Introduction to Elementary Particles (TN2811)

Theory Lecture 6

Dr Juan Rojo

VU Amsterdam and Nikhef Theory group

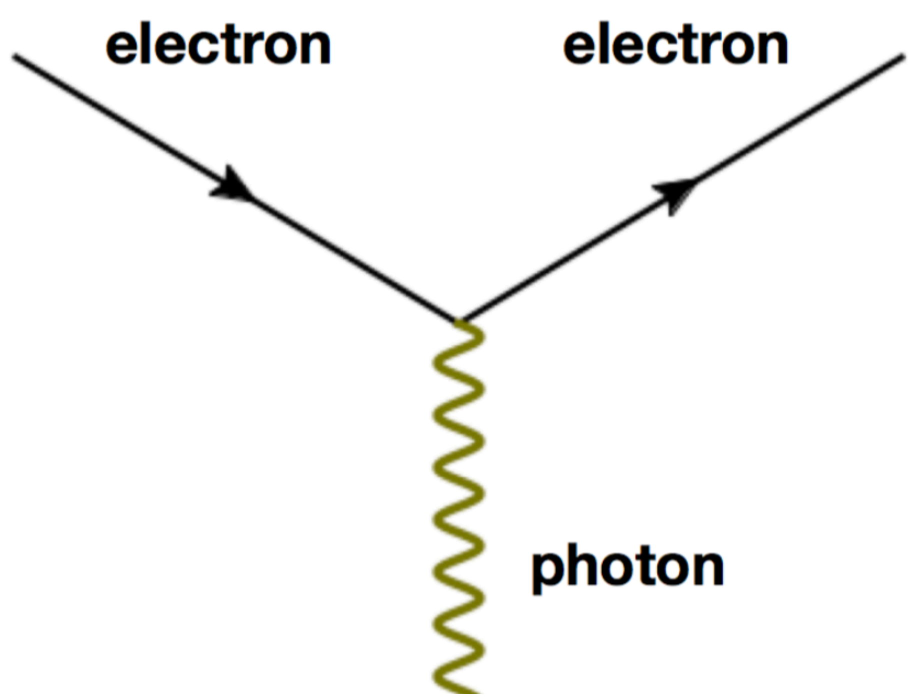
j.rojo@vu.nl / www.juanrojo.com

Today's lecture

- ☑ The **weak interaction** compared to the strong and EM forces
- ☑ The **weak boson *W***: properties and implications
- ☑ Decays of **heavy hadrons**
- ☑ The **weak boson *Z***: properties and implications

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**

Quantum Chromodynamics (QCD)

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

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

- ☑ Gluons are **charged under color** so they can interact with themselves. They are however **electrically neutral** to they don't affect the electric charge in strongly interacting processes

- ☑ The **strength** of the strong force is not constant: it is more at low energies / large distances (leading to quark confinement into hadrons) but less at high energies / low distances (where it behaves like electromagnetism)

- ☑ While quarks have **fractional electric charge** and baryon number, only hadrons with **integer electric charge** and baryon number are physically allowed

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**

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

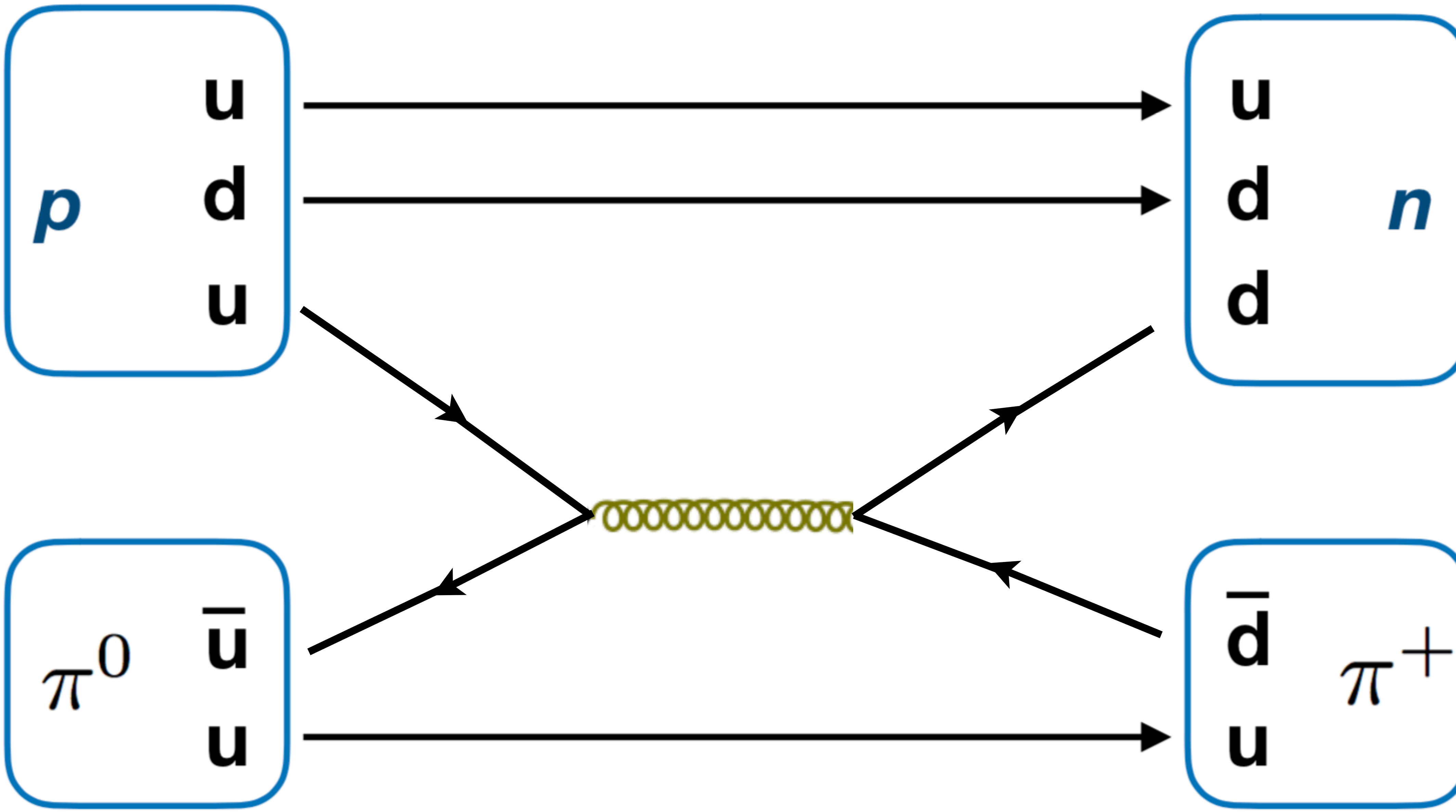
Note also how ***Q, B, S, C, …*** are conserved in this reaction

Scattering reactions in QCD

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

exercise

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



Scattering reactions in QCD

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

exercise

$$\rho^+ \to \pi^+ + \pi^0$$

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

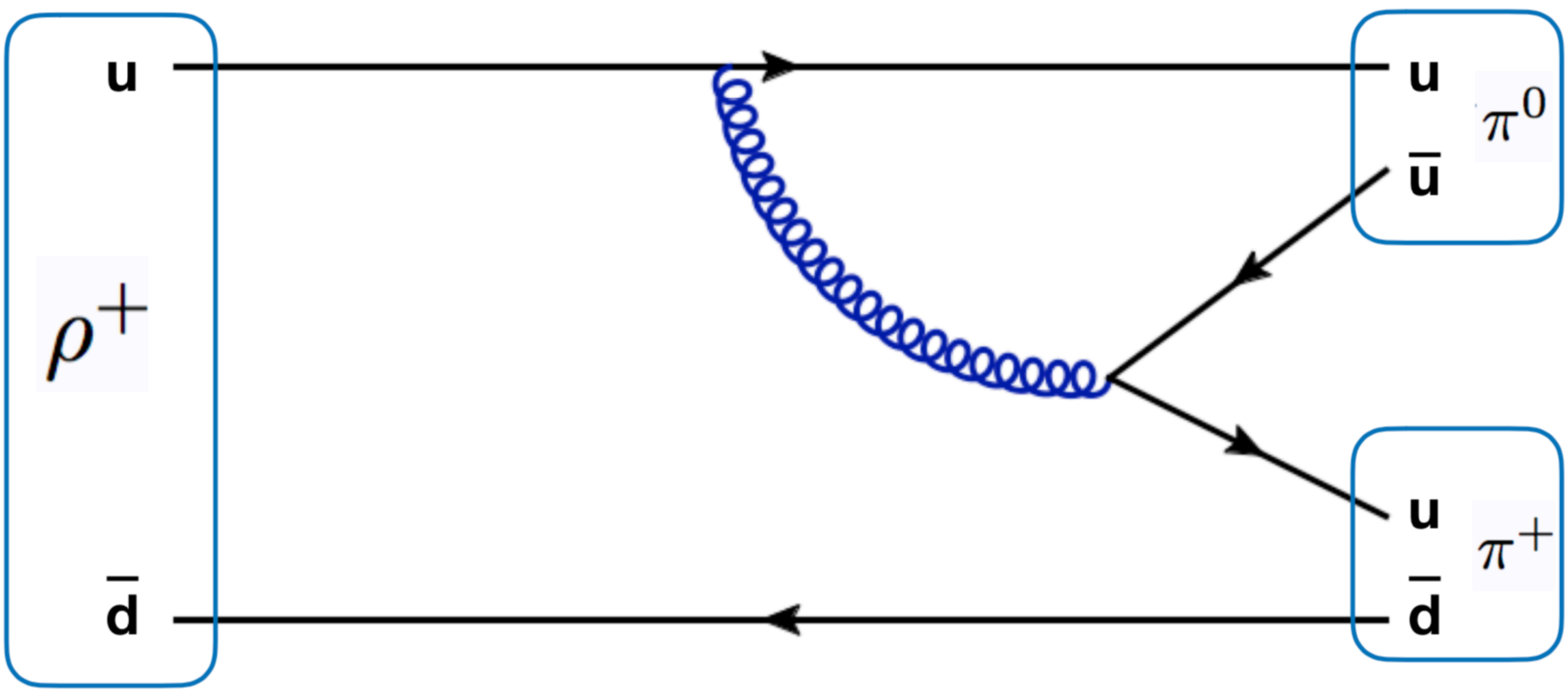
$$\pi^0 = (u\,\bar{u}) \qquad \pi^+ = \left(u\,\bar{d}\right)$$

Scattering reactions in QCD

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

exercise

$$\rho^+ \rightarrow \pi^+ + \pi^0$$



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

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

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

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

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

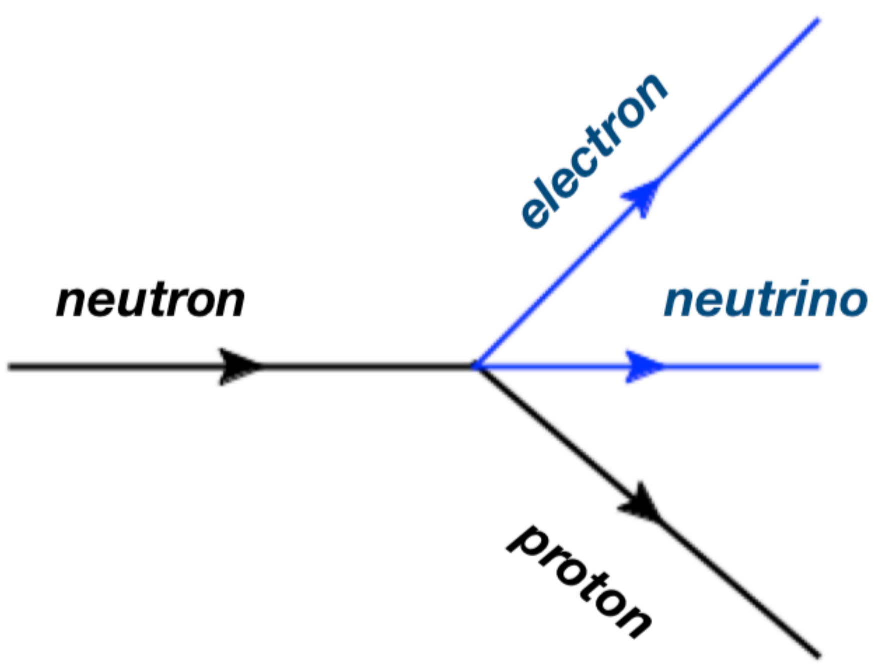
The weak interaction

The weak nuclear force

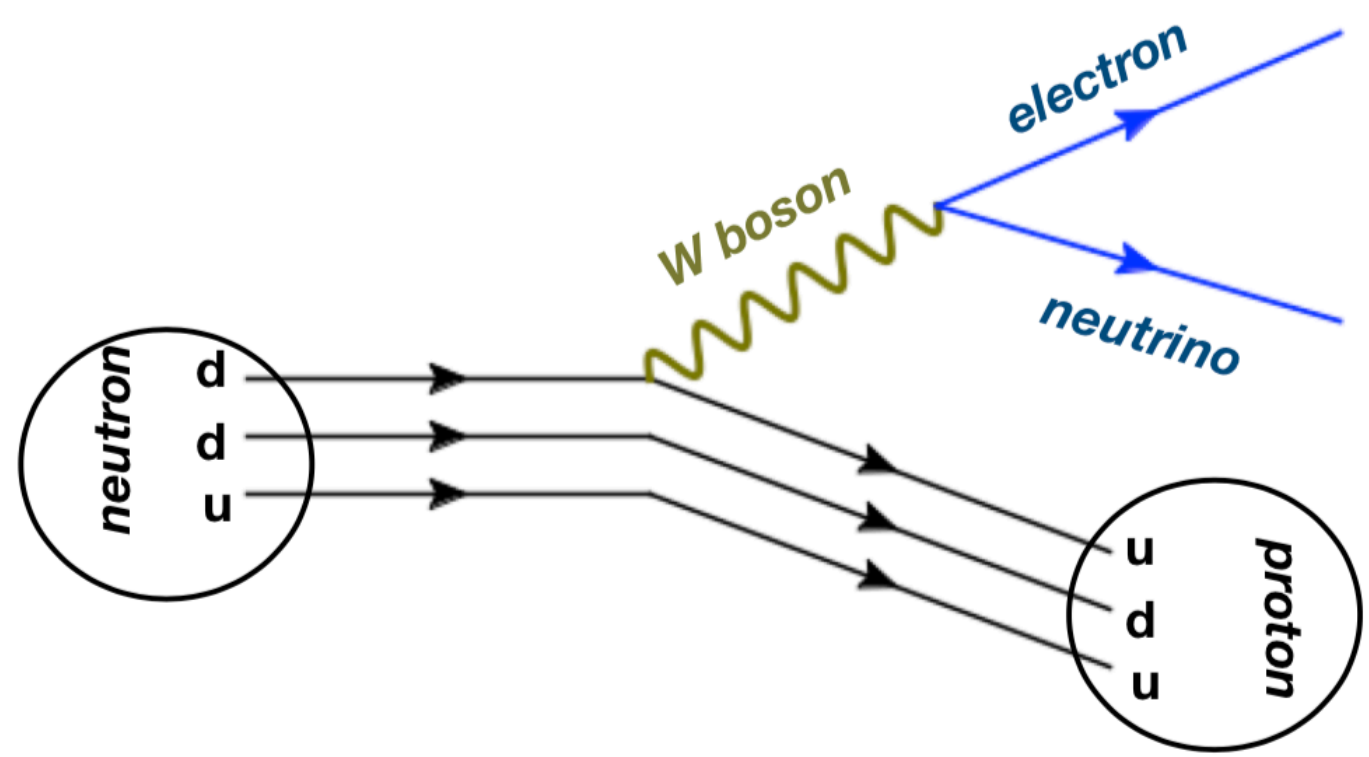
- Fermi (30s) explained **beta-decay of nuclei** by a **four-body interaction** between neutrons, protons, electrons and neutrinos: the **weak nuclear interaction**

- 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



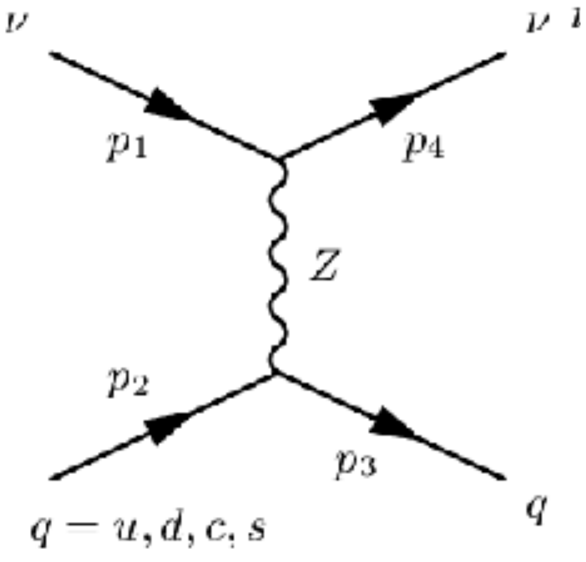
The weak nuclear force

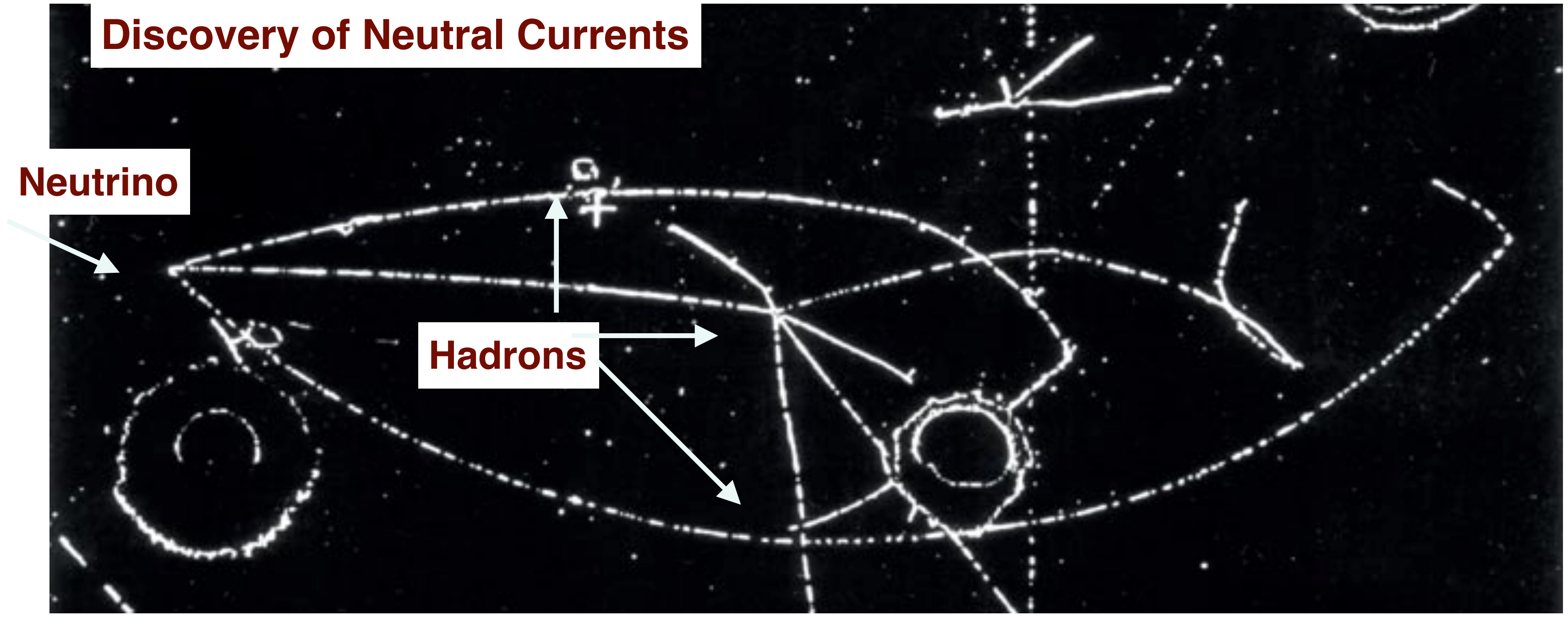
- Fermi (30s) explained **beta-decay of nuclei** by a **four-body interaction** between neutrons, protons, electrons and neutrinos: the **weak nuclear interaction**

- 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**

- 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

Electromagnetism

- A **single type of electric charge** exists: the only thing that varies is its sign and magnitude
- Electromagnetism is transmitted by **photons,** which are **massless** and **charge-neutral**
- The **strength of the electromagnetic interaction** is always small: electromagnetism looks the same at all energies/distances

Weak interactions

- All particles in the SM are carry a **weak charge**, and the specific values **depend on the matter particle**

Weak force vs electromagnetism

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

Electromagnetism

- A **single type of electric charge** exists: the only thing that varies is its sign and magnitude
- Electromagnetism is transmitted by **photons,** which are **massless** and **charge-neutral**
- The **strength of the electromagnetic interaction** is always small: electromagnetism looks the same at all energies/distances

Weak interactions

- All particles in the SM are carry a **weak charge**, and the specific values **depend on the matter particle**
- The strong interaction is transmitted by the ***W*** and ***Z*** bosons**,** which are **massive** and charged under the weak force

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

Weak force vs electromagnetism

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

Electromagnetism

- A **single type of electric charge** exists: the only thing that varies is its sign and magnitude
- Electromagnetism is transmitted by **photons,** which are **massless** and **charge-neutral**
- The **strength of the electromagnetic interaction** is always small: electromagnetism looks the same at all energies/distances

Weak interactions

- All particles in the SM are carry a **weak charge**, and the specific values **depend on the matter particle**
- The strong interaction is transmitted by the ***W*** and ***Z*** bosons, which are **massive** and charged under the weak force
- The weak interaction is always weak and confined to small scales (large value of $m_{W,Z}$)

