SM and BSM (Part 1)

Koichi Hamaguchi (Tokyo U.)

@The 4th International Iwate Collider School (ICS2025), Iwate, Feb.24-Mar.1, 2025.

IWATE COLLIDER SCHOOL 2025

About me:

Koichi Hamaguchi (濱口幸一)

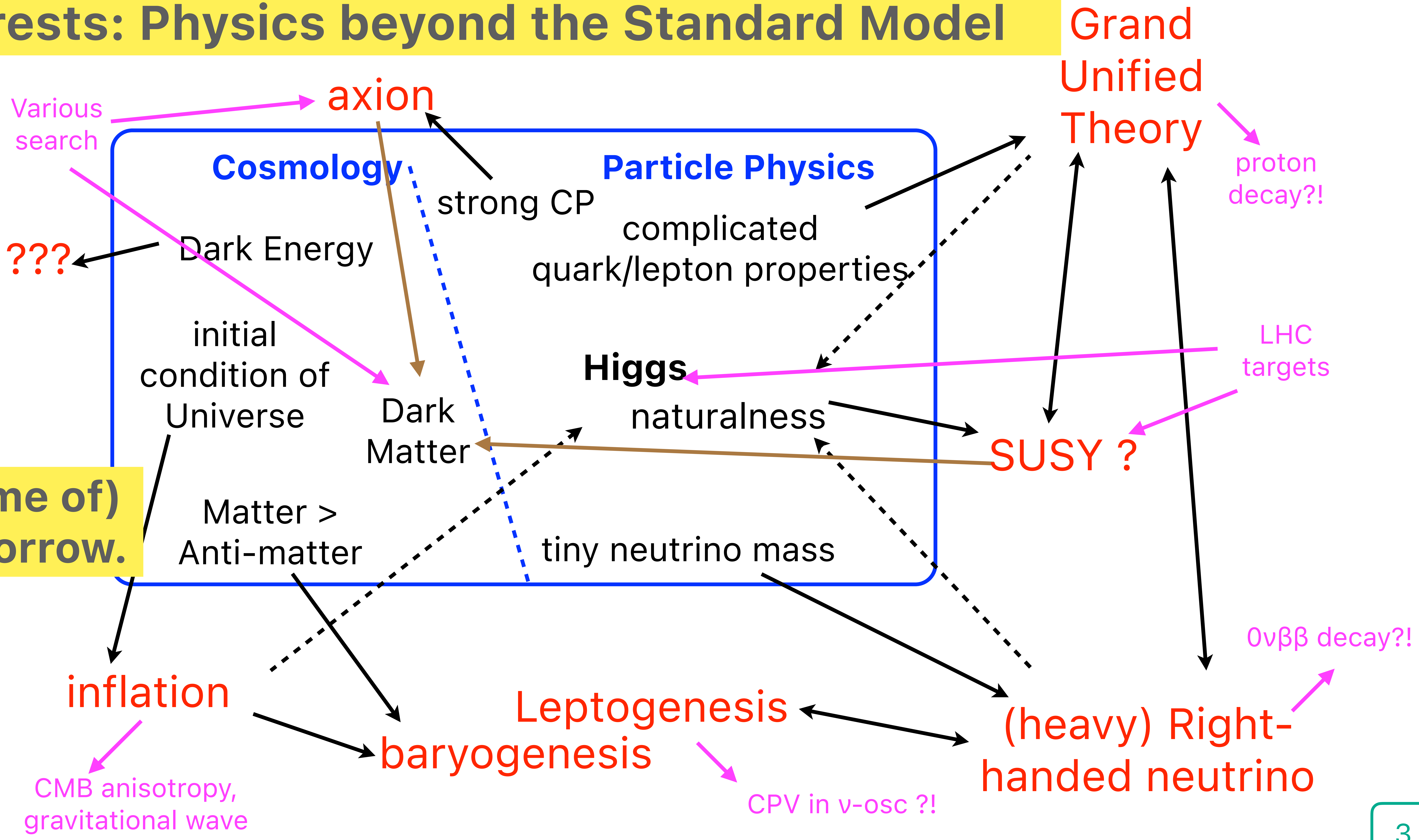
working on theoretical research in particle physics and cosmology.

Research Interests: Physics beyond the Standard Model

Background:

2002	Ph.D., U. of Tokyo
2002-2002	Tohoku U., PD
2002-2004	DESY, PD
2004-2006	DESY, Junior Staff
2006-	U. of Tokyo, Associate Professor

Research Interests: Physics beyond the Standard Model



I'll introduce (some of) these topics tomorrow.

ICS2025 Tutorial; requirements

- Laptop PC (with internet connection)
- Terminal (for shell operation)
- Basic knowledge of shell commands;
  e.g. pwd, mkdir, cd, cp, mv, rm, tar, less, more, …
- python 3.7 (or higher)
- gfortran/gcc 4.6 or higher
- matplotlib (or ROOT) [for MadAnalysis5]
- Mathematica [only for those who want to learn FeynRules]

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• • •

MG5aMC; install other tools

Please also try to install other tools as

- For plots:
  MG5_aMC> install MadAnalysis5
- For parton-shower and hadronization:
  MG5_aMC> install pythia8

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MG5_aMC_v2_9_22 — Python ◂ mg5_aMC — 61×41

```
MG5_aMC>
MG5_aMC>install pythia8
   You are installing 'pythia8', please cite ref(s): arXiv:14
10.3012.
Downloading the HEPToolInstaller at:
```

• • •

```
Command "install pythia8" interrupted with error:
InvalidCmd : Installation of lhapdf6 failed.
MG5_aMC>
```

Looks like I'm not so good at collider physics... in a collider school!
(Maybe one of you can save me after the lecture?)

Please encourage your students/PDs to join the workshop!

Sure!

students/PDs

Fantastic school!

We're doing it again this year.
Please spread the word!

Sure!

students/PDs

Fantastic school!

Lucky them!
I'm jealous!!

I'm glad to hear that they enjoyed.

I'm jealous!

...

I'm jealous!

...

Fine, you're invited this year!

Yay!

Plan

1. **Standard Model** (today) 👉 cf. Hagiwara-san's talk yesterday.
   - Introductory content, with a focus on the Higgs.

     (mainly for undergrad/master's students.)

     (+ homework problem at the end of the lecture.)

2. **BSM (Beyond the Standard Model)** (tomorrow)
   - Broader perspective, including connections to cosmology

Feel free to ask questions at any time during the talk!

Plan

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Elementary particles... the fundamental building blocks of matter.

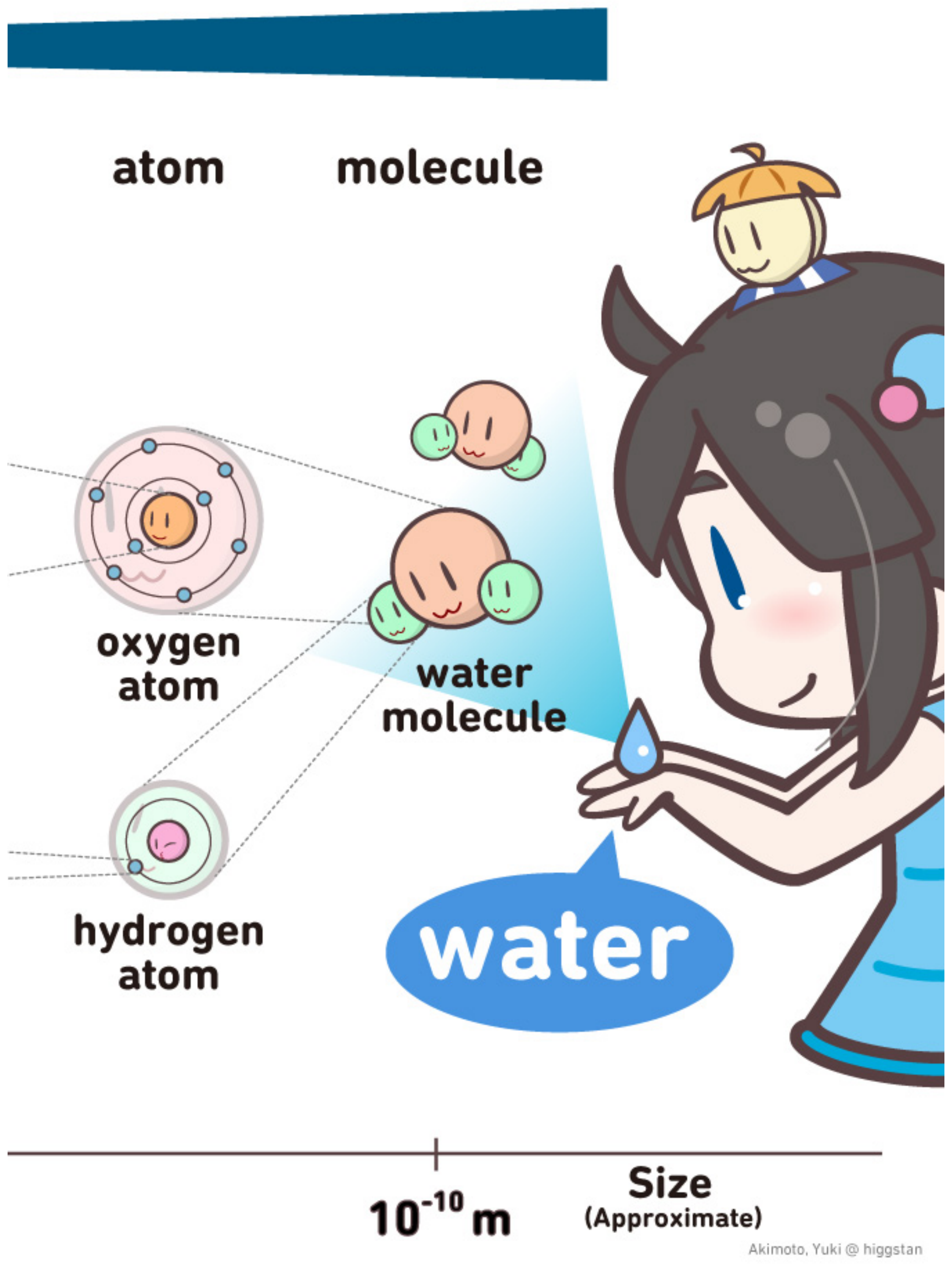
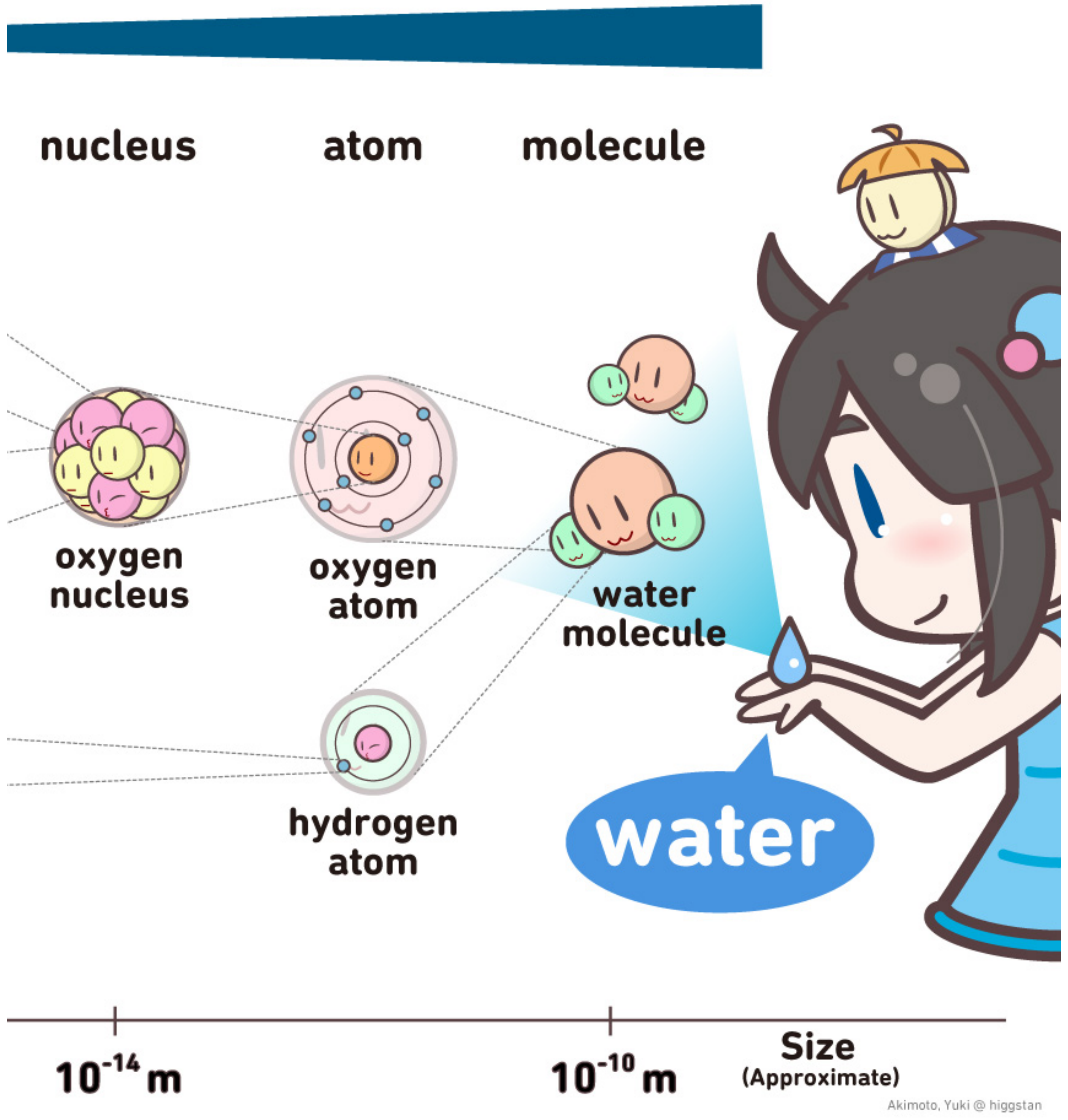


Image from Higgs-tan
https://higgstan.com/

Elementary particles... the fundamental building blocks of matter.



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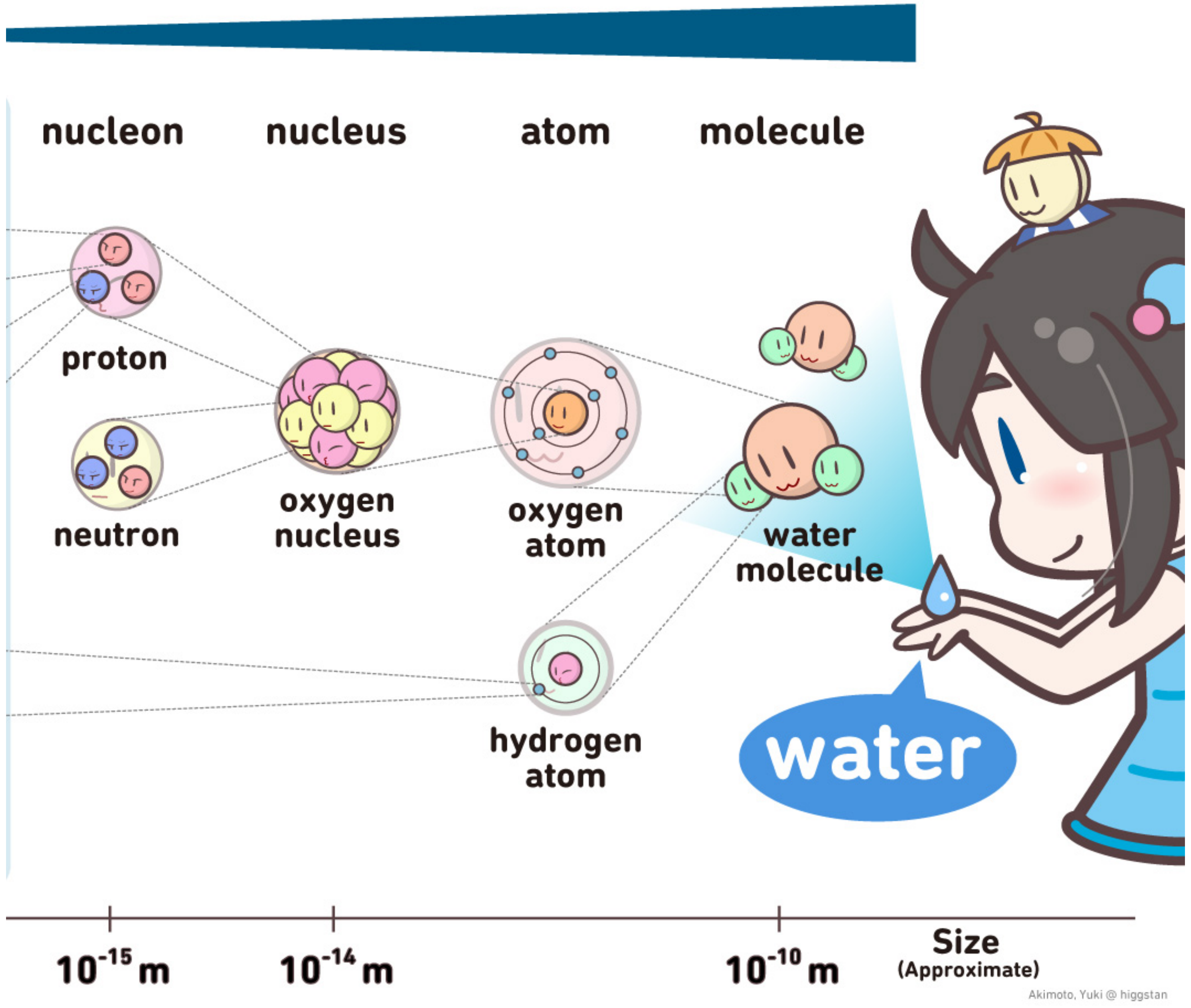

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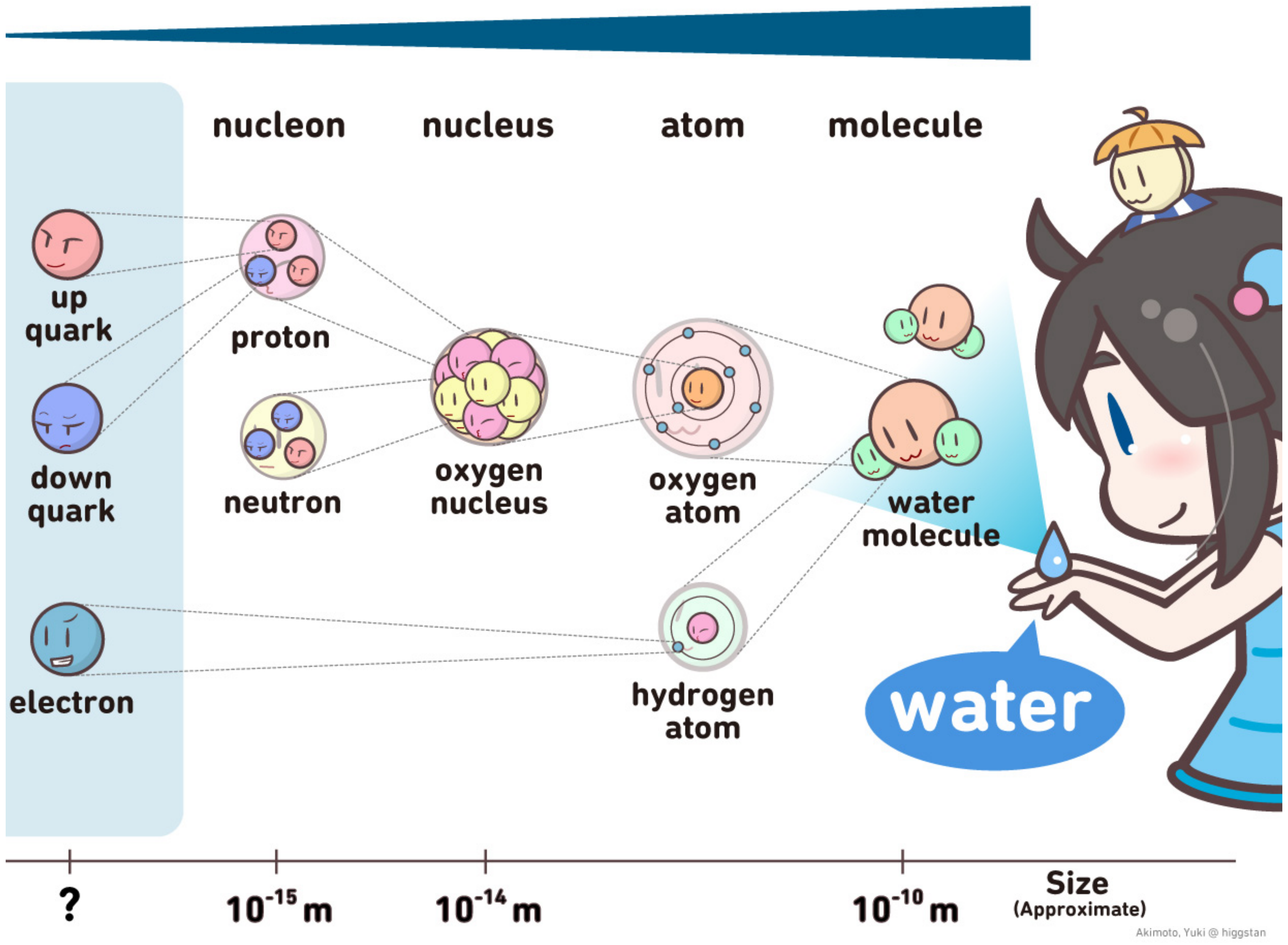

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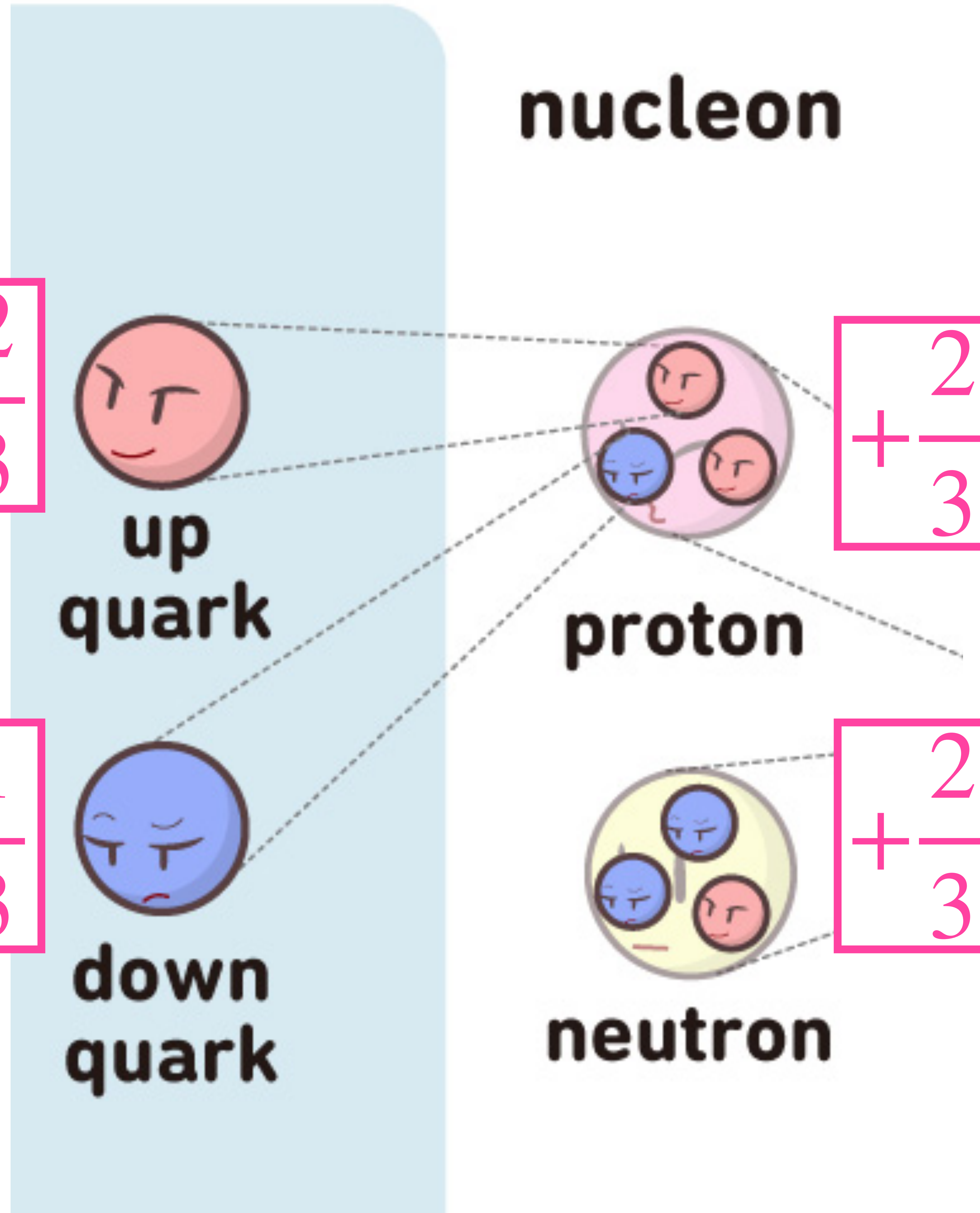
Elementary particles... the fundamental building blocks of matter.

electric charge



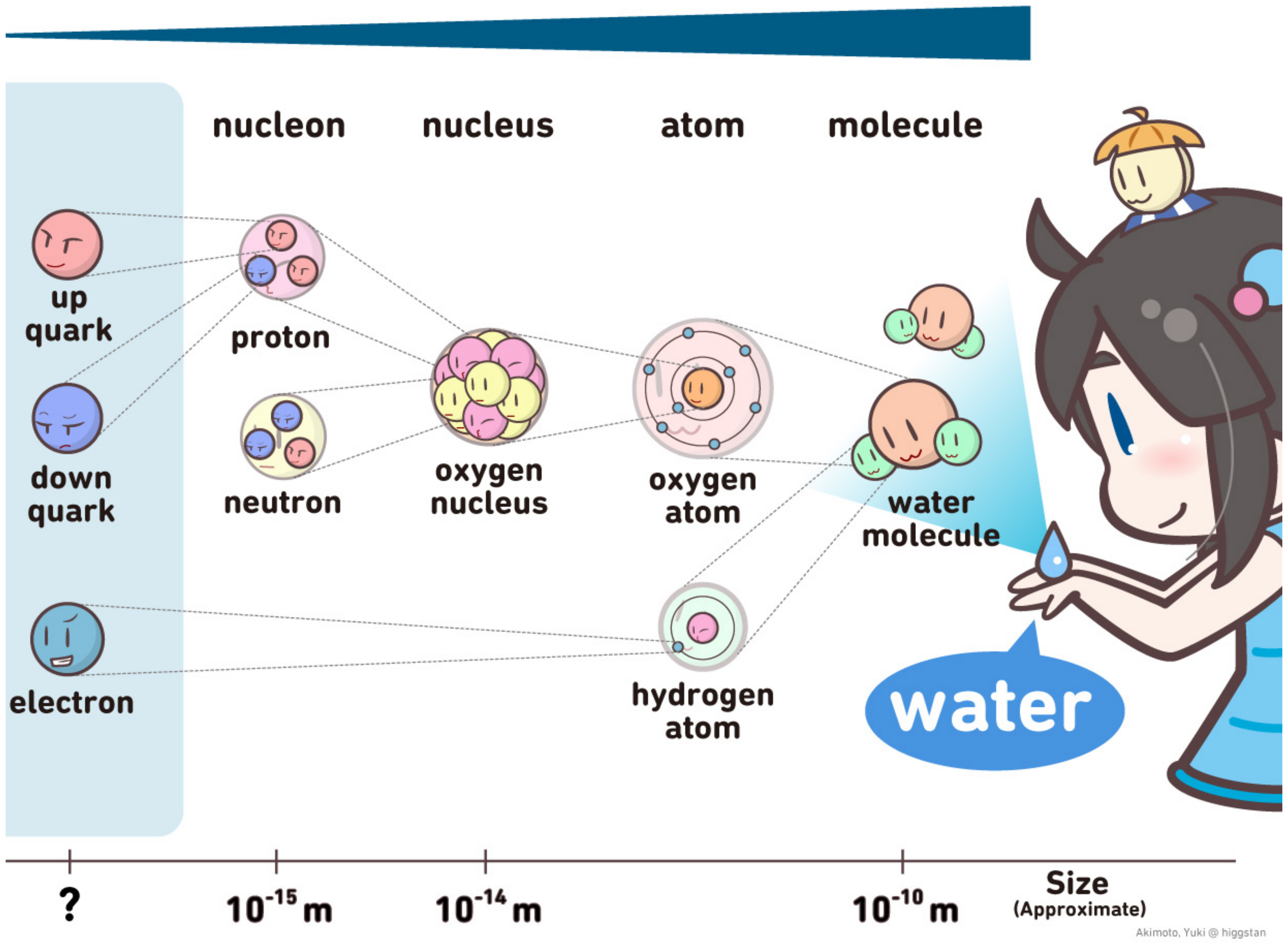
$+\frac{2}{3}$ (up quark)

$-\frac{1}{3}$ (down quark)

$$+\frac{2}{3}+\frac{2}{3}-\frac{1}{3}=+1$$

$$+\frac{2}{3}-\frac{1}{3}-\frac{1}{3}=0$$

Elementary particles... the fundamental building blocks of matter.



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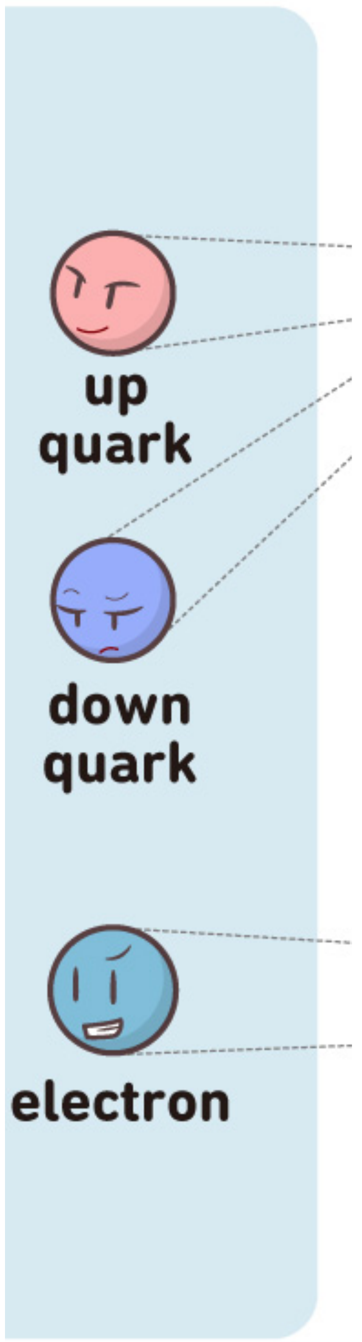

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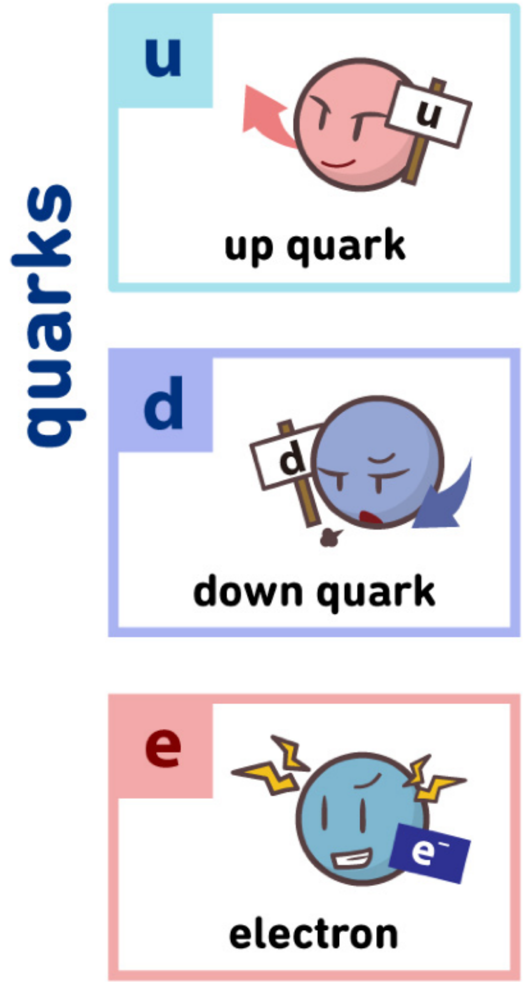

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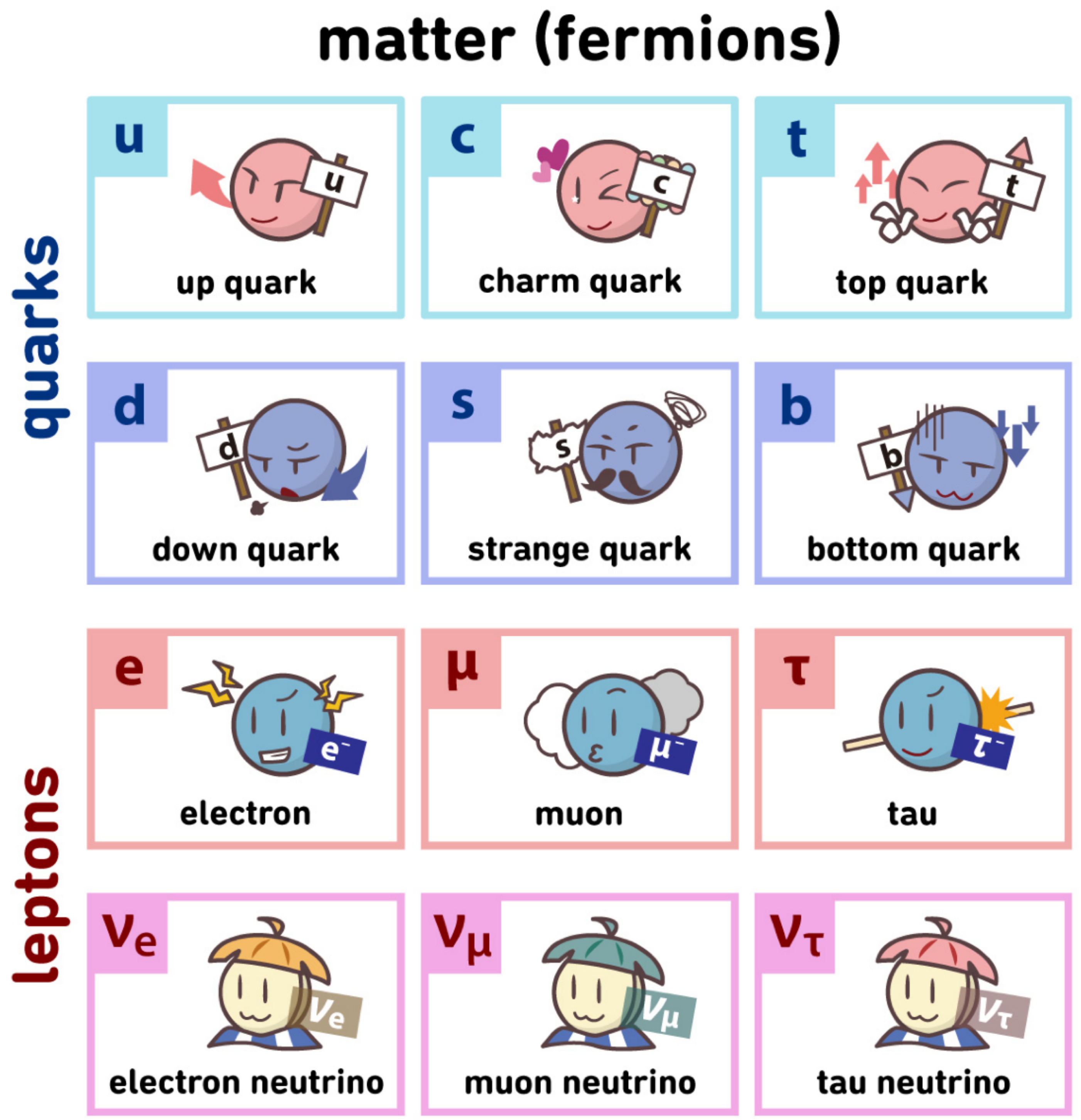
Three generations, or Three flavors



electric charge

$+\frac{2}{3}$

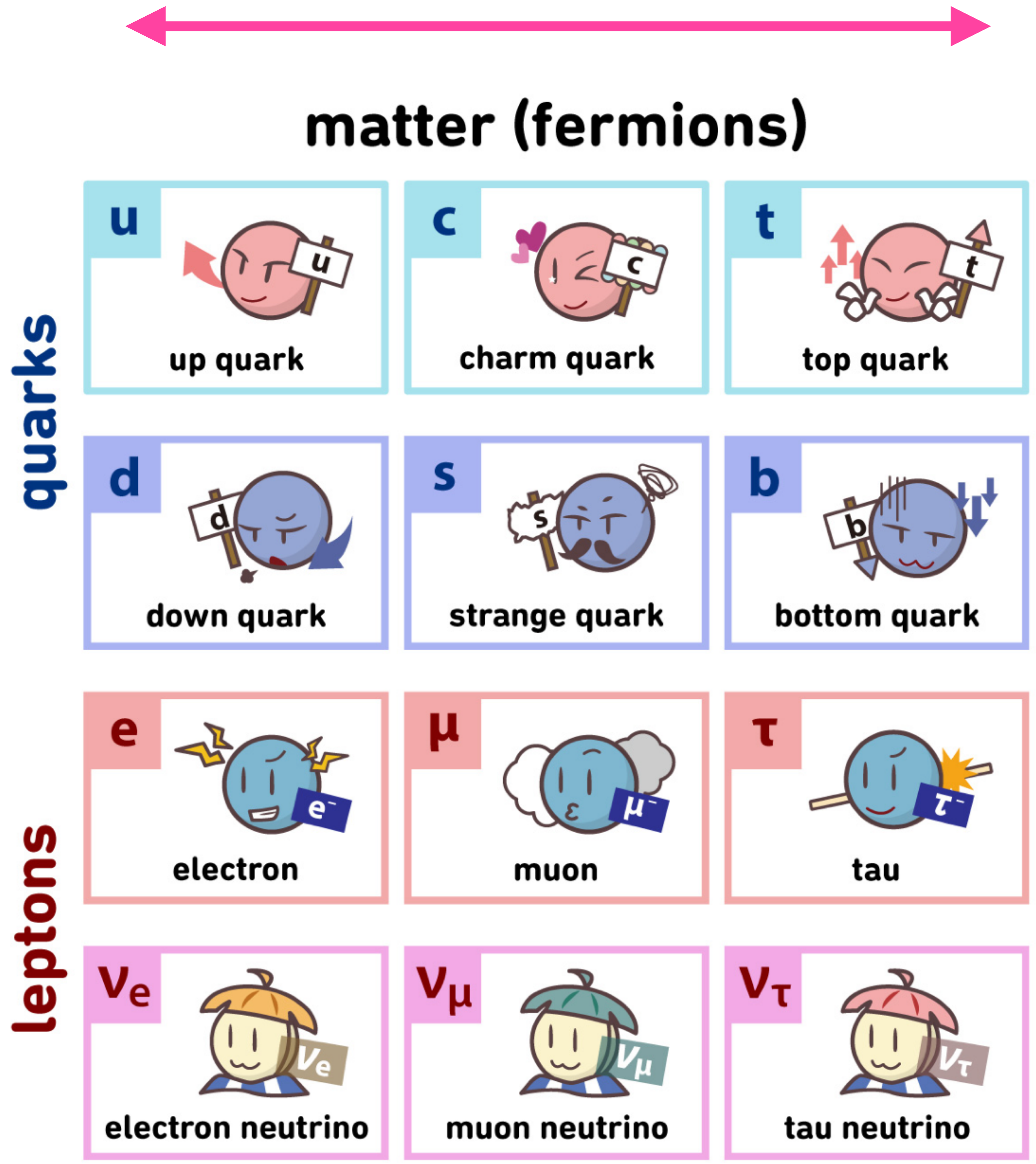
$-\frac{1}{3}$

-1

0

Image from Higgs-tan
https://higgstan.com/

Three generations, or
Three flavors



Why three?

... Nobody knows.

This is one of the puzzles in the SM.
(We won't go into this further in this lecture.)

Image from Higgs-tan
https://higgstan.com/

Standard Model ... the currently established theory of elementary particles.

