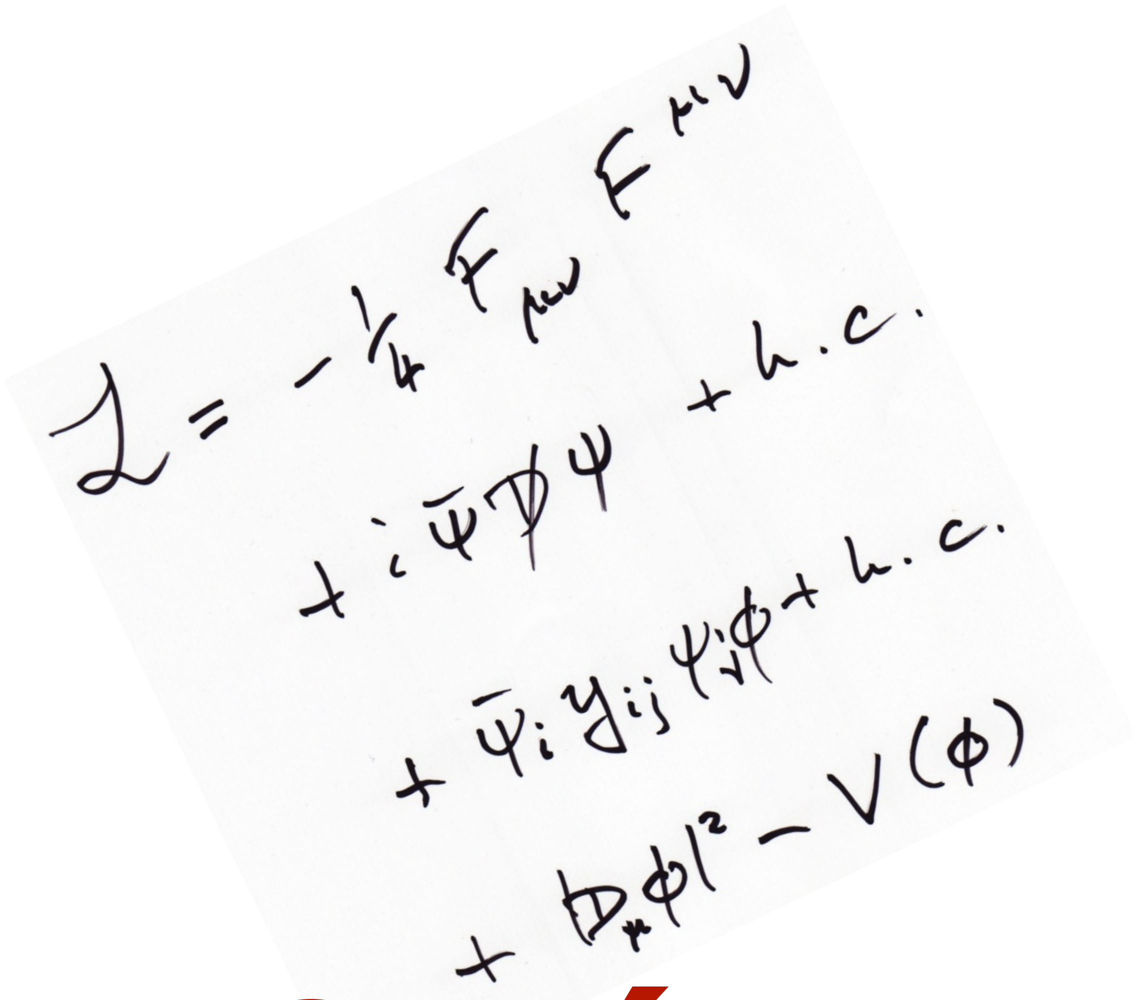

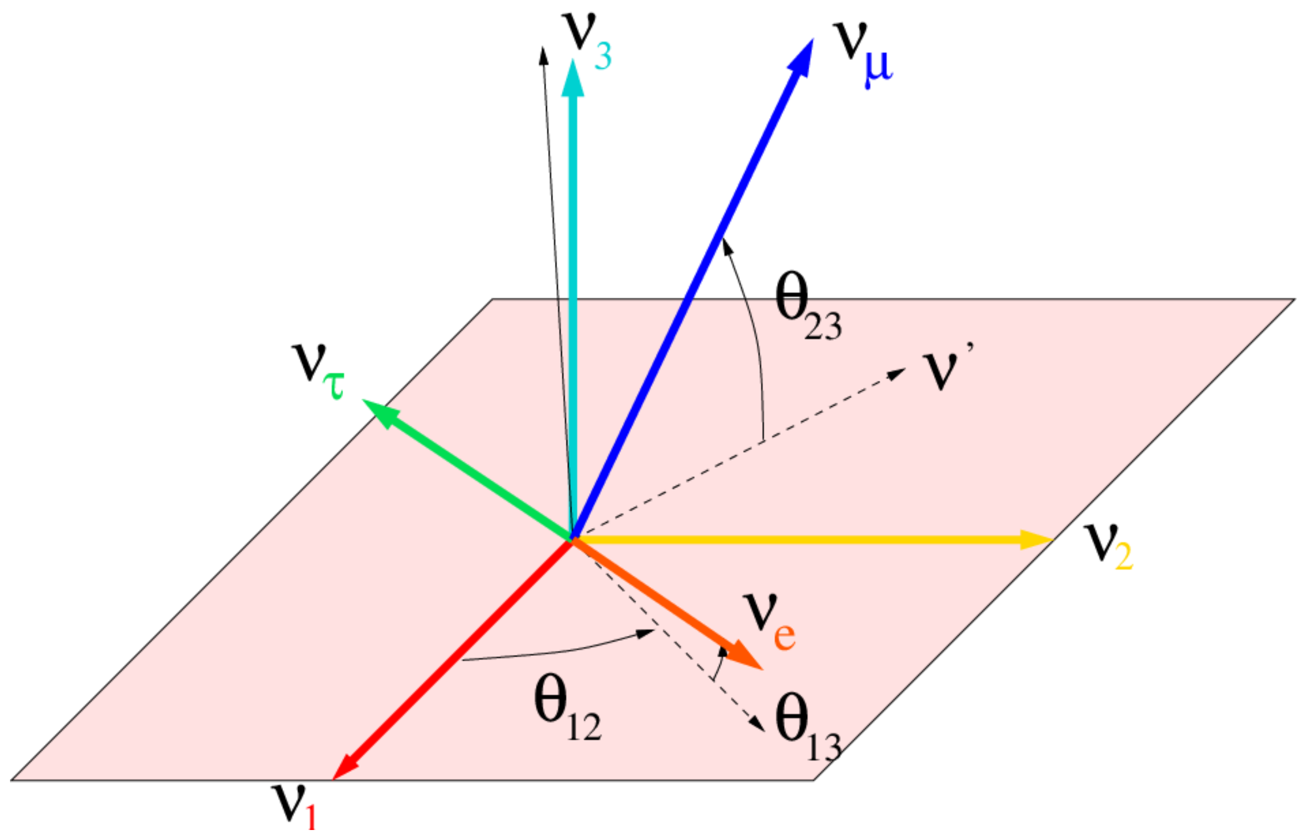

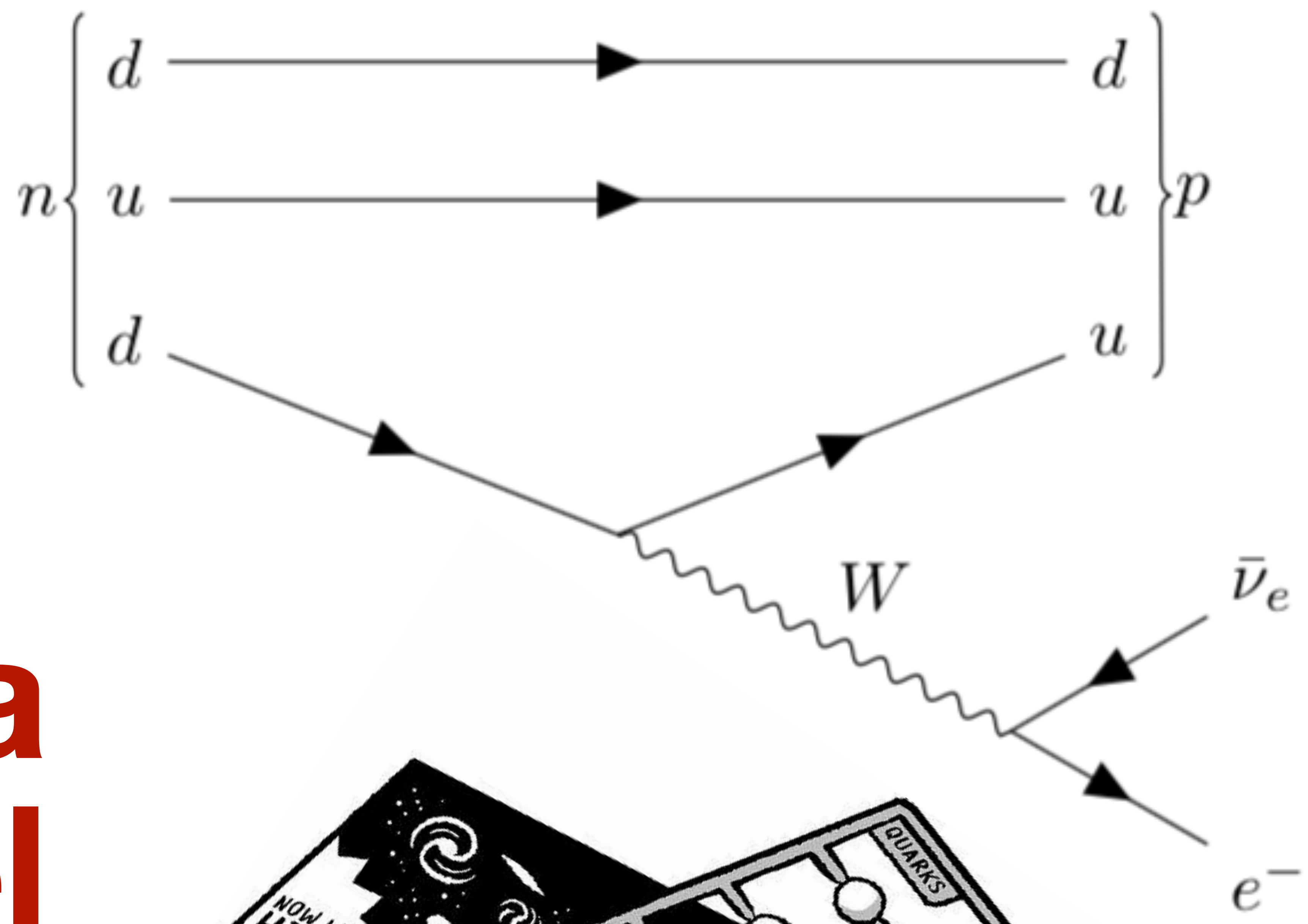

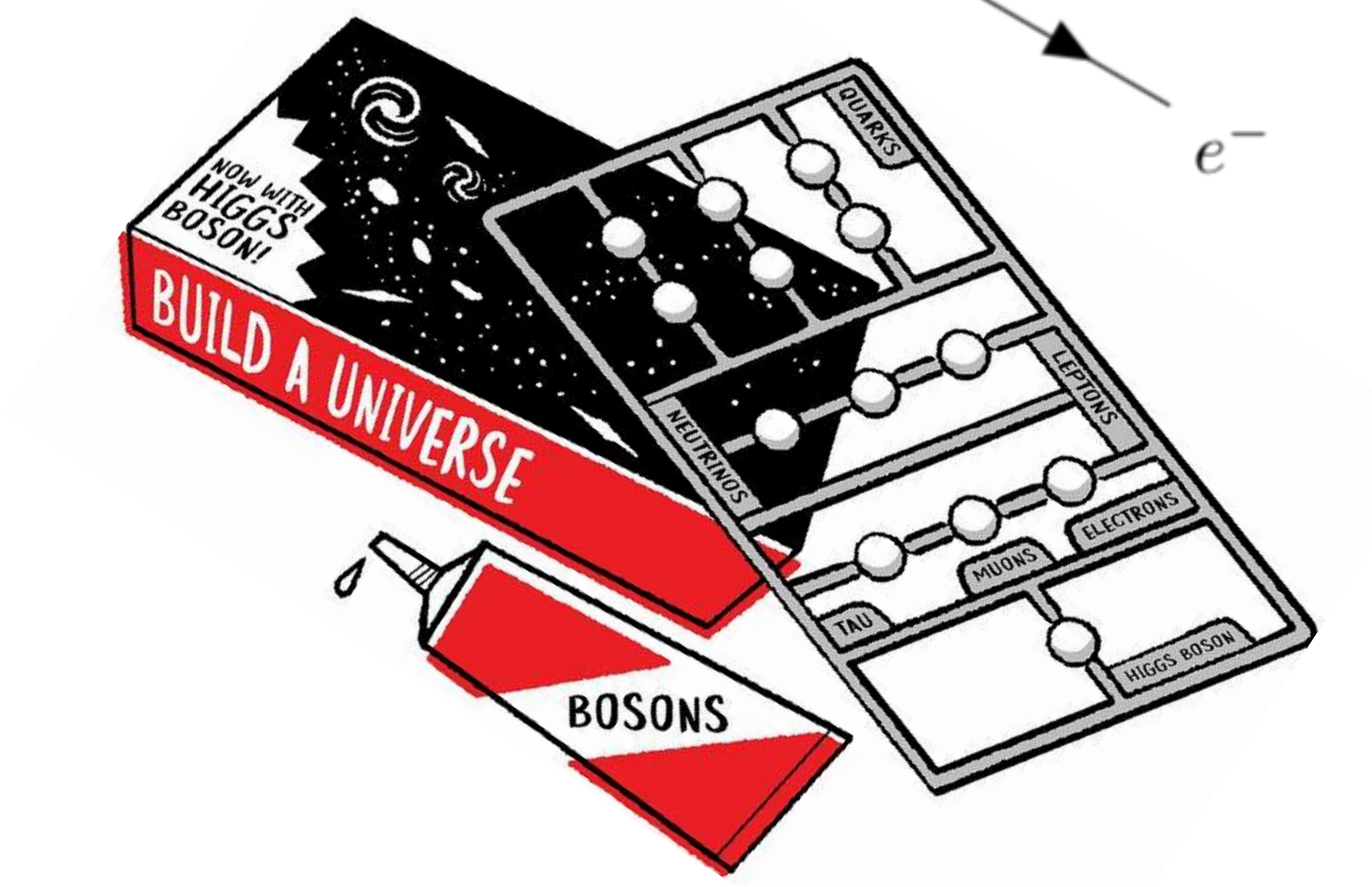

¿Qué nos dice la Teoría Cuántica de Campos sobre el Modelo Estándar y Más Allá?

Presentación realizada para Física Teórica en Río Rimac XIX 2025

Dr. Martín Arteaga Tupia, Febrero del 2025

Contenido

1. QFT y el Modelo Estándar (y Más Allá)
2. Que rol cumplen los teoremas?
3. Teoremas:

    3.1 Feynman sobre partículas sin masa de spin 2
    3.2 Weinberg-Witten
    3.3 Alppesquist-Carrazone
    3.4 Coleman-Mandula

4. Conclusiones

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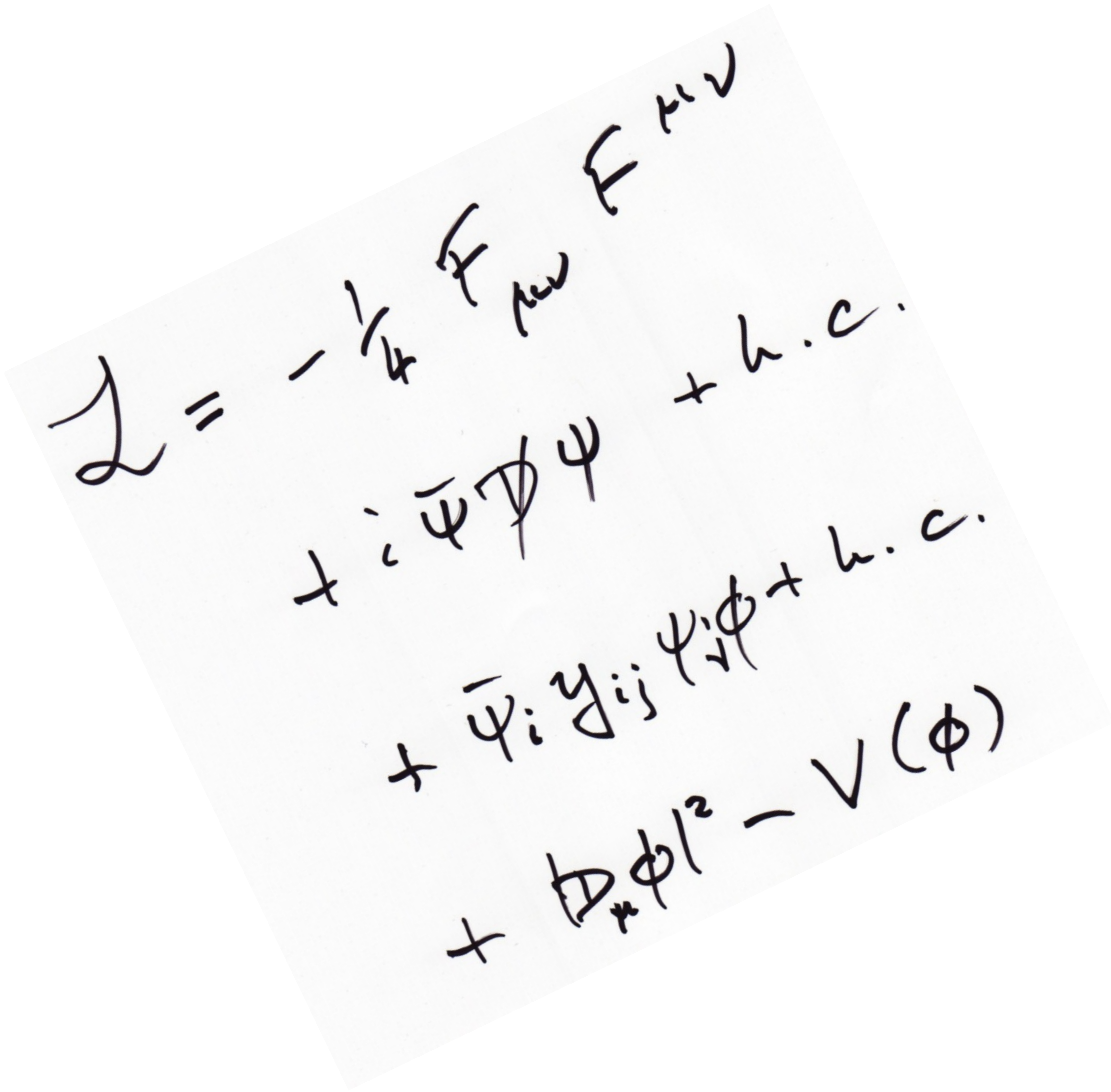
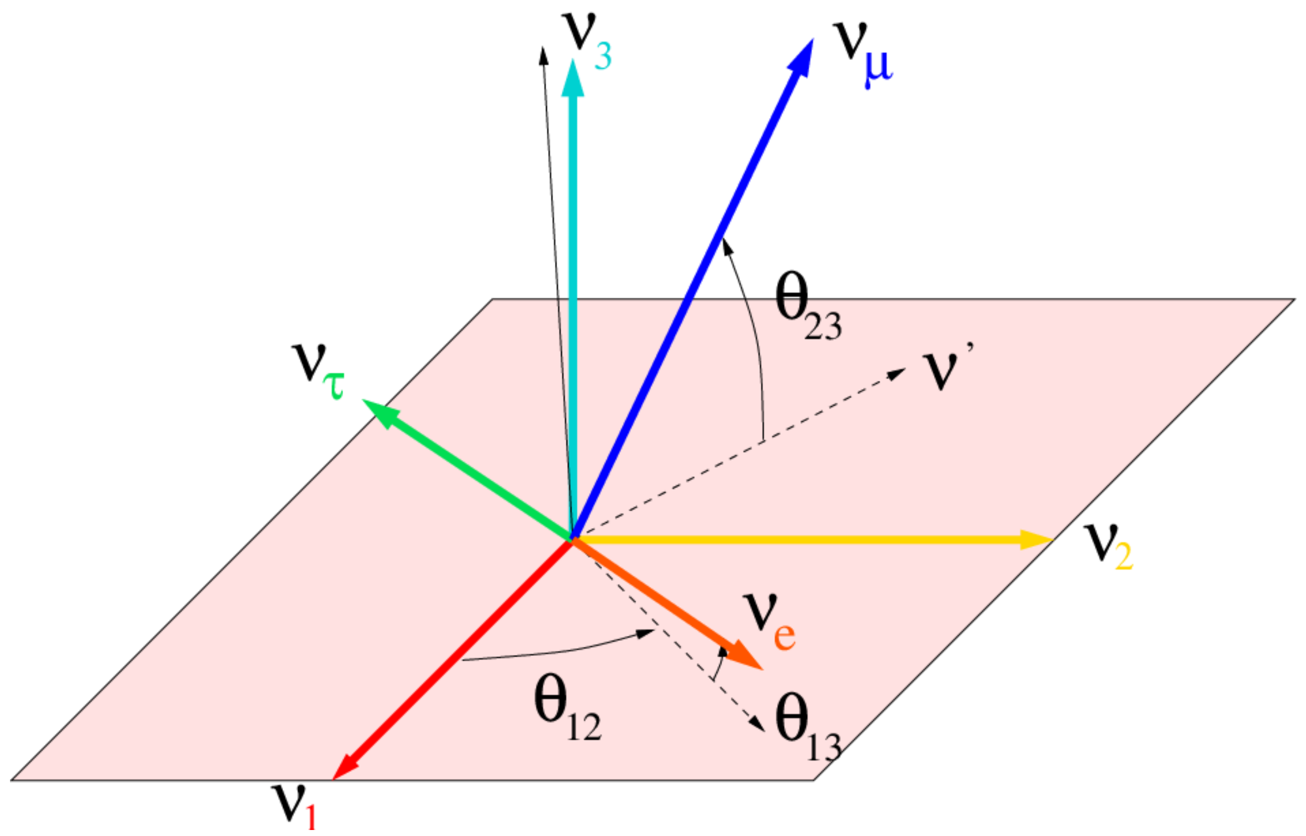
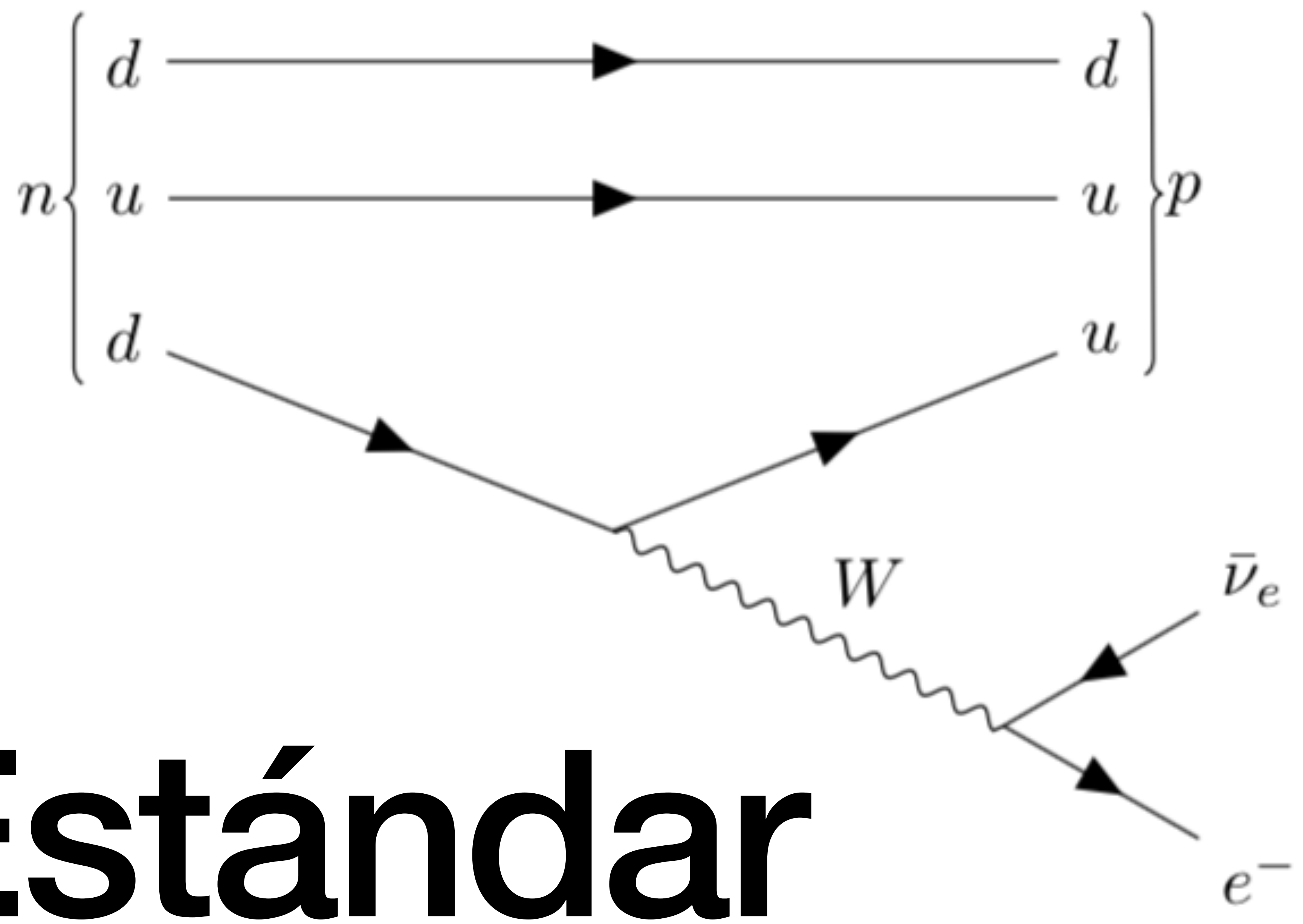
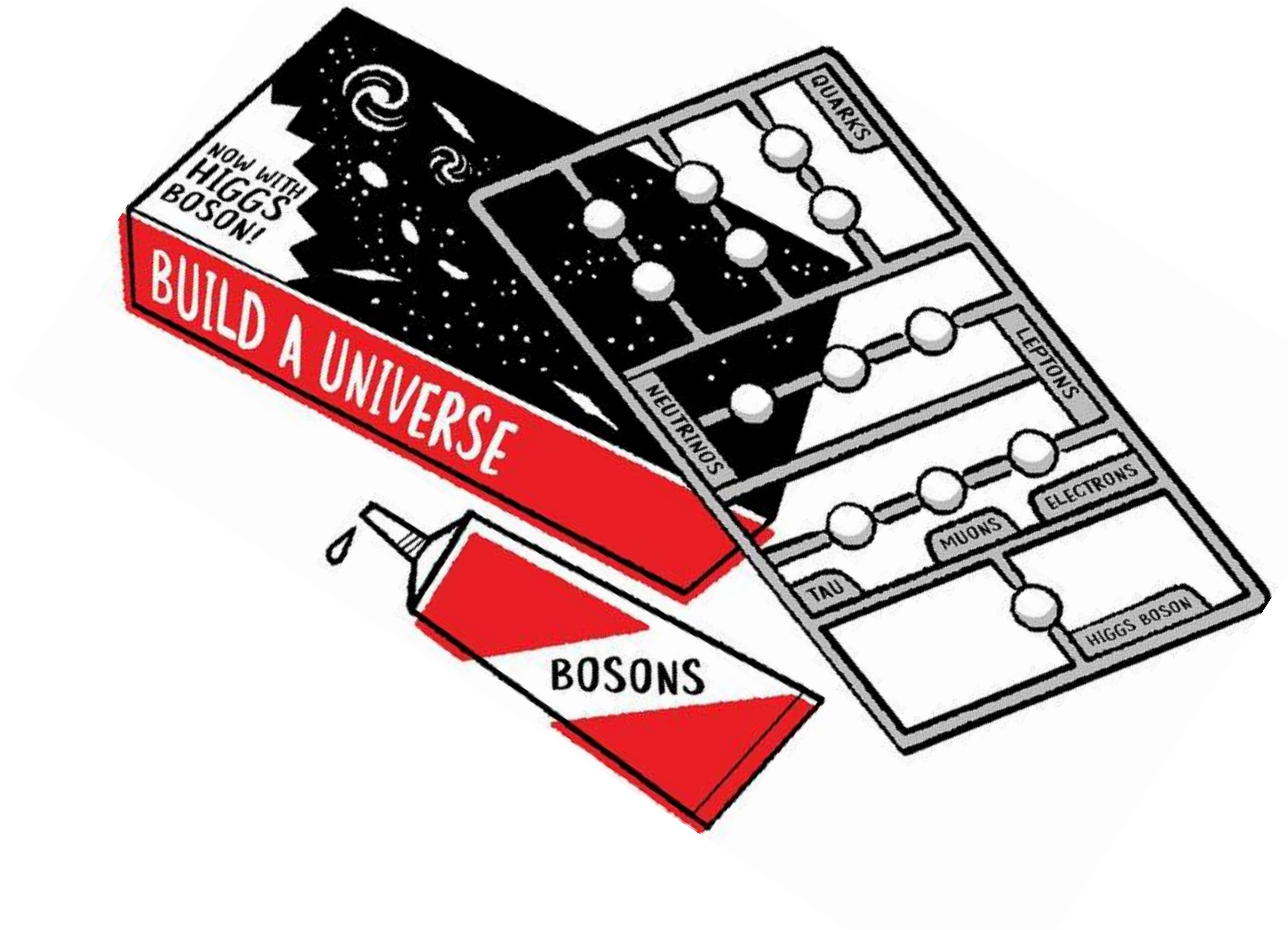




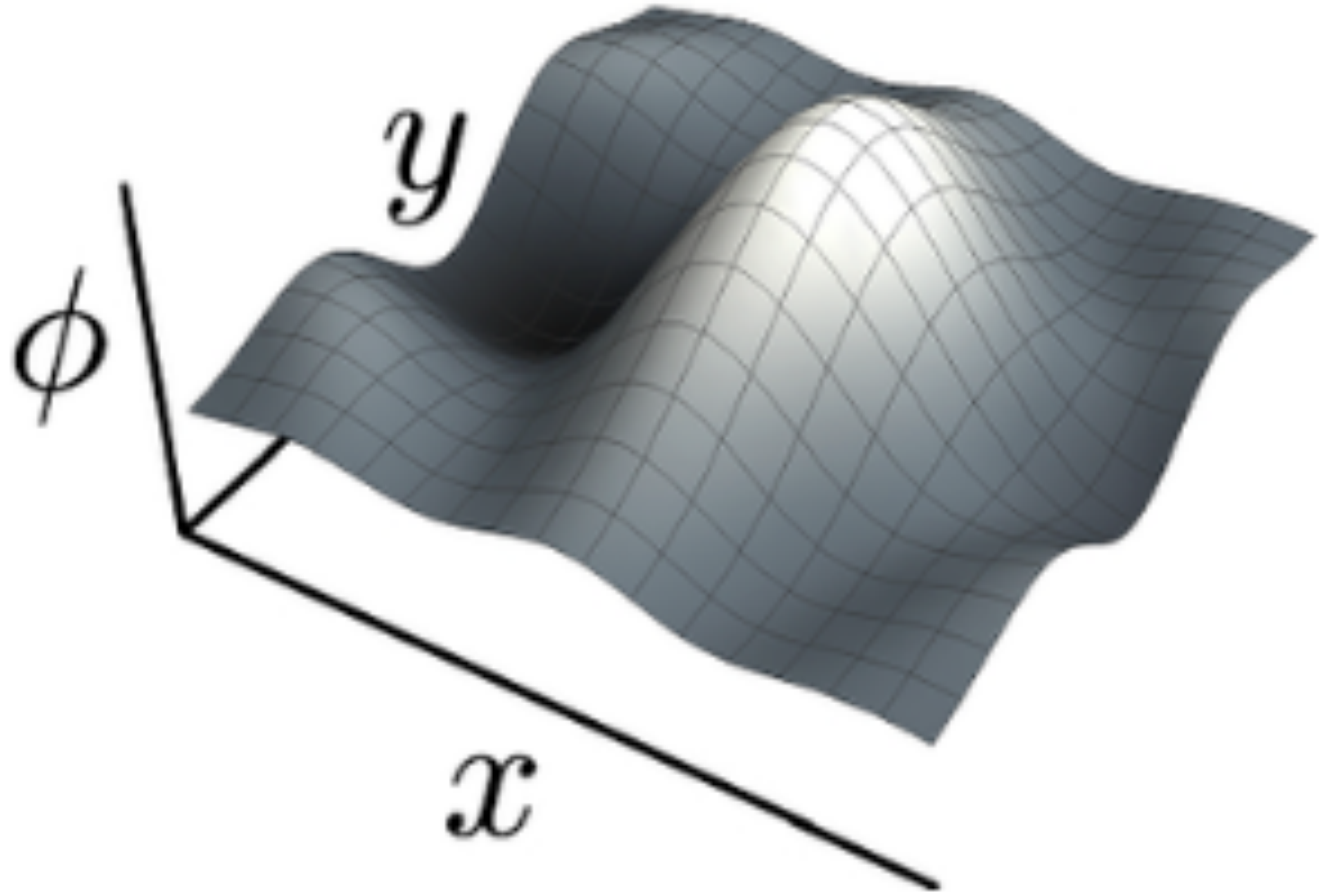


QFT y el Modelo Estándar (Y Más Allá)