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

Weak reactions

A central difference of scattering reactions involving the **weak force** as opposed to the electromagnetic force is that the **quark flavour quantum numbers** (strangeness, charmness, and bottomness) are **not necessarily conserved**

Weak reactions

A central difference of scattering reactions involving the **weak force** as opposed to the electromagnetic force is that the **quark flavour quantum numbers** (strangeness, charmness, and bottomness) are **not necessarily conserved**

Let's illustrate this with two reactions mediated by the weak force

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

$$\left(s\,\bar{d}\right) \to \left(u\,\bar{d}\right) + \left(d\,\bar{u}\right)$$

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

Weak reactions

A central difference of scattering reactions involving the **weak force** as opposed to the electromagnetic force is that the **quark flavour quantum numbers** (strangeness, charmness, and bottomness) are **not necessarily conserved**

Let's illustrate this with two reactions mediated by the weak force

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

$$\left(s\,\bar{d}\right) \rightarrow \left(u\,\bar{d}\right) + \left(d\,\bar{u}\right)$$

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

---

exercise

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

Compute the variation in strangeness in this reaction

Weak reactions

A central difference of scattering reactions involving the **weak force** as opposed to the electromagnetic force is that the **quark flavour quantum numbers** (strangeness, charmness, and bottomness) are **not necessarily conserved**

Let's illustrate this with two reactions mediated by the weak force

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

$$\left(s\,\bar{d}\right) \rightarrow \left(u\,\bar{d}\right) + \left(d\,\bar{u}\right)$$

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

---

exercise

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

$$\left(c\,\bar{d}\right) \rightarrow \left(s\,\bar{d}\right) + e^+ + \nu_e$$

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

The weak boson *W*

The weak boson *W*

The weak interactions are mediated by three massive bosons: $\boldsymbol{W^+}$***,*** $\boldsymbol{W^+}$***,*** $\boldsymbol{Z^0}$

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

$$m_\gamma = 0$$
$$m_g = 0$$
$$m_{W^\pm} = 80.385\,\mathrm{GeV}$$

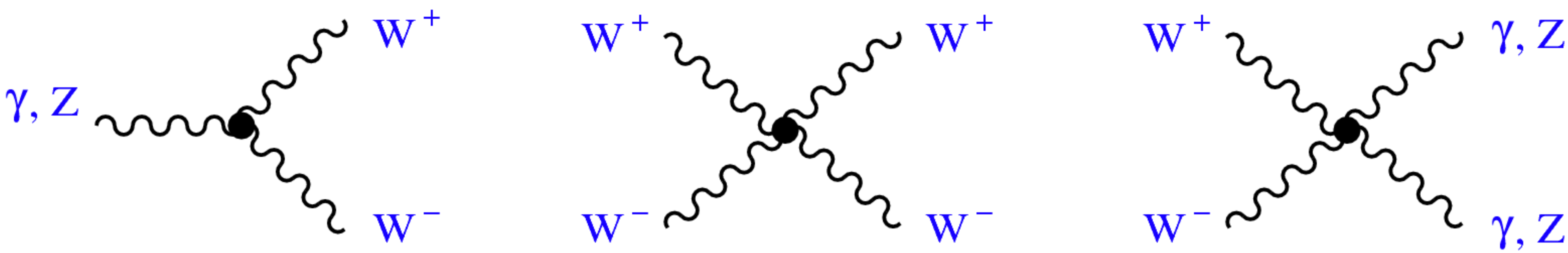
The weak boson *W*

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

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

- As in the case of the gluons (but not the photons), the *W* boson is charged under both **electric** and **weak** charges, and therefore can interact with **itself**



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

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

The weak boson *W*

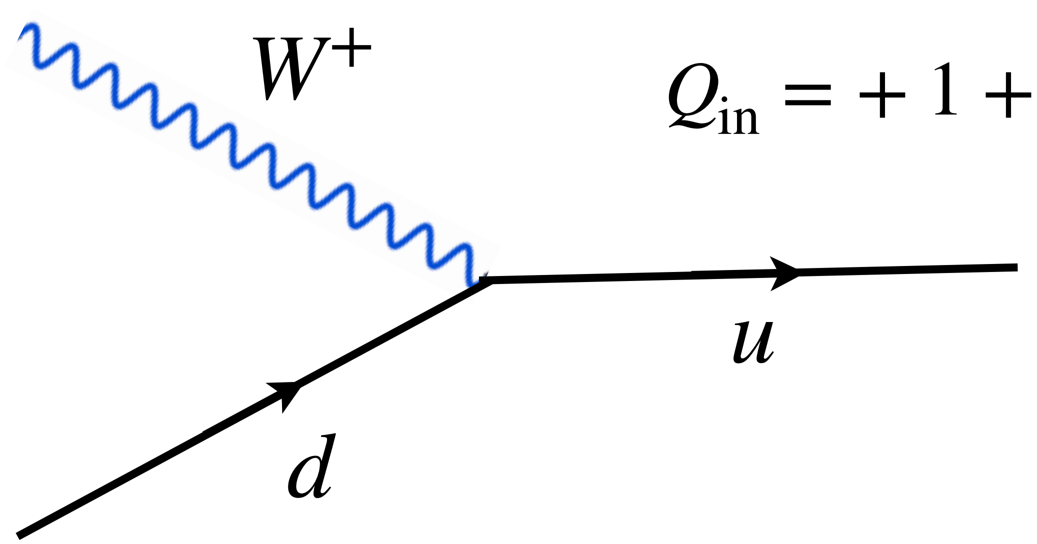
The weak interactions are mediated by three massive bosons: ***W*⁺, *W*⁺, *Z*⁰**

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

- As in the case of the gluons (but not the photons), the *W* boson is charged under both **electric** and **weak** charges, and therefore can interact with **itself**

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



$$Q_{\rm in} = +1 + (-1/3) = +2/3 = Q_{\rm fin}$$

The weak boson *W*

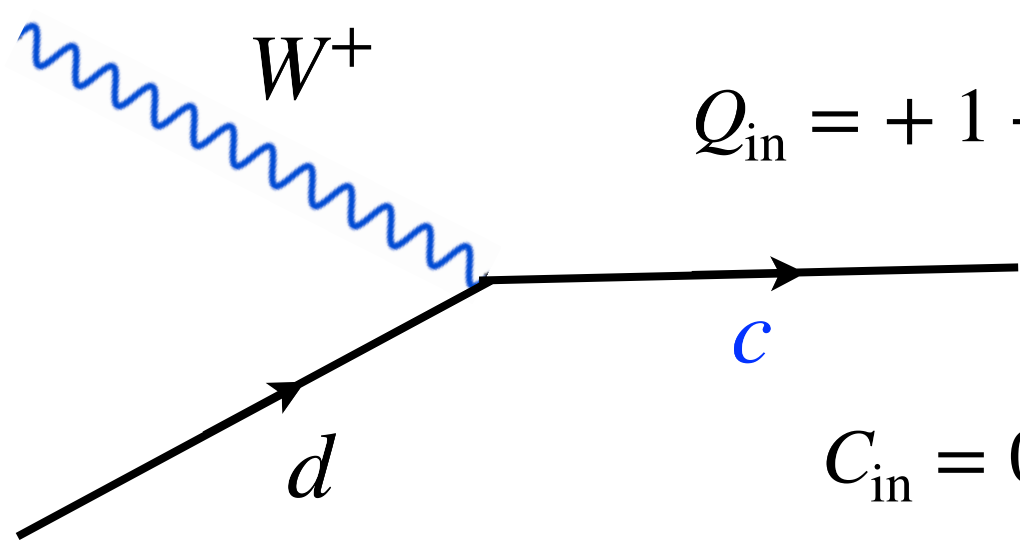
The weak interactions are mediated by three massive bosons: $\boldsymbol{W^+, W^+, Z^0}$

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

- As in the case of the gluons (but not the photons), the *W* boson is charged under both **electric** and **weak** charges, and therefore can interact with **itself**

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



$$Q_{\rm in} = +1 + (-1/3) = +2/3 = Q_{\rm fin}$$

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

The weak boson *W*

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

- ☑ As in the case of the gluons (but not the photons), the *W* boson is charged under both **electric** and **weak** charges, and therefore can interact with **itself**

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

- ☑ 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:

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

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

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

The weak boson *W*

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

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

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

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

☑ **Electric charge** is always conserved

The weak boson W

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

$$
\begin{array}{llll}
u + W^- \to d\,, & u + W^- \to s\,, & d + W^+ \to u\,, & s + W^+ \to u\,, \\
\bar{u} + W^+ \to \bar{d}\,, & \bar{u} + W^+ \to \bar{s}\,, & \bar{d} + W^- \to \bar{u}\,, & \bar{s} + W^- \to \bar{u}\,, \\
W^+ \to u + \bar{d}\,, & W^+ \to u + \bar{s}\,, & W^- \to d + \bar{u}\,, & W^- \to s + \bar{u}\,,
\end{array}
$$

- **Electric charge** is always conserved

- 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:

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

- ☑ **Electric charge** is always conserved

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

- ☑ If a given reaction is allowed, the corresponding reaction involving the **antiparticles** is also physically allowed

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

The weak boson *W*

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

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

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

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

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**

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**

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

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

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

The weak boson *W*

exercise

Draw the Feynman diagram for the following process

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

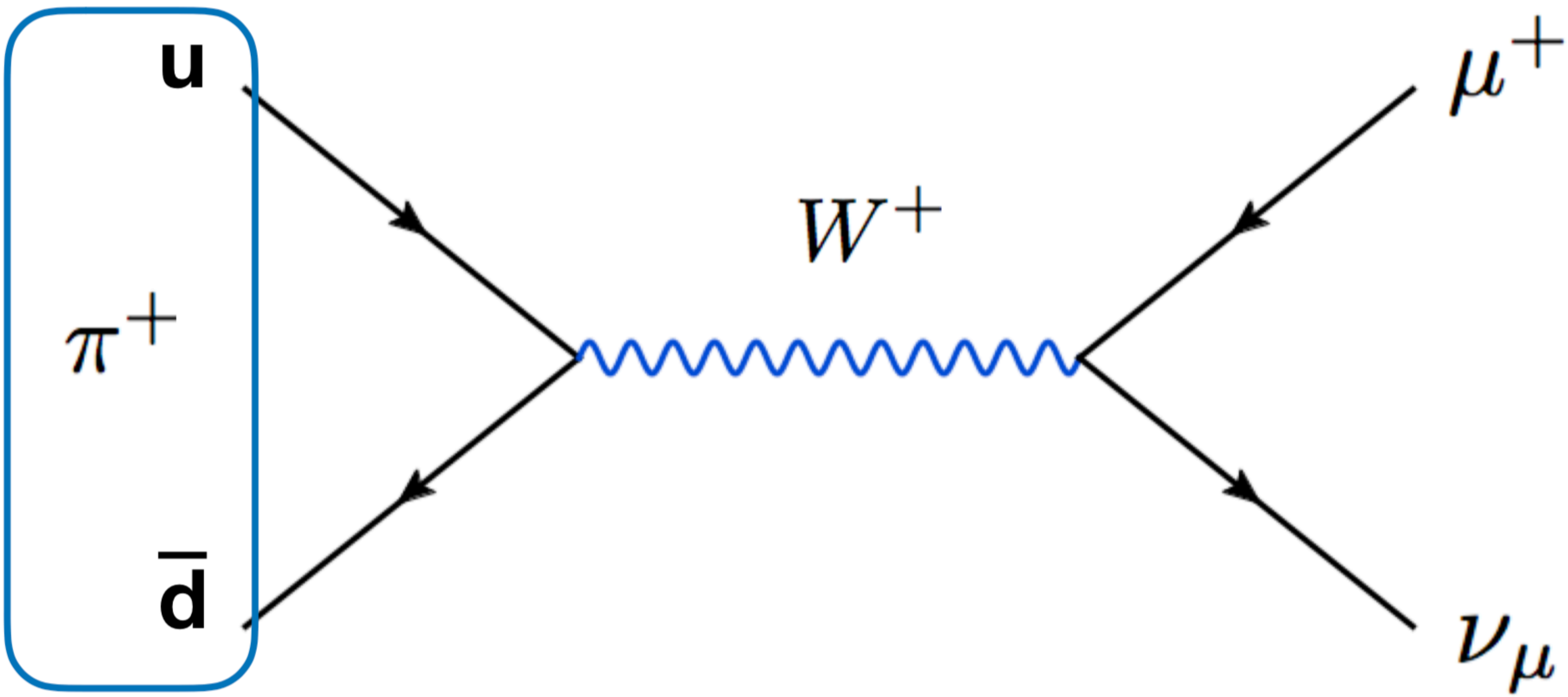
- We have a neutrino in the final state: the **weak interaction** must be involved
- Quarks and leptons only interact indirectly via either photons or *W, Z* bosons
- Since the electric charge is ***Q=+-1,*** then a positively charged ***W boson*** is involved
- We know what **vertices are allowed**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

The weak boson *W*

exercise

Draw the Feynman diagram for the following process

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

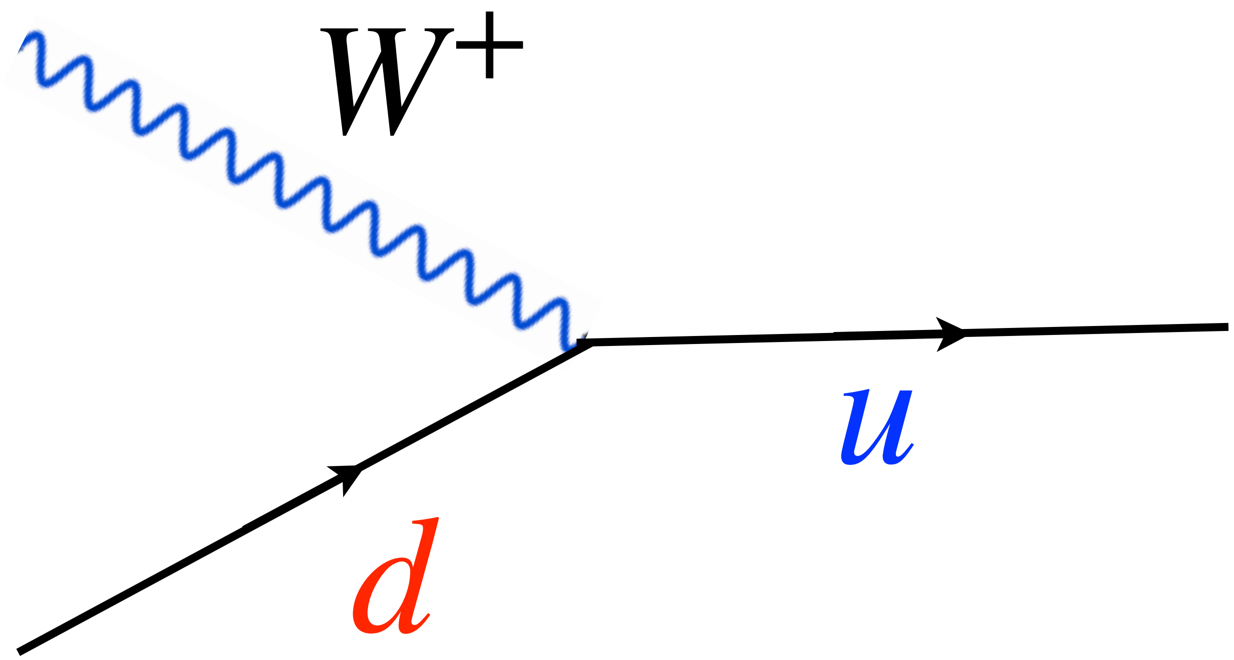


You can check that all relevant quantum numbers are **conserved:** *L, B, Q, …*

Heavy hadron decays

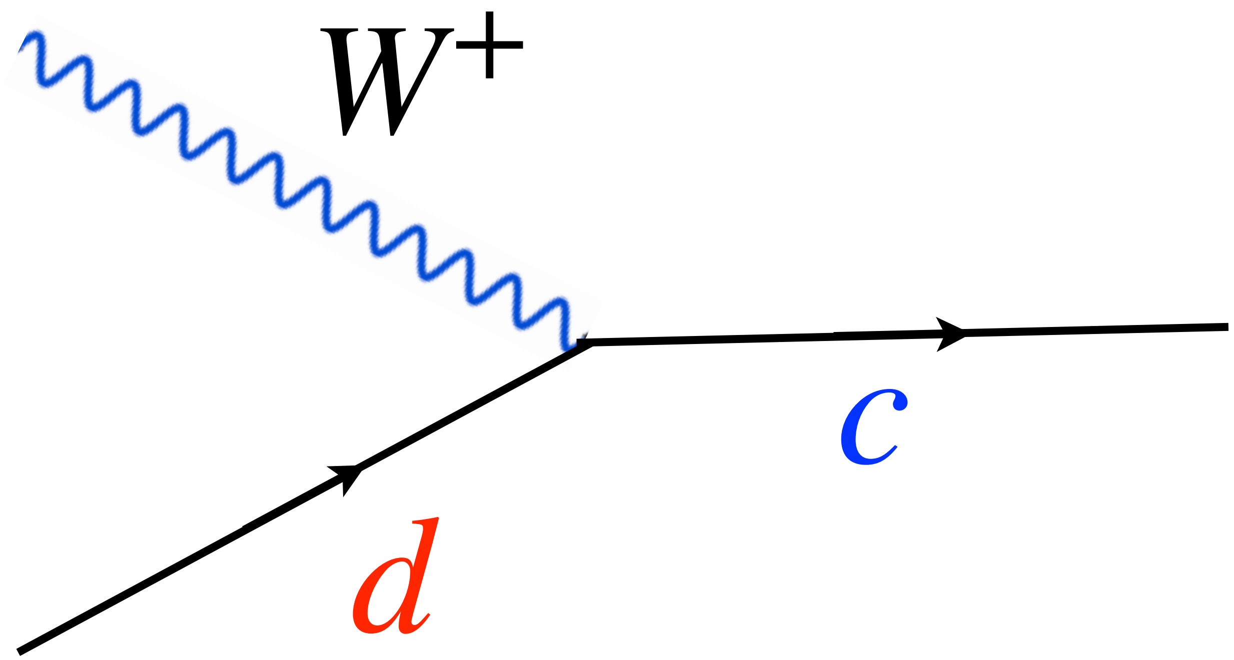
Weak coupling between generations

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



Weak coupling between generations

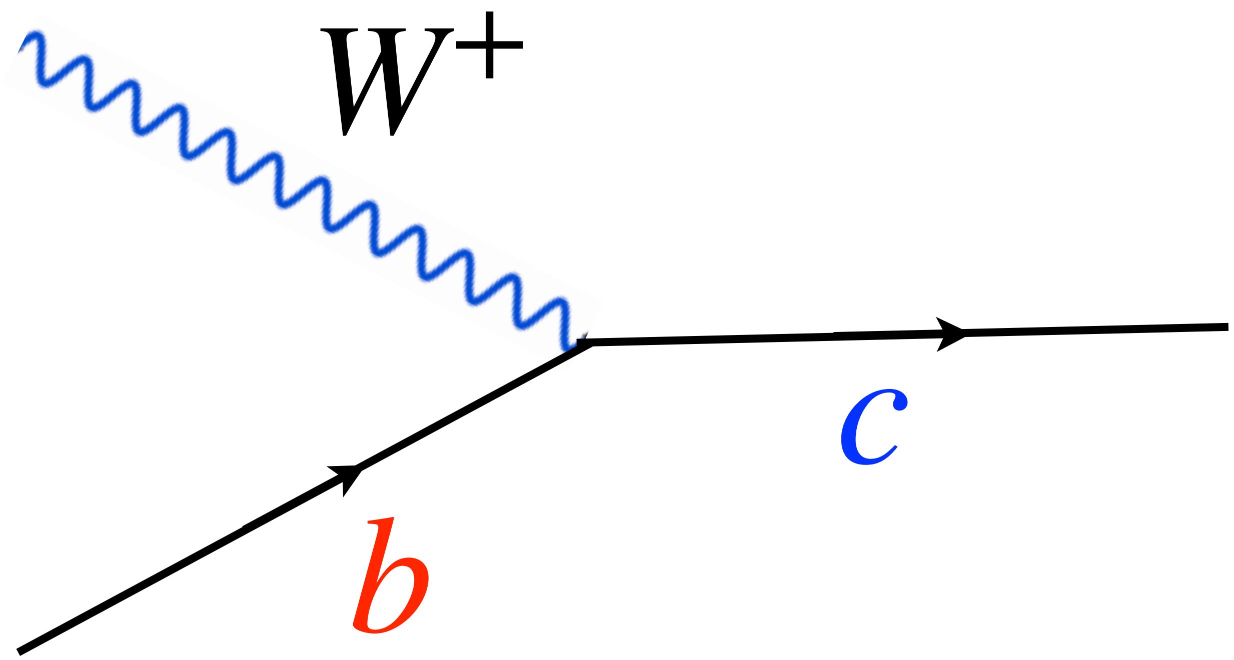
We have seen that in processes mediated by the weak gauge boson *W* the **flavour** of the quarks will **change**



