Karlsruher Institut für Technologie

Vorlesung:

Teilchenphysik I (Particle Physics I)

Particle Detectors

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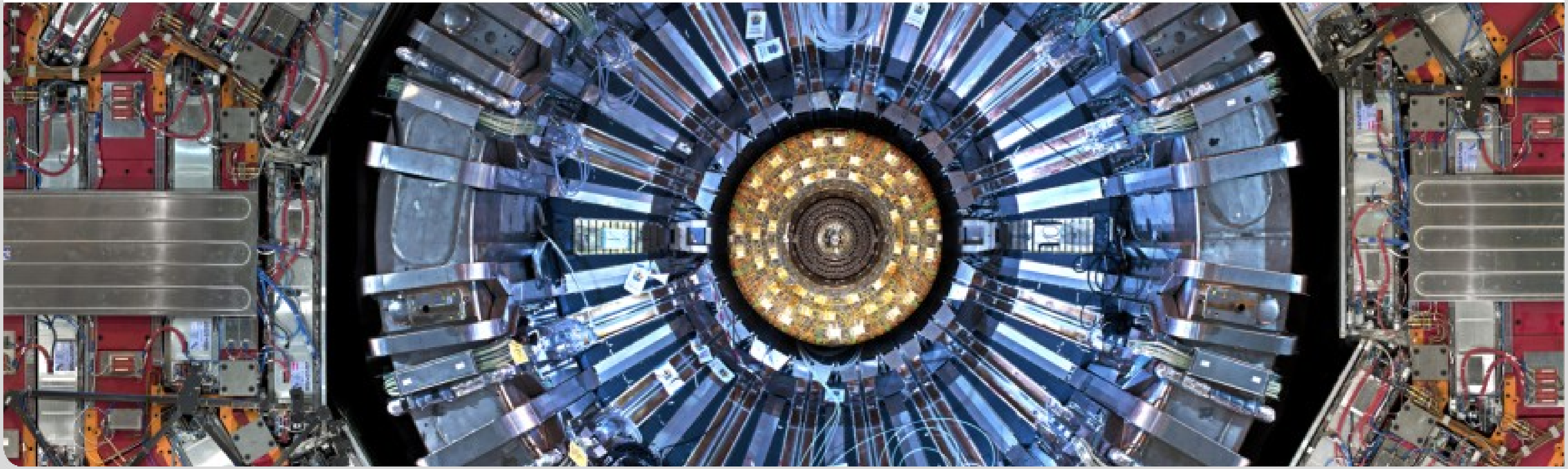
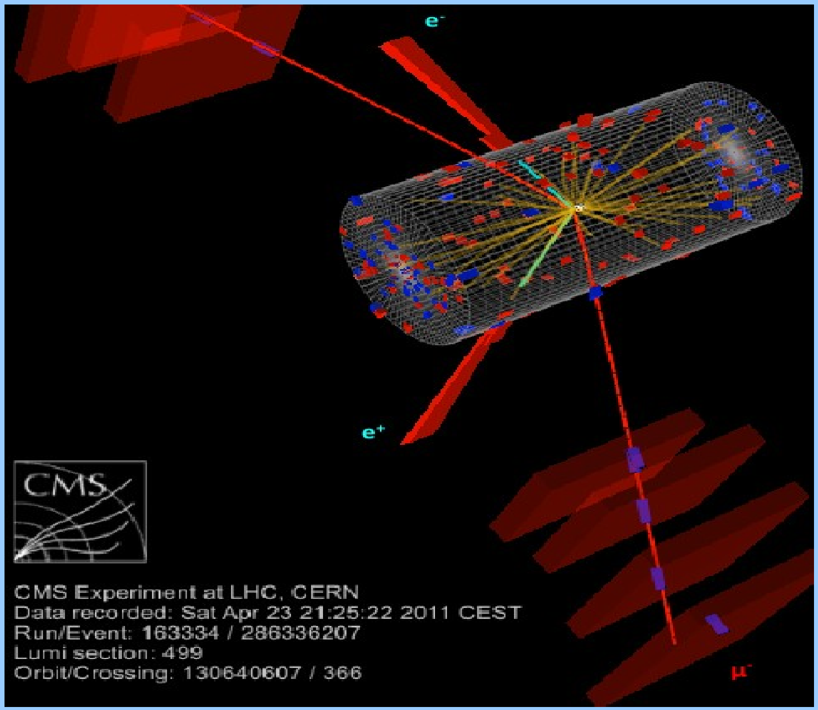
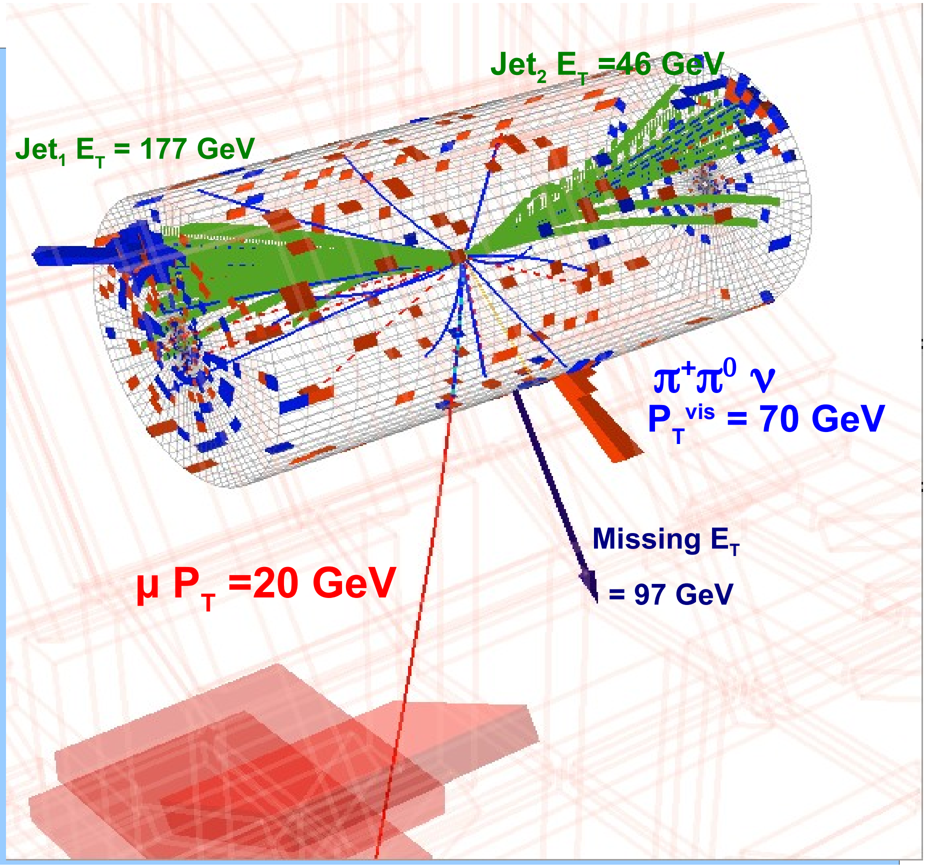
WS 20/21







„Candidate events for Higgs-boson production in pp Collisions

Discoveries and precision Measurements are only possible with complex detectors, which enable the distinction of all (stable) particles and the precise reconstruction of physical quantities.

1. Interactions of particles in Matter

   - electromagnetic interaction of photons and charged particles

   - Cherenkov and transition radiation

   - hadronic interactions

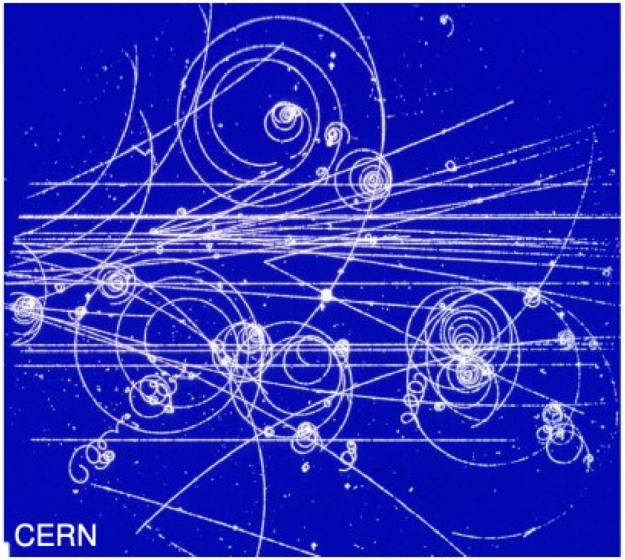
2. Simulation of particle interactions

3. Detectors in Particle Physics

   - Detector systems

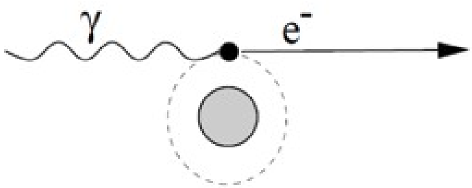
   - Track and vertex reconstruction

   - Calorimetry



Reminder: Interactions of photons with matter

photoeffect

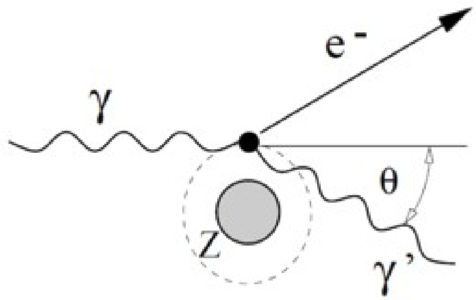


$$\sigma \propto Z^5 E_\gamma^{-3.5}$$

photon transfers all its energy to an electron

→ Photopeak

Compton effect

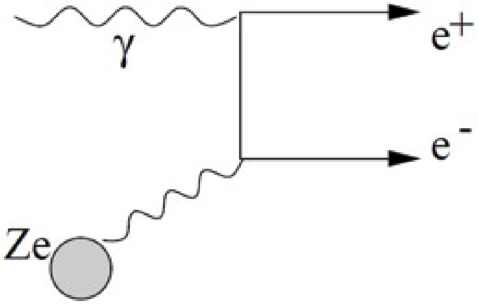


$$\sigma_{\text{Compton}} \propto Z$$

$$E'_{\text{e}}(max) = \frac{2E_\gamma^2}{m_{\text{e}} + 2E_\gamma}$$

→ Compton edge

pair production



$$\sigma_{pair} \propto Z^2$$

$$\sigma_{paar} \approx \frac{7A}{9N_{\text{A}}} X_0$$

at high energies

$$E_\gamma > 2 \times 511\text{keV}$$

(in nuclear field)

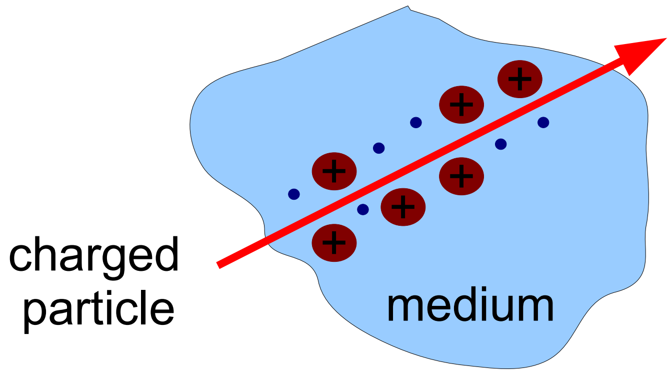
also, but less relevant:

- photo-nuclear reactions
- myon pair production
- Landau-Pomeranchuk-Migdal effect
  (= coherent interactions of low-energy photons)

X_0: „radiation length“

Reminder: interactions of charged particles

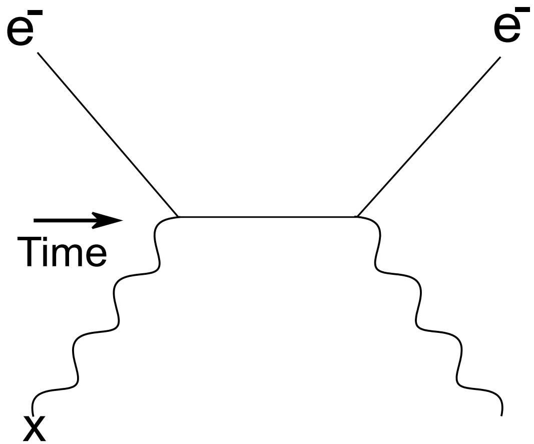
1. charged particles lose energy via **ionisation** and **excitation** of atoms:



