Particles and their interactions

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Content

- Units, scale and language
- Particles of the standard model, their properties
- Bosons and fermions
- Antiparticles
- Composed particles: hadrons
- Four interactions
- Long-lived and short-lived particles
- Interaction with matter

Lecture 3 (next lecture):

- Main processes: scattering and decays
- Amplitudes, cross sections and probabilities
- Feynman diagrams as graphical representation
- Basic kinematics
- Phase space

Bibliography

- Mark Thomson, “Modern particle physics” (2013)
- a detailed detector review in a book by Claus Grupen, Irène Buvat: “Handbook of Particle Detection and Imaging” (2012), https://link.springer.com/referencework/10.1007/978-3-642-13271-1 (available from the publisher for a free download)
- Particle data group http://pdg.lbl.gov/ and reviews therein:
  - https://pdg.lbl.gov/2020/reviews/contents_sports.html

Questions on the lecture

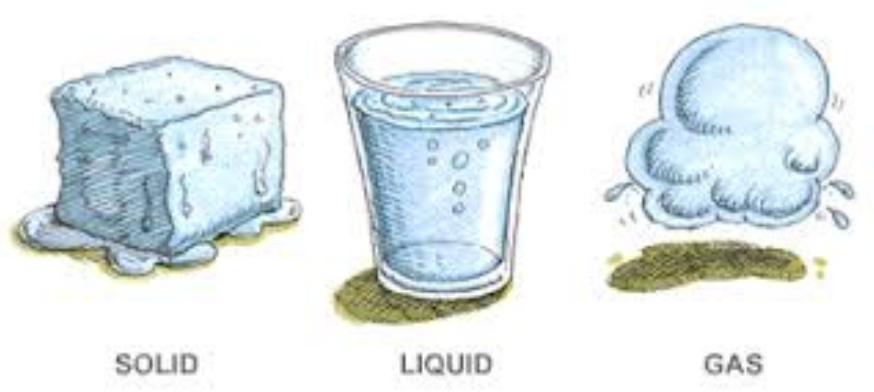
- After going through the material of the lecture, post at least one question through the anonymous google form:
  - https://forms.gle/WWFYYegapPcvm6po6
- We will go over the questions during the live lecture

Particle physics

- There are two basic questions in Particle Physics:
  - 1 What are the fundamental constituents of matter?
  - 2 What are the fundamental interactions between them?
- And there are many approaches and instruments to address these questions!

Elementary particle physics: Matter

What usually people imagine when hear *matter*:

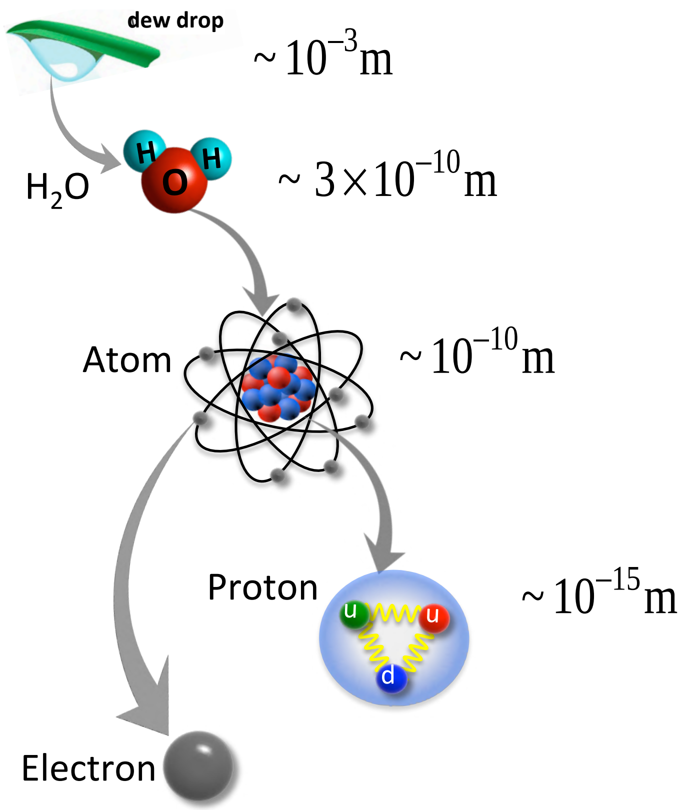


Fundamental constituents of ordinary matter:

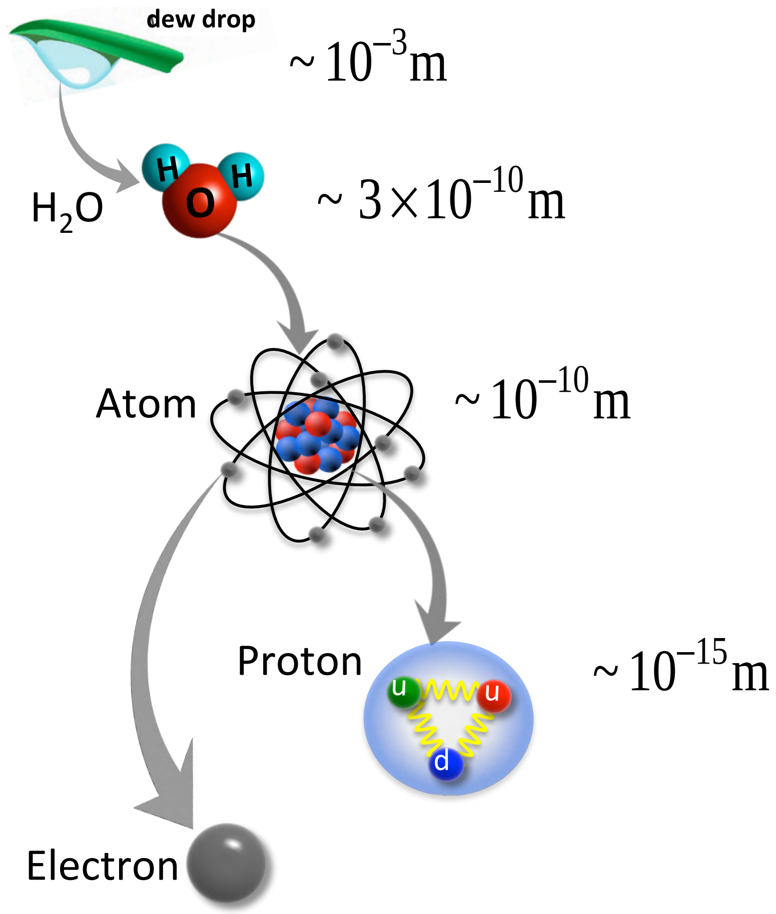
- leptons, e.g. *electron*
- quarks, e.g. *up-* and *down-quarks* making up protons and neutrons

Leptons and quarks together are called fermions

What matter is down to its constituents:



Characteristic scales in particle physics



To deal with particles need to go down several orders of magnitude in everything. E.g. for a proton:

- length (R) $\sim 10^{-15}$ m
- mass (m) $\sim 10^{-27}$ kg
- energy (mc^2) $\sim 10^{-10}$ J

The SI is not well suited at this level $\Rightarrow$

need to rescale our units.

Units in particle physics = Natural units

Or else called Planck units postulate:

- the speed of light in a vacuum $c = 1$
  - speed is measured in units of c: $v \to v/c$
  - m, p and E are measured in the same units: $eV = 1.6 \times 10^{-19}$ J
- the reduced Planck constant $\hbar = 1$:
  - $E = m = \lambda^{-1}$: heavier or more energetic objects have shorter wavelength
  - trick for easy conversion from MeV to m: $\hbar c \approx 200$ MeV· fm, where fm $= 10^{-15}$ m
- the Coulomb constant $\varepsilon_0 = 1$
  - fine structure constant is simply $\alpha = e^2/4\pi \approx 1/137$
- the gravitational constant $G = 1$
- the Boltzmann constant $k_B = 1$

Natural units: Summary

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

In reality, these conversions are rarely needed: we will use GeV throughout the course.

Correct unit dimensions to derive the numbers above:

Energy	GeV	Time	$(\mathrm{GeV}/\hbar)^{-1}$
Momentum	GeV/c	Length	$(\mathrm{GeV}/\hbar c)^{-1}$
Mass	GeV/c^2	Area	$(\mathrm{GeV}/\hbar c)^{-2}$

$c = 2.998 \times 10^8$ m/s

$\hbar = 1.055 \times 10^{-34}$ J s

Known matter

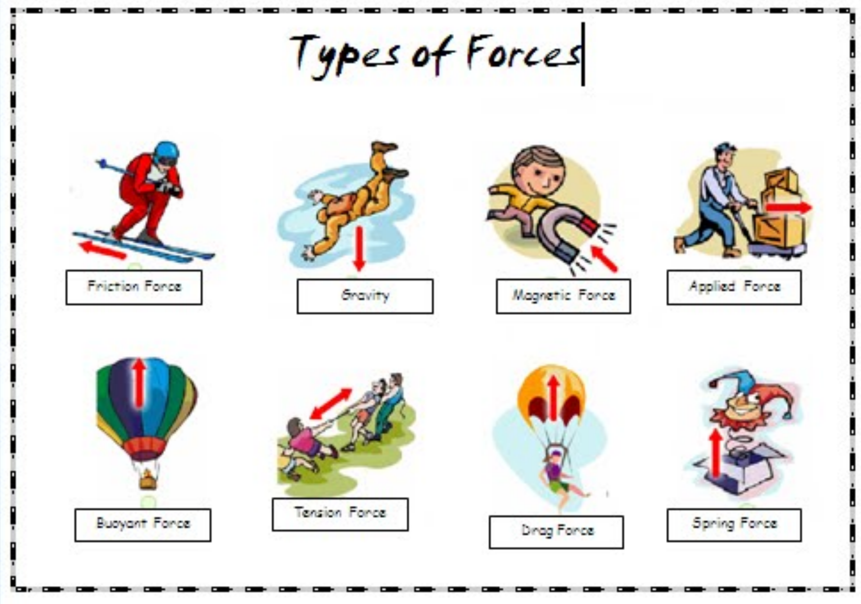
- the fundamental “matter” is described by point-like spin-1/2 fermions

	Leptons				Quarks			
	particle		Q	m/GeV	particle		Q	m/GeV
first generation	electron	e^-	-1	0.0005	down	d	-1/3	0.005
	neutrino	ν_1	0	$< 10^{-9}$	up	u	+2/3	0.003
second generation	muon	μ^-	-1	0.106	strange	s	-1/3	0.1
	neutrino	ν_2	0	$< 10^{-9}$	charm	c	+2/3	1.3
third generation	tau	τ^-	-1	1.78	bottom	b	-1/3	4.2
	neutrino	ν_3	0	$< 10^{-9}$	top	t	+2/3	173

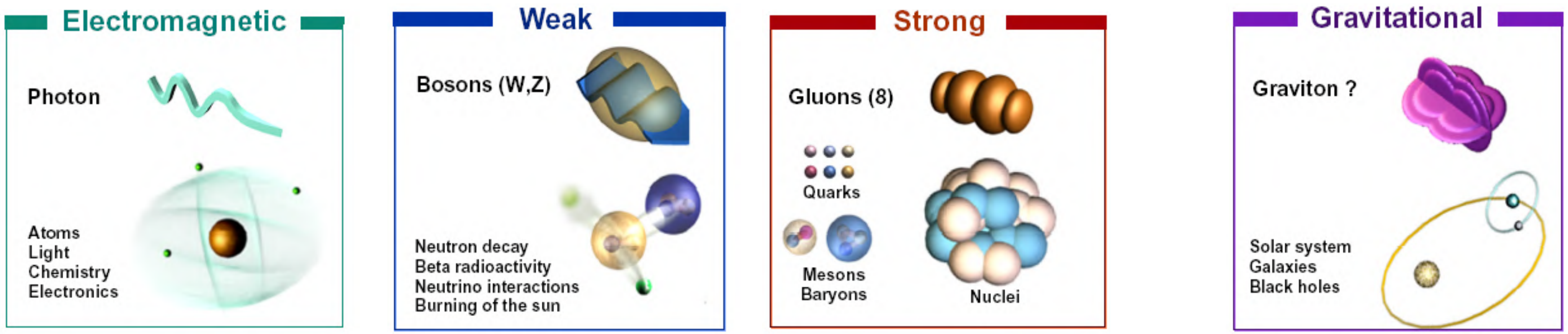
Known matter

- the fundamental “matter” is described by point-like spin-1/2 fermions
- there are three generations: the particles in each generation are copies of each other differing only in mass
  - we do not know why exactly 3
- the neutrinos are much lighter than all other particles (e.g. ν_1 has m < 2 eV): we now know that neutrinos have non-zero mass
  - don’t understand why so small

