ATLAS EXPERIMENT

Western Norway University of Applied Sciences

The Research Council of Norway

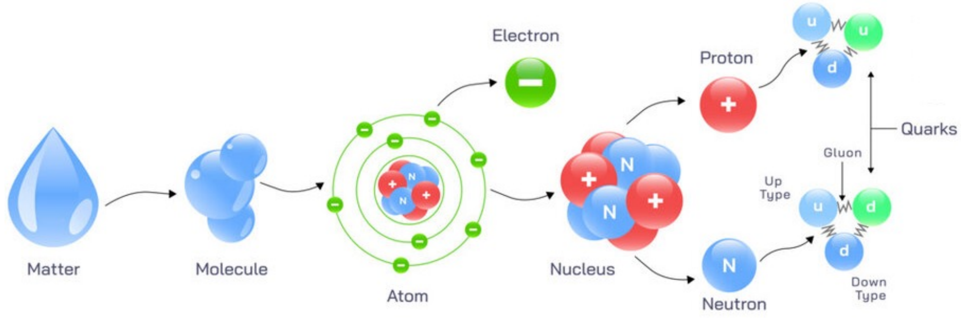
Introduction to The Higgs Boson

UiB Bachelor Visit

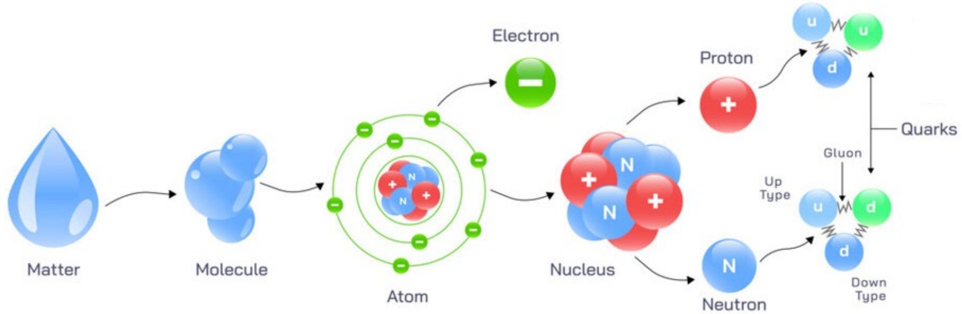
I. Slazyk

19/11/2024

Standard Model

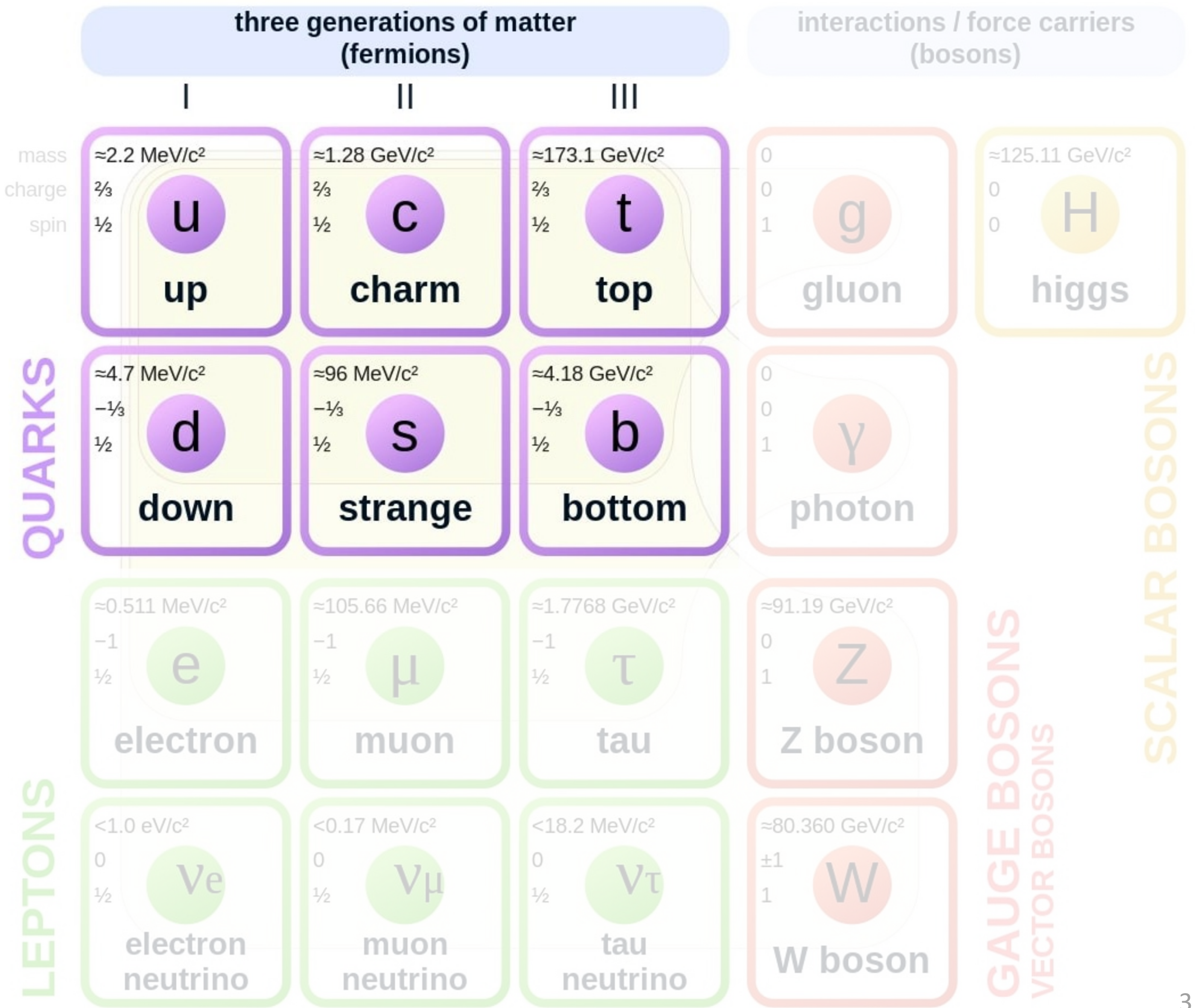


Standard Model
Matter Particles

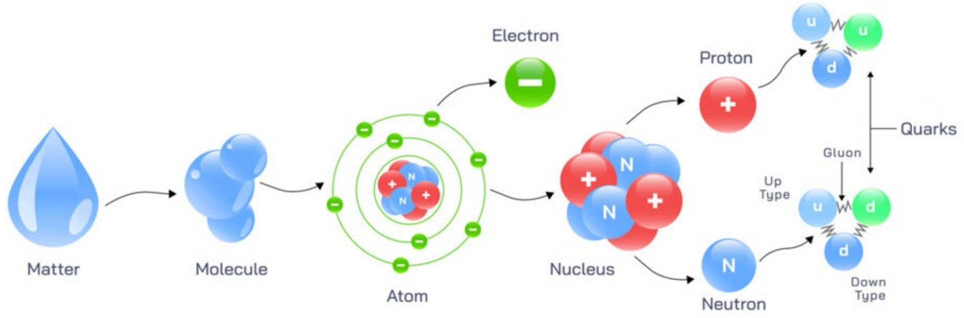


Elementary particles:

- quarks

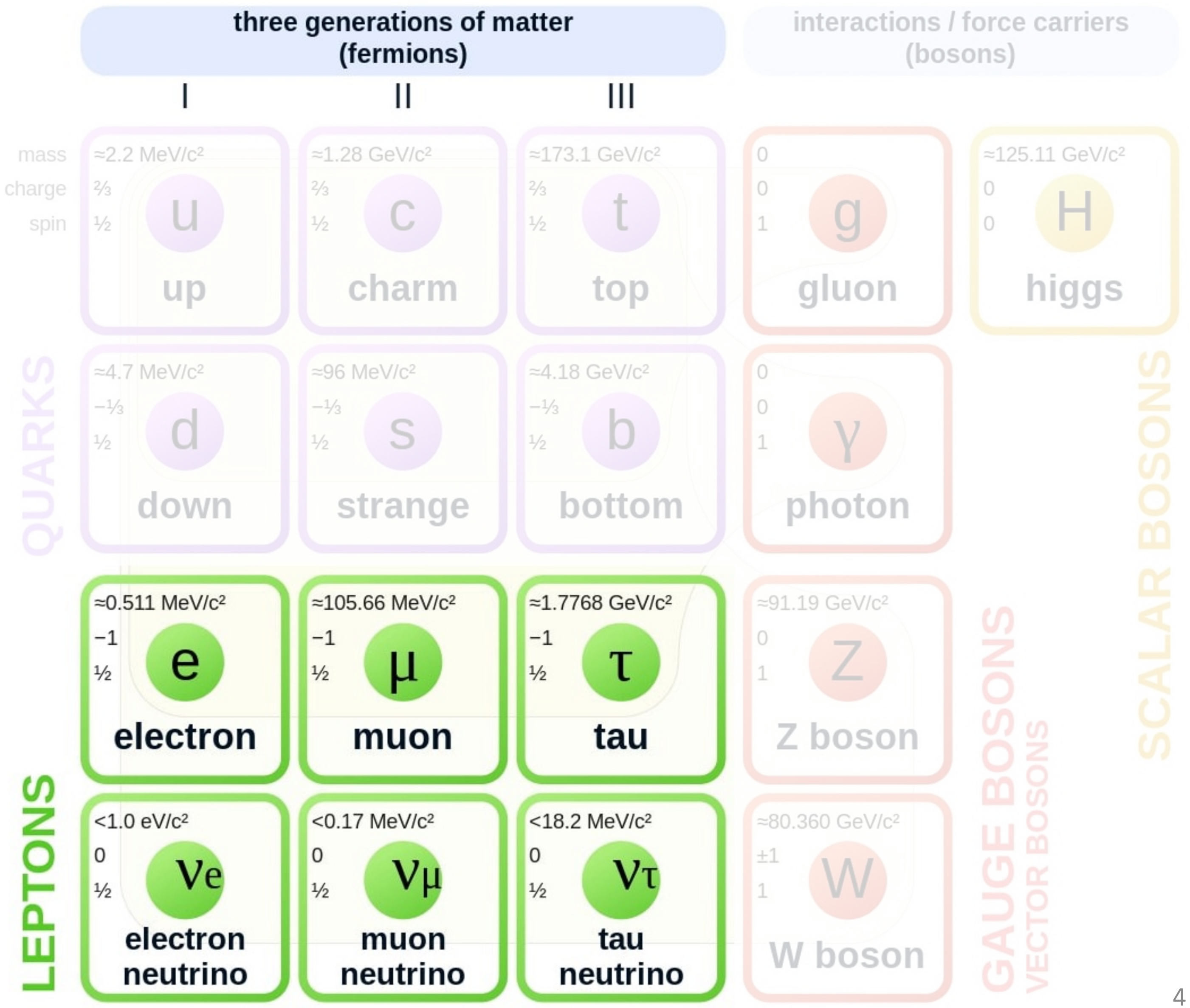


Standard Model
Matter Particles

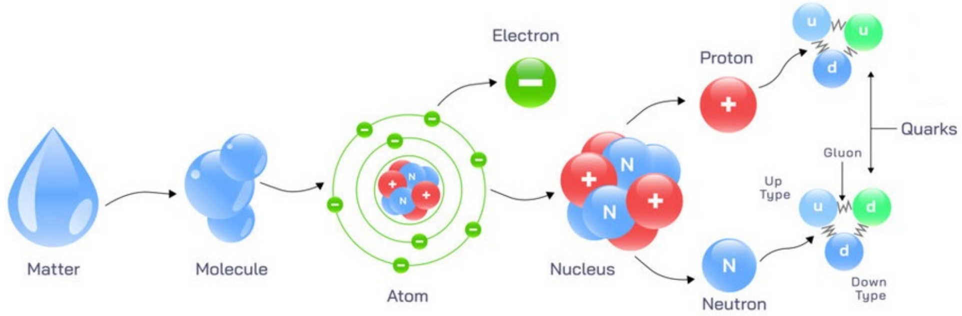


Elementary particles:

- quarks
- leptons

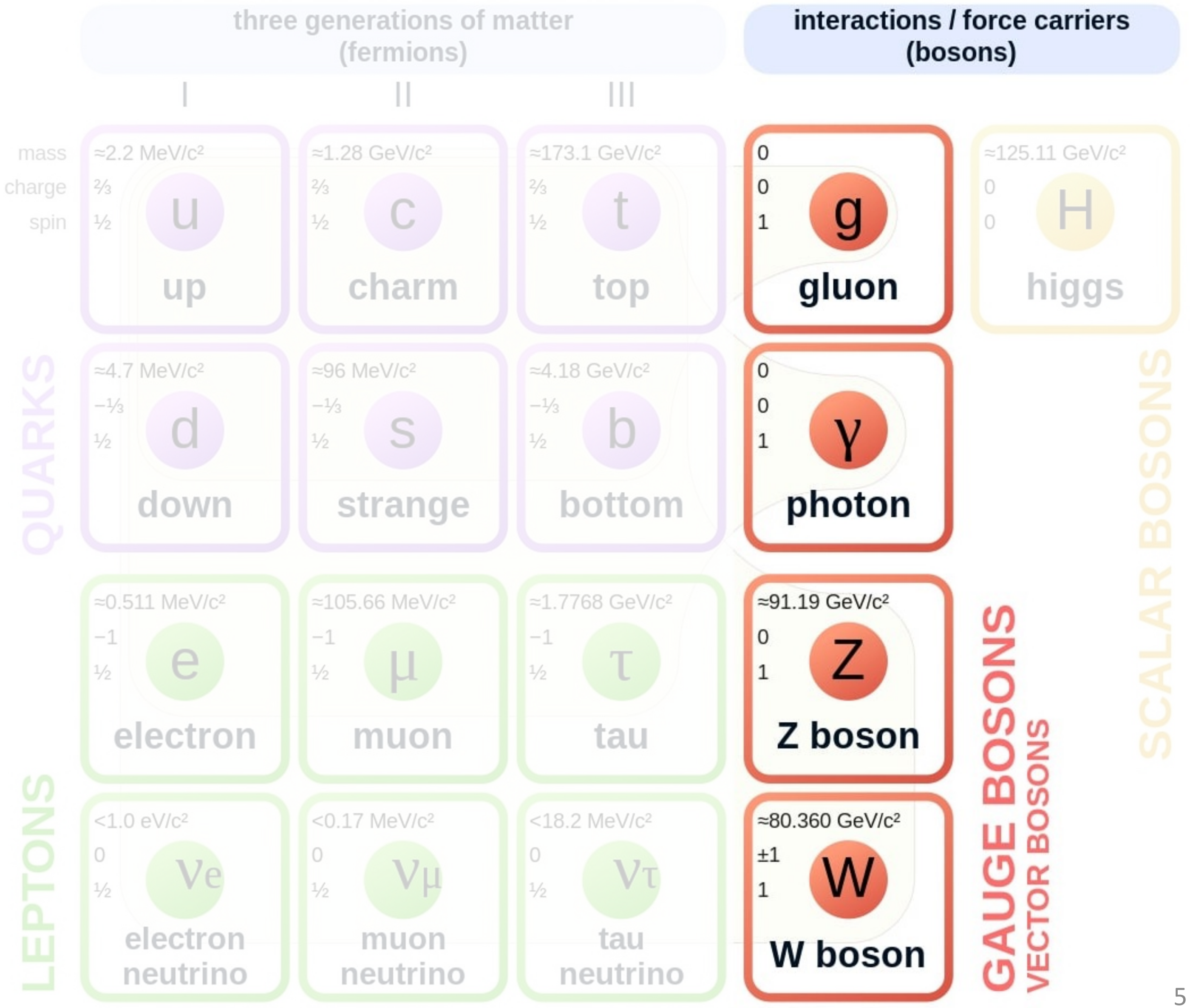


Standard Model
Force Carriers

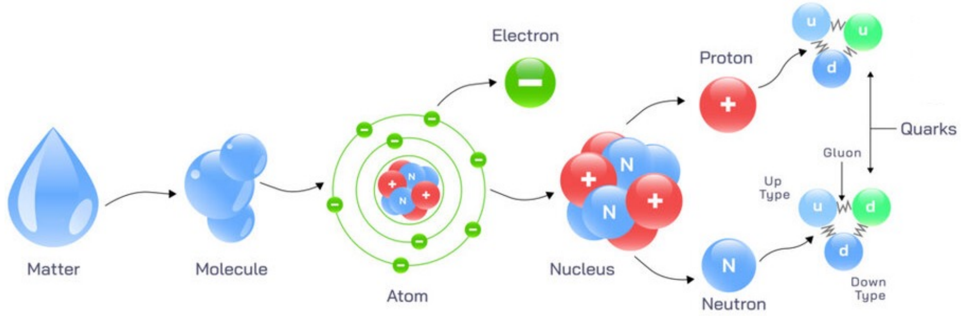


Elementary particles:
- quarks
- leptons
- bosons

Fundamental forces:
- electromagnetic force
- strong force
- weak force



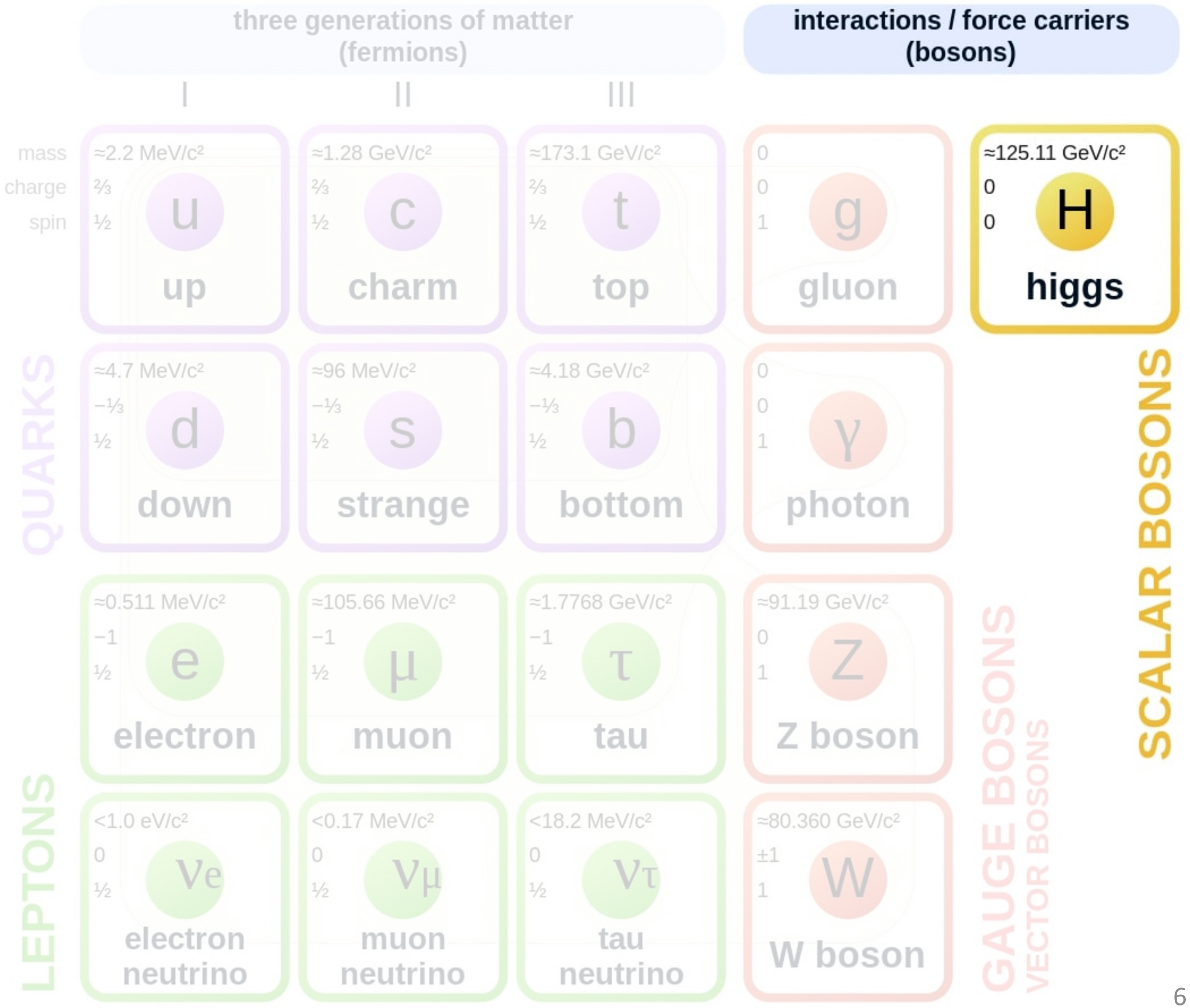
Standard Model
Force Carriers



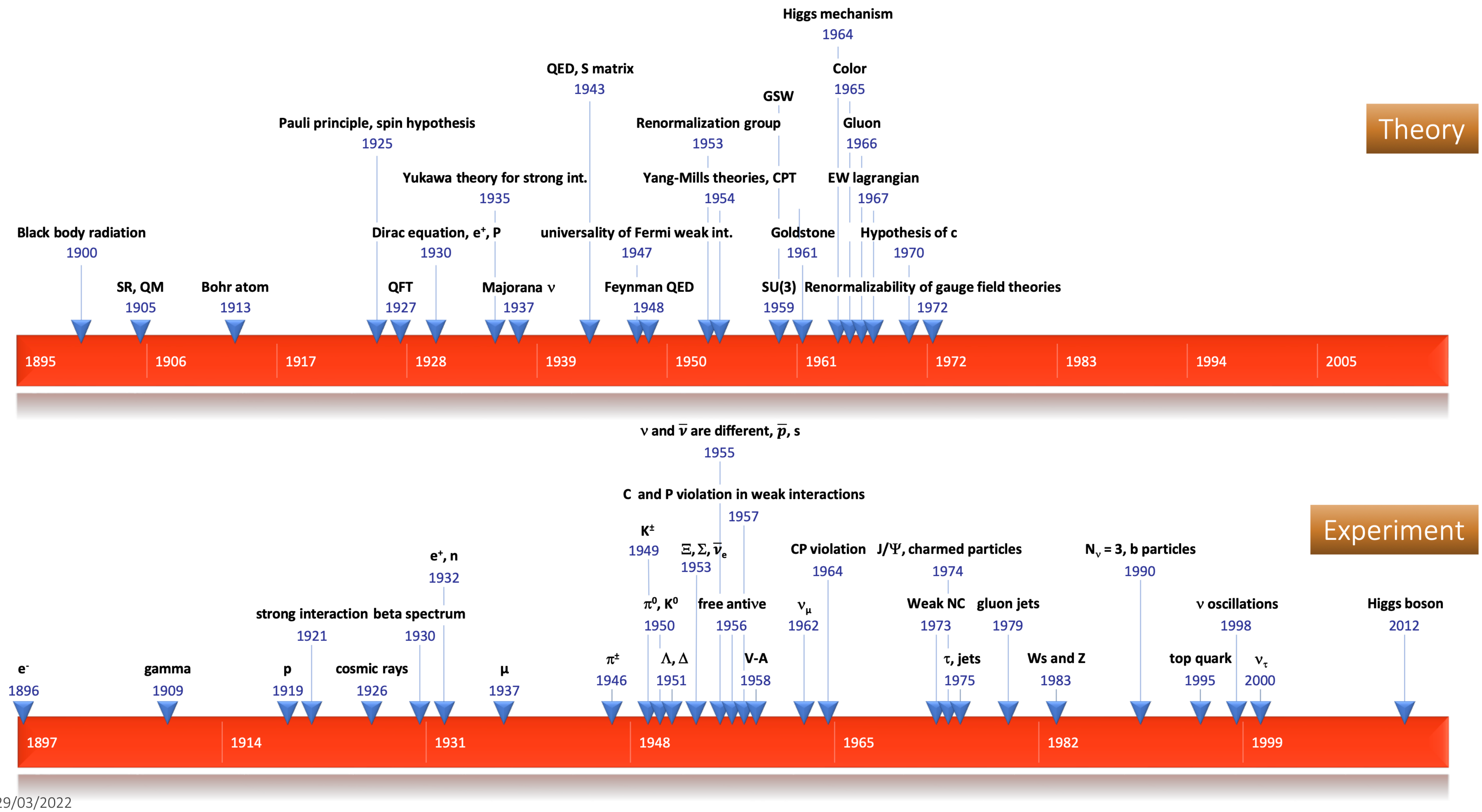
Elementary particles:
- quarks
- leptons
- bosons