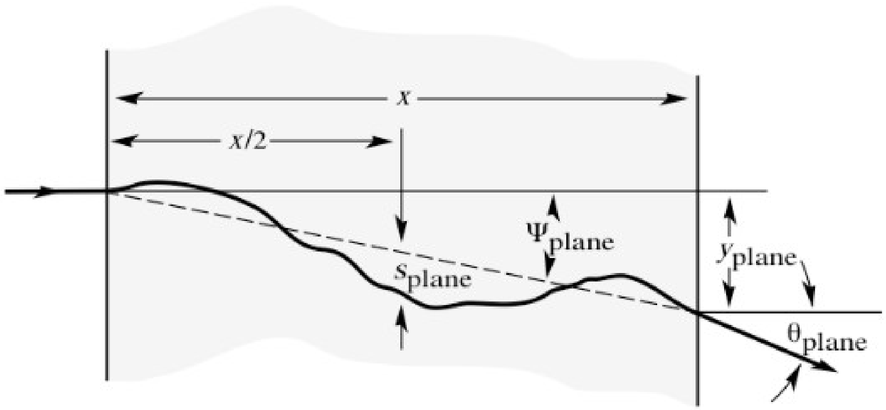
average number of ion-electron pairs is proportional to particle energy

Number N / l of elektron-ion pairs per unit lenght depends on mean energy loss per ionisation process, $W_i > I_0$ (ionisation potential)

2. charged particles emit **bremsstrahlung** in the electrical fields of nuclei

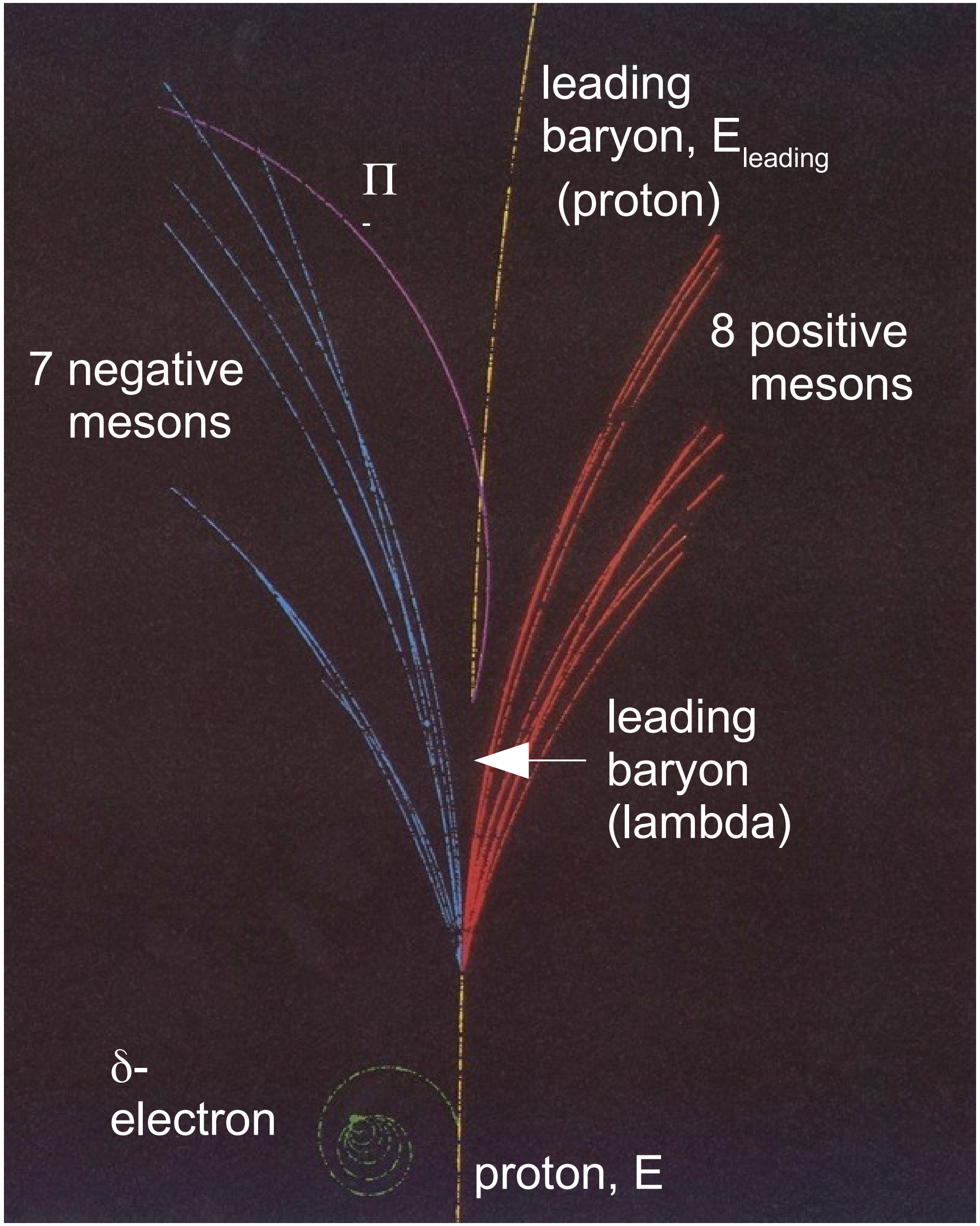


2. multiple scattering
particles passing through matter



Particle Interactions in Matter

- ***Hadrons*** (neutral and charged)
  - Nuclear interactions (strong interaction)
  - Shower of secondary hadrons
  - Ionisation, . . . (cf. charged particles)

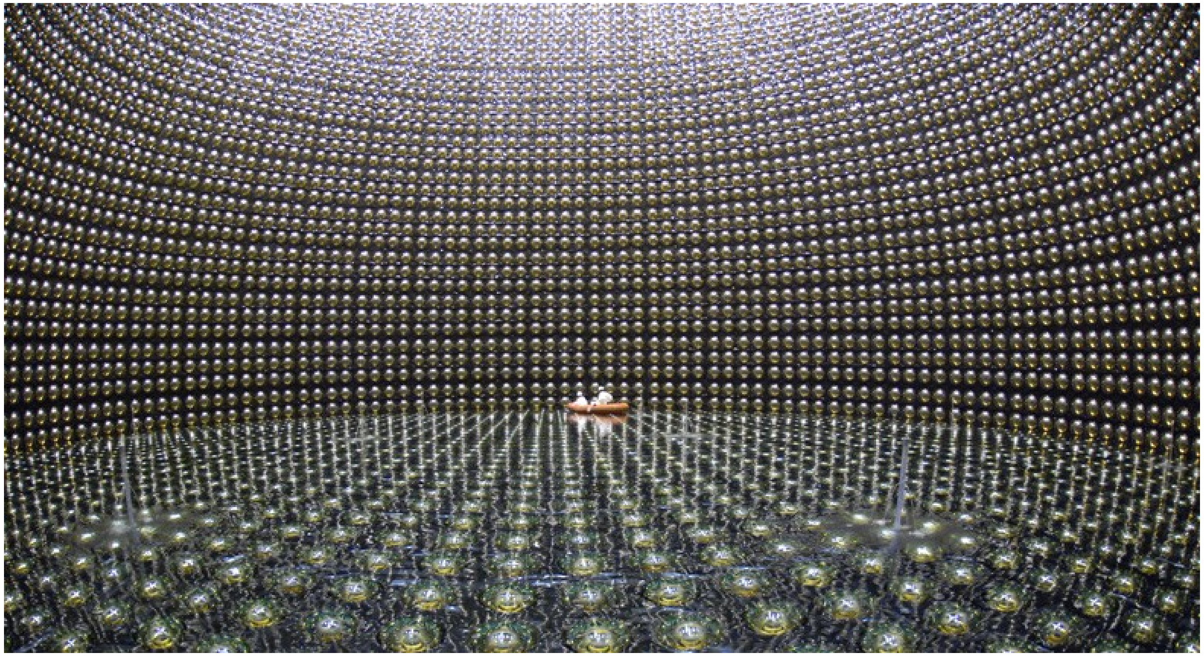


Strong interaction has a very short range →

particle must come close to nucleus

Particle Interactions in Matter

- ***Neutrinos***
  - Only weak interaction
  - Detection via charged particles produced by neutrino
    → need large detectors for direct detection

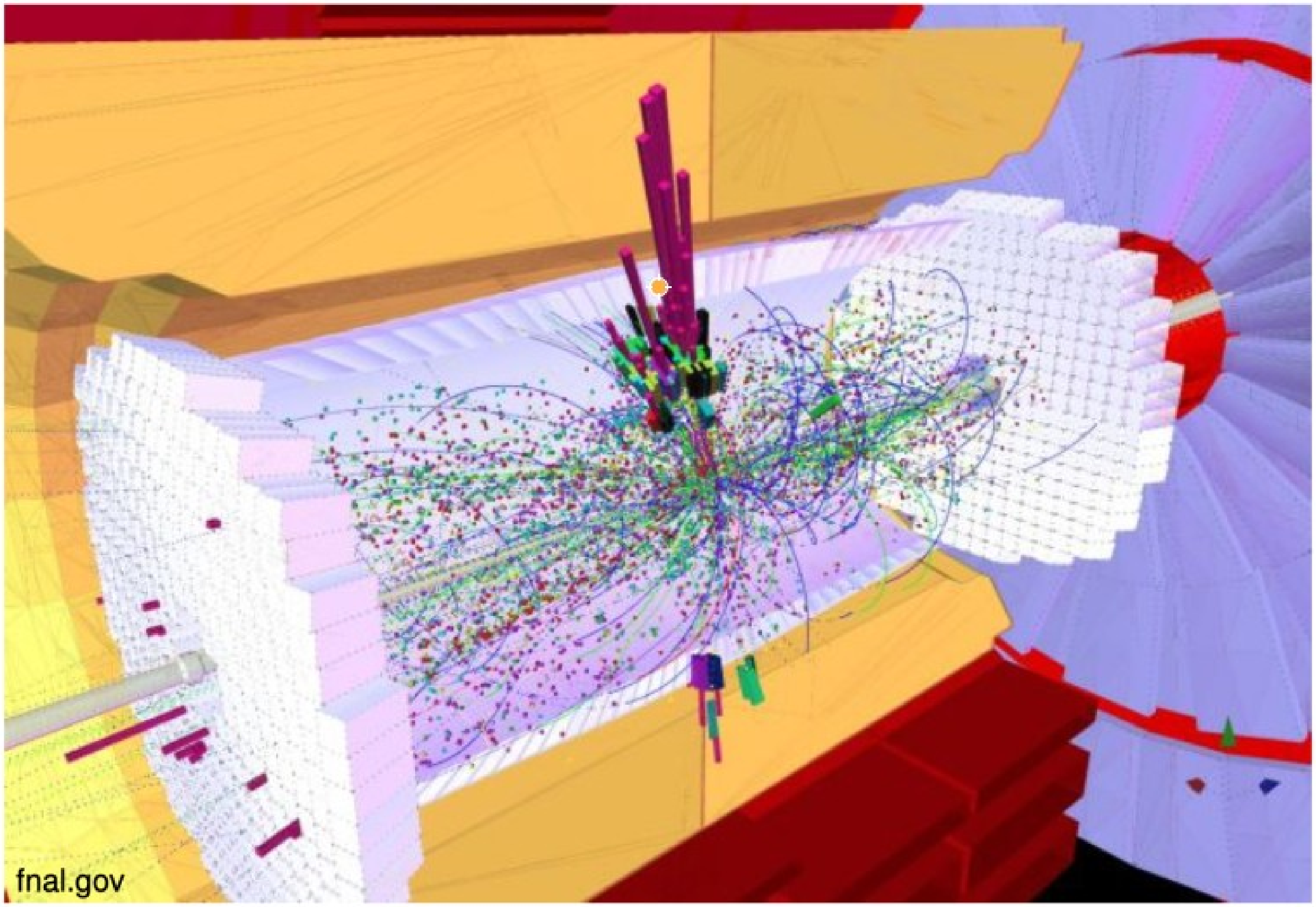


Super-Kamiokande Neutrino Detector

  - Indirect detection via „missing energy“
    (difficult if more than one neutrino in an event)

Overview: Interactions in Matter

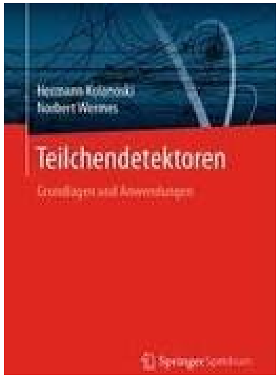
- Effects well-understood but difficult to compute analytically
- In practice, ***Monte Carlo simulation*** used
  - In Particle Physics typically GEANT toolkit → exercises 2 & 3!

