Introducción al Modelo Estándar y el Higgs

Fefo (U. Colima)

Escuela de Física Fundamental

Morelia 2015

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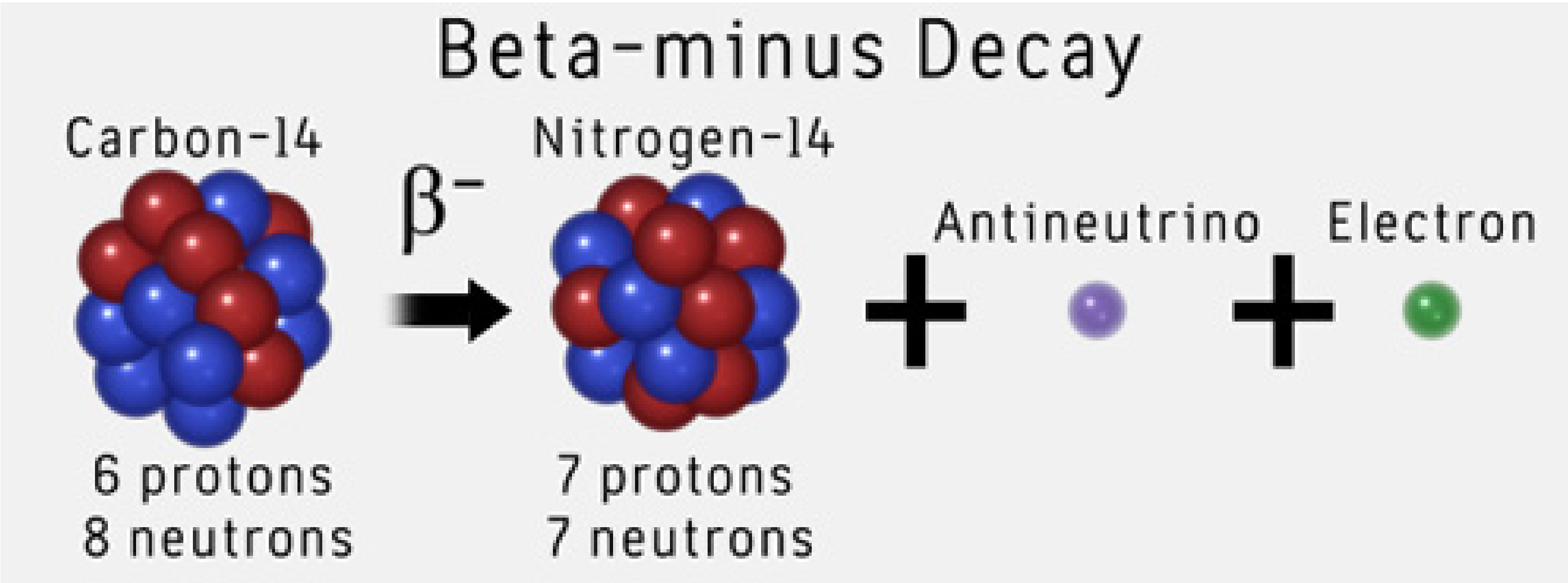
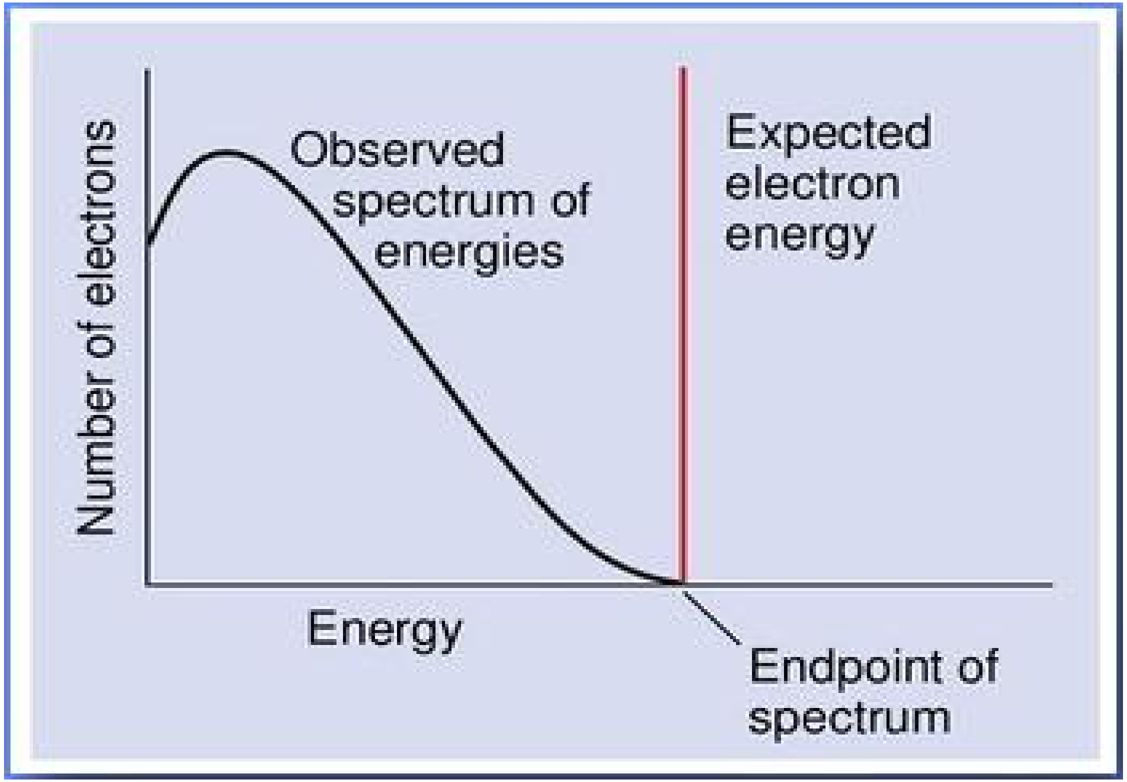
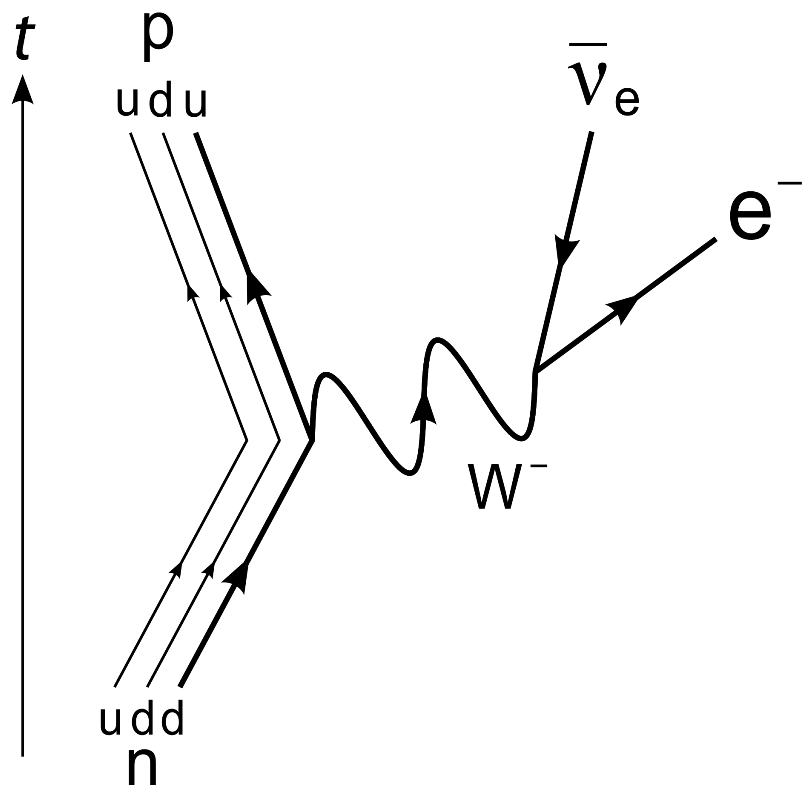
Nacimiento

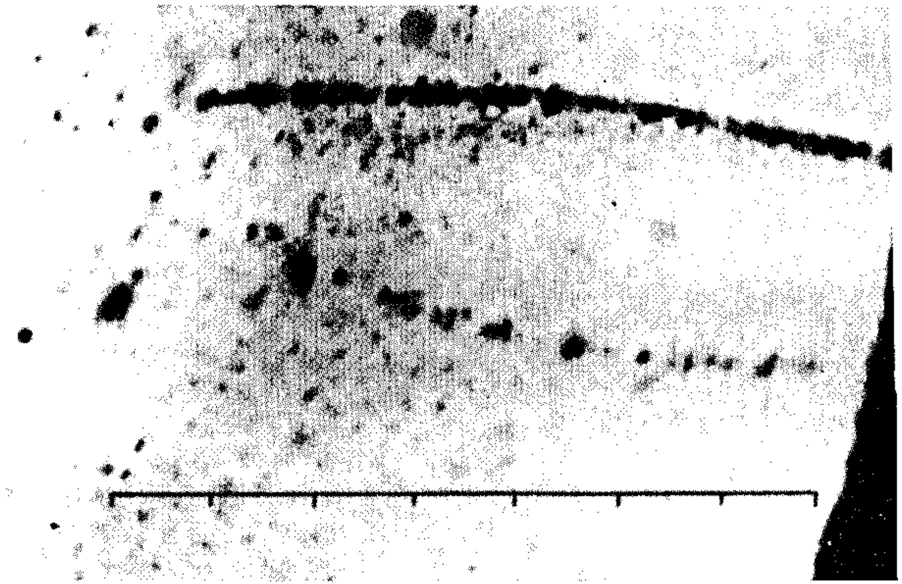


Beta-minus Decay
Carbon-14
β⁻
Nitrogen-14
Antineutrino
Electron
6 protons
8 neutrons
7 protons
7 neutrons


Number of electrons
Observed
spectrum of
energies
Expected
electron
energy
Energy
Endpoint of
spectrum



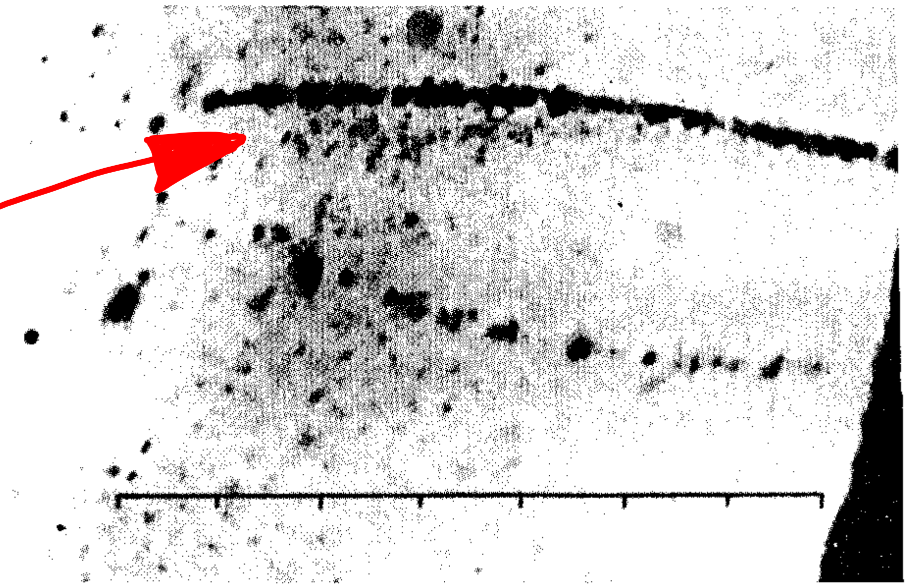
t
p
udu
$\bar{\nu}_e$
e^-
W^-
udd
n



"The other double trace of the same type (figure 5) shows closely together the thin trace of an electron of 37 MeV, and a much more strongly ionizing positive particle whith a much larger bending radius. The nature of this particle is unknown; for a proton it does not ionize enough and for a positive electron the ionization is too strong. The present double trace is probably a segment from a "shower" of particles as they have been observed by Blackett and Occhialini, i.e. the result of a nuclear explosion".

Kunze, P., Z. Phys. 83, (1933) 1

WTF



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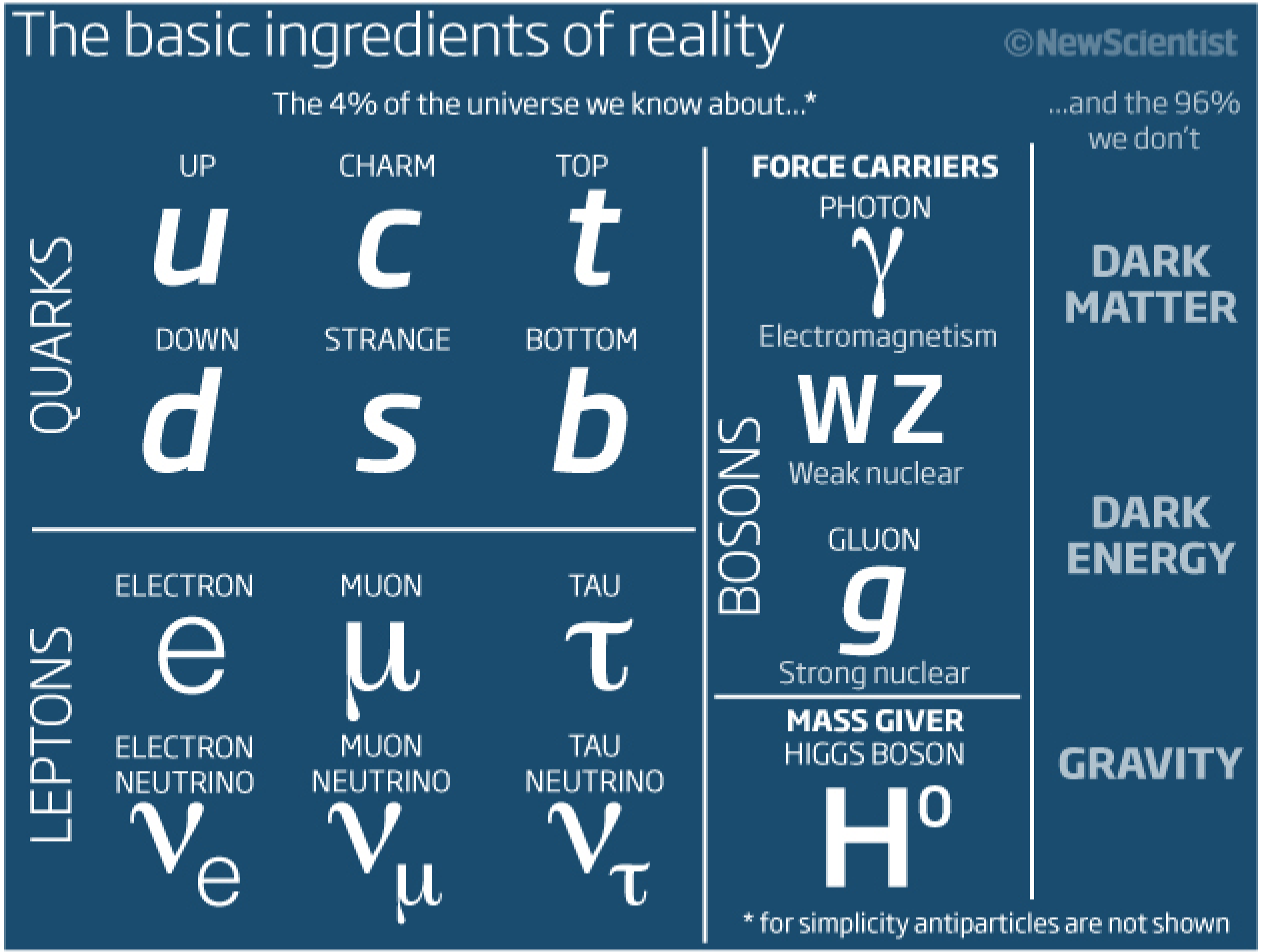
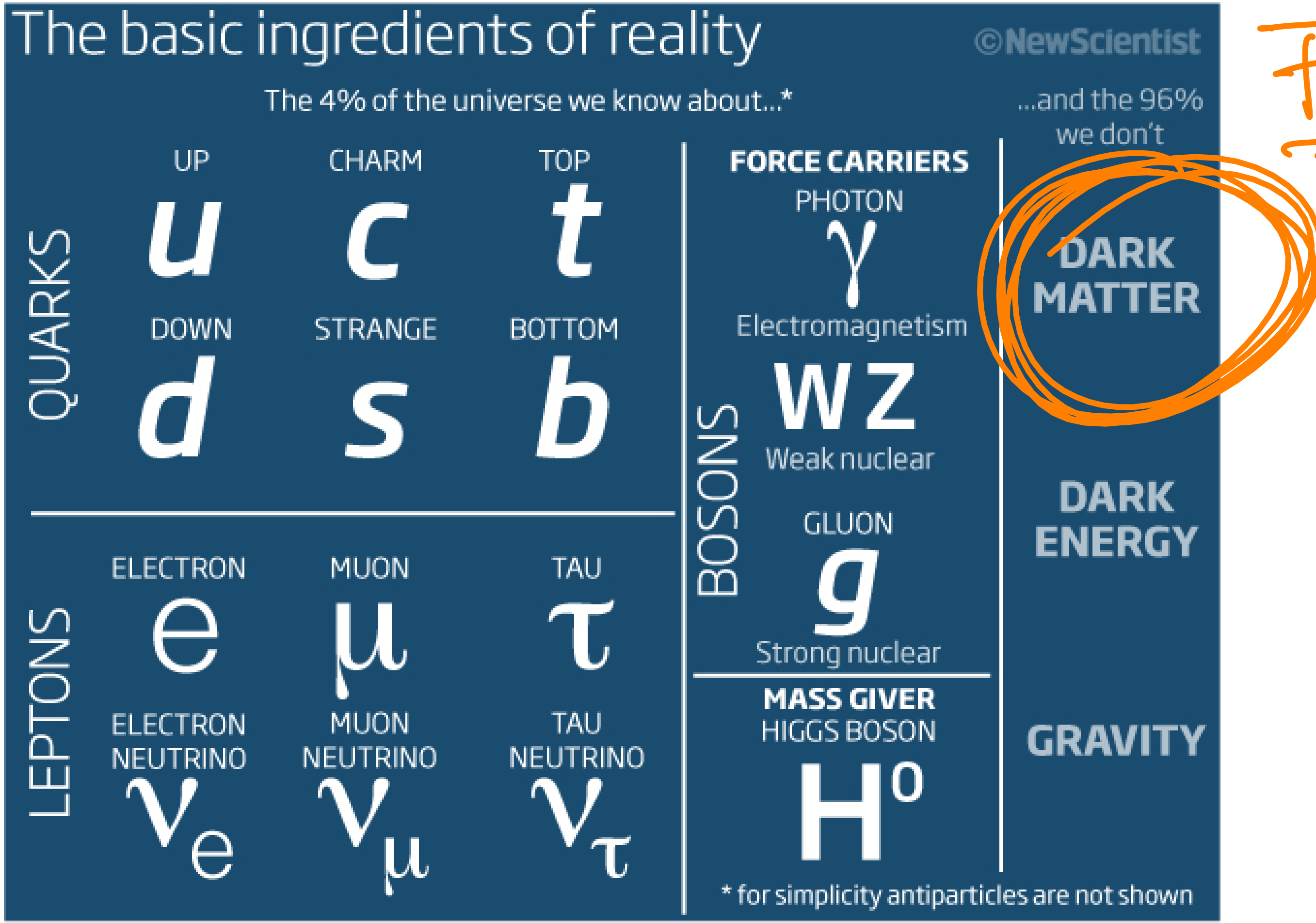
Partículas el día de hoy

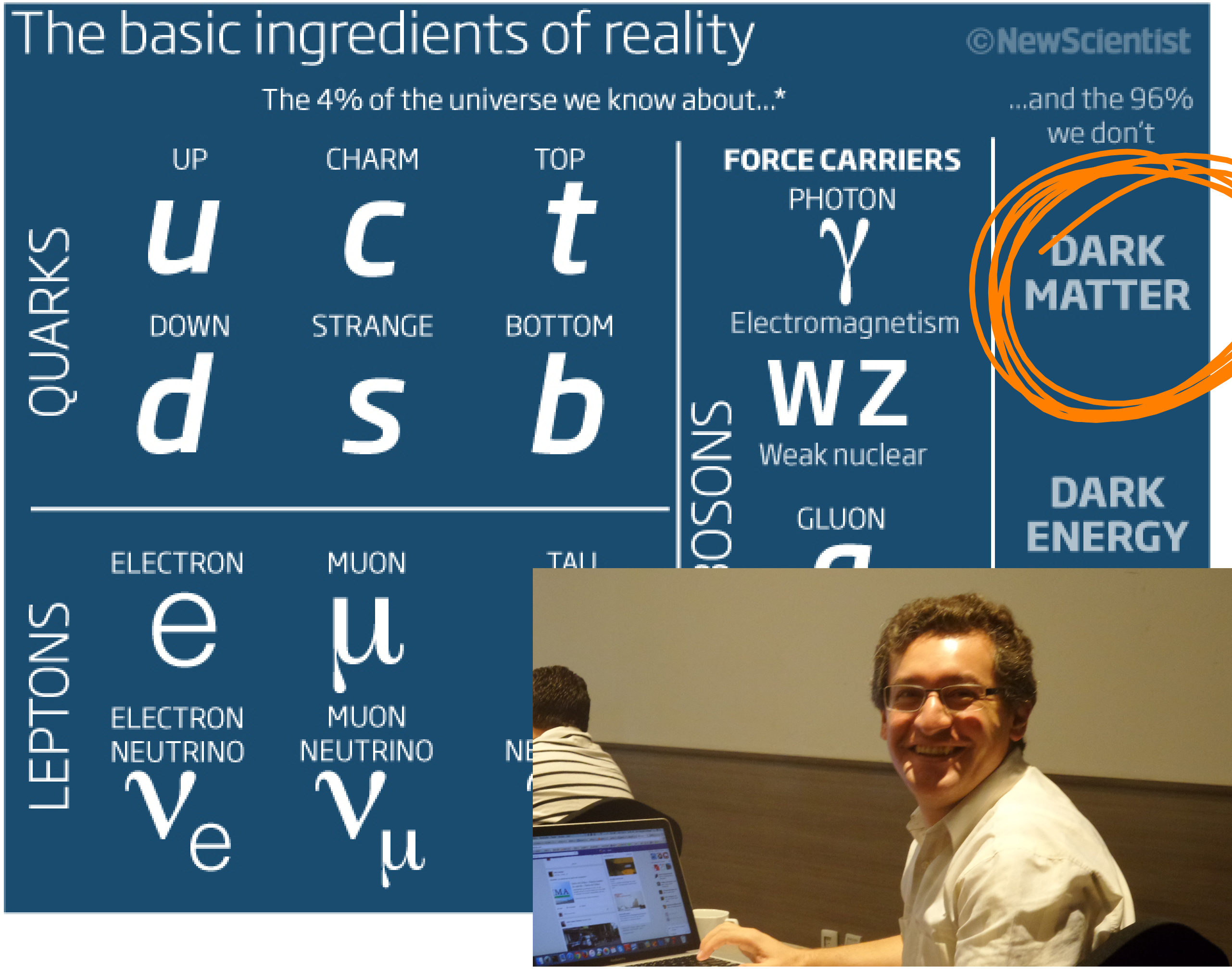

The basic ingredients of reality
©NewScientist
The 4% of the universe we know about...*
...and the 96% we don't
QUARKS
UP u
CHARM c
TOP t
DOWN d
STRANGE s
BOTTOM b
LEPTONS
ELECTRON e
MUON μ
TAU τ
ELECTRON NEUTRINO ν_e
MUON NEUTRINO ν_μ
TAU NEUTRINO ν_τ
BOSONS
FORCE CARRIERS
PHOTON γ
Electromagnetism
W Z
Weak nuclear
GLUON g
Strong nuclear
MASS GIVER
HIGGS BOSON H^0
DARK MATTER
DARK ENERGY
GRAVITY
* for simplicity antiparticles are not shown



