Introduction to Elementary Particle Physics

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Elementary Particle Physics

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Elementary particle dynamics

The four forces

Remarks

- **Classically:** Interaction at a distance is described in term of a potential or field
- **Another idea:** Exchange interaction, where the force carriers (intermediate vector bosons, quanta of force, virtual gauge bosons) carry energy and momentum from one charge to another
- **Note:** Although classical mechanics helps us to visualize events but must never be taken literally as representing quantum phenomena (e.g. a photon does not possess a classical trajectory)
- Energy conservation dictates that the process takes place within a **time-scale** Δt limited by the uncertainty principle

$$\Delta E \Delta t \sim \hbar$$

The four (three) forces

A. Quantum Electrodynamics (QED)

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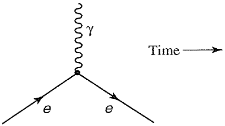
Feynman diagrams: Elementary process in QED

- **Emission or absorption of a photon by an electron** or in general charged lepton/quark



- The time flows horizontally from left to right
- Arrows forwards in time = charged leptons (e.g. electrons) or quarks going forwards in time
- The interaction point is the so called **vertex**
- The interaction (vertex) arises from the following term in the interaction part of the Lagrangian density of QED ($\mathcal{L}_{QED}^{int}$)

$$\mathcal{L}_{QED}^{int} = -e\bar{\psi}\gamma^{\mu}A_{\mu}\psi$$

- No other **primitive vertex** exists in $\mathcal{L}_{QED}$

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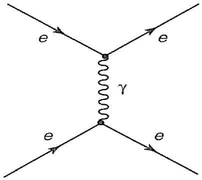
Møller Scattering: $e^- + e^- \rightarrow e^- + e^-$



- Interaction between two electron
- Classically: Coulomb repulsion of similar charges

  a. Two electrons enter
  b. A photon passes between them (the diagram represents both ordering)
  c. Two electrons exit

Note: Arrows **forwards** in time = charged leptons going **forwards** in time

Arrows **backwards** in time = charged **anti**-leptons going **forwards** in time

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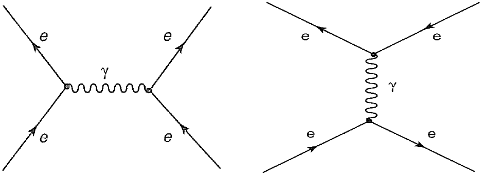
Bhabha Scattering: $e^- + e^+ \to e^- + e^+$

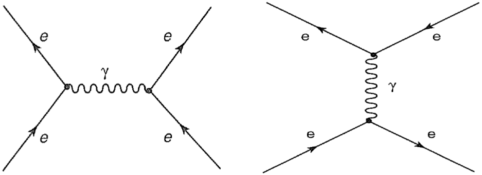


- Interaction between an electron and a positron
- Classically: Coulomb attraction between opposite charges

  a. An electron-positron pair annihilate to create a photon, which in turn creates a new electron-positron pair
  b. **We say:** An electron-positron pair comes in, and an electron-positron pair goes out

incoming (e^-, e^+) **pair** $\leftrightarrow$ **outgoing** (e^-, e^+) **pair**

Bhabha Scattering: $e^- + e^+ \to e^- + e^+$

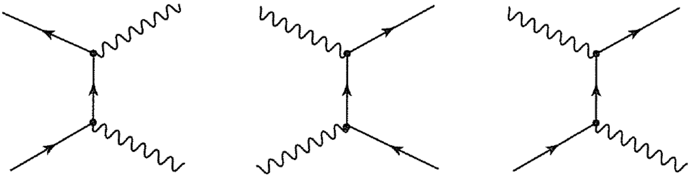


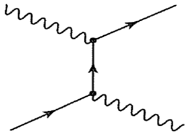
- Two different **channels** (s and t channels)

Note: Both diagrams are necessary to compute the **scattering amplitude** and eventually the **differential and total cross-sections** of the Bhabha scattering

Other important QED processes:

1. Pair annihilation $e^- + e^+ \to 2\gamma$
2. Pair production $2\gamma \to e^- + e^+$
3. Compton scattering $e^- + \gamma \to e^- + \gamma$





Note: All the above Feynman diagrams are in the order

$$\alpha = \frac{e^2}{4\pi}$$

We say: They are first order processes (**tree level diagrams**)

- **External lines** represent real (observable) particles, whose momentum and energy are related through $E^2 = \mathbf{p}^2 + m^2$ (the **on mass-shell condition**)
- **Internal lines** represent particles that cannot be observed (virtual particles). Their energy and momentum do not satisfy the on mass-shell condition, $E^2 = \mathbf{p}^2 + m^2$. They are **off mass-shell**

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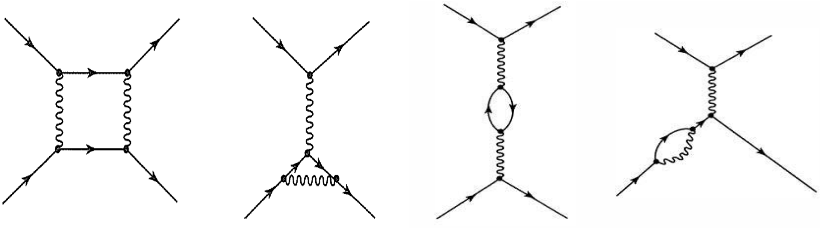
Loop diagrams:

Example: Higher order contributions to Møller scattering $e^- + e^- \to e^- + e^-$



All the above diagrams are of order $\alpha^2 \sim e^4$

Perturbative series in α

Scattering amplitude $\mathcal{M} = \alpha\mathcal{M}_1 + \alpha^2\mathcal{M}_2 + \alpha^3\mathcal{M}_3 + \mathcal{O}(\alpha^4)$

with the fine structure constant

$$\alpha = \frac{e^2}{4\pi}$$

Perturbative computation of $\mathcal{M}$

$$\text{Scattering amplitude } \mathcal{M} = \sum_{n=1}^{\infty} \alpha^n \mathcal{M}_n$$

- Perturbaive series is an infinite polynomial series in the orders of α
- Perturbative calcuation of $\mathcal{M}$ is only valid if $\alpha \sim e^2$ is small enough
- For QED, $\alpha = \frac{1}{137}$ and is small enough
- Because α is such a small number, diagrams with more and more vertices contribute less and less to the final result !!

Question: How to compute $\mathcal{M}_n$'s?