Photons and their interactions

Methods and instrumentation for nuclear and particle physics

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But first, a bit more about electrons

Multiple scattering revisited

Eq. (2.5)

$$\sqrt{\langle \Theta^2 \rangle} = \frac{Z}{Pc\beta}(20\ \mathrm{MeV})\sqrt{\frac{L}{X_0}}$$

$$\frac{1}{X_0} \approx 4\alpha\, r_0^2 \frac{\rho N_A}{A_r} Z_{\mathrm{nucl}}(1 + Z_{\mathrm{nucl}}) \ln\left(\frac{183}{\sqrt[3]{Z_{\mathrm{nucl}}}}\right)$$

Multiple scattering revisited

Tracks in silicon

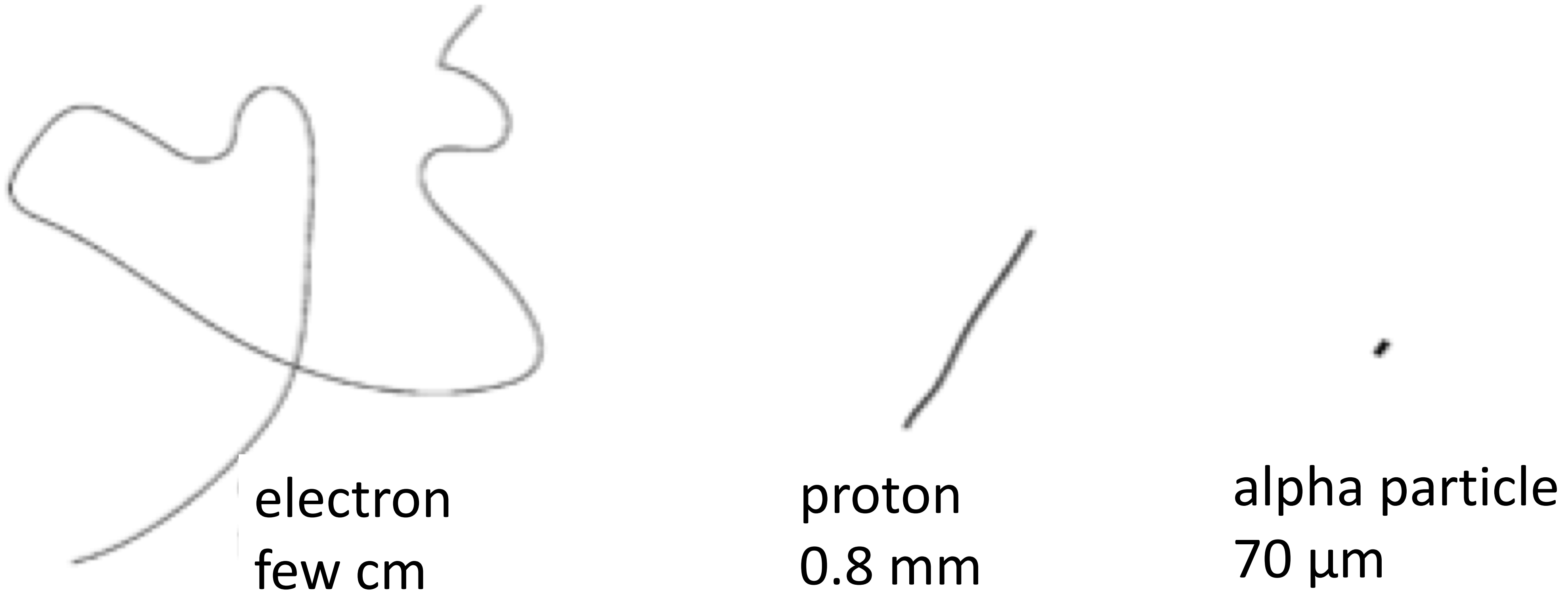


Image: Figure 2.9 from «Experimental Techniques in Nuclear and Particle Physics» by Stefaan Tavernier

Electrons and positrons (and other charged particles for E>1TeV):

$$\left(\frac{dE}{dx}\right)_{tot} = \left(\frac{dE}{dx}\right)_{rad} + \left(\frac{dE}{dx}\right)_{coll}$$

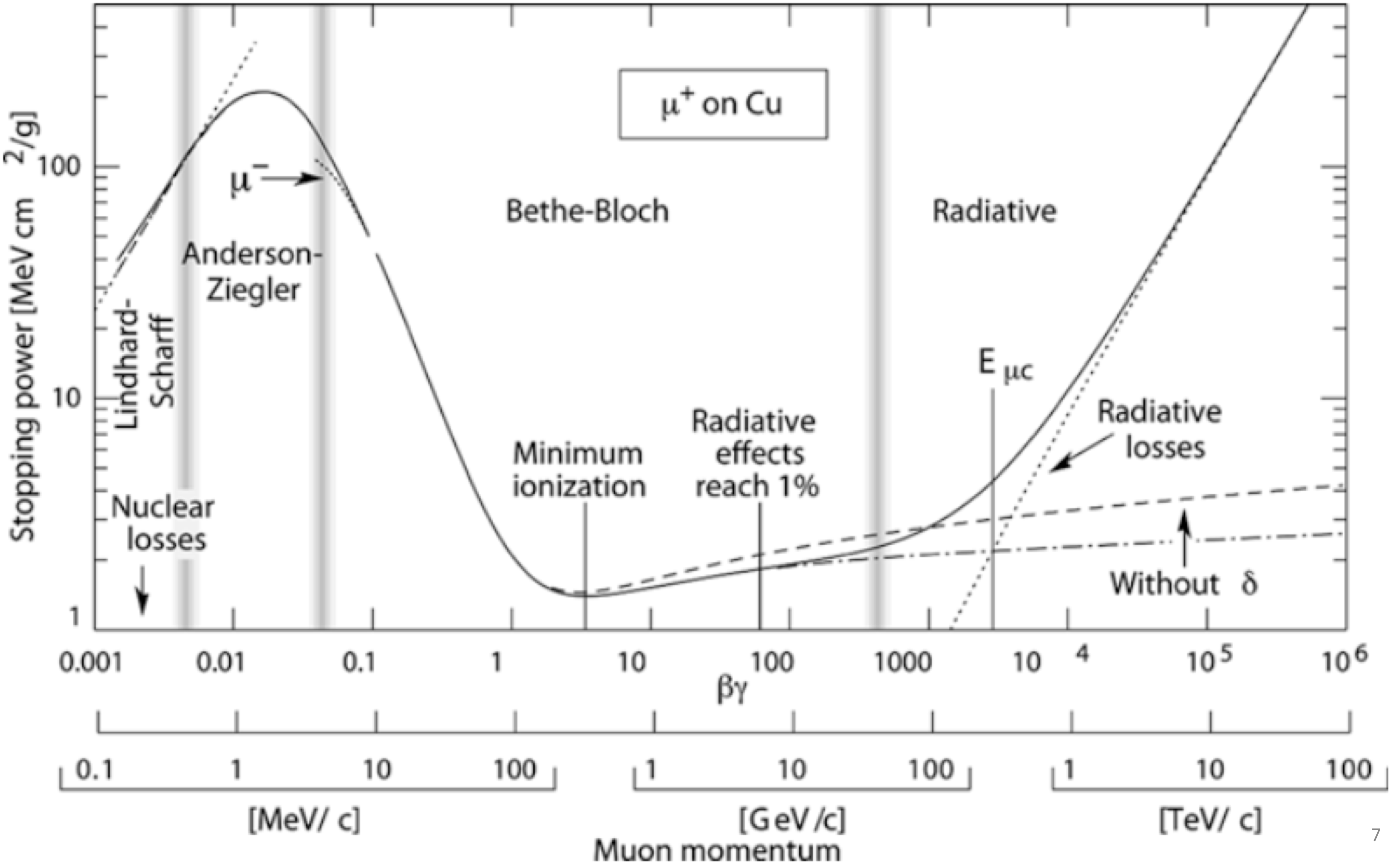
From Leo's «Techniques for Nuclear and Particle Physics»:

$$-\frac{dE}{dx} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{1}{\beta^2}\left[\ln \frac{\tau^2(\tau+2)}{2(I/m_e c^2)^2} + F(\tau) - \delta - 2\frac{C}{Z}\right]$$

where τ is the kinetic energy of particle in units of $m_e c^2$,

$$F(\tau) = 1 - \beta^2 + \frac{\frac{\tau^2}{8} - (2r+1)\ln 2}{(\tau+1)^2} \qquad \text{for } e^-$$

$$F(\tau) = 2\ln 2 - \frac{\beta^2}{12}\left(23 + \frac{14}{\tau+2} + \frac{10}{(\tau+2)^2} + \frac{4}{(\tau+2)^3}\right) \qquad \text{for } e^+$$



