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

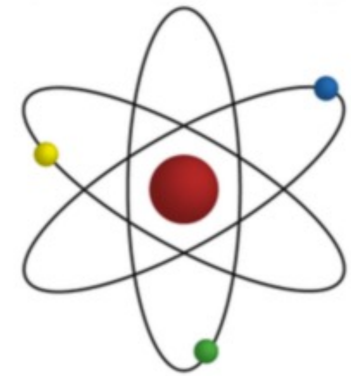
- Matter: Complex Nuclei
- Forces: Strong nuclear force, weak and EM decays
- Complex many body problem (semi-empirical approach)
- Many models
- Historically developed first than particle physics

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

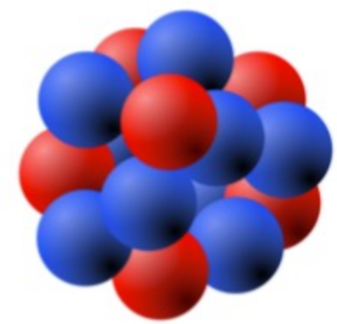
The atom (Binding energy ~10 eV)

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



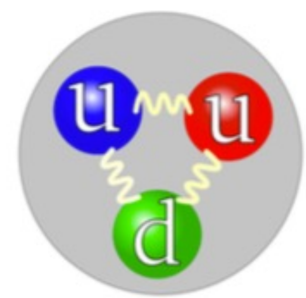
Nucleus (Binding energy ~10 MeV/nucleon)

- 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



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)

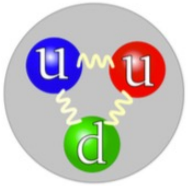
First generation

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

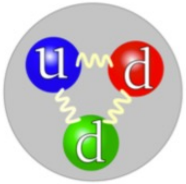
Particle	Symbol	Type	Charge [e]
Electron	e^-	lepton	-1
Neutrino	ν_e	lepton	0
Up quark	u	quark	$+\frac{2}{3}$
Down quark	d	quark	$-\frac{1}{3}$

- 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	μ^-	Tau	τ^-
Electron Neutrino	ν_e	Muon Neutrino	ν_μ	Tau Neutrino	ν_τ
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 μ and τ 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$/c^2$	✗	✓	✓
ν_e	0	< 2 eV$/c^2$	✗	✓	✗
2^{nd} generation					
μ^-	-1	105.7 MeV$/c^2$	✗	✓	✓
ν_μ	0	< 0.19 MeV$/c^2$	✗	✓	✗
3^{rd} generation					
τ^-	-1	1777.0 MeV$/c^2$	✗	✓	✓
ν_τ	0	< 18.2 MeV$/c^2$	✗	✓	✗

