Konzepte für Experimente an zukünftigen Hadroncollidern I

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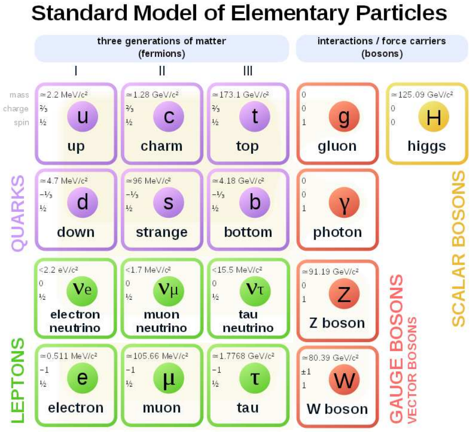
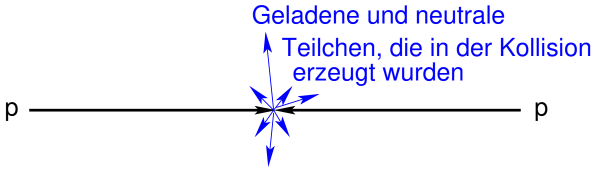
The standard model of particle physics

- Below a scale of 10^{-10} m the matter is not continuously distributed, but discrete, it consists of particles.
- There are the following elementary particles in the so-called standard model of the strond and electroweak interactions:



The standard model predicts the outcome of experiments at particle accelerators with impressive precision.



Particles which can be produced in a pp collision

Leptonen

- Neutrinos: stable, but only weakly charged. $\Rightarrow$ No interaction leading to a measurable electronic signal in the detector components.
- Electrons: stable, electrically charged. $\Rightarrow$ Electronic signals in the detector components.
- Muons: unstable, but ultrarelativistic, hence longlived in the laboratory system that they do not decay in the detector; electrically charged. $\Rightarrow$ Electronic signals in the detector components.
- τ leptons: unstable. $\Rightarrow$ Have to be detected via their decay products.

Further final state particles

Hadrons

- In the pp collision quarks and gluons are formed. Due to the quark confinement, we do not see quarks and gluons in the detector, by so-called "hadron jets" which are created from the initial quarks and gluons.
- Special role of two types of quarks:
  b quarks build longlived b hadrons which makes it possible to identify b quark jets.
  t quarks are so shortlived that they cannot build hadron. They can be identified by the decay $t \to Wb$.
- Jets contain mainly the lightes mesons, namely π^+, π^-, π_0 which are quasistable due to the large Lorentz boost.

Photons

Photons are stable. They are electrically neutral, but can create electromagnetic showers in the detector material which can be detected.

Interaction of particles with matter

Interaction of charged particles with matter

Two effects in the passage of charged particles through matter:

- Energy loss.
- Deflection from the original trajectory.

Processes causing energy loss and deflection

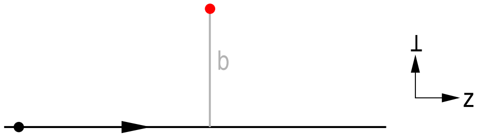
- Inelastice scattering off atomic electrons in the traversed material.
- Elastic scattering off the nuclei of the traversed material.
- Emission of Čerenkov radiation.
- Nuclear reactions.
- Bremsstrahlung.

The radiation field of an accelerated charge is proportional to its acceleration a_{charge}. The energy of the radiation is proportional to $|\vec{E}|^2$ which is proportional to $a_{charge}^2 = \left(\frac{F}{m}\right)^2 \propto \frac{1}{m^2}$. Hence bremsstrahlung is only important for electrons, but not for heavy charged particles.

Interaction of heavy charged particles with matter

- Heavy charged particles: $\mu^{\pm}$, $\pi^{\pm}$, p, $\bar{p}$, α particles, light nuclei.
- Dominant processes for heavy charged particles:
  - Inelastic scattering off atomic electrons of the traversed material.
  - Elastic scattering off the nuclei of the material.