Fundamental forces:
- electromagnetic force
- strong force
- weak force

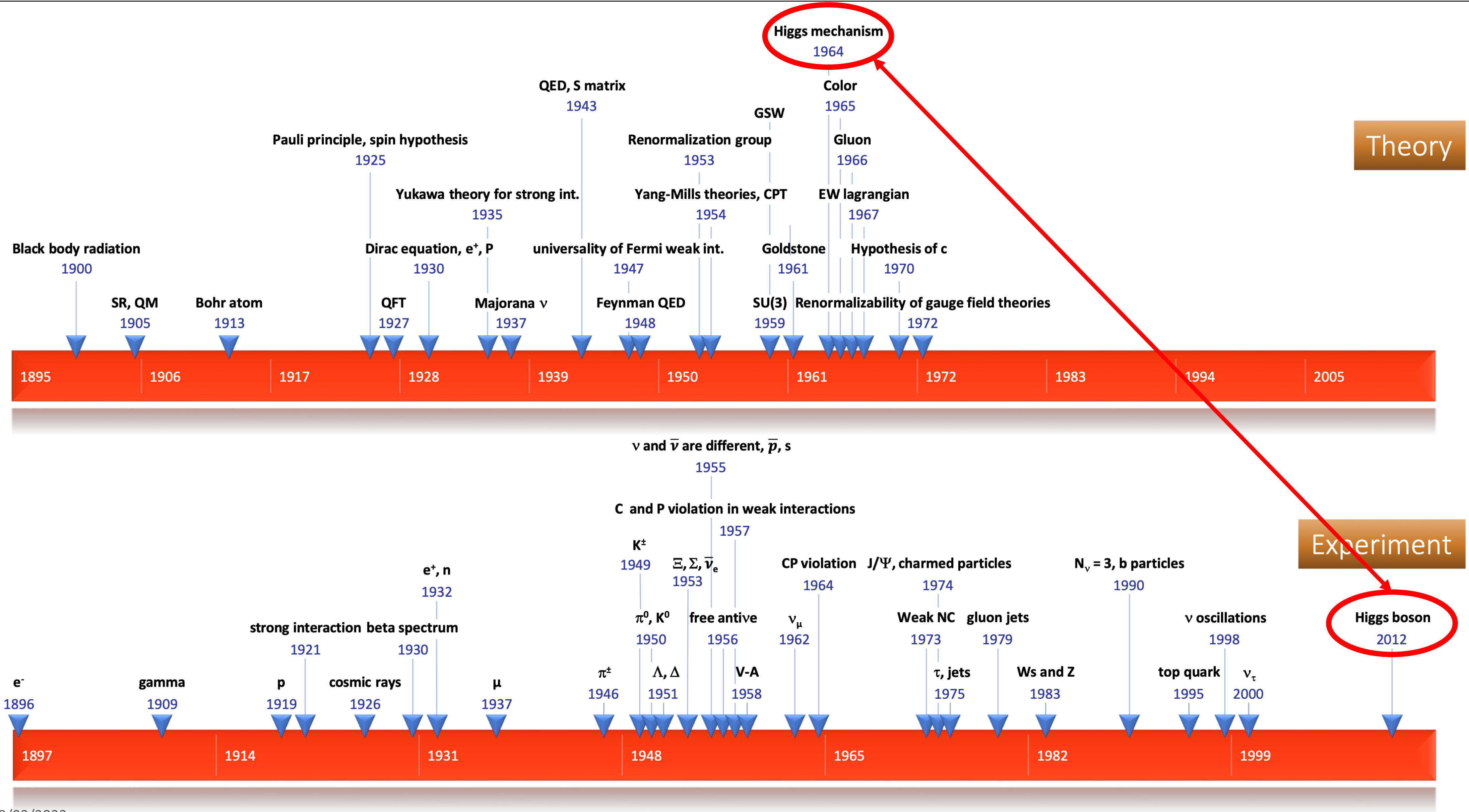
Higgs boson:
- Higgs field
- Higgs potential
- Spontaneous symmetry breaking
- Higgs mechanism
- Discovery
- Unanswered questions



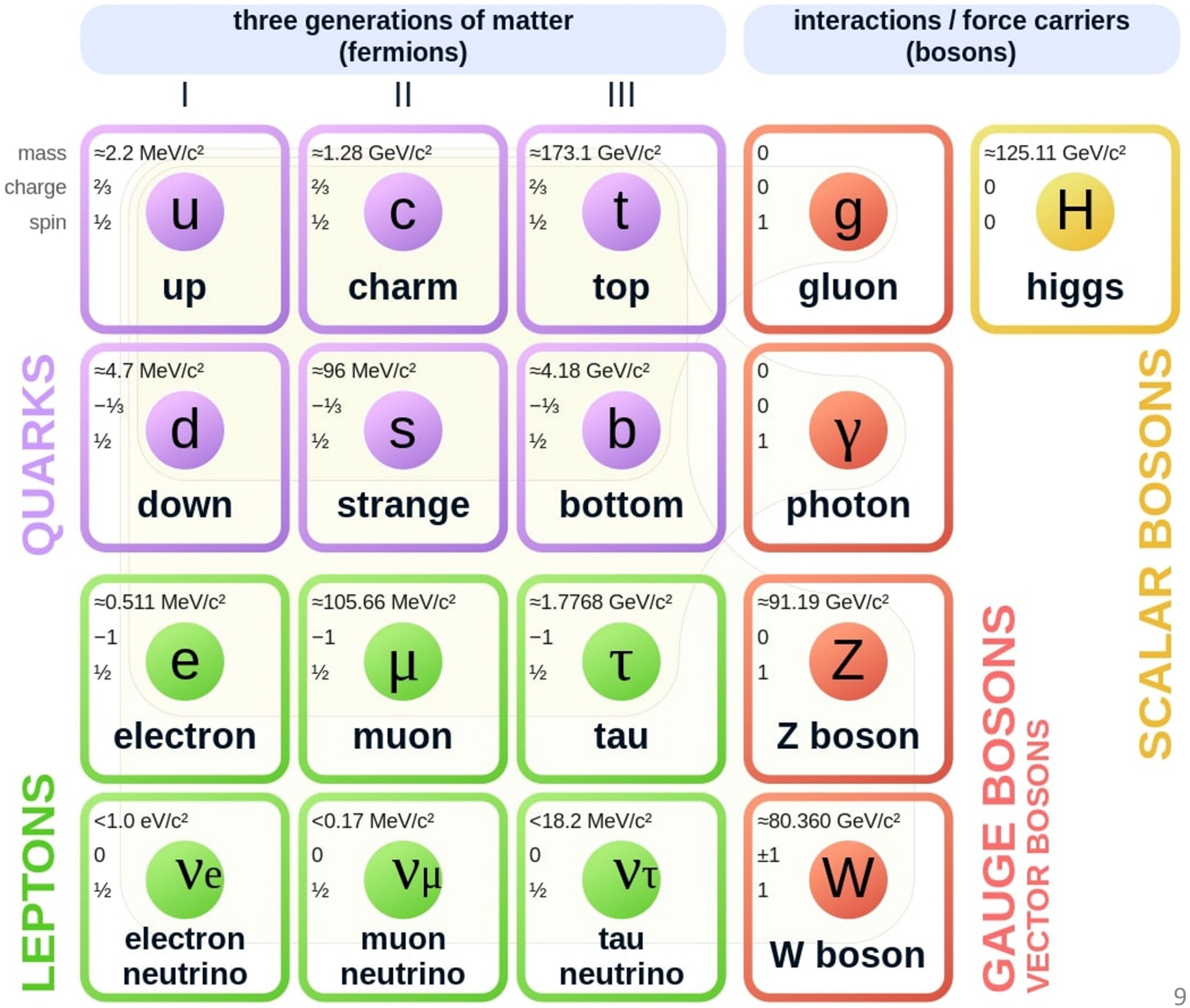
Standard Model
Century of Development



Standard Model
Century of Development



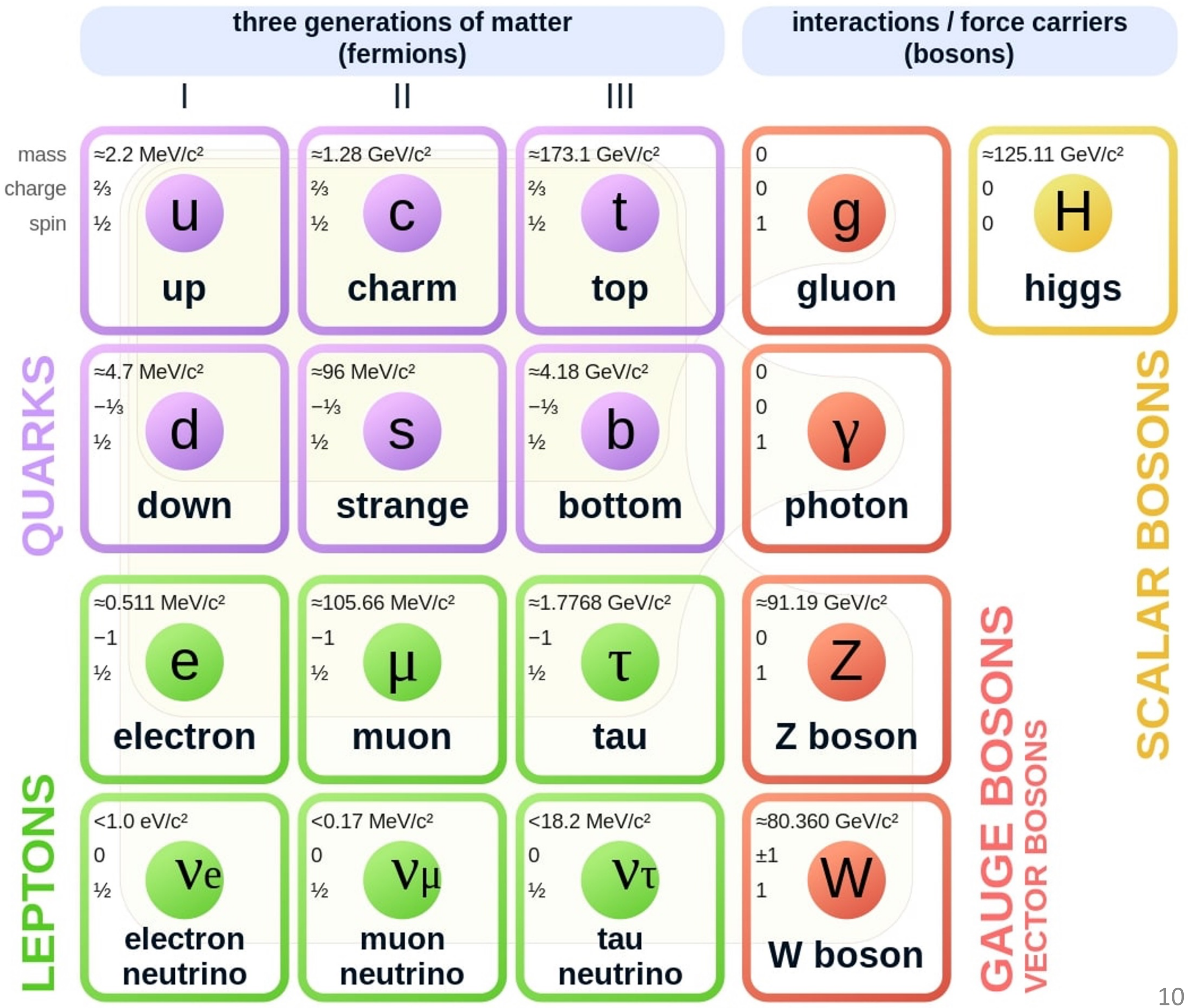
Elementary Particles



Elementary Particles
Properties

Intristic Properties

- Mass
- Charge
- Spin



Elementary Particles
Mass

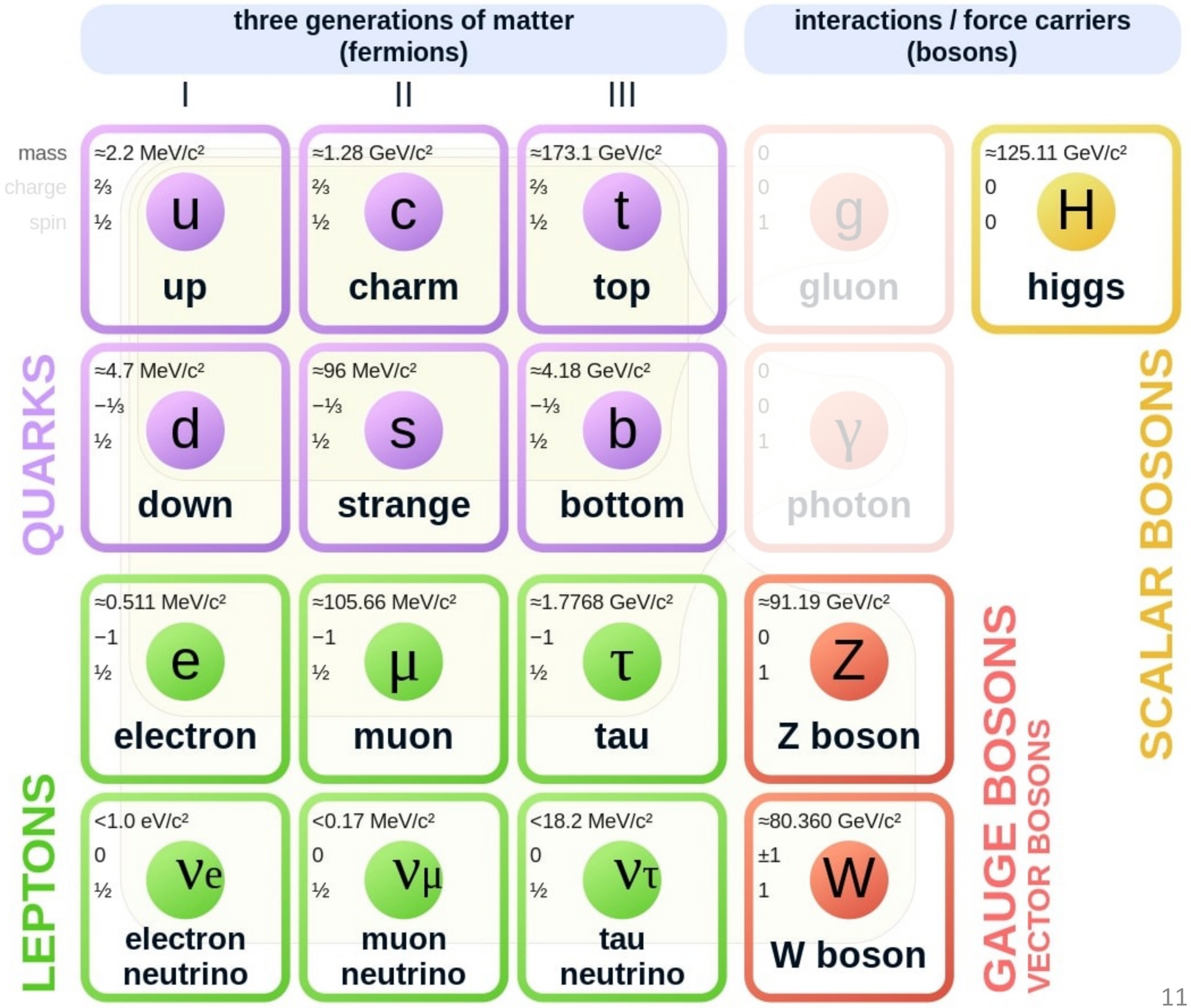
Intristic Properties

- **Mass**
- **Charge**
- **Spin**

Each generation heavier than the previous one

Einstein's mass-energy equivalence:

$$E = mc^2 \rightarrow m = \frac{E}{c^2}$$



Elementary Particles
Mass

Intristic Properties

- **Mass**
- Charge
- Spin

Each generation heavier than the previous one

Einstein's mass-energy equivalence:

$$E = mc^2 \rightarrow m = \frac{E}{c^2}$$

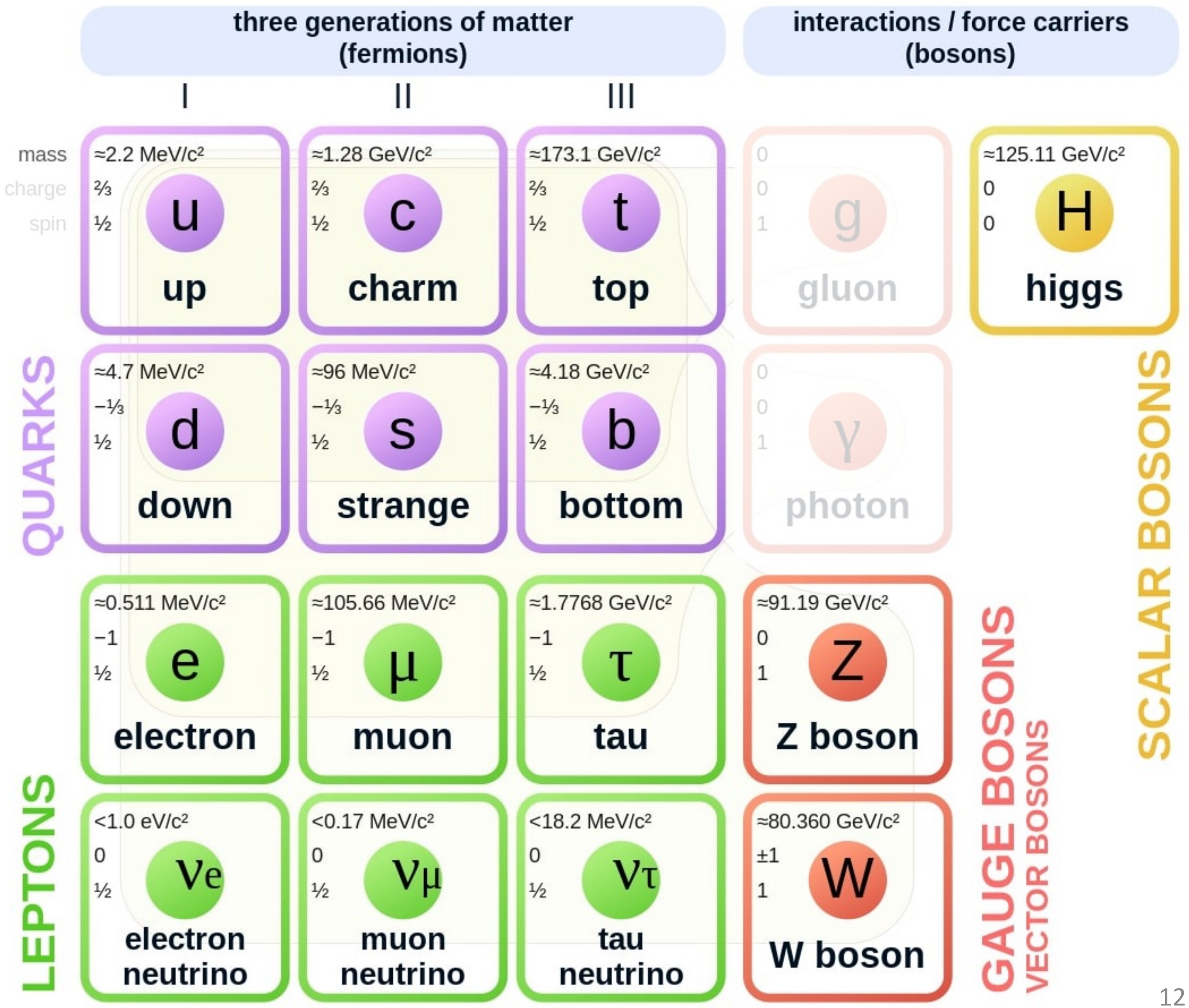
Energy of 1 gram of mass:

$$E = mc^2 \rightarrow 10^{-3}\ \text{kg} \cdot \left(3\times10^{8}\ \frac{m}{s}\right)^2 = 9\times10^{13}\ \text{J}$$

$$1\ \text{J} = 6.242\times10^{18}\ \text{eV}$$

$$E = 5.6\times10^{26}\text{MeV}$$

$$m = 5.6\times10^{26}\frac{\text{MeV}}{c^2}$$



Elementary Particles
Charge

Intristic Properties

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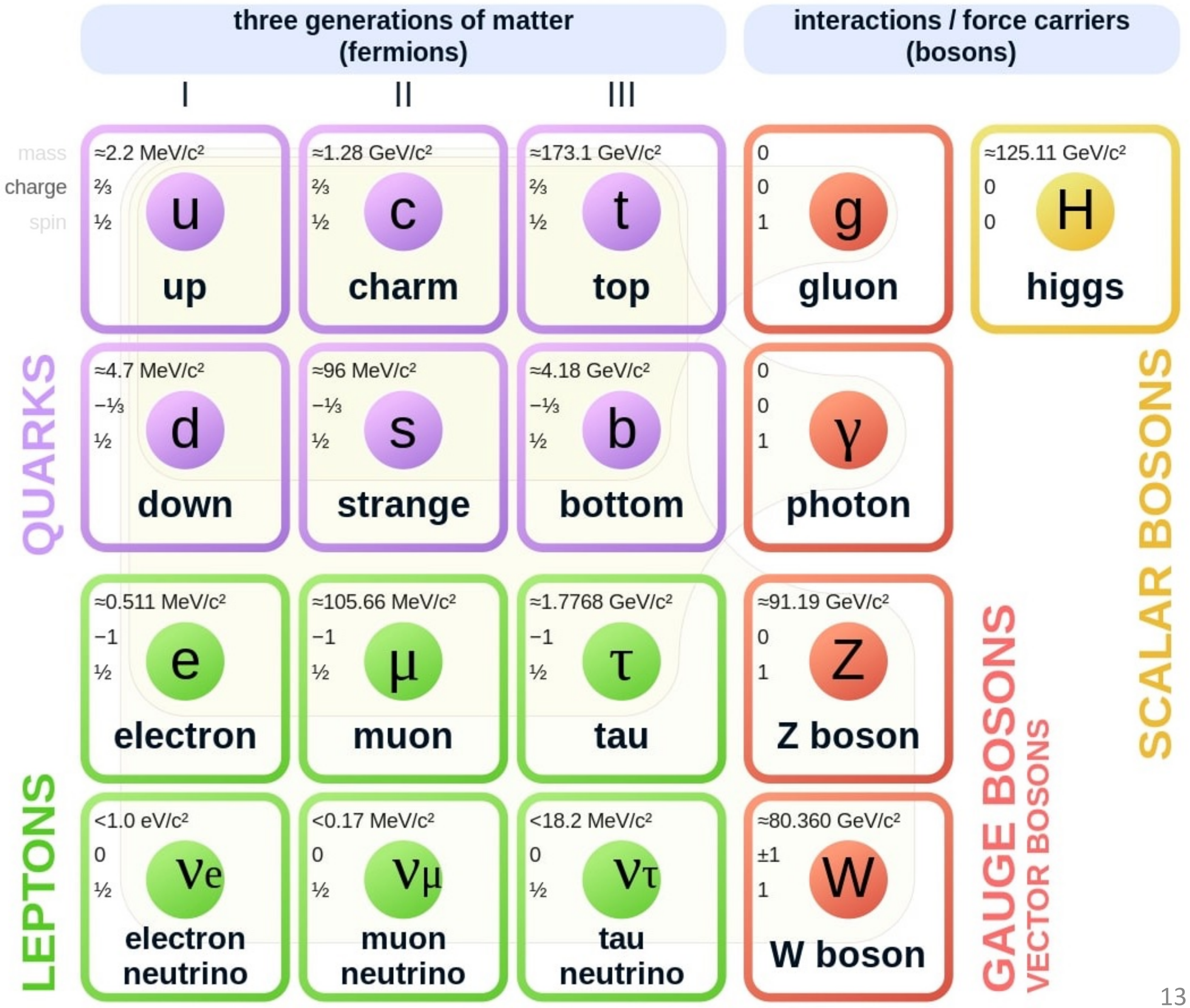


