A visualization of particle tracks, likely from a detector, showing a central interaction point with many tracks radiating outwards. The tracks are represented by thin, glowing yellow lines against a dark background. Some tracks are straight, while others are curved or spiral. The overall appearance is that of a complex, multi-particle event.

# Particle Physics I

## Lecture 1: Overview of Particle Physics

Prof. Radoslav Marchevski  
September 10<sup>th</sup> 2025

# Practical information

- Lecturer: Radoslav Marchevski

web: <https://people.epfl.ch/radoslav.marchevski>

mail: [radoslav.marchevski@epfl.ch](mailto:radoslav.marchevski@epfl.ch)

- Teaching assistant: Pierre Mayencourt

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mail: [pierre.mayencourt@epfl.ch](mailto:pierre.mayencourt@epfl.ch)

- Course material:

Moodle: <https://moodle.epfl.ch/course/view.php?id=14833>

will contain slides, exercises, and solutions

books: [Mark Thomson](#) “Modern Particle Physics” ([library](#))

Particle Data Group “The Review of Particle Physics” <https://pdg.lbl.gov/>



# Provide regular feedback

- For each lecture & exercise session, you can share your feedback via moodle.
- Do not hesitate to talk to us after the lecture/exercise session or send us an email.

## Reading list

The course closely follows the book by [Mark Thomson, "Modern Particle Physics" \(2013\)](#), which is available at the EPFL library.

For summaries, most recent reviews and technical information, please use the Particle Data Group (PDG) website <https://pdg.lbl.gov/>.



FORUM

[Forum for Q&A on the lectures and exercises](#) 



FORUM

[Announcements](#) 



# Course structure

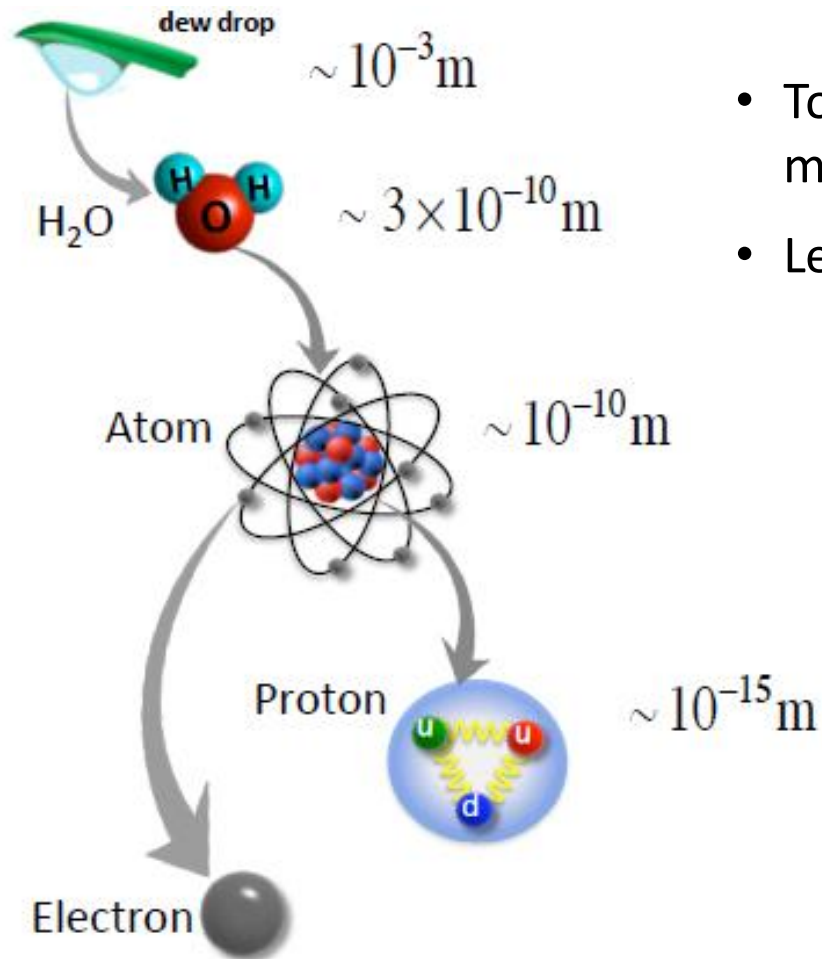
- Particle Physics I (this fall semester)
  - Overview, particle detection, accelerators
  - The Klein-Gordon and Dirac equations, spin
  - Interaction by particle exchange
  - QED: quantum electrodynamics
  - Symmetries and the quark model
- Particle Physics II (next spring semester)
  - QCD: quantum chromodynamics
  - The weak interaction
  - Electroweak unification and the  $W$  and  $Z$  bosons
  - The Higgs boson: theory and discovery
  - Dark matter and beyond-the-standard-model theories
- Particle detection (this fall semester)
  - Interaction of particles with matter (ionization, Bethe-Bloch, interaction of electrons and photons)
  - General characteristics of detectors (linearity, efficiency, resolution)
  - Gas detectors, Semiconductor detectors, Scintillators, Photodetectors
  - Applications: momentum measurement in magnetic fields, calorimetry, particle identification
- Particle Physics: the flavour frontier (next spring semester)
  - Symmetries of the Standard Model
  - Flavour and quark mixing
  - Spontaneous symmetry breaking and the Higgs boson
  - Experimental aspects of flavour physics
  - QCD at low energies
  - Rare decays
  - $CP$  violation

# Today's learning targets

- Introduction to particle physics
  - What are the constituents of matter and how are they organized?
  - How are particle interactions mediated?
  - Which interactions exist and what are their relative strengths?
  - What is the role of the Higgs boson and the Higgs mechanism?
  - Natural units
  - Feynman diagrams

# Scope of particle physics

- Main questions that particle physics aims to address
  - what are the constituents of matter?
  - which are the forces holding them together to form matter?
  - is there a coherent and unified model or framework that describes everything that we observe?



