Introduction to Elementary Particles (TN2811)

Theory Lecture 5

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Today's lecture

- ☑ The **quark model** of hadrons and the **color quantum number**
- ☑ **The electromagnetic interaction**
- ☑ **Feynman diagrams** for scattering processes
- ☑ Reactions mediated by the **strong force**

The quark model of hadrons

The baryonic number

Strongly interacting particles carry a new quantum number: the **baryonic number**

As for the leptonic number, this baryonic quantum number ***B*** is **conserved** in all reactions involving hadrons and the strong interaction

For quarks we have that $B_q = +1/3$

exercise

Work out the values of ***B*** for the **proton** and the **pion**

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$$\pi^+ = \left(u\,\bar{d}\right) \qquad B_{\pi^+} = B_u + B_{\bar{d}} = +\frac{1}{3} + \left(-\frac{1}{3}\right) = 0$$

As for other **quantum charges,** ***B*** for antiquarks is the opposite that for quarks

Same pattern for all other **mesons:** ***B*** **= 0**

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For quarks we have that $\boldsymbol{B_q = +1/3}$

exercise

Work out the values of ***B*** for the **proton** and the **pion**

$$p = (u\,u\,d) \qquad B_p = 2 \times B_u + B_d = 2 \times \frac{1}{3} + \frac{1}{3} = 1$$

Same pattern for all other **baryons** (**antibaryons**): ***B*** **= +1** (***B*** **= -1**)

Particles that do not interact via the strong force, such as **leptons,** have ***B*** **= 0**

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$$n \to p + e^- + \bar{\nu}_e$$

$$p \to e^+ + \nu_e + \pi^0$$

$$\tau^+ \to \bar{p} + \bar{\nu}_\tau$$

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why?

An important consequence of ***B***-conservation is that protons are **absolutely stable**

Isospin

Isospin is an **approximate symmetry** that connects specific hadrons sharing **common properties**, such as mass and spin, among them

Pion	π^+	139.6	0
	π^0	135.0	0
Kaon	K^+	493.7	0
	K^0	497.7	0
Phi	Φ	1019.5	1
D-meson	D^+	1869.4	0
	D^0	1864.5	0
	D_s^+	1968	0
J/psi	J/ψ	3097	1
B-meson	B^+	5279	0
	B^0	5279	0
	B_s^0	5366	0
	B_c^+	6277	0
Upsilon	Υ	9460	1
Proton	p	938.3	1/2
Neutron	n	939.6	1/2
Delta	Δ^+	1232	3/2
	Δ^{++}	1232	3/2
Lambda	Λ^0	1116	1/2
Sigma	Σ^+	1189	1/2

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Why the **neutral** and **charged pions** have almost identical masses?

$$\pi^+ = (u\,\bar{d})$$

$$\pi^0 = \frac{1}{\sqrt{2}}(u\,\bar{u}) - \frac{1}{\sqrt{2}}(d\,\bar{d})$$

$$\pi^- = (d\,\bar{u})$$

Because you can ***``rotate”*** among them by interchanging an up and a down quarks, which have a **very similar mass**

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$$p = (u\,u\,d)$$

$$n = (u\,d\,d)$$

Isospin symmetry relates hadrons that transform into each other by **interchanging *u* and *d* quarks**

Why the **proton** and the **neutron** have almost identical masses?

Strangeness

The **strange quark content of hadrons** has associated another quantum number / quantum charge: **strangeness**

The strangeness quantum number ***S*** is **conserved** in all reactions involving the strong and electromagnetic interactions, but not with the **weak interaction**

$$S_s = -1 \qquad S_{\bar{s}} = +1$$

$$S_u = S_d = S_c = S_b = S_t = 0$$

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As for other quantum charges, **strangeness is additive**

$$K^+ = (u\,\bar{s}) \qquad S_{K^+} = S_u + S_{\bar{s}} = 0 + (+1) = +1$$

$$\Lambda^0 = \left(u\,d\,s\right) \qquad S_{\Lambda^0} = S_u + S_d + S_s = 0 + 0 + (-1) = -1$$

Charmness and bottomness

The **charm** and **bottom quark content of hadrons** has also associated dedicated quantum numbers / quantum charges: **charmness** and **bottomness**

The charmness and bottomness quantum numbers ***C*** and ***b*** are **conserved** in the strong and electromagnetic interactions, but not in the **weak interaction**

$$C_c = +1 \qquad C_{\bar{c}} = -1$$

$$C_u = C_d = C_s = C_b = C_t = 0$$

$$b_b = -1 \qquad b_{\bar{b}} = +1$$

$$b_u = b_d = b_s = b_c = b_t = 0$$

As for other quantum charges, **charmness** and **bottomness** are **additive**

Hadron-building with quarks

We are now in position to determine the **quark content** of arbitrary hadrons exploiting only the knowledge of the quantum numbers of the latter

These are the **instructions** for hadron-building:

- The values of the electric charge ***Q,*** the baryon number ***B,*** and of the strangeness, charmness, and bottomness ***S, C, b*** of the constituent quarks must **add up** to that of the corresponding hadron

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- The **mass** of a given hadron will always be **higher** than the sum of the masses of its constituent quarks

- **Spin** is **not** an additive quantum number, since it is a **vectorial quantity**. For example the proton is a spin-1/2 hadron composed by three spin-1/2 quarks

Hadron-building with quarks

exercise

Determine the **quark composition** of the following two hadrons:

$$\Delta^{++} \;:\; B = +1\,, S = C = b = 0$$

$$\Xi^{-} \;:\; B = +1\,, S = -2\,, C = b = 0$$

Hadron-building with quarks

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- ☑ Since ***B=+1*** this hadron is a baryon composed by thee quarks
- ☑ Since ***Q=+2*** (as indicated by symbol) it must contain either up or charm quarks

$$Q = +2 = 3 \times (+2/3) = 3 \times Q_{u/c}$$

- ☑ Since ***C=0,*** it must contain the same number of charm quarks and antiquarks: zero (per above)

$$\Delta^{++} = (u\,u\,u)$$

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$$\Delta^{++}=(u\,u\,u)$$

$$\Xi^{-} \; : \; B=+1\,, S=-2\,, C=b=0$$

- Since ***B=+1*** this hadron is a baryon composed by three quarks
- Since ***Q=-1*** (as indicated by symbol) it must contain three down or strange quarks

$$Q=-1=3\times(-1/3)=3\times Q_{d/s}$$

- Since ***S=-2,*** it must contain two strange quarks

$$\Xi^{-} = \left(d\,s\,s\right)$$

Hadron-building with quarks

exercise

Determine the **quark composition** of the following two hadrons:

$$J/\psi \,:\, B = 0\,, S = C = b = 0, m_{J/\psi} = 3.1\,\mathrm{GeV}$$

$$\Lambda_b^0 \,:\, B = 1\,, S = C = 0, b = -1$$

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- ☑ Since ***B=0*** this hadron is a meson composed by a quark and and antiquark
- ☑ Since there is no mention of an electric charge, we can say that **Q=0**
- ☑ Since ***S=C=b=0,*** it contains the same number of strange, charm, and bottom quarks than the corresponding antiquarks. Since the mass is roughly twice the charm mass we have:

$$J/\psi = (c\,\bar{c})$$

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- Since ***B=+1*** this hadron is a baryon composed by three quarks
- From the symbol we read that **Q=0**: we need one up-type quark and two down-type quarks
- Since ***b=-1,*** it contains at least one more bottom quark than antiquarks

$$\Lambda_b^0 = \left(u\,d\,b\right) \qquad Q = 0 = +2/3 + 2\times(-1/3)$$

Color: the charge of the strong interaction

The color of quarks

Let's go back to the **quark composition** of the Delta baryon:

$$\Delta^{++} = (u\,u\,u)$$

- Since it contains three identical quarks, its quantum wave function is **symmetric** if two quarks are interchanged

- Moreover since this baryon has spin ***s=+3/2,*** it means that the three quarks have their spins pointing in the same direction: the spin component of the wave function is also **symmetric**

$$|\psi_{\Delta^{++}}\rangle = |u\,u\,u\rangle \otimes |\uparrow\uparrow\uparrow\rangle$$

However a spin-3/2 particle is a **fermion,** whose wave function should be antisymmetric with respect to the exchange of two quarks

What are we missing?

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Quarks carry a **new quantum number** called **color** which is the ``charge" of the strong interactions. Color can exist in three types: ``blue", ``red", ``green"

$$|\psi_{\Delta^{++}}\rangle = |u\,u\,u\rangle \otimes |\uparrow\uparrow\uparrow\rangle \otimes |r\,g\,b\rangle$$

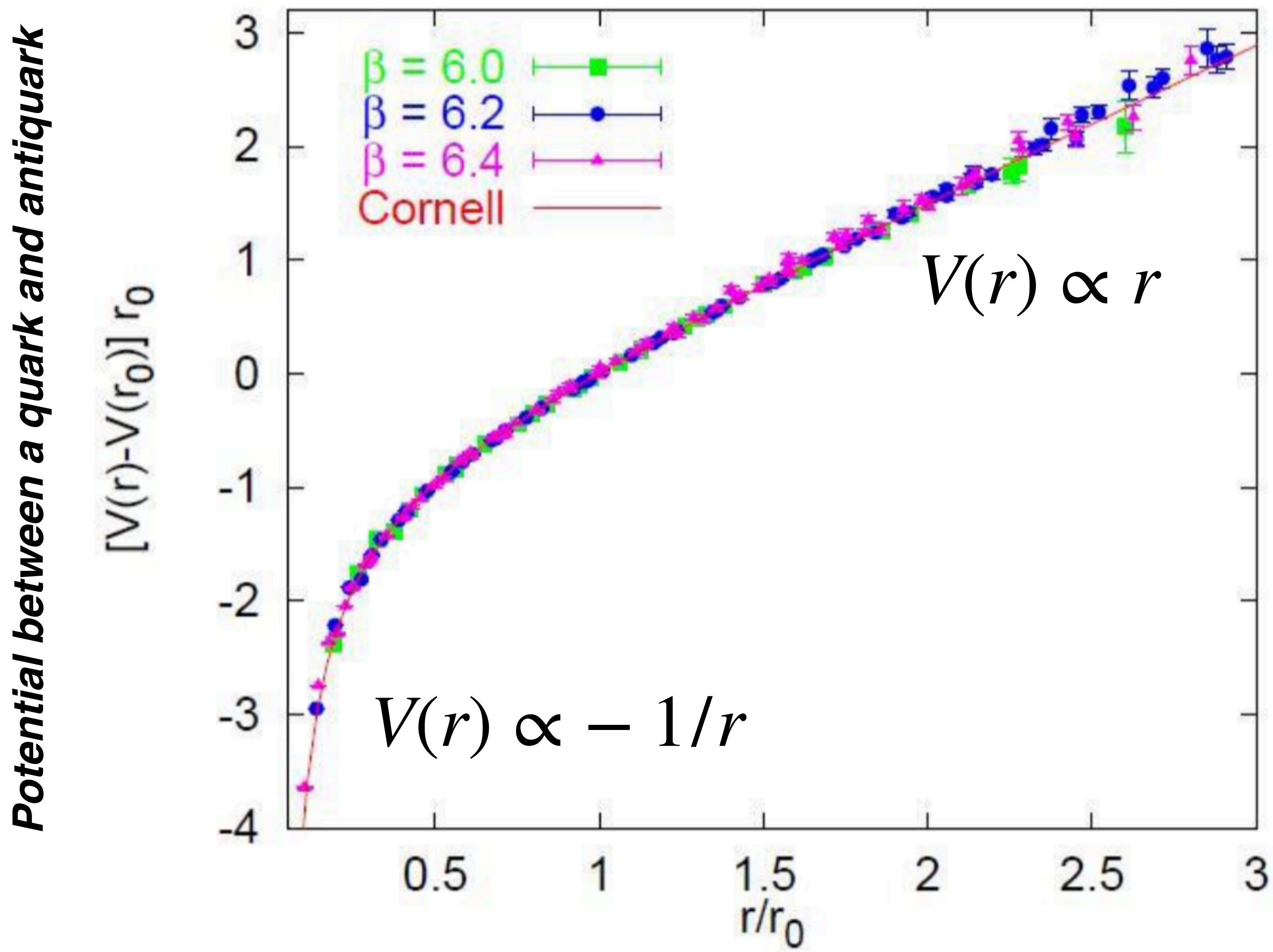
Now when two quarks are interchanged the **color wave function changes sign**, and thus the total hadronic wave function behaves as corresponding to fermions

$$|r\,g\,b\rangle = -\,|r\,b\,g\rangle$$

The strong (?) interaction

A crucial property of color is that is leads to a **confining force at large distances**

Since the interaction strength increases with the distance, we **cannot completely separate two quarks apart** since that would require an infinite force



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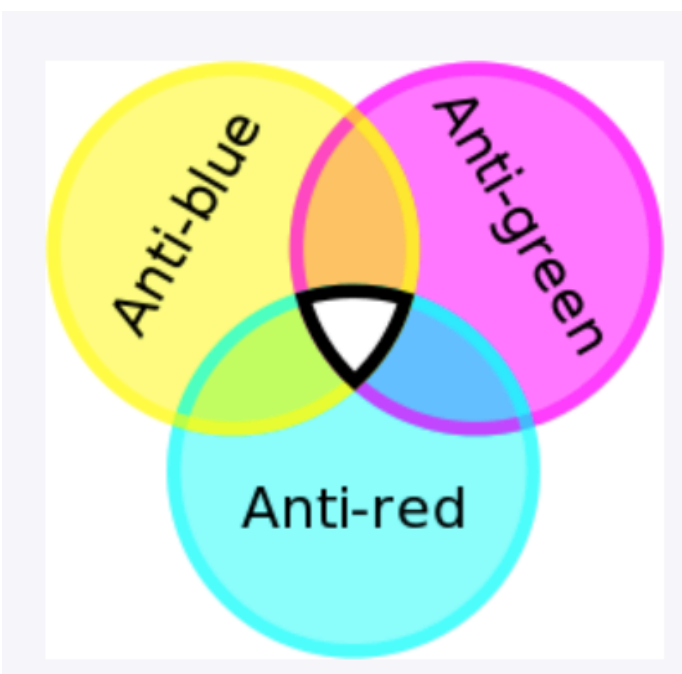
The strong interaction is therefore a **confining force**: only hadrons which are **color-neutral** are physically allowed



An **baryon is ``white"** (color-neutral) if composed by quarks or antiquarks carrying: anti-blue, anti-green, and anti-red color charges

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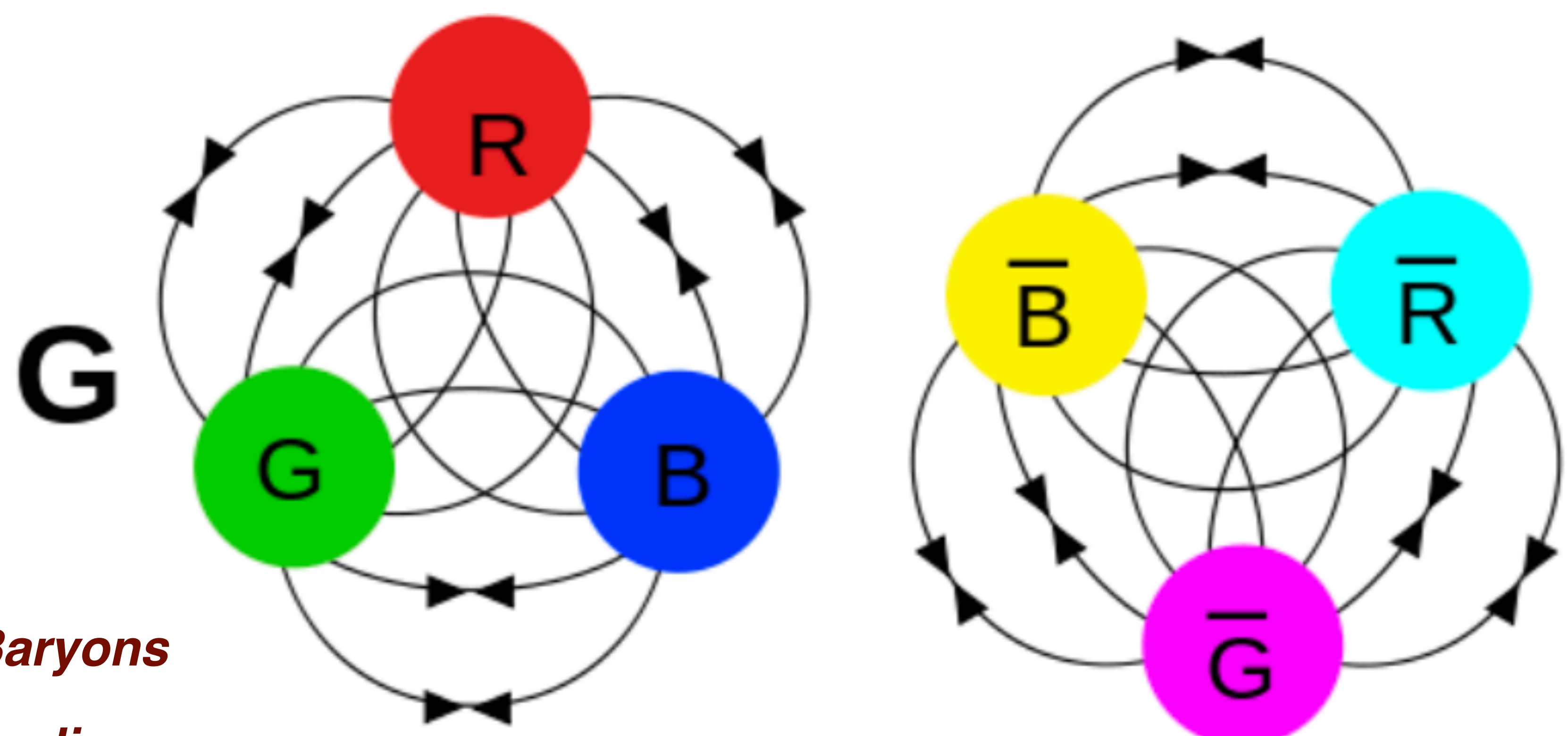

Color fields in Baryons

Note no outgoing lines

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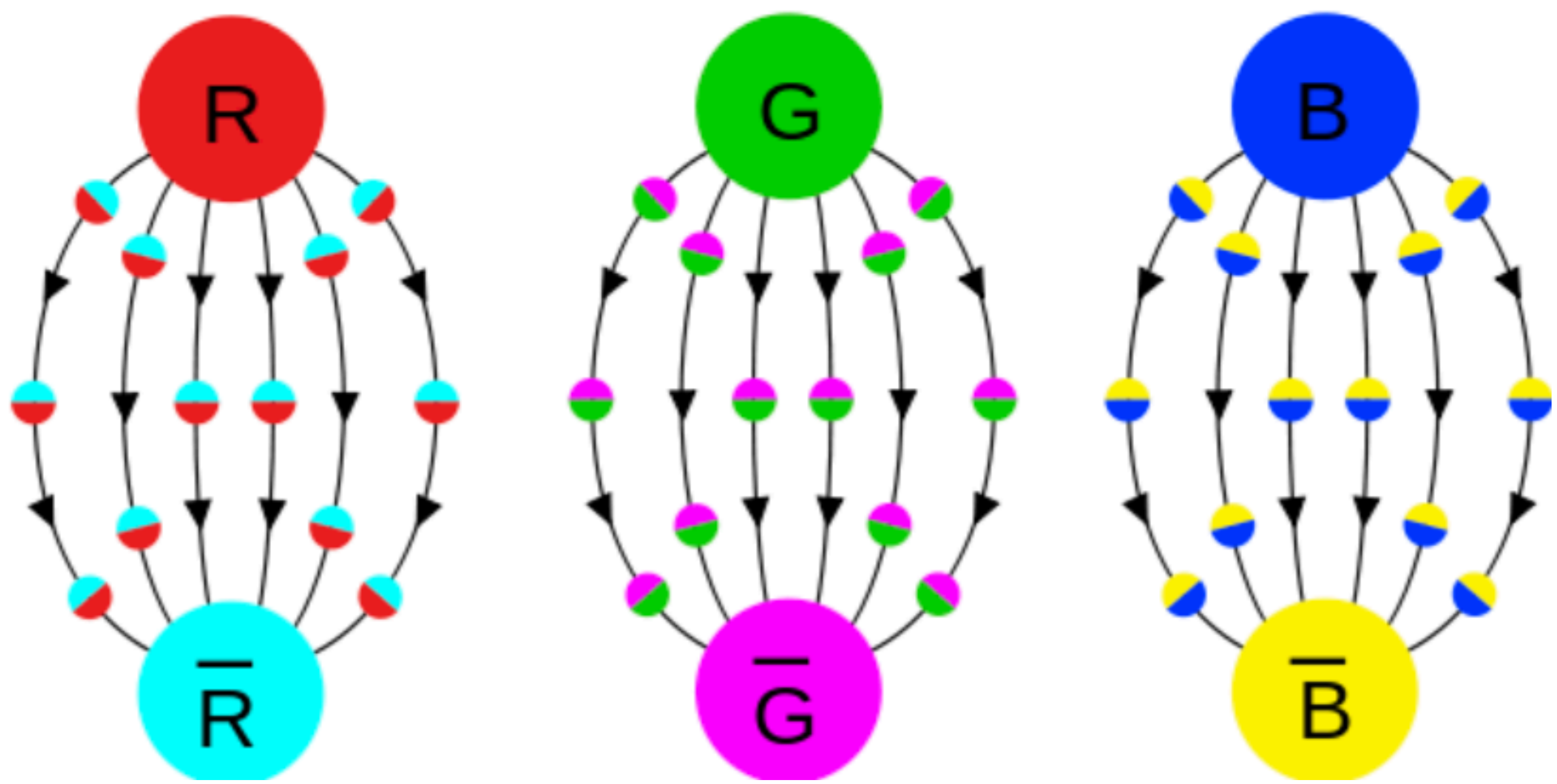

Color fields in Mesons

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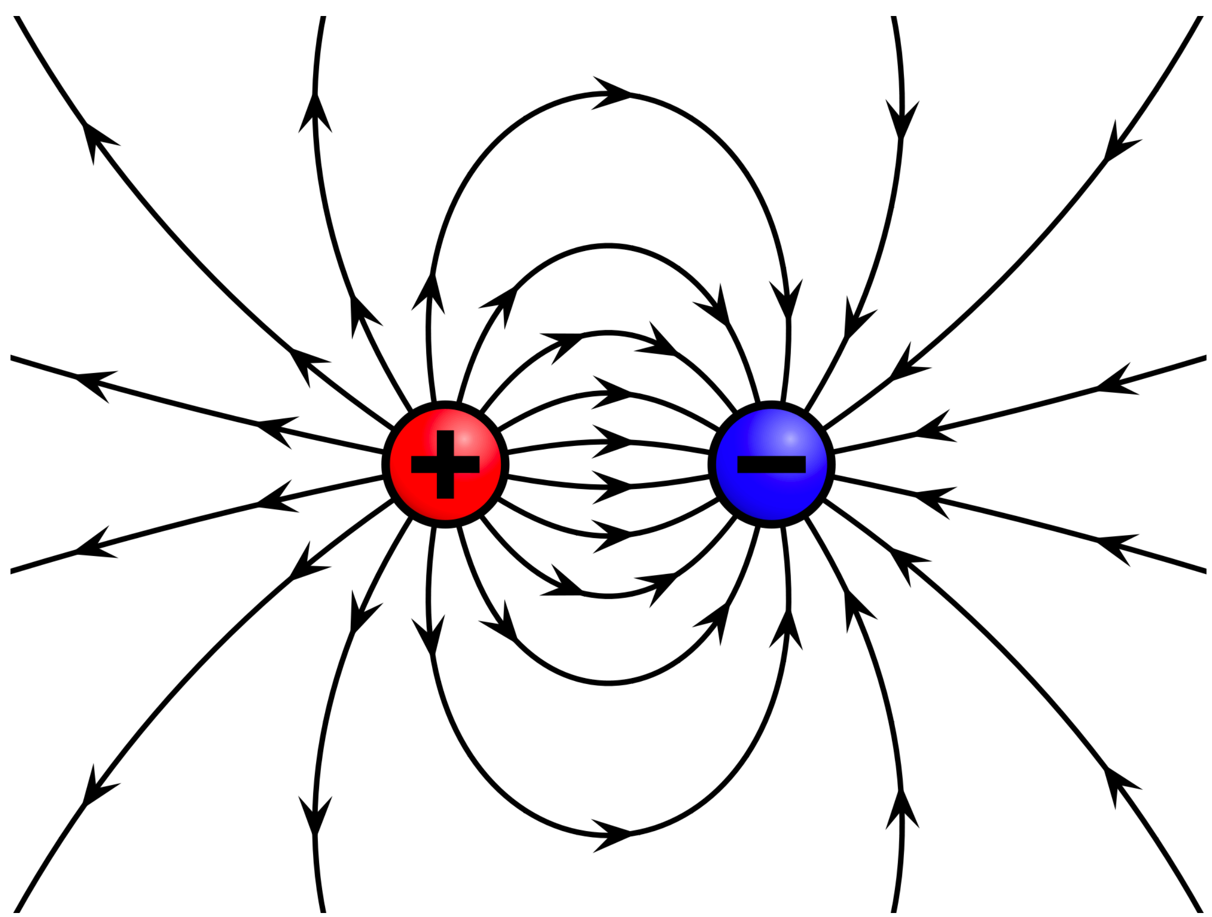
Electromagnetism and Feynman diagrams

Quantum Electromagnetism

In classical electromagnetism, the electric attraction between two charged particles is given by Coulomb's law

$$F_E = k\frac{Q_1 Q_2}{r^2}$$

Each charge generates an electric field which **permeates all space**, and other charges moving in this electric field are attracted/repelled



Quantum Electromagnetism

At the quantum level, **fundamental interactions** look very different that at the classical level

https://www.youtube.com/watch?v=hHTWBc14-mk

Quantum Electromagnetism

At the quantum level, **fundamental interactions** look very different that at the classical level

Elementary particles interact by **exchanging force carriers** among them

The **photon** is the force carried particle of **Quantum Electrodynamics,** the quantum version of classical electromagnetic theory

A useful tool to **visualise** interactions between elementary particles is known as **Feynman diagrams,** that represent the trajectories in space and time of the particles involved in a scattering reaction

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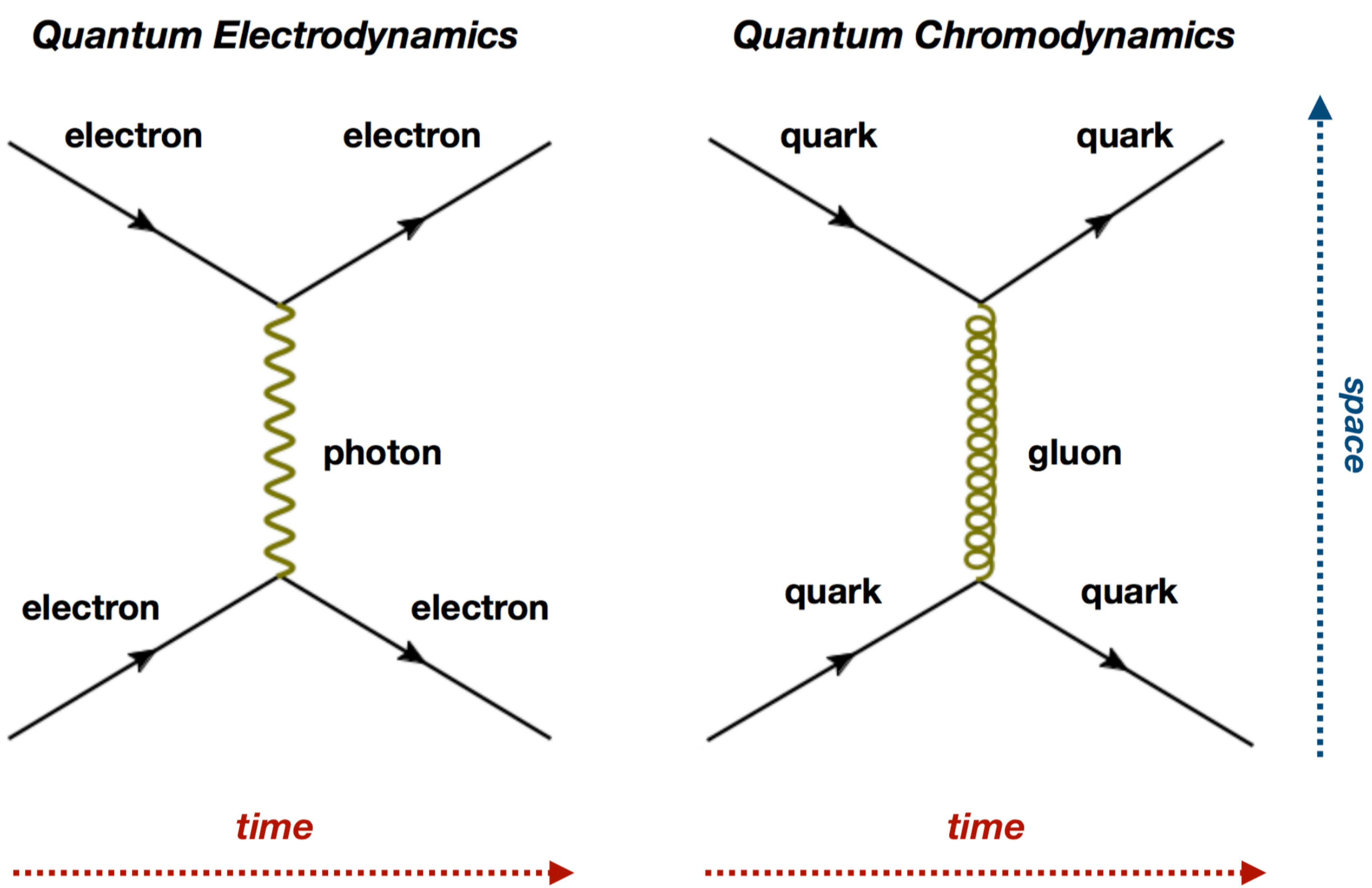
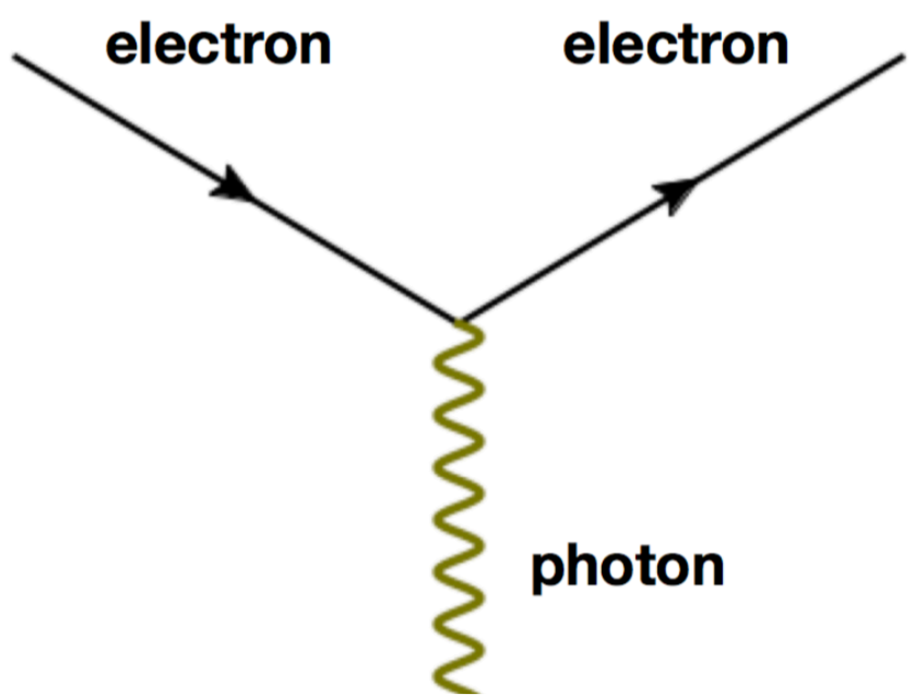