FUTURO

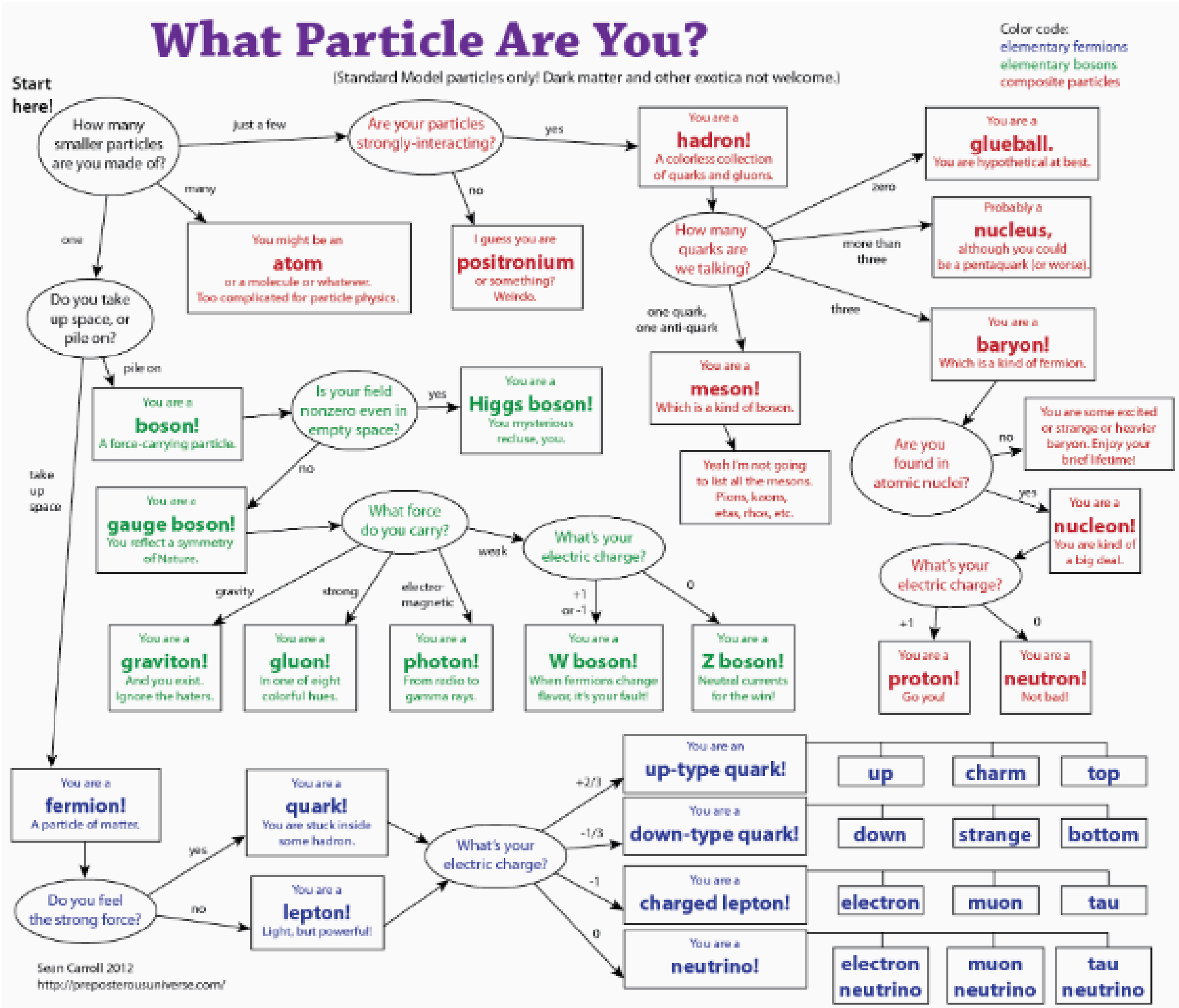
y

PRESENTE



FUTURO
y
PRESENTE

ERIK


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!
up
charm
top
You are a down-type quark!
down
strange
bottom
You are a charged lepton!
electron
muon
tau
You are a neutrino!
electron neutrino
muon neutrino
tau neutrino
Sean Carroll 2012
http://preposterousuniverse.com/

Modelo Estándar

- Tres interacciones

Modelo Estándar

- Tres interaciones

Electromagnética

Modelo Estándar

- Tres interacciones

    Electromagnética

    débil

Modelo Estándar

- Tres interacciones

  Electromagnética

  débil

  fuerte

Modelo Estándar

- Tres interacciones

Electromagnética   Rango infinito

débil   Rango finito

fuerte   Rango finito

Modelo Estándar

- Tres interacciones

Electromagnética Rango infinito $\rightarrow m = 0$

débil Rango finito

fuerte Rango finito

Modelo Estándar

- Tres interacciones

Electromagnética Rango infinito $\rightarrow m = 0$

débil Rango finito $\rightarrow m \neq 0$

fuerte Rango finito $\rightarrow$?

Modelo Estándar

TAREA

- Tres interacciones

Electromagnética Rango infinito → $m = 0$

débil Rango finito → $m \neq 0$

fuerte Rango finito → ?

Modelo Estándar

- Tres interacciones

  Electromagnética Rango infinito $\rightarrow m = 0$

  débil Rango finito $\rightarrow m \neq 0$

  fuerte Rango finito $\rightarrow$?

$\rightarrow$ Teoría GAUGE $SU(3)_c \times SU(2)_L \times U(1)_Y$

Modelo Estándar

- Tres interacciones

Electromagnética Rango infinito $\rightarrow m = 0$

débil Rango finito $\rightarrow m \neq 0$

fuerte Rango finito $\rightarrow$?

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Modelo Estándar

- Tres interacciones

Electrodébil

Electromagnética Rango infinito → $m = 0$

débil Rango finito → $m \neq 0$

fuerte Rango finito → ?

→ Teoría GAUGE $SU(3)_C \times SU(2)_L \times U(1)_Y$

Modelo Estándar

- Tres interacciones

Electromagnética   Rango infinito $\rightarrow m = 0$

débil   Rango finito $\rightarrow m \neq 0$

fuerte   Rango finito $\rightarrow$?

$\rightarrow$ Teoría GAUGE $SU(3)_C \times SU(2)_L \times U(1)_Y$

gluones $\uparrow$ $W^{\pm}, Z^0, \gamma$

(H)

Modelo Estándar

- Materia:

  6 quarks

  6 leptones

Modelo Estándar

- Materia: fuerte débil E&M

6 quarks

6 leptones

Modelo Estándar

• Materia:

	fuerte	débil	E&M
6 quarks	✓		
6 leptones			

Modelo Estándar

- Materia:

	fuerte	débil	E&M
6 quarks	✓	✓	
6 leptones			

Modelo Estándar

- Materia:

	fuerte	débil	E&M
6 quarks	✓	✓	✓
6 leptones			

Modelo Estándar

- Materia:

	fuerte	débil	E&M
6 quarks	✓	✓	✓
6 leptones	✗		

Modelo Estándar

- Materia:

	fuerte	débil	E&M
6 quarks	✓	✓	✓
6 leptones	✗	✓	

Modelo Estándar

- Materia:

	fuerte	débil	E&M
6 quarks	✓	✓	✓
6 leptones	✗	✓	✓ ✗

Modelo Estándar

- Materia:

	fuerte	débil	E&M
6 quarks	✓	✓	✓
6 leptones	✗	✓	✓ ✗

neutrinos

Construcción del Modelo Estándar

- Escalares (Lagrangiano, simetrías, ...)
- fermiones
- Vectores
- Simetría GAUGE $\begin{cases} \text{Abeliana} \\ \text{No.- Abeliana} \end{cases}$

- Construcción de una teoría GAUGE con grupo No-abeliano $SU(3) \times SU(2) \times U(1)$ y con materia.

- Consecuencias fenomenológicas

- Ya.

Unidades "NATURALES"

$$\boxed{\hbar = c = 1}$$

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Utilizaremos unidades de energía: eV

$$[\text{distancia}] = [eV]^{-1} = [\text{tiempo}]$$

$$[\text{masa}] = [eV], \text{ etcétera}$$

Unidades "NATURALES"

$$\boxed{\hbar = c = 1}$$

Utilizaremos unidades de energía: eV

$$[\text{distancia}] = [\text{eV}]^{-1} = [\text{tiempo}]$$

"dimensión de masa"

$$[\text{masa}] = [\text{eV}],$$ etcétera

ESCALARES

Campo escalar real libre $\phi(x)$

$$\mathcal{L} = \frac{1}{2} \partial_\mu \phi(x) \partial^\mu \phi(x) - \frac{m^2}{2} \phi^2(x)$$

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masa de la partícula asociada a $\phi(x)$

ESCALARES

Campo escalar real libre $\phi(x)$

$$\mathcal{L} = \frac{1}{2}\,\partial_\mu \phi(x)\,\partial^\mu \phi(x) - \frac{m^2}{2}\,\phi^2(x)$$

La transformación $\phi(x) \longrightarrow \phi'(x) = -\phi(x)$

deja a $\mathcal{L}$ <u>invariante</u>

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$$[\phi(x)] =$$

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deja a $\mathcal{L}$ invariante $\longrightarrow$ simetría Z_2

$$[\phi(x)] = 1$$

TAREA: Determina la "dimensión" de un campo escalar $\phi(x)$ en un espacio-tiempo n-dimensional.

.

Dos campos escalares reales $\phi_1(x)$ y $\phi_2(x)$:

$$\mathcal{L} = \frac{1}{2}\partial_\mu \phi_1(x)\partial^\mu \phi_1(x) - \frac{m_1^2}{2}\phi_1^2(x)$$
$$+ \frac{1}{2}\partial_\mu \phi_2(x)\partial^\mu \phi_2(x) - \frac{m_2^2}{2}\phi_2(x)$$

Simetrías Z_2 independientes ✓

Juguemos:

* Definamos $\Phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1(x) \\ \phi_2(x) \end{pmatrix}$

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$$\rightarrow \mathcal{L} = \partial_\mu \Phi^T(x)\, \partial^\mu \Phi(x) - \Phi^T M^2 \Phi$$

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* Definamos $\Phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1(x) \\ \phi_2(x) \end{pmatrix}$

$$\rightarrow \mathcal{L} = \partial_\mu \Phi(x)^T \partial^\mu \Phi(x) - \Phi^T(x) M^2 \Phi(x)$$

donde $M^2 \equiv \begin{pmatrix} m_1^2 & 0 \\ 0 & m_2^2 \end{pmatrix}$

$$\mathcal{L} = \partial_\mu \Phi(x)^T \partial^\mu \Phi(x) - \Phi(x)^T M^2 \Phi(x)$$

Las dos simetrías Z_2 corresponden ahora a

$$\mathcal{L} = \partial_\mu \Phi(x)^T \partial^\mu \Phi(x) - \Phi(x)^T M^2 \Phi(x)$$

Las dos simetrías Z_2 corresponden ahora a

$$\Phi(x) \to \Phi'(x) = -\Phi(x)$$

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Las dos simetrías Z_2 corresponden ahora a

$$\Phi(x) \to \Phi'(x) = -\Phi(x)$$

$$\Phi(x) \to \Phi'(x) = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \Phi(x)$$

$$\mathcal{L} = \partial_\mu \Phi(x)^T \partial^\mu \Phi(x) - \Phi(x)^T M^2 \Phi(x)$$

Las dos simetrías Z_2 corresponden ahora a

$$\Phi(x) \longrightarrow \Phi'(x) = -\Phi(x)$$

$$\Phi(x) \longrightarrow \Phi'(x) = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \Phi(x)$$

$$\Phi(x) \longrightarrow \Phi'(x) = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} \Phi(x)$$

Sigamos jugando:

Consideremos la transformación global $\underline{\Phi}'(x) = \underline{O}\,\underline{\Phi}(x)$, donde $\underline{O}$ es una matriz ortogonal de 2×2

"Claramente" el término cinético es invariante:

$$\partial_\mu \underline{\Phi}'^T(x)\, \partial^\mu \underline{\Phi}'(x) = \partial_\mu \underline{\Phi}^T(x)\, \underline{O}^T \partial^\mu \underline{O}\, \underline{\Phi}(x)$$

$$= \partial_\mu \underline{\Phi}^T(x)\, \partial^\mu \underline{\Phi}(x)$$

El término de masa es:

$$\Phi'^T(x)\, M^2\, \Phi'(x) = \Phi^T(x)\, \underline{O}^T M^2 \underline{O}\, \Phi(x)$$

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$$\underline{\Phi}'^{T}(x)\, M^2\, \underline{\Phi}'(x) = \underline{\Phi}^{T}(x)\, \underline{O}^{T} M^2 \underline{O}\, \underline{\Phi}(x)$$

$$\underline{O}^{T} M^2 \underline{O} = M^2 \quad \text{iff} \quad M^2 \propto \mathbb{1}$$

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$\Longrightarrow$ Campos escalares degenerados en masa

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$$\underline{O}^T M^2 \underline{O} = M^2 \quad \text{iff} \quad M^2 \propto \mathbb{1}$$

$\Rightarrow$ Campos escalares degenerados en masa

$\Rightarrow$ $\mathcal{L}$ posee simetría $O(2)$

En realidad nada es tan abumido:

$$\mathcal{L} = \partial_\mu \Phi^T(x)\, \partial^\mu \Phi(x) - \Phi^T(x)\, M^2\, \Phi(x) + \lambda\left(\Phi^T(x)\, \Phi(x)\right)^2$$

- También tiene simetría $O(2)$
- Simetría $O(2)$ "dictamina" forma del potencial!!

En realidad nada es <u>tan</u> aburrido:

$$\mathcal{L} = \partial_\mu \Phi^T(x)\, \partial^\mu \Phi(x) - \Phi^T(x)\, M^2\, \Phi(x)$$
$$+ \lambda\left(\Phi^T(x)\,\Phi(x)\right)^2 + K_3\left(\Phi^T(x)\,\Phi(x)\right)^3 + \ldots$$

- También tiene simetría $O(2)$

- Simetría $O(2)$ "dictamina" forma del potencial!!

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$$[\lambda] = 0 \,, \qquad [K_3] = -2$$

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Renormalizabilidad :

$$\mathcal{L} = \partial_\mu \Phi^T(x)\, \partial^\mu \Phi(x) - \Phi^T(x)\, M^2\, \Phi(x) + \lambda\left(\Phi^T(x)\,\Phi(x)\right)^2 + \cancel{K_3\left(\Phi^T(x)\,\Phi(x)\right)^3} + \dots$$

$$[\lambda] = 0\,, \qquad [K_3] = -2$$

<u>Renormalizabilidad</u>: Términos con acoplamientos con dimensión de masa ≥ 0

"OBVIAMENTE" es fácil generalizar al caso de n campos escalares degenerados en masa.

El Lagrangiano ahora tendrá simetría $O(n)$

Sigamos jugando con dos campos reales $\phi_1(x)$ y $\phi_2(x)$.

Definamos el campo esccalar complejo:

$$\Phi(x) = \frac{1}{\sqrt{2}}\left(\phi_1(x) + i\,\phi_2(x)\right)$$

Notemos que, si son degenerados en masa,

$$\mathcal{L} = \partial_\mu \Phi^*(x)\, \partial^\mu \Phi(x) - m^2 \Phi^*(x)\, \Phi(x)$$

¿Dónde están las simetrías Z_2?

$$\mathcal{L} = \partial_\mu \Phi^*(x)\, \partial^\mu \Phi(x) - m^2 \Phi^*(x)\Phi(x)$$

$$\Phi(x) \to \Phi'(x) = -\Phi(x), \quad \mathcal{L}' = \mathcal{L} \checkmark$$

$$\Phi^{*\prime}(x) = -\Phi^*(x)$$

¿Dónde están las simetrías Z_2?

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$$\Phi(x) \rightarrow \Phi'(x) = -\Phi(x), \quad \mathcal{L}' = \mathcal{L} \checkmark$$
$$\Phi^{*\prime}(x) = -\Phi^*(x)$$

$$\Phi(x) \rightarrow \Phi'(x) = e^{i\alpha}\Phi(x), \quad \mathcal{L}' = \mathcal{L}$$

$\mathcal{L}$ posee simetría $U(1)$

Que siga el juego: Dos campos escalares complejos

$$\Phi_1(x) \quad y \quad \Phi_2(x)$$

- Si son degenerados en masa uno esperaría <u>simetría</u>

Que siga el juego: Dos campos escalares complejos

$$\Phi_1(x) \quad \text{y} \quad \Phi_2(x)$$

- Si son degenerados en masa (equivalente a 4 reales $\rightarrow O(4)$)

uno esperaría <u>simetría</u>

Que siga el juego: Dos campos escalares complejos

$\Phi_1(x)$ y $\Phi_2(x)$

- Si son degenerados en masa (equivalente a 4 reales $\to O(4)$)
  uno esperaría <u>simetría</u>

- definamos $\rho(x) = \begin{pmatrix} \Phi_1(x) \\ \Phi_2(x) \end{pmatrix}$

Entonces

$$\mathcal{L} = \partial_\mu \phi(x)^\dagger \partial^\mu \phi(x) - \phi(x)^\dagger M^2 \phi(x)$$

con $M^2 \sim \mathbb{1}$ para el caso degenerado.

Entonces

$$\mathcal{L} = \partial_\mu \phi(x)^\dagger \partial^\mu \phi(x) - \phi(x)^\dagger M^2 \phi(x)$$

con $M^2 \sim \mathbb{1}$ para el caso degenerado.

Si $\phi(x) \rightarrow \phi'(x) \equiv U\phi(x)$, donde U es una matriz unitaria (con $\det = +1$)

$$\mathcal{L}' = \partial_\mu \rho'^{\dagger}(x)\, \partial^\mu \rho'(x) - \rho'(x)^\dagger M^2 \rho'(x)$$

$$= \partial_\mu \rho^{\dagger}(x)\, U^\dagger \partial^\mu U \rho(x) - \rho(x)^\dagger U^\dagger U \rho(x)\, m^2$$

$$= \partial_\mu \rho^{\dagger}(x)\, \partial^\mu \rho(x) - \rho(x)^\dagger M^2 \rho(x) = \mathcal{L}$$

$\mathcal{L}$ posee simetría $SU(2)$ global

Igual que el caso real, si tenemos N campos escalares complejos degenerados en masa,

$\mathcal{L}$ posee simetría $SU(N)$

TAREA: De seguro observaron que si $U \in U(2)$, el Lagrangiano también es invariante.

¿Por qué decidí SOLO considerar $SU(2)$?

Regresemos al caso real:

$$\mathcal{L} = \frac{1}{2}\partial_\mu \phi(x)\partial^\mu \phi(x) - \frac{m^2}{2}\phi^2(x)$$

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Simetría $\mathbb{Z}_2$

Regresemos al caso real:

$$\mathcal{L} = \frac{1}{2}\partial_\mu \phi(x)\partial^\mu \phi(x) - \frac{m^2}{2}\phi^2(x)$$

Simetría Z_2

- Potencial (interacción)

$$\mathcal{L} = \frac{1}{2}\partial_\mu \phi(x)\partial^\mu \phi(x) - V(\phi)$$

Regresemos al caso real:

$$\mathcal{L} = \frac{1}{2}\partial_\mu \phi(x)\partial^\mu \phi(x) - \frac{m^2}{2}\phi^2(x)$$

Simetría Z_2

- Potencial (interacción)

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$\mu^2 = m^2$ es la $(\text{masa})^2$ ✓

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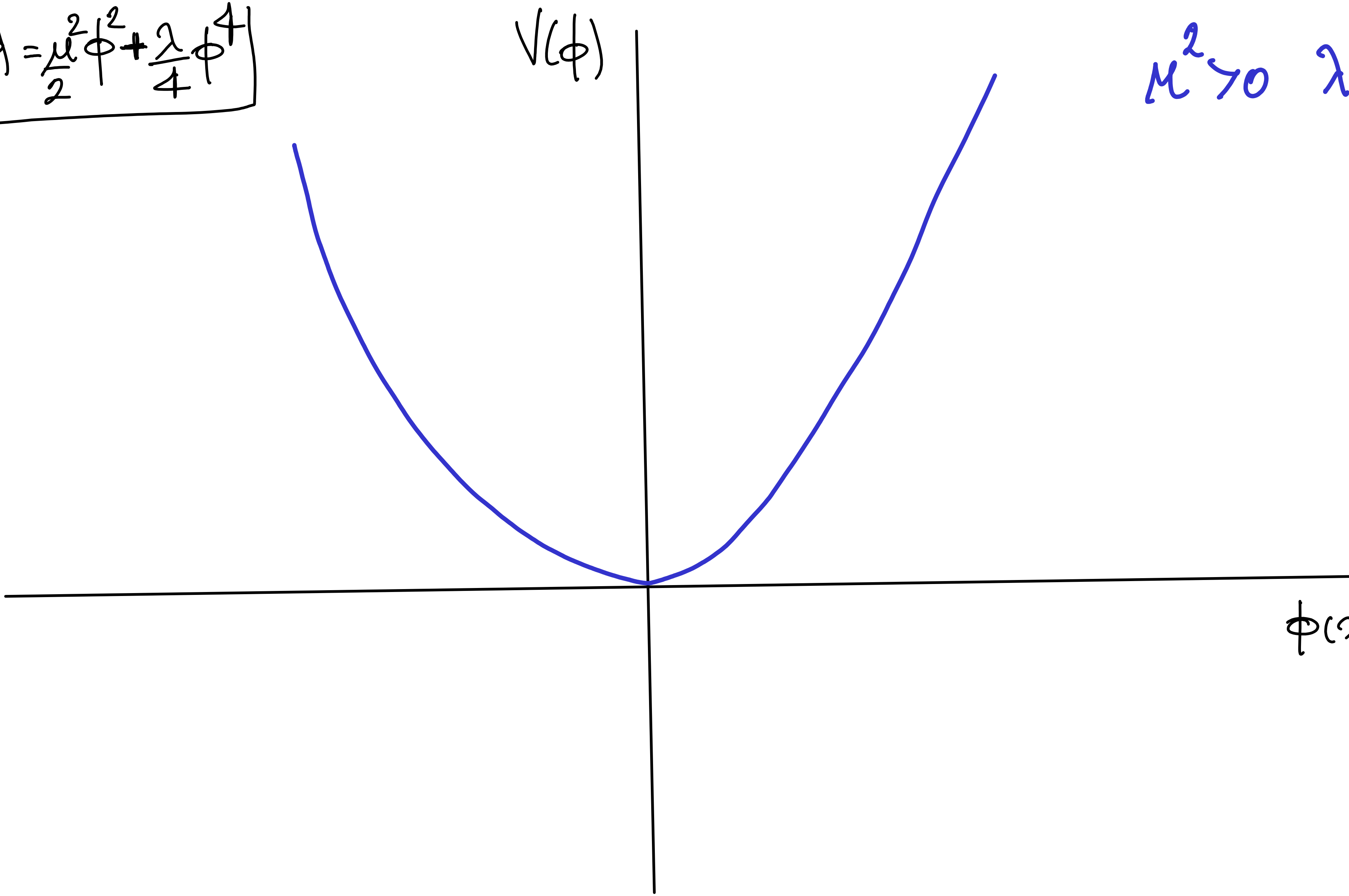
$$\mu^2 \neq m^2 \quad ?$$

$$\boxed{V(\phi) = \frac{\mu^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4}$$

