Concepts for Experiments at Future Colliders I

PD Dr. Oliver Kortner

04.11.2024

Recapitulation of the previous lecture

Interaction of photons with matter

Dominant processes

1. Photoelectric effect.
2. Compton scattering
3. e^+e^- pair production

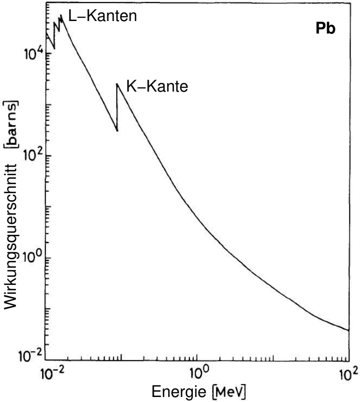
$\Rightarrow$ A beams of photons does not lose energy when passing through matter, but intensity because all three processes remove photons from the beam.

Recapitulation of the previous lecture

Photoelectric effect

Absorption of a photon by an atomic electron

$$E_e = \hbar\omega_\gamma - \text{Binding engery of the electron}$$



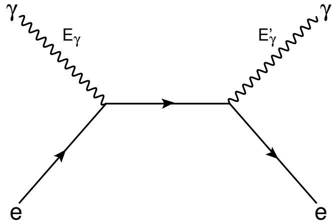
- Cross section decreasing with increasing photon energy.
- Peaks in the cross section when the photon energy reaches the binding energy of the electrons in an atomic shell.
- Process important for $E_\gamma \sim 10 - 100$ keV.

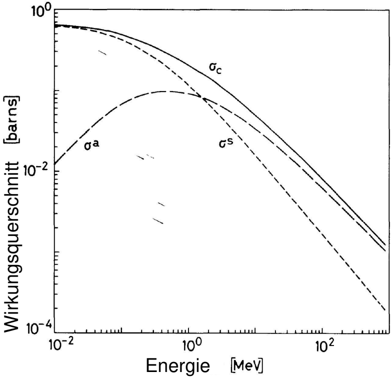
The process is forbidden for free electrons due to energy-momentum conservation. Consider a free electron at rest:

$$m_e^2 + 2E_\gamma m_e = (p_\gamma + p_{e,A})^2 = p_{e,E}^2 = m_e^2 \;\Rightarrow\; E_\gamma = 0.$$

Recapitulation of the previous lecture

Compton scattering





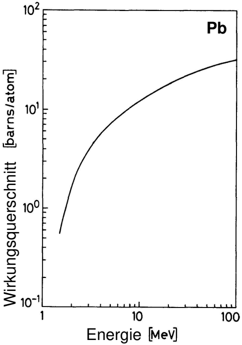
- Scattering of a photon off an electron.

- Compton scattering cross section described by the Klein-Nishina formula.
- σ_C: Compton scattering cross section.
- $\sigma_a := \sigma_C \frac{E'_\gamma}{E_\gamma}$, $\sigma_s := \sigma_C - \sigma_A$.
- Large energy transfer to the electron at $E_\gamma \sim 1$ MeV.

Recapitulation of the previous lecture

e^+e^- pair production

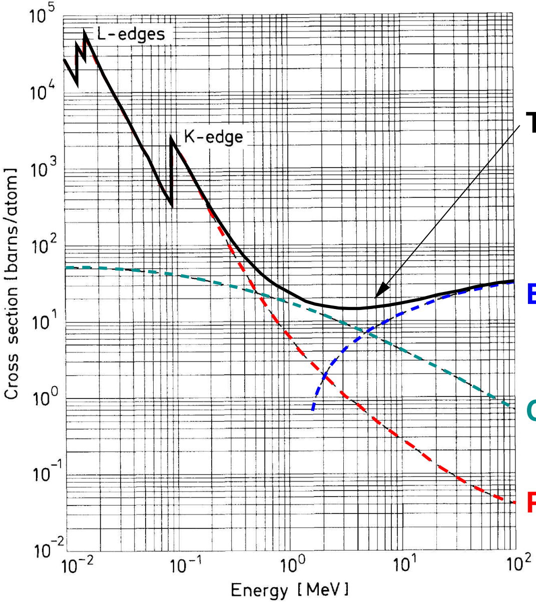
- $\gamma \rightarrow e^+e^-$ only possible when a third body, i.e. a nucleus participate in the process due to energy-momentum conservation $(0 = p_\gamma^2 \neq (p_{e^+} + p_{e^-})^2 > 0)$.
- Cross section for pair production $\propto Z^2$ (Z: atomic number of the material).
- $E_{\gamma,min} = 2m_e$
- Probability for pair production after a distance x is proportional to $\exp(-\frac{x}{\lambda_P})$ with $\lambda_P \approx \frac{9}{7}X_0$.



