# Física de Partículas

## Introducción

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Latin American alliance for Capacity buildiNG in Advanced physics
LA-CoNGA physics

Cofinanciado por el programa Erasmus+ de la Unión Europea

## Nuclear Physics

- Matter: Complex Nuclei
- Forces: Strong nuclear force, weak and EM decays
- Complex many body problem (semi-empirical approach)
- Many models
- Historically developed first than particle physics

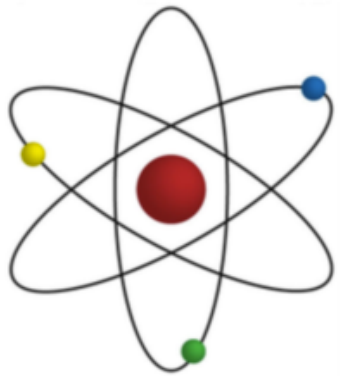
## Particle Physics

- Matter: Elementary particles
- Forces: Basic forces in nature - Electroweak (EM & weak), Strong
- Current understanding is embodied in the Standard Model
  - Forces as exchange of particles
  - Successfully describes all current data (except neutrino masses)
  - It is not a complete theory of nature

# Matter

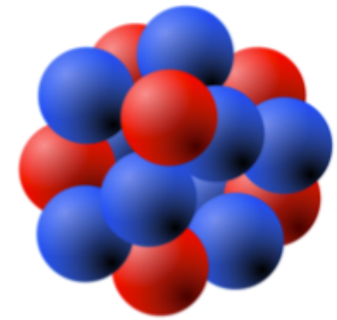
The atom (Binding energy ~10 eV)

- Electrons bond to atoms by EM force
- Size: $10^{-10}$ m



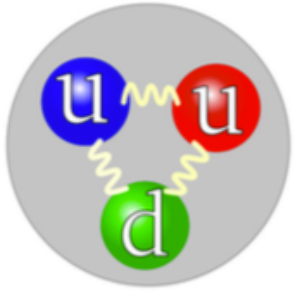
Nucleus (Binding energy ~10 MeV/nucleon)

- Nuclei held together by strong nuclear force
- Size: 5 fm



Nucleon (Binding energy ~1 GeV)

- Protons and neutrons held together by strong force
- Size: 1 fm



# Matter

In the Standard Model, all matter is made of spin 1/2 fundamental particles (fermions)

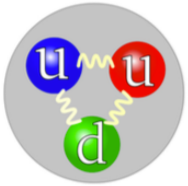

- Two types: leptons and quarks
- 3 generations
- Antiparticles: same mass, spin, but opposite interaction sign (i.e. charge)

Almost all the matter in the universe is made up from just four of the fermions (first generation)

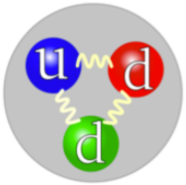
| Particle | Symbol | Type | Charge [$e$] |
|---|---|---|---|
| Electron | $e^-$ | lepton | $-1$ |
| Neutrino | $\nu_e$ | lepton | $0$ |
| Up quark | $u$ | quark | $+\frac{2}{3}$ |
| Down quark | $d$ | quark | $-\frac{1}{3}$ |

- The proton and the neutron are the lowest energy bound states of a system of three quarks: nuclear physics

Proton ($p$)




Neutron ($n$)



# 3 generations

There are other two generations of fermions

| $1^{st}$ generation | | $2^{nd}$ generation | | $3^{rd}$ generation | |
|---|---|---|---|---|---|
| Electron | $e^-$ | Muon | $\mu^-$ | Tau | $\tau^-$ |
| Electron Neutrino | $\nu_e$ | Muon Neutrino | $\nu_\mu$ | Tau Neutrino | $\nu_\tau$ |
| Up quark | $u$ | Charm quark | $c$ | Top quark | $t$ |
| Down quark | $d$ | Strange quark | $s$ | Bottom quark | $b$ |

- Each generation is a replica of the first
- The mass of the particles increases with each generation
- There is a symmetry between the generations, but we do not know why 3 generations