$\mu^2 > 0 \quad \lambda > 0$



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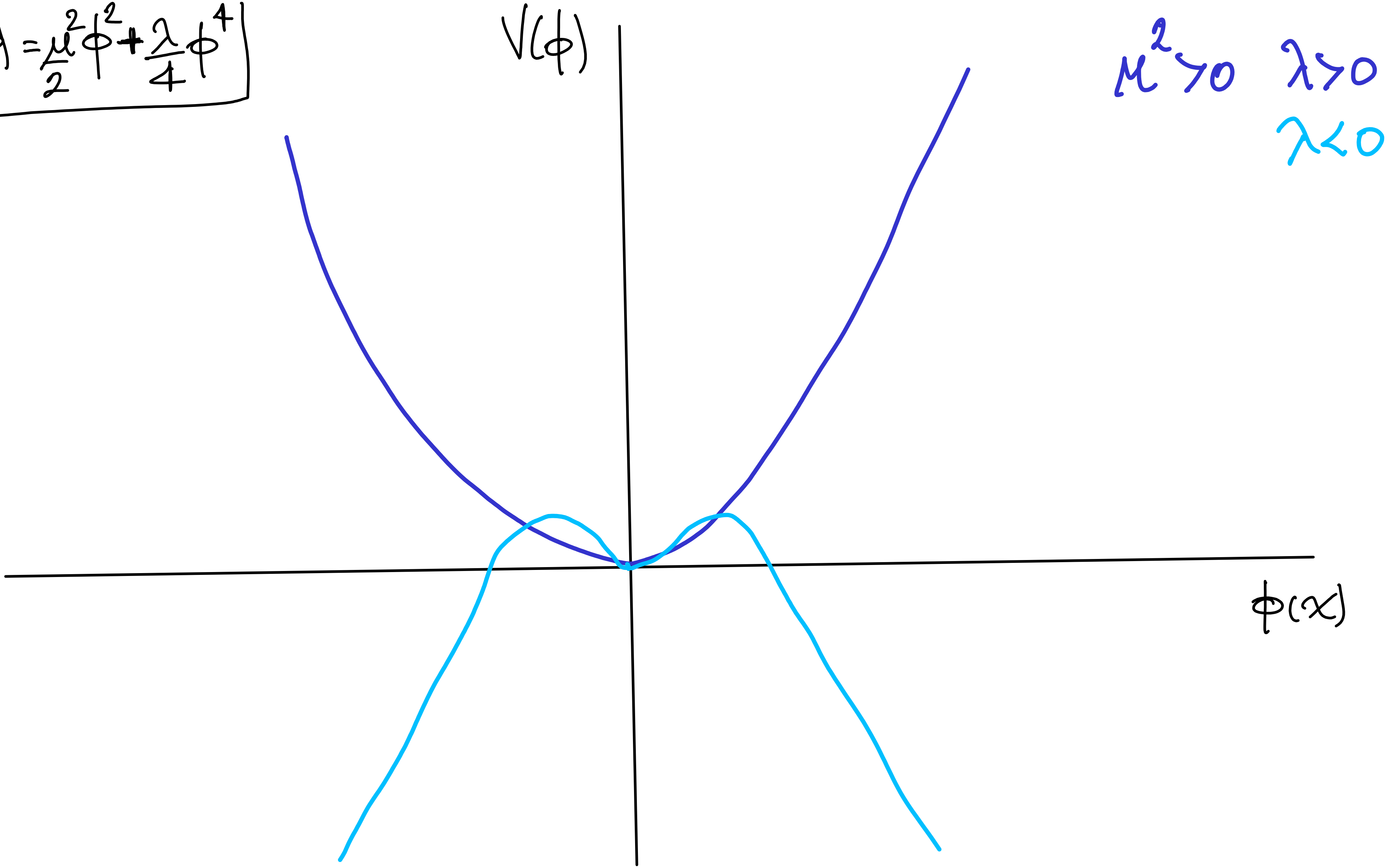

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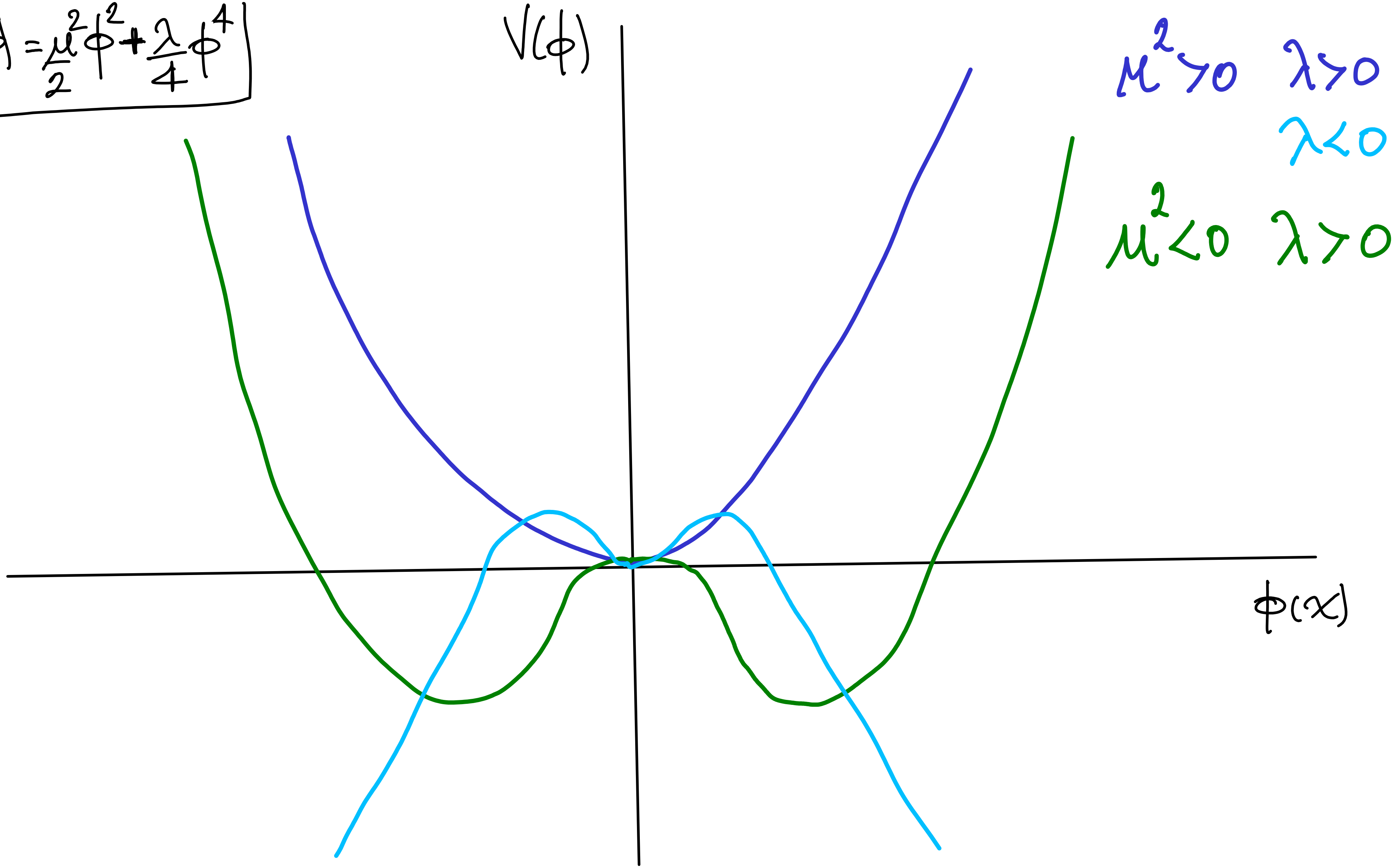

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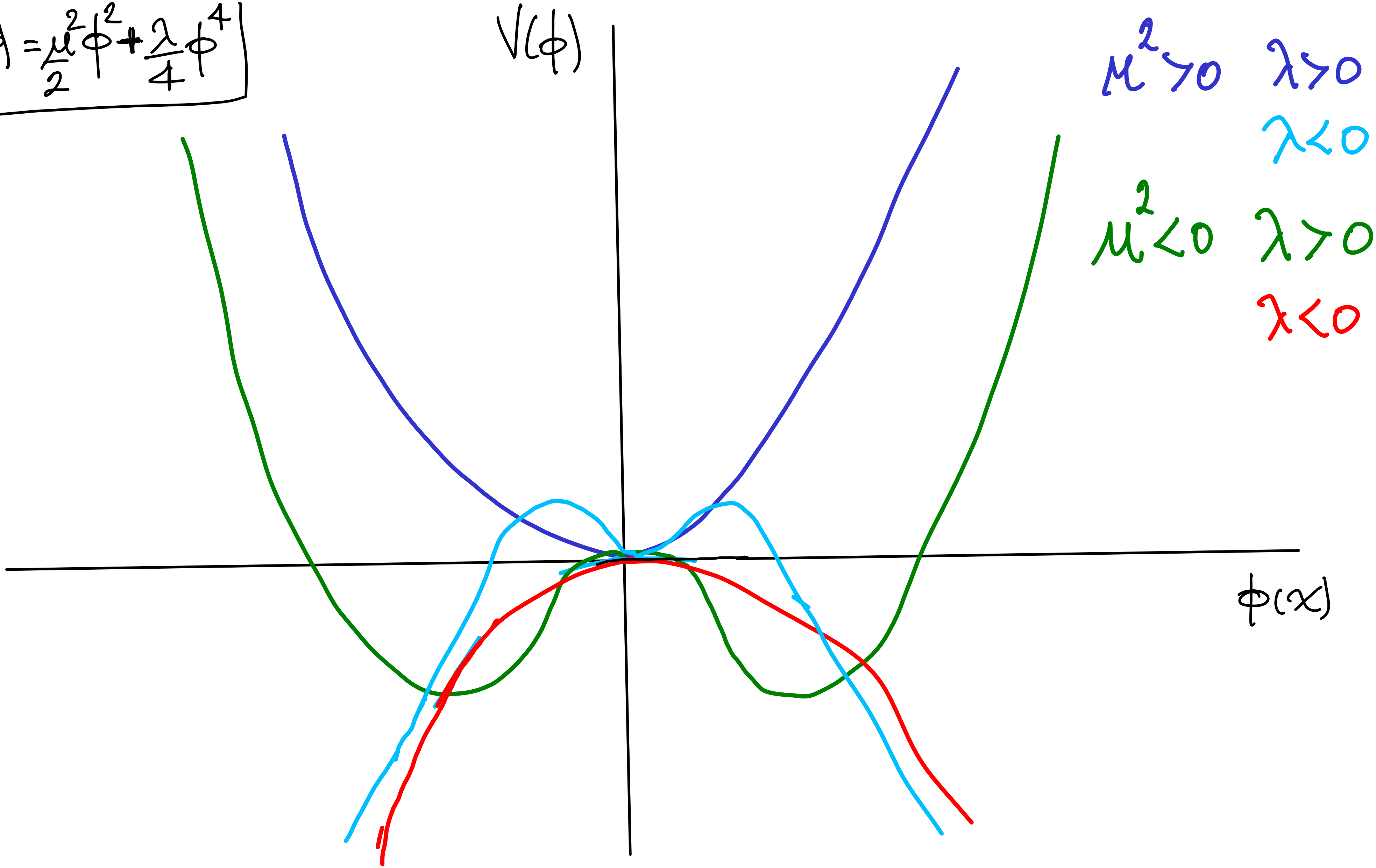

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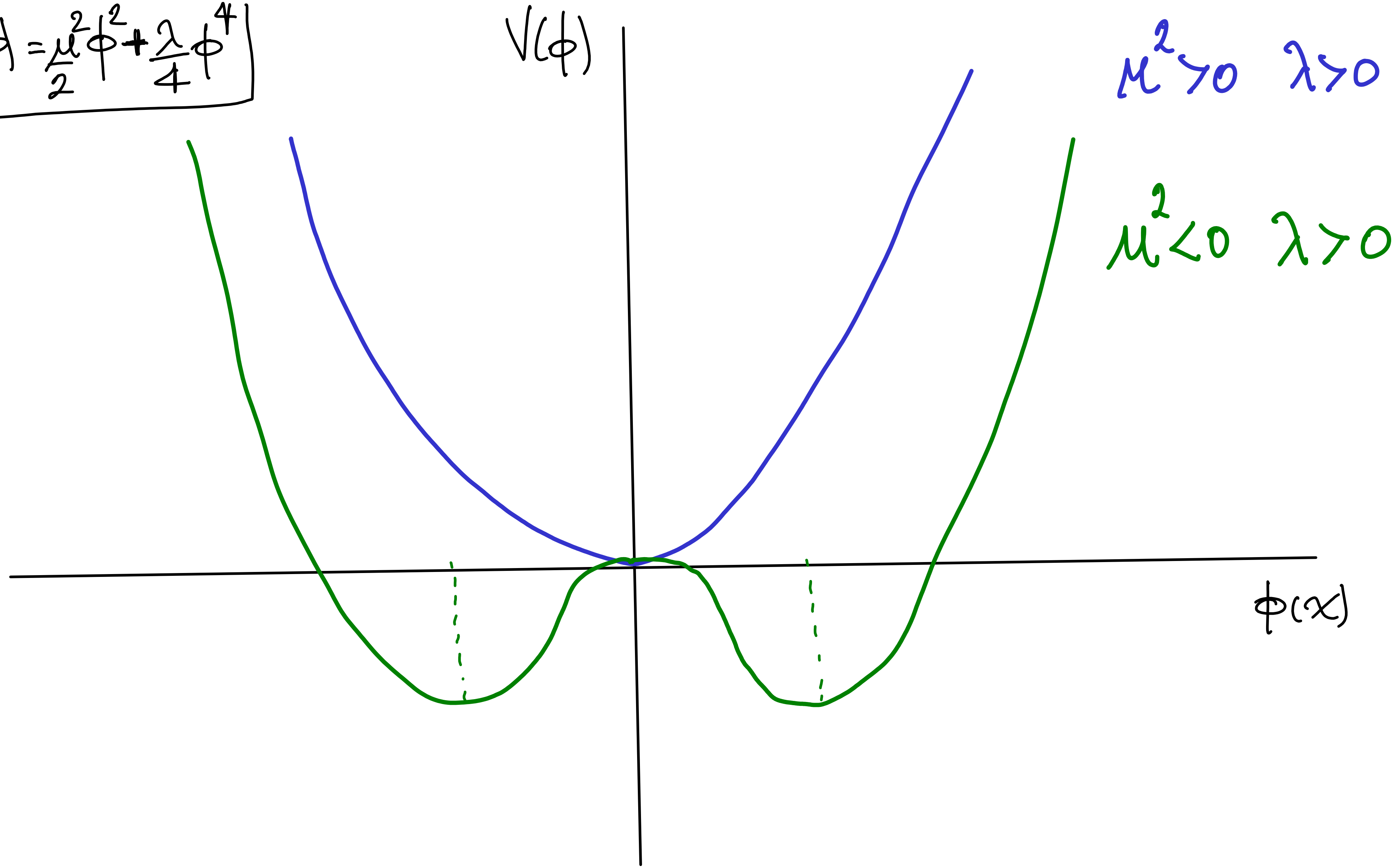
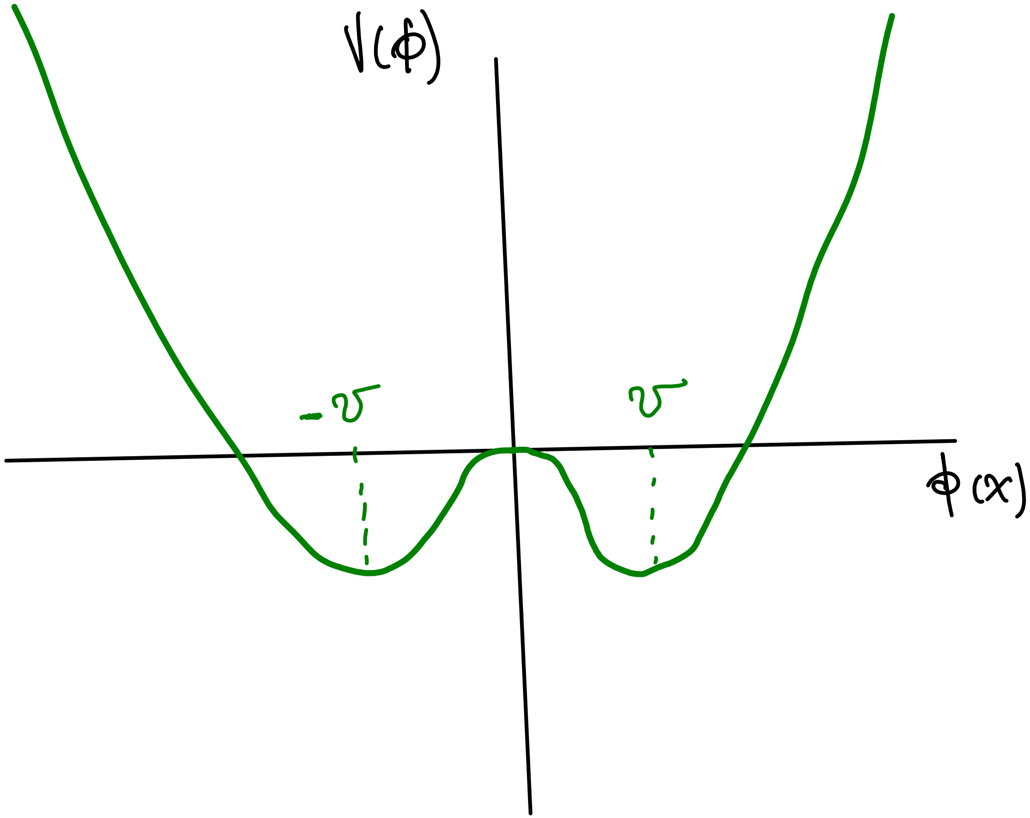


Rompimiento espontáneo de la simetría:



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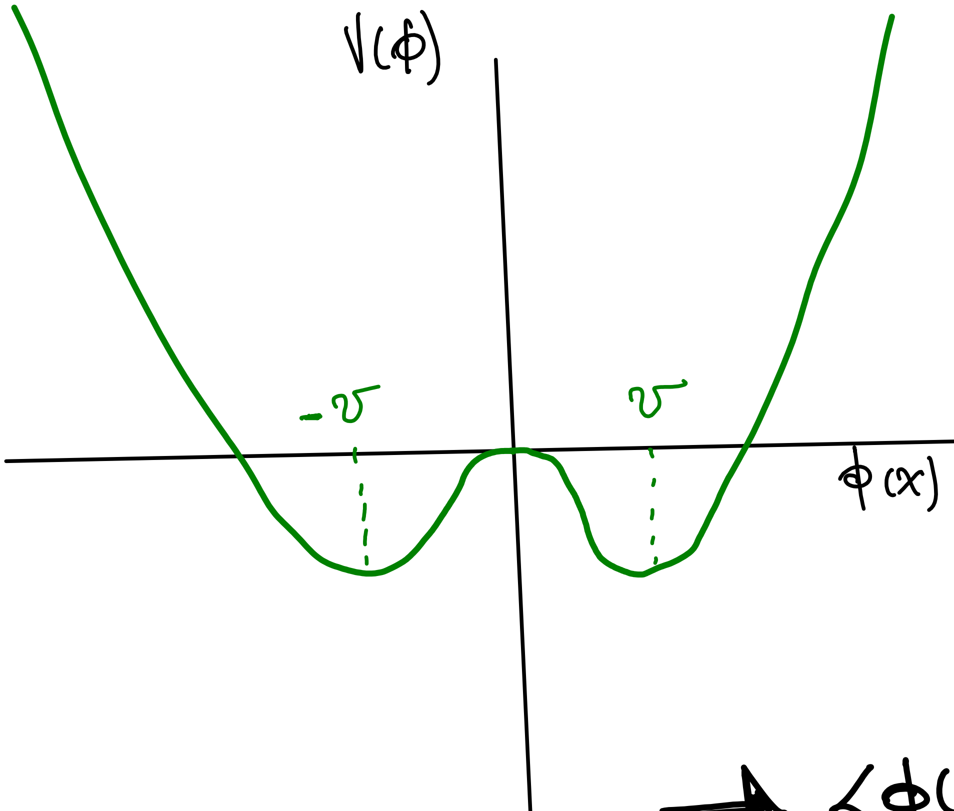

$$\left.\frac{dV(\phi)}{d\phi}\right|_{\langle\phi\rangle} = 0$$

$$\mu^2\langle\phi(x)\rangle + \lambda\langle\phi(x)\rangle^3 = 0$$

$$\Longrightarrow \langle\phi(x)\rangle^2 = -\frac{\mu^2}{\lambda}$$

$$\longrightarrow \langle\phi(x)\rangle \equiv \pm v = \pm\sqrt{\frac{-\mu^2}{\lambda}}$$

$$\phi(x) = \eta(x) + \langle \phi(x) \rangle = \eta(x) + v$$

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$$= \cdots - \left\{ \eta(x)\left(\mu^2 v + \lambda v^3\right) + \eta^2(x)\left(\frac{\mu^2}{2} + \frac{3}{2}\lambda v^2\right) + \eta^3(x)\left(\lambda v\right) + \eta^4(x)\frac{\lambda}{4} + \frac{\mu^2 v^2}{2} + \frac{\lambda v^4}{4} \right\}$$

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$$0$$

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MASA

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Interacción cúbica! Señal de rompimiento de Simetría Z_2

$$= \cdots - \Big\{ \eta(x)\left(\mu^2 v + \lambda v^3\right) + \eta^2(x)\left(\frac{\mu^2}{2} + \frac{3}{2}\lambda v^2\right) \rightarrow \lambda v^2$$

$$+ \eta^3(x)\left(\lambda v\right) + \eta^4(x)\frac{\lambda}{4} + \frac{\mu^2 v^2}{2} + \frac{\lambda v^4}{4} \Big\}$$

0

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Interacción cúbica! Señal de rompimiento de Simetría Z_2

