Particle Interaction

- Many good references available
  - "Passage of Particles through Matter" section of the Particle Data Book
  - Books by Leo and Knoll
  - W. Riegler for the CERN 2008 Summer Student Lecture & A. Weber in his lecture on particle interactions for Oxford graduate students in 2004

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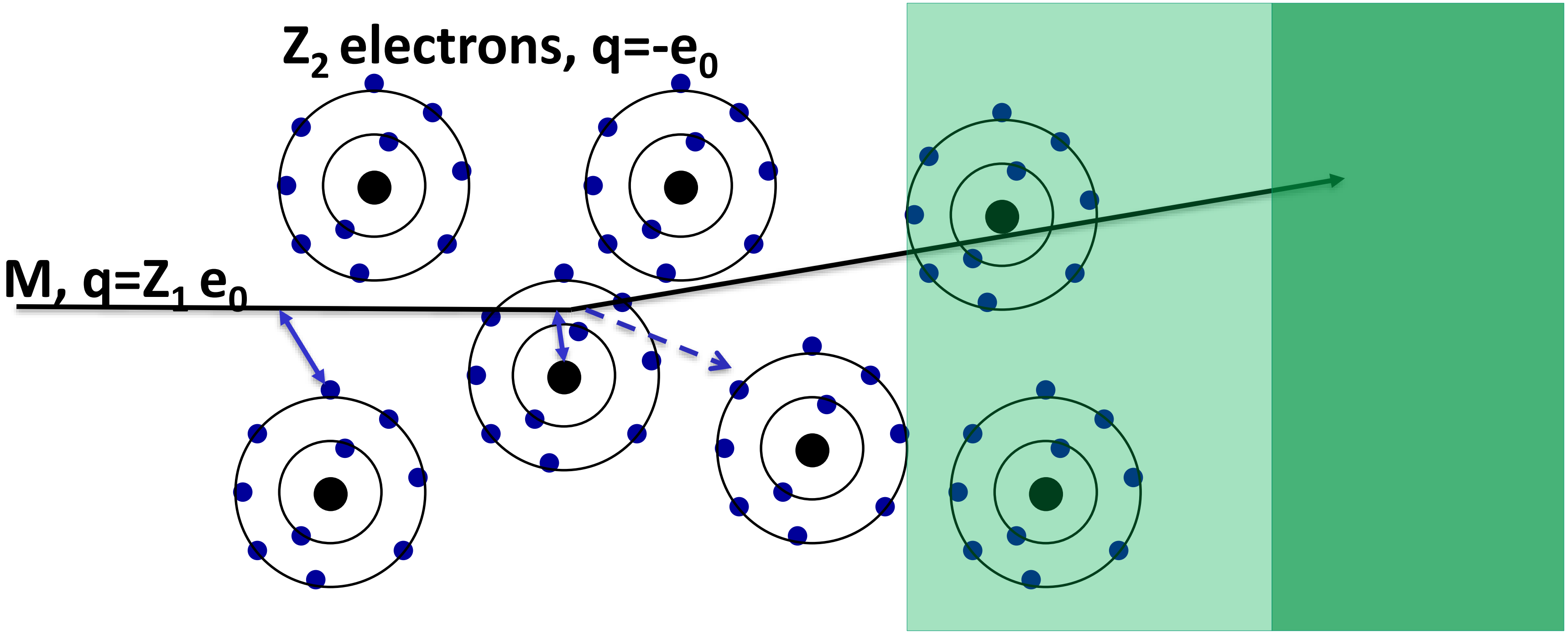
고에너지 검출기학교, 2019년 1월 9-11일

1) Electromagnetic Interaction of Charge Particles



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

Interaction with the atomic nucleus. The particle is deflected (scattered) resulting in multiple scattering of the particle in the material. During these scattering events a Bremsstrahlung photons can be emitted.

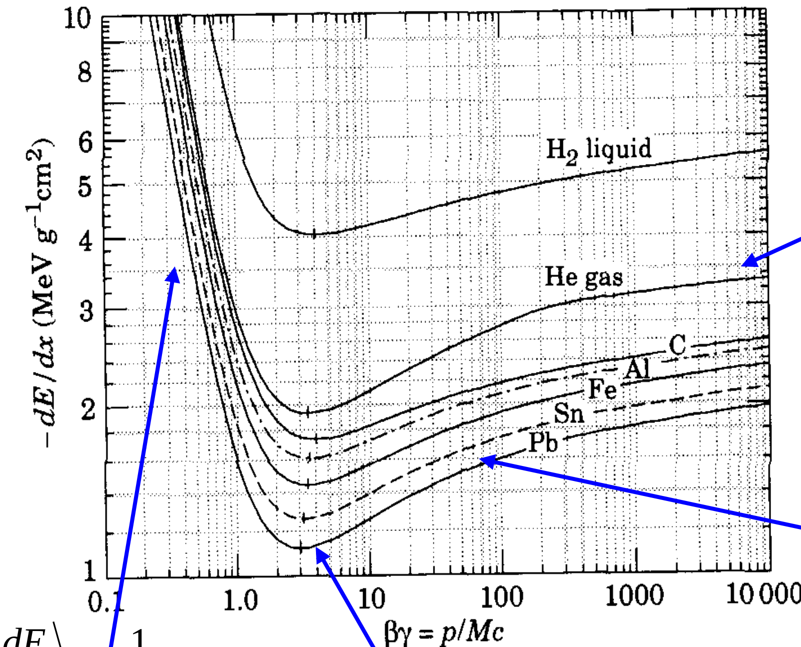
In case the particle's velocity is larger than the velocity of light in the medium, the resulting EM shockwave manifests itself as Cherenkov Radiation. When the particle crosses the boundary between two media, there is a probability of the order of 1% to produce an X ray photon, called Transition radiation.

Bethe-Bloch overview

Energy loss by Ionisation only → <u>Bethe - Bloch formula</u>

$$\left\langle \frac{dE}{dx} \right\rangle = -4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \gamma^2 \beta^2}{I^2} T^{\max} - \beta^2 - \frac{\delta}{2} \right]$$

- dE/dx in [MeV g^{-1} cm^2]
- valid for "heavy" particles ($m \geq m_\mu$).
- First approximation: medium simply characterized by Z/A ~ electron density



Z/A = 1

"Fermi plateau"

Z/A~0.5

$$\left\langle \frac{dE}{dx} \right\rangle \propto \ln \beta^2 \gamma^2$$

"relativistic rise"

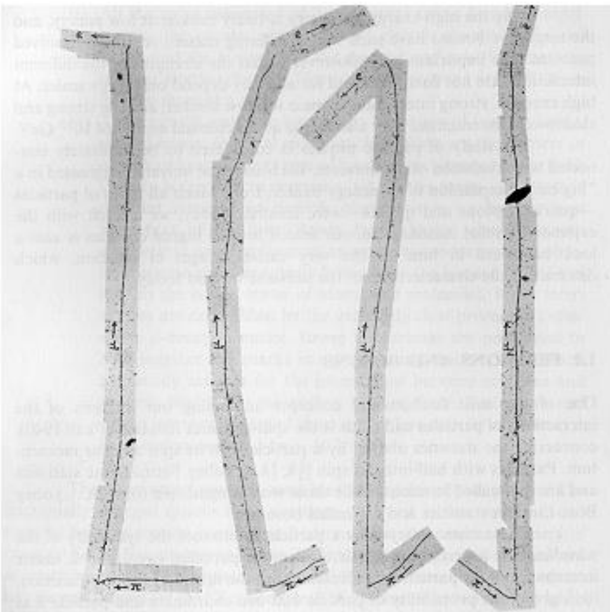
$$\left\langle \frac{dE}{dx} \right\rangle \propto \frac{1}{\beta^2}$$

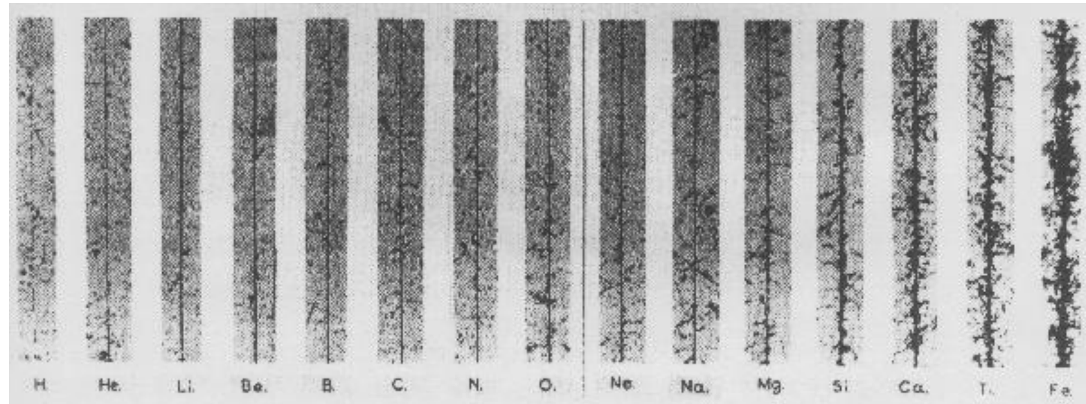
"kinematical term"

$\beta\gamma \approx$ 3-4

minimum ionizing particles, MIPs

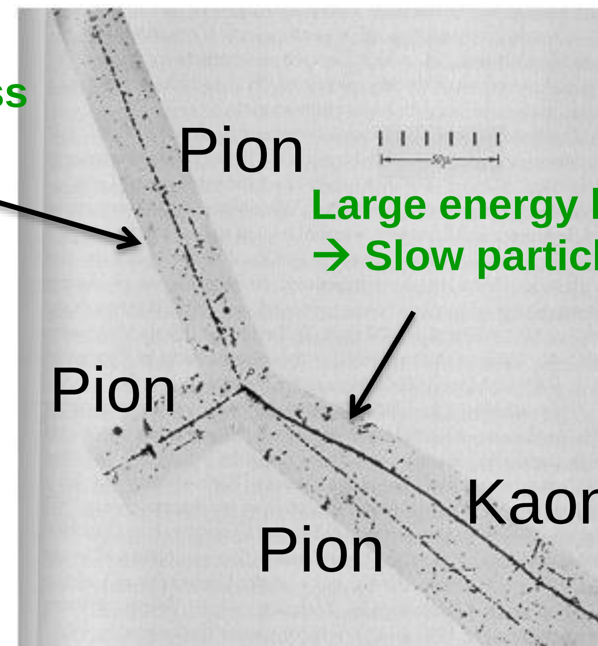
Small energy loss
→ Fast Particle





Cosmis rays: dE/dx α Z^2

Small energy loss
→ Fast particle

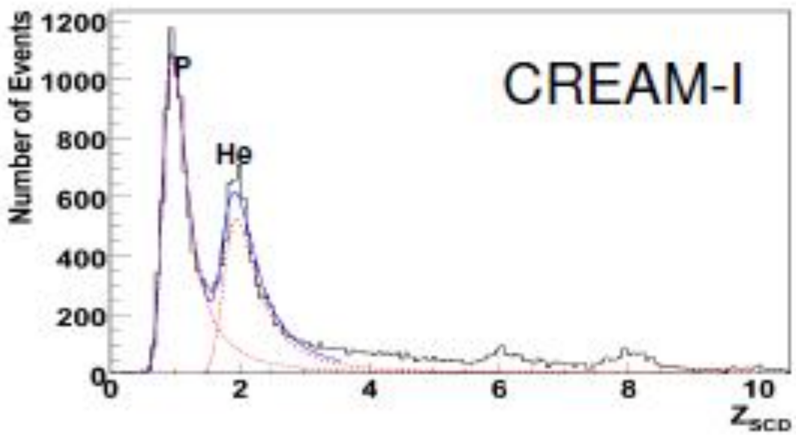


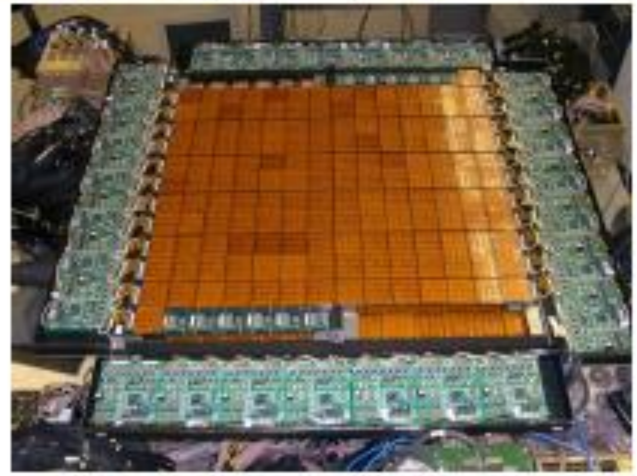
Discovery of muon and pion

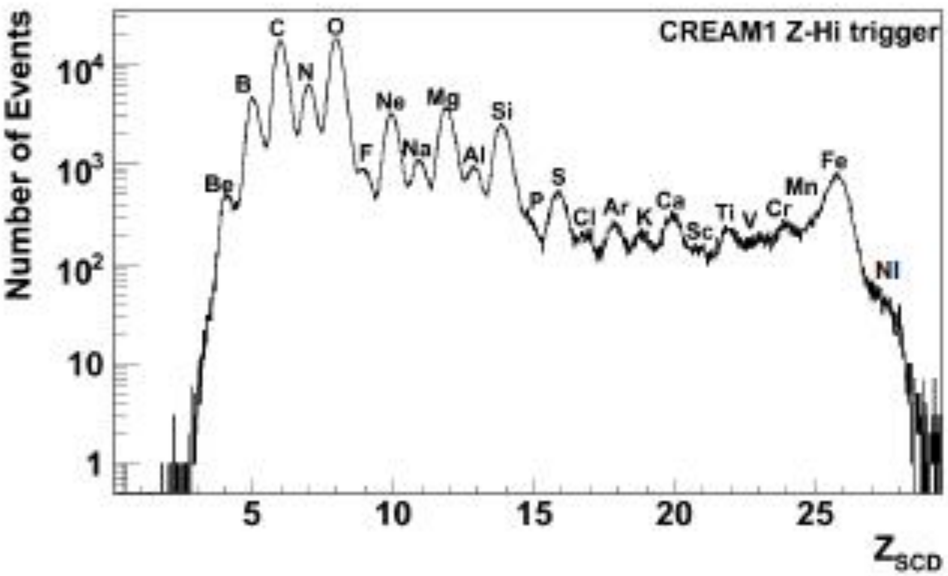
에멀젼, 액체아르곤 (Emulsion & Liquid Argon Precision Detectors)