## Leptons: do not interact via the strong force

- 3 charged leptons
- 3 neutral leptons: neutrinos
- $e$ is stable, but $\mu$ and $\tau$ are not
- neutrinos are stable and almost massless ($<1$ eV/$c^2$)

| Flavour | Charge [$e$] | Mass | Strong | Weak | EM |
|---|---|---|---|---|---|
| **$1^{st}$ generation** | | | | | |
| $e^-$ | $-1$ | $0.511$ MeV$/c^2$ | ✗ | ✓ | ✓ |
| $\nu_e$ | 0 | $< 2$ eV$/c^2$ | ✗ | ✓ | ✗ |
| **$2^{nd}$ generation** | | | | | |
| $\mu^-$ | $-1$ | $105.7$ MeV$/c^2$ | ✗ | ✓ | ✓ |
| $\nu_\mu$ | 0 | $< 0.19$ MeV$/c^2$ | ✗ | ✓ | ✗ |
| **$3^{rd}$ generation** | | | | | |
| $\tau^-$ | $-1$ | $1777.0$ MeV$/c^2$ | ✗ | ✓ | ✓ |
| $\nu_\tau$ | 0 | $< 18.2$ MeV$/c^2$ | ✗ | ✓ | ✗ |

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- Charged leptons experience only EM and weak forces
- Neutrinos experience only the weak force

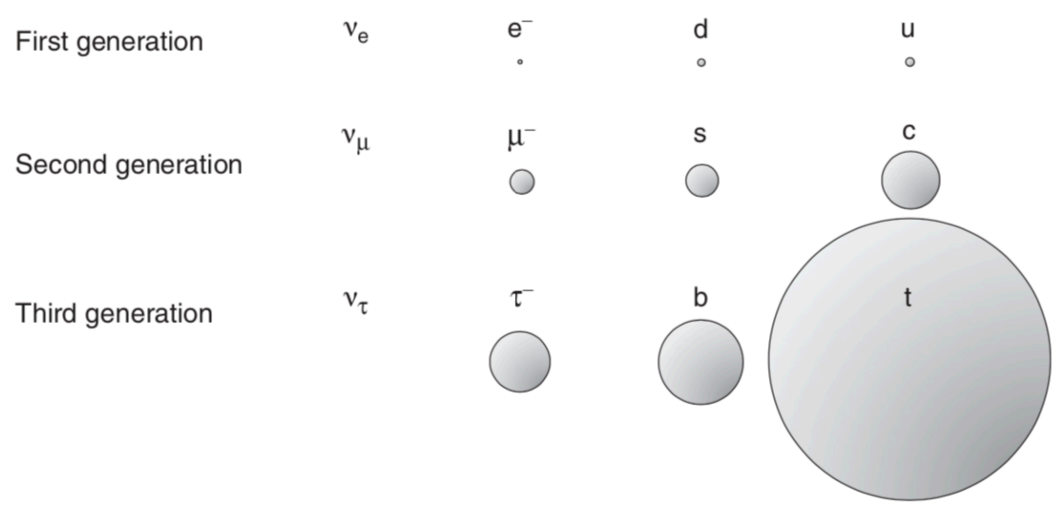
## Quarks: experience all 3 forces

- Fermions of fractional charge
- Antiquarks: $\bar{u}$,$\bar{d}$, etc
- Quarks are confined within hadrons
- 3 colours: Red, Green, Blue
- Colour is the charge of the strong interaction

| Flavour | Charge [$e$] | Mass | Strong | Weak | EM |
|---|---|---|---|---|---|
| **$1^{st}$ generation** | | | | | |
| $u$ | $+\frac{2}{3}$ | $2.3\ \mathrm{MeV}/c^2$ | ✓ | ✓ | ✓ |
| $d$ | $-\frac{1}{3}$ | $4.8\ \mathrm{MeV}/c^2$ | ✓ | ✓ | ✓ |
| **$2^{nd}$ generation** | | | | | |
| $c$ | $+\frac{2}{3}$ | $1.3\ \mathrm{GeV}/c^2$ | ✓ | ✓ | ✓ |
| $s$ | $-\frac{1}{3}$ | $95\ \mathrm{MeV}/c^2$ | ✓ | ✓ | ✓ |
| **$3^{rd}$ generation** | | | | | |
| $t$ | $+\frac{2}{3}$ | $173\ \mathrm{GeV}/c^2$ | ✓ | ✓ | ✓ |
| $b$ | $-\frac{1}{3}$ | $4.7\ \mathrm{GeV}/c^2$ | ✓ | ✓ | ✓ |