Consideremos ahora el caso de simetría $U(1)$:

$$\mathcal{L} = \partial_\mu \Phi^* \partial^\mu \Phi - V(\Phi^* \Phi)$$

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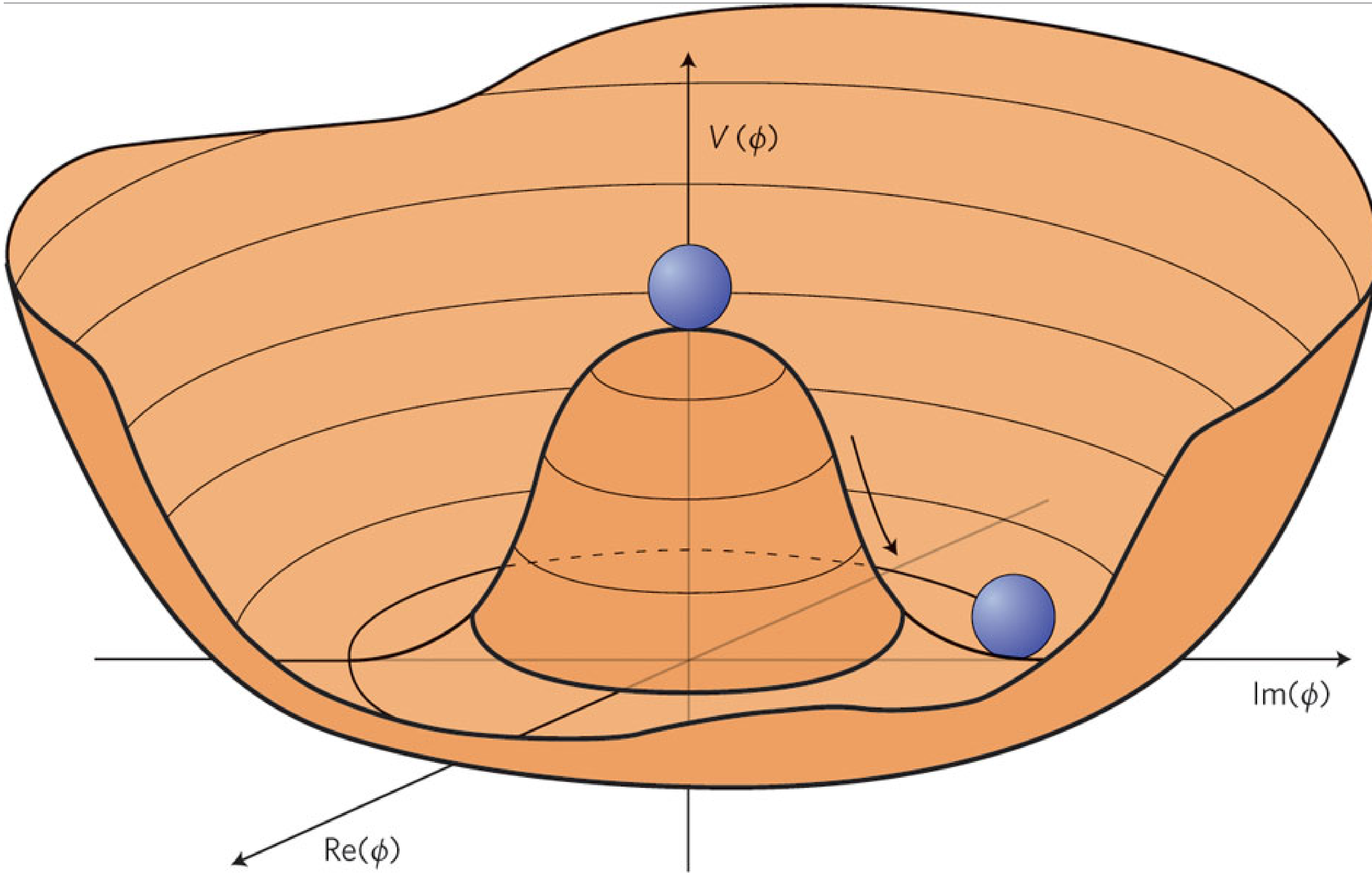
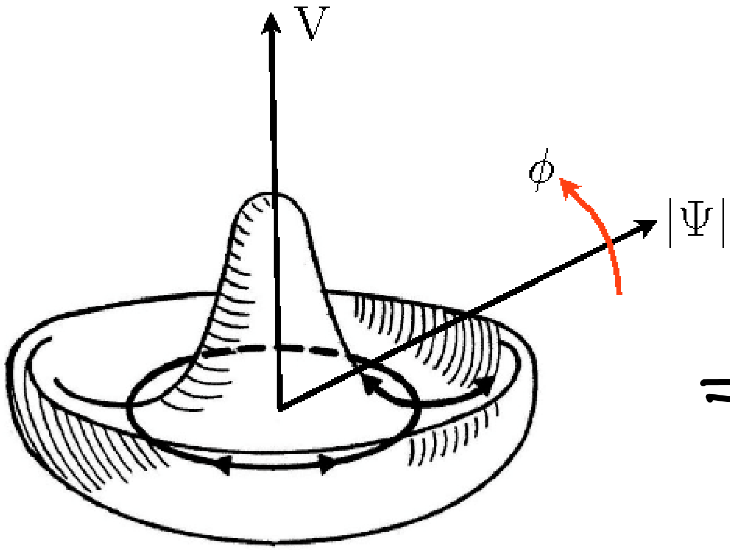
Recordemos que $\Phi = \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2)$

$$\Rightarrow \Phi^* \Phi = \frac{1}{2}(\phi_1^2 + \phi_2^2)$$

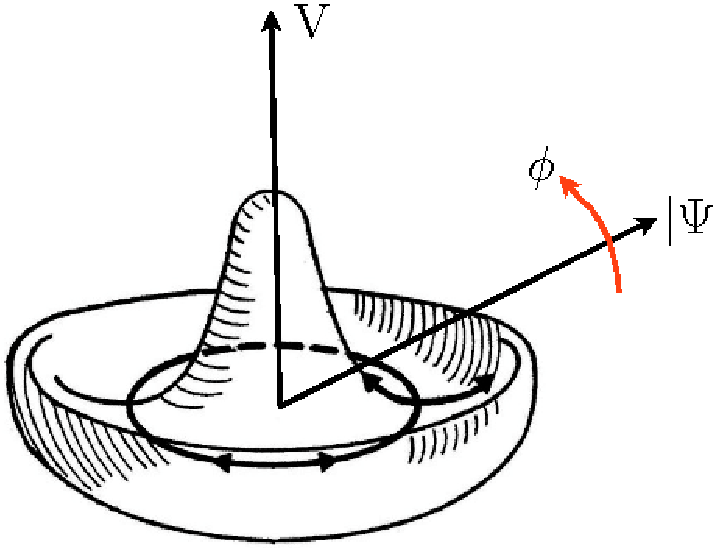

V (ϕ)
Im(ϕ)
Re(ϕ)



Minimización de V

$$\rightarrow \langle \Phi^* \Phi \rangle = -\frac{\mu^2}{2\lambda}$$

$$= \frac{1}{2}\left(\langle \phi_1 \rangle^2 + \langle \phi_2 \rangle^2 \right) = -\frac{\mu^2}{2\lambda} \equiv \frac{v^2}{2}$$



Minimización de V

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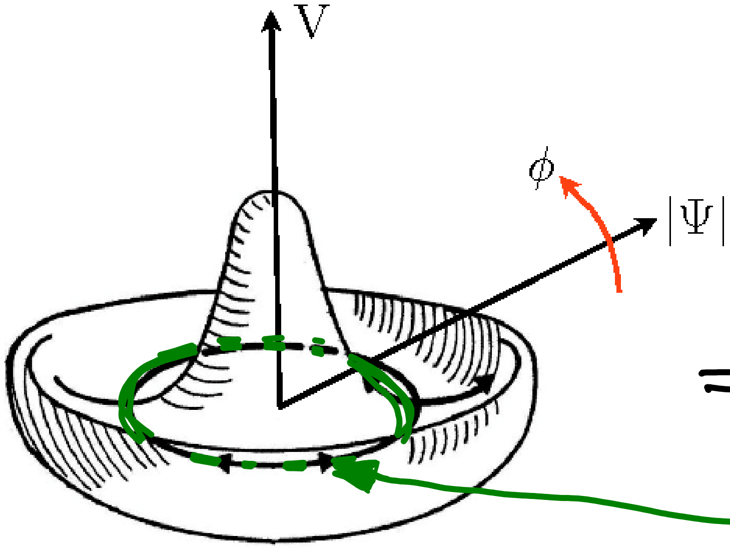
círculo de radio v^2



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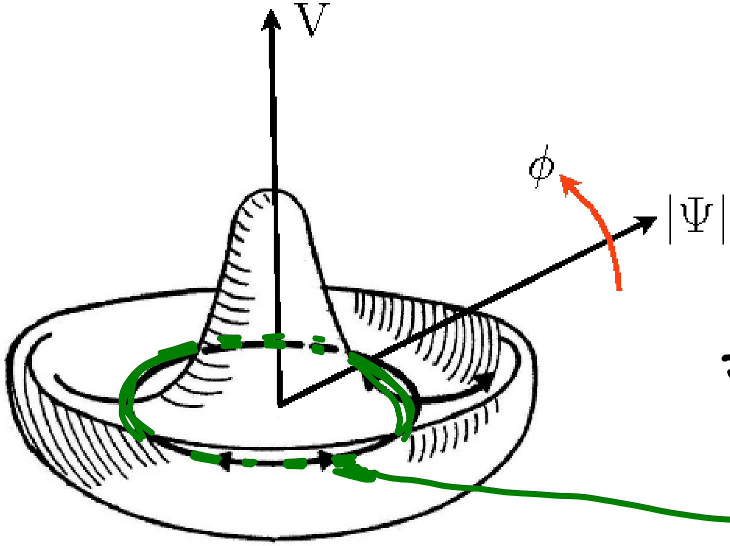

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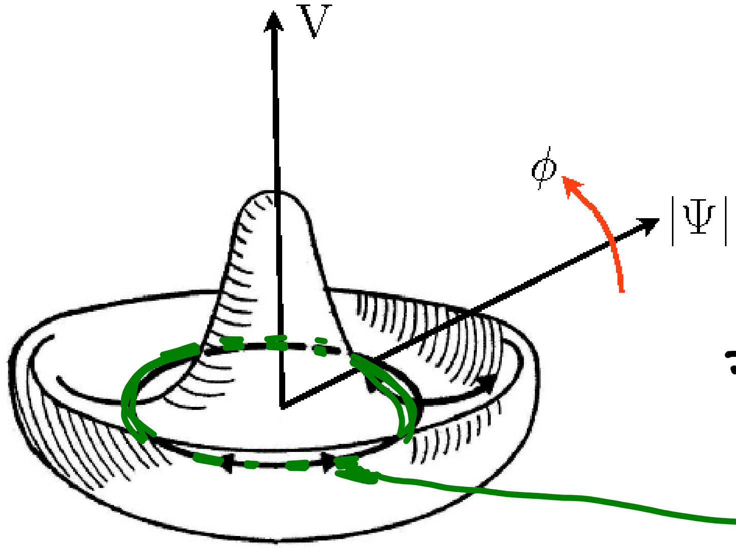
círculo de radio v^2

Cualquier valor da el mismo resultado

$$\Rightarrow \langle \phi_1 \rangle = v \qquad \langle \phi_2 \rangle = 0$$



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círculo de radio v^2

Cualquier valor da el mismo resultado

$$\Rightarrow \langle \phi_1 \rangle = v \qquad \langle \phi_2 \rangle = 0$$

$$\Longrightarrow \quad \Phi(x) = \frac{1}{\sqrt{2}} \left(\eta(x) + v + i \phi_2(x) \right)$$

Recordemos: $V = \mu^2 |\Phi|^2 + \lambda(|\Phi|^2)^2$; $v^2 = -\mu^2/\cancel{2}\lambda$

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Términos de "<u>masa</u>" (proporcionales a $\eta^2(x)$ y a $\phi_2^2(x)$)

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$$\eta^2(x) \Rightarrow \frac{\mu^2}{2} + \frac{3\lambda}{2}v^2 = -\frac{\lambda v^2}{2} + \frac{3}{2}\lambda v^2 = \lambda v^2$$

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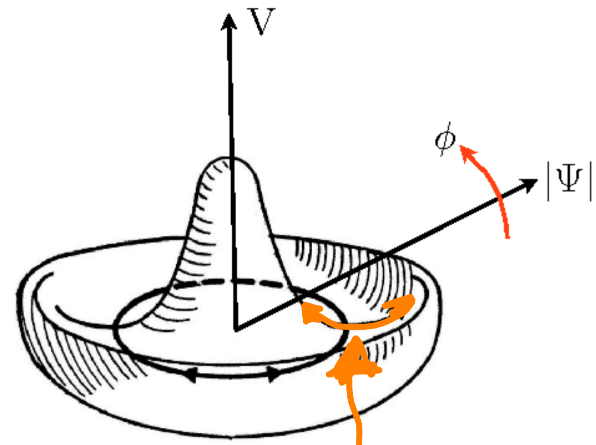
Términos de "masa" (proporcionales a $\eta^2(x)$ y a $\phi_2^2(x)$)

- $\eta^2(x) \Rightarrow \dfrac{\mu^2}{2} + \dfrac{3\lambda}{2}v^2 = -\dfrac{\lambda v^2}{2} + \dfrac{3}{2}\lambda v^2 = \lambda v^2$
- $\phi_2^2(x) \Rightarrow \dfrac{\mu^2}{2} + \dfrac{\lambda v^2}{2} = -\dfrac{\lambda v^2}{2} + \dfrac{\lambda v^2}{2} = \emptyset$

Un campo escalar masivo con masa

$$m_\eta^2 = 2\lambda v^2$$



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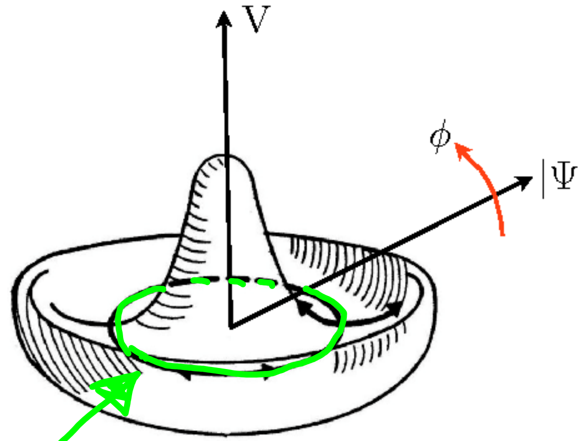

Un campo escalar sin masa

$\phi_2(x)$ es un bosón de GOLDSTONE

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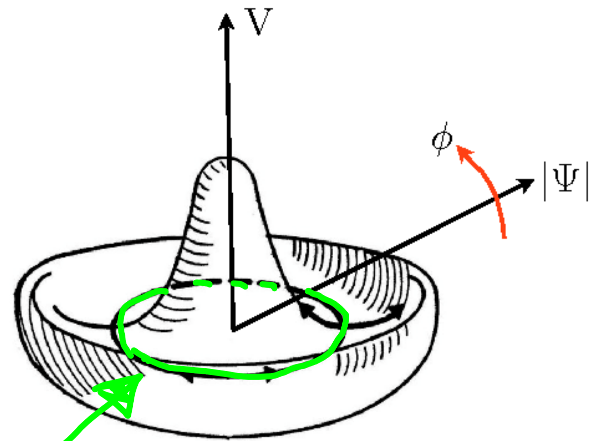

Un campo escalar sin masa

$\phi_2(x)$ es un bosón de GOLDSTONE

$\Longleftrightarrow$ TAREA

Teorema de Goldstone

Por último, ¿recuerdan el caso con simetría $O(2)$?

$$\Phi(x) = \frac{1}{\sqrt{2}}\begin{pmatrix} \phi_1(x) \\ \phi_2(x) \end{pmatrix} \Rightarrow \mathcal{L} = \partial_\mu \Phi^T \partial^\mu \Phi - \Phi^T M^2 \Phi$$

¿Qué pasaría si ahora consideramos $\mathcal{L} = \partial_\mu \Phi^T \partial^\mu \Phi - V(\Phi^T\Phi)$,

con $V(\Phi^T\Phi) = \mu^2 \Phi^T\Phi + \lambda(\Phi^T\Phi)^2$ y $\mu^2 < 0$?

Por último, ¿recuerdan el caso con simetría $O(2)$?

$$\Phi(x) = \frac{1}{\sqrt{2}}\begin{pmatrix} \phi_1(x) \\ \phi_2(x) \end{pmatrix} \Rightarrow \mathcal{L} = \partial_\mu \Phi^T \partial^\mu \Phi - \Phi^T M^2 \Phi$$

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TAREA

Lagrangiano para um fermion $\psi(x)$

Lagrangiano para un fermion $\psi(x)$

$$\mathcal{L} = i\bar{\psi}(x)\gamma_\mu\partial^\mu\psi(x) - m\bar{\psi}(x)\psi(x)$$

- m es la masa (Ecuación de Dirac)
- $\bar{\psi}(x) \equiv \psi^\dagger(x)\gamma^0$ ($\psi^\dagger\psi$ no es escalar)
- $\gamma^\mu \Rightarrow$ matrices de Dirac ($\gamma^\mu p_\mu \equiv \not{p}$)

* $\{\gamma^\mu, \gamma^\nu\} = \gamma^\mu\gamma^\nu + \gamma^\nu\gamma^\mu = 2g^{\mu\nu}$

* $\gamma_5 = \gamma_5^\dagger = i\gamma^0\gamma^1\gamma^2\gamma^3$; $\{\gamma^\mu, \gamma^5\} = 0$

* $\psi(x) = \begin{pmatrix} \eta(x) \\ \chi(x) \end{pmatrix} = \begin{pmatrix} a \\ b \\ c \\ d \end{pmatrix}$

* Base de Weyl (quiral) $\quad \gamma^k = \begin{pmatrix} 0 & \sigma^k \\ -\sigma^k & 0 \end{pmatrix}, \quad \gamma^0 = \begin{pmatrix} 0 & \mathbb{I}_2 \\ \mathbb{I}_2 & 0 \end{pmatrix}$

$$\gamma^5 = \begin{pmatrix} -\mathbb{I}_2 & 0 \\ 0 & \mathbb{I}_2 \end{pmatrix}$$

Algunas identidades útiles:

$$\gamma^\mu \gamma_\mu = 4(\mathbb{1})$$

$$\gamma^\mu \gamma^\nu \gamma_\mu = -2\gamma^\nu$$

$$\gamma^\mu \gamma^\nu \gamma^\rho \gamma_\mu = 4g^{\nu\rho}(\mathbb{1})$$

$$\gamma^\mu \gamma^\nu \gamma^\rho \gamma^\sigma \gamma_\mu = -2\gamma^\sigma \gamma^\rho \gamma^\nu$$

$$\gamma^\mu \gamma^\nu \gamma^\lambda = g^{\mu\nu}\gamma^\lambda + g^{\nu\lambda}\gamma^\mu - g^{\mu\lambda}\gamma^\nu - i\varepsilon^{\sigma\mu\nu\lambda}\gamma_\sigma \gamma^5$$

$$\left(\gamma^5 = i\gamma^0\gamma^1\gamma^2\gamma^3 = \frac{i}{4!}\varepsilon_{\mu\nu\alpha\beta}\gamma^\mu\gamma^\nu\gamma^\alpha\gamma^\beta \right)$$

Algunas identidades útiles:

TAREA

$$\gamma^{\mu}\gamma_{\mu} = 4\,(\mathbb{1})$$

$$\gamma^{\mu}\gamma^{\nu}\gamma_{\mu} = -2\gamma^{\nu}$$

$$\gamma^{\mu}\gamma^{\nu}\gamma^{\rho}\gamma_{\mu} = 4\,g^{\nu\rho}\,(\mathbb{1})$$

$$\gamma^{\mu}\gamma^{\nu}\gamma^{\rho}\gamma^{\sigma}\gamma_{\mu} = -2\gamma^{\sigma}\gamma^{\rho}\gamma^{\nu}$$

$$\gamma^{\mu}\gamma^{\nu}\gamma^{\lambda} = g^{\mu\nu}\gamma^{\lambda} + g^{\nu\lambda}\gamma^{\mu} - g^{\mu\lambda}\gamma^{\nu} - i\varepsilon^{\sigma\mu\nu\lambda}\gamma_{\sigma}\gamma^{5}$$

$$\left(\gamma^{5} = i\gamma^{0}\gamma^{1}\gamma^{2}\gamma^{3} = \frac{i}{4!}\varepsilon_{\mu\nu\alpha\beta}\gamma^{\mu}\gamma^{\nu}\gamma^{\alpha}\gamma^{\beta}\right)$$

Ejemplo:

$$\gamma^\mu \gamma_\mu = g_{\mu\nu} \gamma^\mu \gamma^\nu$$
$$= \frac{1}{2} (g_{\mu\nu} + g_{\nu\mu}) \gamma^\mu \gamma^\nu$$
$$= \frac{1}{2} \left(g_{\mu\nu} \gamma^\mu \gamma^\nu + g_{\nu\mu} \gamma^\nu \gamma^\mu \right)$$
$$= \frac{1}{2} g_{\mu\nu} \{\gamma^\mu, \gamma^\nu\} = g_{\mu\nu} g^{\mu\nu} = 4(\mathbb{I})$$

Trazas:

$$\mathrm{tr}\,\gamma^\mu = 0$$

$$\mathrm{tr}\,(\#\text{ impar de }\gamma^\mu\text{s}) = 0$$

$$\mathrm{tr}\,(\gamma^\mu\gamma^\nu) = 4g^{\mu\nu}$$

$$\mathrm{tr}\,(\gamma^\mu\gamma^\nu\gamma^\rho\gamma^\sigma) = 4\left(g^{\mu\nu}g^{\rho\sigma} - g^{\mu\rho}g^{\nu\sigma} + g^{\mu\sigma}g^{\nu\rho}\right)$$

$$\mathrm{tr}\,\gamma^5 = \mathrm{tr}\,(\gamma^\mu\gamma^\nu\gamma^5) = 0$$

$$\mathrm{tr}\,(\gamma^\mu\gamma^\nu\gamma^\rho\gamma^\sigma\gamma^5) = 4i\,\varepsilon^{\mu\nu\rho\sigma}$$

Término de masa

Recordemos que $\psi(x) = \begin{pmatrix} \eta \\ \chi \end{pmatrix}$.

- $\gamma^5 = \begin{pmatrix} -\mathbb{I}_2 & 0 \\ 0 & \mathbb{I}_2 \end{pmatrix}$; $\dfrac{\mathbb{I}_4 + \gamma_5}{2} = \begin{pmatrix} 0 & 0 \\ 0 & \mathbb{I}_2 \end{pmatrix} \equiv P_R$

$$\frac{\mathbb{I}_4 - \gamma_5}{2} = \begin{pmatrix} \mathbb{I}_2 & 0 \\ 0 & 0 \end{pmatrix} \equiv P_L$$

- $\psi_L(x) = P_L \psi(x)$, $\psi_R(x) = P_R \psi(x)$

Término de masa

$$\Rightarrow \quad \psi(x) = \psi_L(x) + \psi_R(x)$$

$$\bar{\psi}(x) = \bar{\psi}_L(x) + \bar{\psi}_R(x)$$

$$\bar{\psi}(x)\psi(x) = \left(\bar{\psi}_L(x) + \bar{\psi}_R(x)\right)\left(\psi_L(x) + \psi_R(x)\right)$$

$$= \bar{\psi}_L\psi_L + \bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L + \bar{\psi}_R\psi_R$$

$$\overline{\psi_L} = \psi_L^\dagger \gamma^0 = (P_L \psi)^\dagger \gamma^0 = \psi^\dagger P_L^\dagger \gamma^0$$

$$= \psi^\dagger \left(\frac{\mathbb{1} - \gamma_5}{2} \right)^\dagger \gamma^0 = \psi^\dagger \frac{(\mathbb{1} - \gamma_5)}{2} \gamma^0$$

$$= \frac{\psi^\dagger \gamma^0}{2} - \frac{\psi^\dagger \gamma_5 \gamma^0}{2} = \frac{\psi^\dagger \gamma^0}{2} + \frac{\psi^\dagger \gamma^0 \gamma_5}{2}$$

$$= \psi^\dagger \gamma^0 \left(\frac{\mathbb{1} + \gamma_5}{2} \right) = \overline{\psi} P_R$$

$$\overline{\psi_L} = \psi_L^\dagger \gamma^0 = (P_L \psi)^\dagger \gamma^0 = \psi^\dagger P_L^\dagger \gamma^0$$

$$= \psi^\dagger \left(\frac{\mathbb{1} - \gamma_5}{2} \right)^\dagger \gamma^0 = \psi^\dagger \frac{(\mathbb{1} - \gamma_5)}{2} \gamma^0$$

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$$= \psi^\dagger \gamma^0 \left(\frac{\mathbb{1} + \gamma_5}{2} \right) = \overline{\psi} P_R$$

$$\overline{\psi_R} = \overline{\psi} P_L$$

Entonces:

$$\bar\psi(x)\psi(x) = \left(\bar\psi_L(x)+\bar\psi_R(x)\right)\left(\psi_L(x)+\psi_R(x)\right)$$

$$= \cancelto{0}{\bar\psi_L\psi_L} + \bar\psi_L\psi_R + \bar\psi_R\psi_L + \cancelto{0}{\bar\psi_R\psi_R}$$

$$\boxed{\bar\psi(x)\psi(x) = \bar\psi_L\psi_R + \bar\psi_R\psi_L}$$

Entonces:

$$\bar{\psi}(x)\psi(x) = \left(\bar{\psi}_L(x) + \bar{\psi}_R(x)\right)\left(\psi_L(x) + \psi_R(x)\right)$$

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$$\boxed{\bar{\psi}(x)\psi(x) = \bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L}$$

La masa "mezcla" quiralidad

Regresemos al Lagrangiano:

$$\mathcal{L} = i\bar{\psi}\not{\partial}\psi - m\bar{\psi}\psi$$

- $\psi \to \psi' = e^{i\alpha}\psi$ } transformación $U(1)$

  $\bar{\psi}' = \bar{\psi}e^{-i\alpha}$

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$$\mathcal{L}' = i\bar{\psi}'\not{\partial}\psi' - m\bar{\psi}'\psi' = \mathcal{L}$$

