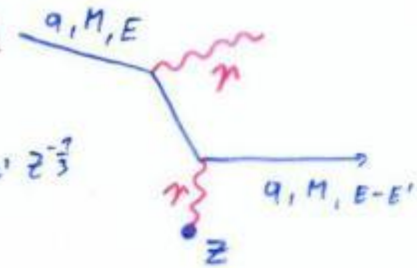
Coulomb-Scattering (Rutherford Scattering) describes the deflection of the particle.

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

→ dE/dx

Bremsstrahlung, QM

2.6 Bremsstrahlung QM.



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

→ highly Relativistic:

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

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

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

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

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

X_0 ... Radiation length

Proportional to Z^2/A of the Material.

Proportional to Z_1^4 of the incoming particle.

Proportional to ρ of the material.

Proportional $1/M^2$ of the incoming particle.

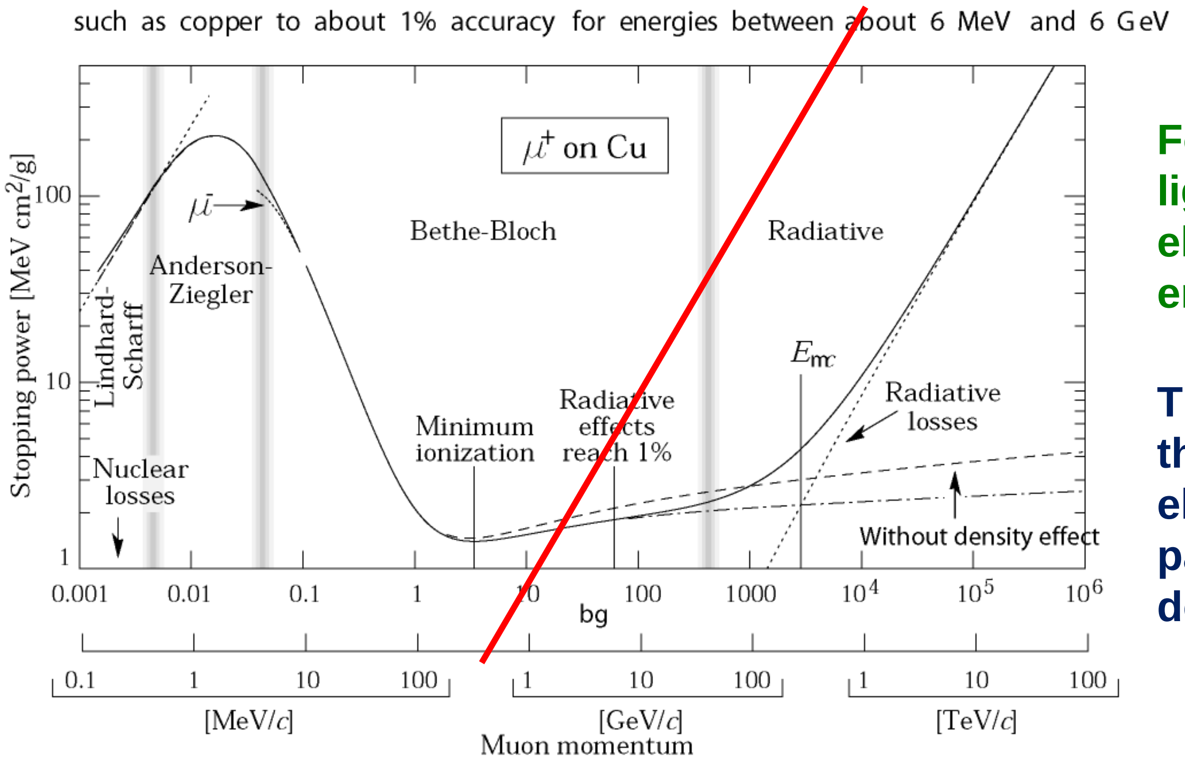
Proportional to the Energy of the Incoming particle →

$E(x)=Exp(-x/X_0)$ – 'Radiation Length'

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

X_0: Distance where the Energy E_0 of the incoming particle decreases $E_0Exp(-1)=0.37E_0$.

Critical Energy



Electron Momentum 5 50 500 MeV/c

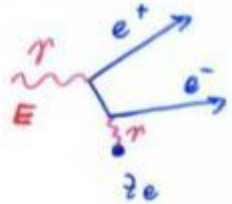
For the muon, the second lightest particle after the electron, the critical energy is at 400GeV.

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

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

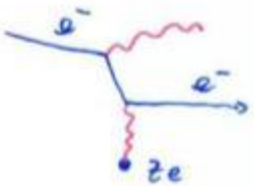
Myon in Copper: p ≈ 400GeV
Electron in Copper: p ≈ 20MeV

Pair Production, QM



γ + Nucl. $\rightarrow$ $e^+ + e^-$ + Nucl

The Diagram is very similar to Bremsstrahlung



e^- + Nucl $\rightarrow$ γ + e^- + Nucl

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

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

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

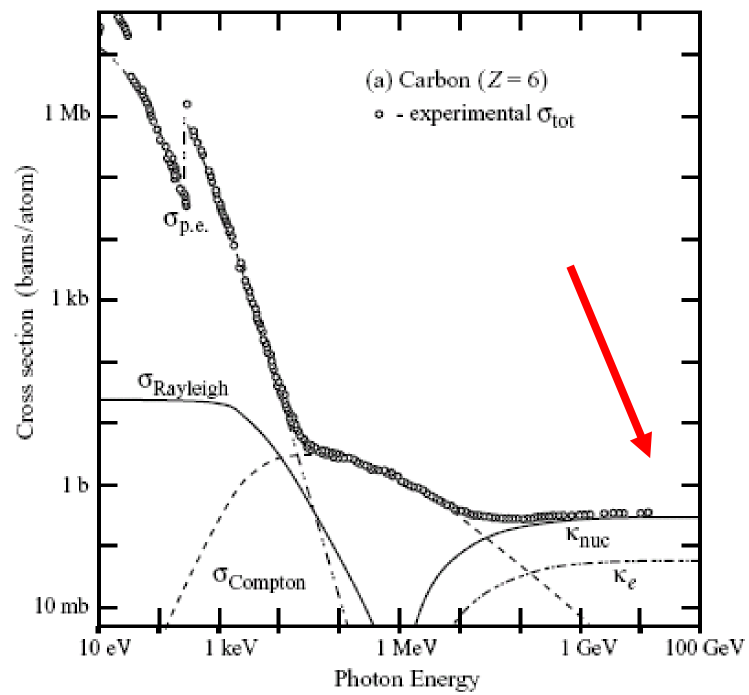
$$\sigma = \int_0^{E-2m_ec^2} \frac{d\sigma}{dE'} dE' = 4\alpha Z^2 r_e^2 \cdot \frac{7}{9} \ln 183 Z^{-\frac{1}{3}}$$

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

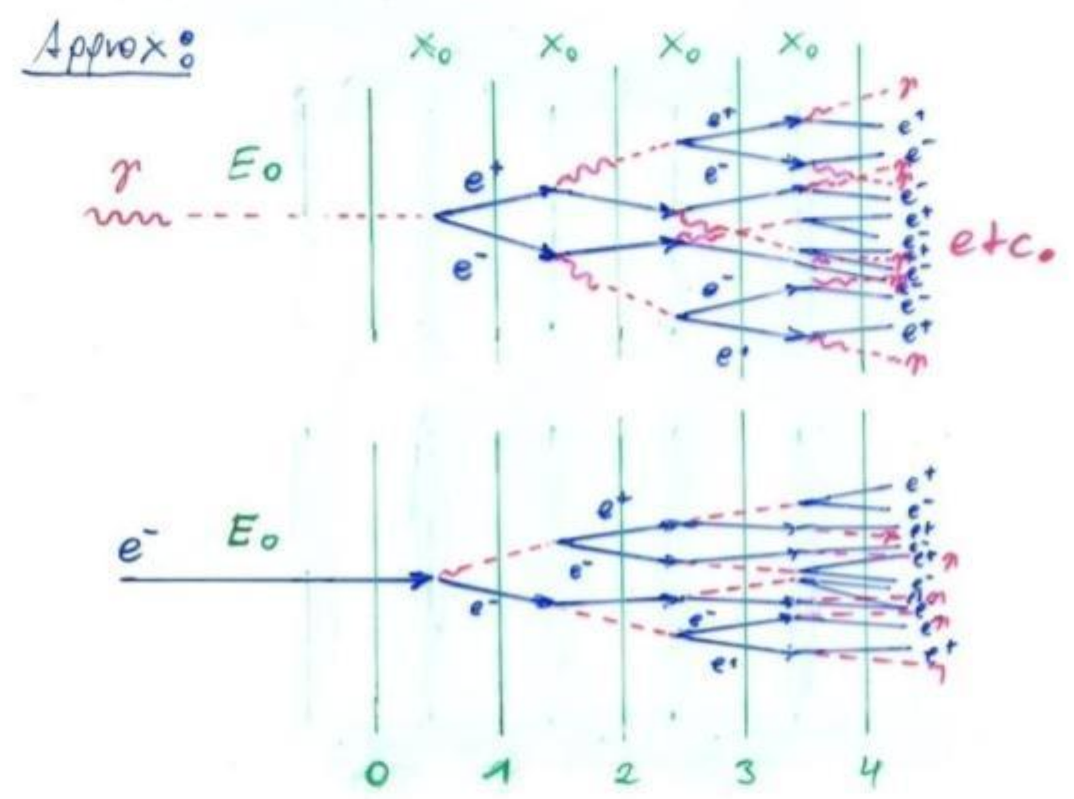
↳ Probability that Photon converts to $e^+ e^-$ after a distance x.

For $E\gamma \gg m_ec^2$=0.5MeV : λ = 9/7X_0

Average distance a high energy photon has to travel before it converts into an $e^+ e^-$ pair is equal to 9/7 of the distance that a high energy electron has to travel before reducing it's energy from E_0 to E_0*Exp(-1) by photon radiation.



Bremsstrahlung + Pair Production → EM Shower



Electromagnetic Shower → EM Calorimeter

Tracking:

Momentum by bending in the B-field

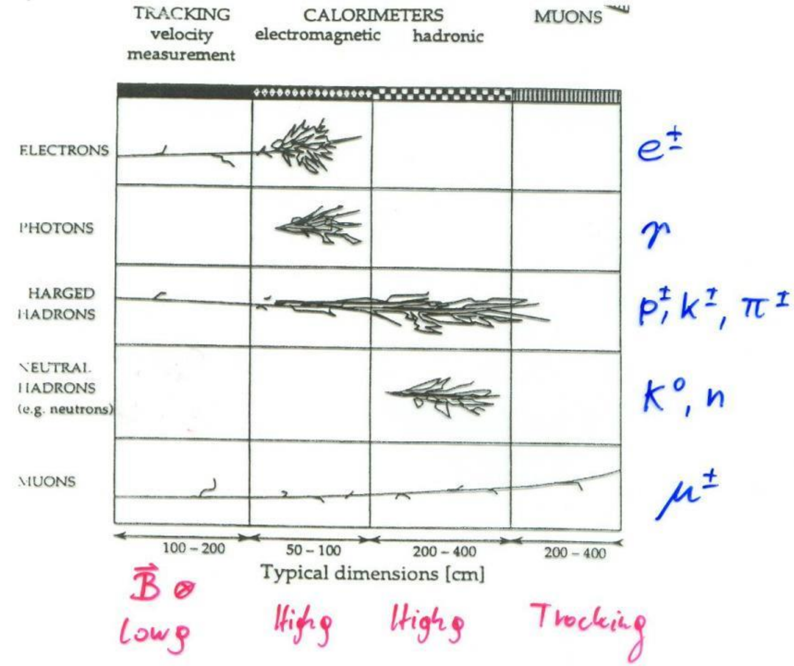
Secondary vertices

Calorimeter:

Energy by absorption

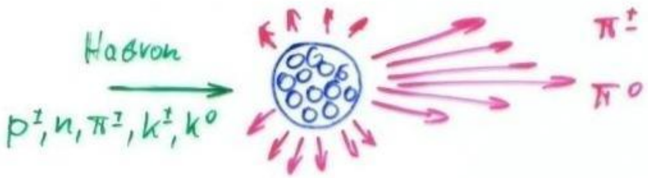
Muons:

Only particles passing through calorimeters



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

Hadronic Calorimetry



Strong Interaction

Approximate Energy Distribution

~50%	~20%	~30%
π^+, π^- $\pi^0 \to \gamma\gamma$	Nuclear Excitation	Slow Nucleons
π^+, π^- $\pi^+, \pi^-, \pi^0 \to \gamma\gamma$	5-30 MeV	
	p, n, γ	

Hadron kaskade

$\pi^0 \to \gamma\gamma \to$ Electromagnetic Component

In Hadronic Cascades the Longitudinal Shower is given by the Absorption Length λ_a $\quad I \sim e^{-\frac{x}{\lambda_a}}$

In typical Detector Materials λ_a is much larger than X_0

$$\lambda \sim \frac{1}{\rho} \cdot 35\, A^{\frac{1}{3}}$$

	ρ	X_0	λ
Fe	7.87	1.76 cm	~17 cm
Pb	11.35	0.56 cm	~17 cm

Energy Resolution:

- A large Fraction of the Energy 'disappears' into
  - Binding Energy of emitted Nucleons
  - $\pi \to \mu + \nu$ which are not absorbed
- π^0's Decaying into $\gamma\gamma$ start an EM Cascade ($\tau \sim 10^{-14}$ s)

– Energy Resolution is worse than for EM Calorimeters

W. Riegler/CERN

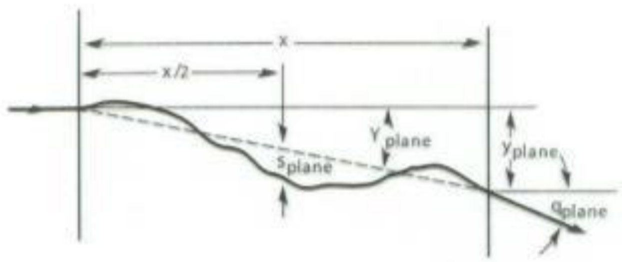
Multiple Scattering

Statistical (quite complex) analysis of multiple collisions gives:

Probability that a particle is defected by an angle θ after travelling a distance x in the material is given by a Gaussian distribution with sigma of:

$$\Theta_0 = \frac{0.0136}{\beta c p[\mathrm{GeV/c}]} Z_1 \sqrt{\frac{x}{X_0}}$$

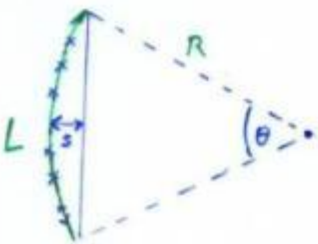
X_0 ... Radiation length of the material
Z_1 ... Charge of the particle
p ... Momentum of the particle



Momentum Measurement

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

$\vec{B}$ $\otimes$



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

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

$$L = R \cdot \theta$$

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

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

$$\Delta s = \frac{\sigma_x}{\sqrt{N}} \qquad \sigma_x \ldots \text{point resolution},\ N \ldots \text{Measurement Points}$$

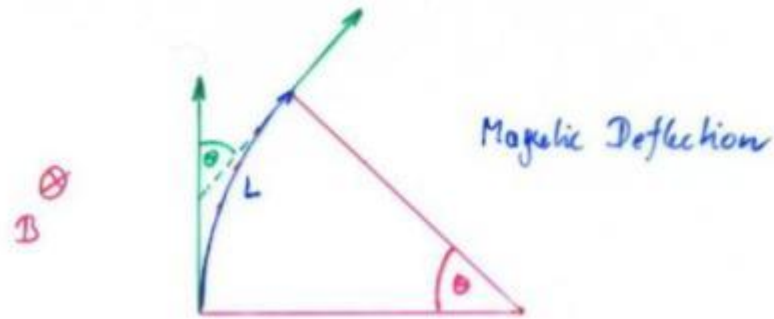
$$\boxed{\frac{\Delta p}{p} = \frac{\Delta s}{s} = \frac{\sigma_x[m]}{\sqrt{N}} \cdot \frac{3.3 \cdot 8\; p\left[\frac{GeV}{c}\right]}{B[T] \cdot L^2[m^2]}}$$

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

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

Limit → Multiple Scattering

Multiple Scattering



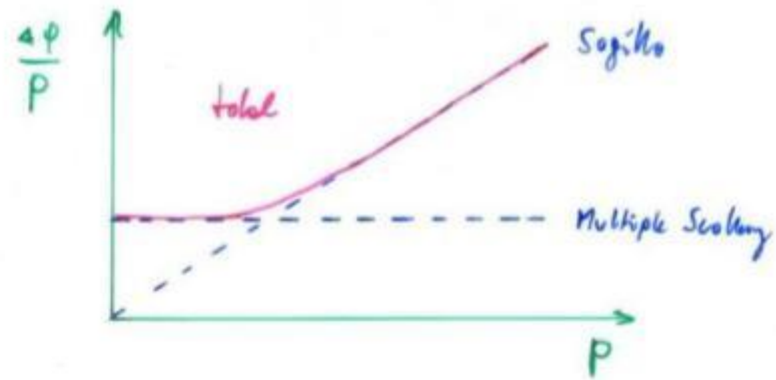
$$p\left[\frac{GeV}{c}\right] = 0.3\, R[m]\, B[T]$$

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

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

→ Independent of p

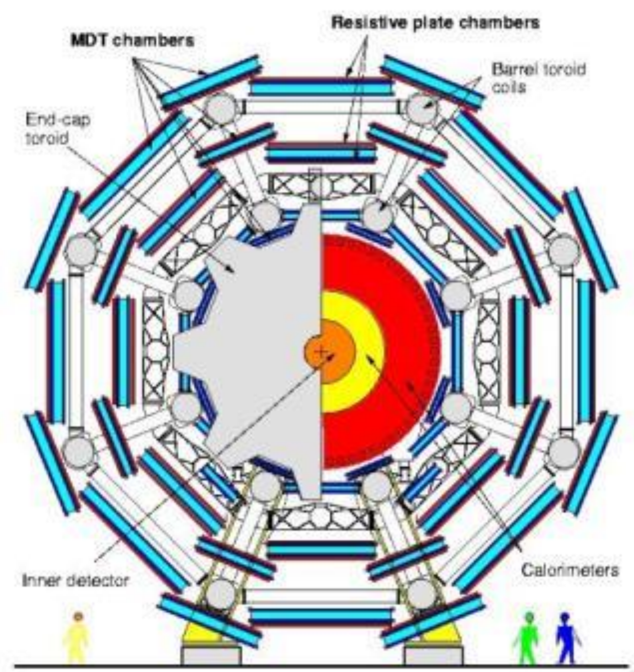
$$\left.\frac{\Delta p}{p}\right|_{tot} = \sqrt{\left(\left.\frac{\Delta p}{p}\right|_{sag}\right)^2 + \left(\left.\frac{\Delta p}{p}\right|_{ms}\right)^2}$$

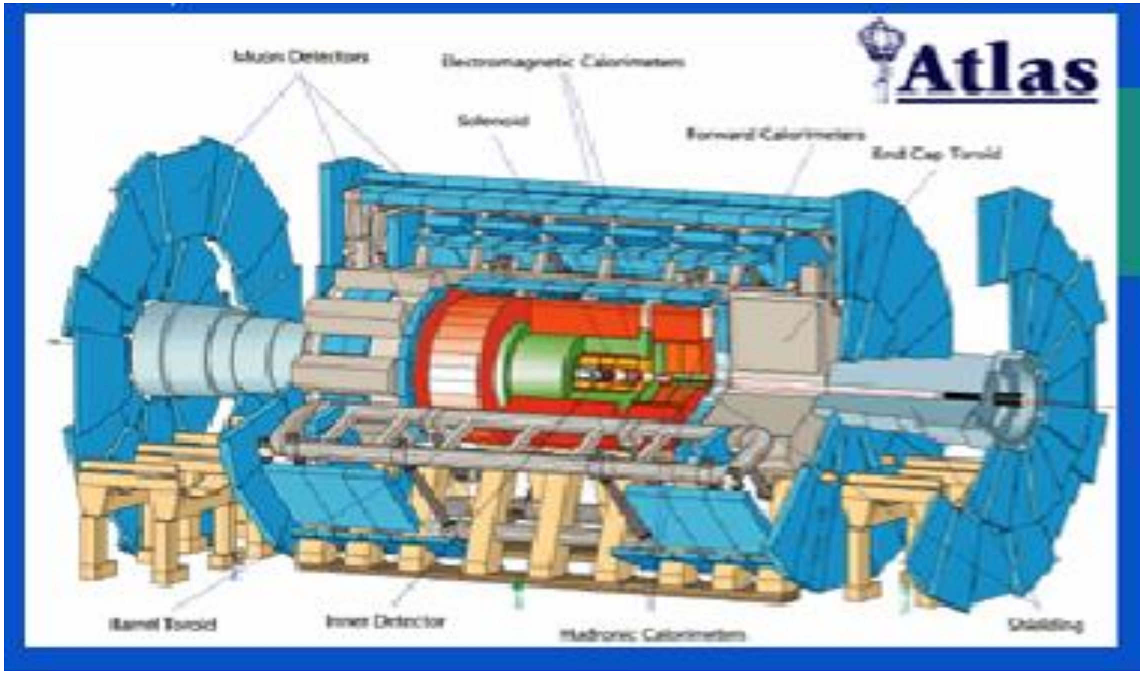


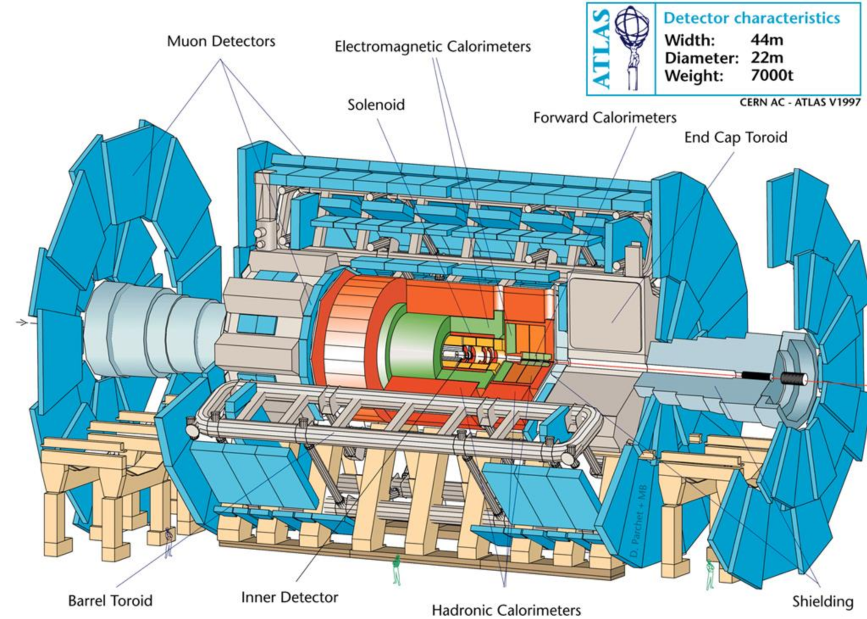
Multiple Scattering

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

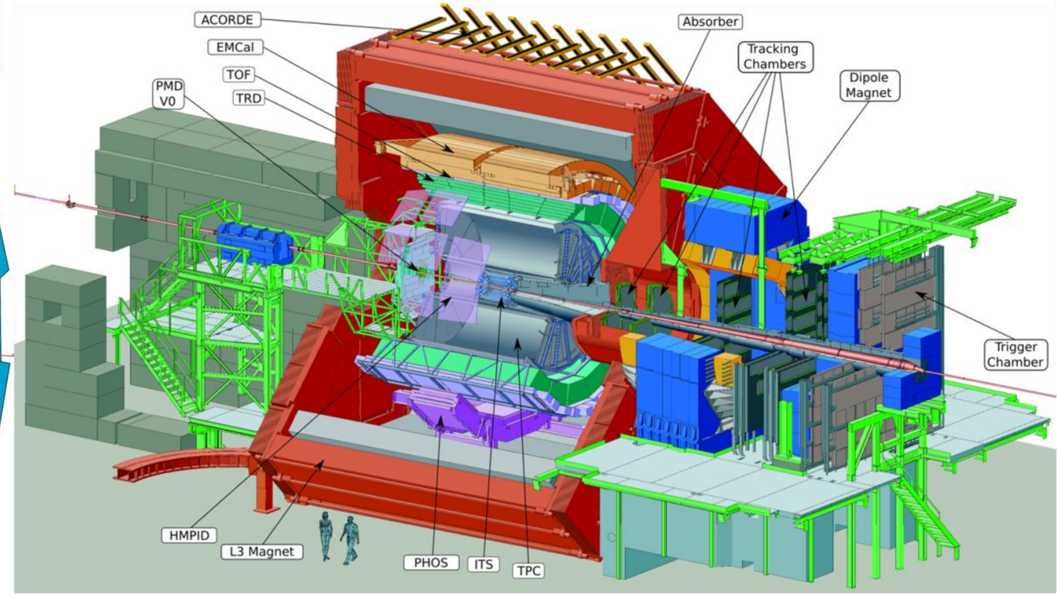
Δp/p ~ 8% for the most energetic muons at LHC