# Fermions

| | Leptons | | | | Quarks | | | |
|---|---|---|---|---|---|---|---|---|
| | Particle | | $Q$ | mass/GeV | Particle | | $Q$ | mass/GeV |
| First generation | electron | $(e^-)$ | $-1$ | 0.0005 | down | (d) | $-1/3$ | 0.003 |
| | neutrino | $(\nu_e)$ | 0 | $< 10^{-9}$ | up | (u) | $+2/3$ | 0.005 |
| Second generation | muon | $(\mu^-)$ | $-1$ | 0.106 | strange | (s) | $-1/3$ | 0.1 |
| | neutrino | $(\nu_\mu)$ | 0 | $< 10^{-9}$ | charm | (c) | $+2/3$ | 1.3 |
| Third generation | tau | $(\tau^-)$ | $-1$ | 1.78 | bottom | (b) | $-1/3$ | 4.5 |
| | neutrino | $(\nu_\tau)$ | 0 | $< 10^{-9}$ | top | (t) | $+2/3$ | 174 |



# Hadrons

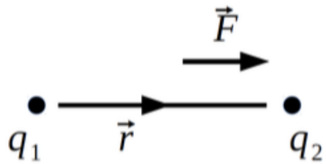
Free quarks have never been observed
Hadrons: bound states of quarks (i.e. the proton)

- Mesons ($q\bar{q}$): bound states of a quark and an anti-quark, integer spin
  - $\pi^+ = (u\bar{d})$
  - $\pi^- = (\bar{u}d)$
  - $\pi^0 = (u\bar{u} - d\bar{d})/\sqrt{2}$
- Baryons ($qqq$): bound states of three quarks, half integer spin
  - $p = (udu)$
  - $n = (dud)$

# Forces

## Classical picture

- Something that pushes matter around and causes objects to change their motion
- In classical physics the EM force acts via the Electric and Magnetic fields

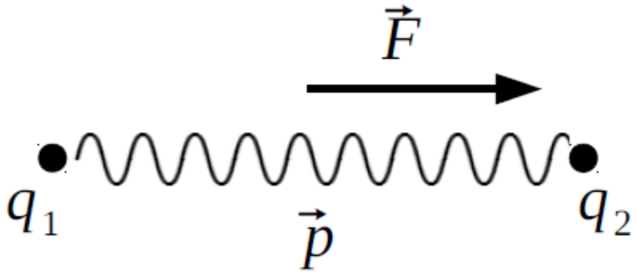



$$\vec{F} = \frac{q_1 q_2 \vec{r}}{r^2}$$

- Newton: "It is inconceivable that inanimate brute matter should, without the mediation of something else which is not material, operate upon and affect other matter without mutual contact "

## Quantum Mechanics

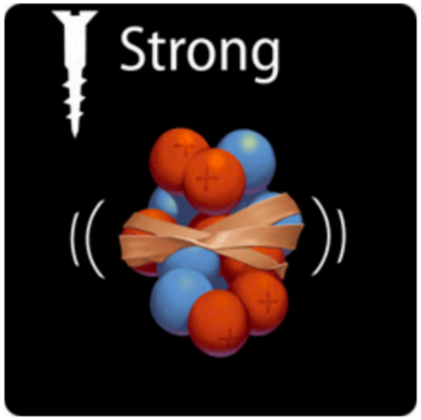
- Matter particles are quantised in QM, and the electromagnetic field should also be quantised (as photons)
- Forces arise through the exchange of virtual field quanta called Gauge Bosons




- The exchanged particle is "virtual"
- Coulomb's law can be regarded as the resultant effect of all virtual exchanges.

