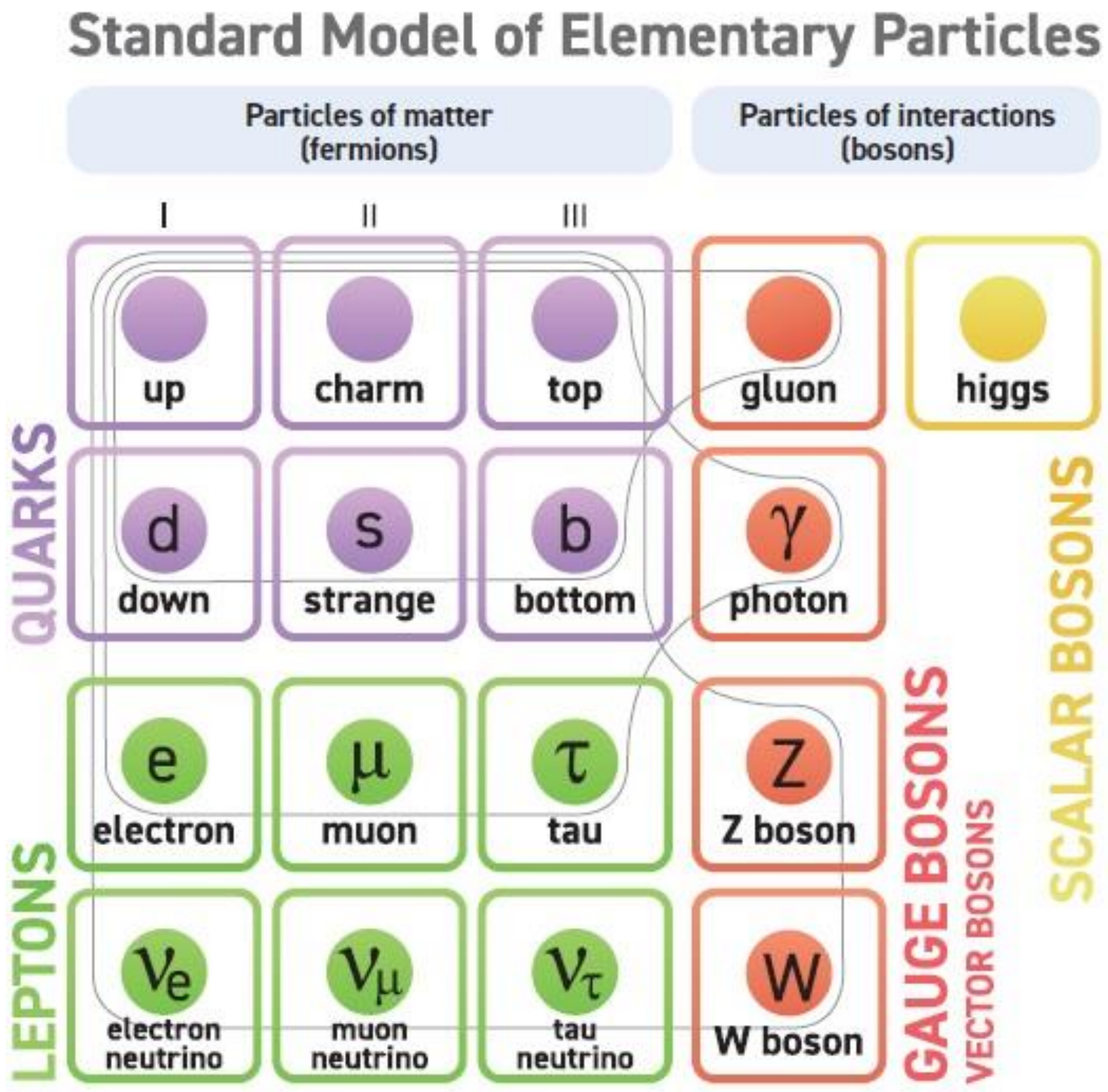
Standard Model of particle physics

Overview of the building blocks of the universe



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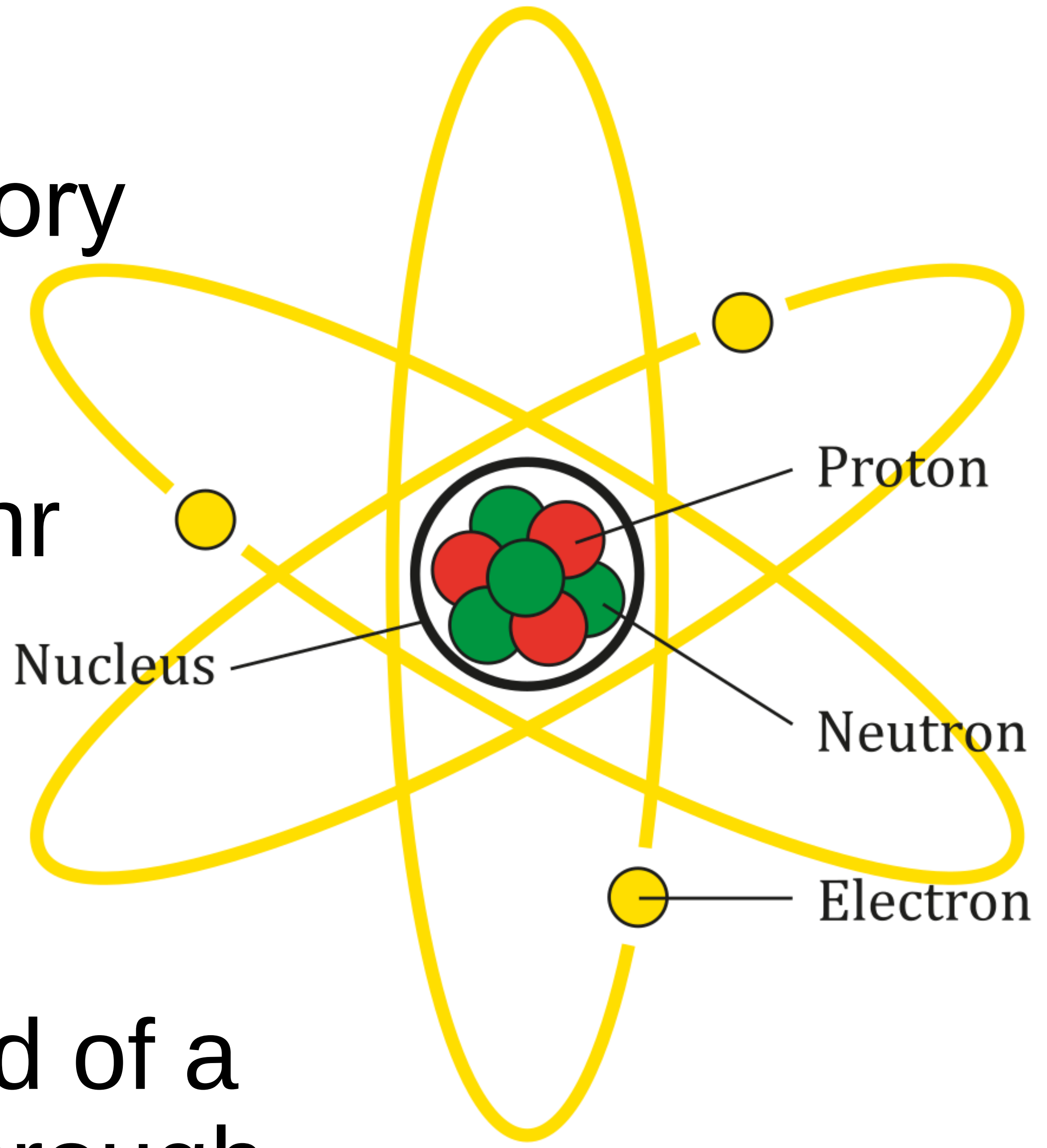
USCMS Undergraduate Summer Internship Program 2023

A little bit of history…

Roots of modern Particle Physics can be traced back to the concept “**Atomism**” in ancient Greek culture. To study the smallest components of nature in order to understand it

- Particle Physics as we know it today began with the discovery of **electron** in 1897 by JJ Thomson
- Followed by the discovery of **photon**. Prior to Einstein’s photoelectric theory (1905) the photon was not recognized as a particle
- In the early 20th century Rutherford discovered the atom, followed by Bohr proposing electrons move around the nucleus in stable orbits
- With the discovery of neutron in 1932, the **atom** was complete!
- Very soon the number of elementary particles grew, and there was a need of a gudiebook to explain their behaviour - the **Standard Model** (developed through late 20th century)



Two key discoveries in the last 30 years

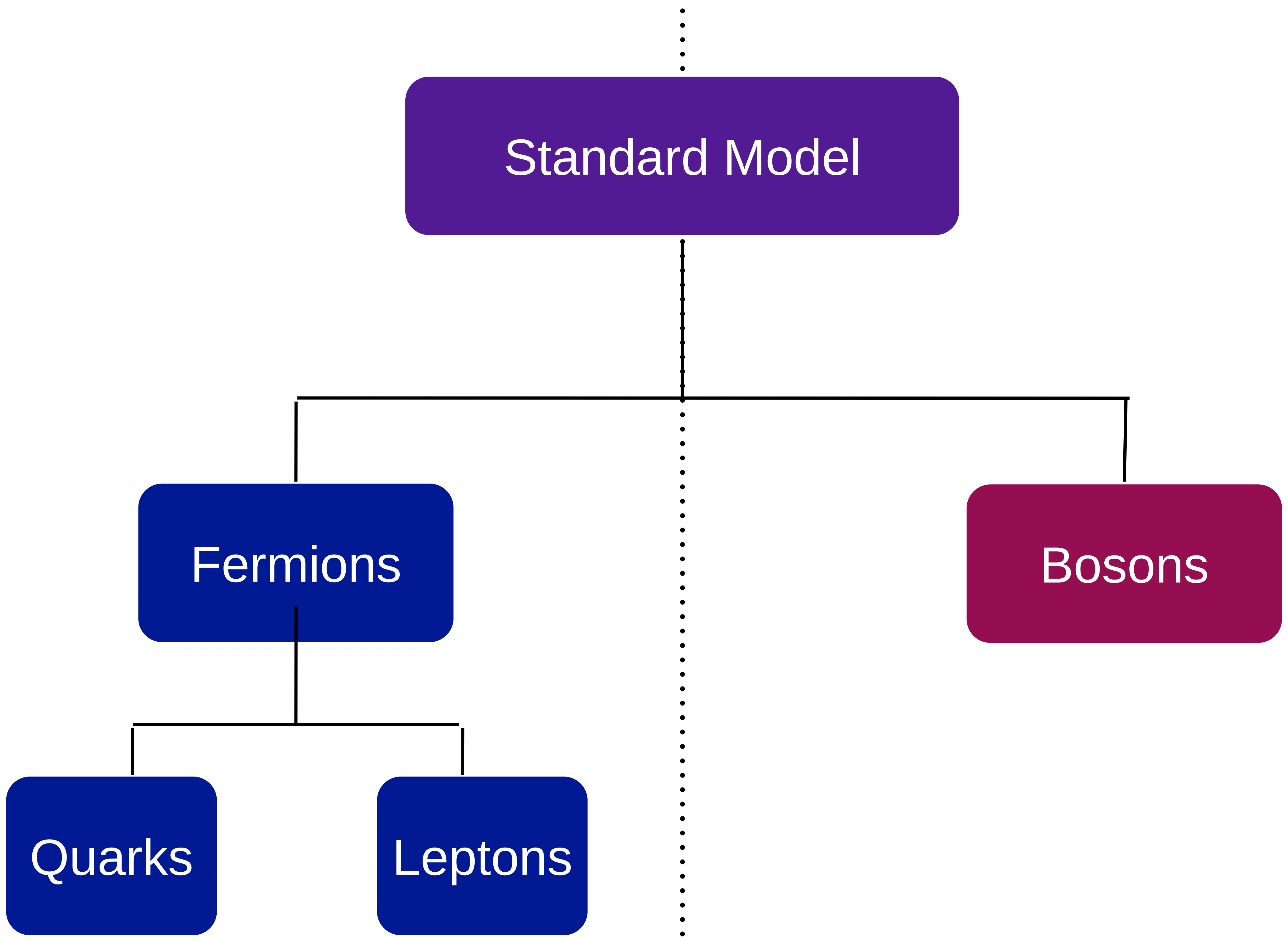
Top quark was discovered in 1995 by the CDF and D0 experiments at Fermilab

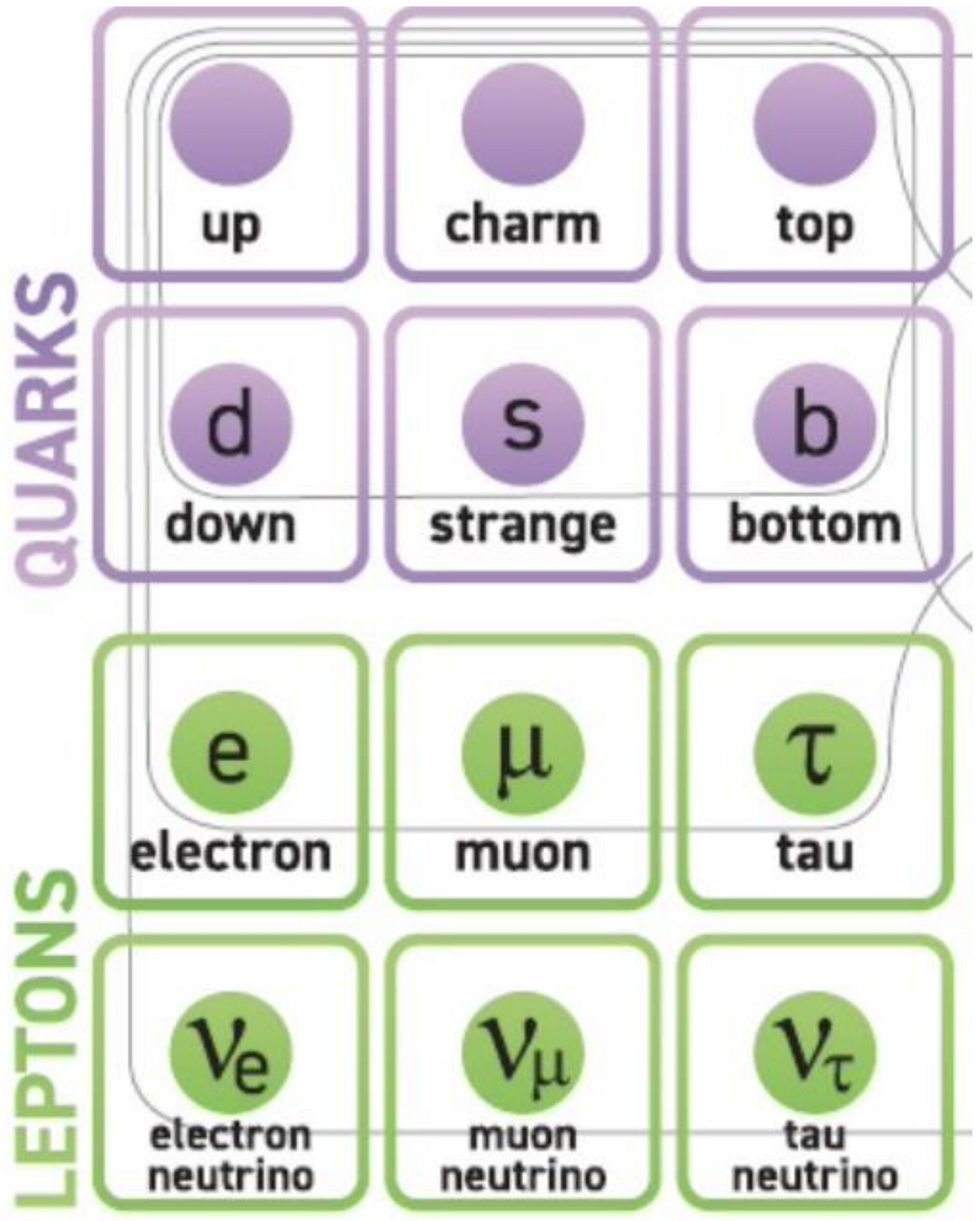
25th anniversary of the discovery of the Top Quark, Femrilab

The Higgs boson discovered by the ATLAS and CMS experiments in 2012

The Higgs announcement at CERN

The Higgs boson was the last missing piece and now the SM of Particle Physics is complete!


