Particle Physics Instrumentation

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2012 ASIA-EUROPE-PACIFIC SCHOOL OF HIGH-ENERGY PHYSICS: AEPSHEP2012
from 14 October to 27 October 2012

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: C.T.R. Wilson, Cloud Chamber
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: Donald Glaser, Bubble Chamber
1968: L. Alvarez, Hydrogen Bubble Chamber & Discoveries
1992: Georges Charpak, Multi Wire Proportional Chamber

The ‘Real’ World of Particles

E. Wigner:

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

Spin=0,1/2,1,3/2 … Mass>0

ANNALS OF MATHEMATICS
Vol. 40, No. 1, January, 1939

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

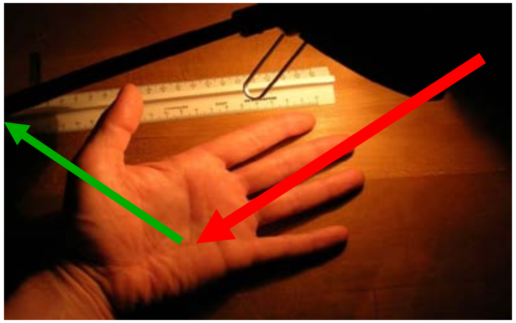
The ‘Real’ World of Particles

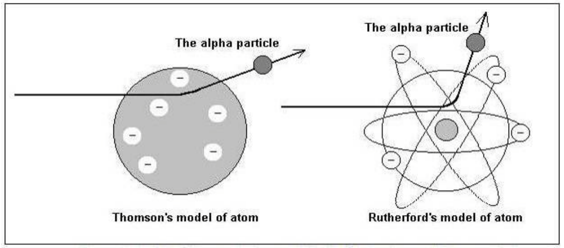
W. Riegler:

“…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 …”





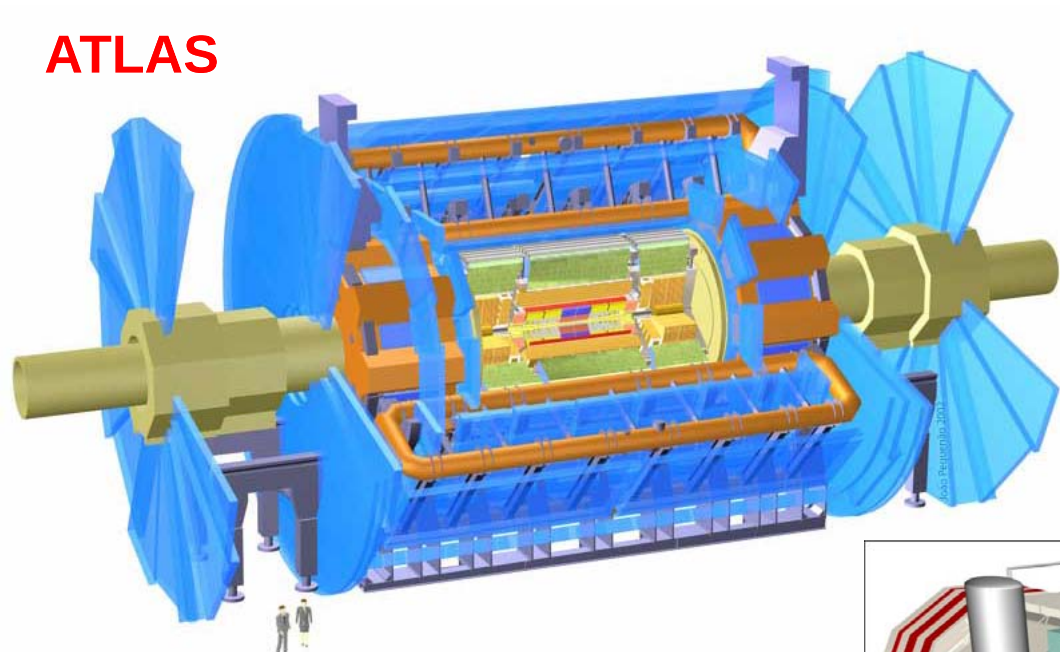
Looking at your hand by scattering light off it is the same thing as looking at the nucleons by scattering alpha particles (or electrons) off it.