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

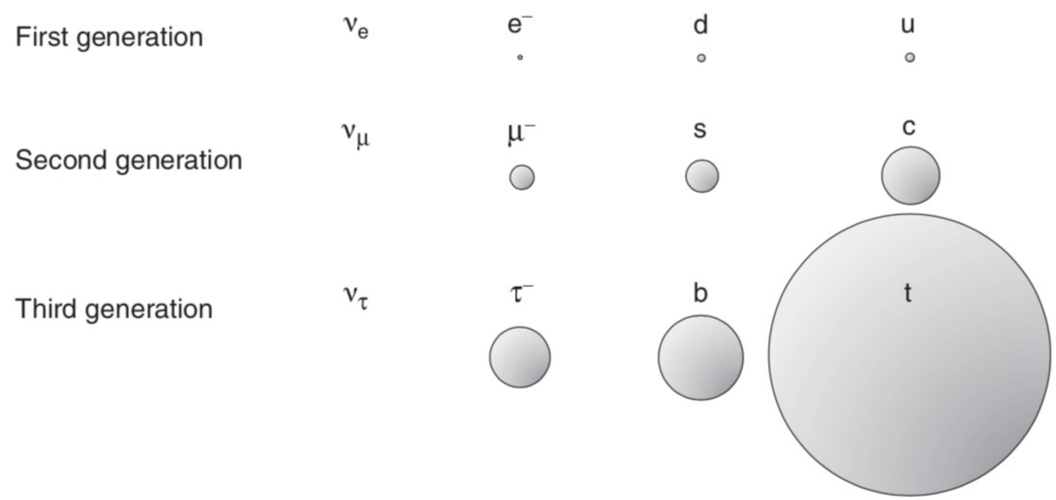
Quarks: experience all 3 forces

- 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 MeV$/c^2$	✓	✓	✓
d	$-\frac{1}{3}$	4.8 MeV$/c^2$	✓	✓	✓
2^{nd} generation					
c	$+\frac{2}{3}$	1.3 GeV$/c^2$	✓	✓	✓
s	$-\frac{1}{3}$	95 MeV$/c^2$	✓	✓	✓
3^{rd} generation					
t	$+\frac{2}{3}$	173 GeV$/c^2$	✓	✓	✓
b	$-\frac{1}{3}$	4.7 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	(ν_e)	0	$< 10^{-9}$	up	(u)	$+2/3$	0.005
Second generation	muon	(μ^-)	-1	0.106	strange	(s)	$-1/3$	0.1
	neutrino	(ν_μ)	0	$< 10^{-9}$	charm	(c)	$+2/3$	1.3
Third generation	tau	(τ^-)	-1	1.78	bottom	(b)	$-1/3$	4.5
	neutrino	(ν_τ)	0	$< 10^{-9}$	top	(t)	$+2/3$	174



Hadrons

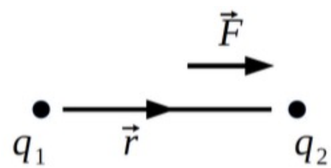
Free quarks have never been observed
Hadrons: bound states of quarks (i.e. the proton)

- 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

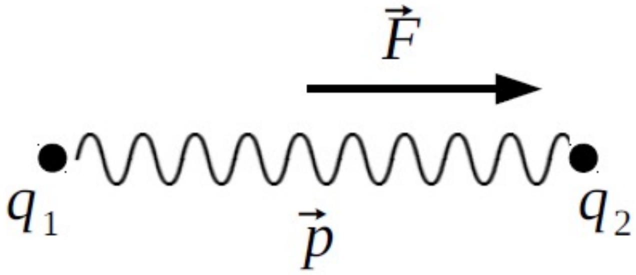


$$\vec{F} = \frac{q_1 q_2 \vec{r}}{r^2}$$

- 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

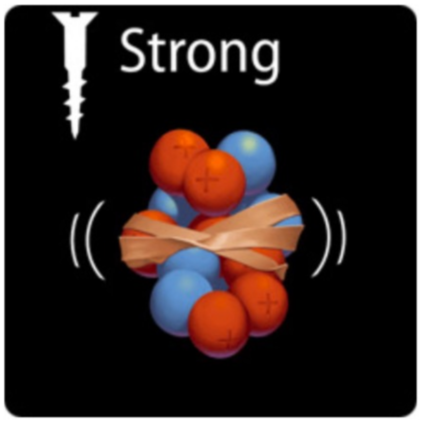
- Matter particles are quantised in QM, and the electromagnetic field should also be quantised (as photons)
- Forces arise through the exchange of virtual field quanta called Gauge Bosons



