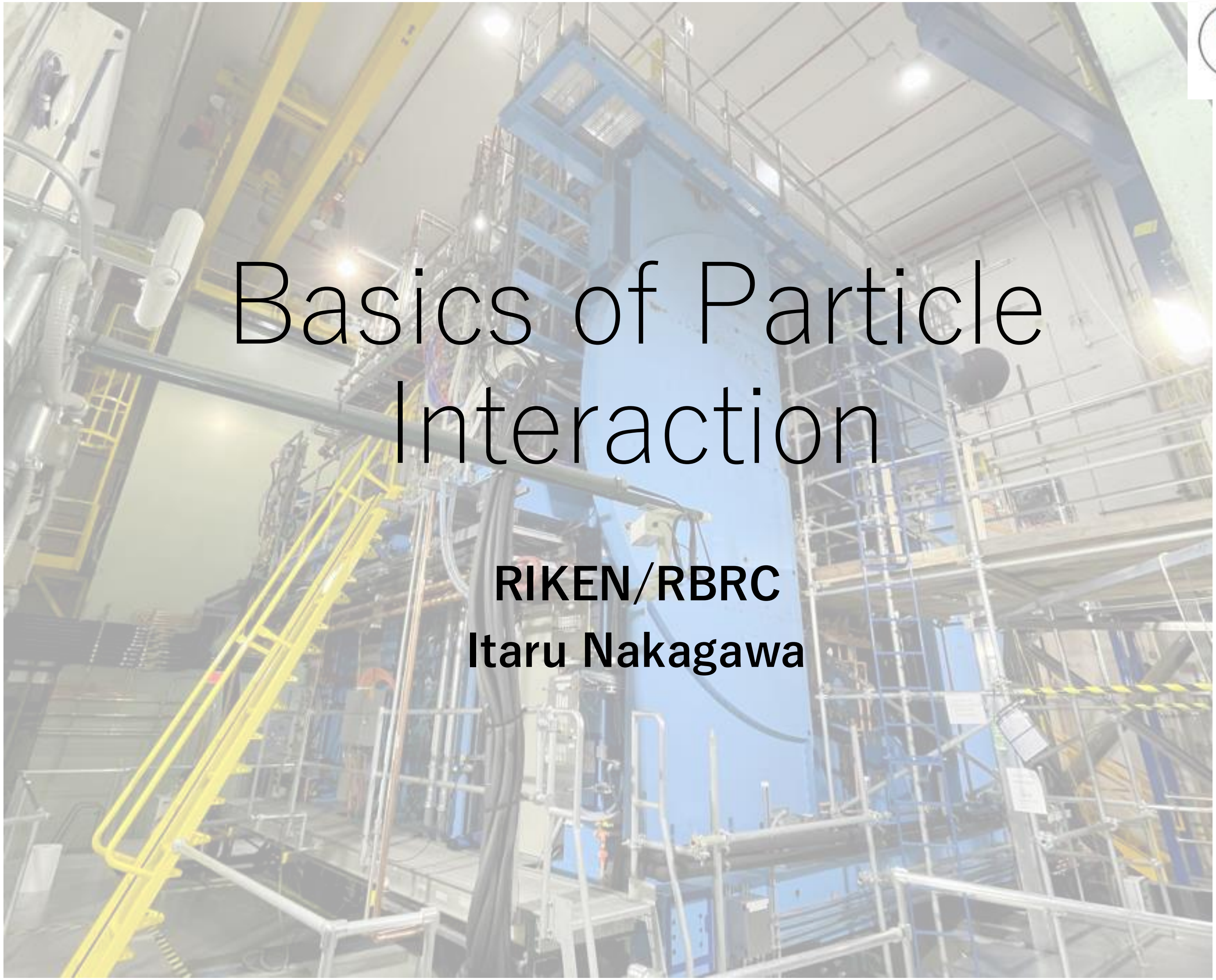
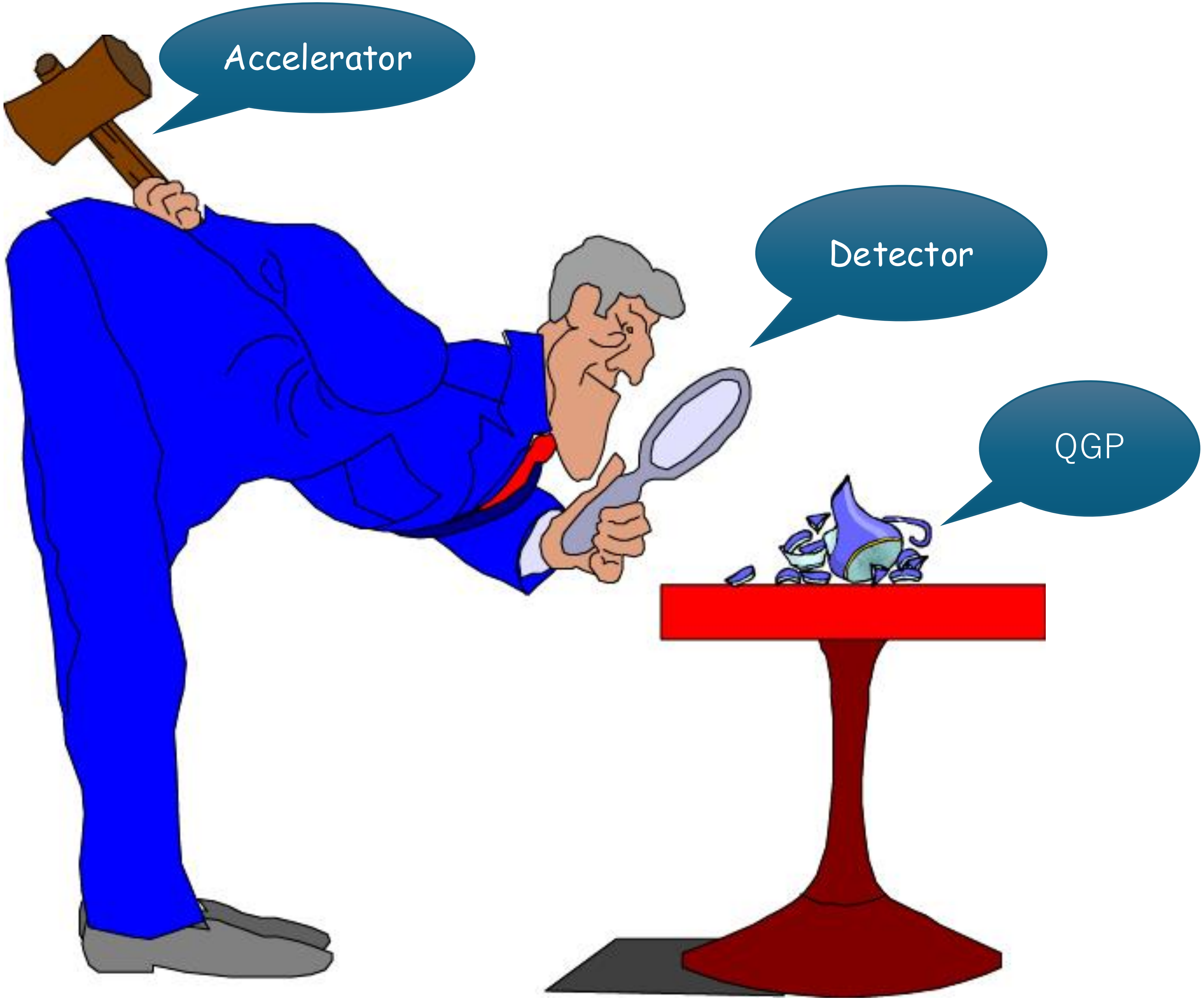
Introduction of sPHENIX & INTT

RIKEN/RBRC
Itaru Nakagawa



Basics of Particle Interaction

RIKEN/RBRC
Itaru Nakagawa


Accelerator
Detector
QGP

sPHENIX detector

General concept of the modern particle collider

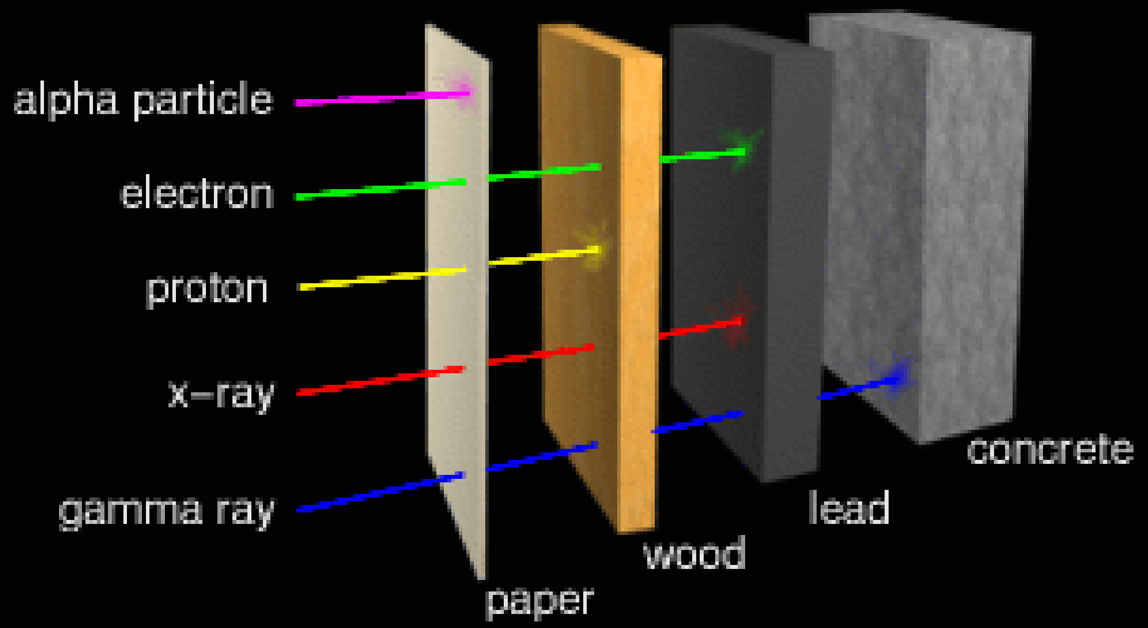
- Particle flow algorithm
- The technologies
  - Calorimeter: sampling (SciFi, Sandwiched, Cherenkov light detection) and homogeneous (CMS ECal made of Lead Tungstate scintillating crystal). The PMT, SiPM
  - Tracker: TPC, wire chamber, silicon, etc
  - Magnet: charged particle curvature by Solenoid, etc
- What is difference between Electromagnetic and Hadronic calorimeters (interaction length and radiation length)?
- The particle identification (dE/dx of TPC, TOF, AC-LGAD, etc)

- Each subsystem of sPHENIX
  - Geometry, technology, specification and performance, and the role of each subsystem
- Review of the sPHENIX construction
- Some physics projections

- INTT
  - Introduction to silicon detector, the technology
  - The detail specifications of INTT
  - Role of INTT in more detail
    - The (out-time) pile-up suppression
      - What is pile-up?
    - How the single-bunch-crossing relevant to tracking (which is important to spin program, but why?)
  - The story of INTT (from scratch to ladder production to detector installation to data taking)
    - Some achievements of INTT (may have some overlaps with the INTT review talk, but should be fine)