- To study the “indivisible” constituents of matter we need to go down several many orders of magnitudes lower than what we are used to in our everyday life
- Let’s take as an example the proton (not indivisible)
  - size/length scale ( $R$ )  $\sim 10^{-15}$  m
  - mass ( $m$ )  $\sim 10^{-27}$  kg
  - energy ( $mc^2$ )  $\sim 10^{-10}$  J
  - time ( $R/c$ )  $\sim 10^{-23}$  s

SI unit system used in everyday life is **not well-suited to describe phenomena at this level**  $\Rightarrow$  **we need a more suitable system to rescale our units**

# Natural units (Plank units)

- Measurement basis for everyday objects and macroscopic phenomena: [kg, m, s]
  - Not a *natural* choice for the properties of particles (e.g.  $m_e = 9.1 \times 10^{-31}$  kg)
- Natural units: [kg, m, s]  $\rightarrow$  [ $\hbar$ ,  $c$ , GeV]
  - Reduced Planck constant:  $\hbar = 1.055 \times 10^{-34}$  J s [kg m<sup>2</sup>s<sup>-1</sup>]
  - Speed of light in vacuum:  $c = 2.998 \times 10^8$  m s<sup>-1</sup>
  - 1 GeV ( $\sim m_p$ ) =  $10^9$  eV =  $1.602 \times 10^{-10}$  J
- All quantities in particle physics can be expressed in GeV by choosing  $\hbar = c = 1$ 
  - velocity is measured in units of  $c$  :  $v \rightarrow v/c$
  - $m, p$  and  $E$  measured in the same units [GeV]
  - Conversion from MeV to m:  $\hbar c = 197$  MeV fm (1 fm =  $10^{-15}$  m)
- Heaviside-Lorentz units:  $\hbar = c = \epsilon_0 = \mu_0 = 1$ 
  - fine structure constant:  $\alpha = \frac{e^2}{4\pi} \approx \frac{1}{137}$
- Gravitational and Boltzmann constants:  $\hbar = c = \epsilon_0 = \mu_0 = G = k_b = 1$

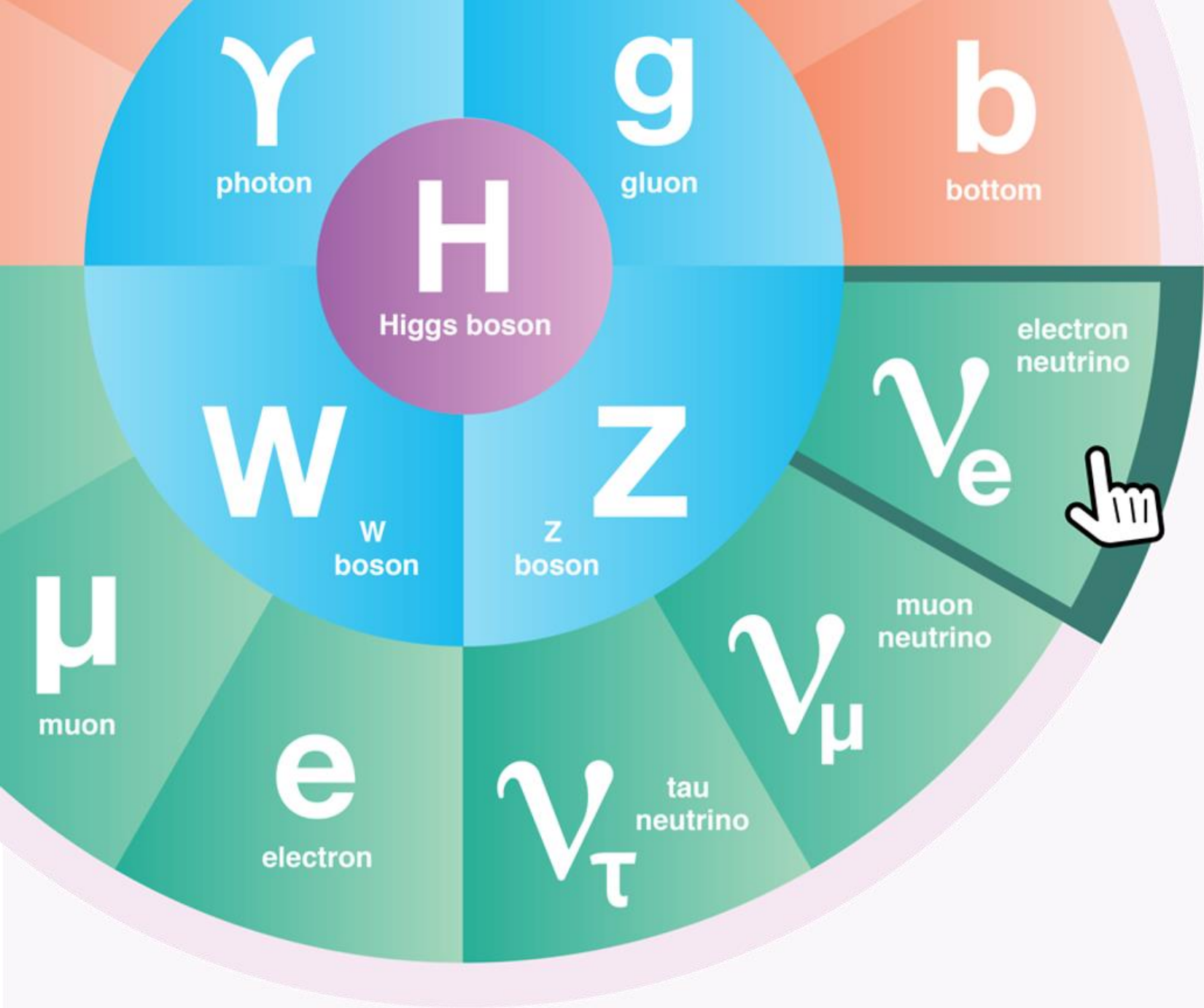
# Natural units (Plank units)

