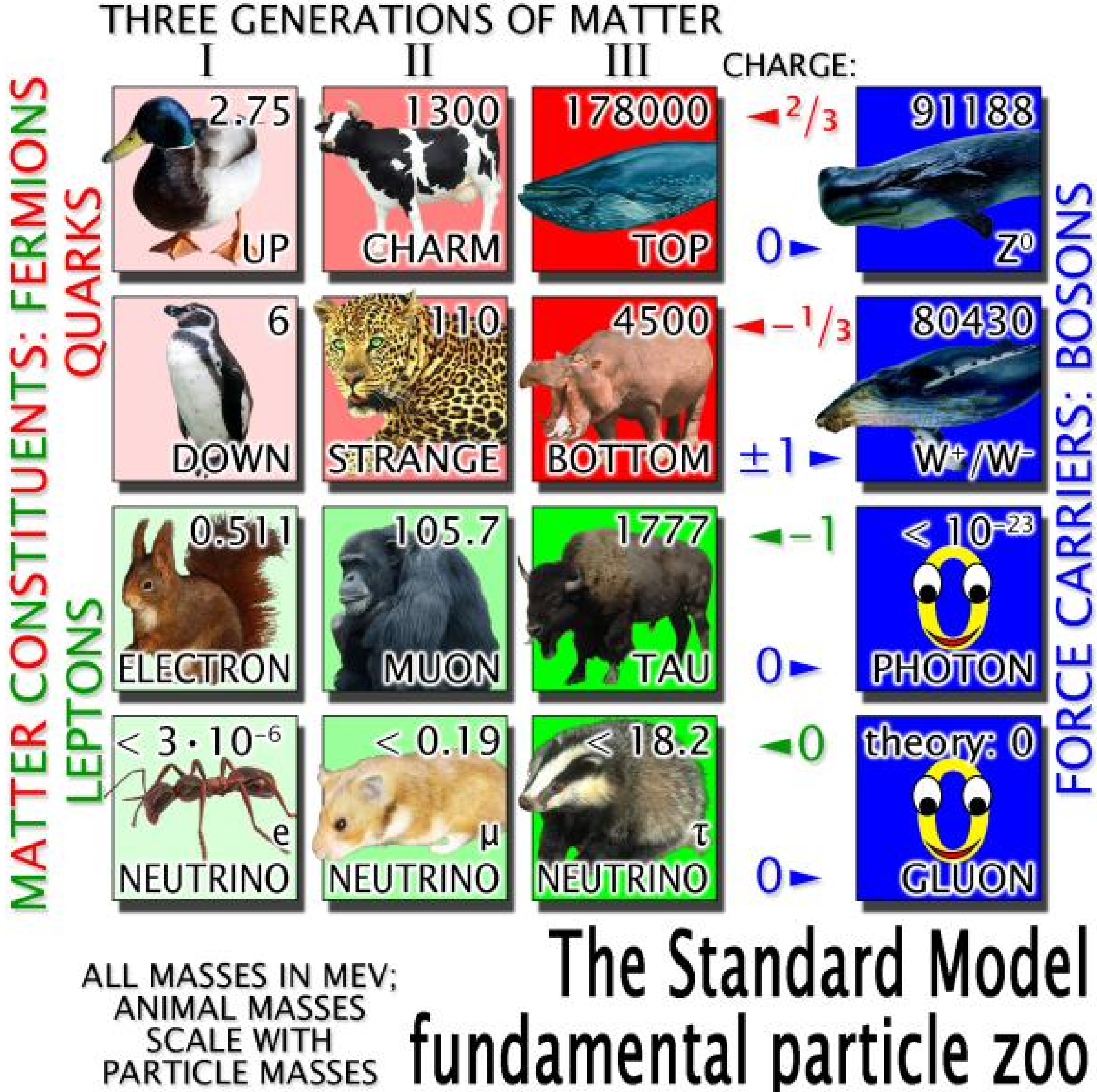
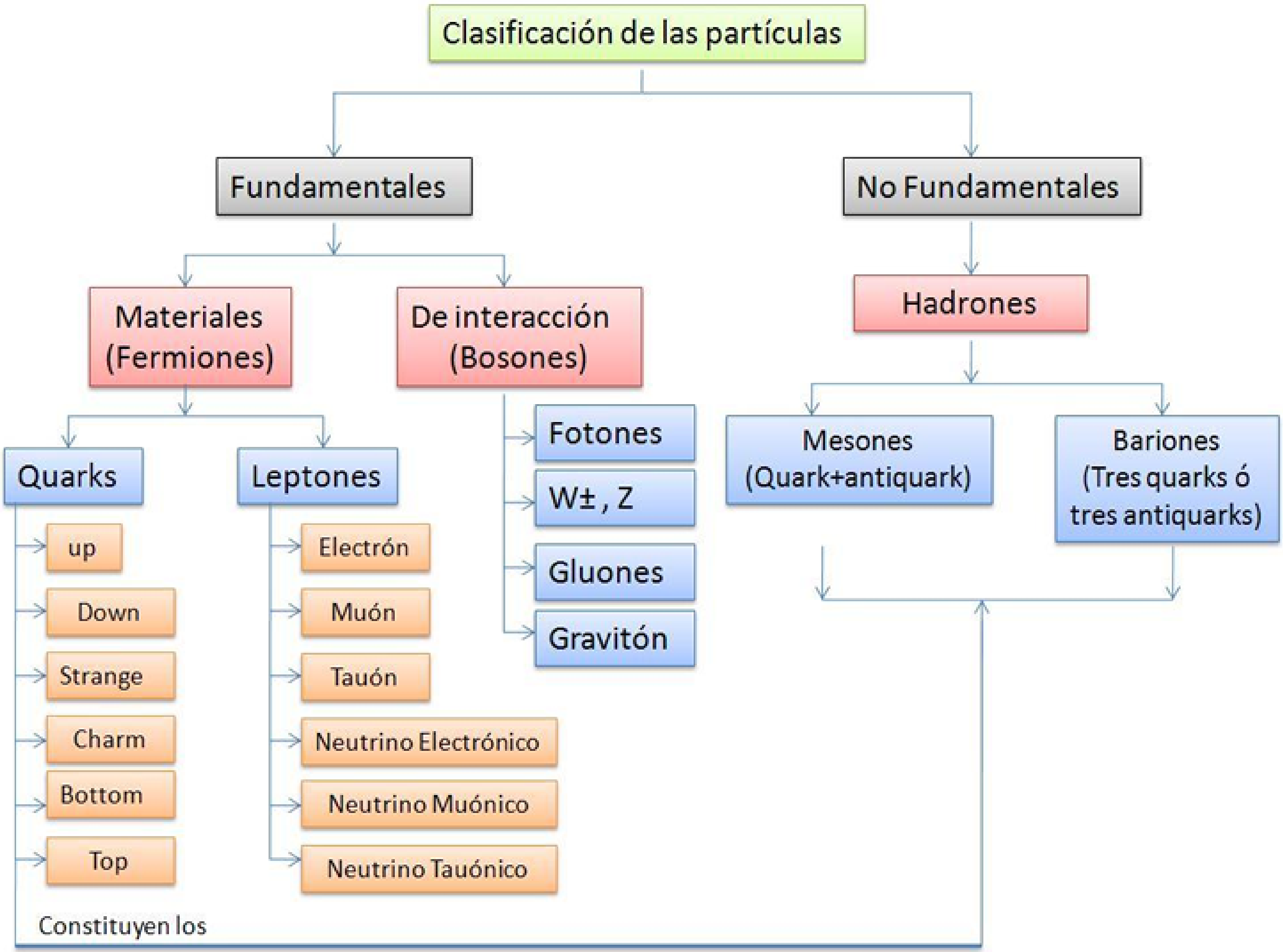
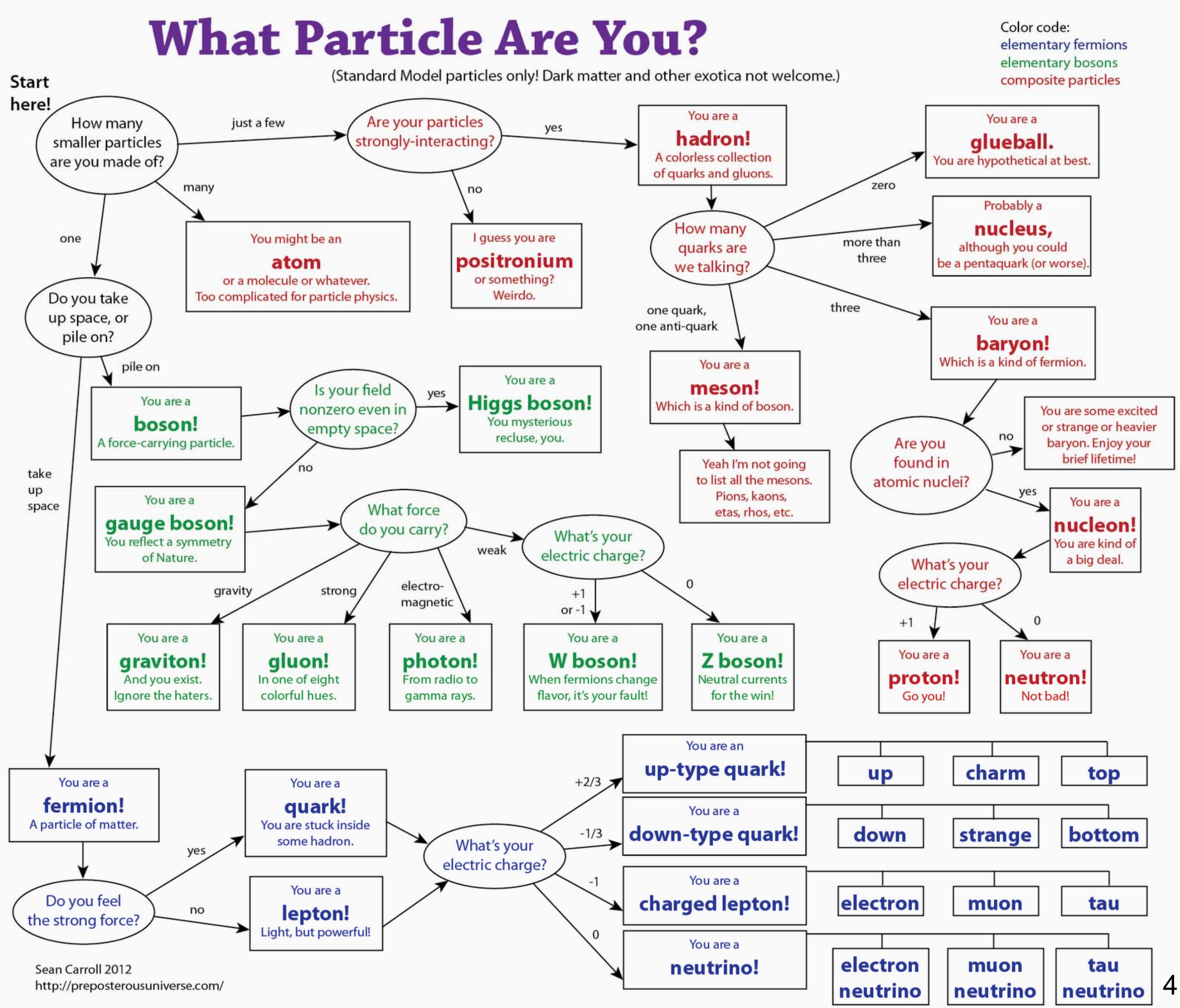
El Modelo Estandar

(Standard Model)


THREE GENERATIONS OF MATTER
I
II
III
CHARGE:
MATTER CONSTITUENTS: FERMIONS
QUARKS
LEPTONS
FORCE CARRIERS: BOSONS
2.75
UP
1300
CHARM
178000
TOP
2/3
0
91188
Z0
6
DOWN
110
STRANGE
4500
BOTTOM
−1/3
±1
80430
W+/W−
0.511
ELECTRON
105.7
MUON
1777
TAU
−1
0
< 10−23
PHOTON
< 3·10−6
e
NEUTRINO
< 0.19
μ
NEUTRINO
< 18.2
τ
NEUTRINO
0
0
theory: 0
GLUON
ALL MASSES IN MEV;
ANIMAL MASSES
SCALE WITH
PARTICLE MASSES
The Standard Model
fundamental particle zoo


Clasificación de las partículas
Fundamentales
No Fundamentales
Materiales (Fermiones)
De interacción (Bosones)
Hadrones
Quarks
Leptones
Fotones
W± , Z
Gluones
Gravitón
Mesones (Quark+antiquark)
Bariones (Tres quarks ó tres antiquarks)
up
Down
Strange
Charm
Bottom
Top
Electrón
Muón
Tauón
Neutrino Electrónico
Neutrino Muónico
Neutrino Tauónico
Constituyen los

