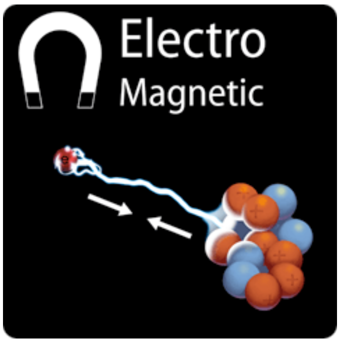
Subatomic Physics:

Particle Physics Lecture 4

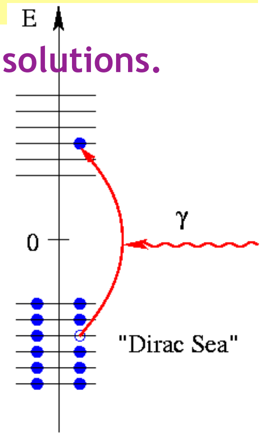
Quantum Electro-Dynamics & Feynman Diagrams



- ✱ Antimatter
- ✱ Feynman Diagram and Feynman Rules
- ✱ Quantum description of electromagnetism
- ✱ Virtual Particles
- ✱ Yukawa Potential for QED

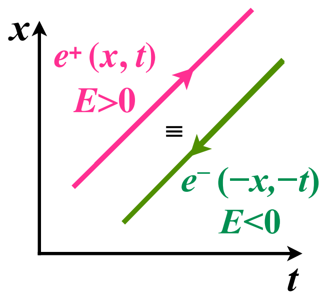
Antimatter

(Lecture 1) **Klein-Gordon equation predicts negative energy solutions.**



Dirac Interpretation:

- The vacuum is composed of negative energy levels with E<0. Each level is filled with two electrons of opposite spin: the "Dirac Sea".
- A "hole" in the sea with charge $-e$ and E<0, appears as a state with charge $+e$ and E>0.
- This idea lead Dirac to predict the **positron**, discovered in 1931.



Feynman-Stueckelberg Interpretation:

- negative energy particles moving backwards in space and time correspond to...
- positive energy antiparticles moving forward in space and time

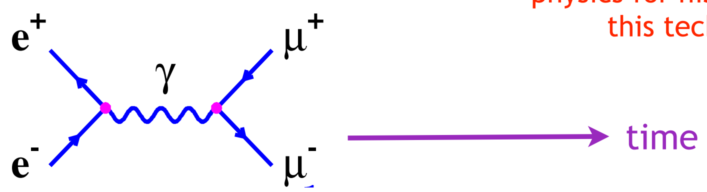
$$\Psi_{e^-}(-\underline{r}, -t) \quad \propto \quad \exp -i/\hbar \left\{(-E)(-t) - (-\underline{p}) \cdot (-\underline{r})\right\}$$

$$\Psi_{e^+}(+\underline{r}, +t) \quad \propto \quad \exp -i/\hbar \left\{(+E)(+t) - (+\underline{p}) \cdot (+\underline{r})\right\}$$

Feynman Diagrams

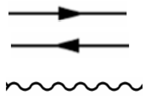
- A Feynman diagram is a pictorial representation of a particular process (decay or scattering) at a **particular order in perturbation theory**.
- Feynman diagrams can be used to **represent** and **calculate** the **matrix elements,** $\mathcal{M}$, for scattering and decays.
- Feynman diagrams are very useful and **powerful** tools. We will use them a lot in this course. We use them a lot in our research!

Richard Feynman receiving the 1967 Noble prize in physics for his invention of this technique.



Conventions

- Time flows from left to right (occasionally upwards)



- Fermions are solid lines with arrows
- Anti-fermion are solid lines with backward pointing arrows.
- Bosons are wavy (or dashed) lines

Use **Feynman Rules** to calculate $\mathcal{M}$ at different orders in perturbation theory.

Quantum Electrodynamics (QED)

QED is the quantum theory of electromagnetic interactions.