Elementary particle physics: Forces



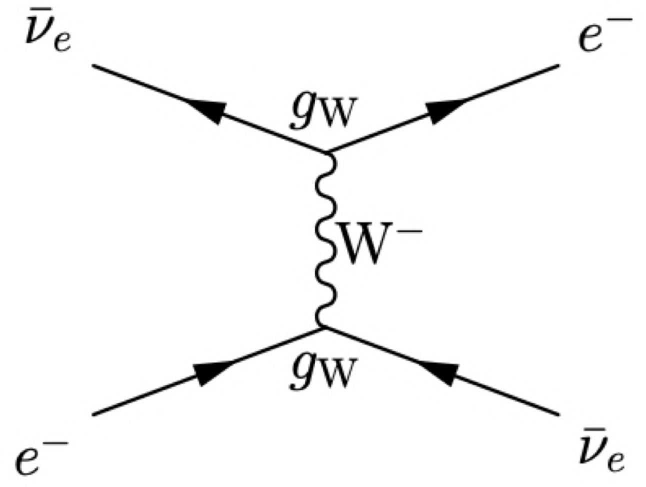
- there exist four fundamental interactions between the matter particles
- the forces are communicated to the matter particles by means of messenger particles – bosons



Known forces

- forces are mediated by the exchange of spin-1 gauge bosons

Force	Strength	Bosons		Spin	m/GeV
strong	1	8 gluons	g	1	0
electromagnetic	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



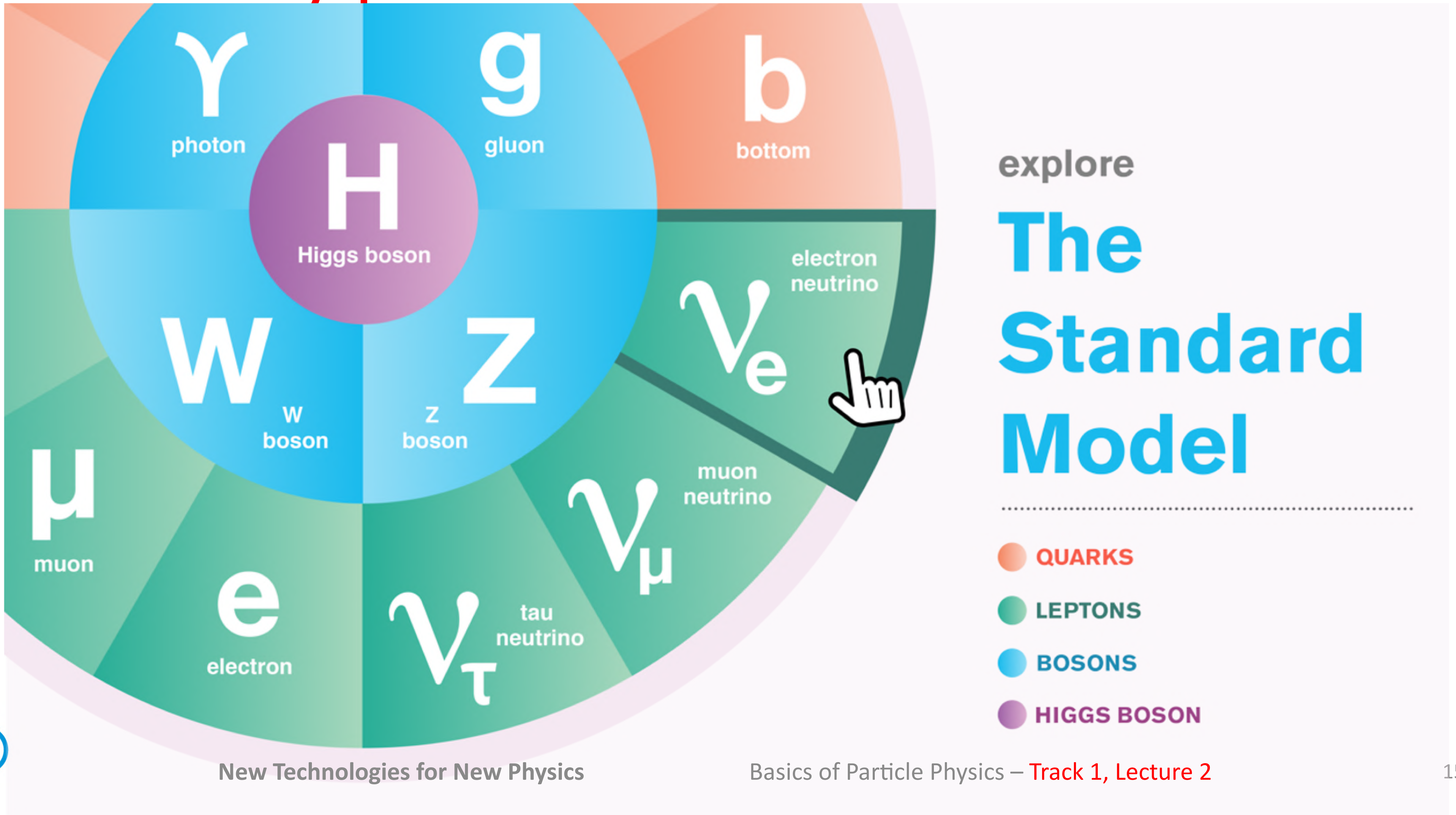
Known forces

- forces are mediated by the exchange of spin-1 gauge bosons
- fundamental interaction strength is given by charge g
- related to the **dimensionless** coupling "constant" α, e.g. QED:

$$\text{in SI } g_{em} = e = \sqrt{4\pi\alpha\epsilon_0\hbar c}$$
$$\text{in natural units: } g_{em} = \sqrt{4\pi\alpha}$$

- convenient to express couplings in terms of α which, being genuinely dimensionless, does not depend on the system of units (this is not true for the numerical value for e)

Elementary particles and forces



The standard model (SM)

The Standard Model (SM) of particle physics describes the fundamental laws of the Universe in terms of only a few input parameters

- Such a theory must include the two pillars of modern physics: (special) relativity and quantum mechanics

  $\Rightarrow$ relativistic quantum field theory

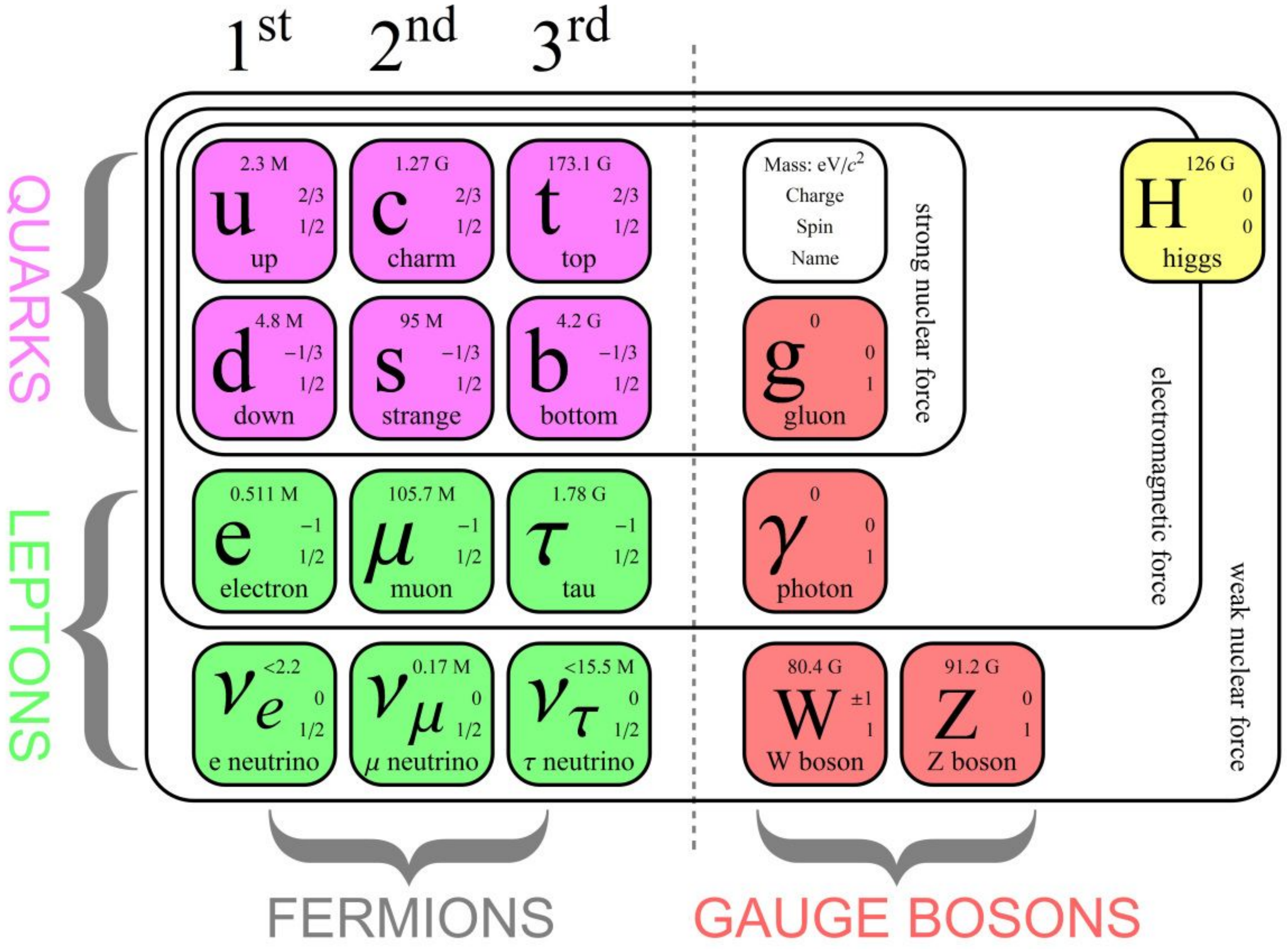
- (Local) gauge symmetries dictate the form of the fundamental interactions:

  $\Rightarrow$ $U(1)\times SU(2)\times SU(3)$ (works for 3 out of 4 forces)

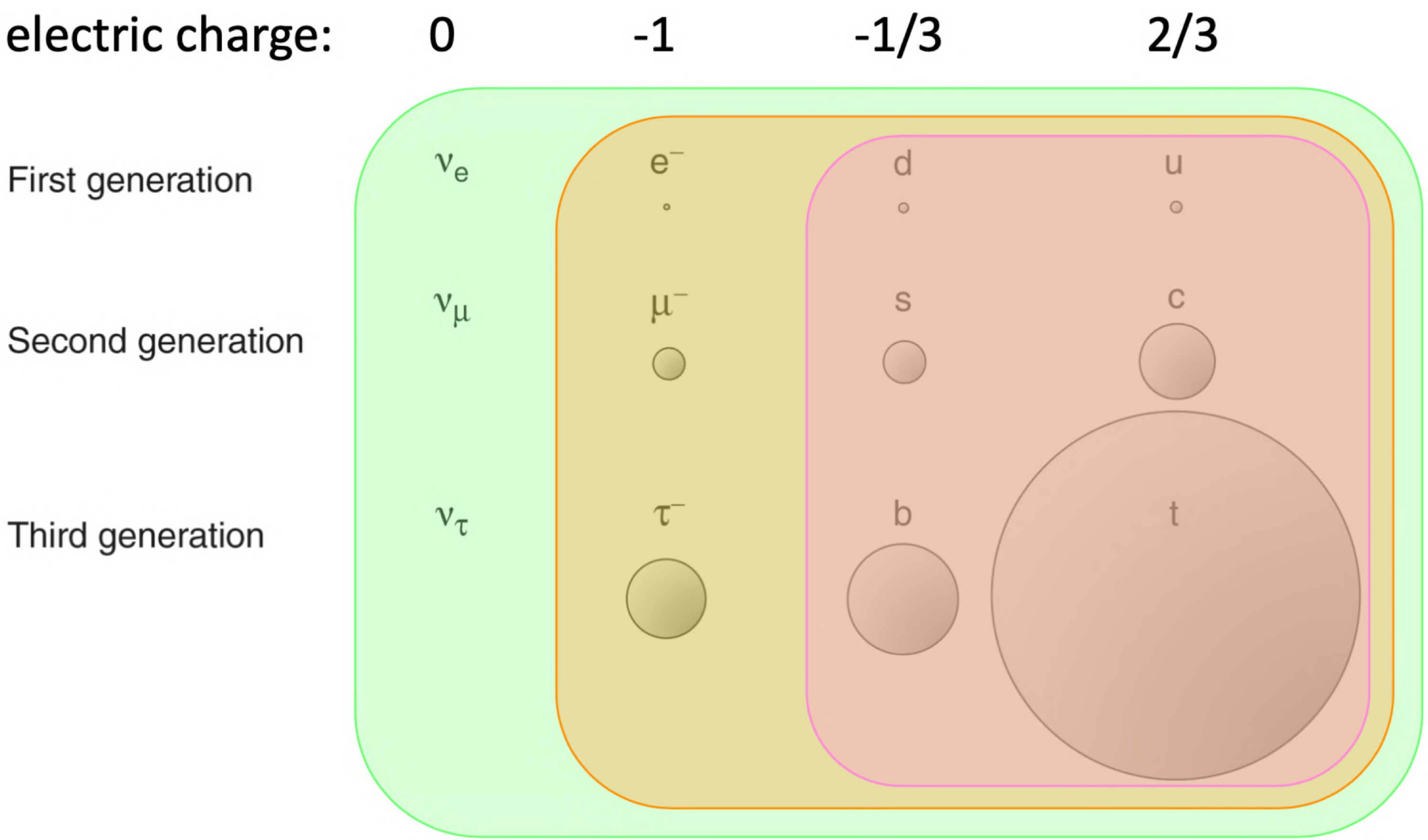
- but it is just a "model" with many unpredicted parameters, e.g. **particle masses**
- it is not the ultimate theory (if such a thing exists), there are many **mysteries**

