Particle Physics Instrumentation

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from 6-19 March 2013, Arequipa, Peru**

Lecture1/3
Detector Systems,
Interaction of particles with Matter

On Tools and Instrumentation

"New directions in science are launched by new tools much more often than by new concepts.

The effect of a concept-driven revolution is to explain old things in new ways.

The effect of a tool-driven revolution is to discover new things that have to be explained"

Freeman Dyson, Imagined Worlds

→ New tools and technologies will be extremely important to go beyond LHC

Physics Nobel Prices for Instrumentation

1927: <u>C.T.R. Wilson, Cloud Chamber</u>

1939: E. O. Lawrence, Cyclotron & Discoveries

1948: P.M.S. Blacket, Cloud Chamber & Discoveries

1950: C. Powell, Photographic Method & Discoveries

1954: Walter Bothe, Coincidence method & Discoveries

1960: <u>Donald Glaser, Bubble Chamber</u>

1968: L. Alvarez, Hydrogen Bubble Chamber & Discoveries

1992: <u>Georges Charpak, Multi Wire Proportional Chamber</u>

The 'Real' World of Particles

E. Wigner:

"A particle is an irreducible representation of the inhomogeneous Lorentz group"

Spin=0,1/2,1,3/2 … Mass>0

ON UNITARY REPRESENTATIONS OF THE INHOMOGENEOUS LORENTZ GROUP*

By E. WIGNER

(Received December 22, 1937)

1. ORIGIN AND CHARACTERIZATION OF THE PROBLEM

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

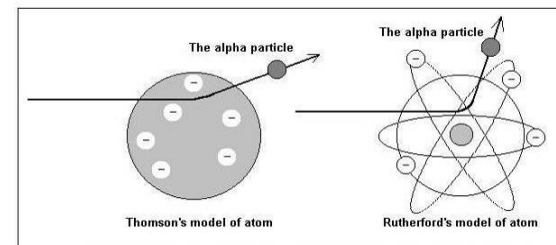**E.g. in Steven Weinberg, The Quantum Theory of Fields, Vol1**

The 'Real' World of Particles

W. Riegler:

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

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

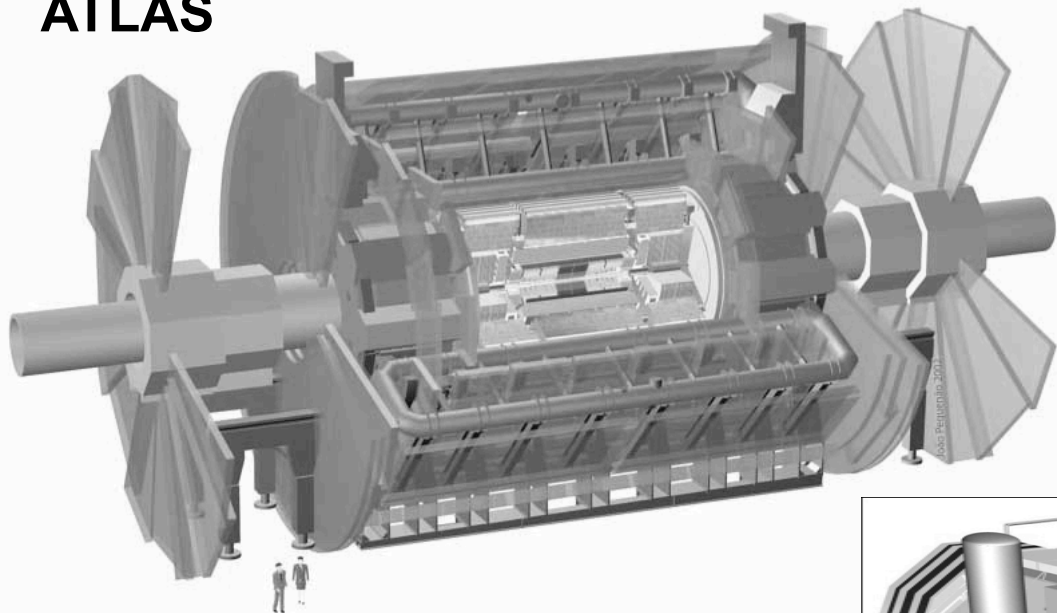**and if you a silly enough to stand in an intense particle beam for some time you will be dead …"**

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

Before discussing the working principles of detectors let's have a look at a few modern →

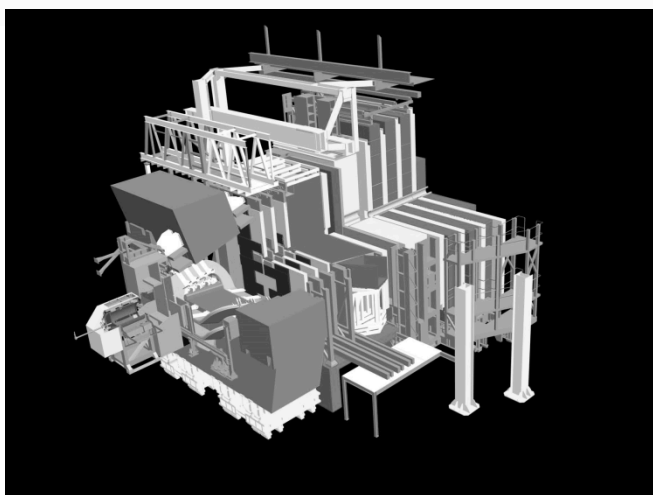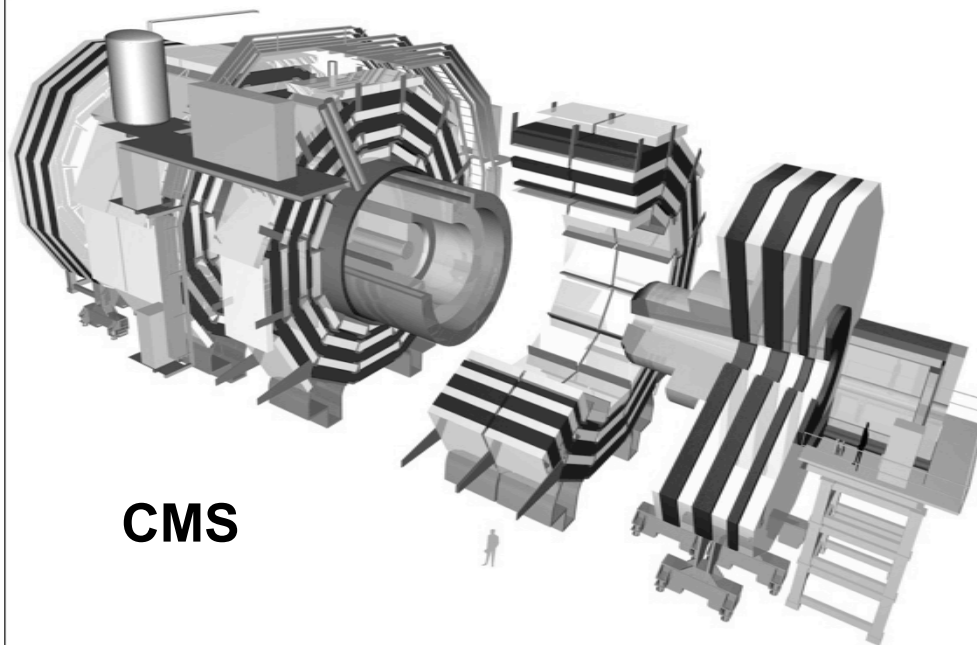# Particle Detector Systems

The Giants at LHC

ATLAS

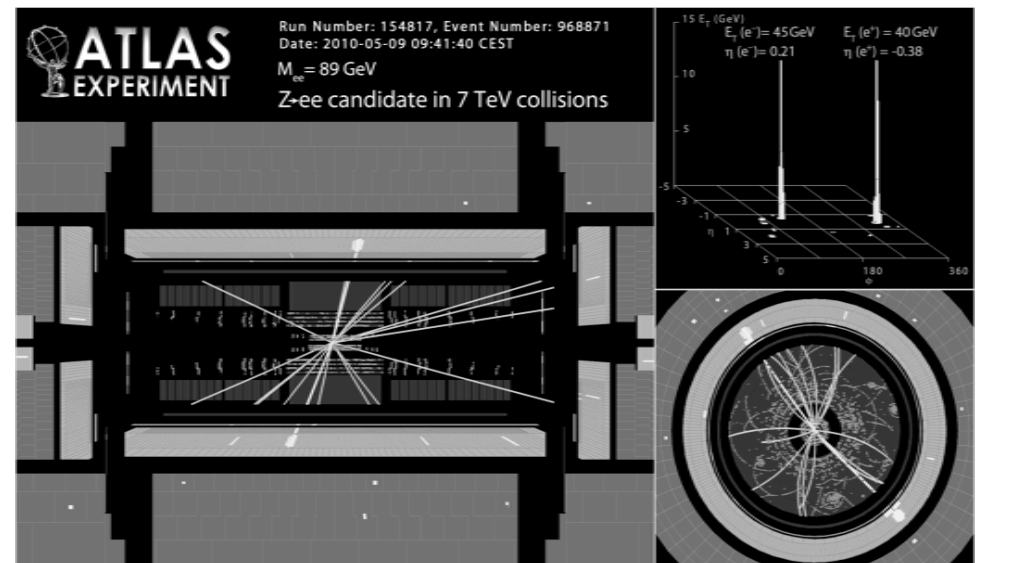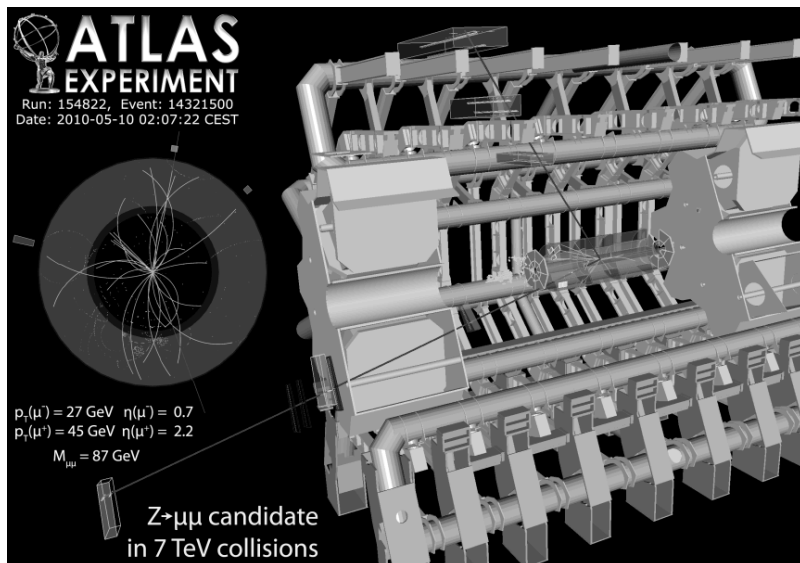ALICE
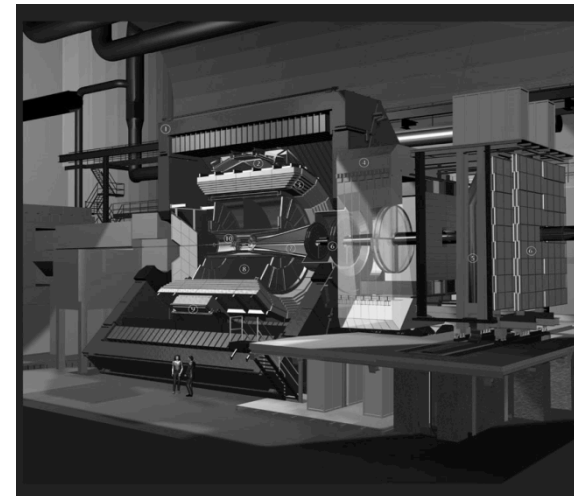
LHCb

CMS

The Giants at LHC

pp Collisions

ATLAS EXPERIMENT

Run Number: 153565, Event Number: 4487360

Date: 2010-04-24 04:18:53 CEST
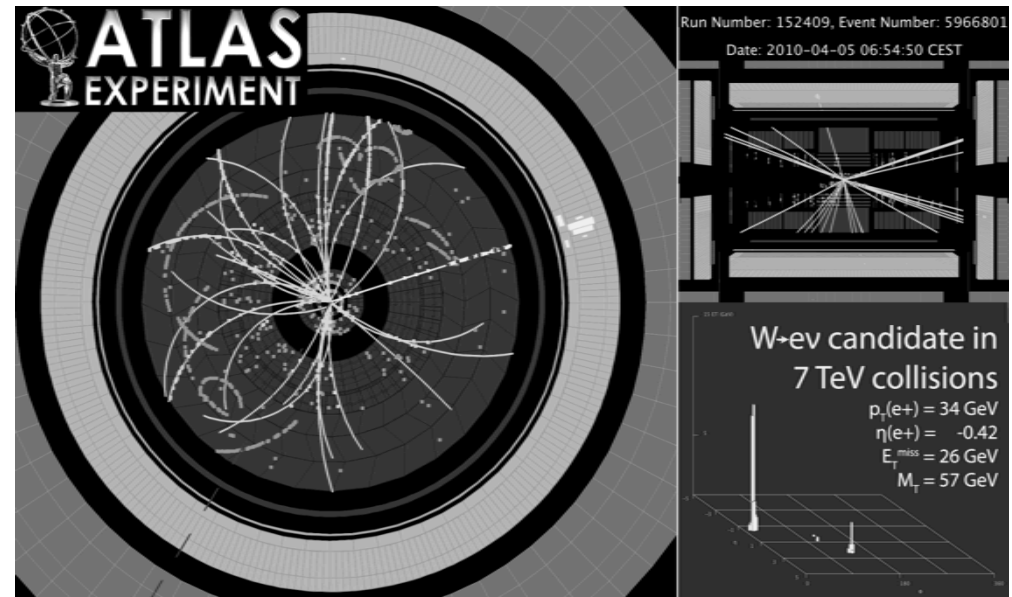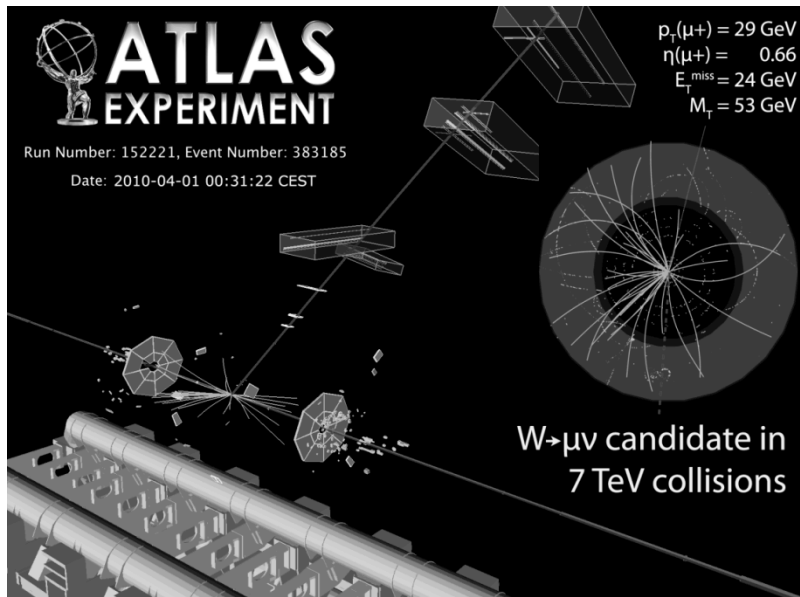
Event with 4 Pileup Vertices
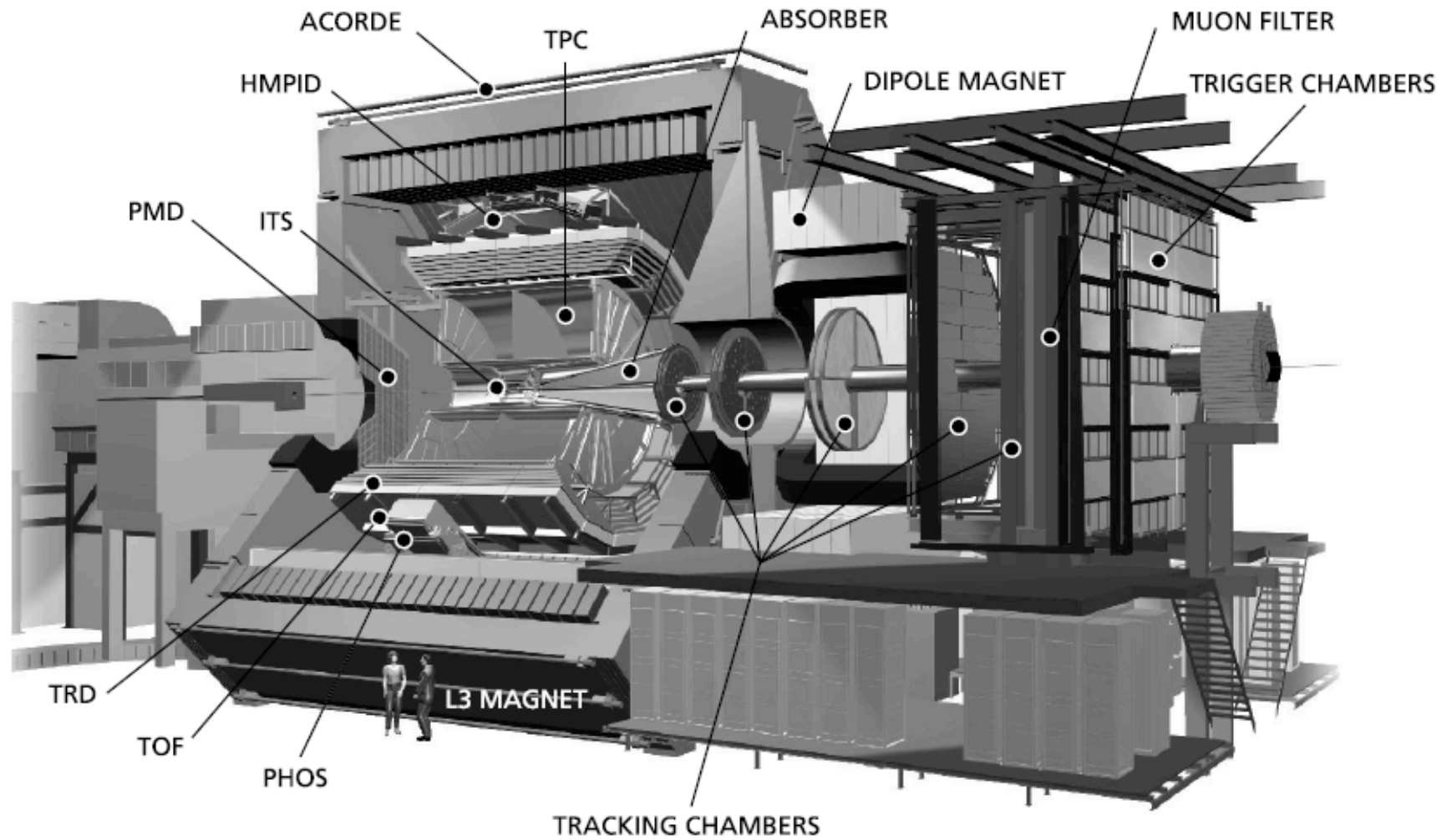in 7 TeV Collisions
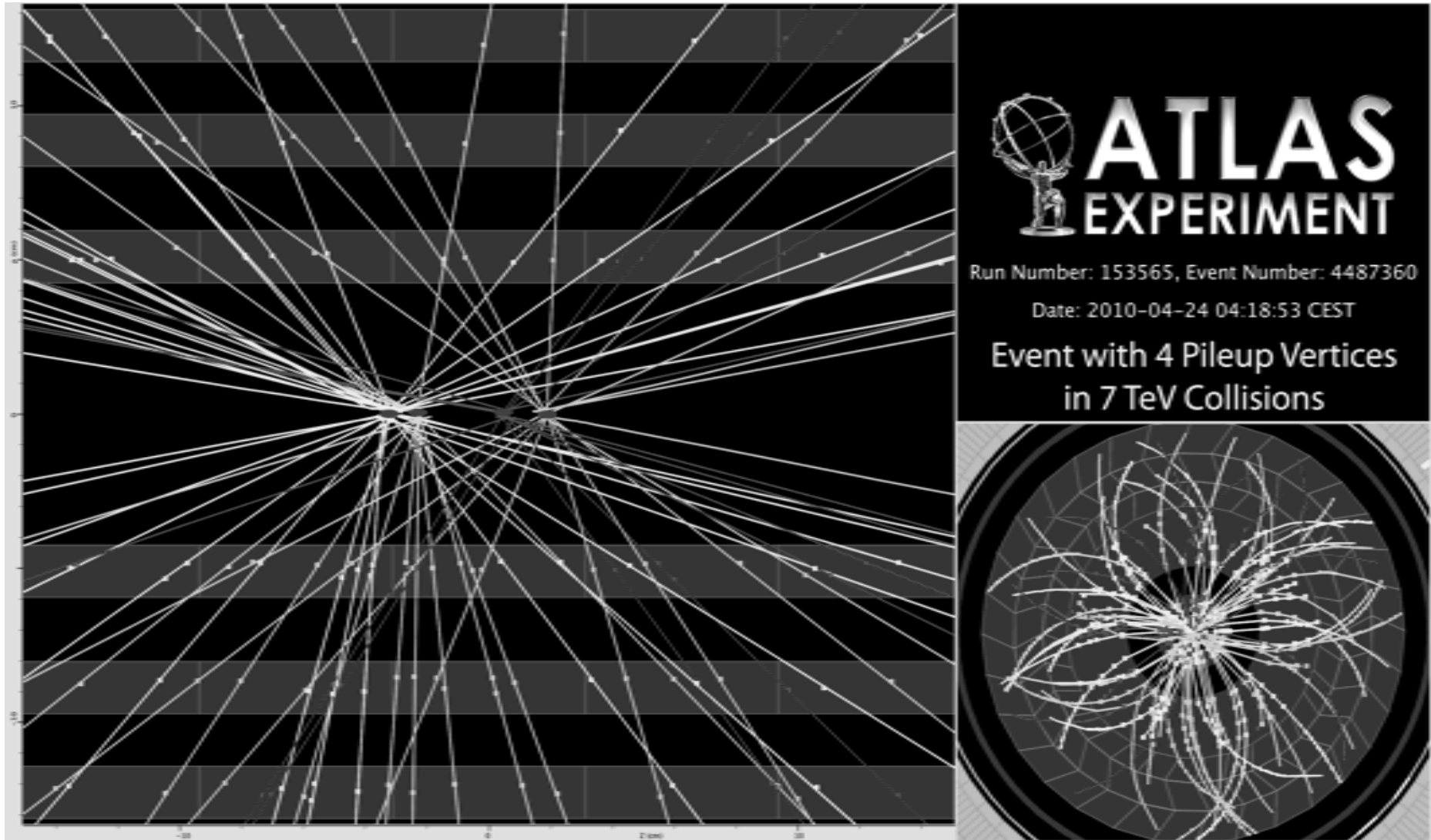
ALICE

ALICE Particle ID

Alice uses ~ all known techniques!

TPC + ITS (dE/dx)   π/K   K/p   e /π

TOF   e /π   π/K   K/p

HMPID (RICH)   π/K   K/p

0   1   2   3   4   5   p (GeV/c)