Quantum Electromagnetism

In QED there is a unique **interaction vertex:**



This fact implies the following **important properties** about the electromagnetic interaction:

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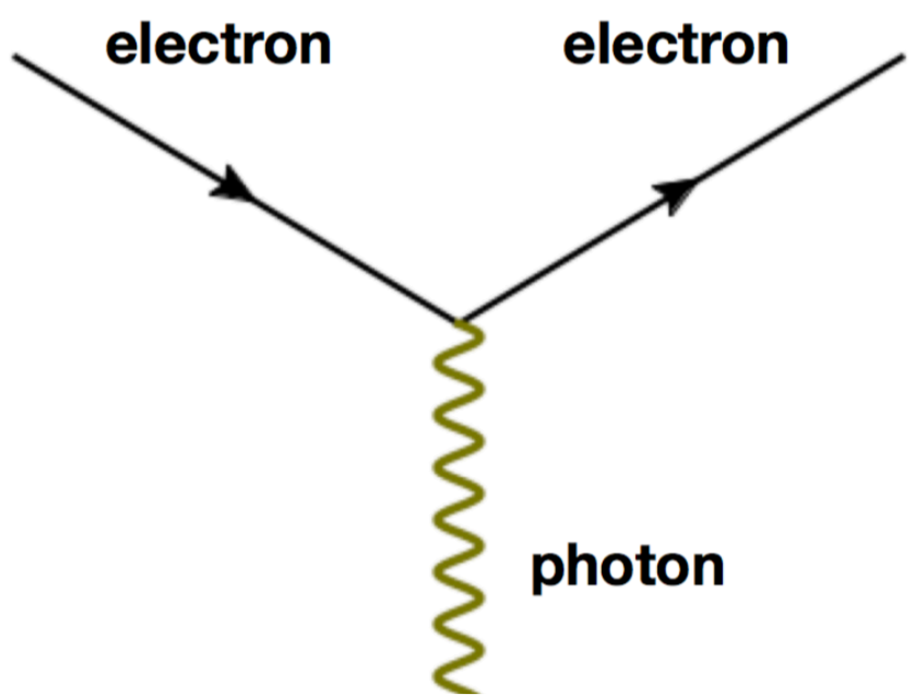

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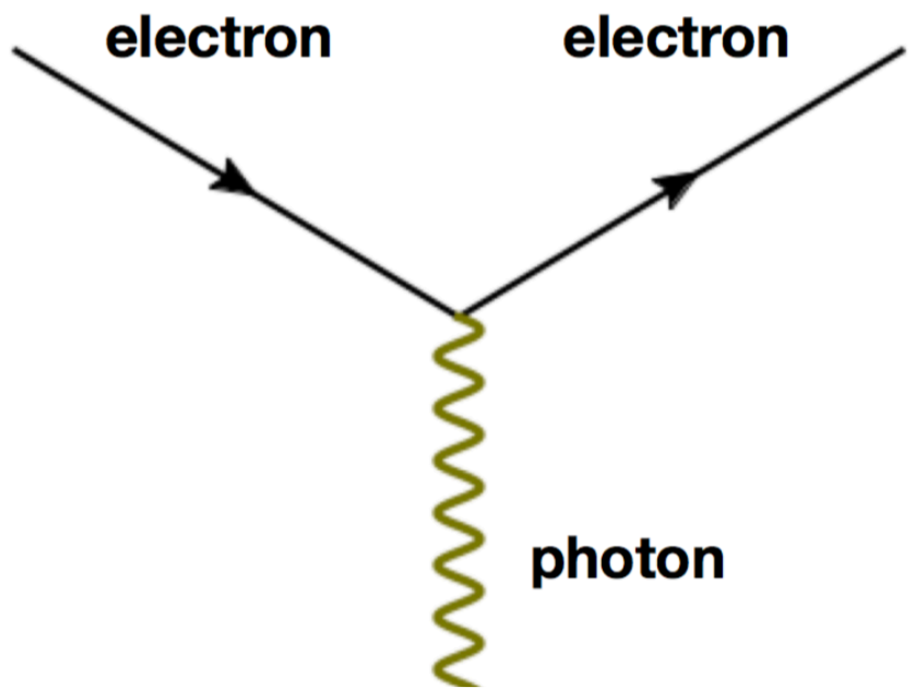

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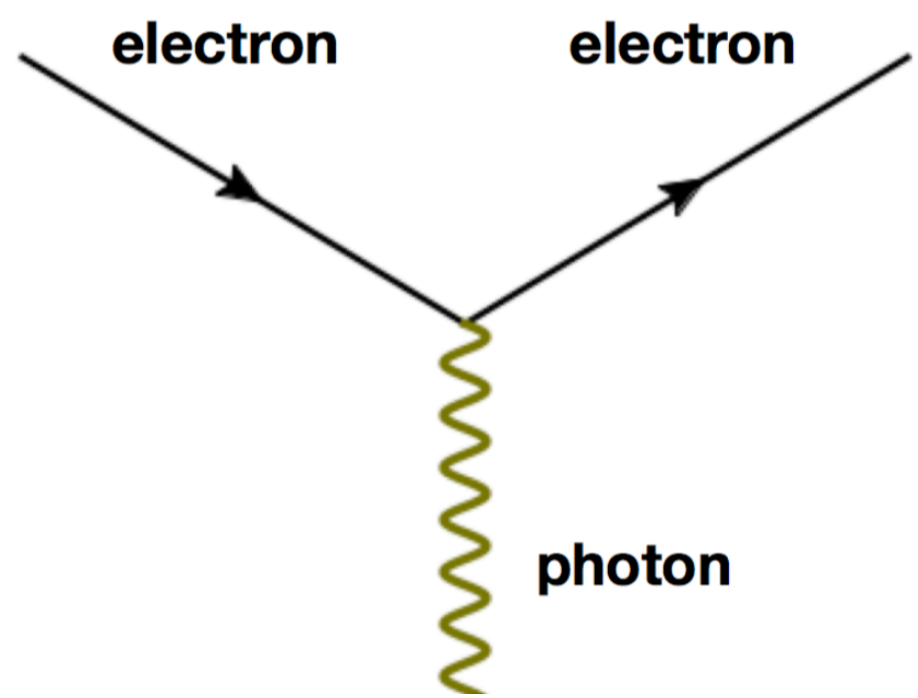

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- **Flavour** is conserved by QED interactions: automatic conservation of leptonic and baryonic numbers, as well as strangeness, charmness, and bottomness
- Since the photon is **exactly massless,** electromagnetism is a **long-range force**

The strong interaction and gluons

Strong force vs electromagnetism

It is useful to enumerate the **properties of the strong interaction** by comparing them with those of the electromagnetic interactions

Electromagnetism

Strong interactions

- ☑ A **single type of electric charge** exists: the only thing that varies is its sign and magnitude

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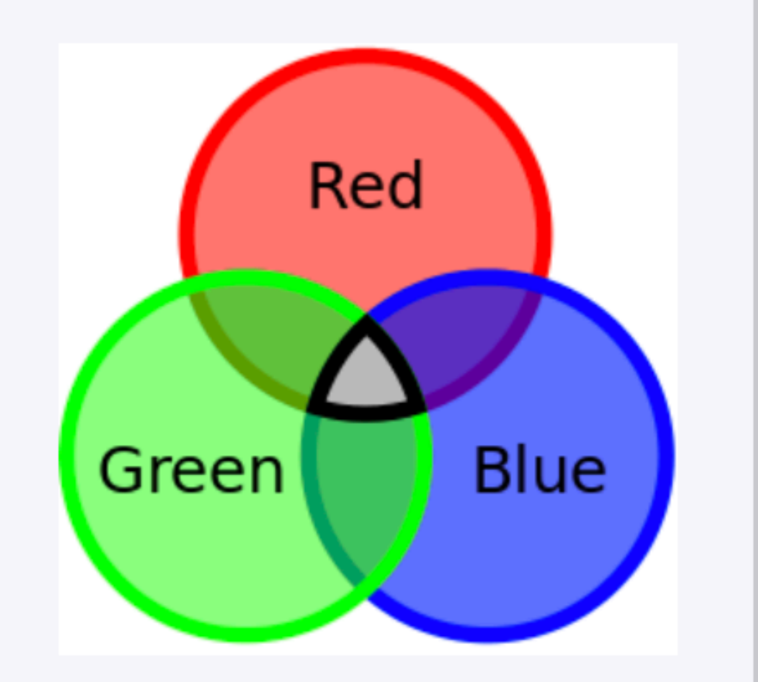
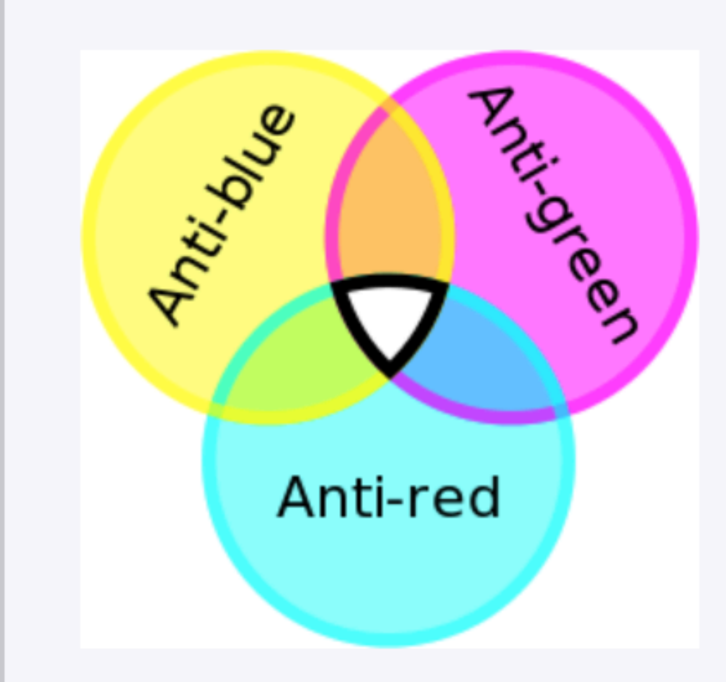
☑ **Three different types of colour charge** exist: ***blue, green, red,*** with their own sign and magnitude





In general, a strongly interacting particle can carry an **arbitrary combination** of the red, green, and/or blue color charges

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Strong interactions

- **Three different types of colour charge** exist: ***blue, green, red,*** with their own sign and magnitude
- The strong interaction is transmitted by **gluons,** which are **massless** but **charged under color**

Since gluons are color-charged, they also **interact among themselves** without the need of quarks

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Strong interactions

- **Three different types of colour charge** exist: ***blue, green, red,*** with their own sign and magnitude
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- The **strength of the strong interaction** varies with the energy/distance: very different behaviour depending on energy/distance

The strong (?) interaction

In the quantum theory of elementary particles, the **strength of an interaction** is not fixed but rather **varies** with the energy of the scattering process

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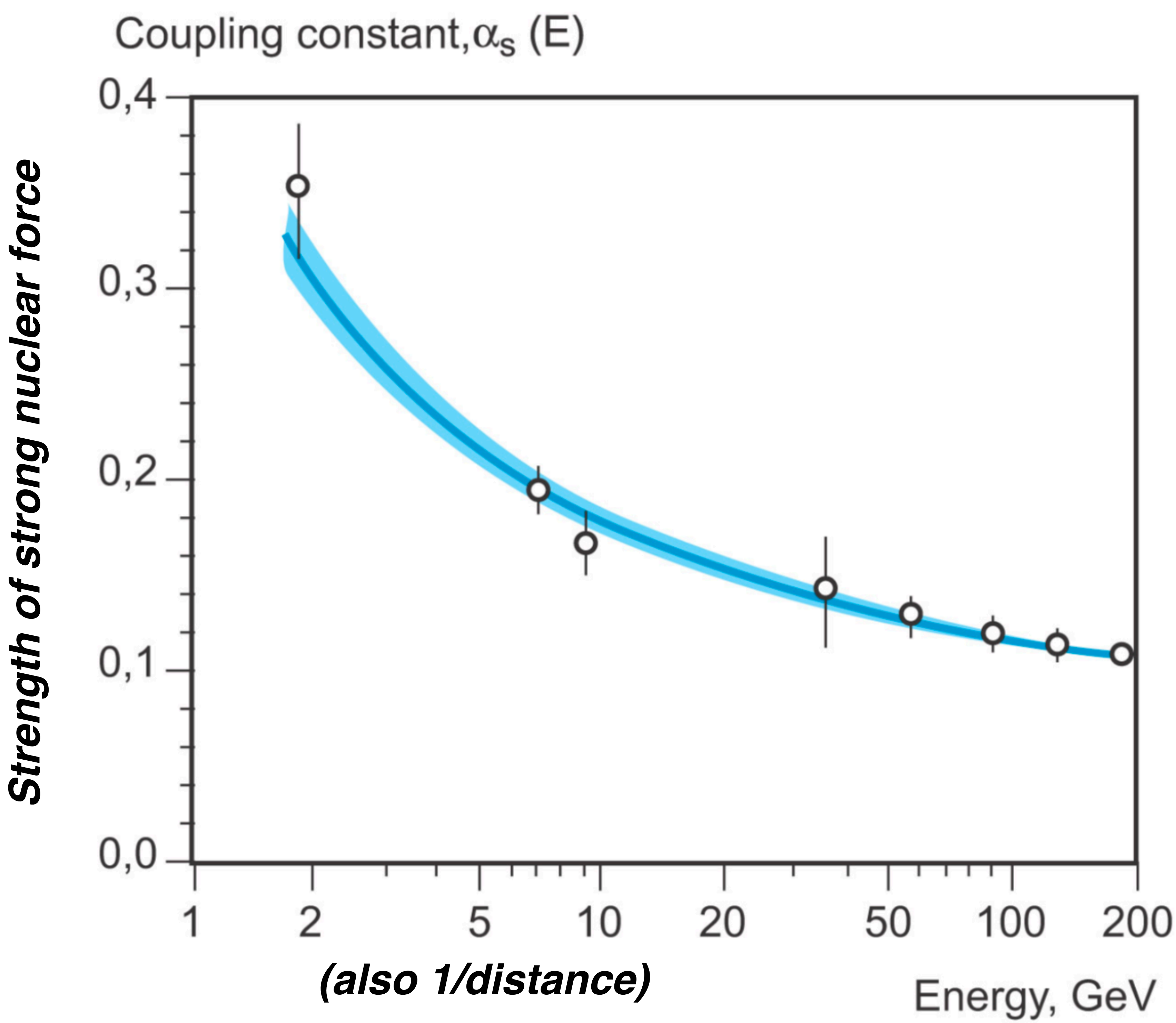

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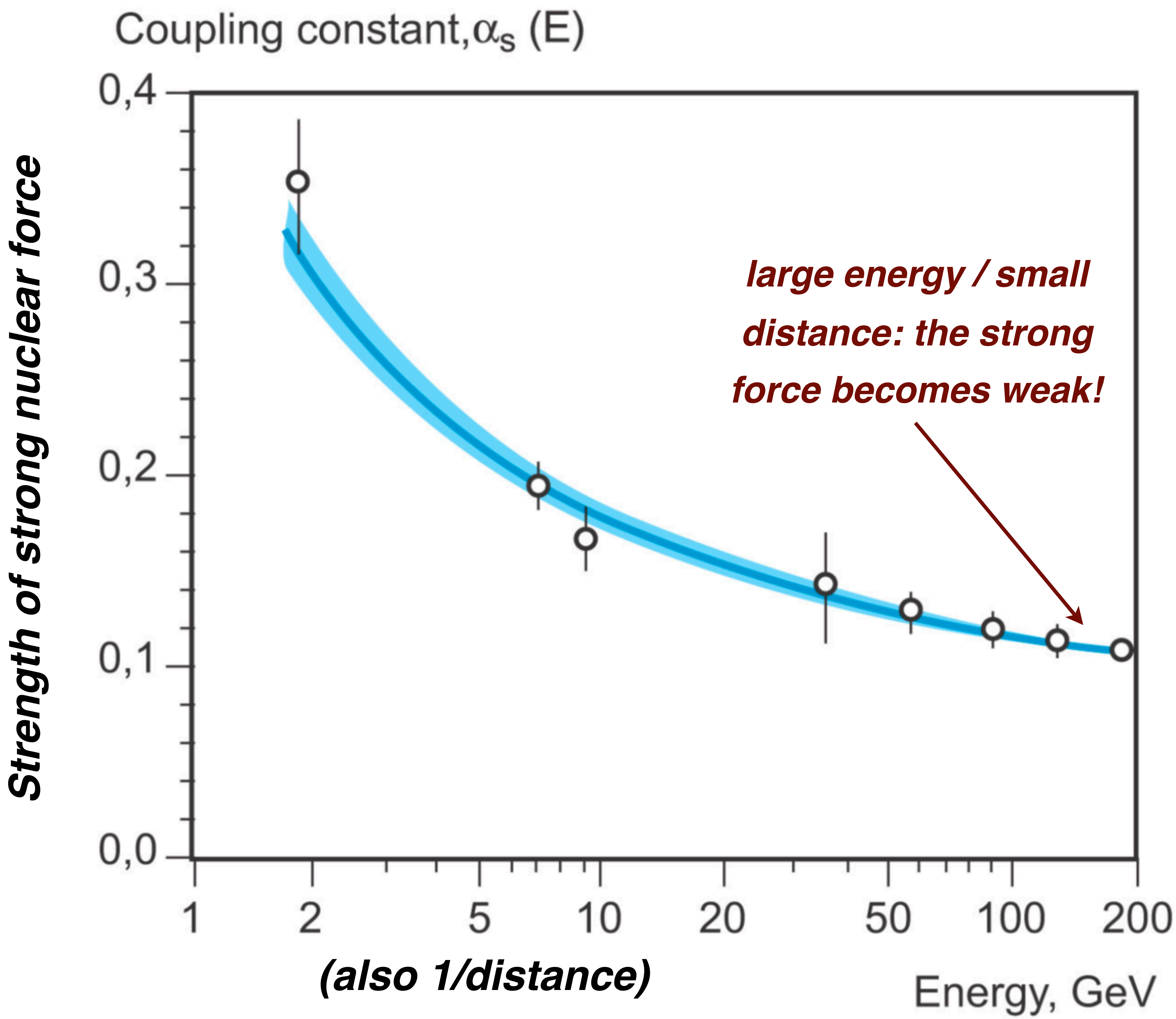

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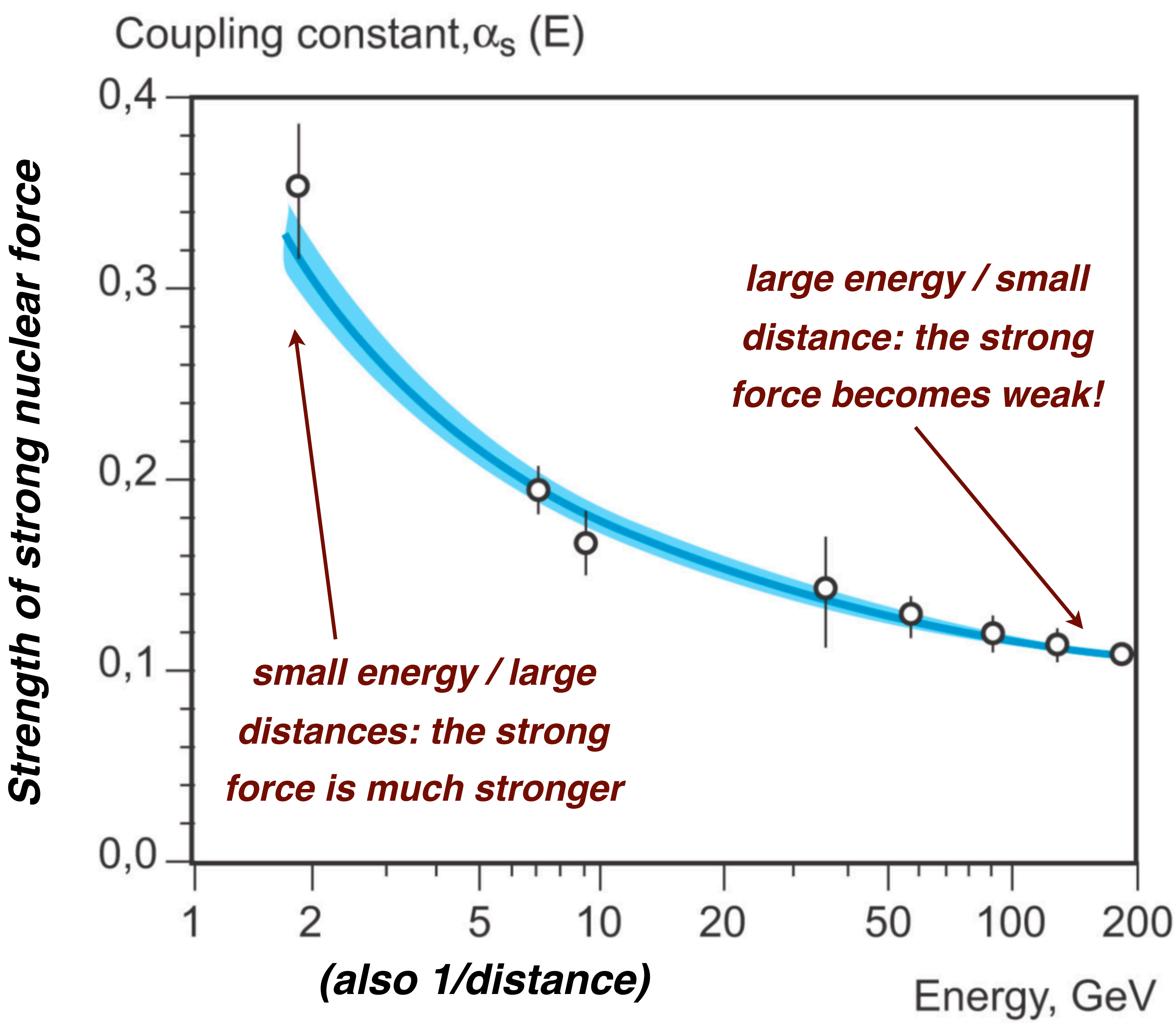
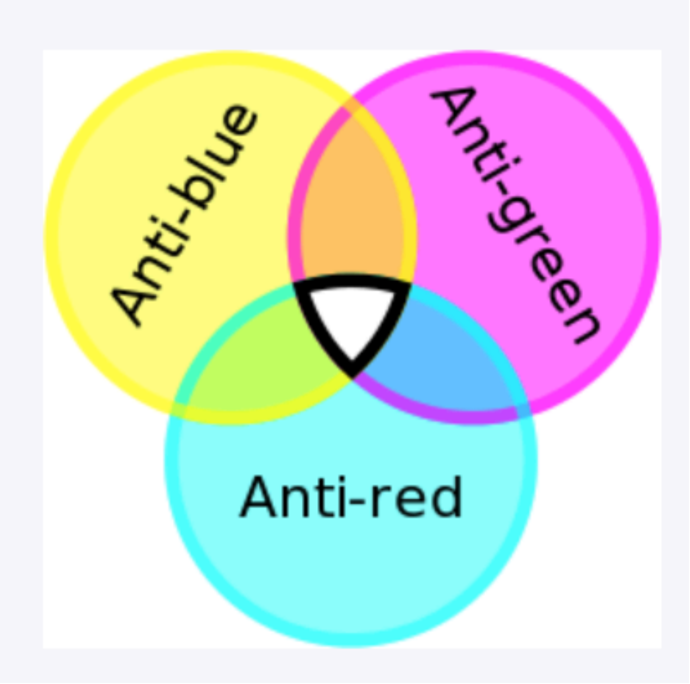


The strong (?) interaction

This behaviour is a consequence of the fact that **gluons are color-charged,** unlike photons which are electrically neutral

Since the interaction strength increases with the distance, we **cannot completely separate two quarks apart** since that would require an infinite force

The strong interaction is therefore a **confining force**: only hadrons which are **color-neutral** are physically allowed



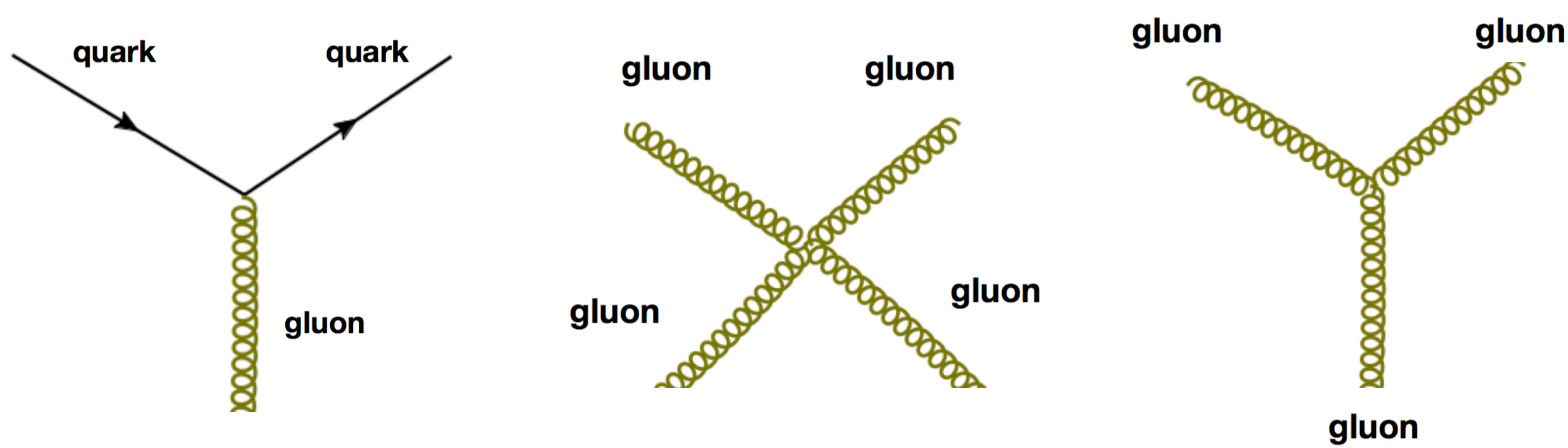
An **baryon is ``white"** (color-neutral) if composed by quarks or antiquarks carrying: anti-blue, anti-green, and anti-red color charges

Quantum Chromodynamics

Let us summarise what we have learned about the **quantum theory of the strong interactions**: Quantum Chromodynamics (QCD)

- **Flavour** is always **conserved** by strong interactions: automatic conservation of leptonic and baryonic numbers, as well as strangeness, charmness, and bottomness

This is a consequence of the fact that the only possible **interaction vertices** are:



And that gluons do not carry **flavour quantum numbers**

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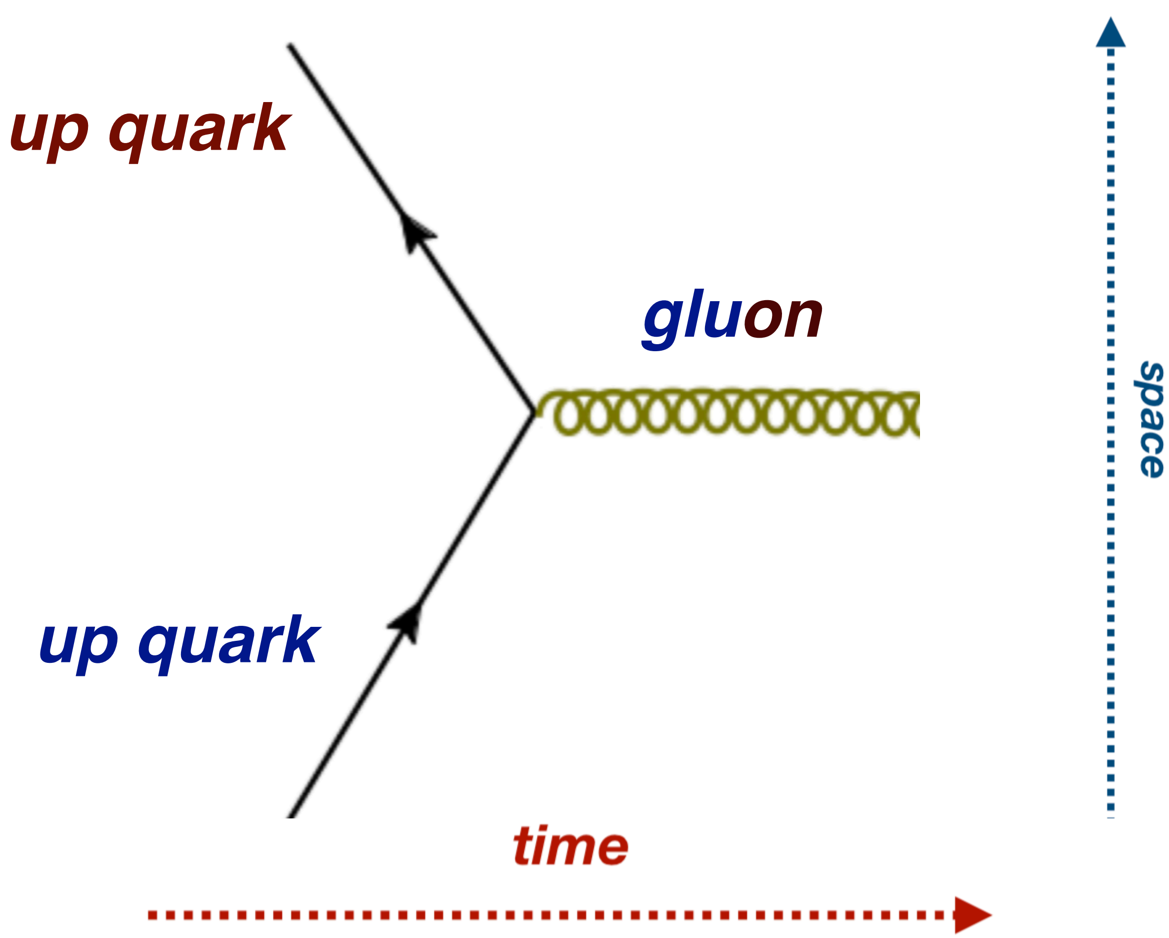

Is this reaction possible?