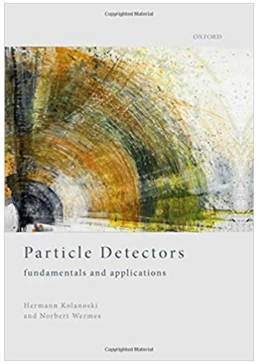


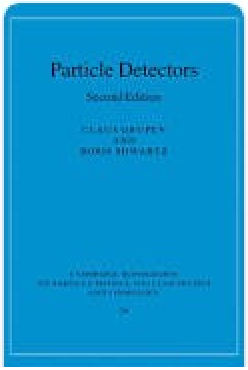
Highly recommended reading: PDG review *Passage of particles through matter*

Literatur Teilchendetektoren

- ***Teilchendetektoren***
  - H. Kolanoski, N. Wermes: *Teilchendetektoren*, Springer-Spektrum (2016)
  - C. Grupen: *Particle Detectors*, Cambridge UP (2008)
  - K. Kleinknecht: *Detektoren für Teilchenstrahlung*, Springer (2005)







https://pdg.lbl.gov/2019/reviews/rpp2018-rev-passage-particles-matter.pdf

https://pdg.lbl.gov/2019/reviews/rpp2019-rev-particle-detectors-accel.pdf

Mean ionization loss of charged particles

(Fast) **charged particles** lose energy by **inelastic collisions** with electrons in absorber
→ **ionization** and **atomic excitation**

Mean energy loss given by

Bethe formula: $-\left\langle \frac{\mathrm{d}E}{\mathrm{d}x} \right\rangle = D\rho z^2 \frac{Z}{A}\beta^{-2}\left[0.5\log\left(\frac{2m_\mathrm{e}c^2\beta^2\gamma^2\Delta T_\mathrm{max}}{I^2_\mathrm{eff}}\right) - \beta^2 - \frac{\delta}{2} - \frac{C}{Z}\right]$

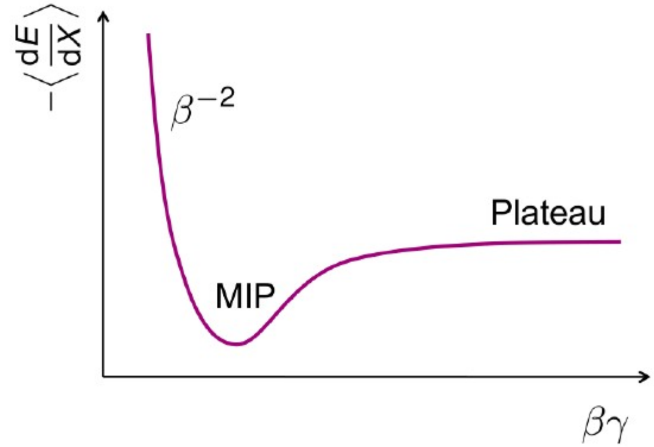
$$\mathrm{D}{=}4\pi N_\mathrm{A} r_\mathrm{e}^2 m_\mathrm{e} c^2 \approx 0.307\frac{\mathrm{MeV cm^2}}{\mathrm{g}}$$

with

z	charge number of incident particle (in units e)
Z	atomic number of absorber
N_A	Avogadro's number
$T_{max} \approx 2m_e\beta^2\gamma^2$	maximum energy transfer in single collision
$\delta(\beta\gamma)$	density effect correction ("Fermi density correction")
I	ionisation energy
C	shell correction for small energies

valid for moderately-relativistic charged heavy particles

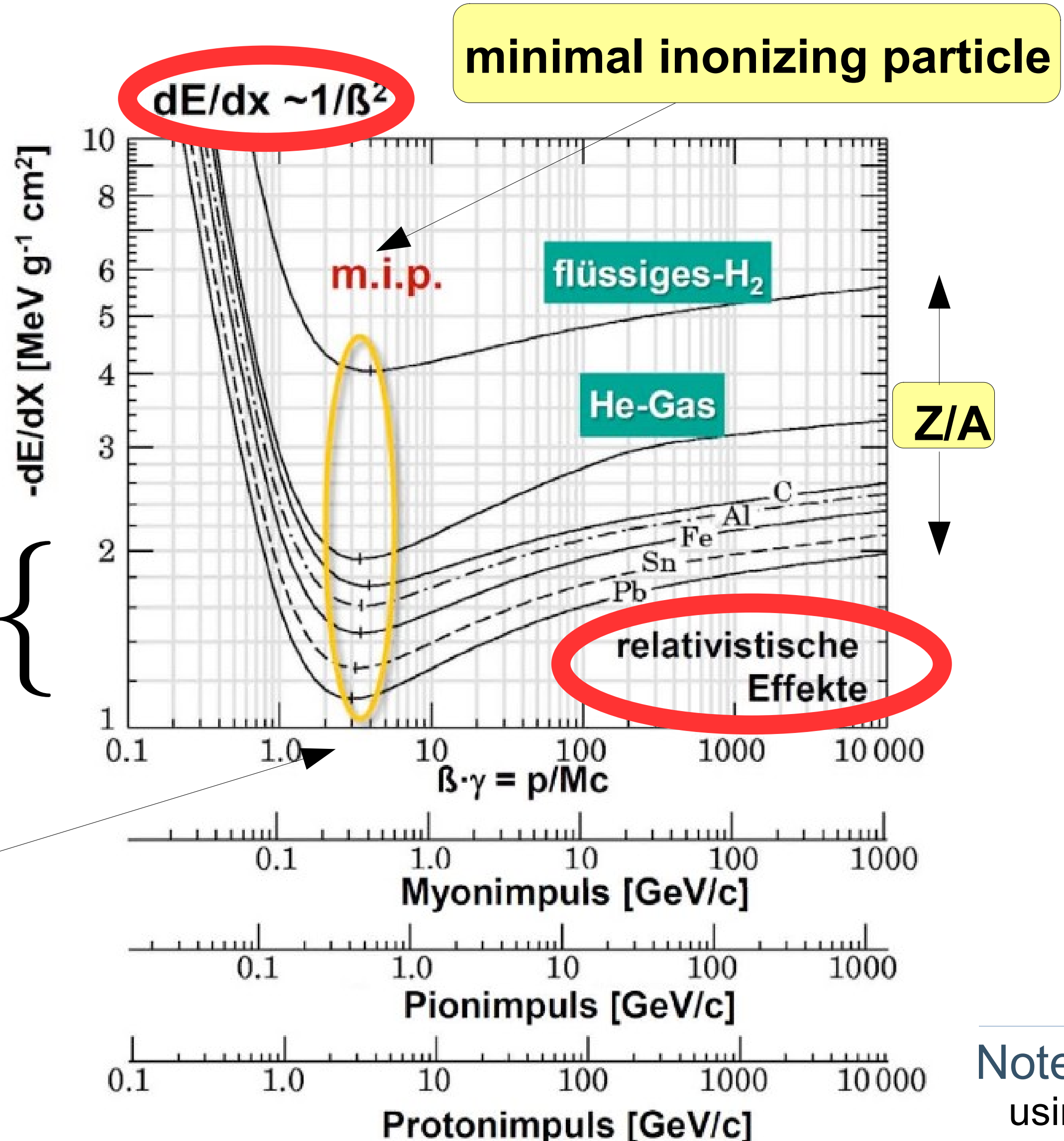
not for electrons (small mass, identical particles in scattering)



Mean energy loss for different materials

1-2 MeV cm² / g

βγ ~ 4



Note:
using $X = x \rho$
leads to similar curves
for different materials

charged particles: Photon Radiation (Bremsstrahlung)

Interaction with virtual photons from electrical field of nucleus:

$$\frac{dE}{dX} = 4\alpha N_\mathrm{A} \frac{z^2 Z^2}{A} \left(\frac{1}{4\pi\epsilon_0} \frac{e^2}{mc^2} \right)^2 E \log \frac{183}{Z^{1/3}}$$

$$\frac{dE}{dX} \propto \frac{E}{m^2}$$

Most important for electrons,
but also for ultra-relativistic myons

Typical for electrons:

$$\frac{dE}{dX} = \frac{E}{X_0}$$

with **radiation length [g/cm²]:**

$$X_0 = \frac{A}{4\alpha N_\mathrm{A} Z^2 r_\mathrm{e}^2 \log \frac{183}{z^{1/3}}}$$

$$\Bigg\} \quad E(X) = E_0 e^{-X/X_0}$$

exponential !

Critical Energy

$$\left(\frac{dE}{dX}\right)_{\mathrm{tot}} = \left(\frac{dE}{dX}\right)_{\mathrm{ion}} + \left(\frac{dE}{dX}\right)_{\mathrm{brems}}$$

definition of **„critcal energy“**

$$\frac{dE}{dX}(E_{\mathrm{c}})\Big|_{\mathrm{brems}} = \frac{dE}{dX}(E_{\mathrm{c}})\Big|_{\mathrm{ion}}$$

$E < E_{\mathrm{c}}$ ionization dominates

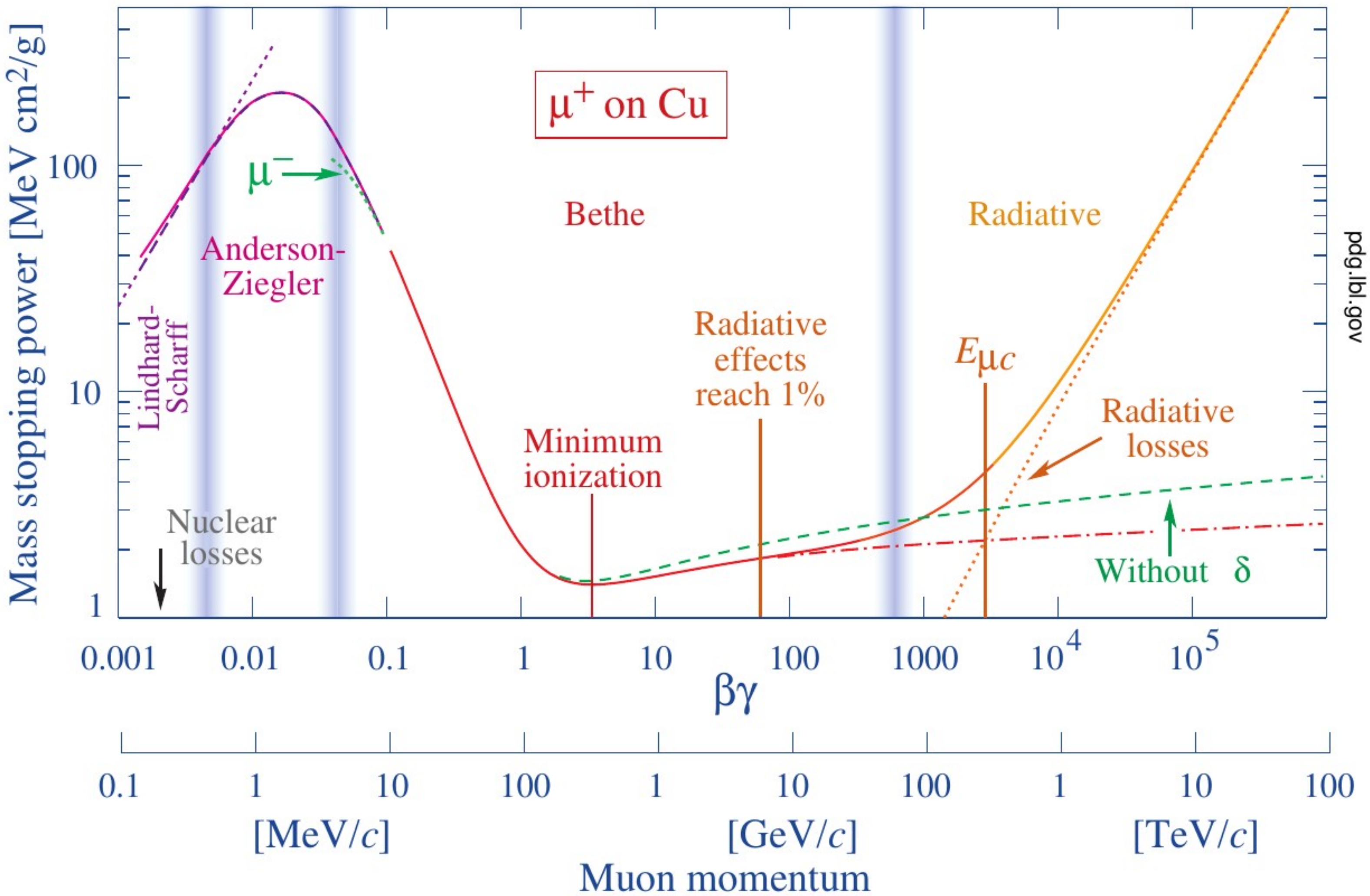
$E > E_{\mathrm{c}}$ photon radiation dominates → showering