TPC (rel. rise)   π /K/p   π/K   K/p
TRD   e /π
PHOS   γ /π⁰

1   10   100   p (GeV/c)
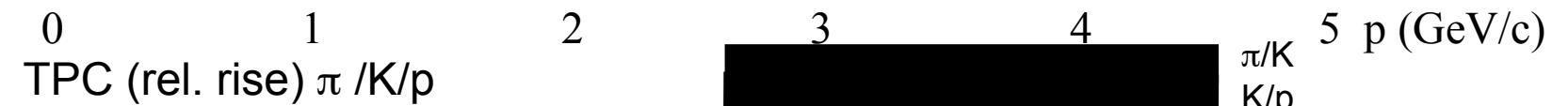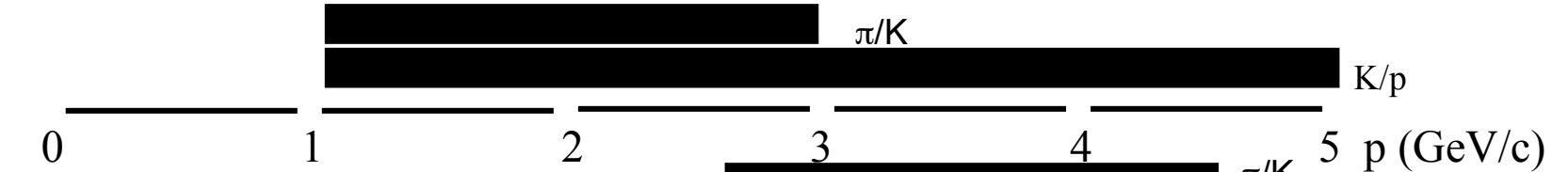
Heavy Ion Collisions, Nov. 2010
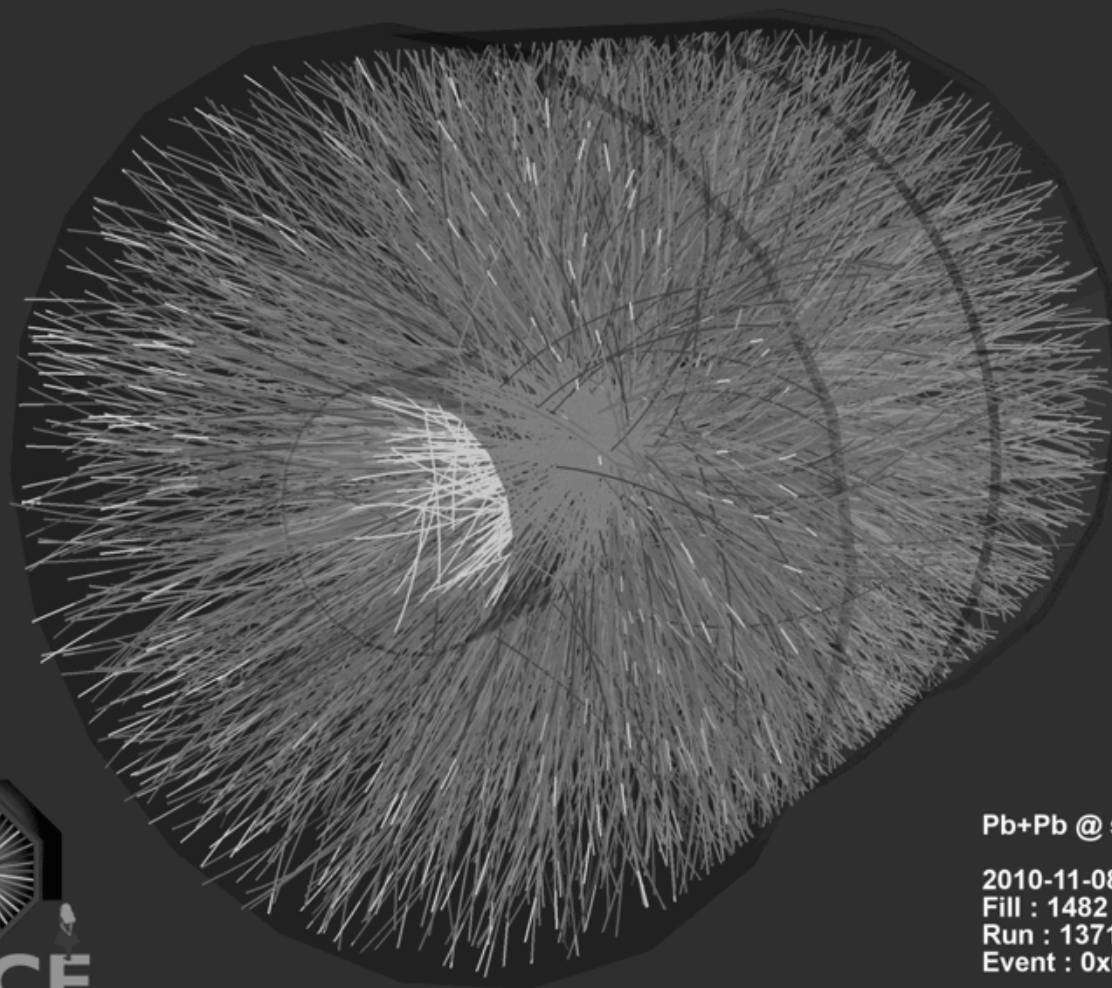
Pb+Pb @ sqrt(s) = 2.76 ATeV
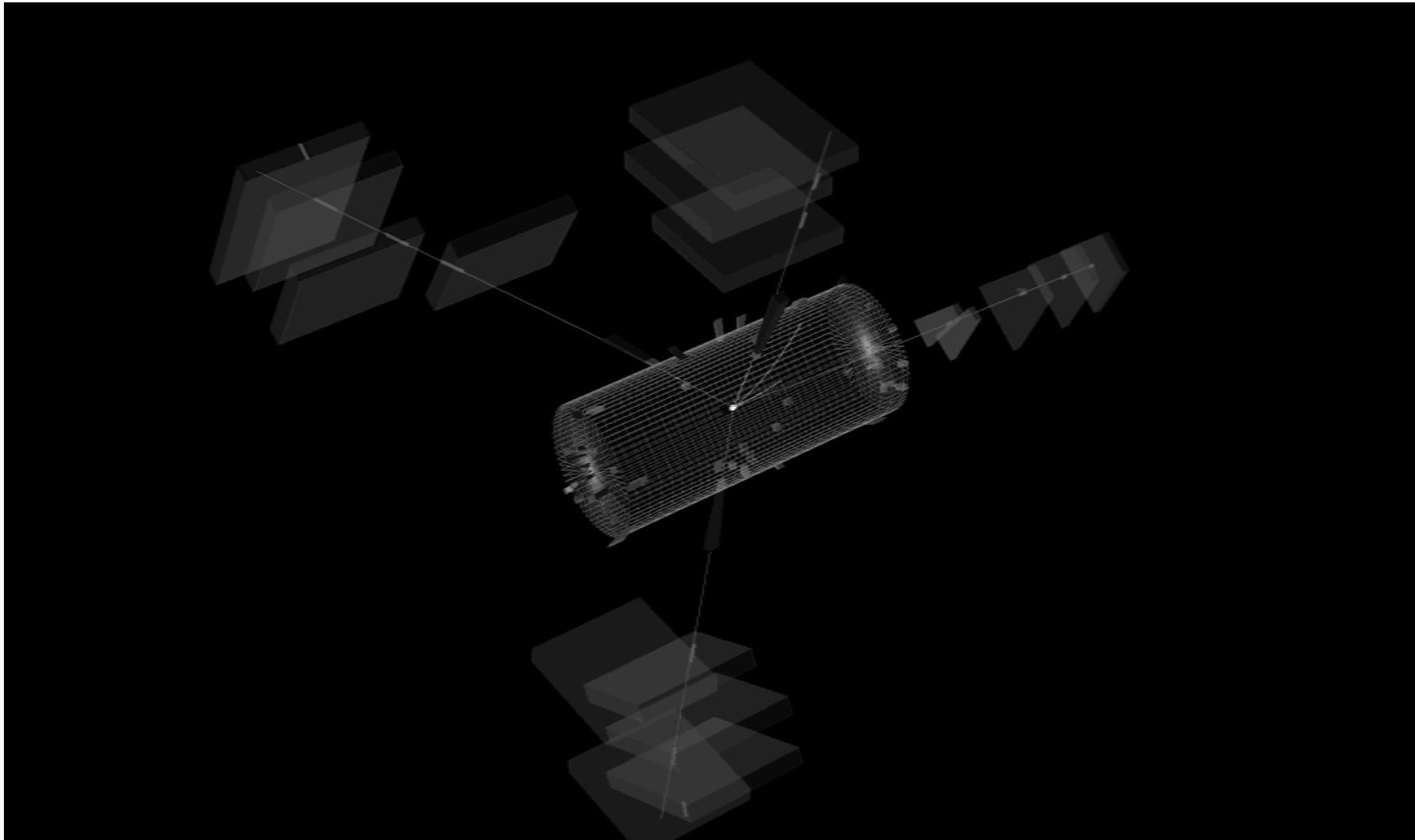
2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE693

ALICE

First ZZ→4μ Event

[N. Pastrone, Talk at Bormio Winter Meeting, 2011]

Small is Beautiful

ALPHA
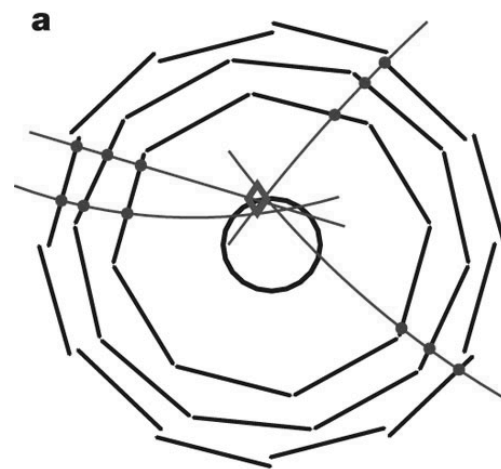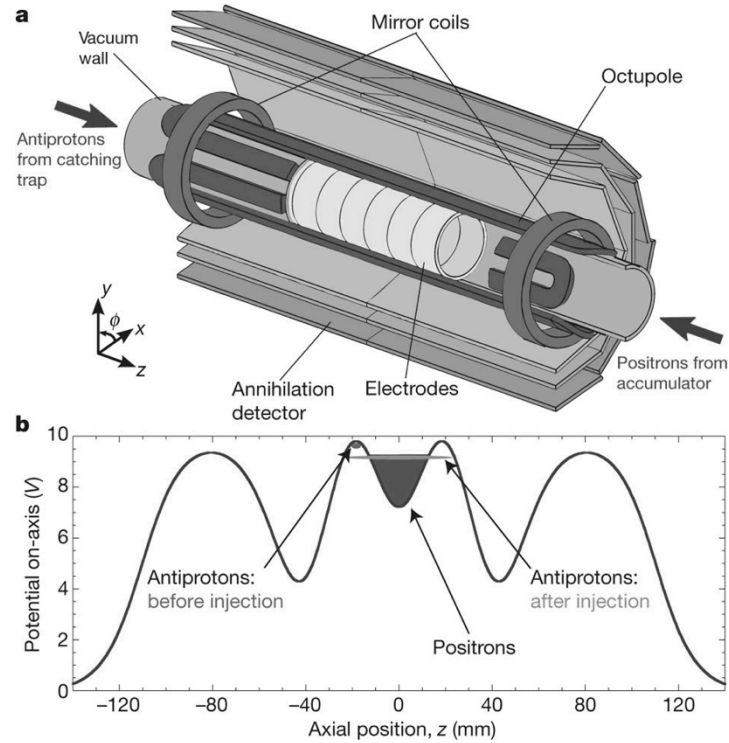
Antiproton annihilation   Cosmic
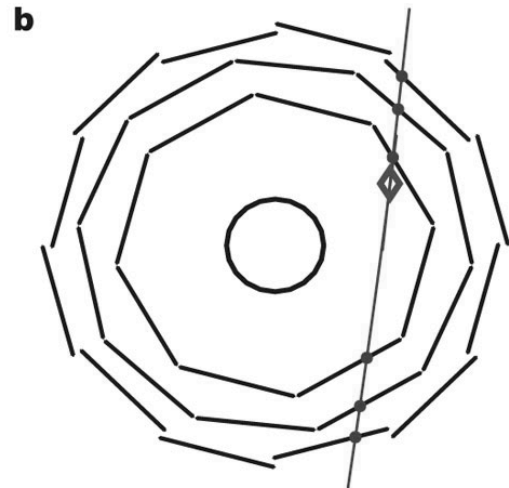
Trapping of antihydrogen for > 178 ms
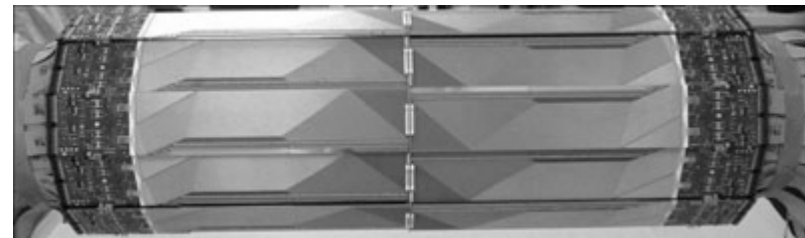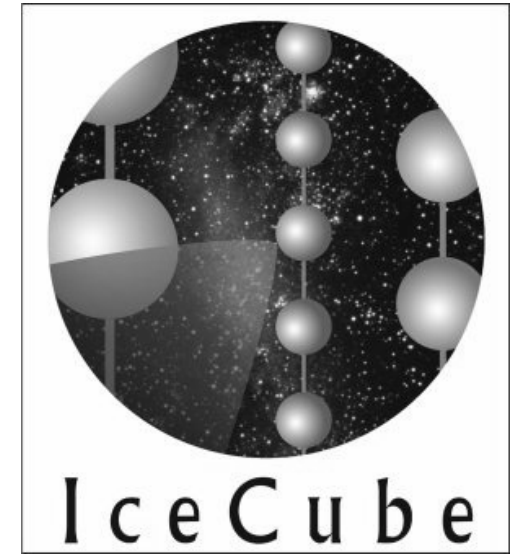
AMANDA

Antarctic **M**uon **A**nd **N**eutrino **D**etector **A**rray

AMANDA

South Pole

AMANDA

AMANDA-II

Depth

top view

← 200 m →

1500 m

2000 m

2500 m

Power,
Signal In/Out

Electronics

Photomultiplier

Optical
Coupling Gel

Glass Pressure
Housing,
13" diameter
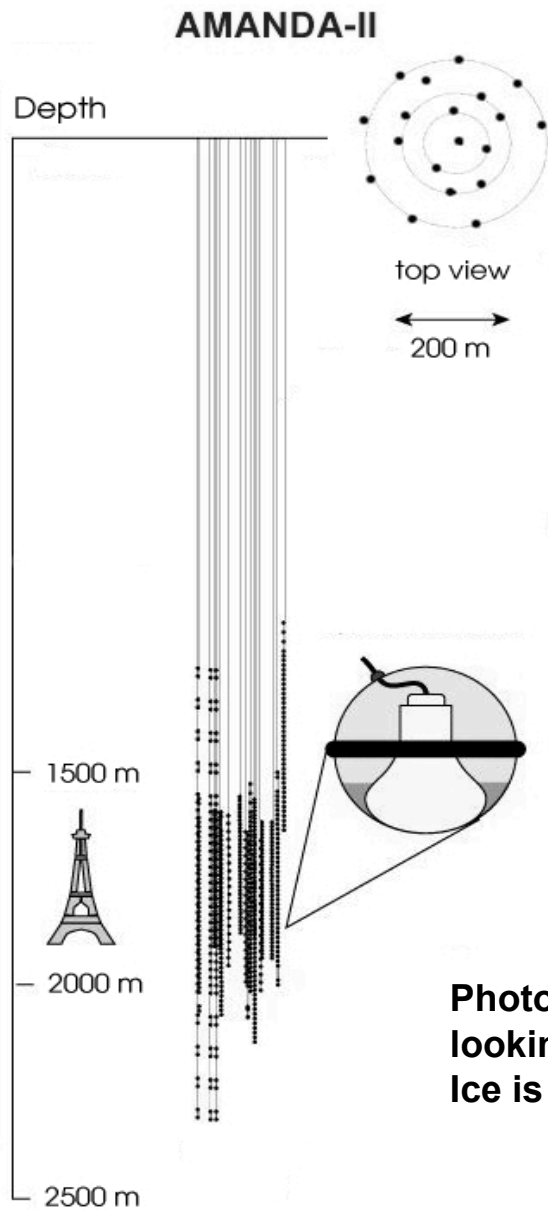
**Photomultipliers in the Ice,
looking downwards.
Ice is the detecting medium.**
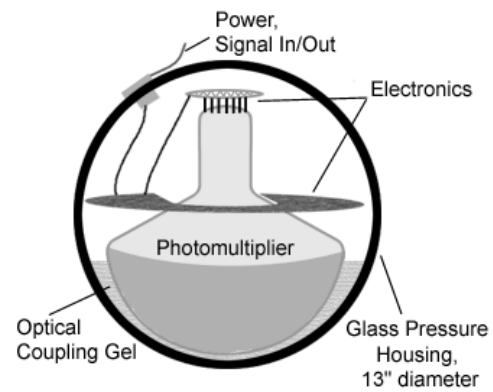
AMANDA

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

→ Find neutrino point sources in the universe !
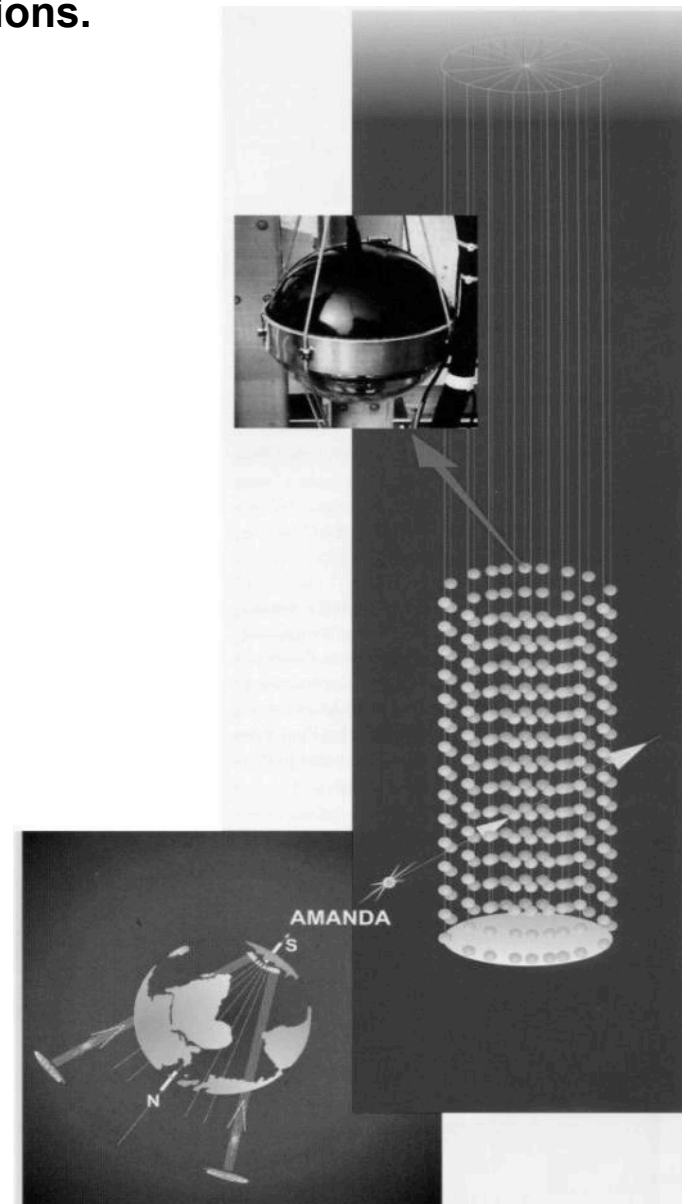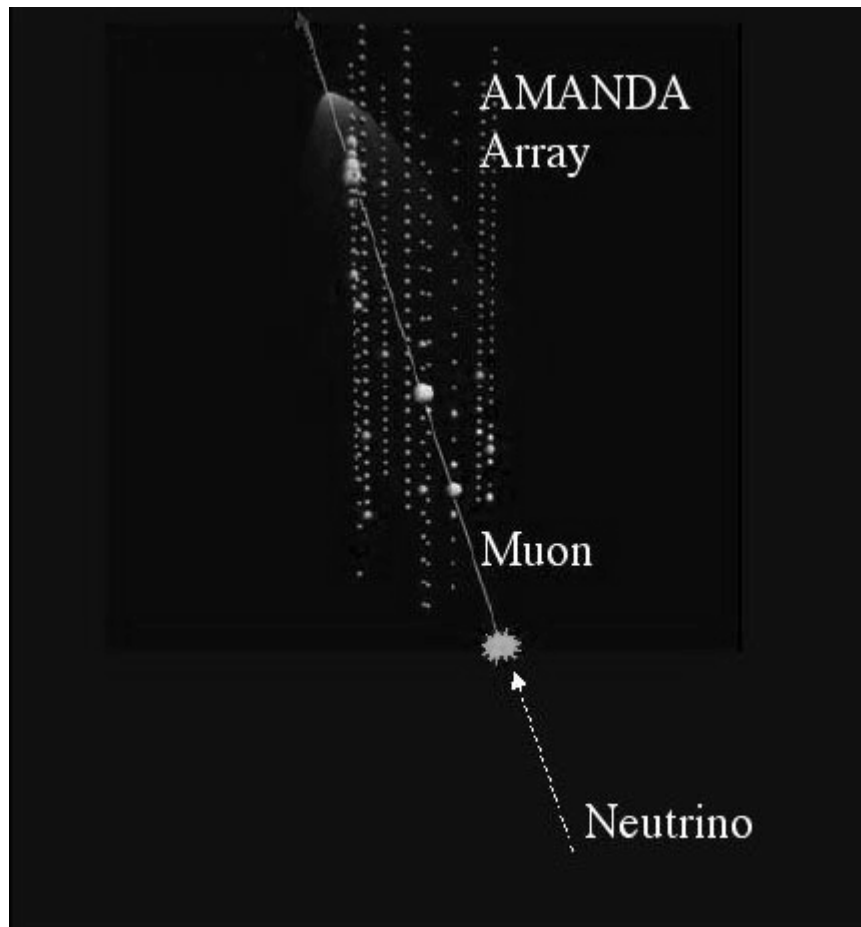
AMANDA

Event Display

The Ice Cube neutrino observatory is designed so that 5,160 optical sensors view a cubic kilometer of clear South Polar ice.
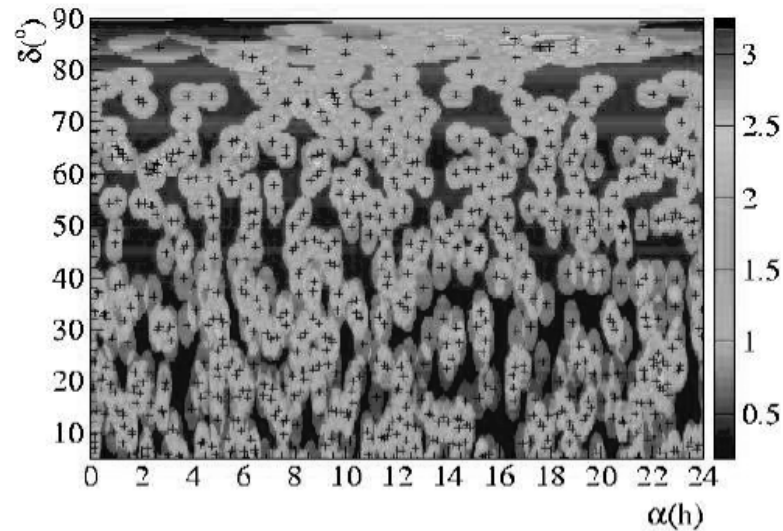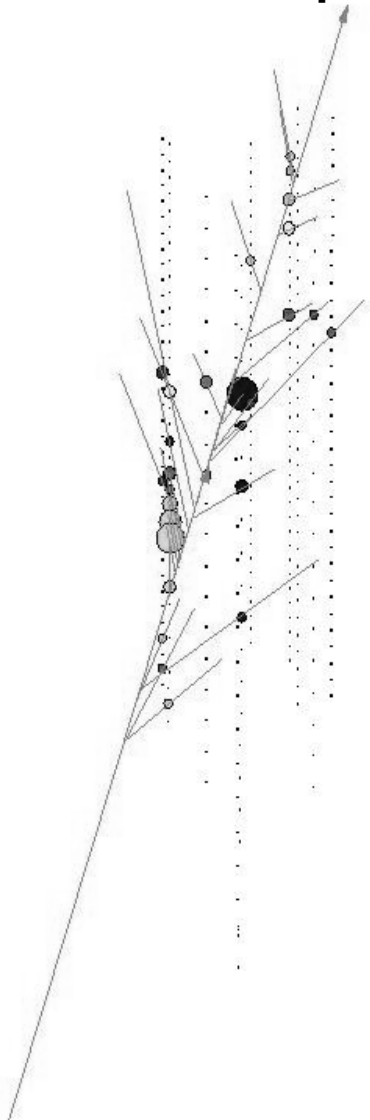
Up to now: No significant point sources but just neutrinos from cosmic ray interactions in the atmosphere were found .

→ Ice Cube for more statistics – data taking stating May 2011 !
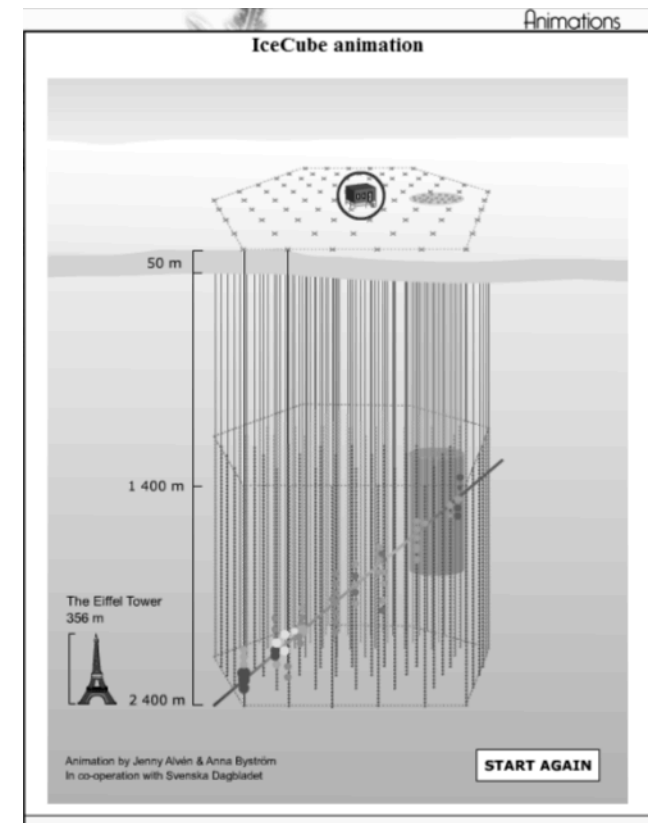
CERN Neutrino Gran Sasso

(CNGS)

CNGS

If neutrinos have mass:

$$\nu_e$$

$$\nu_\mu \longleftrightarrow \nu_\tau$$
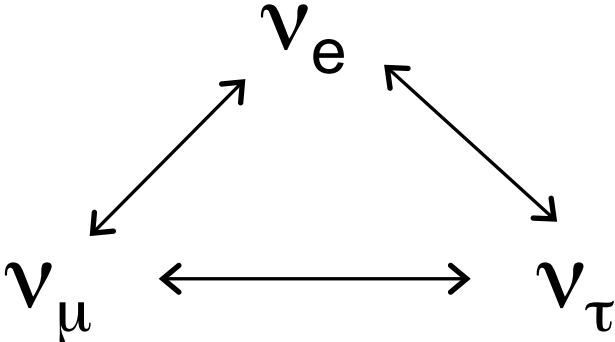
**Muon neutrinos produced at CERN.
See if tau neutrinos arrive in Italy.**

CERN

ν_μ ν_τ ν_μ ν_τ

neutrino trajectory
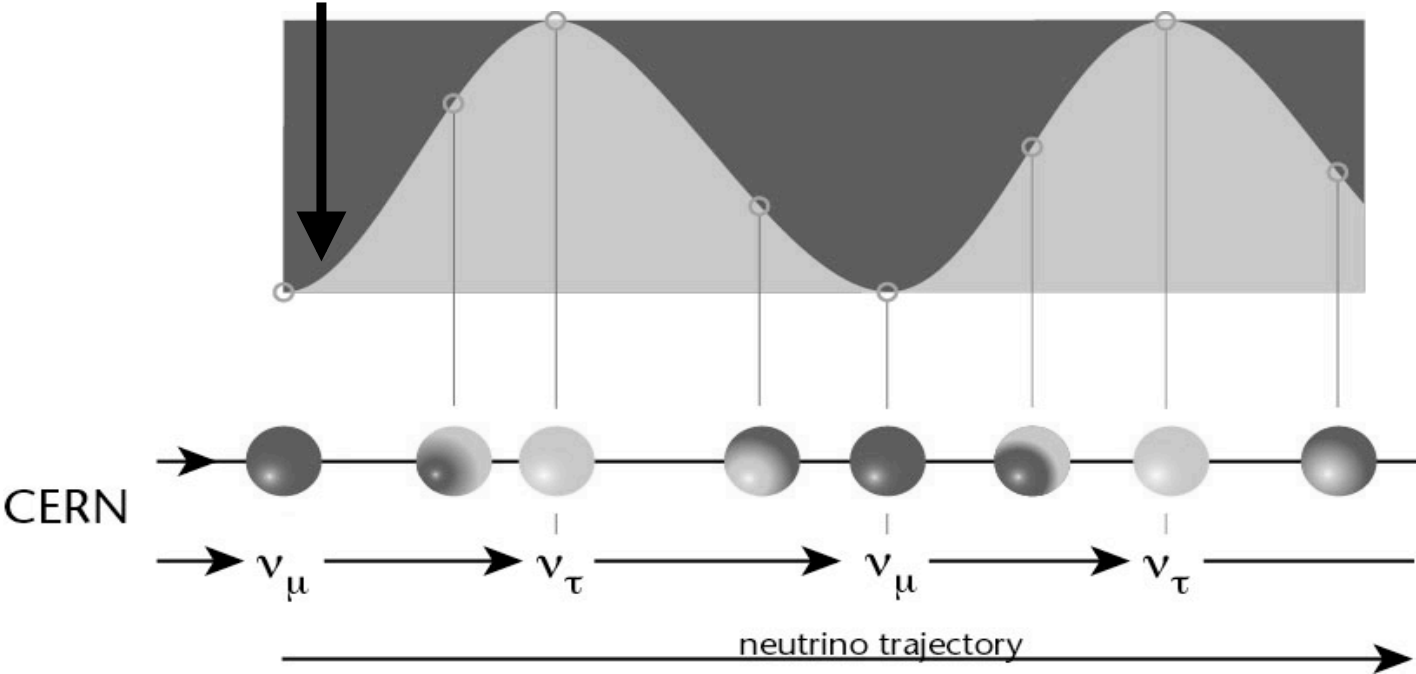
CNGS Project

CNGS (CERN Neutrino Gran Sasso)