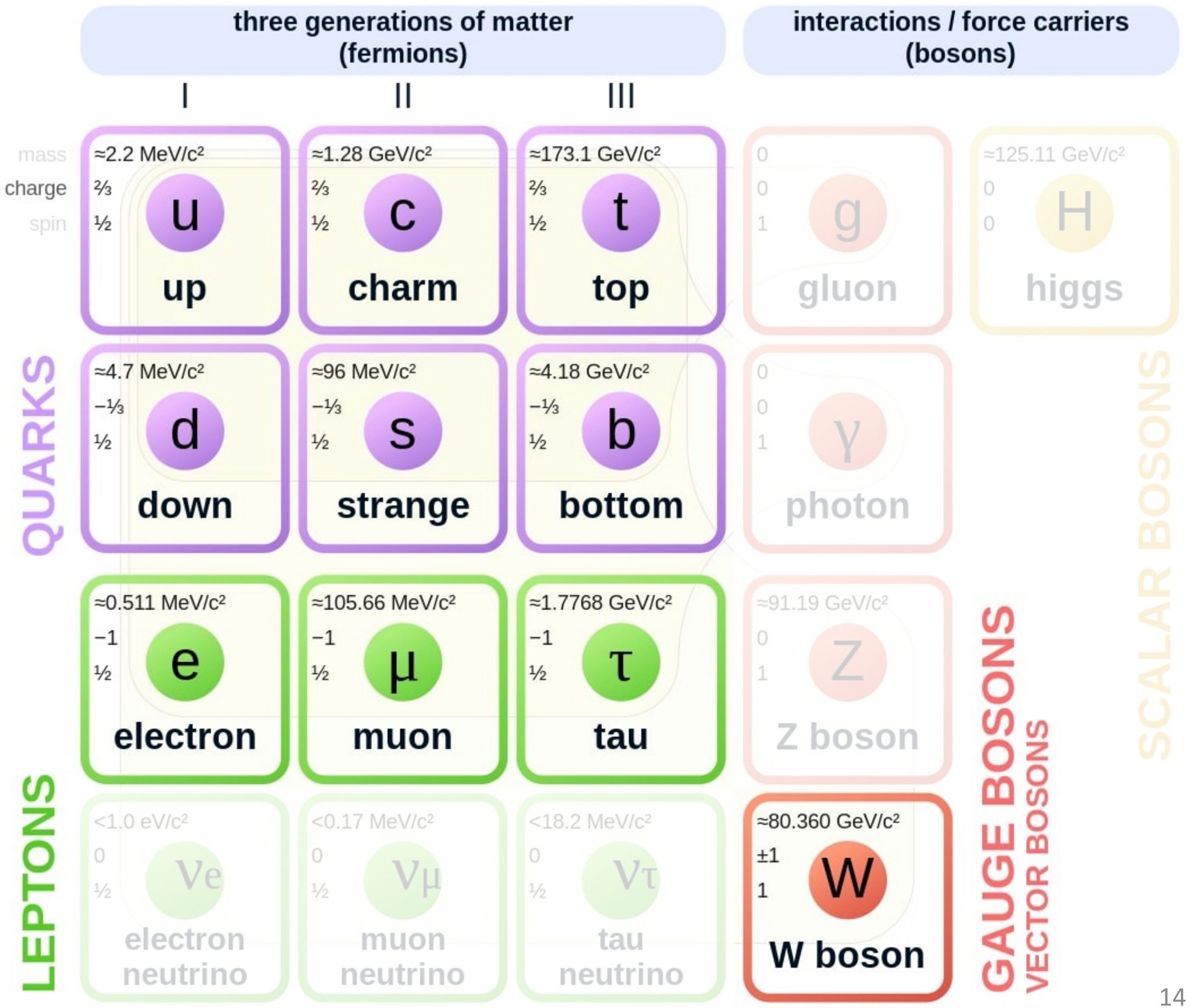
Elementary Particles
Charge

Intristic Properties

Mass | Charge | Spin

charged particles

- quarks
- charged leptons
  - electron
  - muon
  - tau
- charged bosons
  - *W* boson



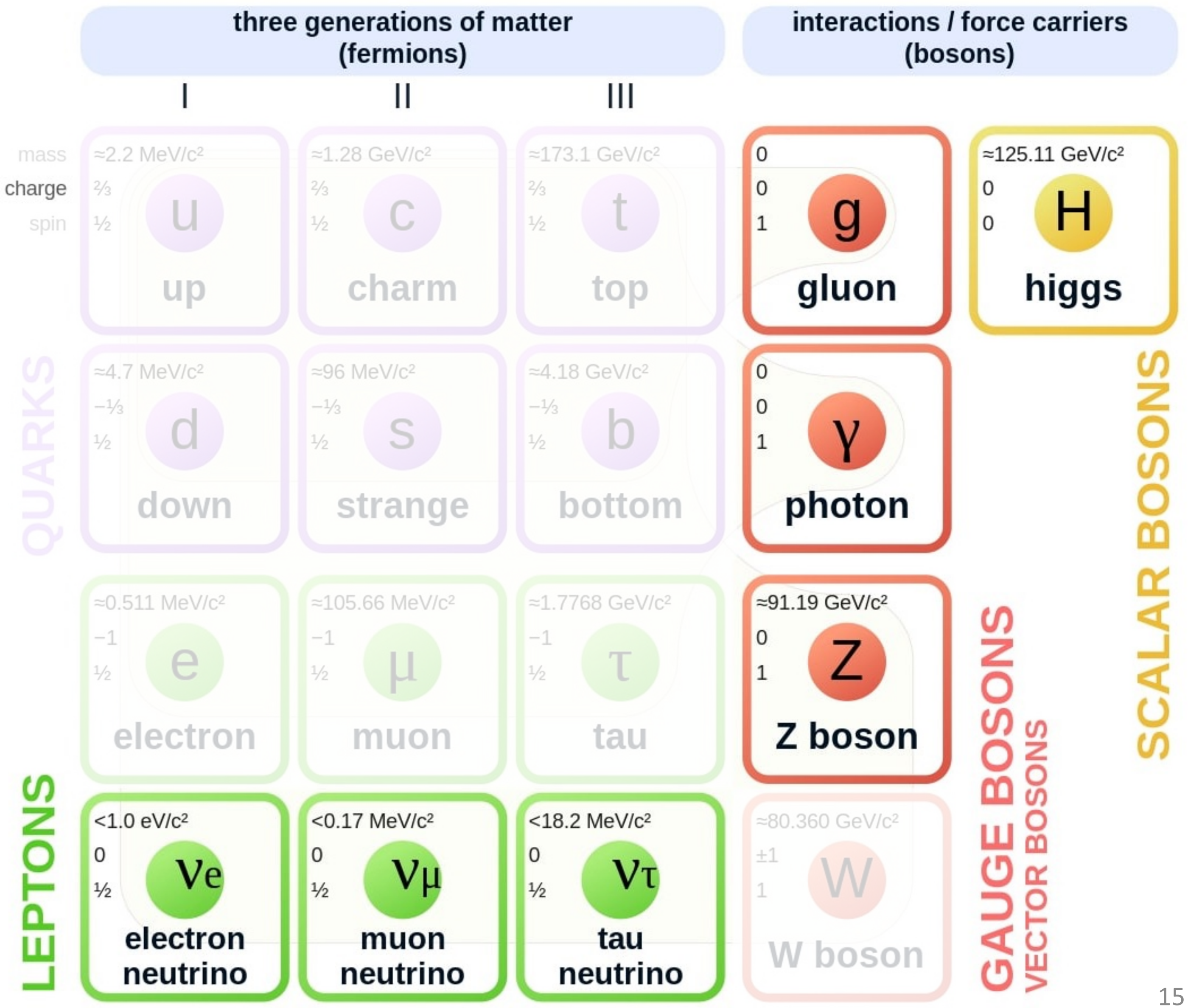
Elementary Particles
Charge

Intristic Properties

- Mass
- Charge
- Spin

neutral particles

- neutral leptons
  - neutrinos
- neutral bosons
  - gluon
  - photon
  - Z boson
  - Higgs boson



Elementary Particles
Charge

Intristic Properties

Mass · Charge · Spin

charged particles
- quarks
- charged leptons
  - electron
  - muon
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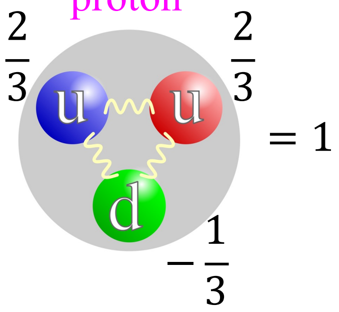
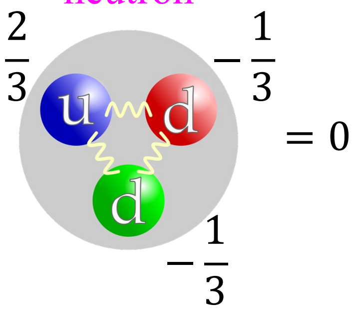
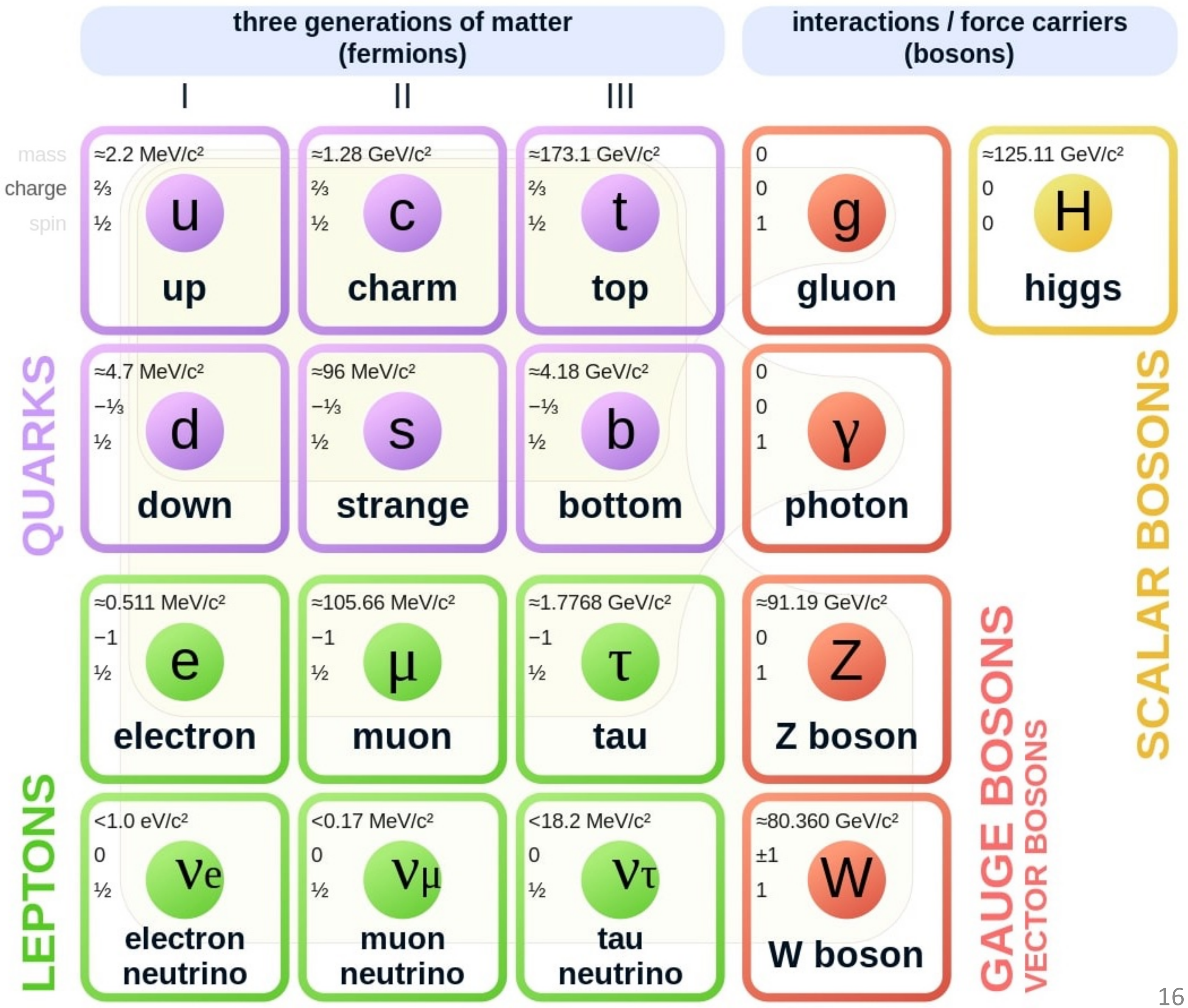
neutral particles
- neutral leptons
  - neutrinos
- neutral bosons
  - gluon
  - photon
  - Z boson
  - Higgs boson

proton



neutron





Elementary Particles
Spin

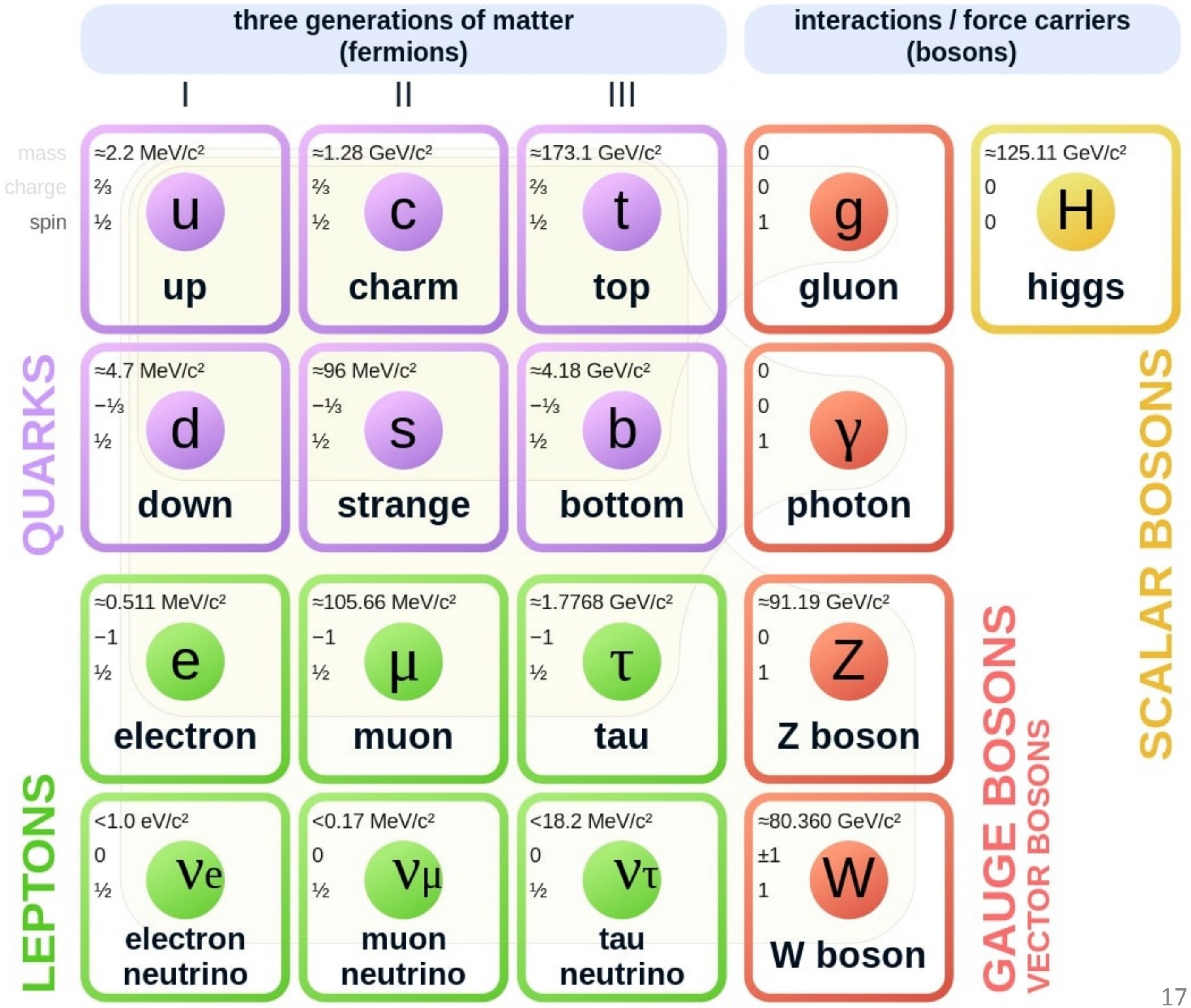
Intristic Properties

Mass

Charge

Spin

spin → intristic angular momentum



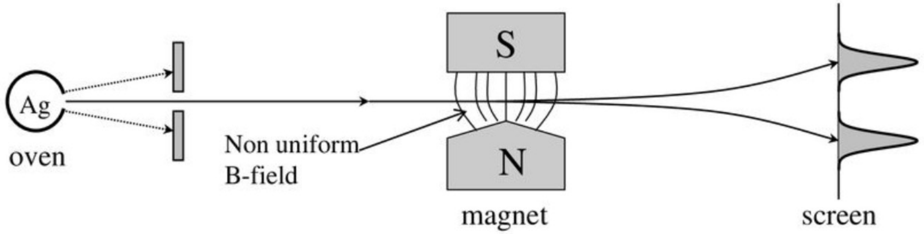
Elementary Particles
Spin

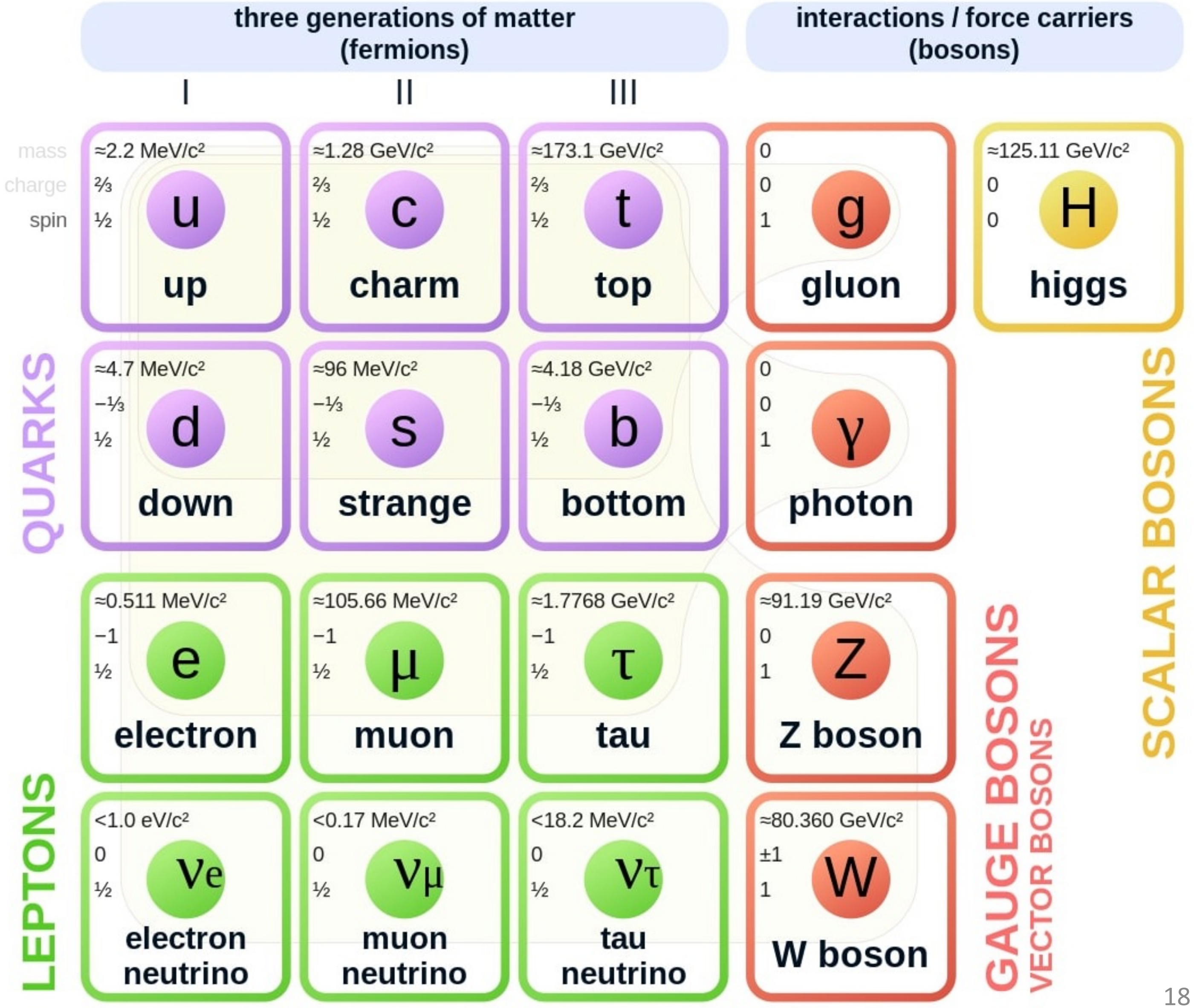
Intristic Properties

Mass — Charge — Spin

spin → intristic angular momentum

Stern-Gerlach experiment:





Elementary Particles
Spin

Intristic Properties

Mass — Charge — Spin

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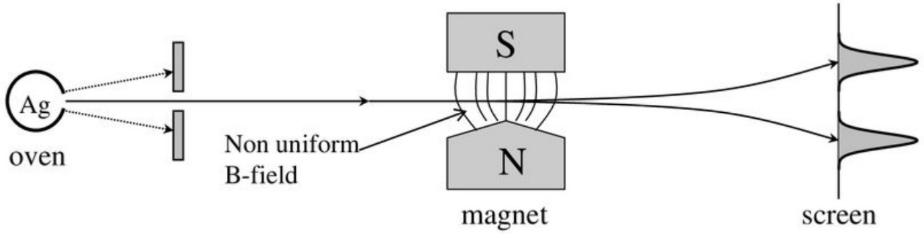
Stern-Gerlach experiment:

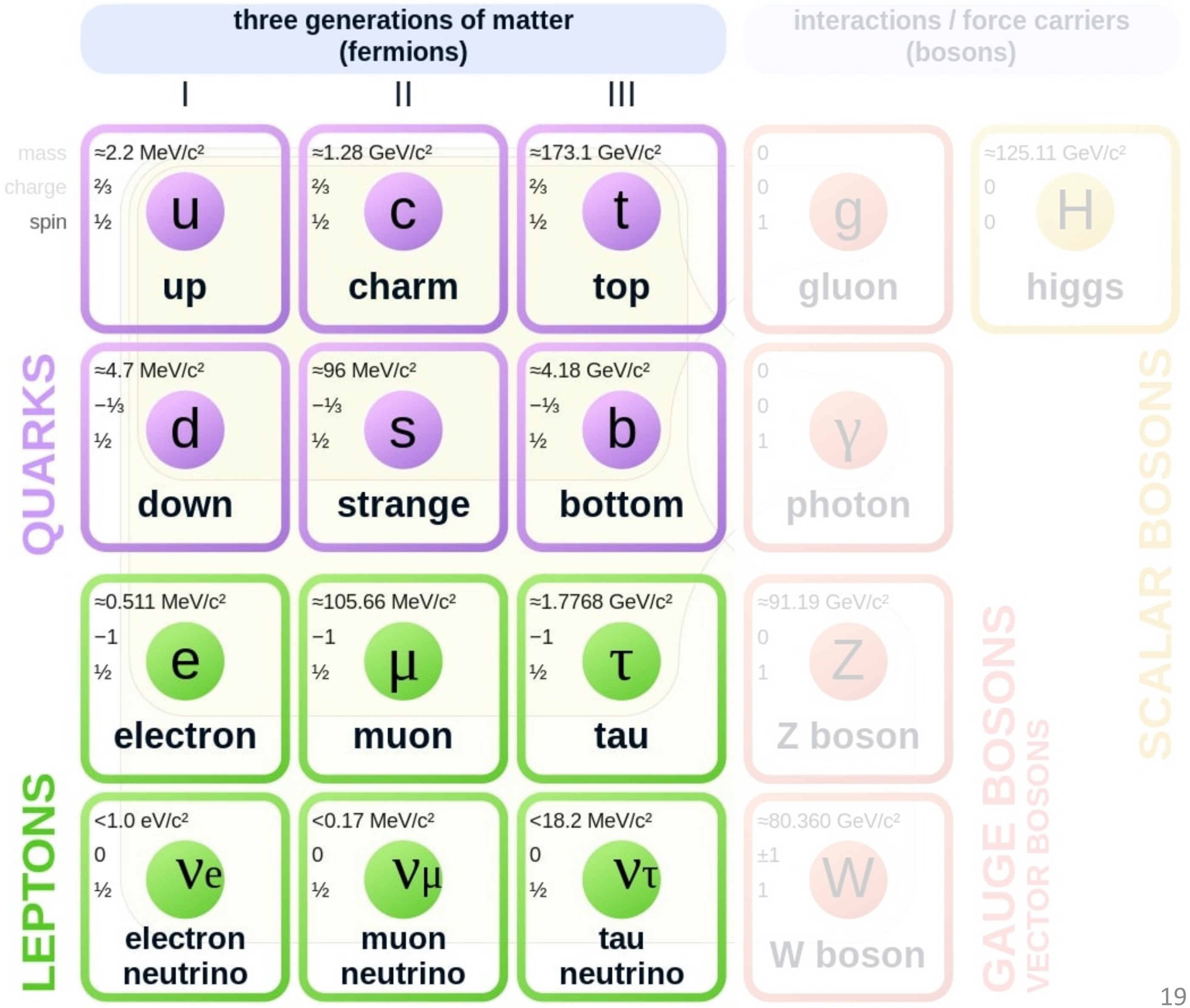


fermions

half-integer spin

$$s = \pm\frac{1}{2}, \pm\frac{3}{2}, \dots$$

Fermi-Dirac statistics



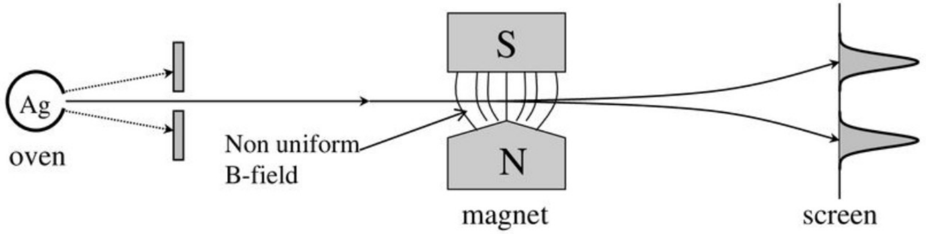
Elementary Particles
Spin

Intristic Properties

Mass | Charge | Spin

spin → intristic angular momentum

Stern-Gerlach experiment:

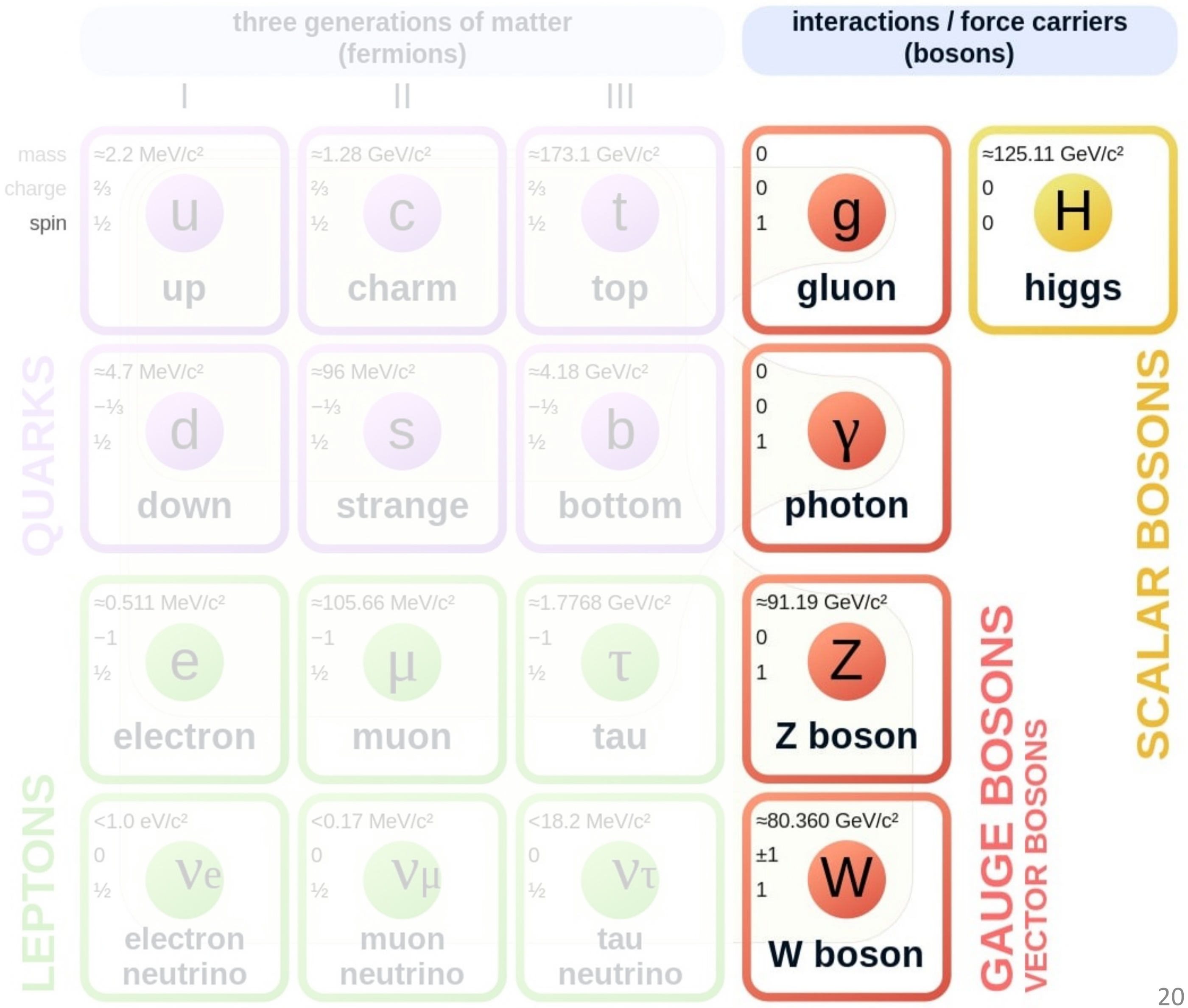


bosons

integer spin

$s = 0, 1, 2, \ldots$

Bose-Einsten statistics



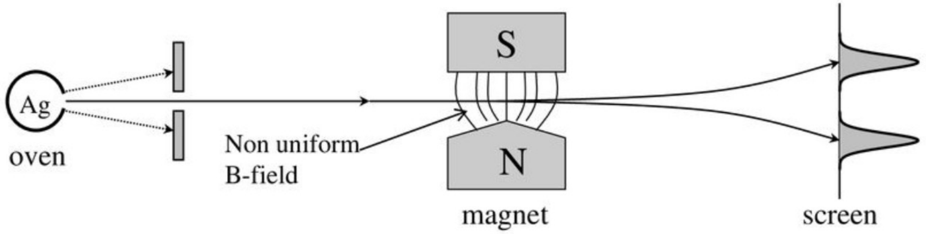
Elementary Particles
Spin

Intristic Properties

Mass   Charge   **Spin**

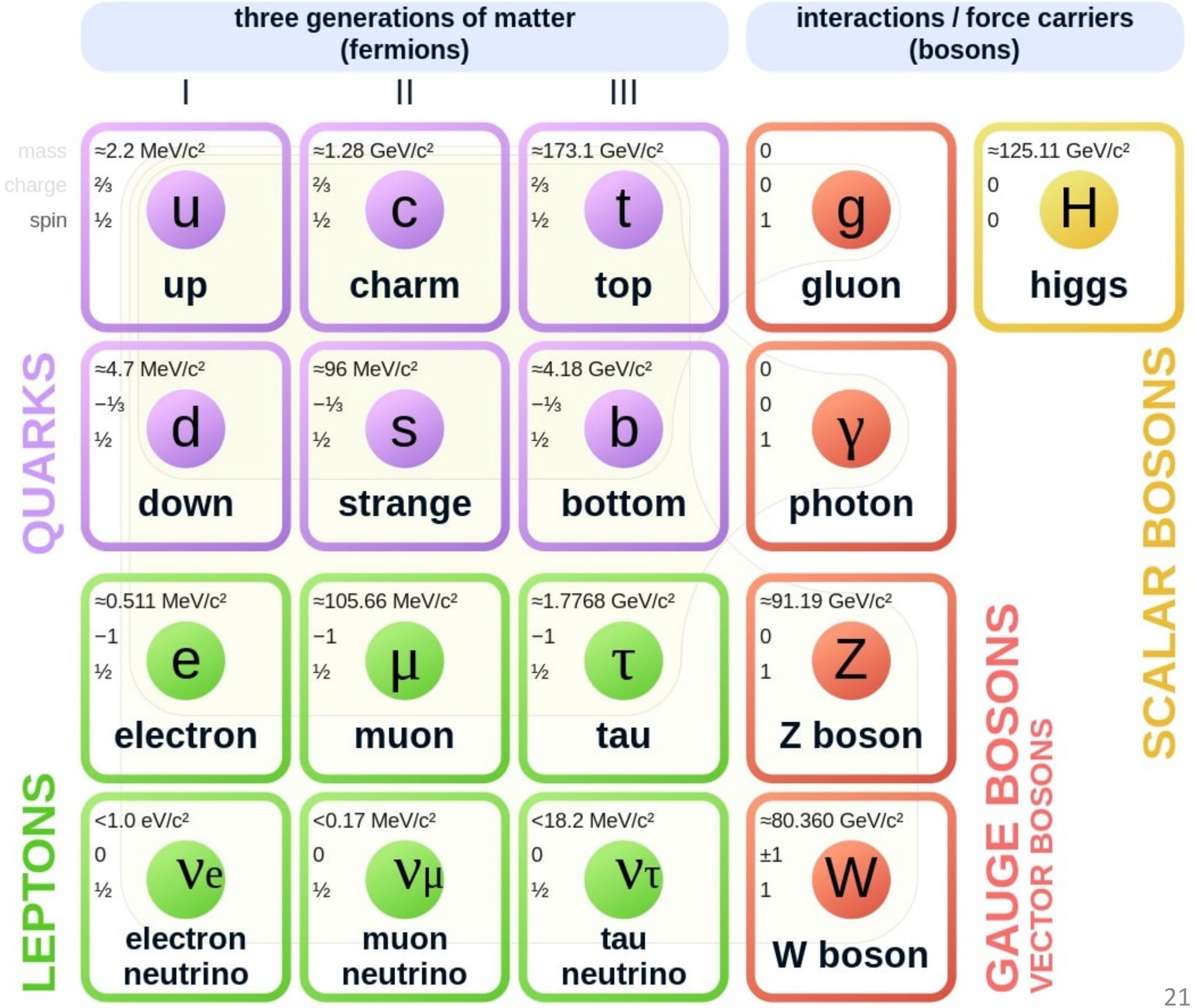
spin → intristic angular momentum

Stern-Gerlach experiment:



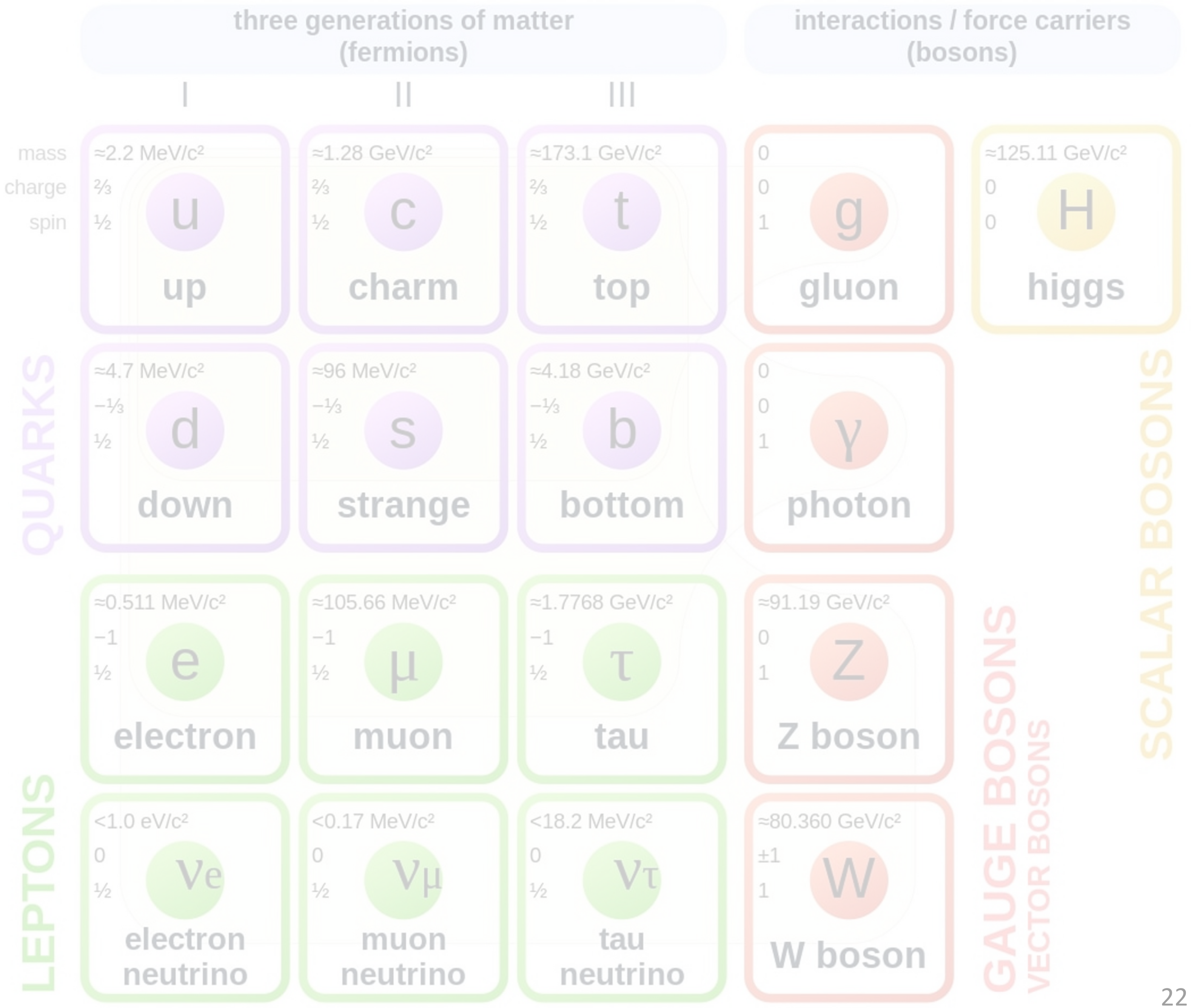
fermions	bosons
half-integer spin	integer spin
$s = \pm\frac{1}{2}, \pm\frac{3}{2}, \ldots$	$s = 0, 1, 2, \ldots$
Fermi-Dirac statistics	Bose-Einsten statistics

good visual explanation: [link]



Fundamental Forces

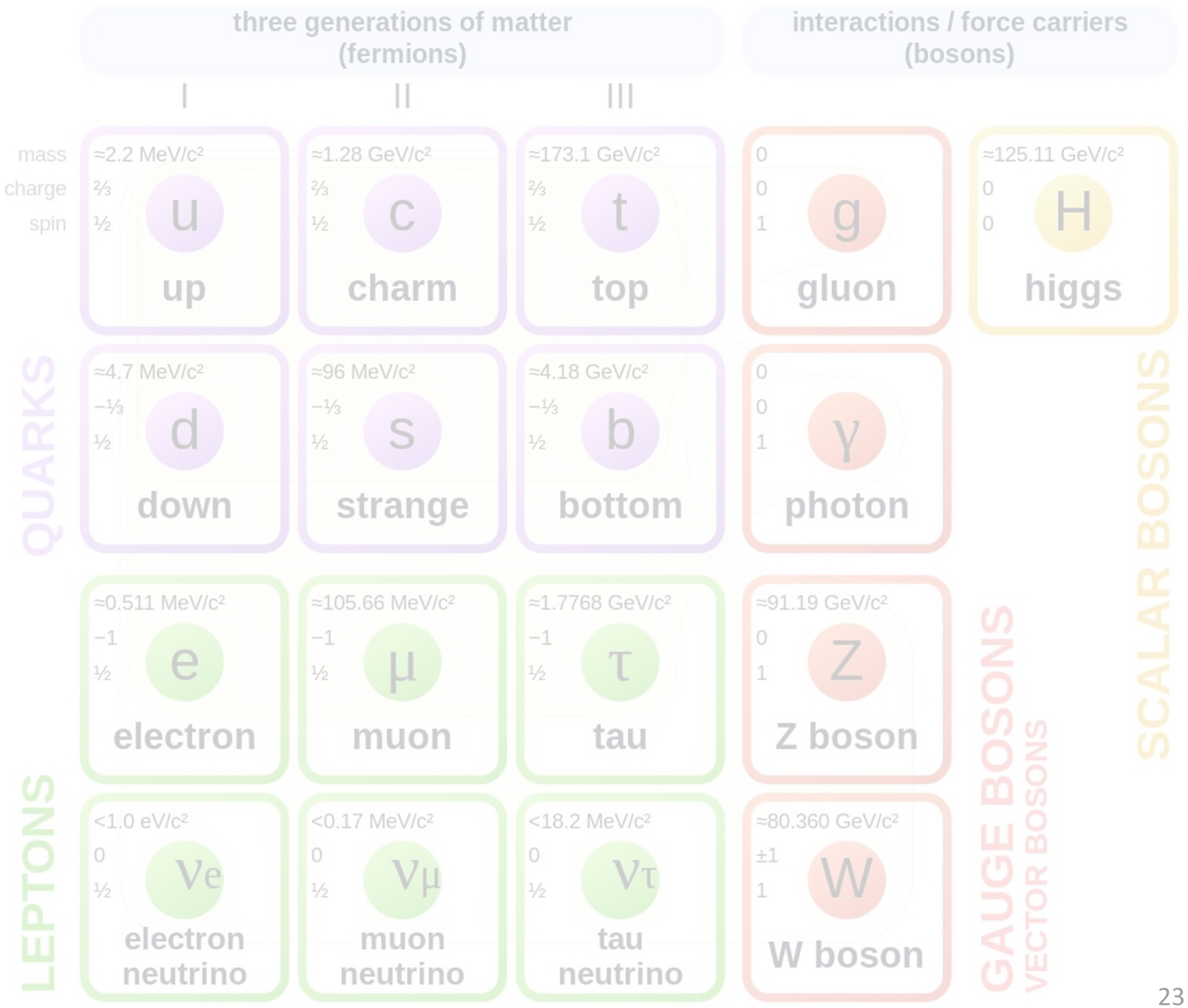
Fundamental Forces included in the SM



Fundamental Forces

Fundamental Forces included in the SM

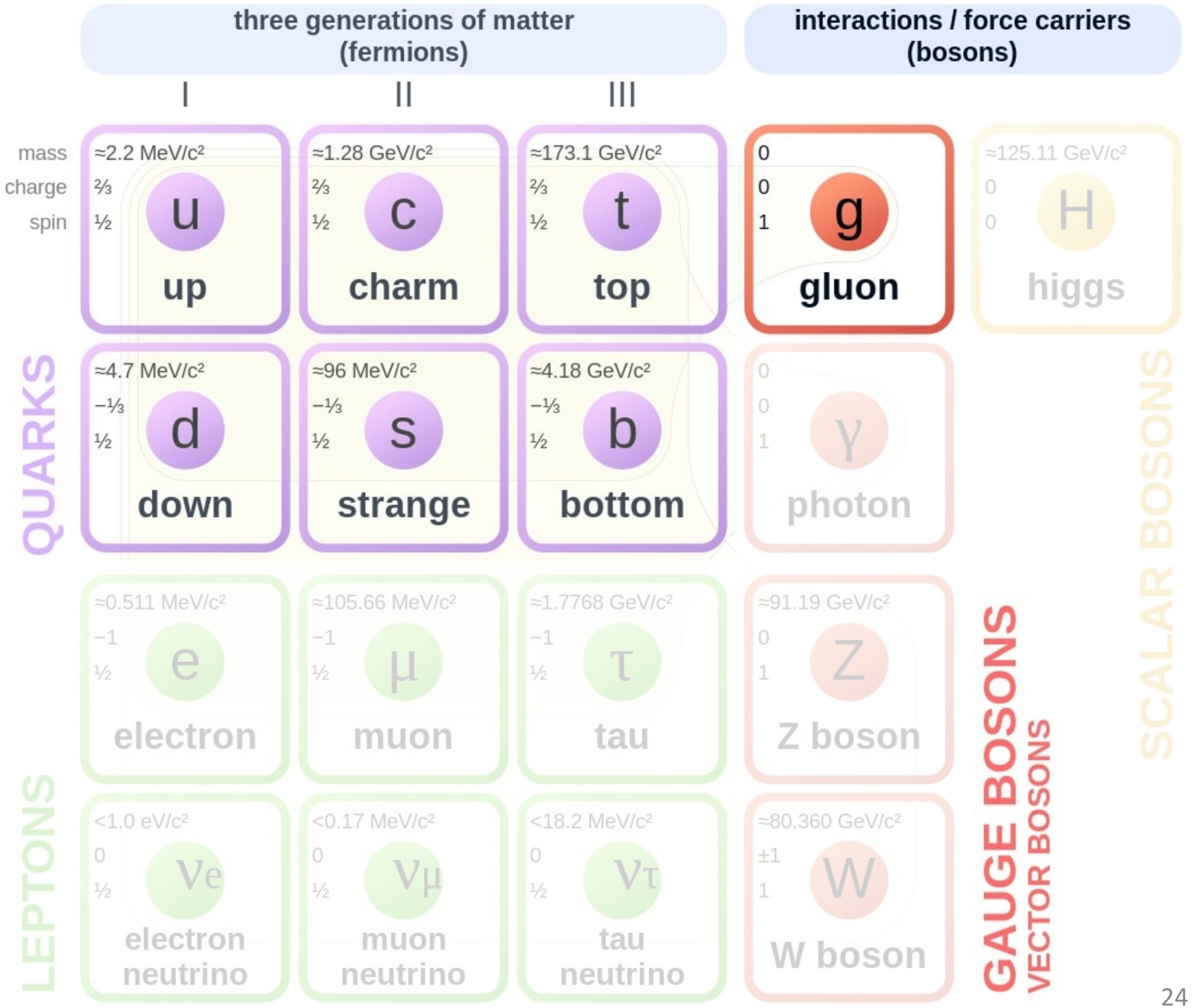
Strong Force | Electromagnetic Force | Weak Force