Standard Model
Fermions
Bosons
Quarks
Leptons


QUARKS
up
charm
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LEPTONS
e
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electron neutrino
νμ
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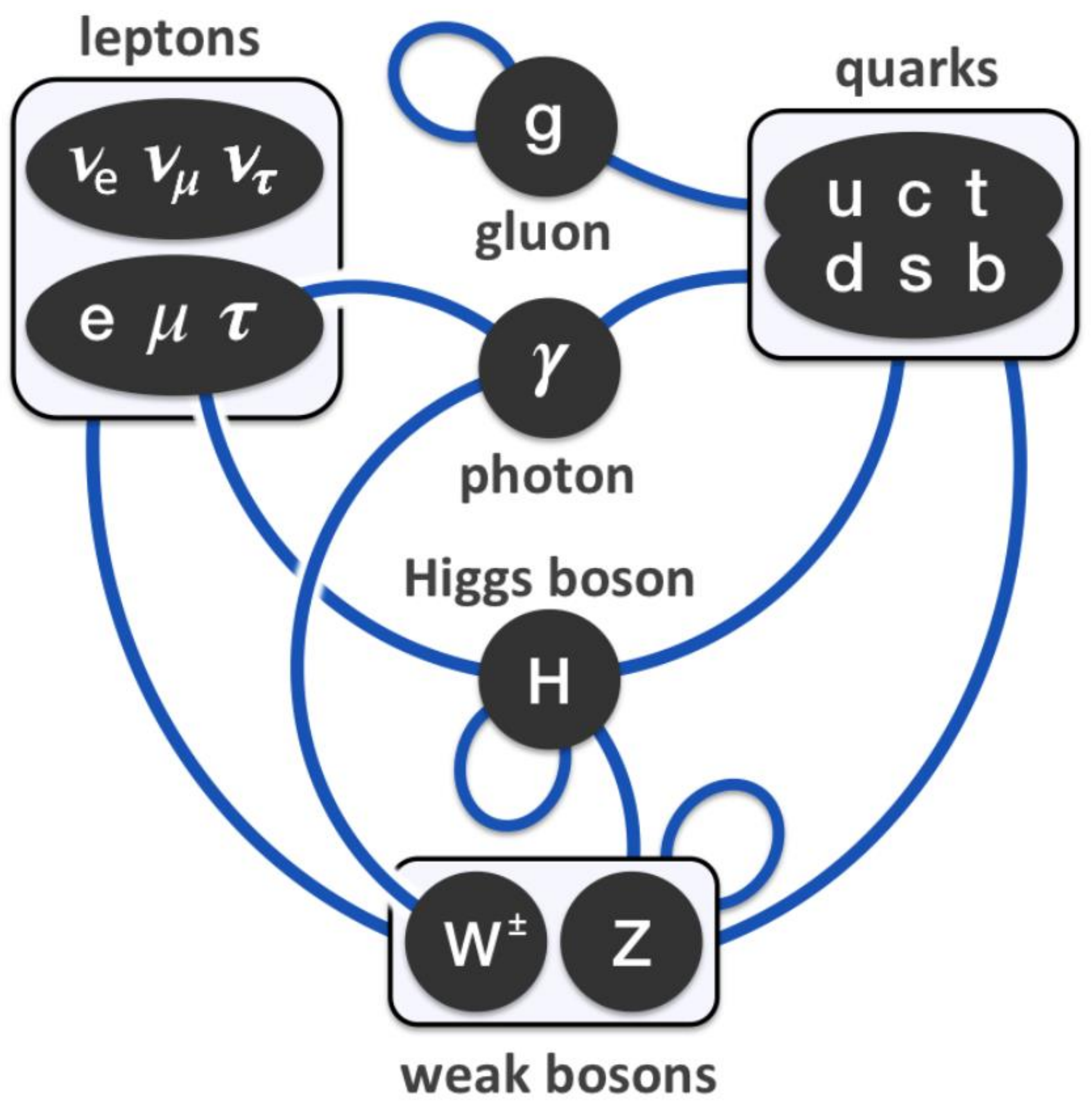
leptons
νe νμ ντ
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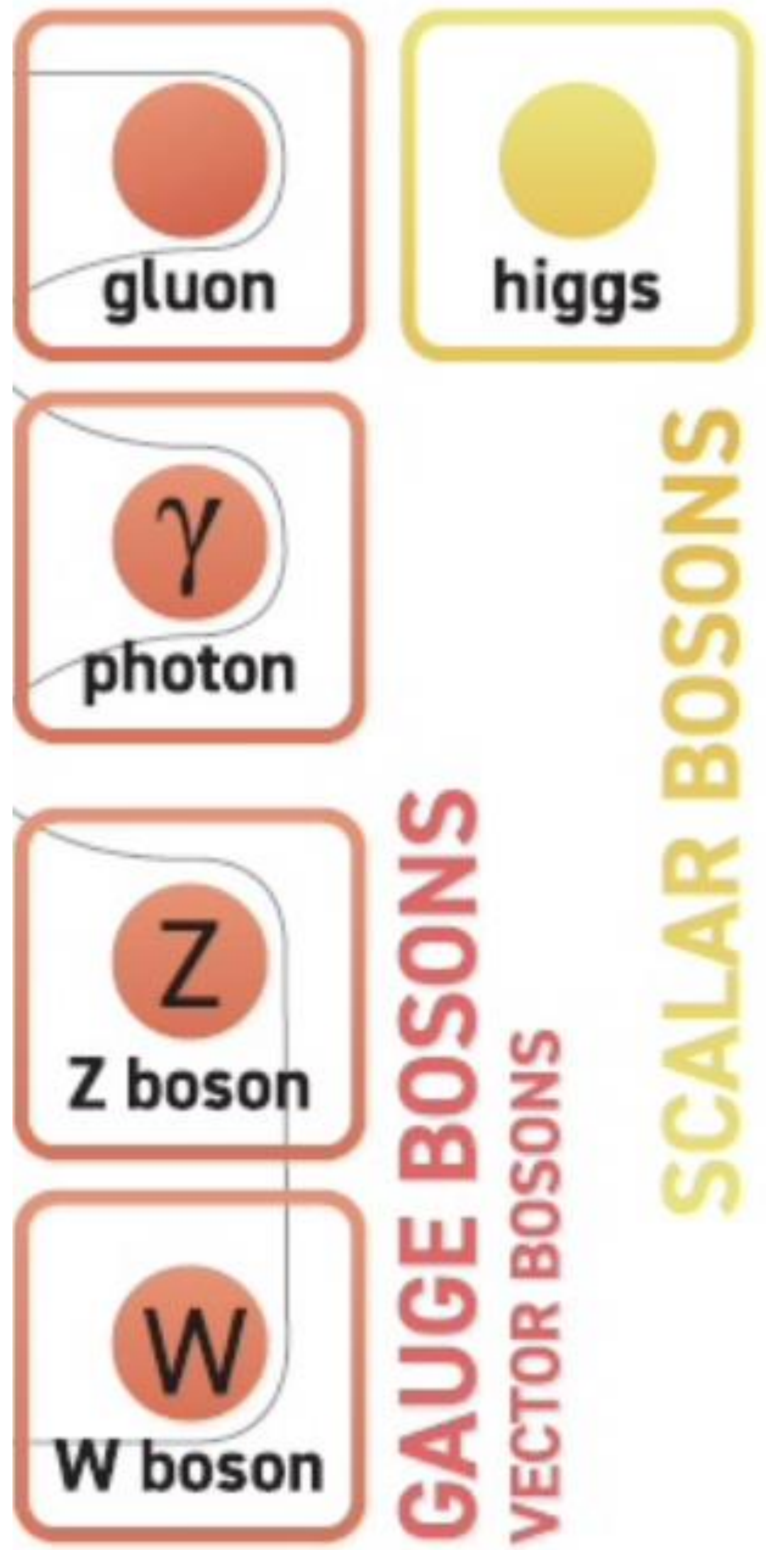
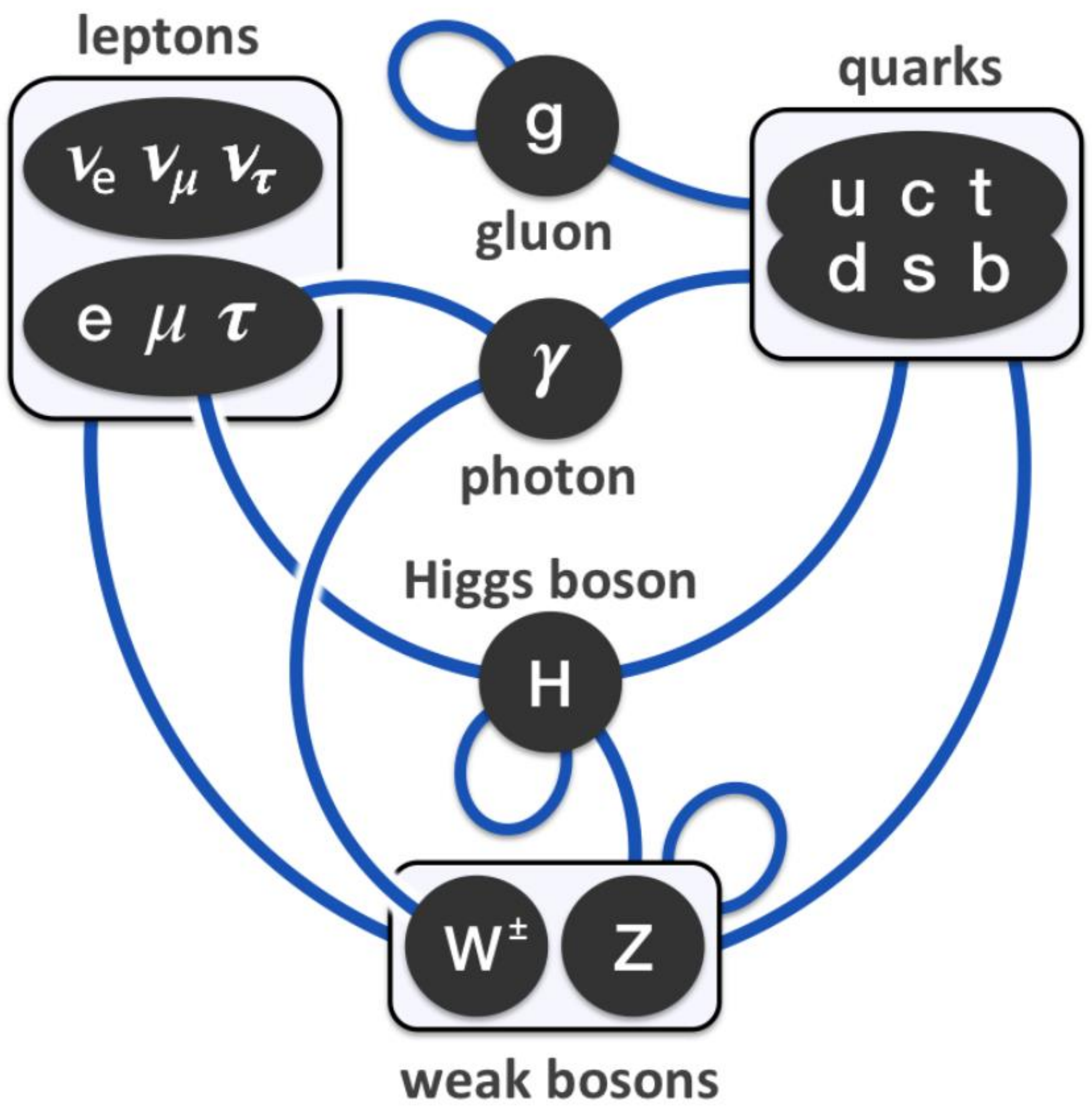
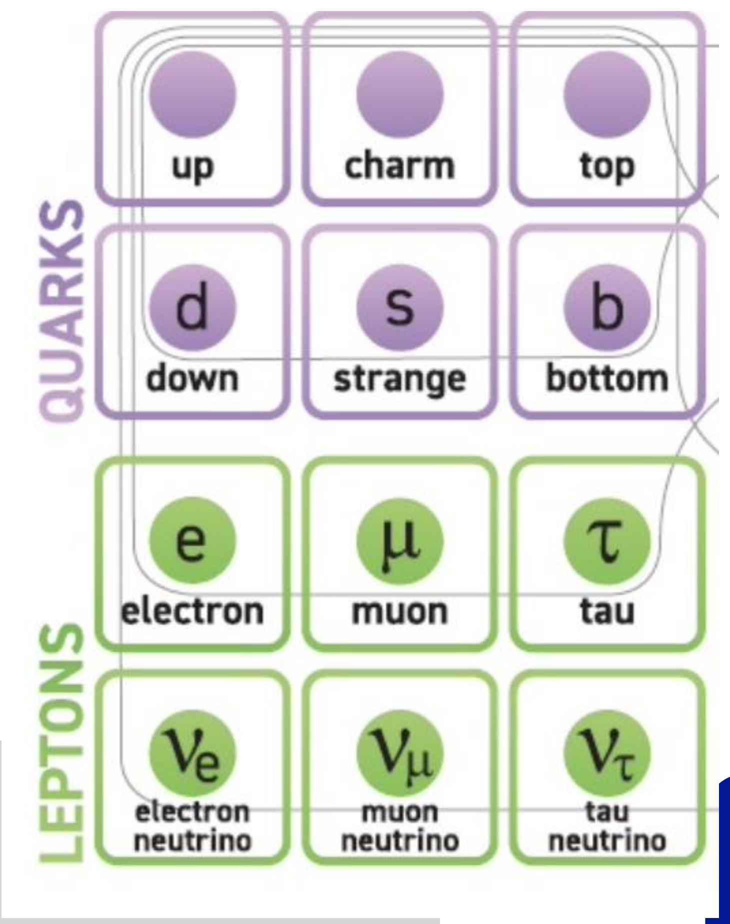
g
gluon
quarks
u c t
d s b
γ
photon
Higgs boson
H
W±
Z
weak bosons


gluon
higgs
γ
photon
Z
Z boson
W
W boson
GAUGE BOSONS
VECTOR BOSONS
SCALAR BOSONS

Fields

gluon	photon	W/Z	graviton?
Strong >>	Electromagnetic >>	Weak >>>	Gravitational
1	10^{-2}	10^{-13}	10^{-38}





Standard Model

Fermions

Quarks

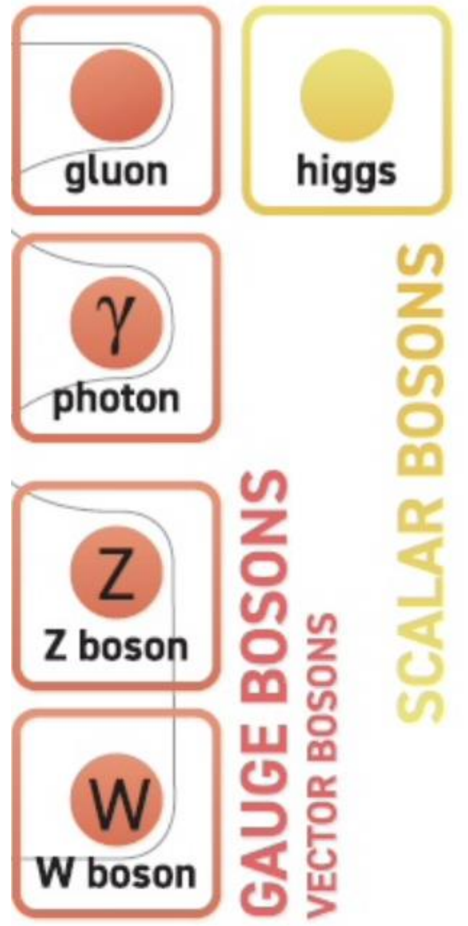
Leptons

Bosons

Composite particles (Hadrons)

Baryons

Mesons



Spin (1/2)ℏ

Quarks carry color and electric charge - strong, EM and weak force

Leptons carry electric charge - EM and weak force

they have corresponding anti-particles

qqq forms **baryons** like protons and neutrons with spin (1/2)ℏ and 0,±1, 2 charge