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

Weak coupling between generations

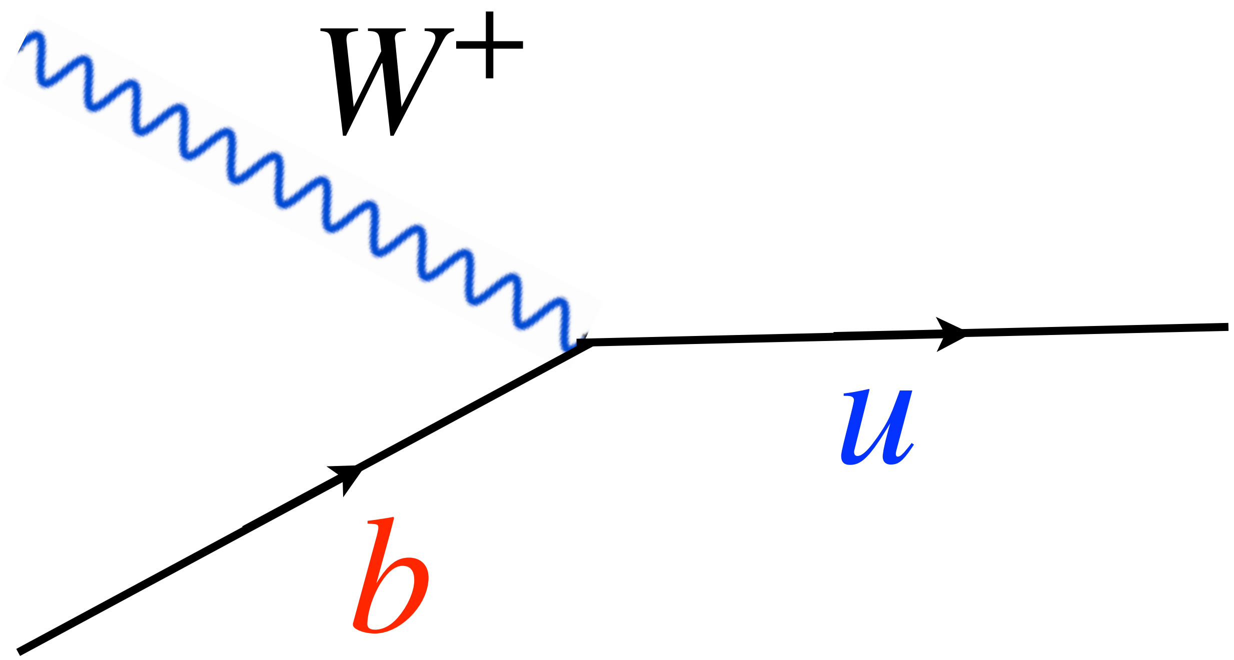
We have seen that in processes mediated by the weak gauge boson *W* the **flavour** of the quarks will **change**



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

Weak coupling between generations

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

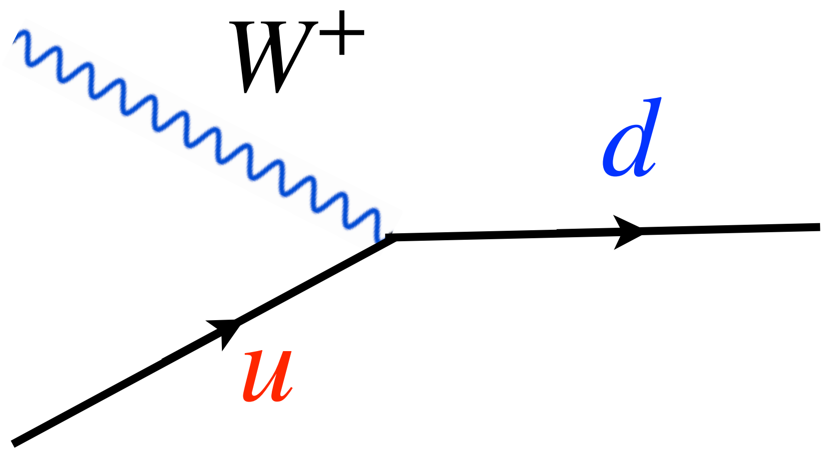


Moreover we can always replace a given quark by the corresponding quark of a **different generation**

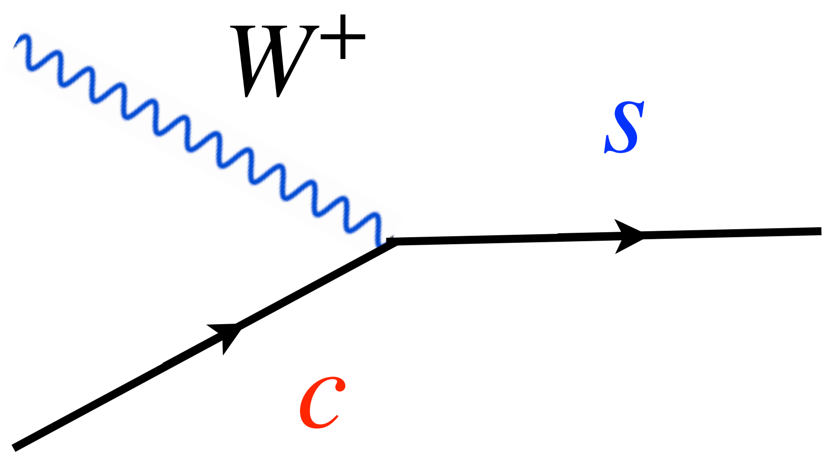
The weak interactions mediates **transitions** between **quarks of different generations**

Weak coupling between generations

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

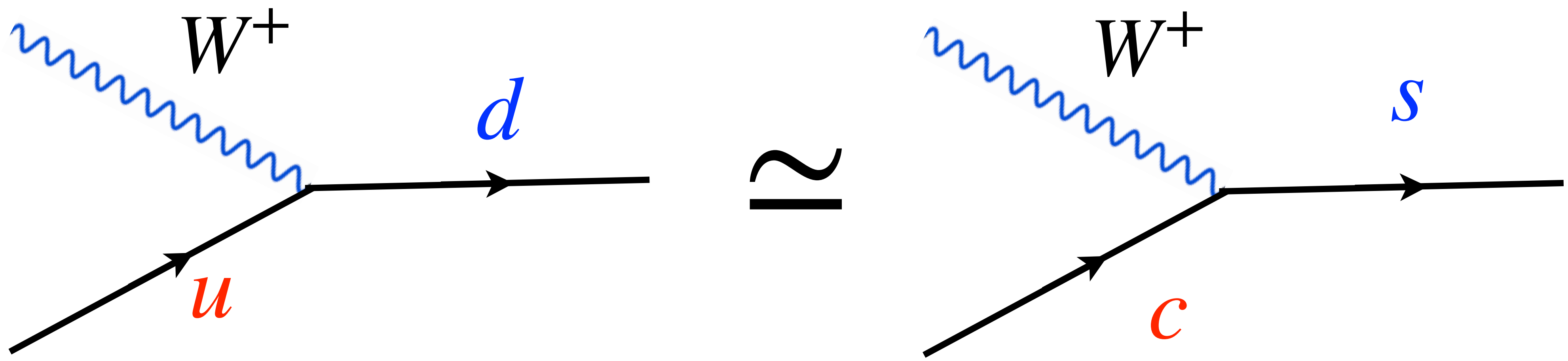


$\simeq$

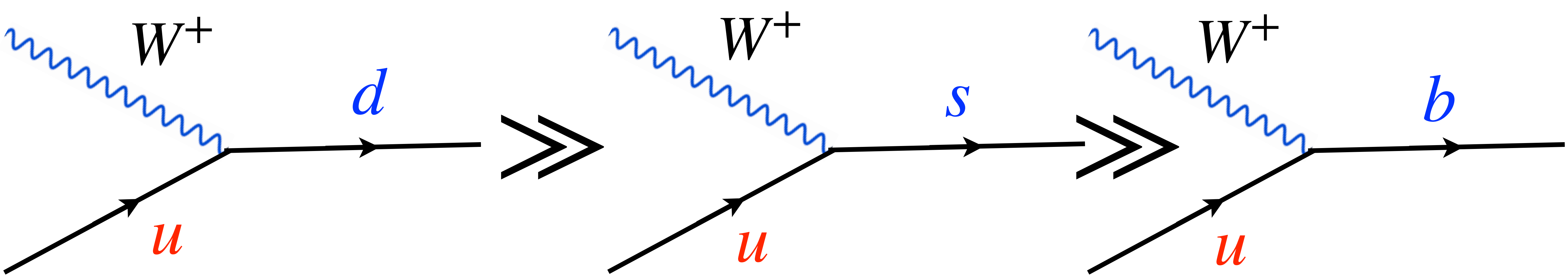


Weak coupling between generations

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



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**

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

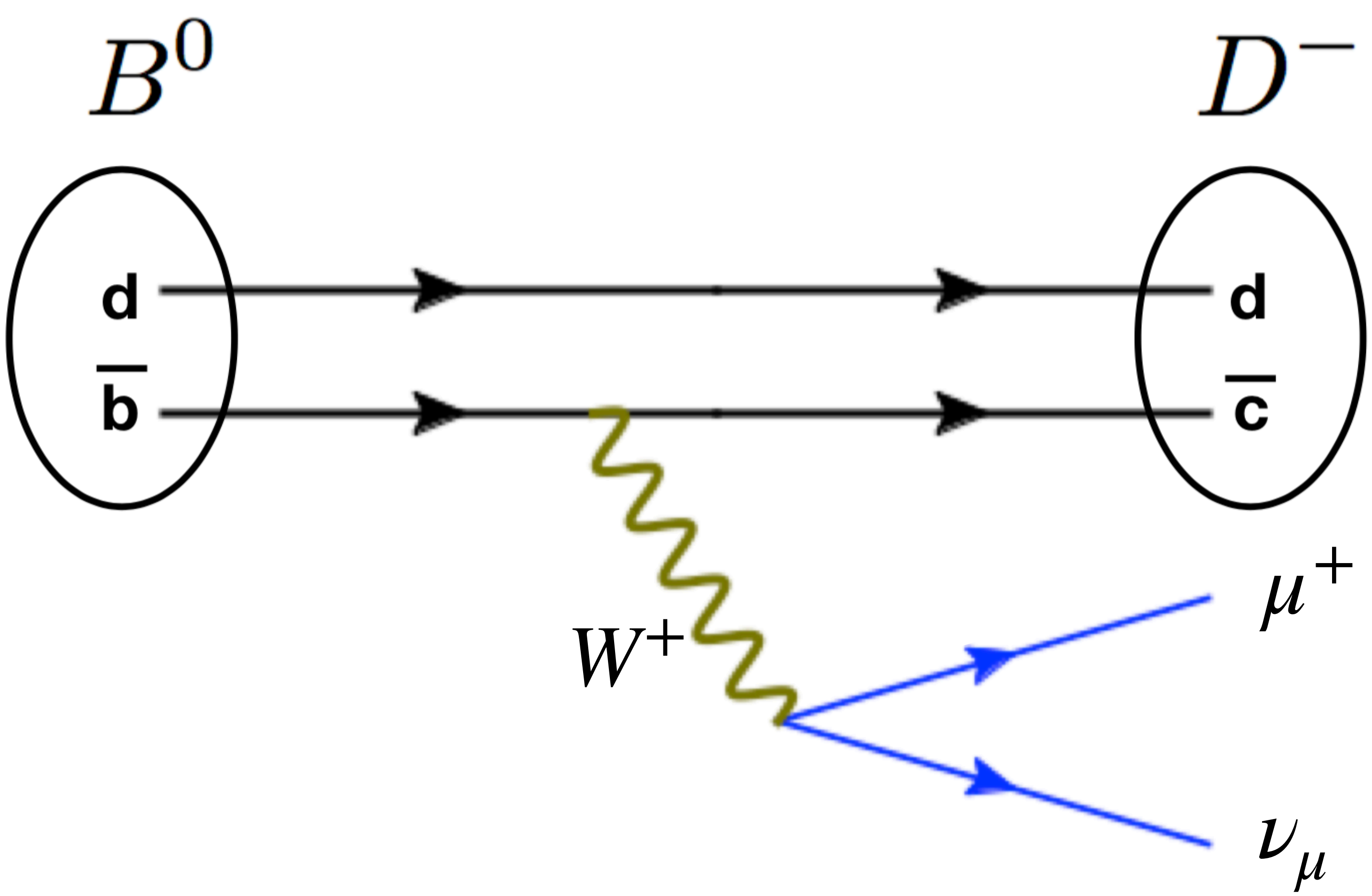
what is the corresponding Feynman diagram?

Heavy hadron decays

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

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

what is the corresponding Feynman diagram?



Heavy hadron decays

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

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

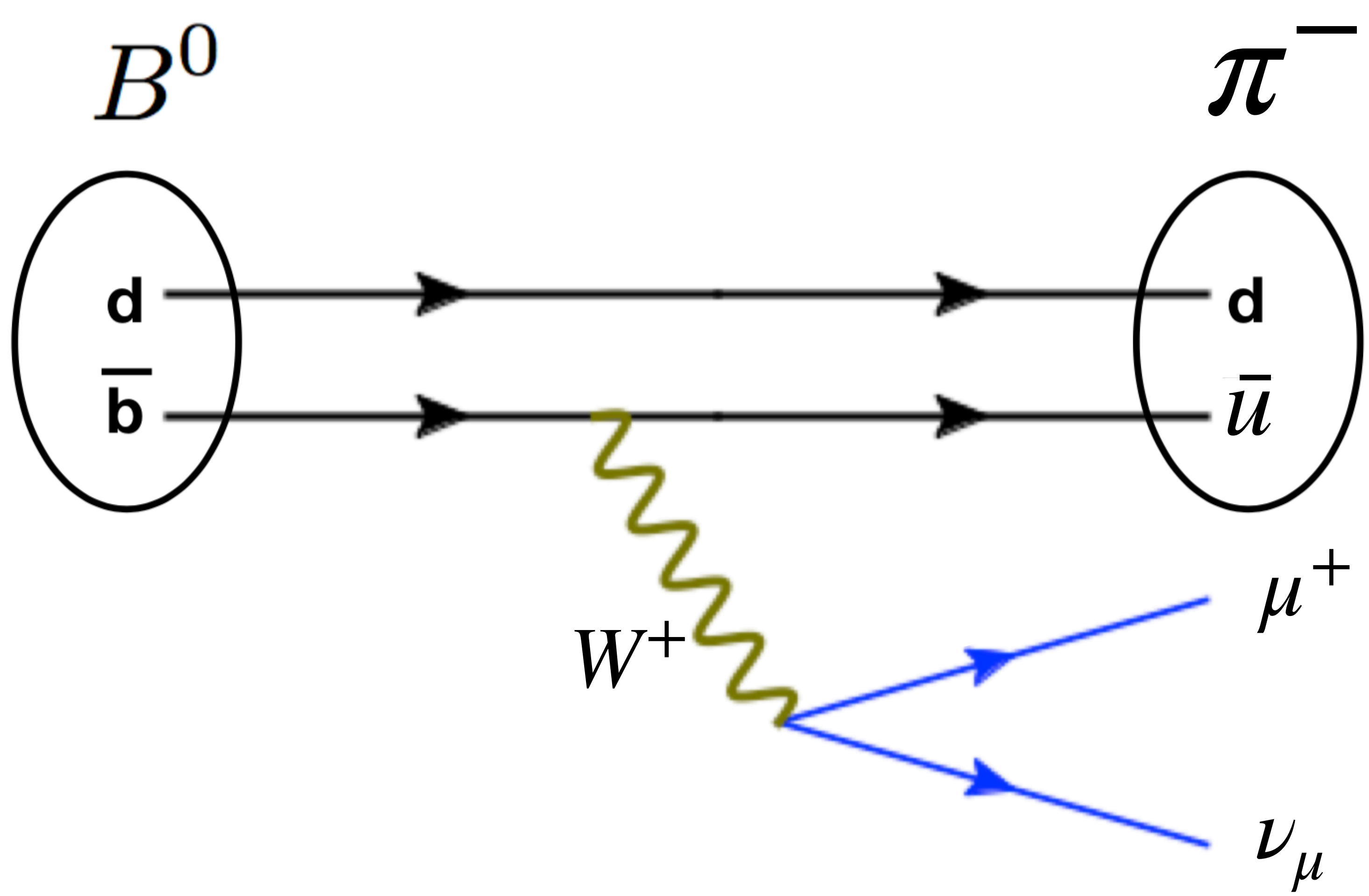
what is the corresponding Feynman diagram?

Heavy hadron decays

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

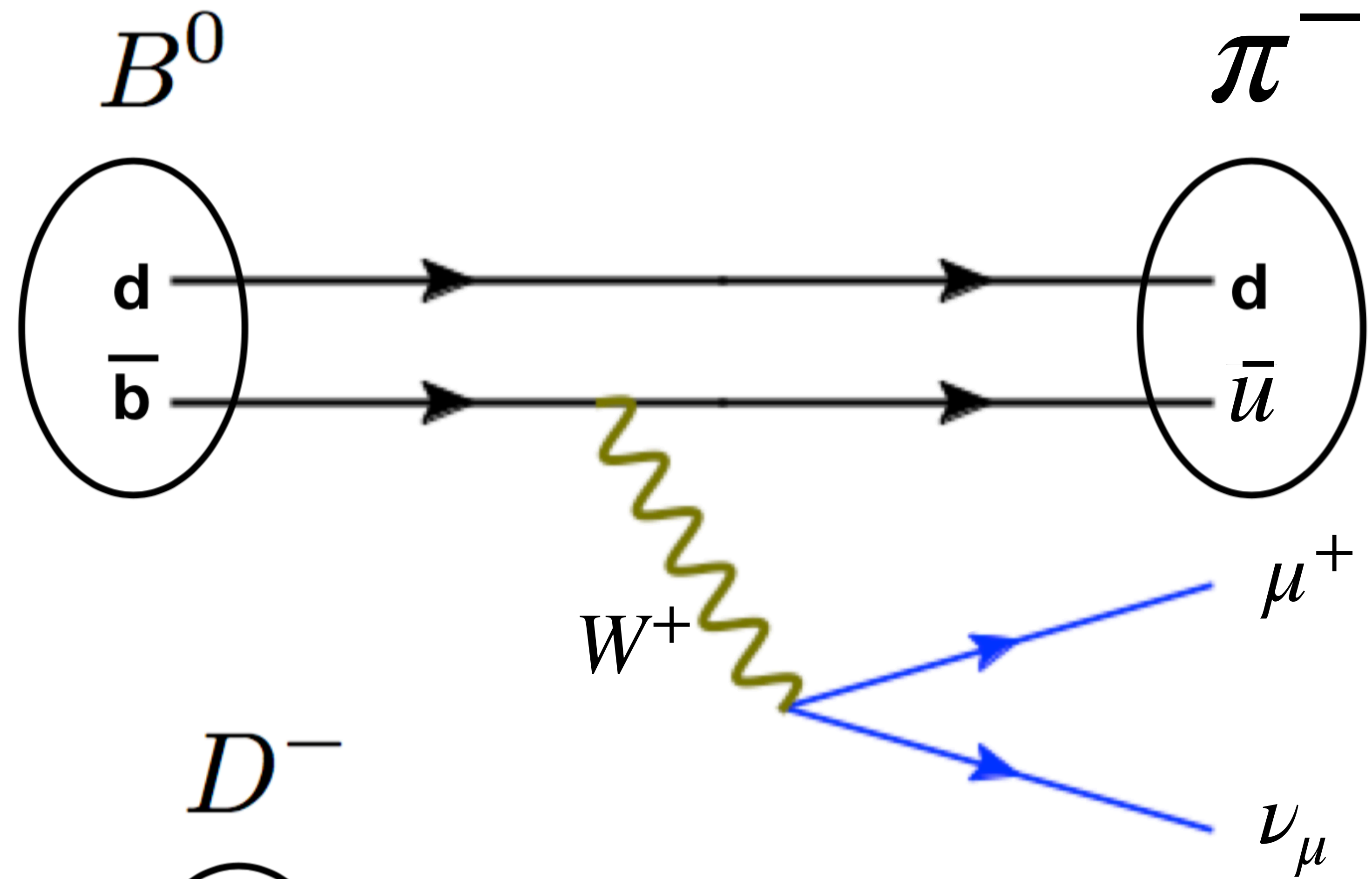
$$B^0 \to \pi^- + \mu^+ + \nu_\mu \qquad B^0 = \left(d\,\bar{b}\right) \qquad \pi^- = \left(d\bar{u}\right)$$

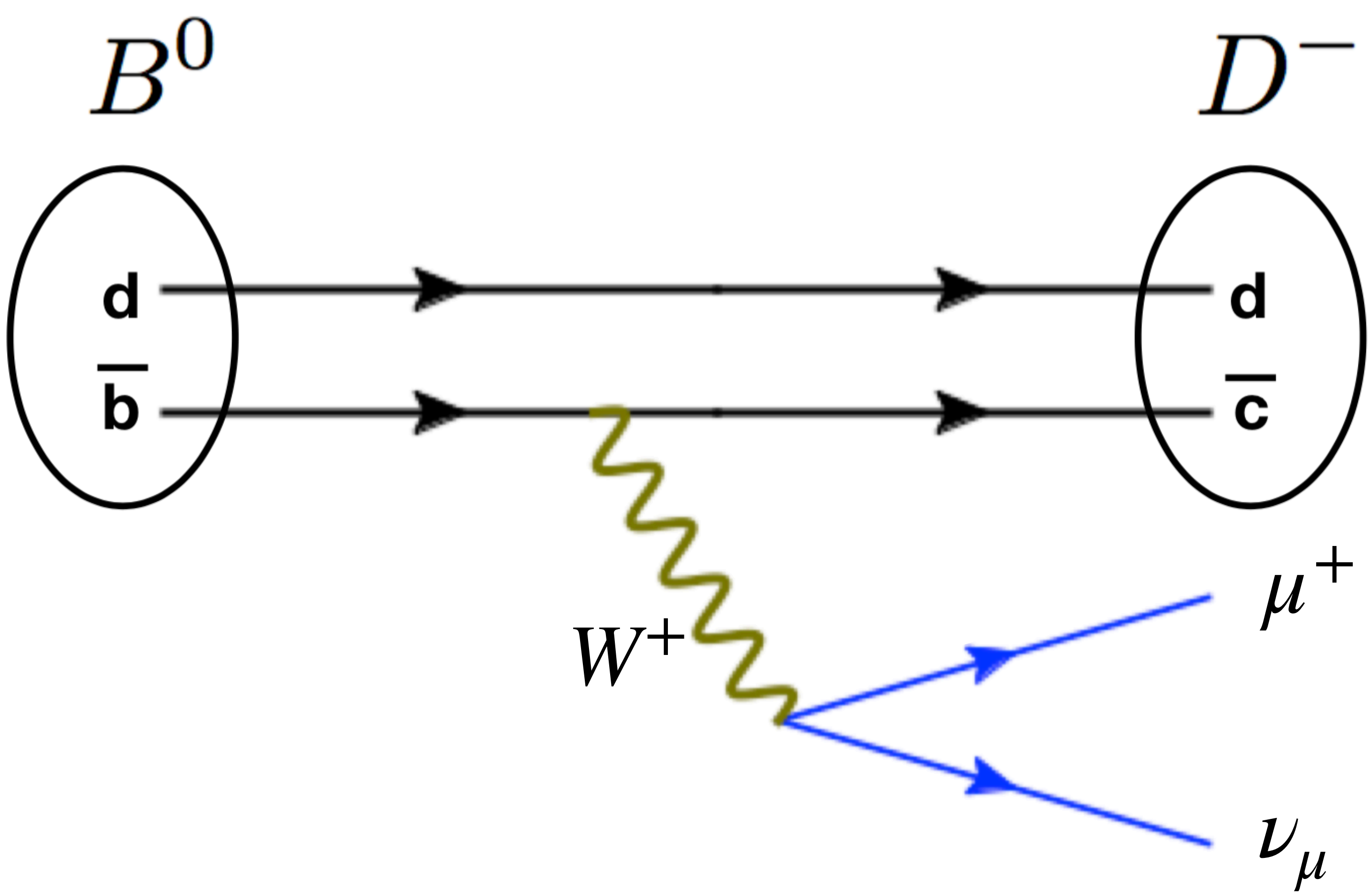
what is the corresponding Feynman diagram?



