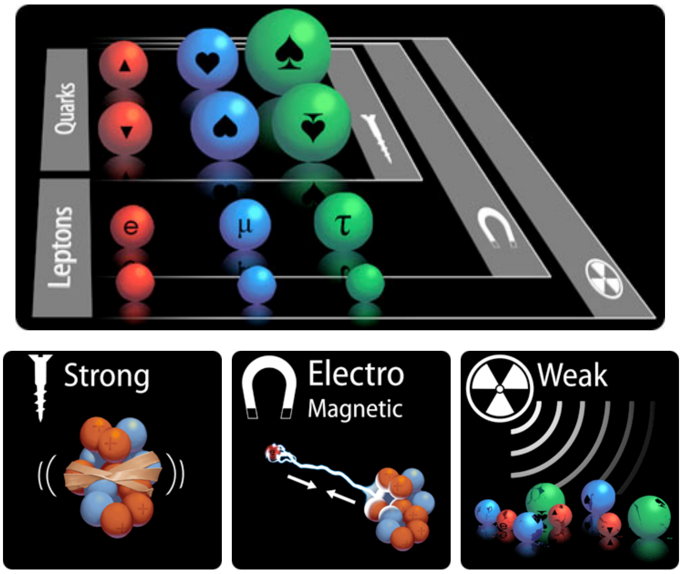
Subatomic Physics:

Particle Physics

Review

April 18th 2011



- ✱ The Standard Model
- ✱ Natural Units
- ✱ Relativistic Dynamics
- ✱ Anti-matter
- ✱ Quarks, Leptons & Hadrons
- ✱ Feynman Diagrams and Feynman Rules
- ✱ Decays
- ✱ QED, QCD, Weak
- ✱ What you don’t need to know

Key Concepts

What’s important are the **concepts** not the **facts and figures.**

Key concepts:

- The **quarks and leptons** - particles which interact (**decay** / **scatter**).
- The **forces** **-** transmitted by **bosons.**
- What **each force interacts on** **-** **what interactions are allowed.**
- The **measurements** used to **quantify decays and scattering.**
- **Feynman diagrams** and **Feynman rules**

LHC concepts:

- Accelerators: **how protons are accelerated** in the LHC.
- Detectors**: how particles produced in** ***pp*** **scattering appear in a detector** (in our case ATLAS detector), what **quantities can be reconstructed.**
- The physics motivation for accelerating particles to high energy.

The Standard Model

The Standard Model describes more-or-less everything we currently know about particle physics: the matter **particles** and the three of the four forces which describe their **interactions**.

Matter: aka the fermions

Leptons			Charge, e
ν_e $e-$	ν_μ $\mu-$	ν_τ $\tau-$	**0** **−1**
Quarks			
u **d**	**c** **s**	**t** **b**	**+2/3** **−1/3**

Matter is grouped into three successively heavier **generations**.

Each generation consists of:

- 2 leptons with $Q=-1e, Q=0$
- 2 quarks with $Q=+2/3e$, $Q=-1/3e$

Forces

- Interactions are propagated by the exchange of bosons

Interaction	Bosons	Q, e
Strong	gluons, g	**0**
Electro-magnetic	photon, γ	**0**
Weak	$W^\pm$, Z^0	**0, ±1**
Gravity	?	?

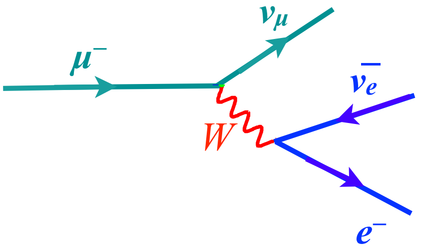
Decays and Scatterings

Decays and scatterings are the main processes used to observe and investigate interactions.

Decay: one particle decays to two or three other particles, via a boson.