Approximate values:

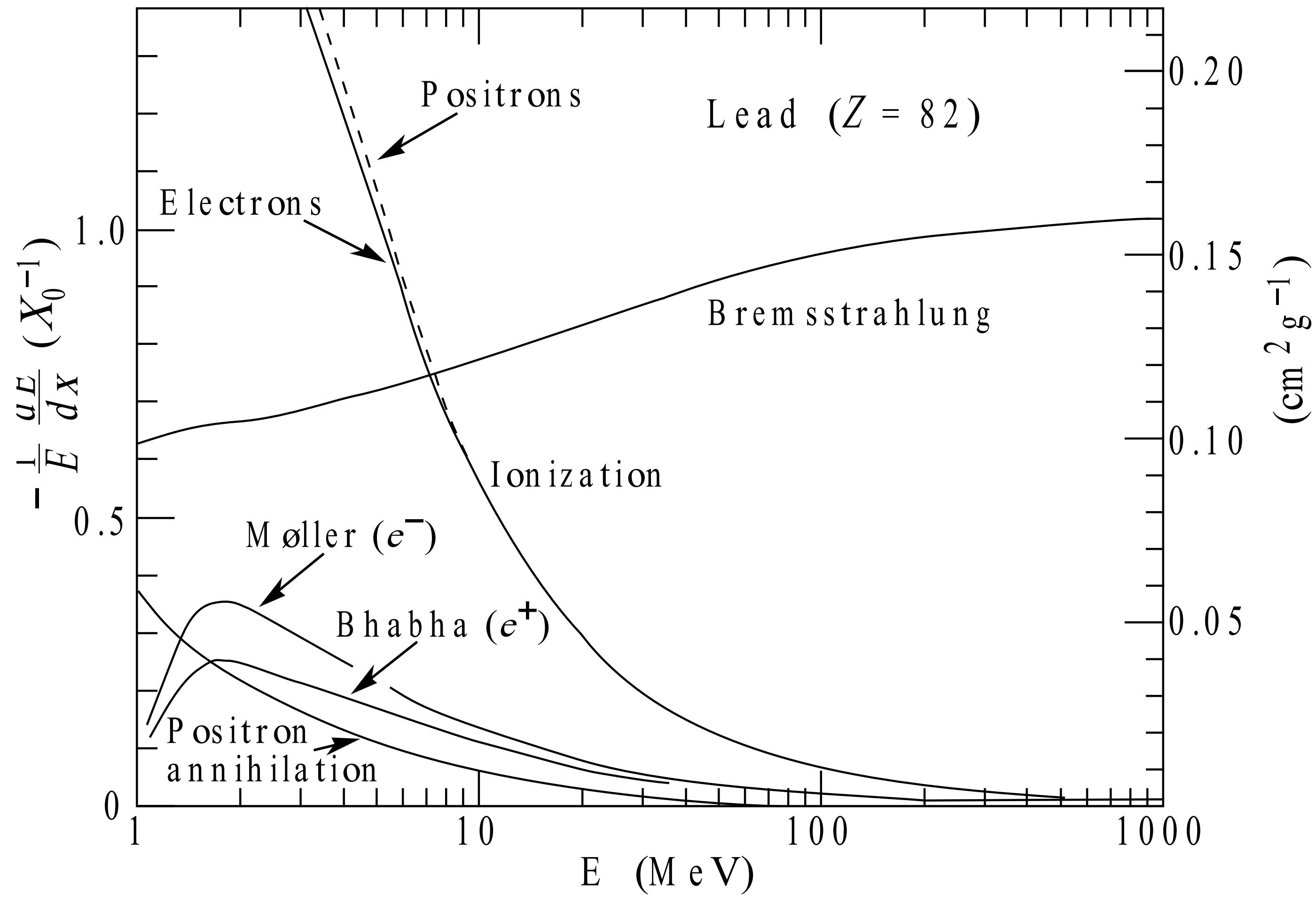
$$E_{\mathrm{c}}^{\mathrm{gas}} = \frac{[710]MeV}{Z + 0.92}$$

$$E_{\mathrm{c}}^{\mathrm{sol/liq}} = \frac{[610]MeV}{Z + 1.24}$$

Energy loss: the full picture

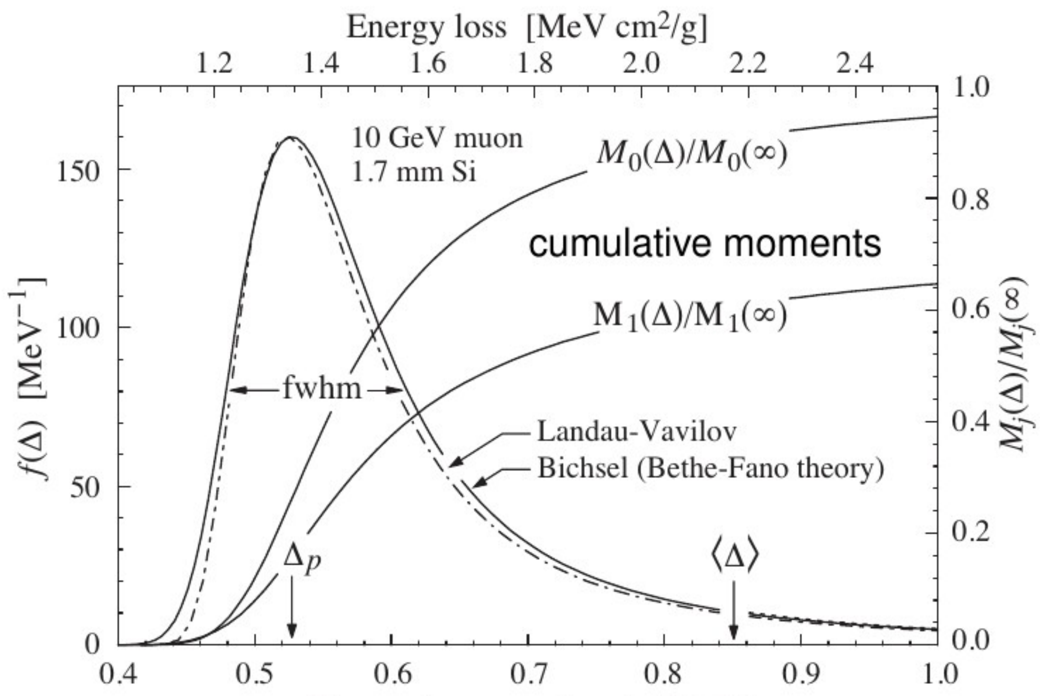


Energy loss of electrons



charged particles: Fluctuations of dE/dx

- Bethe equation: ***mean*** energy loss for given $\beta\gamma$
- In ***thin absorbers***: sizeable ***statistical fluctuations*** in energy loss
  - ***Strongly asymmetric*** distribution around most probable value Δ_p
  - Empirical description: ***Landau-(Vavilov) distribution***

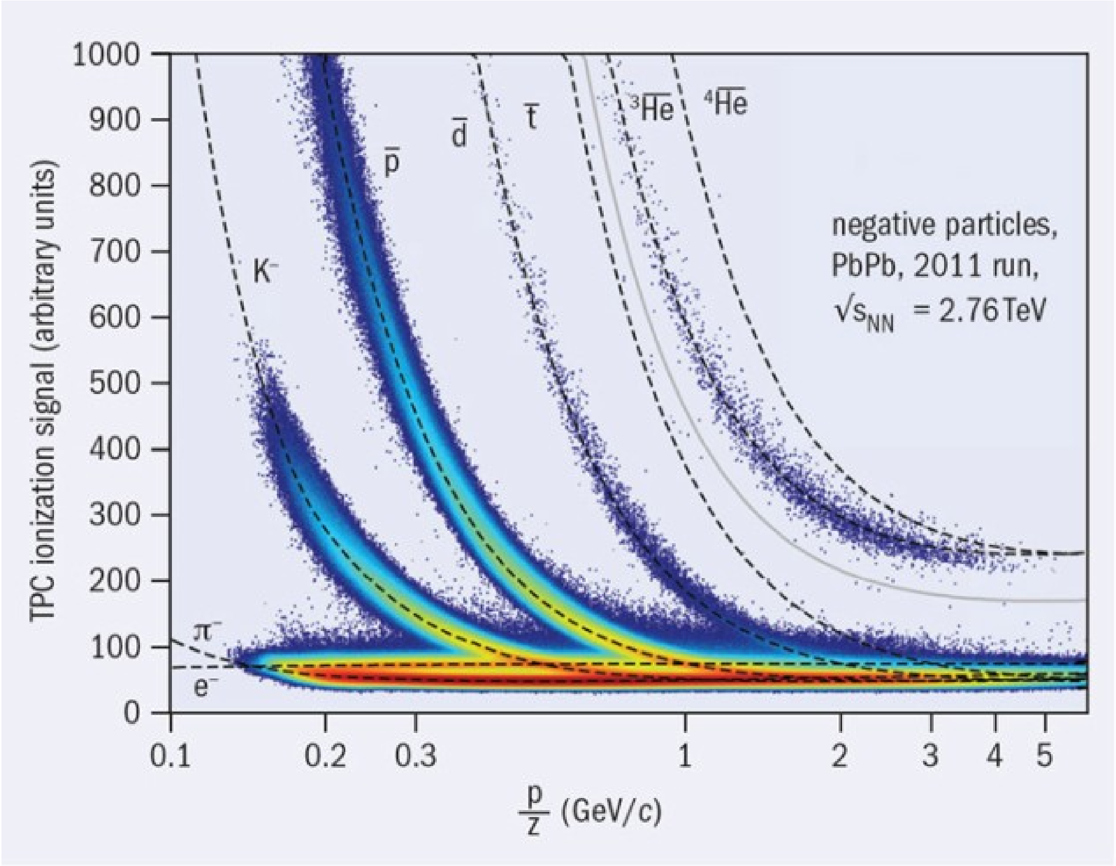


Note: mean and standard deviation of Landau distribution not defined !

→ measurements of dE/dx require special attention in data analyis

dE/dx for particle identification

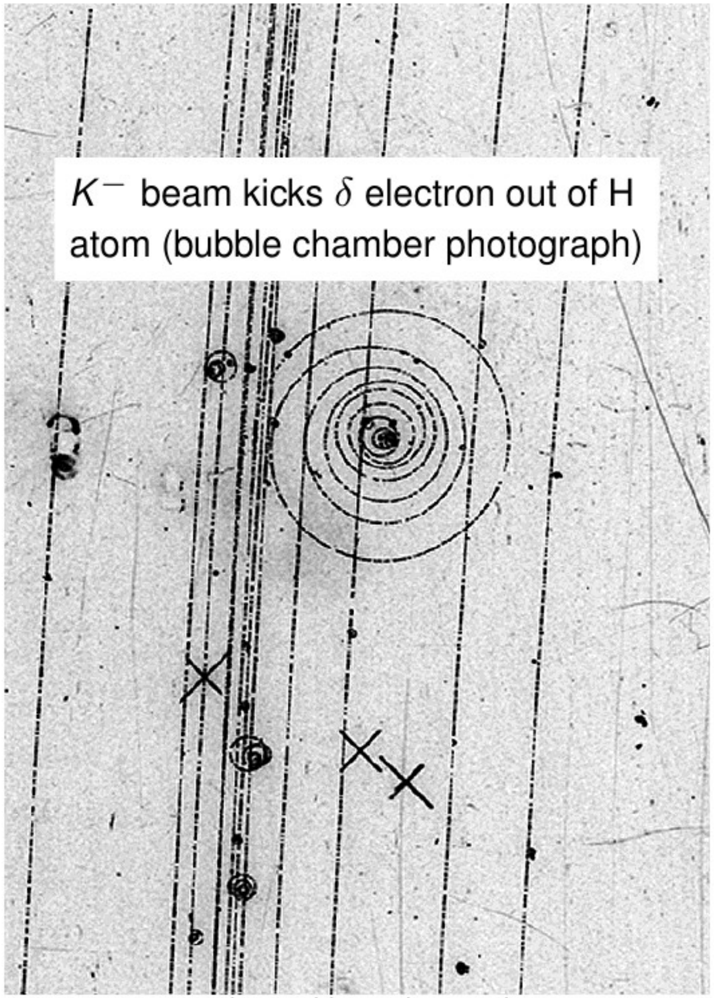
For small momenta,
measurements of ionisation loss (dE/dx) useful for particle identification