Heavy hadron decays

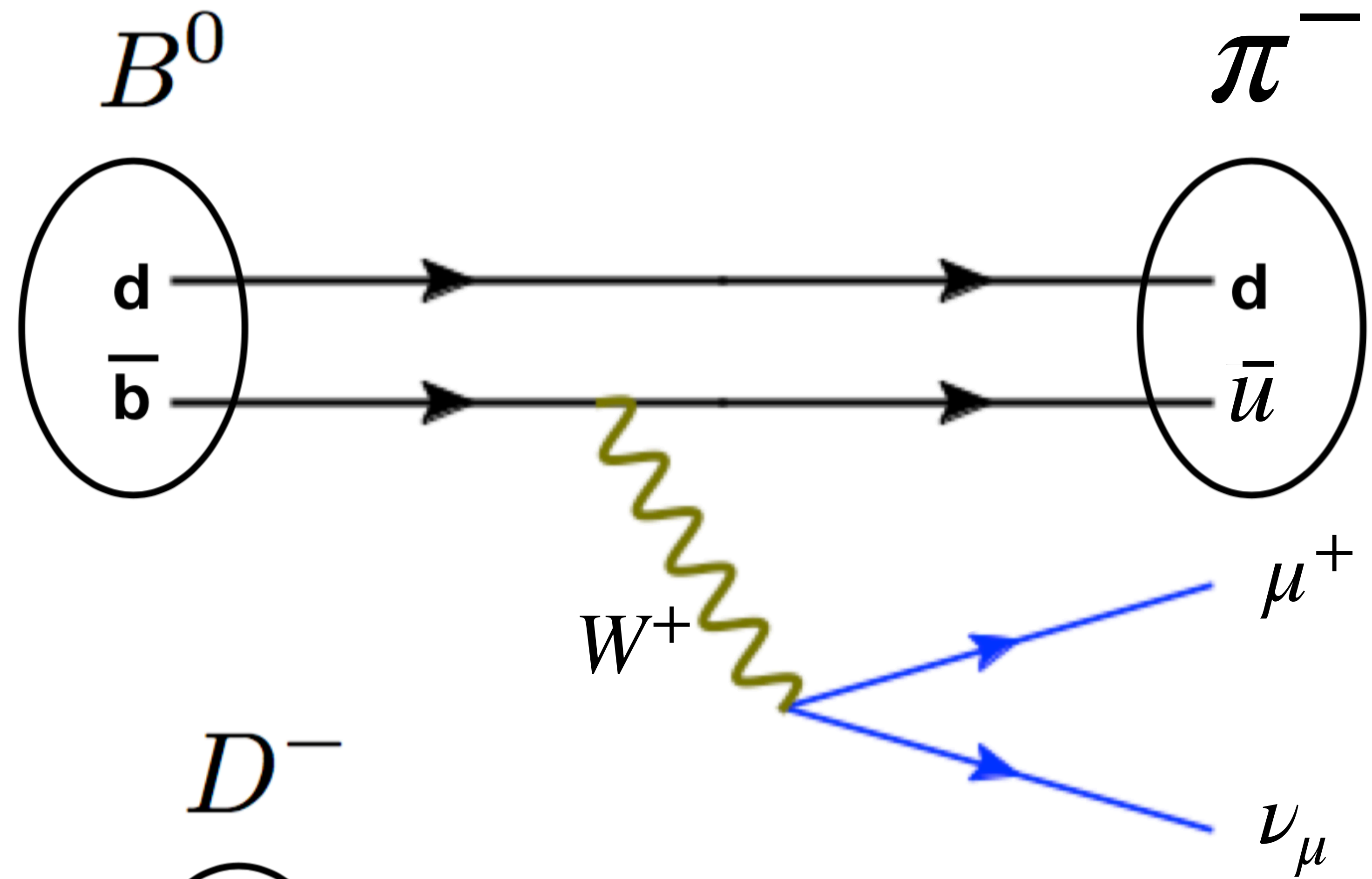
Which of the two reactions is **most likely** to take place?

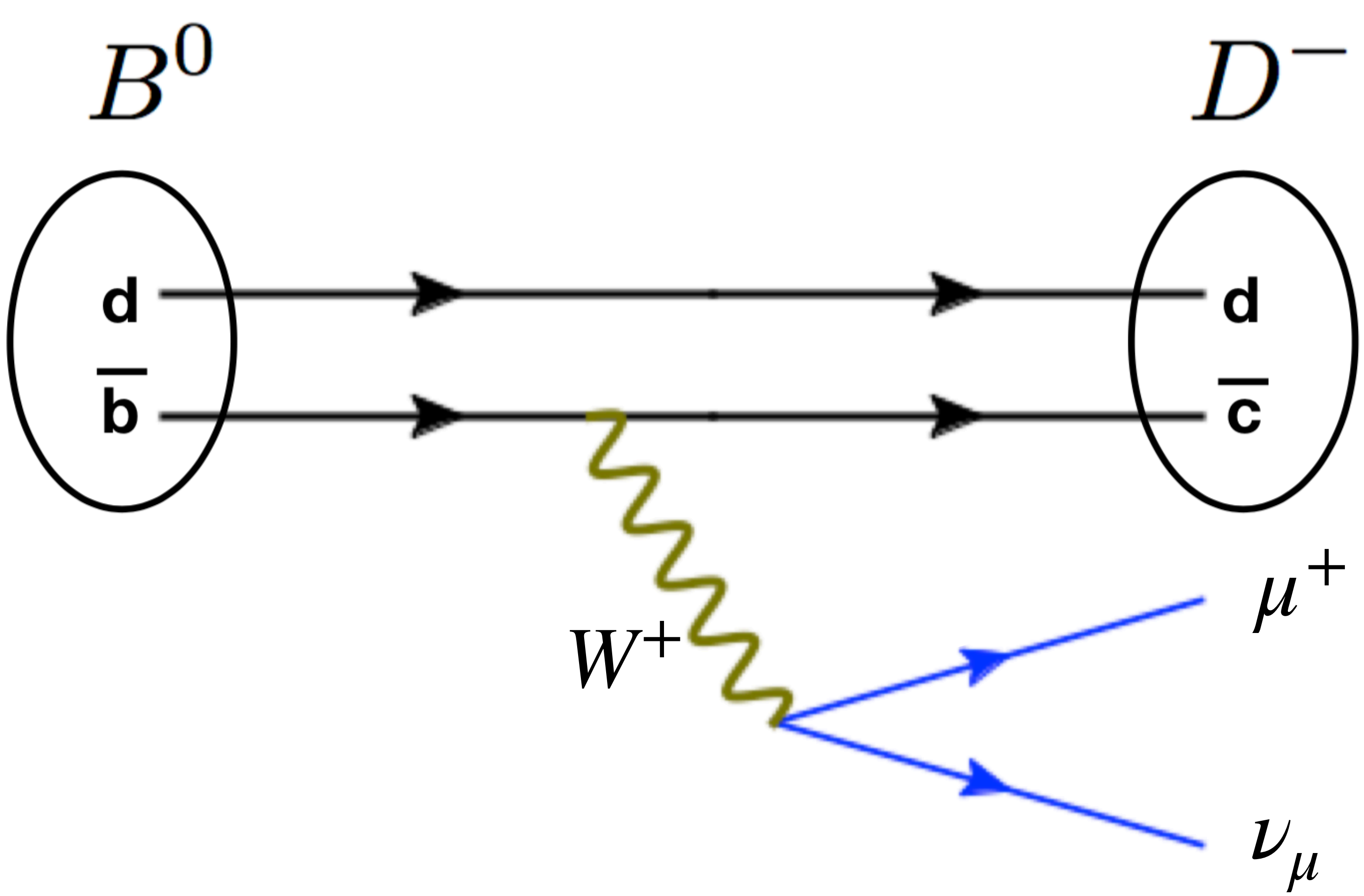




Heavy hadron decays

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





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**

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

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

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

Heavy hadron decays

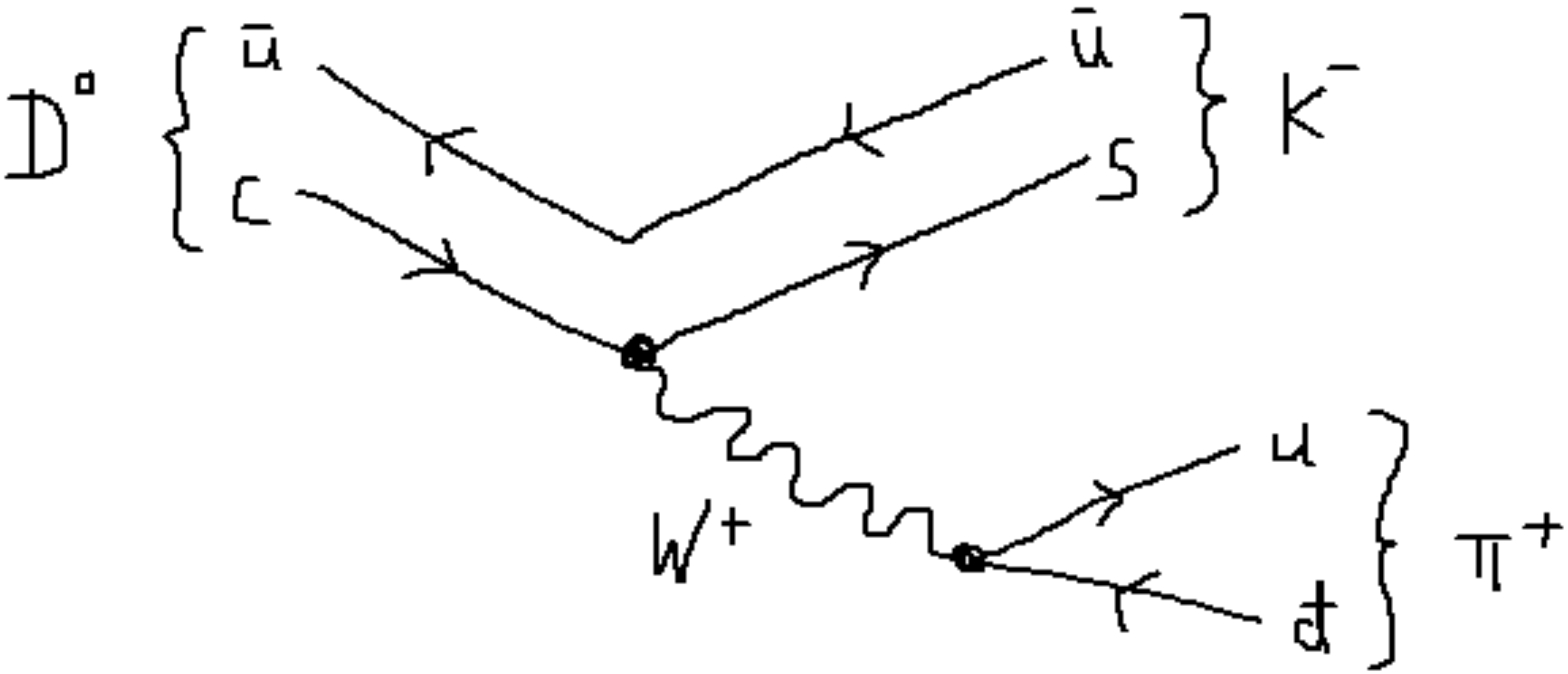
exercise

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

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

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

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



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?

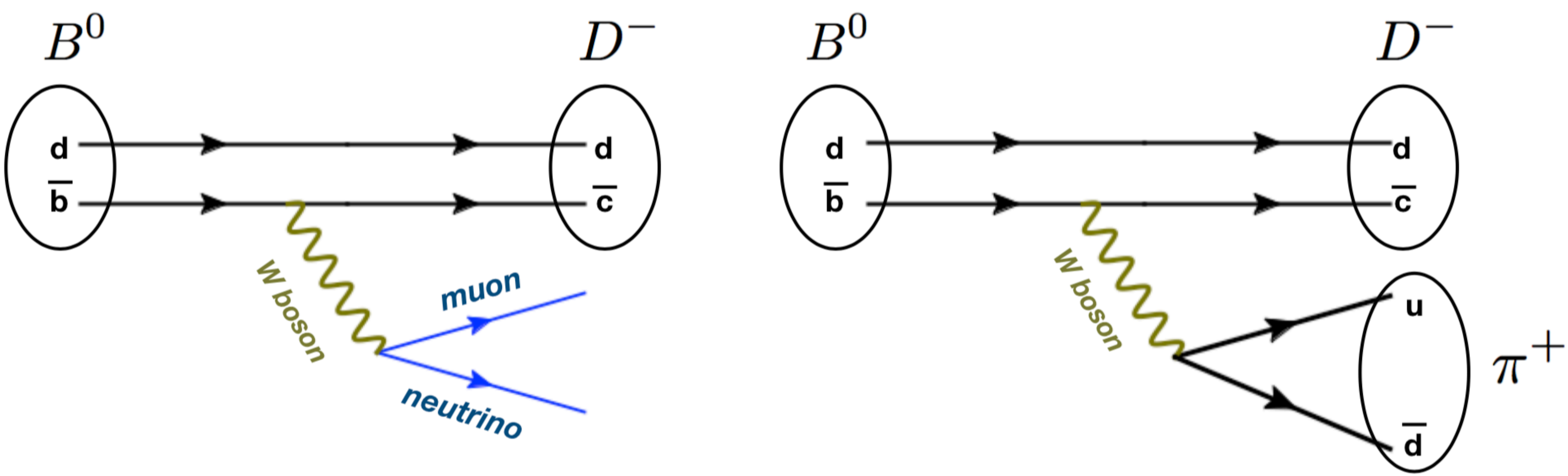
Heavy hadron decays

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

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

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

How do these two decay models relate to each other?



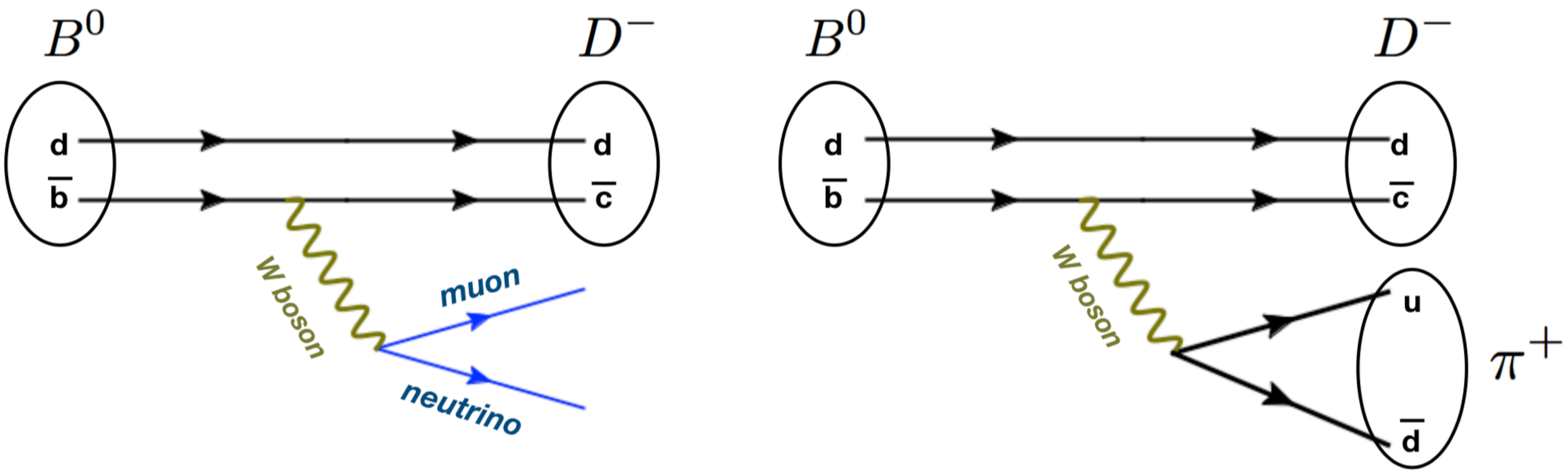
Heavy hadron decays

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

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

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

How do these two decay models relate to each other?



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)

$$m_\gamma = 0$$

$$m_g = 0$$

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

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

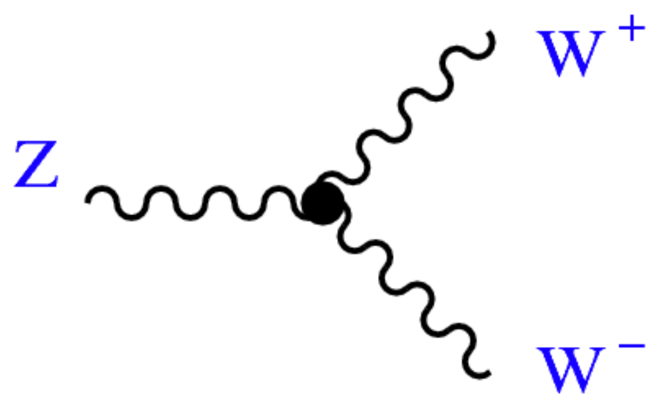
The weak boson *Z*

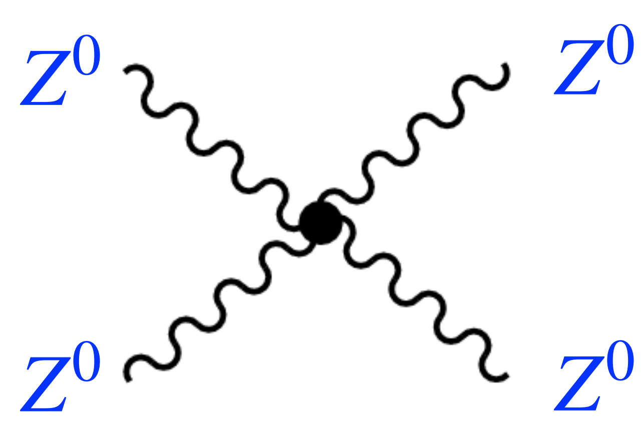
The weak interactions are mediated by three massive bosons: ***W⁺, W⁺, Z⁰***

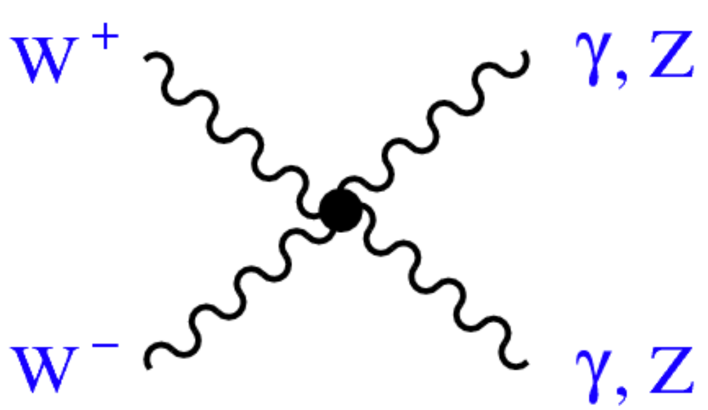
The main properties of the ***Z* bosons** are:

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

- As in the case of the gluons (but not the photons), the *Z* boson is charged under the **weak** charges, and therefore can interact with **itself.** It is **electrically neutral** so it cannot interact via electromagnetism