- **A long base-line neutrino beam facility (732km)**
- **send ν_μ beam produced at CERN**
- **detect ν_τ appearance in OPERA experiment at Gran Sasso**
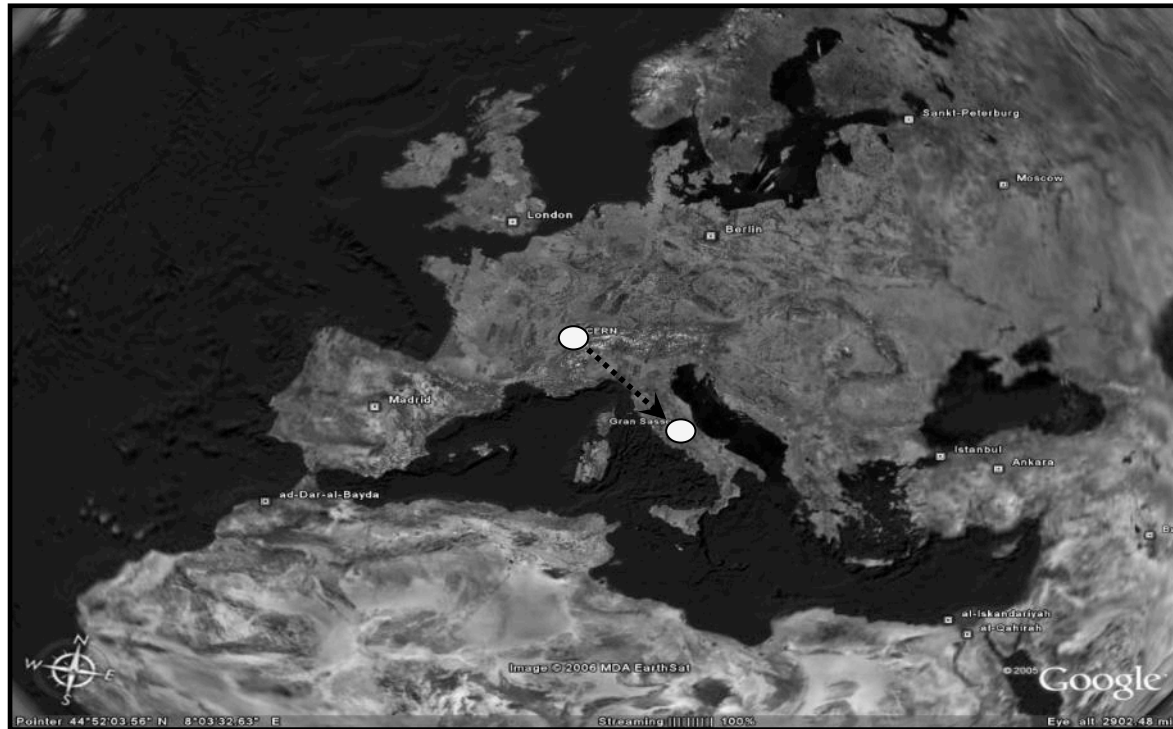
➡ direct proof of ν_μ - ν_τ oscillation (appearance experiment)

CNGS
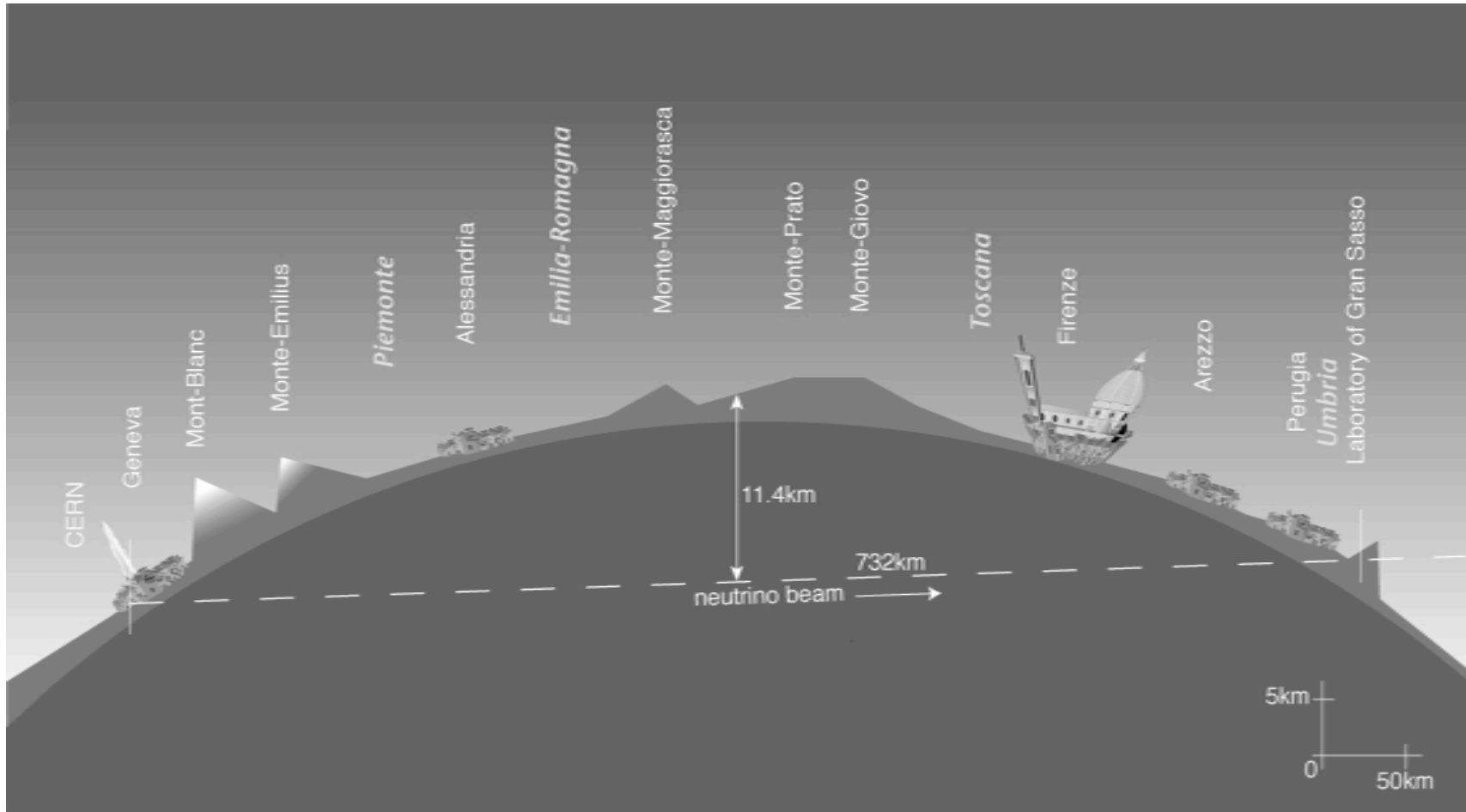
CNGS
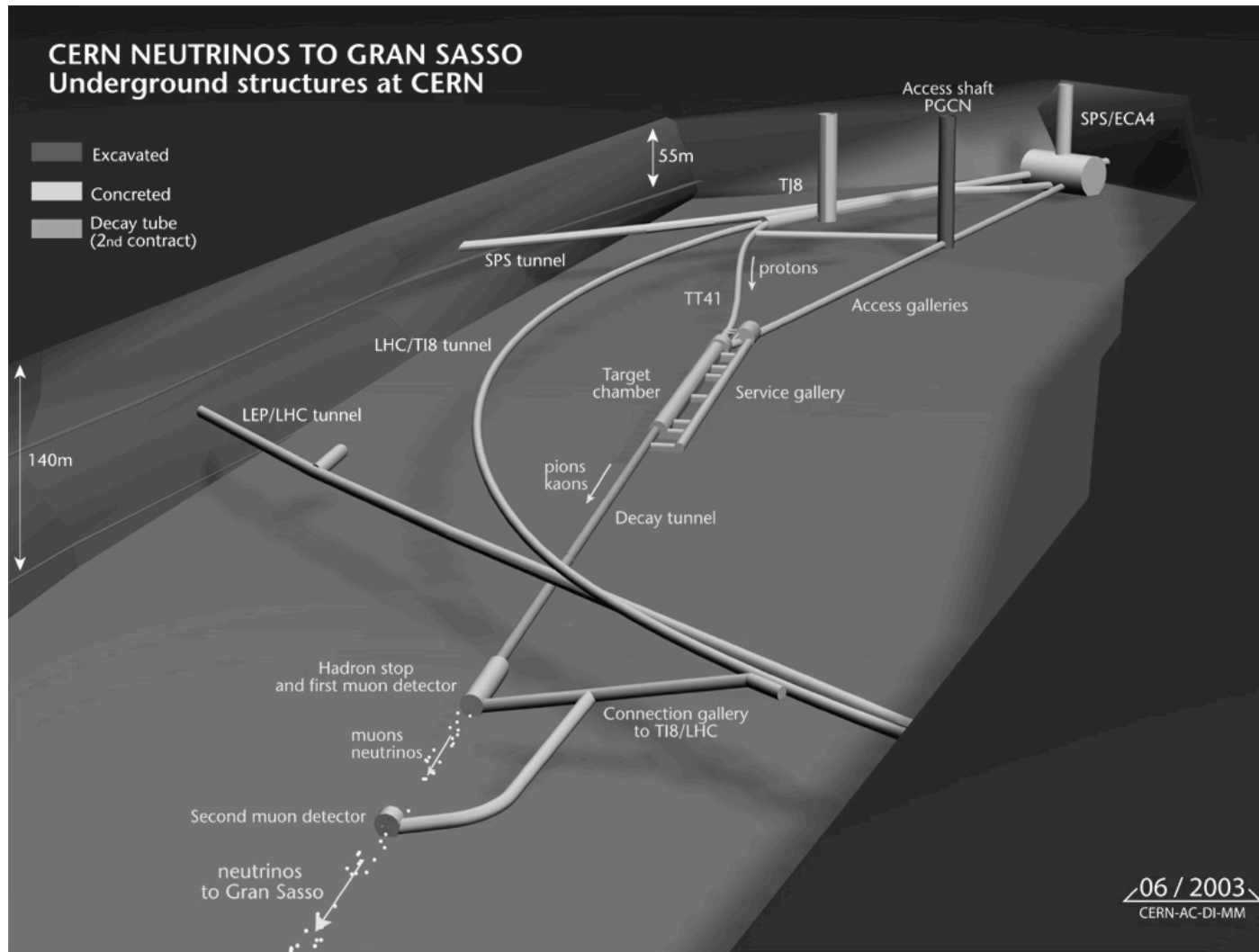
CNGS
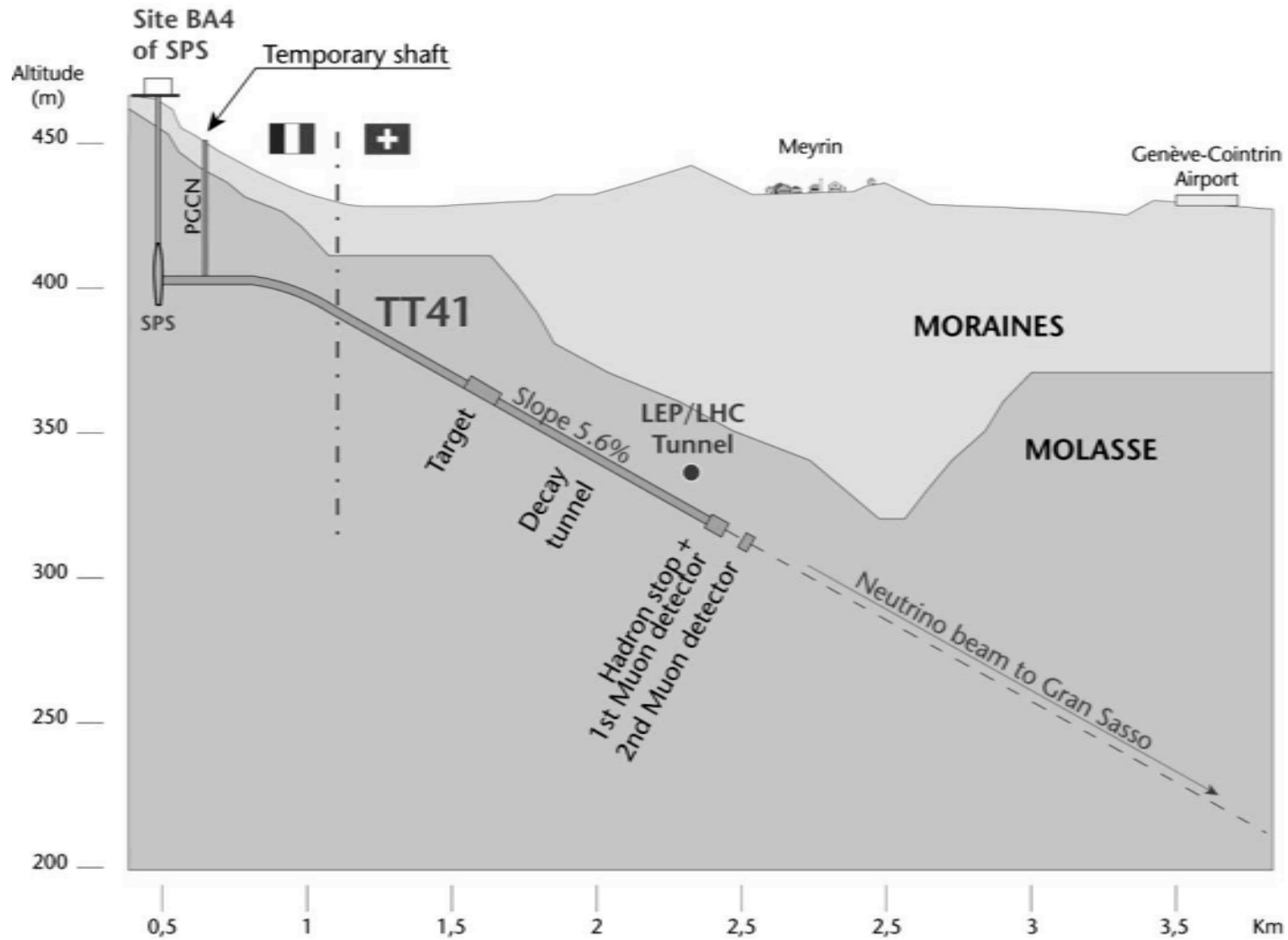
Radial Distribution of the ν_μ-Beam at GS

Flat top: 500m
FWHM: 2800m

typical size of a detector at Gran Sasso
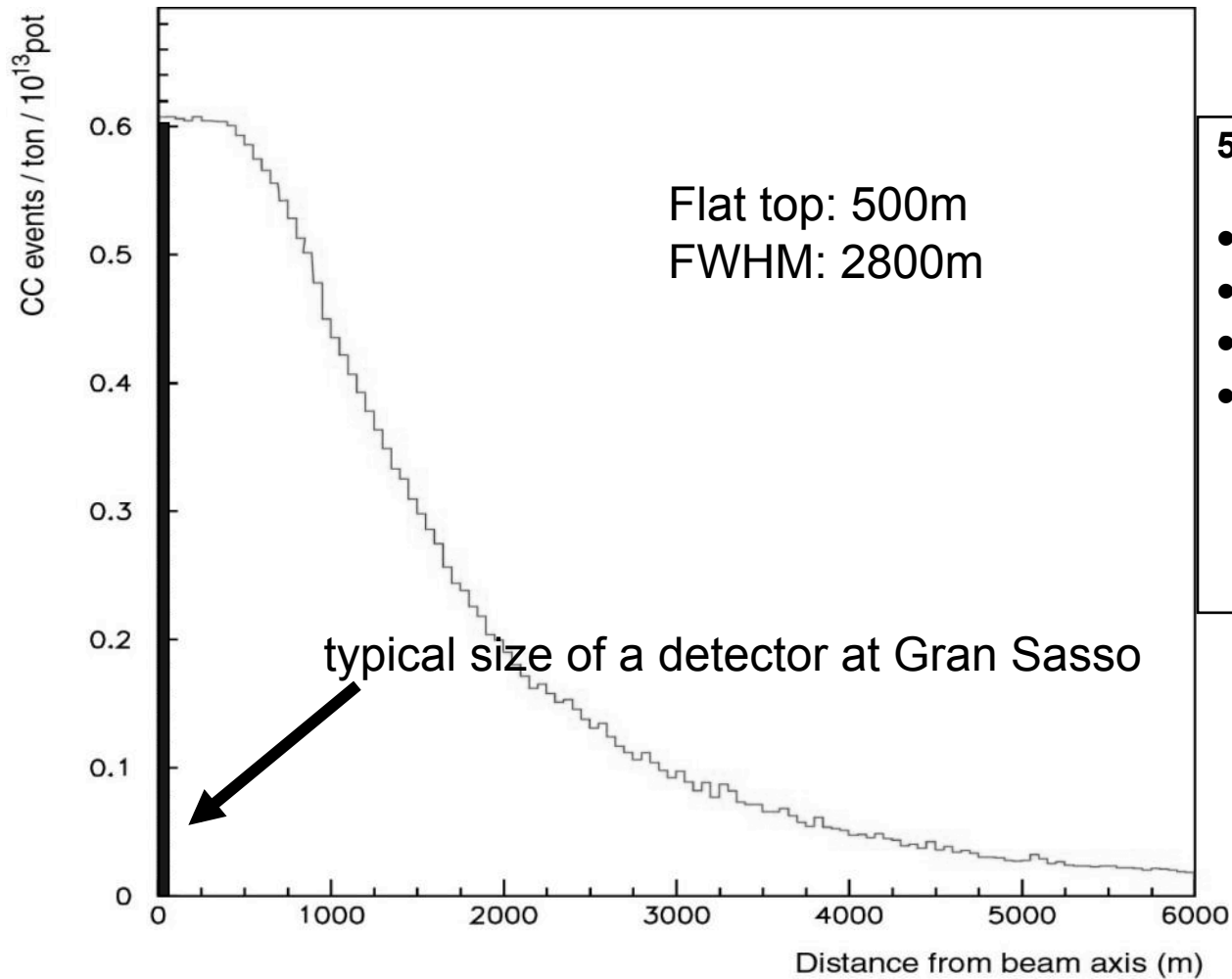
5 years CNGS operation, 1800 tons target:

- **30000 neutrino interactions**
- **~150 ν_τ interactions**
- **~15 ν_τ identified**
- **< 1 event of background**

E. Gschwendtner, CERN

W. Riegler/CERN

Neutrinos at CNGS: Some Numbers

For 1 year of CNGS operation, we expect:

protons on target	2×10^{19}
pions / kaons at entrance to decay tunnel	3×10^{19}
ν_μ **in direction of Gran Sasso**	10^{19}
ν_μ **in 100 m² at Gran Sasso**	3×10^{14}
ν_μ **events per day in OPERA**	≈ 2500
ν_τ **events (from oscillation)**	≈ 2

W. Riegler/CERN

Opera Experiment at Gran Sasso

Basic unit: brick

56 Pb sheets + 56 photographic films (emulsion sheets)

**Lead plates: massive target
Emulsions: micrometric precision**

Brick

1 mm

ν

τ

Pb

Couche de gélatine
photographique 40 μm

brick

8.3kg
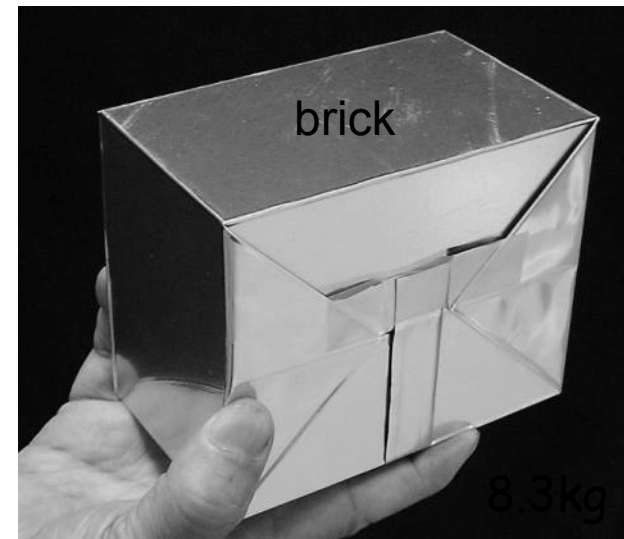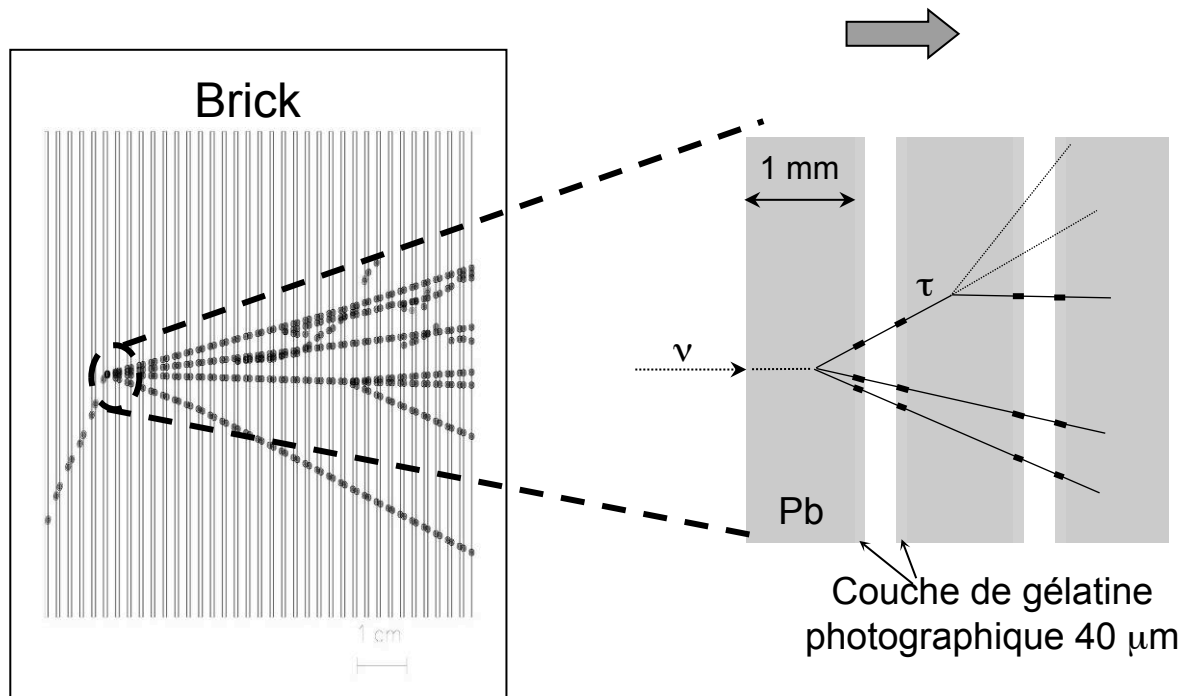
10.2 x 12.7 x 7.5 cm^3

Opera Experiment at Gran Sasso

31 target planes / supermodule   In total: 206336 bricks, 1766 tons
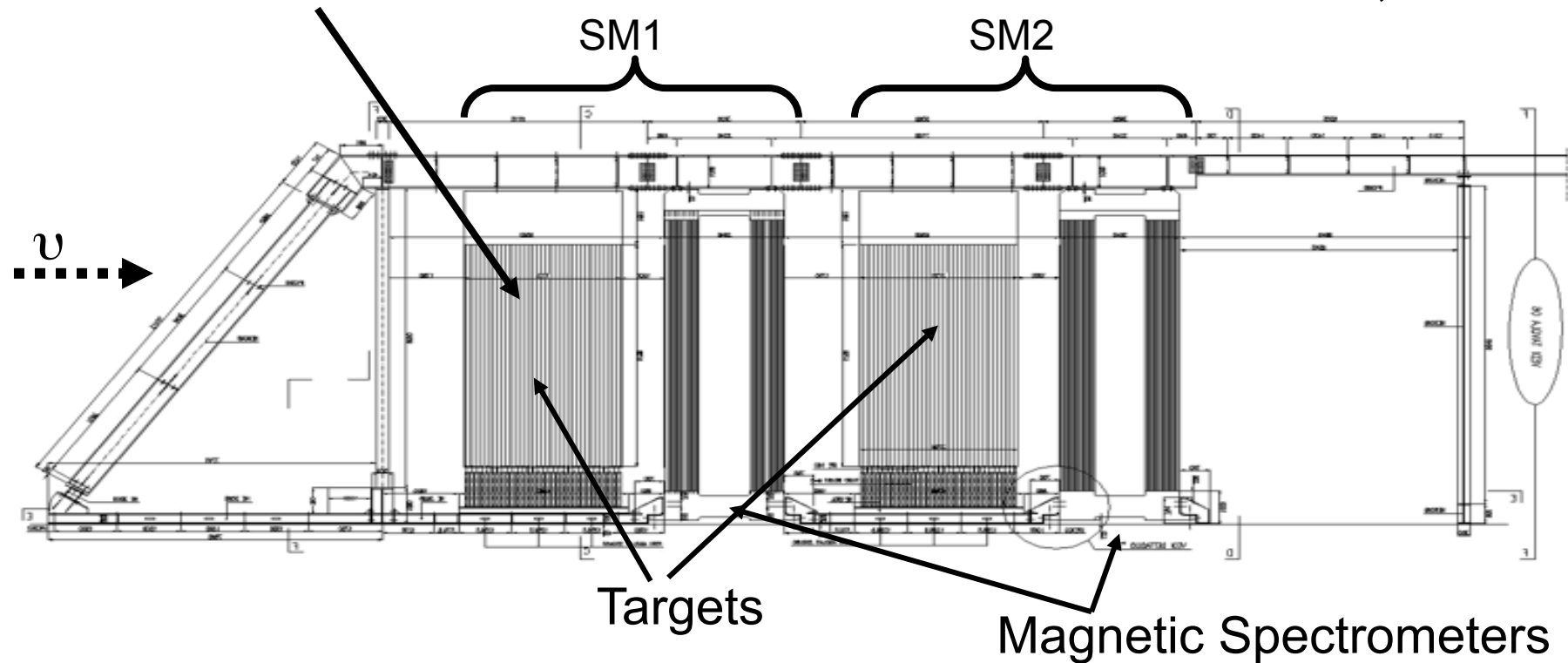
First observation of CNGS beam neutrinos : August 18th, 2006

Opera Experiment at Gran Sasso

Second Super-module

Details of the first spectrometer
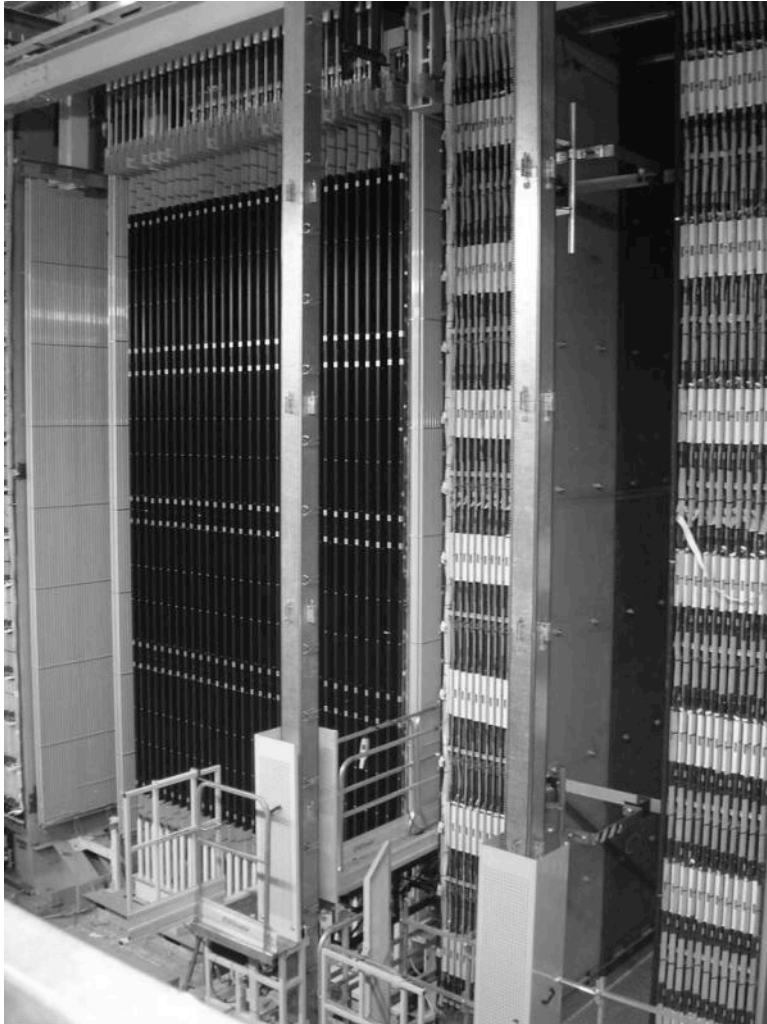
Scintillator planes 5900 m^2
8064 7m long drift tubes
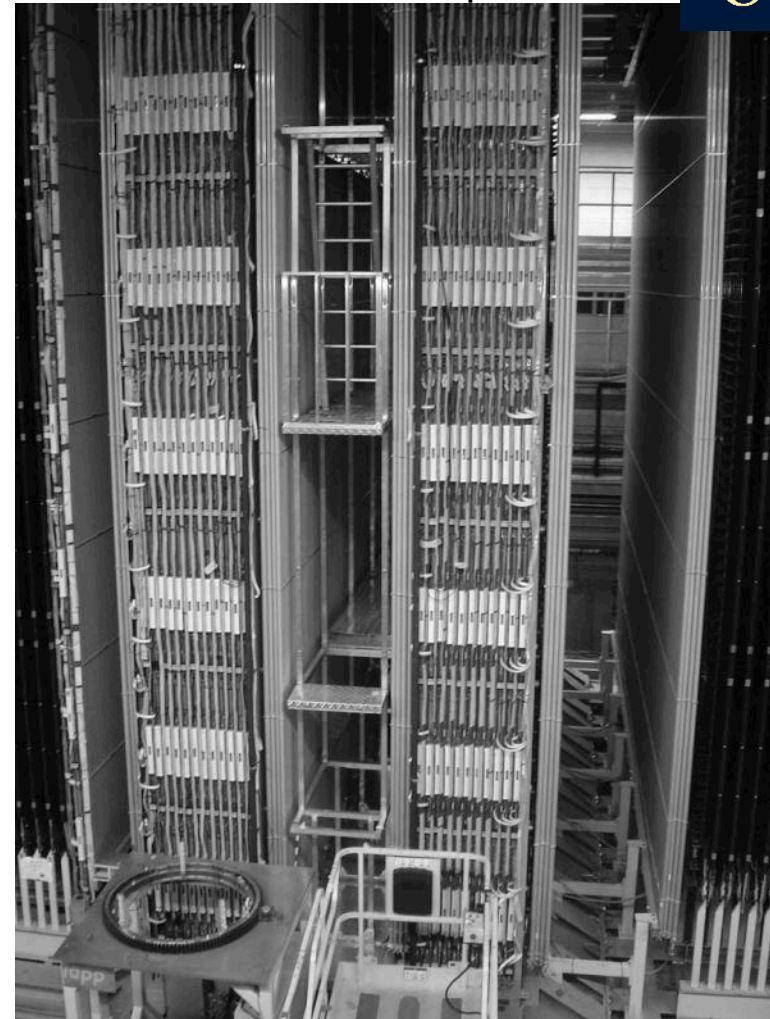
3050 m^2 Resistive Plate Counters
2000 tons of iron for the two magnets

W. Riegler/CERN

Opera Experiment at Gran Sasso

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

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

Tests with the prototype wall

"Carousel" brick dispensing and storage system

First Tau Candidate seen!