Introducción

Quantum Field Theory



$$\phi(x) = \int \frac{\mathrm{d}^3k}{\sqrt{(2\pi)^3 2k^0}} \left(e^{-ik\cdot x}a(\mathbf{k}) + e^{ik\cdot x}a^\dagger(\mathbf{k})\right)$$

$$\pi(x) = \dot{\phi}(x) = -i\int \mathrm{d}^3k \sqrt{\frac{k^0}{2(2\pi)^3}} \left(e^{-ik\cdot x}a(\mathbf{k}) - e^{ik\cdot x}a^\dagger(\mathbf{k})\right)$$

$$[\phi(t,\boldsymbol{x}), \pi(t,\boldsymbol{y})] = i\delta^{(3)}(\boldsymbol{x}-\boldsymbol{y})$$

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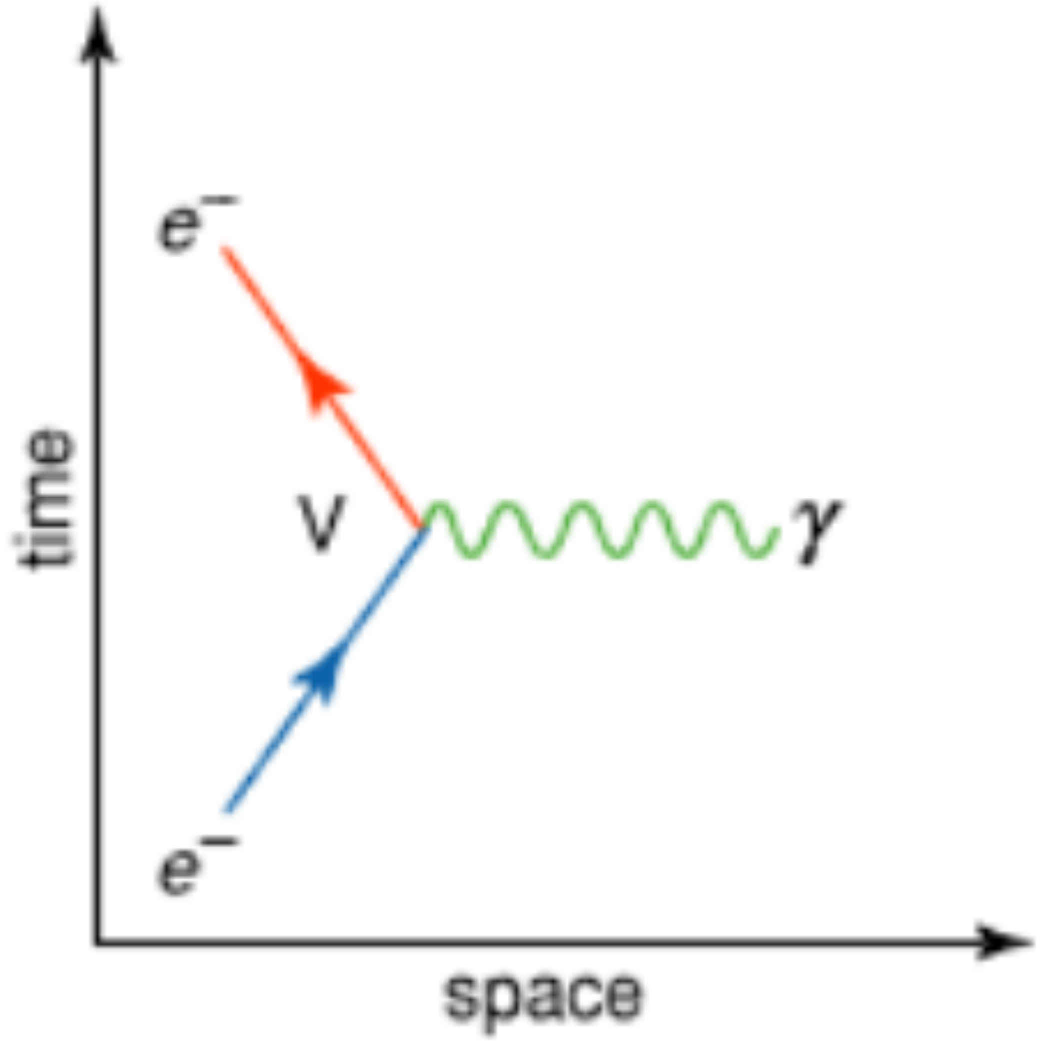

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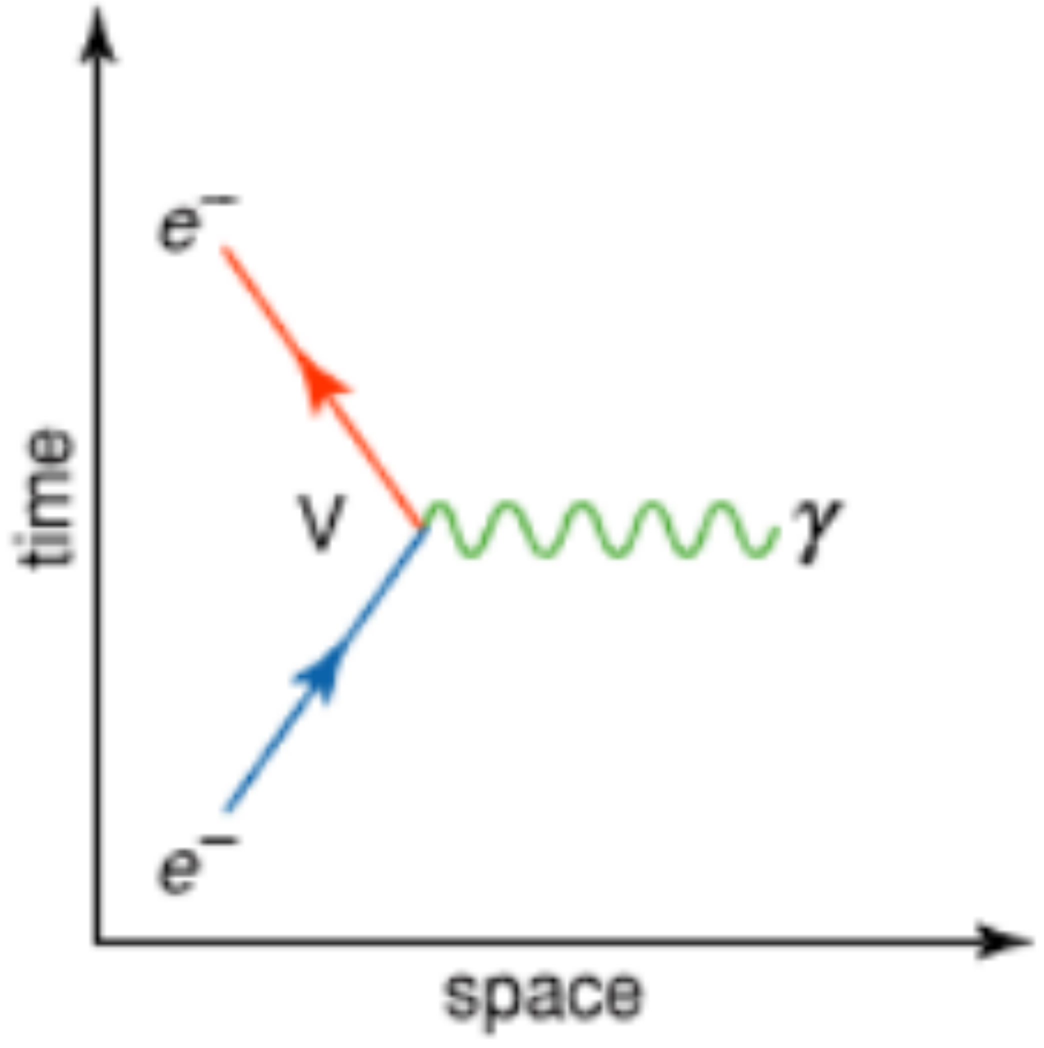

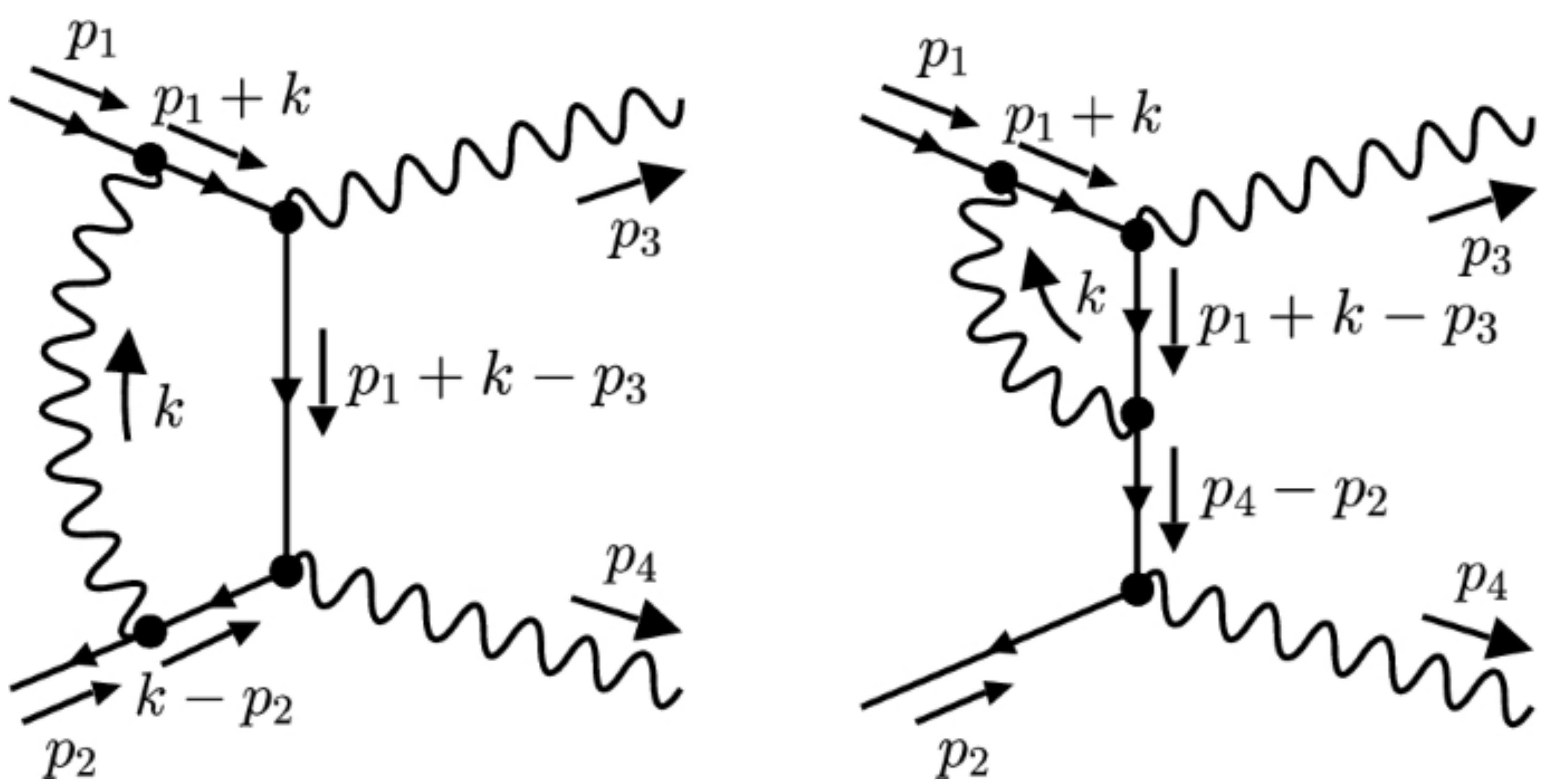

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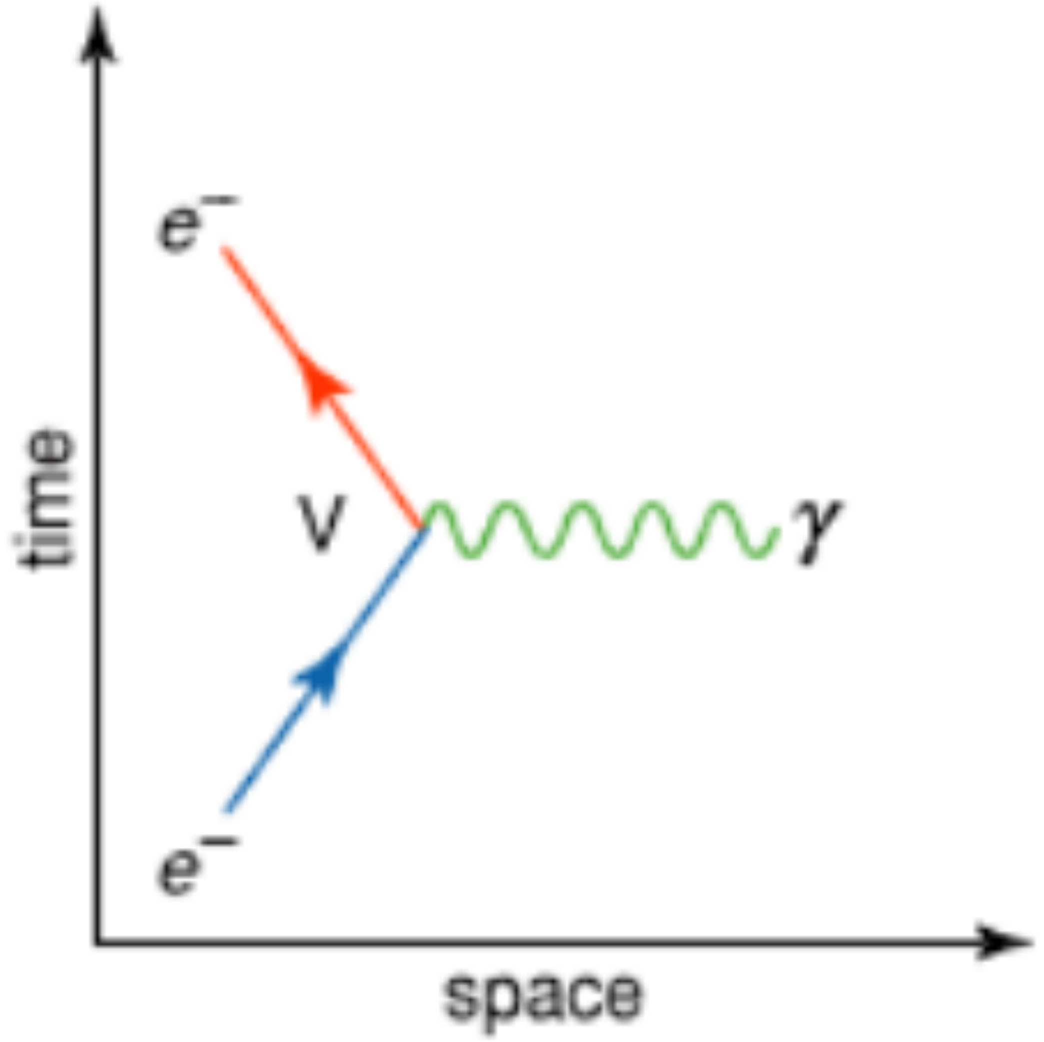

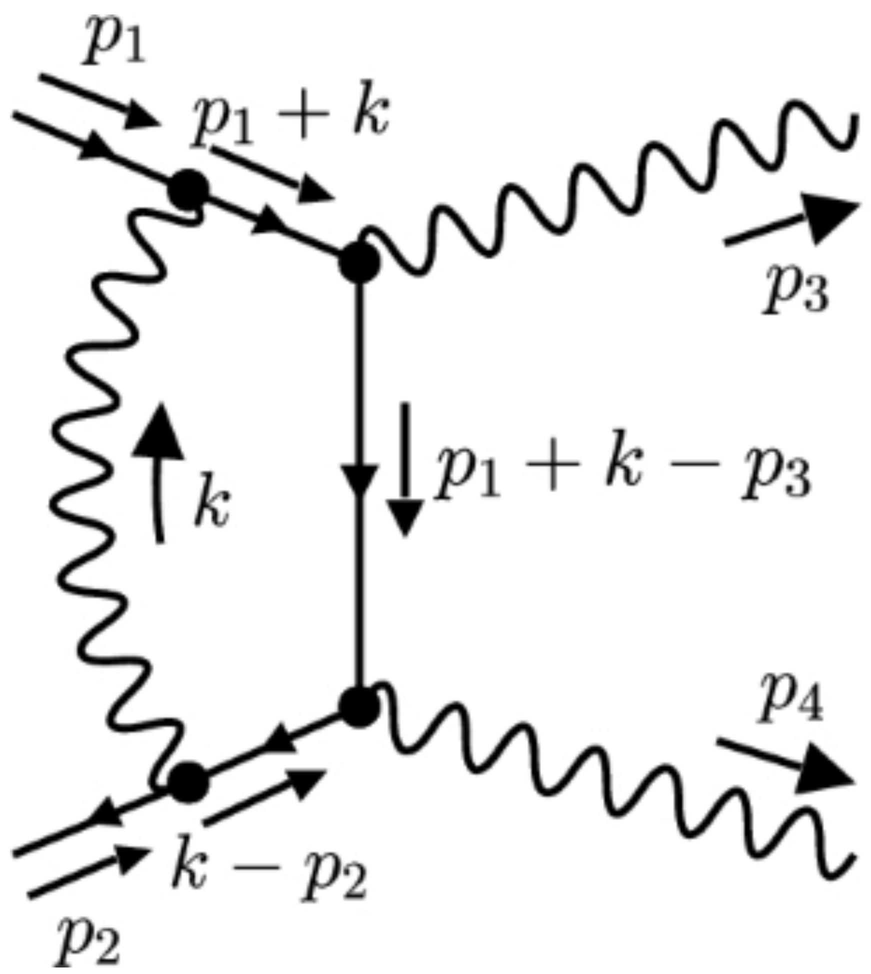

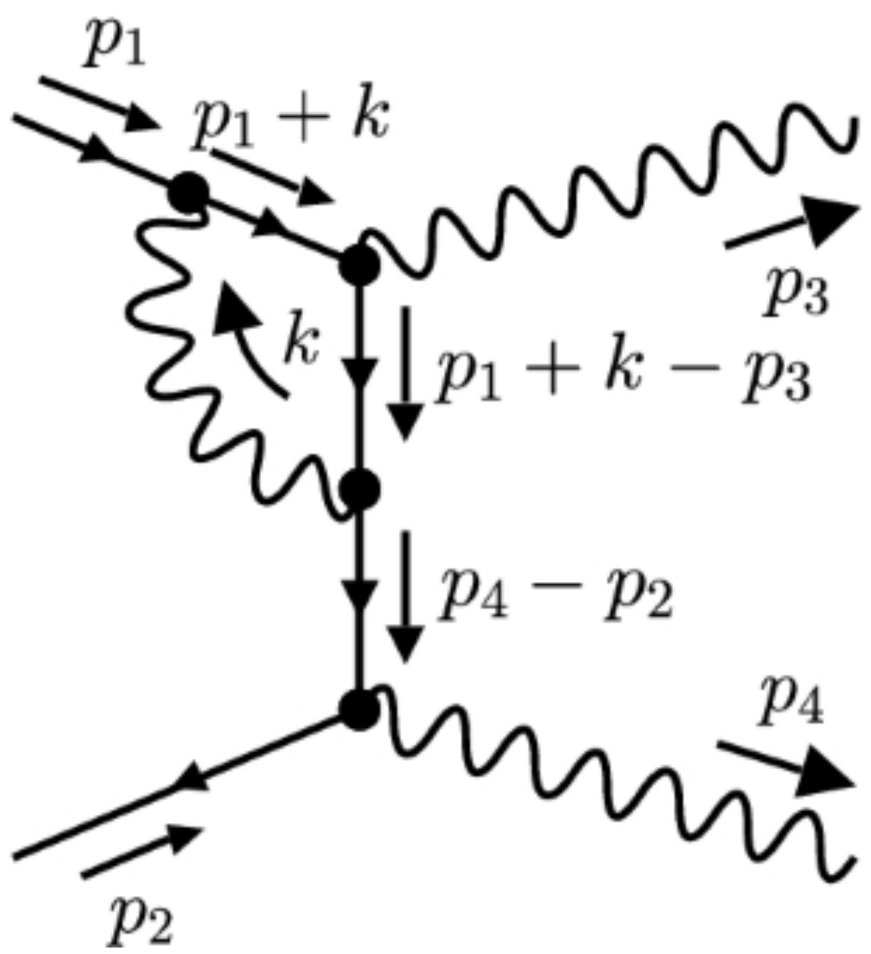

Introducción

The Standard Model

S. Weinberg S. Glashow. A. Salam

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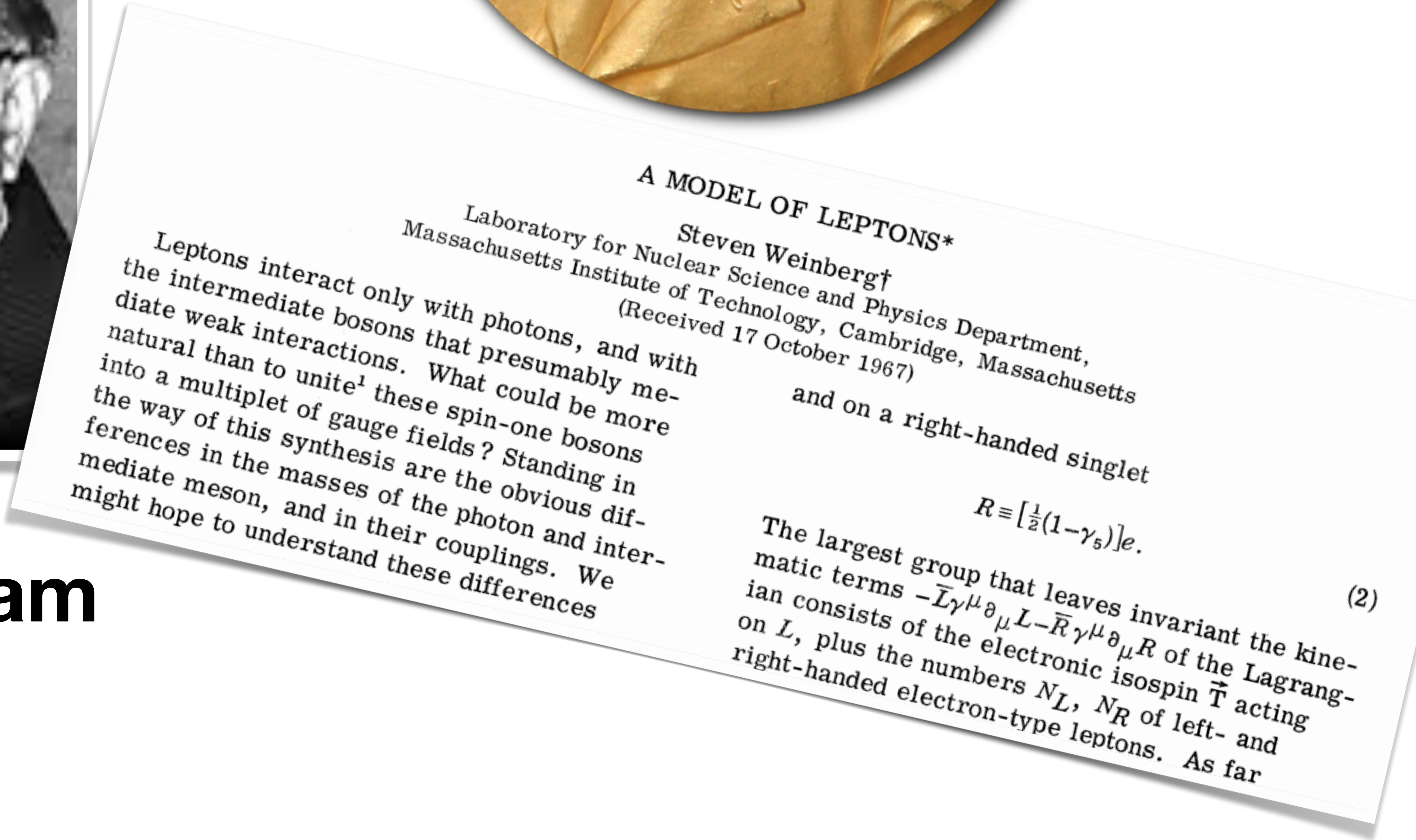


A MODEL OF LEPTONS*

Steven Weinberg†

Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(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 intermediate meson, and in their couplings. We might hope to understand these differences

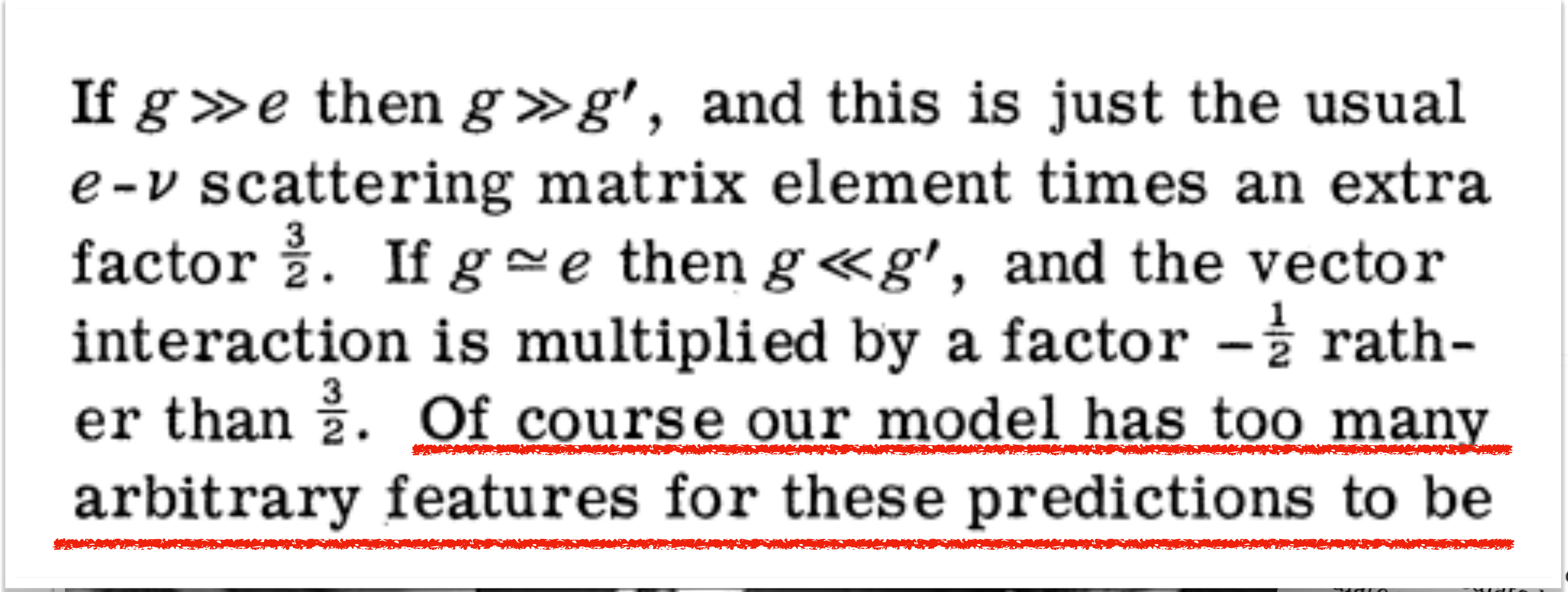
and on a right-handed singlet

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

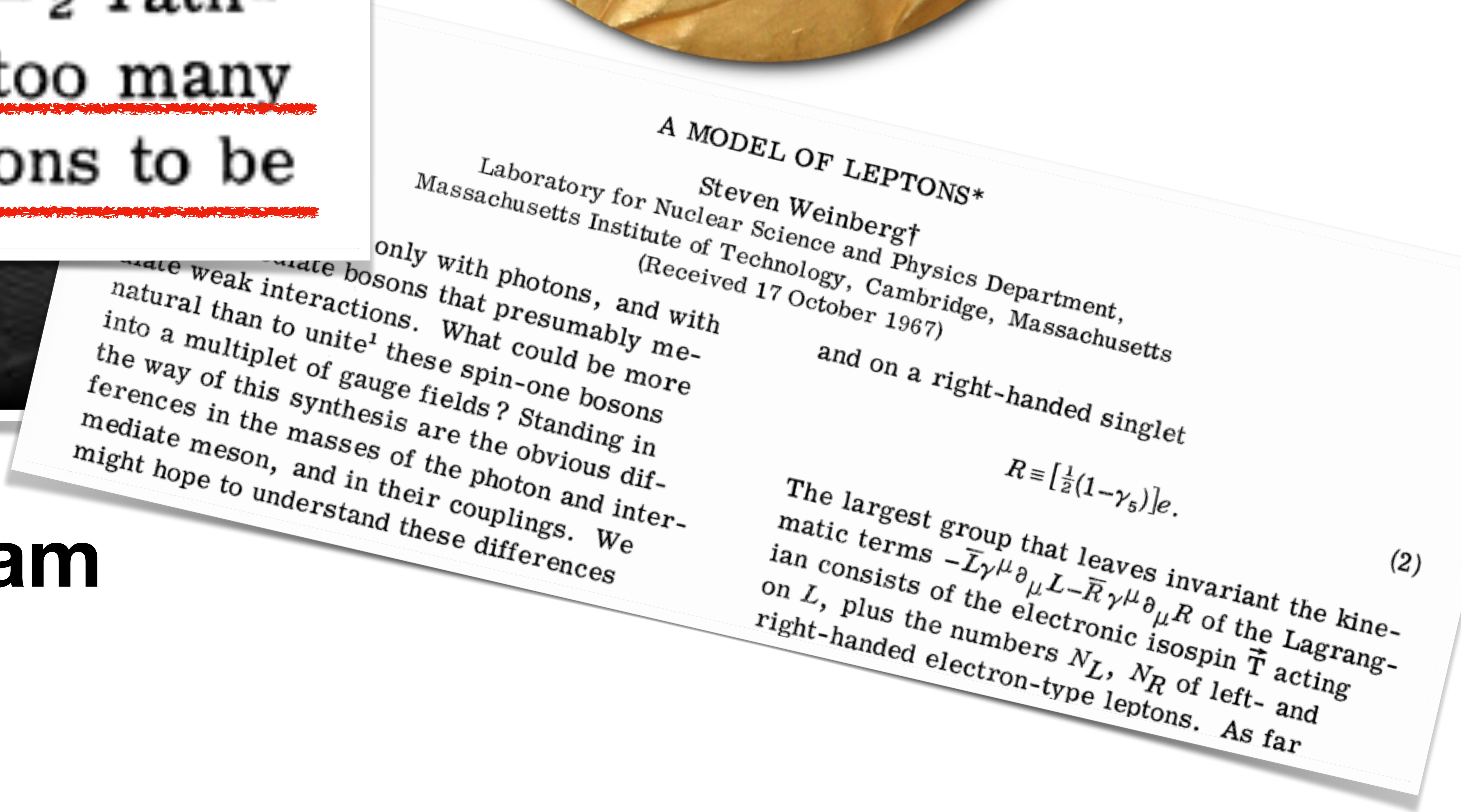
The largest group that leaves invariant the kinematic terms $-\bar{L}\gamma^\mu\partial_\mu L - \bar{R}\gamma^\mu\partial_\mu R$ of the Lagrangian consists of the electronic isospin $\vec{T}$ acting on L, plus the numbers N_L, N_R of left- and right-handed electron-type leptons. As far