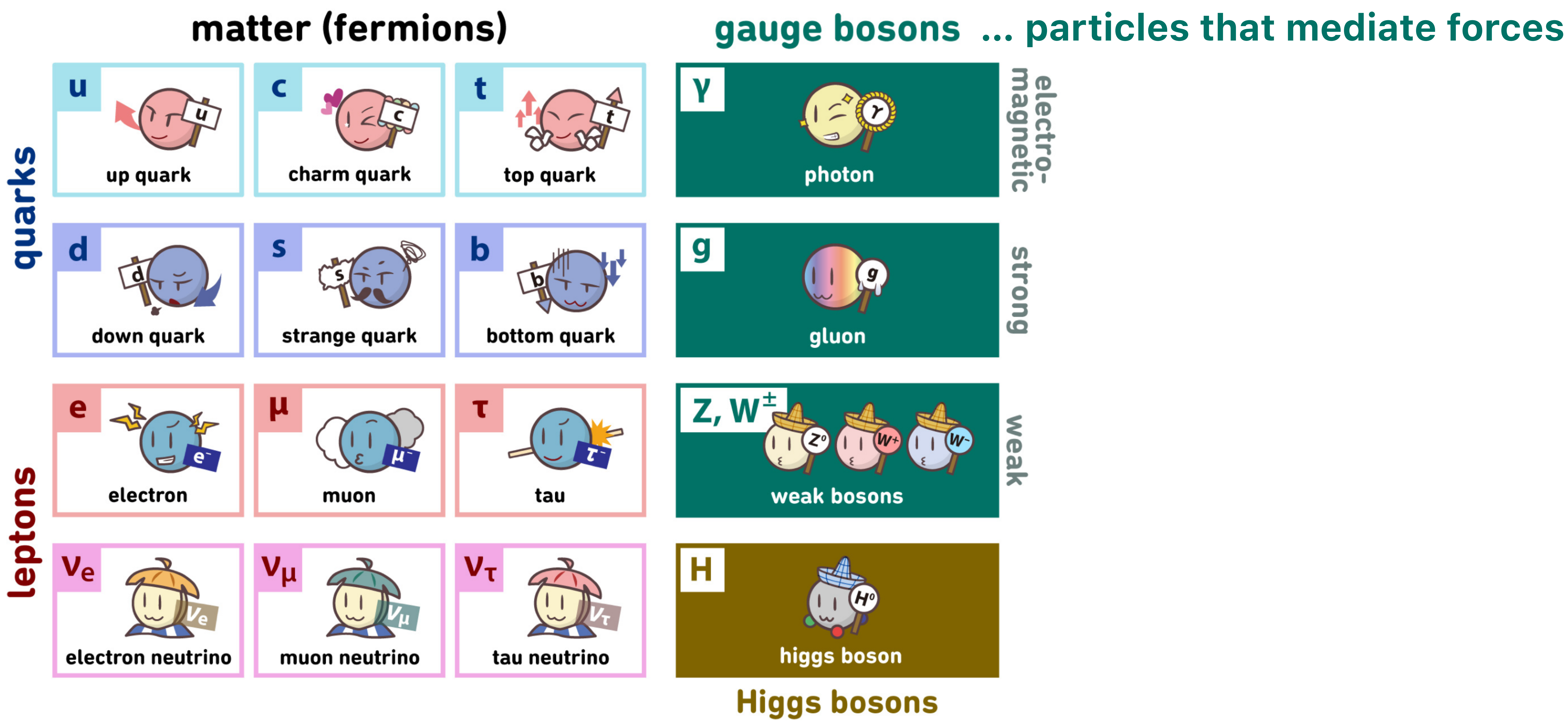
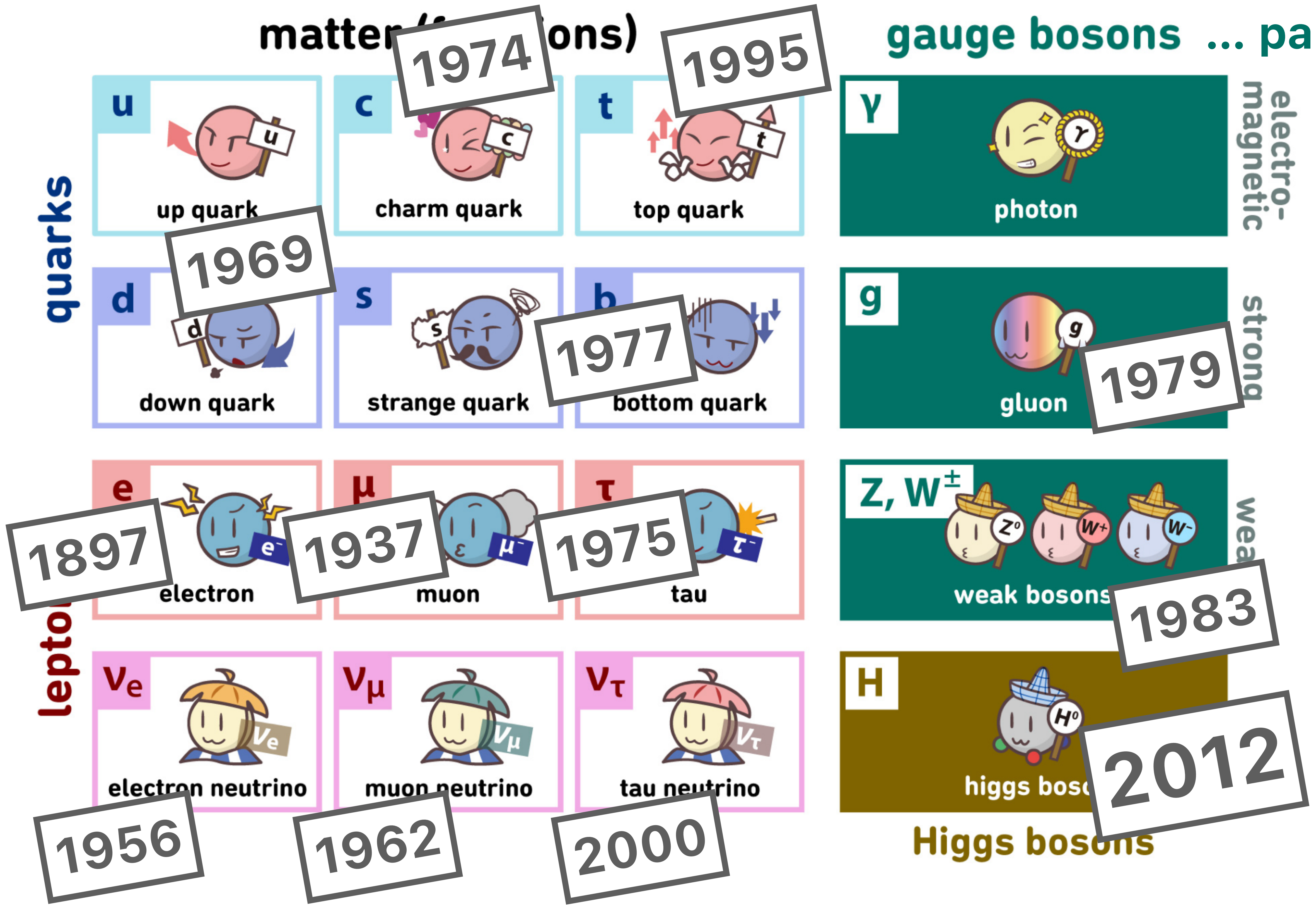


Image from Higgs-tan
https://higgstan.com/

Years of discovery



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mass comparison

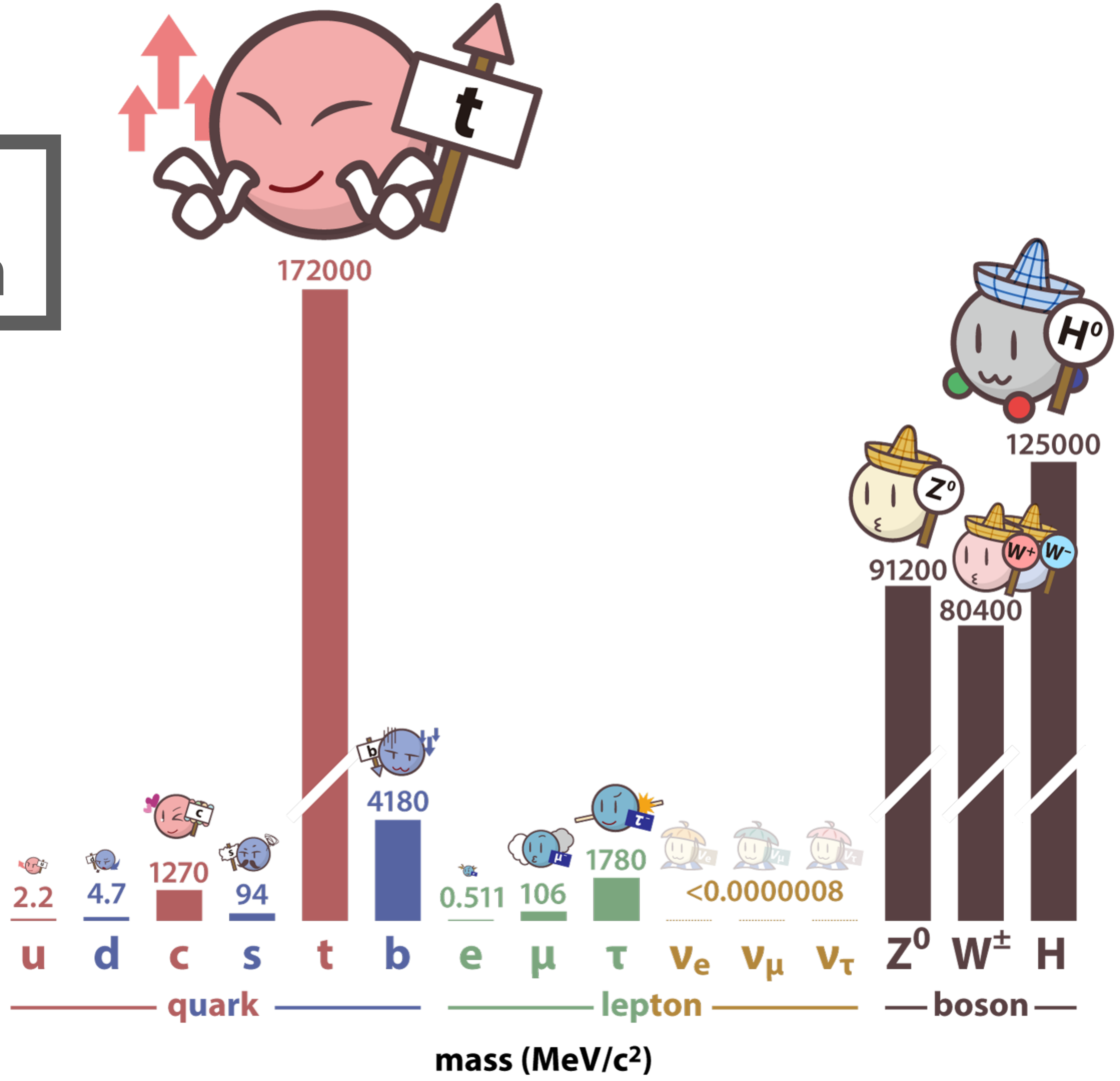

Image from Higgs-tan
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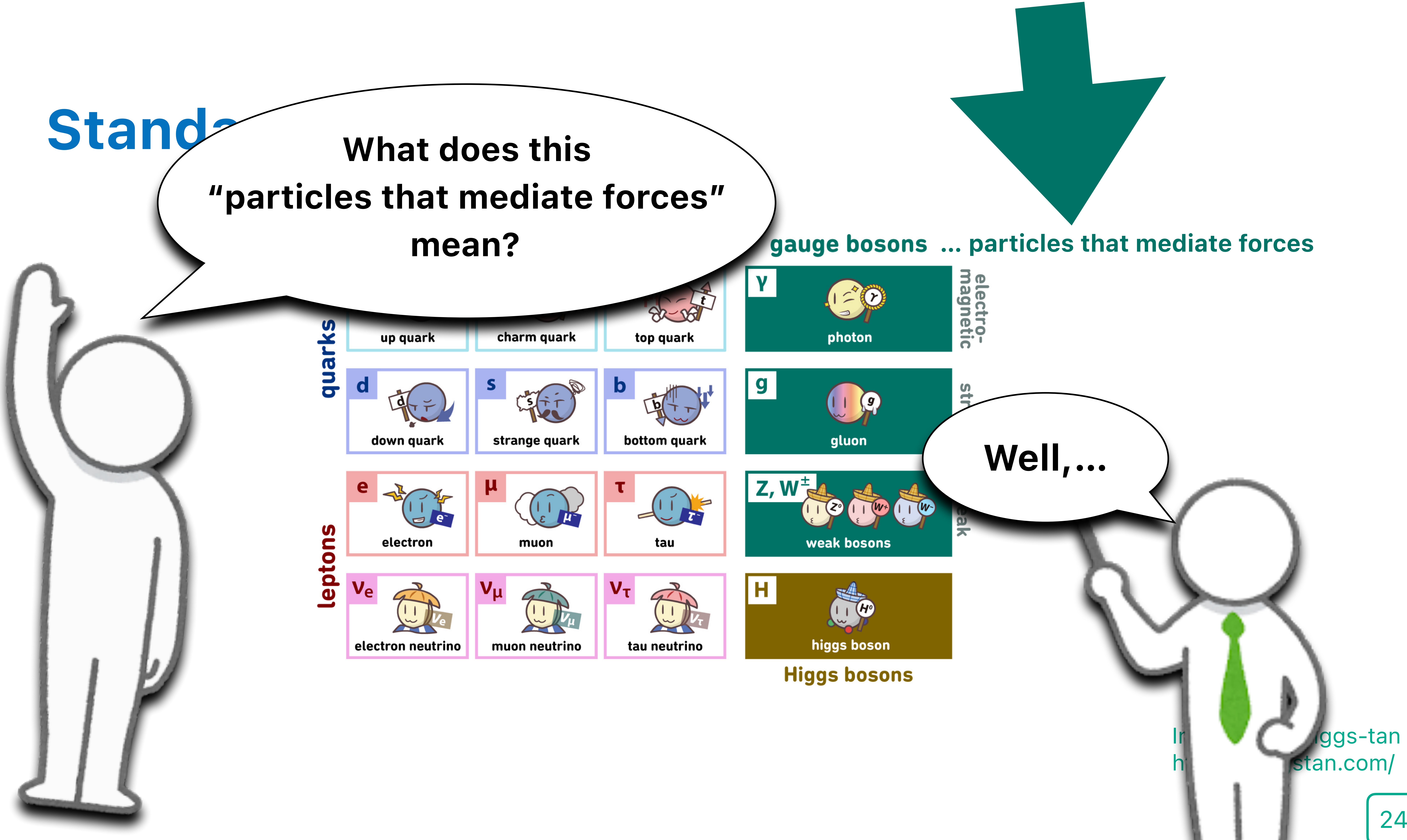
Standa


What does this "particles that mediate forces" mean?
gauge bosons ... particles that mediate forces
quarks
up quark
charm quark
top quark
d
down quark
s
strange quark
b
bottom quark
leptons
e
electron
μ
muon
τ
tau
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
γ
photon
electro-magnetic
g
gluon
Z, $W^\pm$
weak bosons
H
higgs boson
Higgs bosons
Well,...

Interactions (forces) acting on elementary particles

- **Electromagnetic Interaction**
  (Electromagnetic Force)

- **Weak Interaction**
  (Weak Force)

- **Strong Interaction**
  (Strong Force)

- **Gravitational Interaction**
  (Gravitational Force)

Interactions (forces) acting on elementary particles

- Electromagnetic Interaction

For example, negative charges repel each other.

- Weak Interaction

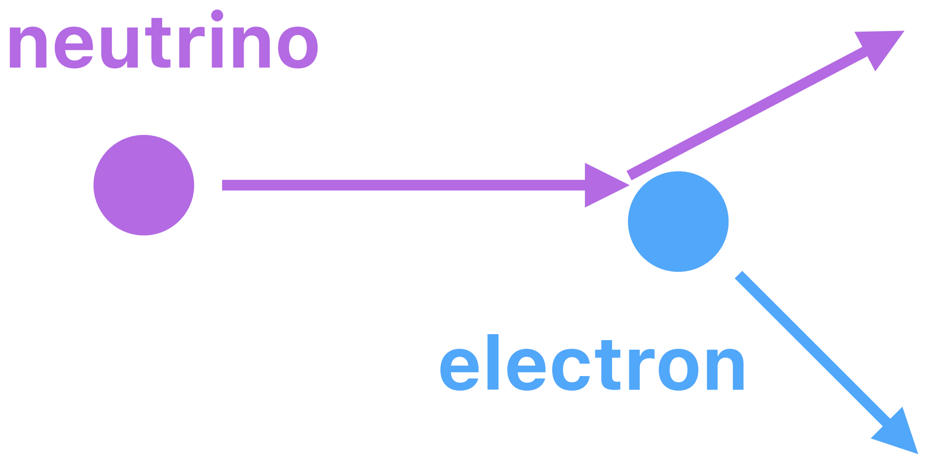
- Strong Interaction

- Gravitational Interaction

Interactions (forces) acting on elementary particles

- Electromagnetic Interaction

- Weak Interaction

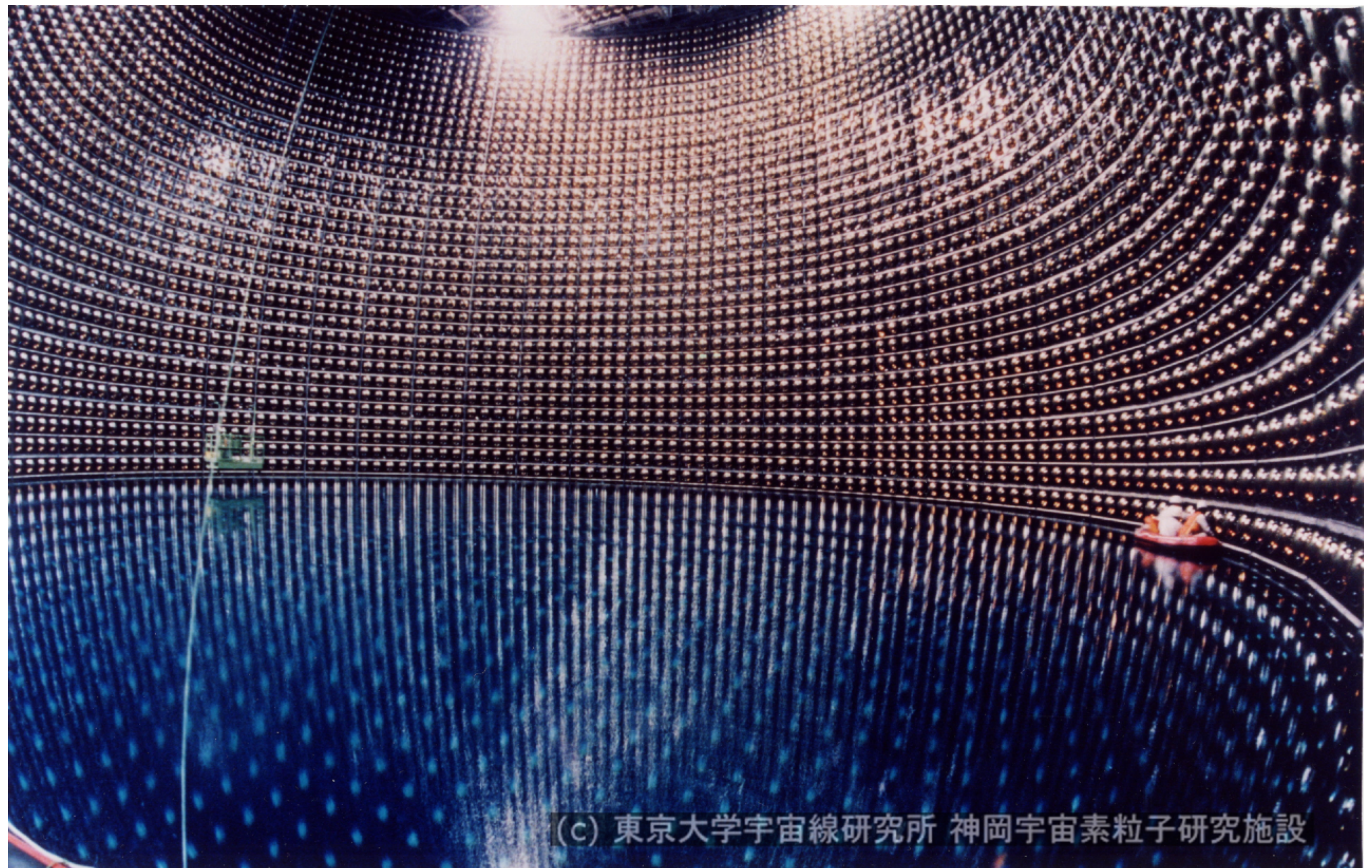


Neutrinos have no electric charge, but can bounce off electrons through the **weak interactions.**

- Strong Interaction

Neutrino experiments such as Kamiokande use scattering from this **weak interaction** to detect neutrinos.

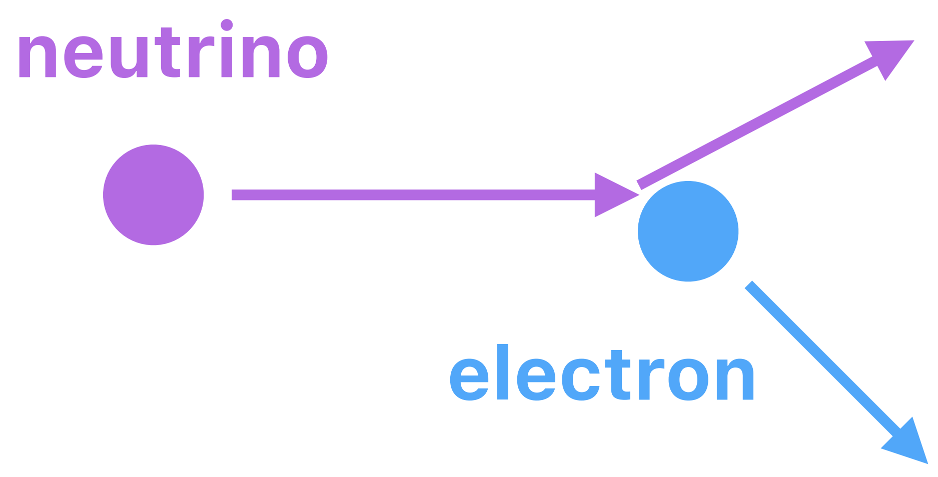
- Gravitational Interaction



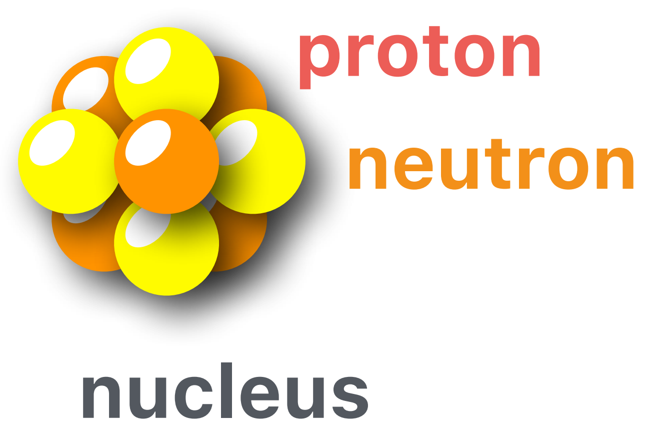
Interactions (forces) acting on elementary particles

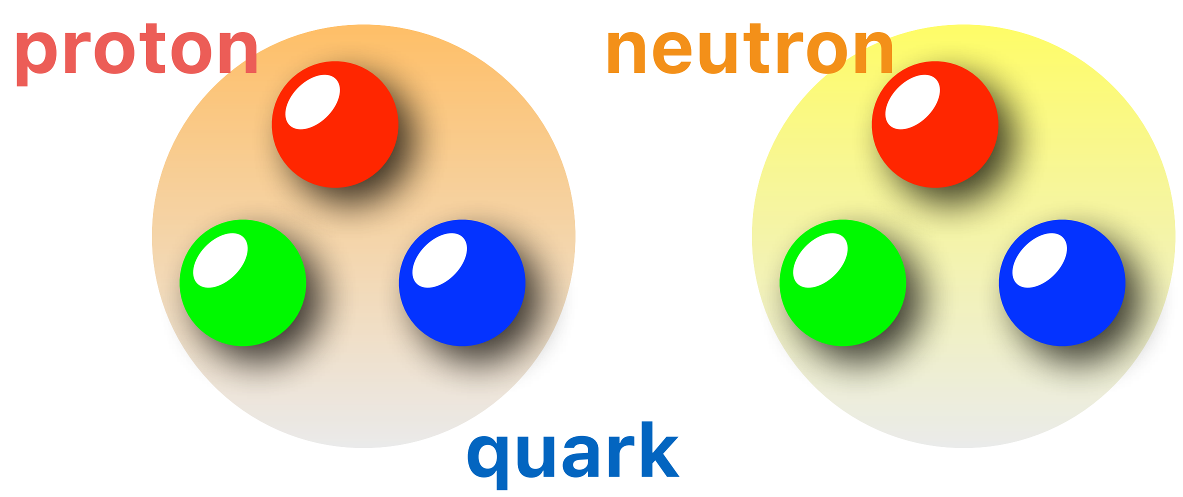
- Electromagnetic Interaction

- Weak Interaction



- **Strong Interaction**





Why don't protons break apart
while they have a positive charge?
→ They are attached by the **strong force.**

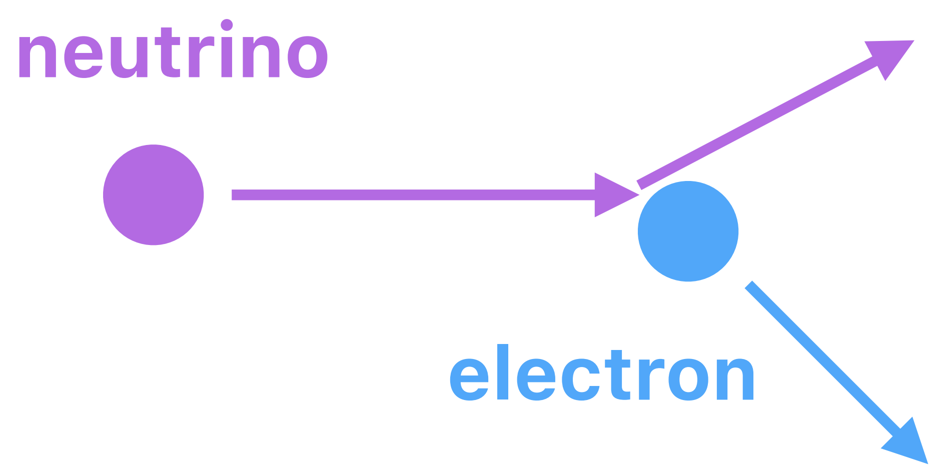
Quarks are trapped inside
protons and neutrons,
due to the **strong force.**
(The force is too strong to get out!)

- Gravitational Interaction

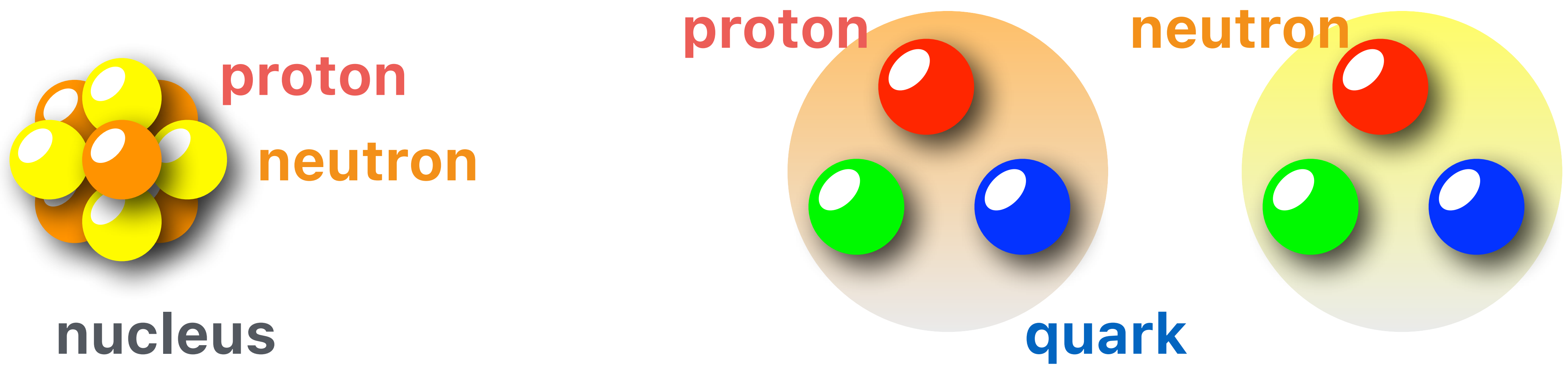
Interactions (forces) acting on elementary particles

- Electromagnetic Interaction

- Weak Interaction



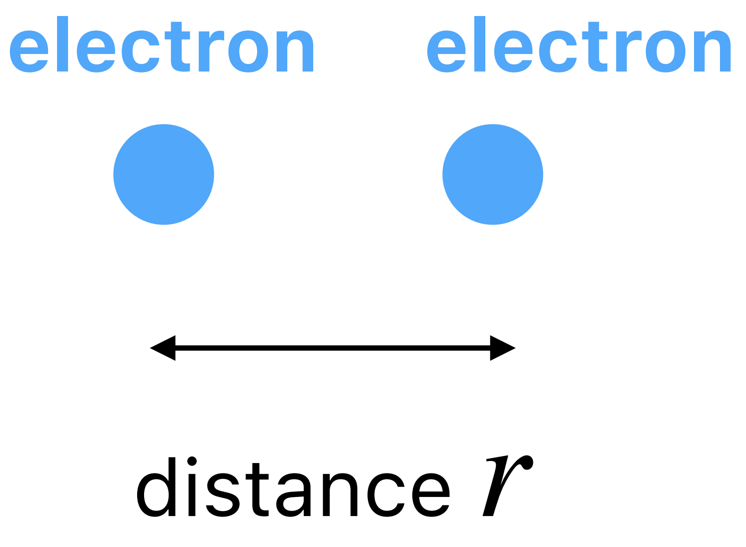
- Strong Interaction



- **Gravitational Interaction**

The most familiar force.
<u>But as a force acting on elementary particles, it is extremely weak!</u>

Gravitational force vs Electromagnetic force



Gravitational force : $F_{\text{grav}} = G\dfrac{m_e^2}{r^2}$ (G :Newton const., m_e :electron mass)

Electromagnetic force : $F_{\text{elec}} = \dfrac{e^2}{4\pi r^2}$ (natural unit, $\dfrac{e^2}{4\pi} \simeq \dfrac{1}{137}$)

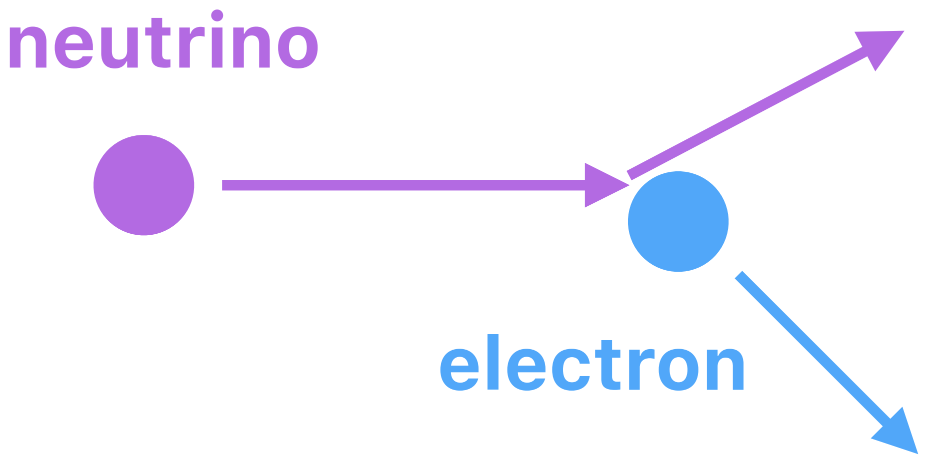
—> taking the ratio, $\dfrac{F_{\text{grav}}}{F_{\text{elec}}} = \dfrac{4\pi G m_e^2}{e^2} = \cdots = 2.4 \times 10^{-43}$

For electrons, gravitational force is weaker than the electric force by this factor!

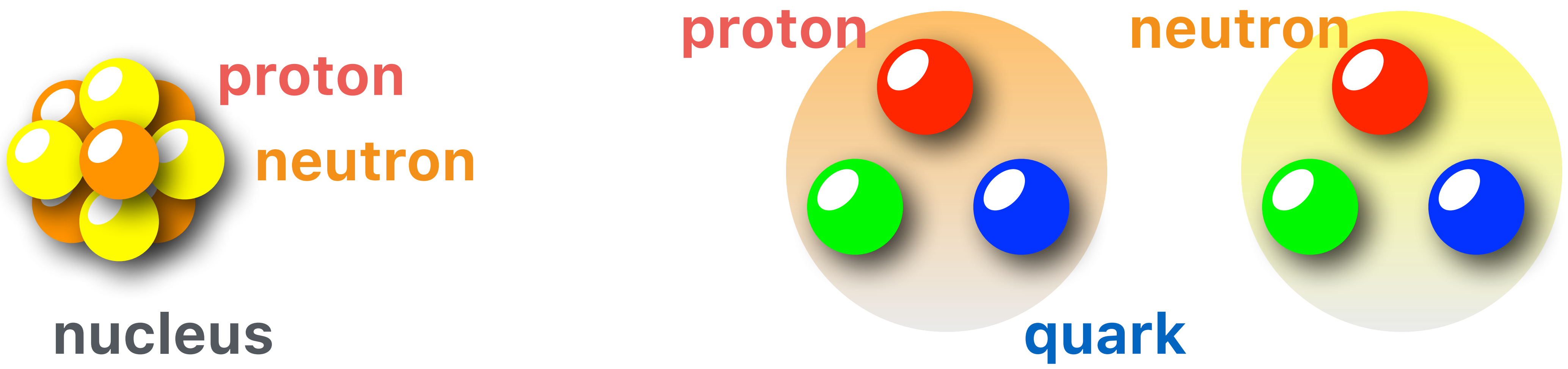
Interactions (forces) acting on elementary particles

- Electromagnetic Interaction

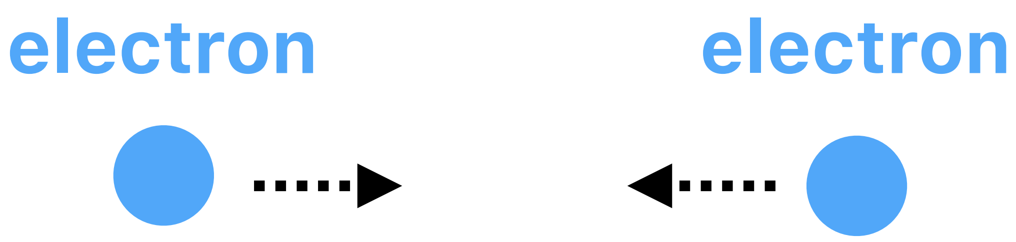
- Weak Interaction



- Strong Interaction



- **Gravitational Interaction**



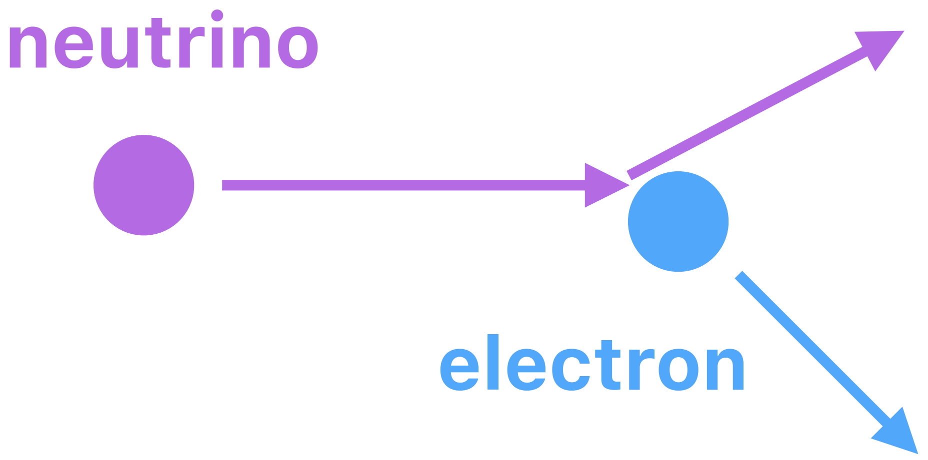
The most familiar force.
<u>But as a force acting on elementary particles, it is extremely weak!</u>

And, unlike other interactions, the **quantum description** is incomplete.
(...I won't go any further on gravity in this lecture.)

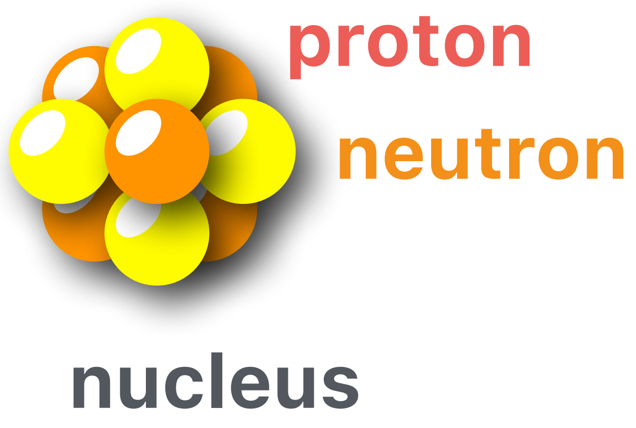
Interactions (forces) acting on elementary particles

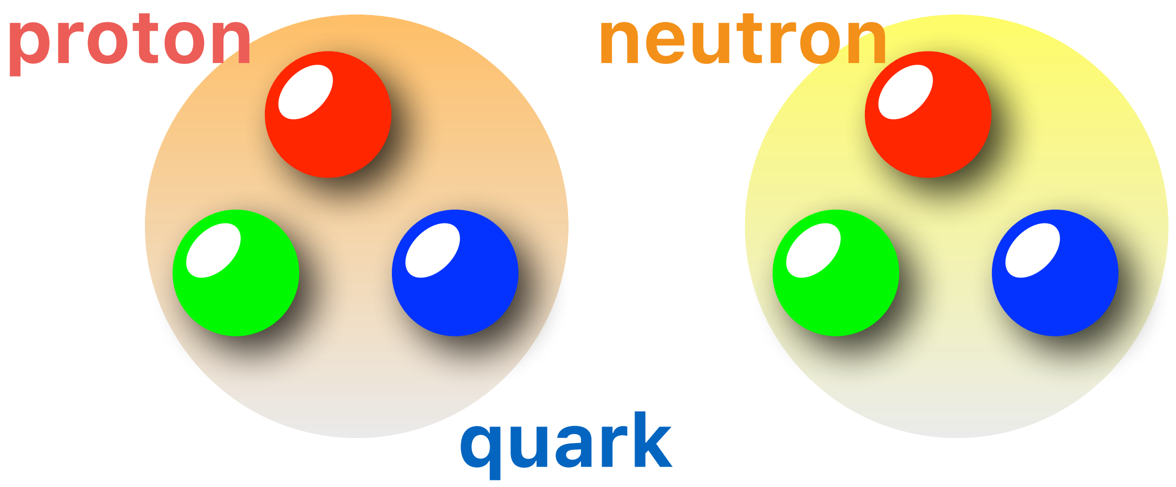
- Electromagnetic Interaction

- Weak Interaction



- Strong Interaction

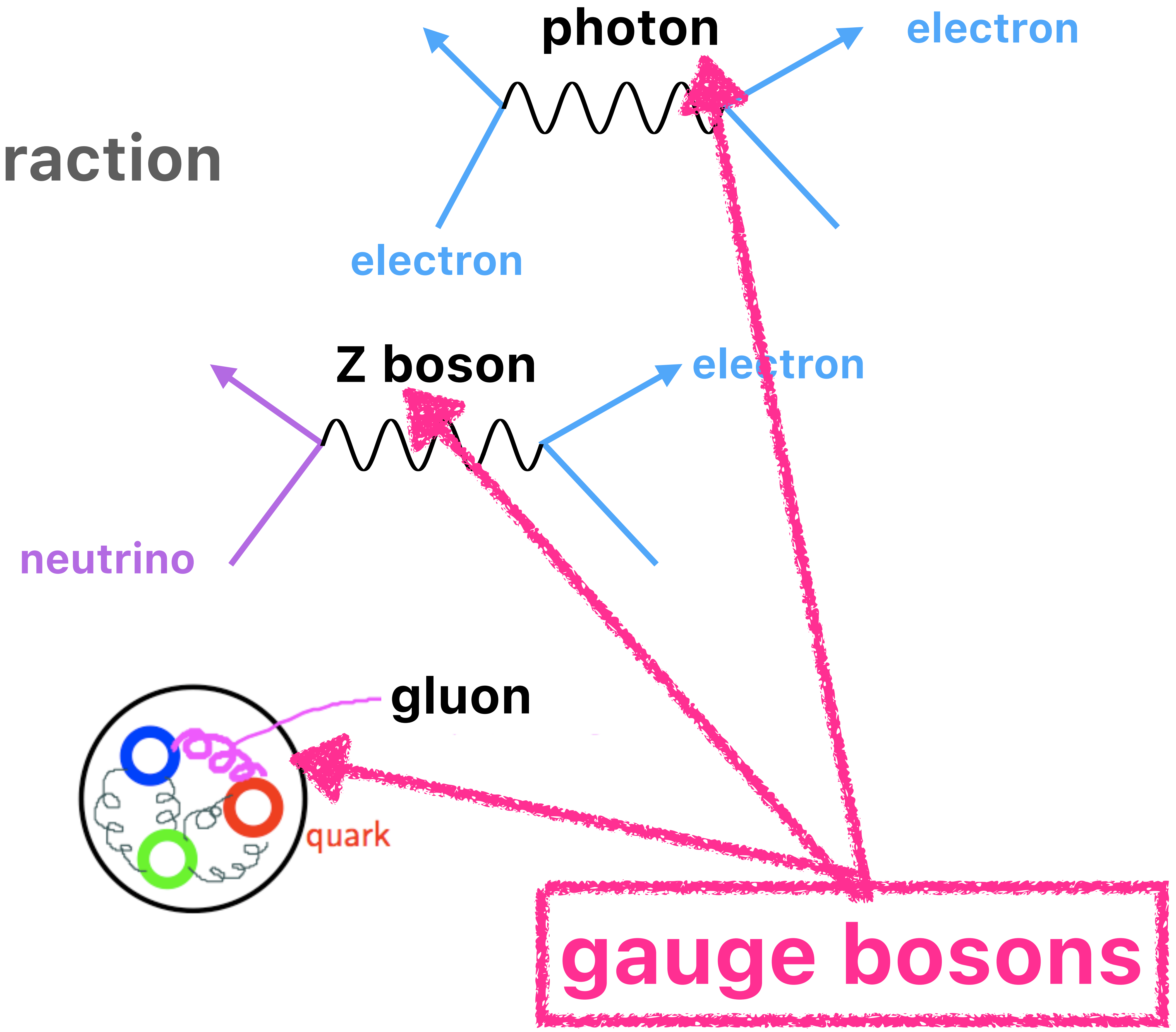




Interactions (forces) between elementary particles are also mediated by elementary particles.

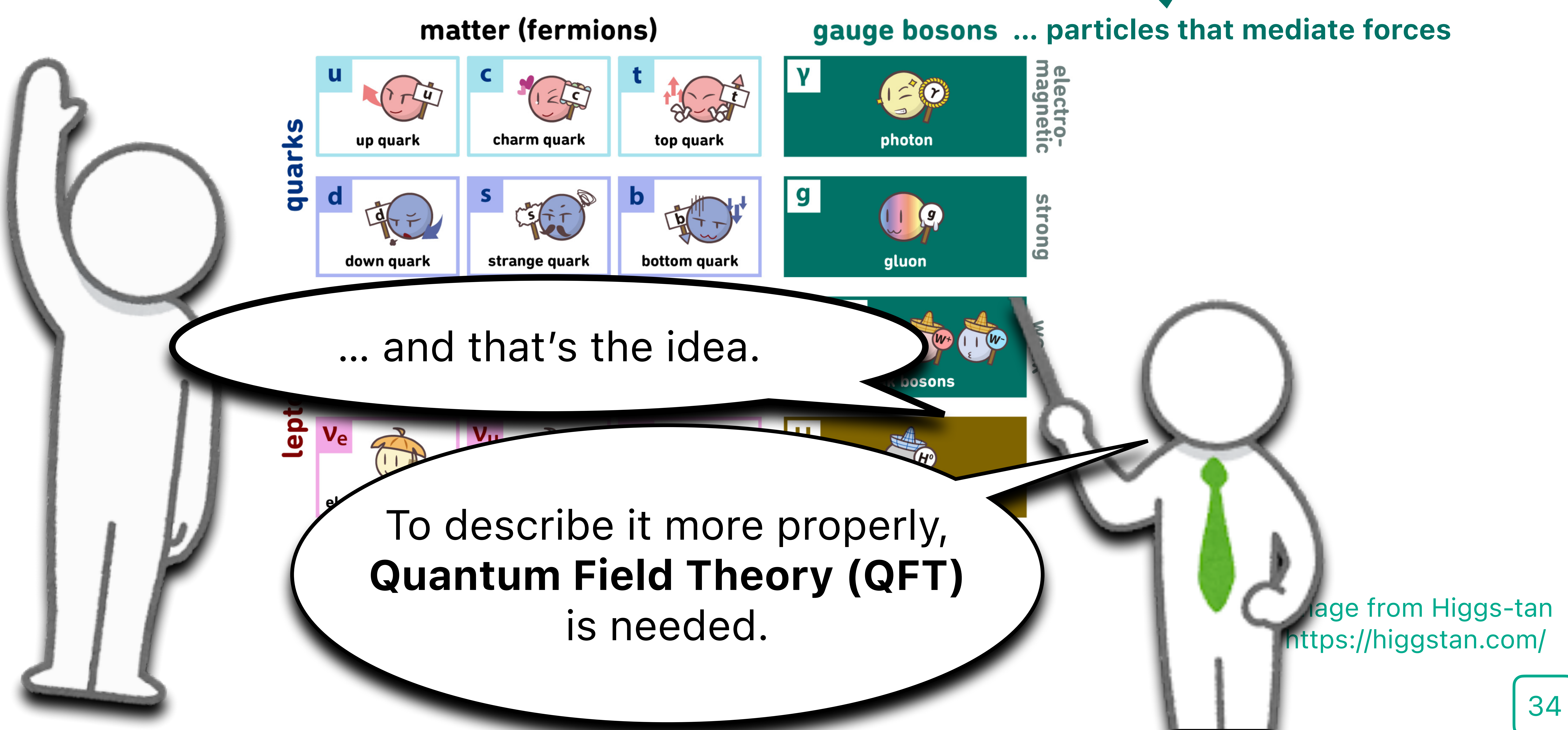
Interactions (forces) between elementary particles are also mediated by elementary particles.