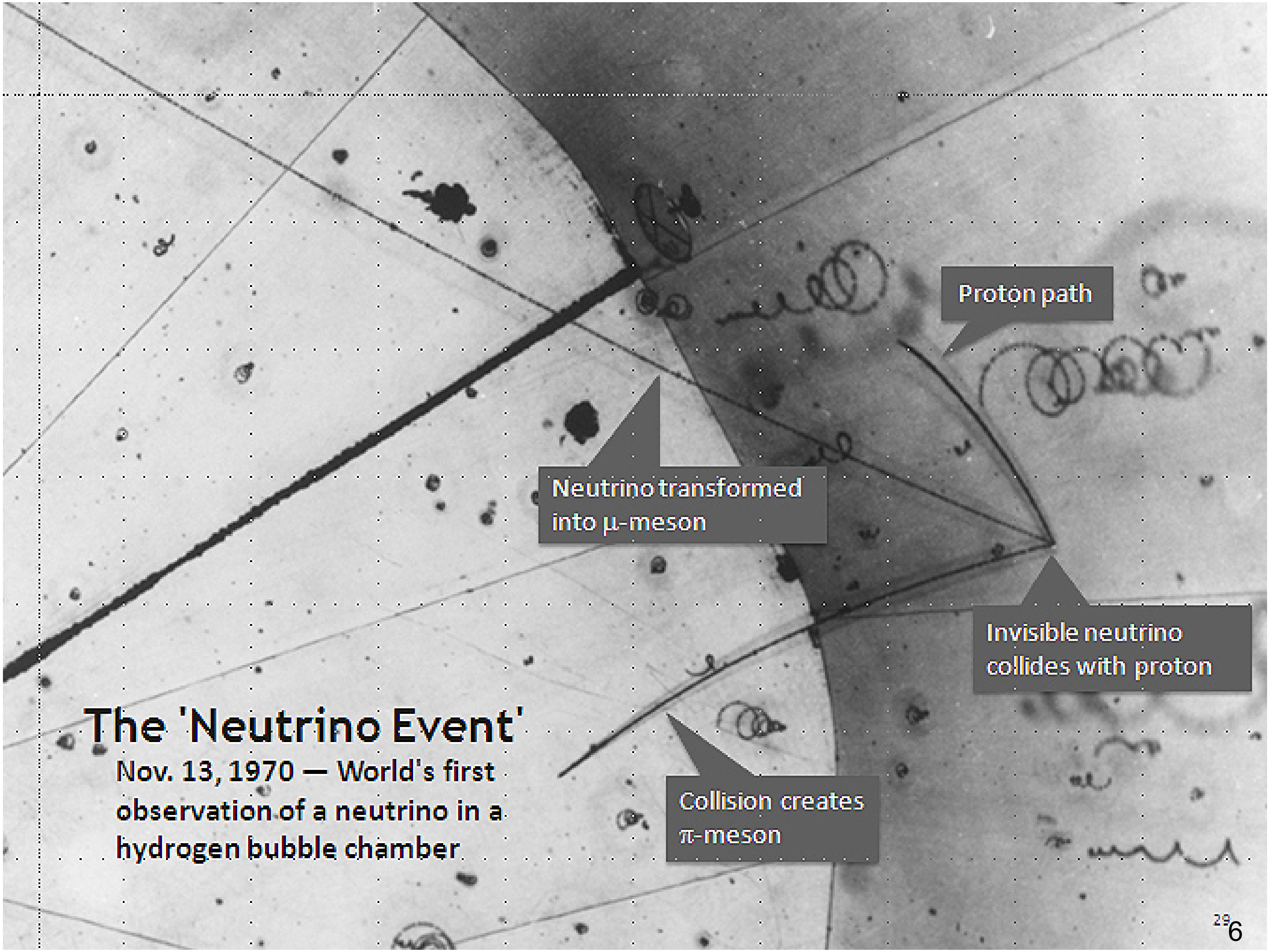


What Particle Are You?
(Standard Model particles only! Dark matter and other exotica not welcome.)
Color code:
elementary fermions
elementary bosons
composite particles
Start here!
How many smaller particles are you made of?
just a few
many
one
Are your particles strongly-interacting?
yes
no
You are a hadron! A colorless collection of quarks and gluons.
You might be an atom or a molecule or whatever. Too complicated for particle physics.
I guess you are positronium or something? Weirdo.
How many quarks are we talking?
zero
more than three
three
one quark, one anti-quark
You are a glueball. You are hypothetical at best.
Probably a nucleus, although you could be a pentaquark (or worse).
You are a baryon! Which is a kind of fermion.
You are a meson! Which is a kind of boson.
Yeah I'm not going to list all the mesons. Pions, kaons, etas, rhos, etc.
Are you found in atomic nuclei?
no
yes
You are some excited or strange or heavier baryon. Enjoy your brief lifetime!
You are a nucleon! You are kind of a big deal.
What's your electric charge?
+1
0
You are a proton! Go you!
You are a neutron! Not bad!
Do you take up space, or pile on?
pile on
take up space
You are a boson! A force-carrying particle.
Is your field nonzero even in empty space?
yes
no
You are a Higgs boson! You mysterious recluse, you.
You are a gauge boson! You reflect a symmetry of Nature.
What force do you carry?
gravity
strong
electro-magnetic
weak
What's your electric charge?
+1 or -1
0
You are a graviton! And you exist. Ignore the haters.
You are a gluon! In one of eight colorful hues.
You are a photon! From radio to gamma rays.
You are a W boson! When fermions change flavor, it's your fault!
You are a Z boson! Neutral currents for the win!
You are a fermion! A particle of matter.
Do you feel the strong force?
yes
no
You are a quark! You are stuck inside some hadron.
You are a lepton! Light, but powerful!
What's your electric charge?
+2/3
-1/3
-1
0
You are an up-type quark!
You are a down-type quark!
You are a charged lepton!
You are a neutrino!
up
charm
top
down
strange
bottom
electron
muon
tau
electron neutrino
muon neutrino
tau neutrino
Sean Carroll 2012
http://preposterousuniverse.com/

Fermiones (estadística Fermi, afecta PE Pauli)

Fermion J=1/2)	Fam 1 2 3	Q (EM)	T_3 (I-h)	Color	m (MeV/c2)	Δm (MeV/c2)	Descubierta en
Leptones	e	-1	-½	0	0.510998928	±0.000000011	1897
	ν_e	0	+½	0	<0.000002		1956
	μ	-1	-½	0	105.6583715	±0.0000035	1937
	ν_μ	0	+½	0	<0.19		1962
	τ	-1	-½	0	1776.82	±0.16	1975
	ν_τ	0	+½	0	<18.2		2000
Quarks	u	+2/3	+½	rgb	2.3	+0.7 −0.5	1969
	d	-1/3	-½	rgb	4.8	+0.7 −0.3	1969
	c	+2/3	+½	rgb	1275	±25	1974
	s	-1/3	-½	rgb	95	±5	1969
	t	+2/3	+½	rgb	173500	±600	1995
	b	-1/3	-½	rgb	4180	±30	1977

http://pdg.lbl.gov/2012/listings/contents_listings.html



The 'Neutrino Event'

Nov. 13, 1970 — World's first observation of a neutrino in a hydrogen bubble chamber

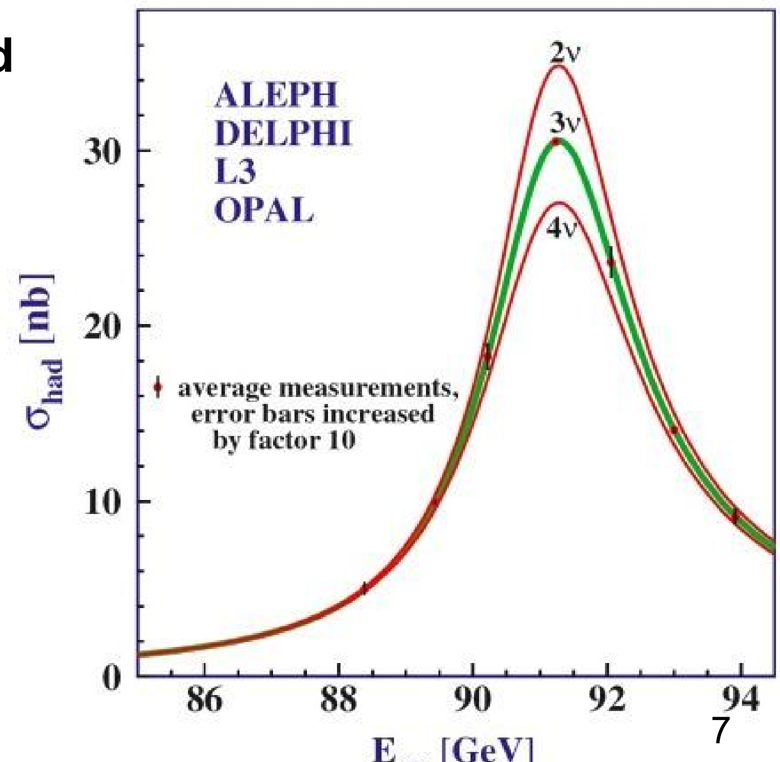
¿Por qué 3 familias?

Conservación de “familias”

$$
\begin{array}{lccccccccc}
 & \mu^- & \rightarrow & e^- & + & \overline{\nu}_e & + & \nu_\mu \\
L: & 1 & = & 1 & - & 1 & + & 1 \\
L_e: & 0 & = & 1 & - & 1 & + & 0 \\
L_\mu: & 1 & = & 0 & + & 0 & + & 1
\end{array}
\longleftarrow
$$

Matriz identidad en e,μ,τ,ν

Los datos apuntan a <u>3 y sólo 3</u> generaciones



V_{CKM}

$$
\begin{bmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{bmatrix}
$$

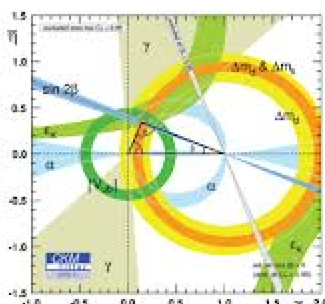
4 parámetros

$$
\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97428 \pm 0.00015 & 0.2253 \pm 0.0007 & 0.00347^{+0.00016}_{-0.00012} \\ 0.2252 \pm 0.0007 & 0.97345^{+0.00015}_{-0.00016} & 0.0410^{+0.0011}_{-0.0007} \\ 0.00862^{+0.00026}_{-0.00020} & 0.0403^{+0.0011}_{-0.0007} & 0.999152^{+0.000030}_{-0.000045} \end{bmatrix}
$$

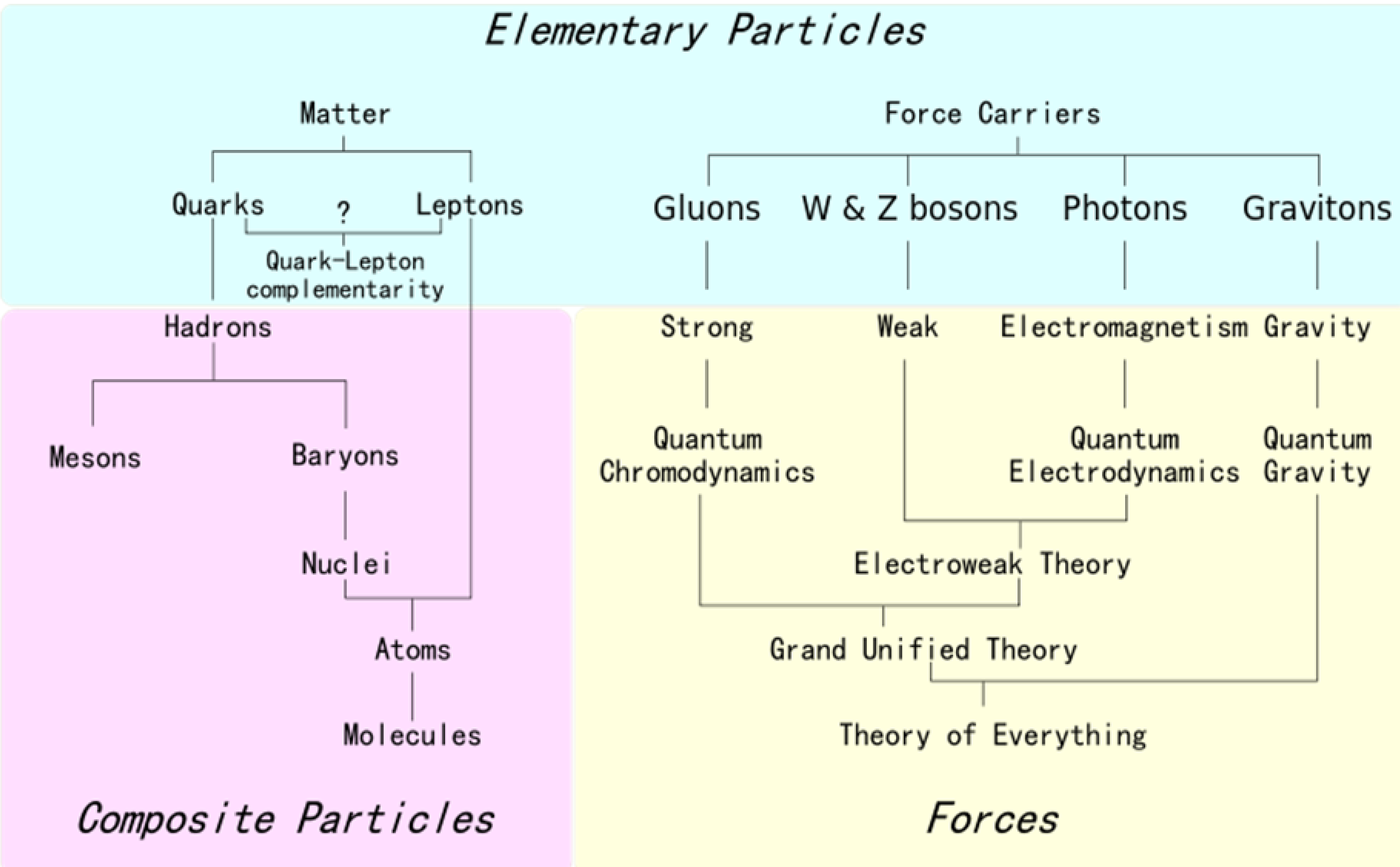
Quark	Symbol	Flavor	Charge	Mass (MeV)
Up	u	$I_z = +1/2$	+2/3	1.5 to 4.0
Down	d	$I_z = -1/2$	-1/3	4 to 8
Strange	s	S = -1	-1/3	80 to 130
Charm	c	C = 1	+2/3	1150 to 1350
Bottom	b	B' = -1	-1/3	4100 to 4400
Top	t	T = 1	+2/3	171400 ± 2100

$$
\begin{array}{cc}
 & \begin{array}{ccc} d & s & b \end{array} \\
V \approx & \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 1 \end{pmatrix} \begin{array}{c} u \\ c \\ t \end{array}
\end{array}
$$

$\lambda \approx 0.22$: Cabibbo angle



$\sin\theta_c \approx 0.22$; $\theta_c \sim 13º$


Elementary Particles
Matter
Force Carriers
Quarks
?
Leptons
Quark-Lepton
complementarity
Gluons
W & Z bosons
Photons
Gravitons
Hadrons
Strong
Weak
Electromagnetism
Gravity
Mesons
Baryons
Quantum
Chromodynamics
Quantum
Electrodynamics
Quantum
Gravity
Nuclei
Electroweak Theory
Atoms
Grand Unified Theory
Molecules
Theory of Everything
Composite Particles
Forces

Bosones (estadística B-E, no afecta PE Pauli)

Boson	J	Q	Color	T_3	Interacción	Masa (GeV/c2)	τ (B-W)	Teoría	Predicha	Descubierta
γ	1	0		0	EM	0 (<10−18 eV /c2)	Estable	QED	1900	1900
W±	1	±1		±1	Débil	80.385± 0.015	3.15 x 10-25s	QED	1968	1983
Z	1	0		0	Débil	91.1876± 0.0021	2.63x 10-25s	QED	1968	1973
g (8)	1	0	Color + Acolo (octet)		Fuerte	0 (<0.0002eV /c2)	-	QCD	1962	1978
H	0	0			Masa	~125±1	1.56×10 −22 s	EW	1964	2012 ?
G	2	0			Gravedad	0 (<7 × 10−32 eV)	Estable	QFT	1930	(no SM)

http://pdg.lbl.gov/2012/listings/contents_listings.html

Modelo Estándar

Tipo	Sabor	Generación	Antipartícula	Color	Total
quarks	2	3	2	3	36
leptones	2	3	2		12
gluon	1	1	1	8	8
W	1	1	2		2
Z	1	1	1		1
γ	1	1	1		1
H	1	1	1		1
Total					61

LEPTONS

e^-	μ^-	τ^-
ν_e	ν_μ	ν_τ

ANTILEPTONS

e^+	μ^+	τ^+
$\bar{\nu}_e$	$\bar{\nu}_\mu$	$\bar{\nu}_\tau$

18 parámetros libres (incluyendo 9 masas de fermiones) en primer orden

Quarks			Antiquarks		
u	c	b	$\bar{u}$	$\bar{c}$	$\bar{b}$
d	s	t	$\bar{d}$	$\bar{s}$	$\bar{t}$

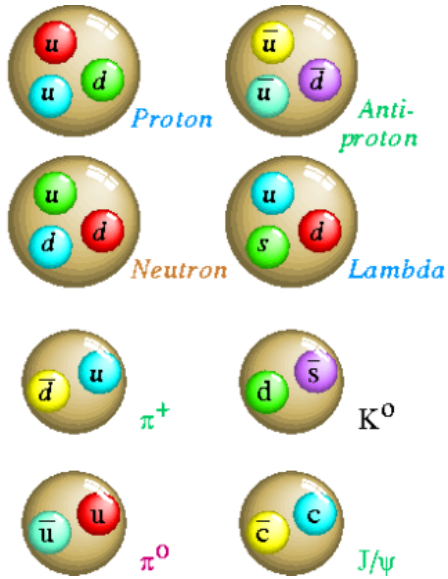
-Q

-T3

-Color

Comparativa de fuerzas

Fuerza	Boson	Carga	Masa	Alcance	Acoplamiento
Fuerte	g	Color, g tiene carga	0	Limitado por interacción mutua de g (1fm)	α_s =1
EM	γ	Eléctrica, γ no tiene	0	∞	α=1/137
Débil	Z,$W^{\pm}$	Débil, W y Z la tienen	80,90 GeV/c2	10^{-3} fm (10^{-18} m)	$\alpha_W=10^{-6}$
Gravitatoria	G	Masa, G no tiene	0	∞	$\alpha_g=10^{-39}$



Fuerza fuerte. "Carga" de color:

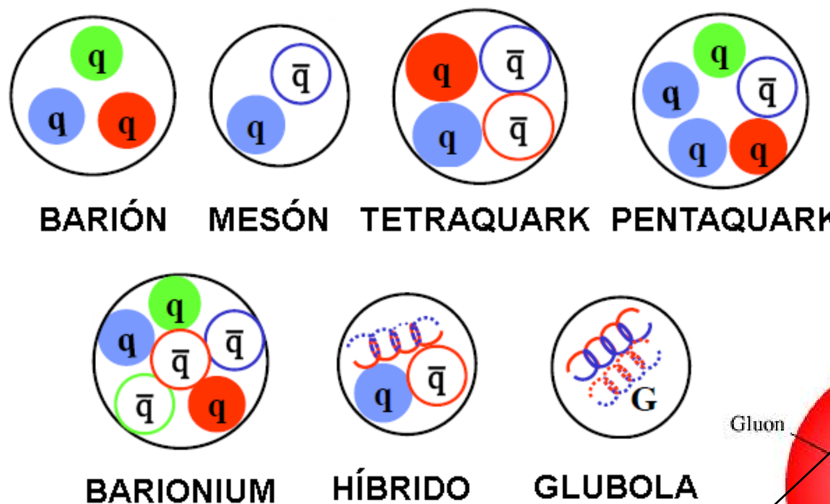
- no tiene nada que ver con cromatismos… es un nombre
- partículas libres→carga neutra
- la energía del campo de color aumenta con la distancia, cae tras 1fm (**Asymptotic Freedom)**
- surge del PE de Pauli

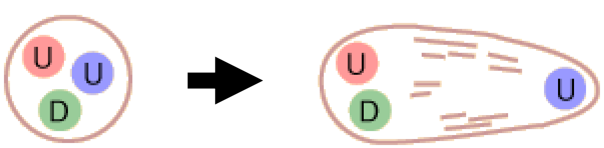
$$V(r) = k \cdot r - 4\alpha_s/3r$$

k ≈1 GeV/fm=160000N

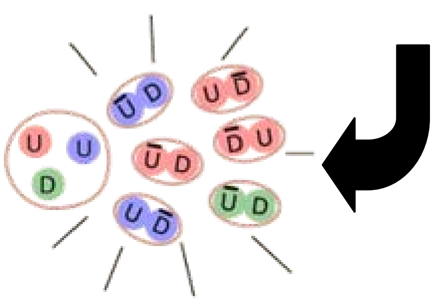
El propio portador de la fuerza (g), está cargado!!