- e.g. $\mu^- \to e^- \bar{\nu}_e \nu_\mu$

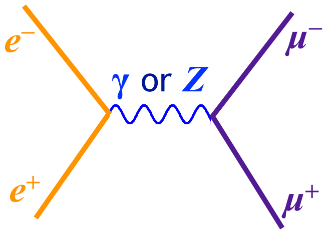
$$\underline{\underline{p}}_{\mu} = \underline{\underline{p}}_{e} + \underline{\underline{p}}_{\bar{\nu}_e} + \underline{\underline{p}}_{\nu_\mu}$$



Scattering: two particles collide

- e.g. $pp \to$… , $e^+e^- \to \mu^+\mu^-$
- Hadron collisions: individual constituents (quarks, gluons…) interact
- Important quantity is Lorentz invariant s: sum of colliding particles four momenta

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



Collider: two beams of particles collide

Fixed target: beam of particles incident on a target

Relativistic Dynamics

Relativistic Dynamics is used to describe kinematics in **decays** and **scattering**.

- Four momentum:

$$\underline{\underline{p}} = (E/c, p_x, p_y, p_z) = (E/c, \vec{p})$$

- If we square four-momentum:

$$\underline{\underline{p}}^2 = \frac{E^2}{c^2} - \vec{p}\cdot\vec{p} = m^2c^2$$ we get the mass squared!

- In **decay** the four-momentum is conserved $\sum \underline{\underline{p}}_{\text{initial}} = \sum \underline{\underline{p}}_{\text{final}}$
  e.g. in $\mu^- \to e^- \bar{\nu}_e \nu_\mu$

  $$\underline{\underline{p}}_{\mu} = \underline{\underline{p}}_{e} + \underline{\underline{p}}_{\overline{\nu}_e} + \underline{\underline{p}}_{\nu_\mu}$$ Square both sides: $$m_\mu^2 c^2 = (\underline{\underline{p}}_{e} + \underline{\underline{p}}_{\overline{\nu}_e} + \underline{\underline{p}}_{\nu_\mu})^2$$

- In a **scattering** the four-momentum is conserved $\sum \underline{\underline{p}}_{\text{initial}} = \sum \underline{\underline{p}}_{\text{final}}$
  e.g. $e^+e^- \to \mu^+\mu^-$ $$\underline{\underline{p}}_{e^+} + \underline{\underline{p}}_{e^-} = \underline{\underline{p}}_{\mu^+} + \underline{\underline{p}}_{\mu^-}$$

- In a scattering, the square of the initial four momentum is s. Energy in the Centre of Mass frame is $\sqrt{s}$, *e.g.* $s = (\underline{\underline{p}}_{e^+} + \underline{\underline{p}}_{e^-})^2$

In both decay and scattering: boson transfers momentum from initial to final state!

Natural Units

- Natural units: set $c = \hbar = 1$
  - All quantities can be expressed as a power of energy.
- Mass, momentum and energy measured in the same units: **MeV** or **GeV**

- Two important quantities for Lorentz transformations:

$$\beta = v/c \qquad \gamma(v) = 1/\sqrt{1-\beta^2}$$

Natural Units

Lorentz boosts: $\gamma = E/m \quad \gamma\beta = |\vec{p}|/m \quad \beta = |\vec{p}|/E$

Four momentum: $\underline{\underline{p}} = (E,\, p_x,\, p_y,\, p_z)$

Invariant mass $\underline{\underline{p}}^2 = E^2 - \vec{p}^2 = m^2$

Quark and Lepton Quantum Numbers

Quantum Numbers

- **Leptons:**
  - Individual lepton numbers: L_e, L_μ, L_τ
  - Total lepton number $L = L_e + L_\mu + L_\tau$
  - Electric Charge, Q
  - All lepton numbers always conserved!

	L_e	L_μ	L_τ
$e-$	+1	0	0
$\mu-$	0	+1	0
$\tau-$	0	0	+1
ν_e	+1	0	0
ν_μ	0	+1	0
ν_τ	0	0	+1

- **Quarks:**
  - Electric Charge, Q
  - Quark number, $N_q = N(q) - N(\bar{q})$
  - Up, down, strange, charm ,bottom & top quark number e.g. $N_u = N(u) - N(\bar{u})$ etc
  - Every quark carries a colour charge: red, blue or green

- Q and N_q are conserved in all interactions.
- $N_u, N_d, N_s, N_c, N_b, N_t$ are not always conserved in W-boson interactions.

