Introduction to particle detectors and applications

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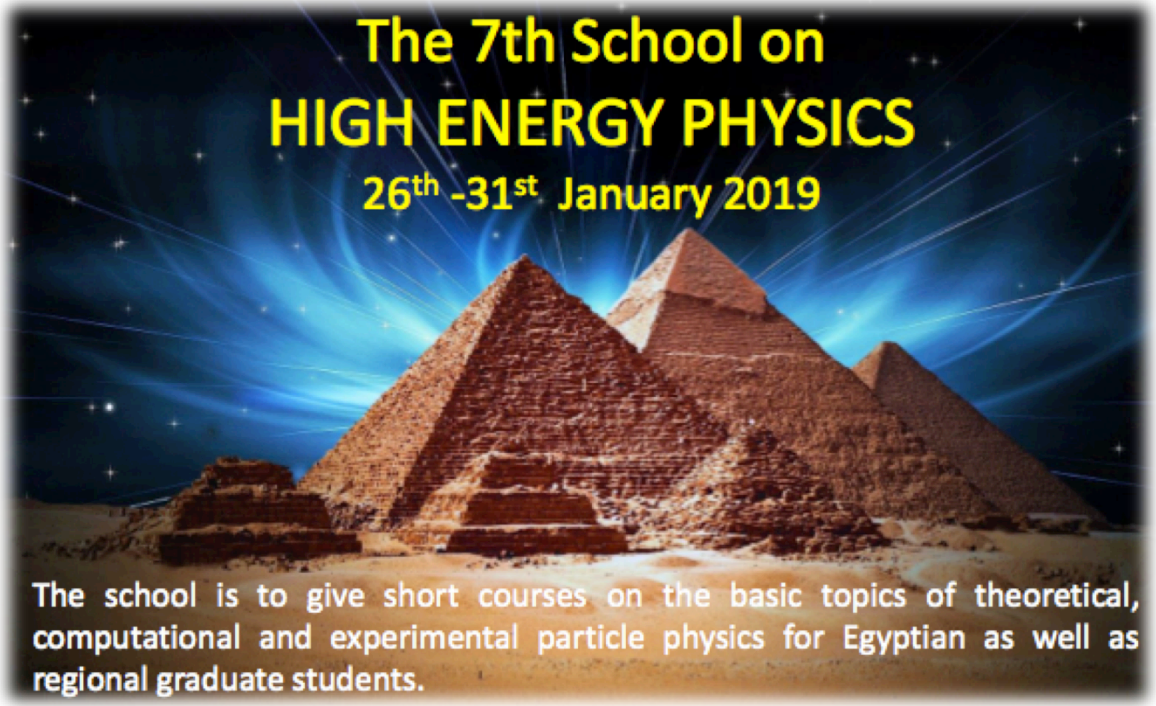
Universidad Iberoamericana
Mexico city

السلام عليكم

شكرا لدعوتك



7th ENHEP School on High Energy Physics

Contents

passage of particles through matter

- Some probability considerations
- Classical case
- Bethe formula
  - Stopping power
  - Particle ID (Energy dependence)
  - Bragg curve
- Hadro-Therapy vs X-Rays
  - Hadrons vs Photon case
- Muon case
  - Mips
  - HEP Experiments Layout
  - Muon lifetime
- Helwan collaboration
  - PMTs, RPC.
- List of other applications of HEP

How particles interact with matter?

Let's consider the case of the interaction of a particle traveling through any thickness *x* of material, so in terms of probability we can ask:

What is the probability for a particle not to sufer an interaction in a distance *x*?

P(*x*): probability of not having an interaction after a distance *x*

w d*x*: probability of having an interaction beteen *x* and *x*+d*x*

$$P(x+dx) = P(x)(1-wdx)$$

$$P(x) + \frac{dP}{dx}dx = P - P\,w\,dx$$

$$dP = -wPdx$$

$$P = C\,e^{-2}$$

The probability of a particle surviving a distance *x* is thus exponential in distance

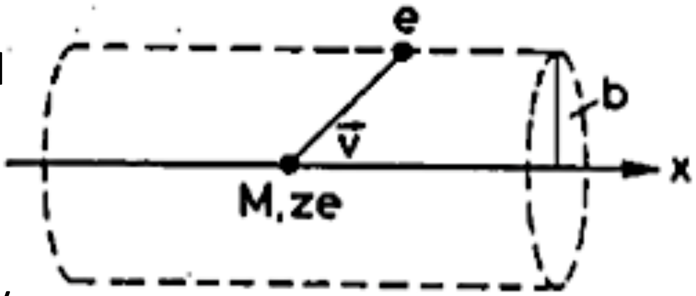
And then the probability of having an interaction in *x* is

$$P(x)_{int} = 1 - e^{-wx}$$

While the probability of the particle suffering a collision between *x* and *x*+d*x* after surviving a *x* distance is $P(x)dx = e^{-wx} w\,dx$

Bohr's calculation (Classical case)*

Consider a heavy particle with charge *ze*, mass *M* and velocity *v* passing through some material and if we suppose that there is an atomic electron at some distance *b* (from the trajectory). We will assume that the electron is free and initially at rest, and to simplify more, that it only moves very slightly during the interaction with the heavy particle so that the electric field acting on the electron may be taken at its initial position. Also we will assume that the incident particle ($M \gg m_e$), so it will not deflect after the interaction.

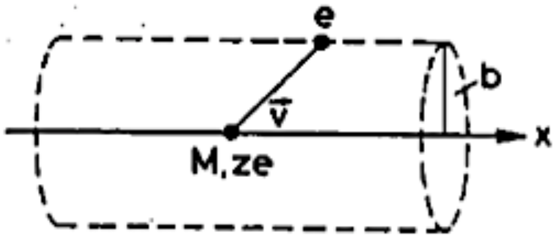


This derivation will works reasonable for the energy loss for heavy particles such as the α-particle. However, for lighter particles, like the proton, the quantum mechanical efects most be consider.

*W.R. Leo; Tech for Nuclear and Particle

Bohr's calculation (Classical case)

Lets calculate the energy gained by the electron with the impulse (*I*) receiving from the heavy particle:



$$I = \int F\,dt = e\int E_{\perp}dt = e\int E_{\perp}\frac{dt}{dx}\,dx = \frac{e}{v}\int E_{\perp}dx = \frac{e}{v}\left(\frac{2ze}{b}\right)$$

where $\int E_{\perp}\,2\pi\,b\,dx = 4\pi\,z\,e$ with $\int E_{\perp}\,dx = \frac{2ze}{b}$

Then $$I = \frac{2ze^2}{b\,v}$$

And the energy gain by the electron is $\Delta E(b) = \frac{I^2}{2\,m_e} = \frac{2\,z^2\,e^4}{m_e\,v^2\,b^2}$

Bethe formula (intermediate energies)*

The mean rate of energy loss by moderately relativistic charged heavy particles is well-described by the "Bethe equation,"

$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] .$$

It describes the mean rate of energy loss in the region $0.1 \lesssim \beta\gamma \lesssim 1000$ for intermediate-Z materials with an accuracy of a few percent.

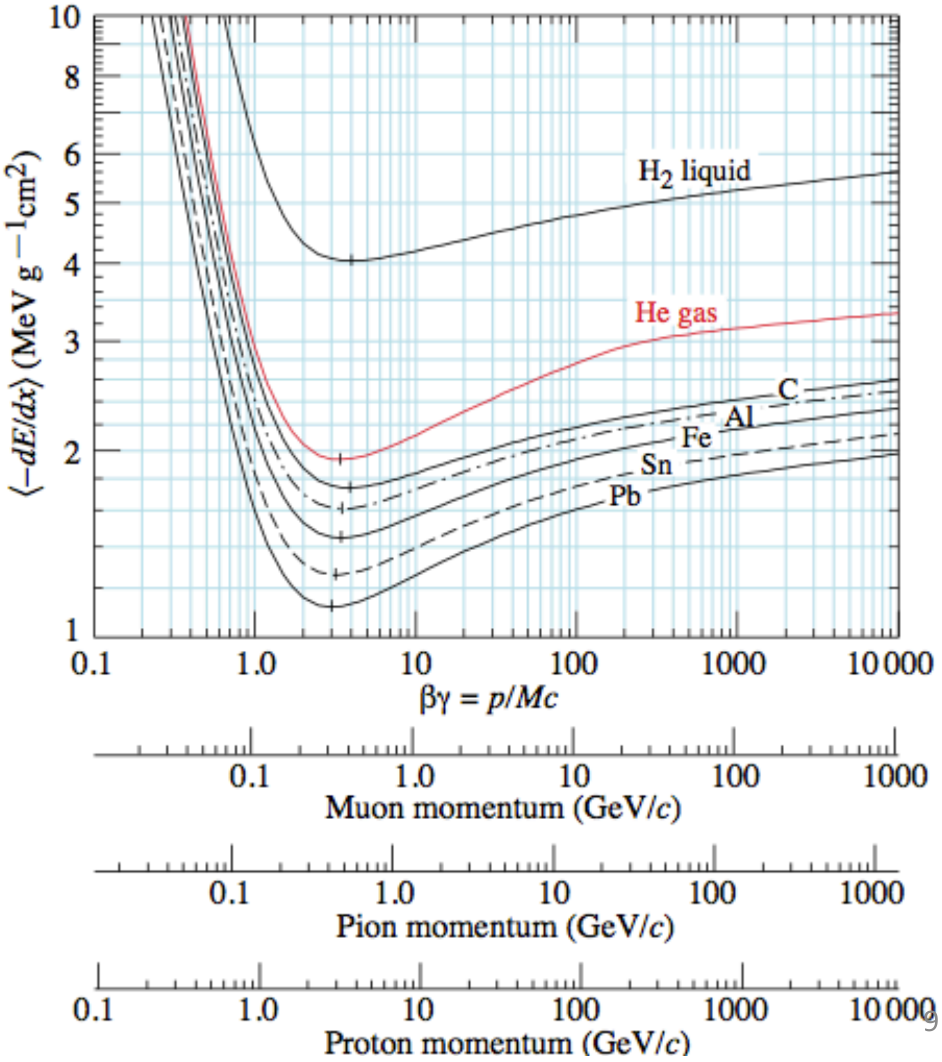
This is the mass stopping power; with the symbol definitions and values given in next Table, the units are MeV g^{-1} cm^2 .   As can be seen <-dE/dx> definded in this way is about the same for most materials, decreasing slowly with Z.

* PDG

ρ	density	g cm^{-3}
x	mass per unit area	g cm^{-2}
M	incident particle mass	MeV/c^2
E	incident part. energy γMc^2	MeV
T	kinetic energy, $(\gamma - 1)Mc^2$	MeV
W	energy transfer to an electron in a single collision	MeV
k	bremsstrahlung photon energy	MeV
z	charge number of incident particle	
Z	atomic number of absorber	
A	atomic mass of absorber	g mol^{-1}
K	$4\pi N_A r_e^2 m_e c^2$ (Coefficient for dE/dx)	0.307 075 MeV mol^{-1} cm^2
I	mean excitation energy	eV (*Nota bene!*)
$\delta(\beta\gamma)$	density effect correction to ionization energy loss	

* PDG

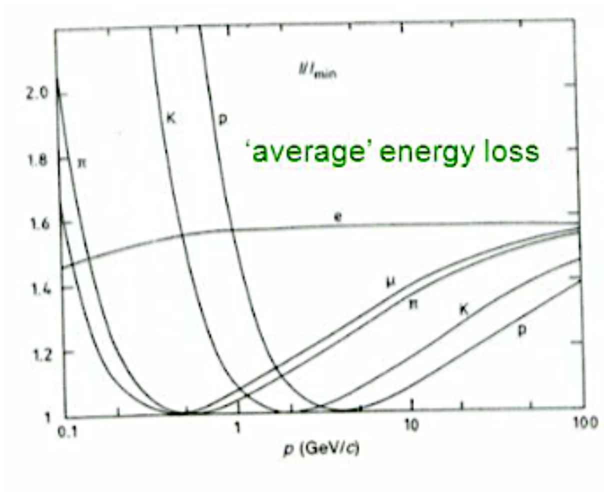
Stopping power

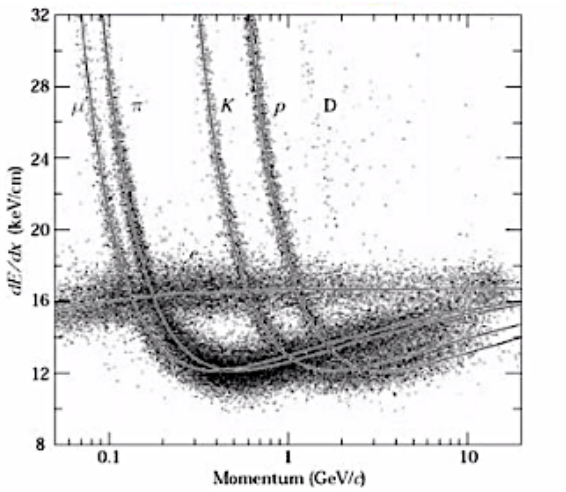


* PDG

Energy dependence (Particle identification)