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

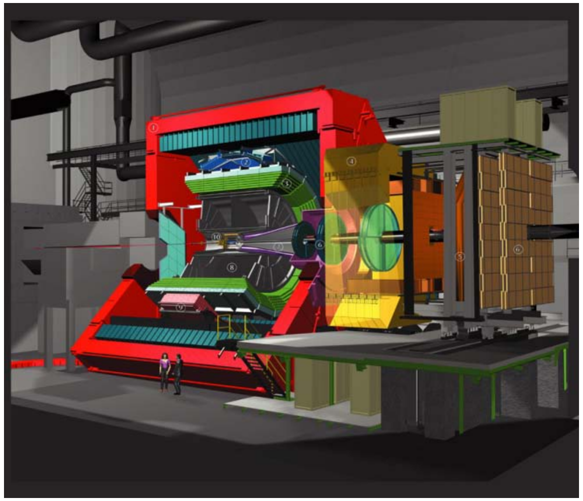
Particle Detector Systems

The Giants at LHC

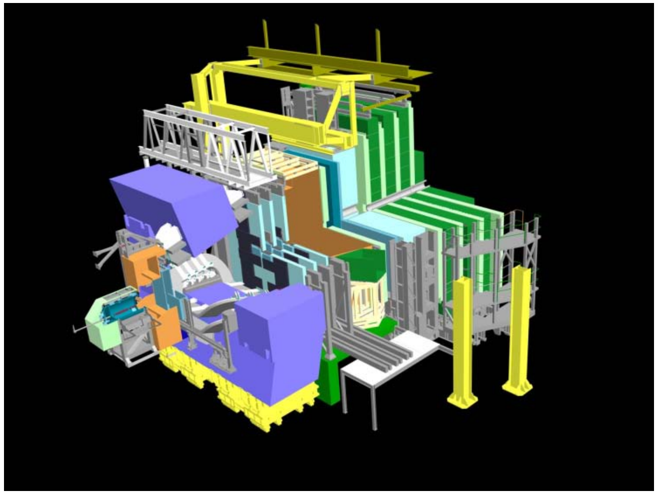
ATLAS

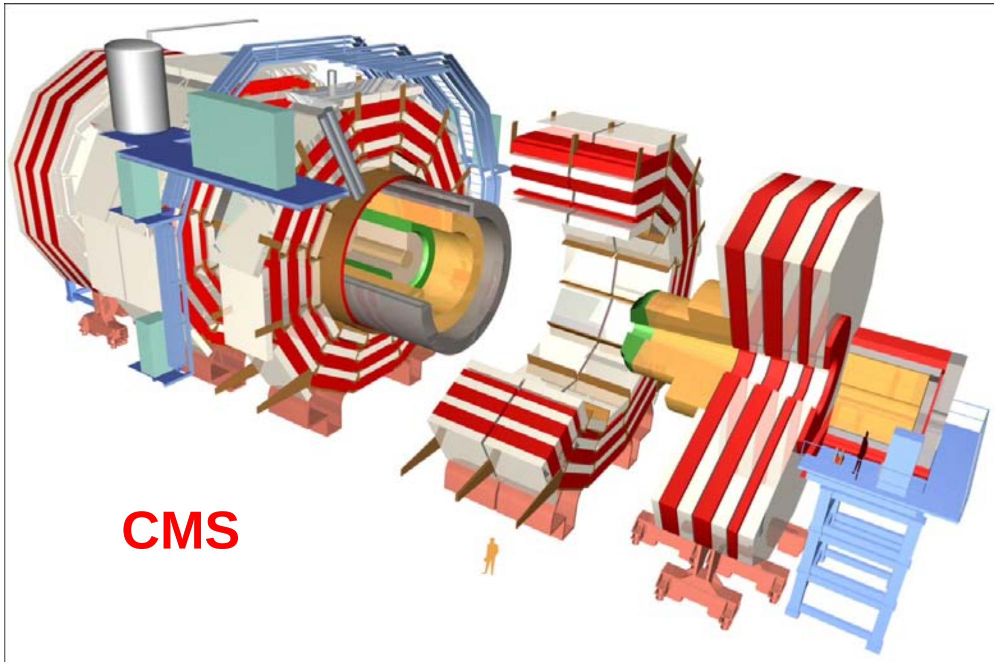


ALICE



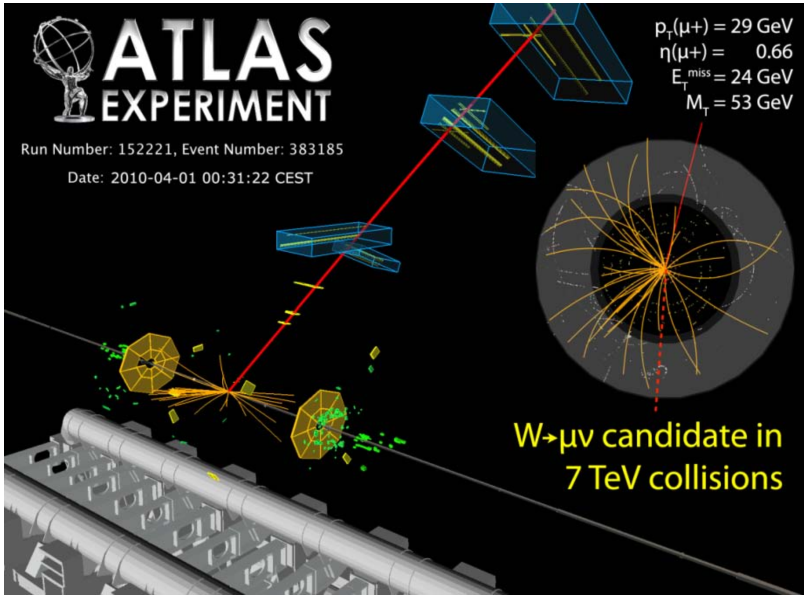
LHCb

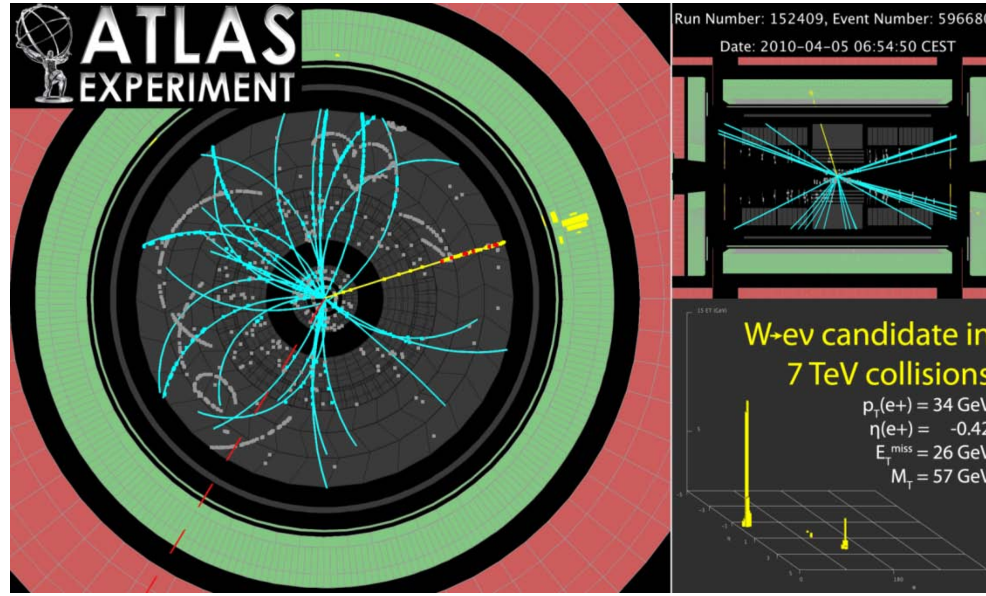


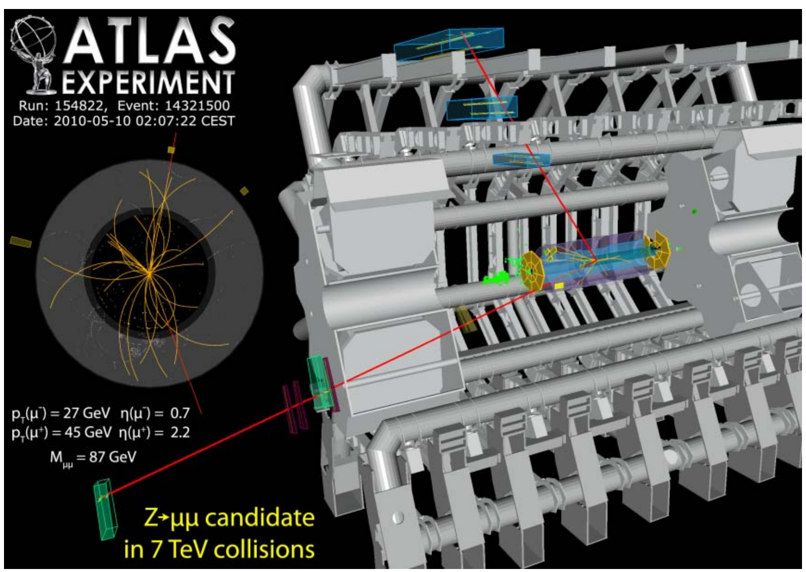


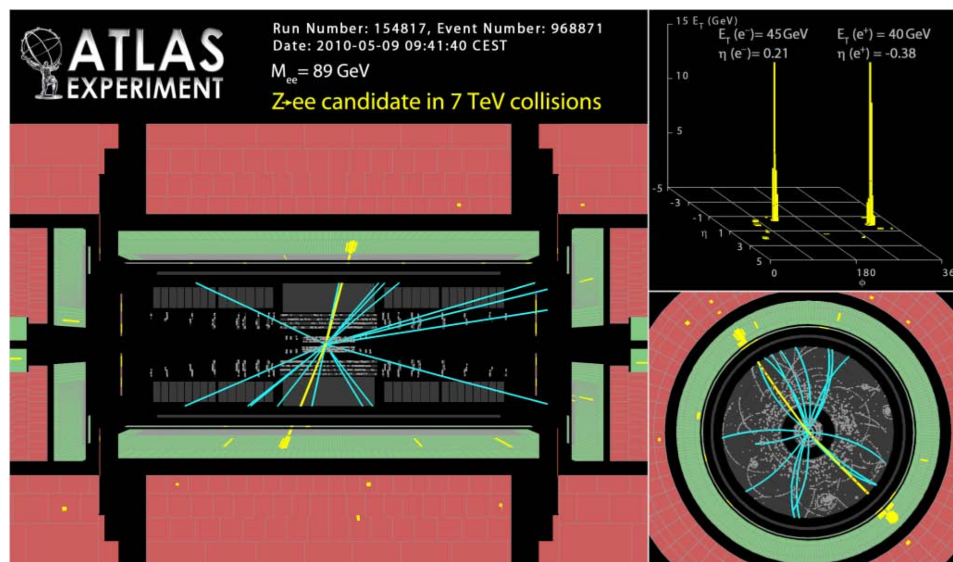
CMS

The Giants at LHC

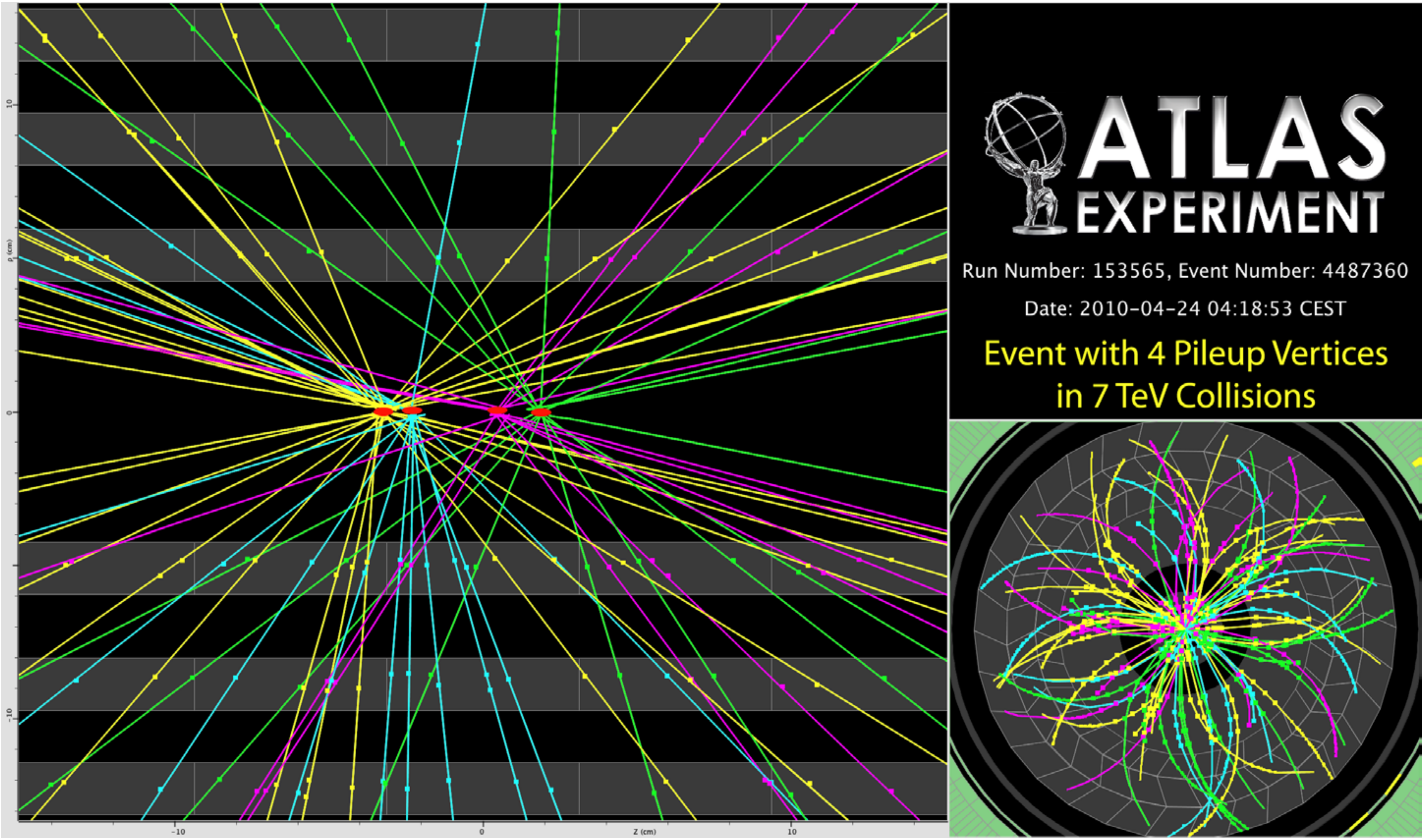




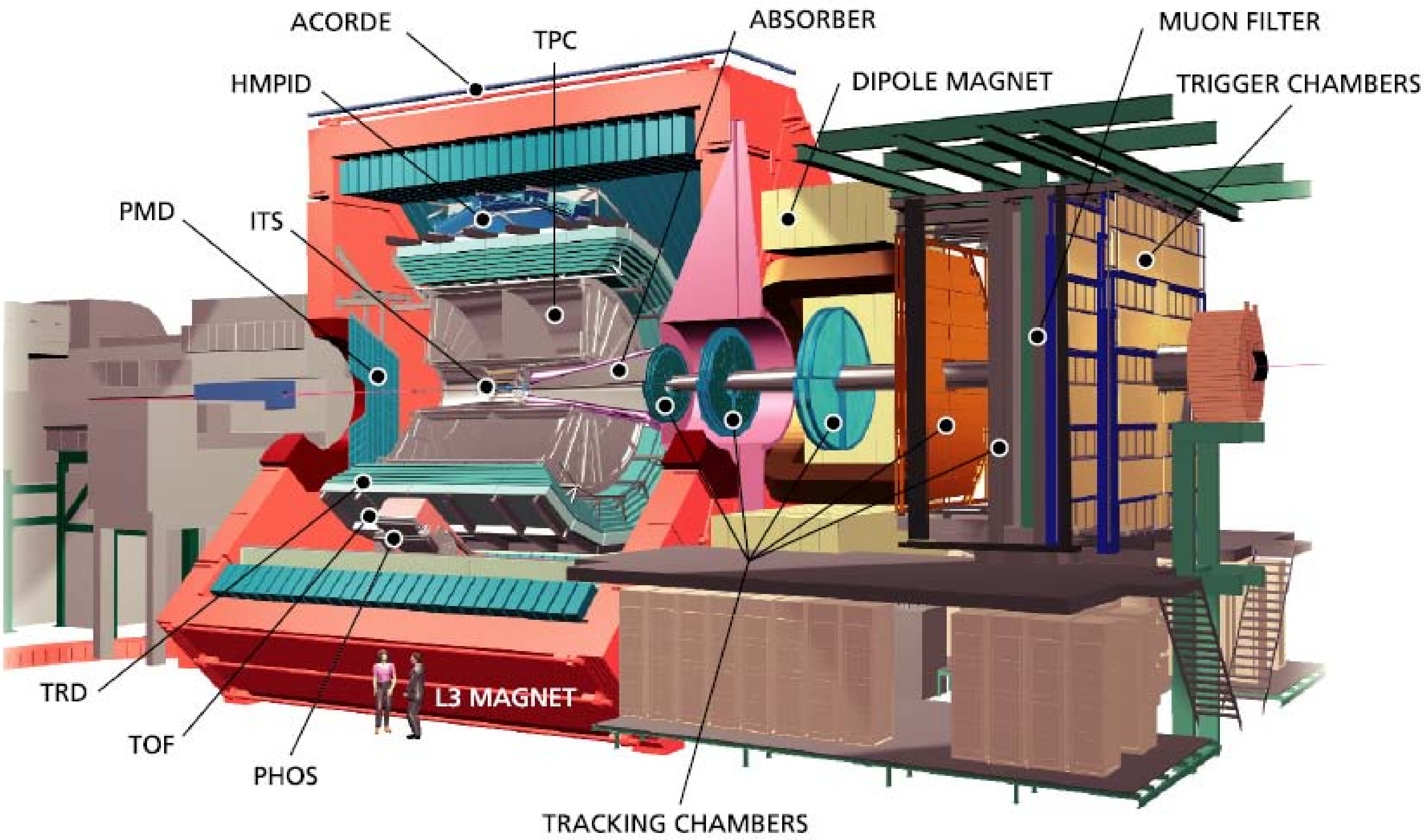




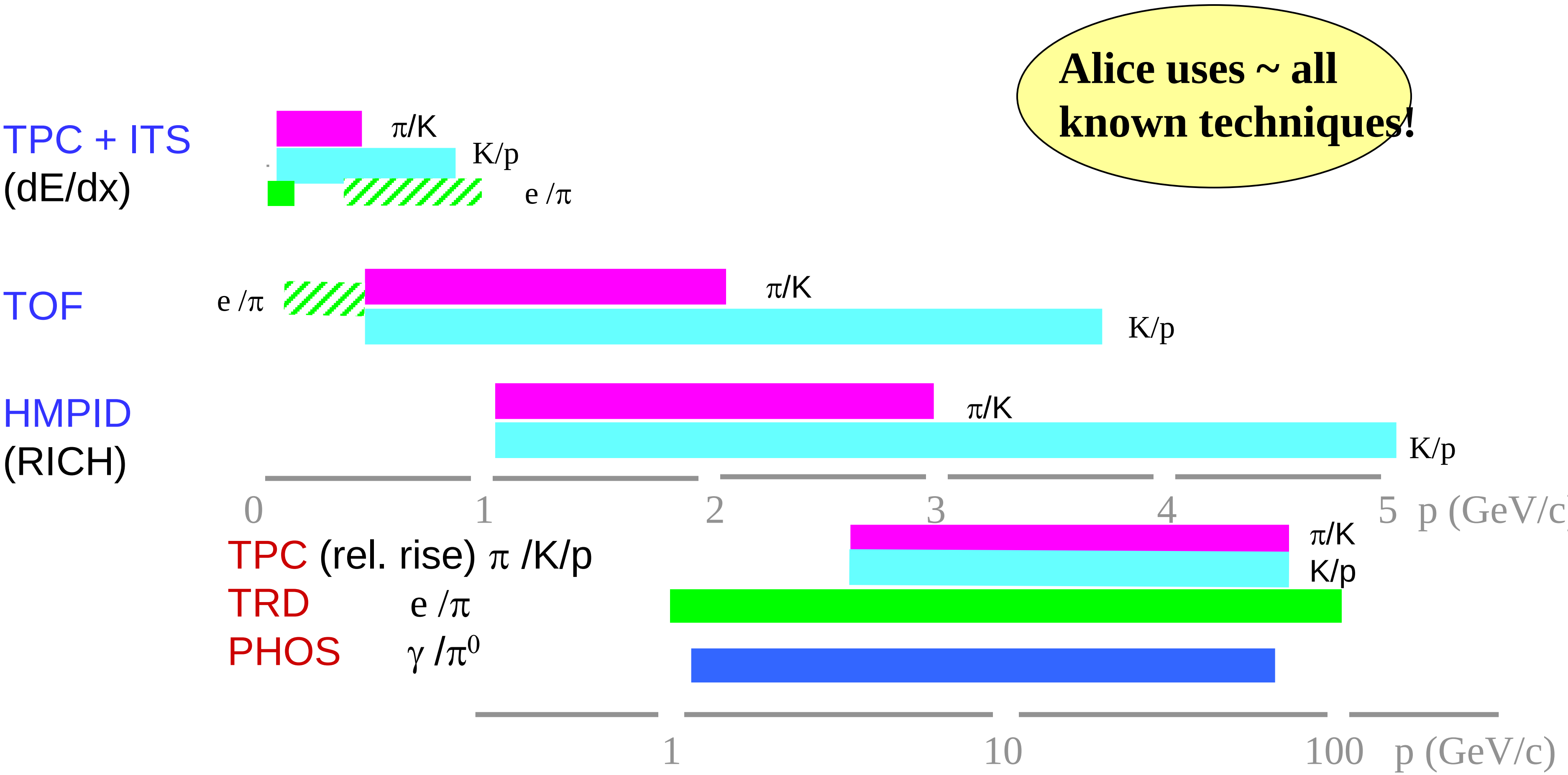
pp Collisions



ALICE

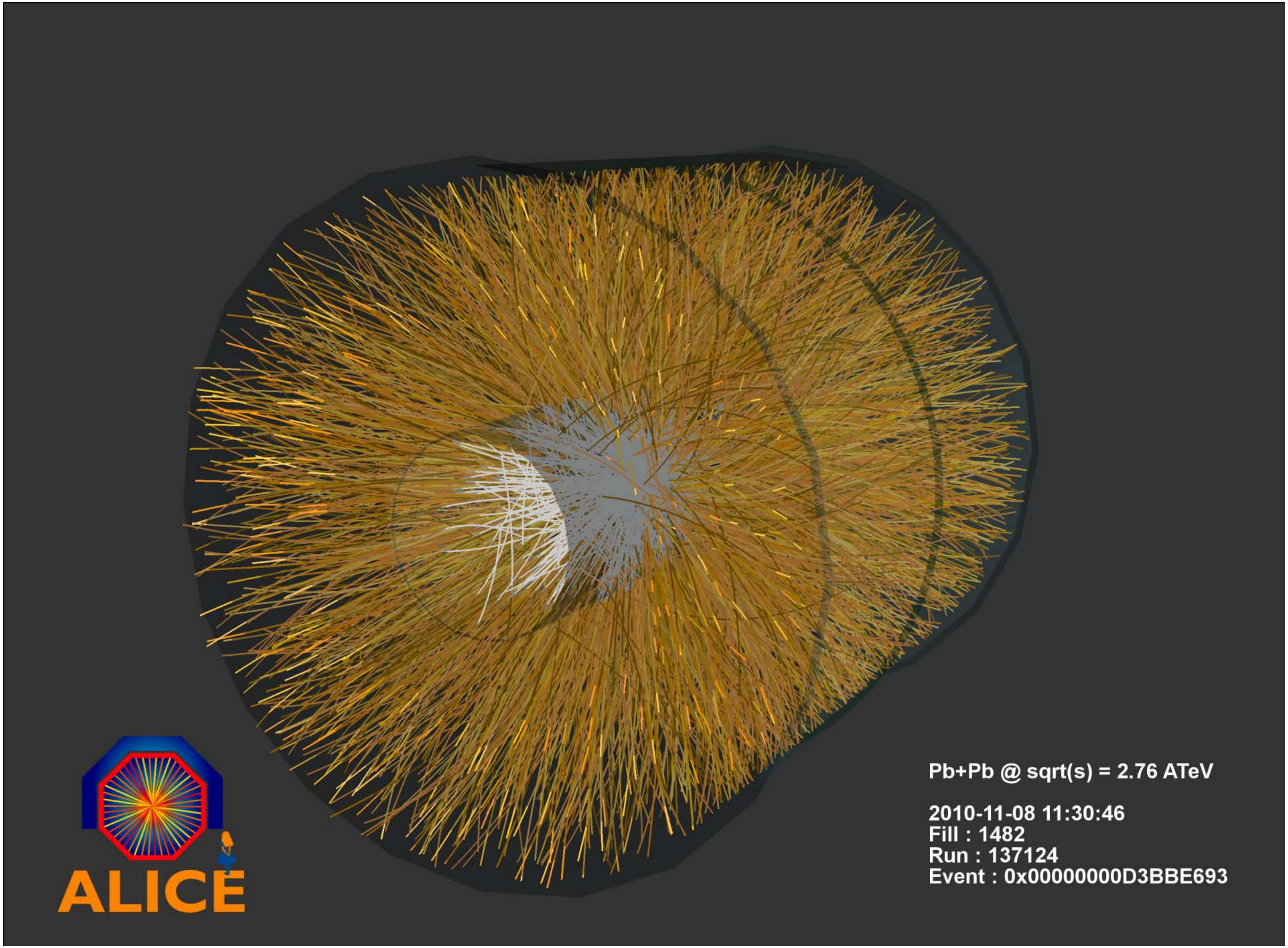

ACORDE
TPC
ABSORBER
MUON FILTER
HMPID
DIPOLE MAGNET
TRIGGER CHAMBERS
PMD
ITS
TRD
TOF
PHOS
L3 MAGNET
TRACKING CHAMBERS

ALICE Particle ID

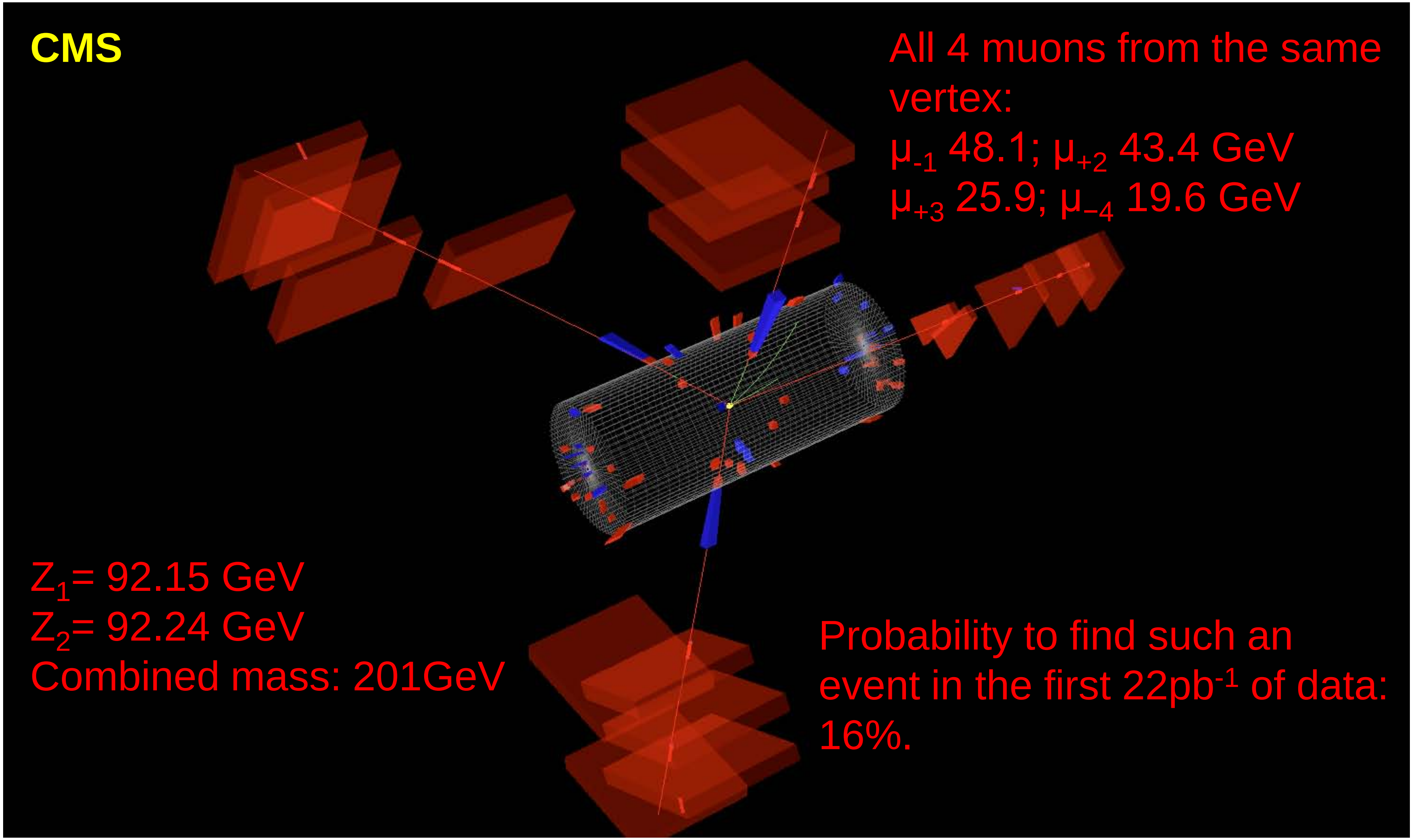


 W. Riegler/CERN

Heavy Ion Collisions, Nov. 2010



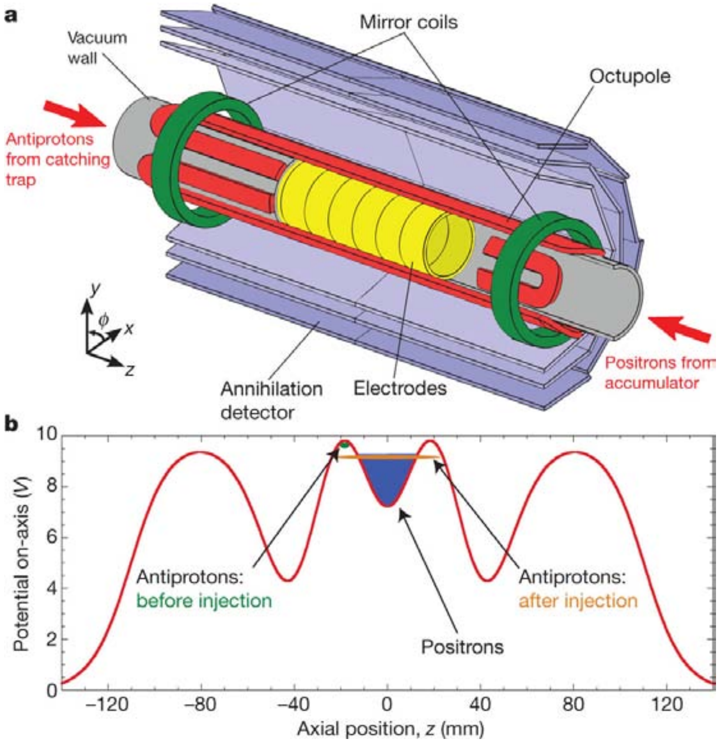
First ZZ→4μ Event

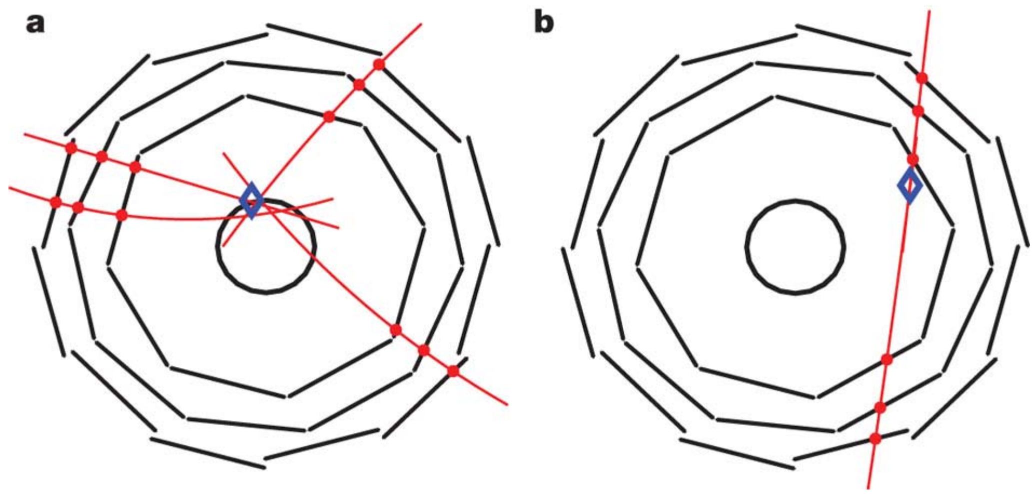


[N. Pastrone, Talk at Bormio Winter Meeting, 2011]

Small is Beautiful

ALPHA





Antiproton annihilation

Cosmic

Trapping of antihydrogen for > 178 ms

GB Andresen *et al. Nature* **000**, 1-4 (2010) doi:10.1038/nature09610

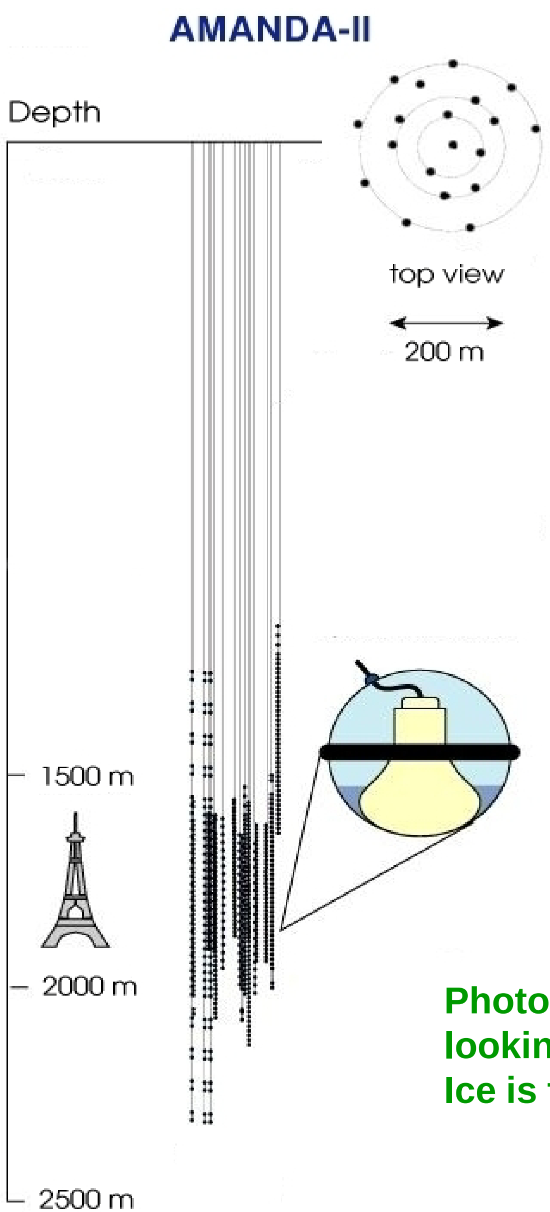
AMANDA

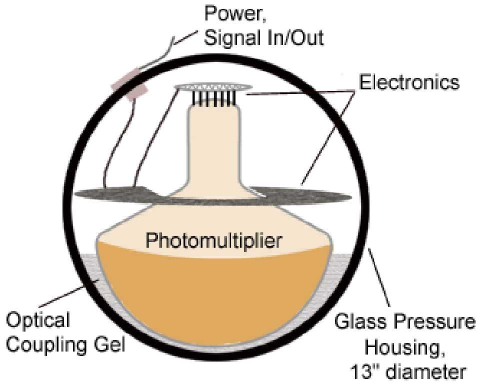
Antarctic **M**uon **A**nd **N**eutrino **D**etector **A**rray

AMANDA

South Pole

AMANDA



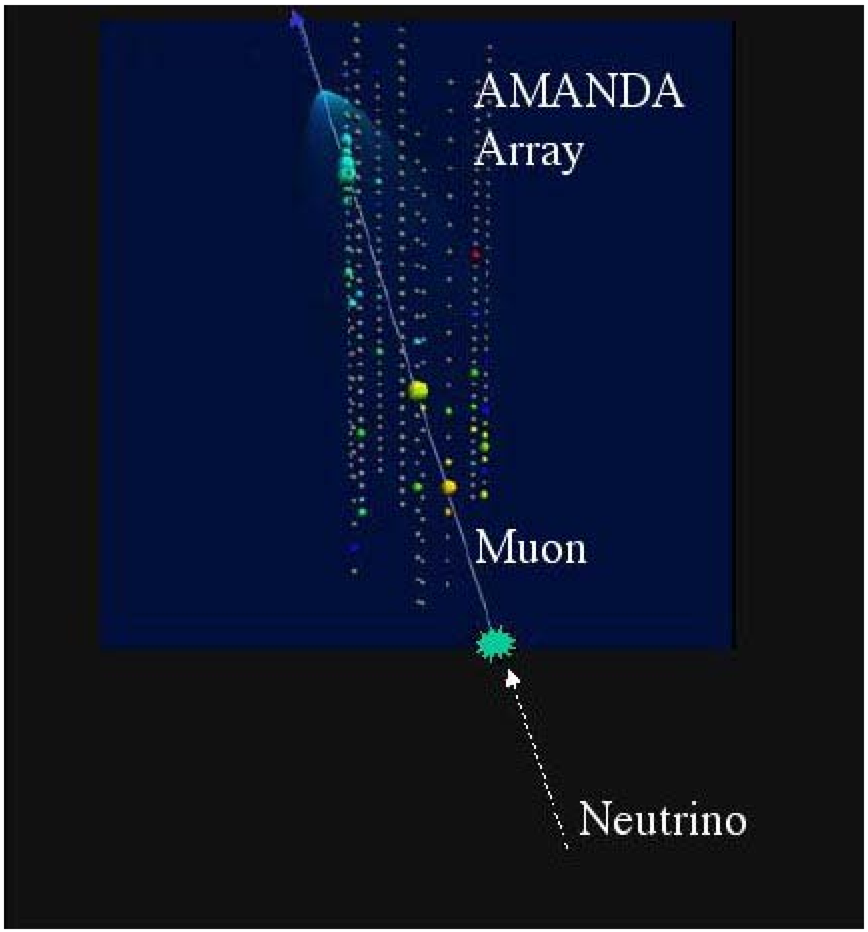


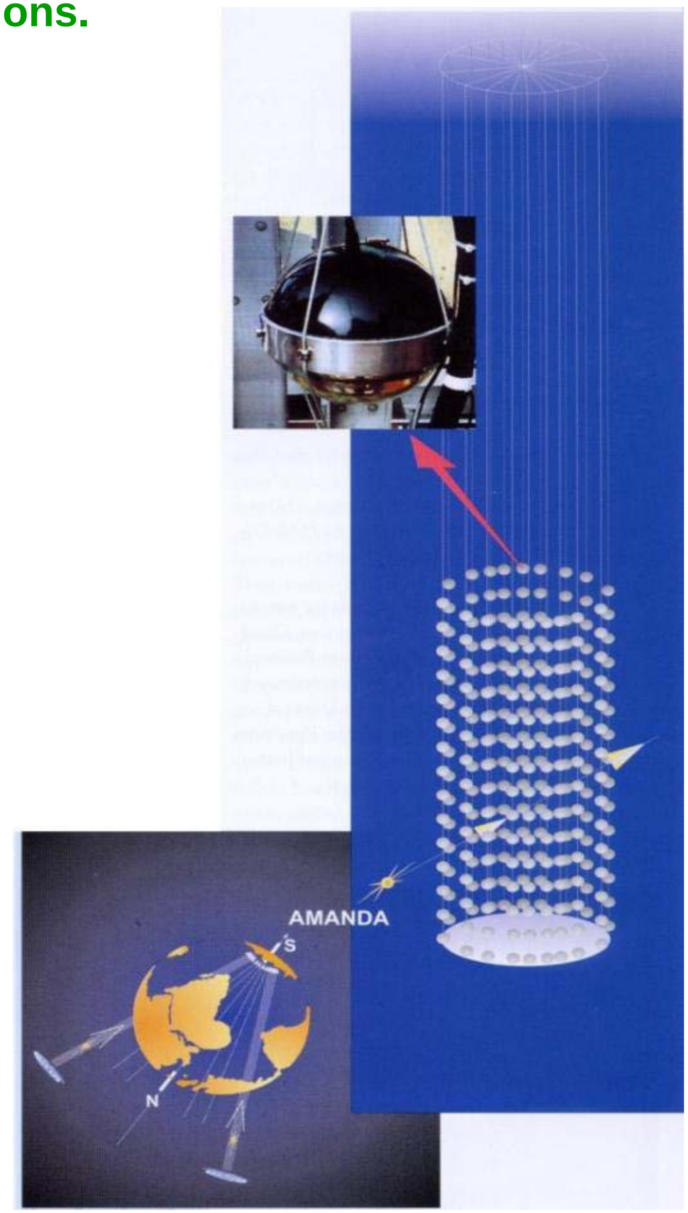
Photomultipliers in the Ice, looking downwards.
Ice is the detecting medium.

AMANDA

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

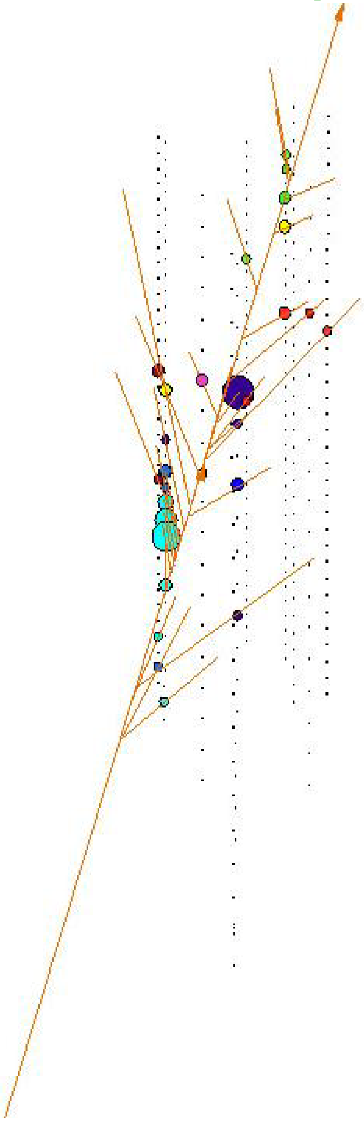
→ Find neutrino point sources in the universe !

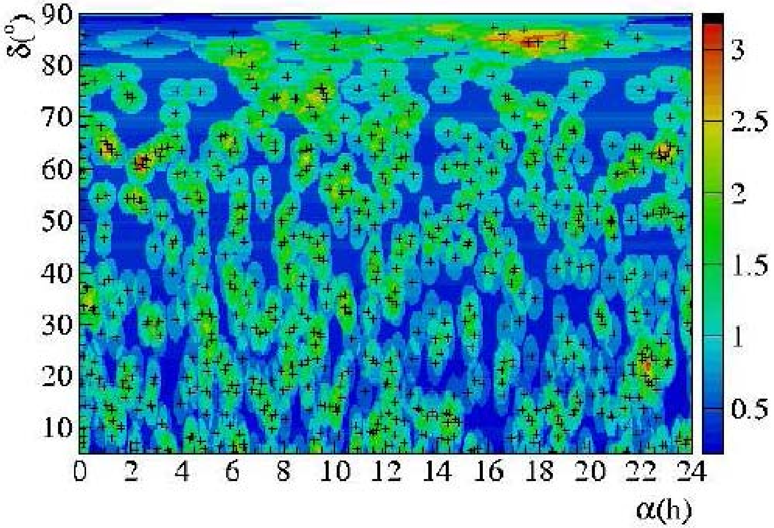




AMANDA

Event Display

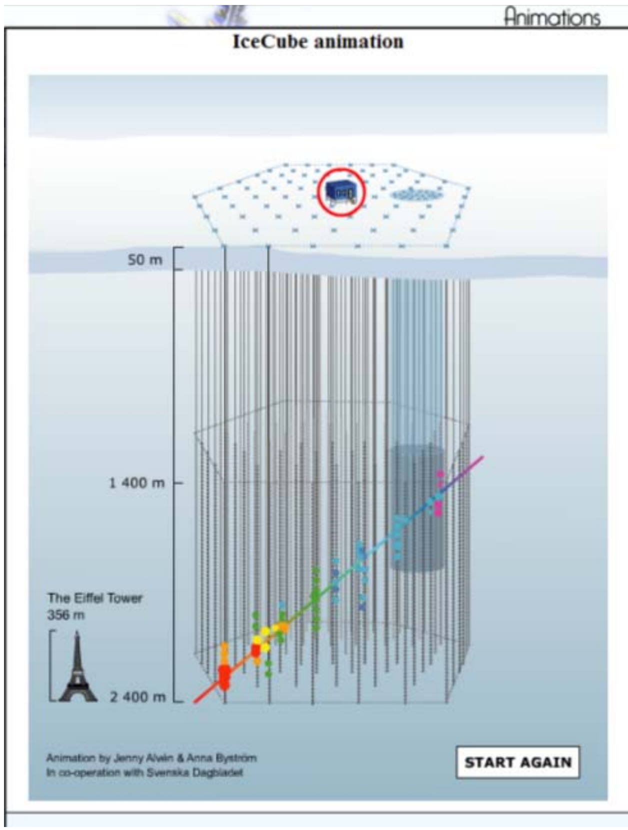




Up to now: No significant point sources but just neutrinos from cosmic ray interactions in the atmosphere were found .

→ Ice Cube for more statistics – data taking stating May 2011 !

The Ice Cube neutrino observatory is designed so that 5,160 optical sensors view a cubic kilometer of clear South Polar ice.

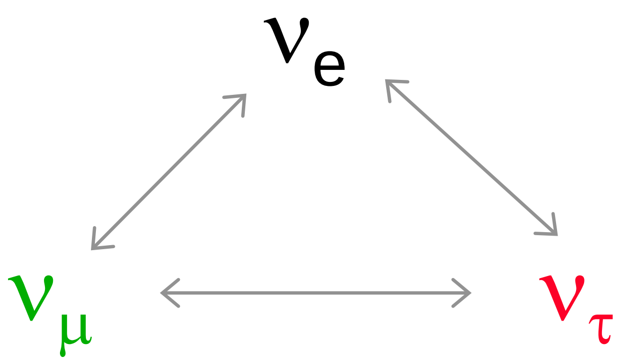


CERN Neutrino Gran Sasso

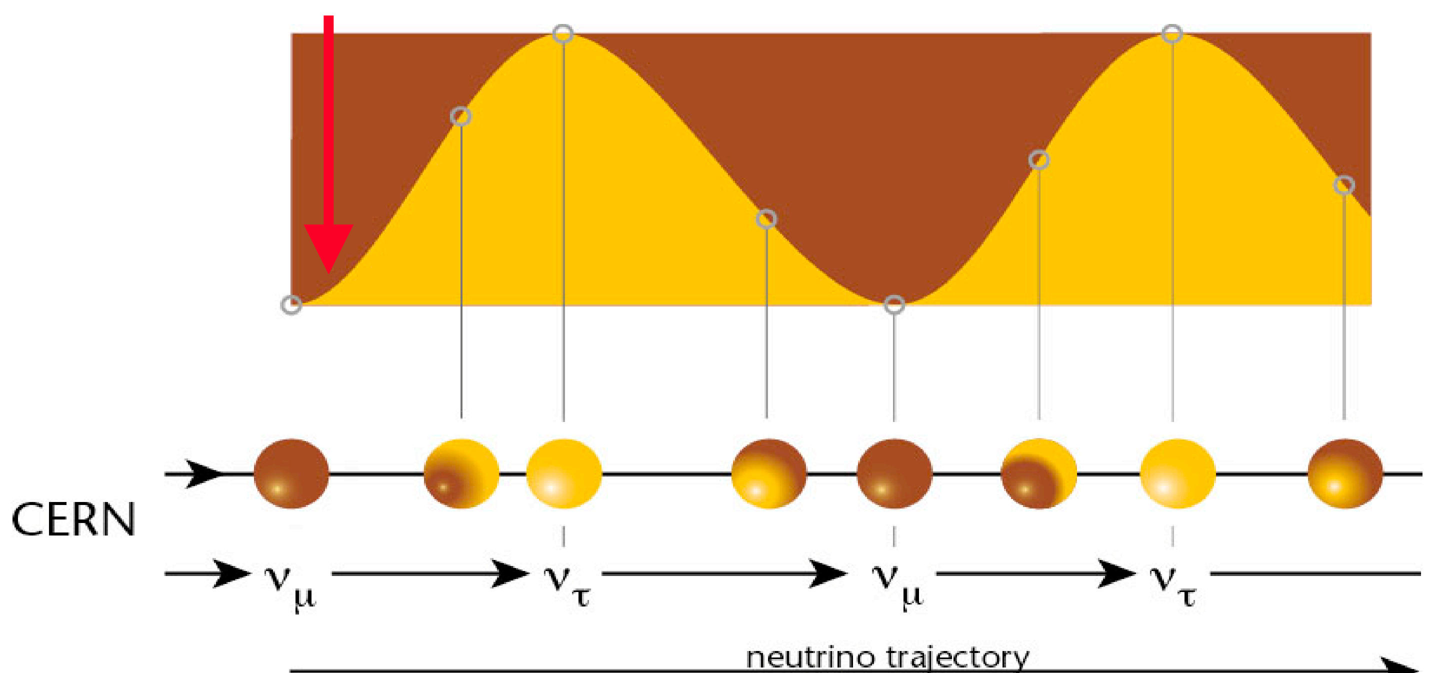
(CNGS)

CNGS

If neutrinos have mass:



Muon neutrinos produced at CERN.
See if tau neutrinos arrive in Italy.