Un "doblete" de fermiones:

Consideremos dos fermiones $\psi_1(x)$ y $\psi_2(x)$

con masas m_1 y m_2

$$\Rightarrow \mathcal{L} = \bar{\psi}_1(x)(i\not{\partial} - m_1)\psi_1(x) + \bar{\psi}_2(x)(i\not{\partial} - m_2)\psi_2(x)$$

Un "doblete" de fermiones:

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$$\Rightarrow \mathcal{L} = \bar{\psi}_1(x)(i\partial\!\!\!/ - m_1)\psi_1(x) + \bar{\psi}_2(x)(i\partial\!\!\!/ - m_2)\psi_2(x)$$

$$\Psi(x) = \begin{pmatrix} \psi_1(x) \\ \psi_2(x) \end{pmatrix} \Rightarrow \mathcal{L} = \bar{\Psi}(x)(i\partial\!\!\!/ - M)\Psi(x)$$

con $M = \begin{pmatrix} m_1 & 0 \\ 0 & m_2 \end{pmatrix}$

Consideremos un doblete escalar de $SU(2)$ (global)

$$\Phi(x) = \begin{pmatrix} \phi_a(x) \\ \phi_b(x) \end{pmatrix} \quad ; \quad \begin{aligned} \phi_a &= \frac{1}{\sqrt{2}}\left(\eta_1(x) + i\eta_2(x)\right) \\ \phi_b &= \frac{1}{\sqrt{2}}\left(\eta_3(x) + i\eta_4(x)\right) \end{aligned}$$

Supongamos que su Lagrangiano es
$$\mathcal{L} = \partial_\mu \Phi^\dagger(x)\, \partial^\mu \Phi(x) - V(\Phi^\dagger \Phi)$$

donde $V(\Phi^\dagger\Phi) = \mu^2 \Phi^\dagger(x)\Phi(x) + \lambda\left(\Phi^\dagger(x)\Phi(x)\right)^2$

$$\phi^\dagger(x)\,\phi(x) = \frac{1}{2}\left(\eta_1^2(x) + \eta_2^2(x) + \eta_3^2(x) + \eta_4^2(x)\right)$$

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

Minimizando: $\langle\phi^\dagger\phi\rangle = \dfrac{-\mu^2}{2\lambda} = \dfrac{1}{2}\left(\langle\eta_1\rangle^2 + \dots\right)$

$$= \langle\eta_1\rangle^2 + \langle\eta_2\rangle^2 + \langle\eta_3\rangle^2 + \langle\eta_4\rangle^2 = \frac{-\mu^2}{\lambda} = v^2$$

Escogemos $\langle\eta_1\rangle = +v = \sqrt{-\mu^2/\lambda}$

Entonces $\quad \Phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} h(x) + v + i\,\eta_2(x) \\ \eta_3(x) + i\,\eta_4(x) \end{pmatrix}$

$$\Rightarrow \Phi^{\dagger}(x)\,\Phi(x) = \frac{1}{2}\left\{ \left[h(x)+v\right]^2 + \eta_2^2(x) + \eta_3^2(x) + \eta_4^2(x) \right\}$$

$$\left[\Phi^{\dagger}(x)\,\Phi(x)\right]^2 = \frac{1}{4}\left\{ \left[h(x)+v\right]^4 + \left(\eta_2^2+\eta_3^2+\eta_4^2\right)^2 + 2\left(h(x)+v\right)^2\left(\eta_2^2+\eta_3^2+\eta_4^2\right) \right\}$$

$h^2(x)$: $\quad \frac{\mu^2}{2} + \frac{3}{2}\lambda v^2 = -\frac{\lambda v^2}{2} + \frac{3}{2}\lambda v^2 = \lambda v^2$

$\eta_i^2(x)$: $\quad \frac{\mu^2}{2} + \frac{\lambda v^2}{2} = 0 \quad \Longrightarrow$ 3 bosones de Goldstone

Campo Vectorial

$$A^\mu \Longrightarrow F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$$

$$\partial_\mu F^{\mu\nu} = 0 \qquad \text{Ecs. de Maxwell}$$

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$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$A^\mu \longrightarrow A'^\mu = A^\mu + \partial^\mu \alpha(x)$$

local transf. Gauge

$$F'_{\mu\nu} = \partial^\mu A^\nu + \partial^\mu \partial^\nu \alpha(x)$$
$$- \partial^\nu A^\mu - \partial^\nu \partial^\mu \alpha(x) = F_{\mu\nu}$$

$$\Longrightarrow \quad \mathcal{L}' = \mathcal{L}$$

"Evidentemente" $A_\mu \to A'_\mu = e^{i\alpha} A_\mu$

$F'_{\mu\nu} = e^{i\alpha} F_{\mu\nu}$

no es una simetría $\Rightarrow \mathcal{L}' \neq \mathcal{L}$

"Evidentemente" $A_\mu \rightarrow A'_\mu = e^{i\alpha} A_\mu$

no es una simetría $F'_{\mu\nu} = e^{i\alpha} F_{\mu\nu}$

$\Longrightarrow \mathcal{L}' \neq \mathcal{L}$

Notemos que $\mathcal{L}$ NO contiene término de masa

$\Longrightarrow$ Vector sin masa

(2 grados de libertad)

Incluyendo un término de masa en la ec. de mov:

$$\partial_\mu F^{\mu\nu} + m^2 A^\nu = 0$$

Ec. de Procca

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{m_A^2}{2} A_\mu A^\mu$$

Campo vectorial masivo (3 grados de libertad)

Simetrías

$$\Phi' = e^{i\alpha}\Phi \longrightarrow \mathcal{L}_{\Phi} \text{ es invariante}$$

$$\psi' = e^{i\alpha}\psi \longrightarrow \mathcal{L}_{\psi} \text{ es invariante}$$

$$A'_\mu = A_\mu - \frac{1}{g}\partial_\mu \alpha(x) \longrightarrow \mathcal{L}_{A} \text{ es invariante}$$

Consideremos $\psi' = e^{i\alpha(x)}\psi$,

claramente $\mathcal{L}'_{\psi} \neq \mathcal{L}_{\psi}$:

$$\mathcal{L}' = \bar{\psi}'(i\not{\partial} - m)\psi'$$

$$\neq \bar{\psi}(i\not{\partial} - m)\psi' = \mathcal{L}$$

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Los términos de masa sí son invariantes

$m\bar{\psi}'\psi' = m\bar{\psi}\psi$

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$$\neq \bar{\psi}(i\not{\partial} - m)\psi' = \mathcal{L}$$

Los términos de masa sí son invariantes

$m\bar{\psi}'\psi' = m\bar{\psi}\psi$

Los términos cinéticos NO

$$i\bar{\psi}'\gamma_\mu\partial^\mu\psi' = i\bar{\psi}\gamma_\mu\partial^\mu\psi - \bar{\psi}\gamma_\mu\partial^\mu\alpha(x)\psi$$

$$i\bar{\psi}'\gamma_\mu\partial^\mu\psi' = i\bar{\psi}\gamma_\mu\partial^\mu\psi - \bar{\psi}\gamma_\mu\partial^\mu\alpha(x)\psi$$

Término "extra" $\propto \partial^\mu\alpha(x)$

$$\rightarrow \mathcal{L}' \neq \mathcal{L}$$

$$i\bar{\psi}'\gamma_\mu\partial^\mu\psi' = i\bar{\psi}\gamma_\mu\partial^\mu\psi - \bar{\psi}\gamma_\mu\partial^\mu\alpha(x)\psi$$

✔ ✘ Término "extra" $\propto \partial^\mu\alpha(x)$

$$\to \mathcal{L}' \neq \mathcal{L}$$

Consideremos agregar a nuestra teoría un campo vectorial

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}(i\not{\partial}-m)\psi + \text{int.}$$

$$i\bar{\psi}'\gamma_\mu\partial^\mu\psi' = i\bar{\psi}\gamma_\mu\partial^\mu\psi - \bar{\psi}\gamma_\mu\partial^\mu\alpha(x)\psi$$

Término "extra" $\propto \partial^\mu\alpha(x)$

$$\rightarrow \mathcal{L}' \neq \mathcal{L}$$

Consideremos agregar a nuestra teoría un campo vectorial

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}(i\partial\!\!\!/ - m)\psi + c\,\bar{\psi}\gamma_\mu\psi A^\mu$$

Ya que $A_\mu \rightarrow A'_\mu = A_\mu - \frac{1}{g}\partial_\mu \alpha(x)$, $\psi' = e^{i\alpha(x)}\psi$

$$\mathcal{L}' = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \bar{\psi}'(i\not{\partial} - m)\psi' + c\,\bar{\psi}'\gamma^\mu\psi' A'_\mu$$

Ya que $A_\mu \to A'_\mu = A_\mu - \frac{1}{g}\partial_\mu \alpha(x)$, $\psi' = e^{i\alpha(x)}\psi$

$$\mathcal{L}' = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \bar{\psi}'(i\not{\partial} - m)\psi' + c\,\bar{\psi}'\gamma^\mu\psi' A'_\mu$$

$$= -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}(i\not{\partial} - m)\psi - \bar{\psi}\gamma_\mu\partial^\mu\alpha(x)\psi$$

$$+ c\left\{\bar{\psi}\gamma_\mu\psi A^\mu - \frac{1}{g}\bar{\psi}\gamma_\mu\partial^\mu\alpha(x)\psi\right\}$$

Ya que $A_\mu \to A'_\mu = A_\mu - \frac{1}{g}\partial_\mu \alpha(x)$, $\psi' = e^{i\alpha(x)}\psi$

$$\mathcal{L}' = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \bar{\psi}'(i\partial\!\!\!/ - m)\psi' + c\,\bar{\psi}'\gamma^\mu \psi' A'_\mu$$

$$= -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}(i\partial\!\!\!/ - m)\psi - \bar{\psi}\gamma_\mu \partial^\mu \alpha(x)\psi$$

$$+ c\left\{\bar{\psi}\gamma_\mu \psi A^\mu - \frac{1}{g}\bar{\psi}\gamma_\mu \partial^\mu \alpha(x)\psi\right\}$$

$$= \mathcal{L} \quad \text{si} \quad c = -g$$

si $c = -g$

$$\mathcal{L}' = -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \bar{\psi}'(i\partial\!\!\!/ - m)\psi' - g\,\bar{\psi}'\gamma^\mu\psi' A'_\mu$$

$$= -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\psi}(i\partial\!\!\!/ - m)\psi - g\bar{\psi}\gamma^\mu\psi A_\mu = \mathcal{L}$$

Definimos la derivada COVARIANTE

$$D_\mu \equiv \partial_\mu + igA_\mu \quad \Rightarrow \mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\psi}(iD\!\!\!/ - m)\psi$$

De la misma manera, para un campo escalar complejo con simetría $U(1)$ global

$$\mathcal{L} = \partial_\mu \Phi^* \partial^\mu \Phi - m^2 \Phi^* \Phi ,$$

definimos la derivada covariante $D_\mu = \partial_\mu + igA_\mu$ correspondiente a la simetría $U(1)$ LOCAL

$$\Rightarrow \mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + D_\mu \Phi^* D^\mu \Phi - m^2 \Phi^* \Phi$$

Interacción entre Φ y A_μ

Convención: Para el caso de teorías Gauge $U(1)$, la derivada covariante se define como:

$$D_\mu = \partial_\mu + i g q A_\mu$$

en múltiplos de g

"carga" de la partícula en la que se actúe

Constante de acoplamiento gauge

¿Qué pasa si $\Phi(x)$ adquiere un vev $\neq 0$ en el caso de simetría $U(1)$ local?

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + D_\mu \Phi^*(x) D^\mu \Phi(x) - V(\Phi^*(x)\Phi(x))$$

donde $D_\mu \equiv \partial_\mu + i g A_\mu$,

$$V(\Phi^*(x)\Phi(x)) = \mu^2 \Phi^*(x)\Phi(x) + \lambda \left(\Phi^*(x)\Phi(x)\right)^2$$

$$\Rightarrow \langle \Phi^* \Phi \rangle = \frac{-\mu^2}{2\lambda} = \frac{1}{2}\left(\langle \phi_1 \rangle^2 + \langle \phi_2 \rangle^2\right)$$

$$\Rightarrow \langle \phi_1 \rangle^2 = v^2 = -\mu^2/\lambda \,, \quad \langle \phi_2 \rangle^2 = 0$$

$$\Phi(x) = \frac{1}{\sqrt{2}}\left(h(x) + v + i\,\phi_2(x)\right)$$

$$\mathcal{L} = \underbrace{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}}_{\text{Ni se entera}} + \underbrace{D_\mu^*\Phi^*(x)\,D^\mu\Phi(x)}_{} \underbrace{-\mu^2\Phi^*(x)\Phi(x) + \lambda(|\Phi|^2)^2}_{\text{Ya lo hicimos}}$$

$$\frac{1}{2}D_\mu^*\left(h(x)+v+i\phi_2(x)\right)^* D^\mu\left(h+v+i\phi_2\right)$$

$$\Rightarrow \frac{1}{2}\left(\partial_\mu - igA_\mu\right)\left(h(x)+v-i\phi_2(x)\right)\left(\partial^\mu + igA^\mu\right)\left(h+v+i\phi_2\right)$$

$$= \frac{1}{2}\Big\{\partial_\mu(h-i\phi_2)\,\partial^\mu(h+i\phi_2) - (i)^2g^2A_\mu A^\mu\left|h+v+i\phi_2\right|^2$$
$$+\left[ig\,\partial_\mu(h-i\phi_2)A^\mu(h+v+i\phi_2) + c.c\right]\Big\}$$

$$= \frac{1}{2}\Big\{ \partial_\mu (h - i\phi_2)\,\partial^\mu (h+i\phi_2) - (i)^2 g^2 A_\mu A^\mu |h+v+i\phi_2|^2 + \left[ig\,\partial_\mu(h-i\phi_2)A^\mu(h+v+i\phi_2) + c.c \right] \Big\}$$

$$\frac{g^2}{2} A_\mu A^\mu \left(h^2 + 2hv + v^2 + \phi_2^2 \right)$$

$$\Rightarrow \frac{g^2 v^2}{2} A_\mu A^\mu$$

Se ha "generado" un término de masa para A_μ !!

El rompimiento espontáneo de la simetría generó masa para el campo de gauge A_μ

- 3 grados de libertad $\Rightarrow$ se apropió del bosón de Goldstone!

$\Rightarrow$ $\boxed{\text{Mecanismo de Higgs.}}$

Teorías de Yang-Mills

Generalización para grupos No-Abelianos

Denotemos campos escalares y fermiónicos de manera general con ϕ.

Colectamos varios ϕ_A en un campo de varios componentes $\phi \equiv (\phi_A)$

- ϕ transforma como una representación irreducible $U(g)$ del grupo de gauge G.

∴

- Invariancia GLOBAL de $\mathcal{L}_M$:

$$\mathcal{L}_M\left(U(g)\phi, \partial_\mu[U(g)\phi]\right) = \mathcal{L}_M(\phi, \partial_\mu\phi)$$

$\Longrightarrow$ corrientes conservadas

Construcción de la teoría Gauge:

* Invariante bajo $\Phi \rightarrow U(g(x))\,\Phi$

- Sea $T_a \in \mathcal{G}$ una base del álgebra de Lie $\mathcal{G}$ de G.

- Introducimos un campo vectorial

$$A_\mu(x) = \sum_a A_\mu^a(x)\, T_a$$

Campo vectorial valuado en $\mathcal{G}$

$\mathfrak{G}$ es el espacio tangente de G en el elemento unidad $e \in G$.

En la parametrización $g(s) \in G$, con $g(0) = e$, los elementos X de $\mathfrak{G}$ son

$$X = \frac{d}{ds} g(s) \Big|_{s=0}$$

– Reemplazamos $\partial_\mu \phi$ por $D_\mu \phi$

donde

$$D_\mu \phi = \partial_\mu \phi + U_*(A_\mu)\,\phi$$

Representación del Álgebra de Lie correspondiente a $U(g)$

- D_μ debe transformar como ϕ (covariante)

$$D'_\mu \left(U(g(x)) \phi(x) \right) = U(g(x)) D_\mu \phi'(x) \,,$$

donde $D'_\mu = \partial_\mu + U_*(A'_\mu)$

$$D'_\mu \left(U(g(x))\,\phi(x) \right) \quad ; \quad D'_\mu = \partial_\mu + U_*(A'_\mu)$$

$$= \partial_\mu \left[U(g(x))\,\phi(x) \right] + U_*(A'_\mu)\,U(g(x))\,\phi(x)$$

$$= U(g(x)) \left[\partial_\mu \phi(x) + U_*(A_\mu)\,\phi(x) \right]$$

debe cumplirse para $\phi(x)$ arbitrario

$$\Rightarrow \partial_\mu U(g) + U_*(A'_\mu)\,U(g) = U(g)\,U_*(A_\mu)$$

$$\Rightarrow U_*(A'_\mu) = U(g)\,U_*(A_\mu)\,U(g)^{-1} - \left[\partial_\mu U(g)\right] U(g)^{-1}$$

Para el caso de la representación identidad $g \to g$

$$A'_\mu(x) = g(x) A_\mu(x) g^{-1}(x) - (\partial_\mu g(x)) g^{-1}(x)$$

Para transformaciones infinitesimales:

$$g(s,x) \equiv g(0,x) + s \frac{d}{ds} g(s,x) \Big|_{s=0}$$

$$= e + s\, T(x)$$

donde $T(x) \equiv \sum \varepsilon^a(x) T_a(x)$

$$\Rightarrow \quad \delta A_\mu(x) = A'_\mu(x) - A_\mu(x)$$

$$= \left[T(x), A_\mu(x)\right] - \partial_\mu T(x) \,, \quad T \in \mathfrak{g}$$

En componentes:

$$\delta A_\mu^a T_a = \left[\varepsilon^b T_b , A_\mu^c T_c\right] - \partial_\mu \varepsilon^a T_a$$

$$= \left[T_b , T_c\right] \varepsilon^b A_\mu^c - \partial_\mu \varepsilon^a T_a$$

Usando $[T_b, T_c] = f^a{}_{bc} T_a$

$$\Longrightarrow \boxed{\delta A^a_\mu(x) = f^a{}_{bc}\, \varepsilon^b A^c_\mu - \partial_\mu \varepsilon^a}$$

Ya que ϕ y $D_\mu \phi$ tienen las mismas propiedades de transformación, la invarianza global de $\mathcal{L}_M$

$\longrightarrow$ invariancia bajo transf. locales!

Por último consideremos $\mathcal{L}_F = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$

donde

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu + [A_\mu, A_\nu]$$

o

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + f^a{}_{bc} A^b_\mu A^c_\nu$$

$$\Longrightarrow \quad \mathcal{L} = \mathcal{L}_M(\phi, D\phi) + \mathcal{L}_F$$

Construcción de Modelos

- Especificar el grupo de Gauge G (Interacciones)
  - ¿Espontáneamente roto? ¿Cómo?
  - En caso afirmativo, introducir escalares necesarios para conseguirlo.

- Especificar el contenido de materia (fermiones)
  - "Cargas" y/o representaciones "bajo" G

Modelo Estándar

* Tres interacciones codificadas por el grupo G_{SM}

$$G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$$

color

left (weak)

hipercarga

Modelo Estándar

* Tres interacciones codificadas por el grupo G_{SM}

$$G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$$

color

left (weak)

hipercarga

* Espontáneamente roto: $G_{SM} \longrightarrow SU(3)_C \times U(1)_{EM}$

Electro magnética

$SU(3)_C \times SU(2)_L \times U(1)_Y$ ⟿ Teoría electrodébil

$\Longrightarrow$

$U(1)_{EM}$

Mecanismo de Higgs

Consideremos por el momento la teoría electrodébil:

. $SU(2)_L \times U(1)_Y \Longrightarrow$ 4 generadores

$$W_\mu^a(x), \quad a=1,2,3 \quad (SU(2))$$

$$B_\mu(x) \quad (U(1))$$

Consideremos por el momento la teoría electrodébil:

$$SU(2)_L \times U(1)_Y \Longrightarrow 4 \text{ generadores}$$

$$W_\mu^a(x), \quad a=1,2,3 \quad (SU(2))$$

$$B_\mu(x) \quad (U(1))$$

$$\downarrow$$

$$U(1)_{EM} \Longrightarrow 1 \text{ generador } A_\mu(x)$$

Consideremos por el momento la teoría electrodébil:

$$SU(2)_L \times U(1)_Y \Longrightarrow 4 \text{ generadores}$$

$$m=0 \begin{cases} W_\mu^a(x), \quad a=1,2,3 & (SU(2)) \\ B_\mu(x) & (U(1)) \end{cases}$$

$$\downarrow$$

$$U(1)_{EM} \Longrightarrow 1 \text{ generador } \left. A_\mu(x) \right\} m_A = 0$$

Consideremos por el momento la teoría electrodébil:

$$SU(2)_L \times U(1)_Y \Rightarrow 4 \text{ generadores}$$

$$m = 0 \begin{cases} W_\mu^a(x), \quad a = 1,2,3 & (SU(2)) \\ B_\mu(x) & (U(1)) \end{cases}$$

$\ast$ 3 vectores masivos $W_\mu^\pm$, Z_μ

$$\downarrow$$

$$U(1)_{EM} \Rightarrow 1 \text{ generador } \left. A_\mu(x) \right\} m_A = 0$$

- Para lograr el rompimiento requerimos, AL MENOS, 4 campos escalares reales (3 Goldstones y un escalar con VEV).

- Para lograr el rompimiento requerimos, AL MENOS, 4 campos escalares reales (3 Goldstones y un escalar con VEV).

- Para poder "dar masa" a los bosones de gauge de $SU(2) \times U(1)$, los campos escalares tienen que "sentir" al menos la interacción $SU(2)$ (si no, no la "rompe"). Supongamos que "siente" las dos (por generalidad).

Empecemos con el mínimo:

$$\Phi(x) = \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} \frac{1}{\sqrt{2}}$$ como "doblete" de $SU(2)$.

Llamemos la hipercarga de $\Phi(x)$ Y_h.