Quantity	SI	Natural units	Conversion
Mass	kg	GeV	$1 \text{ GeV} = 1.8 \times 10^{-27} \text{ kg}$
Length	m	$1/\text{GeV}$	$1 \text{ GeV}^{-1} = 0.197 \times 10^{-15} \text{ m}$
Time	s	$1/\text{GeV}$	$1 \text{ GeV}^{-1} = 6.58 \times 10^{-25} \text{ s}$
Energy	$\text{kg m}^2/\text{s}^2$	GeV	$1 \text{ GeV} = 1.602 \times 10^{-10} \text{ J}$
Momentum	kg m/s	GeV	$1 \text{ GeV} = 5.39 \times 10^{-19} \text{ kg m/s}$
Force	$\text{kg m}/\text{s}^2$	$\text{GeV}^2$	$1 \text{ GeV}^2 = 8.19 \times 10^5 \text{ N}$
Area (cross section)	$\text{m}^2$	$1/\text{GeV}^2$	$1 \text{ GeV}^{-2} = 0.389 \text{ mb} = 0.389 \times 10^{-31} \text{ m}^2$
Charge	C = A s	none	$1 = 5.28 \times 10^{-19} \text{ C}$ $e = 0.303 = 1.602 \times 10^{-19} \text{ C}$

- Correct unit dimensions to derive the numbers in the table:

Energy	GeV	Time	$(\text{GeV}/\hbar c)^{-1}$	$c = 2.998 \times 10^8 \text{ m/s}$ $\hbar = 1.055 \times 10^{-34} \text{ J s}$
Momentum	GeV/c	Length	$(\text{GeV}/\hbar c)^{-1}$	
Mass	$\text{GeV}/c^2$	Area	$(\text{GeV}/\hbar c)^{-2}$	

- These conversions are rarely needed in practice: we will use GeV throughout the course



explore

# The Standard Model

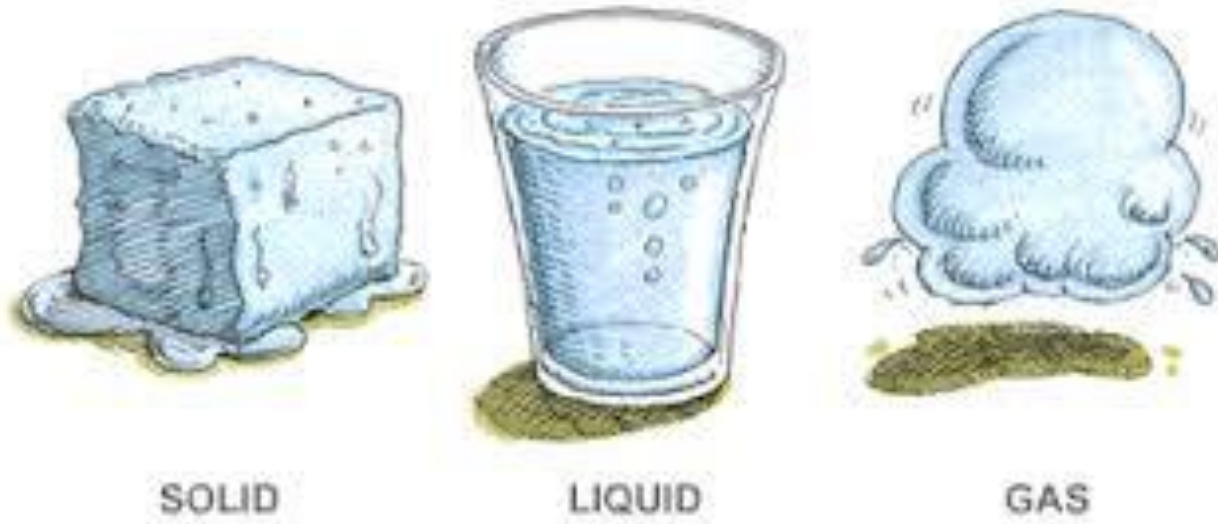
- 
-  **QUARKS**
  -  **LEPTONS**
  -  **BOSONS**
  -  **HIGGS BOSON**

# Elementary particle physics

- Particle physics is the study of:
  - **Matter:** the *“fundamental”* building blocks of the universe – elementary particles
  - **Force:** the *“fundamental”* interactions between the elementary particles
- Try to categorise the particles and the interactions between them in as simple and fundamental manner as possible

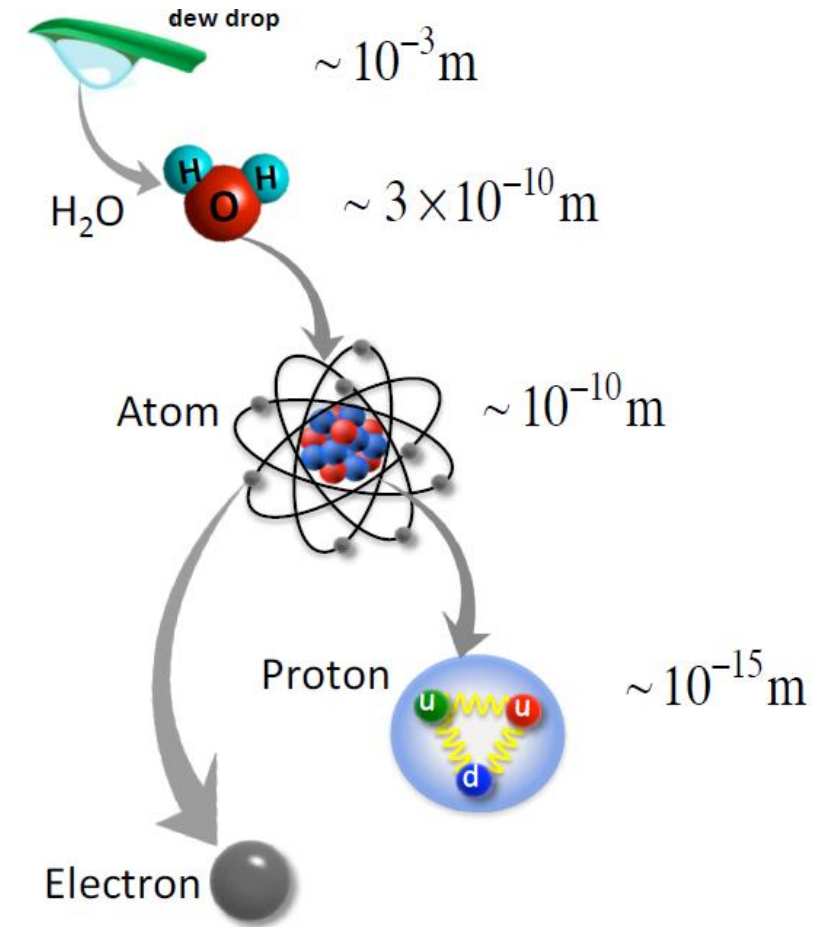
# Elementary particle physics: Matter

What people usually imagine when hearing *matter*



- Fundamental constituents of ordinary matter
  - leptons (e.g. *electron*)
  - Quarks (e.g. *up* and *down* quarks, making up the protons and neutrons)
- Leptons and quarks are called **fermions**: particles with  $\frac{1}{2}$  (half-integer) spin