Classical electromagnetism:

- Force between charged particle arise from the electric field

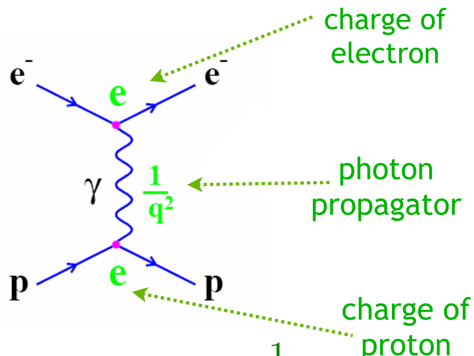
$$\vec{E} = \frac{Q\,\hat{r}}{4\pi\epsilon_0 r^2}$$

- act instantaneously at a distance

Quantum Picture:

- **Force between charged particle described by exchange of photons.**
- Strength of interaction is related to charge of particles interacting.

e.g. electon-proton scattering $ep \to ep$ propagated by the exchange of photons



$$\mathcal{M}(ep \to ep) \propto e \cdot \frac{1}{\underline{q}^2 - m_\gamma^2} \cdot e$$

Feynman rules:

- **Vertex term**: each photon–charged particle interaction gives a factor of fermion charge, Q.
- **Propagator term**: each photon gives a factor of $1/(\underline{q}^2 - m_\gamma^2) = 1/\underline{q}^2$ where $\underline{q}$ is the photon four-momentum.
- Matrix element is proportional to product of **vertex** and **propagator** terms.

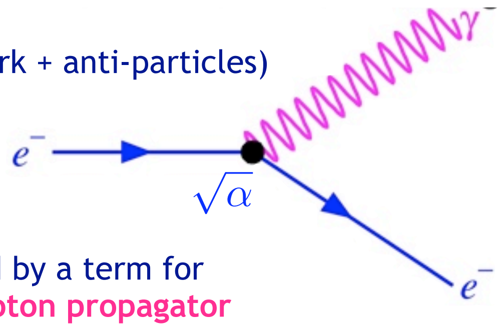
Electromagnetic Vertex

Basic electromagnetic process:

- Initial state charged fermion (*e, μ, τ* or quark + anti-particles)
- Absorption or emission of a photon
- Final state charged fermion

Examples: $e^- \rightarrow e^- \gamma$; $e^- \gamma \rightarrow e^-$

Mathematically, EM interactions are described by a term for the interaction **vertex** and a term for the **photon propagator**



QED Conservation Laws

- Momentum, energy and charge is conserved at each vertex
- Fermion flavour (*e, μ, τ, u, d ...*) is conserved: *e.g.* $u \rightarrow u\gamma$ allowed, $c \rightarrow u\gamma$ forbidden

Coupling strength

- Matrix element is proportional to the fermion charge: $\mathcal{M} \propto e$
- Alternatively use the fine structure constant, α

$$\alpha = \frac{e^2}{4\pi\epsilon_0 \hbar c} = \frac{e^2}{4\pi} \approx \frac{1}{137}$$

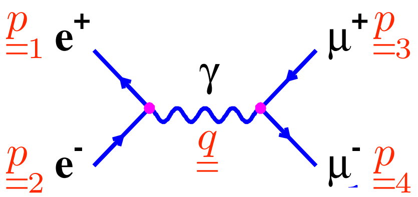
$\Rightarrow$ strength of the coupling at the vertex is $\propto \sqrt{\alpha}$

Virtual Particles

The force between two charged particles is propagated by **virtual photons.**

- A particle is virtual when its four-momentum squared, does not equal its rest mass: $m_X^2 \neq E_X^2 - \vec{p}_X^{\,2}$
- Allowed due to **Heisenberg Uncertainty Principle**: can borrow energy to create particle if energy ($\Delta E = mc^2$) repaid within time (Δt), where $\Delta E \Delta t \approx \hbar$

Example: electron-positron scattering creating a muon pair: $e^+e^- \rightarrow \mu^+\mu^-$.



$$\underline{\underline{q}}^2 \neq m_\gamma^2$$

- Four momentum conservation:

$$\underline{\underline{p}}_1 + \underline{\underline{p}}_2 = \underline{\underline{p}}_3 + \underline{\underline{p}}_4$$

- Momentum transferred by the photon is:

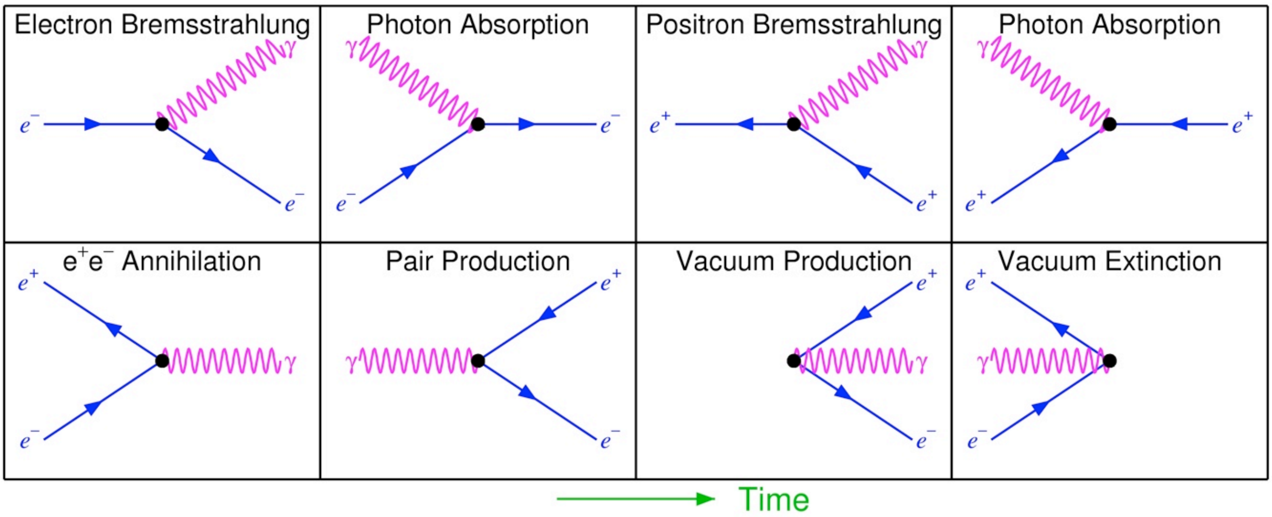
$$\underline{\underline{q}} = (\underline{\underline{p}}_1 + \underline{\underline{p}}_2) = (\underline{\underline{p}}_3 + \underline{\underline{p}}_4)$$

- Squaring,

$$\begin{aligned} \underline{\underline{q}}^2 &= (\underline{\underline{p}}_1)^2 + (\underline{\underline{p}}_2)^2 + 2\underline{\underline{p}}_1 \cdot \underline{\underline{p}}_2 \\ &= 2m_e^2 + 2(E_1E_2 - \vec{p}_1 \cdot \vec{p}_2) \; > \; 0 \end{aligned}$$

- In QED interactions mass of photon propagator is non-zero.
- Only intermediate photons may be virtual. Final state ones must be real!

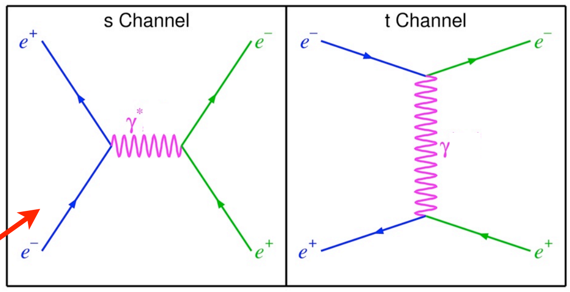
Basic QED Processes



- All of these described by the same basic vertex term, $\propto Q$
- None of above processes is physical as they violate energy-momentum conservation:

$$p_\gamma^2 = (p_{e_1} - p_{e_2})^2 \neq m_\gamma^2$$

- Join two together to get a real processes

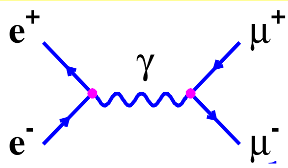


Perturbation Theory

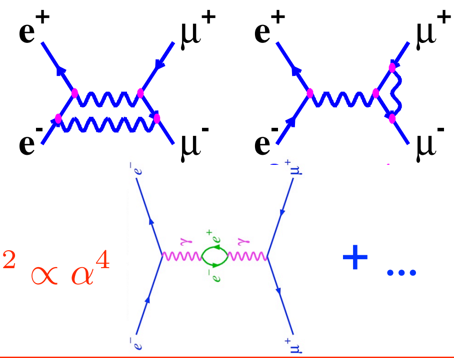
- QED is formulated from time dependent **perturbation theory**.
- Perturbation series: break up the problem into a piece we can solve exactly plus a small correction.
- *e.g.* for $e^+e^- \to \mu^+\mu^-$ scattering.
  - Many more diagrams have to be considered for a accurate prediction of $\boldsymbol{\sigma}(e^+e^- \to \mu^+\mu^-)$.
- As α is small the lowest order in the expansion dominates, and the series quickly converges!
- For most of the course, we will only consider lowest order contributions to processes.

Lowest Order

$|\mathcal{M}|^2 \propto \alpha^2$

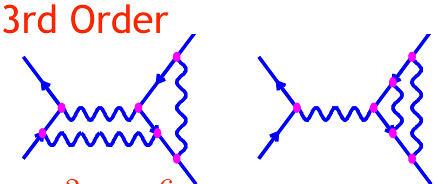


2nd Order



$|\mathcal{M}|^2 \propto \alpha^4$ + ...

3rd Order

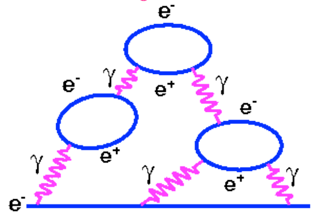


+ ...

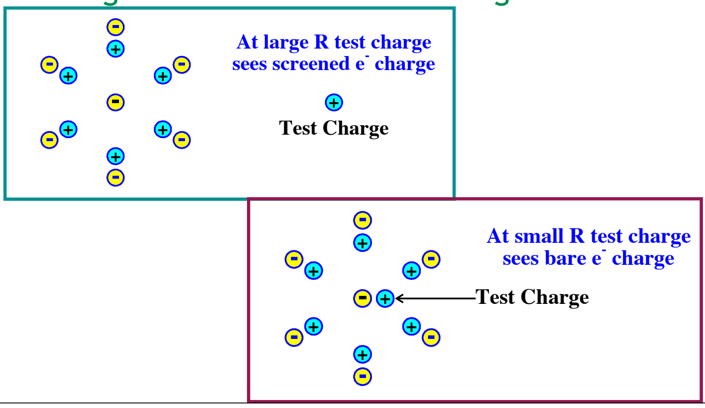
$|\mathcal{M}|^2 \propto \alpha^6$

QED Coupling Constant

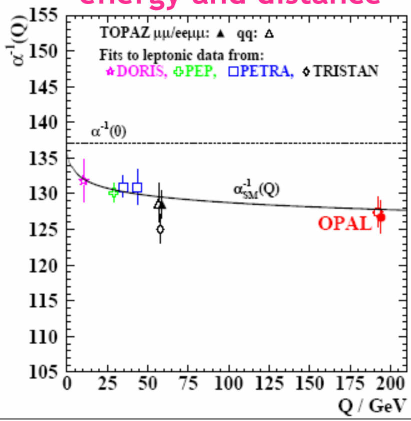
- Strength of interaction between electron and photon $\propto \alpha = \dfrac{e^2}{4\pi\epsilon_0} \approx \dfrac{1}{137}$
- However, α is not really a constant...
- An electron is never alone:
  - it emits virtual photons, these can convert to electron positron pairs...



- Any test charge will feel the e^+e^- pairs: true charge of the electron is **screened**.
- At higher energy (shorter distances) the test charge can see the "bare" charge of the electron.



α **varies as a function of energy and distance**



Yukawa Potential

The quantum and classical descriptions of electromagnetism should agree.

Yukawa developed theory whereby exchange of bosons describes force / potential.

