Introduction to Elementary Particles (TN2811)

Theory Lecture 7

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Today's lecture

- ☑ More on the **weak interaction**
- ☑ The **Higgs boson** and symmetry breaking
- ☑ **Collider** phenomenology and **Statistics** for particle physics

The *W* boson continued

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

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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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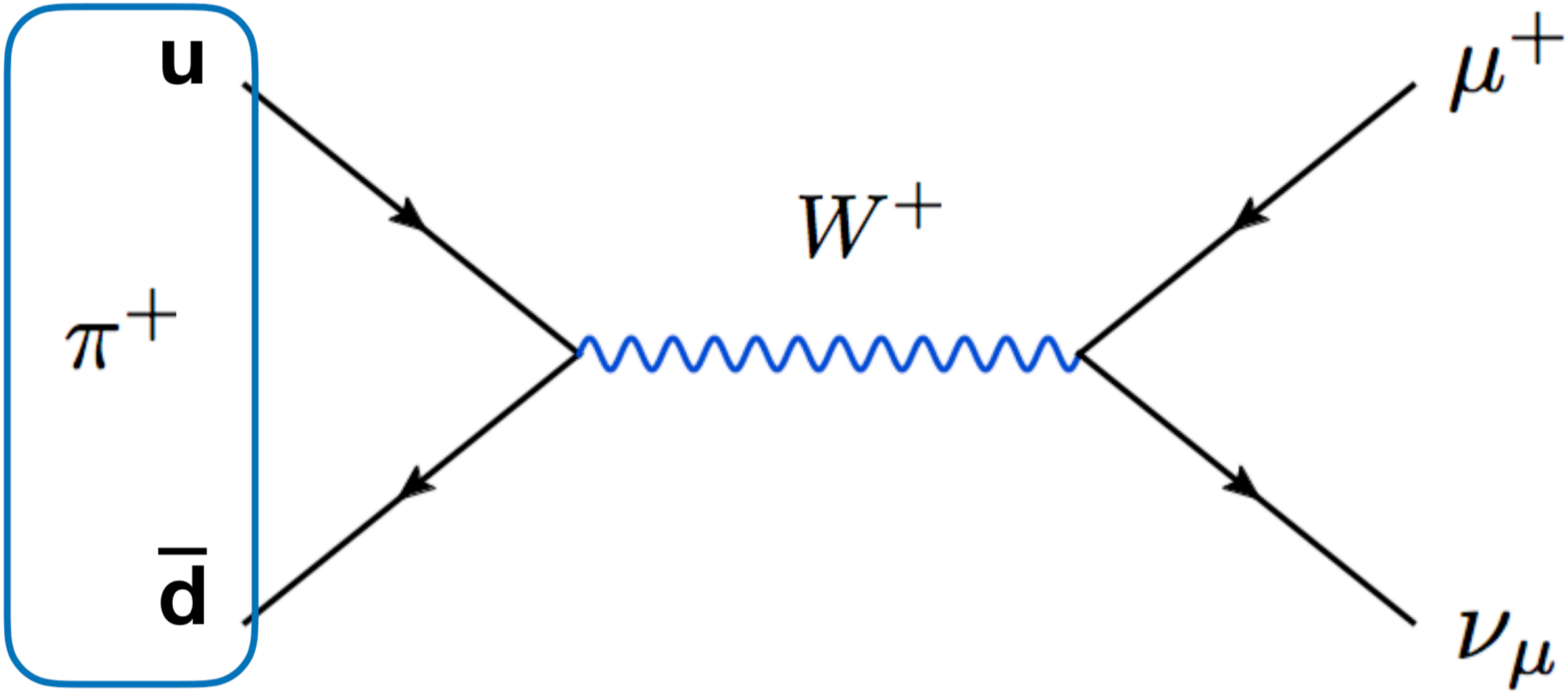
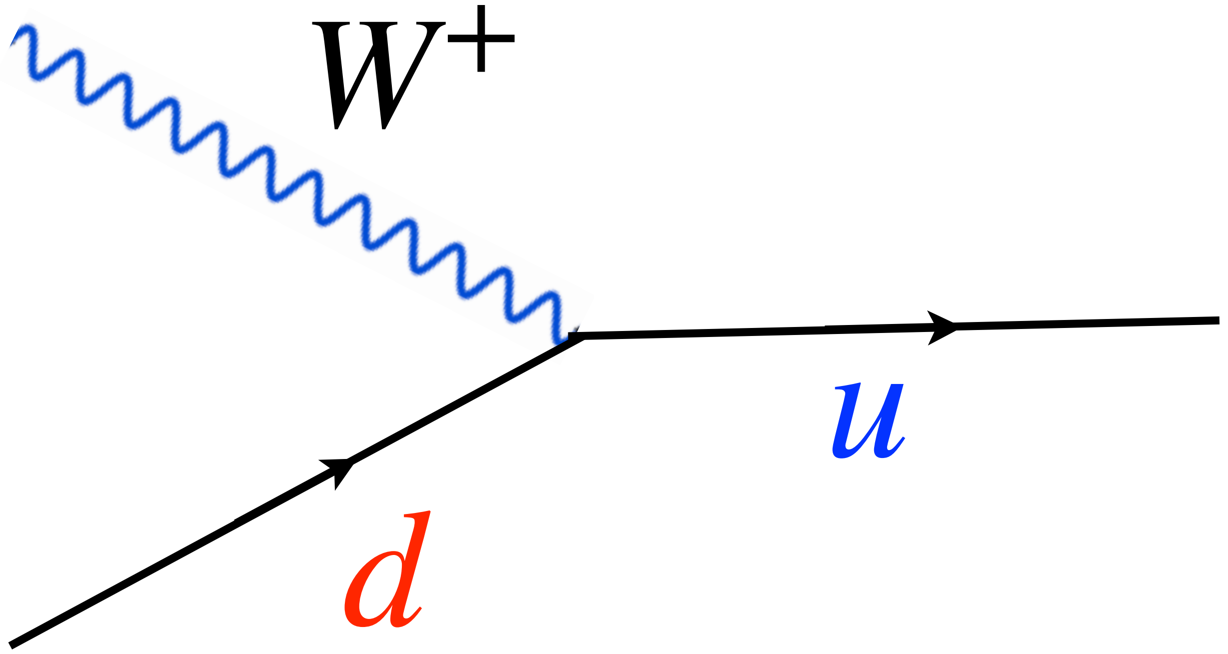


You can check that all relevant quantum numbers are **conserved:** *L, B, Q, …*

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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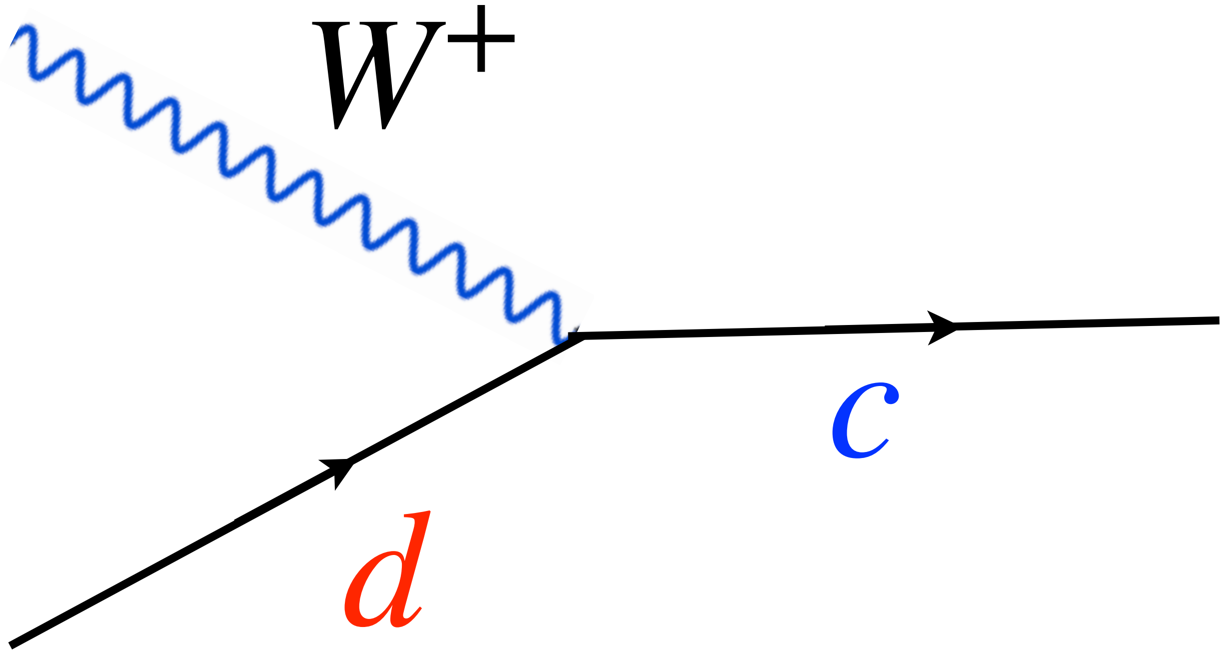

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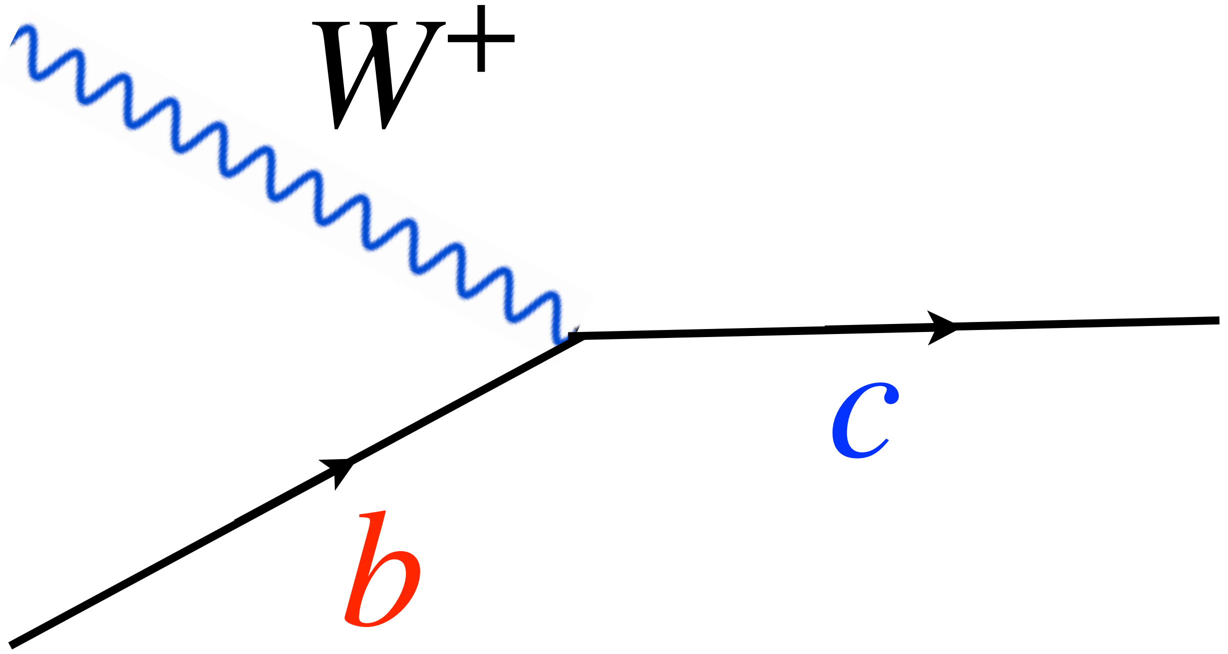

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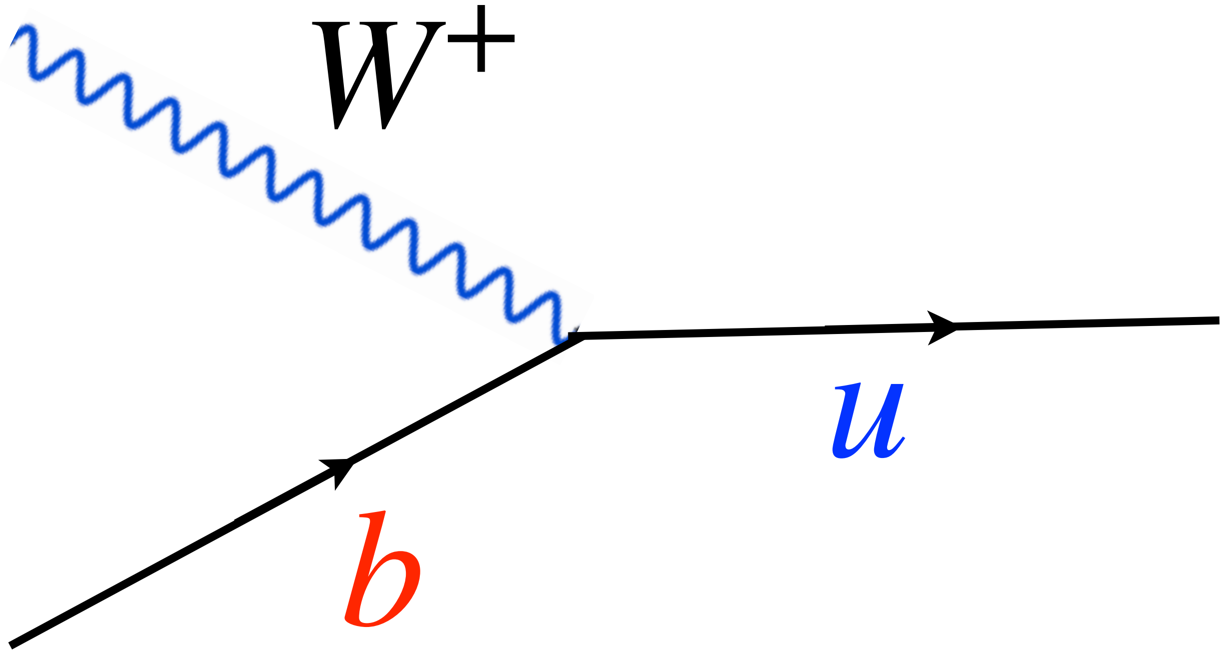

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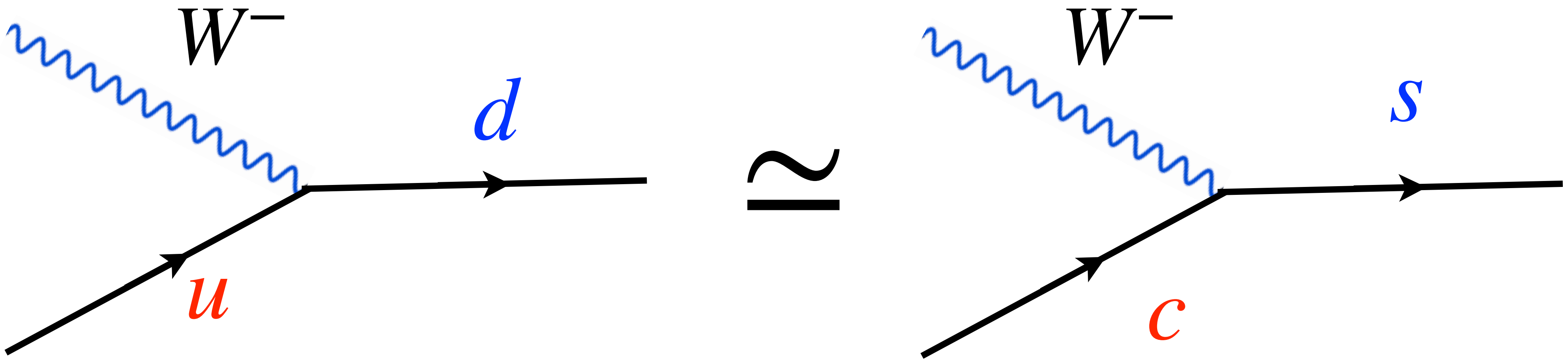
The weak interactions mediates **transitions** between **quarks of different generations**

