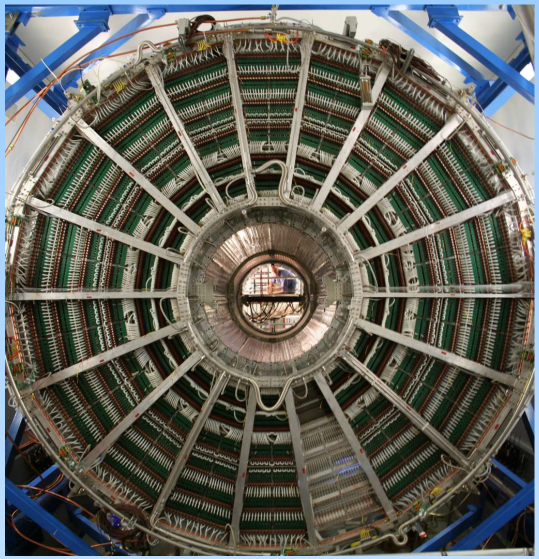
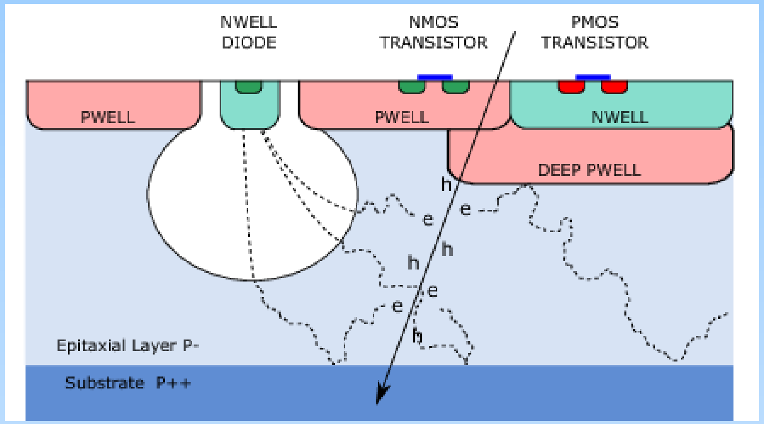




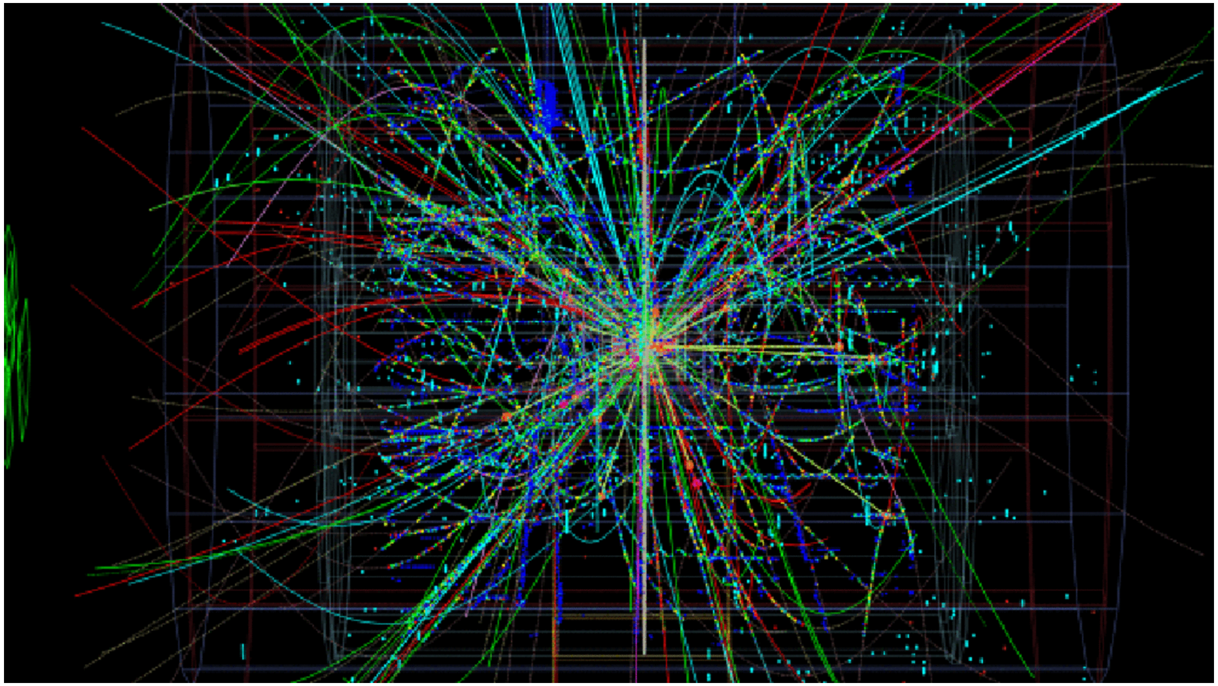
Detectors for particle tracking and identification

Silvia Masciocchi
GSI Darmstadt and University of Heidelberg

39th Heidelberg Physics Graduate Days, HGSFP
Heidelberg
October 9, 2017

Why particle detectors?

An essential tool to look at the small and the “invisible”



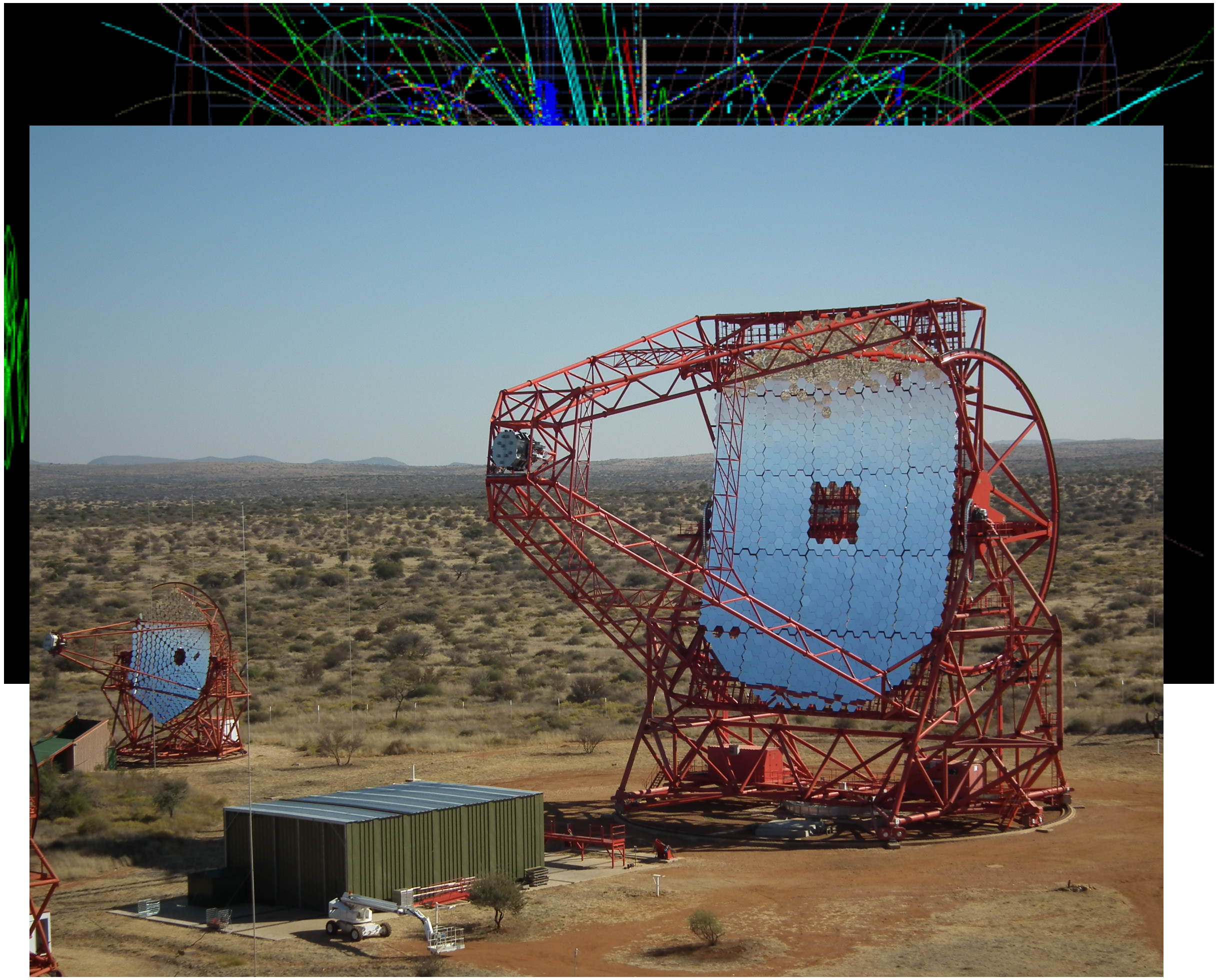
Particles produced in a collision at the LHC

From fundamental research:

- Particle collisions at accelerators

Why particle detectors?

An essential tool to look at the small and the "invisible"



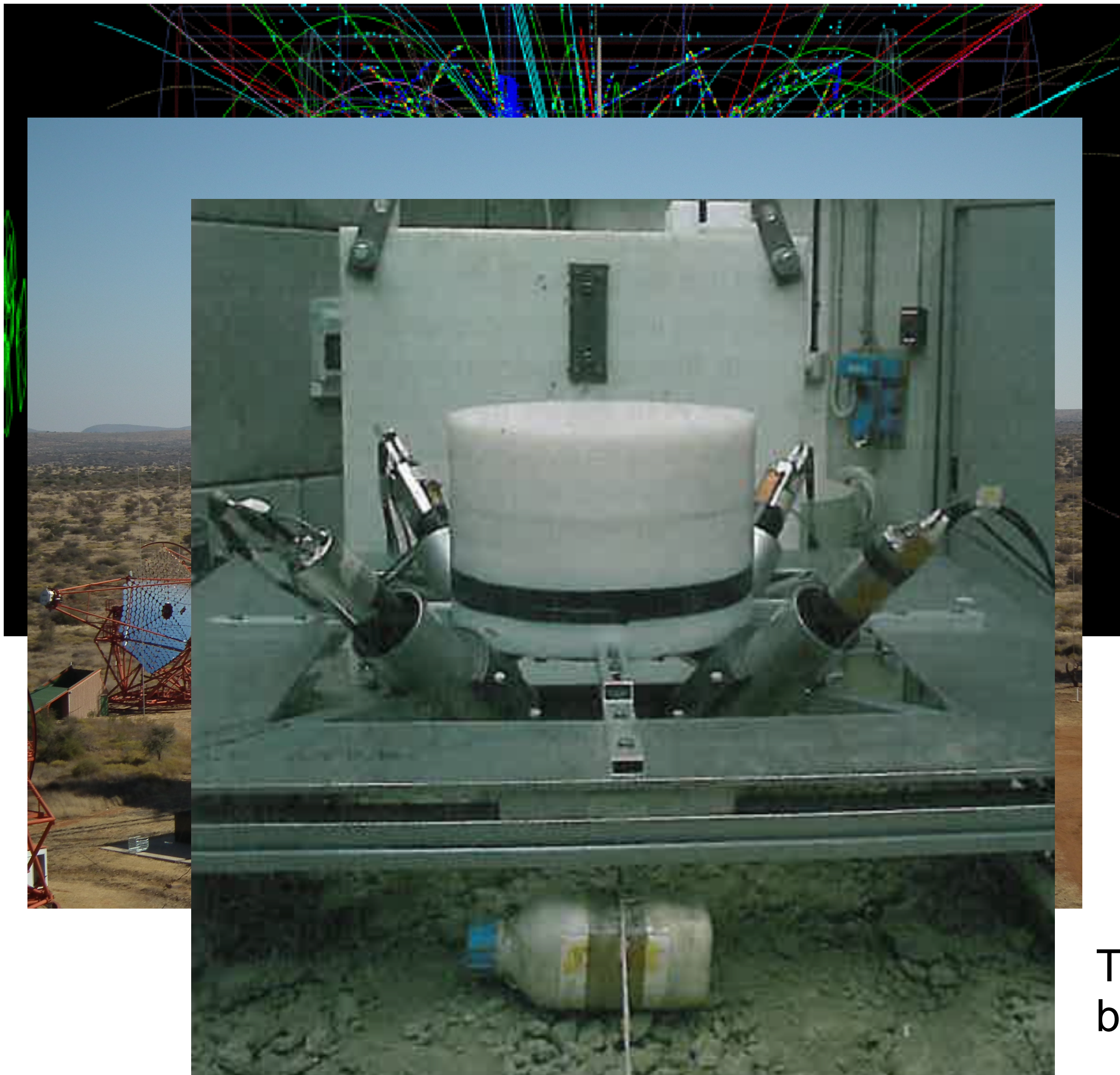
High Energy Stereoscopic System
HESS telescope in Namibia

From fundamental research:

- Particle collisions at accelerators
- Telescopes for gamma-ray astrophysics

Why particle detectors?

An essential tool to look at the small and the “invisible”



From fundamental research:

- Particle collisions at accelerators
- Telescopes for gamma-ray astrophysics

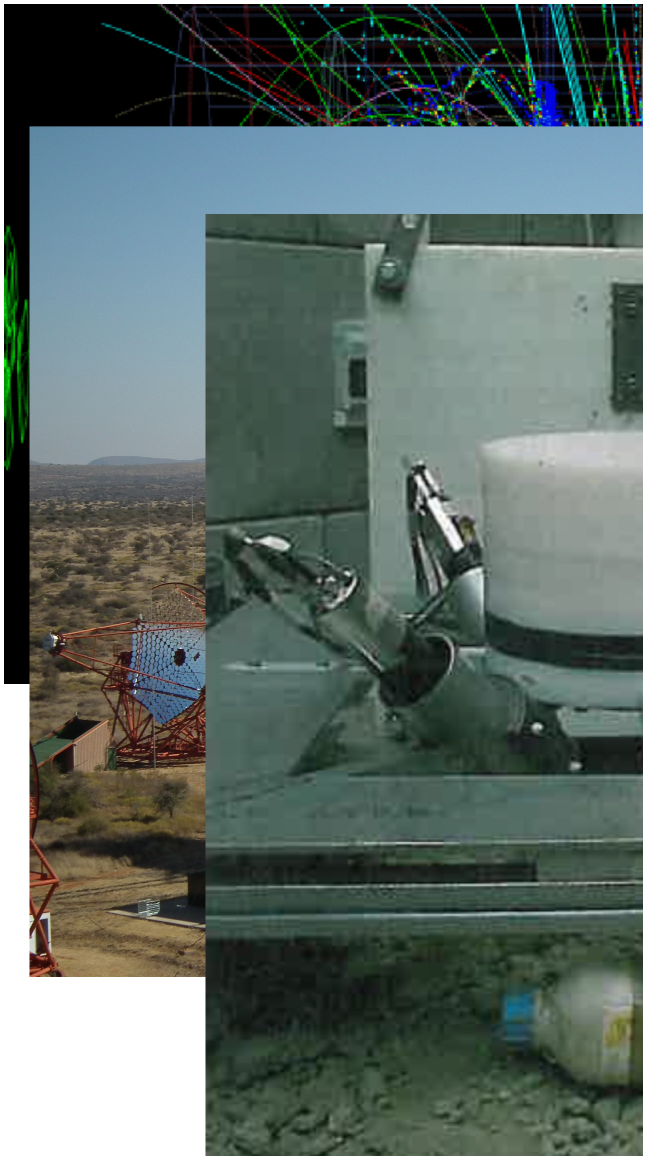
To applications:

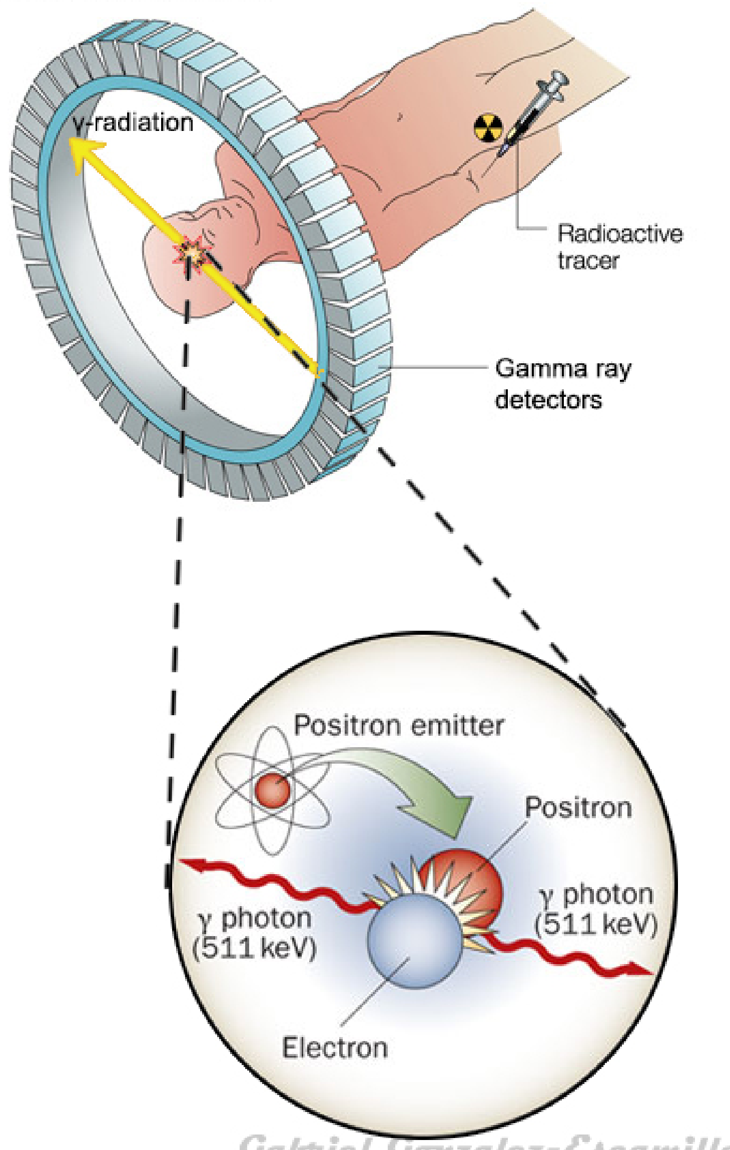
- Security: dirty bombs detection

Thermal neutron sensor to detect bomb remnants and explosives

Why particle detectors?

An essential tool to look at the small and the “invisible”





From fundamental research:

- Particle collisions at accelerators
- Telescopes for gamma-ray astrophysics

To applications:

- Security: dirty bombs detection
- Medical imaging: Positron-Electron Tomography (PET)

Research in physics

Curiosity, questions
Structure of matter?
Fundamental interactions?
Origin of universe?

Theory

Experiments, accelerators

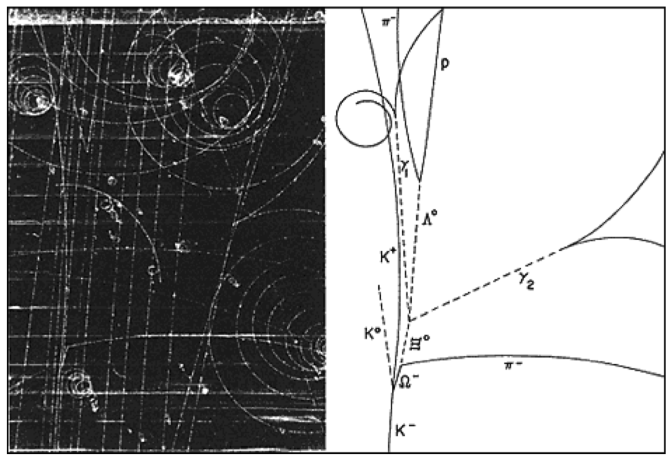
DETECTORS

Data analysis
(statistical treatment, etc.)

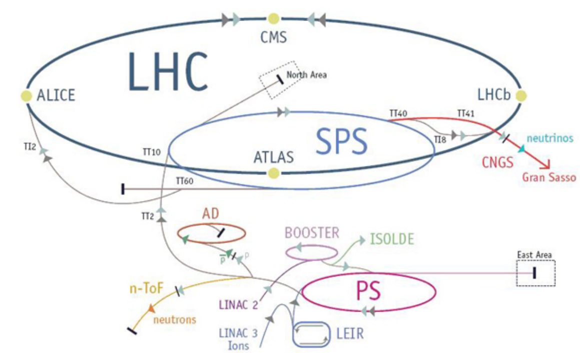
Nuclear and particle physics

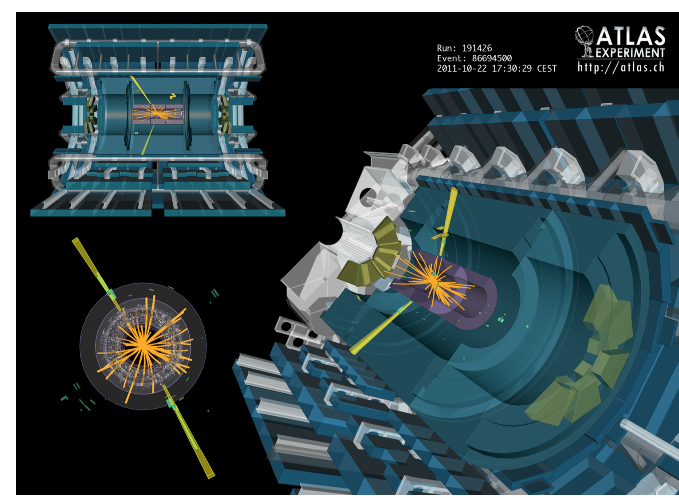
Progress has been:

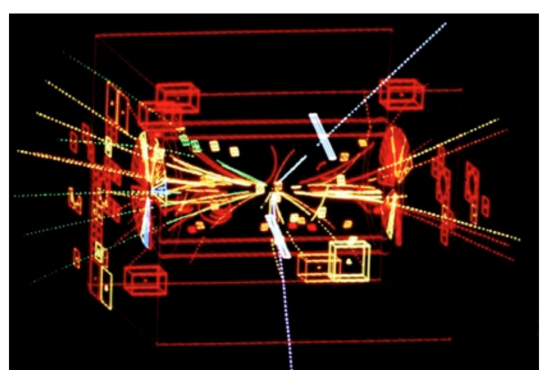
- mostly driven by experimental observations
- critically coupled with the development of new methods in particle acceleration and particle detection



first Ω⁻ event seen in the 80” bubble chamber at the BNL Alternating Gradient Synchrotron

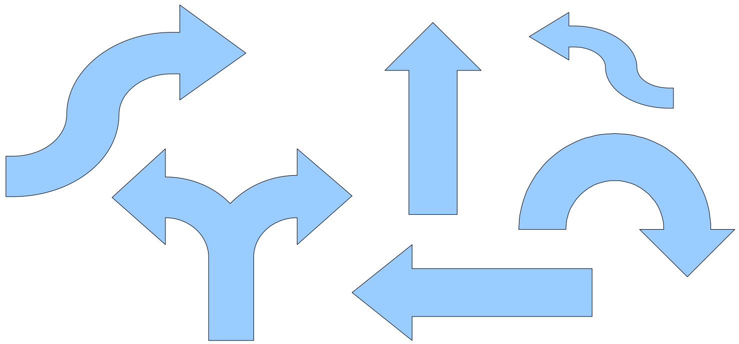






$Z^0 \rightarrow e^+e^-$ in UA1

Nuclear and particle physics

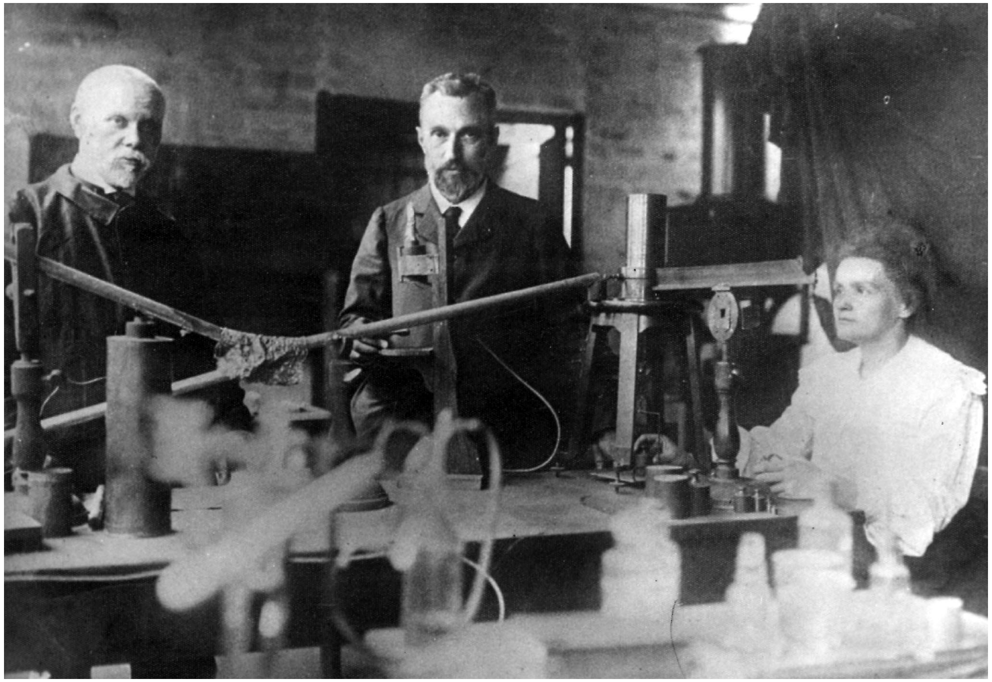


- Accidental observation brings to a physics discovery
  Example: radioactivity
- Some instruments have been developed as tools to support the work of the physicist
  Example: Geiger counter
- Large scale experiments at accelerators were built to prove expectations from a theory

Discovery of radioactivity

1896: first detection of natural radioactivity (α and β decays)

Henri Becquerel (mineralogist), Marie and Pierre Curie, Paris

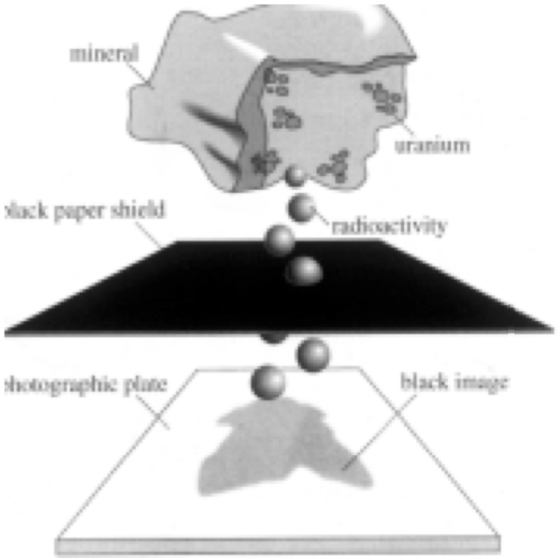


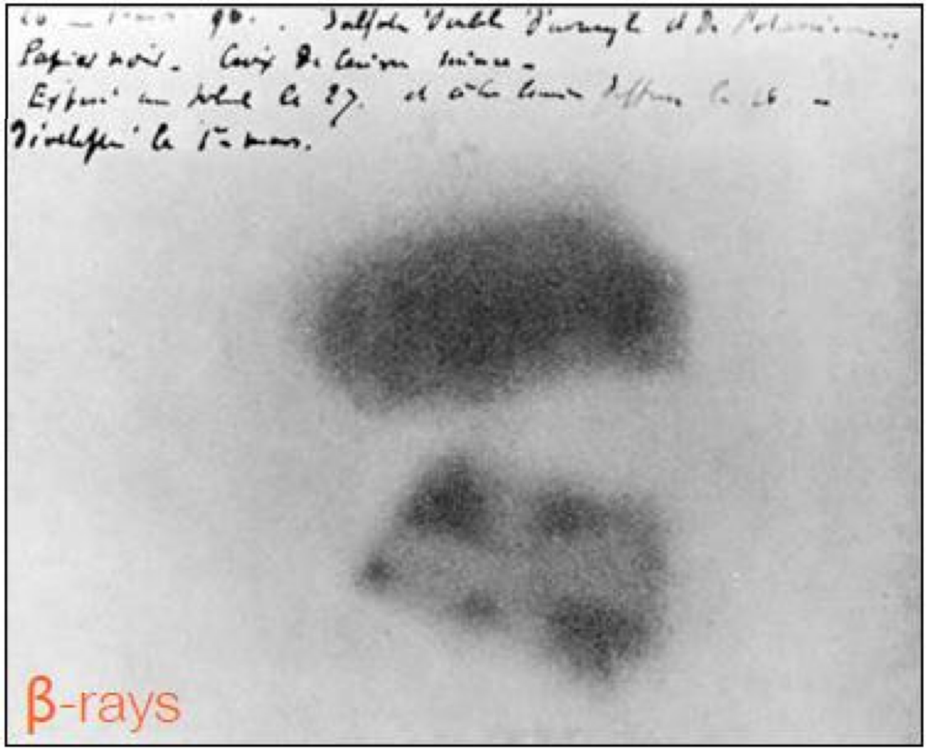
Becquerel's (wrong) assumption: minerals made phosphorescent by visible light might emit x-rays. Wrap a photographic plate in black paper, place a phosphorescent uranium mineral on top of it and expose to sun.