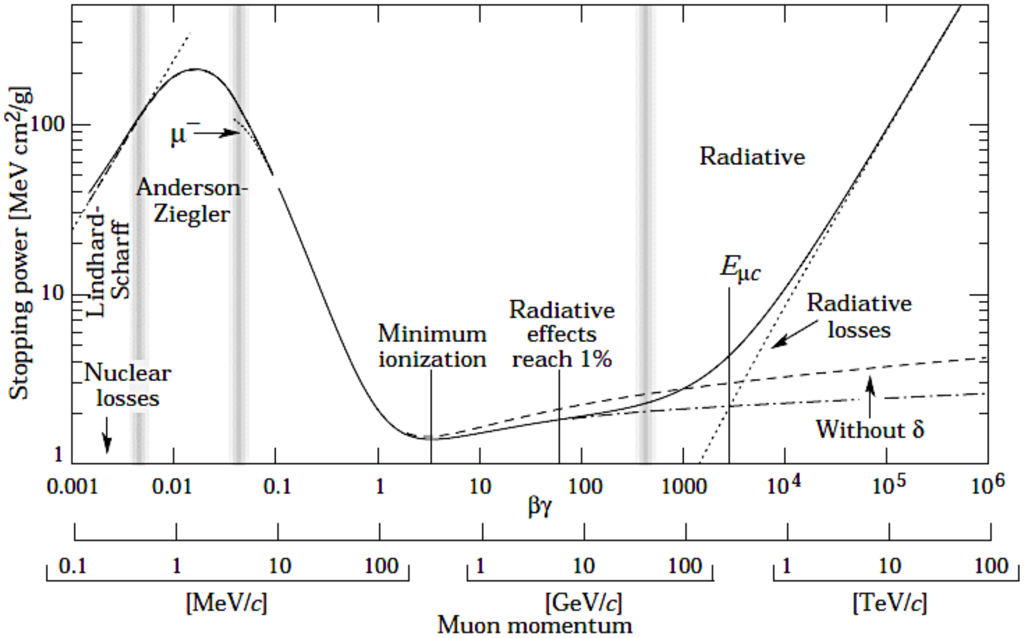
For energies below the minimum ionizing value, each particle exhibits a <dE/dx> curve, in most of the cases distinct from other particles types.
This can be exploited in particle physics as a means for identifying particles (in this range)



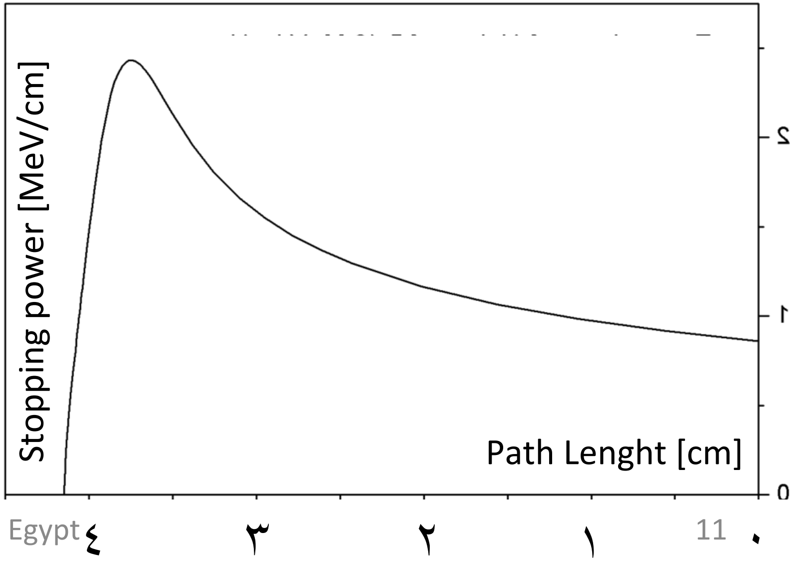


In certain momentum ranges, particles can be identifie if we meassure the energy loss

Bragg curve



Stopping power [MeV cm²/g]
100
10
1
μ⁻
Anderson-Ziegler
Lindhard-Scharff
Nuclear losses
Radiative
$E_{\mu c}$
Radiative losses
Minimum ionization
Radiative effects reach 1%
Without δ
0.001 0.01 0.1 1 10 100 1000 10⁴ 10⁵ 10⁶
βγ
0.1 1 10 100
[MeV/c]
1 10 100
[GeV/c]
1 10 100
[TeV/c]
Muon momentum



Stopping power [MeV/cm]
Path Lenght [cm]
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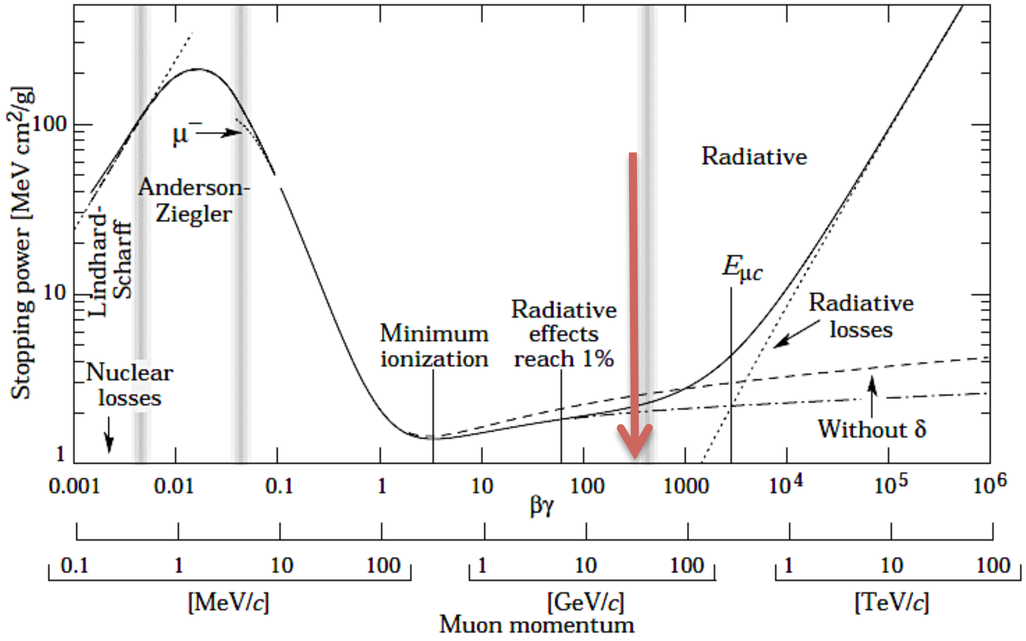
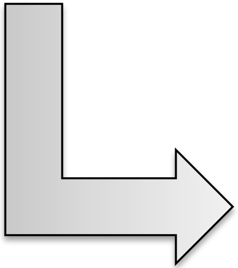
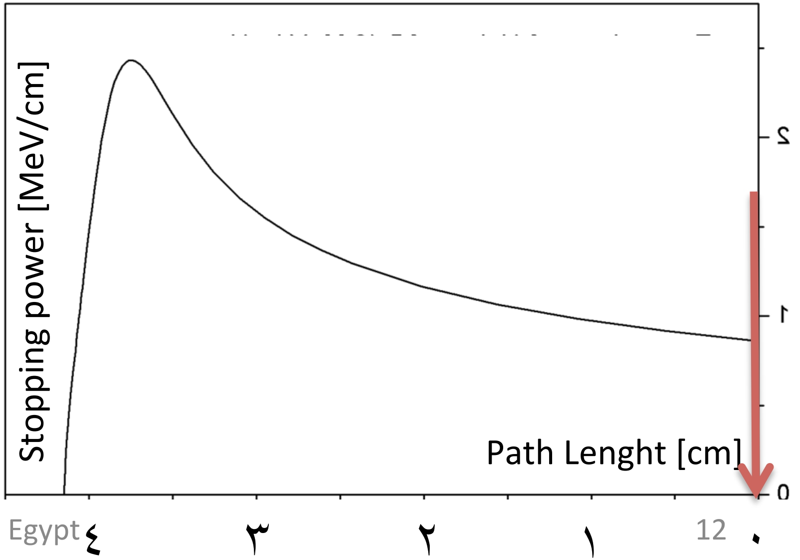
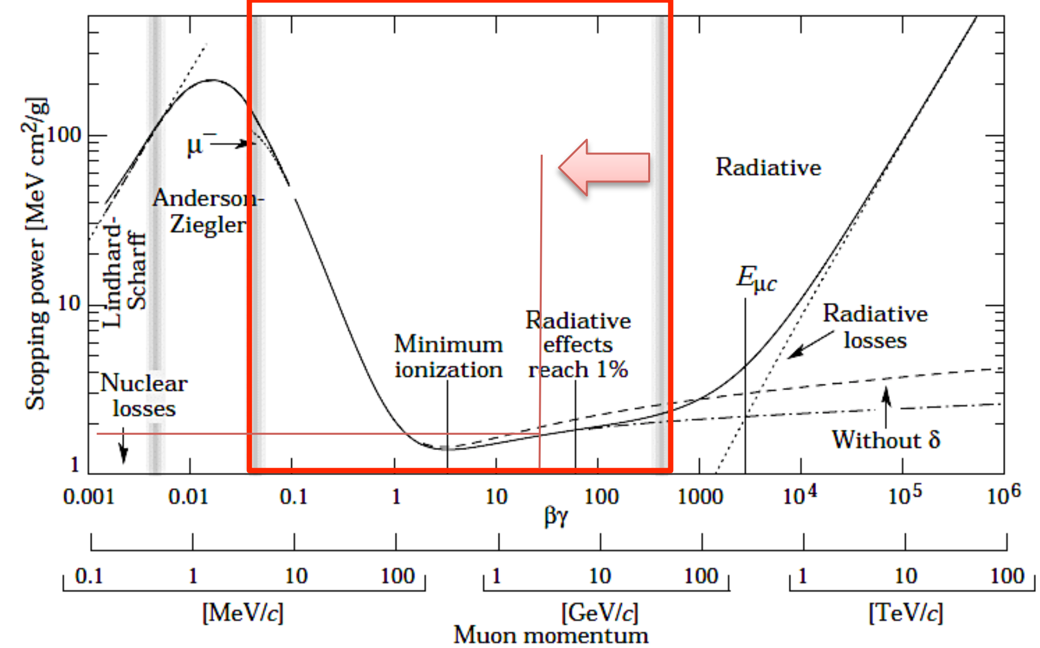
Bragg curve


Stopping power [MeV cm²/g]
Lindhard-Scharff
Anderson-Ziegler
Nuclear losses
Minimum ionization
Radiative effects reach 1%
Radiative
Radiative losses
Without δ
βγ
[MeV/c]
[GeV/c]
[TeV/c]
Muon momentum

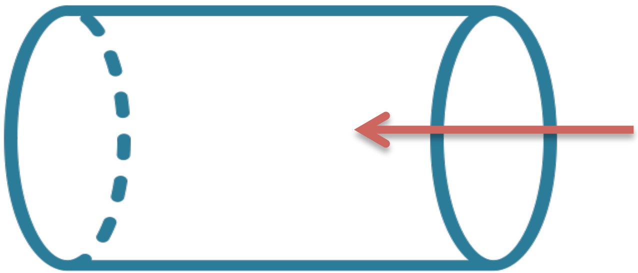


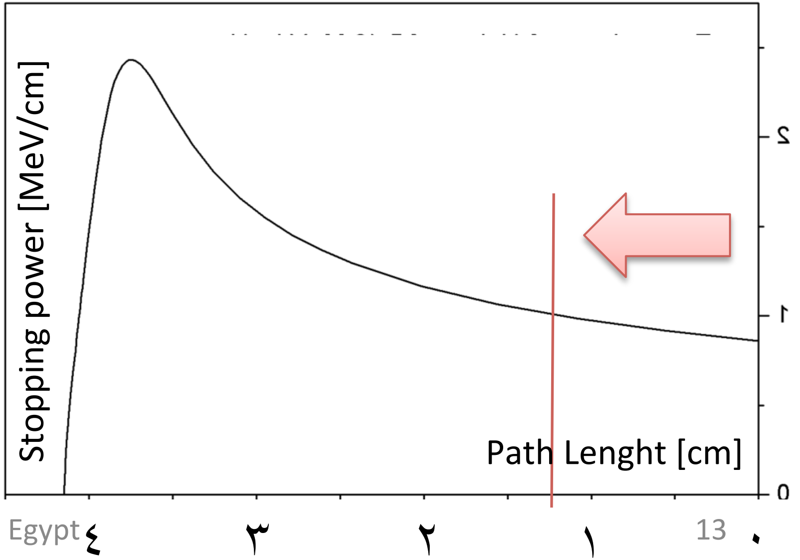

Stopping power [MeV/cm]
Path Lenght [cm]