Weak coupling between generations

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



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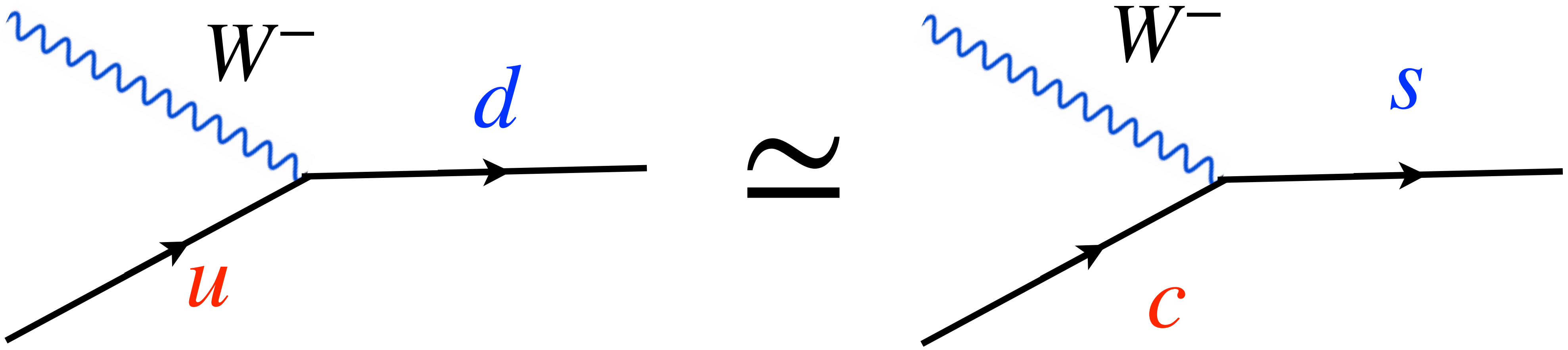
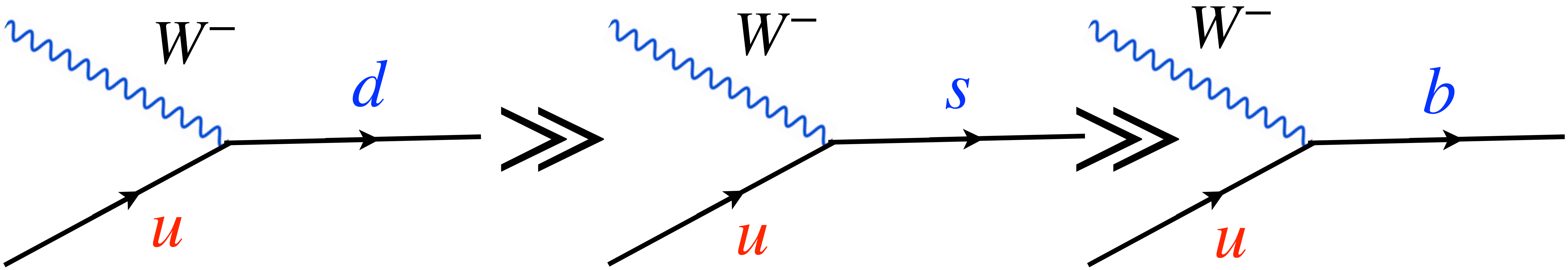


The **strength of the weak coupling** is smaller between **quarks of different generation**



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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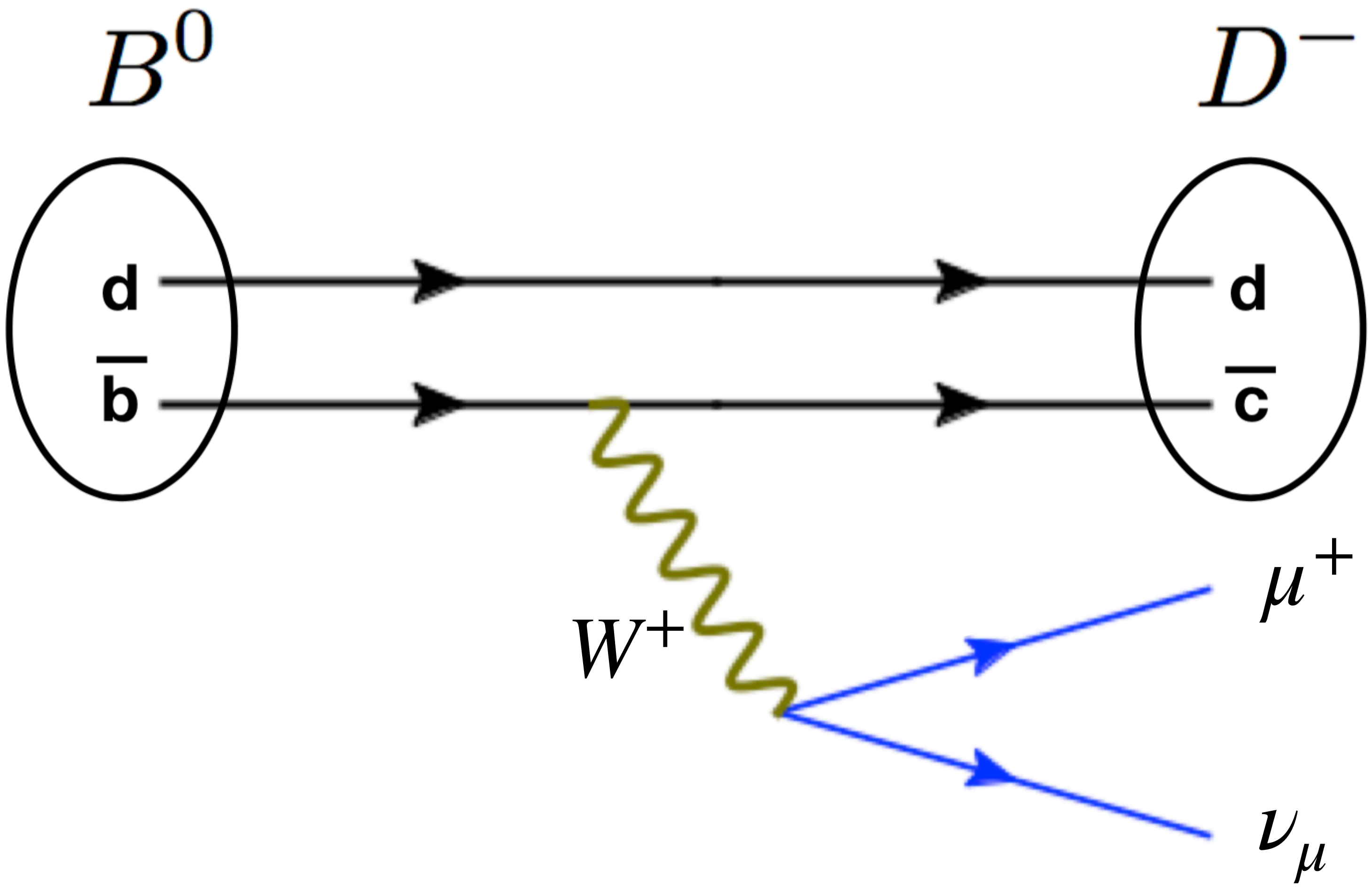

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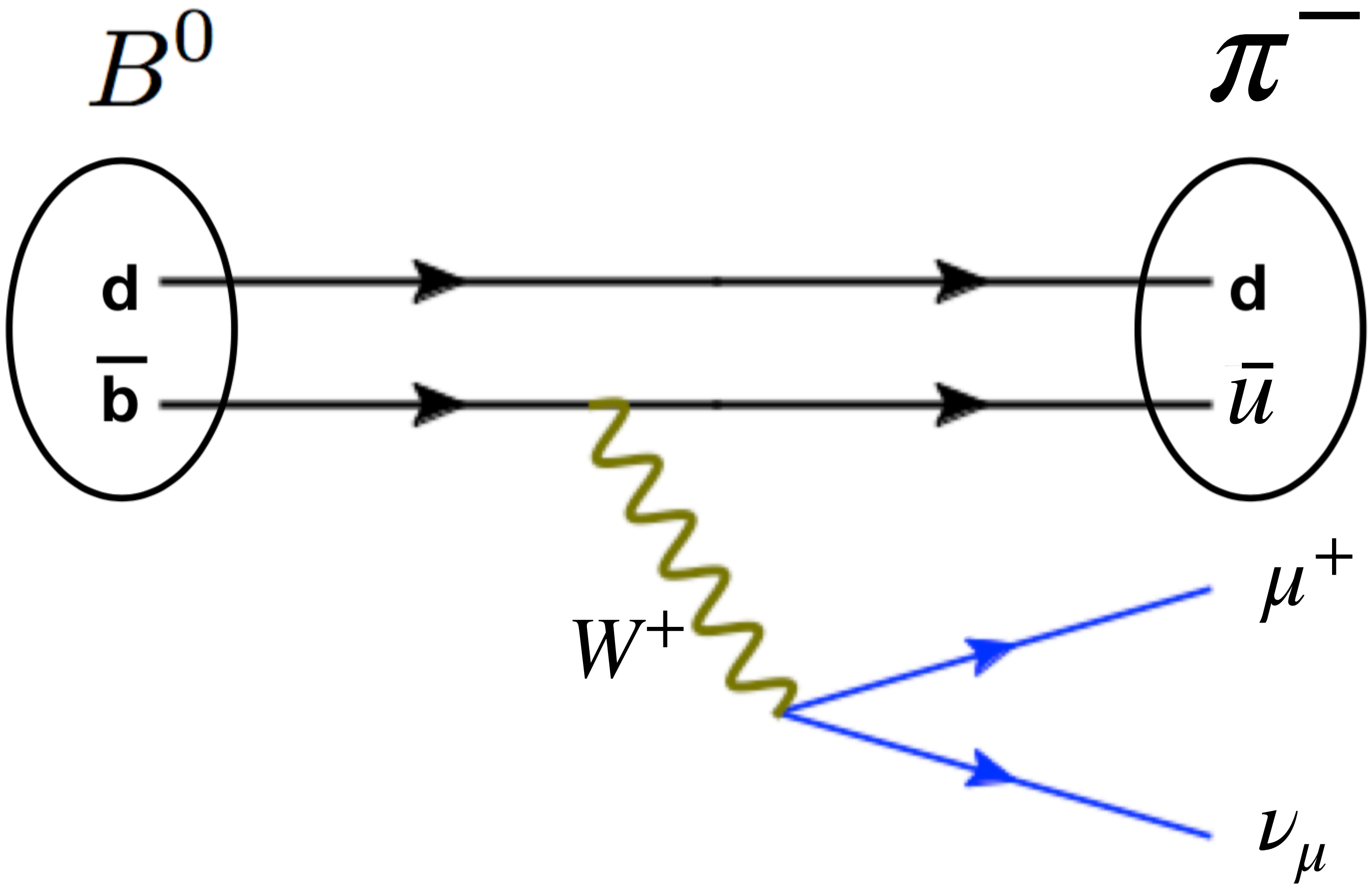
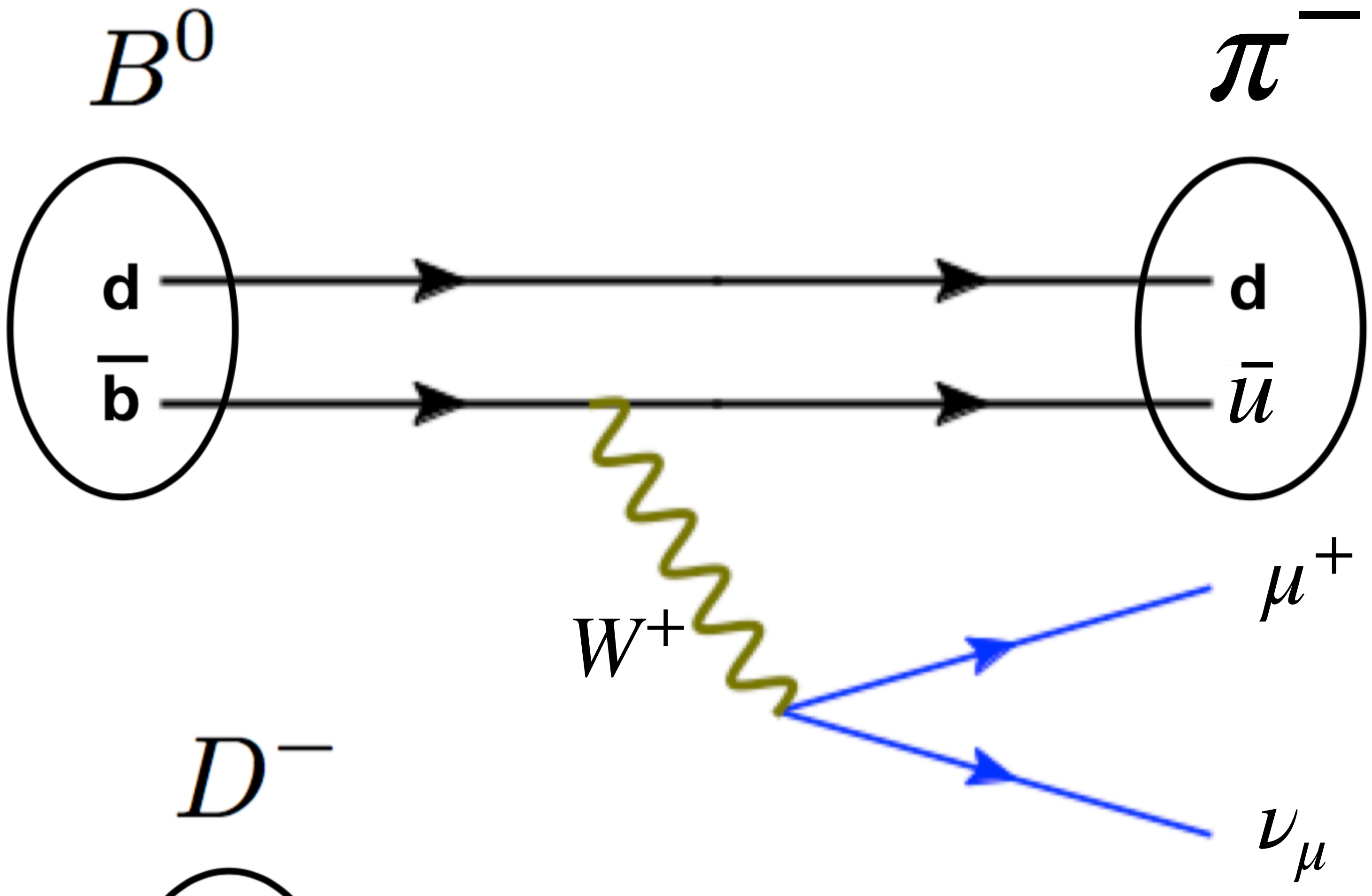
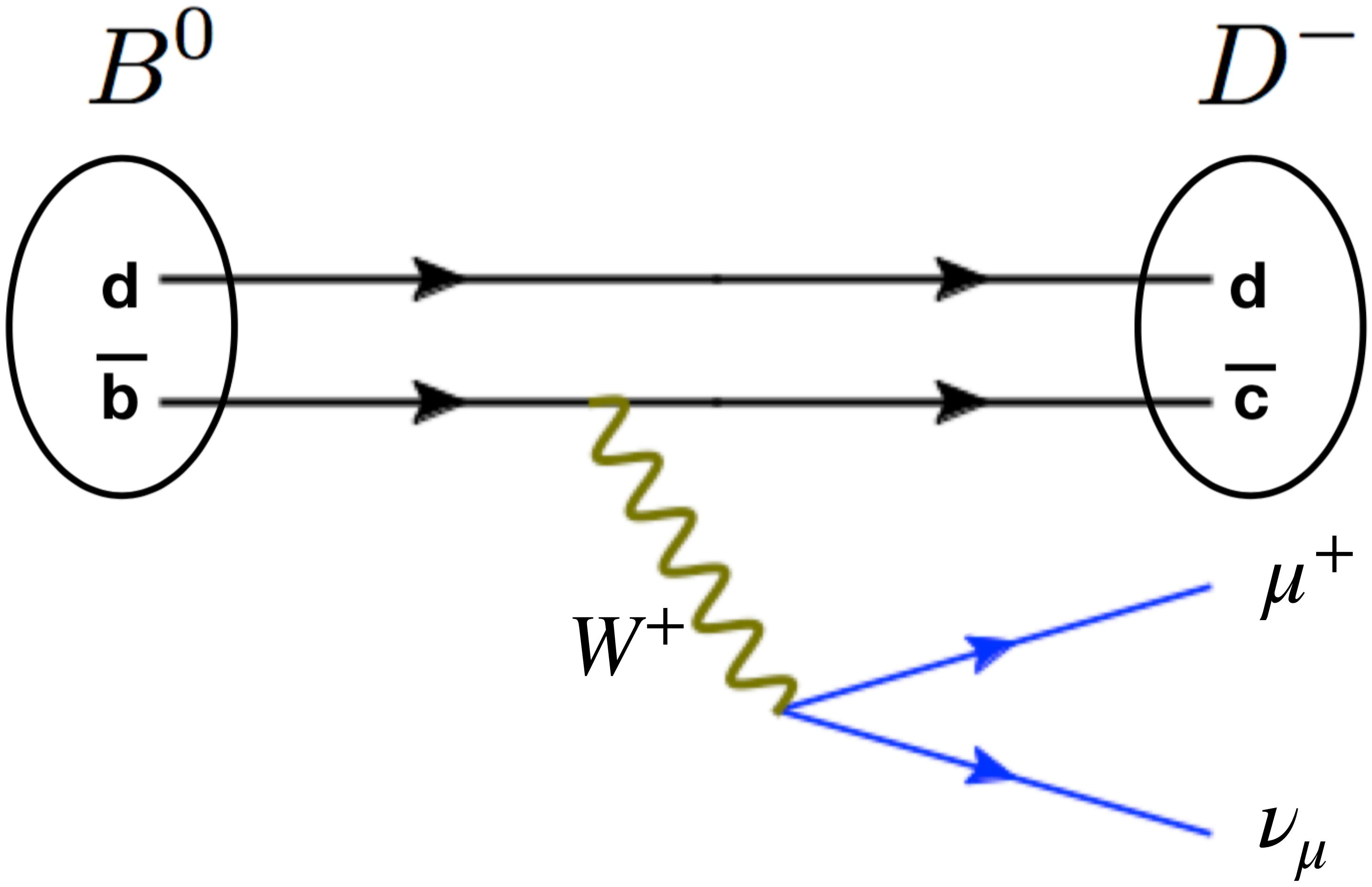