What matter is down to its constituents



# Known matter

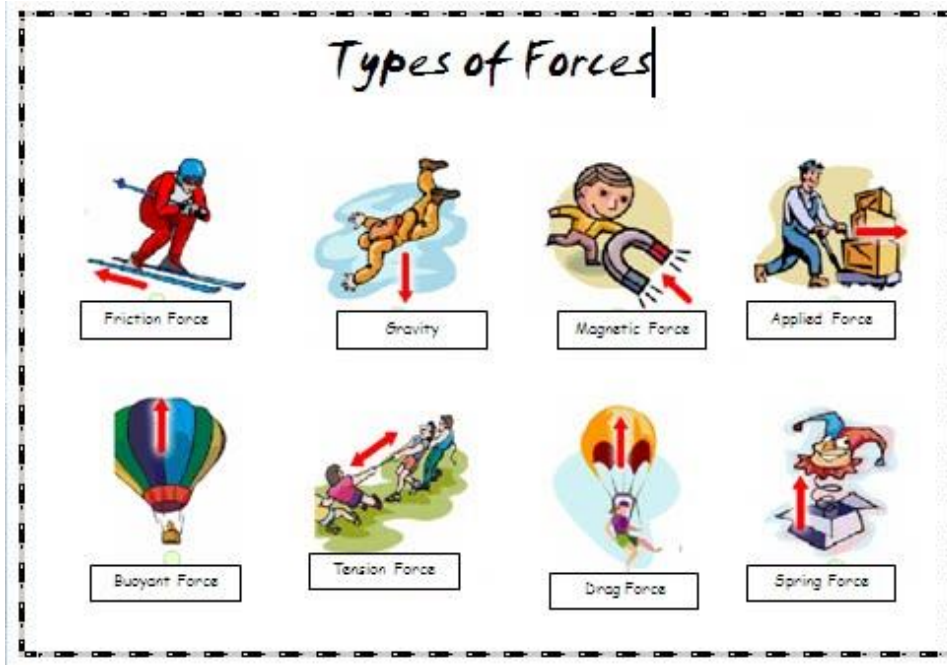
Generation	Leptons				Quarks			
	particle		$Q$	$m/\text{GeV}$	particle		$Q$	$m/\text{GeV}$
1 <sup>st</sup>	electron	$e^-$	-1	0.0005	down	d	-1/3	0.005
1 <sup>st</sup>	neutrino	$\nu_1$	0	$< 10^{-9}$	up	u	+2/3	0.003
2 <sup>nd</sup>	muon	$\mu^-$	-1	0.106	strange	s	-1/3	0.1
2 <sup>nd</sup>	neutrino	$\nu_2$	0	$< 10^{-9}$	charm	c	+2/3	1.3
3 <sup>rd</sup>	tau	$\tau$	-1	1.78	bottom	b	-1/3	4.2
3 <sup>rd</sup>	neutrino	$\nu_3$	0	$< 10^{-9}$	top	t	+2/3	173

# Known matter

Generation	Leptons				Quarks			
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- “Matter” is described by **point-like spin-½ fermions**
- Anti-particles have the same mass as particles (in the table) but with opposite charge
- Three generations of quarks/leptons: copies of each other, only differing in mass
  - **We don't know why exactly three generations**
- Neutrinos are much lighter than all other particles ( **$< 1\text{eV}$** )
  - We know that neutrinos can't be massless because of neutrino oscillations
  - **We don't know why the neutrino masses are so small**

# Elementary particle physics: Forces



- Four fundamental interactions between elementary particles
- The forces are transmitted to the matter particles by means of mediator particles: **bosons** (particles with integer spin)
- The gravitational force **is not included** in the Standard Model
  - Force between individual particles extremely small and can be neglected in the discussion of particle interactions



### Electromagnetic

**Photon**

**Atoms**  
Light  
Chemistry  
Electronics

### Weak

**Bosons (W,Z)**

**Neutron decay**  
Beta radioactivity  
Neutrino interactions  
Burning of the sun

### Strong

**Gluons (8)**

**Quarks**

**Mesons**  
**Baryons**

**Nuclei**

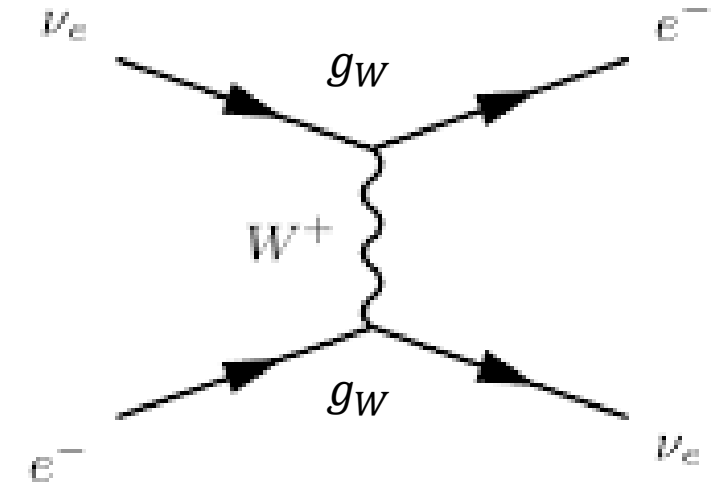
### Gravitational

**Graviton ?**

**Solar system**  
**Galaxies**  
**Black holes**

# Known forces

Force	Strength	Bosons	Spin	$m/\text{GeV}$	
Strong	1	8 gluons	g	1	0
Electromagnetic	$10^{-3}$	Photon	$\gamma$	1	0
Weak	$10^{-8}$	W boson	$W^\pm$	1	80.4
		Z boson	Z	1	91.2
Gravitational	$10^{-37}$	Graviton?	G	2	0