Spin 0 and 1ℏ

Vector bosons- spin 1ℏ

gluon- strong force

γ - EM force

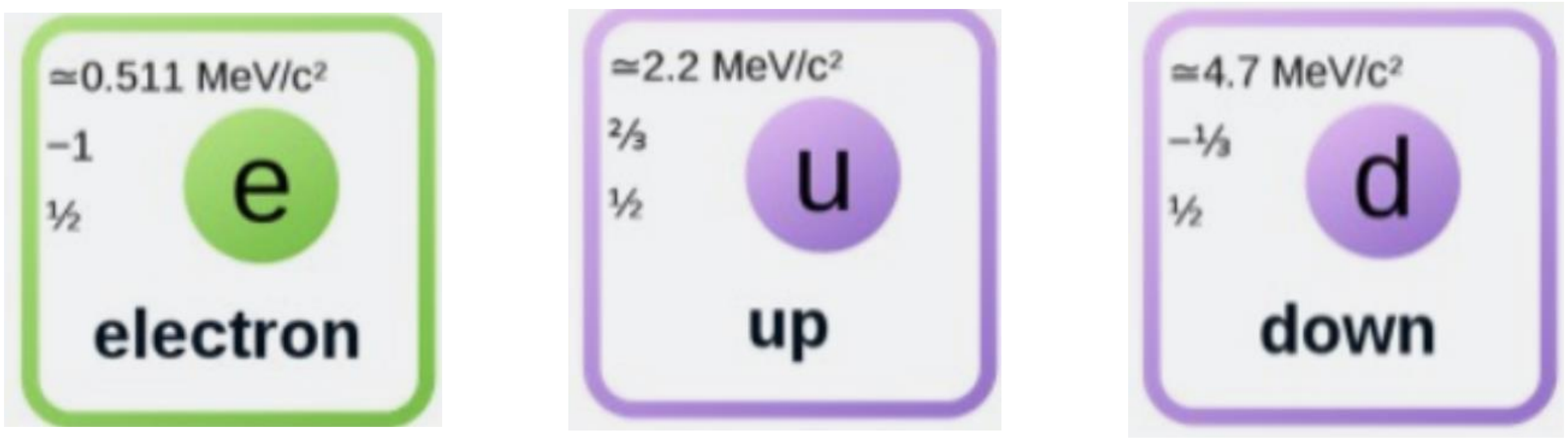
W and Z boson - weak force

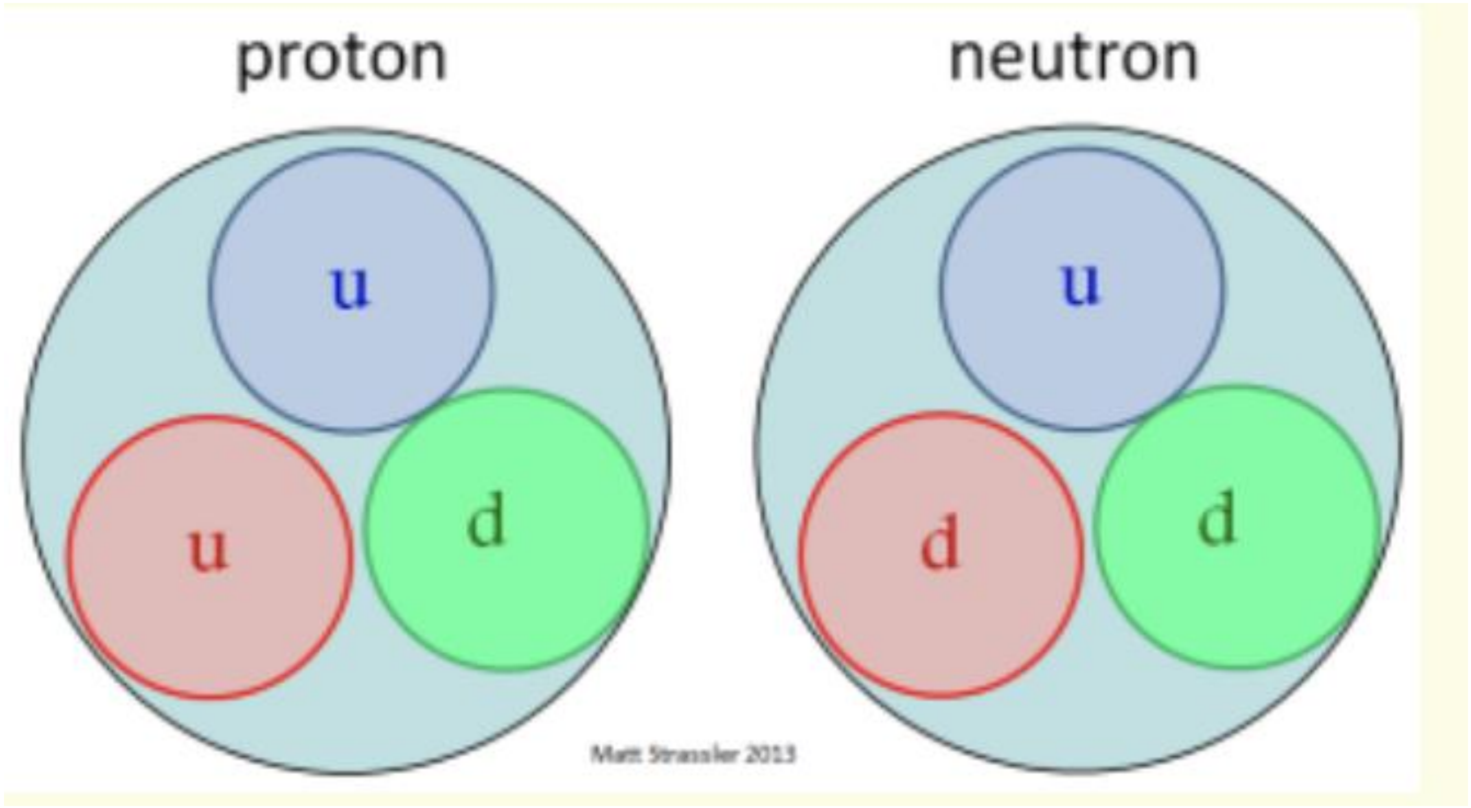
Higgs is a scalar boson with spin 0

$q\bar{q}$ forms **mesons** like pions π

$q\bar{q}$ forms **mesons** like pions π with spin 1ℏ and ±1, 0 charge

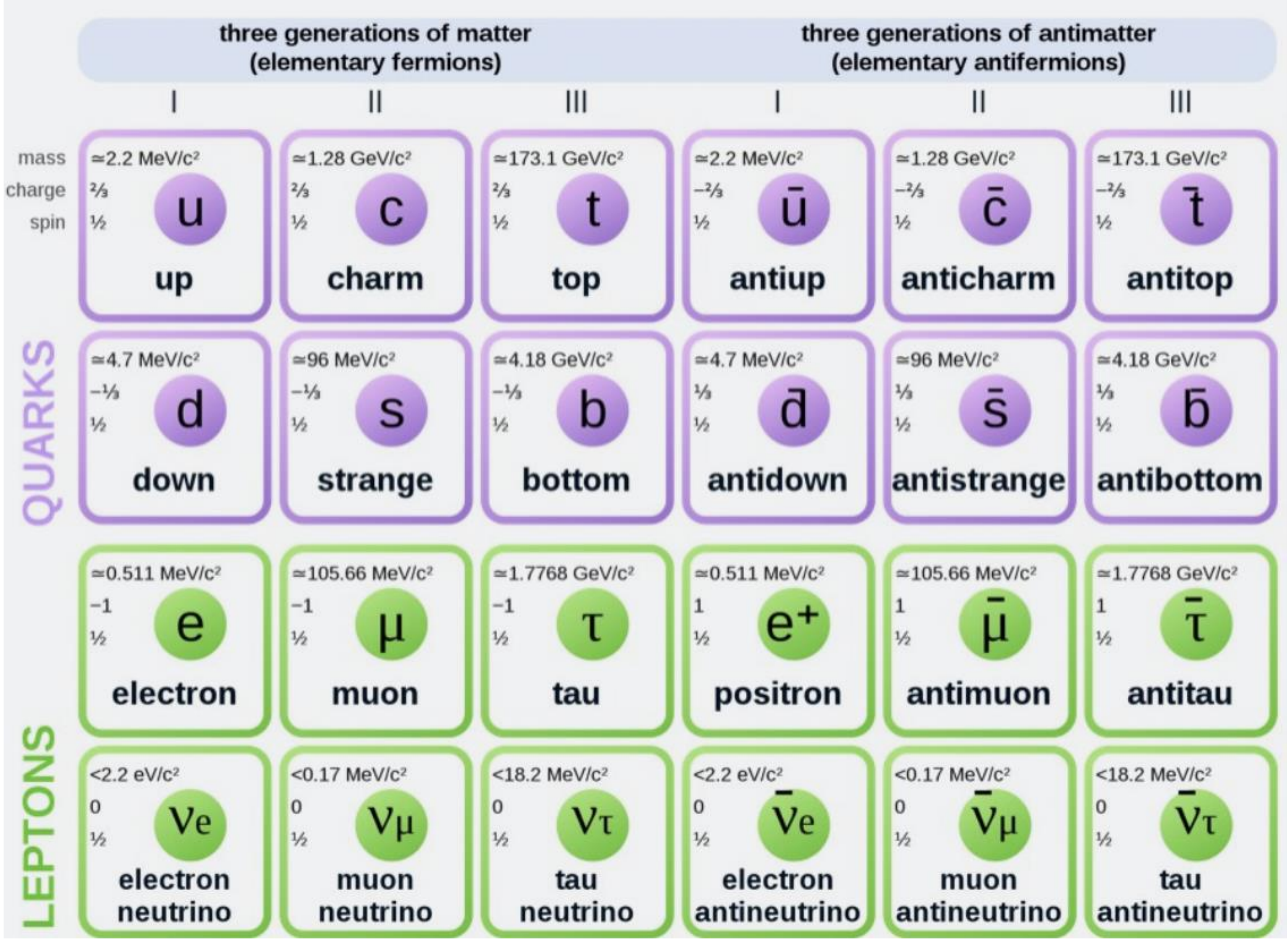
What we see around us





- Proton and neutron together make a nucleus
- electrons+nucleus = atoms
- Different combinations of these three particles make the world around us
- There is also the neutrino, that is all around us like some cosmic ghost. More on that later…

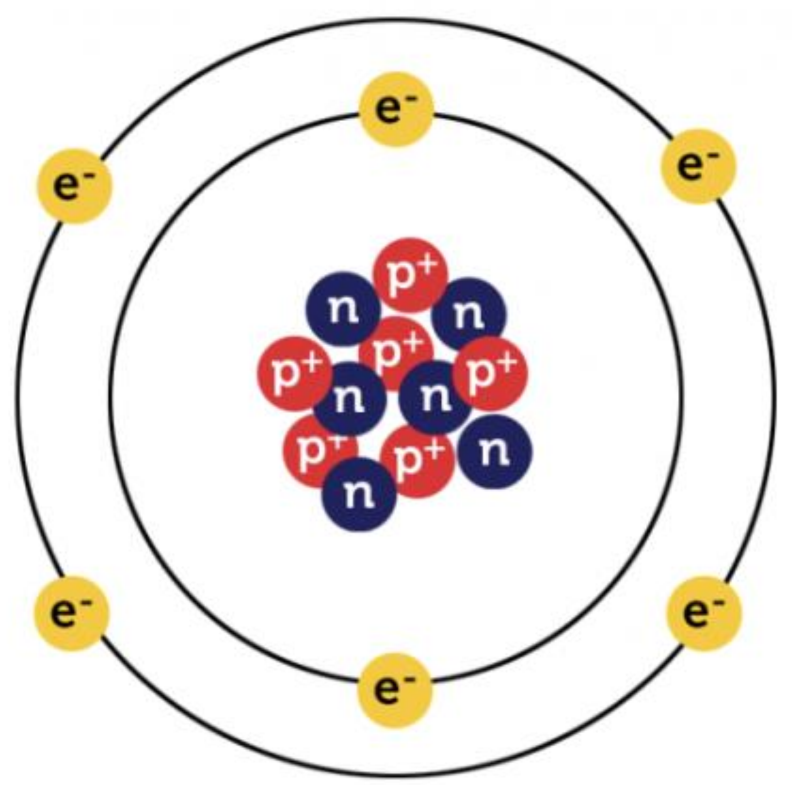
Three generations of fermions



- They differ mainly by **mass**
- Why are there 3 generations? Are there more?
- We dont see the 2nd and 3rd generation particles around us, we have to go searching for them and create them in our accelerators.
  - They quickly decay to the first generation fermions

Fermions and Bosons

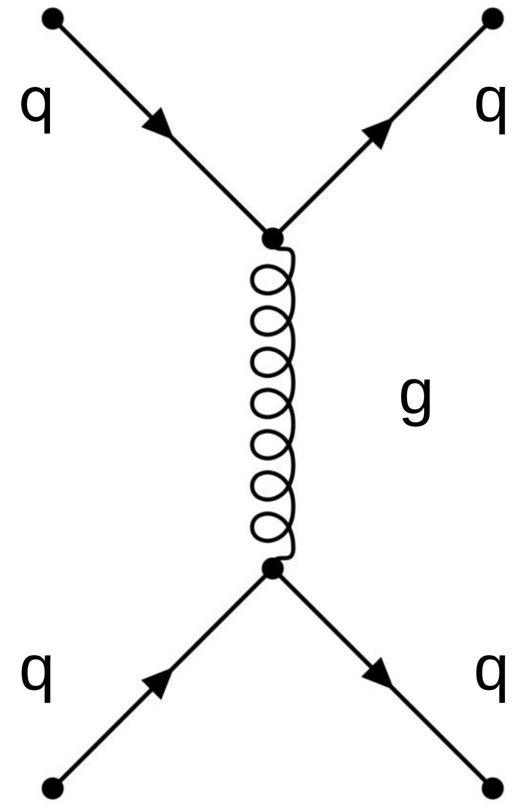
- Fermions and Bosons differ on one key aspect - their **spin**
  - Spin is the intrinsic angular momentum of the elementary particle.
  - All elementary particle can be thought of as a wave
    - for **spin 1** particles, the wave looks the same after **1 full rotation**
    - for **spin 1/2** particles, you need **2 full rotations.**
- Fermions follow **Pauli exclusion principle -** no two identical particle can be in the same state
- Bosons follows **Boson statistics** - applying to a system of particles applying the same state of energy



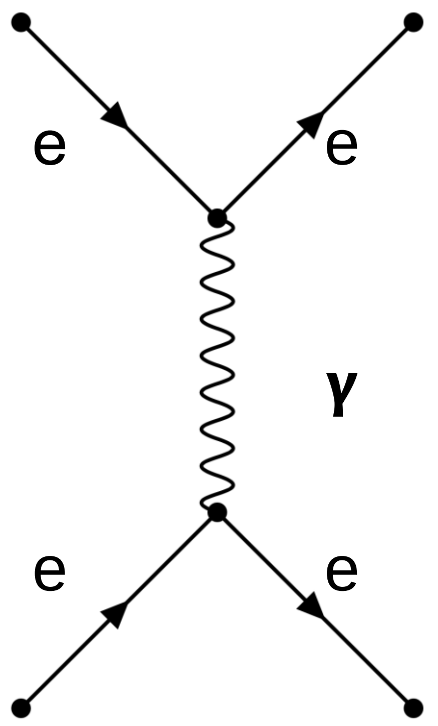
Fields

gluon	photon	W/Z
Strong >>	Electromagnetic >>	Weak
10	10^{-2}	10^{-13}

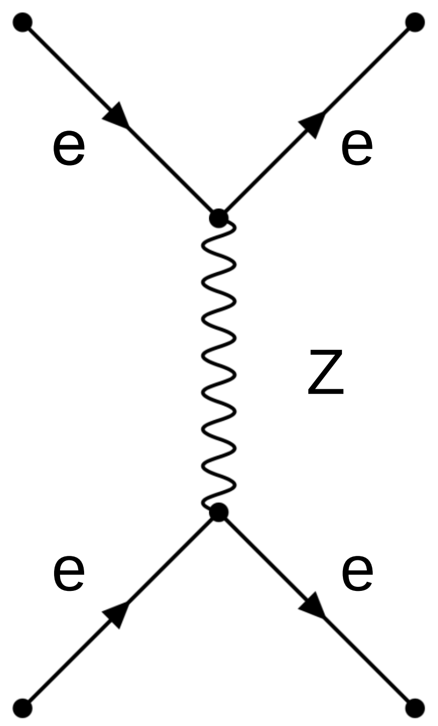
Quantum Field Theory tells us that every particle is associated with a field



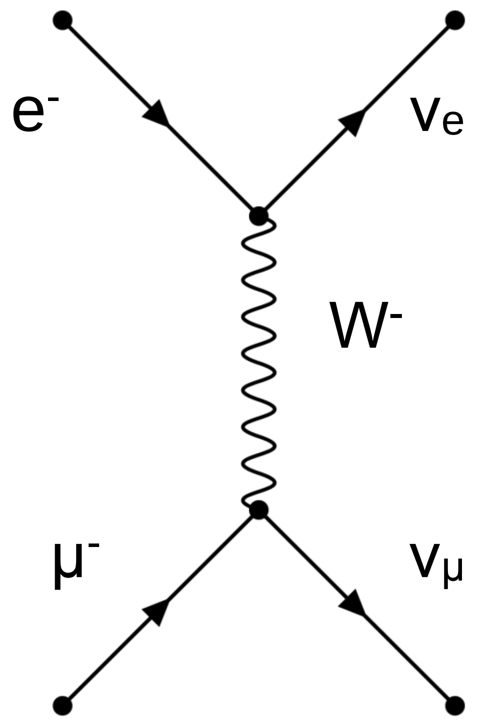
Chromodynamics



Electrodynamics

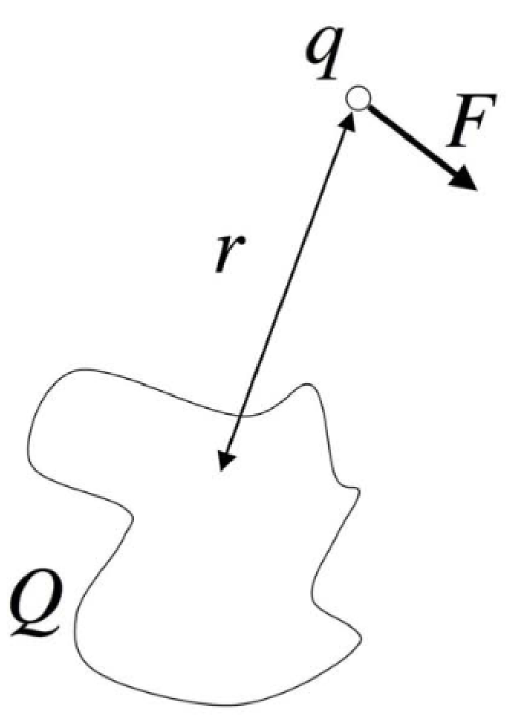


Flavourdynamics

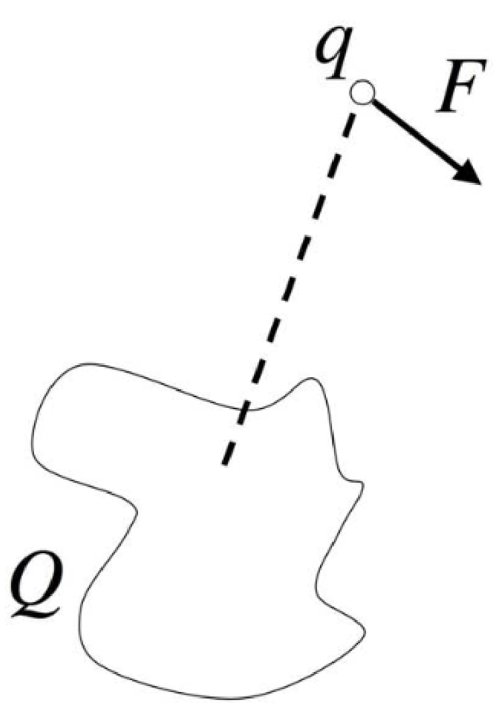


time

Classical



Quantum



Understanding the symmetry in SM

- Gauge theory is a "field theory where equations of motion do not change under coordinate transformations"
- SM can be explained by a perturbative **gauge theory** and is **Lorentz invariant**
- It can be described by the symmetry group : **$SU(3)_C$ x $SU(2)_W$ x $U(1)_Y$**
- C denotes the **color**, W the **weak isospin** and Y the **hypercharge**

S=strangeness
B'=bottomness
C=charmness
T=topness
B=Baryon number

$$Y = S + B' + C + T + B$$

$$Q = I_3 + \frac{1}{2}Y$$

I_3= z component of weak Isospin I

- SU(3): related to the **strong interaction** mediated by **gluons**
- SU(2): related to the **weak interaction** and mediated by **$W^{\pm}$ and Z^0** bosons
- U(1): related to the **EM interaction** and mediated by the **photon**

Symmetry and Conservation Laws in nature

There is symmetry if unchanged by a certain transformation - for physics to be meaningful all laws should be invariant to the change of status of the observer

Transformation	Conserved variable
Translation in space-time	Momemtum-Energy
Rotation in space	Angular momemtum
Reflection	Parity

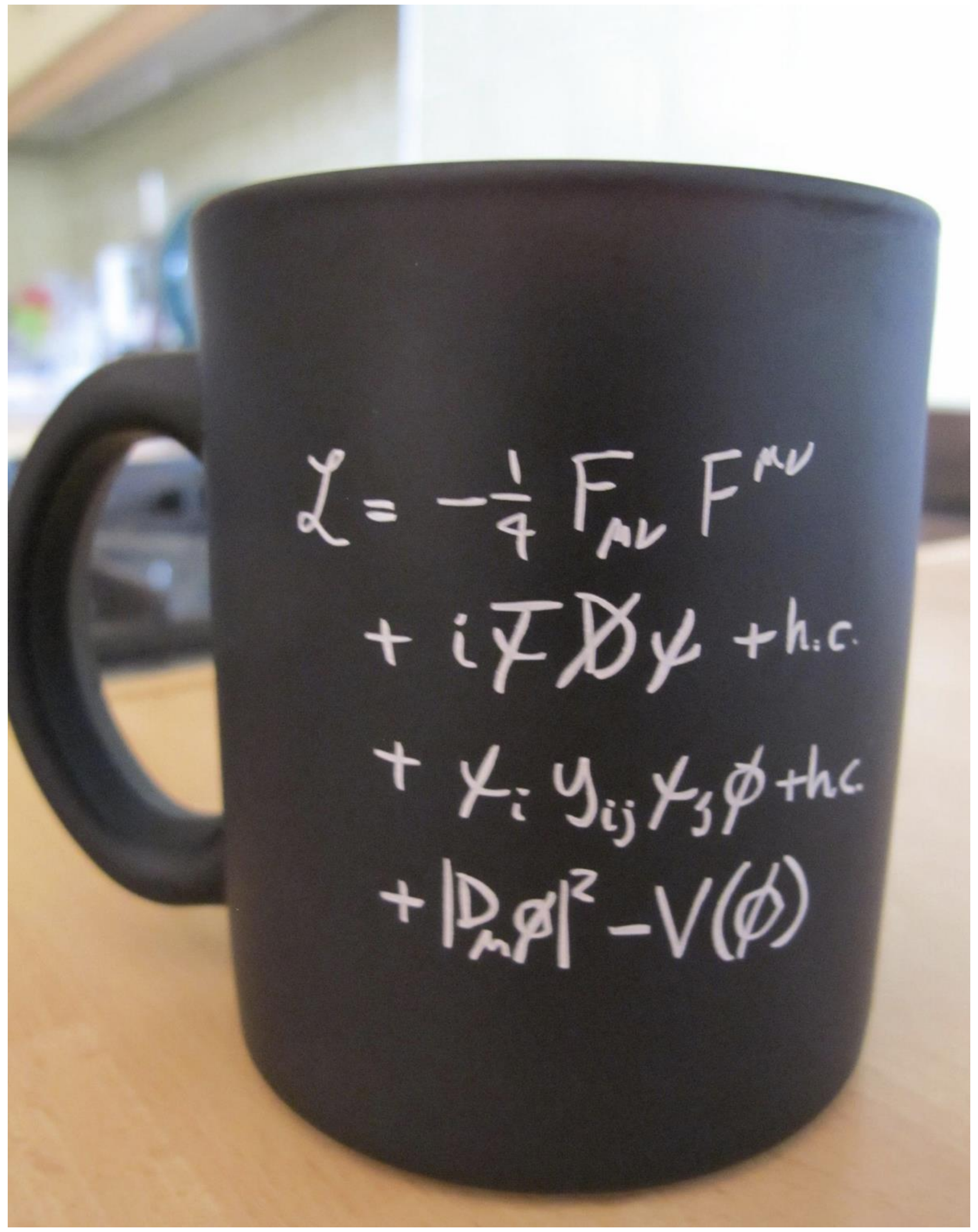
There are also internal transformations that deal with the conservation of quantum numbers of a system