Bragg curve



Stopping power [MeV cm²/g]
100
10
1
μ⁻
Anderson-Ziegler
Lindhard-Scharff
Nuclear losses
Minimum ionization
Radiative effects reach 1%
Radiative
$E_{\mu c}$
Radiative losses
Without δ
0.001
0.01
0.1
1
10
100
1000
10^4
10^5
10^6
βγ
0.1
1
10
100
[MeV/c]
1
10
100
[GeV/c]
1
10
100
[TeV/c]
Muon momentum





Stopping power [MeV/cm]
Path Lenght [cm]
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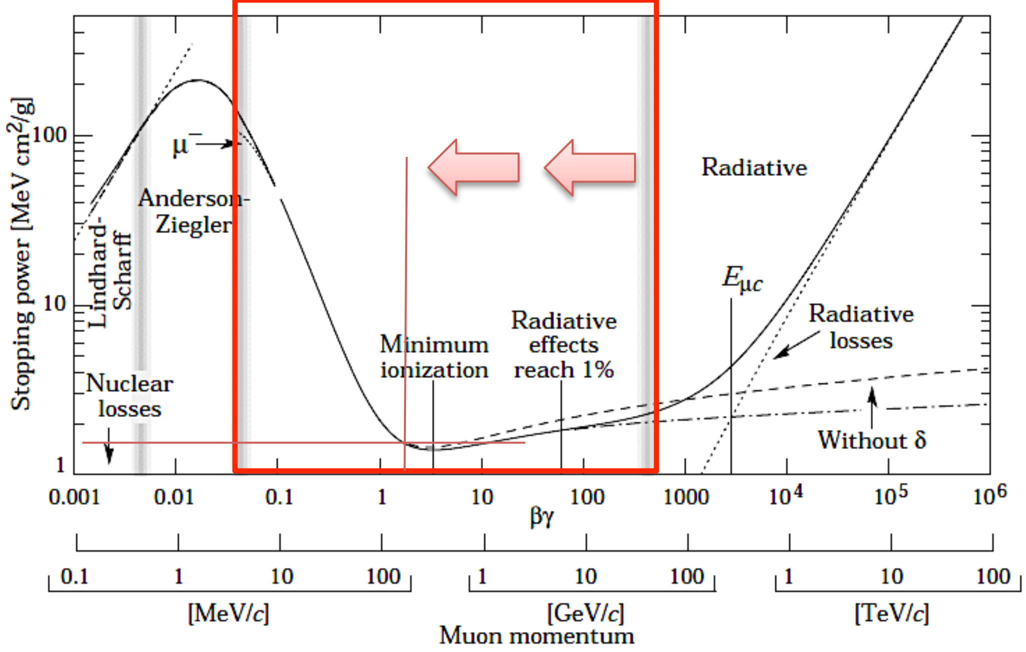
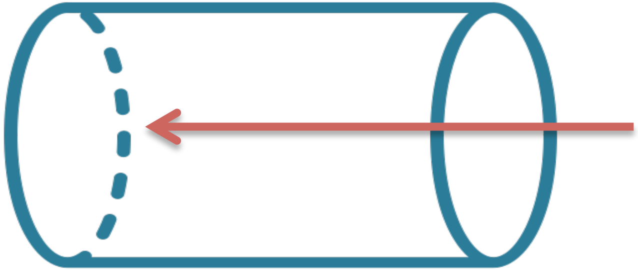
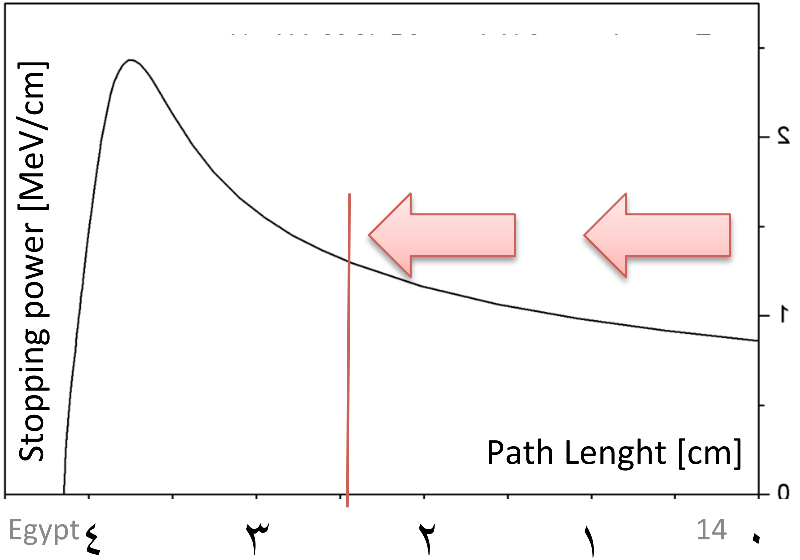
Bragg curve


Stopping power [MeV cm^2/g]
Lindhard-Scharff
Anderson-Ziegler
μ^-
Nuclear losses
Minimum ionization
Radiative effects reach 1%
Radiative
$E_{\mu c}$
Radiative losses
Without δ
0.001
0.01
0.1
1
10
100
1000
10^4
10^5
10^6
βγ
0.1
1
10
100
[MeV/c]
1
10
100
[GeV/c]
1
10
100
[TeV/c]
Muon momentum




Stopping power [MeV/cm]
Path Lenght [cm]
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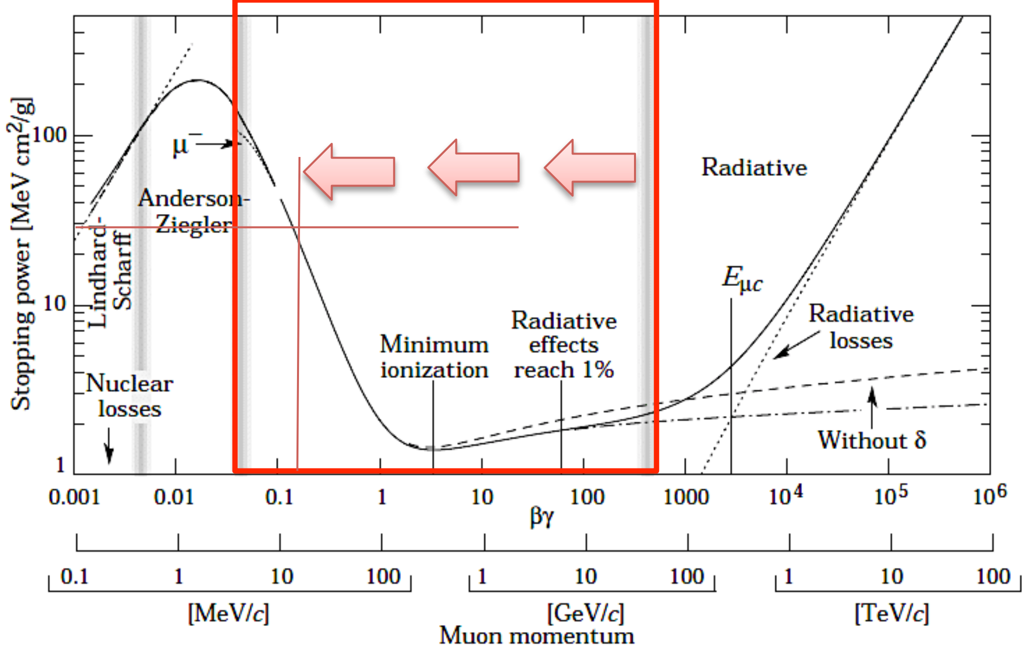
Bragg curve



Stopping power [MeV cm²/g]
100
10
1
μ⁻
Anderson-Ziegler
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Eμc
Radiative losses
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1
10
100
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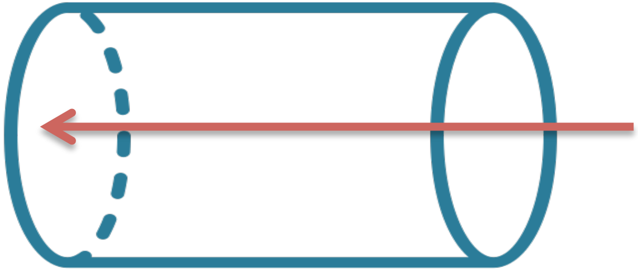
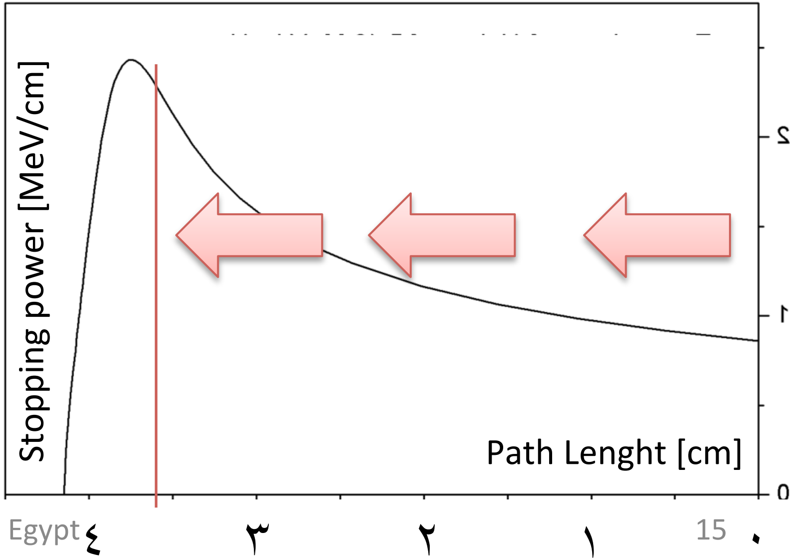
10⁴
10⁵
10⁶
βγ
0.1
1
10
100
[MeV/c]
1
10
100
[GeV/c]
1
10
100
[TeV/c]
Muon momentum





Stopping power [MeV/cm]
Path Lenght [cm]
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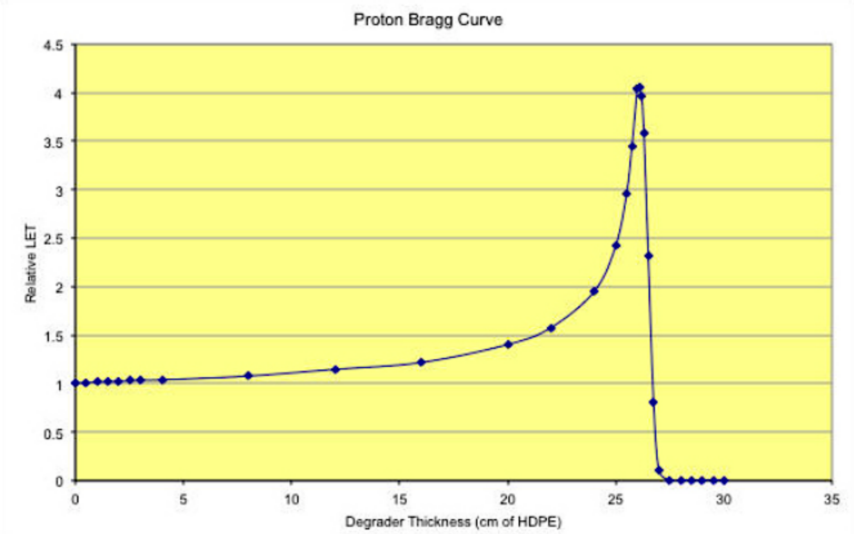


Figure 1: Bragg Curve for 205 MeV protons. Range in HDPE is 26.100 cm where the peak of the curve occurs. The LET at the entrance point is 0.4457 keV/micron in water.

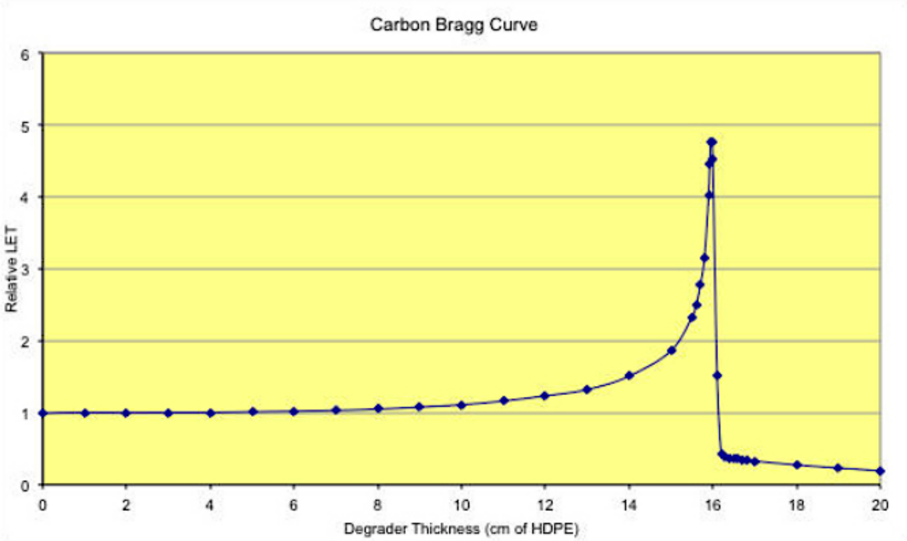


Figure 2: Bragg curve for 292.7 MeV/n Carbon ions. Range is 15.950 cm in HDPE. LET on entrance is 24.33 keV/micron in water. For degrader thicknesses beyond the Bragg Peak, 16 cm, you can see the tail produced by low-Z fragments.