Hypothesis:

τ **(parent)** $\rightarrow$ **hadron (daughter)** $+ \pi_0$ **(decaying instantly to** γ_1**,** γ_2**)+** ν_τ **(invisible)**
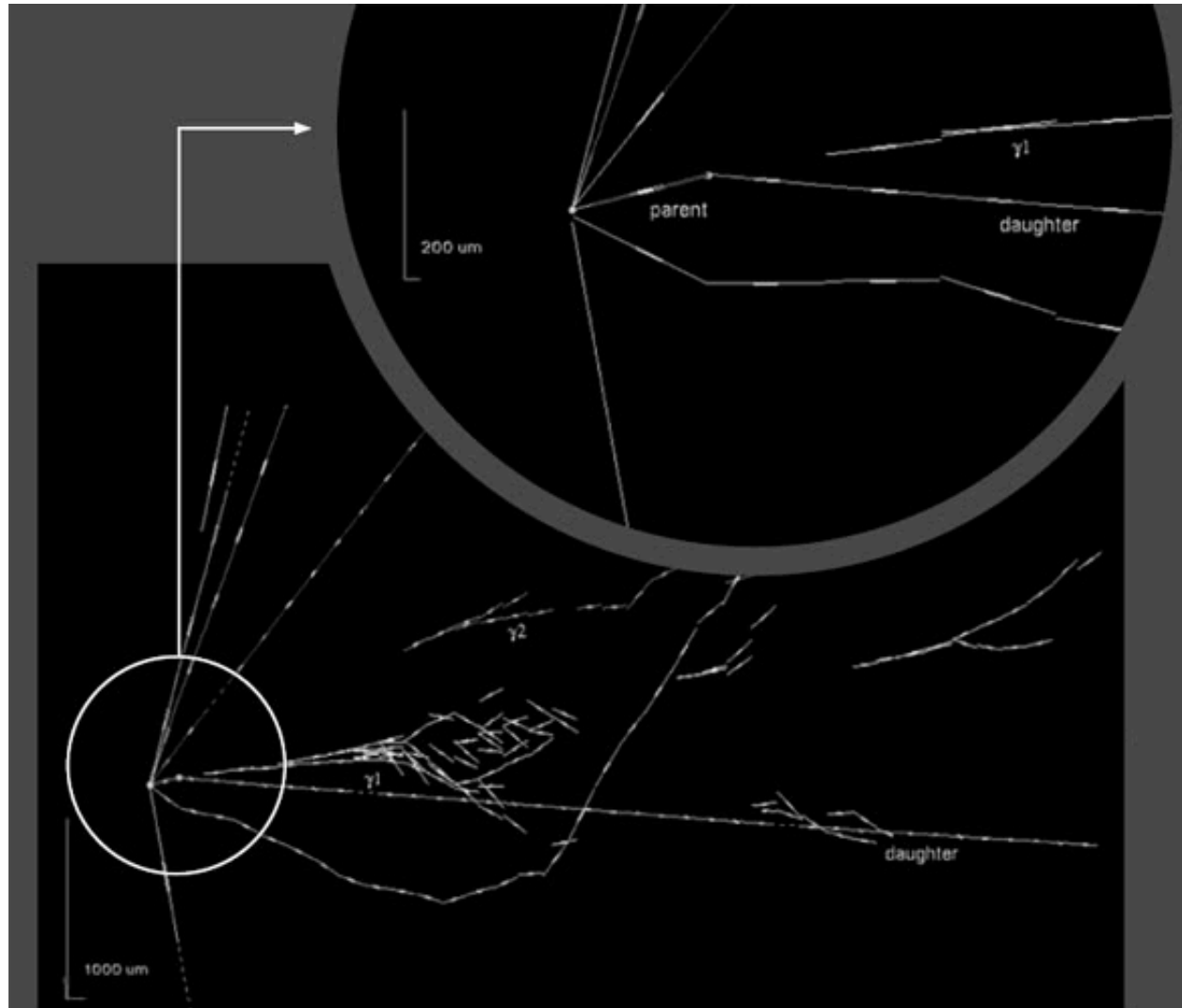
AMS
Alpha Magnetic Spectrometer

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

Was launched into space on STS-134 on 16 May 2011.
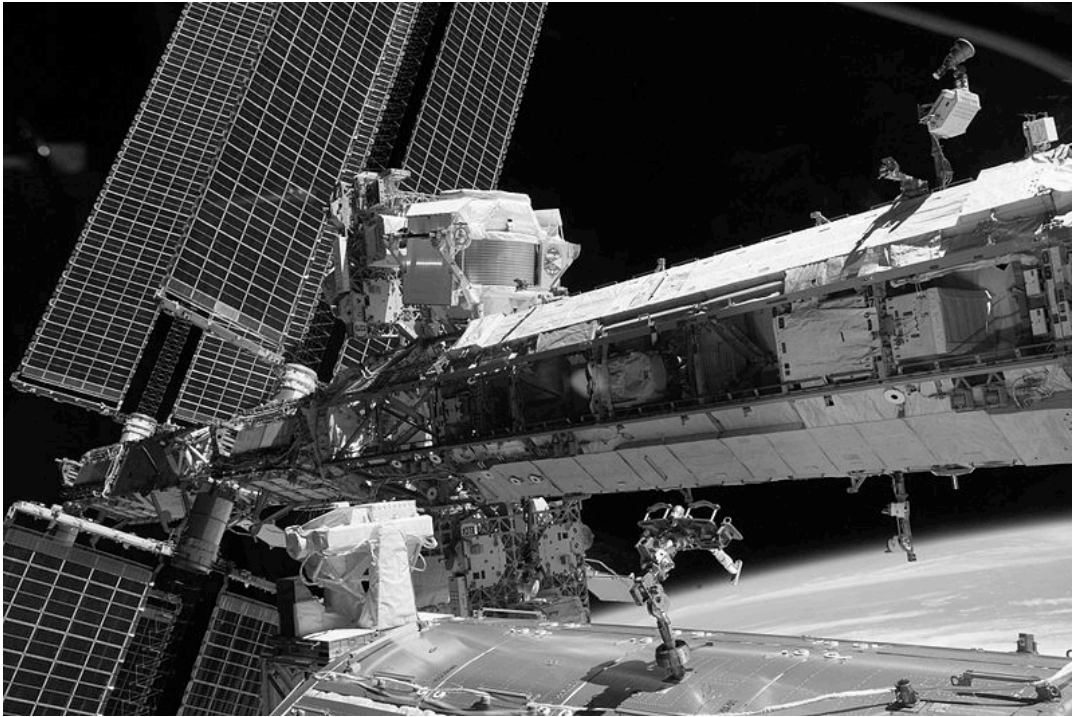
AMS Installed on the space station.

AMS

W. Riegler/CERN
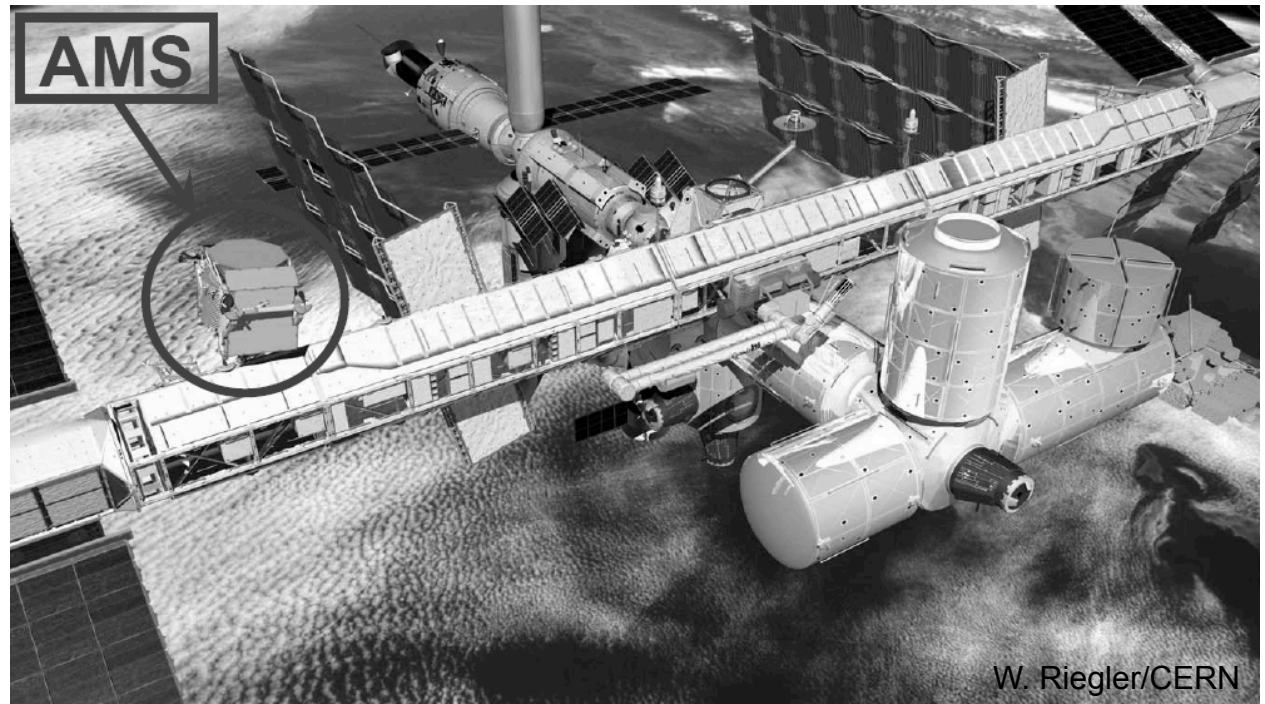
AMS

A state of the art particle detector with many 'earth bound' techniques going to space !
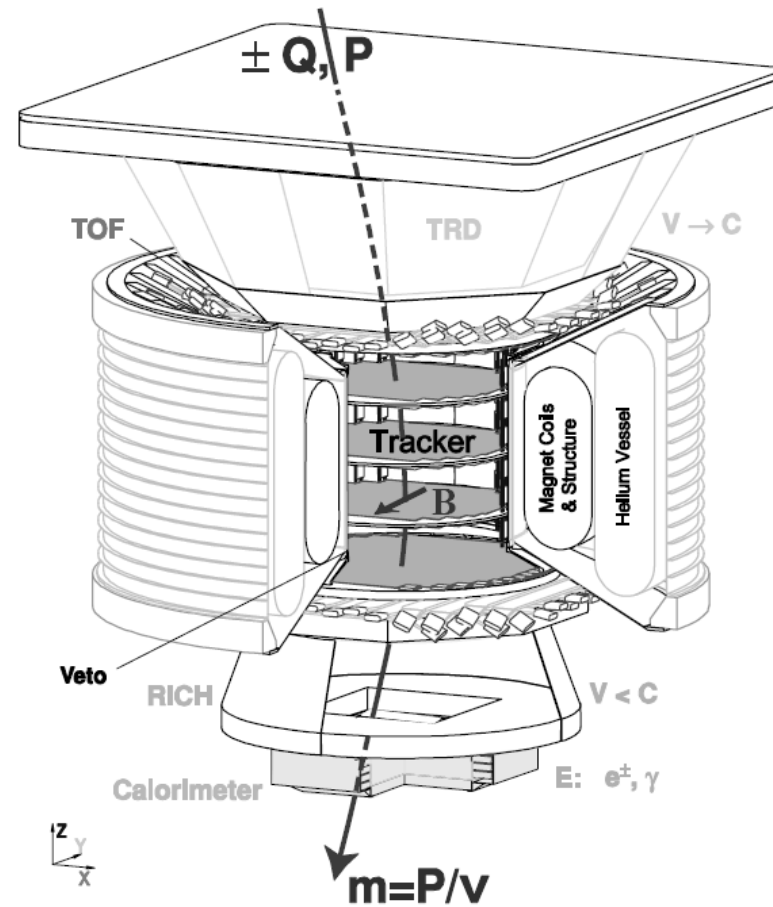
AMS
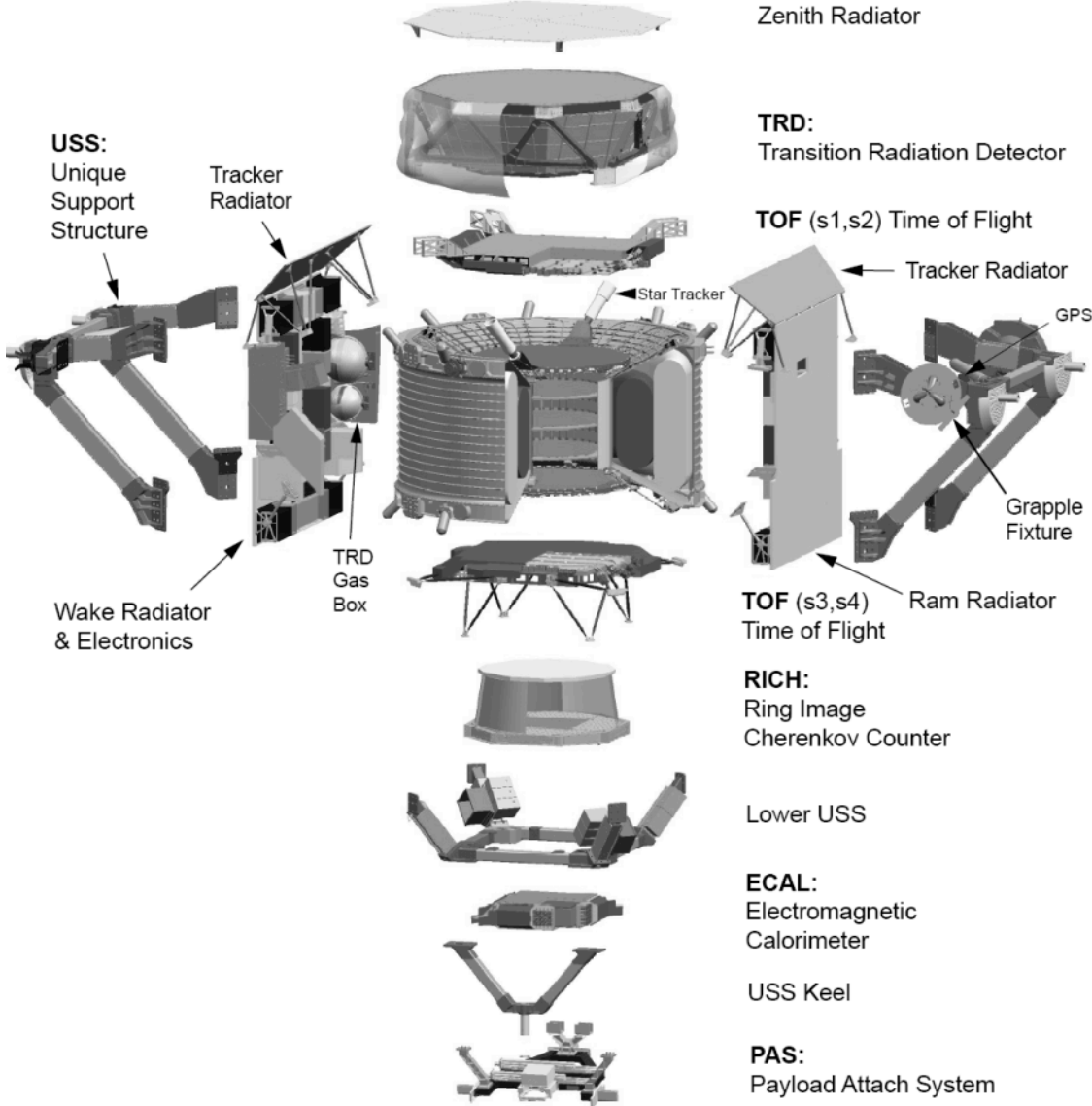
How can a particle detector distinguish the hundreds of particles that we know by now ?

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

γ, $W^{\pm}$, Z^0, g, e, μ, τ, ν_e, ν_m, 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_S^0, K_L^0, $K^*(892)$,
$K_1(1270)$, $K_1(1400)$, $K^*(1410)$, $K_0^*(1430)$, $K_2^*(1430)$, $K^*(1680)$,
$K_2(1770)$, $K_3^*(1780)$, $K_2(1820)$, $K_4^*(2045)$, $D^{\pm}$, D^0, $D^*(2007)^0$,
$D^*(2010)^{\pm}$, $D_1(2420)^0$, $D_2^*(2460)^0$, $D_2^*(2460)^{\pm}$, $D_s^{\pm}$, $D_s^{*\pm}$,
$D_{s1}(2536)^{\pm}$, $D_{sJ}(2573)^{\pm}$, $B^{\pm}$, 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

These are all the known 27 particles with a lifetime that is long enough such that at GeV energies they travel more than 1 micrometer.

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

Particle	Mass (meV)	Life time γ (s)	$c\gamma$	
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	"Secondary
$B^{\pm}$ $(u\bar{b}, \bar{u}b)$	5279	$1.7 \cdot 10^{-12}$	502 μm	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	
Λ^{0} (uds)	1115.7	$2.6 \cdot 10^{-10}$	7.89 cm	
Σ^{+} (uus)	1189.4	$8.0 \cdot 10^{-11}$	2.404 cm	
Σ^{-} (dds)	1197.4	$1.5 \cdot 10^{-10}$	4.434 cm	
Ξ^{0} (uss)	1315	$2.9 \cdot 10^{-10}$	8.71 cm	
Ξ^{-} (dss)	1321	$1.6 \cdot 10^{-10}$	4.91 cm	
Ω^{-} (sss)	1672	$8.2 \cdot 10^{-11}$	2.461 cm	
Λ_{c}^{+} (udc)	2285	$\sim 2 \cdot 10^{-13}$	60 μm	
Ξ_{c}^{+} (usc)	2466	$4.4 \cdot 10^{-13}$	132 μm	
Ξ_{c}^{0} (dcs)	2472	$\sim 1 \cdot 10^{-13}$	29 μm	
Ω_{c}^{0} (ssc)	2698	$6.0 \cdot 10^{-14}$	19 μm	
Λ_{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 $c\gamma > \sim 1\mu m$ i.e. they can be seen as 'tracks' in a Detector.

~13 of the 27 have $c\gamma < 500\mu m$ i.e. only ~mm range at GeV Energies.
→ 'short' tracks measures 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.

The 8 Particles a Detector must be able to Measure and Identify

$$e^{\pm} \quad m_e = 0.511 \text{ MeV}$$
$$\mu^{\pm} \quad m_\mu = 105.7 \text{ MeV} \sim 200 \, m_e$$
$$\gamma \quad m_\gamma = 0 \,, \quad Q = 0$$

$\left.\right\}$ EM

$$\pi^{\pm} \quad m_\pi = 139.6 \text{ MeV} \sim 270 \, m_e$$
$$K^{\pm} \quad m_k = 493.7 \text{ MeV} \sim 1000 \, m_e$$
$$p^{\pm} \quad m_p = 938.3 \text{ MeV} \sim 2000 \, m_e$$

$\left.\right\}$ EM, Strong $\sim 3.5 \, m_\pi$

$$K^0 \quad m_{k^0} = 497.7 \text{ MeV} \quad Q = 0$$
$$n \quad m_n = 939.6 \text{ MeV} \quad Q = 0$$

$\left.\right\}$ Strong

The Difference in

Mass, Charge, Interaction

is the key to the Identification

The 8 Particles a Detector must be able to Measure and Identify

- 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

TRACKING velocity measurement	CALORIMETERS electromagnetic hadronic		MUONS	
ELECTRONS				$e^{\pm}$
PHOTONS				γ
CHARGED HADRONS				$p^{\pm}, k^{\pm}, \pi^{\pm}$
NEUTRAL HADRONS (e.g. neutrons)				k^{0}, n
MUONS				$\mu^{\pm}$

100 – 200   50 – 100   200 – 400   200 – 400

Typical dimensions [cm]

$\vec{B} \otimes$

Low   High   High   Tracking
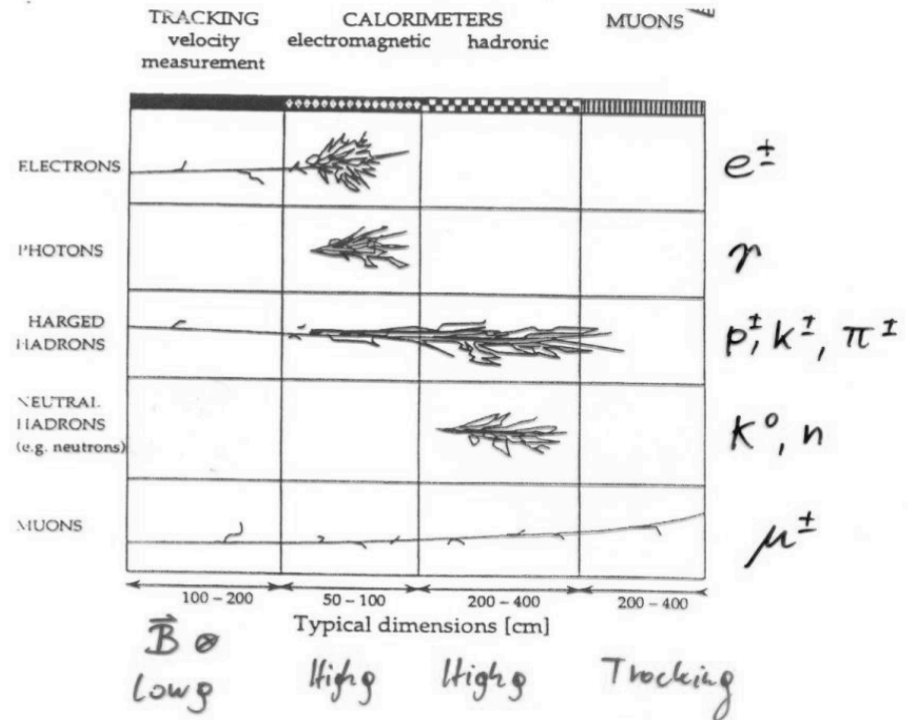
Detector Physics

Precise knowledge of the processes leading to signals in particle detectors is necessary.

The detectors are nowadays working close to the limits of theoretically achievable measurement accuracy – even in large systems.

Due to available computing power, detectors can be simulated to within 5-10% of reality, based on the fundamental microphysics processes (atomic and nuclear crossections).

Particle Detector Simulation

Electric Fields in a Micromega Detector

Electric Fields in a Micromega Detector
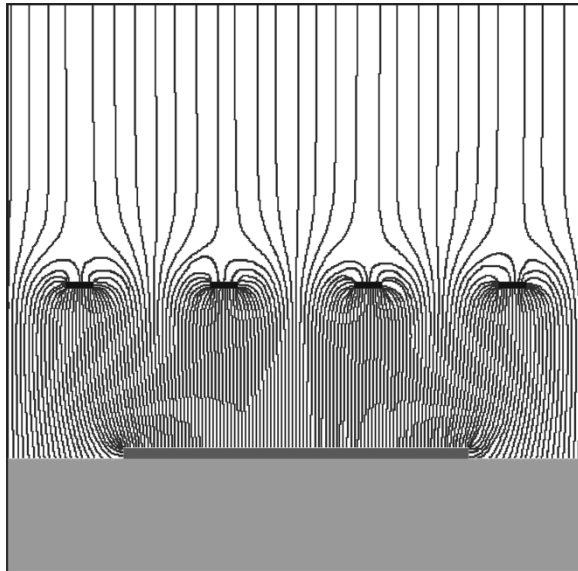
Very accurate simulations of particle detectors are possible due to availability of Finite Element simulation programs and computing power.

Follow every single electron by applying first principle laws of physics.