To understand the the transformation of a system we write what is called a “**Lagrangian**” equation, describing the motions and interactions in a system during a transformation

The Standard Model Lagrangian

This was written by Italian physicist Matilde Marcolli

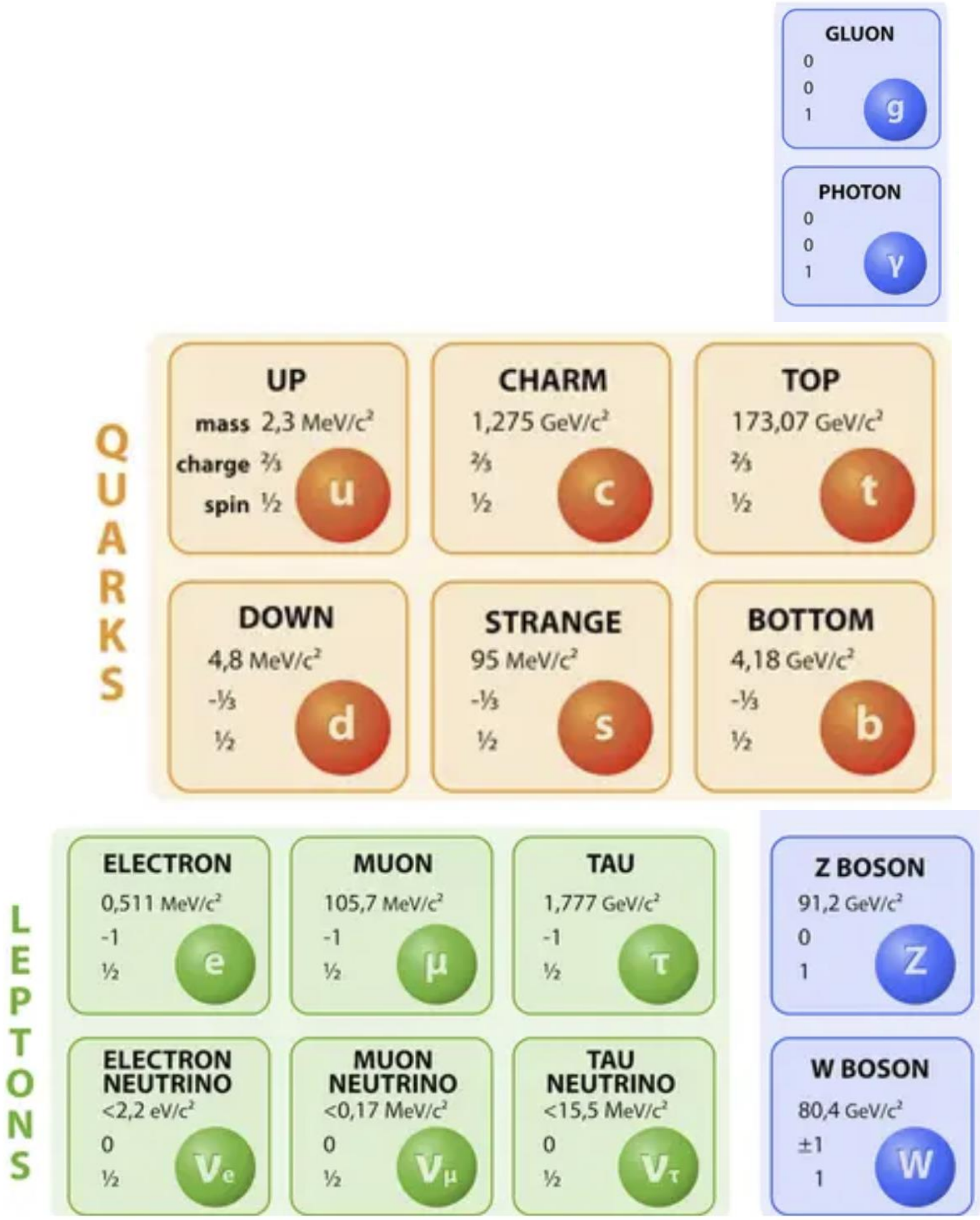
$$
\begin{gathered}
\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g^2_s f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c^2_w} M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \\
igs_w(\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)) - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c^2_w (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s^2_w (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w (A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
\beta_h \left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h - \\
g\alpha_h M\left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
\tfrac{1}{8}g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2\right) - \\
gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c^2_w}Z^0_\mu Z^0_\mu H - \\
\tfrac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \\
\tfrac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
M\left(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\tfrac{s^2_w}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - \\
W^-_\mu\phi^+) - ig\tfrac{1-2c^2_w}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
\tfrac{1}{4}g^2 W^+_\mu W^-_\mu\left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \tfrac{1}{8}g^2\tfrac{1}{c^2_w}Z^0_\mu Z^0_\mu\left(H^2 + (\phi^0)^2 + 2(2s^2_w - 1)^2\phi^+\phi^-\right) - \\
\tfrac{1}{2}g^2\tfrac{s^2_w}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s^2_w}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c^2_w - 1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^2 s^2_w A_\mu A_\mu\phi^+\phi^- + \tfrac{1}{2}ig_s\lambda^a_{ij}(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + \\
m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right) + \\
\tfrac{ig}{4c_w}Z^0_\mu\{(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s^2_w - 1 - \gamma^5)e^\lambda) + (\bar{d}^\lambda_j\gamma^\mu(\tfrac{4}{3}s^2_w - 1 - \gamma^5)d^\lambda_j) + \\
(\bar{u}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s^2_w + \gamma^5)u^\lambda_j)\} + \tfrac{ig}{2\sqrt{2}}W^+_\mu\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) + \\
\tfrac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa\right) - \tfrac{g}{2}\tfrac{m^\lambda_\nu}{M}H(\bar{\nu}^\lambda\nu^\lambda) - \\
\tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M}\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda) - \tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa - \\
\tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j\right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \\
\tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu + \\
\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c^2_w})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \\
\partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \\
\partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) - \tfrac{1}{2}gM\left(\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c^2_w}\bar{X}^0 X^0 H\right) + \tfrac{1-2c^2_w}{2c_w}igM\left(\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-\right) + \\
\tfrac{1}{2c_w}igM\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) + igMs_w\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) + \\
\tfrac{1}{2}igM\left(\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0\right).
\end{gathered}
$$



the coffee cup version 😃

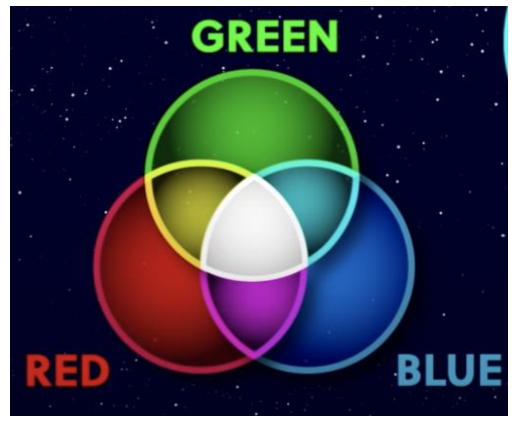
Some intrinsic properties of elementary particles

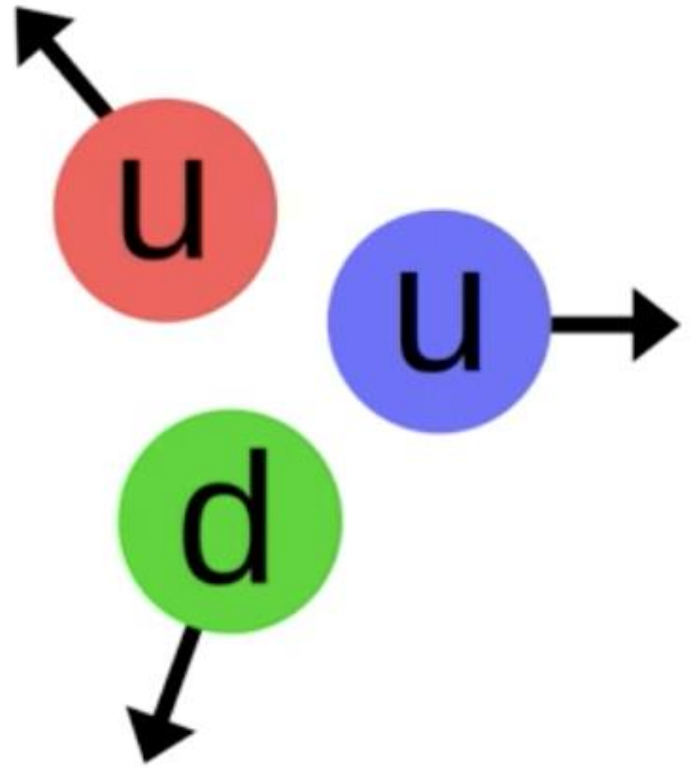
- **Charge** - can be positive or negative and is quantized. 1e= 1.6x10^-19 C. Charge is conserved in all interactions
- **Color** - gluons and quarks carry color. Only plays a role in strong interactions and is conserved.
- **Baryon number** - all quarks have baryon numbers and they are conserved in all strong interactions. $B=1/3(n_q-n_{\bar{q}})$
- **Lepton number** - if a lepton goes in, a lepton comes out. Conserved in all EM and weak interactions.
- **Spin** angular momentum (related to space-time symmetry) is an intrinsic property of an elementary particle. Conserved in all interactions.
- **Isospin** intrinsic quantum number described by SU(3) group- relating to quark composition. Isospin transformation can change up quark to down quark
- **Flavour** - the flavour of the quarks are conserved in strong and EM interactions



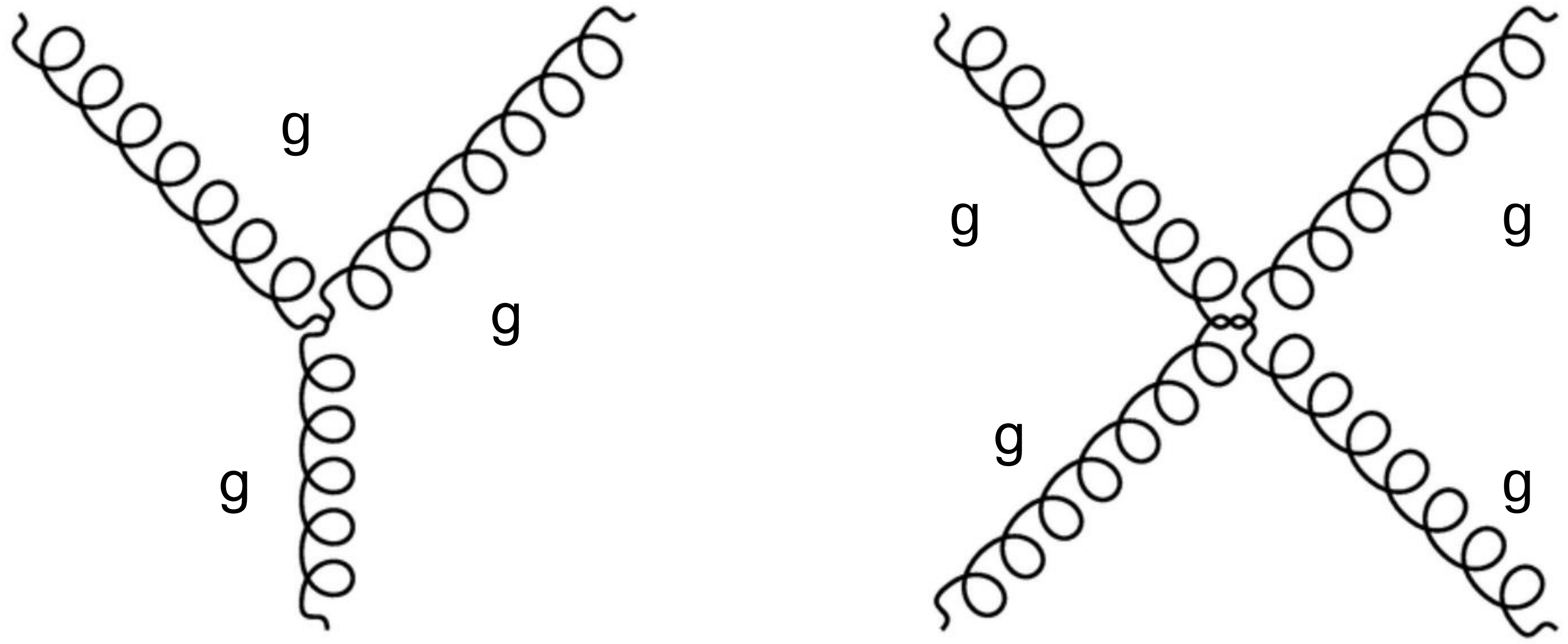
Qaurks and color

- **Pauli's exclusion principle** tells us no two identical fermion can occupy the same state. But we know baryons(qqq) and mesons ($q\bar{q}$) exist
- A new quantum number "color" was born to explain this
- Quarks not only come in different flavours, they come in 3 different "colors"- "red", "green" and "blue". Three/two different colors made up baryon/meson thus solving the conflict.
- 8 types of gluons: each carrying a color and anti-color. Gluons are responsible for all strong interactions.
- Composite particles are color singlets





Force strengthens as you pull them apart



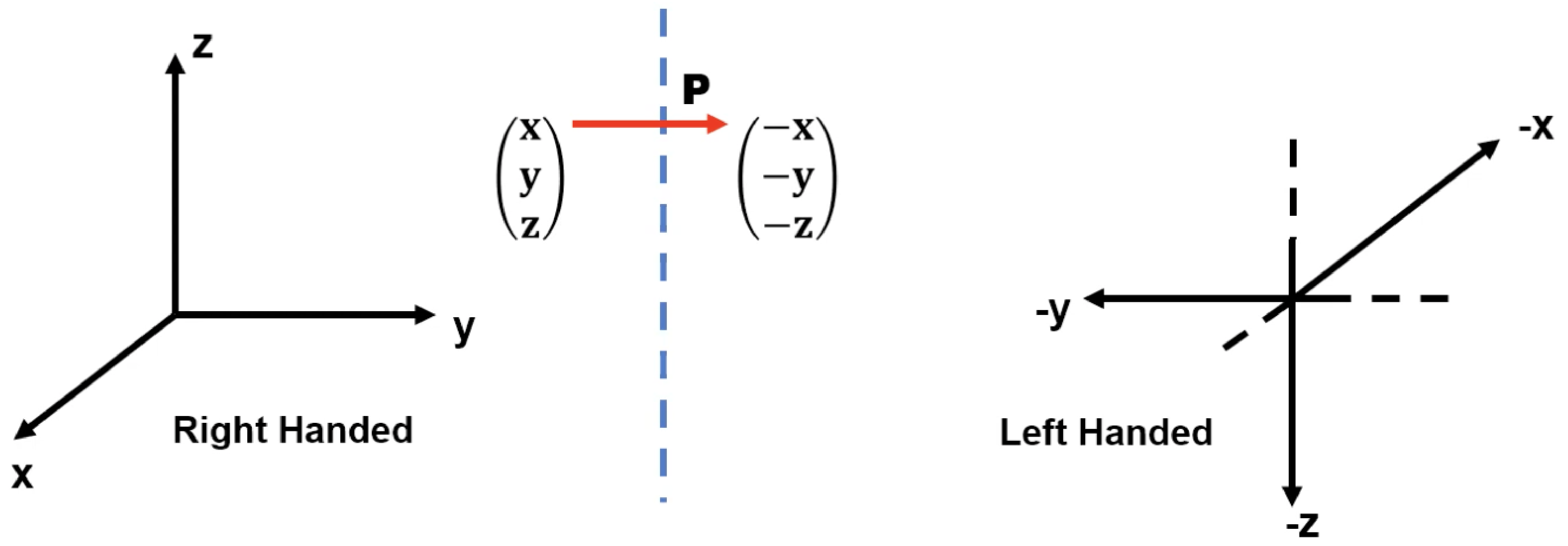
Helicity

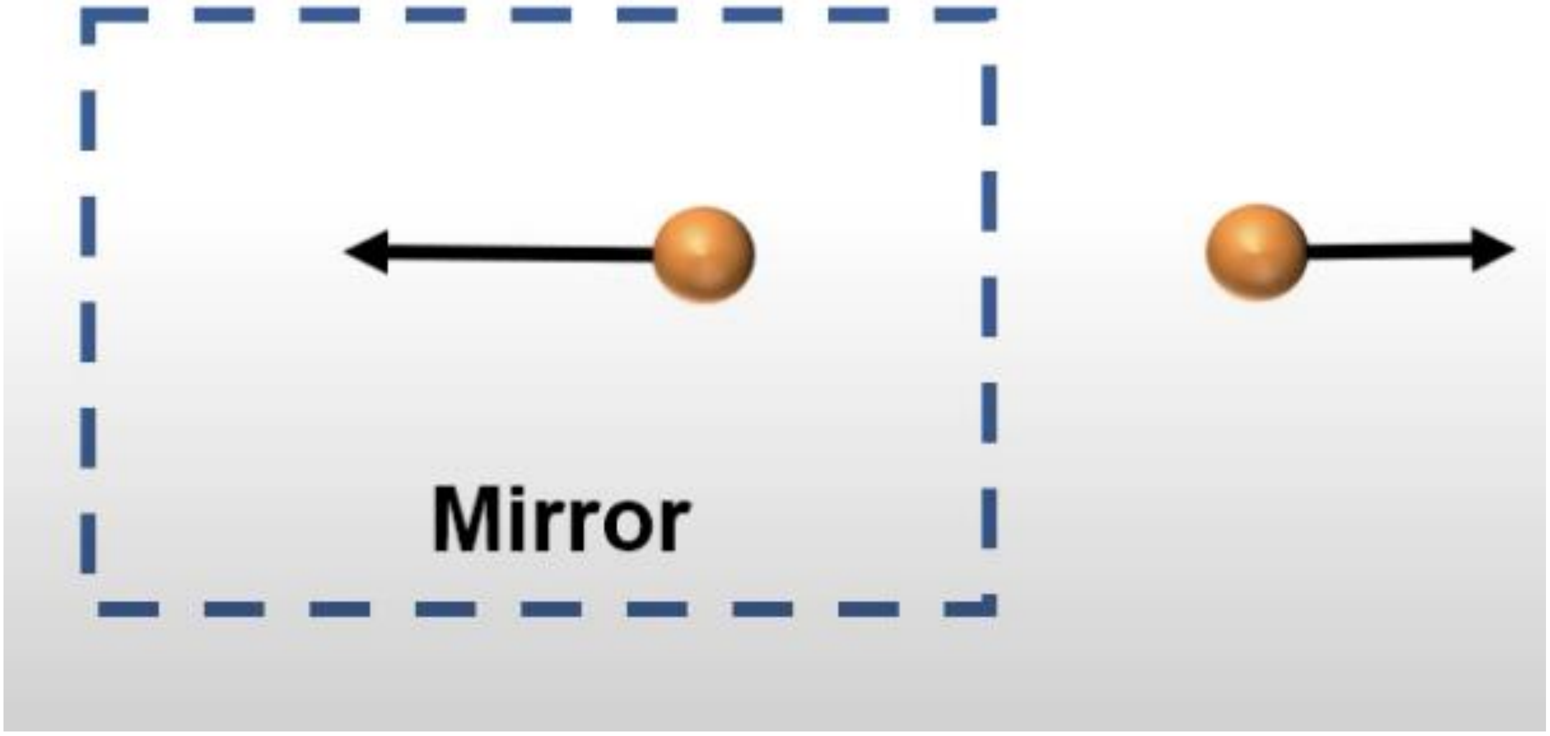
- **Helicity** - observable of an elementary particle. **Projection of spin on the momemtum**

$$h > 0; \vec{S} \parallel \vec{p}, right\ handed \quad h < 0; \vec{S} \nparallel \vec{p}, left\ handed$$