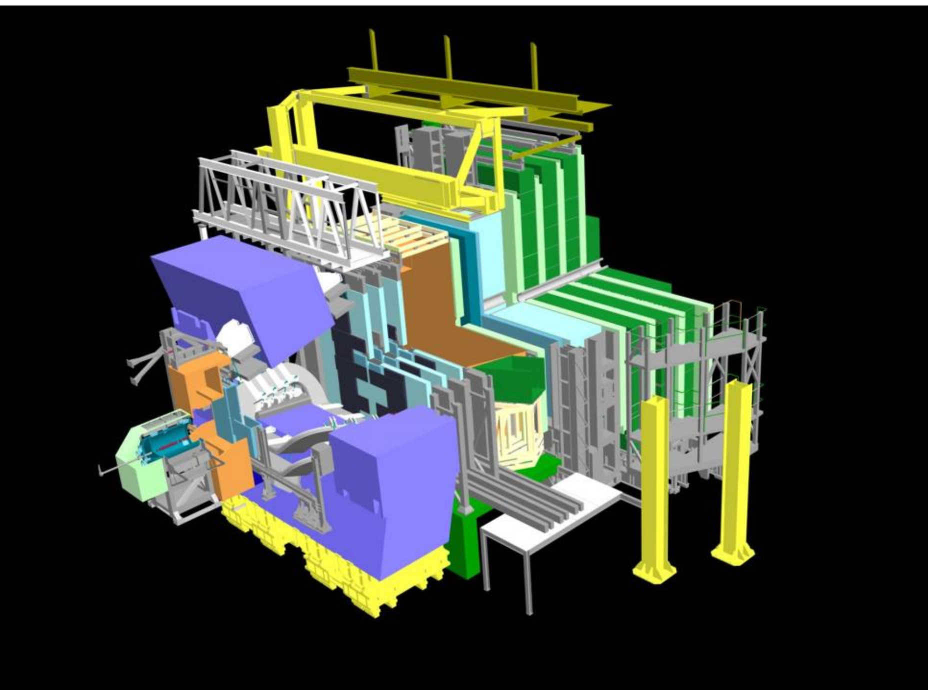


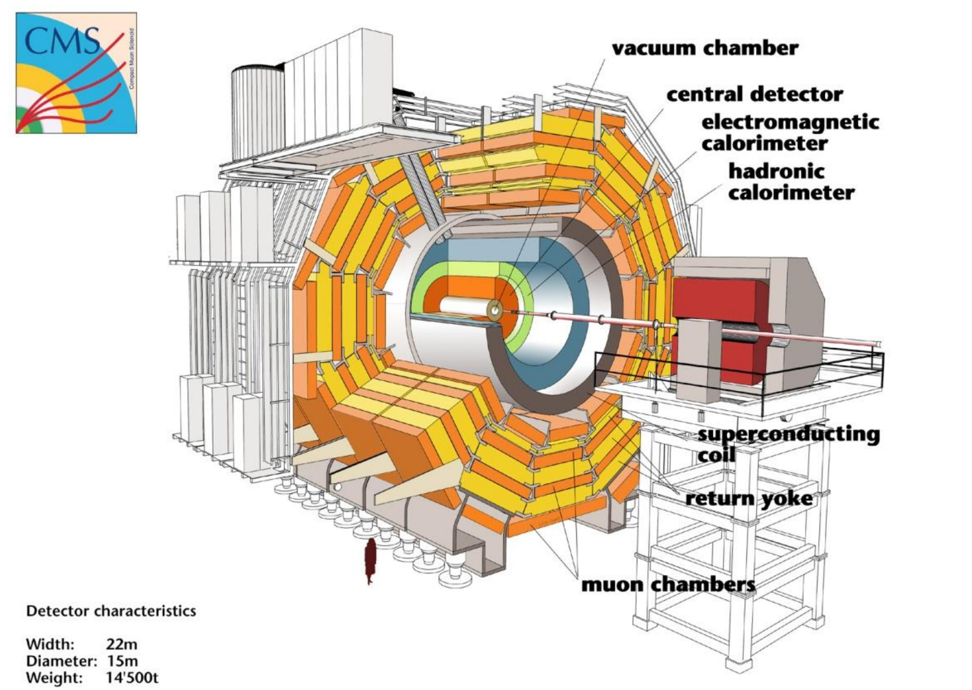


Detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t
ATLAS
CERN AC - ATLAS V1997
Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding



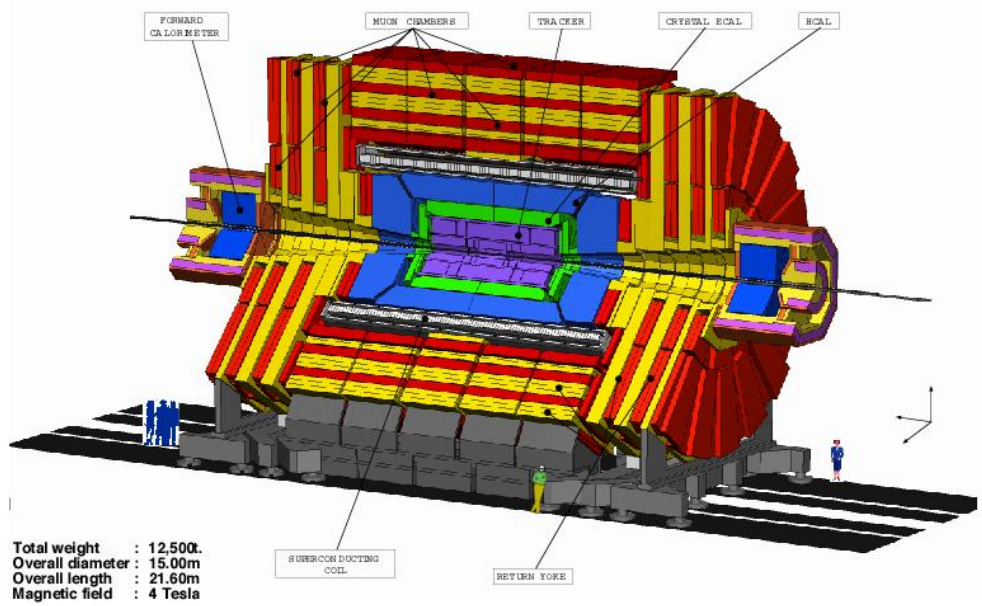
ACORDE
EMCal
TOF
TRD
PMD
V0
Absorber
Tracking Chambers
Dipole Magnet
Trigger Chamber
HMPID
L3 Magnet
PHOS
ITS
TPC

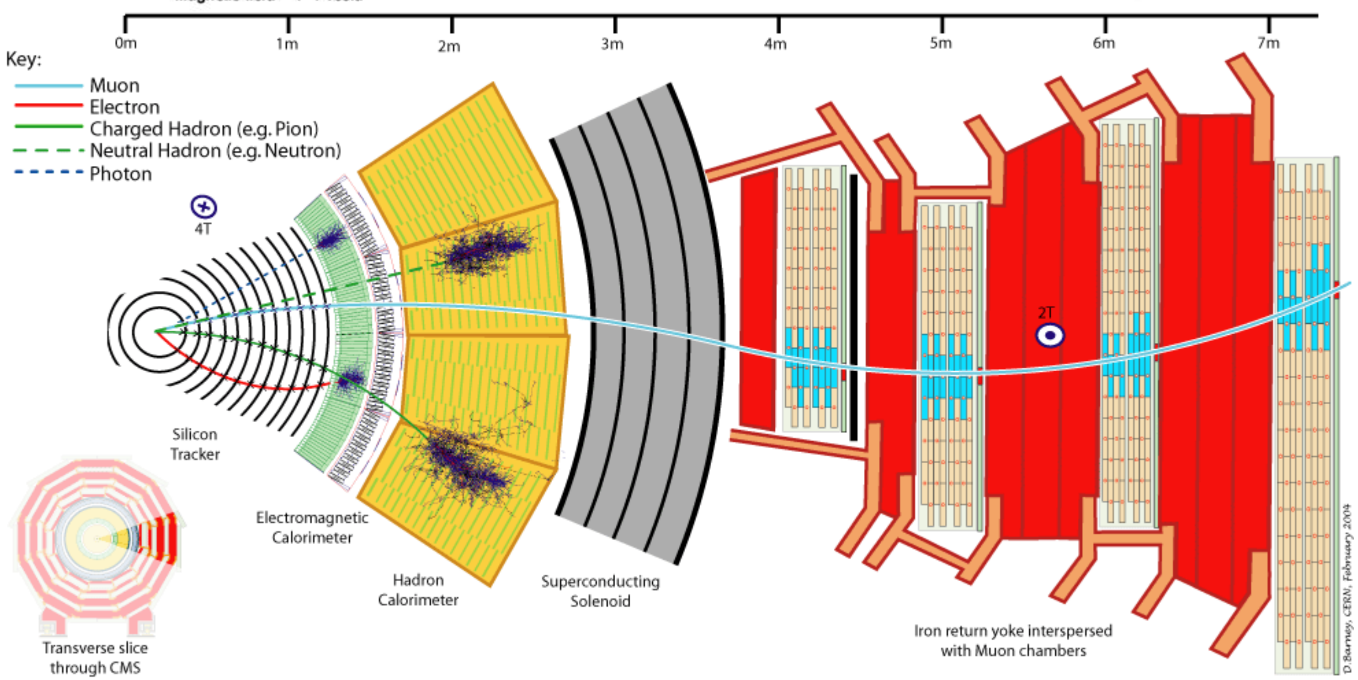




CMS
vacuum chamber
central detector
electromagnetic calorimeter
hadronic calorimeter
superconducting coil
return yoke
muon chambers
Detector characteristics
Width: 22m
Diameter: 15m
Weight: 14'500t