Denotamos los representaciones/cargas de $\Phi(x)$ bajo $SU(2)_L \times U(1)_Y$ como $\Phi(x) \sim (2, Y_h)$

$\Rightarrow$ Construyamos el Lagrangiano:

$$\mathcal{L} = -\frac{1}{4} W_{\mu\nu} W^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$

$$+ (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi^\dagger \Phi) ,$$

$$\mathcal{L} = -\frac{1}{4} W_{\mu\nu} W^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$

$$+ (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi^\dagger \Phi) ,$$

donde

$$W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu + [W_\mu, W_\nu]$$

con $W_\mu(x) = \sum_a W_\mu^a(x) \tau^a$

$$\mathcal{L} = -\frac{1}{4} W_{\mu\nu} W^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$

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con $\quad W_\mu(x) = \sum_a W_\mu^a(x) \tau^a$

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

$$\mathcal{L} = -\frac{1}{4} W_{\mu\nu} W^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$

$$+ (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi^\dagger \Phi) ,$$

donde

$$W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu + [W_\mu, W_\nu]$$

con $W_\mu(x) = \sum_a W_\mu^a(x) \tau^a$

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

$$D_\mu = \partial_\mu + i g_2 \frac{\sigma_a}{2} W_\mu^a + i g_1 \frac{Y}{2} B_\mu$$

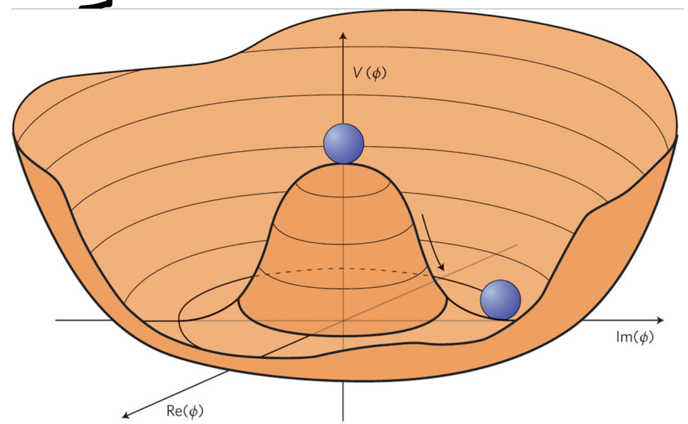
$$\mathcal{L} = -\frac{1}{4} W_{\mu\nu} W^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$

$$+ (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi^\dagger \Phi),$$

donde

$$W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu + [W_\mu, W_\nu]$$

con $\quad W_\mu(x) = \sum_a W^a_\mu(x)\, \tau^a$



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

$$D_\mu = \partial_\mu + i\, g_2 \frac{\sigma_a}{2} W^a_\mu + i\, g_1 \frac{Y}{2} B_\mu$$

Convención (normalización) $\tau^a \equiv \dfrac{\sigma^a}{2}$

$$\sigma^1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma^2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma^3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

- $\sigma^+ = \dfrac{\sigma^1 + i\sigma^2}{2} = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \qquad \Uparrow$

- $\sigma^- = \dfrac{\sigma^1 - i\sigma^2}{2} = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix} \qquad \Downarrow$

$$W_\mu^a(x)\,\tau^a = \sqrt{2}\,W_\mu^+\sigma^+ + \sqrt{2}\,W_\mu^-\sigma^- + W_\mu^3\sigma^3$$

donde $W_\mu^\pm = \dfrac{W_\mu^1 \mp i W_\mu^2}{\sqrt{2}}$

$$\Rightarrow D_\mu = \partial_\mu + i\frac{g_2}{2}\left[\sqrt{2}\,W_\mu^+\sigma^+ + \sqrt{2}\,W_\mu^-\sigma^- + W_\mu^3\sigma^3\right]$$

$$+ i\frac{g_1}{2}Y B_\mu$$

Ya sabemos que $\langle|\Phi|^2\rangle = -\dfrac{\mu^2}{2\lambda}$

$$= \frac{1}{2}\left(\langle\phi_1\rangle^2 + \langle\phi_2\rangle^2 + \langle\phi_3\rangle^2 + \langle\phi_4\rangle^2\right)$$

Escogemos $\langle\phi_1\rangle = \langle\phi_2\rangle = \langle\phi_4\rangle = 0$, $\langle\phi_3\rangle = +v = \sqrt{\dfrac{-\mu^2}{\lambda}}$

$$\Rightarrow \Phi(x) = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi_1 + i\phi_2 \\ h + v + i\phi_3\end{pmatrix} = H(x) + \langle\Phi\rangle$$

con $H(x) = \dfrac{1}{\sqrt{2}}\begin{pmatrix}\phi_1 + i\phi_2 \\ h + i\phi_3\end{pmatrix}$ $\quad \langle\Phi\rangle = \dfrac{1}{\sqrt{2}}\begin{pmatrix}0 \\ v\end{pmatrix}$

$$\mathcal{L} \supset (D_\mu \Phi)^\dagger (D^\mu \Phi)$$

- $$D^\mu \Phi = \left\{ \partial^\mu + i\frac{g_2}{2}\left(\sqrt{2}W^{\mu+}\sigma^+ + \sqrt{2}W^{\mu-}\sigma^- + W^{\mu 3}\sigma^3\right) + i\frac{g_1}{2} y_h B^\mu \right\}\left(H(x) + \langle\Phi\rangle\right)$$

$$= \left\{ i\frac{g_2}{2}\left(\sqrt{2}W^{\mu+}\sigma^+\langle\Phi\rangle + \sqrt{2}W^{\mu-}\sigma^-\langle\Phi\rangle + W^{\mu 3}\sigma^3\langle\Phi\rangle\right) + i\frac{g_1}{2} y_h B^\mu \, \mathbb{I}_2 \langle\Phi\rangle \right\} + \ldots$$

$$\Rightarrow D^\mu \langle\Phi\rangle = i\frac{g_2}{2}\left(W^{\mu+}\begin{pmatrix} v \\ 0 \end{pmatrix} + W^{\mu 3}\begin{pmatrix} 0 \\ -v \end{pmatrix}\frac{1}{\sqrt{2}} \right) + i\frac{g_1}{2} y_h B^\mu \begin{pmatrix} 0 \\ v \end{pmatrix}\frac{1}{\sqrt{2}}$$

$$\Rightarrow D^\mu \langle \Phi \rangle = i\frac{g_2}{2}\left(W^{\mu +}\begin{pmatrix} v \\ 0 \end{pmatrix} + W^{\mu 3}\begin{pmatrix} 0 \\ -v \end{pmatrix}\frac{1}{\sqrt{2}} \right)$$

$$+ i\frac{g_1}{2} y_h B^\mu \begin{pmatrix} 0 \\ v \end{pmatrix}\frac{1}{\sqrt{2}}$$

$$|D^\mu \langle \Phi \rangle|^2 = \frac{g_2^2}{4}\left\{ (v \;\; 0)\begin{pmatrix} v \\ 0 \end{pmatrix} W_\mu^+ W^{\mu -} \right.$$

$$\left. + \frac{1}{2}(0 \;\; -v)\begin{pmatrix} 0 \\ -v \end{pmatrix} W^{\mu 3} W_\mu^3 \right\}$$

$$+ \frac{g_1^2}{8} y_h^2 (0 \;\; v)\begin{pmatrix} 0 \\ v \end{pmatrix} B_\mu B^\mu$$

$$+ \frac{g_1 g_2}{4} y_h (0 \;\; -v)\begin{pmatrix} 0 \\ v \end{pmatrix} W_\mu^3 B^\mu$$

$$
\begin{aligned}
|D^{\mu}\langle\Phi\rangle|^{2} = \frac{g_2^2}{4}\Big\{ & (v \;\; 0)\begin{pmatrix} v \\ 0 \end{pmatrix} W_{\mu}^{+} W^{\mu -} \\
& + \frac{1}{2}(0 \;\; -v)\begin{pmatrix} 0 \\ -v \end{pmatrix} W^{\mu 3} W_{\mu}^{3} \Big\} \\
& + \frac{g_1^2}{8} y_h^2 \, (0 \;\; v)\begin{pmatrix} 0 \\ v \end{pmatrix} B_{\mu} B^{\mu} \\
& + \frac{g_1 g_2}{4} y_h \, (0 \;\; -v)\begin{pmatrix} 0 \\ v \end{pmatrix} W_{\mu}^{3} B^{\mu}
\end{aligned}
$$

$$
= \frac{g_2^2}{4} v^2 W_{\mu}^{+} W^{\mu -} + v^2 \left(W_{\mu}^{3} \;\; B_{\mu} \right) \begin{pmatrix} \frac{g_2^2}{8} & -\frac{g_1 g_2}{8} y_h \\ -\frac{g_1 g_2}{8} y_h & \frac{g_1^2 y_h^2}{8} \end{pmatrix} \begin{pmatrix} W^{3\mu} \\ B^{\mu} \end{pmatrix}
$$

Diagonalizamos:

$$\begin{pmatrix} W_\mu^3 \\ B_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_w & \sin\theta_w \\ -\sin\theta_w & \cos\theta_w \end{pmatrix} \begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix}$$

$$\Rightarrow \quad Z_\mu \equiv -\sin\theta_w B_\mu + \cos\theta_w W_\mu^3$$

$$= \frac{-g_2 B_\mu + g_1 W_\mu^3}{\sqrt{g_1^2 + g_2^2}}$$

$$\tan\theta_w = \frac{g_2}{g_1}$$

$$\operatorname{sen}\theta_w = \frac{g_2}{g_z}$$

$$g_z = \sqrt{g_1^2 + g_2^2}$$

$$\Rightarrow \quad A_\mu \equiv \cos\theta_w B_\mu + \sin\theta_w W_\mu^3$$

$$\Rightarrow \quad M_W^2 W_\mu^+ W^{\mu -} + \frac{M_Z^2}{2} Z_\mu Z^\mu$$

con $M_W = \frac{gv}{2}$, $M_Z = \frac{g_Z v}{2} = \frac{M_W}{\cos\theta_W}$

y $M_A = 0$

$$\Rightarrow \quad SU(2)_L \times U(1)_Y \longrightarrow U(1)_{EM}$$

$\uparrow$ generador $Q = ?$

τ_1 , τ_2 están rotos : $\tau_{1,2}\langle\Phi\rangle \neq 0$

τ_3 y Y $\Longrightarrow$ $\tau_3 + Y$

$\tau_3 - Y$

$$\Longrightarrow Q = \tau_3 + Y \; ; \; Q\langle\Phi\rangle = 0$$

$$\Longrightarrow \text{doblete } \begin{pmatrix} a \\ b \end{pmatrix}_Y \quad Q = \begin{pmatrix} 1/2 + Y \\ -1/2 + Y \end{pmatrix}$$

$$\Longrightarrow y_h = 1/2$$

Materia

Quarks:

doblete de $SU(2)$

$$Q_L^i \sim (3, 2, 1/6) \qquad i = 1, 2, 3$$

triplete de $SU(3)$

hipercarga

$$Q_L^1 = \begin{pmatrix} u \\ d \end{pmatrix}_L \Rightarrow \begin{array}{l} 1/2 + 1/6 = +2/3 \\ -1/2 + 1/6 = -1/3 \end{array}$$

$$U_R^i \sim (3, 1, 2/3)$$

$$D_R^i \sim (3, 1, -1/3)$$

Quarks

$$Q_L^i \sim (3, 2, 1/6)$$

$$U_R^i \sim (3, 1, 2/3)$$

$$D_R^i \sim (3, 1, -1/3)$$

Leptones

$$L_L^i \sim (1, 2, -1/2) \Rightarrow L_L^1 = \begin{pmatrix} \nu_e \\ e \end{pmatrix}$$

$$E_R^i \sim (1, 1, -1)$$

Quarks

$Q_L^i \sim (3, 2, 1/6)$

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Leptones

$L_L^i \sim (1, 2, -1/2) \Rightarrow L_L^1 = \begin{pmatrix} \nu_e \\ e \end{pmatrix}$

$E_R^i \sim (1, 1, -1)$

$$\mathcal{L}_f = i \bar{Q}_L^j \not{D} Q_L^j + i \bar{L}_L^j \not{D} L_L^j$$
$$+ i U_R^j \not{D} U_R^j + i D_R^j \not{D} D_R^j + i E_R^j \not{D} E_R$$

Quarks

$Q_L^i \sim (3, 2, 1/6)$

$U_R^i \sim (3, 1, 2/3)$

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Leptones

$L_L^i \sim (1, 2, -1/2) \Rightarrow L_L^1 = \begin{pmatrix} \nu_e \\ e \end{pmatrix}$

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$$\mathcal{L}_f = i\bar{Q}_L^j \not{D} Q_L^j + i\bar{L}_L^j \not{D} L_L^j + i\,\bar{U}_R^j \not{D} U_R^j + i\,\bar{D}_R^j \not{D} D_R^j + i\,\bar{E}_R^j \not{D} E_R$$

+ MASAS ?

Ejemplo de término de masa

$$\bar{u}_L u_R + \bar{u}_R u_L = \bar{u}\, u$$

$$Q'_L = \begin{pmatrix} u_L \\ d_R \end{pmatrix} \sim (3,\ 2,\ 1/6)$$

$$U'_R = u_R \sim (1,\ 1,\ +2/3)$$

$$D'_R = d_R \sim (1,\ 1,\ +2/3)$$

$$m\,\bar{Q}'_L U'_R \sim (1,\ 2,\ -1/2) \neq (1,1,0)$$

$$m\,\bar{Q}'_L D'_R \sim (1,\ 2,\ +1/2) \neq (1,1,0)$$

$$\overline{Q}_L'\, \nu_R' \sim (1, 2, -1/2) \neq (1,1,0)$$

$$\overline{Q}_L'\, D_R' \sim (1, 2, +1/2) \neq (1,1,0)$$

<u>Pero</u> $\Phi \sim (1, 2, 1/2)$

Consideremos el término $\overline{Q}_L' \Phi D_R'$

- Escalar
- dimensión $= 4$
- $(1, 1, 0)$

Términos de Yukawa

No son opcionales !

$$\mathcal{L}_Y = y^d_{ij}\,\overline{Q}^i_L\,\Phi\,D^j_R + h.c.$$

$$+\, y^u_{ij}\,\overline{Q}^i_L\,\tilde{\Phi}\,U^j_R + h.c.$$

$$+\, y^l_{ij}\,\overline{L}^i_L\,\Phi\,E^j_R + h.c.$$

$$\tilde{\Phi} \equiv i\sigma_2\Phi^\dagger \sim (1, 2, -1/2)$$

$\Longrightarrow$ masas : $\Phi = H + \langle\Phi\rangle$, $\langle\Phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v\end{pmatrix}$

$$y^d_{11}\,\overline{Q}^1_L\langle\Phi\rangle D^1_R = y^d_{11}\begin{pmatrix}\overline{u}_L & \overline{d}_L\end{pmatrix}\frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v\end{pmatrix} d_R$$

$$= \frac{y^d_{11}v}{\sqrt{2}}\,\overline{d}_L d_R$$

$\Downarrow$

$\underline{\underline{\text{Masa}}} \Rightarrow$ Matriz de masa

$$\left.\begin{aligned} M^d_{ij} &= \frac{v}{\sqrt{2}} Y^d_{ij} \\ M^u_{ij} &= \frac{v}{\sqrt{2}} Y^u_{ij} \\ M^\ell_{ij} &= \frac{v}{\sqrt{2}} Y^\ell_{ij} \end{aligned}\right\}$$

En general **no diagonales**

$$\bar{u}^i_L M^u_{ij} u^j_R \,, \quad \bar{d}^i_L M^d_{ij} d^j_L \,, \quad \bar{e}^i_L M^\ell_{ij} \bar{e}_R$$

$m = 0$ para ν_L

Cambiemos a la base de masa:

los términos de masa tienen la forma

$$\bar{f}_L^{\,i} M_{ij}^f f_R^j$$

$$M_D^f = V_L^f M V_R^{f\dagger} \longrightarrow M^f = V_L^{f\dagger} M_D^f V_R^f$$

Cambiemos a la base de masa :

los términos de masa tienen la forma

$$\bar{f}_L^{\,i} \, M^f_{ij} \, f_R^{\,j}$$

$$M^f_D = V^f_L M \, V^{f\dagger}_R \longrightarrow M^f = V^{f\dagger}_L M^f_D V^f_R$$

$$\bar{f}_L V^{f\dagger}_L M^f_D V^f_R f_R = \bar{f}'_L M^f_D f'_R$$

$f'_L = V^f_L f_L \;,\; f'_R = V^f_R f_R \Rightarrow$ campos físicos

Quarks:

De la derivada covariante obtenemos:

$$-\frac{g_2}{\sqrt{2}}\left[\bar{d}_L \gamma^\mu u_L W_\mu^- + \bar{u}_L \gamma^\mu d_L W_\mu^+\right]$$

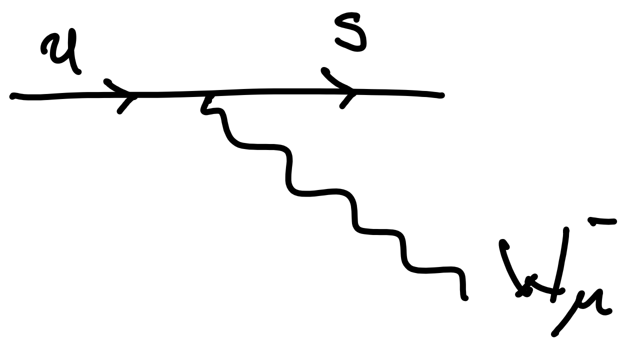
$$= -\frac{g_2}{\sqrt{2}}\left[\bar{d}'_L V_L^{d\dagger} \gamma^\mu V_L^u u'_L W_\mu^- + h.c.\right]$$

$$= -\frac{g_2}{\sqrt{2}}\left[\bar{d}'_L \gamma^\mu V_{CKM}^\dagger u'_L W_\mu^- + h.c\right]$$

$$V_{CKM} = V_L^{u\dagger} V_L^{d}$$

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

$\Rightarrow$



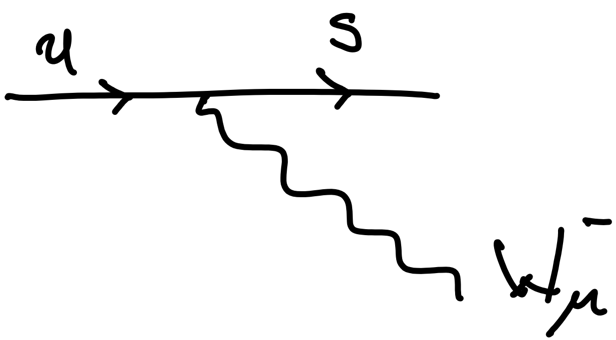
$$V_{CKM} = V_L^{u\dagger} V_L^{d}$$

$$= \left.\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}\right\} \begin{array}{l} \text{3 ángulos} \\ \text{1 fase (violación de CP)} \end{array}$$

$$V_{CKM} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

$$\lambda = 0.23$$

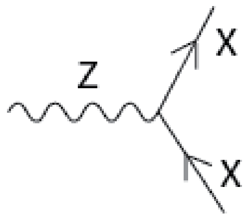
$\Longrightarrow$



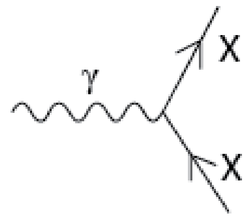
Laguangiano

$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu +$$
$$\frac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu\partial_\nu W^-_\mu -$$
$$M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu\partial_\mu A_\nu - \frac{1}{2}\partial_\mu H\partial_\mu H -$$
$$\frac{1}{2}m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} +$$
$$\frac{2M}{g}H + \frac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu -$$
$$W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu -$$
$$W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu +$$
$$\frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) +$$
$$g^2s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] -$$
$$\frac{1}{8}g^2\alpha_h[H^4+(\phi^0)^4+4(\phi^+\phi^-)^2+4(\phi^0)^2\phi^+\phi^-+4H^2\phi^+\phi^-+2(\phi^0)^2H^2] -$$
$$gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) -$$
$$W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ -$$
$$\phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) +$$
$$igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) +$$
$$igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2W^+_\mu W^-_\mu[H^2+(\phi^0)^2+2\phi^+\phi^-] -$$
$$\frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2+(\phi^0)^2+2(2s_w^2-1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) + \frac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- -$$
$$g^1s_w^2A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial+m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial+m_u^\lambda)u^\lambda_j -$$
$$\bar{d}^\lambda_j(\gamma\partial+m_d^\lambda)d^\lambda_j + igs_wA_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] +$$
$$\frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2 -$$
$$1-\gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1-\frac{8}{3}s_w^2-\gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) +$$
$$(\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+$$
$$\gamma^5)u^\lambda_j)] + \frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] -$$
$$\frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_jC_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) +$$
$$m_u^\lambda(\bar{u}^\lambda_jC_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_jC^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_jC^\dagger_{\lambda\kappa}(1-$$
$$\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}^\lambda_ju^\lambda_j) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar{d}^\lambda_jd^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5u^\lambda_j) -$$
$$\frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5d^\lambda_j) + \bar{X}^+(\partial^2-M^2)X^+ + \bar{X}^-(\partial^2-M^2)X^- + \bar{X}^0(\partial^2 -$$
$$\frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2Y + igc_wW^+_\mu(\partial_\mu\bar{X}^0X^- - \partial_\mu\bar{X}^+X^0) + igs_wW^+_\mu(\partial_\mu\bar{Y}X^- -$$
$$\partial_\mu\bar{X}^+Y) + igc_wW^-_\mu(\partial_\mu\bar{X}^-X^0 - \partial_\mu\bar{X}^0X^+) + igs_wW^-_\mu(\partial_\mu\bar{X}^-Y -$$
$$\partial_\mu\bar{Y}X^+) + igc_wZ^0_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) + igs_wA_\mu(\partial_\mu\bar{X}^+X^+ -$$
$$\partial_\mu\bar{X}^-X^-) - \frac{1}{2}gM[\bar{X}^+X^+H + \bar{X}^-X^-H + \frac{1}{c_w^2}\bar{X}^0X^0H] +$$
$$\frac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] +$$
$$igMs_w[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0]$$

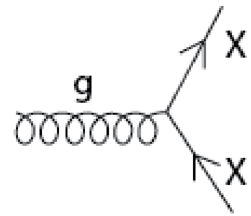
Standard Model Interactions
(Forces Mediated by Gauge Bosons)



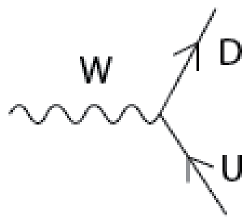
X is any fermion in the Standard Model.



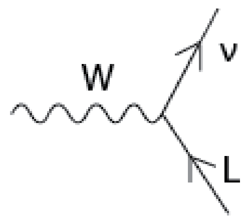
X is electrically charged.



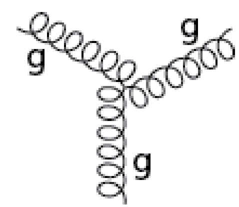
X is any quark.

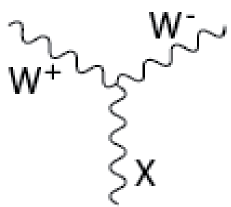


U is a up-type quark; D is a down-type quark.

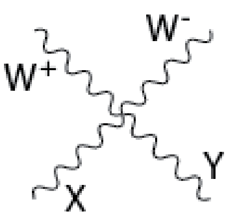


L is a lepton and ν is the corresponding neutrino.

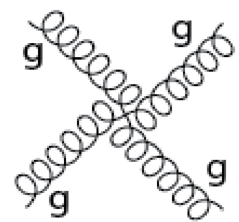




X is a photon or Z-boson.



X and Y are any two electroweak bosons such that charge is conserved.



[11] In obtaining the expression (11) the mass difference between the charged and neutral has been ignored.

[12]M. Ademollo and R. Gatto, Nuovo Cimento 44A, 282 (1966); see also J. Pasupathy and R. E. Marshak, Phys. Rev. Letters 17, 888 (1966).

[13]The predicted ratio [eq. (12)] from the current algebra is slightly larger than that (0.23%) obtained from the ρ-dominance model of Ref. 2. This seems to be true also in the other case of the ratio $\Gamma(\eta\to\pi^+\pi^-\gamma)/\Gamma(\gamma\gamma)$ calculated in Refs. 12 and 14.

[14]L. M. Brown and P. Singer, Phys. Rev. Letters 8, 460 (1962).

A MODEL OF LEPTONS*

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(Received 17 October 1967)

Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite[1] these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differences in the masses of the photon and inter-

and on a right-handed singlet

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

The largest group that leaves invariant the kinematic terms $-\bar{L}\gamma^\mu\partial_\mu L-\bar{R}\gamma^\mu\partial_\mu R$ of the Lagrangian consists of the electronic isospin $\vec{T}$ acting

and

$$\varphi_1 \equiv (\varphi^0 + \varphi^{0\dagger} - 2\lambda)/\sqrt{2} \quad \varphi_2 \equiv (\varphi^0 - \varphi^{0\dagger})/i\sqrt{2}. \qquad (5)$$

The condition that φ_1 have zero vacuum expectation value to all orders of perturbation theory tells us that $\lambda^2 \cong M_1^2/2h$, and therefore the field φ_1 has mass M_1 while φ_2 and φ^- have mass zero. But we can easily see that the Goldstone bosons represented by φ_2 and φ^- have no physical coupling. The Lagrangian is gauge invariant, so we can perform a combined isospin and hypercharge gauge transformation which eliminates φ^- and φ_2 everywhere[6] without changing anything else. We will see that G_e is very small, and in any case M_1 might be very large,[7] so the φ_1 couplings will also be disregarded in the following.