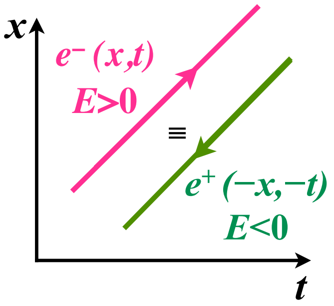
Anti-matter

Every matter particle has an anti-matter partner.

$$E^2 = \vec{p}^2c^2 + m^2c^4 \Rightarrow E = \pm\sqrt{\vec{p}^2c^2 + m^2c^4}$$

- Particle is the positive energy solution
- Anti-particle is negative energy solution

Leptons			Charge
ν_e	ν_μ	ν_τ	0
$e-$	$\mu-$	$\tau-$	−1
Quarks			
u	c	t	+2/3
d	s	b	−1/3



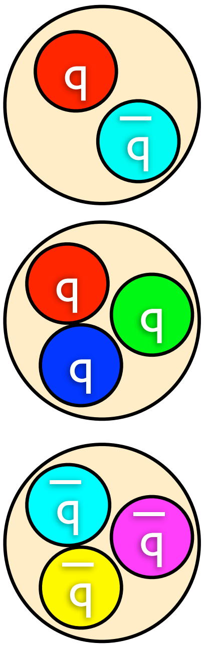
Feynman's interpretation: negative energy particle with charge Q moving backward in space & time appears as positive energy particle with charge $-Q$ moving forward in space & time.

Anti-matter particle has:

- Opposite electric charge, opposite colour charge
- Same mass & lifetime
- Opposite N_q, L_e, L_μ & L_τ

Anti-leptons			Charge
$\bar{\nu}_e$	$\bar{\nu}_\mu$	$\bar{\nu}_\tau$	0
$e+$	$\mu+$	$\tau+$	+1
Anti-quarks			
$\bar{u}$	$\bar{c}$	$\bar{t}$	−2/3
$\bar{d}$	$\bar{s}$	$\bar{b}$	+1/3

Hadrons



Free quarks are never observed.

Quarks are always found in bound colour-neutral states:

- Mesons: a quark and an anti-quark
- Baryons: three quarks
- Anti-baryons: three anti-quarks

Colour confinement

- The quarks are confined to hadrons due to strong force
- gluon self-interactions
- coupling constant α_S increases as quarks become further apart

Interactions: scattering and **decays**

- Consider the interactions of the individual quarks inside the hadrons. e.g. at the LHC its the individual quarks and gluons that interact!

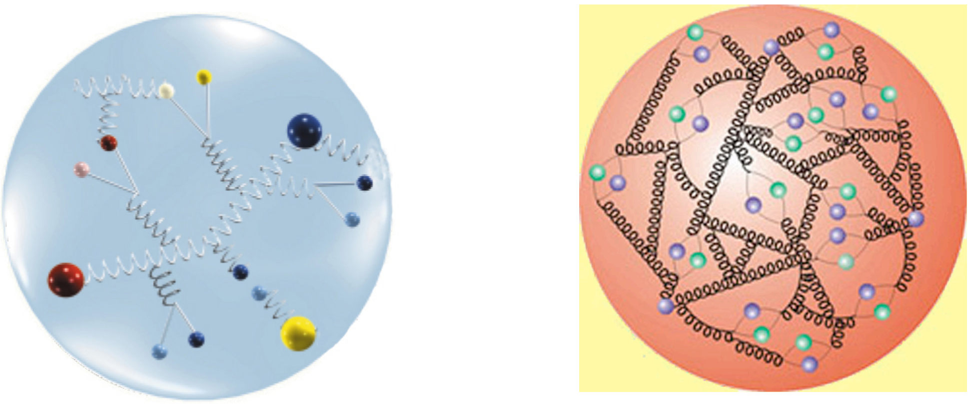
Partons

We must consider interactions of individual constituents, **partons**, of the proton.

