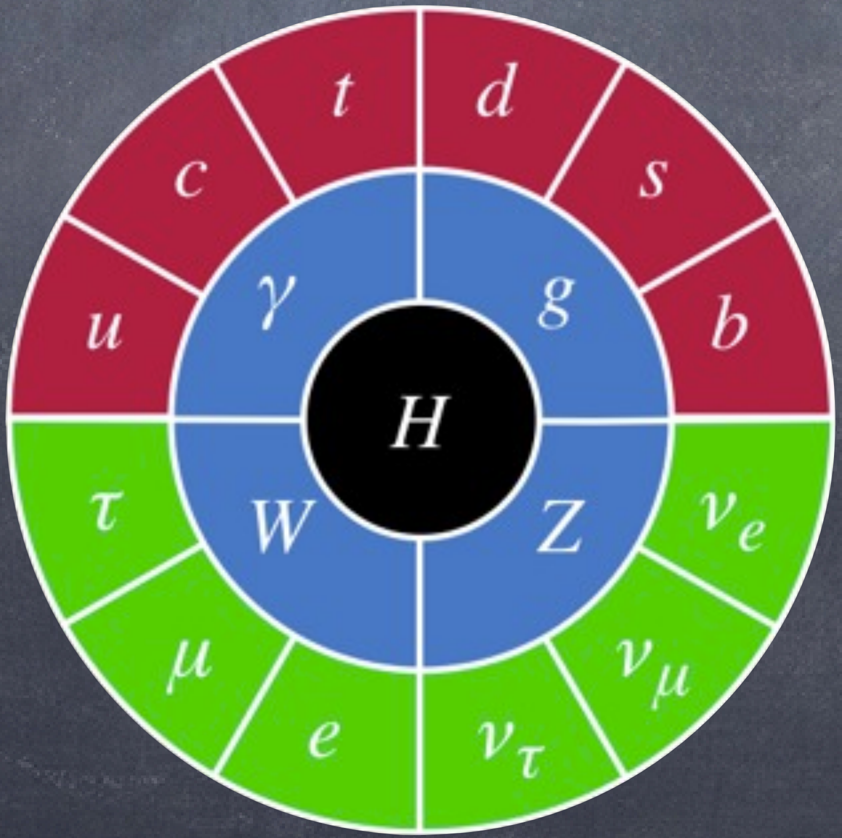
Adam Falkowski

Introduction to Physics beyond the Standard Model

Part 1: The Standard Model

Osaka, 15 May 2014



What is the Standard Model?

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

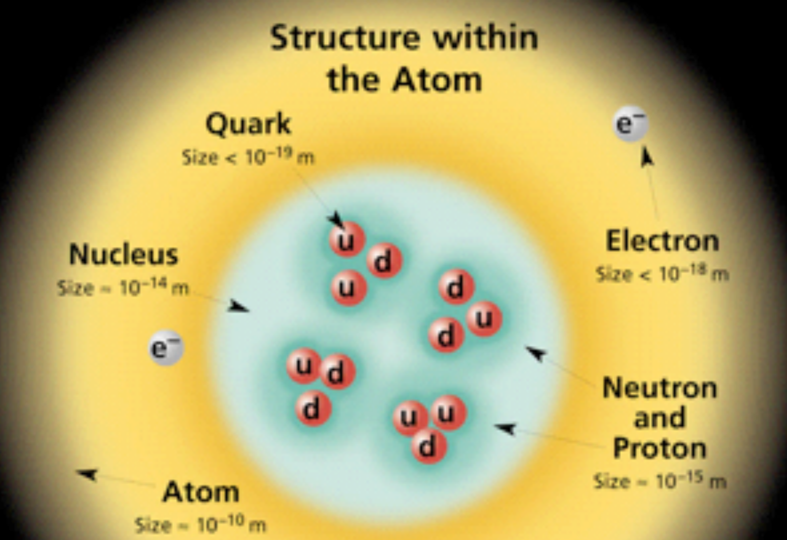
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $= 1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

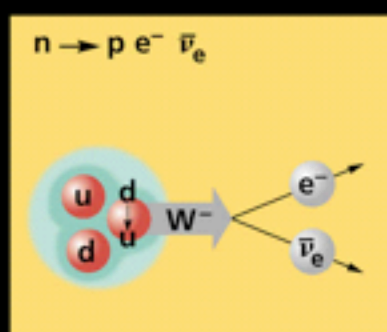
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Matter and Antimatter

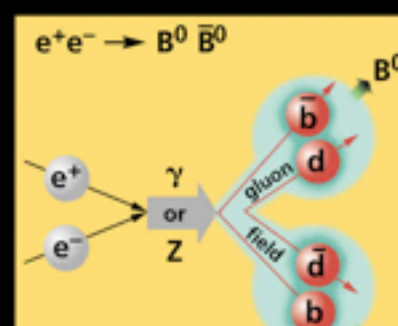
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

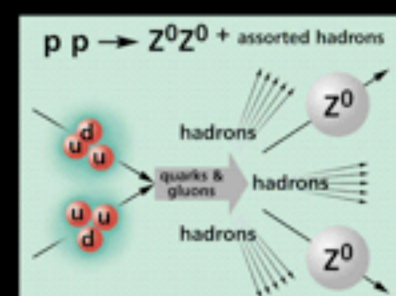
These diagrams are an artist's conception of physical processes. They are *not* exact and have *no* meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at
http://ParticleAdventure.org

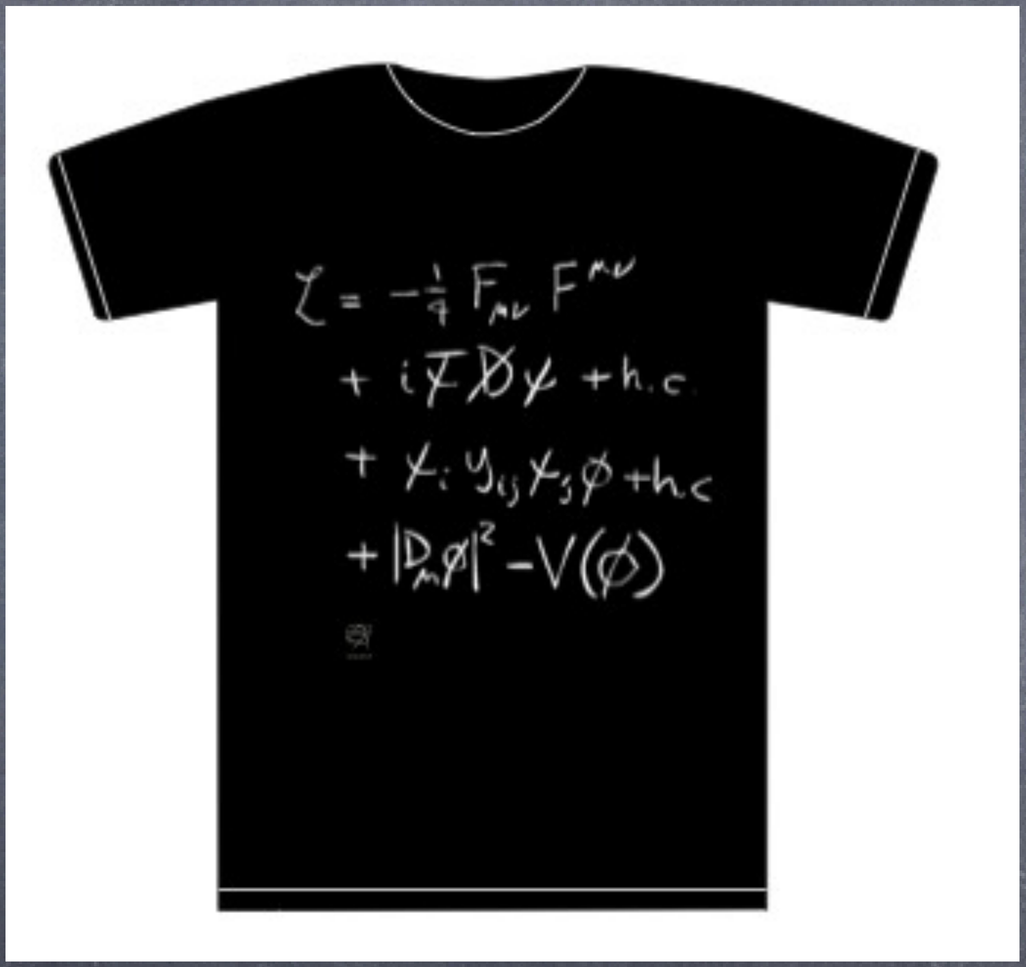
This chart has been made possible by the generous support of:
U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.