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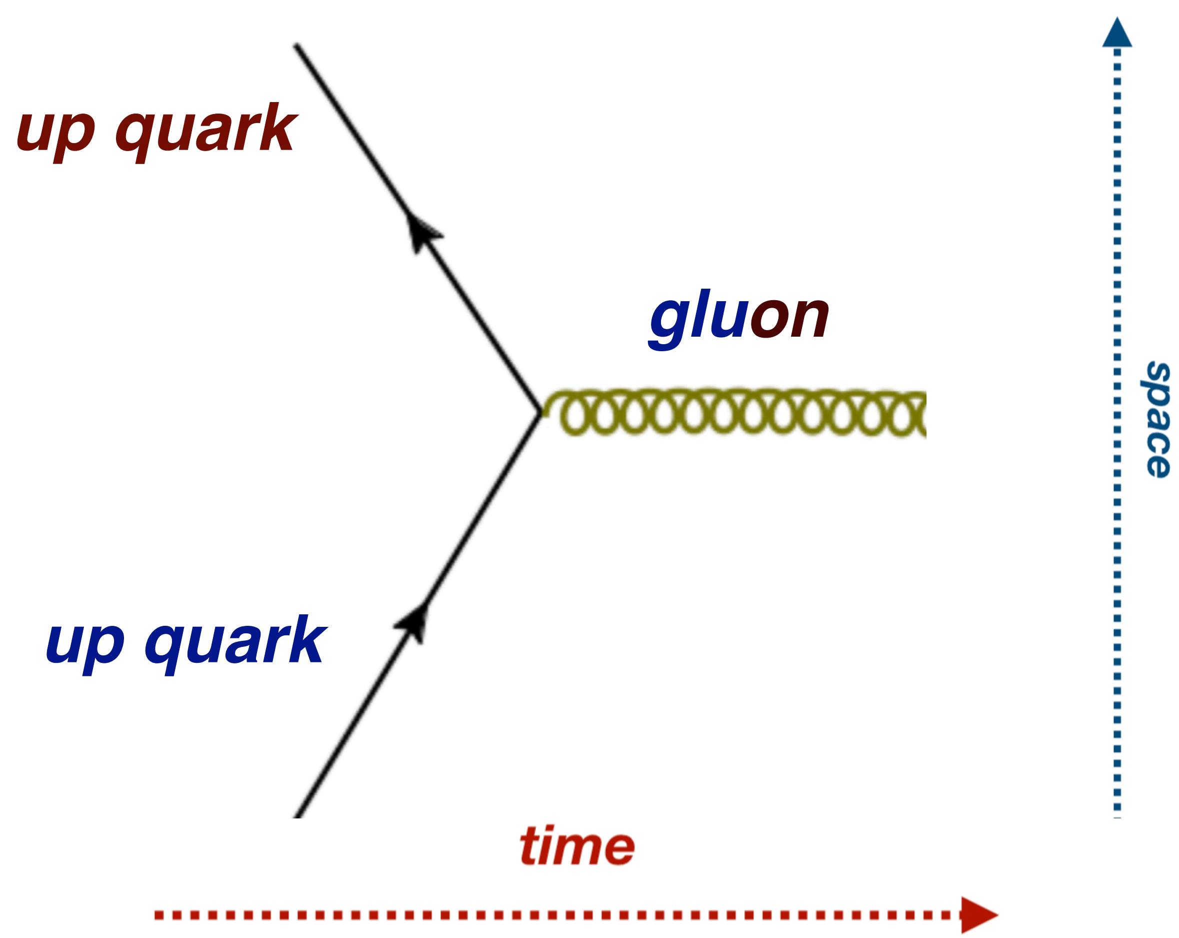

It is not possible since:

$$Q_{\rm in} = \frac{2}{3} + \frac{2}{3} = \frac{4}{3} \neq Q_{\rm fin} = 0$$

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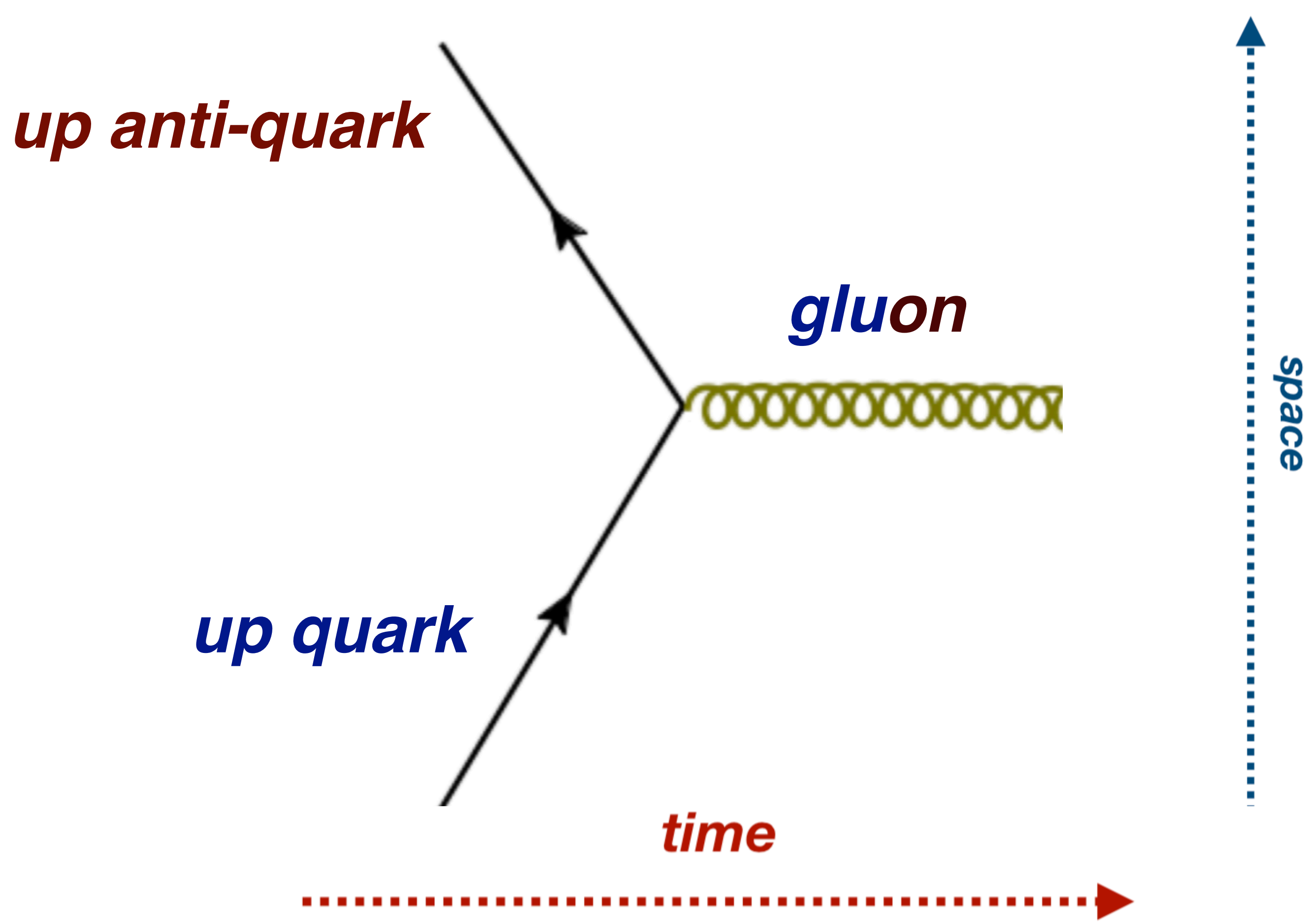

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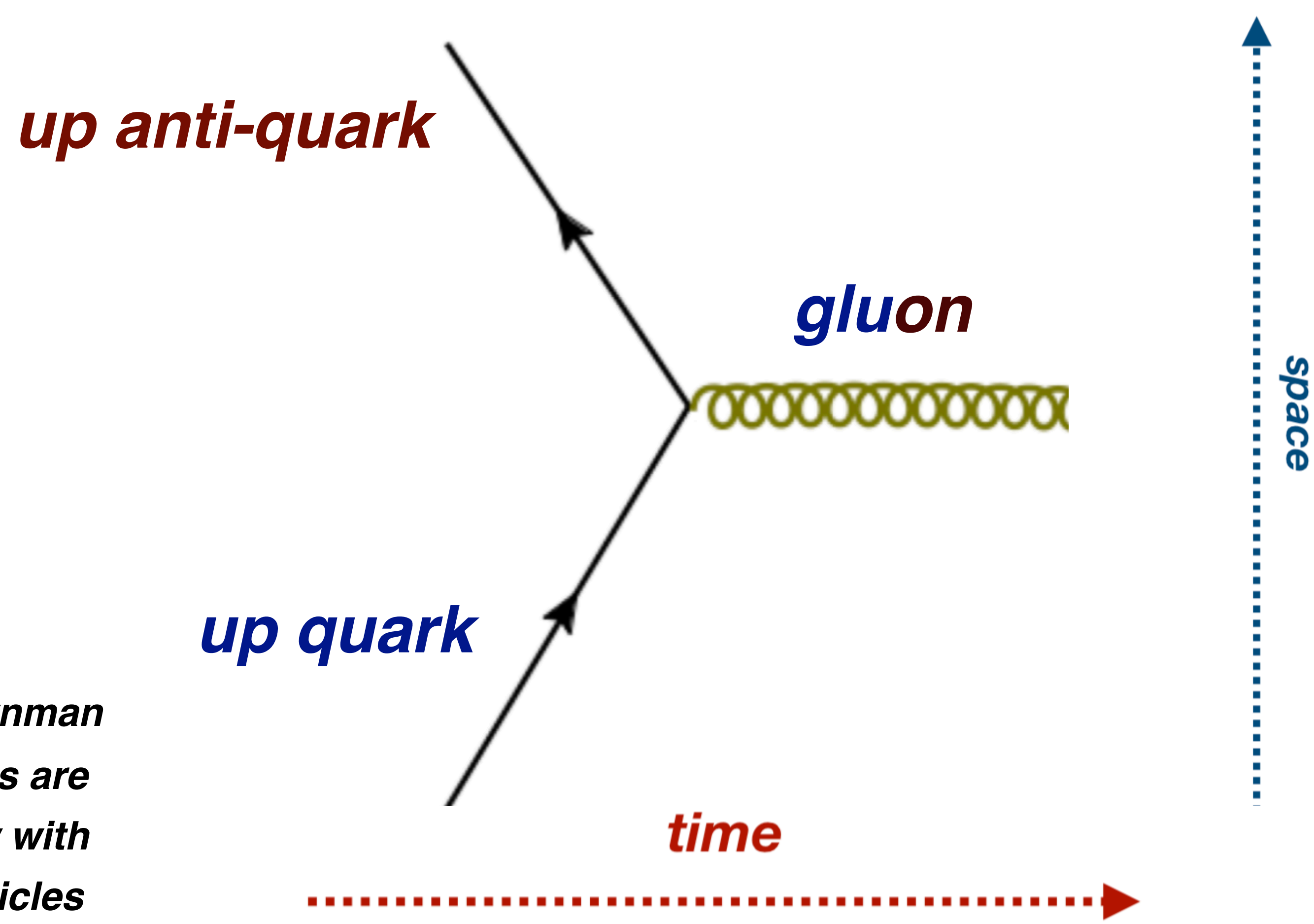

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by convention, in Feynman diagrams antiparticles are indicated by an arrow with opposite sign as particles

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Scattering reactions in QCD

Let's try to understand some **strong-interacting scattering processes** in terms of QCD

exercise

$$\pi^0 + p \to n + \pi^+$$

Write the corresponding Feynman diagram using **only quarks and gluons**

$$\pi^0 = (u\,\bar{u}) \qquad \pi^+ = \left(u\,\bar{d}\right)$$

Note also how ***Q, B, S, C, …*** are conserved in this reaction

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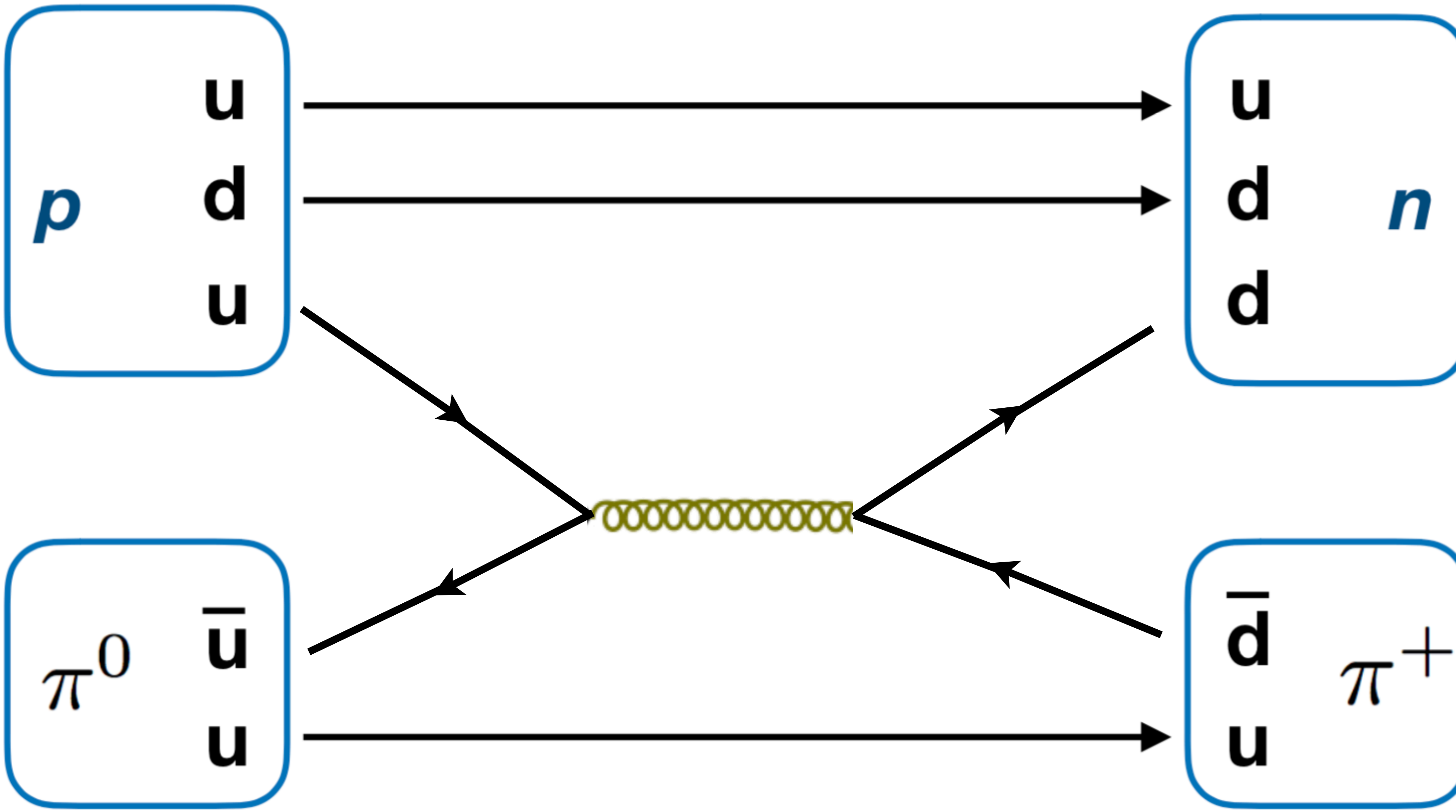
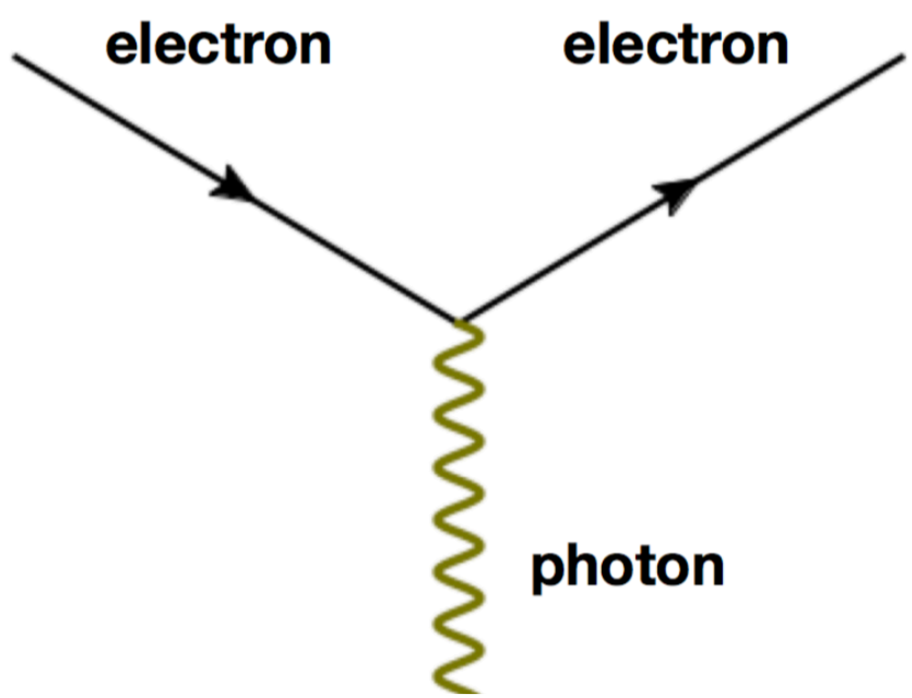


Quantum Electromagnetism (QED)

In QED there is a unique **interaction vertex:**



This fact implies the following **important properties** about the electromagnetic interaction:

- ☑ Electric charge is always conserved because the photon **does not carry electric charge**
- ☑ Being electrically neutral, the photon **cannot interact with itself**
- ☑ **Flavour** is conserved by QED interactions: automatic conservation of leptonic and baryonic numbers, as well as strangeness, charmness, and bottomness
- ☑ Since the photon is **exactly massless,** electromagnetism is a **long-range force**

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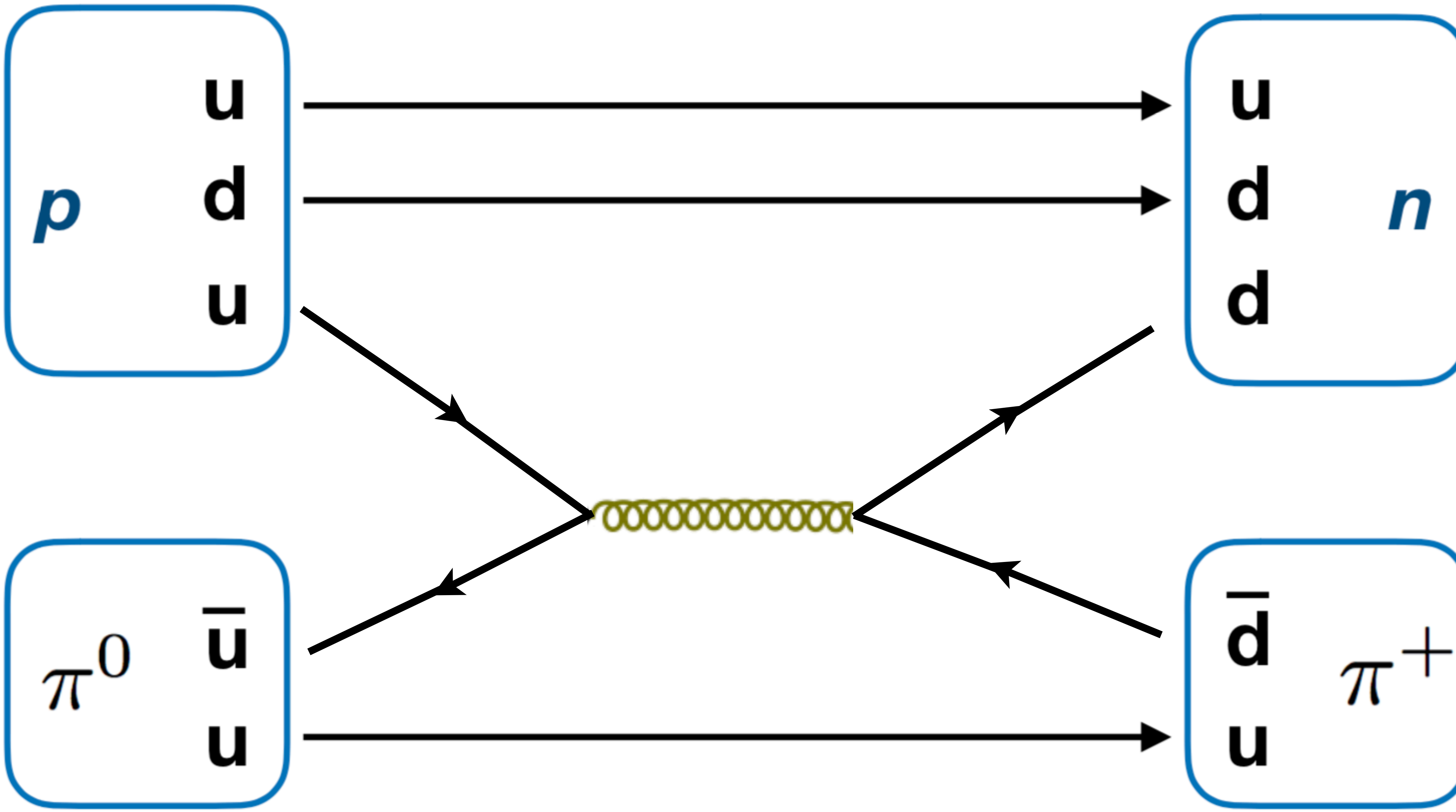

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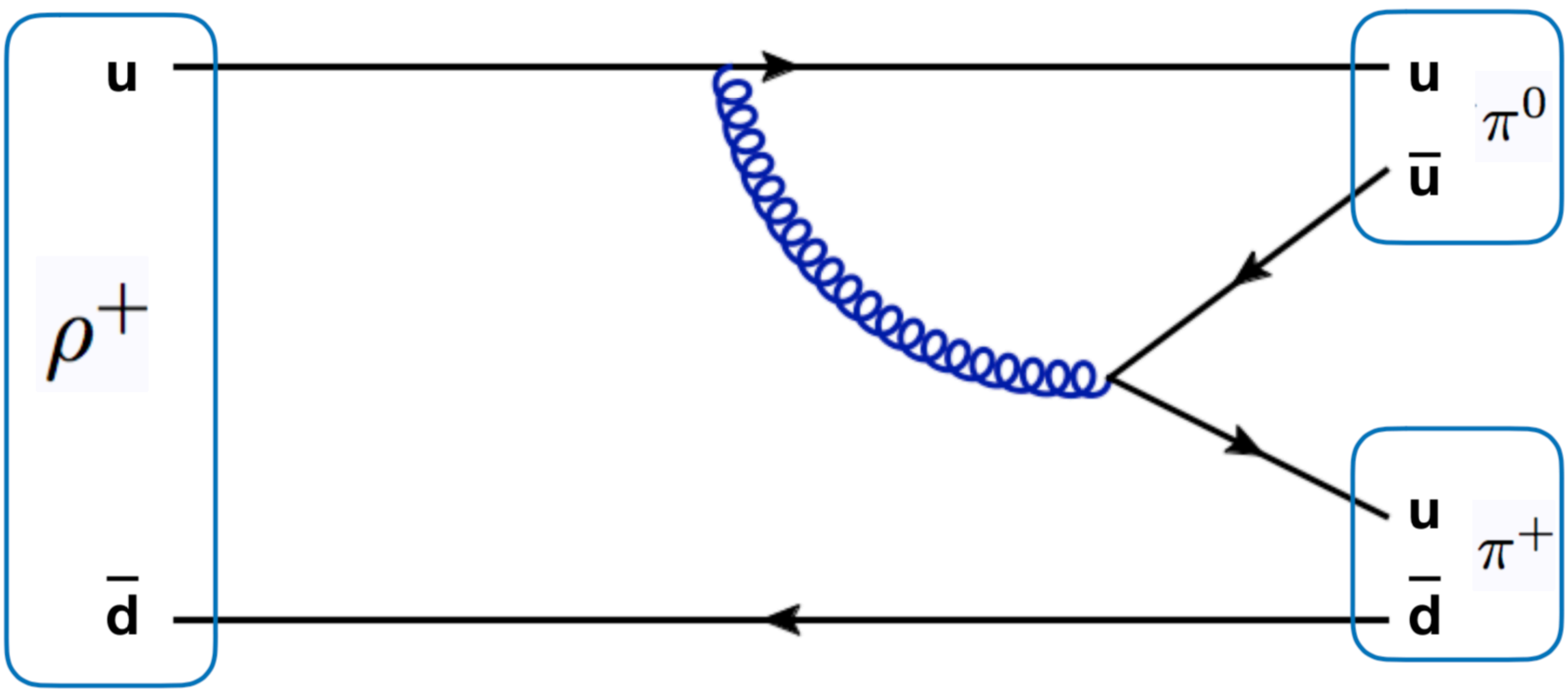

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Drawing Feynman diagrams

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- Make sure that all interaction vertices **conserve the corresponding quantum numbers:** for example, if gluons or photons are conserved, then ***Q, B, S, C, b, …*** should be conserved

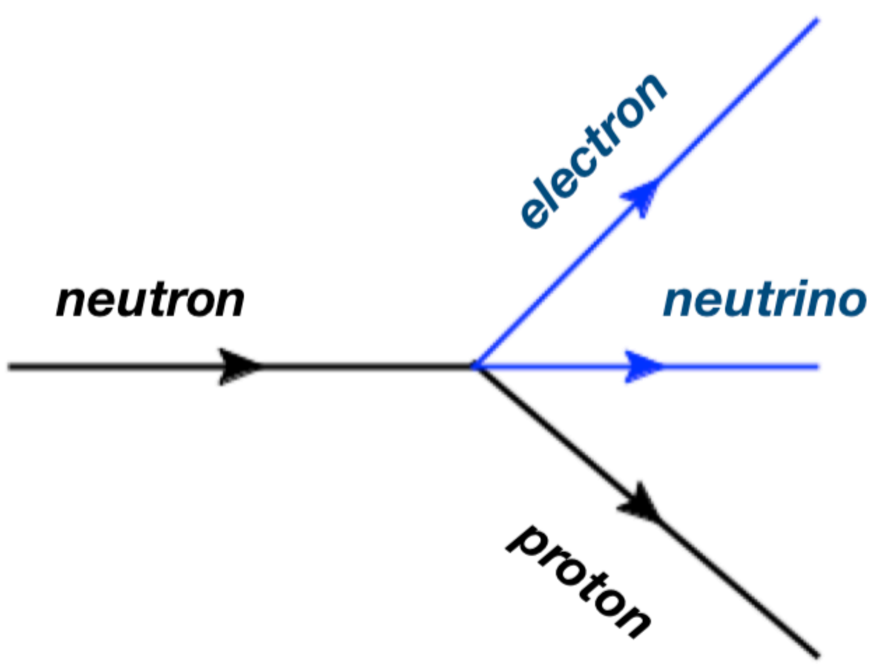
The weak interaction

The weak nuclear force

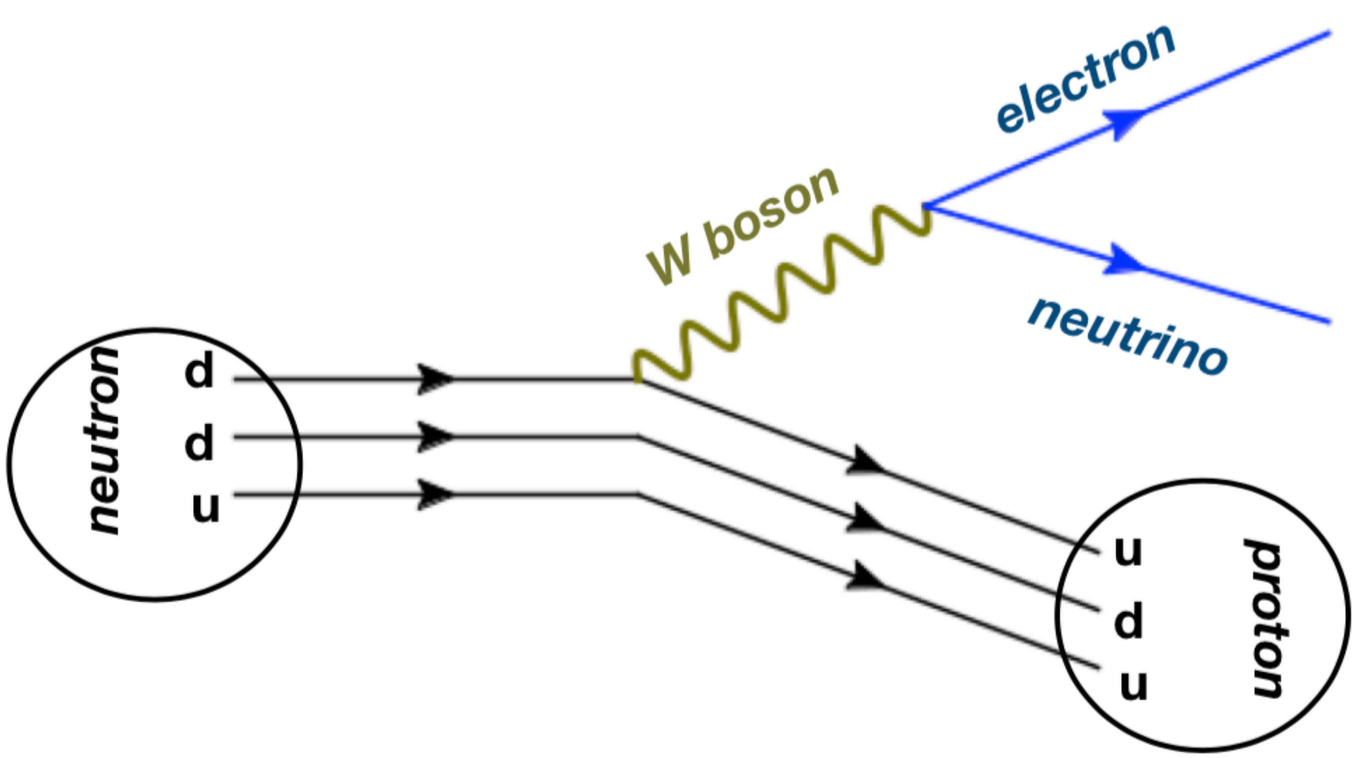
- Fermi (30s) explained **beta-decay of nuclei** by a **four-body interaction** between neutrons, protons, electrons and neutrinos: the **weak nuclear interaction**

- Weak interaction also similar to electromagnetism, but with **massive vector bosons, the W and Z particles.** Due to **large masses** (80 and 91 GeV) their interactions are **point-like at low energies**