At high energies (e.g. at the LHC) protons consist of the following partons:

- three net quarks: u, u, d
- quarks and anti-quarks in pairs e.g. $\bar{u}u, \bar{d}d, \bar{s}s$ or $\bar{c}c$
- gluons, g, (from interaction of consistent quarks and anti-quarks)

Sketches of the proton illustrating the parton content:

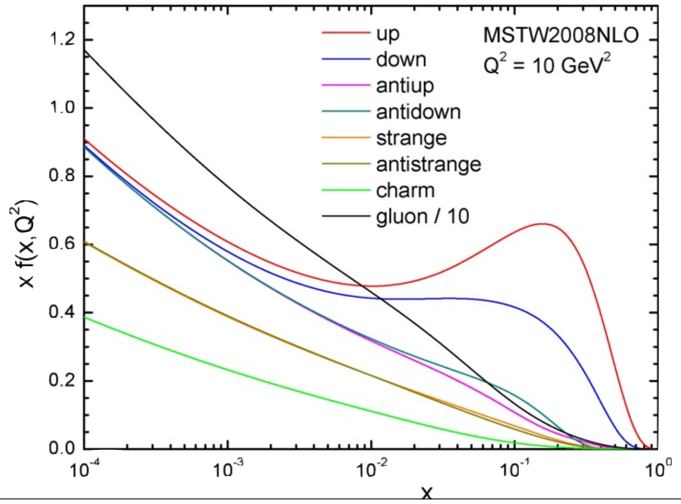


LHC Collisions

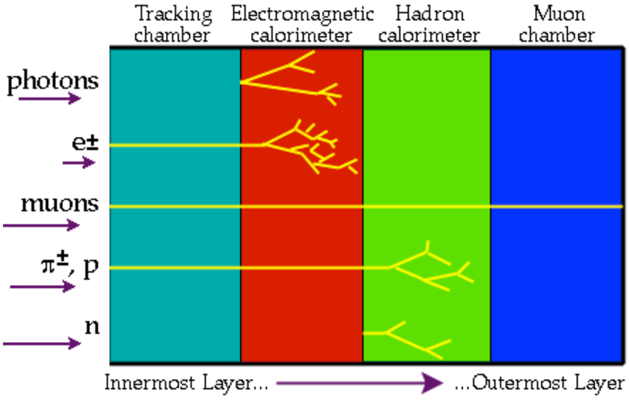
- LHC collisions will be a mixture of: quark-quark, quark-gluon, gluon-gluon, anti-quark–quark, anti-quark–gluon etc.
- We do not know on a collision-by-collision basis which of these scatterings took place.
- Variable Feynman x is used to characterise the proton's parton content

$$x = \frac{|\vec{p}_{\mathrm{parton}}|}{|\vec{p}_{\mathrm{proton}}|} \qquad 0 < x < 1.$$

The flavours of quarks and gluon found in the proton as a function of x.