μ^+ on Cu
Stopping power [MeV cm^2/g]
Lindhard-Scharff
Anderson-Ziegler
μ^-
Bethe-Bloch
Radiative
Nuclear losses
Minimum ionization
Radiative effects reach 1%
$E_{\mu c}$
Radiative losses
Without δ
$\beta\gamma$
[MeV/ c]
[GeV /c]
[TeV/ c]
Muon momentum

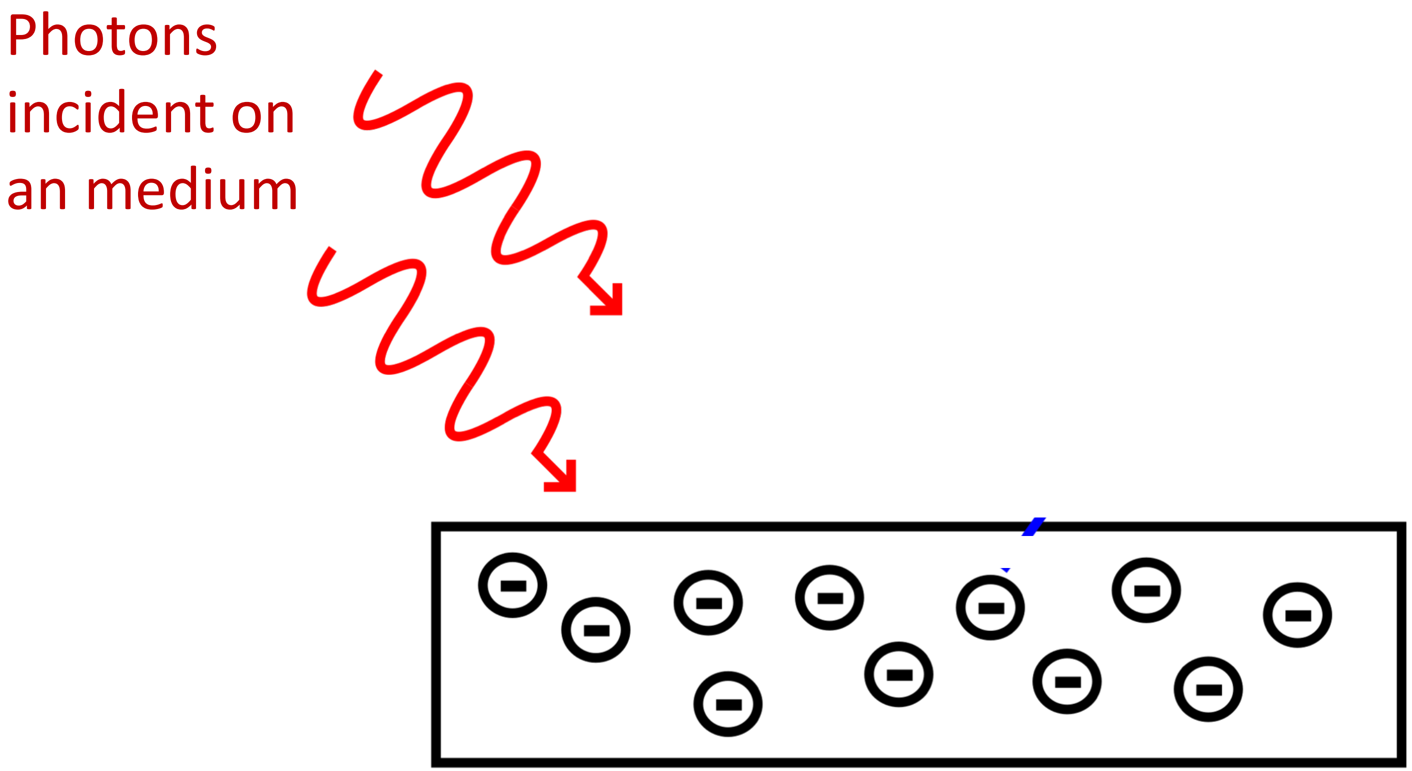
Photon interactions

We’ll start with the interactions that are important for low energy photons (1 keV and up) and continue until we arrive at high energy photons