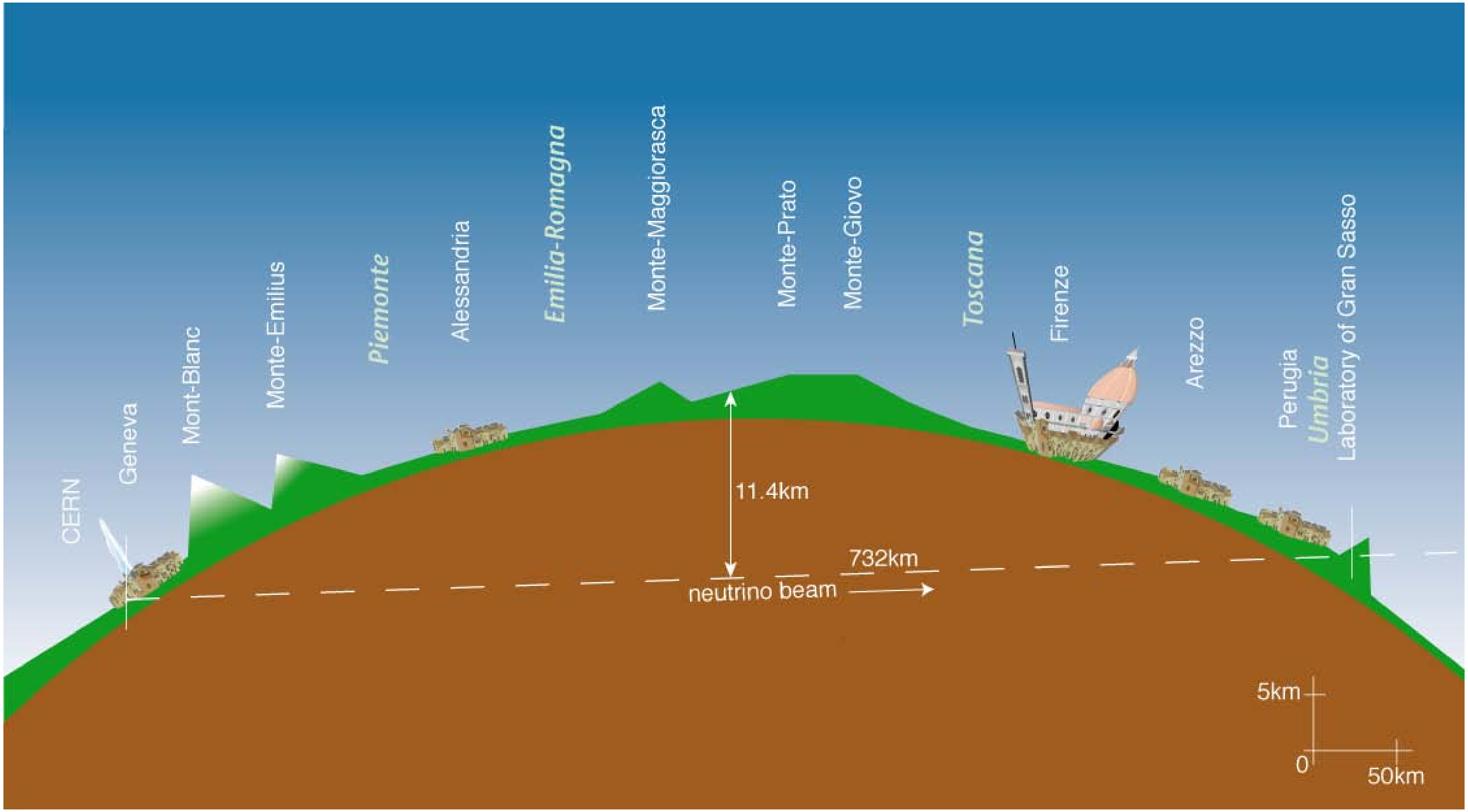
CNGS Project

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**

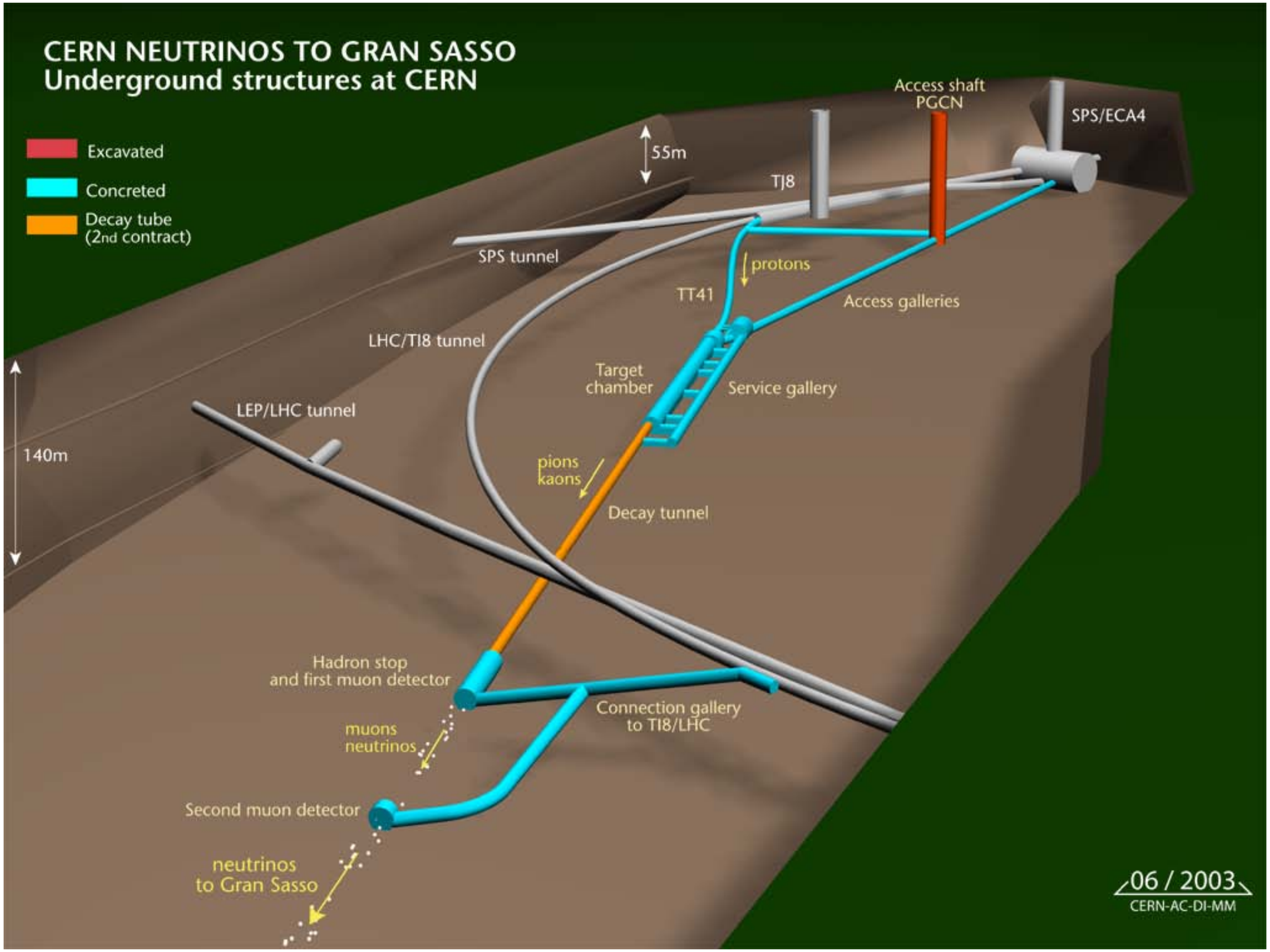
➔ direct proof of ν_μ - ν_τ oscillation (appearance experiment)

CNGS



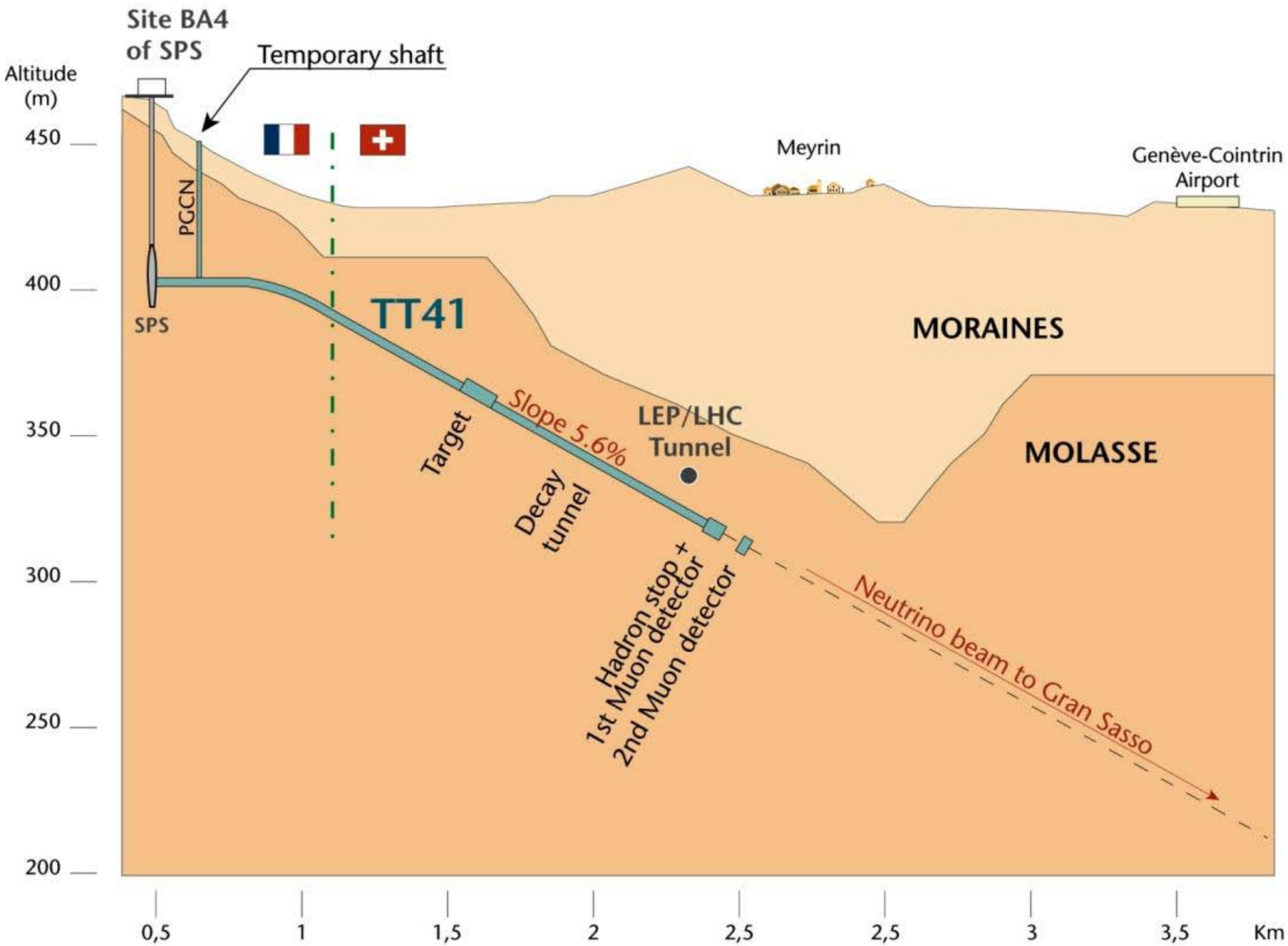
CERN
Geneva
Mont-Blanc
Monte-Emilius
Piemonte
Alessandria
Emilia-Romagna
Monte-Maggiorasca
Monte-Prato
Monte-Giovo
Toscana
Firenze
Arezzo
Perugia
Umbria
Laboratory of Gran Sasso
11.4km
732km
neutrino beam
5km
0
50km

CNGS



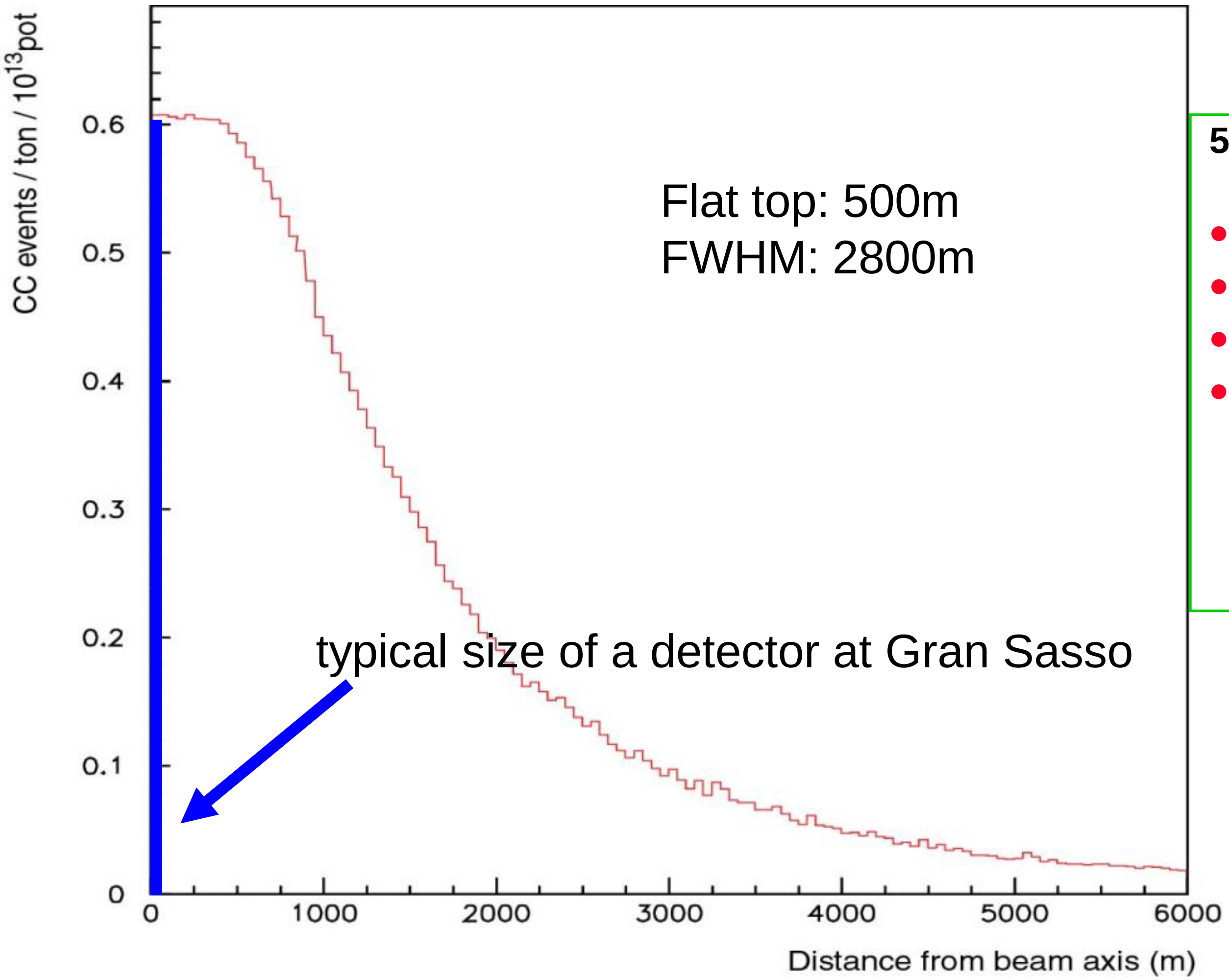
CERN NEUTRINOS TO GRAN SASSO
Underground structures at CERN
Excavated
Concreted
Decay tube
(2nd contract)
55m
TJ8
Access shaft
PGCN
SPS/ECA4
SPS tunnel
protons
TT41
Access galleries
LHC/TI8 tunnel
Target
chamber
Service gallery
LEP/LHC tunnel
140m
pions
kaons
Decay tunnel
Hadron stop
and first muon detector
Connection gallery
to TI8/LHC
muons
neutrinos
Second muon detector
neutrinos
to Gran Sasso
06 / 2003
CERN-AC-DI-MM

CNGS



Site BA4
of SPS
Temporary shaft
Altitude
(m)
450
400
350
300
250
200
PGCN
SPS
Meyrin
Genève-Cointrin
Airport
TT41
MORAINES
MOLASSE
Slope 5.6%
LEP/LHC
Tunnel
Target
Decay
tunnel
Hadron stop +
1st Muon detector
2nd Muon detector
Neutrino beam to Gran Sasso
0,5
1
1,5
2
2,5
2,5
3
3,5
Km

Radial Distribution of the ν_μ-Beam at GS



5 years CNGS operation, 1800 tons target:

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

Neutrinos at CNGS: Some Numbers

For 1 year of CNGS operation, we expect:

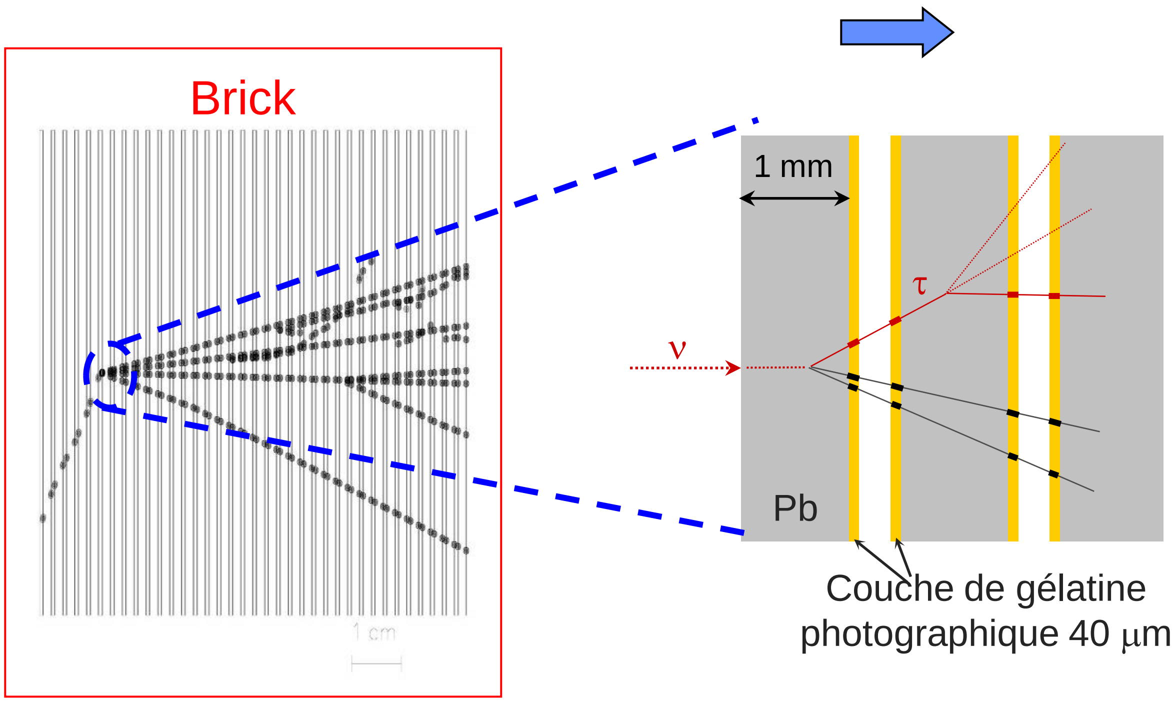
protons on target	2×10^{19}
pions / kaons at entrance to decay tunnel	3×10^{19}
ν_μ in direction of Gran Sasso	10^{19}
ν_μ in 100 m^2 at Gran Sasso	3×10^{14}
ν_μ events per day in OPERA	≈ 2500
ν_τ events (from oscillation)	≈ 2