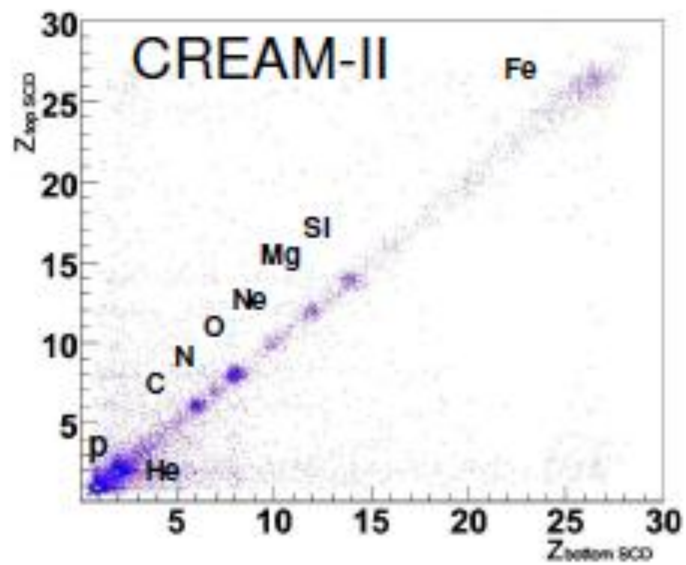
Charge Measurements: 2 layers of SCD

Park et al, Nucl. Instr. and Meth. A , 570, 286-291, 2007





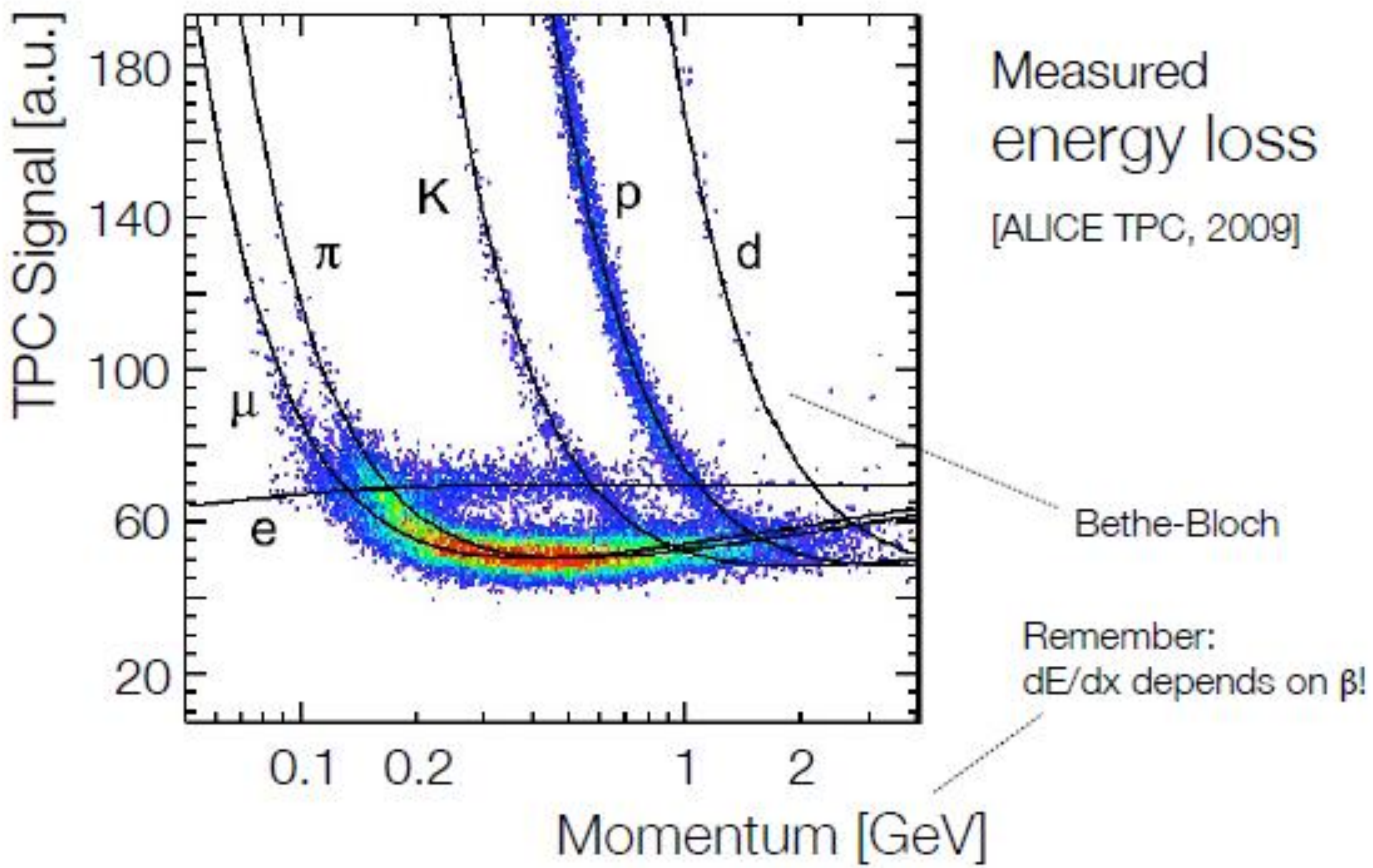




실리콘검출기 (Semiconductor detector) - Vertex & Track measurements

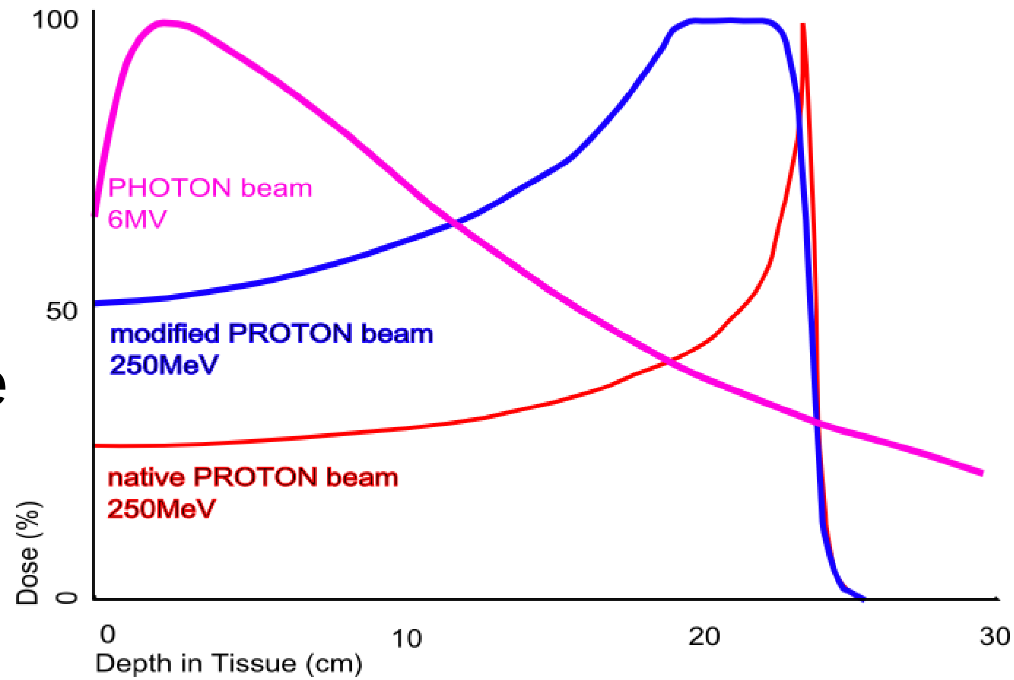
Speaker: Prof. Inkwon Yoo (부산대학교)

Application in Particle ID



Bragg peak

- Monoenergetic proton beam loses energy more rapidly as it slows down; gives sharp Bragg peak in ionization versus depth (used in proton radiation therapy)
- Using a range of proton energies allows a varied profile versus depth
- Photon beam (x-rays) deposits most energy near entrance into tissue



Multiple Scattering

- Particles don't only loose energy but also they also change direction. Average scattering angle is roughly Gaussian for small deflection angles with

$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p} z \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \ln\left(\frac{x}{X_0} \right) \right]$$

$$X_0 \equiv \text{ radiation length}$$

- Multiple scattering will make worse resolution for charged particle tracking.

- Energy loss distribution is not Gaussian around mean. In rare cases a lot of energy is transferred to a single electron :

δ-Ray

δ−Rays

- Energy loss distribution is not Gaussian around mean.
- In rare cases a lot of energy is transferred to a single electron

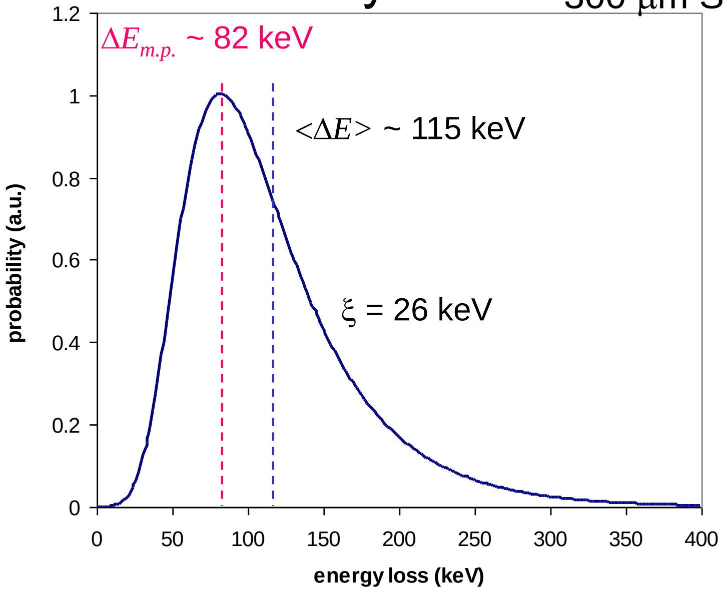
δ-Ray

- If one excludes δ-rays, the average energy loss changes
- Equivalent of changing E_{max}

Landau in thin layers

“Theory”

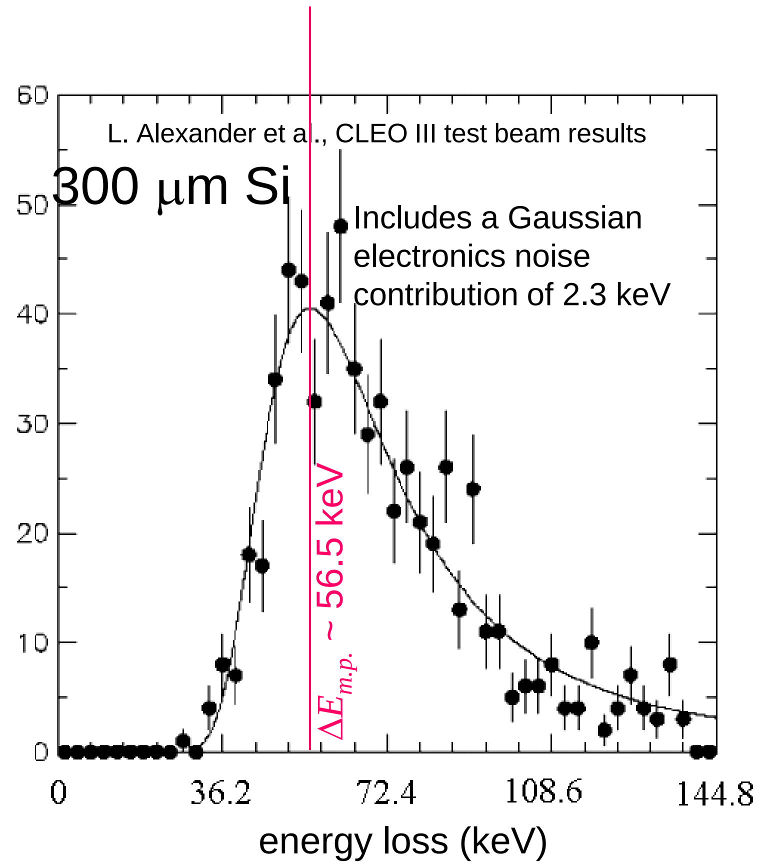
300 μm Si



뮤온검출기의 세계 (World of muon detectors) - RPC, Drift Tube, CSC

Speaker: Dr Kyonsei Lee (고려대학교)

charge collection
is not 100%



Landau’s theory J. Phys (USSR) 8, 201 (1944)

$$f(x, \Delta E) = \frac{1}{\xi}\Omega(\lambda) \qquad \Omega(\lambda) \approx \frac{1}{\sqrt{2\pi}} \exp\left\{-\tfrac{1}{2}(\lambda + e^{-\lambda})\right\}$$

$$\lambda = \frac{\Delta E - \Delta E_{m.p.}}{\xi}$$

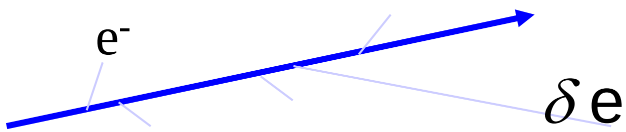
$$\xi = \frac{2\pi N e^4}{m_e v^2}\frac{Z}{A}x$$

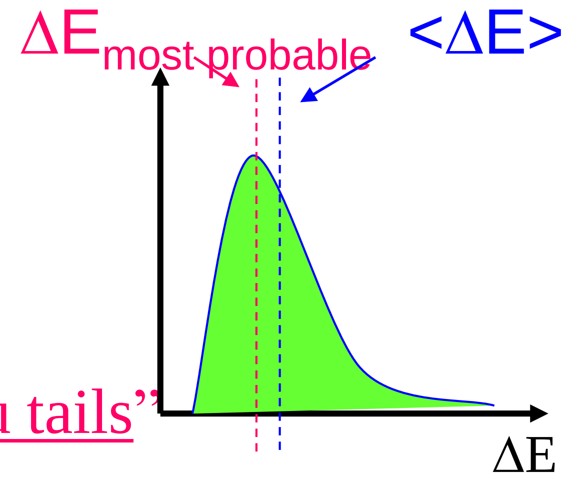
x (300 μm Si) = 69 mg/cm^2

δ-Ray : Landau distribution in thin layers

For thin layers or low density materials:

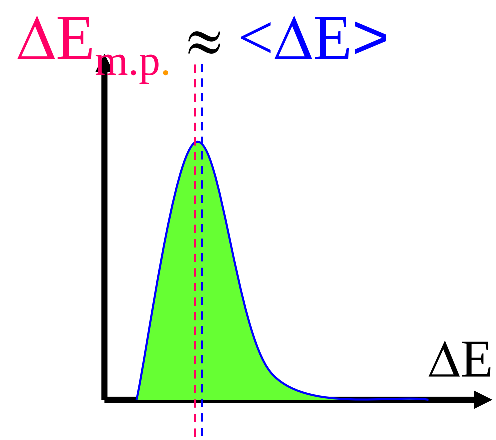
→ Few collisions, some with high energy transfer.





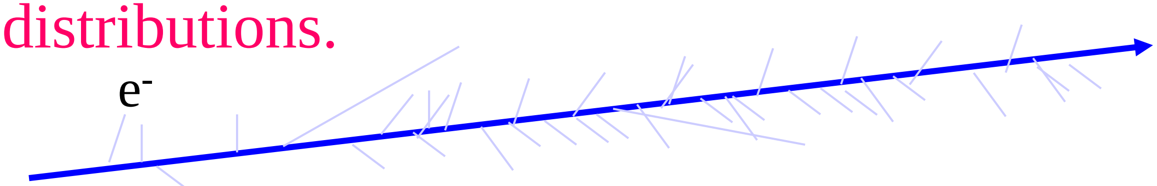
→ Energy loss distributions show large fluctuations towards high losses: ”Landau tails”

For thick layers and high density materials:



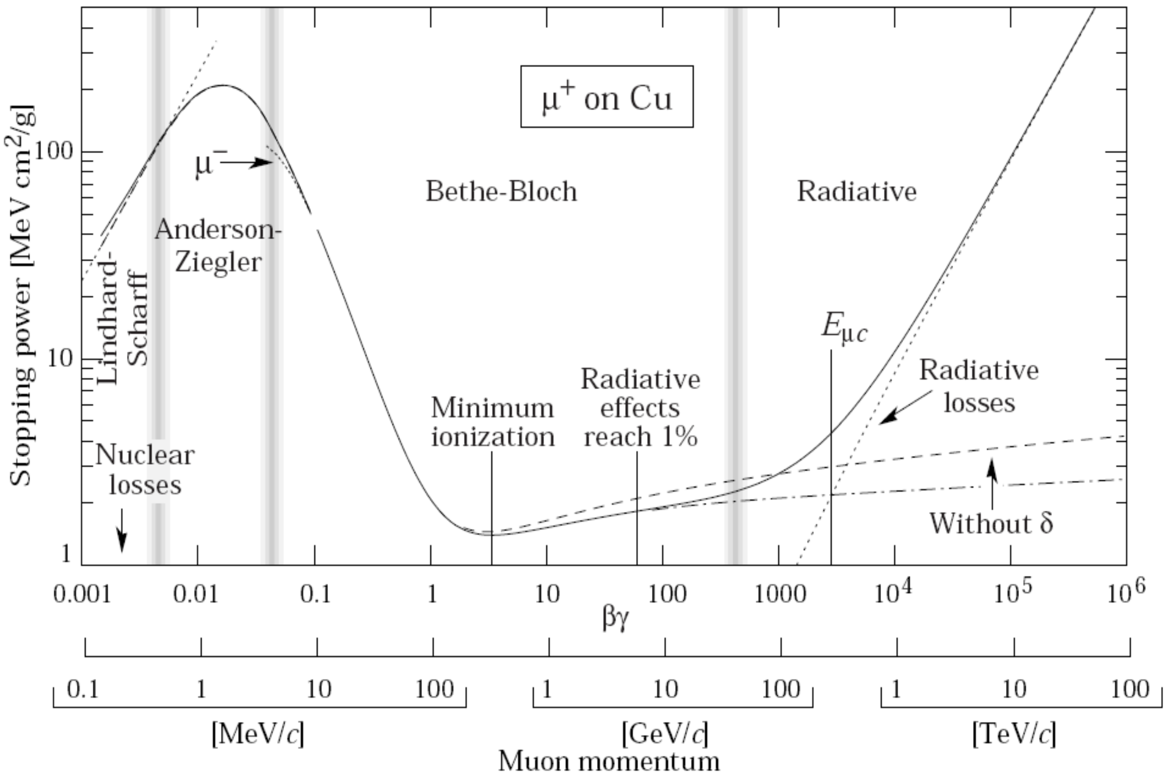
→ Many collisions.

→ Central Limit Theorem → Gaussian shaped distributions.