- Electromagnetic Interaction
- Weak Interaction
- Strong Interaction

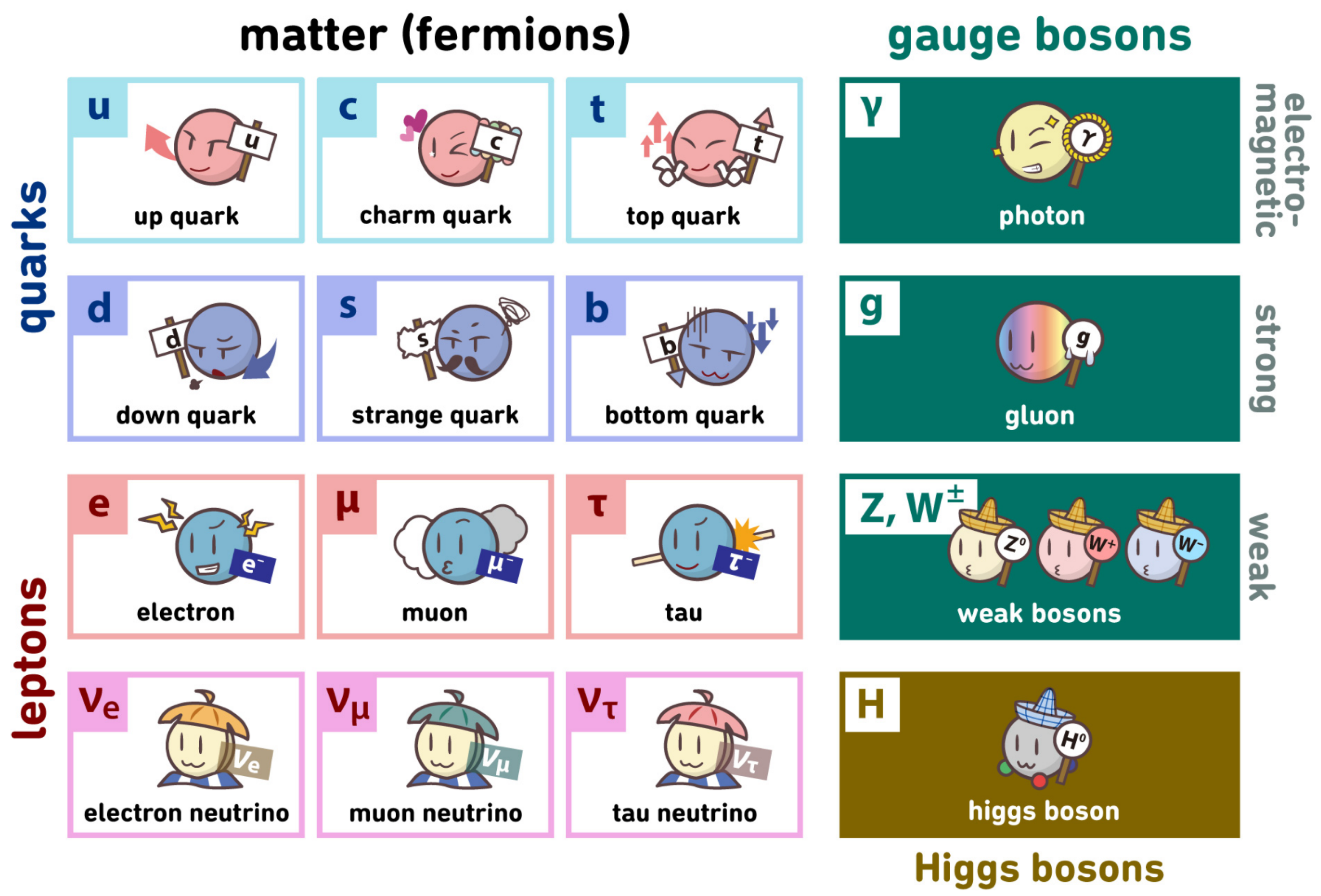


The three interactions (forces) are
gauge interactions mediated by **gauge bosons.**

Standard Model



Standard Model

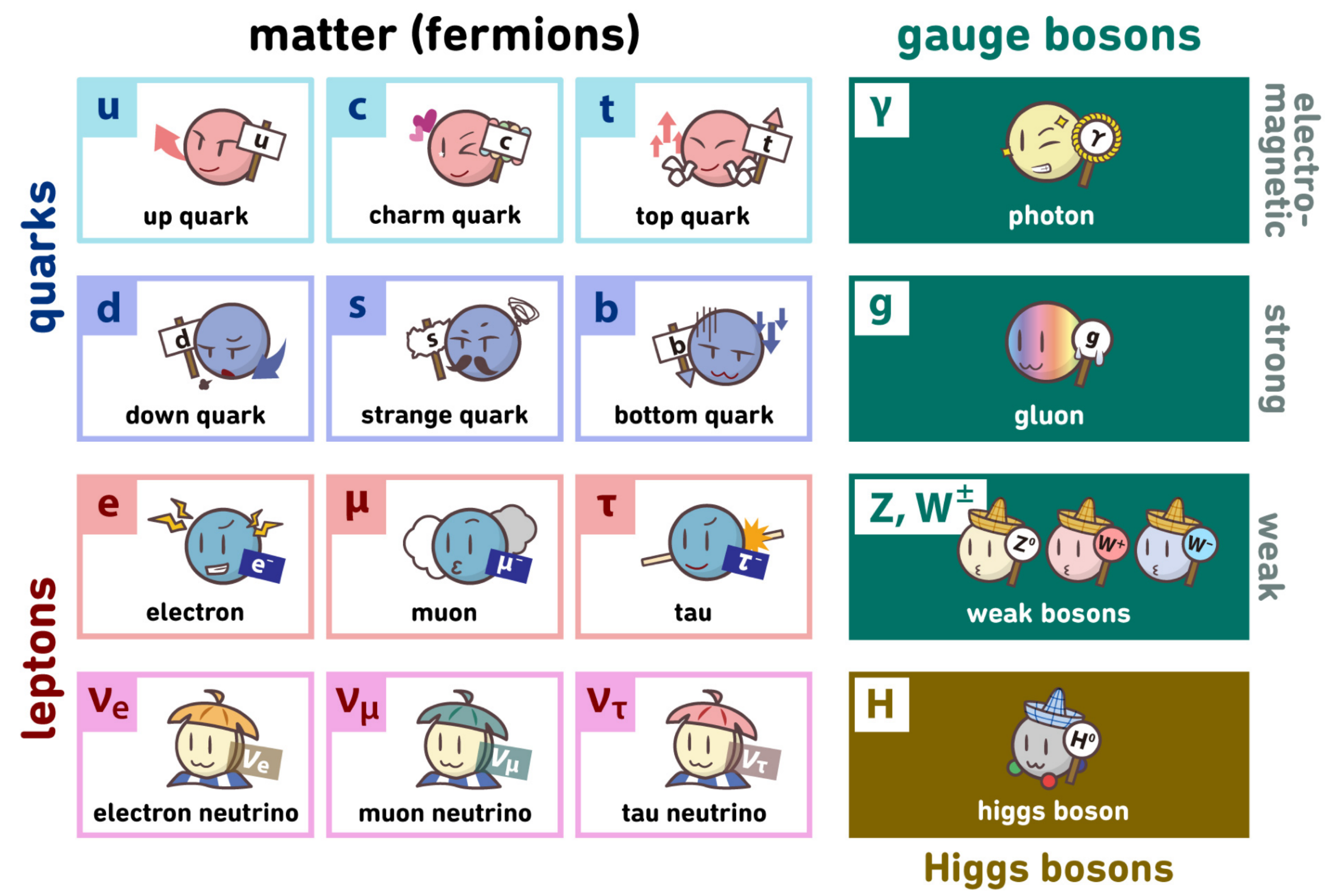


$\mathscr{L} = -\sum \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu}$	… gauge fields
$+ \sum i\bar{\psi}\gamma^\mu D_\mu \psi$	… matter fields + gauge interactions
$+ \lvert D_\mu \phi \rvert^2 - V(\phi)$	… Higgs fields
$+ \sum y\phi\bar{\psi}\psi + \mathrm{h.c.}$	… Yukawa interactions

These few lines describe countless experimental facts of particle physics with incredible precision.

This is currently the most successful theory in particle physics.

Standard Model



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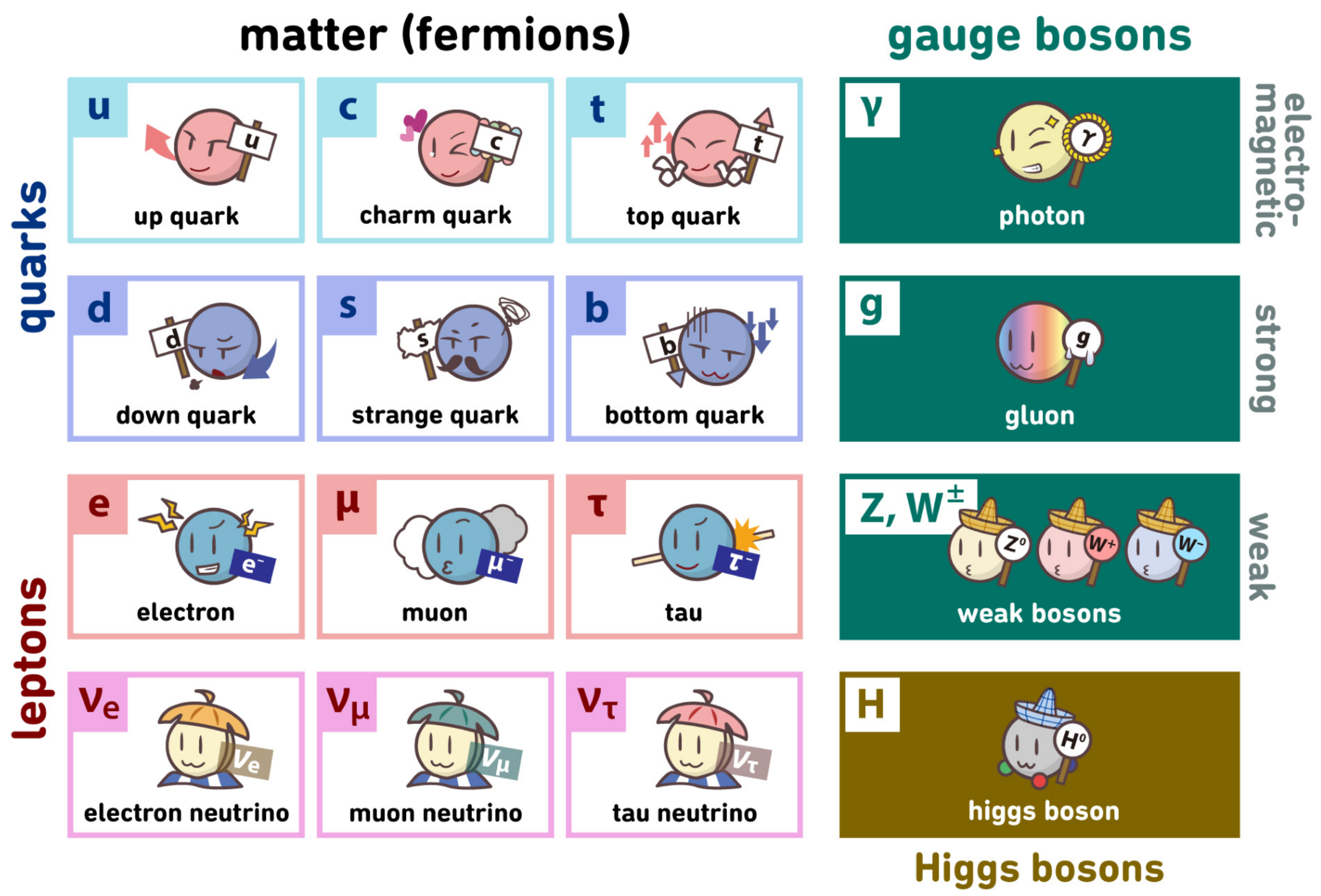
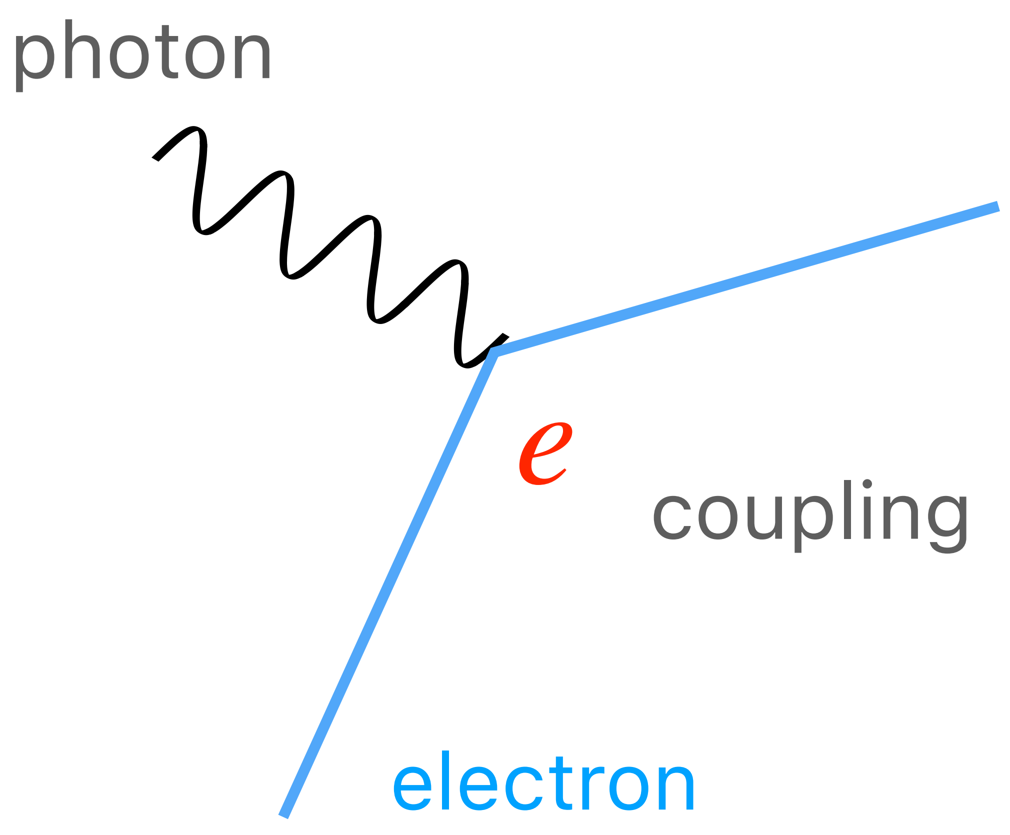
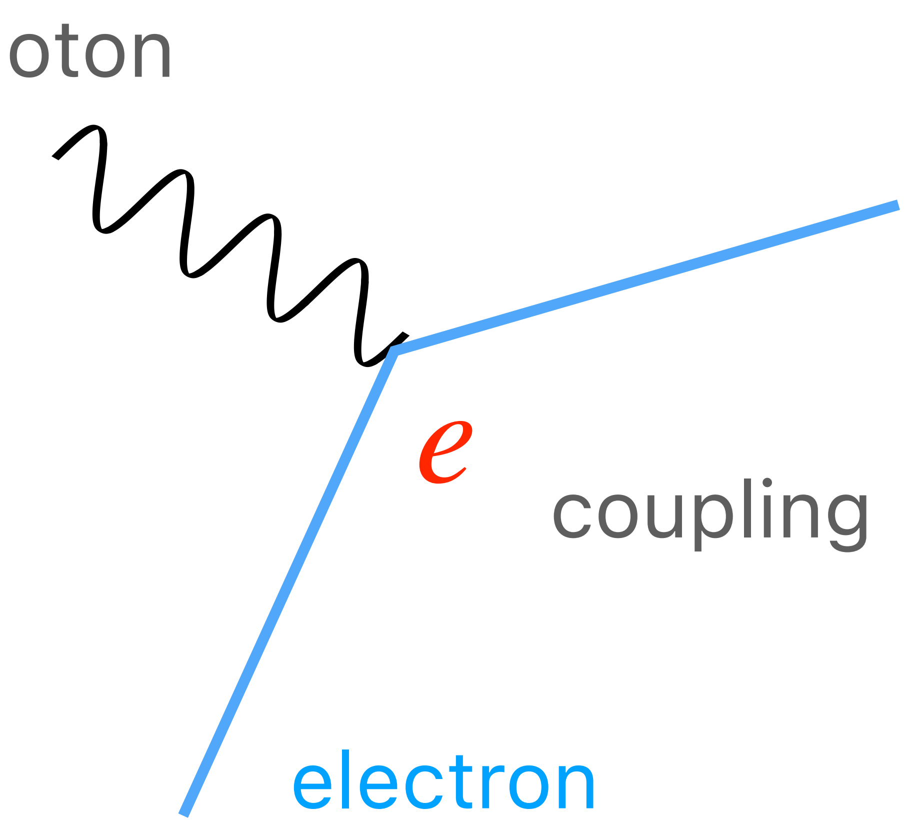


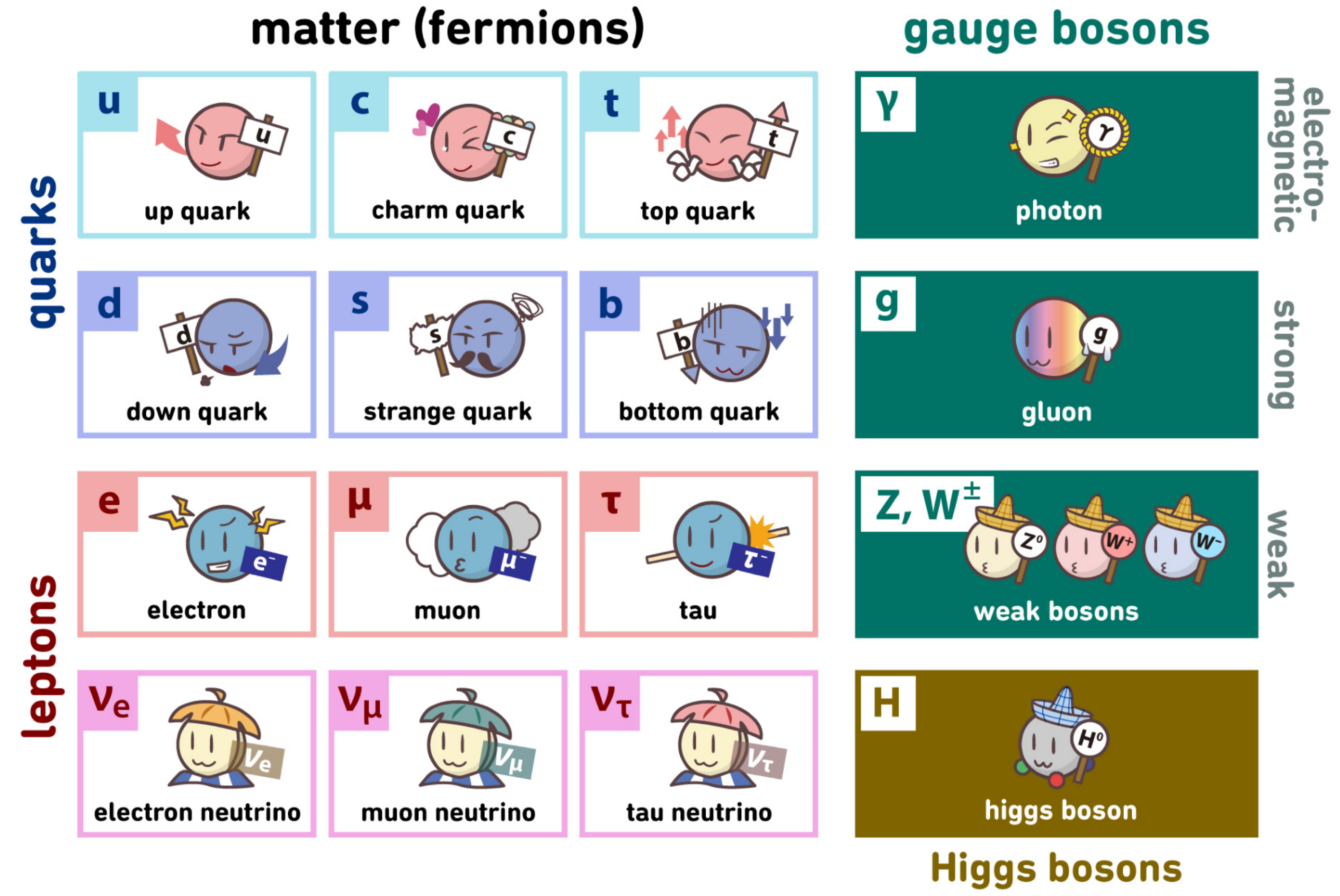
$$+\sum i\bar{\psi}\gamma^{\mu}D_{\mu}\psi \quad \ni \quad e\,A_{\mu}\,\bar{\psi}\gamma^{\mu}\psi$$

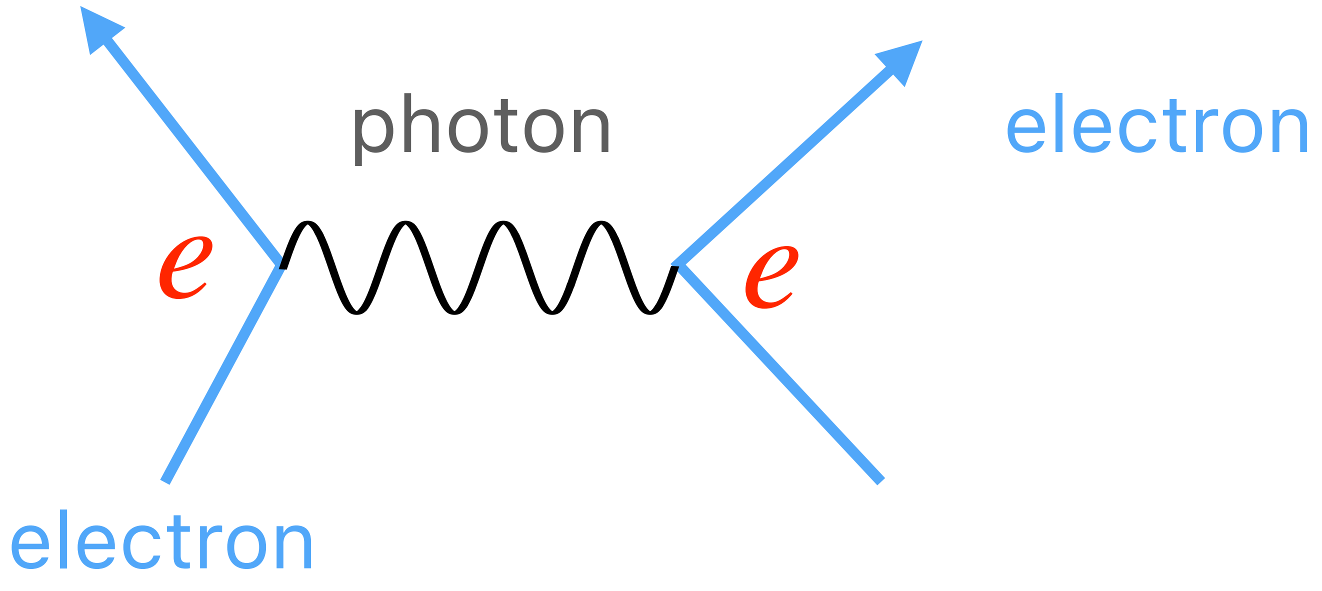


$(e = 0.3028\cdots)$

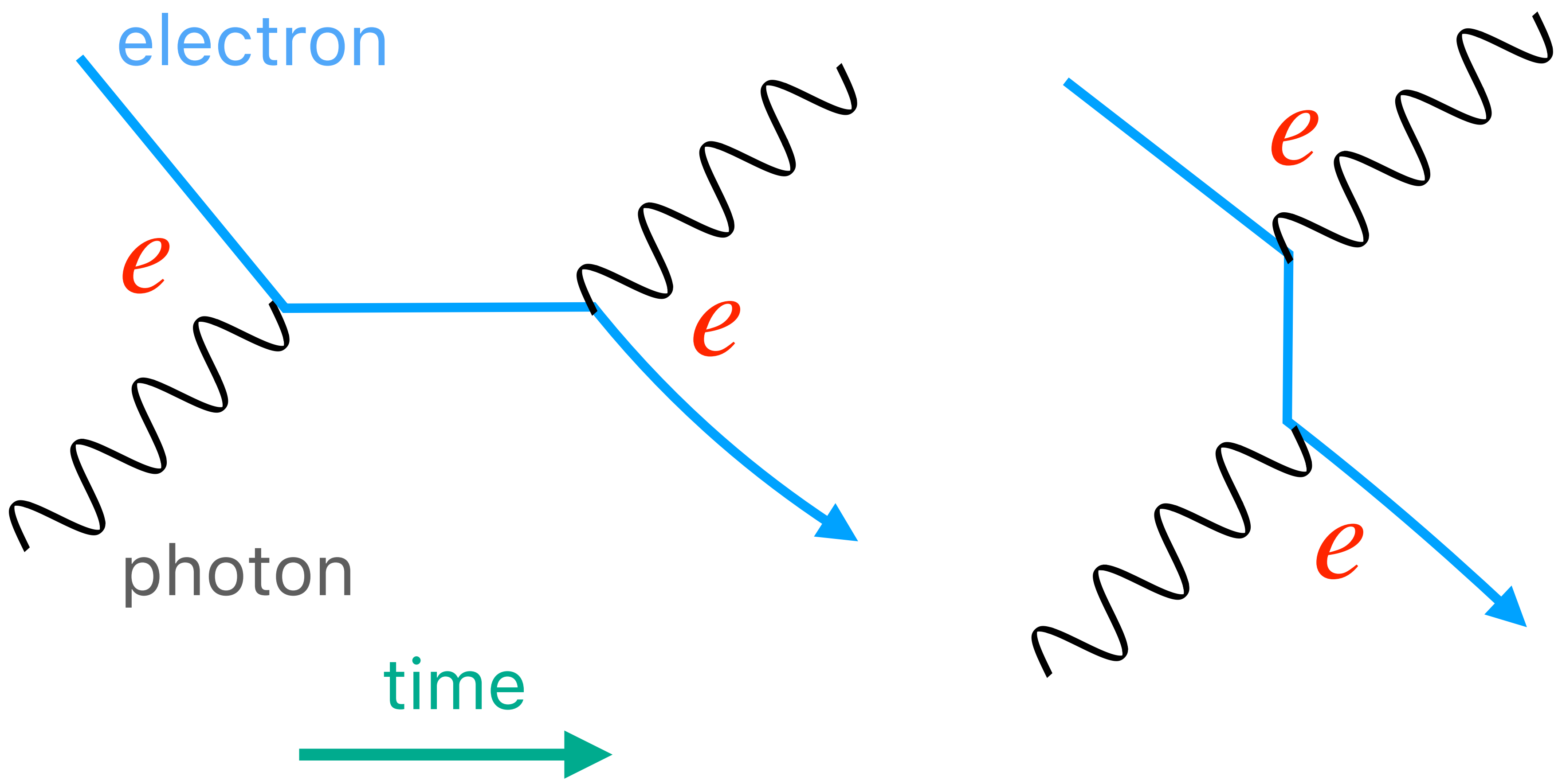
$$e\, A_\mu\, \bar{\psi}\gamma^\mu\psi$$







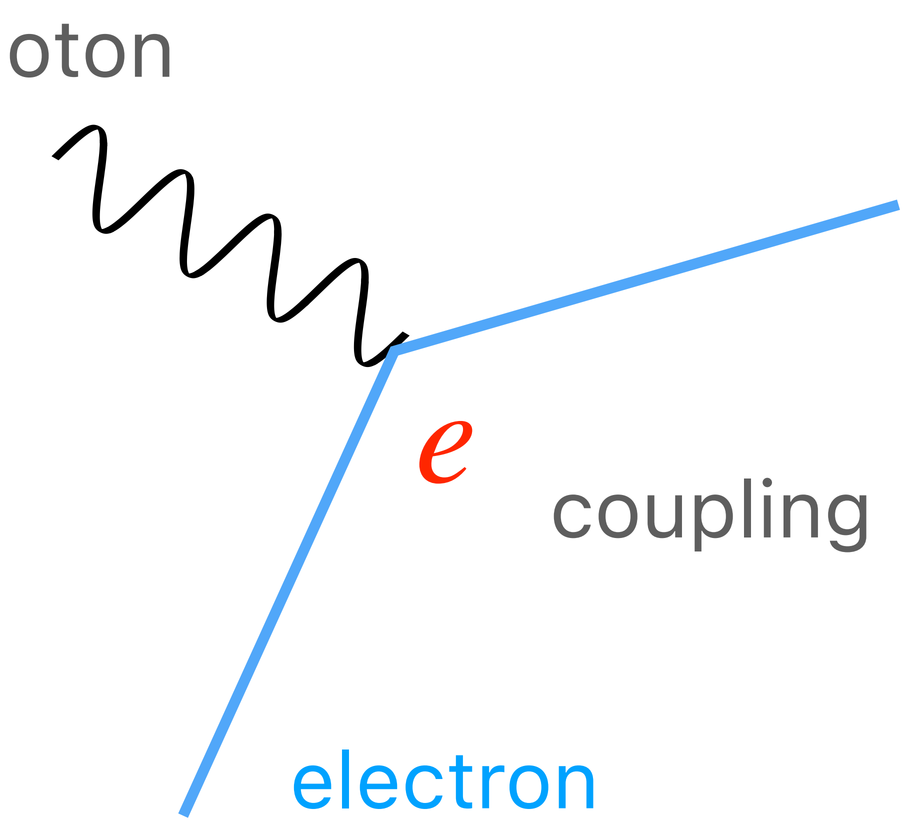
Electrons repel each other.



Compton scattering:

$$e + \gamma \to e + \gamma$$

The same interaction describes various processes.

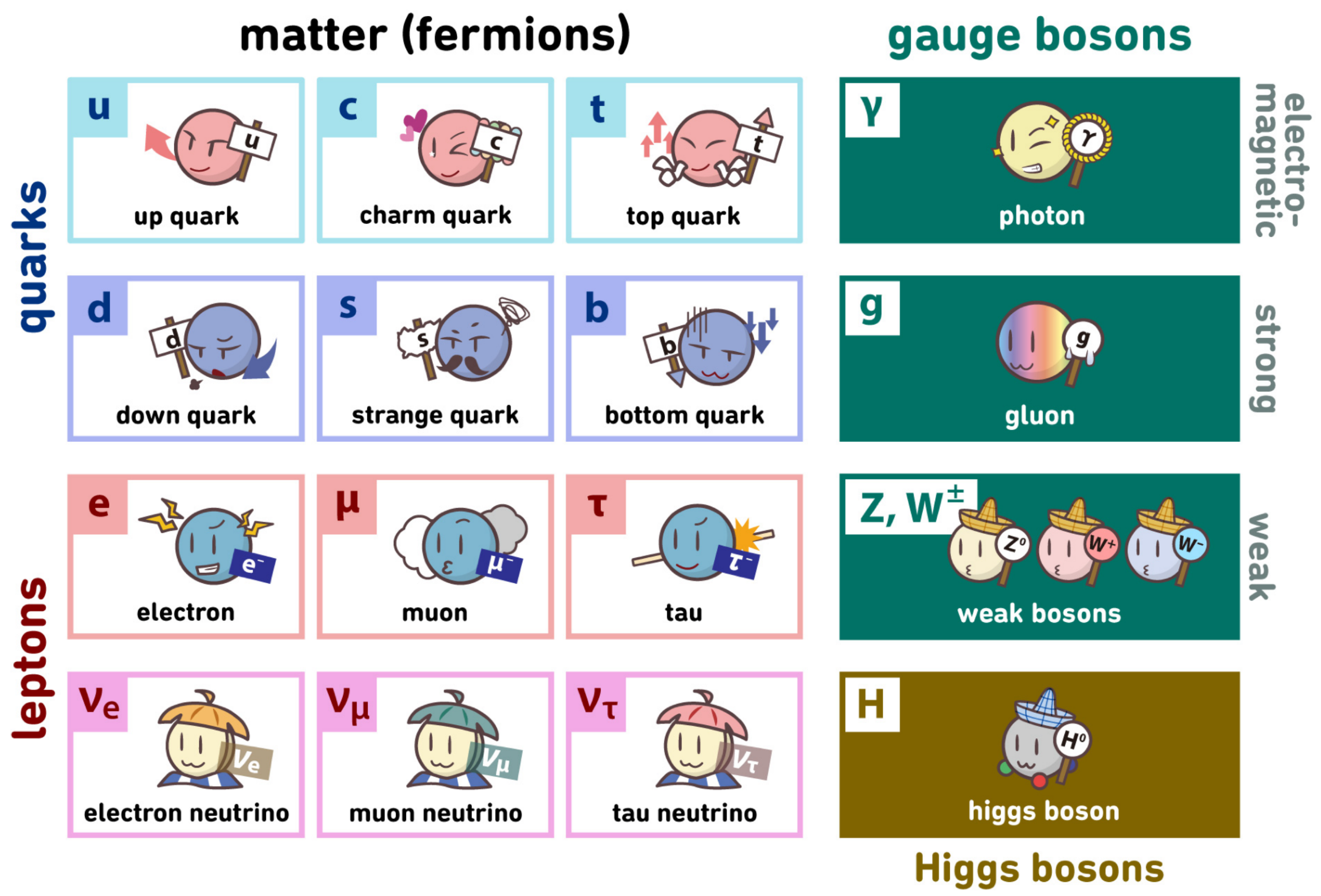


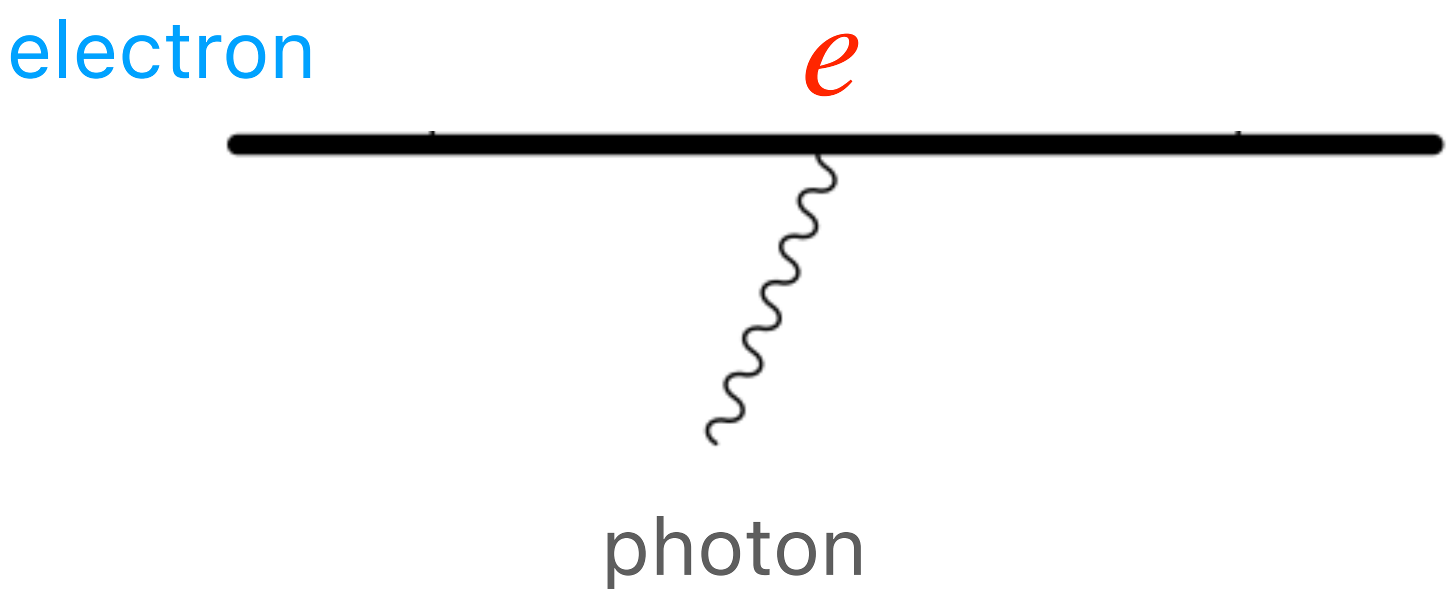
$$e\,A_\mu\,\bar{\psi}\gamma^\mu\psi$$

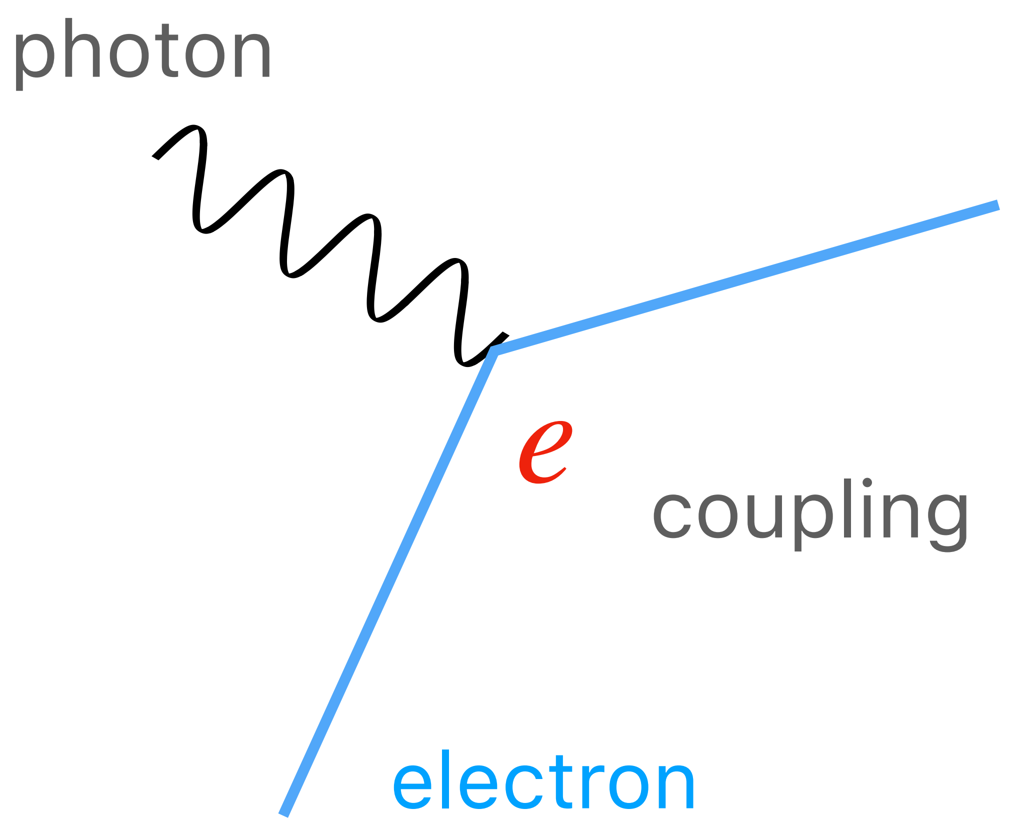
- Magnetic moment of the electron

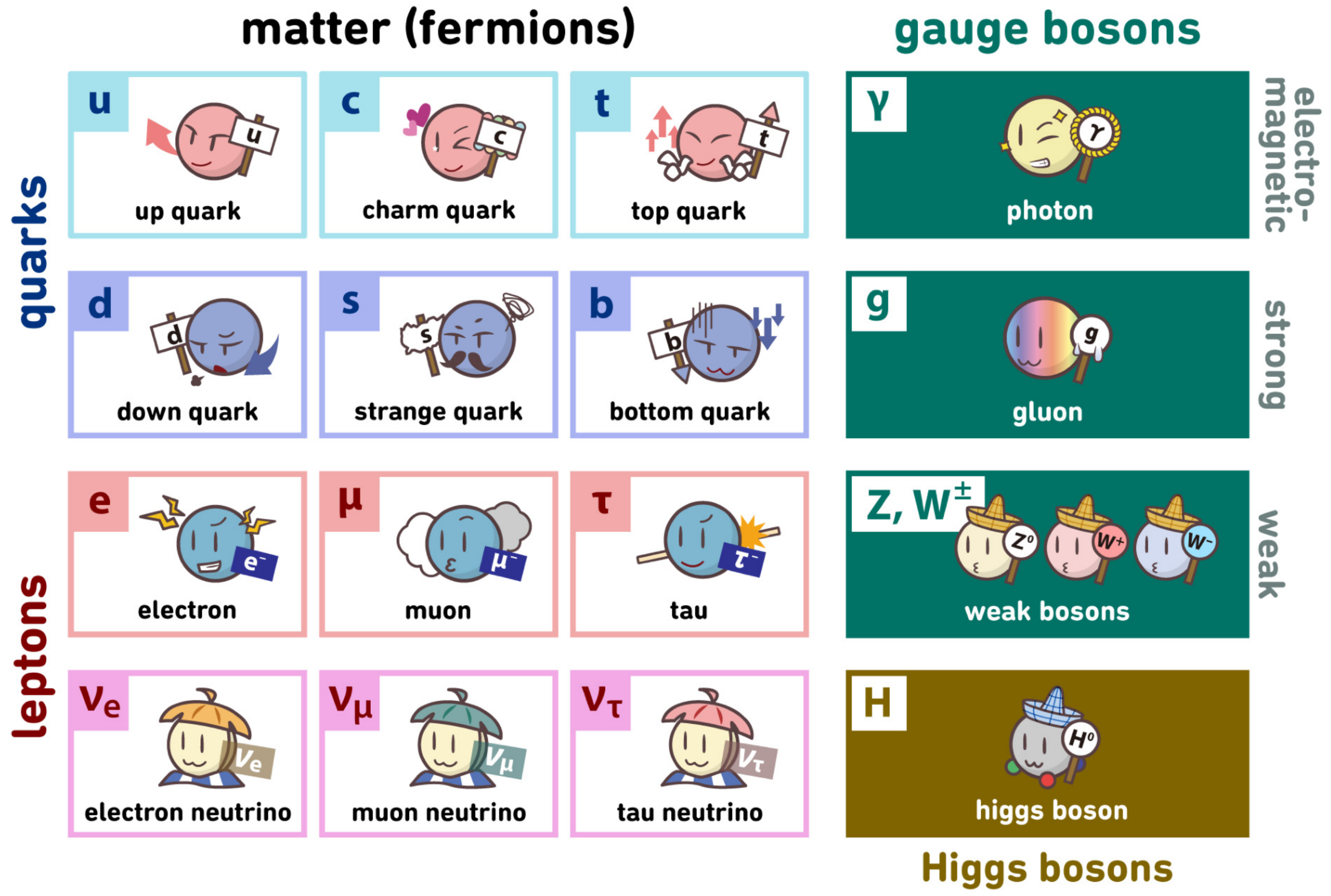
Hamiltonian: $H = -\,g\dfrac{e}{2m_e}\vec{s}\cdot\vec{B}$