Semiclassical treatment



heavy charged
particle with mass M
charge ze, speed v

Momentum transferred to the electron:

$$\int_{-\infty}^{\infty} F_\perp dt = \int_{-\infty}^{\infty} e \cdot E_\perp dt = e \int_{-\infty}^{\infty} E_\perp \frac{dz}{v} = \frac{e}{v} \int_{-\infty}^{\infty} E_\perp dz \cdot \frac{2\pi b}{2\pi b} = \frac{e}{2\pi b v} \cdot 2\pi b \int_{-\infty}^{\infty} E_\perp dz$$

$2\pi b \int_{-\infty}^{\infty} E_\perp dz$: Flux through the shall of a cylinder with radius b around the heavy particle.

$$\Rightarrow \Delta p := \int_{-\infty}^{\infty} F_\perp dt = \frac{ze^2}{2\pi\epsilon_0 b v}$$

Inelastic scattering off atomic electrons

Energy obtained by the electron:

$$\Delta E(b) = \frac{(\Delta p)^2}{2m_e} = \frac{z^2 e^4}{8\pi^2 \epsilon_0^2 m_e v^2 b^2}$$

N_e: Electron number density in the material.

$\Rightarrow$ Energy loss of electrons at distance between b and $b + db$ from the heavy particle in a thin layer dx:

$$-dE(b) = \Delta E(b) \cdot N_e \cdot 2\pi b \, db \, dx = \frac{z^2 e^4}{4\pi \epsilon_0^2 m_e v^2} \frac{1}{b} db \, dx$$

$$-\frac{dE}{dx} = \int_{b_{min}}^{b_{max}} dE(b) = \frac{x^2 e^4}{4\pi \epsilon_0^2 m_e v^2} N_e \ln \frac{b_{max}}{b_{min}} = \frac{x^2 e^4}{8\pi \epsilon_0^2 m_e v^2} N_e \ln \frac{b_{max}^2}{b_{min}^2}$$

Inelastic scattering off atomic electrons

Energy loss of the heavy charged particle:

$$-\frac{dE}{dx} = \frac{x^2 e^4}{8\pi\epsilon_0^2 m_e v^2} N_e \ln \frac{b_{max}^2}{b_{min}^2}$$

- b_{min} can be computed from the largest possible energy transfer to the electron:

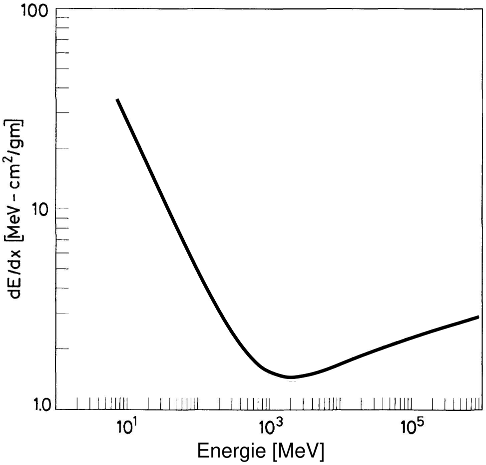
$$2\gamma^2 m_e v^2 = \frac{z^2 e^4}{8\pi^2\epsilon_0^2 m_e v^2 b_{min}^2} \Leftrightarrow b_{min}^2 = \frac{x^2 e^4}{16\pi^2\gamma^2 m_e^2 v^4 \epsilon_0^2}$$

- b_{max} can be computed from the smallest allowed energy transfer following from the quantization of the electron's binding energy:

$$\Delta E_{min} = \frac{z^2 e^4}{8\pi^2\epsilon_0^2 m_e v^2 b_{max}^2} \Leftrightarrow b_{max}^2 = \frac{z^2 e^4}{8\pi^2\epsilon_0^2 m_e v^2} \frac{1}{\Delta E_{min}}$$

$\Rightarrow$ Bohr's approximation of the Bethe-Bloch formula:

$$\boxed{-\frac{dE}{dx} = \frac{z^2 e^4}{8\pi\epsilon_0^2 m_e v^2} N_e \ln \frac{2 m_e \gamma^2 v^2}{\Delta E_{min}}}$$



- First rapid decrease of the energy loss with increasing energy of the charged particle.
- After a minimum weak, only logarthmic increase of the energy loss with increasing energy of the heavy charged particle.
- Particles with an energy for which the energy loss is minimum are called minimum ionizing particle.

Scaling of the Bethe-Block formula

Let us consider two particles with different mass and charge traversing the same material.

$$-\frac{dE}{dx} = z^2 f(\beta)$$

$E_{kin} = (\gamma - 1)Mc^2$, d.h. $\beta = g(\frac{E_{kin}}{M})$, also

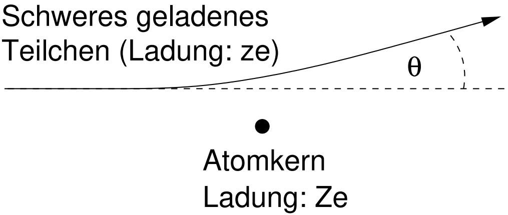
$$-\frac{dE}{dx} = z^2 \tilde{f}\left(\frac{E_{kin}}{M}\right)$$