Introducción

The Standard Model



If $g \gg e$ then $g \gg g'$, and this is just the usual e-ν scattering matrix element times an extra factor $\frac{3}{2}$. If $g \simeq e$ then $g \ll g'$, and the vector interaction is multiplied by a factor $-\frac{1}{2}$ rather than $\frac{3}{2}$. Of course our model has too many arbitrary features for these predictions to be



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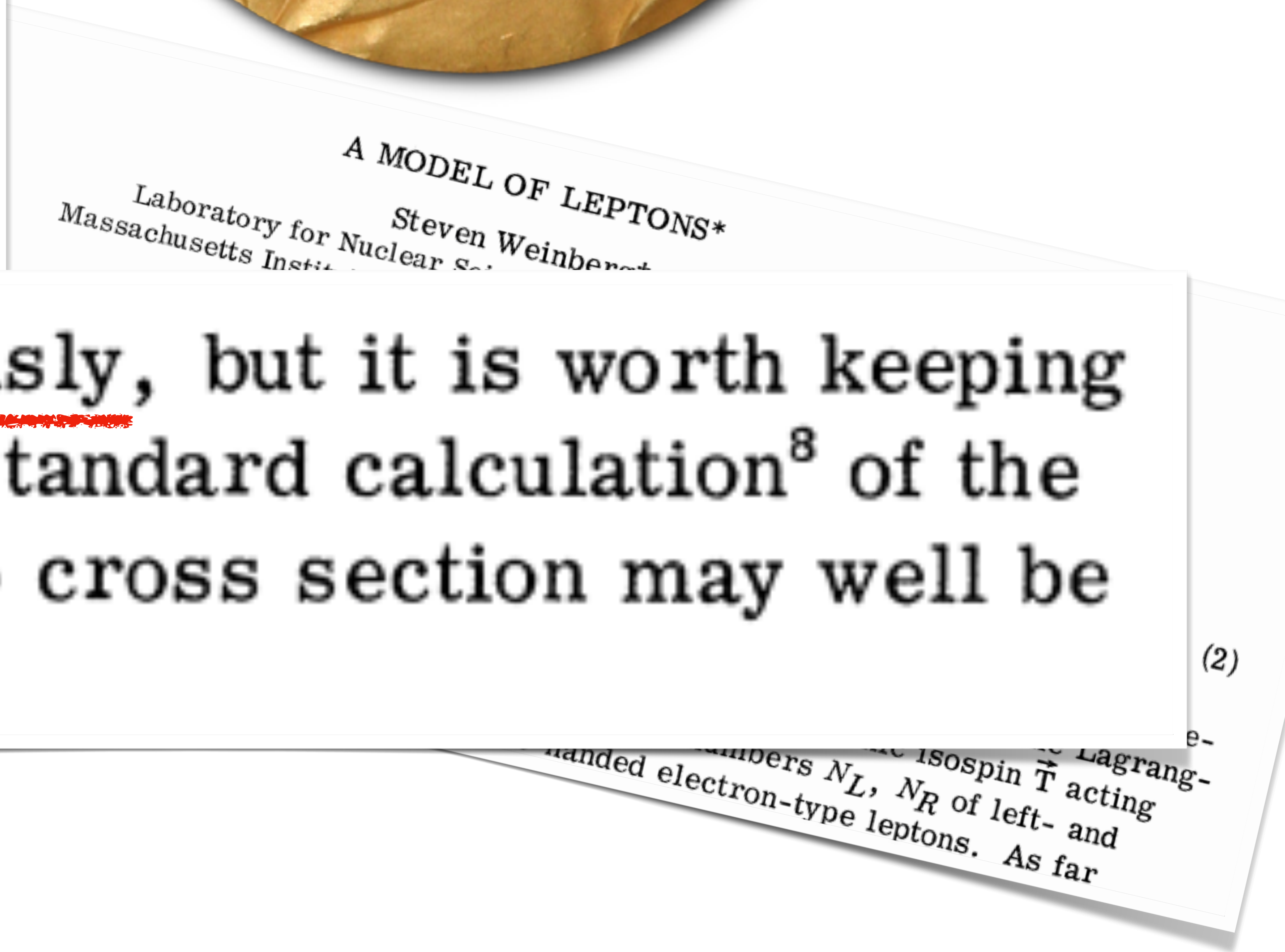

S. Weinberg S. Glashow.

Introducción

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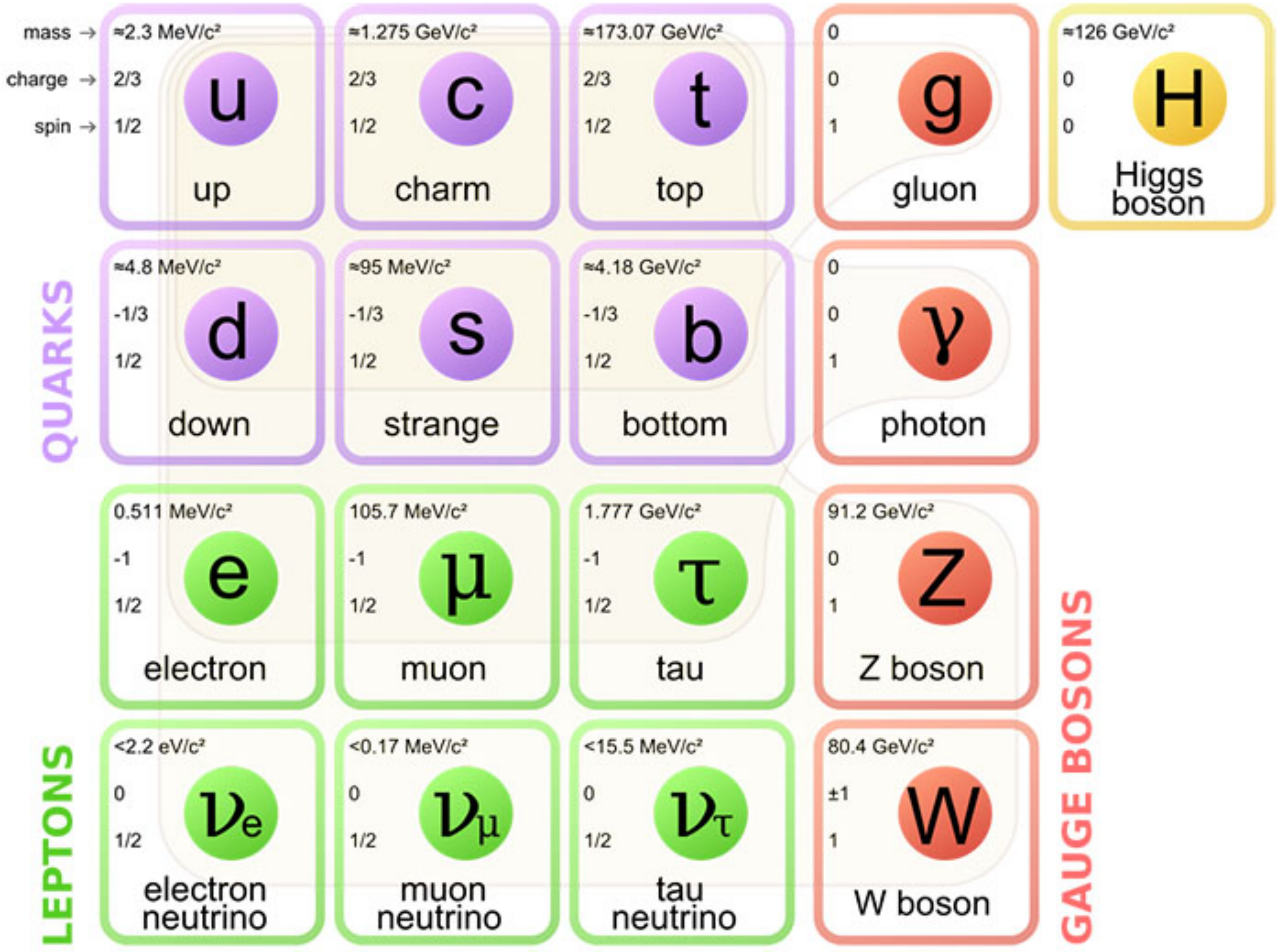

Introducción

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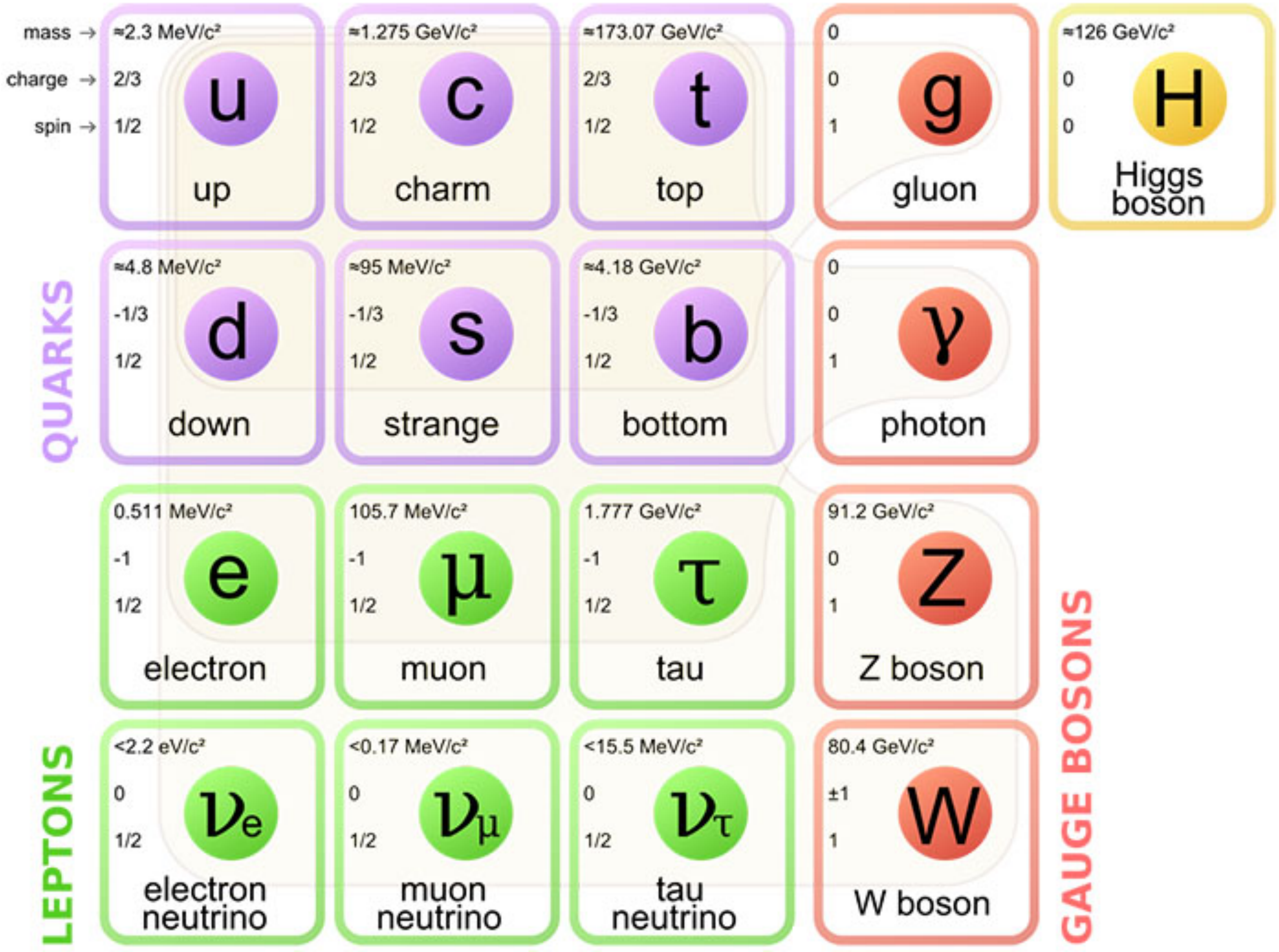

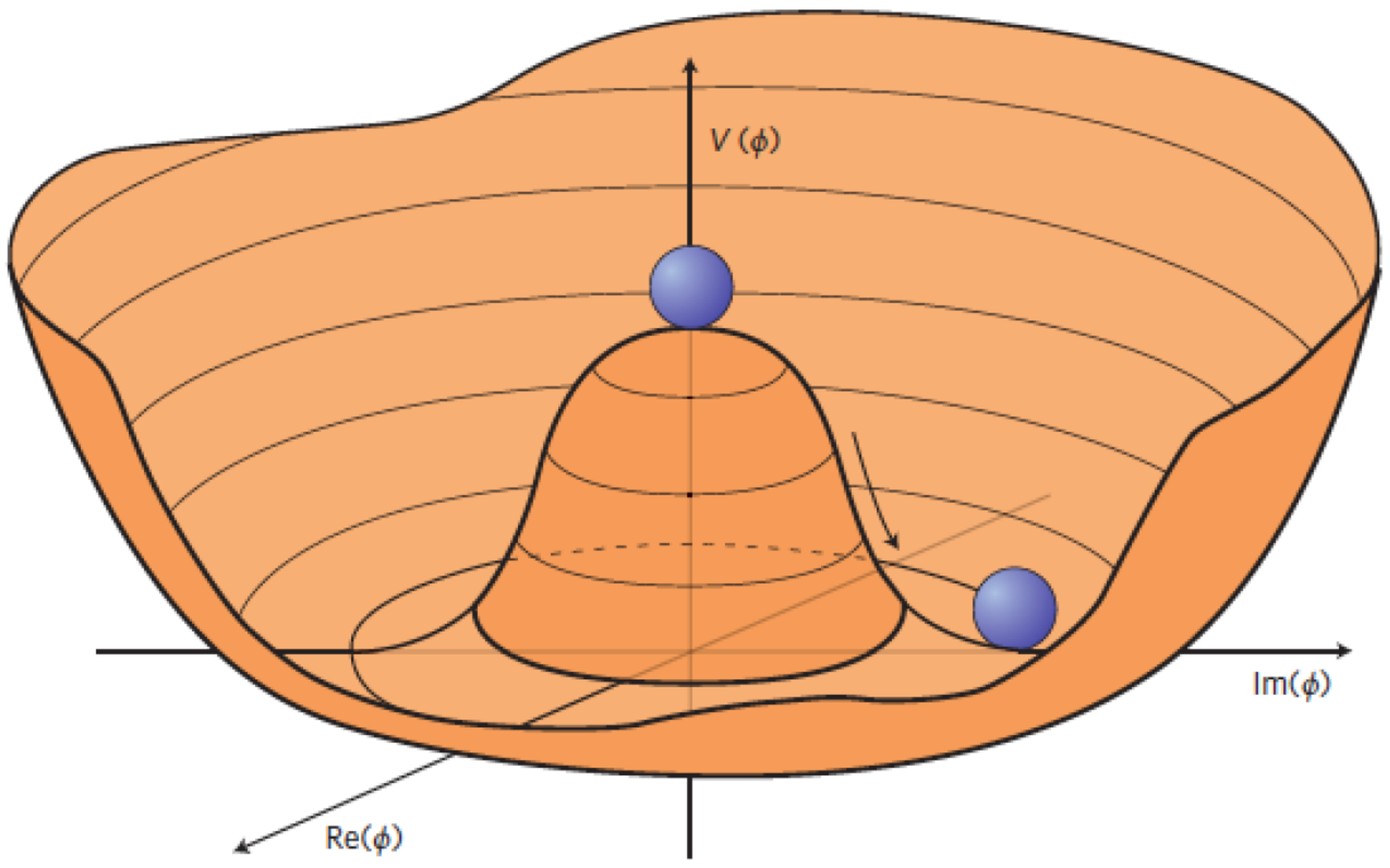

Introducción

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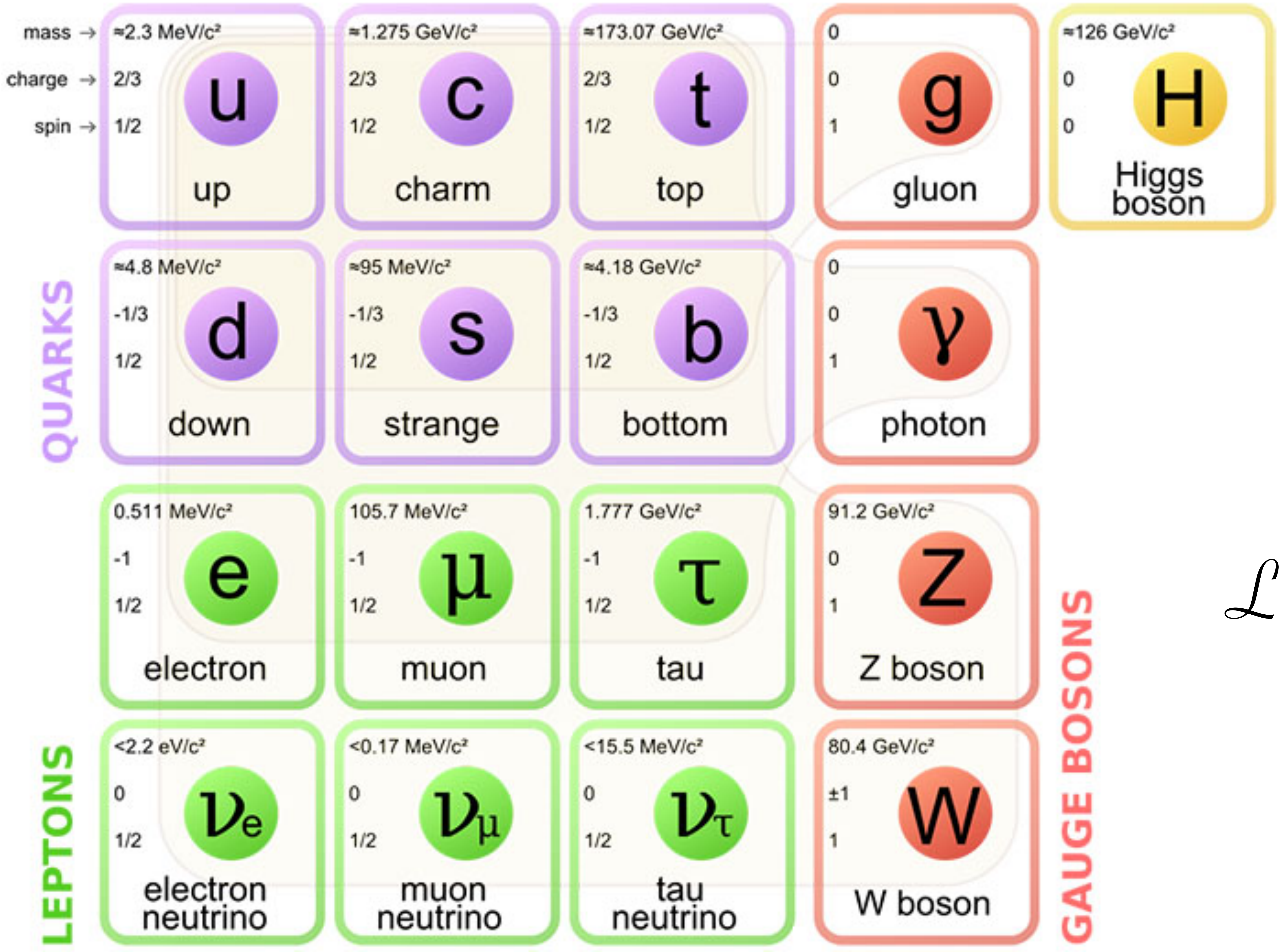
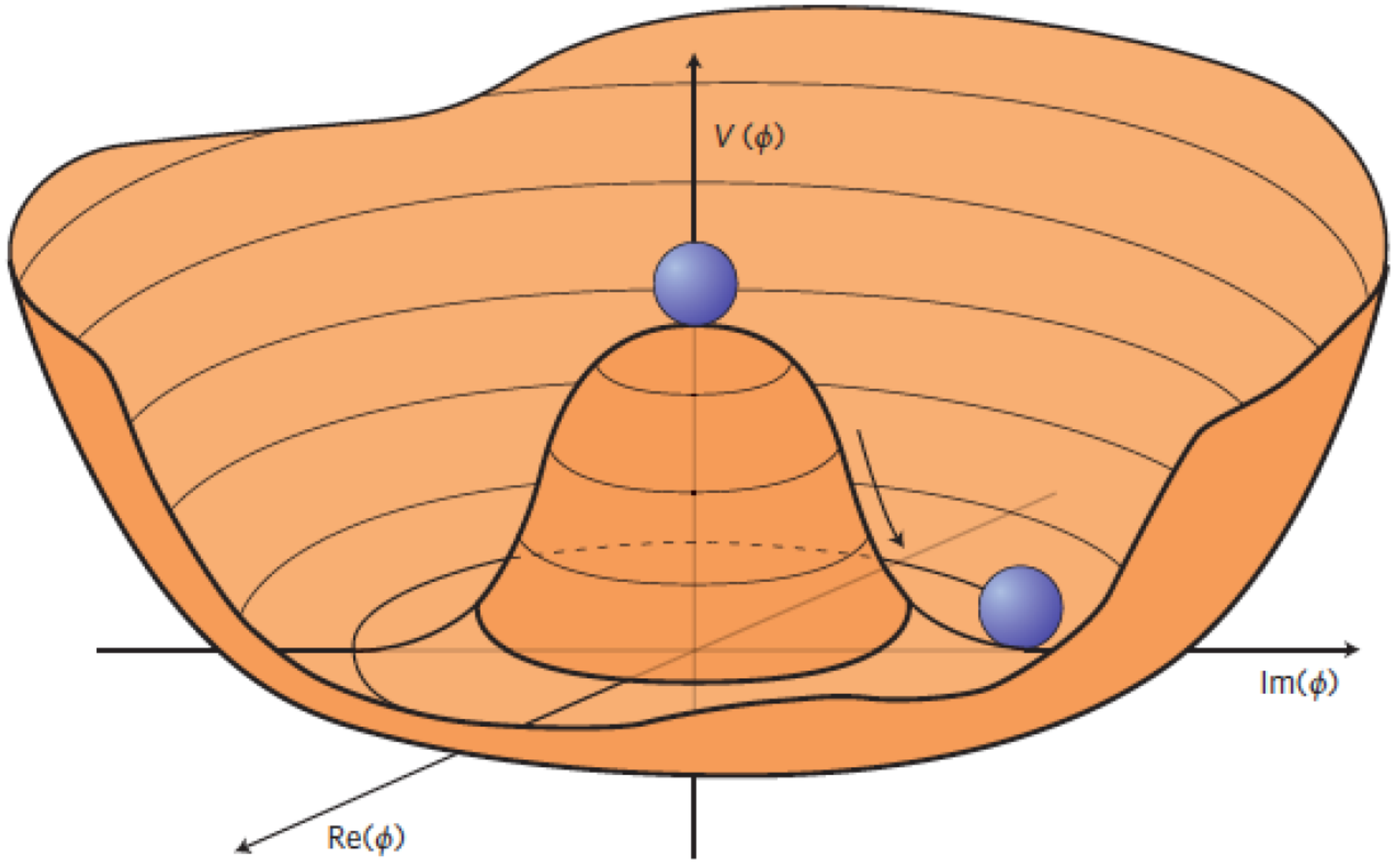


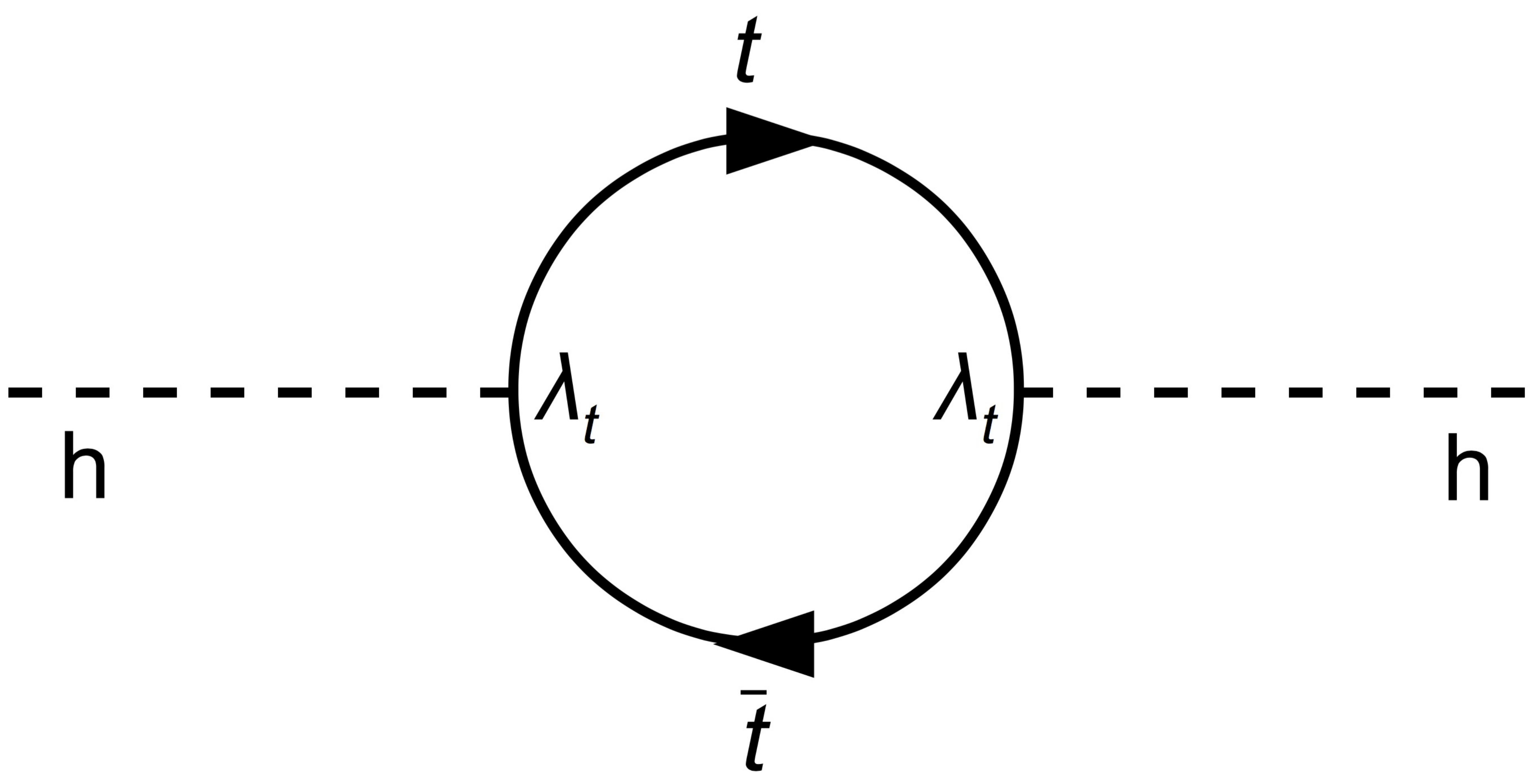


$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}D\psi + h\cdot c\,.$$

$$+\bar{\psi}_i y_{ij}\psi_j\phi + h\,.\,c\,. + \left|D_\mu\phi\right|^2 - V(\phi)$$