Accidental discovery in February 1896 (bad weather)

Discovery of radioactivity

1896





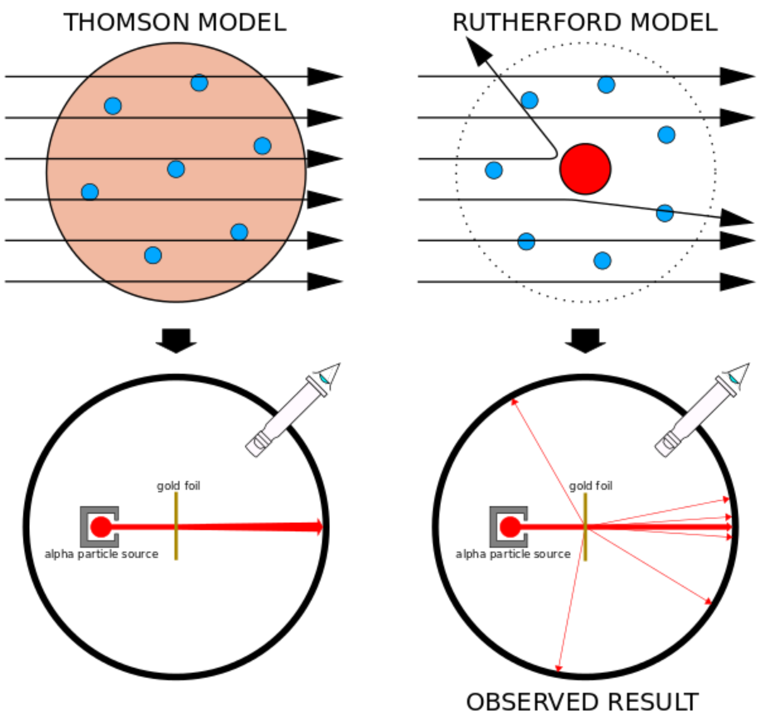
Becquerel: photographic plate which was exposed to radiation from a uranium salt. Radiation resulted to be **charged.**

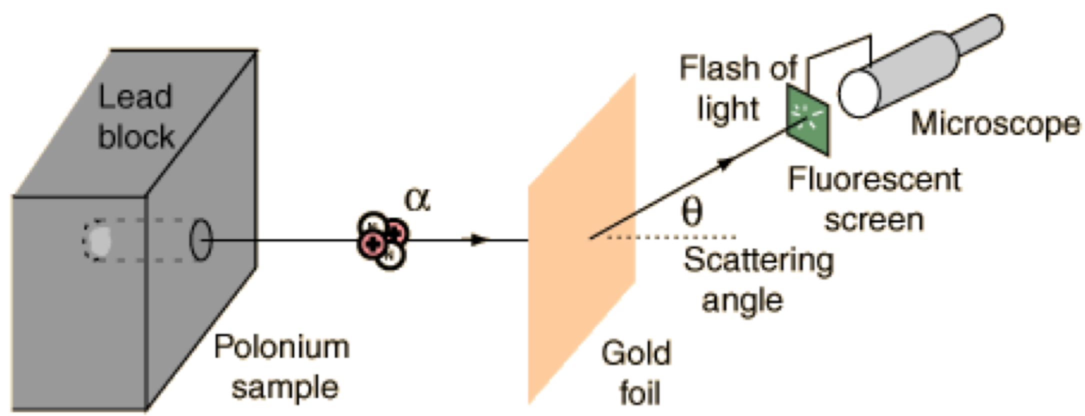
Soon after Marie and Pierre Curie identified other radioactive materials: Polonium, Radium, Thorium

Nobel prize physics 1903

Rutherford scattering

1911: Rutherford (University of Manchester)
with Geiger (visiting) and Marsden (undergraduate student)
discover the atomic nucleus





Schematic view of Rutherford's scattering experiment

Rutherford scattering

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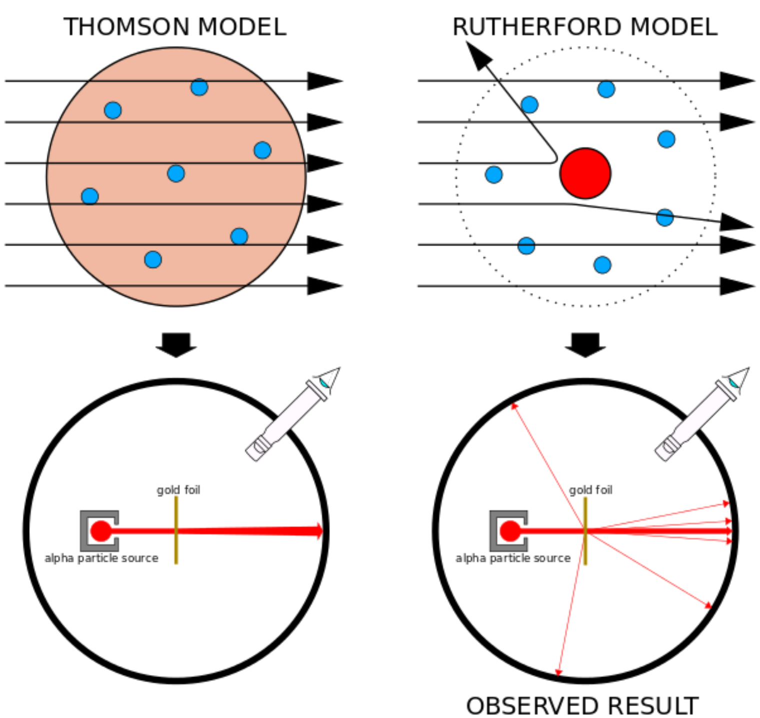
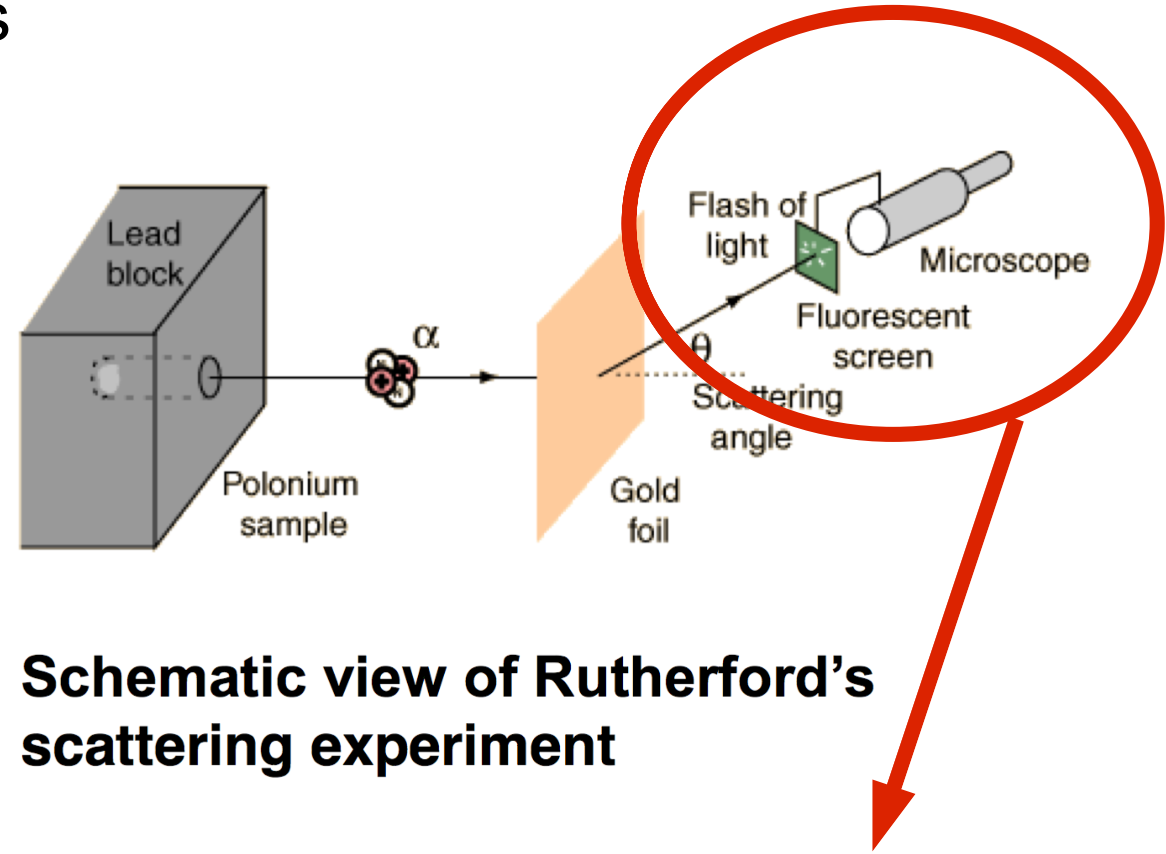


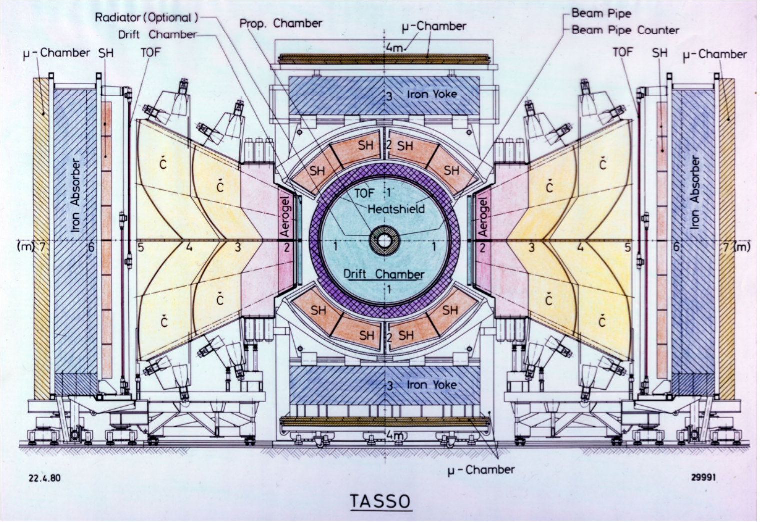


Schematic view of Rutherford's scattering experiment

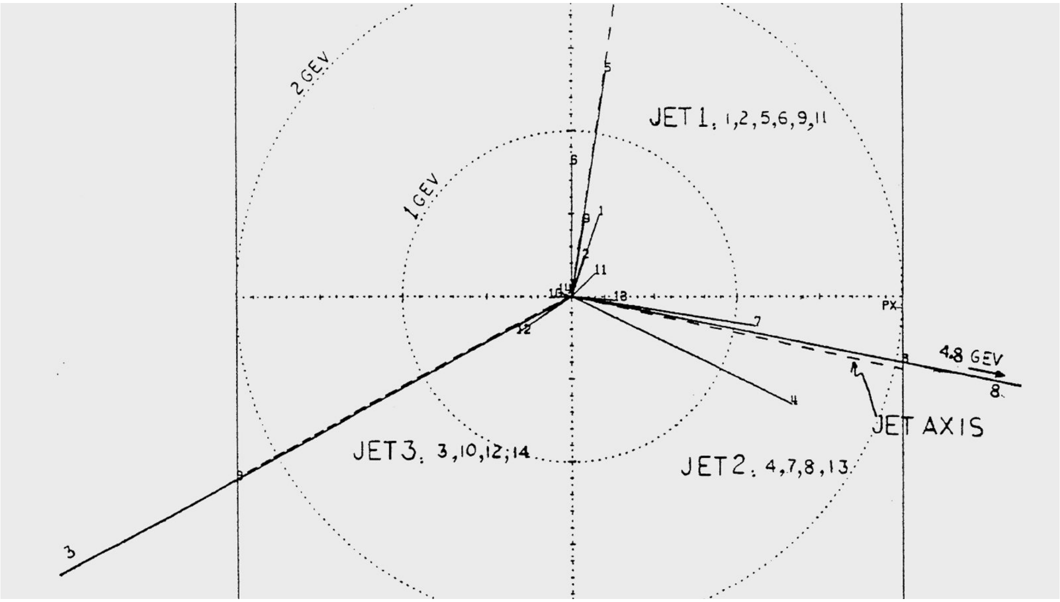
Geiger counter developed to measure α particles

TASSO experiment at DESY (1979)

- Theory of the strong interaction
- PETRA collider: e^+e^- at $\sqrt{s}$ = **27.4 GeV**
- TASSO experiment: large drift chamber



- Planar 3-jet event



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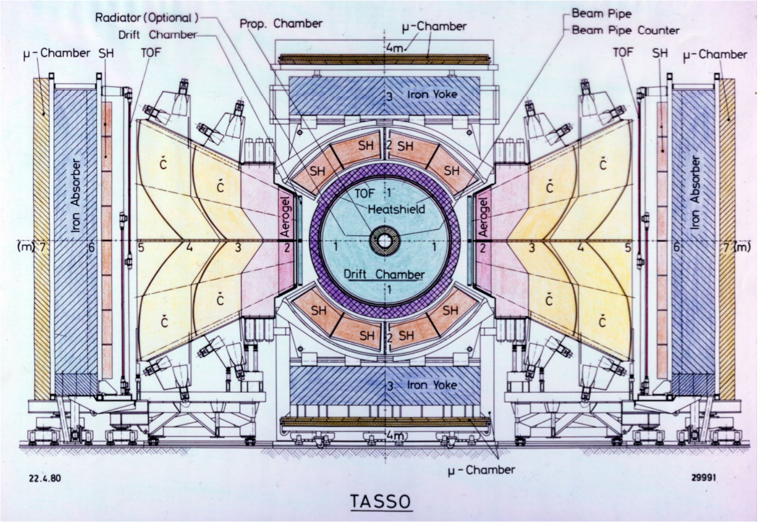

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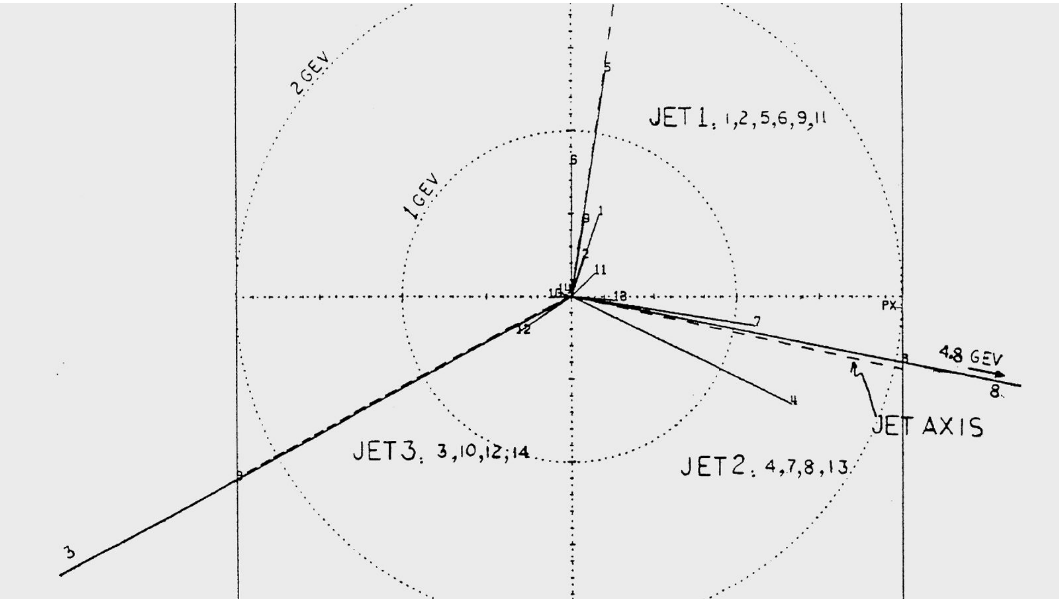


Discovery of the gluon

This course

1. **Interaction of particles with matter**
2. **Gaseous detectors**
   for very large acceptance, 3D tracking, particle identification
3. **Semiconductor detectors**
   for high precision position measurements
4. **Calorimetry for energy measurements**
   More particle identification techniques
5. **How a full experiment is put together**

Radiation detection

Absolute basic principles:

- Particle must INTERACT with the material of the detector
- It has to transfer energy / momentum in some way
- Knowing the interaction of the particle with the detector material in detail allows us to deduce extended, precise and quantitative information about the particle properties

Particle detection happens via the energy the particle deposits in the material it traverses

Interactions with matter

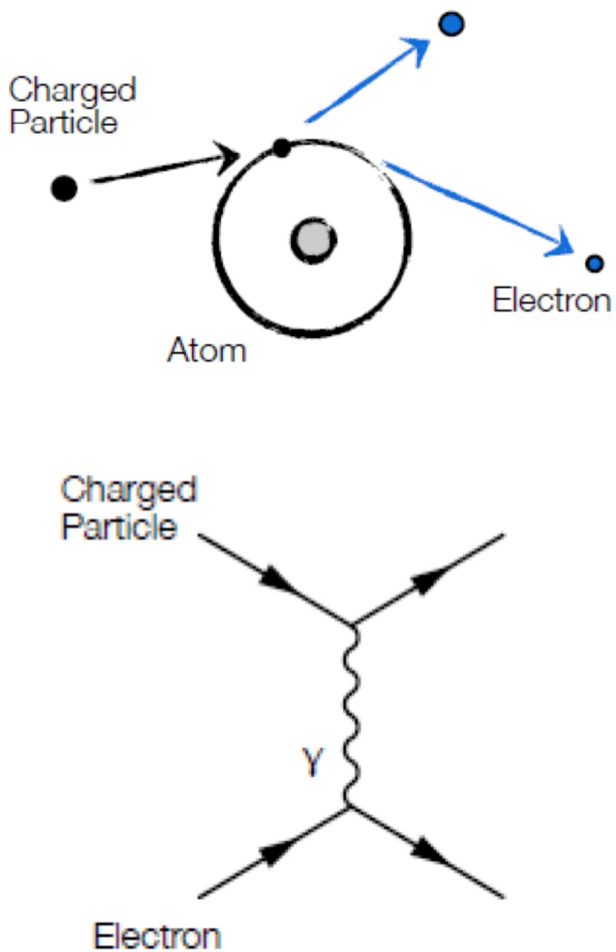
Mechanisms through which radiation interacts with the material it traverses, in a detector:

- **Charged particles:**
  - Ionization
  - Excitation
  - Bremsstrahlung
  - Cherenkov radiation
  - Transition radiation
- **Photons:**
  - Photo effect
  - Compton effect
  - Pair production
- **Neutrinos**: weak interaction
- **Hadrons:** nuclear interactions

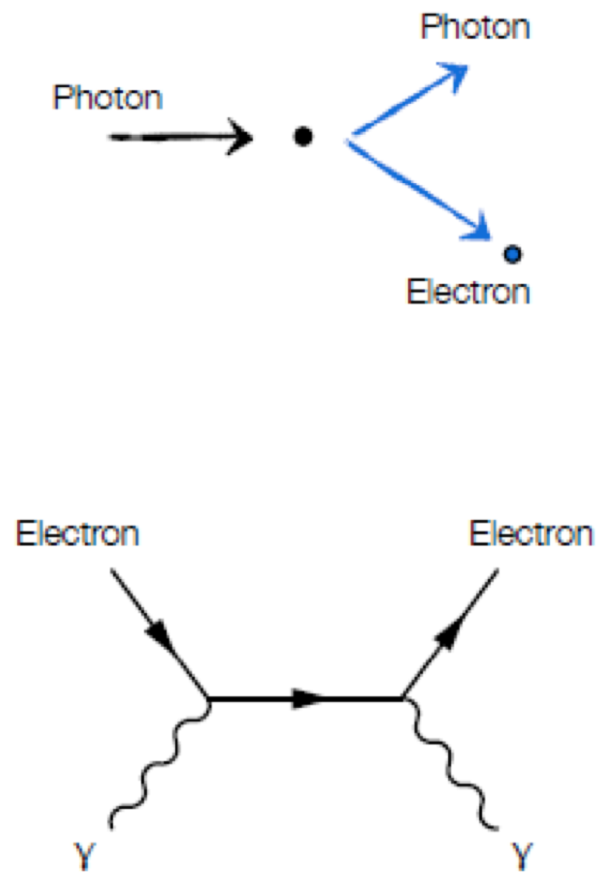
Distinguish between energy loss via multiple interactions and total energy loss in a single interaction (e.g. pair production)

Interactions with matter - examples

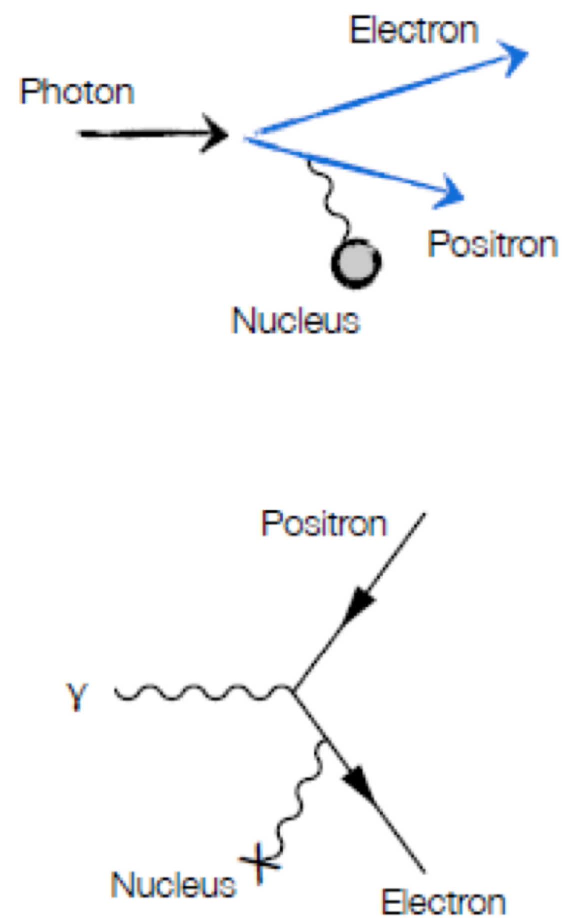
Ionization



Compton scattering



Pair production



Interaction with matter

Outline for today:

- Energy loss by ionization (by “heavy” particles)
- Interaction of electrons with matter:
  - Energy loss by ionization
  - Bremsstrahlung
- Cherenkov effect
- Transition radiation
- Interaction of photons
  - Photoelectric effect
  - Compton scattering
  - Pair production

Charged particles

Interaction of charged particles

Charged particle X, with $Mc^2 \gg m_e c^2$ (electrons are discussed later)

Dominant: Coulomb interaction between the particle X and the atom →
2 electromagnetic processes:

1) elastic scattering from nuclei

$$\text{atom} + X \quad \rightarrow \quad \text{atom}^* + X \qquad \text{excitation}$$

$$\hookrightarrow \ \text{atom} + \gamma \qquad \text{de-excitation}$$

2) inelastic collisions with the atomic electrons of the material

$$\text{atom} + X \quad \rightarrow \quad \text{atom}^+ + e^- + X \qquad \text{ionization}$$

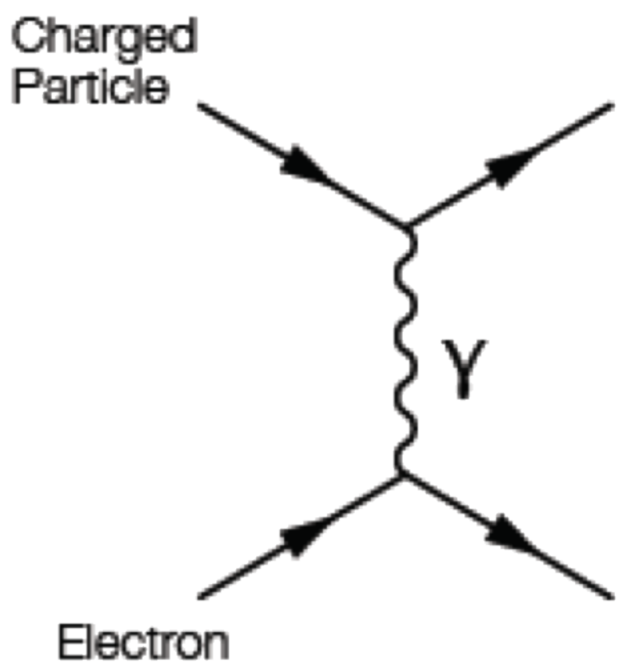
Energy loss by ionization dE/dx

- Charged particle: ze
- "heavy" particle: $Mc^2 \gg m_e c^2$ (electrons are discussed later)
- Energy high enough to "resolve" the inside of the atom: from the uncertainty principle

$$\lambda = \hbar / p \qquad \text{e.g. } 1\ \text{GeV/c} \rightarrow 1\ \text{fm}$$

Collisions with electrons:

- Classical derivation by N. Bohr (1913)
- Quantum mechanical derivation by H. Bethe (1930) and F. Bloch (1933)



Bethe-Bloch equation

Considering quantum mechanical effects:

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

density

$K = 4\pi N_A r_e^2 m_e c^2 = 0.307$ MeV g^{-1} cm^2

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

[Max. energy transfer in single collision]

$N_A = 6.022 \cdot 10^{23}$

[Avogardo's number]

$r_e = e^2/4\pi\varepsilon_0 m_e c^2 = 2.8$ fm

[Classical electron radius]

$m_e = 511$ keV

[Electron mass]

$\beta = v/c$

[Velocity]

$\gamma = (1-\beta^2)^{-2}$

[Lorentz factor]

z : Charge of incident particle

M : Mass of incident particle

Z : Charge number of medium

A : Atomic mass of medium

I : Mean excitation energy of medium

δ : Density correction [transv. extension of electric field]

Validity:

$.05 < \beta\gamma < 500$

$M > m_\mu$

Bethe-Bloch equation

Considering quantum mechanical effects:

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

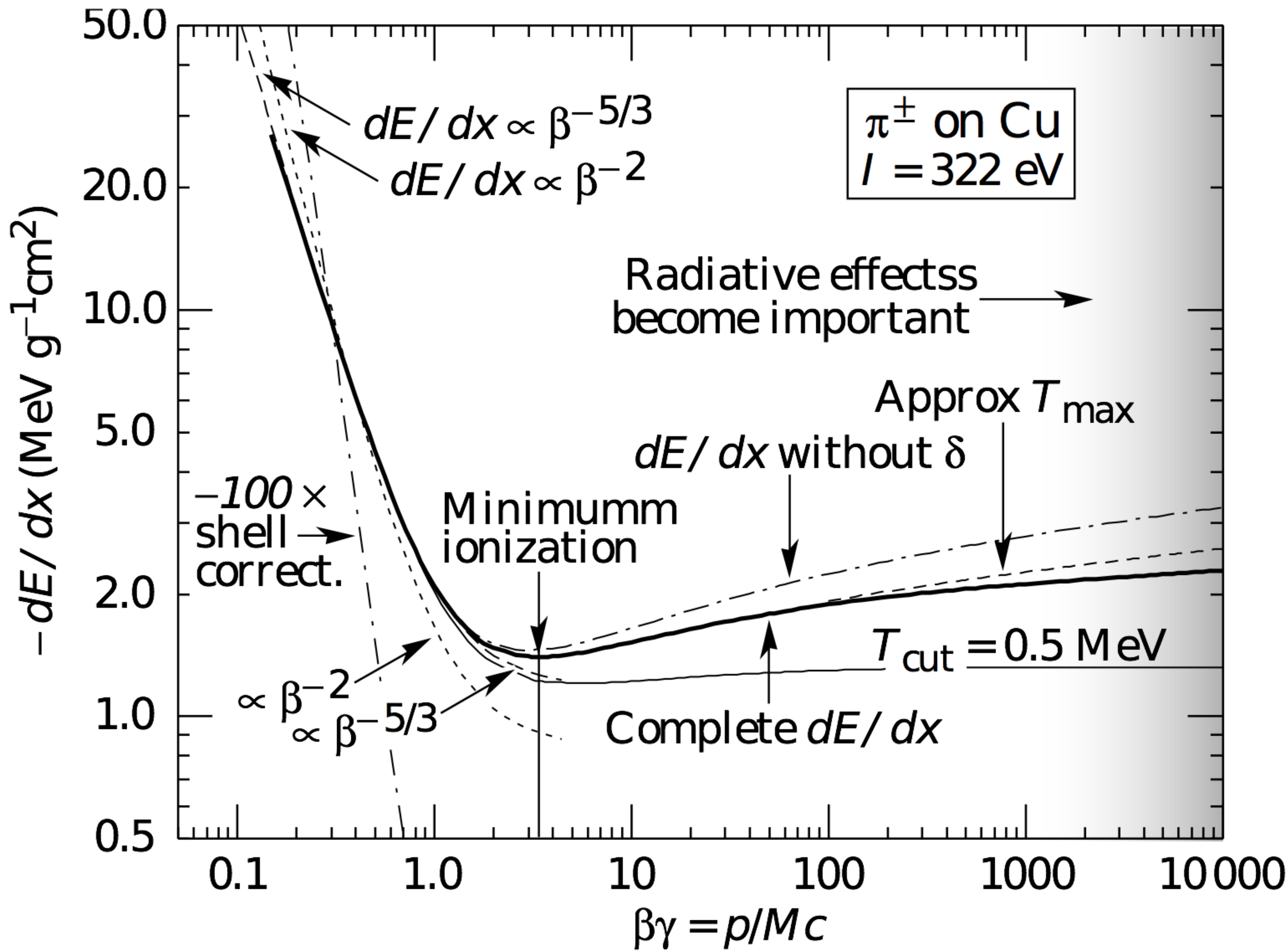
density

I = $\hbar$ <ν> = effective ionization potential
Or mean excitation energy of the medium
<ν> = average revolution frequency of electron