Hence

$$-\frac{dE}{dx}\bigg|_{particle\ 1/2} (E_{kin,1/2}) = z_{1/2}^2 \tilde{f}\left(\frac{E_{kin,1/2}}{M_{1/2}}\right),$$

leading to $\boxed{-\frac{dE}{dx}\bigg|_{particle\ 2} (E_{kin,2}) = \frac{z_2^2}{z_1^2}\left(-\frac{dE}{dx}\right)_{particle\ 1}\left(E_{kin,2}\frac{M_1}{M_2}\right).}$

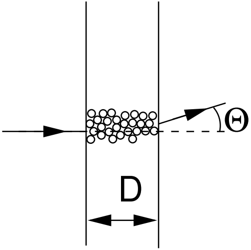
Multiple scattering



Scattering off a single nucleus:

$$\theta = \frac{\Delta p}{p} \propto \frac{z \cdot Z}{p}.$$

$$< \theta >= 0, 0 \neq \theta_0^2 := Var(\theta) \propto \frac{z^2 \cdot Z^2}{p^2}.$$



Scattering off many nuclei:

$$< \Theta > \quad = \quad 0$$

$$\Theta_0^2 := Var(\Theta) = \sum_{collisions} \theta_0^2 \propto D \cdot z^2 \cdot Z^2 p^2.$$

Hence $\boxed{\Theta_0 \propto \frac{\sqrt{D}}{p}.}$

The exact treatment gives

$$\theta_0 := \frac{13,6 \text{ MeV}}{E} \sqrt{\frac{d}{X_0}},$$

where the term under the square root happens to be equal to the radiation length X_0 of the material which we will introduce later.

Energy loss of electrons (and positrons)

m_e is so small that the acceleration that an electron experiences in collisions with the atomic nuclei becomes so large that bremsquanta can be emitted.

$$\left.\frac{dE}{dx}\right|_e = \left.\frac{dE}{dx}\right|_{collision} + \left.\frac{dE}{dx}\right|_{bremsstrahlung}.$$

- $\left.\frac{dE}{dx}\right|_{Collision}$ denotes the energy loss due to excitation and ionization of atoms. The corresponding formula is similar to the Bethe-Bloch formula, but differs in details because
  - the electrons are deflected when scattering off atomic electrons,
  - and the impinging electron is indistinguashable from the atomic electron.
- $\left.\frac{dE}{dx}\right|_{Bremsstrahlung}$ denotes the energy loss via bremsstrahlung.

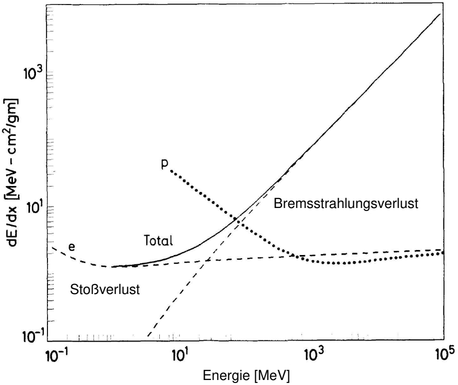
Energy loss of electrons due to bremsstrahlung

- Radiation field of an accelerated charge $\propto a_{Ladung}$.
- Energy of the radiation $\propto$ $|field|^2 \propto a_{charge}^2 = \left(\frac{F}{m_e}\right)^2 \propto \frac{1}{m_e^2}$.
  I.e. unlike for heavy charged particles we cannot neglect bremsstrahlung of electrons.
- $$-\left.\frac{dE}{dx}\right|_{bremsstrahlung} = N \cdot E_e \cdot \Phi_{radiation}$$

  N: Number of atom per volume.
  E_e: Electron energy.
  $\Phi_{radiation}$: material dependent factor.

$\Rightarrow$ Linear increase of the energy loss via bremsstrahlung with increasing electron energy.

Critical energy and radiation length



Critical energy E_k

$$\left.\frac{dE}{dx}\right|_{collisions}(E_k) = \left.\frac{dE}{dx}\right|_{Bremsstrahlung}(E_k).$$

$E_k \approx \frac{800\ \text{MeV}}{Z+1/2}$ so bremsstrahlung is the dominant process for $E_{e^\pm} > 1$ GeV.

Radiation length X_0

$$-\left.\frac{dE}{dx}\right|_{bremsstrahlung} = N \cdot E_e \cdot \Phi_{radiation},$$

hence

$$E_e(x) = E_e(0)e^{\frac{-x}{X_0}}.$$