The effect of all this is just to replace φ everywhere by its vacuum expectation value

$$\langle\varphi\rangle = \lambda\binom{1}{0}. \qquad (6)$$

The first four terms in $\mathfrak{L}$ remain intact, while the rest of the Lagrangian becomes

$$-\tfrac{1}{8}\lambda^2 g^2[(A_\mu{}^1)^2 + (A_\mu{}^2)^2] - \tfrac{1}{8}\lambda^2(gA_\mu{}^3 + g'B_\mu)^2 - \lambda G_e \bar{e}e. \qquad (7)$$

We see immediately that the electron mass is λG_e. The charged spin-1 field is

$$W_\mu = 2^{-1/2}(A_\mu{}^1 + iA_\mu{}^2) \qquad (8)$$

and has mass

$$M_W = \tfrac{1}{2}\lambda g. \qquad (9)$$

The neutral spin-1 fields of definite mass are

$$Z_\mu = (g^2 + g'^2)^{-1/2}(gA_\mu{}^3 + g'B_\mu), \qquad (10)$$

$$A_\mu = (g^2 + g'^2)^{-1/2}(-g'A_\mu{}^3 + gB_\mu). \qquad (11)$$

Their masses are

$$M_Z = \tfrac{1}{2}\lambda(g^2 + g'^2)^{1/2}, \qquad (12)$$

$$M_A = 0, \qquad (13)$$

so A_μ is to be identified as the photon field. The interaction between leptons and spin-1 mesons is

$$\frac{ig}{2\sqrt{2}}\bar{e}\gamma^\mu(1+\gamma_5)\nu W_\mu + \text{H.c.} + \frac{igg'}{(g^2+g'^2)^{1/2}}\bar{e}\gamma^\mu e A_\mu + \frac{i(g^2+g'^2)^{1/2}}{4}\left[\left(\frac{3g'^2-g^2}{g'^2+g^2}\right)\bar{e}\gamma^\mu e - \bar{e}\gamma^\mu\gamma_5 e + \bar{\nu}\gamma^\mu(1+\gamma_5)\nu\right]Z_\mu. \qquad (14)$$

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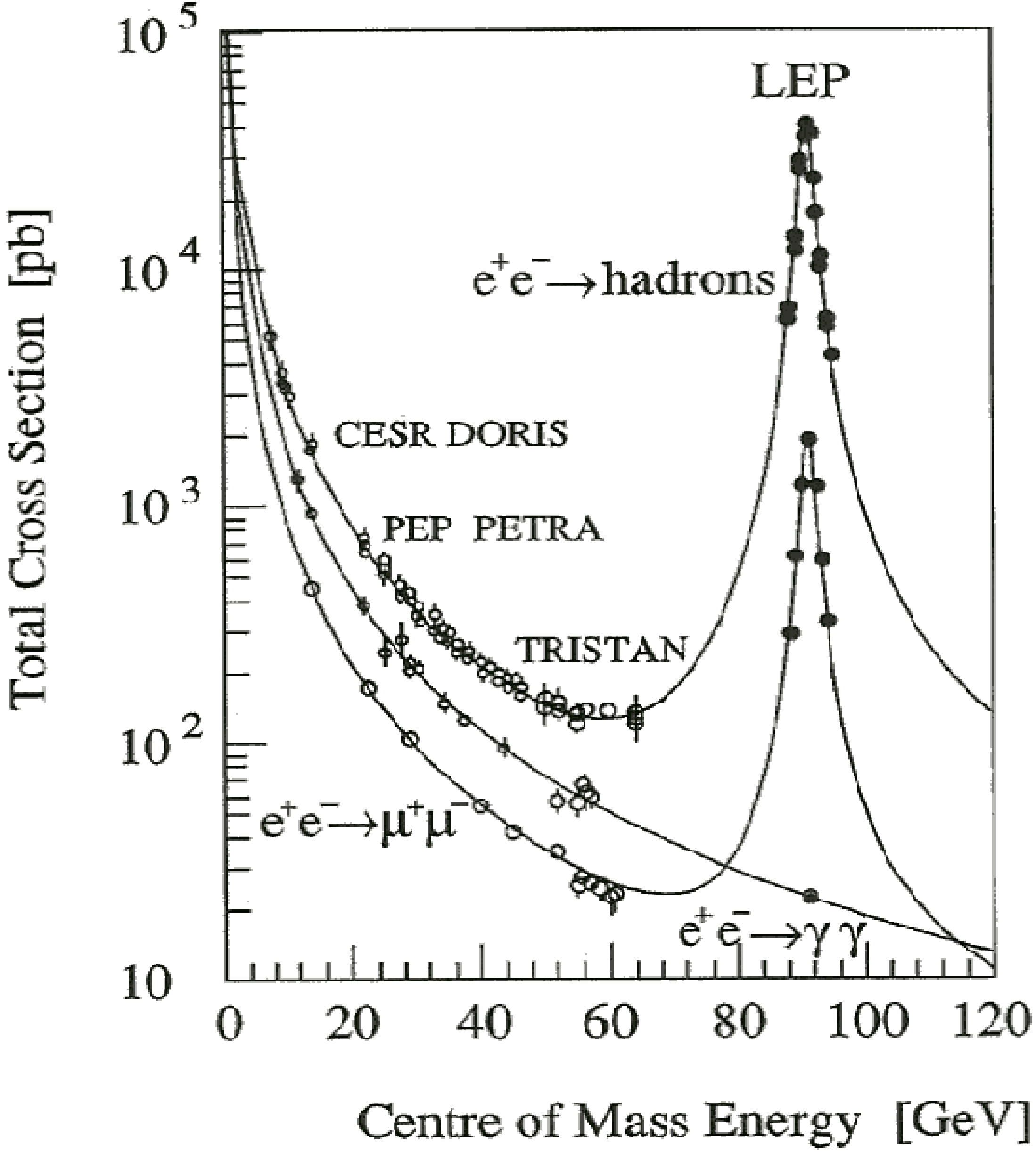
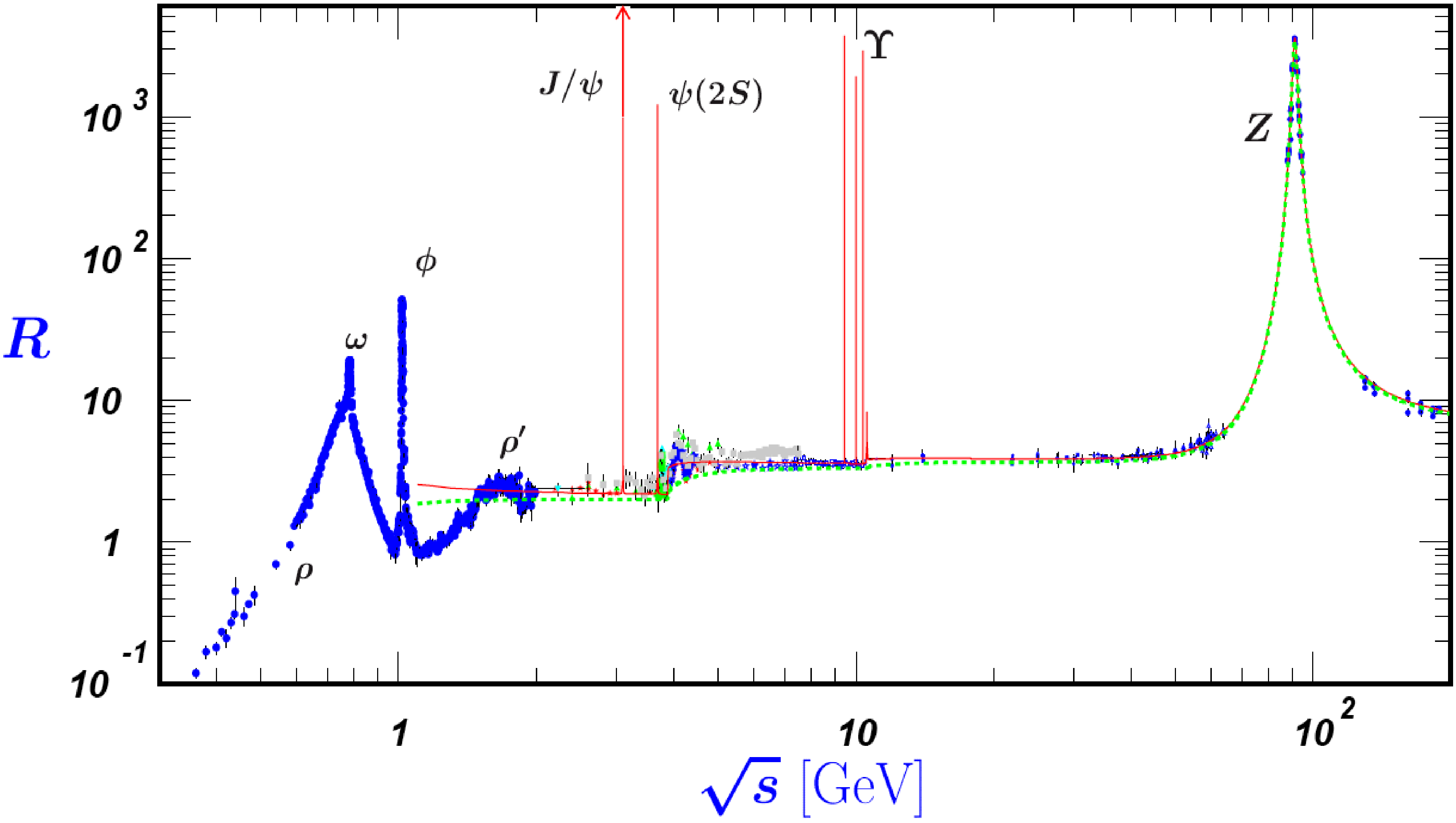
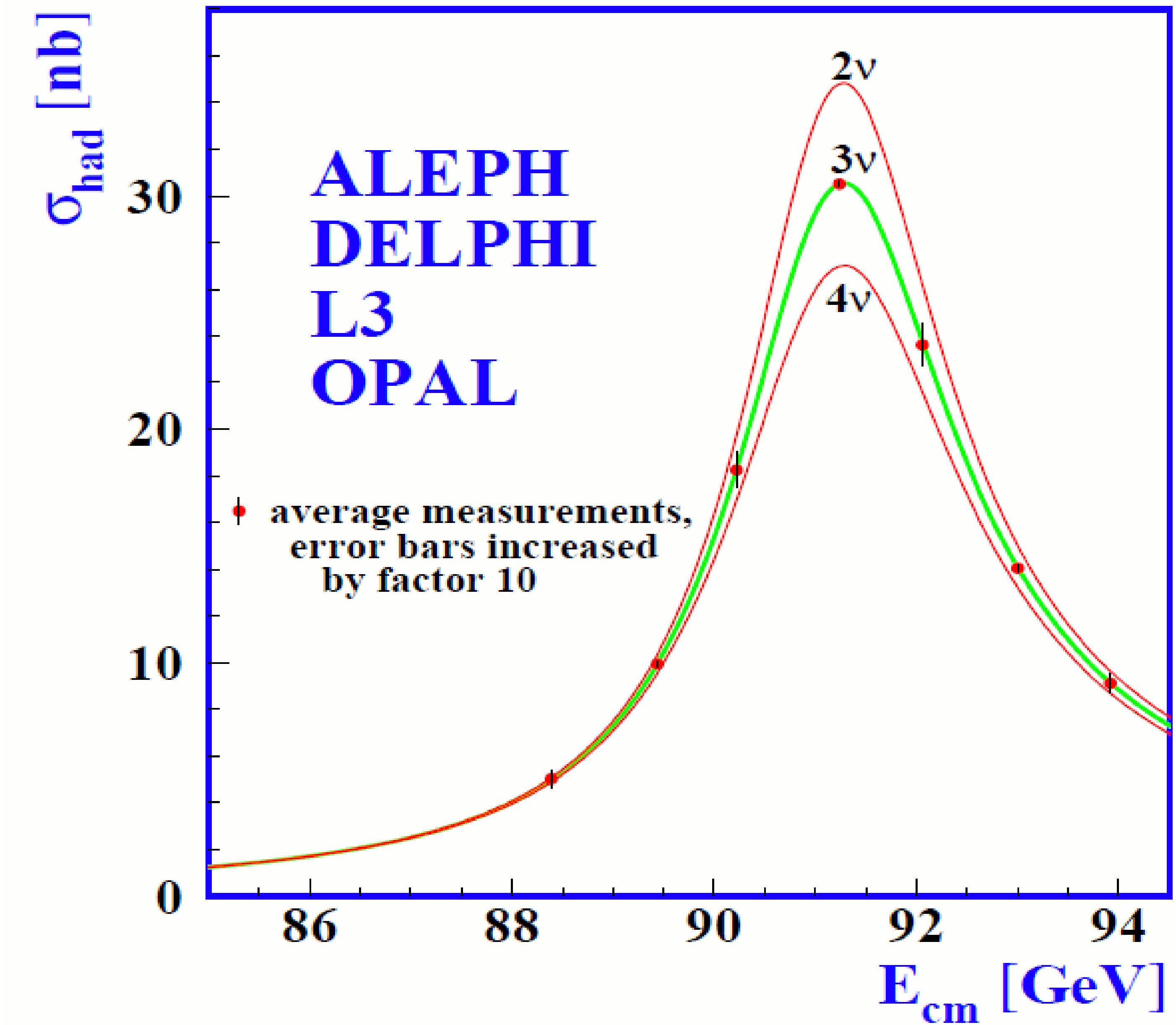


Total Cross Section [pb]
Centre of Mass Energy [GeV]
LEP
$e^+e^- \to$ hadrons
CESR DORIS
PEP PETRA
TRISTAN
$e^+e^- \to \mu^+\mu^-$
$e^+e^- \to \gamma\gamma$
10^5
10^4
10^3
10^2
10
0
20
40
60
80
100
120



R
10^3
10^2
10
1
10^-1
1
10
10^2
√s [GeV]
J/ψ
ψ(2S)
Υ
Z
φ
ω
ρ
ρ′

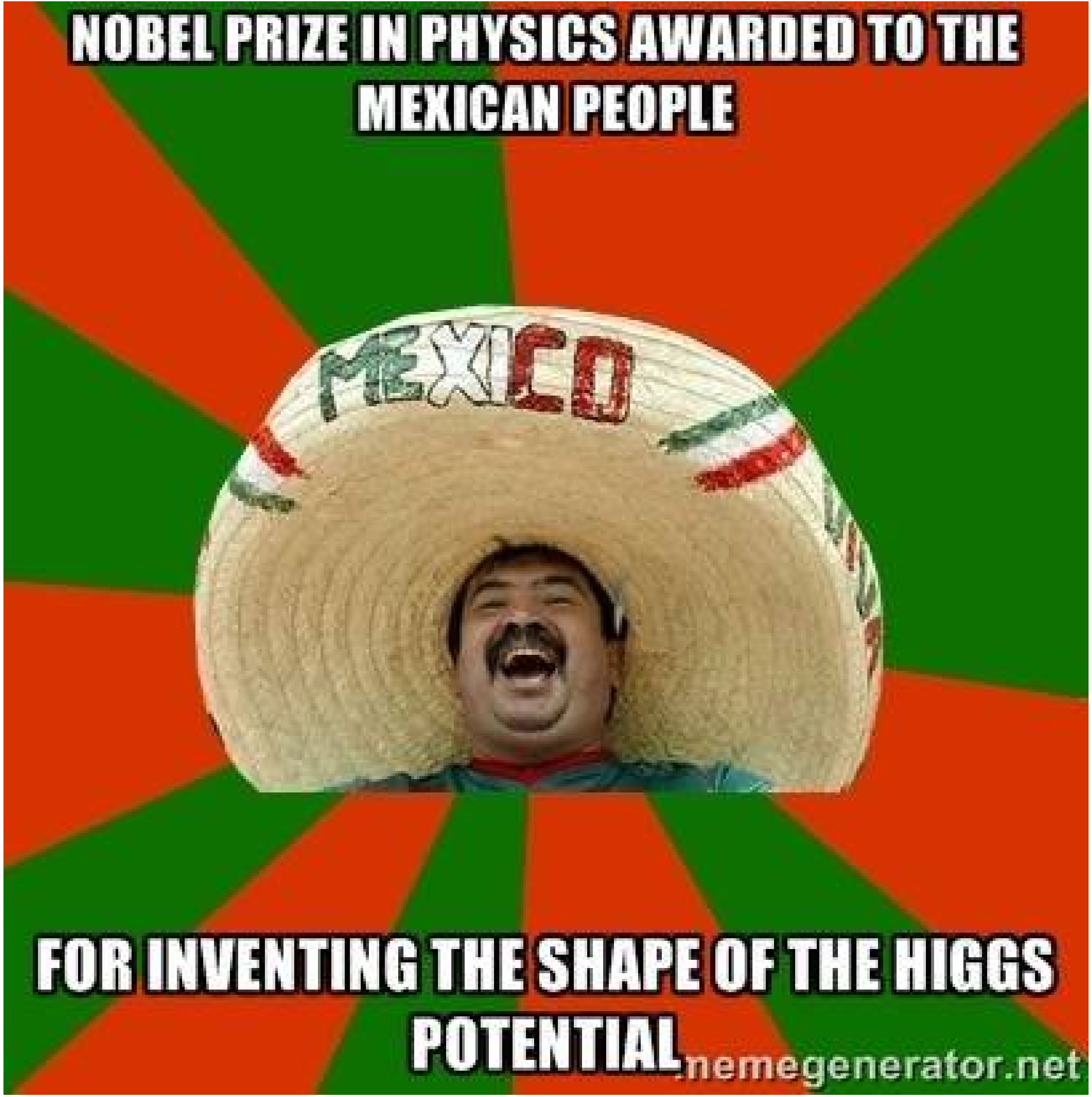


σ_{had} [nb]
ALEPH
DELPHI
L3
OPAL
2ν
3ν
4ν
average measurements,
error bars increased
by factor 10
0
10
20
30
86
88
90
92
94
E_{cm} [GeV]

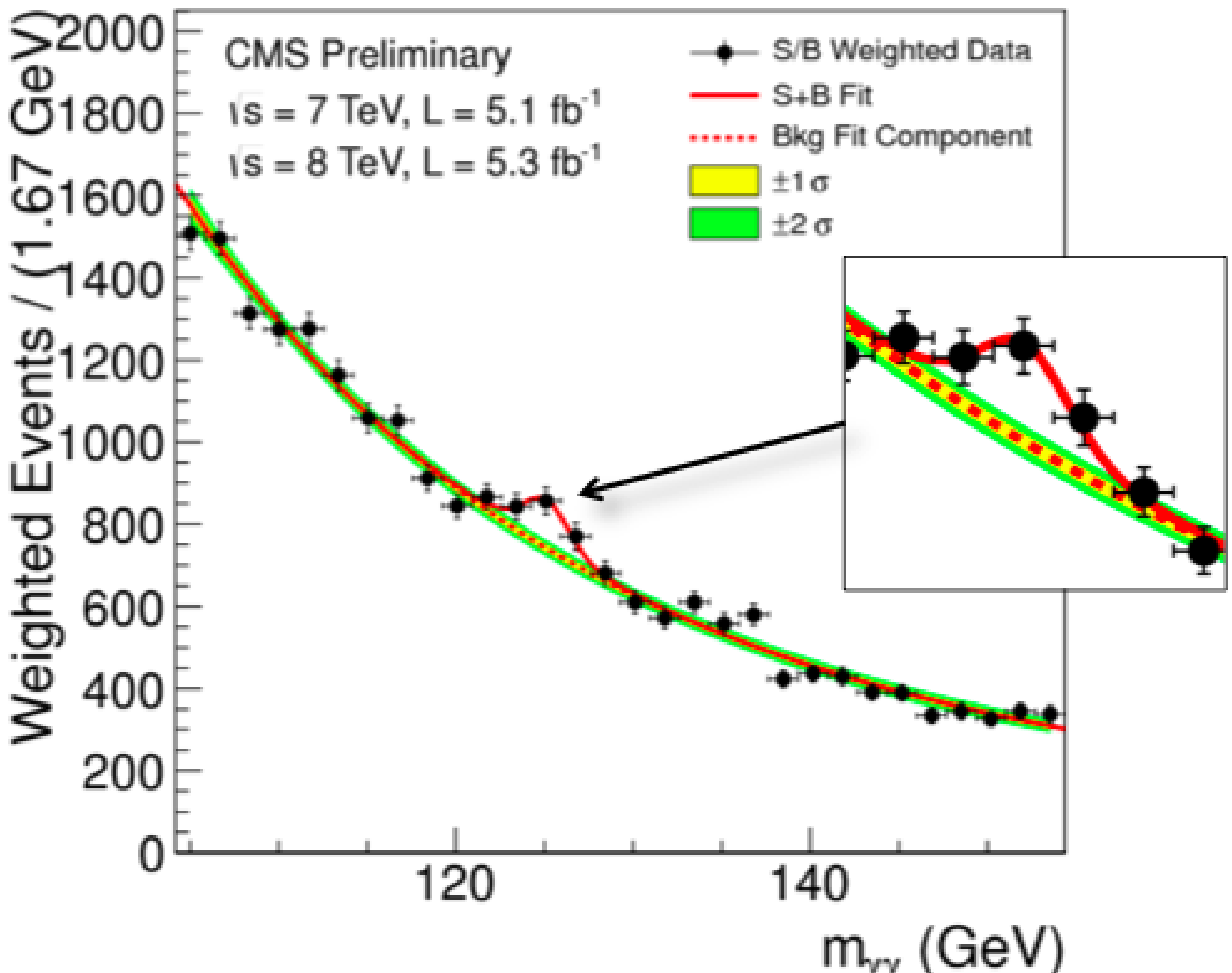
Higgs

No, no lo descubrieron

mexicanos


NOBEL PRIZE IN PHYSICS AWARDED TO THE MEXICAN PEOPLE
MEXICO
FOR INVENTING THE SHAPE OF THE HIGGS POTENTIAL
memegenerator.net


SAY GOD PARTICLE
ONE MORE
GODDAMN TIME



CMS Preliminary
√s = 7 TeV, L = 5.1 fb^-1
√s = 8 TeV, L = 5.3 fb^-1
S/B Weighted Data
S+B Fit
Bkg Fit Component
±1 σ
±2 σ
Weighted Events / (1.67 GeV)
m_γγ (GeV)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
120
140

Selected for a Viewpoint in *Physics*
PRL **114,** 191803 (2015) PHYSICAL REVIEW LETTERS week ending 15 MAY 2015

Combined Measurement of the Higgs Boson Mass in pp Collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS Experiments

G. Aad *et al.*[*]

(ATLAS Collaboration)[†]
(CMS Collaboration)[‡]
(Received 25 March 2015; published 14 May 2015)

A measurement of the Higgs boson mass is presented based on the combined data samples of the ATLAS and CMS experiments at the CERN LHC in the $H \to \gamma\gamma$ and $H \to ZZ \to 4\ell$ decay channels. The results are obtained from a simultaneous fit to the reconstructed invariant mass peaks in the two channels and for the two experiments. The measured masses from the individual channels and the two experiments are found to be consistent among themselves. The combined measured mass of the Higgs boson is $m_H = 125.09 \pm 0.21\,(\mathrm{stat}) \pm 0.11\,(\mathrm{syst})$ GeV.