Heavy hadron decays

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





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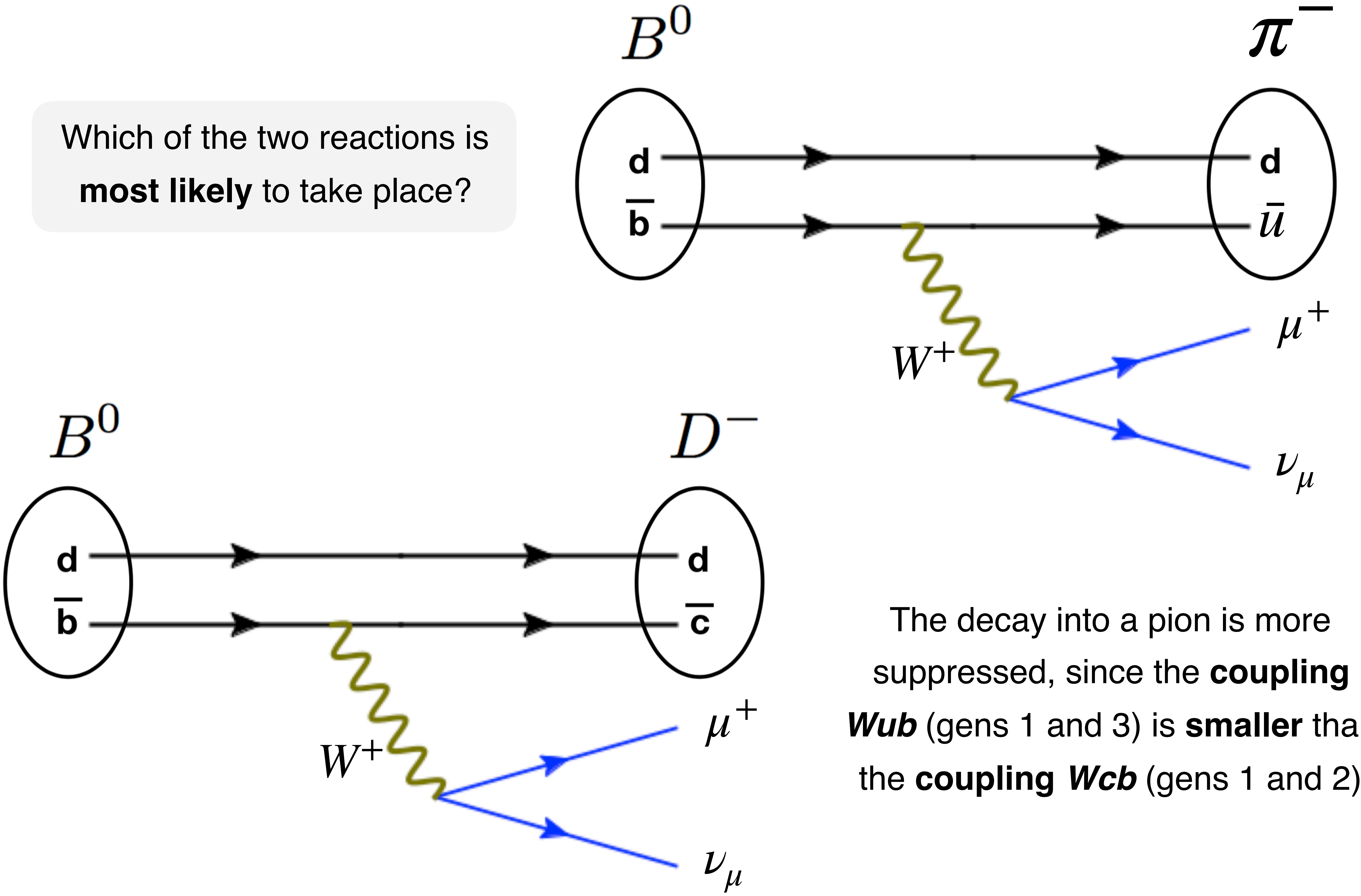

The decay into a pion is more suppressed, since the **coupling *Wub*** (gens 1 and 3) is **smaller** than the **coupling *Wcb*** (gens 1 and 2)

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**

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

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

How do these two decay models relate to each other?

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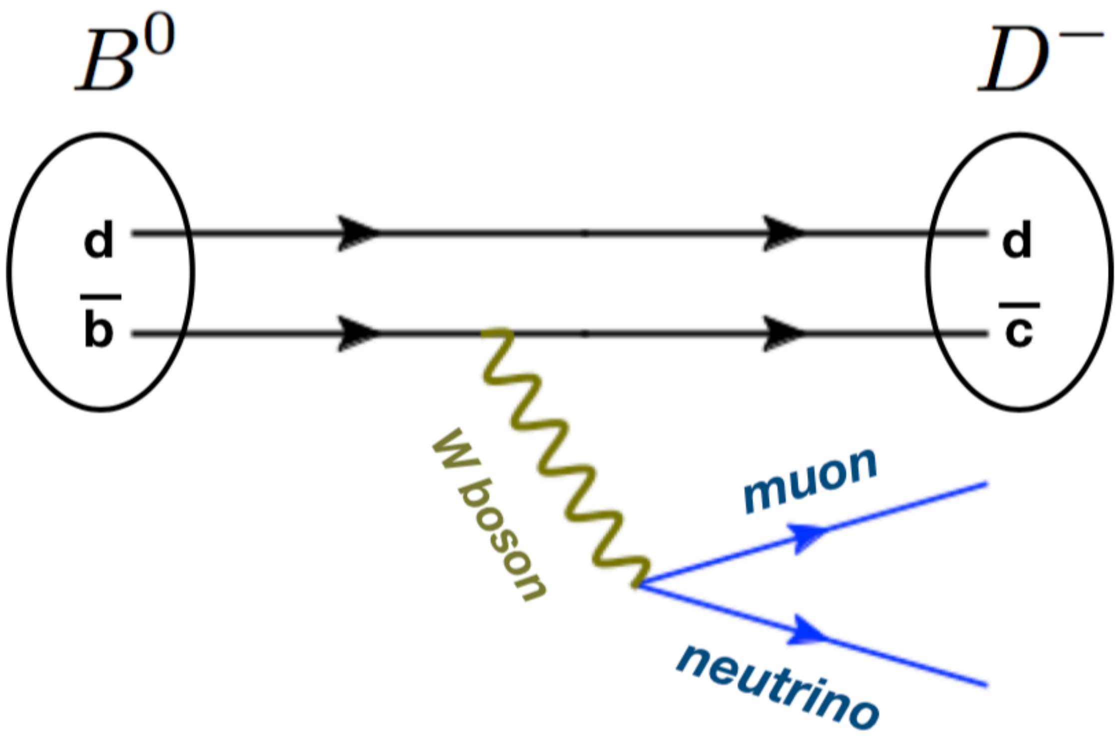

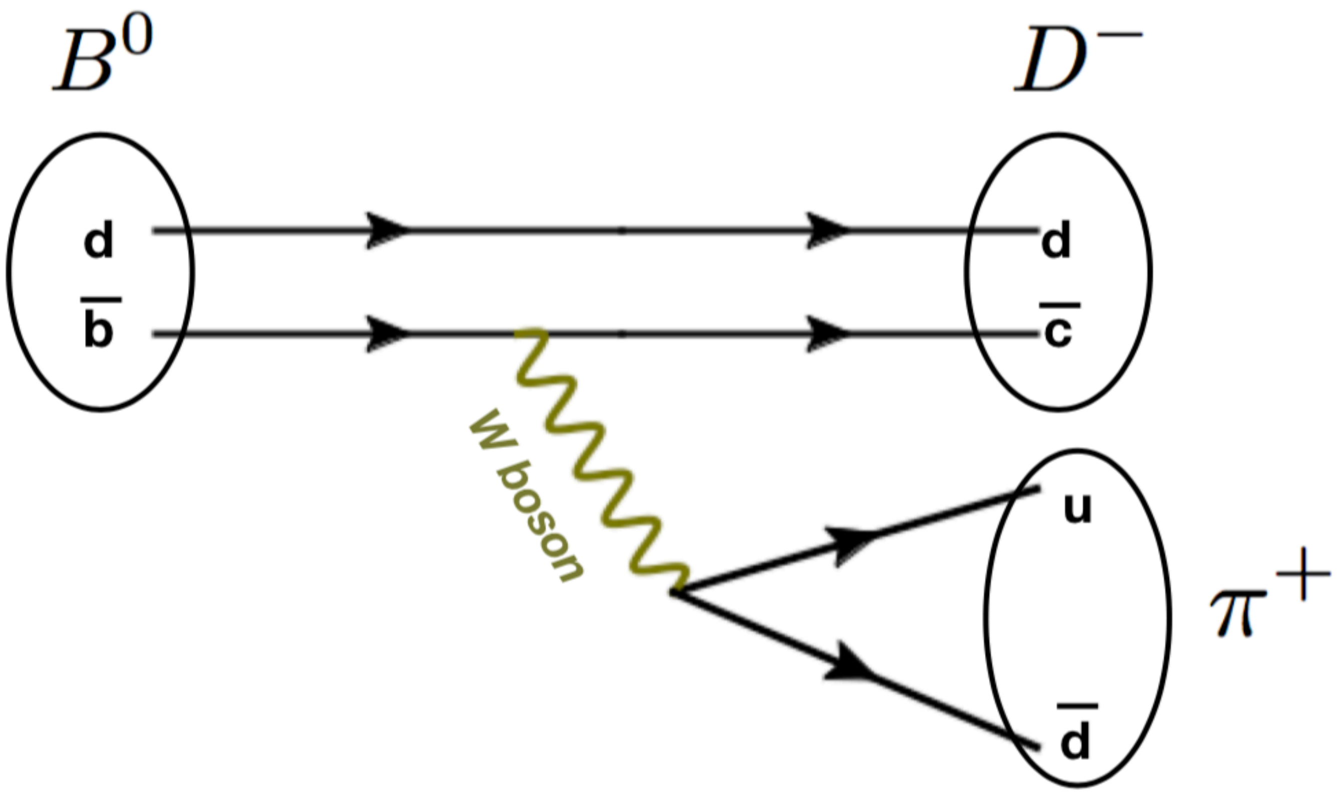

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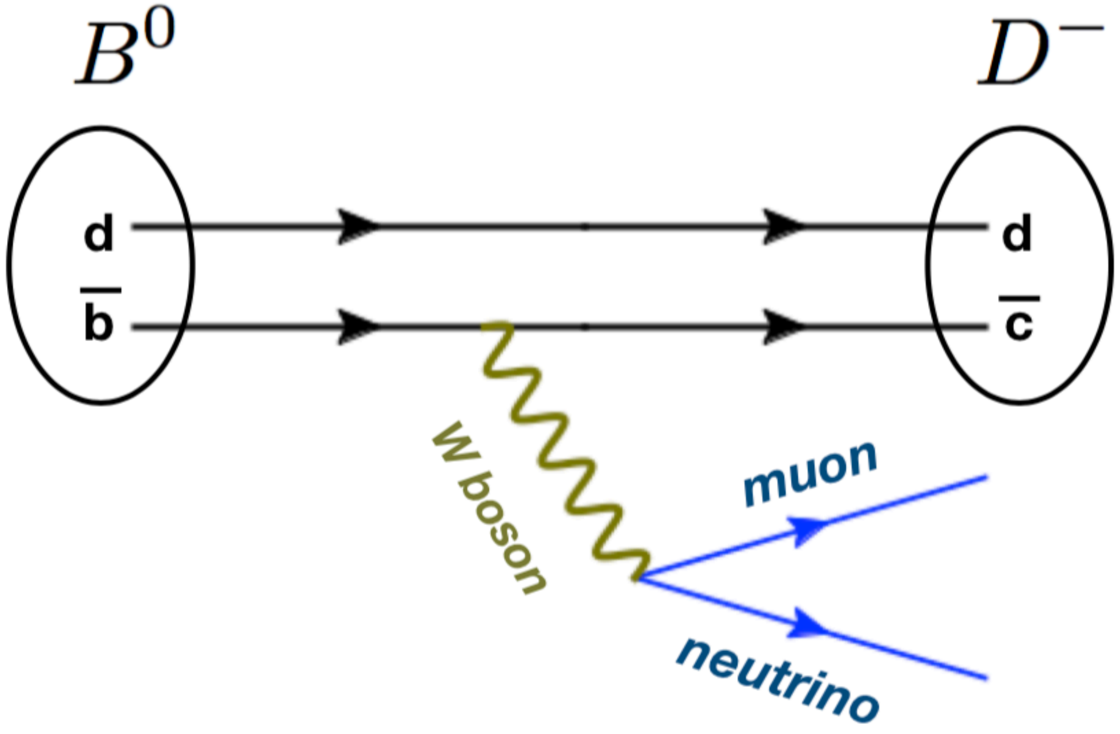

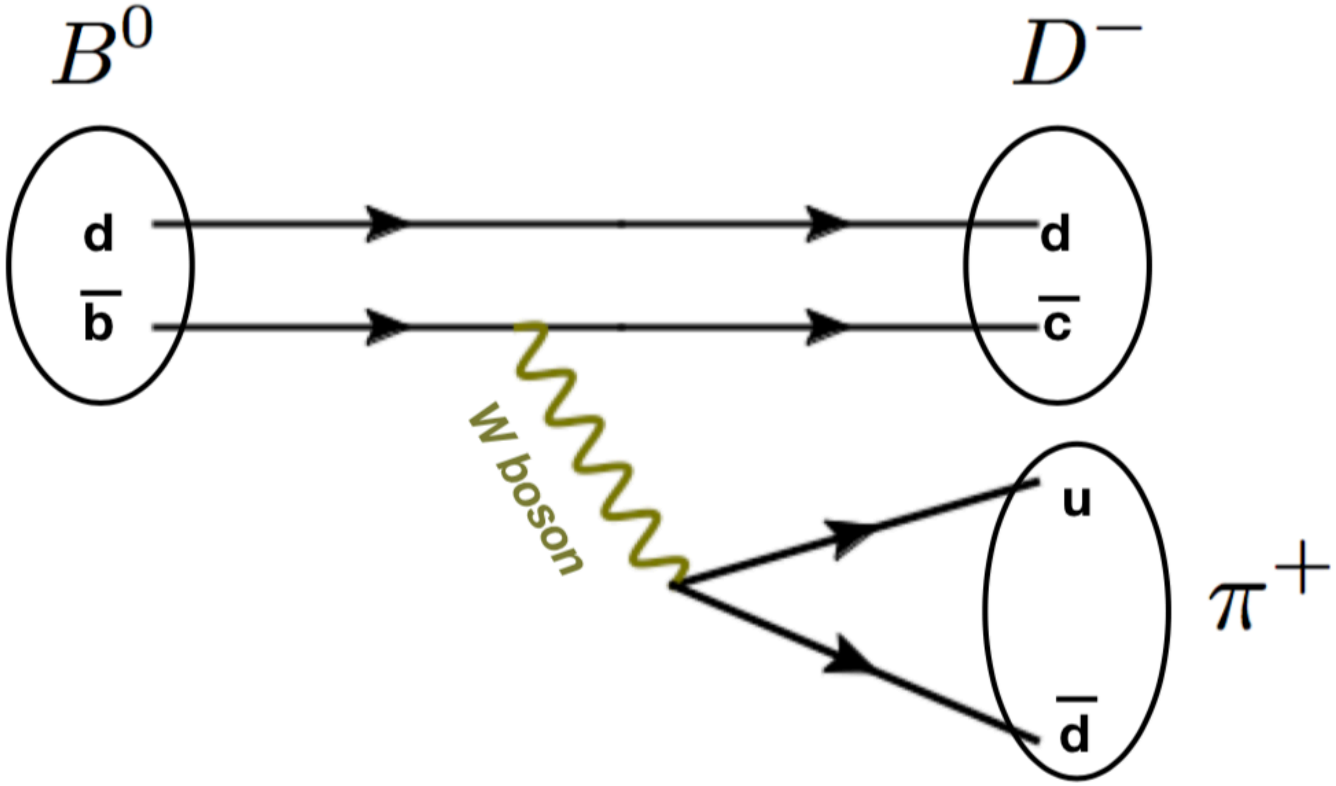

These two processes have a very **similar probability** to happen!