CPEP is a non-profit organization of teachers, physicists, and educators. Send mail to: CPEP, MS 50-308, Lawrence Berkeley National Laboratory, Berkeley, CA, 94720. For information on charts, text materials, hands-on classroom activities, and workshops, see:

http://CPEPweb.org

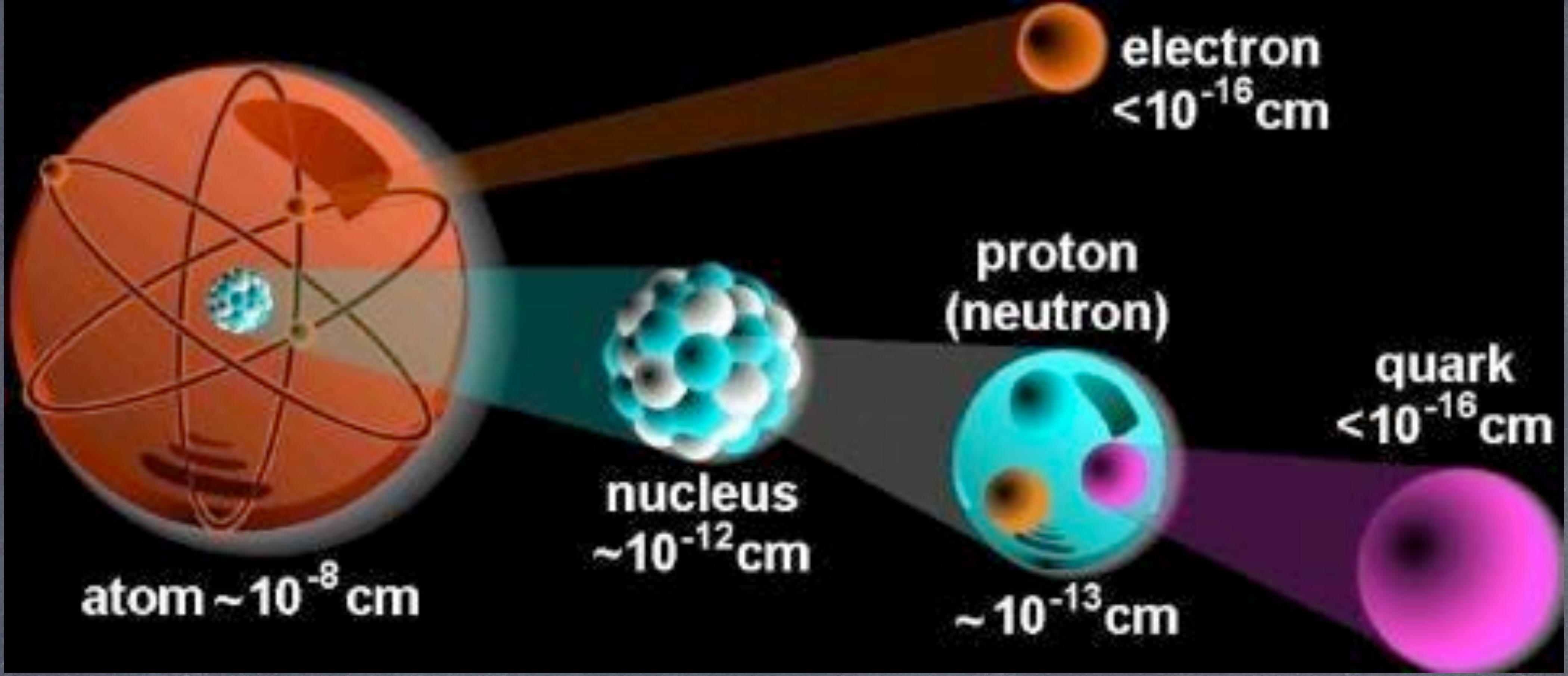
What is the Standard Model

A fundamental theory that describes almost all phenomena that humans have ever observed...



...yet so simple it fits into a T-shirt :)

Where does the Standard Model theory can be applied?



- In theory, everywhere
- In practice, to describe the smallest known components of matter: quarks, electrons, etc.
- For larger objects, we rather use effective theories that can be derived from the SM. But in some cases SM may be useful for precision calculations

How do we construct the Standard Model?

Standard Model Lagrangian

$$\mathcal{L}_{\rm SM} = -\frac{1}{2}{\rm Tr}F^2 + i\bar{\psi}\bar{\sigma}D\psi - (\psi Y\psi H + {\rm h.c.}) + |DH|^2 + m_H^2|H|^2 - \lambda|H|^4$$

Framework

- Quantum theory with manifest invariance under Lorentz transformations, a.k.a. relativistic quantum field theory
- Particles described by fields with definite transformation properties under Lorentz transformations Λ fixed by particle's spin
- Interactions are described through a Lorentz invariant Lagrangian. The Lagrangian has to be Hermitian to preserve unitarity.

Standard Principles

In addition to Lorentz invariance

- Invariance under local symmetry SU(3)xSU(2)xU(1)
- Renormalizability
- Spontaneous symmetry breaking

Gauge Invariance

- Invariance under local symmetry, that is a different symmetry transformation at every space-time point
- In practice, it strongly constrains the structure of particle interactions
- For each symmetry generator there has to be a vector field interacting with the particle charged under local symmetry
- This vector field cannot have mass terms in the Lagrangian which leads to the appearance of a long range force

Gauge Invariance

$$\mathcal{L}_G = -\frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} - \frac{1}{4}W^i_{\mu\nu}W^{i\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

$$G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu + g_s f_{abc} G^b_\mu G^c_\nu$$

$$W^i_{\mu\nu} = \partial_\mu W^i_\nu - \partial_\nu W^i_\mu + g\epsilon_{ijk} W^j_\mu W^k_\nu$$

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

Slide borrowed from Y. Gao

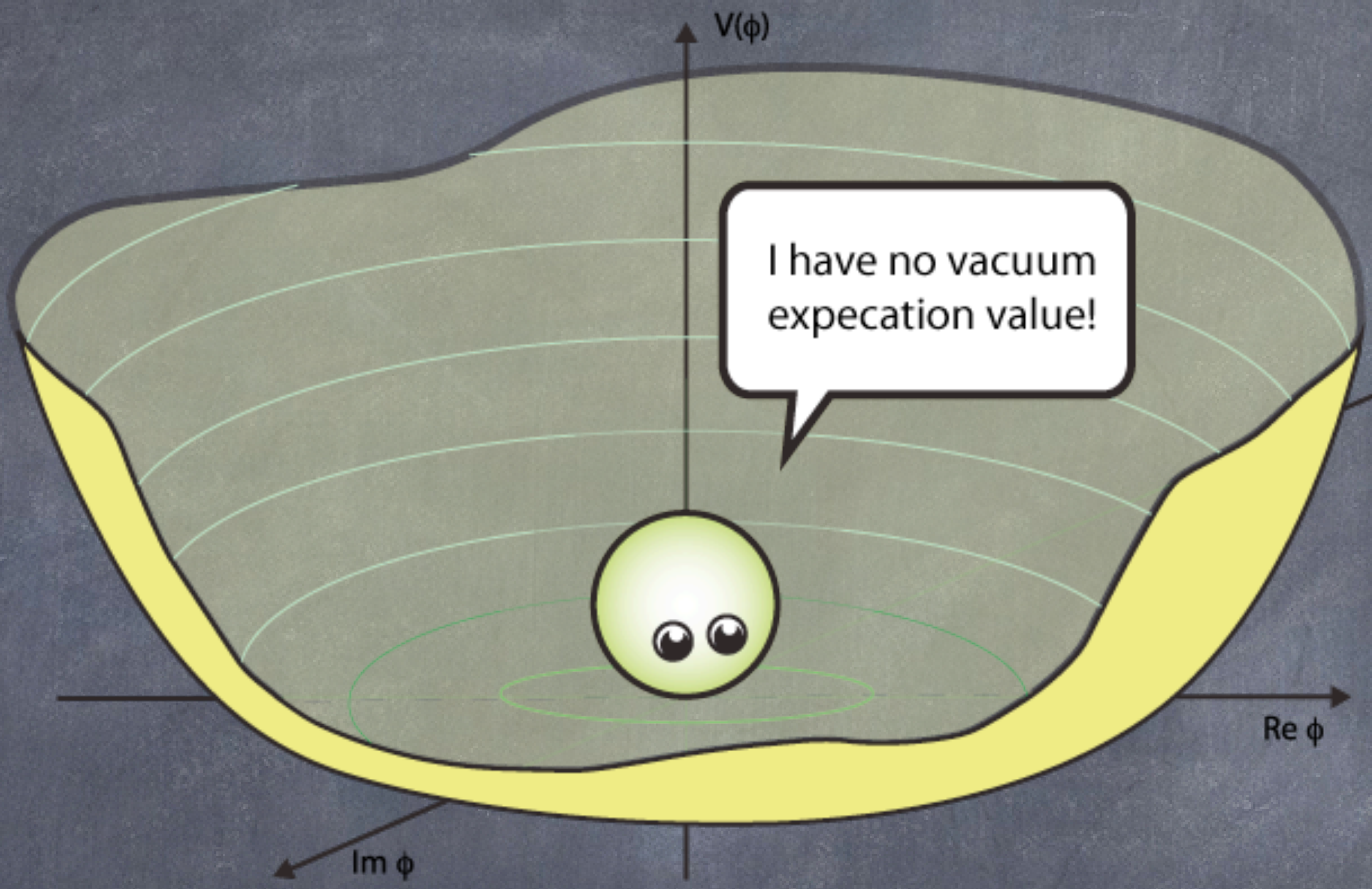
Renormalizability

- Only contact interactions allowed are those with a small enough number of particles
- The exact criterion is the dimension of the interaction term, given the canonical dimensions of fields
- Renormalizability implies that theory is predictive with infinite precision: all observables can be expressed via a finite numbers of parameters

Spontaneous symmetry breaking

- A symmetry of the Lagrangian is not a symmetry of the particle spectrum and their interactions
- Vacuum state does not respect symmetry
- (Anderson-)Brout-Englert-Higgs mechanism to give masses to spin-1 particles and get rid of unwanted massless particles