Comparar con EM (γ)

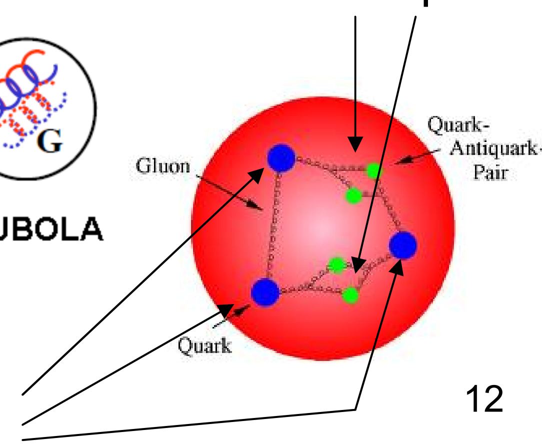




Bag model of **Quark Confinement**



sea quarks



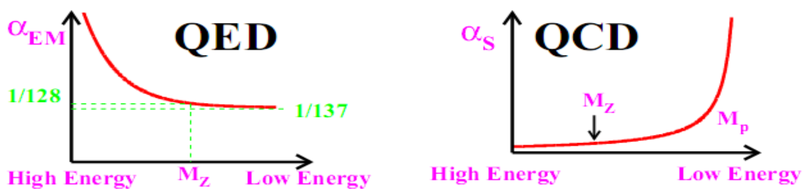
valence quarks

QED vs QCD

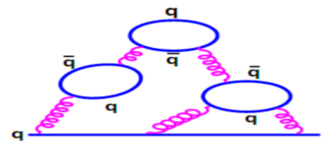
- ★ α_S specifies the strength of the strong interaction
- ★ BUT just as in QED, α_S isn't a constant, it "runs"
- ★ In QED the bare electron charge is screened by a cloud of virtual electron-positron pairs.
- ★ In QCD a similar effect occurs.

Colour Anti-Screening

- ★ Due to the gluon self-interactions bare colour charge is screened by both virtual quarks and virtual gluons
- ★ The cloud of virtual gluons carries colour charge and the effective colour charge INCREASES with distance !
- ★ At low energies (large distances) α_S becomes large $\rightarrow$ can't use perturbation theory (not a weak perturbation)

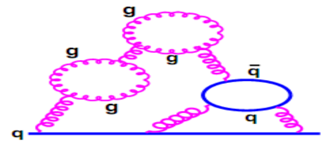


In QCD quantum fluctuations lead to a 'cloud' of virtual $q\overline{q}$ pairs

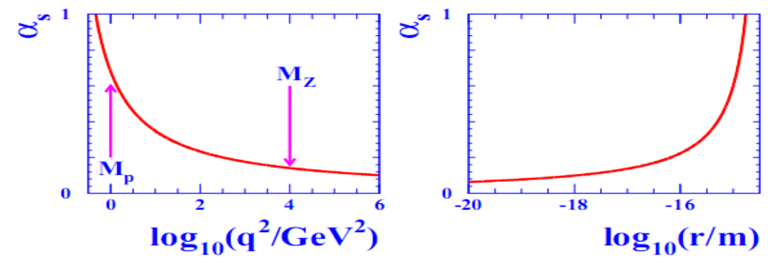


one of many (an infinite set) such diagrams analogous to those for QED.

In QCD the gluon self-interactions ALSO lead to a 'cloud' of virtual gluons



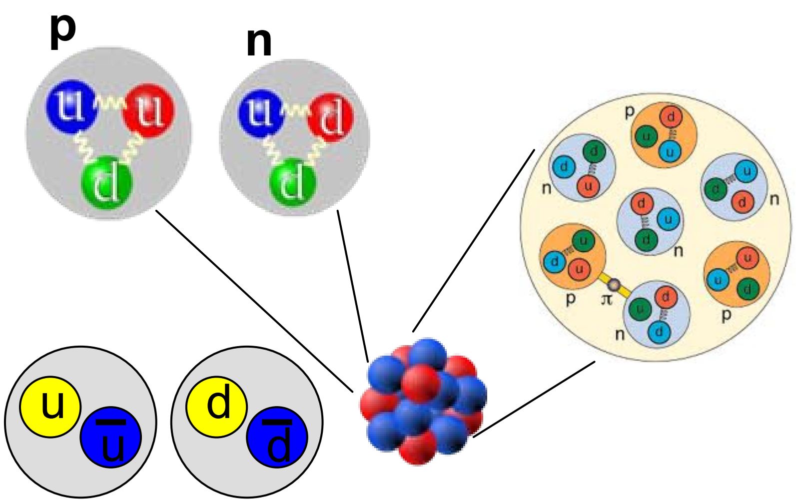
one of many (an infinite set) such diagrams. Here there is no analogy in QED, photons don't have self-interactions since they don't carry the charge of the interaction.



- ★ At High energies (short distances) α_S is small. In this regime treat quarks as free particles and can use perturbation theory **ASYMPTOTIC FREEDOM**
- ★ At $\sqrt{s} = 100$ GeV, $\alpha_S = 0.12$.

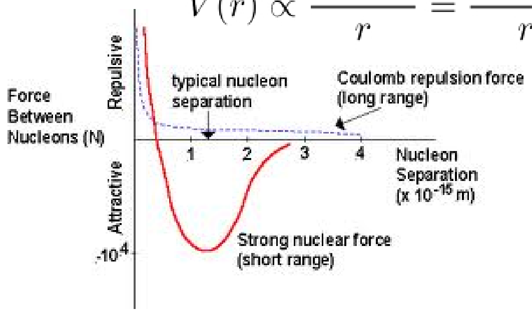
Fuerza nuclear

- Fuerza que une nucleones en el núcleo (n,p)
- Efecto residual de la interacción fuerte (≡VdW)

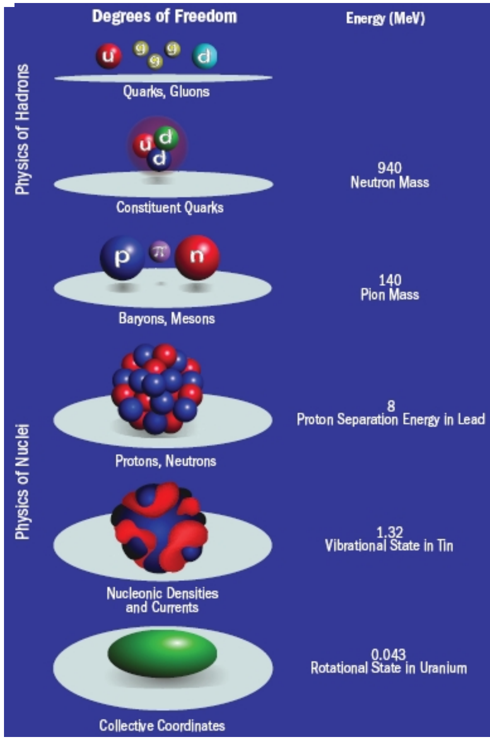


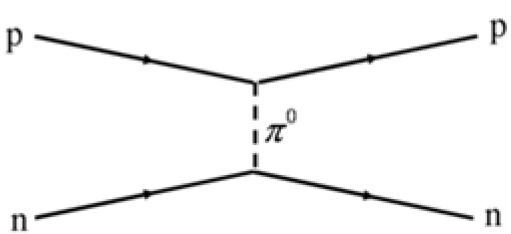
$\pi^0 = (u\bar{u}-d\bar{d})/\sqrt{2}$

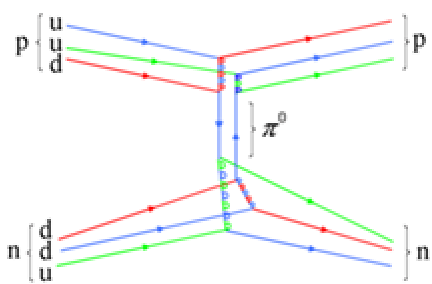
$$V(r) \propto \frac{e^{-m_{\mathrm{ex}} r}}{r} = \frac{e^{-r/\lambda_{\mathrm{ex}}}}{r}$$

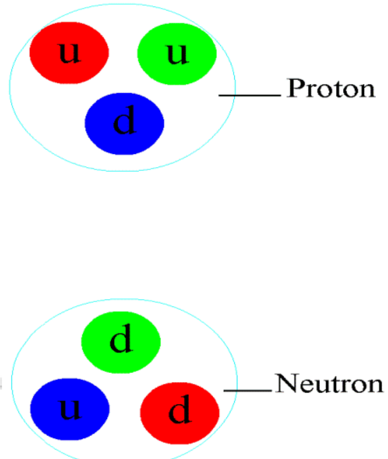


Potencial de Yukawa



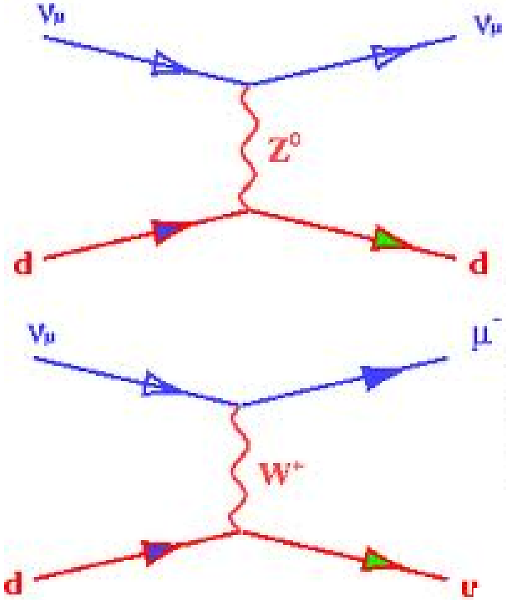






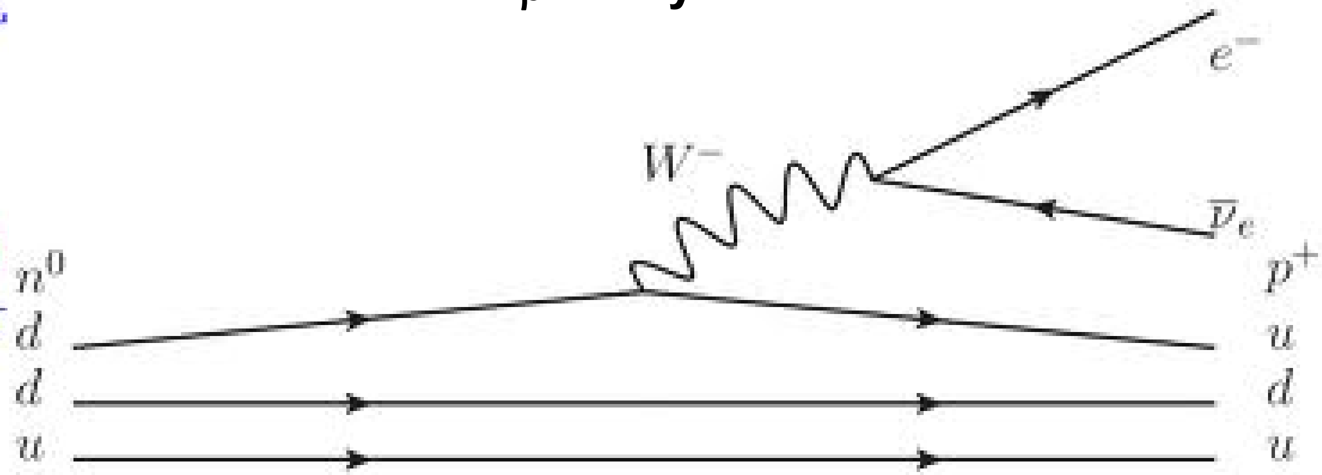
Neutral Currents, Charged Currents

Neutral

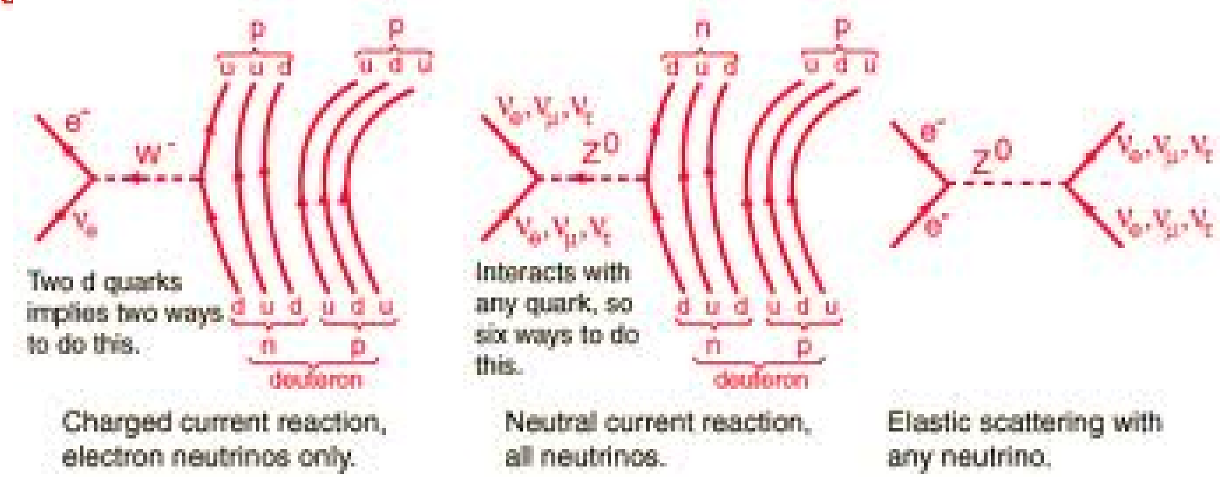


Charged

Neutron β decay



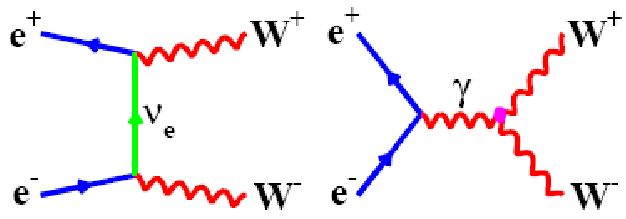
Corrientes cargadas se explicaban por intercambio de W±



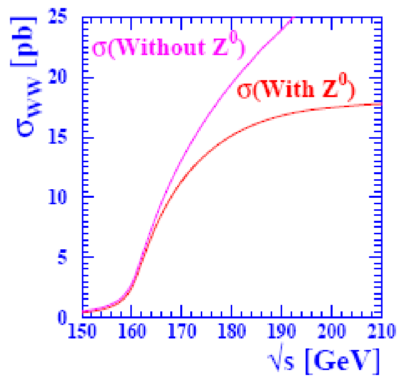
Carga (Electro)débil (I)

Consider $e^+e^- \rightarrow W^+W^-$

2 Diagrams
(+interference)

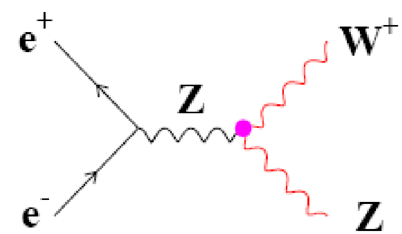


★ Cross section diverges at high energy



Divergence CURED by introducing Z^0

Extra Diagram
$e^+e^- \rightarrow W^+W^-$



★ Only works if γ, $W^\pm$, Z^0 couplings related !
★ ELECTRO-WEAK UNIFICATION

Carga (Electro)débil (II)

Glashow (1961), Weinberg (1967) and Salam (1968) model treats EM and WEAK interactions as different manifestations of a UNIFIED force.