**Note:** interaction strength only indicative – it depends on the considered distance and energy scales

- Strength of the fundamental interaction represented by the charge  $g$
- Related to the **dimensionless** coupling “constant”  $\alpha$ , e.g. QED
  - In SI  $g_{em} = e = \sqrt{4\pi\alpha\epsilon_0\hbar c}$
  - In natural units:  $g_{em} = \sqrt{4\pi\alpha}$
- Convenient to express couplings in terms of  $\alpha$ 
  - $\alpha$  is dimensionless and does not depend on the system of units (not true for the numerical value of  $e$ )

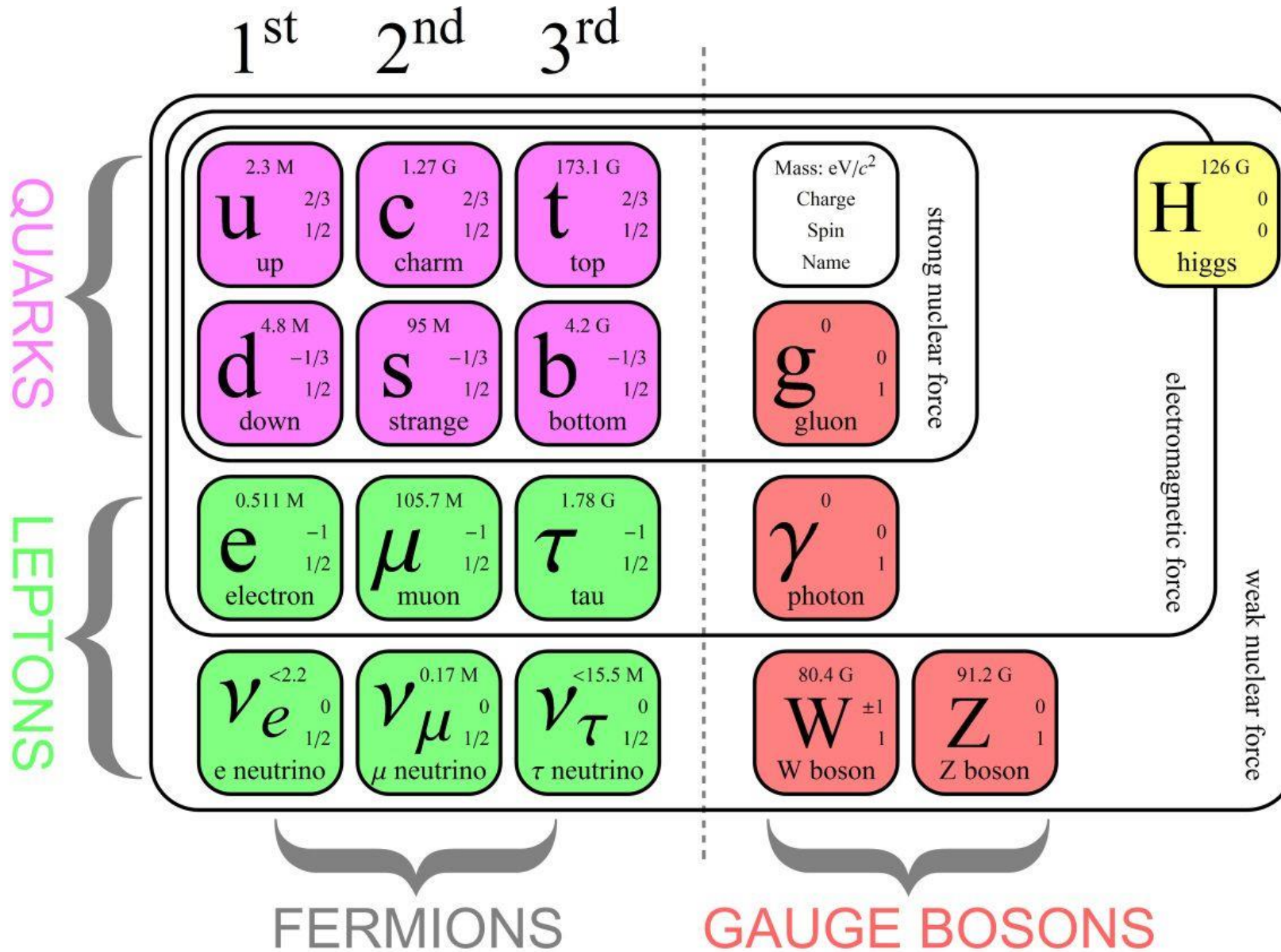
# The Higgs boson

- Final element of the Standard Model of particle physics:  $m_H \approx 125\text{GeV}/c^2$  particle discovered in 2012 by the CMS in ATLAS collaborations at the LHC
- The Higgs boson is **different** from most fundamental particles in the Standard Model
  - **fermions**: particles with spin  $\frac{1}{2}$
  - **gauge bosons**: particles with spin 1
  - **Higgs boson**: **fundamental scalar particle with spin 0 (the only one discovered to date)**
- The Higgs boson provides a mechanism (non-zero Higgs field) by which all fundamental particles acquire mass
- **Note**: proton and neutron masses are largely due to binding energy (don't directly come from the Higgs boson)

# The Standard Model (SM)

- The Standard Model (SM) of particle physics describes three of the four known fundamental forces in the universe and classifies all known elementary particles
  - Theory combining **quantum mechanics** and **special relativity**  $\Rightarrow$  **relativistic quantum field theory**
  - **19 free parameters** related to quarks, charged leptons, and gauge bosons (26 if we include  $\nu$  masses/mixing parameters)
  - Global Poincare symmetry (translation, rotation, change of reference frame from special relativity)
  - Local  $SU(3) \times SU(2) \times U(1)$  gauge symmetry  $\Rightarrow$  **gives rise to the strong, electromagnetic, and weak interactions**
- Many indications that the SM is not the final theory: still many **mysteries** and **open questions** left unanswered
- The SM does not describe gravitational interactions
  - Negligible on atomic and sub-atomic length scales ( $10^{-10} - 10^{-18}$  m)
  - Relevant close to the Planck scale:  $l_P = \frac{\sqrt{\hbar G}}{c^3} \approx 10^{-35}$  m (far away from current experimental sensitivity)