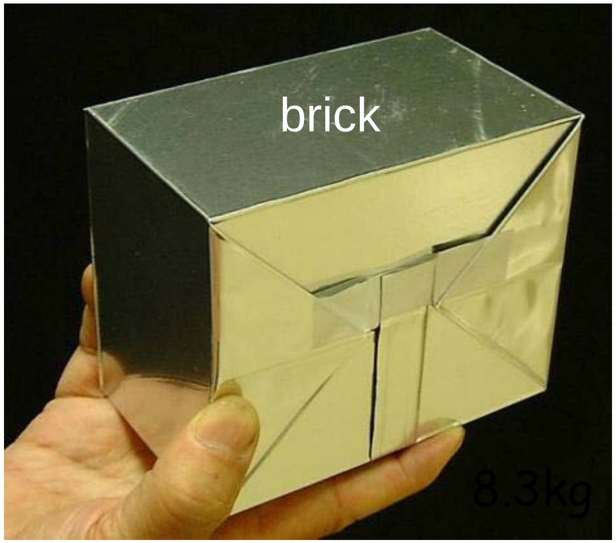
Opera Experiment at Gran Sasso

Basic unit: brick

56 Pb sheets + 56 photographic films (emulsion sheets)

Lead plates: massive target
Emulsions: micrometric precision



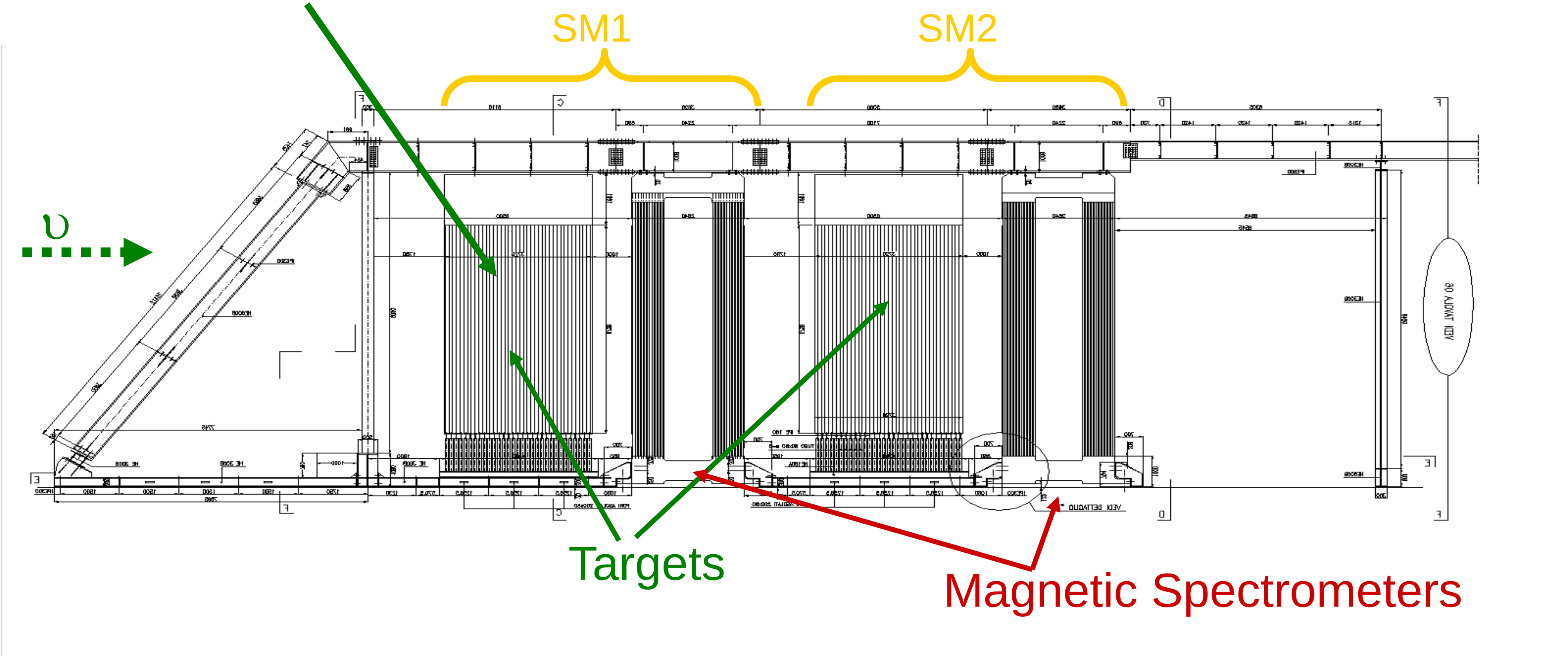


10.2 x 12.7 x 7.5 cm^3

Opera Experiment at Gran Sasso

31 target planes / supermodule

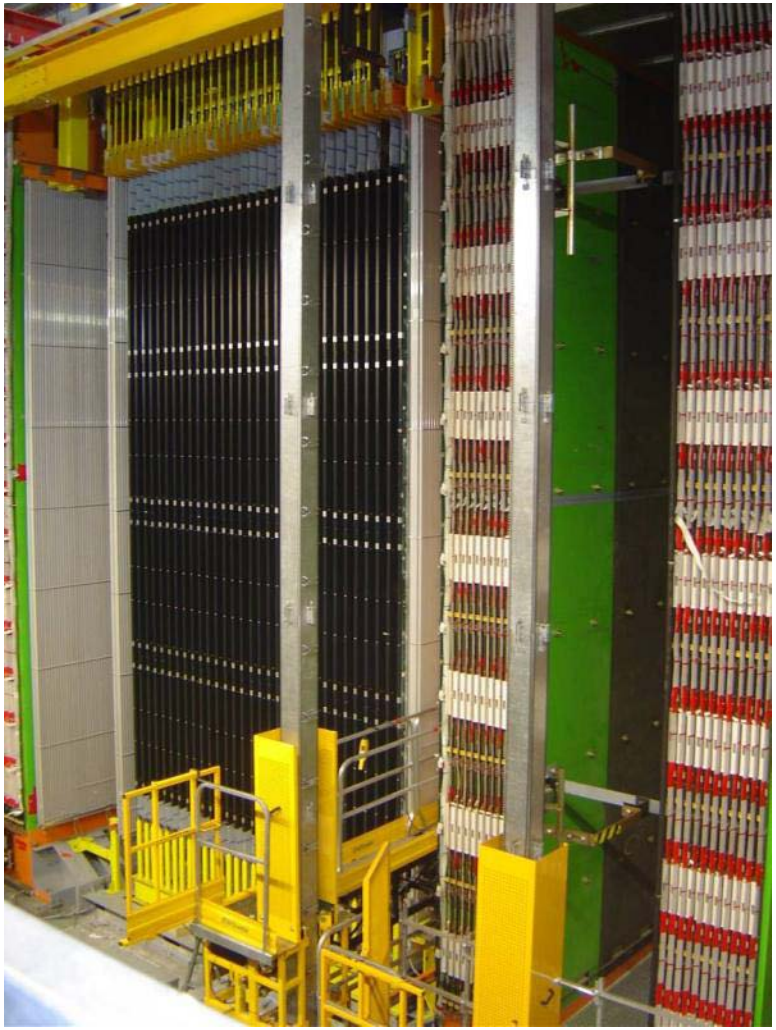
In total: 206336 bricks, 1766 tons



First observation of CNGS beam neutrinos : August 18th, 2006

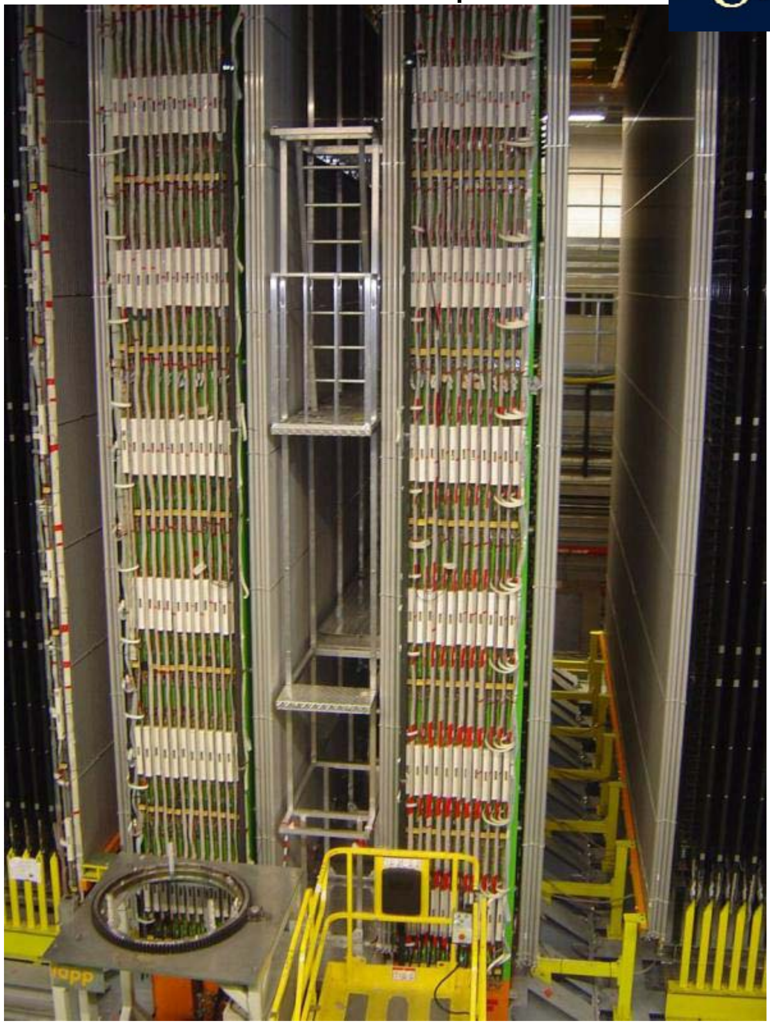
Opera Experiment at Gran Sasso

Second Super-module



Scintillator planes 5900 m^2
8064 7m long drift tubes

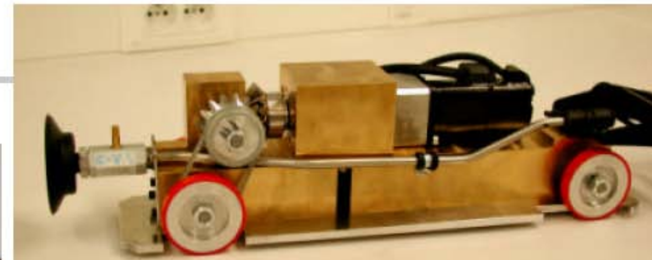
Details of the first spectrometer



3050 m^2 Resistive Plate Counters
2000 tons of iron for the two magnets

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

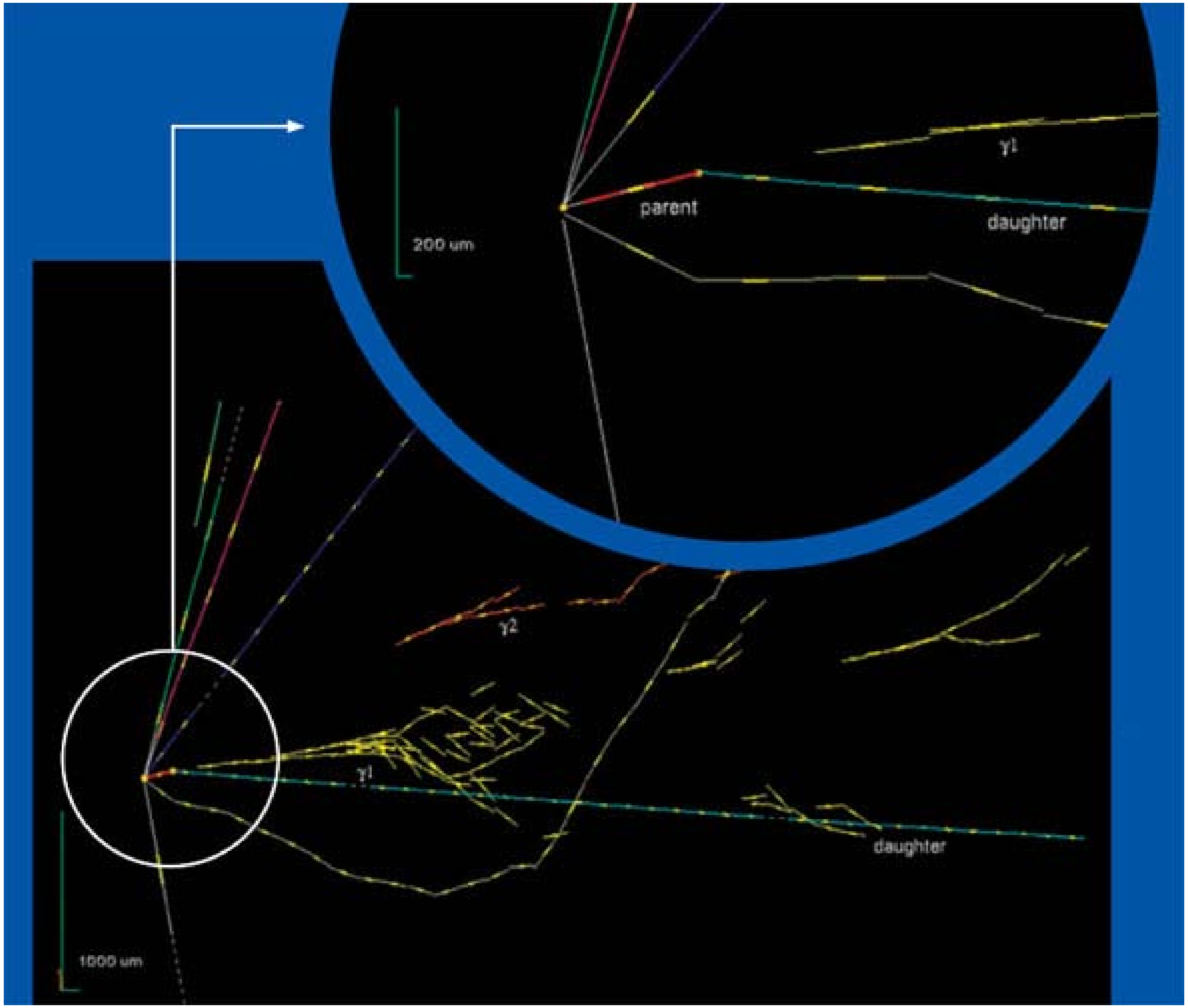
Tests with the prototype wall

"Carousel" brick dispensing and storage system

First Tau Candidate seen!

Hypothesis:

τ (parent) → hadron (daughter) + π_0 (decaying instantly to γ_1, γ_2)+ ν_τ (invisible)



AMS

Alpha Magnetic Spectrometer

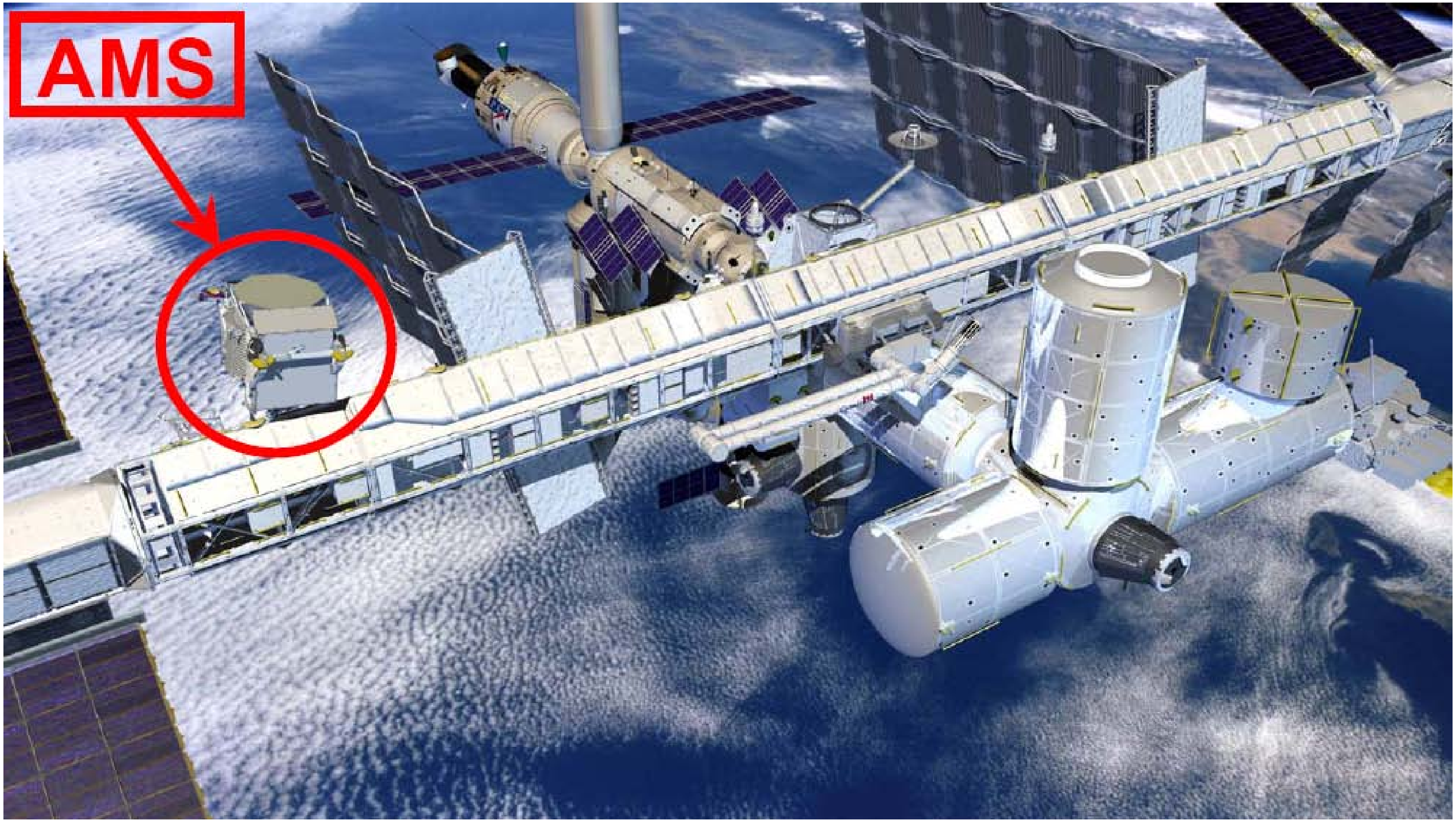
Try to find Antimatter in the primary cosmic rays.
Study cosmic ray composition etc. etc.

Launch to Space Station with the last Shuttle flight scheduled for April 19, 2011 7:48 PM Eastern !

Check out the countdown: http://ams-02project.jsc.nasa.gov

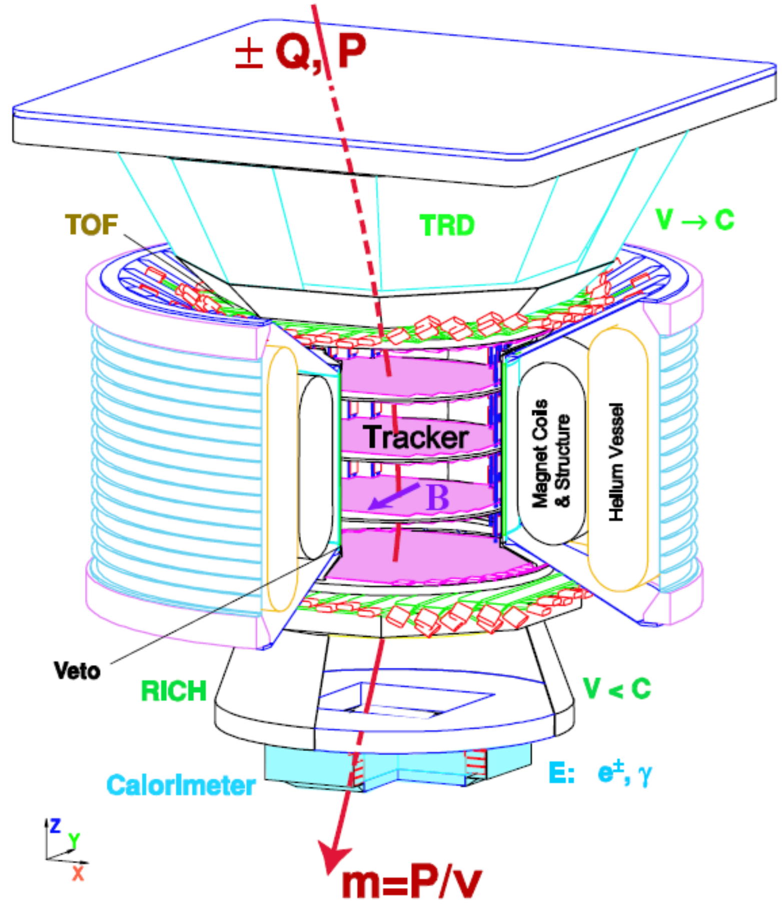
AMS

Will be installed on the space station.

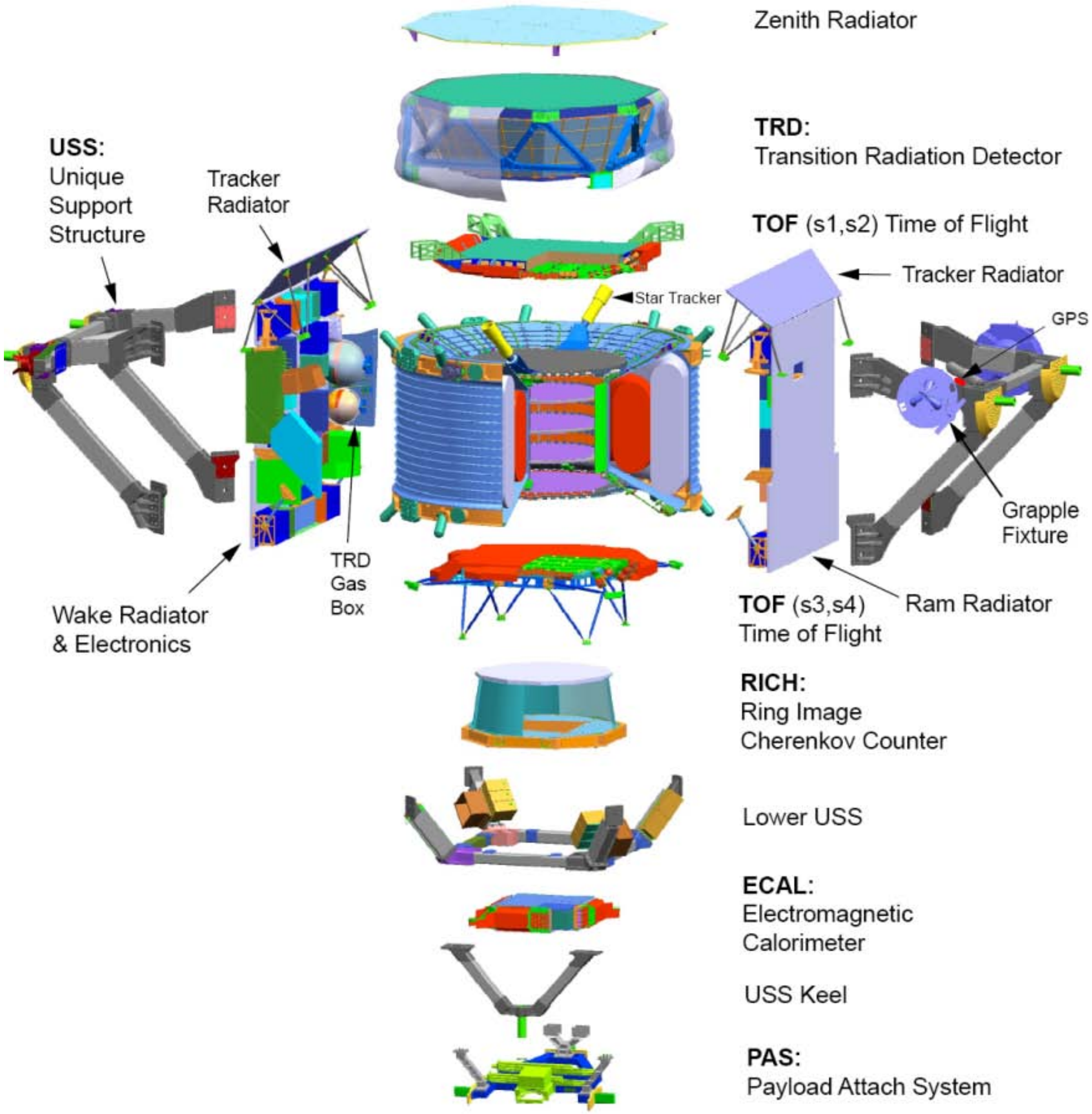


AMS

A state of the art particle detector with many 'earth bound' techniques going to space !



AMS


Zenith Radiator
TRD:
Transition Radiation Detector
USS:
Unique
Support
Structure
Tracker
Radiator
TOF (s1,s2) Time of Flight
Tracker Radiator
Star Tracker
GPS
Grapple
Fixture
TRD
Gas
Box
Wake Radiator
& Electronics
TOF (s3,s4)
Time of Flight
Ram Radiator
RICH:
Ring Image
Cherenkov Counter
Lower USS
ECAL:
Electromagnetic
Calorimeter
USS Keel
PAS:
Payload Attach System

How can a particle detector distinguish the hundreds of particles that we know by now ?

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

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

There are many more

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 $c\tau > 1\mu m$ @ GeV Level

Particle	Mass (MeV)	Lifetime τ (s)	$c\tau$	
γ	0	∞	∞	
$\pi^\pm (u\bar{d}, d\bar{u})$	140	$2.6 \cdot 10^{-8}$	7.8 m	
$K^\pm (u\bar{s}, \bar{u}s)$	494	$1.2 \cdot 10^{-8}$	3.7 m	
$K^0 (d\bar{s}, \bar{d}s)$	497	$5.1 \cdot 10^{-8}$ $8.9 \cdot 10^{-11}$	15.5 m 2.7 cm	
$D^\pm (c\bar{d}, \bar{c}d)$	1869	$1.0 \cdot 10^{-12}$	315 μm	
$D^0 (c\bar{u}, u\bar{c})$	1864	$4.1 \cdot 10^{-13}$	123 μm	
$D_s^\pm (c\bar{s}, \bar{c}s)$	1969	$4.9 \cdot 10^{-13}$	147 μm	"Secondary Vertices"
$B^\pm (u\bar{b}, \bar{b}u)$	5279	$1.7 \cdot 10^{-12}$	502 μm	
$B^0 (b\bar{d}, d\bar{b})$	5279	$1.5 \cdot 10^{-12}$	462 μm	
$B_s^0 (s\bar{b}, \bar{s}b)$	5370	$1.5 \cdot 10^{-12}$	438 μm	
$B_c^\pm (c\bar{b}, \bar{c}b)$	~6400	$\sim 5 \cdot 10^{-13}$	150 μm	
p (uud)	938.3	$> 10^{33}$ y	∞	
n (udd)	939.6	885.7 s	$2.655 \cdot 10^{8}$ km	
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	

W. Riegler/CERN

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.

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

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

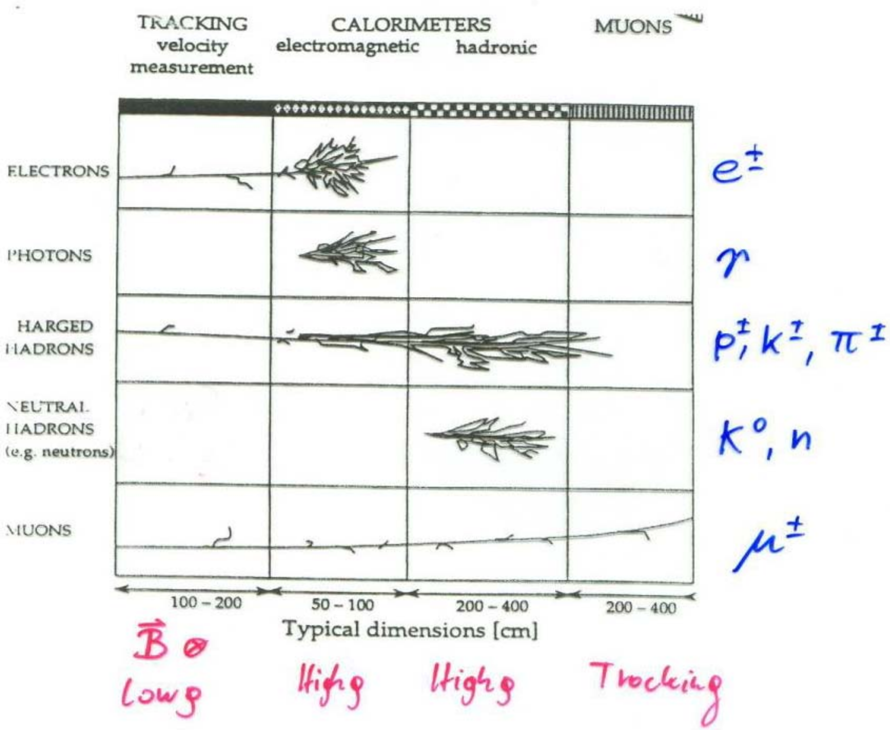
The Difference in

Mass, Charge, Interaction

is the key to the Identification

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



Detector Physics

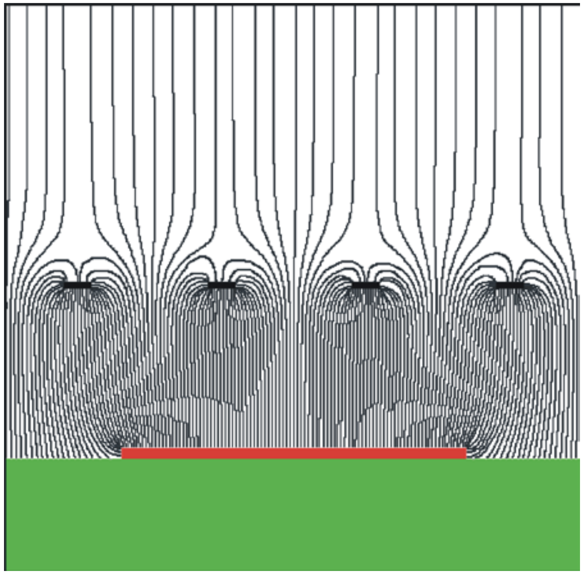
Precise knowledge of the processes leading to signals in particle detectors is necessary.

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

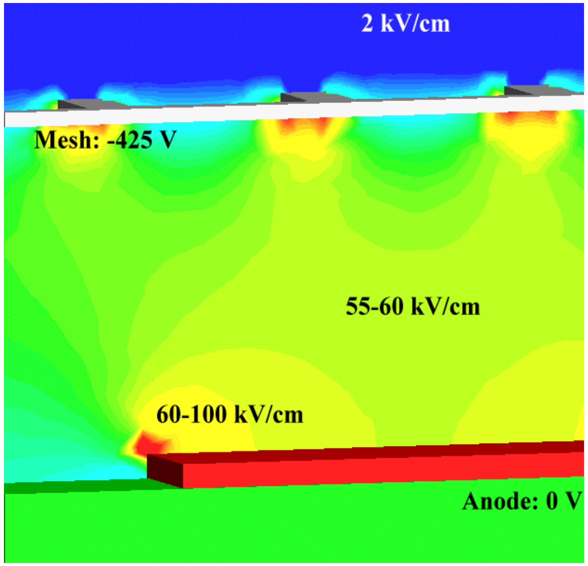


Very accurate simulations of particle detectors are possible due to availability of Finite Element simulation programs and computing power.

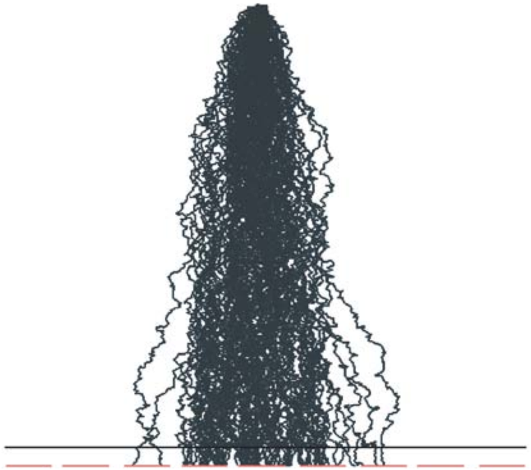
Follow every single electron by applying first principle laws of physics.