Basics

~particle interactions in matter~



alpha particle
electron
proton
x-ray
gamma ray
paper
wood
lead
concrete

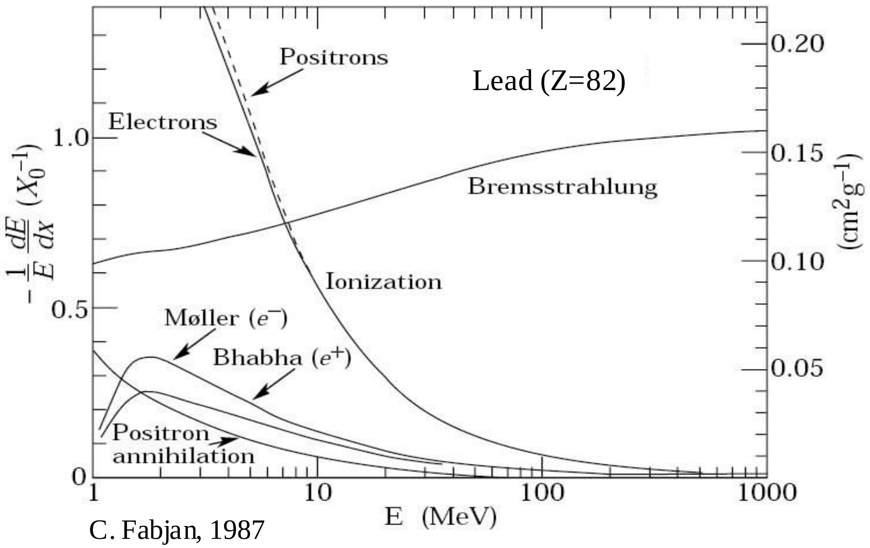
祈祷者昇殿
門の外右側で
PLEASE

I am exhausted !

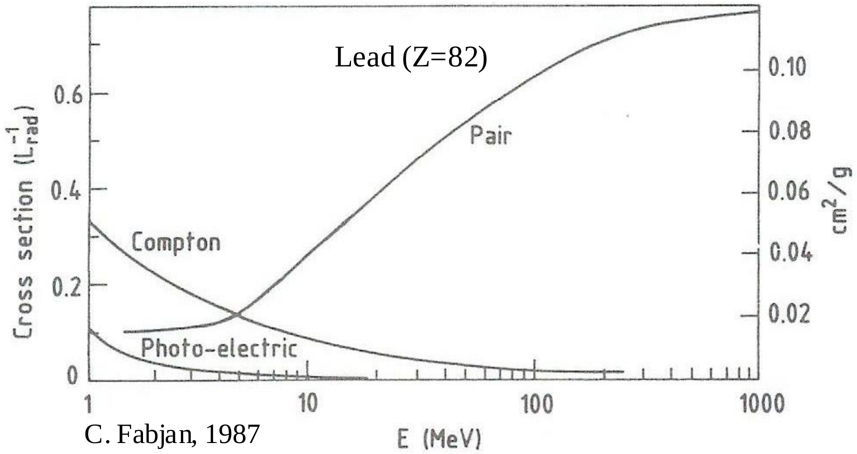
You've lost energy by interacting with people …

Interaction of particles with matter

- **Overview of interaction processes**
  - Particles created in the collision of high-energy particle beams experience electromagnetic and/or nuclear interactions in the detector material they pass through
  - Understanding these processes are vital for the design of any detector system!
  - Main processes for charged particles:
    - Ionization
    - Cherenkov radiation
    - Bremsstrahlung
  - Main processes for photons:
    - Photoelectric effect
    - Compton scattering
    - Pair production



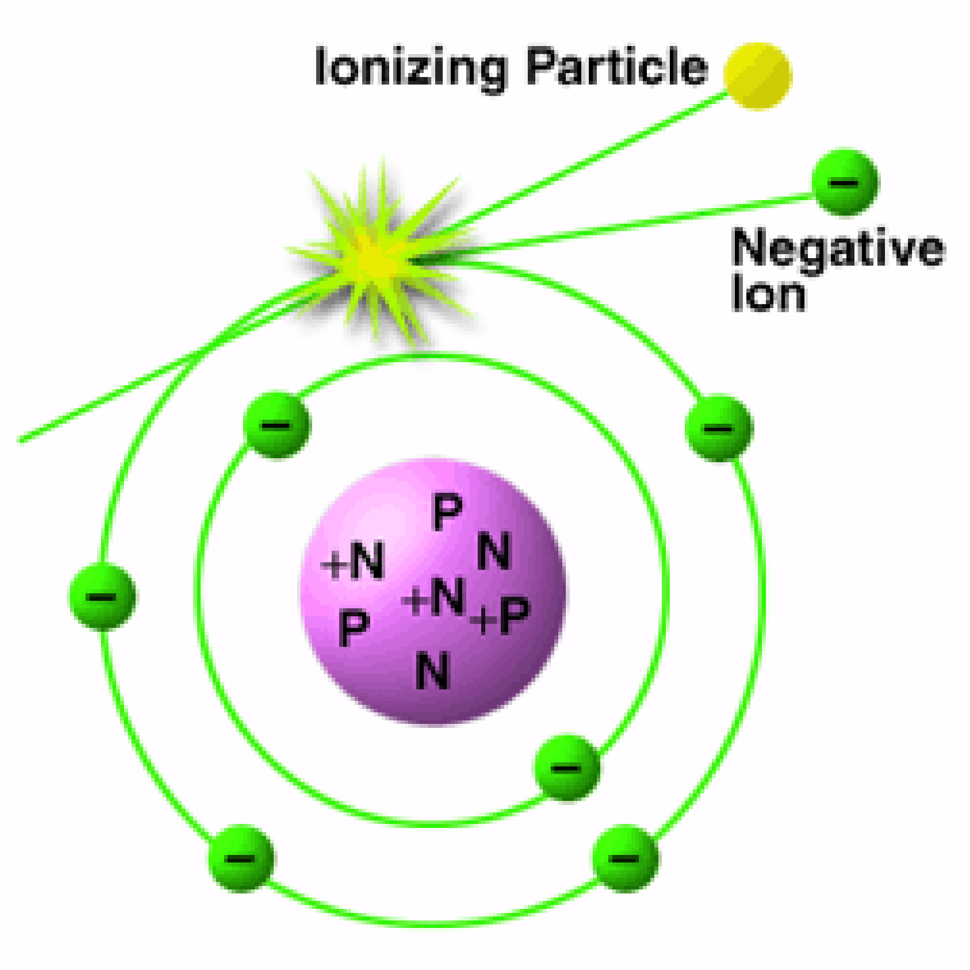
C. Fabjan, 1987

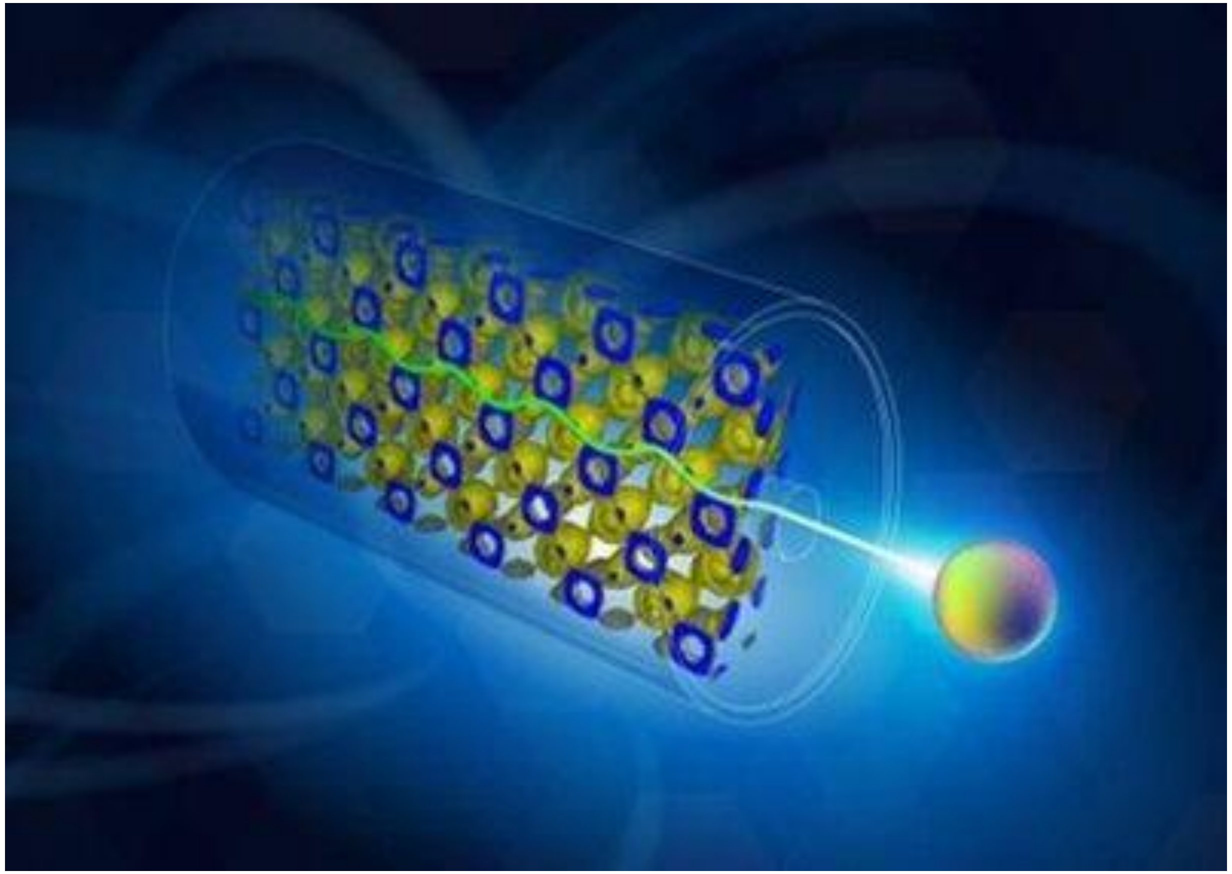


C. Fabjan, 1987

Depending on mass, momentum, species…

Ionization Energy Loss





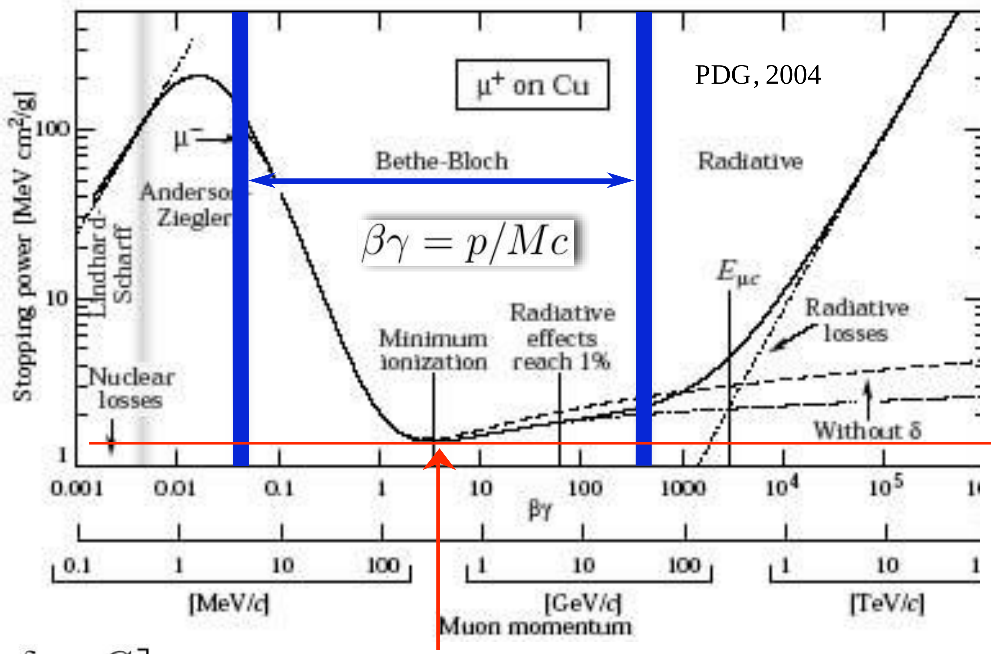
Bethe-Bloch Formula

- **Ionization**
  - Bethe-Bloch equation: Mean energy (or stopping power)