# The Standard Model (SM)



# Elementary particles and their interactions

electric charge:

0

-1

-1/3

2/3

First generation

$\nu_e$

$e^-$

d

u

Second generation

$\nu_\mu$

$\mu^-$

s

c

Third generation

$\nu_\tau$

$\tau^-$

b

t

**H:**  
**Higgs**

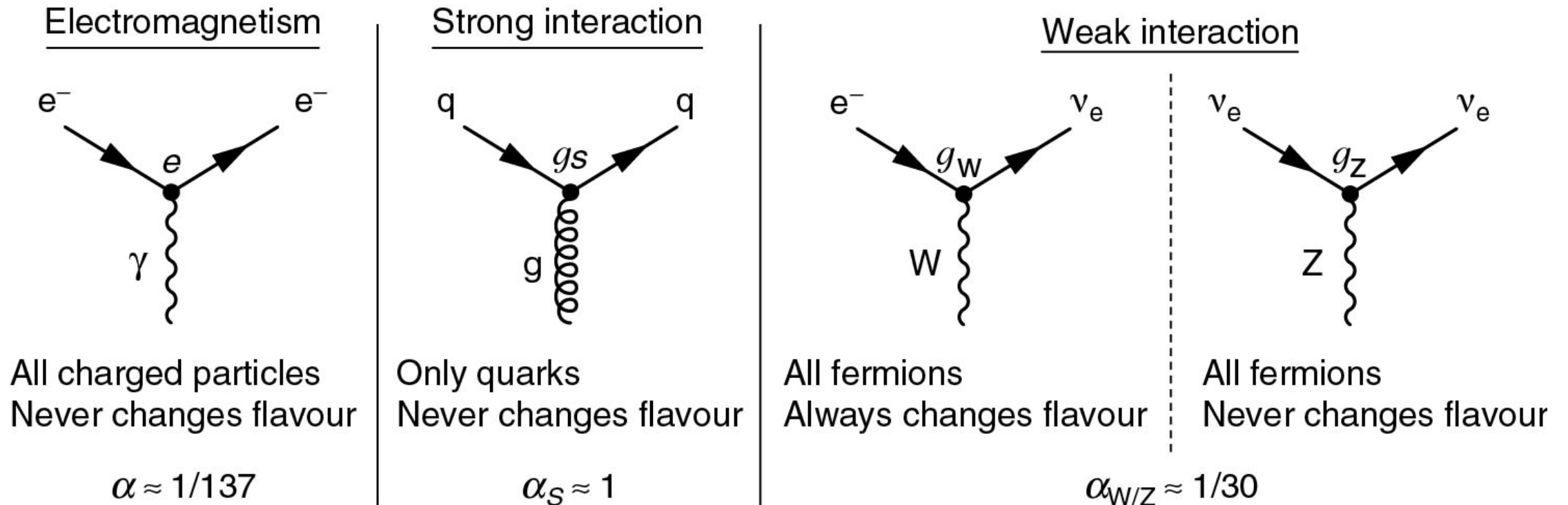
**$W^\pm, Z$ :**  
**weak**

**$\gamma$ :**  
**electromagnetic**

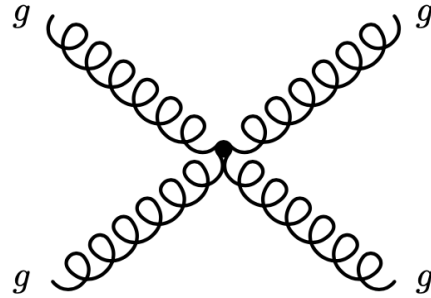
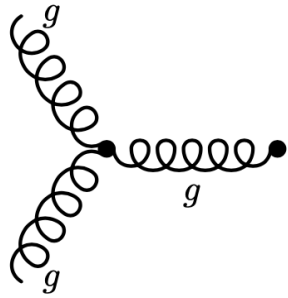
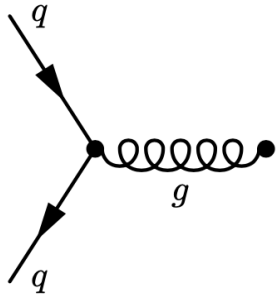
**g:**  
**strong**

# Standard Model vertices

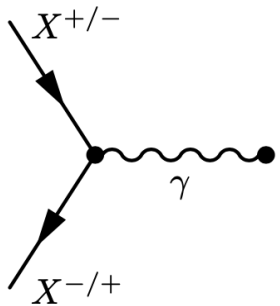
- The coupling of the force-carrying gauge bosons to the fermions is represented by the SM interaction vertices
- Three-point vertex of the gauge boson and an incoming and outgoing fermion
- A particle couples to a force-carrying gauge boson only if it carries the charge of the interaction



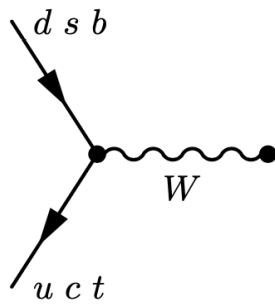
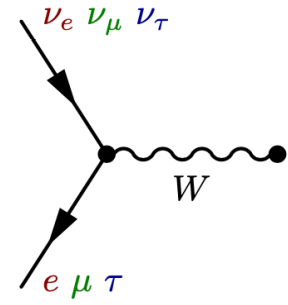
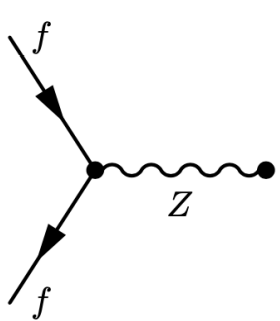
# All Standard Model vertices