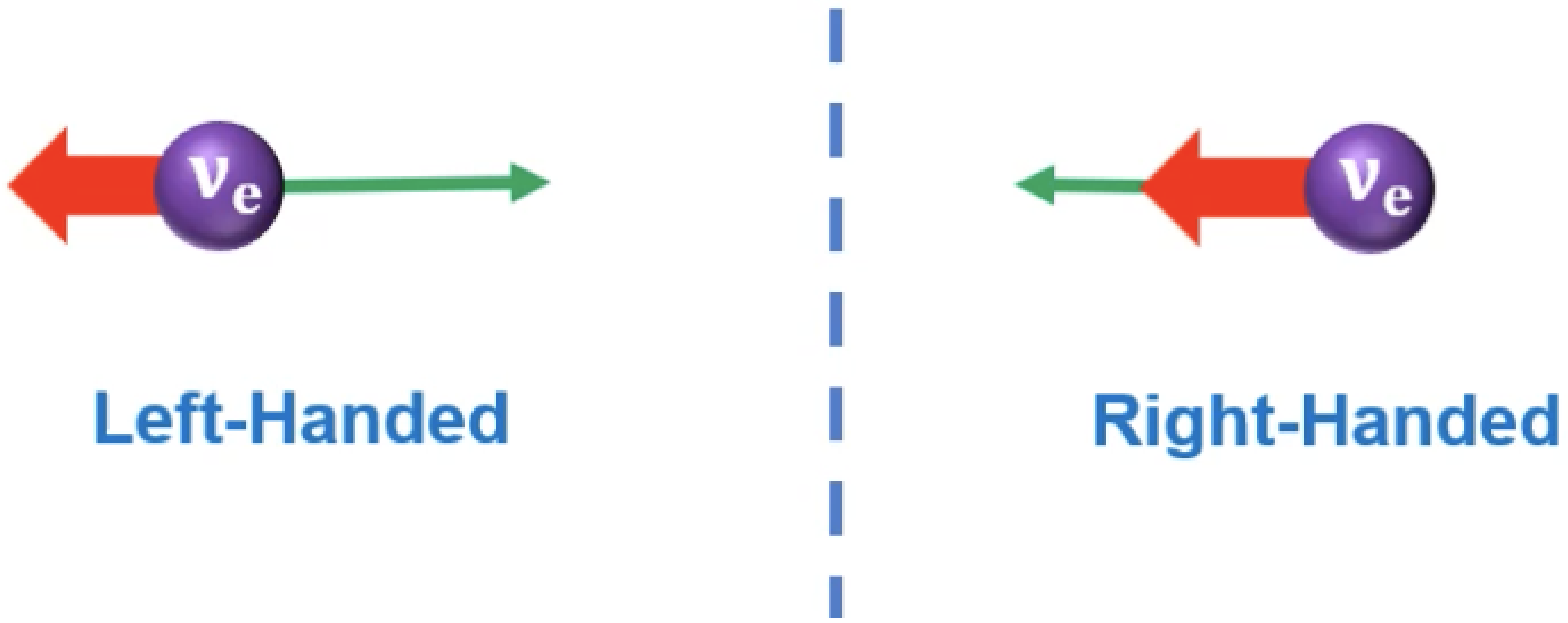
- Weak interactions will effect : left chiral particle, right chiral antiparticle

Parity and Helicity

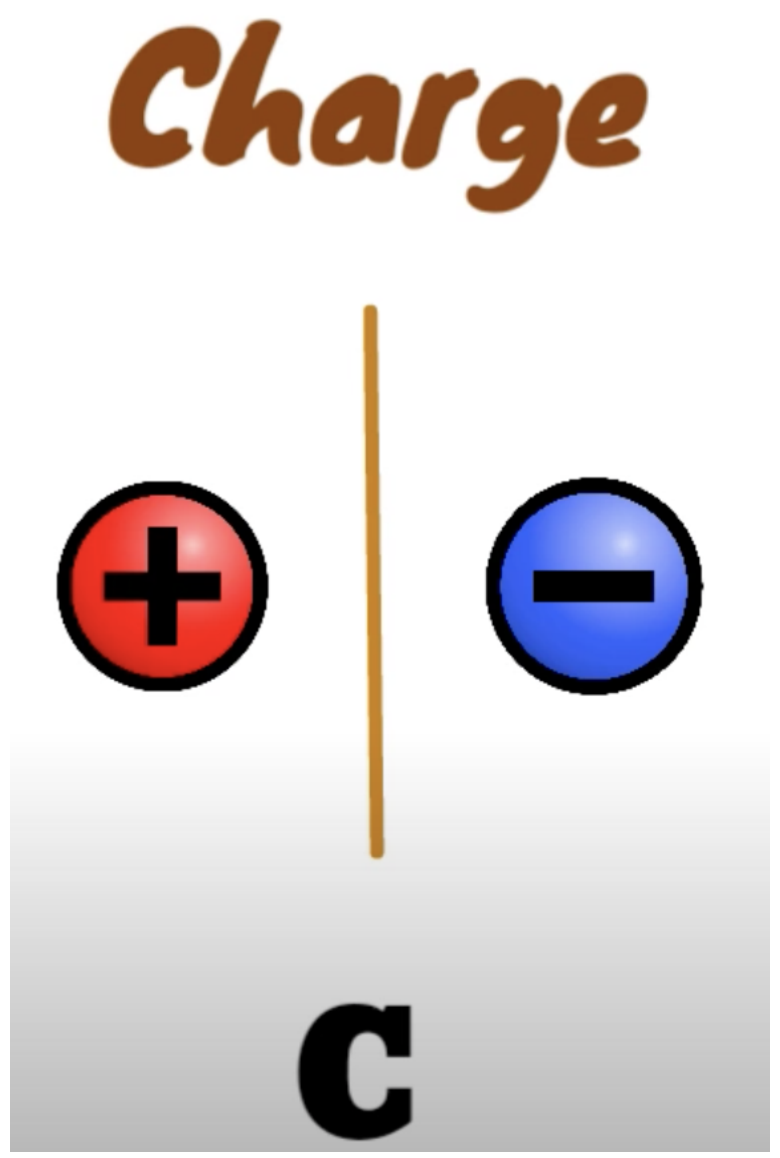


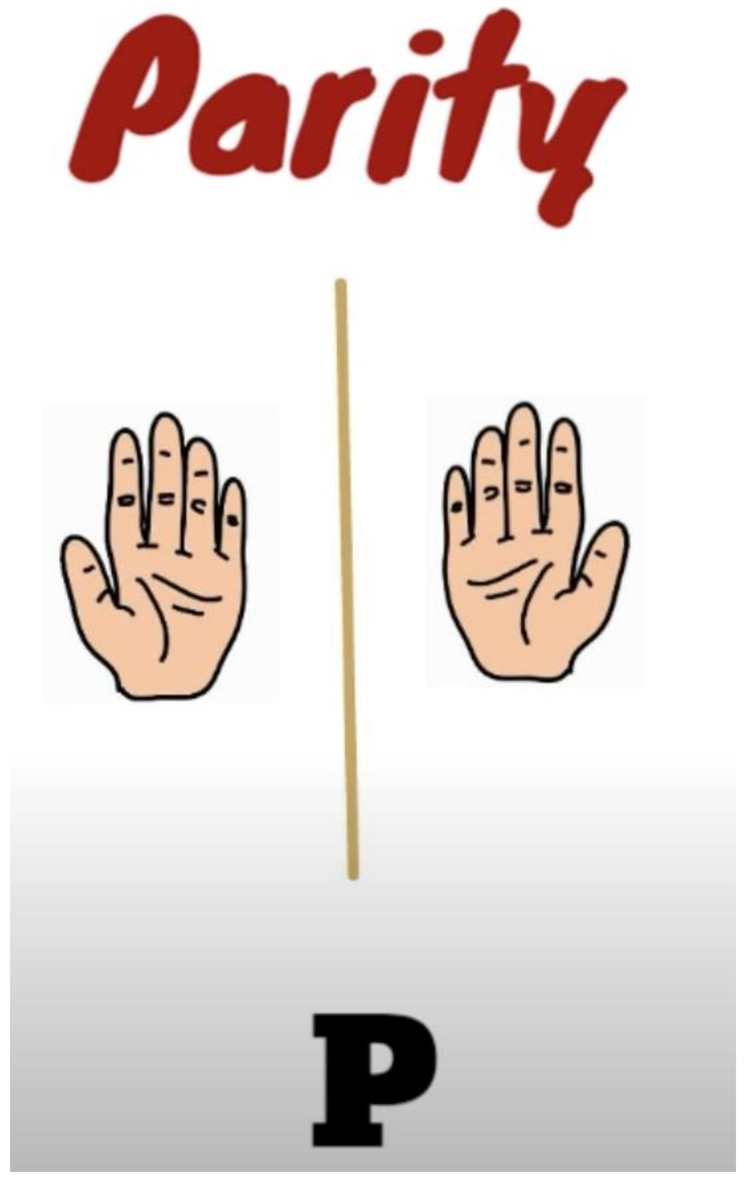


- **Right handed neutrinos do not exist**, hence violating parity



Charge Parity and kaons





$$Kaons = \{u, d, s\}$$

$$\{\overline{u}s, \overline{s}u, \overline{d}s, \overline{s}d\}$$

$$K^{-} K^{+} \quad \overline{K}^{0} \quad K^{0}$$

$$P|K^0> = -|K^0>$$

$$C|K^0> = +|K^0>$$

$$CP|K^0> = -|K^0>$$

$$K_L^0 --> \pi + \pi$$

$$(-1) --> (-1)^2$$

- On combining charge conjugation and parity:
- Parity transforms **left handed neutrino to right handed neutrino** (does not exist)
- Charge conjugation transforms **right handed neutrino to right handed anti-neutrino** , which **does exist**!
- **Kaons violated CP**, K^0_L sometimes decays to two pions (even parity) instead of 3 pions (odd parity) — could this point to why we are missing all the antimatter?

Symmetry and Conservation Laws for elementary particles

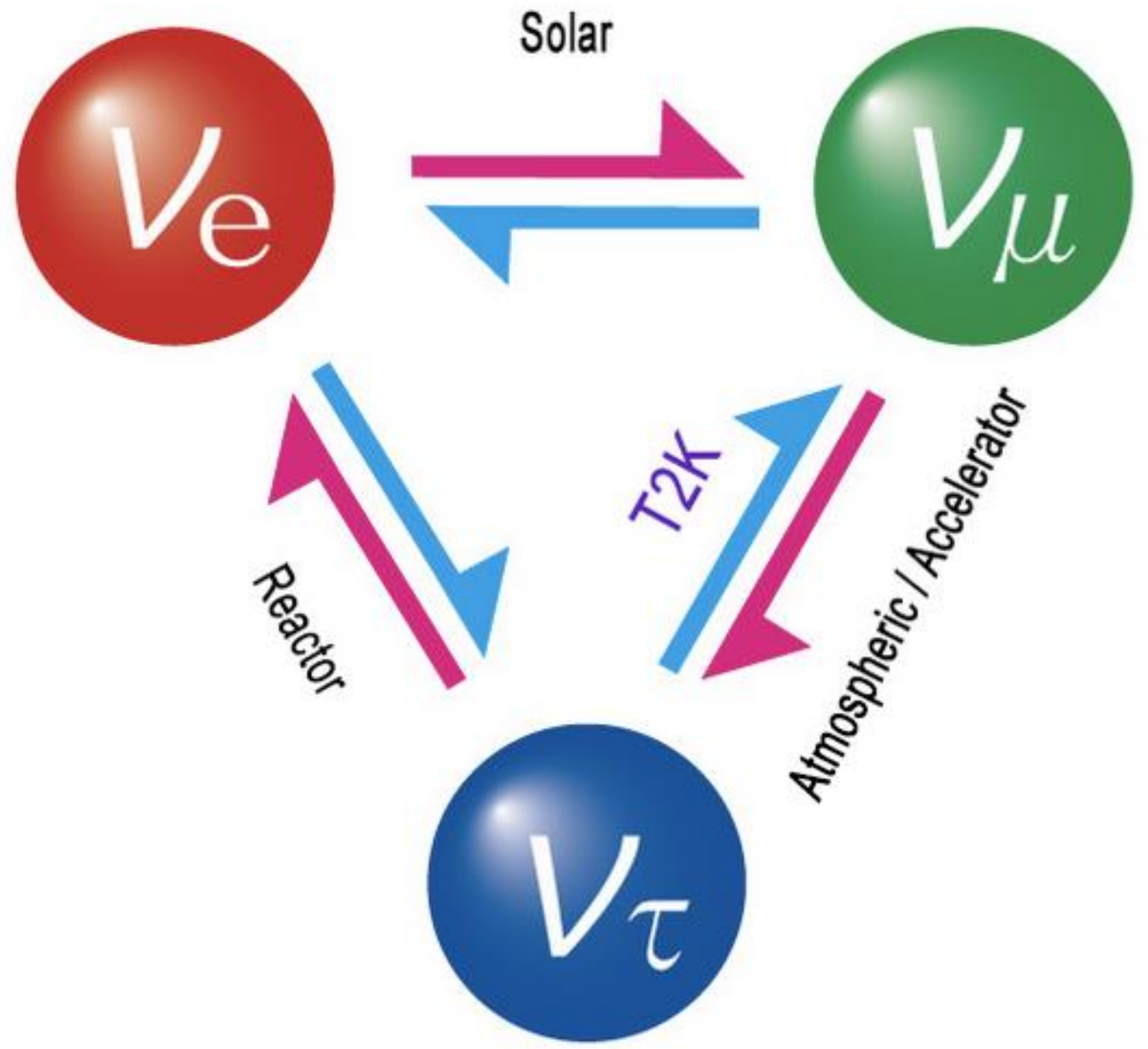
	Strong	EM	Weak
Energy	✓	✓	✓
Linear momemtum	✓	✓	✓
Angular momemtum	✓	✓	✓
Isospin I_z	✓	✓	✗
Isospin magnitude	✓	✗	✗
Charge	✓	✓	✓
Color	✓	✓	✓
Baryon number	✓	✓	✓
Lepton number	✓	✓	✓
S, C, T, B	✓	✓	✗
Parity	✓	✓	✗
Charge conjugation	✓	✓	✗
Charge Parity	✓	✓	✓
Charge Parity Time	✓	✓	✓

} thanks to neutrinos (Parity, Charge conjugation)

except “kaons” (Charge Parity)

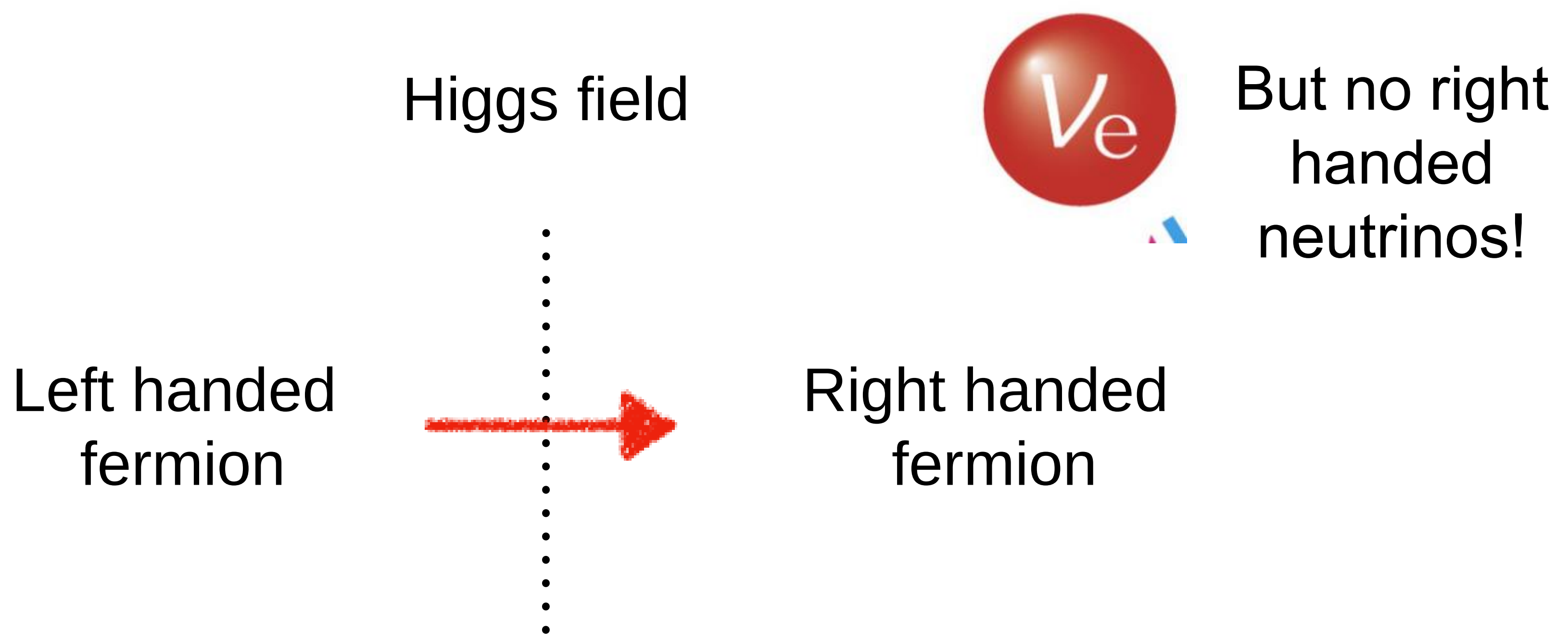
What is special about the neutrino?