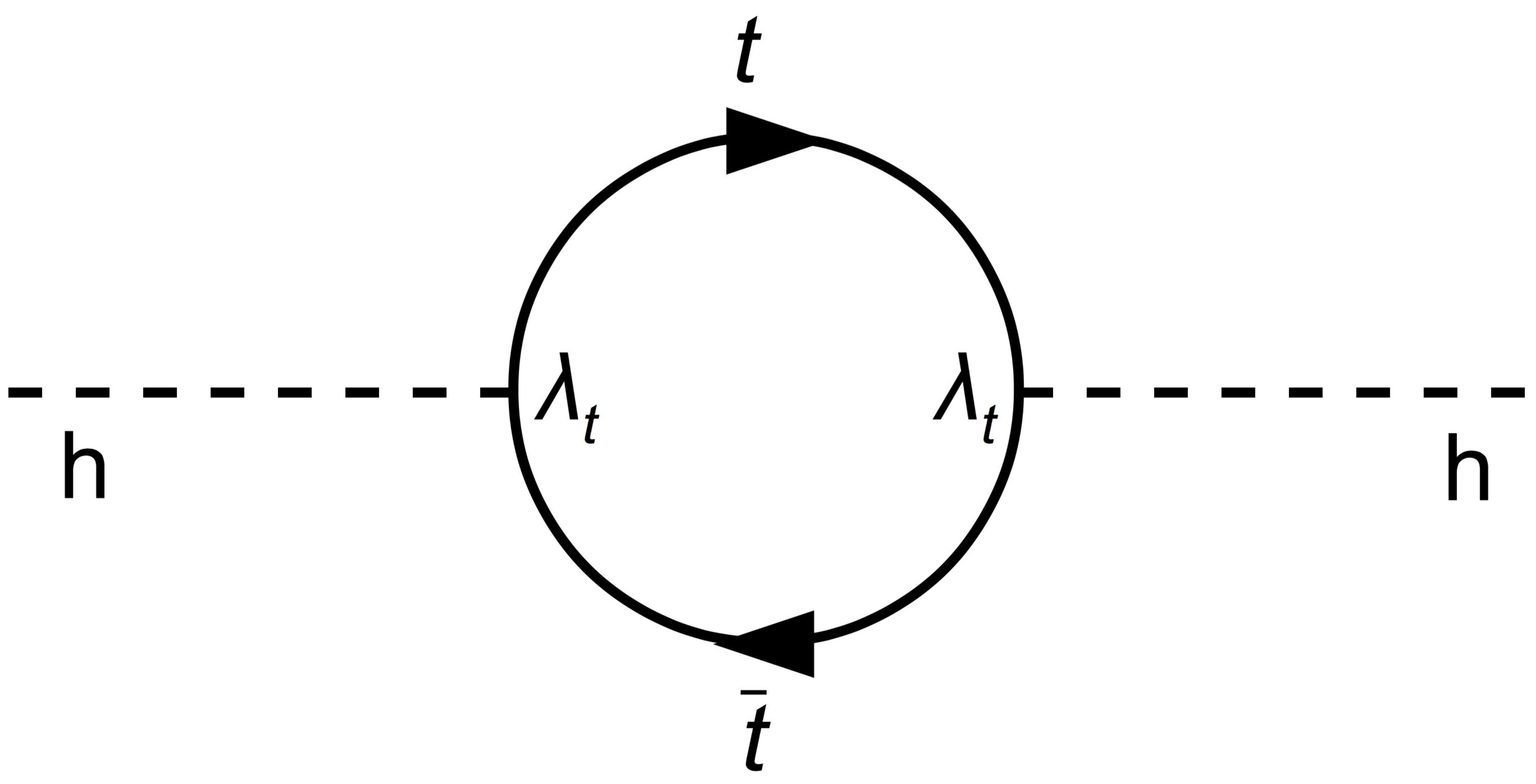
Introducción

Beyond the Standard Model



Introducción

Beyond the Standard Model

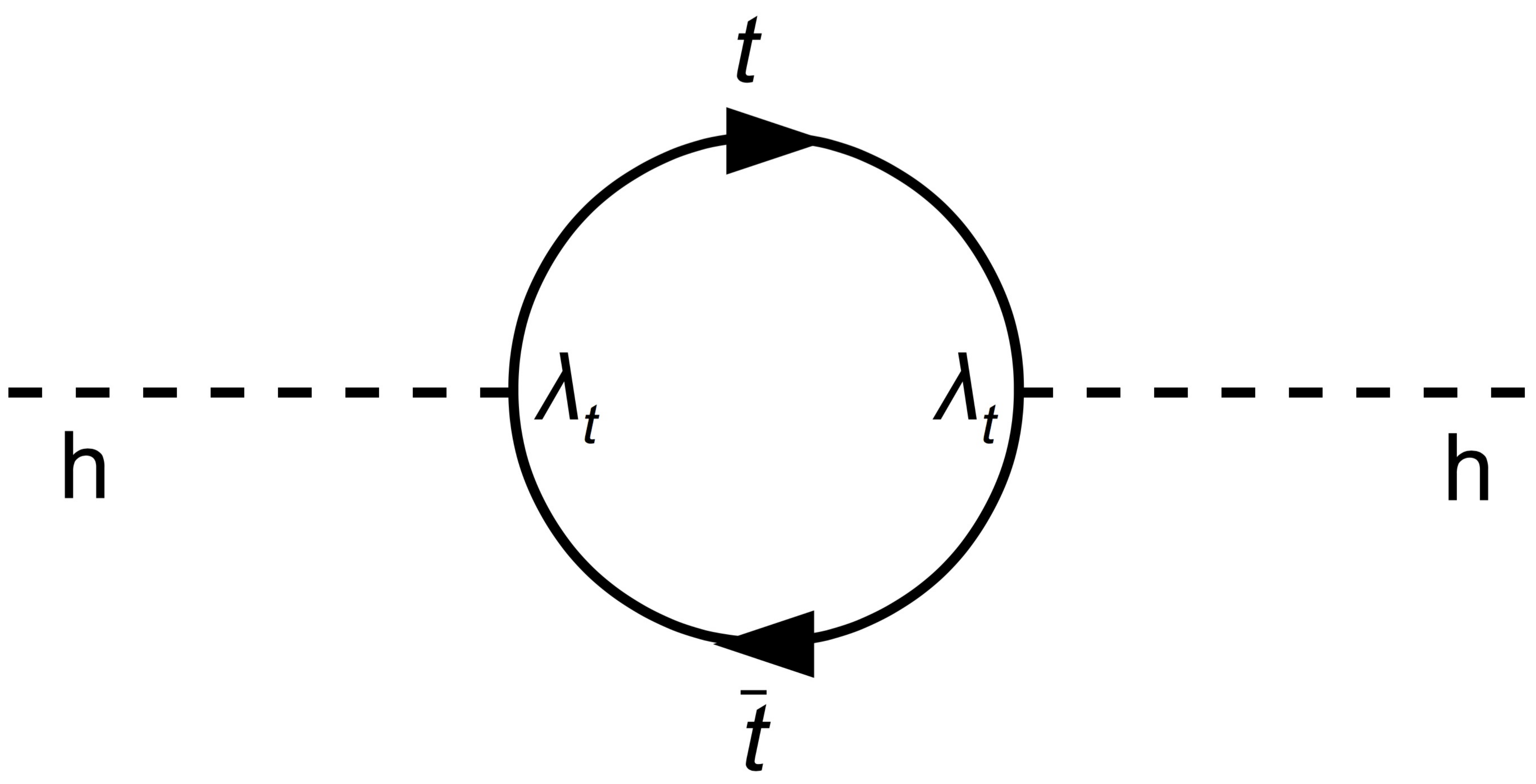


$$\delta m_h^2 = \frac{\left|y_t\right|^2}{16\pi^2}\left[-2\Lambda^2 + 6m_t^2 \ln\left(\Lambda/m_t\right)\right]$$

Introducción

Beyond the Standard Model

Problema de la Jerarquía



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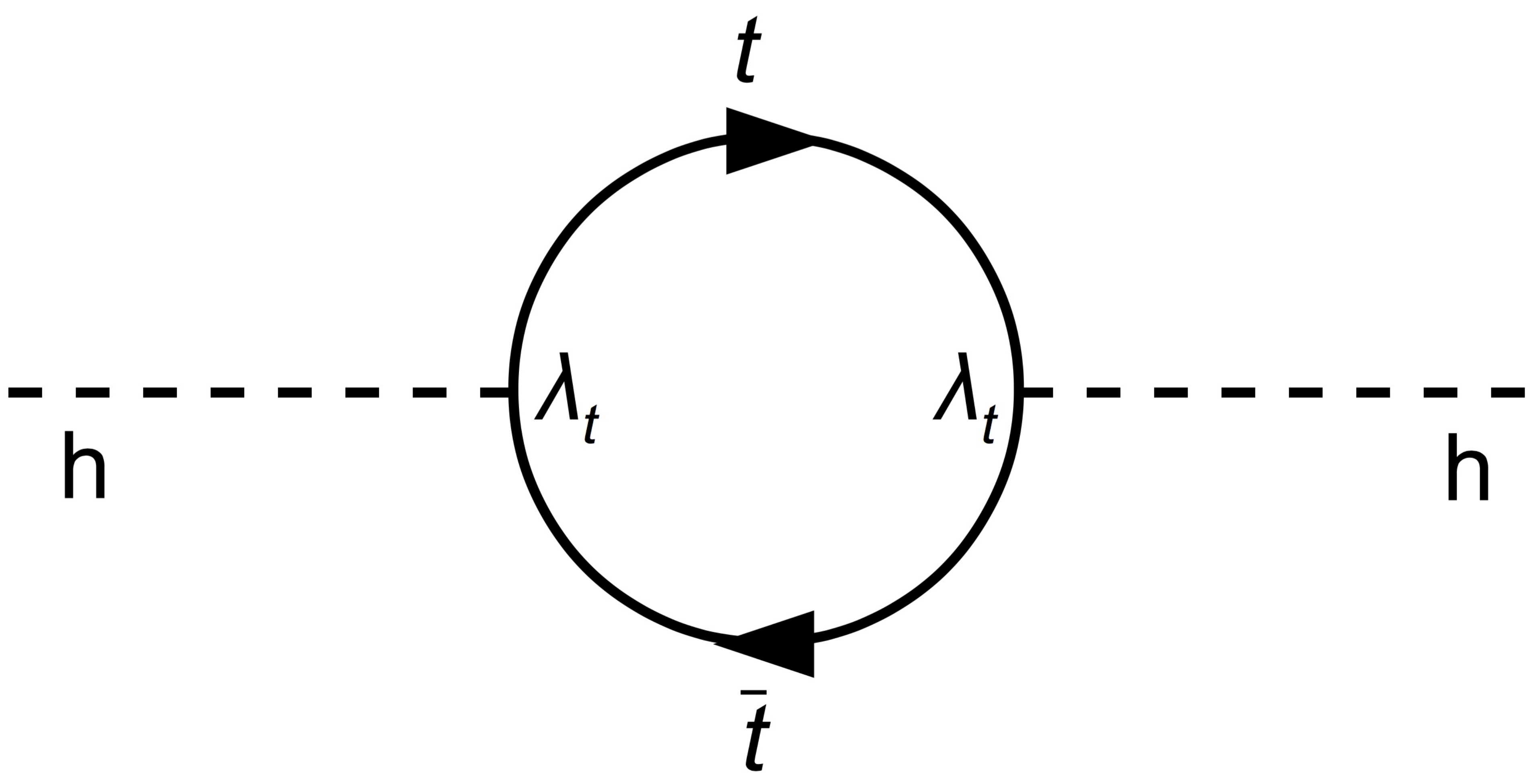

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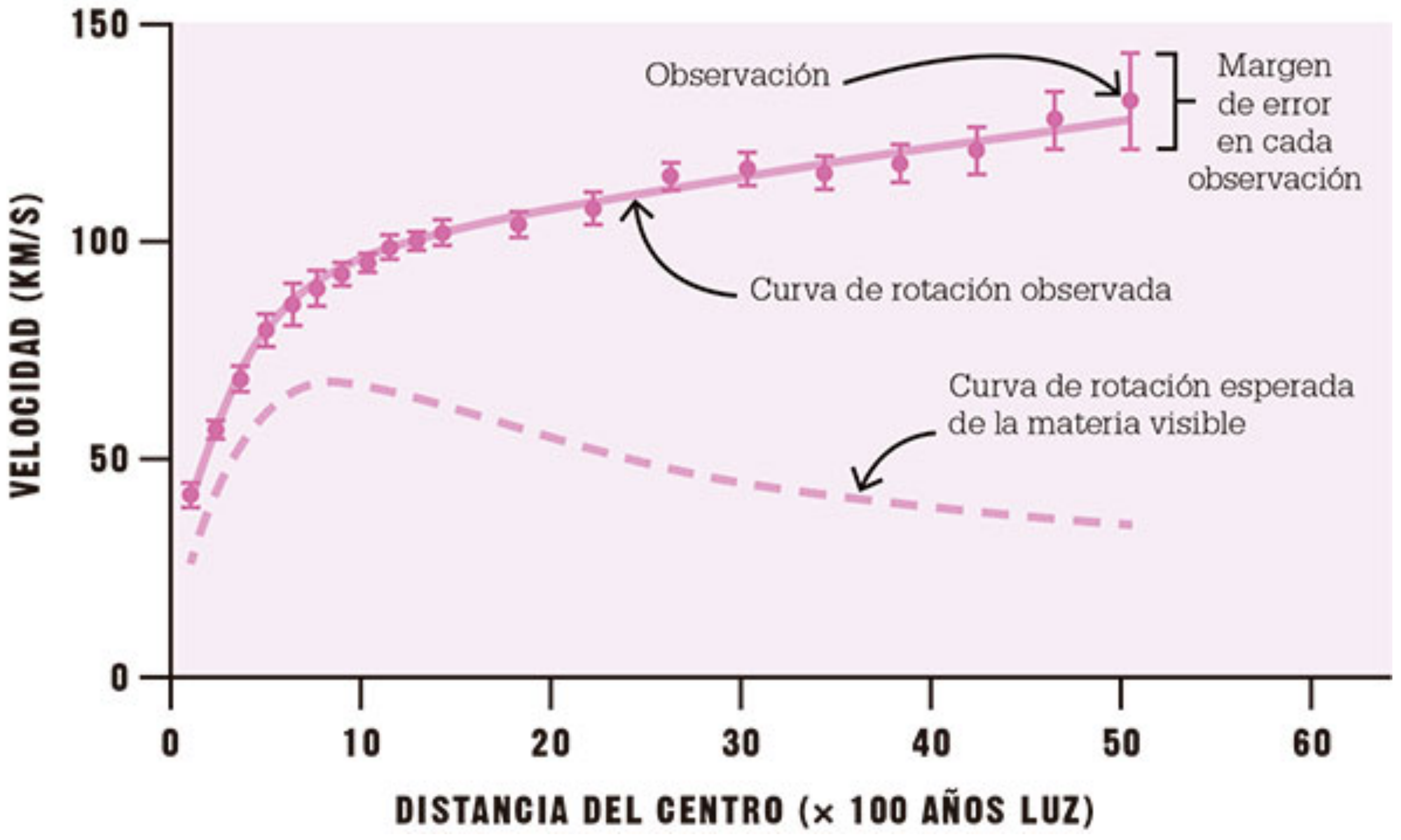
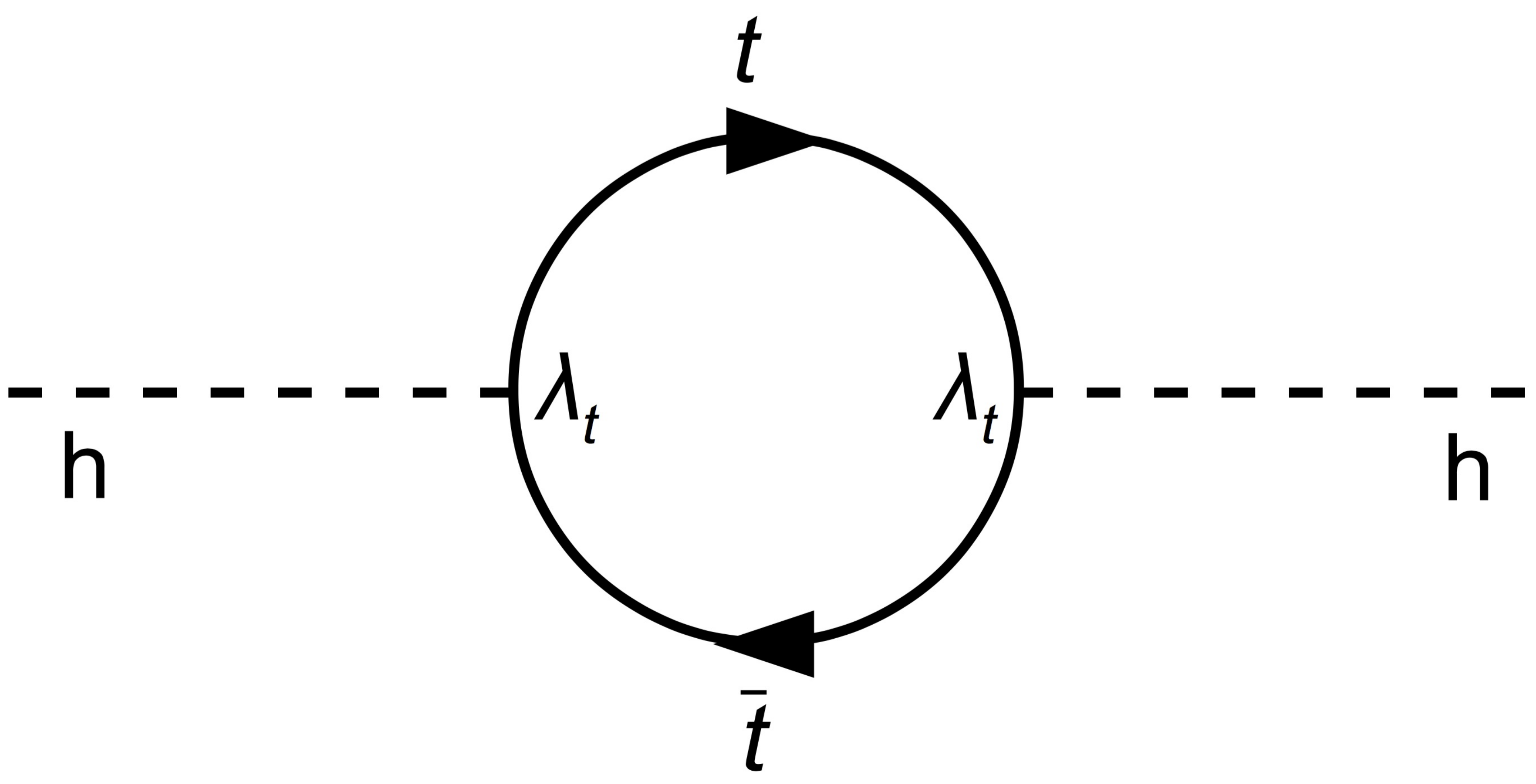


Introducción

Beyond the Standard Model



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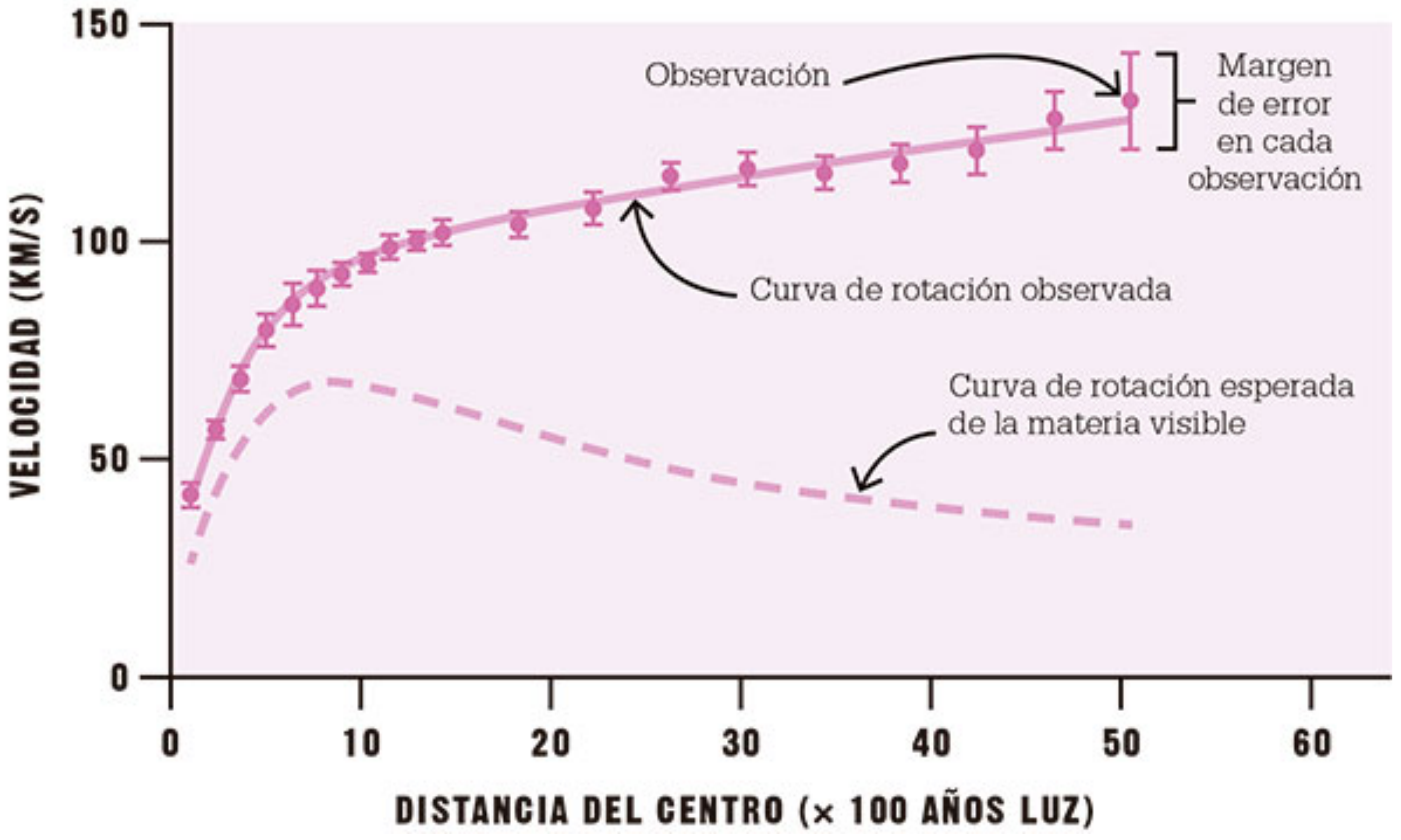
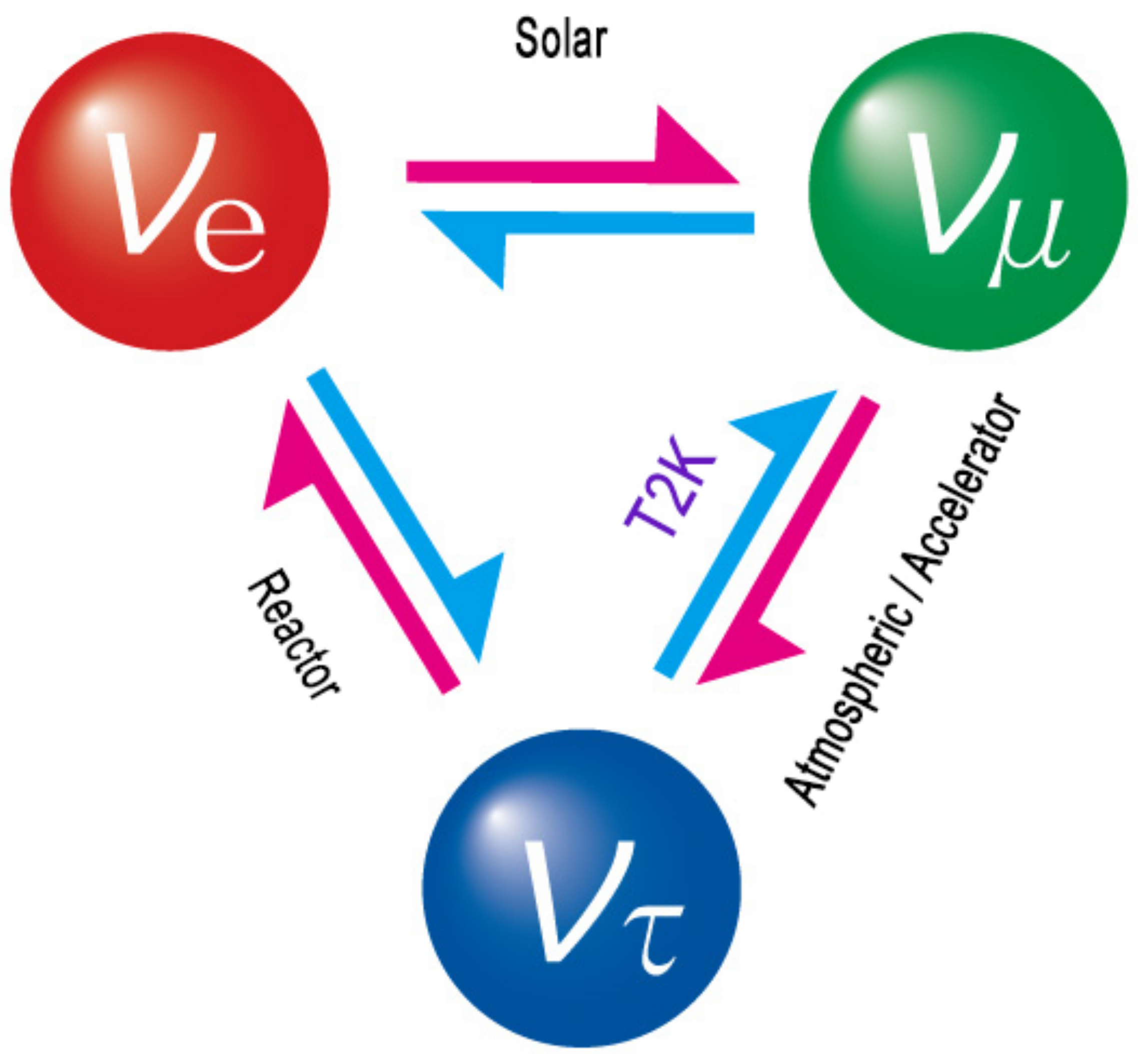
Dark Matter