- Cross section increasing with increasing E_γ.
- Dominant process for $E_\gamma \gtrsim 10$ MeV.

Recapitulation of the previous lecture

Total photon absorption cross section for Pb



Total cross section

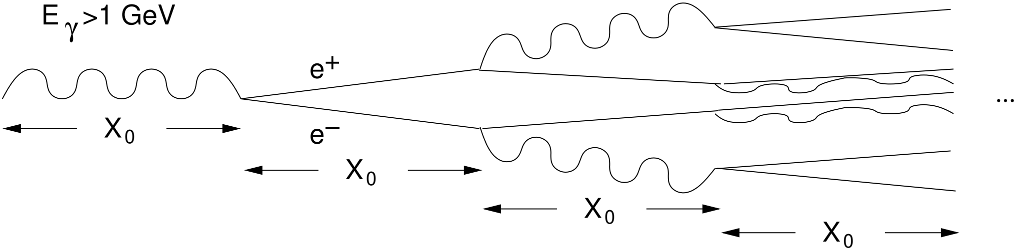
Electron positron pair production

Compton effect

Photoelectric effect

Recapitulation of the previous lecture

Electron photon showers



- After a distance $n \cdot X_0$: 2^n particles with energy $E_n \approx \frac{E_\gamma}{2^n}$.
- End of the cascade (shower), if $E_n = E_k$: $n = \frac{\ln \frac{E_\gamma}{E_k}}{\ln 2}$.
- Shower length: $n \cdot X_0 = X_0 \cdot \frac{\ln \frac{E_\gamma}{E_k}}{\ln 2}$.

Example

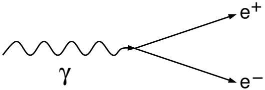
- $E_\gamma = 100$ GeV.
- Material: iron, d.h. $X_0 \approx 2$ cm, $E_k \approx 20$ MeV.

$\Rightarrow$ $n = 12$, d.h. ~ 4000 particles.

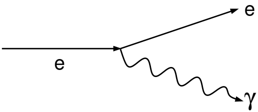
Shower length: $L_{longitudinal} \approx 24$ cm.

Recapitulation of the previous lecture

Transverse size of an electron photon shower



bzw.



Kinematics in the approximation of massless particles

Initial state

Final state

$$p_i = (E_i, \underbrace{0, 0, E_i}_{\vec{p}_i})$$

$$p_{1/2} = (E_{1/2}, p_{1/2,\perp}, 0, p_{1/2,\parallel})$$

$$p_{1/2}^2 = 0 \;\Rightarrow\; E_{1/2} = \sqrt{p_{1/2,\perp}^2 + p_{1/2,\parallel}^2}$$