-dE/dx in units of:

(MeV/cm)/(g/cm^3)=(MeV cm^2/g)

-dE/x for charged particles: M » m_e



Minimum at approx.: $\beta\gamma \approx 3$

(-dE/dx of relativistic particles: Close to minimum-ionizing particle (MIP))

$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{max}}{I^2} - \beta^2 - \frac{\delta}{2} - \frac{C}{Z}\right]$$

with:

$$T_{max} = \frac{2m_ec^2\beta^2\gamma^2}{1+2\gamma_e m_e/M + (m_e/M)^2}$$

$$K = 4\pi N_A r_e^2 m_e c^2$$

Note:

1. Density (δ) and shell (C) corrections at high and low energies, respectively
2. -dE/dx for electrons modified due to the kinematics, spin and identity of the incident electron with the medium electrons

Bethe-Block Formula

27.2. Electronic energy loss by heavy particles [1–22, 24–30, 82]

Moderately relativistic charged particles other than electrons lose energy in matter primarily by ionization and atomic excitation. The mean rate of energy loss (or stopping power) is given by the Bethe-Bloch equation,

$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] . \qquad (27.1)$$

Here $T_{\max}$ is the maximum kinetic energy which can be imparted to a free electron in a single collision, and the other variables are defined in Table 27.1. With K as defined in Table 27.1 and A in g mol^{-1}, the units are MeV g^{-1}cm^2.

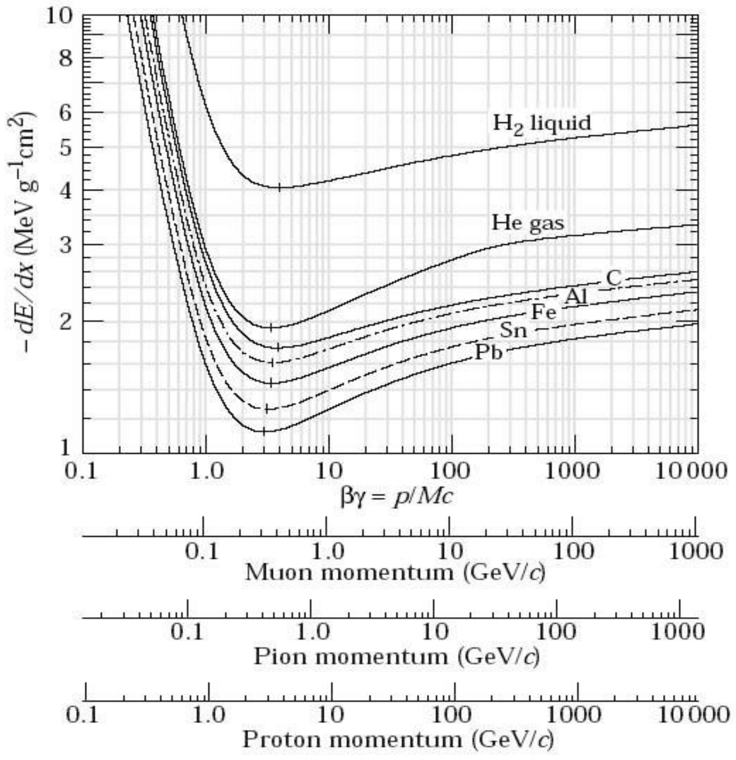
https://pdg.lbl.gov/2006/reviews/passagerpp.pdf

dE/dx for Various Elements

- Ionization

Material	Z	A	Z/A	dE/dx min ($MeV cm^2/g$)	Density (g/cm^3)
H_2 (liquid)	1	1.008	0.992	4.034	0.0708
He	2	4.002	0.500	1.937	0.125
C	6	12.01	0.500	1.745	2.27
Al	13	26.98	0.482	1.615	2.70
Cu	29	63.55	0.456	1.403	8.96
Pb	82	207.2	0.396	1.123	11.4
W	74	183.8	0.403	1.145	19.3
U	92	238.0	0.387	1.082	19.0
Scint.			0.538	1.936	1.03
BGO			0.421	1.251	7.10
CsI			0.416	1.243	4.53
NaI			0.427	1.305	3.67

- Medium dependence
  - Weak dependence on the medium, since Z/A ≈ 0.5:



PDG, 2004

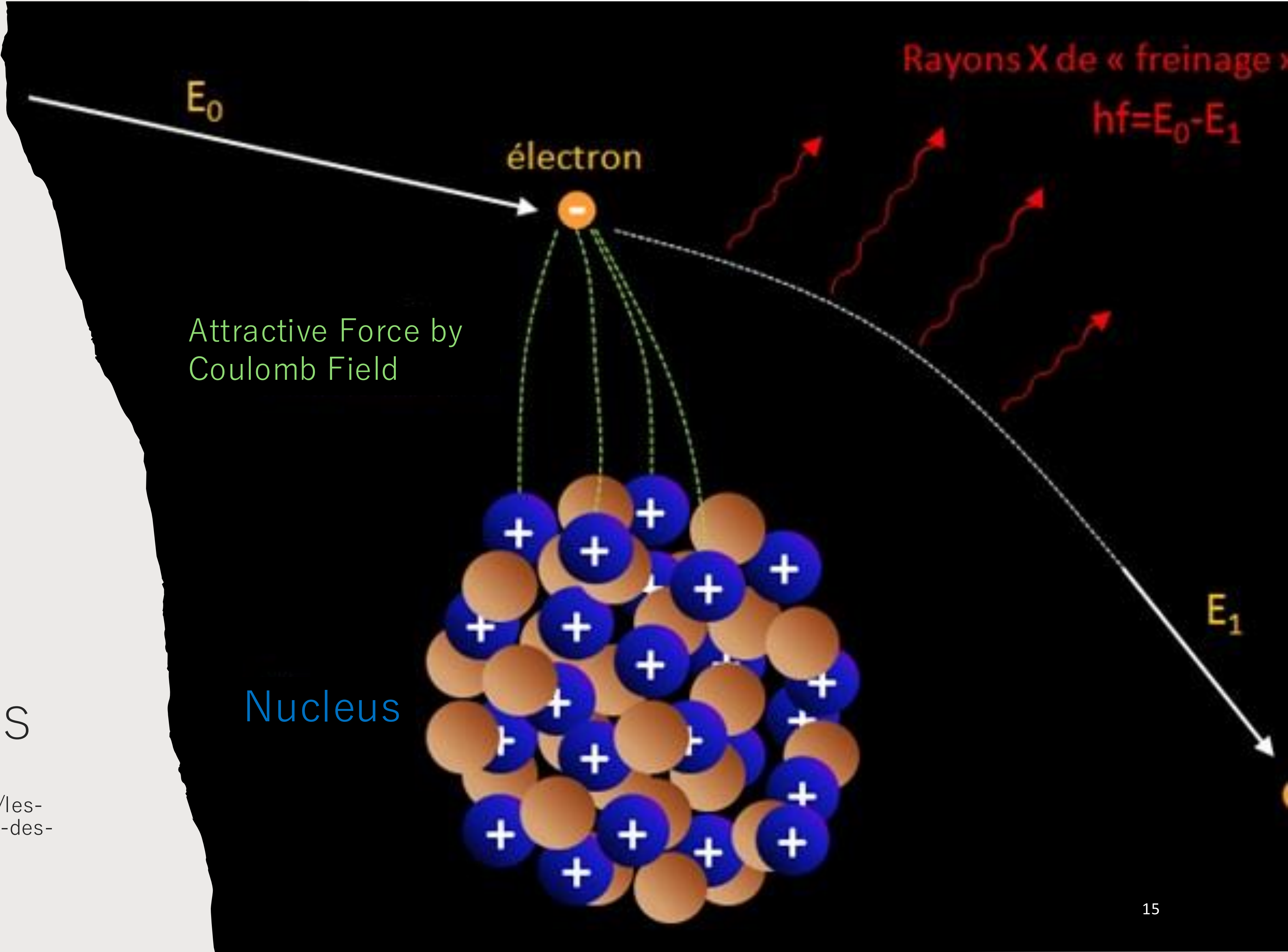
- Scintillator: $dE/dx|_{min} \approx 2 MeV/cm$
- Tungsten: $dE/dx|_{min} \approx 22 MeV/cm$

What do you drop?

https://www.photo-ac.com/main/search?q=この先急カーブ&srt=dlrank

Radiative Energy Loss

https://www.cloudylabs.fr/wp/les-processus-de-pertes-denergie-des-particules/



Bremsstrahlung : electromagnetic radiative energy loss

A decelerated or accelerated charged particle radiates photons. The mean radiative energy loss is given by :

fine structure constant = 1/137

medium atomic number

incoming particle energy

$$-\frac{dE^{rad}}{dx}\left(\frac{MeV}{g/cm^2}\right)=\frac{0.3071}{A(g)}\frac{\alpha}{\pi}Z^2 z^2\left(\frac{m_e}{m}\right)^2\frac{E}{m_e}\ln\left(\frac{183}{Z^{1/3}}\right)$$

incoming particle mass

incoming particle charge state

The mean radiative energy loss of a particle of charge z and mass m is a function of the mean radiative energy loss of an electron :

$$\frac{dE^{rad}}{dx}(z,m)=\left(\frac{m_e}{m}\right)^2 z^2\ \frac{dE^{rad}}{dx}(e^-)$$

Electrons are much more sensitive to this effect.