Fermi picture of the weak interaction



The weak interaction in the Standard Model



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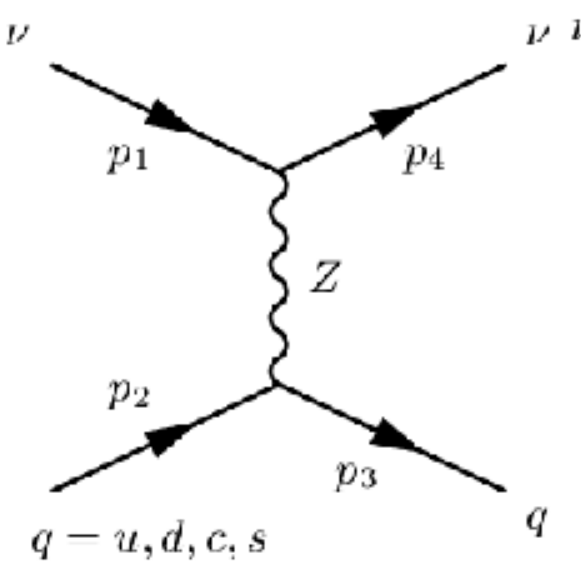
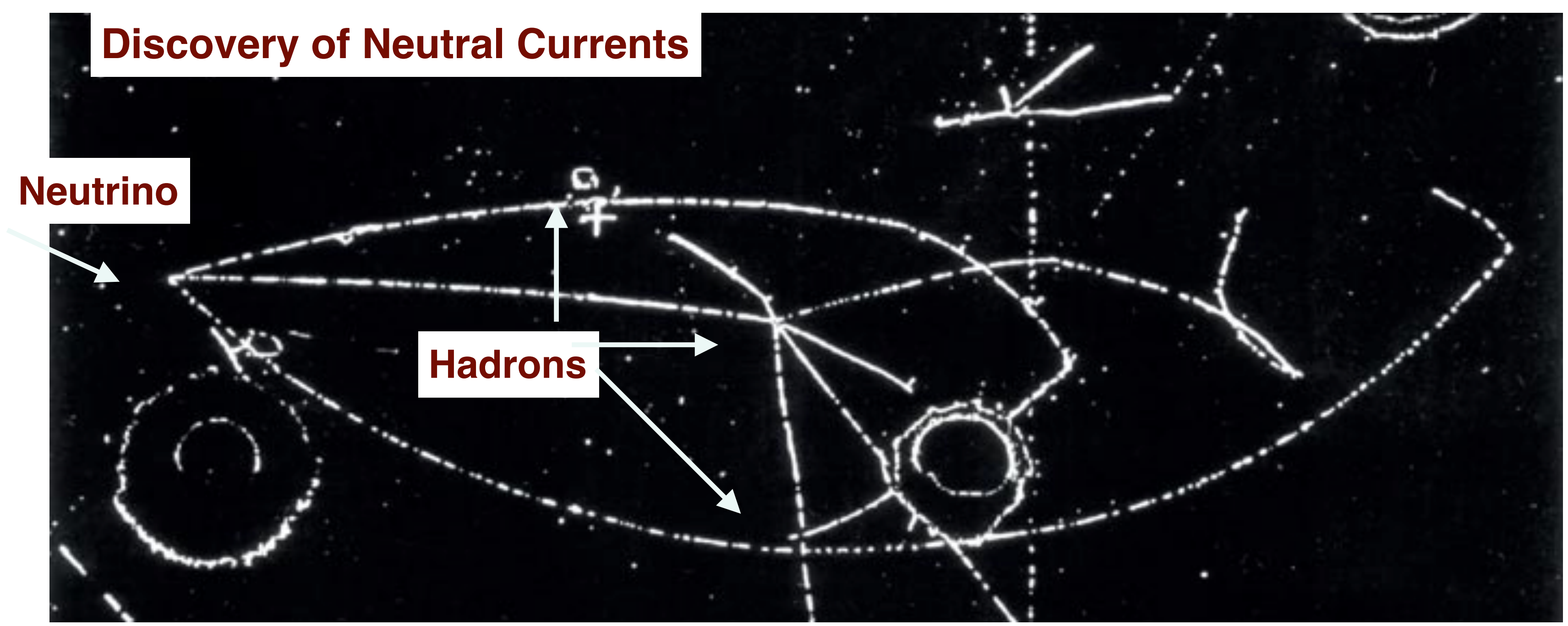
- Evidence for **Neutral Currents** (73) followed by the **discovery of the W and Z** bosons at the CERN (83)

Neutral currents in neutrino scattering: indirect evidence for the Z boson





Weak force vs electromagnetism

It is useful to enumerate the **properties of the weak interaction** by comparing them with those of the electromagnetic interactions

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$$m_{W^\pm} = 80.385\,\mathrm{GeV}$$
$$m_{Z^0} = 91.1876\,\mathrm{GeV}$$

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- The weak interaction is always weak and confined to small scales (large value of $m_{W,Z}$)

$$\text{range} : \Delta r \sim m^{-1} \quad \begin{cases} \Delta r \simeq \infty \quad (\text{EM, QCD}) \\ \Delta r \simeq 10^{-18}\,\text{m} \quad (\text{weak}) \end{cases}$$

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$$\overline{K^0} \to \pi^+ + \pi^-$$

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exercise

$$D^+ \rightarrow \overline{K^0} + e^+ + \nu_e$$

Compute the variation in strangeness in this reaction

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$$S_{\rm in} = 0 \neq S_{\rm fin} = -1 \quad \to \quad \Delta S = -1$$

The weak boson *W*

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The weak interactions are mediated by three massive bosons: ***W+, W+, Z0***

The main properties of the ***W* bosons** are:

☑ As opposed to the **massless** gluons and photons, the W boson is **very massive,** around 80 times the proton mass

$$m_\gamma = 0$$
$$m_g = 0$$
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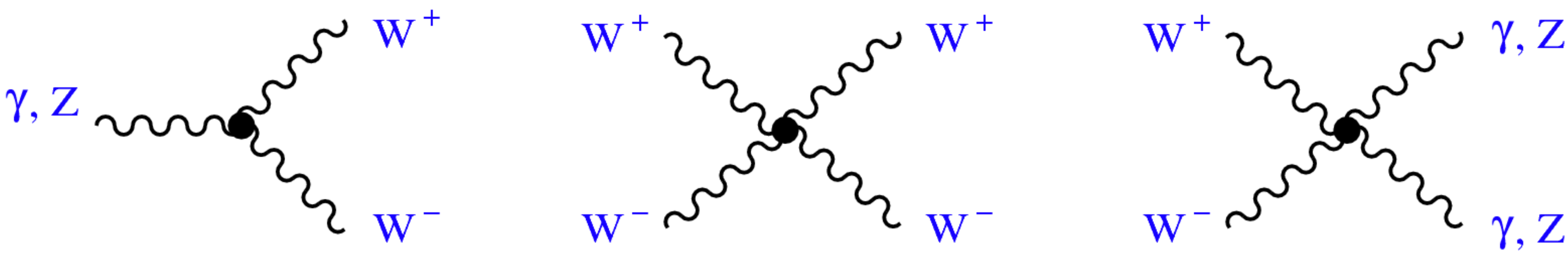

Note how all these **interaction vertices** satisfy electric charge conservation

$$Q_{\rm in} = +1 + (-1) = 0 = Q_{\rm fin}$$

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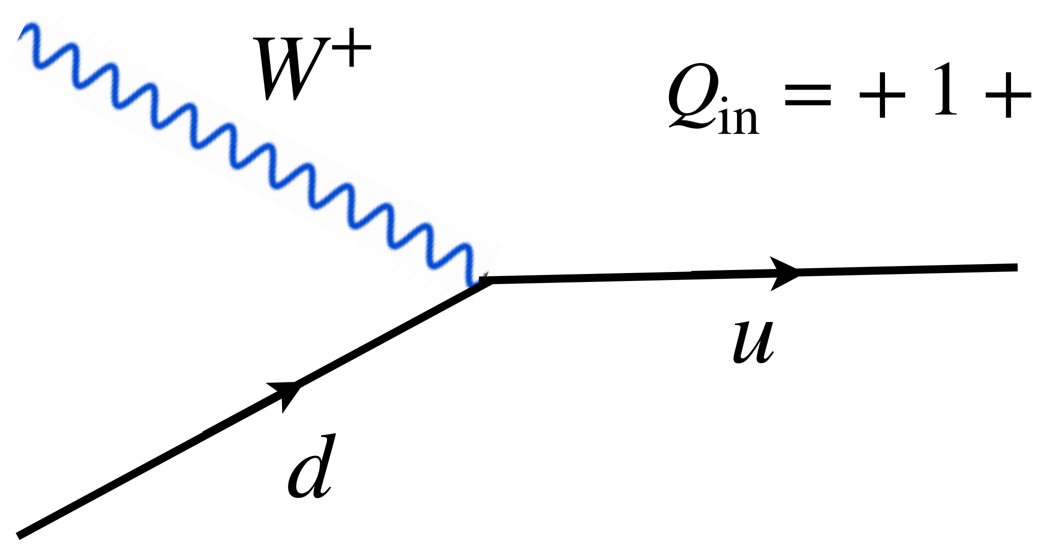
- When interacting with **quarks,** the *W* boson will change its charge by **one unit** and therefore also **its flavour** (including possibly across generations)



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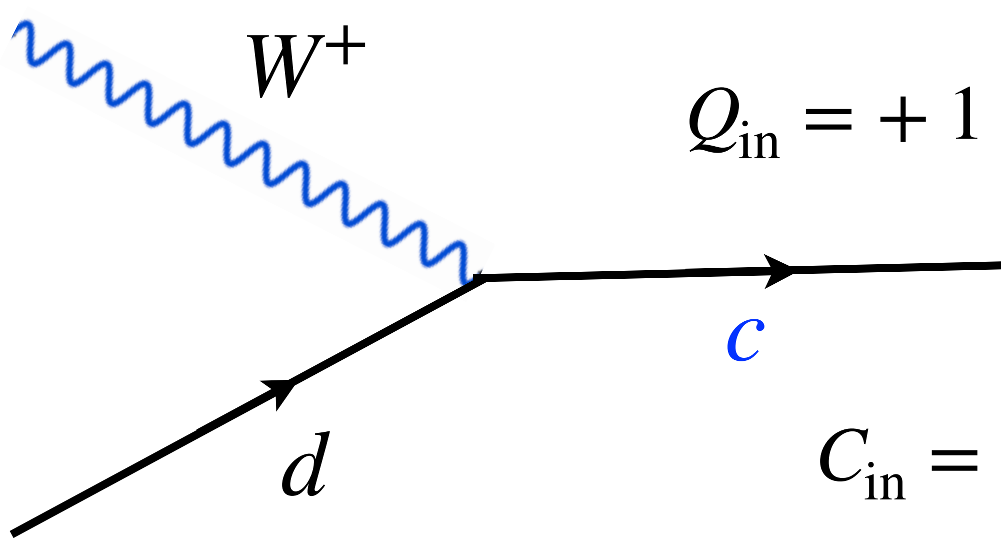

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$$C_{\rm in} = 0 \neq C_{\rm fin} = +1$$

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- In weak interaction processes **mediated by the *W* boson,** the flavour quantum numbers (strangeness, charmness, botomness) are **not conserved** quantities

The weak boson *W*

Taking into account these properties, some of the physically allowed reactions involving **quarks** and ***W* bosons** will be:

$$u + W^- \to d\,, \quad u + W^- \to s\,, \quad d + W^+ \to u\,, \quad s + W^+ \to u\,,$$

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- You can always **replace** a given quark by the corresponding quark of a **different generation**: for example a down antiquark by a strange antiquark

The weak boson W

Taking into account these properties, some of the physically allowed reactions involving **quarks** and ***W* bosons** will be:

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The weak boson *W*

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$$e^+ + W^- \to \bar{\nu}_e \quad \Rightarrow \quad \tau^+ + W^- \to \bar{\nu}_\tau$$

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- ☑ The **individual leptonic quantum numbers** are always conserved in weak reactions

The weak boson W

exercise

Draw the Feynman diagram for the following process

$$\pi^+ \to \mu^+ + \nu_\mu \qquad \pi^+ = (u\,\bar{d})$$

The weak boson *W*

exercise

Draw the Feynman diagram for the following process

$$\pi^+ \to \mu^+ + \nu_\mu \qquad \pi^+ = (u\,\bar{d})$$

- ☑ We have a neutrino in the final state: the **weak interaction** must be involved
- ☑ Quarks and leptons only interact indirectly via either photons or *W, Z* bosons
- ☑ Since the electric charge is ***Q=+-1,*** then a positively charged ***W boson*** is involved
- ☑ We know what **vertices are allowed** involving quarks or leptons and a *W* boson

The weak boson *W*

exercise

Draw the Feynman diagram for the following process

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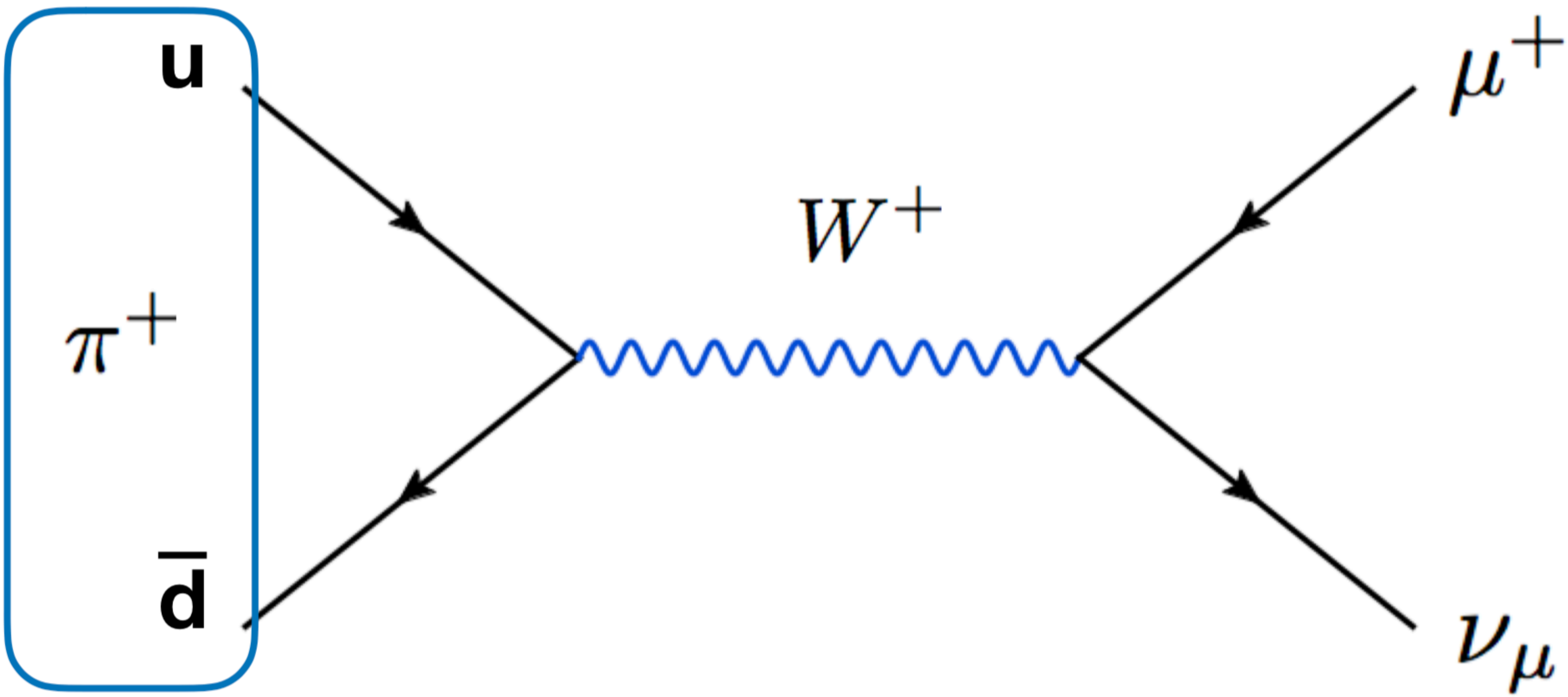
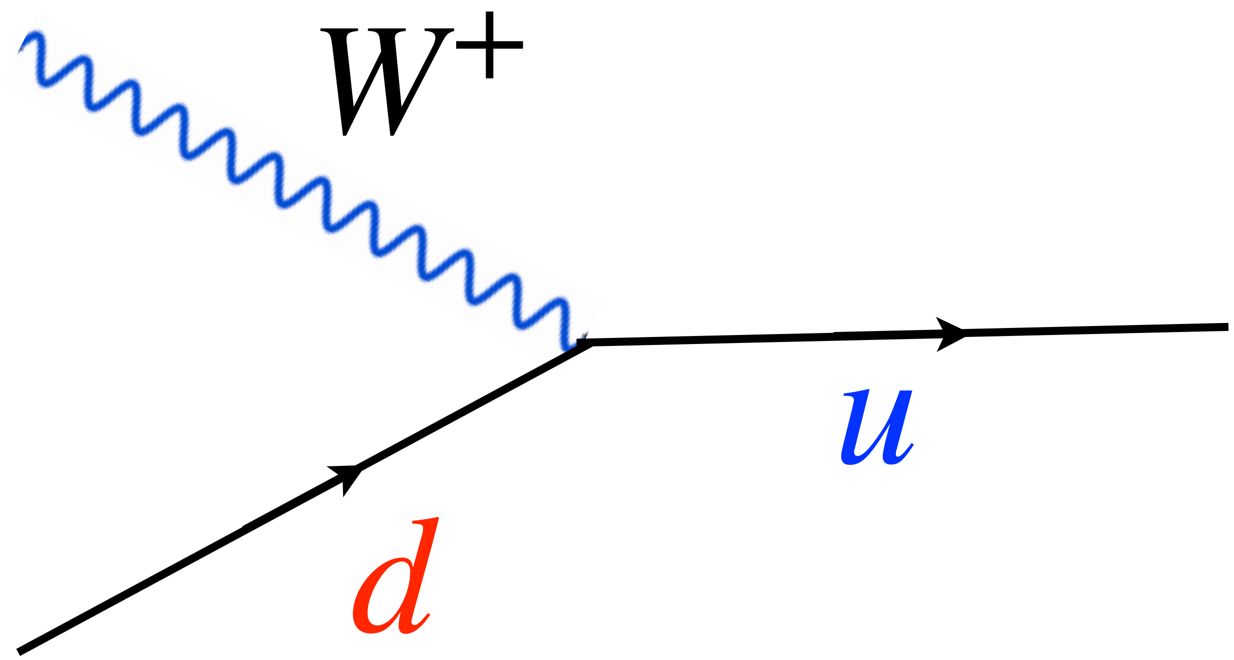


You can check that all relevant quantum numbers are **conserved:** *L, B, Q, …*

Heavy hadron decays

Weak coupling between generations

We have seen that in processes mediated by the weak gauge boson *W* the **flavour** of the quarks will **change**



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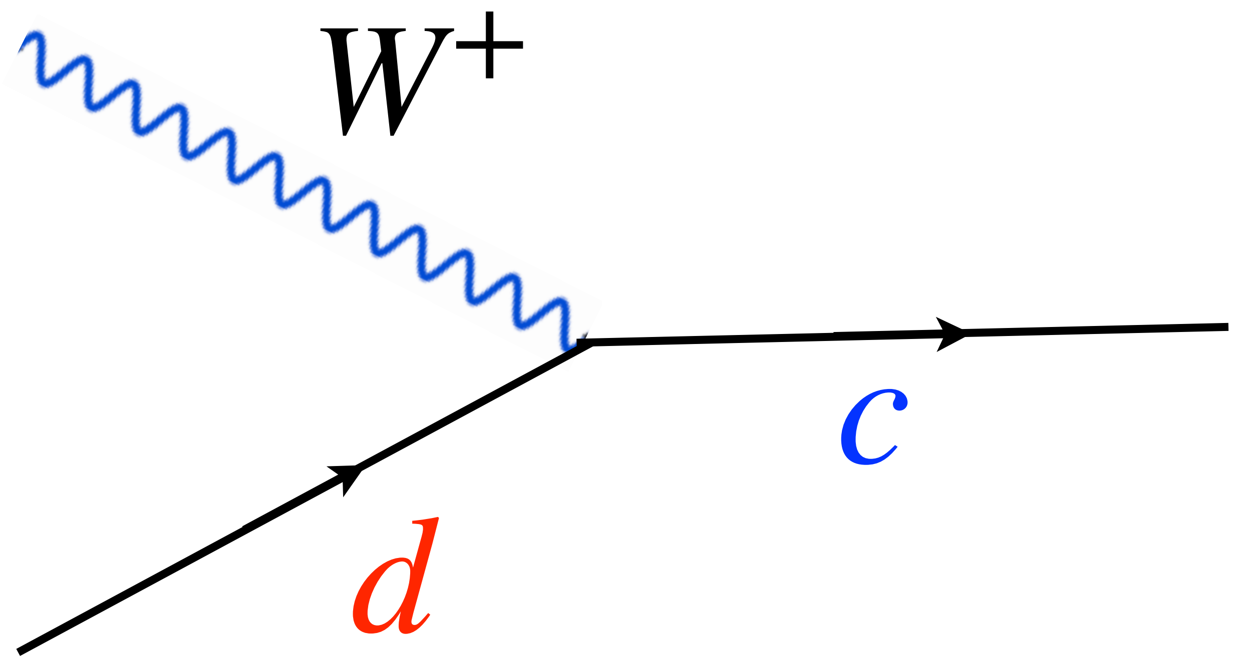

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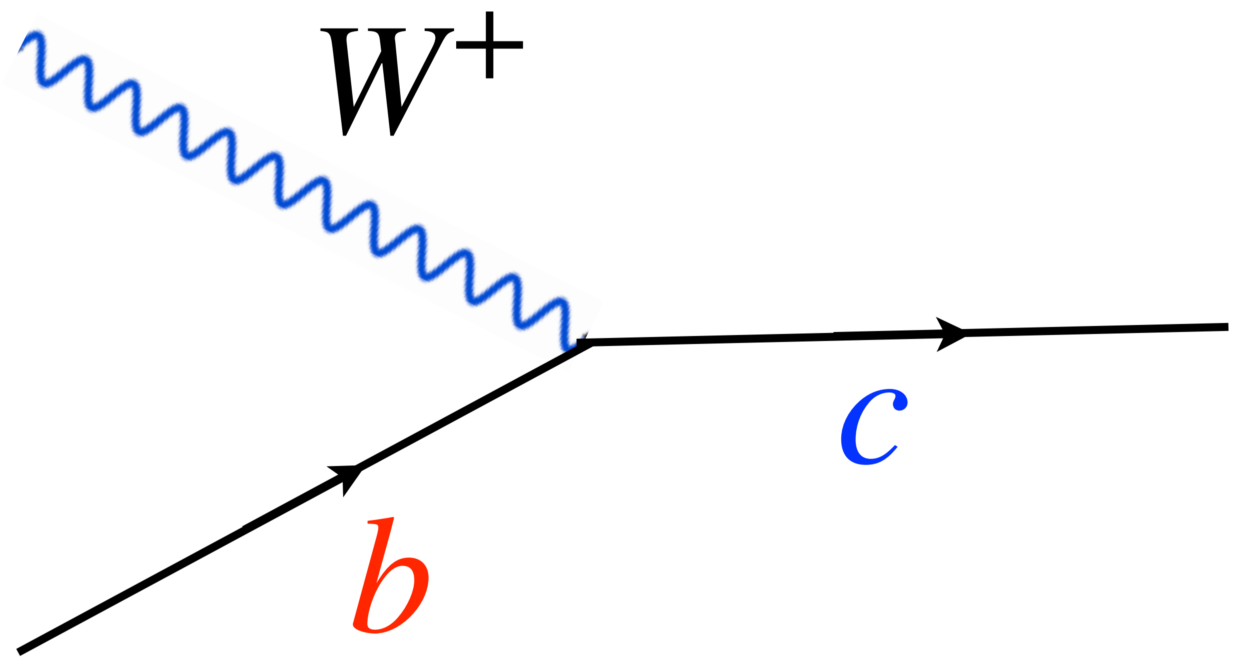

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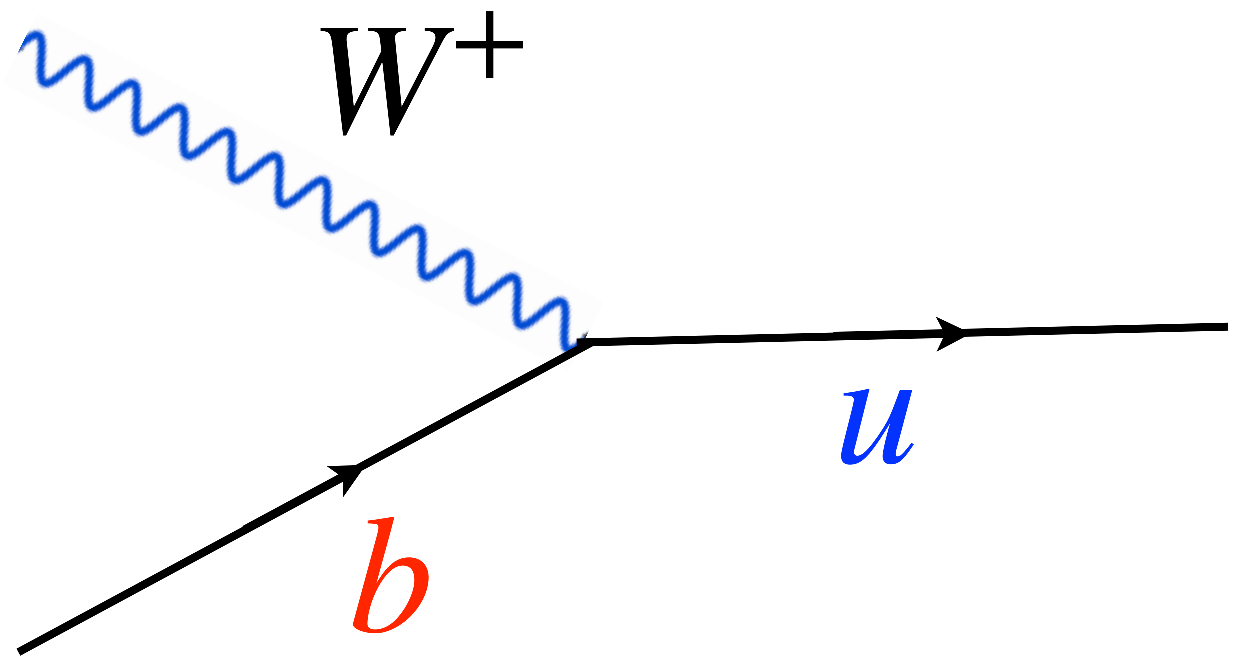
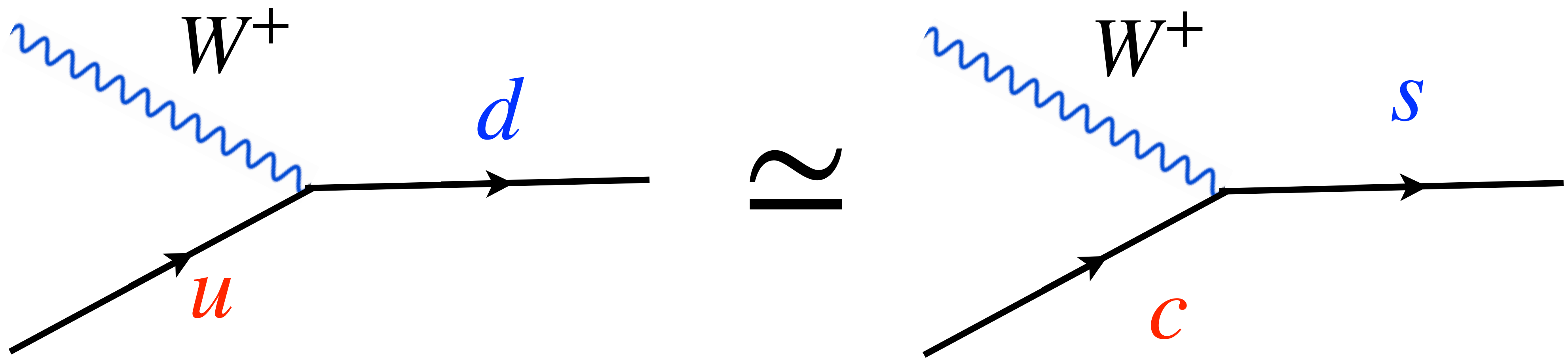


Moreover we can always replace a given quark by the corresponding quark of a **different generation**

The weak interactions mediates **transitions** between **quarks of different generations**

Weak coupling between generations

The **strength of the weak coupling** is similar between **quarks of the same generation**



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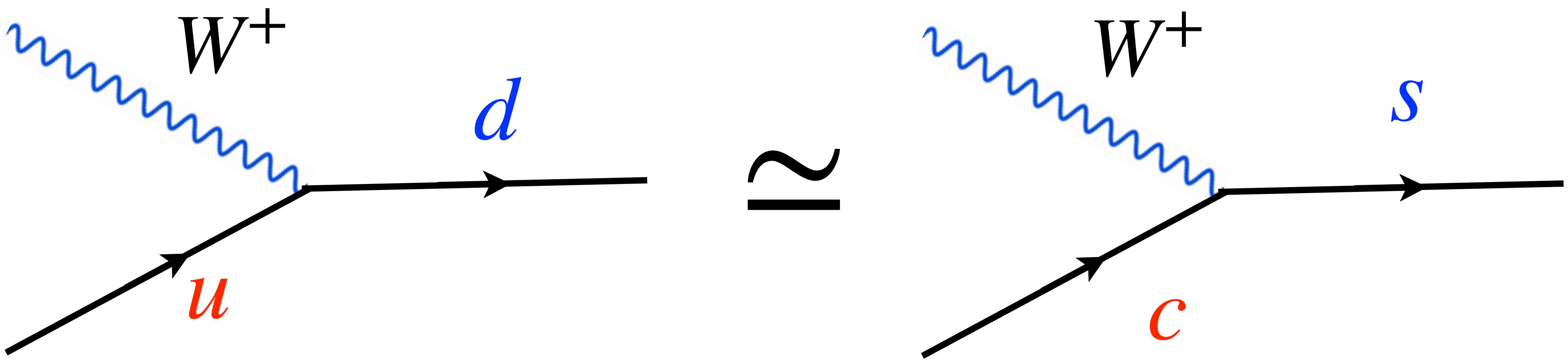
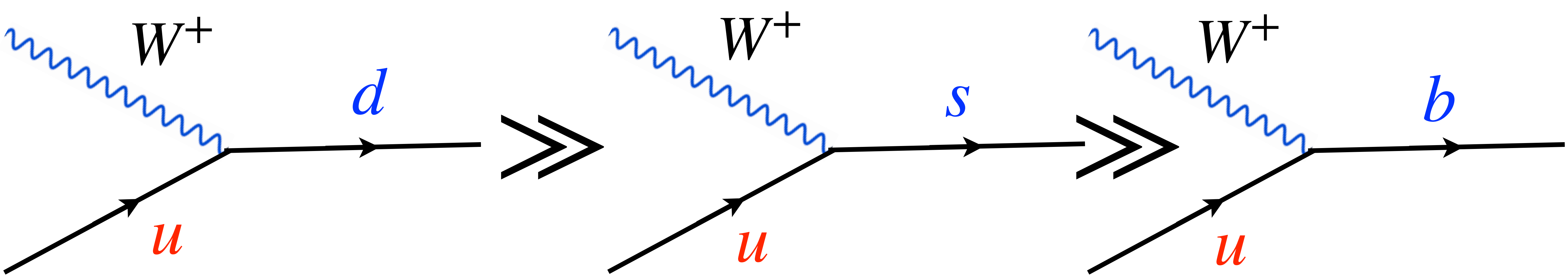


The **strength of the weak coupling** is smaller between **quarks of different generation**



Weak coupling between **gens 1 and 2** bigger than between **gens 1 and 3**

Drawing Feynman diagrams

- ☑ If the scattering reaction involves composite particles (hadrons) first of all determine their **quark decomposition** making sure all quantum numbers add up consistently

- ☑ Then put at the **left** of the diagram the **initial-state particles** and at the **right** of the diagram the **final-state** particles

- ☑ Attempt to connect the initial and final state particles among them. Note that some particles will not interact and will be just **spectators** in the reaction

- ☑ Make sure that all interaction vertices **conserve the corresponding quantum numbers:** for example, if gluons or photons are conserved, then ***Q, B, S, C, b, …*** should be conserved

Heavy hadron decays

exercise

This **hierarchy of the weak couplings** between quark generations is particularly important in order to understand the decays of **hadrons** that contain **heavy quarks**

$$B^0 \to D^- + \mu^+ + \nu_\mu \qquad B^0 = \left(d\,\bar{b}\right) \qquad D^- = \left(d\bar{c}\right)$$

what is the corresponding Feynman diagram?