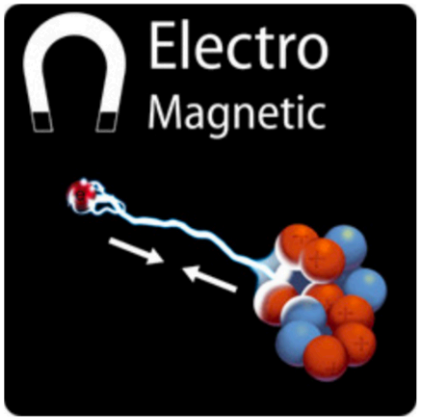
# Forces

All known particle interactions can be explained by four fundamental forces




- Carried by the gluon
- "Glues" atomic nuclei

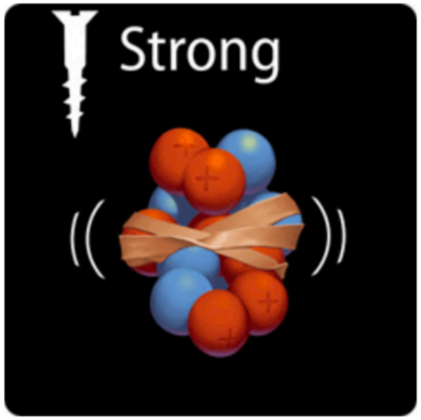

- Carried by W and Z bosons
- Radioactive decays




- Carried by the photon
- Acts between charged particles

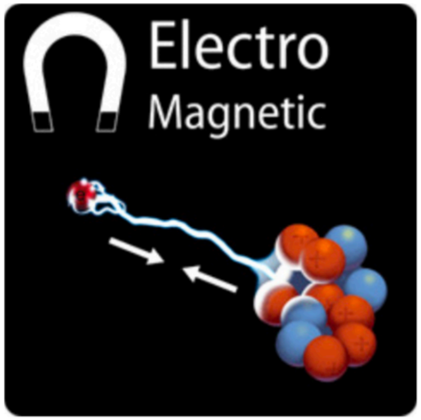

- Carried by the graviton?
- Acts between massive particles

Relative strengths for the forces between two atoms separated $10^{-15}$m




- 1


- $10^{-8}$




- $10^{-3}$


- $10^{-37}$

# Forces – Gauge bosons

Gauge bosons mediate the fundamental forces

- Spin 1 particles i.e. Vector Bosons
- Interact in a similar way with all fermion generations
- The exact way in which the Gauge Bosons interact with each type of lepton or quark determines the nature of the fundamental forces – Standard Model

| Force | Strength | Boson | | Spin | Mass/GeV |
|---|---|---|---|---|---|
| Strong | 1 | Gluon | g | 1 | 0 |
| Electromagnetism | $10^{-3}$ | Photon | $\gamma$ | 1 | 0 |
| Weak | $10^{-8}$ | W boson | $W^{\pm}$ | 1 | 80.4 |
| | | Z boson | Z | 1 | 91.2 |
| Gravity | $10^{-37}$ | Graviton? | G | 2 | 0 |

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- The Standard Model does not include gravity

# Units

It is usual in particle and nuclear physics to use Natural Units

- Energies are measured in units of eV:
  - Nuclear Physics: keV – MeV
  - Particle Physics: GeV – TeV
- Masses are quoted in units of $MeV/c^2$ or $GeV/c^2$ ($m_e = 9.11\times10^{-31}$ kg = 0.511 $MeV/c^2$)
- Atomic/nuclear masses are often quoted in unified (or atomic) mass units (1 u = mass of a 12C atom /12 = $1.66\times10^{-27}$ kg = 931.5 $MeV/c^2$)
- Cross-sections are usually quoted in barns: 1b = $10^{-28}$ $m^2$

# Natural Units

We choose energy as the basic unit of measurement
And simplify by choosing $c = \hbar = 1$

| Quantity | [kg, m, s] | [$\hbar$, $c$, GeV] | $\hbar = c = 1$ |
|---|---|---|---|
| Energy | $\mathrm{kg\,m^2\,s^{-2}}$ | GeV | GeV |
| Momentum | $\mathrm{kg\,m\,s^{-1}}$ | GeV/$c$ | GeV |
| Mass | kg | GeV/$c^2$ | GeV |
| Time | s | $(\mathrm{GeV}/\hbar)^{-1}$ | $\mathrm{GeV}^{-1}$ |
| Length | m | $(\mathrm{GeV}/\hbar c)^{-1}$ | $\mathrm{GeV}^{-1}$ |
| Area | $\mathrm{m^2}$ | $(\mathrm{GeV}/\hbar c)^{-2}$ | $\mathrm{GeV}^{-2}$ |