$T_{max} \approx 2\, m_e c^2 \beta^2 \gamma^2$ maximum energy transfer in a single collision, for $M \gg m_e$

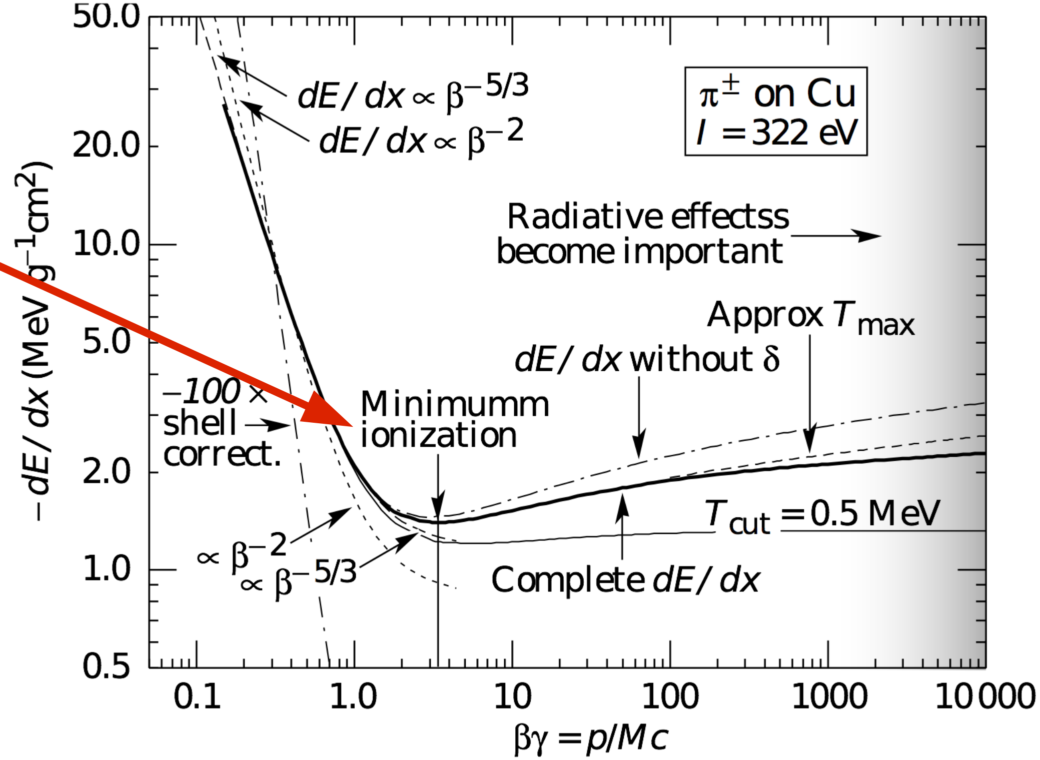
dE/dx of pions in copper

pdg.lbl.gov/2016/reviews/rpp2016-rev-passage-particles-matter.pdf



Bethe-Bloch: main features

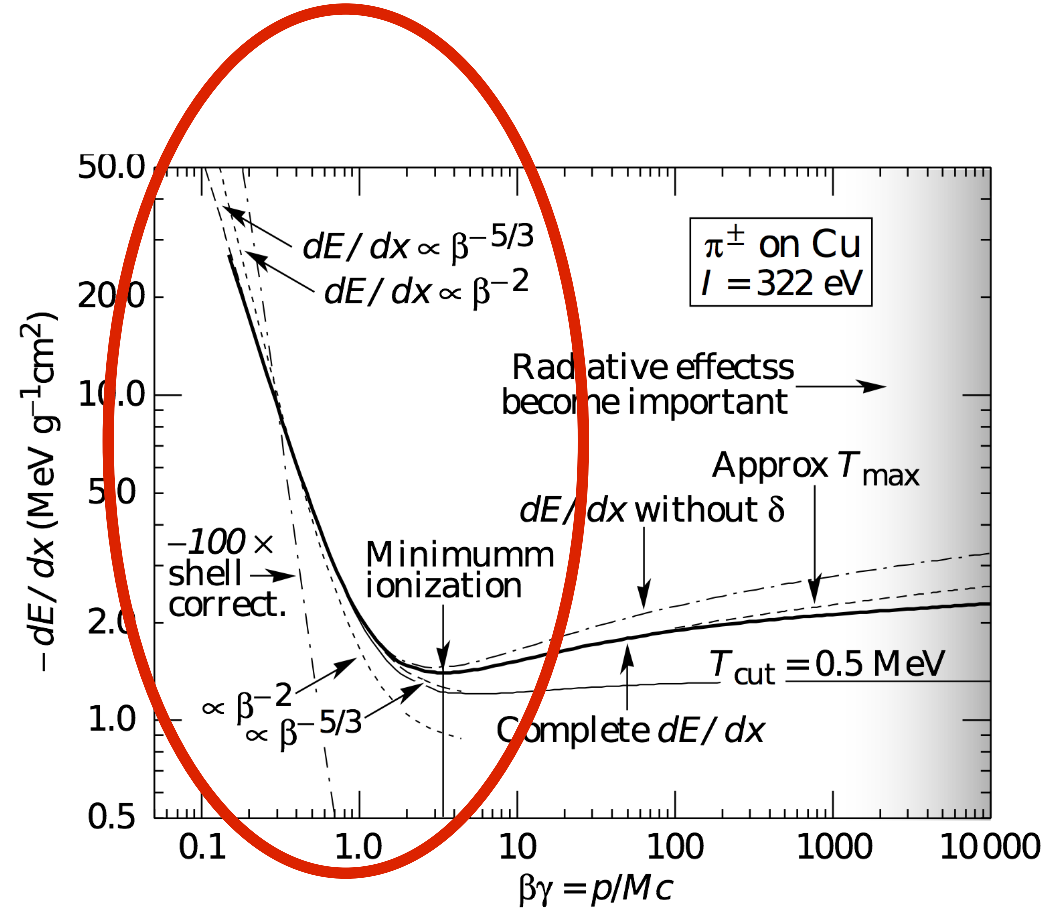
- Minimum ionization:
  MIP = minimum ionizing particles
  for $\beta\gamma \approx$ 3-4
- Units: MeV g^{-1} cm^2
  dE/dx_{min} ~ 1-2 MeV g^{-1} cm^2
- Density of copper: ρ=9.94 g/cm^2
  → MIP looses ~ 13 MeV/cm



Bethe-Bloch: main features

Small βγ

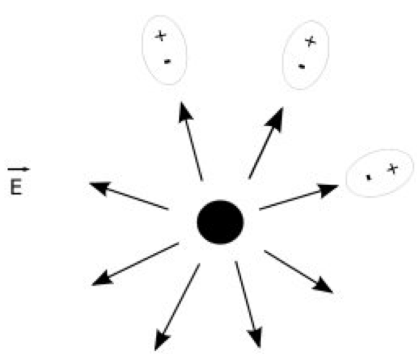
- quick fall of dE/dx as β^{-2} (Bohr)
- Precisely it is $\beta^{-5/3}$: slower particles experience the electric field for a longer time → stronger energy loss!
- **Shell corrections**: particle velocity can get close to the electron orbital velocity ($\beta c \sim v_e$):
  - Assumption of electron to be at rest is no longer valid
  - Capture processes become possible



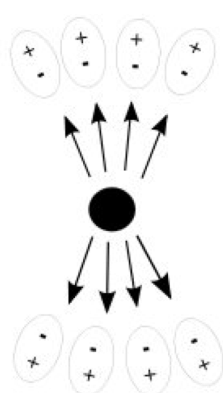
Bethe-Bloch: main features

Large βγ

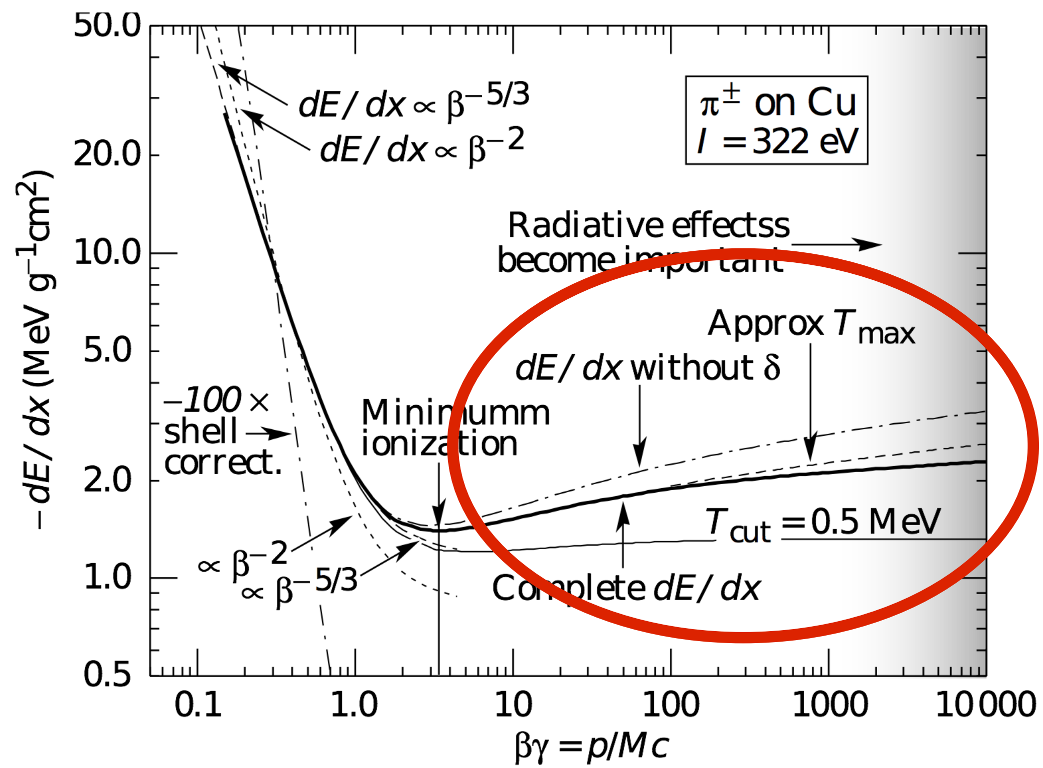
- Relativistic rise ~ ln $\beta^2\gamma^2$
  The transverse electric field increases due to Lorentz transformation → increase of contribution from larger b



left: for small γ,



right: for large γ

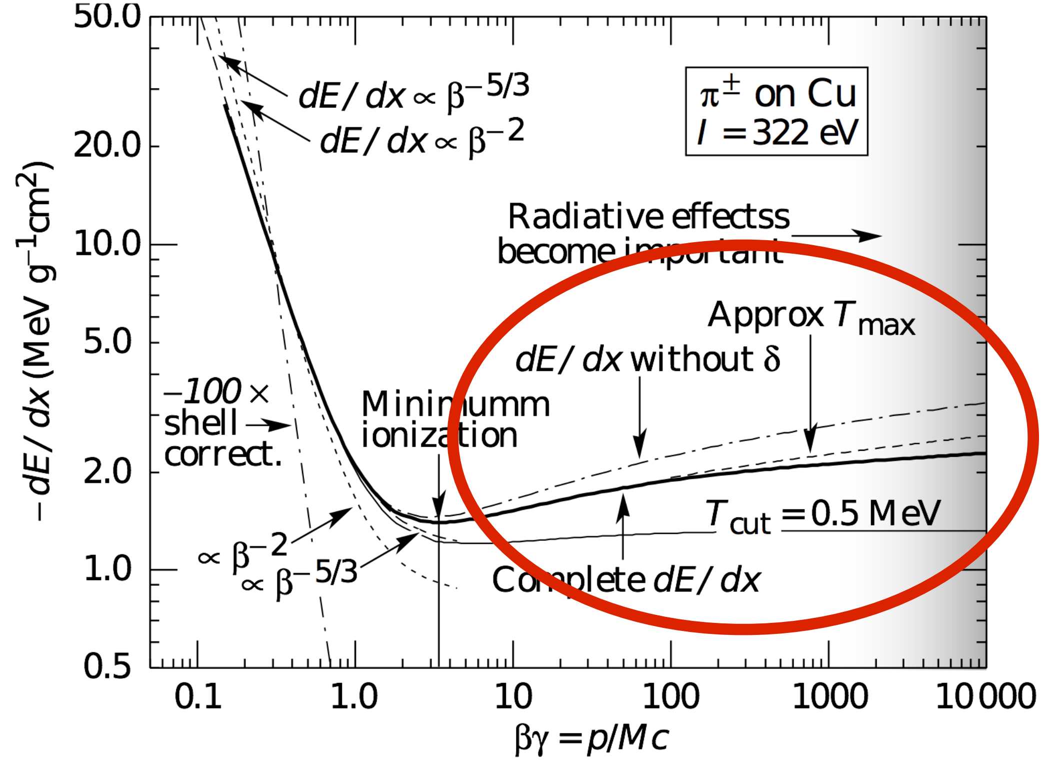


- Density correction must be considered: Fermi plateau →

Bethe-Bloch: main features

Large βγ: density correction $-\frac{\delta}{2}$

- Real media are polarized $\rightarrow$ effective shielding of electric field far from particle path $\rightarrow$ effectively reduces the long range contribution to relativistic rise
- effectively dE/dx grows like ln(βγ)
- Correction much larger for liquids and solids! Logarithmic rise ~20% in liquids and solids, ~50% in gases



dE/dx

Particle Data Group:

pdg.lbl.gov/2016/reviews/rpp2016-rev-passage-particles-matter.pdf

Different detector materials

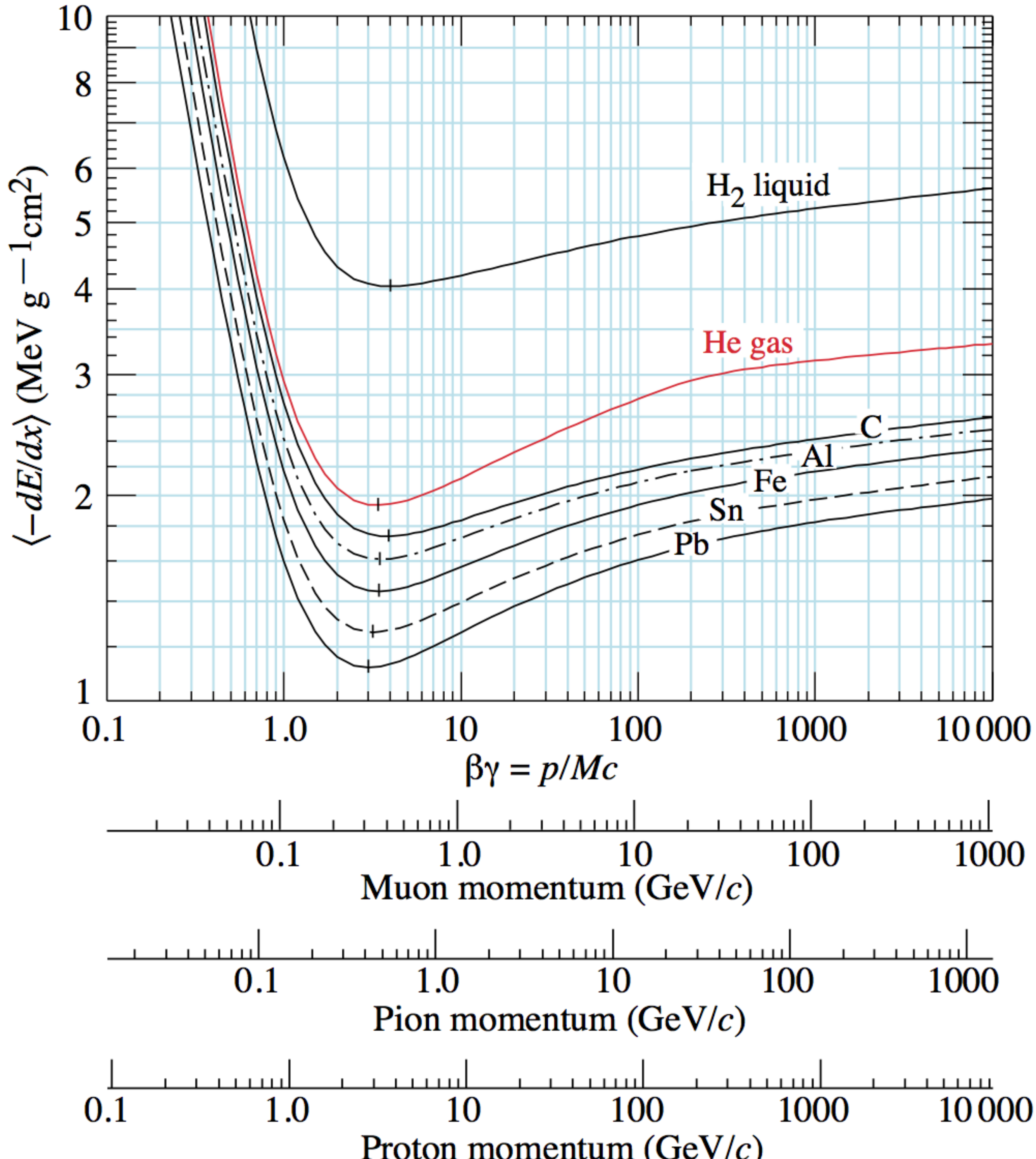
$$\frac{dE}{dx} \approx \frac{Z}{A}$$

(remember density!)

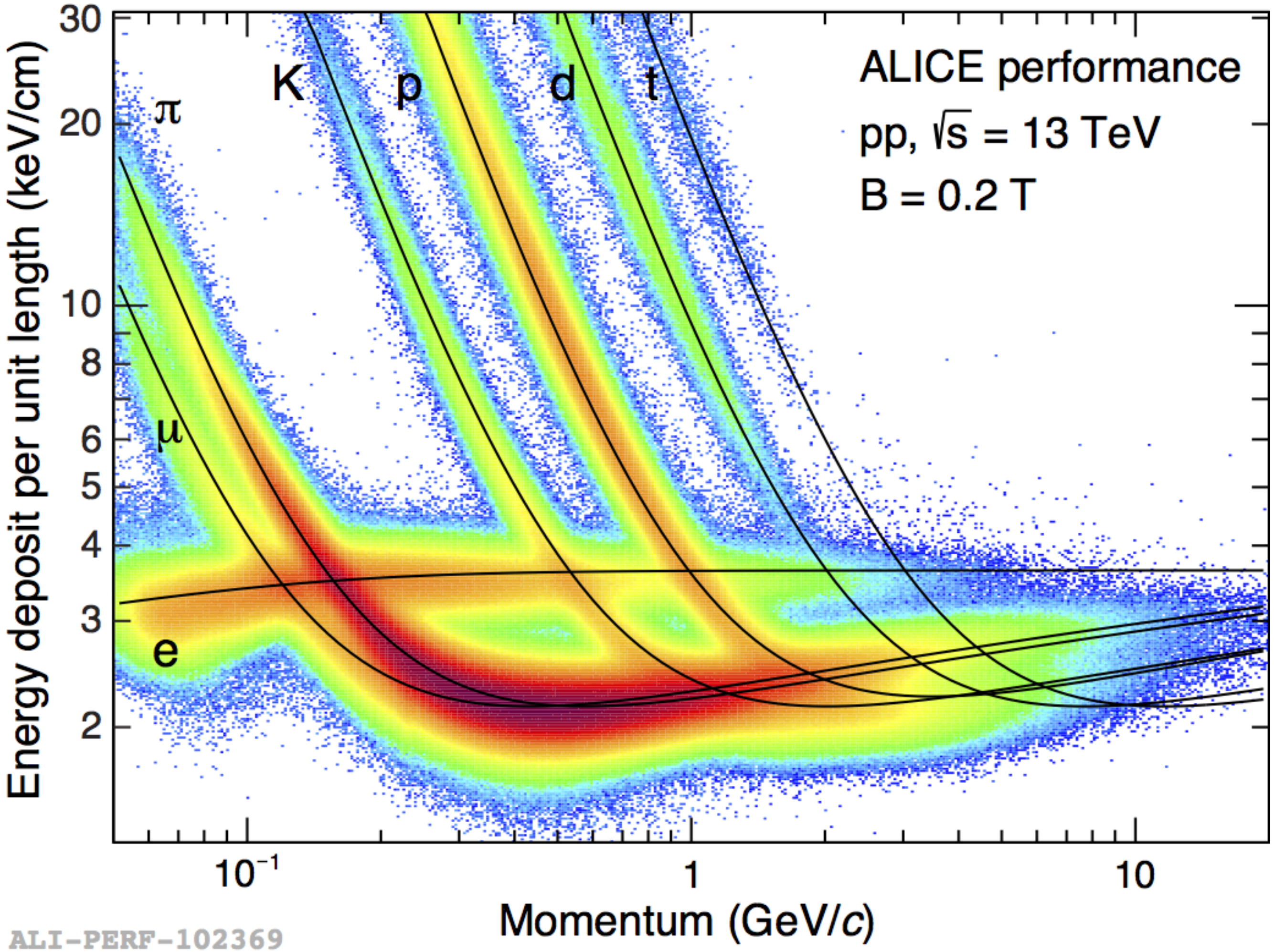
dE/dx depends on

$\beta\gamma = p/(Mc)$

→ at a given p, dE/dx is different for particles with different mass M



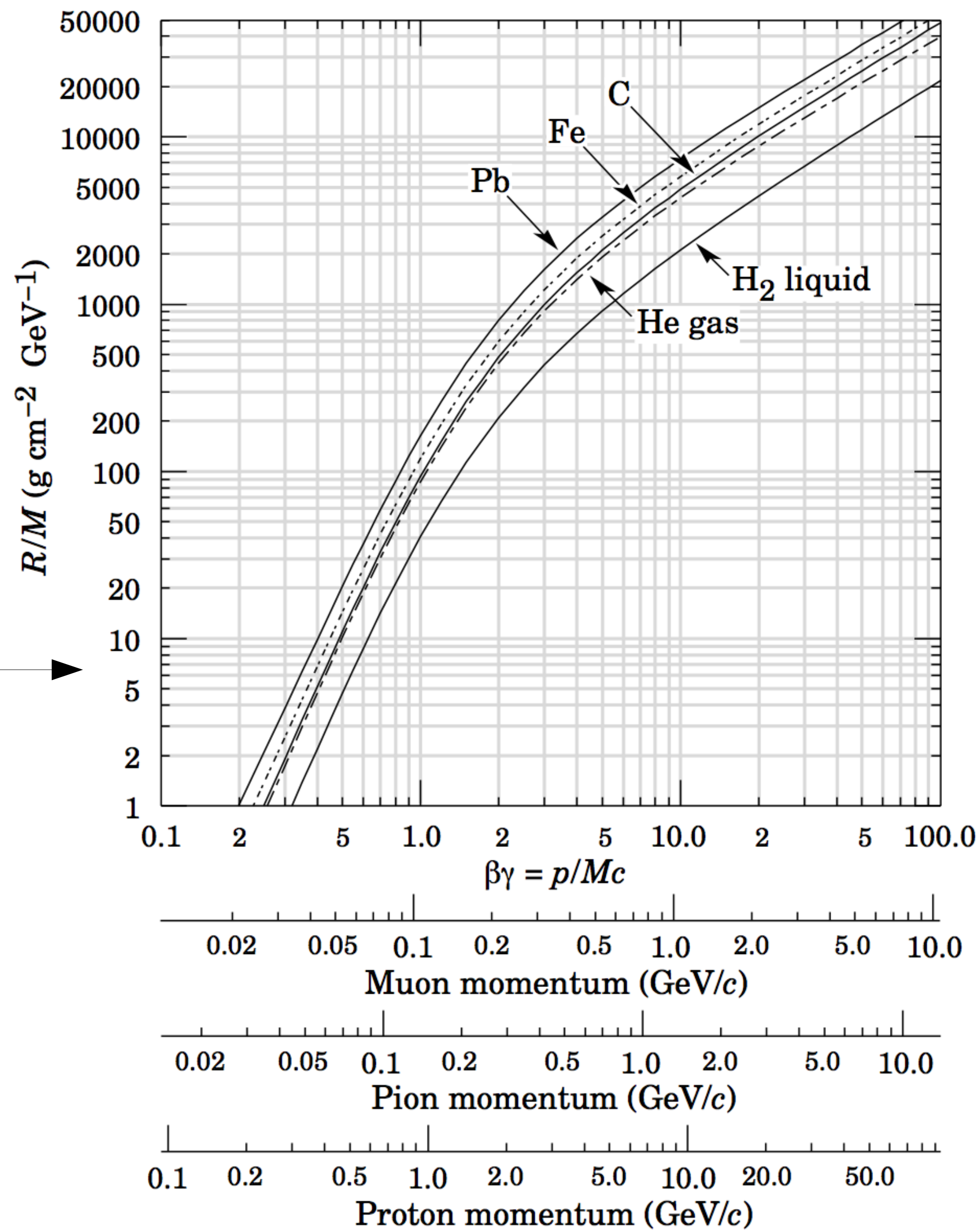
dE/dx used in practice
the ALICE Time Projection Chamber



Range of particles

Integrate over (changing!!) energy loss from initial energy E to 0, to calculate the range:

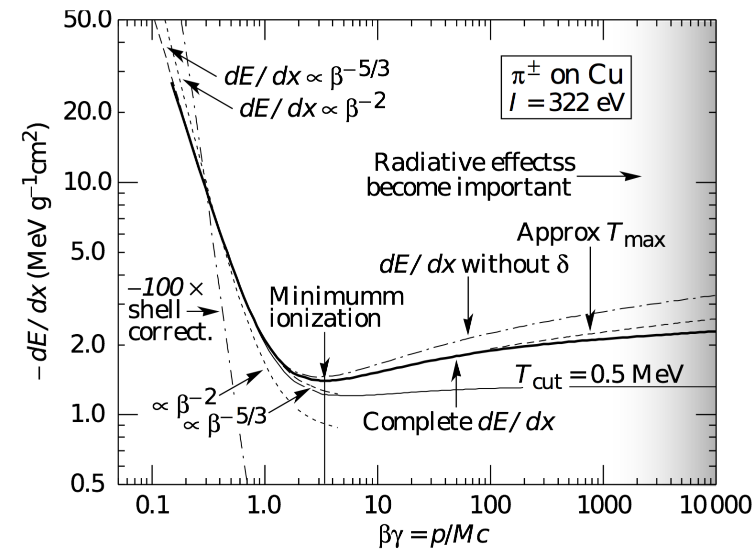
$$R = \int_E^0 \frac{dE}{dE/dx}$$



Here: Range of heavy charged particles in liquid (bubble chamber) hydrogen, helium gas, carbon, iron, and lead. For example:

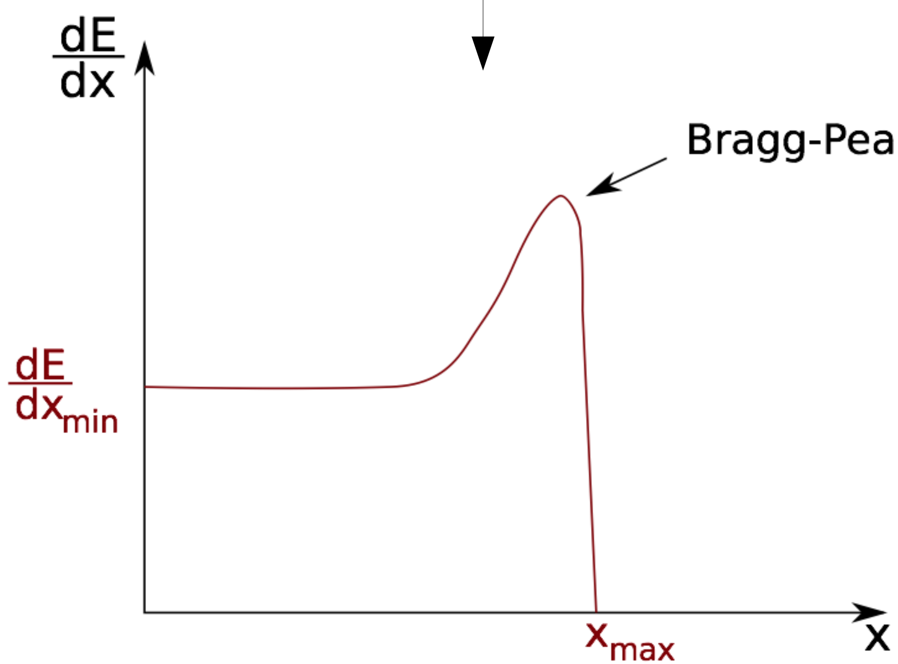
- For a K^+ whose momentum is 700 MeV/c, $\beta\gamma = 1.42$. For lead we read $R/M \approx 396$, and so the range is 195 g cm^{-2} (17 cm).