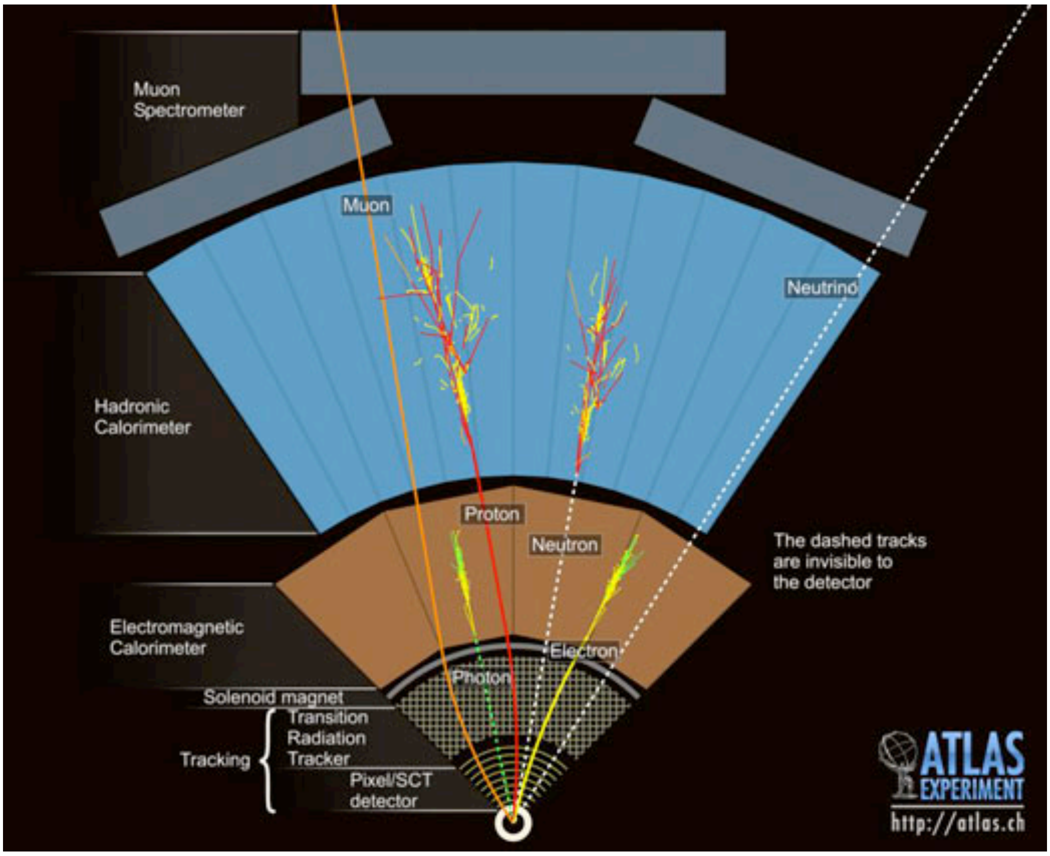


Detector Signals



- **Charged particles** leave several position measurements in the tracking detector. Positions are joined up to trace out a 'track', used to reconstruct the momentum. Measures $\vec{p}$
- Energies of **electrons, photons** and **hadrons** are absorbed in calorimeter, allowing energy to be measured. Measure E.
- **Neutrinos** do not interact at all in detector. Observed imbalance in momentum perpendicular to the beam. If beam is along z-direction, measure $p_x(\nu), p_y(\nu)$ but **not** $p_z(\nu)$.
- Quarks "hadronise", producing series of hadrons. Appear in detector as narrow "jet" of particles.

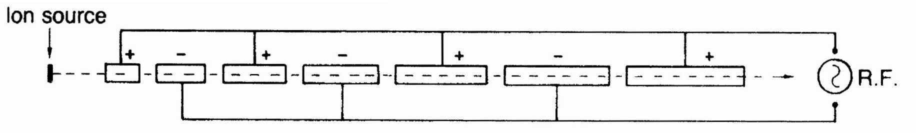
Particle Signals in the ATLAS Detector



The dashed tracks are invisible to the detector

Accelerators

- Variable electric and/or magnetic fields are used to accelerate bunches of charged particles.
- Linear accelerators (linacs) are use high frequency ***E***-field to accelerate charged particles in a straight line to obtain higher energies



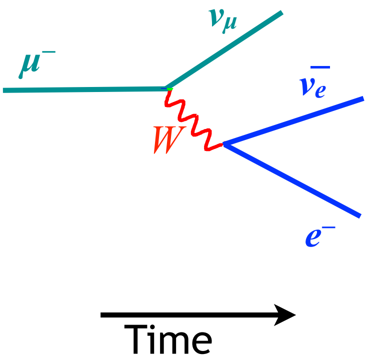
- Circular accelerators (synchrotrons) are used accelerate charged particles around a circle, to obtain higher energies and to store the particles.

- Synchrotron accelerators use variable ***B***-field strength and high frequency ***E***-field, synchronised with particle speed to accelerate charged particles to relativistic energies.
- Magnets are series of dipole (bending) and quadrapole (focussing) magnets
- Stored particles in a synchrotron lose energy due to synchrotron radiation. This must be added back into the beam at each turn.

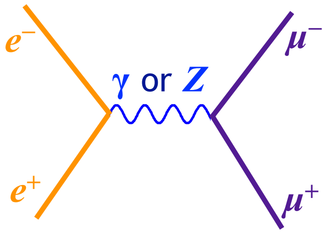
Feynman Diagrams

Feynman diagrams are used to **illustrate** and **calculate** rates of decays and scattering.