We say that a photon beam is attenuated

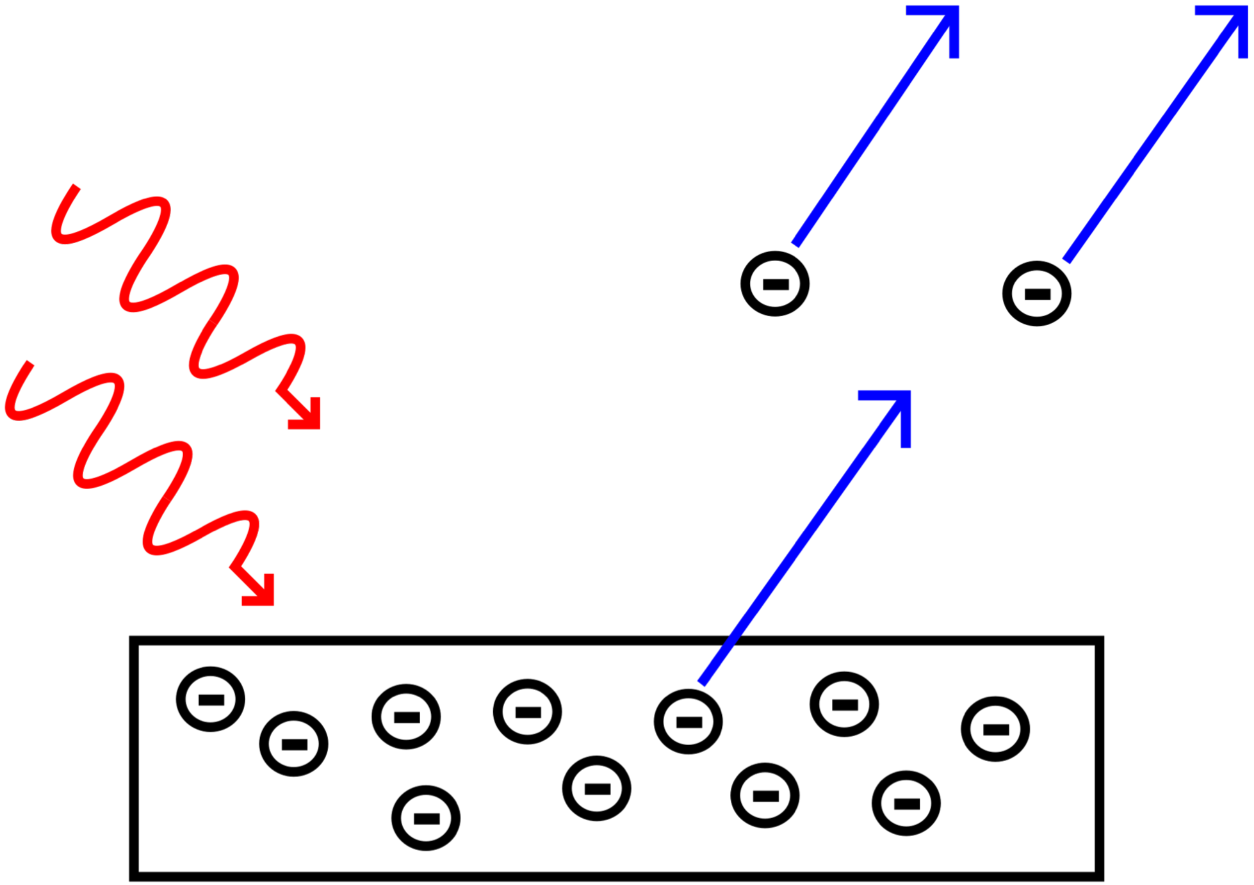
$$I(x) = I_0 \, e^{-x\mu}$$

The photoelectric effect



The photoelectric effect

Photons incident on an medium

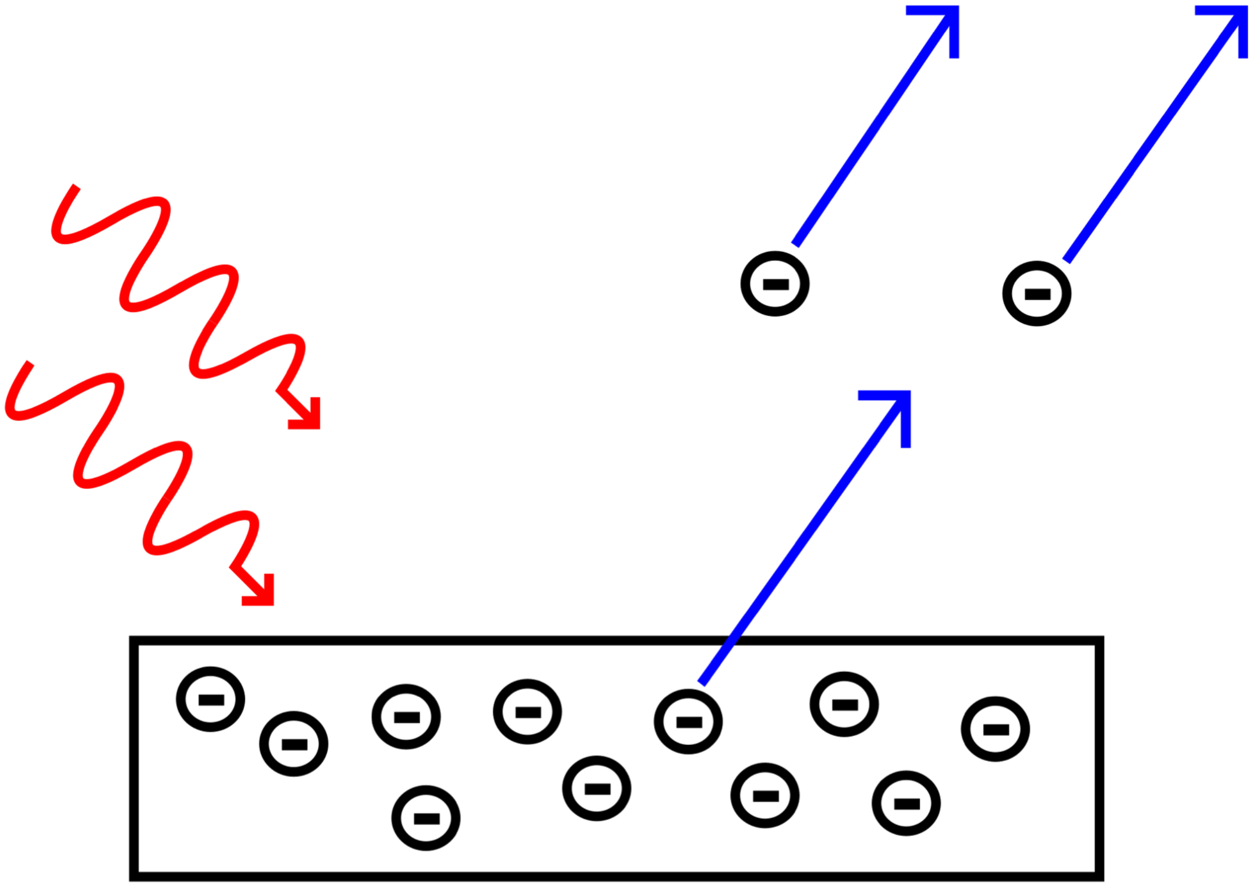


Electrons are emitted.

Image credit: By Wolfmankurd (en:Inkscape) [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC-BY-SA-3.0 (http://creativecommons.org/licenses/by-sa/3.0/)], via Wikimedia Commons

The photoelectric effect

Photons incident on an medium



Electrons are emitted.

The electron energy corresponds to the photon energy minus the binding energy of the electron. **Keep in mind the shell structure of atoms.**

Image credit: By Wolfmankurd (en:Inkscape) [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC-BY-SA-3.0 (http://creativecommons.org/licenses/by-sa/3.0/)], via Wikimedia Commons

The cross section of the photoelectric effect

Z is the
proton number
of the medium

n = 4 - 5

$$\sigma \approx \text{Const}\frac{Z^n}{E_\gamma^{3.5}}$$

Energy of the photon

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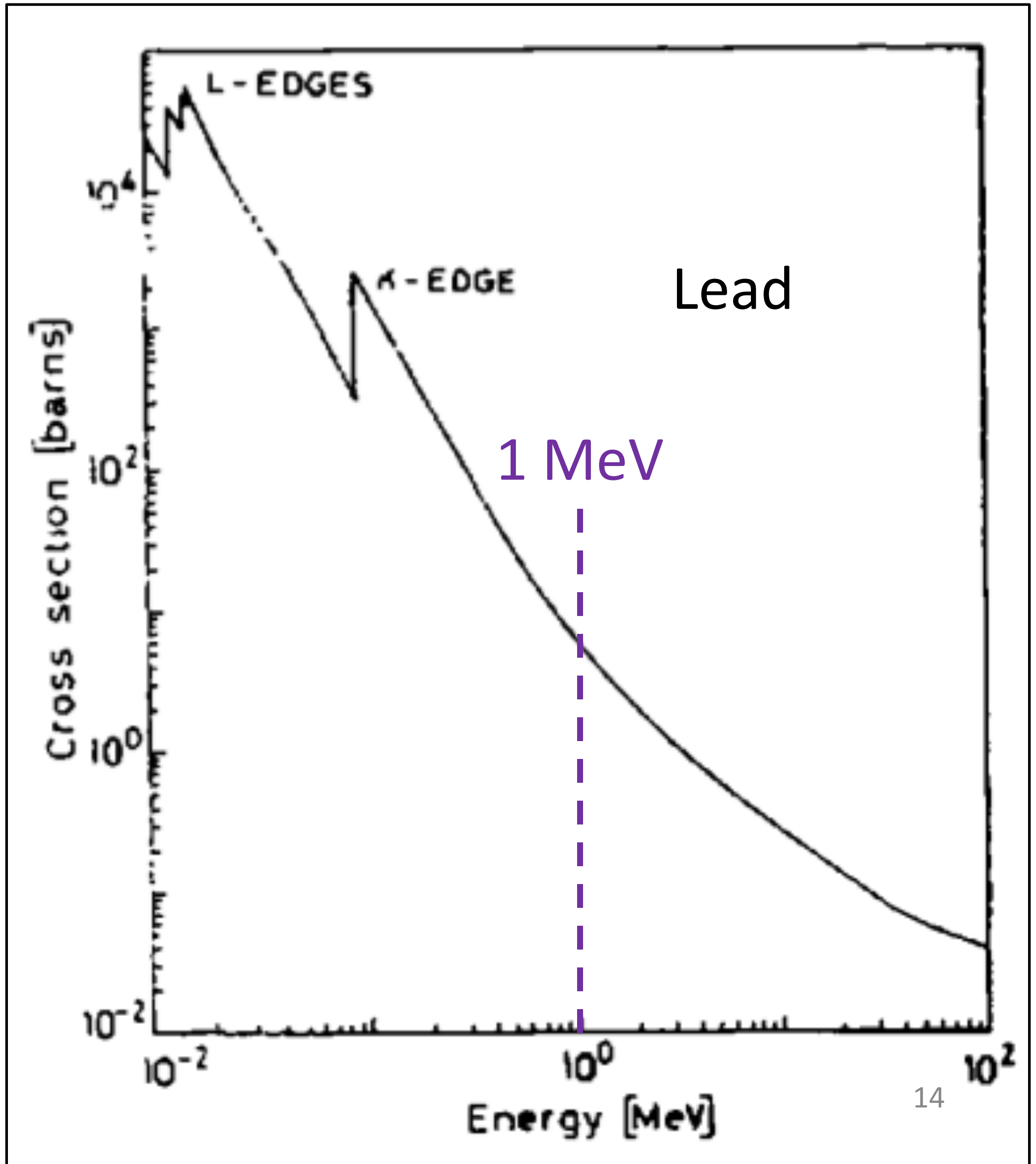
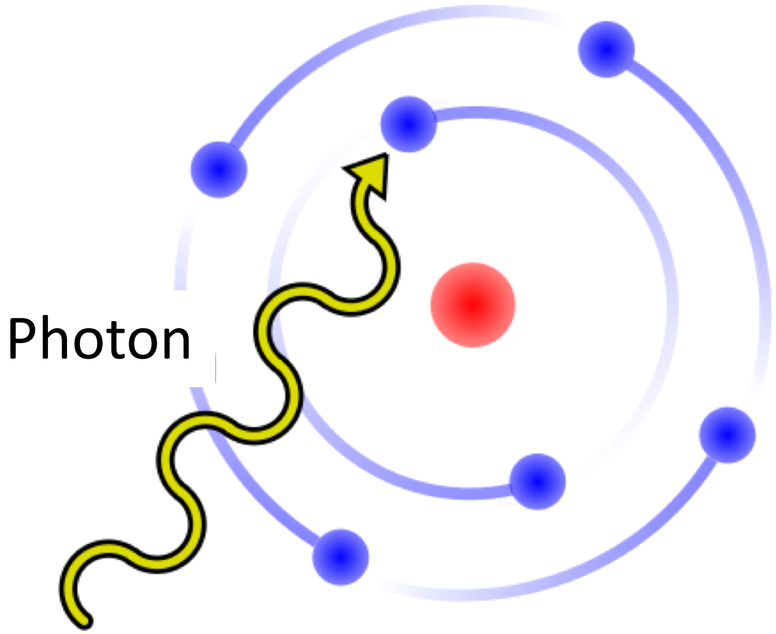
Energy of the photon



The Compton scattering

In Compton scattering, the electron does not absorb the full energy of the photon.