Linear Energy Transfer (LET)

BROOKHAVEN NATIONAL LABORATORY NASA Space Radiation Laboratory

Bragg Curves

Charged particles, such as protons and heavy ions, lose energy when passing through material primarily through ionization. The Bethe-Bloch equation describes that energy loss. The Bragg Curve is a graph of the energy loss rate, or Linear Energy Transfer (LET) as a function of the distance through a stopping medium. The energy loss is characterized primarily by the square of the nuclear charge, Z, and the inverse square of the projectile velocity, β. **This gives the Bragg Curve its familiar shape, peaking at very low energies, just before the projectile stops**. It is this Bragg Peak that makes ion therapy advantageous over X-ray treatment for cancer. The Bragg Curve falls with increasing energy until a minimum is reached near a velocity of $\beta = 0.9$, about 2.2 GeV for protons. LET increases slowly, rising logarithmically for energies above the minimum.

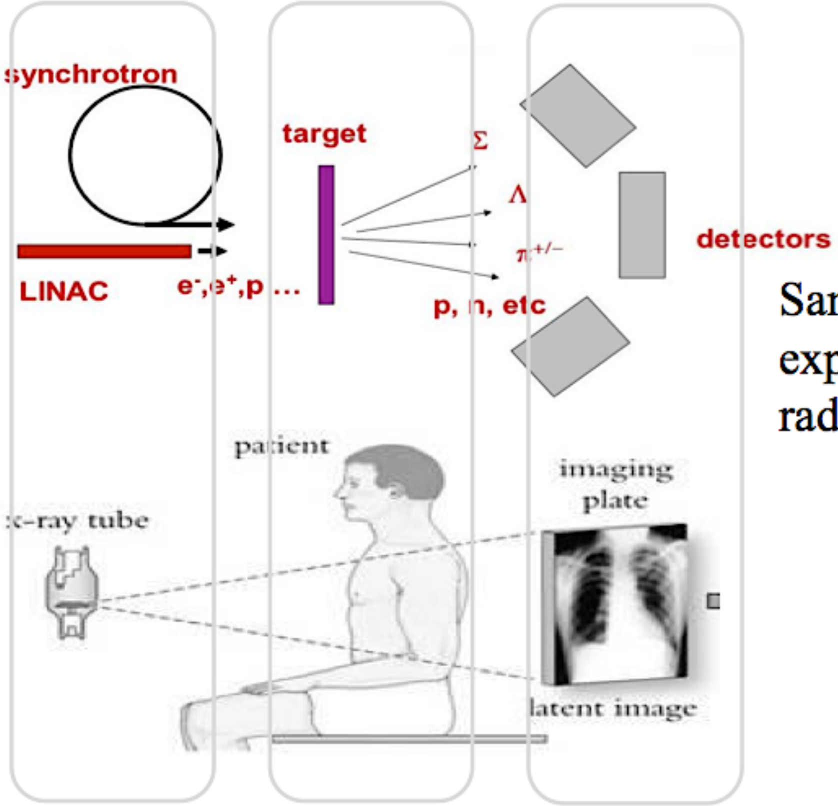
Interaction of Photons

The Interaction of Photons in matter (x-rays) is drammatically different from charged particles. In particular the photon's lack of an electric charge makes this big difference.   Now, instead, the main interactions of x-rays in matter will be

1) Photoelectric Effect
2) Compton Scattering
3) Pair Production

As a summary of the interaction a beam of photons is not degrateded in energy as it passes through a thickness of matter, it will only attenuate in intensity! (Absorption coeffiicent)

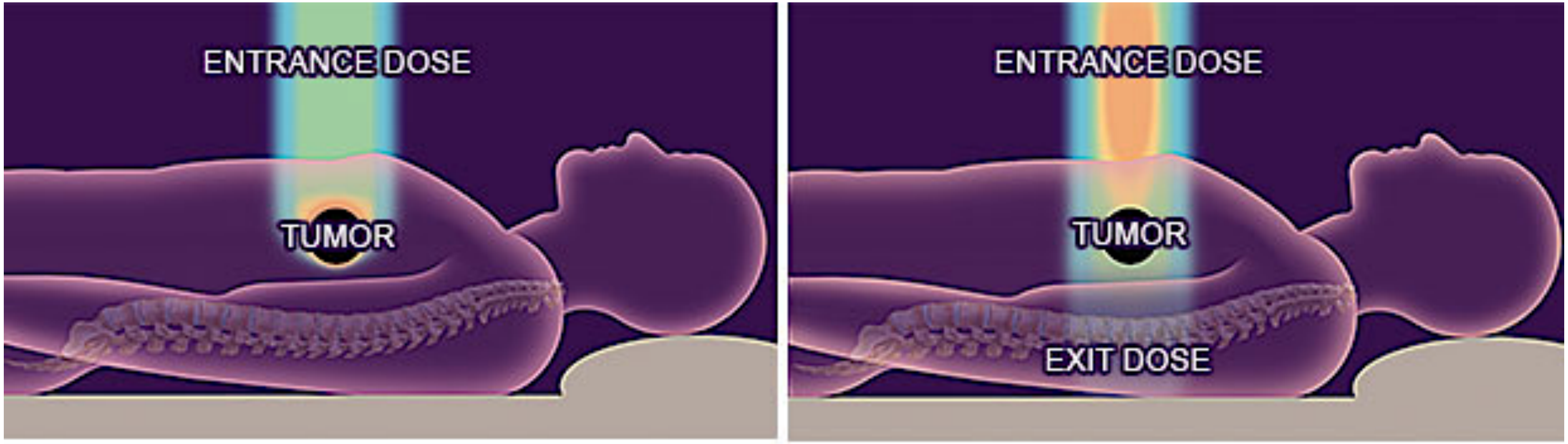
HEP technologies for medicine



Same concept for an HEP experiment and a radiological investigation

Application

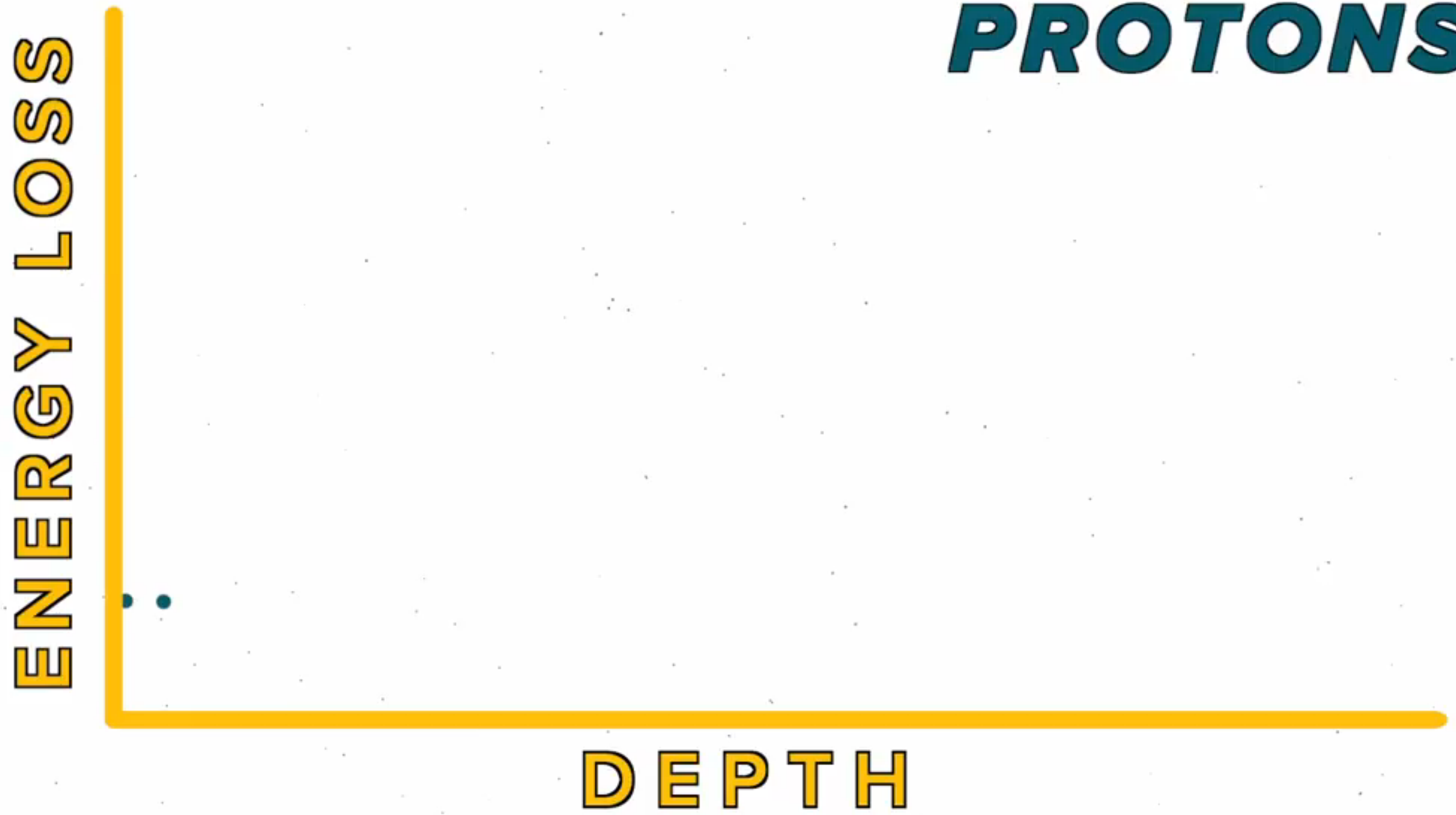
Hadon Therapy vs X-Rays



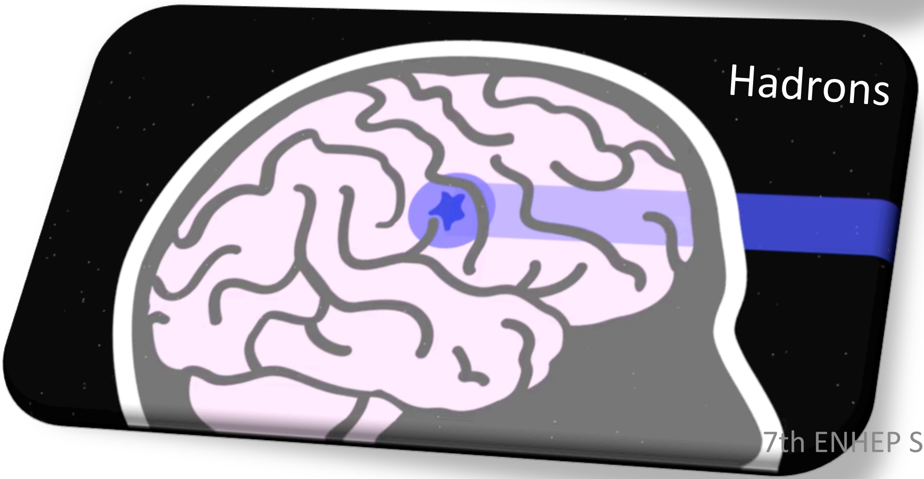
TARGETED PROTON THERAPY: Deposits most energy on target