The weak boson *Z*

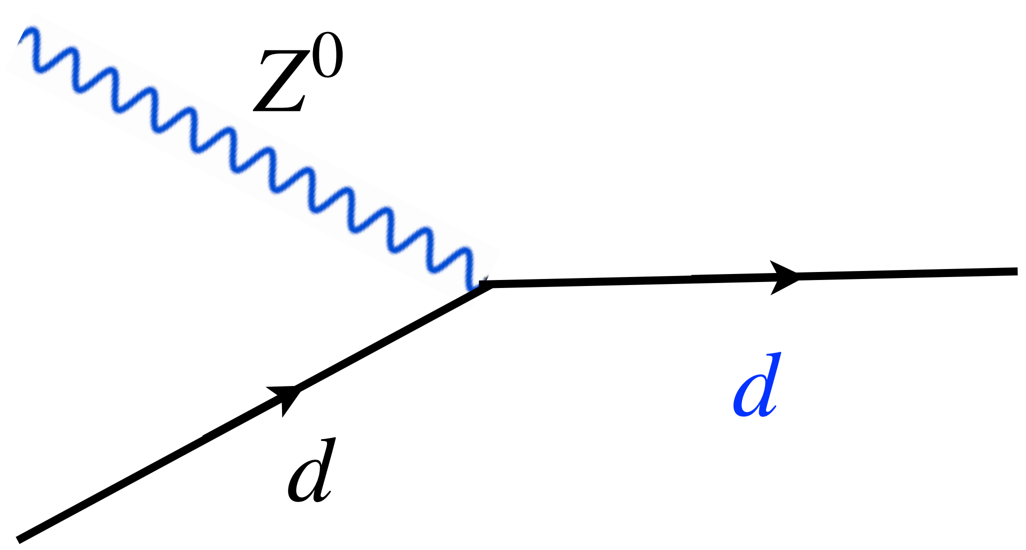
The weak interactions are mediated by three massive bosons: ***W+, W+, Z0***

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)

- ☑ As in the case of the gluons (but not the photons), the *Z* boson is charged under the **weak** charges, and therefore can interact with **itself.** It is **electrically neutral** so it cannot interact via electromagnetism

- ☑ When interacting with **quarks,** the Z boson does **not change the quark flavour**



The weak boson *Z*

The weak interactions are mediated by three massive bosons: $\boldsymbol{W^+}$, $\boldsymbol{W^+}$, $\boldsymbol{Z^0}$

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)

- As in the case of the gluons (but not the photons), the *Z* boson is charged under the **weak** charges, and therefore can interact with **itself.** It is **electrically neutral** so it cannot interact via electromagnetism

- When interacting with **quarks,** the Z boson does **not change the quark flavour**

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

The weak boson Z

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**

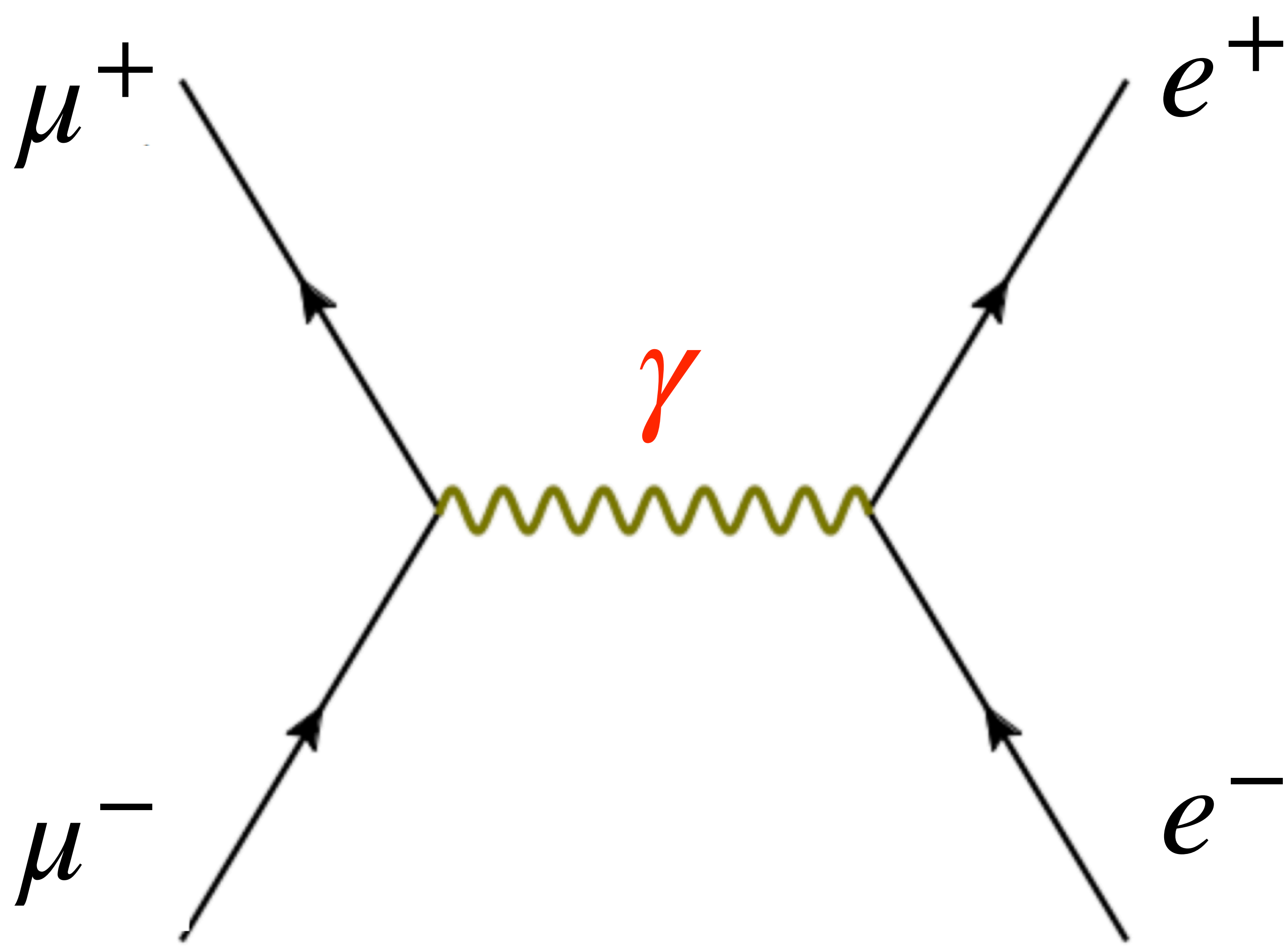
$$\mu^+ + \mu^- \rightarrow e^+ + e^-$$

The weak boson Z

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**

$$\mu^+ + \mu^- \rightarrow e^+ + e^-$$

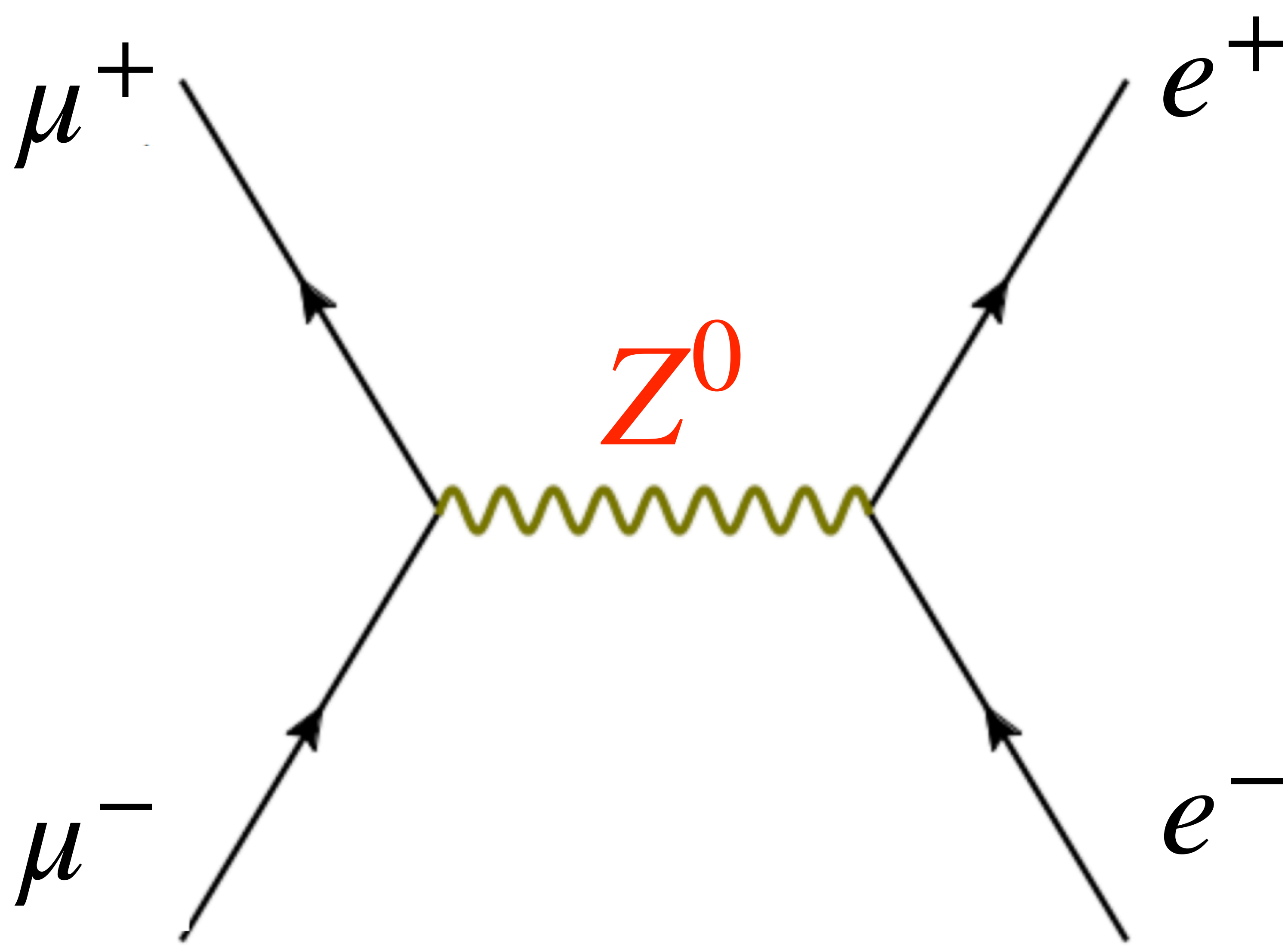


The weak boson Z

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**

$$\mu^+ + \mu^- \to e^+ + e^-$$

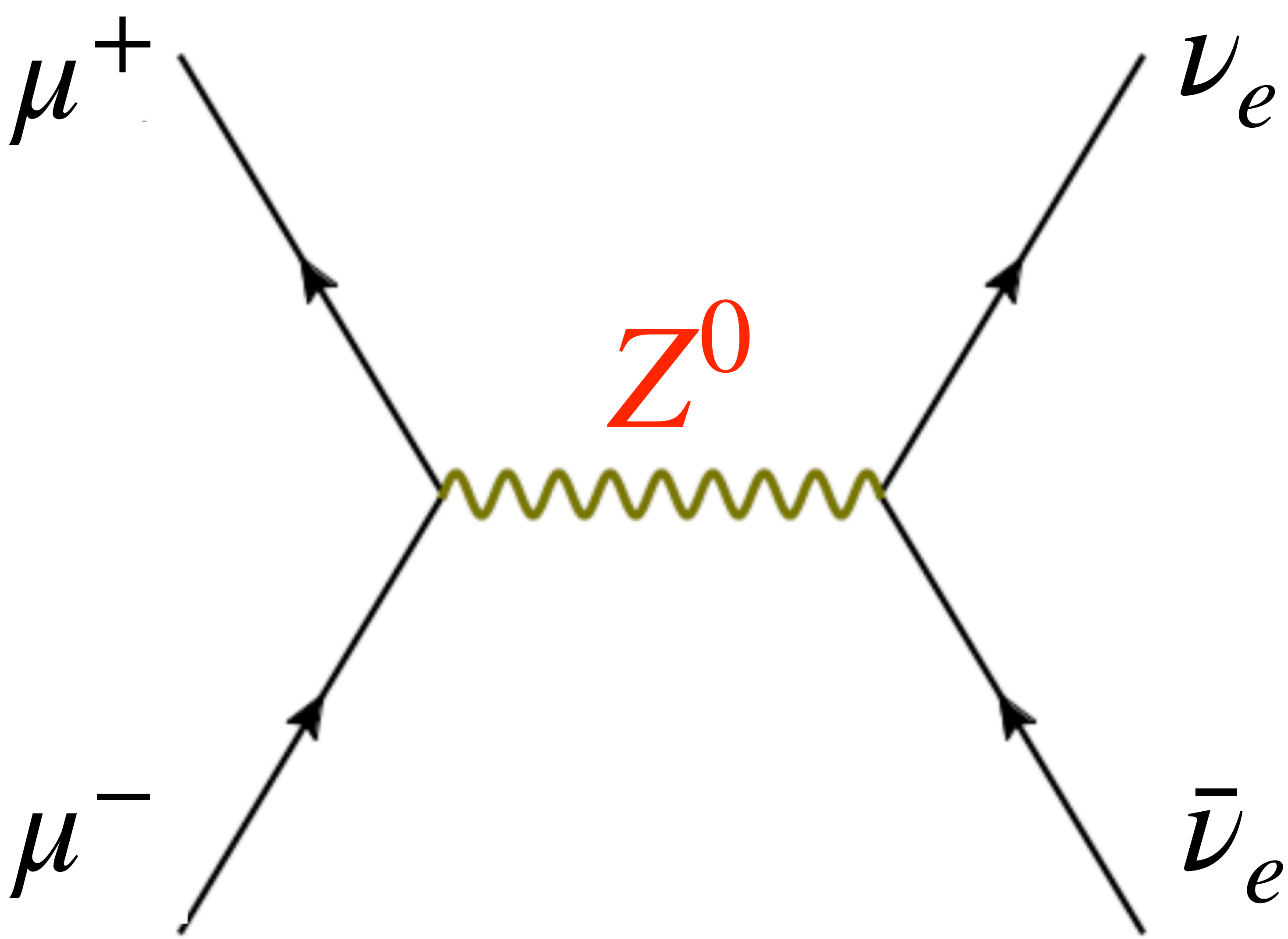


The weak boson Z

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

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

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

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

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

The weak boson Z

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

with quarks

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

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

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

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)

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)

- The individual leptonic numbers, electric charge, and the baryonic number are **conserved** in reactions mediated by the weak interaction

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)

- ☑ The individual leptonic numbers, electric charge, and the baryonic number are **conserved** in reactions mediated by the weak interaction

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

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)

- The individual leptonic numbers, electric charge, and the baryonic number are **conserved** in reactions mediated by the weak interaction

- 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**

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)

- ☑ The individual leptonic numbers, electric charge, and the baryonic number are **conserved** in reactions mediated by the weak interaction

- ☑ 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:

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

- ☑ **Electric charge** is always conserved

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

- ☑ If a given reaction is allowed, the corresponding reaction involving the **antiparticles** is also physically allowed

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

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

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

The weak boson W

exercise

Draw the Feynman diagram for the following process

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

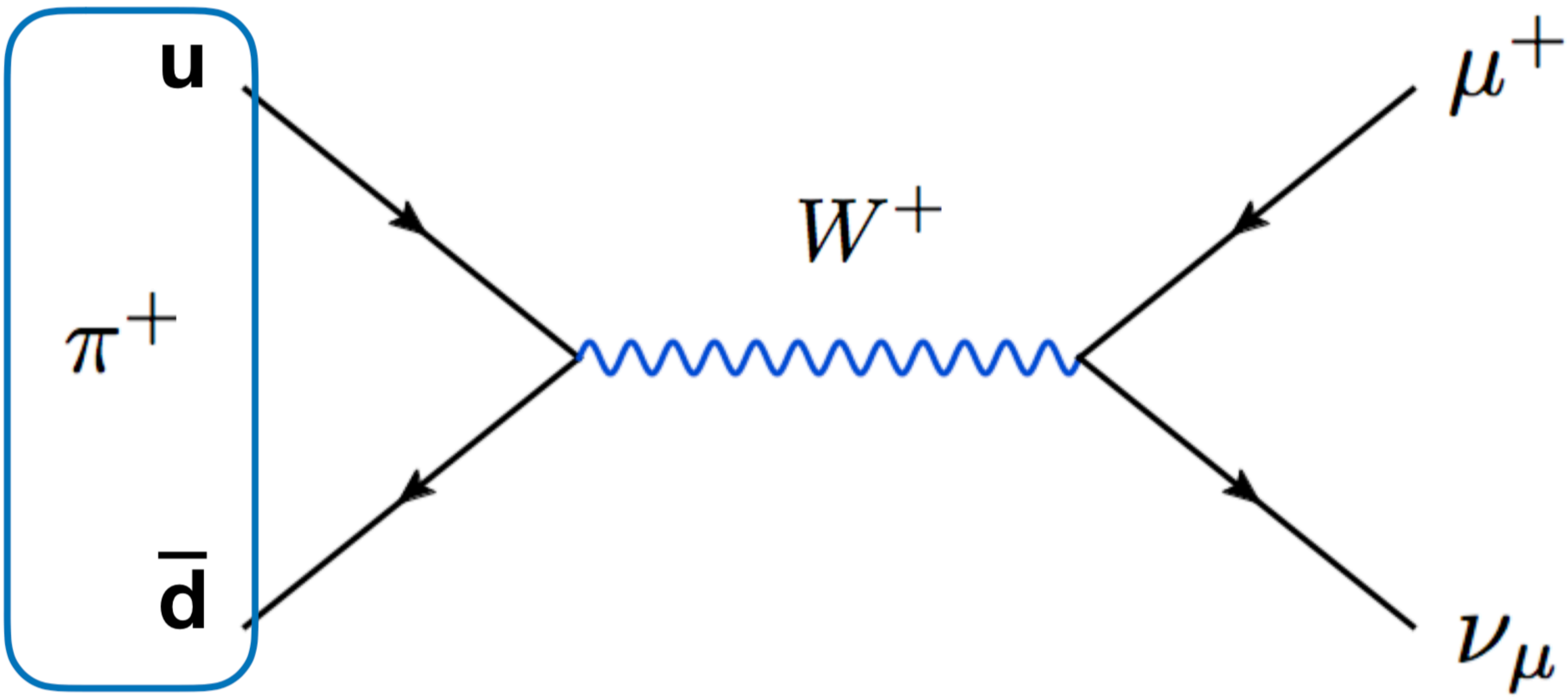
- ☑ We have a neutrino in the final state: the **weak interaction** must be involved
- ☑ Quarks and leptons only interact indirectly via either photons or *W, Z* bosons
- ☑ Since the electric charge is ***Q=+-1,*** then a positively charged ***W boson*** is involved
- ☑ We know what **vertices are allowed**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