CMS
A Compact Solenoidal Detector for LHC

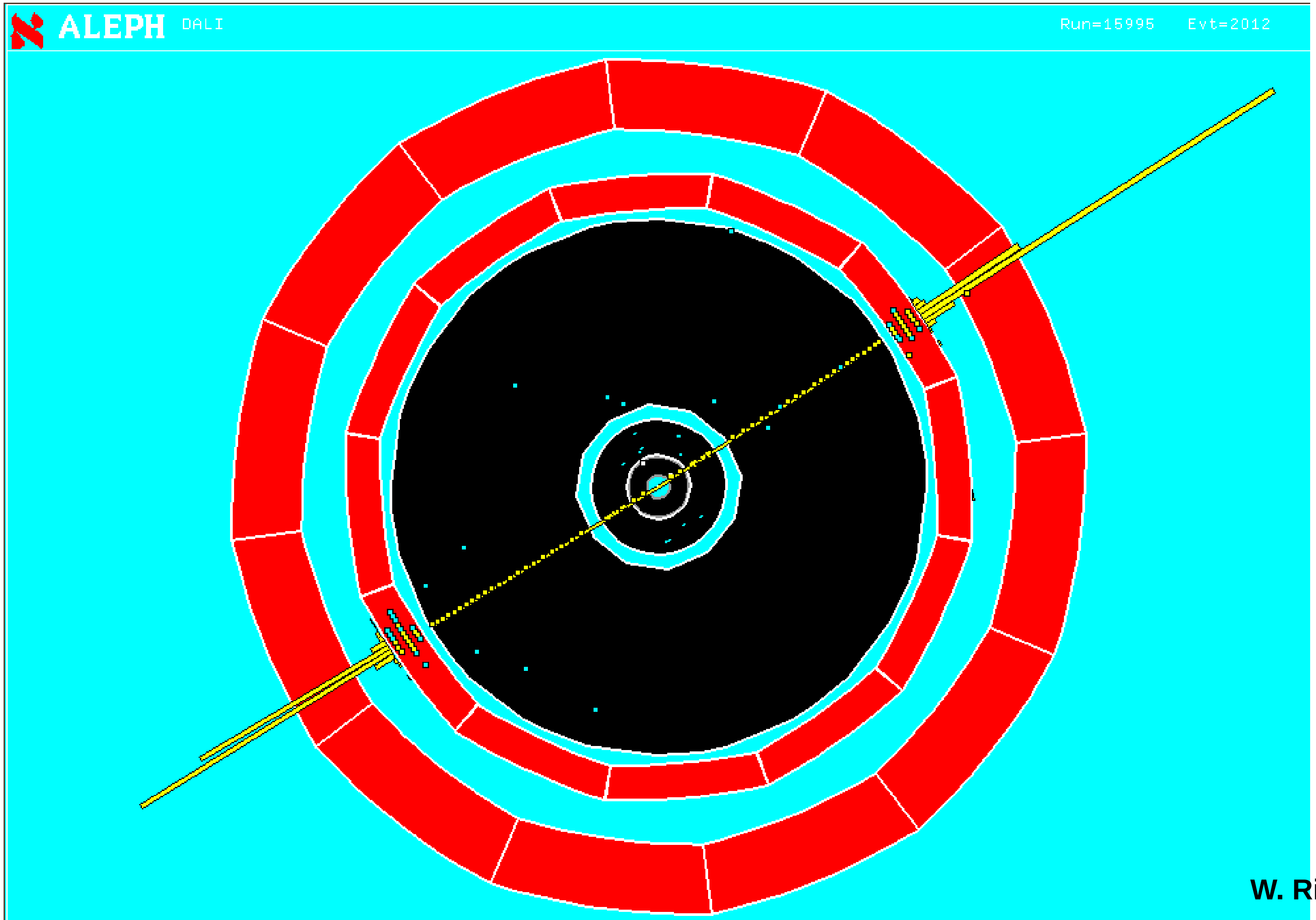




W. Riegler/CERN

$Z \rightarrow e^+ e^-$

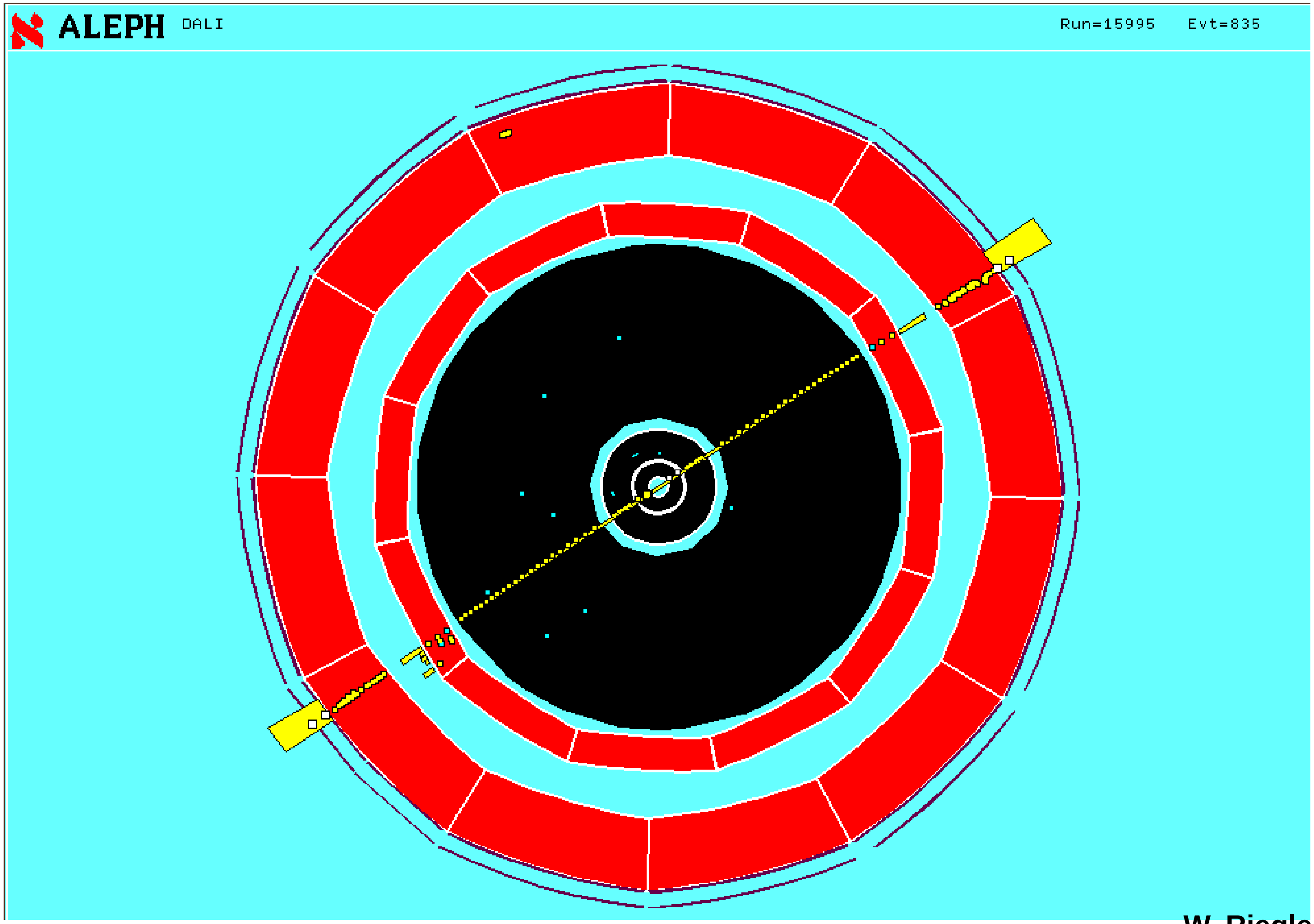
Two high momentum charged particles depositing energy in the Electro Magnetic Calorimeter



W. Riegler/CERN

Z → $\mu^+ \mu^-$

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



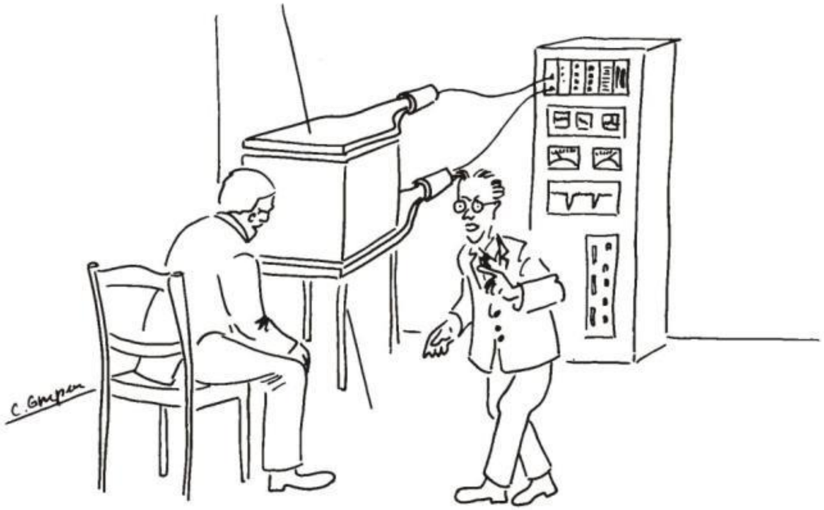
W. Riegler/CERN

Interaction of Particles with Matter

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

In many experiments neutrinos are measured by missing transverse momentum.

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

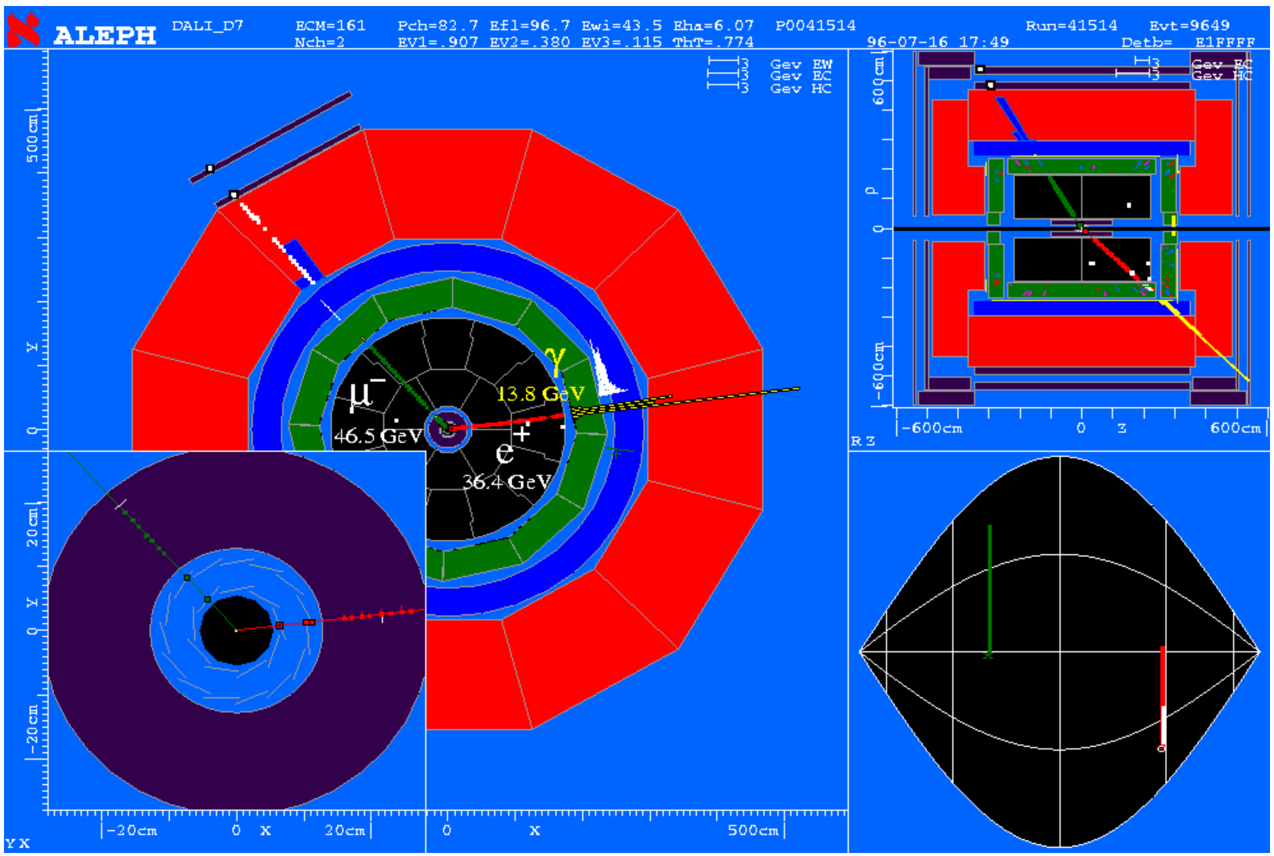


"Did you see it?"
"No nothing."
"Then it was a neutrino!"