$g = 2$









$$e\, A_\mu \bar{\psi} \gamma^\mu \psi$$

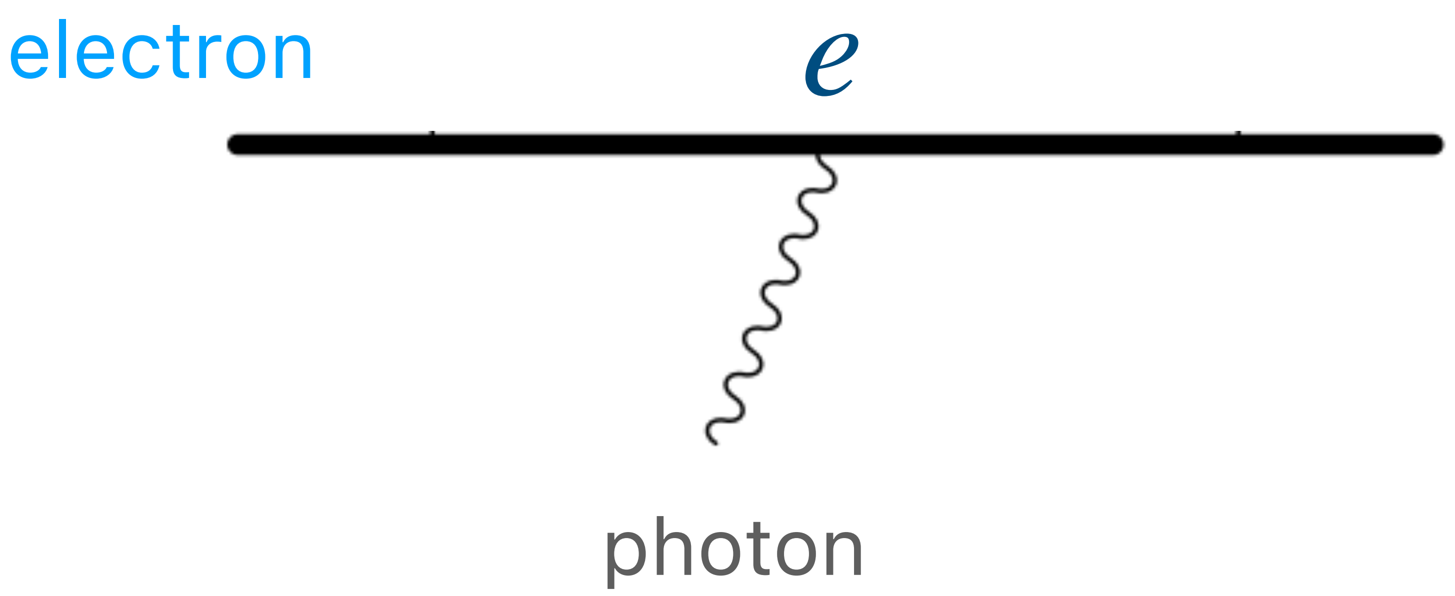
- Magnetic moment of the electron

Hamiltonian: $H = -g \dfrac{e}{2m_e} \vec{s} \cdot \overrightarrow{B}$

$$g = 2\left(1 + \frac{1}{2}\frac{\alpha}{\pi} + \cdots\right)$$

$$\alpha = \frac{e^2}{4\pi} = \frac{1}{137.0\cdots}$$

fine structure constant



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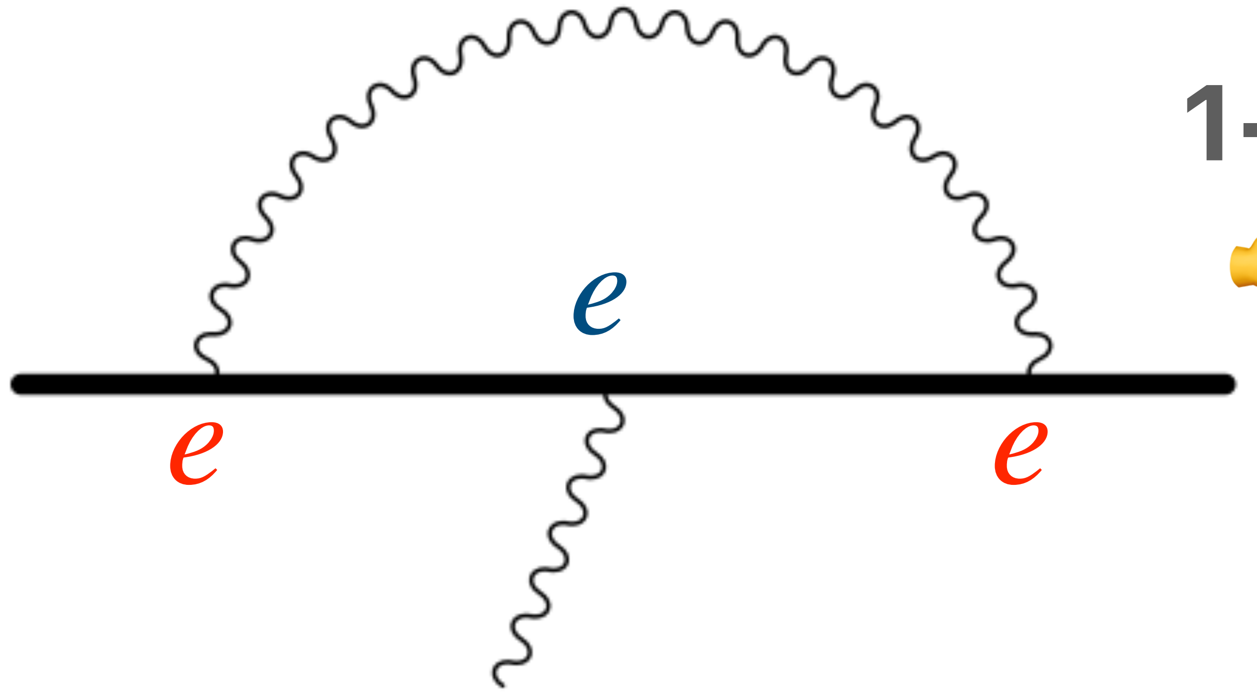
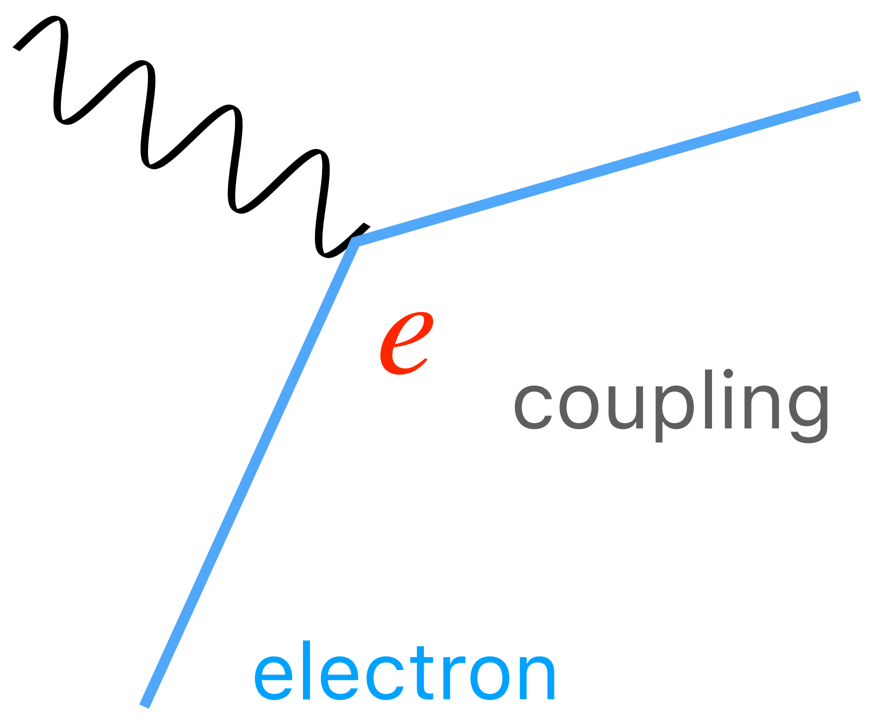
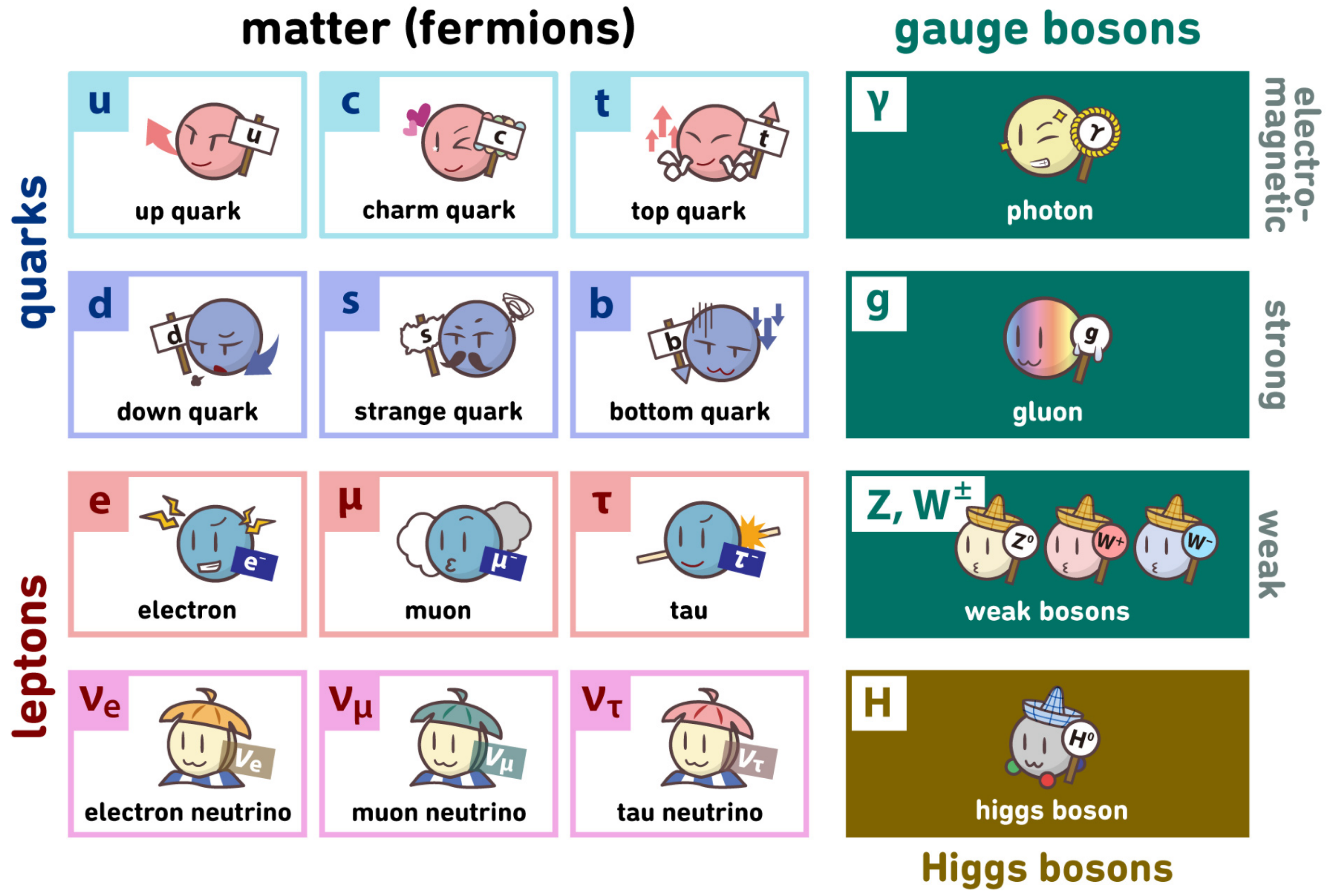


1-loop radiative correction.

👉 **Quantum Field Theory textbook**



$$e A_\mu \bar{\psi}\gamma^\mu \psi$$



- Magnetic moment of the electron

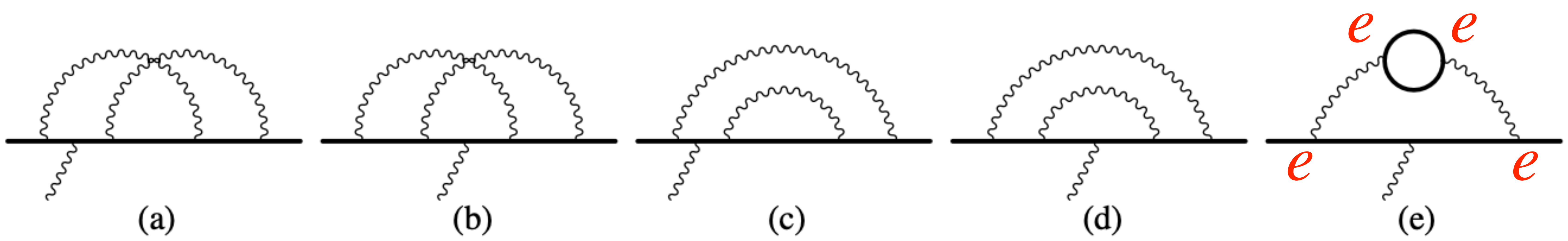
Hamiltonian: $H = -g\dfrac{e}{2m_e}\vec{s}\cdot\overrightarrow{B}$

$$g = 2\left(1 + \frac{1}{2}\frac{\alpha}{\pi} + \left(\frac{\alpha}{\pi}\right)^2 A^{(4)} + \cdots\right)$$

$$\alpha = \frac{e^2}{4\pi} = \frac{1}{137.0\cdots}$$

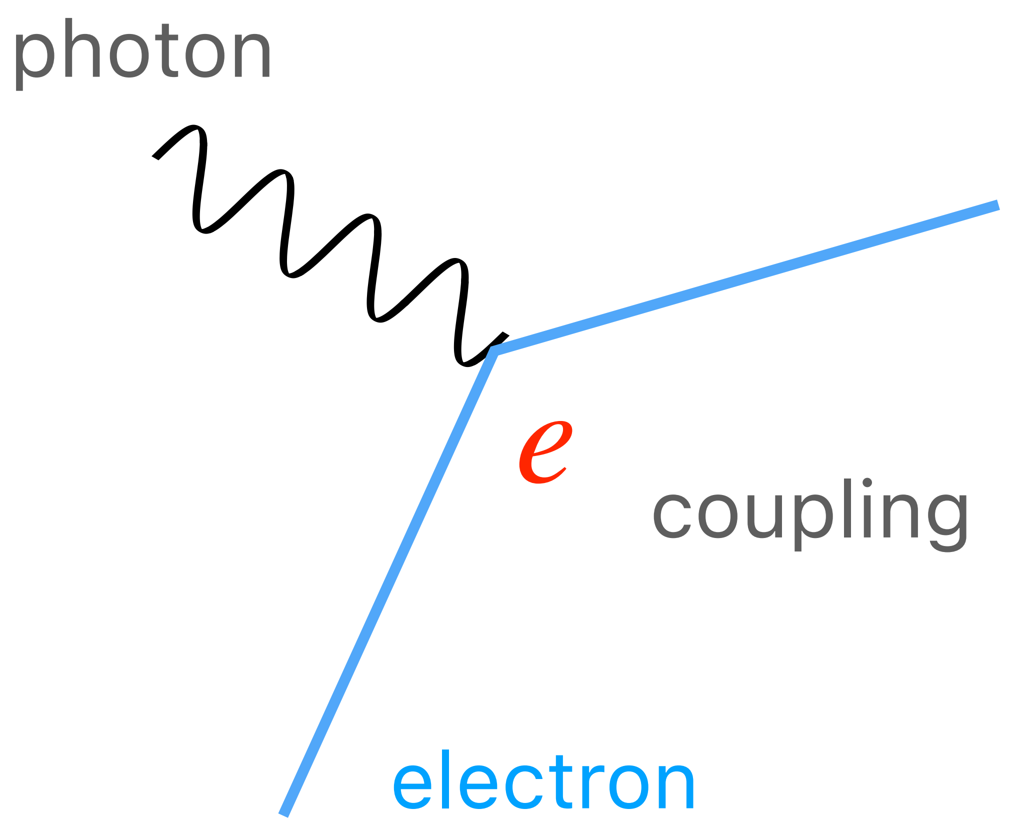
$$A^{(4)} = -0.328\cdots$$

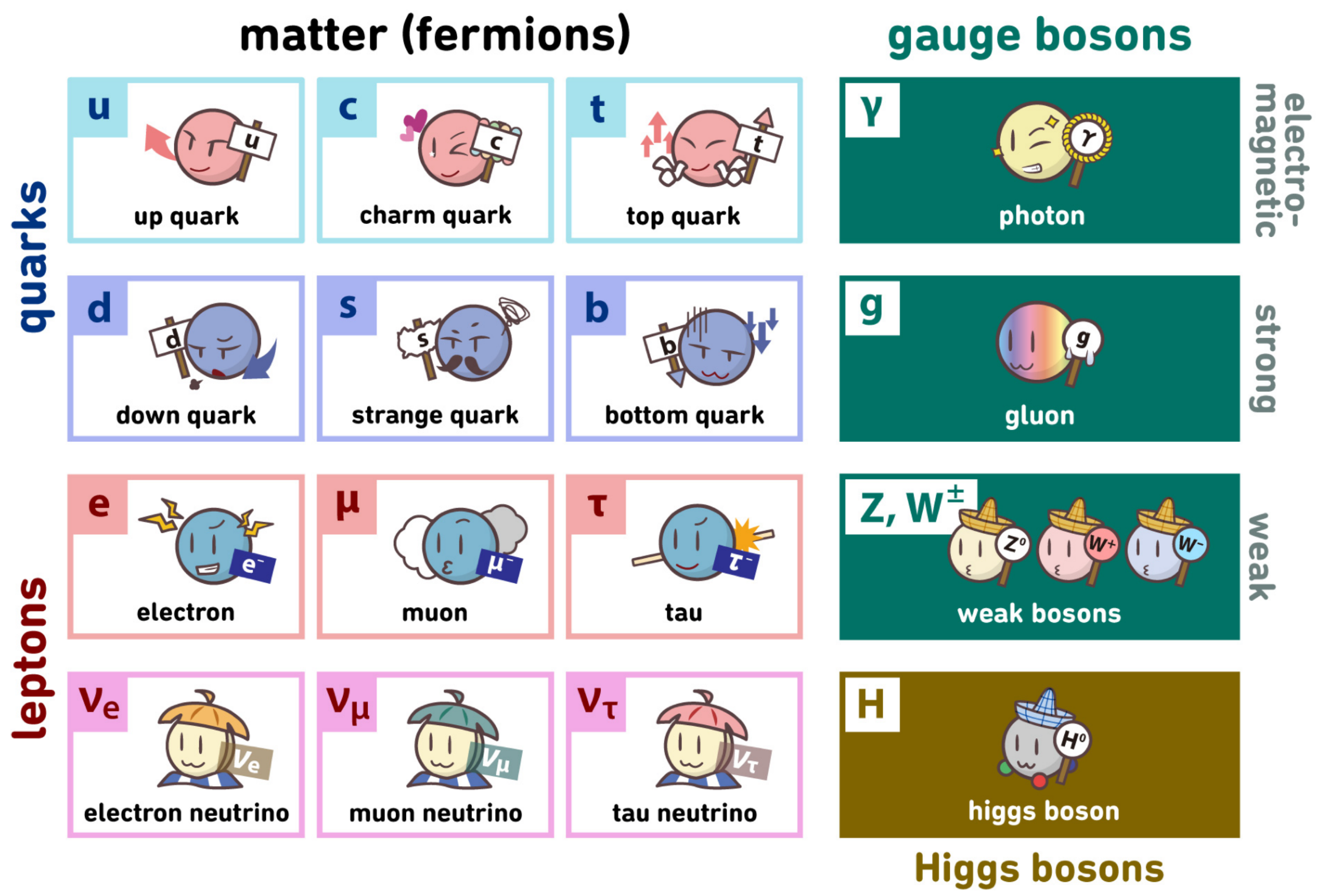
- **2-loop**, 7 diagrams in total



Aoyama, Hayakawa, Kinoshita, Nio, 2012, 2018, 2019
Fig. from Aoyama, Kinoshita, Nio, [Atoms 7, 28 (2019)]

$$e\, A_\mu \bar{\psi}\gamma^\mu\psi$$





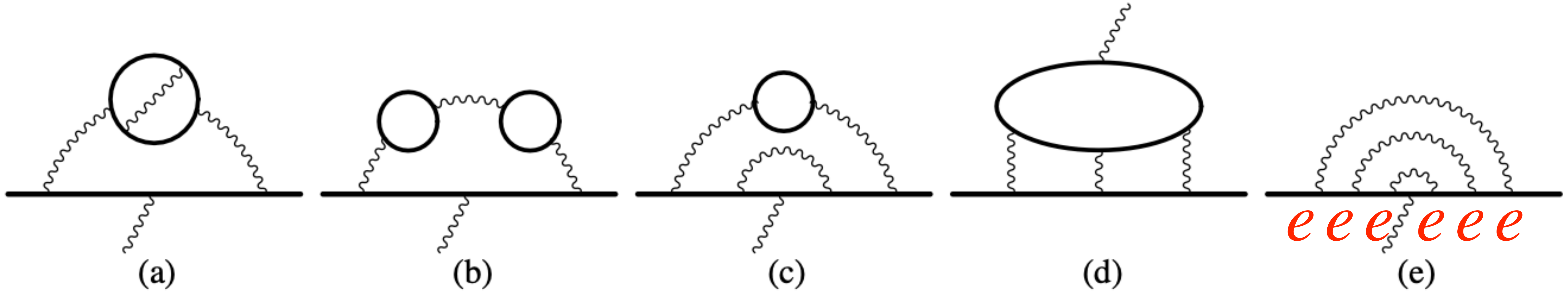
- Magnetic moment of the electron

Hamiltonian: $H = -g\dfrac{e}{2m_e}\vec{s}\cdot\overrightarrow{B}$

$$g = 2\left(1 + \frac{1}{2}\frac{\alpha}{\pi} + \left(\frac{\alpha}{\pi}\right)^2 A^{(4)} + \left(\frac{\alpha}{\pi}\right)^3 A^{(6)} + \cdots\right)$$

$$A^{(6)} = 1.182\cdots$$

- **3-loop**, 72 diagrams in total



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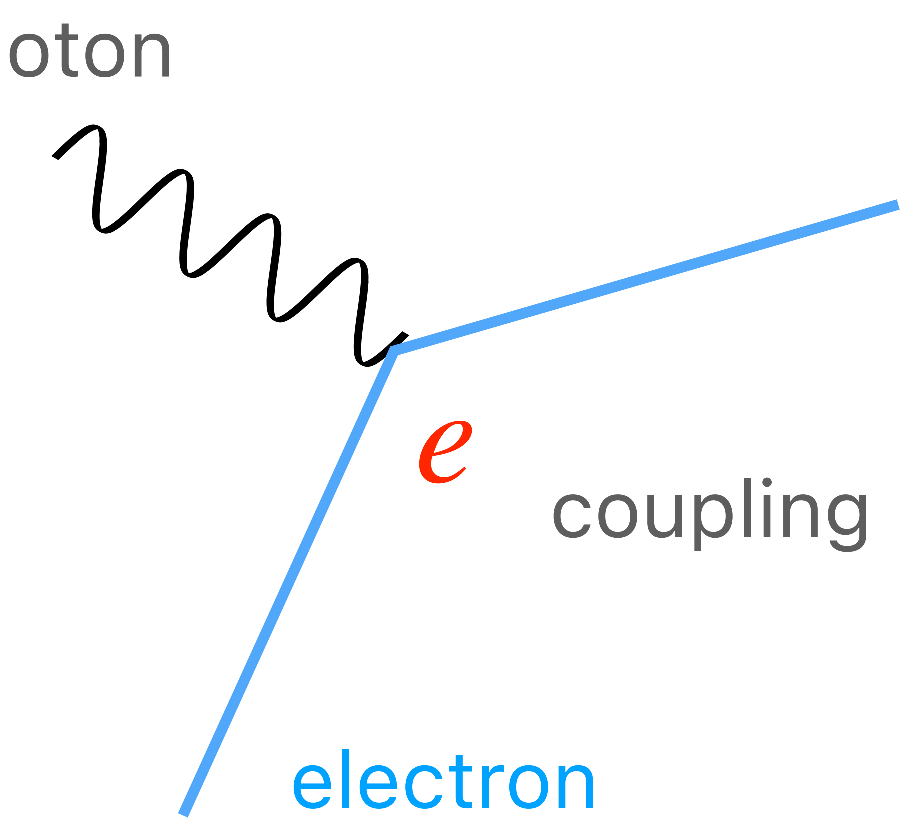
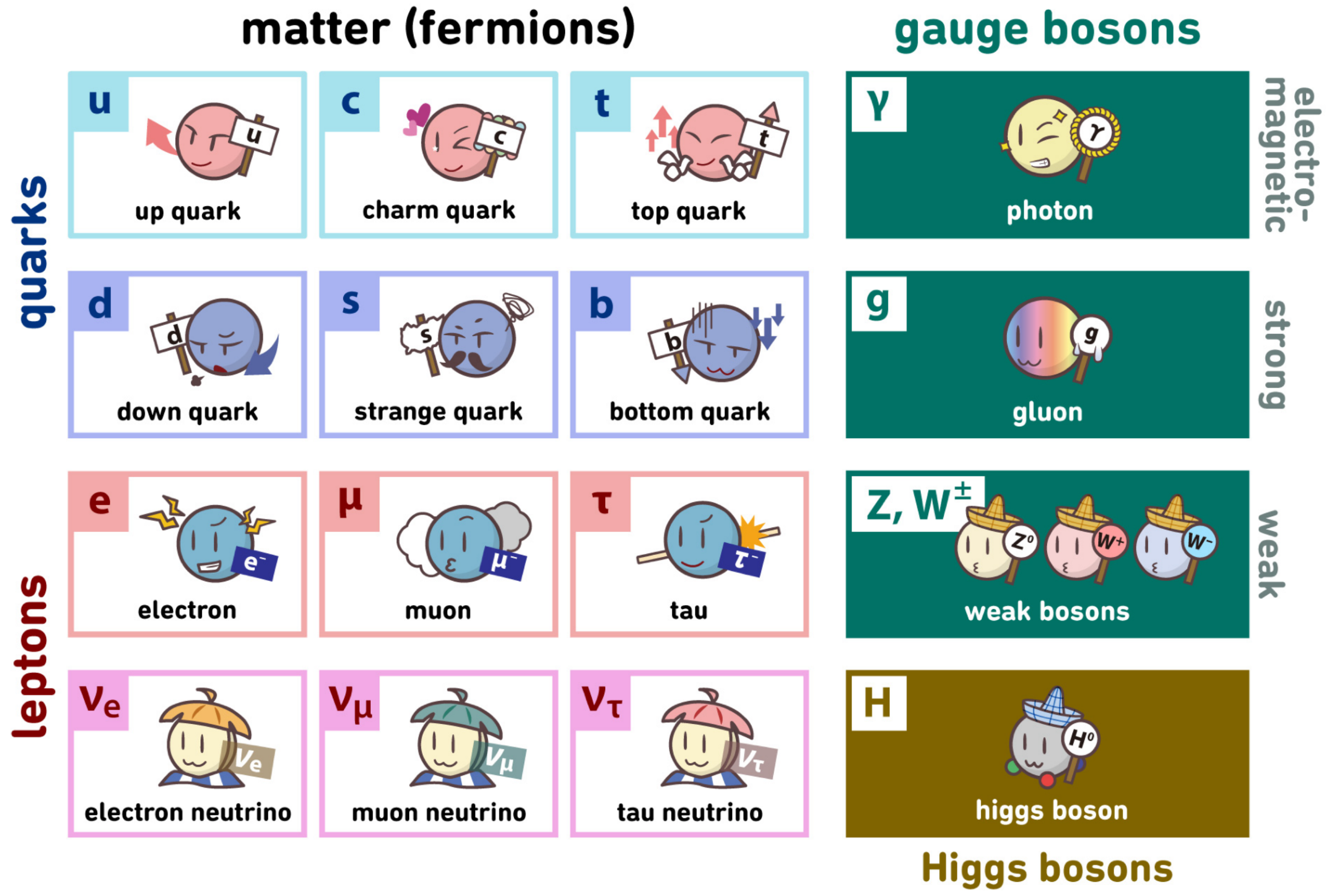


$$e\, A_\mu \bar{\psi}\gamma^\mu\psi$$



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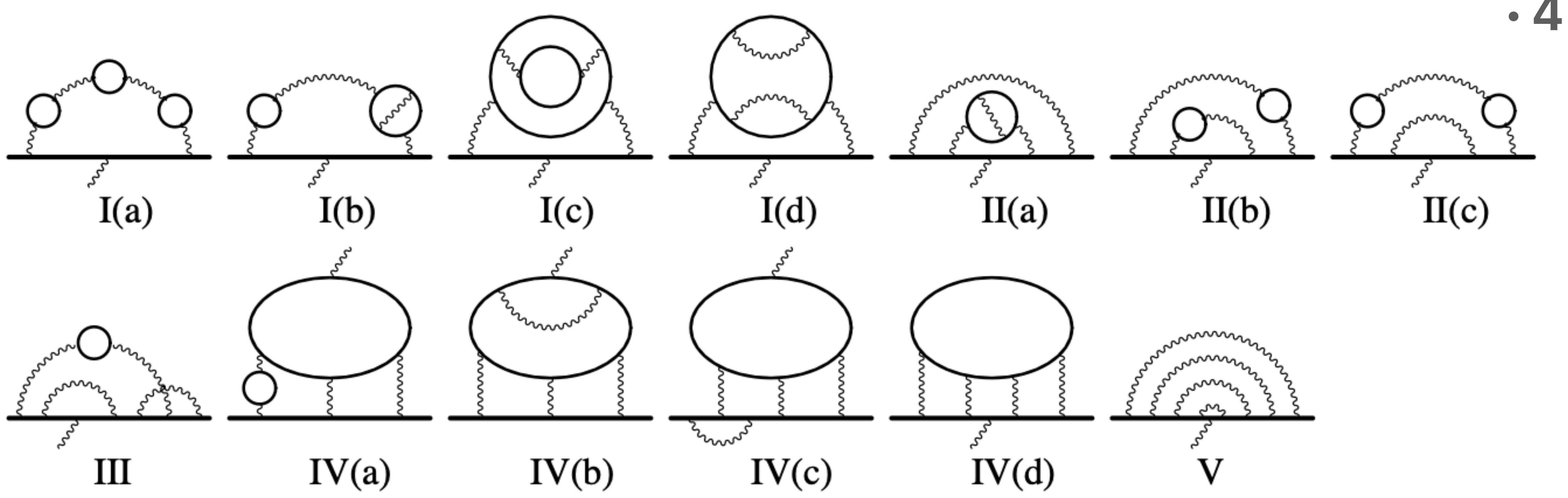
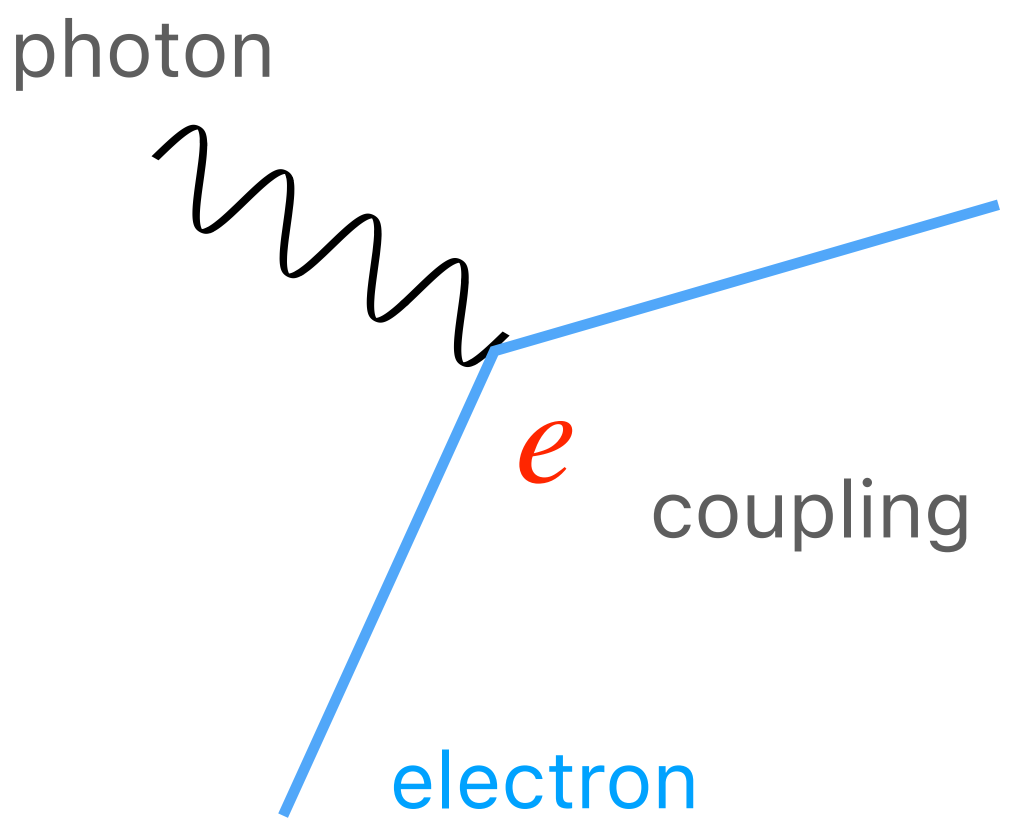
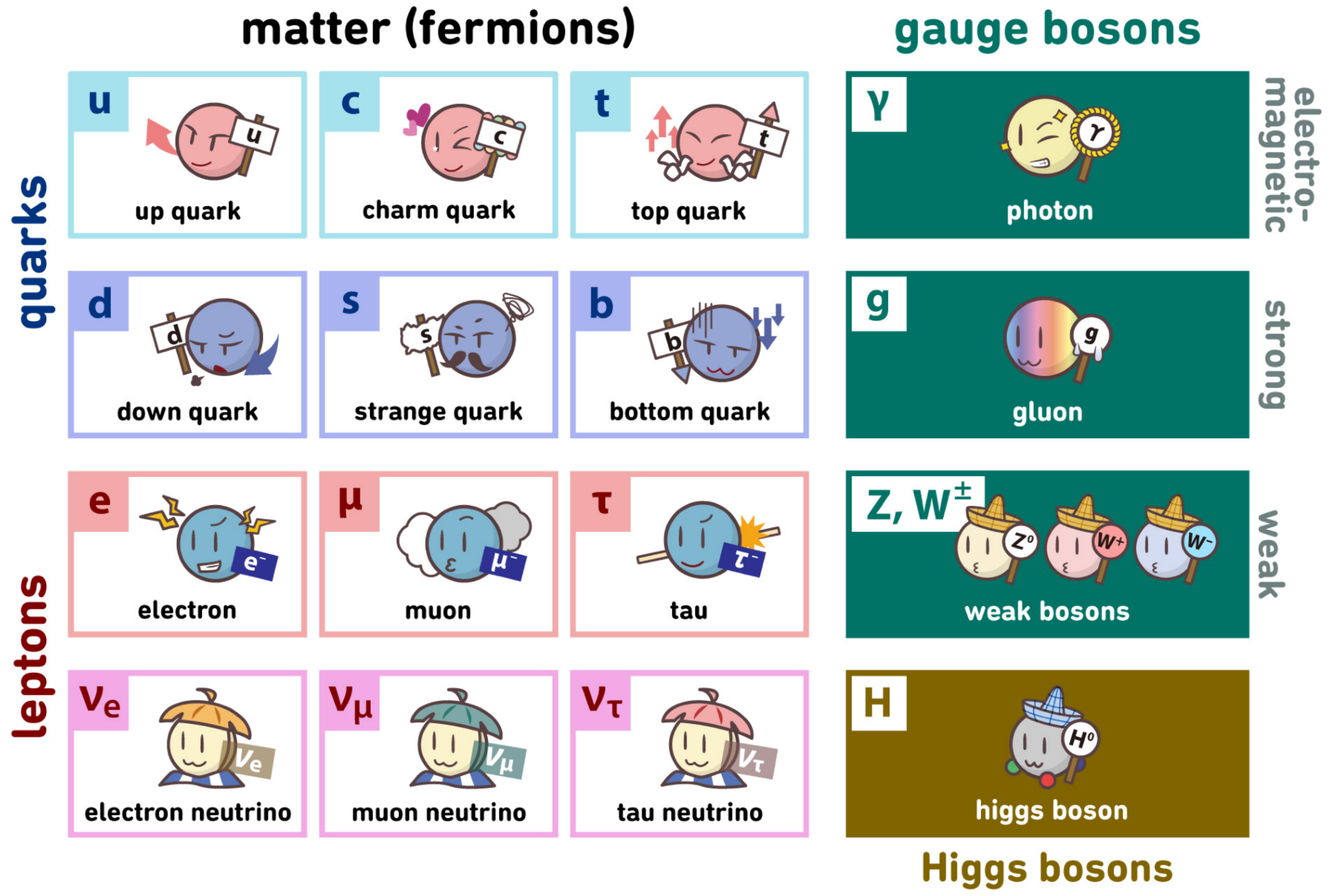
- **4-loop**, 891 diagrams in total



Aoyama, Hayakawa, Kinoshita, Nio, 2012, 2018, 2019
Fig. from Aoyama, Kinoshita, Nio, [Atoms 7, 28 (2019)]



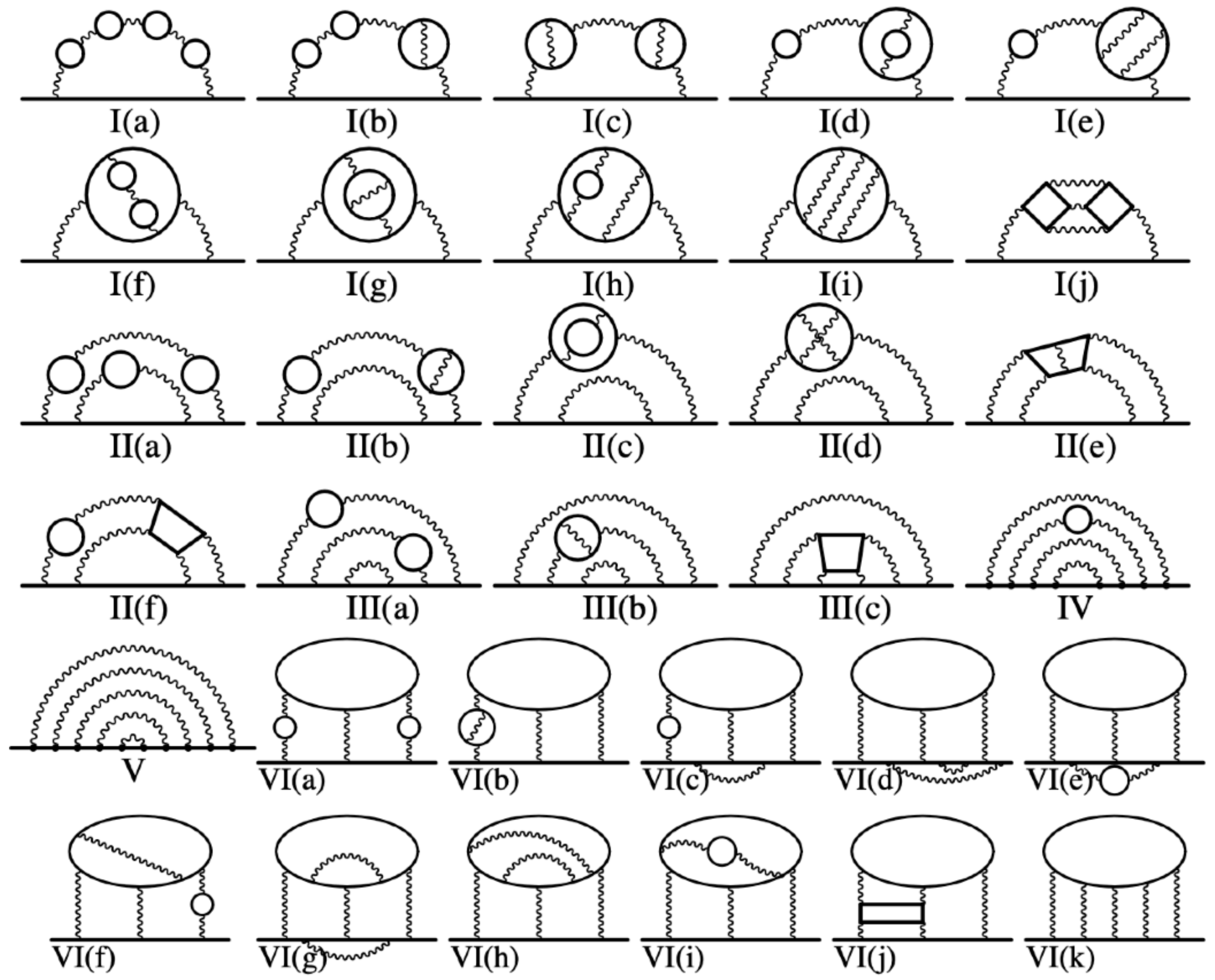
$$e\,A_\mu\,\bar{\psi}\gamma^\mu\psi$$



- Magnetic moment of the electron

Hamiltonian: $H = -\,g\dfrac{e}{2m_e}\vec{s}\cdot\vec{B}$

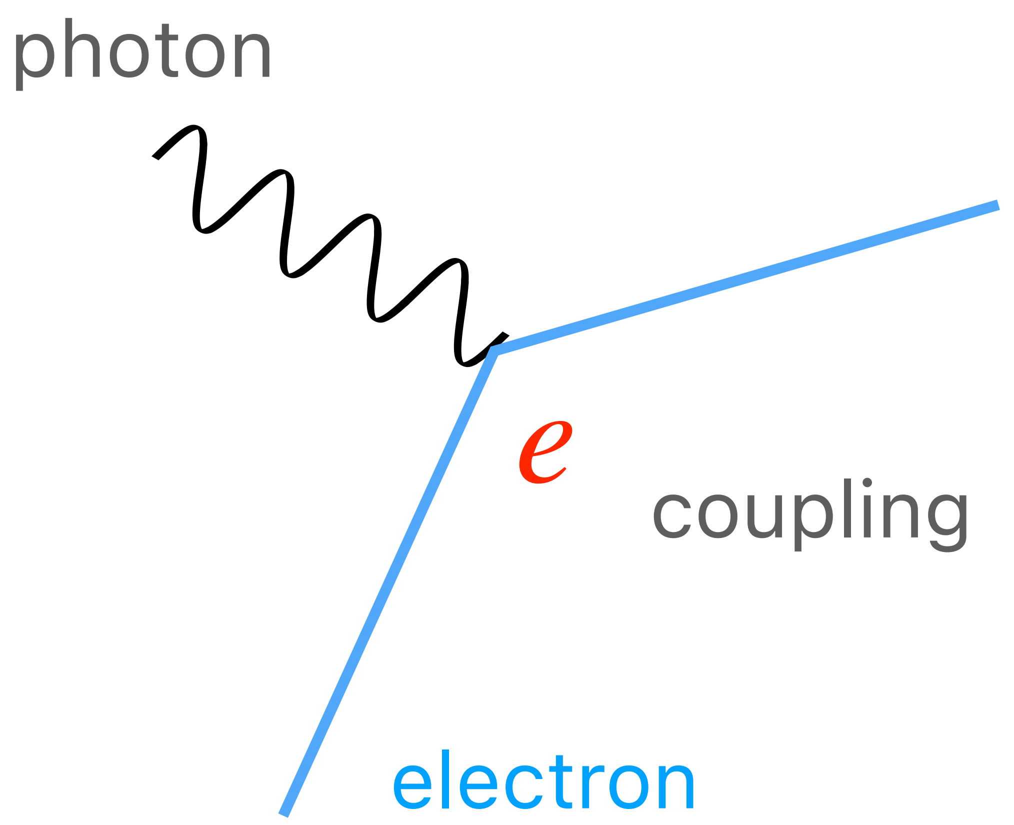
$$g = 2\left(1 + \frac{1}{2}\frac{\alpha}{\pi} + \left(\frac{\alpha}{\pi}\right)^2 A^{(4)} + \left(\frac{\alpha}{\pi}\right)^3 A^{(6)} + \left(\frac{\alpha}{\pi}\right)^4 A^{(8)} + \left(\frac{\alpha}{\pi}\right)^5 A^{(10)} + \cdots\right)$$

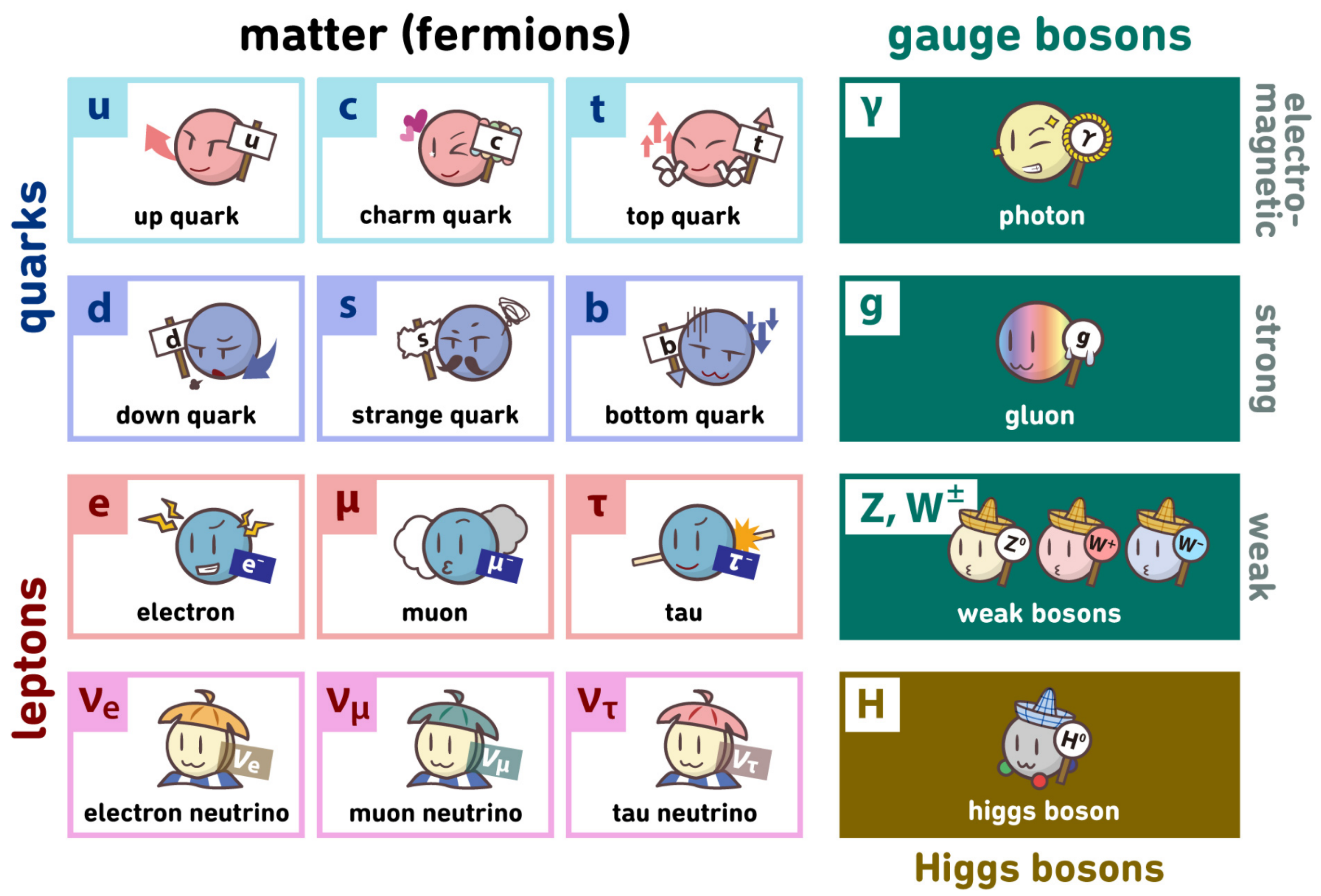


- **5-loop**, 12672 diagrams in total

Aoyama, Hayakawa, Kinoshita, Nio, 2012, 2018, 2019
Fig. from Aoyama, Kinoshita, Nio, [Atoms 7, 28 (2019)]

$e A_\mu \bar{\psi}\gamma^\mu\psi$





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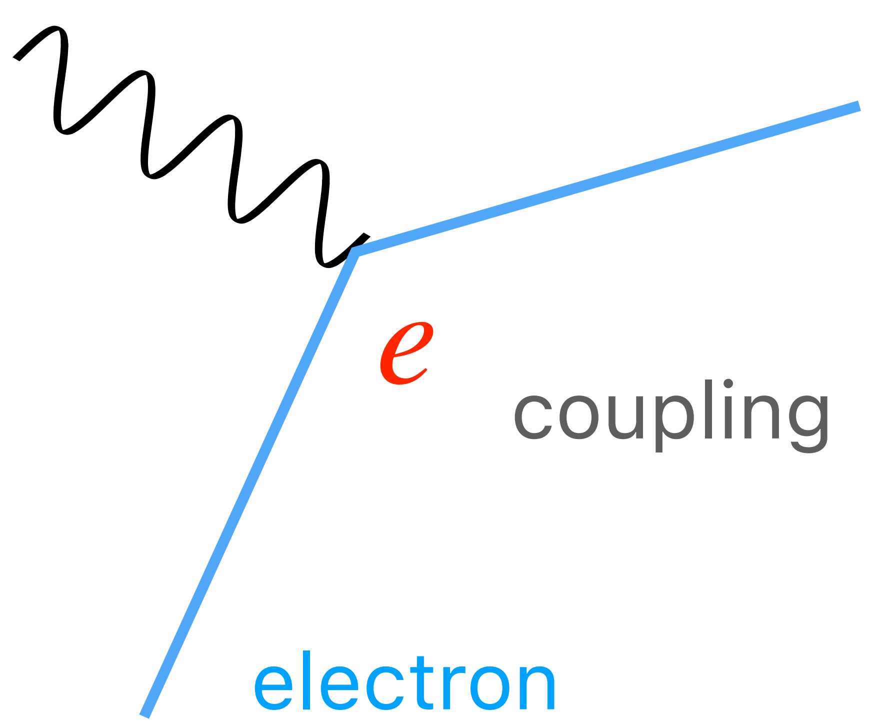
On the other hand, the electron magnetic moment has also been measured experimentally with extreme precision.