The weak boson *W*

exercise

Draw the Feynman diagram for the following process

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

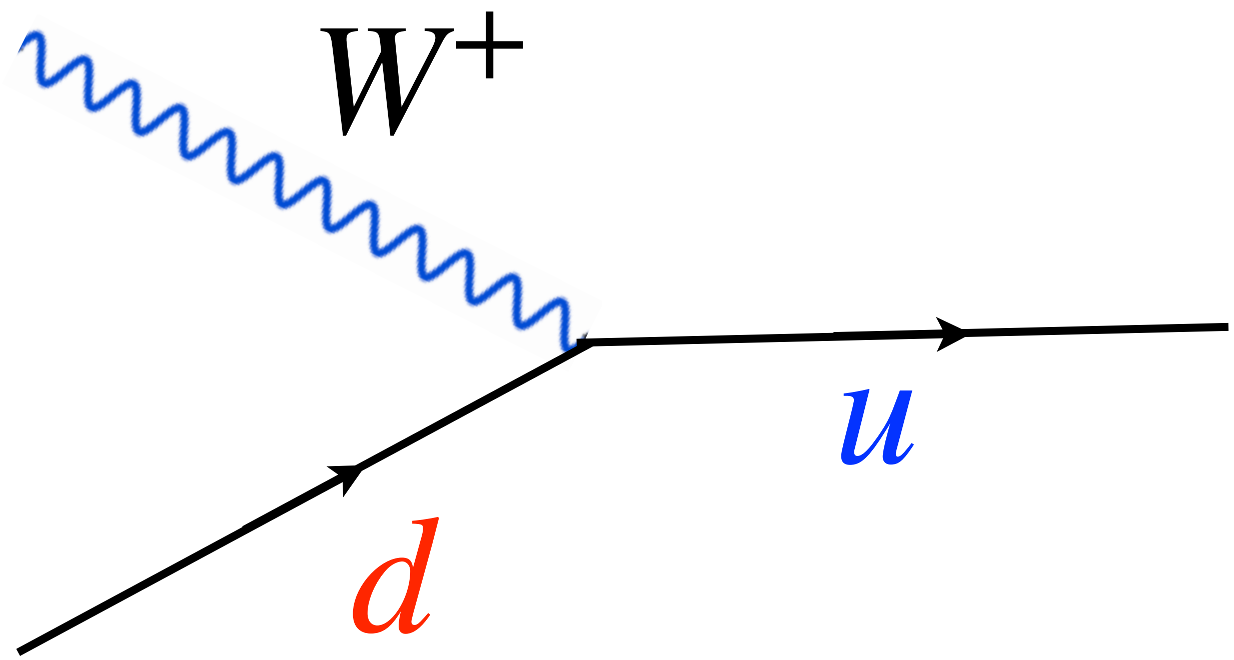


You can check that all relevant quantum numbers are **conserved:** *L, B, Q, …*

Heavy hadron decays

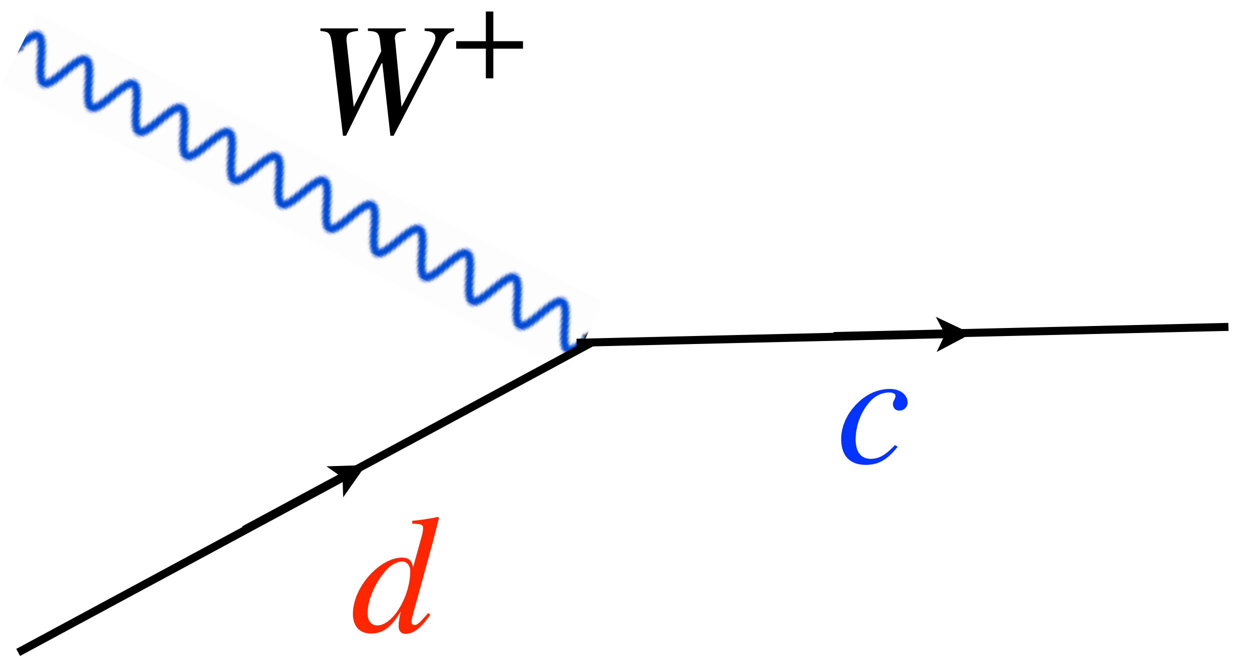
Weak coupling between generations

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



Weak coupling between generations

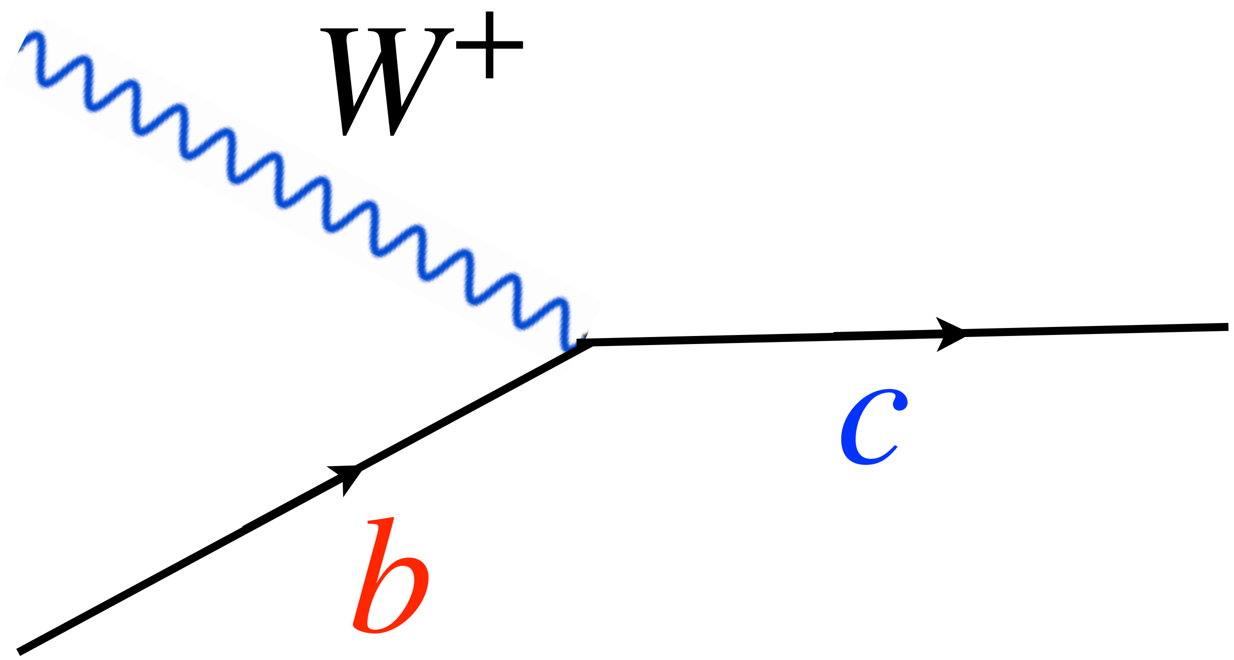
We have seen that in processes mediated by the weak gauge boson W the **flavour** of the quarks will **change**



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

Weak coupling between generations

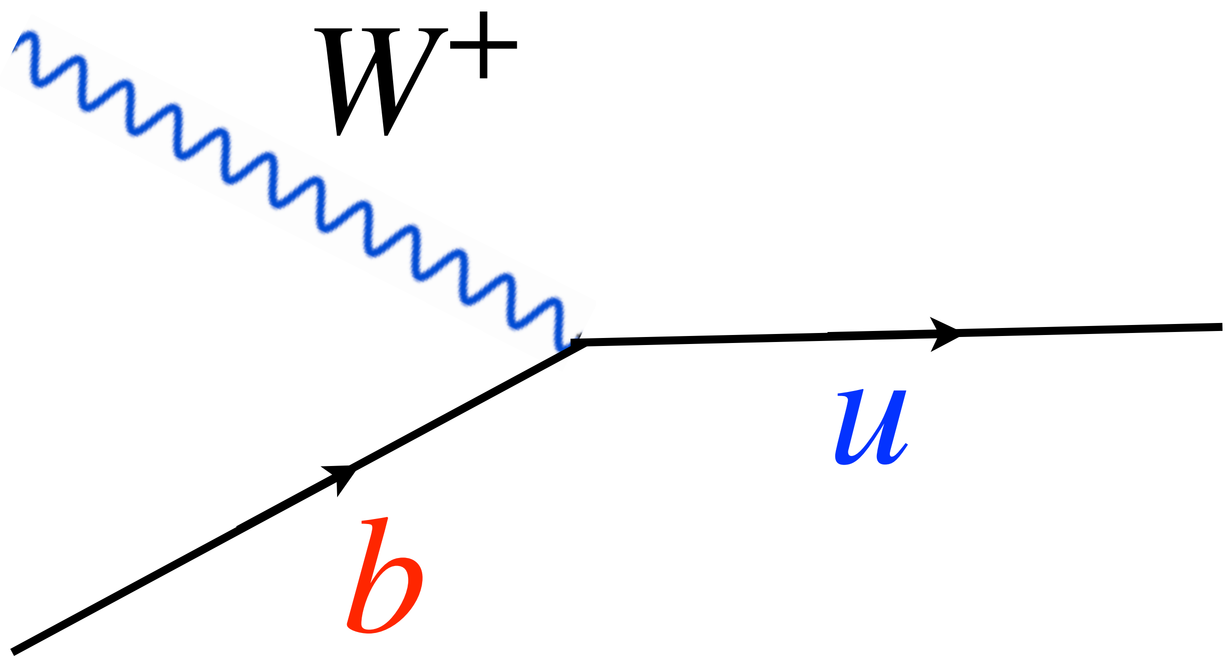
We have seen that in processes mediated by the weak gauge boson *W* the **flavour** of the quarks will **change**



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

Weak coupling between generations

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

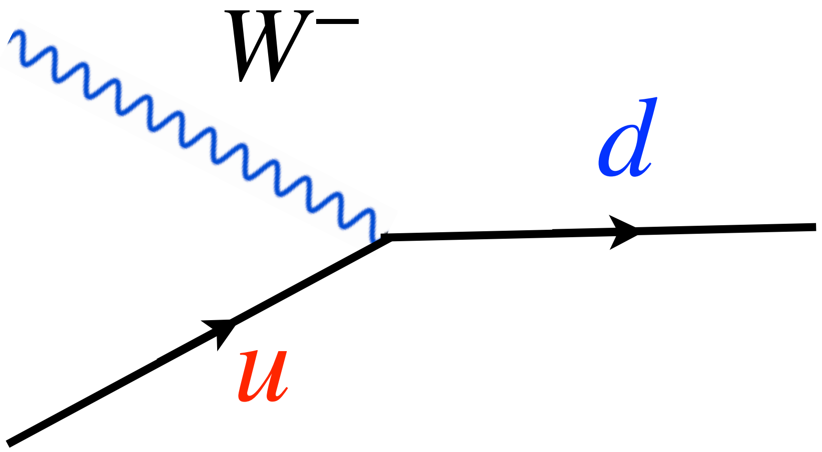


Moreover we can always replace a given quark by the corresponding quark of a **different generation**

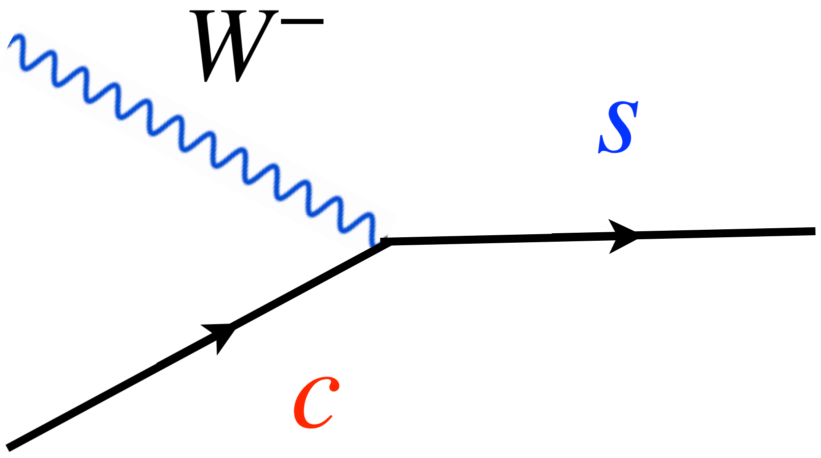
The weak interactions mediates **transitions** between **quarks of different generations**

Weak coupling between generations

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

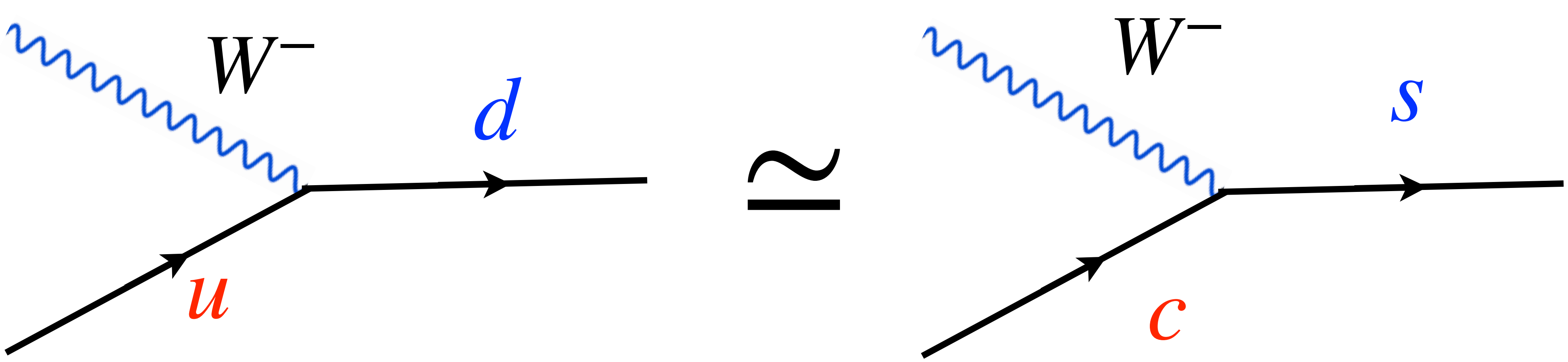


$\simeq$

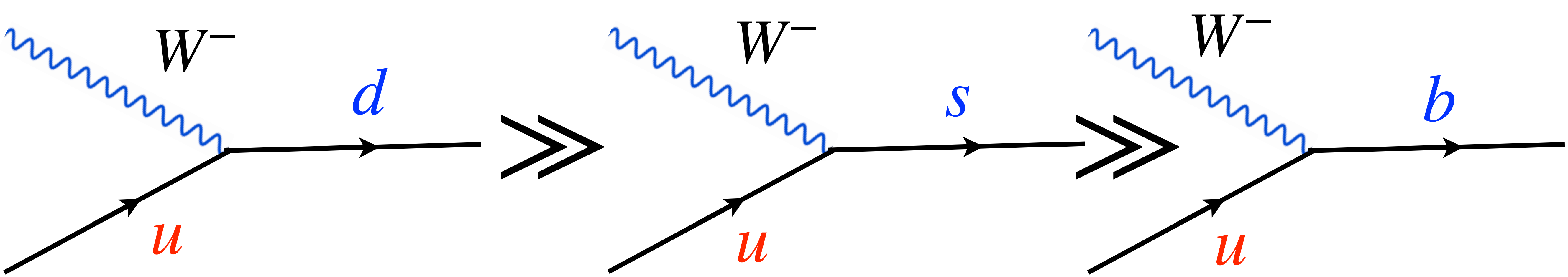


Weak coupling between generations

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



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**

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

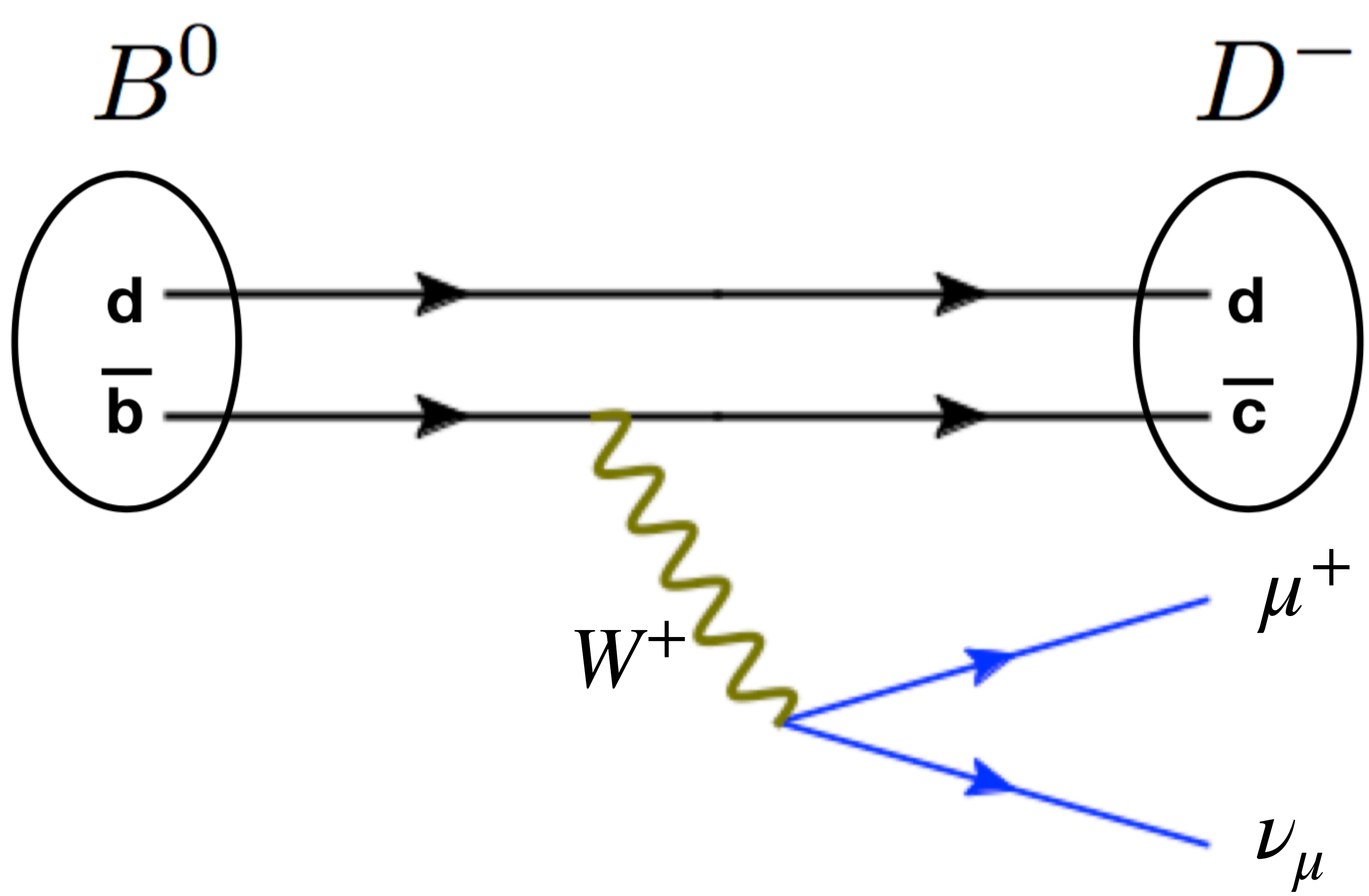
what is the corresponding Feynman diagram?

Heavy hadron decays

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?



Heavy hadron decays

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

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

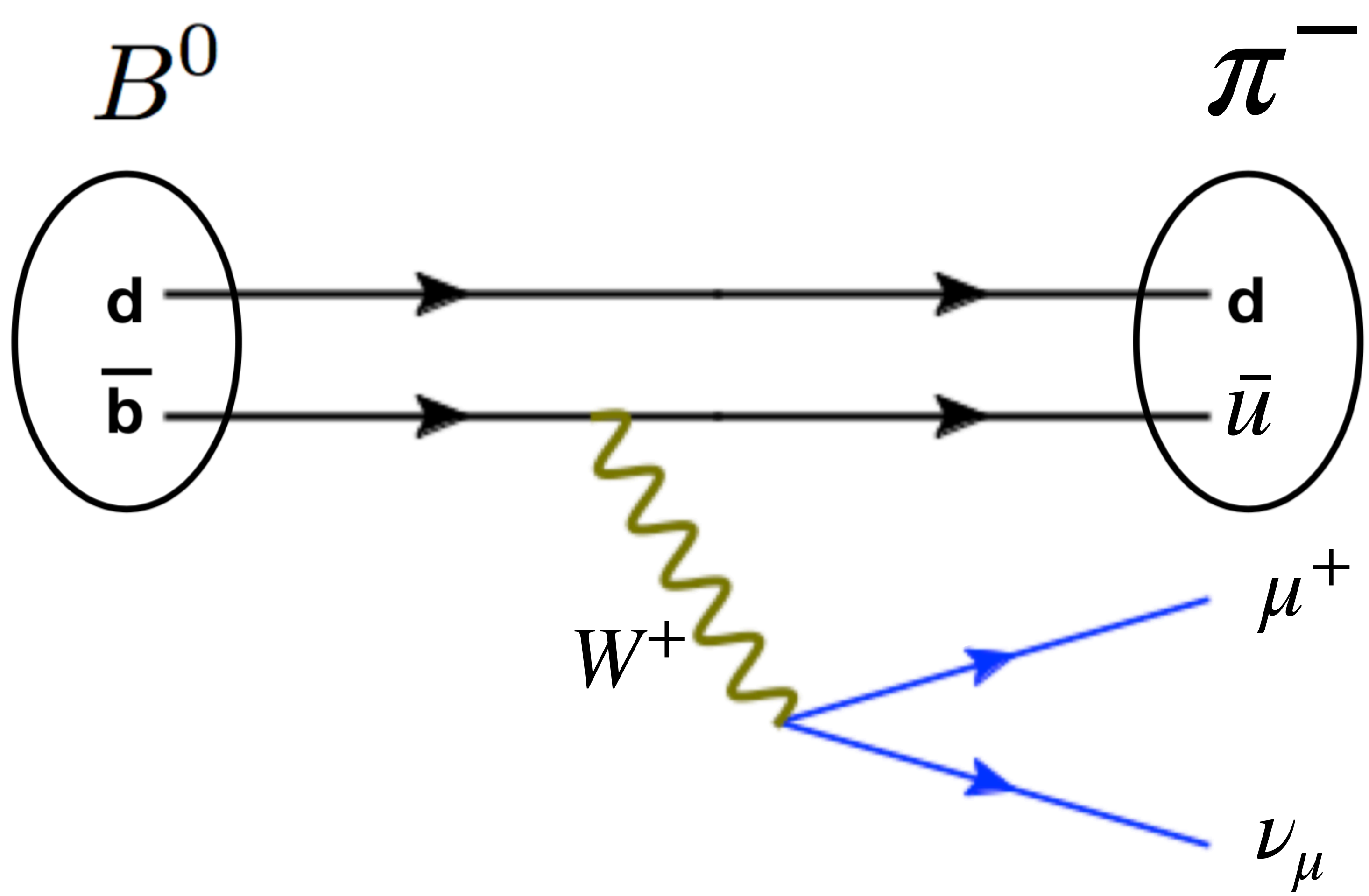
what is the corresponding Feynman diagram?