The standard model (SM)

It took almost a century to build the standard model and to experimentally prove it is a closed self-consistent theory:



Elementary particles and acting on them forces:



H: **Higgs**

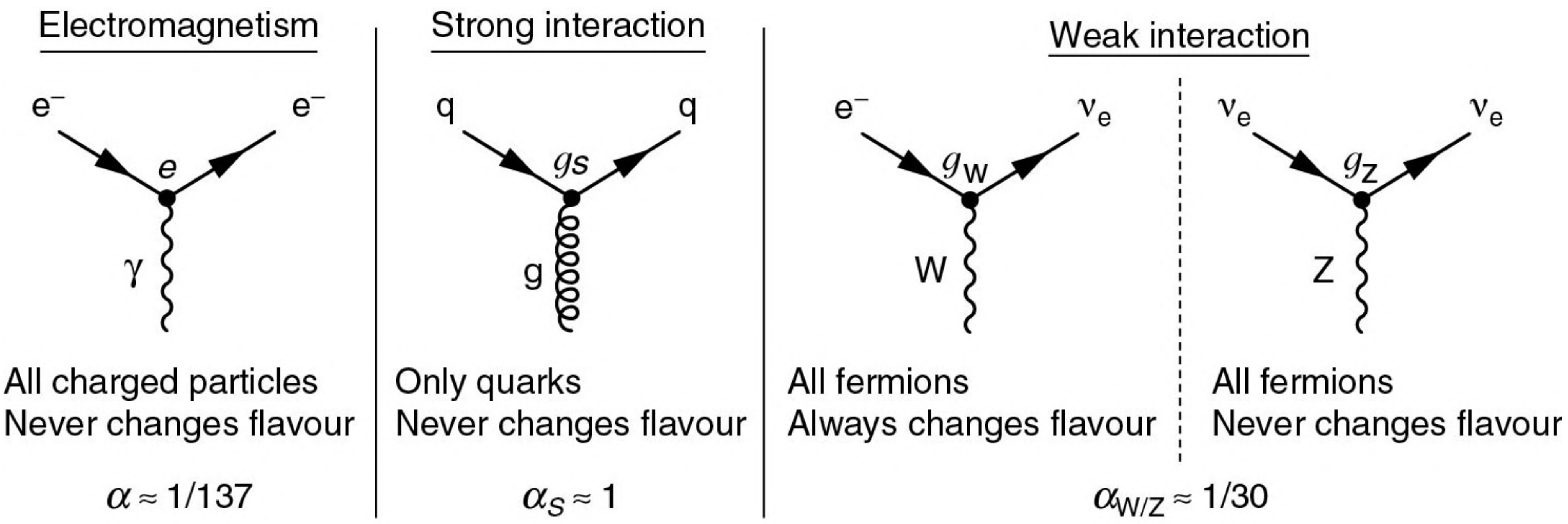
$W^{\pm}$, Z: **weak**

γ: **electromagnetic**

g: **strong**

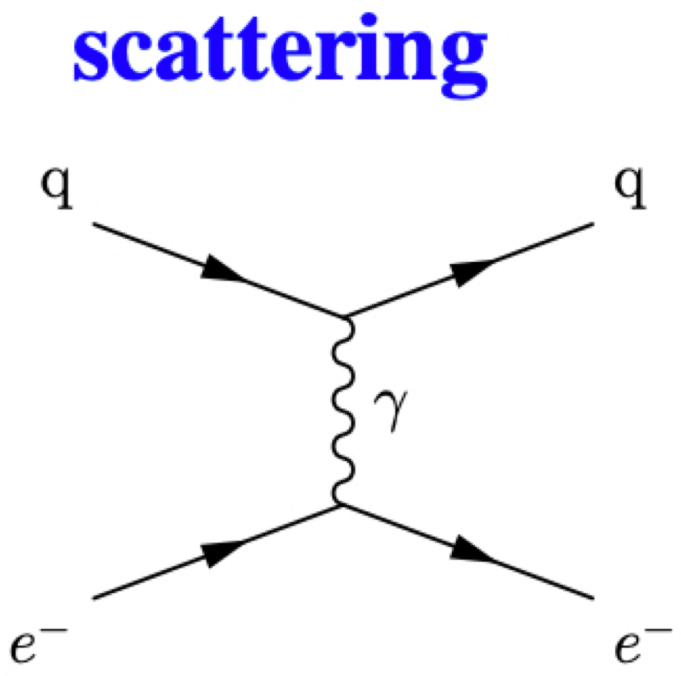
Standard model vertices

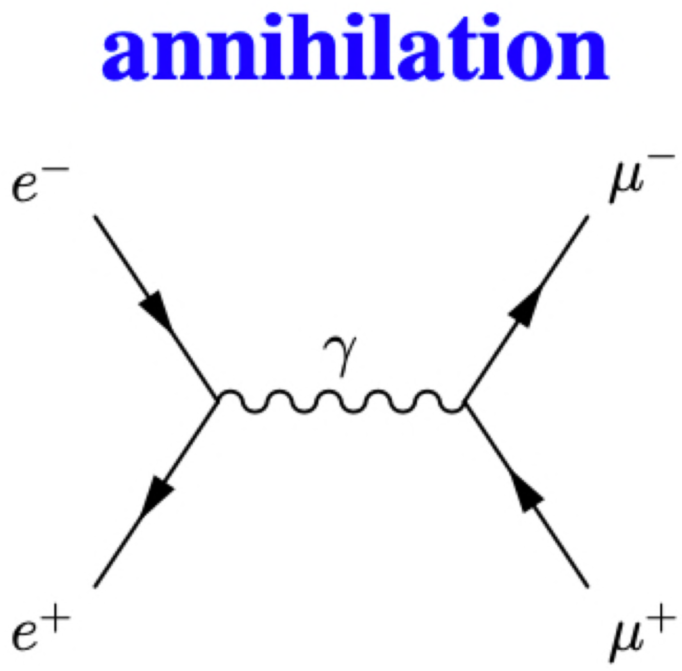
- interaction of gauge bosons with fermions described by SM vertices
- properties of the gauge bosons and nature of the interaction between the bosons and fermions determine the properties of the interaction



Feynman diagrams

Particle interactions can be described in terms of Feynman diagrams:

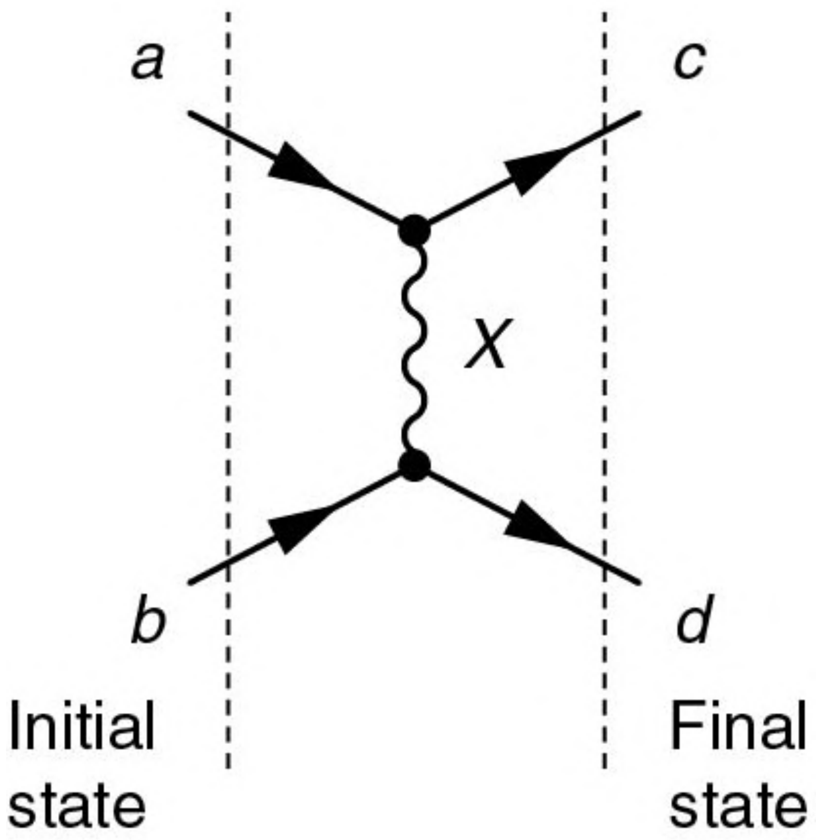




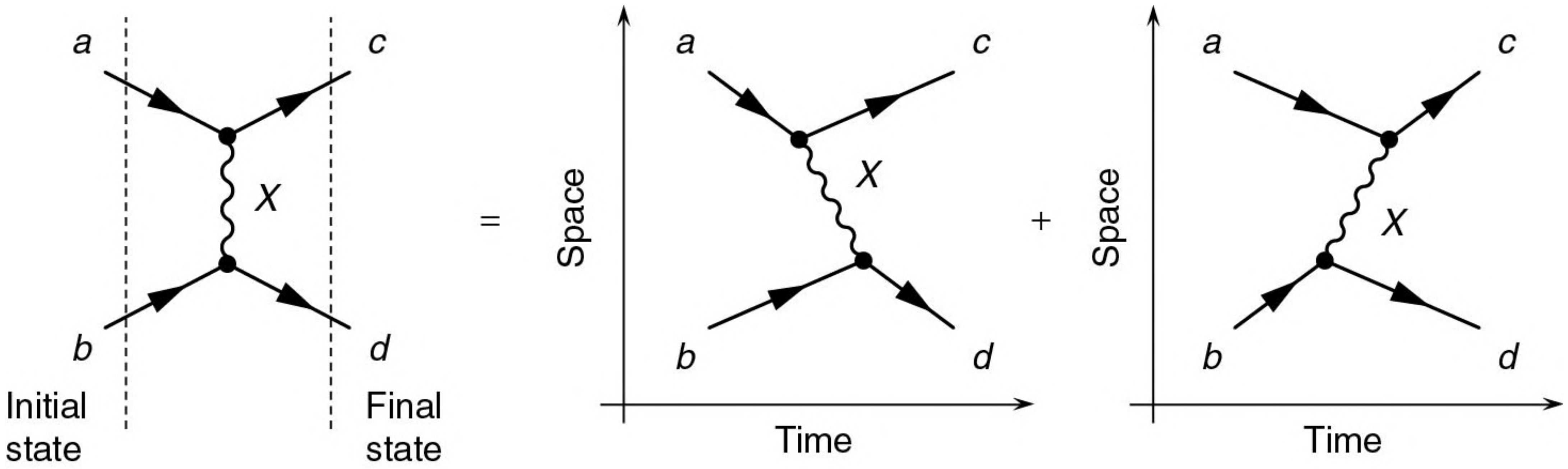
Feynman diagrams

- “time” runs from left – right, only in sense that:
  - LHS of diagram is initial state
  - RHS of diagram is final state
  - Middle is “how it happened”
- anti-particle arrows in –“time” direction
- energy, momentum, angular momentum, etc. conserved at all interaction vertices
- all intermediate particles are “virtual”, i.e.

$$E^2 \neq |\vec{p}|^2 + m^2$$



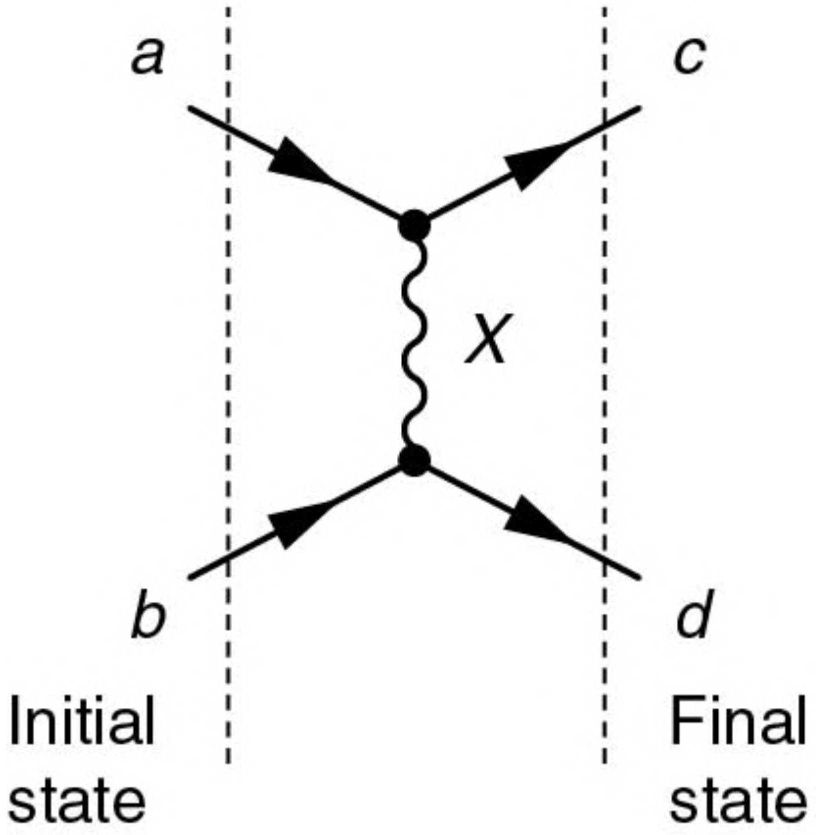
Feynman diagrams



- a generic Feynman diagram represents the sum of the quantum mechanical amplitudes for the two possible time-orderings