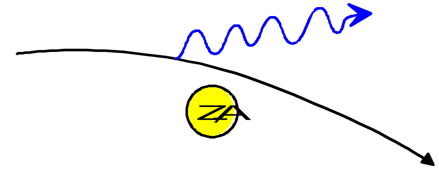


Light mass particle energy Loss

- At very low βγ, large energy loss due to atomic effects
- For large (and relevant) range of relativistic βγ, energy loss is small (minimium ionizing particle – “mip”)
- Ultra-relativistic particles lose energy mostly via gamma radiation



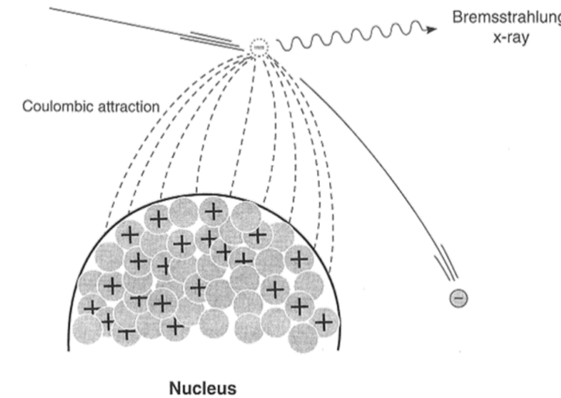
Bremsstrahlung



- Energy loss by Bremsstrahlung

Radiation of real photons in the Coulomb field of the nuclei of the absorber medium

$$-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} z^2 \left(\frac{1}{4\pi\varepsilon_0} \frac{e^2}{mc^2} \right)^2 E \ln \frac{183}{Z^{1/3}} \propto \frac{E}{m^2}$$



Effect plays a role only for $e^{\pm}$ and ultra-relativistic m (>1000 GeV)

For electrons:

$$-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^2 E \ln \frac{183}{Z^{1/3}}$$

$$-\frac{dE}{dx} = \frac{E}{X_0} \quad \Longrightarrow \quad E = E_0 \, e^{-x/X_0}$$

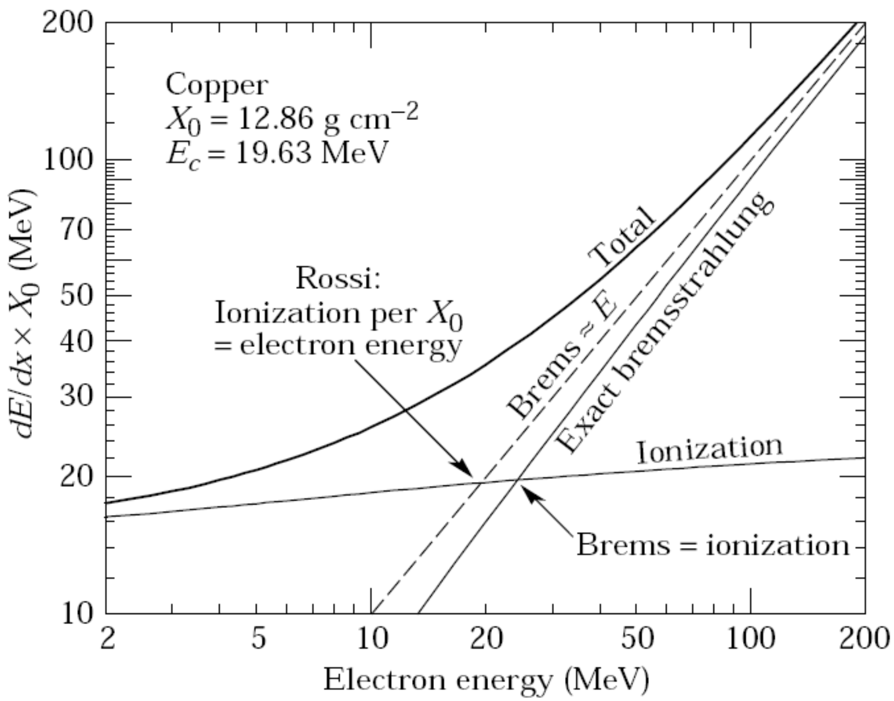
$$X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln \frac{183}{Z^{1/3}}}$$

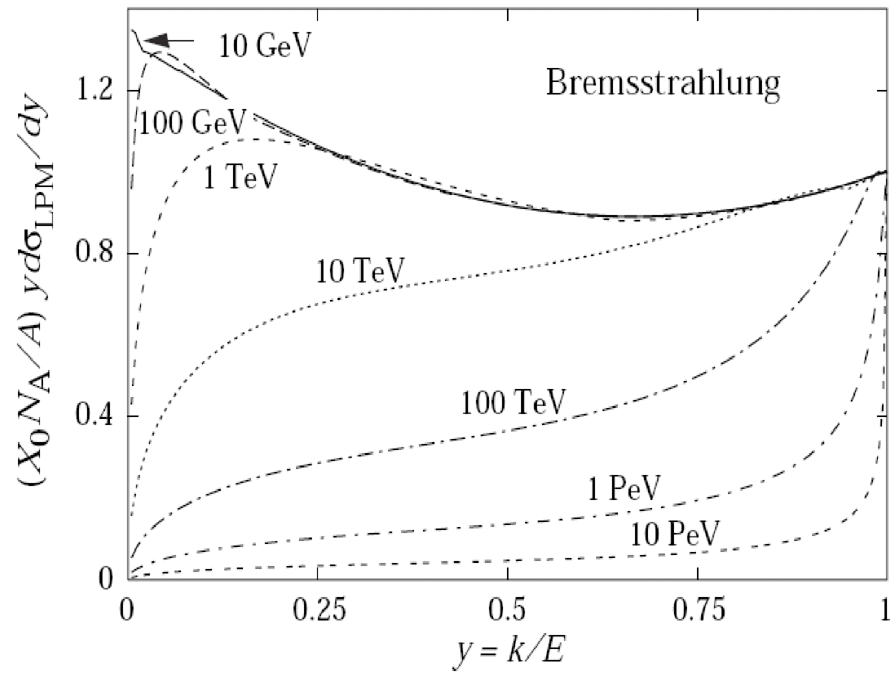
radiation length [g/cm²]

(divide by specific density to get X_0 in cm)

Electrons

- Electrons are different ➔light
  - Bremsstrahlung
  - Pair production





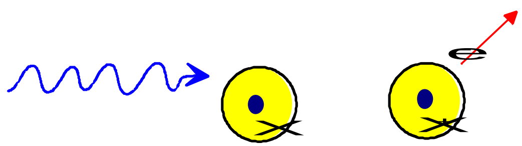
2) γ and X-ray interaction

- γ and X-ray are neutral : No direct interaction with target.
- Photon interaction by
  - Photo-electric effect
  - Compton scattering
  - Pair production

Interaction of photons

In order to be detected, a photon has to create charged particles and / or transfer energy to charged particles

- **Photo-electric effect:**



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

Only possible in the close neighborhood of a third collision partner - photo effect releases mainly electrons from the K-shell.

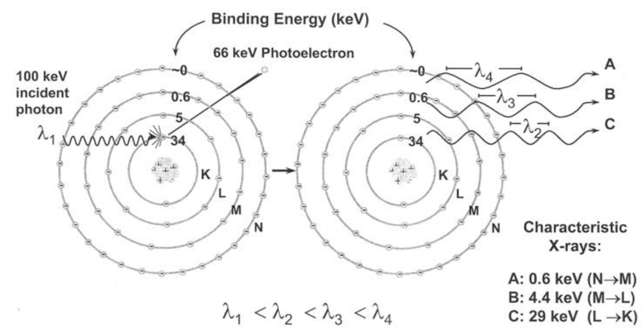
Cross section shows strong modulation if $E_\gamma \approx E_{shell}$

$$\sigma^K_{photo} = \left(\frac{32}{\varepsilon^7}\right)^{\frac{1}{2}} \alpha^4 Z^5 \sigma^e_{Th} \qquad \varepsilon = \frac{E_\gamma}{m_e c^2} \qquad \sigma^e_{Th} = \frac{8}{3}\pi r_e^2 \quad \text{(Thomson)}$$

At high energies

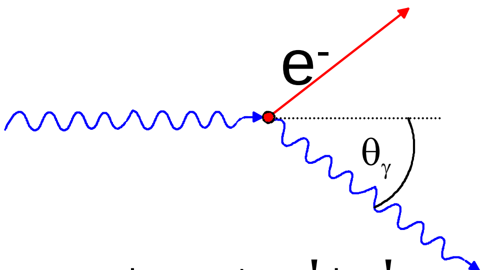
$$\sigma^K_{photo} = 4\pi r_e^2 \alpha^4 Z^5 \frac{1}{\varepsilon}$$

$$\sigma_{photo} \propto Z^5$$



Interaction of photons

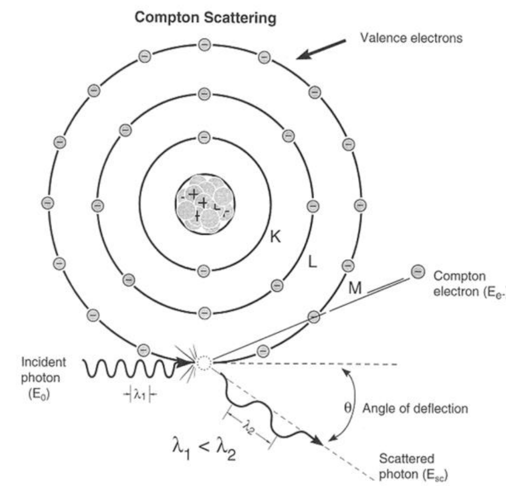
- Compton scattering:



$$\gamma + e \rightarrow \gamma' + e'$$

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

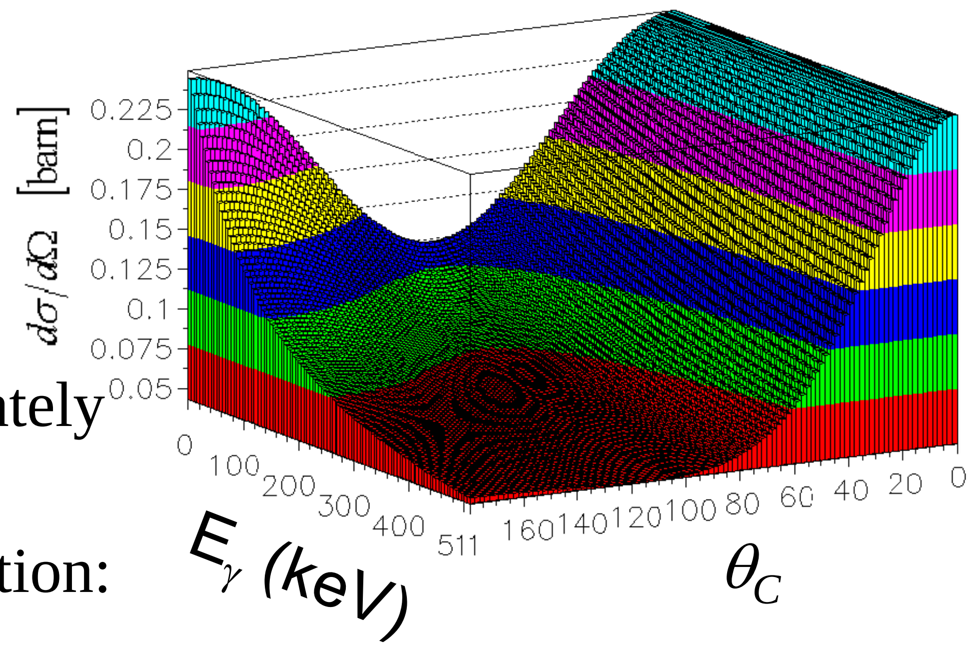
$$E_e = E_\gamma - E'_\gamma$$



Assume electron as quasi-free.

Klein-Nishina $\frac{d\sigma}{d\Omega}(\theta,\varepsilon)$ →

Compton cross-section (Klein-Nishina)



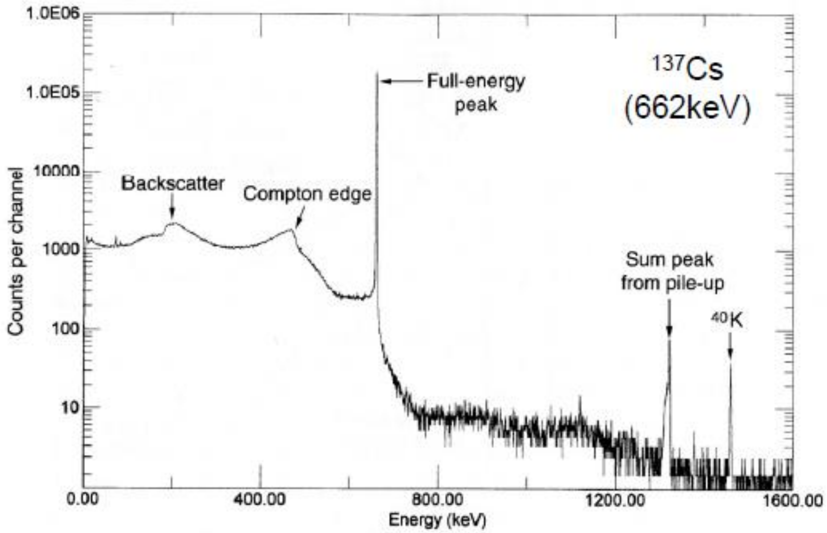
At high energies approximately

$$\sigma_c^e \propto \frac{\ln\varepsilon}{\varepsilon}$$

Atomic Compton cross-section:

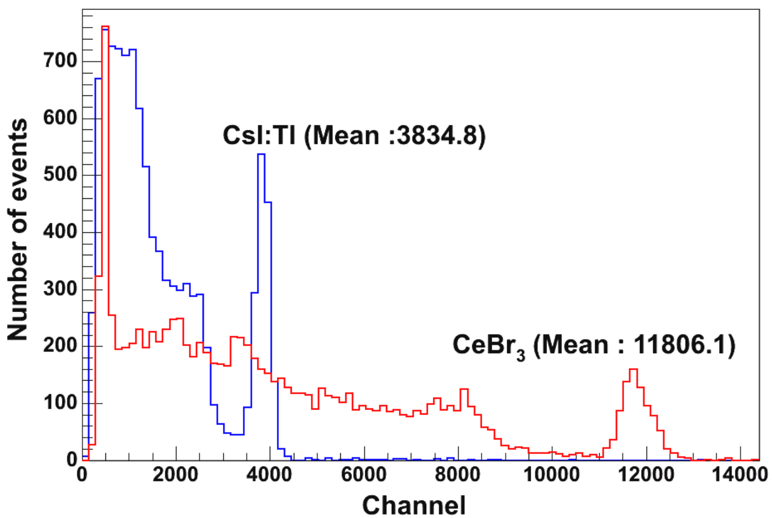
$$\sigma_c^{atomic} = Z \cdot \sigma_c^e$$

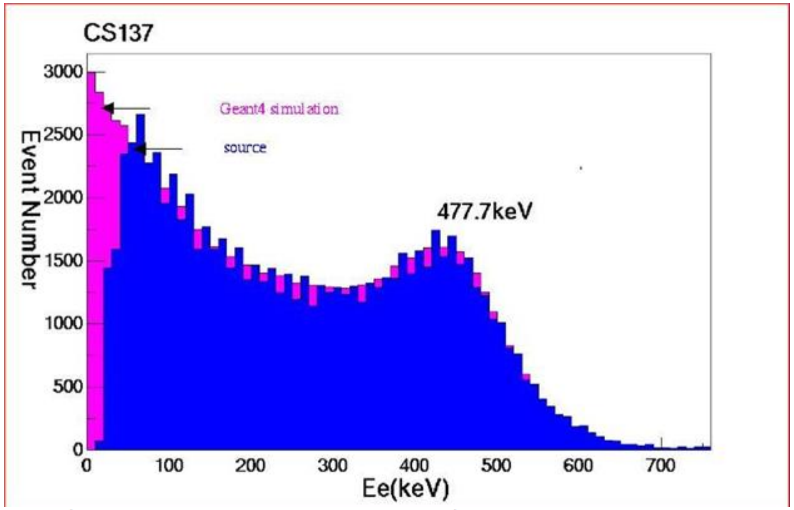
Detector Response with ^{137}Cs γ source



HPGe

Liquid scintillator (C,H)





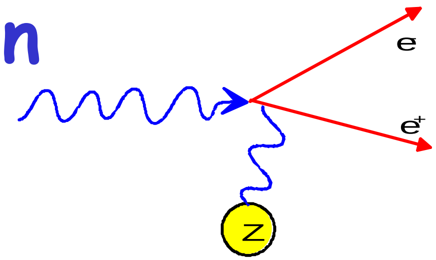
Scintillator

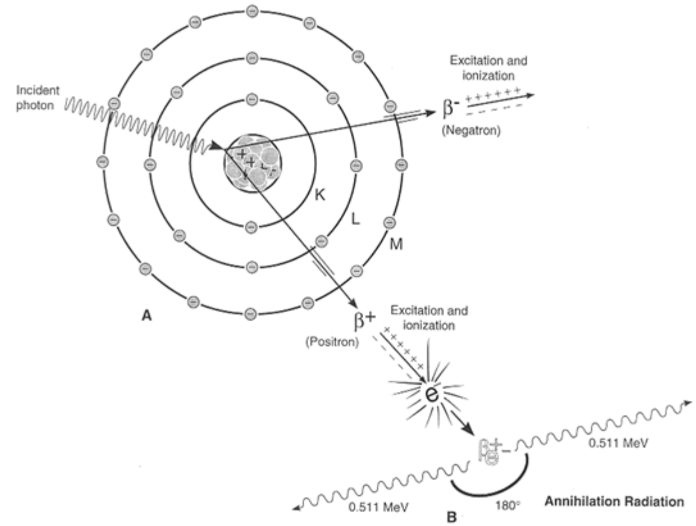
섬광검출기와 PMT (Scintillation detector & PMT)

Speaker: Dr Jongwon Lee (고려대학교)

Interaction of photons

Pair production





$$\gamma + nucleus \rightarrow \quad e^+e^- + nu$$

Only possible in the Coulomb field of a nucleus (or an electron) if $E_\gamma \geq 2m_e c^2$

Cross-section (high energy approximation)

$$\sigma_{pair} \approx 4\alpha r_e^2 Z^2 \left(\frac{7}{9} \ln \frac{183}{Z^{\frac{1}{3}}} \right)$$