Heavy hadron decays

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

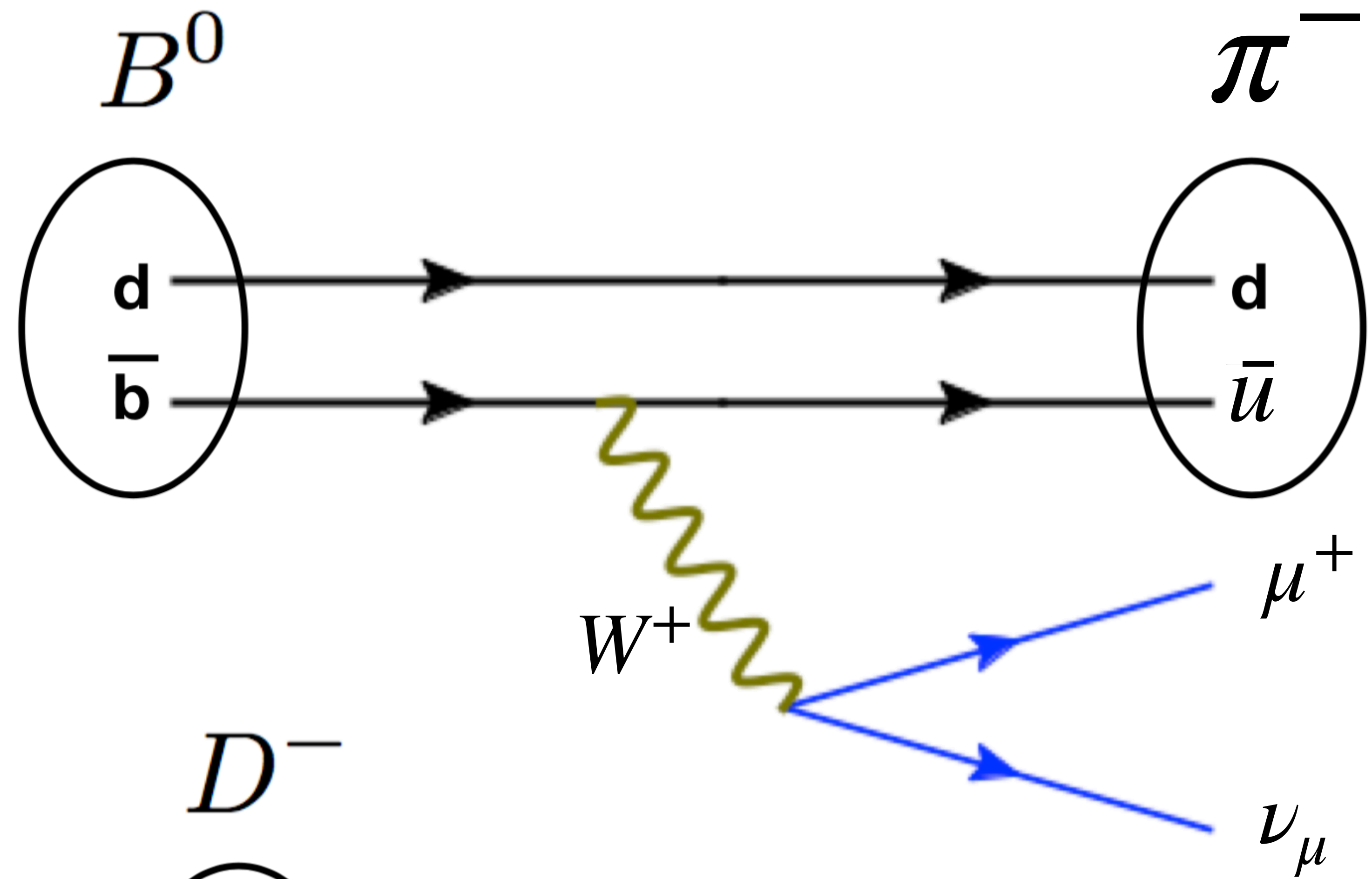
$$B^0 \to \pi^- + \mu^+ + \nu_\mu \qquad B^0 = \left(d\,\bar{b}\right) \qquad \pi^- = \left(d\bar{u}\right)$$

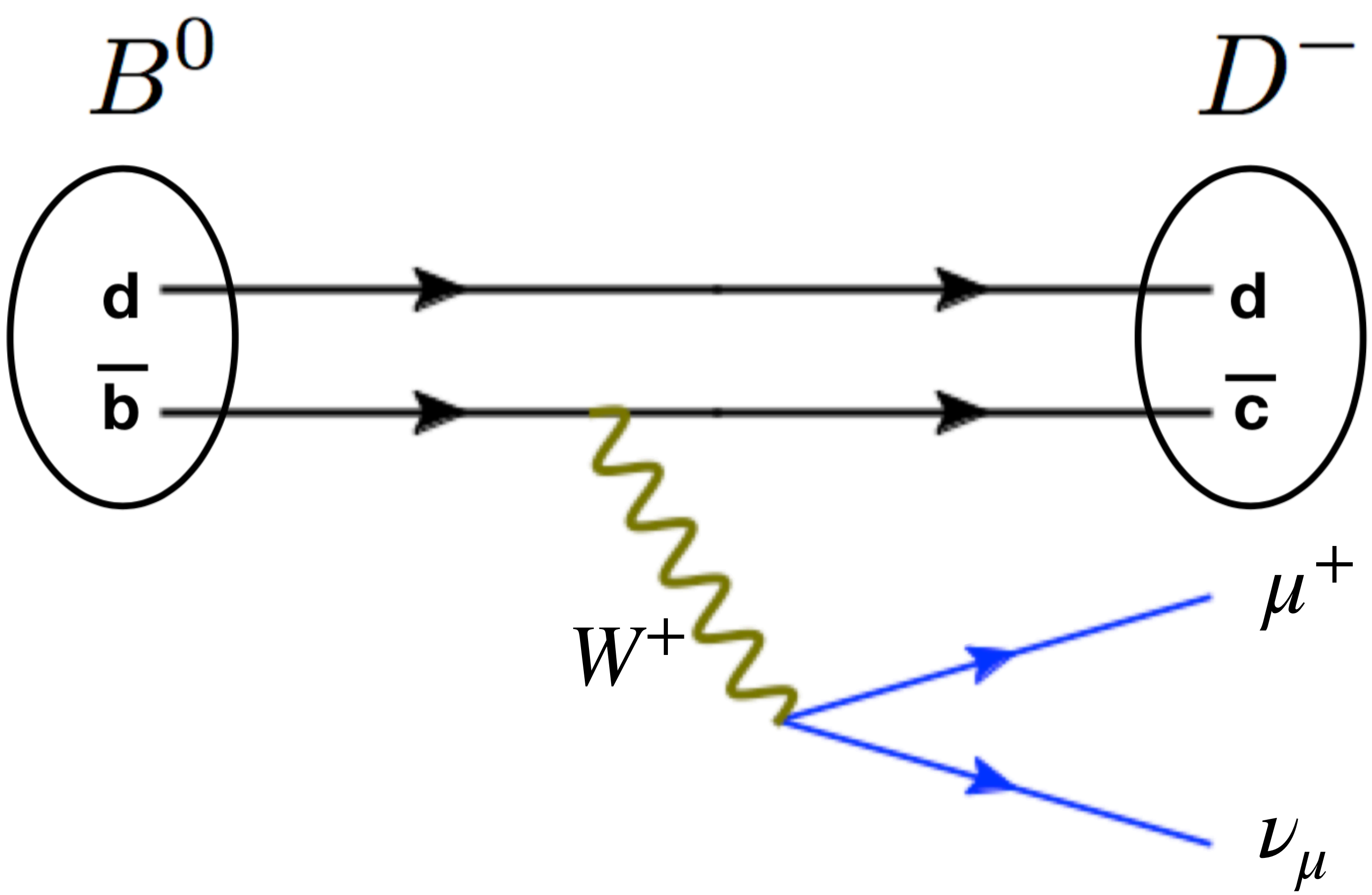
what is the corresponding Feynman diagram?



Heavy hadron decays

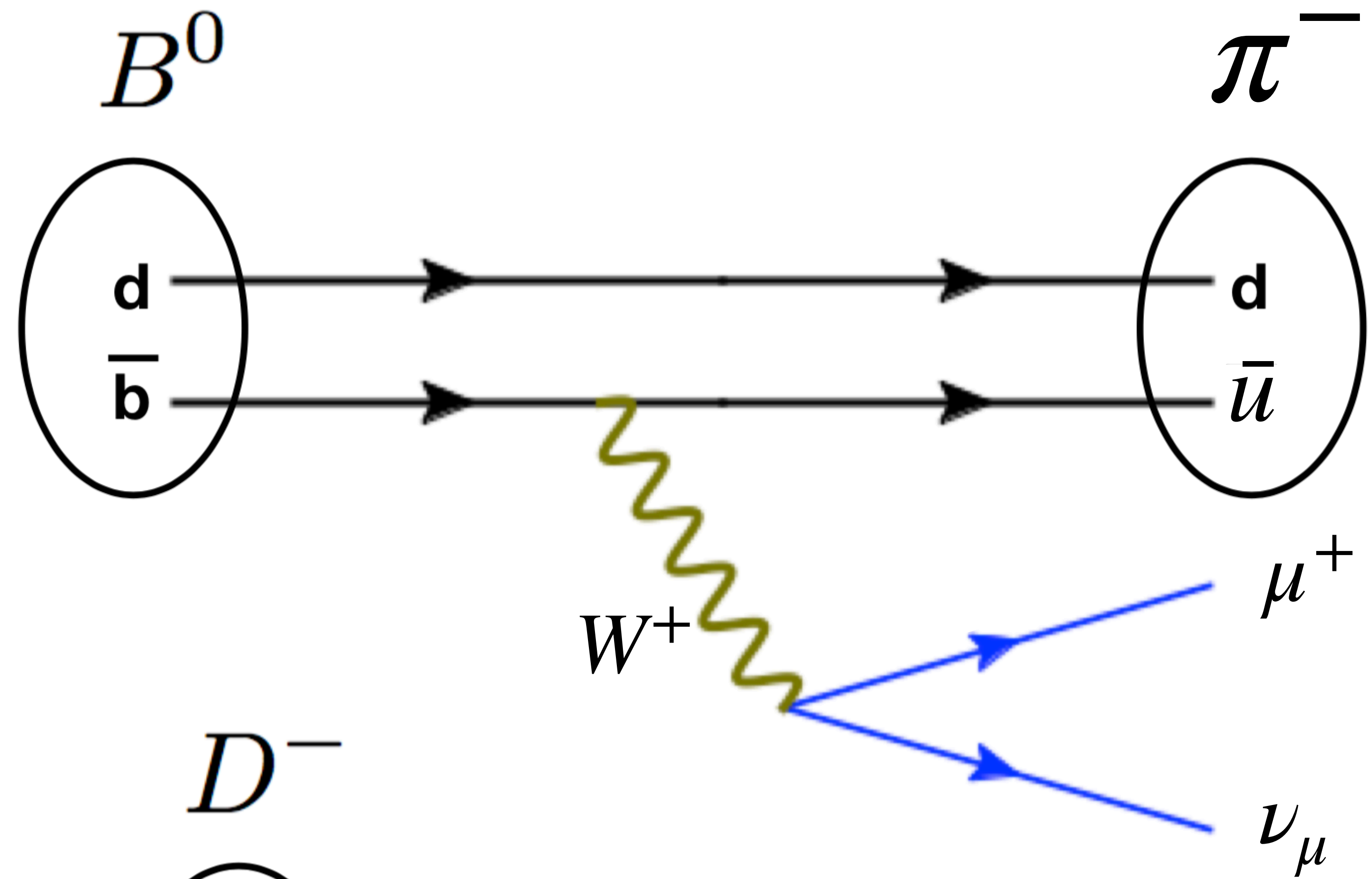
Which of the two reactions is **most likely** to take place?

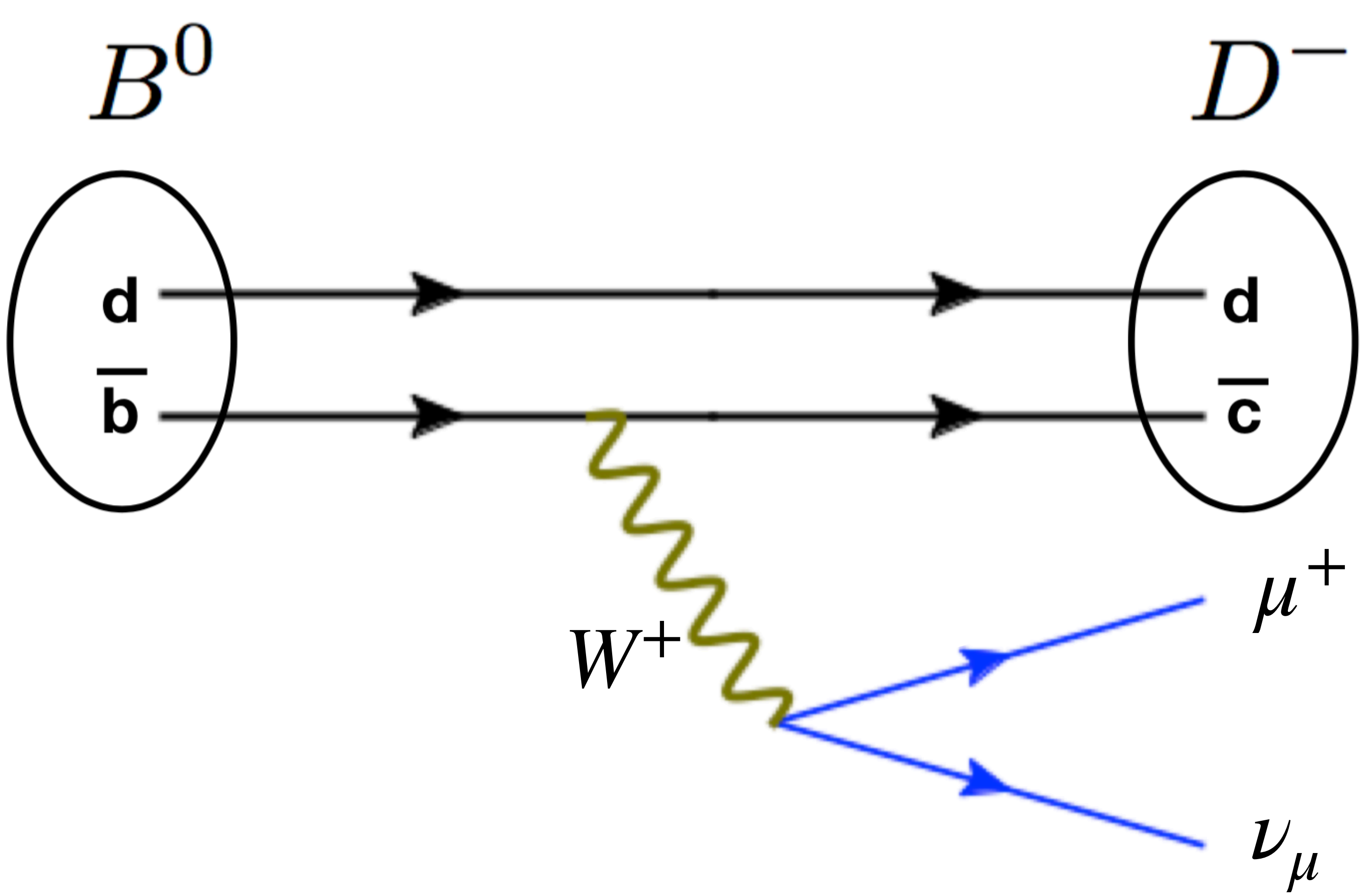




Heavy hadron decays

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





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**

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

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

How do these two decay models relate to each other?

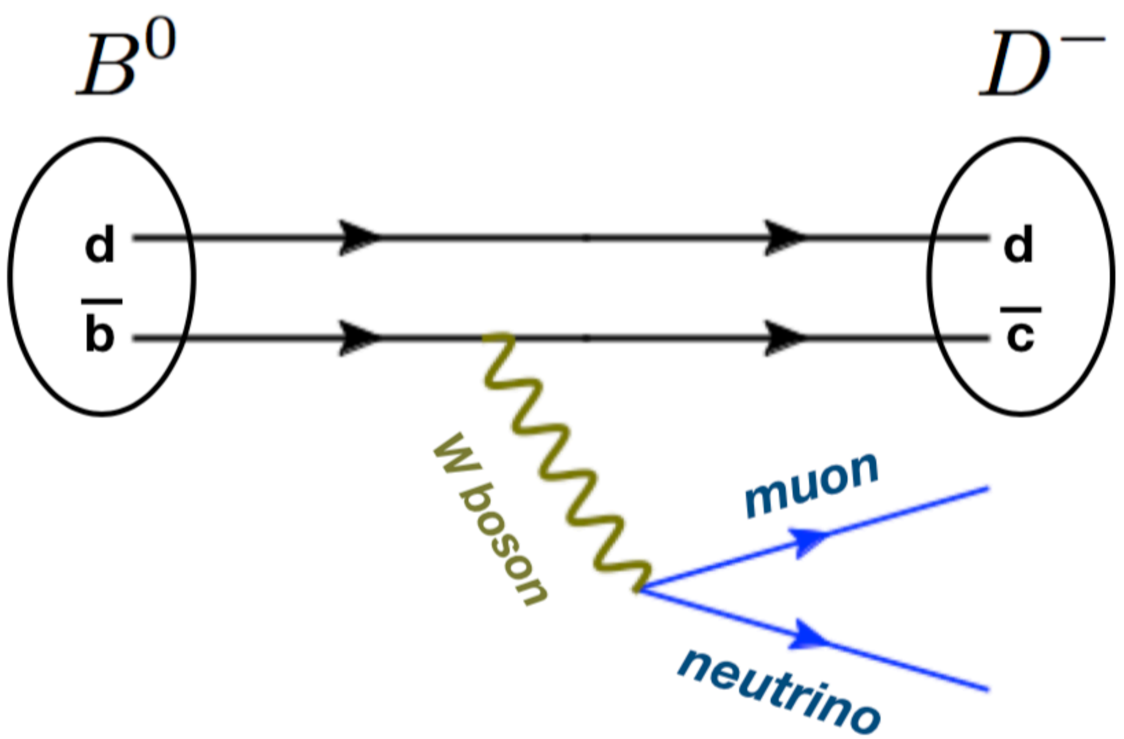
Heavy hadron decays

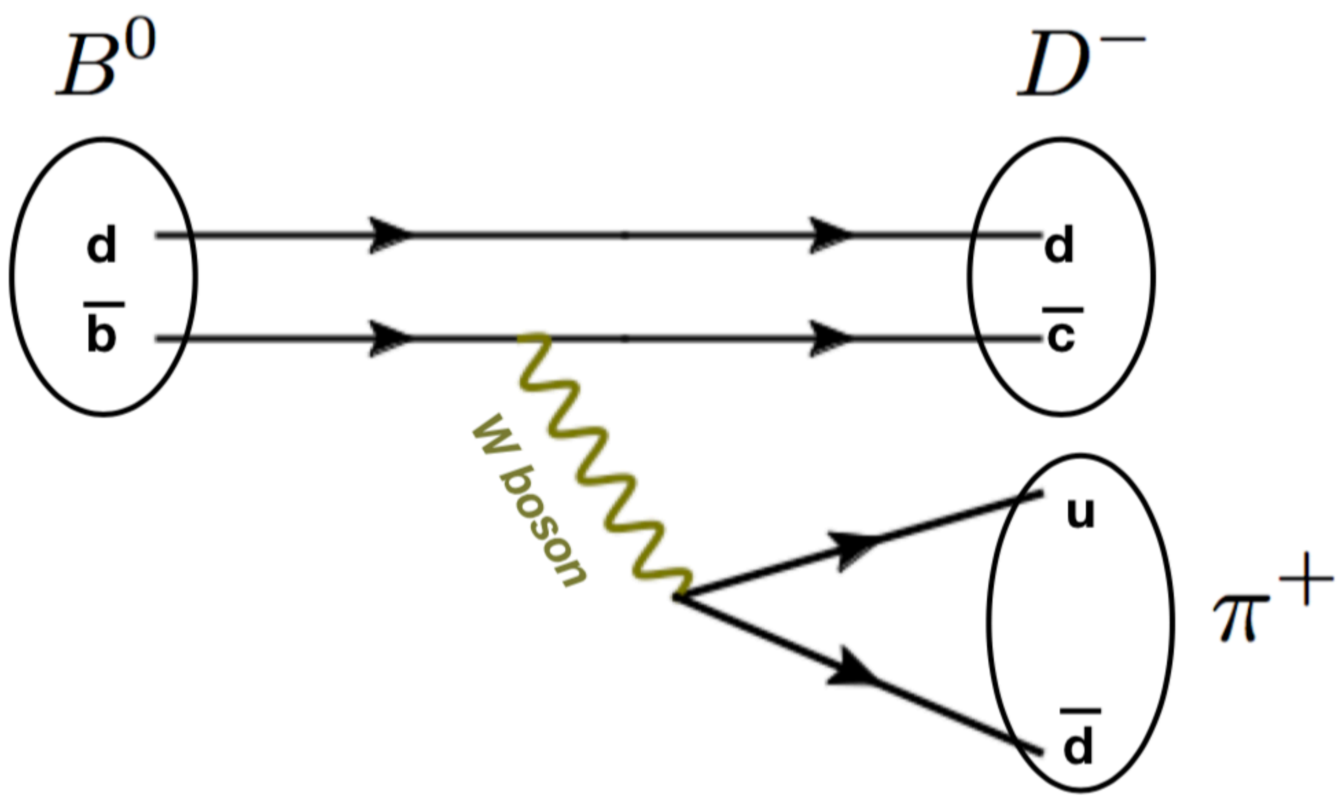
Note that some reaction processes might look **very different from the outside**, but their similarities become apparent at the **Feynman diagram level**

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

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

How do these two decay models relate to each other?