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

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

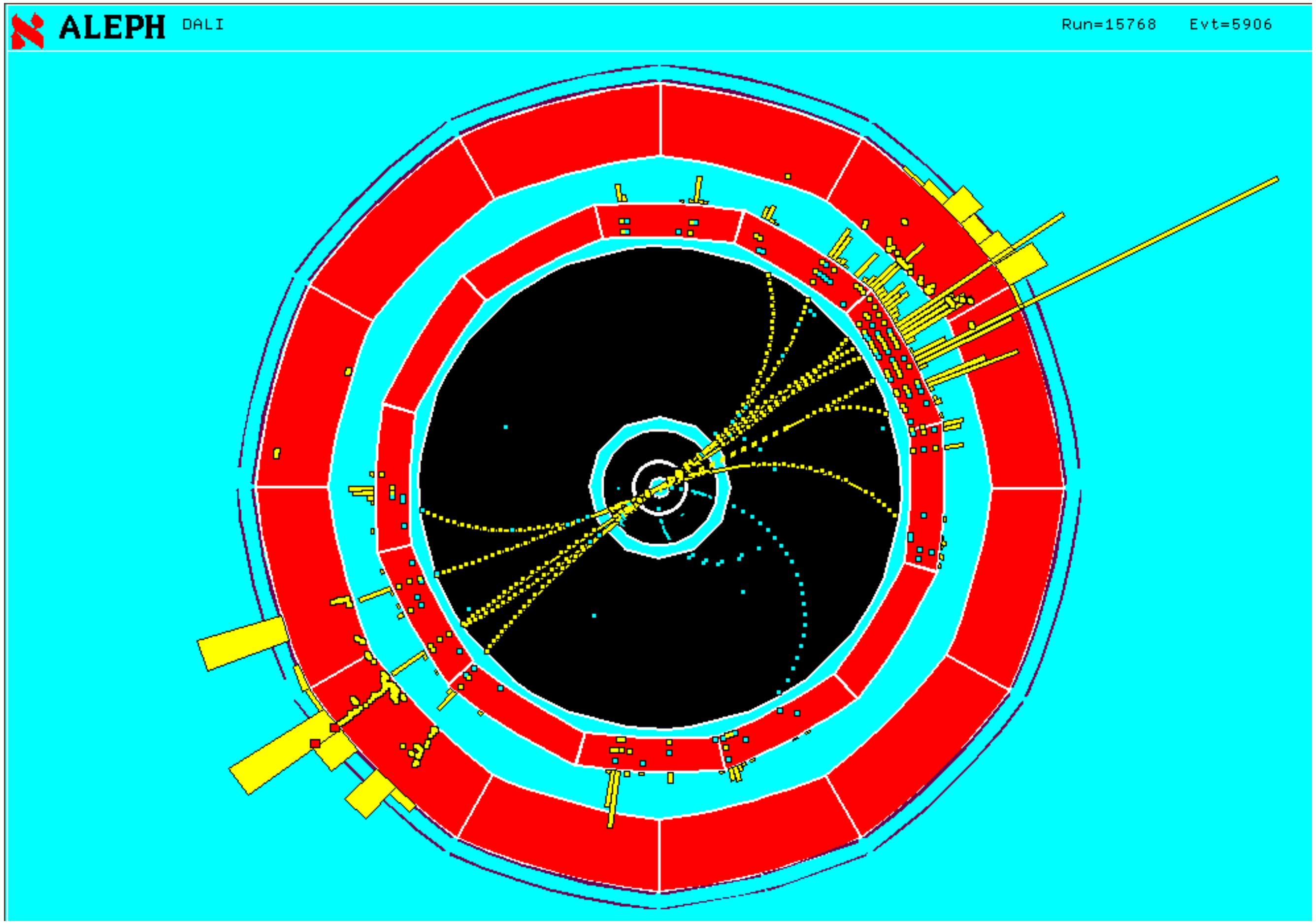
Single electron, single Muon, Missing Momentum



W. Riegler/CERN

$Z \rightarrow q\bar{q}$

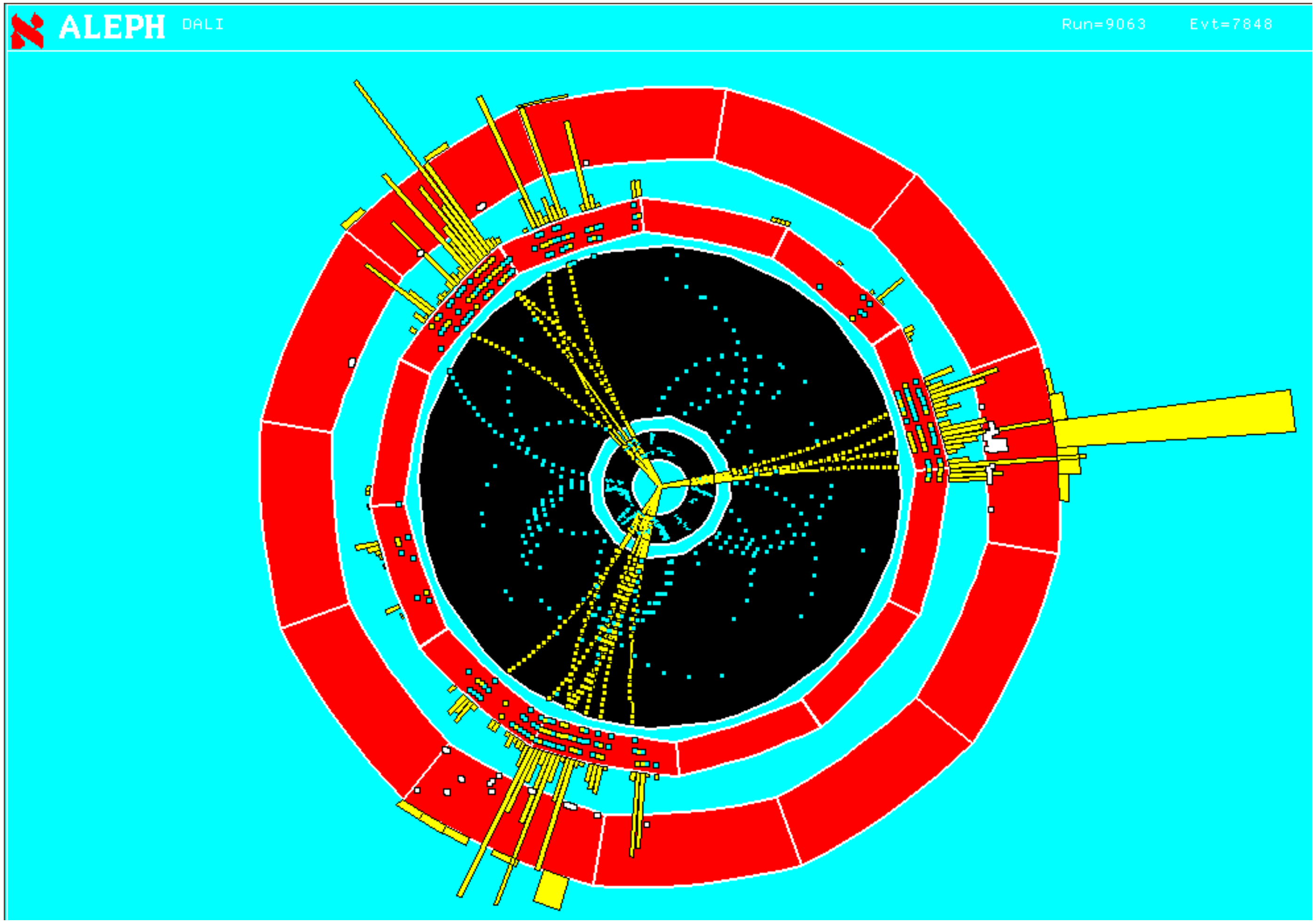
Two jets of particles



W. Riegler/CERN

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

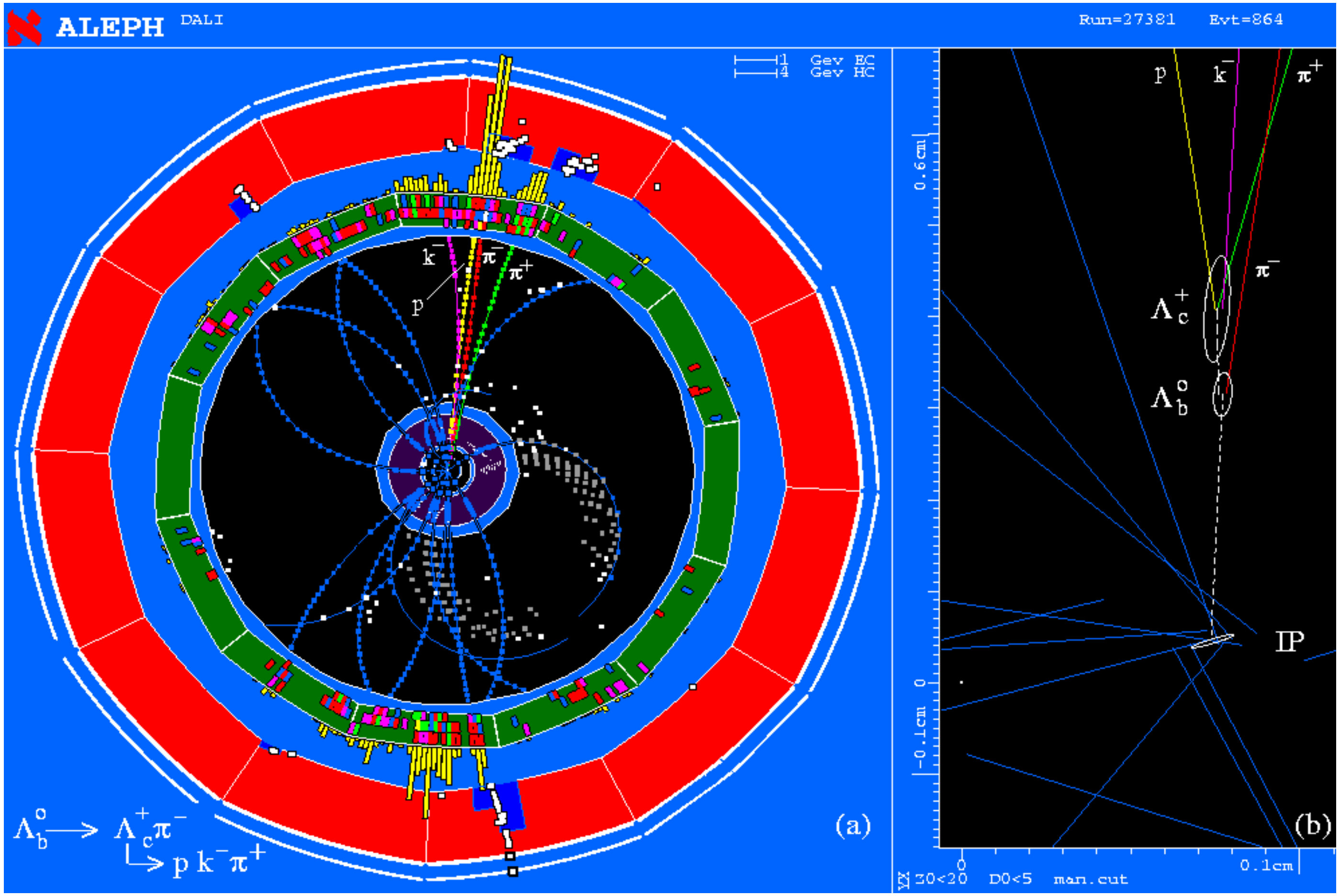
Three jets of particles



W. Riegler/CERN

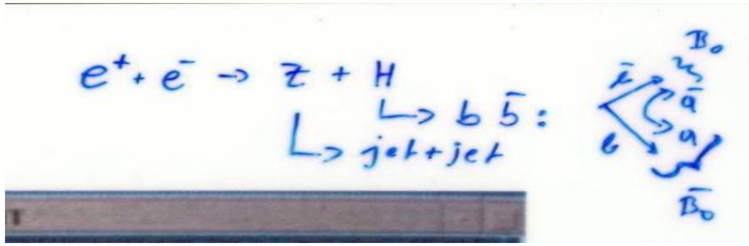
Two secondary vertices with characteristic decay particles giving invariant masses of known particles.