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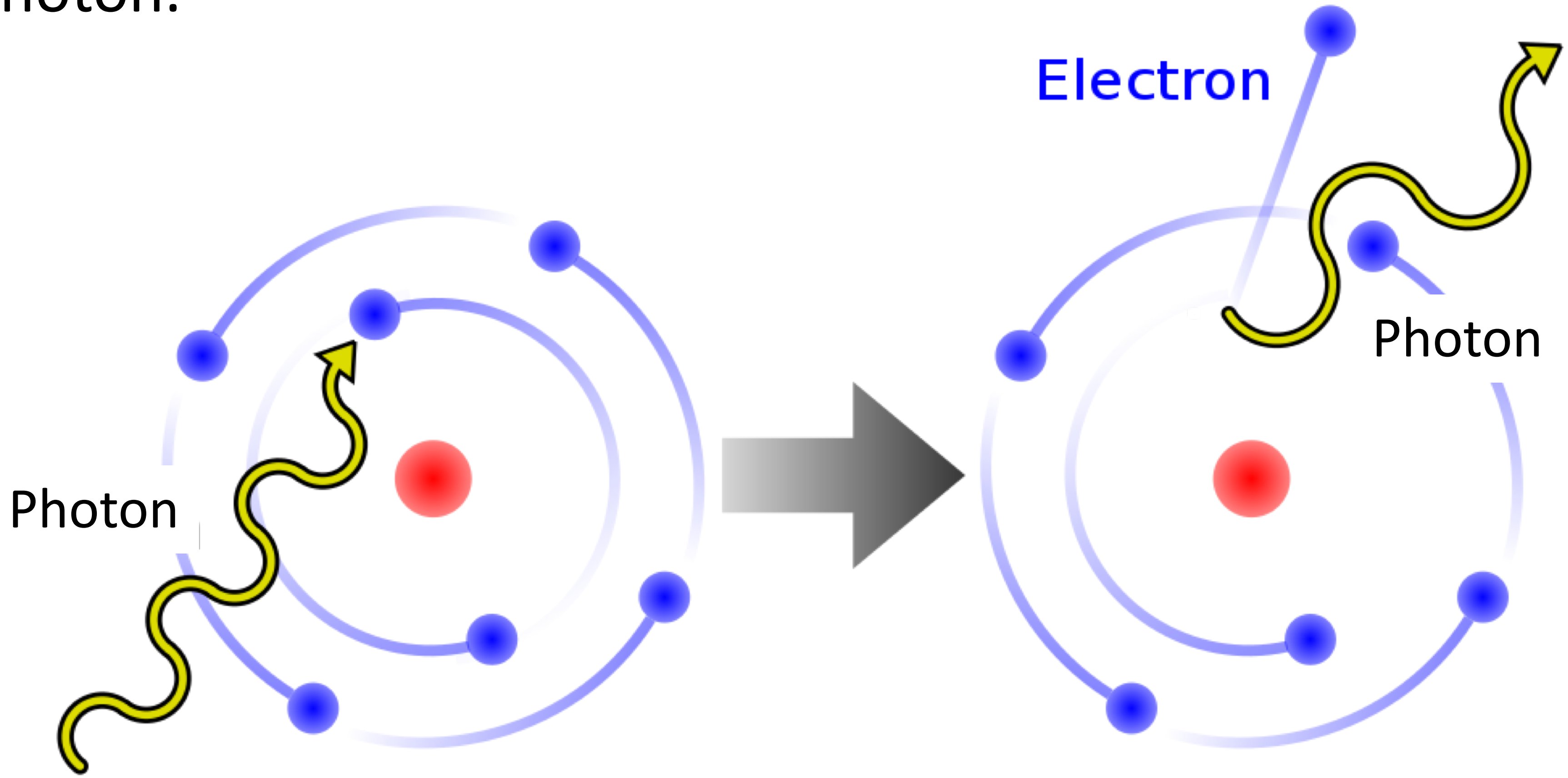


By Victor Blacus (Derived from File:Compton Effect Schematic-de.svg)

The energy of the scattered photon depends on the scattering angle θ

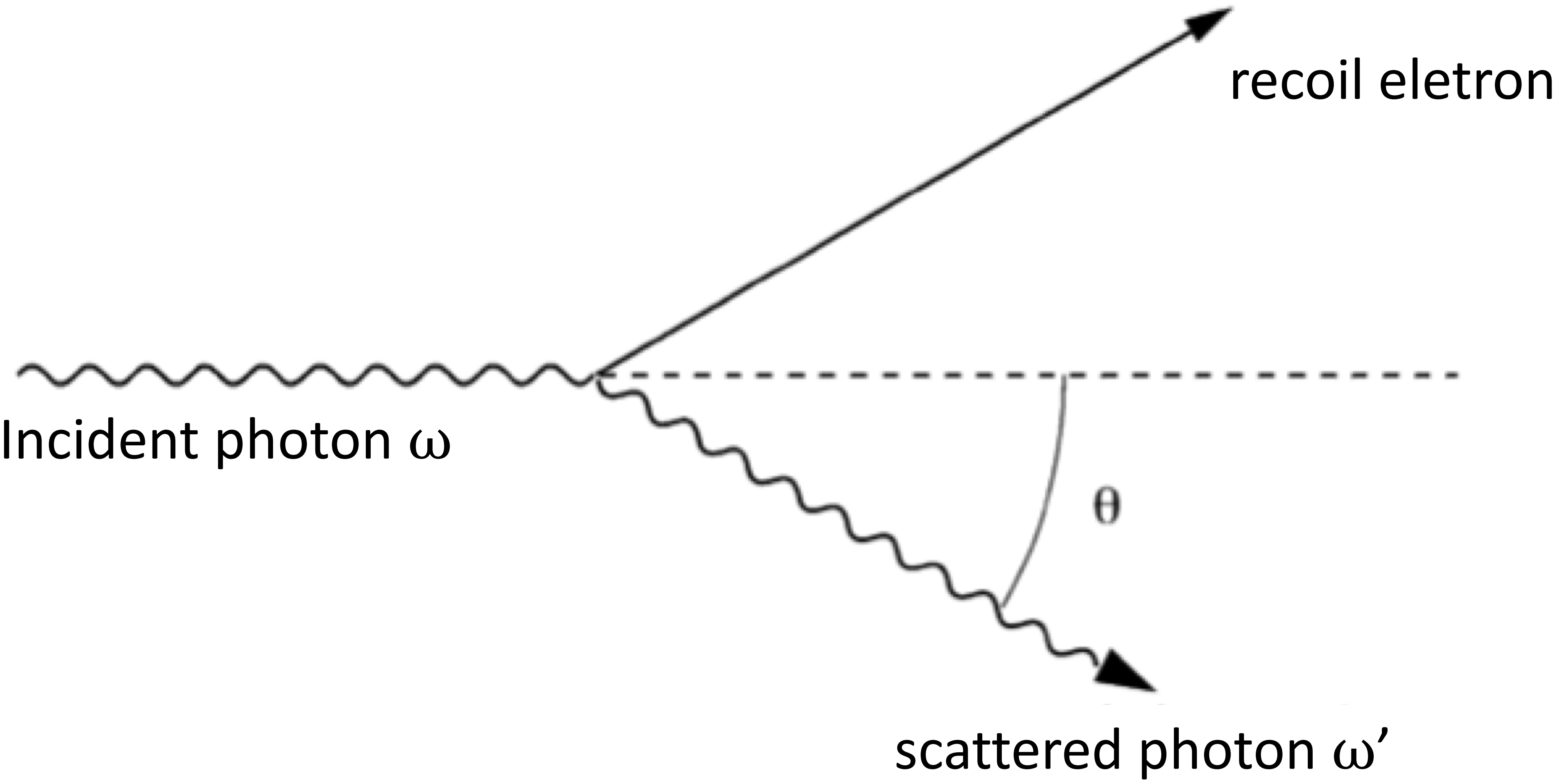


Image: Figure 2.14 from «Experimental Techniques in Nuclear and Particle Physics» by Stefaan Tavernier

The energy of the scattered photon depends on the scattering angle θ

$$\hbar\omega' = \frac{\hbar\omega}{\left(1 + \frac{\hbar\omega}{m_e c^2}(1-\cos\theta)\right)}$$