CERN Courier, August 2012

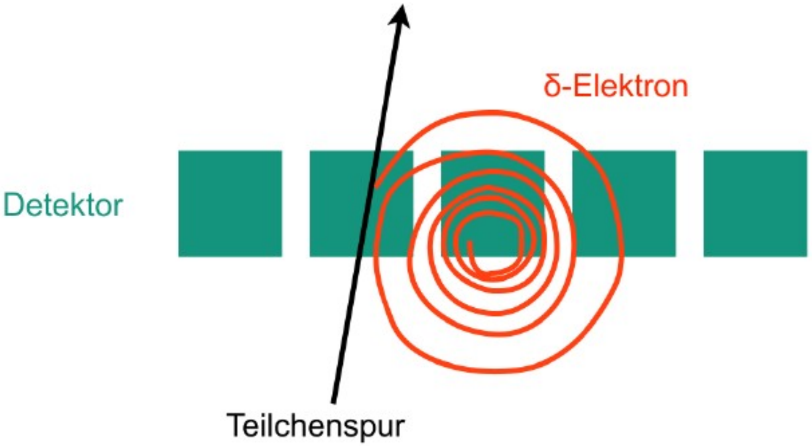
Measurements of ionization in the Time Projection Chamber
(TPC, a large gas detector) of the ALICE experiment

charged particles: δ electrons



hst-archive.web.cern.ch

- Close-to ***maximum energy transfer*** T_{max} to electrons in medium in single collision
  - "δ electrons" ("knock-on electrons")
  - ***Very rare*** (long tail of Landau distribution)
- Relevant for detectors: ***degrade position resolution*** in tracking detectors



electrons & positrons: interaction with matter

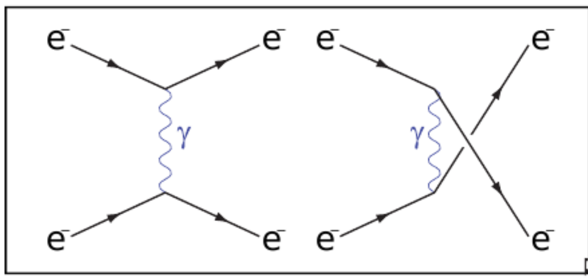
- Energy loss of electrons in addition to ionisation by

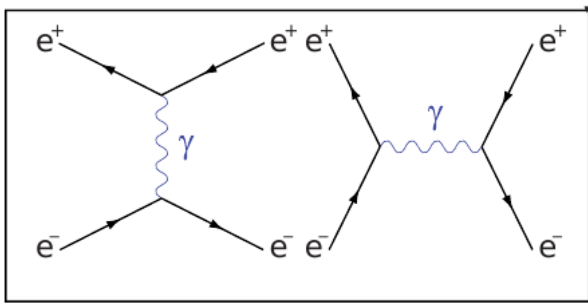
Low energies

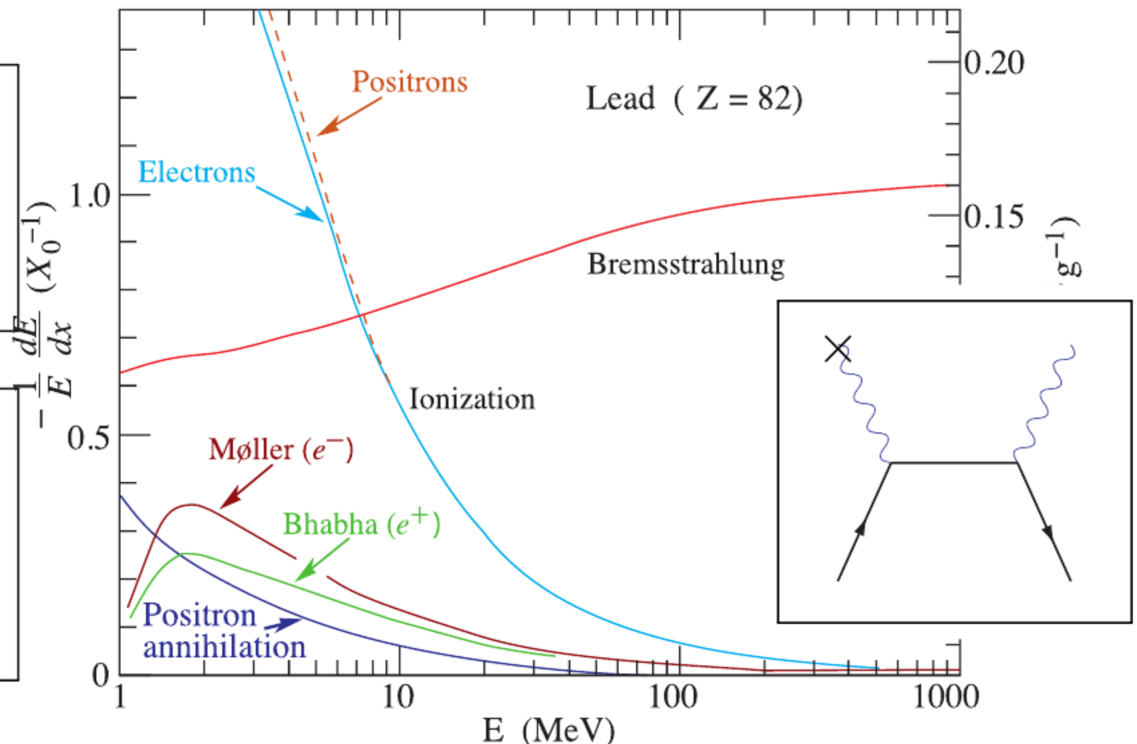
- e^-: Møller scattering
- e^+: Bhabha scattering, pair annihilation

High energies

- Bremsstrahlung: dominant above critical energy[1] $E_c \approx 600\,\text{MeV}/Z$







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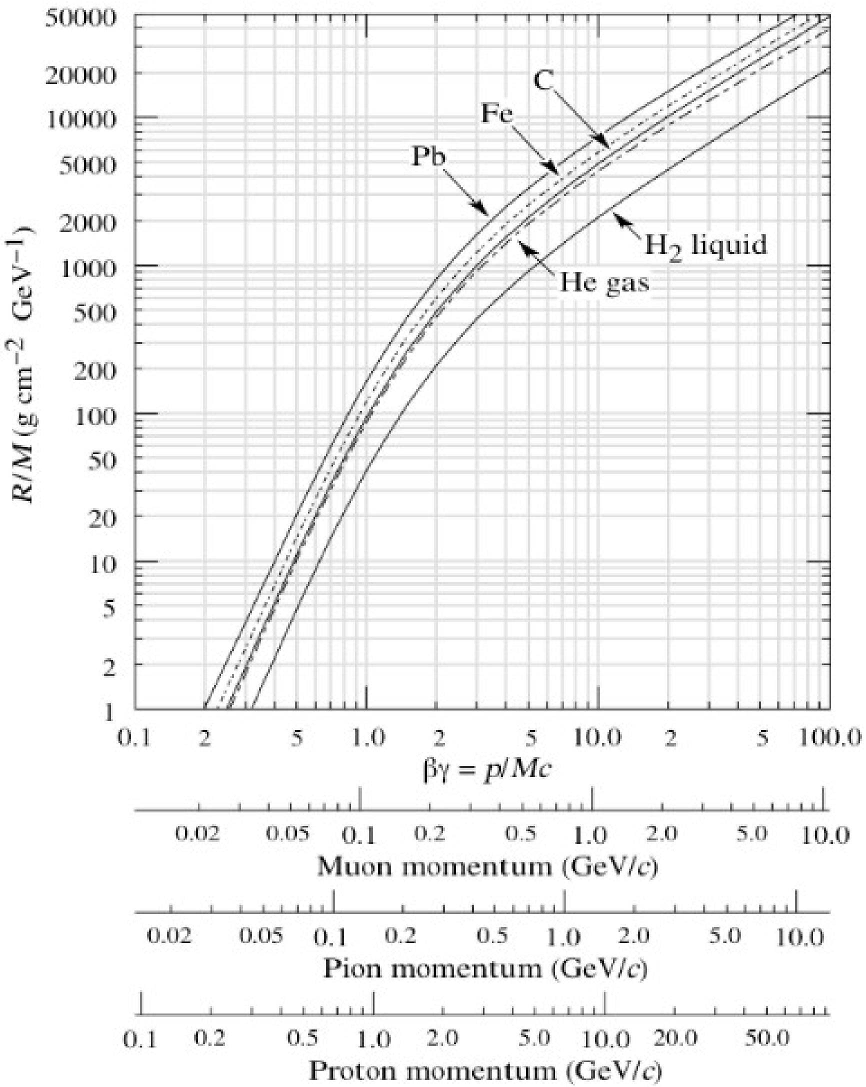
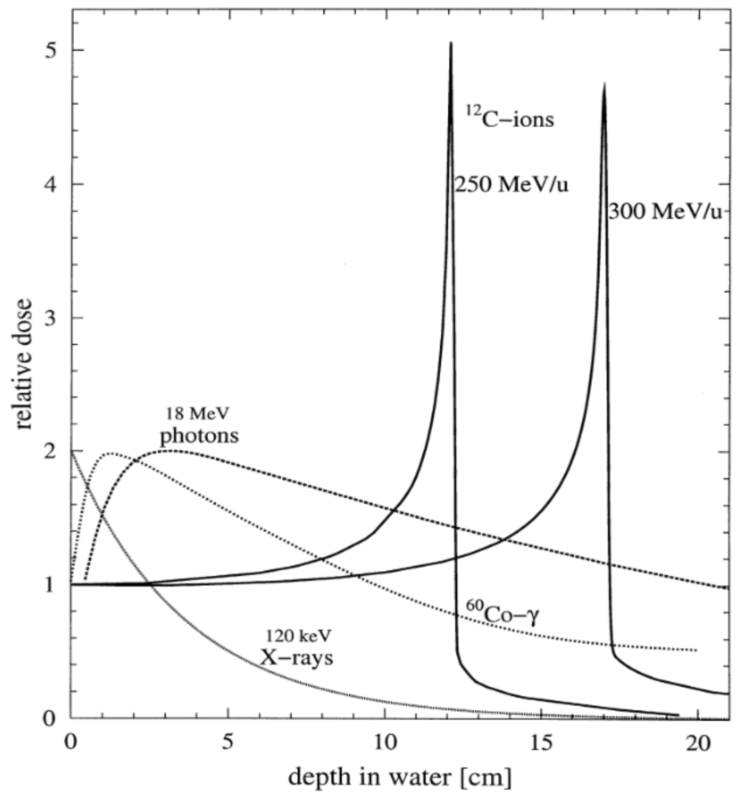
charged particles: range in matter

$$R = \int_E^0 \frac{dE}{(dE/dX)}$$



Teilchen/Material	Luft	Wasser	Aluminium	Blei
Elektronen 1 MeV 10 MeV	3.8 m 40 m	4.3 mm 4.8 cm	2.1 mm 2 cm	6.7 mm 5.3 mm
Protonen 1 MeV 10 MeV	25 cm 1.25 m	0.02 mm 1.2 mm	0.014 mm 0.63 mm	8.8 µm 0.3 mm
Alpha 1 MeV	5 mm		3.3 µm	2.4 µm

Large peak („Bragg peak“) in
energy depostion at end of range ...