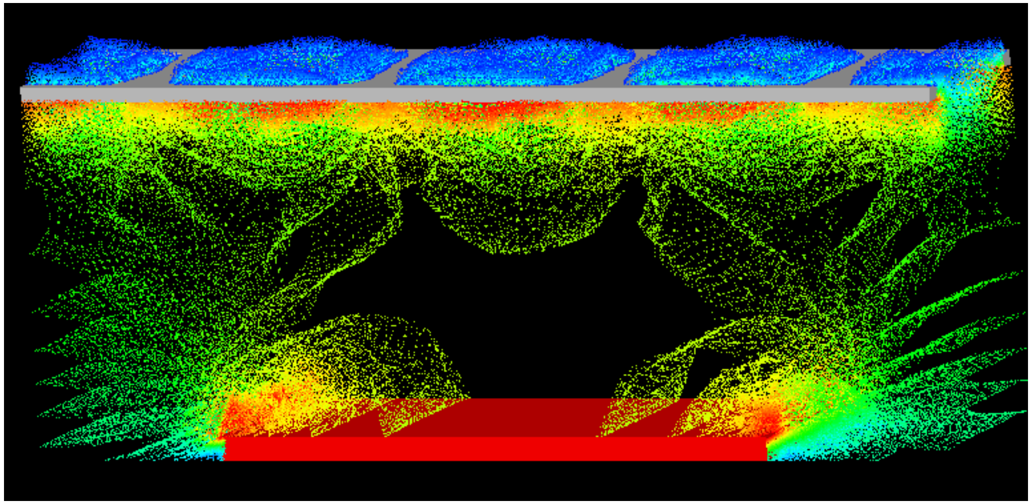
For Gaseous Detectors: GARFIELD by R. Veenhof

Electric Fields in a Micromega Detector



Electrons avalanche multiplication



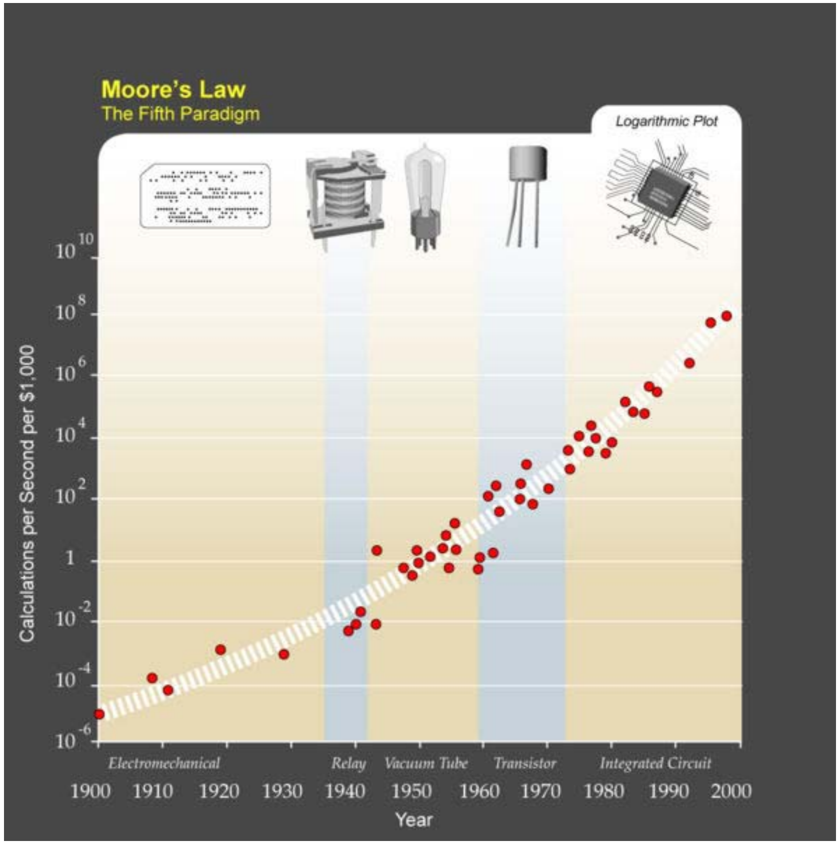


Particle Detector Simulation

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) = ...



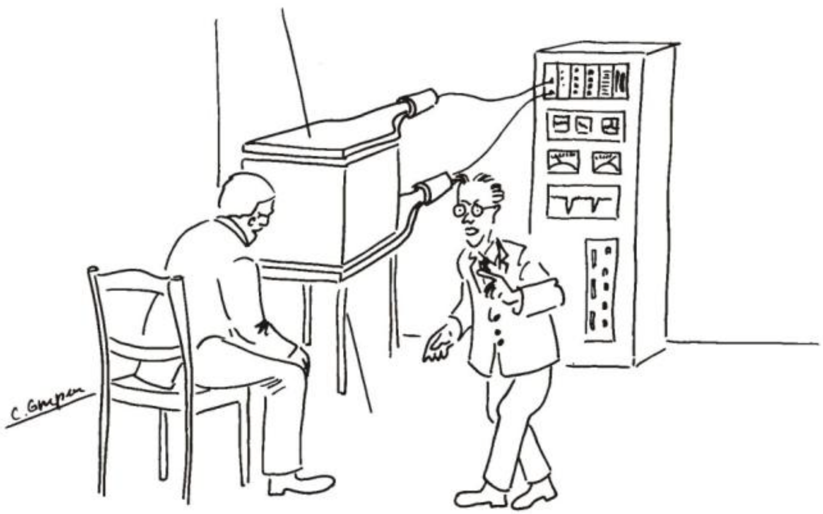
Knowing the basics of particle detectors is essential …

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.

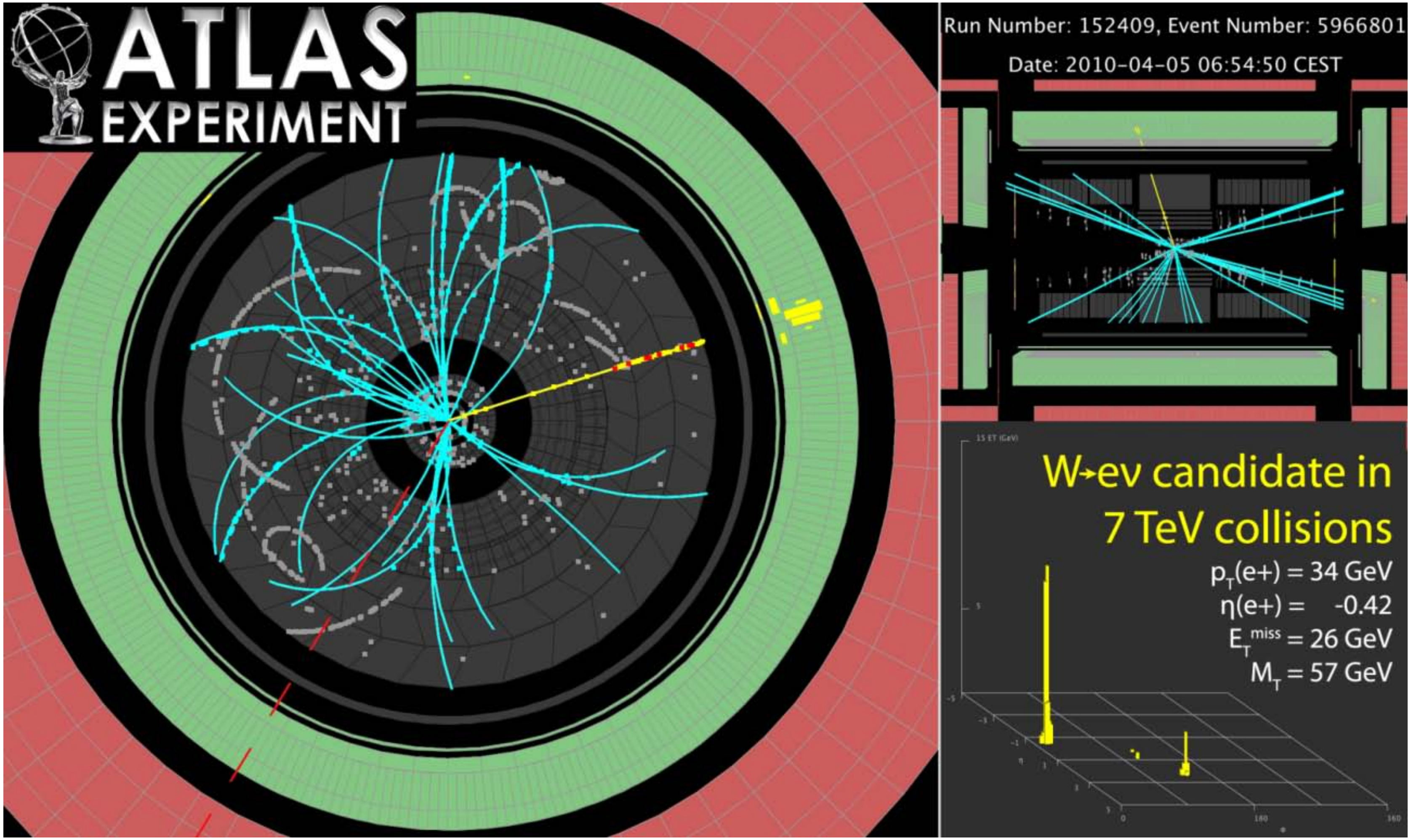
E.g. e^+e^- collider. $P_{tot}=0$,
If the $\Sigma\, p_i$ of all collision products is $\neq 0$ → neutrino escaped.



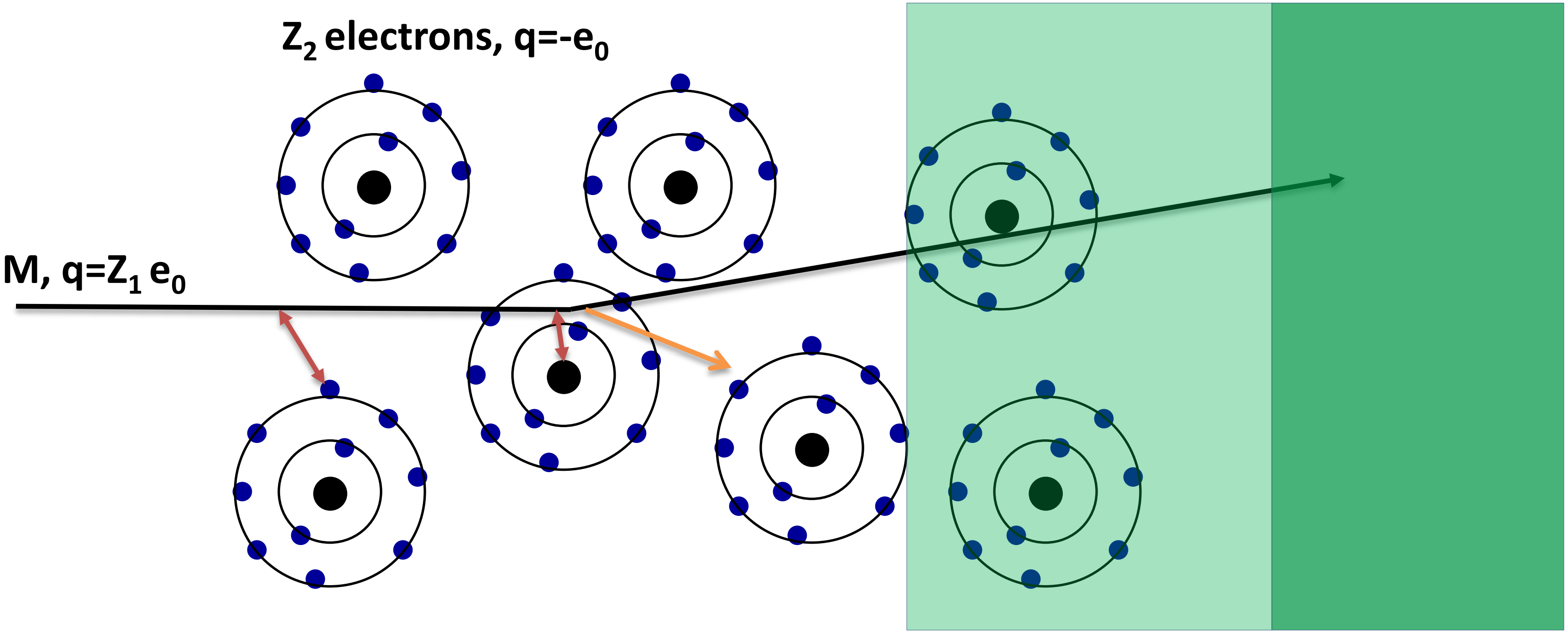
"Did you see it?"
"No nothing."
"Then it was a neutrino!"

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

Interaction of Particles with Matter



Electromagnetic Interaction of Particles with Matter

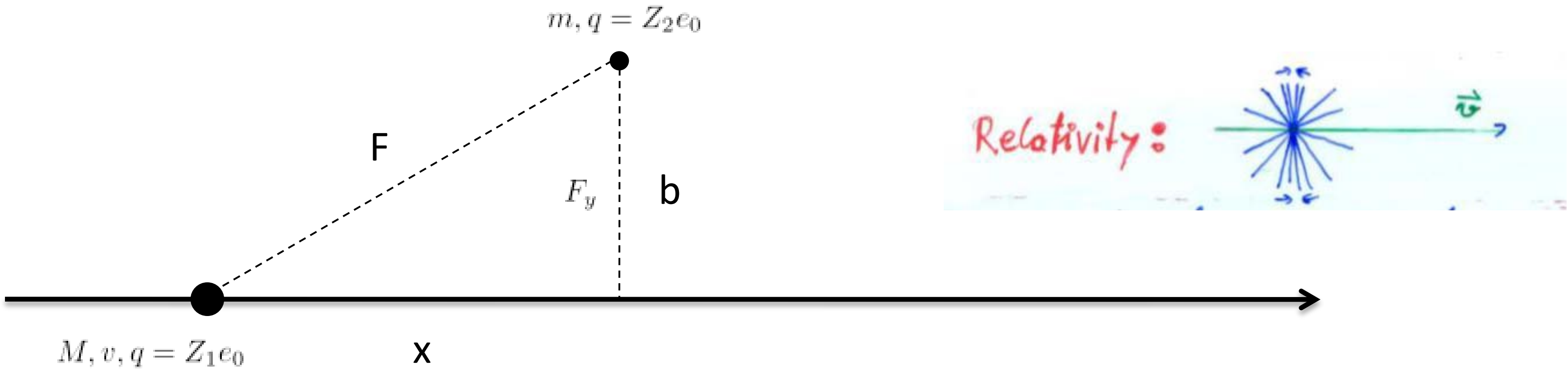


Interaction with the atomic electrons. The incoming particle loses energy and the atoms are <u>excited</u> or <u>ionized.</u>

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



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]

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

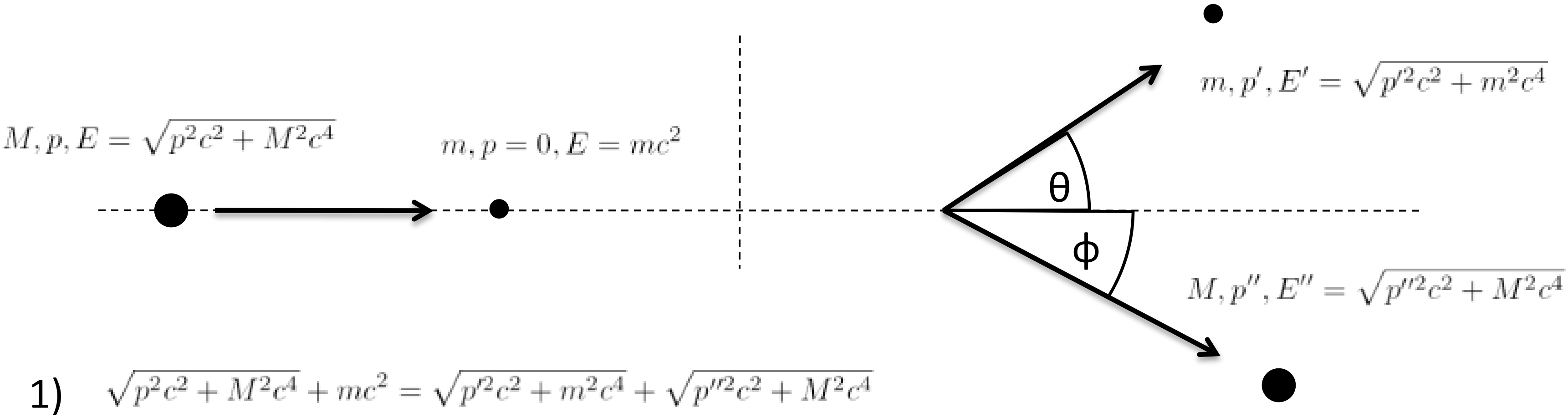
$$dE = -\int_{b_{min}}^{b_{max}} n_e \Delta E dx 2b\pi db = -\frac{4\pi Z_2 Z_1^2 m_e c^2 r_e^2}{\beta^2} \frac{N_A \rho}{A} \int_{b_{min}}^{b_{max}} \frac{db}{b}$$

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

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

$E_{min} \approx I$ (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) $E^{k'} = \sqrt{p'^2c^2 + m^2c^4} - mc^2 = \dfrac{2mc^2\, p^2c^2 \cos^2\theta}{\left[mc^2 + \sqrt{p^2c^2 + M^2c^4}\right]^2 - p^2c^2\cos^2\theta}$

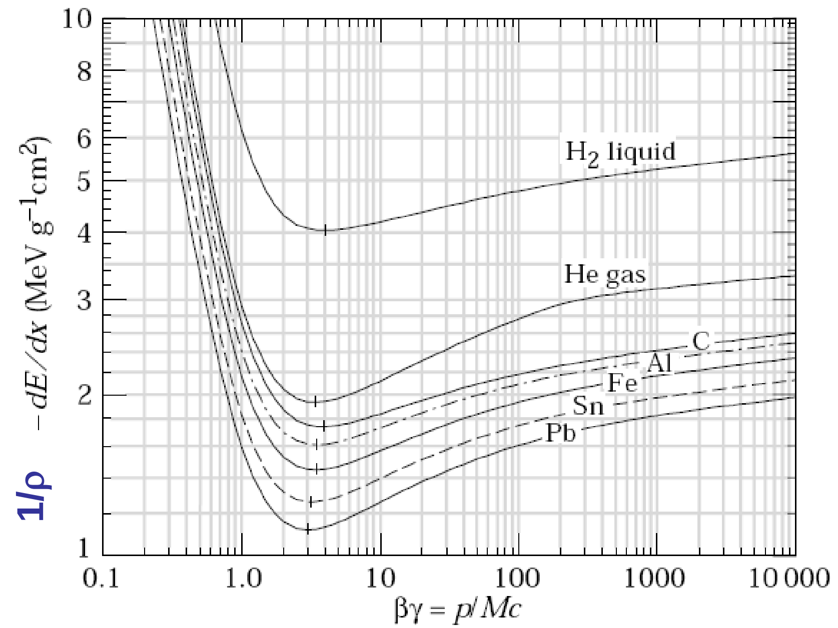
$$E^{k'}{}_{max} = \frac{2mc^2p^2c^2}{(m^2 + M^2)c^4 + 2m\sqrt{p^2c^2 + M^2c^4}} = 2mc^2\beta^2\gamma^2 F \qquad F = \left(1 + \frac{2m}{M}\sqrt{1 + \beta^2\gamma^2} + \frac{m^2}{M^2}\right)^{-1}$$

Classical Scattering on Free Electrons

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

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

Bethe Bloch Formula



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

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 ≈16Z $^{0.9}$ eV

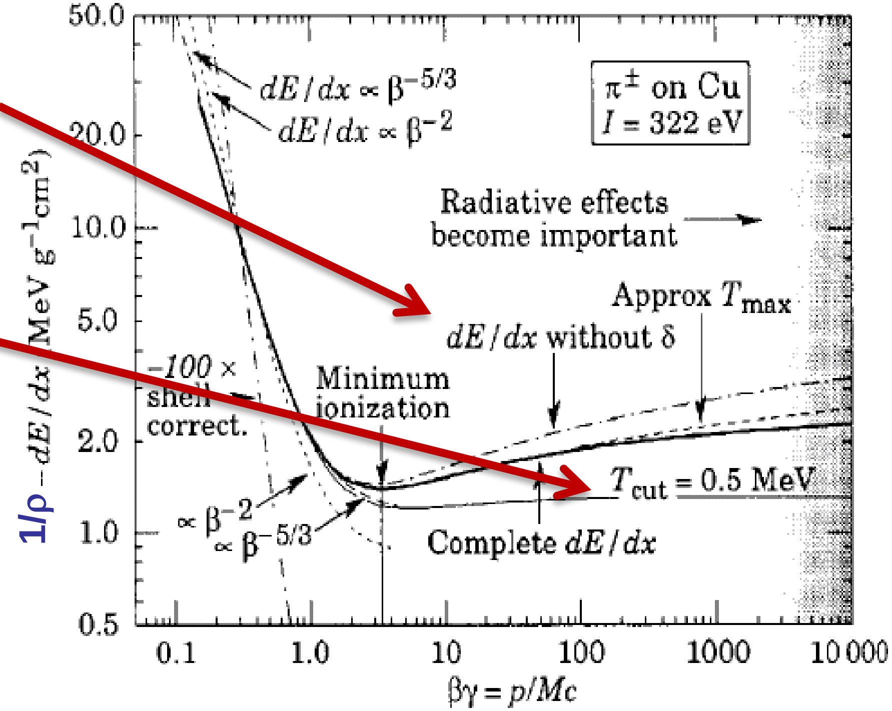
For Large βγ the medium is being polarized by the strong transverse fields, which reduces the rise of the energy loss → density effect

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).

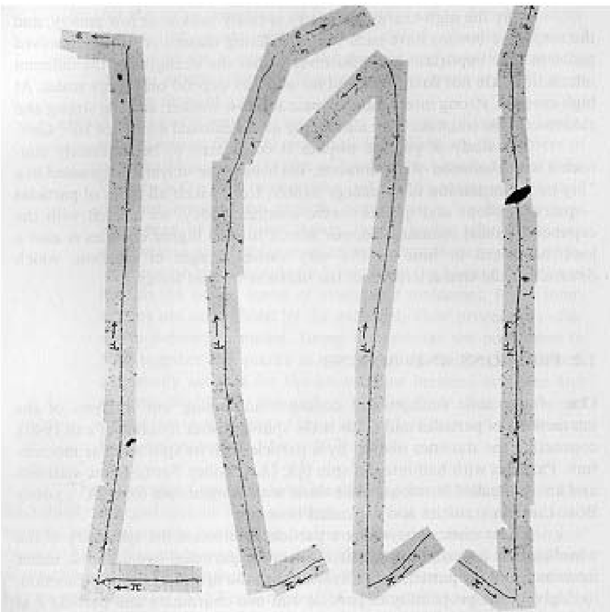
Characteristics of the energy loss as a function of the particle velocity (βγ)

The specific Energy Loss 1/ρ dE/dx

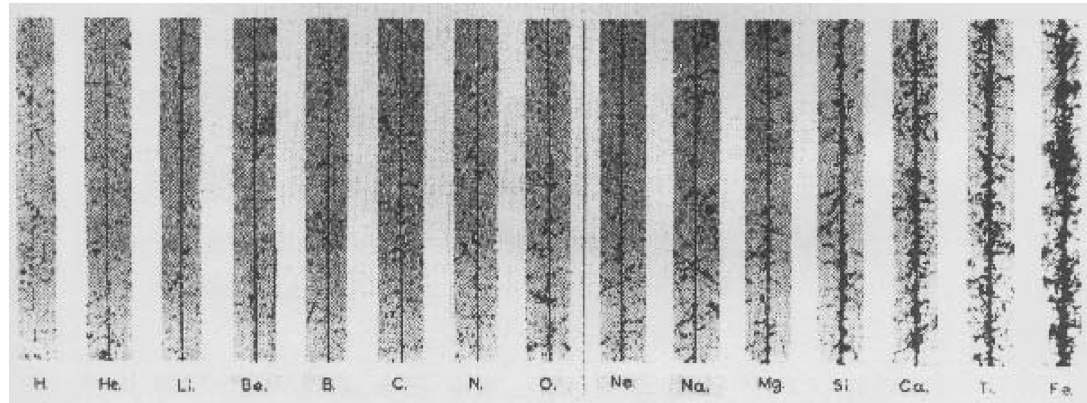
- **first decreases as $1/\beta^2$**
- **increases with ln γ for β =1**
- **is ≈ independent of M ($M \gg m_e$)**
- **is proportional to Z_1^2 of the incoming particle.**
- **is ≈ independent of the material (Z/A ≈ const)**
- **shows a plateau at large βγ (>>100)**
- **dE/dx ≈ 1-2 x ρ [g/cm³] MeV/cm**



Small energy loss
→ Fast Particle



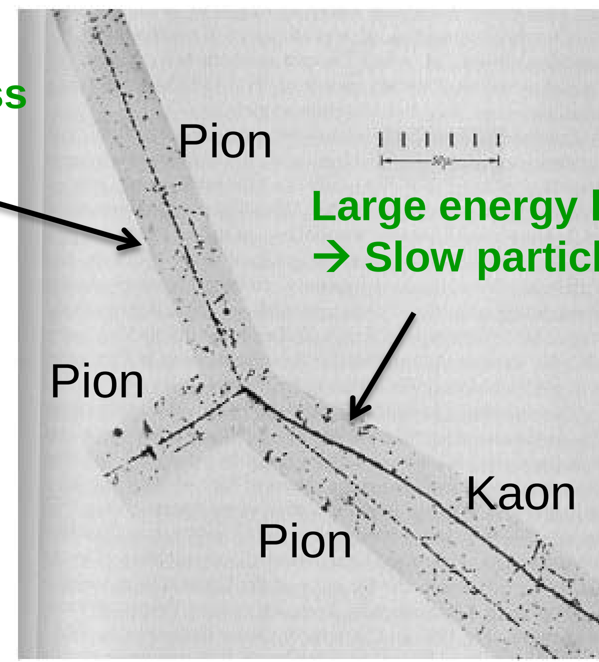
Discovery of muon and pion



Cosmis rays: dE/dx α Z^2

Small energy loss
→ Fast particle

Large energy loss
→ Slow particle



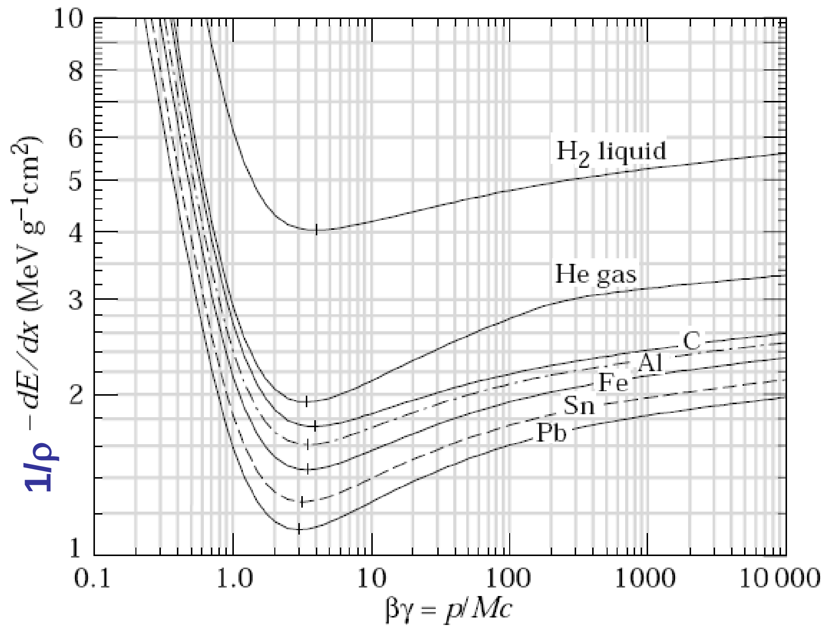
Bethe Bloch Formula

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; ρ = 7.87 g/cm^3
dE ≈ 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]

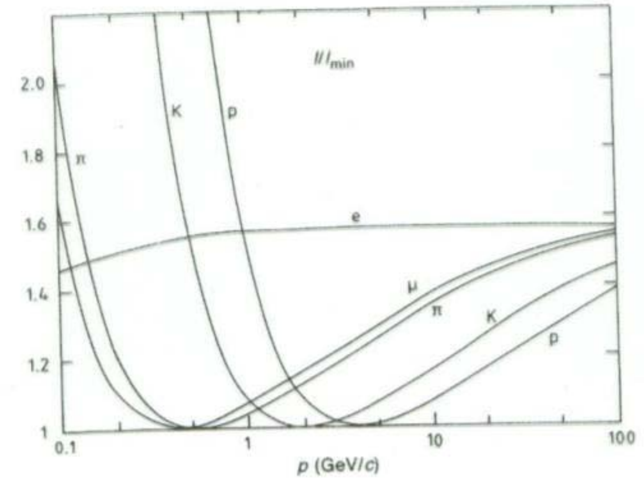
Energy Loss as a Function of the Momentum

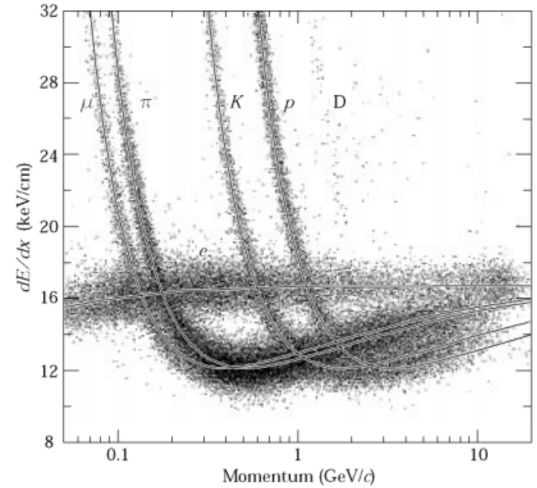
Energy loss depends on the particle velocity and is ≈ independent of the particle's mass M.