Radiation Length X_0

induced by atomic electrons :

classical radius of electron : $r_e = \alpha / m_e$

$$-\frac{dE}{dx}^{rad}(e^-) = 4\alpha N_A \frac{Z(Z+1)}{A} r_e^2 E \ln\left(\frac{183}{Z^{1/3}}\right)$$

which can be rewritten as :

$$-\frac{dE}{dx}^{rad}(e^-) = \frac{E}{X_0}$$

where X_0 is the medium radiation length

then over a path x in the medium, the mean radiated energy of an electron reads :

$$E^{rad}(e^-) = E\left(1 - e^{-x/X_0}\right)$$

where x is expressed in cm or g/cm²

and :

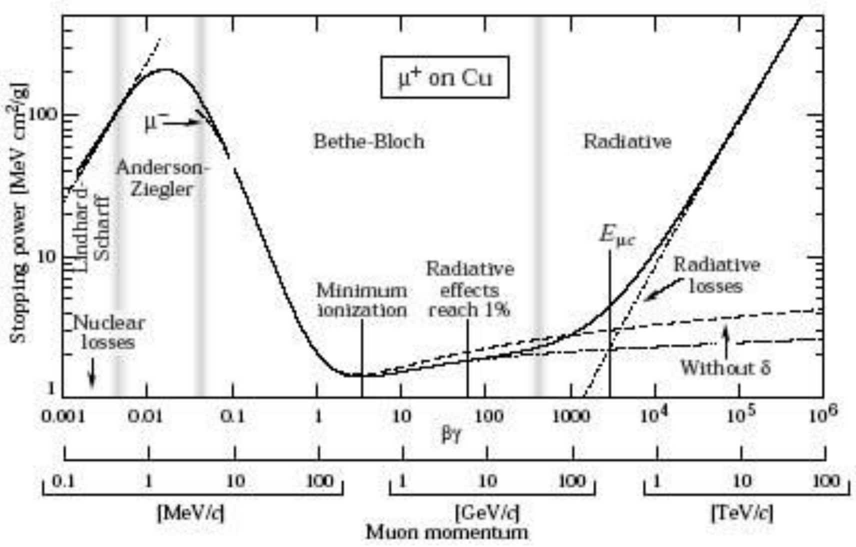
$$X_0(g/cm^2) = \frac{716.4\ A(g)}{Z(Z+1)\ln\left(\frac{287}{Z^{1/2}}\right)}$$

Radiation Length X_0 for Various Elements

- **Bremsstrahlung**
  - Material dependence in radiation length X_0
  - Critical energy:

$$E_c \approx \frac{800MeV}{Z+1.2}$$

$$E_c(\mu^- \text{ for Cu } Z=29) \approx 800GeV$$



Material	Z	A	Z/A	X_0 (cm)	Density (g/cm^3)
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$$X_0(g/cm^2) = \frac{716.4\ A(g)}{Z(Z+1)\ln\left(\frac{287}{Z^{1/2}}\right)}$$

Cherenkov Radiation

- Cherenkov radiation
  - Definition: Cherenkov radiation arises when a charged particle in a material moves faster than the speed of light in that same medium:

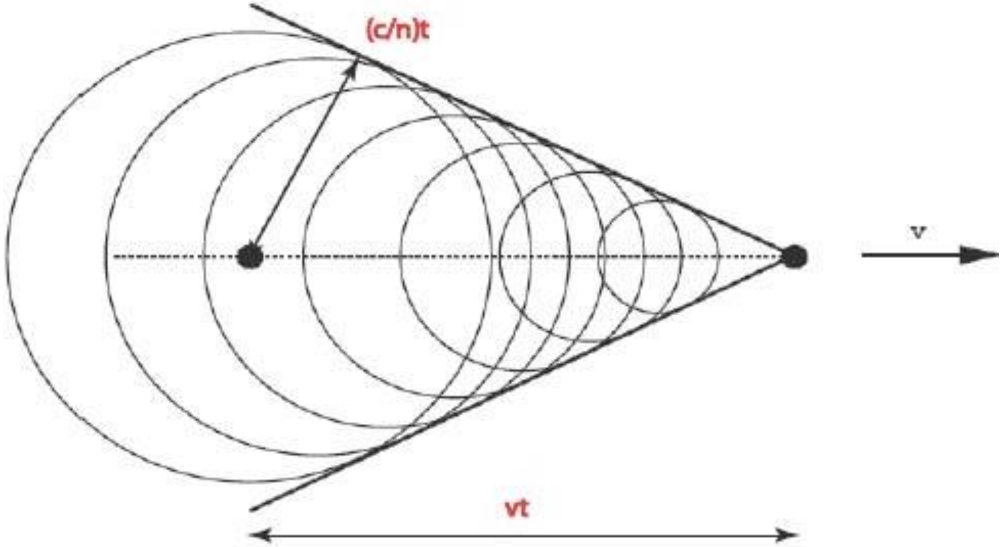
    $$\beta c = v = c/n$$

  - Condition for Cherenkov radiation to occur:

    $$\cos\theta_c = \frac{1}{\beta n} \qquad v_{particle} > c/n$$

  - Energy emitted per unit path length:

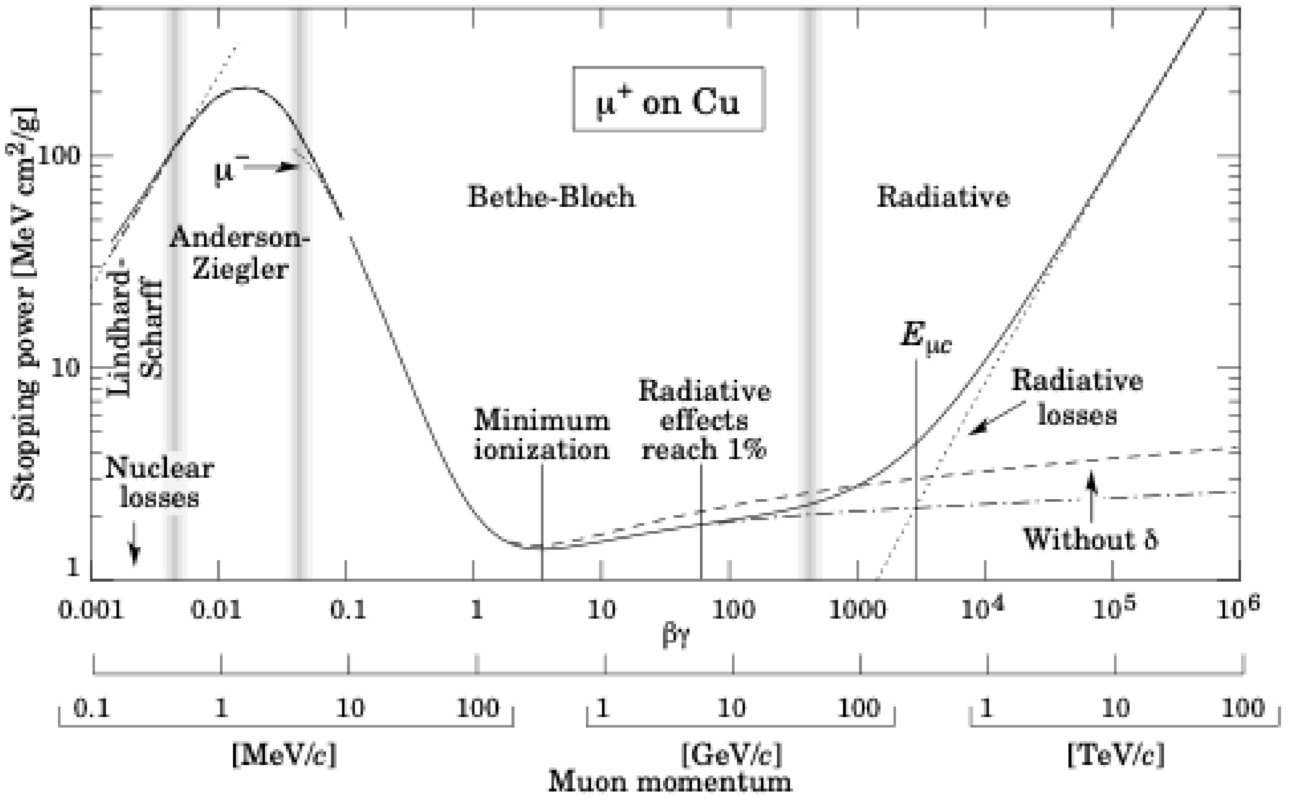
    $$\frac{dE}{dx} = 4\pi^2 e^2 \int_{\beta n > 1} \frac{1}{\lambda^3}\left(1 - \frac{1}{\beta^2 n^2}\right) d\lambda$$

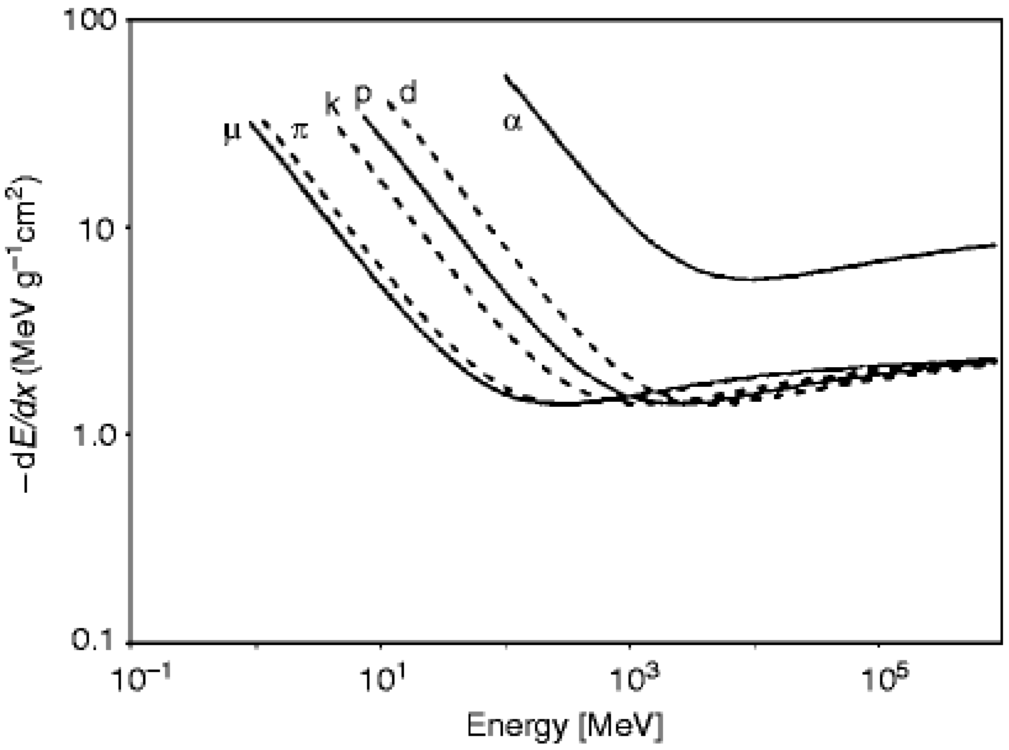


  - Example: Lead-glass (Passive absorber material = Active detector material) calorimeter (Type SF5):
    - Density: ρ = 4.08g/cm
    - Radiation length: X_0 = 2.54cm
    - Index of refraction: n = 1.67