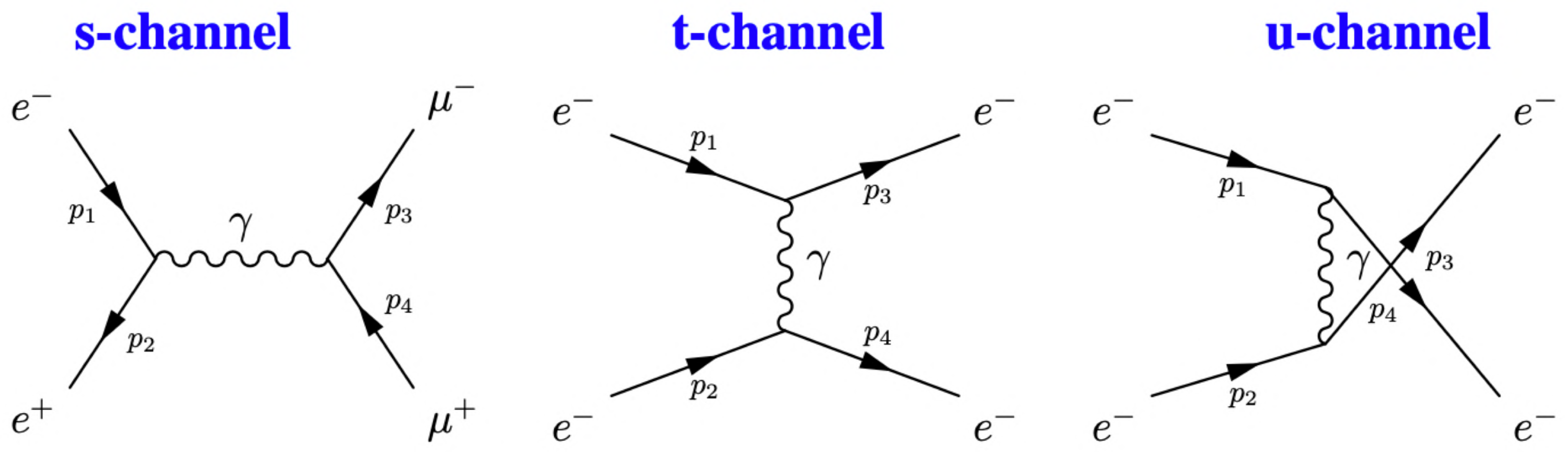
Feynman diagrams

- the central part of the Feynman diagram shows the particles exchanged and the SM vertices involved in the interaction, but not the order in which these processes occurred
- once the Feynman diagram has been drawn, it is straightforward to write down the quantum-mechanical transition matrix element using the relevant Feynman rules, thus avoiding the need to calculate each process from first principles in Quantum Field Theory



Mandelstam s, t, and u

- in particle scattering/annihilation there are three particularly useful Lorentz Invariant quantities: s, t and u
- consider the scattering process 1 + 2 → 3 + 4
- (simple) Feynman diagrams can be categorized according to the four-momentum of the exchanged particle



Mandelstam s, t, and u

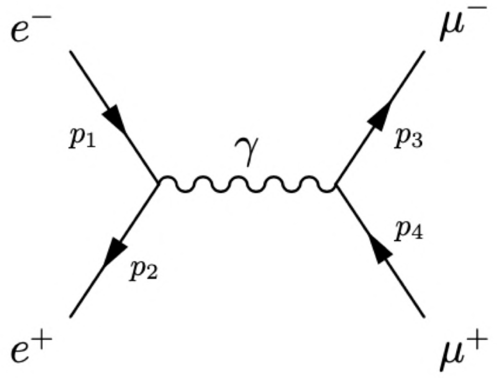
- can define three kinematic variables: s, t and u from the following four vector scalar products (squared 4-momentum of exchanged particle)

$$s = (p_1 + p_2)^2; t = (p_1 - p_3)^2; u = (p_1 - p_4)^2$$

$$\text{Note: } s + t + u = m_1^2 + m_2^2 + m_3^2 + m_4^2$$

E.g. Center-of-mass energy, s:

- this is a scalar product of two four-vectors ⇒ Lorentz Invariant
- since this is a L.I. quantity, can evaluate in any frame
- choose the most convenient, i.e. the center-of-mass frame:
  $p_1 = (E_1, \vec{p}), p_2 = (E_2, -\vec{p}) \Rightarrow s = (E_1 + E_2)^2$



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

- $\sqrt{s}$ is the total energy of collision in the center-of-mass frame

From Feynman diagrams to Physics

Particle Physics = Precision Physics

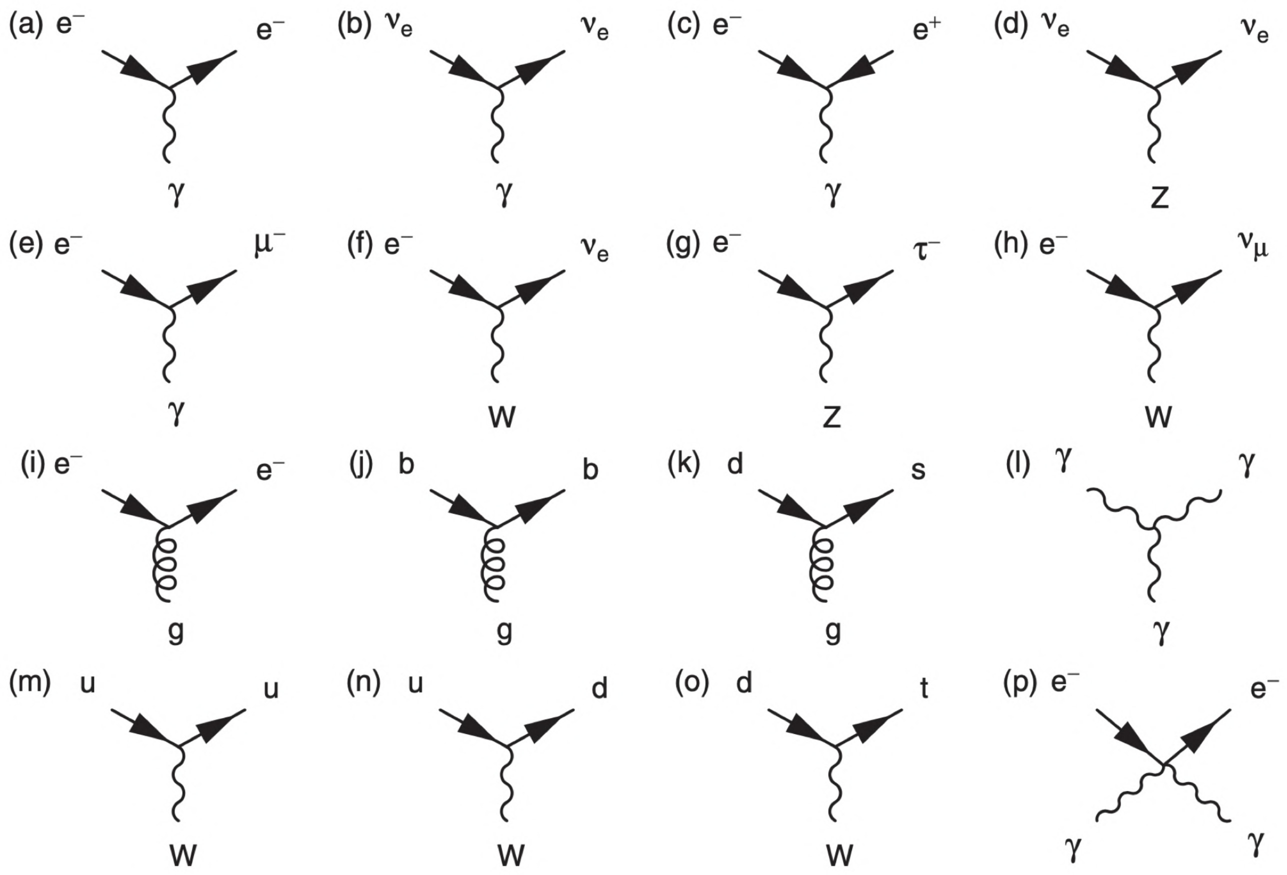
- particle physics is about building fundamental theories and testing their predictions against precise experimental data
  - dealing with fundamental particles and can make very precise theoretical predictions – not complicated by dealing with many-body systems
  - many beautiful experimental measurements ⇒ precise theoretical predictions challenged by precise measurements
  - for all its flaws, the standard model describes all experimental data!
  - This is a (the?) remarkable achievement of late 20th century physics

Requires understanding of theory and experimental data

- in this course, Feynman diagrams mainly used to describe how particles interact
- as an additional material, can show how to use Feynman diagrams and associated Feynman rules to perform calculations of some processes

Quiz

Which diagram represents a valid SM vertex:



Quiz

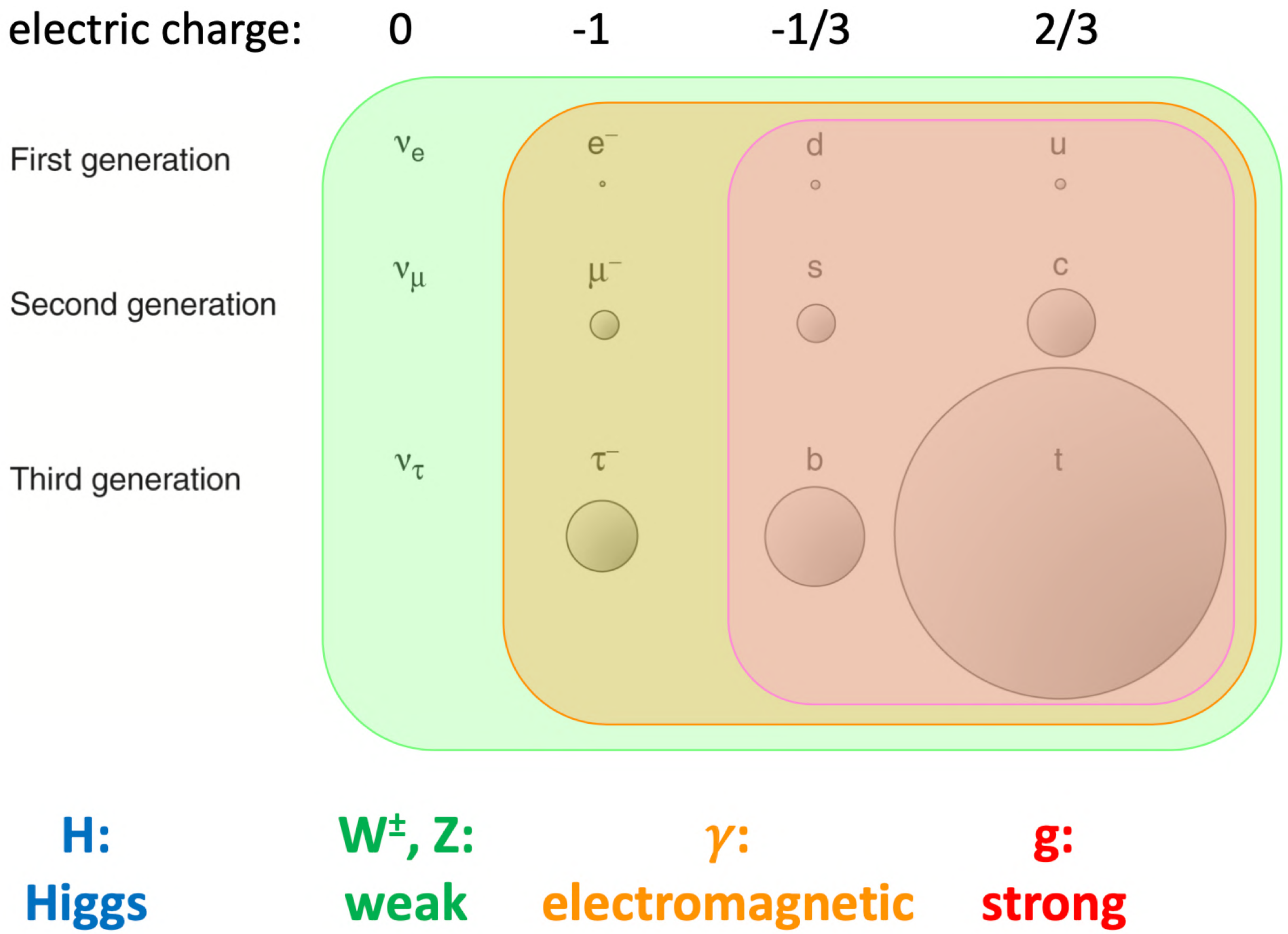
Draw possible Feynman diagrams for a given transition or interaction:

- $e^+e^- \longrightarrow \mu^+\mu^-$
- $\pi^+ \longrightarrow \mu^+\nu$
- $\pi^0 \longrightarrow \gamma\gamma$

Nonelementary particles

Elementary particles and forces

- Leptons (3 generations)
  - neutral/charged
  - e/μ/τ
- Quarks (3 generations)
  - charges of -1/3; 2/3
  - u/d/s/c/b/t
- Bosons (3 interactions + H)
  - W/Z, γ, g, and Higgs boson