Particles stopped in medium



for $\beta\gamma \simeq 3.5$ $\qquad \langle \frac{dE}{dx} \rangle \simeq \frac{dE}{dx}_{min}$

for $\beta\gamma \lesssim 3.5$ $\qquad$ steep rise $\langle \frac{dE}{dx} \rangle \gg \frac{dE}{dx}_{min}$



Energy loss curve vs depth showing Bragg peak

Application: tumor therapy

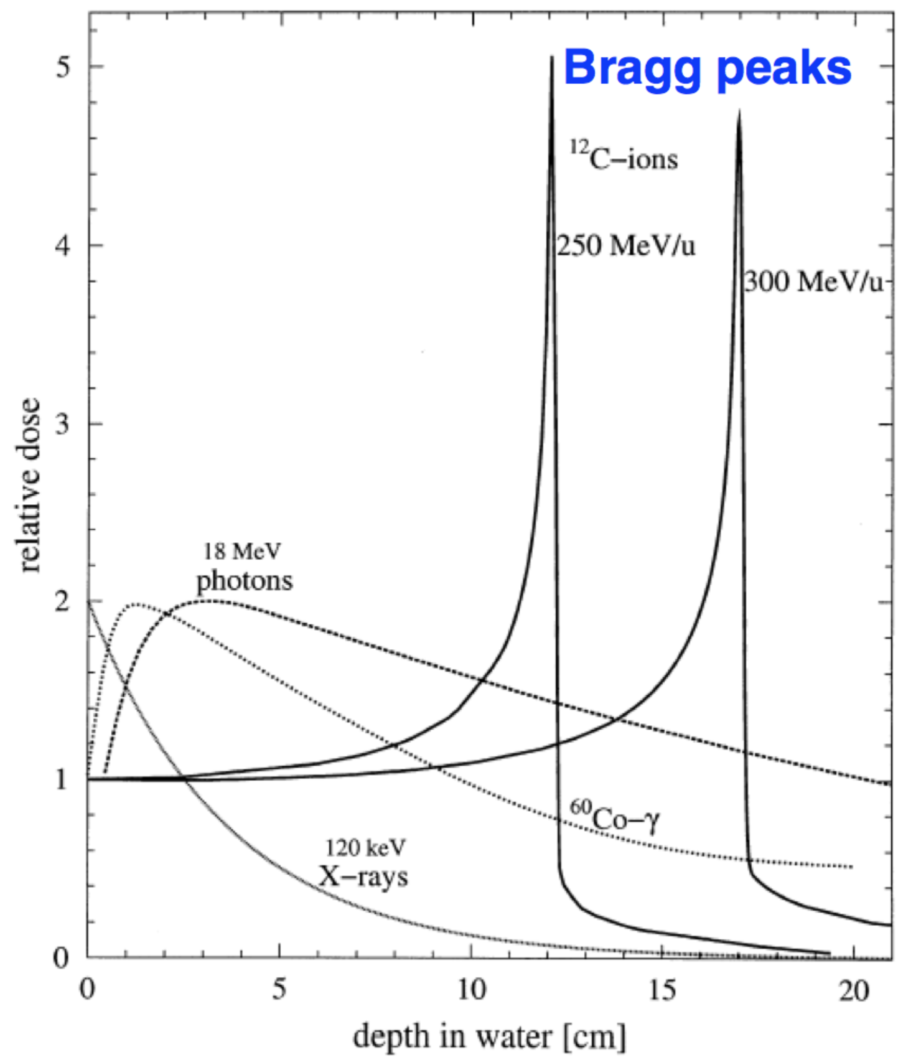
Possibility to deposit a rather precise dose at a well defined depth (body), by variation of the beam energy

Initially with protons, later also with heavier ions such as ^{12}C.

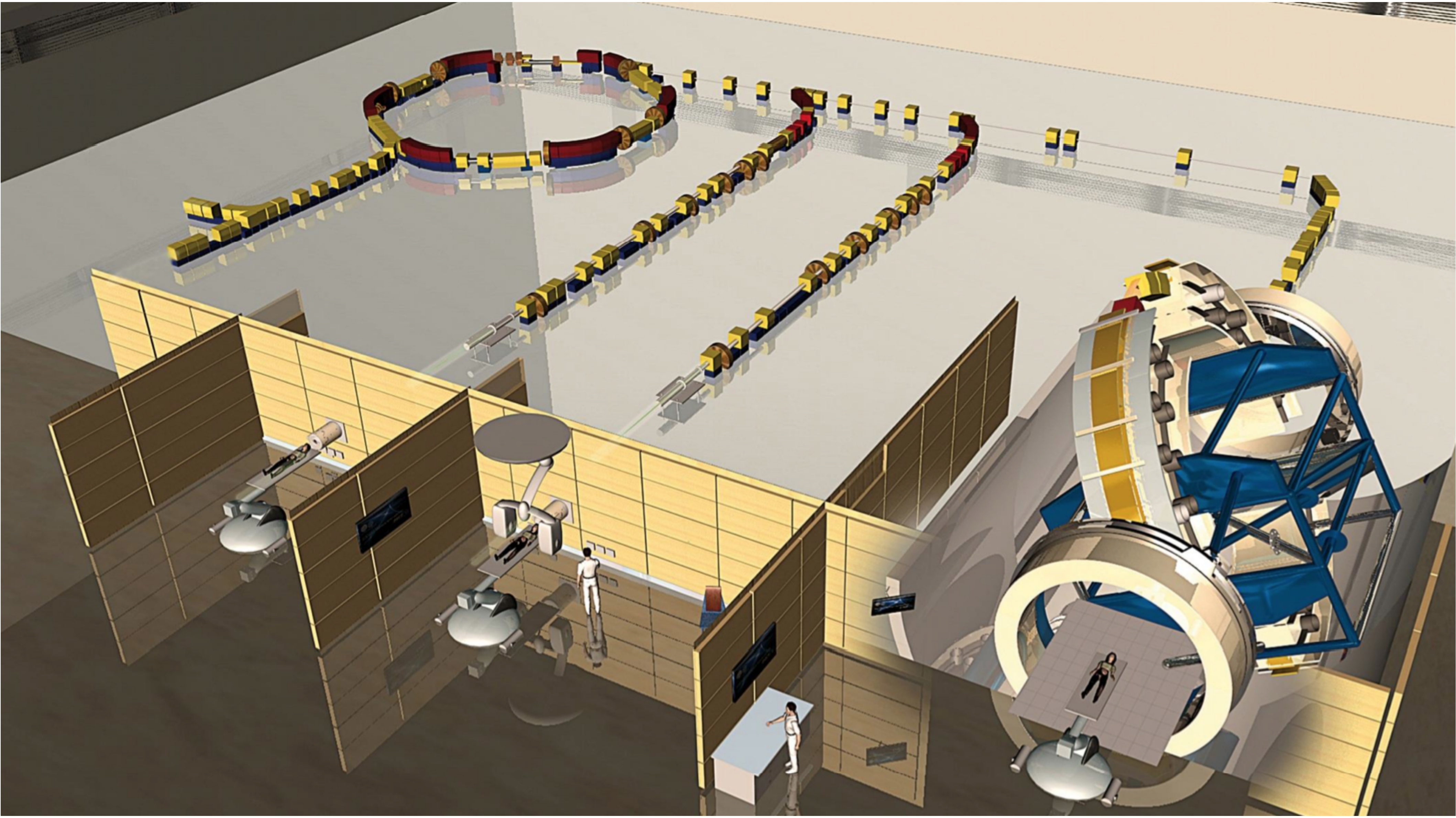
Precise 3D irradiation profile, also with suitably shaped absorbers (custom made for patient).

High precision beam scanning.

Tumor treatment at HIT (Heidelberg Ion-Beam Therapy center) in collaboration between DKFZ and GSI



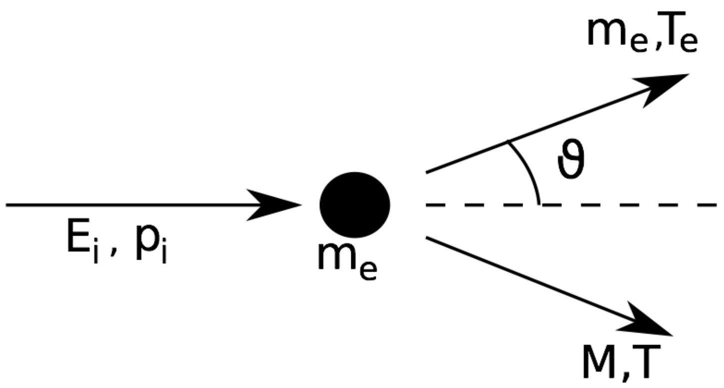
Heidelberg Ion-beam Therapy Center (HIT)



Delta electrons

Electrons liberated by ionization can have large energies. Above a certain threshold (e.g. T_{cut}) they are called **δ electrons**.

Early observation in emulsions.

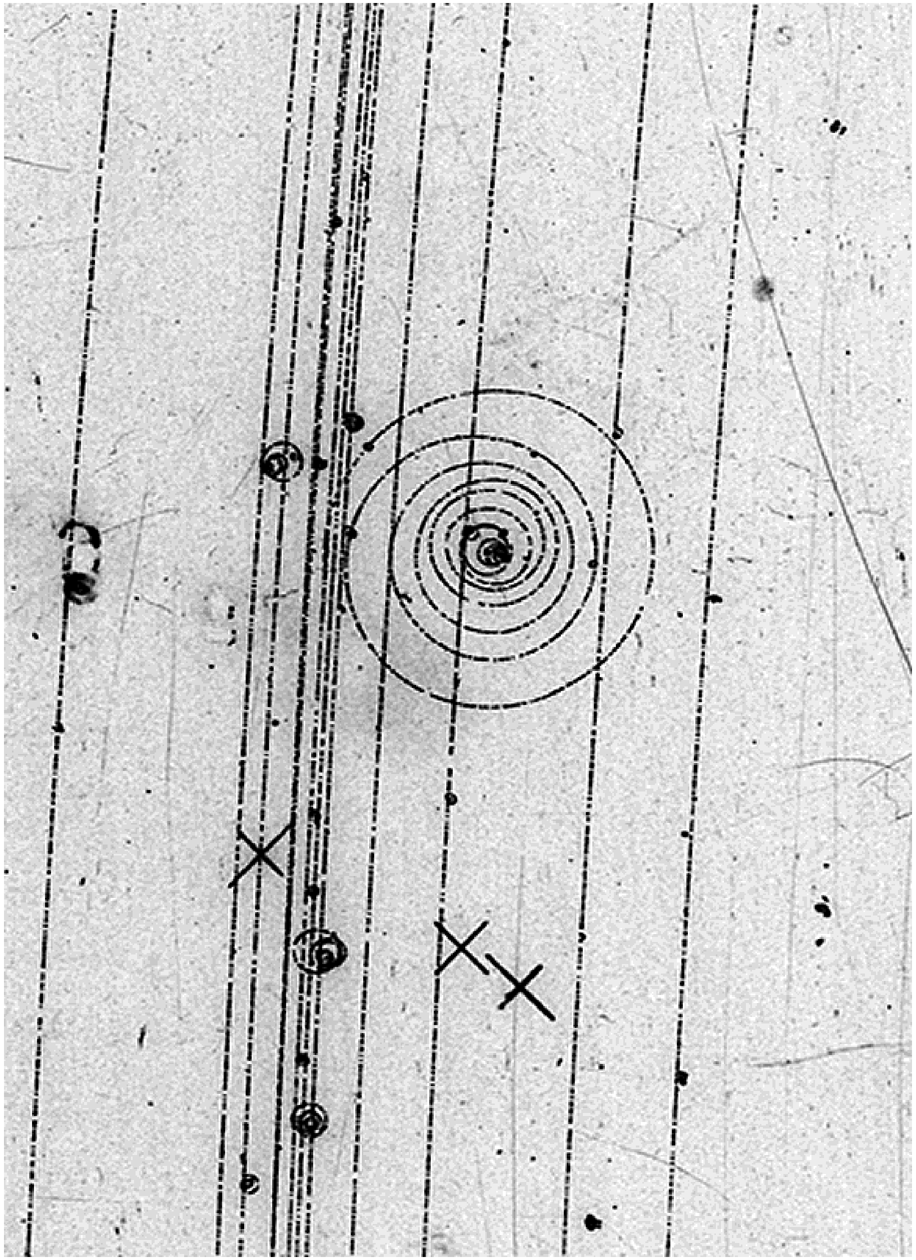


Massive highly relativistic particle can transfer practically all its energy to a single electron!

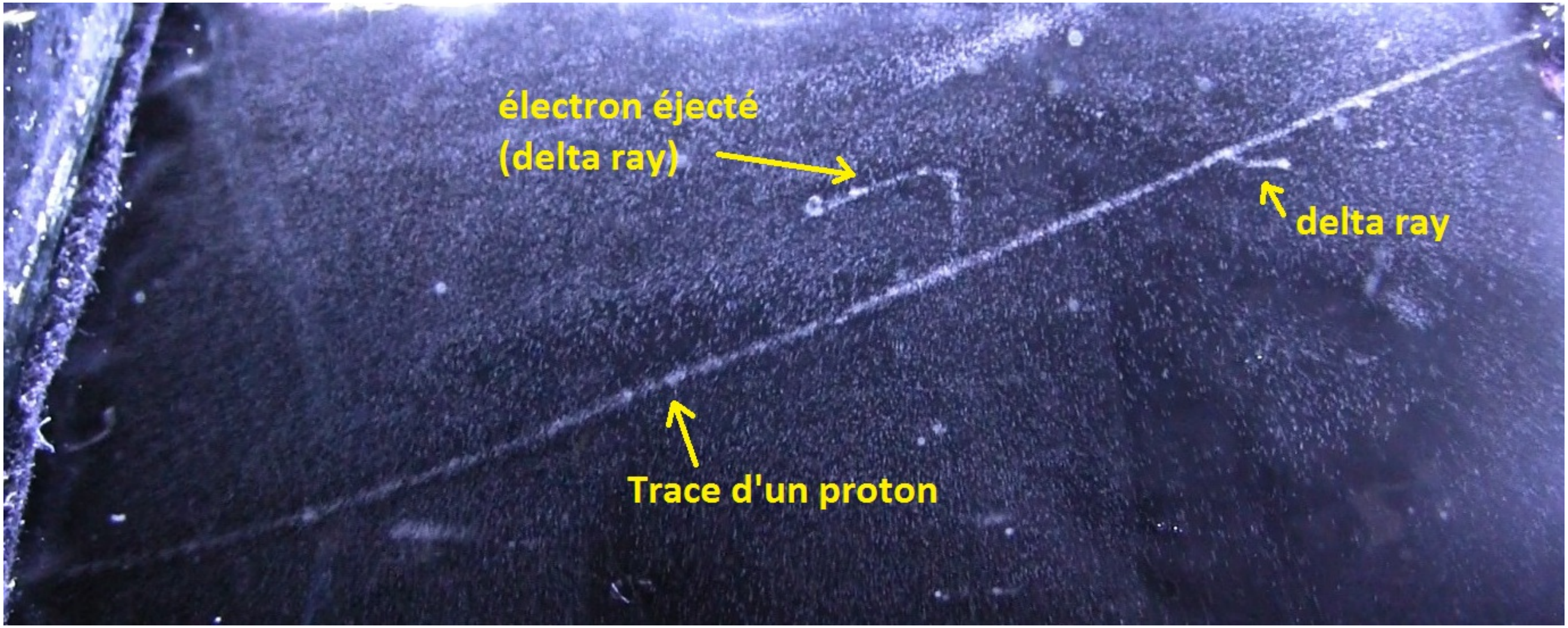
Delta electrons

Picture from CERN 2-meter hydrogen bubble chamber exposed to a beam of negative kaons K^-, with energy 4.2 GeV. This piece corresponds to about 70 cm in the bubble chamber.

The 12 parallel lines are trails of bubbles – initiated by the ionization of hydrogen by the beam particles, which enter at the bottom of the picture.



Delta electrons



Cloud chamber

Limitation to the measurement of the incoming particle: most often the δ electron is NOT detected as part of the ionization trail

→ broadening of track

→ broadening of energy loss distribution

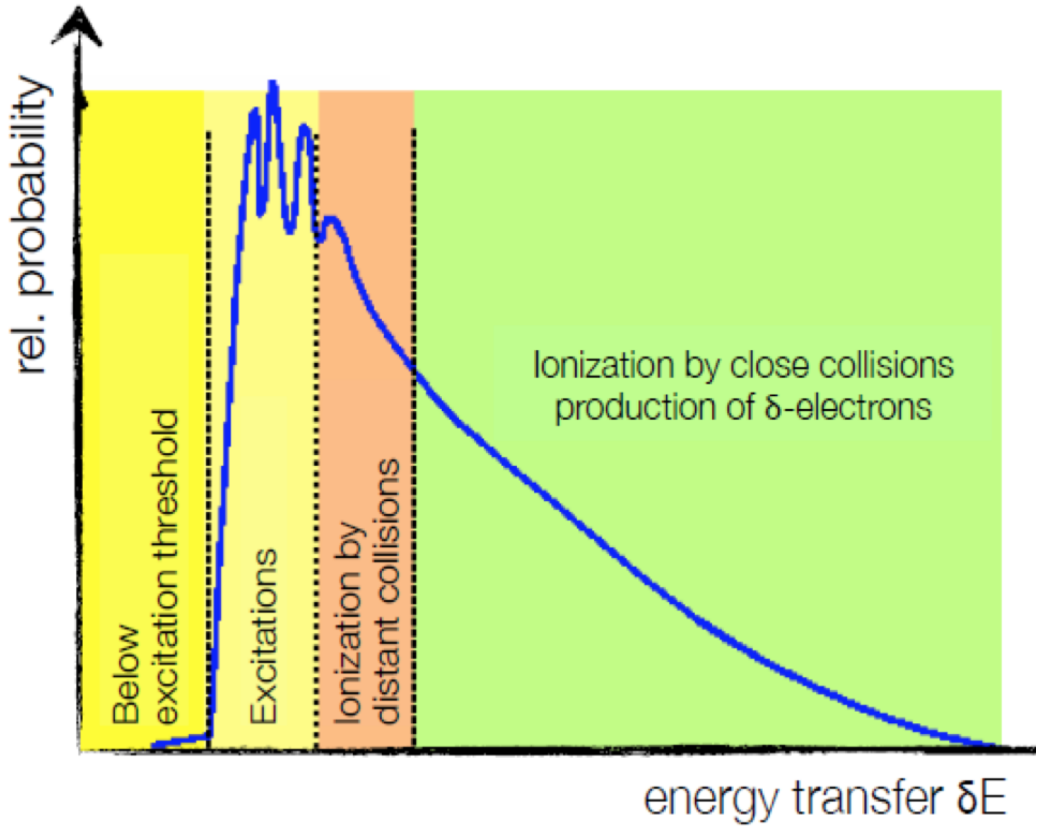
dE/dx fluctuations

- The Bethe-Bloch formula describes the MEAN energy loss
  The energy loss is measured in a detector of finite thickness Δx with
  - N = number of collisions
  - δE = energy loss in a single collision

$$\Delta E = \sum_{n=1}^{N} \delta E_n$$

- The single energy loss is a statistical process, δE is distributed statistically $\rightarrow$ energy loss "straggling"
  (strong fluctuations, complex problem)

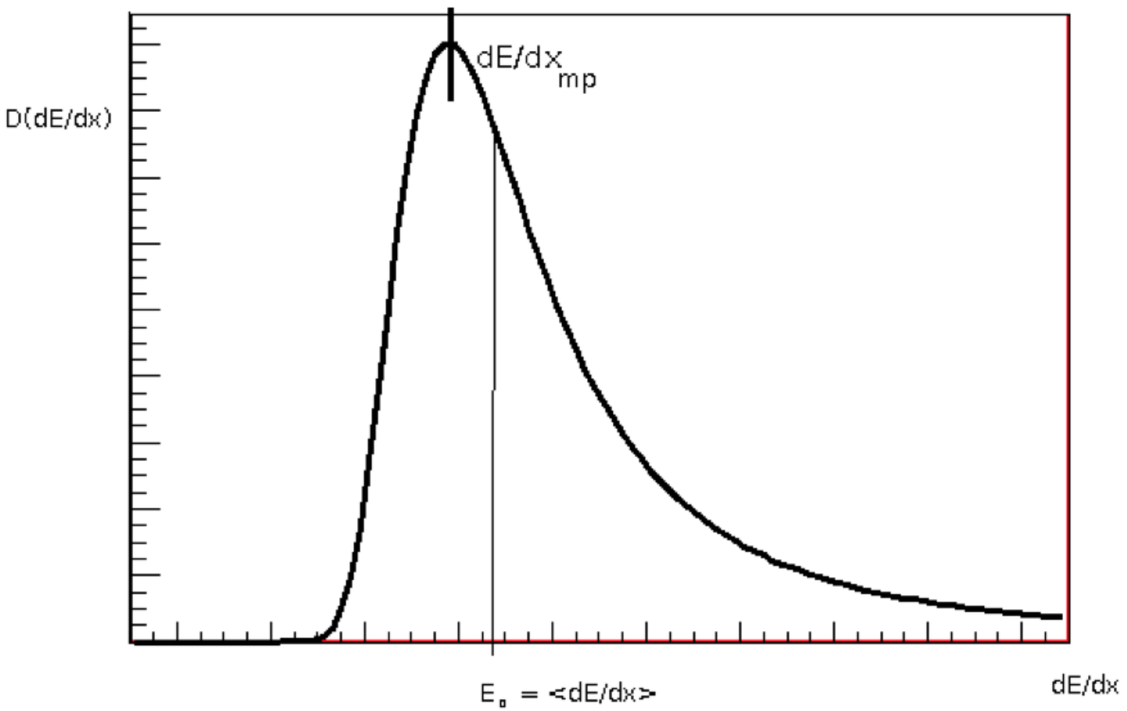
- For thin absorbers: Landau distribution (see next)



dE/dx Landau distribution

Distribution of energy loss in single collisions: Gauss plus tail towards high losses due to the δ electrons

Landau for thin absorbers, approximation for thicker ones: (Vavilov 1957)



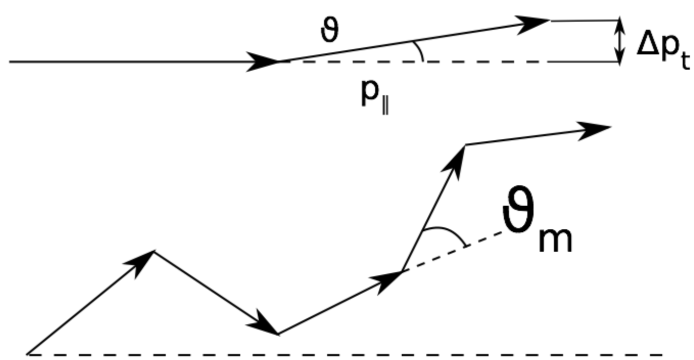
Multiple (Coulomb) scattering

Incident particle can also scatter in the Coulomb field of the NUCLEUS !

Deflection of trajectory will be more significant because of the factor Z !

$$\theta \simeq \frac{\Delta p_\perp}{p_{||}} \simeq \frac{\Delta p_\perp}{p}$$

$$= \frac{2Zze^2}{b}\frac{1}{pv}$$



after k collisions

$$\langle\theta_k^2\rangle = \sum_{m=1}^{k} \theta_m^2 = k\langle\theta^2\rangle$$

- Single collision (thin absorber): Rutherford scattering $d\sigma/d\Omega \propto \sin^{-4}\theta/2$
- Few collisions: difficult problem
- Many (>20) collisions: statistical treatment “Molière theory”

Multiple (Coulomb) scattering: Molière theory

Obtain the mean deflection angle in a plane by averaging over many collisions and integrating over b:

$$\sqrt{\langle\theta^2(x)\rangle} = \theta_{\rm rms}^{\rm plane} = \frac{13.6\ \text{MeV}}{\beta pc} z \sqrt{\frac{x}{X_0}} \left(1 + 0.038 \ln \frac{x}{X_0}\right)$$

- Material constant X_0: radiation length
- $\propto \sqrt{x}$ → use thin detectors
- $\propto 1/\sqrt{X_0}$ → use light detectors
- $\propto 1/\beta p$ → serious problem at low momenta

In 3 dimensions: $\theta_{\rm rms}^{\rm space} = \sqrt{2}\ \theta_{\rm rms}^{\rm plane}$ $\quad 13.6 \to 19.2$

Multiple scattering limits the momentum and tracking resolution, particularly at low momenta!

Ionization yield

Mean number of electron-ion pairs produced along the track of the ionizing particle:

- Total ionization = primary ionization + secondary ionization due to energetic primary electrons $n_t = n_p + n_s$
- Consider also the energy loss by excitation (smaller)

→ mean energy W to produce an electron-ion pair: $n_t = \frac{\Delta E}{W}$

W > ionization potential I_0 since:

- Also ionization of inner shells
- Excitation that may not lead to ionization

  $n_t \approx 2\text{-}6\, n_p$

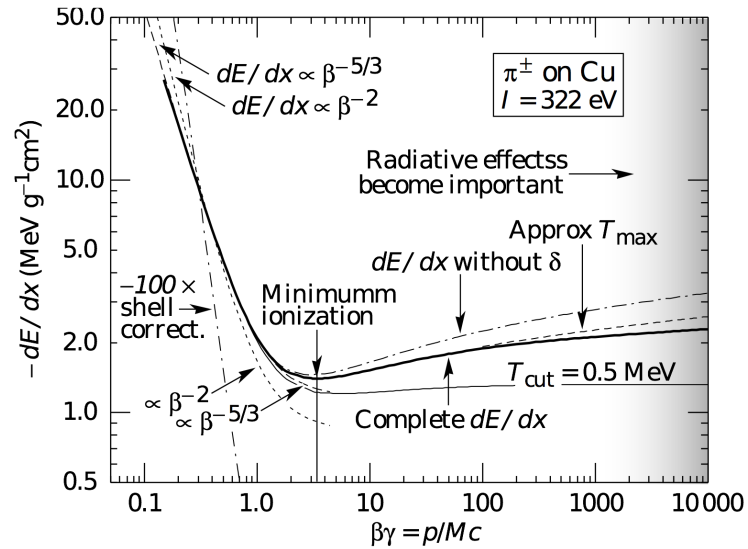
Ionization yield

typical values				
	I_0 (eV)	W (eV)	n_p (cm^{-1})	n_t (cm^{-1})
H_2	15.4	37	5.2	9.2
N_2	15.5	35	10	56
0_2	12.2	31	22	73
Ne	21.6	36	12	39
Ar	15.8	26	29	94
Kr	14.0	24	22	192
Xe	12.1	22	44	307
CO_2	13.7	33	34	91
CH_4	13.1	28	16	53
		in gases $\approx$ 30 eV	diff. due to ρ and Z	diff. due to electronic struct.

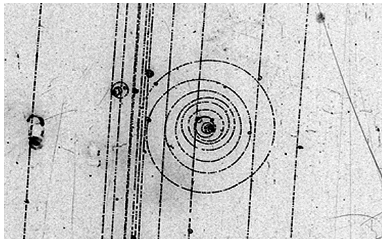
In comparison, in semiconductors: W = 3.6 eV in Si, 2.85 eV in Ge
Additional factor 103 due to density → many more electron-ion pairs!!