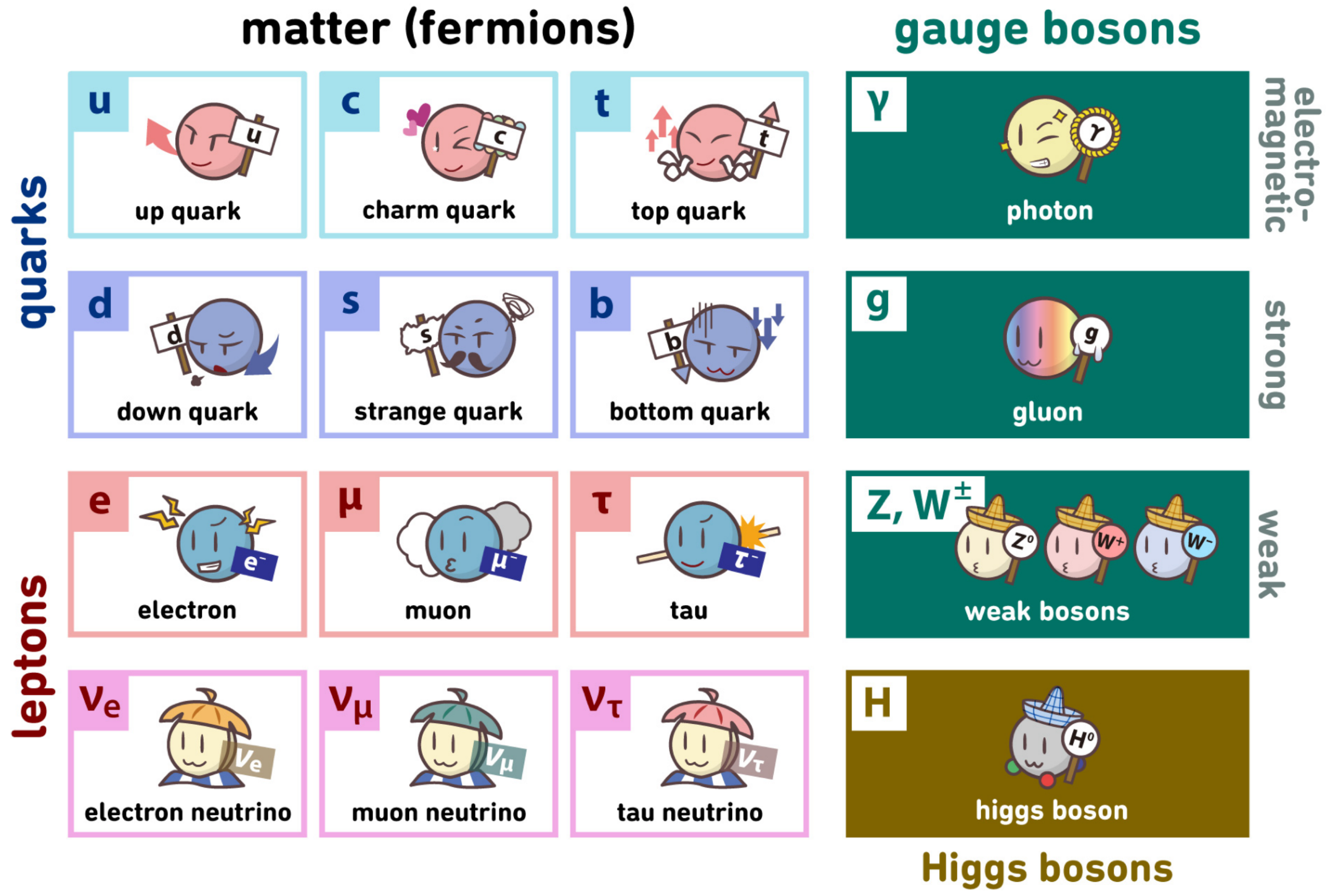
$g = 2(1.001\ 159\ 652\ 180\ 59 \pm 0.000\ 000\ 000\ 000\ 13)$ [Fan et. al. 2209.13084]

By combining theory and experiment, we can determine the value of α as:

$\alpha^{-1} = 137.035\ 999\ 166 \pm 0.000\ 000\ 015$

👉 This is one of the most precise measurement of α !





$$e\,A_\mu \bar{\psi}\gamma^\mu\psi$$

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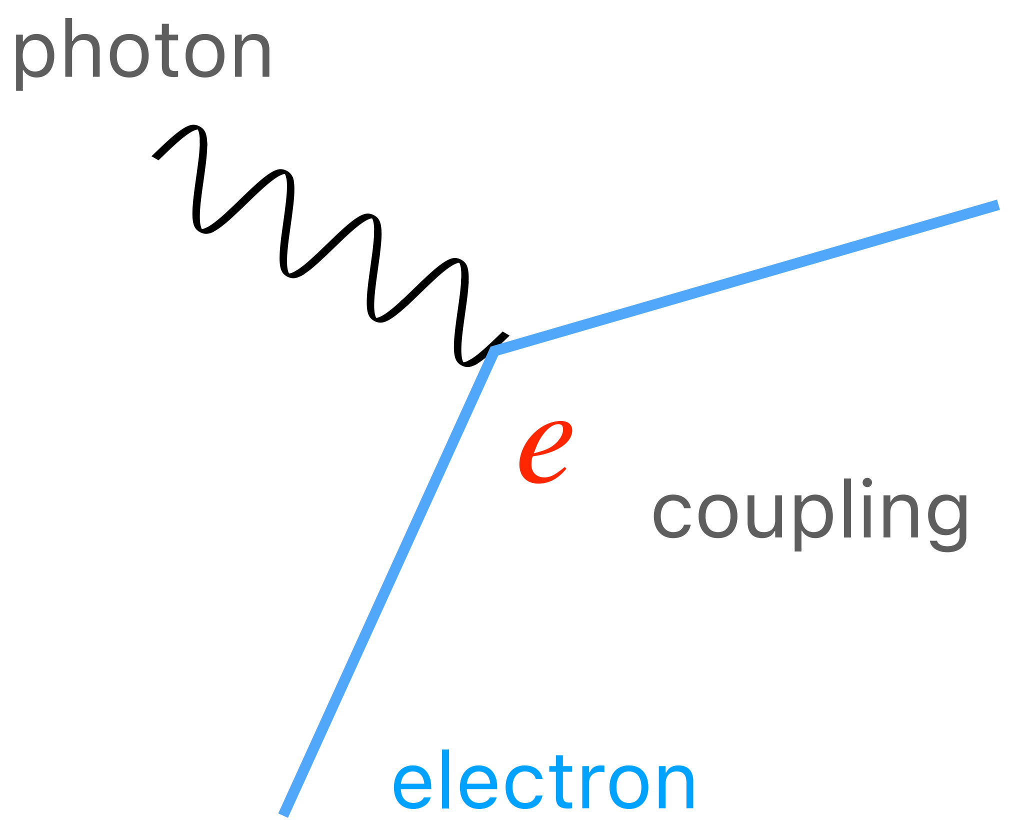
agreement at $\mathcal{O}(10^{-10})$ level!

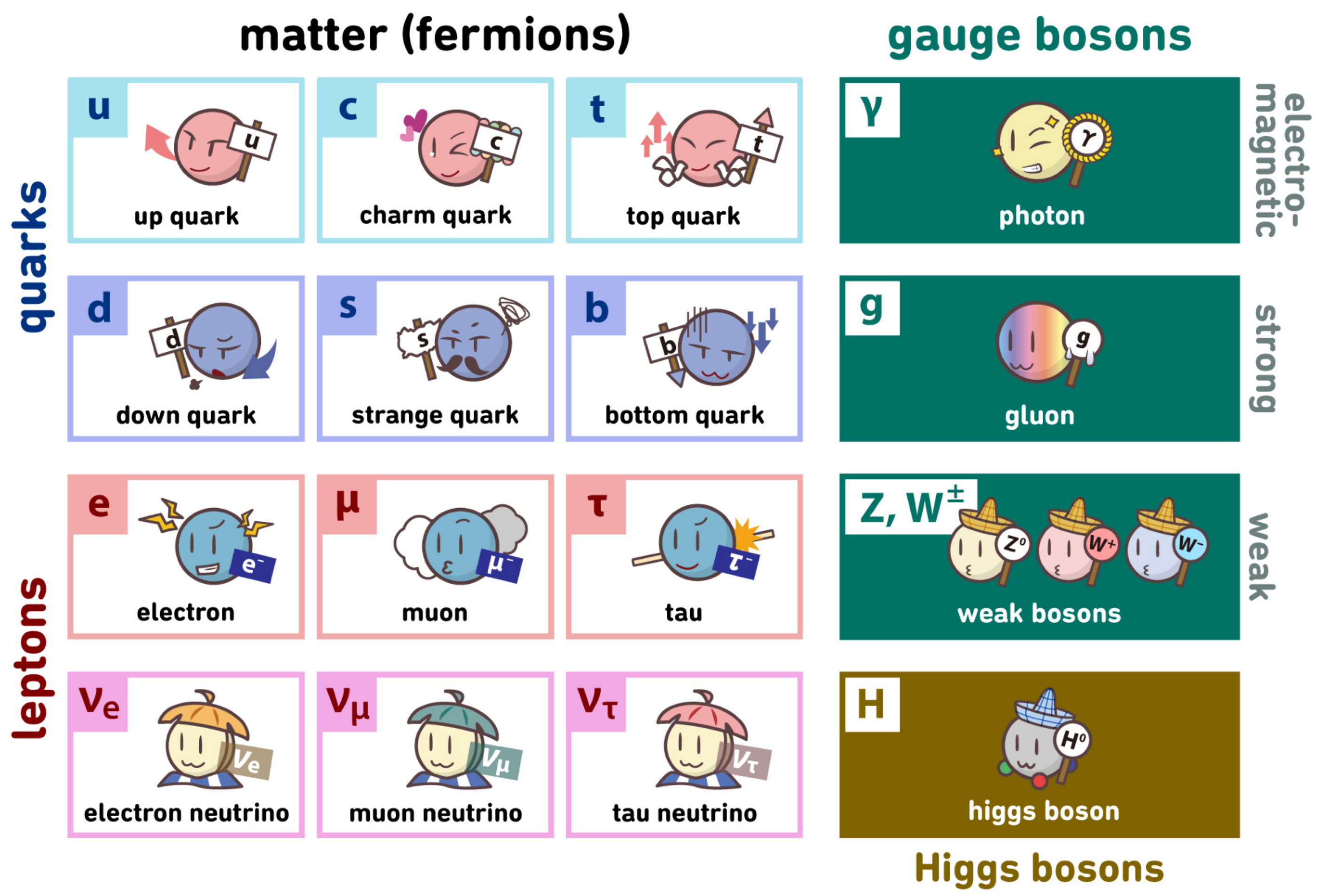
Comparison with the independent measurements of α:

$\alpha^{-1} = 137.035\ 999\ 046 \pm 0.000\ 000\ 027$ (Cs) [Parker et. al. 1812.04130]

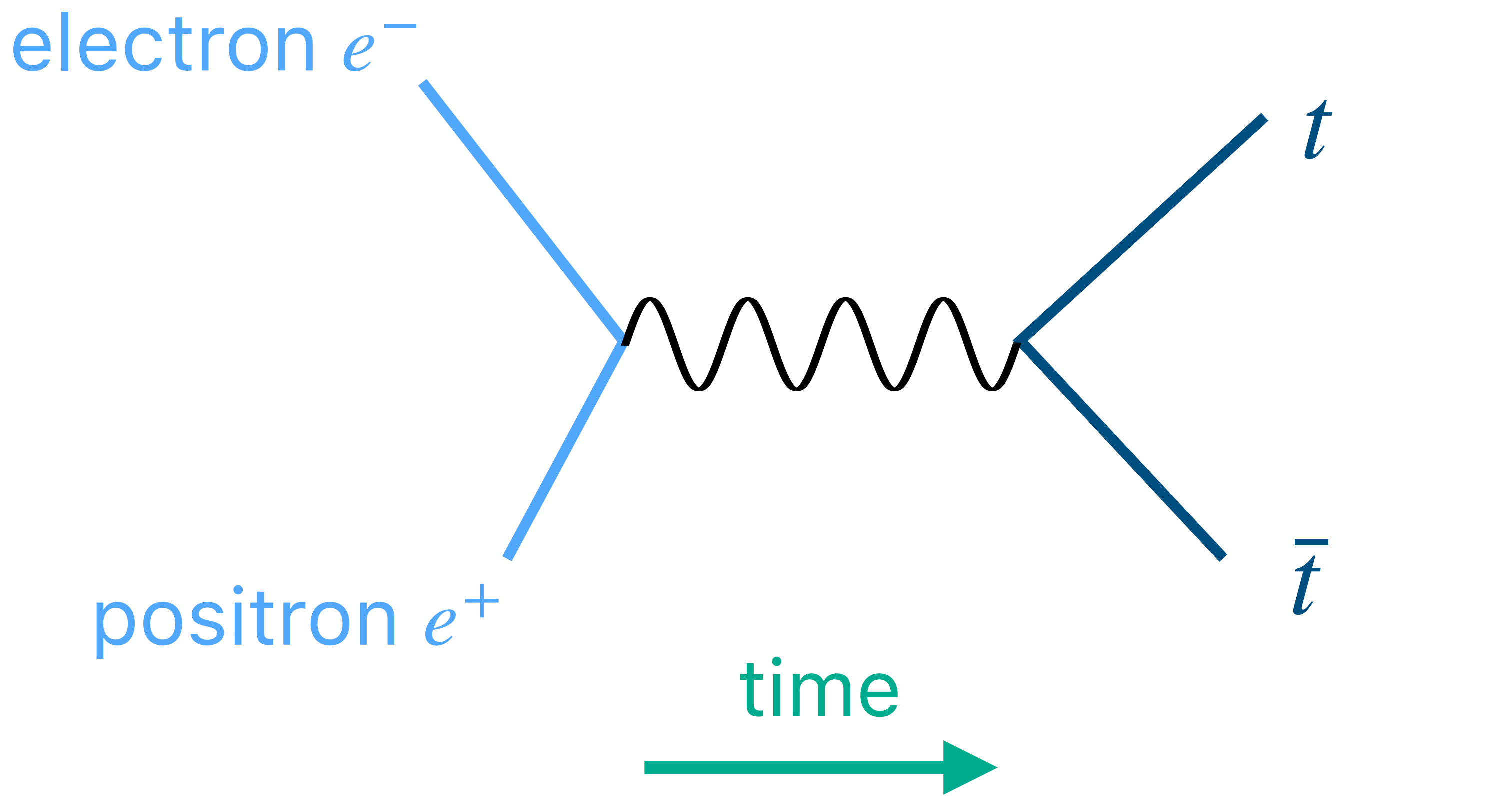
$\alpha^{-1} = 137.035\ 999\ 206 \pm 0.000\ 000\ 011$ (Rb) [Morel et. al. Nature, 2020]

$$e\,A_\mu\,\bar{\psi}\gamma^\mu\psi$$

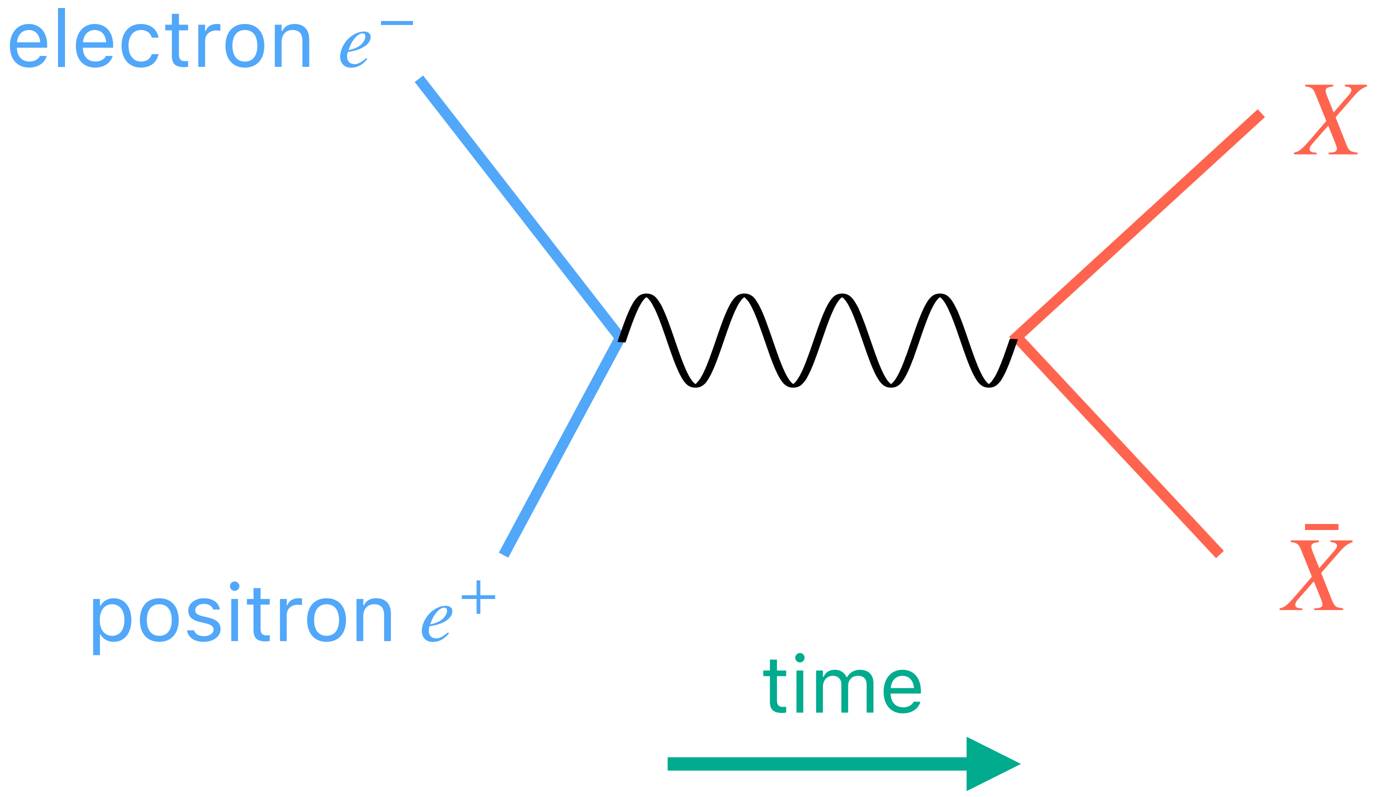




- At e^+e^- colliders, for example,...

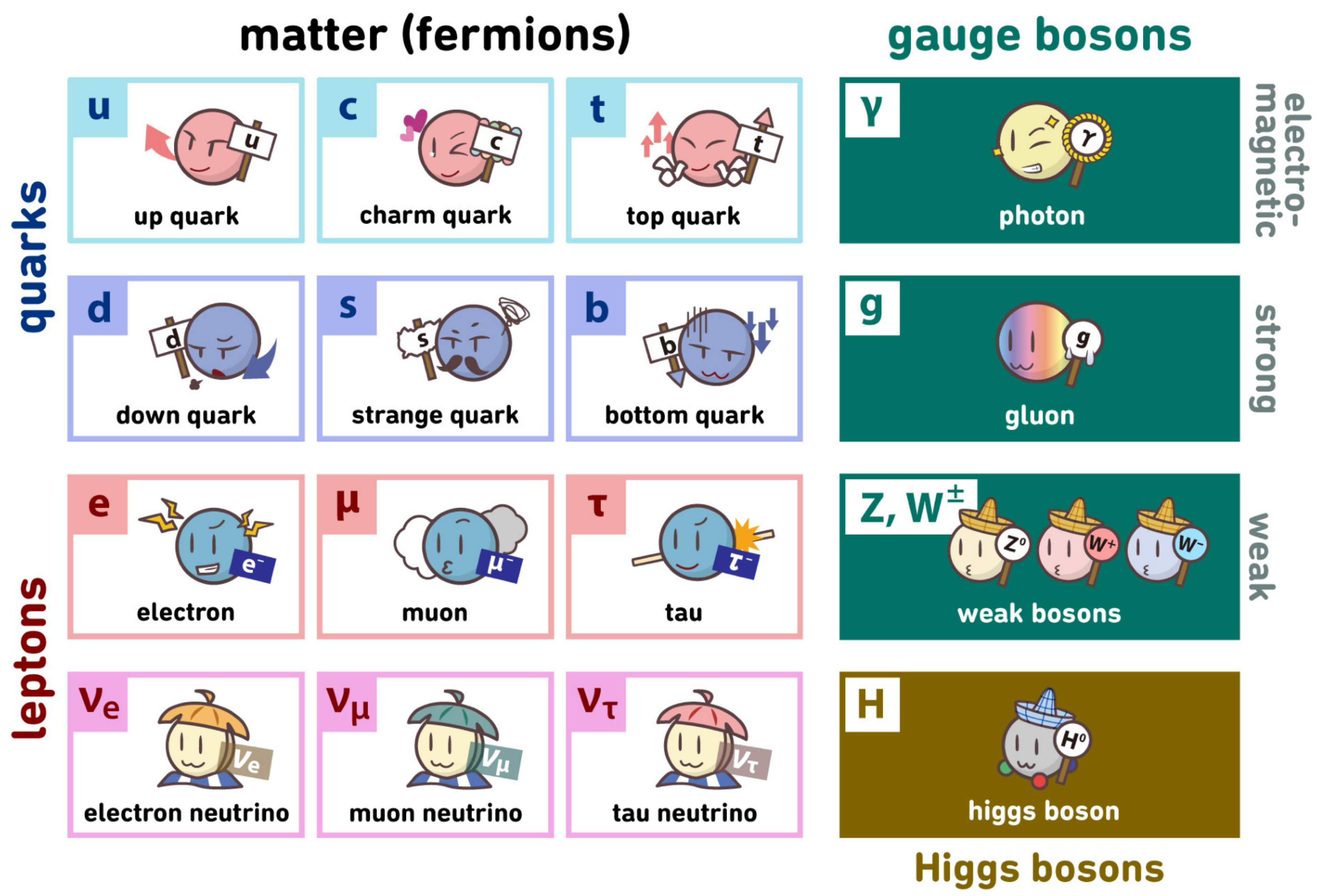


Top anti-top pair production.

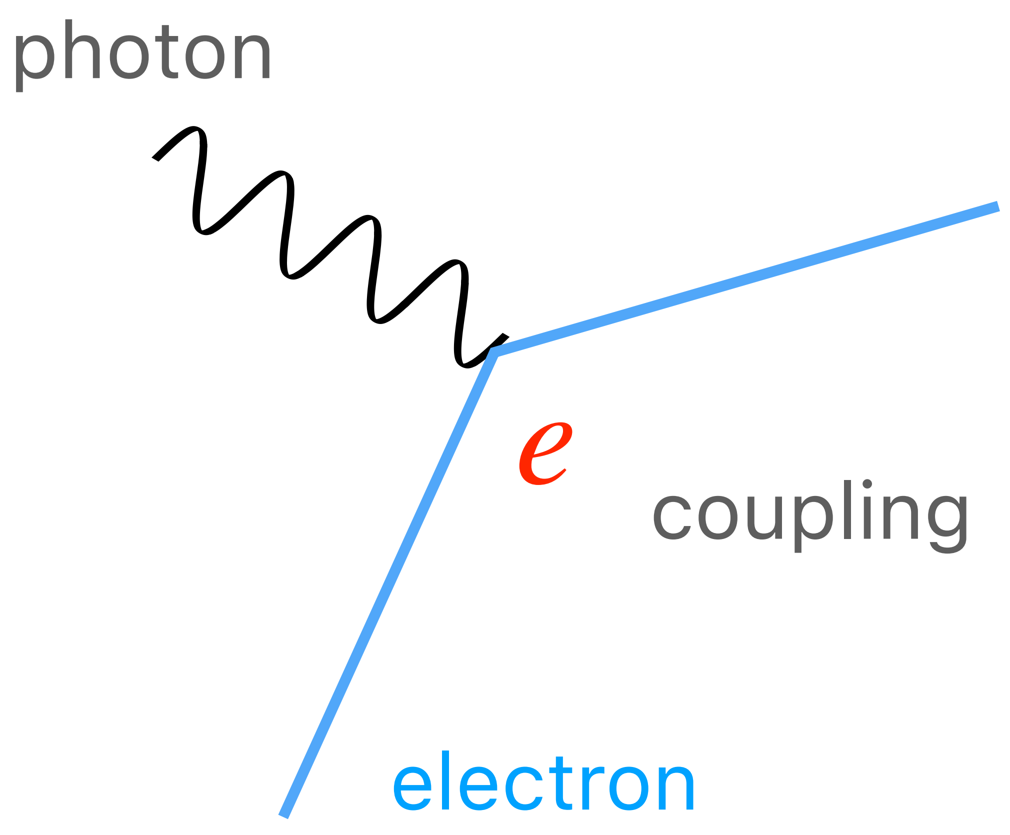


New particle production.

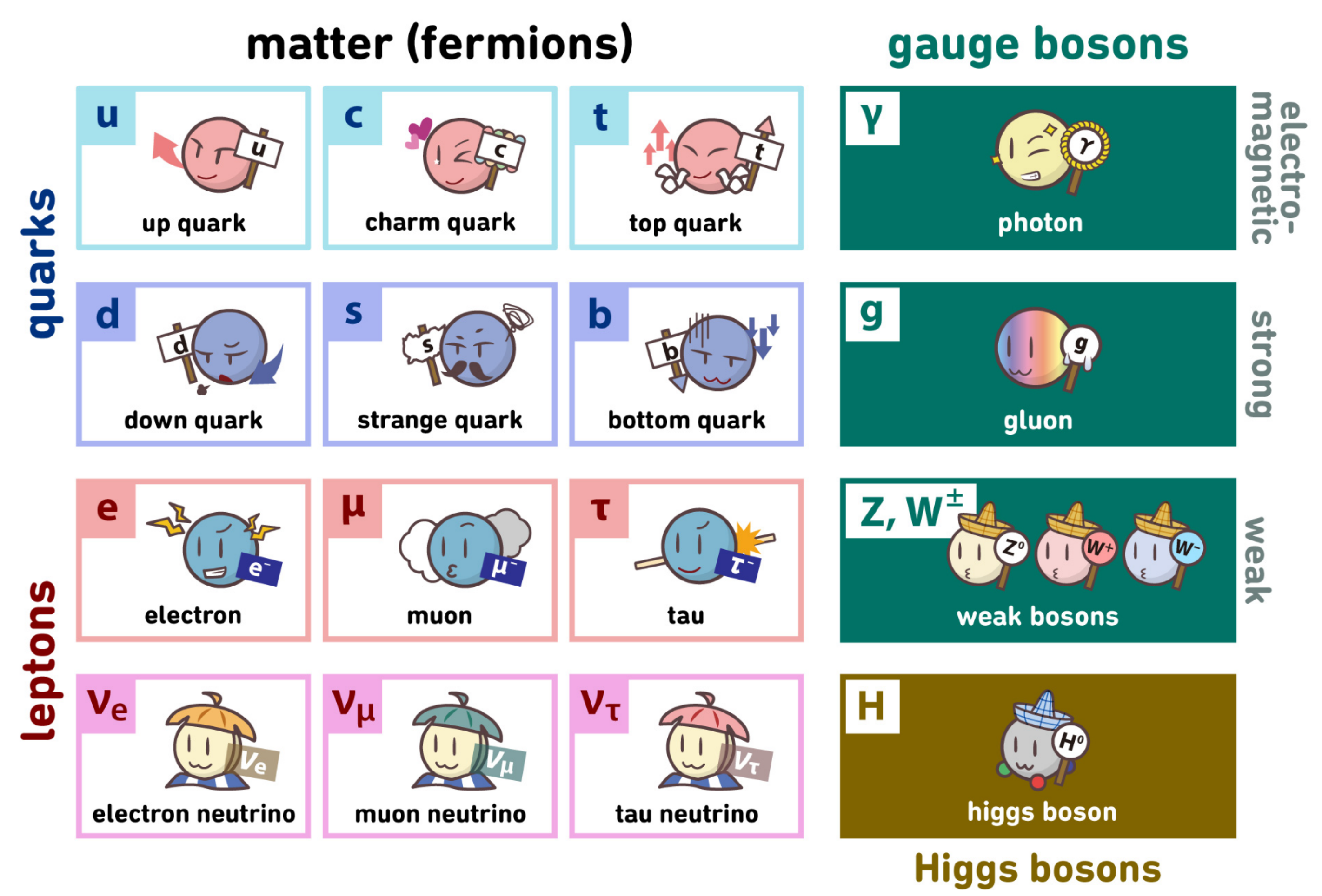
We'll learn how to simulate these kinds of processes at this school.



$$+\sum i\bar{\psi}\gamma^{\mu}D_{\mu}\psi \quad \ni \quad {\color{red}e}\,A_{\mu}\,\bar{\psi}\gamma^{\mu}\psi$$



Standard Model



$\mathscr{L} = -\sum \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu}$	… gauge fields
$+\sum i\bar{\psi}\gamma^\mu D_\mu \psi$	… matter fields + gauge interactions
$+ \lvert D_\mu \phi \rvert^2 - V(\phi)$	… Higgs fields
$+\sum y\phi\bar{\psi}\psi + \mathrm{h.c.}$	… Yukawa interactions

These few lines describe countless experimental facts of particle physics with incredible precision.

This is currently the most successful theory in particle physics.

Plan

1. **Standard Model** (today) 👉 cf. Hagiwara-san's talk yesterday.
   - Introductory content, with a focus on the Higgs.

     (mainly for undergrad/master's students.)

     (+ homework problem at the end of the lecture.)

Let's have a little break.
Any question so far?

Plan

1. **Standard Model** (today) 👉 cf. Hagiwara-san's talk yesterday.
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Higgs

1. The **last** particle discovered in the Standard Model.

2. The **origin of** all the elementary particles′ **masses**.

3. The **origin of electroweak symmetry breaking.**

4. The **only elementary scalar** particle in the Standard Model.

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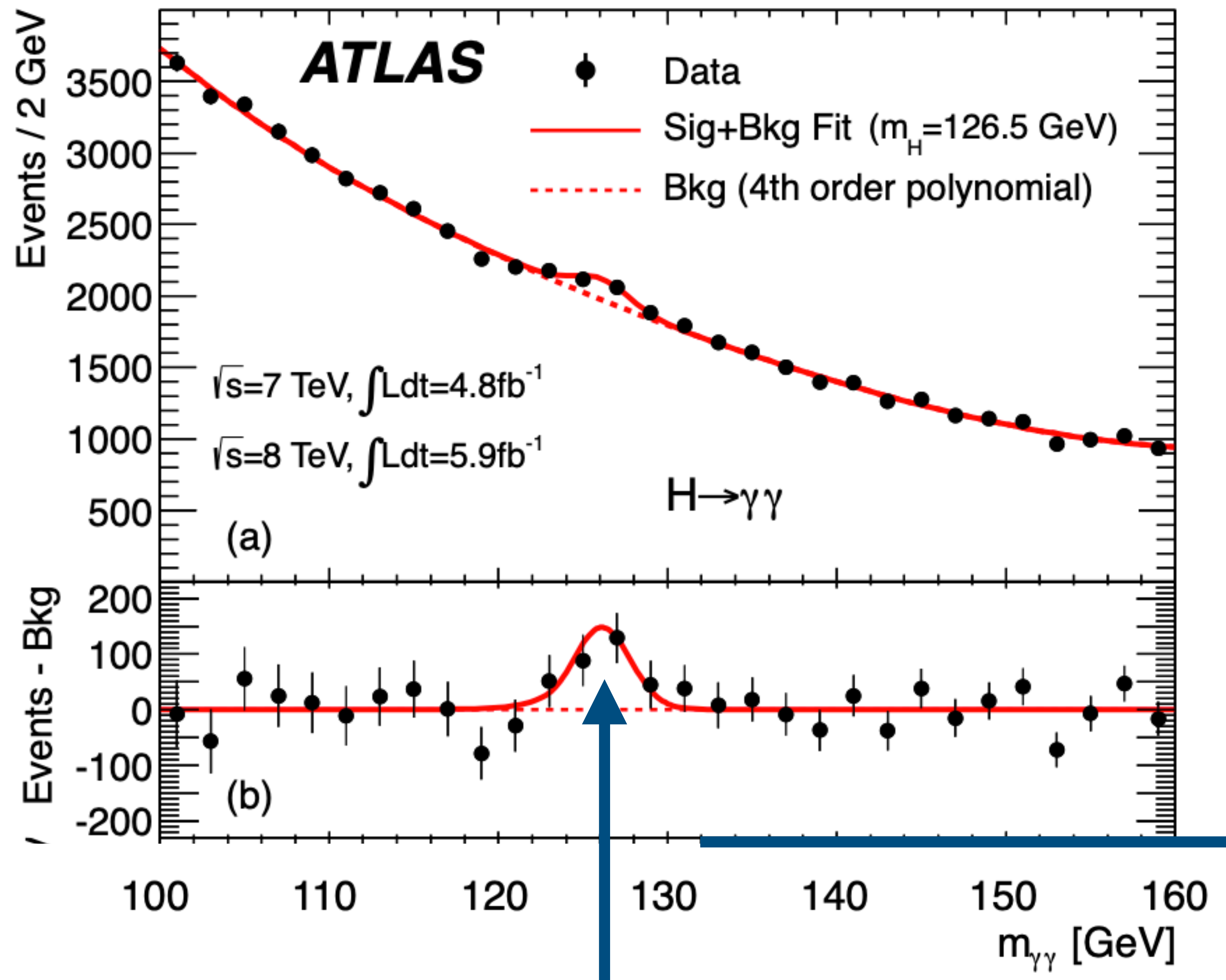
July 2012.

Example, $p + p \to H \to \gamma + \gamma$.

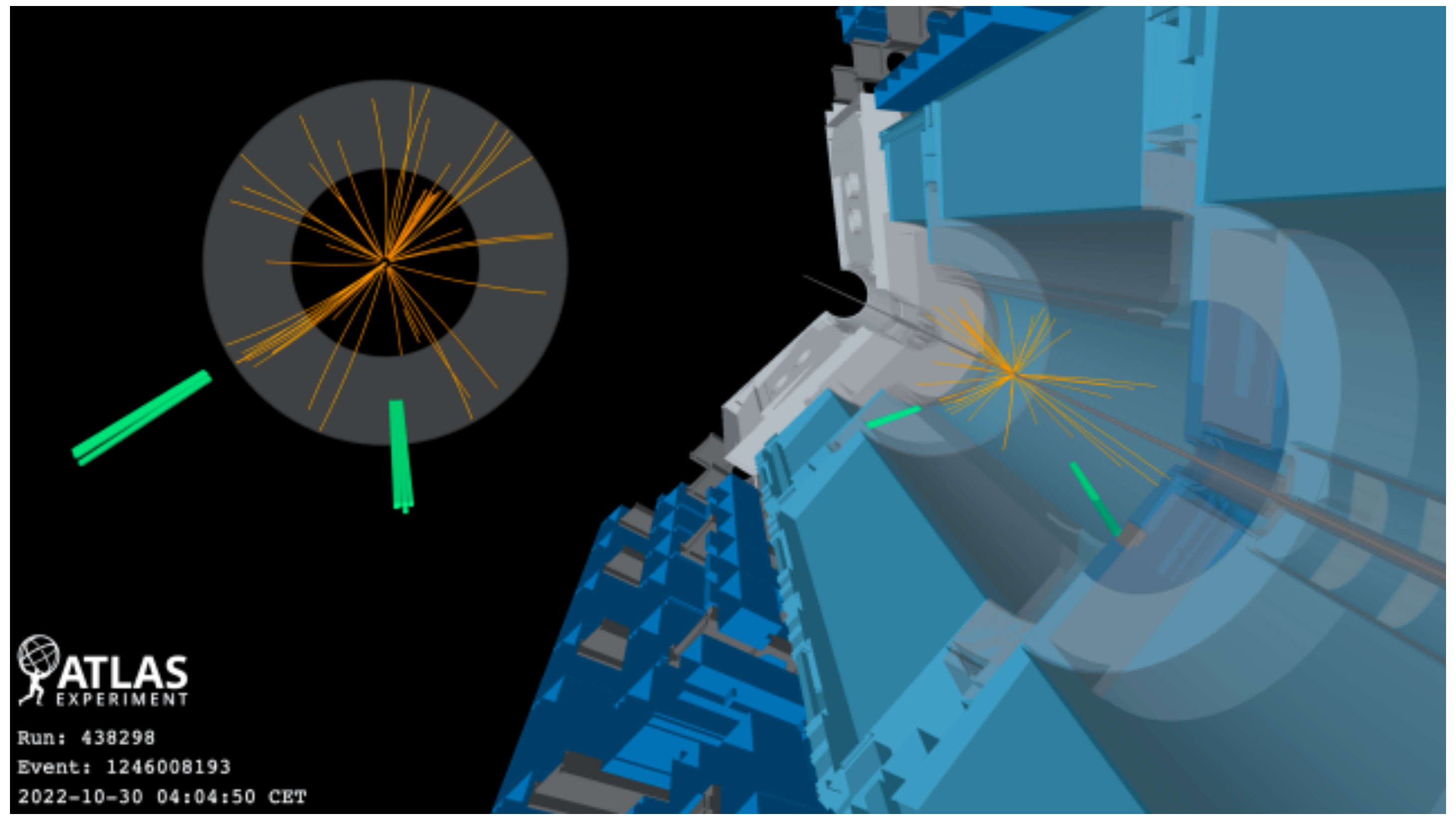


ATLAS, Phys.Lett. B716 (2012) 1-29

4-momentum

$m_{\gamma\gamma}\,(m_{\gamma\gamma}^2 \equiv (p_{\gamma_1} + p_{\gamma_2})^2)$

m_H

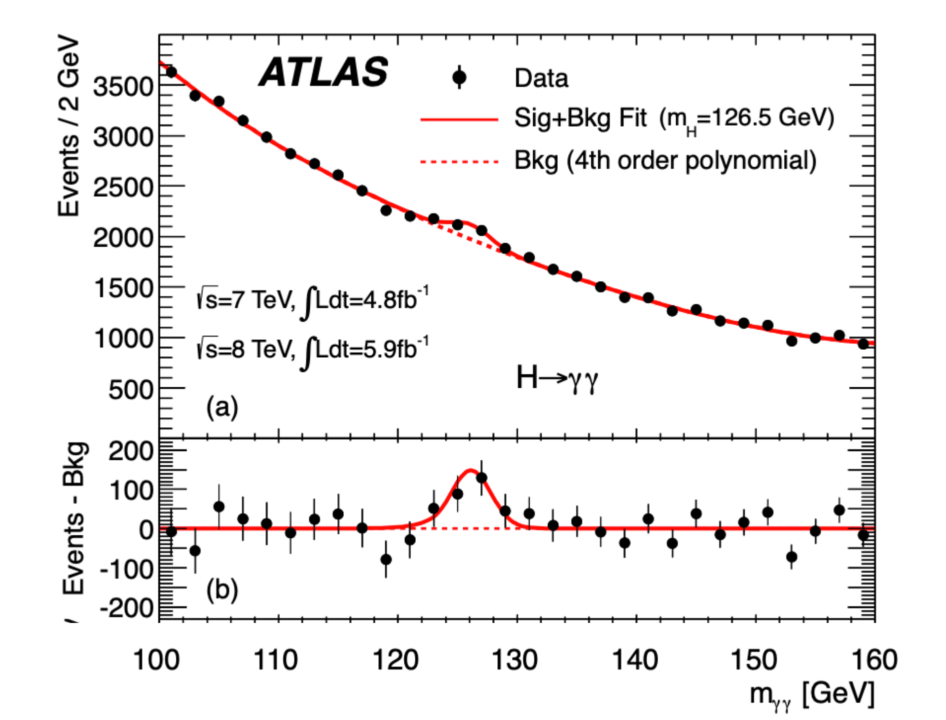


Event displays for a $H \to \gamma\gamma$ candidate event
ATLAS Event Displays

For the two photons produced from Higgs decay,
from energy-momentum conservation, $(p_{\gamma_1} + p_{\gamma_2})^2 = p_H^2 = m_H^2$.

(I guess we'll also learn this kind of kinematics/simulation in this school, right?)