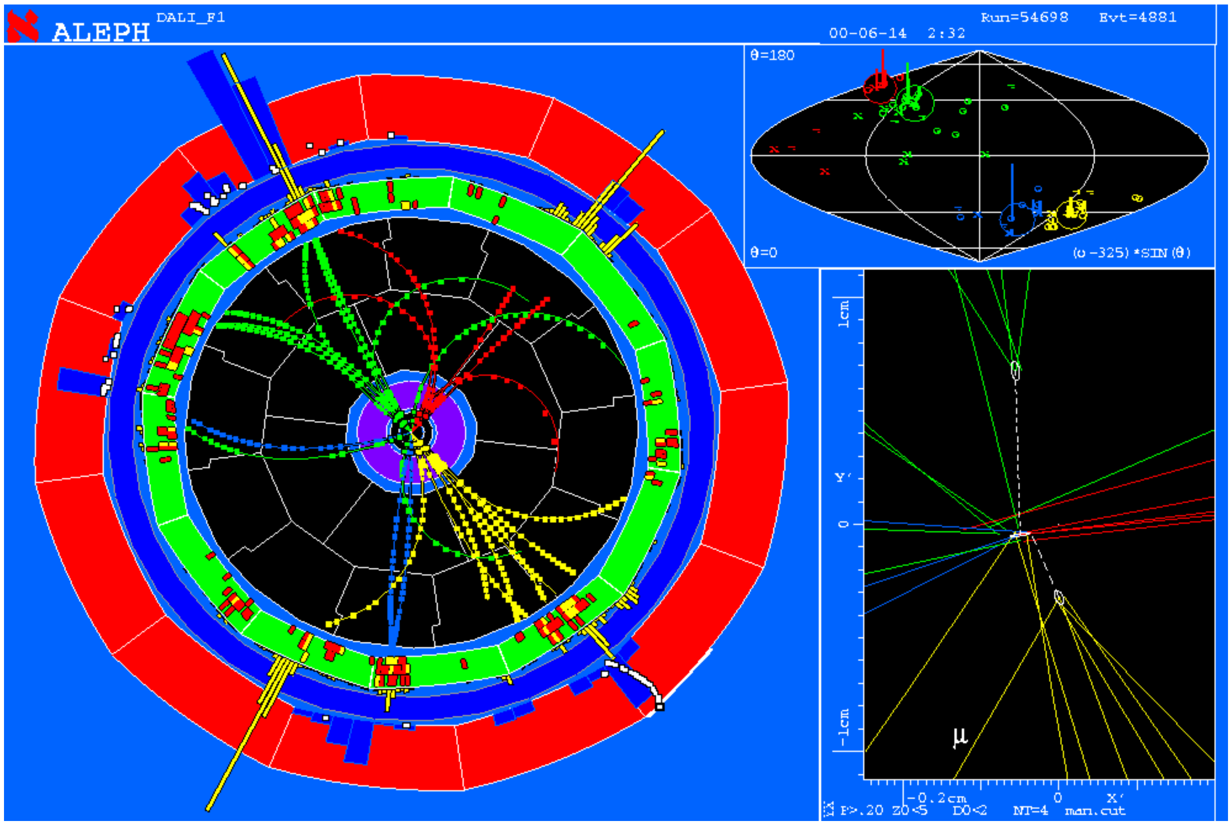
Bubble chamber like – a single event tells what is happening. Negligible background.



W. Riegler/CERN

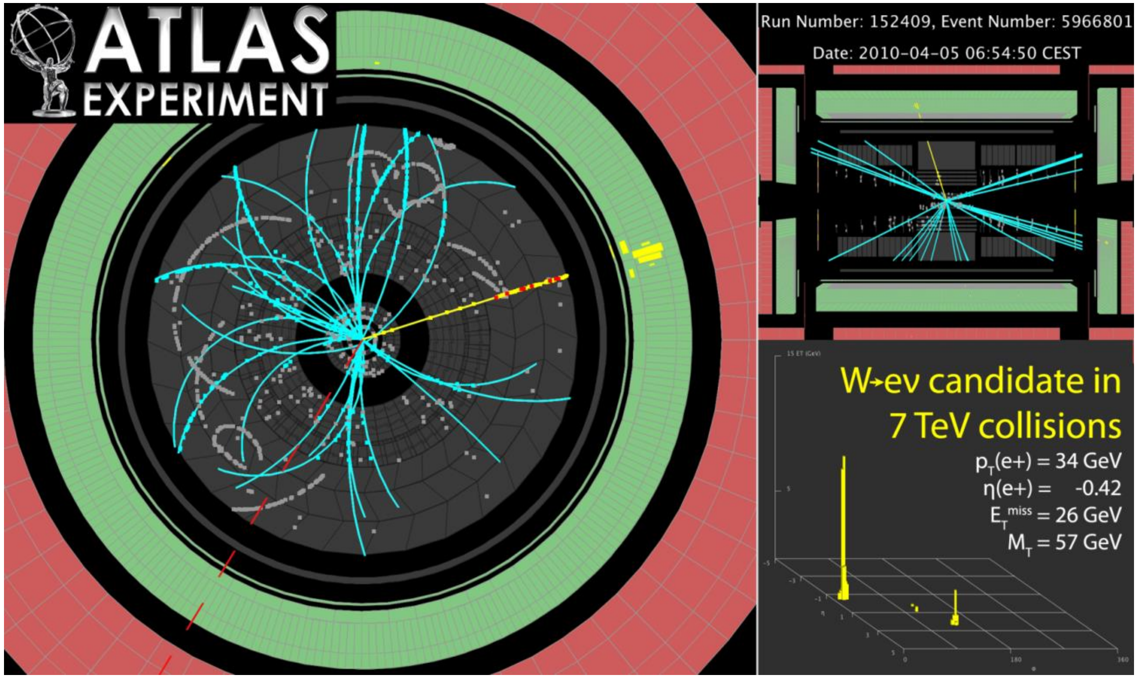
ALEPH Higgs Candidate

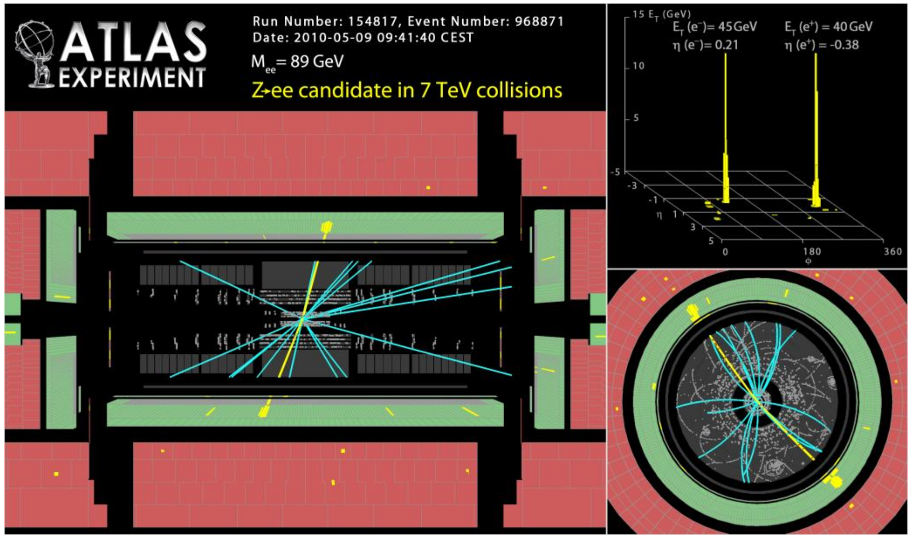




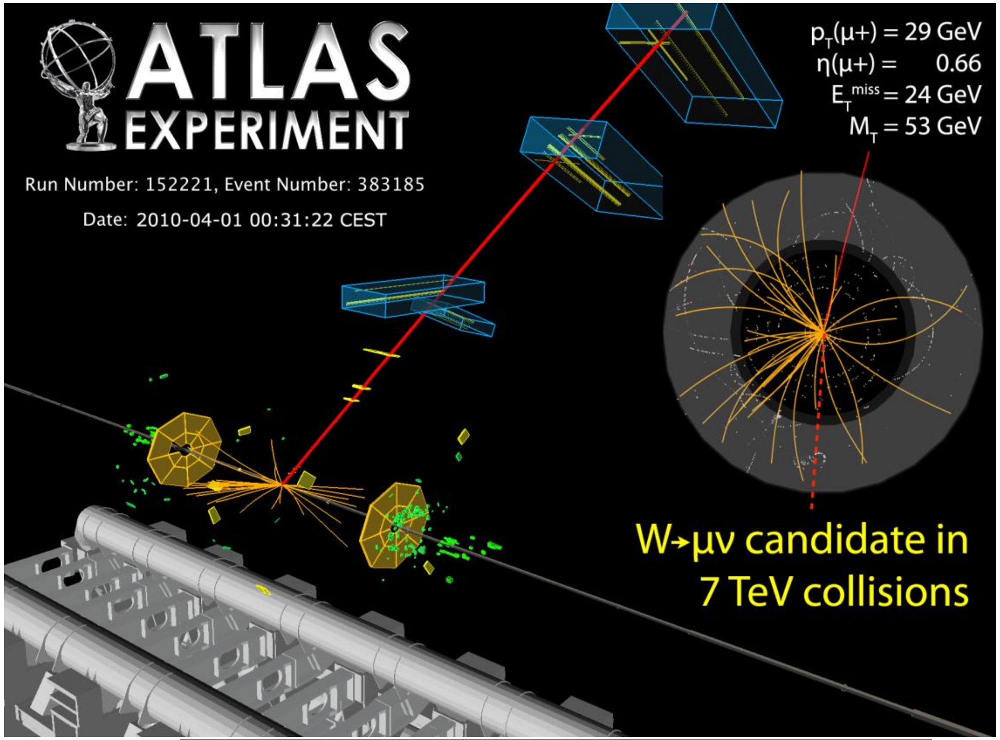
Undistinguishable background exists. Only statistical excess gives signature.