$$p_i = p_1 + p_2$$

Recapitulation of the previous lecture

Kinematics in the approximation of massless particles

Hence

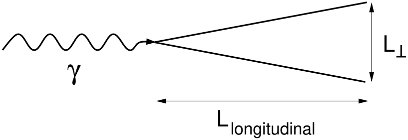
$$
\begin{aligned}
p_{1,\perp} + p_{2,\perp} = 0 \quad &\Leftrightarrow \quad p_{2,\perp} = -p_{1,\perp} \\
E_i = p_{1,\parallel} + p_{2,\parallel} \quad &\Leftrightarrow \quad p_{2,\parallel} = E_i - p_{1,\parallel} \\
E_i = E_1 + E_2 \quad &\Leftrightarrow \quad E_i - E_1 = E_2 = \sqrt{p_{2,\parallel}^2 + p_{2,\perp}^2} = \sqrt{(E_i - p_{1,\parallel})^2 + p_{1,\parallel}^2} \\
(E_i - E_1)^2 \quad &= \quad (E_i - p_{1,\parallel})^2 + p_{1,\perp}^2 \\
E_i^2 - 2E_iE_1 + E_1^2 \quad &= \quad E_i^2 - 2E_ip_{1,\parallel} + p_{1,\parallel}^2 + p_{1,\perp}^2 = E_i^2 - 2E_ip_{1,\parallel} + E_1^2 \\
E_1 = p_{1,\parallel} \quad &\Rightarrow \quad p_{1,\perp} = 0 = p_{2,\perp}
\end{aligned}
$$

The transverse size of the shower is 0 independently of $E_{\gamma/e^\pm}$ in the limiting case of massless particles.

Recapitulation of the previous lecture

Transverse size of an electron photon shower

The full treatment with massive electrons and positrons leads to the following result.

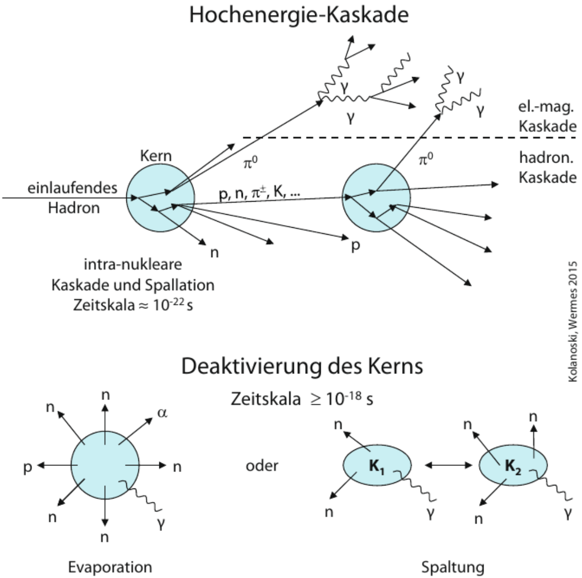


$$L_\perp \approx 4R_M = 4X_0 \frac{21,2\ \text{MeV}}{E_k}$$

R_M: Molière radius

- The transvers size of the shower $L_\perp$ is independent of $E_{\gamma/e^\pm}$.
- $L_{T,Fe} = 4 \cdot 1,8\ \text{cm} \cdot \frac{21{,}2\text{MeV}}{30{,}2\text{MeV}} \approx 5\ \text{cm}$.
- Characteristic for electromagnetic showers: small transverse size which is independent of $E_{\gamma,e^\pm}$.
- The number of generated particles is a measure for $E_{\gamma,e^\pm}$ and proportional to $E_{\gamma,e^\pm}$.

Hadron showers



Similar behaviour like electromagnetic showers:

- Shower length proportional to $\lambda_A \approx 35\ \text{g}\,\text{cm}^{-2}\frac{A^{1/3}}{\rho} \gg X_0$.
- Transverse size independent of the energy of the primary hadron: λ_A.
- But much stronger variations of the shower size than in case of electromagnetic showers.

Shower components and shower fluctuations

Contributions to the energy E_{dep} deposited in a block of material

$$E_{dep} = \underbrace{(f_{em} + \underbrace{f_{ion} + f_n + f_\gamma + f_B}_{=: f_h})}_{=1 \text{ per definitionem}} E_{dep}$$

- f_{em}. Fraction of the energy deposited by photons from π^0 decays. As neutral pions are created again and again, f_{em} increases with the particle multiplicity in the cascade, hence with the energy of the incoming hadron.
- f_{ion}. Fraction of the energy deposited by a charged shower particle by ionization.
- f_n. Fraction of the energy deposited by neutrons via elastic scattering or nuclear reactions.
- f_γ. Fraction of the energy deposited by photons which are created in nuclear reactions. $E_\gamma \sim$ keV...MeV $\Rightarrow$ energy transfer by Compton scattering or photoelectric effect. This contribution can occur with a large delay $\gtrsim \mu$s.
- f_B. The binding energy which is required to break up a nucleus is not measured and does not contribute to the calorimeter signal. One has a similar situation with neutrinos which are usually take into account in f_B.