The weak boson *Z*

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

$$m_\gamma = 0$$

$$m_g = 0$$

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

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

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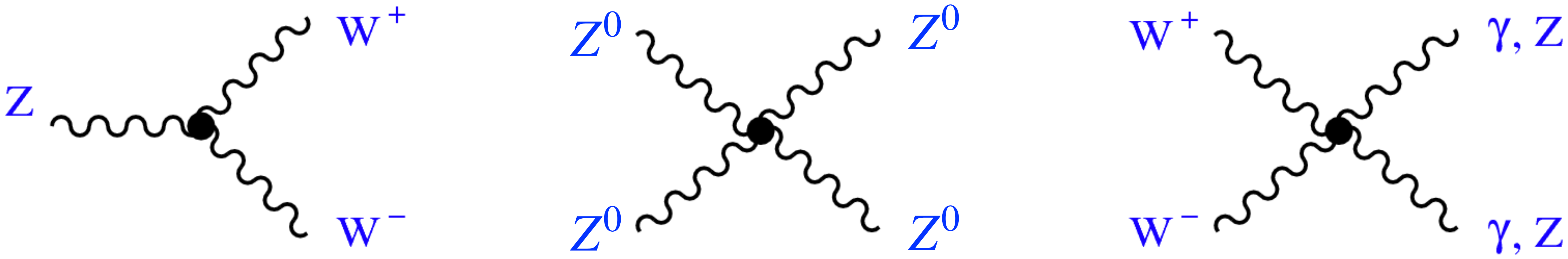

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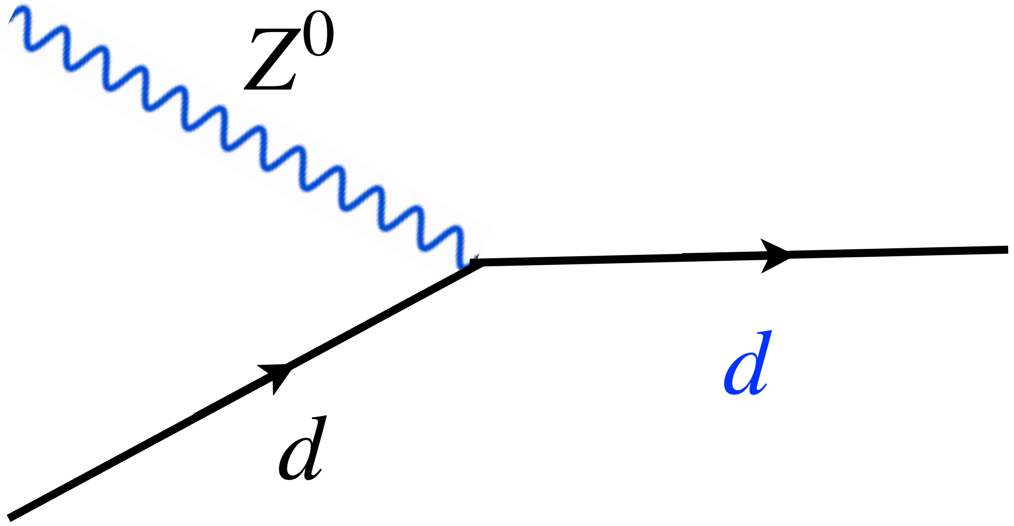

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- ☑ When interacting with **quarks,** the Z boson does **not change the quark flavour**

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

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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**

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

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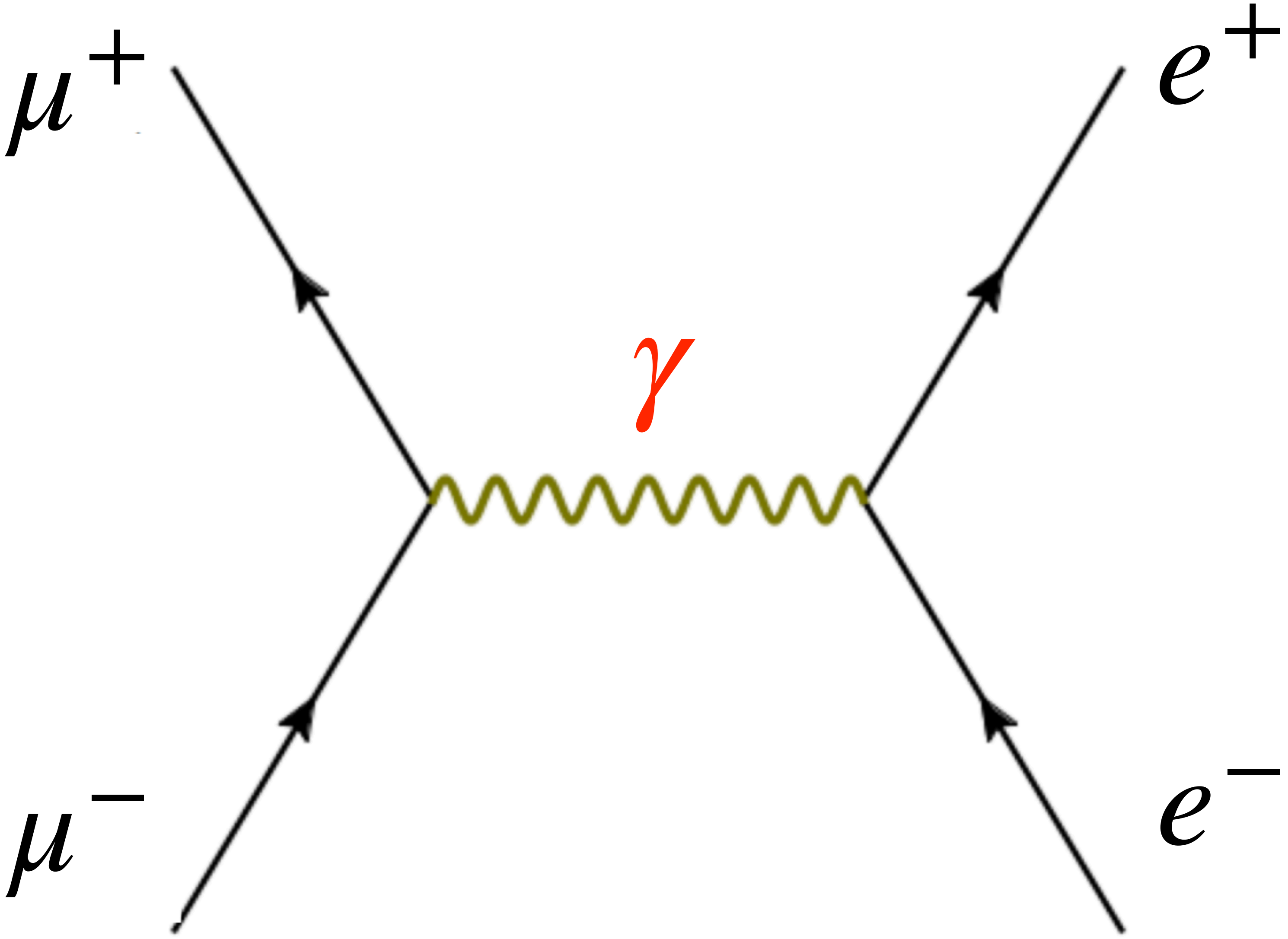

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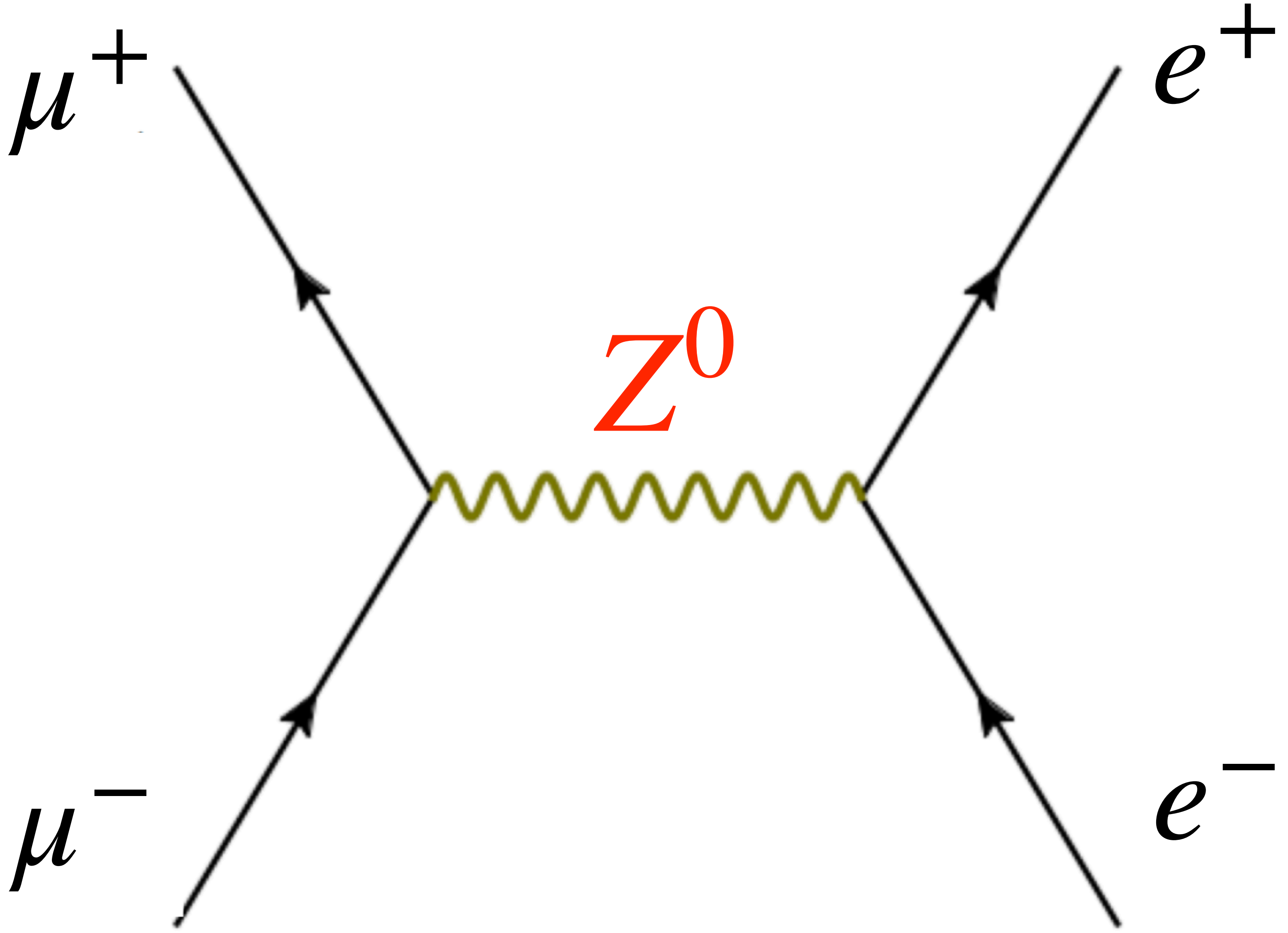

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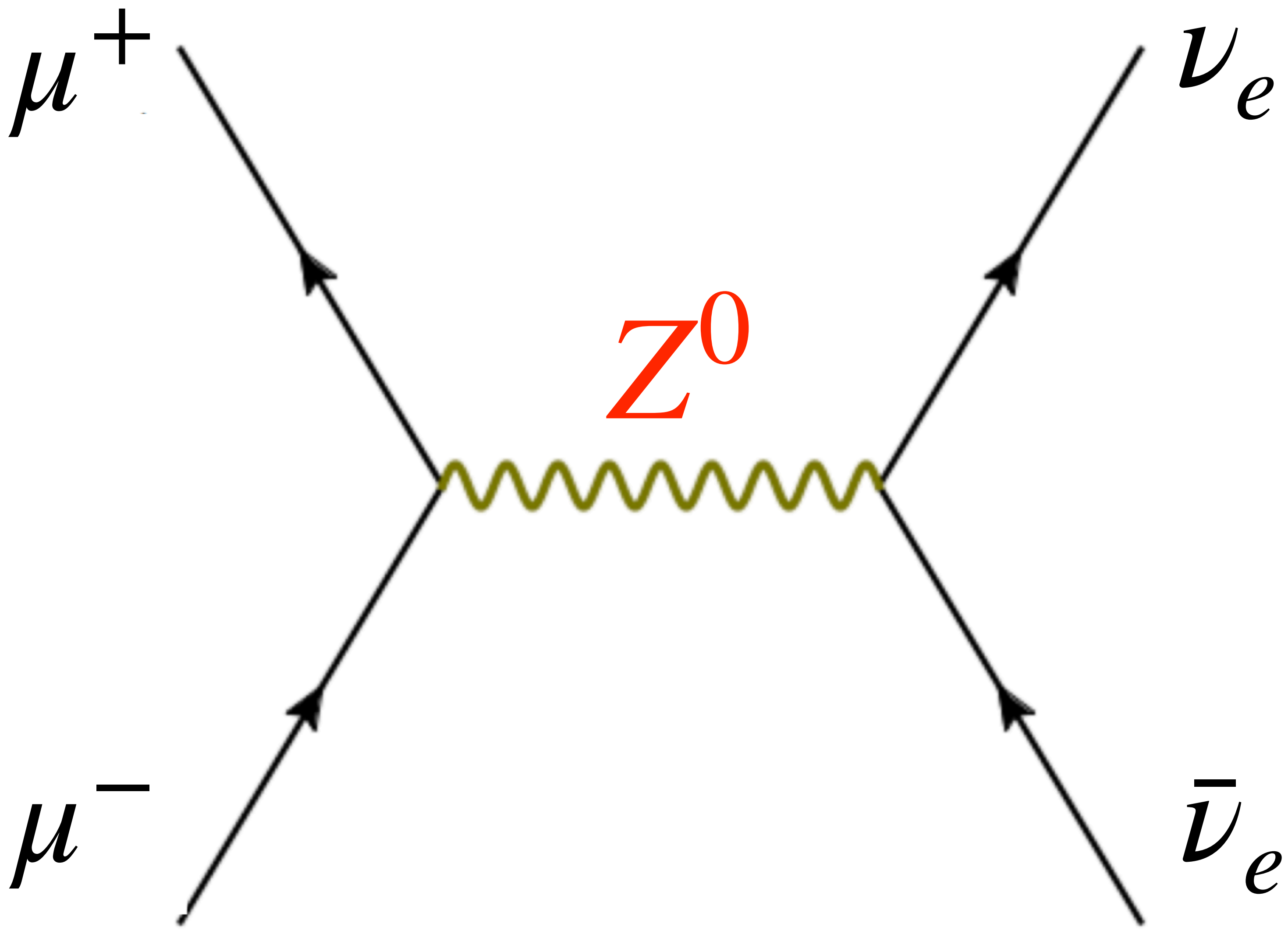
The *Z* boson also mediates processes involving **neutrinos**

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



The weak boson *Z*

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

with quarks

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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**