CONVENTIONAL RADIATION THERAPY: Deposits most energy before target

PROTONS



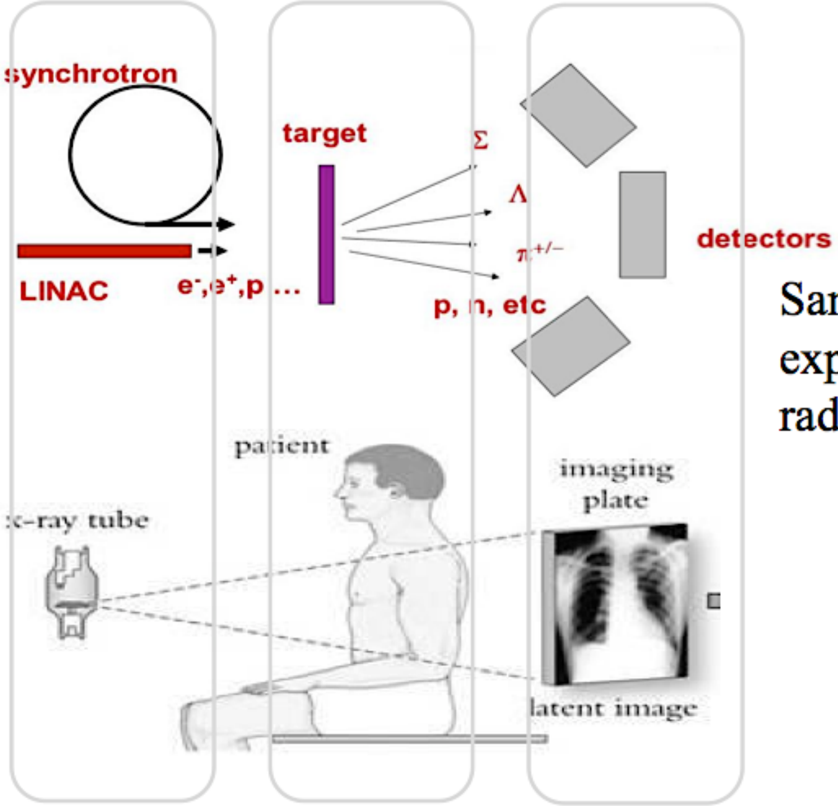
Hadro-Therapy



Radiological Use of Fast Protons

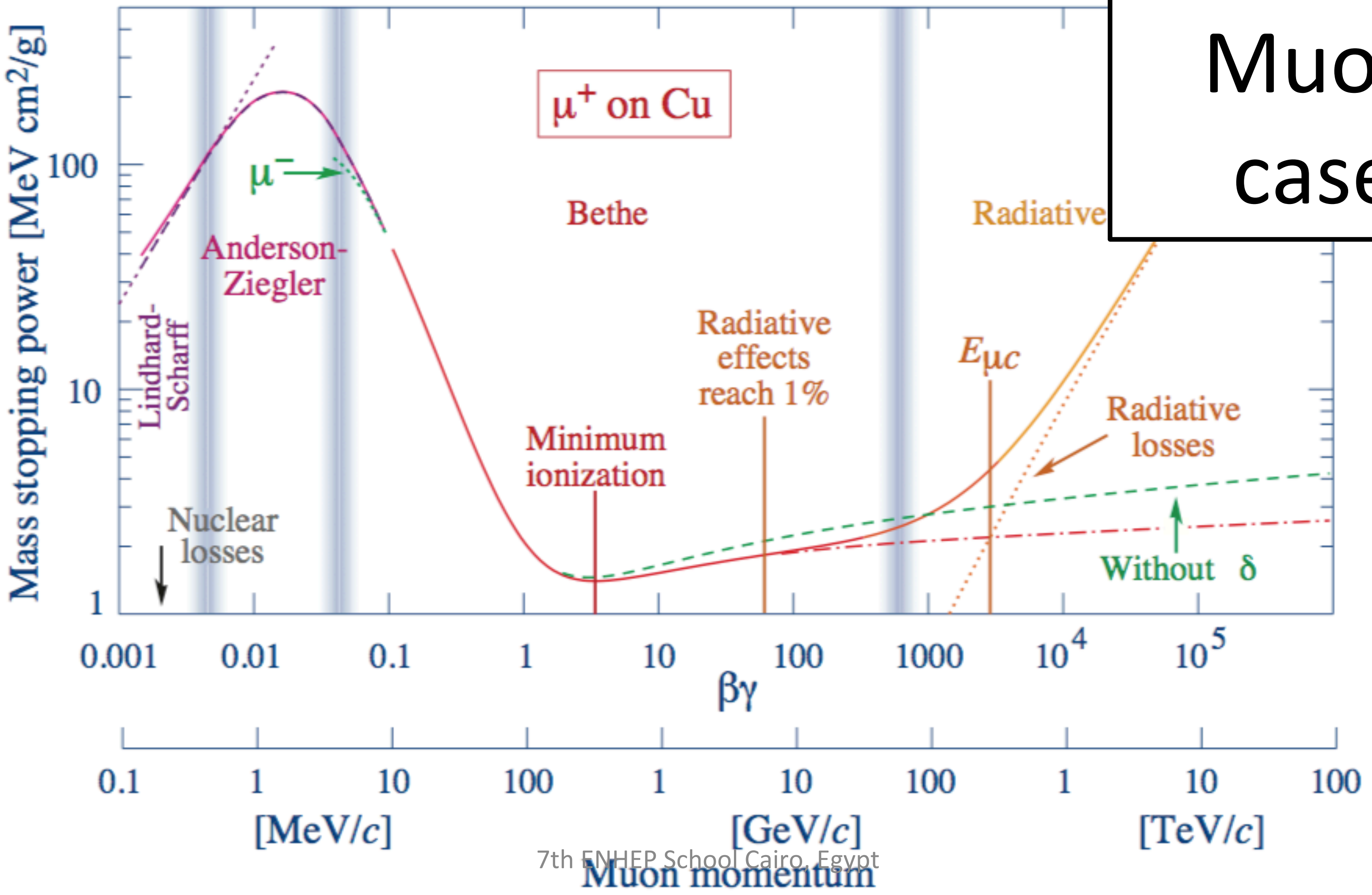
ROBERT R. WILSON
Research Laboratory of Physics, Harvard University
Cambridge, Massachusetts

HEP technologies for medicine

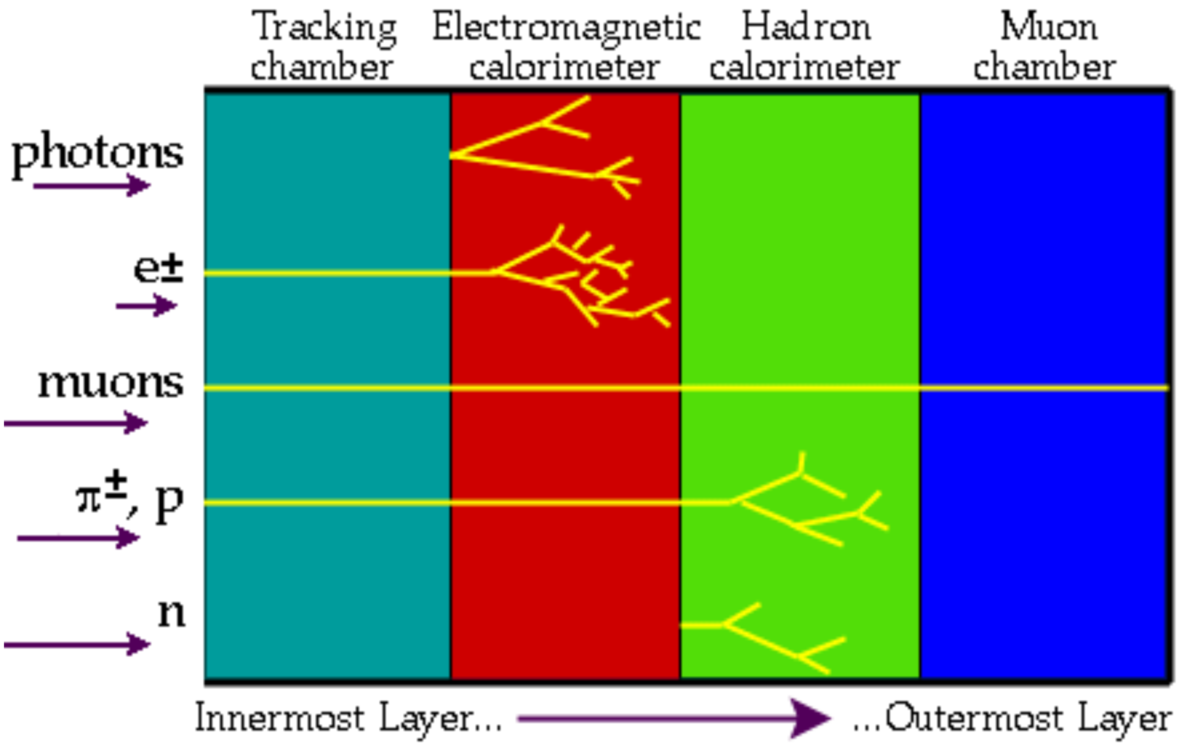


Same concept for an HEP experiment and a radiological investigation

Muon case

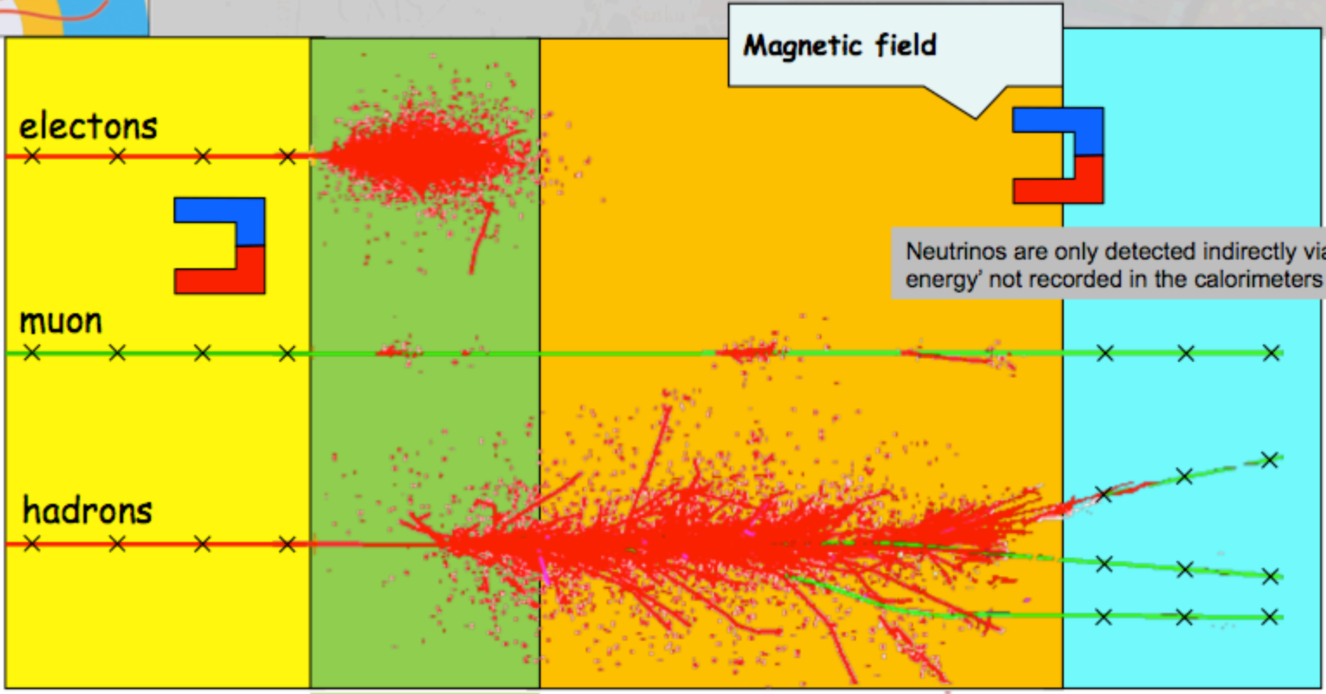

μ⁺ on Cu
Mass stopping power [MeV cm²/g]
100
10
1
μ⁻
Anderson-
Ziegler
Lindhard-
Scharff
Nuclear
losses
Bethe
Radiative
Minimum
ionization
Radiative
effects
reach 1%
Eμc
Radiative
losses
Without δ
0.001
0.01
0.1
1
10
100
1000
10⁴
10⁵
βγ
0.1
1
10
100
1
10
100
1
10
100
[MeV/c]
[GeV/c]
[TeV/c]
Muon momentum