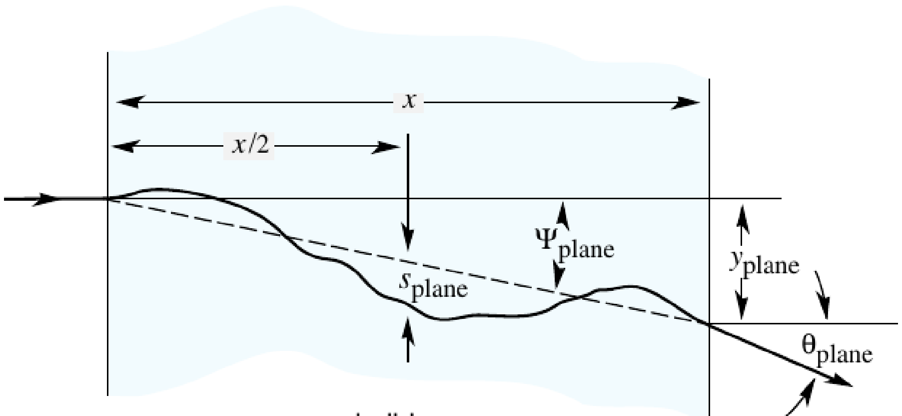


... used in medical tumor therapy

charged particles: multiple (Coulomb) scattering

- Charged particle traversing medium: deflected by many small-angle scatters ("***multiple scattering***")
  - Mostly Coulomb scattering (Rutherford)
  - Hadrons also strong contributions
- Many scatters: net scattering-angle distribution $f(\theta)$ approximately ***Gaussian*** (central limit theorem)
  - Less frequent hard scatters produce non-Gaussian tails
- Standard deviation of $f(\theta)$ after distance x through medium:

$$\theta_0 \approx 13.6\,\mathrm{MeV} \cdot \frac{Z}{\beta}\sqrt{\frac{x}{X_0}}$$



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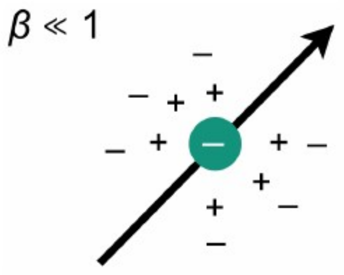
- Important ***implications for position resolution*** of tracking detectors
  - e. g. momentum resolution of CMS tracking detector ultimately limited by multiple scattering

charged particles: Cherenkov Radiation

- Characteristic radiation emitted by charged particles when passing a medium at a ***speed*** β ***greater than the phase velocity of light*** in that medium (even for non-accelerated charge):

  $\beta > \frac{1}{n}$ (with refractive index *n* of medium)

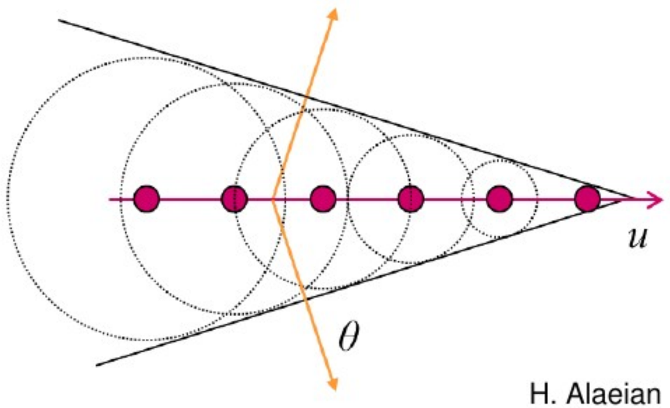


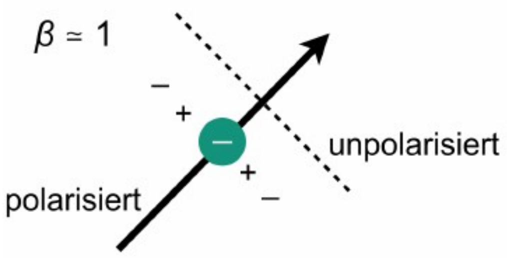
$\langle\text{dipole moment}\rangle = 0$

$\rightarrow$ no radiation

- Emission under ***Cherenkov angle***

$$\boxed{\cos\theta = \frac{1}{n\beta}}$$





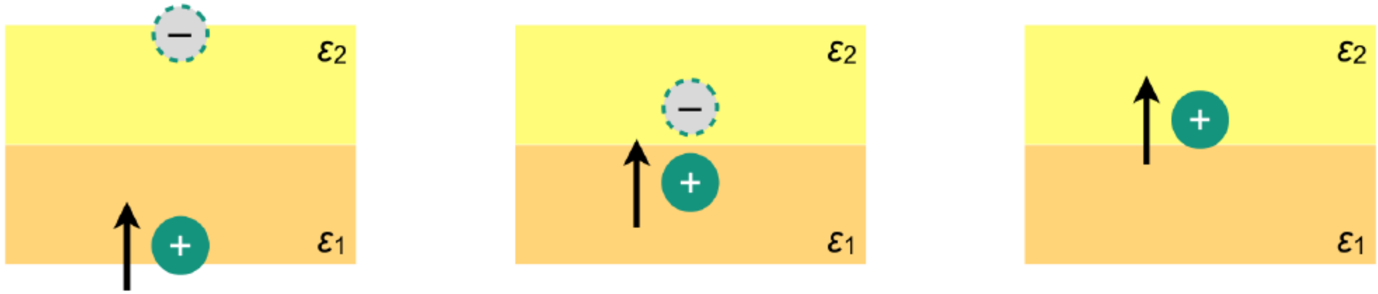
$\langle\text{dipole moment}\rangle \neq 0$

$\rightarrow$ Cherenkov radiation

- Origin: asymmetric polarisation of medium

charged particles: Transition Radiation

- Radiation emitted when charged particle passes through inhomogeneous media, e. g. boundary between two media of ***different permittivity*** ϵ (Ginzburg, Frank 1945)
  - Classical model: radiation by a time dependent ***dipole between charge and image charge***



  - Intensity $I = \alpha z^2 \gamma \frac{\omega_p}{3}$ with plasma frequency $\omega_p^2 = \frac{n_e e^2}{\epsilon_r \epsilon_0 m_e}$

    $\rightarrow$ intensity proportional to γ

- Application: measurement of relativistic ***Lorentz factor*** γ
  - With known momentum p and $\gamma = E/m$: ***mass*** (particle identification)

Interactions of photons with Matter

- Low energies $E_\gamma \lesssim 1$ MeV: ***photo effect***
  - Absorption of photon
- Low-to-medium energies $E_\gamma = \mathcal{O}(1\text{ MeV})$: ***Compton scattering***
  - Decrease of photon energy (gets replaced by photon with lower energy)
- Energies $\geq 2m_e$: ***pair production***
  - Creation of electron-positron pair from photon

If photon transfers all its energy to electron(s) and does no longer exist after interaction

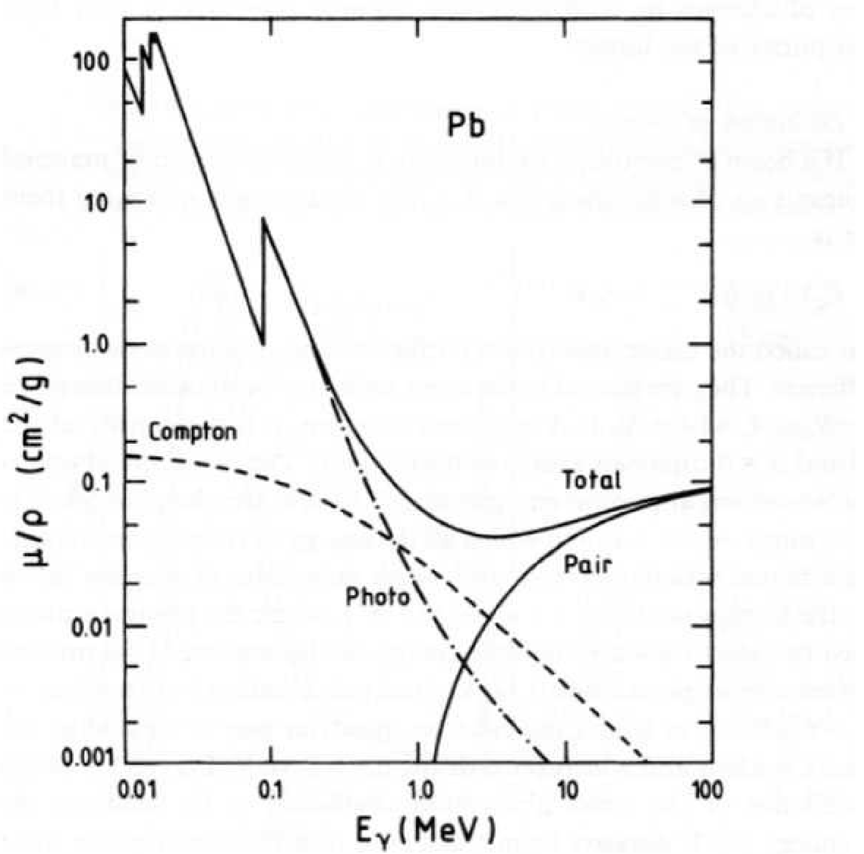
→

Reduction of intensity I of a photon beam beam along distance x due to absorption in matter: **Beer-Lambert law**

$$I(x) = I_0 e^{-\mu x} \text{ with absorption coefficient } \mu$$

- 1/μ ist mean free path
- μ is proportional to cross section of photon interaction in matter

Fig. 1.3. Mass absorption coefficient μ/ρ for photons in lead.



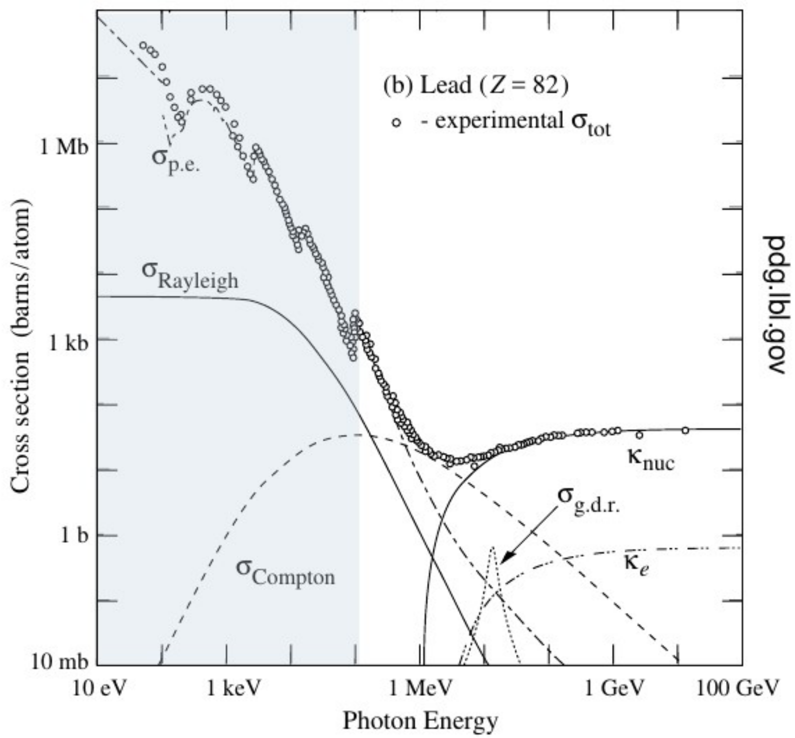
Photoeffect

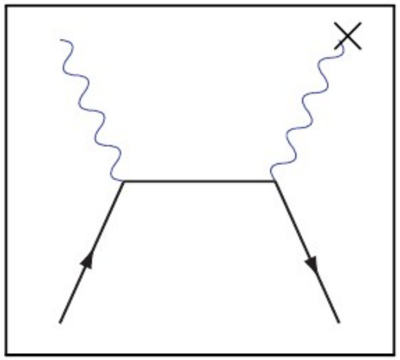
- Cross section (approximation)

$$\sigma_{\text{p.e.}} = \frac{8\pi}{3} r_e^2 Z^5 \alpha^4 \left(\frac{1}{\epsilon}\right)^{\delta}$$

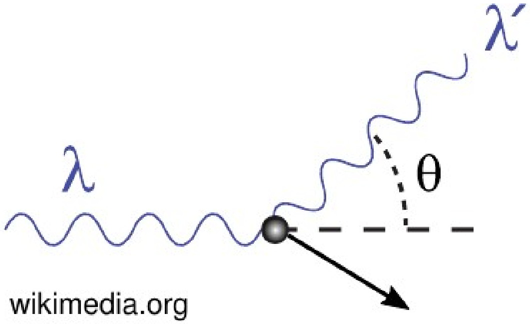
  - Reduced photon energy $\epsilon = \frac{E_\gamma}{m_e}$
  - $\delta = \begin{cases} 3.5 & \text{for } \epsilon \ll 1 \\ 1 & \text{for } \epsilon \gg 1 \end{cases}$
  - $r_e \approx 2.8\,\text{fm}$ classical electron radius
  - $\alpha \approx \frac{1}{137}$ fine-structure constant
- Decreasing with photon energy
- Strong dependence on Z^5
- In addition: absorption edges due to atomic energy levels

Photon total cross-section in lead





Photons: Compton Effect



- Energy after scattering (relativistic kinematics)