Higgs



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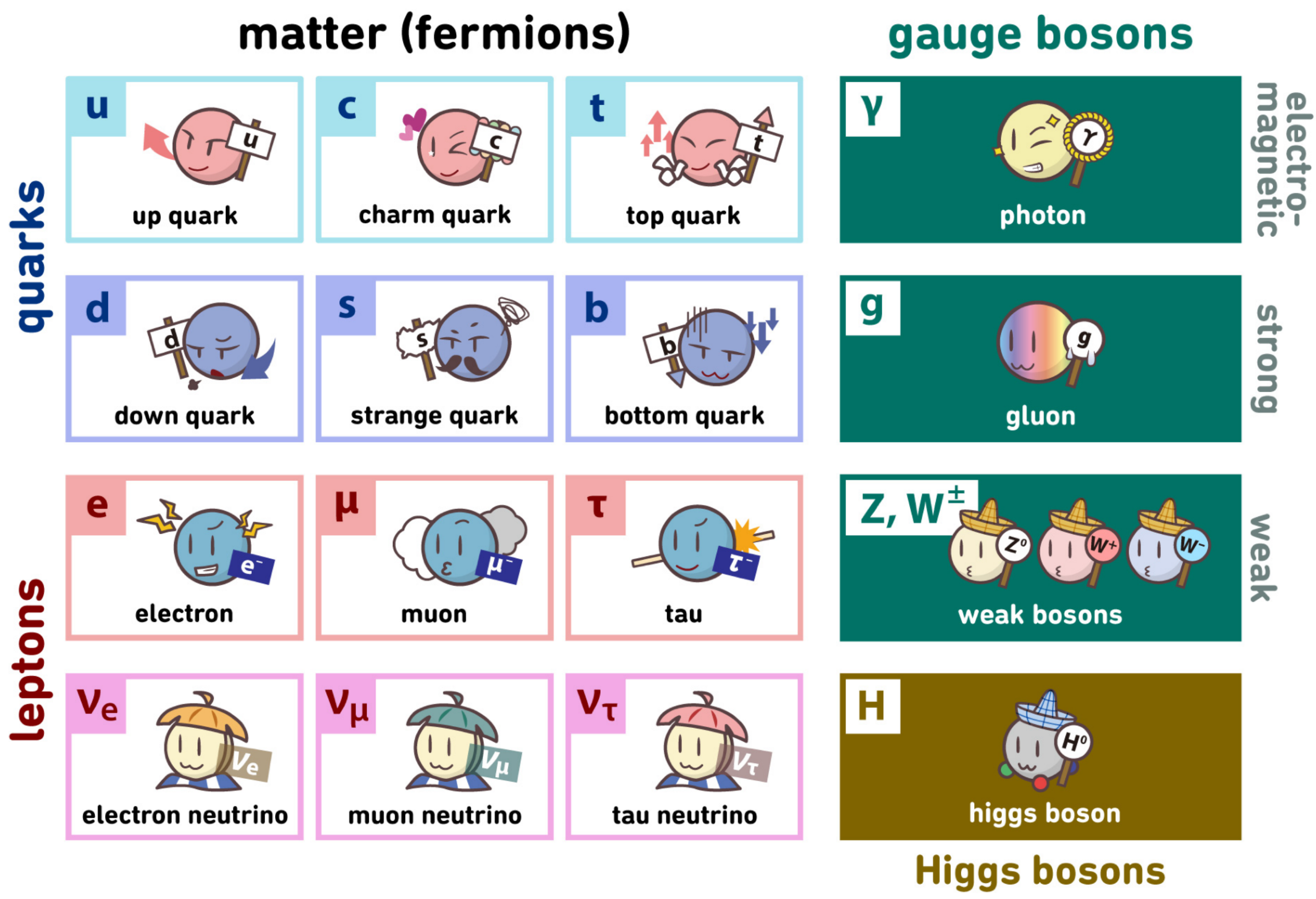

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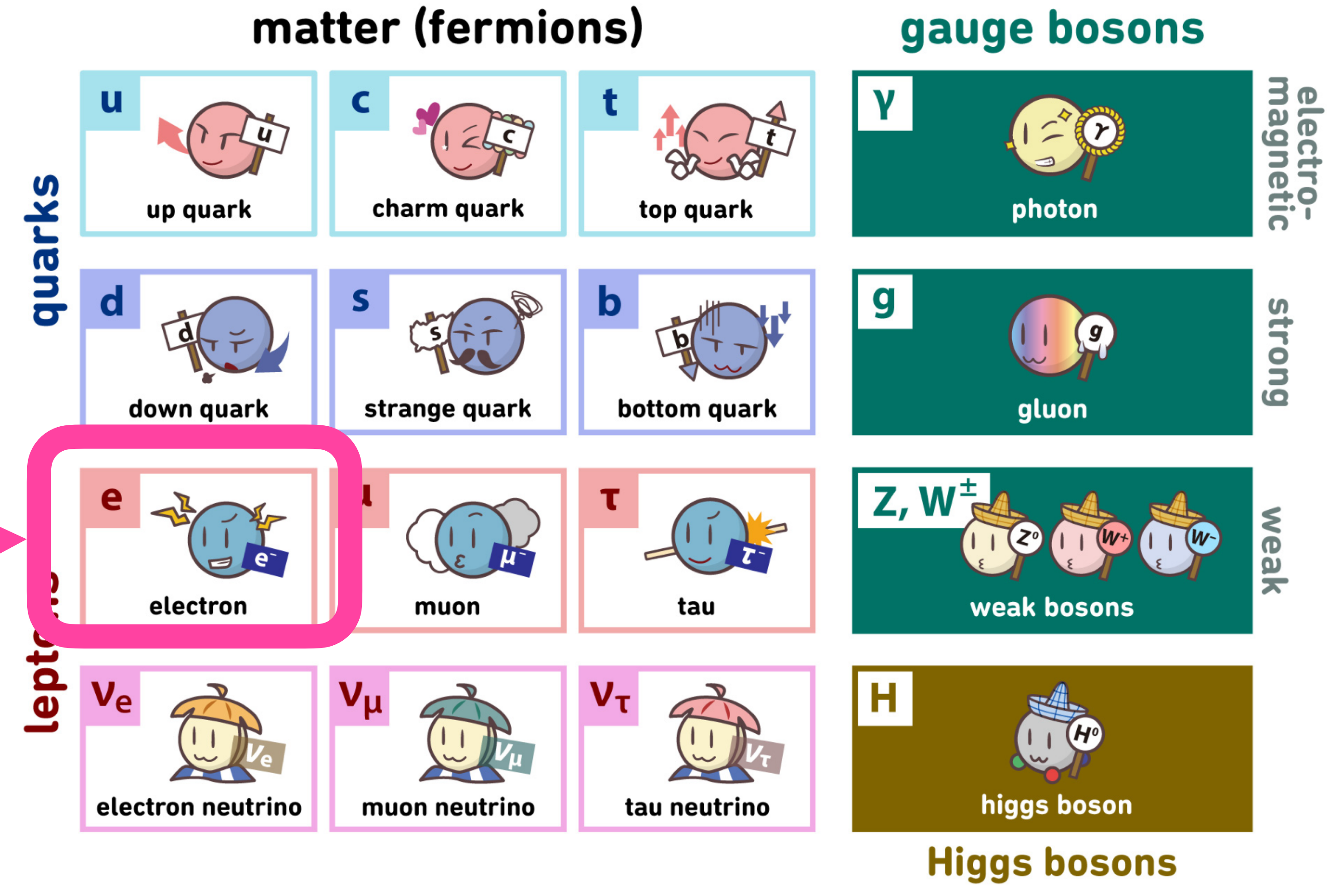

e.g. electron:

Higgs

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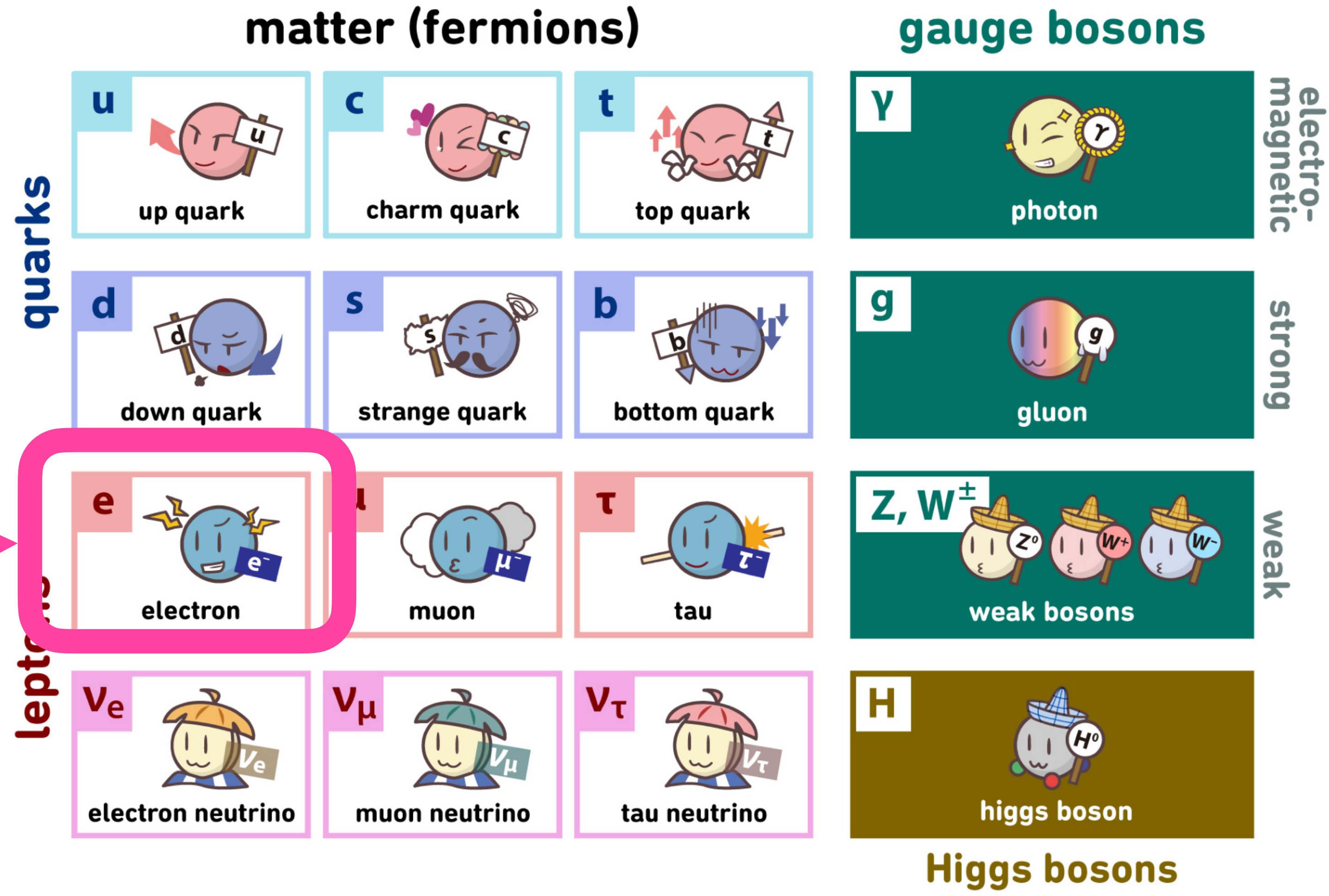

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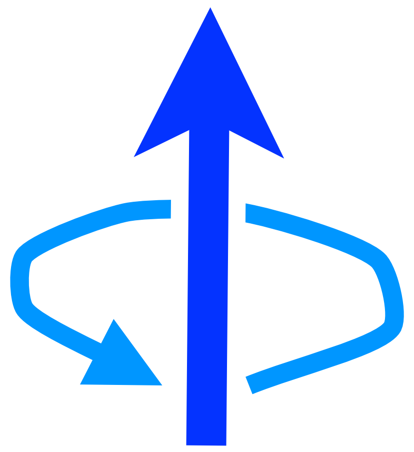

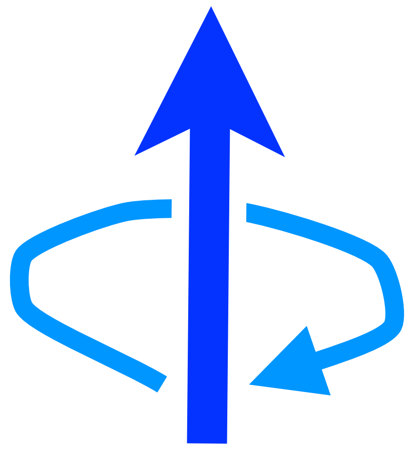

e = right-handed e_R + left-handed e_L

(not weakly interacting) (weakly interacting)

Higgs

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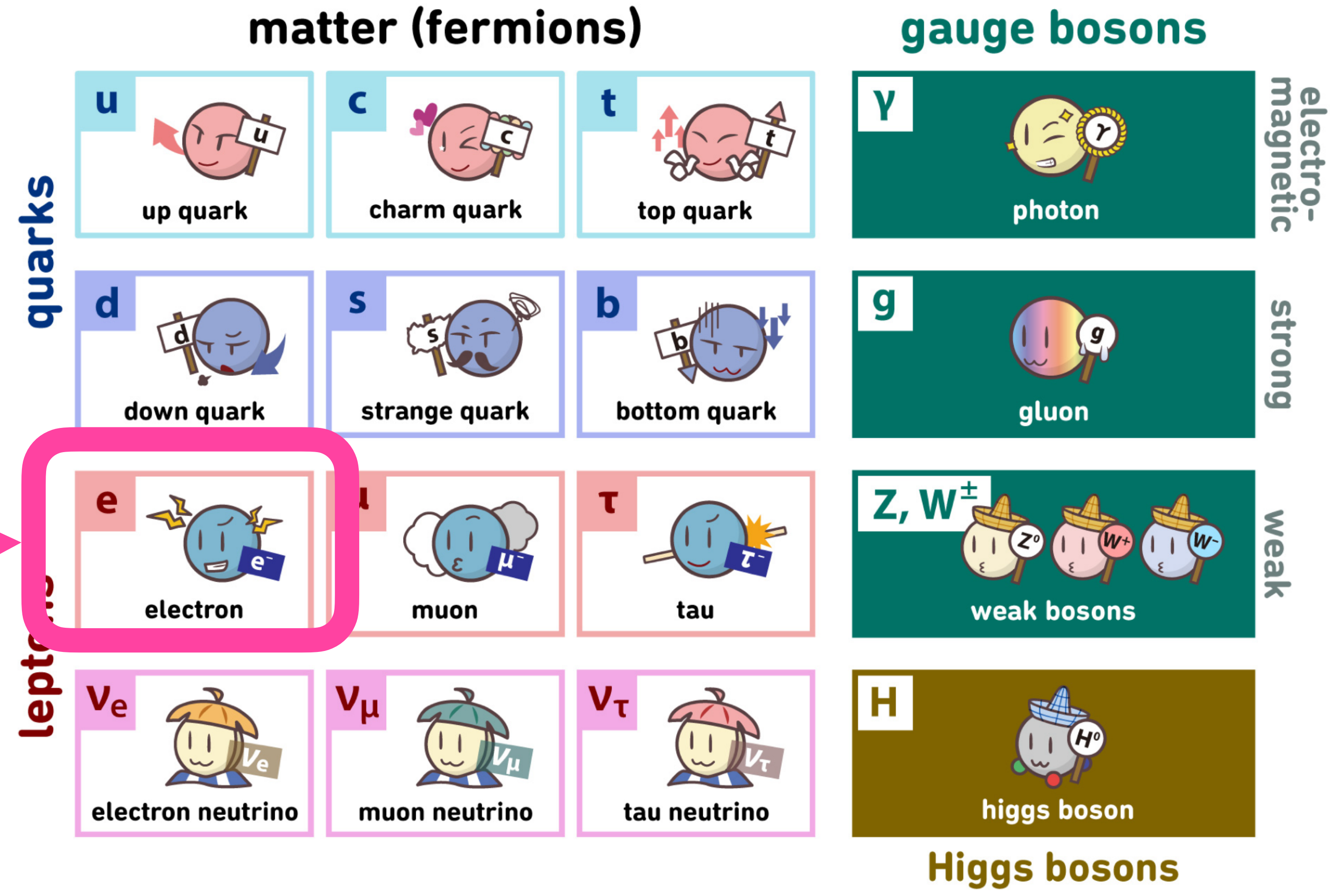

e.g. electron: **without Higgs,.....**

(not weakly interacting)

right-handed e_R

left-handed e_L

(weakly interacting)

different particles
zero masses
(moving with a speed of light)

Higgs

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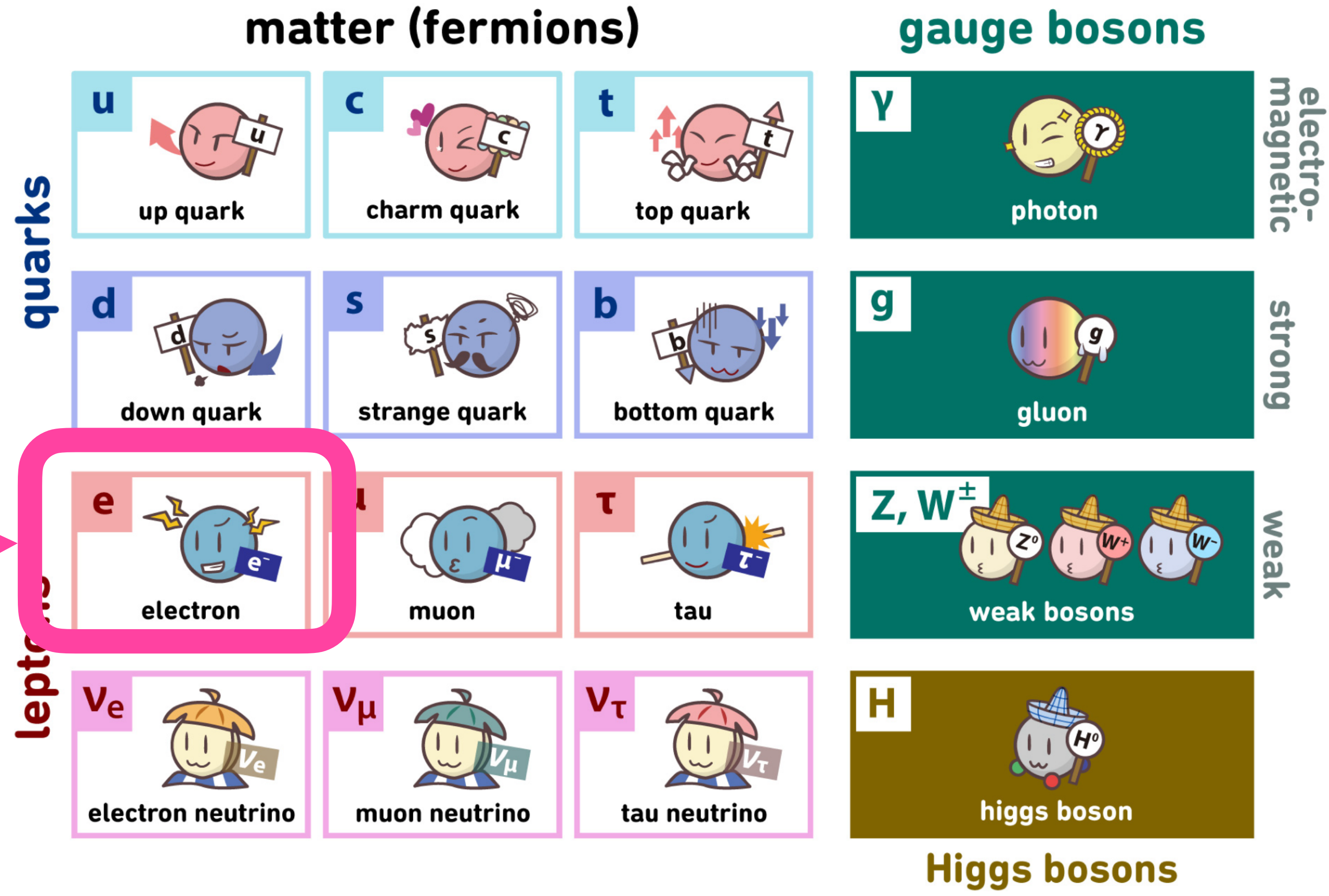

e.g. electron: the **Higgs** connects the two components.

(not weakly interacting)

right-handed e_R

left-handed e_L

(weakly interacting)

Higgs

Yukawa interaction

Higgs

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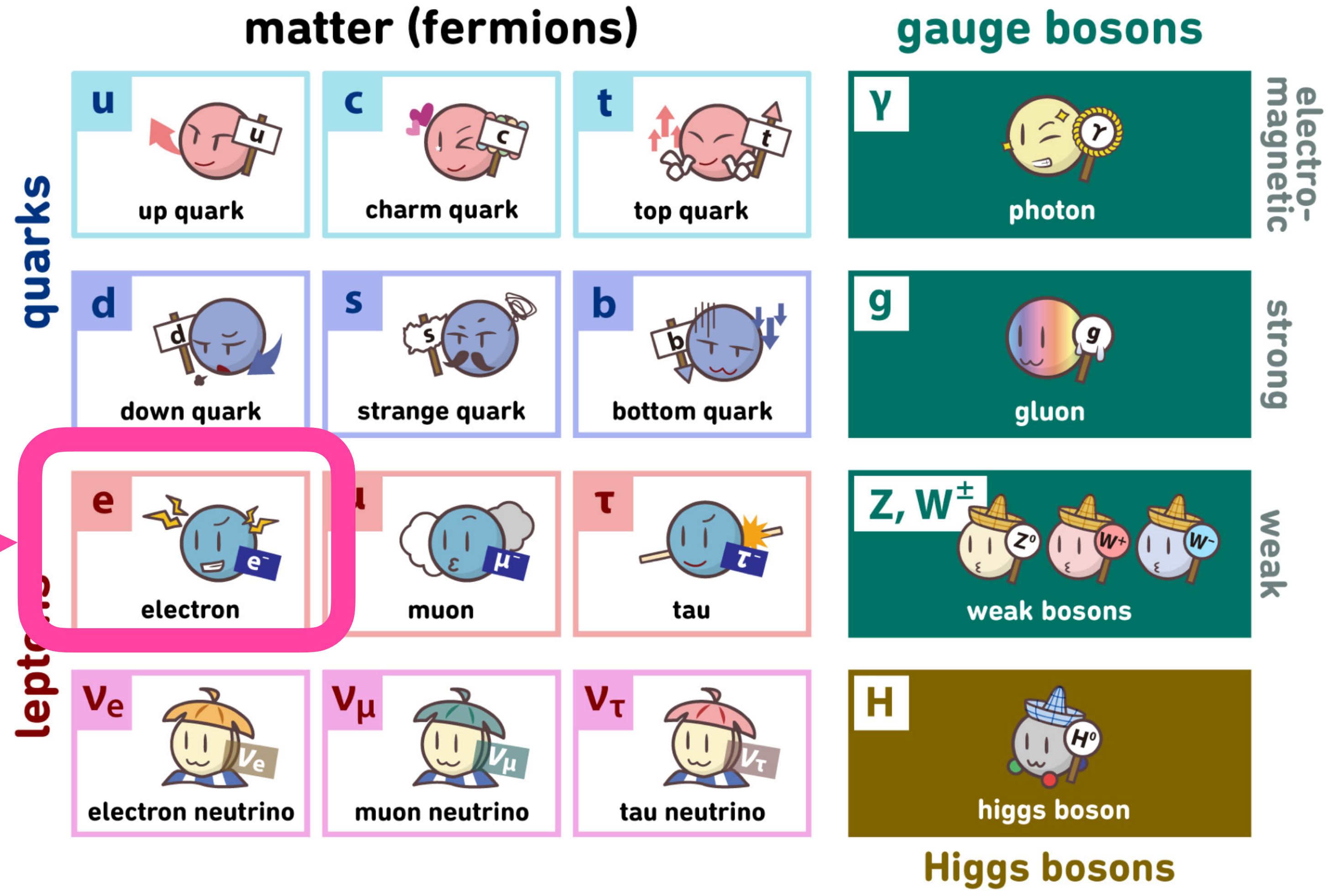
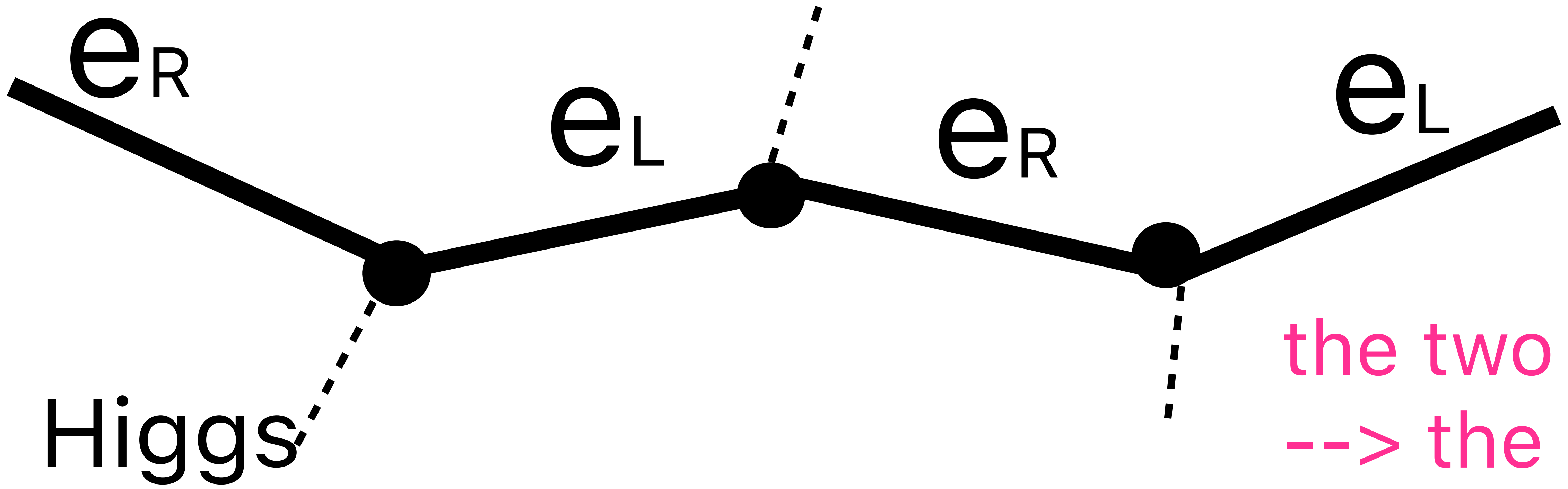


e.g. electron:

thanks to the "Higgs condensation in vacuum"....



the two components are exchanged
--> the electron gets a **mass.**

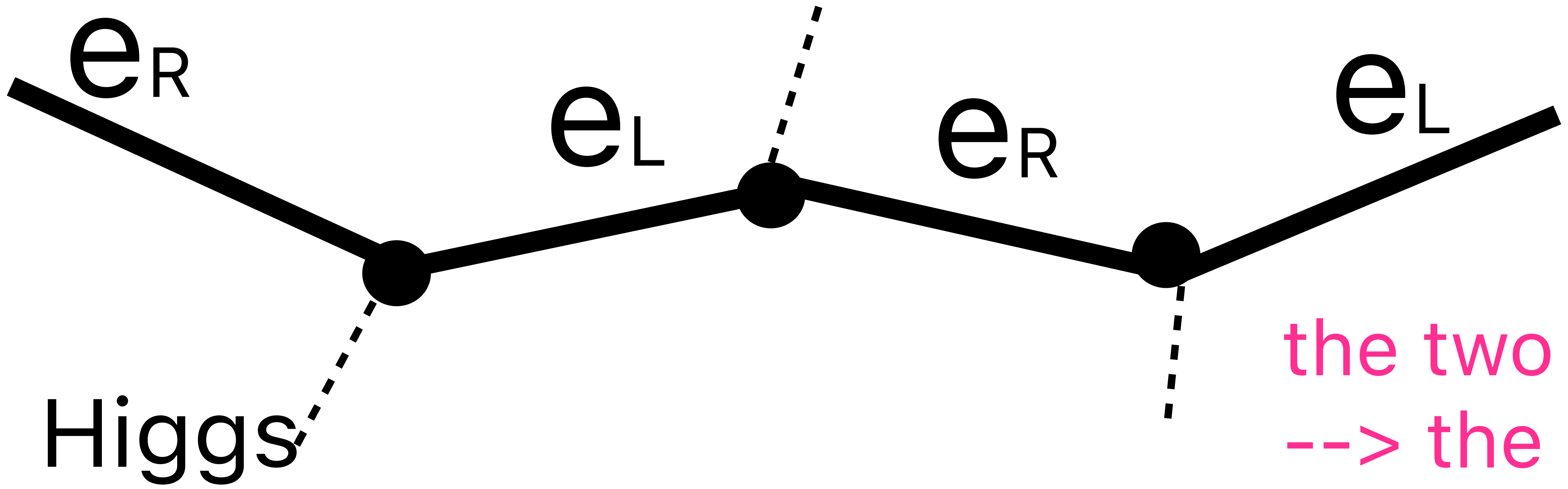
Higgs

What does this
"Higgs condensation in vacuum"
mean?

Well,...

e.g. electron:

thanks to the "Higgs condensation in vacuum"....



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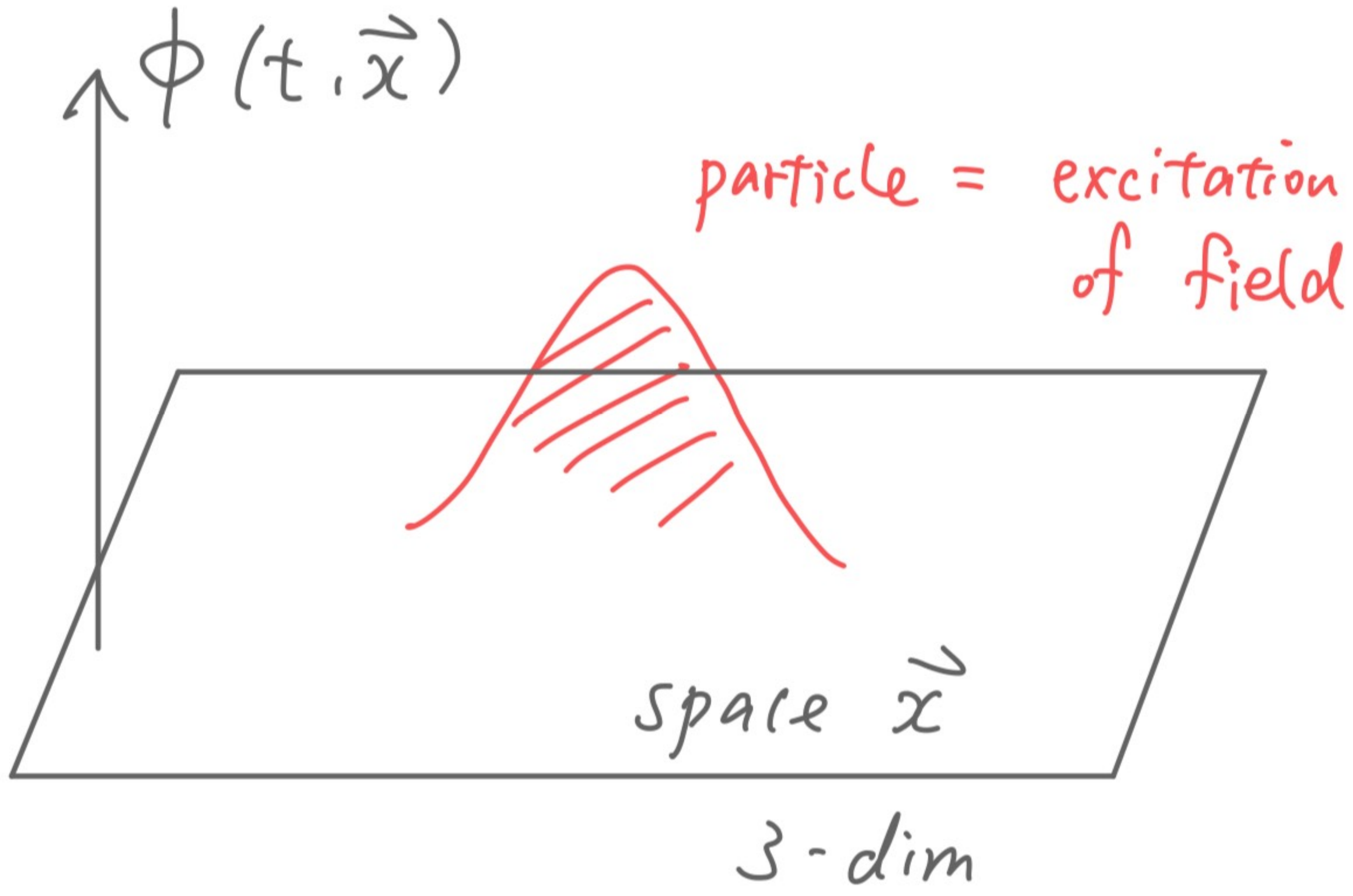
Higgs

- In quantum field theory, the particles are described by excitations of fields.

particle $\phi \leftrightarrow \phi(t, \vec{x})$



… like a wave packet in quantum mechanics

Higgs

- In quantum field theory, the particles are described by excitations of fields.
- Vacuum = ground state = minimum of Hamiltonian.
- Hamiltonian of the Higgs field, $H(t,\vec{x})$, is given by

$$\mathscr{H} = \int d^3x \left[\left(\frac{d}{dt} H(t,\vec{x}) \right)^2 + \left(\vec{\nabla} H(t,\vec{x}) \right)^2 + V\left(H(t,\vec{x})\right) \right]$$

minimize

$$\frac{d}{dt} H(t,\vec{x}) = 0$$

minimize

$$\vec{\nabla} H(t,\vec{x}) = 0$$

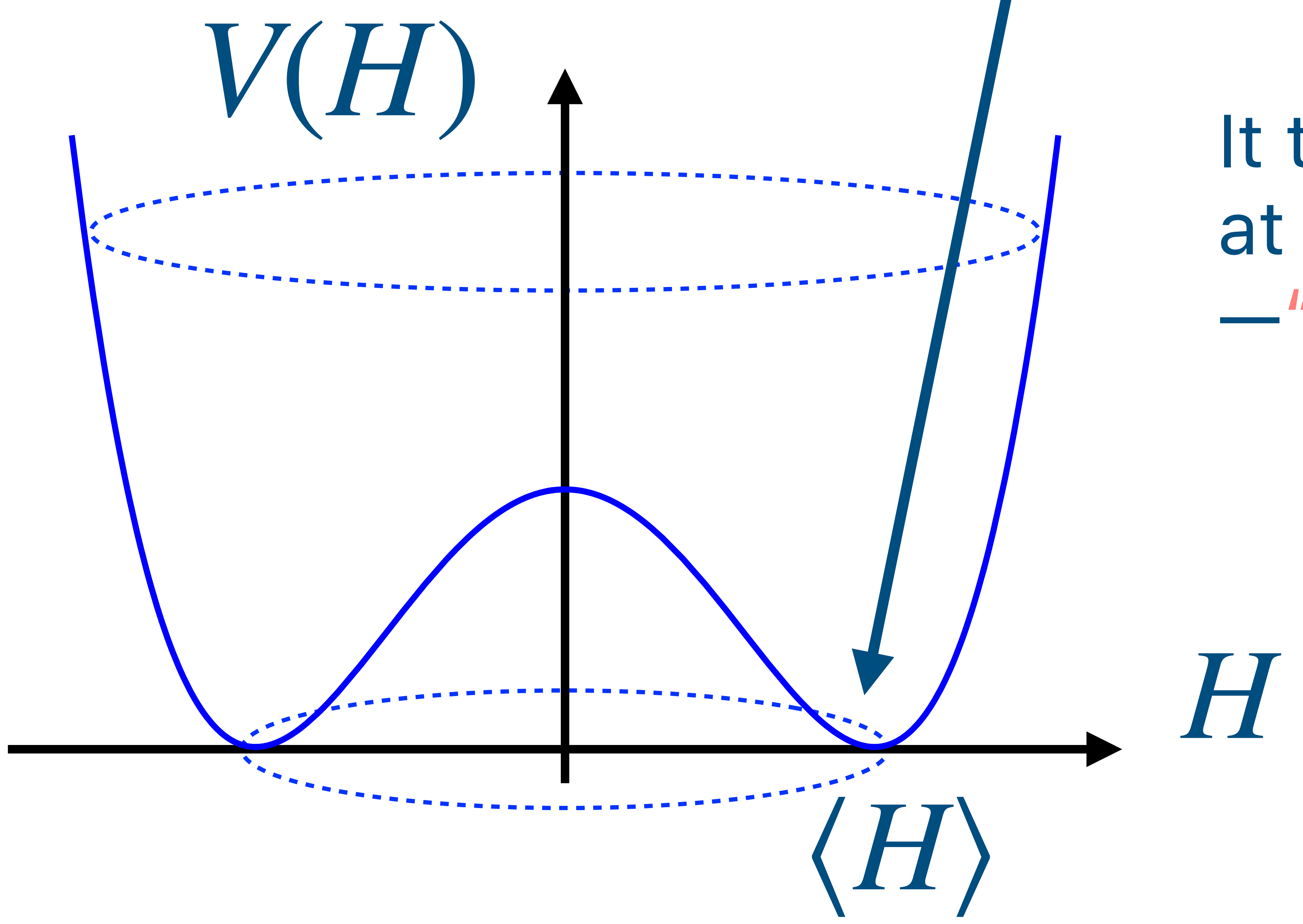
$\rightarrow H(t,\vec{x}) =$ constant.

Higgs

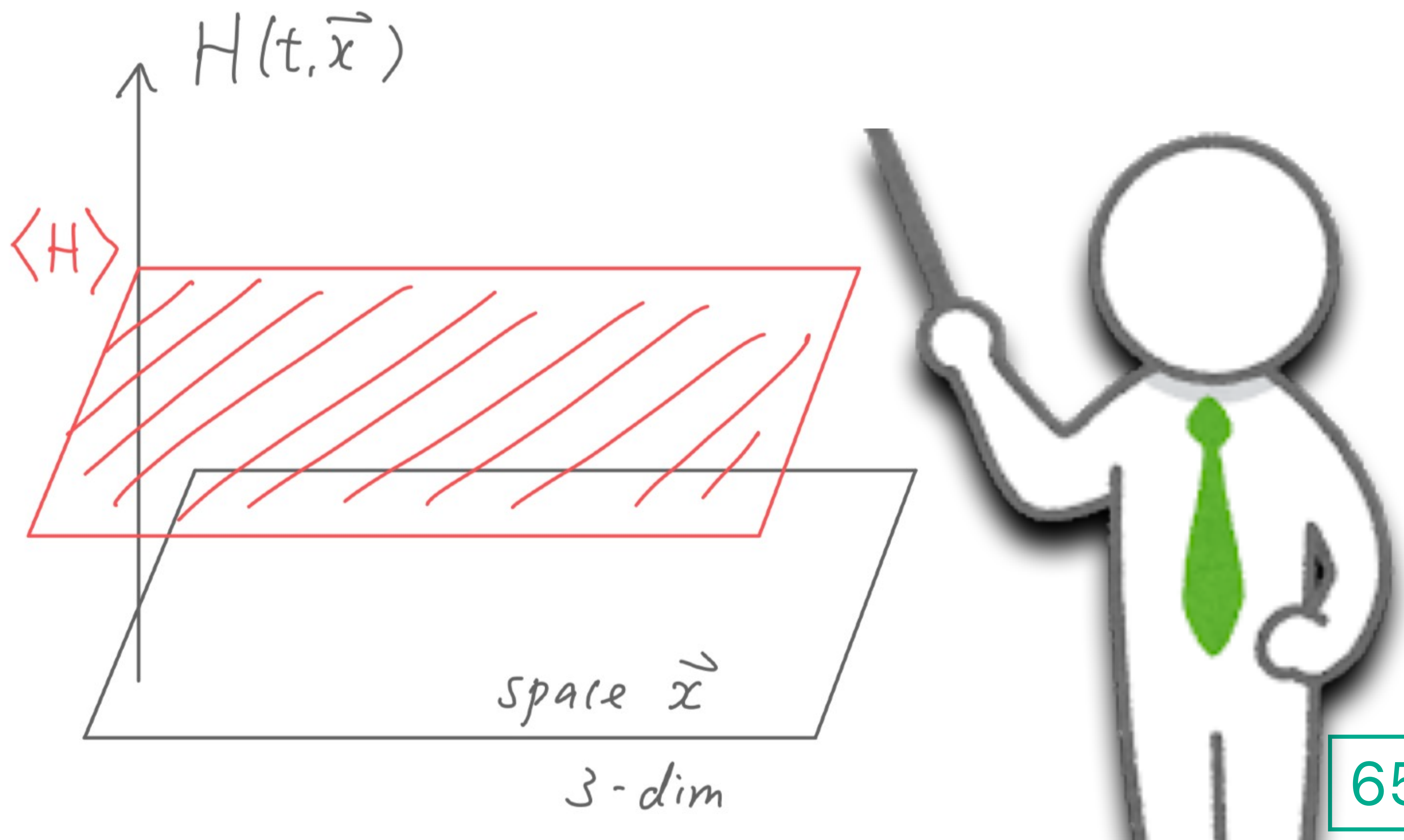
- In quantum field theory, the particles are described by excitations of fields.
- Vacuum = ground state = minimum of Hamiltonian.
- Hamiltonian of the Higgs field, $H(t,\vec{x})$, is given by

$$\mathscr{H} = \int d^3x\, V\left(H(t,\vec{x})\right)$$

minimize $\to H(t,\vec{x}) = \langle H \rangle \simeq 174\ \text{GeV}.$



It takes the same nonzero value
at every point in spacetime
—"Higgs condensation in vacuum"



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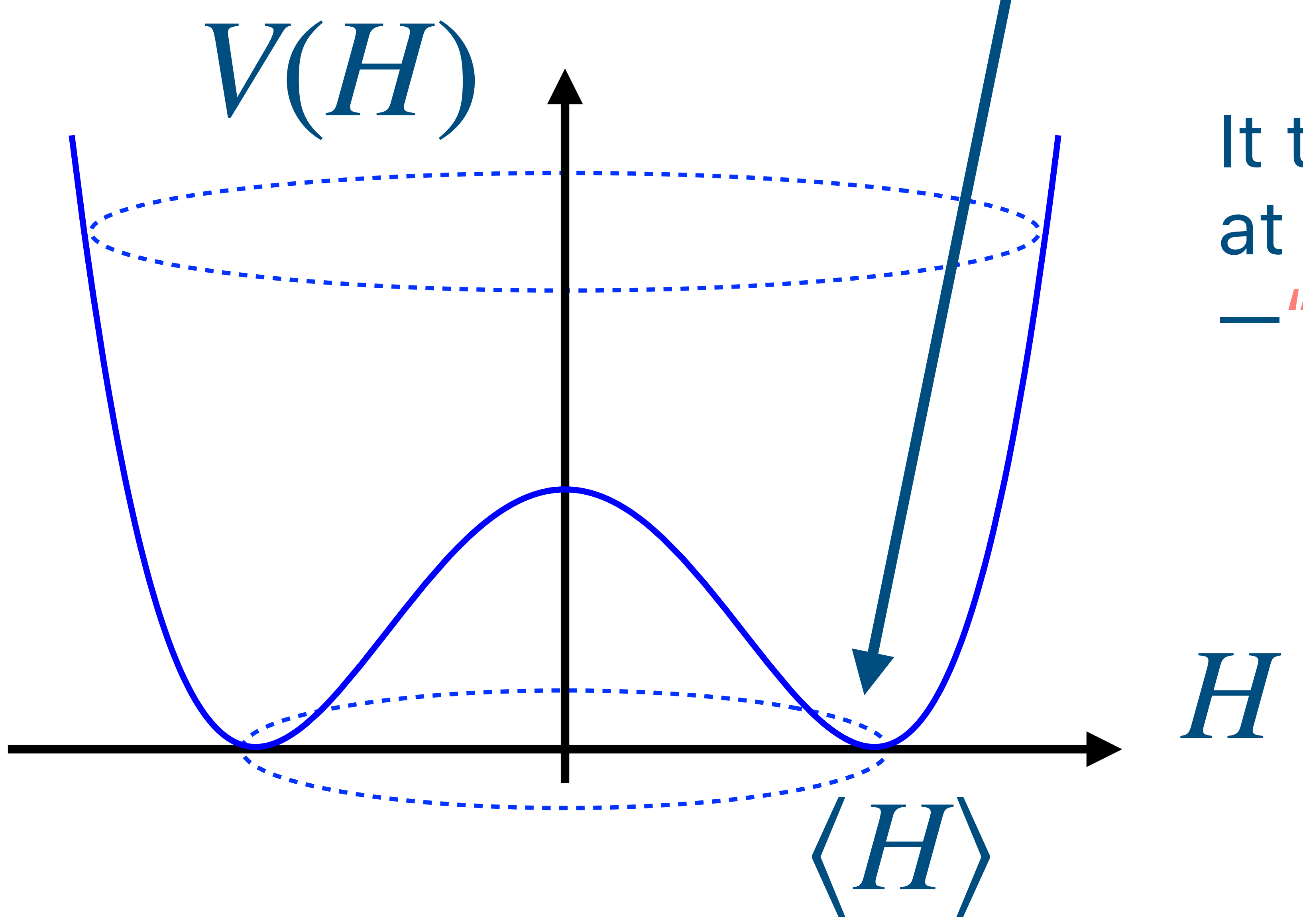