Summary of energy loss by ionization

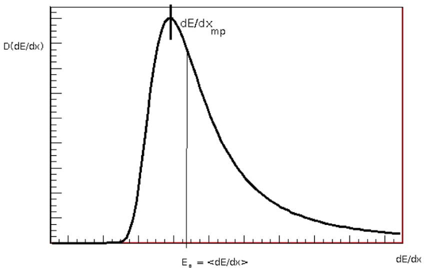
- Charged particles, em interaction
- Bethe-Bloch parametrization: $\frac{dE}{dx}$ vs $\beta\gamma$



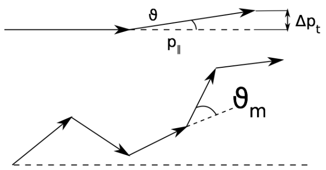
- Delta electrons

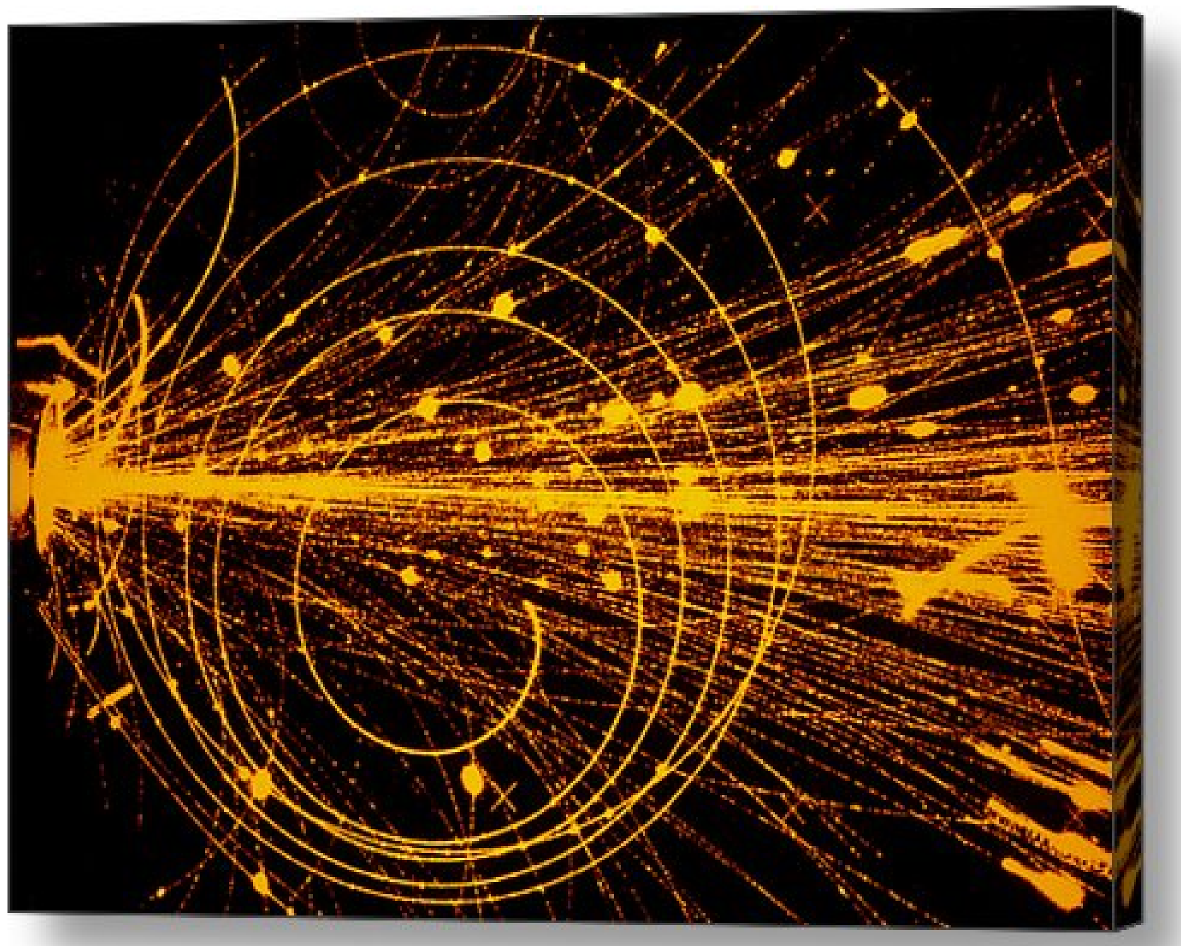


- Landau distribution of deposited energy



- Multiple scattering





Streamer chamber image

Interaction of electrons with matter

Energy loss by ionization

Bethe-Bloch equation must be modified to account for:

- Small mass of electron → deflections become more important
- Incident and target electron have the same mass m_e (T_{max} = T/2)
- Quantum mechanics: after the scattering, the incoming electron and the one from ionization are indistinguishable

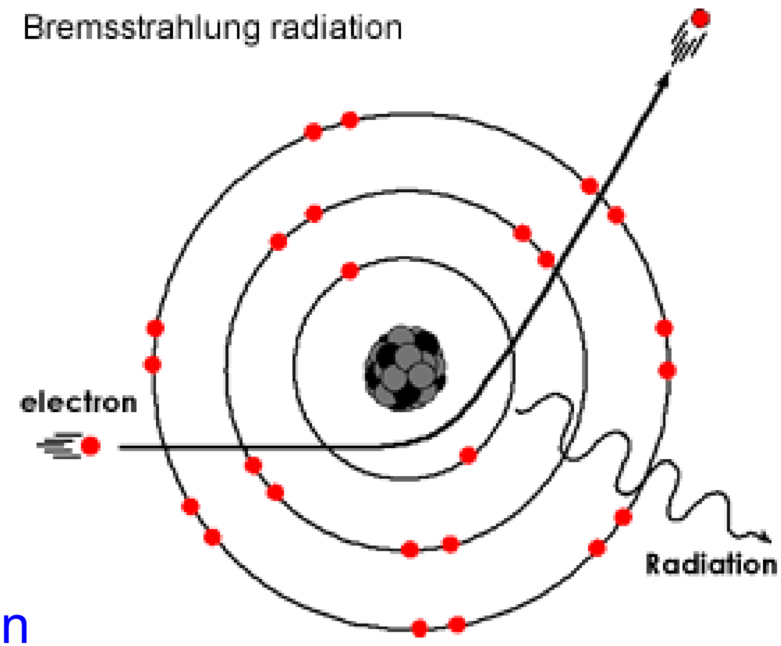
$$-\left\langle \frac{dE}{dx} \right\rangle_{\text{el.}} = K \frac{Z}{A} \frac{1}{\beta^2} \left[\ln \frac{m_e \beta^2 c^2 \gamma^2 T}{2 I^2} + F(\gamma) \right]$$

Energy loss for electrons and positrons is DIFFERENT:

- positron is not indistinguishable from electron in atom
- Low energy positrons have larger energy loss because of annihilation
- At same β, the difference is within 10%

Bremsstrahlung

Acceleration of charged particles in the Coulomb field of the nucleus:



QED process (Fermi 1924, Weizsäcker-Williams 1938)

Emission of a real photon

$$\frac{dE}{dx} = 4\alpha N_A \frac{z^2 Z^2}{A} \left(\frac{1}{4\pi\epsilon_0} \frac{e^2}{mc^2} \right)^2 E \ \ln \frac{183}{Z^{\frac{1}{3}}} \propto \frac{E}{m^2}$$

Relevant for electron and positrons in the range up to few hundred GeV/c

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

$$\frac{dE}{dx} = \frac{E}{X_0} \quad \text{with} \quad X_0 = \frac{A}{4\alpha N_A \ Z^2 r_e^2 \ \ln \frac{183}{Z^{\frac{1}{3}}}}$$

[Radiation length in g/cm^2]

Radiation length X_0

Bremsstrahlung: radiation length

$$-\frac{dE}{dx} = \frac{E}{X_0} \qquad \rightarrow \qquad E(x) = E_0 \exp\left(-\frac{x}{X_0}\right)$$

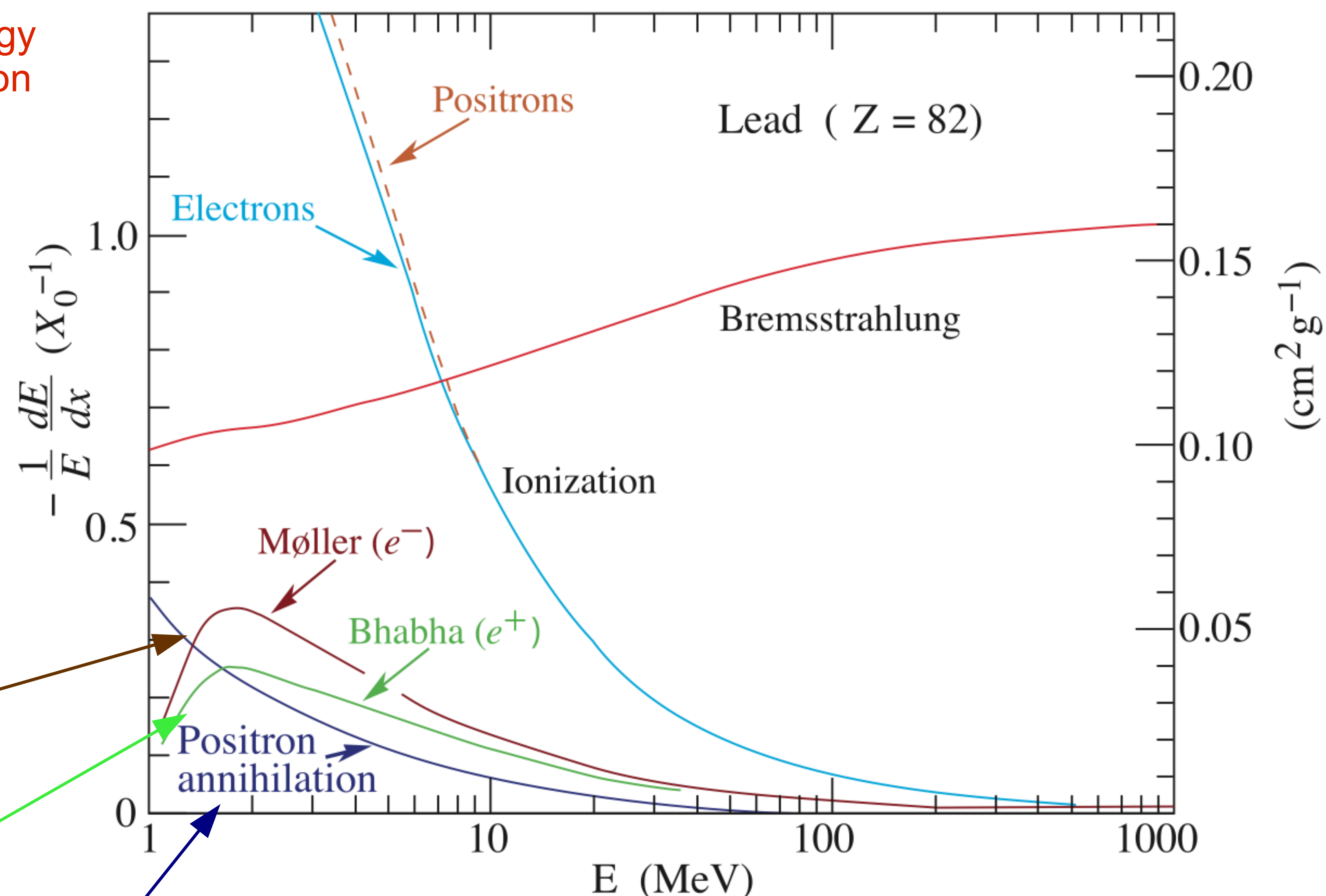
X_0: distance after which the energy of the electron is reduced to E_0/e

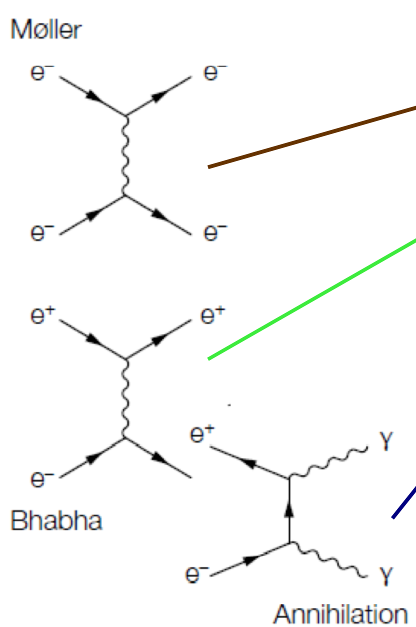
For materials which are mixtures of more components:

$$\frac{1}{X_0} = \sum_i \frac{w_i}{X_{0i}} \qquad w_i \text{ weight fraction of substance } i$$

Overview: energy loss by electrons

Fractional energy loss per radiation length

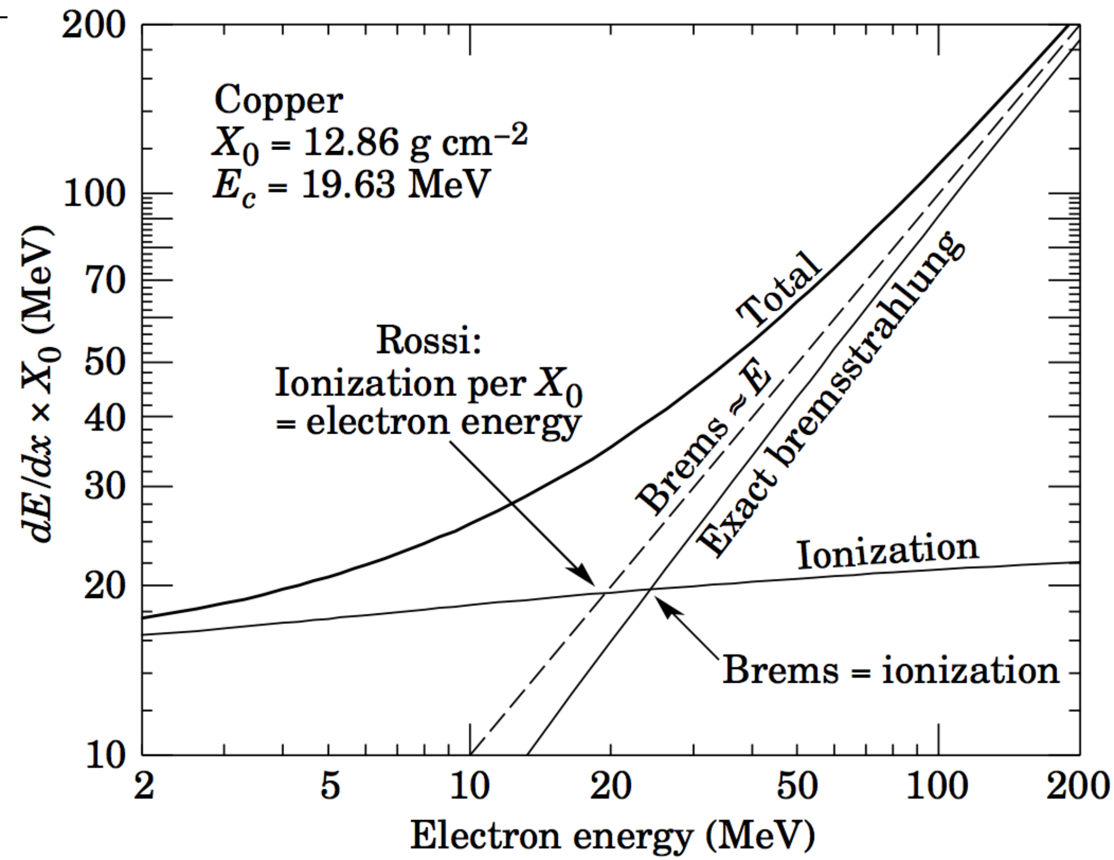




Critical energy

Total energy loss of electrons:

$$\left(\frac{dE}{dx}\right)_{Tot} = \left(\frac{dE}{dx}\right)_{Ion} + \left(\frac{dE}{dx}\right)_{Brems}$$



Critical energy:

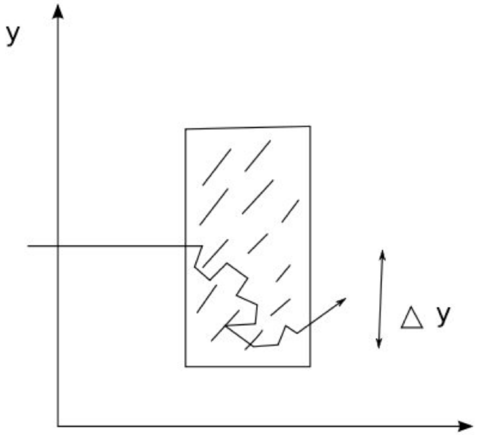
$$\left(\frac{dE}{dx}(E_c)\right)_{Brems} = \left(\frac{dE}{dx}(E_c)\right)_{Ion}$$

Approximation:

$$E_c^{Gas} = \frac{710\,\text{MeV}}{Z+0.92} \qquad E_c^{Sol,Liq} = \frac{610\,\text{MeV}}{Z+1.24}$$

Example: Cu $E_c \approx 610/30$ MeV ≈ 20 MeV

Multiple scattering



Difference between heavy particles and electrons:

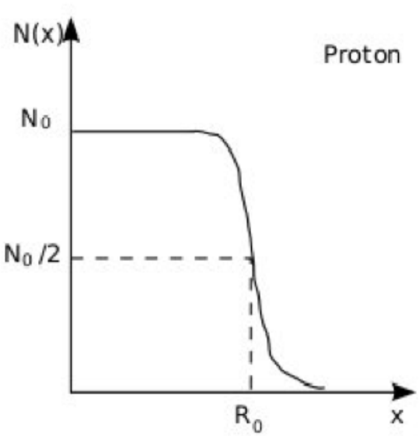
- Heavy particle: the track is more or less straight
- Electron: can be scattered to large angles!

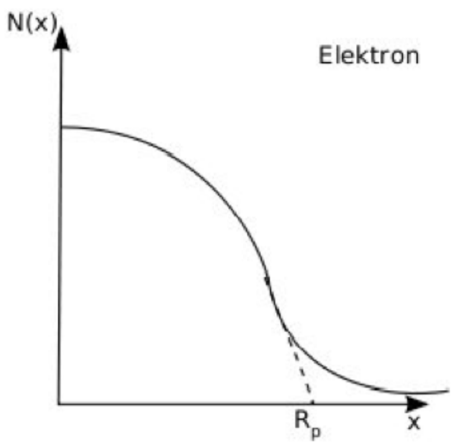
Transverse deflection of an electron of energy $E=E_c$, after traversing a distance X_0 (= one radiation length):

	E_c (MeV)	R_M (cm)	X_0 (cm)
Pb	7.2	1.6	0.56
scint.	80	9.1	42
NaI	12.5	4.4	2.6

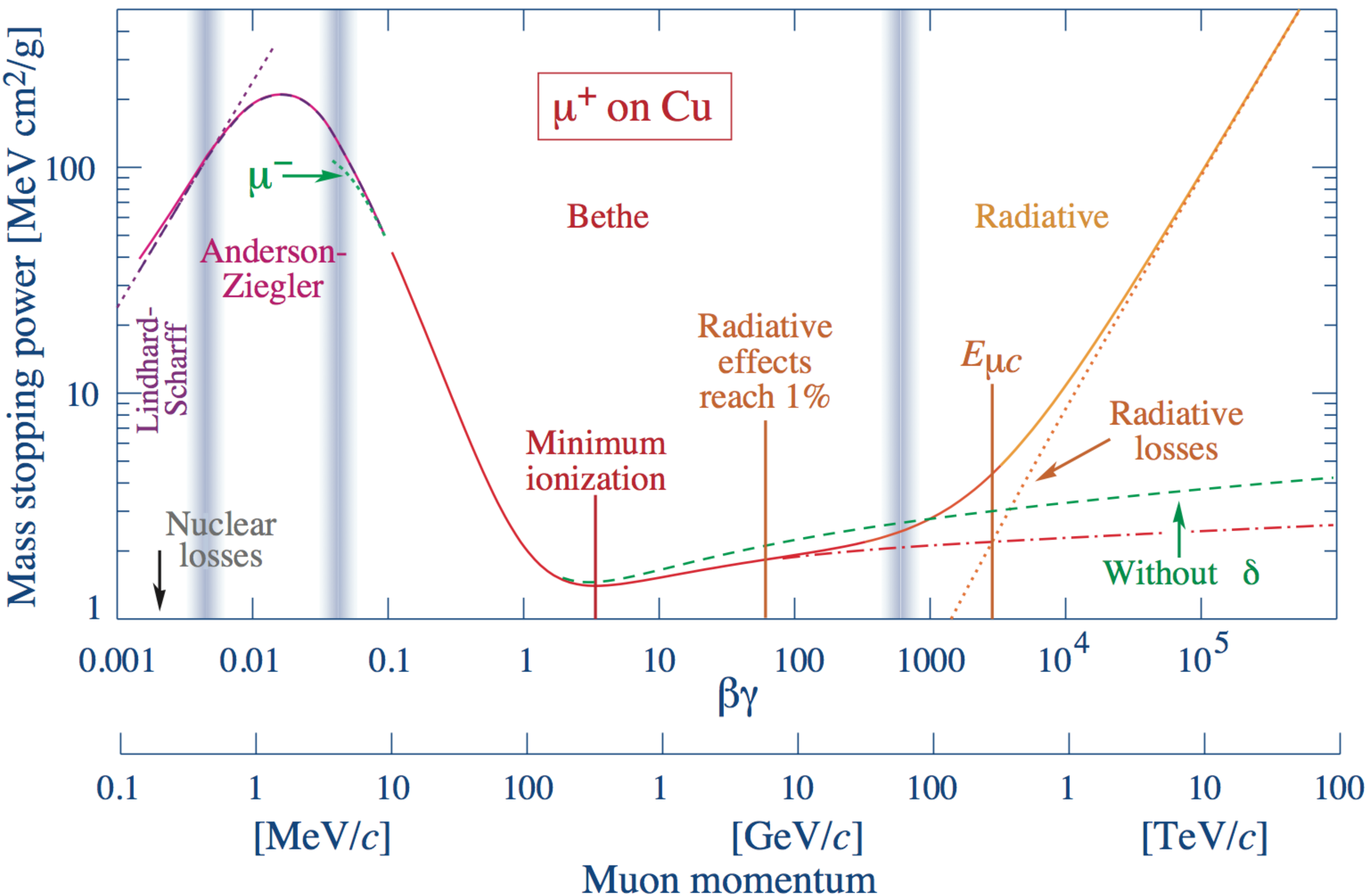
Molière radius:

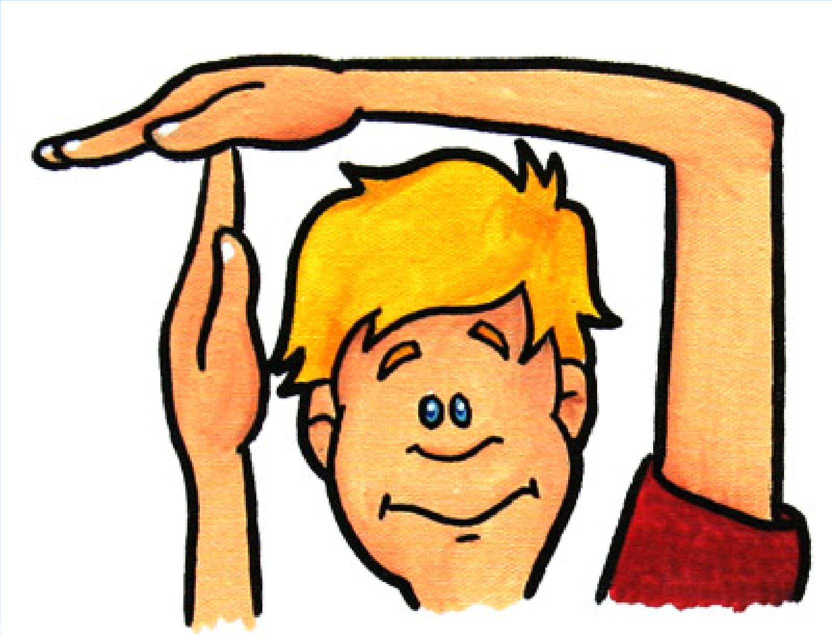
$$\Delta y = R_M = \frac{21\,\mathrm{MeV}}{E_c} X_0$$





Bethe-Bloch curve for muons





Interaction with matter

Outline for today:

- Energy loss by ionization (by “heavy” particles)
- Interaction of electrons with matter:
  - Energy loss by ionization
  - Bremsstrahlung
- Cherenkov effect
- Transition radiation
- Interaction of photons
  - Photoelectric effect
  - Compton scattering
  - Pair production

Charged particles

Cherenkov effect

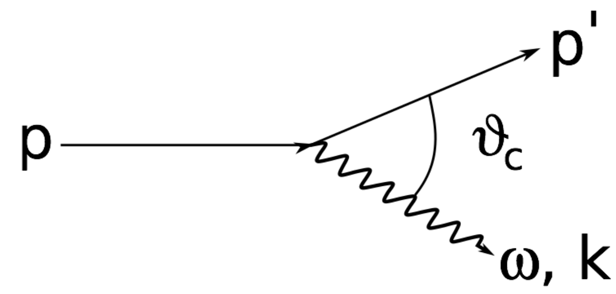
Cherenkov 1934

A charged particle with mass M and velocity $\beta = v/c$ travels in a medium with refractive index n:

$$n^2 = \varepsilon_1 = (c/c_m)^2$$

ε_1 = real part of the medium dielectric constant

c_m = speed of light in medium = c/n

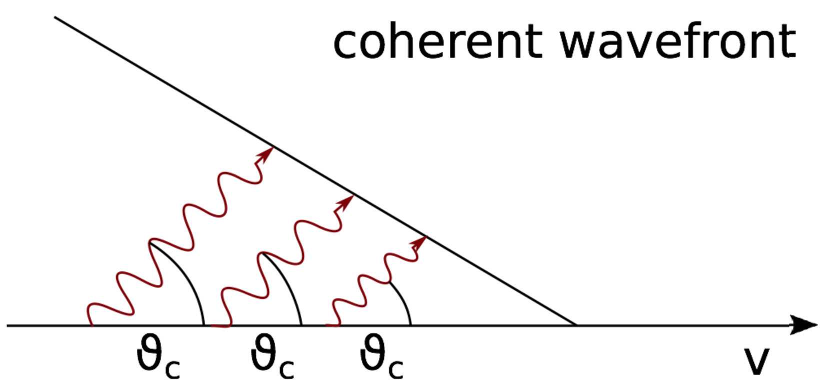


If $v > c_m$, namely $\beta > \beta_{thr} = 1/n \rightarrow$ real photons are emitted:

- Photons are "soft"

$$|p| \approx |p'|$$
$$\omega \ll \gamma M c^2$$

- Characteristic emission angle

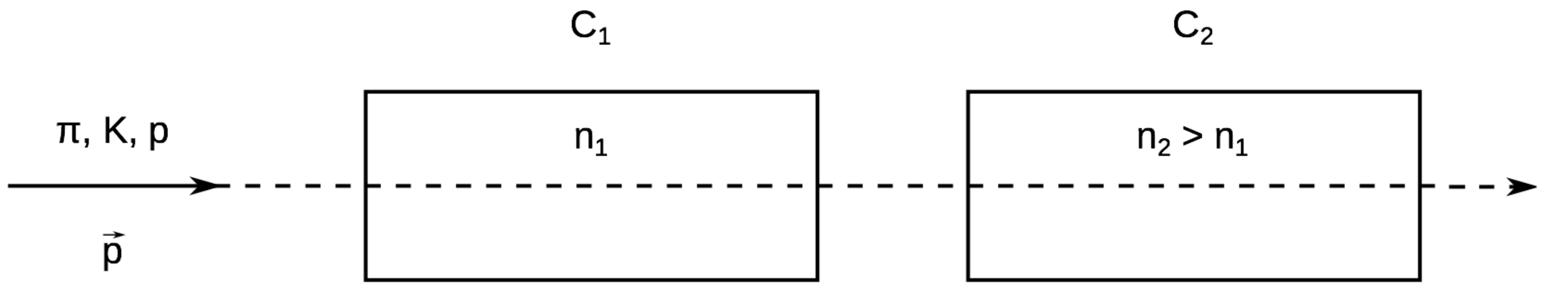


$$\cos\theta_c = \frac{\omega}{k \cdot v} = \frac{1}{n\beta}$$

Cherenkov angle

Cherenkov: first application

Threshold detector: use different materials (refractive indices) such that particles of different masses, at equal momentum p, produce Cherenkov radiation of not (pass the threshold or not):



Choose n_1, n_2 such that for a given p ($\beta = p/E$):

$$\beta_\pi > \frac{1}{n_1} \qquad \beta_K, \beta_p < \frac{1}{n_1}$$

$$\beta_\pi, \beta_K > \frac{1}{n_2} \qquad \beta_p < \frac{1}{n_2}$$

Particle identification: light in C_1 and C_2 → pion

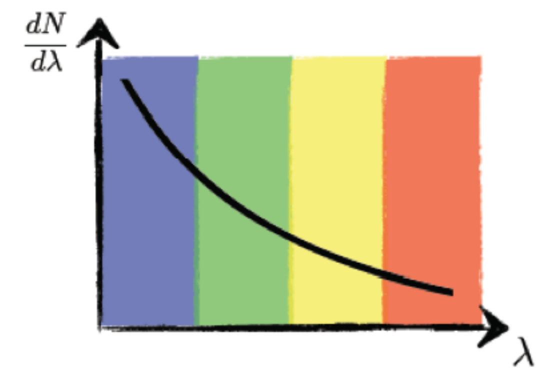
light in C_1 and not in C_2 → kaon

no light in both C_1 and C_2 → proton

Cherenkov radiation: spectrum

Consider the spectrum of emitted photons per unit length versus **wavelength**: short wavelengths dominate (blue)

$$\frac{d^2N}{d\lambda dx} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right) = \frac{2\pi\alpha z^2}{\lambda^2}\sin^2\theta_C$$