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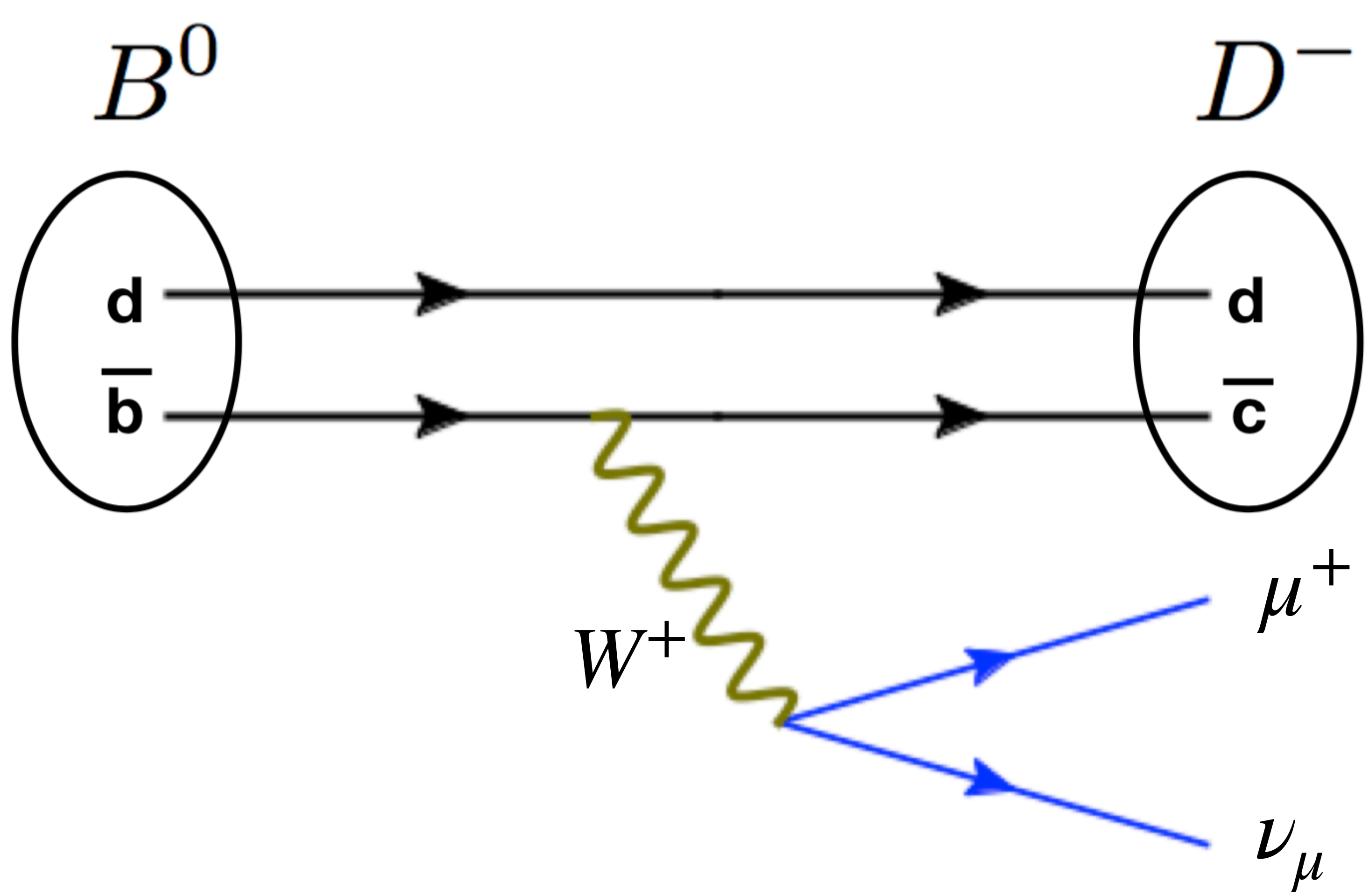

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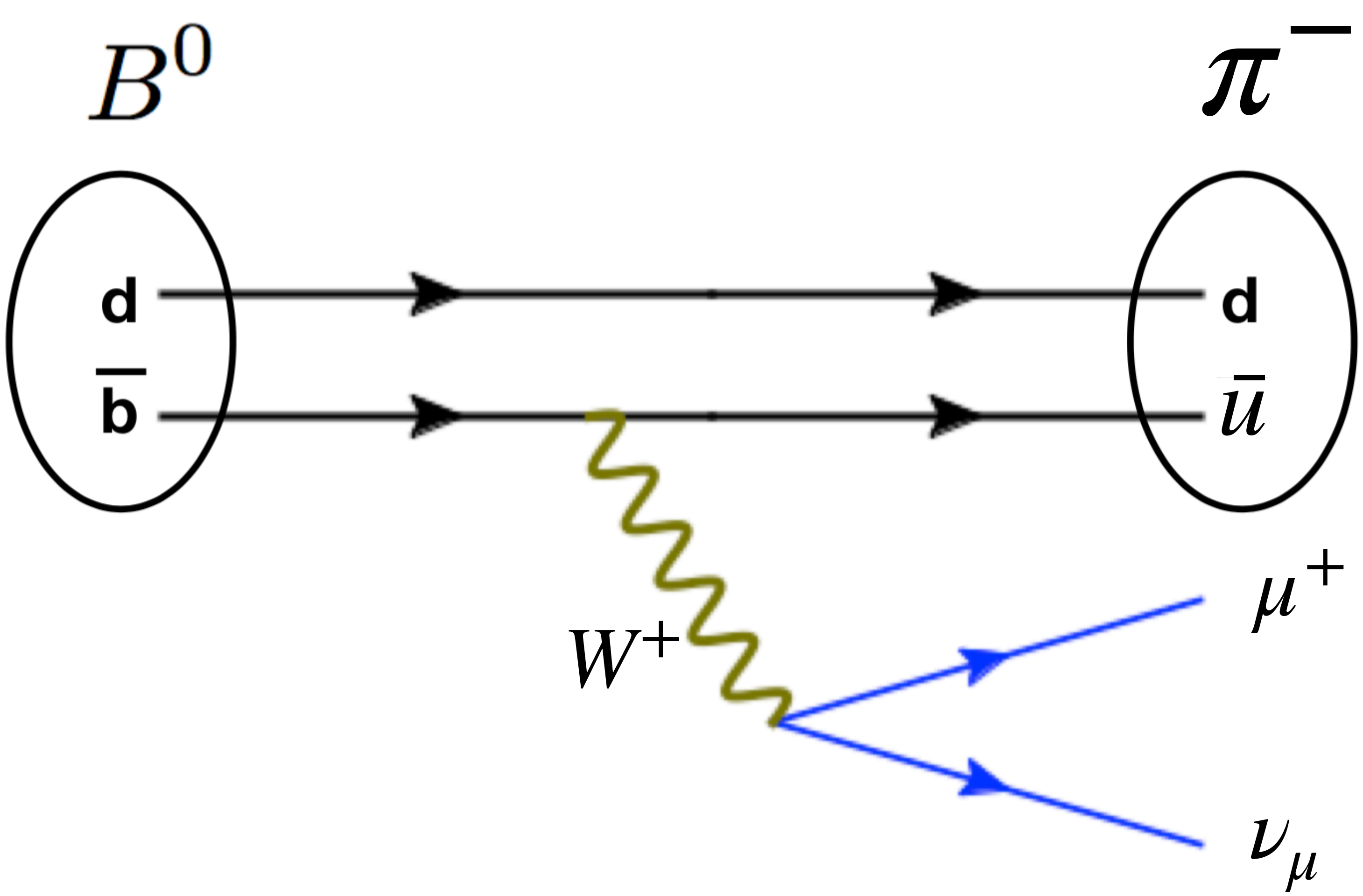
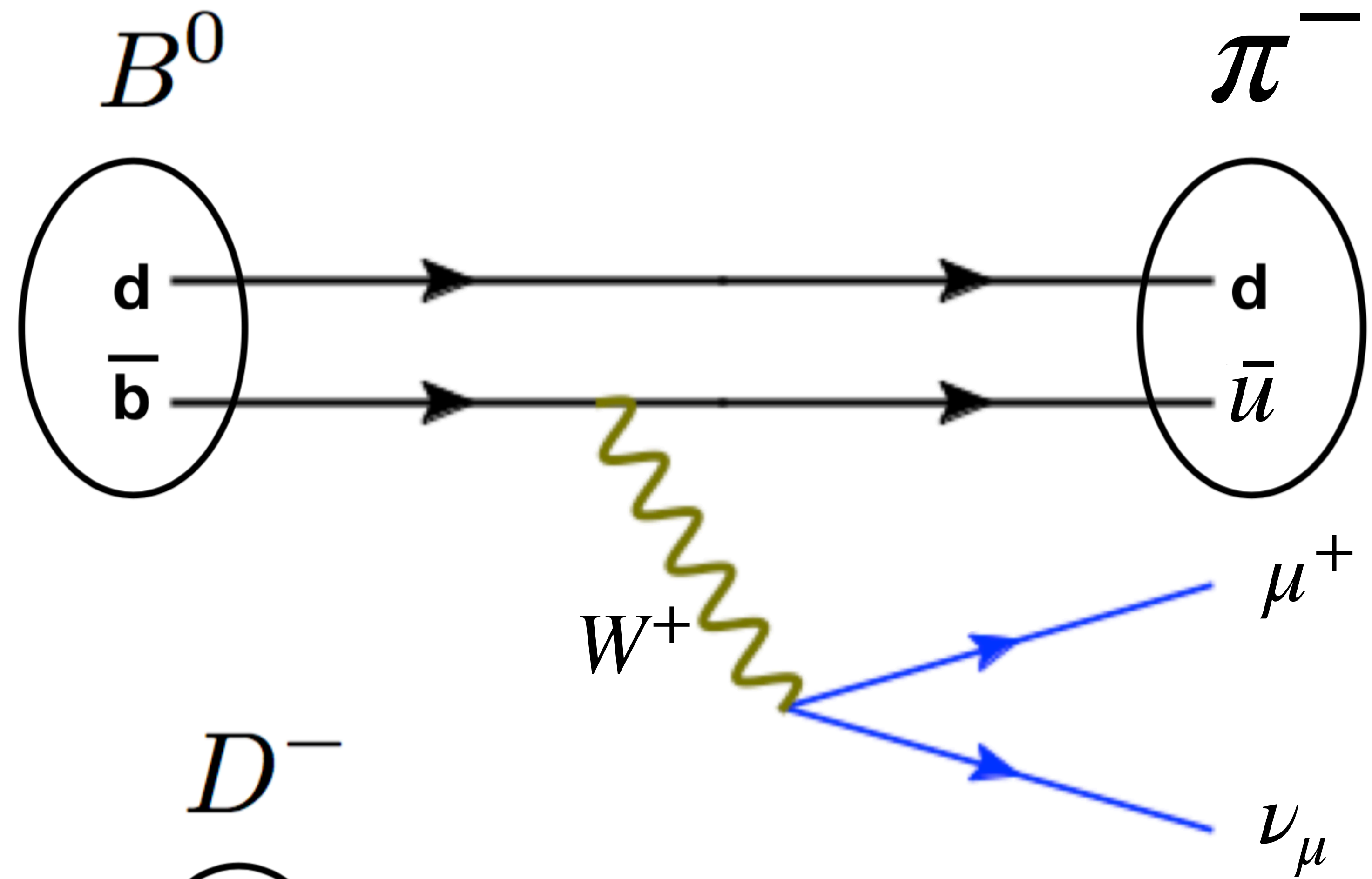
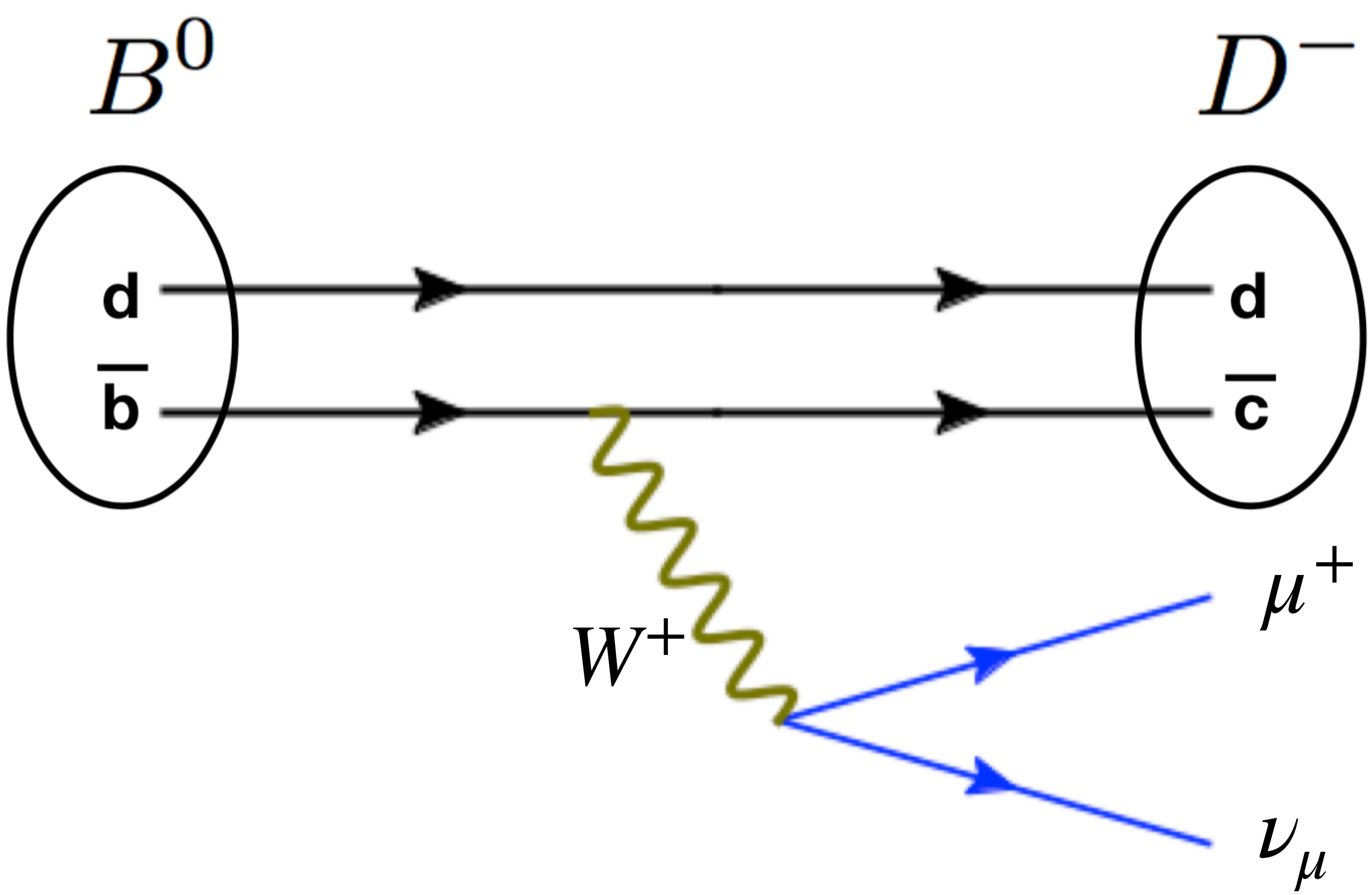


Heavy hadron decays

Which of the two reactions is **most likely** to take place?





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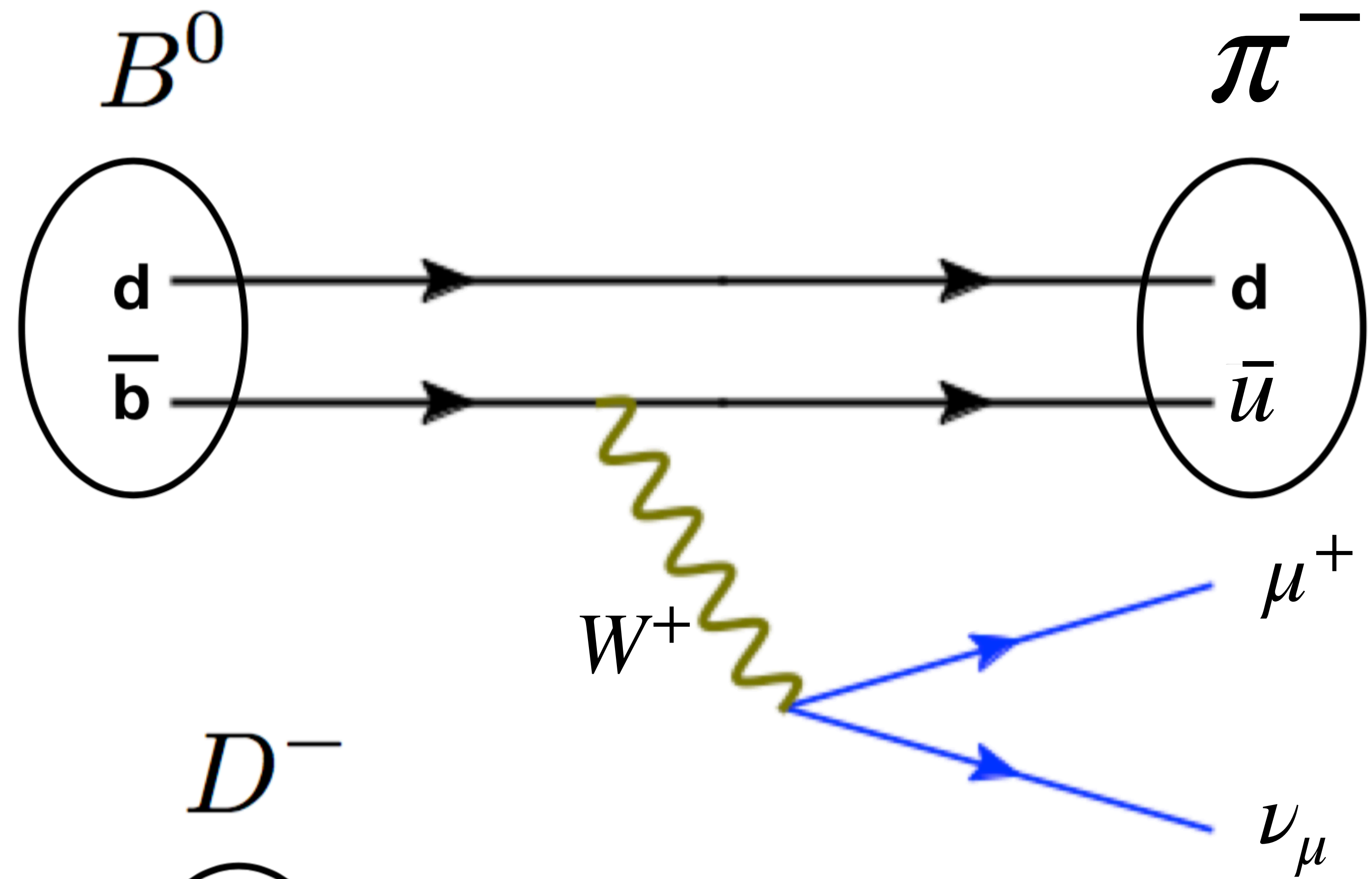

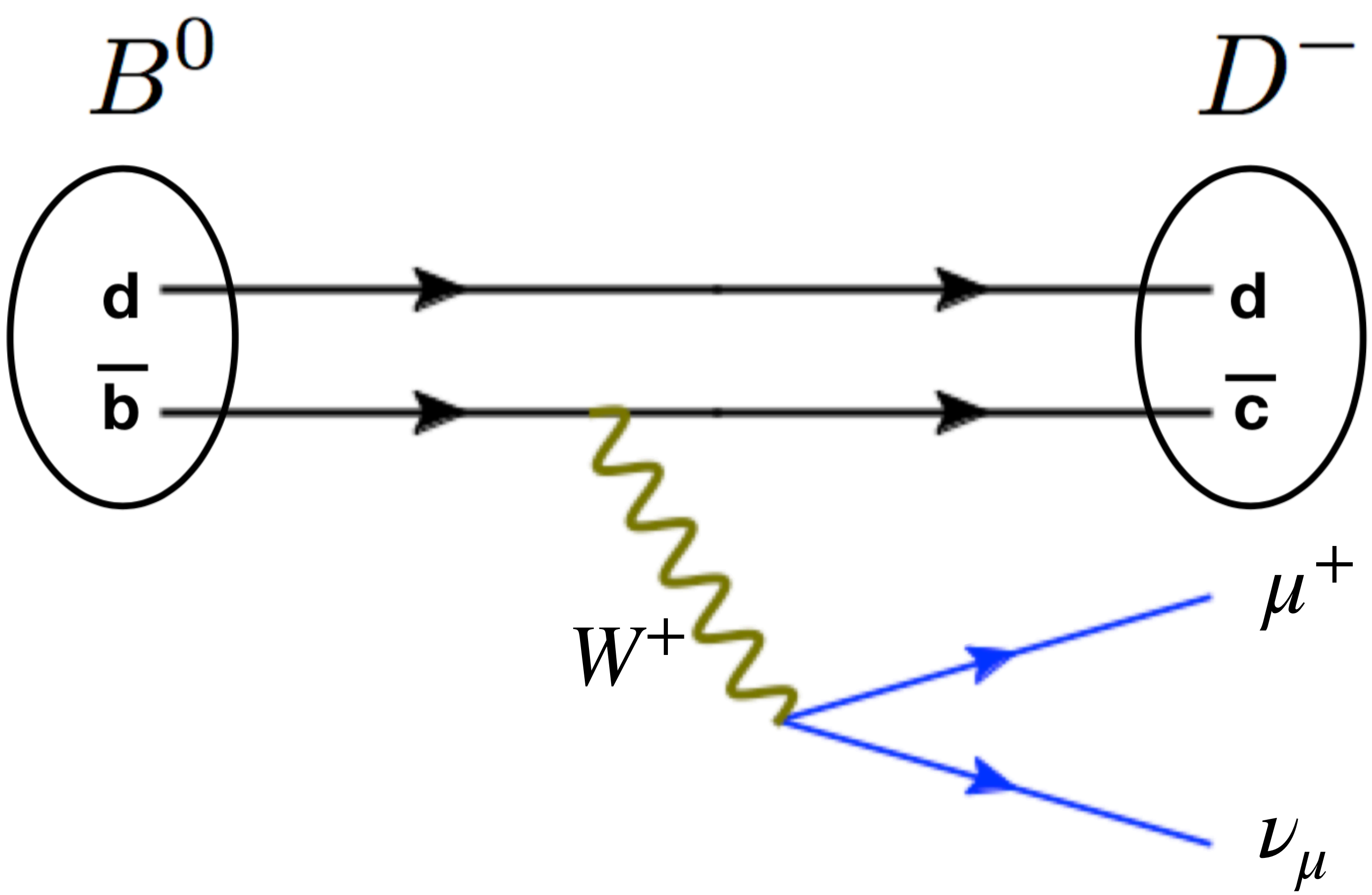

The decay into a pion is more suppressed, since the **coupling *Wub*** (gens 1 and 3) is **smaller** than the **coupling *Wcb*** (gens 1 and 2)

Heavy hadron decays

exercise

Draw the Feynman diagram associated to this **heavy hadron decay**

$$D^0 \to \pi^- + K^- + \pi^+ \qquad \pi^+ = (u\,\bar{s})$$

$$S_{K^-} = +1\,, C_{K^-} = b_{K^-} = B_{K^-} = 0$$

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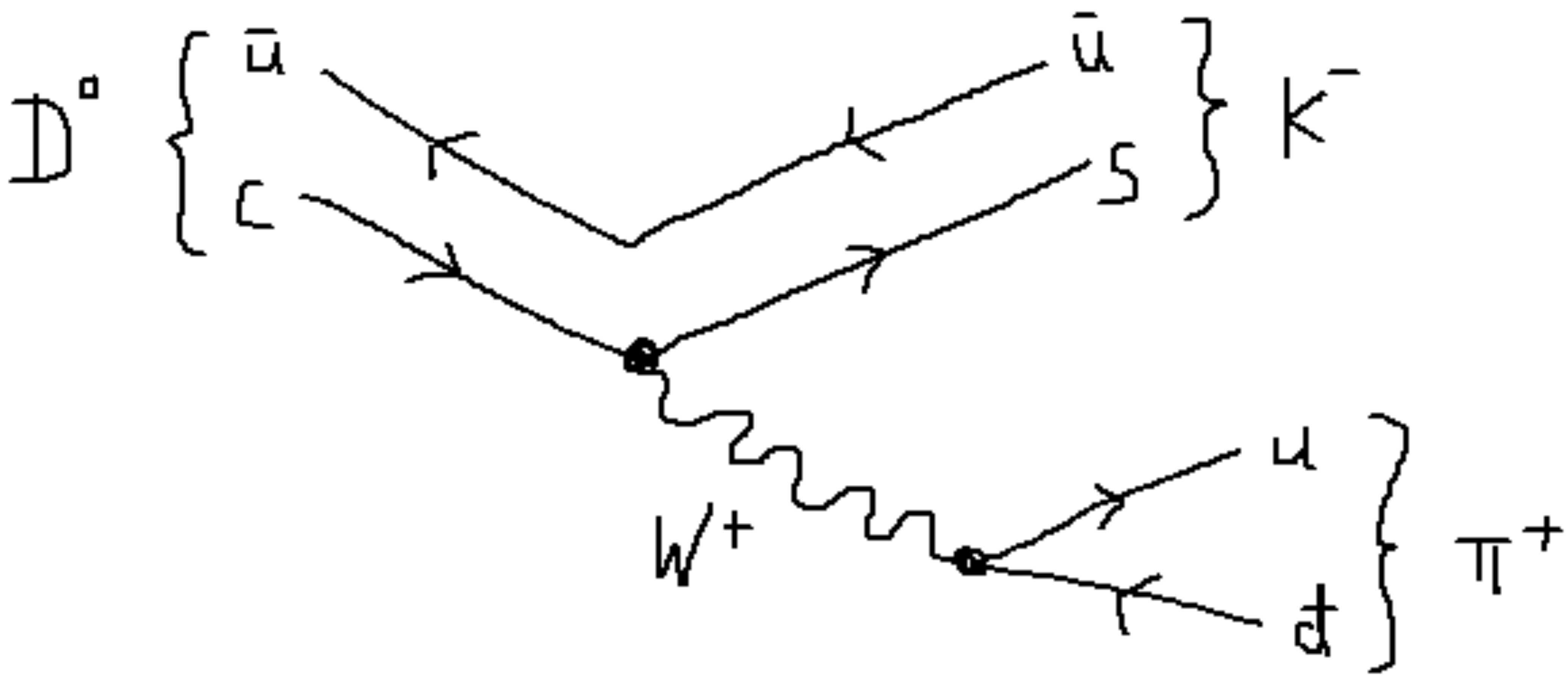

Heavy hadron decays

Note that some reaction processes might look **very different from the outside**, but their similarities become apparent at the **Feynman diagram level**

$$B^0 \to D^- + \mu^+ + \nu_\mu$$

$$B^0 \to D^- + \pi^+$$

How do these two decay models relate to each other?

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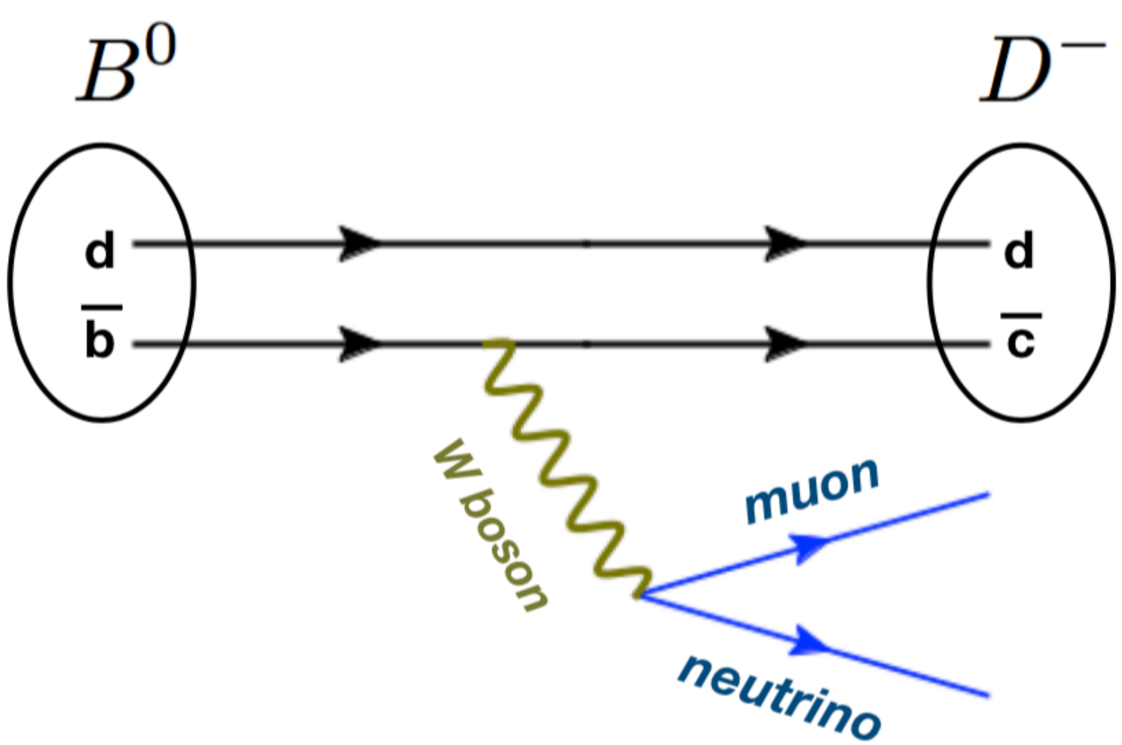