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

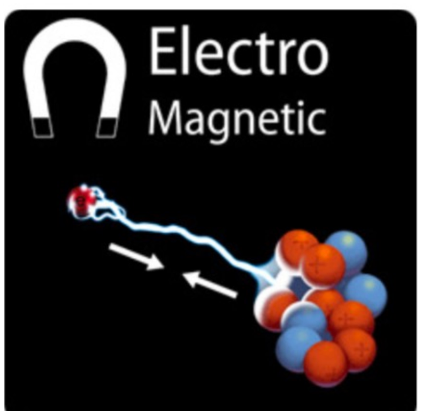
Forces

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

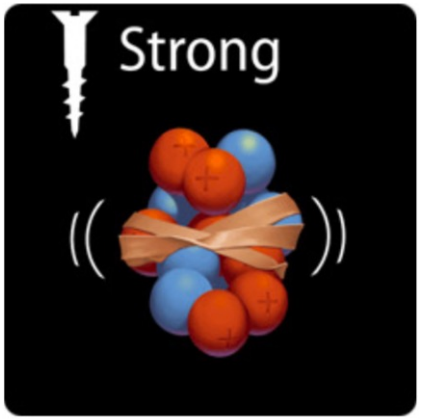


- Carried by the photon
- Acts between charged particles

- Carried by the graviton?
- Acts between massive particles

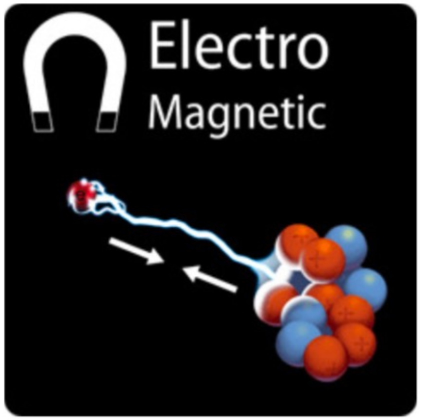
Forces

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	γ	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 = 1.66×10^{-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	$(\mathrm{GeV}/\hbar)^{-1}$	GeV^{-1}
Length	m	$(\mathrm{GeV}/\hbar c)^{-1}$	GeV^{-1}
Area	m^2	$(\mathrm{GeV}/\hbar c)^{-2}$	GeV^{-2}

Elementary particle dynamics

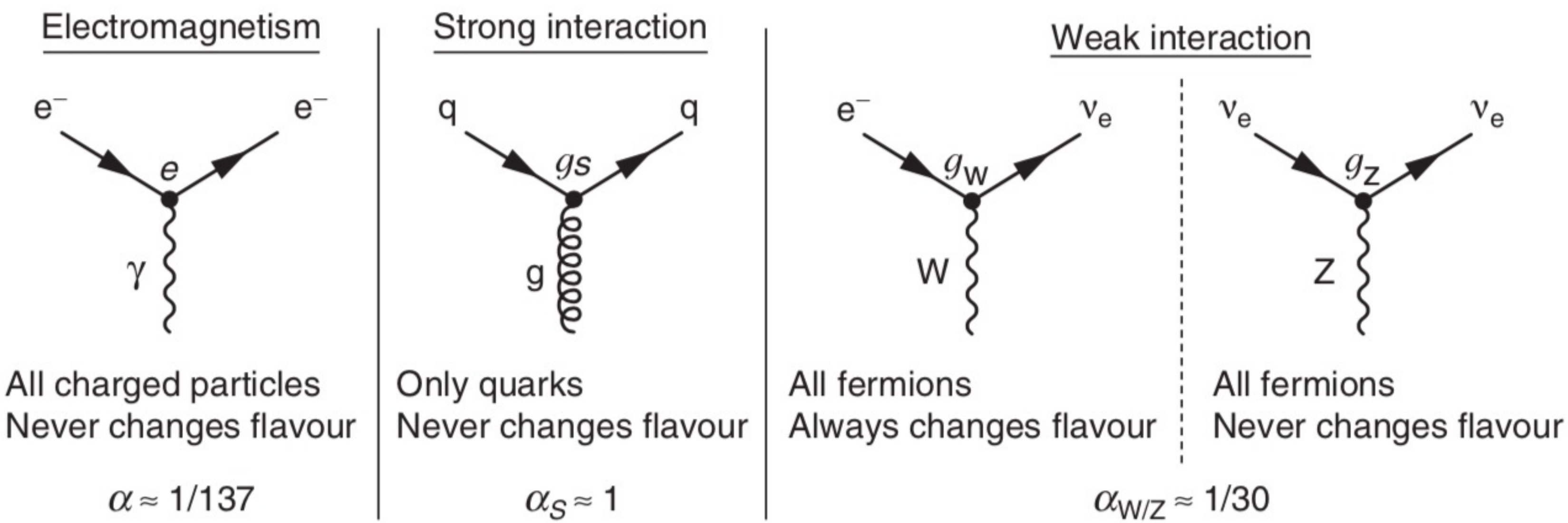
In modern particle physics, each force is described by a Quantum Field Theory