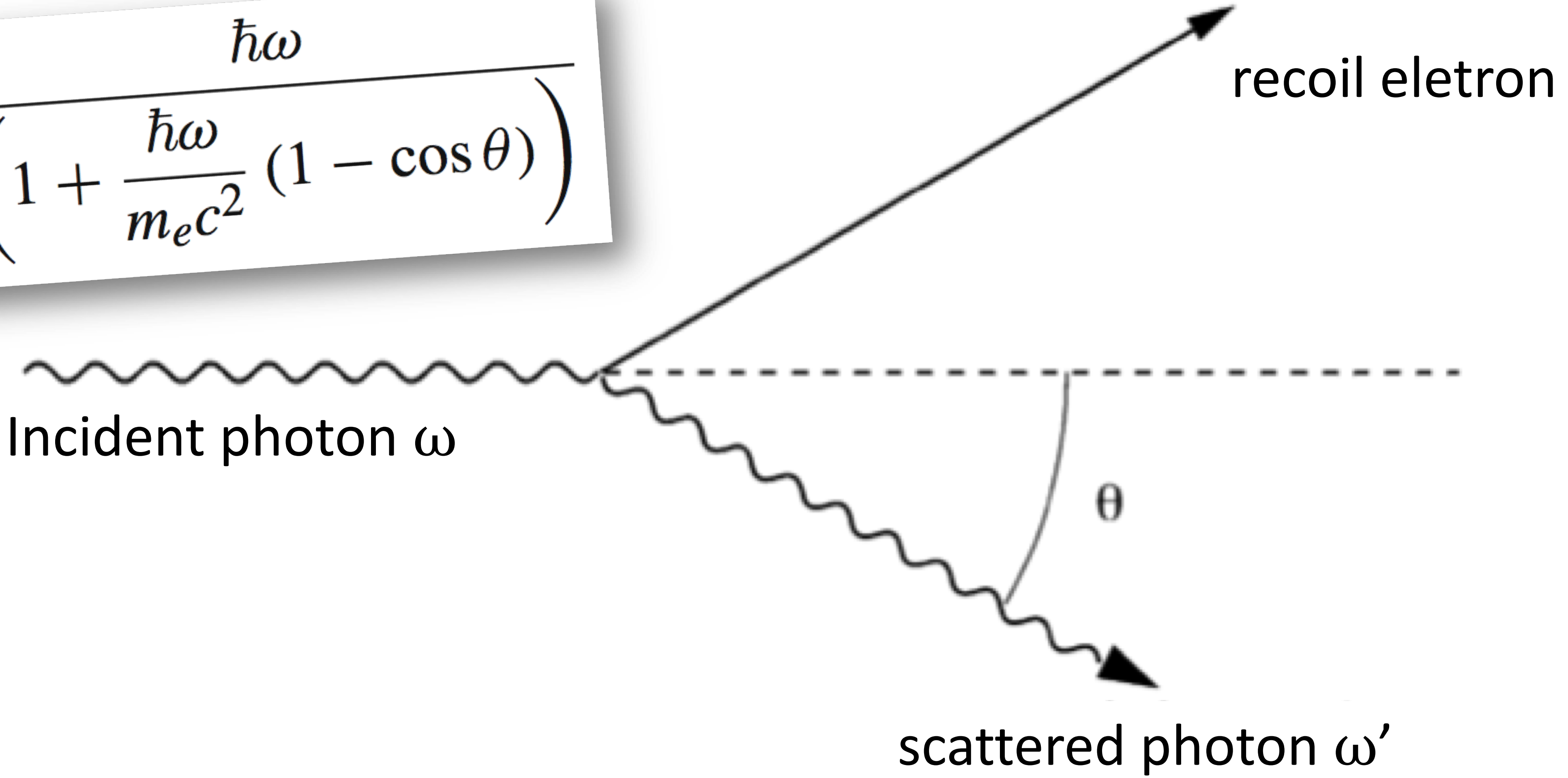


Image: Figure 2.14 from «Experimental Techniques in Nuclear and Particle Physics» by Stefaan Tavernier

The differential cross section is given by the Klein-Nishina formula

$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{2}\left(\frac{\hbar\omega'}{\hbar\omega}\right)^2\left(\frac{\hbar\omega}{\hbar\omega'} + \frac{\hbar\omega'}{\hbar\omega} - \sin^2\theta\right)$$

Integrate over all angles to get the total cross section

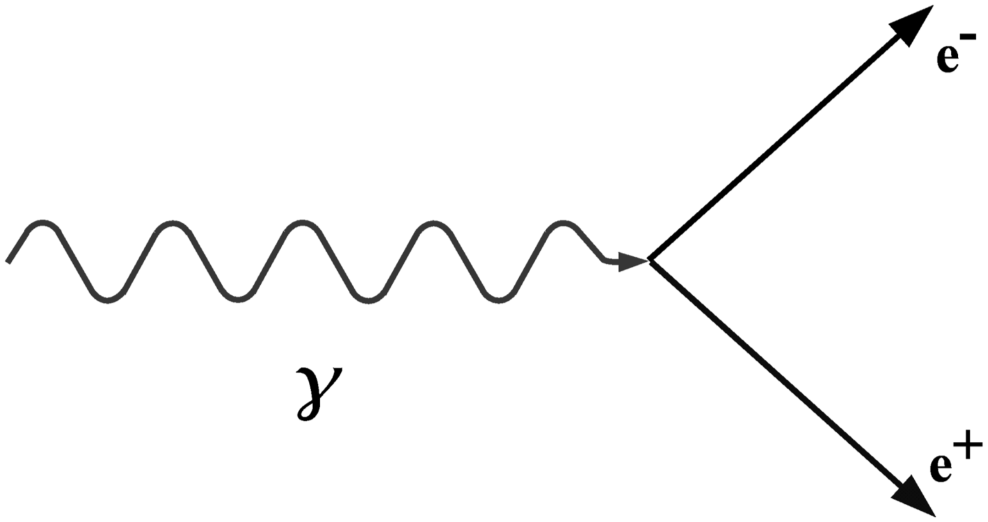
$$\sigma = \frac{8\pi}{3} r_0^2 \qquad \hbar\omega << m_e c^2$$

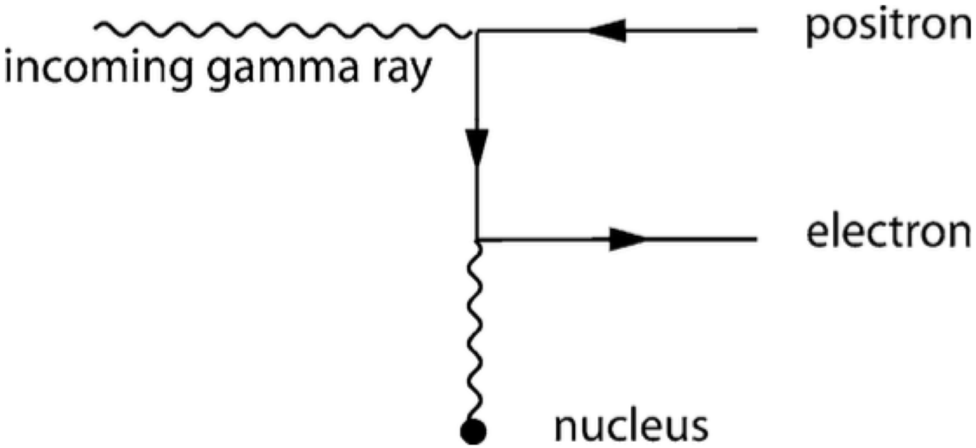
$$\sigma = r_0^2 \, \pi \, \frac{m_e c^2}{\hbar\omega} \left[\ln\left(\frac{2\hbar\omega}{m_e c^2} \right) + \frac{1}{2} \right] \qquad \hbar\omega >> m_e c^2$$