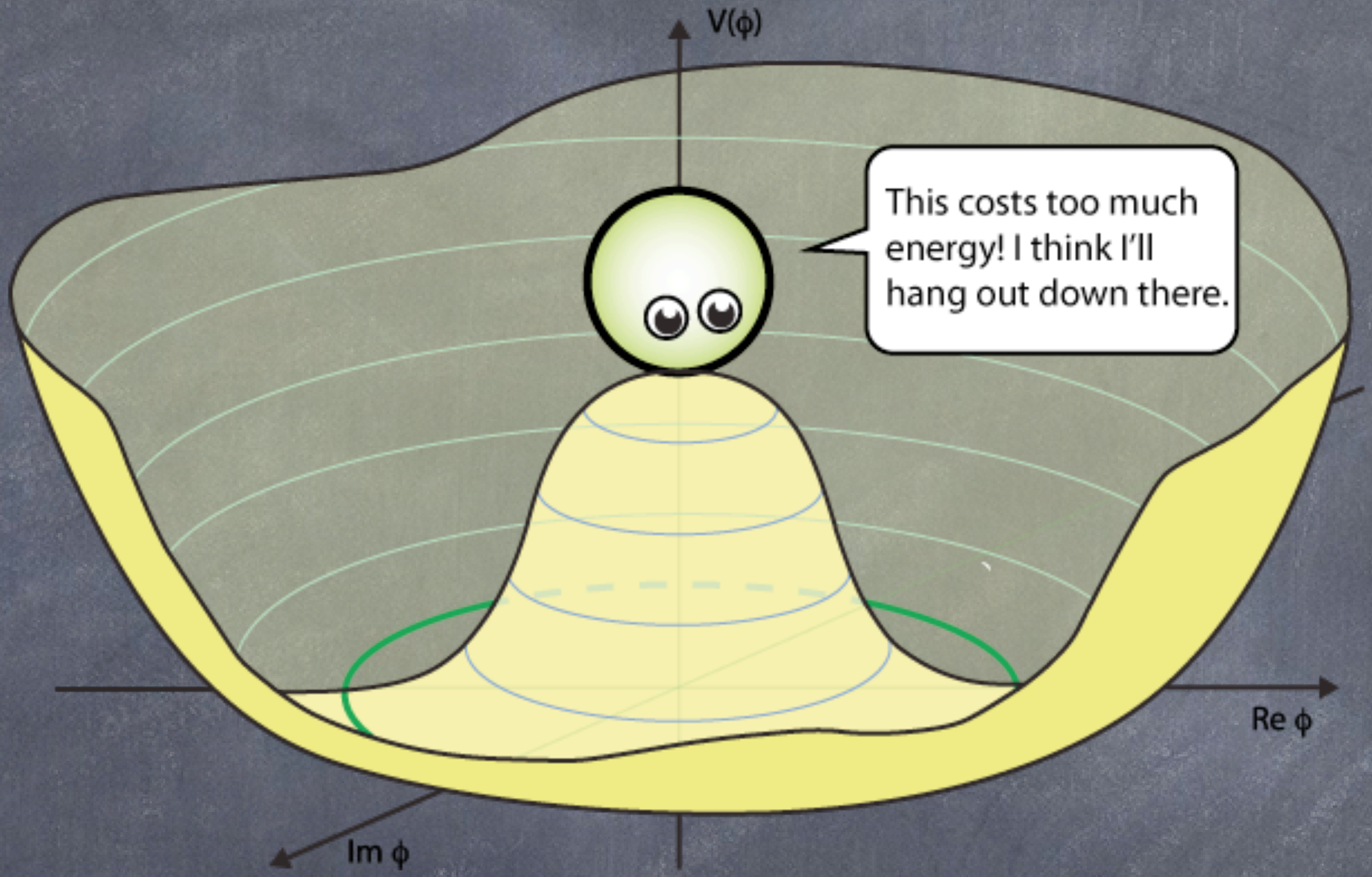
Spontaneous symmetry breaking



Pictures borrowed from Flip Tanedo

http://www.quantumdiaries.org

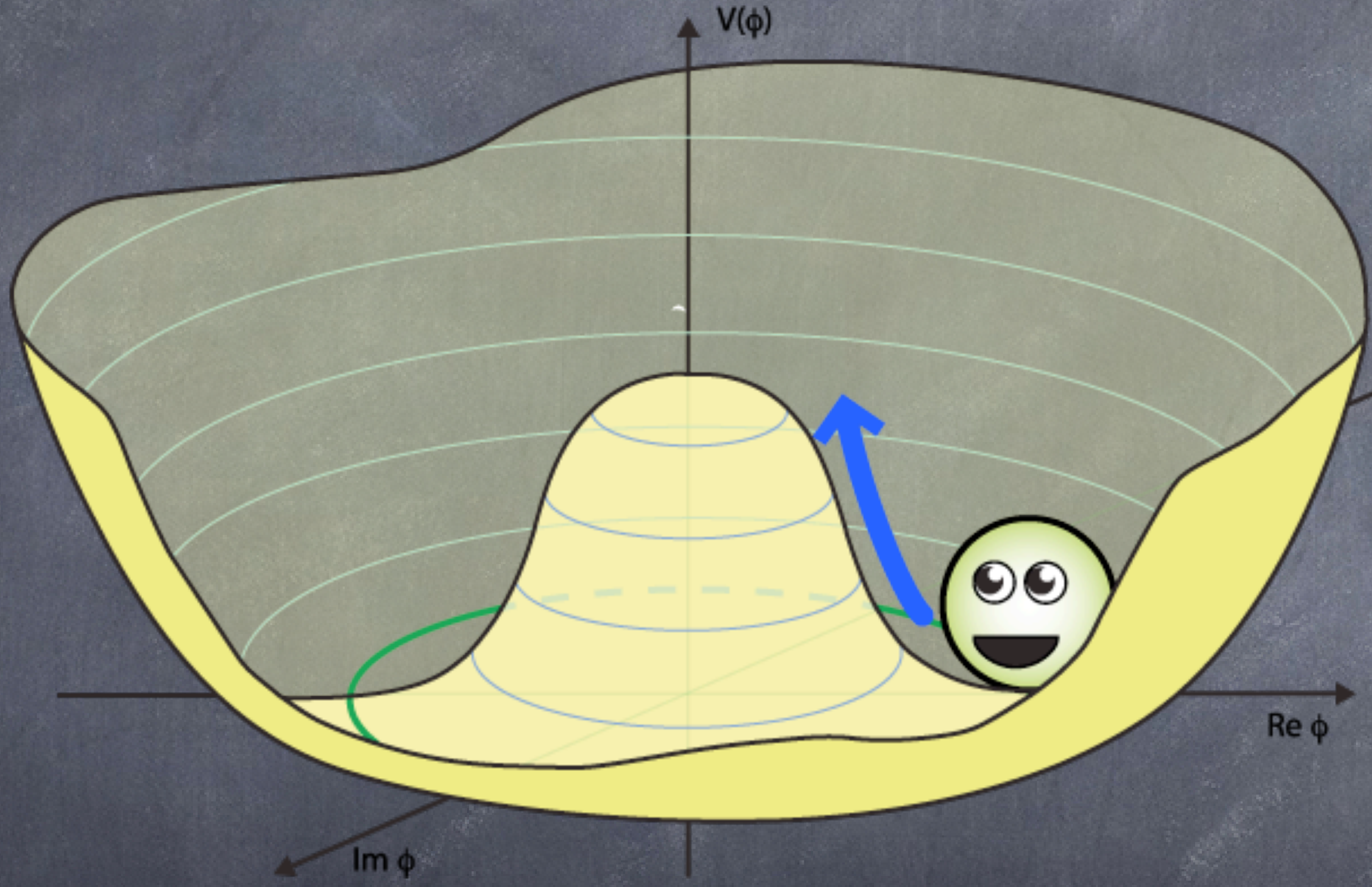
Spontaneous symmetry breaking



Pictures borrowed from Flip Tanedo

http://www.quantumdiaries.org

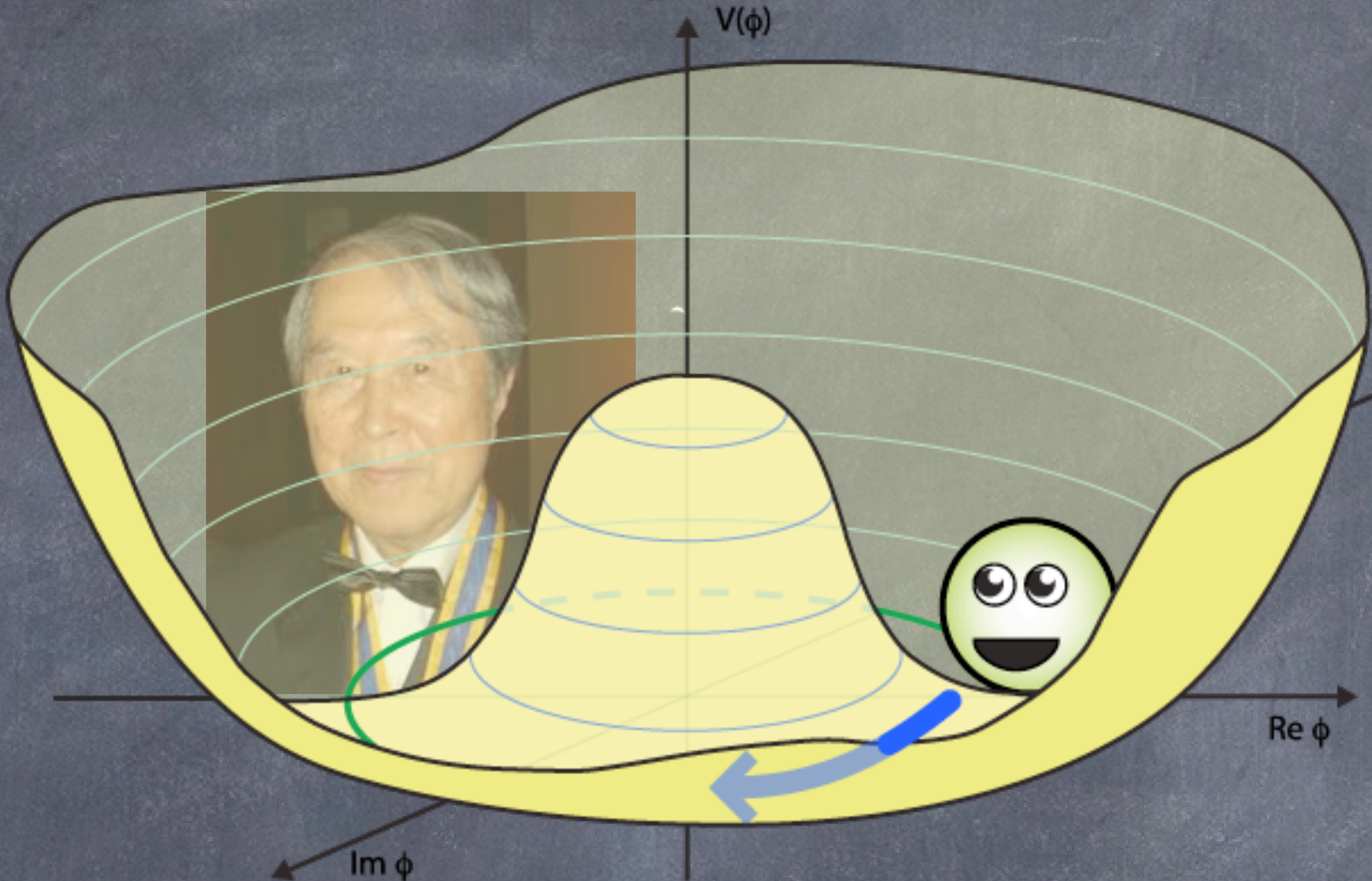
Spontaneous symmetry breaking



Pictures borrowed from Flip Tanedo

http://www.quantumdiaries.org

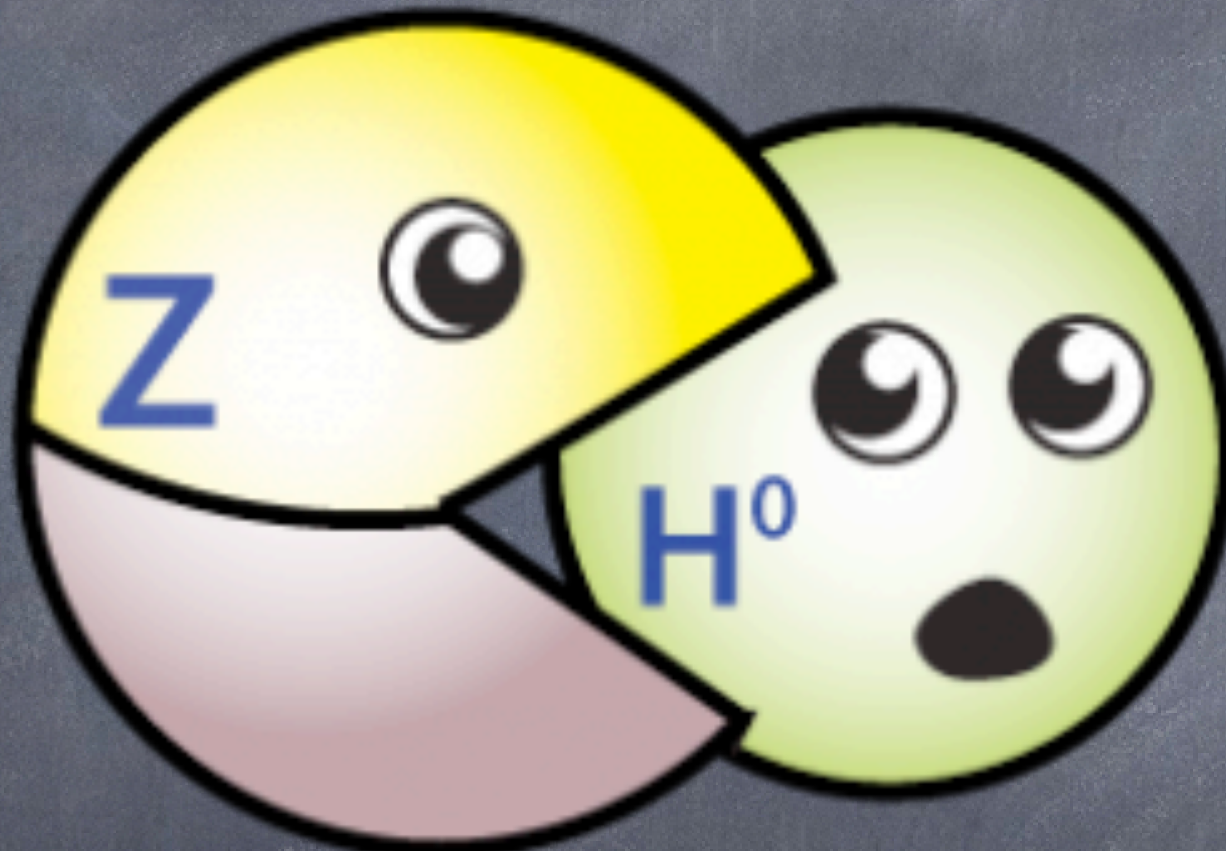
Spontaneous symmetry breaking



Pictures borrowed from Flip Tanedo

http://www.quantumdiaries.org

Spontaneous symmetry breaking



Pictures borrowed from Flip Tanedo
http://www.quantumdiaries.org

Spontaneous symmetry breaking