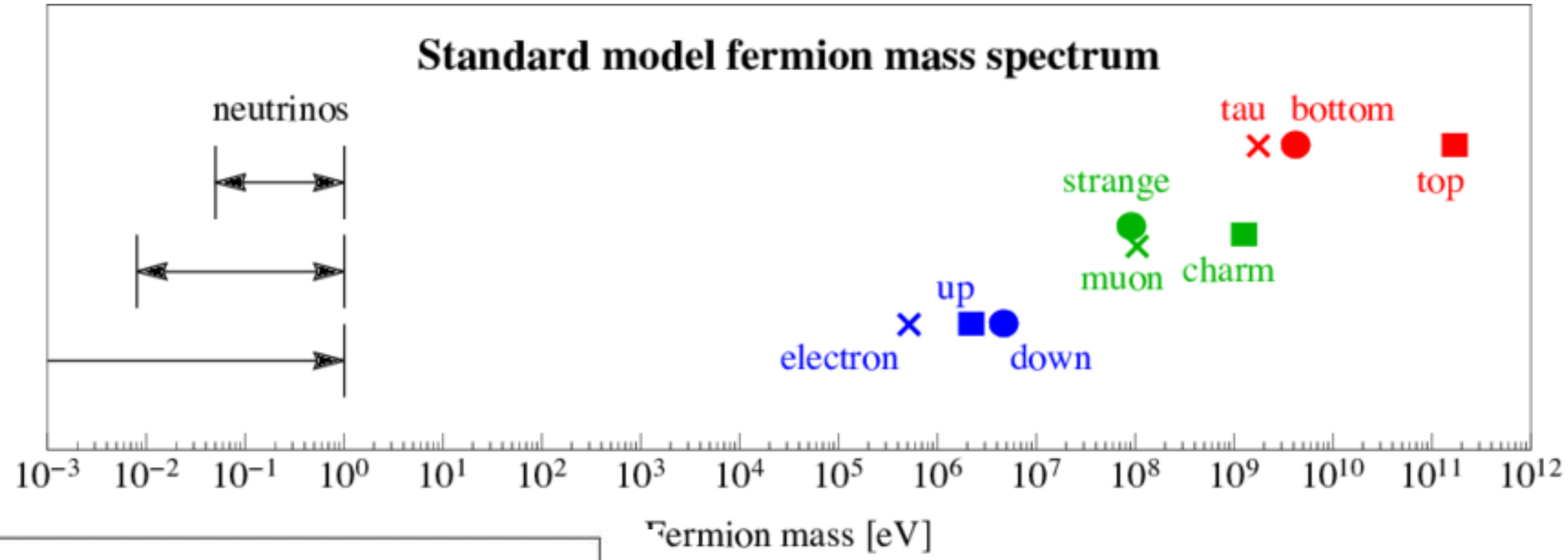
Introducción

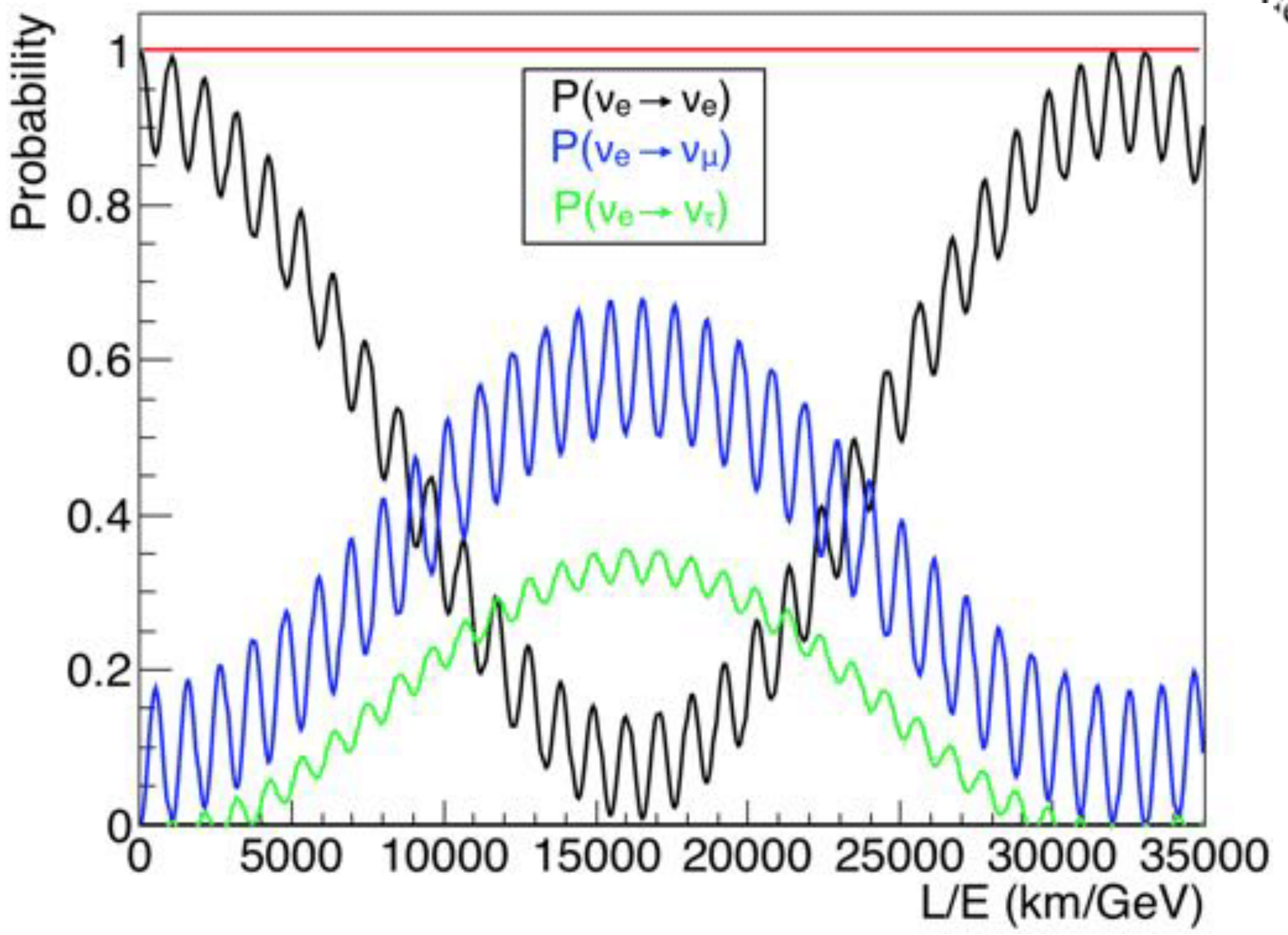
Beyond the Standard Model

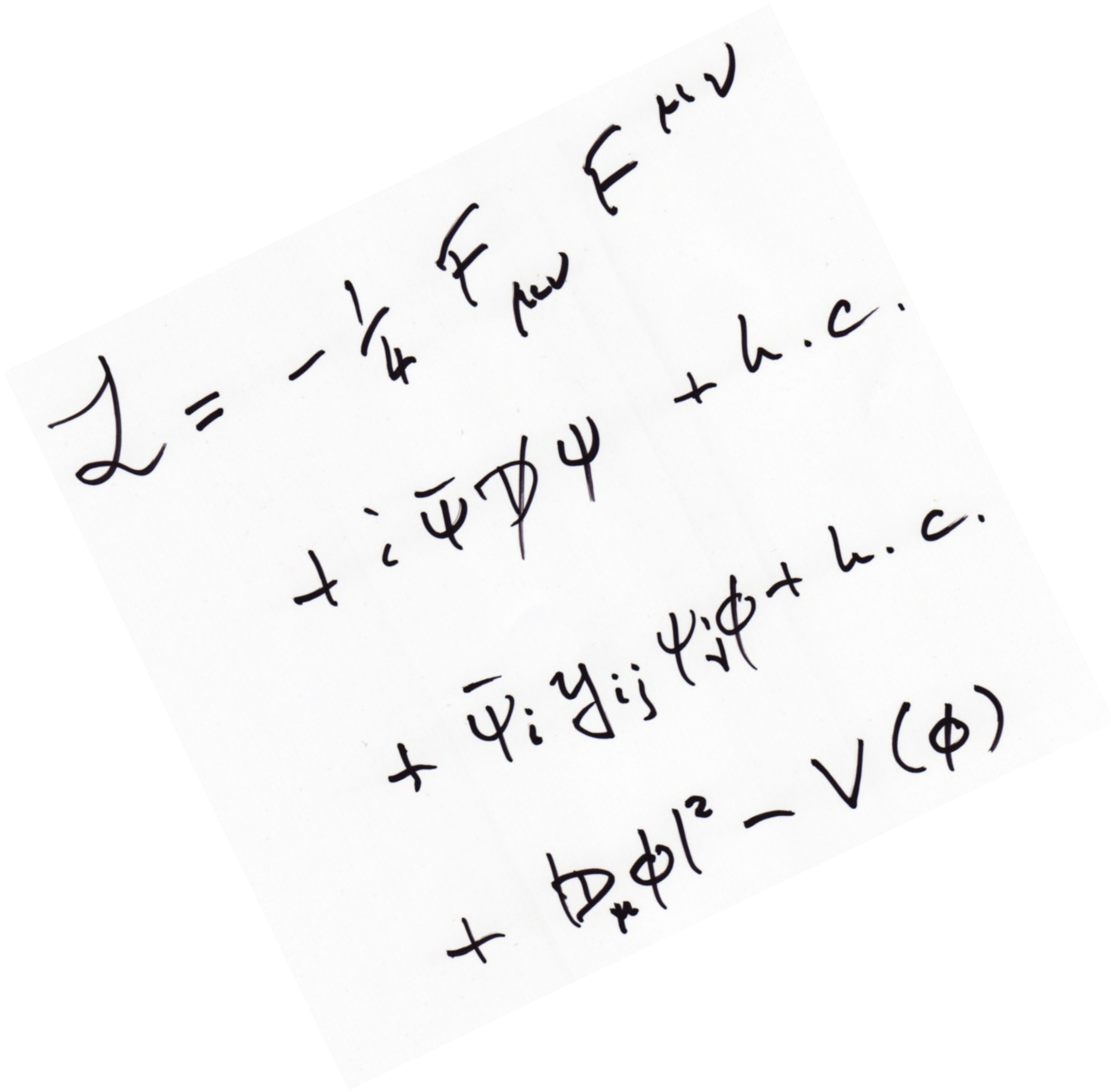
Problema de la masa de los neutrinos

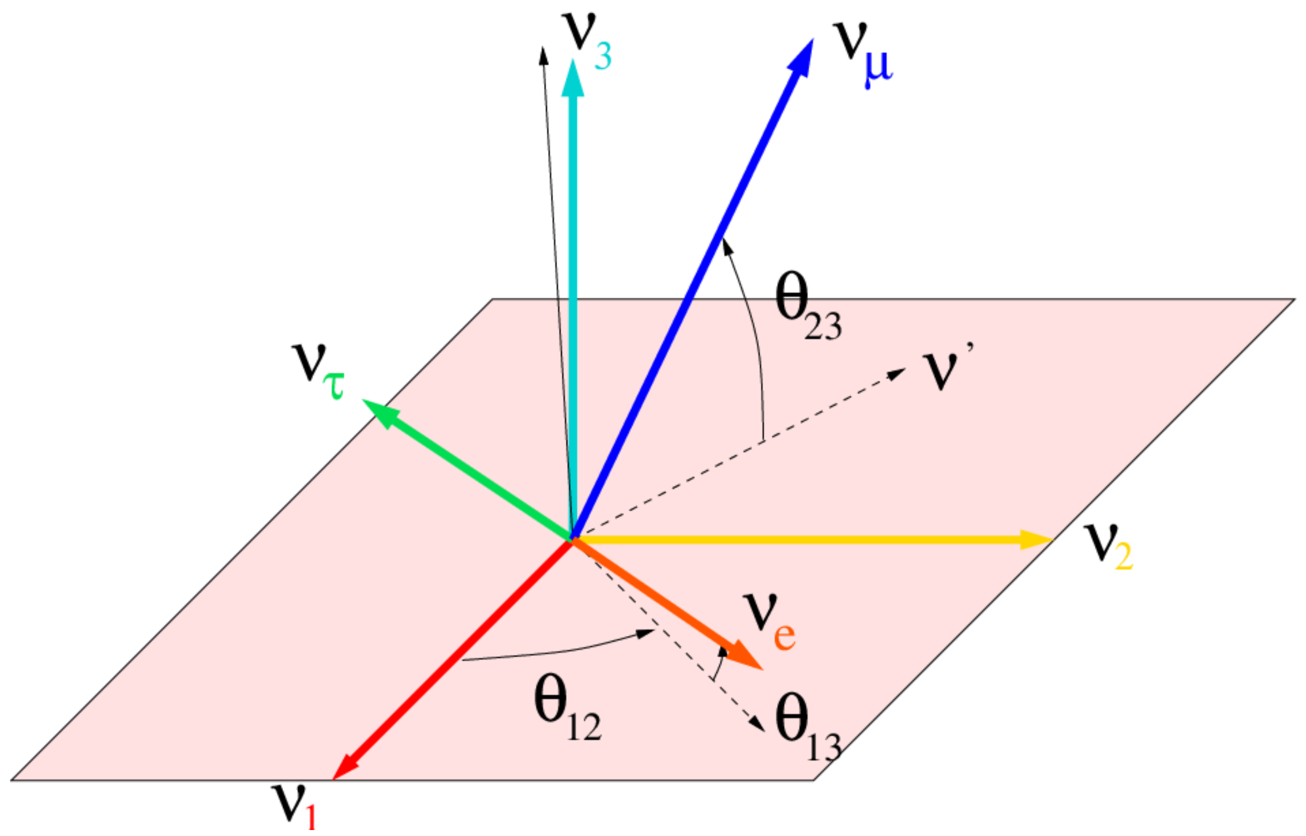


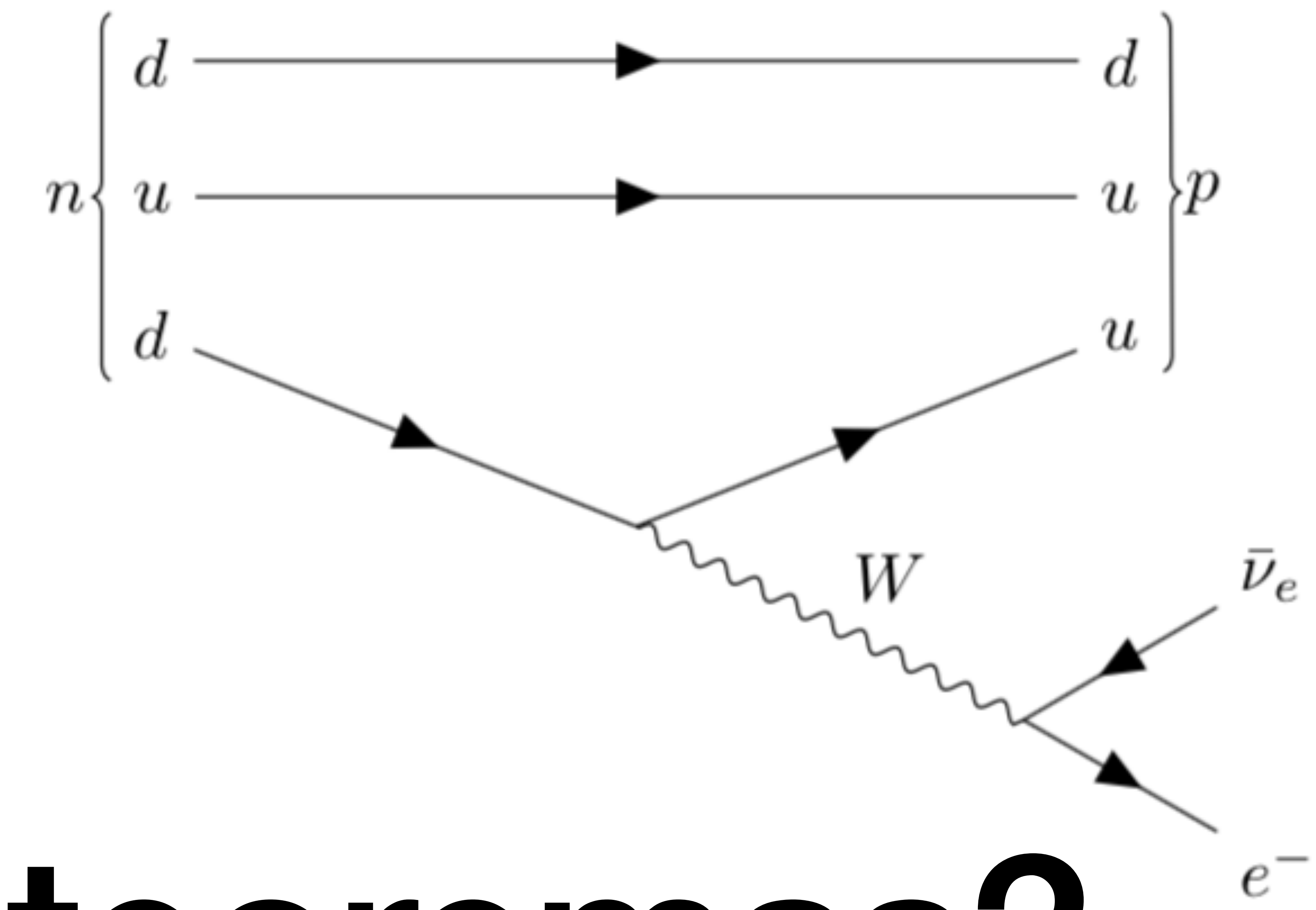
Neutrino oscillation between three generations



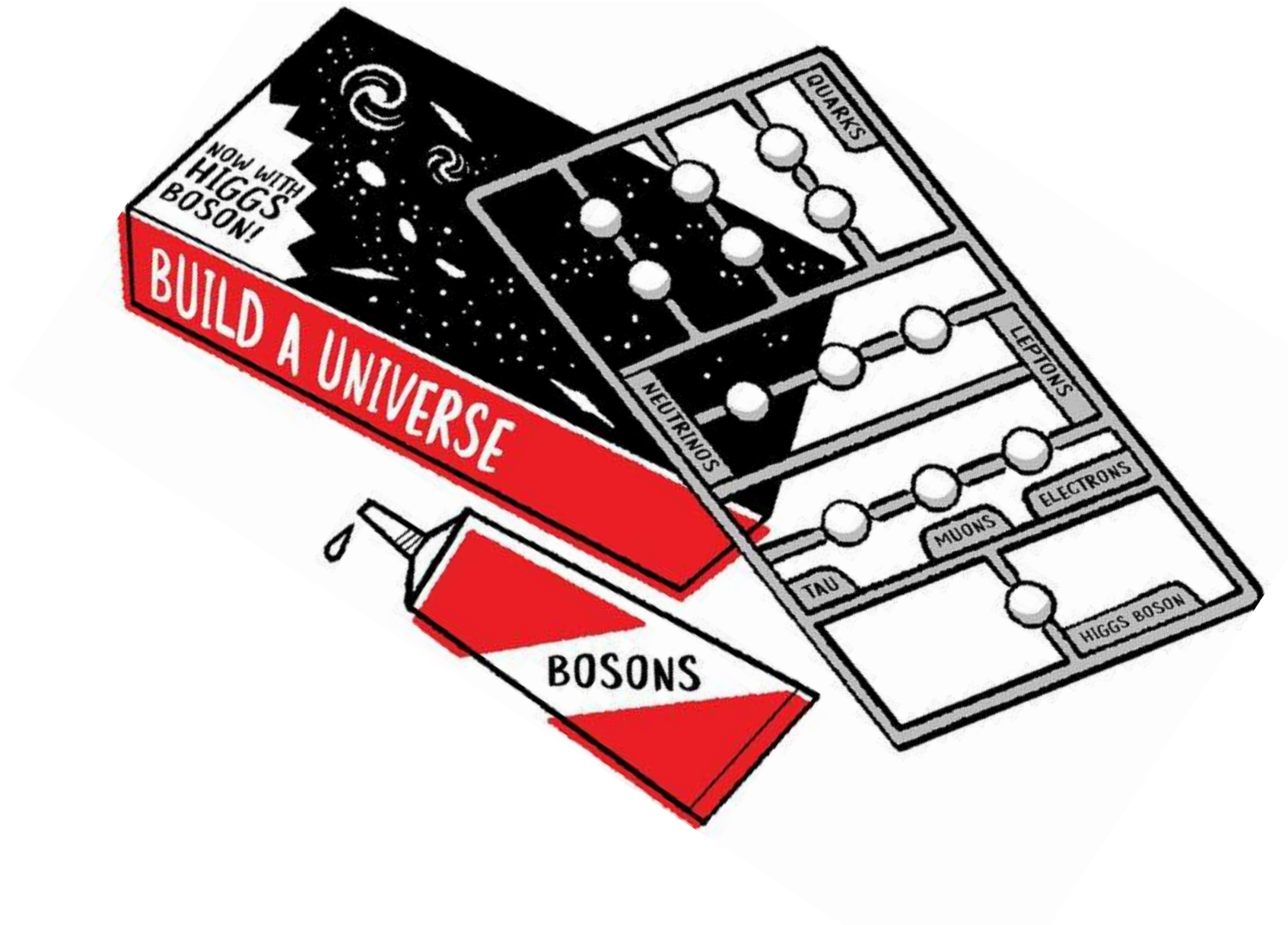


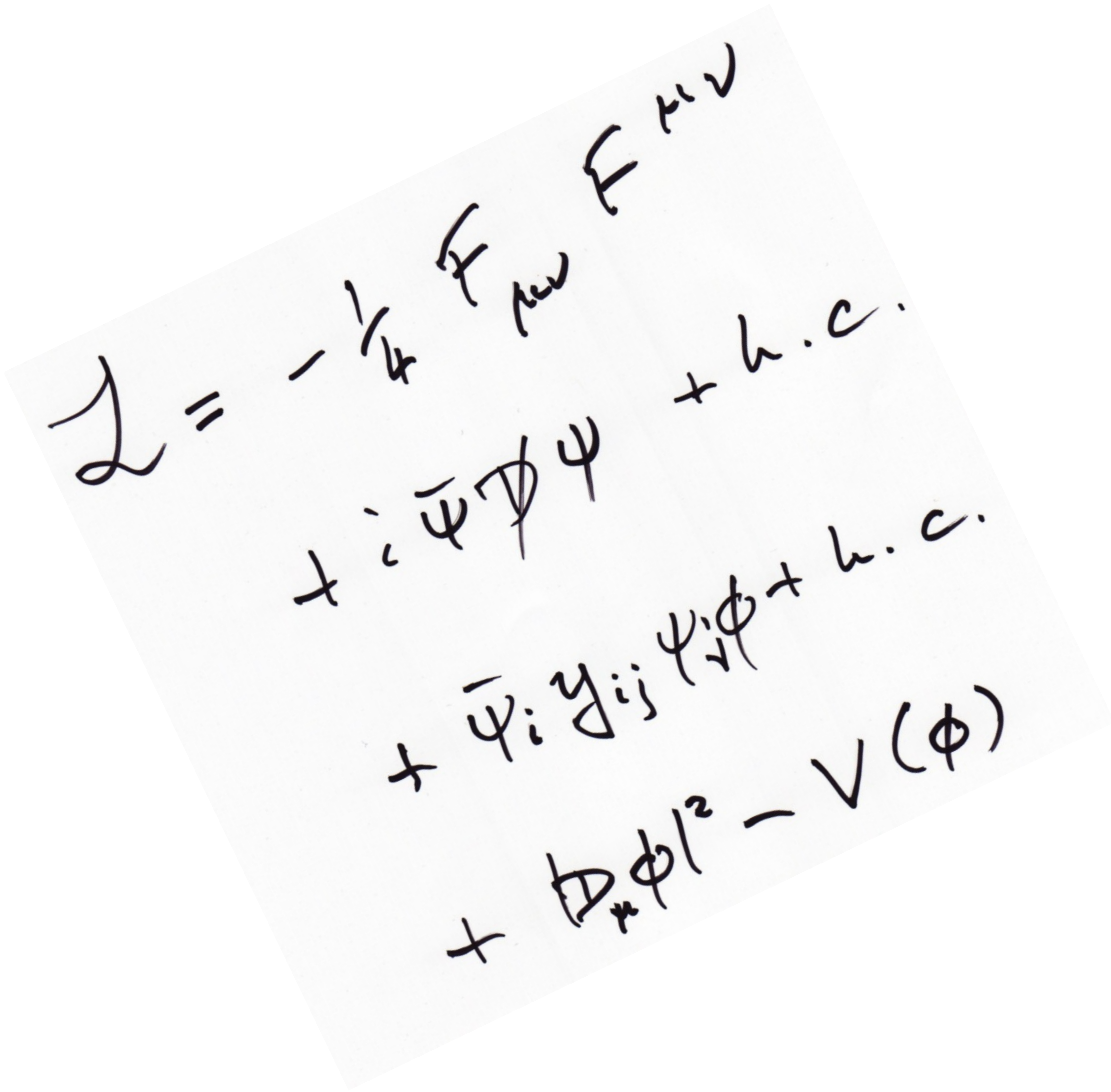






Qué rol cumplen los teoremas?

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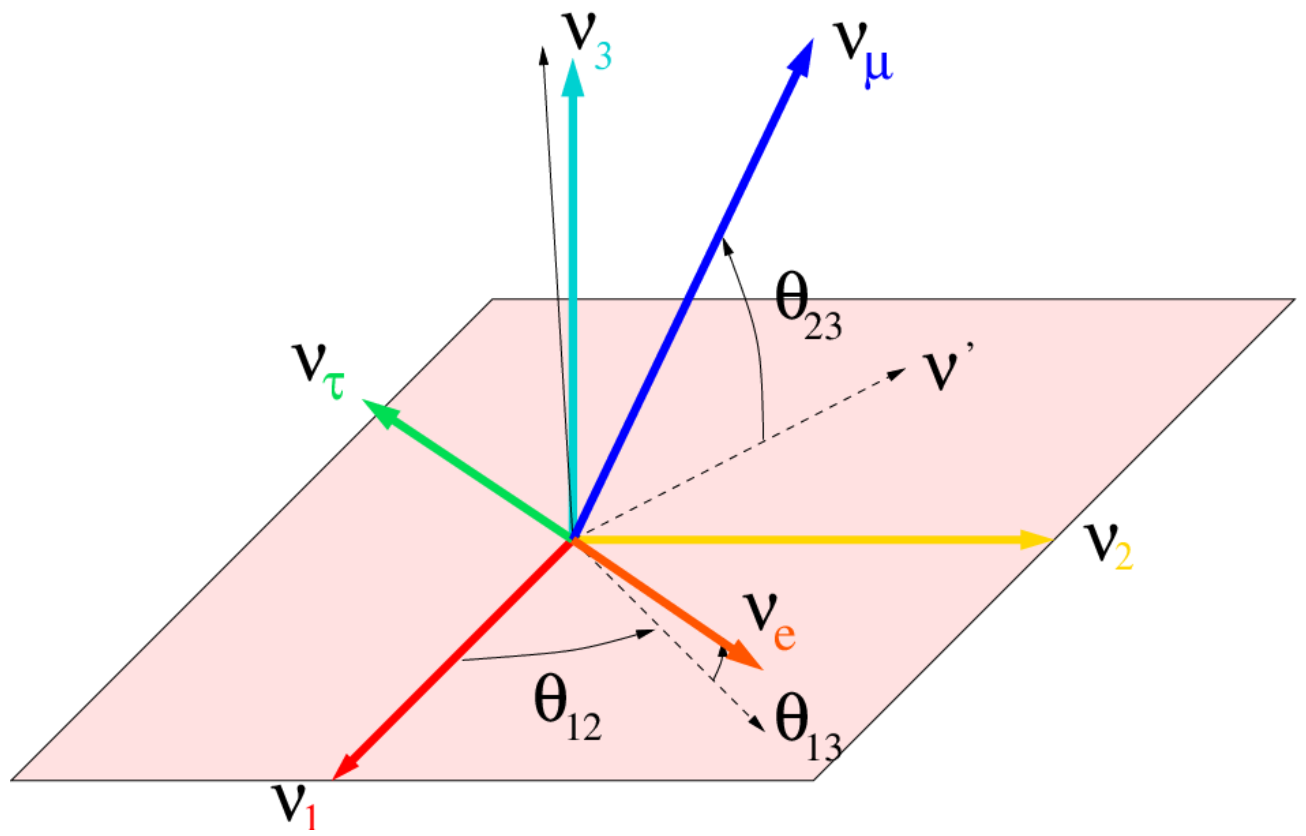
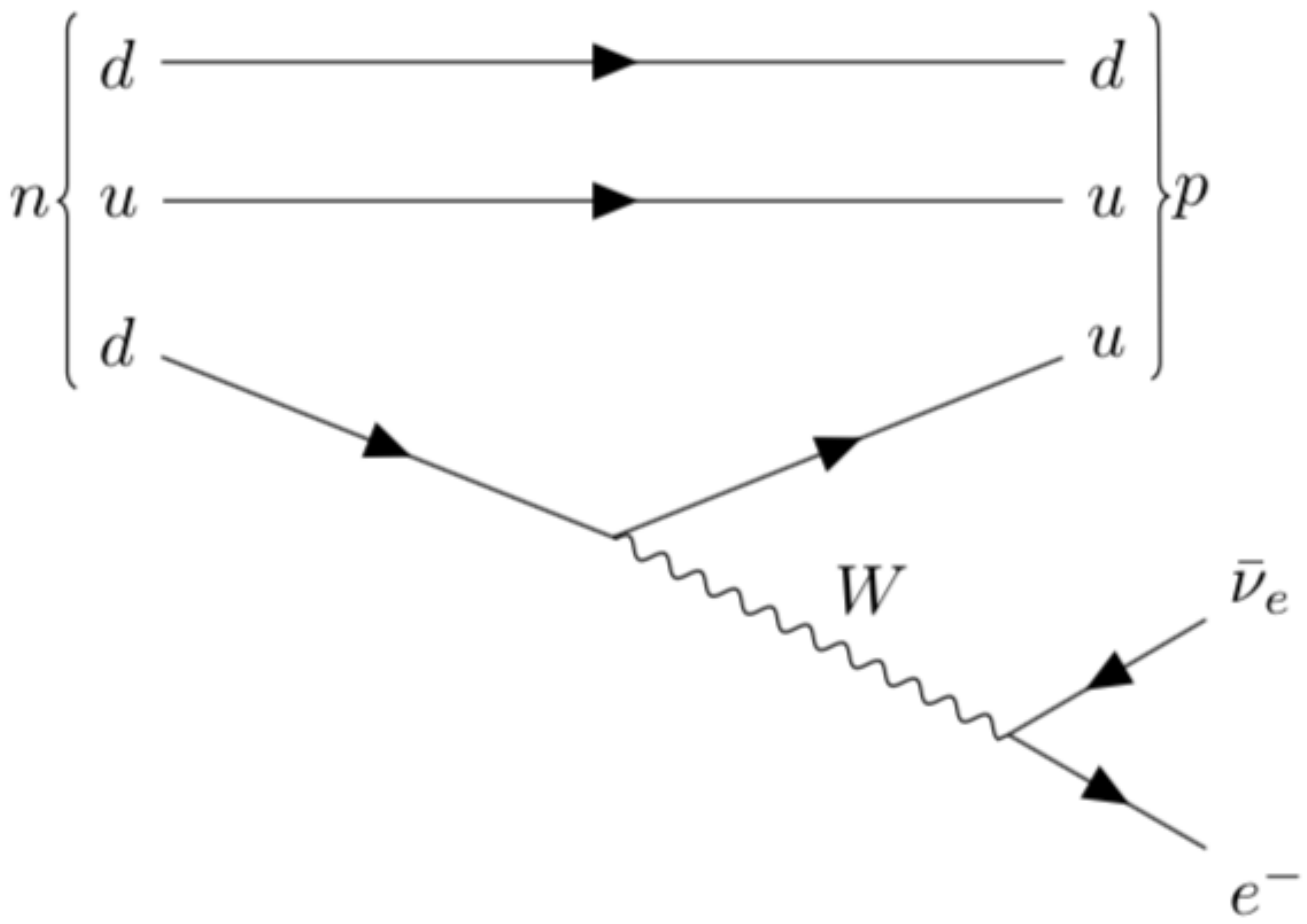
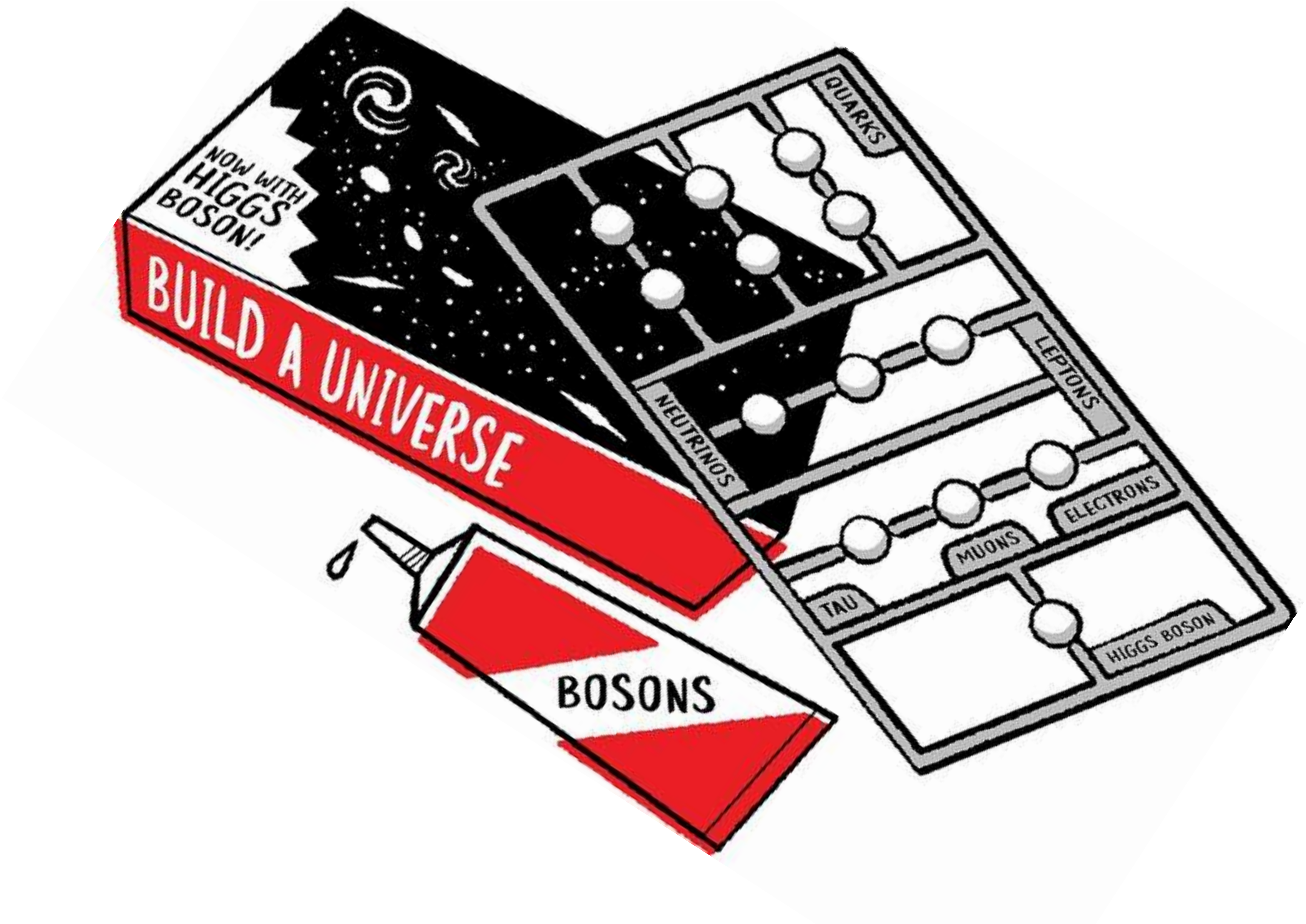
$+ i \bar{\psi} \not{D} \psi + h.c.$
$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$