For Gaseous Detectors: GARFIELD by R. Veenhof
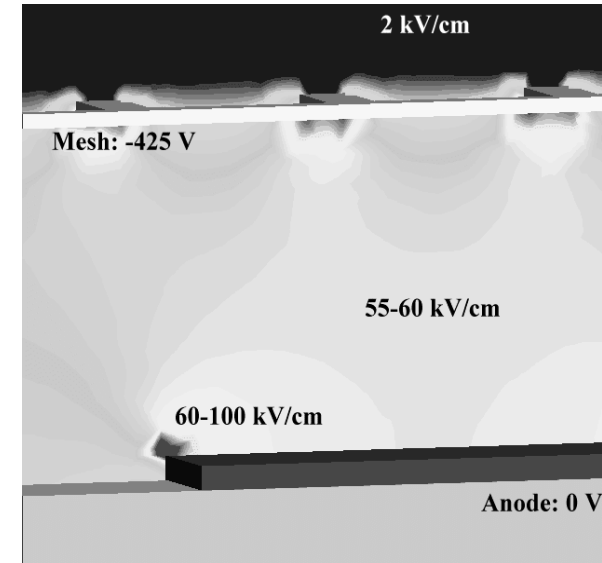
Electrons avalanche multiplication
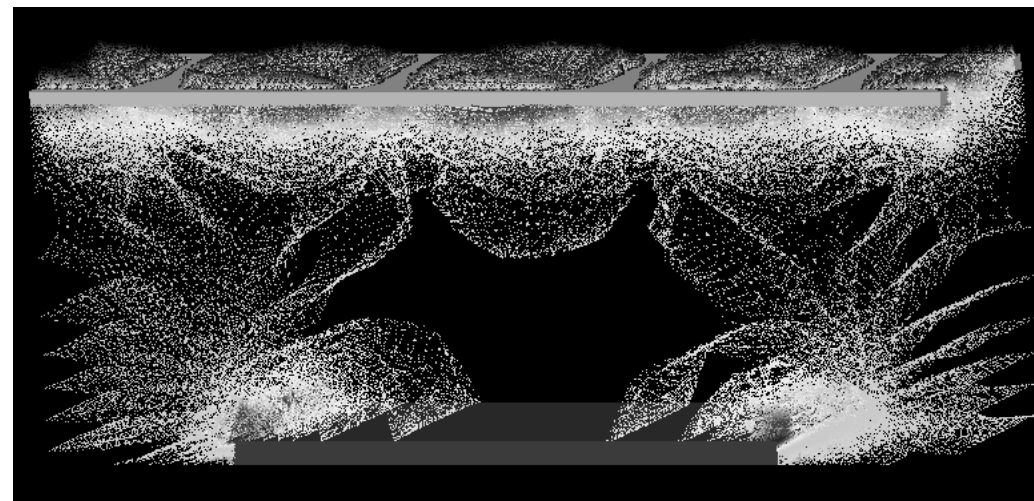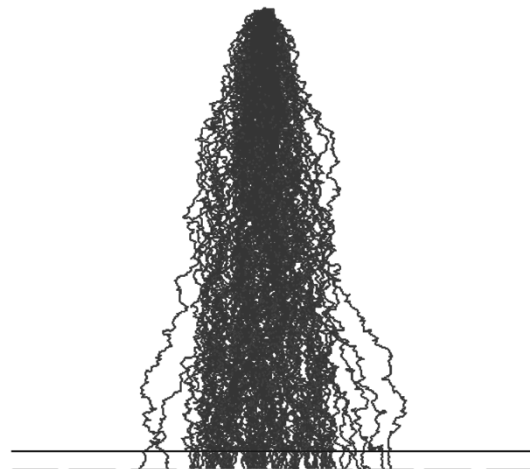
Particle Detector Simulation

I) C. Moore's Law:
Computing power doubles 18 months.

II) W. Riegler's Law:
The use of brain for solving a problem is inversely proportional to the available computing power.

→ I) + II) = ...
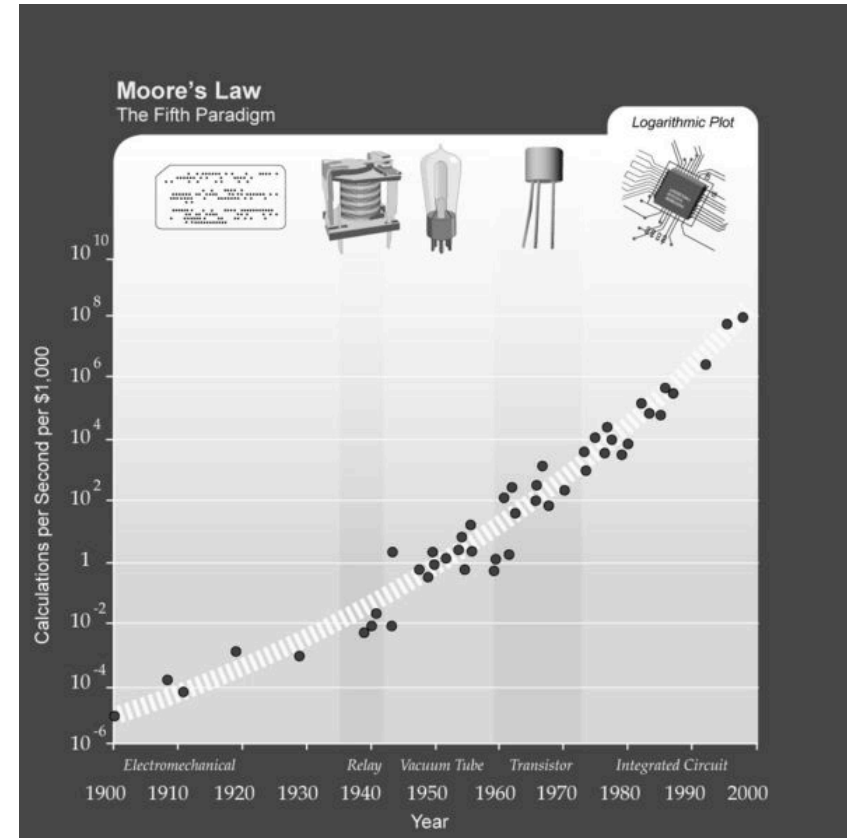
Knowing the basics of particle detectors is essential …

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 ≠0 → neutrino escaped.

"Did you see it?"
"No nothing."
"Then it was a neutrino!"
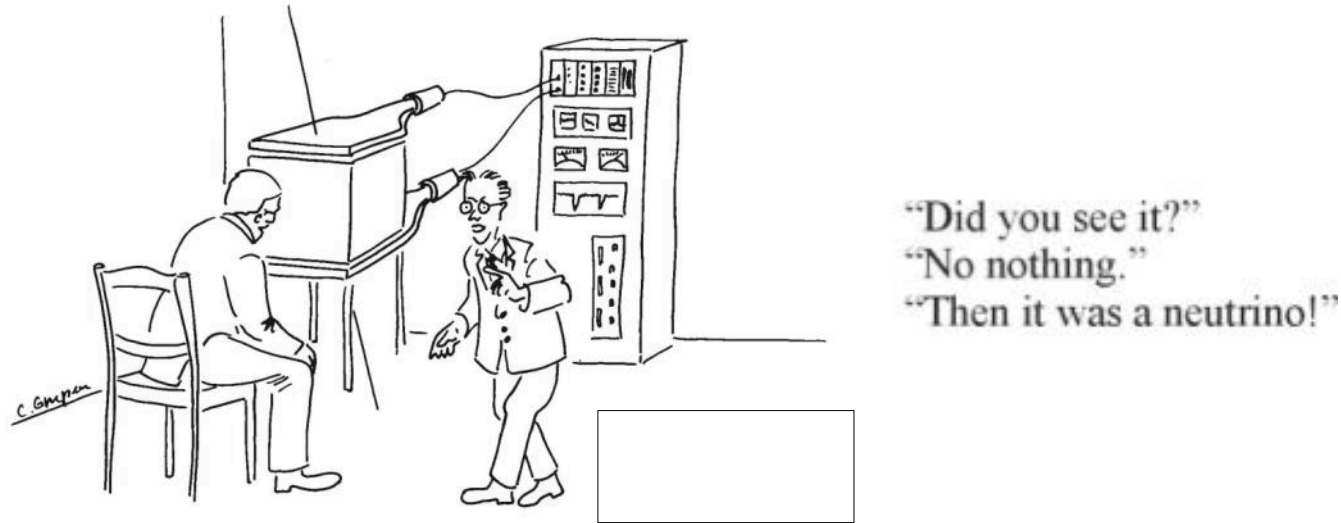
Interaction of Particles with Matter
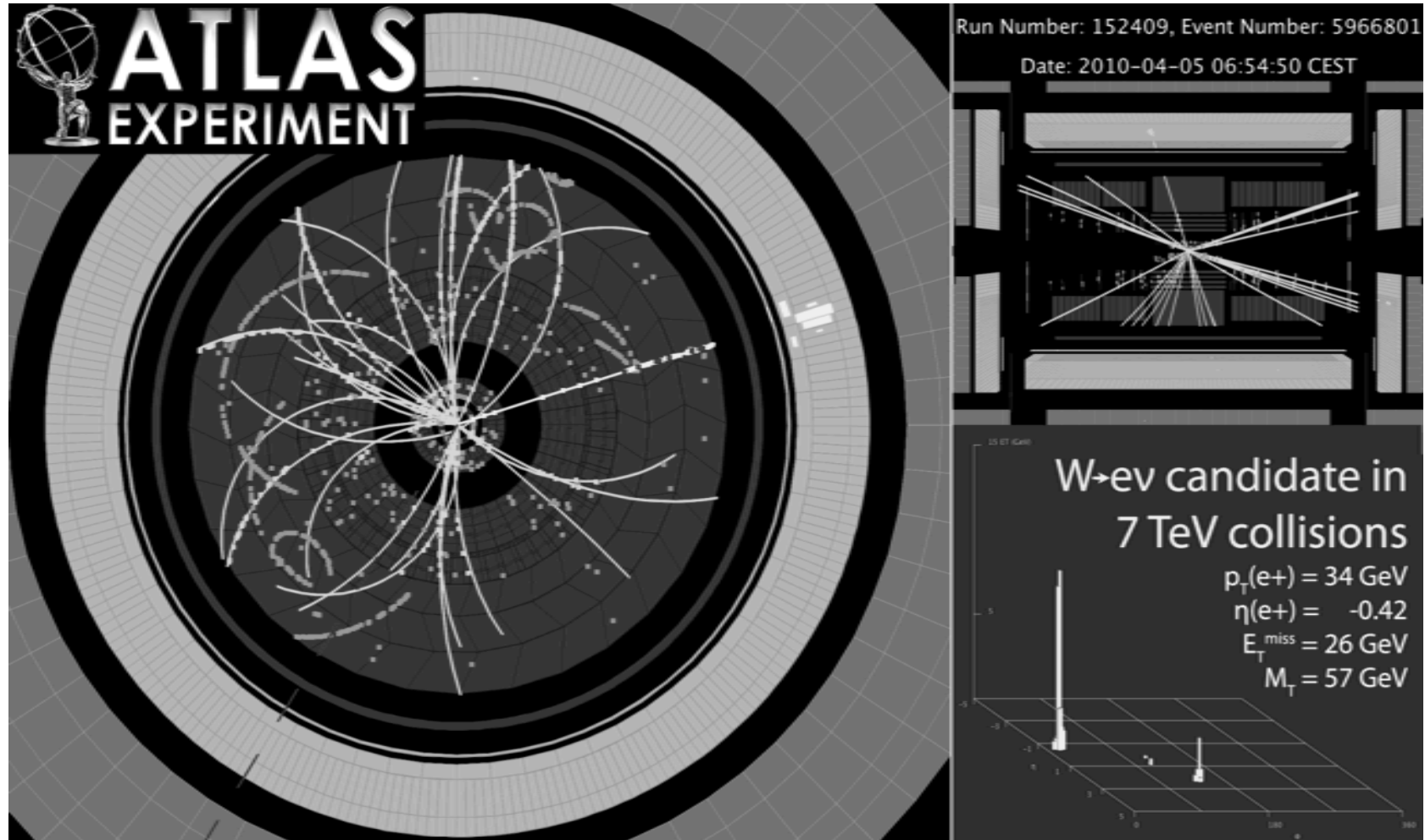
Electromagnetic Interaction of Particles with Matter

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

Interaction with the atomic nucleus. The particle is deflected (scattered) causing <u>multiple scattering</u> of the particle in the material. During this scattering a <u>Bremsstrahlung</u> 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 <u>Cherenkov Radiation</u>. 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>.

Ionization and Excitation

$$m, q = Z_2 e_0$$

F

F_y b

Relativity:

$\vec{v}$

$$M, v, q = Z_1 e_0$$

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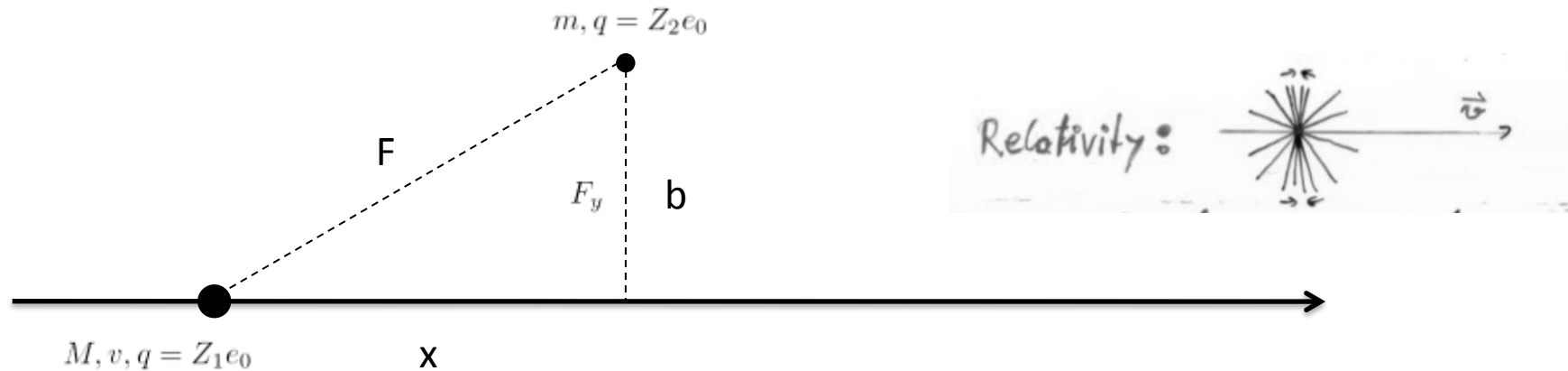
While the charged particle is passing another charged particle, the Coulomb Force is acting, resulting in momentum transfer

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

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/cm³], Avogadro number N_A

A gramm → N_A Atoms: Number of atoms/cm³ $n_a = N_A \rho / A$ [1/cm³]

Number of electrons/cm³ $n_e = N_A \rho Z_2 / A$ [1/cm³]

$$\Delta E(electrons) = \frac{2 Z_2 Z_1^2 m_e c^2}{\beta^2 b^2} \frac{e_0^4}{(4\pi\varepsilon_0 m_e c^2)^2} = \frac{2 Z_2 Z_1^2 m_e c^2}{\beta^2 b^2} r_e^2$$
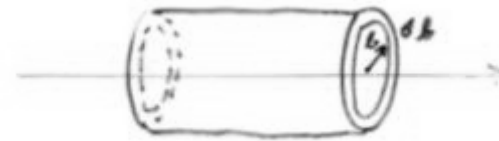
$$dE = -\int_{b_{min}}^{b_{max}} n_e \Delta E\, dx\, 2 b\pi\, db = -\frac{4\pi Z_2 Z_1^2 m_e c^2 r_e^2}{\beta^2} \frac{N_A \rho}{A} \int_{b_{min}}^{b_{max}} \frac{db}{b}$$

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

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

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

Relativistic Collision Kinematics, E_{max}

$M, p, E = \sqrt{p^2c^2 + M^2c^4}$ $m, p = 0, E = mc^2$

$m, p', E' = \sqrt{p'^2c^2 + m^2c^4}$

θ

ϕ
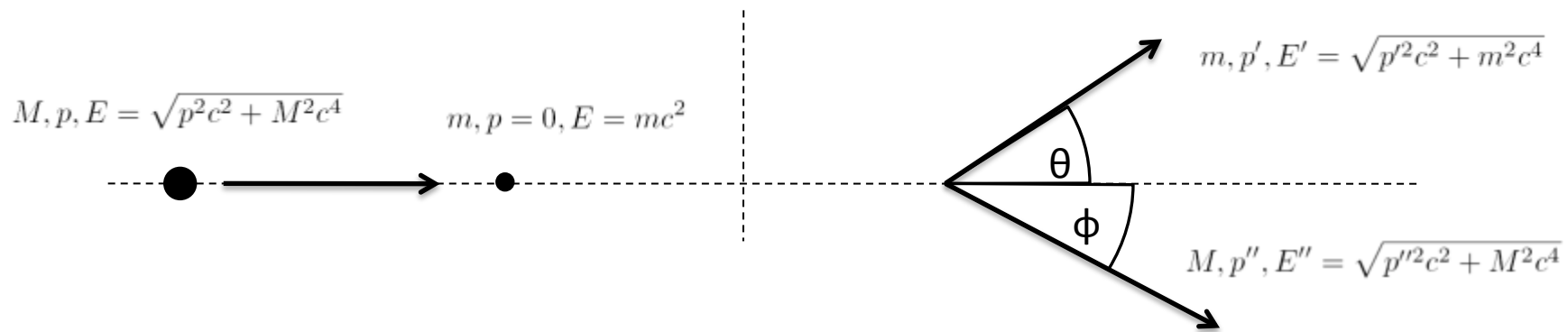
$M, p'', E'' = \sqrt{p''^2c^2 + M^2c^4}$

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

$0 = p'\sin\theta + p''\sin\phi$

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

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

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

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

Electron Spin

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

Bethe Bloch Formula
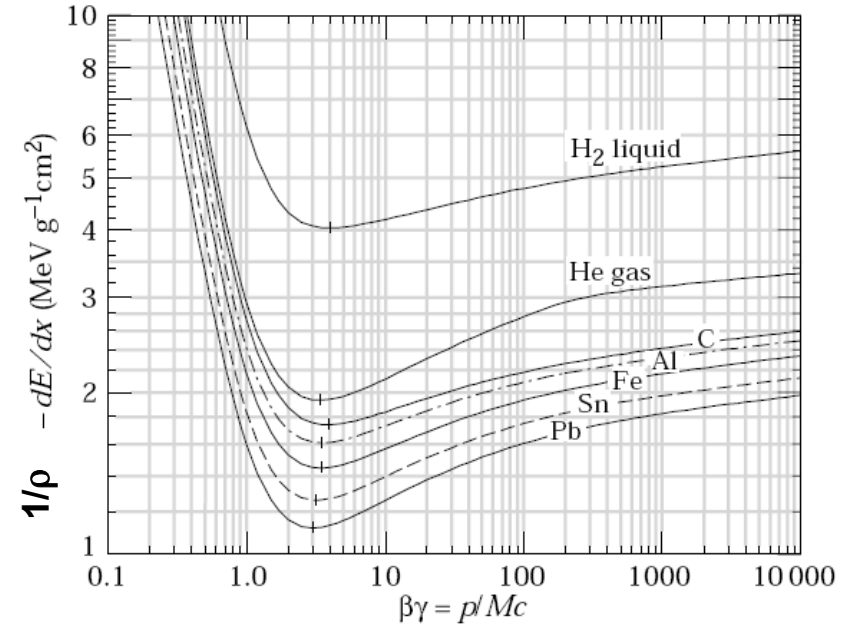
$$\frac{1}{\rho}\frac{dE}{dx} = -4\pi r_e^2\, m_e c^2\, \frac{Z_1^2}{\beta^2}\, N_A \frac{Z}{A}\left[\ln\frac{2m_e c^2 \beta^2 \gamma^2 F}{I} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$
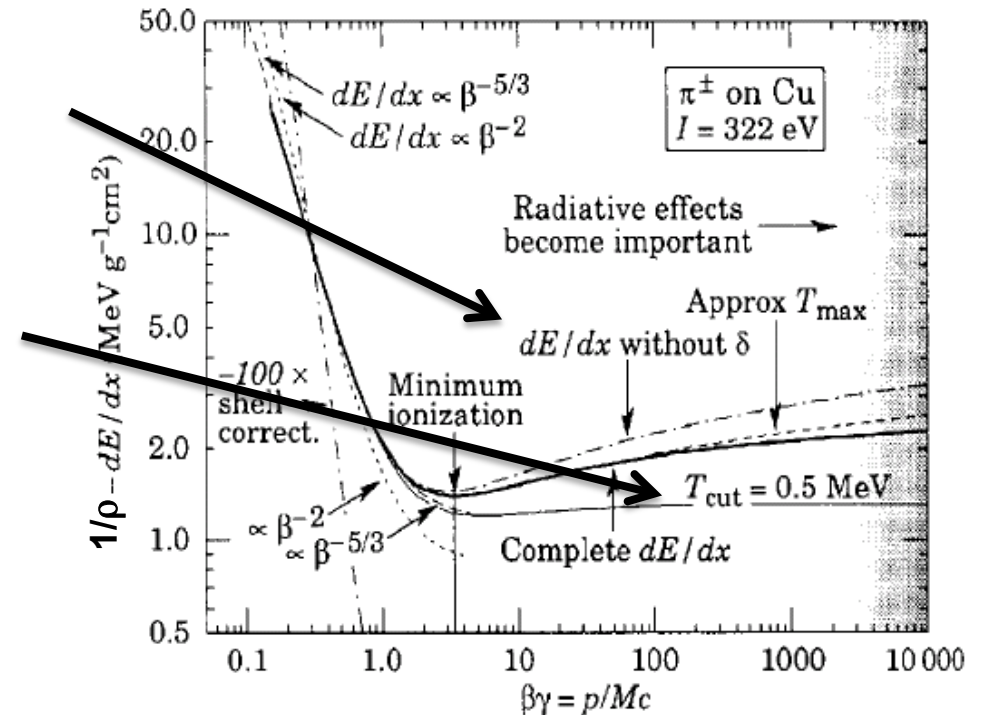
Für Z>1, I $\approx$16Z $^{0.9}$ eV

**For Large $\beta\gamma$ the medium is being polarized by the strong transverse fields, which reduces the rise of
the energy loss $\rightarrow$ 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 ($\beta\gamma$)

The specific Energy Loss 1/ρ dE/dx

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

Energy Loss by Excitation and Ionization

Small energy loss
→ Fast Particle

Cosmis rays: dE/dx α Z^2
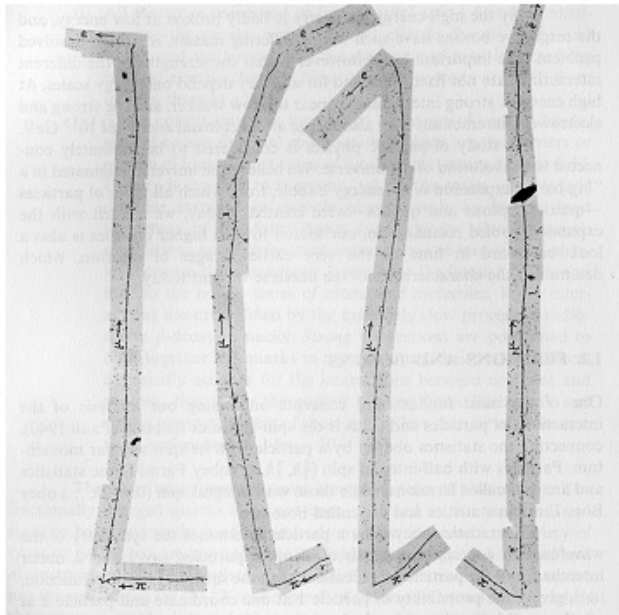
Discovery of muon and pion
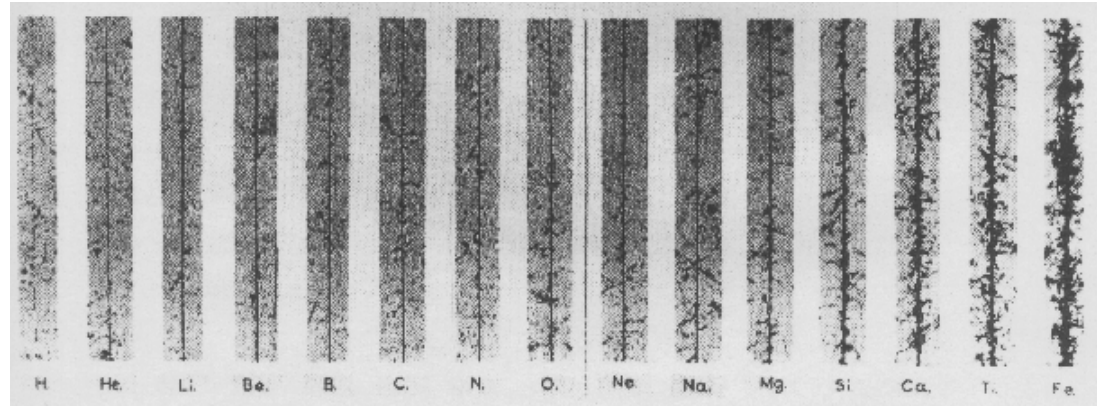
Small energy loss
→ Fast particle
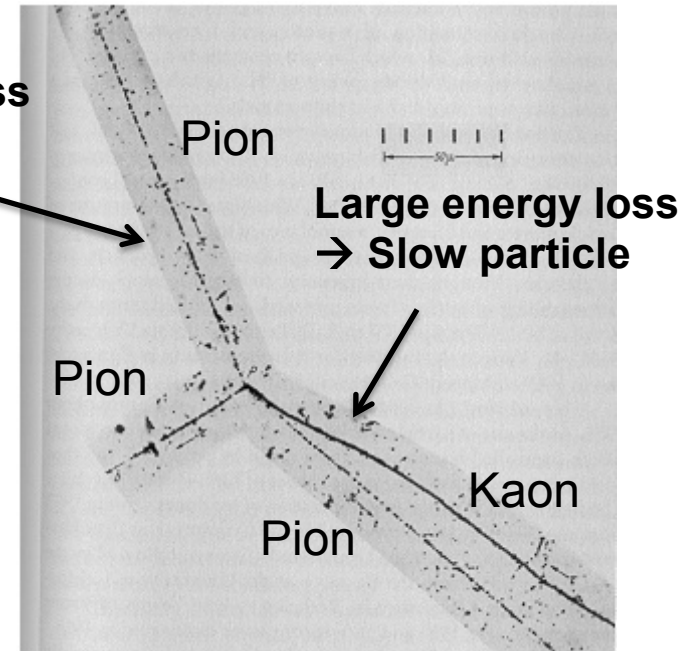
Pion

Large energy loss
→ Slow particle

Pion

Kaon

Pion

Bethe Bloch Formula

Bethe Bloch Formula, a few Numbers:

For Z $\approx$ 0.5 A

1/ρ dE/dx $\approx$ 1.4 MeV cm^2/g for ßγ $\approx$ 3

Example :

Iron: Thickness = 100 cm; ρ = 7.87 g/cm^3

dE $\approx$ 1.4 * 100* 7.87 = 1102 MeV

$\rightarrow$ A 1 GeV Muon can traverse 1m of Iron
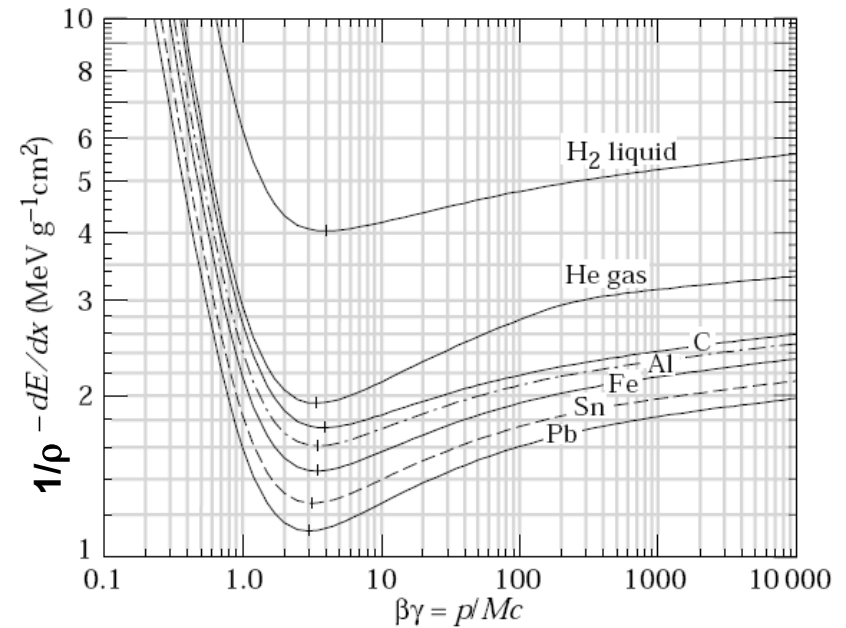
This number must be multiplied with ρ [g/cm^3] of the Material $\rightarrow$ dE/dx [MeV/cm]