Stopping Power of Minimum Ionazation Particle

MIP



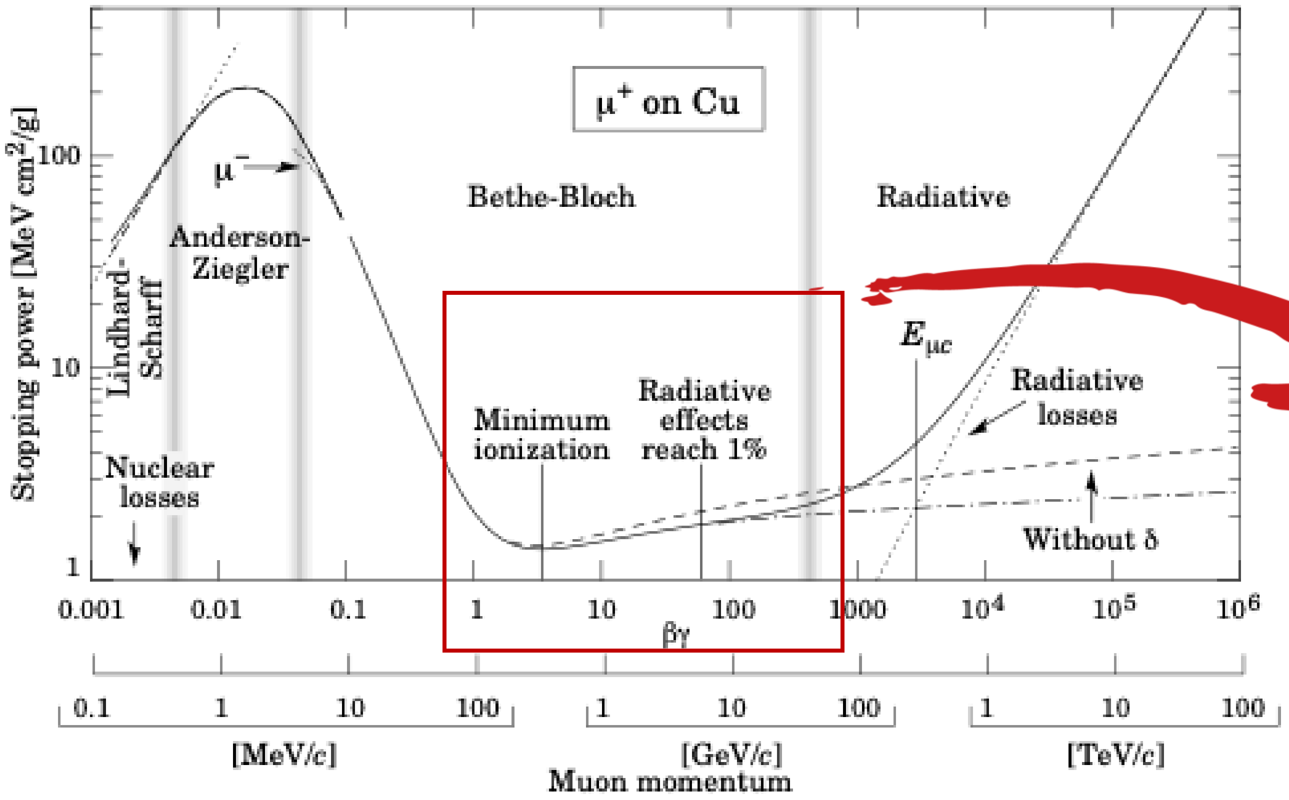


https://link.springer.com/referenceworkentry/10.1007/978-1-4419-0720-2_8/figures/3_8

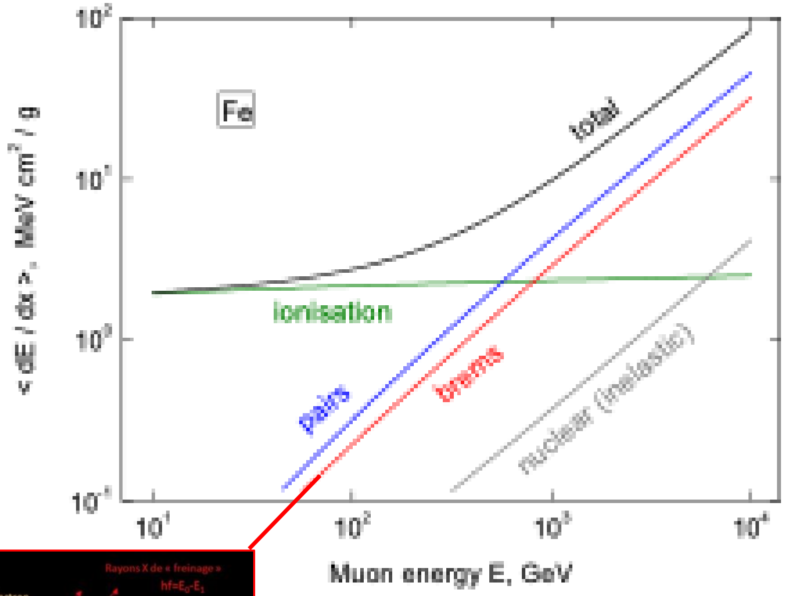
https://pdg.lbl.gov/2006/reviews/passagerpp.pdf

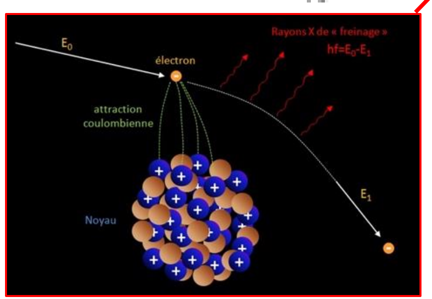
Stopping Power of Minimum Ionazation Particle

MIP



https://www.researchgate.net/figure/Average-energy-loss-of-muons-in-iron_fig2_4154863





Photon induced Electrons

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Editorial

Interactions of Electromagnetic Radiation and Subatomic Particles with Matter — Part 1

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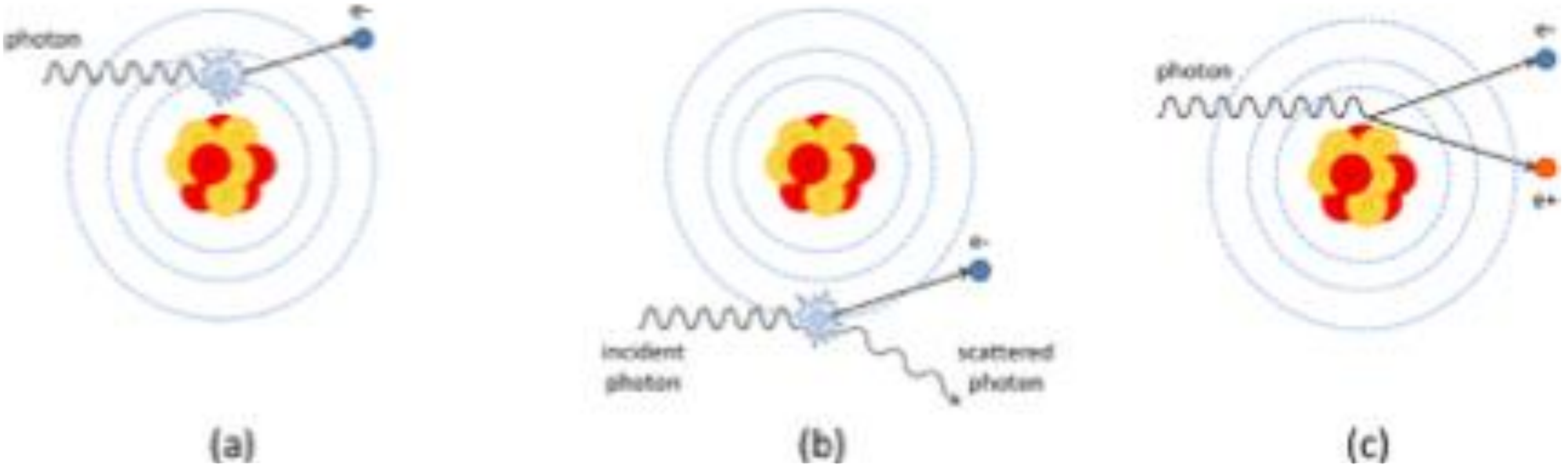
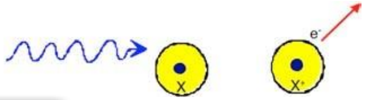


Fig 2. The three main photon interaction processes of interest in radiotherapy. (a) Photoelectric effect, (b) Compton effect, (c) pair production. Electrons are labelled as e− and positrons as e+.

Interaction of photon with matter

- Interactions of photons with matter
  - Photoelectric effect



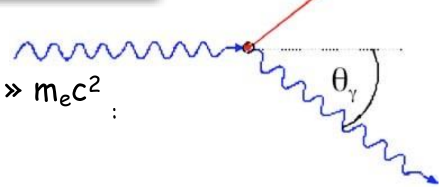
$$\gamma + X \rightarrow e^- + X^+$$

For Eη « $m_e c^2$ and the fact that for Eη above the K shell, almost only K electrons are involved one finds:

$$\sigma_{photo} = \sqrt{\left(\frac{32}{\epsilon^7}\right)}\alpha^4 Z^5 \sigma_{th} \qquad \sigma_{th} = \frac{8}{3}\pi r_e^2 \qquad \epsilon = \frac{E_\gamma}{m_e c^2}$$

  - Compton scattering

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



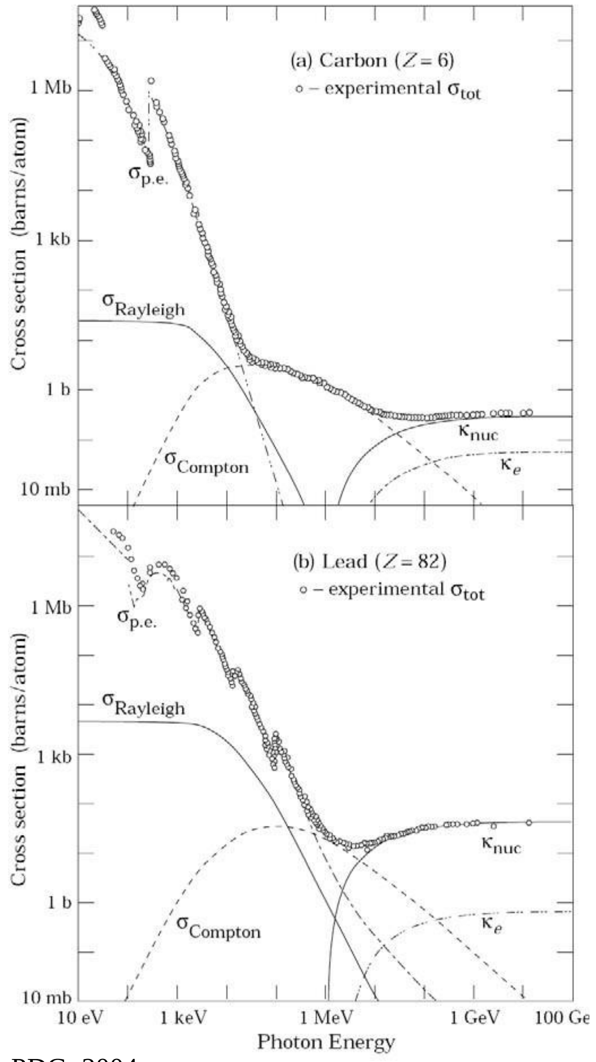
Assume electrons as quasi-free and Eη » $m_e c^2$:

$$\sigma_c = \frac{3}{8}\sigma_{th}\frac{1}{\epsilon}\left\{\ln(\epsilon) + \frac{1}{2}\right\}$$