- In SM Higgs field breaks the SU(3)xSU(2)xU(1) local symmetry down to SU(3)xU(1) symmetry
- W and Z boson acquire masses, while photon and gluon remain massless

$$W^{\pm}_{\mu} \equiv \frac{1}{\sqrt{2}}\left(W^{1}_{\mu} \mp iW^{2}_{\mu}\right)$$

$$Z_{\mu} \equiv \cos\theta_W W^{3}_{\mu} - \sin\theta_W B_{\mu}$$

$$A_{\mu} \equiv \sin\theta_W W^{3}_{\mu} + \cos\theta_W B_{\mu}$$

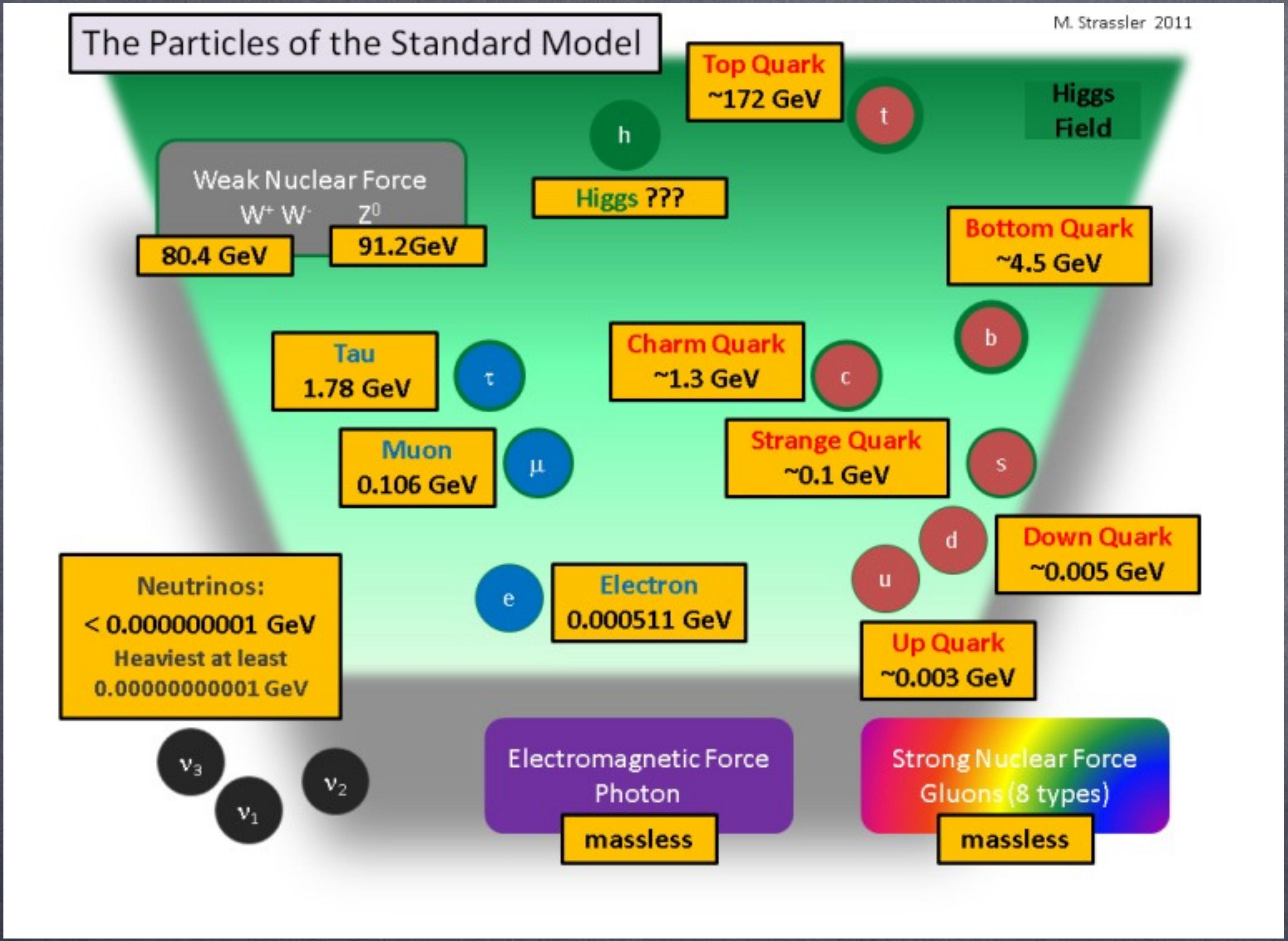
$$\tan\theta_W \equiv \frac{g'}{g}$$

$$e \equiv g\sin\theta_W$$

$$\rightarrow \quad M^2_W = \frac{1}{4}g^2\upsilon^2, \quad M^2_Z = M^2_W \Big/ \cos^2\theta_W, \quad M^2_A = 0$$

Slide borrowed from Y. Gao

What are the particles in the Standard Model?