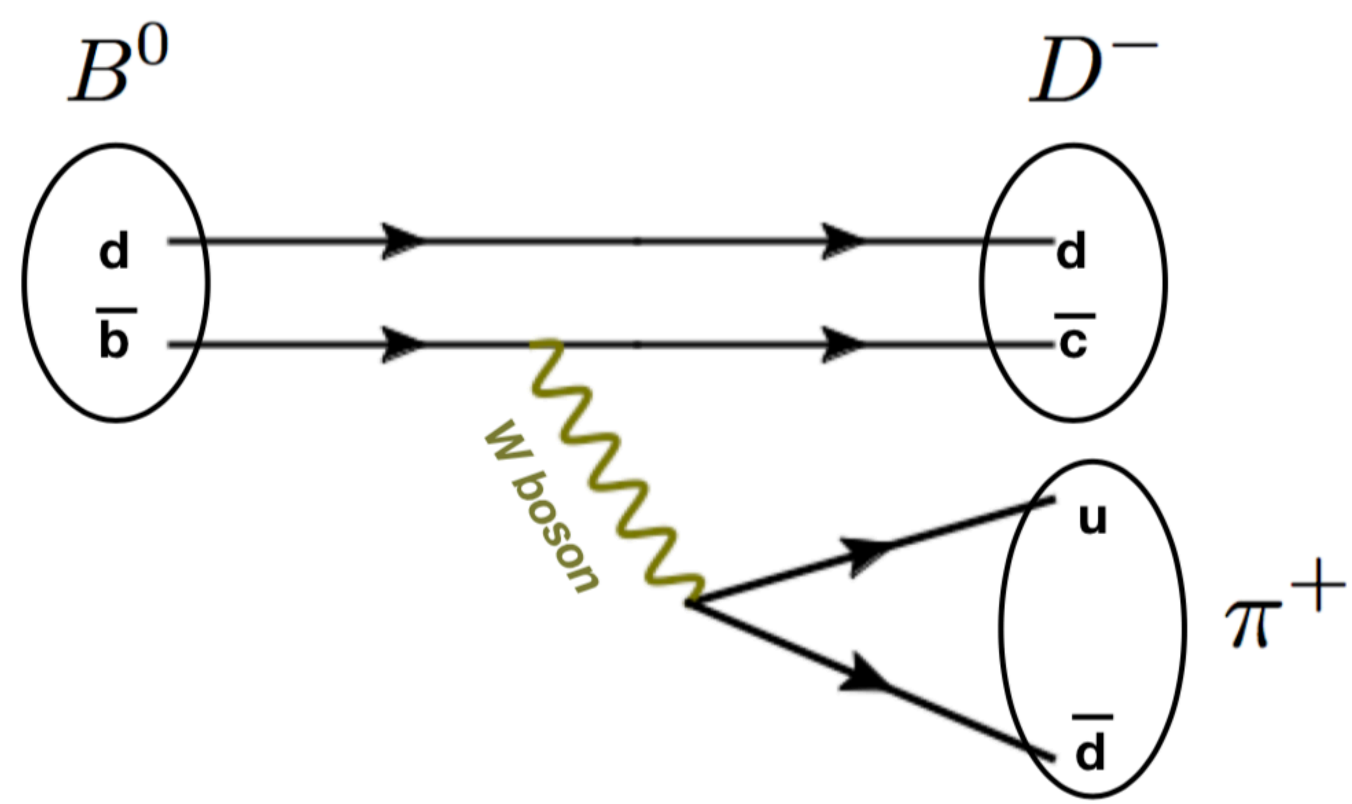

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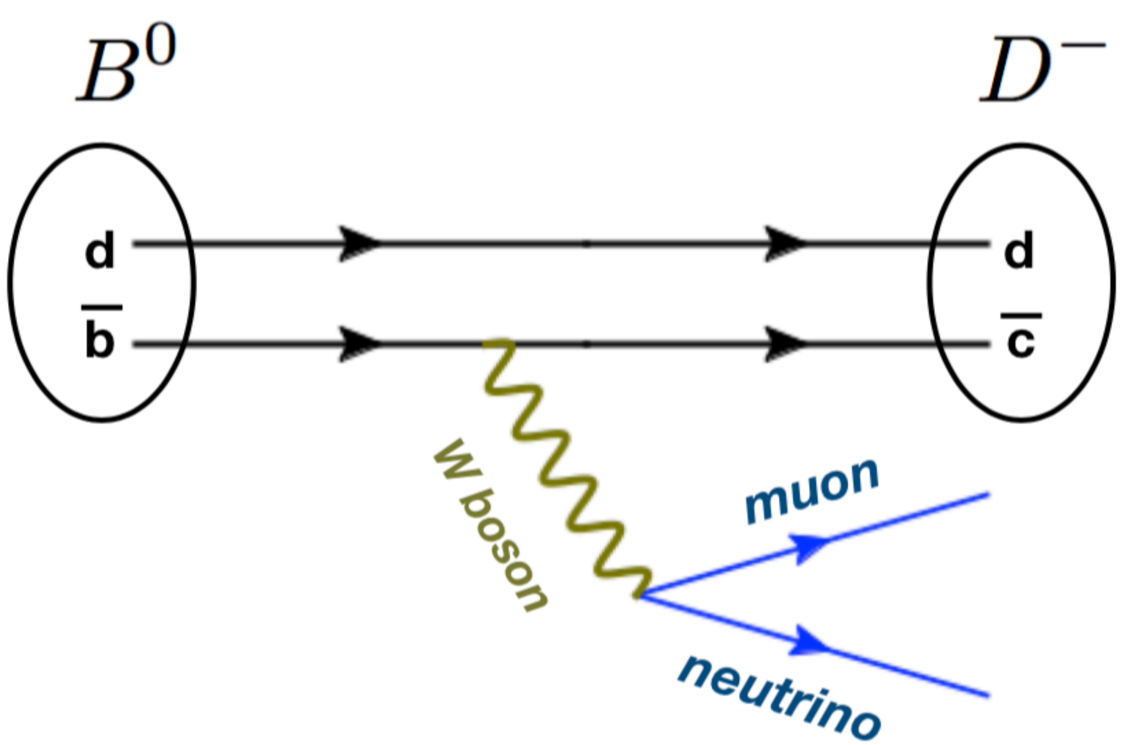

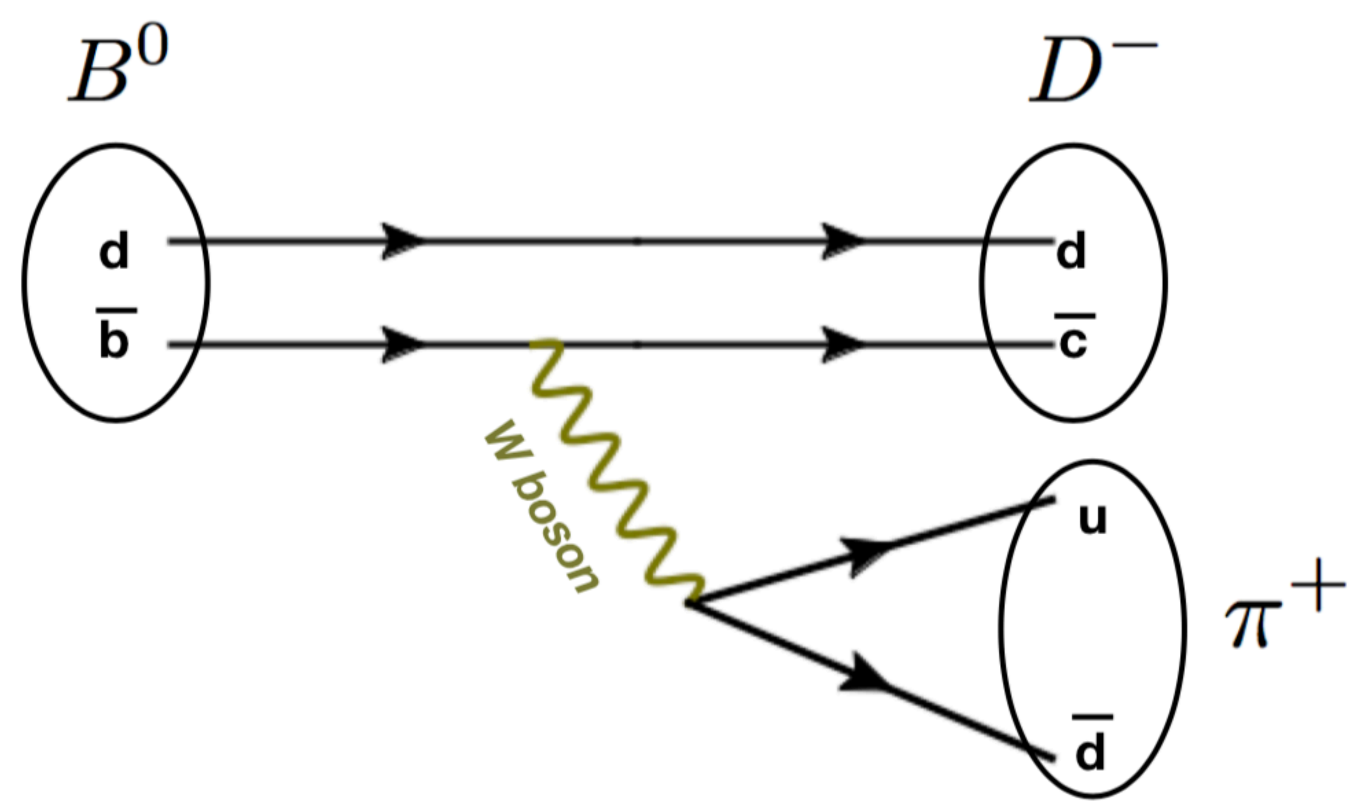

These two processes have a very **similar probability** to happen!

The weak boson *Z*

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The weak interactions are mediated by three massive bosons: ***W***

The main properties of the ***Z* bosons** are:

- As opposed to the **massless** gluons and photons, the **Z** boson is **very massive,** around 91 times the proton mass (similar to *W* boson)

$$m_\gamma = 0$$

$$m_g = 0$$

$$m_{W^\pm} = 80.385\,\mathrm{GeV}$$

$$m_{Z^0} = 91.1876\,\mathrm{GeV}$$

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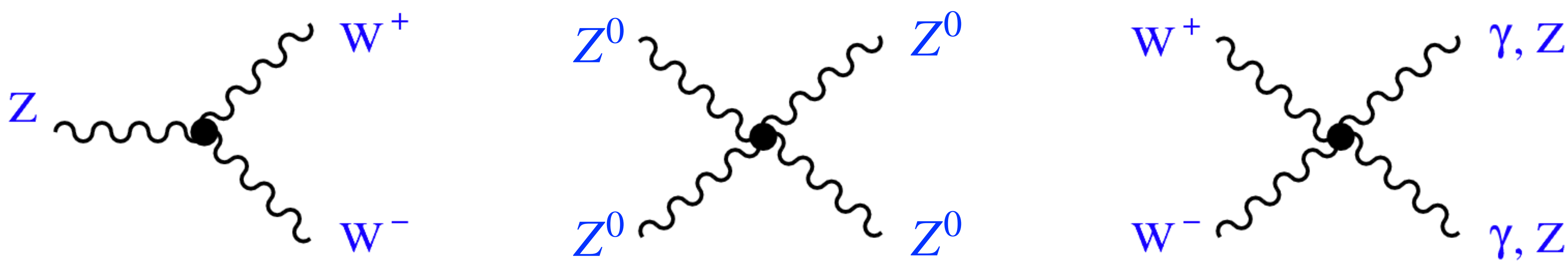

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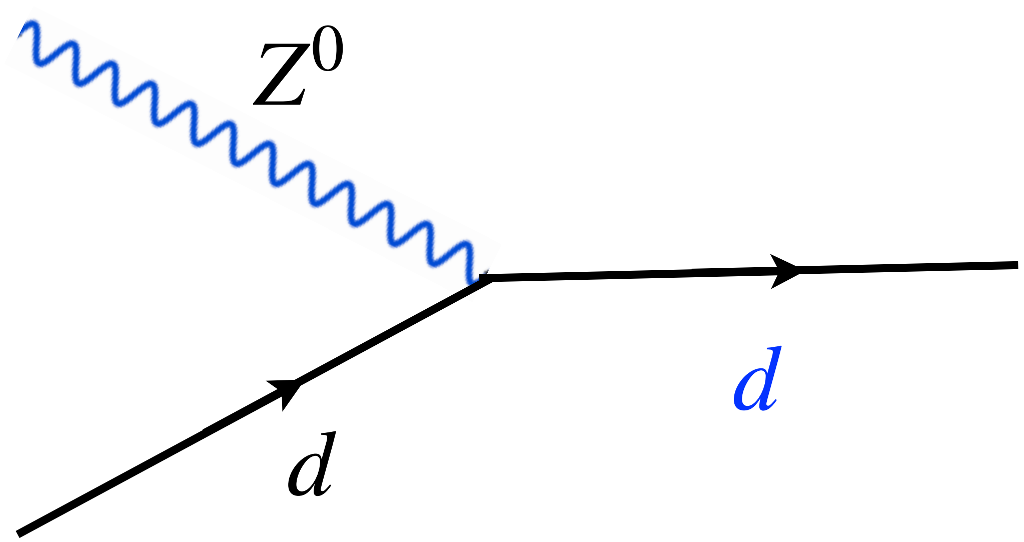

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- In weak interaction processes **mediated by the *Z* boson,** the flavour quantum numbers (strangeness, charmness, botomness) are always **conserved** quantities

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In terms of its interactions, the weak boson Z is a kind of ***``heavy photon"***

In diagrams involving quarks and charged leptons, and where the photon mediates the interaction, one can **replace the photon by a Z boson**

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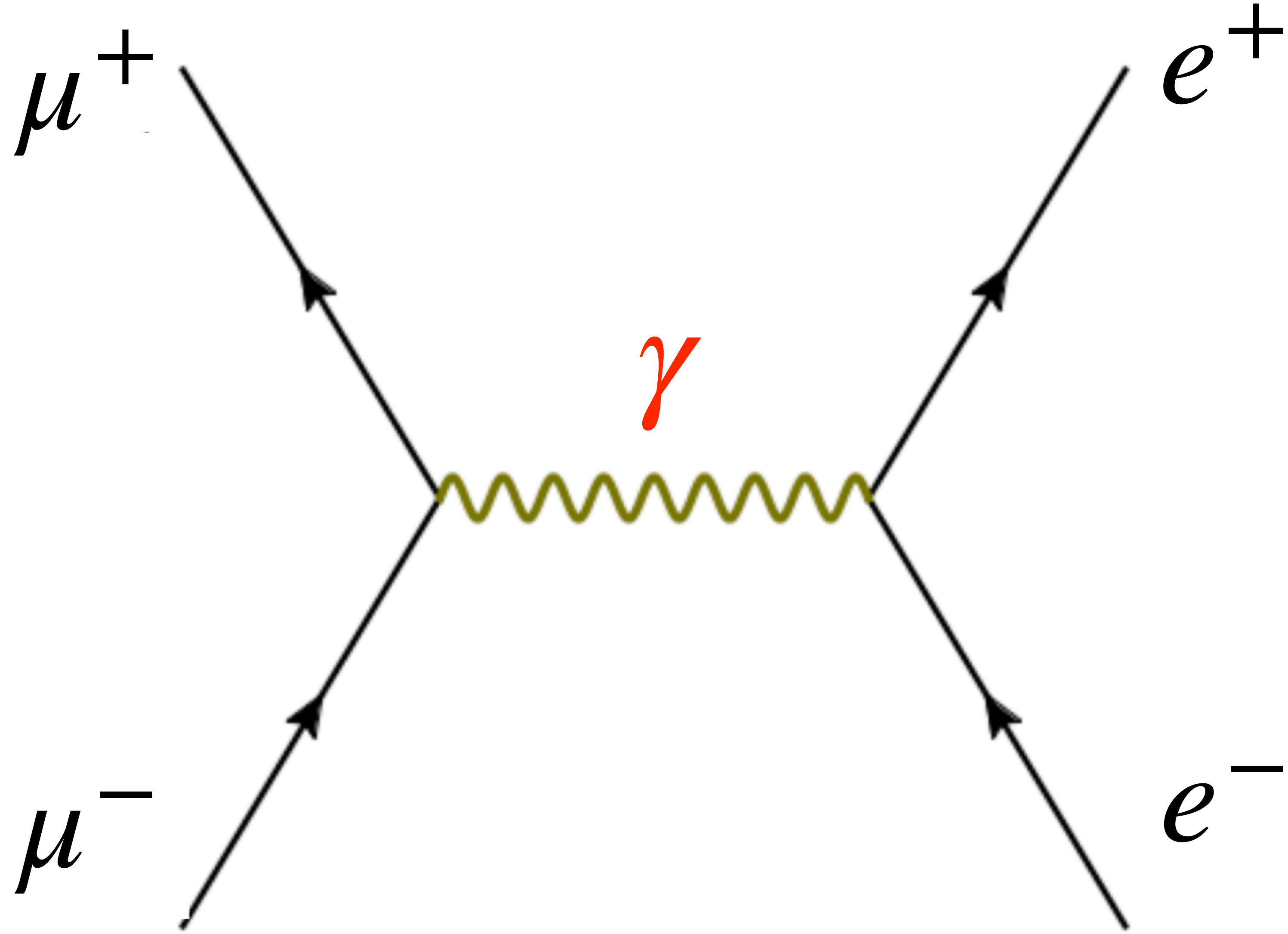

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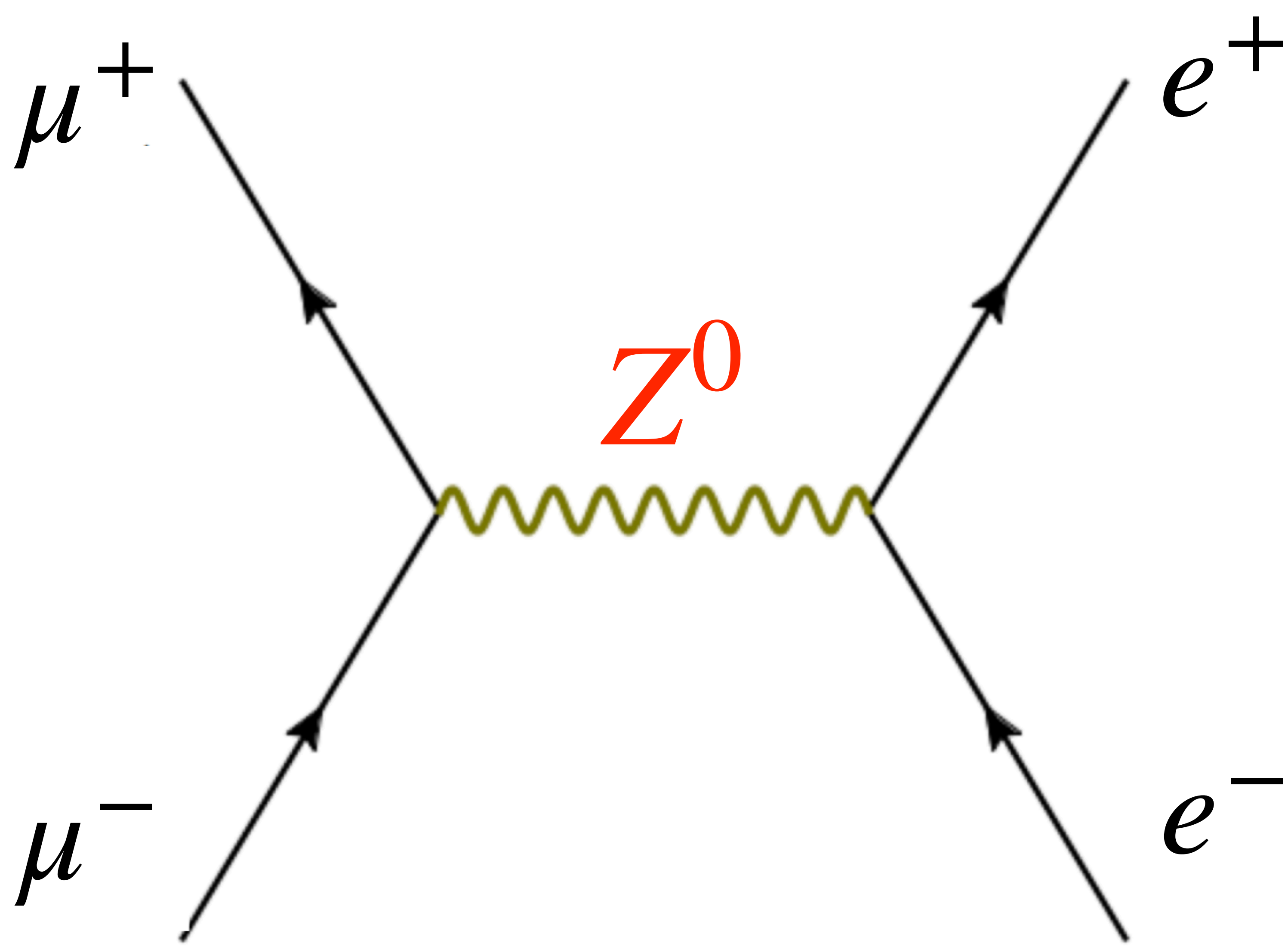

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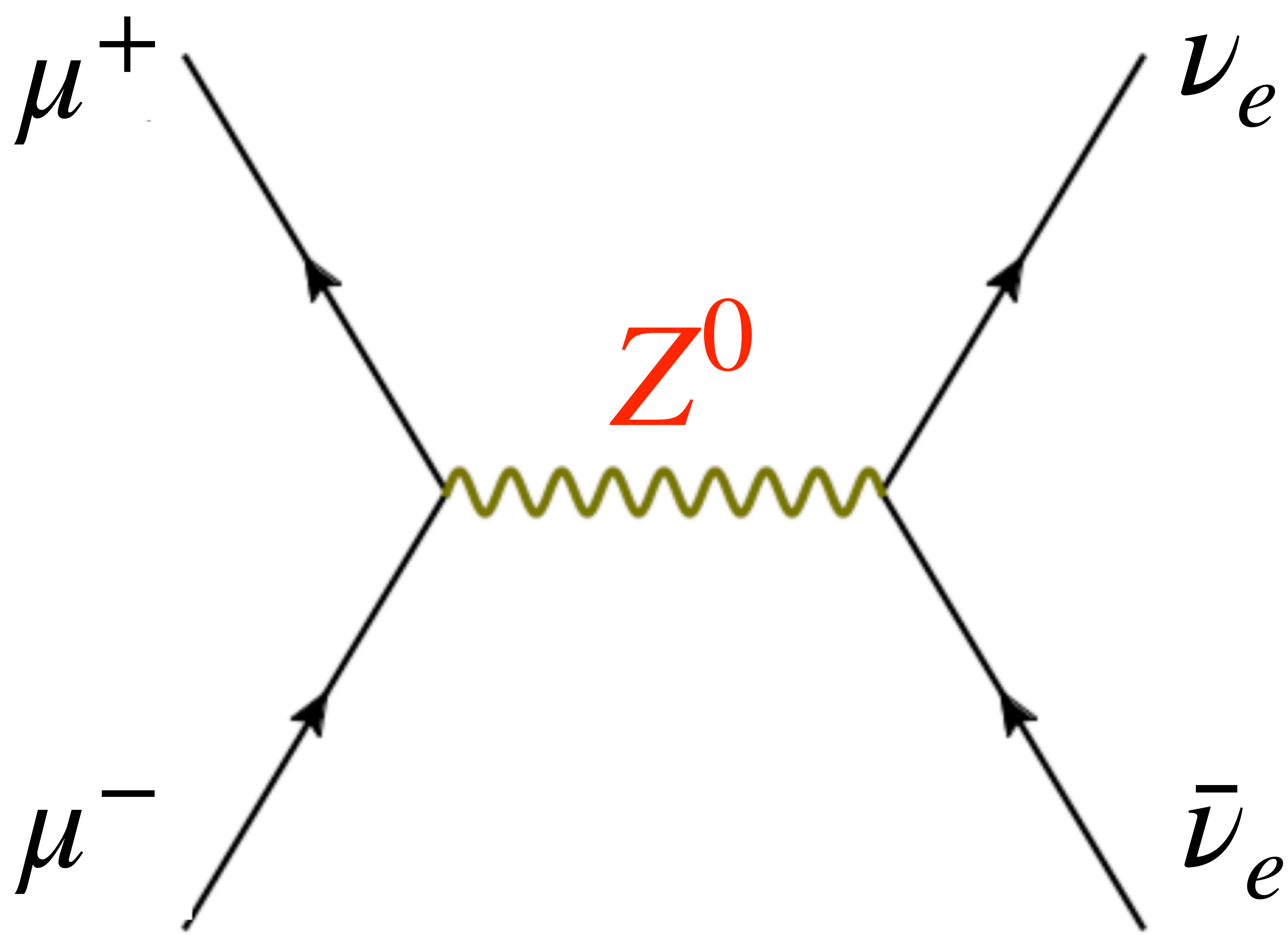
The Z boson also mediates processes involving **neutrinos**

$$\mu^+ + \mu^- \rightarrow \nu_e + \bar{\nu}_e$$



The weak boson Z

We can now summarise the **weak interaction vertices** involving the Z boson

with quarks

$$u + \bar{u} \to Z^0 , \quad d + \bar{d} \to Z^0 , \quad s + \bar{s} \to Z^0 , \ldots$$

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with leptons

$$e^+ + e^- \rightarrow Z^0, \quad \mu^+ + \mu^- \rightarrow Z^0, \quad \nu_e + \bar{\nu}_e \rightarrow Z^0, \ldots$$

$$e^- + Z^0 \rightarrow e^-, \quad \nu_e + Z^0 \rightarrow \nu_e, \quad \tau^+ + Z^0 \rightarrow \tau^+, \ldots$$

$$Z^0 \rightarrow e^- + e^+, \quad Z^0 \rightarrow \tau^+ + \tau^-, \quad Z^0 \rightarrow \nu_\mu + \bar{\nu}_\mu, \ldots$$

Any allowed reaction when **particles are interchanged by antiparticles** is also **allowed**

The weak interactions

Let us summarise what we have learned about the **weak interactions**

- ☑ **Flavour** is **not necessarily conserved** by the weak interactions: strangeness, charmness, and bottomness can vary in reactions mediated by the ***W* bosons** (but not by the *Z* boson)

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- The weak interaction is a **short range form** due to the masses of the *W* and *Z* bosons

- The strength of the weak interaction is **larger** between quarks of the **same generation** than between quarks of **different generation**

- From the point of view of the interactions with **leptons** and **charged quarks,** the Z boson behaves as it it was a **heavy photon**

The weak boson *W*

Taking into account these properties, some of the physically allowed reactions involving **quarks** and ***W* bosons** will be:

$$u + W^- \to d\,, \quad u + W^- \to s\,, \quad d + W^+ \to u\,, \quad s + W^+ \to u\,,$$

$$\bar{u} + W^+ \to \bar{d}\,, \quad \bar{u} + W^+ \to \bar{s}\,, \quad \bar{d} + W^- \to \bar{u}\,, \quad \bar{s} + W^- \to \bar{u}\,,$$

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$$\bar{u} + W^+ \to \bar{s} \quad \Rightarrow \quad u + W^- \to s$$

The weak boson *W*

Taking into account these properties, some of the physically allowed reactions involving **leptons** and ***W* bosons** will be:

$$e^+ + W^- \to \bar{\nu}_e \,, \quad e^- + W^+ \to \nu_e \,, \quad \nu_e + W^+ \to e^- \,, \quad \bar{\nu}_e + W^+ \to e^+$$

$$W^+ \to e^+ + \nu_e \,, \quad W^- \to e^- + \bar{\nu}_e \,, \quad e^+ + \nu_e \to W^+ \,, \quad e^- + \bar{\nu}_e \to W^-$$

- ☑ **Electric charge** is always conserved
- ☑ Each interaction vertex involves a **charged** and a **neutral lepton** that belong to the **same lepton generation**
- ☑ You can always **replace** the two leptons of a given generation for the corresponding two leptons of **another generation**
- ☑ The **individual leptonic quantum numbers** are always conserved in weak reactions

The weak boson W

exercise

Draw the Feynman diagram for the following process

$$\pi^+ \to \mu^+ + \nu_\mu \qquad \pi^+ = (u\,\bar{d})$$

The weak boson *W*

exercise

Draw the Feynman diagram for the following process

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- We have a neutrino in the final state: the **weak interaction** must be involved
- Quarks and leptons only interact indirectly via either photons or *W, Z* bosons
- Since the electric charge is ***Q=+-1,*** then a positively charged ***W boson*** is involved
- We know what **vertices are allowed** involving quarks or leptons and a *W* boson

The weak boson W

exercise

Draw the Feynman diagram for the following process

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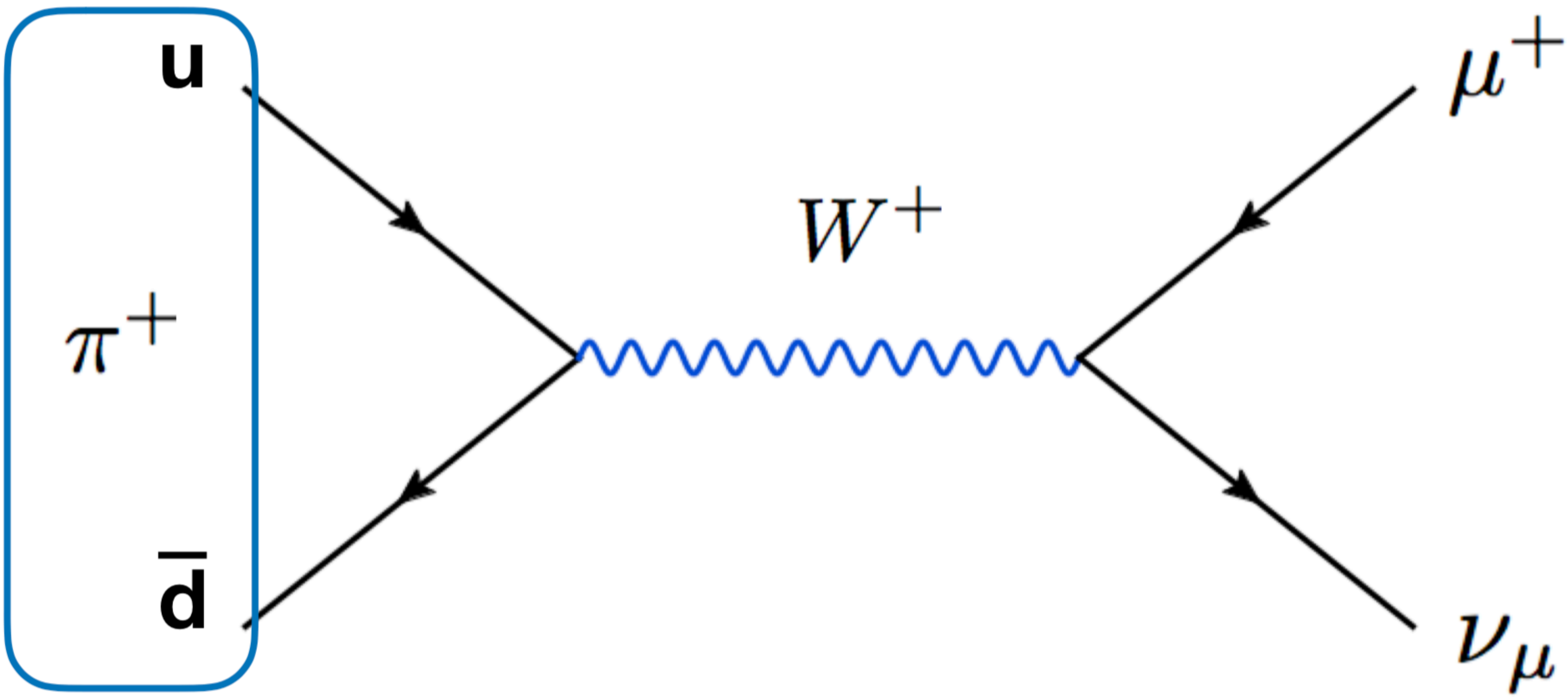
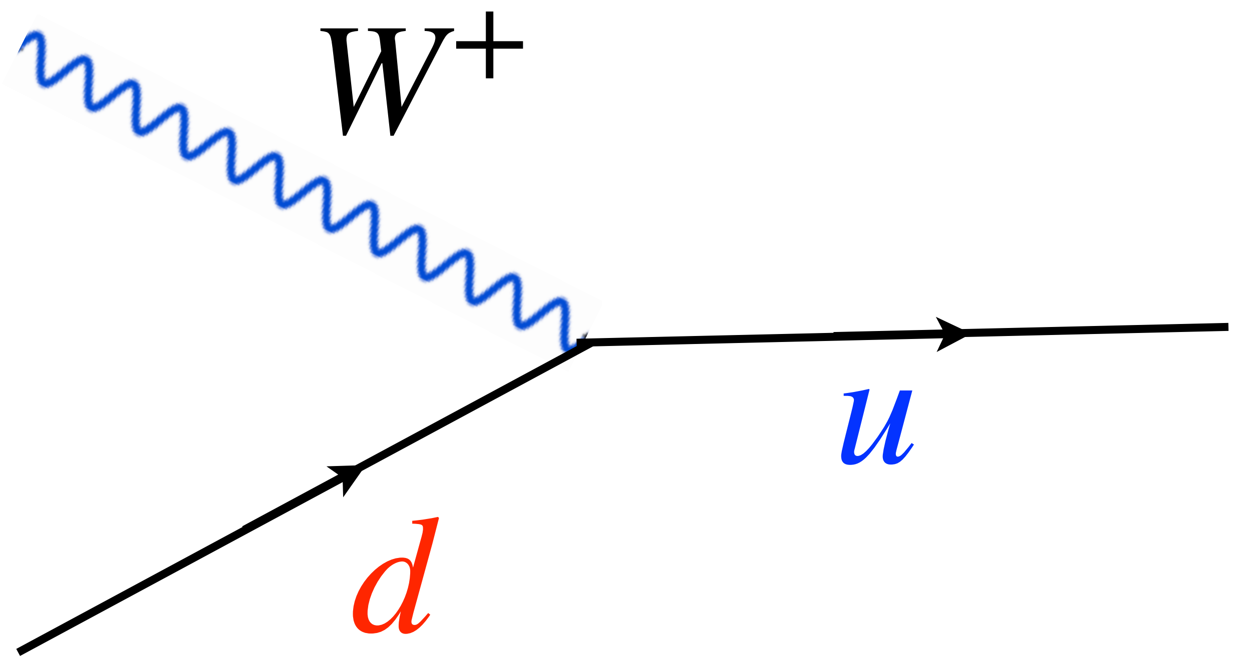