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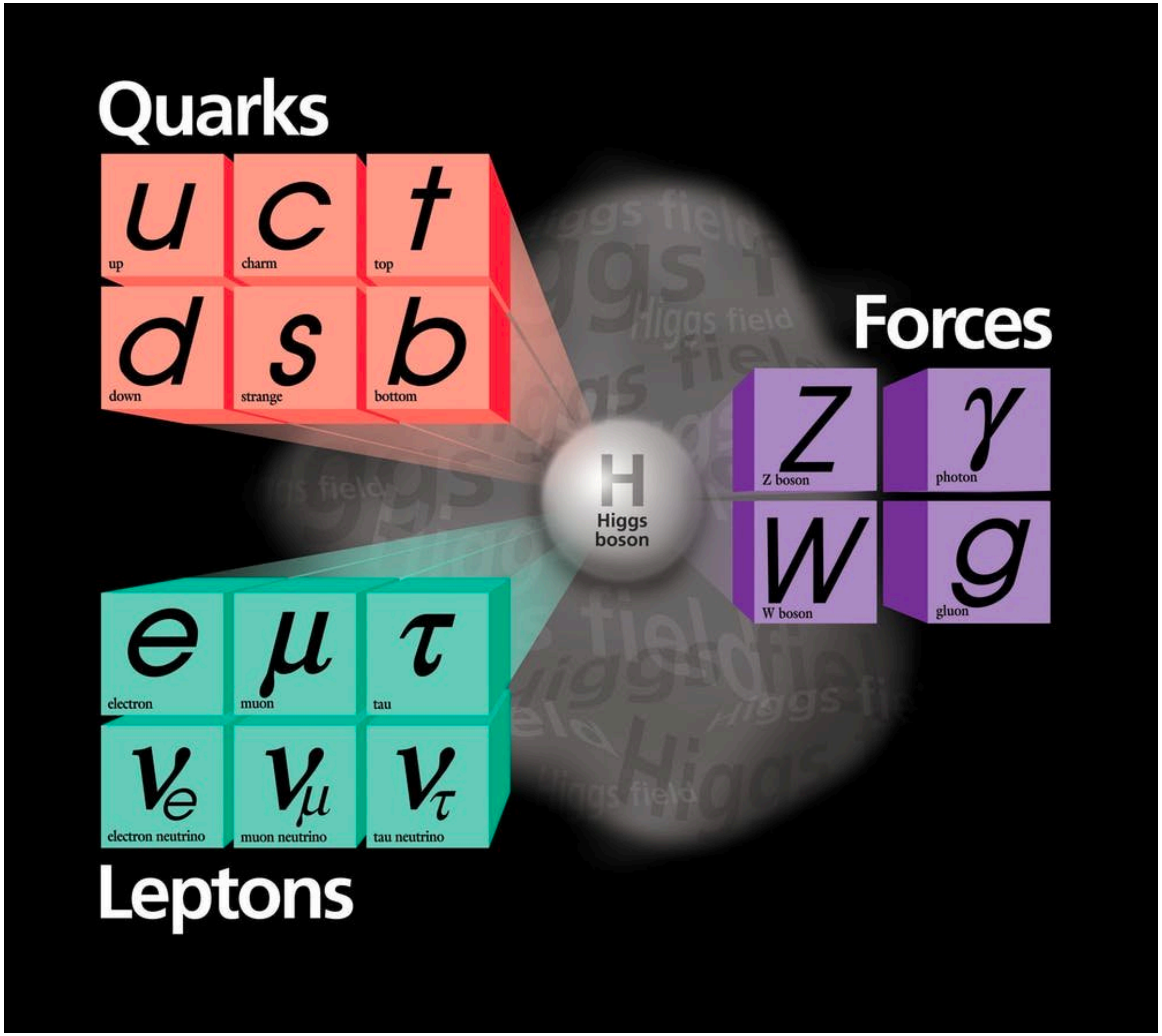
☑ The strength of the weak interaction is **larger** between quarks of the **same generation** than between quarks of **different generation**

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

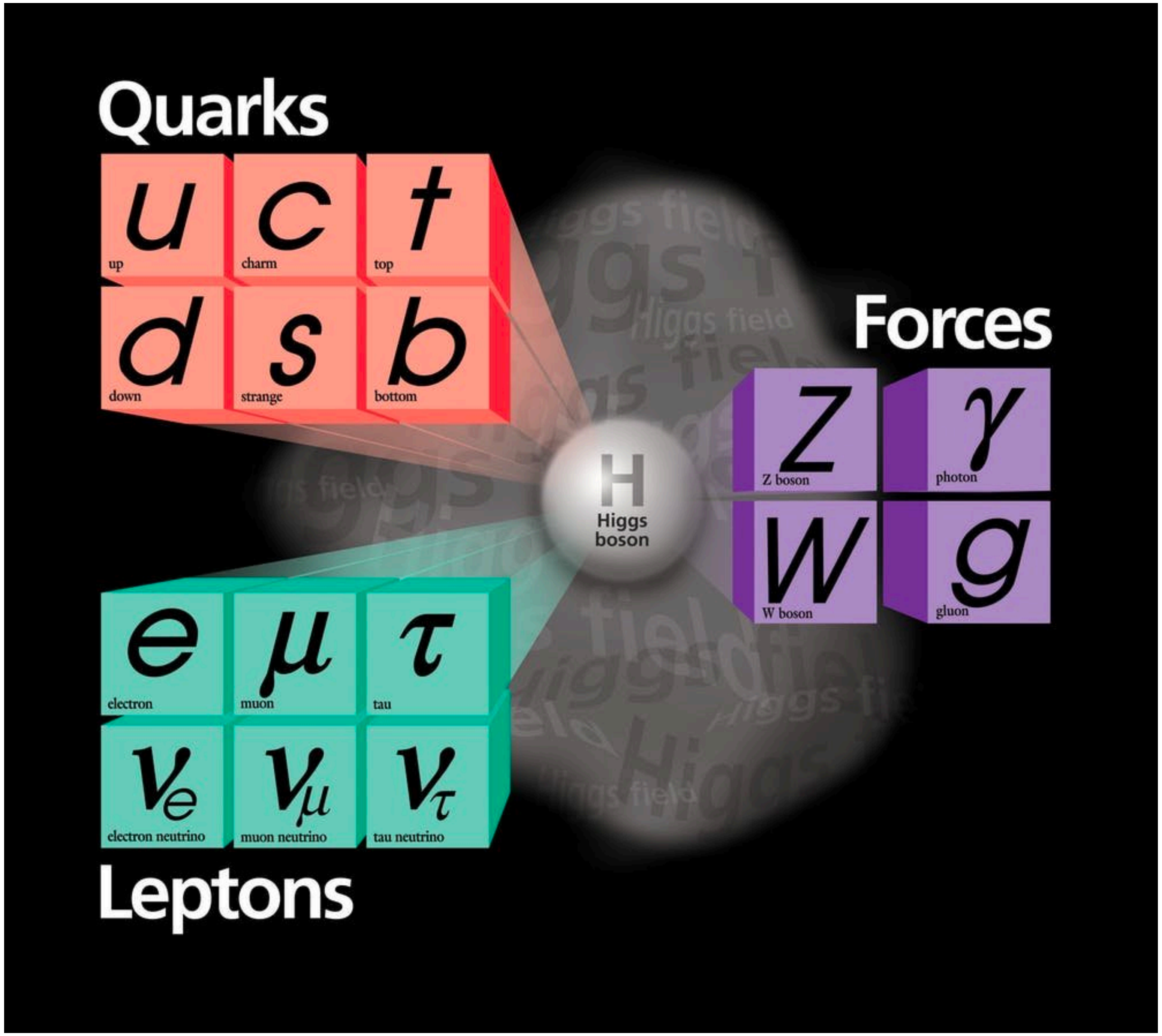
The Higgs boson

The Standard Model of particle physics



We are by know familiar with the different types of **matter particles** (leptons and quarks) and their interactions, mediated by the **force carrier particles**

The Standard Model of particle physics



The only missing ingredient to **complete the Standard Model** is the **Higgs boson**

The Higgs boson

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- ☑ It is **elementary**, without any (known) substructure
- ☑ It interacts with **matter particles** (quarks and charged leptons) and gives them **mass**
- ☑ It is also responsible for the mass of the ***W*** and ***Z*** bosons

Without the Higgs, elementary particles would be **massless** and the Universe as we know it would be **impossible**

Electroweak symmetry breaking

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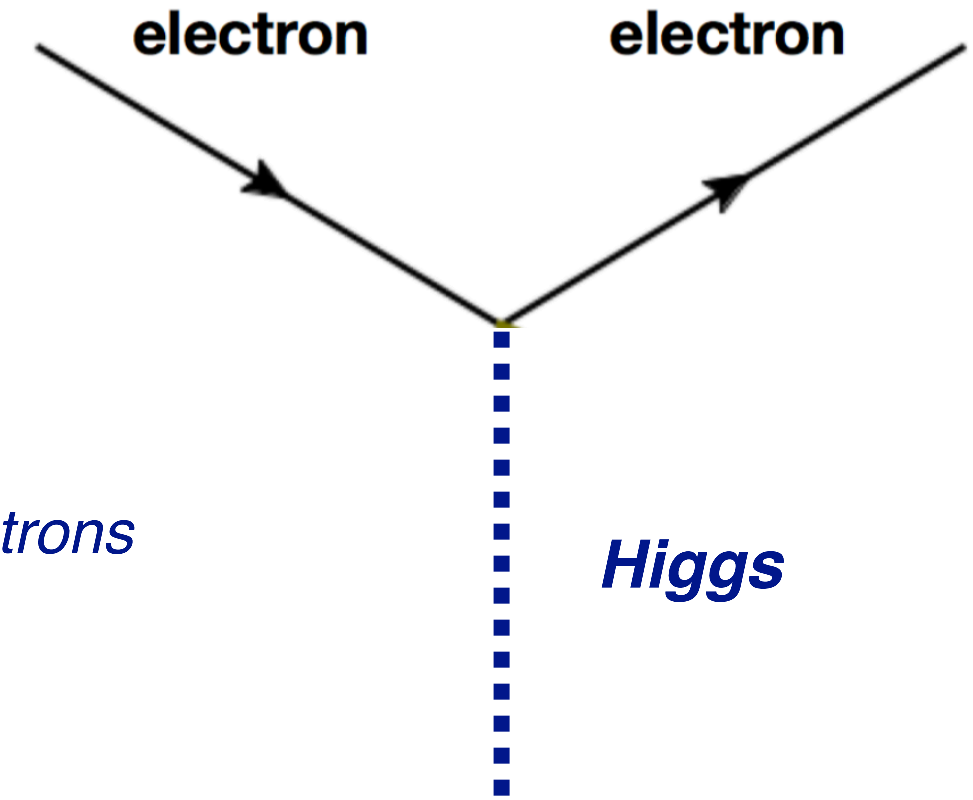
- ☑ Let us start with a theory of massless particles, and add an extra **scalar field** (without spin) that interacts with all other particles and has its **own potential**

$$\phi\bar{\psi}_e\psi_e$$

Interaction between Higgs field and electrons



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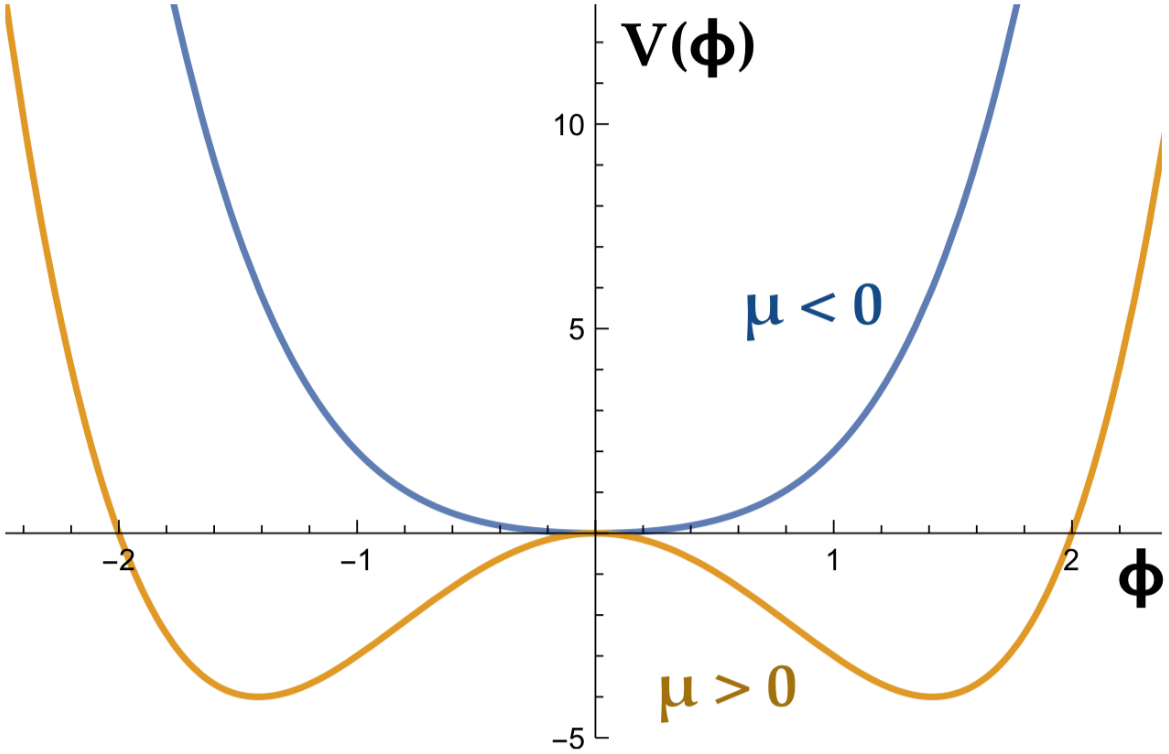
Interaction of Higgs field with itself



Electroweak symmetry breaking

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$$V(\phi) = -\mu\phi^2 + \lambda\phi^4$$

- ☑ The ground state of the system corresponds to the **minimum of the potential**

- ☑ First let us consider the case for which ***μ < 0*** (we always have ***λ > 0***)

$$\frac{d}{d\phi}V(\phi) = 0 = 2|\mu|\phi + 4\lambda\phi^3$$

- ☑ This equation can only be satisfied if ***ϕ=0:*** the ground state of the theory is the one where the field vanishes (so there is no Higgs field)

Electroweak symmetry breaking

- ☑ What determines the **ground state** (state with minimum energy) for a system with potential energy given by ***V(ϕ)*** *?*

$$V(\phi) = -\mu\phi^2 + \lambda\phi^4$$

- ☑ The ground state of the system corresponds to the **minimum of the potential**

- ☑ Now we consider the case for which ***μ > 0*** (we always have ***λ > 0***)

$$\frac{d}{d\phi}V(\phi) = 0 = -2|\mu|\phi + 4\lambda\phi^3$$

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$$\phi = \pm\sqrt{\frac{|\mu|}{2\lambda}}$$