DOI: 10.1103/PhysRevLett.114.191803 PACS numbers: 14.80.Bn, 13.85.Qk

The study of the mechanism of electroweak symmetry breaking is one of the principal goals of the CERN LHC program. In the standard model (SM), this symmetry breaking is achieved through the introduction of a complex doublet scalar field, leading to the prediction of the Higgs boson H [1–6], whose mass m_H is, however, not predicted by the theory. In 2012, the ATLAS and CMS

This Letter describes a combination of the Run 1 data from the two experiments, leading to improved precision for m_H. Besides its intrinsic importance as a fundamental parameter, improved knowledge of m_H yields more precise predictions for the other Higgs boson properties. Furthermore, the combined mass measurement provides a first step towards combinations of other quantities, such

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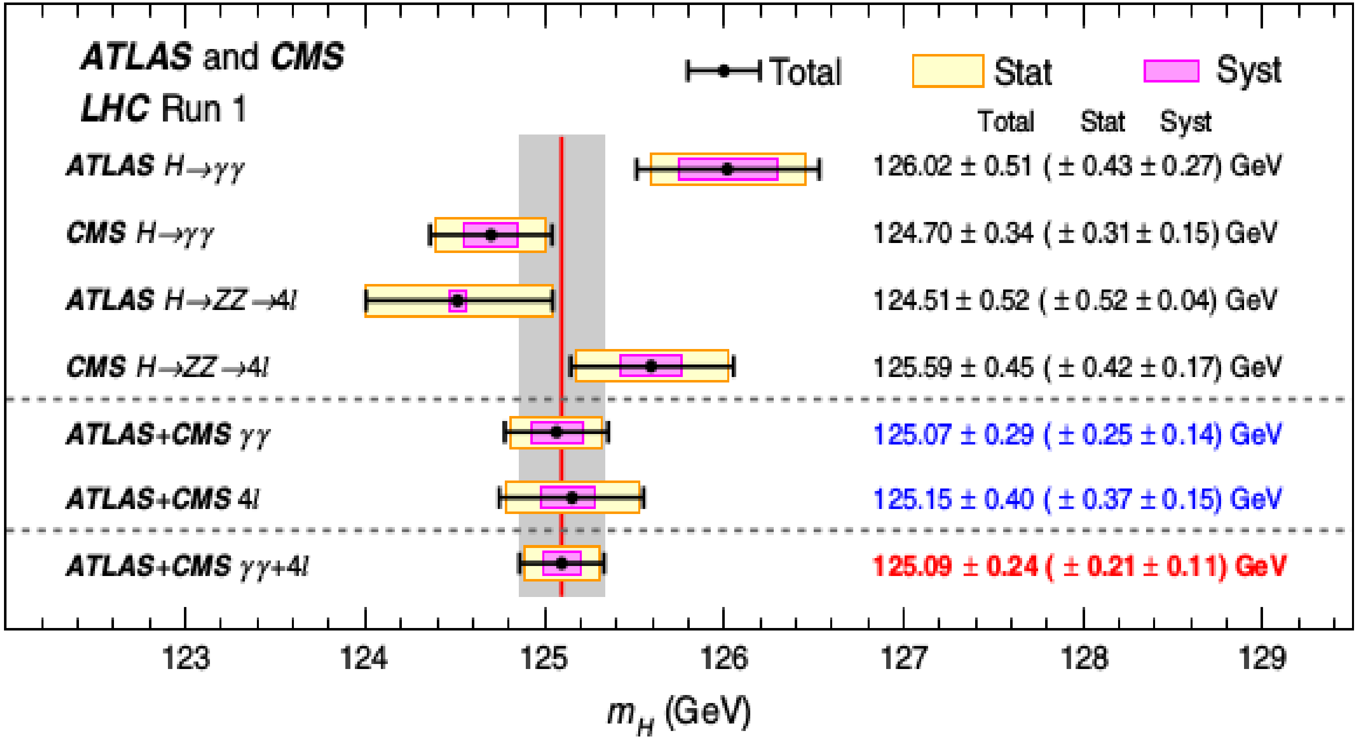


FIG. 2 (color online). Summary of Higgs boson mass measurements from the individual analyses of ATLAS and CMS and from the combined analysis presented here. The systematic (narrower, magenta-shaded bands), statistical (wider, yellow-shaded bands), and total (black error bars) uncertainties are indicated. The (red) vertical line and corresponding (gray) shaded column indicate the central value and the total uncertainty of the combined measurement, respectively.

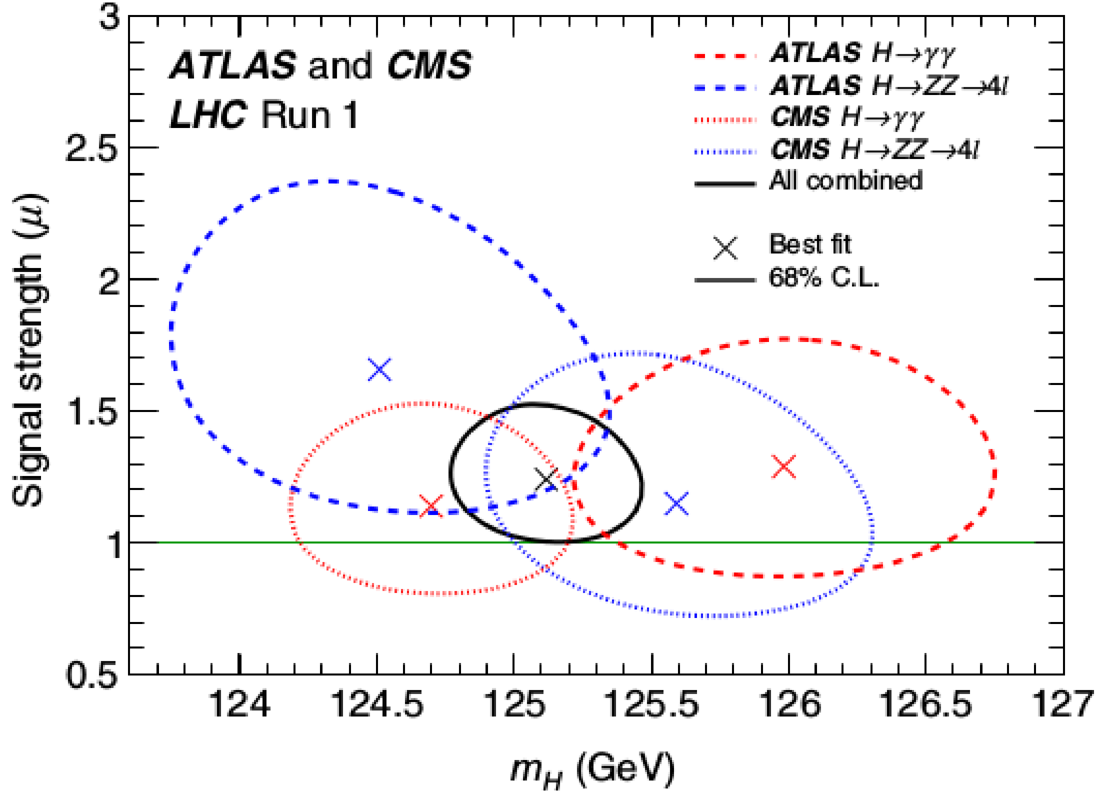
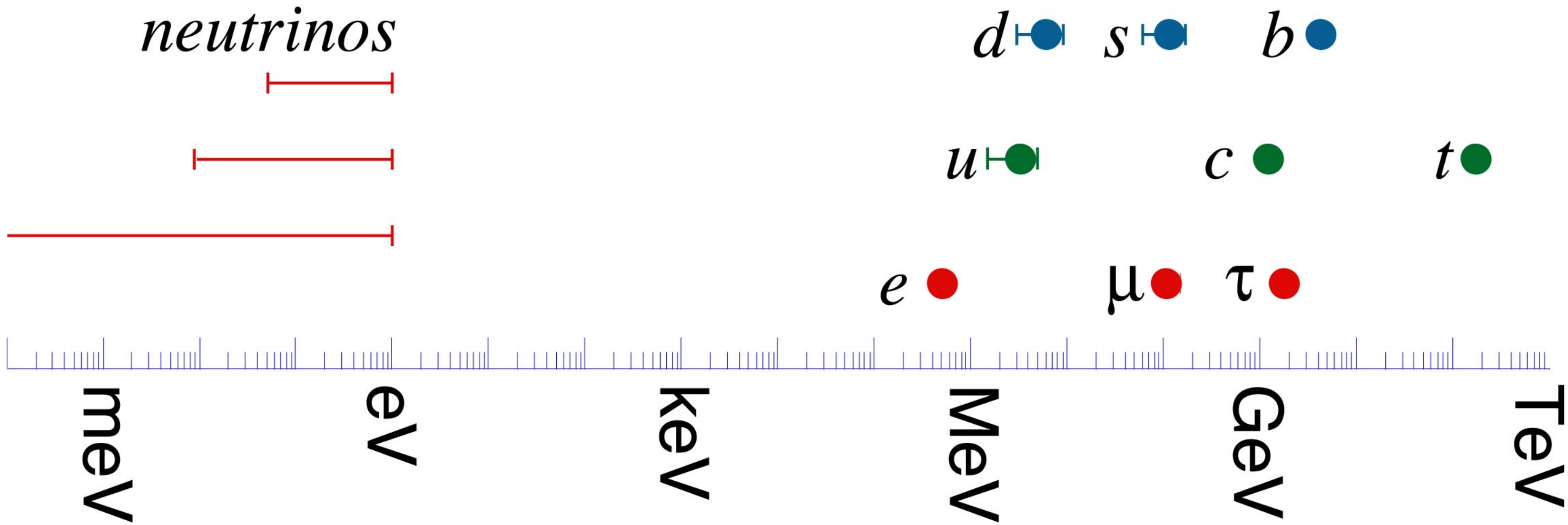


FIG. 4 (color online). Summary of likelihood scans in the 2D plane of signal strength μ versus Higgs boson mass m_H for the ATLAS and CMS experiments. The 68% C.L. confidence regions of the individual measurements are shown by the dashed curves and of the overall combination by the solid curve. The markers indicate the respective best-fit values. The SM signal strength is indicated by the horizontal line at $\mu = 1$.

Masa


neutrinos
d
s
b
u
c
t
e
μ
τ
meV
eV
keV
MeV
GeV
TeV

¿Problemas con el Modelo estándar?

Measurement of the Ratio of Branching Fractions $\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)$

R. Aaij *et al.*[*]

(LHCb Collaboration)

(Received 30 June 2015; published 9 September 2015; corrected 14 September 2015)

The branching fraction ratio $\mathcal{R}(D^*) \equiv \mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)$ is measured using a sample of proton-proton collision data corresponding to 3.0 fb^{-1} of integrated luminosity recorded by the LHCb experiment during 2011 and 2012. The tau lepton is identified in the decay mode $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$. The semitauonic decay is sensitive to contributions from non-standard-model particles that preferentially couple to the third generation of fermions, in particular, Higgs-like charged scalars. A multidimensional fit to kinematic distributions of the candidate $\bar{B}^0$ decays gives $\mathcal{R}(D^*) = 0.336 \pm 0.027(\mathrm{stat}) \pm 0.030(\mathrm{syst})$. This result, which is the first measurement of this quantity at a hadron collider, is 2.1 standard deviations larger than the value expected from lepton universality in the standard model.

DOI: 10.1103/PhysRevLett.115.111803 PACS numbers: 13.20.He, 14.80.Fd

Lepton universality, enshrined within the standard model (SM), requires equality of couplings between the gauge bosons and the three families of leptons. Hints of lepton nonuniversal effects in $B^+ \to K^+e^+e^-$ and $B^+ \to K^+\mu^+\mu^-$

data correspond to integrated luminosities of 1.0 fb^{-1} and 2.0 fb^{-1}, collected at proton-proton (pp) center-of-mass energies of 7 TeV and 8 TeV, respectively. The $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$ decay with $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$ (the signal channel) and

Measurement of the Ratio of Branching Fractions $\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)$

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(LHCb Collaboration)

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The branching fraction ratio $\mathcal{R}(D^*) \equiv \mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)$ is measured using a sample of proton-proton collision data corresponding to 3.0 fb^{-1} of integrated luminosity recorded by the LHCb experiment during 2011 and 2012. The tau lepton is identified in the decay mode $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$. The semitauonic decay is sensitive to contributions from non-standard-model particles that preferentially couple to the third generation of fermions, in particular, Higgs-like charged scalars. A multidimensional fit to kinematic distributions of the candidate $\bar{B}^0$ decays gives $\mathcal{R}(D^*) = 0.336 \pm 0.027(\text{stat}) \pm 0.030(\text{syst})$. This result, which is the first measurement of this quantity at a hadron collider, is 2.1 standard deviations larger than the value expected from lepton universality in the standard model.

?

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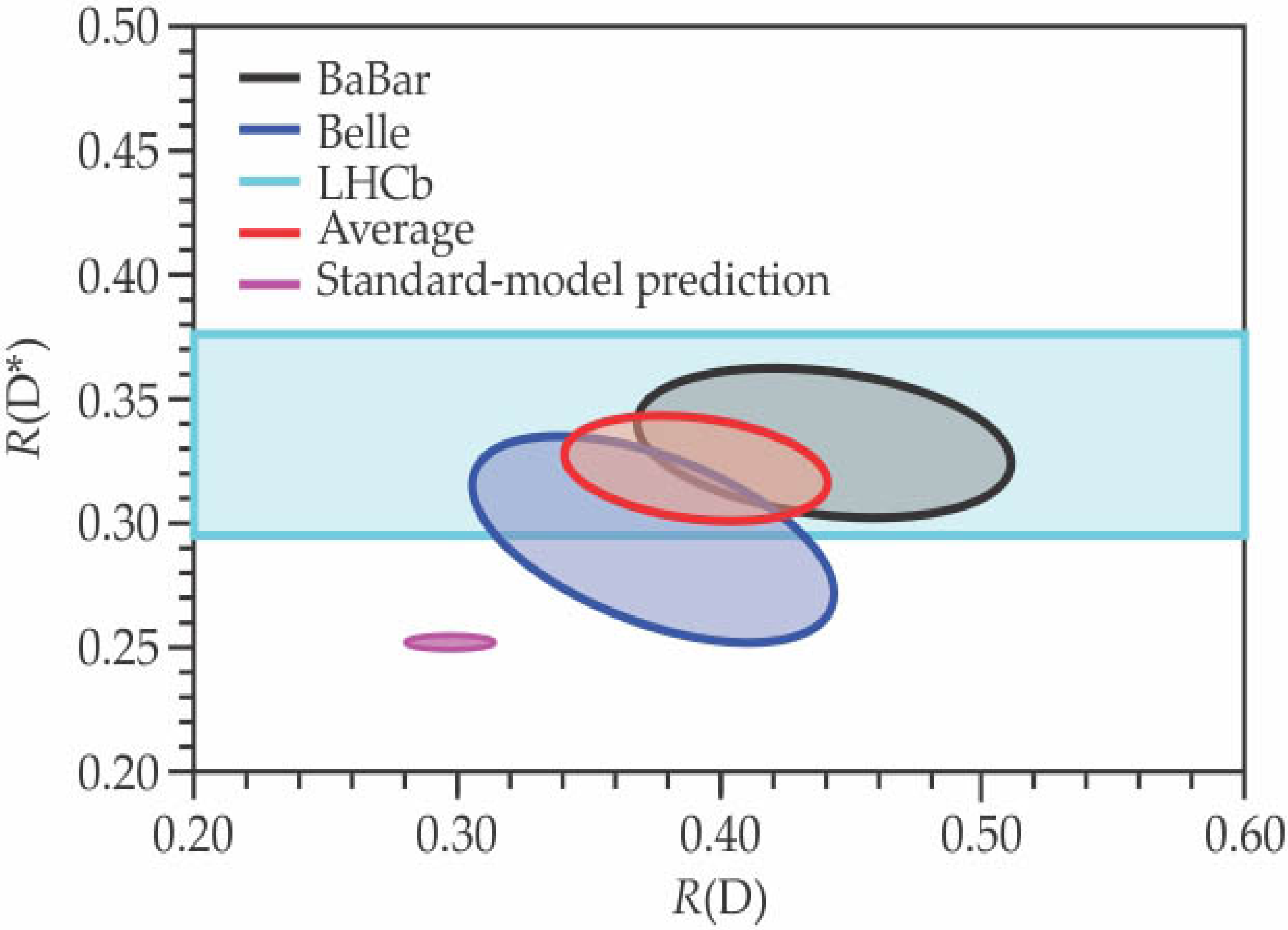
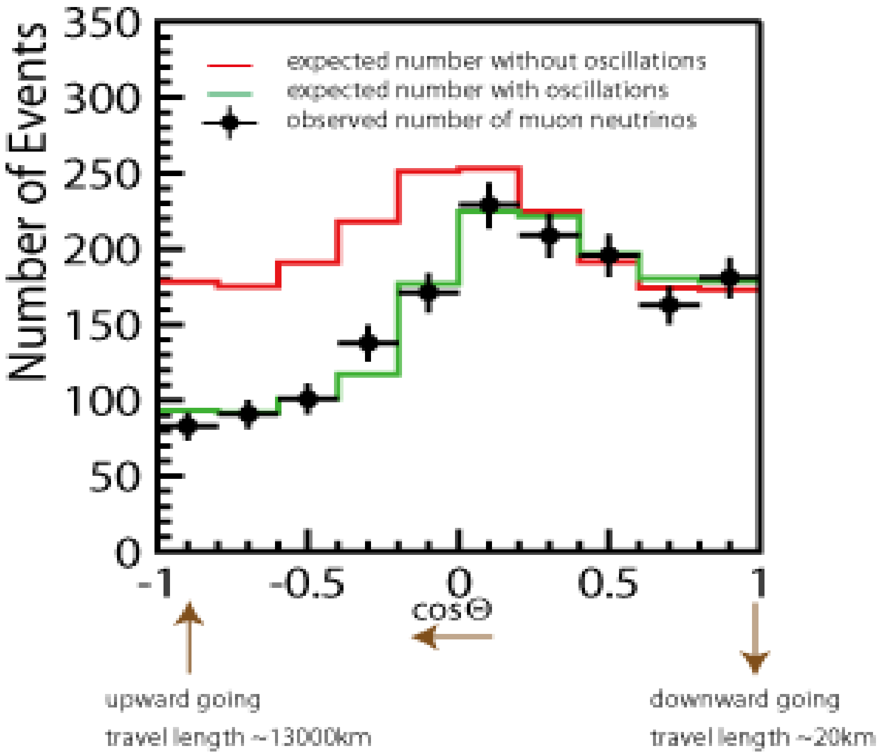
Lepton universality, enshrined within the standard model (SM), requires equality of couplings between the gauge bosons and the three families of leptons. Hints of lepton nonuniversal effects in $B^+ \to K^+e^+e^-$ and $B^+ \to K^+\mu^+\mu^-$

data correspond to integrated luminosities of 1.0 fb^{-1} and 2.0 fb^{-1}, collected at proton-proton (pp) center-of-mass energies of 7 TeV and 8 TeV, respectively. The $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$ decay with $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$ (the signal channel) and


BaBar
Belle
LHCb
Average
Standard-model prediction
0.50
0.45
0.40
0.35
0.30
0.25
0.20
R(D*)
0.20
0.30
0.40
0.50
0.60
R(D)

Neutrinos tienen masa



¿Gran Unificación?

¿Supersimetría?

¿Dimensiones extras?

¿Sectores gauge extendidos?

¿Nada?

masas

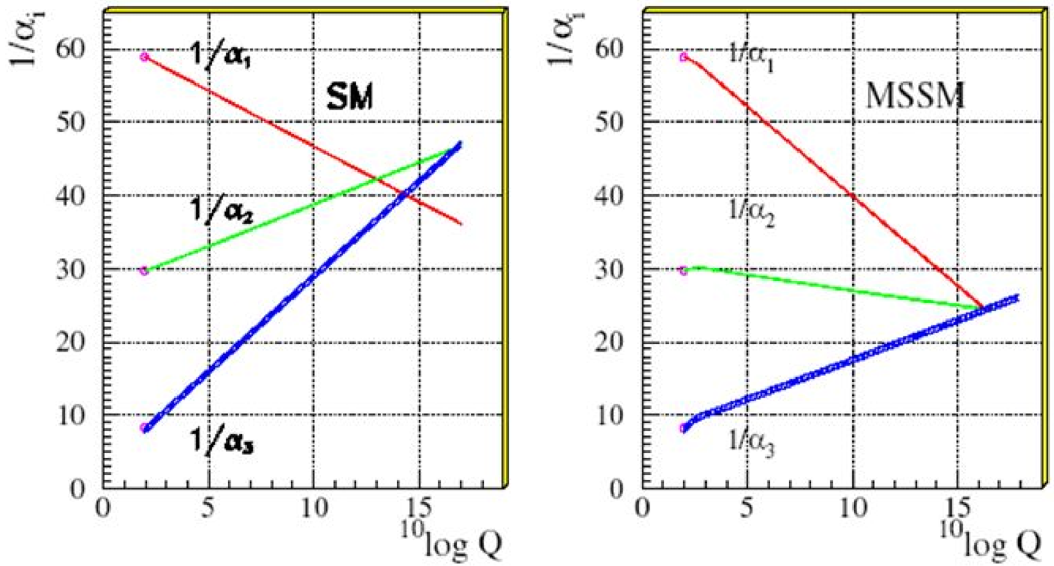
neutrinos

BAU

dark matter

⋮

Gauge Coupling Unification in SUSY

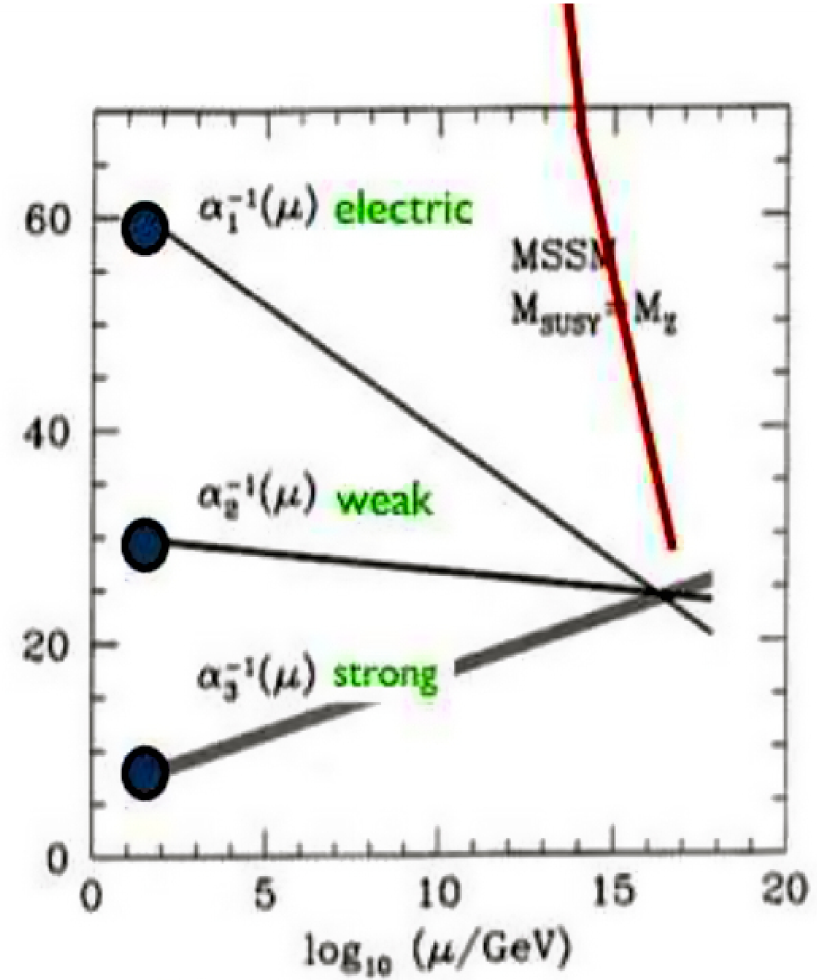


U. Amaldi, W. de Boer, H. Fürstenau, PL B260(1991)

$\alpha_1, \alpha_2, \alpha_3$ coupling constants of electromagnetic –, weak–, and strong interactions

$1/\alpha_\mathrm{i} \propto \log \mathrm{Q}^2$ due to radiative corrections (LO)

↑
inverse
coupling
strength



large energy, short distance→

Gravity fits too!
(roughly)

Standard Model and beyond