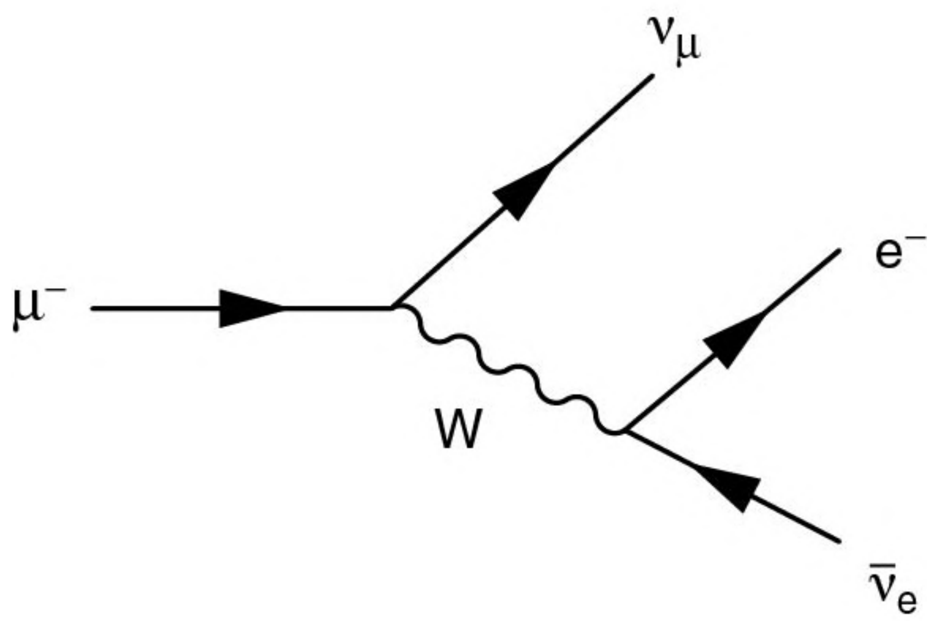
Elementary particles decays

- all decays of the elementary particles go via weak charged current ($W^{\pm}$):
  - this is the only interaction which can change **flavor**
- for a decay to occur, there should be particles with lower mass (energy conservation)
- electron is the lightest charged particle ⇒ nothing to decay to ⇒ electron is stable
- also neutrinos are stable

Elementary particles decays: example

- example of a muon decay

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

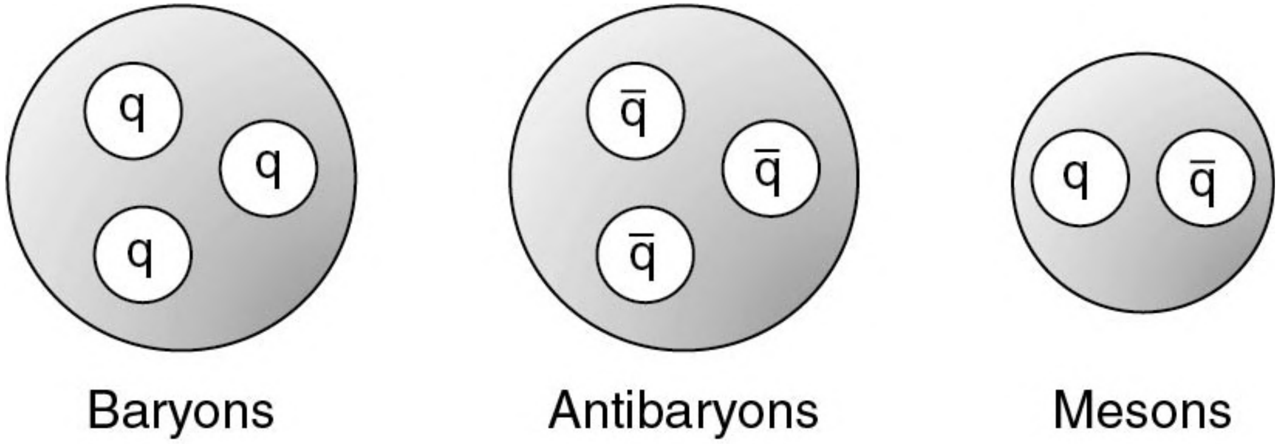


- note an antiparticle $\bar{\nu}_e$ in the decay: to conserve lepton number

Nonelementary particles

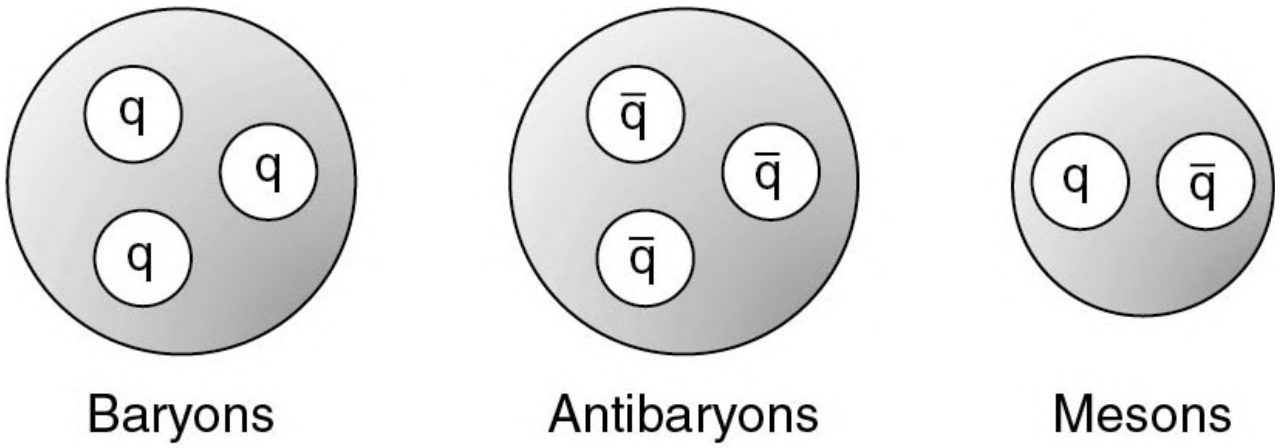
Quarks form bound states - hadrons - thanks to the strong force:

- **baryons** half-integer spin: three quarks (qq′q″, e.g. p, n, Δ), pentaquarks (also referred to as *exotic baryons*)
- **mesons** integer spin: quark-antiquark pair ($q\bar{q}'$, e.g. π, ρ, K, B), tetraquarks (also referred to as *exotic mesons*)



Nonelementary particles

- quarks are *fermions* ⇒ they cannot have identical quantum numbers in a baryon, i.e. should quark flavors be always different in a baryon?
- but baryons out of 3 identical quarks exist ⇒ there is another quantum number: **color** which is changed by strong interaction during a gluon emission



Lightest hadrons examples

- **proton and neutron**: $|p\rangle = |uud\rangle$ and $|n\rangle = |udd\rangle$
  - proton is stable: a baryon number conservation in the SM
  - neutron (and other baryons) decay down to a proton:

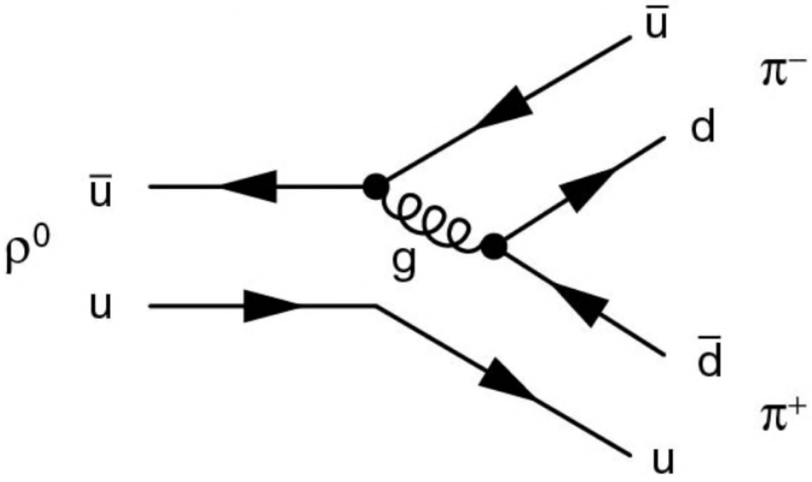
  $n \to p e^- \bar{\nu}_e$, where weak transition $d \to u e^- \bar{\nu}_e$ is an underlying process

- **pions** $\pi^{\pm}, \pi^{+}$: $|\pi^+\rangle = |u\bar{d}\rangle, |\pi^-\rangle = |\bar{u}d\rangle, |\pi^0\rangle = \frac{1}{\sqrt{2}}|u\bar{u} - d\bar{d}\rangle$
  - $\pi^+ \to \mu^+ \nu_\mu$ - dominating decay mode (quark annihilation into W)
  - $\pi^0 \to \gamma\gamma$ - electromagnetic process

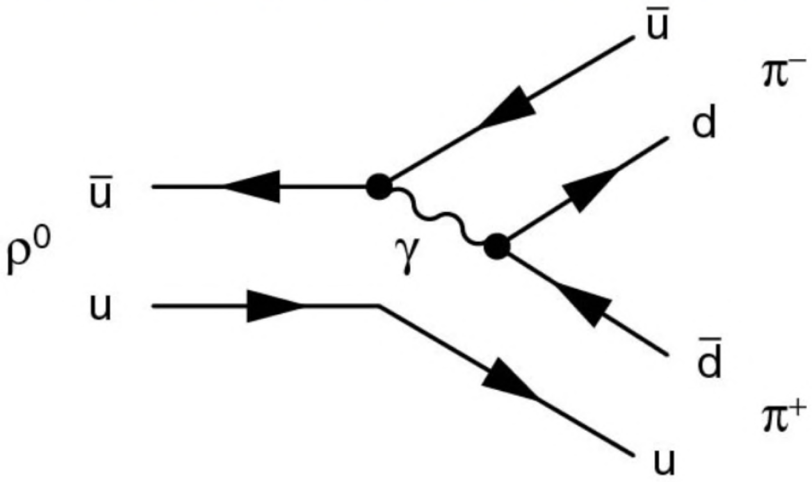
Nonelementary particles decays

- numerous decay modes are possible (see in the PDG)
- their relative strength depends on a process a decay goes through:

via strong interaction $\propto \alpha_s^2$:



via electromagnetic interaction $\propto \alpha^2$:

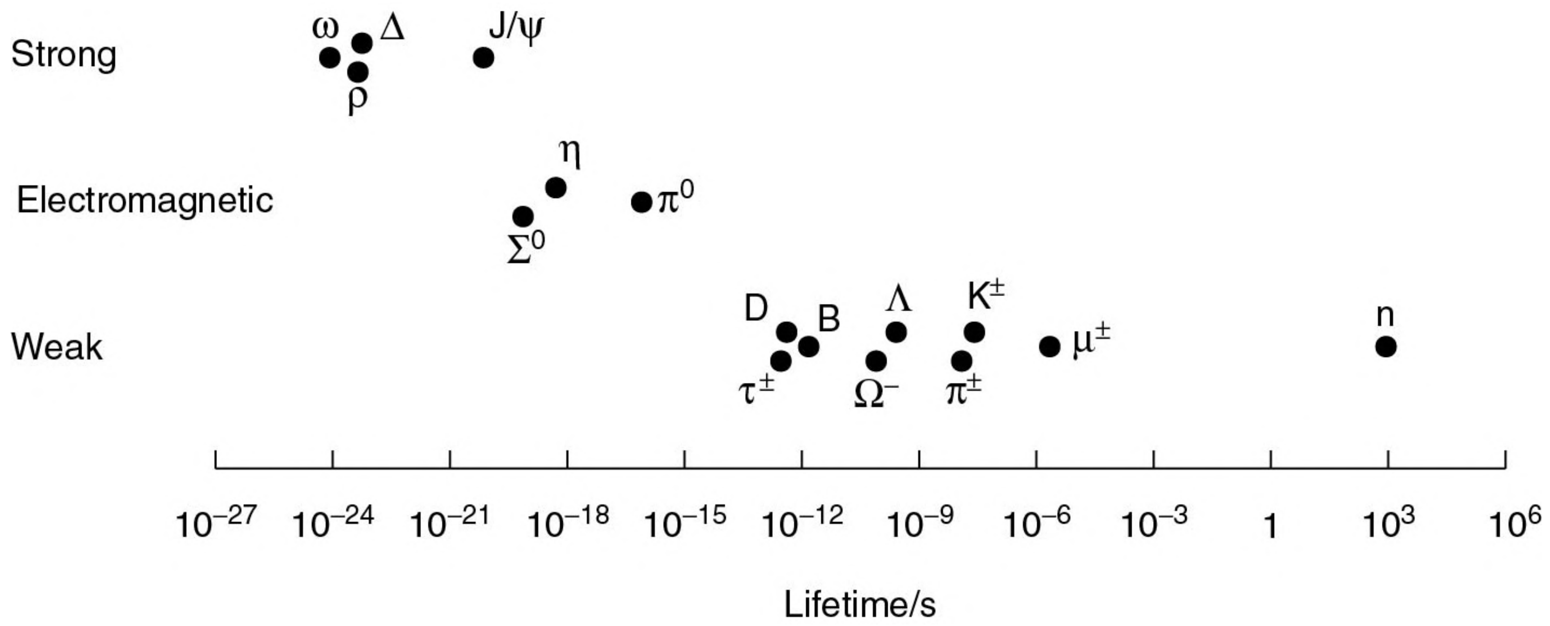


- as $\alpha \sim 1$ and $\alpha \sim 10^{-2}$, decays via strong interaction dominates
- in the same way, decays via EM interaction dominate over the weak one