Pair production

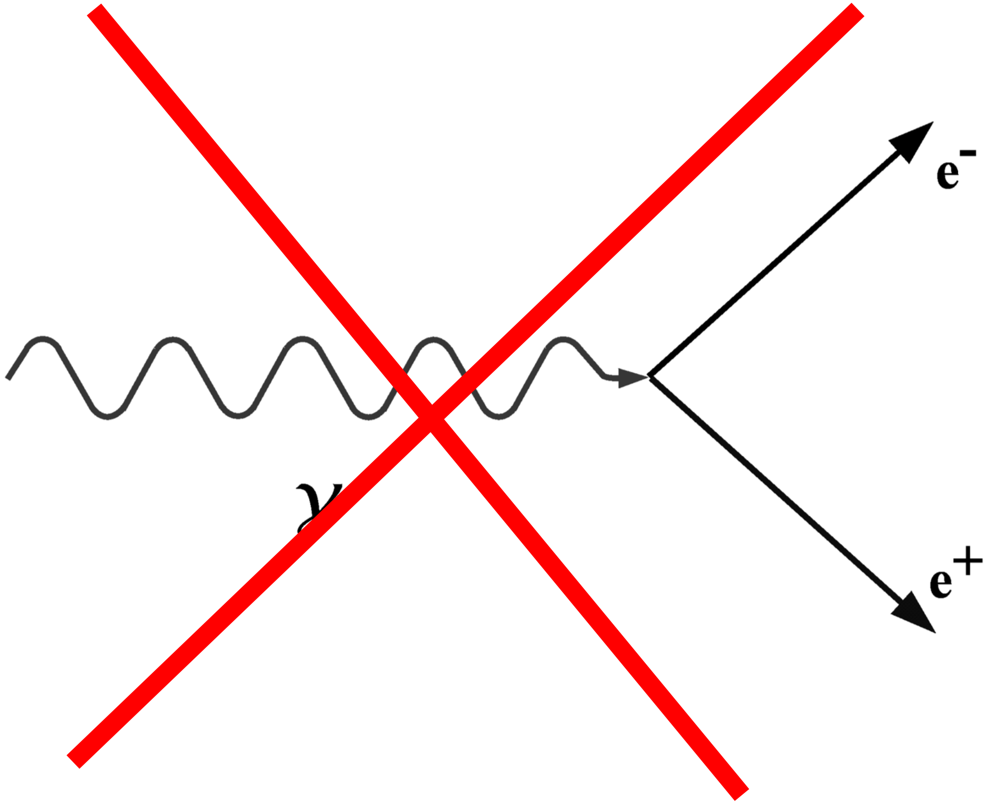
When the photon has an energy of at least twice the mass of an electron, the photon energy can produce an electron-positron pair.

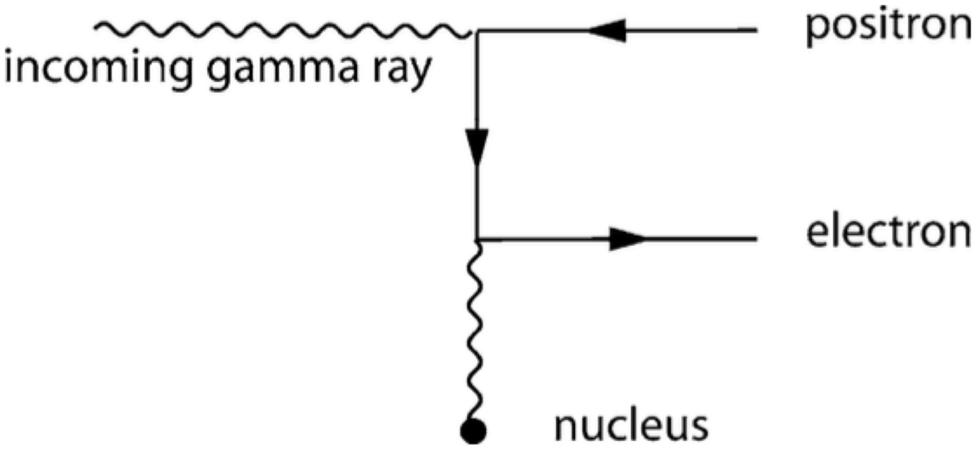
Why does pair production not happen in empty space, but only in the presence of matter/an electrical field?


e^-
γ
e^+


positron
incoming gamma ray
electron
nucleus

We still need to conserve momentum!





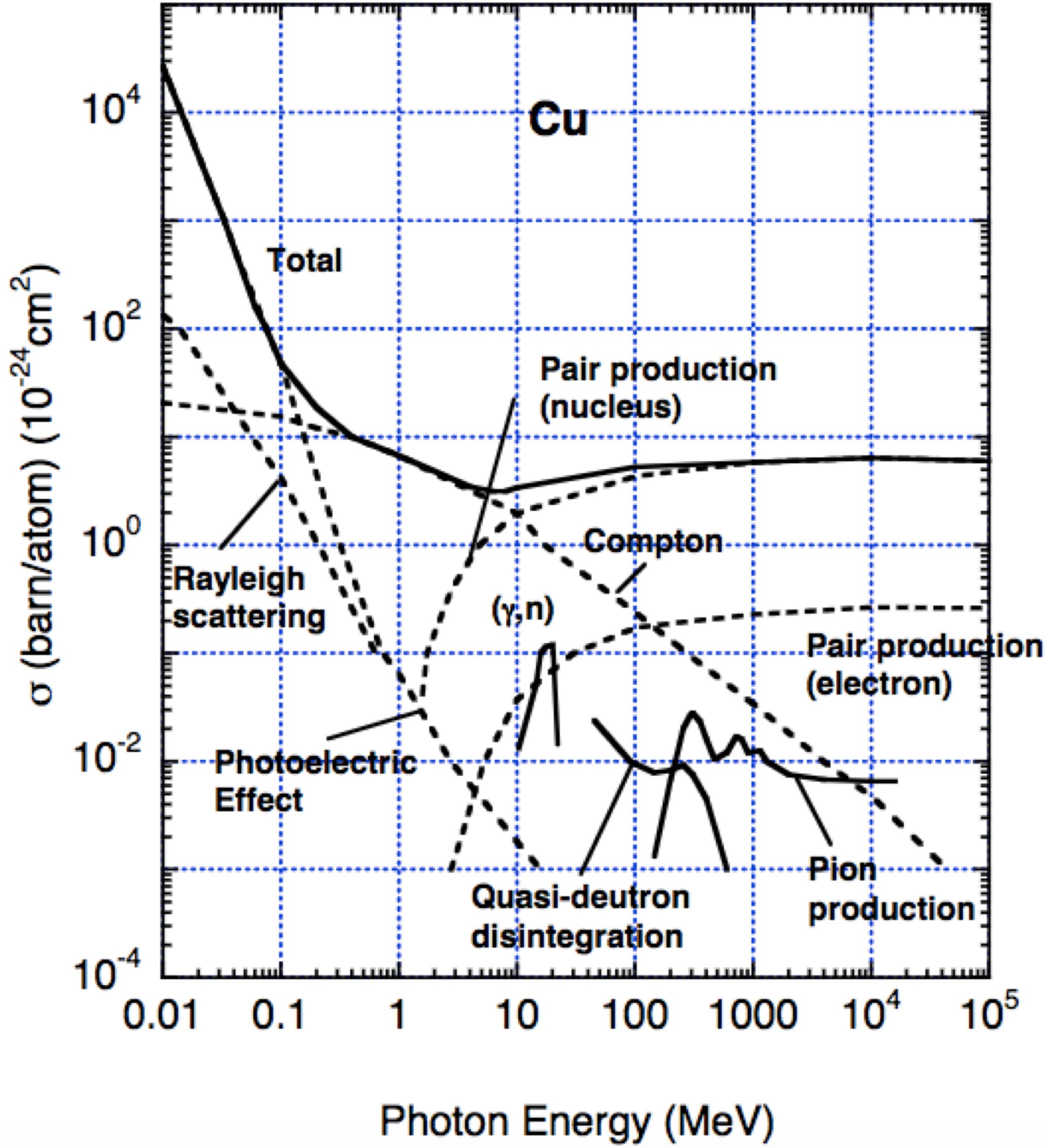
The cross section for pair production

$$\sigma = \frac{7}{9} 4\alpha r_0^2 Z_{nucl} (Z_{nucl} + 1) \ln \left(\frac{183}{3\sqrt{Z_{nucl}}} \right)$$