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

The nature of the forces is determined by

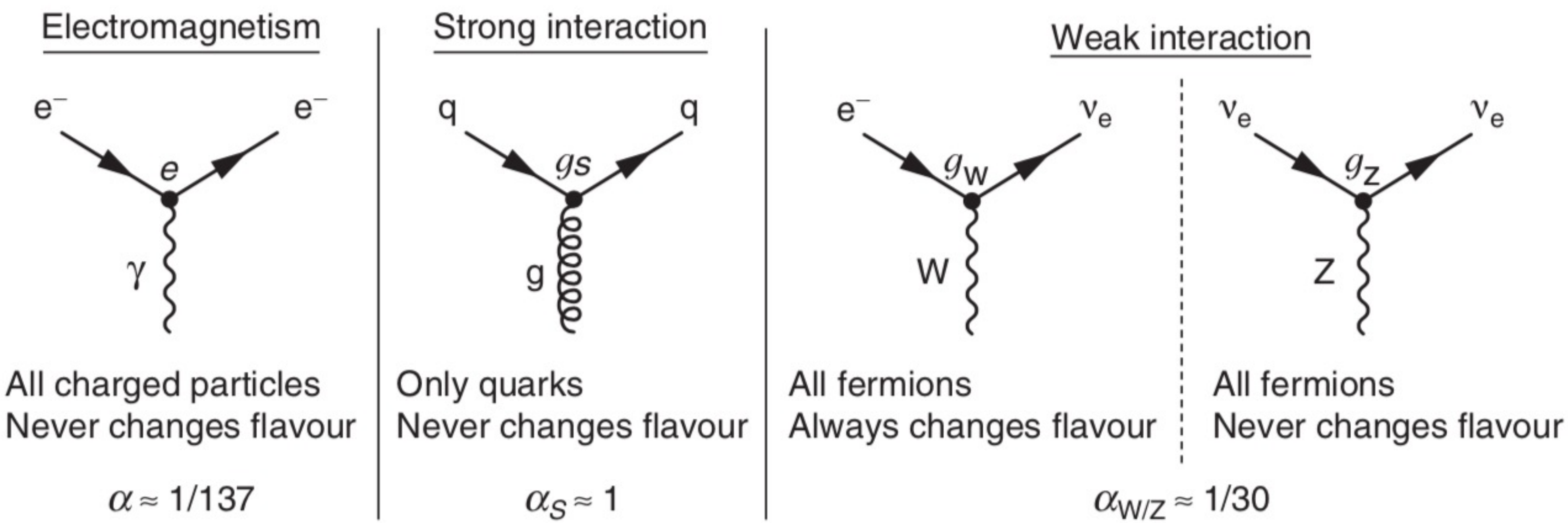
- The properties of the associated bosons
- The way in which these bosons couple to fermions

Elementary particle dynamics



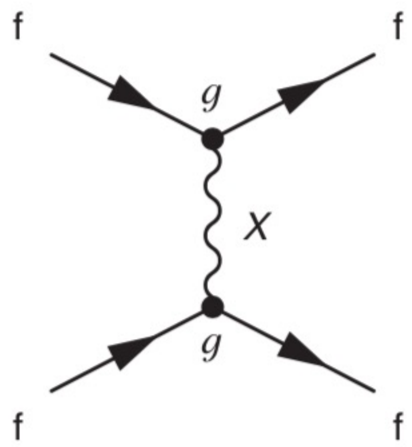
- The coupling of the bosons to the fermions is described by the SM interaction vertices
- For each type of interaction there is an associated coupling strength: g
- A particle couples to a force-carrying boson only if it carries the charge of the interaction

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

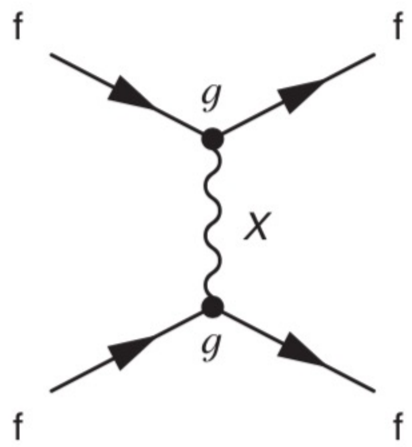
Elementary particle dynamics



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

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

Elementary particle dynamics



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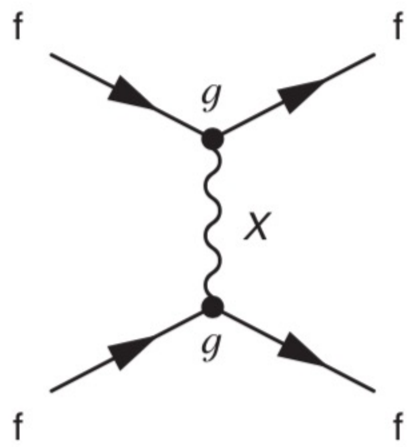
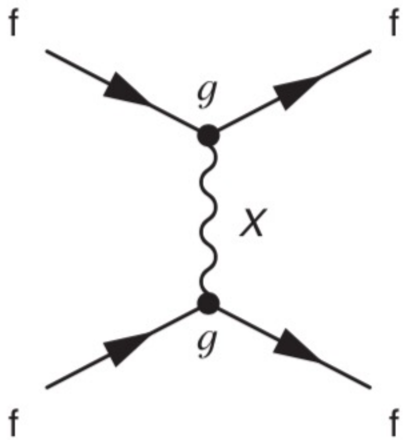
Intrinsic strength of the forces:

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



- 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) ≪ 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 $x^\mu x_\mu$

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

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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 $x_\mu = g_{\mu\nu} x^\nu$

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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  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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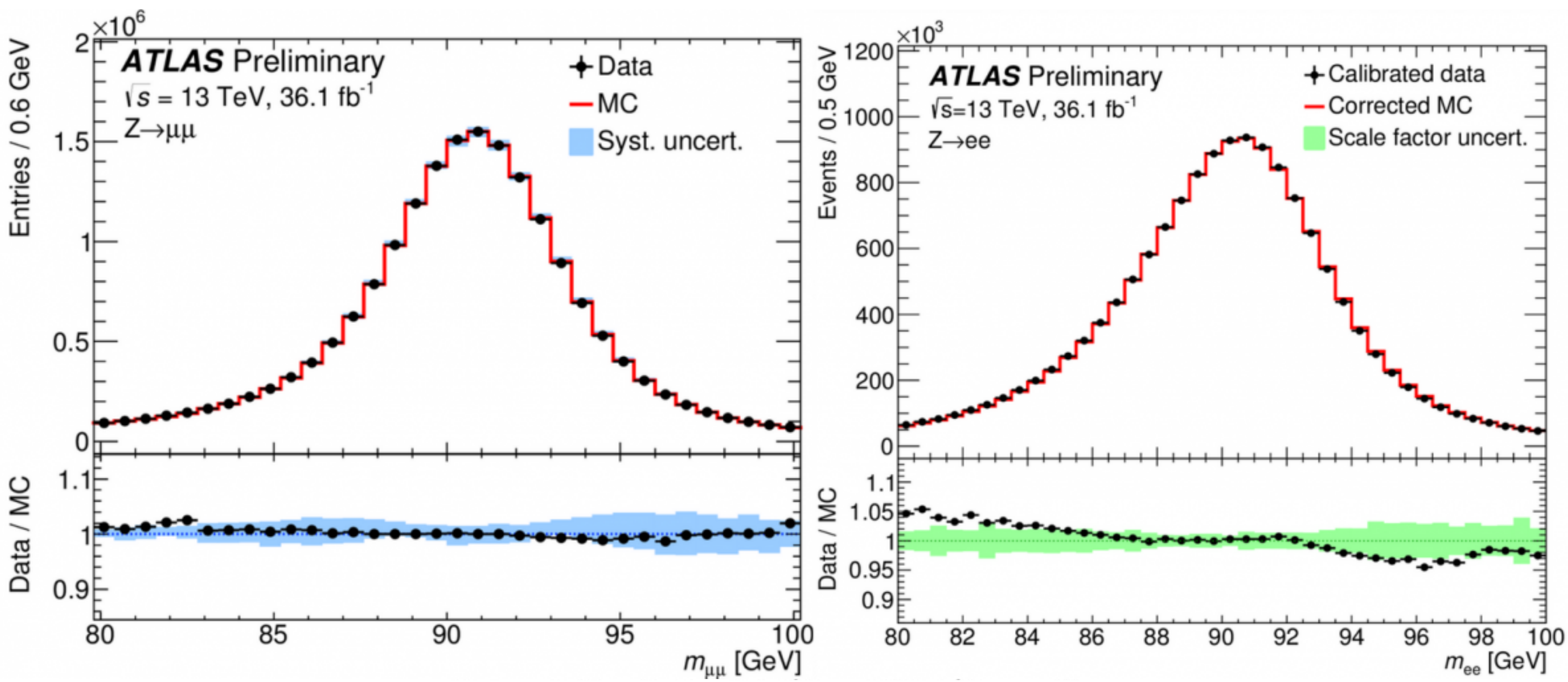
- If a→1+2:

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

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