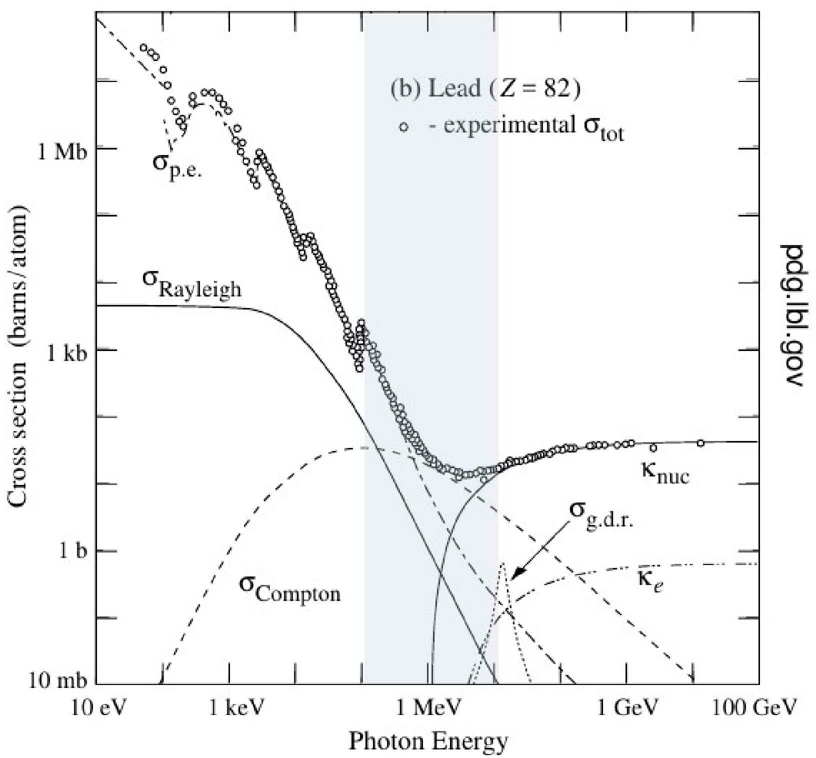
$$E'_\gamma = \frac{E_\gamma}{1+\epsilon(1-\cos\theta)}$$

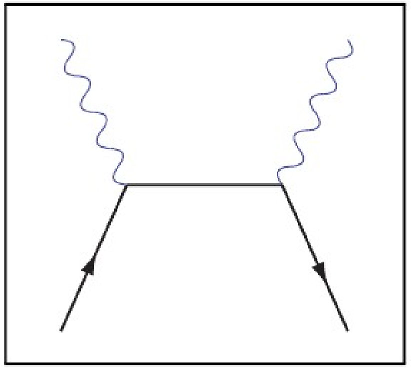
with reduced photon energy $\epsilon = E_\gamma / m_e$

- Cross section (approximation for $\epsilon \gg 1$): ***Klein-Nishina formula***

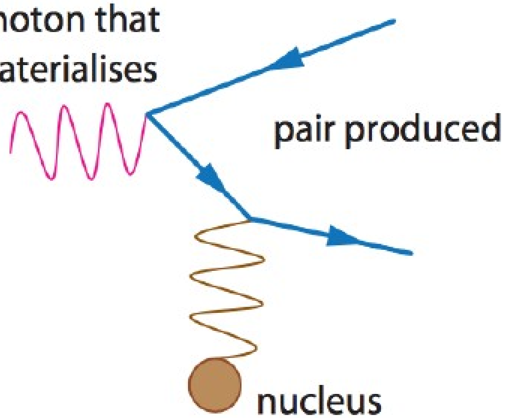
$$\sigma_C = \pi r_e^2 \frac{1}{\epsilon}\left[\frac{1}{2} + \ln(2\epsilon) + \mathcal{O}\left(\frac{1}{\epsilon}\right)\right]$$

Photon total cross-section in lead





Photons: Pair Production



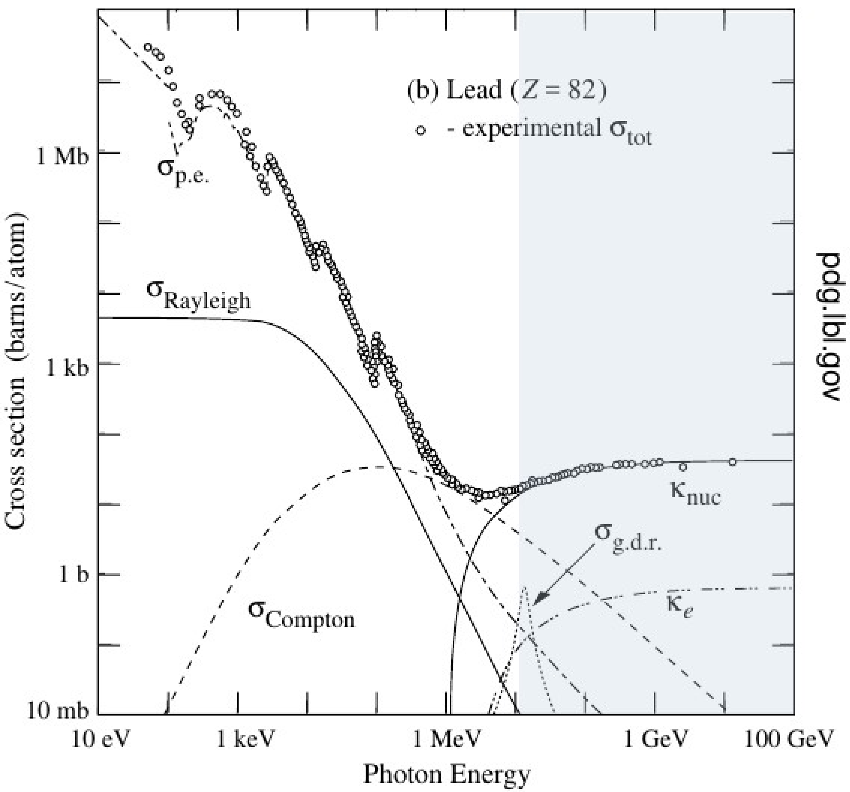
- Kinematic constraints
  - ***Threshold effect***: only for $\epsilon > 2$
  - ***4-momentum conservation***: only within electric field of nucleus (nucleus receives recoil)
- Cross section (for $\epsilon \gg 1$)
  (integration of ***Tsai's formula***)

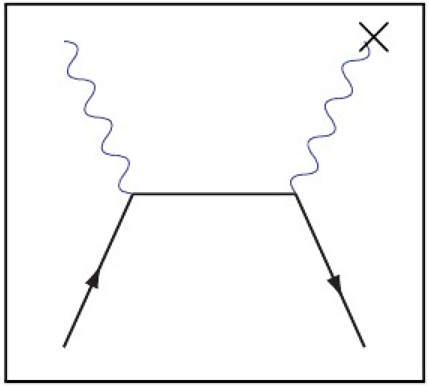
$$\sigma_p = 4\alpha r_e^2 Z^2 \left[\frac{7}{9}\ln\frac{183}{Z^{1/3}} - \frac{1}{54}\right]$$

  - ***Independent of energy***
  - $Z^2 \ln Z^{-1/3}$ dependence
  - Absorption coefficient

$$\mu_p = \sigma_p \frac{N_A}{A}$$

Photon total cross-section in lead





Radiation length X_0

- **Reminder:** radiation length in bremsstrahlung processes:

$$X_0 = \frac{A}{4\alpha N_\mathrm{A} Z^2 r_\mathrm{e}^2 \log \frac{183}{z^{1/3}}}$$

- Comparison to absorption coefficient in pair production:

$$\mu_p \simeq \frac{7}{9} X_0$$

Mean free path of a photon is 9/7 of X_0

→ after traversing one radiation length of material, the intensity of a photon beam is reduced to exp(-7/9) ≈ 46%

Electromagnetic showers

An avalanche of successive **bremsstrahlung** and **pair-production** processes

(simple) Heitler Model

$$N_n = 2^n$$

$$X_n = n\,X_{1/2}$$

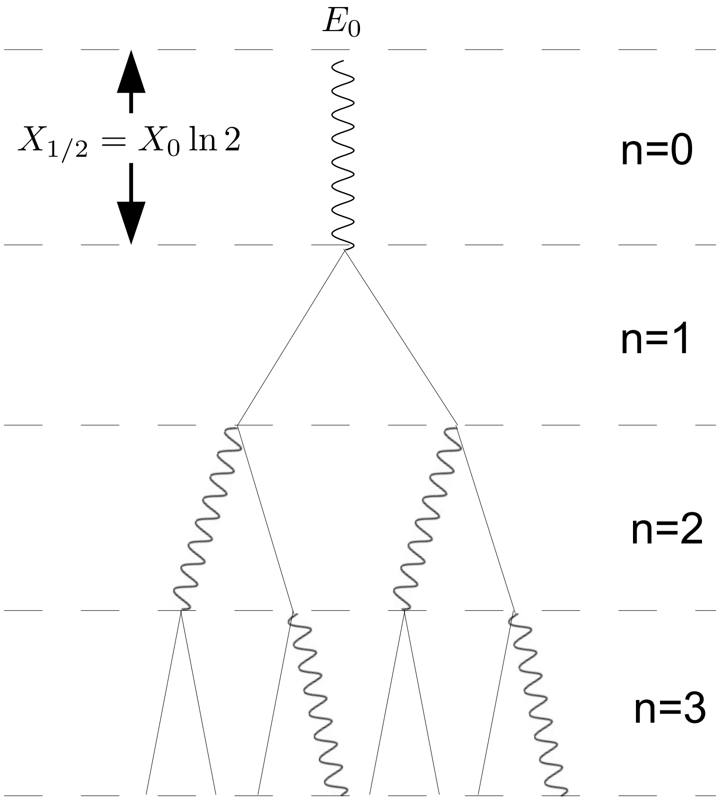
$$E_n = E_0/N_n$$

$$E_n \leq E_{\text{crit}}$$

$$n_{\text{max}} = \ln\frac{E_0}{E_{\text{crit}}}/\ln 2$$

$$X_{\text{max}} = X_0\ \ln\frac{E_0}{E_{\text{crit}}}$$

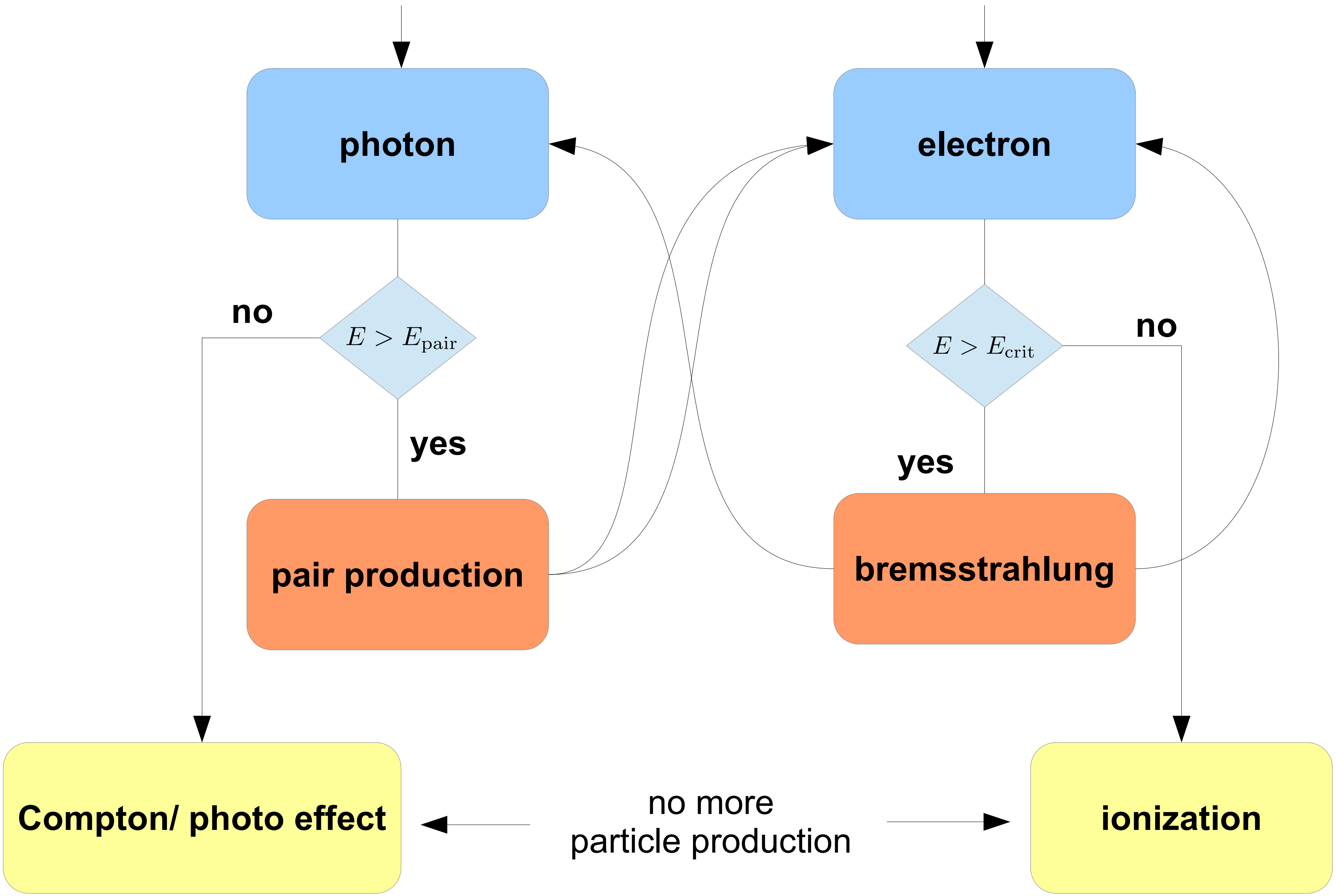
$$N_{\text{max}} = \frac{E_0}{E_{\text{crit}}}$$



etc.