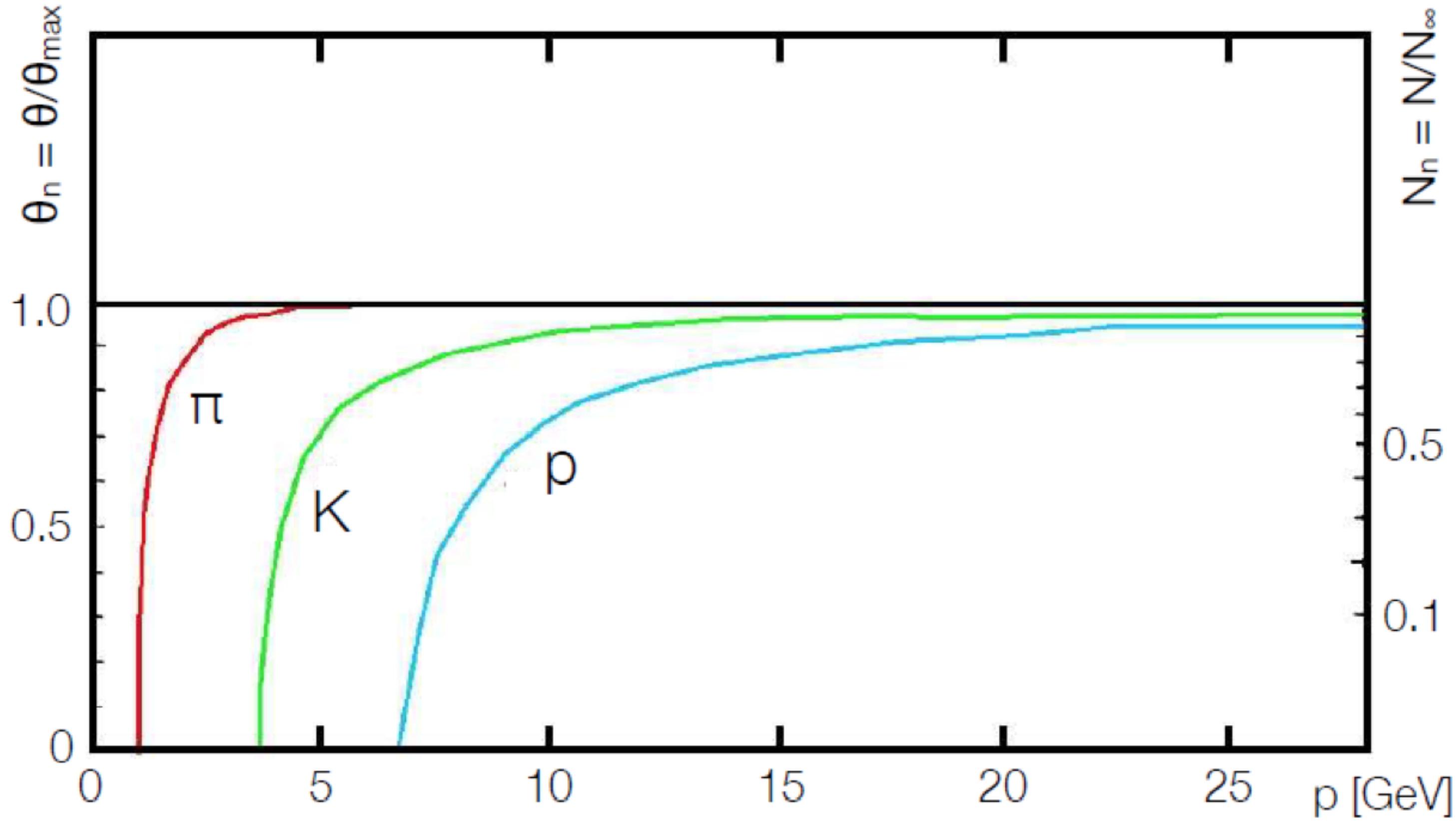
→ consider the typical sensitivity range of a good/typical photomultiplier (300-600 nm):

Energy loss: the energy loss by Cherenkov radiation is negligible wrt the one by ionization!

typical photon energy:	$\simeq 3$ eV
in water	$\left.\frac{dE}{dx}\right\|_{cher} = 0.5$ keV/cm $= 0.5$ keV/g/cm^2
cf. ionization	$\left.\frac{dE}{dx}\right\|_{ion} \geq 2$ MeV/g/cm^2

Cherenkov effect: momentum dependence

Asymptotic behavior of the Cherenkov angle and the number of produced photons, as a function of the particle momentum p (for $\beta \rightarrow 1$):



$$\cos\theta_C \rightarrow \cos\theta_C^\infty = \frac{1}{n}$$

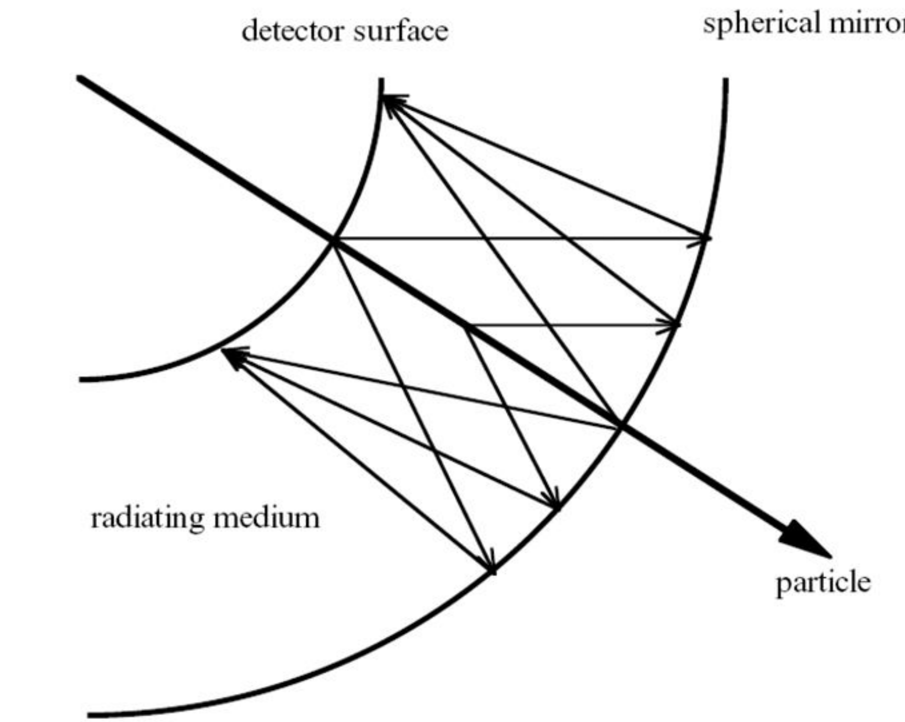
$$N_\gamma = x \cdot 370/\text{cm}\left(1 - \frac{1}{\beta^2 n^2}\right) \rightarrow x \cdot 370/\text{cm}\left(1 - \frac{1}{n^2}\right)$$

Application: measurement of β

In a medium of known refractive index n, measure the Cherenkov angle and therefore determine the particle $\beta = p/E$ (→ identity)

Principle of:

RICH – Ring Imaging CHerenkov Detector



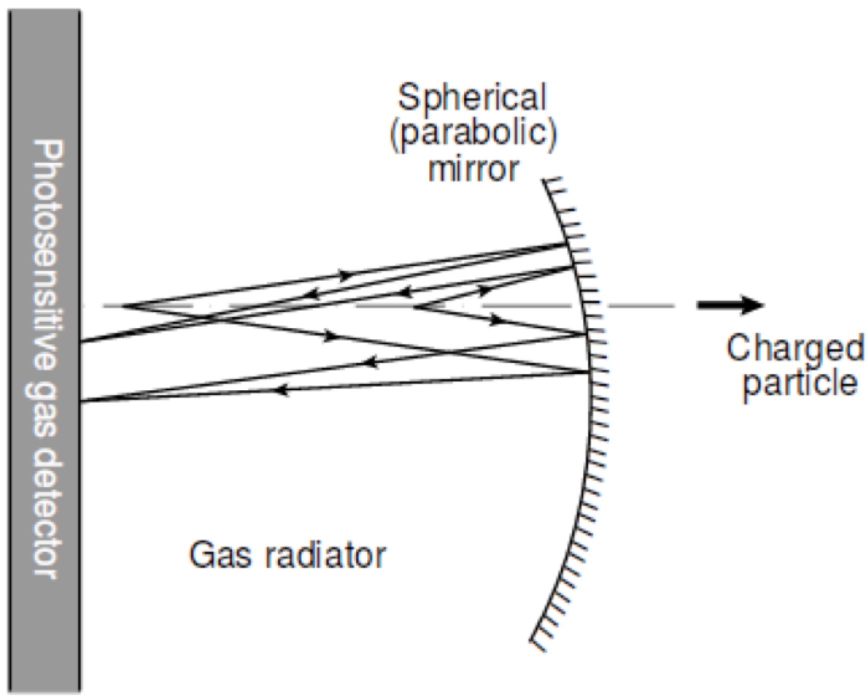
DIRC – Detection of Internally Reflected Cherenkov light

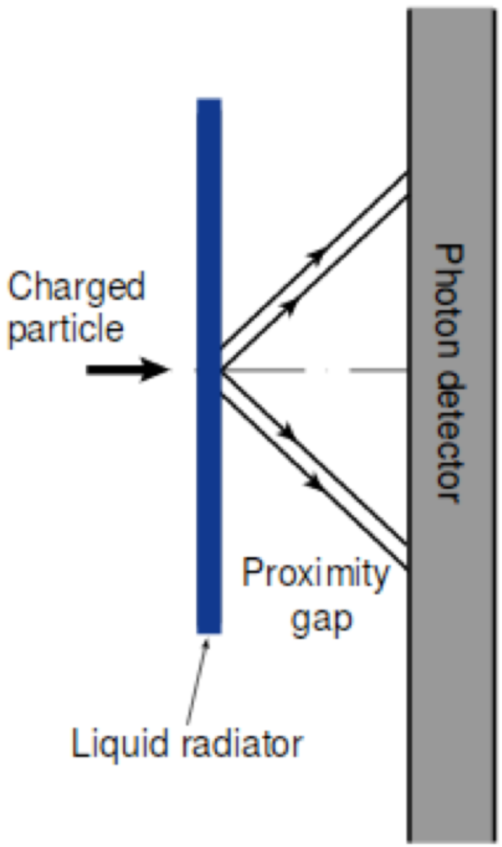
DISC – special variant of DIRC

RICH detectors

Principle: image the Cherenkov cone into a ring, of which measure the radius. Particle momentum provided by other detectors

Components: radiator (+ mirror) + photon detector



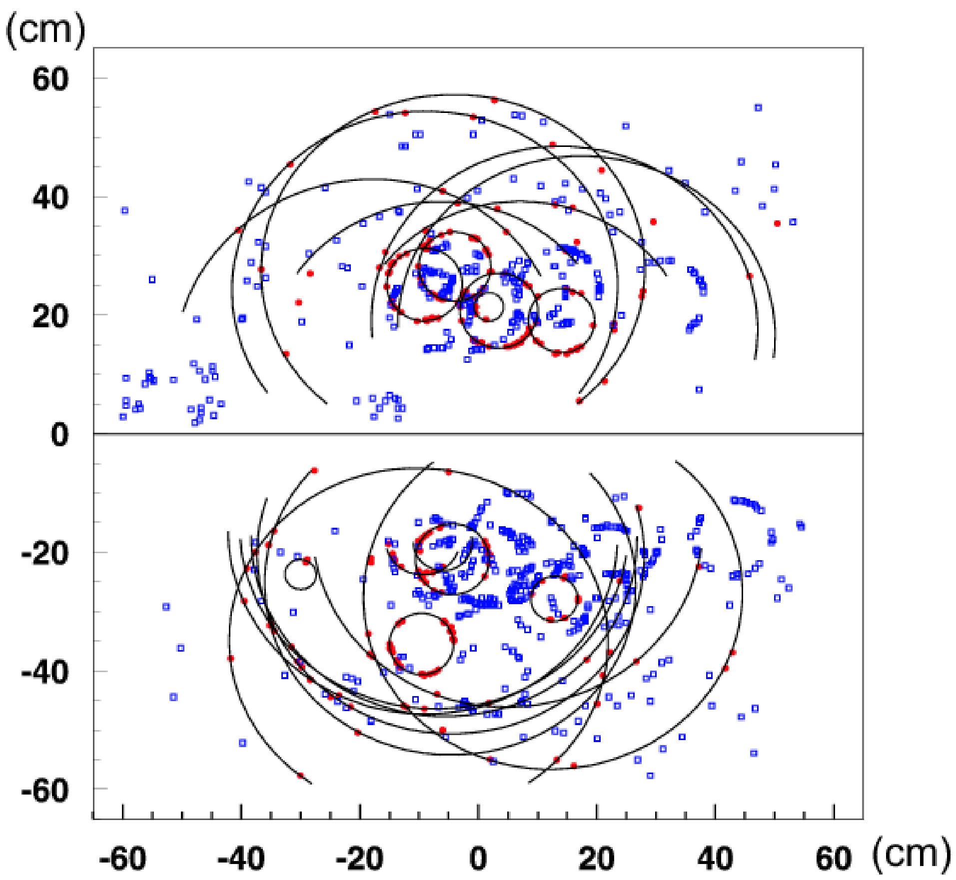


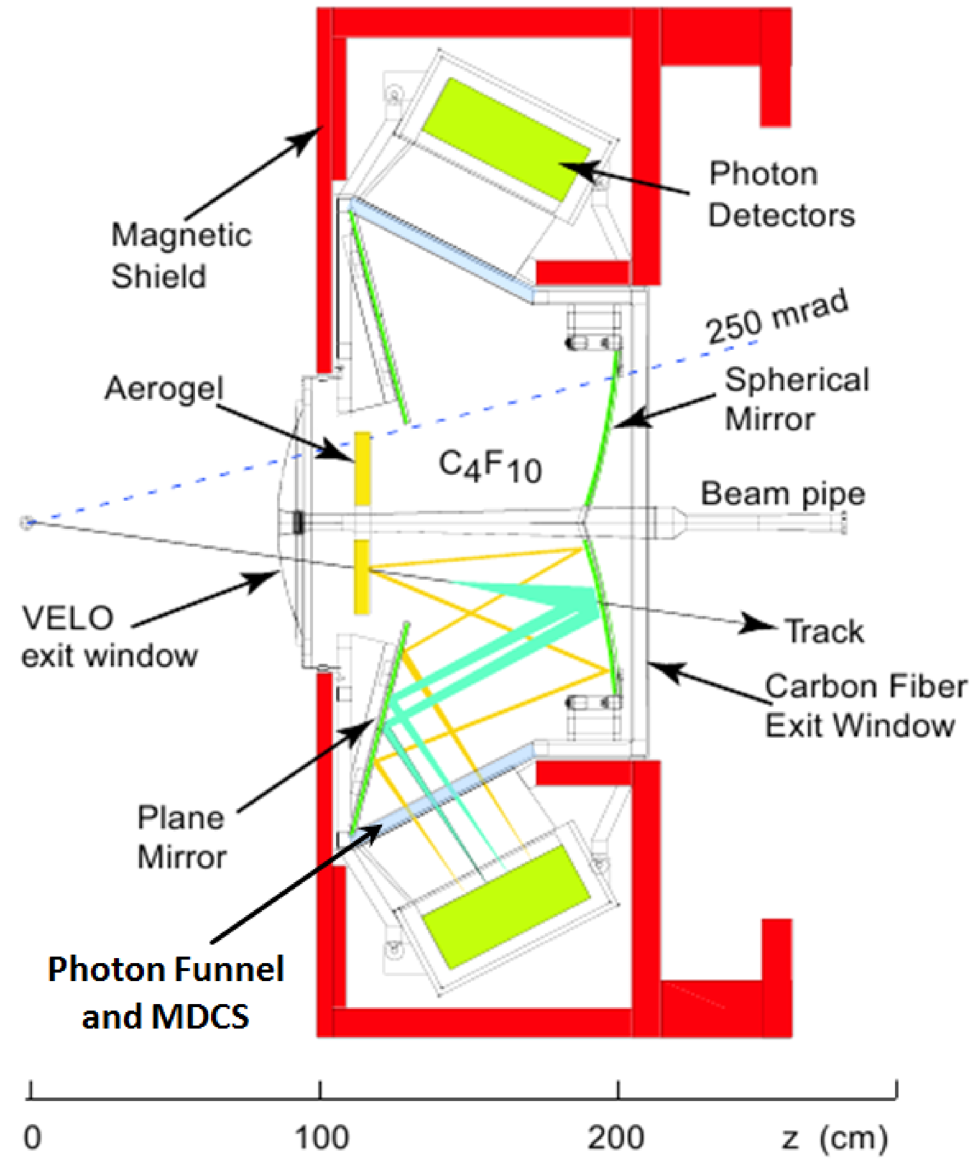
The LHCb RICH-1 detector

Two radiators: aerogel + C_4F_{10}

Spherical + flat mirrors

Hybrid Photon Detectors

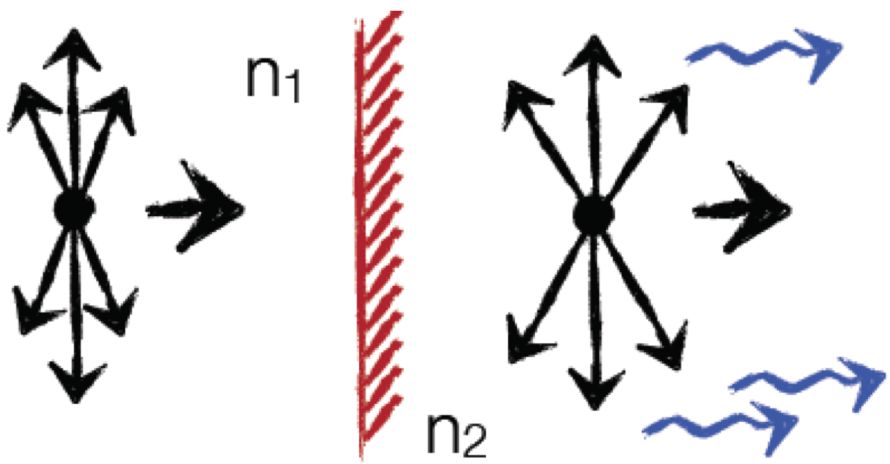




Spherical mirror array: LHCb

Transition radiation

A particle at high energy (= large γ) crossing the boundary between two different dielectrics, having different indices of refraction, can produce "transition radiation" → can emit real photons



- Predicted by Ginzburg and Frank (1946)
- Observed (optically) by Goldsmith and Jelley (1959)
- Experimental confirmation with X-ray measurement (1970s)

Explanation: re-arrangement of electric field

Transition radiation: full calculation

Full quantum mechanical calculation:

- Interference: coherent superposition of radiation from neighboring points in vicinity of the track
  → angular distribution strongly peaked forward
- Depth from boundary up to which contributions add coherently → formation length D

$$\theta \simeq \frac{1}{\gamma}$$

$$D \simeq \frac{\gamma \cdot c}{\omega_p}$$

Typical values: polyethylene CH_2 ω_p = 20 eV, ρ=1 g/cm^3 → D ≈ 10 μm

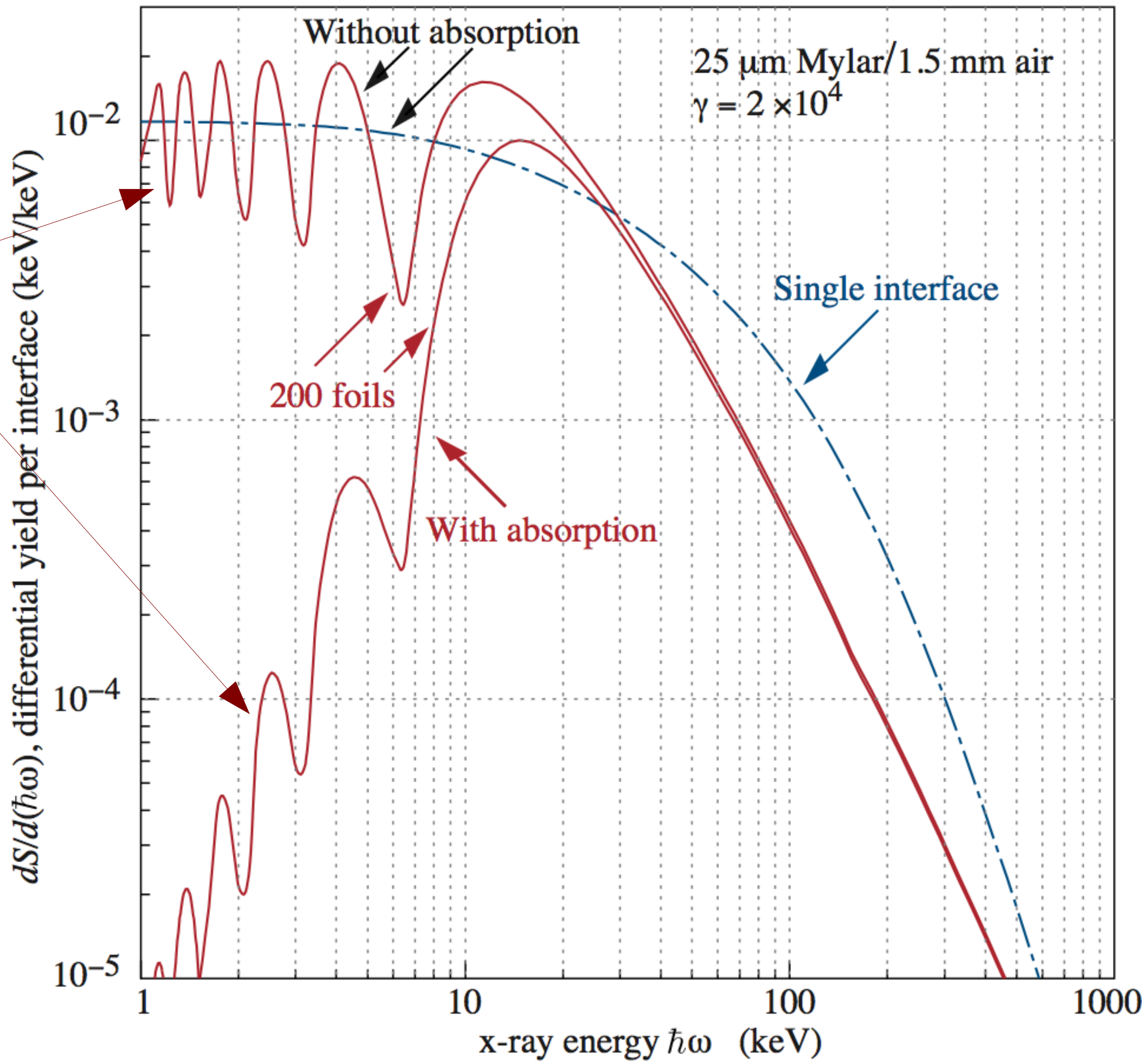
For d > D → absorption effects important! Consider foils of thickness D!

Per boundary: ~ α photons → many boundaries !!

O(100 foils) → $\langle n_\gamma \rangle$ ~ 1-2

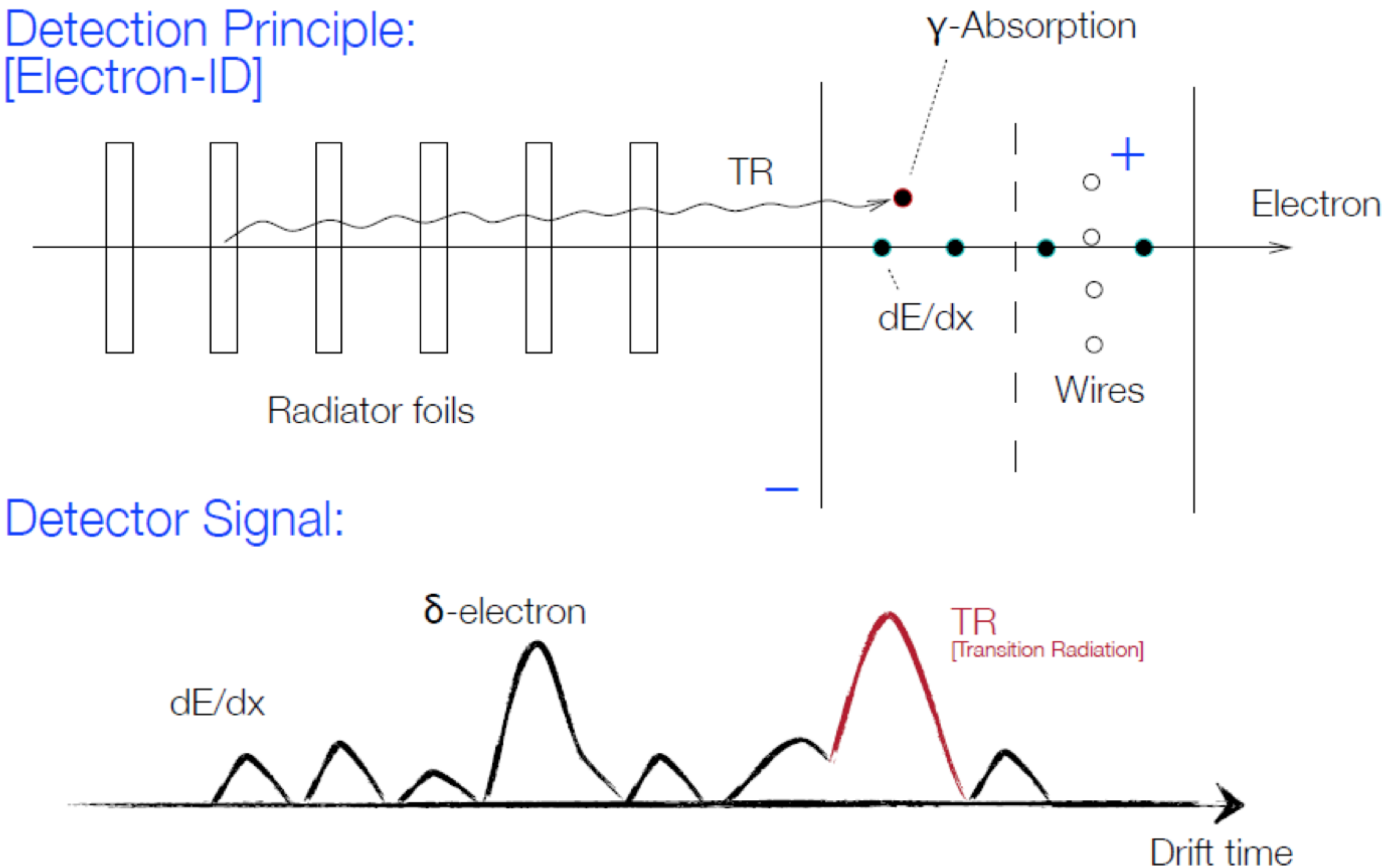
Transition radiation spectrum

Oscillations are due to interference between successive boundaries

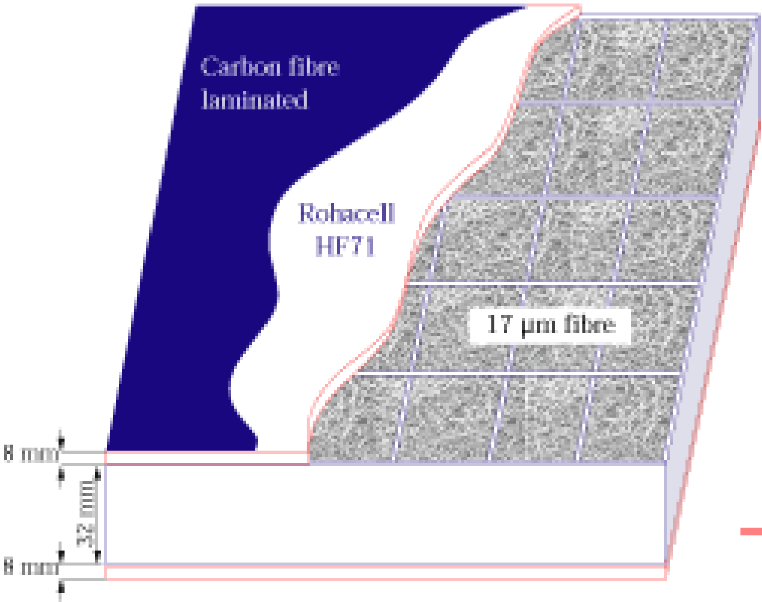


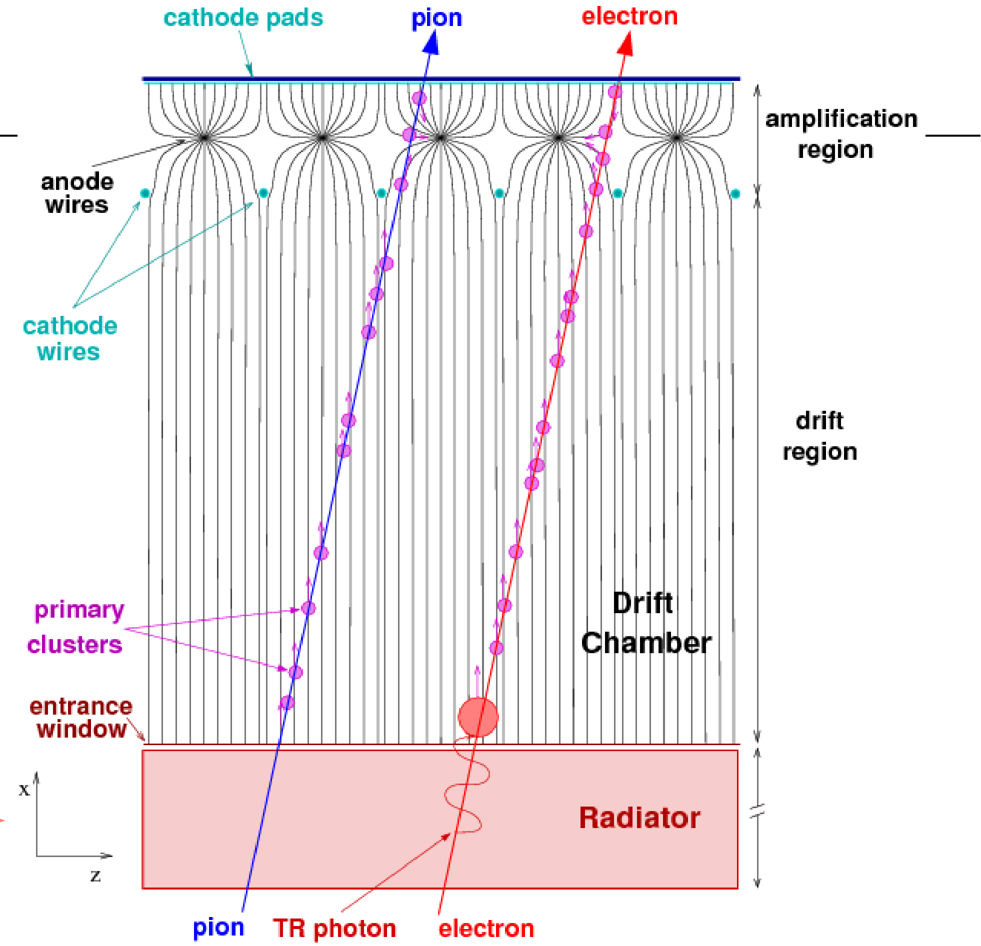
X-ray photon energy spectra for a radiator consisting of 200 25 μm thick foils of Mylar and for a single surface