Fundamental Forces
Strong Force

Fundamental Forces included in the SM

- **Strong Force**
- Electromagnetic Force
- Weak Force



Fundamental Forces
Strong Force

Fundamental Forces included in the SM

- **Strong Force**
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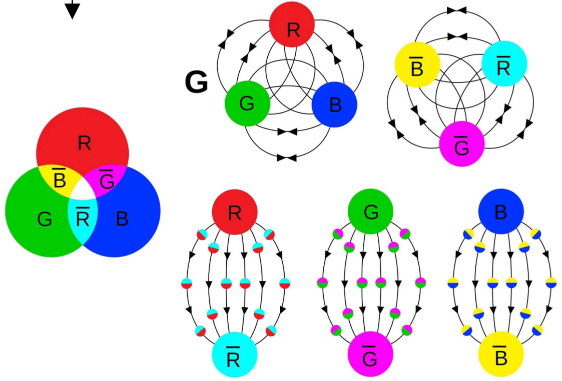
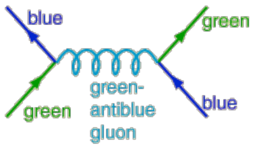
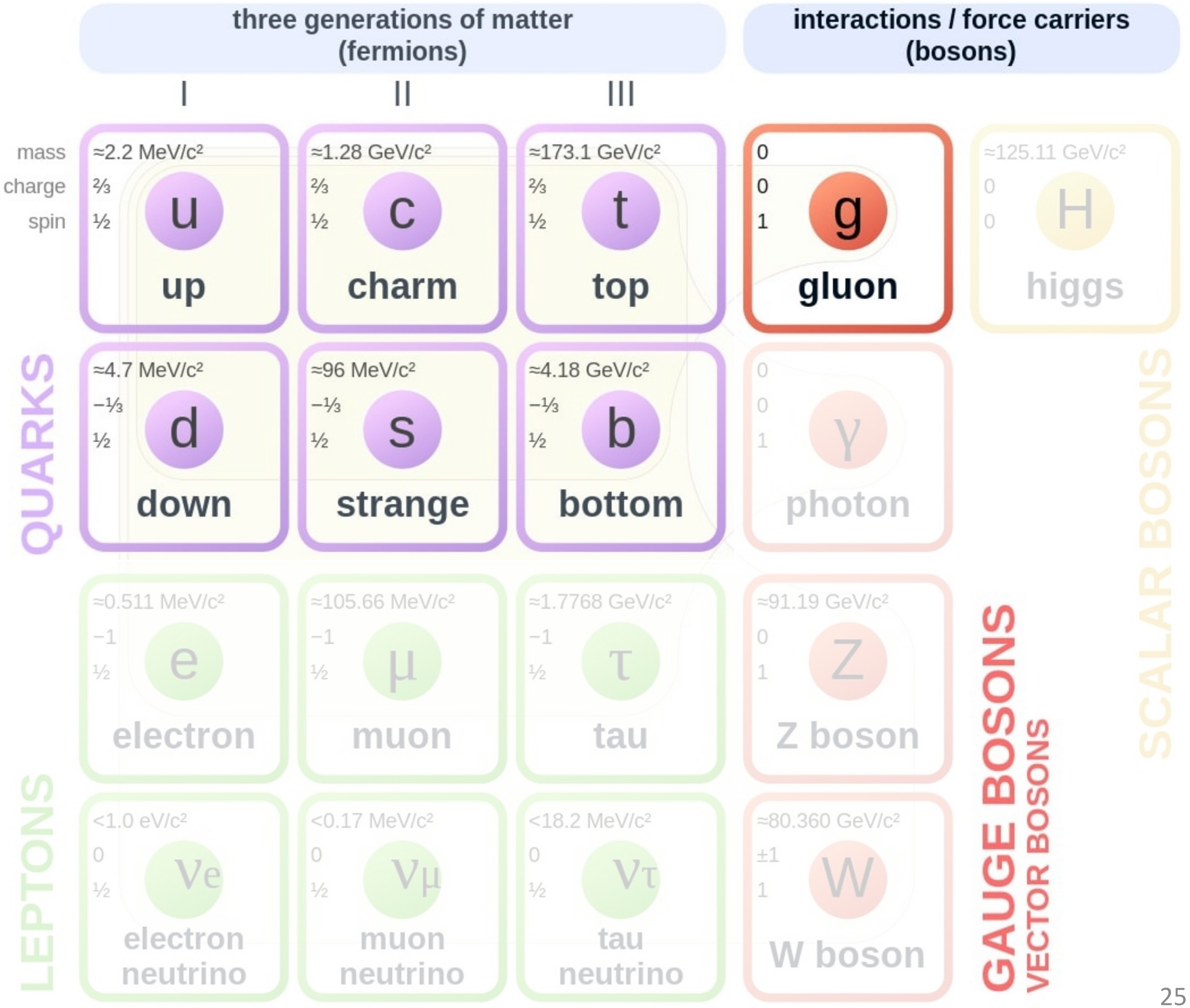
- Weak Force



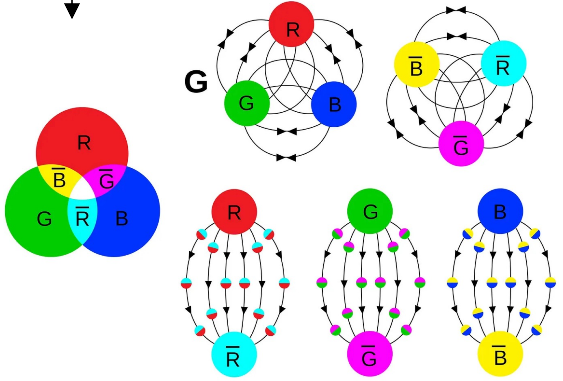


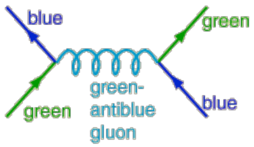


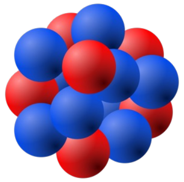
Fundamental Forces
Strong Force

Fundamental Forces included in the SM

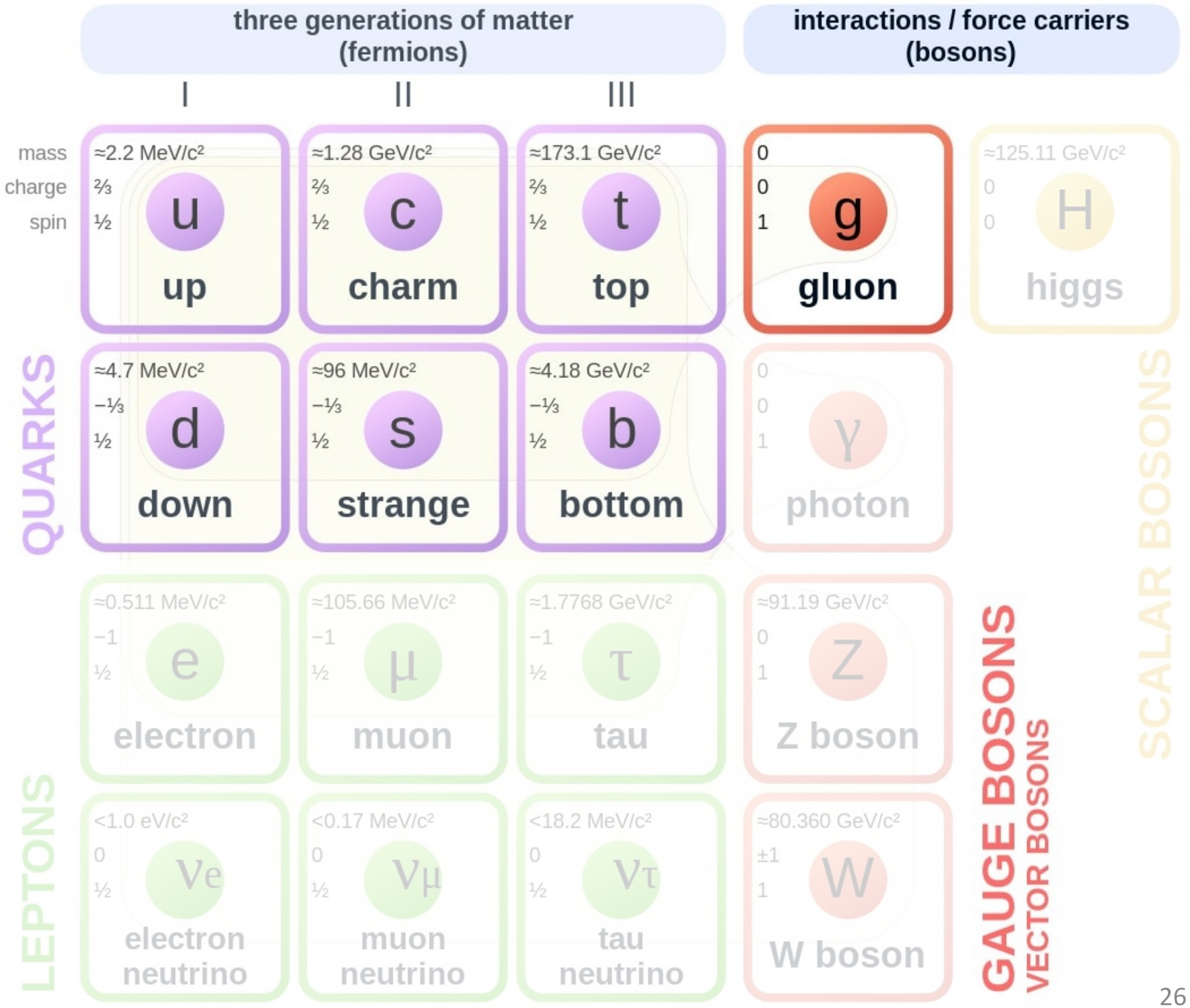
- **Strong Force**
- Electromagnetic Force
- Weak Force







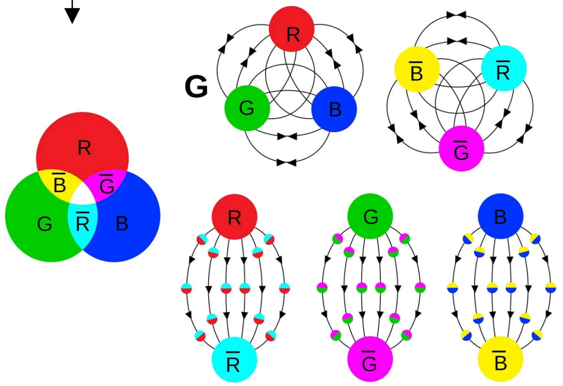
range of strong force: ~2.5 fm
size of proton: < 1 fm

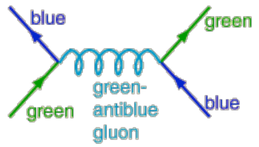


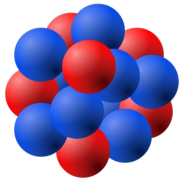
Fundamental Forces
Strong Force

Fundamental Forces included in the SM

- **Strong Force**
- Electromagnetic Force
- Weak Force







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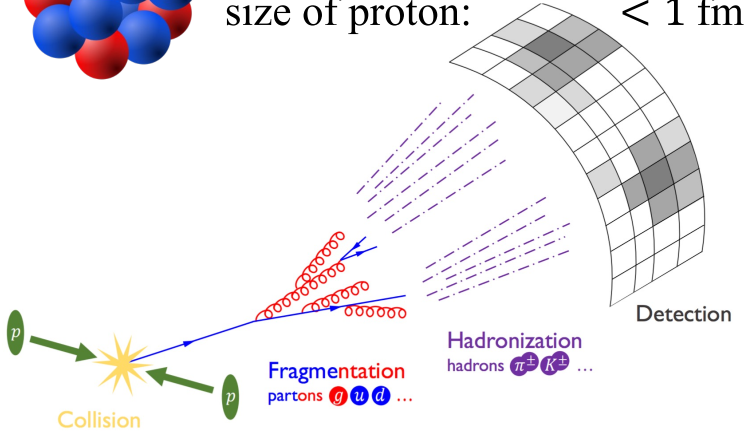
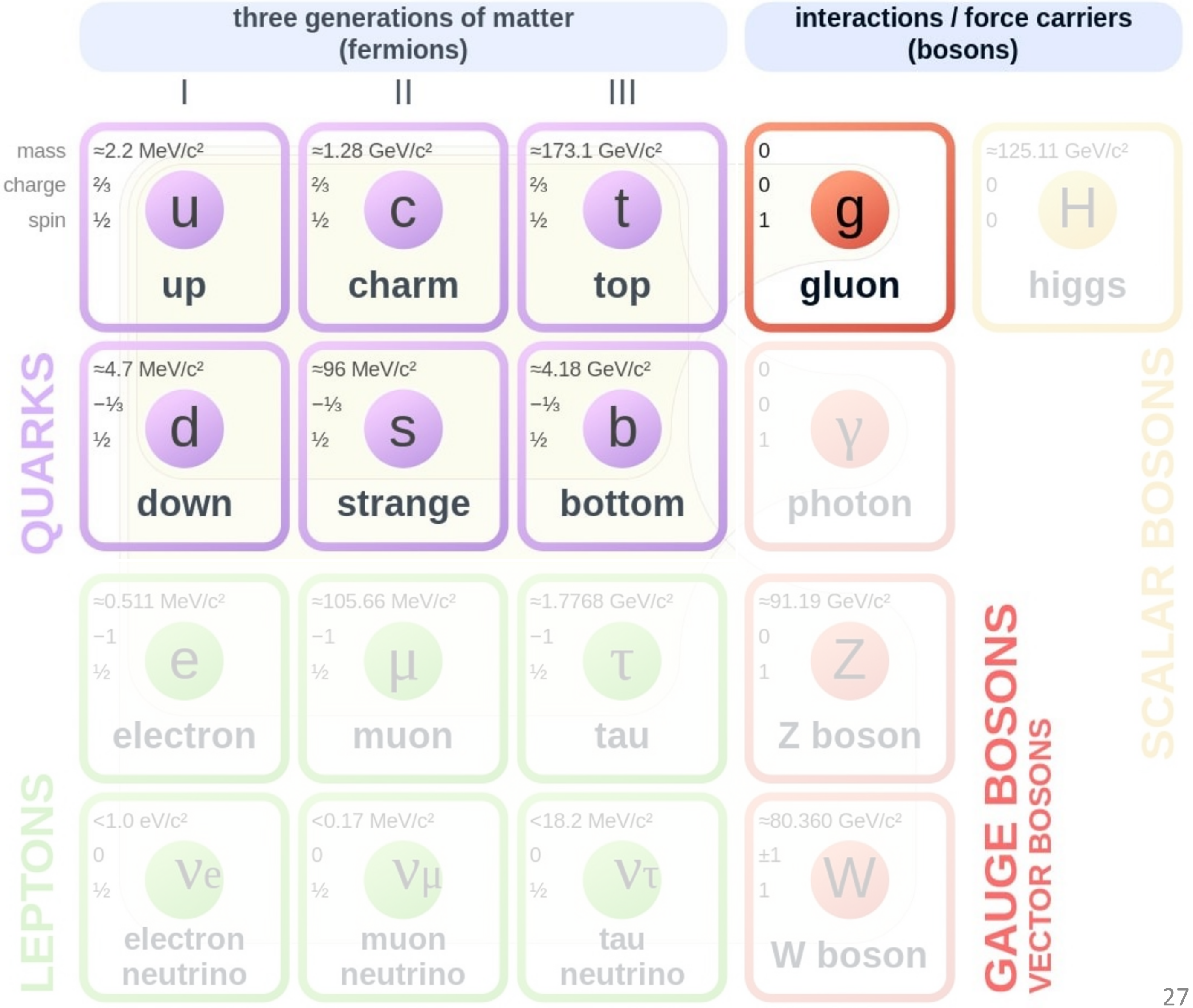
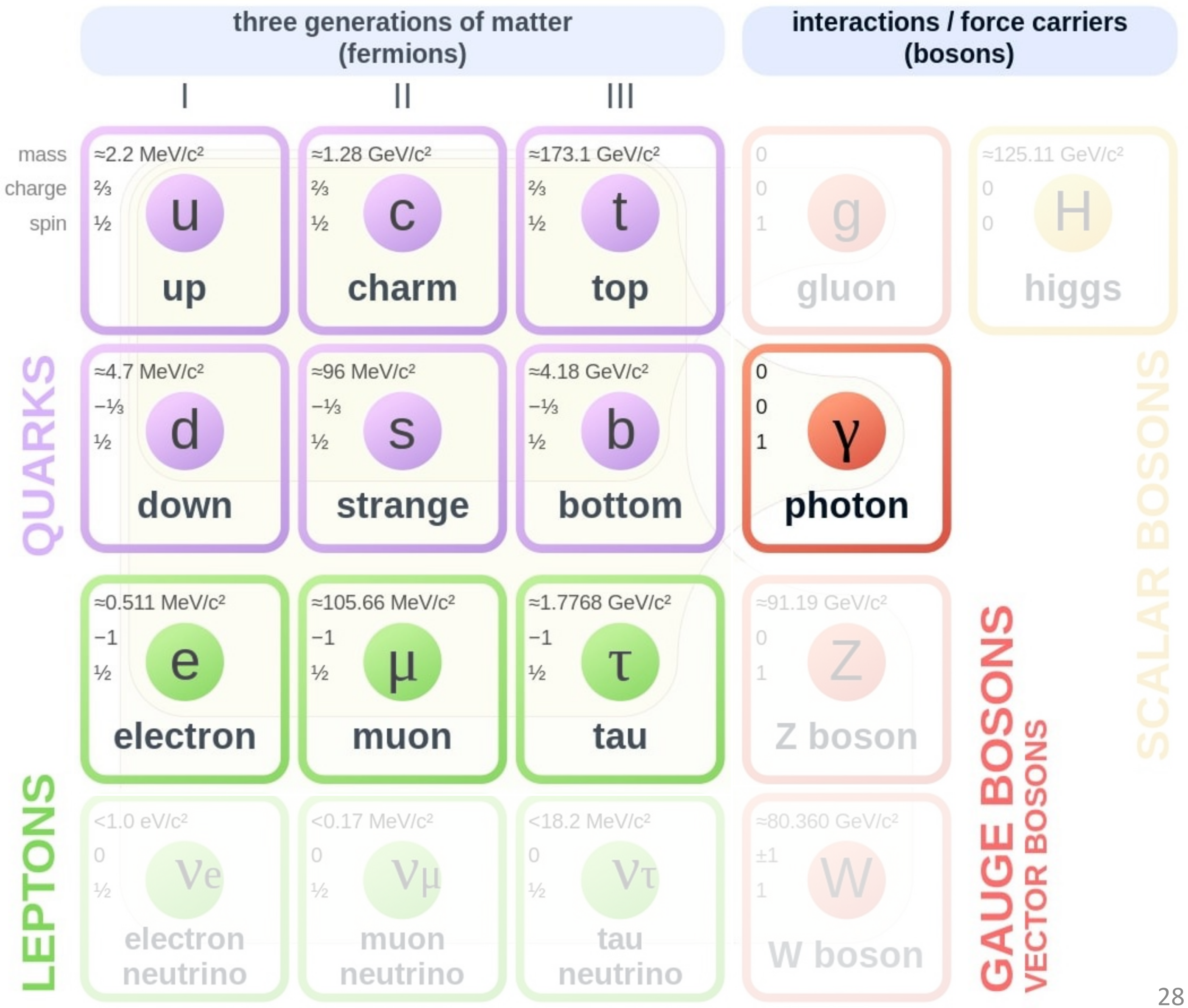




Fundamental Forces
Electromagnetic Force

Fundamental Forces included in the SM

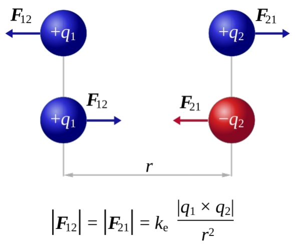
- Strong Force
- **Electromagnetic Force**
- Weak Force

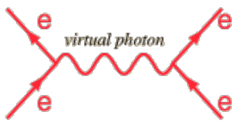


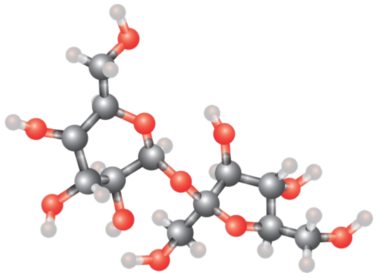
Fundamental Forces
Electromagnetic Force