- ★ It is somewhat *ad hoc*
- ★ But gives concrete predictions - i.e. a testable theory
- ★ provides perfect description of precise data

"Basic idea" - start with 4 massless bosons, $\{W^+, W^0, W^-\}$ and B^0. The neutral bosons mix to give physical BOSONs, (the particles we see), *i.e.* the $W^\pm$, Z^0 and γ.

$$\begin{pmatrix} W^+ \\ W^0 \\ W^- \end{pmatrix}, B \rightarrow \begin{pmatrix} W^+ \\ Z^0 \\ W^- \end{pmatrix}, \gamma$$

Physical Fields : W^+, W^+ Z^0, A (photon)

$$\begin{aligned} \mathrm{Z}^0 &= W^0 \cos\theta_W - B \sin\theta_W \\ A &= W^0 \sin\theta_W + B \cos\theta_W \end{aligned}$$

θ_W : weak mixing angle

(Weinberg angle ~30º)

Carga (Electro)débil (III)

$W^{\pm}$ and Z^0 'acquire' mass via the HIGGS MECHANISM

The beauty of the model is that it makes exact predictions:

- ★ Weak coupling constant: $e = g \sin\theta_w$
- ★ The mass of the Z^0 boson

$$M_{Z^0} = \frac{M_W}{\cos\theta_W}$$

$\sin^2\theta_W = 0.2324 \pm 0.0012$

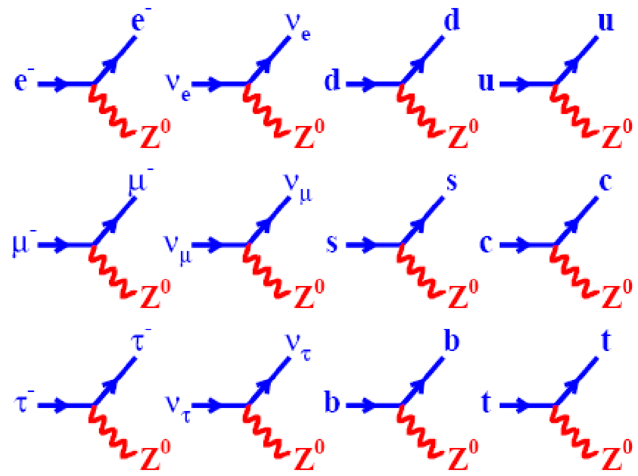
- ★ The couplings of the Z^0 boson
- ★ ONLY 3 free parameters !

IF we know $\{\alpha_{em}, G_F, \sin\theta_W\}$ everything else is FIXED, i.e. predict M_W, M_{Z^0}, couplings, etc.

$$\frac{G_F}{(\hbar c)^3} = \frac{\sqrt{2}}{8}\frac{g^2}{m_W^2} = 1.16637(1)\times 10^{-5}\ \mathrm{GeV}^{-2}\ .$$

Carga (Electro)débil (IV)

★ WEAK Neutral Current (NC) interactions are mediated by the Z^0 boson.



Neutral Currents

Nuevo número cuántico: Isospin débil **(T) y su tercera componente T_3**

- ★ WEAK NC NEVER changes flavour
- ★ Z^0 couplings are a "MIXTURE" of weak and electro-magnetic couplings
- ★ WEAK NC couplings therefore depend on $\sin^2\theta_W$

Z^0 couplings are a mixture of EM (VECTOR) and WEAK (VECTOR—AXIAL-VECTOR) couplings

En la práctica:

$g_Z = g_W (T_3 - Q\ \mathrm{sen}^2\theta_W) / \cos\theta_W$

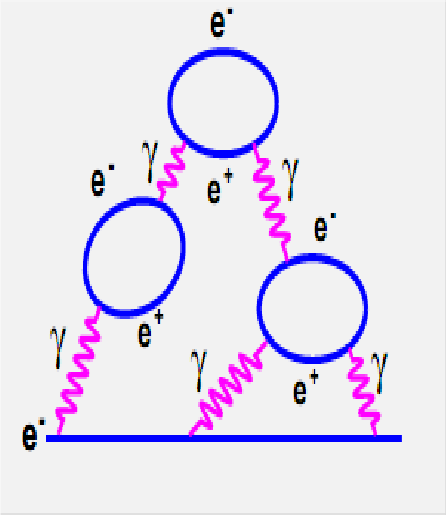
$$\frac{g}{\cos\theta_W}\frac{1}{2}\gamma^\mu(C_V - C_A\gamma^5)$$

Form of neutral current couplings are determined by the WEAK MIXING ANGLE θ_W

QED

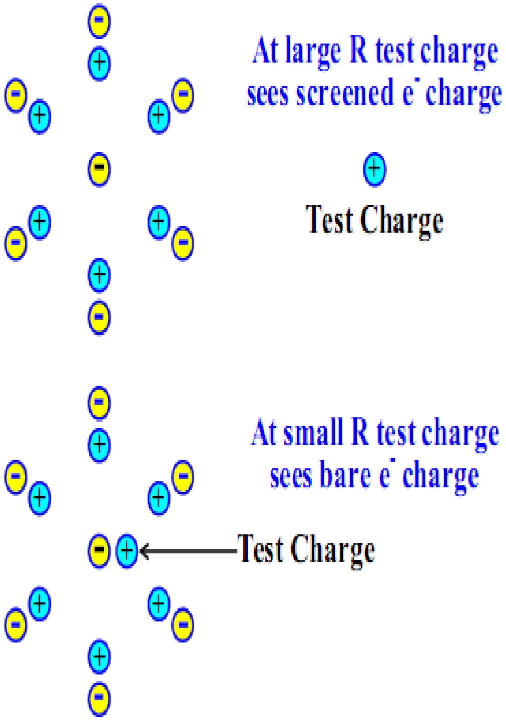
- ★ $\alpha = \frac{e^2}{4\pi}$ specifies the strength of the interaction between an electron and photon.
- ★ BUT α isn't a constant

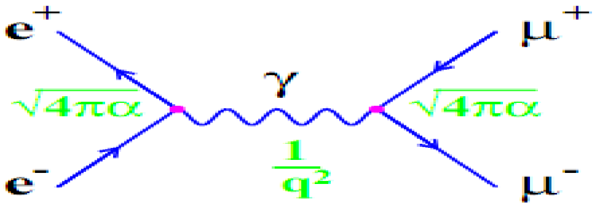
Consider a free electron: Quantum fluctuations lead to a 'cloud' of virtual electron/positron pairs

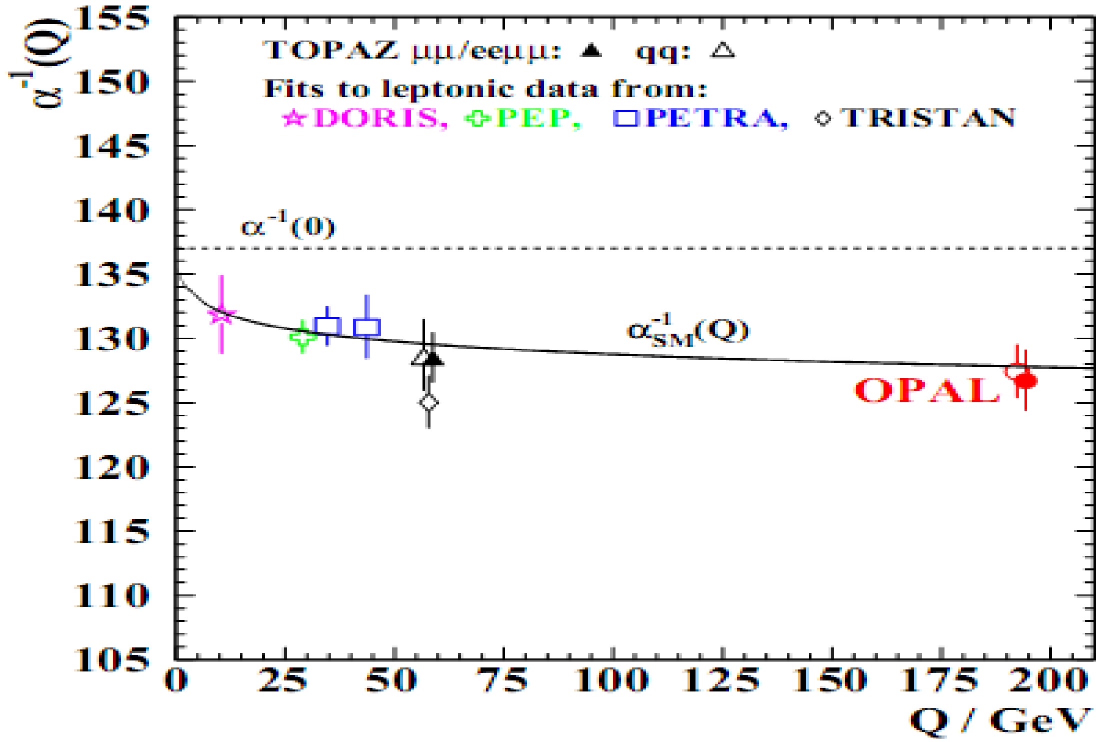


this is just one of many (an infinite set) such diagrams.

- ★ The vacuum acts like a dielectric medium
- ★ The virtual e^+e^- pairs are polarized
- ★ At large distances the bare electron charge is screened.



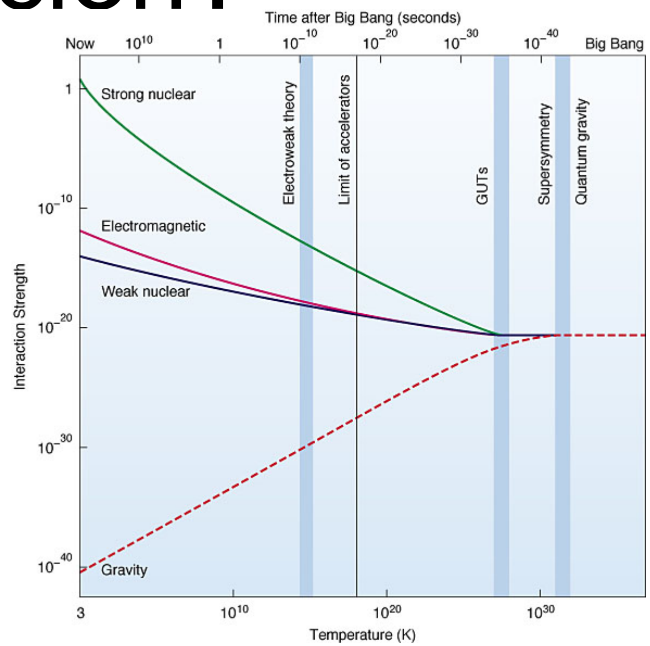




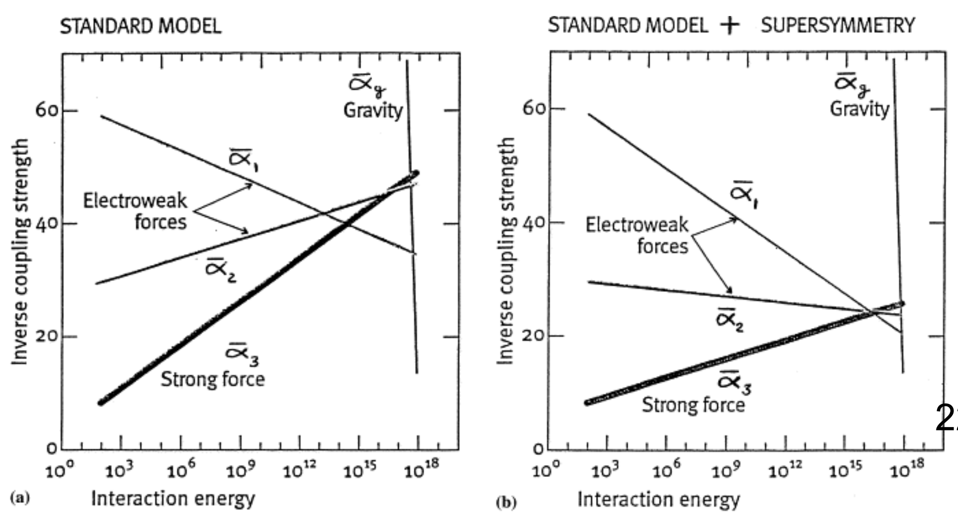
- ★ α increases with the increasing q^2 (i.e. closer to the bare charge).
- ★ At $q^2 = 0$: $\alpha = 1/137$
- ★ At $q^2 = (100\ \mathrm{GeV})^2$: $\alpha = 1/128$

Comparación de fuerzas: unificación?