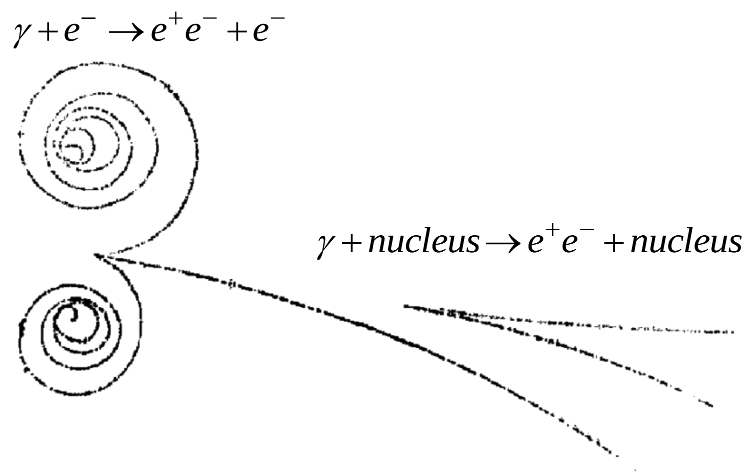
independent of energy !

$$\approx \frac{7}{9} \frac{A}{N_A} \frac{1}{X_0}$$

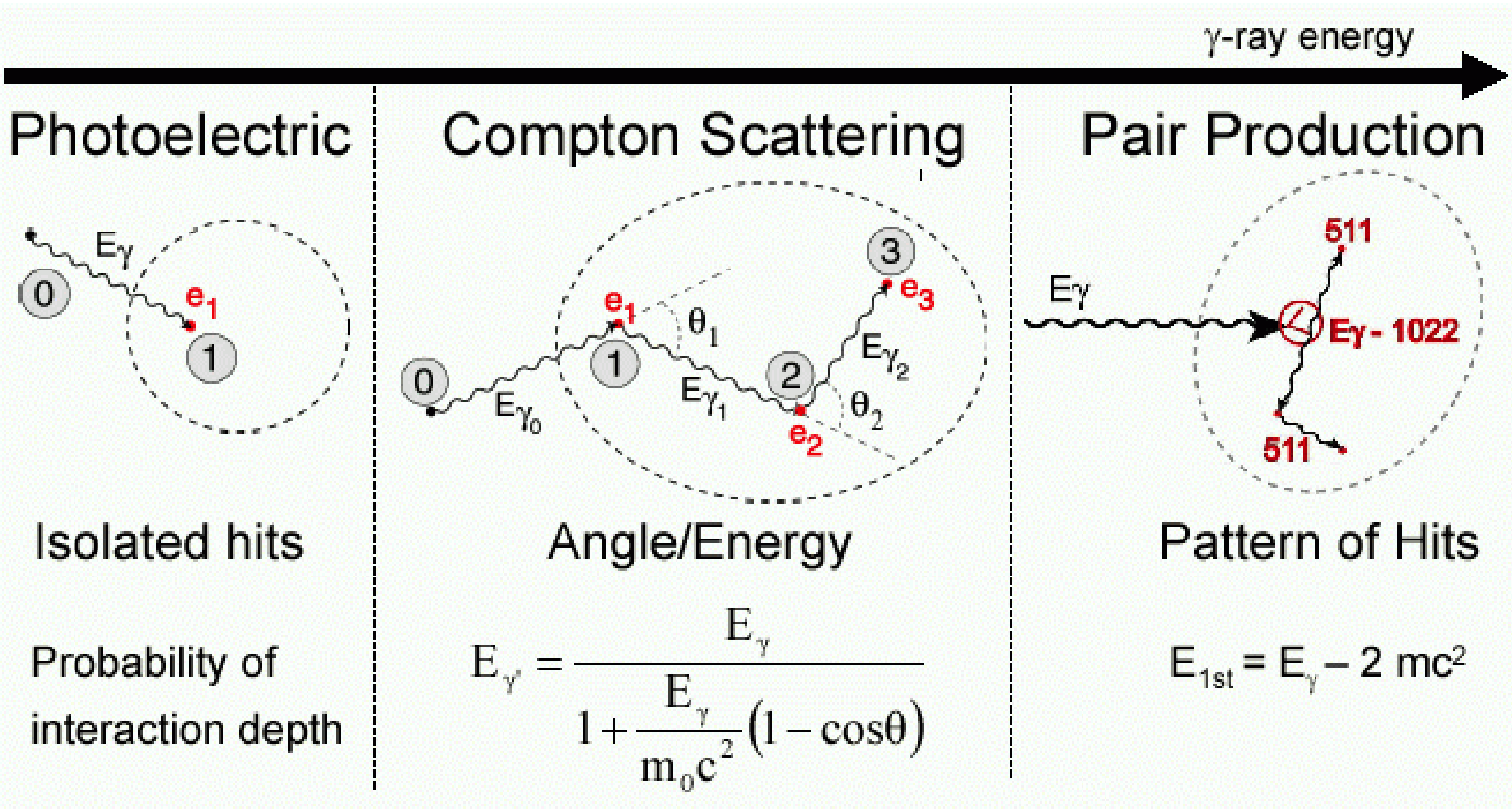
$$\approx \frac{A}{N_A} \frac{1}{\lambda_{pair}}$$

$$\lambda_{pair} = \frac{9}{7} X_0$$

Energy sharing between e$^+$ and e$^-$ becomes asymmetric at high energies.



Energy Loss of γ

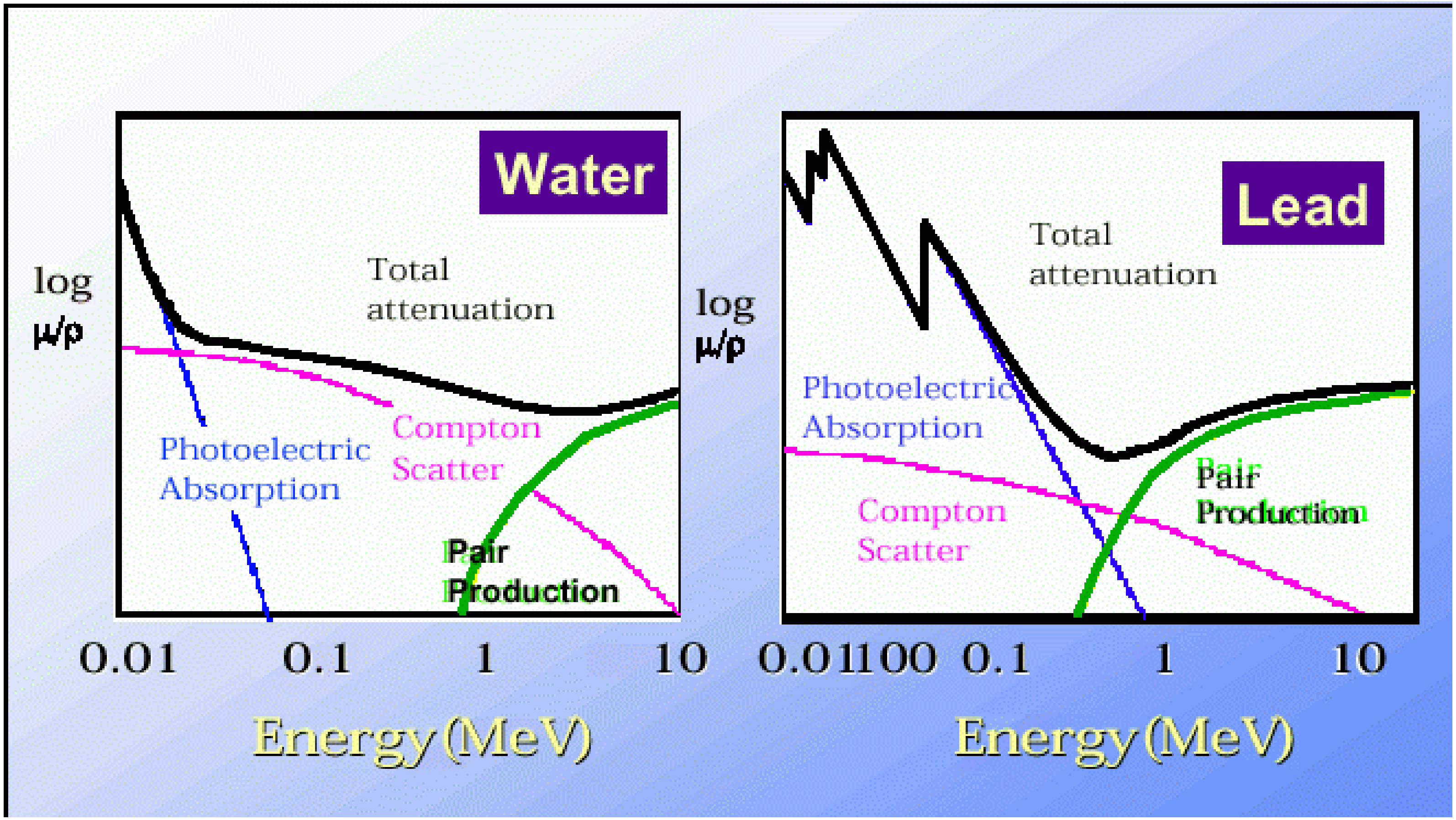


Dependence of Type of interaction	Energy σ	Z cm^2/atom	Z cm^2/g
Photoelectric Effect	$E^{-3.5}$	Z^4 to Z^5	Z^3 to Z^4
Compton Effect	$E^{-0.5}$ to E^{-1}	Z	≈ independent
Pair Production	E^1 to ln E	Z^2	Z

Interactions of photons with water and lead

In summary: $I_\gamma = I_0 e^{-\mu x}$

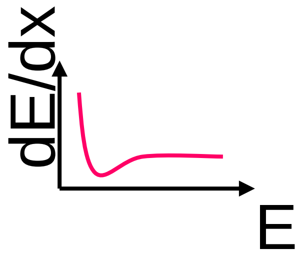
μ: mass attenuation coefficient $\mu_i = \frac{N_A}{A}\sigma_i \quad [cm^2/g] \quad \mu = \mu_{photo} + \mu_{Compton} + \mu_{pair} + \dots$



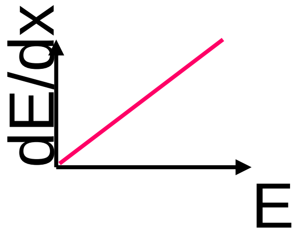
Reminder: basic electromagnetic interactions

e^+ / e^-

- Ionisation

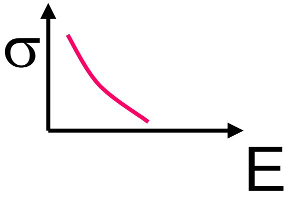


- Bremsstrahlung

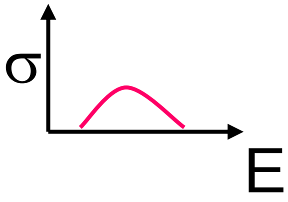


γ

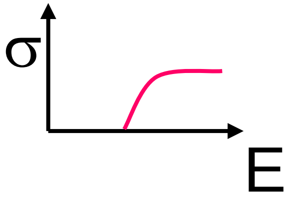
- Photoelectric effect



- Compton effect

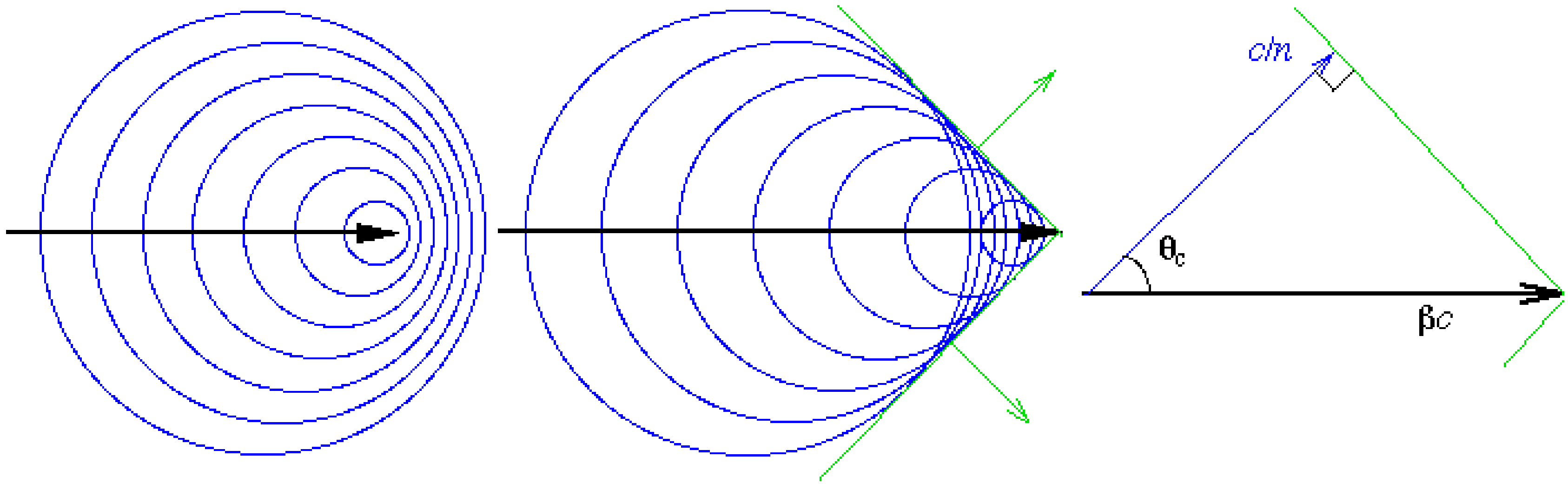


- Pair production



3) Cherenkov Radiation

- Wave front comes out at certain angle



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

- That's the trivial result!

체렌코프 검출기와 활용 (Cherenkov detector and its applications) - RICH, Water Cherenkov

Speaker: Prof. Youngjoon Kwon (연세대학교)

Cherenkov Radiation

- How many Cherenkov photons are detected?

$$N_\gamma = L\frac{\alpha z^2}{r_e m_e c^2}\int \varepsilon(E)\sin^2\theta_c(E)\,\mathrm{d}E$$

$$= L\frac{\alpha z^2}{r_e m_e c^2}\int \varepsilon(E)\left(1-\frac{1}{\beta^2 n^2}\right)\mathrm{d}E$$

$$\approx LN_0\left(1-\frac{1}{\beta^2\langle n^2\rangle}\right)$$

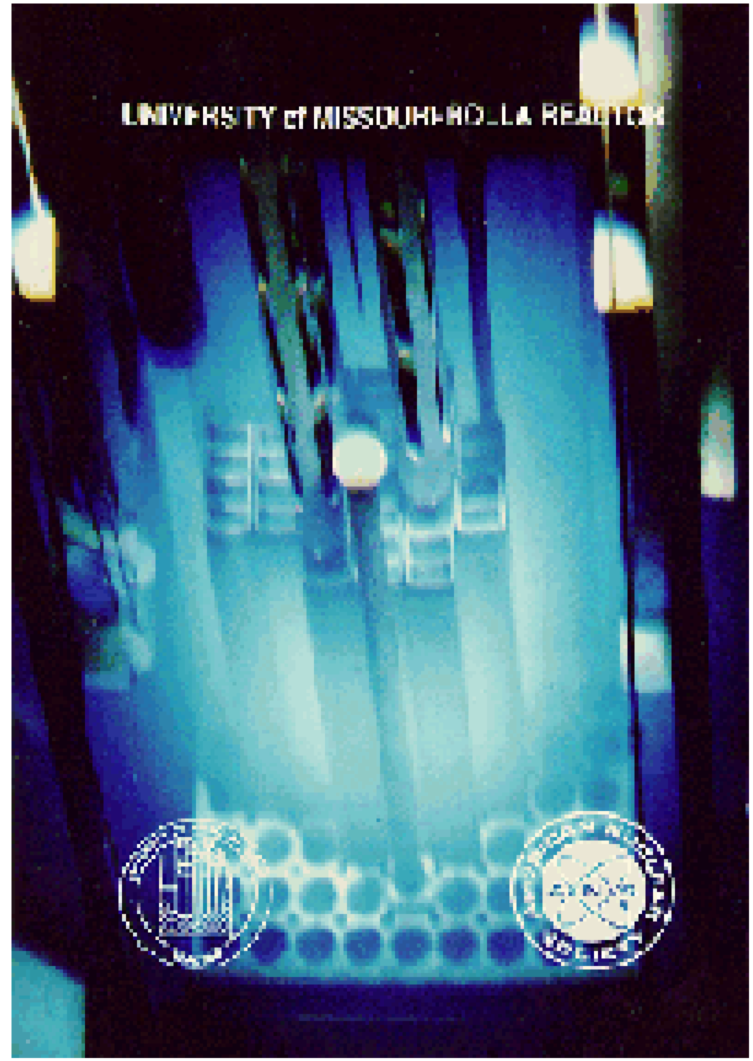
with $\varepsilon(E) =$ Efficiency to detect photons of energy E