# Elementary particle dynamics

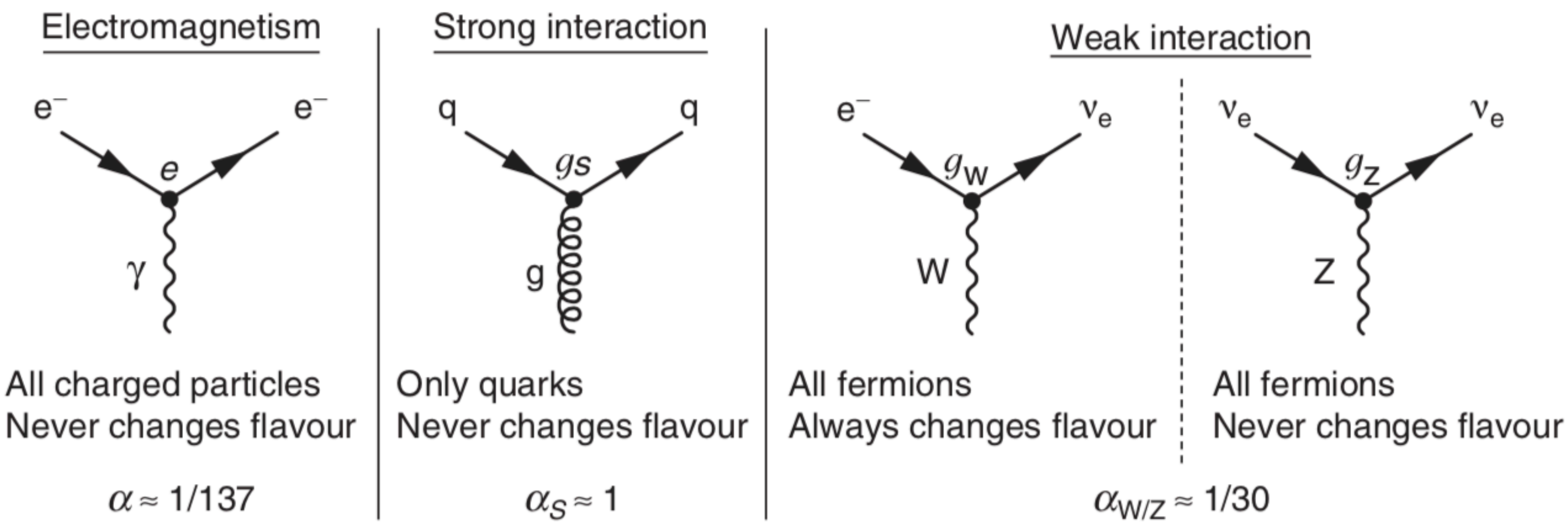
In modern particle physics, each force is described by a Quantum Field Theory

- EM: Quantum Electrodynamics (QED)
- Strong: Quantum Chromodynamics (QCD)
- Weak: Weak interactions (flavour dynamics, GWS model)

The nature of the forces is determined by

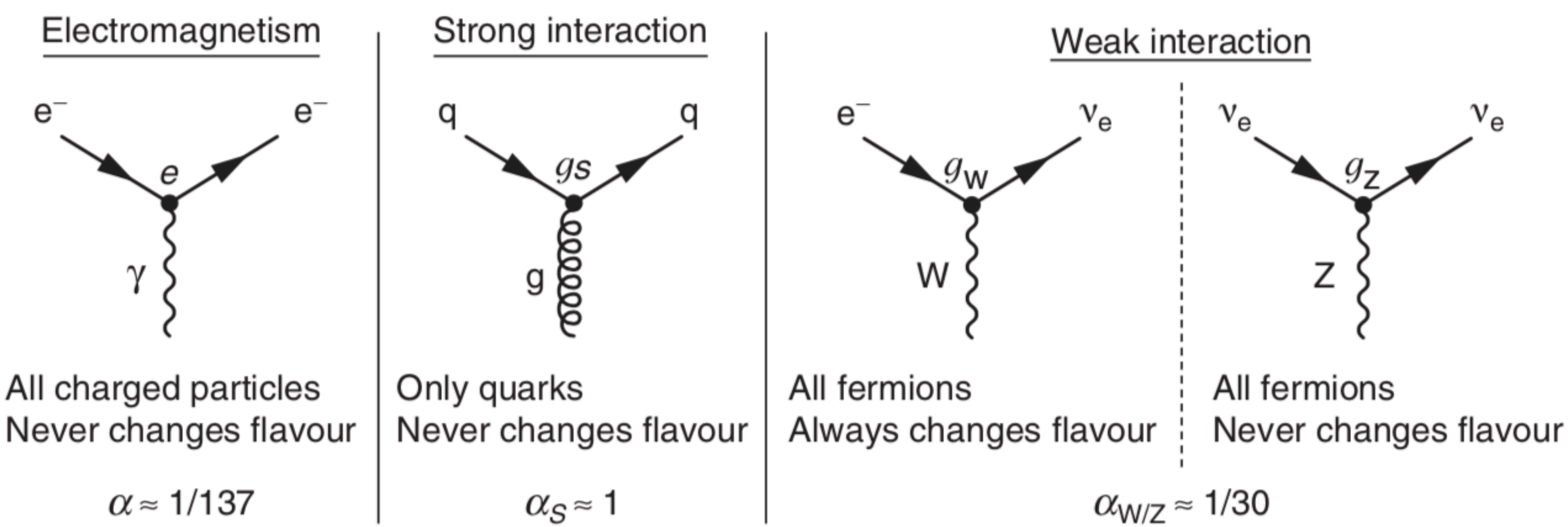
- The properties of the associated bosons
- The way in which these bosons couple to fermions