Fuerza	$\alpha = g^2/4\pi$	Carga (g)
EM	α_{EM}	$e = g_W \text{ sen } \theta_W$
Debil	α_W	g_W
Fuerte	α_S	g_S



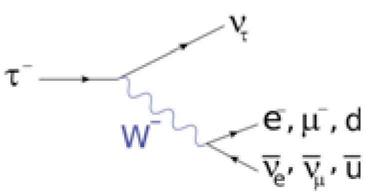
La fortaleza intrínseca de la interacción Débil es mayor que la EM, pero a bajas energías (q^2) parece más débil debido a la gran masa de los propagadores W y Z



Leyes de conservación

- **Cantidades físicas conservadas**: Energía (E), momento (p), momento angular (L), carga (Q), color (g_S), número bariónico (B=1 para bariones, B=0 para mesones) y los tres números leptónicos (L_e,L_μ,L_τ)
- Las **paridades C** (inversión de carga) y **P** (inversión en el espacio) se conservan en la fuerza Fuerte y EM. En la Débil no:
  - **CC**: violación de la paridad máxima, fermiones l-h and anti fermiones r-h
  - **NC**: violación parcial de la simetría de paridad
- **Sabor**: Sólo la **CC** transforma un tipo de quark en otro tipo (de diferente sabor) y un tipo de leptón en otro → **el sabor se conserva** en el resto de interacciones

$$\mu^- \rightarrow e^- \overline{\nu}_e \nu_\mu,$$
$$\tau^- \rightarrow e^- \overline{\nu}_e \nu_\tau,$$
$$\pi^+ \rightarrow \mu^- \overline{\nu}_\mu,$$
$$n \rightarrow p e^- \overline{\nu}_e, \ldots.$$



$$\mathbf{p + \mu^- \rightarrow \pi^0 + n}$$

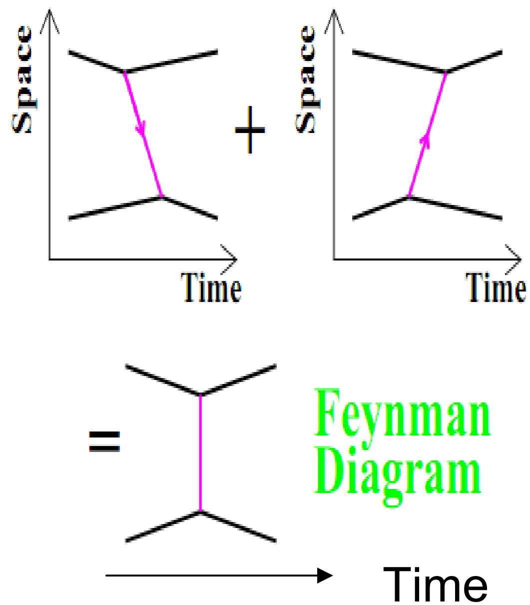
$$\mathbf{e^+ + e^- \rightarrow \nu_\mu + \nu_\mu}$$

$$\mathbf{\pi^- \rightarrow e^- + \nu_e}$$

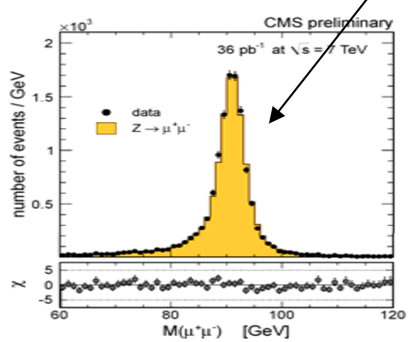
$$\mathbf{\tau^- \rightarrow \pi^- + \nu_e}$$

Diagramas de Feynman (I)

★ The sum of time orderings are represented by FEYNMAN DIAGRAMS



★ Energy and Momentum are conserved at the interaction vertices



Virtual Particles:

★ Forces due to exchanged particle X which is termed VIRTUAL.

★ The exchanged particle is off mass-shell, *i.e.* for the unobservable exchanged VIRTUAL particle $E^2 \neq p^2 + m_X^2$.

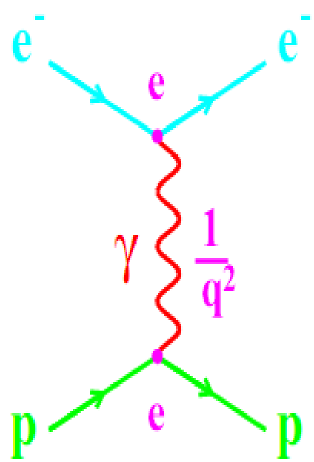
★ *i.e.* $m^2 = E_X^2 - p_X^2$ does not give the physical mass, m_X. The mass of the virtual particle $m^2 = E_X^2 - p_X^2$ can be +ve or -ve.

Qualitatively: the propagator is inversely proportional to how far the particle is off-shell. The further off-shell, the smaller the probability of producing such a virtual state.

Diagramas de Feynman (II)

Scattering cross sections calculated from:

- ★ Fermion wave functions
- ★ Vertex Factors : coupling strength
- ★ Propagator
- ★ Phase Space



Electron Current

Propagator

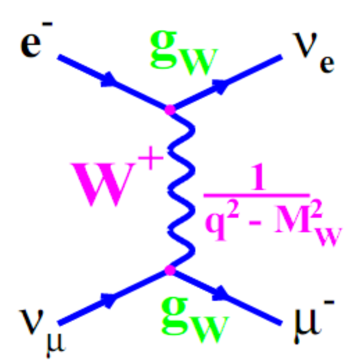
Proton Current

Matrix element M factorises into 3 terms :

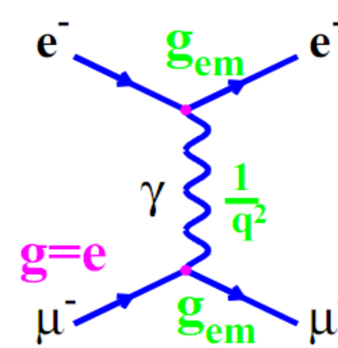
$$-iM = \langle \overline{u}_e | ie\gamma^\mu | u_e \rangle \quad \text{Electron Current}$$
$$\times \frac{-ig^{\mu\nu}}{q^2} \quad \text{Photon Propagator}$$
$$\times \langle \overline{u}_p | ie\gamma^\nu | u_p \rangle \quad \text{Proton Current}$$

The factors γ^μ and $g^{\mu\nu}$ are 4×4 matrices which account for the spin-structure of the interaction

WEAK INTERACTION

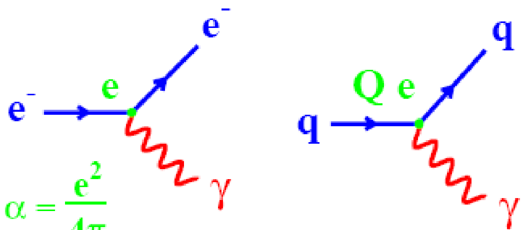


QED



Resumen de Vértices en el SM

ELECTROMAGNETIC (QED)

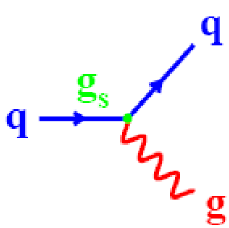


$\alpha = \frac{e^2}{4\pi}$

Couples to CHARGE

Does NOT change FLAVOUR

STRONG (QCD)



$\alpha_s = \frac{g_s^{\,2}}{4\pi}$

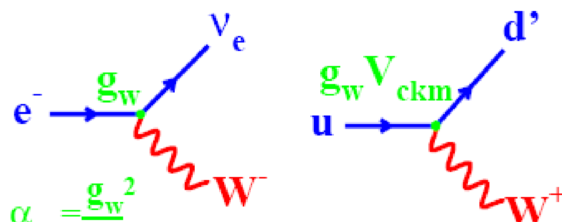
Couples to COLOUR

Does NOT change FLAVOUR

El elemento de matriz es proporcional a:

- **fuerza de la interacción (vértice → g)**
- **momento intercambiado (propagador →q)**

WEAK Charged Current



$\alpha_W = \frac{g_W^{\,2}}{4\pi}$

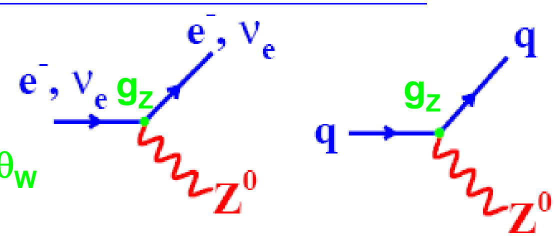
Changes FLAVOUR

For QUARKS: coupling BETWEEN generations

Cualitativamente, se traduce en una probabilidad:

M → $\sigma \sim |M|^2$

WEAK Neutral Current

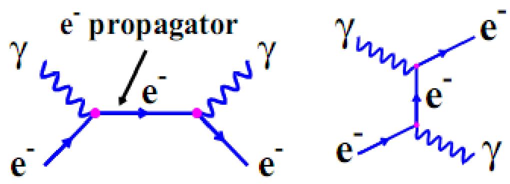


$g_Z = g_W / \cos\theta_W$

Does NOT change FLAVOUR

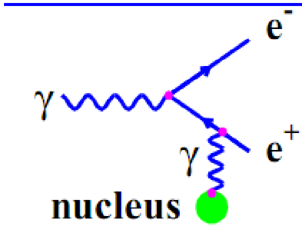
Ejemplo (I)

Compton Scattering



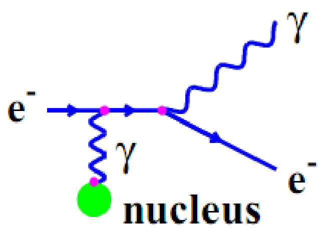
$$M \sim e^2$$
$$\sigma \sim |M|^2 \sim e^4$$
$$\sigma \sim (4\pi)^2\alpha^2$$

e^+e^- Pair Production



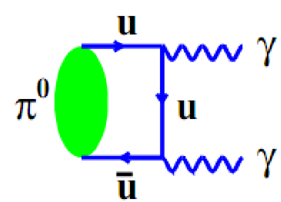
$$M \sim e.e.Ze$$
$$|M|^2 \sim Z^2e^6$$
$$\sigma \sim (4\pi)^3 Z^2\alpha^3$$

Bremsstrahlung



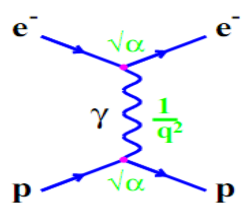
$$M \sim Ze.e.e$$
$$|M|^2 \sim Z^2e^6$$
$$\sigma \sim (4\pi)^3 Z^2\alpha^3$$

π^0 Decay



$$M \sim Q_u e.Q_u e$$
$$|M|^2 \sim Q_u^4 e^4$$
$$\sigma \sim (4\pi)^2 Q_u^4 \alpha^2$$

Electron-Proton Scattering

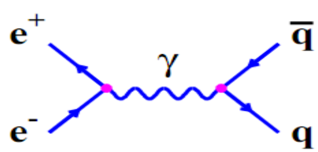


$$M \sim e.e$$
$$|M|^2 \sim e^4$$
$$\sigma \sim (4\pi)^2\alpha^2$$

Coupling strength determines 'order of magnitude' of matrix element. For particles interacting/decaying via electromagnetic interaction: typical values for cross sections/lifetimes

$$\sigma_{em} \sim 10^{-2}\ \text{mb}$$
$$\tau_{em} \sim 10^{-20}\ \text{s}$$

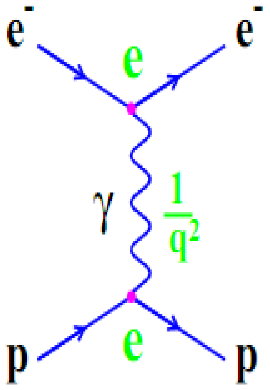
e^+e^- Annihilation

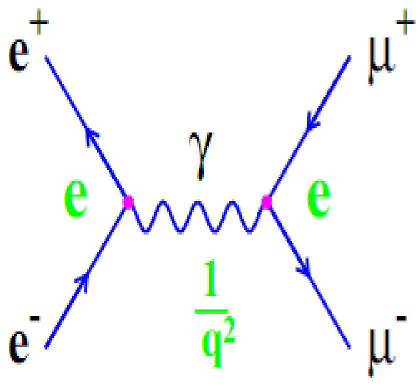


$$M \sim e.Q_u e$$
$$|M|^2 \sim Q_u^2 e^4$$
$$\sigma \sim (4\pi)^2 Q_u^2 \alpha^2$$

Ejemplo (II)

★ electron-proton scattering
★ electron-positron annihilation





Here we will consider the case where all particles are spin-0, (see lecture on Dirac Equation for complete treatment)

Fermi's Golden rule and Born Approximation:

$$\frac{d\sigma}{d\Omega} = 2\pi|M|^2 d\rho(E_f)/d\Omega$$

For both processes write the SAME matrix element

$$M = \frac{e^2}{q^2} = \frac{4\pi\alpha}{q^2}$$

However, the four-momentum transfer ($q^2 = E^2 - \tilde{q}^2$) is very different ($\tilde{q}$ is the 3-momentum of the virtual photon)

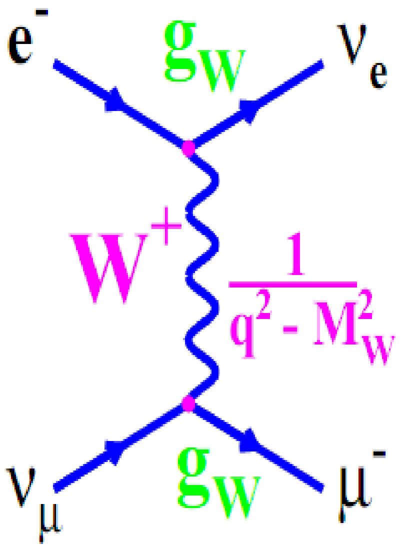
★ Elastic e^--proton scattering : $q = (0, \tilde{q})$

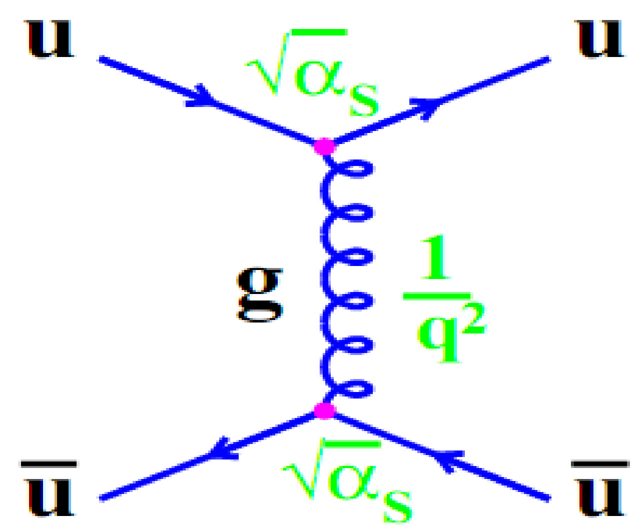
$$q^2 = -|\tilde{q}|^2$$

★ e^+e^- annihilation : $q = (2E, 0)$

$$q^2 = +4E^2$$

Ejemplo (III)





$$\frac{d\sigma}{dq^2} = \frac{1}{32\pi}\frac{g_w^4}{(q^2 - M_W{}^2)^2}$$

$$M \sim \frac{1}{q^2}\sqrt{\alpha_S}\sqrt{\alpha_S} \Rightarrow \frac{d\sigma}{d\Omega} \sim \frac{(\alpha_S)^2}{\sin^4\theta/2}$$

Genericamente: M ~ α_x / (q^2 – ($M_{propagador}$)^2) ; x = S, EM, W

Reglas generales

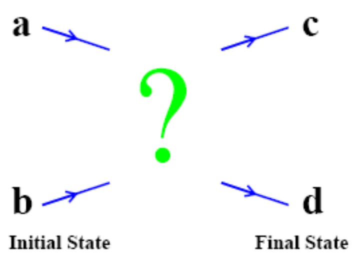
If all are particles (or all anti-particles) *e.g.*

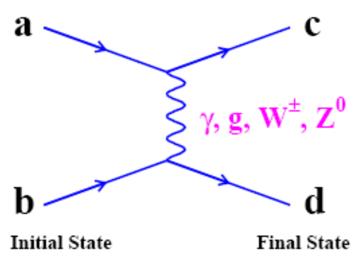
$$a + b \to c + d$$

★ First write down initial/final state particles/anti-particles.

★ Only scattering diagrams involved

★ Work out which bosons can be exchanged





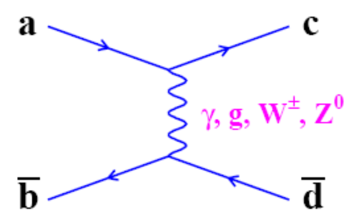
If particles and anti-particles *e.g.*

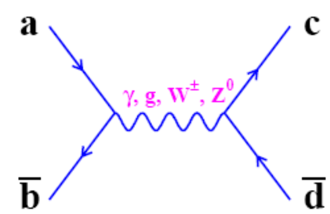
$$a + \overline{b} \to c + \overline{d}$$

★ First write down initial/final state particles/anti-particles.

★ Can have scattering and/or annihilation diagrams

★ Again work out which bosons can be exchanged





★ In all cases onlv Standard Model vertices allowed.