Shower components and shower fluctuations

Contribution of the energy E_{dep} deposited to a block of matter

$$E_{dep} = \underbrace{(f_{em} + \underbrace{f_{ion} + f_n + f_\gamma + f_B}_{=:f_h})}_{=1 \ \text{per definitionem}} E_{dep}$$

- f_{em} varies strongly in a hadronic shower between 0 and 1 if no or only neutral pions are generated in the first interactions.
- The composition of the hadron component is independent of the type and energy of the incoming hadron.

Concepts for future hadron colliders

Future cicular colliders as an origins explorer

Experiments at future circular colliders will allow us to address the following questions:

Origin of matter

Electroweak phase transition, CP violation, baryogenesis, ecc.

Origins of the Higgs boson

Sypersymmetry, compositeness, ecc.

Origins of flavour

Beyond the Standard Model flavour models.

Origin of dark matter

So-called "dark sector" in general.

Origin of neutrinos

Beyond Standard Model neutrino modesl, neutrino portal, ecc.

Origin of the Standard Model

The Standard Model is ultimately an effective field theory of an underlying UV theory from which it originates.

For further information see "The physics case for next-generation colliders" by Tevong You (https://indico.cern.ch/event/1273702/timetable/?view=standard)

Current roadmap

Approved projects

- LHC operation until the middle of 2026.
- HL-LHC operation from 2030 to ∼2040.

Future projects (to be approved)

- e^+e^- linear or circular collider.
- 100 TeV hadron collider.

Likely future: A circular e^+e^- collider in a ring of 91.1 km circumference at CERN around 2042 followed by a 100 TeV proton proton collider in the same ring around 2060, i.e. first FCC-ee, than FCC-hh.

Concepts for future colliders

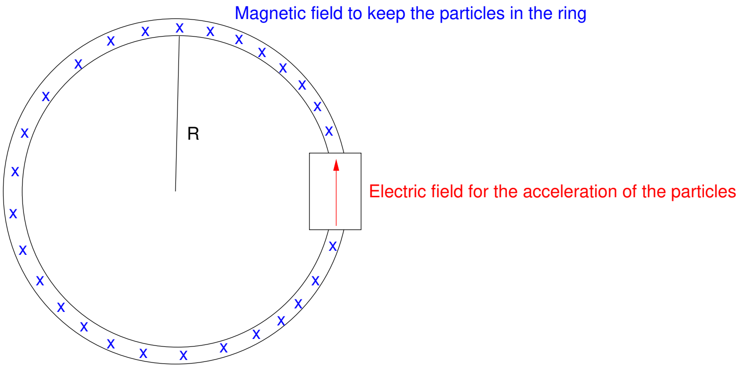
Goals:
- Precision tests of the Standard Model.
- Search for new particles or interactions.

Method: Study of collisions of highly energetic particles.

- The colliding particles must be electrically charged so that they can be accelerated.
- The colliding particles must be stable so that they can be accumulated in a storage ring.

⇒ Only two particles can be used:
- Electrons (and positrons)
- protons (and antiprotons)

Basic principle of a collider



- The size of the magnetic field B and the radius of the ring R determine the maximum achievable beam energy.

$$p = eBR$$

- LHC: B=8 T, R=4,3 km, d.h. $p \approx$10 TeV.
- FCC: B=16 T, $R \approx$16 km, d.h. $p \approx$70 TeV.

Luminosity and event rate

(Instantaneous) luminosity

$$\mathcal{L} = \frac{n_b f_r n_1 n_2}{A}$$

n_b: Number of particle bunches in the storage ring.
f_r: Collision frequency.
$n_{1,2}$: Number of the protons in the colliding bunches.
A: Effective area of the colliding particle bunches.