- e.g. muon decay: $\mu^- \to e^- \bar{\nu}_e \nu_\mu$



- e.g. $e^+e^- \to \mu^+\mu^-$ scattering



Use the Feynman Rules to calculate the matrix element, $\mathcal{M}$, from diagram

- For decay the partial width of the decay, Γ, is proportional to $\mathcal{M}^2$
- For scattering the cross section, σ, is proportional to $\mathcal{M}^2$

Use four momentum conservation to calculate boson four momentum, $\underline{\underline{q}}$

- Muon decay

$$\underline{\underline{q}} = \underline{\underline{p}}_\mu - \underline{\underline{p}}_{\nu_\mu} = \underline{\underline{p}}_e + \underline{\underline{p}}_{\nu_e}$$

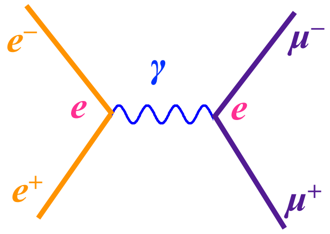
- $e^+e^- \to \mu^+\mu^-$ scattering

$$\underline{\underline{q}} = \underline{\underline{p}}_{e^+} + \underline{\underline{p}}_{e^-} = \underline{\underline{p}}_{\mu^+} + \underline{\underline{p}}_{\mu^-}$$

Feynman Rules

The matrix element, $\mathcal{M}$, is the amplitude, per unit time, for a given process to happen.

We calculate $\mathcal{M}$ from:
- the vertex couplings at the vertex
- the boson propagator term



The Feynman Rules

- Write down the **coupling at the each vertex**:
  - *charge of the fermion* (for EM), g_S (for QCD)
  - g_W (for W-ℓ-ν vertex), $g_W V_{qq'}$ (for W-q-q' vertex),
- Work out the four-momentum transferred by the boson, $\underline{\underline{q}}$
- Write down the **propagator term** for each boson: $1/(\underline{\underline{q}}^2 - m^2_{\text{boson}})$

$\mathcal{M}$ is proportional to vertex couplings and propagator terms *e.g.*

$$\mathcal{M}(e^+e^- \to \mu^+\mu^-) = e^2/\underline{\underline{q}}^2$$

- If process involves hadrons: consider interactions of the constituent quarks

Decays

We use **decays** and **scattering cross section** to understand interactions.

- A decay can only occur if $m_{\text{initial}} > \sum m_{\text{final}}$
- The stronger the interaction, the quicker the particle will decay.

Force	Typical Lifetimes
Strong	10^{-20} - 10^{-23} s
EM	10^{-20} - 10^{-16} s
Weak	10^{-13} - 10^{3} s

Measurable quantities:

- **lifetime:** τ Dimensions: time.
- **total width:** $\Gamma=\hbar/\tau$ Dimensions: energy.
- **Partial width of decay mode** *e.g.* $\Gamma(\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau)$

$$\Gamma(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau) \propto \left(\mathcal{M}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)\right)^2$$

- The **total width** is the sum of **all** the individual decay modes *e.g.*

$$\Gamma_\tau = \Gamma(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau) + \Gamma(\tau^- \to e^- \bar{\nu}_e \nu_\tau) + \Gamma(\tau^- \to \nu_\tau + \text{hadrons})$$

- The **branching ratio** is the fraction of time a particle decays into a particular final state, *e.g.*

$$\text{BR}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau) = \frac{\Gamma(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{\Gamma_\tau}$$

- The sum of all possible branching ratios adds to 1.

Scatterings

The cross section of a scattering process is proportional to the matrix element squared.

$$\sigma(e^+e^- \to \mu^+\mu^-) \propto |\mathcal{M}(e^+e^- \to \mu^+\mu^-)|^2$$

e.g. (from two slides back)

$$\sigma(e^+e^- \to \mu^+\mu^-) \propto e^4/\underline{\underline{q}}^4$$

- This relationship is only proportional, you do not have the tools (yet) to calculate the full cross section.
- But still useful for calculating the ratios of cross sections, or dynamics of the scattering process, e.g. if $\underline{\underline{q}}$ is a function of the incident angle.

Forces & Interactions

Three forces to consider: strong (QCD), electromagnetic (QED) & weak.

- Weak force has two bosons: W and Z

Forces are propagated by the exchange of bosons.