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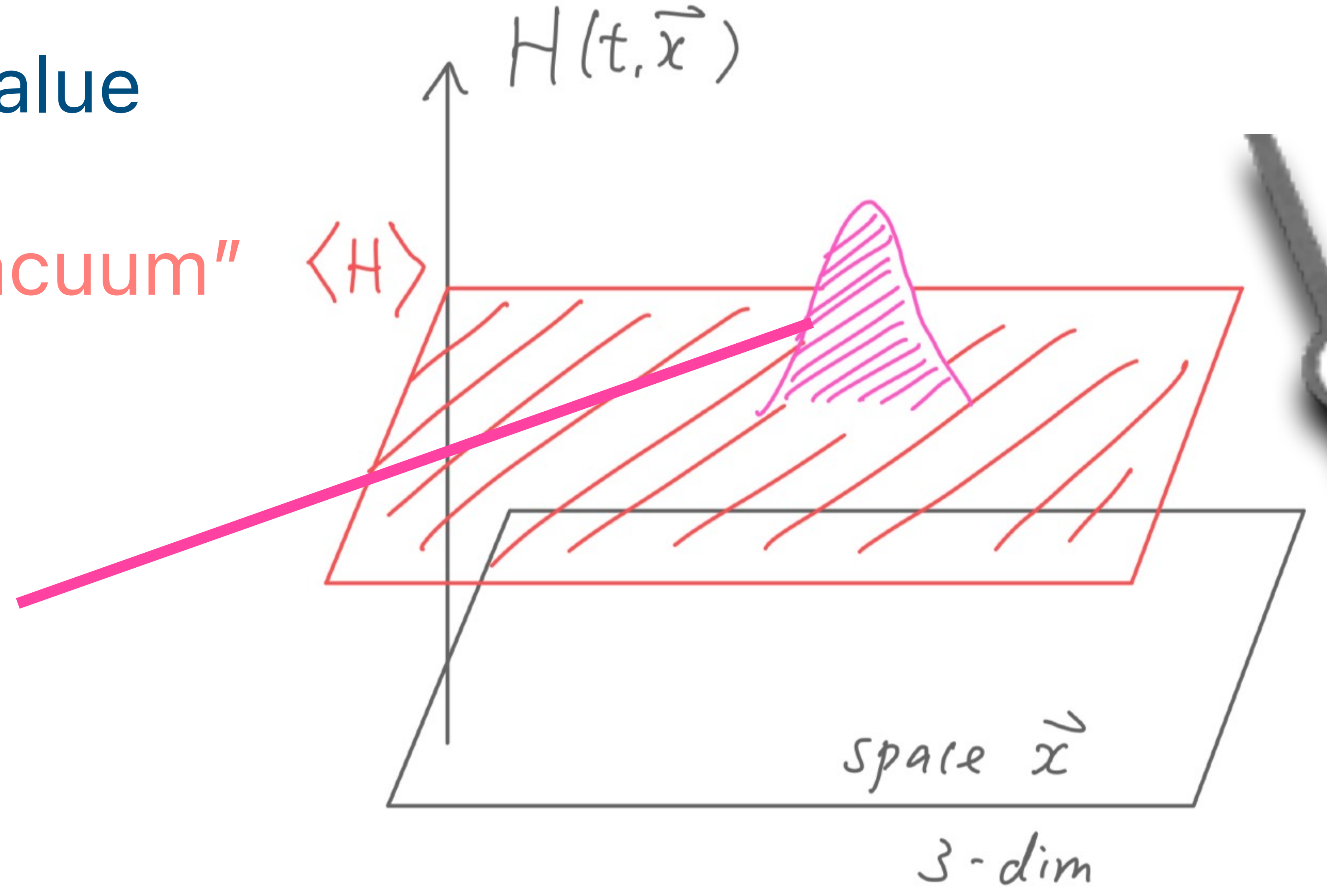
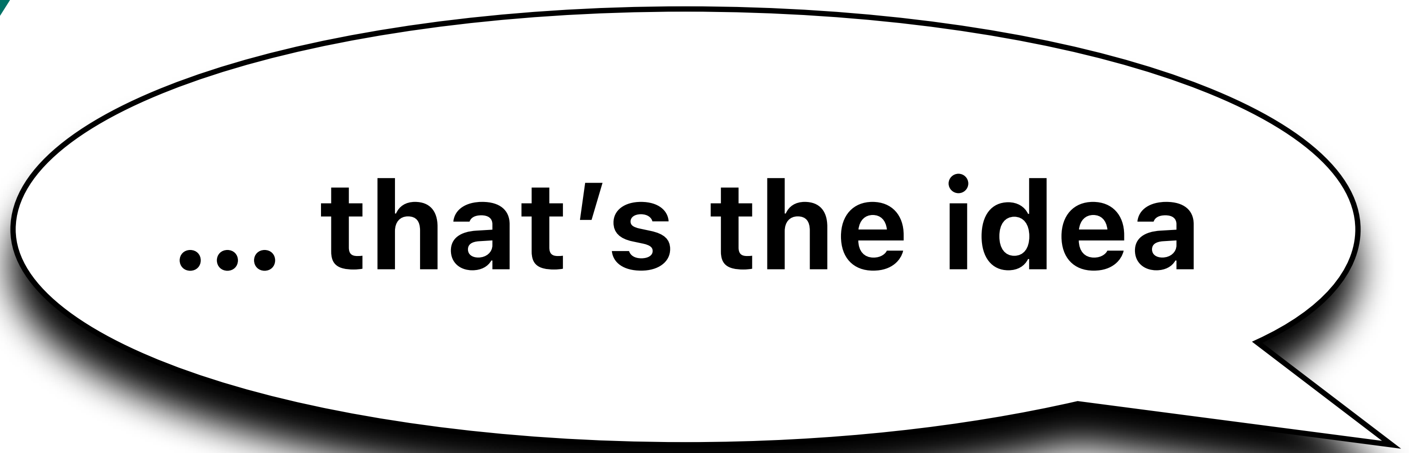


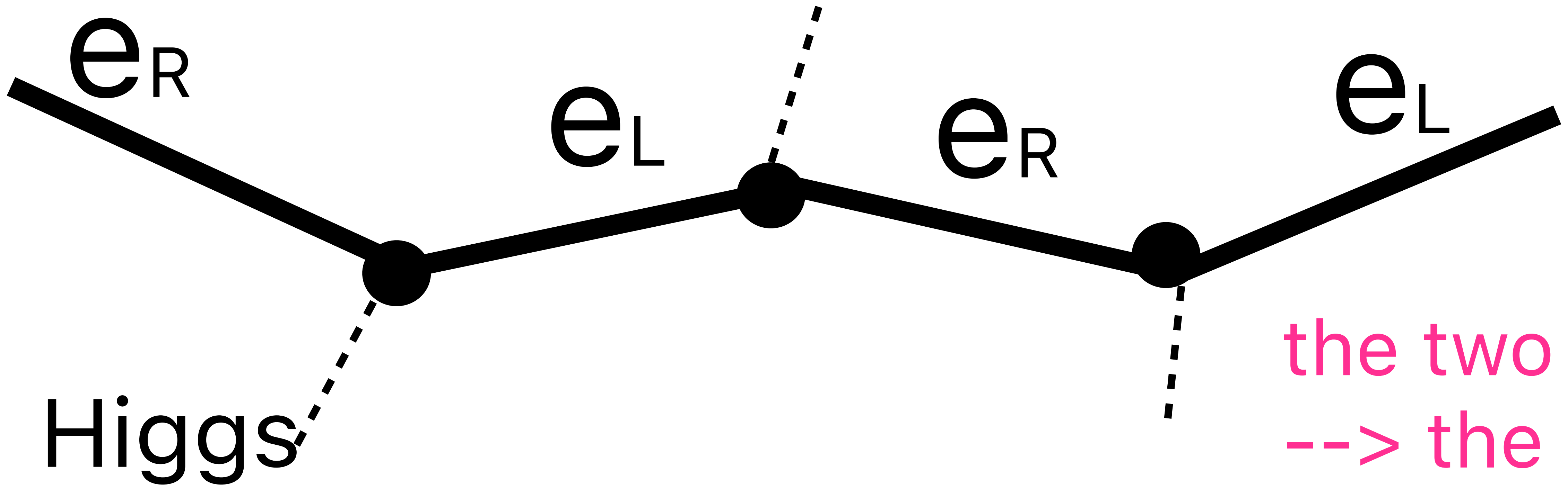
Higgs boson
(particle)

Higgs



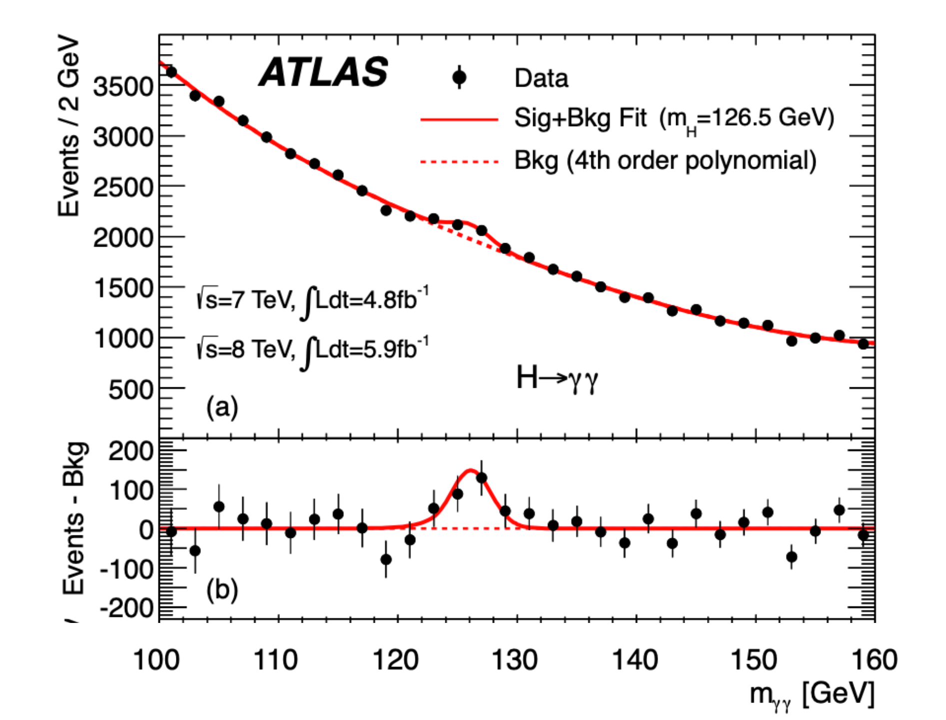
e.g. electron:

thanks to the "Higgs condensation in vacuum"....



the two components are exchanged
--> the electron gets a **mass.**

Higgs



ATLAS, Phys.Lett. B716 (2012) 1-29

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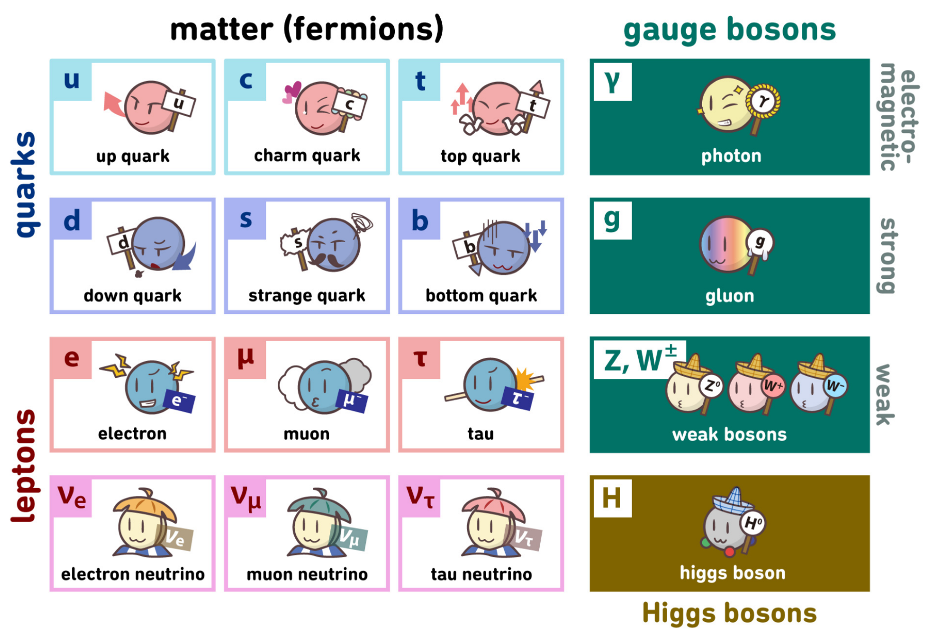
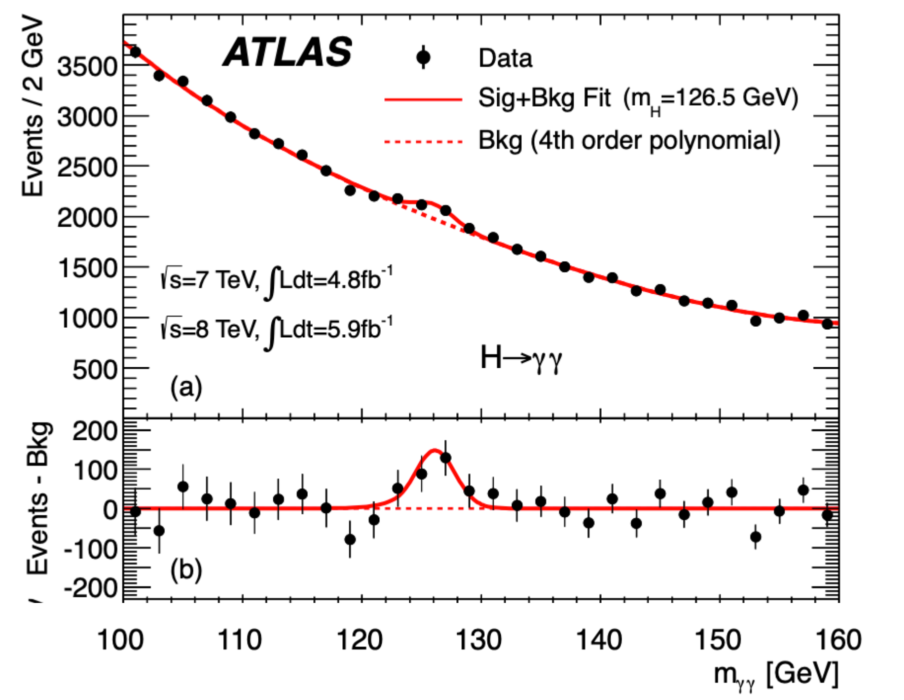


Higgs



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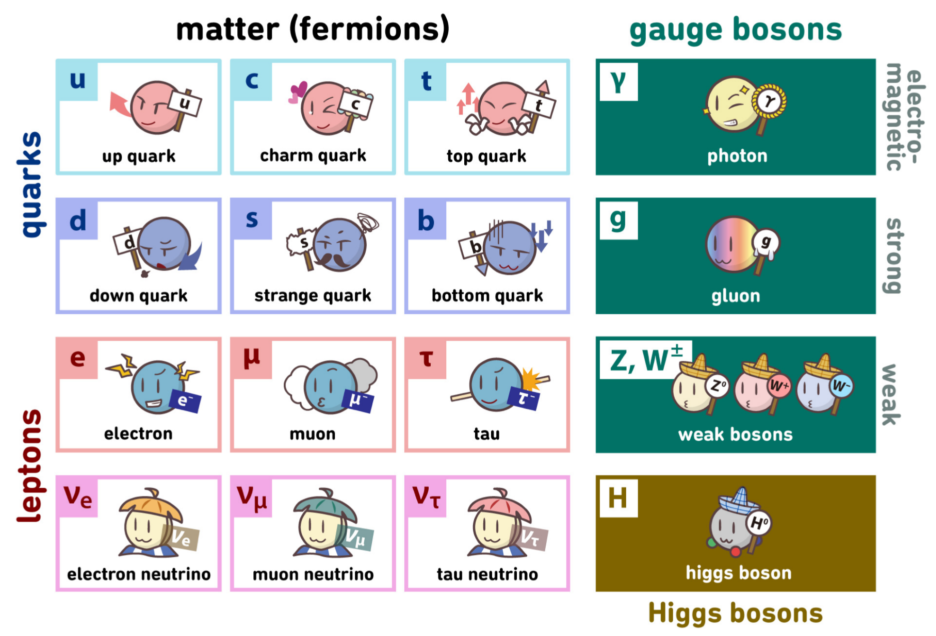


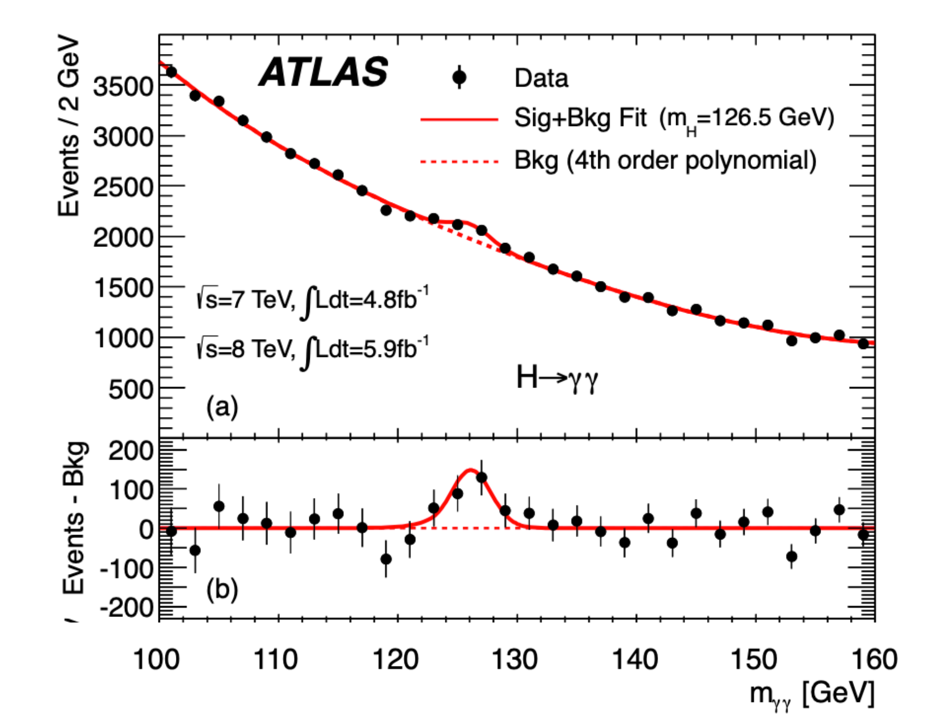
2. The **origin of** all the elementary particles' **masses**.

3. The **origin of electroweak symmetry breaking.**

Several key aspects:

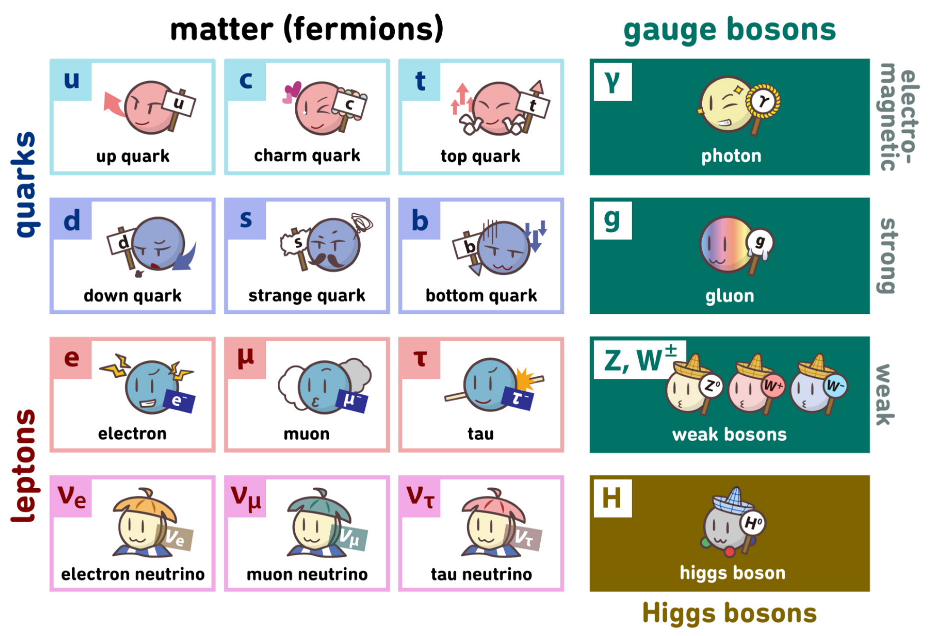
- **Spontaneous gauge symmetry breaking (Higgs mechanism):** Massless gauge bosons become massive.

Higgs



ATLAS, Phys.Lett. B716 (2012) 1-29

1. The **last** particle discovered in the Standard Model.



2. The **origin of** all the elementary particles' **masses**.

3. The **origin of electroweak symmetry breaking.**

Several key aspects:

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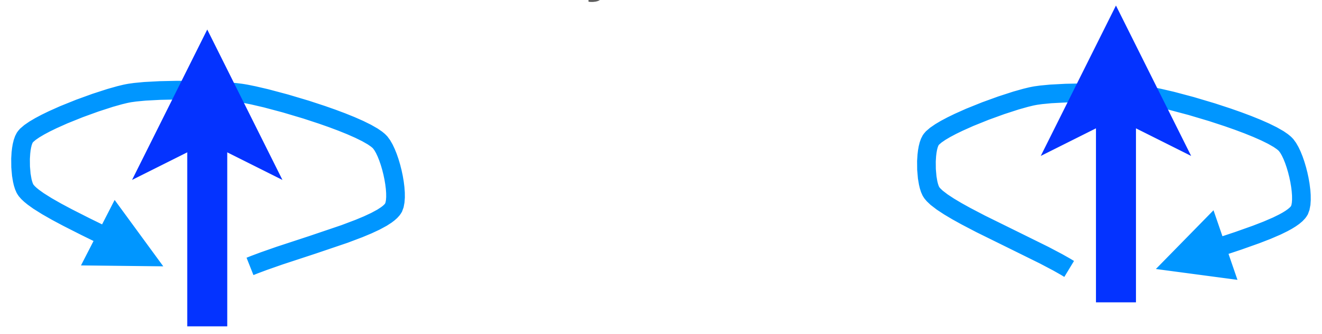
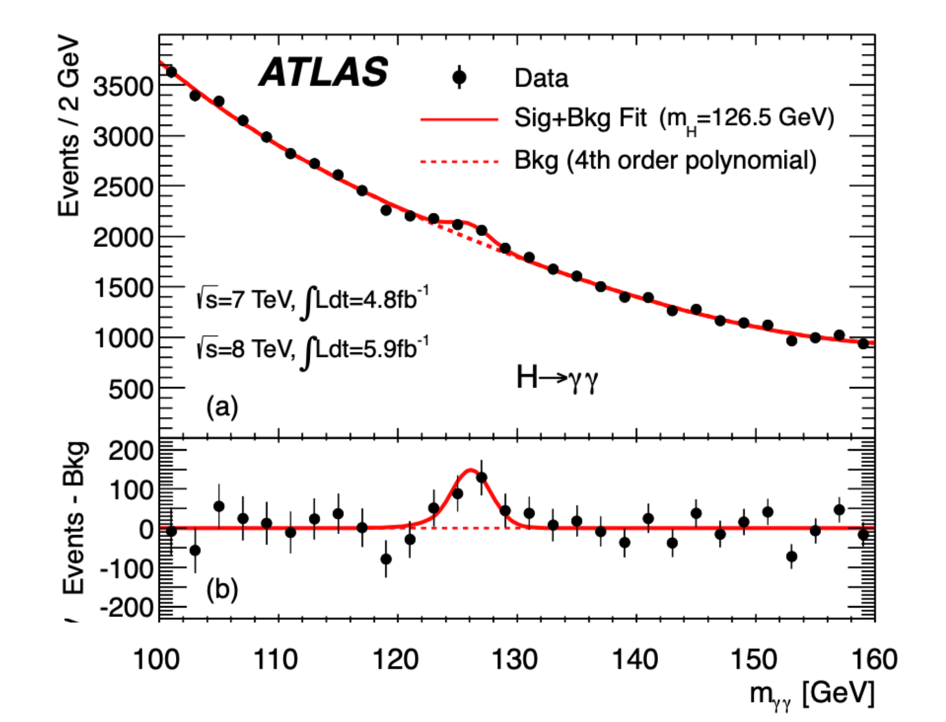
- **Chiral** gauge theory: left- and right-handed components interact differently.



e = right-handed eR + left-handed eL
(not weakly interacting) (weakly interacting)

Higgs



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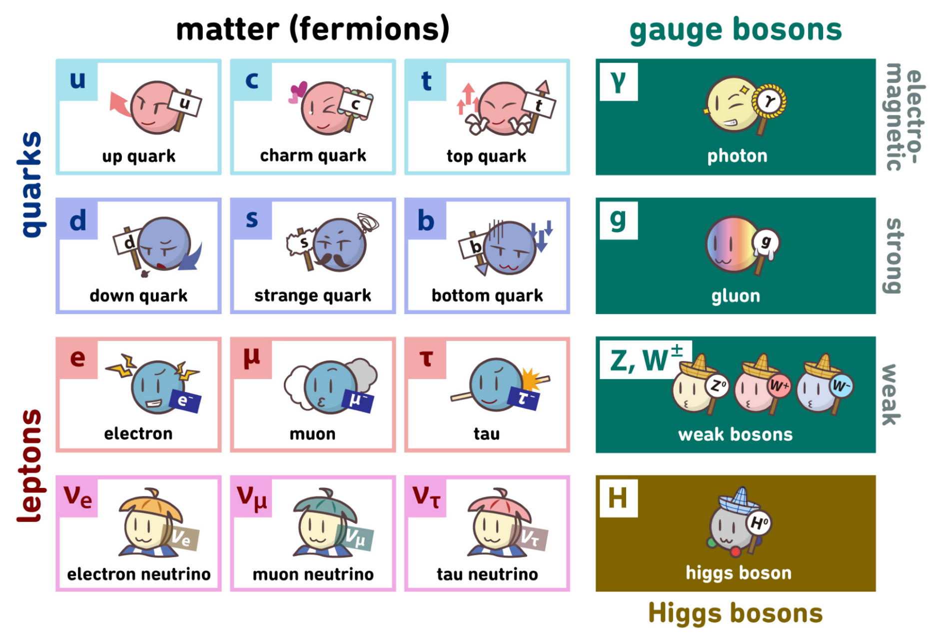

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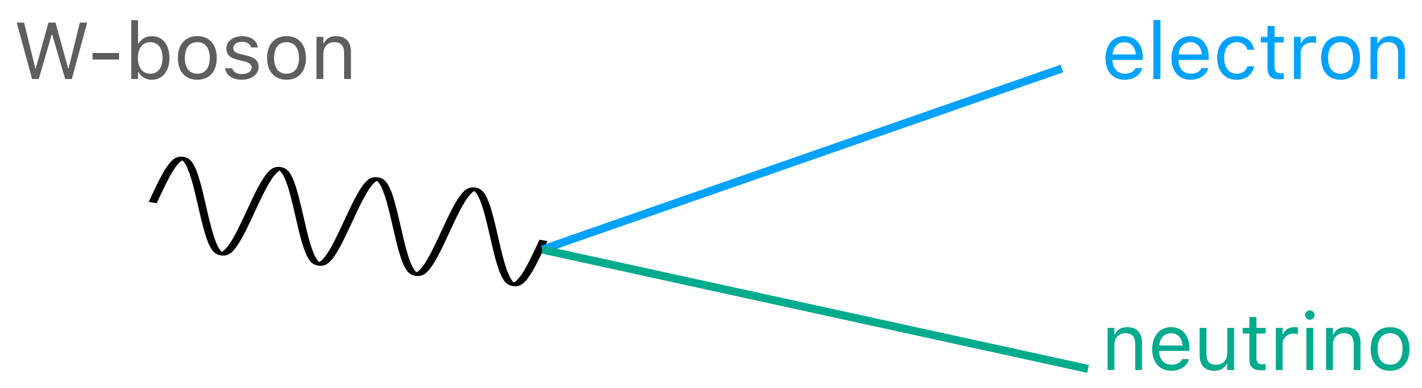
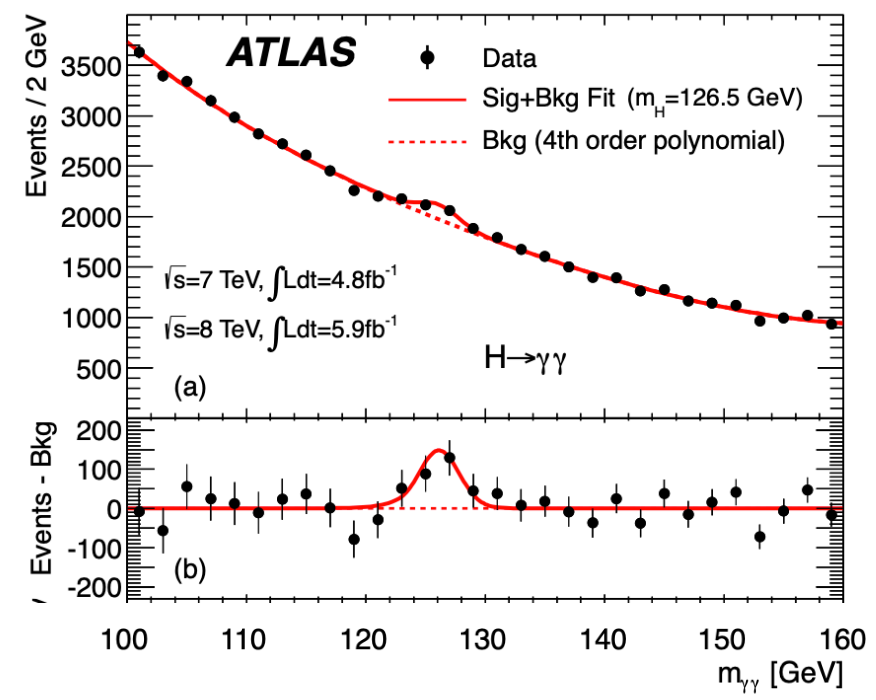


Non-Abelian Gauge interaction can change the particle species.

Higgs



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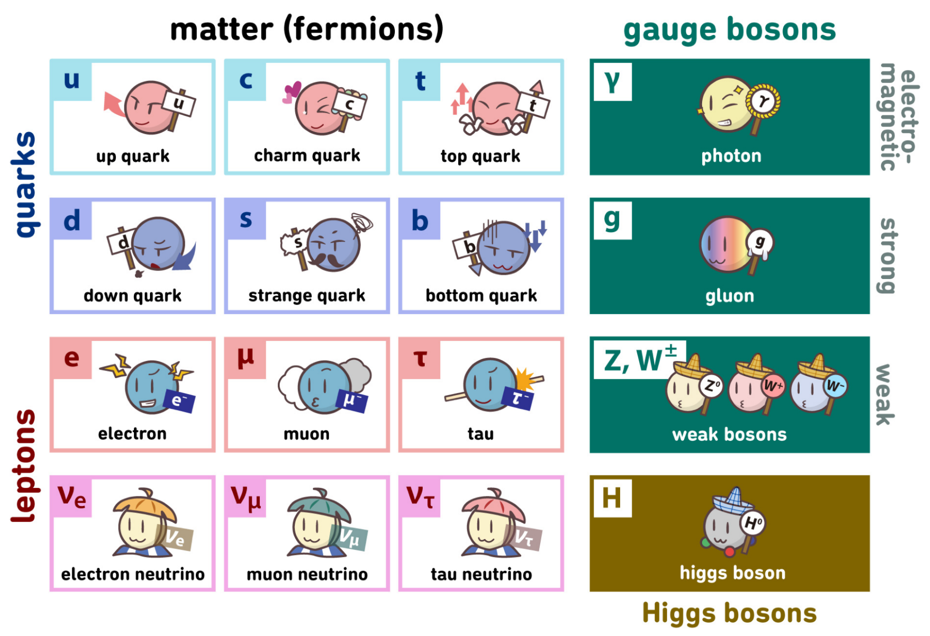

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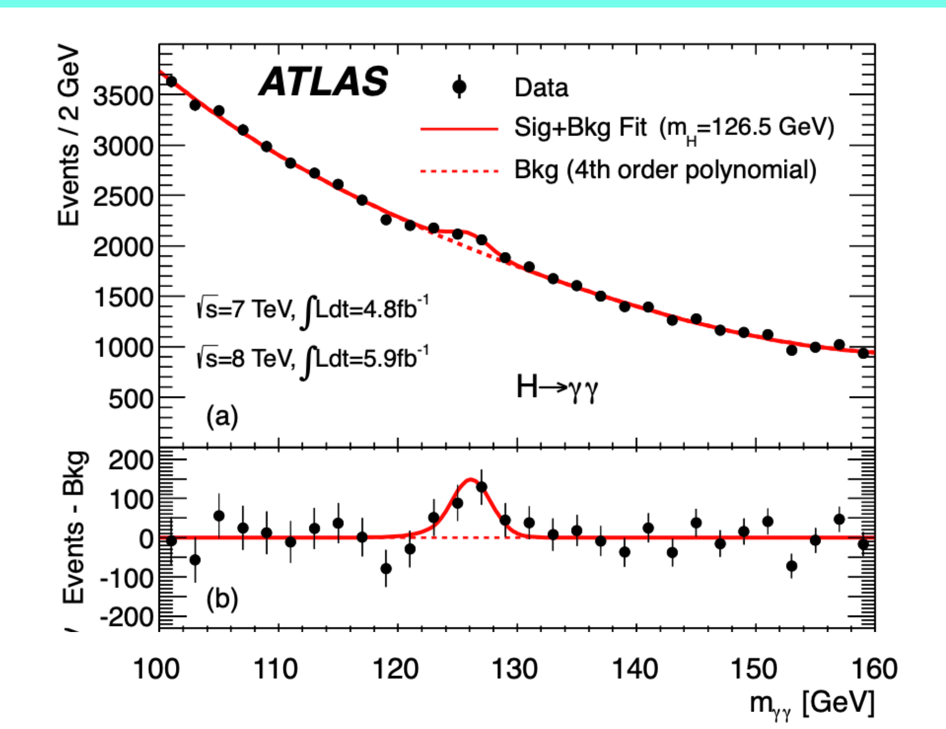
Higgs



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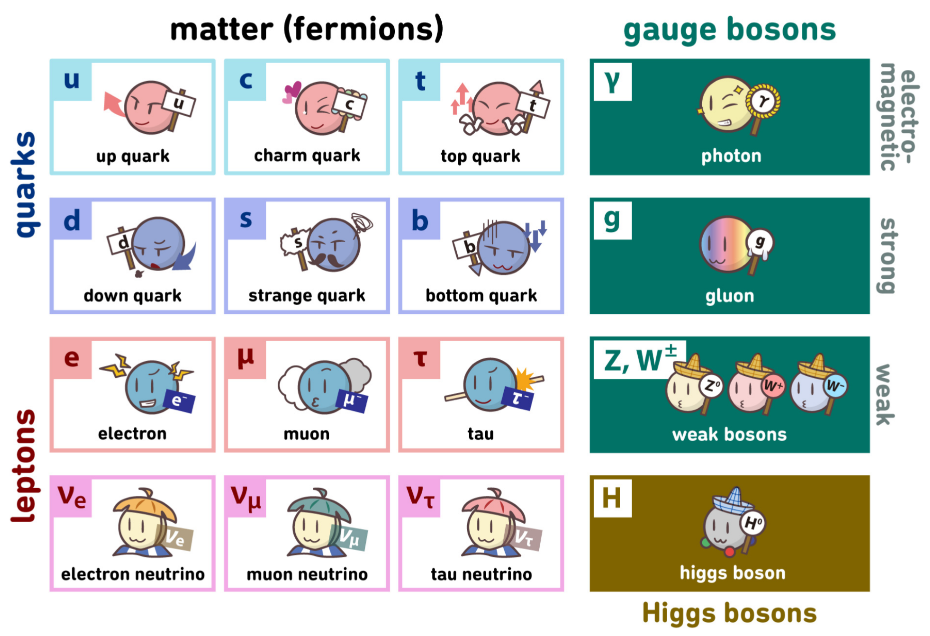

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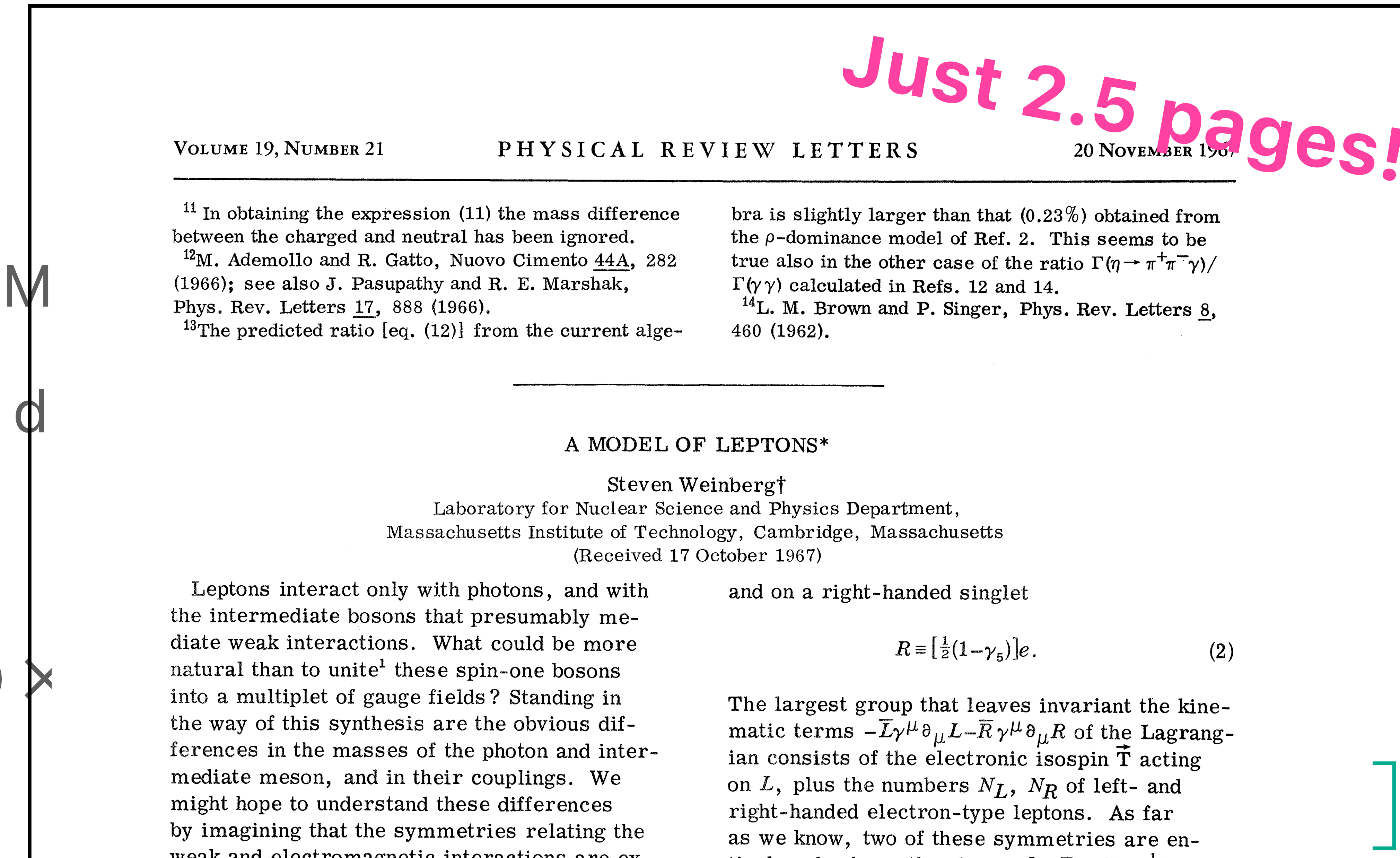
Just 2.5 pages!



VOLUME 19, NUMBER 21 PHYSICAL REVIEW LETTERS 20 NOVEMBER 1967

[11] In obtaining the expression (11) the mass difference between the charged and neutral has been ignored.
[12] M. Ademollo and R. Gatto, Nuovo Cimento 44A, 282 (1966); see also J. Pasupathy and R. E. Marshak, Phys. Rev. Letters 17, 888 (1966).
[13] The predicted ratio [eq. (12)] from the current algebra is slightly larger than that (0.23%) obtained from the ρ-dominance model of Ref. 2. This seems to be true also in the other case of the ratio $\Gamma(\eta\to\pi^+\pi^-\gamma)/\Gamma(\gamma\gamma)$ calculated in Refs. 12 and 14.
[14] L. M. Brown and P. Singer, Phys. Rev. Letters 8, 460 (1962).