$$X_{\text{max}} \propto \ln E_0 \qquad N_{\text{max}} \propto E_0$$

Electromagnetic showering process



Longitudinal shower shape

Parametrization:
[Longo 1975]

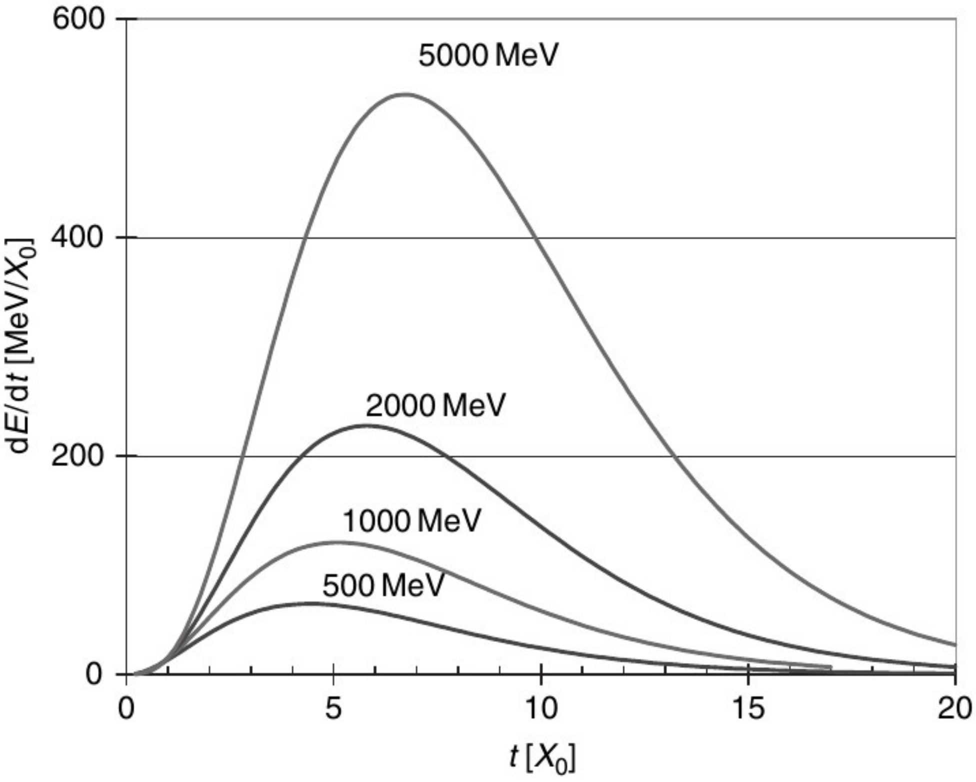
$$\frac{dE}{dt} = E_0 \; t^{\alpha} e^{-\beta t}$$

α, β : free parameters

t^{α} : at small depth number of secondaries increases ...

$e^{-\beta t}$: at larger depth absorption dominates ...

Numbers for E = 2 GeV (approximate):
$\alpha = 2$, $\beta = 0.5$, $t_{max} = \alpha/\beta$



Hadronic showers

Strong interactions of hadrons in matter

in addition to ionization, photon radiation etc.

very simple model , Mathews et al.
[Astropart.Phys. 22 (2005) 387]

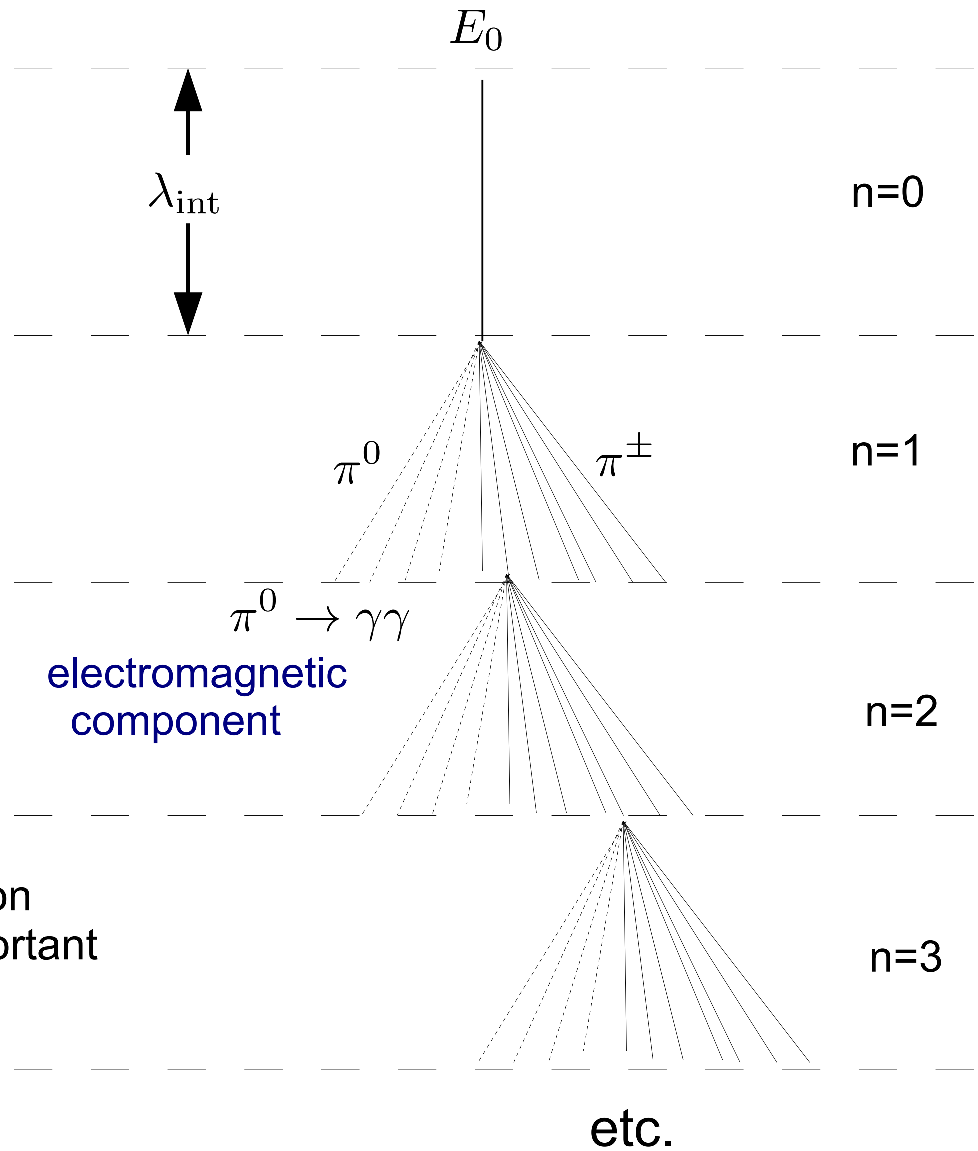
$E > E_{\mathrm{crit}}^{\mathrm{had}}$ $\quad \pi^{\pm} + A \rightarrow \mathrm{hadrons}$

$E < E_{\mathrm{crit}}^{\mathrm{had}}$ $\quad \pi^{\pm} \rightarrow \mu^{\pm}\nu$

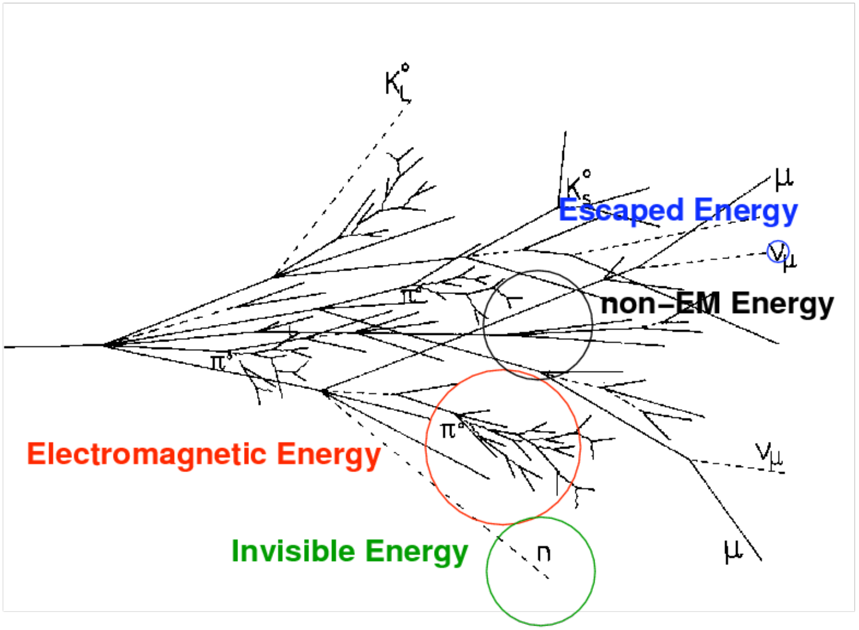
~1/3 of energy goes to $\pi^0 \rightarrow \gamma\gamma$

in nuclear reactions, nuclear excitation
and nuclear fission etc. become important

Hadronic showers are complex !



Hadronic showers



- ***Hadronic showers***
  - $\approx 90\,\%$ pions, $\frac{1}{3}$ of them π^0
  - ***Electromagnetic component*** (em shower induced by $\pi^0 \to \gamma\gamma$ decays): fraction f_{em} energy dependent ($\propto \ln E$) and strongly fluctuating
- Complex ***nuclear interactions***
  - 20–40 % ***'invisible' energy***: nuclear binding energy in spallation, 'delayed' photons (from de-excitation), neutrons
  - ***Undetectable*** particles (ν, μ) and ***strongly ionising*** particles (α)
  - Relatively few high-energetic particles, but strongly fluctuating
- Consequence: ***different detector response*** e to electrons and h to hadrons ($e/h \neq 1$)
  - Measured hadron energy $E_{\text{meas}} = [f_{em}e + (1 - f_{em})h] \cdot E_{\text{in}}$
  - Since $f_{em} = f_{em}(E)$: ***non-linear response to hadrons if $e/h \neq 1$***

based on C. Grupen, Teilchendetektoren

hadron showers: Neutral hadrons and nuclear fragments

- neutral, long-lived hadrons carry energy away from shower centre

  → hadronic showers have „satellites“

- losses of detectable energy
  - weak decays of (slow) hadrons in showers produce undetectable neutrinos
  - slow neutrons escape from detector volume
  - nuclear fragments absorbed in inactive media

- fission energy adds to detectable energy
  - exploited in uranium calorimeters

Absorption of hadrons in matter characterized by

hadronic interaction length λ

$$\langle E \rangle (x) = E_0 \exp\left[-\frac{x}{\lambda}\right] \quad \text{with} \quad \lambda = \left(\sigma_{\text{inel}} \frac{N_A}{A} \rho\right)^{-1} \quad \text{(values tabulated)}$$

σ_{inel}: inelastic cross-section of nuclear reactions

λ ***larger by factor 20–30 than*** X_0***, large fluctuations around*** $\langle \lambda \rangle$