$L =$ radiator length

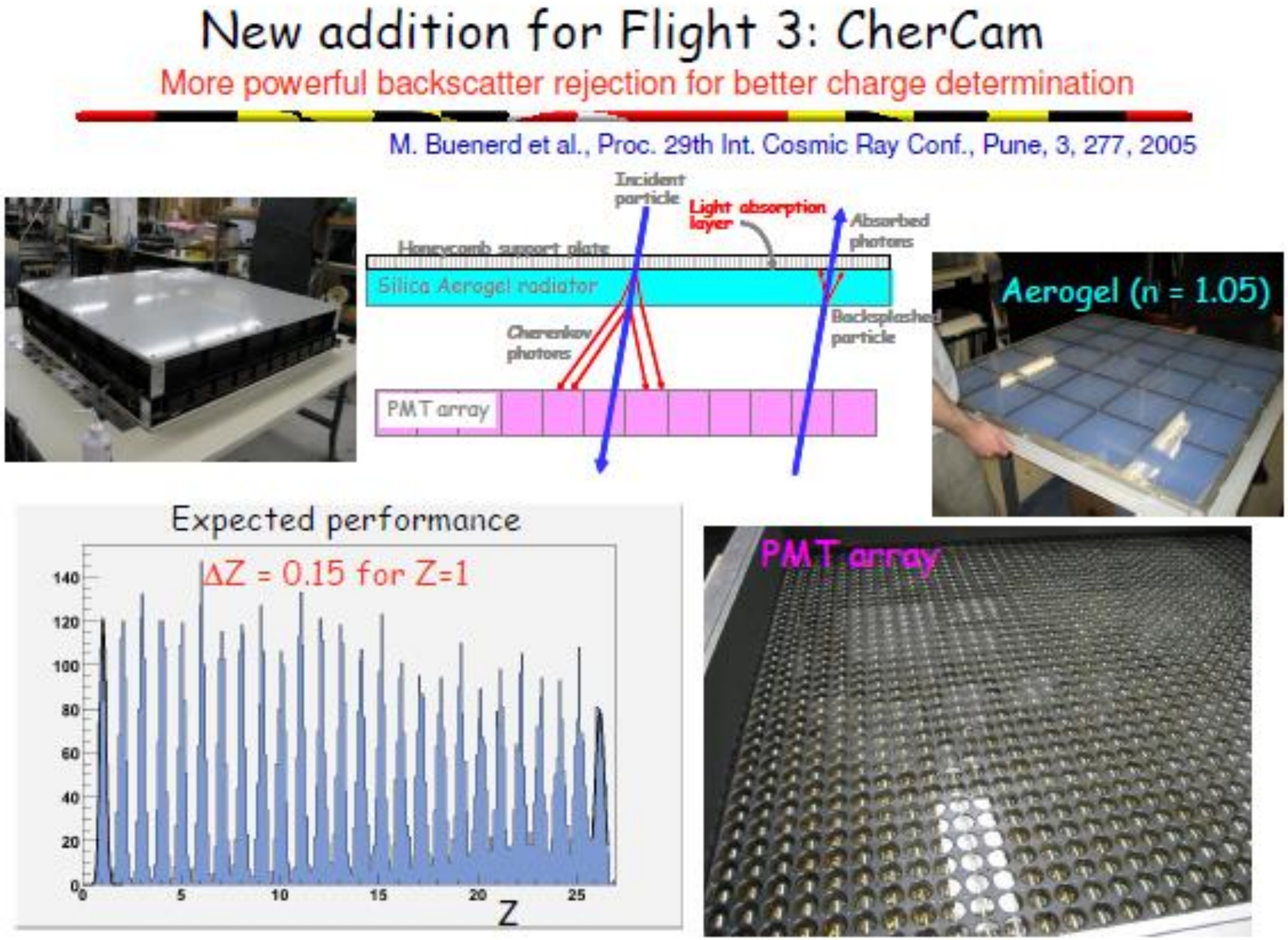
$r_e =$ electron radius

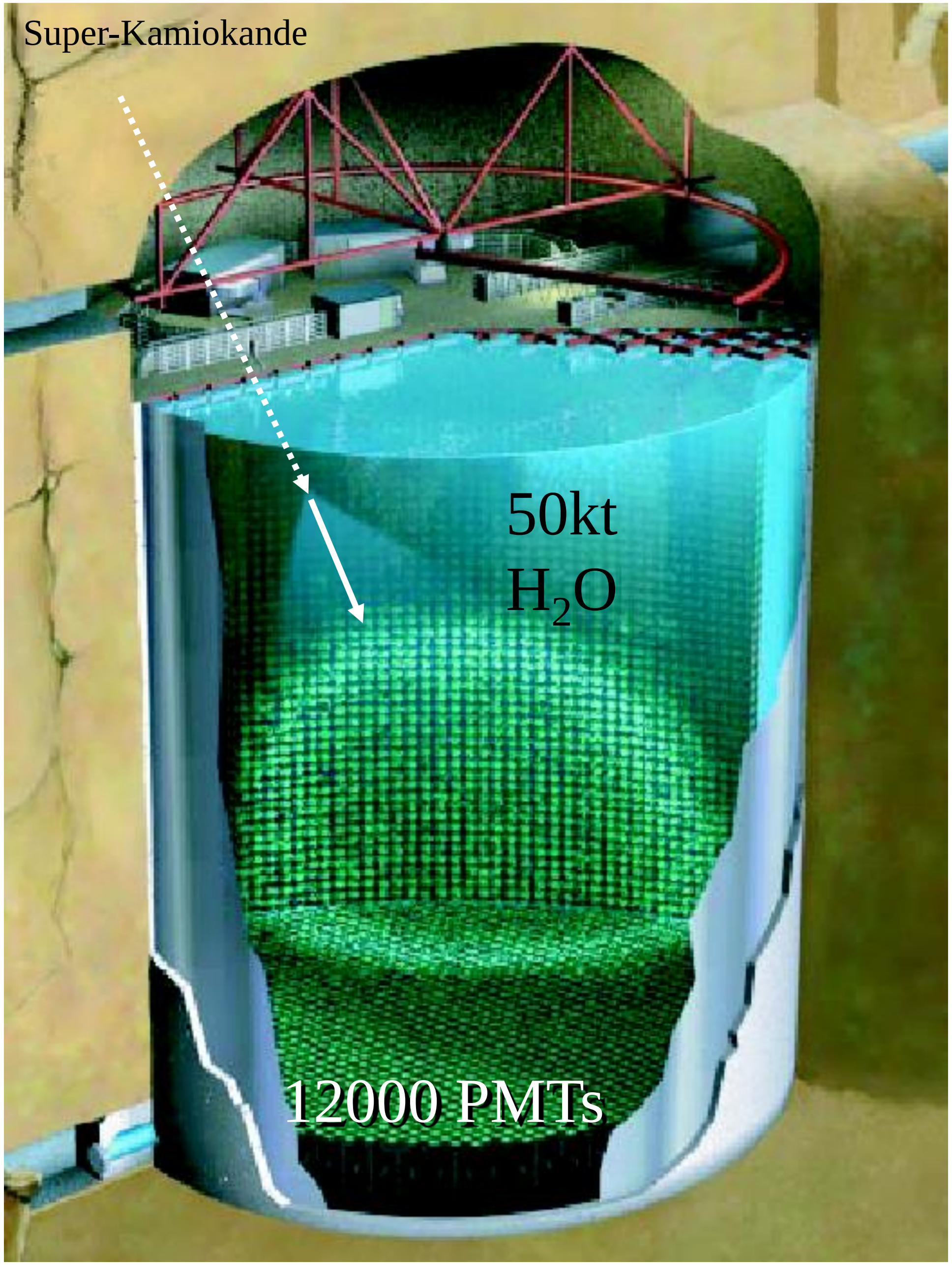
Cerenkov Radiation in Popular Culture…

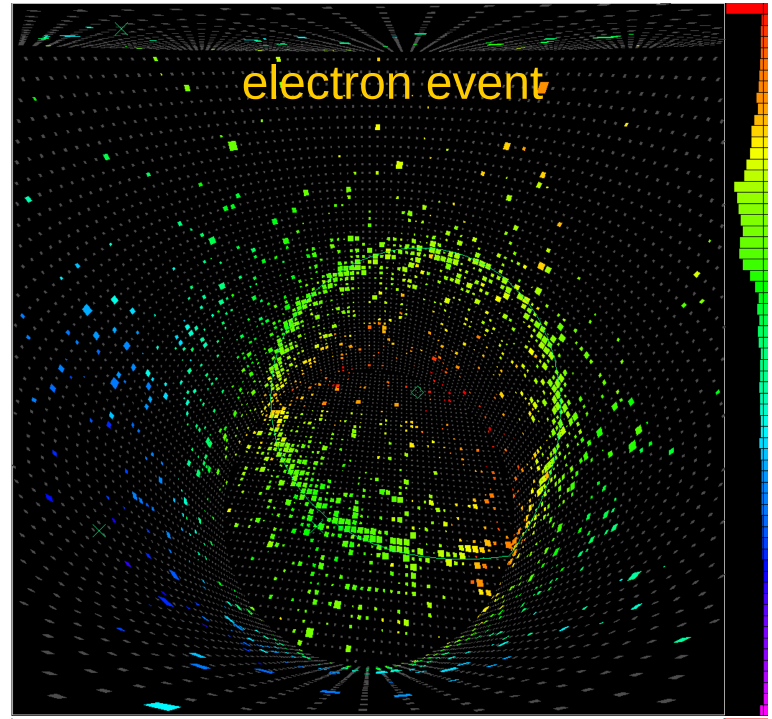
- Picture of Cerenkov radiation from the core of a water-cooled nuclear reactor.
- given off by fast electrons emerging from fission reactions

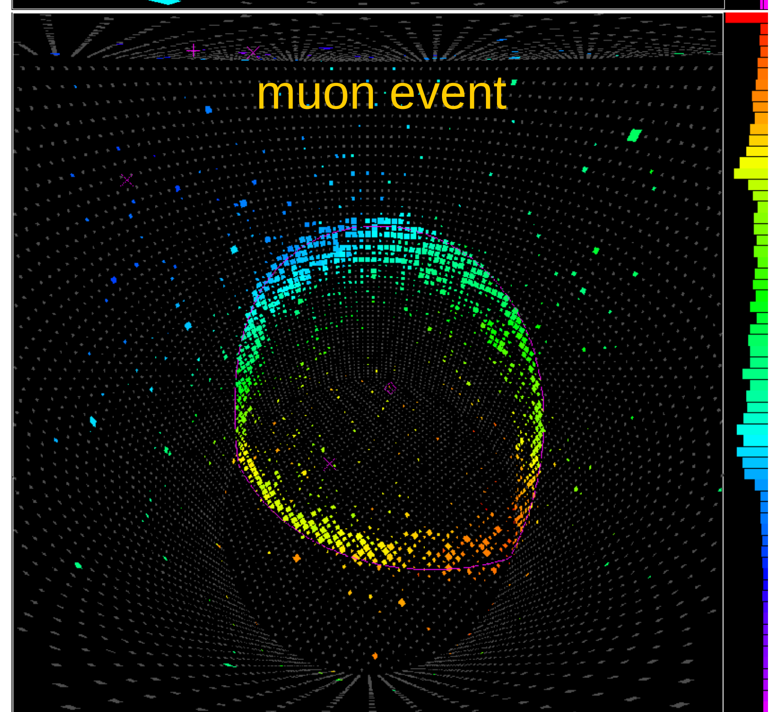


CREAM Cosmic ray experimenet




Super-Kamiokande
50kt
H_2O
12000 PMTs


electron event


muon event

Transition Radiation

- **Transition radiation** is closely related to Cerenkov radiation.
- Occurs when a charged particle crosses the boundary between materials of different refractive indices.

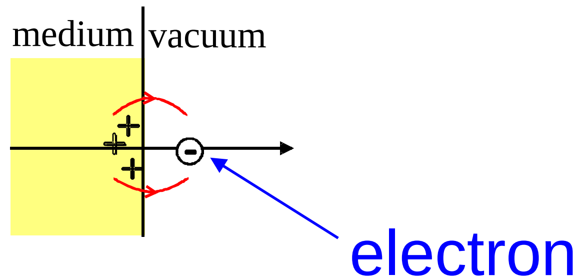
4) Transition radiation

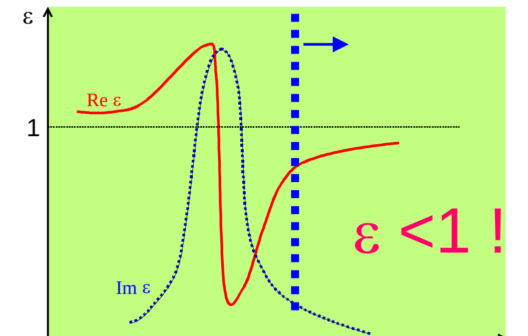
by B. Dolgoshein (NIM A 326 (1993) 434))

TR is electromagnetic radiation emitted when a charged particle traverses a medium with a discontinuous refractive index, e.g. the boundaries between vacuum and a dielectric layer.

TR is also called sub-threshold Cherenkov radiation

A (too) simple picture





regime:	optical	absorptive	X-ray
effect:	Cherenkov radiation	ionisation	transition radiation

A correct relativistic treatment shows that…

(G. Garibian, Sov. Phys. JETP63 (1958) 1079)

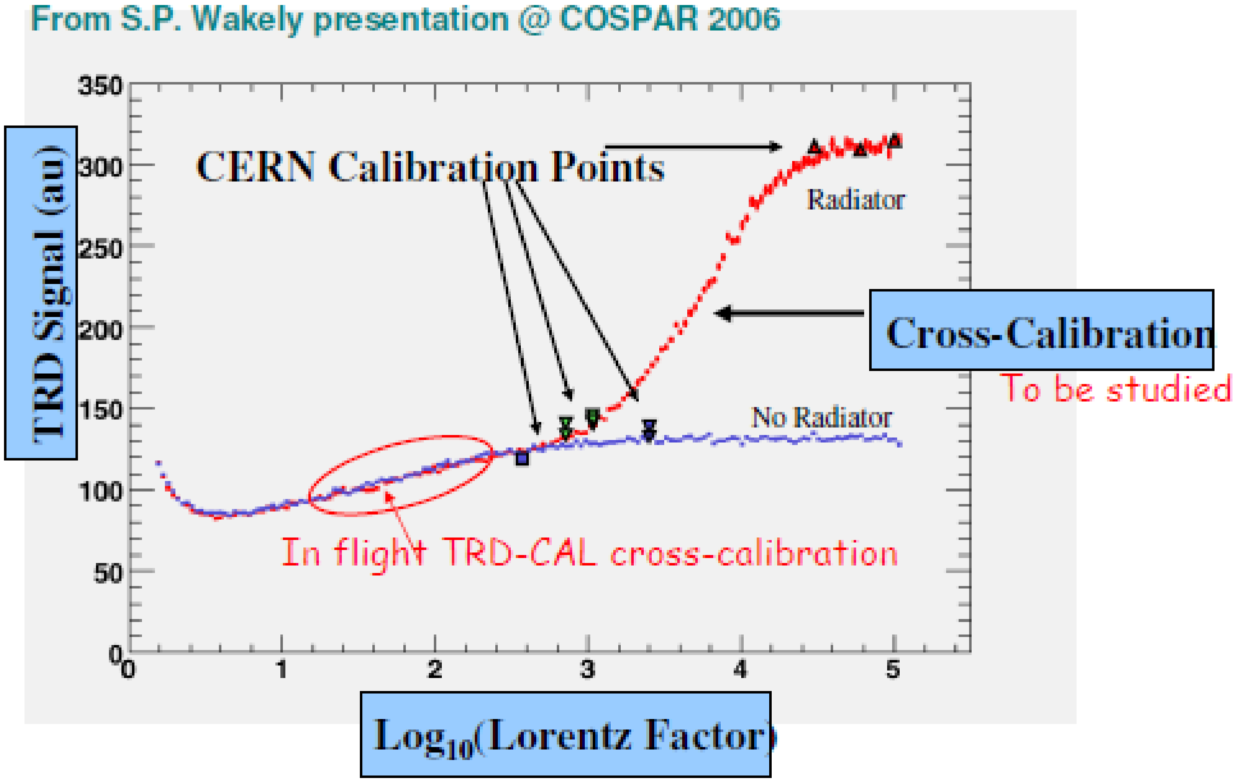
• Radiated energy per medium/vacuum boundary