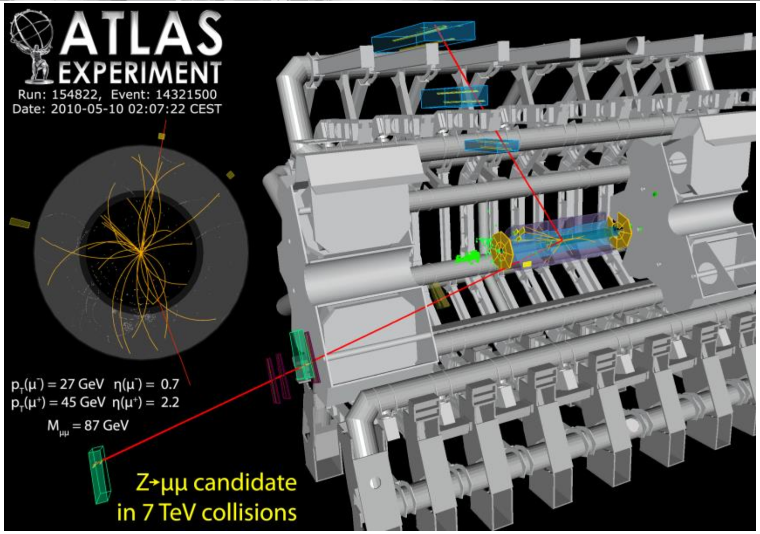
2010 ATLAS W, Z candidates



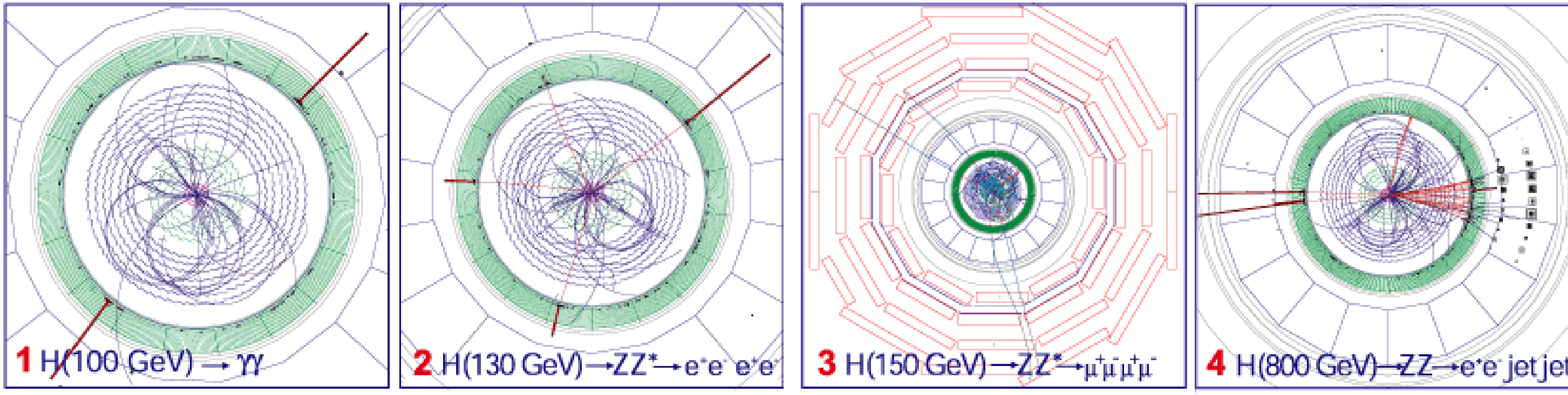


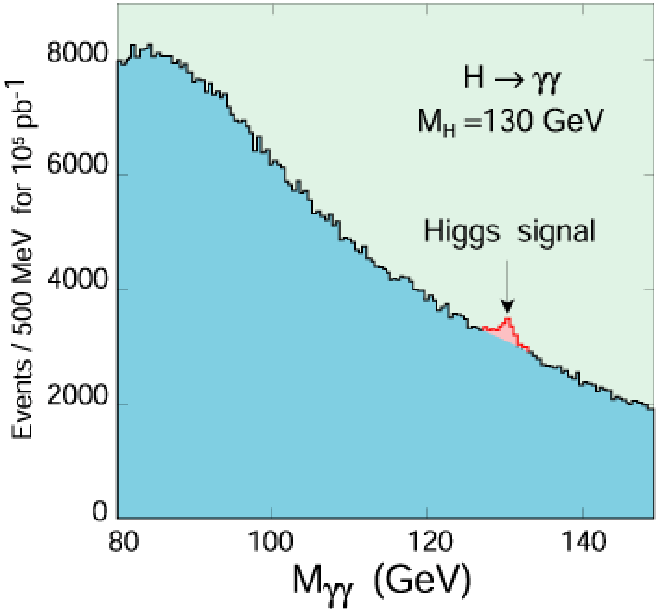
2010 ATLAS W, Z candidates



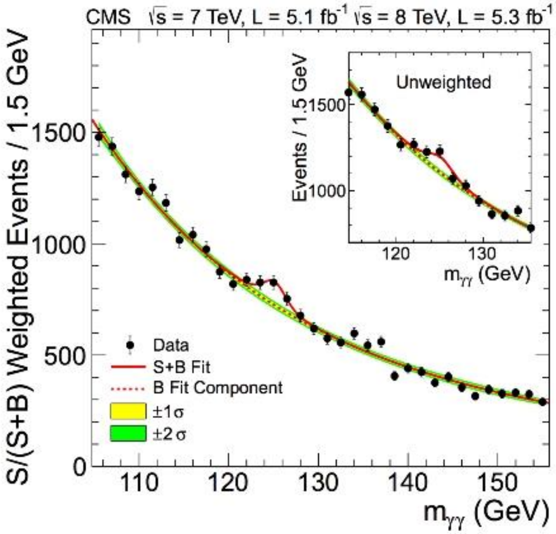


Simulated Higgs Boson at CMS





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



W. Riegler/CERN

Principles:

Only a few of the numerous known particles have lifetimes that are long enough to leave tracks in a detector.

Most of the particles are measured though the decay products and their kinematic relations (invariant mass). Most particles are only seen as an excess over an irreducible background.

Some short lived particles (b,c –particles) reach lifetimes in the laboratory system that are sufficient to leave short tracks before decaying → identification by measurement of short tracks.

In addition to this, detectors are built to measure the

8 particles

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

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

Backup

Cherenkov Radiation

If we describe the passage of a charged particle through material of dielectric permittivity ♏ (using Maxwell's equations) the differential energy crossection is >0 if the velocity of the particle is larger than the velocity of light in the medium is

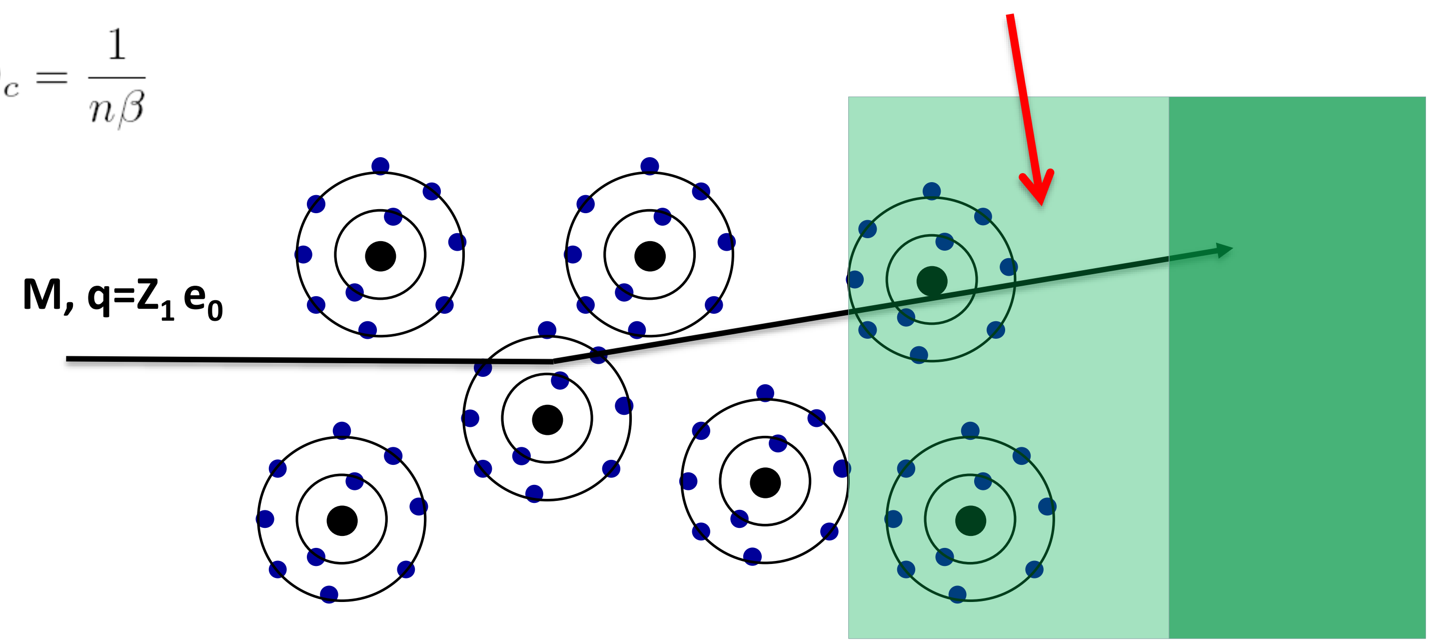
$$\frac{d\sigma}{dE} = \frac{\alpha}{\beta^2 \pi} \frac{A}{N_A \rho Z_2 \hbar c}\left(\beta^2 - \frac{1}{\epsilon_1}\right) \quad \rightarrow \quad \frac{N_A \rho Z_2}{A} \frac{d\sigma}{d\omega} \frac{d\omega}{dE} = \frac{\alpha}{c}\left(1 - \frac{1}{\beta^2 n^2}\right) \qquad n = \sqrt{\epsilon_1} \qquad E = \hbar\omega$$

$$\frac{dE}{dx d\omega} \frac{1}{\hbar} = \frac{\alpha}{c}\left(1 - \frac{1}{\beta^2 n^2}\right) \quad \rightarrow \quad \frac{dN}{dx d\lambda} = \frac{2\pi\alpha}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2}\right) \qquad \omega = \frac{2\pi c}{\lambda}$$

N is the number of Cherenkov Photons emitted per cm of material. The expression is in addition proportional to Z_1^2 of the incoming particle.

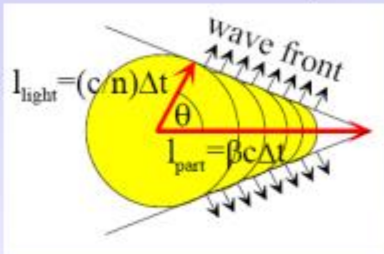
The radiation is emitted at the characteristic angle ❑$_c$, that is related to the refractive index n and the particle velocity by

$$\cos\Theta_c = \frac{1}{n\beta}$$

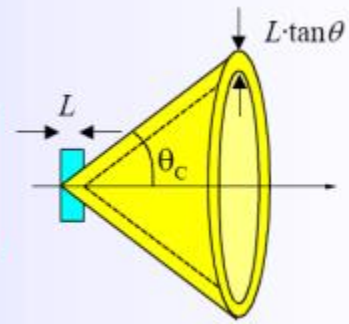


Cherenkov Radiation

with velocity $\beta \geq \beta_{thr} = \frac{1}{n}$ n : refractive index



$$\boxed{\cos\theta_C = \frac{1}{n\beta} \quad \text{with } n = n(\lambda) \geq 1}$$



- $\beta_{thr} = \frac{1}{n} \rightarrow \theta_C \approx 0$ Cherenkov threshold
- $\theta_{max} = \arccos\frac{1}{n}$ 'saturated' angle (β=1)

If the velocity of a charged particle is larger than the velocity of light in the medium $v > \frac{c}{n}$ (n... Refractive Index of material) it emits 'Cerenkov' radiation at a characteristic angle of $\cos\theta_c = \frac{1}{n\beta}$ $(\beta = \frac{v}{c})$

Material	n-1	β threshold	γ threshold
solid Sodium	3.22	0.24	1.029
lead glass	0.67	0.60	1.25
water	0.33	0.75	1.52
silica aerogel	0.025-0.075	0.93-0.976	2.7 - 4.6
air	$2.93 \cdot 10^{-4}$	0.9997	41.2
He	$3.3 \cdot 10^{-5}$	0.99997	123

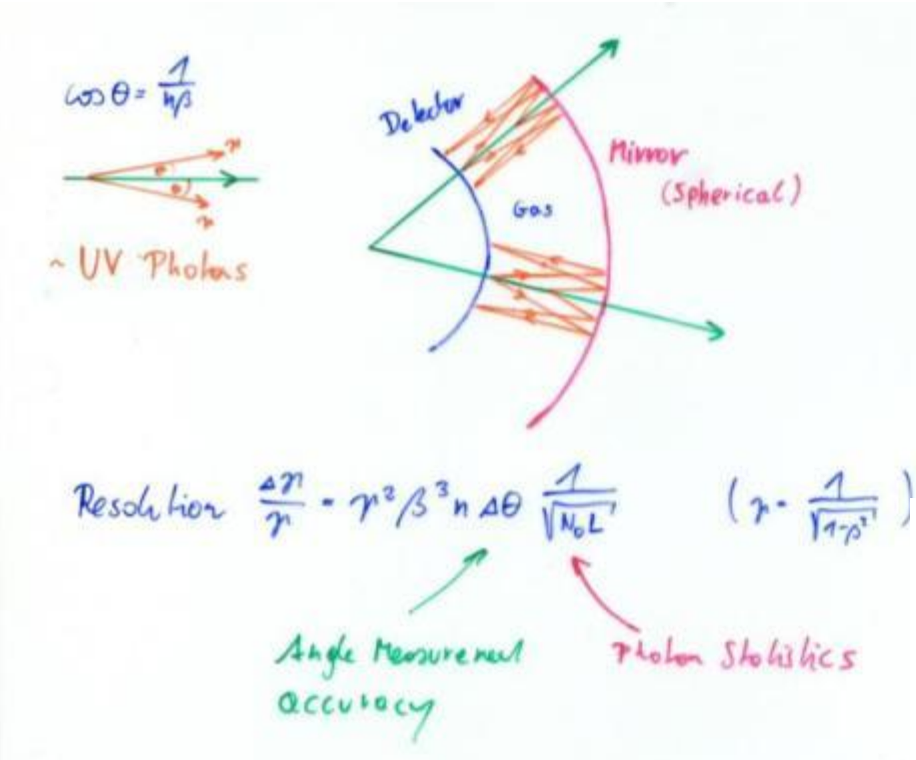
$$\frac{dN}{dx} \sim 2\pi\alpha z_1^2 \left(1 - \frac{1}{\beta^2 n^2}\right) \frac{\lambda_2 - \lambda_1}{\lambda_2 \cdot \lambda_1}$$

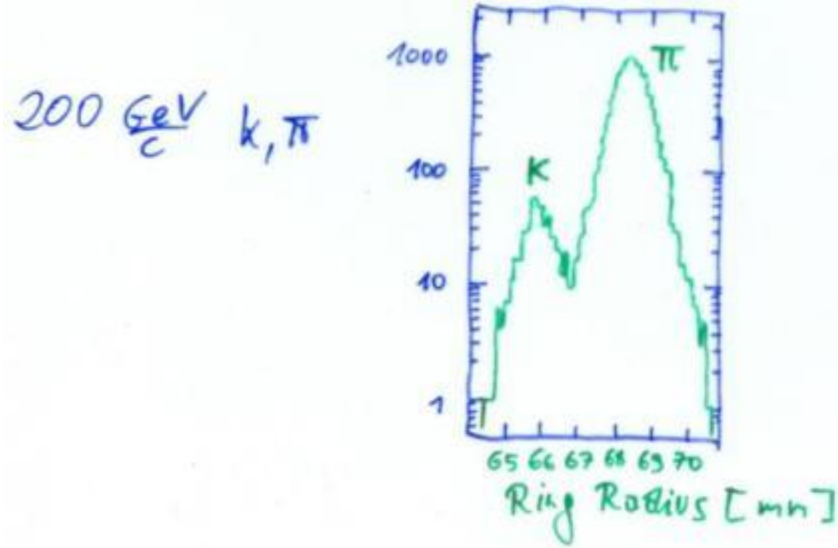
- Number of emitted Photons/length with λ between λ_1 and λ