(Klein-Nishina)

$$E'_\gamma = E_\gamma \frac{1}{1 + \epsilon(1 - \cos\theta_\gamma)}$$

Atomic Compton cross-section: $\sigma_c^{atomic} = Z\sigma_c$

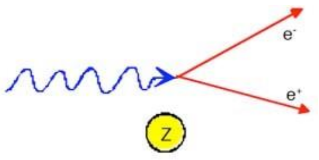


PDG, 2004

Interaction of photon with matter

- Interactions of photons with matter
  - Pair production

$$\sigma_{pair} = 4\alpha Z(Z+1)r_e^2\left[\frac{7}{9}\ln(183Z^{-1/3}) - \frac{1}{54}\right]$$



$$\frac{1}{\lambda_{pair}} = \frac{N_A\rho}{A}\sigma_{pair} \approx \frac{7}{9}4\alpha\frac{\rho N_A}{A}Z(Z+1)r_e^2\ln(183Z^{-1/3}) = \frac{7}{9}\frac{1}{X_0}$$

$$\frac{1}{\lambda_{pair}} \approx \frac{7}{9}\frac{1}{X_0}$$

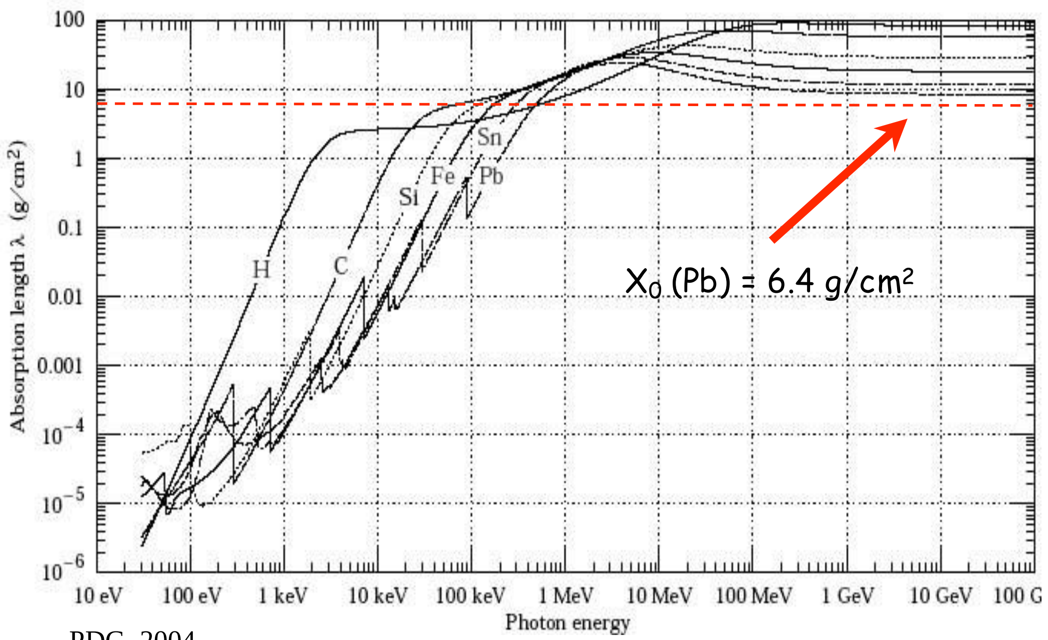
  - Absorption coefficient

Total probability for η inter-action in matter:

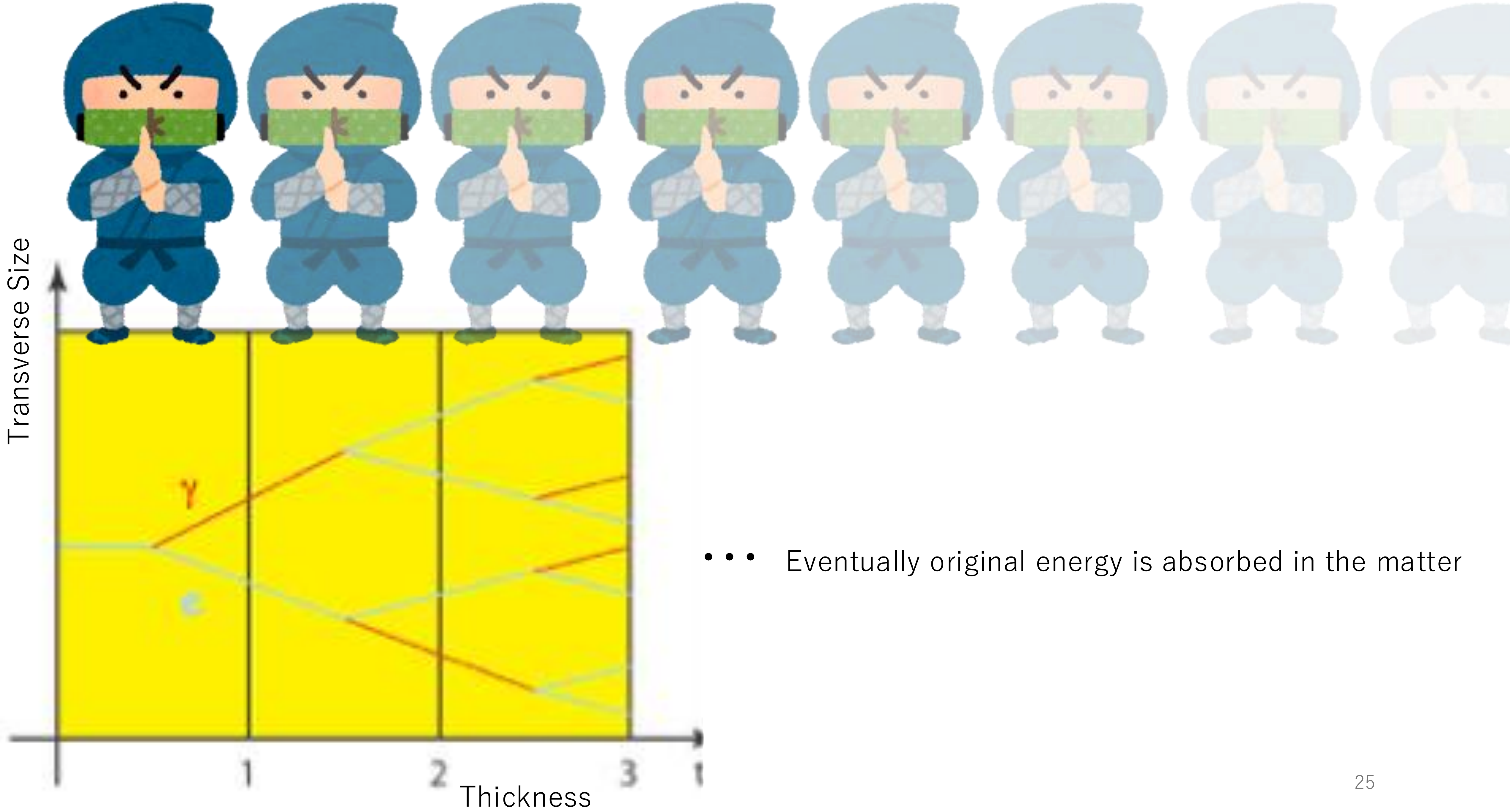
$$\sigma = \sigma_{photo} + Z\sigma_c + \sigma_{pair}$$

Probability per unit length or total absorption coefficient (Inverse of absorption length λ of η):