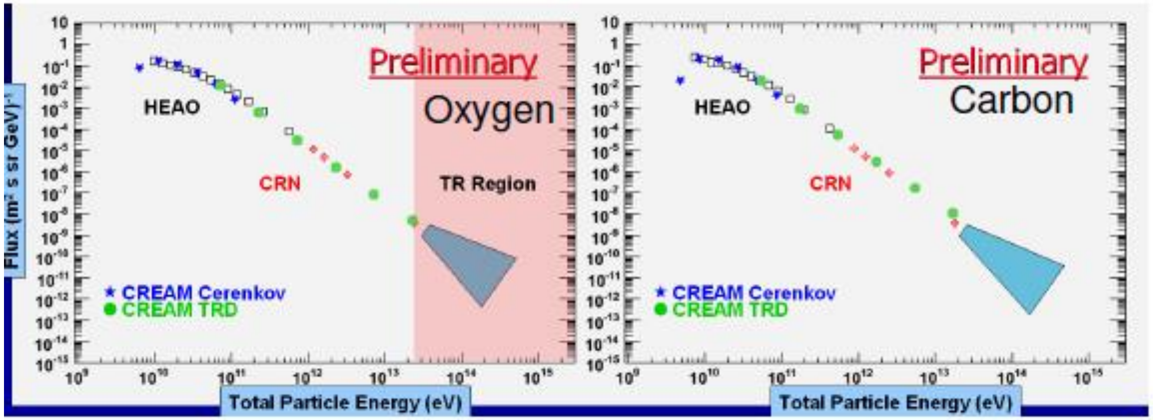
$$W = \frac{1}{3}\alpha\hbar\omega_p\gamma \qquad \boxed{W \propto \gamma} \longrightarrow$$

only high energetic $e^{\pm}$ emit TR of detectable intensity.
→ particle ID

$$\omega_p = \sqrt{\frac{N_e e^2}{\varepsilon_0 m_e}} \quad \left(\begin{array}{c}\text{plasma}\\ \text{frequency}\end{array}\right) \quad \hbar\omega_p \approx 20\text{eV} \ \ (\text{plastic radiators})$$

TRD for CREAM experiment

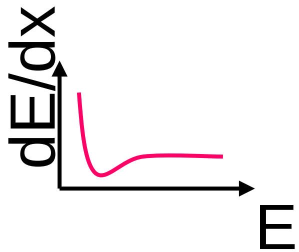




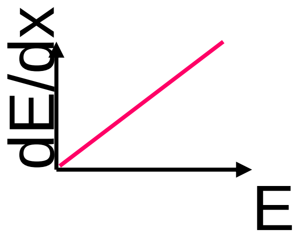
Summary of particle-matter electromagnetic interactions

e^+ / e^-

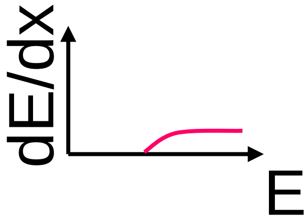
- Ionisation



- Bremsstrahlung

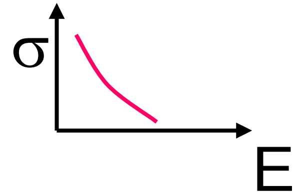


- Cerenkov radiation

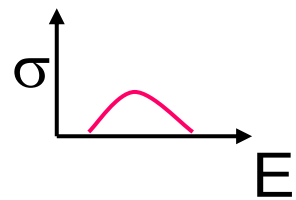


γ

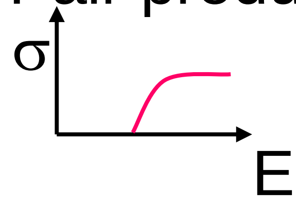
- Photoelectric effect



- Compton effect



- Pair production



5) Neutron interaction with matter

1) Introduction

2) Elastic scattering of neutrons

3) Inelastic scattering of neutrons

4) Neutron capture

6) Spallation reactions, hadron shower

Introduction

Neutron has not electric charge → interaction only by strong nuclear interaction

Magnetic moment of neutron → interaction by electromagnetic interaction, mostly negligible influence

Different energy ranges of neutrons:

Ultracold: E < 10^{-6} eV
Cold and very cold: E = (10^{-6} eV – 0,0005 eV)
Thermal neutrons – (0,002 eV – 0,5 eV) neutrons are in thermal equilibrium with neighborhood, Maxwell distribution of velocities, for 20°C is the most probable velocity v = 2200 m/s → E = 0,0253 eV

Epithermál neutrons and resonance neutrons: E = (0,005 eV – 1000 eV)

Slow neutrons: E < 0,3 eV
Fast neutrons: E = (0,3 eV – 20 MeV)
Neutrons with high energies: E = (20 MeV – 100 MeV)
Relativistic neutrons: 0,1 – 10 GeV
Ultrarelativistic neutrons: E > 10 GeV

Elastic scattering of neutrons

Maximal transferred energy (nonrelativistic case of head-head collision):

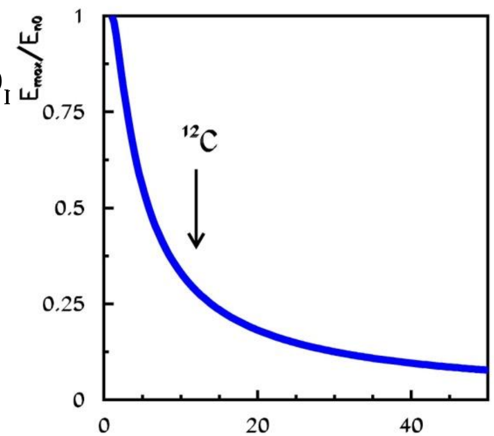
MCL: $p_{n0} = p_A - p_n$ **ECL:** $E_{n0KIN} = E_{AKIN} + E_{nKIN} \Rightarrow p_{n0}^2/2m_n = p_A^2/2m_A + p_n^2/2m_n$

MCL: $p_n^2 = p_A^2 - 2p_A p_{n0} + p_{n0}^2 \Rightarrow \quad m_A p_n^2 = m_A p_A^2 - 2m_A p_A p_{n0} + m_A p_{n0}^2$

ECL: $m_A p_n^2 = - m_n p_A^2 \qquad + m_A p_{n0}^2$

We subtract equation:

$0 = m_A p_A^2 + m_n p_A^2 - 2m_A p_A p_{n0} \Rightarrow m_A p_A + m_n p_A = 2m_A p$



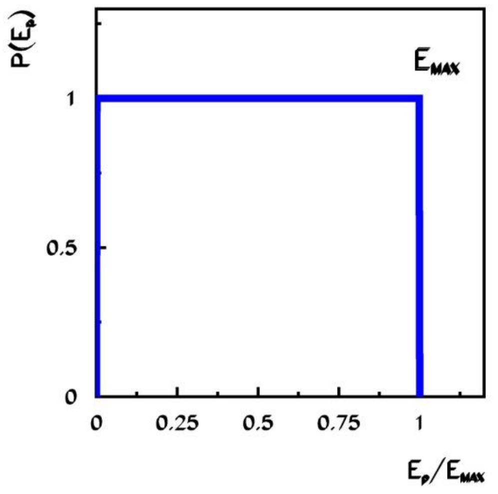
Nucleon number A

The heavier nucleus the lower energy can neutron transferred to it:

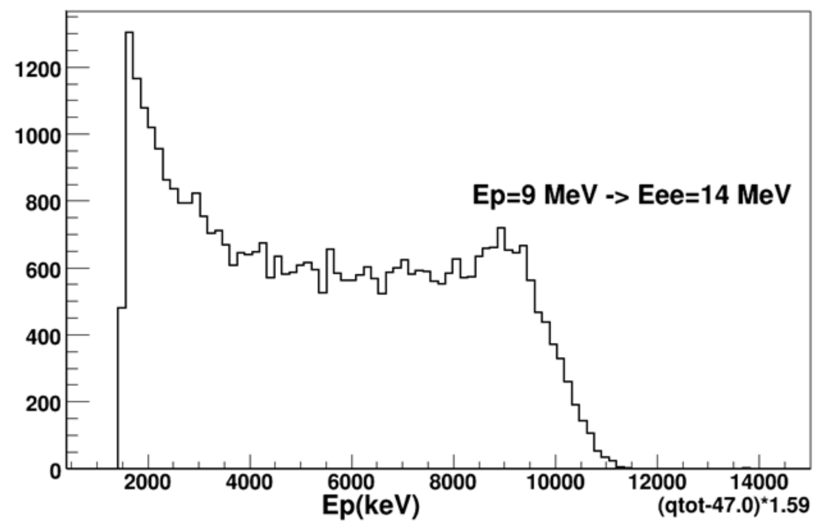
$$p_A = \frac{2m_A p_{n0}}{m_A + m_n} \Rightarrow E_A = \frac{4m_A m_n E_{n0}}{(m_A + m_n)^2} = \frac{4A \cdot E_{n0}}{(A+1)^2}$$

Recoil Energy distribution of Elastic scattering of neutrons

$$P(E_A) = \frac{1}{4}\frac{(1+A)^2}{A}\frac{1}{E_{n0}}$$



Energy distribution of reflected protons for E_{n0} < 10 MeV



14 MeV neutron recoil with H

Inelastic neutron scattering

Competitive process to elastic scattering on nuclei heavier than proton

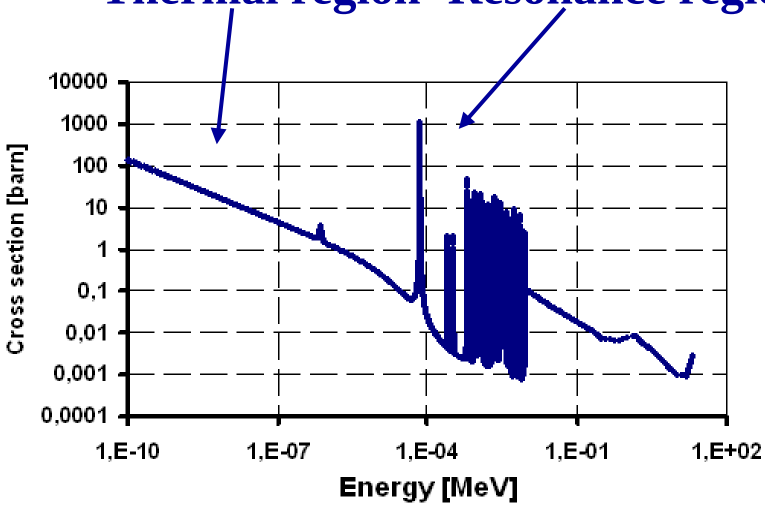
Part of energy is transformed to excitation → accuracy of energy determination is given by their fate

Its proportion increases with increasing energy

Nuclear reactions of neutrons

Thermal region Resonance region

Neutron capture: **(n,γ)**



High values of cross sections for low energy neutrons

Cross section of reaction $^{139}La(n,\gamma)^{140}La$

$^{157}Gd(n,\gamma)$ – for thermal neutrons cross section is biggest σ ~ 255 000 barn

Total 8 MeV gamma+conversion electrons

Reactions (n,d), (n,t), (n,α) ...

Reactions used for detection of low energy neutrons :

(two particle decay of compound nucleus at rest, nonrelativistic approximation)

$$E_N + E_P = Q$$
$$m_N v_N = m_P v_P \longrightarrow \quad \sqrt{2m_N E_N} = \sqrt{2m_P E_P} \to E_N = \frac{m_P}{m_N} E_P \quad \Bigg\} \quad E_P = \frac{m_N}{m_P + m_N} Q$$

$^{10}B(n,\alpha)^{7}Li$ Q = 2,792 and 2,310 MeV, E_α = MeV, E_{Li} = MeV σ_{th} = 3840 b 1/v up to 1 keV

$^{6}Li(n,\alpha)^{3}H$ Q = 4,78 MeV, E_α = 2,05 MeV, E_H = 2,73 MeV σ_{th} = 940 b 1/v up to 10 keV

$^{3}He(n,p)^{3}H$ Q = 0,764 MeV, E_p = 0,573 MeV, E_H = 0,191 MeV σ_{th} = 5330 b 1/v up to 2 keV

Induced fission: (n,f)

Induced by low energy neutrons (thermal): ^{233}U, ^{235}U, ^{239}Pu

Exothermic with very high Q ~ 200 MeV

Induced by fast neutrons: ^{238}U, ^{237}Np, ^{232}Th

Induced by „relativistic“ neutrons: ^{208}Pb

Spallation reactions, hadron shower

Interaction of realativistic and ultrarelativistic neutrons

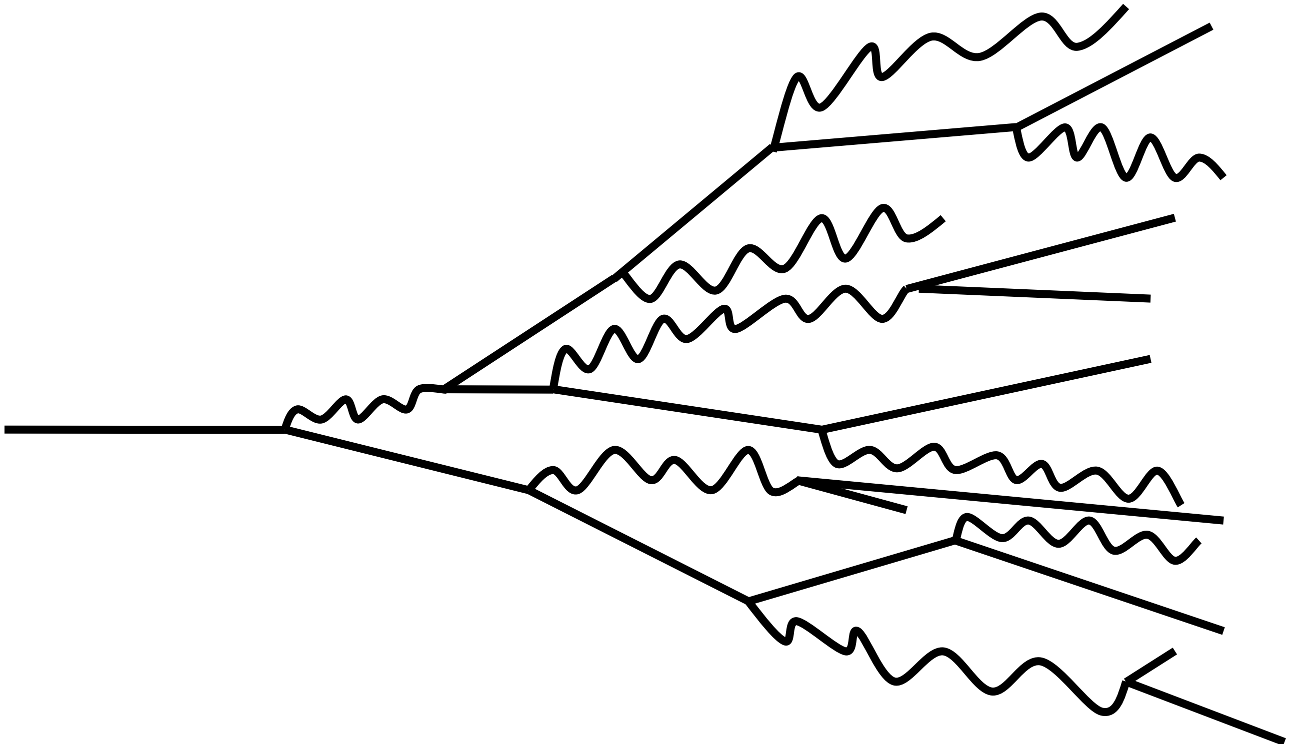
Same behavior as for protons and nuclei

6) Electromagnetic and Hadronic Showers

전자기열량계와 하드론열량계 (EM & Hadron Calorimeters)

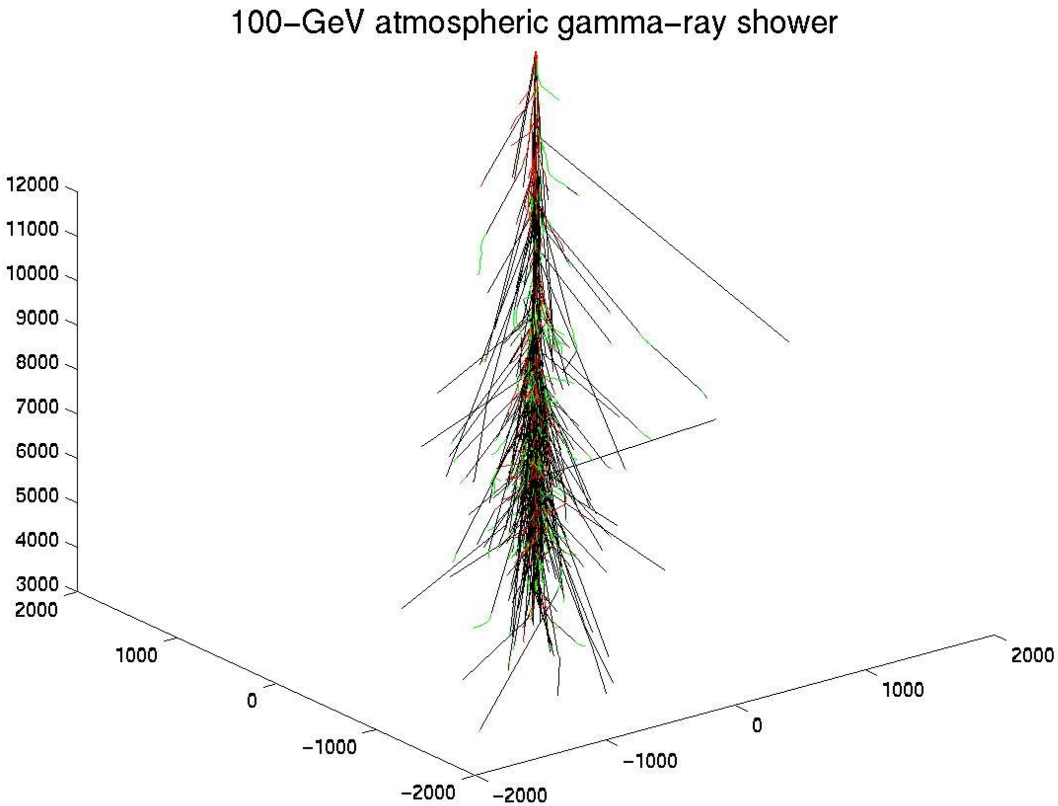
Speaker: Prof. Sehwook Lee (경북대학교)

Electromagnetic Showers

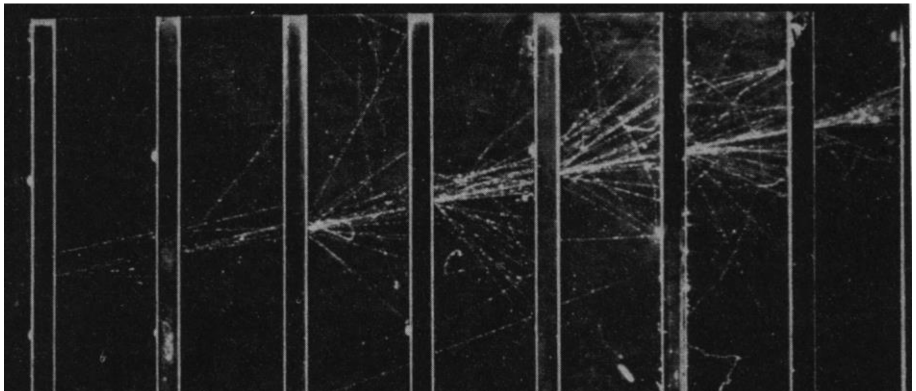


- High energy electron produces photon through bremsstrahlung
- Photon produces $e^+ e^-$ through pair production

Example of E&M Shower at High Energy



Primary photon can convert into $e^+ e^-$-pair; electron and positron generate bremsstrahlung photons which produce pairs in their turns. The shower develops until the energies of photons become less than necessary to create pairs.