Event rate

$$\sigma_{pp\to X} \cdot \mathcal{L}$$

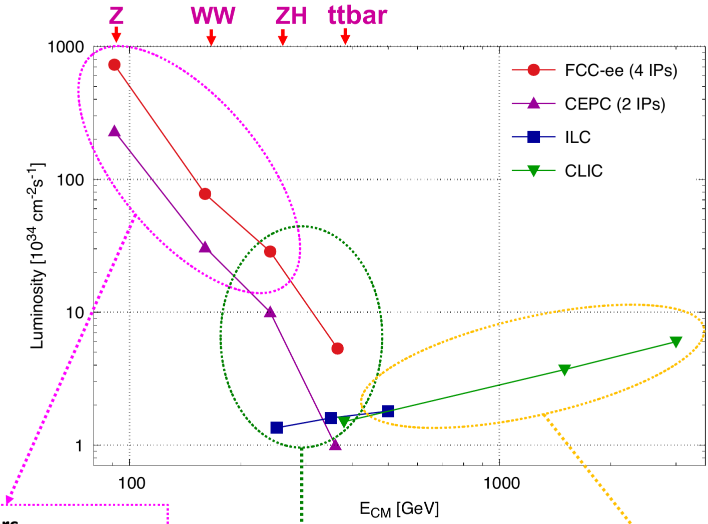
e^+e^- collider vs pp collider

Particle	Advantages	Disadvantages
$e^\pm$	$e^\pm$ elementary particles	Creation of a lot of synchrotron radiation in circular colliders
p ($\bar{p}$)	Less synchrotron radiation due to higher mass acceleration to very high energies in circular colliders	Proton composite particle. Collision of partons.

- The only option for collisions at centre-of-mass energies $\gtrsim$10 TeV: pp collisions.
- $p\bar{p}$ not advantageous, because
  - parton luminosities of pp and $p\bar{p}$ are similar and
  - much lower luminosities are achievable for $p\bar{p}$ than for pp, because it is difficult to generate and accumulate sufficiently many antiprotons.

High-energy e^+e^- accelerator landscape

Mogens Dam



Circular colliders
Extremely high luminosities at lower energies:
Z, W, Higgs, and top factories

Overlap region, 240-380 GeV
Higgs Factories (and top)

Linear colliders
High centre-of-mass energies

FCC-ee physics landscape

Mogens Dam

"Higgs Factory" Programme

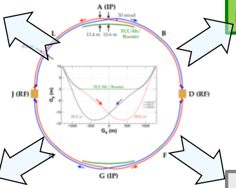
- At two energies, 240 and 365 GeV, collect in total
  - 2M HZ events and 125k WW → H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (2-4 σ) via loop diagrams
- Unique possibility: measure electron coupling in s-channel production $e^+e^- \rightarrow H$ @ $\sqrt{s}$ = 125 GeV

Ultra Precise EW Programme & QCD

Measurement of EW parameters with factor ~300 improvement in *statistical* precision wrt current WA

- 6×10^{12} hadronic Z and 2×10^{8} WW
  - m_Z, Γ_Z, Γ_{inv}, $\sin^2\theta_W^{eff}$, R^Z_ℓ, R_b, α_s, m_W, Γ_W…
- 2×10^{6} tt
  - m_{top}, Γ_{top}, EW couplings

Indirect sensitivity to new phys. up to Λ=70 TeV scale



Heavy Flavour Programme

- Enormous statistics: 1.3×10^{12} bb, cc; 2.8×10^{11} ττ
- Extremely clean environment, favourable kinematic conditions (boost) from Z decays
- CKM matrix, CP measurements, "flavour anomaly" studies, e.g. b → sττ, rare decays, CLFV searches, lepton universality, PNMS matrix unitarity