Borrowed from Matt Strassler blog:
http://profmattstrassler.com/

Particle Physics Units

SI Units

$$h = 6.415 \cdot 10^{-27} \frac{g \cdot cm^2}{\text{sec}} = 6.415 \cdot 10^{-34} \frac{kg \cdot m^2}{\text{sec}}$$

$$k = 1.340 \cdot 10^{-16} \frac{g \cdot cm^2}{\text{sec}^2 \cdot \text{deg}} = 1.340 \cdot 10^{-23} \frac{kg \cdot m^2}{\text{sec}^2 \cdot \text{deg}}$$

$$c = 3 \cdot 10^{10} \frac{cm}{\text{sec}} = 3 \cdot 10^{8} \frac{m}{\text{sec}}$$

$$G = 6.685 \cdot 10^{-8} \frac{cm^3}{g \cdot \text{sec}^2} = 6.685 \cdot 10^{-11} \frac{m^3}{kg \cdot \text{sec}^2}$$

Natural Units

$$\hbar = 1$$

$$c = 1$$

Then mass, distance, time, energy can be measured in the same units

Particle Physics Units

Silly basic unit choice in particle physics

$$1\ \mathrm{GeV} = 1.60217657 \times 10^{-10}\ \mathrm{Joule}$$

In natural units

$$1\ \mathrm{GeV} = 1.78 \times 10^{-27}\ \mathrm{kg}$$

$$1\ \mathrm{GeV} = 1.52 \times 10^{24}\ \mathrm{sec}^{-1}$$

$$1\ \mathrm{GeV} = 5.07 \times 10^{15}\ \mathrm{m}^{-1}$$

Building Blocks

- 6 spinor pairs spinors for each quark q = d,u,s,c,b,t
- 3 pairs of spinors for each charged lepton l = e,μ,τ
- 3 spinors for each neutrino
- 8 vectors for a gluon
- 3 vectors for weak gauge bosons
- 1 vector for the photon
- 1 scalar for the Higgs boson

Quantum numbers of SM fermions

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
$q = \begin{pmatrix} u \\ d \end{pmatrix}$	$\mathbf{3}$	$\mathbf{2}$	1/6
u^c	$\bar{\mathbf{3}}$	$\mathbf{1}$	-2/3
d^c	$\bar{\mathbf{3}}$	$\mathbf{1}$	1/3
$l = \begin{pmatrix} \nu \\ e \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	-1/2
e^c	$\mathbf{1}$	$\mathbf{1}$	1

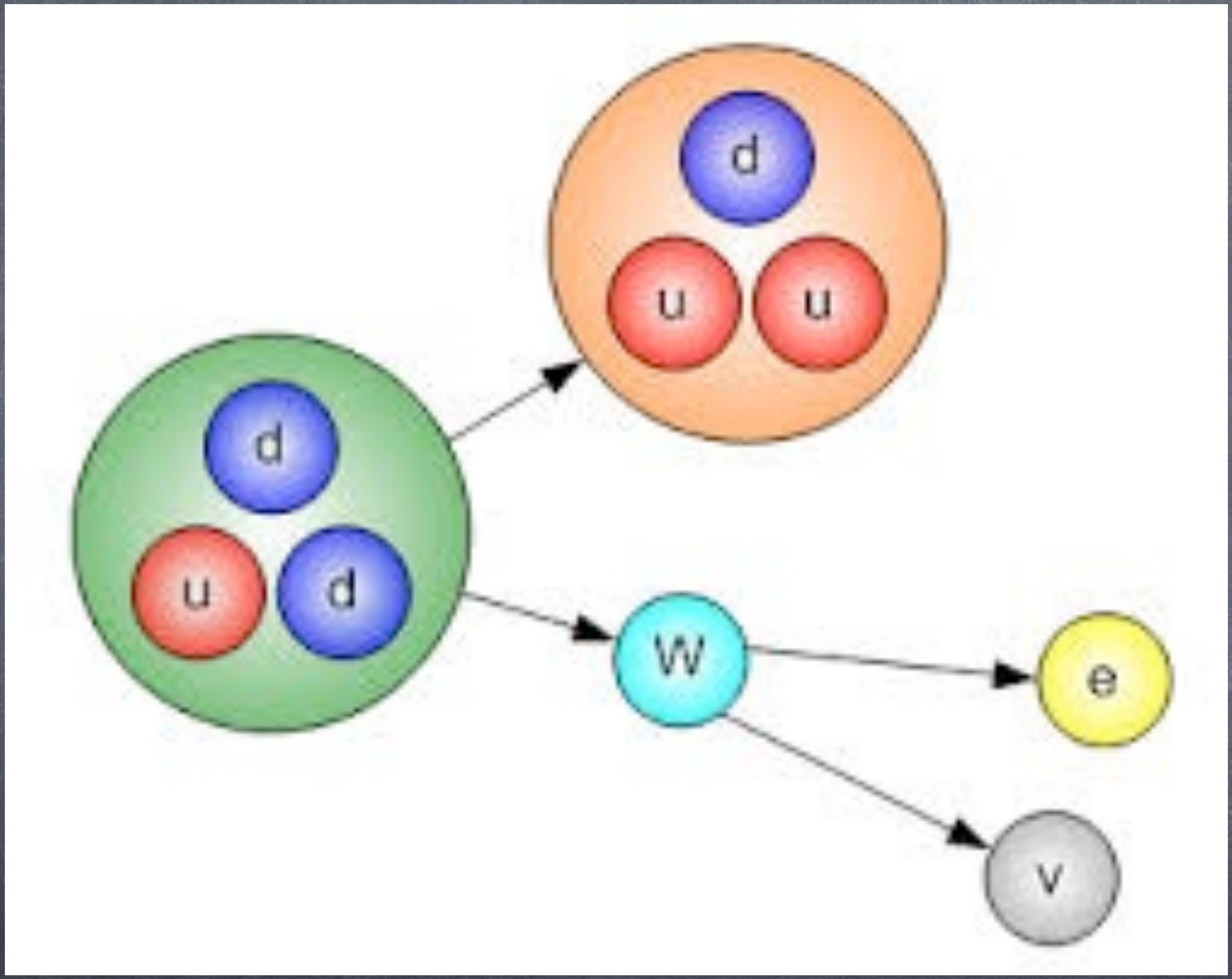
Standard Model Lagrangian

$$\mathcal{L}_{\rm SM} = -\frac{1}{2}{\rm Tr}F^2 + i\bar{\psi}\bar{\sigma}D\psi$$
$$-(\psi Y\psi H + {\rm h.c.})$$
$$+|DH|^2 + m_H^2|H|^2 - \lambda|H|^4$$