Particle lifetime

Order of magnitude of a particle lifetime depends on the processes available for a decay, e.g.:

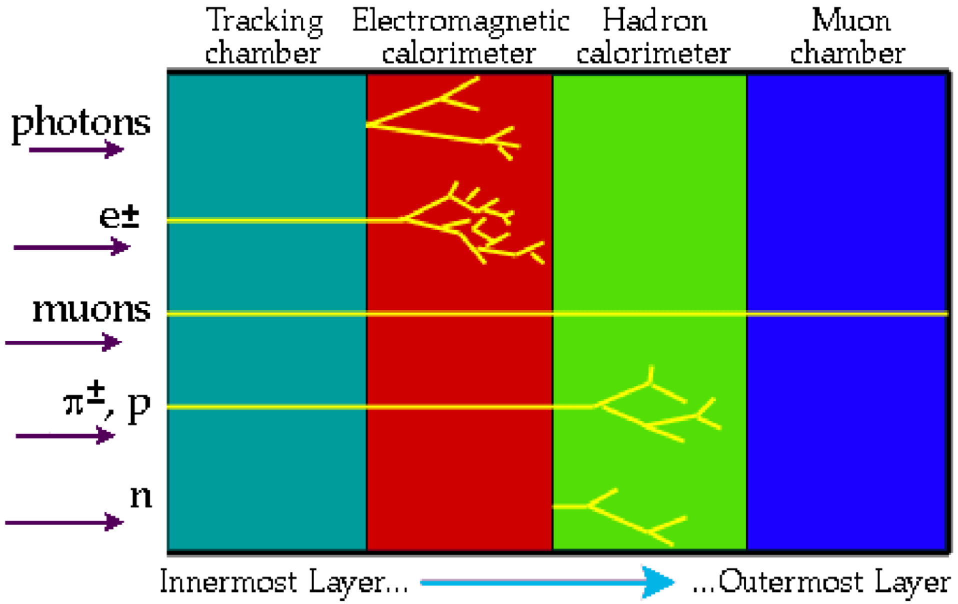
- $\pi^{\pm}$ and n decay only via a **weak** interaction ⇒ large lifetimes, long-lived
- π^{0} decays **electromagnetically** ⇒ an intermediate lifetime
- ρ can decay via a **strong** interaction ⇒ a very short lifetime, short-lived



Particle properties measurement

To understand an underlying process need to be able to determine properties of particles in a considered event:

- most of the particles decay shortly after production
- particles which are seen in the detectors are: photons, electrons, muons, pions, kaons, neutral hadrons



Complex particle detectors combine information about each particle which allows to deduce the initial picture.

Particle properties measurement

To understand an underlying process need to be able to determine properties of particles in a considered event:

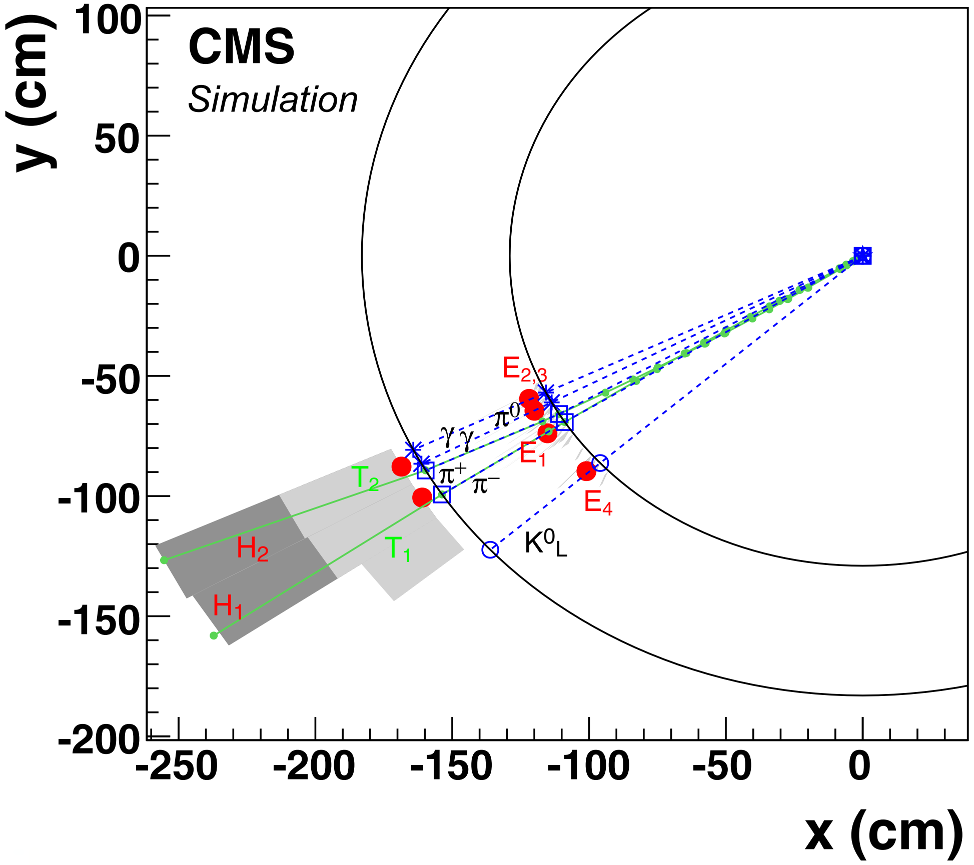
- need to detect these ones and use them to reconstruct mother particles

For this need a complete information on each particle in the event:

- its charge
- energy and momentum
- kind of particle (so-called *particle identification* or *PID*)
- point where the particle was produced (called *production vertex*) or decayed (*decay vertex*)
- what was the mother particle

When have the properties of all the “stable” particles in the detector, try to reconstruct an initial process in a collision.

Reconstruction with kinematics



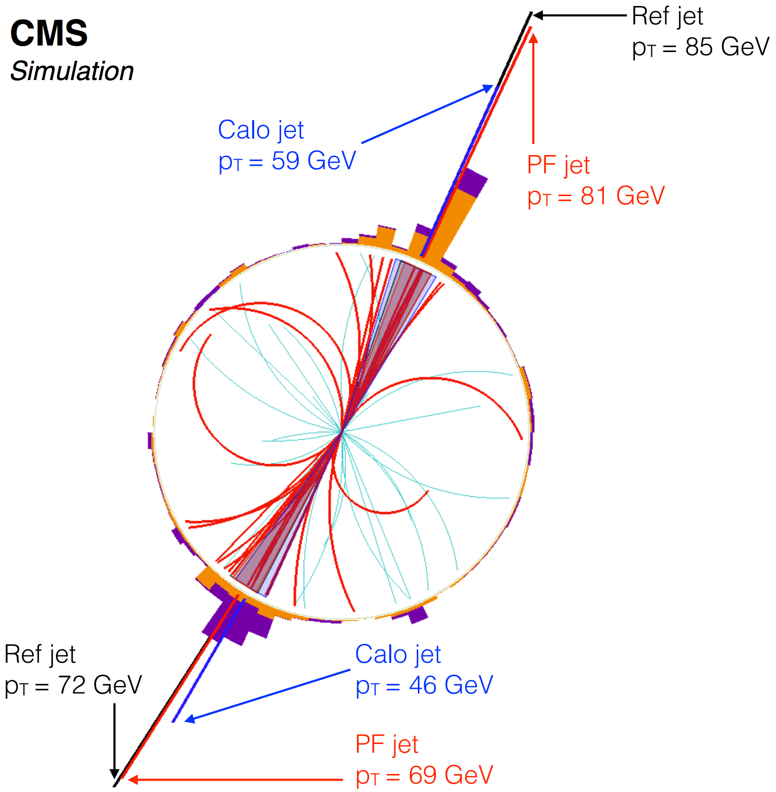
Deduce the properties of short-lived particles by kinematic reconstruction from the measured momenta and energies of their decay products:

- mass of the decayed particle

$$M^2 = \left(\sum E_i\right)^2 - \left|\sum \vec{p}_i\right|^2,$$

where the sum goes over all particle daughters *i*

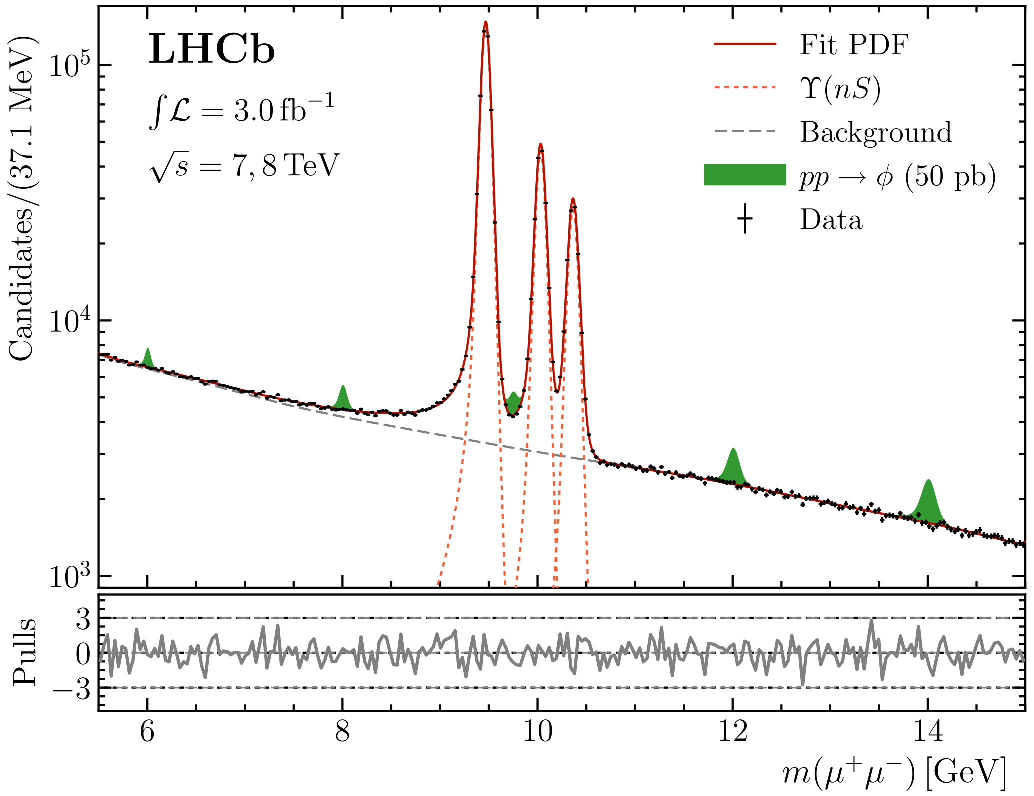
Reconstruction with kinematics



For this need to:

- either measure **both** energies **and** momenta of all particles: usually not possible or lacks precision
- or measure a combination: energy+mass or momentum+mass, where mass is inferred from the particle type ($e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, p, etc)

Example of particle properties measurement: dimuons



Decayed particle mass determination:

- measure the momenta of μ^+ and μ^-
- calculate muon energies

$$E_{\mu^\pm}^2 = m_\mu^2 + |\vec{p}_{\mu^\pm}|^2$$

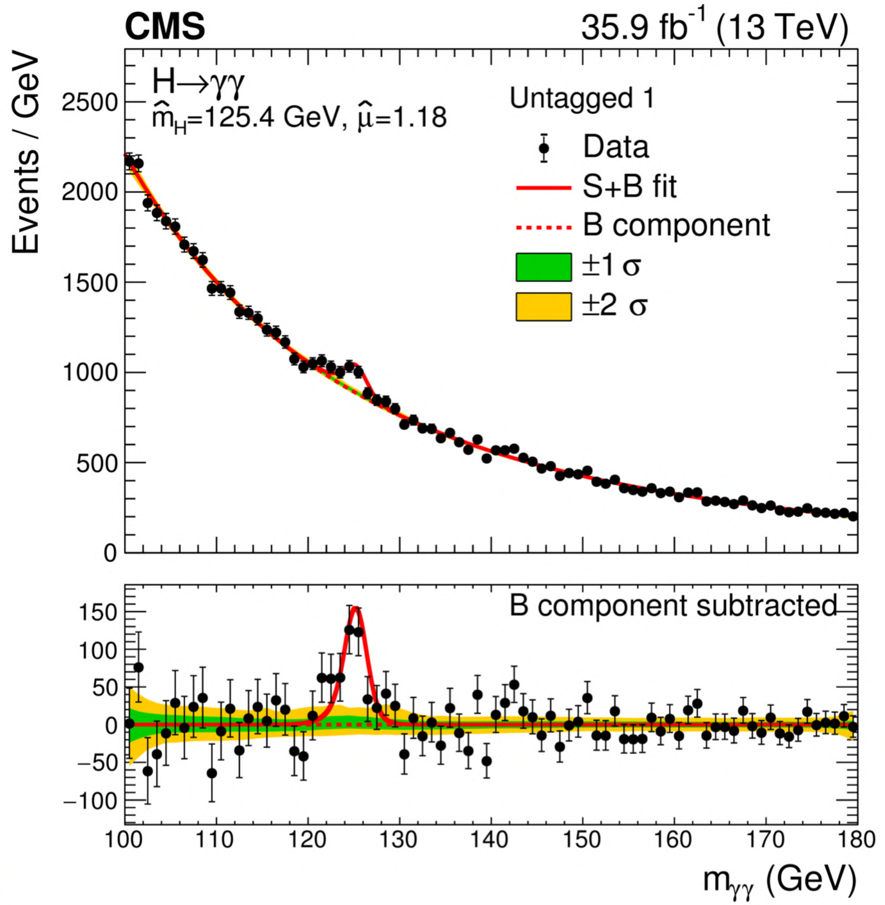
- calculate mass of the decayed particle

$$M^2 = (E_{\mu^+} + E_{\mu^-})^2 - |\vec{p}_{\mu^+} + \vec{p}_{\mu^-}|^2$$

Result:

- narrow peaks: known resonances
- flat distribution: background from random muon combinations
- green peaks: example of a new particle signal (not observed in data!)