# Elementary particle dynamics



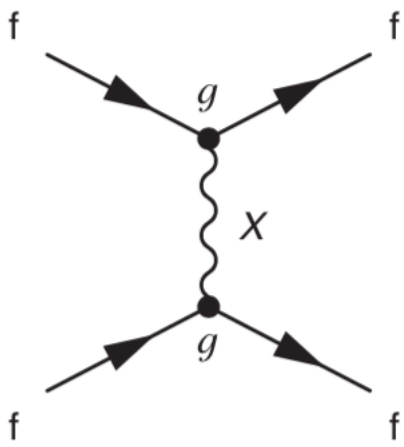

- The coupling of the bosons to the fermions is described by the SM interaction vertices
- For each type of interaction there is an associated coupling strength: $g$
- A particle couples to a force-carrying boson only if it carries the charge of the interaction

# Elementary particle dynamics



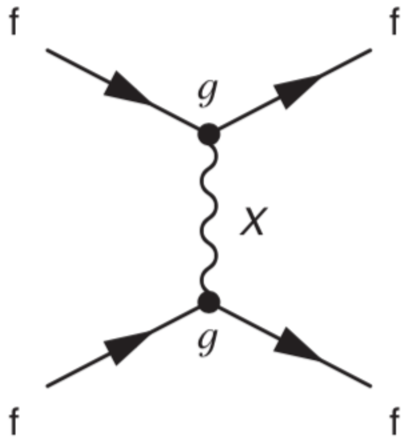

- $g$: a measure of the probability that a given fermion will emit or absorb a boson in the interaction
- The QM transition matrix element for an interaction contains a factor $g$ for each vertex

# Elementary particle dynamics




- Matrix element: $\mathcal{M} \propto g^2$
- Interaction probability: $|\mathcal{M}|^2 \propto g^4$

It is common to use the dimensionless constant: $\alpha \propto g^2$

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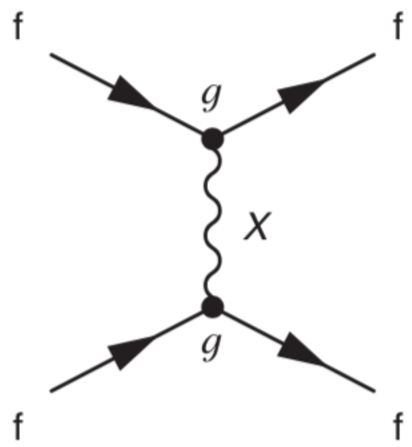
Intrinsic strength of the forces:

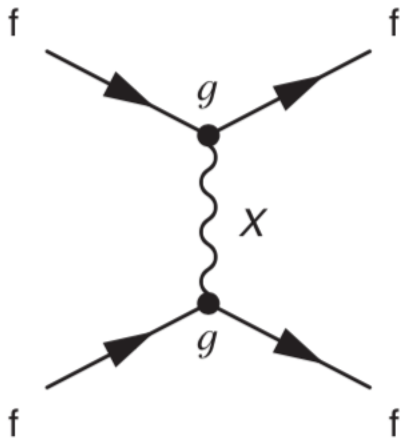
$\alpha \approx 1/137$ $\alpha_S \approx 1$ $\alpha_{W/Z} \approx 1/30$

# Feynman diagrams




- Essential in Particle Physics
- Representation of transitions between states in QFT
- Represent all possible orderings in which a process can occur