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

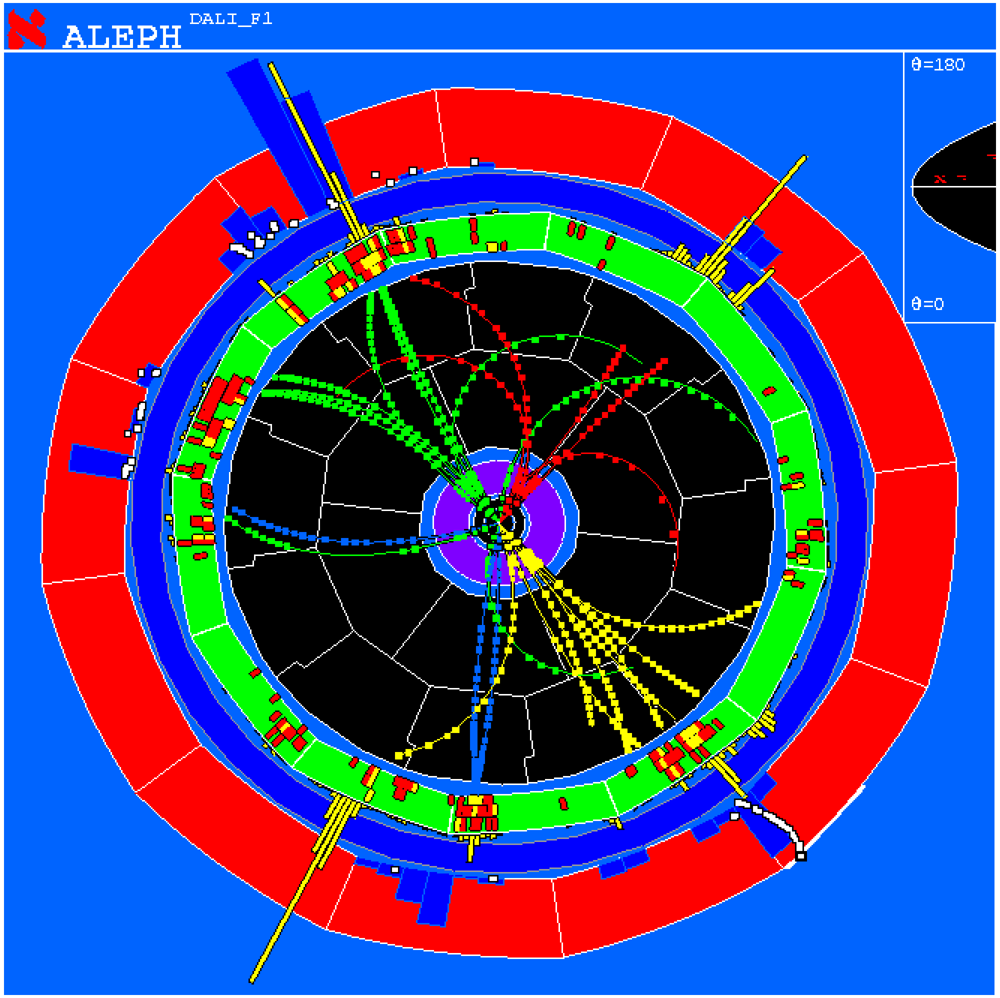
→ Particle Identification !





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

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

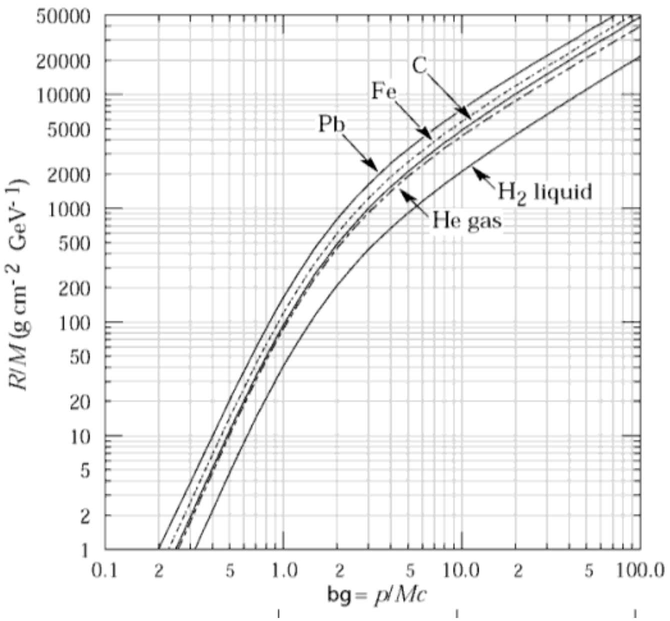
Particle of mass M and kinetic Energy E_0 enters matter and looses energy until it comes to rest at distance R.

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

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

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

≈Independent of the material

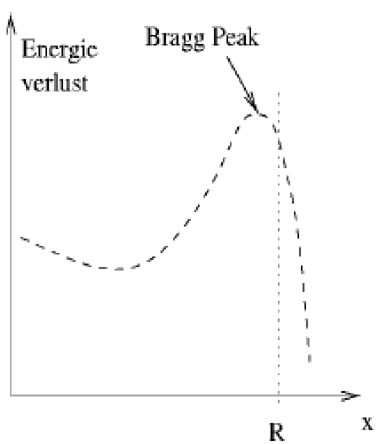


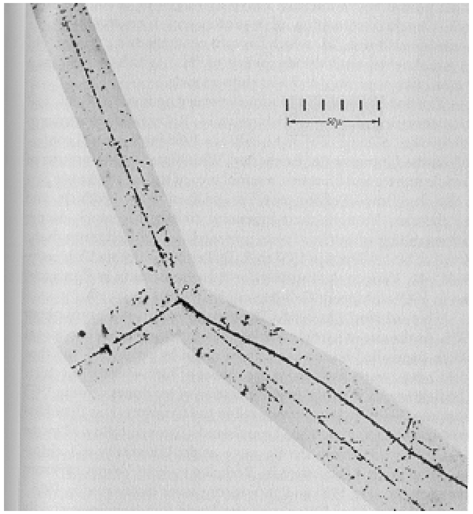
Bragg Peak:

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.

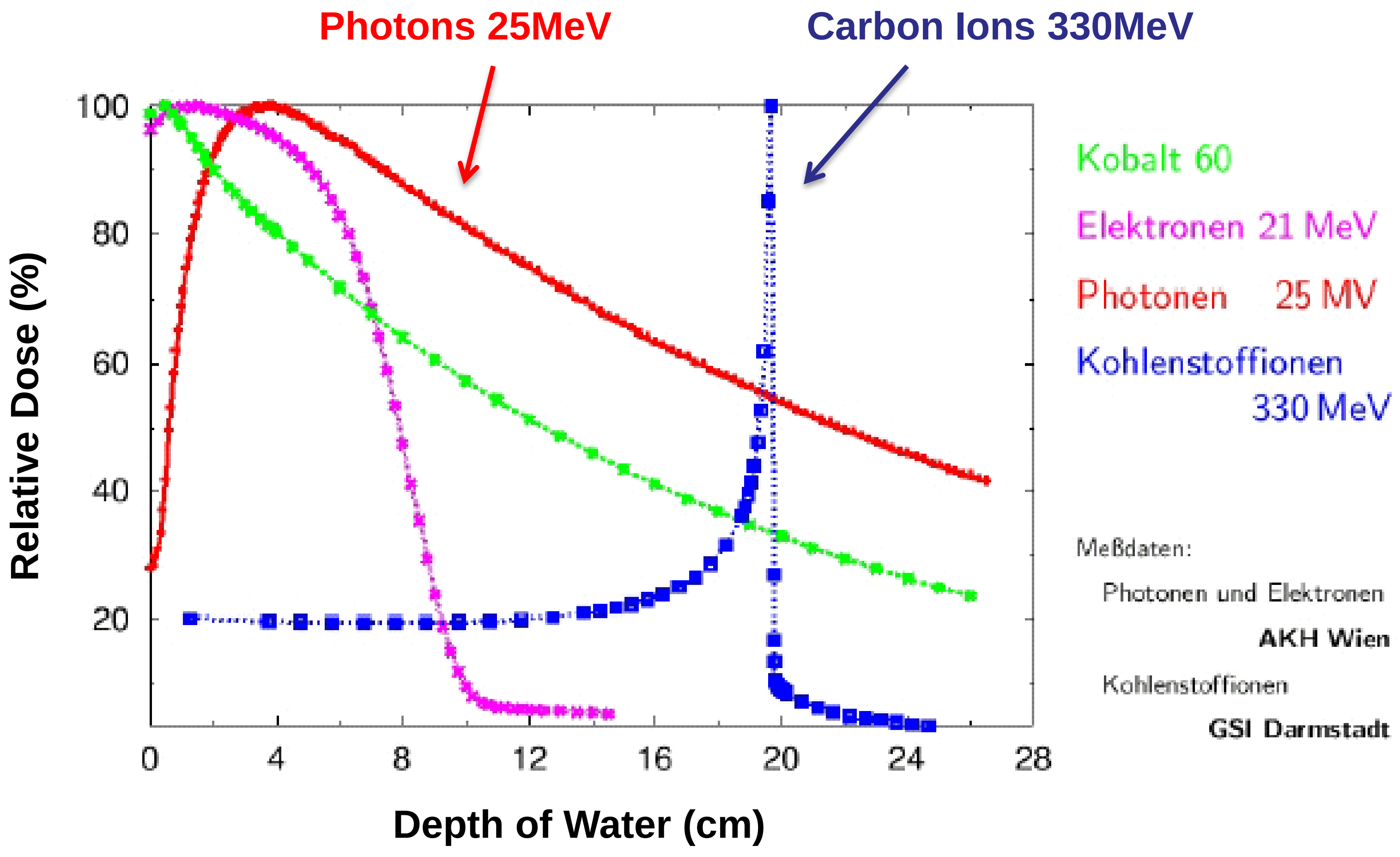




Range of Particles in Matter

Average Range:

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



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, (E) descending passageway, (F) ascending passageway, (G) underground chamber, (H) Grand Gallery, (I) King's Chamber, (J) Queen's Chamber, (K) center line of the pyramid.

6 FEBRUARY 1970

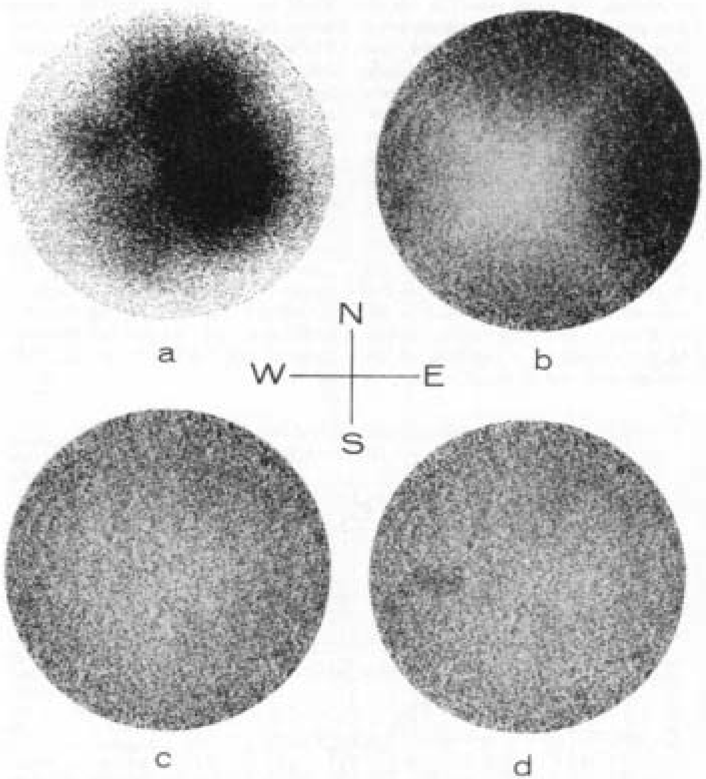
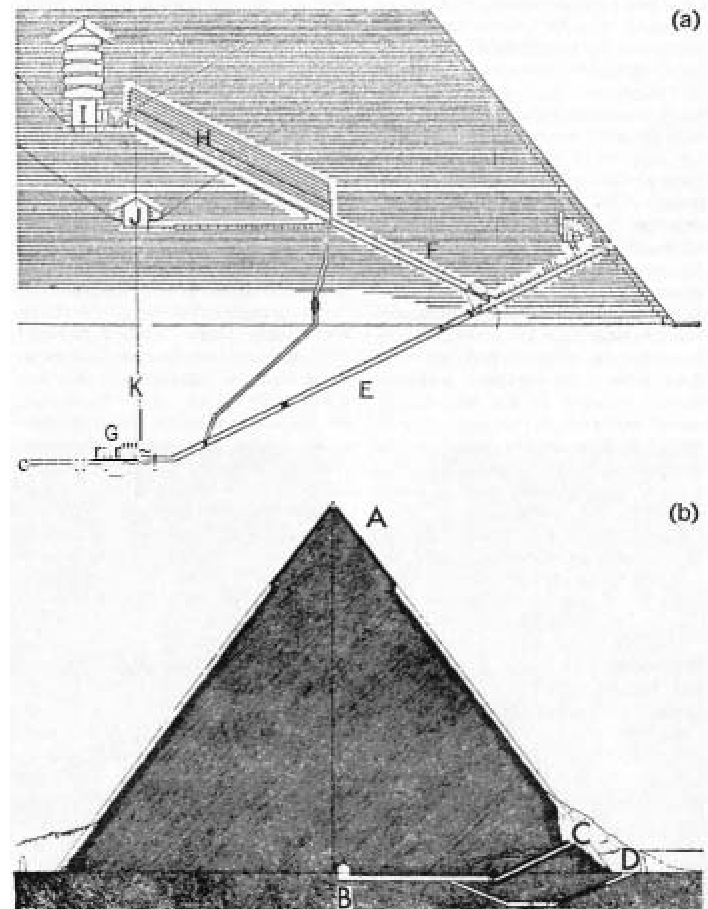


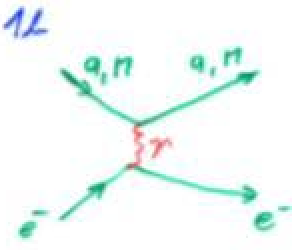
Fig. 13. Scatter plots showing the three stages in the combined analytic and visual analysis of the data and a plot with a simulated chamber. (a) Simulated "x-ray photograph" of uncorrected data. (b) Data corrected for the geometrical acceptance of the apparatus. (c) Data corrected for pyramid structure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

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.



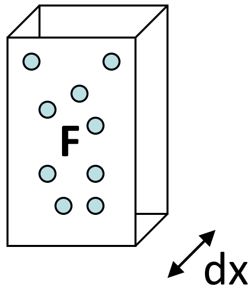
Intermezzo: Crossection



Crossection σ: Material with Atomic Mass A and density ρ contains n Atoms/cm^3

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

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 $p = N\sigma/F = N_A \rho\, \sigma /A\, dx$ =
Probability that an incoming particle hits an atom in dx.

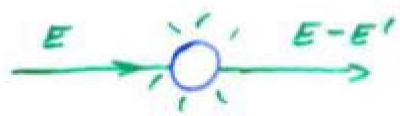
What is the probability P that a particle hits an atom between distance x and x+dx ?
P = probability that the particle does NOT hit an atom in the m=x/dx material layers and that the particle DOES hit an atom in the mth layer

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

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

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

Intermezzo: Differential Crossection



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

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

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

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

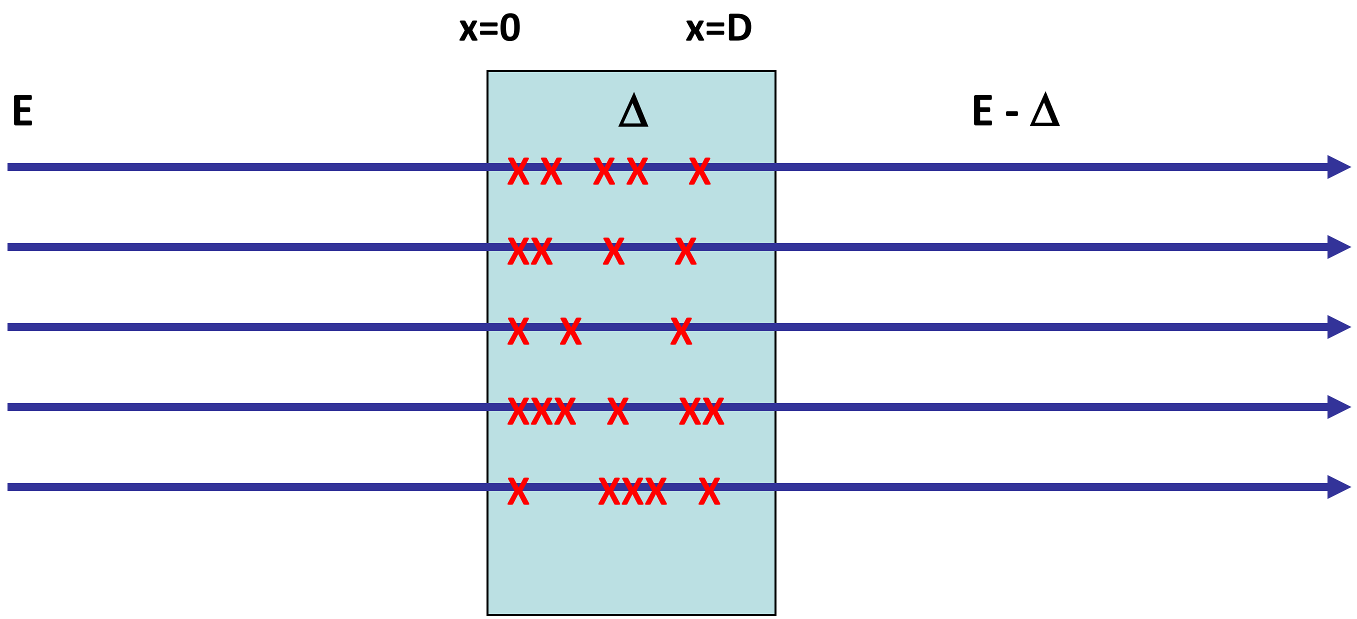
$$P(E,E')dE' = \frac{1}{\sigma(E)} \frac{d\sigma(E,E')}{dE'} dE'$$

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

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

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.



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/ λ exp(-x/λ) dx with λ = A/ N_Aρ σ

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 n^{th} a
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

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

→Poisson Distribution !

<u>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 $\overline{n}$=D/λ.</u>

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 ?

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

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

$$F(s) = \mathcal{L}\left[f(E)\right] = \int_0^\infty f(E)e^{-sE}dE$$

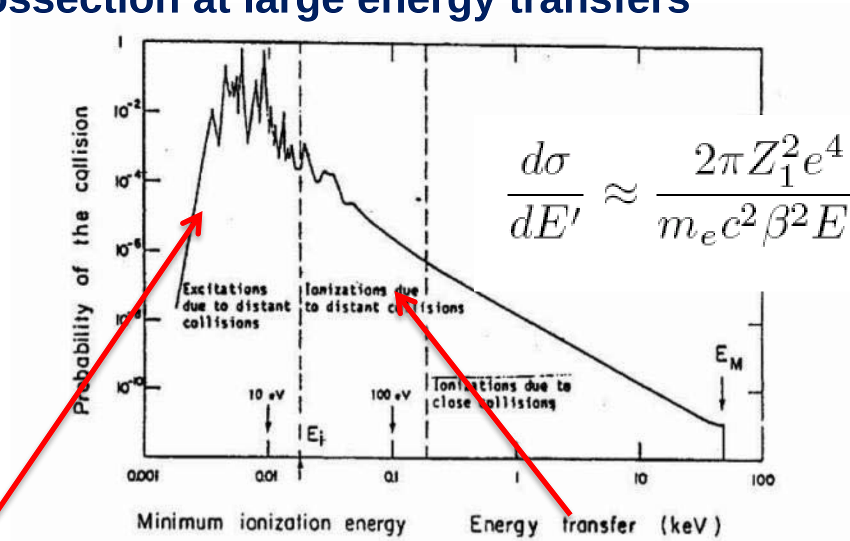
$$\mathcal{L}\left[p(E)\right] = P(1)F(s)+P(2)F(s)^2+P(3)F(s)^3+\dots = \sum_{n=1}^\infty P(n)F(s)^n = \sum_{n=1}^\infty \frac{\overline{n}^n F^n}{n!} e^{-\overline{n}} = e^{\overline{n}(F(s)-1)} - 1 \approx e^{\overline{n}(F(s)-1)}$$

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

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

dσ (E,E')/dE'/ σ(E)



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

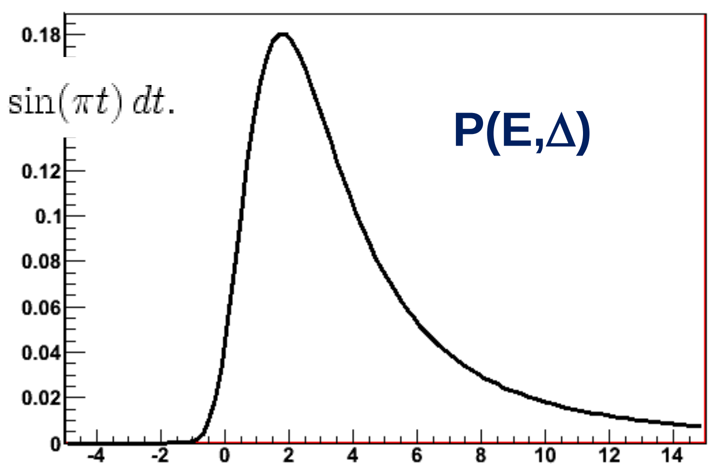
Excitation and ionization

Scattering on free electrons

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

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

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



Landau Distribution

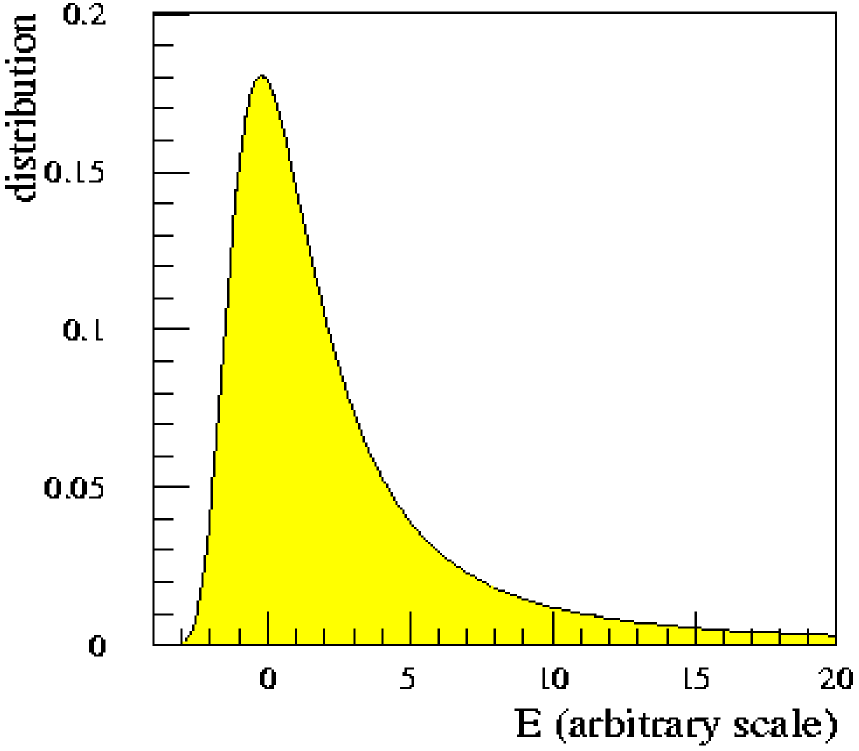
P(Δ): Probability for energy loss Δ in matter of thickness D.