- Although abundant in nature, very difficult to detect as they interact with matter rarely and only feels the **weak force**
- In the SM, the neutrino is massless. But recent experiments have proved that neutrinos can change flavour - “**neutrino oscillations**”.
  - For this to work neutrinos need to have some tiny mass
- Fermilab has designed the Deep Underground Neutrino Experiment (**DUNE**) where the neutrinos travel a long distance (800 miles) and scientists will record and study the neutrinos at the start and end as well as all interactions during the journey.
- At the LHC, neutrinos are studied at a much higher energy scale from W,Z, b or c decays - for cross section measurements, decays and probe for physics beyond SM

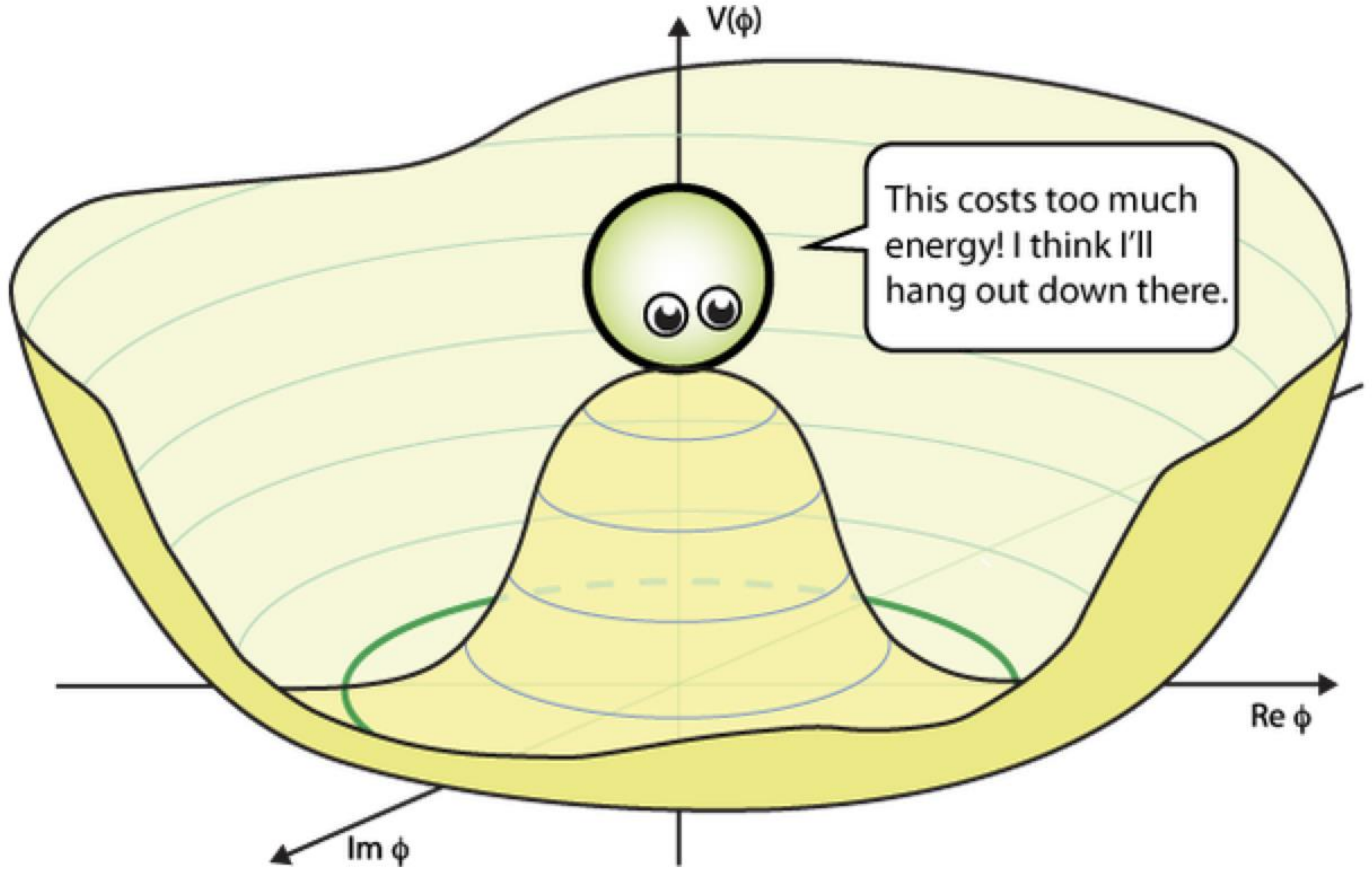


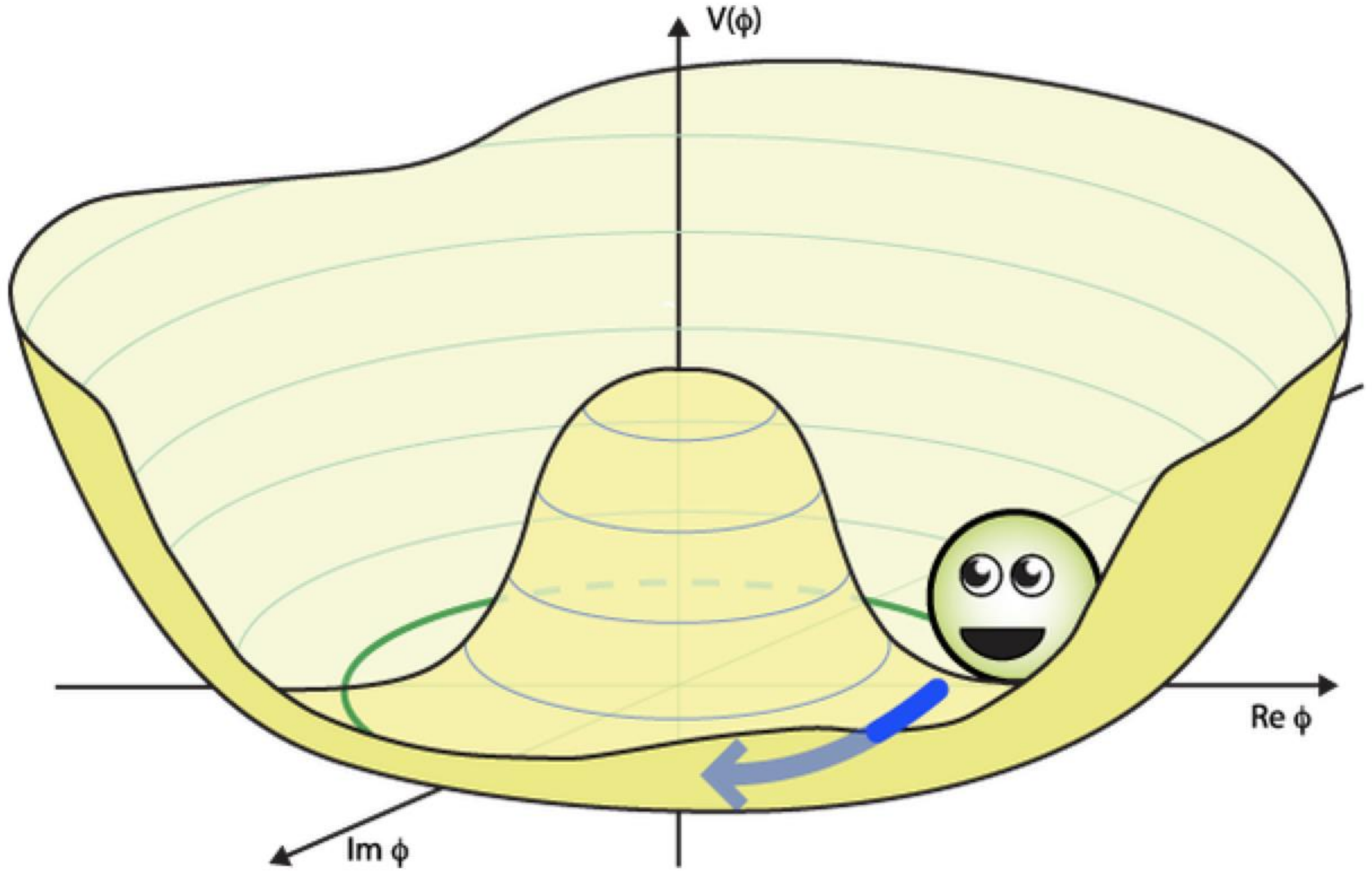
Higgs boson and Fermion mass

- The Higgs boson first proposed in 1926 by Peter Higgs and Francois Englert
- It is a manifestation of the Higgs field where the Higgs boson wants to be at the lowest possible value - but this breaks the symmetry in the field
- At the lower point the **Vacuum Expectation Value** (VEV) - has a non zero value , but the energy is lower than before.

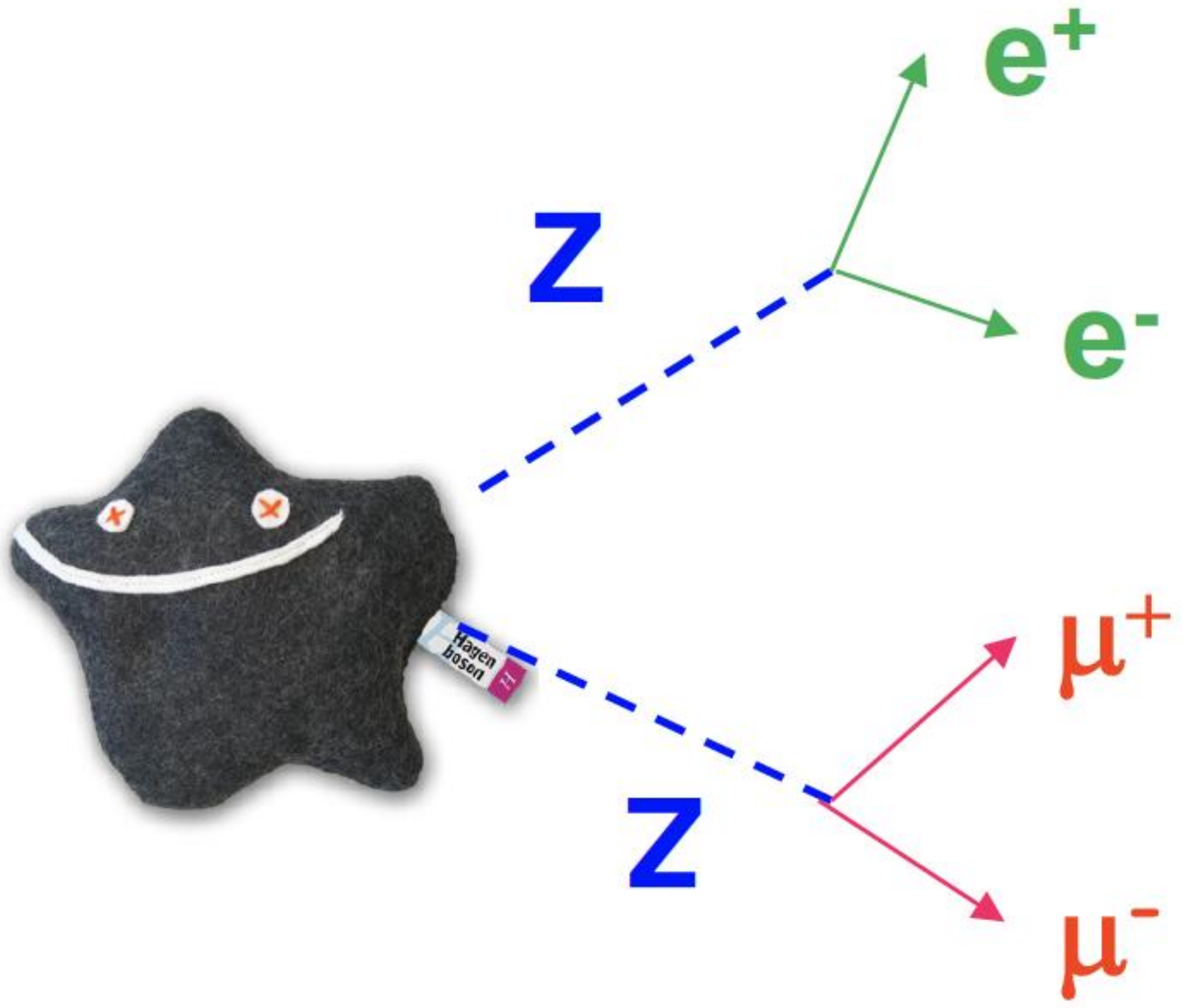


This interaction with the Higgs field gives fermions their masses and the coupling with the Higgs field is called the **Yukawa** coupling