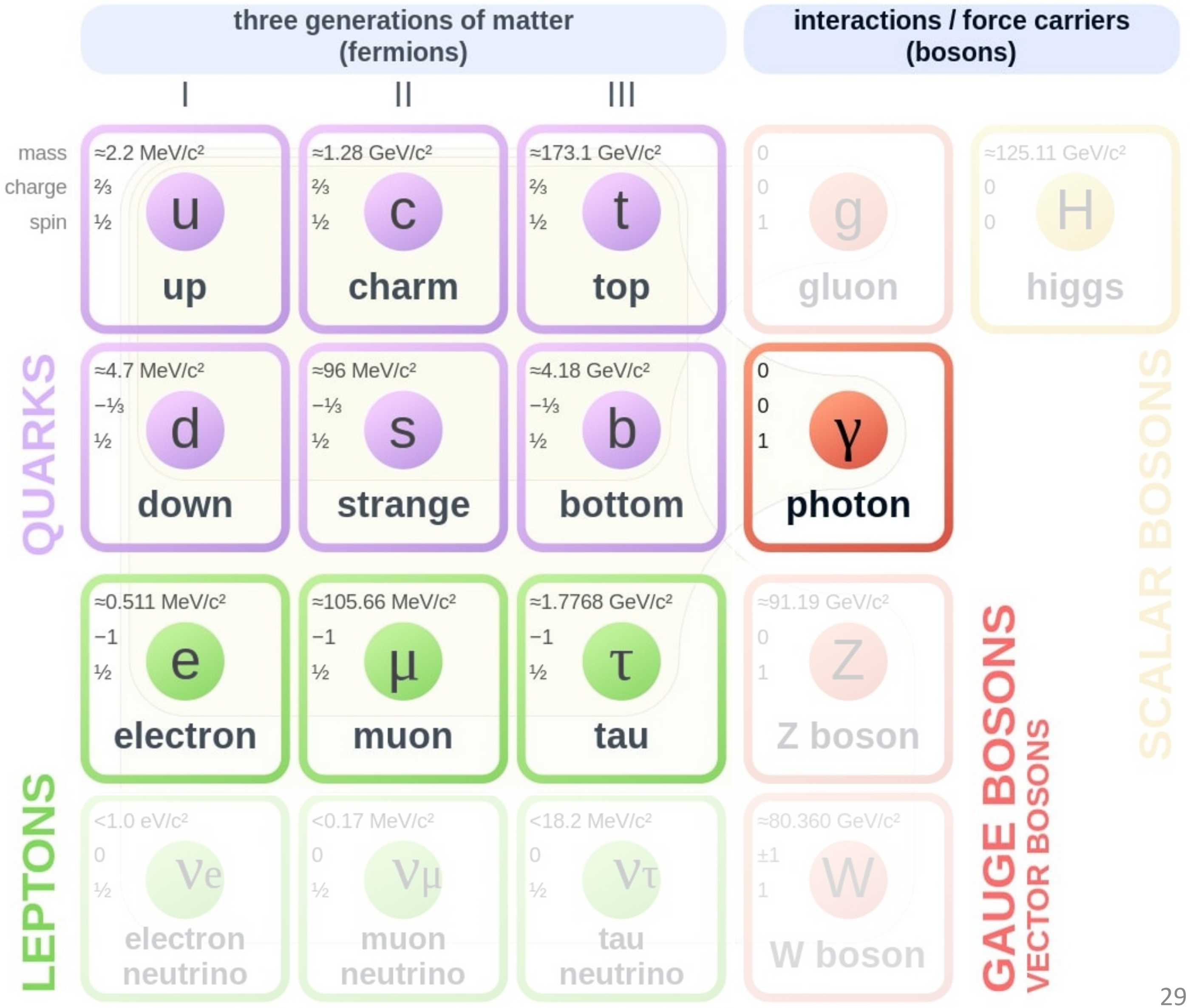
Fundamental Forces included in the SM

Strong Force | **Electromagnetic Force** | Weak Force





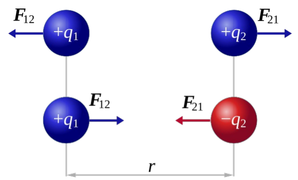




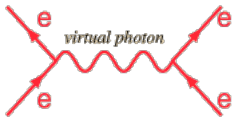
Fundamental Forces
Electromagnetic Force

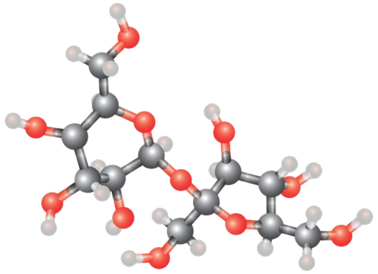
Fundamental Forces included in the SM

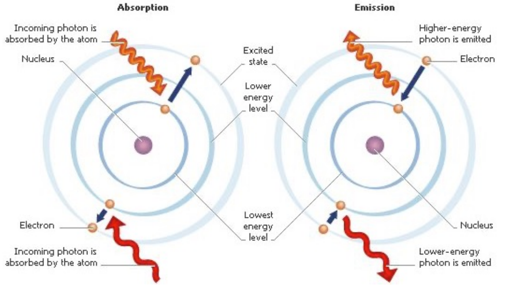
Strong Force | **Electromagnetic Force** | Weak Force

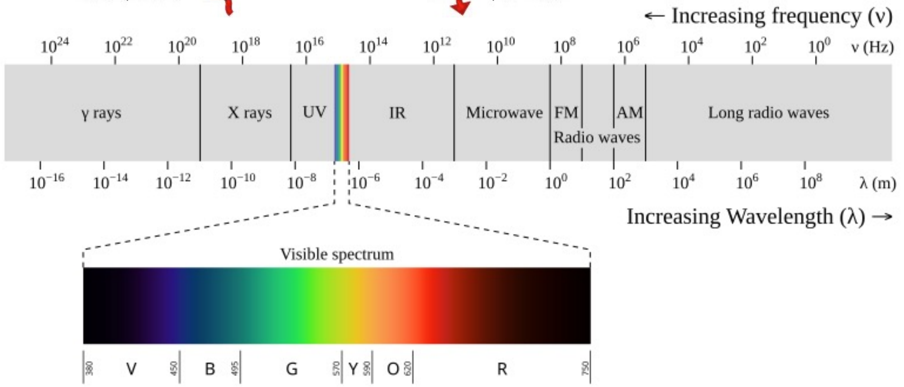


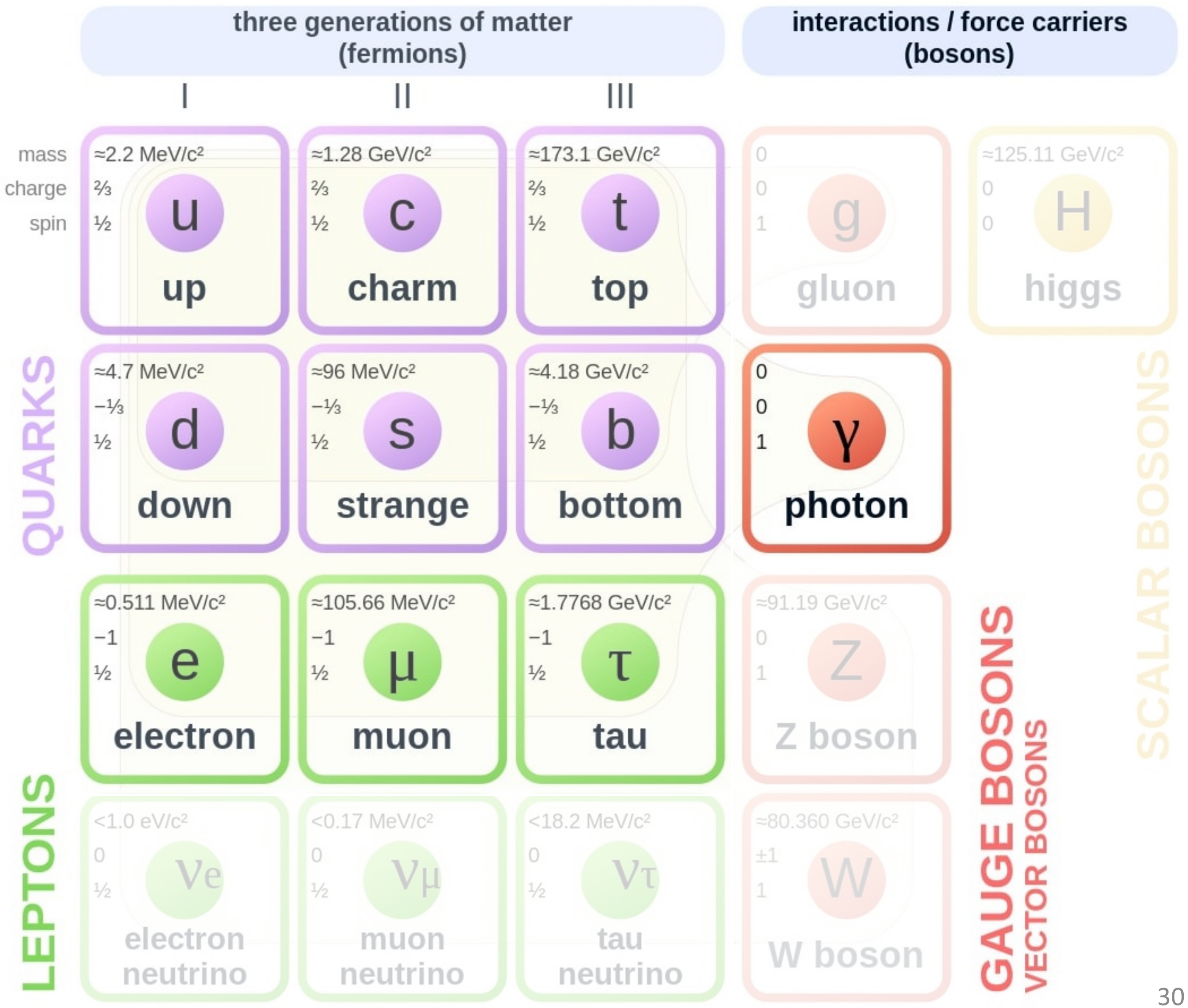
$$|F_{12}| = |F_{21}| = k_e \frac{|q_1 \times q_2|}{r^2}$$







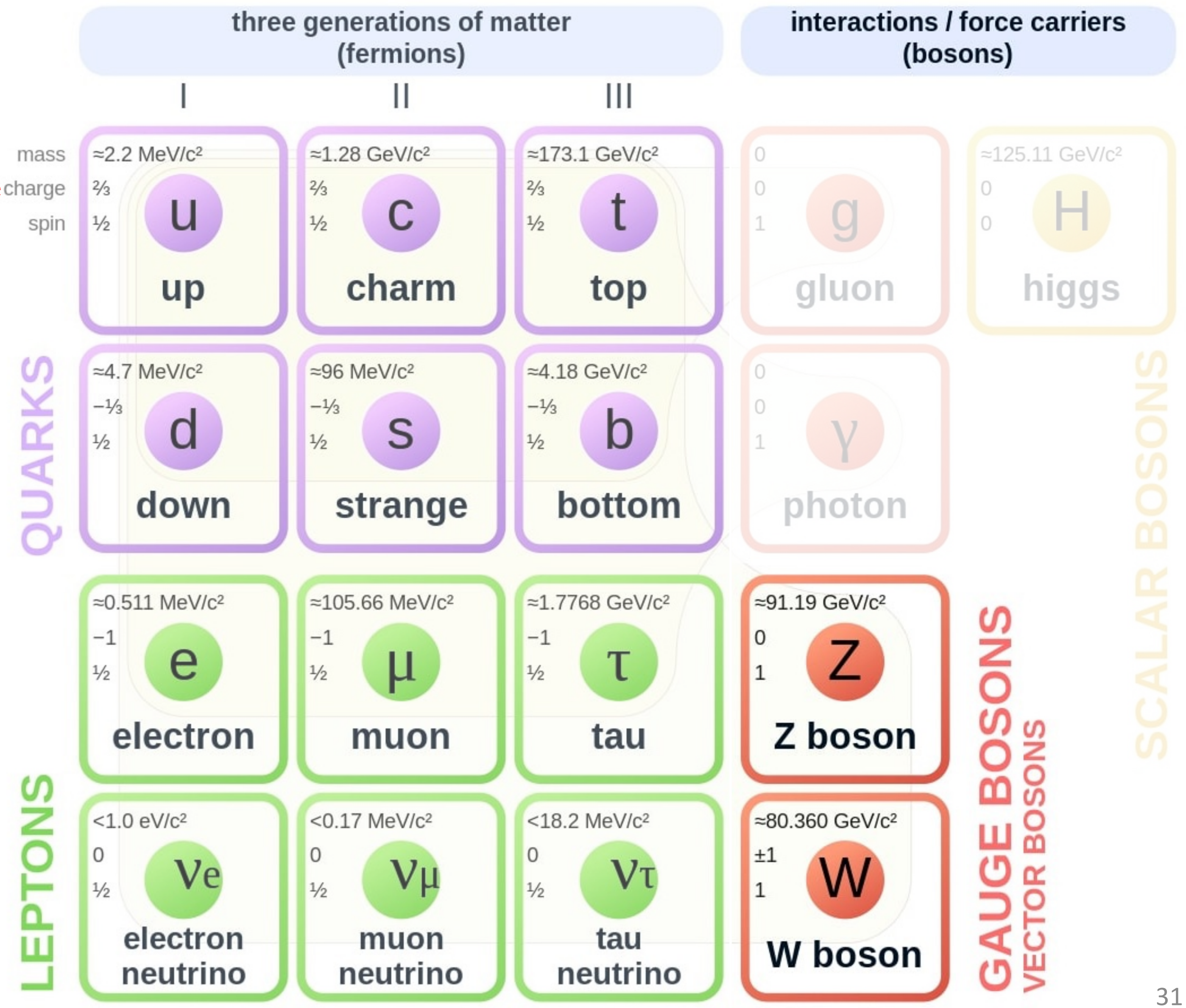




Fundamental Forces
Weak Force

Fundamental Forces included in the SM

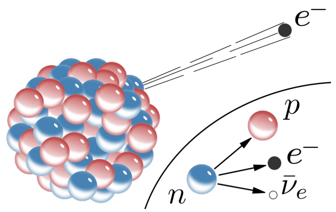
- Strong Force
- Electromagnetic Force
- **Weak Force**

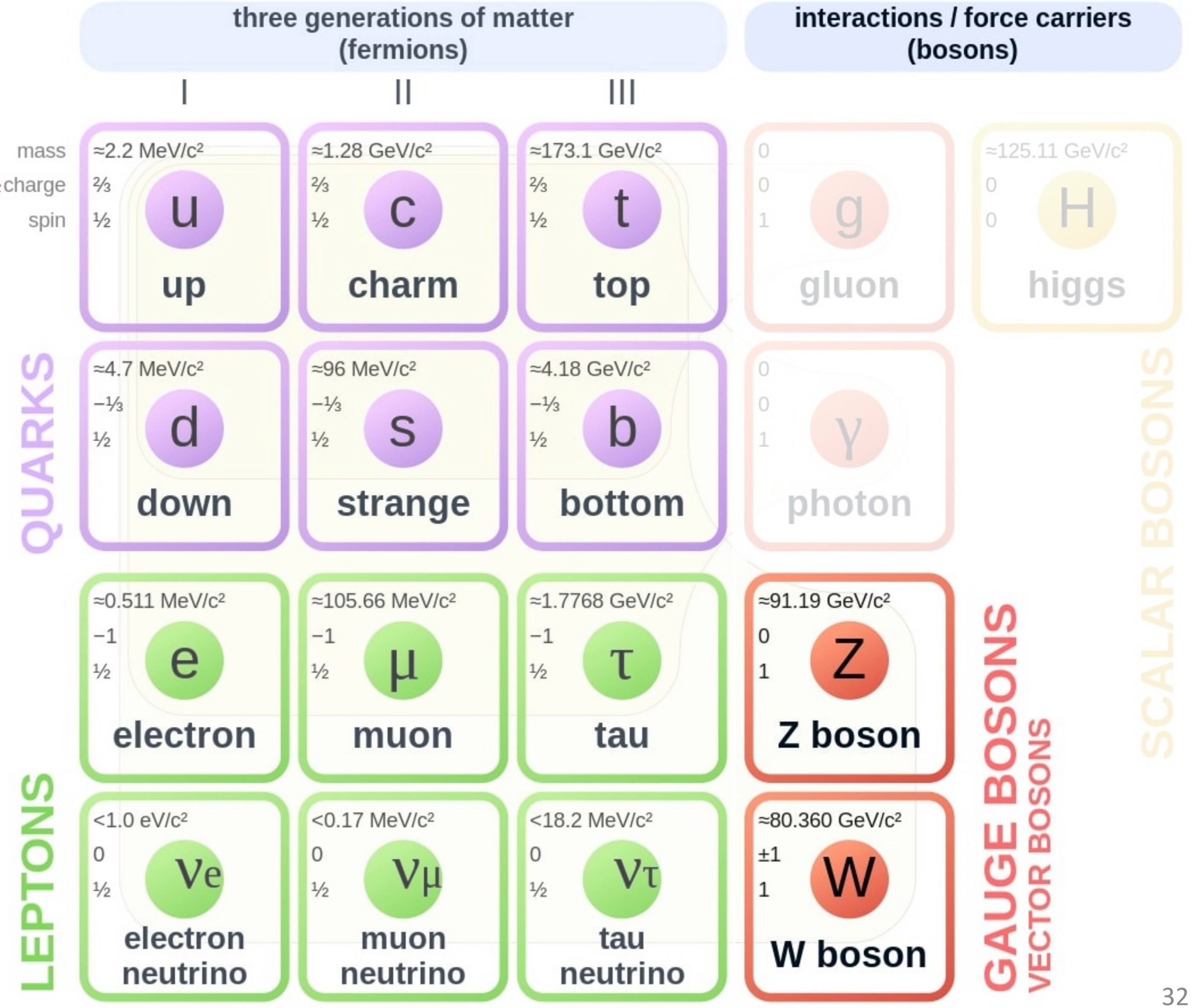


Fundamental Forces
Weak Force

Fundamental Forces included in the SM

Strong Force | Electromagnetic Force | **Weak Force**

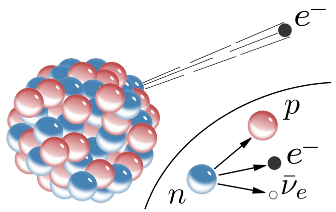




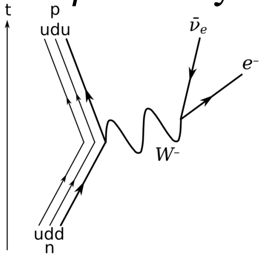
Fundamental Forces
Weak Force

Fundamental Forces included in the SM

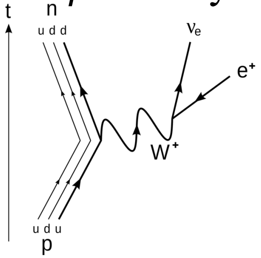
Strong Force | Electromagnetic Force | **Weak Force**