Muons are mips



Anna Colaleo

How to detect particles in a detector

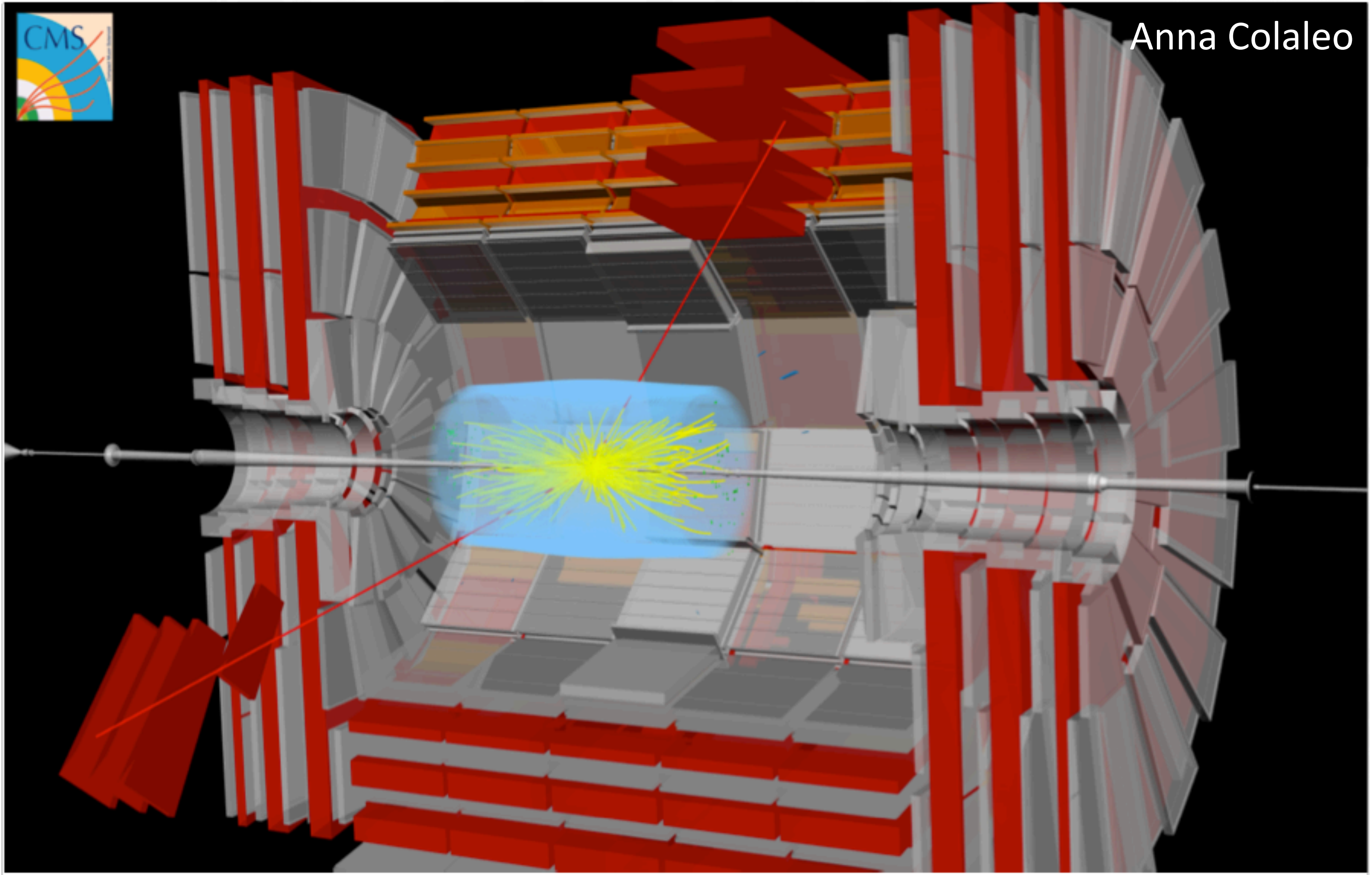


Tracking detector
–Measure charge and momentum of charged particles in magnetic field

Electro-magnetic calorimeter
–Measure energy of electrons, positrons and photons

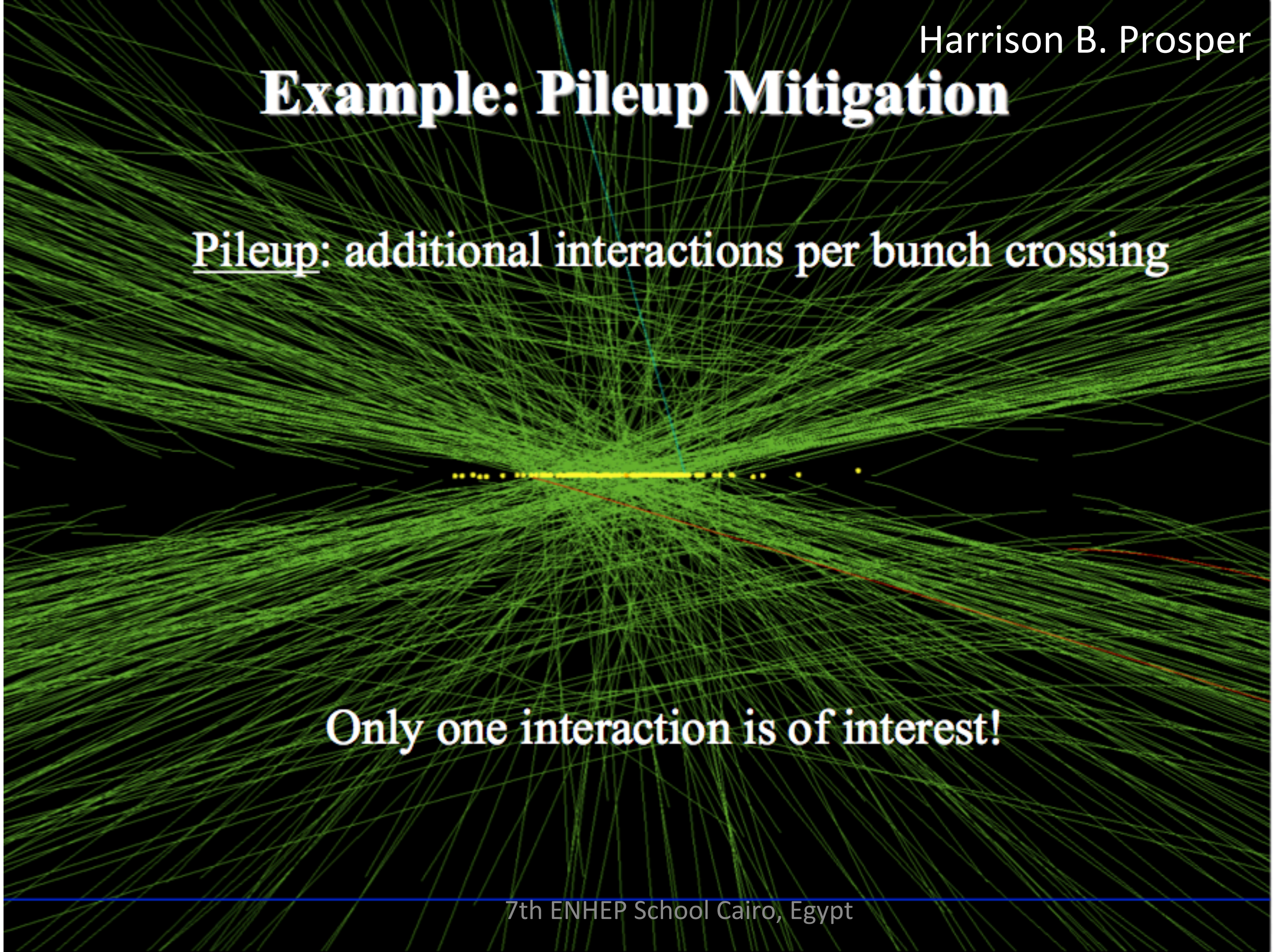
Hadronic calorimeter
–Measure energy of hadrons, such as protons, neutrons, pions, etc.

Muon detector
–Measure charge and momentum of muons


Anna Colaleo
CMS

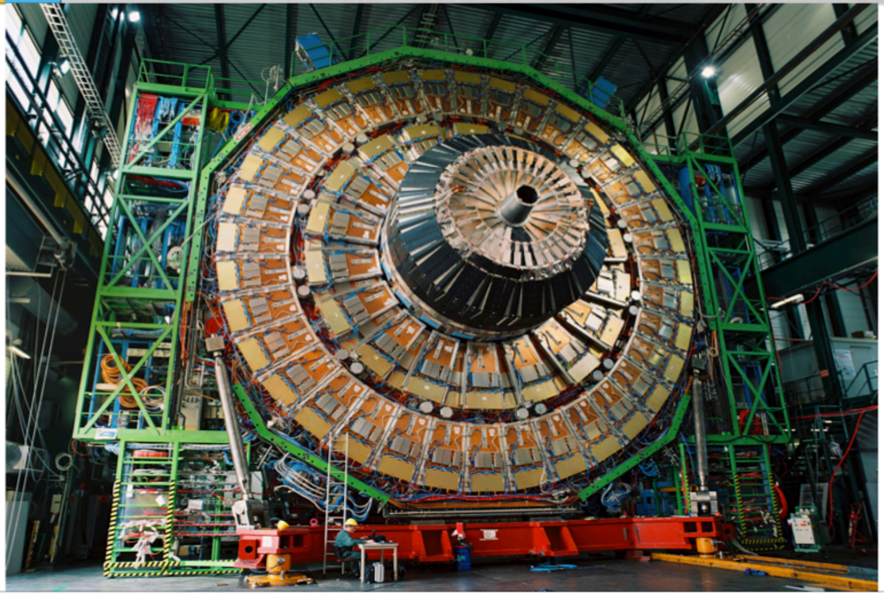
Example: Pileup Mitigation

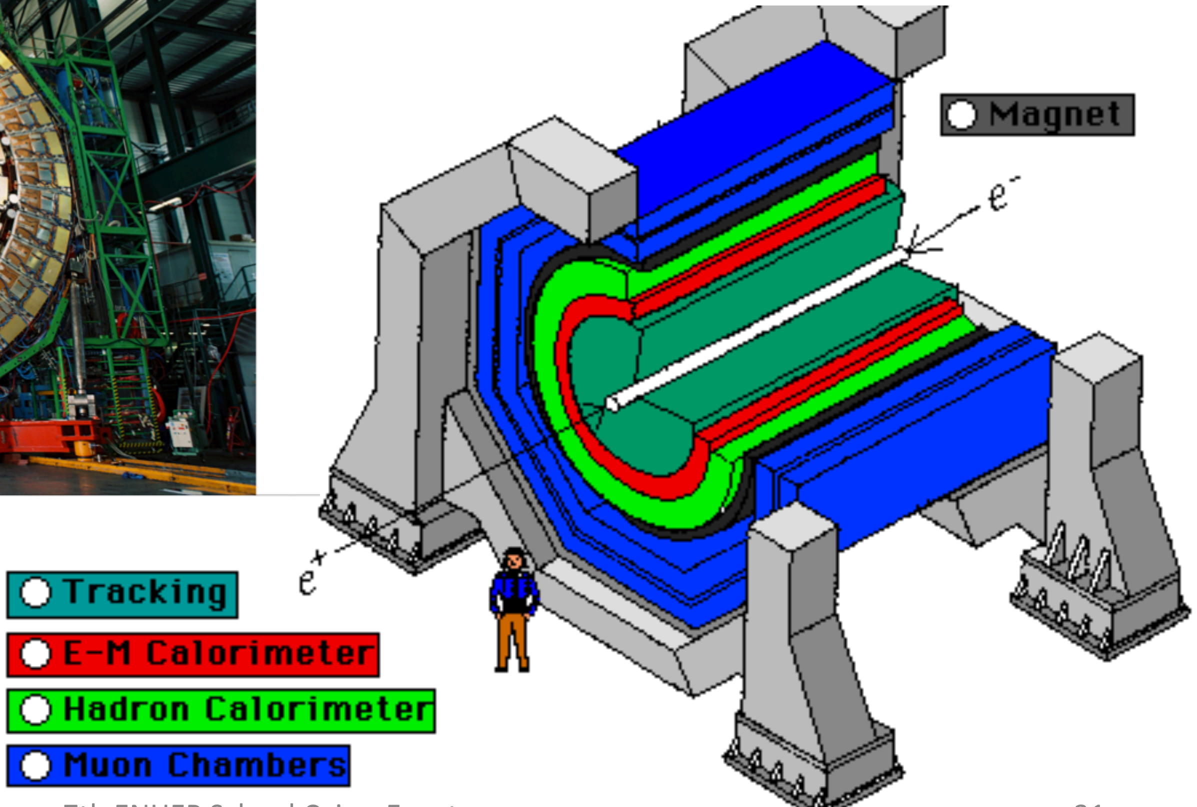
<u>Pileup</u>: additional interactions per bunch crossing