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

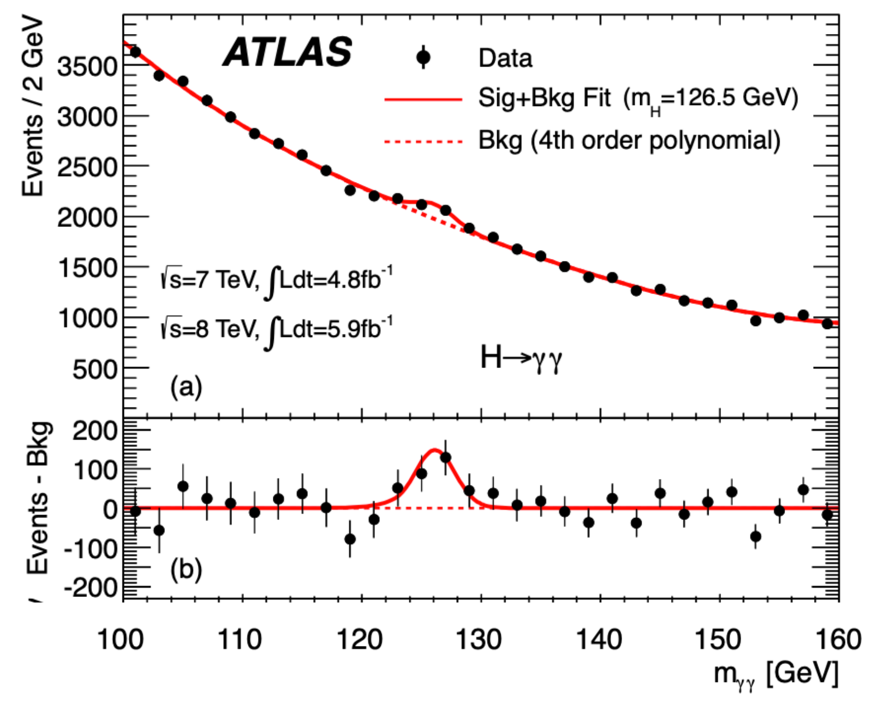
Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite[1] these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differences in the masses of the photon and intermediate meson, and in their couplings. We might hope to understand these differences by imagining that the symmetries relating the weak and electromagnetic interactions are ex

and on a right-handed singlet

$$R\equiv[\tfrac{1}{2}(1-\gamma_5)]e. \quad (2)$$

The largest group that leaves invariant the kinematic terms $-\bar{L}\gamma^\mu\partial_\mu L-\bar{R}\gamma^\mu\partial_\mu R$ of the Lagrangian consists of the electronic isospin $\vec{T}$ acting on L, plus the numbers N_L, N_R of left- and right-handed electron-type leptons. As far as we know, two of these symmetries are en-

Higgs



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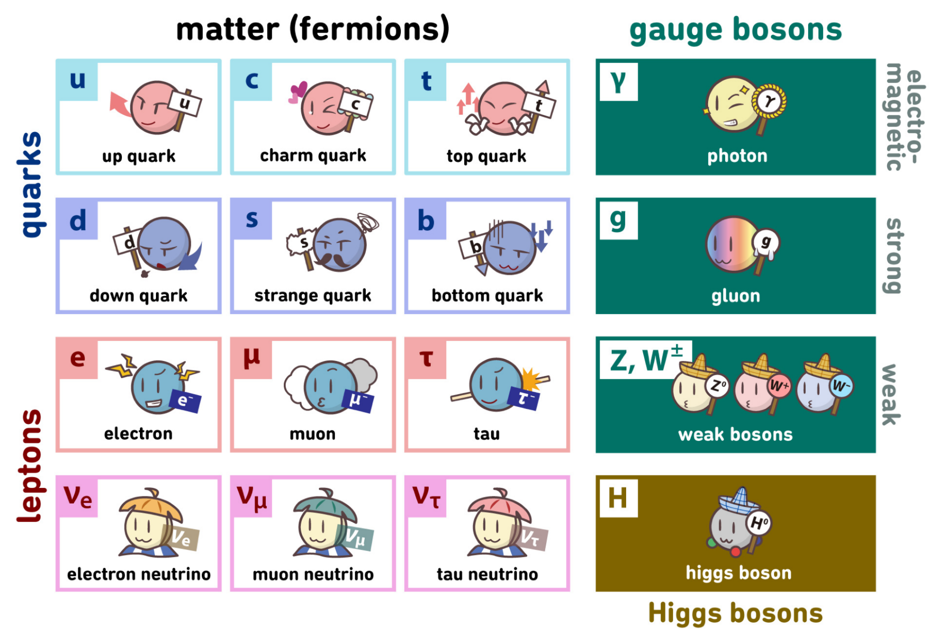

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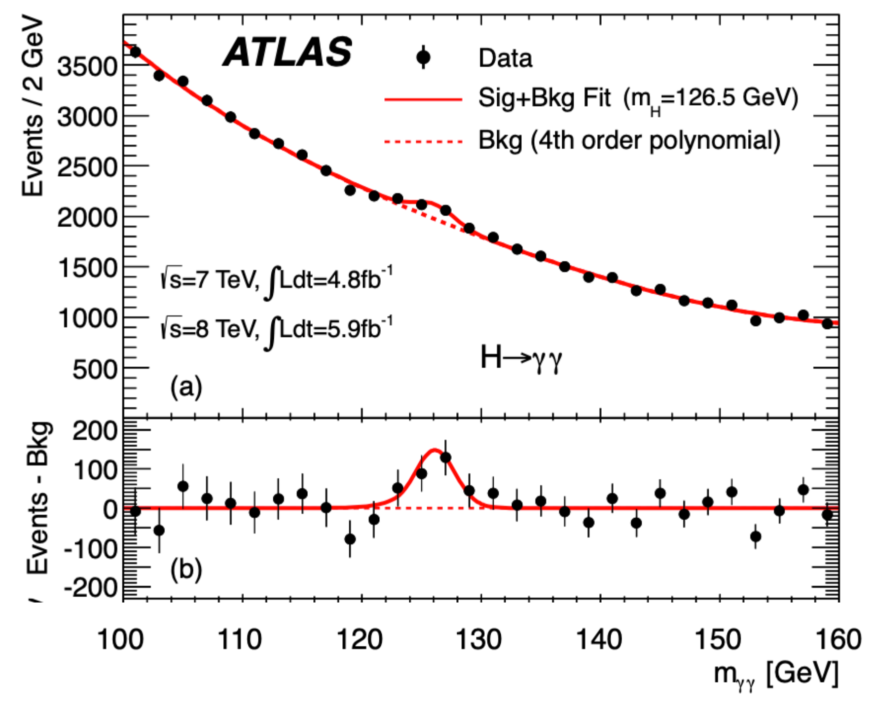
👉 **More details on the whiteboard if requested / if time permits.**

Higgs



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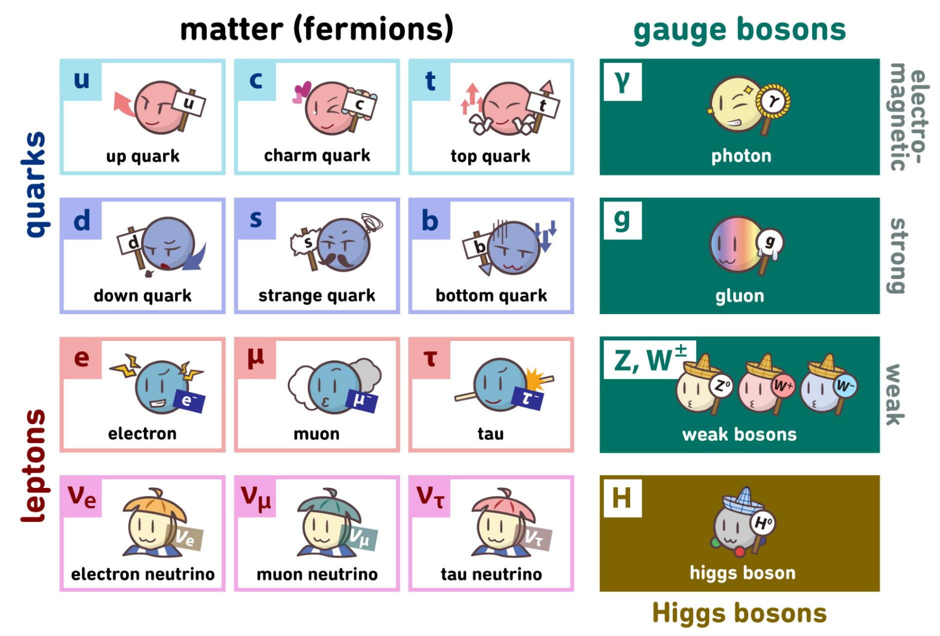


2. The **origin of** all the elementary particles' **masses**.

3. The **origin of electroweak symmetry breaking.**

4. The **only elementary scalar** particle in the Standard Model.

→ The only particle receiving **quadratic radiative correction.**

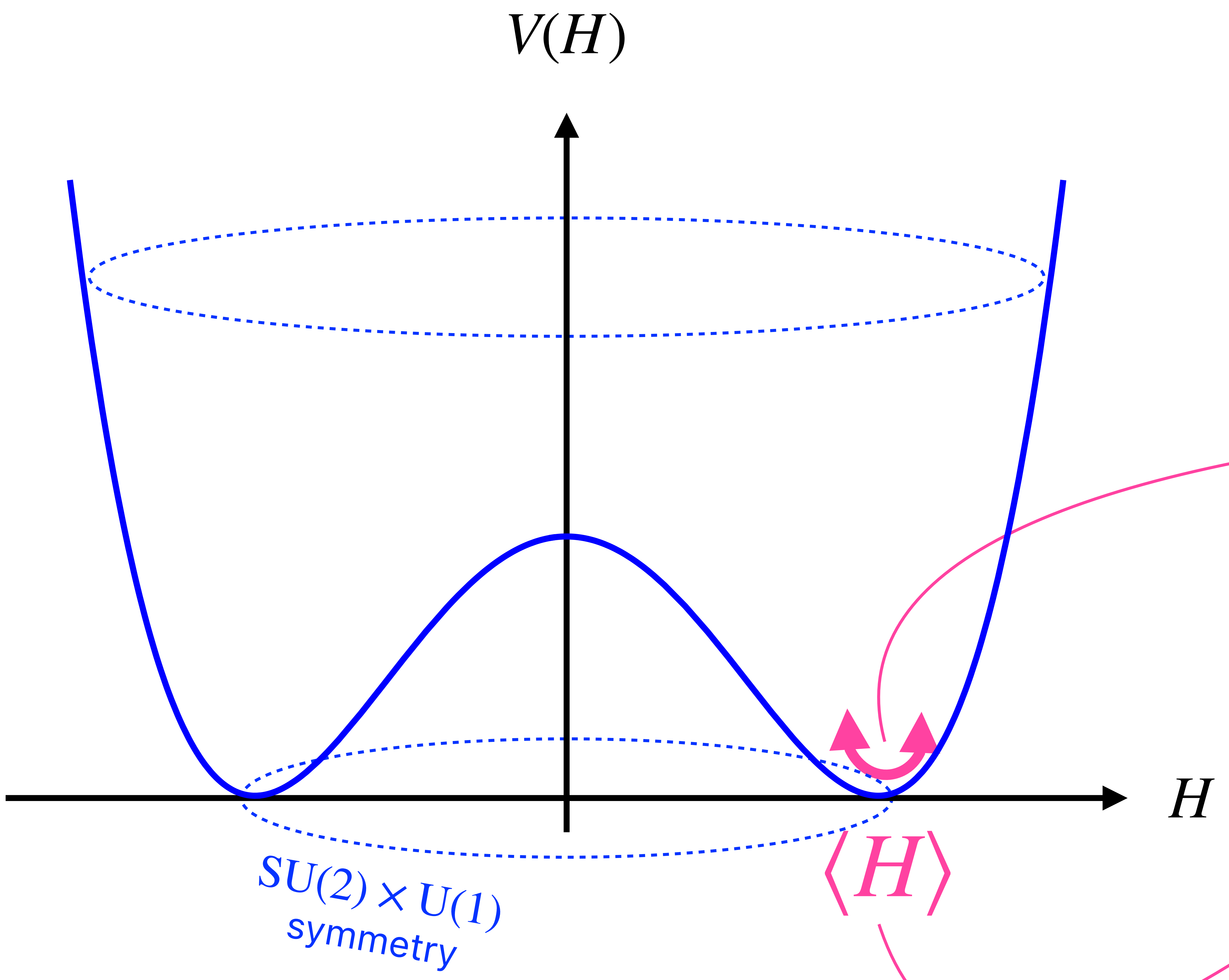
$$m^2_{\text{Higgs}} \sim \underbrace{m^2_{\text{Higgs},0} + \Lambda^2_{\text{new physics}}}_{\text{Fine tuning?}}$$

cf. quarks, leptons: $m \sim m_0 \left(1 + \ln \Lambda_{\text{new physics}}\right)$

👉 more on it tomorrow

Higgs

Higgs potential:



- Higgs mass $m_H = 125\ \mathrm{GeV}$
- Higgs VEV

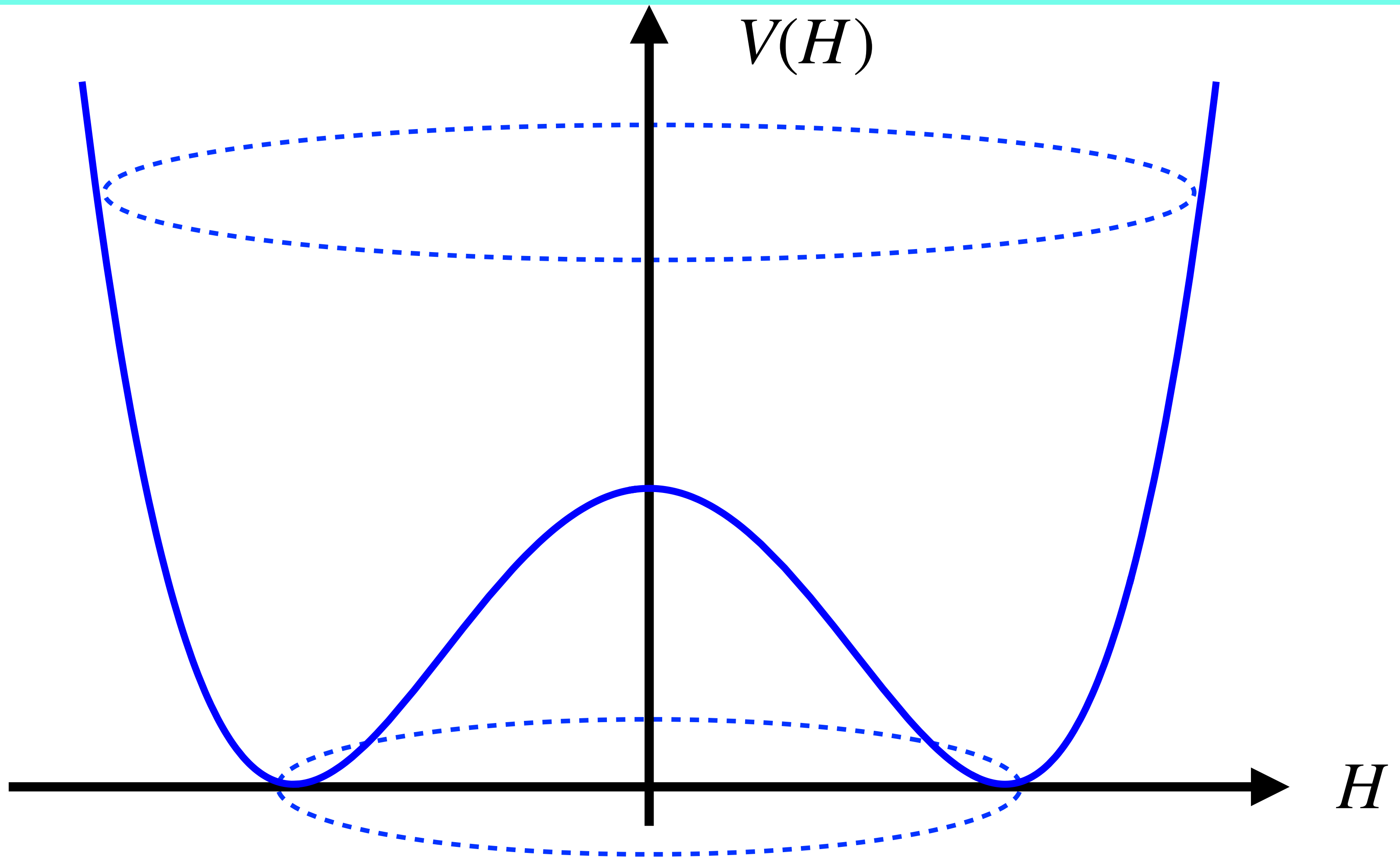
$$\langle H \rangle^2 = \frac{1}{2\sqrt{2}G_F} = (174\ \mathrm{GeV})^2$$

$G_F = 1.17 \times 10^{-5}\mathrm{GeV}^{-2}$

Higgs

Assuming the SM(-like) potential,...

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



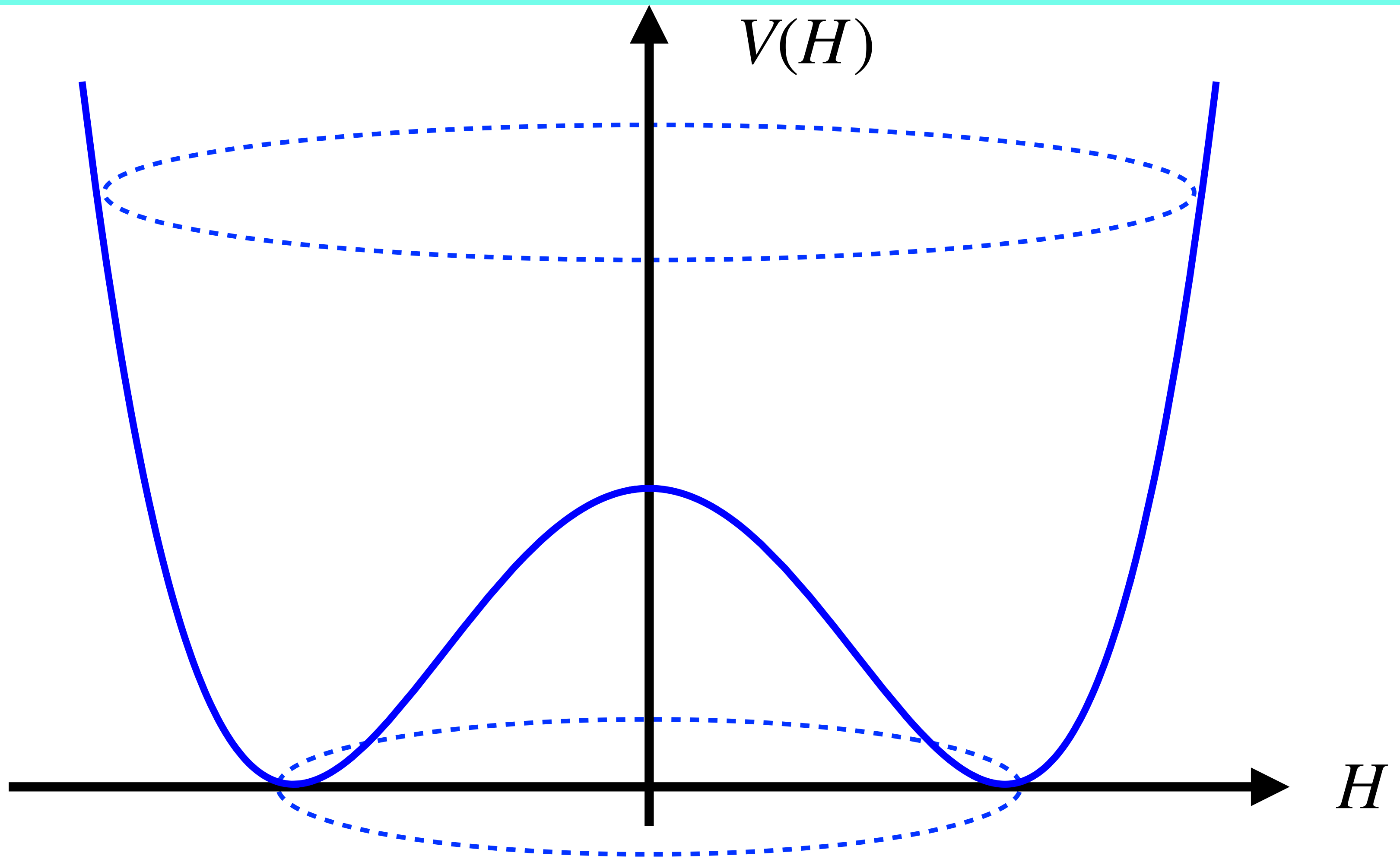
Higgs

Assuming the SM(-like) potential,...

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

$$\longrightarrow \begin{cases} \langle H \rangle^2 = \frac{\mu^2}{2\lambda} = (174\ \text{GeV})^2 \\ m_H^2 = 2\mu^2 = (125\ \text{GeV})^2 \end{cases}$$

$$\xrightarrow[\text{2 inputs}]{\text{2 parameters}} \begin{cases} \mu^2 = \frac{m_H^2}{2} \simeq (89\ \text{GeV})^2 \\ \lambda = \frac{m_H^2}{4\langle H \rangle^2} \simeq 0.13 \end{cases}$$



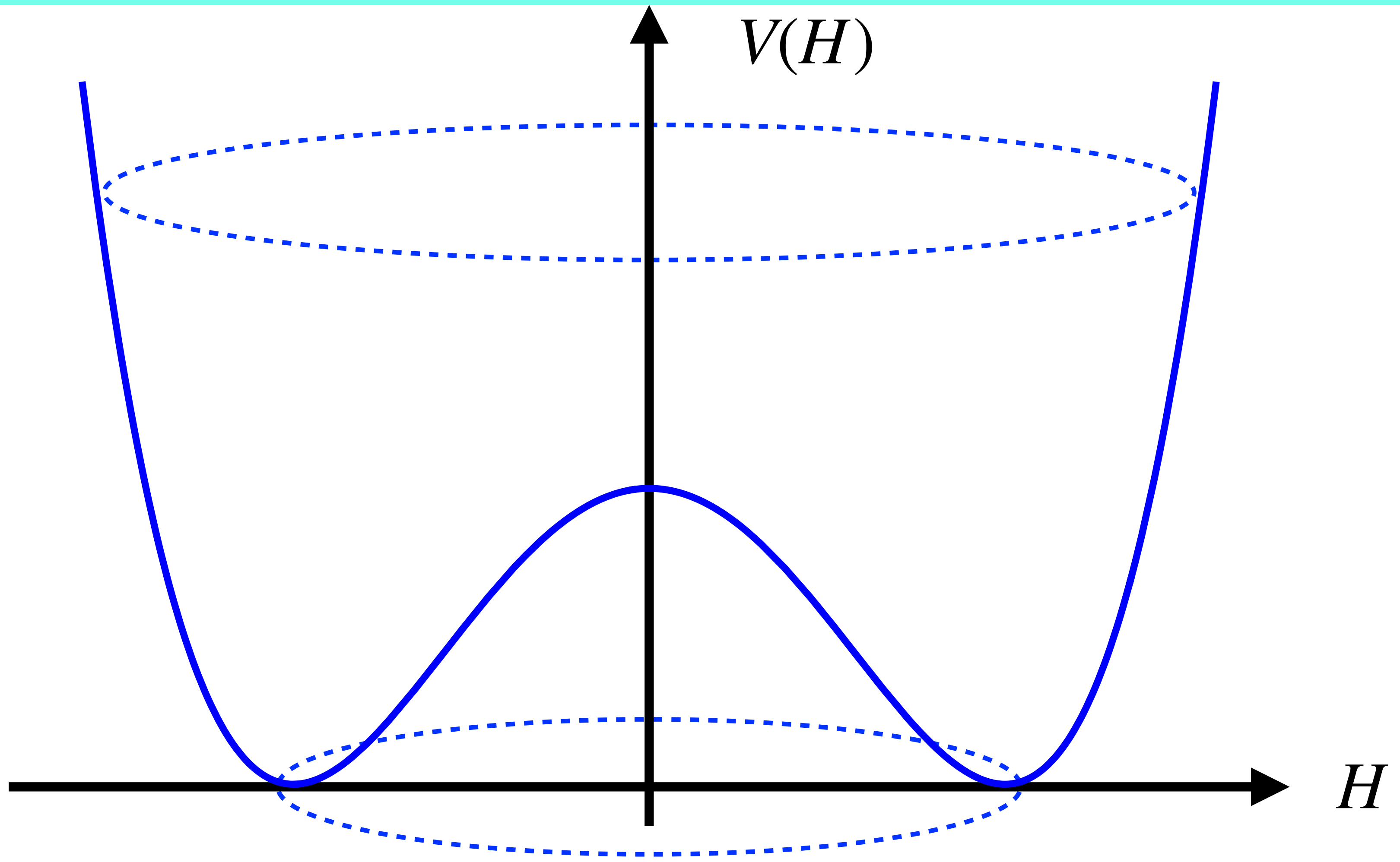
Higgs

Assuming the SM(-like) potential,...

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

μ^2: $(89\ \mathrm{GeV})^2$

λ: 0.13



2 parameters
2 inputs

$$\longrightarrow \begin{cases} \mu^2 = \dfrac{m_H^2}{2} \simeq (89\ \mathrm{GeV})^2 \\ \lambda = \dfrac{m_H^2}{4\langle H \rangle^2} \simeq 0.13 \end{cases}$$

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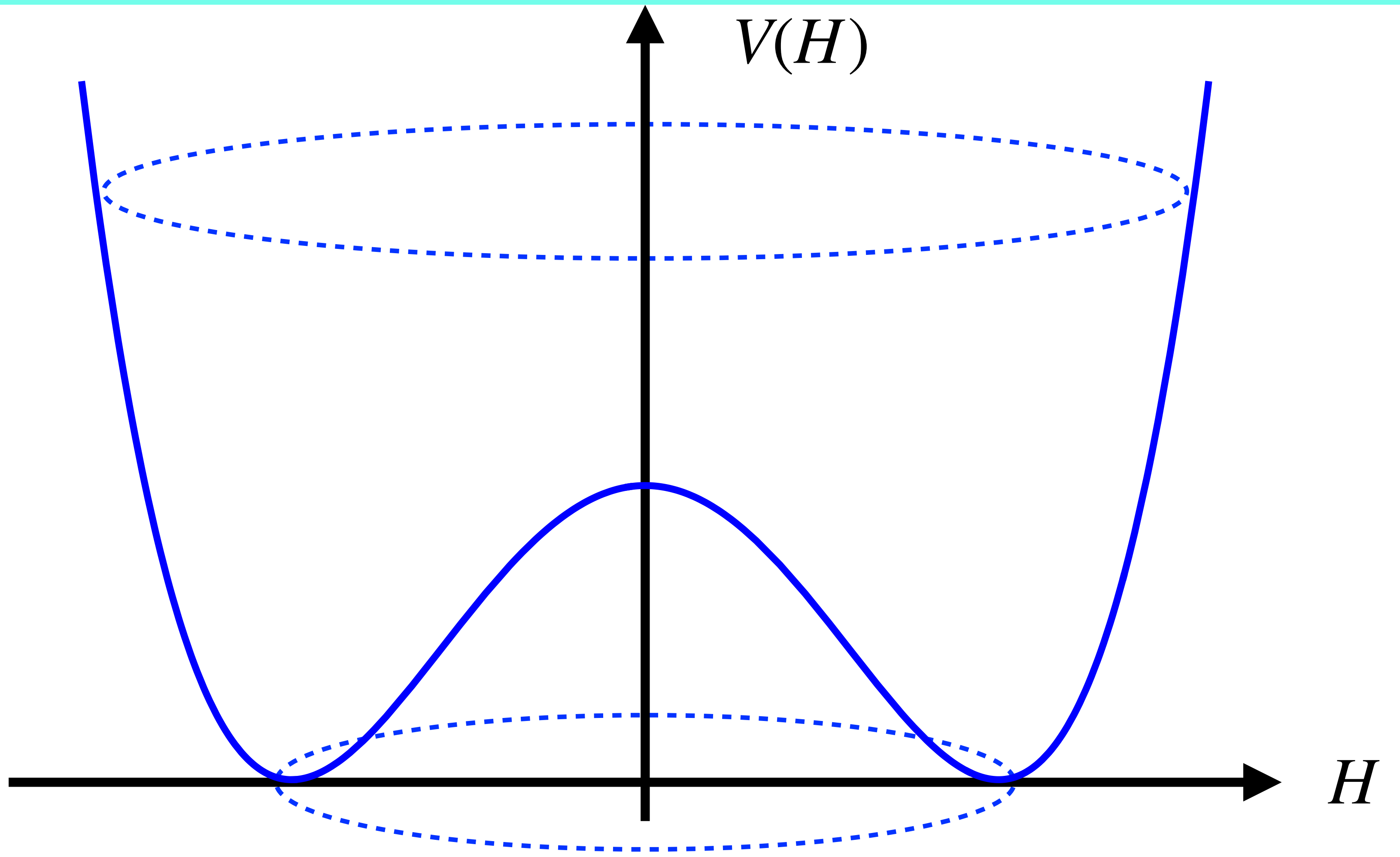


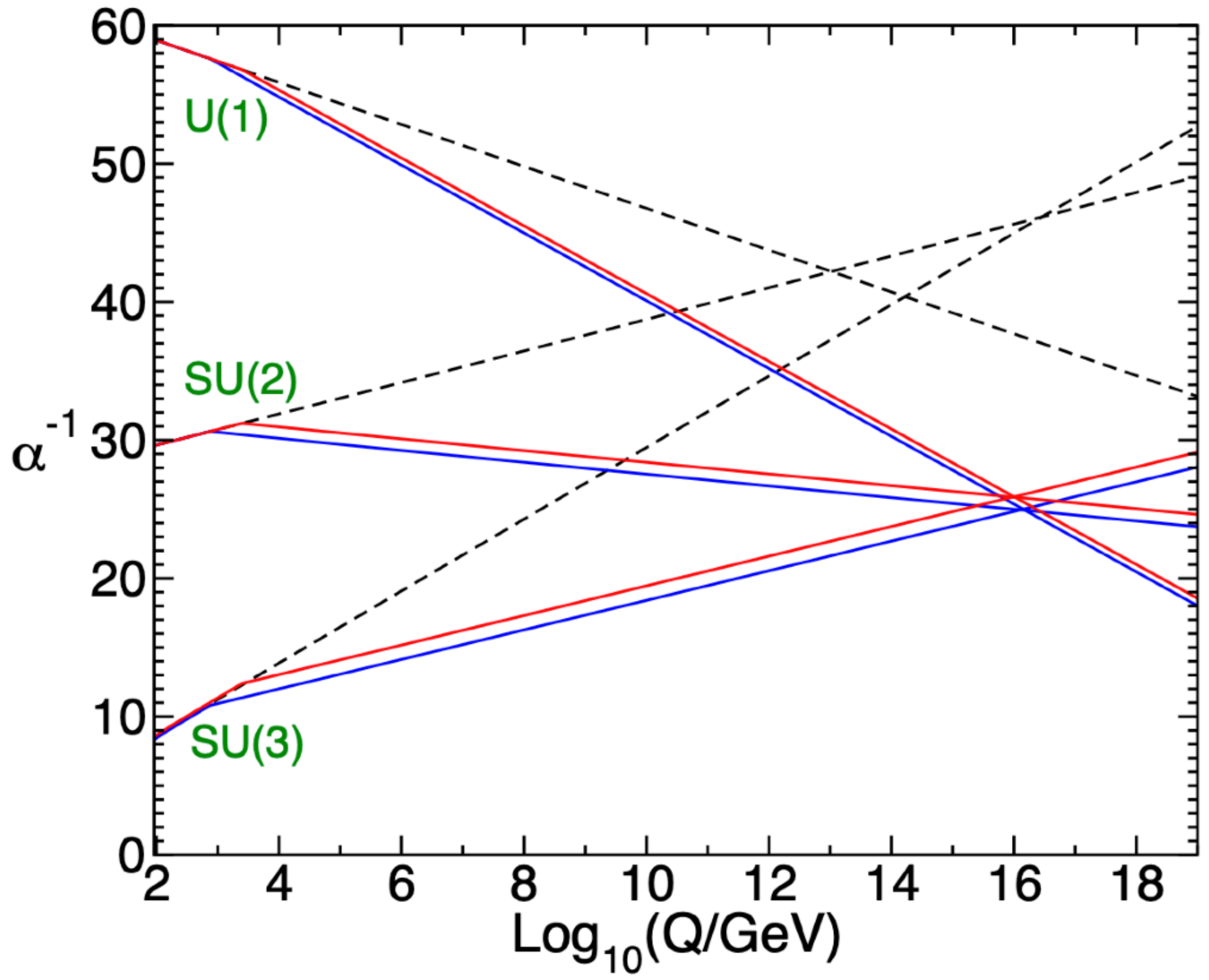
It seems... Higgs sector is described by weakly coupled, perturbative QFT.

It is compatible with:

- SUSY
- GUT and coupling unification
- seesaw and leptogenesis (heavy right-handed neutrino)

👉 more on it tomorrow

Fig. from S.P.Martin, hep-ph/9709356



Higgs

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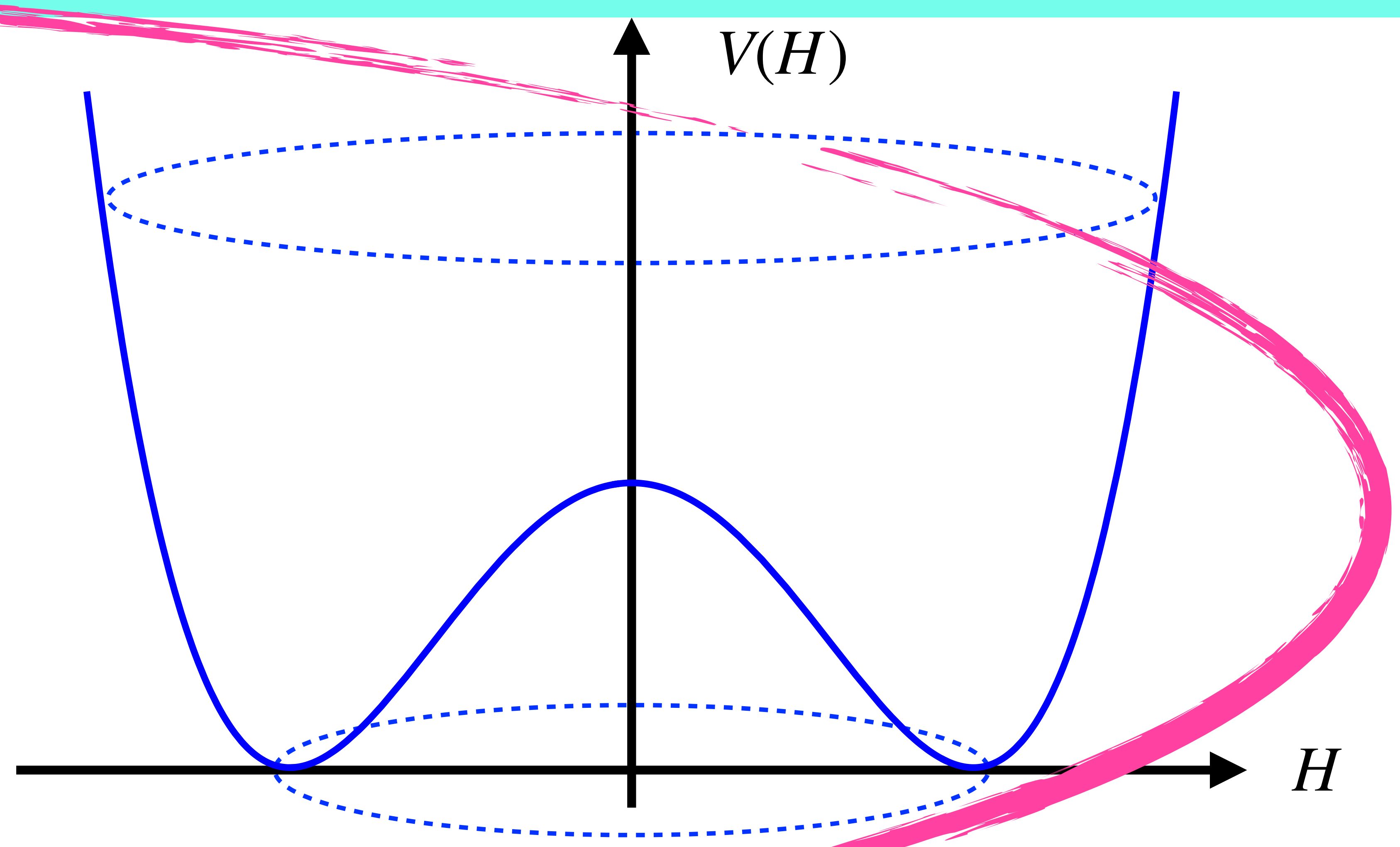
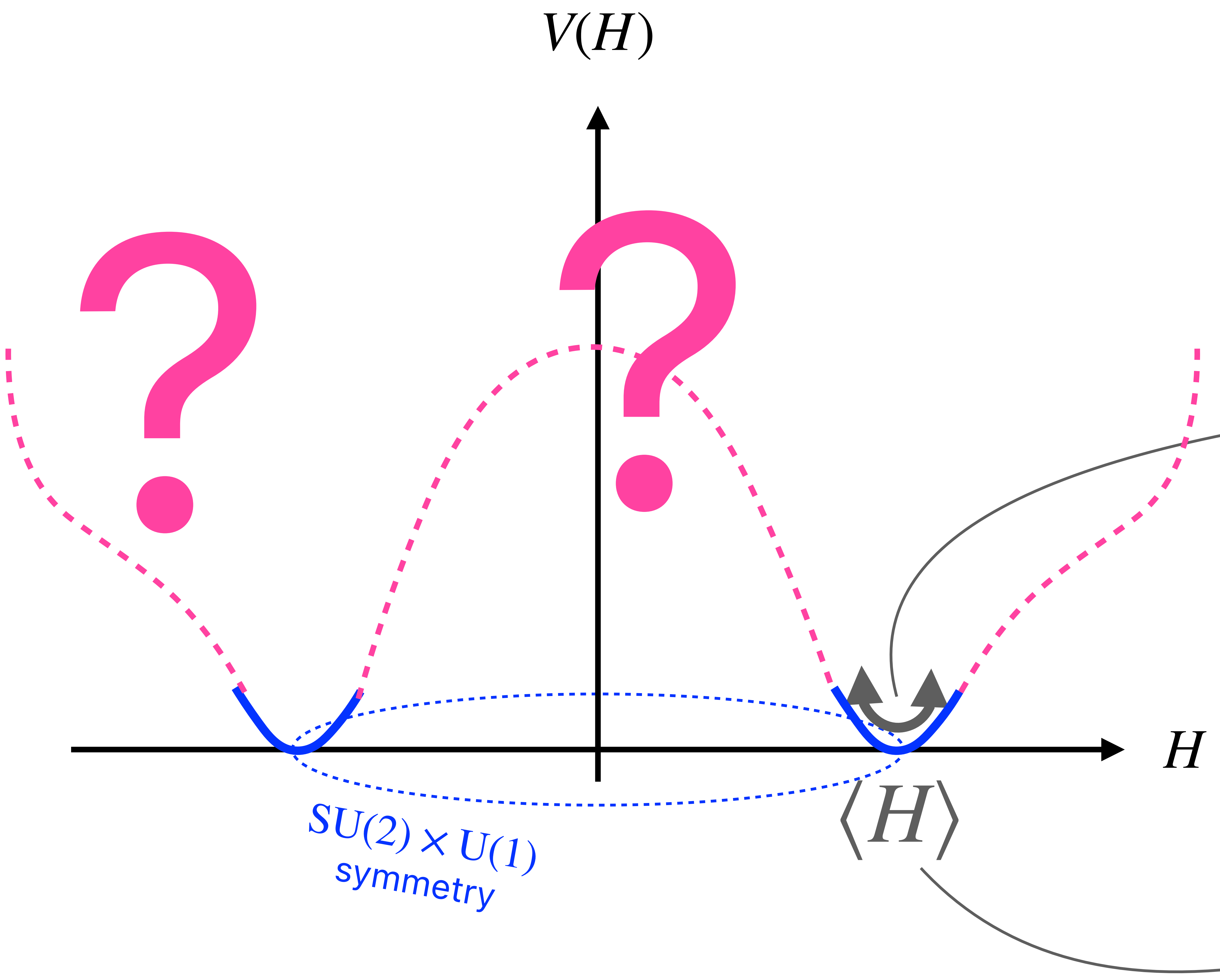


But wait,...
Are we sure about this?

Higgs

What we really know is just...

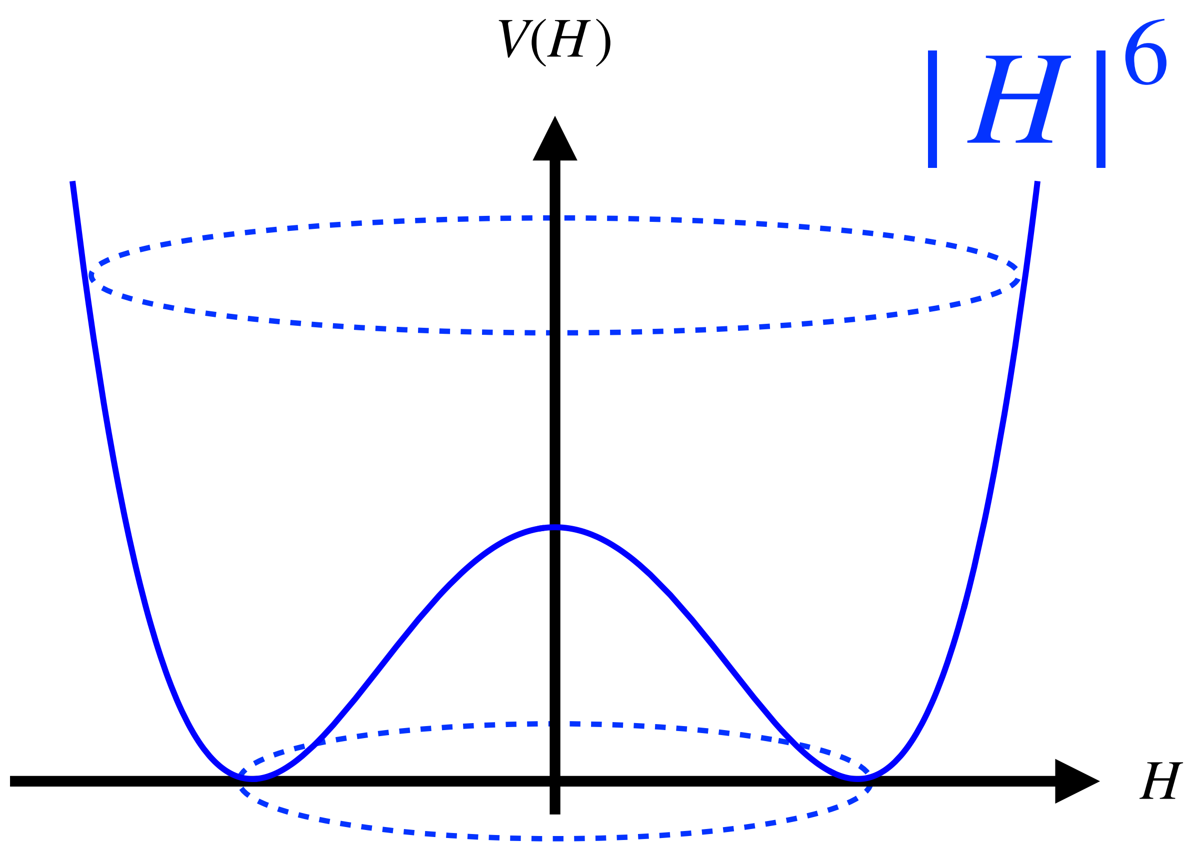


- Higgs mass $m_H = 125\ \mathrm{GeV}$
- Higgs VEV $\langle H \rangle^2 = (174\ \mathrm{GeV})^2$

Higgs

For example,... what if $|H|^6$ instead of $|H|^4$?

$$V(H) = -\mu^2 |H|^2 + \frac{|H|^6}{\Lambda^2}$$



Higgs

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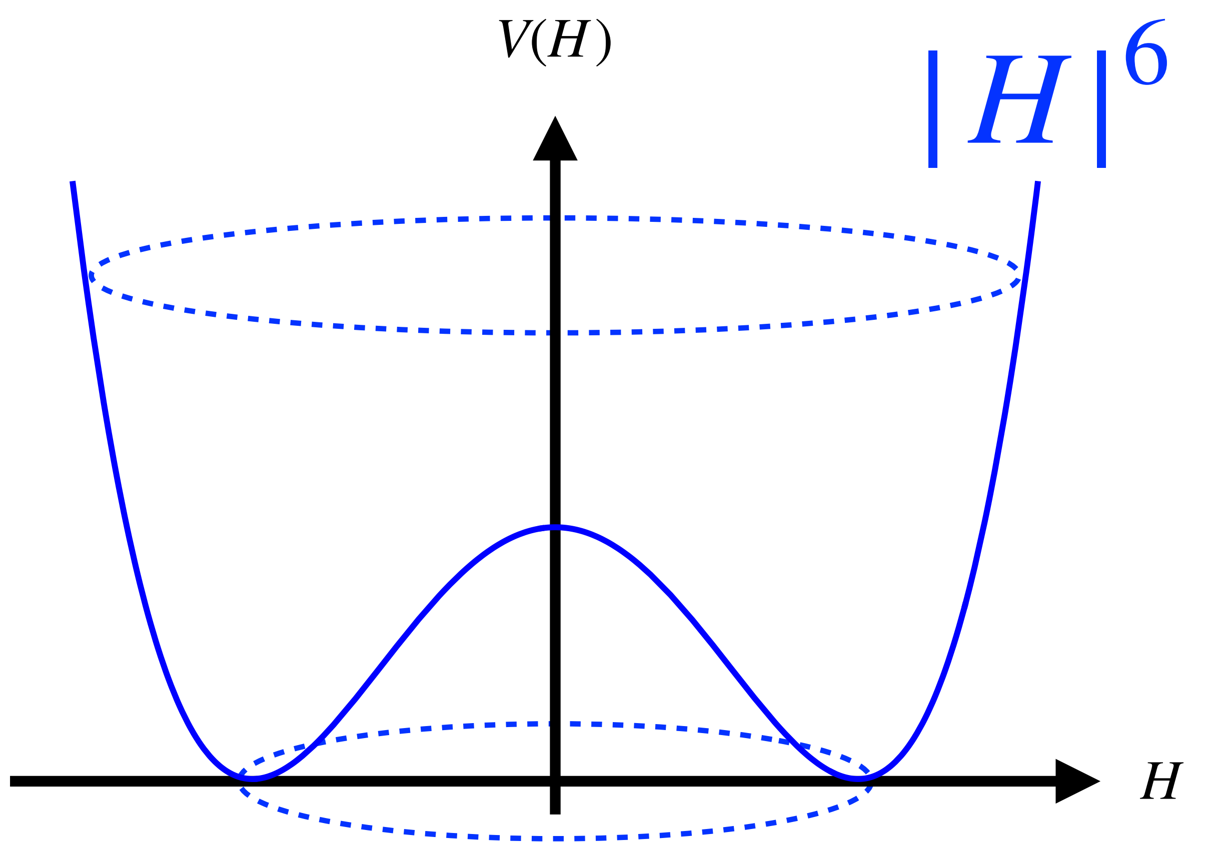

$$\longrightarrow \begin{cases} \langle H \rangle^2 = \dfrac{\mu\Lambda}{\sqrt{3}} = (174\ \text{GeV})^2 \\ m_H^2 = 4\mu^2 = (125\ \text{GeV})^2 \end{cases}$$

$$\longrightarrow \begin{cases} \mu^2 = \dfrac{m_H^2}{4} \simeq (63\ \text{GeV})^2 \\ \Lambda = \dfrac{2\sqrt{3}\langle H \rangle^2}{m_H} \sim 0.8\ \text{TeV} \end{cases}$$

2 parameters
2 inputs

Higgs

$$\begin{cases} \langle H \rangle^2 = (174\ \text{GeV})^2 \\ m_H^2 = (125\ \text{GeV})^2 \end{cases}$$

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

vs

$$V(H) = -\mu^2 |H|^2 + \frac{|H|^6}{\Lambda^2}$$

$$\begin{cases} \mu^2 = \frac{m_H^2}{2} \simeq (89\ \text{GeV})^2 \\ \lambda = \frac{m_H^2}{4\langle H \rangle^2} \simeq 0.13 \end{cases}$$

?

$$\begin{cases} \mu^2 = \frac{m_H^2}{4} \simeq (63\ \text{GeV})^2 \\ \Lambda = \frac{2\sqrt{3}\langle H \rangle^2}{m_H} \sim 0.8\ \text{TeV} \end{cases}$$

Higgs

$$\begin{cases} \langle H \rangle^2 = (174\ \text{GeV})^2 \\ m_H^2 = (125\ \text{GeV})^2 \end{cases}$$

$$V(H) = -\mu^2 |H|^2 + \lambda |H|^4 \quad \text{vs} \quad V(H) = -\mu^2 |H|^2 + \frac{|H|^6}{\Lambda^2}$$

$$\begin{cases} \mu^2 = \frac{m_H^2}{2} \simeq (89\ \text{GeV})^2 \\ \lambda = \frac{m_H^2}{4\langle H \rangle^2} \simeq 0.13 \end{cases}$$

?

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Homework:

Think about this before tomorrow (no submission required 😁).

1. **Is this $|H|^6$ model still viable?**
2. **If so, what kind of future experiments can test it?**

Plan

1. **Standard Model** (today) 👉 cf. Hagiwara-san's talk yesterday.
   - Introductory content, with a focus on the Higgs.

     (mainly for undergrad/master's students.)

     (+ homework problem at the end of the lecture.)
2. **BSM (Beyond the Standard Model)** (tomorrow)
   - Broader perspective, including connections to cosmology

Feel free to ask questions — even on the slopes!