Landau distribution is very asymmetric.

Average and most probable energy loss must be distinguished !

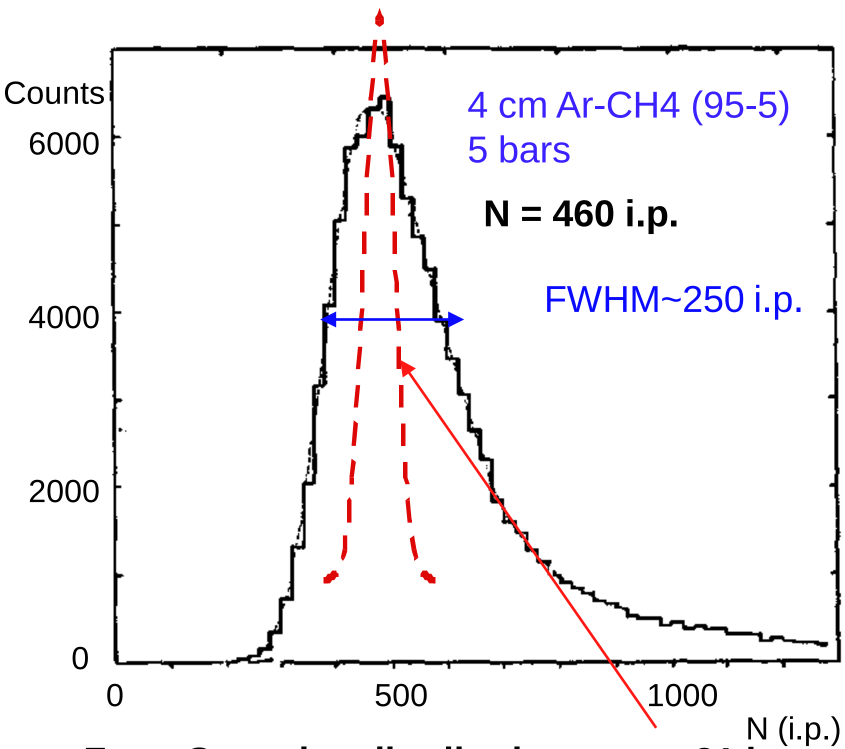
Measured Energy Loss is usually smaller that the real energy loss:

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



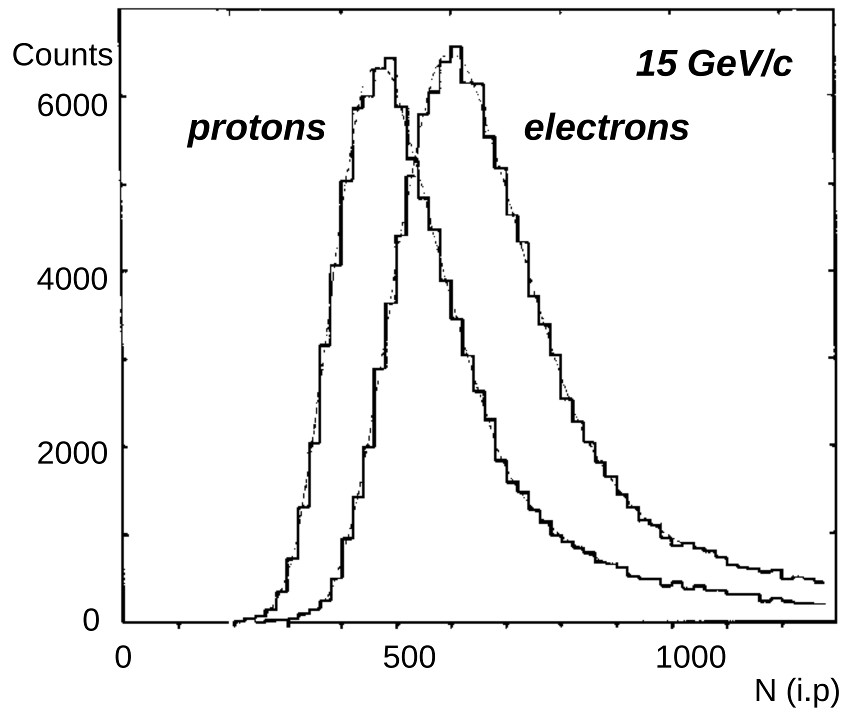
Landau Distribution

LANDAU DISTRIBUTION OF ENERGY LOSS:



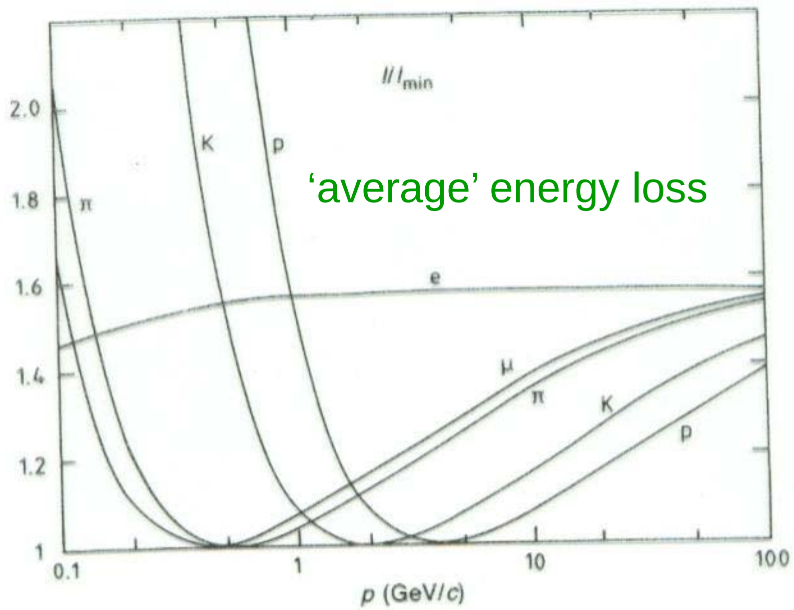
For a Gaussian distribution: **σ_N ~ 21 i.p.**
FWHM ~ 50 i.p.

PARTICLE IDENTIFICATION
Requires statistical analysis of hundreds of samples

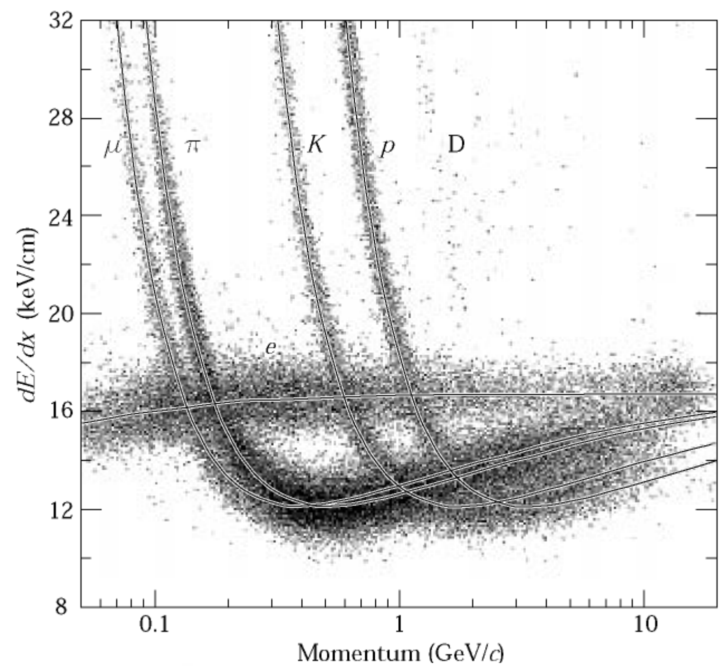


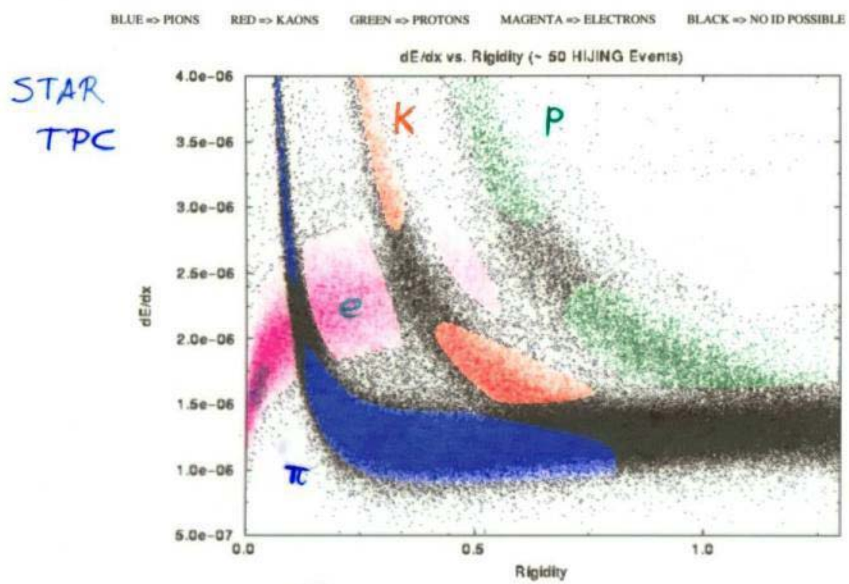
I. Lehraus et al, Phys. Scripta 23(1981)727

Particle Identification



Measured energy loss

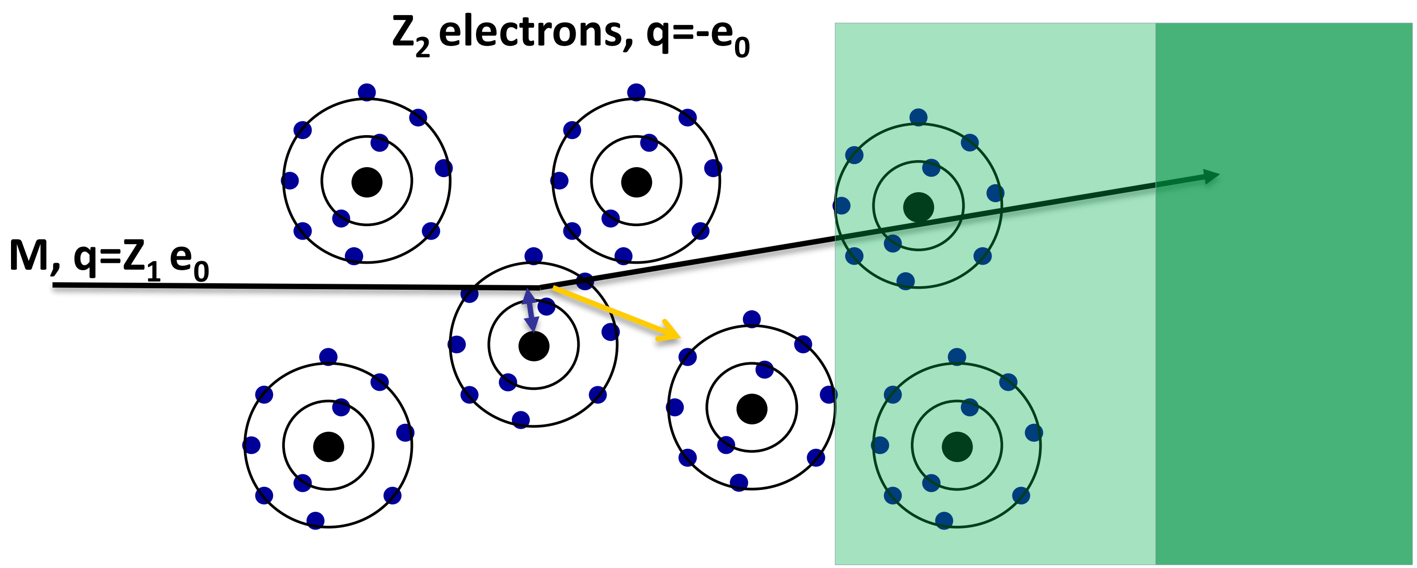




In certain momentum ranges, particles can be identified by measuring the energy loss.

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

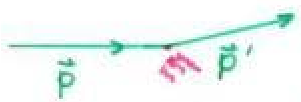
$q = Z_1 \cdot e$

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

"Rutherford Scattering"

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

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



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

→ From Maxwell's Eq (Jackson)

$$\lim_{\omega \to 0} \frac{dI}{d\omega} \sim \frac{2}{3\pi} \frac{Z_1^2 e^2}{M^2 c^3} \frac{1}{4\pi\epsilon_0} Q^2$$ Radiated Energy between $\omega, \omega + d\omega$

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

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

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

A charged particle of mass M and charge $q=Z_1 e$ is deflected by a nucleus of Charge Ze.

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

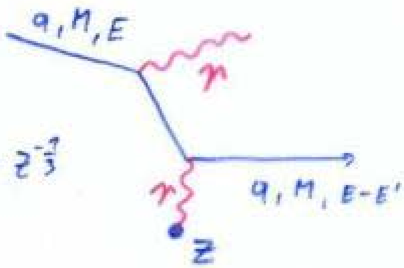
Coulomb-Scattering (Rutherford Scattering) describes the deflection of the particle.

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

→ dE/dx

Bremsstrahlung, QM

2.6 Bremsstrahlung Q.M.



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

→ 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.

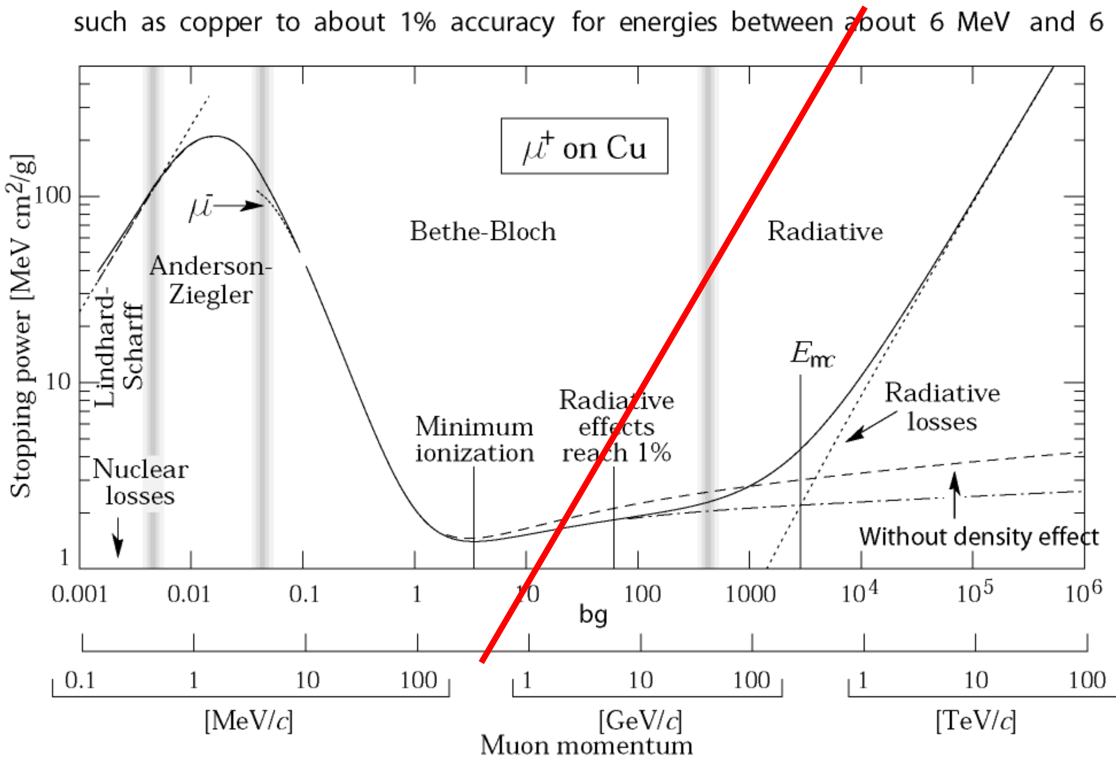
Proportional to the Energy of the Incoming particle →

$E(x)=Exp(-x/X_0)$ – ‘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 $E_0 Exp(-1)=0.37E_0$.

Critical Energy



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

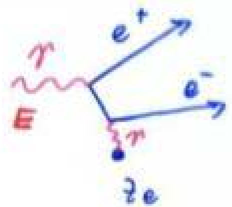
The EM Bremsstrahlung is therefore only relevant for electrons at energies of past and present detectors.

Electron Momentum 5 50 500 MeV/c

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

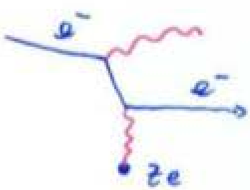
Myon in Copper: p ≈ 400GeV
Electron in Copper: p ≈ 20MeV

Pair Production, QM



$\gamma + \text{Nucl.} \rightarrow e^+ + e^- + \text{Nucl}$

The Diagram is very similar to Bremsstrahlung



$e^- + \text{Nucl} \rightarrow \gamma + e^- + \text{Nucl}$

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

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

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

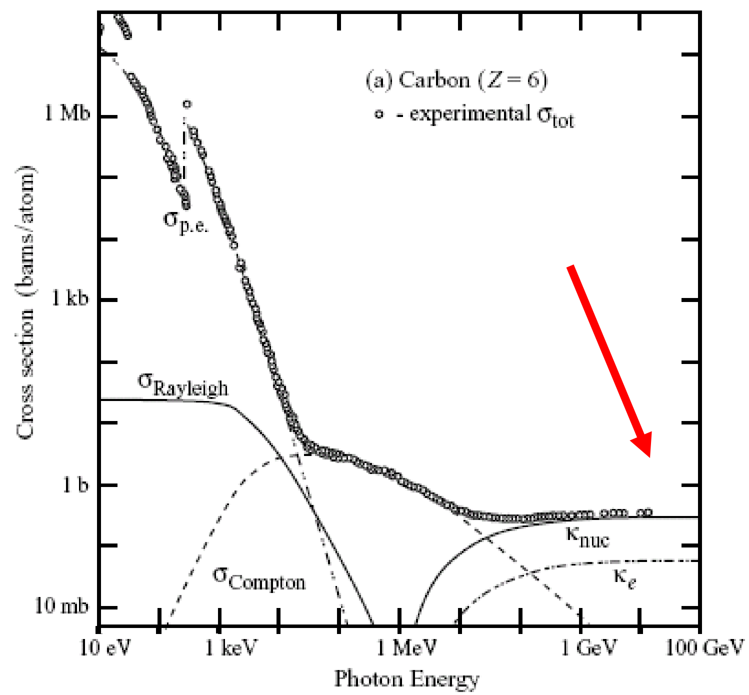
$$\sigma = \int_0^{E-2m_ec^2} \frac{d\sigma}{dE'} dE' = 4\alpha Z^2 r_e^2 \cdot \frac{7}{9} \ln 183 Z^{-\frac{1}{3}}$$

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

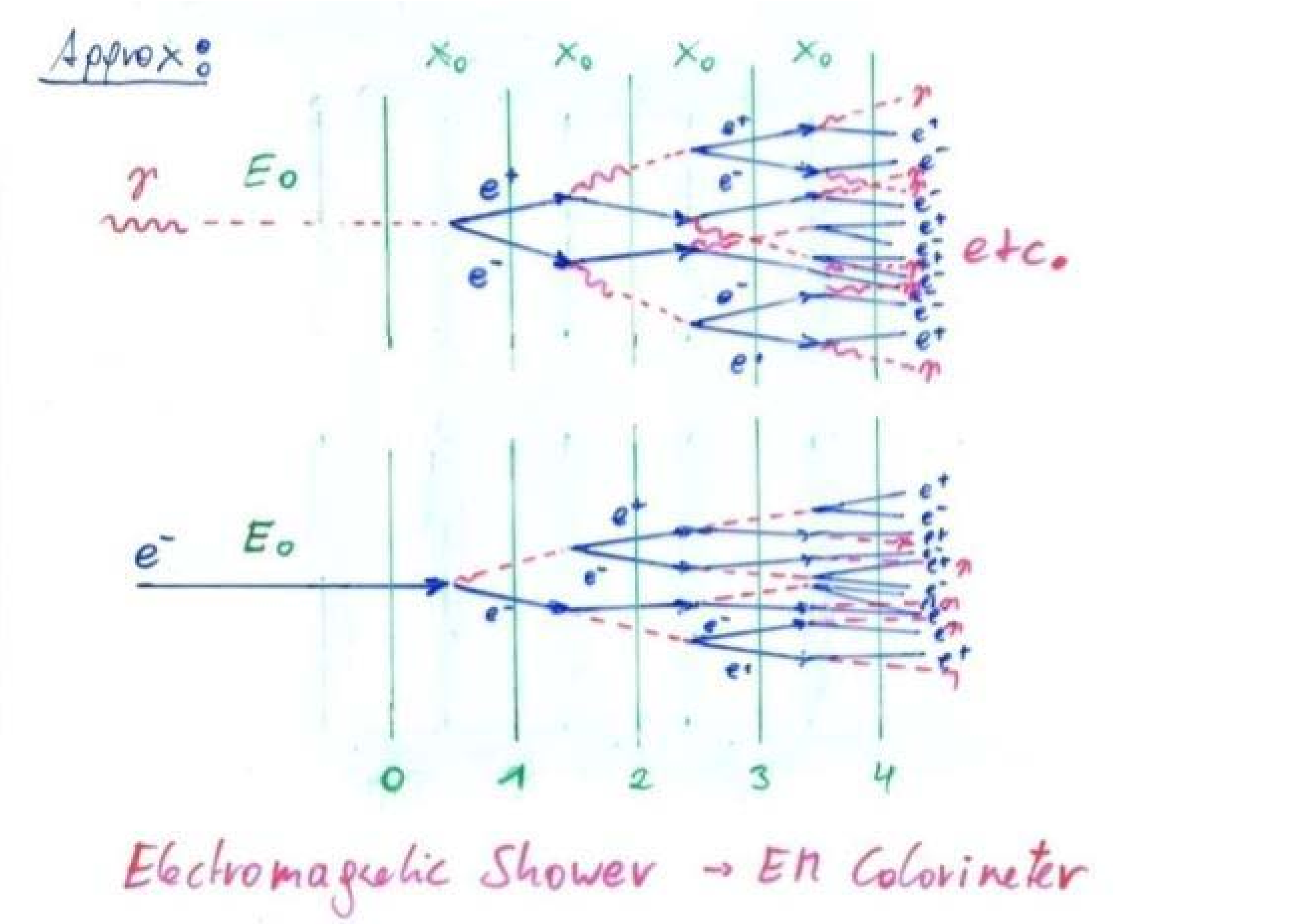
↳ Probability that Photon converts to $e^+ e^-$ after a distance x.

For $E\gamma \gg m_e c^2 = 0.5$ 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*Exp(-1) by photon radiation.