- Bosons exchange four momentum, $\underline{\underline{q}}$, between the initial and final state

Strength of interaction is acts on some properties of the particle, *e.g.* electromagnetic force is couples to electric charges of interacting particles

Strong	exchange of gluons	couples to colour charge
Electromagnetic	exchange of photons	couples to electric charge
Weak Neutral Current	exchange of Z^0 boson	couples to **all fermions**
Weak Charged Current	exchange of $W^{\pm}$ boson	couples to **all fermions**

The exchanged bosons are often **virtual** (as opposed to real).

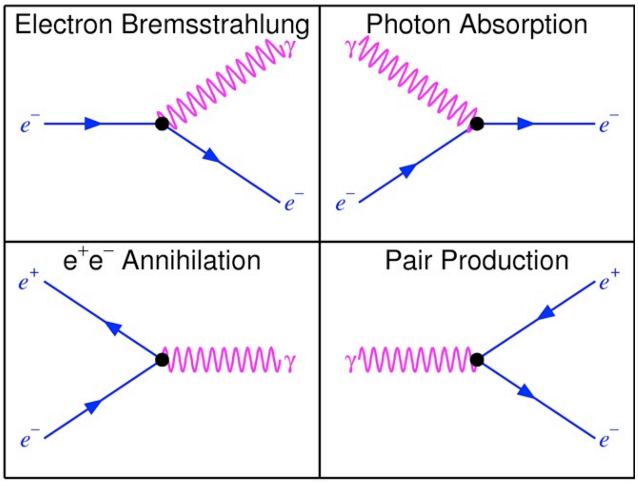
Virtual: square of four momentum is not mass squared: $\underline{\underline{q}}^2 = E^2 - \vec{p}\cdot\vec{p} \neq m^2_{\mathrm{boson}}$

Allowed by HUP; we can never directly detect virtual bosons: only their effects.

Quantum Electrodynamics

QED is quantum theory of electromagnetic interactions.

- All charged particles interact via QED
- All interactions are described by fermion-fermion-photon (γ) vertex:
  - Fermion emits or absorbs a photon
  - **γ→fermion anti-fermion** or **fermion anti-fermion→γ**
- **Fermion flavour does not change** when it emits or absorbs a photon *e.g.* an e^- remains an e^-, **b**-quark remains a **b**-quark



- Strength of vertex is proportional to charge of fermion
- Cross sections, decay width ∝ $\mathcal{M}^2$ write in powers of α

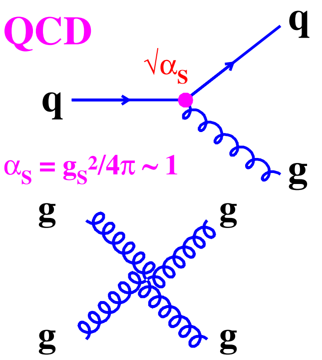
$$\alpha = \frac{e^2}{4\pi\epsilon_0} \approx \frac{1}{137}$$

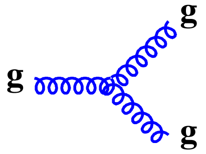
QED conserves:
Q, N_u, N_d, N_s, N_c, N_b, N_t, L_e, L_μ, L_τ

Quantum Chromodynamics

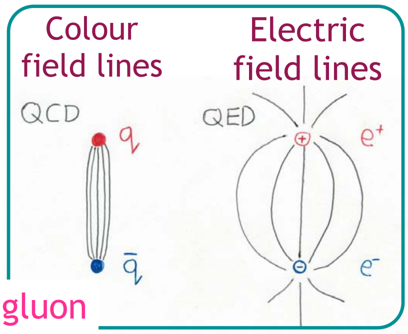
QCD is quantum theory of strong interactions.

- Acts on colour charged *i.e.* only quarks and gluons interact via QCD
- quark-quark-gluon vertex:
  - A quark emits or absorbs a gluon
  - **gluon→quark + anti-quark** or **quark + anti-quark→gluon**
- Quark flavour does not change, but colour charge changes





- As gluons also carry colour charge, the gluons interact with other gluons



- Potential between two quarks is:

$$V_{\text{QCD}}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$

quark-gluon interaction

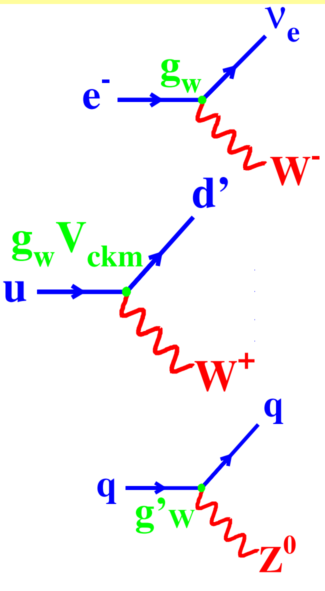
gluon-gluon interactions

- Almost impossible to pull two quarks apart: **colour confinement**

QCD conserves:
$Q, L_e, L_\mu, L_\tau, N_u, N_d, N_s, N_c, N_t, N_b$
No flavour changes!