Example of particles properties measurement



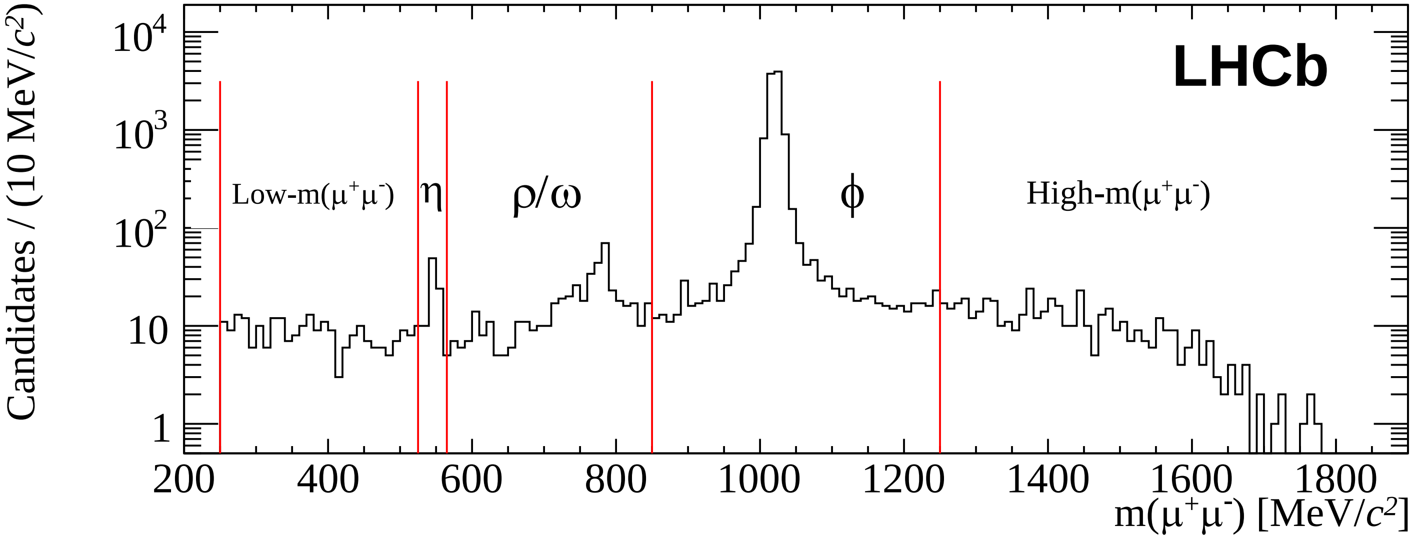
- to observe and measure Higgs boson mass, look at various decay modes
- H→ γγ is one of the "easiest" since it allows to fully reconstruct mass peak
- photons must be well measured!
- use energy-momentum conservation:

$$(E, \vec{p})_{\mathrm{H}} = (E_1 + E_2, \vec{p}_1 + \vec{p}_2)$$

- compute $M_H \approx 125$ GeV

Quiz

- Which particles are stable:
  - Positron, muon, tau neutrino, charged pion, photon, antiproton
- Taking the momentum of particles to be p = 100 GeV, compute average decay length for:
  - muons, charged kaons, B mesons, tau leptons, neutral pions, J/psi
- Why particles look like a peak in the invariant mass spectrum?




Les billets de banque sont protégés par le droit pénal.
Le banconote sono protette dal diritto penale.
20
Interaction with matter

Particle detection

Particle size: ≤ 10^{-15} m (proton radius)
Wavelength reached by an electron microscope: $\lambda \sim 10^{-10}$ m

⇒ visualizing by eye is impossible

⇒ need an indirect detection with devoted instruments

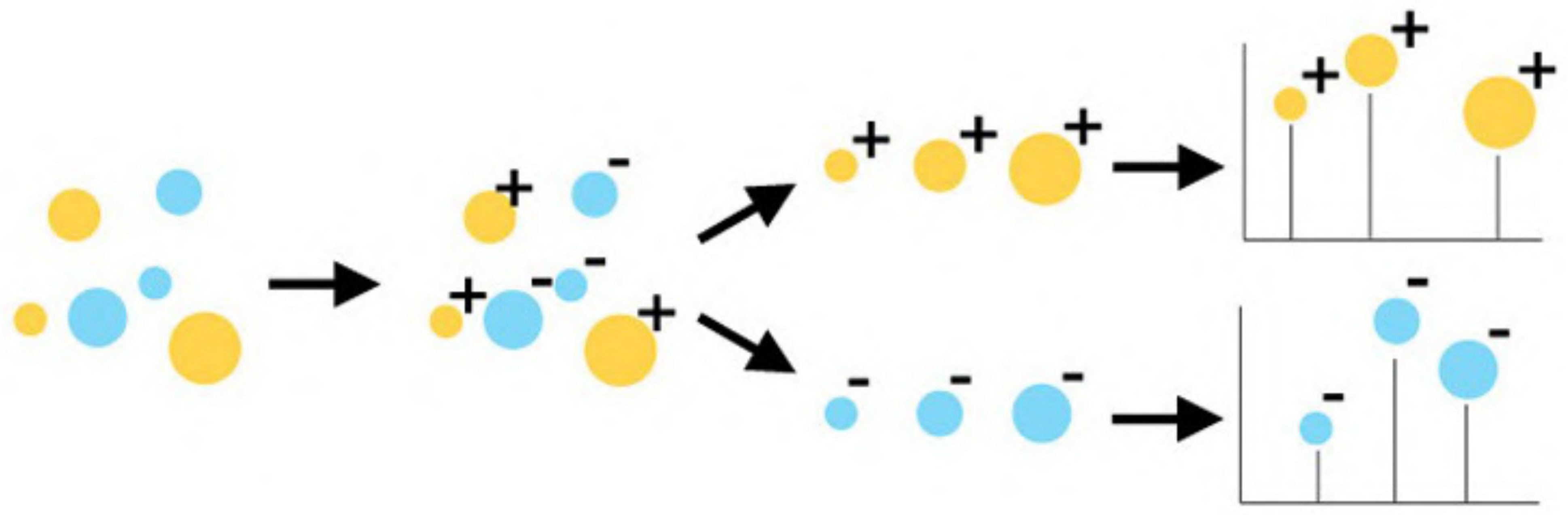
- there exist many different types of particle detectors: scintillators, bubble or cloud chambers, wire chambers etc
- all of them rely on the detection of a **perturbation** induced in matter by a passing particle
- in most cases, the perturbation is either an **ionization** (electrical signal) or **excitation** (scintillation light) of atoms through **electromagnetic** interactions between the incident particle and the atomic electrons

⇒ works only for **charged particles and a photon**

- all detectors have a sensitive volume in which the perturbation occur:
  - gas (e.g. Ar or CO_2)
  - liquid (e.g. water, C_3H_8)
  - solid (e.g. Si, emulsion, ice)

Ionization

- A track of positive and negative ions is formed by a charged particle that kicks out an electron from the atom:



Ionization

- The ionization energy loss per unit length traversed is given by the Bethe-Bloch equation:

$$\frac{\mathrm{d}E}{\mathrm{d}x} \approx -4\pi\hbar^2 c^2 \alpha^2 \frac{nZ}{m_e v^2} \left\{ \ln \left[\frac{2\beta^2\gamma^2 c^2 m_e}{I_e} \right] - \beta^2 \right\} \qquad (1)$$

where $v = \beta c$ is a speed of the traversing particle;

Z is the atomic number of the material;

n its number density;

$I_e \sim 10Z$ eV is the effective ionization potential of the material averaged over all atomic electrons.

Ionization

- The rate of ionization energy loss does not depend significantly on the material except through its density ρ:

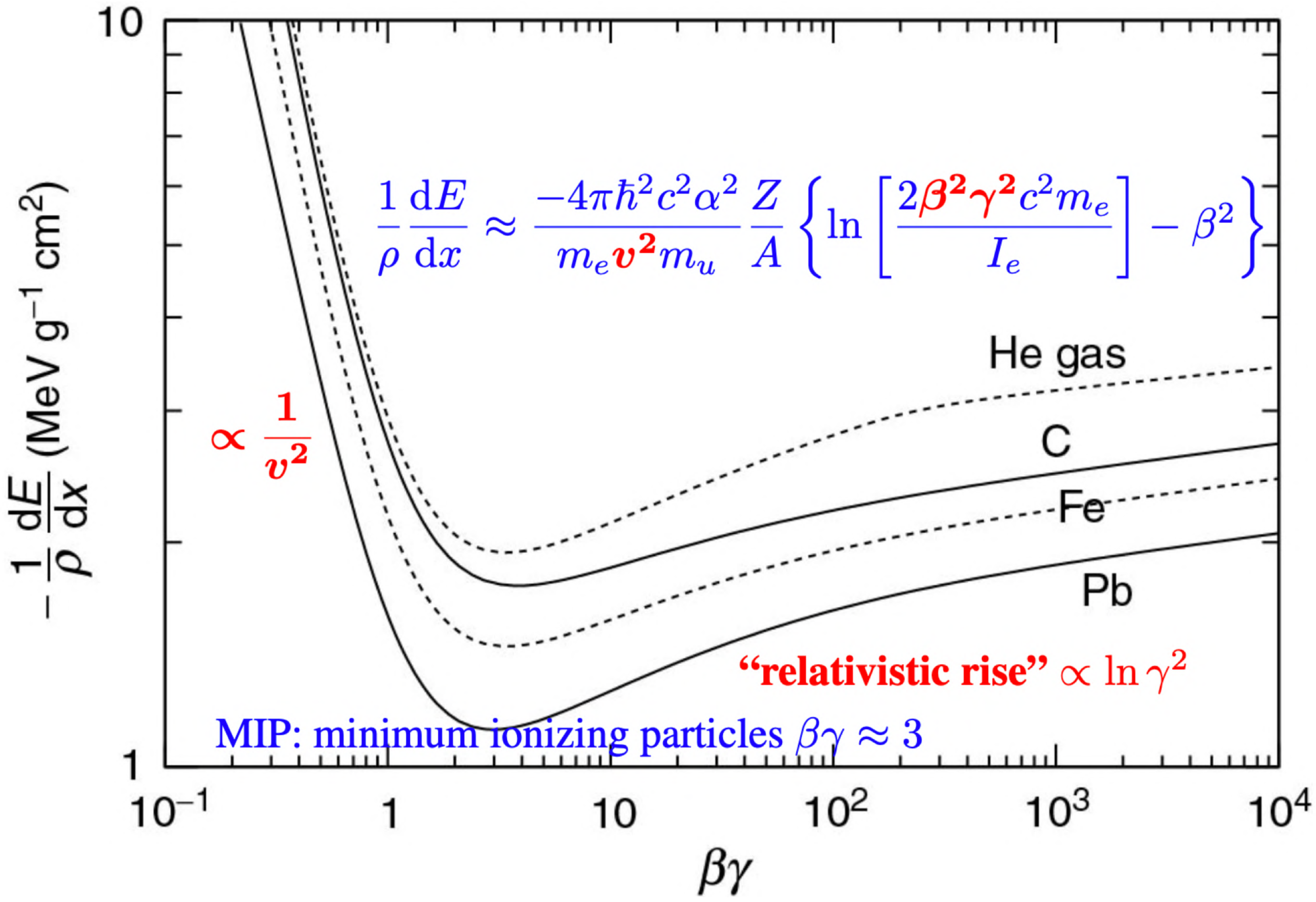
$n = \frac{\rho}{A m_u}$, where A is the atomic mass number and
$m_u = 1.66 \times 10^{-27}$ kg is the unified atomic mass unit

$$\frac{1}{\rho}\frac{\mathrm{d}E}{\mathrm{d}x} \approx \frac{-4\pi\hbar^2 c^2 \alpha^2}{m_e v^2 m_u}\frac{Z}{A}\left\{\ln\left[\frac{2\beta^2\gamma^2 c^2 m_e}{I_e}\right] - \beta^2\right\} \qquad (2)$$

$$\Longrightarrow \frac{1}{\rho}\frac{\mathrm{d}E}{\mathrm{d}x} \propto \frac{Z}{A} \approx const$$

Ionization graph

In case no other energy losses present for a particle, at MIP level it can travel
a long distance: e.g. muons in iron lose 13 MeV/cm and have a range of several meters.