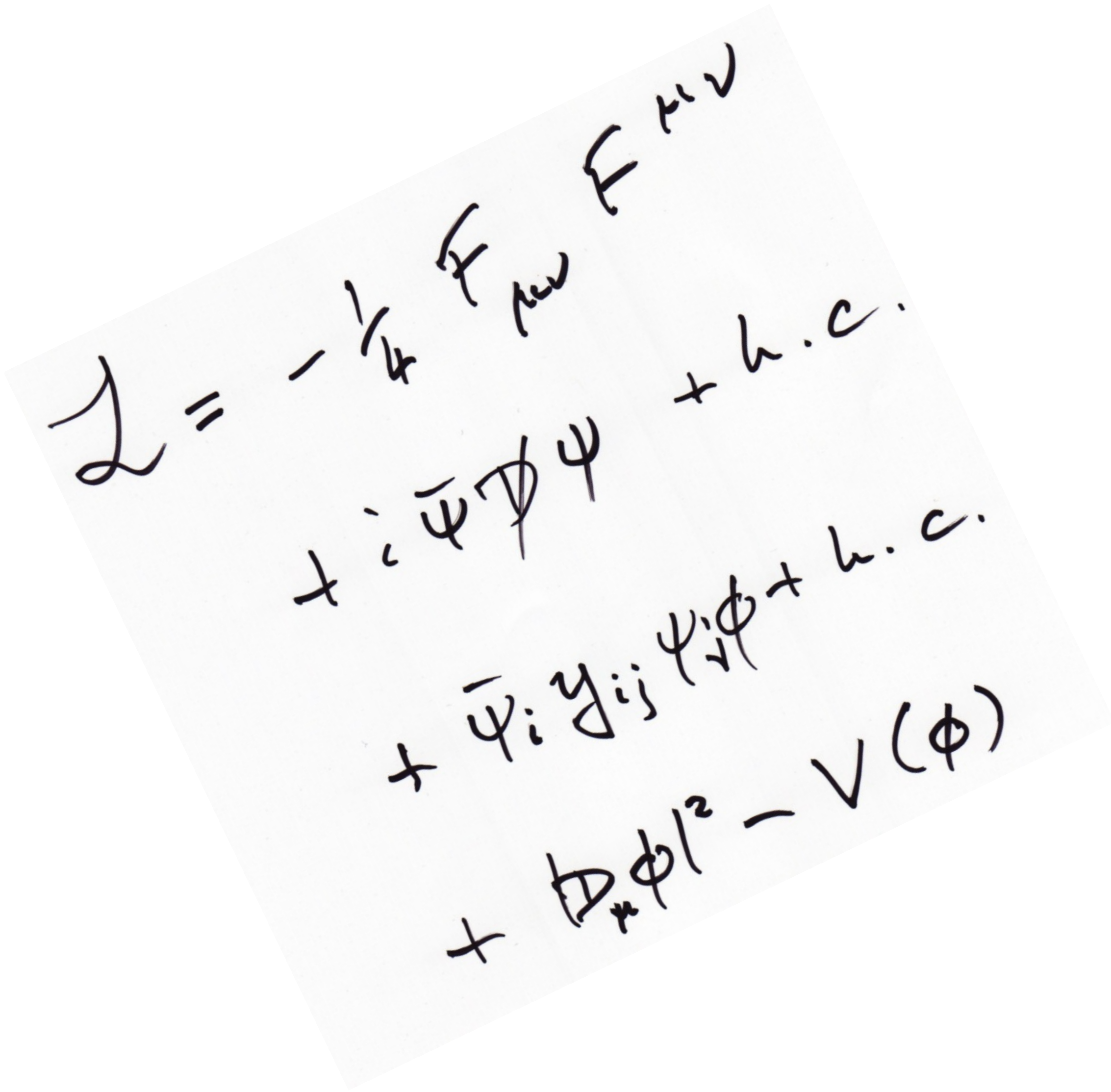

ν_3
ν_μ
θ_{23}
ν_τ
ν'
ν_2
ν_e
θ_{12}
θ_{13}
ν_1

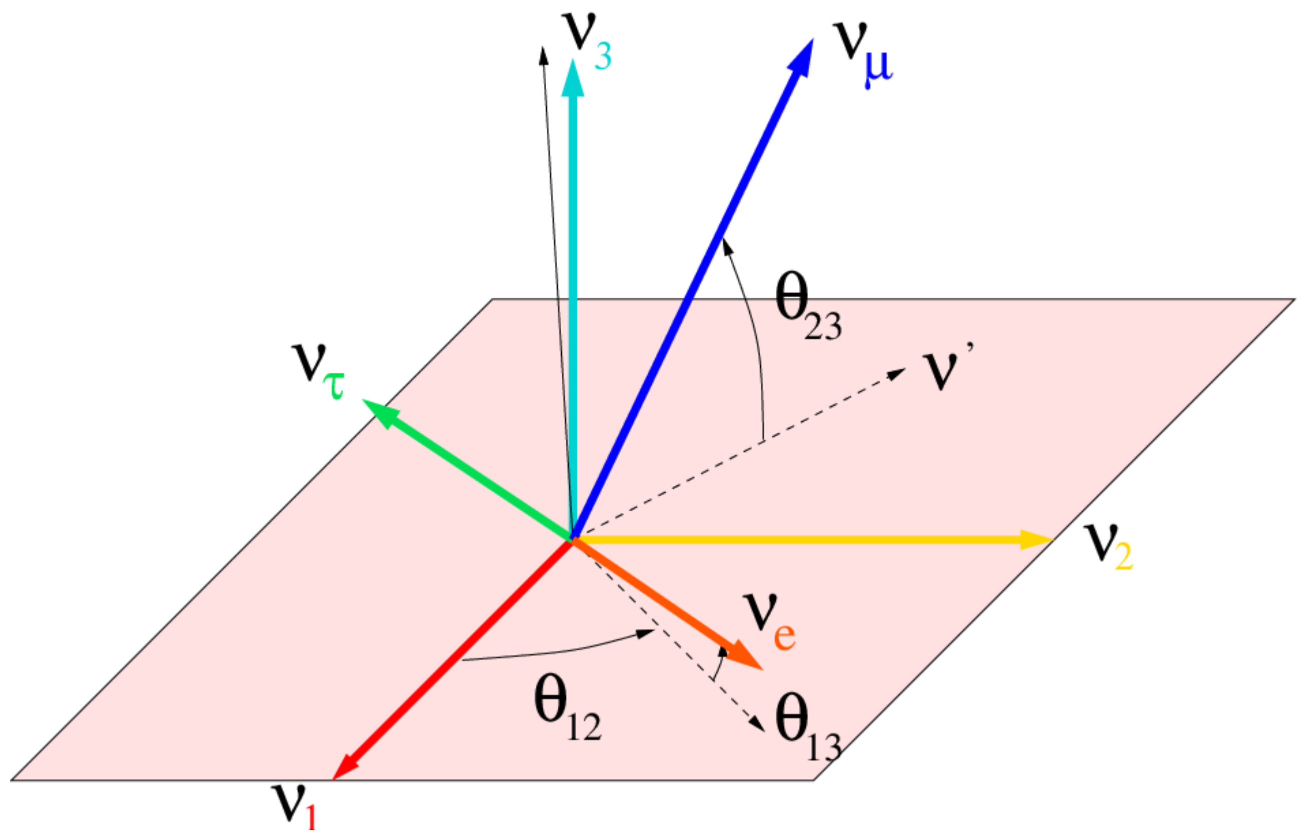

n
d
u
d
d
u
u
p
W
$\bar{\nu}_e$
e^-

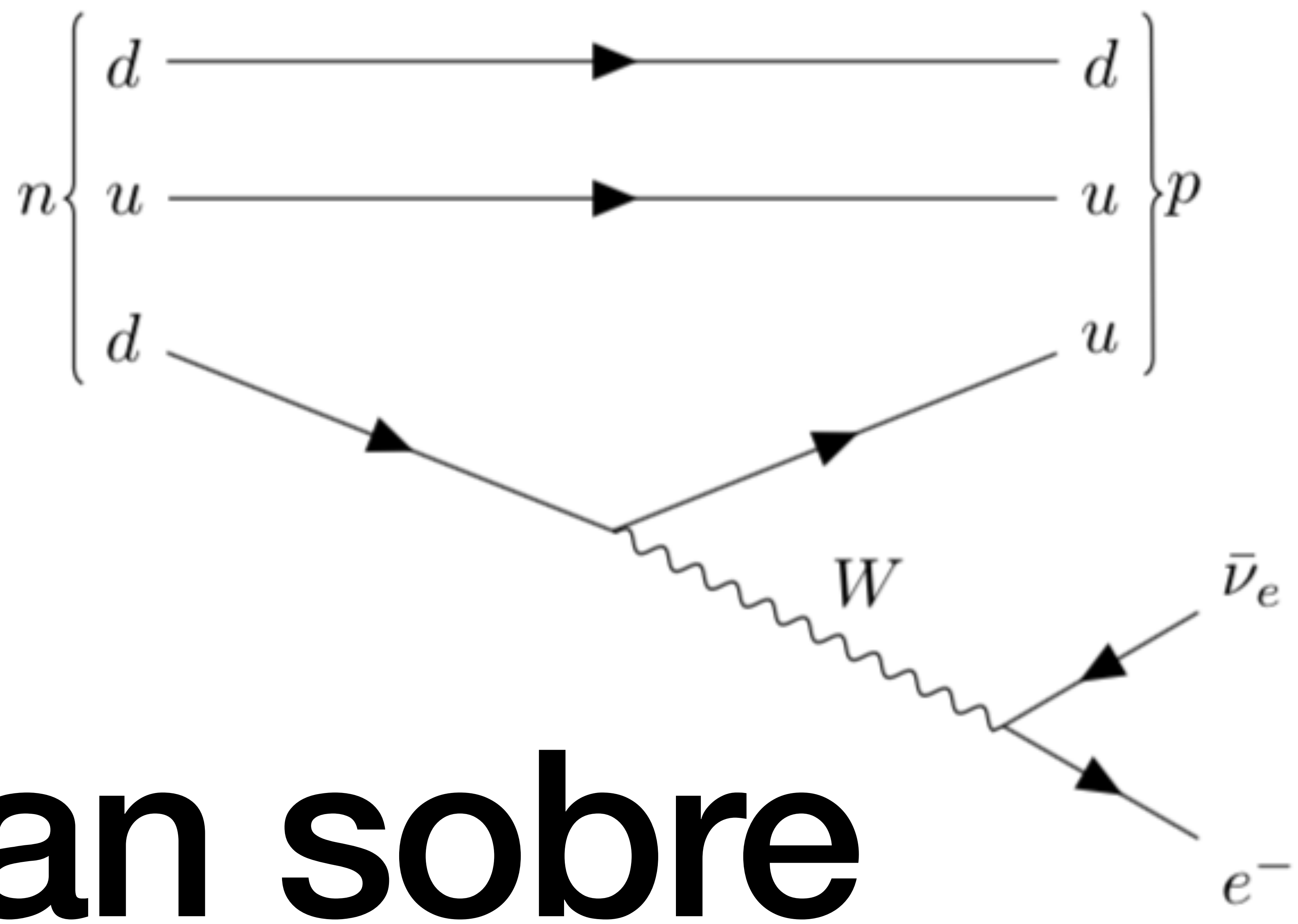
Teoremas


QUARK!

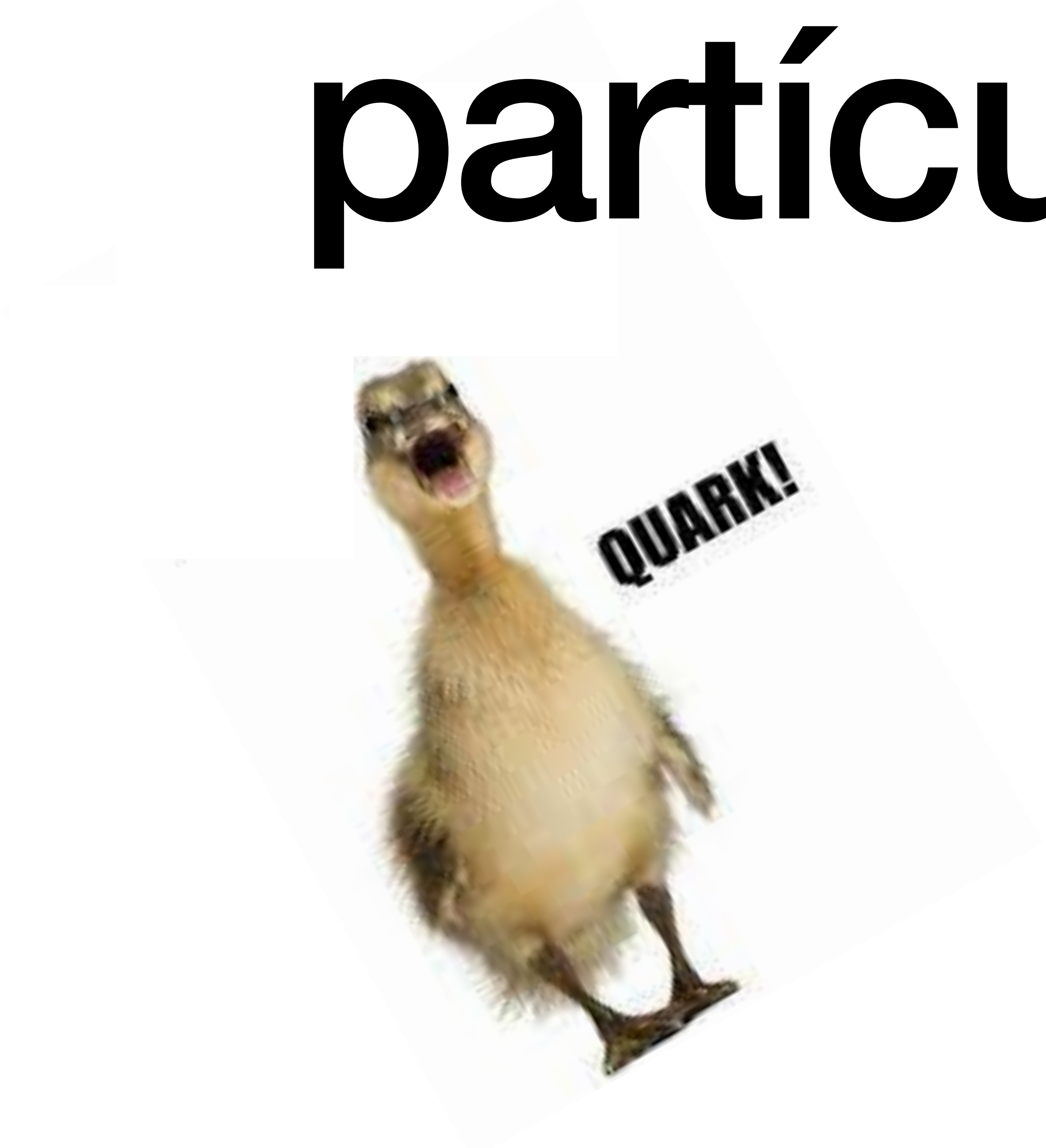

NOW WITH HIGGS BOSON!
BUILD A UNIVERSE
QUARKS
LEPTONS
NEUTRINOS
ELECTRONS
MUONS
TAU
HIGGS BOSON
BOSONS

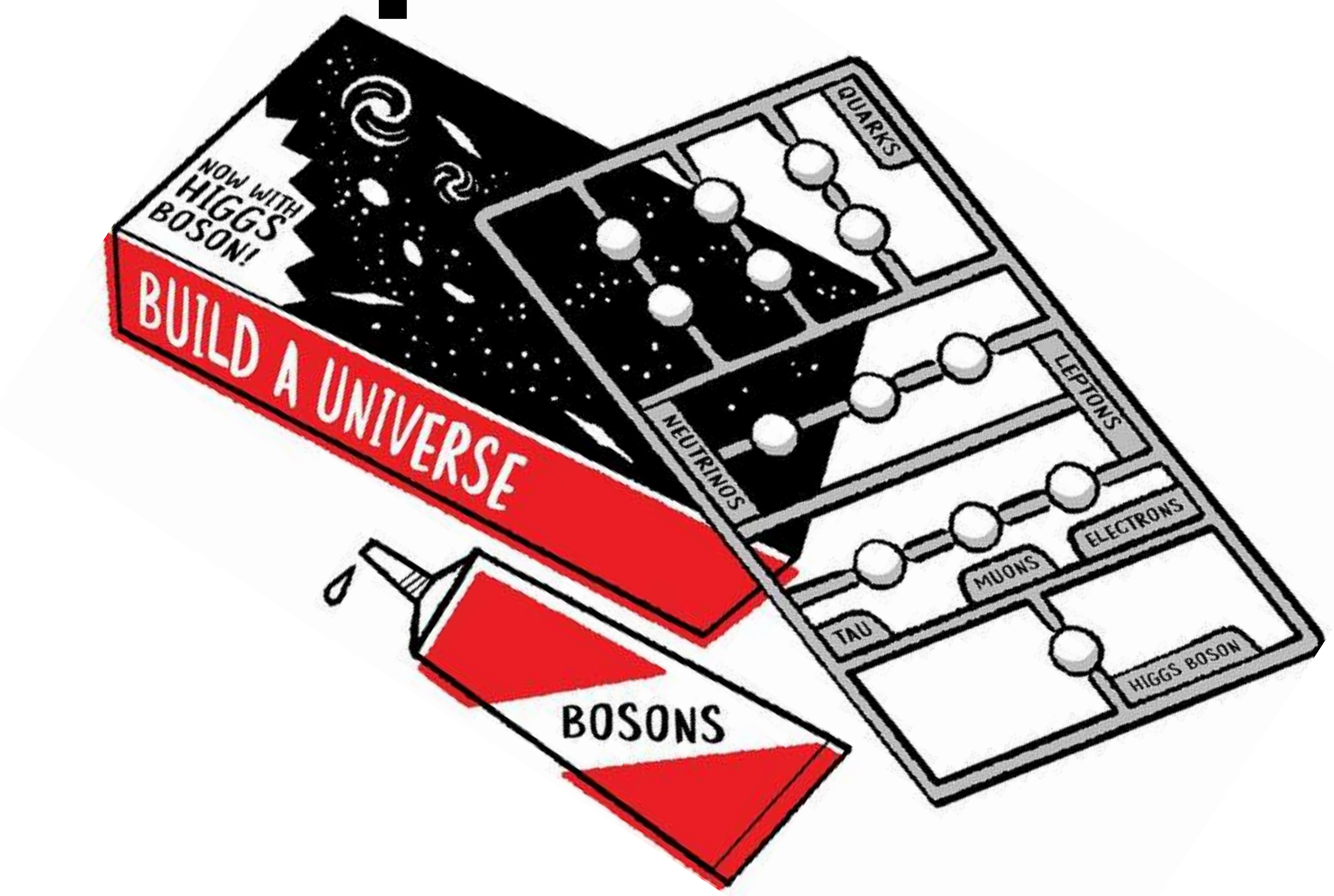




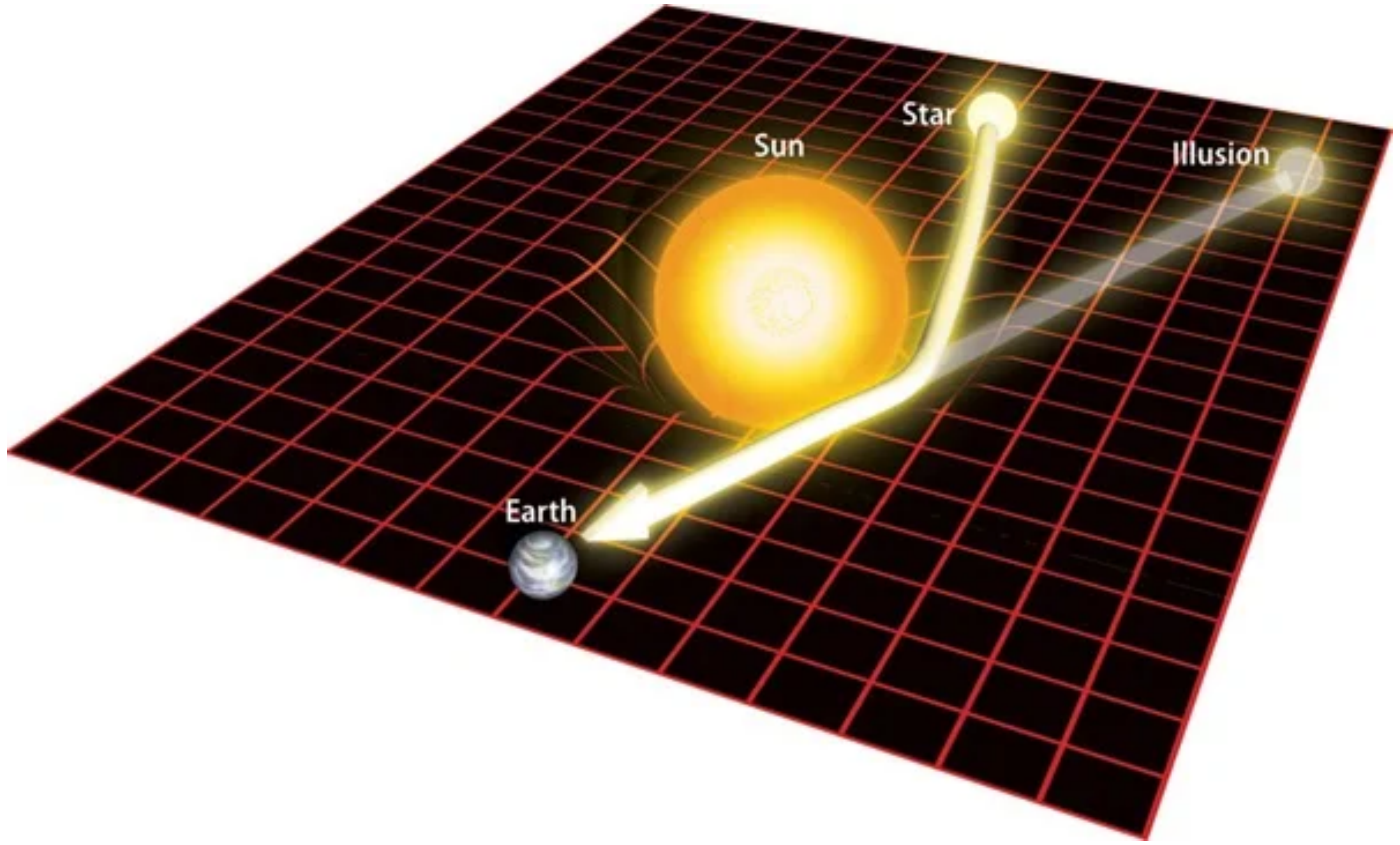


Teorema 1: Feynman sobre partículas sin masa de spin 2

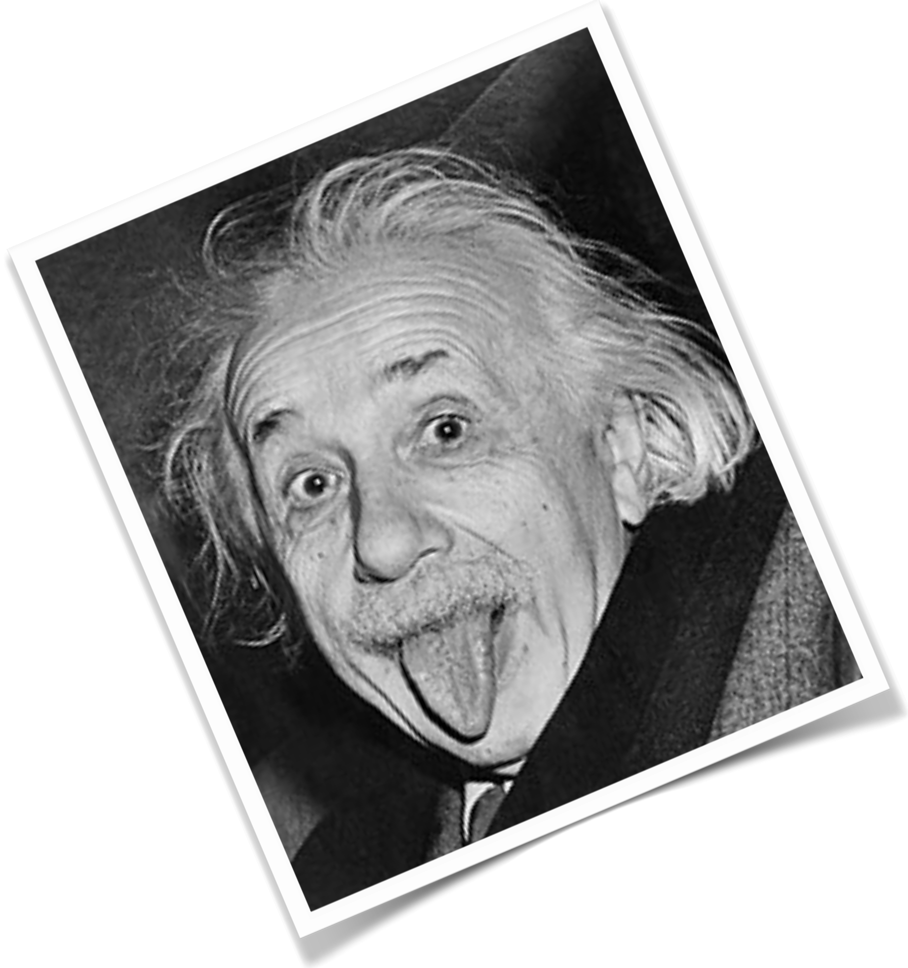




Teorema 1: Feynman spin 2 massless particle



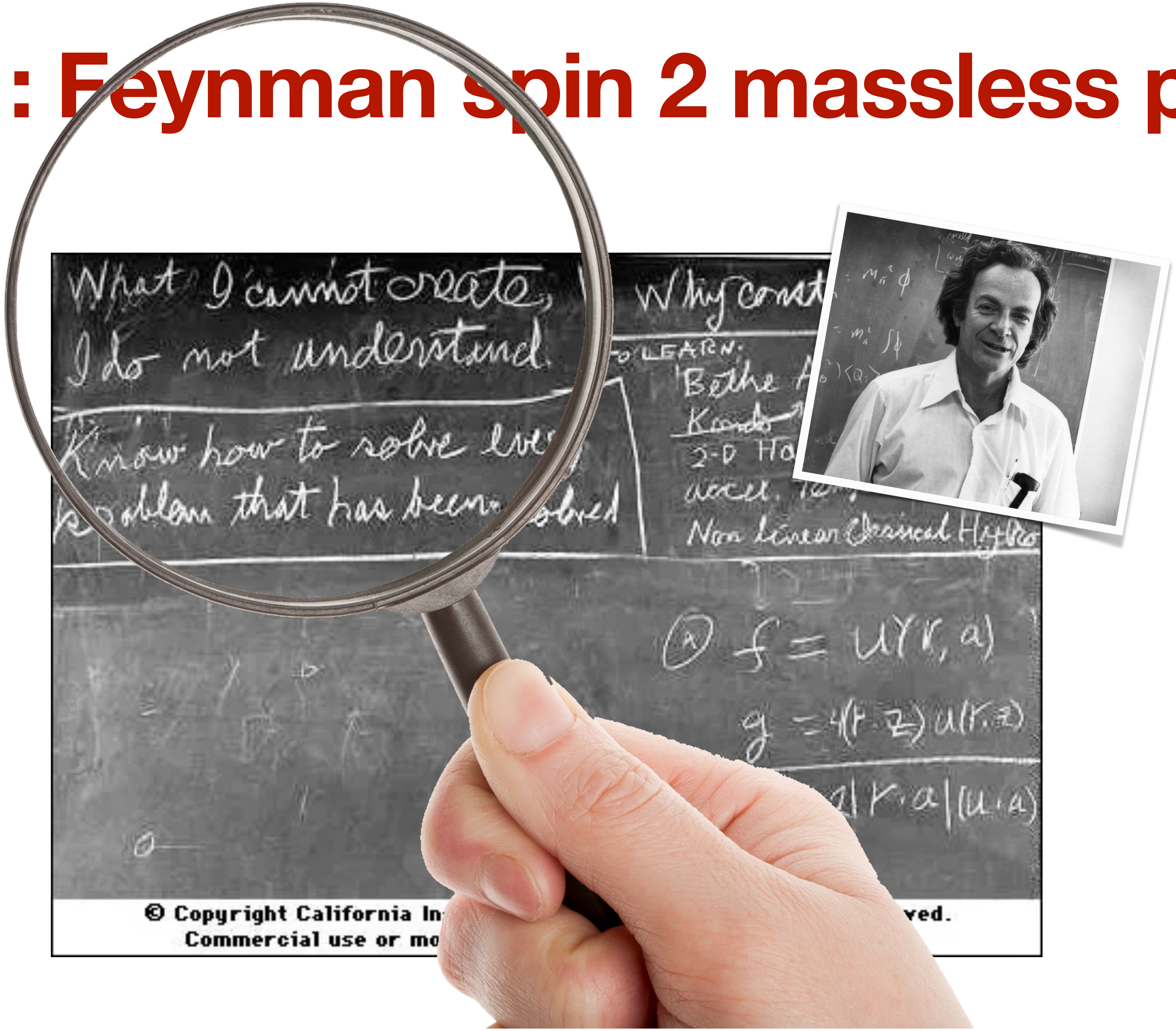
$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = 8\pi G T_{\mu\nu}$$



Gravedad

Geometría

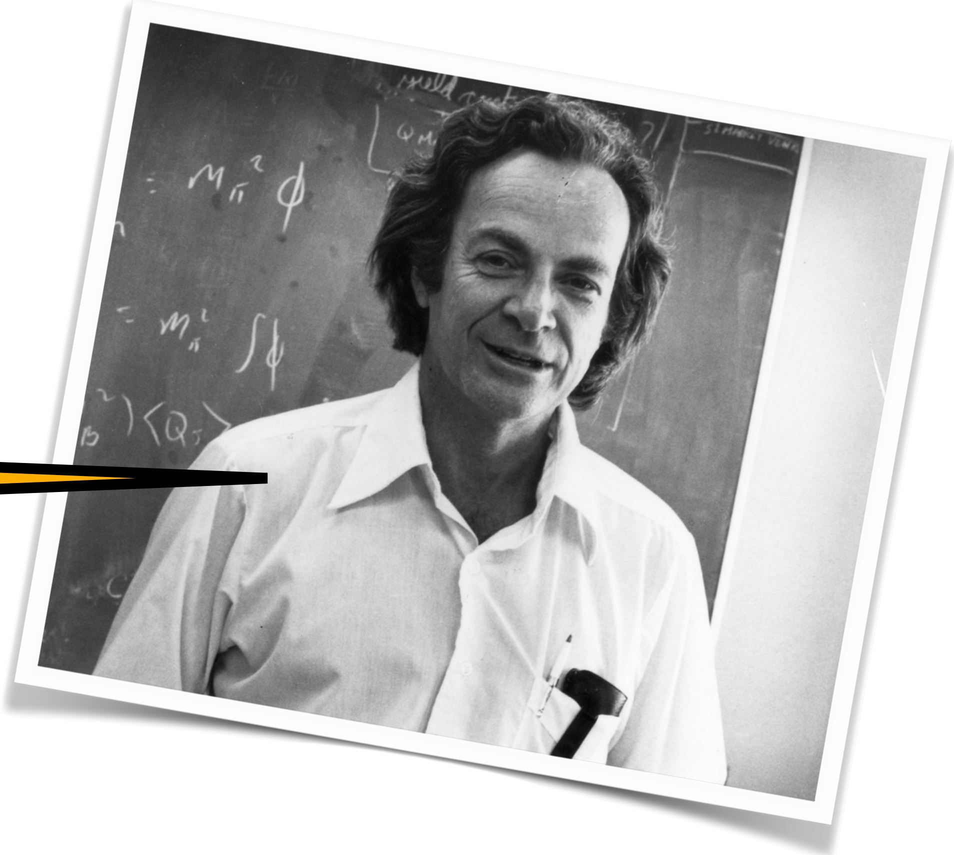
Teorema 1: Feynman spin 2 massless particle

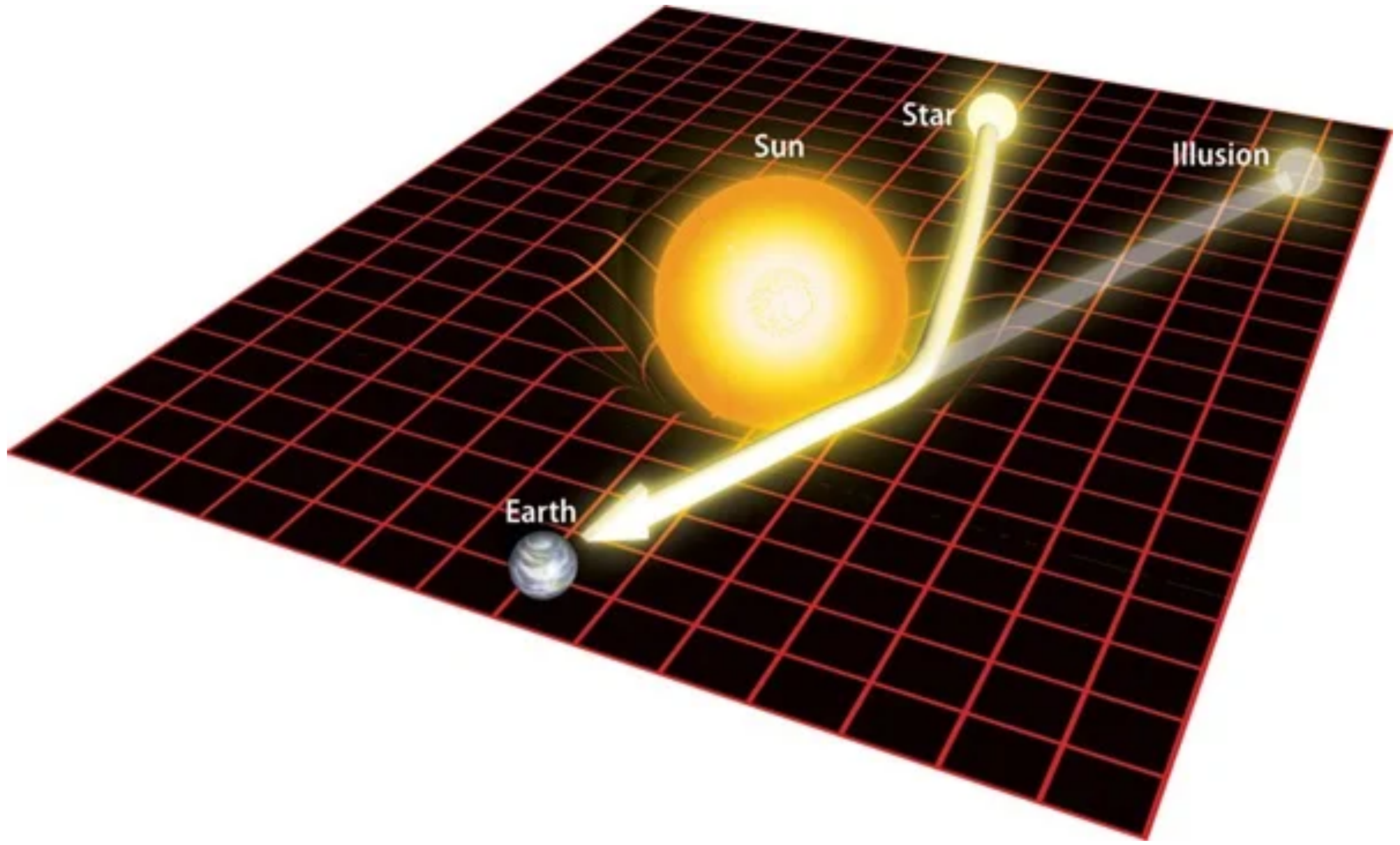


"What I cannot create I do not understand"