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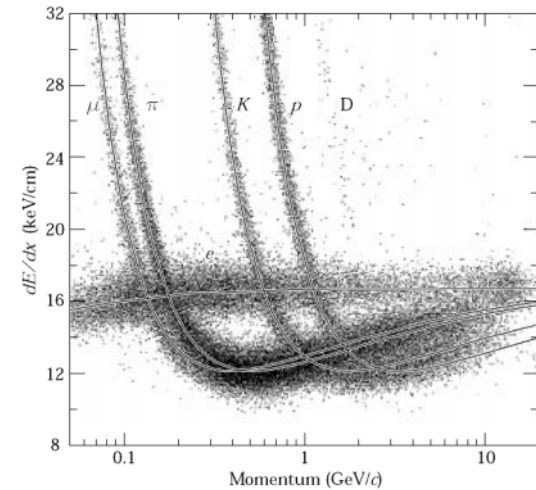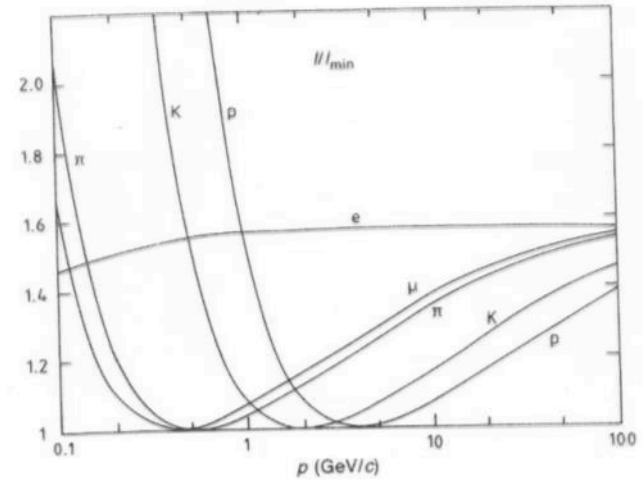
$$\frac{1}{\rho}\frac{dE}{dx} = -4\pi r_e^2\, m_e c^2\, Z_1^2 \frac{p^2 + M^2 c^2}{p^2}\, N_A \frac{Z}{A} \left[\ln \frac{2m_e c^2 F}{I} \frac{p^2}{M^2 c^2} - \frac{p^2}{p^2 + M^2 c^2} \right]$$

Energy Loss by Excitation and Ionization

Energy Loss as a Function of the Momentum
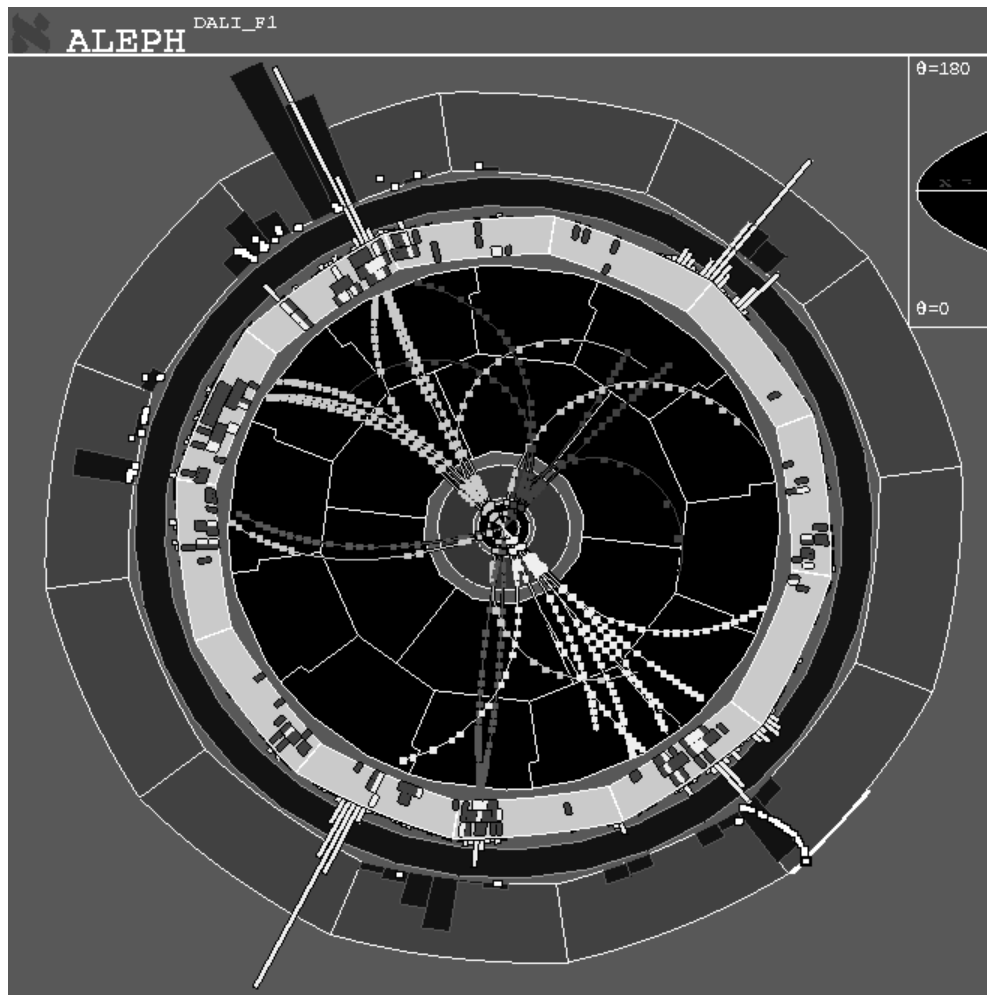
Measure momentum by curvature of the particle track.

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.

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

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

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

$\approx$**Independent of the material**
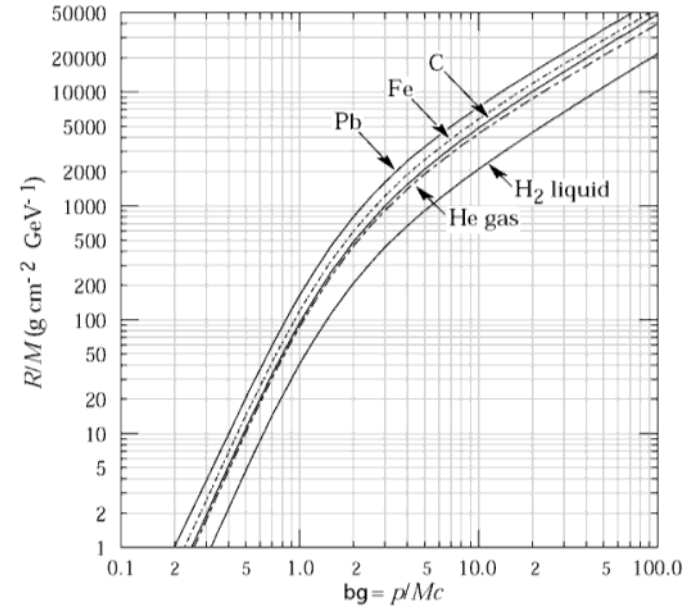
Bragg Peak:

For $\beta\gamma > 3$ the energy loss is $\approx$ constant (Fermi Plateau)

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

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

Energy Loss by Excitation and Ionization
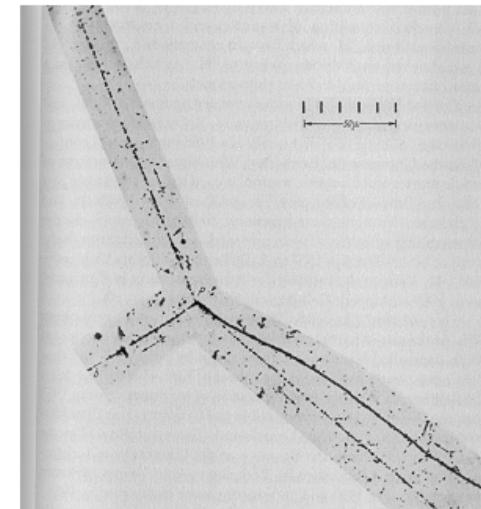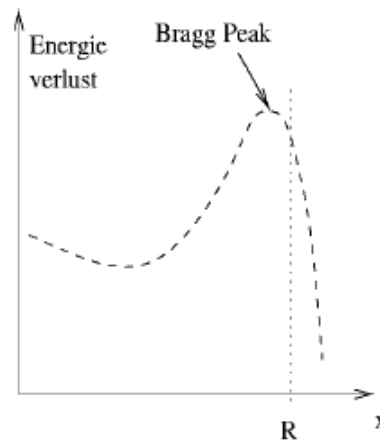
Range of Particles in Matter

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

Energy Loss by Excitation and Ionization
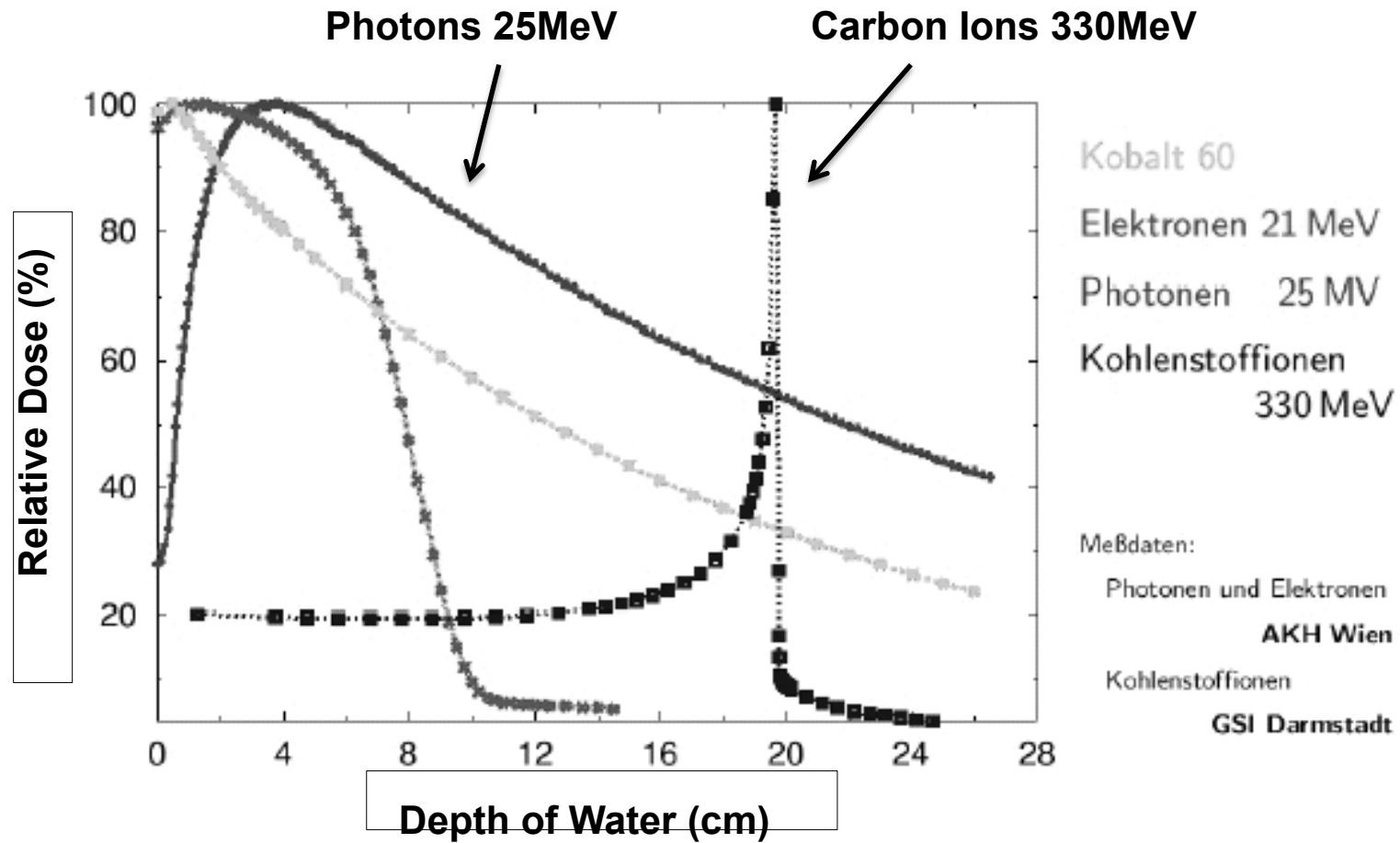
Search for Hidden Chambers in the Pyramids

The structure of the Second Pyramid of Giza is determined by cosmic-ray absorption.

Luis W. Alvarez, Jared A. Anderson, F. El Bedwei, James Burkhard, Ahmed Fakhry, Adib Girgis, Amr Goneid, Fikhry Hassan, Dennis Iverson, Gerald Lynch, Zenab Miligy, Ali Hilmy Moussa, Mohammed-Sharkawi, Lauren Yazolino

Fig. 2 (bottom right). Cross sections of (a) the Great Pyramid of Cheops and (b) the Pyramid of Chephren, showing the known chambers: (A) Smooth limestone cap, (B) the Belzoni Chamber, (C) Belzoni's entrance, (D) Howard-Vyse's entrance, *un* descending passageway, (F) ascending passageway, (G) underground chamber, (/-1) Grand Gallery, (I) King's Chamber, (I) Queen's Chamber, (K) center line of the pyramid.

6 FEBRUARY 1970
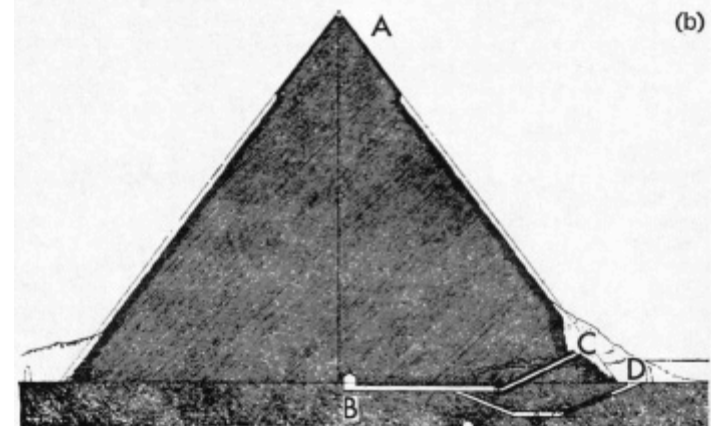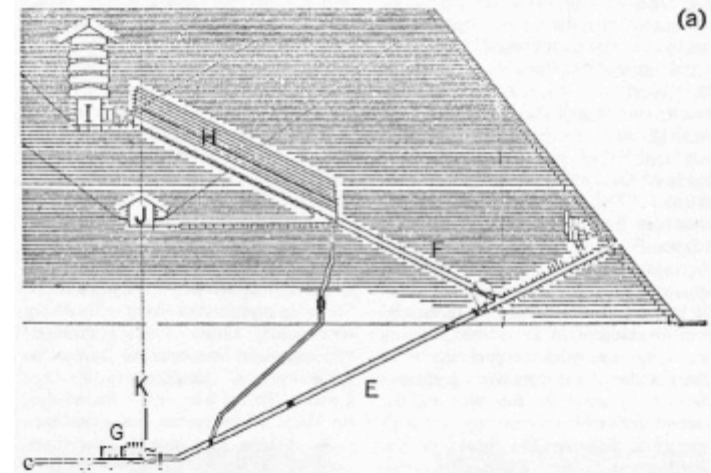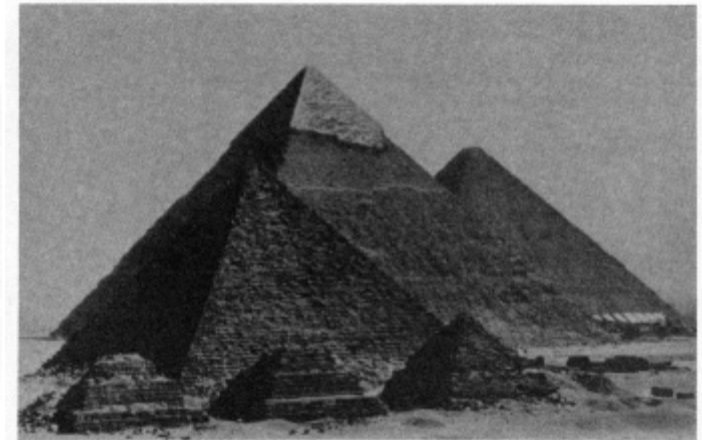
Luis Alvarez used the attenuation of muons to look for chambers in the Second Giza Pyramid → Muon Tomography

He proved that there are no chambers present.

Fig. 13. Scatter plots showing the three stages in the combined analytic and visual analysis of the data and a plot with a simulated chamber. (a) Simulated "x-ray photograph" of uncorrected data. (b) Data corrected for the geometrical acceptance of the apparatus. (c) Data corrected for pyramid structure as well as geometrical acceptance. (d) Same as (c) but with simulated chamber, as in Fig. 12.

W. Riegler, Particle Detectors

Intermezzo: Crossection

Crossection σ: Material with Atomic Mass A and density ρ contains n Atoms/cm³

$$n[\mathrm{cm}^{-3}] = \frac{N_A[\mathrm{mol}^{-1}]\,\rho[\mathrm{g/cm}^3]}{A[\mathrm{g/mol}]} \qquad N_A = 6.022 \times 10^{23}\,\mathrm{mol}^{-1}$$

E.g. Atom (Sphere) with Radius R: Atomic Crossection $\sigma = R^2\pi$

A volume with surface F and thickness dx contains N=nFdx Atoms.
**The total 'surface' of atoms in this volume is N σ.**
The relative area is p = N σ/F = $N_A \rho \sigma$ /A dx =
Probability that an incoming particle hits an atom in dx.

What is the probability P that a particle hits an atom between distance x and x+dx ?
P = probability that the particle does NOT hit an atom in the m=x/dx material layers and that the particle DOES hit an atom in the mth layer

$$P(x)dx = (1-p)^m\, p \approx e^{-m}\, p = \exp\left(-\frac{N_A\rho\sigma}{A}x\right)\frac{N_A\rho\sigma}{A}dx = \frac{1}{\lambda}\exp\left(-\frac{x}{\lambda}\right)dx \qquad \lambda = \frac{A}{N_A\rho\sigma}$$

Mean free path $\displaystyle = \int_0^\infty xP(x)dx = \int_0^\infty \frac{x}{\lambda}e^{-\frac{x}{\lambda}}dx = \lambda$

Average number of collisions/cm $\displaystyle = \frac{1}{\lambda} = \frac{N_A\rho\sigma}{A}$

3/12/13
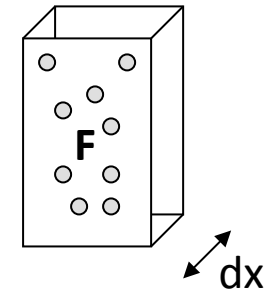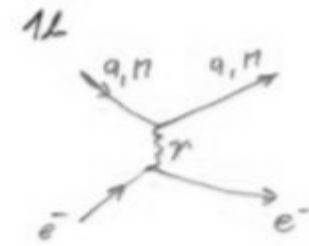
Intermezzo: Differential Crossection

Differential Crossection: $\dfrac{d\sigma(E, E')}{dE'}$

→ **Crossection for an incoming particle of energy E to lose an energy between E' and E'+dE'**

Total Crossection: $\sigma(E) = \displaystyle\int \dfrac{d\sigma(E, E')}{dE'} dE'$

Probability P(E) that an incoming particle of Energy E loses an energy between E' and E'+dE' in a collision:

$$P(E, E')dE' = \dfrac{1}{\sigma(E)} \dfrac{d\sigma(E, E')}{dE'} dE'$$

Average number of collisions/cm causing an energy loss between E' and E'+dE' $= \dfrac{N_A \rho}{A} \dfrac{d\sigma(E, E')}{dE'}$

Average energy loss/cm: $\dfrac{dE}{dx} = -\dfrac{N_A \rho}{A} \displaystyle\int E' \dfrac{d\sigma(E, E')}{dE'} dE'$

3/12/13

Fluctuation of Energy Loss

Up to now we have calculated the average energy loss. The energy loss is however a statistical process and will therefore fluctuate from event to event.

x=0   **x=D**

E   **Δ**   **E - Δ**
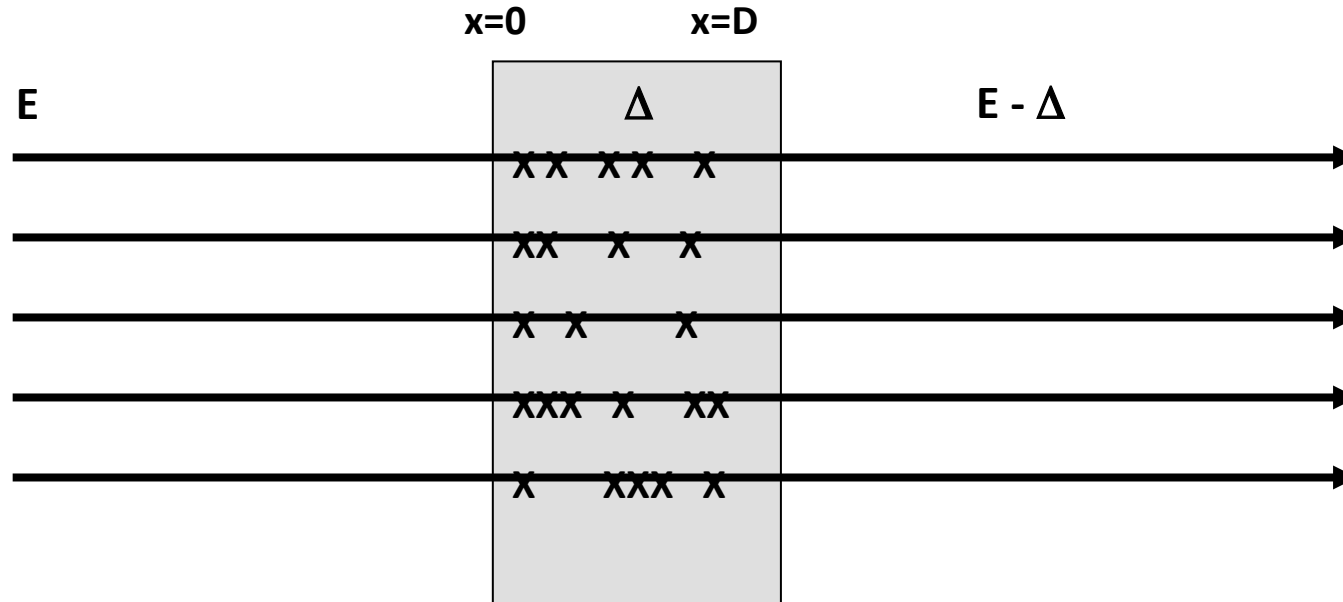
P(Δ) = ? Probability that a particle loses an energy Δ when traversing a material of thickness D

We have see earlier that the probability of an interaction ocuring between distance x and x+dx is exponentially distributed

$$P(x)dx = \frac{1}{\lambda} \exp\left(-\frac{x}{\lambda}\right) dx \qquad \lambda = \frac{A}{N_A \rho \sigma}$$

Probability for n Interactions in D

We first calculate the probability to find n interactions in D, knowing that the probability to find a distance x between two interactions is $P(x)dx = 1/\lambda \exp(-x/\lambda) dx$ with $\lambda = A/ N_A \rho \sigma$

Probability to have no interaction between 0 und D:

$$P(x > D) = \int_D^\infty P(x_1)dx_1 = e^{-\frac{D}{\lambda}}$$

Probability to have one interaction at x_1 and no other interaction:

$$P(x_1, x_2 > D) = \int_D^\infty P(x_1)P(x_2 - x_1)dx_2 = \frac{1}{\lambda}e^{-\frac{D}{\lambda}}$$

Probability to have one interaction independently of x_1:

$$\int_0^D P(x_1, x_2 > D) = \frac{D}{\lambda}e^{-\frac{D}{\lambda}}$$

Probability to have the first interaction at x_1, the second at x_2 .... the nth at x_n and no other interaction:

$$P(x_1, x_2...x_n > D) = \int_D^\infty P(x_1)P(x_2 - x_1)...P(x_n - x_{n-1})dx_n = \frac{1}{\lambda^n}e^{-\frac{D}{\lambda}}$$

Probability for n interactions independently of $x_1, x_2...x_n$

$$\int_0^D \int_0^{x_{n-1}} \int_0^{x_{n-1}} ... \int_0^{x_1} P(x_1, x_2..., x_n > D)dx_1...dx_{n-1} = \frac{1}{n!}\left(\frac{D}{\lambda}\right)^n e^{-\frac{D}{\lambda}}$$

Probability for n Interactions in D

For an interaction with a mean free path of λ , the probability for n interactions on a distance D is given by

$$P(n) = \frac{1}{n!} \left(\frac{D}{\lambda}\right)^n e^{-\frac{D}{\lambda}} = \frac{\bar{n}^n}{n!} e^{-\bar{n}} \qquad \bar{n} = \frac{D}{\lambda} \qquad \lambda = \frac{A}{N_A \rho \sigma}$$

→Poisson Distribution !

If the distance between interactions is exponentially distributed with an mean free path of λ→ the number of interactions on a distance D is Poisson distributed with an average of n̄=D/λ.