Photons with energies >> 1 MeV cause electromagnetic showers

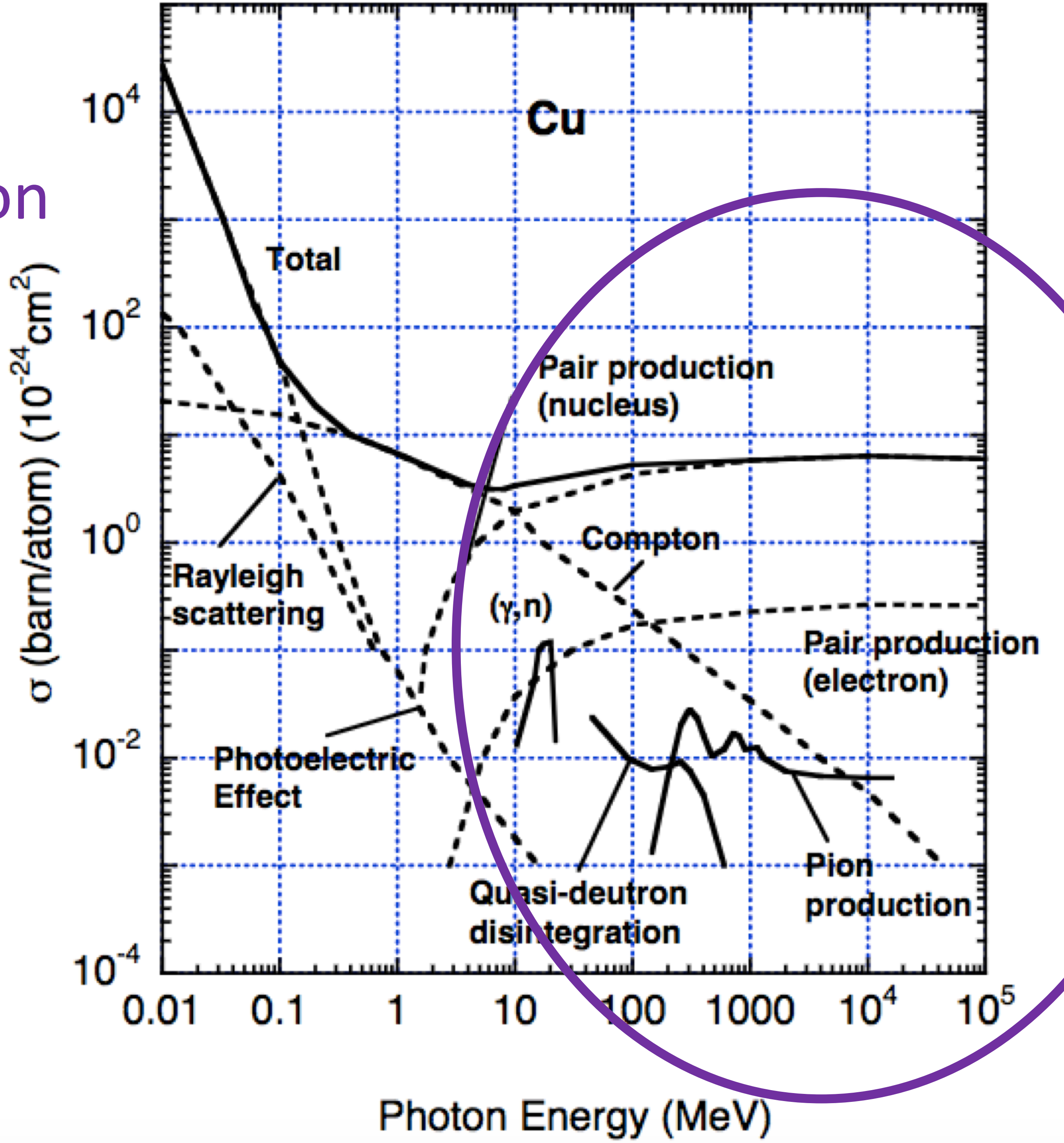
- Photons produce electron-positron pairs
- The electrons and positrons emit secondary photons due to the bremsstrahlung
- This process will repeat itself
- In one «radiation length» an electron or positron will radiate about half its kinetic energy

By Mircea Madau [Public domain], via Wikimedia Commons



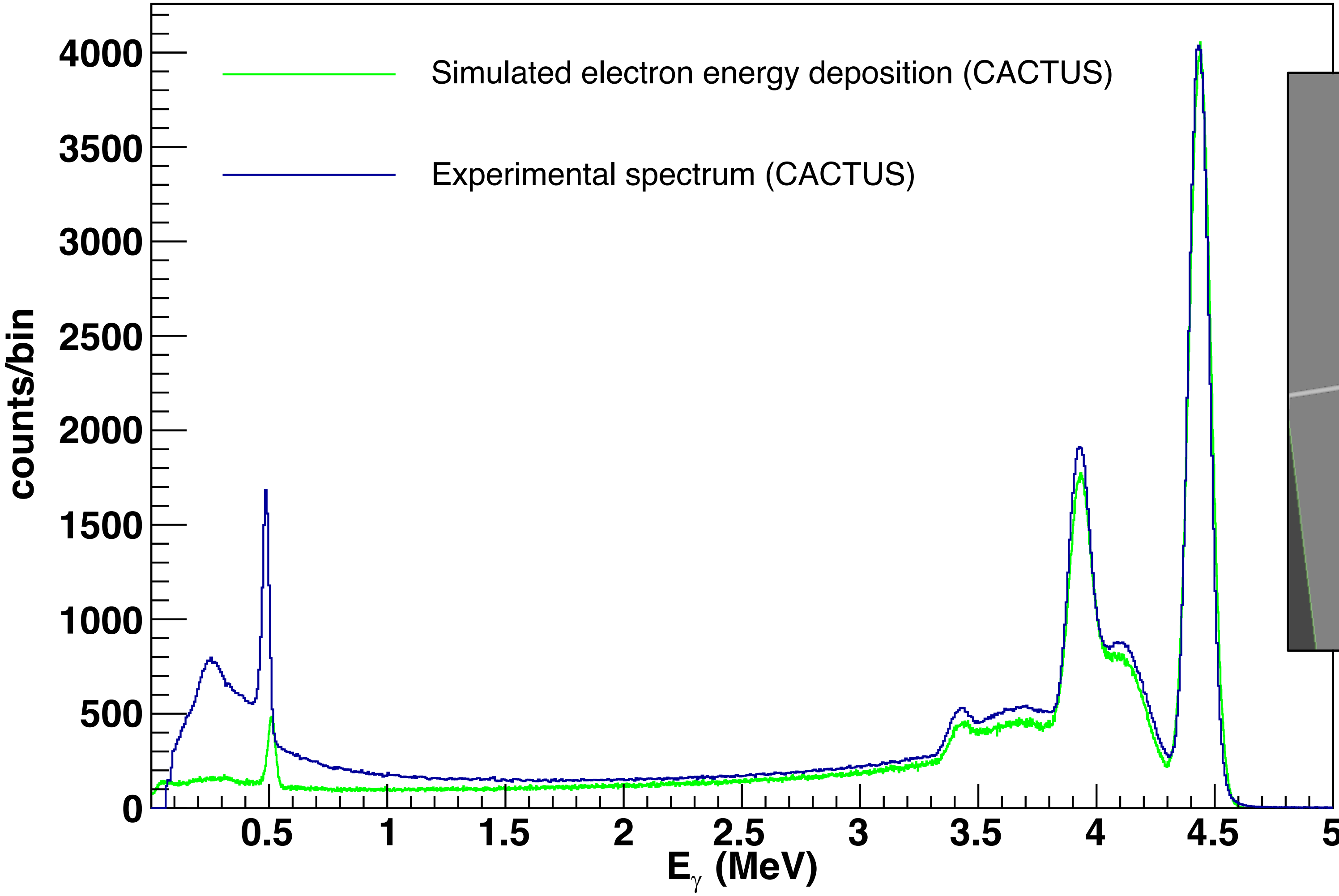
E. F rytag, " Strahlenschutz an hochenergiebschleunigern",
(G. Braum, Karlsruhe, 1072).

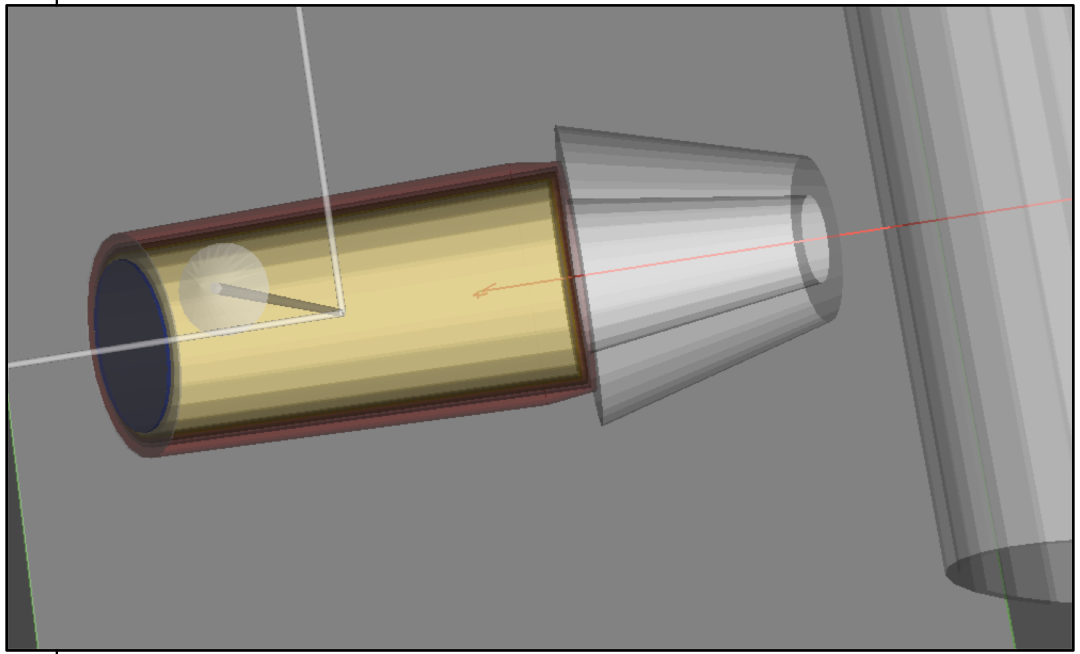
Photon energies > 10 MeV
Dominated by pair production