Finding the Higgs boson



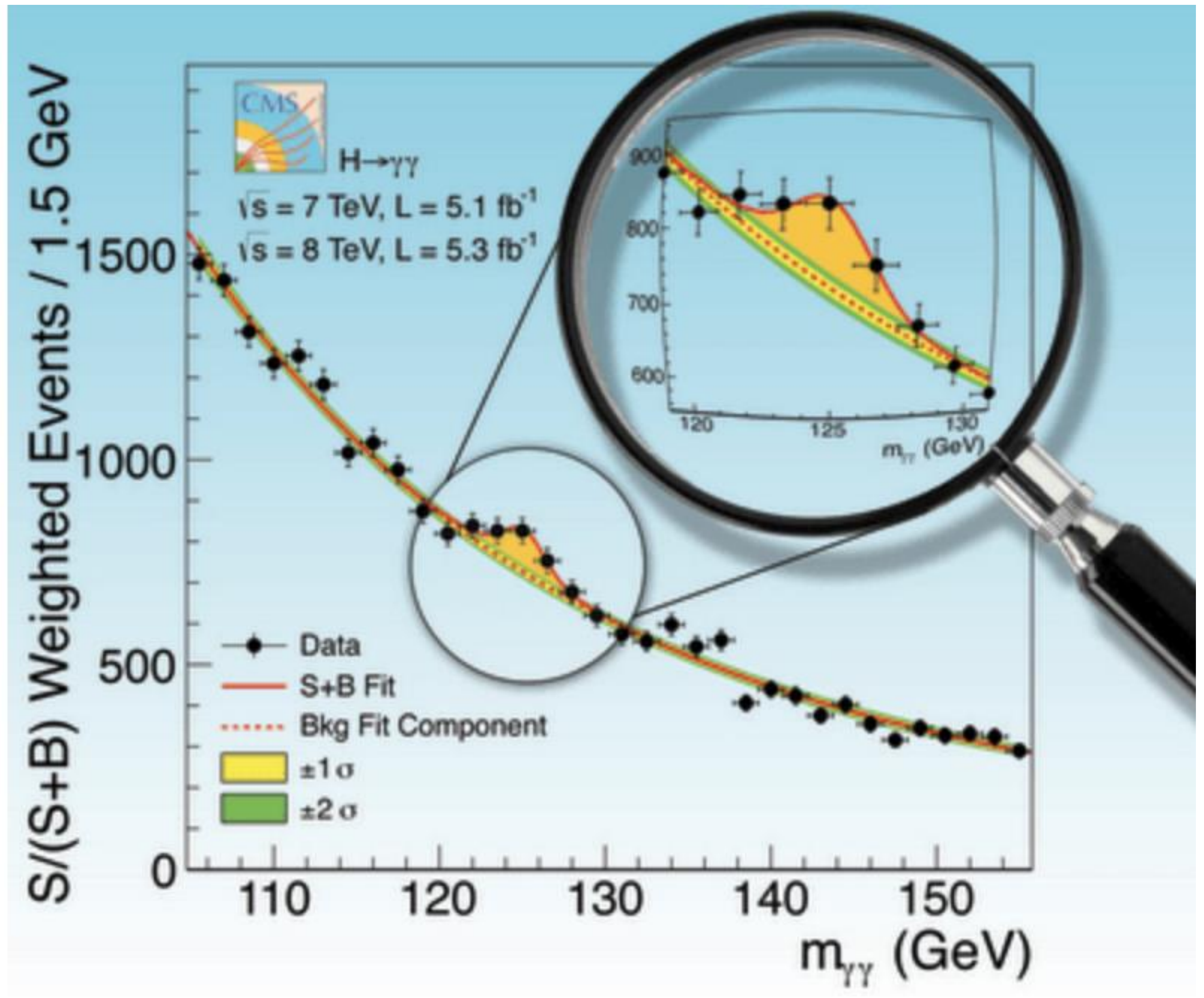
$$E^2 = p^2 + (mc^2)^2$$

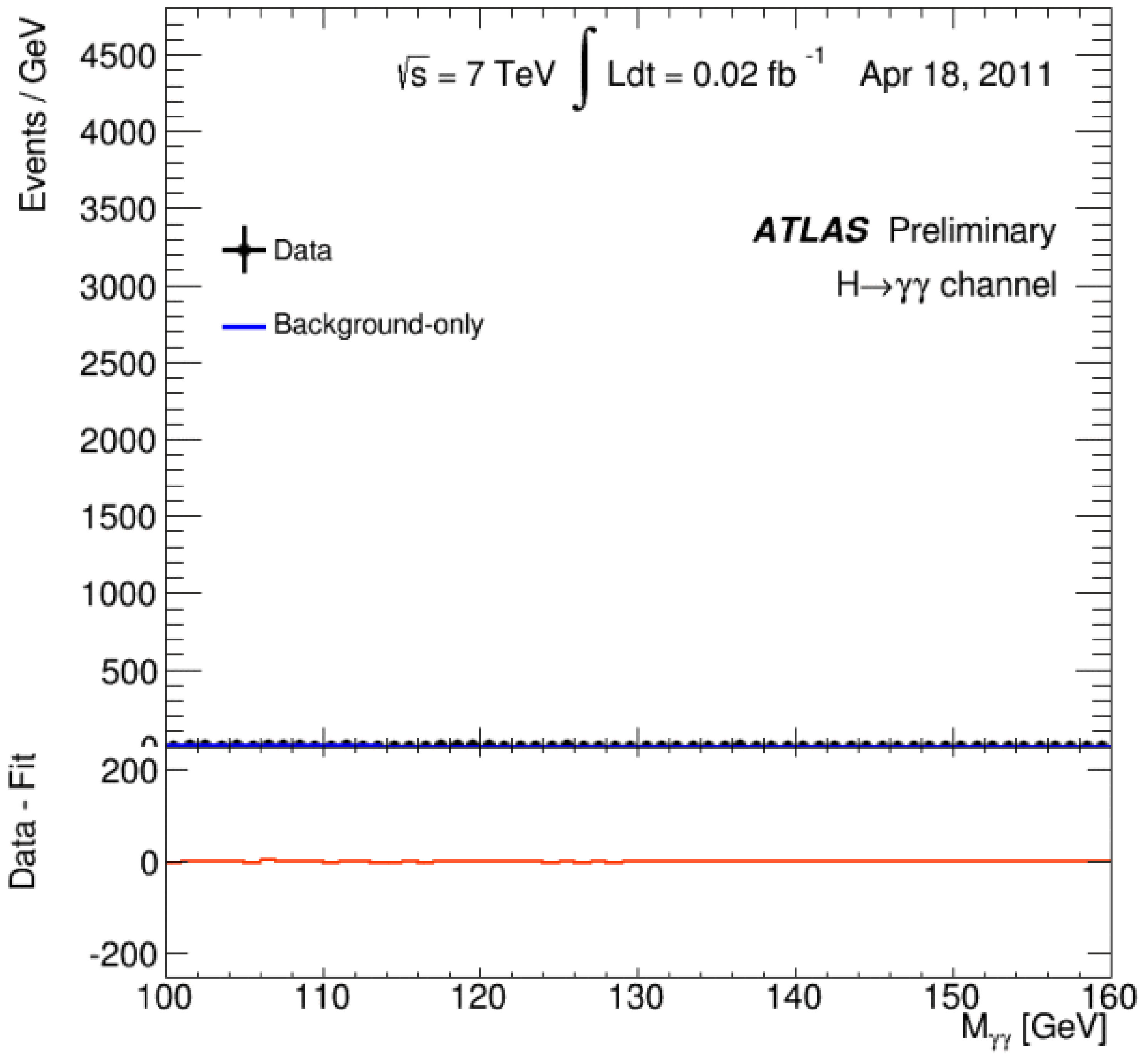
H—> Z + Z—> $e^+ e^- e^+ e^-$

H—> Z + Z—> $e^+ e^- \mu^+ \mu^-$

H—> Z + Z—> $\mu^+ \mu^- e^+ e^-$

H—> Z + Z—> $\mu^+ \mu^- e^+ e^-$

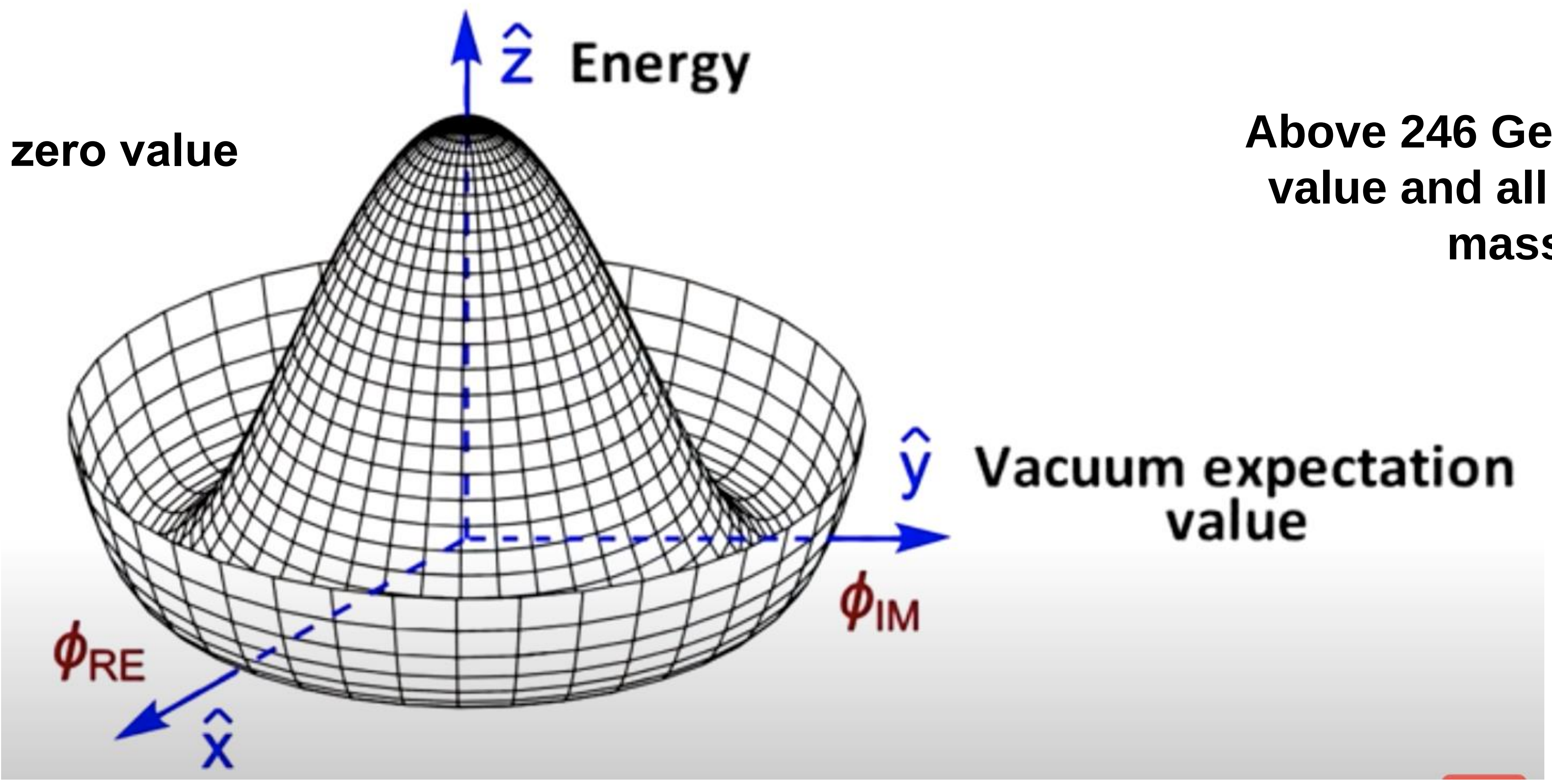




Electro weak force and spontaneous symmetry breaking

- It is the unification of electromagnetic and weak nuclear interaction based on $\mathbf{SU(2)_W \times U(1)_Y}$ gauge symmetry.
- Glashow, Weinberg and Salam said these the two forces can be understood by the same principle - with **4 massless mediators**
  - However we have **one massless (γ) and three massive mediators ($W^{\pm}$, Z)**
- **Higgs** field below **246 GeV** acquires a non zero vacuum expectation energy (VEV) and interacts with the SU(2) and **breaks the symmetry** giving all **three mediators mass**.
- As energy falls below **246 GeV**, this **gauge symmetry is spontaneously broken** - leading to the **Higgs field**
- However U(1) remains intact and stays massless - stays in the VeV= 0 plane

Below 246 GeV, VeV has a non zero value

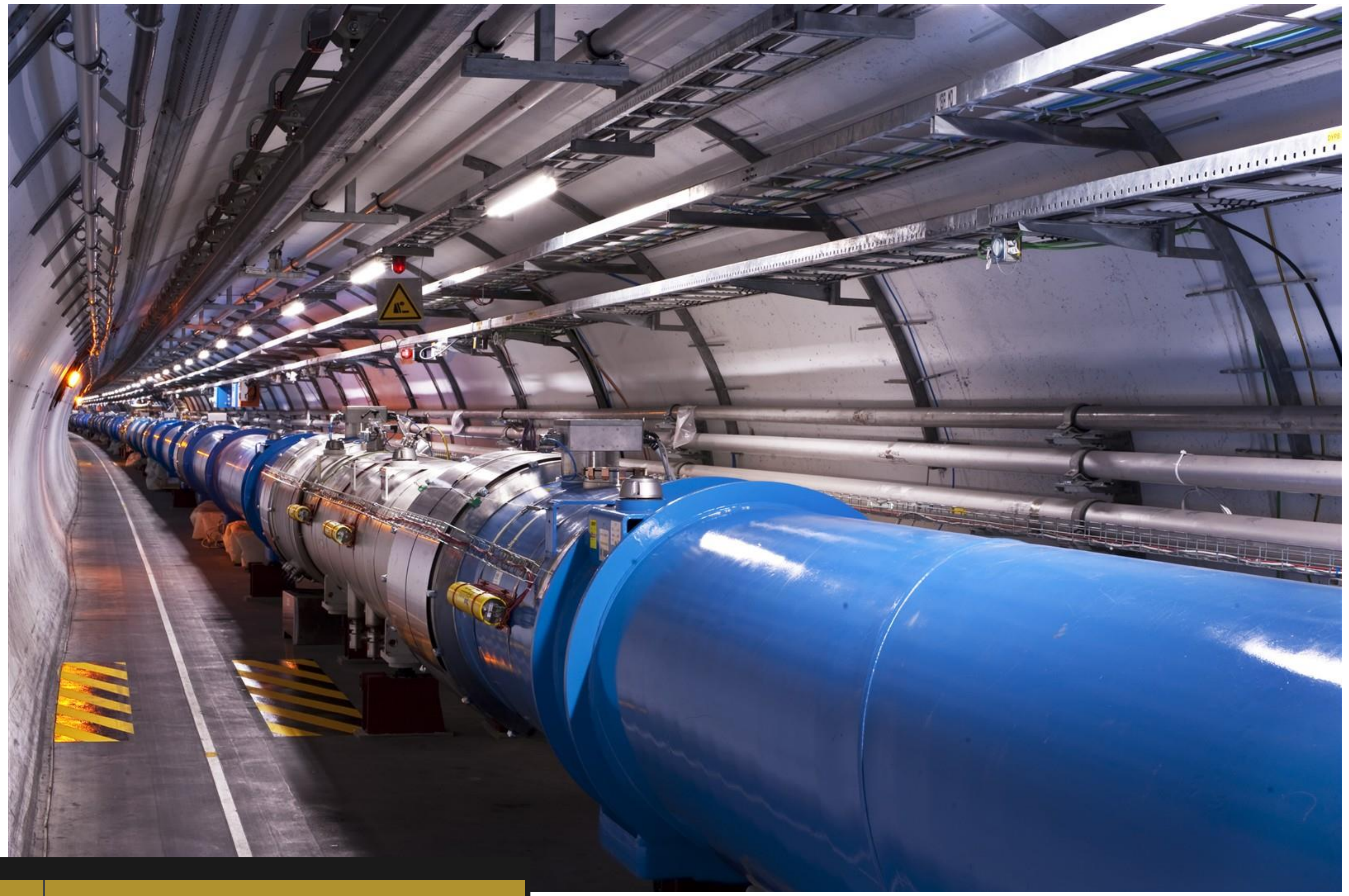


Above 246 GeV, VeV is zero value and all particles are massless

How do we study the SM?

- Scientists have been conducting experiements and discovering particles since the 19th century. Started with the Cathode ray tube, Geiger Counter, cloud chamber and so on…
- It was understood by the early 20th century smashing atoms at high energy at a target leads to splitting of the target - giving scientists the oppurtunity to study its components.
- The first accelerator was made by Cockcroft and Walton in 1932 using a **400 keV generator** to accelerate protons and shoot them at a lithium target.

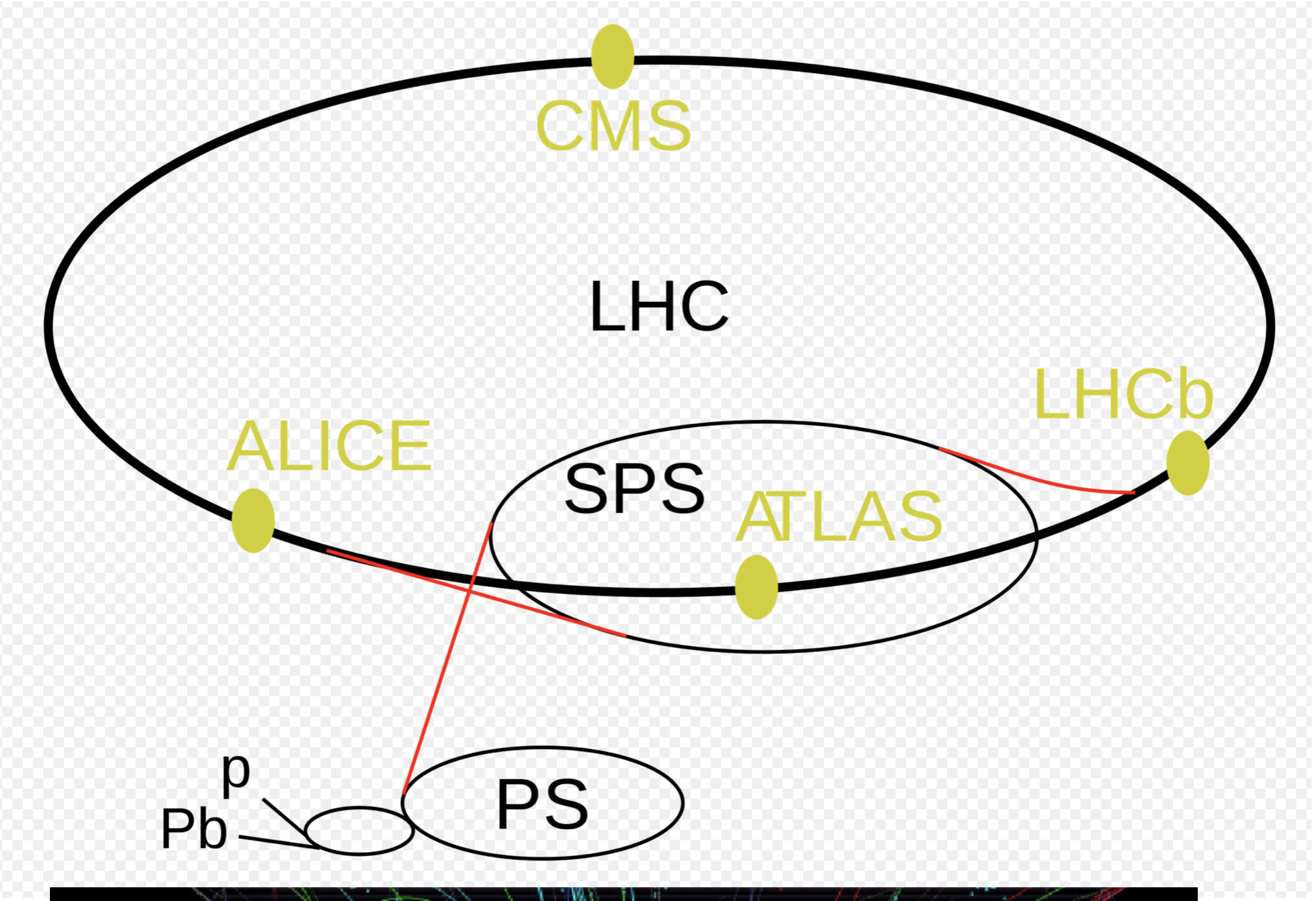
The Large Hadron Collider

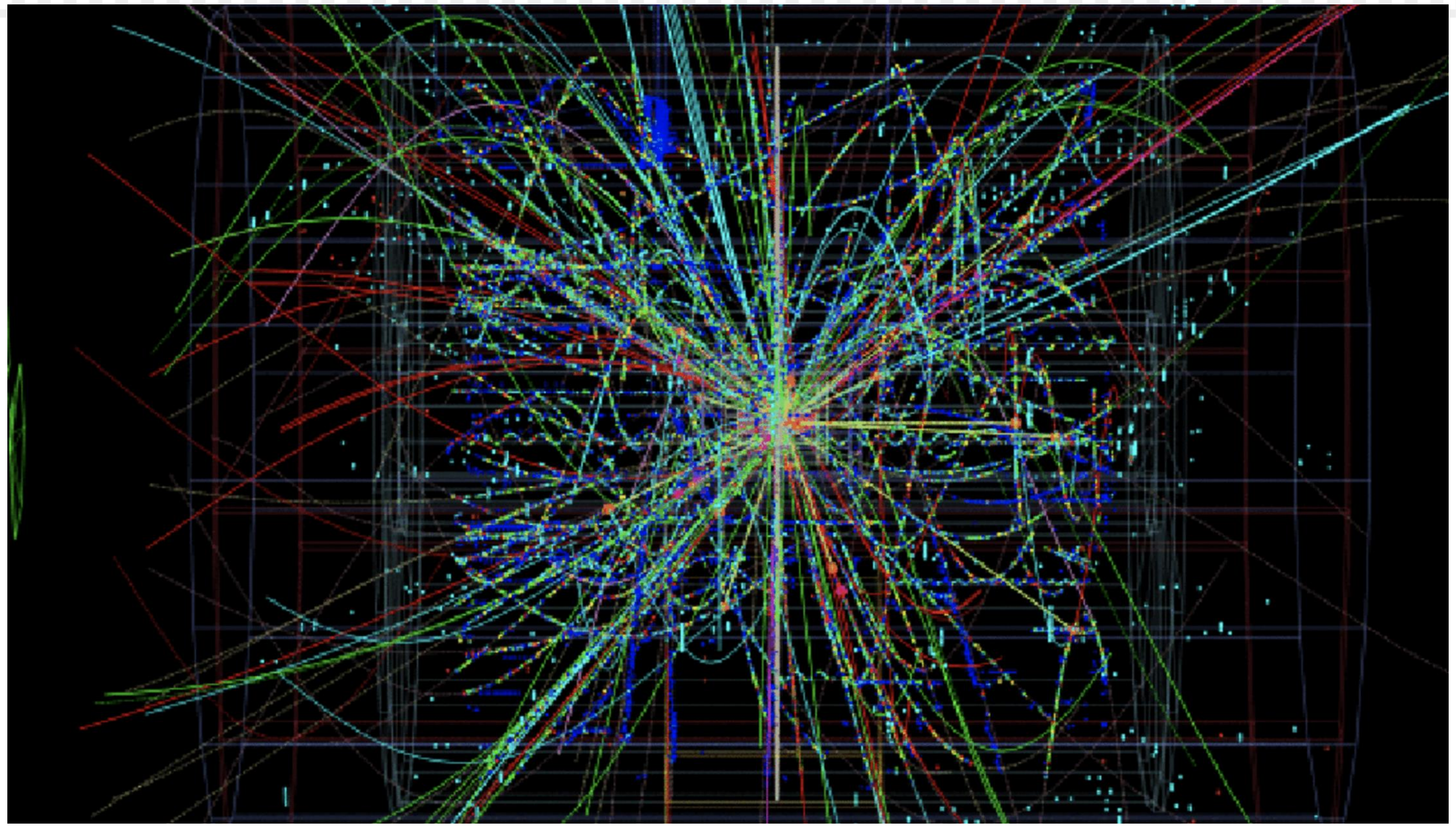


Year	Particle	Accelerator Name	Accelerator Type	Location
1955	antiproton	Bevatron	proton synchrotron	LBNL, U.S.
1962	muon neutrino	AGS	proton synchrotron	BNL, U.S.
1974	J/ψ meson	SLAC	electron linac	California, U.S
1975	tau lepton	SLAC	electron linac	California, U.S
1978/1979	gluon	DORIS/PETRA	electron synchrotron	DESY, Germany
1983	W, Z bosons	SPS	proton synchrotron	CERN, Switzerland
1995	top quark	Tevatron	proton synchrotron	Fermilab, U.S.
2000	tau neutrino	Tevatron	proton synchrotron	Fermilab, U.S.
2012	Higgs boson	LHC	proton synchrotron	CERN, Switzerland