How do we find the energy loss distribution ?
If f(E) is the probability to lose the energy E' in an interaction, the probability p(E) to lose an energy E over the distance D ?

$$f(E) = \frac{1}{\sigma} \frac{d\sigma}{dE}$$

$$p(E) = P(1)f(E) + P(2) \int_0^E f(E-E')f(E')dE' + P(3) \int_0^E \int_0^{E'} f(E-E'-E'')f(E'')f(E')dE''dE' + \ldots$$

$$F(s) = \mathcal{L}\left[f(E)\right] = \int_0^\infty f(E)e^{-sE}dE$$
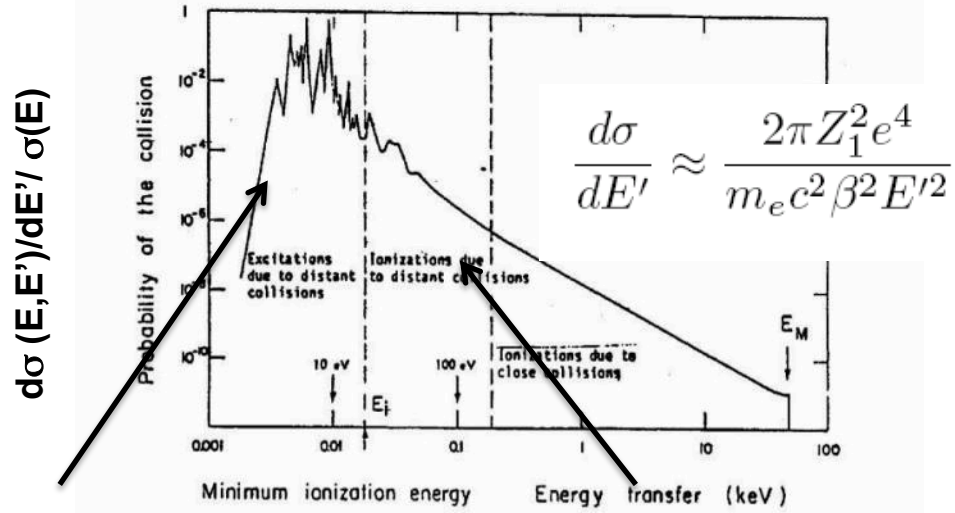
$$\mathcal{L}\left[p(E)\right] = P(1)F(s) + P(2)F(s)^2 + P(3)F(s)^3 + \ldots = \sum_{n=1}^\infty P(n)F(s)^n = \sum_{n=1}^\infty \frac{\bar{n}^n F^n}{n!} e^{-\bar{n}} = e^{\bar{n}(F(s)-1)} - 1 \approx e^{\bar{n}(F(s)-1)}$$

$$p(E) = \mathcal{L}^{-1}\left[e^{\bar{n}(F(s)-1)}\right] = \frac{1}{2\pi i} \int_{\sigma-i\infty}^{\sigma+i\infty} e^{\bar{n}(F(s)-1)+sE}ds$$

Fluctuations of the Energy Loss

Probability f(E) for loosing energy between E' and E'+dE' in a single interaction is given by the differential crossection dσ (E,E')/dE'/ σ(E) which is given by the Rutherford crossection at large energy transfers

$$\frac{d\sigma}{dE'} \approx \frac{2\pi Z_1^2 e^4}{m_e c^2 \beta^2 E'^2}$$

Excitation and ionization   Scattering on free electrons

$$p(x) = \frac{1}{2\pi i} \int_{c-i\infty}^{c+i\infty} \exp(s \log s + xs)\, ds. = \frac{1}{\pi} \int_0^\infty \exp(-t\log t - xt) \sin(\pi t)\, dt.$$

$$x = \frac{E}{n\epsilon} + C_\gamma - 1 - \ln \overline{n} \qquad \overline{n} = \frac{N_A \rho Z_2 k D}{A\epsilon}$$

$$\ln \epsilon = \ln \frac{I^2}{E_{max}} + 2\beta^2$$

P(E,Δ)

Energy Loss by Excitation and Ionization
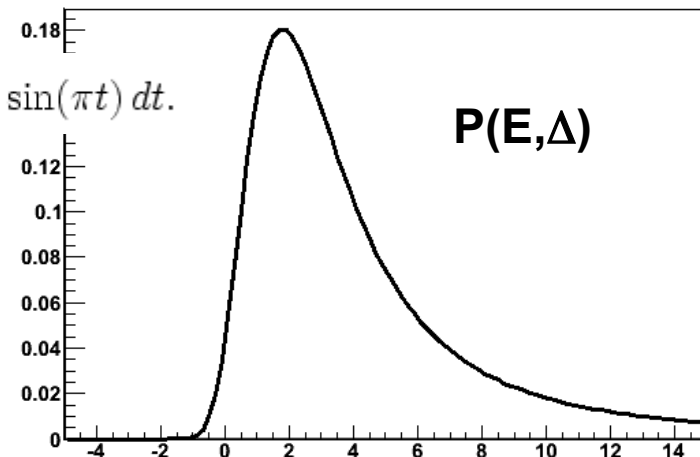
Landau Distribution

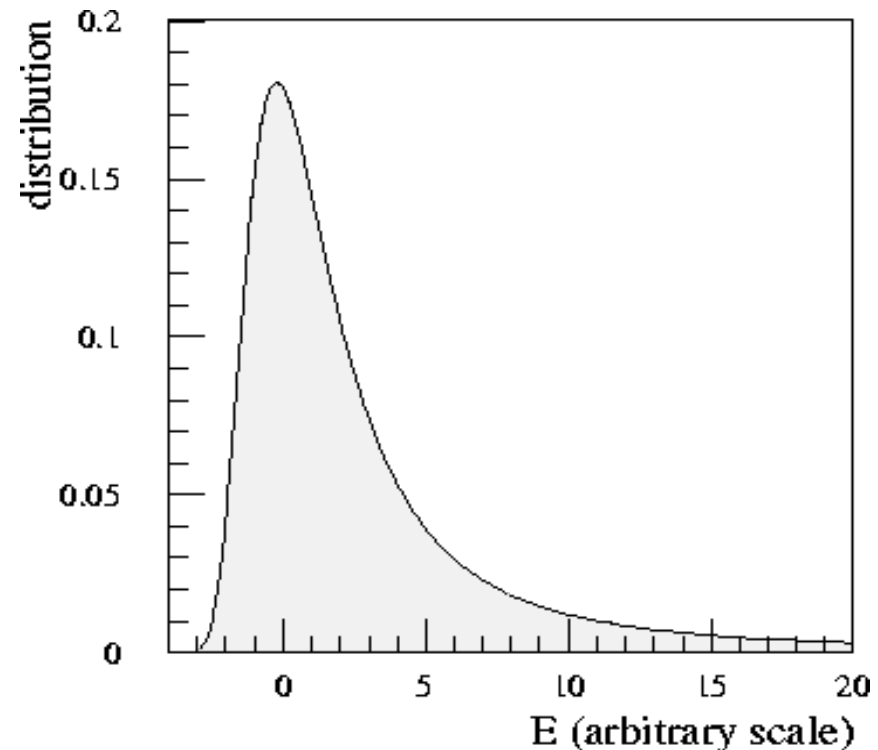## Landau Distribution

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.

Energy Loss by Excitation and Ionization

Landau Distribution

LANDAU DISTRIBUTION OF ENERGY LOSS:

4 cm Ar-CH4 (95-5)
5 bars

N = 460 i.p.

FWHM~250 i.p.

Counts

For a Gaussian distribution: $\sigma_N \sim 21$ **i.p.**
FWHM ~ 50 i.p.
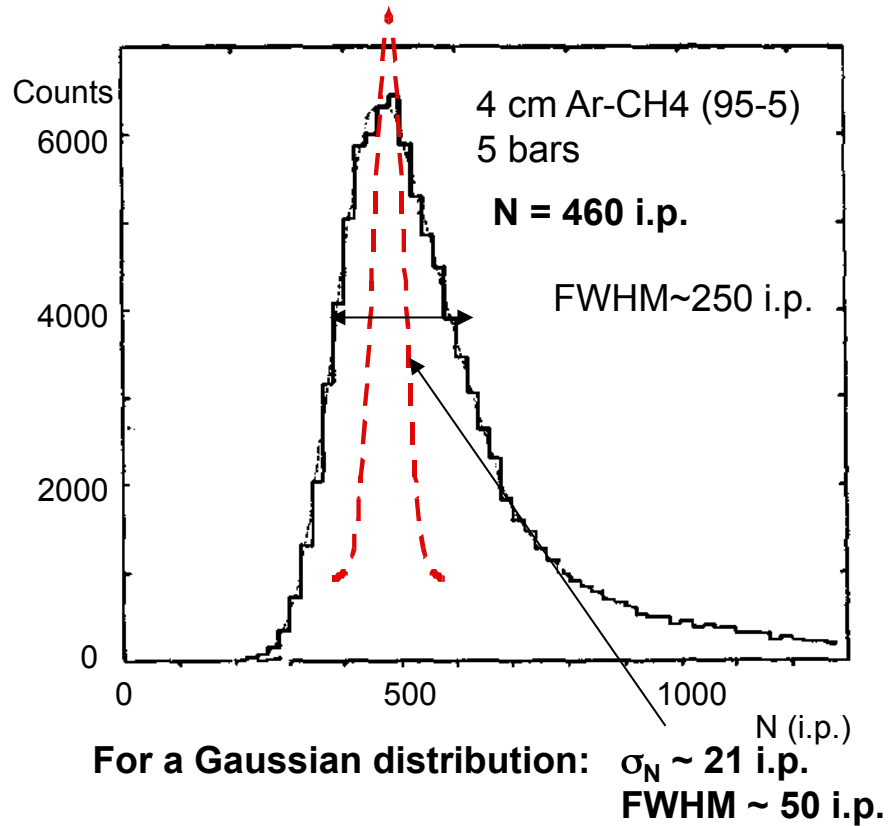
PARTICLE IDENTIFICATION
Requires statistical analysis of hundreds of samples

15 GeV/c

protons   *electrons*

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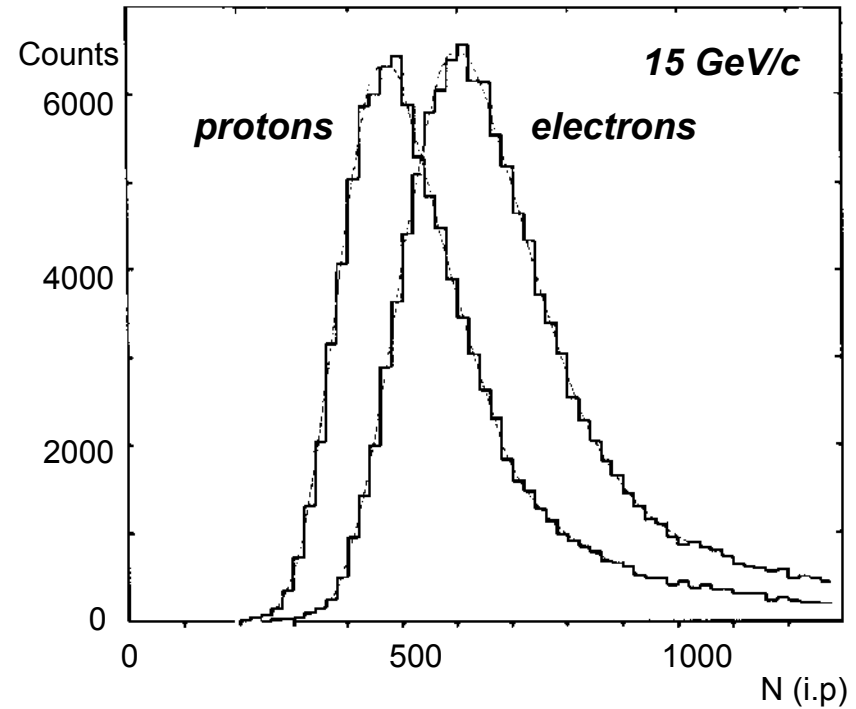
I. Lehraus et al, Phys. Scripta 23(1981)727

Particle Identification

Measured energy loss

'average' energy loss
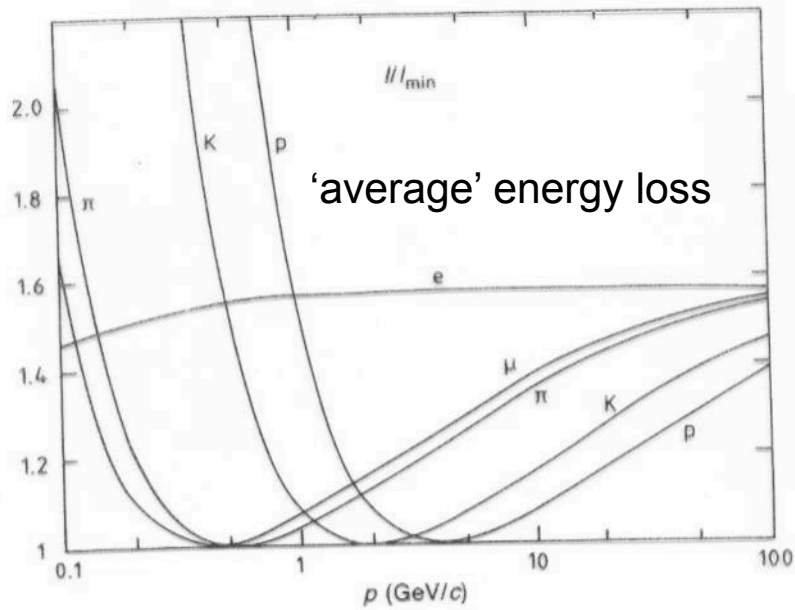
In certain momentum ranges, particles can be identified by measuring the energy loss.
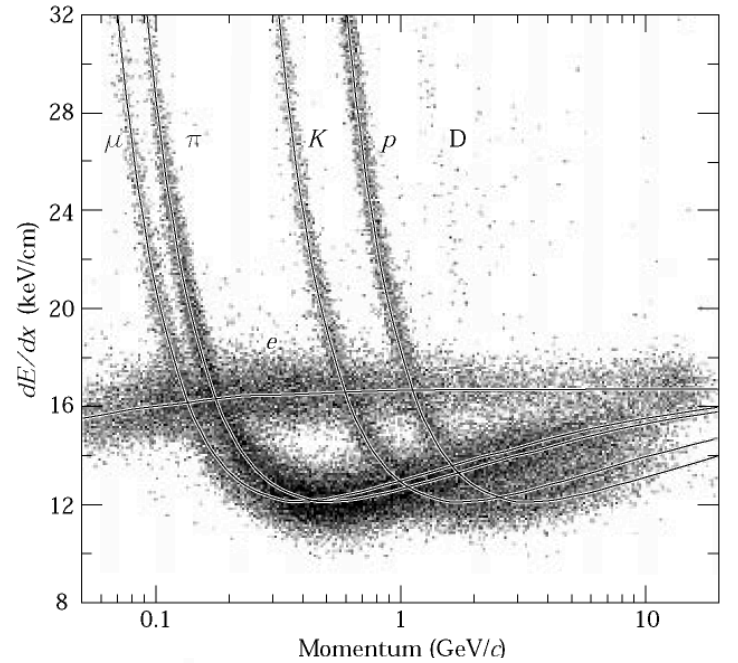
BLUE => PIONS   RED => KAONS   GREEN => PROTONS   MAGENTA => ELECTRONS   BLACK => NO ID POSSIBLE

dE/dx vs. Rigidity (~ 50 HIJING Events)

STAR TPC

Energy Loss by Excitation and Ionization
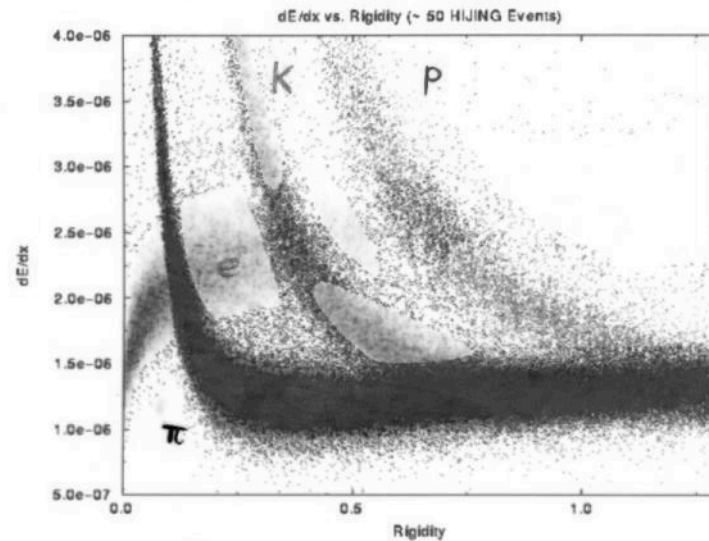
Bremsstrahlung

A charged particle of mass M and charge $q = Z_1 e$ 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.
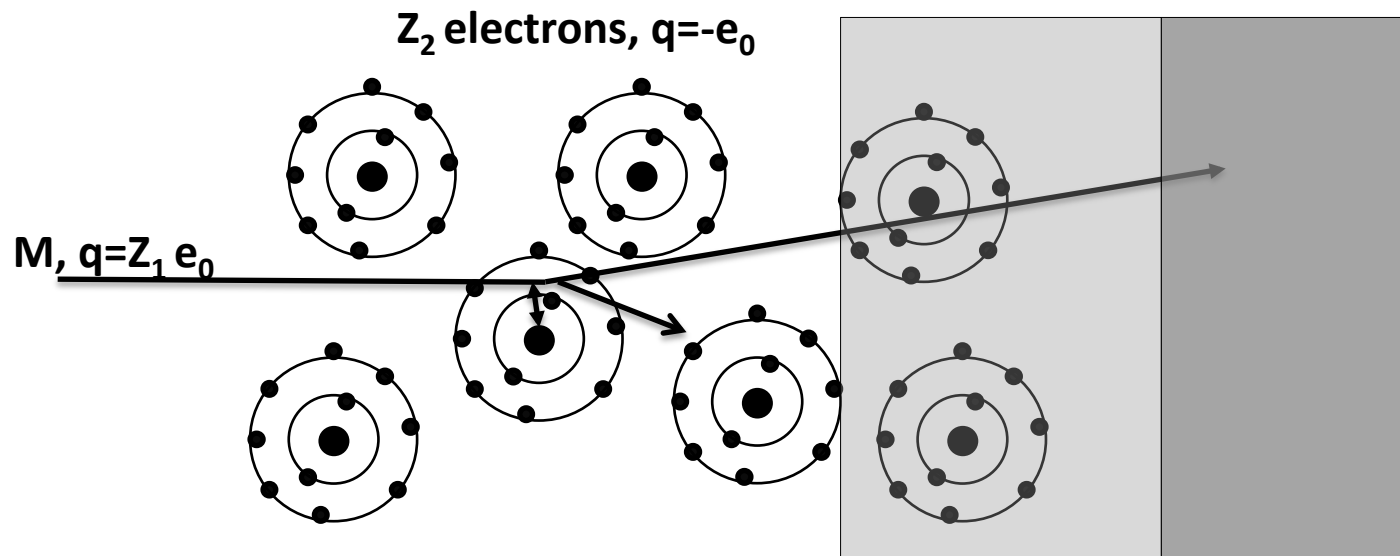
Bremsstrahlung, Classical

q, M $\bigotimes_{Ze}$ $q = Z_1 \cdot e$

$$\frac{d\sigma}{d\Omega} = \left(\frac{2 Z_1 Z_2 e^2}{4\pi\epsilon_0 \, p \cdot v}\right)^2 \frac{1}{(2 \sin\frac{\theta}{2})^4} \qquad p = M v \gamma$$

"Rutherford Scattering"

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

$$\frac{d\sigma}{dQ} = 8\pi \left(\frac{Z_1 Z_2 e^2}{4\pi\epsilon_0 \, \beta c}\right)^2 \cdot \frac{1}{Q^3}$$

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

$\longrightarrow$ From Maxwell's Eq (Jackson)

$$\lim_{\omega \to 0} \frac{dI}{d\omega} \sim \frac{2}{3\pi} \frac{Z_1^2 e^2}{M^2 c^3} \frac{1}{4\pi\epsilon_0} Q^2, \text{ Radiated Energy between } \omega, \omega + d\omega$$
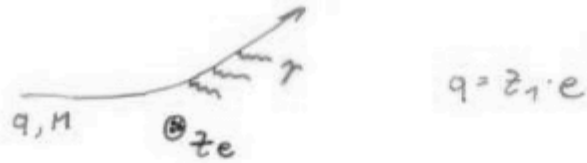
$$\frac{dE}{dx} = \frac{N_A \, \rho}{A} \cdot \int_0^{\omega_{max}} d\omega \int_{Q_{min}}^{Q_{max}} dQ \frac{dI}{d\omega} \cdot \frac{d\sigma}{dQ} \qquad , \quad \omega_{max} = \frac{E}{\hbar}$$

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

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

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

Because of the acceleration the particle radiated EM waves → 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

Proportional to Z^2/A of the Material.

Proportional to Z_1^4 of the incoming particle.

Proportional to ρ of the material.

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

Proportional to the Energy of the Incoming particle →

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

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

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

Critical Energy

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

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.
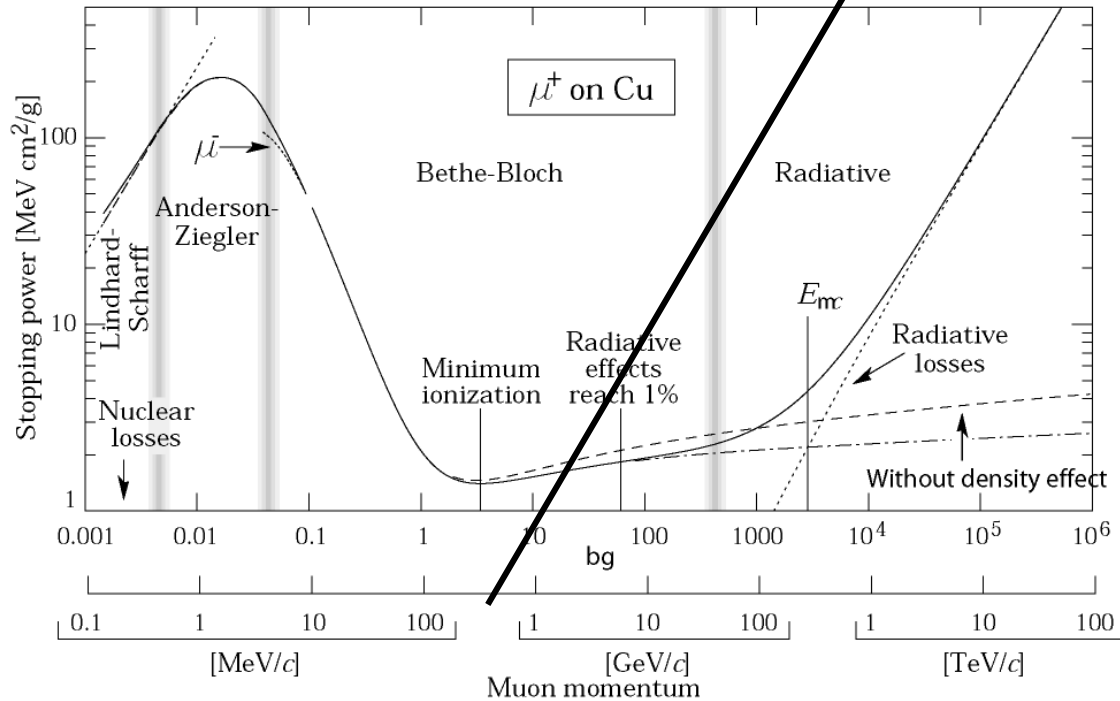
Electron Momentum   5   50   500   MeV/c

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

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

Pair Production, QM
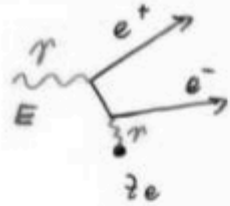
The Diagram is very similar to Bremsstrahlung

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

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

"Crossing Symetry: bring particle to the other side and make it the antiparticle" → "same" Crossection ...

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

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

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

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

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

For $E\gamma \gg m_e c^2 = 0.5 MeV$: $\lambda = 9/7 X_0$

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

(a) Carbon (Z = 6)
○ - experimental σ_{tot}

$\sigma_{p.e.}$

$\sigma_{Rayleigh}$

κ_{nuc}

κ_e

$\sigma_{Compton}$

Cross section (barns/atom)

Photon Energy

Bremsstrahlung + Pair Production → EM Shower
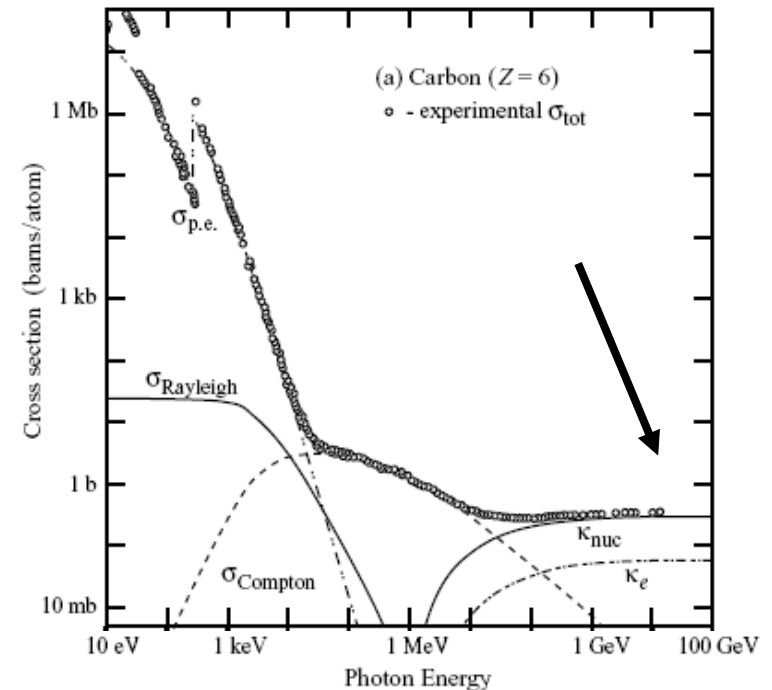
Multiple Scattering

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:

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

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

Multiple Scattering

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

$$\vec{B} \quad \otimes$$

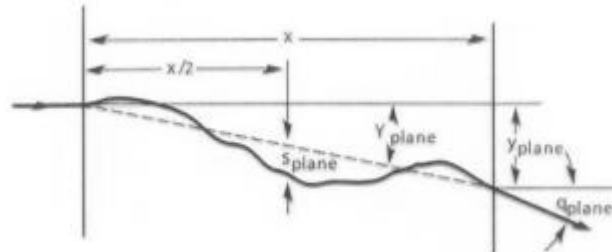$$p = q \cdot R \cdot B$$

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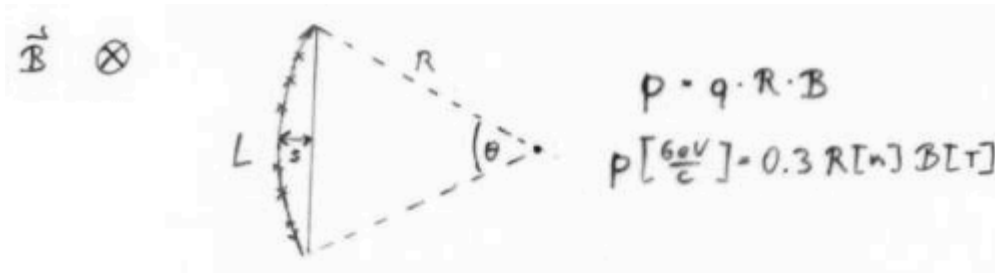
$$L = R \cdot \theta$$

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

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

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

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

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

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

Limit → Multiple Scattering

Multiple Scattering

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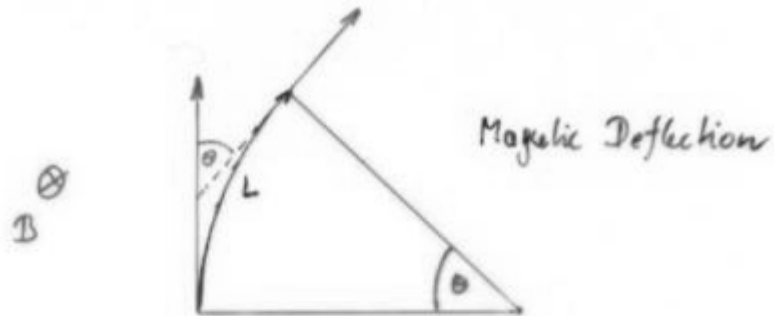
$$p \left[\frac{GeV}{c} \right] = 0.3 \; R \, [m] \; B \, [T]$$

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

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

$\rightarrow$ Independent of p

$$\frac{\Delta p}{P}\bigg|_{tot} = \sqrt{\left(\frac{\Delta p}{P}\bigg|_{Sag} \right)^2 + \left(\frac{\Delta p}{P}\bigg|_{ms} \right)^2}$$
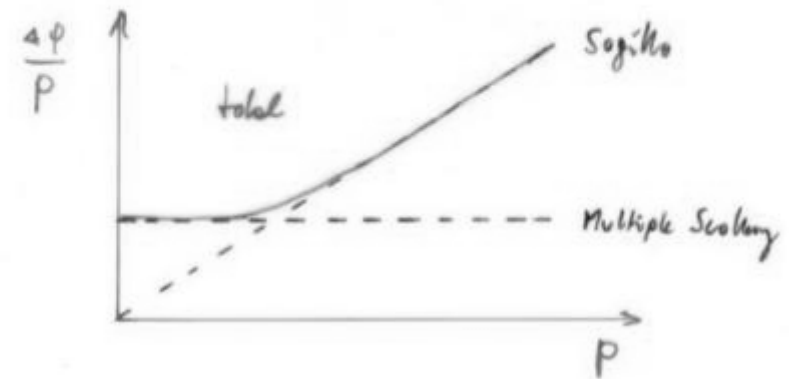
Multiple Scattering