- Klein-Gordon equation:

$$-\hbar^2 \frac{\partial^2}{\partial t^2}\Psi(\vec{r},t) = -\hbar^2 c^2 \nabla^2 \Psi(\vec{r},t) + m^2 c^4 \Psi(\vec{r},t)$$

- Non-time dependent solutions obey:

$$\nabla^2 \Psi(\vec{r}) = \frac{m^2 c^2}{\hbar^2}\Psi(\vec{r})$$

- Spherically symmetric solutions of this are:

$$\Psi(|\vec{r}|) = -\frac{g^2}{4\pi r}\exp\left(-\frac{mc}{\hbar}|\vec{r}|\right)$$

- Interpret this as a potential, V, caused by a particle of mass, m.

$$V(r) = -\frac{g^2}{4\pi r}\exp\left(-\frac{r}{R}\right) \quad \text{with } R = \frac{\hbar}{mc}$$

- For electromagnetic force, $m=0$, $g=e$.

$$V_{\mathrm{EM}}(r) = -\frac{e^2}{4\pi r}$$

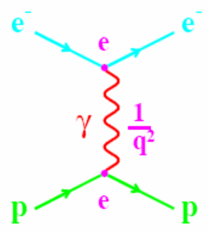
- **Potential felt by a charged particle due to the exchange of a photon.**

QED Scattering Examples

- **Elastic electron-proton scattering:** $e^- p \to e^- p$

$$\mathcal{M} \propto \frac{e^2}{\underline{\underline{q}}^2} = \frac{4\pi\alpha}{\underline{\underline{q}}^2}$$

$$\sigma \propto |\mathcal{M}|^2 \propto \frac{e^4}{\underline{\underline{q}}^4} = \frac{16\pi^2\alpha^2}{\underline{\underline{q}}^4}$$



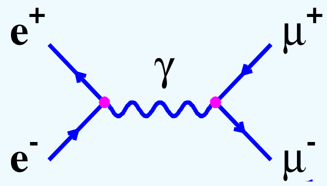
- Momentum transferred to photon from e^-:

$$\begin{aligned} \underline{\underline{q}}^2 &= (\underline{\underline{p}}_f - \underline{\underline{p}}_i)^2 = \underline{\underline{p}}_f^2 + \underline{\underline{p}}_i^2 - 2\underline{\underline{p}}_f \cdot \underline{\underline{p}}_i \\ &= 2m_e^2 - 2(E_f E_i - |\vec{p}_f||\vec{p}_i|\cos\theta) \\ &\approx -4E_f E_i \sin^2(\theta/2) \end{aligned}$$

- **Rutherford scattering:** $e^- Au \to e^- Au$, can neglect recoil of the gold atoms: $E=E_i=E_f$

$$\sigma \propto \frac{Z^2\pi^2\alpha^2}{E^4 \sin^4(\theta/2)}$$

- **Inelastic** $e^- e^+ \to \mu^+ \mu^-$



- Momentum transferred by photon:

$$\underline{\underline{q}}^2 = (\underline{\underline{p}}_{e^+} + \underline{\underline{p}}_{e^-})^2 = s$$

$$\mathcal{M} \propto \frac{e^2}{s} = \frac{4\pi\alpha}{s}$$

- For this situation need full density of states, ρ, (which we won't do...)

$$\sigma = \frac{16\pi E^2}{3}|\mathcal{M}|^2 = \frac{4\pi\alpha^2}{3s}$$

Summary of Lecture 4

Relativistic quantum mechanics predicts negative energy particles: **antiparticles.** Two interpretations:
- a negative energy particle travelling backwards in time.
- a 'hole' in a vacuum filled with negative energy states.

Quantum Electro Dynamics (QED) is the quantum mechanical description of the electromagnetic force.
Electromagnetic force propagated by virtual photons: $\underline{\underline{q}}^2 \neq m_\gamma^2$

Feynman diagrams can be used to **illustrate** QED processes. Use Feynman rules to **calculate** the matrix element, $\mathcal{M}$.

All QED interactions are described by a **fermion-fermion-photon vertex:**
- Strength of the vertex is the charge of the fermion, Q_f.
- Fermion flavour and energy-momentum are conserved at vertex.

The **photon propagator** ~$1/\underline{\underline{q}}^2$ where $\underline{\underline{q}}$ is the 4-momentum transferred by the photon.
$\mathcal{M}$ is proportional to product of vertex and propagator terms.