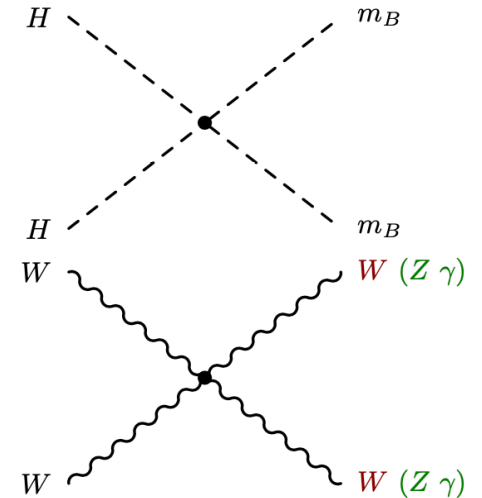
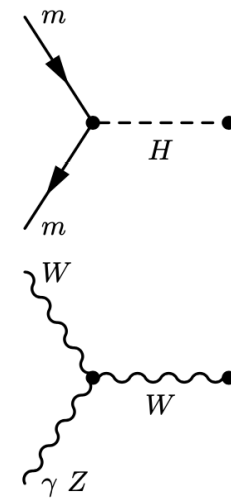
**strong interaction**



**EM interaction**



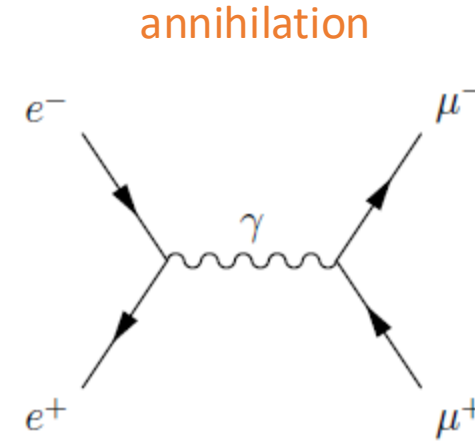
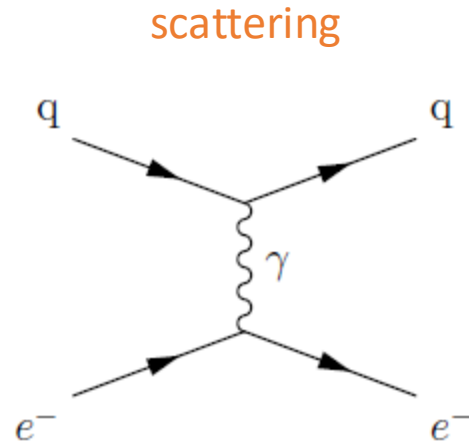
**weak interaction**



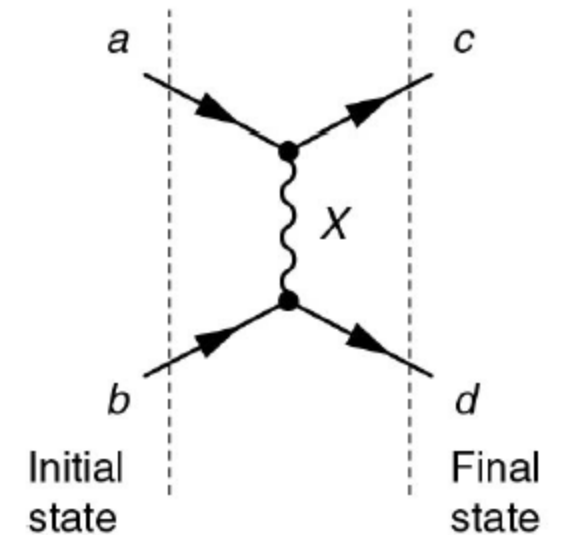
**Higgs, EWK**

# Feynman diagrams

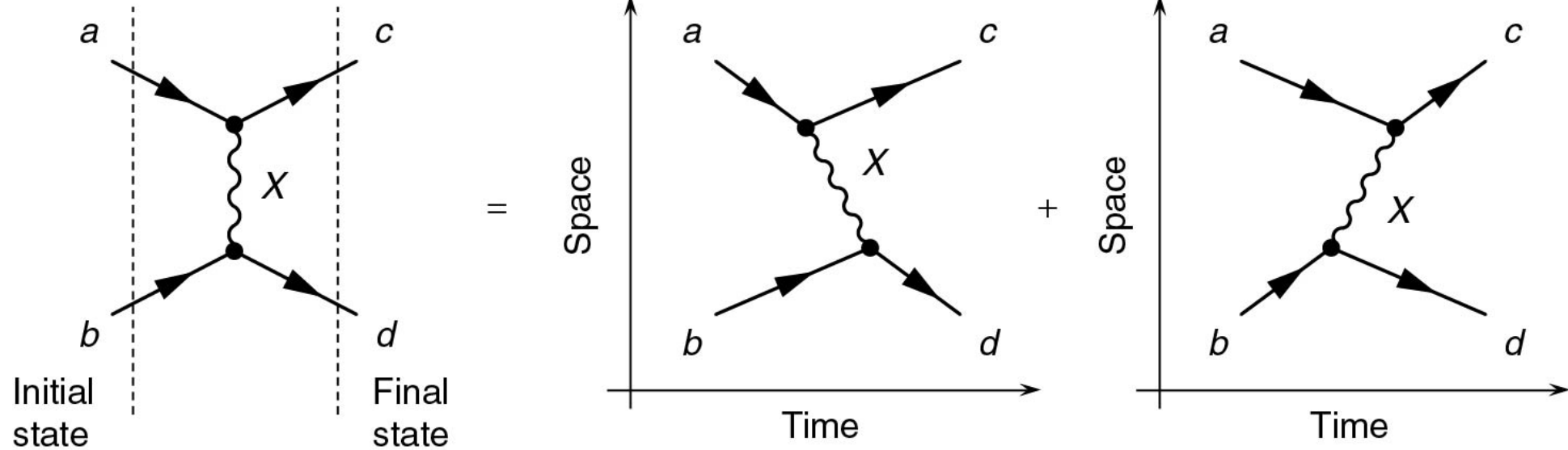
- Particle interactions can be represented as Feynman diagrams:



- “Time” in the diagrams runs from left to right only in a sense that
  - Left-hand side of the diagram represents the **initial state**
  - Right-hand side of the diagram represents the **final state**
  - Central part shows the **particles exchanged** and the **SM vertices involved**
- Negative “time” arrow corresponds to anti-particles
- Energy, (angular) momentum, etc. **conserved at all interaction vertices**
- All intermediate particles are “virtual” :  $E^2 \neq p^2 + m^2$