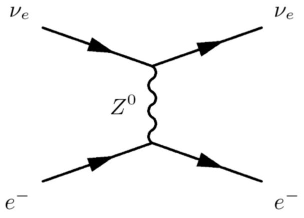
β^- decay

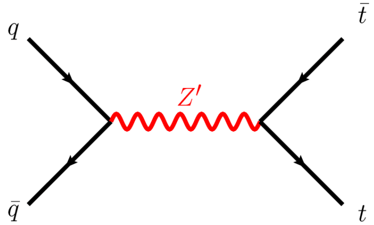


β^+ decay



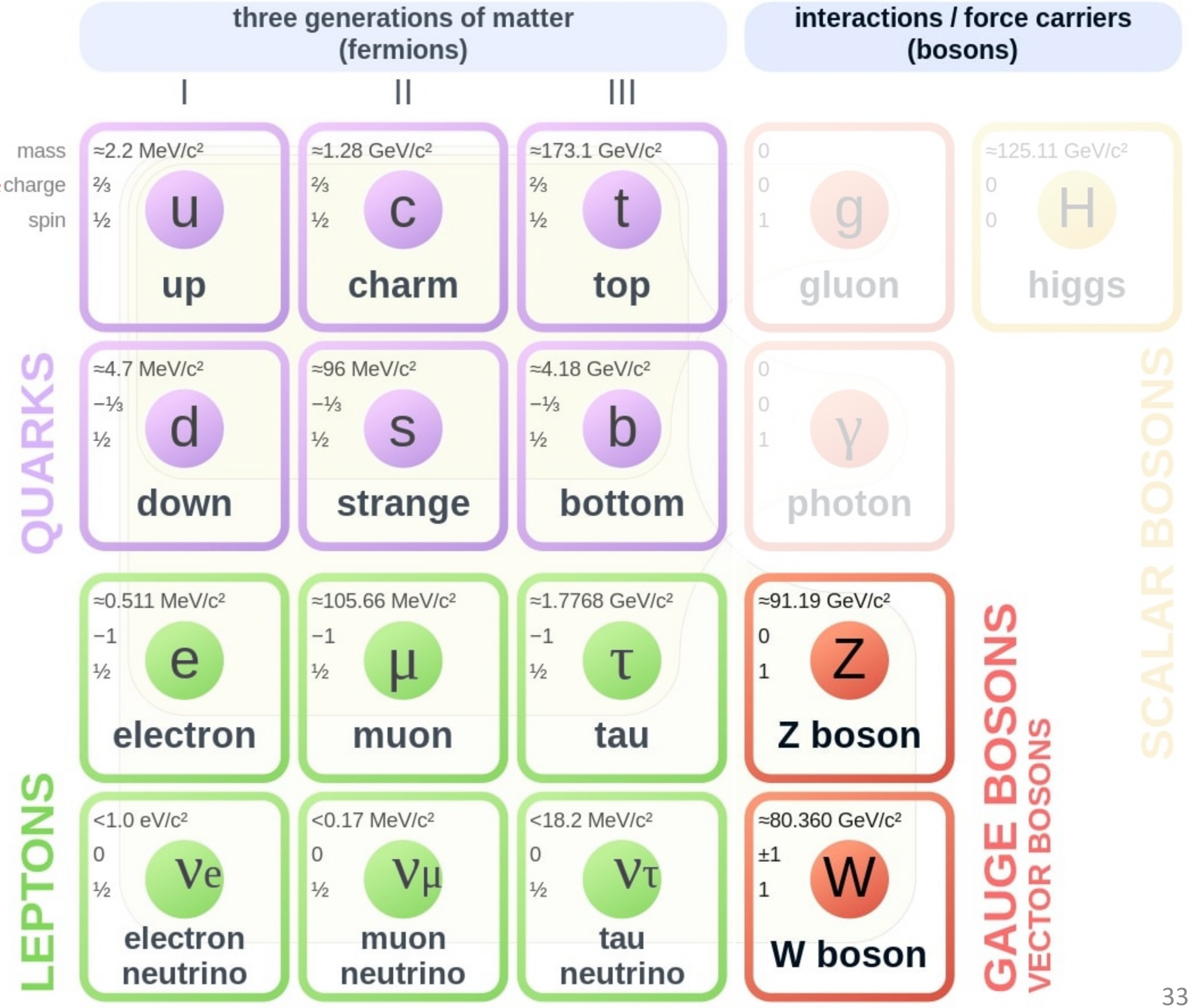
weak neutral current



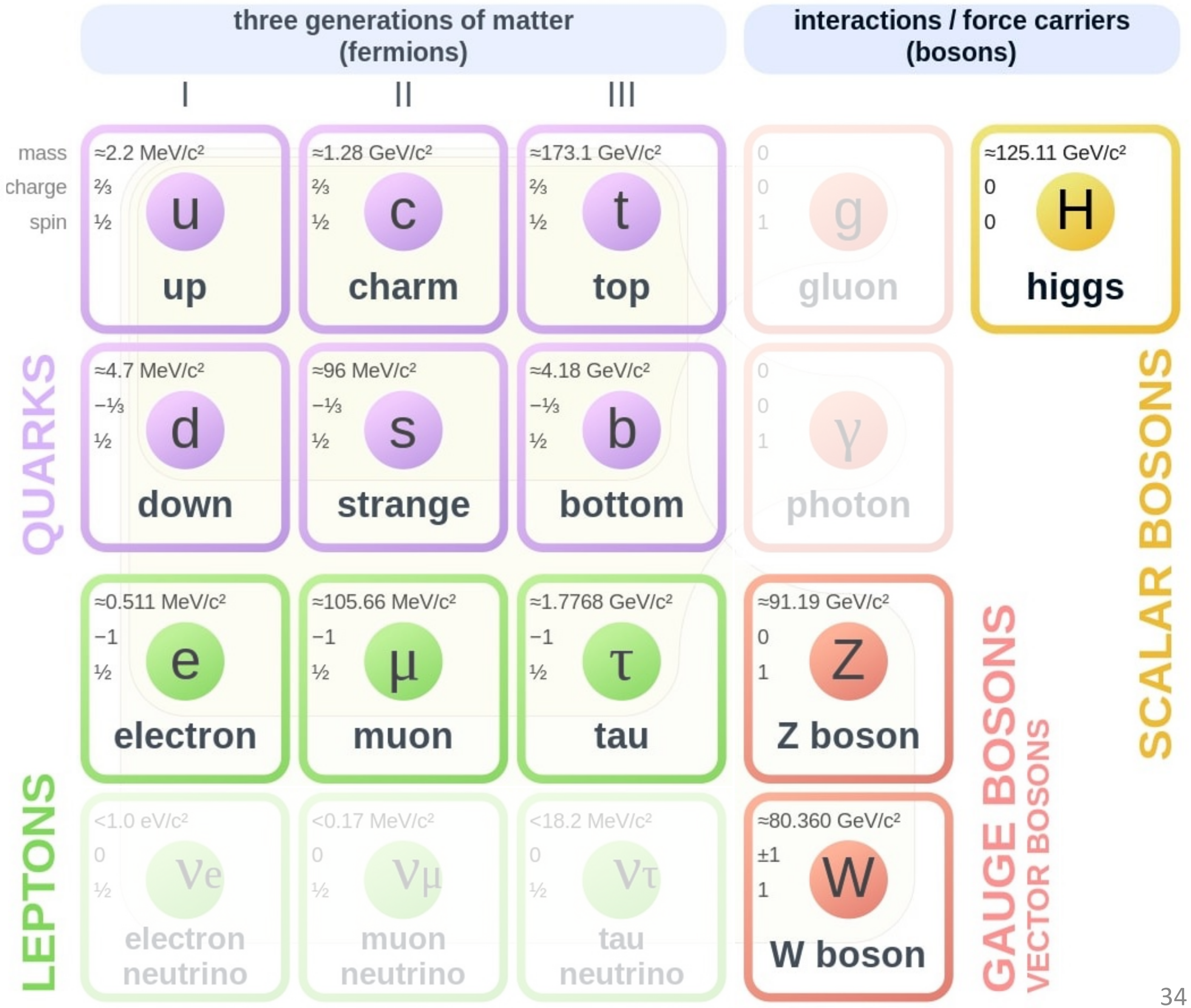


$W^{\pm} = 3\times10^{-25}$ s

$Z = 3\times10^{-25}$ s



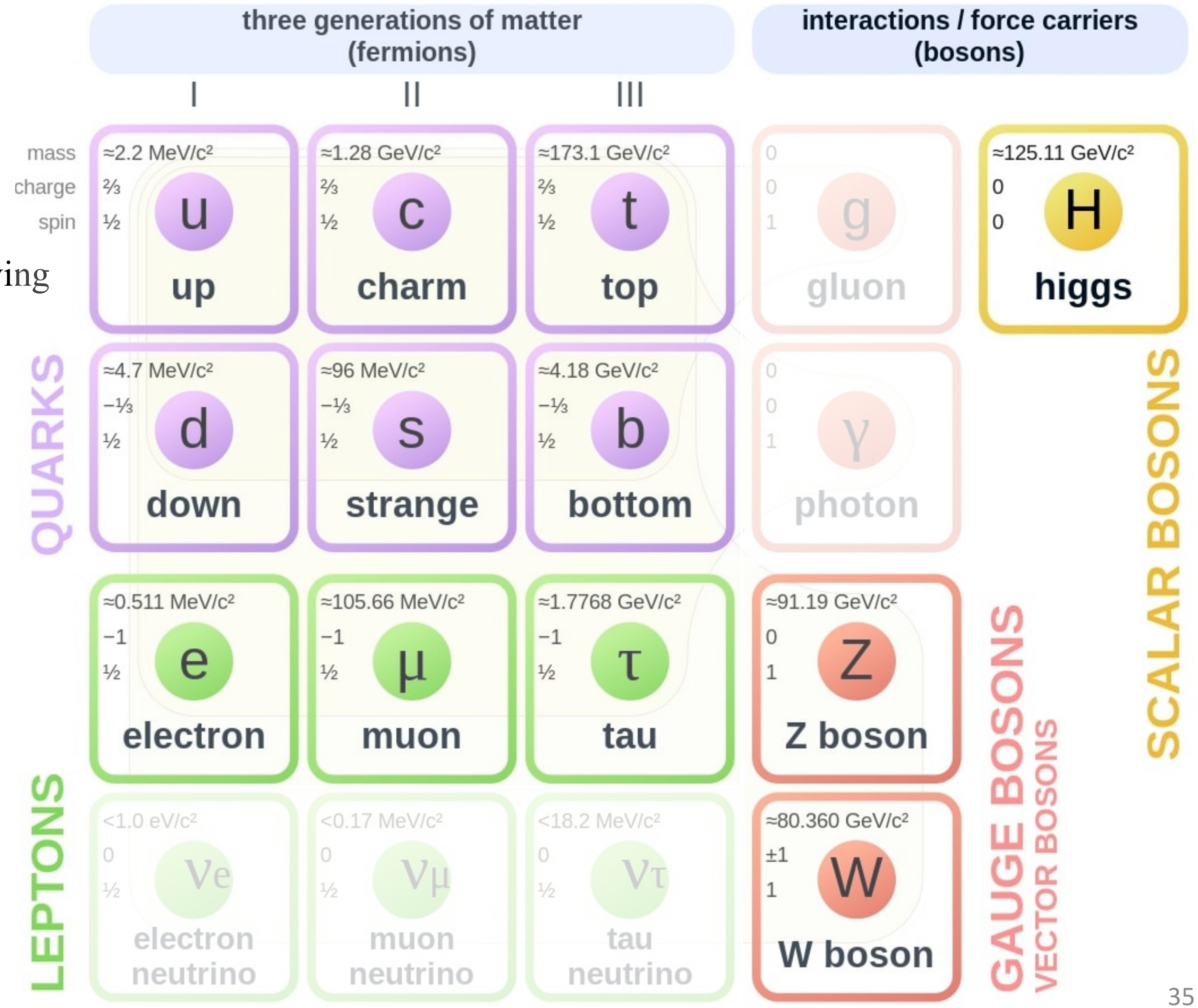
Standard Model
The Missing Puzzle



Standard Model
The Missing Puzzle

Conflict (early version of SM):
- particles assumed to be massless
- yet, experiments showed they have masses

Idea:
- mechanism to give these particles mass while preserving the mathematical structure and symmetry of SM



Standard Model
The Missing Puzzle

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- yet, experiments showed they have masses

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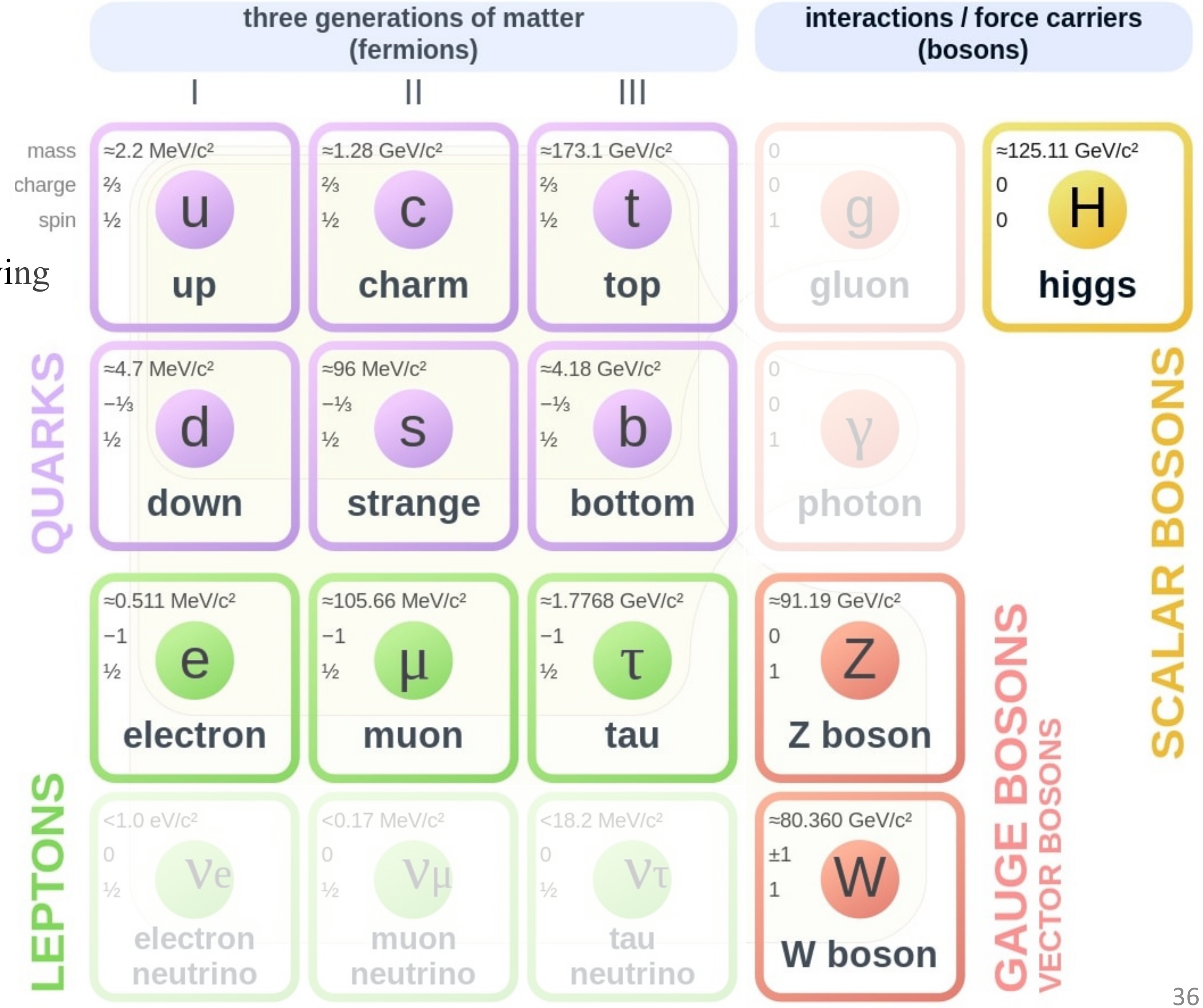
Explanation:

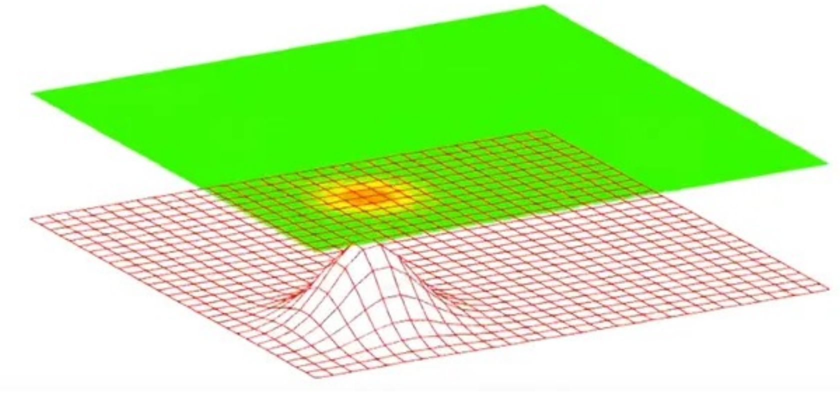
direct evidence of the existence of the Higgs field, validating the Higgs mechanism that explains how particles aquire mass



Higgs Field & Higgs Potential

Higgs field

- a scalar field that permeates the entire universe
- has a non-zero value everywhere in space, even in vacuum
- elementary particles that interact with the Higgs field acquire mass
- the more they interact, the more mass they gain
- elementary particles that do not interact with the Higgs field remain massless



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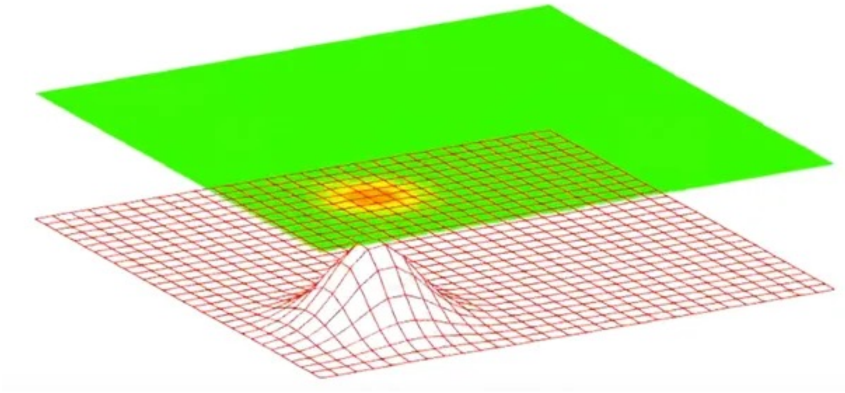

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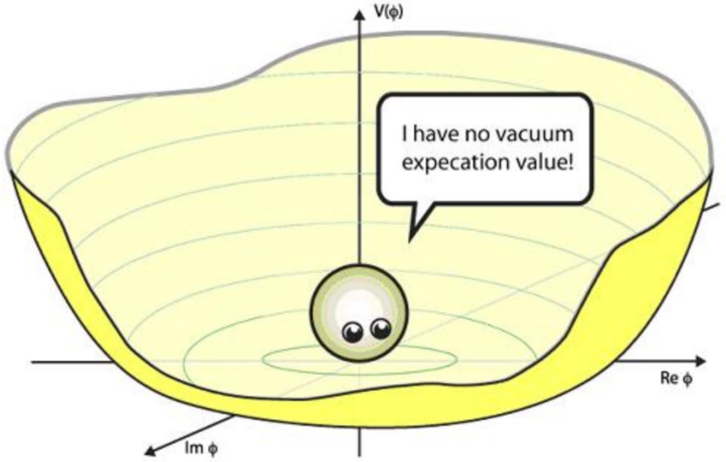
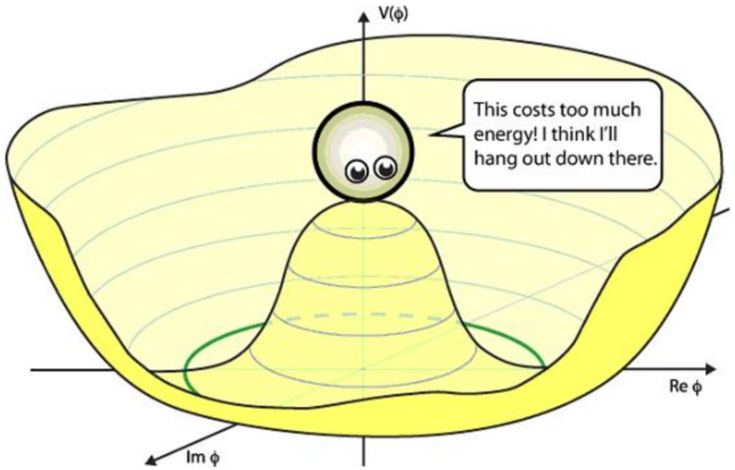
Higgs potential

- the function that describes the energy of the Higgs field
- unique potential shape, often referred as a "mexican hat" or "wine bottle" potential
- this shape allows the field to have a non-zero value even in its lowest-energy state
- non-zero value = Vacuum Expectation Value (VEV)

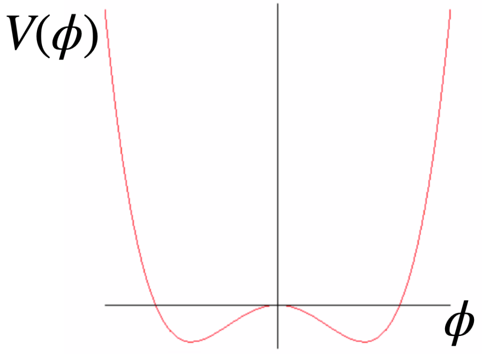


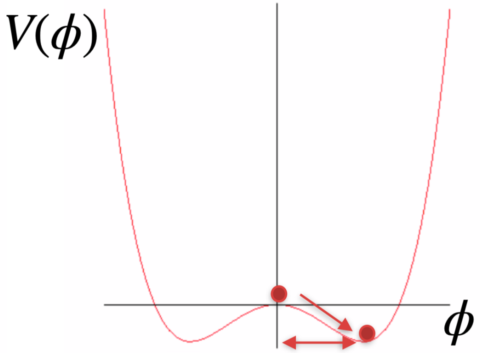


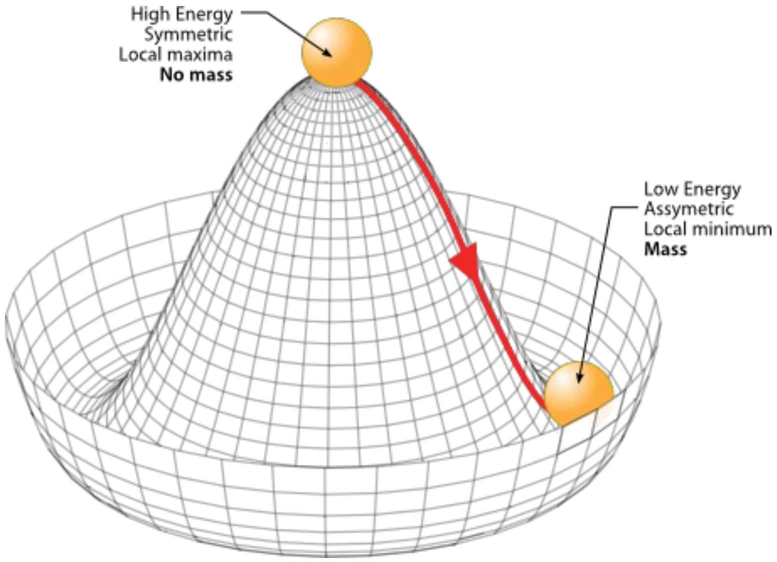
Spontaneous Symmetry Breaking

Energy state at $\phi = 0$:

- rotational symmetric → fully symmetric in all directions
- false vacuum (high-energy state) → no excitation in the field ϕ
- no interactions → no mass generated
- unstable → potential not at its lowest







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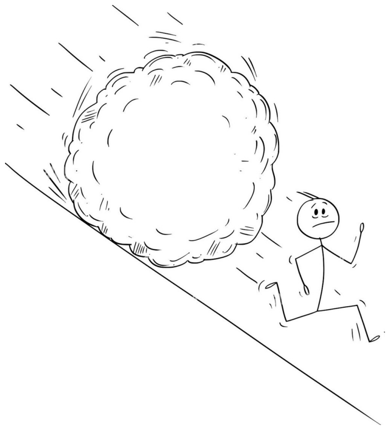
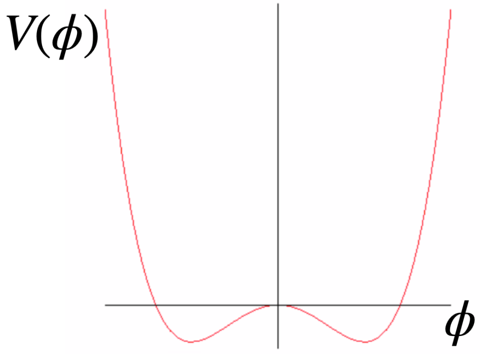
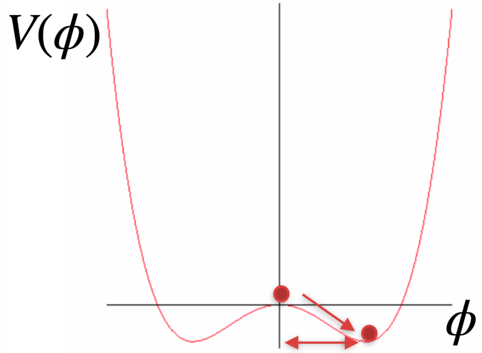


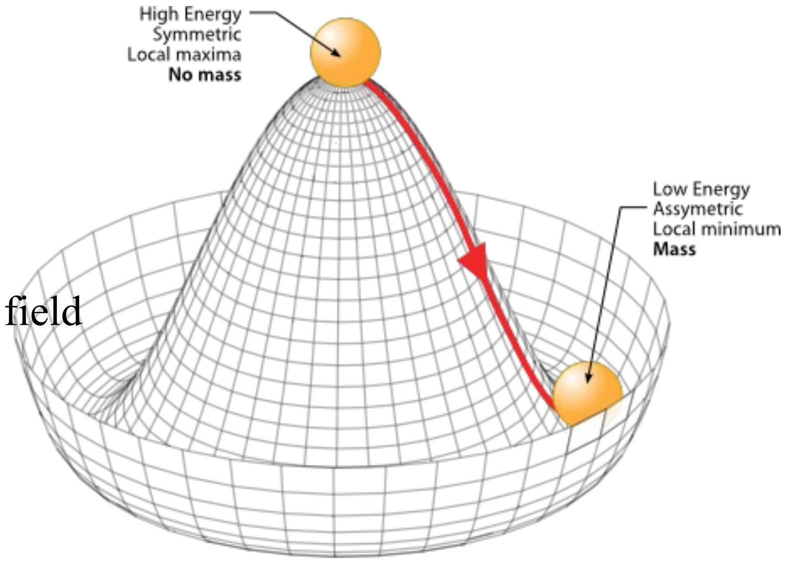




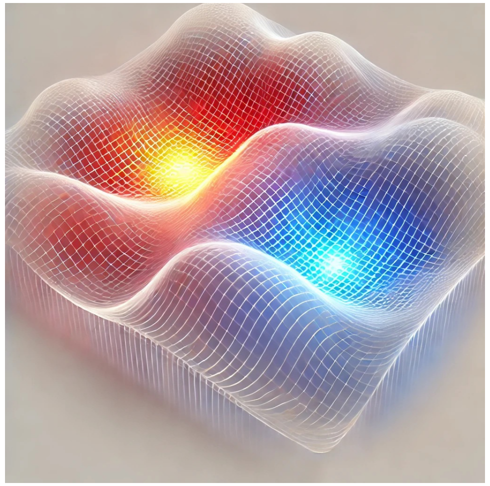
→ breaks the rotational symmetry of the field