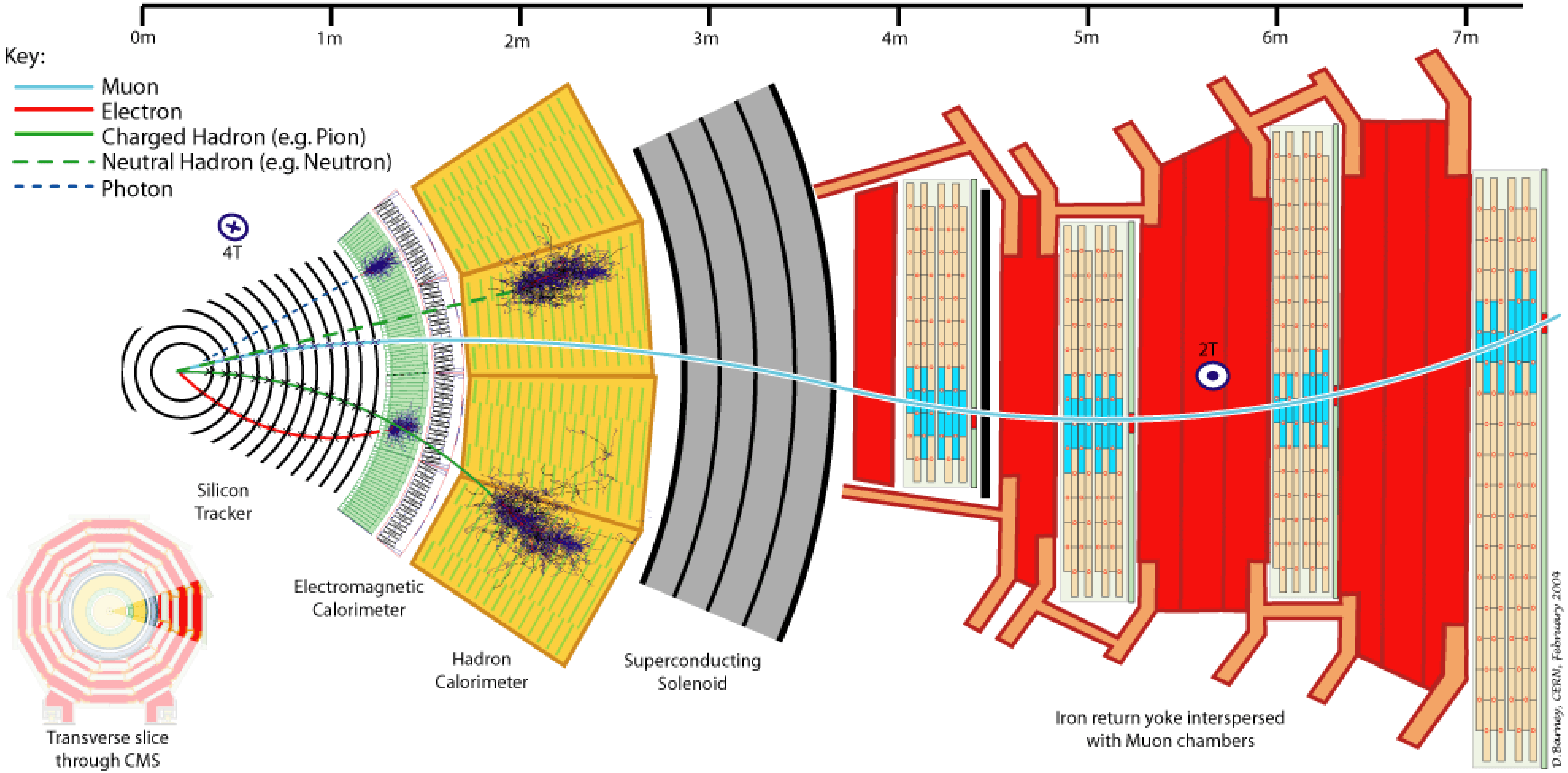
The Large Hadron collider

- It is a circular accelerator colliding **two proton beams at 6.8 TeV each**. The two proton beams travel in two separate beam pipes kept at ultra high vacuum, traveling at a speed close to light before they collide.
- Thousands of superconducting magnets guide the beams and focus them to an extremely small diameter of the order of microns. Bunches are designed to collide every 25ns
- These collisions produce massive particles like the Higgs boson and top quarks
- The higher the energy, the more interesting the physics and the chance of discovering something new



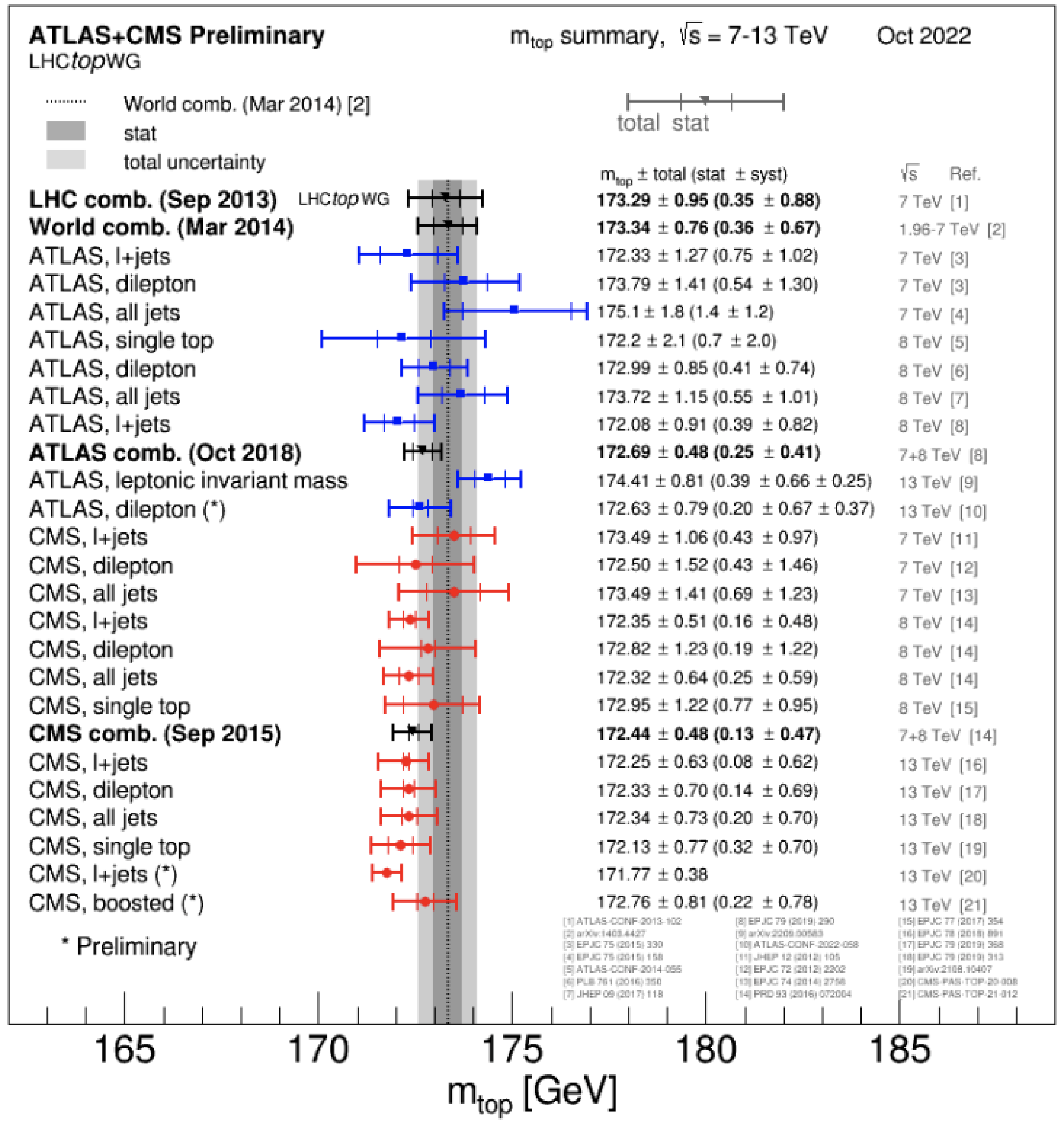


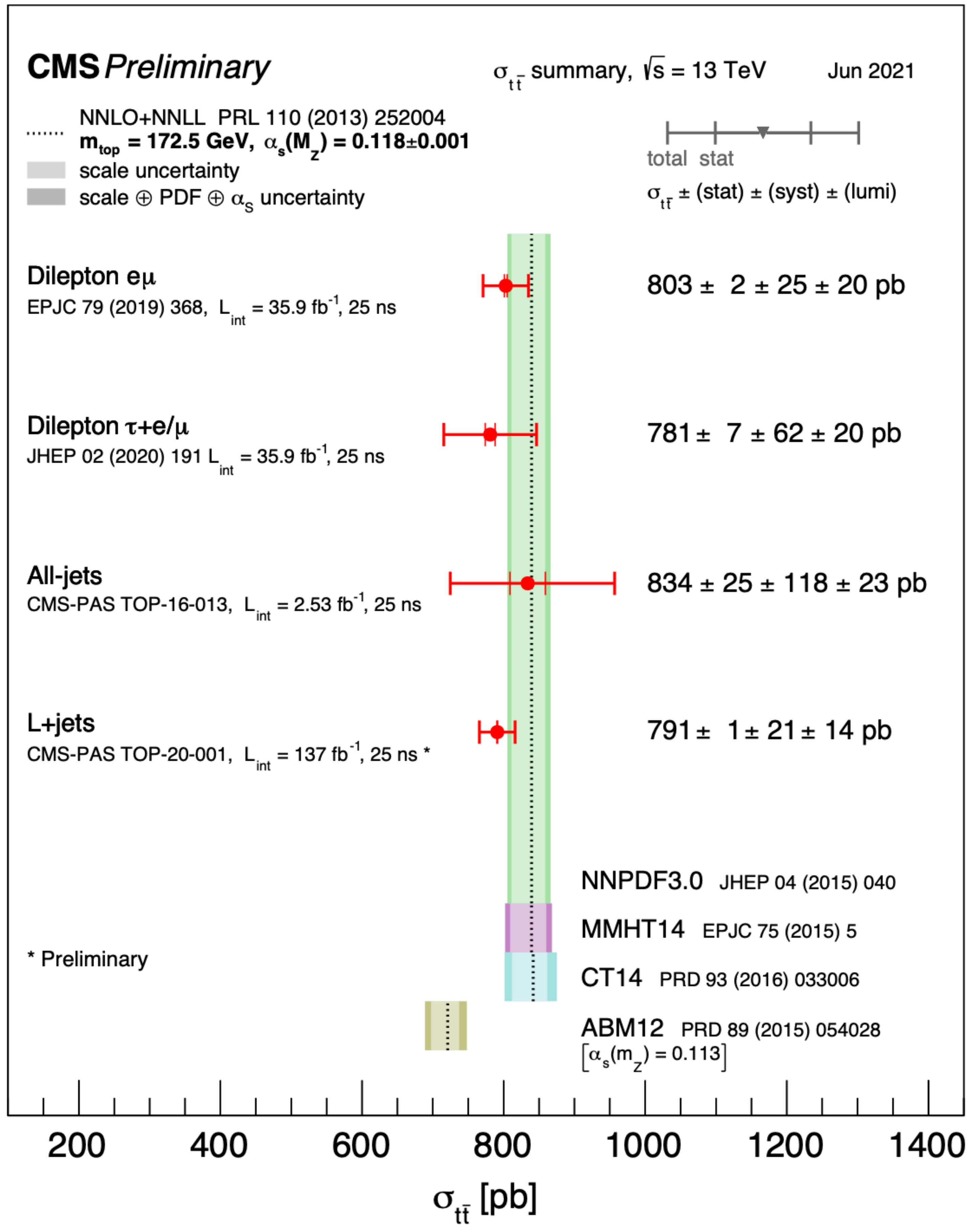
The CMS detector

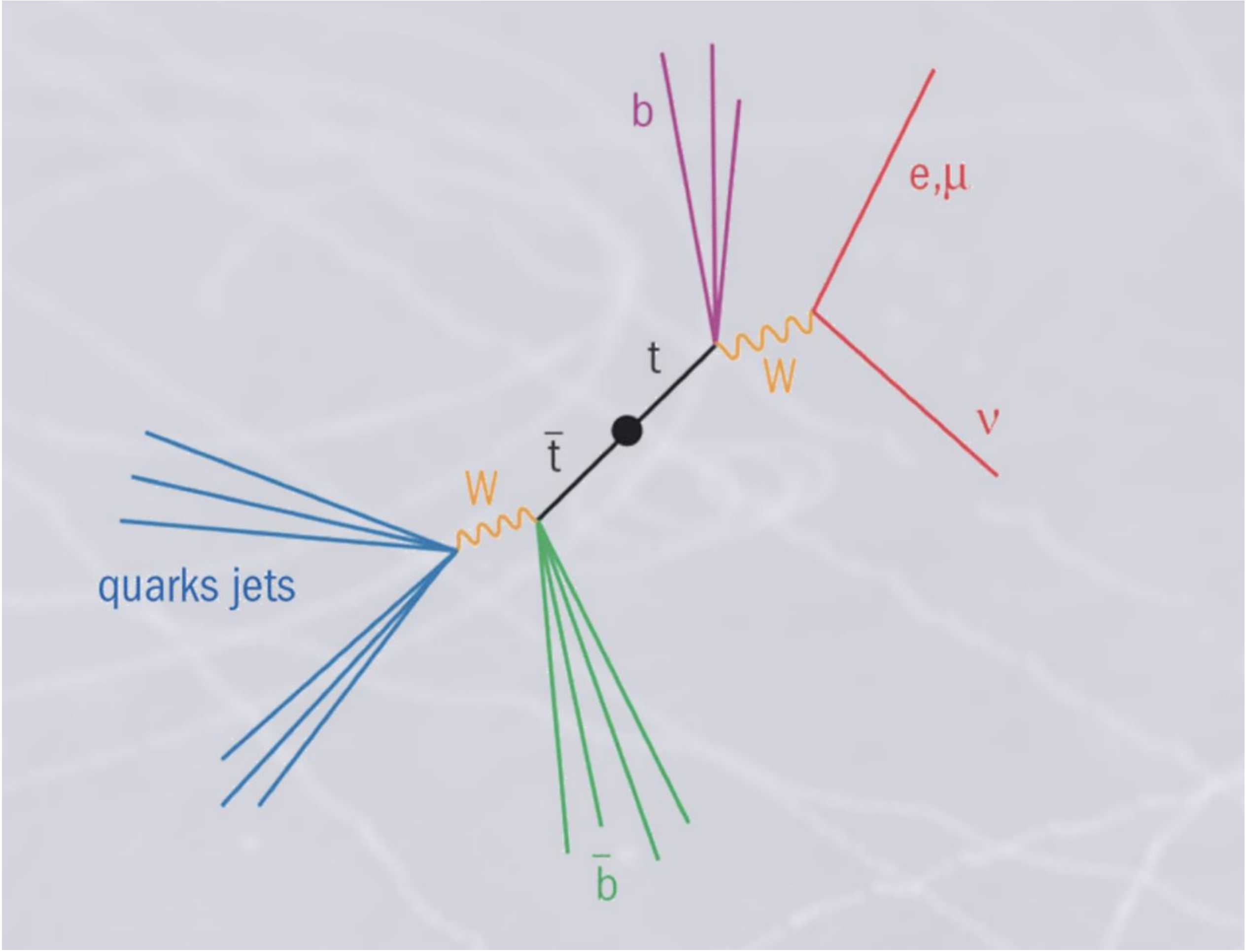


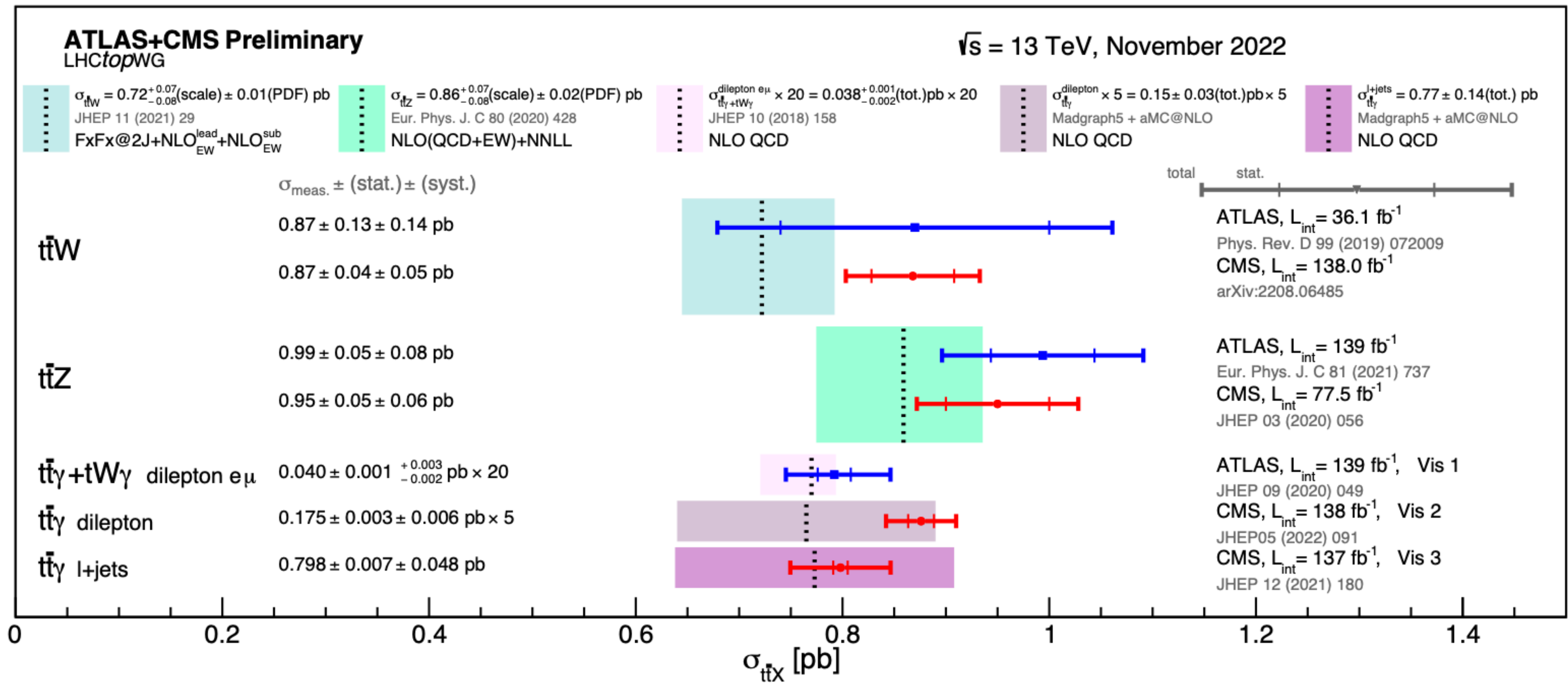
Top Physics

- The LHC is known as the top factory. Being the heaviest elementary particle, it makes for interesting study









m_t=171.77±0.38 GeV

Beyond the Standard Model

- The Standard Model although a very successful model, many questions remain unanswered
  - Are the three forces actually different or manifestation of grand unified field theory?
  - How can we explain gravity?
  - What about dark matter and dark energy which makes up more than 90% of the universe?
  - What happened to antimatter?

“See that the imagination of nature is far, far greater than the imagination of man”
- Richard Feynmann

Back up

Where is all the antimatter?

Some more Lagrangians

- The Quantum Field theories on which the SM is based:
  - Quantum Electrodynamics (QED): leptons interact with each other through the EM force mediated by the photon

$$\mathcal{L}_{QED} = \overline{\psi}(i\gamma^{\mu}\delta_{\mu} - m) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - q\overline{\psi}\gamma^{\mu}A_{\mu}\psi$$

  - Electroweak sector: Gauge bosons are mediators between fermions

$$\mathcal{L}_{\mathrm{EW}} = \sum_{\psi} \bar{\psi}\gamma^{\mu}\left(i\partial_{\mu} - g'\frac{1}{2}Y_{\mathrm{W}}B_{\mu} - g\frac{1}{2}\boldsymbol{\tau}\mathbf{W}_{\mu}\right)\psi$$

  - Quantum Chromodynamics (QCD): quarks and gluons interact through the strong force mediated by gluons

$$\mathcal{L}_{QCD} = \overline{\psi_i}(i(\gamma^{\mu}D_{\mu})_{ij} - m\delta_{ij})\psi_i - \frac{1}{4}G^{a}_{\mu\nu}G^{\mu\nu}_{a}$$