$$\mu = \sigma\left(\frac{N_A\rho}{A}\right) \qquad I = I_0 e^{-\mu x}$$



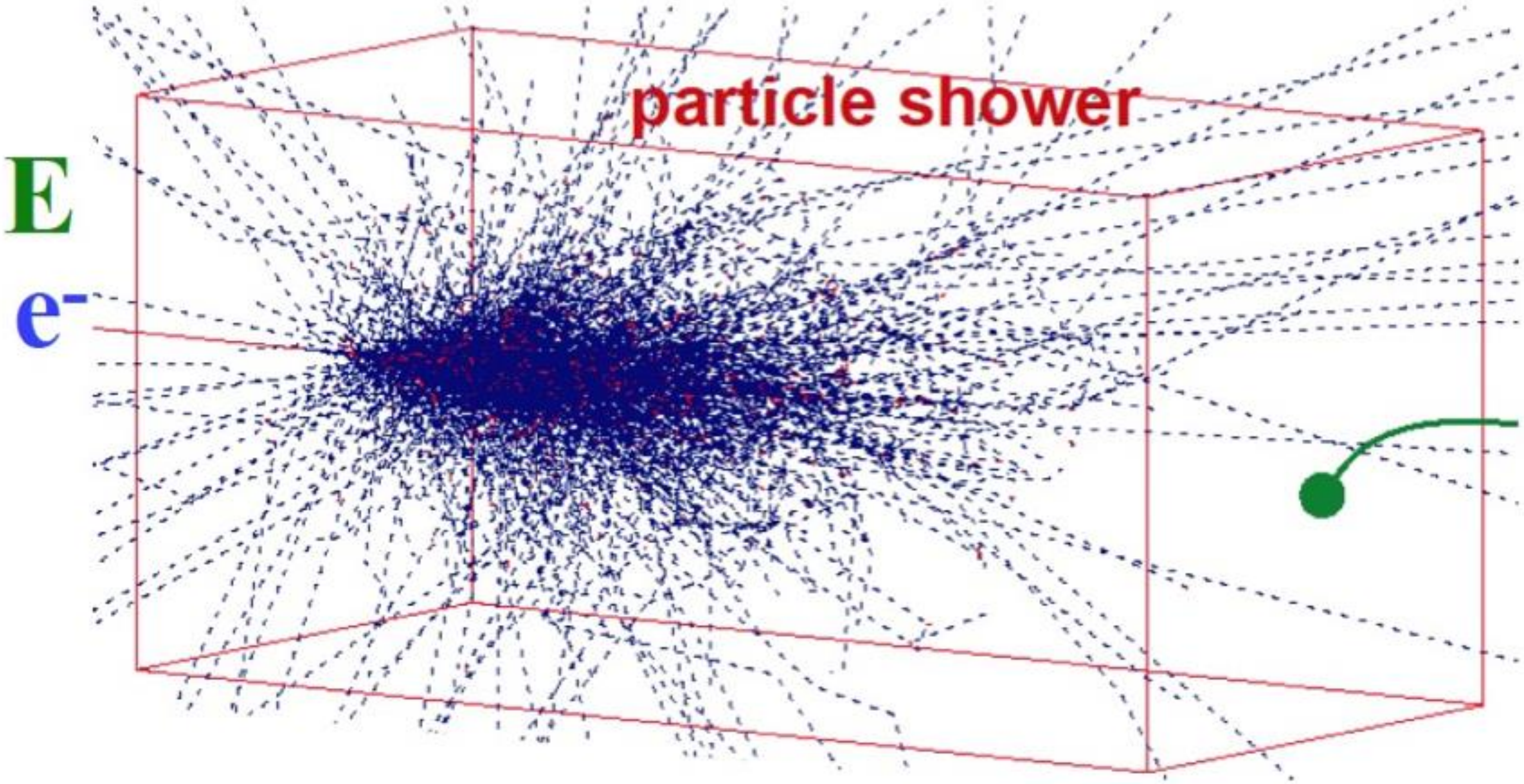
PDG, 2004



• • • Eventually original energy is absorbed in the matter

Electro-Magnetic Shower

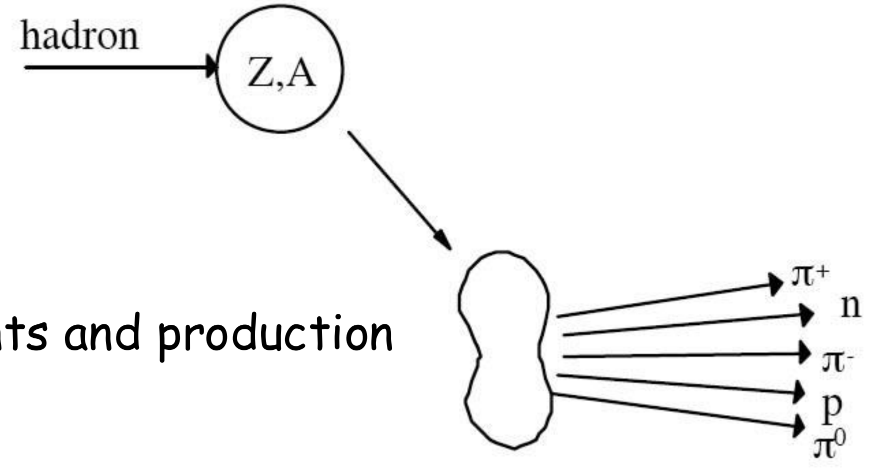
https://www.physi.uni-heidelberg.de/~sma/teaching/GraduateDays2017/sma_Detectors_4_Calorimeters.pdf



Ends up with multiple particles and the primary particle may stop in the material

Nuclear Interaction

- Nuclear interactions
  - The interaction of energetic hadrons (charged or neutral) is determined by various nuclear processes:



Multiplicity $\propto$ ln(E) P_t < 1 GeV/c

- Excitation and finally breakup of nucleus: nuclear fragments and production of secondary particles
- For high energies (> 1GeV) the cross-sections depend only little on the energy and on the type of the incident particle (p, π, K, …)
- Define in analogy to X_0 a hadronic interaction length λ_I:

$$\lambda_I = \frac{A}{N_A \sigma_{total}} \propto A^{\frac{1}{3}}$$

Nuclear Interaction Length in Various Elements

- Comparison of nuclear interaction length (in cm) and radiation length (in cm)

Material	Z	A	Z/A	X_0 (cm)	λ_I (cm)	Density (g/cm^3)
H_2 (liquid)	1	1.008	0.992	866	718	0.0708
He	2	4.002	0.500	756	520	0.125
C	6	12.01	0.500	18.8	38.1	2.27
Al	13	26.98	0.482	8.9	39.4	2.70
Cu	29	63.55	0.456	1.43	**15.1**	8.96
Pb	82	207.2	0.396	0.56	17.1	11.4
W	74	183.8	0.403	0.35	9.58	19.3
U	92	238.0	0.387	0.32	10.5	19.0
Scint.			0.538	42.4	81.5	1.03
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CsI			0.416	1.85	36.9	4.53
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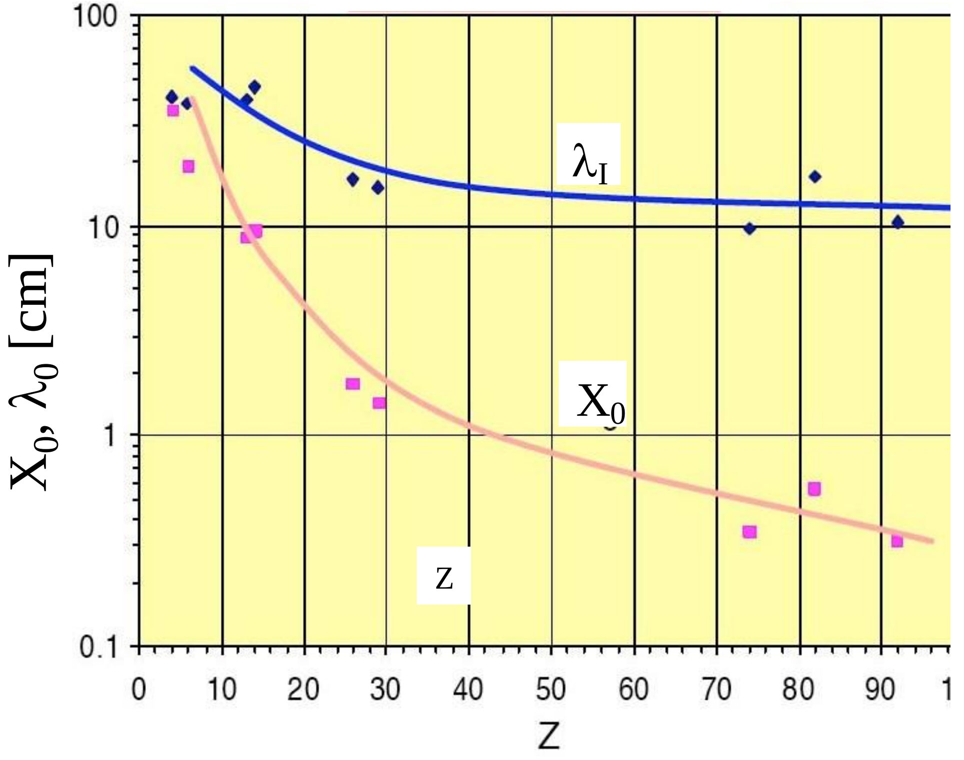
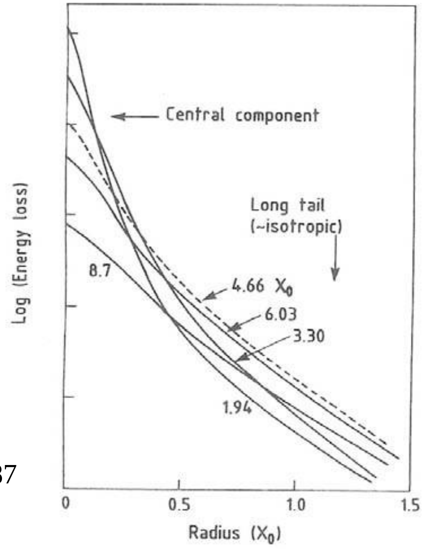


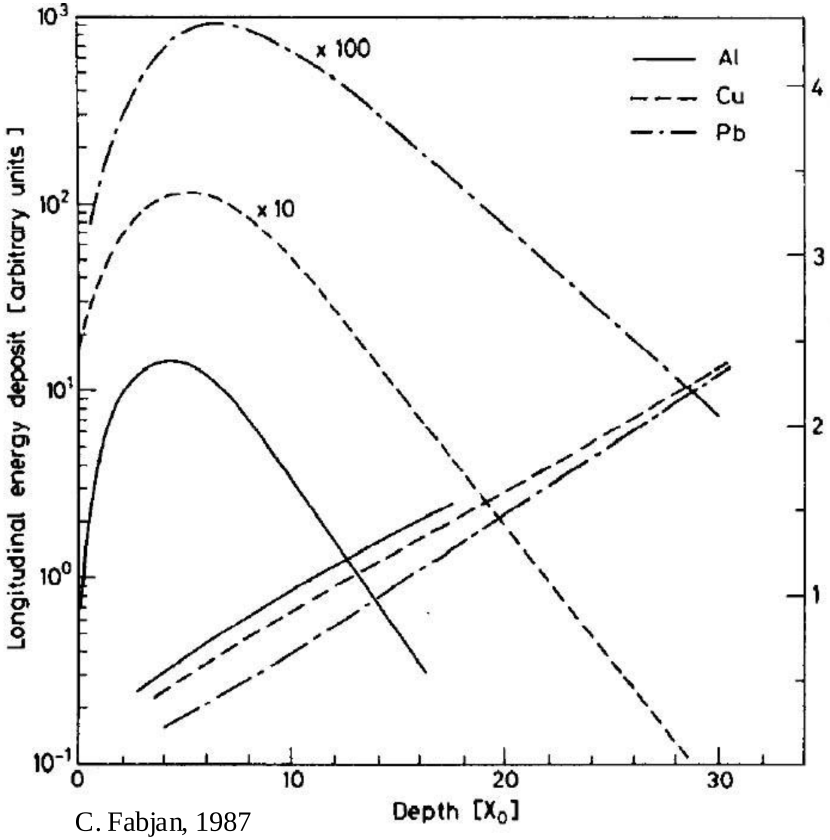
EM vs Hadron showers

- Shower profile



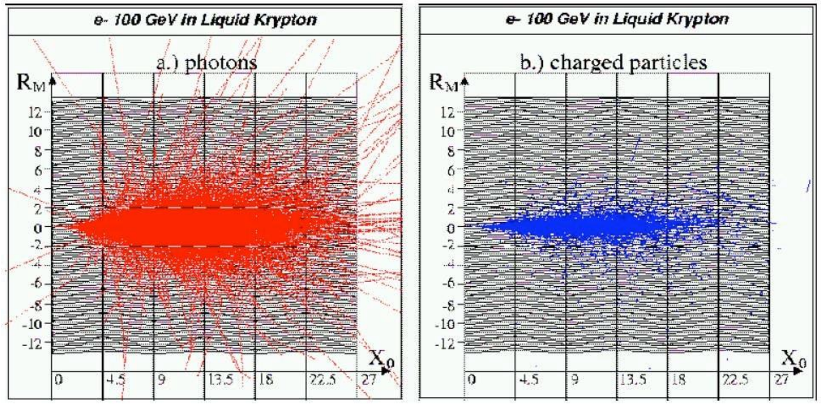
C. Fabjan, 1987

6GeV electrons in different materials:



C. Fabjan, 1987

MC simulation:



D. Wegener, 2001

sPHENIX Detectors

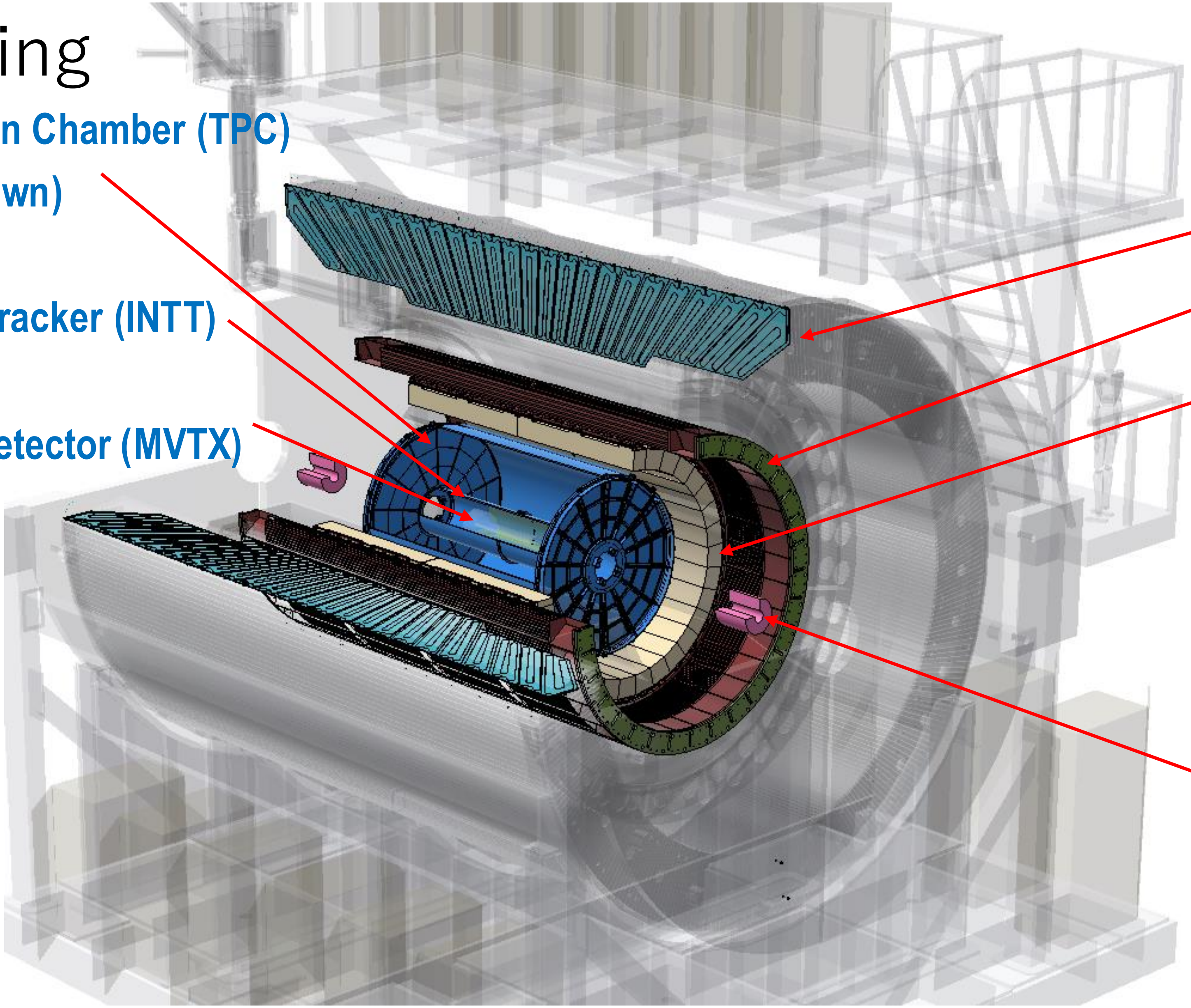
Tracking

Time Projection Chamber (TPC)

(TPOT not shown)

Intermediate Tracker (INTT)

MicroVertex Detector (MVTX)



Calorimetry

Hadronic Calorimeters

Outer

Inner

Electromagnetic Calorimeter

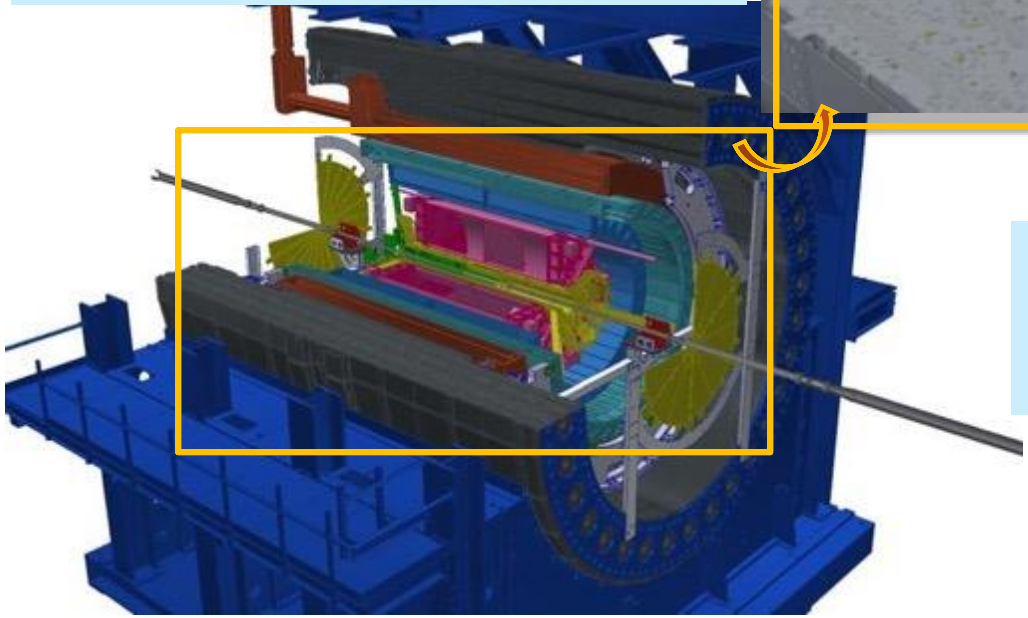
Trigger/event characterization :

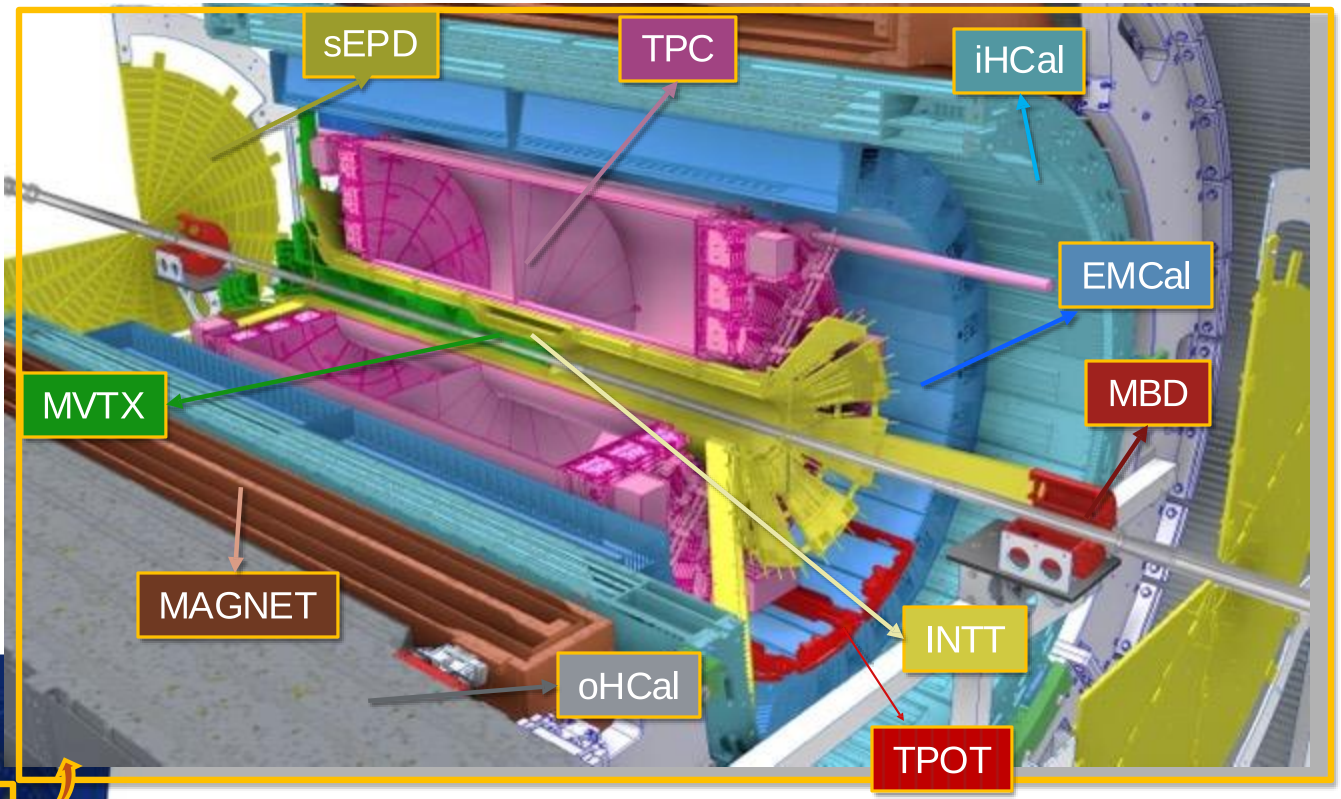
Minimum Bias Detector (MBD)

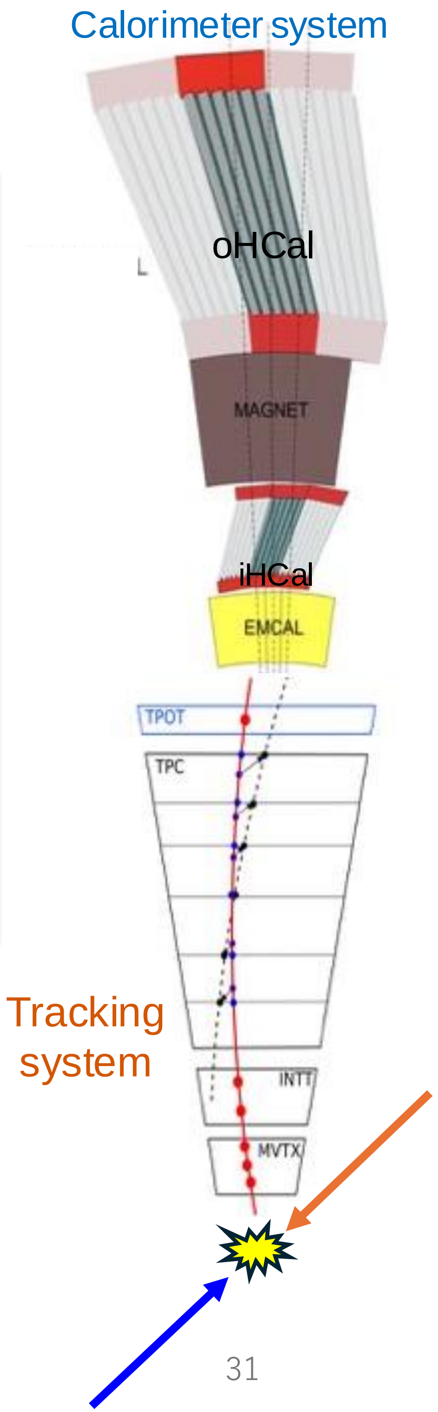
Event Plane (sEPD) (not shown)

sPHENIX Detector

- 1.4T Solenoid from BaBar
- Hermetic coverage:
  $|\eta|<1.1$, 2π in φ
- Large-acceptance EM+H calorimeters: brings first full jet reconstruction & b-jet tagging at RHIC!!
- High data rates: 15 kHz for all subdetectors
- Precise tracking with tracking system in stream readout







2023 : Commissioning Au+Au
2024 : p+p, Au+Au
2025 : Au+Au ⋯ p+A?

$\sqrt{s}$ =200GeV

Modern Experimental Detector Layout