# Feynman diagrams




- Essential in Particle Physics
- Representation of transitions between states in QFT
- Represent all possible ways in which a process can occur
- Very powerful tool: We will see that one can derive rules (Feynman rules) for vertices and particles
- Once we have the diagram we can write the transition Matrix

# Relativistic Kinematics

Nuclear reactions:
- Low energy, typically $\mathcal{O}$(10 MeV) $\ll$ nucleon rest energies
- Non-relativistic kinematics works (except for β-decay)

Particle physics:
- Energies $\mathcal{O}$(100 GeV) >> rest energies
- Relativistic kinematics essential

## Energy and momentum:

$$E = \gamma m \quad \text{and} \quad \mathbf{p} = \gamma m \boldsymbol{\beta}. \qquad \gamma = (1-\beta^2)^{-\frac{1}{2}} \qquad \beta = \mathrm{v}/c$$

$$E^2 - \mathbf{p}^2 = m^2$$

- Particle at rest: $\vec{p} = 0, \ E = m,$
- Massless particle: $m = 0, \ E = |\vec{p}|,$
- Ultra-relativistic particle: $E \gg m, \ E \sim |\vec{p}|$

Lorentz transformations: $\mathbf{X}' = \Lambda \mathbf{X}$

$$\begin{pmatrix} t' \\ x' \\ y' \\ z' \end{pmatrix} = \begin{pmatrix} \gamma & 0 & 0 & -\gamma\beta \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\gamma\beta & 0 & 0 & \gamma \end{pmatrix} \begin{pmatrix} t \\ x \\ y \\ z \end{pmatrix}$$

- The quantity $t^2 - x^2 - y^2 - z^2$ is Lorentz invariant
- This can be written as the product of two four-vectors $x^{\mu} x_{\mu}$

$$x^{\mu} = (t, x, y, z)$$
$$x_{\mu} = (t, -x, -y, -z)$$

# Relativistic Kinematics – Four-Vectors

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$$x^\mu = (t, x, y, z)$$

$$x_\mu = (t, -x, -y, -z)$$

$$g_{\mu\nu} \equiv \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

- Related by the metric tensor $x_\mu = g_{\mu\nu} x^\nu$

# Relativistic Kinematics – Lorentz Invariance

In general $$a^\mu b_\mu = a_\mu b^\mu = g_{\mu\nu} a^\mu b^\nu,$$
is Lorentz Invariant

- With the four-momentum

$$p^\mu = (E, p_x, p_y, p_z).$$

- We see that

$$p^\mu p_\mu = E^2 - \mathbf{p}^2$$

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- For a particle at rest $p^\mu = (m, 0, 0, 0)$

  and $p^\mu p_\mu = m^2$

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- For a particle at rest $p^{\mu} = (m, 0, 0, 0)$
  and $p^{\mu}p_{\mu} = m^2$

- Therefore: $E^2 - \mathbf{p}^2 = m^2$

# Relativistic Kinematics – Invariant Mass

- For a system of n particles

$$p^{\mu} = \sum_{i=1}^{n} p_i^{\mu}$$

- Therefore

$$p^{\mu} p_{\mu} = \left( \sum_{i=1}^{n} E_i \right)^2 - \left( \sum_{i=1}^{n} \mathbf{p}_i \right)^2$$