Electron shower in a cloud chamber with lead absorbers

Hadronic Showers

- High-energy **hadrons** give **hadronic showers**.
- Hadron interacts with nucleus by the **strong** interaction.
- Number of particles produced in each collision $\propto \ln(E)$
- Length scale :

$$\lambda_I = \frac{1}{n\sigma_I} = \frac{A}{\rho N_A \sigma_I}$$

-
  - σ_I is nuclear cross-section for strong interaction
  - λ_I = hadronic **interaction length**

Hardronic shower

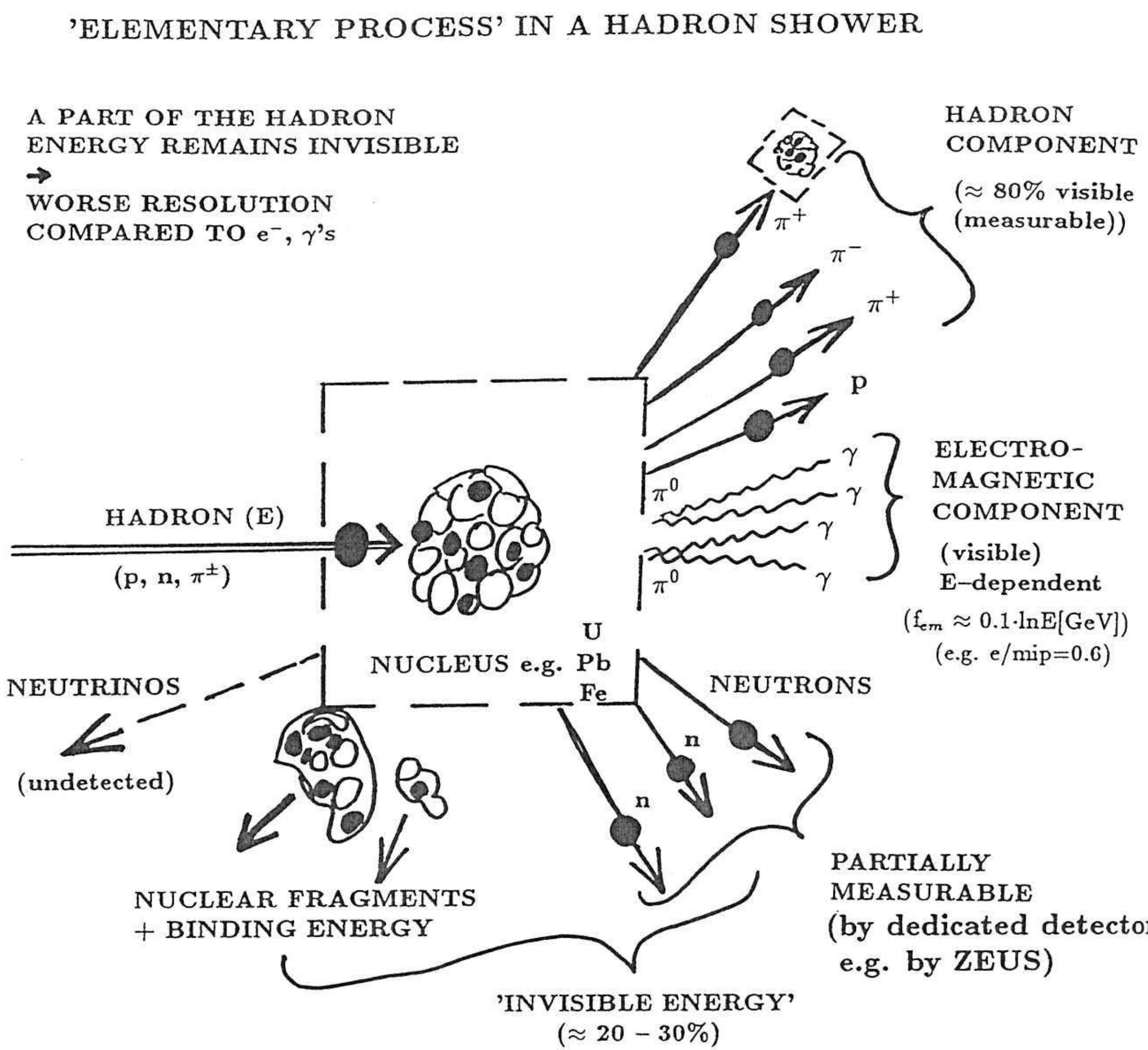
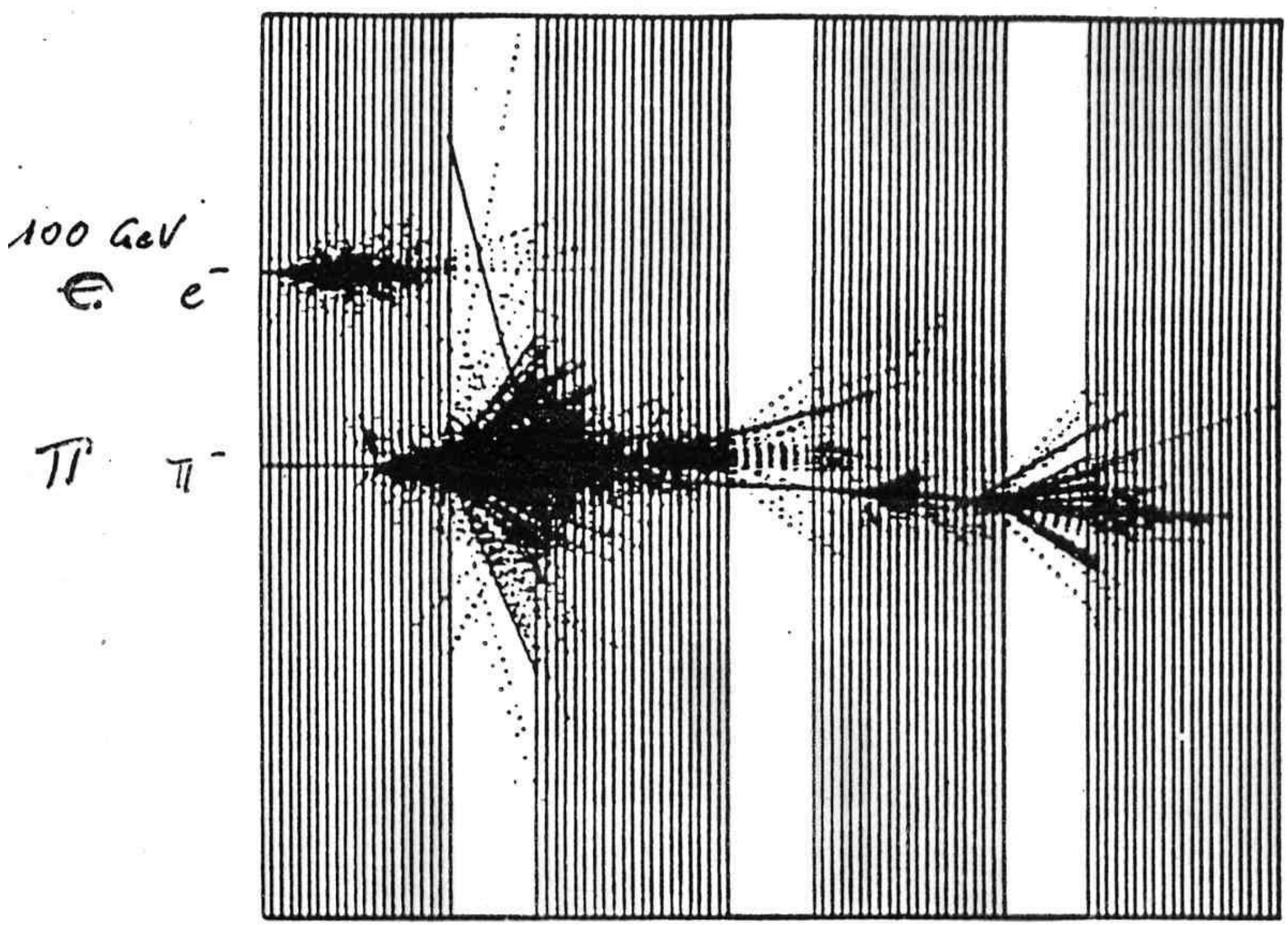
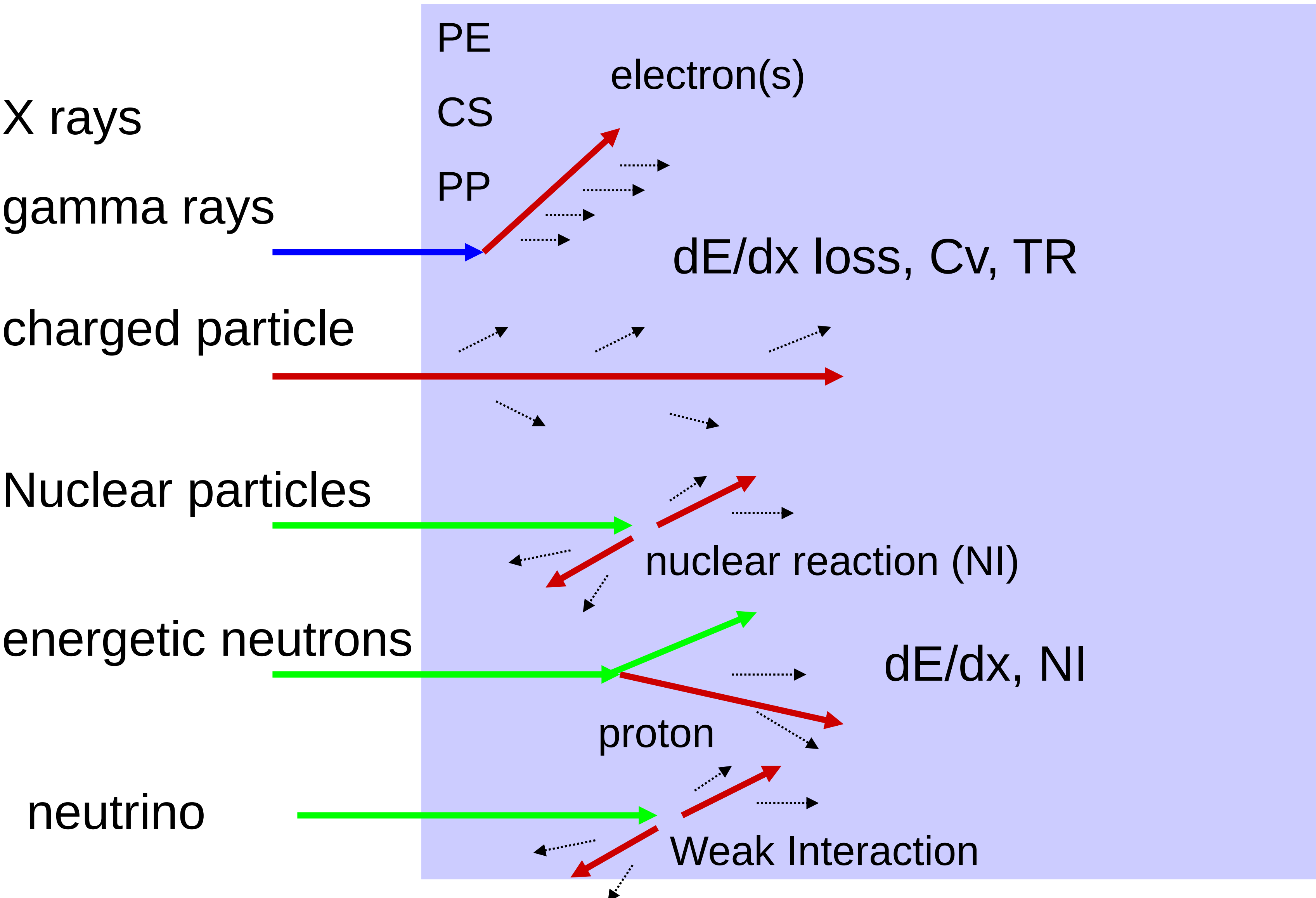


Fig. 3.6 'Elementary physical process' in a hadron shower.