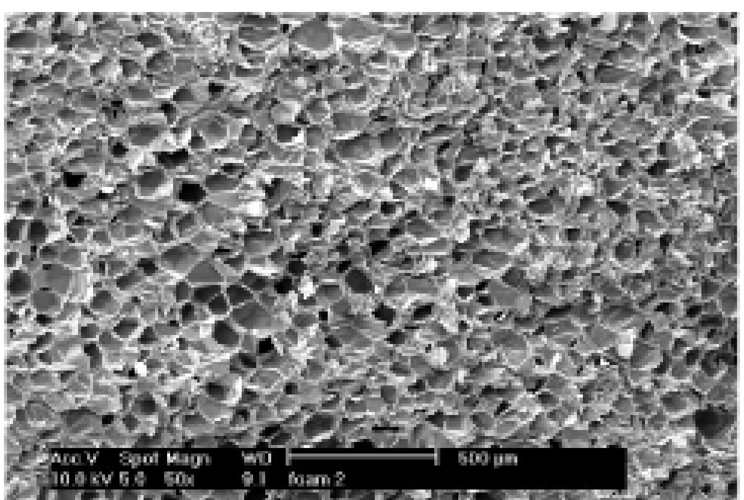
Principle of a transition radiation detector

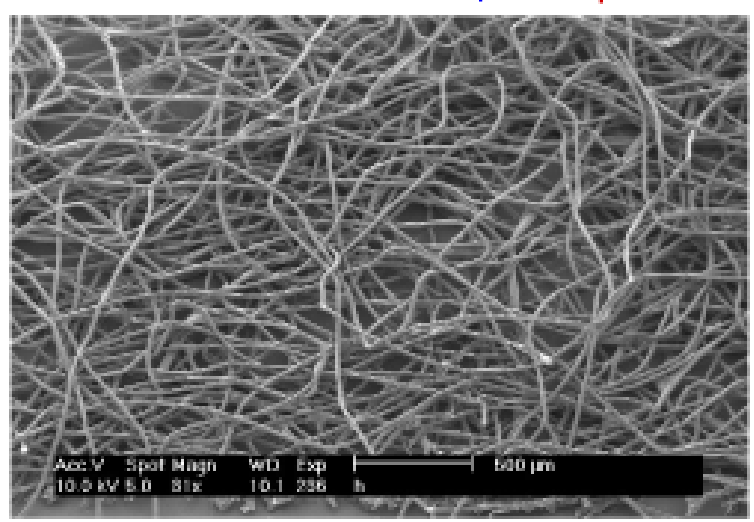


ALICE TRD

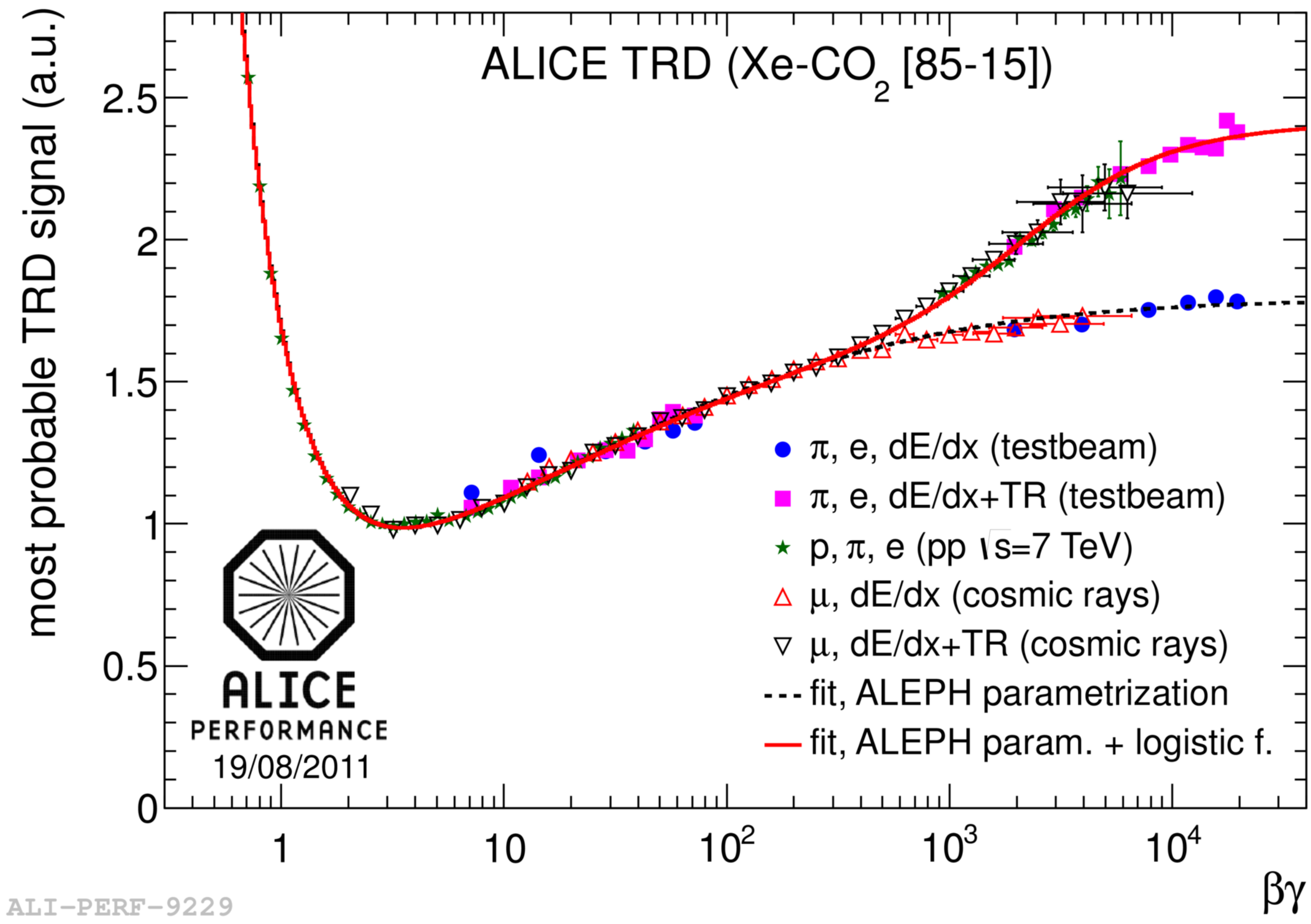

Carbon fibre laminated
Rohacell HF71
17 µm fibre
8 mm
32 mm
8 mm


cathode pads
pion
electron
amplification region
anode wires
cathode wires
drift region
primary clusters
Drift Chamber
entrance window
x
z
Radiator
pion
TR photon
electron





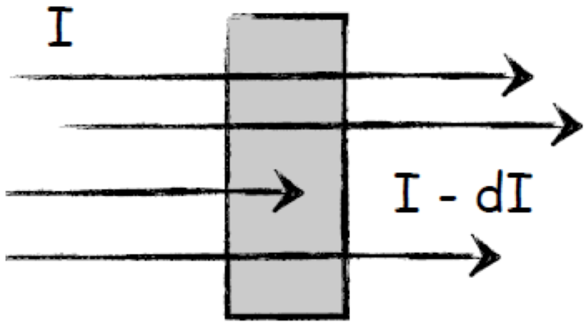
ALICE TRD



Demonstration of the onset of TR at $\beta\gamma \approx 500$ (X. Lu, Hd)

Interaction of photons with matter

Characteristic of photons: can be removed from incoming beam of intensity "I", with one single interaction:



$dI = - I \mu dx$

$\mu (E, Z, \rho)$: absorption coefficient

Lambert-Beer law of attenuation:

$I(x) = I_0 \exp(- \mu x)$

- Mean free path of photon in matter: $$\lambda = \frac{1}{n\sigma} = \frac{1}{\mu}$$
- To become independent from state (liquid, gaseous): mass absorption coefficient: $$\tau = \frac{\mu}{\rho} = N_A \frac{\sigma}{A}$$

Example: E_γ = 100 keV, Z=26 (iron), λ= 3 g/cm^2 or 0.4 cm

Interaction processes

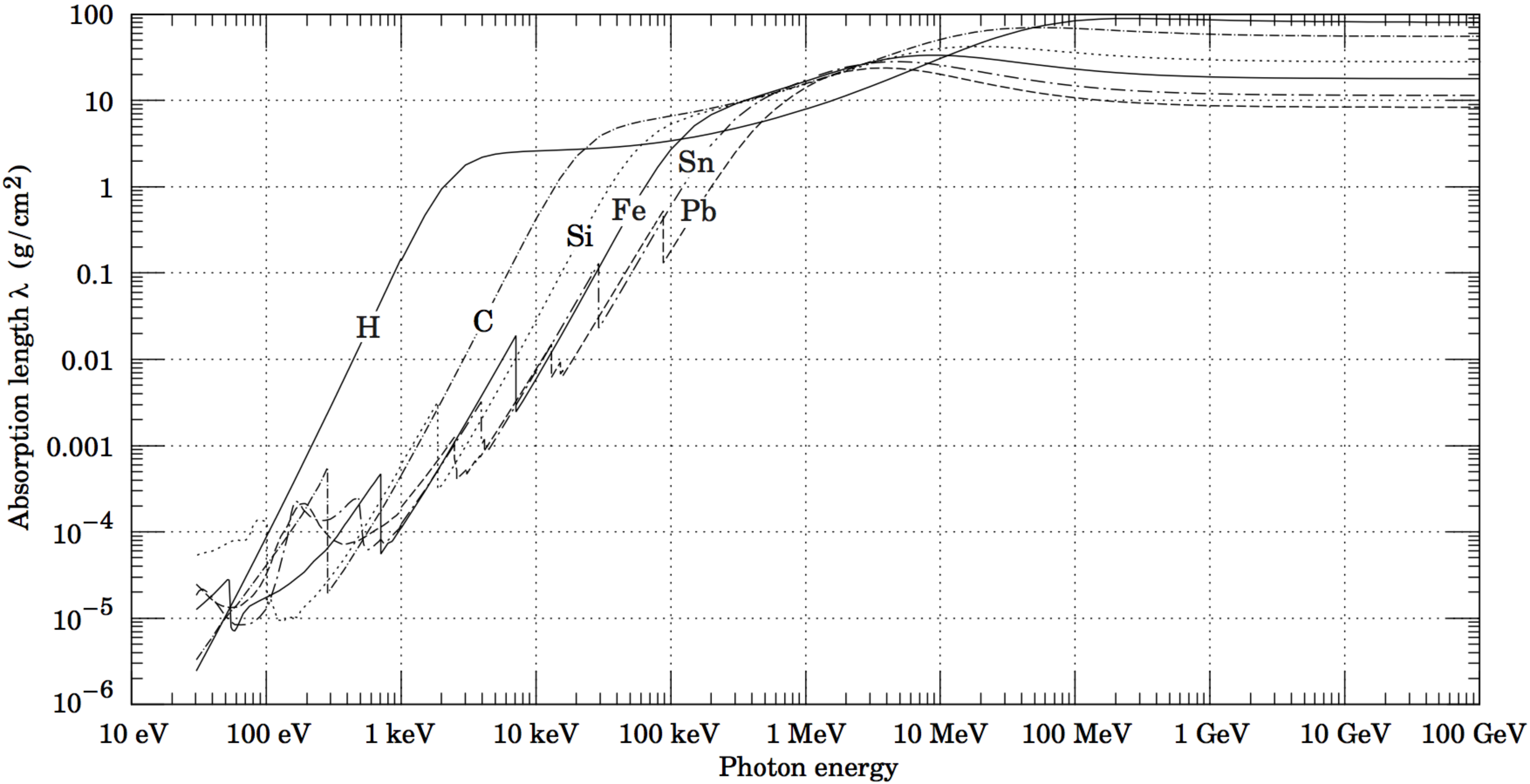
The most important processes of interaction of photons with matter, in order of growing importance with increasing photon energy E, are:

- Photoelectric effect
- Compton scattering: incoherent scattering off an electron
- Pair production: interaction in nuclear field

Other processes, not as important for energy loss:

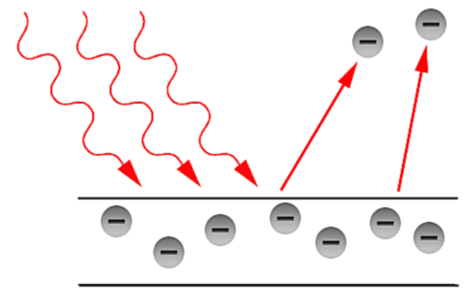
- Rayleigh scattering: coherent $\gamma + A \rightarrow \gamma + A$: atom neither ionized nor excited
- Thomson scattering: elastic scattering $\gamma + e \rightarrow \gamma + e$
- Photo nuclear absorption: γ + nucleus $\rightarrow$ (p or n) + nucleus
- Hadron pair production: $\gamma + A \rightarrow h^{+} + h^{-} + A$

Absorption length



Particle Data Group, 2016

Photoelectric effect



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

$$E_e = h\nu - I_b$$

Where: $h\nu = E\gamma$ = photon energy,

I_b = binding energy of the electron (K, L, M absorption edges)

Binding energy depends strongly on Z → the cross section will depend strongly on Z:

- $I \ll E_\gamma \ll mc^2$: $\sigma_{Ph} = \alpha \pi a_b Z^5 \left(\frac{I_0}{E_\gamma}\right)^{\frac{7}{2}}$

  where:

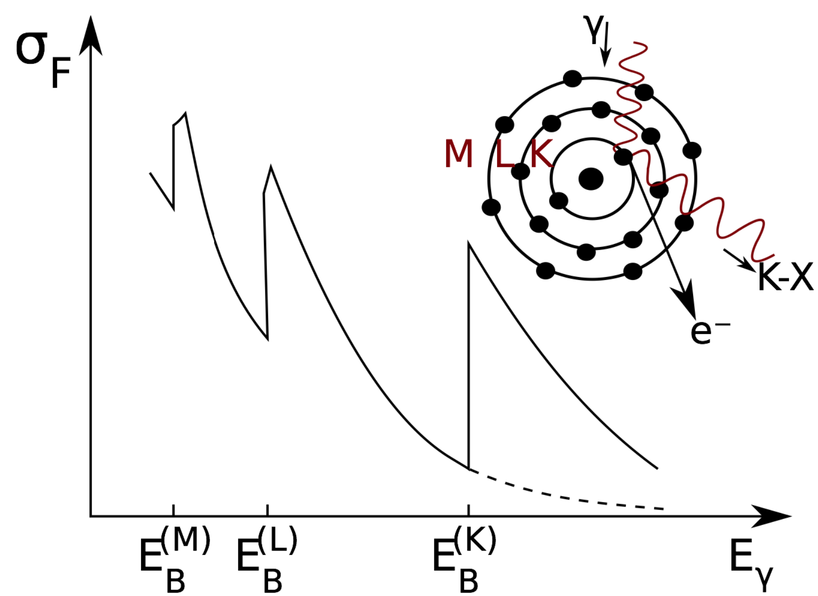
  $a_b = 0.53 \times 10^{-10}$ m

  $I_0 = 13.6$ eV

  e.g. = 0.1 MeV → $\sigma_{Ph}(Fe) = 29$ b

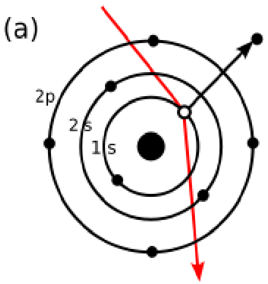
  $\sigma_{Ph}(Pb) = 5$ kb

- $E_\gamma \gg mc^2$: $\sigma_{Ph} \propto \frac{Z^5}{E_\gamma}$



Photoelectric effect - 2

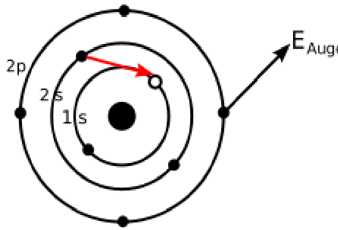
The de-excitation of the excited atom can happen via two main processes:



Electron collision

- Auger electrons: atom$^{**\ +} \rightarrow$ atom$^{*\ +}$ + e^-

  Auger electrons deposit their energy locally due to their very small energy (<10 keV)



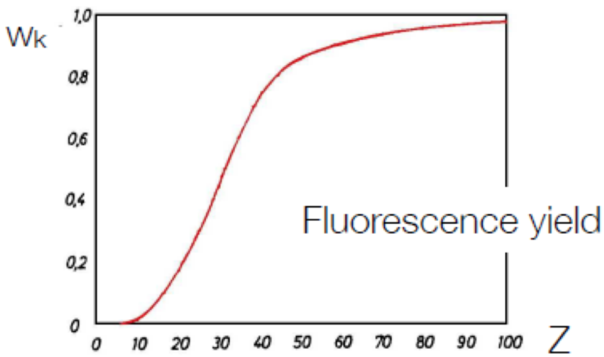
Auger electron emission

- Fluorescence: atom$^{**\ +} \rightarrow$ atom$^{*\ +}$ + γ

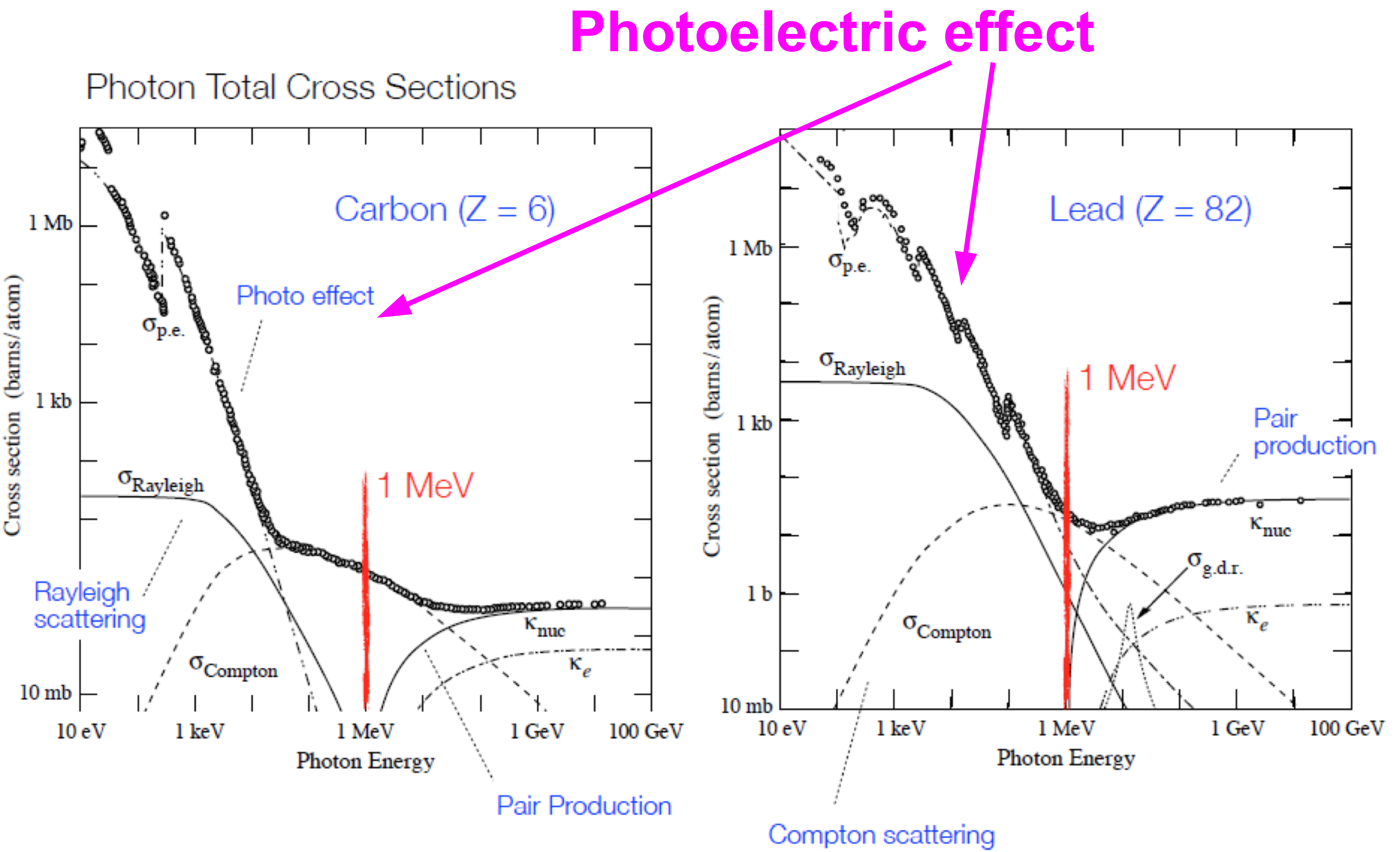
  Fluorescence photons (X-rays) must interact via the photoelectric effect $\rightarrow$ much longer range

  The relative fluorescence yield increases with Z

  w_K = P(fluor.) / [P(fluor.) + P(Auger)]



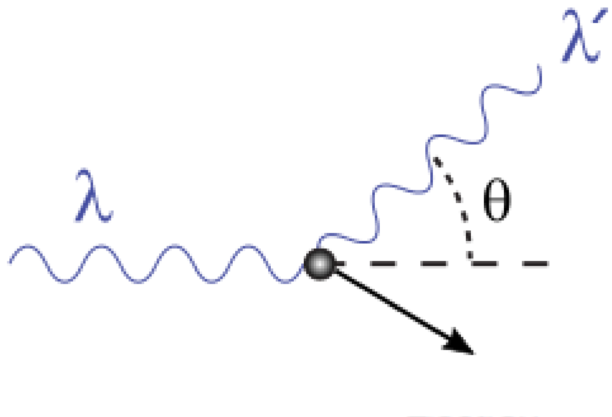
Photon total cross section



Compton scattering

Incoherent scattering of photon off an electron:

γ + e⁻ → (γ)' + (e⁻)'



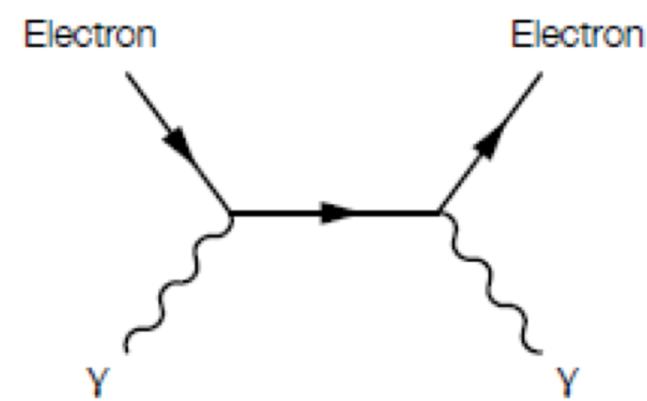
Energy of the outgoing photon:

$$E'_\gamma = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_e c^2}(1 - \cos\theta)}$$

Kinetic energy of the outgoing electron:

$$T_e = \frac{\frac{E_\gamma^2}{m_e c^2}(1 - \cos\theta)}{1 + \frac{E_\gamma}{m_e c^2}(1 - \cos\theta)}$$

Feynman diagram



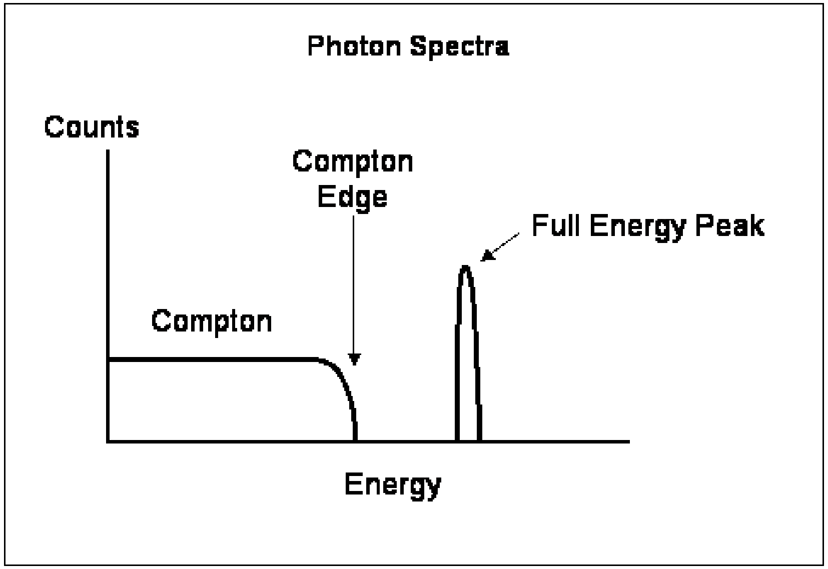
Max energy transfer in back scattering:

$$\left(\frac{T_e}{E_\gamma}\right)_{max} = \frac{E_\gamma}{m_e c^2} \frac{2}{1 + \frac{2E_\gamma}{m_e c^2}}$$

$$\Delta E = E_\gamma - T_{e,max} = \frac{E_\gamma}{1 + \frac{2E_\gamma}{m_e c^2}} \rightarrow \frac{m_e c^2}{2}$$

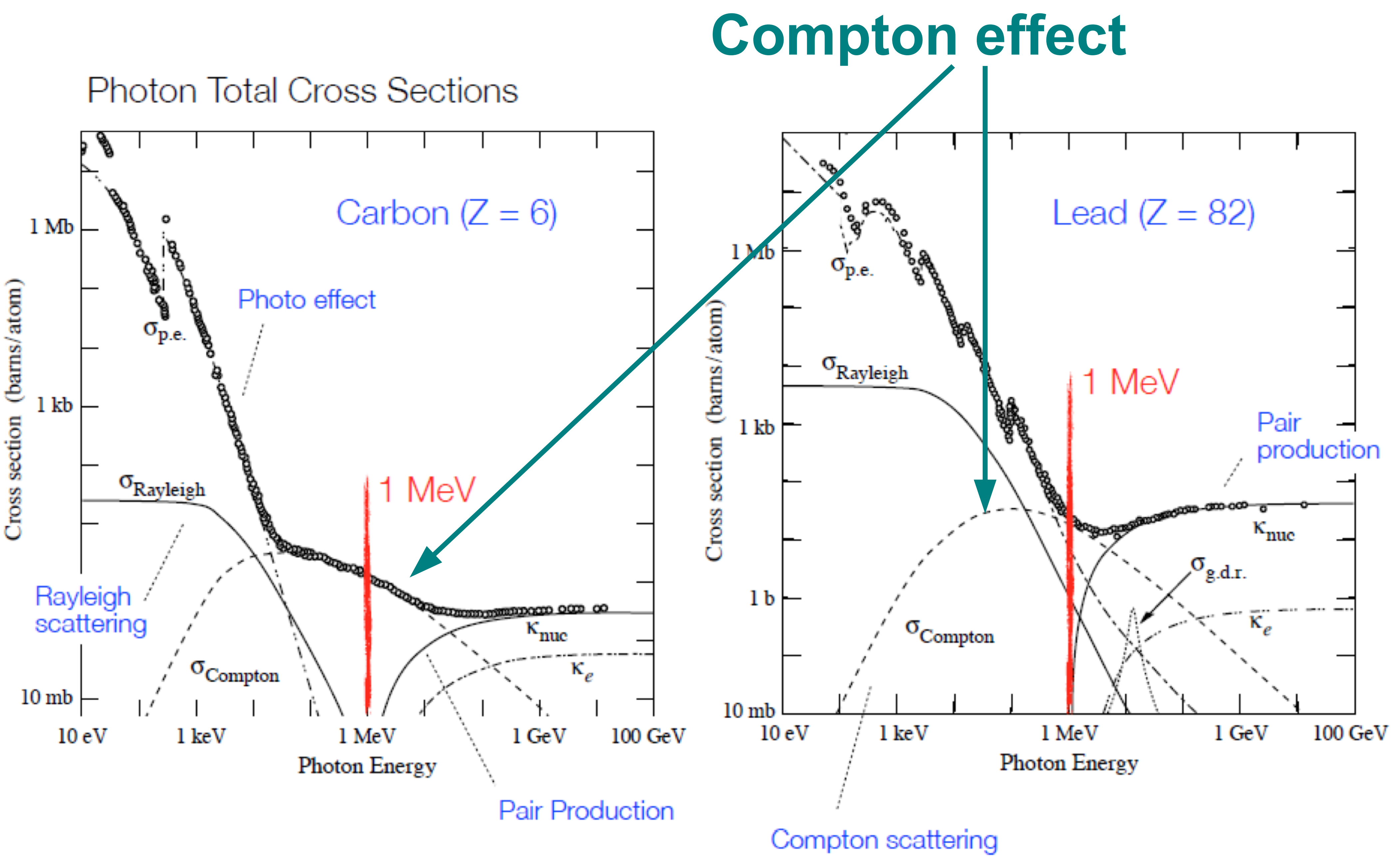
Compton edge

If the scattered photon is not absorbed in the detector material, there will be a small amount of energy “missing” from the Full Energy Peak (FEP) → Compton edge



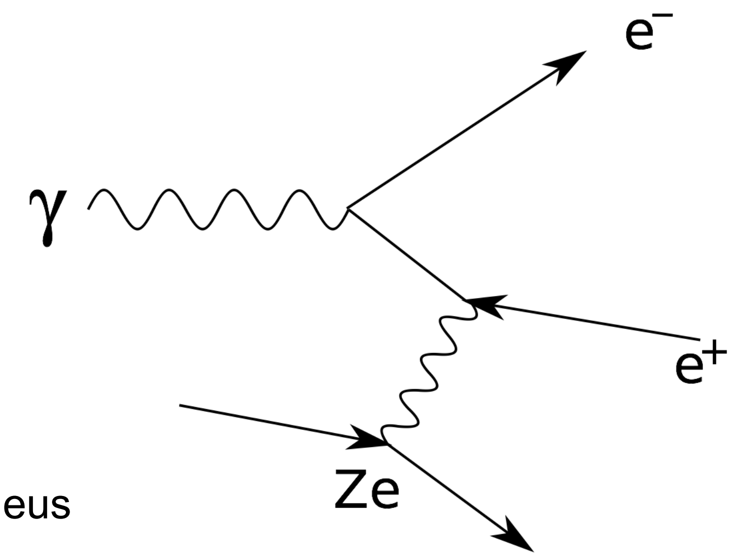
FEP: photoelectric effect and Compton effect when the scattered photon is absorbed in the detector. Intensity depends on detector volume, width depends on detector resolution.