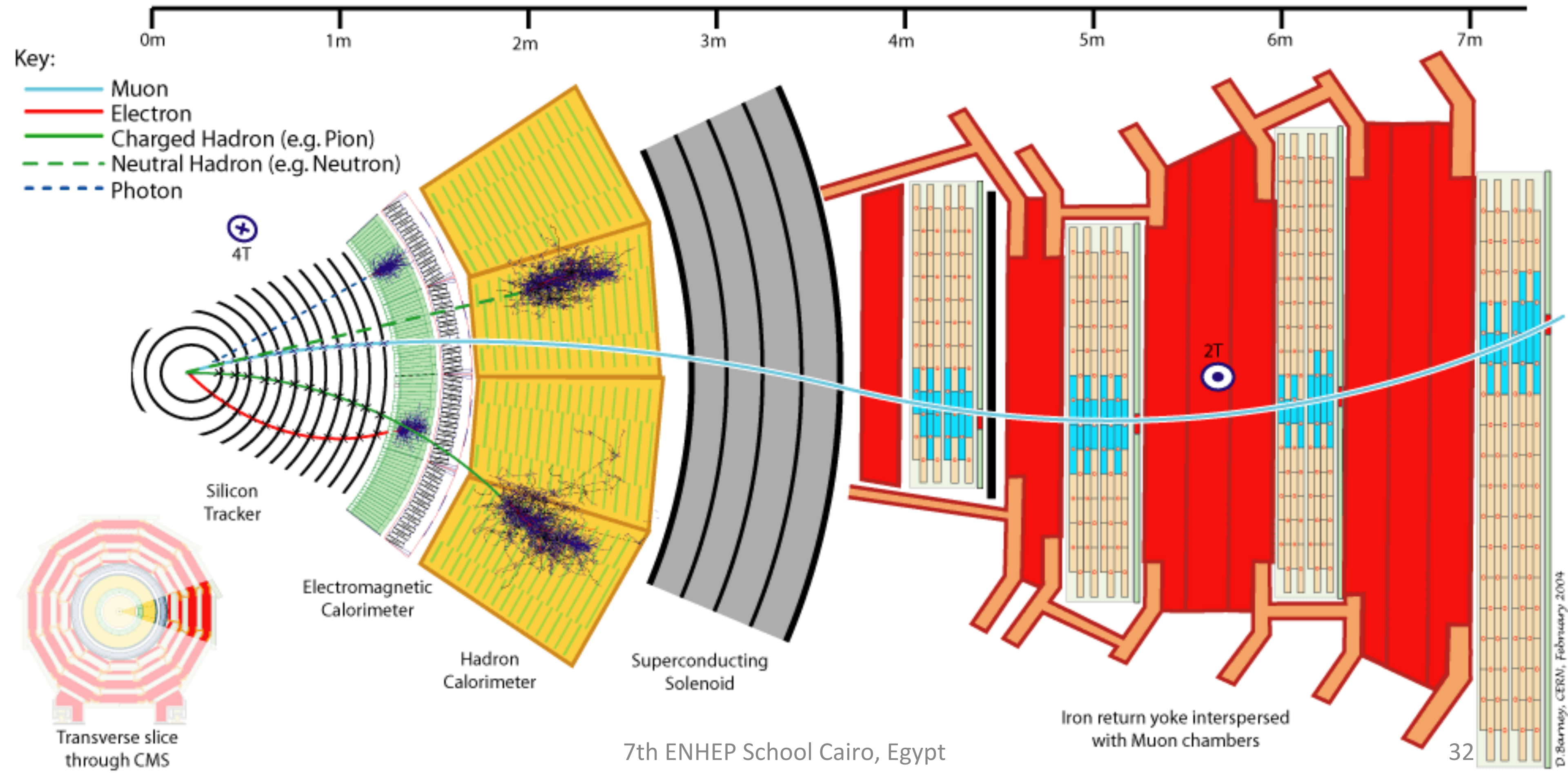


Only one interaction is of interest!

Historically – All Installed in Surface Hall

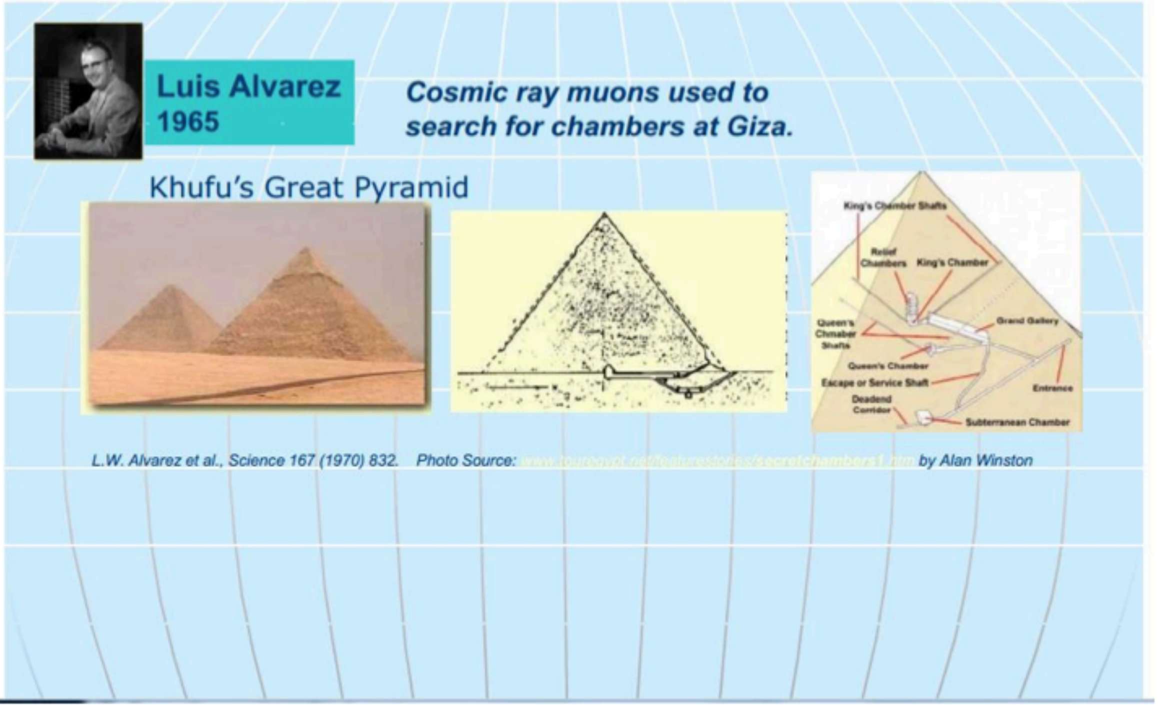





0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004

Detecting particles

The concept is not new, but now we can profit of advanced instruments



Search for Hidden Chambers in the Pyramids

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

Science, New Series, Vol. 167, No. 3919. (Feb. 6, 1970), pp. 832-839.

Muon Tomography

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

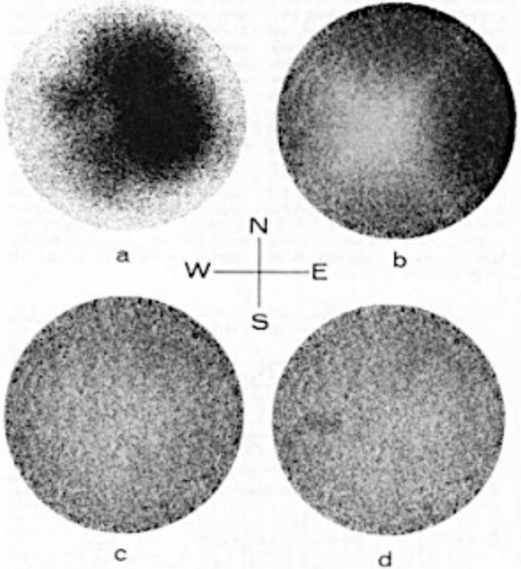
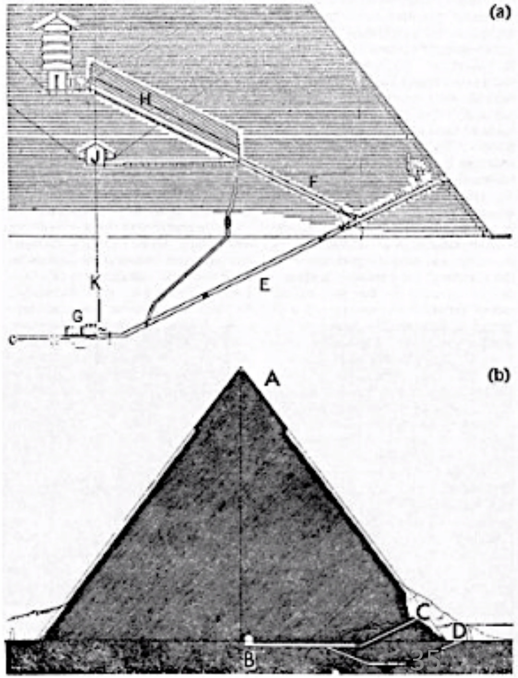


Fig. 13. Scatter plots showing the three stages in the combined analytic and visual analysis of the data and a plot with a simulated chamber. (a) Simulated "x-ray photograph" of uncorrected data. (b) Data corrected for the geometrical acceptance of the apparatus. (c) Data corrected for pyramid structure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

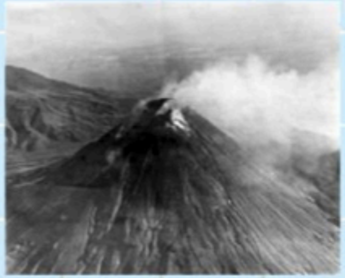
Luis Alvarez used the attenuation of muons to look for chambers in the Second Giza Pyramid → Muon Tomography

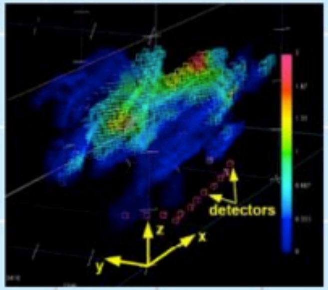
He proved that there are no chambers present.



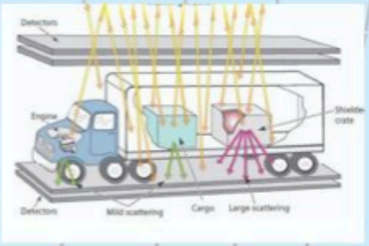
Detecting particles

Muon Geotomography





Muon Tomography for Security Applications

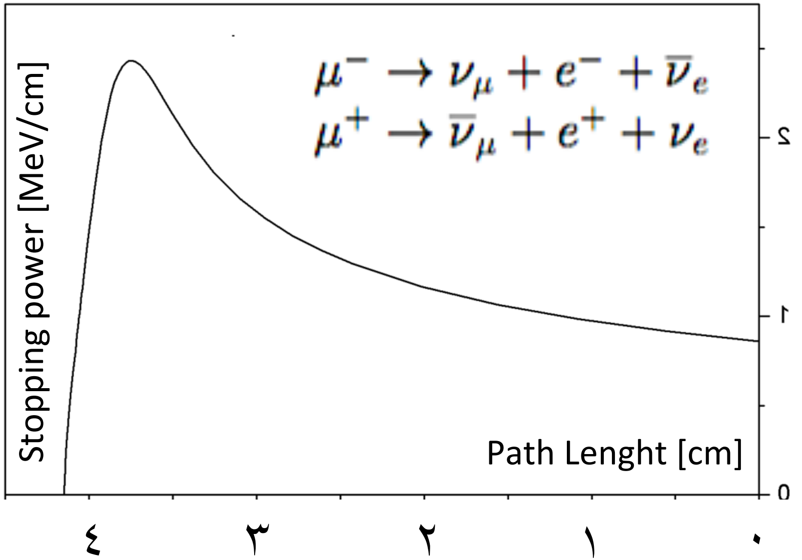


Large scale gaseous detector with high spatial resolution are needed

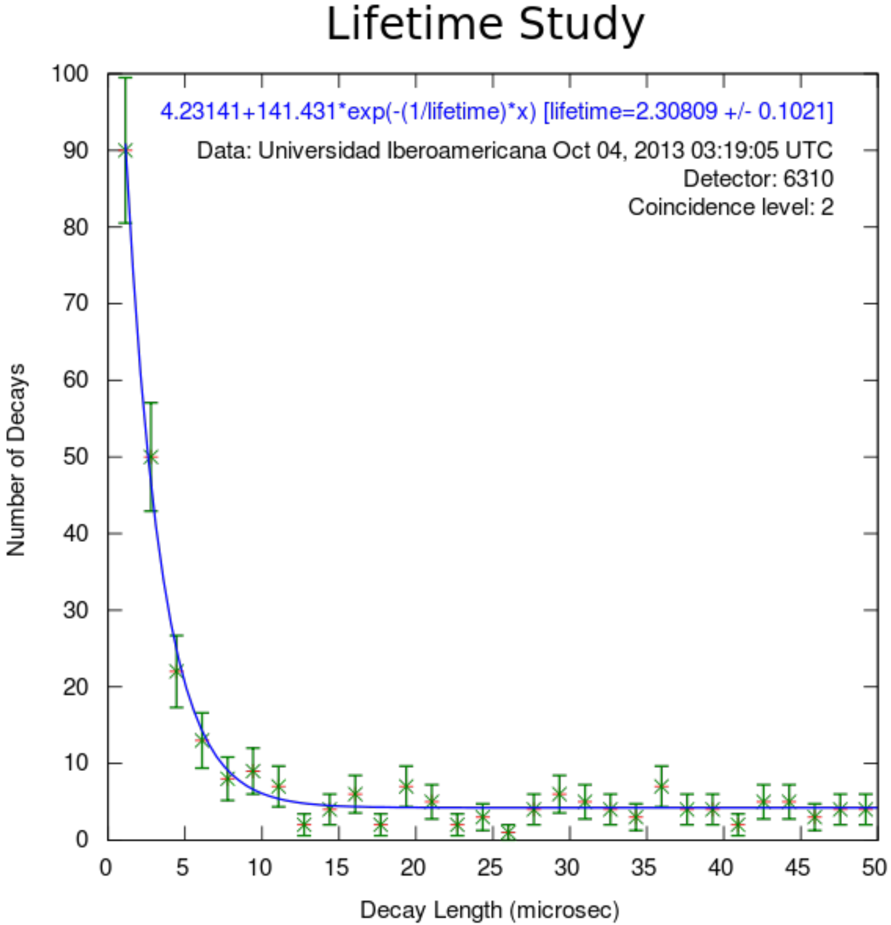
Image reconstruction can spot material of different density