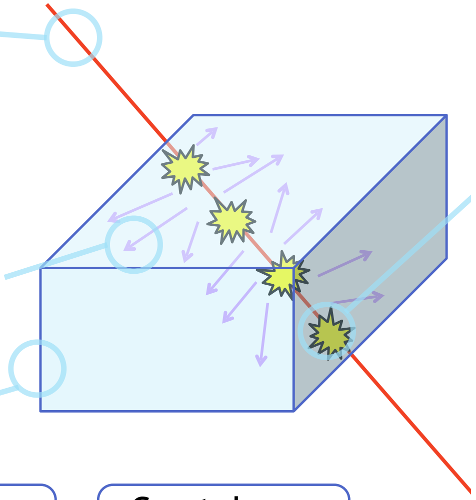


Scintillation

- scintillator molecules are excited by a traversing charged particle or a photon which leads to emission of photons
- if the medium is transparent to these emitted photons, they can be detected
- the light is guided to photodetectors for amplifying and detecting the signal

Incident particle deposits energy in the scintillator

About 20 photons are detected by a photosensor for a scintillating bar of 5mm thickness



Two categories of scintillators are common:

Organic	Inorganic
• Plastics • Low density and low Z • Fast!	• Crystals • High density and high Z • Good for γ

Cherenkov radiation

is a coherent photon emission at a fixed angle θ to the trajectory of the charged particle: happens when the velocity of the particle is greater than the speed of light in the medium, v > c/n

This threshold behavior is utilized to aid the identification of particles of a given momentum p!

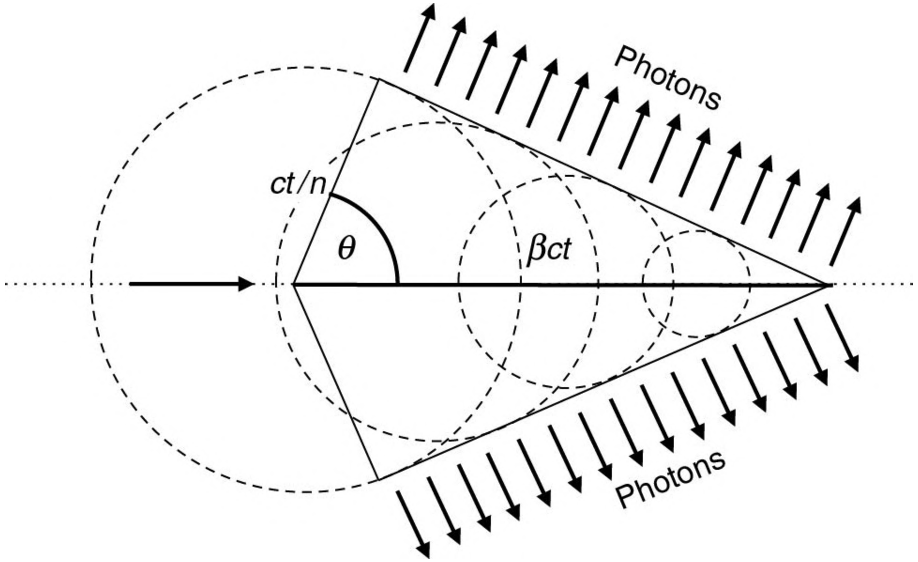
- light is produced at the angle

$$\cos\theta = \frac{1}{n\beta}$$

- light is emitted if: β > 1/n

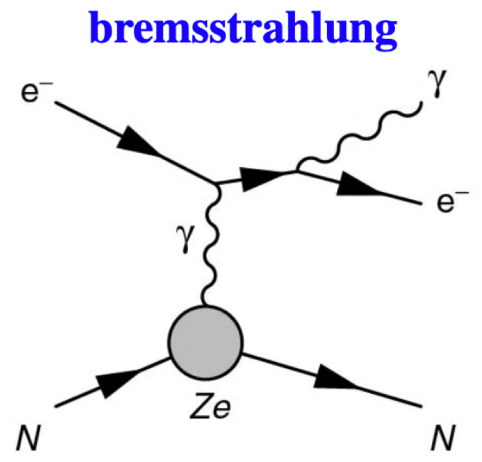
$$\beta = pc/E = p/\sqrt{p^2 + m^2c^2}$$

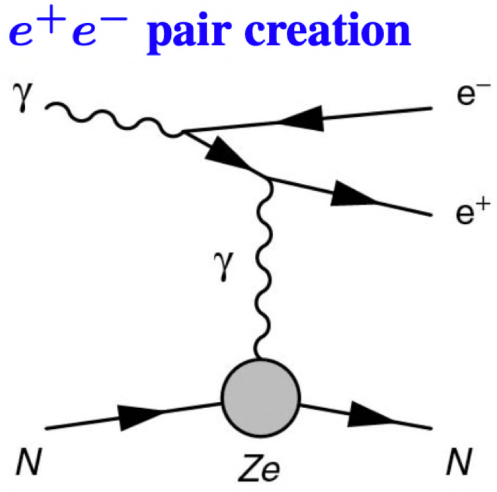
$$\Longrightarrow \ mc < p\sqrt{n^2 - 1}$$



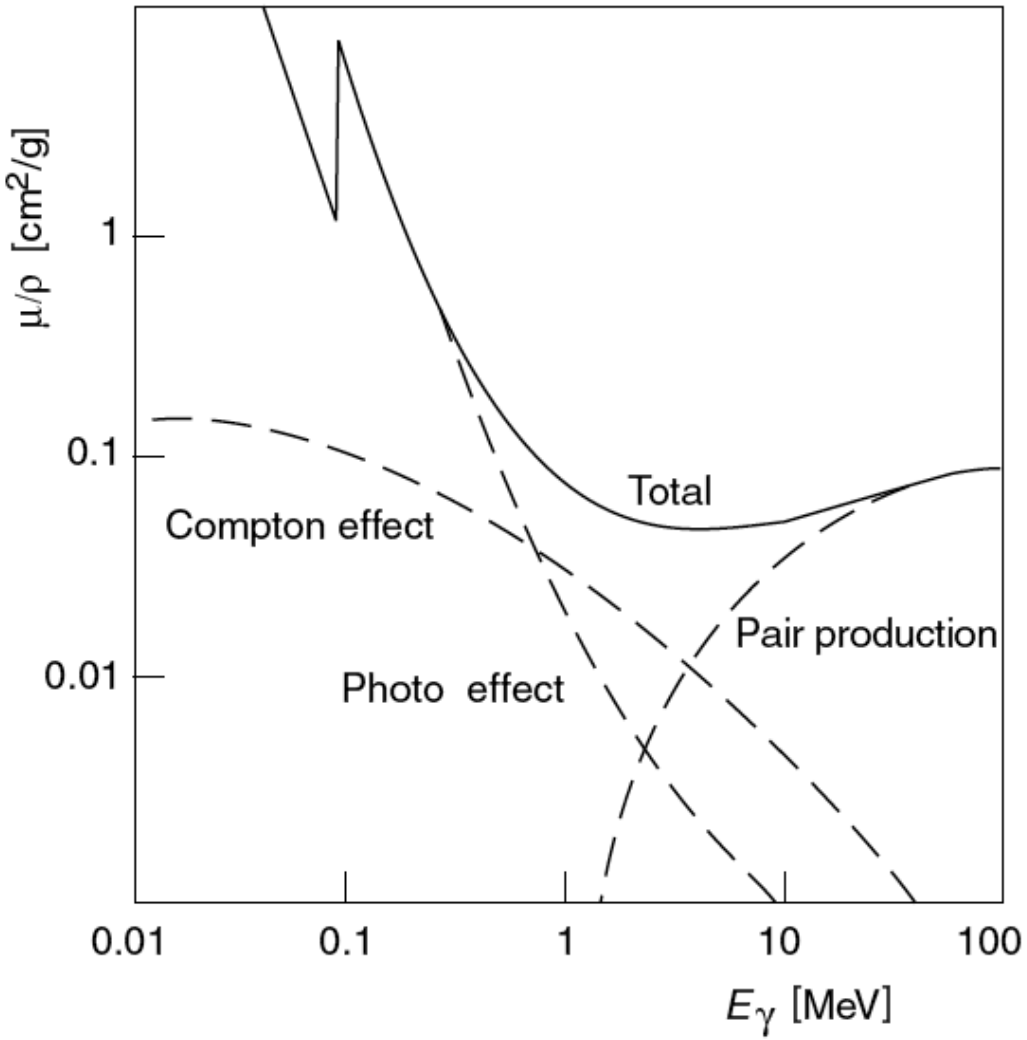
Bremsstrahlung and e^+e^- production

- **Bremsstrahlung**:
  - is the main energy loss mechanism for electrons with energies above a "critical energy" $E_c \sim 800/Z$ MeV, i.e. practically always in current particle physics experiments;
  - $\propto m^{-2} \Rightarrow$ not important for muons and heavier particles
- **Pair creation**: dominant energy loss mechanism for γ with $E_\gamma > 10$ MeV
- **Compton scattering**: $\gamma e^- \to \gamma e^-$ important for $E_\gamma \sim 1$ MeV
- **Photoelectric effect**: low-energy photon absorption by an atomic electron, ejected from the atom





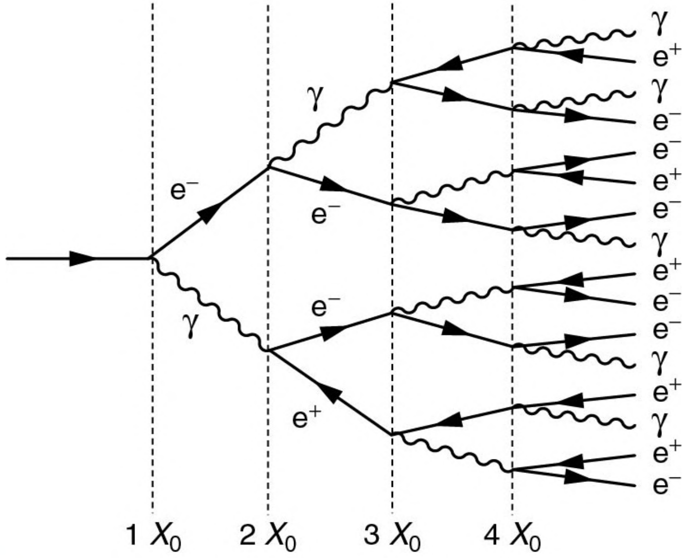
Balance of various processes for a photon



Radiation length

Important material characteristic – radiation length X_0:

- average distance over which the energy of an electron is reduced by bremsstrahlung by a factor of 1/e
- ≈ 7/9 of the mean free path of the e^+e^- pair-creation for a photon

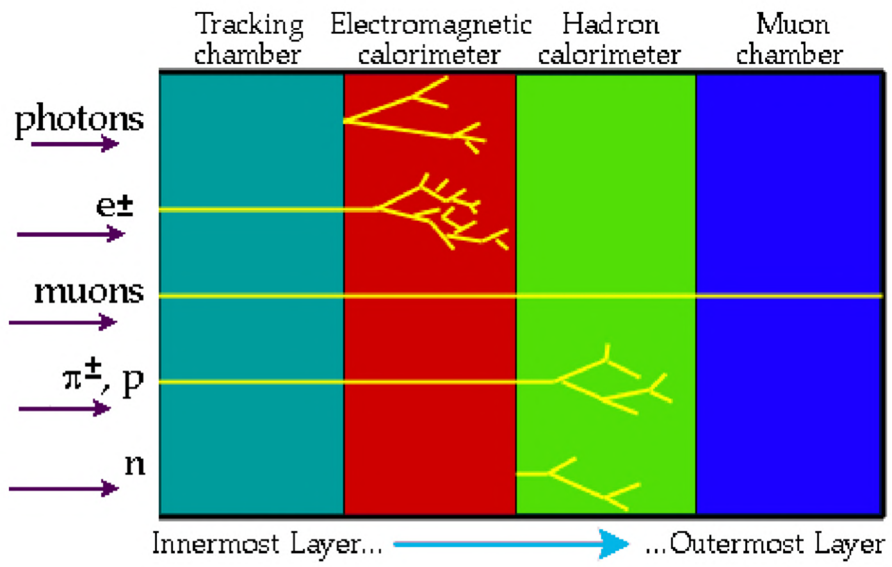


- Examples for typical high-Z materials:
  - $X_0(Fe) = 1.76$ cm
  - $X_0(Pb) = 0.56$ cm

  ⇒ X_0 is rather short
- EM shower: alternating bremsstrahlung and pair creation processes

Summary

Layout and main components of particle physics experiments:



- tracking detectors measure momentum of charged particles and their charge
- calorimeters (electromagnetic an hadronic) measure the energy of particles
- Cherenkov detectors allow to determine particle speed
- relative position of various types of particle detectors is optimized to collect all possible information

Quiz

- Which particles can traverse all the LHC detectors and fly further?
  - electron, muon, tau lepton, neutrino, charged kaon
- Mass spectrum:
  - what determines the width of these peaks?
  - why some peaks are wider and some are more narrow?