Electroweak symmetry breaking

$$V(\phi) = -|\mu|\phi^2 + \lambda\phi^4$$

- Which of these three solutions has the **lowest potential energy?**

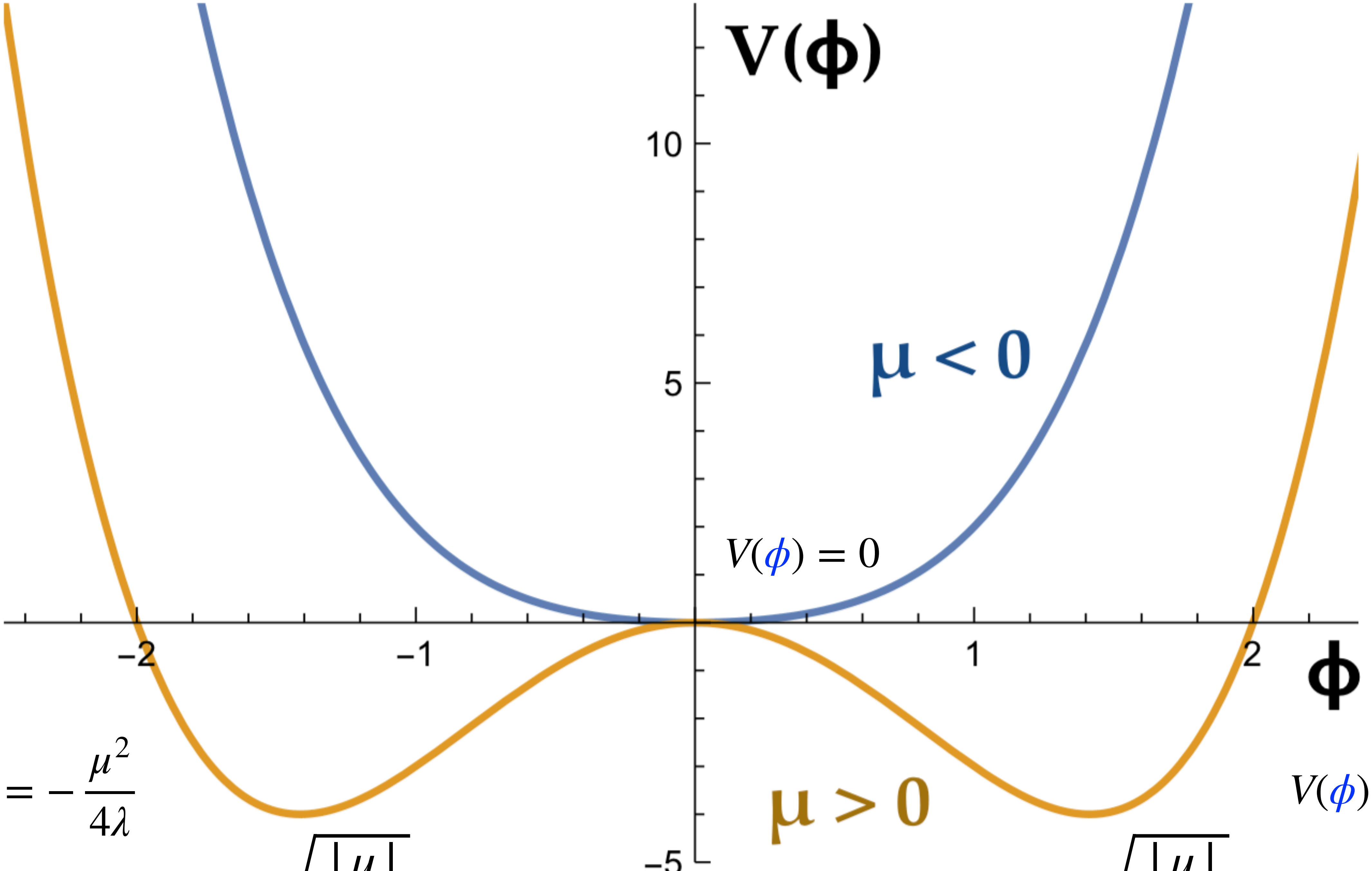
$$\phi = \pm\sqrt{\frac{|\mu|}{2\lambda}} \qquad V(\phi) = -\frac{\mu^2}{4\lambda}$$

$$\phi = 0 \qquad V(\phi) = 0$$

The lowest energy configuration (ground state of the theory) is one where the **Higgs field is different from zero!**

The Higgs field permeates all space and **elementary particles acquire their mass** by interacting with it

Higgs mechanism I



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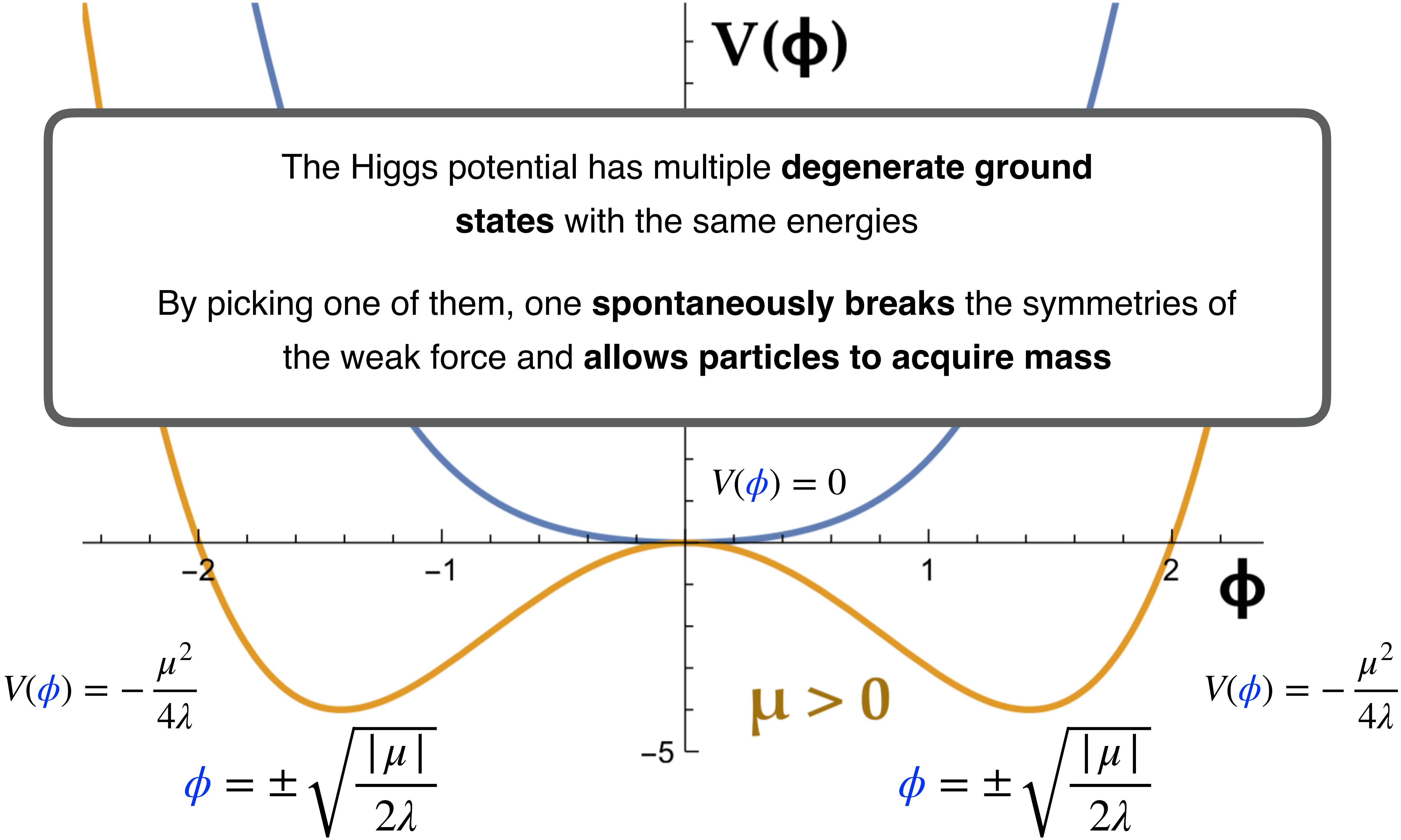

The Higgs potential has multiple **degenerate ground states** with the same energies

By picking one of them, one **spontaneously breaks** the symmetries of the weak force and **allows particles to acquire mass**

$V(\phi) = 0$

$$V(\phi) = -\frac{\mu^2}{4\lambda}$$

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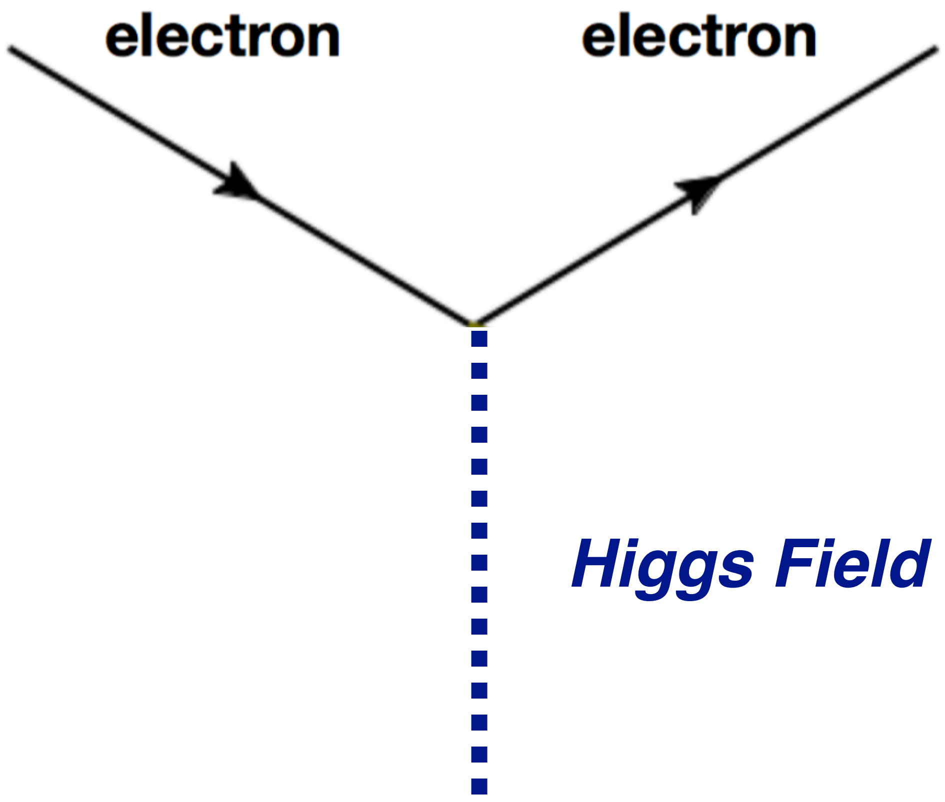
Higgs mechanism II