Teorema 1: Feynman spin 2 massless particle

FORMULACIÓN
NO GEOMÉTRICA





Teorema 1: Feynman spin 2 massless particle

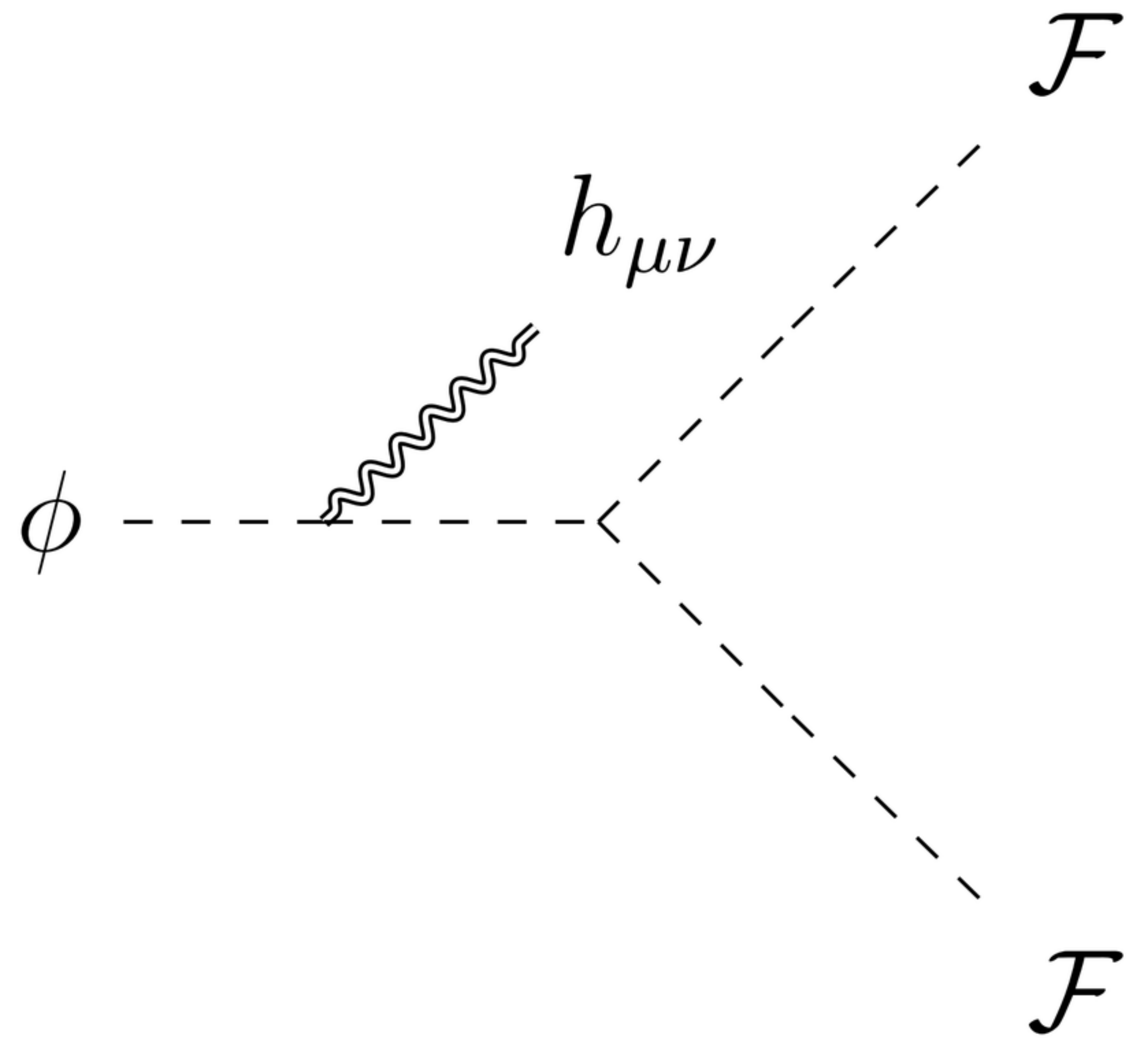
TEORIA DE CAMPOS → **reproduce**

$$F = -G\frac{m_1 m_2}{r^2}$$

Teorema 1: Feynman spin 2 massless particle

$$F = -G\frac{m_1 m_2}{r^2} \Rightarrow m_{\text{mediador}} = 0$$

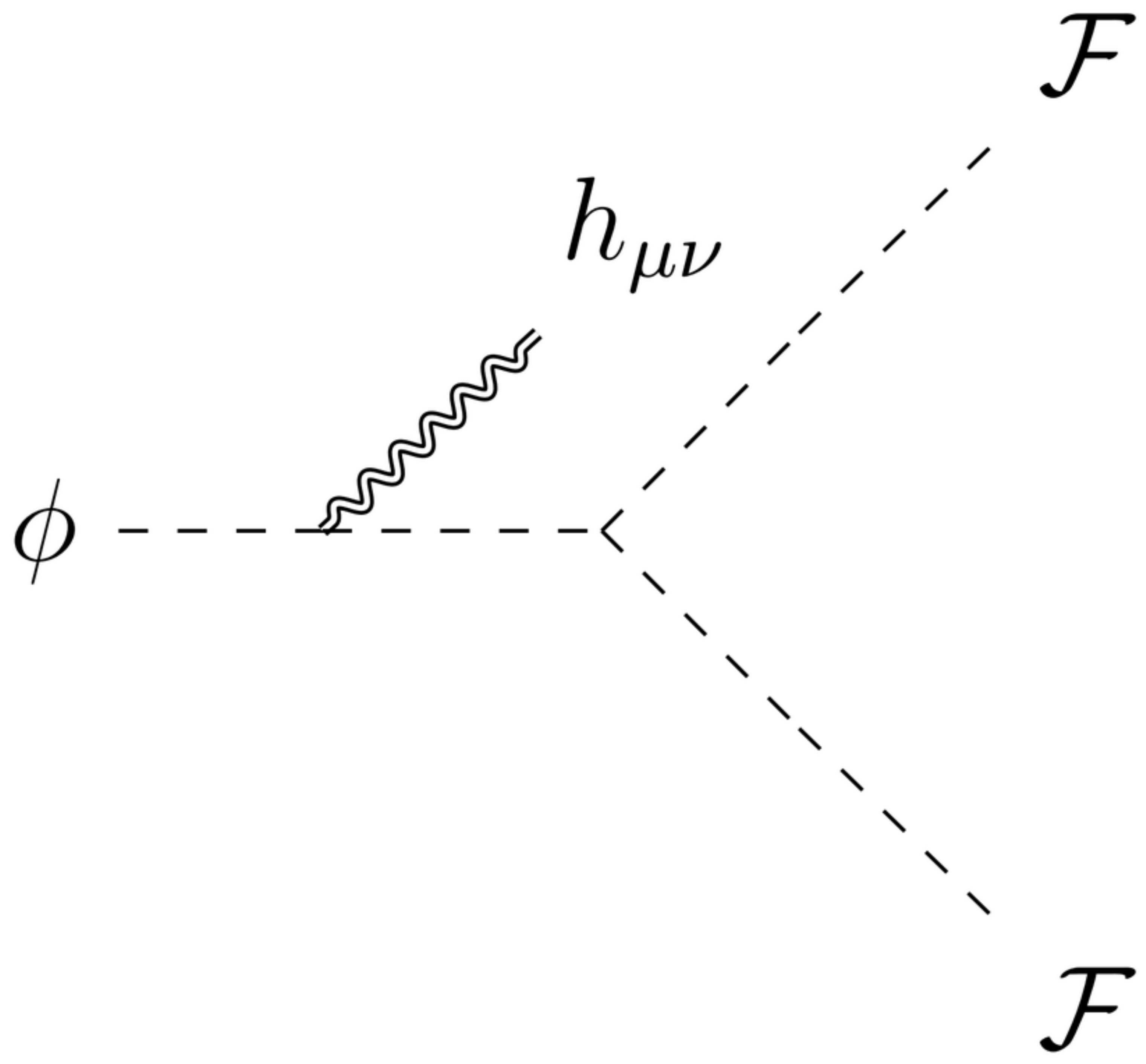
FUERZA ESTÁTICA



Teorema 1: Feynman spin 2 massless particle

$$F = -G\frac{m_1 m_2}{r^2}$$

$$m_{\text{mediador}} = 0$$

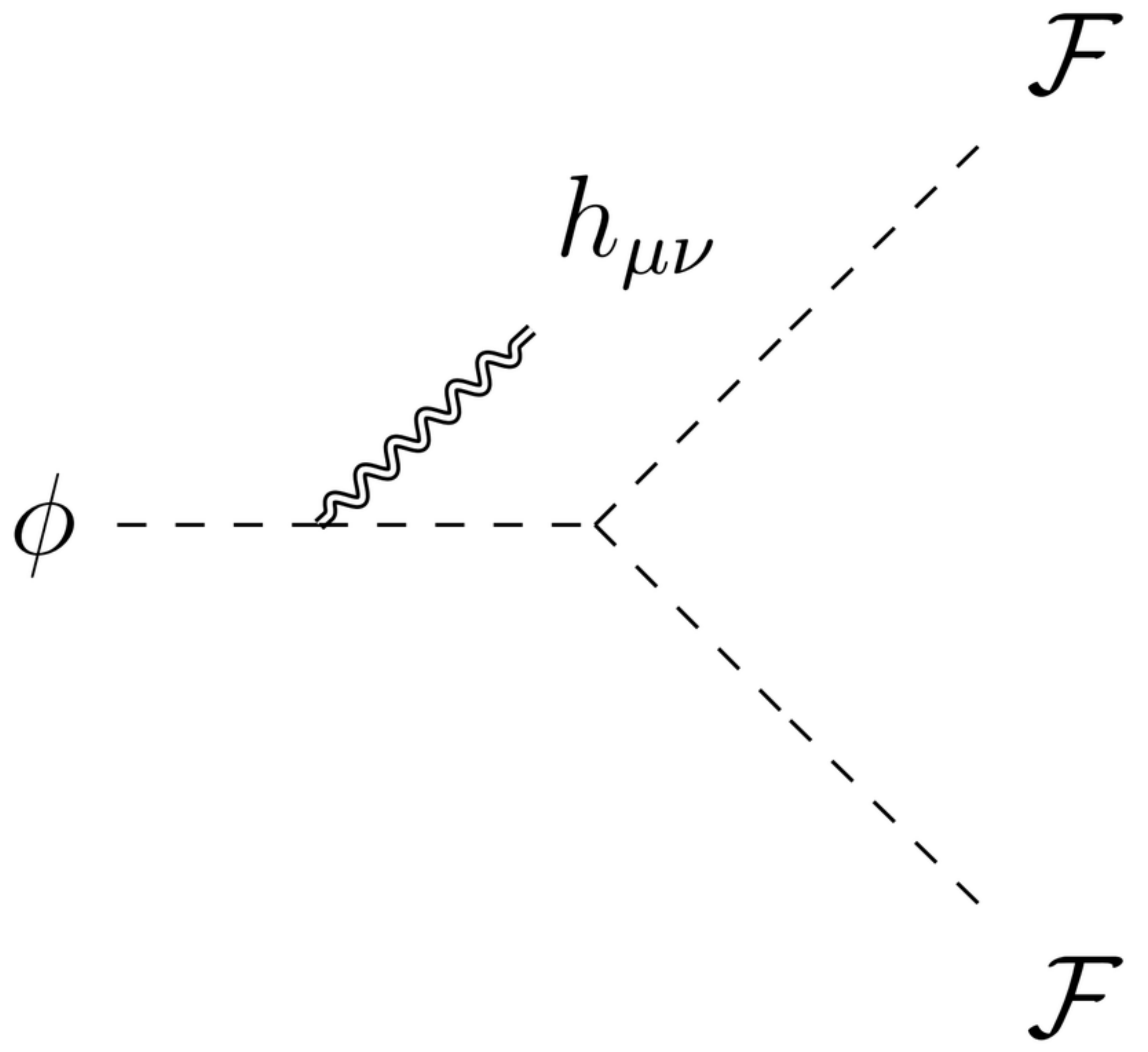


FUERZA ESTÁTICA

$$s = 1/2$$

Teorema 1: Feynman spin 2 massless particle

$$F = -G\frac{m_1 m_2}{r^2} \quad \Rightarrow \quad m_{\text{mediador}} = 0$$



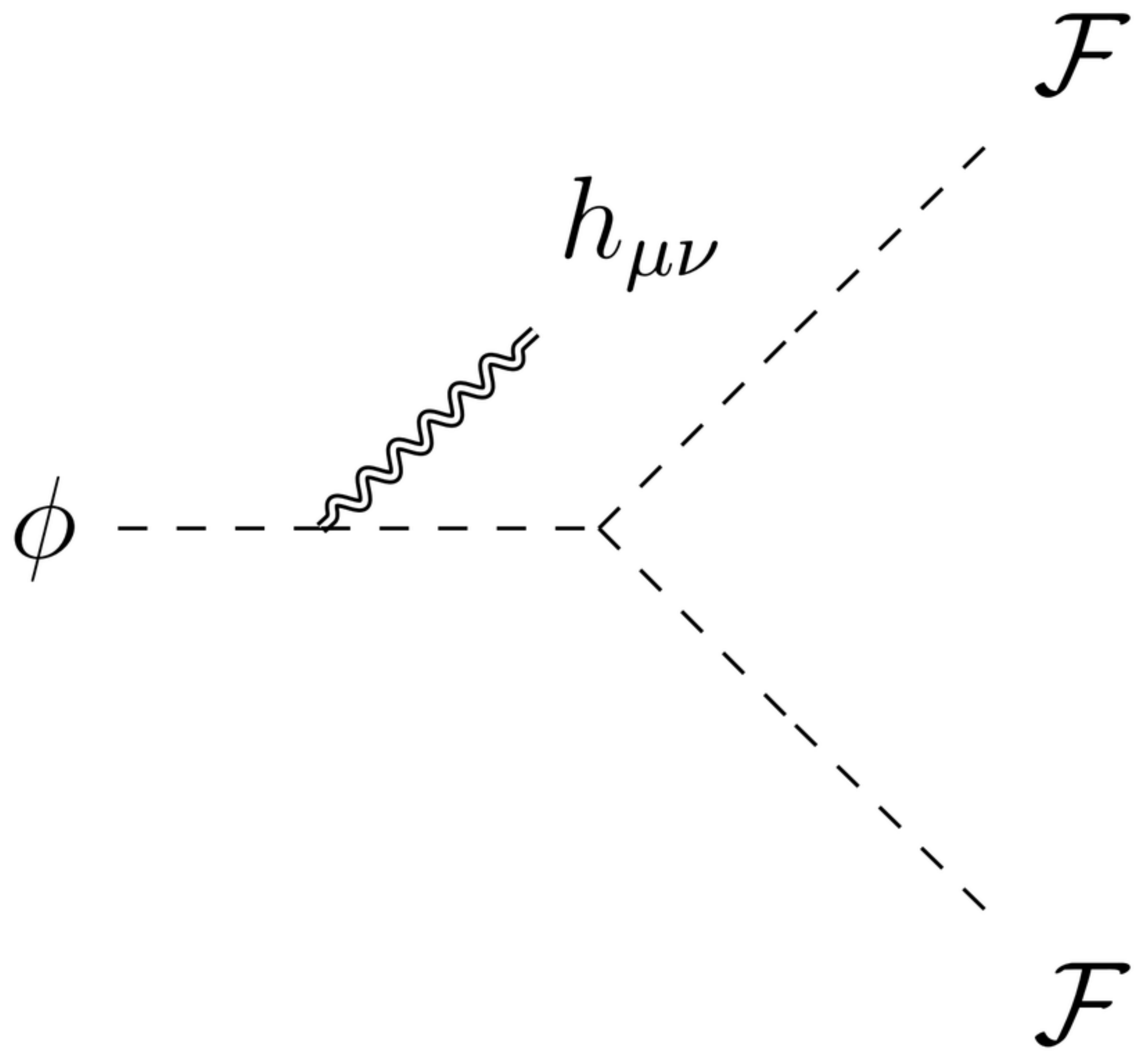
FUERZA ESTÁTICA

$s = 1/2$

$s =$ **entero**

Teorema 1: Feynman spin 2 massless particle

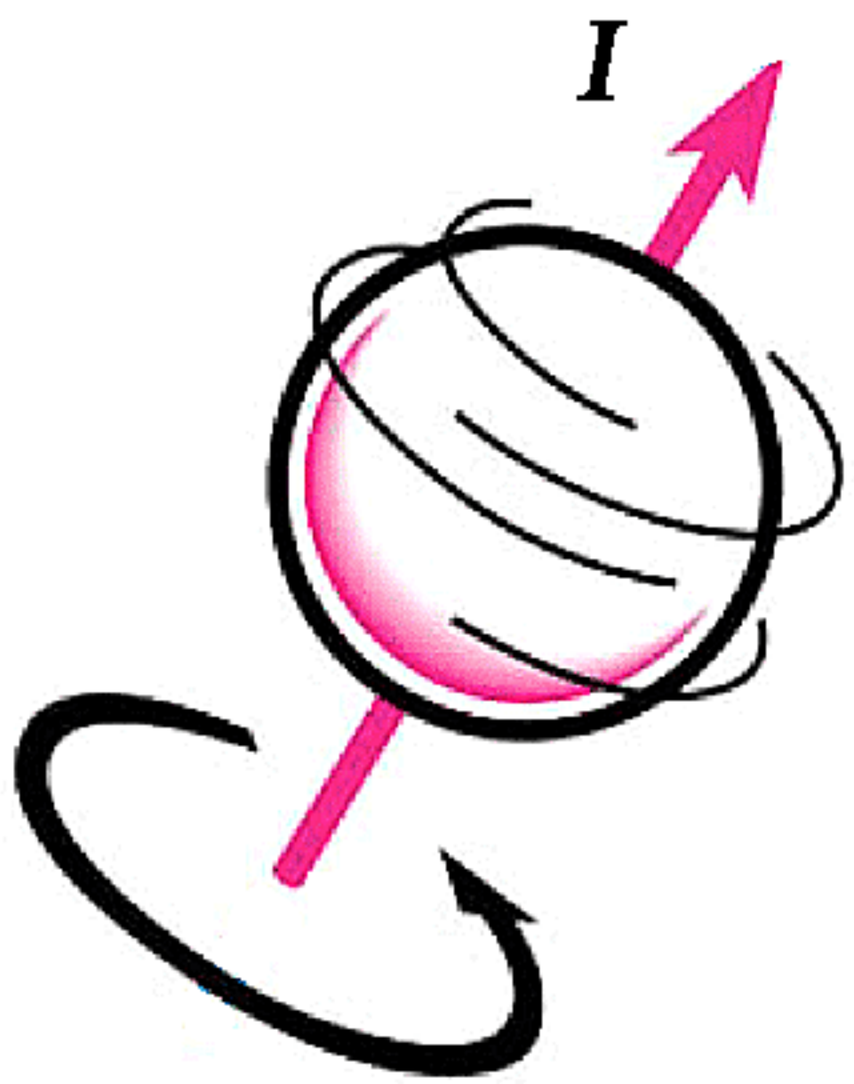
$$F = -G\frac{m_1 m_2}{r^2} \Rightarrow m_{\text{mediador}} = 0$$