You can check that all relevant quantum numbers are **conserved:** *L, B, Q, …*

Heavy hadron decays

Weak coupling between generations

We have seen that in processes mediated by the weak gauge boson *W* the **flavour** of the quarks will **change**



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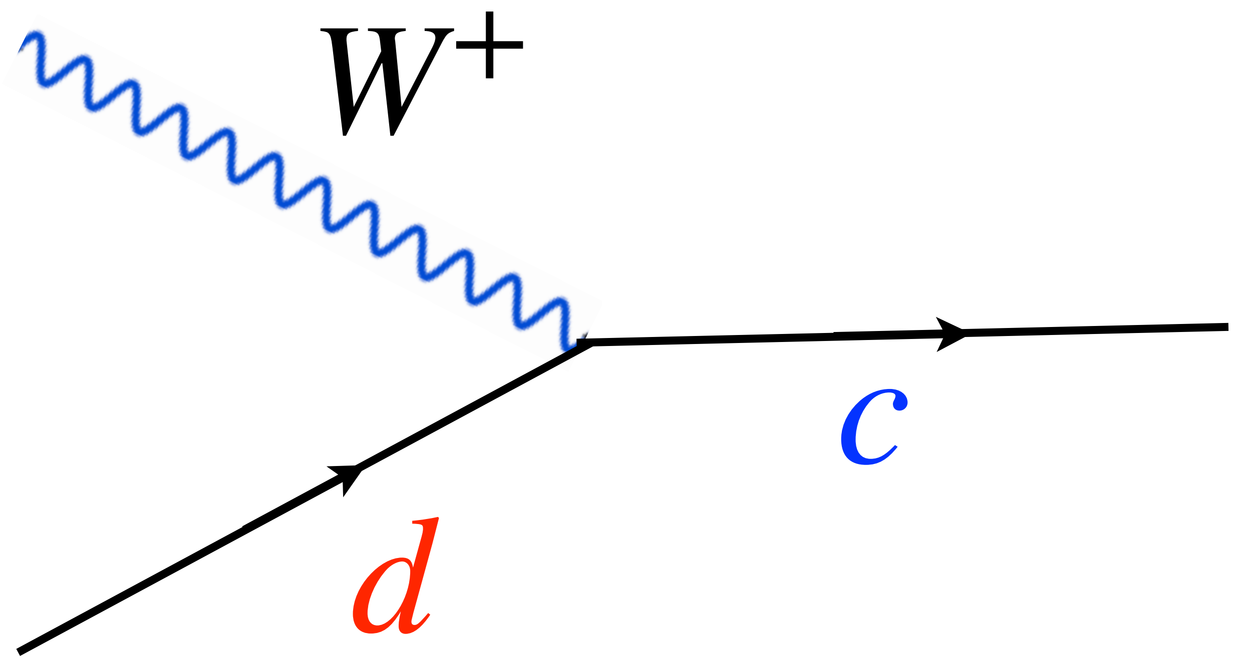

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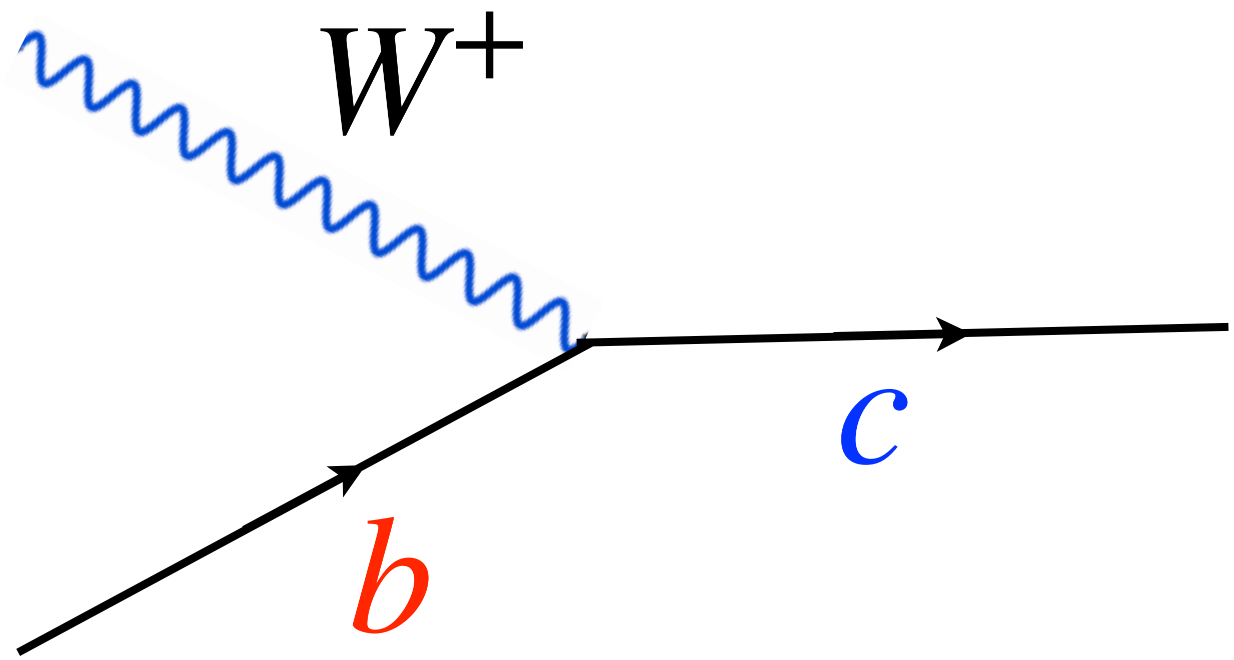

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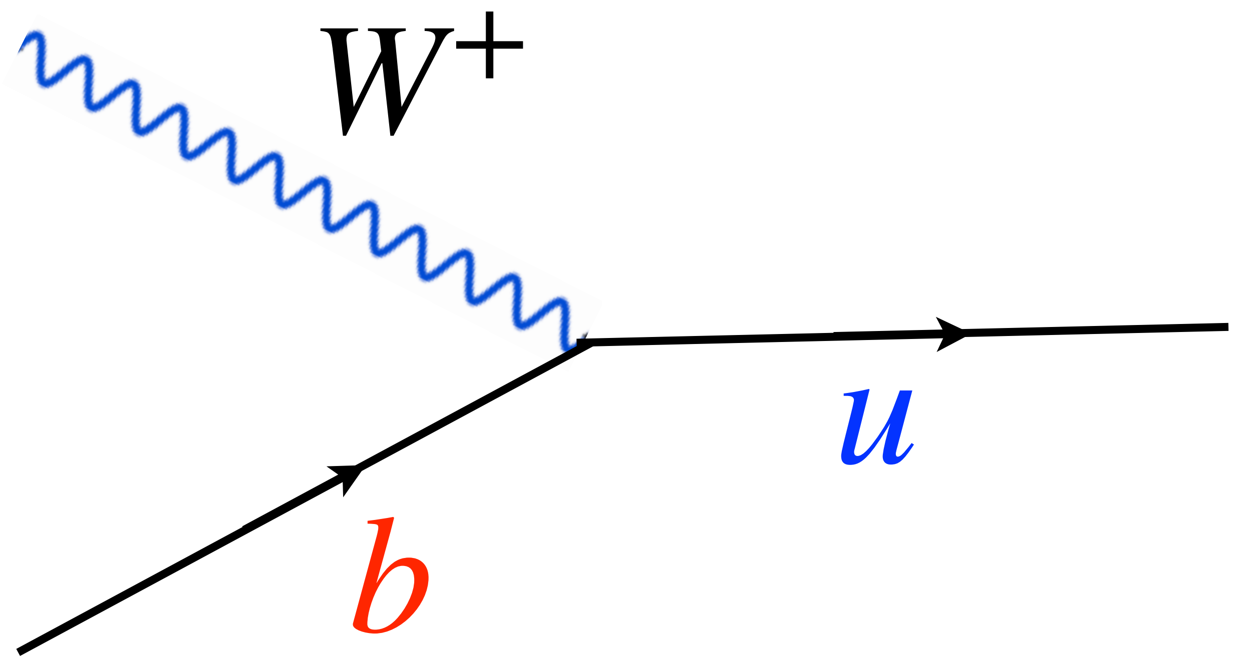
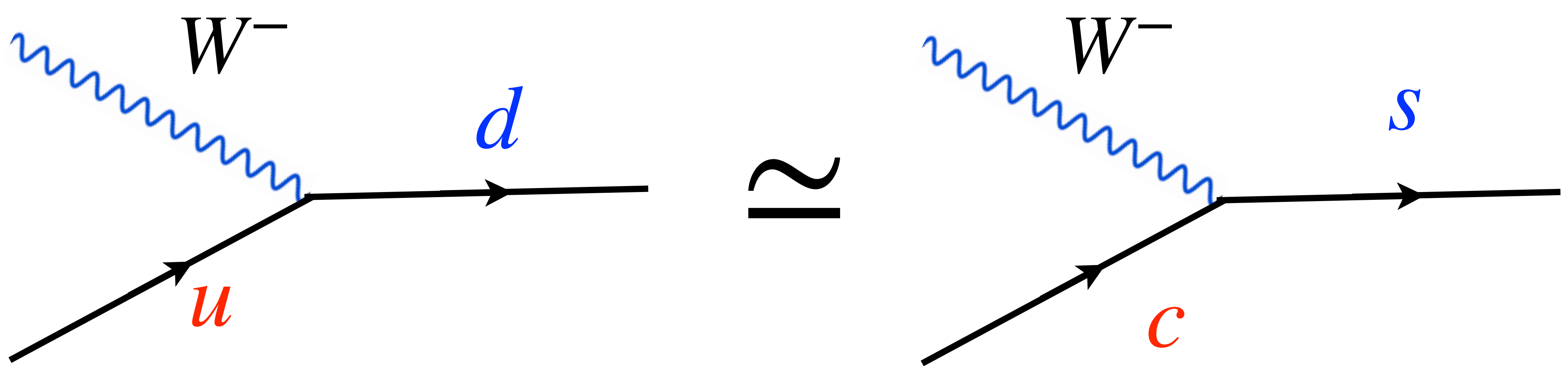


Moreover we can always replace a given quark by the corresponding quark of a **different generation**

The weak interactions mediates **transitions** between **quarks of different generations**

Weak coupling between generations

The **strength of the weak coupling** is similar between **quarks of the same generation**



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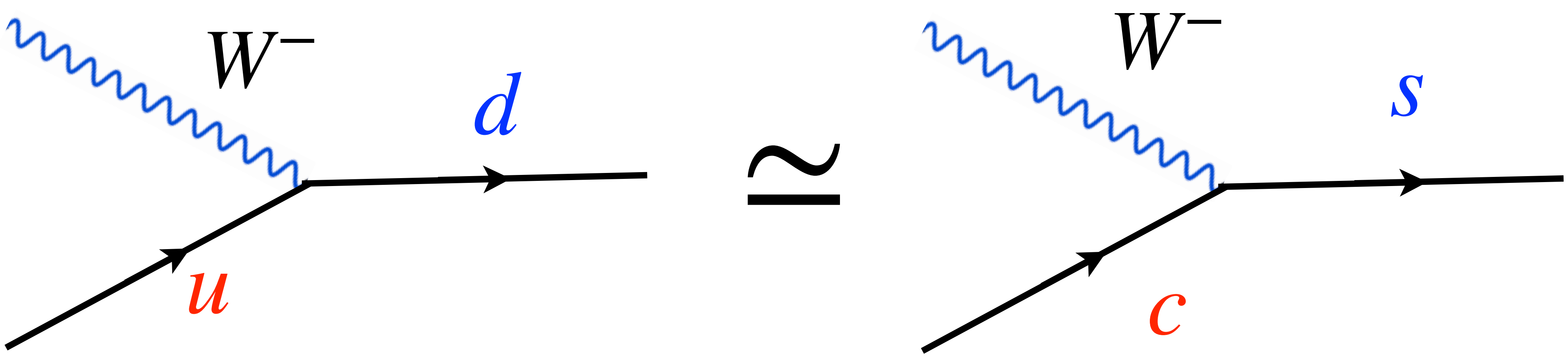
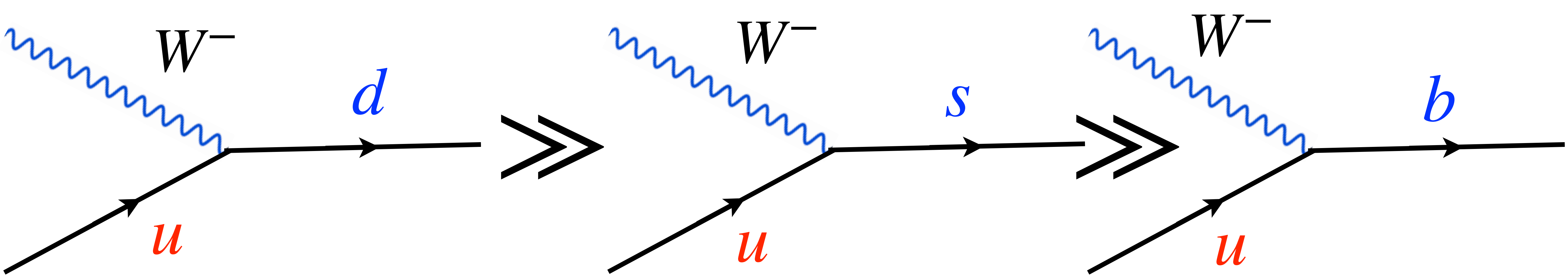


The **strength of the weak coupling** is smaller between **quarks of different generation**



Weak coupling between **gens 1 and 2** bigger than between **gens 1 and 3**

Drawing Feynman diagrams

- If the scattering reaction involves composite particles (hadrons) first of all determine their **quark decomposition** making sure all quantum numbers add up consistently

- Then put at the **left** of the diagram the **initial-state particles** and at the **right** of the diagram the **final-state** particles

- Attempt to connect the initial and final state particles among them. Note that some particles will not interact and will be just **spectators** in the reaction

- Make sure that all interaction vertices **conserve the corresponding quantum numbers:** for example, if gluons or photons are conserved, then ***Q, B, S, C, b, …*** should be conserved

Heavy hadron decays

exercise

This **hierarchy of the weak couplings** between quark generations is particularly important in order to understand the decays of **hadrons** that contain **heavy quarks**

$$B^0 \to D^- + \mu^+ + \nu_\mu \qquad B^0 = \left(d\,\bar{b}\right) \qquad D^- = \left(d\bar{c}\right)$$

what is the corresponding Feynman diagram?

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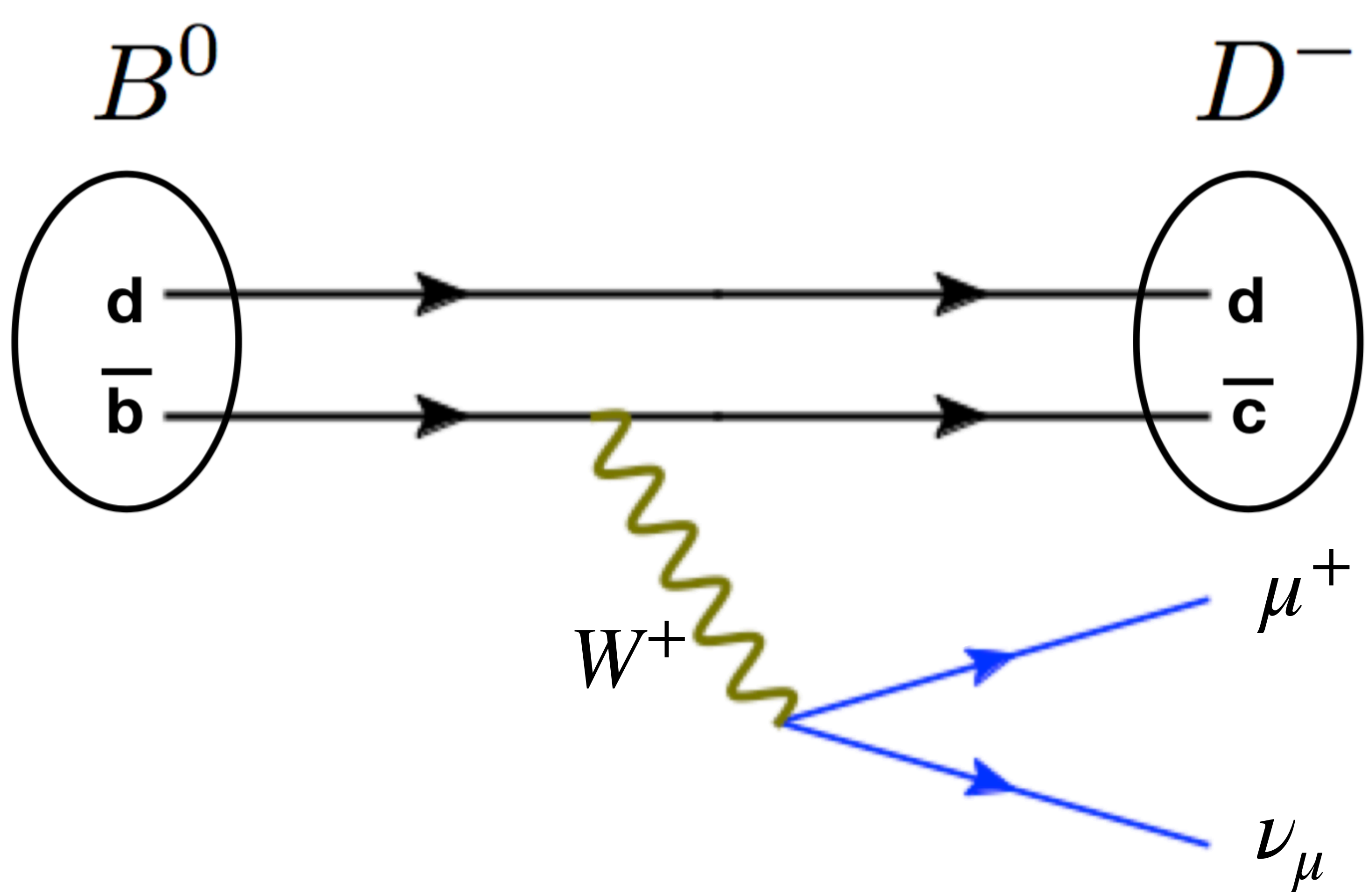

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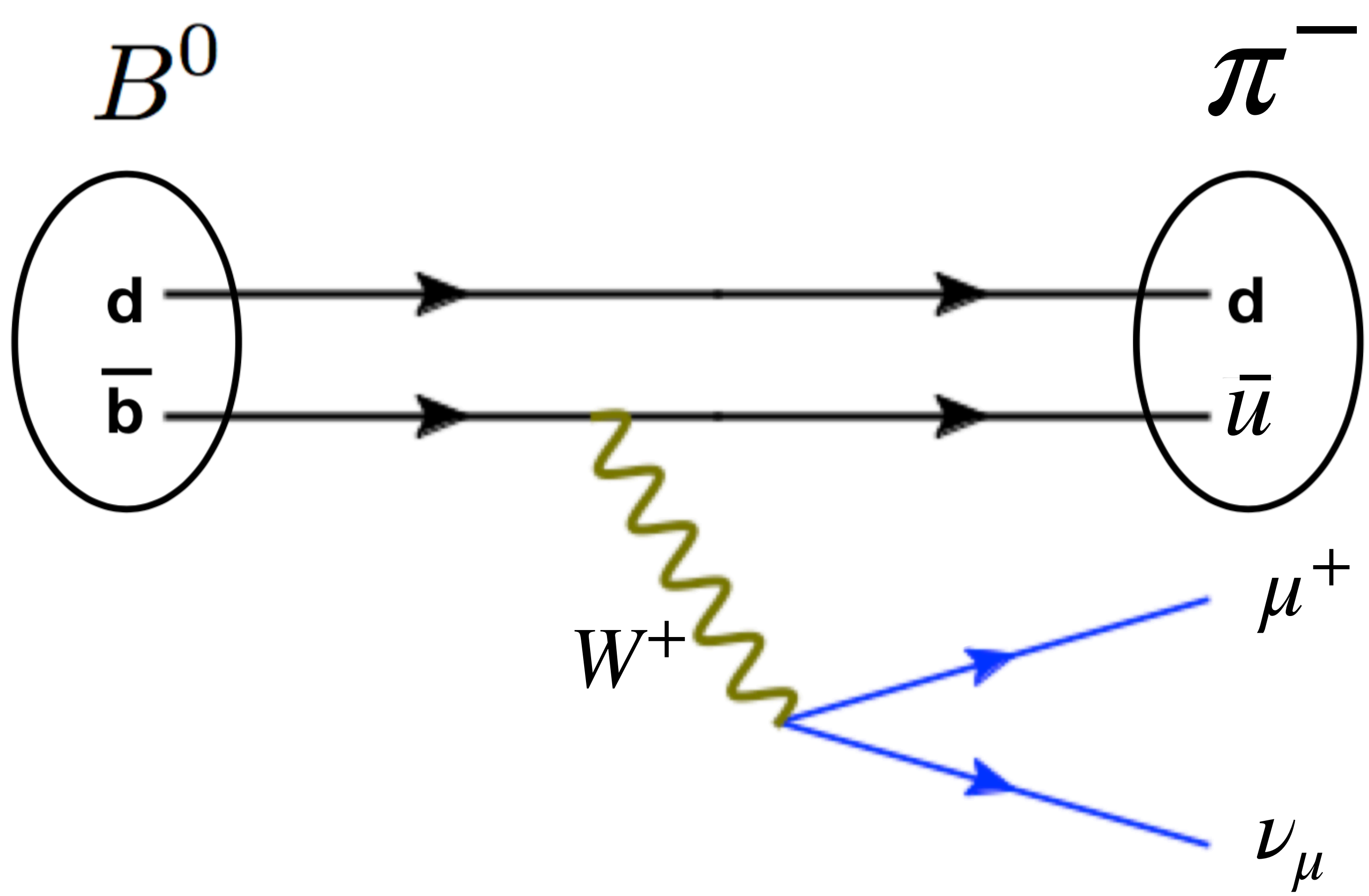
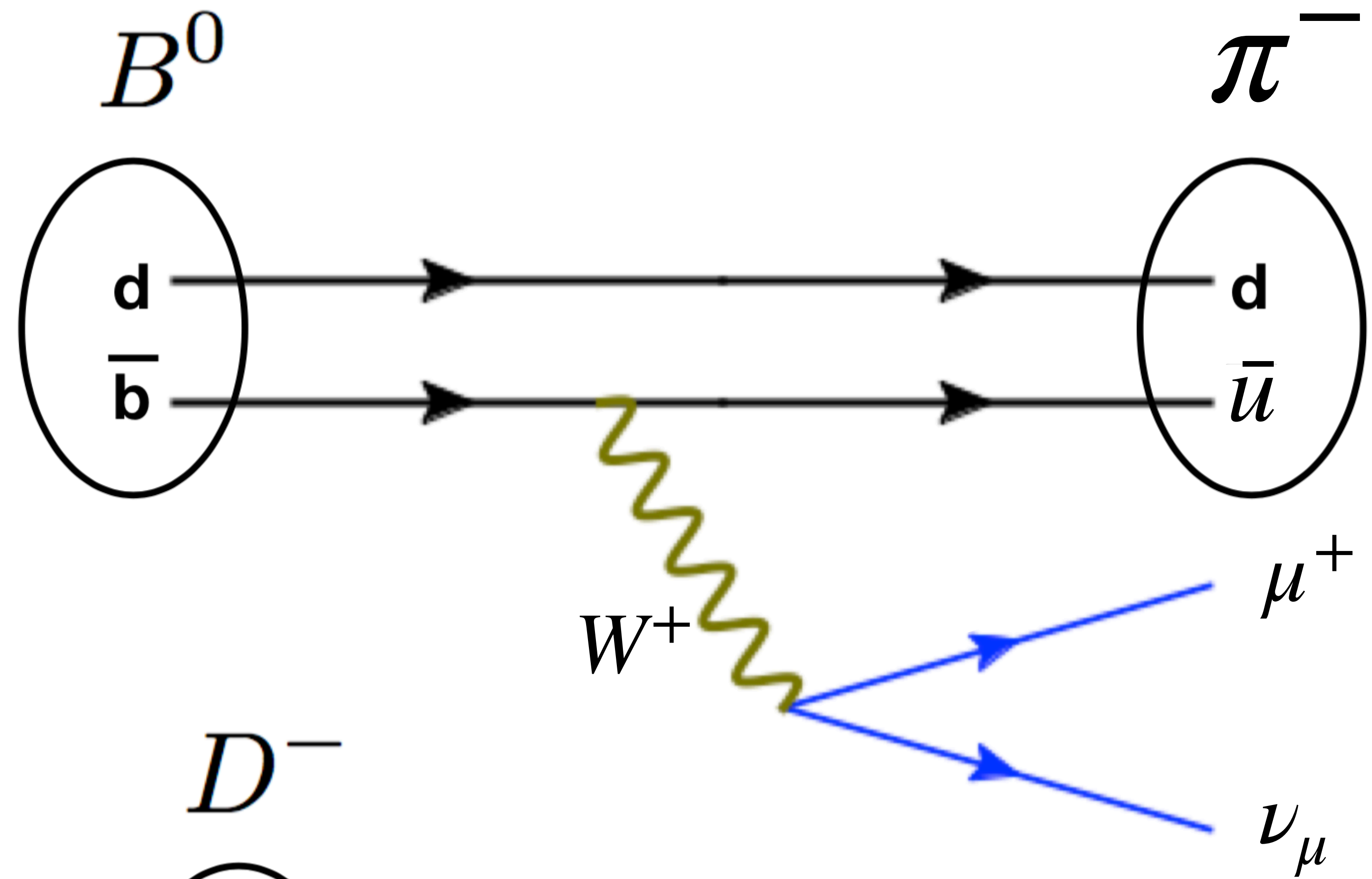
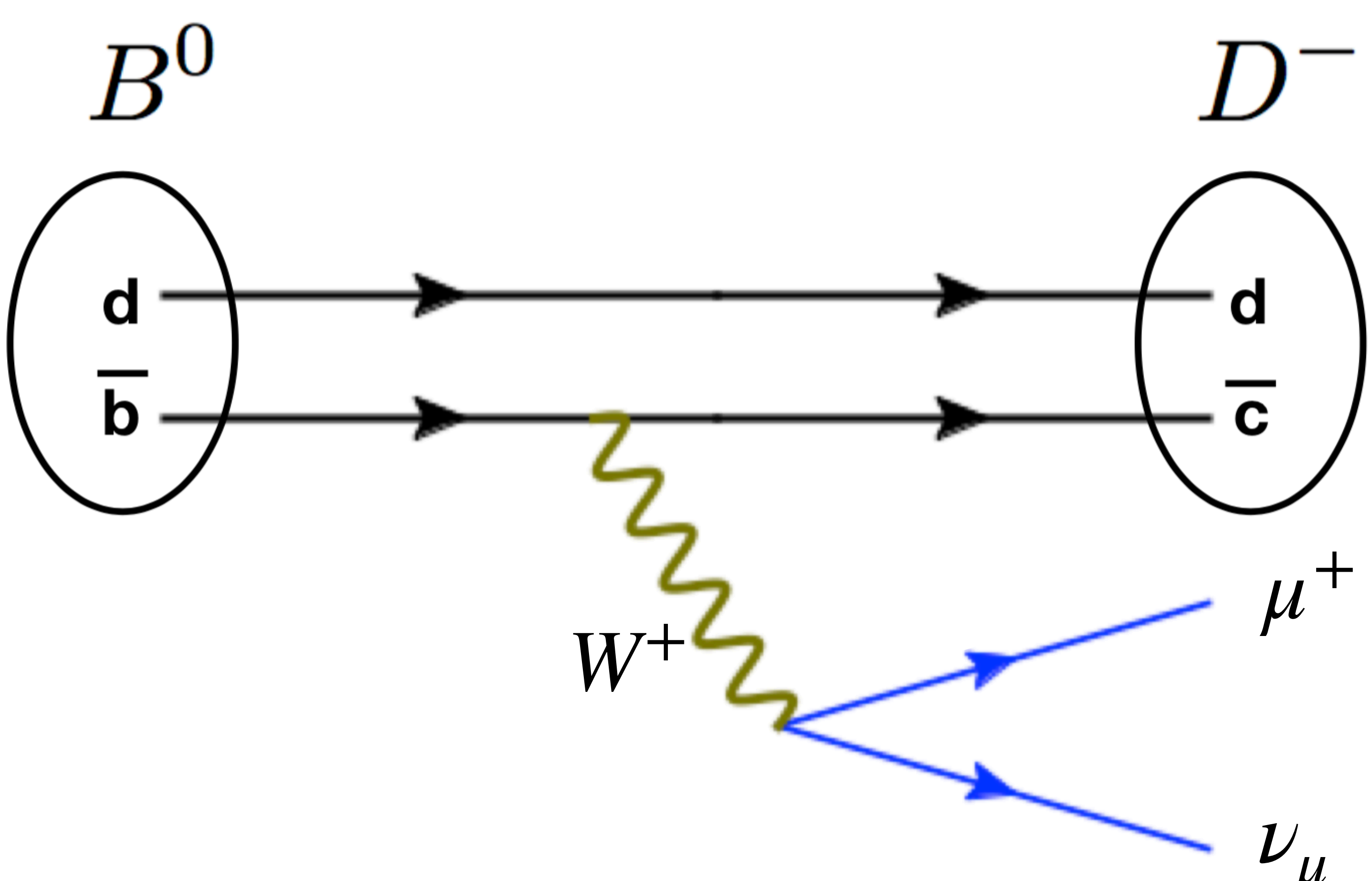


Heavy hadron decays

Which of the two reactions is **most likely** to take place?