Before symmetry breaking

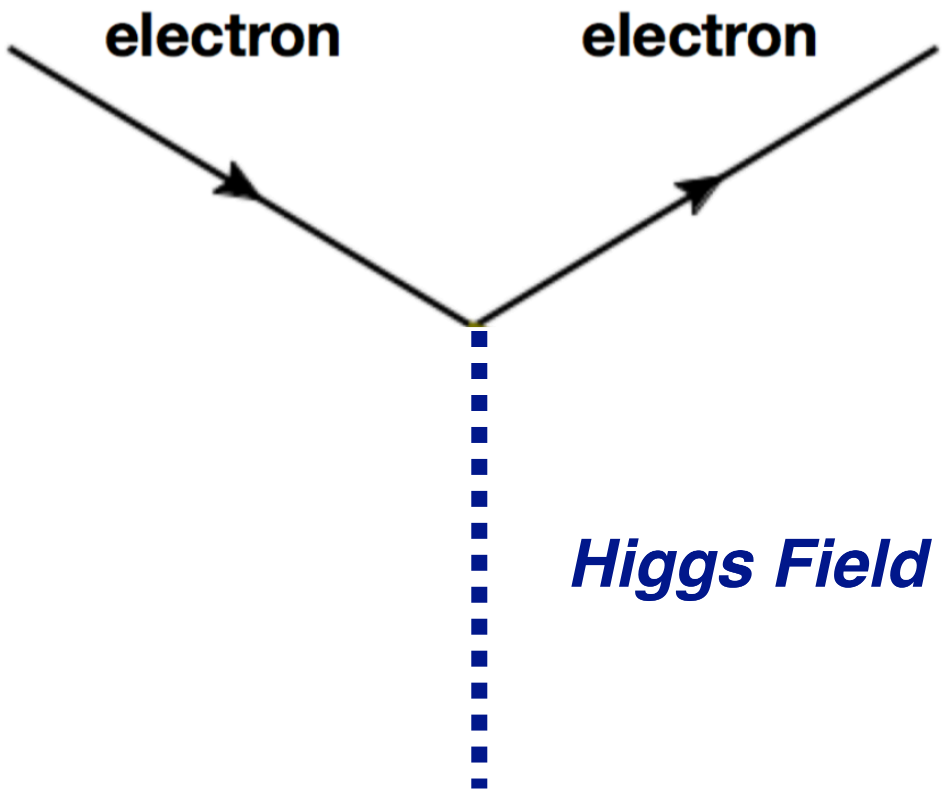
$$\phi\bar{\psi}_e\psi_e$$



Higgs mechanism II

Before symmetry breaking

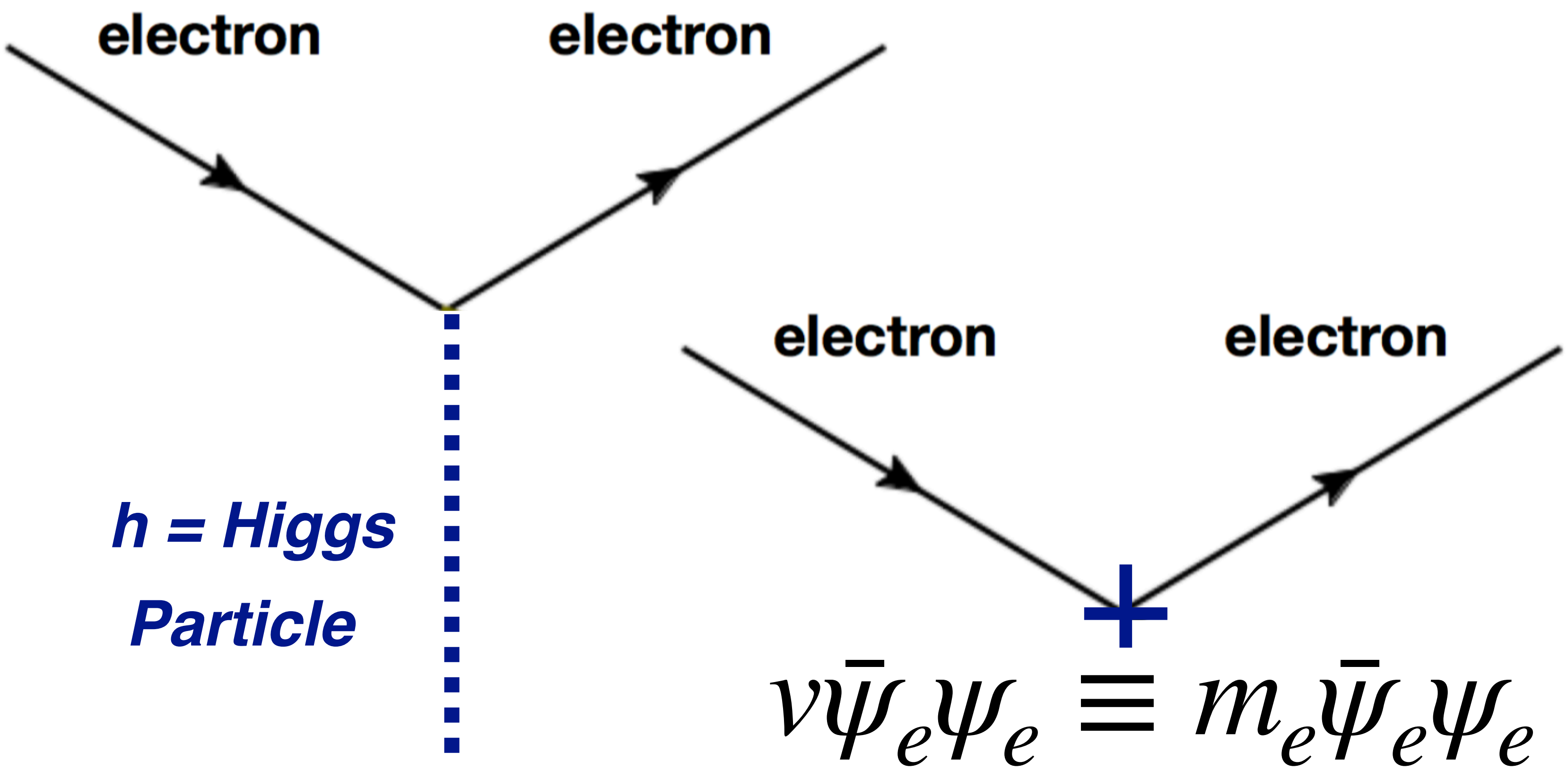
$$\phi\bar{\psi}_e\psi_e$$



After symmetry breaking

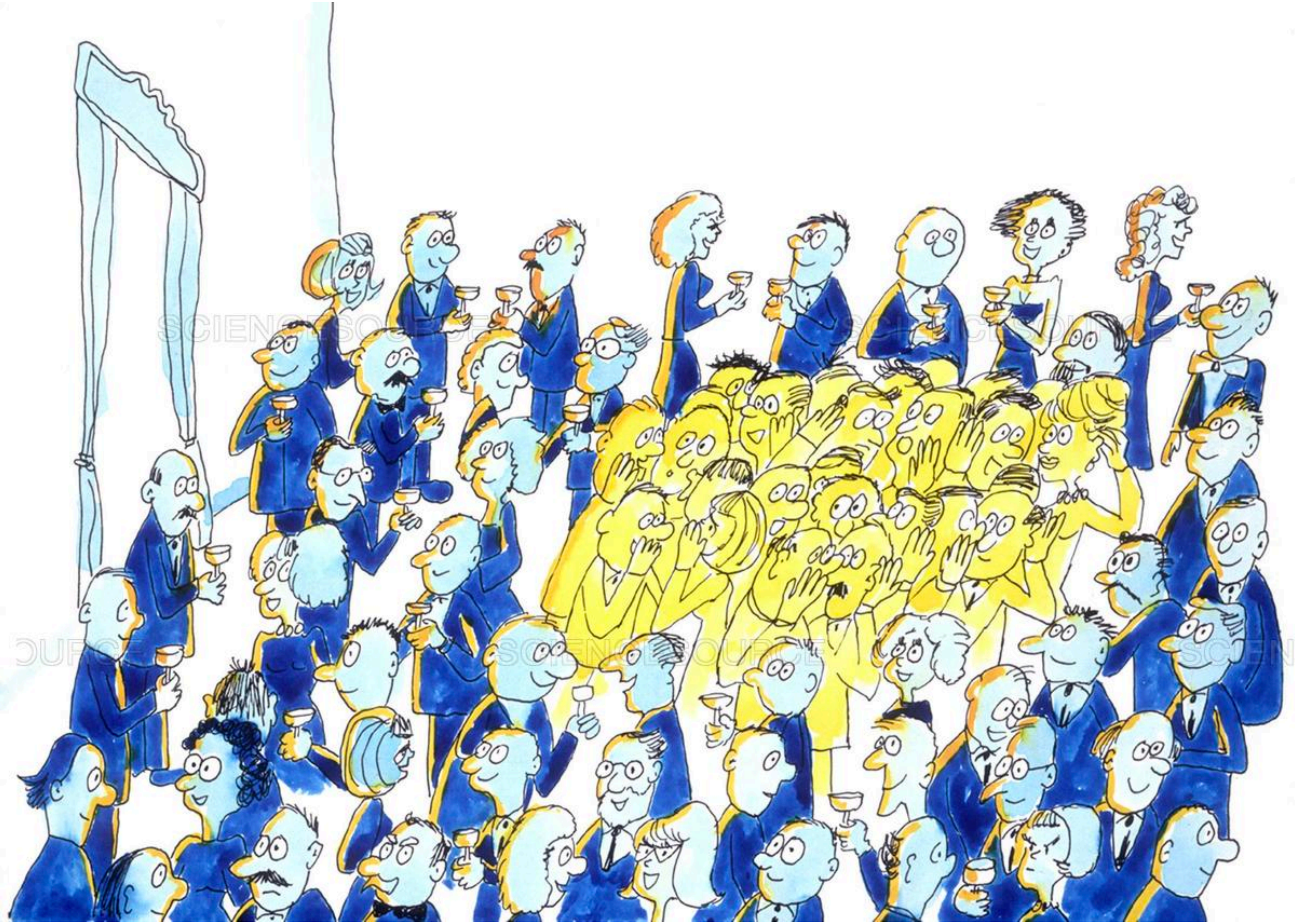
$$(v + h)\bar{\psi}_e\psi_e$$

Expand around minimum of potential



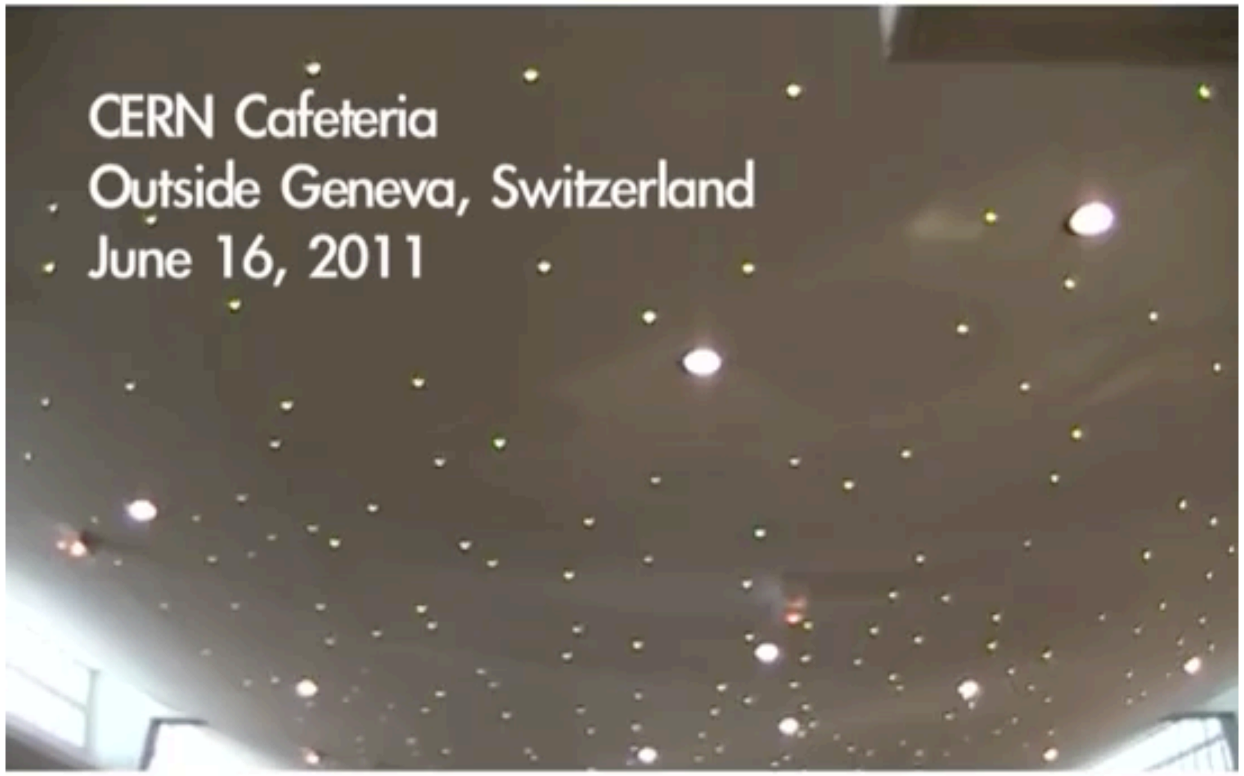
$$v\bar{\psi}_e\psi_e \equiv m_e\bar{\psi}_e\psi_e$$

Higgs mechanism III



Higgs boson recap I

Higgs boson recap II



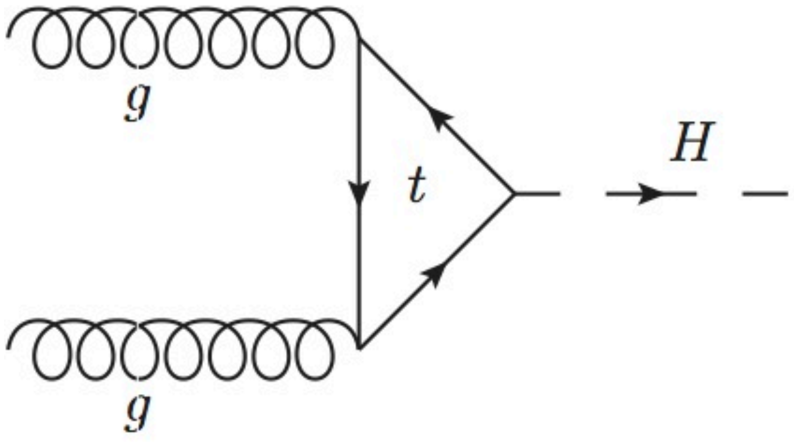
PhD Comics: https://www.youtube.com/watch?v=lqAWqwh3Etw

Higgs production
and collider phenomenology

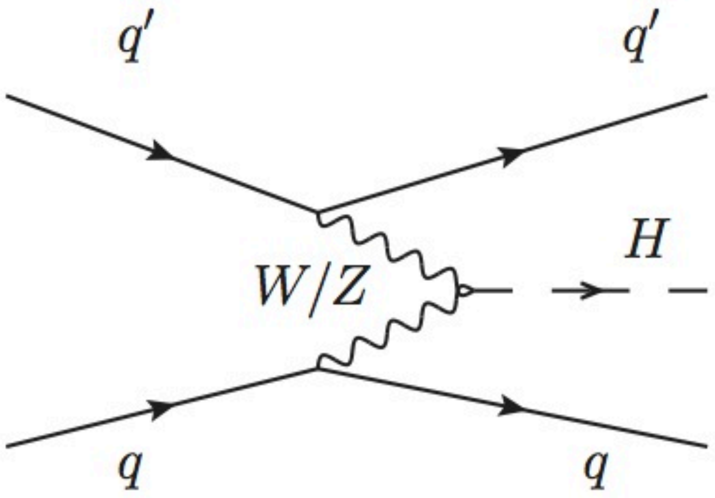
Higgs boson production

At proton-proton colliders such as the LHC, **multiple ways** to produce Higgs bosons

gluon-fusion



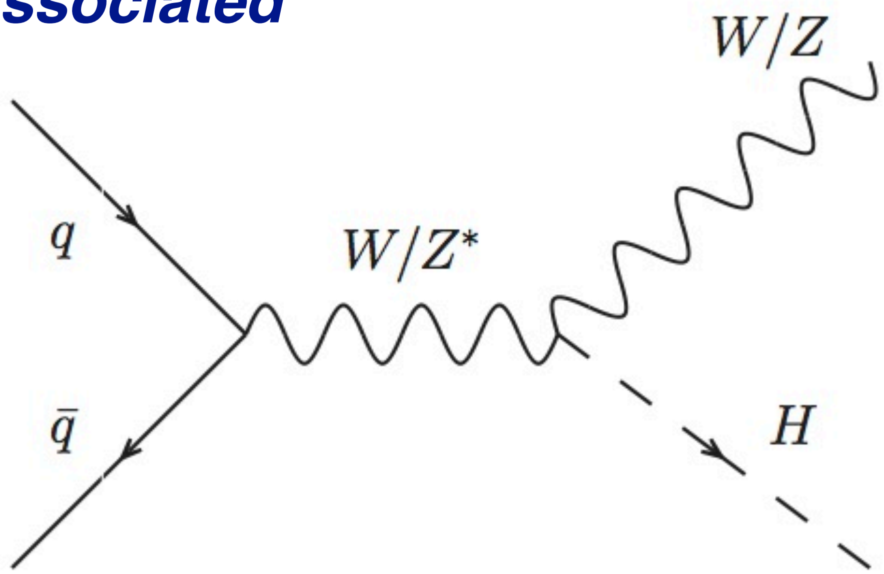
$a)$



Weak boson fusion

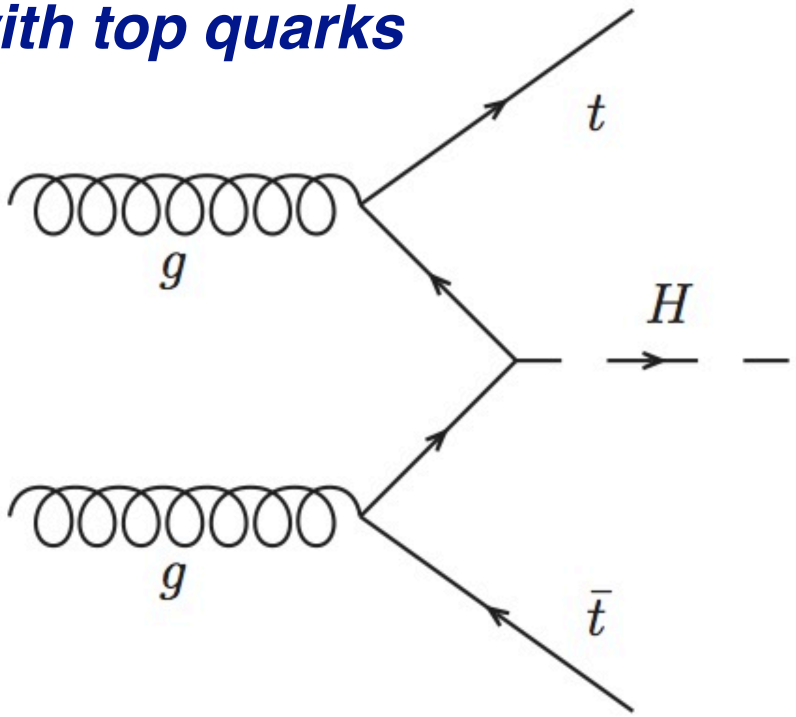
$b)$

W/Z associated



$c)$

with top quarks

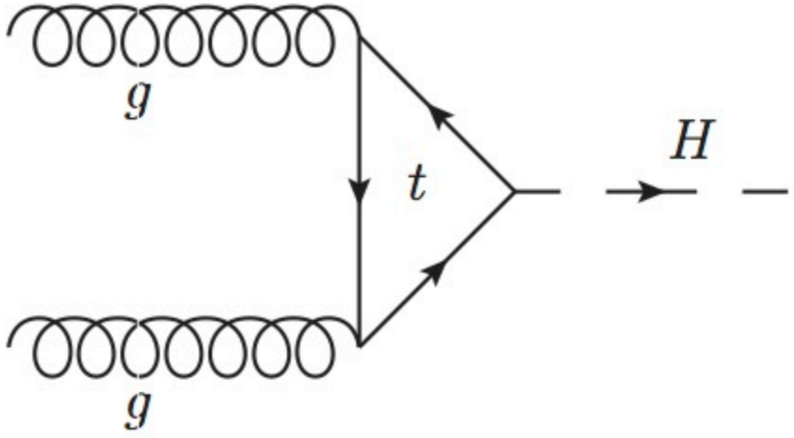


$d)$

Higgs boson production

Which processes are **more likely** to happen? Strength of Higgs boson coupling to a particle is **proportional to the particle mass**

gluon-fusion



$a)$

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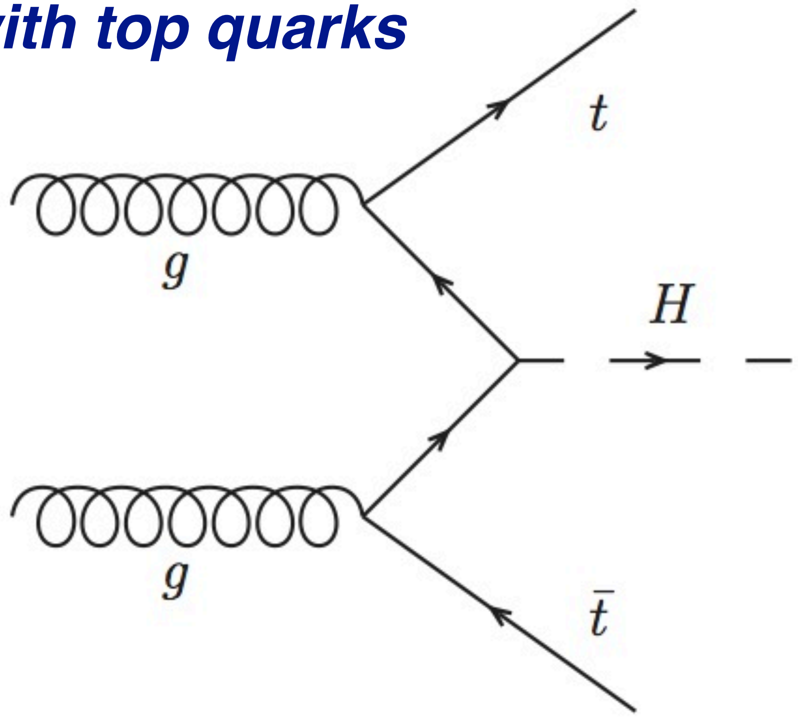