Bremsstrahlung + Pair Production → EM Shower



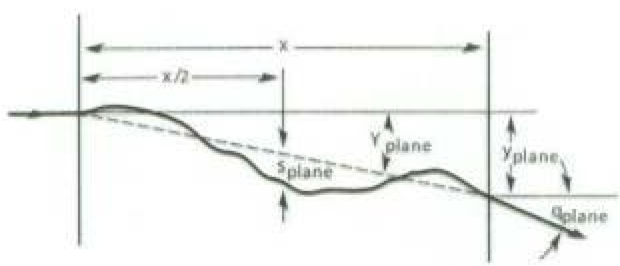
Multiple Scattering

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:

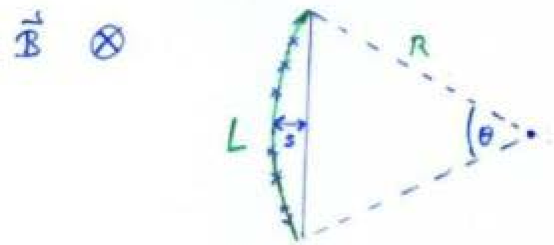
$$\Theta_0 = \frac{0.0136}{\beta c p[\mathrm{GeV/c}]} Z_1 \sqrt{\frac{x}{X_0}}$$

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



Multiple Scattering

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



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

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

$$L = R \cdot \theta$$

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

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

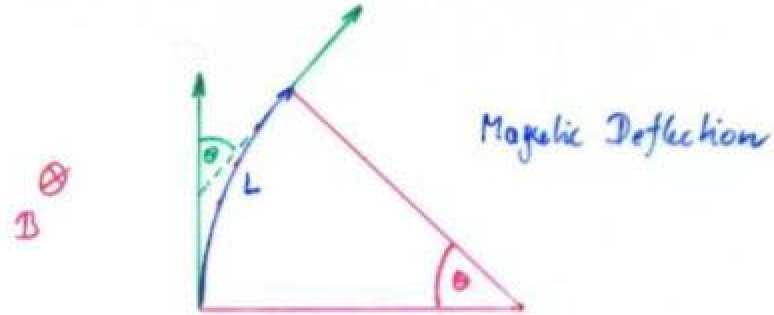
$$\Delta s = \frac{\sigma_x}{\sqrt{N}}$$ σ_x ... point resolution, N ... Measurement Points

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

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

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

Limit → Multiple Scattering



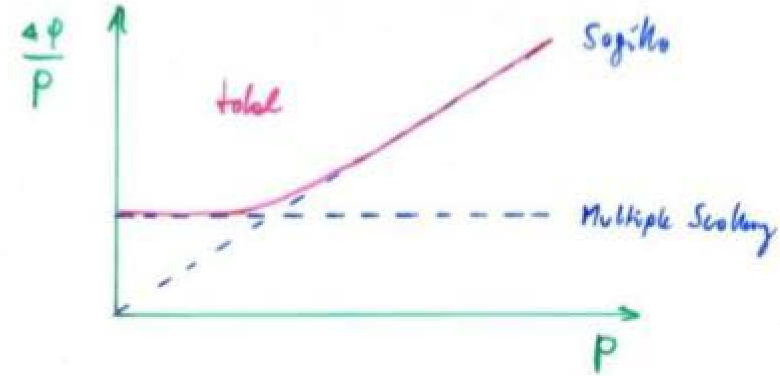
$$p\left[\frac{\mathrm{GeV}}{c}\right] = 0.3\,R[\mathrm{m}]\,B[\mathrm{T}]$$

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

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

→ Independent of p

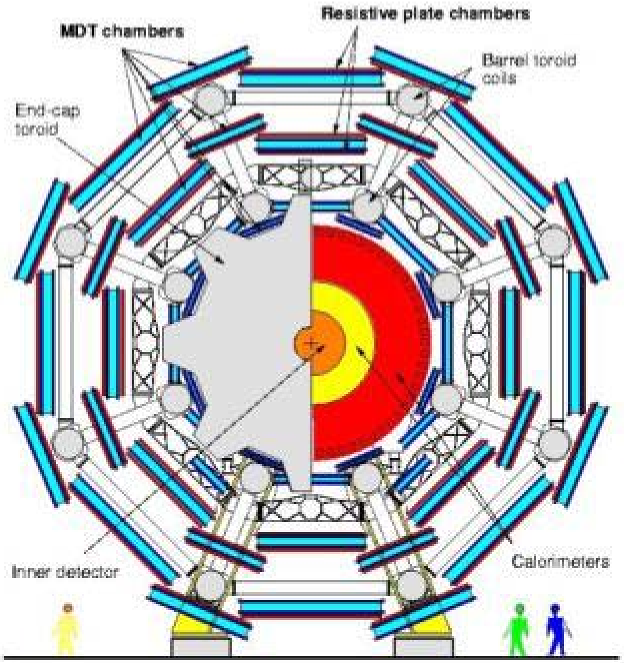
$$\left.\frac{\Delta p}{p}\right|_{tot} = \sqrt{\left(\left.\frac{\Delta p}{p}\right|_{sag}\right)^2 + \left(\left.\frac{\Delta p}{p}\right|_{ms}\right)^2}$$

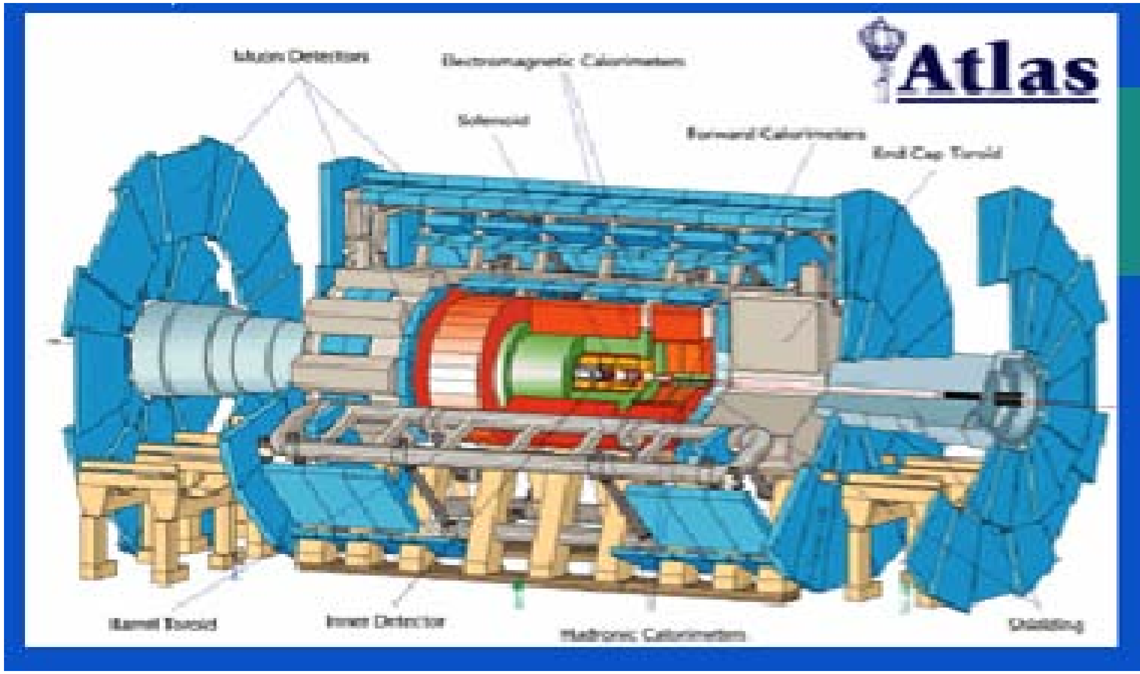


Multiple Scattering

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

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





Cherenkov Radiation

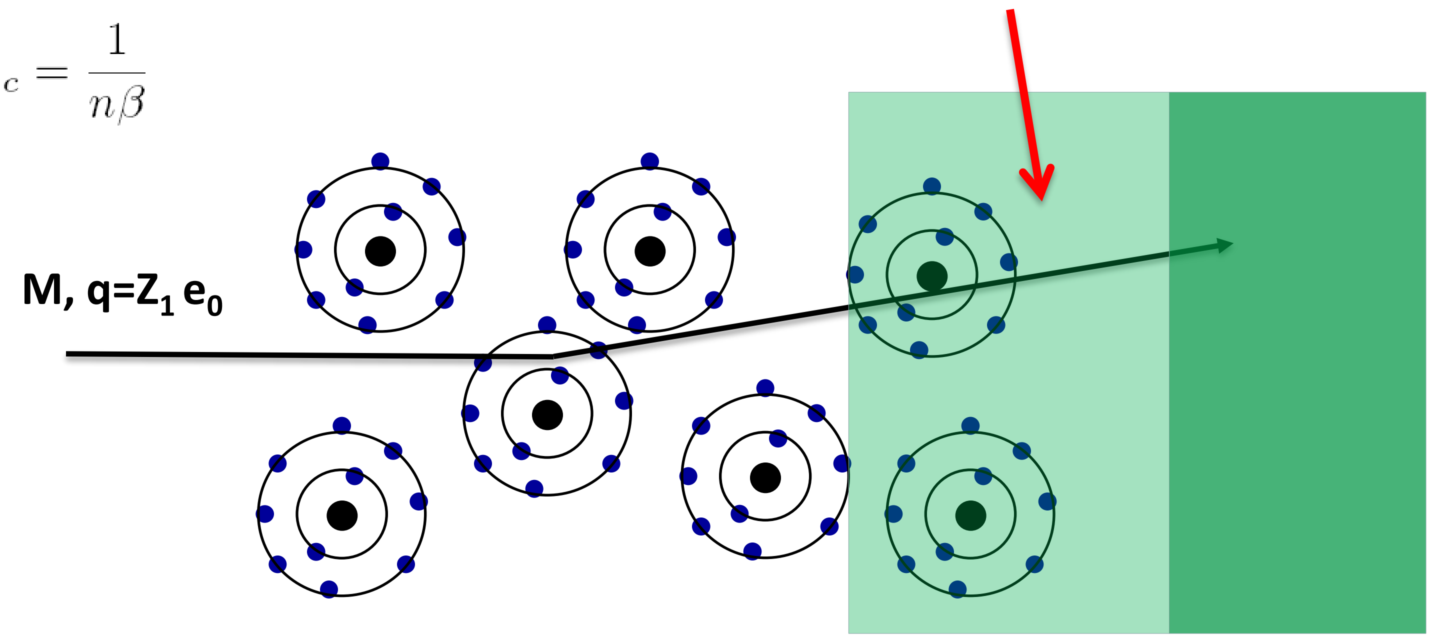
If we describe the passage of a charged particle through material of dielectric permittivity ϵ_1 (using Maxwell's equations) the differential energy crossection is >0 if the velocity of the particle is larger than the velocity of light in the medium is

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

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

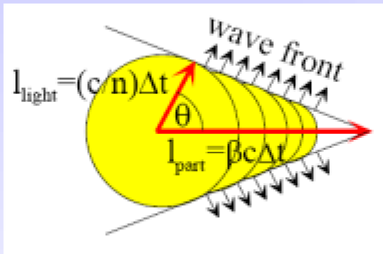
N is the number of Cherenkov Photons emitted per cm of material. The expression is in addition proportional to Z_1^2 of the incoming particle.
The radiation is emitted at the characteristic angle Θ_c, that is related to the refractive index n and the particle velocity by

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



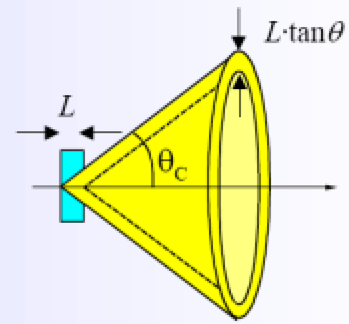
Cherenkov Radiation

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



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

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 'Cherenkov' 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

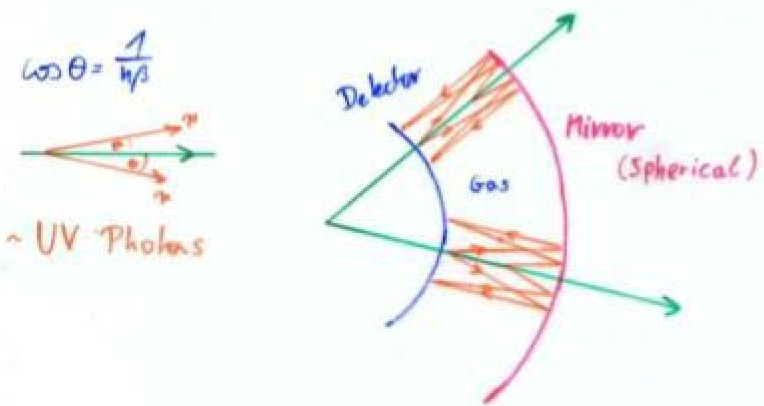
$$\frac{dN}{dx} \sim 2\pi\alpha z_1^2 \left(1 - \frac{1}{\beta^2 n^2}\right) \frac{\lambda_2 - \lambda_1}{\lambda_2 \cdot \lambda_1}$$

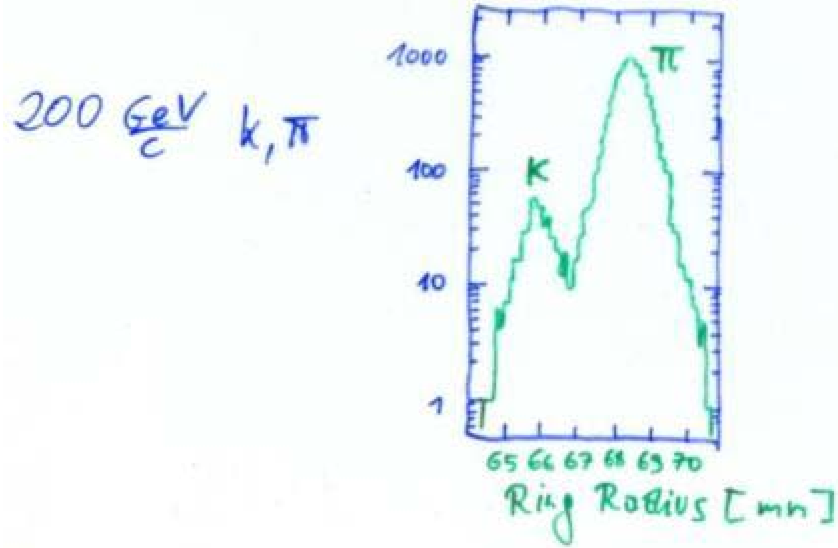
= Number of emitted Photons / length with λ between λ_1 and λ

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)

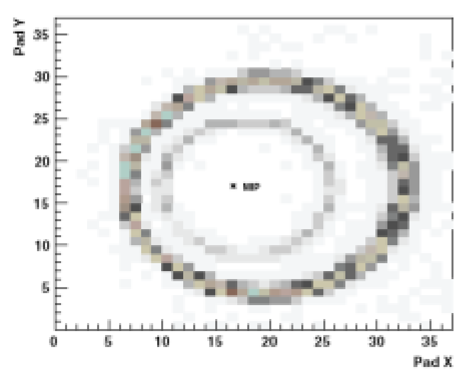


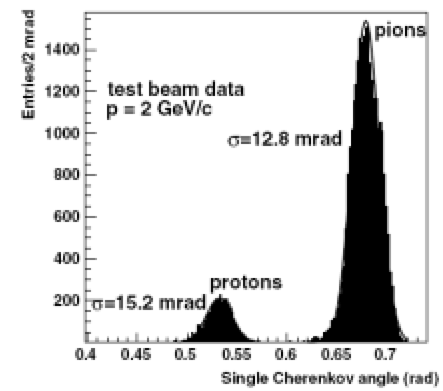


Resolution $\frac{\Delta \gamma}{\gamma} = \gamma^2 \beta^3 n \, \Delta\theta \, \frac{1}{\sqrt{N_0 L}}$ $\left(\gamma = \frac{1}{\sqrt{1-\beta^2}}\right)$

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

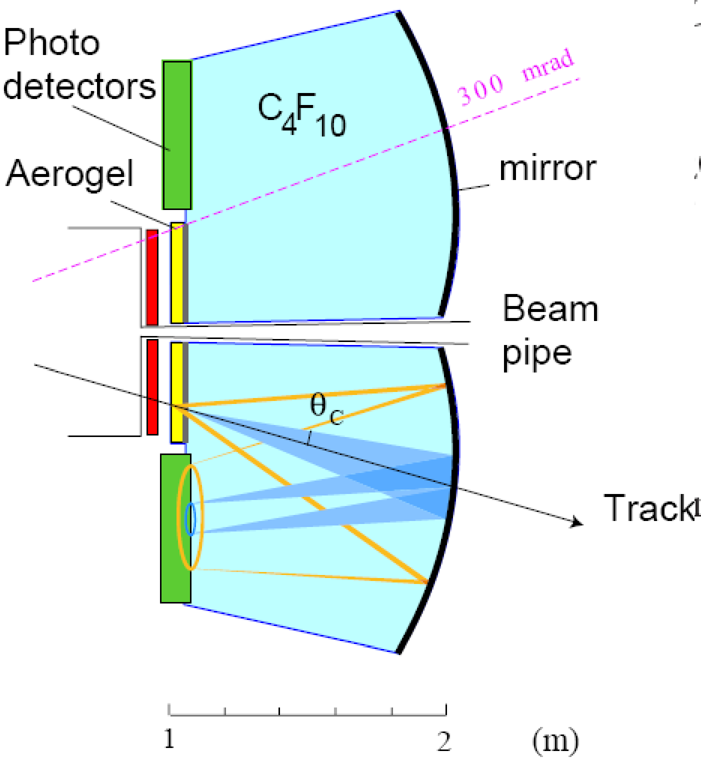
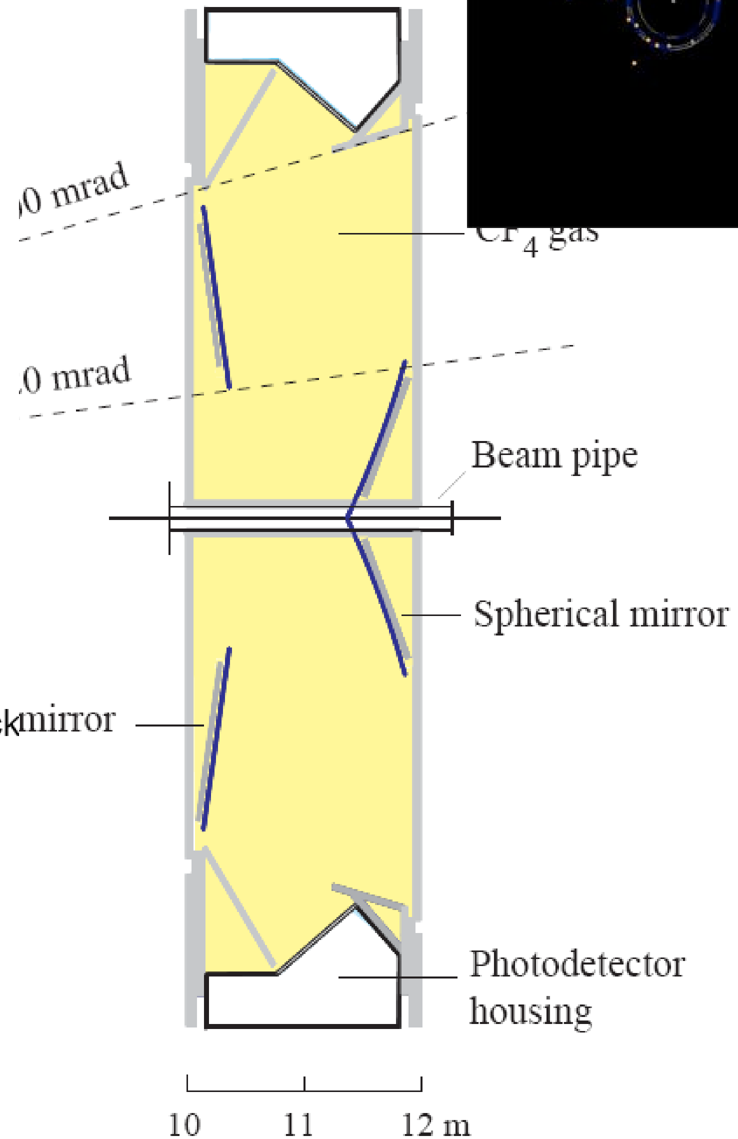
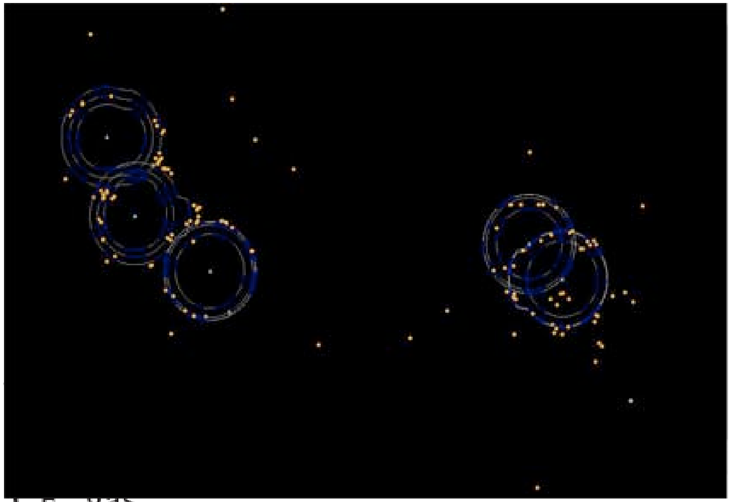


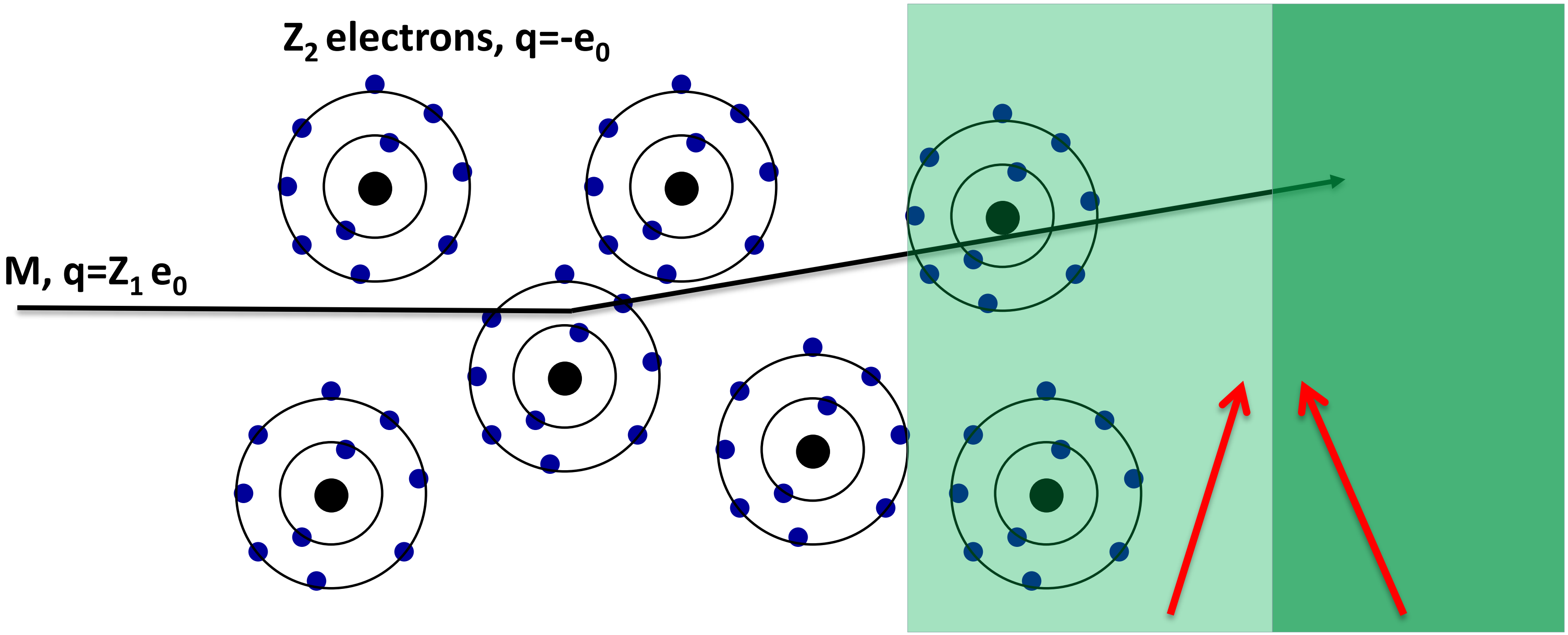
Photo detectors
C_4F_{10}
300 mrad
mirror
Aerogel
Beam pipe
θ_C
Track
1
2
(m)



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 ($\varepsilon_1, \varepsilon_2$)

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

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

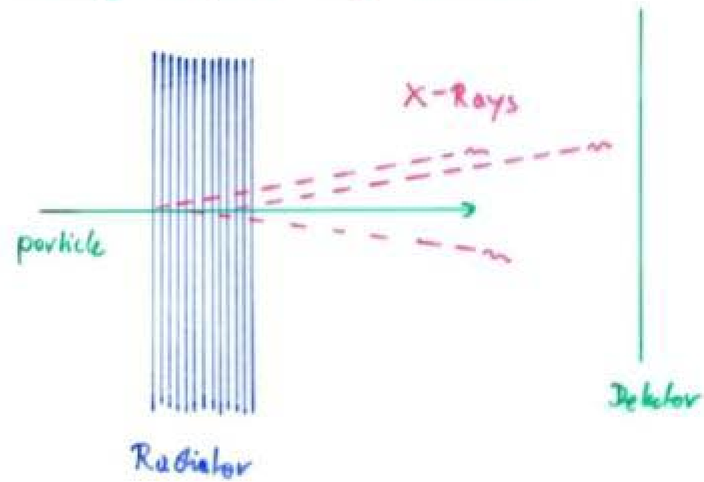
E.g. $\gamma = 1000$ 2-20 keV X-Rays

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

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.



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 2^{nd} power of the particle mass, so it is only relevant for electrons.

Electromagnetic Interaction of Particles with Matter

Cherenkov Radiation:

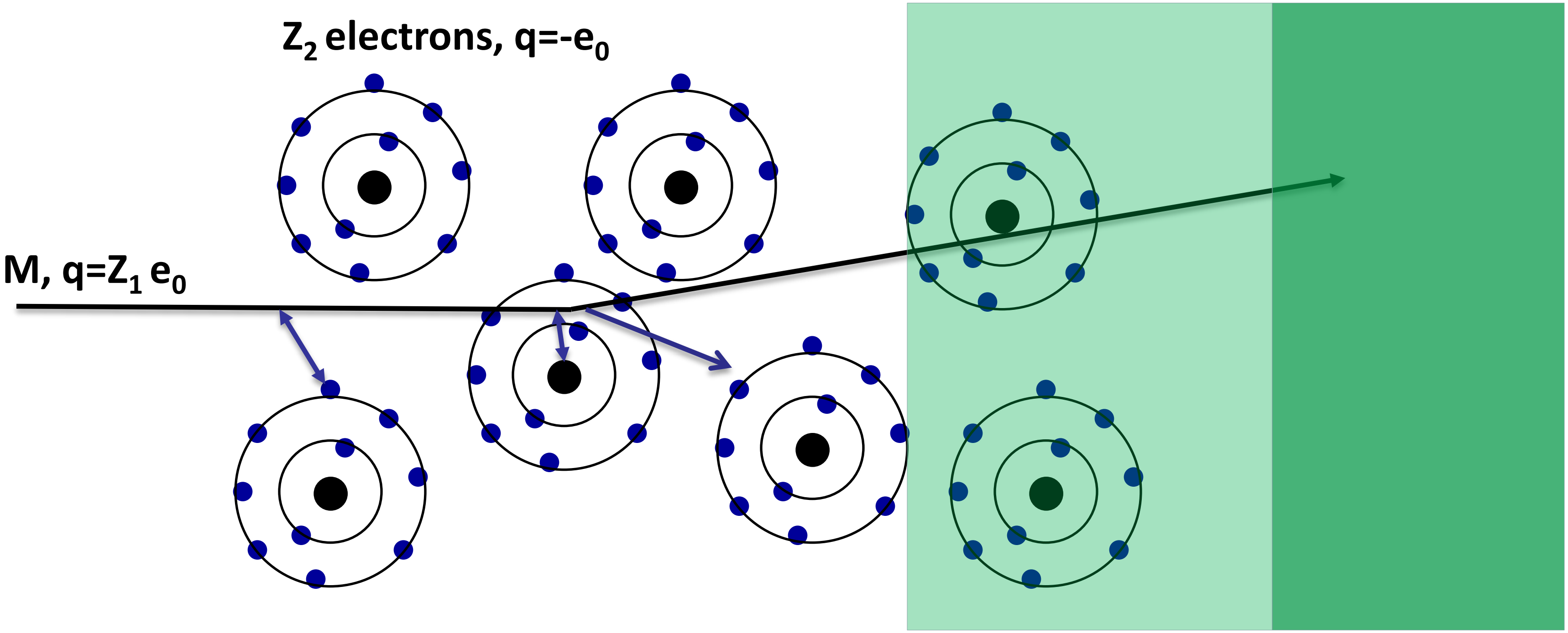
If a particle propagates in a material with a velocity larger than the speed of light in this material, Cherenkov radiation is emitted at a characteristic angle that depends on the particle velocity and the refractive index of the material.

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.

Electromagnetic Interaction of Particles with Matter



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>.

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