Photon total cross section



Pair production: Bethe-Heitler process

Interaction in the Coulomb field of the atomic nucleus (not possible in free space)



Energy threshold:

$$E_\gamma \geq 2 m_e c^2 \left(1 + \frac{m_e}{m_n}\right)$$

2x electron mass — kinetic energy transferred to nucleus

Angular distribution: the produced electrons are in a narrow forward cone, with opening angle of $\theta = m_e / E_\gamma$

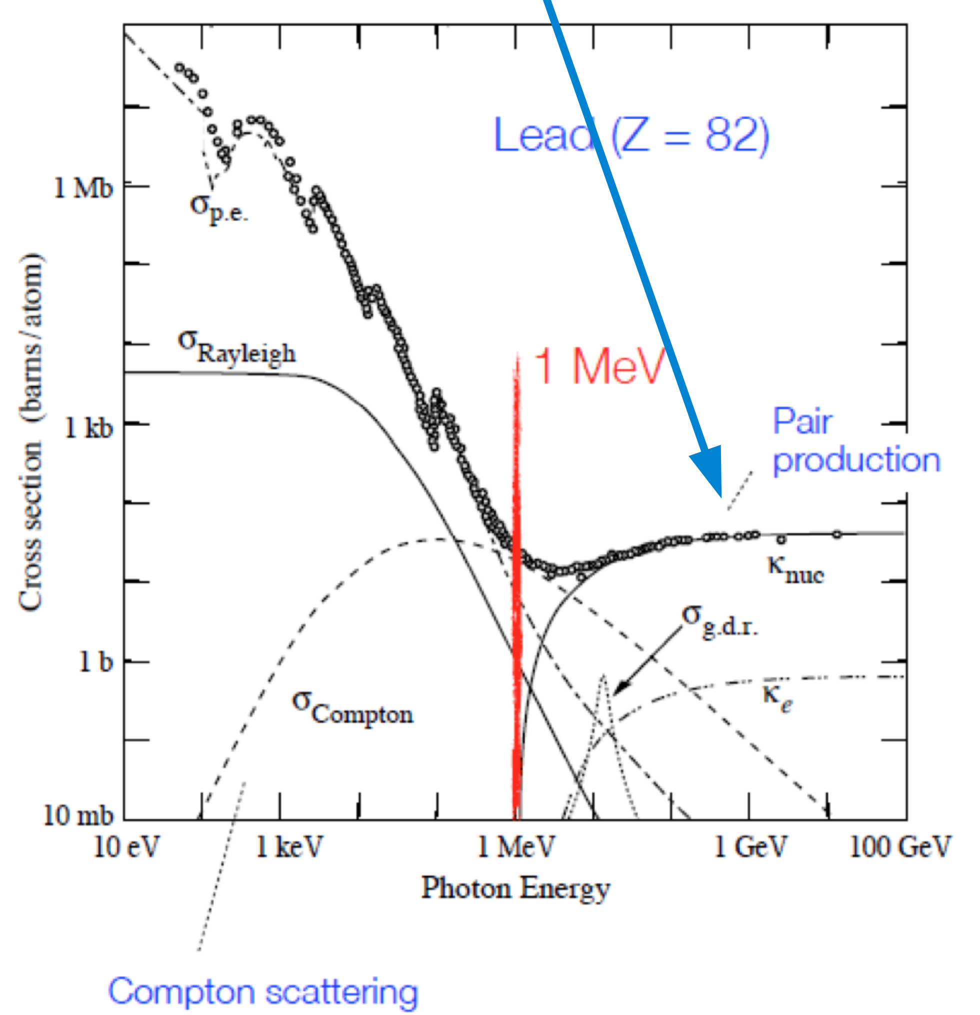
Pair production: Bethe-Heitler process

Cross section: raises above threshold, but eventually saturates at large E_γ because of screening effects of the nuclear charge

$E_\gamma \gg m_e c^2$

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

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



Pair production: Bethe-Heitler process

Pair production cross section

$$\sigma_{\text{Pair}} \approx \frac{7}{9} 4 \alpha r_e^2 Z^2 \ln\frac{183}{Z^{1/3}} = \frac{7}{9}\frac{A}{N_A} X_0$$

X_0: radiation length (in cm or g/cm^2)

Absorption coefficient:

(μ = nσ n=particle density)

$$\mu_{\text{Pair}} = \rho \cdot \frac{N_A}{A} \sigma_{\text{Pair}}$$

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

	ρ (g/cm^3)	X_0 (cm)
liq H_2	0.071	865
C	2.27	18.8
Fe	7.87	1.76
Pb	11.35	0.56
air	0.0012	30 420

Total photon cross section and absorption length

$$\sigma_{tot} = \sigma_{Ph} + \sigma_c + \sigma_p$$

$$\mu = \mu_{Ph} + \mu_c + \mu_p$$

$$\mu_i = n\sigma_i = \frac{N_A \rho}{A}\sigma_i$$

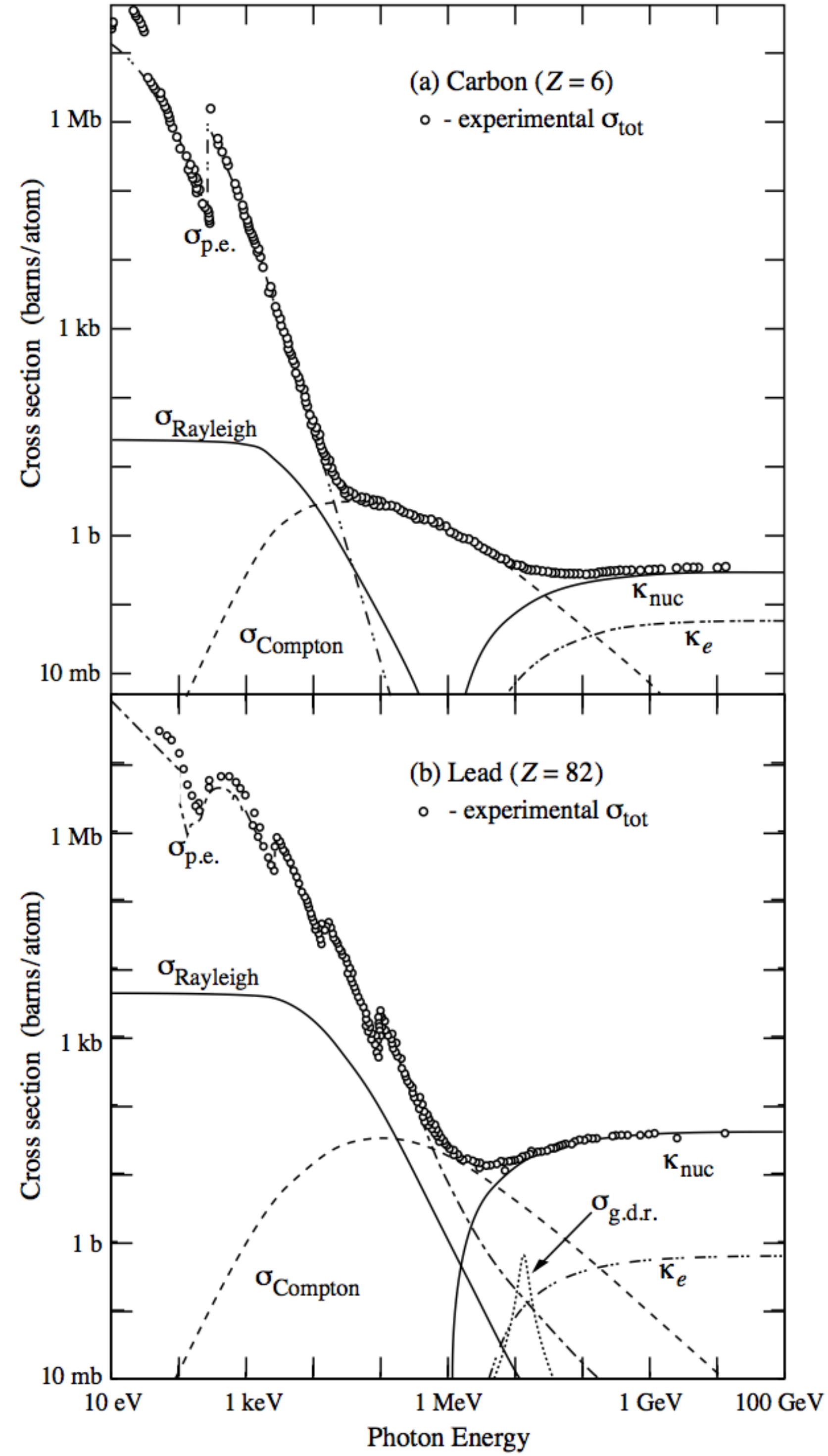
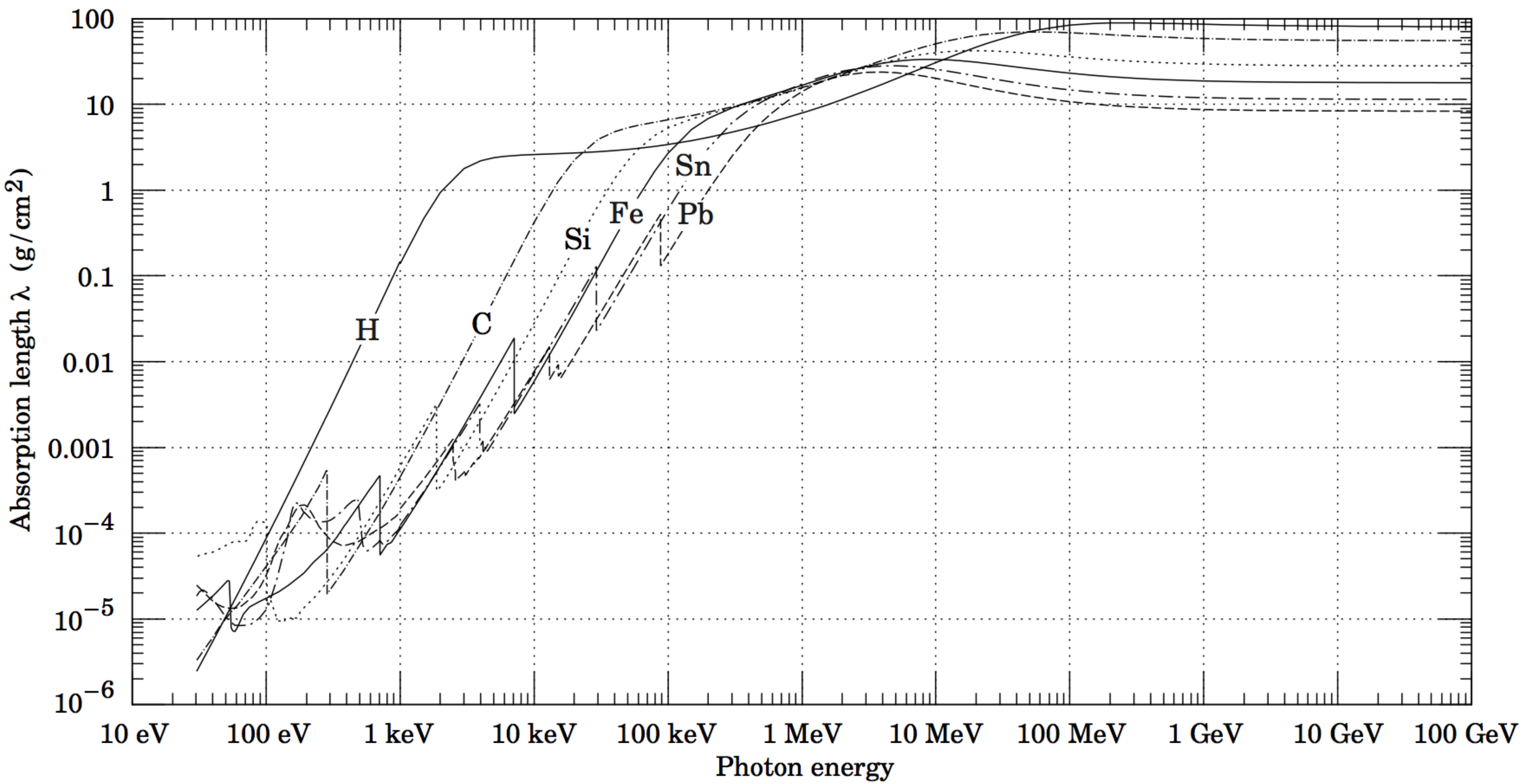


Figure 33.15: Photon total cross sections as a function of energy in carbon and lead, showing the contributions of different processes [51]:

$\sigma_{\text{p.e.}}$ = Atomic photoelectric effect (electron ejection, photon absorption)
σ_{Rayleigh} = Rayleigh (coherent) scattering–atom neither ionized nor excited
σ_{Compton} = Incoherent scattering (Compton scattering off an electron)
κ_{nuc} = Pair production, nuclear field
κ_e = Pair production, electron field
$\sigma_{\text{g.d.r.}}$ = Photonuclear interactions, most notably the Giant Dipole Resonance [52]. In these interactions, the target nucleus is broken up.

Original figures through the courtesy of John H. Hubbell (NIST).

Photon absorption length

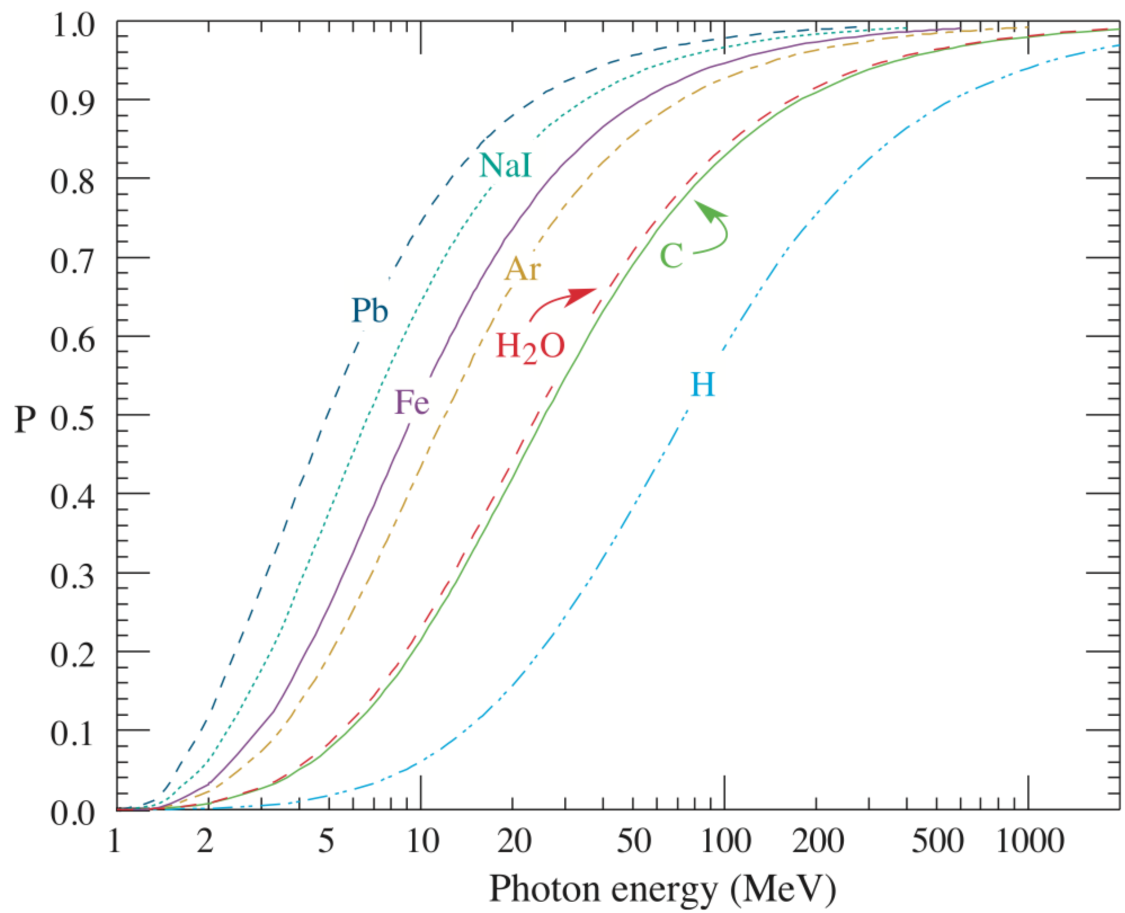


$$I(x) = I_0 \exp(-x/\lambda)$$

1 MeV photon travels about 1 cm in Pb, about 5 cm in C

Contribution by pair production

Probability P that a photon interaction will result in conversion to an e^+e^- pair



For increasing photon energy, pair production becomes dominant:

for Pb beyond 4 MeV

for H beyond 70 MeV

Summary: interaction with matter

- **Charged particles:**
  - Energy loss by ionization
    - Bethe-Bloch
    - Delta electrons
    - Landau distribution
  - Excitation
  - Multiple scattering
  - Bremsstrahlung (electrons, TeV μ)
  - Cherenkov effect
  - Transition radiation
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  - Pair production

- **Hadrons: strong interaction**
- **Neutrinos: weak interaction**

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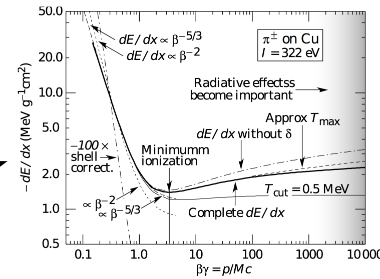

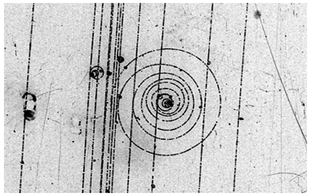

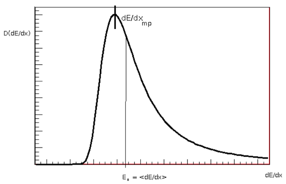

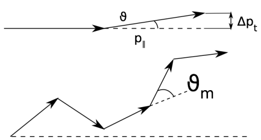

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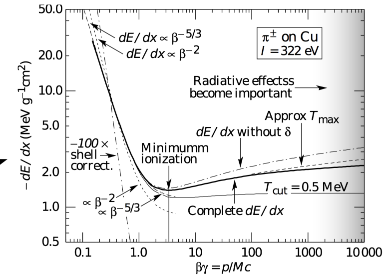

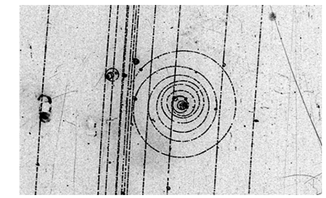

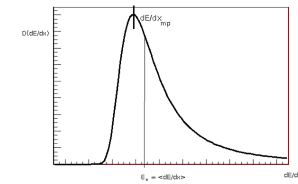

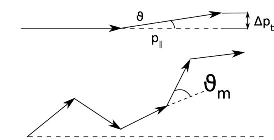

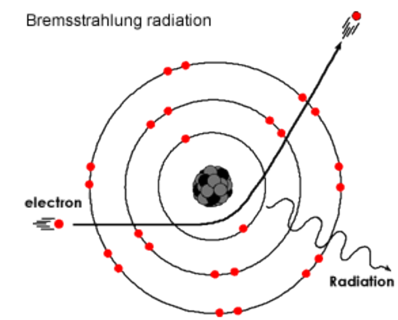

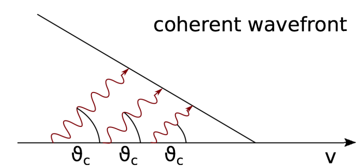

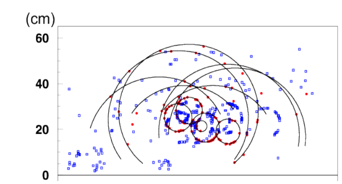

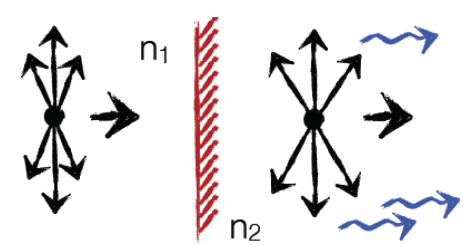

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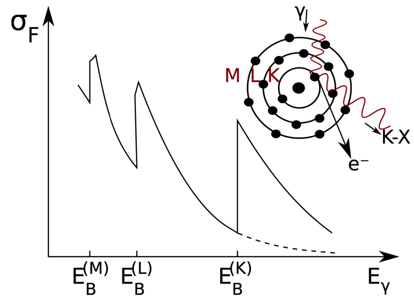

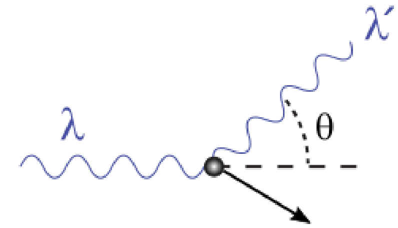

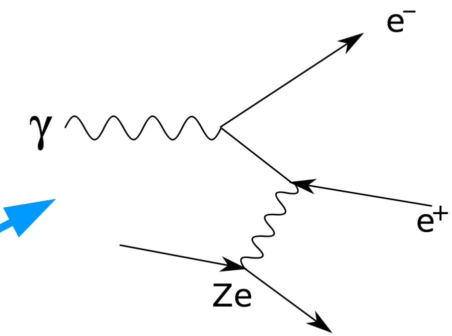

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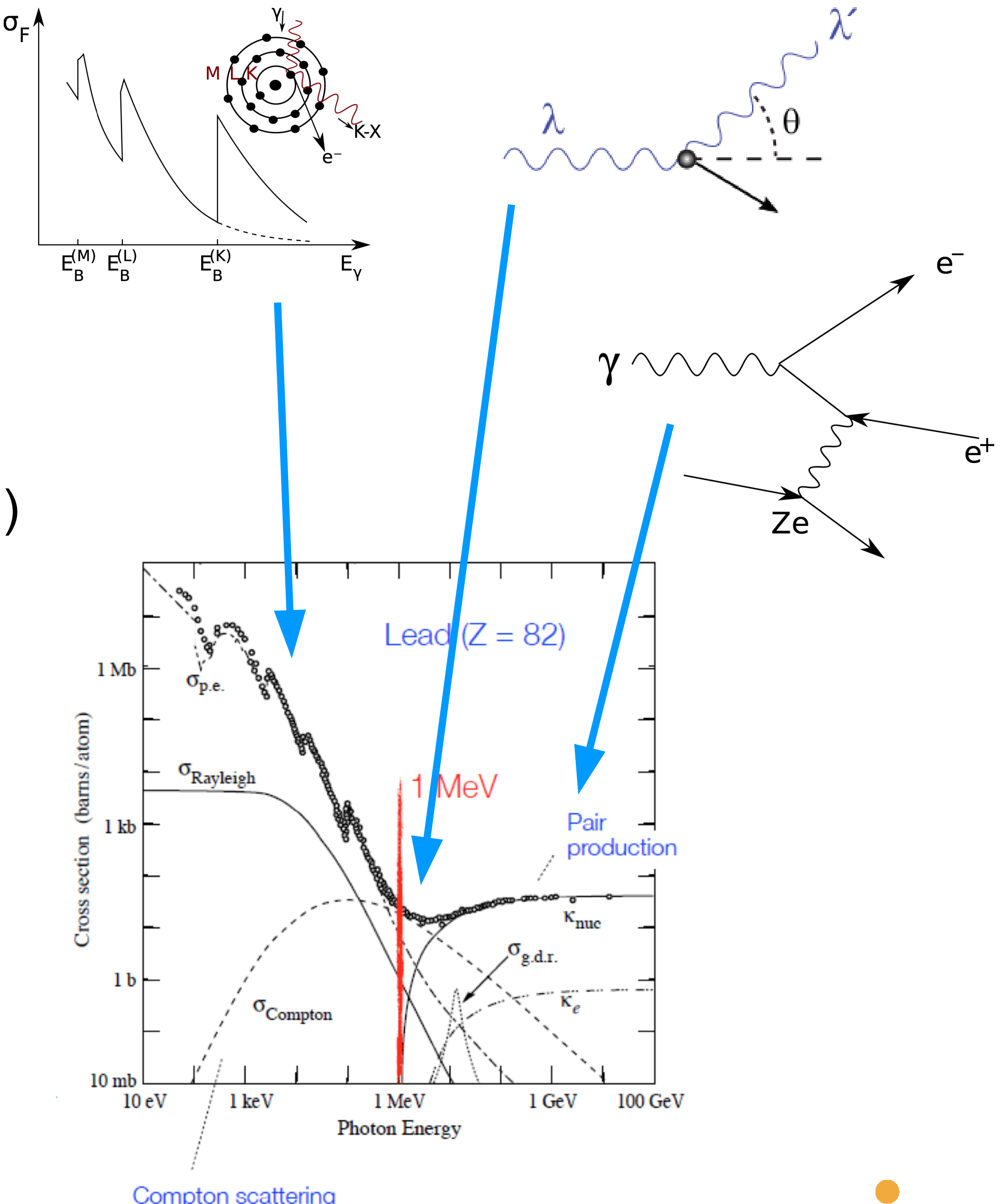

Next lectures

We review the most important type of particle detectors in use in particle and nuclear physics:

- Gas detectors
- Semiconductor detectors
- Calorimeters

Tomorrow

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