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

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

Cherenkov Radiation

If we describe the passage of a charged particle through material of dielectric permittivity ϵ (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

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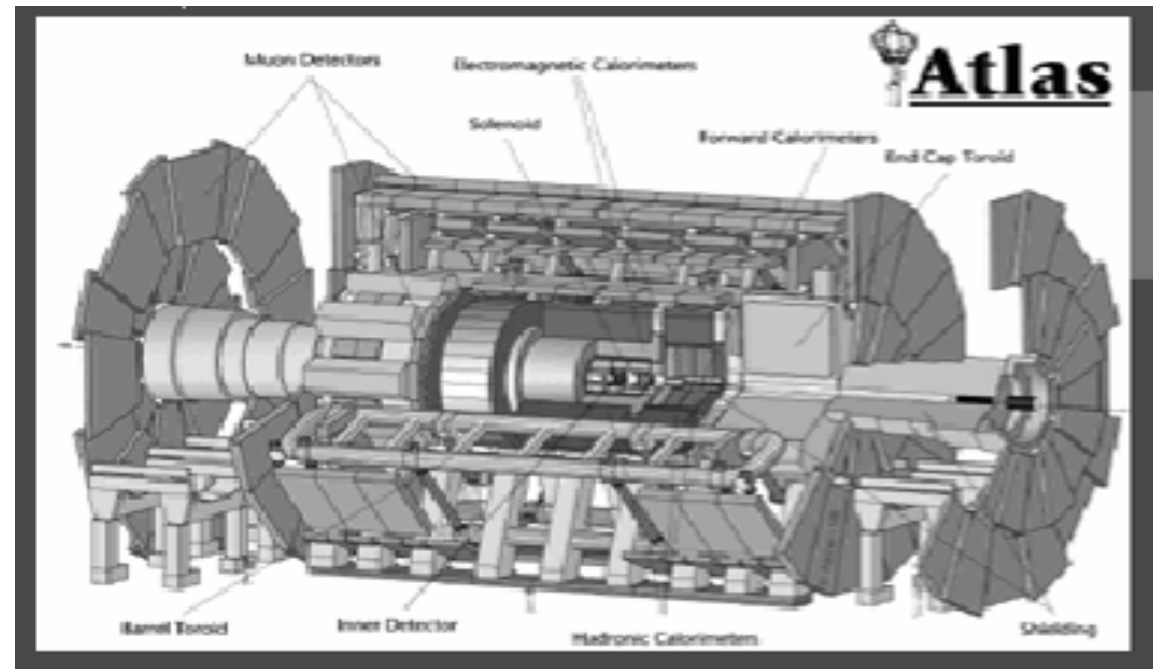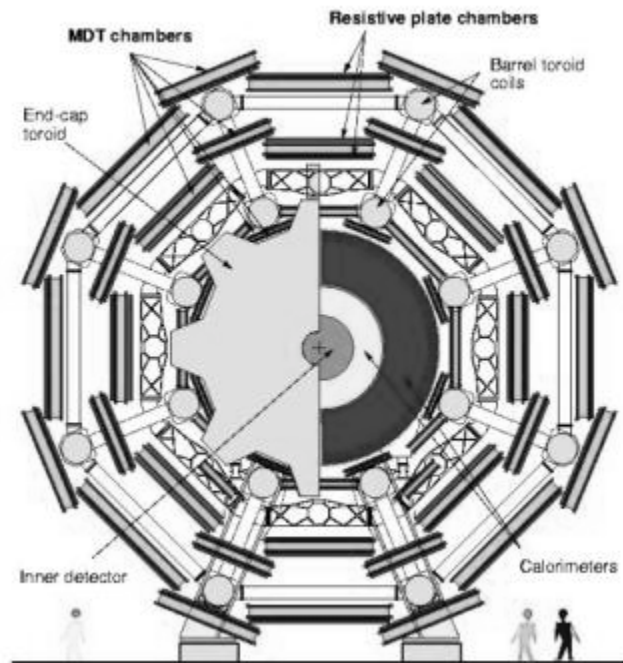
$$\frac{dE}{dxd\omega}\frac{1}{\hbar} = \frac{\alpha}{c}\left(1 - \frac{1}{\beta^2 n^2}\right) \qquad \rightarrow \qquad \frac{dN}{dxd\lambda} = \frac{2\pi\alpha}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2}\right) \qquad \omega = \frac{2\pi c}{\lambda}$$

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 Θ_c , that is related to the refractive index n and the particle velocity by

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

M, q=$Z_1 e_0$
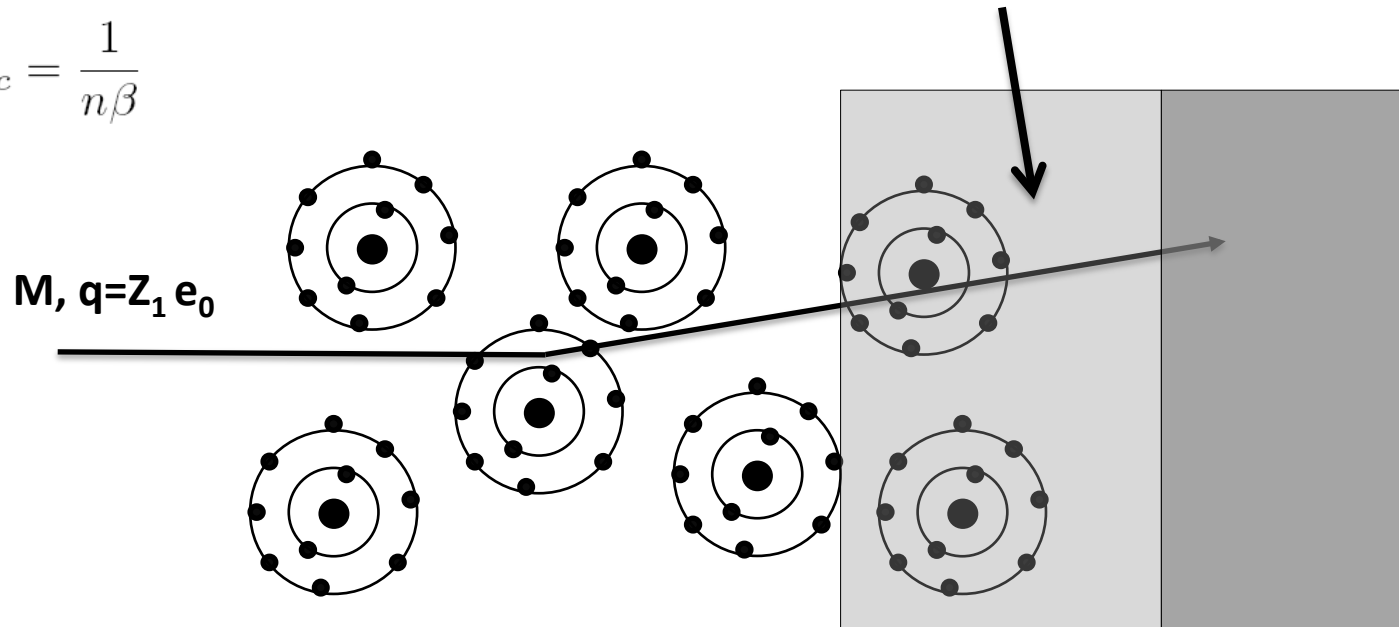
Cherenkov Radiation

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

$l_{light} = (c/n)\Delta t$

wave front

θ

$l_{part} = \beta c \Delta t$

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

with $n = n(\lambda) \geq 1$

$L \cdot \tan\theta$

L

θ_C

- $\beta_{thr} = \dfrac{1}{n}$ $\rightarrow$ $\theta_C \approx 0$ Cherenkov threshold

- $\theta_{max} = \arccos \dfrac{1}{n}$ 'saturated' angle (β=1)

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

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

= Number of emitted Photons/length with λ between λ_1 and λ_2

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

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

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	0.83-0.976	2.7 - 4.6
air	$2.93 \cdot 10^{-4}$	0.9997	41.2
He	$3.3 \cdot 10^{-5}$	0.99997	123

Ring Imaging Cherenkov Detector (RICH)

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

~ UV Photons

Detector

Mirror (Spherical)

Gas

$200 \frac{GeV}{c} \ k, \pi$

Resolution $\frac{\Delta\eta}{\eta} = \eta^2 \beta^3 n \Delta\theta \frac{1}{\sqrt{N_0 L'}}$ $\left(\eta = \frac{1}{\sqrt{1-\beta^2}}\right)$

Angle Measurement accuracy

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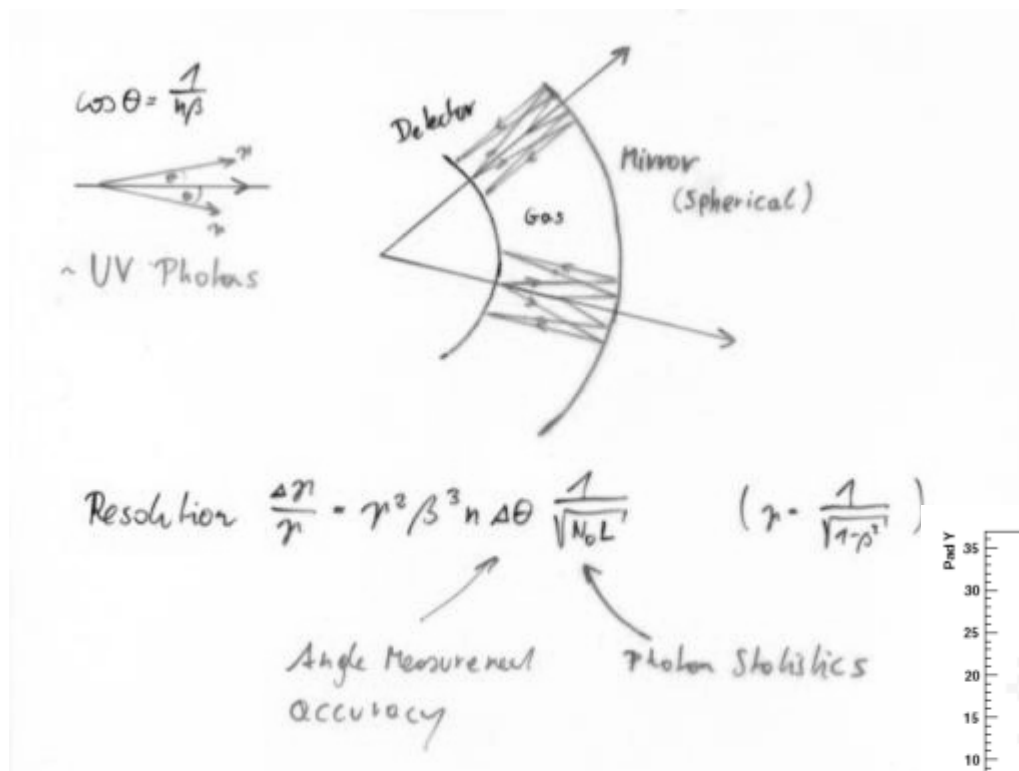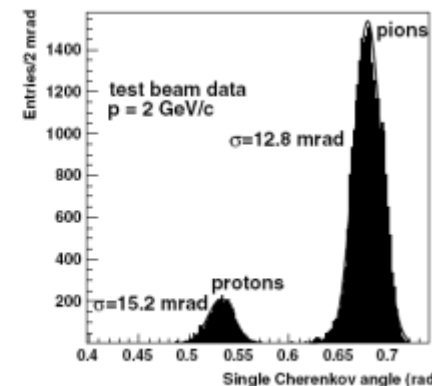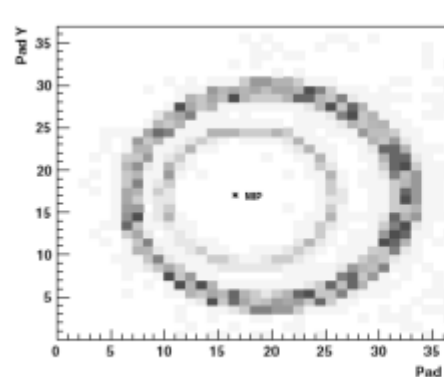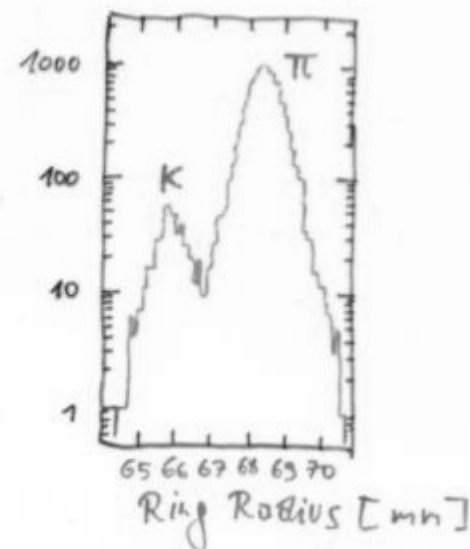
medium	n	θ_{max} (deg.)	N_{ph} (eV^{-1} cm^{-1})
air*	1.000283	1.36	0.208
isobutane*	1.00127	2.89	0.941
water	1.33	41.2	160.8
quartz	1.46	46.7	196.4

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

LHCb RICH
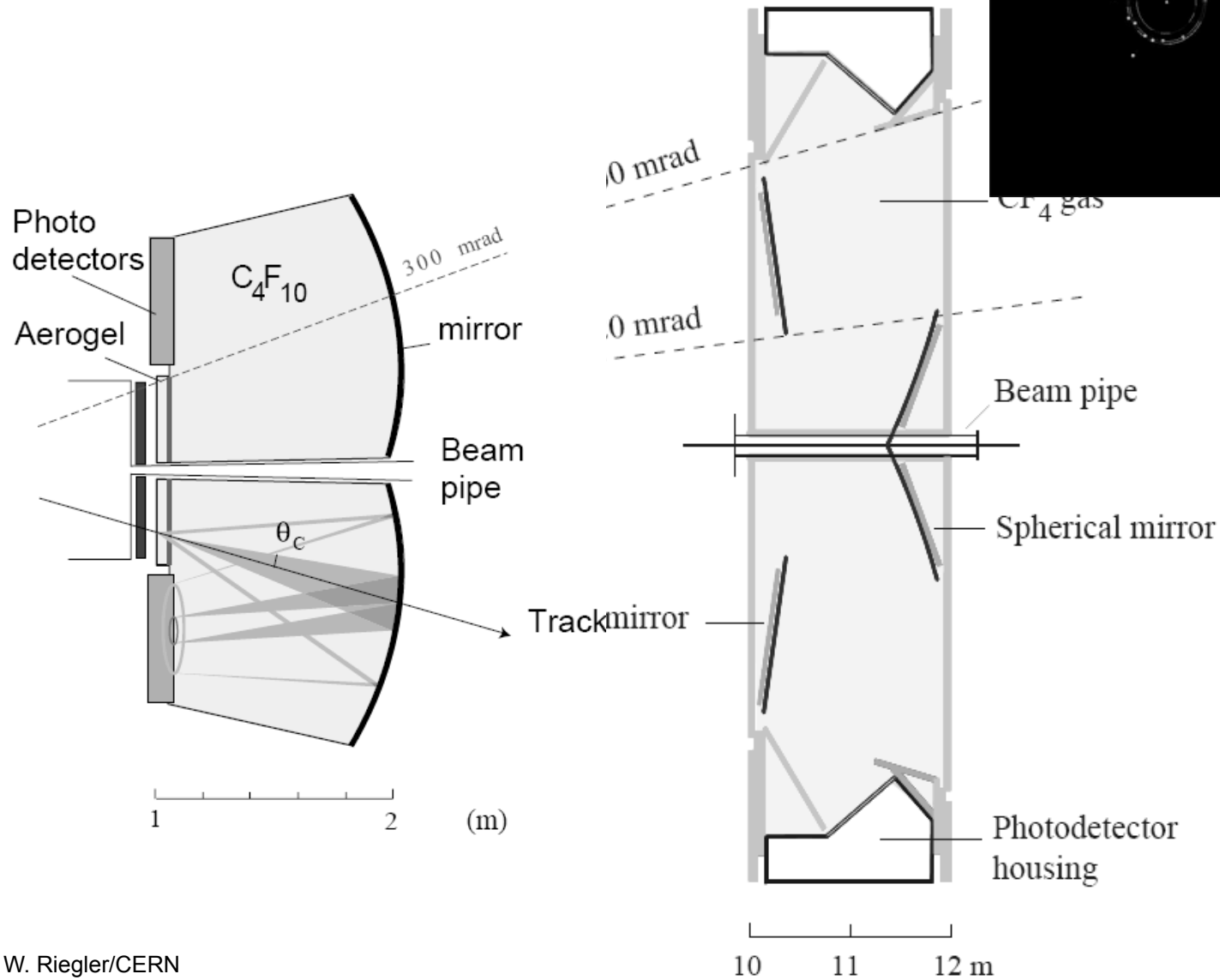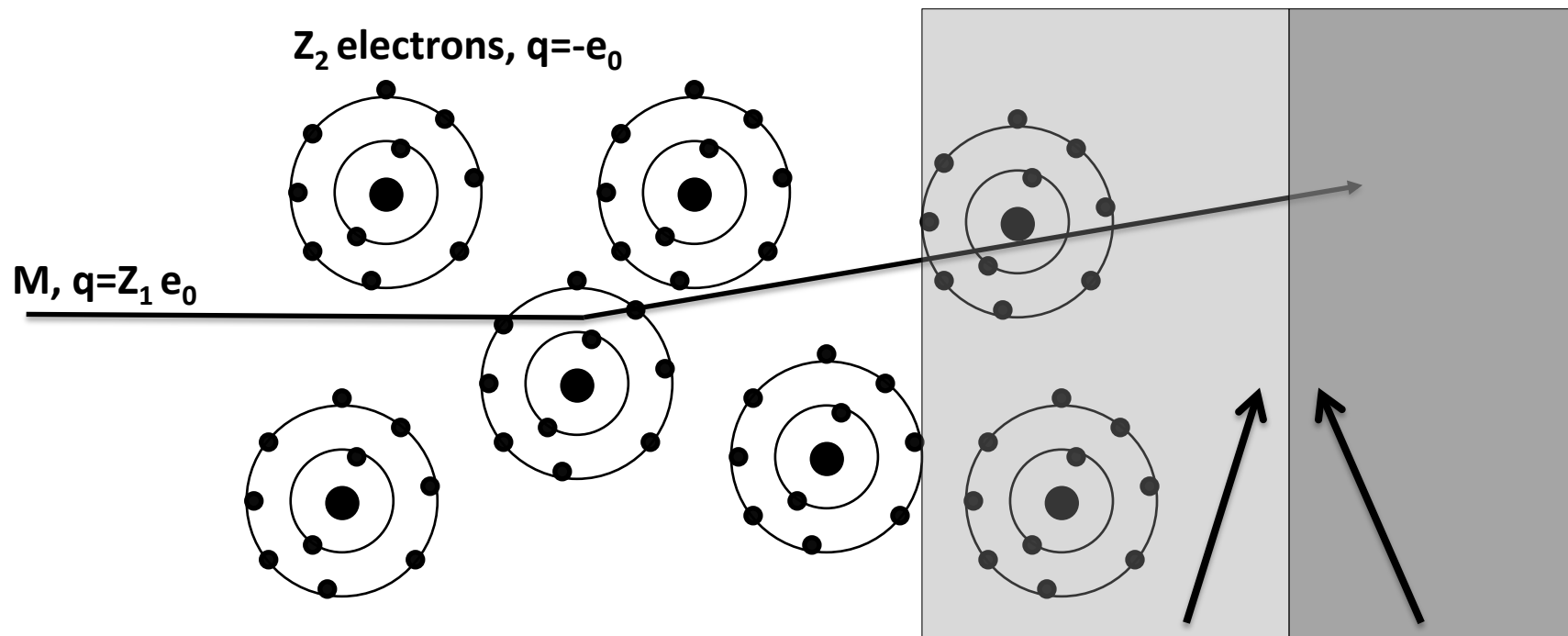
Photo detectors

C_4F_{10}

Aerogel

300 mrad

mirror

Beam pipe

θ_C

Track mirror

1   2   (m)

0 mrad

0 mrad

CF$_4$ gas

Beam pipe

Spherical mirror

mirror

Photodetector housing

10   11   12 m

Transition Radiation

Z$_2$ electrons, q=-e$_0$

M, q=Z$_1$ e$_0$

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>.

3/12/13

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 $\quad \varepsilon_0 \quad | \quad \varepsilon_2$

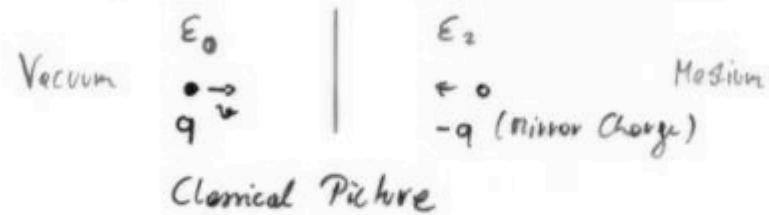$q \quad \bullet \xrightarrow{v} \quad | \quad \leftarrow \circ \quad$ Medium

$\quad \quad | \quad -q$ (Mirror Charge)

Classical Picture

$q = Z_1 e$

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

$\hbar \omega_p$ .... 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. $\gamma = 1000 \quad 2 - 20 \, keV$ 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.

X-Rays

particle

Detector

Radiator
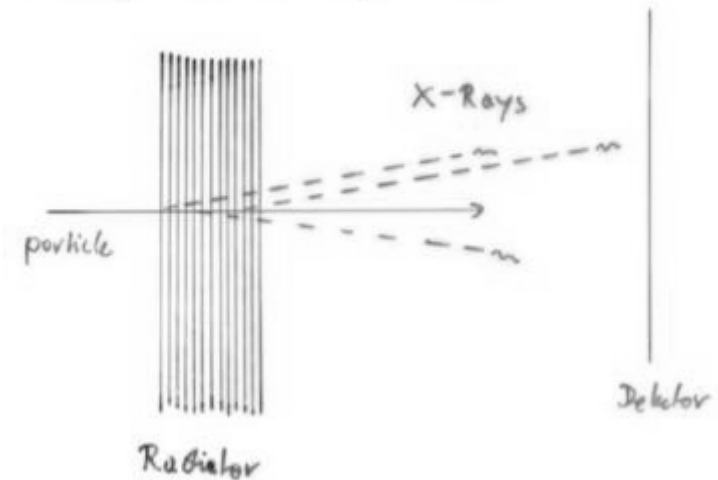
Electromagnetic Interaction of Particles with Matter

Ionization and Excitation:

Charged particles traversing material are exciting and ionizing the atoms.

The average energy loss of the incoming particle by this process is to a good approximation described by the Bethe Bloch formula.

The energy loss fluctuation is well approximated by the Landau distribution.

Multiple Scattering and Bremsstrahlung:

The incoming particles are scattering off the atomic nuclei which are partially shielded by the atomic electrons.

Measuring the particle momentum by deflection of the particle trajectory in the magnetic field, this scattering imposes a lower limit on the momentum resolution of the spectrometer.

The deflection of the particle on the nucleus results in an acceleration that causes emission of Bremsstrahlungs-Photons. These photons in turn produced e+e- pairs in the vicinity of the nucleus, which causes an EM cascade. This effect depends on the 2nd power of the particle mass, so it is only relevant for electrons.

3/12/13

Electromagnetic Interaction of Particles with Matter
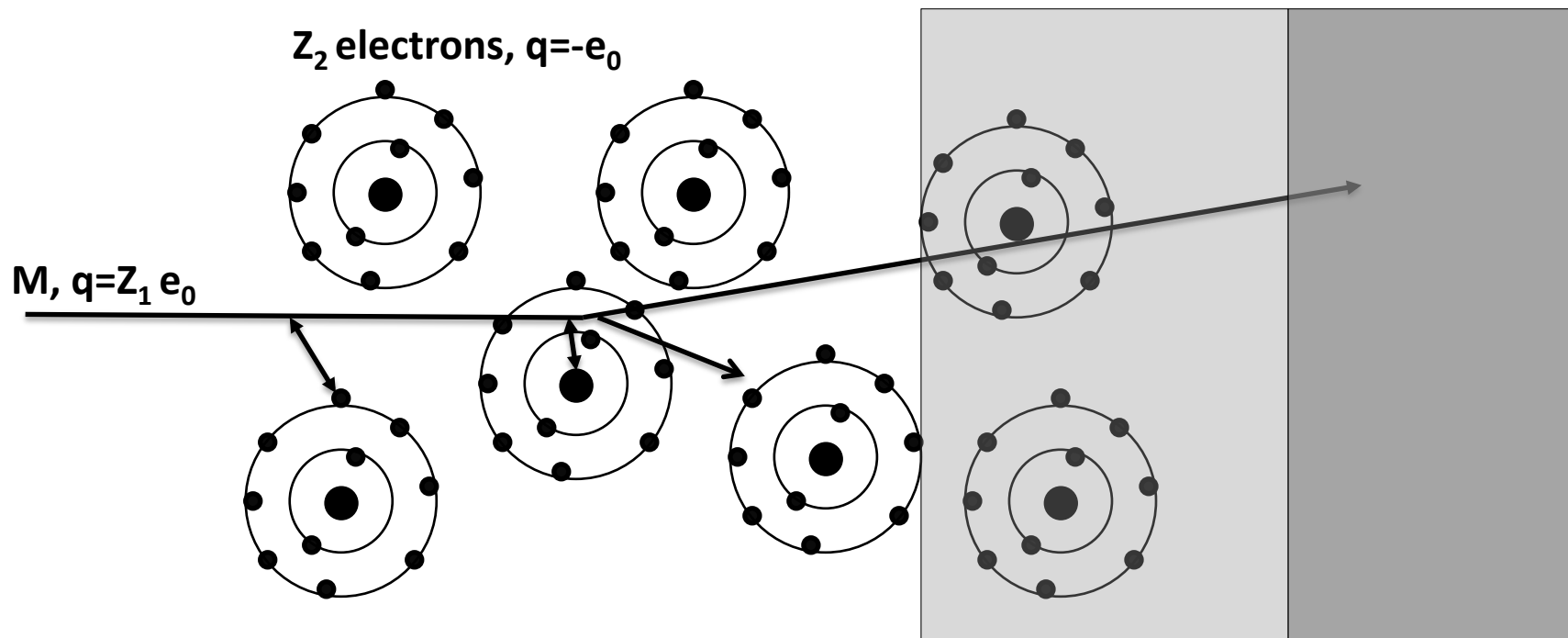
Cherenkov Radiation:

If a particle propagates in a material with a velocity larger than the speed of light in this material, Cherenkov radiation is emitted at a characteristic angle that depends on the particle velocity and the refractive index of the material.

Transition Radiation:

If a charged particle is crossing the boundary between two materials of different dielectric permittivity, there is a certain probability for emission of an X-ray photon.

→ The strong interaction of an incoming particle with matter is a process which is important for Hadron calorimetry and will be discussed later.

3/12/13

Electromagnetic Interaction of Particles with Matter

Z_2 electrons, $q=-e_0$

M, $q=Z_1 e_0$

Now that we know all the Interactions we can talk about Detectors !

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

Interaction with the atomic nucleus. The particle is deflected (scattered) causing <u>multiple scattering</u> of the particle in the material. During this scattering a <u>Bremsstrahlung</u> 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 <u>Cherenkov Radiation</u>. 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>.

3/12/13

Now that we know all the Interactions we can talk about Detectors !