Weak Interactions

Weak Force is propagated by massive $W^\pm$ and Z^0 bosons



Weak force interacts on all quarks and leptons.

Charged current **changes the flavour of the fermion**:

- Allowed flavour changes: $\mathcal{B}$, L_e, L_μ and L_τ conserved

$e^-\leftrightarrow\nu_e \quad \mu^-\leftrightarrow\nu_\mu \quad \tau^-\leftrightarrow\nu_\tau \quad e^+\leftrightarrow\overline{\nu_e} \quad \mu^+\leftrightarrow\overline{\nu_\mu} \quad \tau^+\leftrightarrow\overline{\nu_\tau}$

(Q=+2/3 quark) ↔ (Q=−1/3 quark)

(Q=−2/3 anti-quark) ↔ (Q=+1/3 anti-quark)

Strength of charged current:

- Leptons vertices, universal coupling: g_W
- Quark vertices, depends on quark flavour *e.g.* for **W-u-d:** $g_W V_{ud}$

Neutral current no **fermion flavour change.**

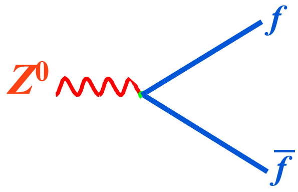
Handy hint: neutrinos are only involved in weak interactions.

Weak force conserves:
Q, L_e, L_μ, L_τ

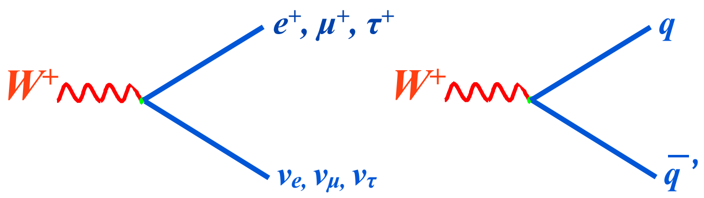
W and Z bosons

Virtual W and Z bosons propagate the weak interaction: $\underline{\underline{q}}^2 \neq m^2_{W,Z}$

- Also possible to create real W and Z s at colliders if $\sqrt{s} > m_W, m_Z$ (e.g. at LHC): $\underline{\underline{q}}^2_W \approx m^2_W, \;\; \underline{\underline{q}}^2_Z \approx m^2_Z,$
- W, Z decay into anything they are allow to interact with, provided all usual rules about decays are obeyed ($m_{\text{boson}} > m_{\text{daughters}}$, electric charge, quantum numbers conserved).



Z can decay into any fermion –anti-fermion pair (except top quarks, as $2m_t > m_Z$)



$W^\pm$ can decay into any quark–anti-quark or charged lepton and neutrino (provided Q and L_e, L_μ, L_τ are conserved)

What you don't need to know...

The masses of the particles; they are **given on the constant sheet!** Except:

- neutrino mass is so small you can always ignore it $m_\nu \approx 0$!
- electron mass so small you can ignore it compared to other masses.
- W and Z bosons are much more massive than all lepton and hadron masses.

The lifetimes of the particles, they will be given if required. But remember typical lifetimes for the different forces.

The quark content of the hadrons. Except...

- proton is uud anti-proton is: $\bar{u}\,\bar{u}\,\bar{d}$
- neutron is udd anti-neutron is: $\bar{u}\,\bar{d}\,\bar{d}$
- You can work out the charge of a particle from its symbol *e.g.* $Q(\Delta^{++})=+2e$
- exceptions:
  - p and n don't have superscript (but I hope you know the charge of these)
  - quarks have charge $+2/3e$, $-1/3e$