❶ Draw SIMPLEST Feynman diagram using Standard Model vertices. Bearing in mind:

★ Similar diagrams for particles/anti-particles

★ NEVER have a vertex connecting a LEPTON to a QUARK
  conservation of lepton number
  conservation of baryon number

★ Only the WEAK CC vertex changes FLAVOUR
  within generations for leptons
  within/between generations for quarks

❷ Conservation of

★ Energy - is it kinematically allowed

★ Charge

★ Angular Momentum

❸ Parity

★ Conserved in EM/STRONG interactions

★ CAN be violated in CC and NC WEAK interactions

❹ Check SYMMETRY for IDENTICAL particles in the final state

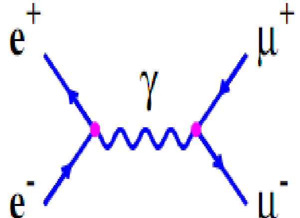
★ BOSONS : $\psi(1,2) = +\psi(2,1)$

★ FERMIONS : $\psi(1,2) = -\psi(2,1)$

LO vs NLO, NNLO,….

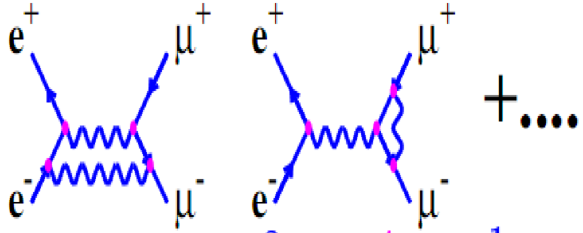
So far only considered lowest order term in the perturbation series. Higher order terms also contribute

Lowest Order:



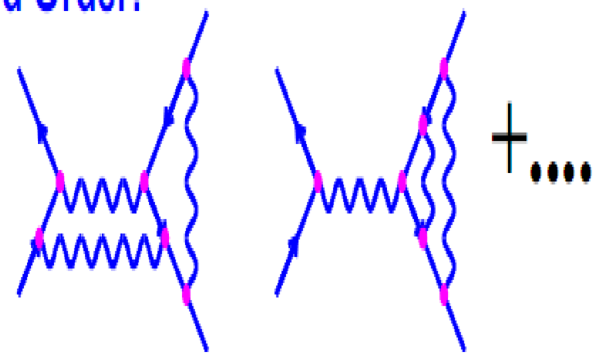
$$|M|^2 \propto \alpha^2 \sim \frac{1}{137^2}$$

Second Order:



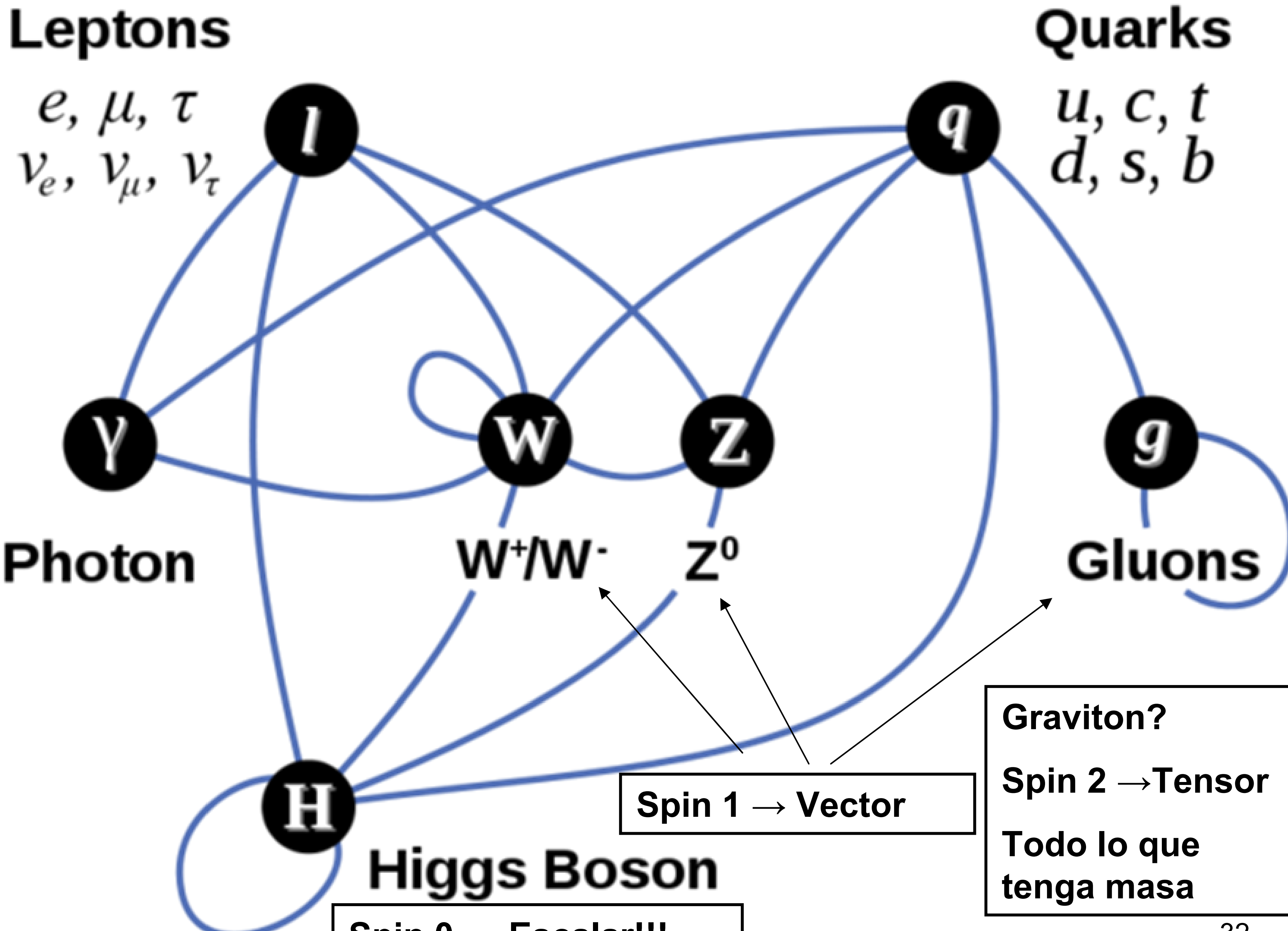
$$|M|^2 \propto \alpha^4 \sim \frac{1}{137^4}$$

Third Order:



$$|M|^2 \propto \alpha^6 \sim \frac{1}{137^6}$$

Second order suppressed by α^2 relative to first order. Provided α is small, *i.e.* perturbation is small, lowest order dominates.



Spin 1 → Vector

Spin 0 → Escalar!!!

Graviton?

Spin 2 →Tensor

Todo lo que tenga masa

Spontaneous Symmetry Breaking


Spontaneous
Symmetry
Breaking

Ruptura espontánea de la simetría electrodébil (EWSB)

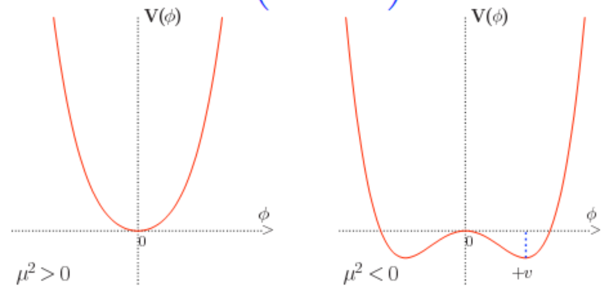
In the SM, if gauge boson and fermion masses are put by hand in $\mathcal{L}_{\rm SM}$

breaking of gauge symmetry $\Rightarrow$ spontaneous EW symmetry breaking

$\Rightarrow$ introduce a doublet of complex scalar fields: $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$, $\mathbf{Y}_{\Phi} = +1$

with a Lagrangian that is invariant under $\mathrm{SU}(2)_{\mathbf{L}} \times \mathrm{U}(1)_{\mathbf{Y}}$

$$\mathcal{L}_{\mathbf{S}} = (\mathbf{D}^{\mu}\mathbf{\Phi})^{\dagger}(\mathbf{D}_{\mu}\mathbf{\Phi}) - \mu^2\mathbf{\Phi}^{\dagger}\mathbf{\Phi} - \lambda(\mathbf{\Phi}^{\dagger}\mathbf{\Phi})^2$$

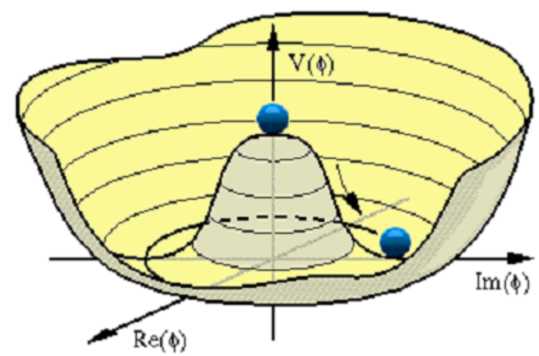


$\mu^2 > 0$: 4 scalar particles.

$\mu^2 < 0$: Φ develops a vev:

$$\langle 0|\mathbf{\Phi}|0\rangle = \begin{pmatrix} \mathbf{0} \\ \mathbf{v}/\sqrt{\mathbf{2}} \end{pmatrix}$$

$$\text{with } \mathrm{v} \equiv \mathrm{vev} = (-\mu^2/\lambda)^{\frac{1}{2}}$$

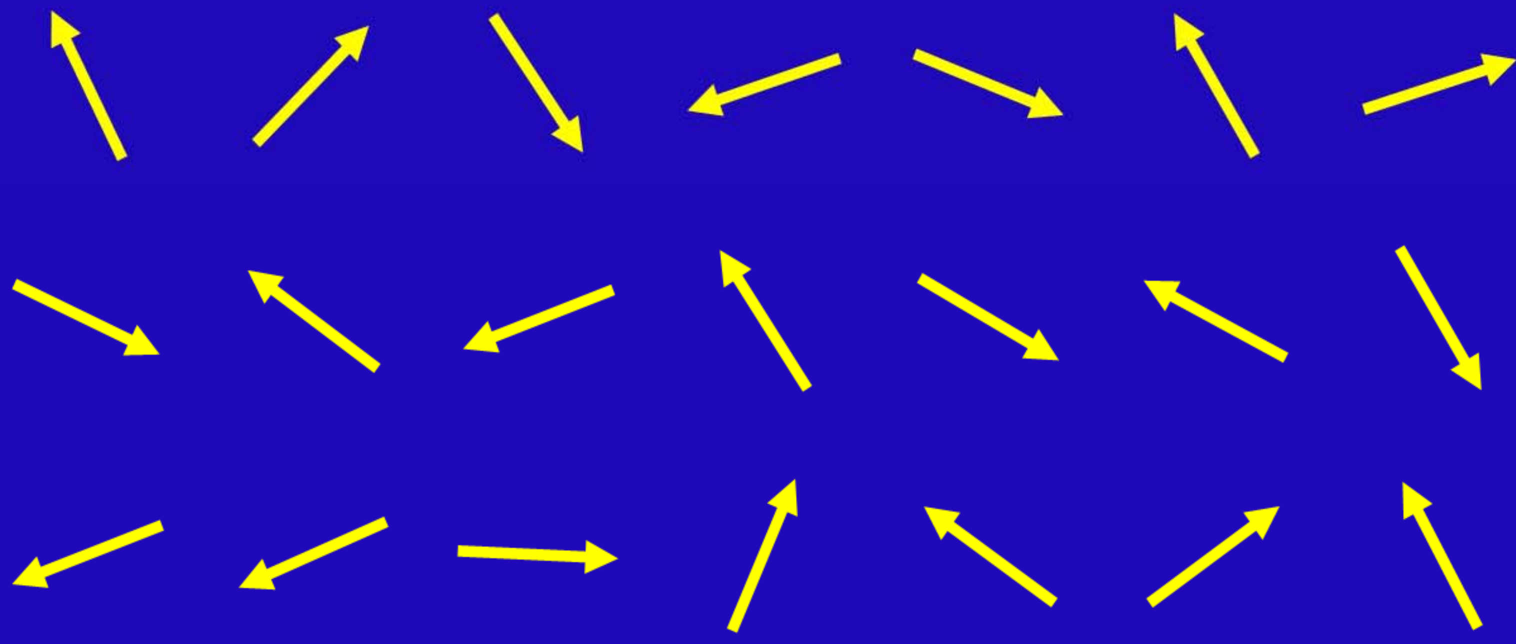


To obtain the physical states,

write $\mathcal{L}_S$ with the true vacuum:

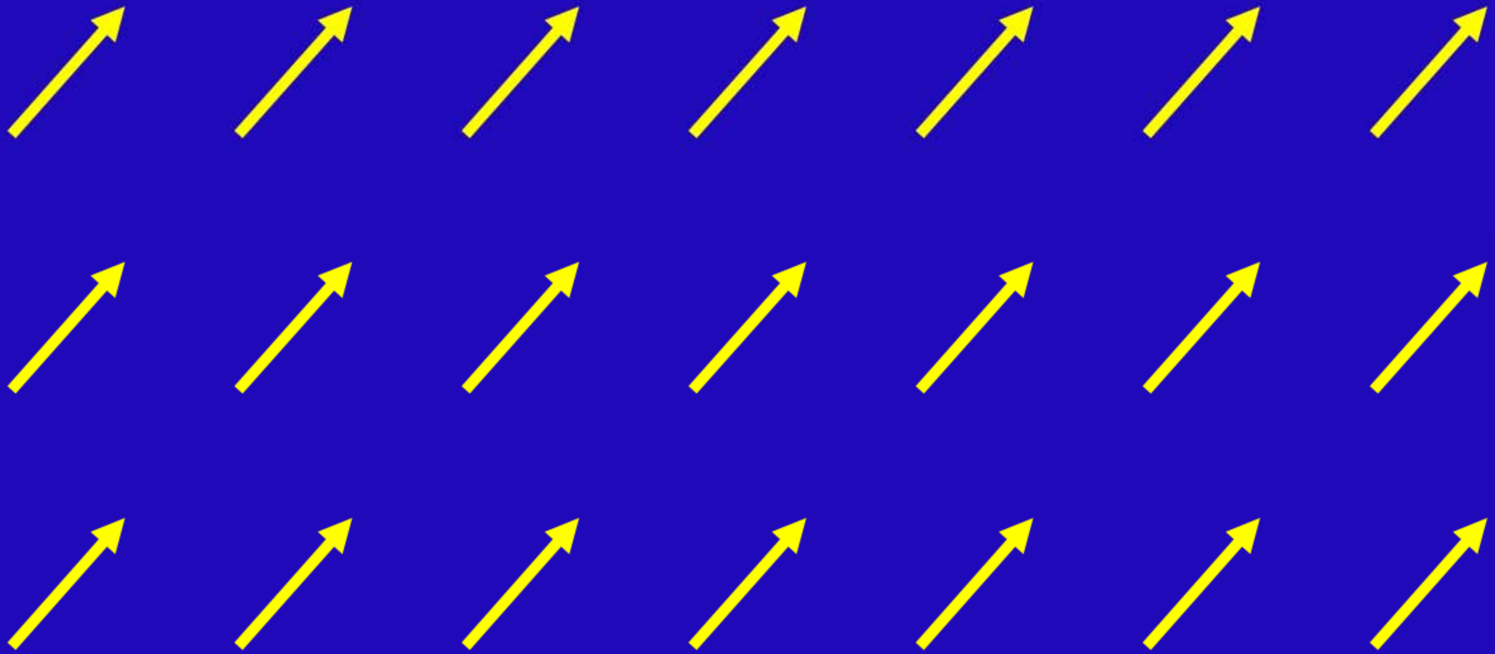
FERROMAGNET

$T > T_C$

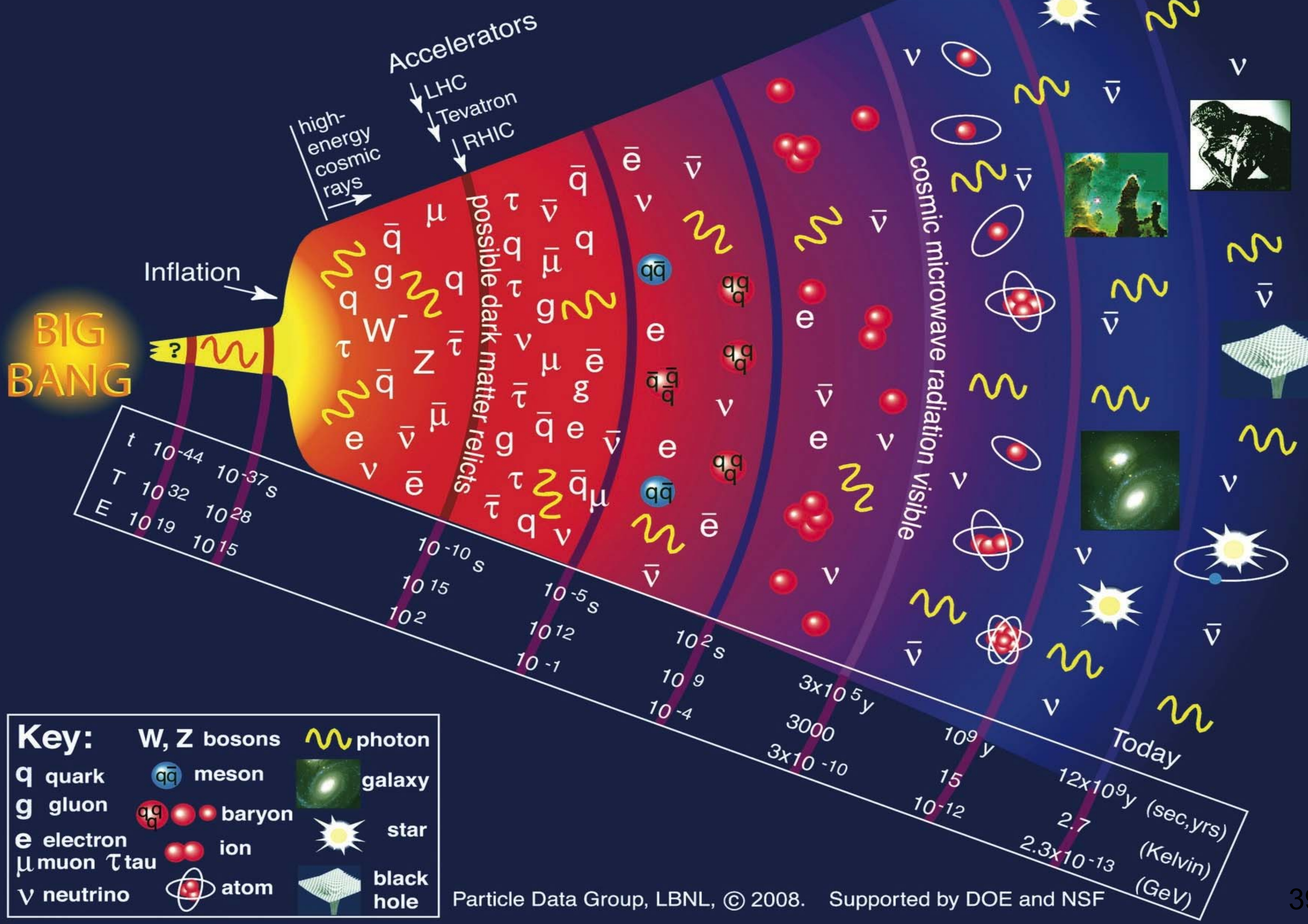


FERROMAGNET

$T < T_C$



History of the Universe



Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

SCALAR POTENCIAL

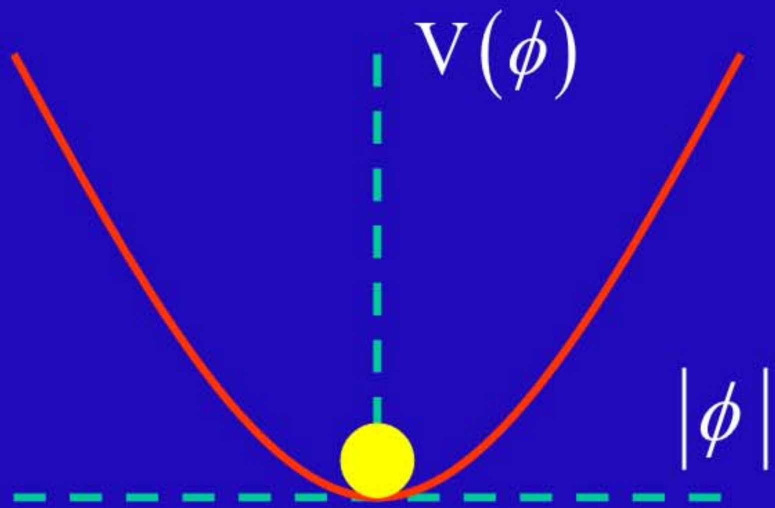
$$\mathcal{L}(\phi) = \partial_\mu \phi^\dagger \, \partial^\mu \phi - V(\phi)$$

$$\mathrm{V}(\phi) = \mu^2 \, \phi^\dagger \phi + h \, (\phi^\dagger \phi)^2$$

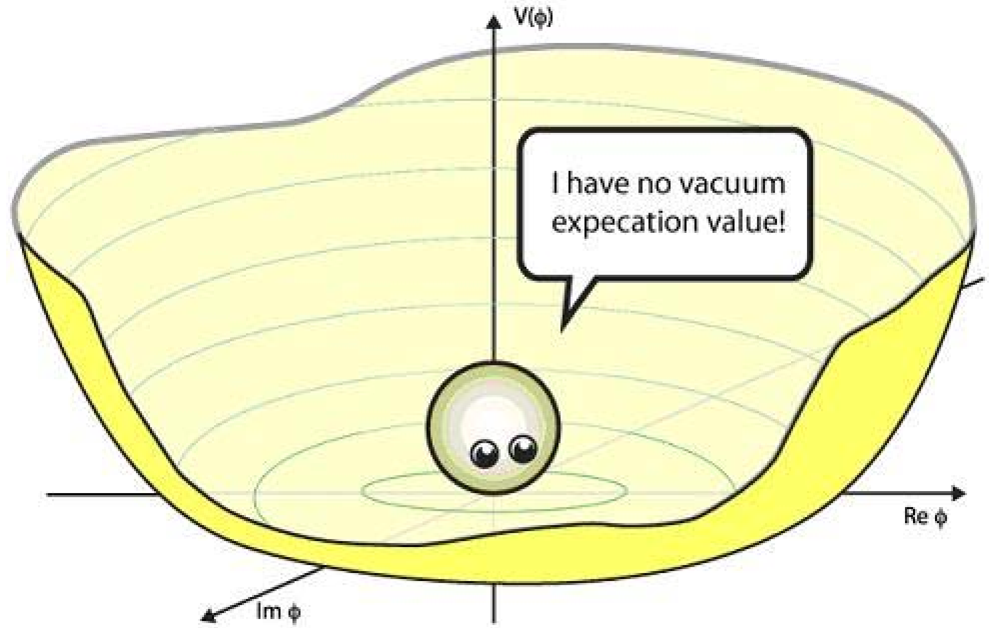
Phase Symmetry: $\phi(x) \rightarrow \mathrm{e}^{i\theta} \, \phi(x)$

$h > 0 \quad ; \quad \mu^2 > 0$

$M_\phi = \mu$



Trivial Minimum (Ground State / Vacuum): $\phi = \phi_0 = 0$

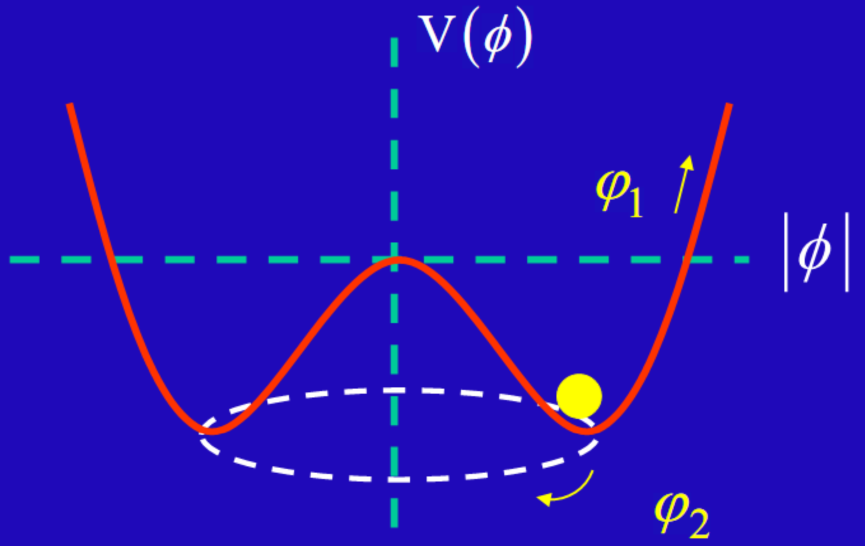

V(ϕ)
I have no vacuum expecation value!
Re ϕ
Im ϕ

$$V(\phi) = \mu^2 \; \phi^\dagger \phi + h \; (\phi^\dagger \phi)^2$$

Phase Symmetry:

$$\phi(x) \to e^{i\theta} \phi(x)$$

$$\mu^2 < 0$$



Degenerate Minima

(Ground State / Vacuum)

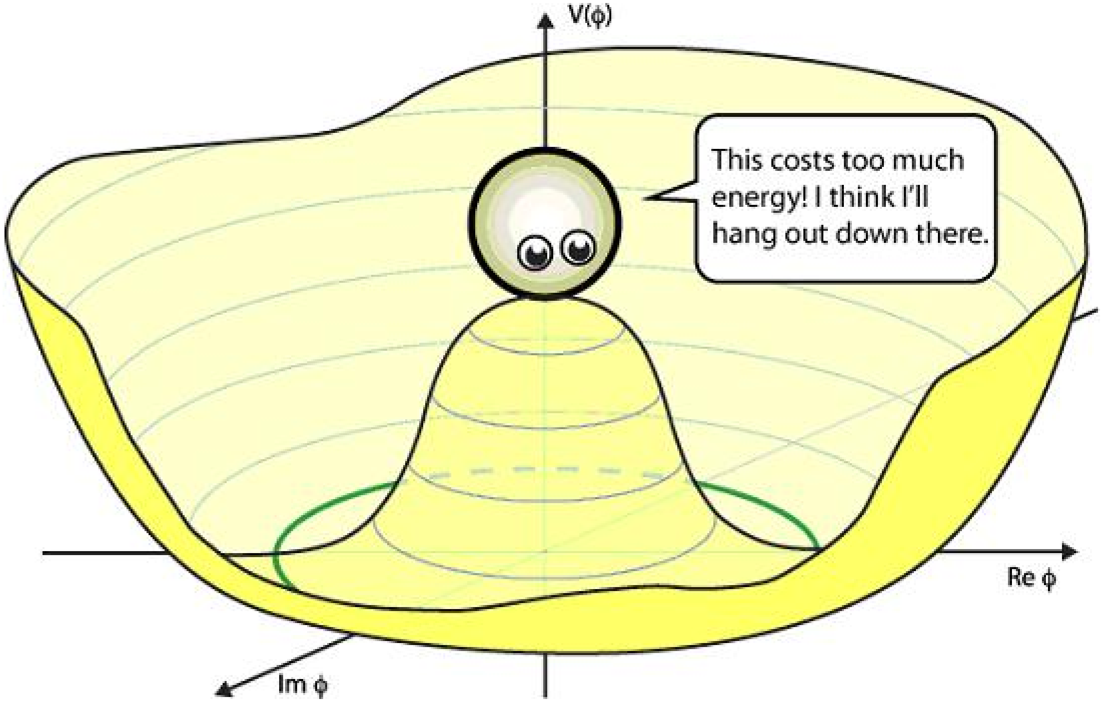
$$|\phi_0| = \sqrt{\frac{-\mu^2}{2h}} \equiv \frac{v}{\sqrt{2}} > 0 \quad ; \quad V(\phi_0) = -\frac{1}{4} h v^4$$

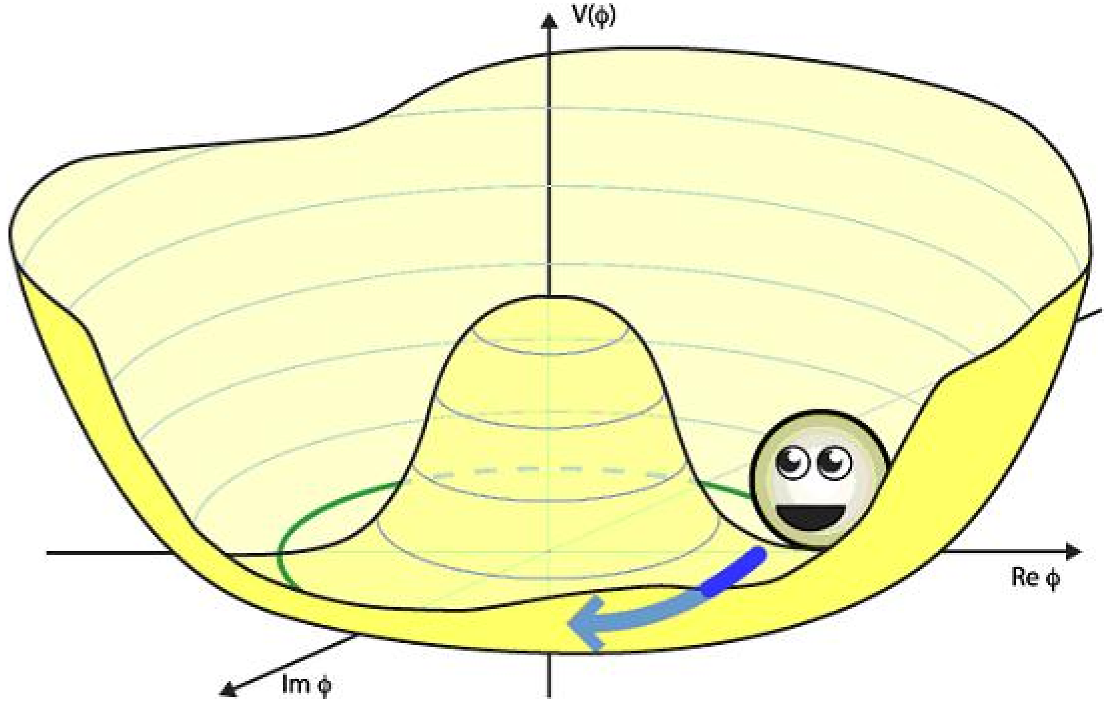
Spontaneous Symmetry Breaking:

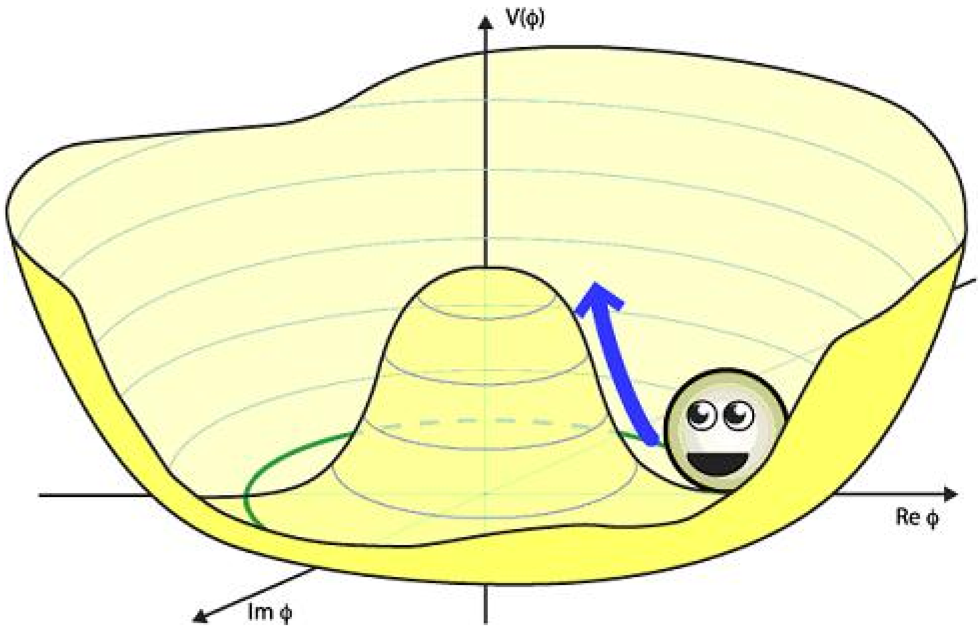
$$\phi \equiv \frac{1}{\sqrt{2}} [v + \varphi_1(x)] \; e^{i \varphi_2(x)/v}$$