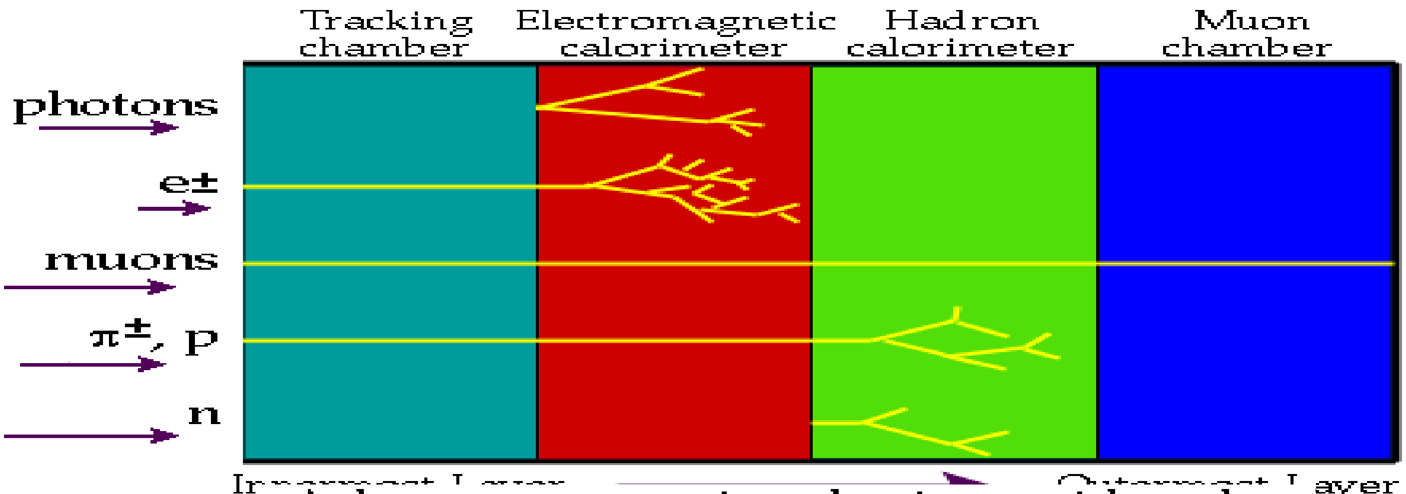
e/p separation



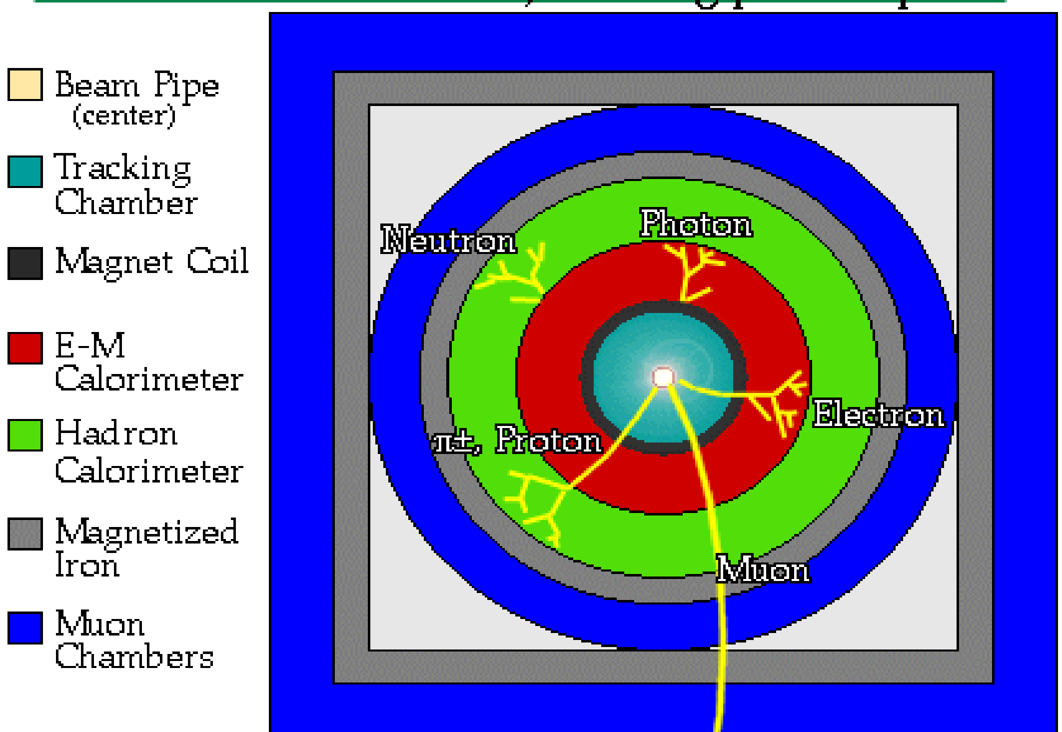
Particle energy loss in matter



Identifying particles

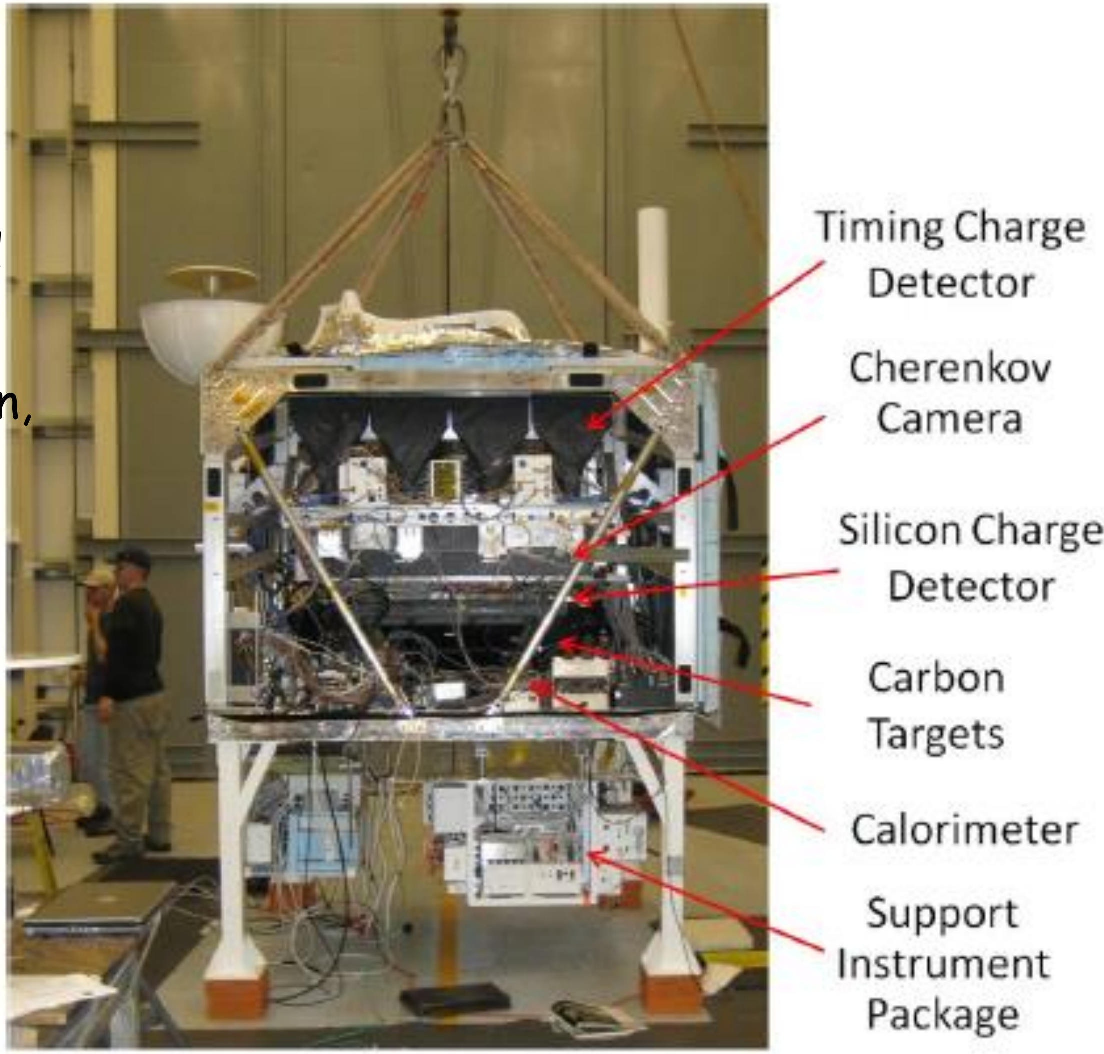


A detector cross-section, showing particle paths

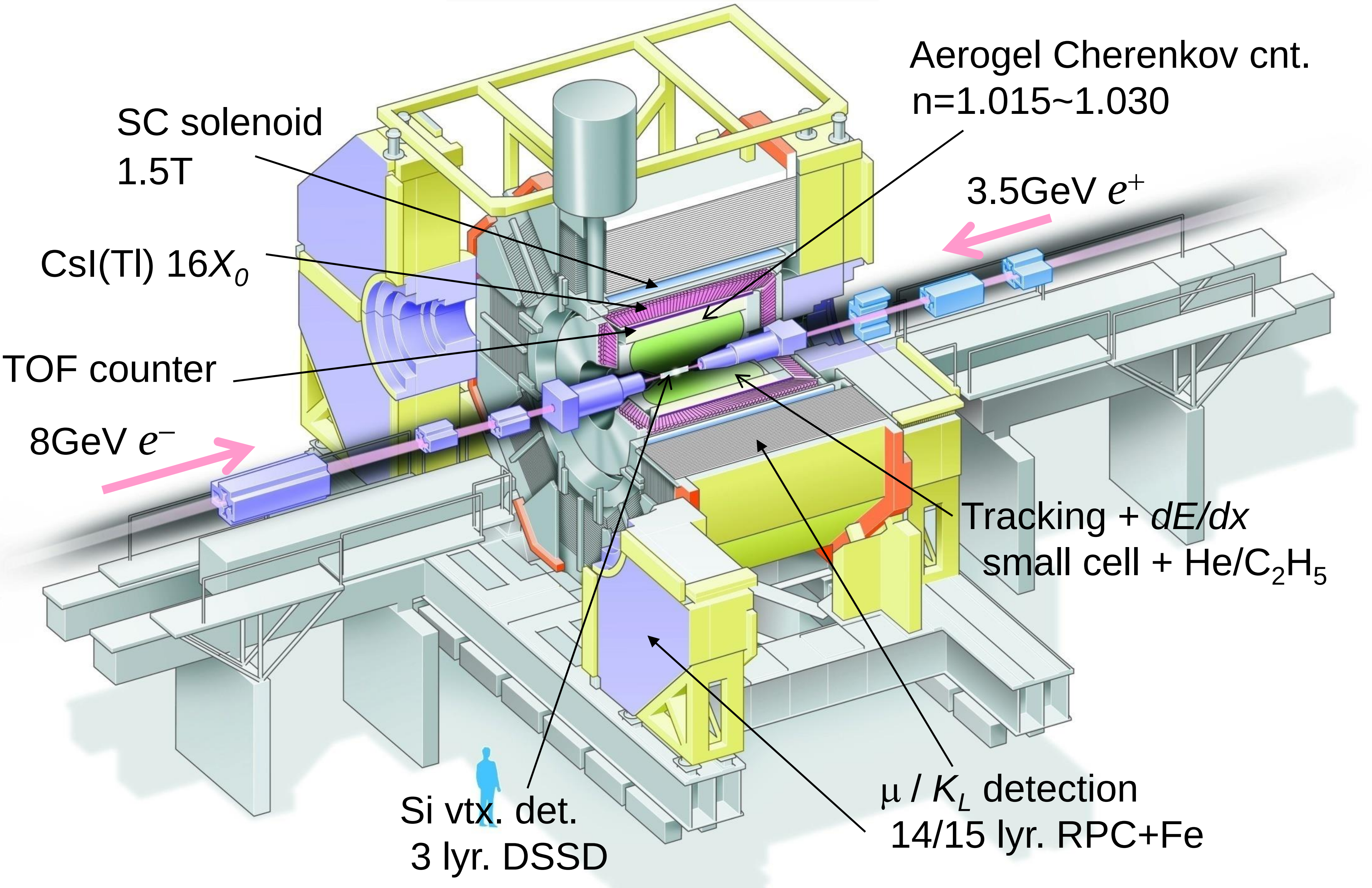


Cosmic Ray Energetics And Mass (CREAM)

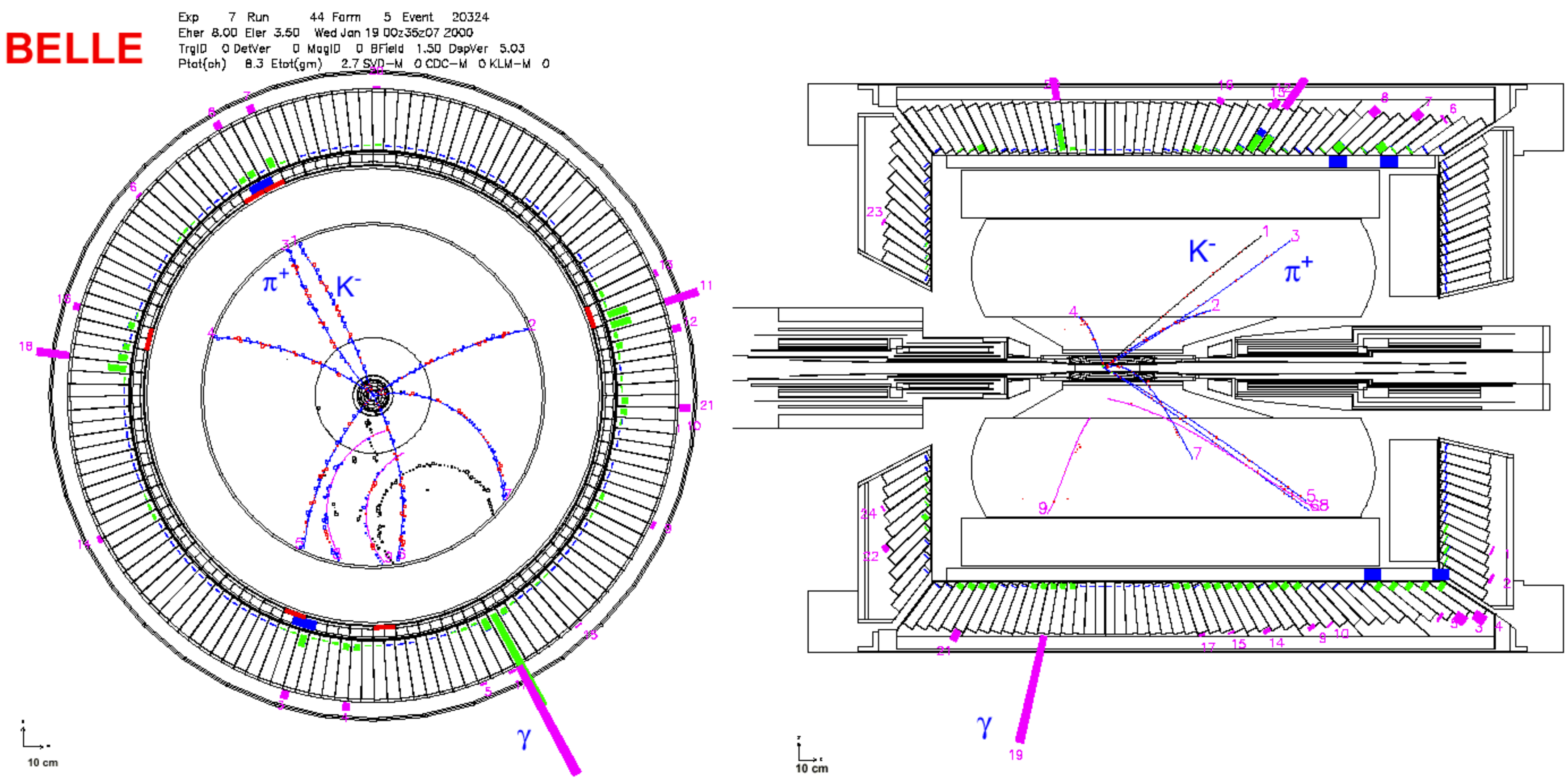
- To extend direct measurements of elemental spectra to the highest energy practical with balloon experiments
- To have enough overlap with ground based indirect measurements
- To understand whether/how the "knee" is related to the acceleration, propagation and confinement



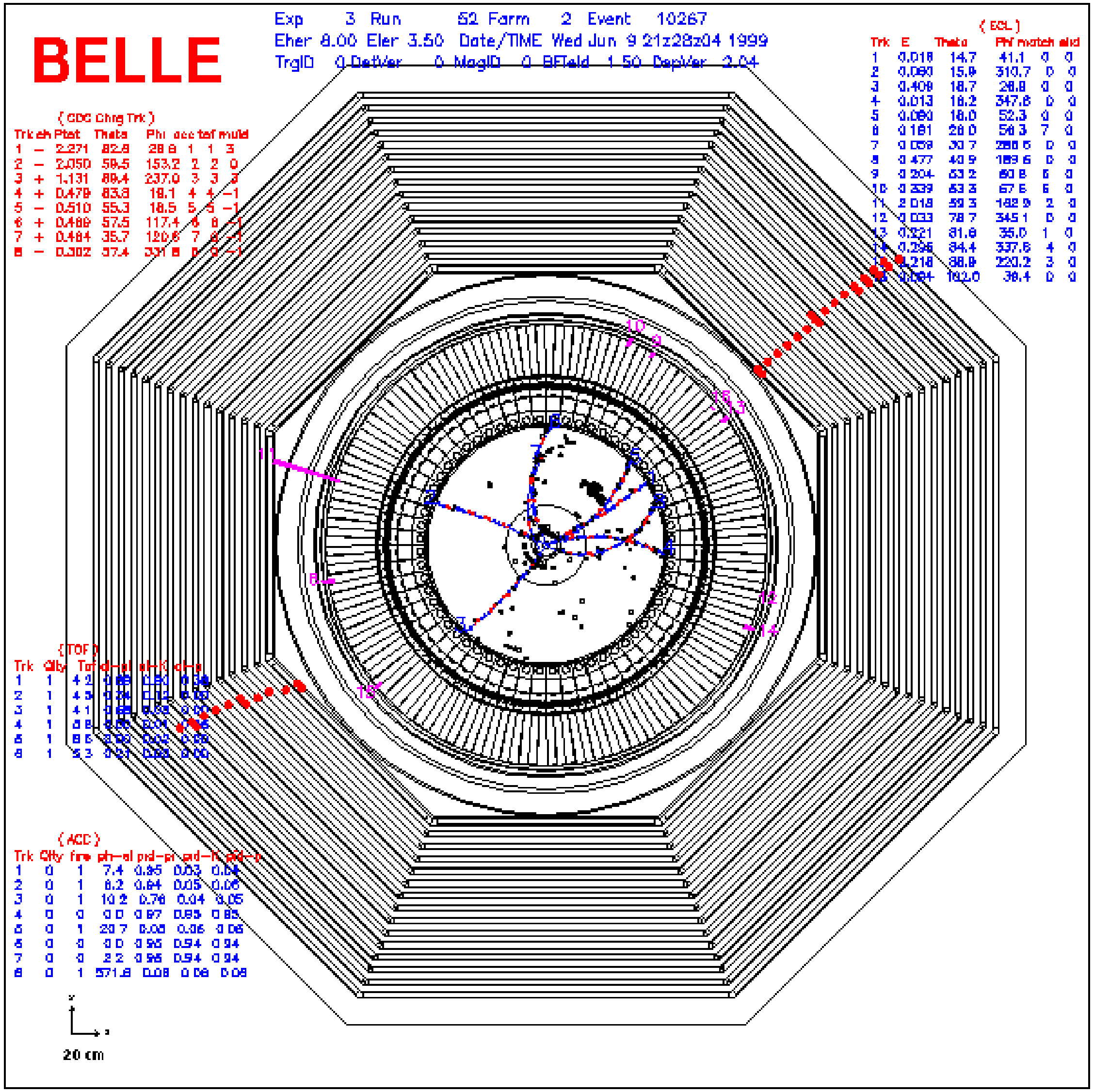
Belle Detector



$B \to K^* \gamma$ Candidate at Belle



We observed a dimuon event



- $J/\psi \rightarrow \mu\mu$
  - $M(\mu\mu) = 3.1$ GeV
  - both muons tracks clearly evident in magnet return yoke

This events is *consistent* with

$$B \rightarrow J/\Psi\, K_L$$

although there were no hits in the RPCs