Reconstruction software is crucial

Muon lifetime



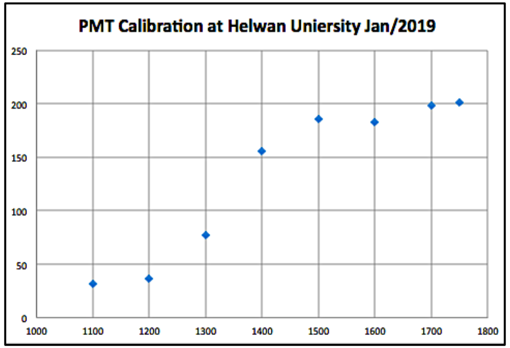
$$\mu^- \to \nu_\mu + e^- + \overline{\nu}_e$$
$$\mu^+ \to \overline{\nu}_\mu + e^+ + \nu_e$$

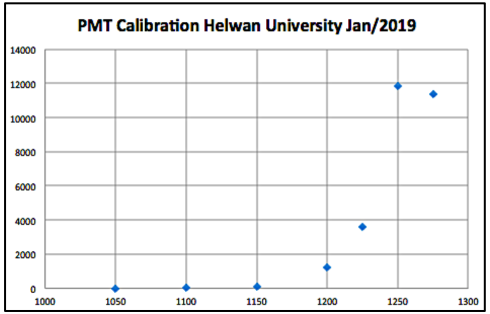


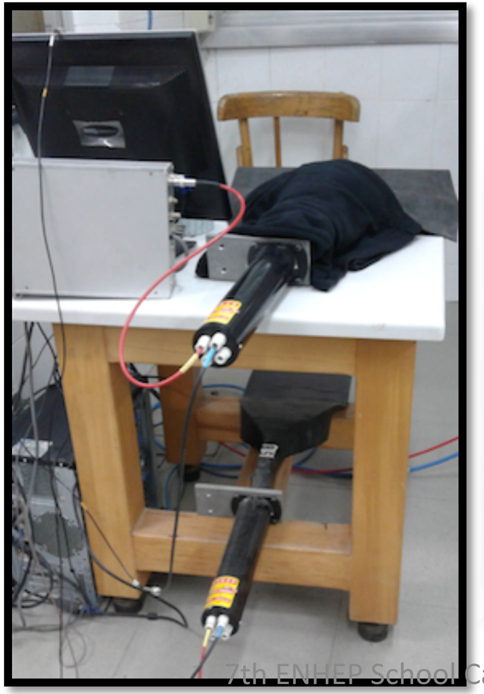
Helwan University (this week)

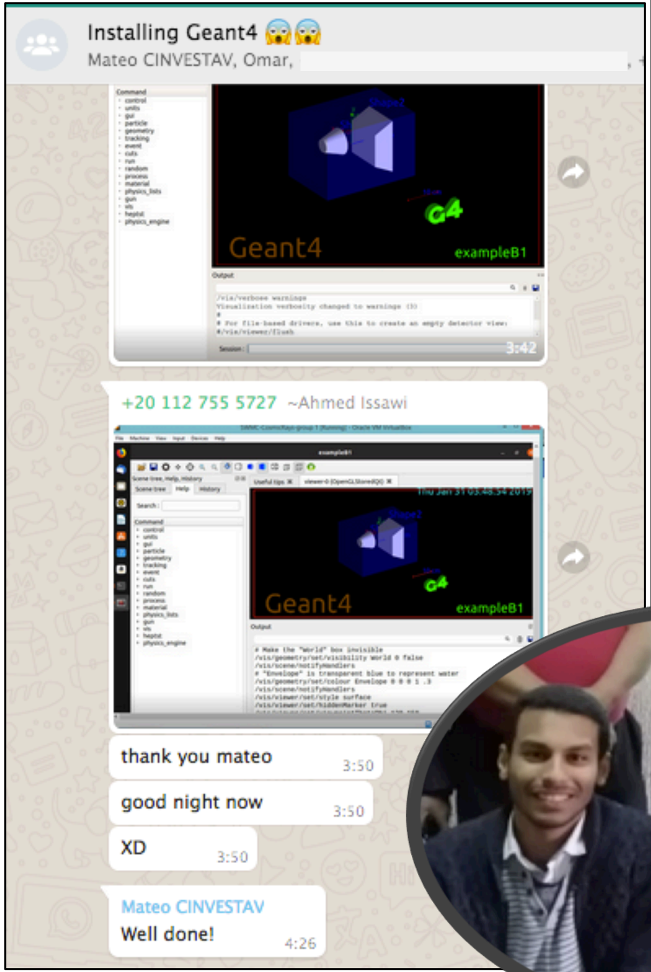
1. Professor Ayman Mahrous (Helwan University)
2. Ass.Prof.Yasser Assran (BUE)
3. Shereen Aly(PhD student, Helwan university)
4. Asmaa Hassan (PhD student, Helwan university)
5. Tahany Ahmed(Master student, Helwan university)
6. Sara Ragab (Master student, Helwan university)
7. Ahmed Issawi(Master student, Helwan university)
8. Omar Nasr(Master student, Helwan university)

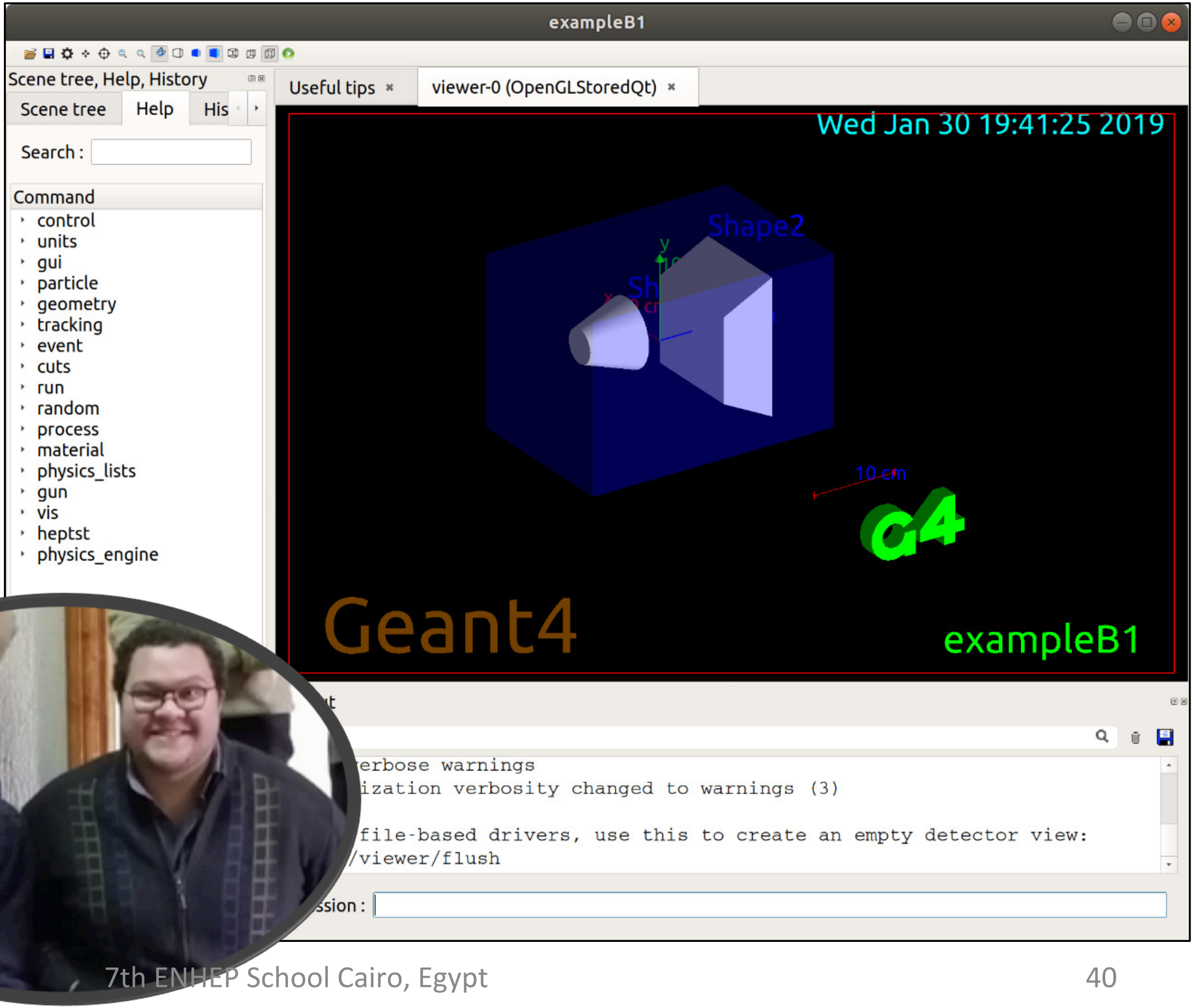
Calibration runs








Installing Geant4
Mateo CINVESTAV, Omar,
Geant4
exampleB1
+20 112 755 5727 ~Ahmed Issawi
thank you mateo 3:50
good night now 3:50
XD 3:50
Mateo CINVESTAV
Well done! 4:26


exampleB1
Scene tree, Help, History
Scene tree
Help
His
Search :
Command
control
units
gui
particle
geometry
tracking
event
cuts
run
random
process
material
physics_lists
gun
vis
heptst
physics_engine
Useful tips
viewer-0 (OpenGLStoredQt)
Wed Jan 30 19:41:25 2019
Shape2
10 cm
Geant4
exampleB1
erbose warnings
ization verbosity changed to warnings (3)
file-based drivers, use this to create an empty detector view:
/viewer/flush
ssion :

Thank you for your time

Dr. Salvador Carrillo Moreno
Universidad Iberoamericana
Mexico city

Medicine: cancer therapy
Every major medical center in the nation uses accelerators producing x-rays, protons, neutrons or heavy ions for the diagnosis and treatment of disease. It is estimated that there are over 7,000 operating medical linacs around the world that have treated over 30,000,000 patients.

Medicine: diagnostic instrumentation
Particle detectors first developed for particle physics are now ubiquitous in medical imaging. Positron emission tomography, the technology of PET scans, came directly from detectors initially designed for particle physics experiments sensing individual photons of light.

Homeland security: monitoring nuclear waste nonproliferation
In nuclear reactors, the amount of plutonium builds up as the uranium fuel is used. Because plutonium and uranium emit different kinds of particles, a particle detector can be used to monitor and analyze the contents of the nuclear reactor core. A prototype detector, originally developed by physicists for experiments, has already demonstrated the potential use of this new monitoring technology.

Industry: power transmission
Cables made of superconducting material can carry far more electricity than conventional cables with minimal power losses. Further superconducting technology advances in particle physics will help advance this industry, offering an opportunity to meet continued power needs in densely populated areas where underground copper transmission lines are near their capacity.

Industry: understanding turbulence
From long distance oil pipelines to models for global weather prediction, turbulence determines the performance of virtually all fluid systems. Silicon strip detectors and low-noise amplifiers developed for particle physics are used to detect light scattered from microscopic particles in a turbulent fluid, permitting detailed studies of this challenging area.

Computing: the World Wide Web
Particle physicists developed the World Wide Web to give them a tool to communicate quickly and effectively with colleagues around the world. Few other technological advances in history have more profoundly affected the global economy and societal interactions than the Web. In 2001, revenues from the World Wide Web exceeded one trillion dollars, with exponential growth continuing.

Computing: the Grid
The Grid is the newest particle physics computing tool that allows physicists to manage and process unprecedented amounts of data across the globe by combining the strength of hundreds of thousands of individual computing farms. Industries such as medicine and finance are examples other fields that also generate large amounts of data and benefit from advanced computing technology.

Sciences: synchrotron light sources
Researchers use the ultra-powerful X-ray beams of dedicated synchrotron light sources to create the brightest lights on earth. These luminous sources provide tools for such applications as protein structure analysis, pharmaceutical research, materials science and restoration of works of art.