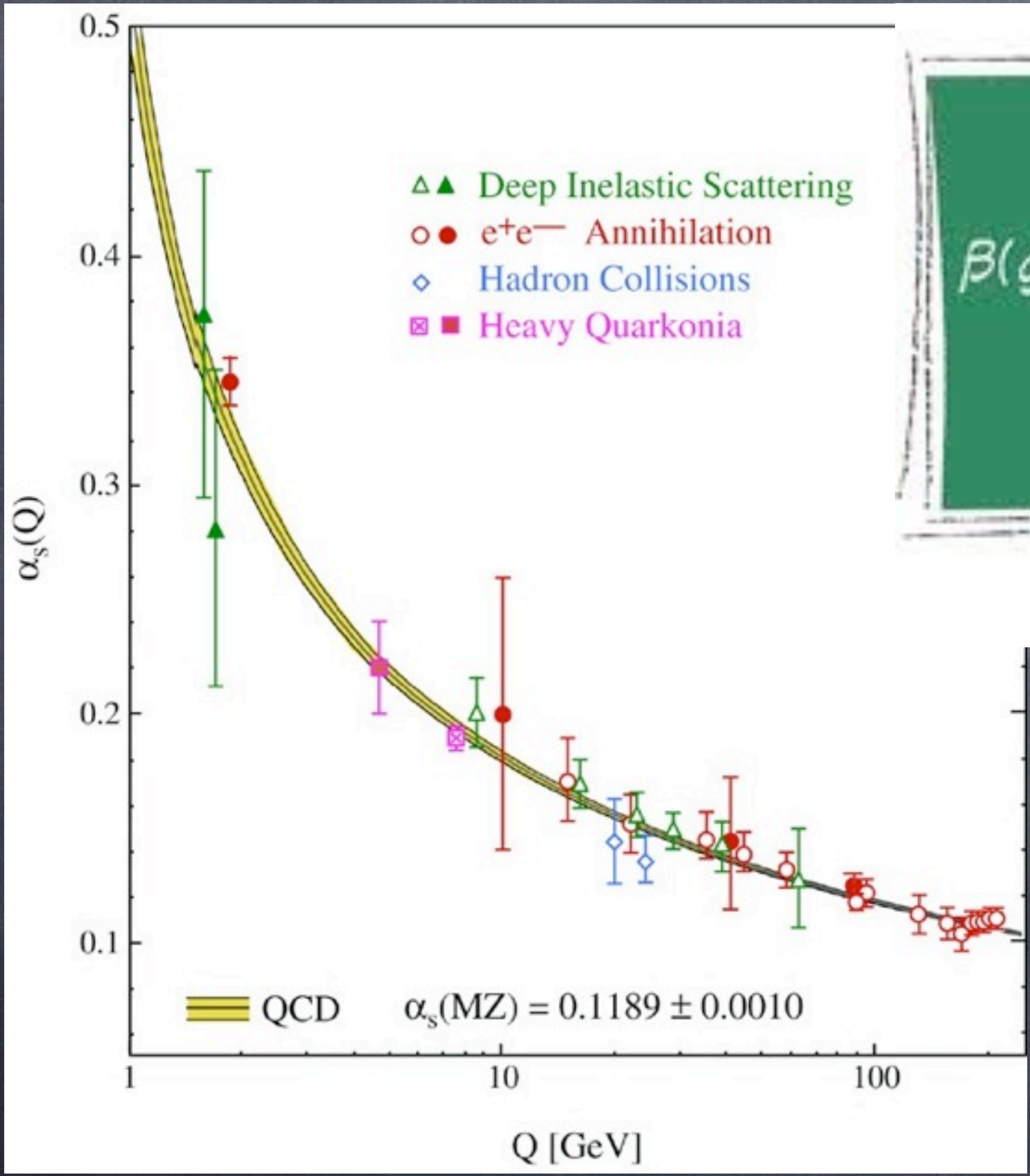
Direct Consequences

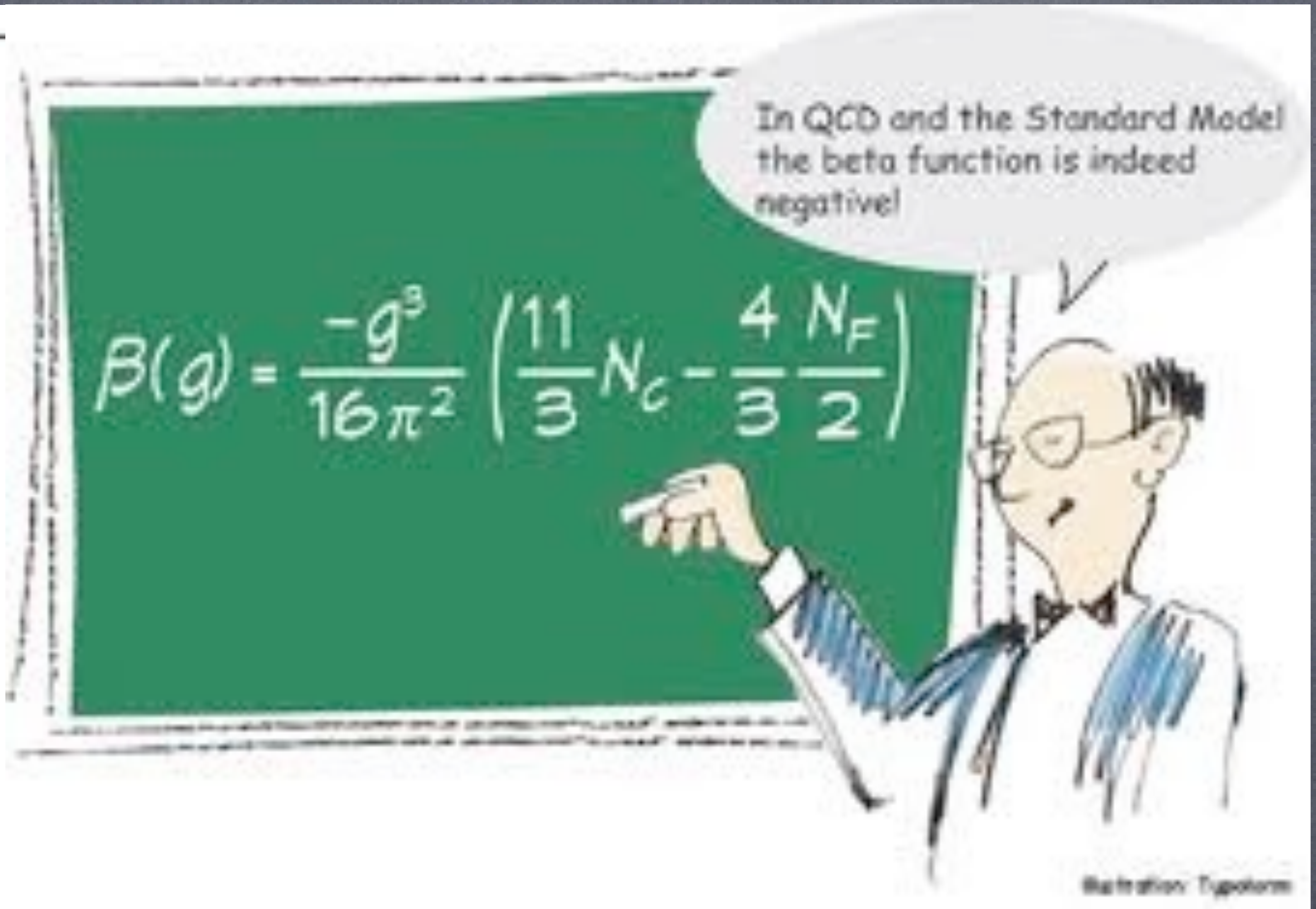
- Long range force known as electromagnetic interactions
- Short range force known as weak interactions
- Strong force leading to emergence of composite objects made of quarks
- Baryon and lepton number conservation
- Mixing of quarks but no mixing of leptons
- Observable C, P, and CP violation
- Existence of a fundamental scalar particle called the Higgs boson (a new short range