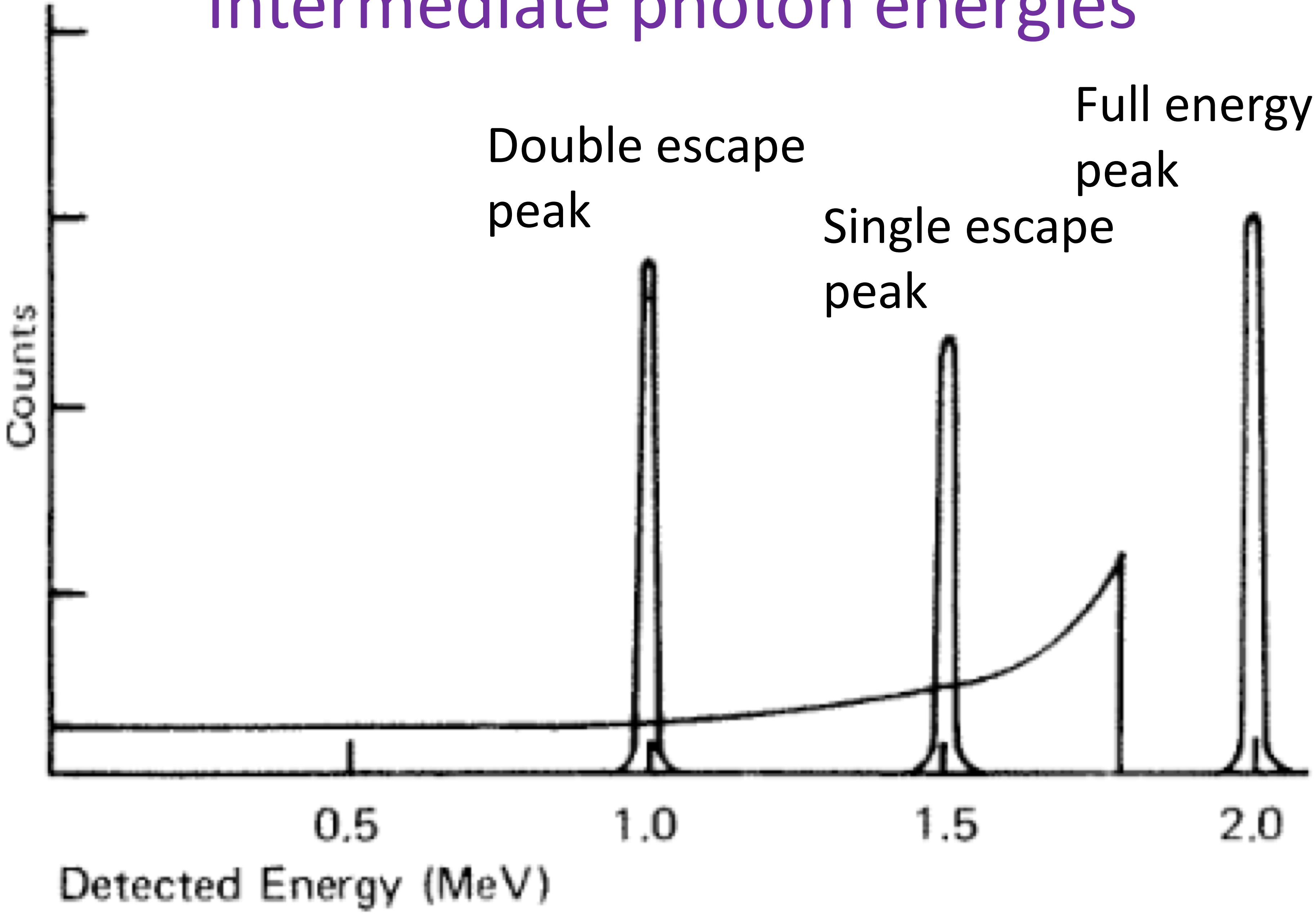
E. F rytag, " Strahlenschutz an hochenergiebschleunigern",
(G. Braun, Karlsruhe, 1072).

Example: 4.4 MeV gamma into a detector





Intermediate photon energies



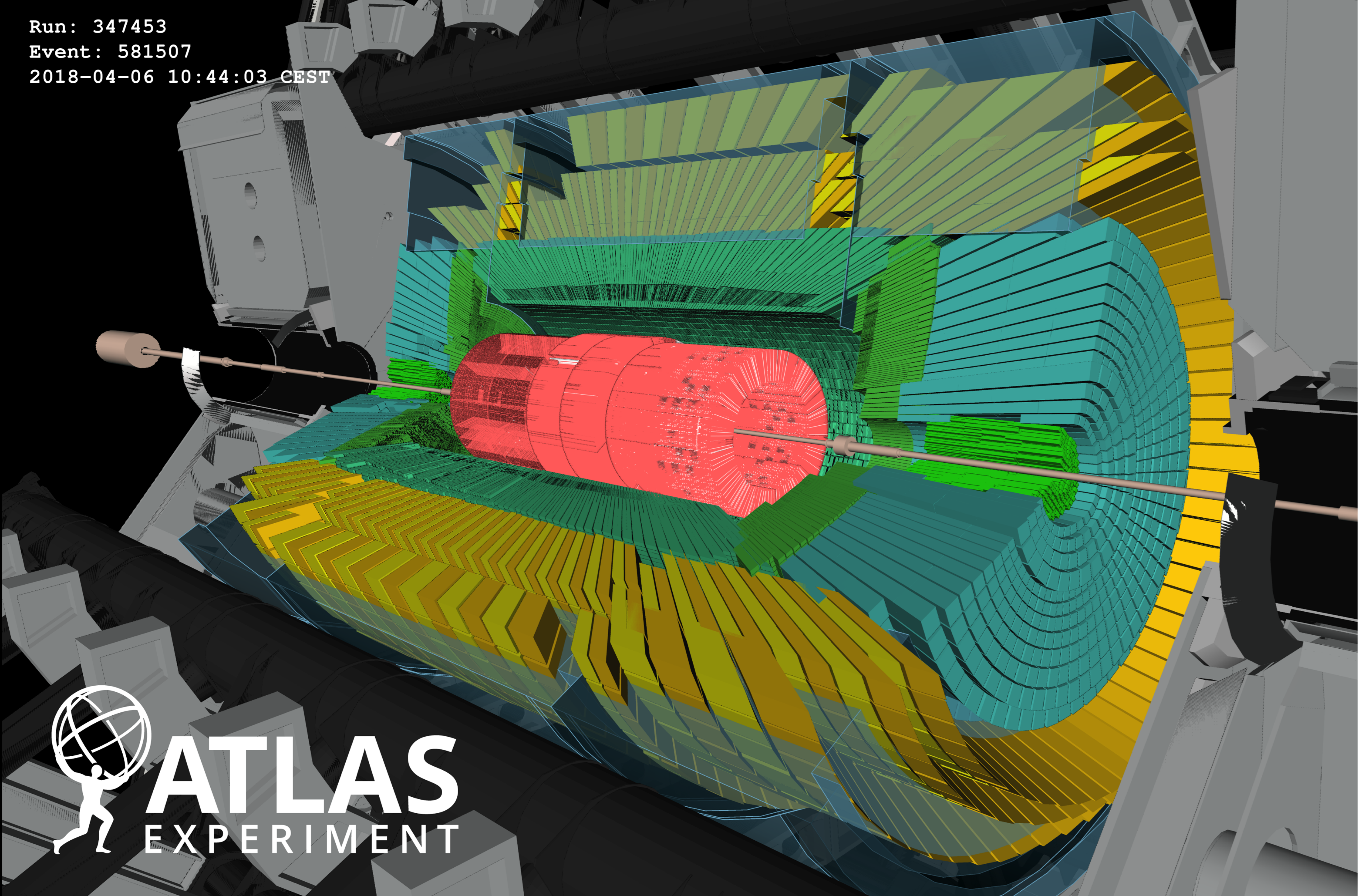


Image credit: CERN
Photograph: ATLAS Collaboration
Date: 12-04-2018

Red:
inner tracking
Green:
Electromag.
calorimeter
Yellow:
hadronic
calorimeter