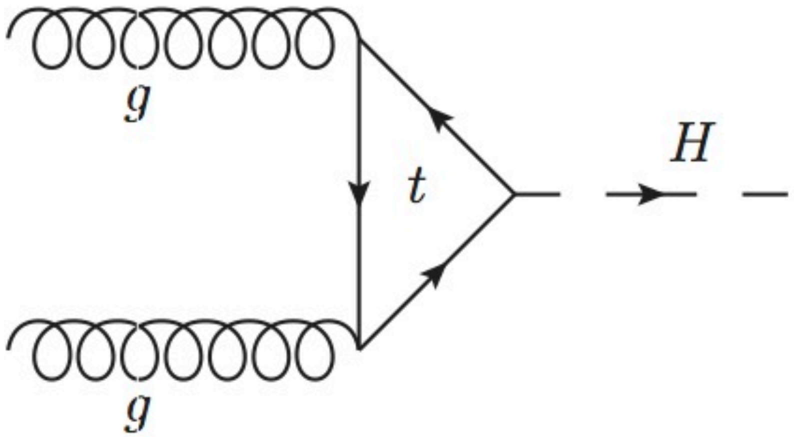
$c)$

$d)$

Higgs boson production

Which processes are **more likely** to happen? Strength of Higgs boson coupling to a particle is **proportional to the particle mass**

gluon-fusion



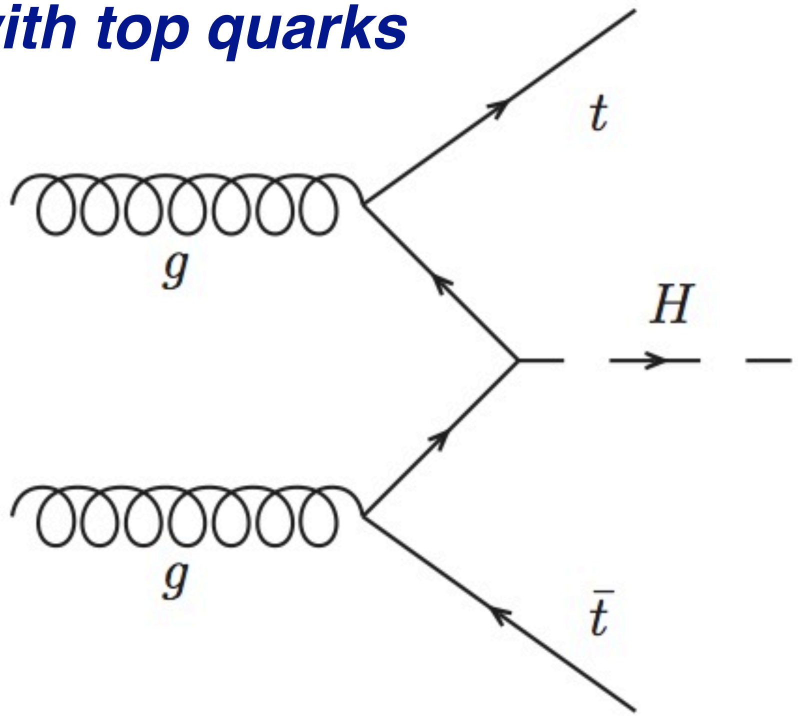
a)

>

with top quarks

Same coupling between Higgs and top quarks …

But in one case one needs to produce **in addition a top quark pair** which requires a lot of extra energy



c)

d)

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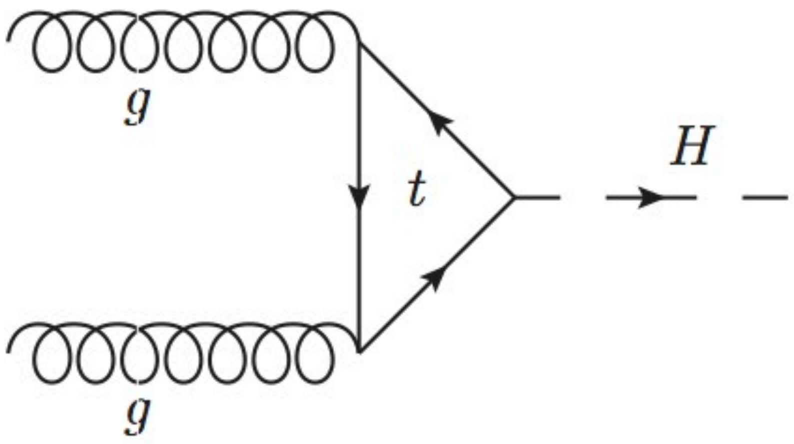

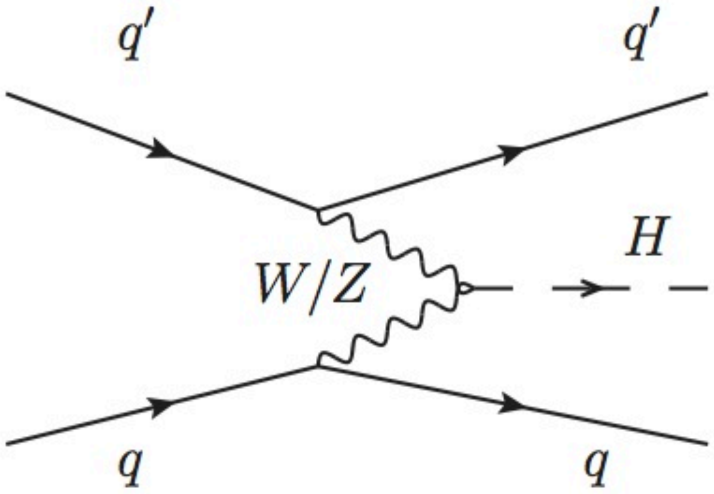

Weak boson fusion

Higgs boson production

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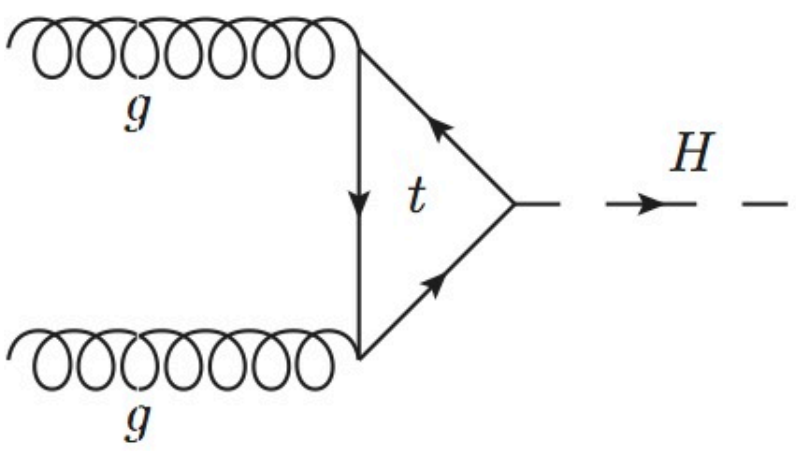

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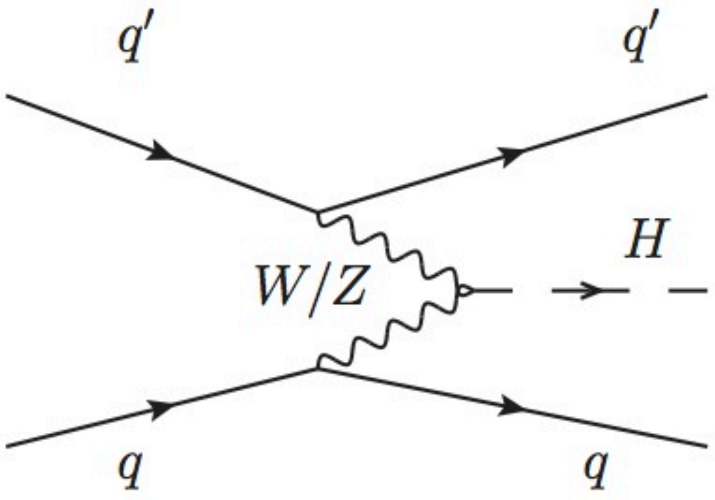
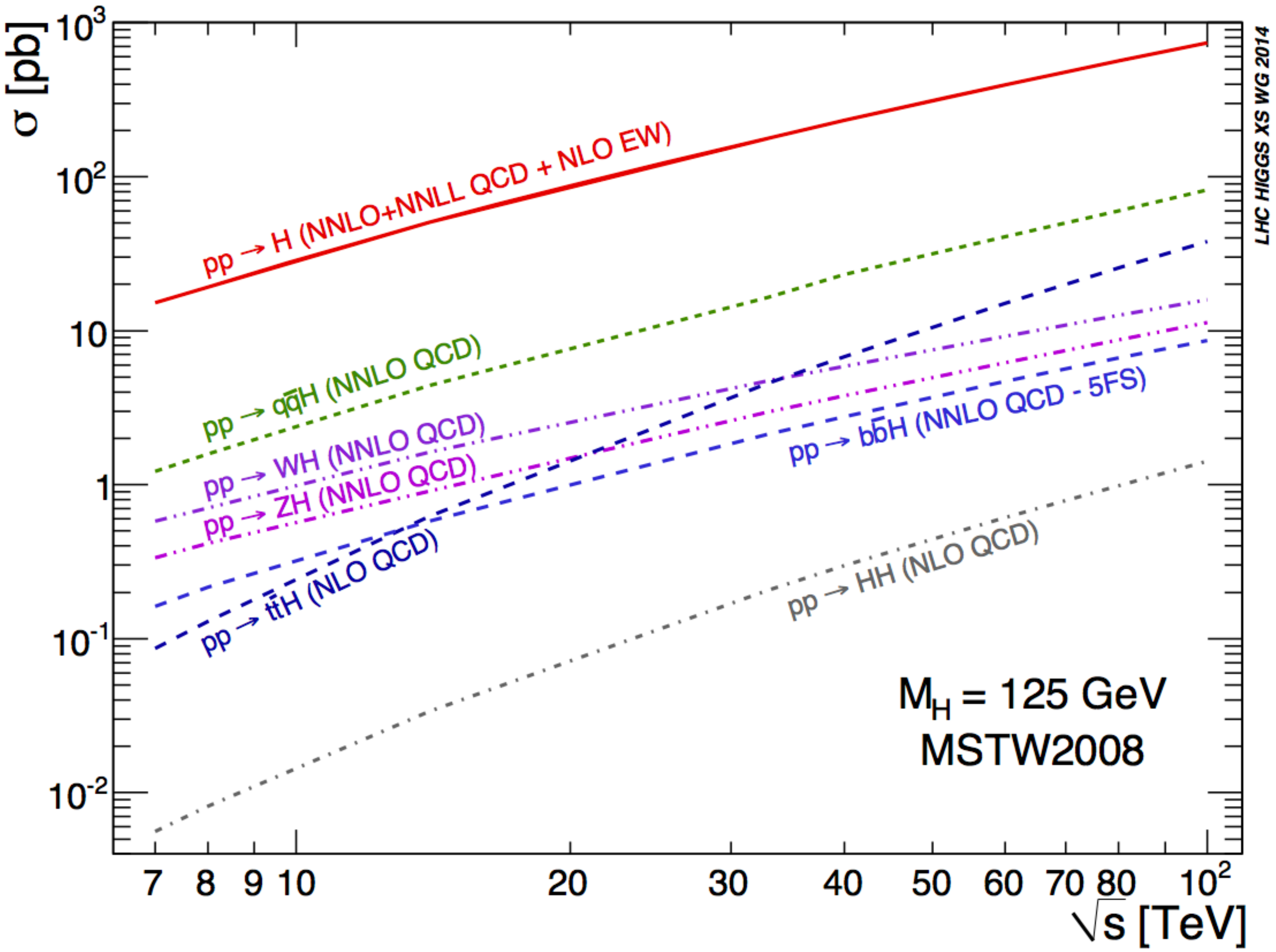


Weak boson fusion

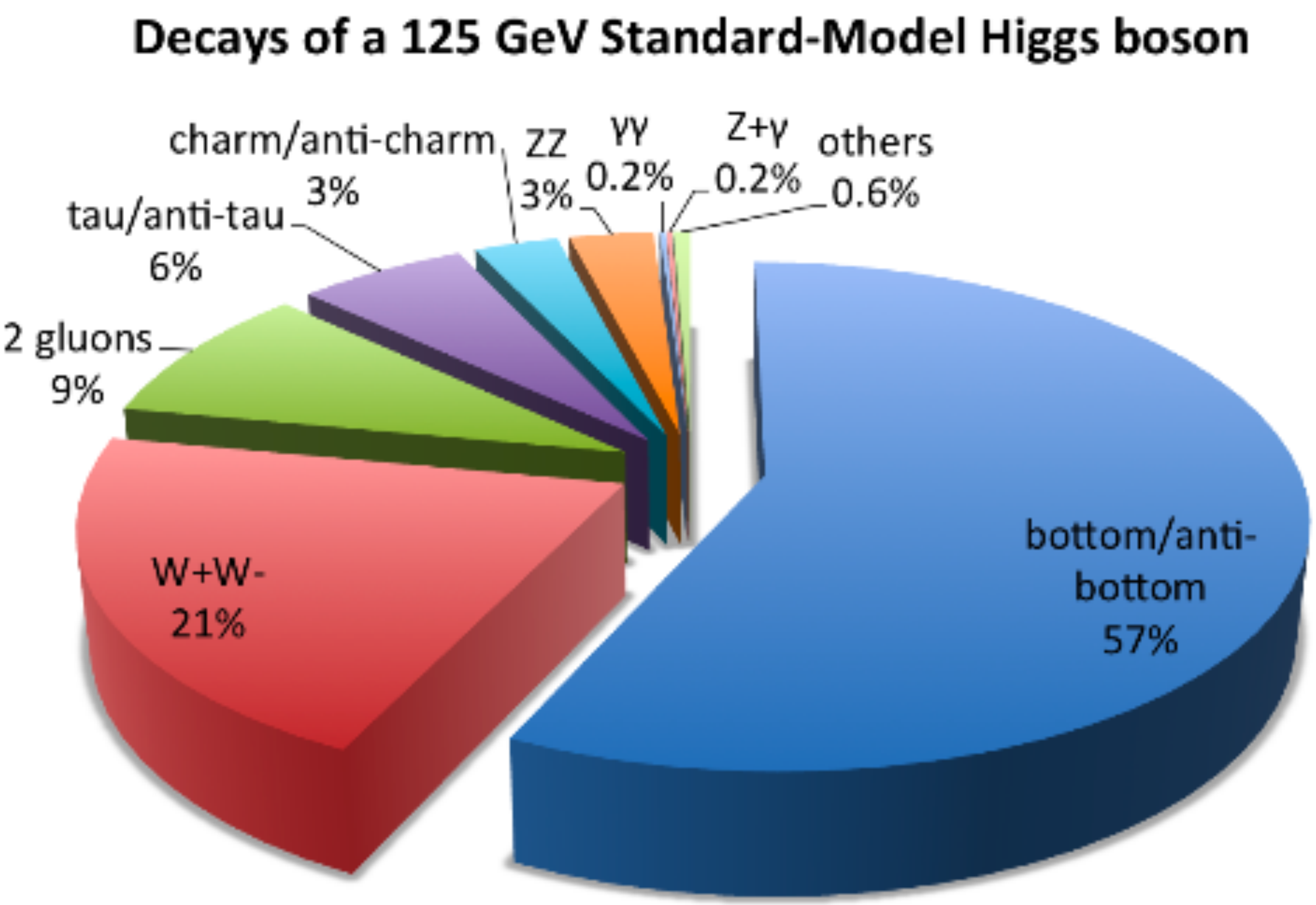
The **top quark mass**, 173 GeV, is l**arger than the weak boson masses**, 80 GeV and 91 GeV, therefore the Higgs coupling to tops is larger and the gluon-fusion process is more likely to happen

Higgs boson production



Higgs boson decays

Once produced, the Higgs boson **decays almost instantaneously**



The define a **branching ratio BR** as the likelihood that a particle **decays to a given final state**, normalised to all possible final states

Higgs boson decays

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$$BR(h \to b\bar{b}) = 0.57$$

$$BR(h \to W^+W^-) = 0.21$$

$$BR(h \to \tau^+\tau^-) = 0.21$$

$$BR(h \to \gamma\gamma) = 0.003$$

$$BR(h \to ZZ) = 0.03$$

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The Higgs tends to decay more into particles to which **it couples more strongly** (so with higher mass), but there is also a suppression factor if the decay products **have similar or bigger mass** than the Higgs

From cross-sections to event rates

The **interaction cross-section σ** measures how likely a given scattering reaction is to take place. It is a kind of **effective collision area** and the units are cm^{-2}

The number of Higgs bosons produced at the LHC will be

$$N_h = \mathscr{L}_{\rm int} \times \sigma(pp \to h + X) \times BR(h \to Y)$$

where the **integrated luminosity** measures how many protons are available for scattering in a given period of time

For elementary particles, the **barn** is a more suitable unit for cross-sections

$$1\,{\rm b} = 10^{-24}\,{\rm cm}^2$$

$$1\,{\rm pb} = 10^{-36}\,{\rm cm}^2$$ (picobarn)

$$1\,{\rm fb} = 10^{-39}\,{\rm cm}^2$$ (femtobarn)

Counting Higgs bosons

exercise

Up to 2018, the LHC has accumulated ***L = 150 fb*** of luminosity

Compute the number of Higgs bosons produced in *i) gluon fusion* and *ii) associated production with a W,* and in each case in the *i) diphoton* and *ii) bottom-antibottom* final states