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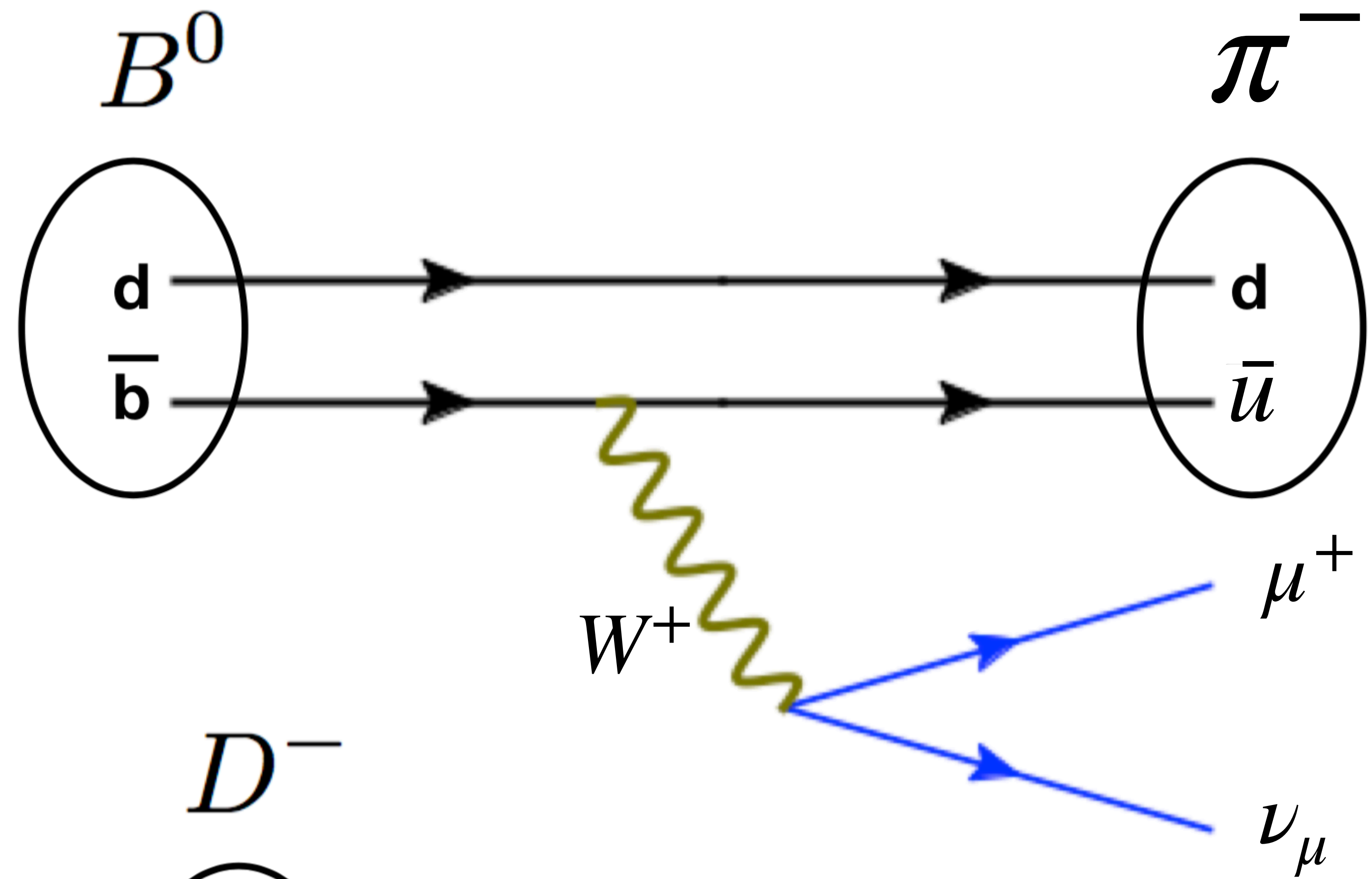

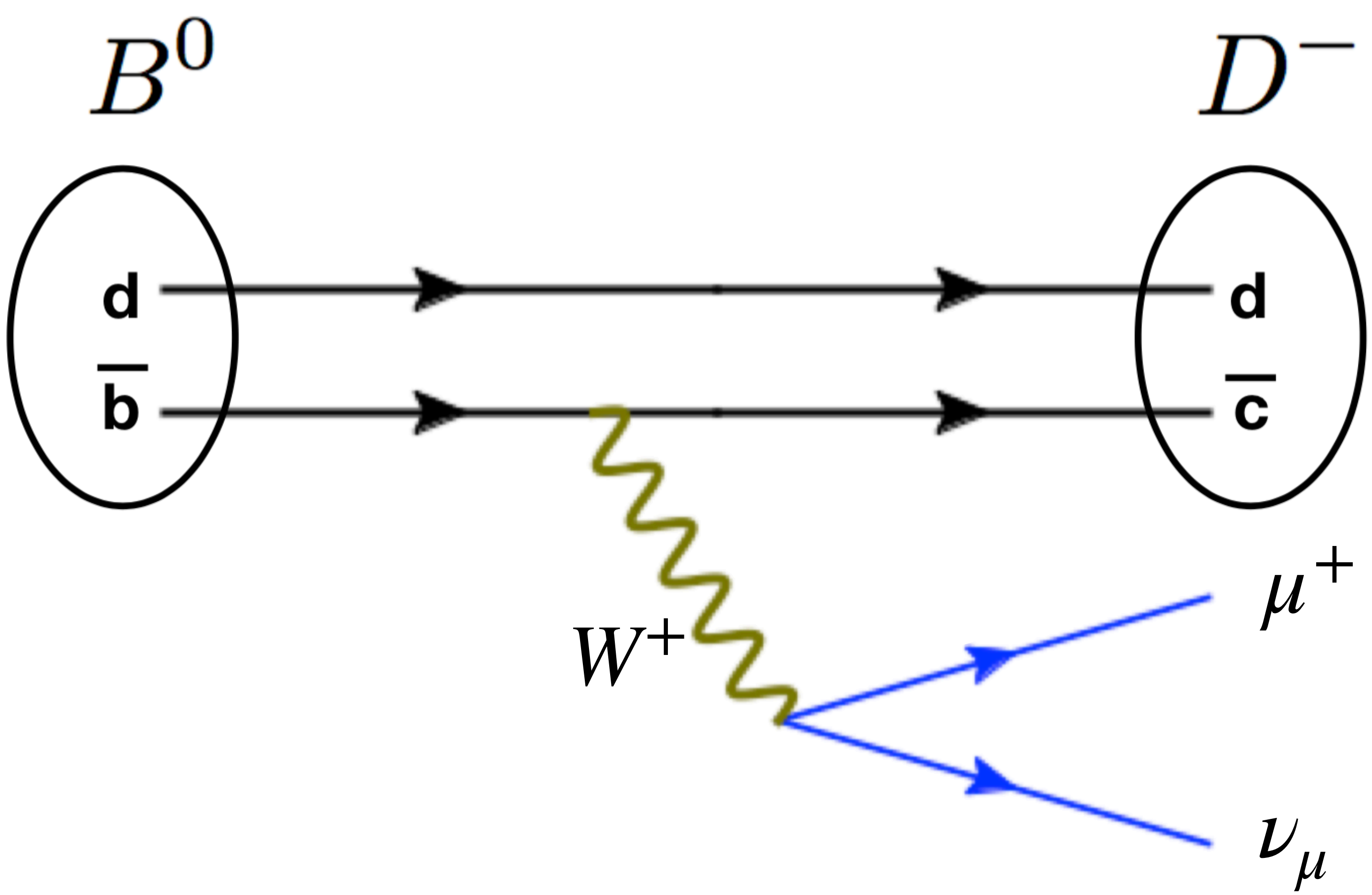

The decay into a pion is more suppressed, since the **coupling *Wub*** (gens 1 and 3) is **smaller** than the **coupling *Wcb*** (gens 1 and 2)

Heavy hadron decays

Note that some reaction processes might look **very different from the outside**, but their similarities become apparent at the **Feynman diagram level**

$$B^0 \to D^- + \mu^+ + \nu_\mu$$

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How do these two decay models relate to each other?

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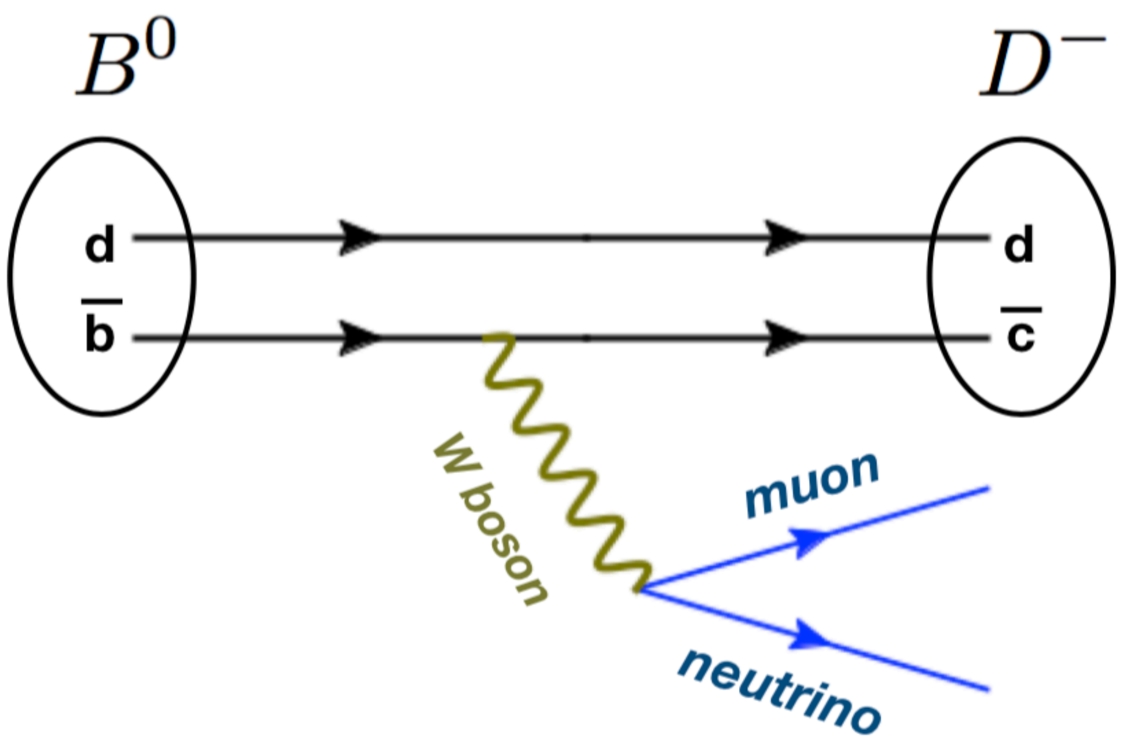

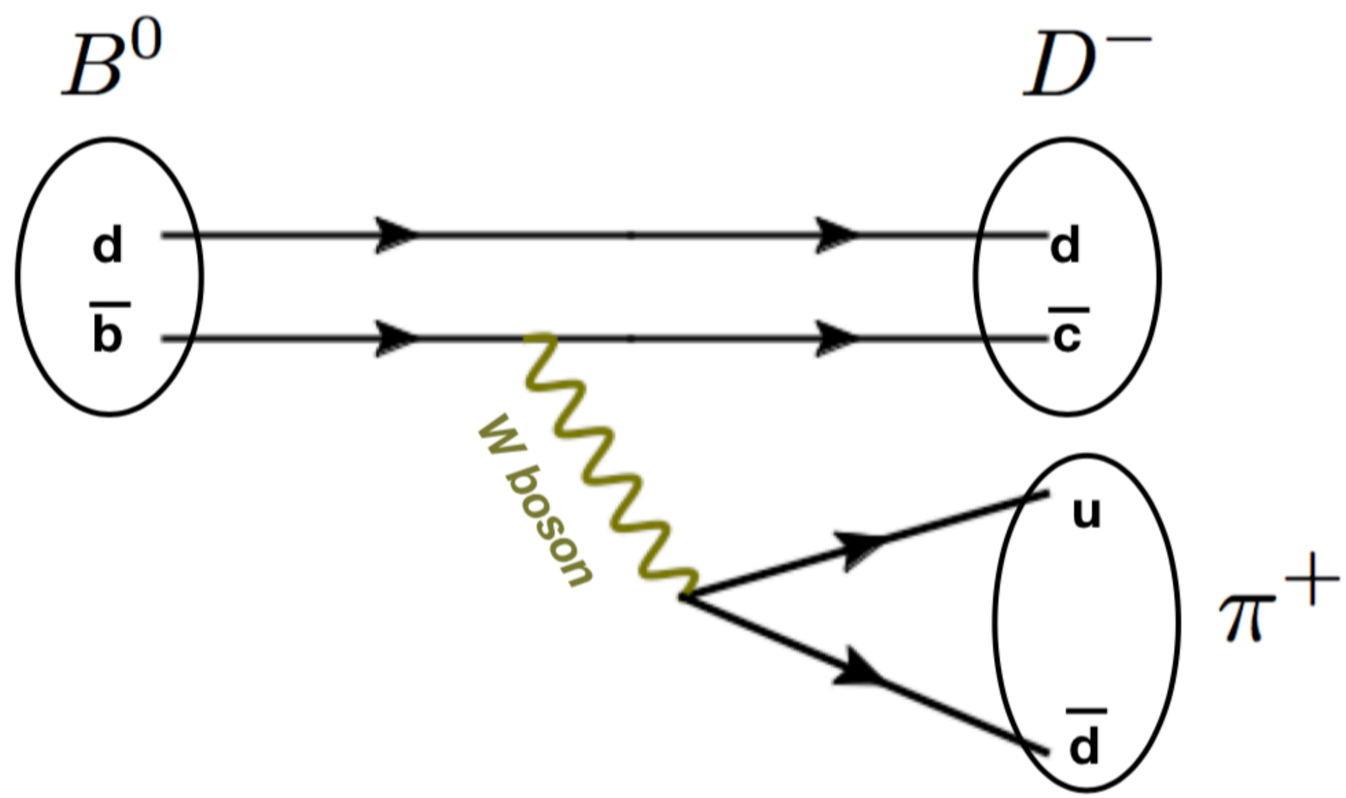

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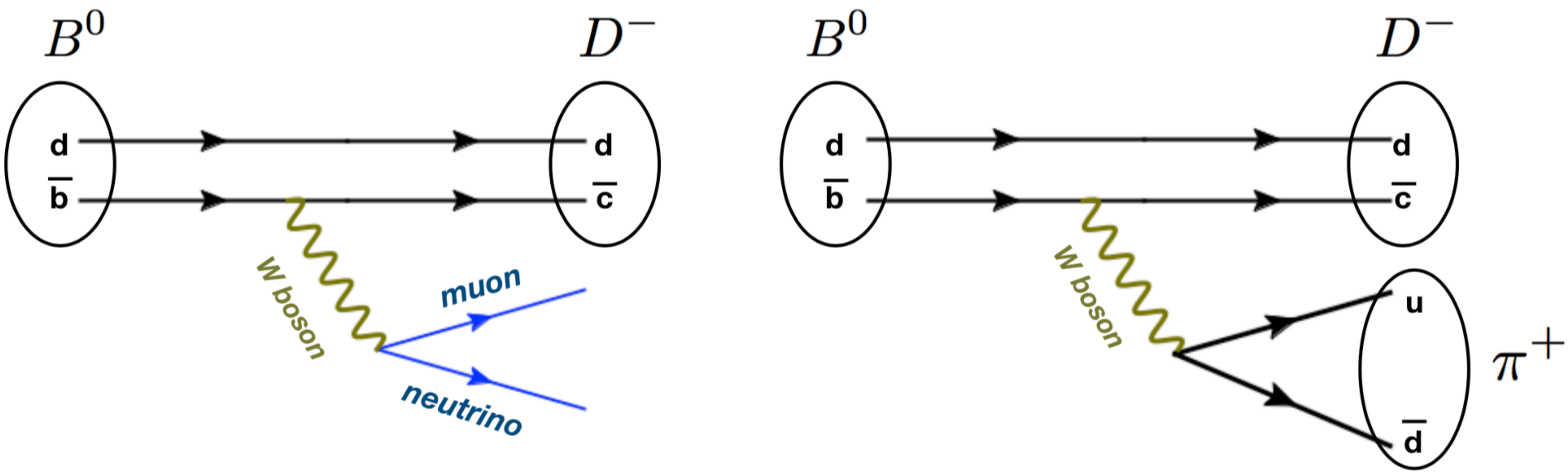

These two processes have a very **similar probability** to happen!

The weak boson Z

The weak boson Z

The weak interactions are mediated by three massive bosons: ***W^+, W^+, Z^0***

The main properties of the ***Z* bosons** are:

- As opposed to the **massless** gluons and photons, the **Z** boson is **very massive,** around 91 times the proton mass (similar to *W* boson)

$$m_\gamma = 0$$

$$m_g = 0$$

$$m_{W^\pm} = 80.385\,\text{GeV}$$

$$m_{Z^0} = 91.1876\,\text{GeV}$$

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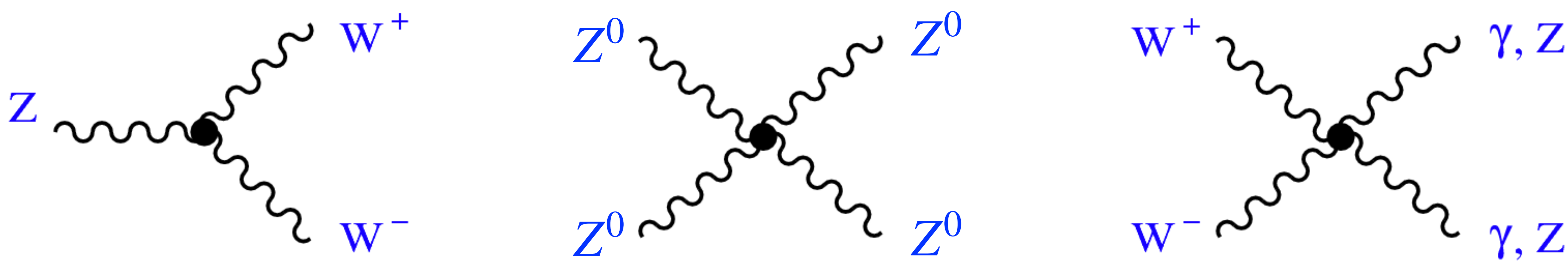

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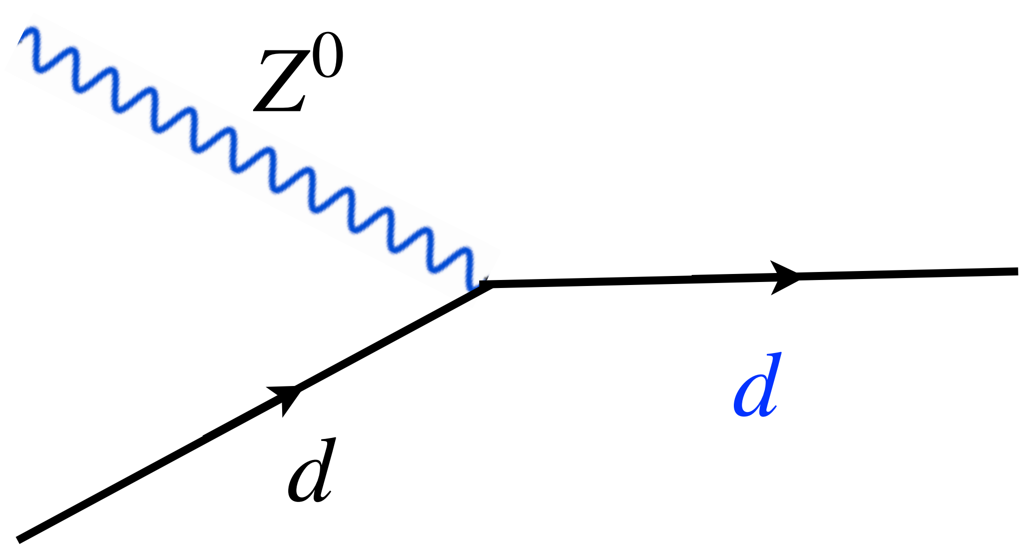

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- ☑ In weak interaction processes **mediated by the *Z* boson,** the flavour quantum numbers (strangeness, charmness, botomness) are always **conserved** quantities

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In terms of its interactions, the weak boson Z is a kind of ***``heavy photon”***

In diagrams involving quarks and charged leptons, and where the photon mediates the interaction, one can **replace the photon by a Z boson**

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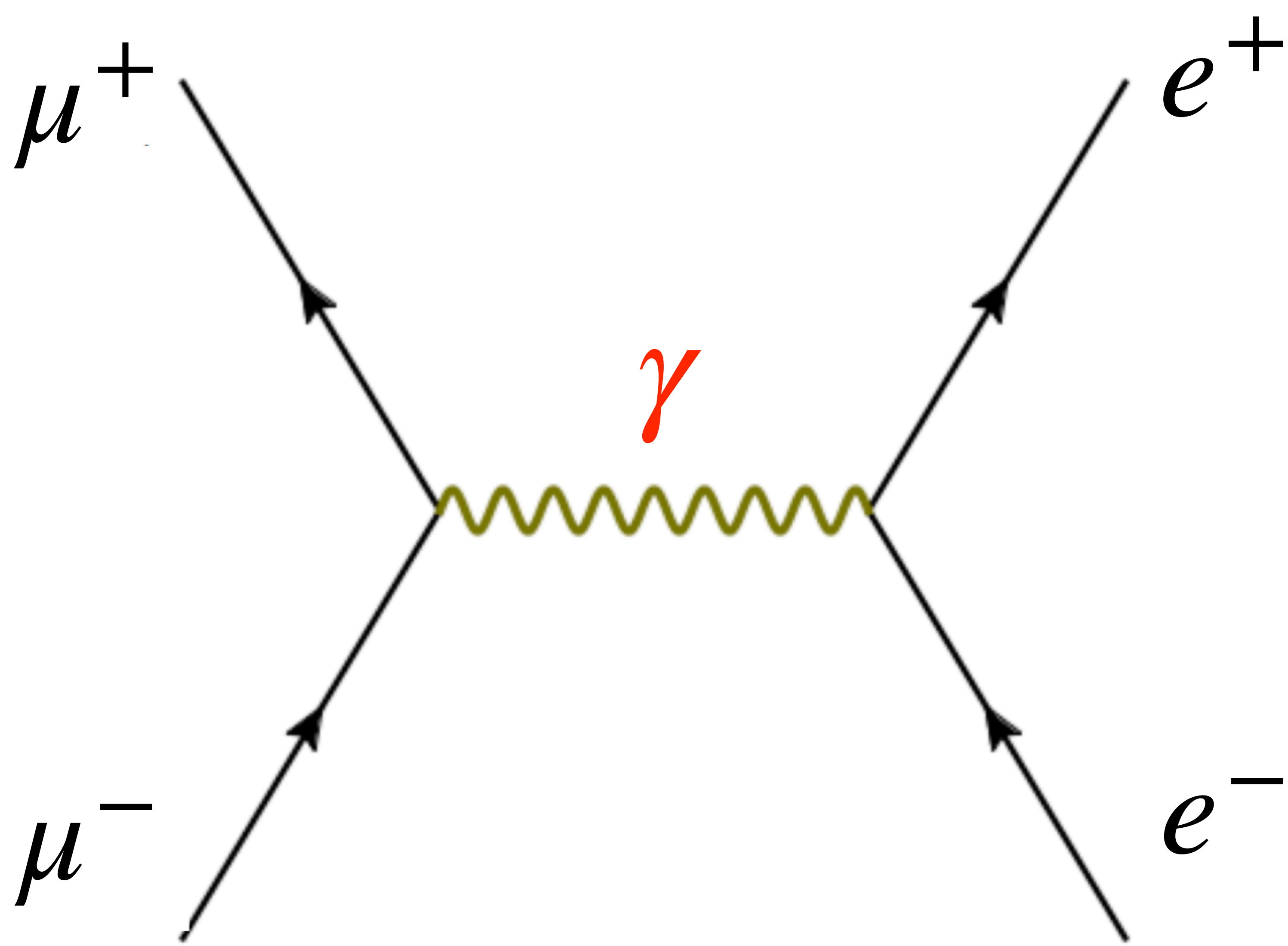

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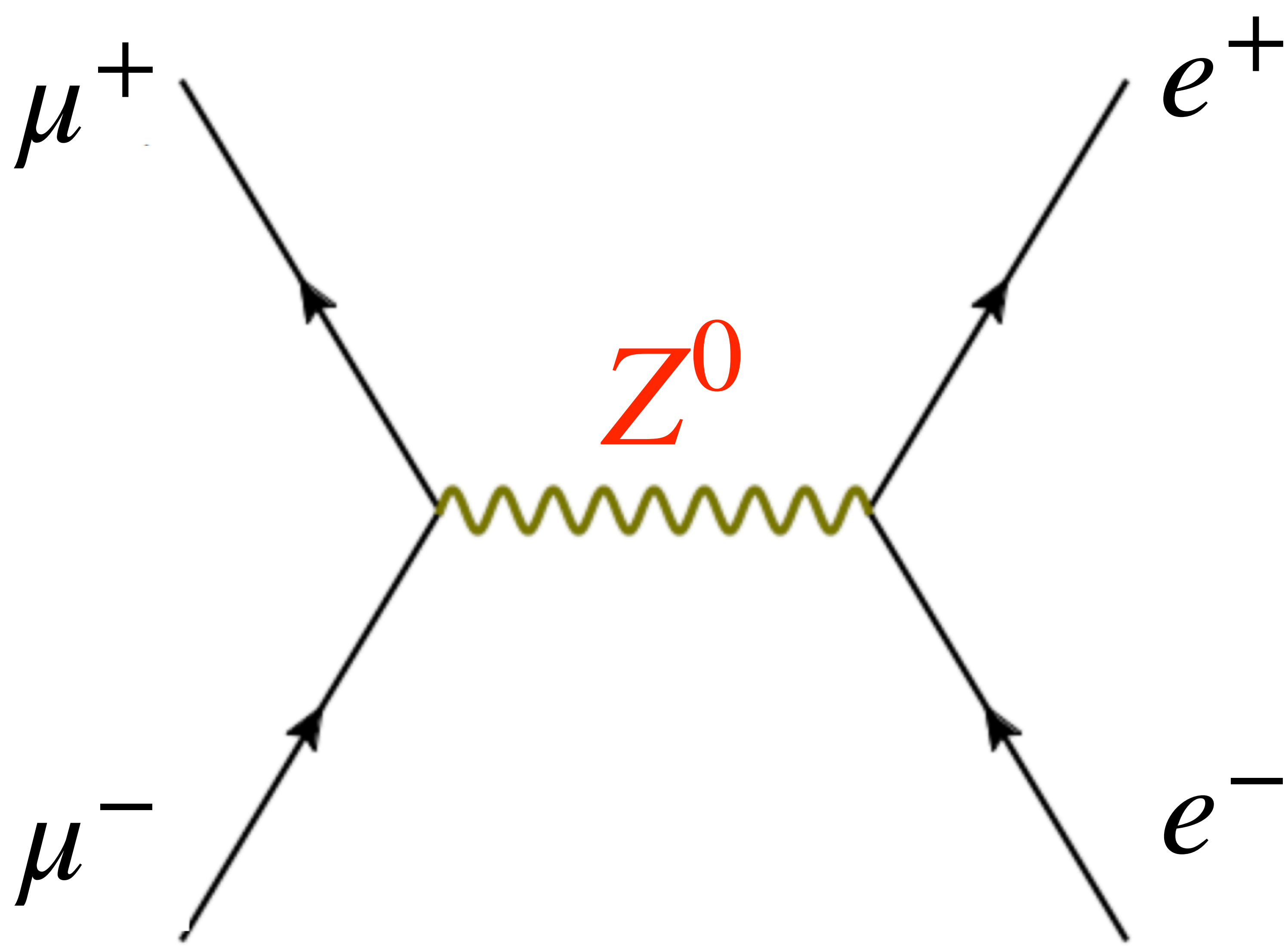

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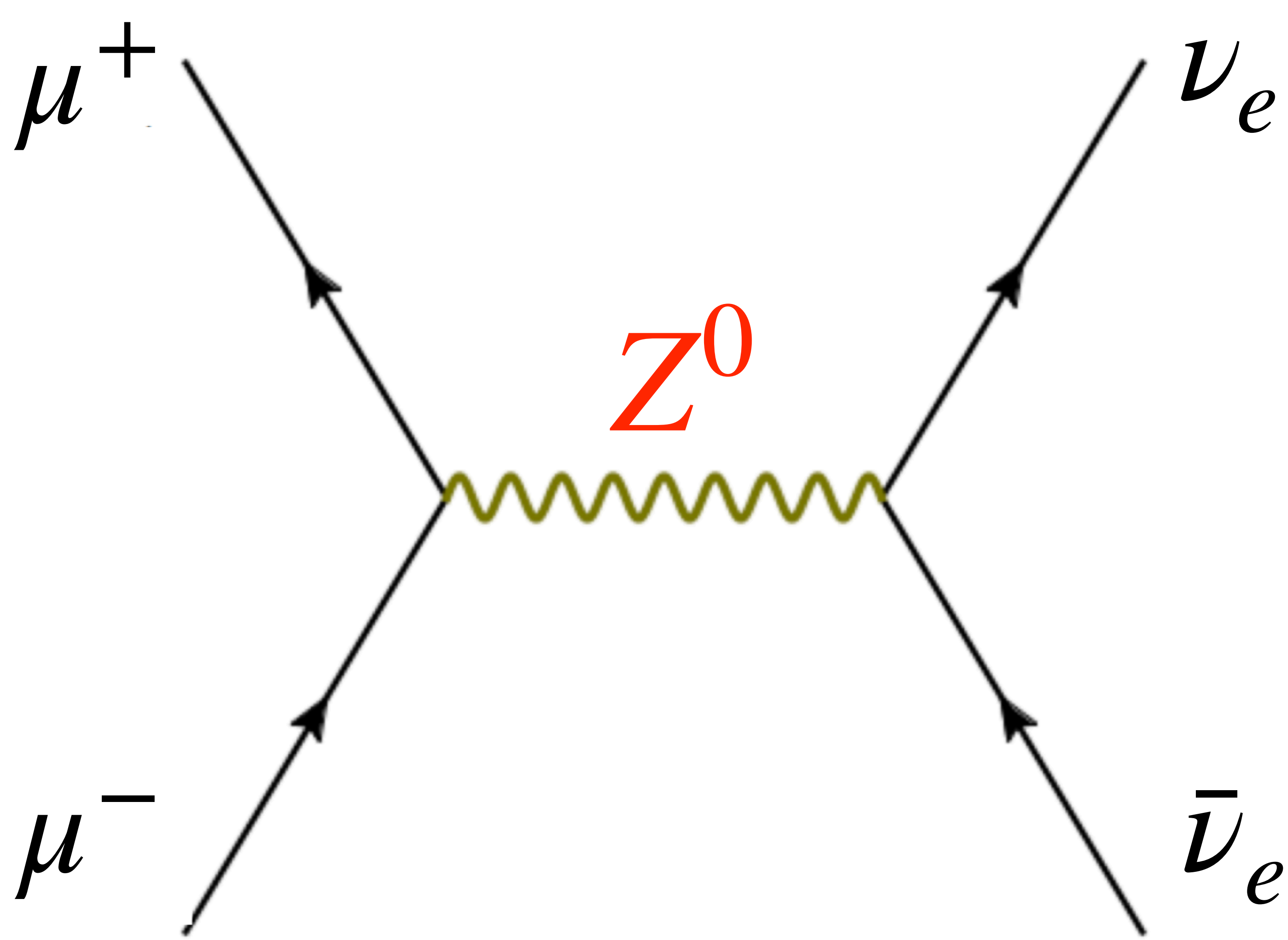
The Z boson also mediates processes involving **neutrinos**

$$\mu^+ + \mu^- \to \nu_e + \bar{\nu}_e$$



The weak boson Z

We can now summarise the **weak interaction vertices** involving the Z boson

with quarks

$$u + \bar{u} \to Z^0, \quad d + \bar{d} \to Z^0, \quad s + \bar{s} \to Z^0, \ldots$$

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with leptons

$$e^+ + e^- \to Z^0, \quad \mu^+ + \mu^- \to Z^0, \quad \nu_e + \bar{\nu}_e \to Z^0, \ldots$$

$$e^- + Z^0 \to e^-, \quad \nu_e + Z^0 \to \nu_e, \quad \tau^+ + Z^0 \to \tau^+, \ldots$$

$$Z^0 \to e^- + e^+, \quad Z^0 \to \tau^+ + \tau^-, \quad Z^0 \to \nu_\mu + \bar{\nu}_\mu, \ldots$$

Any allowed reaction when **particles are interchanged by antiparticles** is also **allowed**

The weak interactions

Let us summarise what we have learned about the **weak interactions**

- ☑ **Flavour** is **not necessarily conserved** by the weak interactions: strangeness, charmness, and bottomness can vary in reactions mediated by the ***W* bosons** (but not by the Z boson)

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- From the point of view of the interactions with **leptons** and **charged quarks,** the Z boson behaves as it it was a **heavy photon**