Energy state at $\phi \neq 0$:

- rotational symmetry broken → **spontaneous symmetry breaking**
- true vacuum (lowest-energy state) → the field ϕ settles in a new minimum, VEV
- interactions possible → mass generated for particles interacting with the field
- non-zero energy vacuum state → energy due to the Higgs field's VEV
- higgs boson → excitations as Higgs boson



Higgs Mechanism



Higgs mechanism

- process by which particles acquire mass through interaction with the Higgs field's VEV

- the Higgs field settles after the symmetry breaking and has a non-zero value everywhere
- other quantum fields are able to interact with the Higgs field
- while interacting, they experience a sort of resistance which is interpreted as mass gain

No interaction:

- photons (and gluons) → no mass

Direct interaction:

- W and Z bosons

the mass differentiation between the W and Z bosons and photons leads to the separation of the weak and electromagnetic forces after symmetry breaking

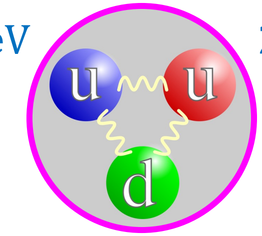
Indirect interaction:

- fermions
- interaction through Yukawa coupling
- Yukawa coupling determines the strength of the interaction between a particular fermion and the Higgs field

proton

2.2 MeV

2.2 MeV



4.7 MeV

→ $\frac{9.1\text{ MeV}}{938.3\text{ MeV}} \approx 1\%$

mass of quarks ↗ 9.1 MeV

mass of proton ↘ 938.3 MeV

Mass is proportional to Yukawa coupling:

- photon: $\mathrm{m}_\gamma = 0$ (no coupling)
- electron: $\mathrm{m_e} = 0.511$ MeV (small Yukawa coupling)
- top quark: $\mathrm{m_t} = 173.1$ GeV (very strong Yukawa coupling)

SM Lagrangian

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

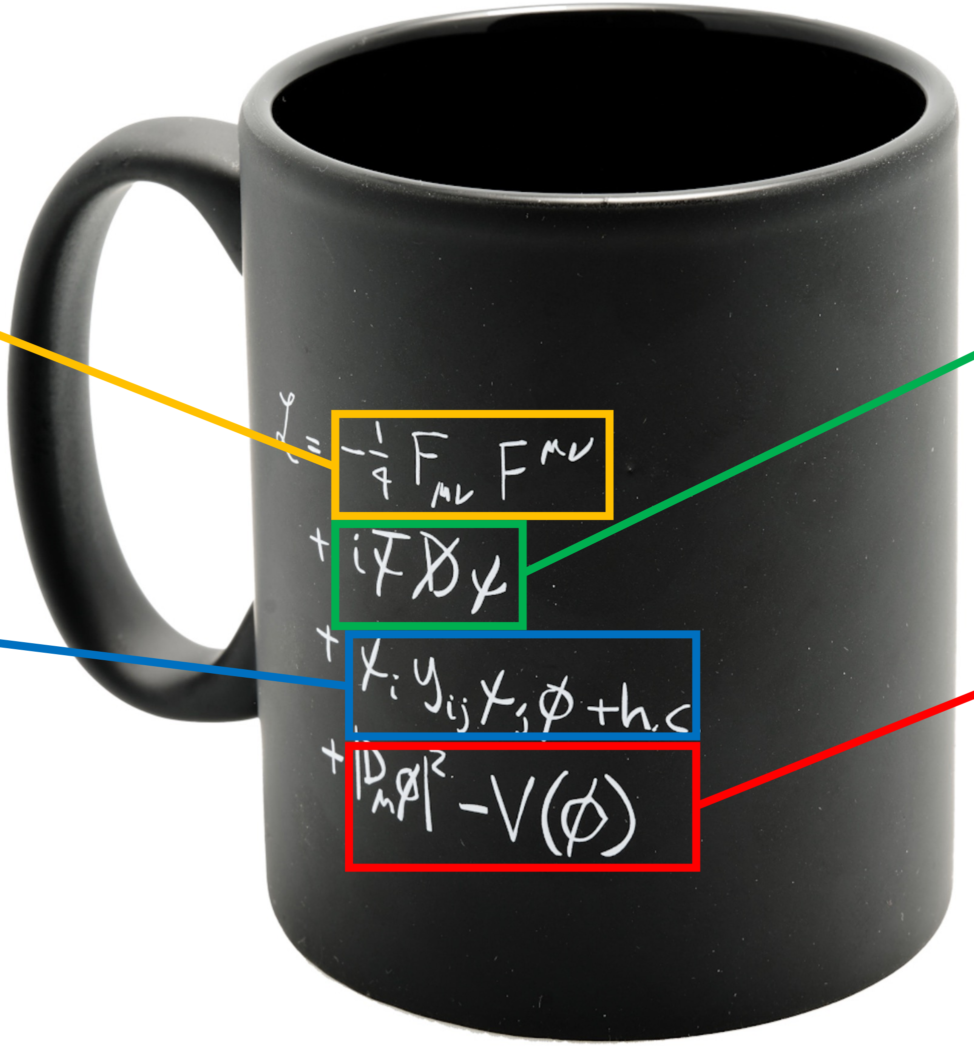
Standard Model Cup

Dynamics of gauge fields associated with the force carriers:

- γ → electromagnetic force
- W and Z → weak force
- g → strong force

Yukawa coupling term describing how fermions gain mass through their interaction with the Higgs field ϕ.

- y_{ij} → Yukawa coupling constant determining the strength of interaction with the Higgs field



Kinetic term for fermions and their interactions with the gauge fields.

- ψ → fermion field
- D → covariant derivative showing interactions with gauge fields

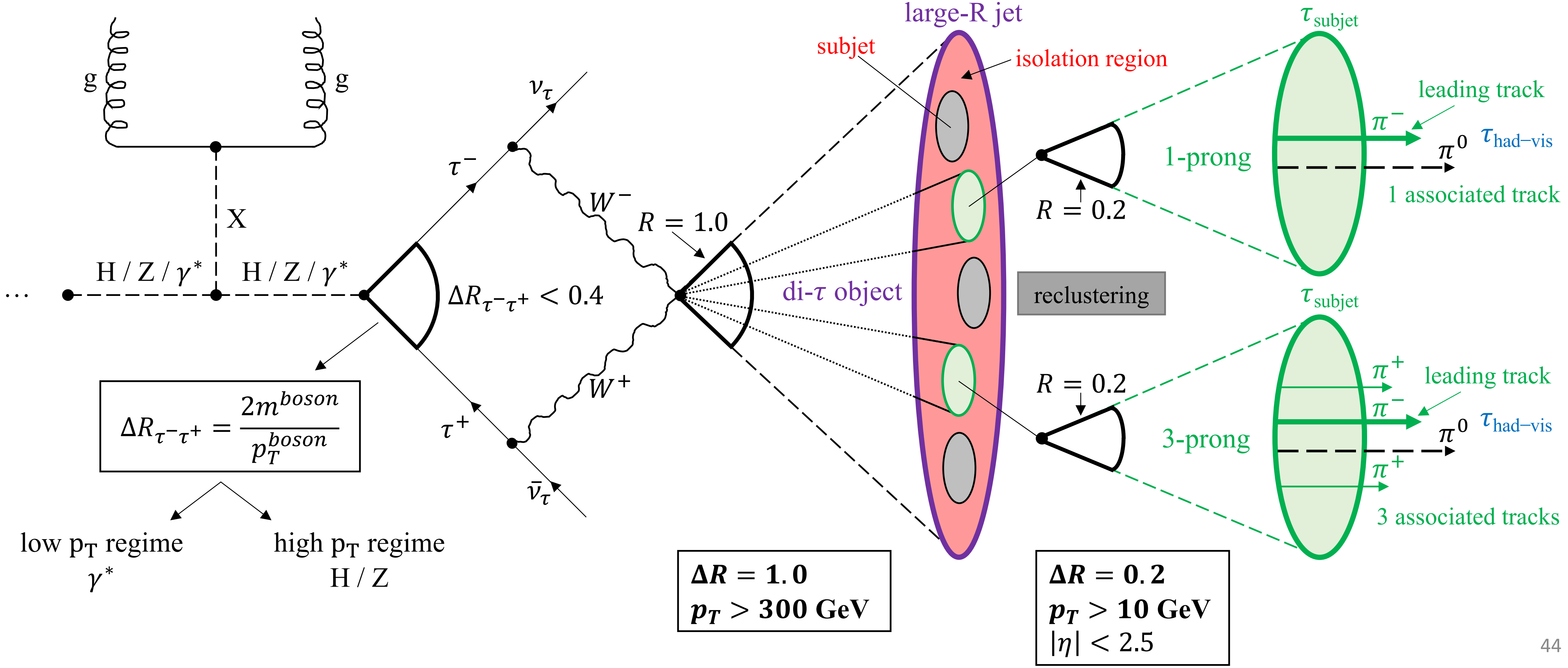
Higgs field's kinetic and potential terms.

- $|D_\mu \phi|^2$ → kinetic term for the Higgs field
- $V(\phi)$ → Higgs potential driving the Higgs mechanism for giving mass to particles

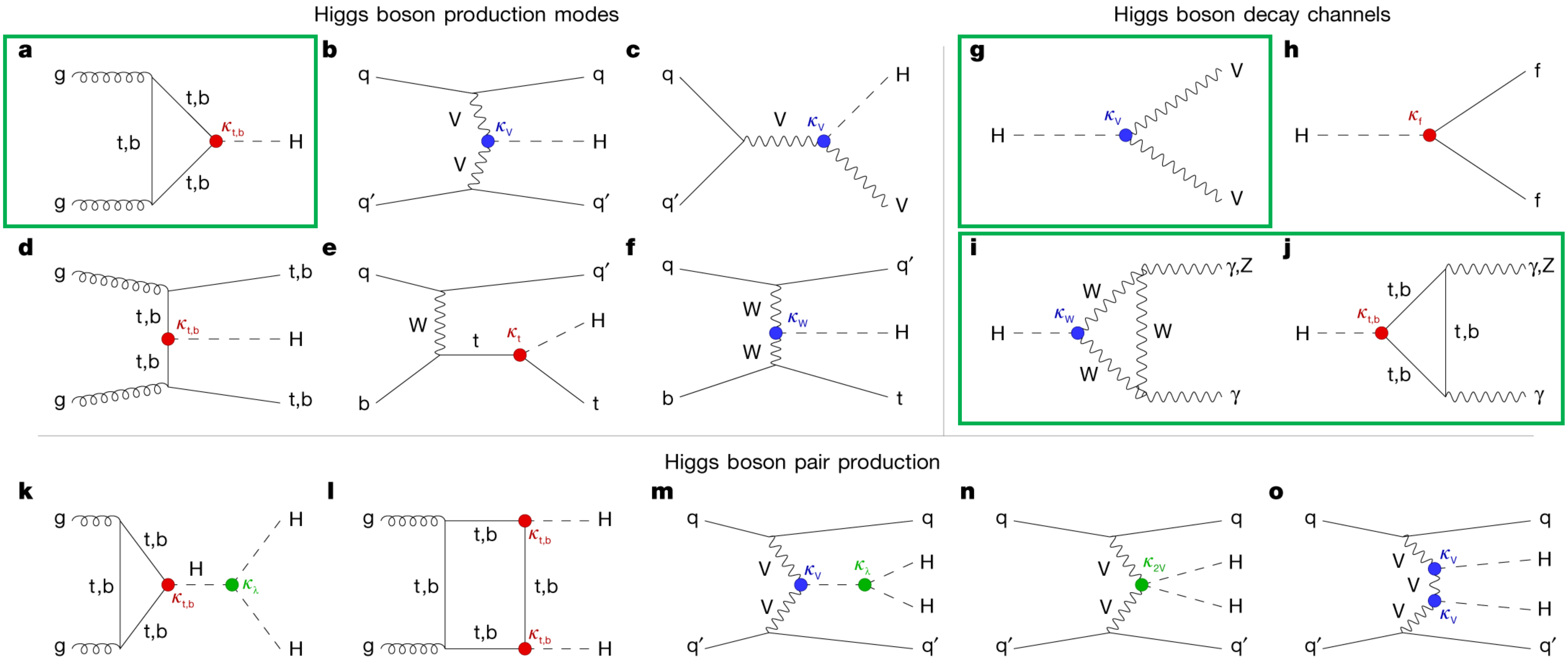
Higgs → Di-Tau

By using large radius jet ($\Delta R < 1.0$), there is no competition at the seed jet level → The 2τ are contained in a large radius jet and the 2τ become τ_{subjets}

- loose: di-$\tau_{\text{had-vis}}$ matched with large-R jet
- medium: at least 2 subjets in large-R jet
- tight: 2 $\tau_{\text{had-vis}}$ matched with 2 unique subjets



Modes & Channels



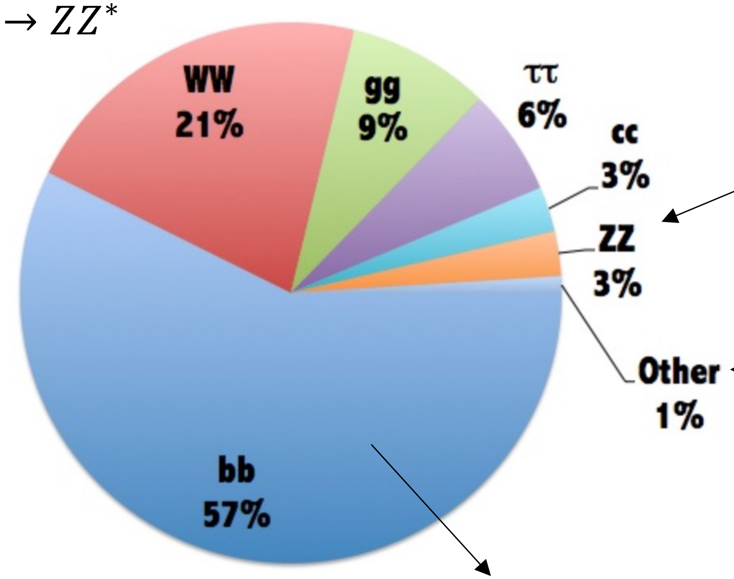
Branching Ratios

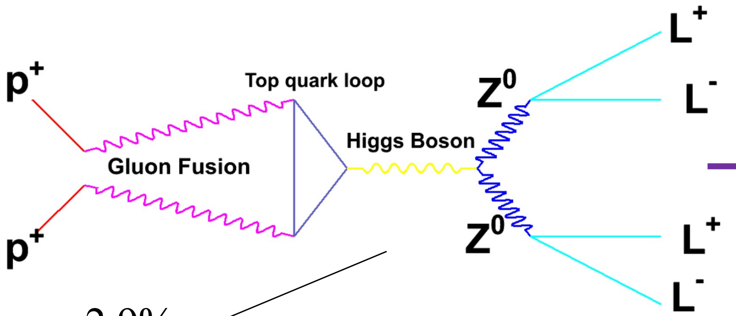
Probability

- Extremely low probability for production → one Higgs per 10 billion collisions
- Clean channels not that common
- Lifetime: 1.6×10^{-22} s

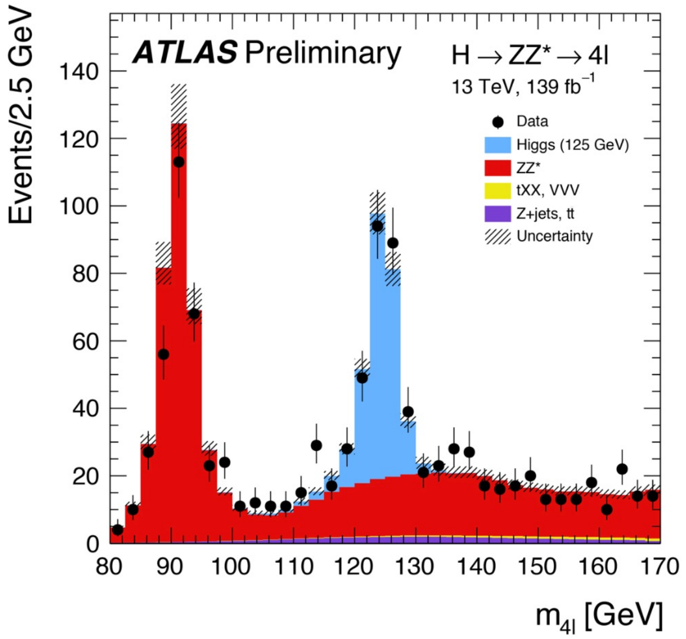
Most visible channels:

- $H \to \gamma\gamma$
- $H \to ZZ^*$





2.9%



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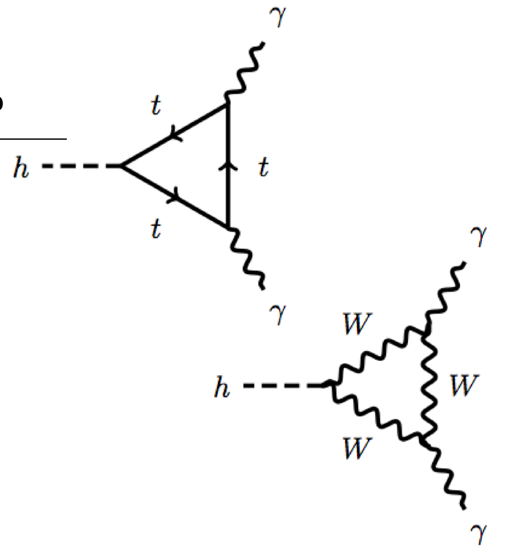
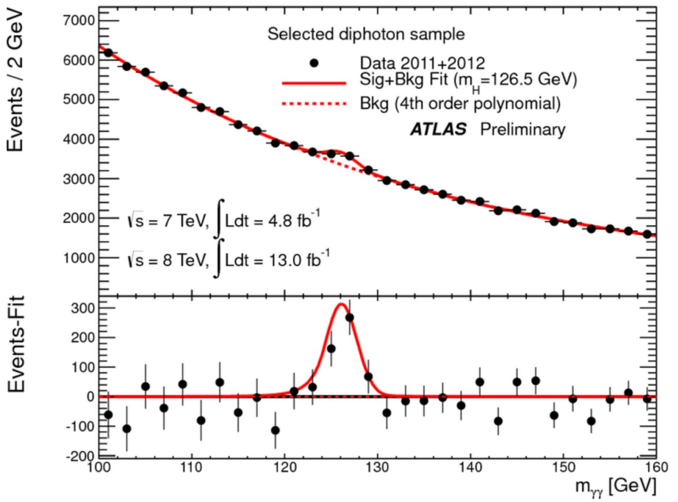




difficult channel
(lots of background)

Discovery

50 years journey:

- predicted in 1964 by Peter Higgs
- contribution from other physicists: François Englert, Robert Brout, Gerald Guralnik, C.R. Hagen, and Tom Kibble

- Mass anywhere between 10 – 1000 GeV
- Decays instantaneously, very tiny window to observe it

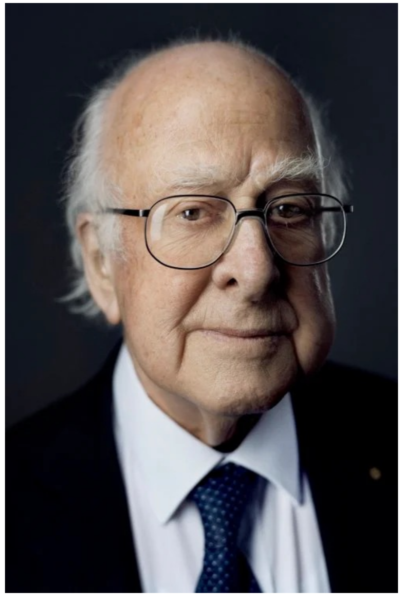
- The search was considered almost impossible:

> We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

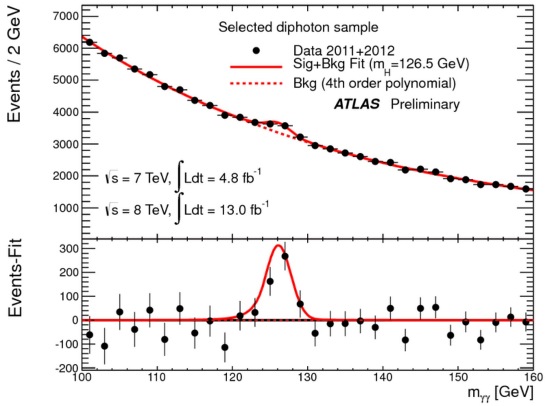


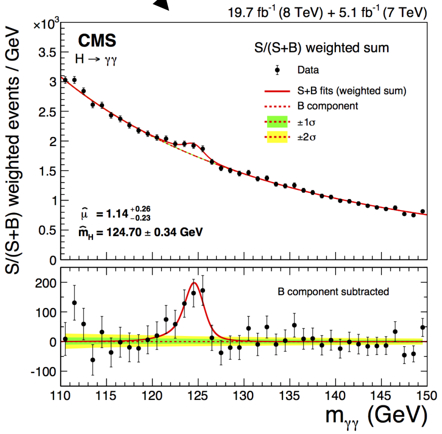
- Technology cought up in 80s with particle colliders
- Still evaded detection for a few decades
- Each null result narrowed the possible mass range
- Early days of the LHC → mass window narrowed down to 115 – 130 GeV

Discovery

- LHC launch: September, 2008
- First collisions: March 30, 2010
- Discovery: July 4, 2012 →

- Discovered by the **ATLAS** and **CMS** experiments



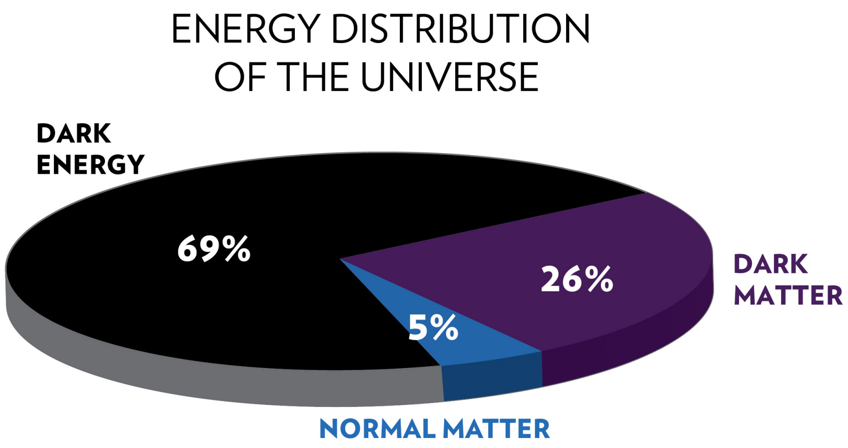


Nobel Prize in Physics 2013

What Now?

So far so good:
- Since the discovery, more data was accumulated
- Everything points the Higgs boson being consistent with the SM

Still, many unanswered questions:
- What explains the Higgs mass at 125.35 GeV?
- Are there more Higgs bosons?
- Is it connected to Dark Matter?
- Where is all the antimatter in the universe?



Thank you for your attention!