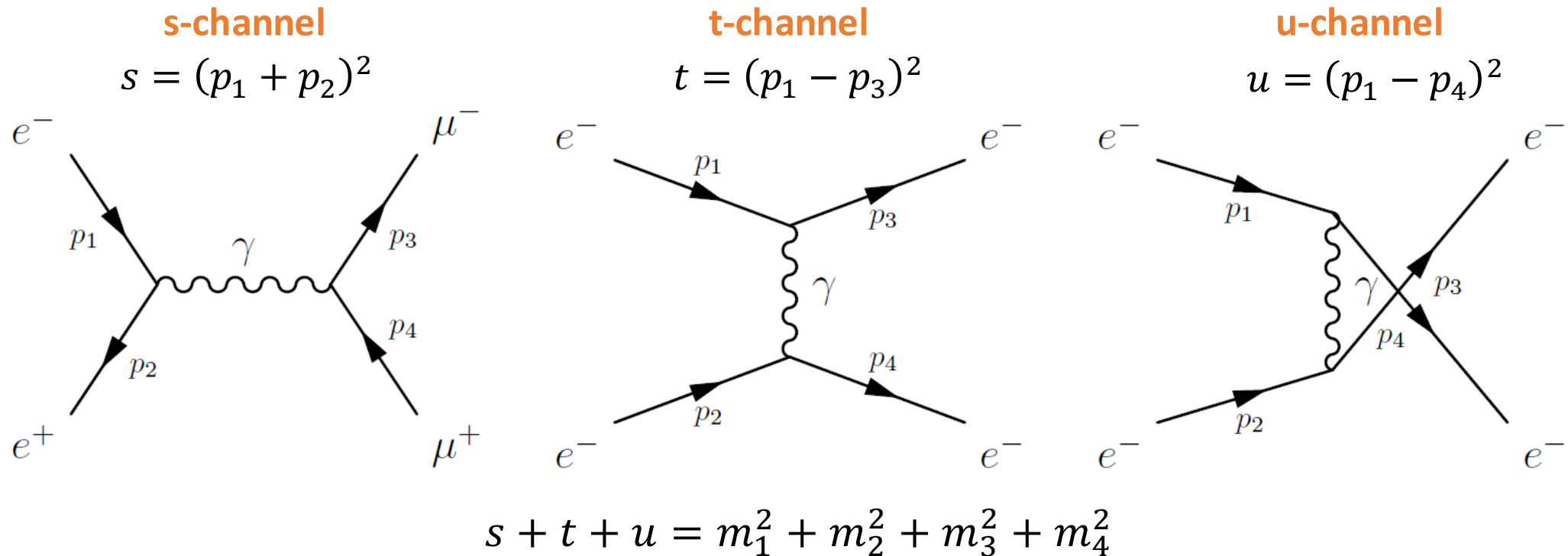
# Feynman diagrams



- Generic Feynman diagrams much more than pictorial representation of the fundamental physics underlying a process
  - represents the sum of the quantum-mechanical amplitudes for all possible time orderings (we can only observe initial and final states)
- Once the Feynman diagram is drawn, it is straightforward to write down the transition matrix element using the relevant Feynman rules  $\Rightarrow$  avoid the need to calculate each process from first principles in Quantum Field Theory
- In principle, for each process considered there will be infinite number of diagrams
  - We will concern ourselves only with the simple (lowest order) Feynman diagrams for a given process – higher order diagrams are suppressed by higher orders of the coupling constants involved in the interaction

# Mandelstam variables $s$ , $t$ , and $u$

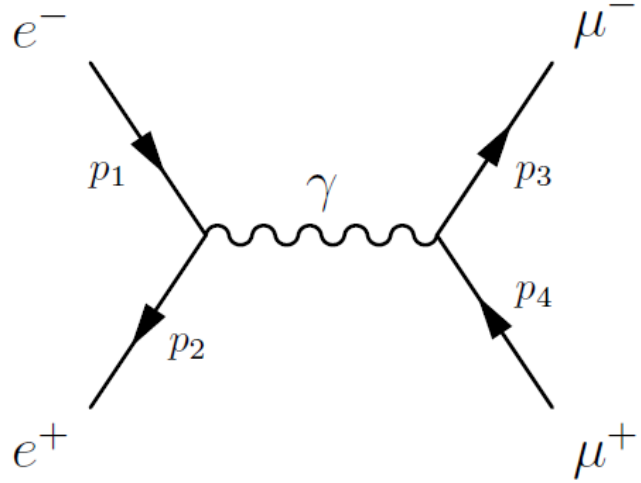
- In particle scattering/annihilation there are three particularly useful **Lorentz-invariant** quantities:  **$s$** ,  **$t$** , and  **$u$**
- Consider a scattering process  $1 + 2 \rightarrow 3 + 4$
- (Simple) Feynman diagrams can be categorized according to the four-momenta of the exchanged particles



**Note:** u-channel diagram only if the final state particles are indistinguishable

# Example: Mandelstam s

- Centre-of-mass energy  $s$ :



$$s = (p_1 + p_2)^2 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2$$

- A scalar vector product of two four-vectors  $\Rightarrow$  Lorentz-Invariant quantity  $\Rightarrow$  valid for any frame of reference
- Choose the most convenient (center-of-mass) frame:  $p_1 = (E_1, \vec{p}), p_2 = (E_2, -\vec{p}) \Rightarrow s = (E_1 + E_2)^2$
- $\sqrt{s}$  is the total collision energy in the centre-of-mass frame

# From Feynman diagrams to physics

- Particles physics involves the building of theories of fundamental particles and their interactions and testing their predictions against experimental data
  - dealing with fundamental particles and make precise theoretical predictions – not complicated by dealing with many-body systems
  - many beautiful experimental measurements: **precise theoretical predictions challenged by precise measurements**
  - For all its flaws, the SM describes “all” experimental data  $\Rightarrow$  one of the most remarkable achievements of the 20<sup>th</sup> century
- Requires understanding of both theory and experimental data
  - first part of the course: Feynman diagrams mainly used to describe how particles interact
  - second part of the course: use Feynman diagrams and their associated rules to perform calculations of some processes

# Summary of first lecture

## Main learning outcomes

- What is the scope of particle physics
- What are the fundamental matter particles, how they interact, and which bosons are mediate their interactions
- How to describe particle kinematics
- How to describe particle interactions with Feynman diagrams