Vacuum Choice

$$M_H = \sqrt{-2\mu^2} = \sqrt{2h} \; v$$

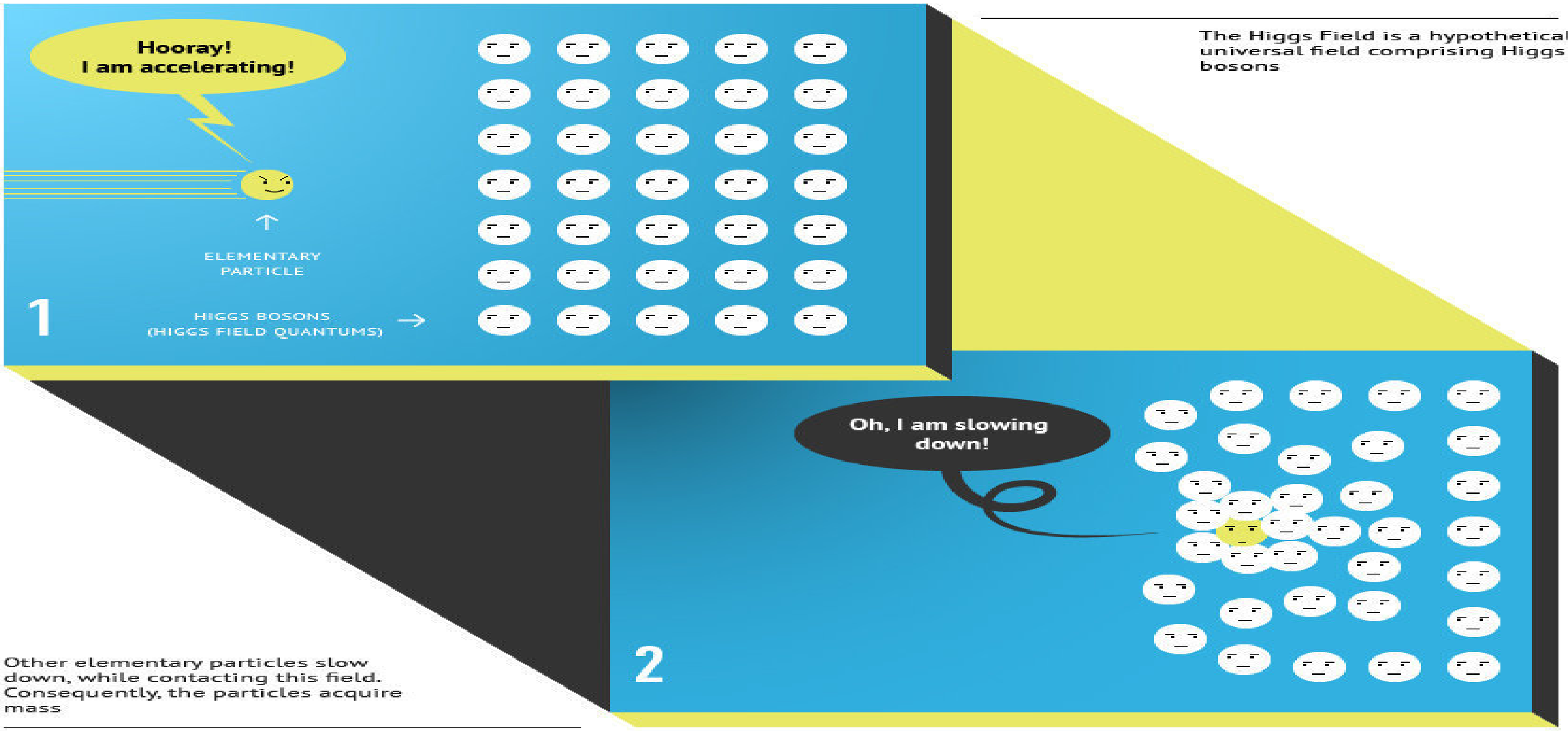

V(ϕ)
This costs too much energy! I think I'll hang out down there.
Re ϕ
Im ϕ


V(ϕ)
Re ϕ
Im ϕ

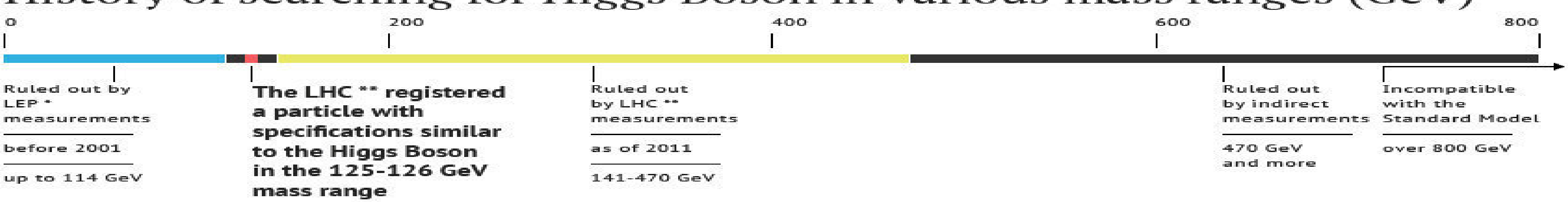

V(ϕ)
Re ϕ
Im ϕ

Higgs Boson – Missing Particle of Standard Model

The modern Standard Model of particle physics presupposes the existence of a particle responsible for the mass of other particles. The discovery of a similar particle was announced on July 4, 2012



History of searching for Higgs Boson in various mass ranges (GeV)

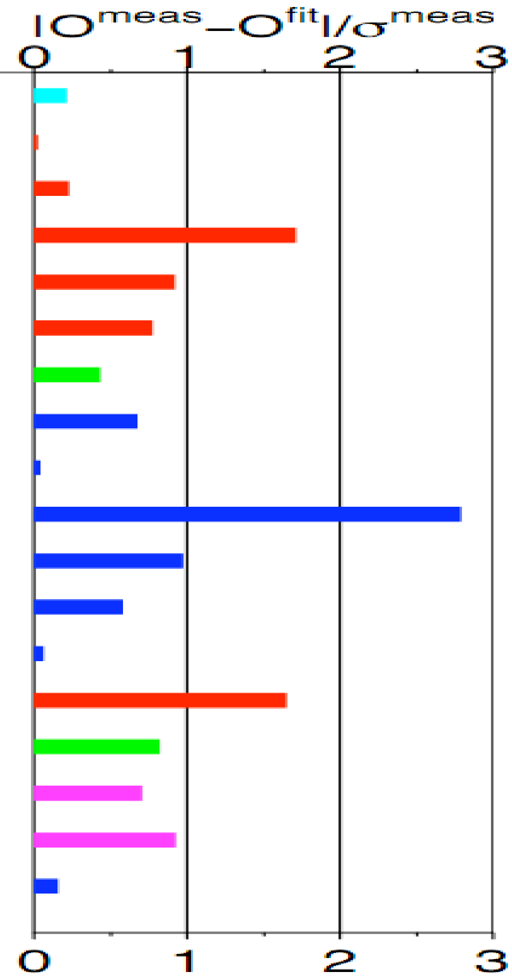


* LEP – Large Electron Positron Collider, the predecessor of the LHC (was located inside the same tunnel)
** LHC – Large Hadron Collider, the largest particle accelerator in terms of its energy levels. Searching for the Higgs Boson is one of its main tasks

RIANOVOSTI © 2012 WWW.RIA.RU

¿Es el SM suficiente?

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02766
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ_{had}^{0} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01640
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1479
R_b	0.21629 ± 0.00066	0.21585
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0741
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
$A_l(SLD)$	0.1513 ± 0.0021	0.1479
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.392 ± 0.029	80.371
Γ_W [GeV]	2.147 ± 0.060	2.091
m_t [GeV]	171.4 ± 2.1	171.7



Problemas del SM

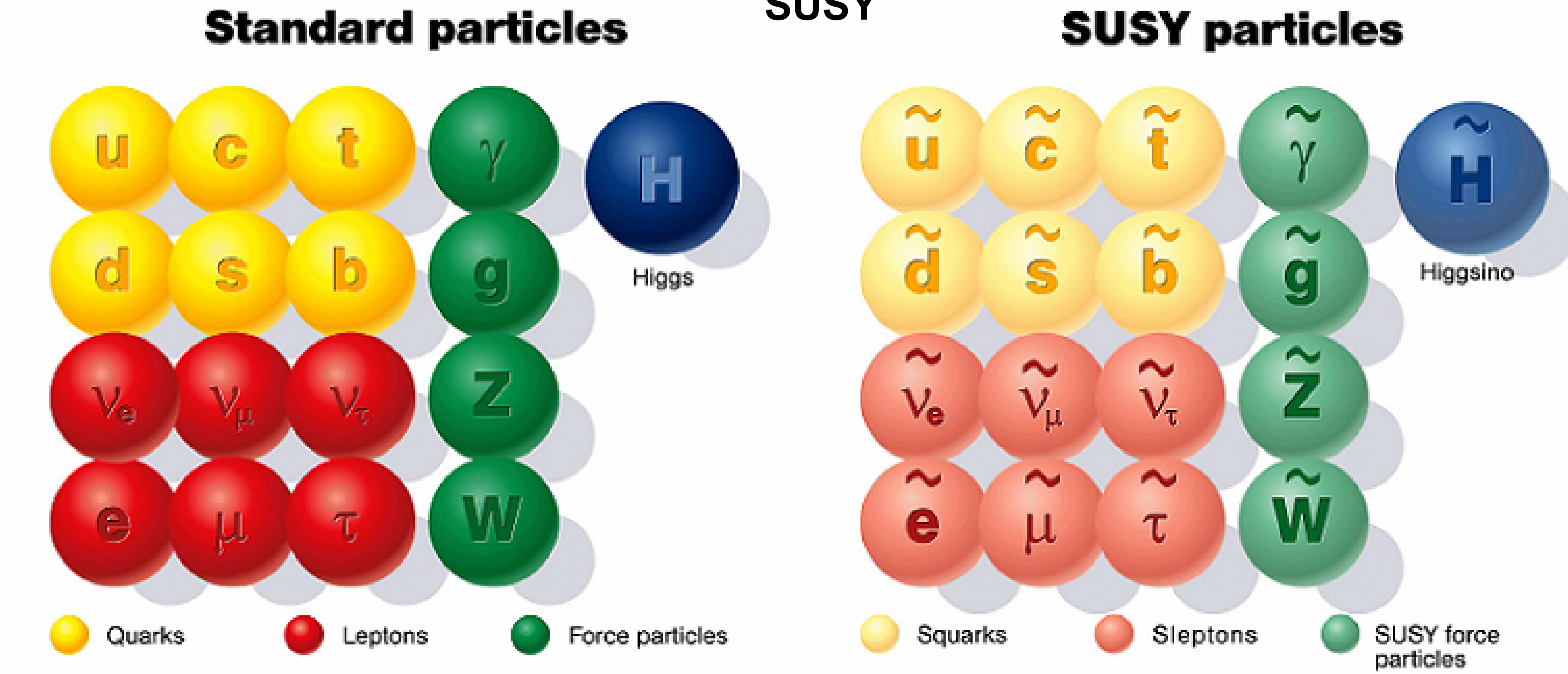
- Problema de la jerarquía: masas diversas y acoplamientos diferentes (fuerza fuerte vs débil) → Renormalización
- Materia oscura → neutrinos ? No parece…
- Modelo Higgs tiene problemas con la constante cosmológica → Expansión del Universo
- Unificación de fuerzas
- Strong CP → ¿Por qué QCD no viola la simetría CP?
- Oscilaciones de neutrinos (relacionado con masa)
- **Demasiados parámetros libres (más de 20) : 12 masas de fermiones, matrices de mezcla de quarks y neutrinos, la masa del bosón de Higgs**
- El SM es simplemente eso, un modelo, más que algo fundamental
- ¿Por qué 3 familias/generaciones?
- ¿Son los leptones/quarks subestructuras fundamentales?

~~Modelos~~ Teorías SUSY

- No hay evidencia directa (aun) de la existencia de supersimetría: están motivadas por posibles soluciones a varios problemas teóricos
- Como no se han observado “superpartners” de las partículas del SM, la SUSY debe ser una simetría rota (si es realmente una simetría de la naturaleza) → Superpartículas más pesadas que sus correspondientes en el SM
- Pros:
  – Si la supersimetría existe en energías cercanas a la escala de TeV, permite la solución del problema de la jerarquía
  – Permite la unificación de fuerzas (S y EW) a alta energía
  – Proporciona un candidato a materia oscura: neutralino (LSP)
  – Proporciona un mecanismo natural para la EWSB
- Cons:
  – Aun no han sido comprobadas experimentalmente….

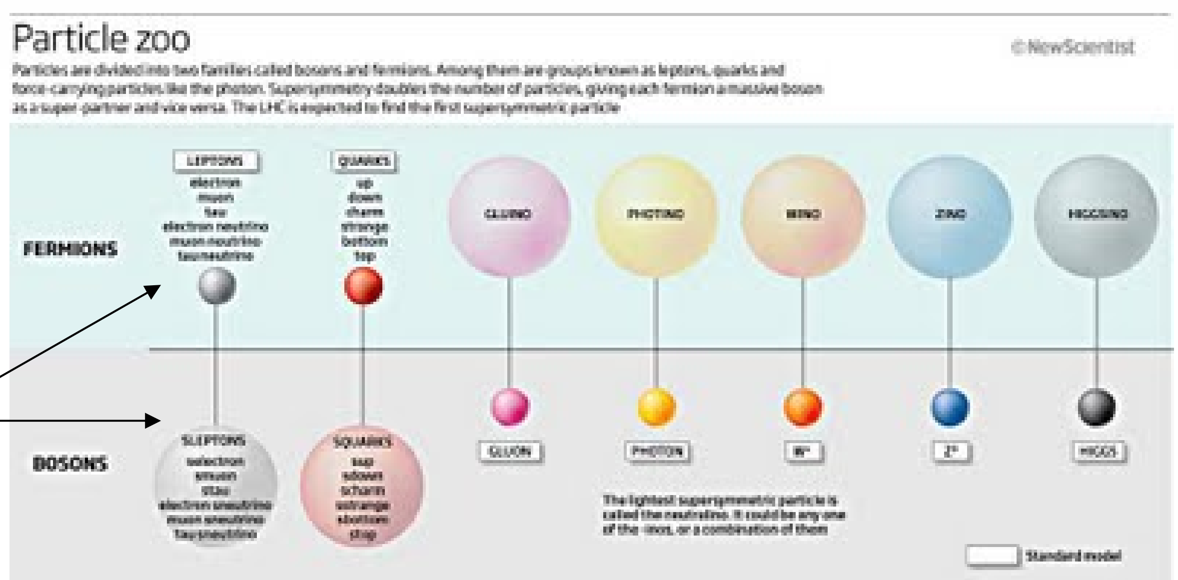
- Teorías:
  – Minimal Supersymetric Standard Model (MSSM)
  – Superstring Theory
  – Supergravity

SUSY



Números cuánticos identicos (salvo J)

Masas diferentes (simetría aun rota)



Difieren en spin por ½

E.g. Higgsino J= ½ ; sfermions J=0