Weak Force

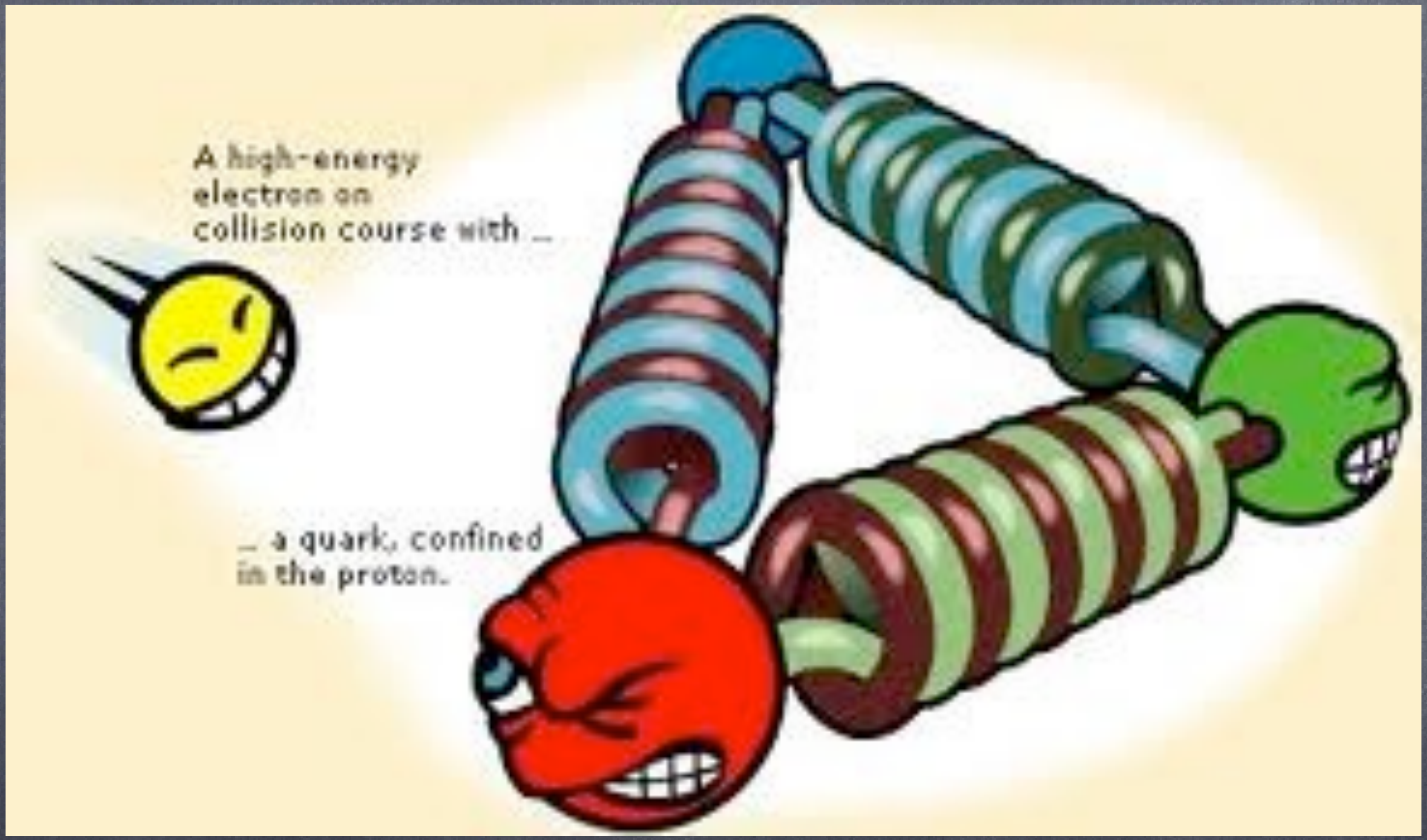


Running of the Strong Coupling

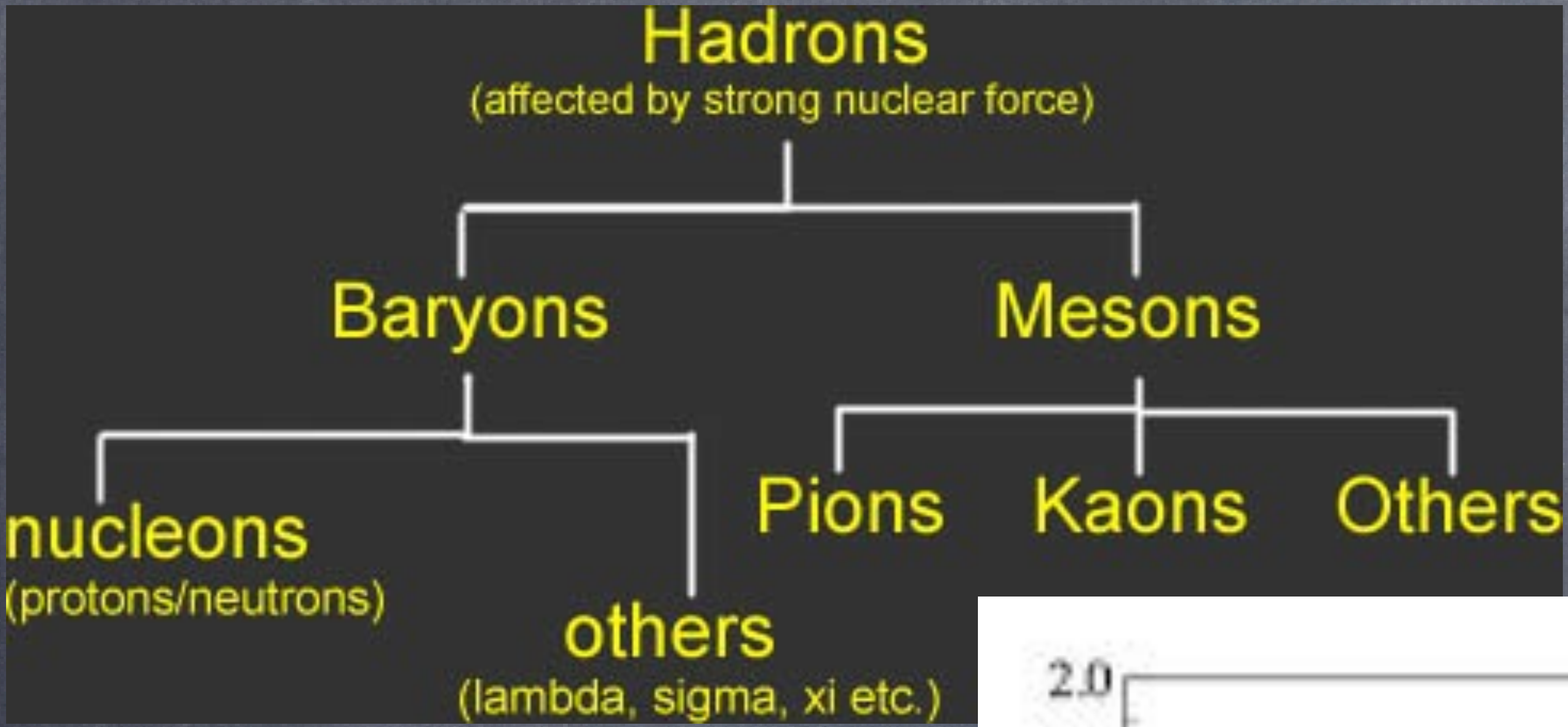


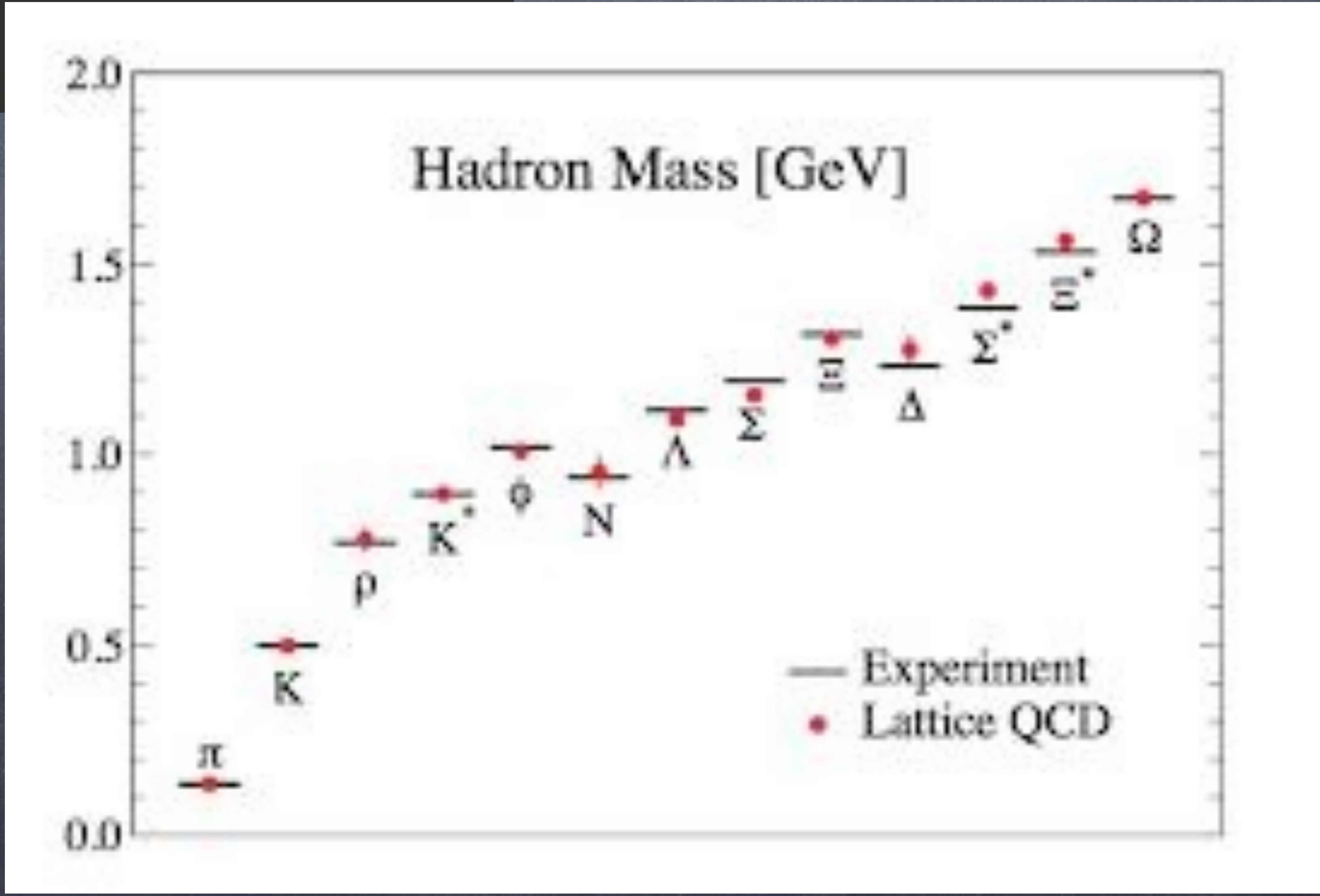


Confinement of strongly interacting particles

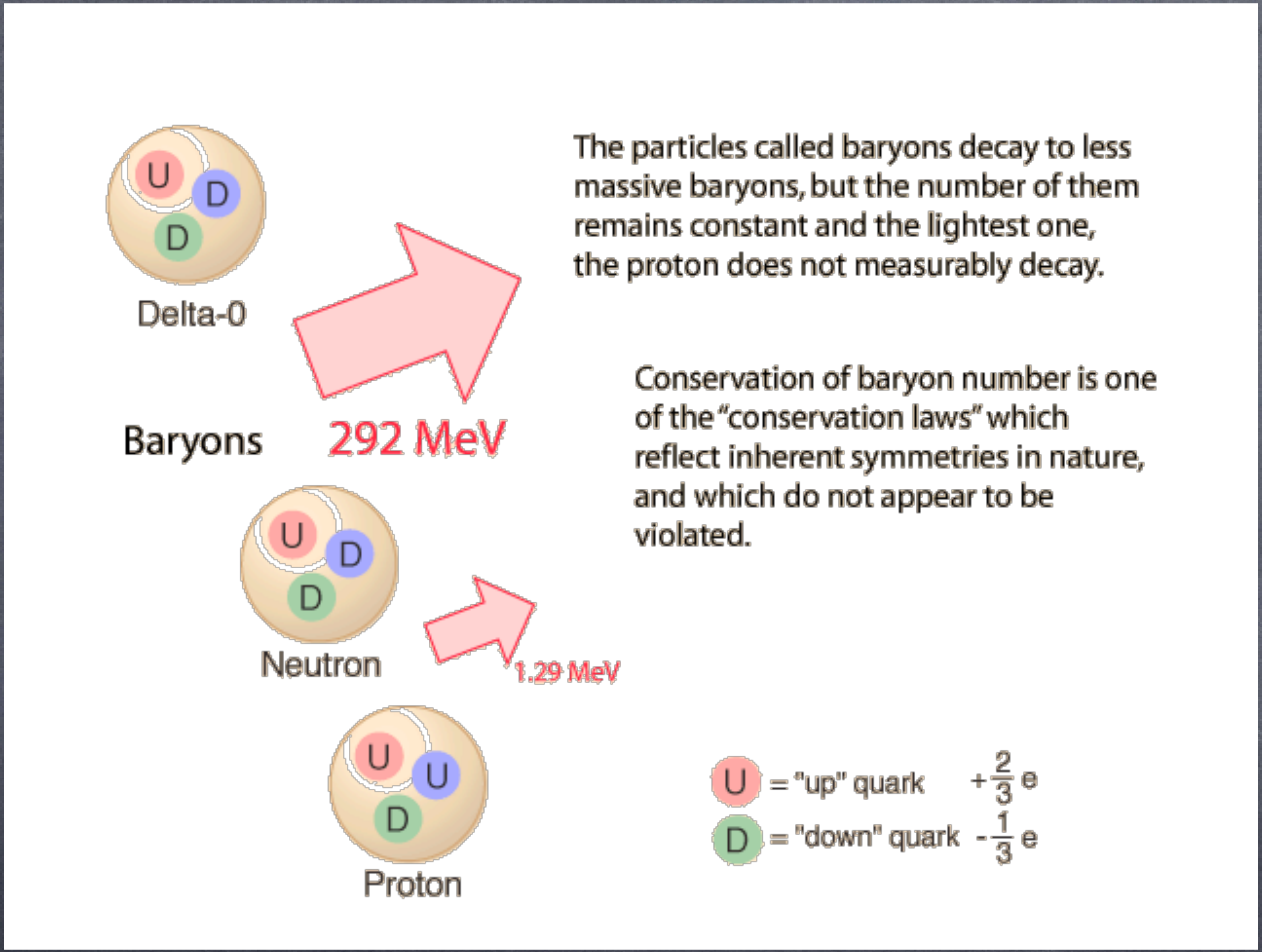


Confinement of strongly interacting particles



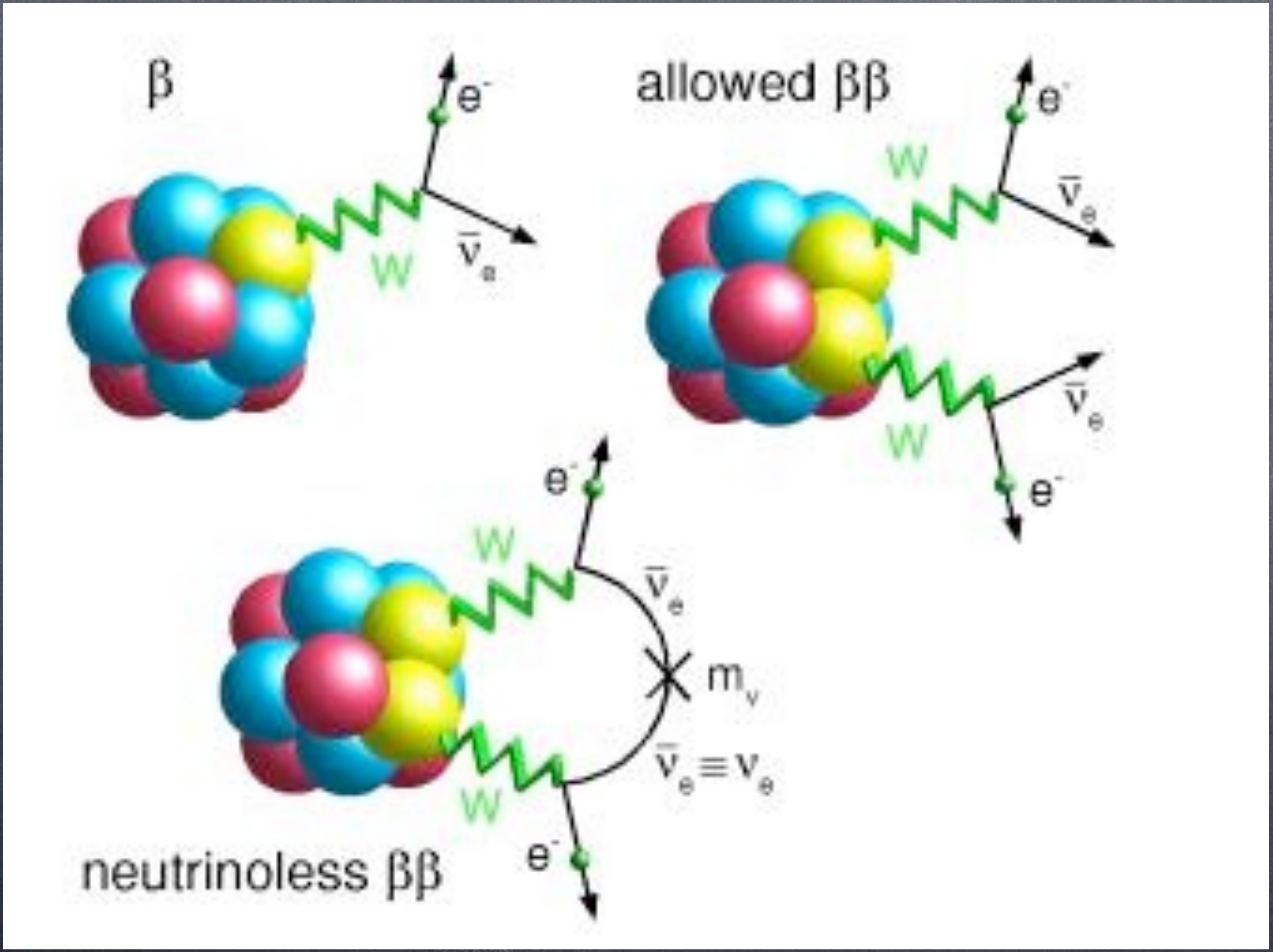


Baryon number conservation



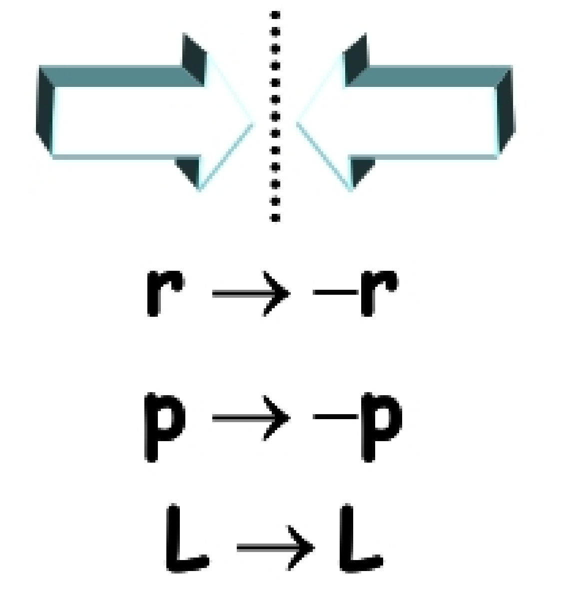
Borrowed from http://hyperphysics.phy-astr.gsu.edu

Lepton number conservation

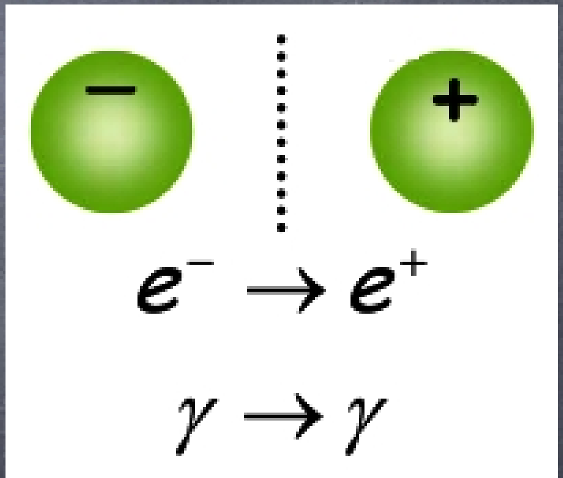


Discrete spacetime symmetries

- Parity changes sign of spatial coordinates, and all vectors (not pseudo-vectors). For spin 1 and 1/2 relates opposite helicities



- Charge conjugation changes particle into anti-particle with the same helicity



- What really makes difference between matter and anti-matter is the CP symmetry

Graphics borrowed from Marcela Bona's lectures

Quark mixing

- No symmetry reason for Yukawa couplings to be diagonal
- After Higgs gets vacuum expectation values this leads to non-diagonal mass matrix for quarks and leptons
- Via unitary rotation we can choose the new basis of quarks and leptons such that masses are diagonal, at the price of flavor non-diagonal interactions of the quarks with the W boson

CP violation and quark mixing

$$\mathcal{L}_{\rm CC} = -\frac{g}{\sqrt{2}}\left(\bar{\tilde{U}}_L \gamma^\mu W_\mu^+ V \tilde{D}_L + \bar{\tilde{D}}_L \gamma^\mu W_\mu^- V^\dagger \tilde{U}_L\right).$$

CKM matrix

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Graphics borrowed from Marcela Bona's lectures