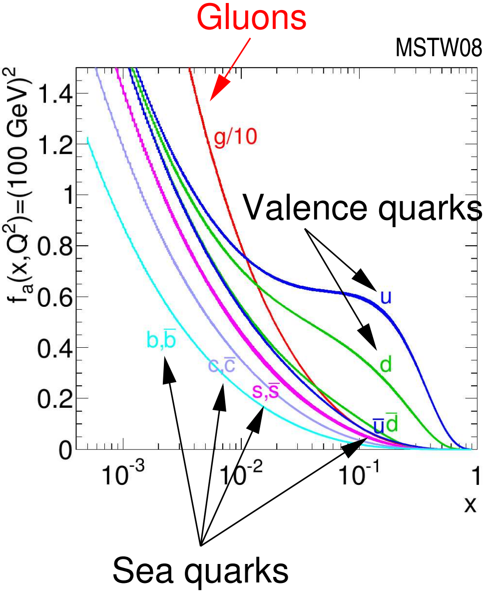
Feebly Coupled Particles - LLPs

Intensity frontier: Opportunity to directly observe new feebly interacting particles with masses below m_Z:

- Axion-like particles, dark photons, Heavy Neutral Leptons
- Signatures: long lifetimes – LLPs

Parton densities

Let us move to hadron (pp) colliders!



- x: Fraction of the proton momentum carried by a single parton.
- Q: Momentum scale of the parton collision.

$$\sqrt{s_{Parton\ 1,Parton\ 2}} = \sqrt{x_1 \cdot x_2}\sqrt{s_{pp}},$$

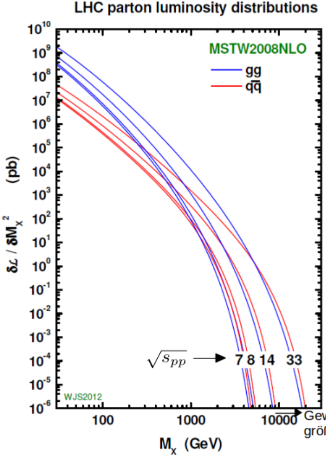
i.e. collisions with $\sqrt{s_{Parton\ 1,Parton\ 2}} = \sqrt{s_{pp}}$ are very rare.

Parton luminosity

General formula for the cross section of a process:

$$\sigma_{pp\to X} = \sum_{a,b=q,g} \int\limits_0^1 \int\limits_0^1 \hat{\sigma}_{ab\to X} \cdot \underbrace{f_a(x_a, Q^2) \cdot f_b(x_b, Q^2)}_{\text{partonluminosity}} \, dx_a dx_b$$

$\hat{\sigma}_{ab\to X}$: Cross section of the process at parton level.

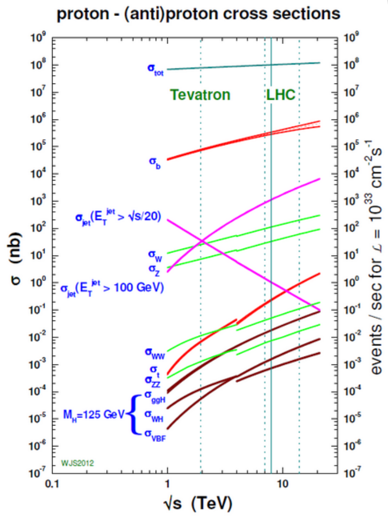


→ Gewinn durch größeres $\sqrt{s_{pp}}$

$= \sqrt{s_{Parton\ 1, Parton\ 2}}$

- Parton luminosities increase with $\sqrt{s_{pp}}$ because more and more sea quarks and gluons will be created.
- Gluons dominate at small values of $\sqrt{s_{parton\ 1, parton\ 2}}$ because the parton densities are dominated by gluons at small values of x.

Cross sections for pp collisions



- σ increases with $\sqrt{s_{pp}}$.
- σ for interesting processes like the production of Higgs bosons very small and much smaller than for QCD processes as $pp \to b\bar{b}$.

$\Rightarrow$
  - Large pp collision rates (large luminosity) required to become sensitive to rare processes.
  - Selective triggers for the selection of interesting pp collisions mandatory.

Hadron collider strategy for the next years

- Increase the LHC luminosity by an order of magnitude → HL-LHC.
- Increase the centre-of-mass energy $\sqrt{s_{pp}}$ by an order of magnitude → FCC-hh.