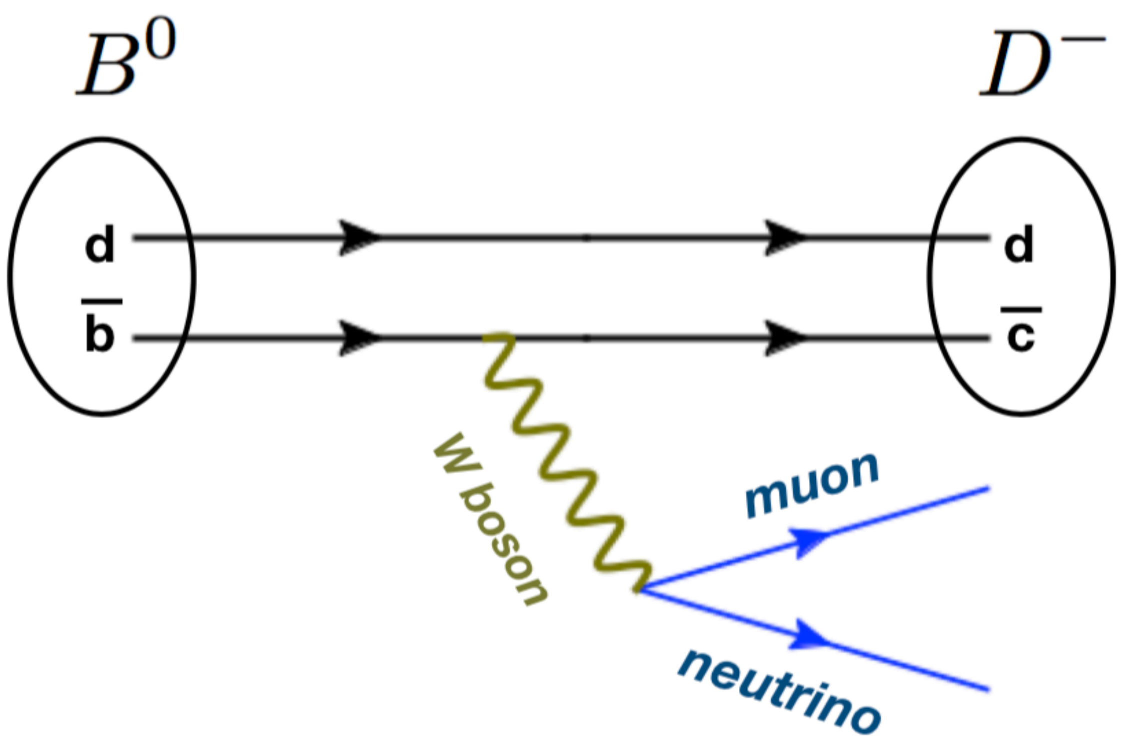
Heavy hadron decays

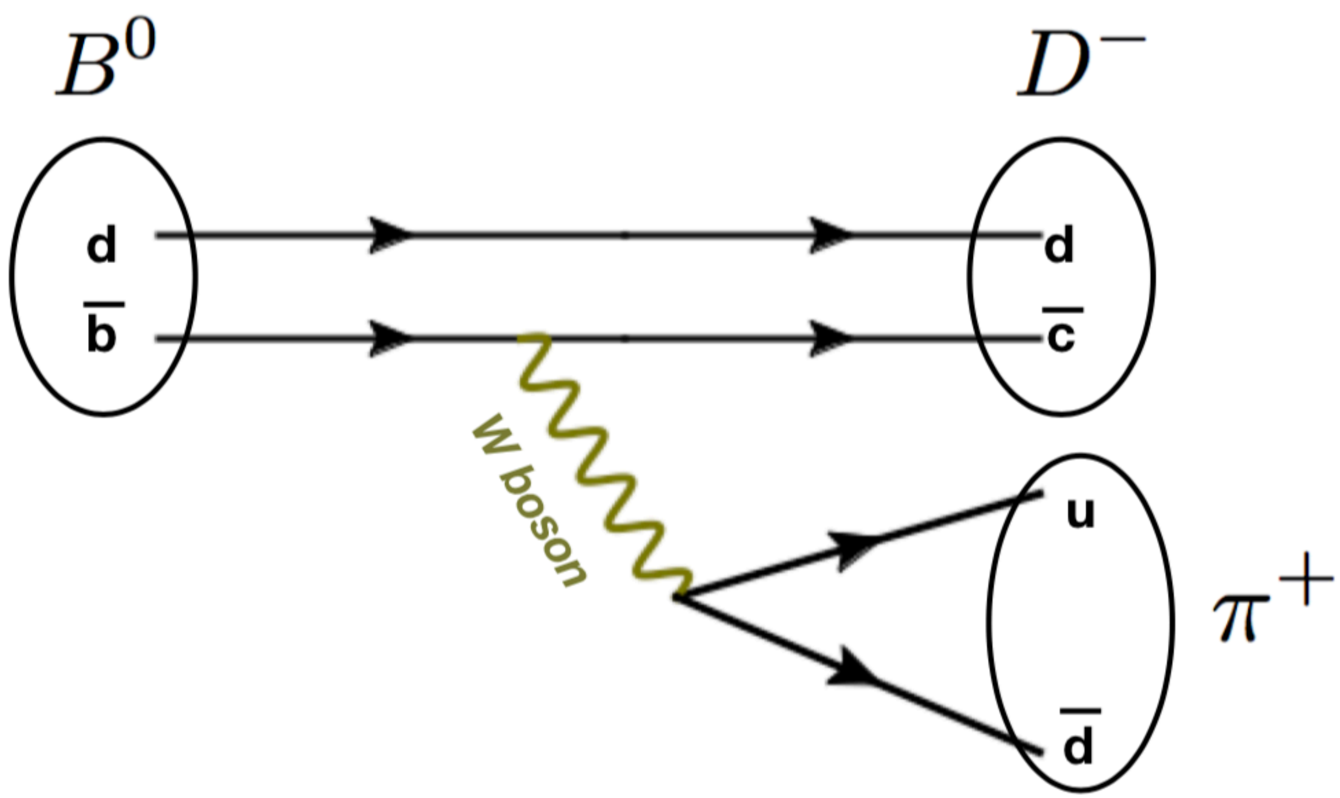
Note that some reaction processes might look **very different from the outside**, but their similarities become apparent at the **Feynman diagram level**

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

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

How do these two decay models relate to each other?





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+, Z0***

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)

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

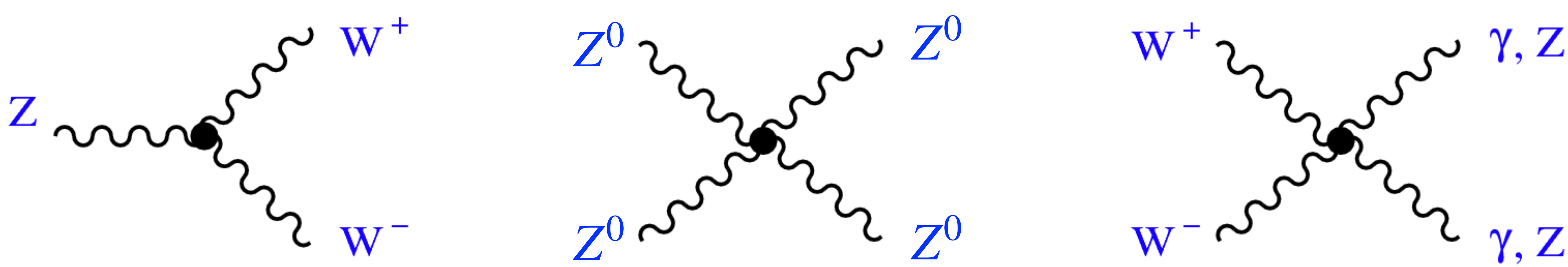
The weak boson *Z*

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)

- As in the case of the gluons (but not the photons), the *Z* boson is charged under the **weak** charges, and therefore can interact with **itself.** It is **electrically neutral** so it cannot interact via electromagnetism



The weak boson *Z*

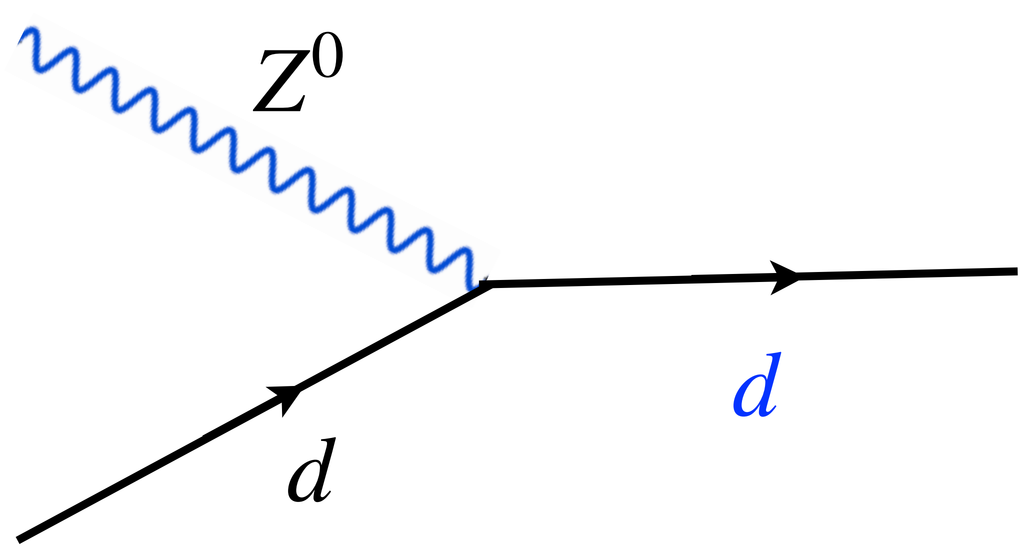
The weak interactions are mediated by three massive bosons: $\boldsymbol{W^+, W^+, Z^0}$

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)

- ☑ As in the case of the gluons (but not the photons), the *Z* boson is charged under the **weak** charges, and therefore can interact with **itself.** It is **electrically neutral** so it cannot interact via electromagnetism

- ☑ When interacting with **quarks,** the Z boson does **not change the quark flavour**



The weak boson *Z*

The weak interactions are mediated by three massive bosons: $\boldsymbol{W^+}$, $\boldsymbol{W^+}$, $\boldsymbol{Z^0}$

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)

- ☑ As in the case of the gluons (but not the photons), the *Z* boson is charged under the **weak** charges, and therefore can interact with **itself.** It is **electrically neutral** so it cannot interact via electromagnetism

- ☑ When interacting with **quarks,** the Z boson does **not change the quark flavour**

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

The weak boson Z

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**

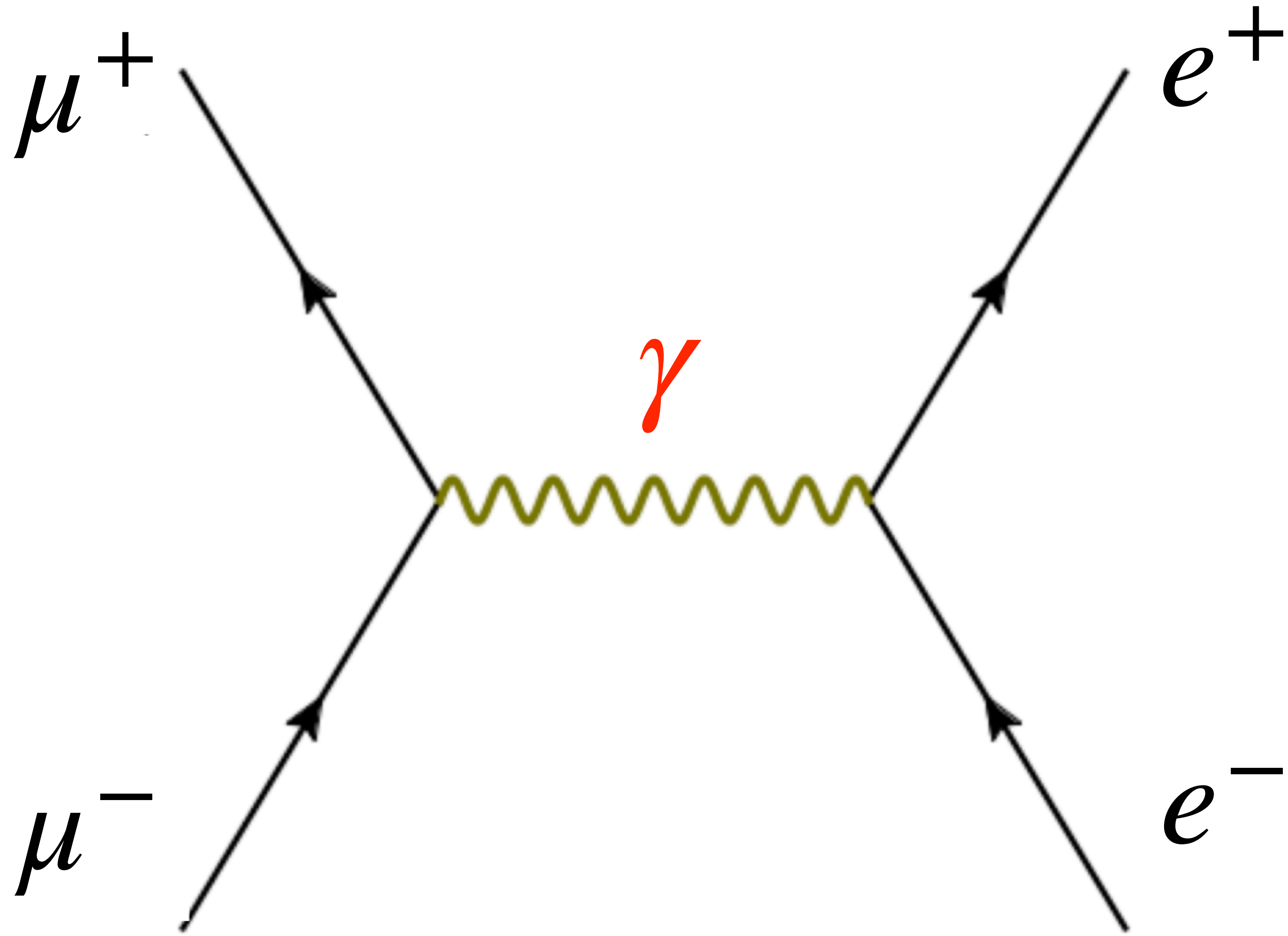
$$\mu^+ + \mu^- \rightarrow e^+ + e^-$$

The weak boson Z

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**

$$\mu^+ + \mu^- \rightarrow e^+ + e^-$$

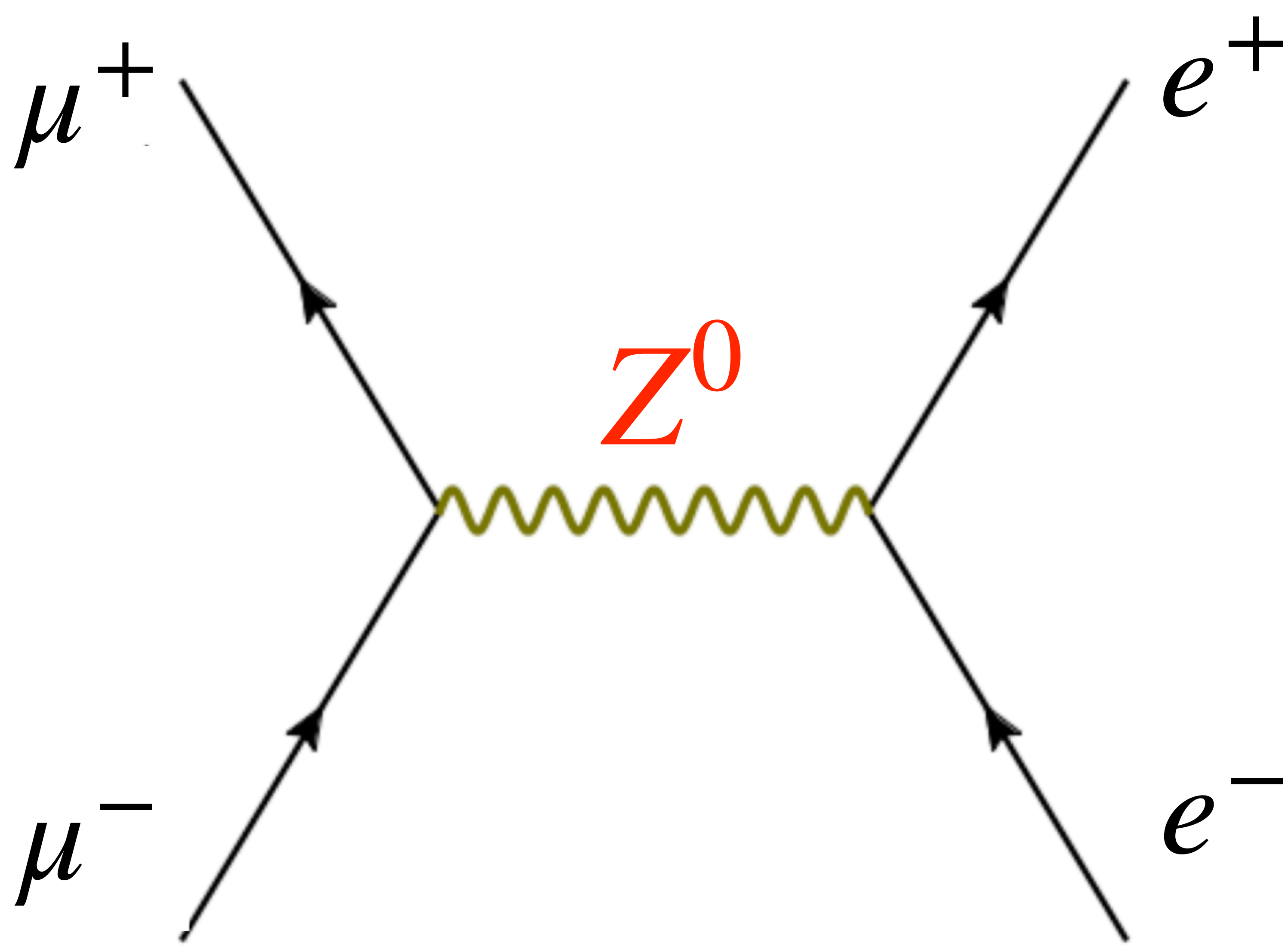


The weak boson Z

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**

$$\mu^+ + \mu^- \rightarrow e^+ + e^-$$

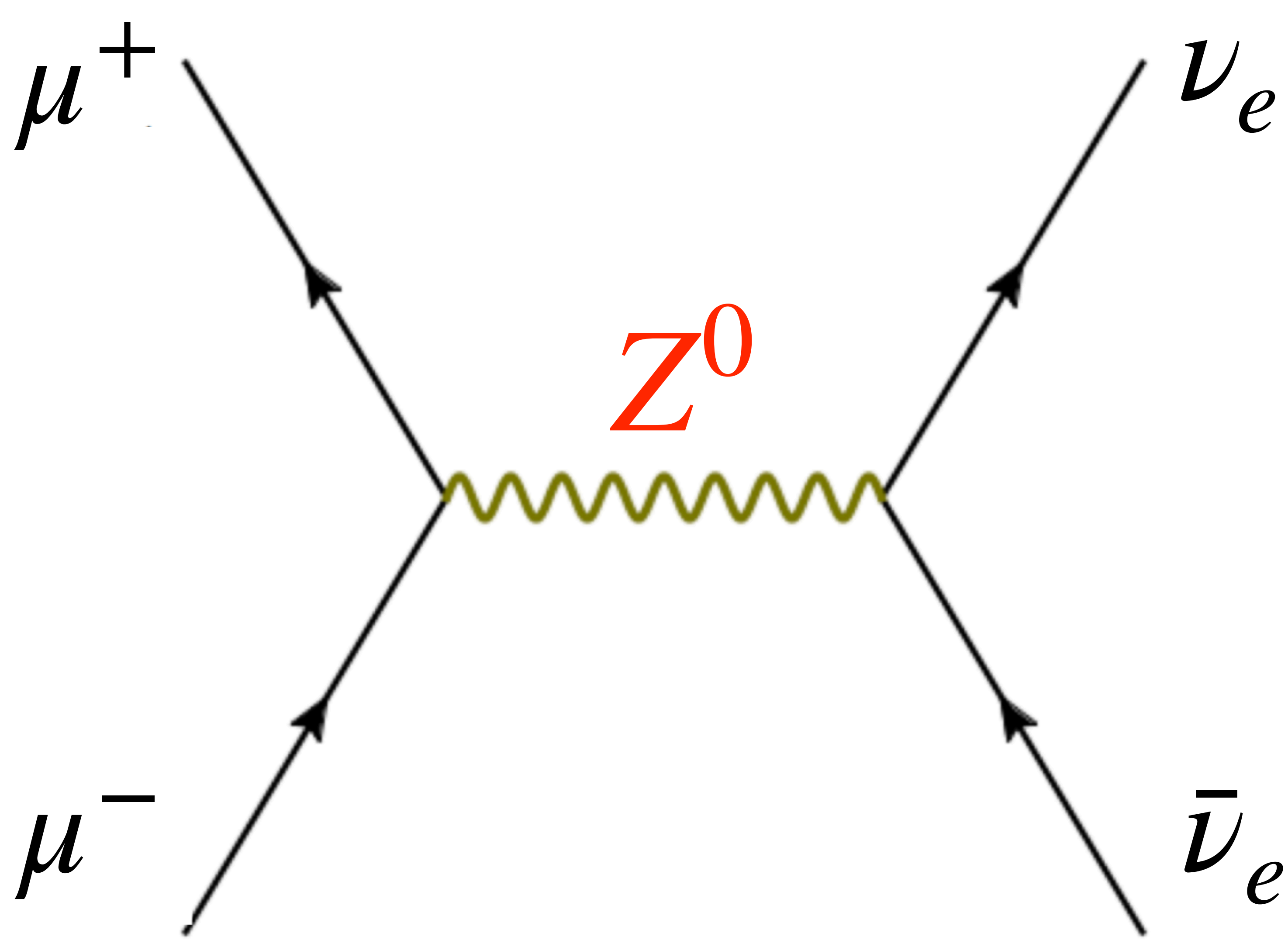


The weak boson Z

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

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

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

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

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

The weak boson Z

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

with quarks

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

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

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

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)

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)

- The individual leptonic numbers, electric charge, and the baryonic number are **conserved** in reactions mediated by the weak interaction

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)

- ☑ The individual leptonic numbers, electric charge, and the baryonic number are **conserved** in reactions mediated by the weak interaction

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

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)

- ☑ The individual leptonic numbers, electric charge, and the baryonic number are **conserved** in reactions mediated by the weak interaction

- ☑ 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**

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)

- The individual leptonic numbers, electric charge, and the baryonic number are **conserved** in reactions mediated by the weak interaction

- 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**