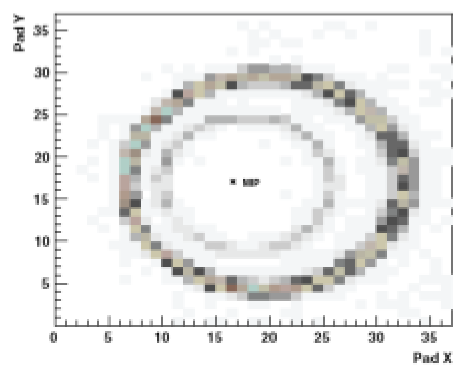
With $\lambda_1 = 400nm$ $\lambda_2 = 700nm$

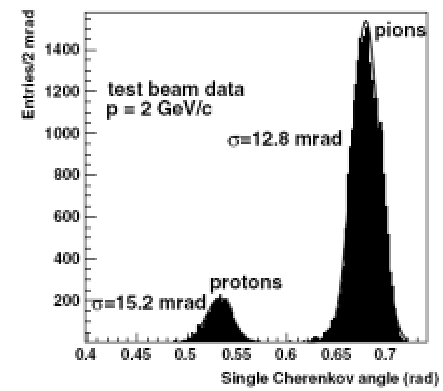
$$\frac{dN}{dx} = 490 \left(1 - \frac{1}{\beta^2 n^2}\right) \left[\frac{1}{cm}\right]$$

Ring Imaging Cherenkov Detector (RICH)









medium	n	θ_{max} (deg.)	N_{ph} (eV^{-1} cm^{-1})
air*	1.000283	1.36	0.208
isobutane*	1.00127	2.89	0.941
water	1.33	41.2	160.8
quartz	1.46	46.7	196.4

There are only 'a few' photons per event →one needs highly sensitive photon detectors to measure the rings !

LHCb RICH

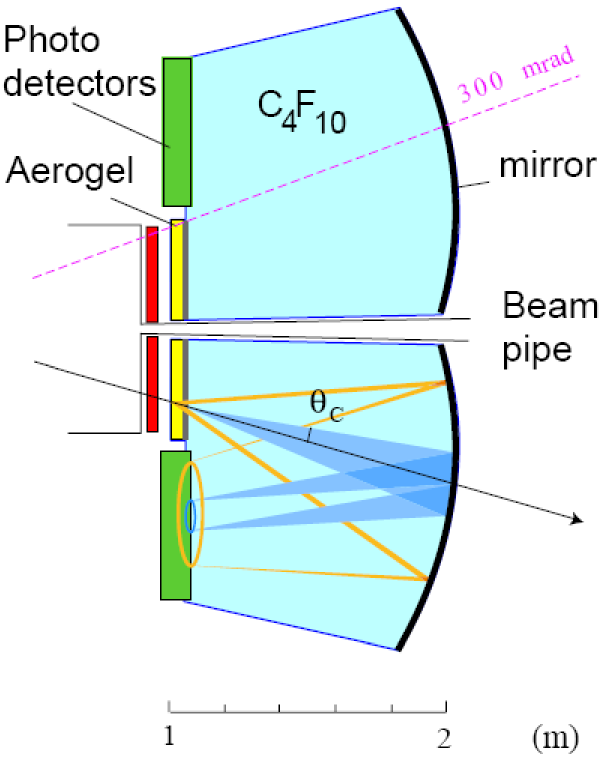
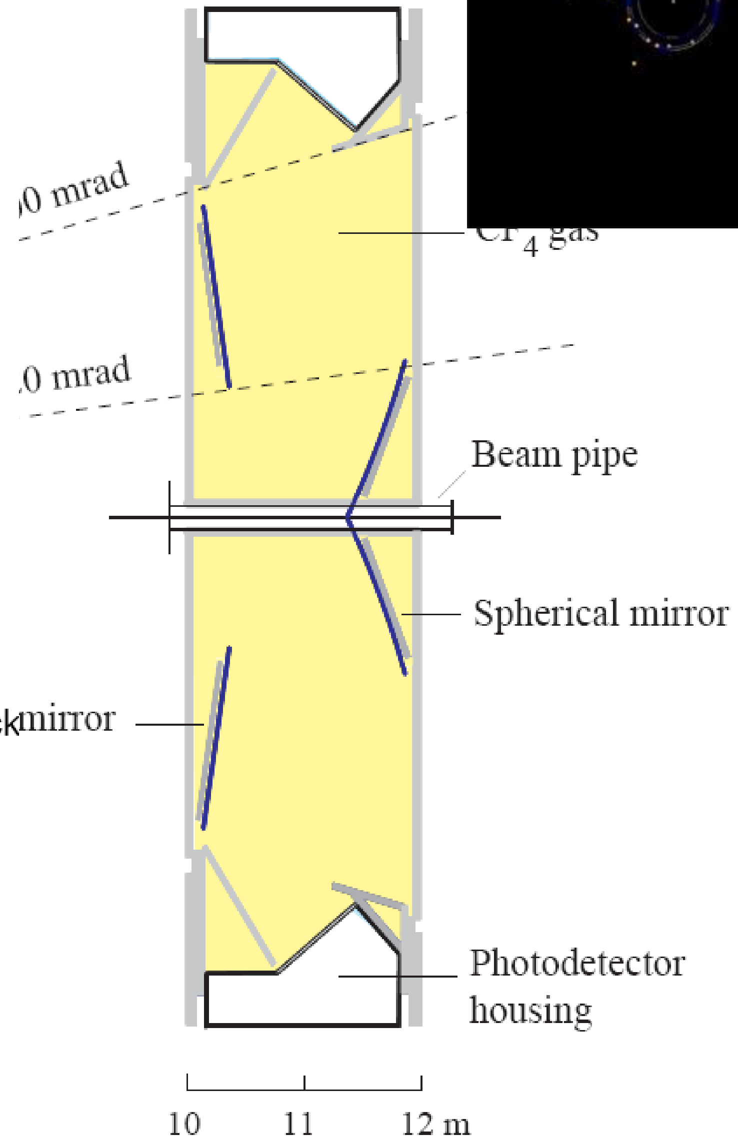
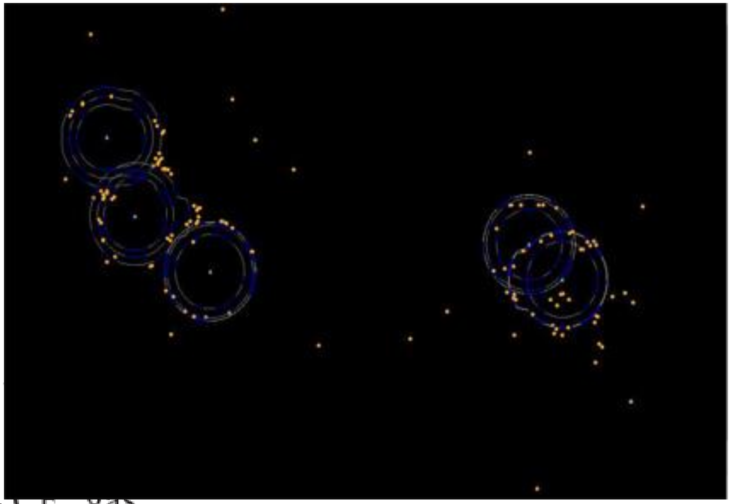


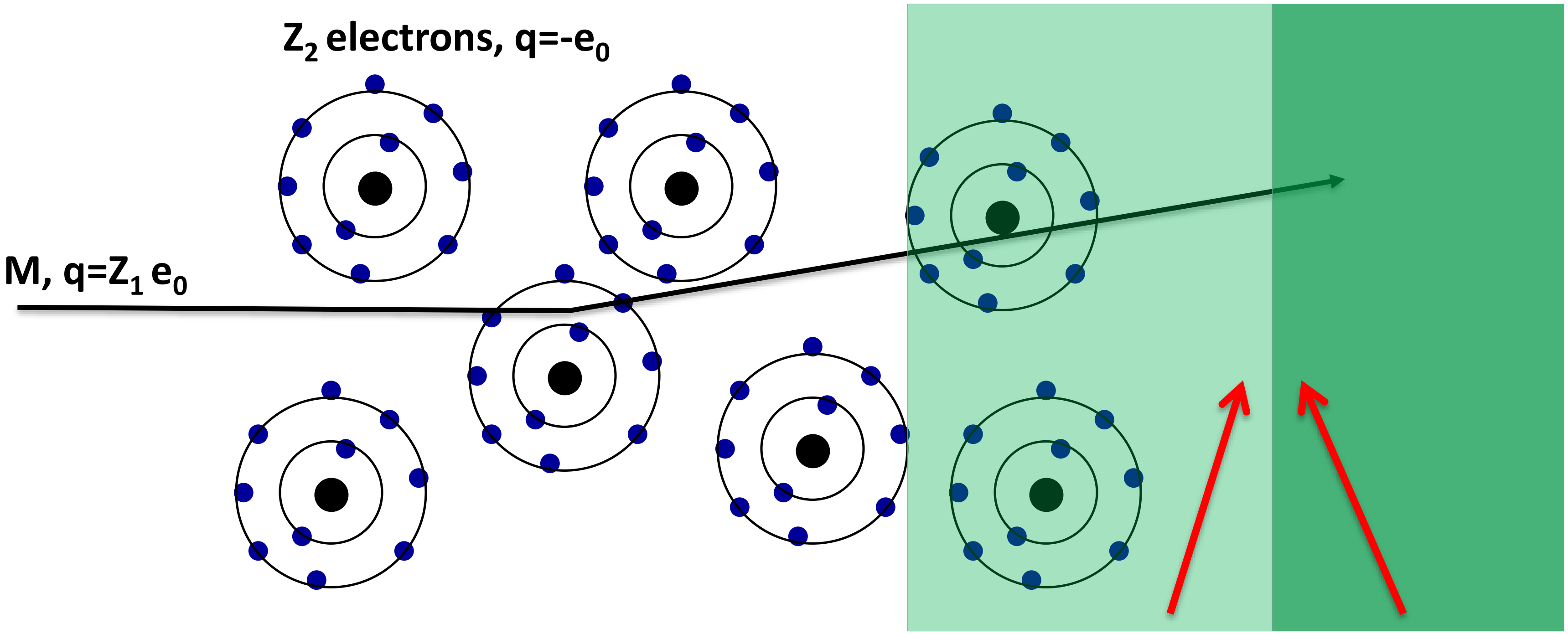
Photo detectors
C_4F_{10}
Aerogel
300 mrad
mirror
Beam pipe
θ_C
Track
1
2
(m)



Beam pipe
Spherical mirror
mirror
Photodetector housing
10
11
12 m



Transition Radiation



When the particle crosses the boundary between two media, there is a probability of the order of 1% to produced and X ray photon, called <u>Transition radiation</u>.

Transition Radiation

Radiation (~keV) emitted by ultra-relativistic Particles when they traverse the boarder of 2 Materials of different Dielectric Permittivity ($\varepsilon_1, \varepsilon_2$)

Vacuum ε_0 | ε_2 Medium

q | $-q$ (Mirror Charge)

Classical Picture

$q = Z_1 e$

$$I = \frac{1}{3} \alpha Z_1^2 (\hbar \omega_p) \gamma$$ ... Radiated Energy per Transition

$\hbar \omega_p$ .... plasma Frequency of the Medium

.... ~20 eV for Styrene

About half the Energy is radiated between

$$0.1 \, \hbar \omega_p \gamma < \hbar \omega < \hbar \omega_p \gamma$$

E.g. $\gamma = 1000$ 2-20 keV X-Rays

$$N_\gamma \sim \frac{2}{3} \alpha Z_1^2 \sim 5 \cdot 10^{-3} \cdot Z_1^2$$

γ - Dependence from hardening rather than N_γ

Emission Angle ~ $\frac{1}{\gamma}$

The Number of Photons can be increased by placing many foils of Material.