is also Lorentz invariant: squared Invariant mass of the system

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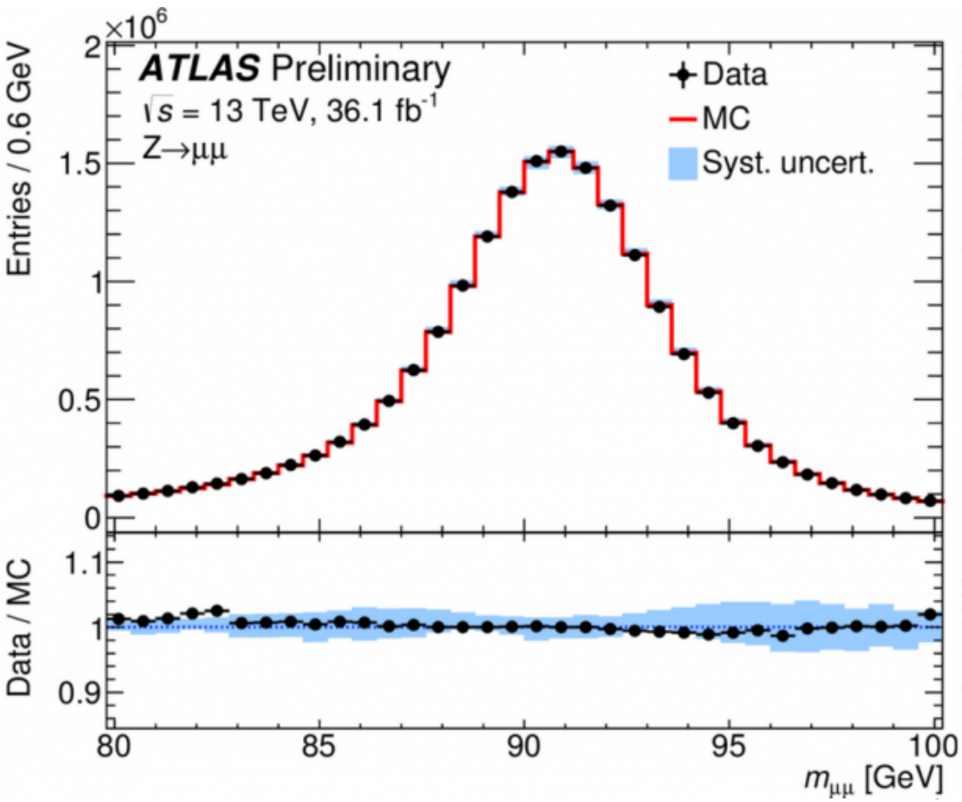
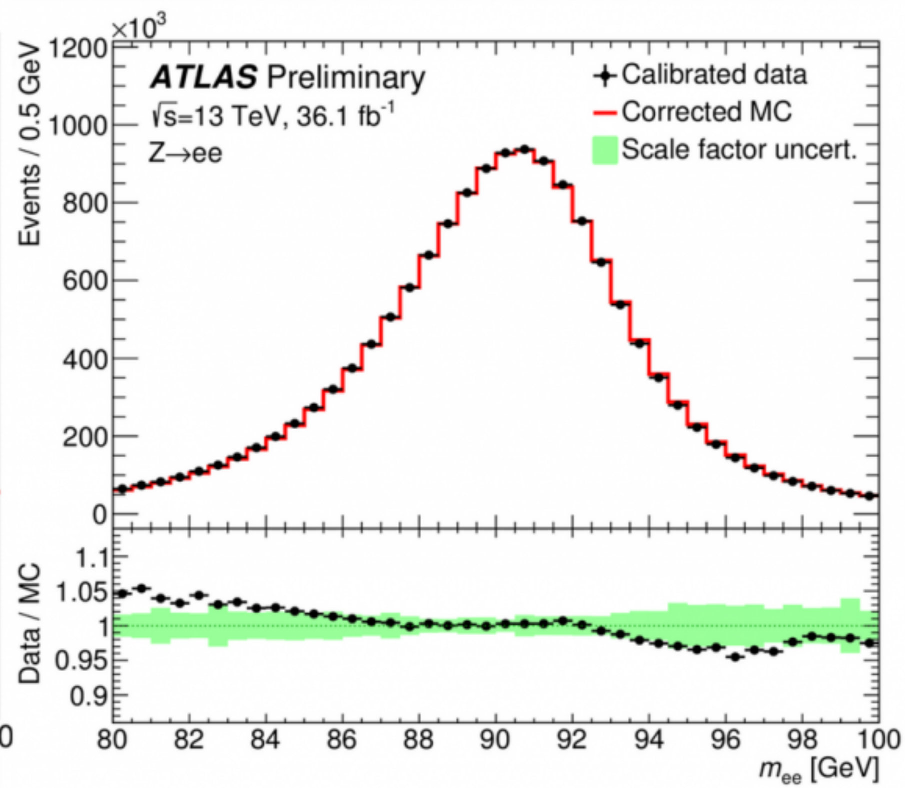
- If a→1+2:

$$(p_1 + p_2)^{\mu}(p_1 + p_2)_{\mu} = p_a^{\mu} p_{a\mu} = m_a^2.$$

# Relativistic Kinematics – Invariant Mass



Example: Consider a charged pion decaying at rest in the lab frame $\pi^- \rightarrow \mu^- \bar{\nu}_\mu$. Find the momenta of the decay products