FUERZA ESTÁTICA

~~$s = 1/2$~~

$s =$ **entero**



Teorema 1: Feynman spin 2 massless particle

$$F = -G\frac{m_1 m_2}{r^2} \Rightarrow \boxed{m_{\text{mediador}} = 0}$$

FUERZA ESTÁTICA

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

Teorema 1: Feynman spin 2 massless particle

$$m_s = 0$$

CONTENIDO DE MATERIA

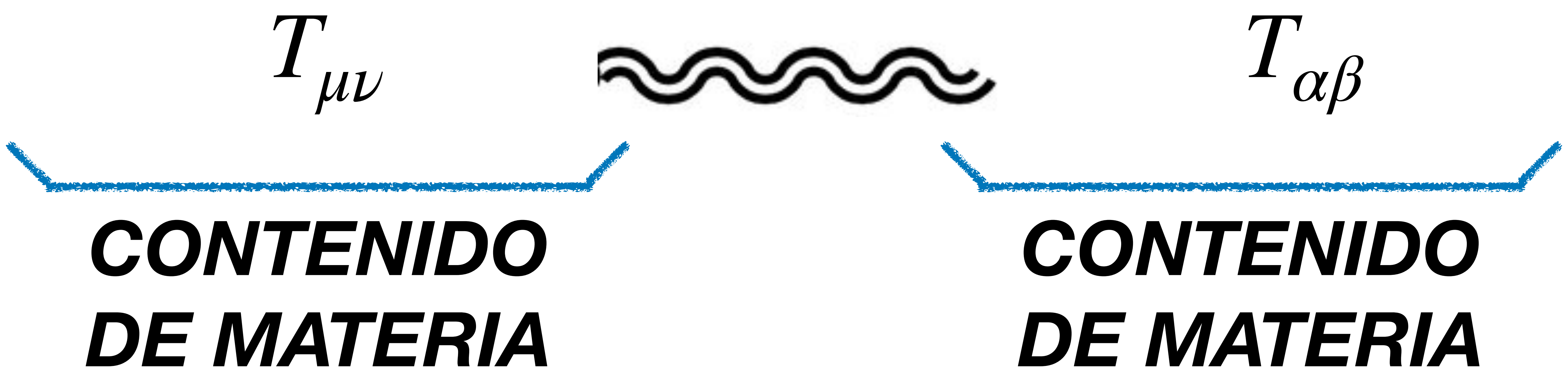
CONTENIDO DE MATERIA

FUERZA ESTÁTICA

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

Teorema 1: Feynman spin 2 massless particle

$$m_s = 0$$

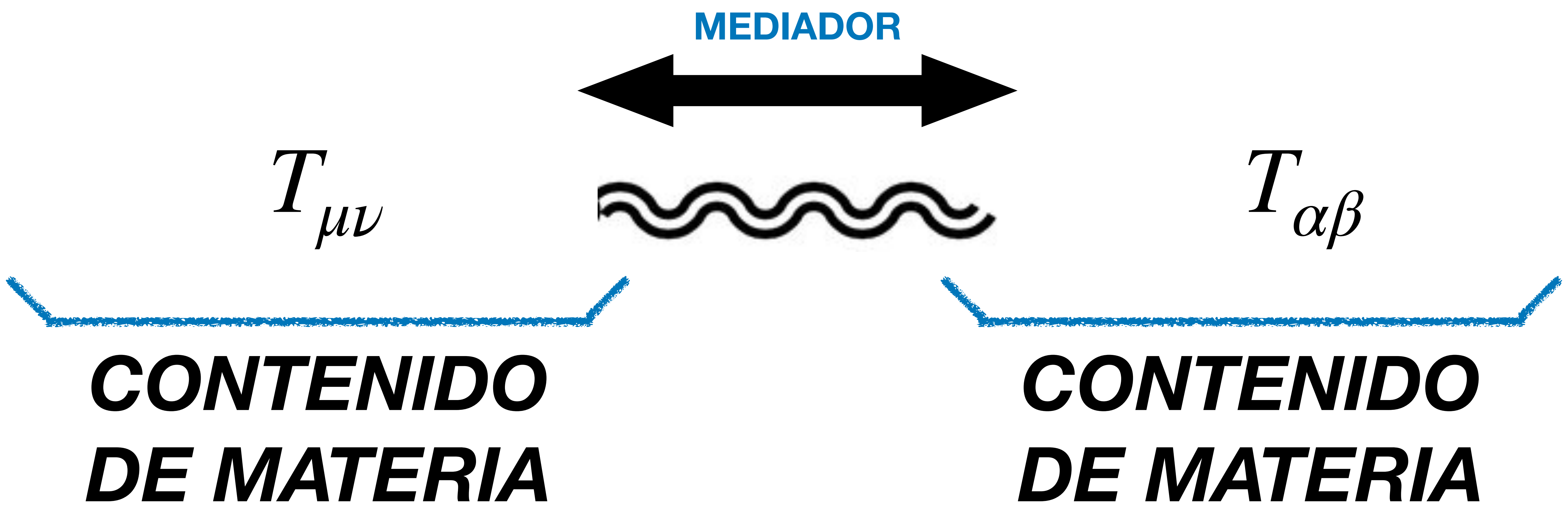


FUERZA ESTÁTICA

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

Teorema 1: Feynman spin 2 massless particle

$$m_s = 0$$

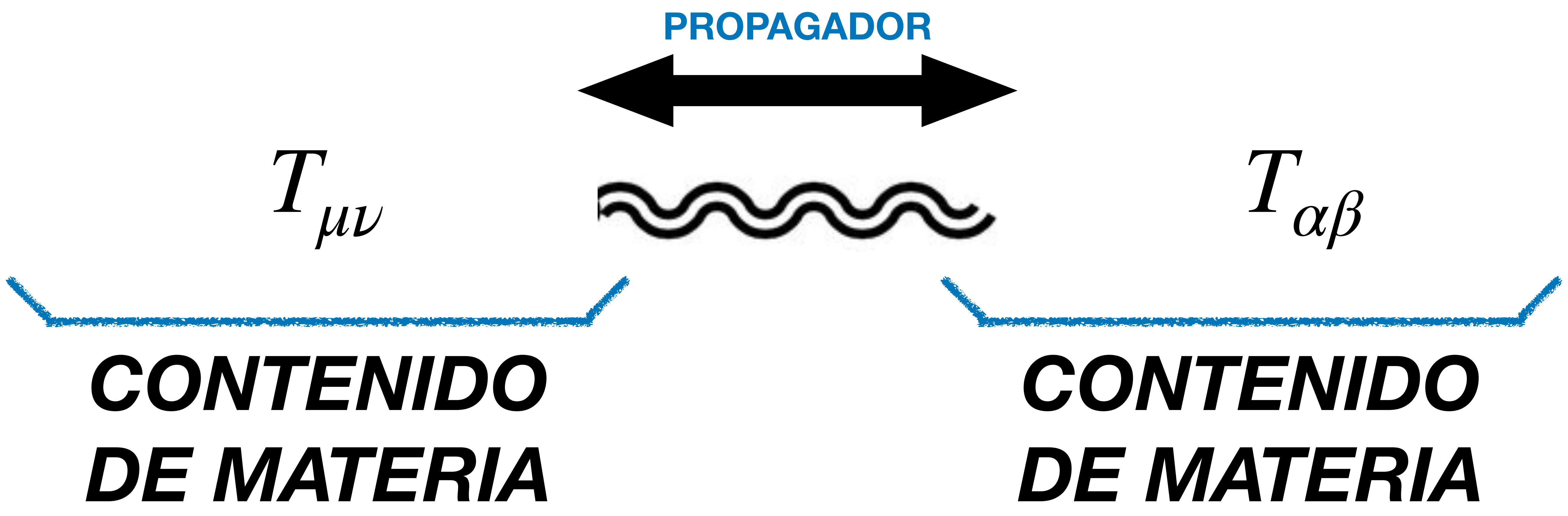


FUERZA ESTÁTICA

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

Teorema 1: Feynman spin 2 massless particle

$$m_s = 0$$

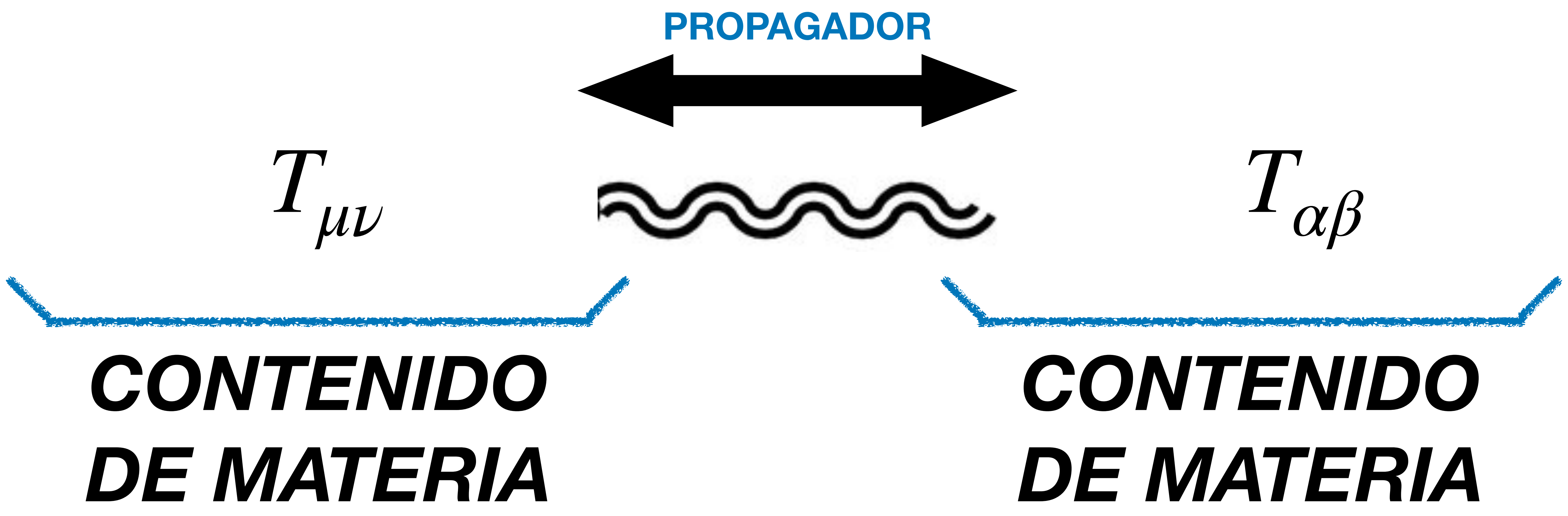


FUERZA ESTÁTICA

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

Teorema 1: Feynman spin 2 massless particle

$$m_s = 0$$

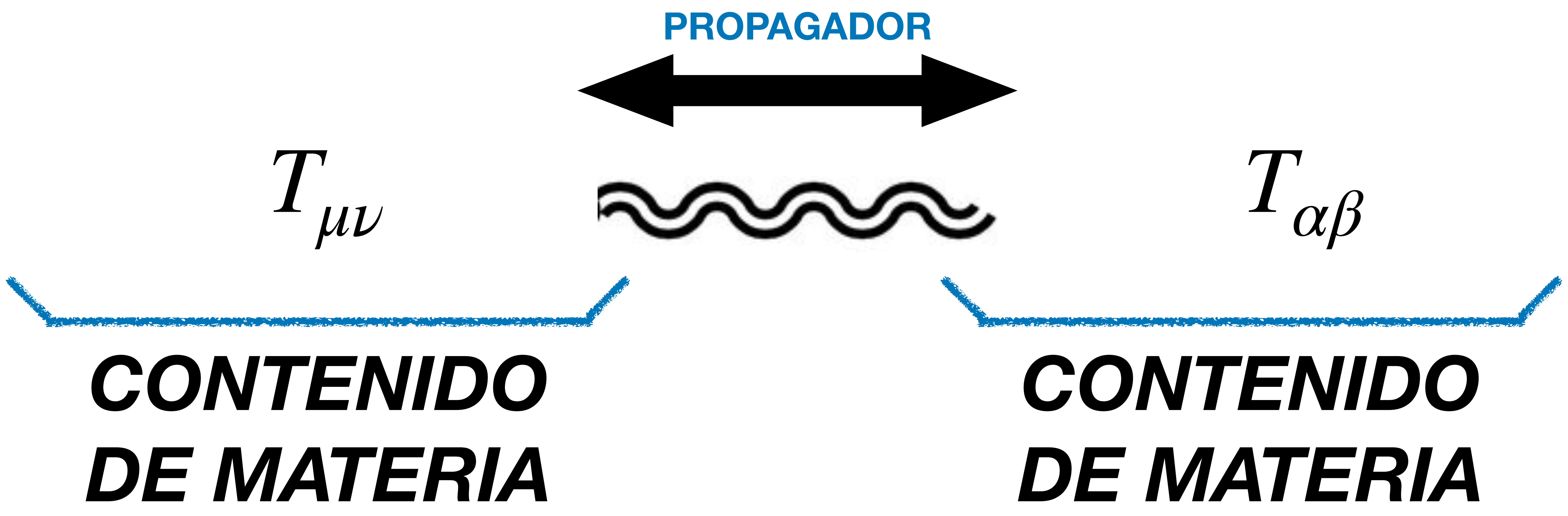


FUERZA ESTÁTICA

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

Teorema 1: Feynman spin 2 massless particle

$$m_s = 0$$



FUERZA ESTÁTICA

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

$$s = 0 \qquad \Delta_0 \simeq \frac{1}{k^2}$$

$$s = 1 \qquad \Delta_1 \simeq \frac{\eta_{\mu\nu}}{k^2}$$

$$s = 2 \qquad \Delta_2 \simeq \frac{\eta_{\mu\nu}\eta_{\alpha\beta}}{k^2}$$

Teorema 1: Feynman spin 2 massless particle

$$m_s = 0$$

$s = 0$

$T_{\mu\nu}$  $T_{\alpha\beta}$

CONTENIDO DE MATERIA — **_CONTENIDO DE MATERIA_**

$$\Delta_0 \simeq \frac{1}{k^2}$$

FUERZA ESTÁTICA

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

Teorema 1: Feynman spin 2 massless particle

$s = 0$

$m_s = 0$

$T_{\mu\nu}$

$T_{\alpha\beta}$

$$\Delta_0 \simeq \frac{1}{k^2}$$

FUERZA ESTÁTICA

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

Teorema 1: Feynman spin 2 massless particle

$s = 0$

$$m_s = 0$$

$$T^{\mu}{}_{\mu} \qquad \frac{1}{k^2} \qquad T^{\alpha}{}_{\alpha}$$

FUERZA ESTÁTICA

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

Teorema 1: Feynman spin 2 massless particle

$s = 0$

$$T^{\mu}{}_{\mu} \qquad \frac{1}{k^2} \qquad T^{\alpha}{}_{\alpha}$$

$m_s = 0$

FUERZA ESTÁTICA

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

Teorema 1: Feynman spin 2 massless particle

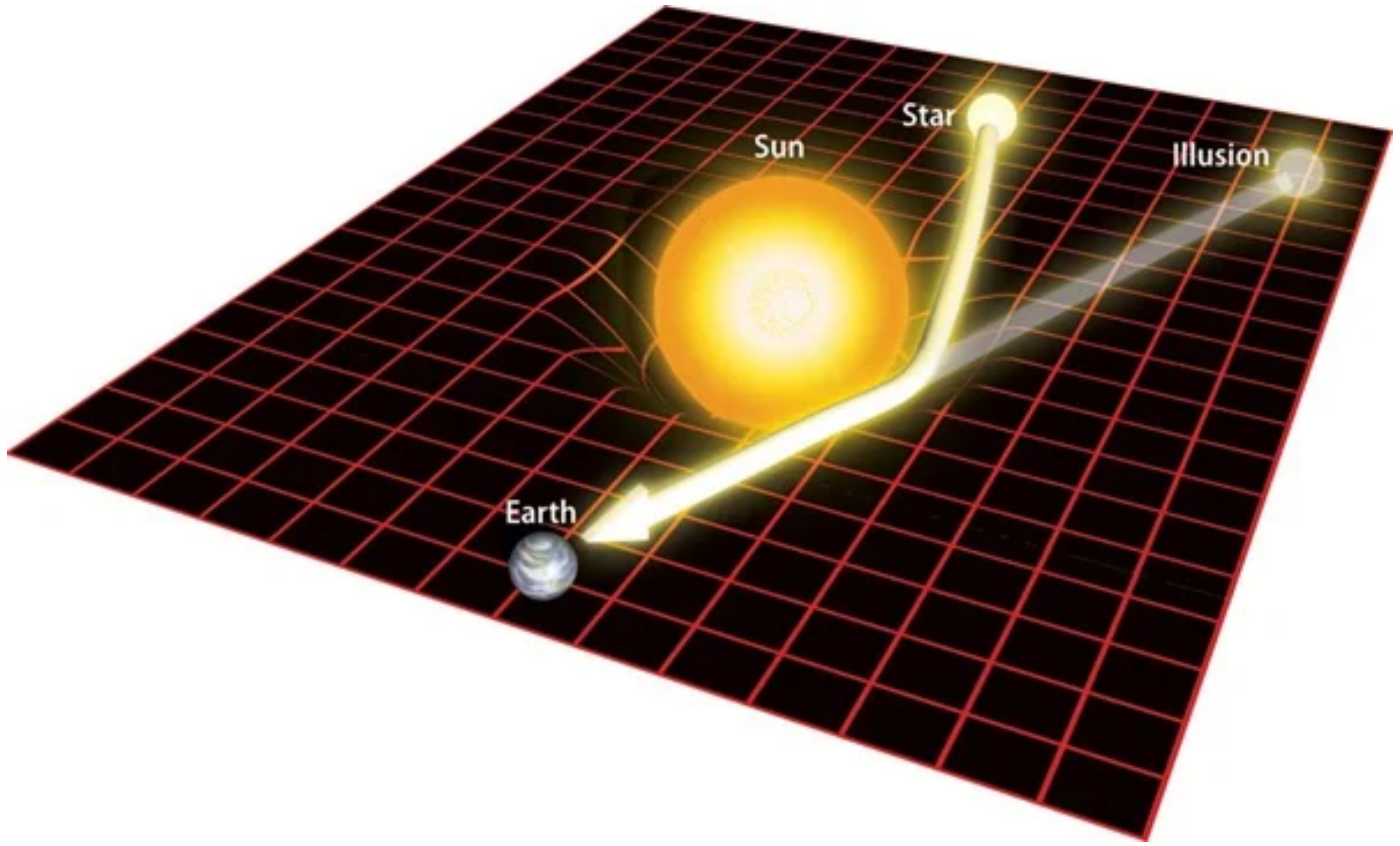
$$m_s = 0$$

$$s = 0$$

$$T^{\mu}{}_{\mu} \qquad \frac{1}{k^2} \qquad T^{\alpha}{}_{\alpha}$$

FUERZA ESTÁTICA

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



Teorema 1: Feynman spin 2 massless particle

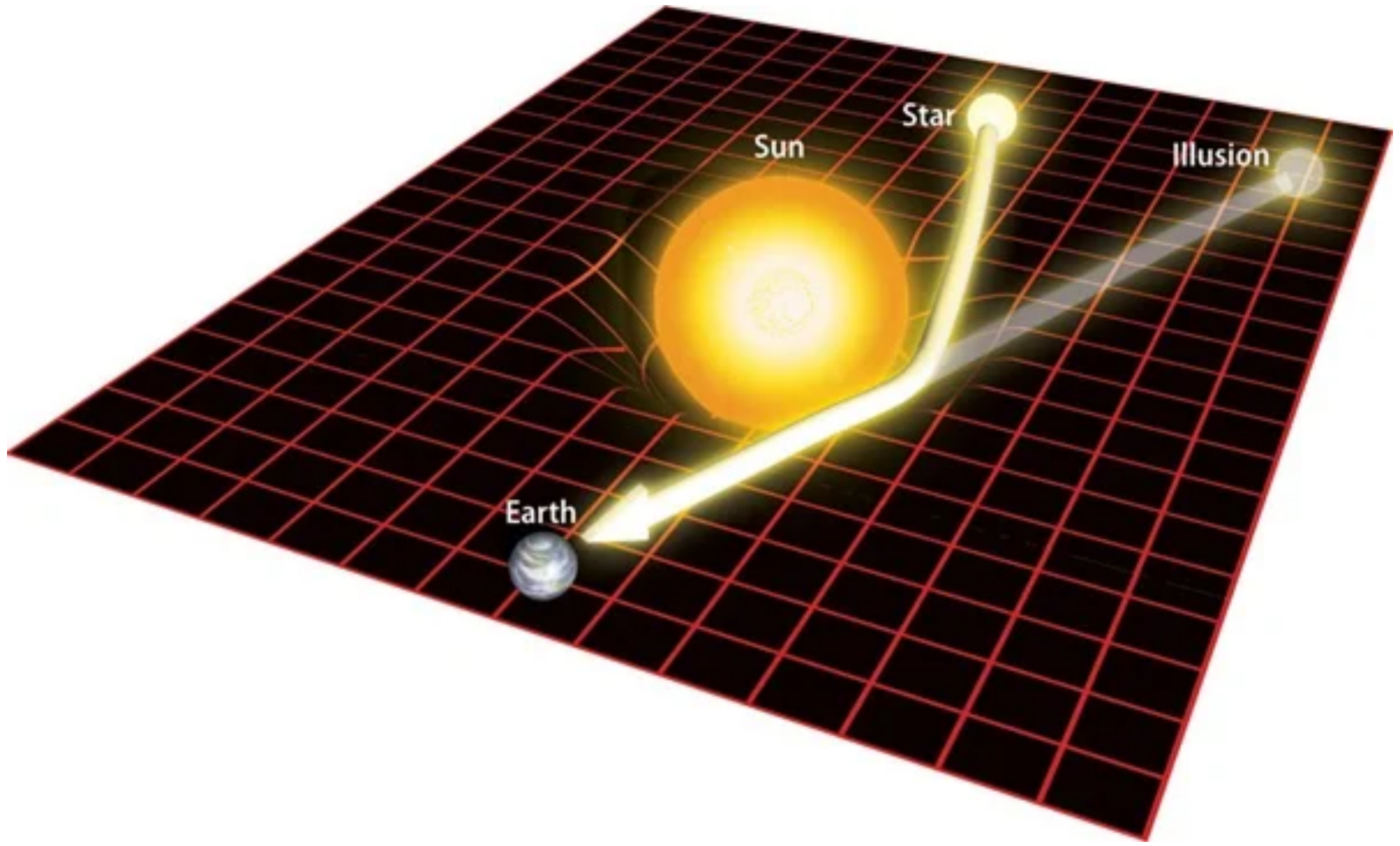
$s = 0$

$T^{\mu}{}_{\mu}$ $\frac{1}{k^2}$ $T^{\alpha}{}_{\alpha}$

$m_s = 0$

FUERZA ESTÁTICA

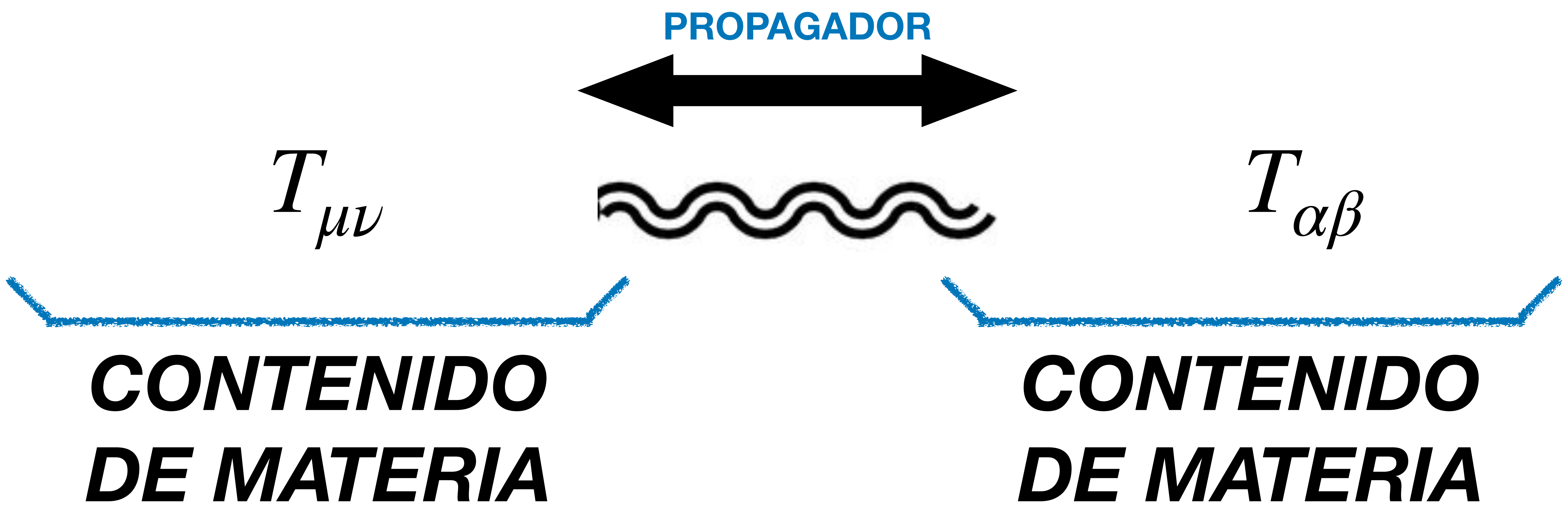
$s = \{0,1,2,\ldots\}$



$T^{\mu}{}_{\mu} = 0$

Teorema 1: Feynman spin 2 massless particle

$$m_s = 0$$



FUERZA ESTÁTICA

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

~~$s = 0 \qquad \Delta_0 \simeq \frac{1}{k^2}$~~

$$s = 1 \qquad \Delta_1 \simeq \frac{\eta_{\mu\nu}}{k^2}$$

$$s = 2 \qquad \Delta_2 \simeq \frac{\eta_{\mu\nu}\eta_{\alpha\beta}}{k^2}$$

Teorema 1: Feynman spin 2 massless particle

$m_s = 0$

PROPAGADOR

$T_{\mu\nu}$  $T_{\alpha\beta}$

CONTENIDO DE MATERIA ***CONTENIDO DE MATERIA***

FUERZA ESTÁTICA

$s = \{0,1,2,\ldots\}$ →

~~$s = 0 \quad \Delta_0 \simeq \frac{1}{k^2}$~~

~~$s = 1 \quad \Delta_1 \simeq \frac{\eta_{\mu\nu}}{k^2}$~~

$s = 2 \quad \Delta_2 \simeq \frac{\eta_{\mu\nu}\eta_{\alpha\beta}}{k^2}$

Teorema 1: Feynman spin 2 massless particle

$$m_s = 0$$

$$s = 2$$

PROPAGADOR

$T_{\mu\nu}$ — **CONTENIDO DE MATERIA** — $\dfrac{\eta_{\mu\nu}\eta_{\alpha\beta}}{k^2}$ — $T_{\alpha\beta}$ — **CONTENIDO DE MATERIA**

Contando Grados de libertad → $G_{\mu\nu}$

Simétrico
10 d.o.f.

Teorema 1: Feynman spin 2 massless particle

$m_s = 0$

$s = 2$

PROPAGADOR

$T_{\mu\nu}$

$T_{\alpha\beta}$

CONTENIDO DE MATERIA

$$\frac{\eta_{\mu\nu}\eta_{\alpha\beta}}{k^2}$$

CONTENIDO DE MATERIA

$m_s = 0$, ***2 polarizaciones***

Contando Grados de libertad →

$G_{\mu\nu}$

Simétrico

10 d.o.f.

Teorema 1: Feynman spin 2 massless particle

$$m_s = 0$$

$$s = 2$$

PROPAGADOR

$T_{\mu\nu}$ $\qquad$ $T_{\alpha\beta}$

CONTENIDO DE MATERIA $\qquad \dfrac{\eta_{\mu\nu}\eta_{\alpha\beta}}{k^2}$ $\qquad$ ***CONTENIDO DE MATERIA***

$m_s = 0$***, 2 polarizaciones***

Contando Grados de libertad ⇒

$G_{\mu\nu}$

Simétrico
10 d.o.f.

$\nabla_\mu G^{\mu\nu} = 0$***, 4 d.o.f.***

Teorema 1: Feynman spin 2 massless particle

$$m_s = 0$$

$$s = 2$$

PROPAGADOR

$T_{\mu\nu}$

$T_{\alpha\beta}$

CONTENIDO DE MATERIA

$$\frac{\eta_{\mu\nu}\eta_{\alpha\beta}}{k^2}$$

CONTENIDO DE MATERIA

Contando Grados de libertad

$G_{\mu\nu}$

Simétrico
10 d.o.f.

$m_s = 0$, ***2 polarizaciones***

$\nabla_\mu G^{\mu\nu} = 0$, ***4 d.o.f.***

10 - 2 - 4 = 4 d.o.f restantes

Teorema 1: Feynman spin 2 massless particle

$$m_s = 0$$

$$s = 2$$

PROPAGADOR

$T_{\mu\nu}$ — **_CONTENIDO DE MATERIA_**

$$\frac{\eta_{\mu\nu}\eta_{\alpha\beta}}{k^2}$$

$T_{\alpha\beta}$ — **_CONTENIDO DE MATERIA_**

Contando Grados de libertad →

$G_{\mu\nu}$

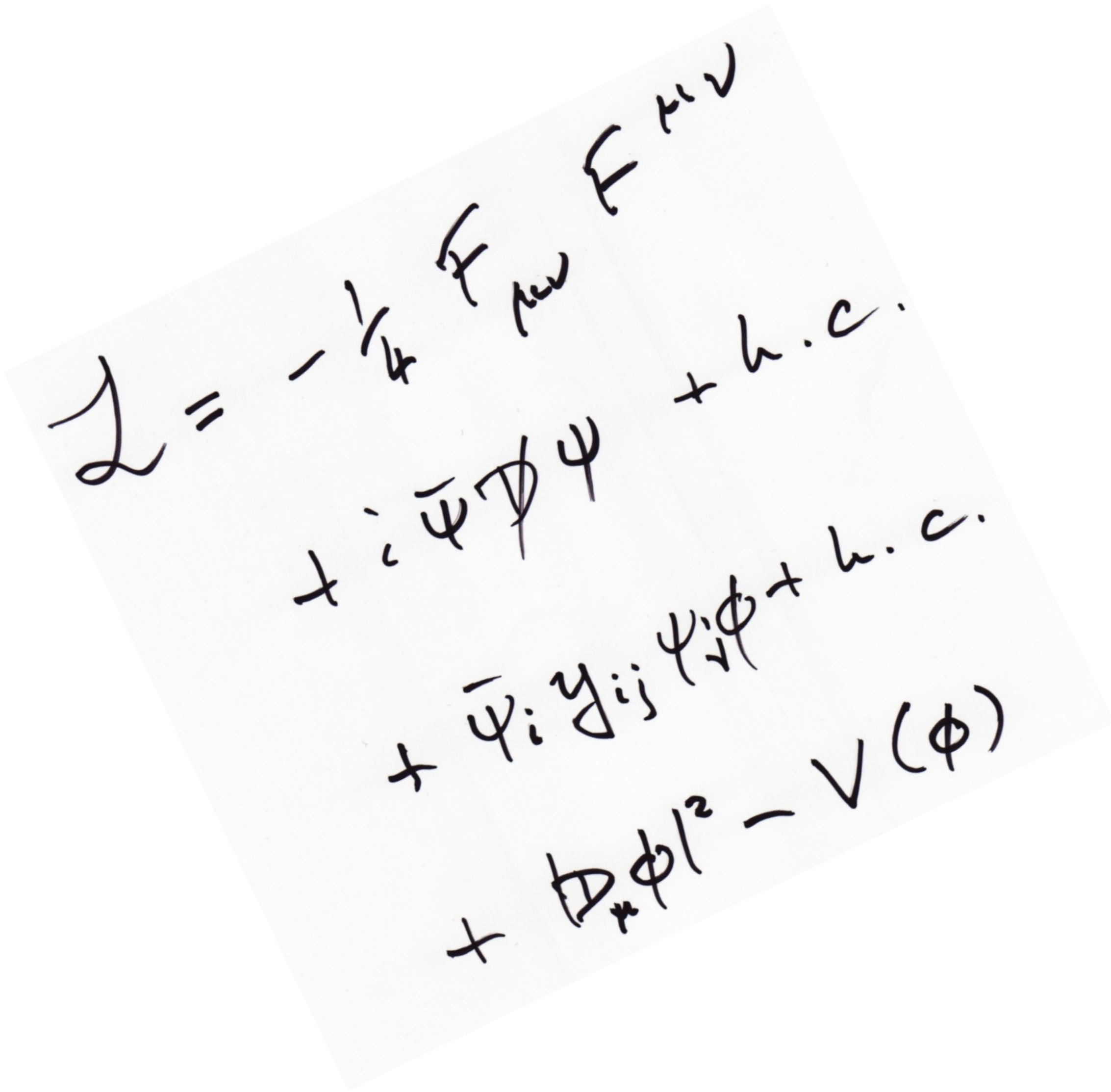
Simétrico 10 d.o.f.

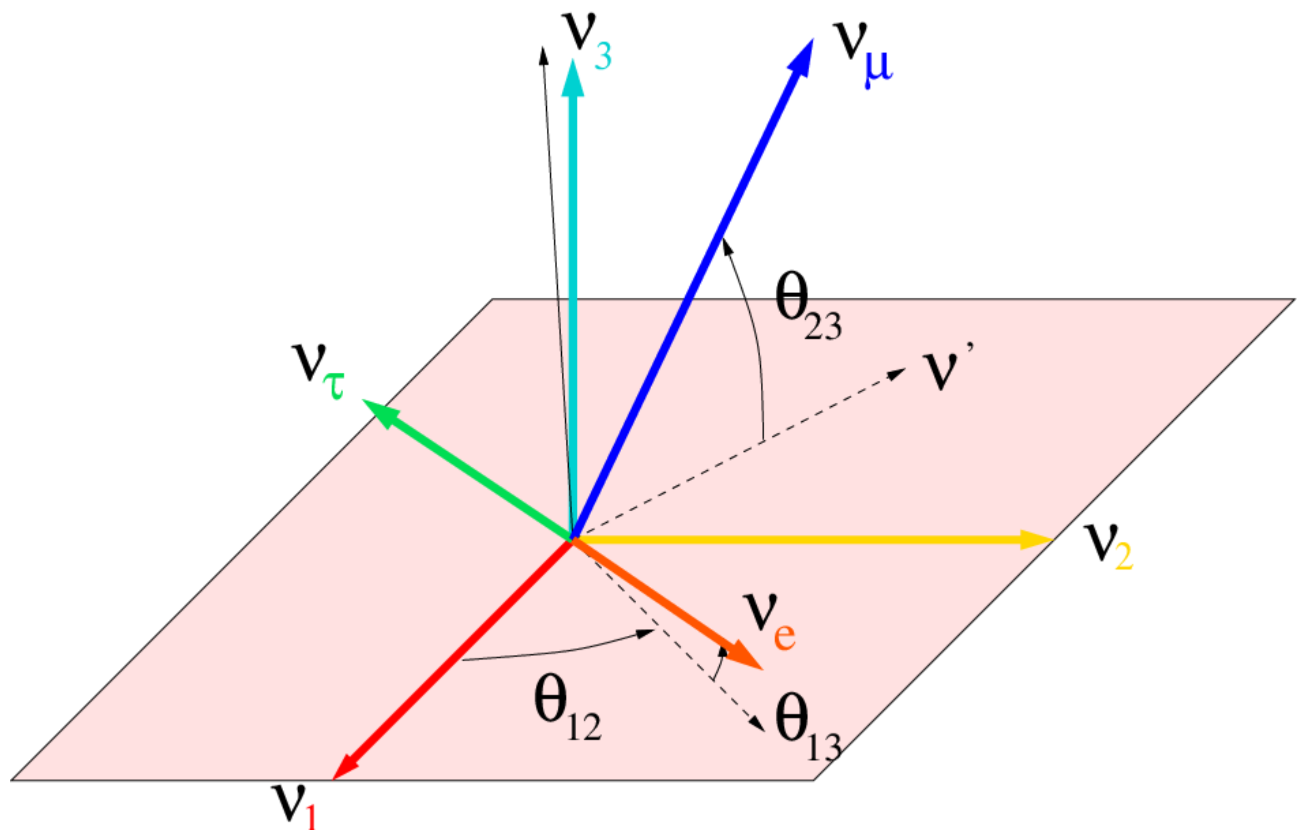
$m_s = 0$, ***2 polarizaciones***

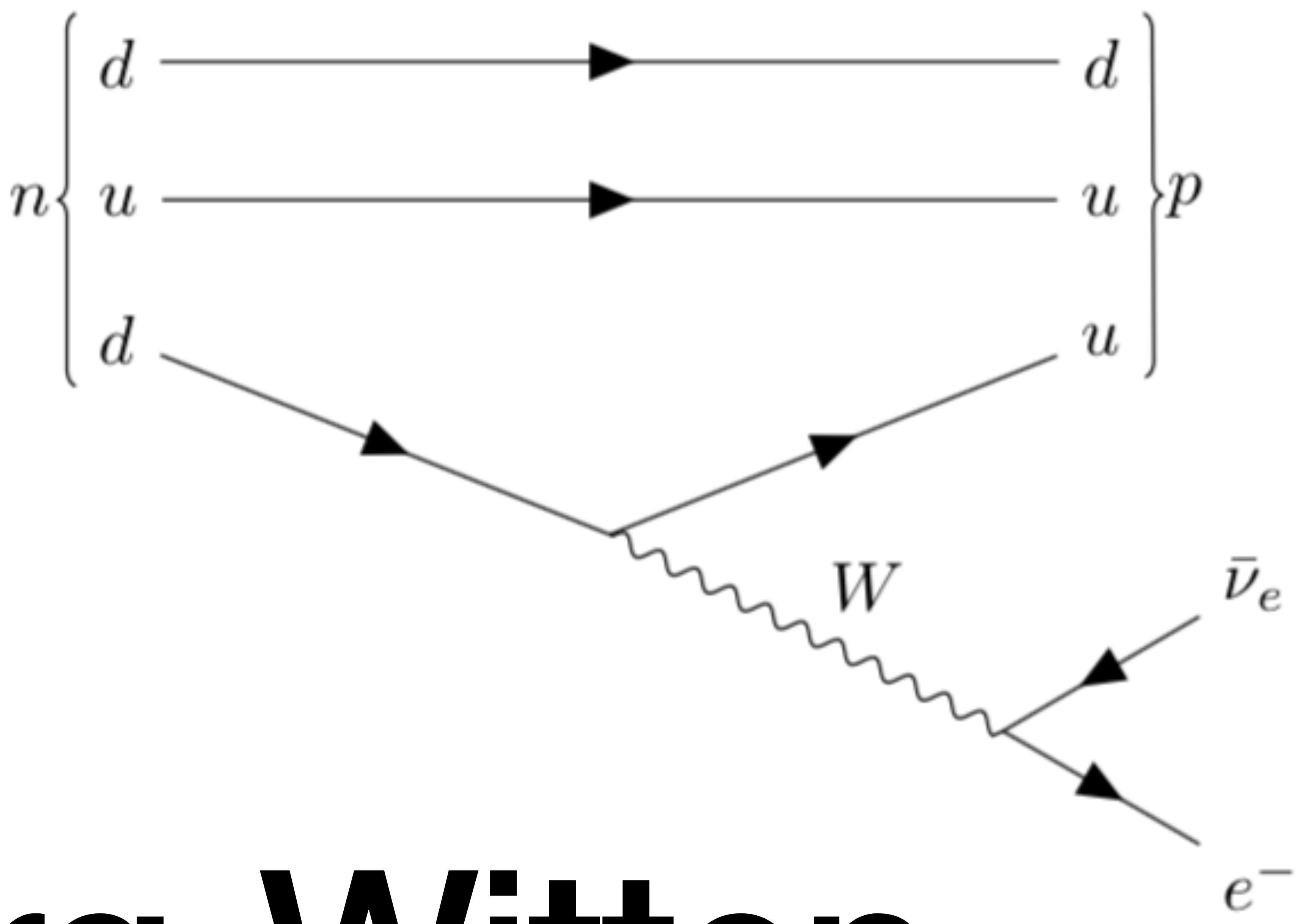
$\nabla_\mu G^{\mu\nu} = 0$, ***4 d.o.f.***

10 - 2 - 4 = 4 d.o.f restantes

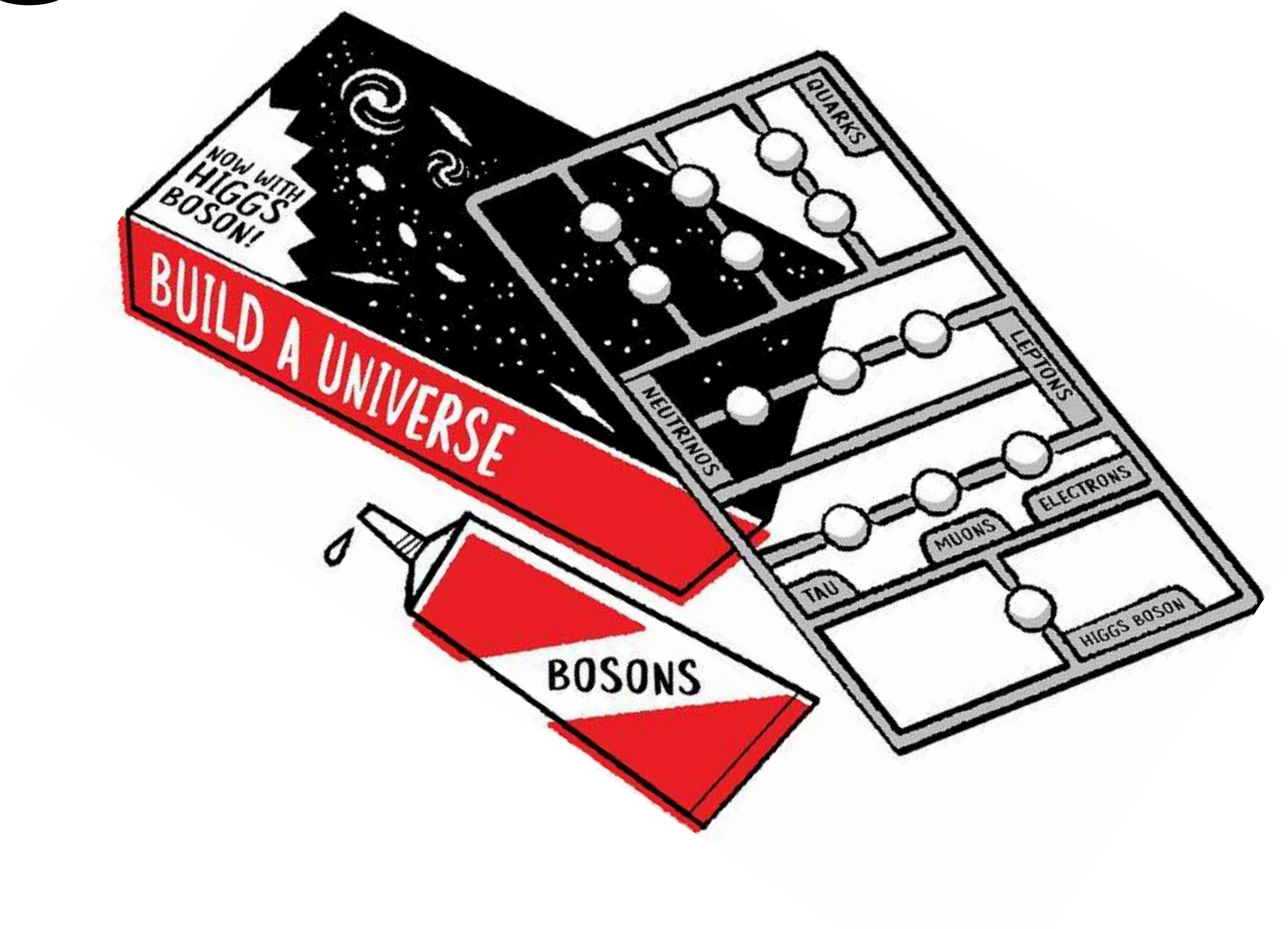
→ DIFEOMORFISMOS!



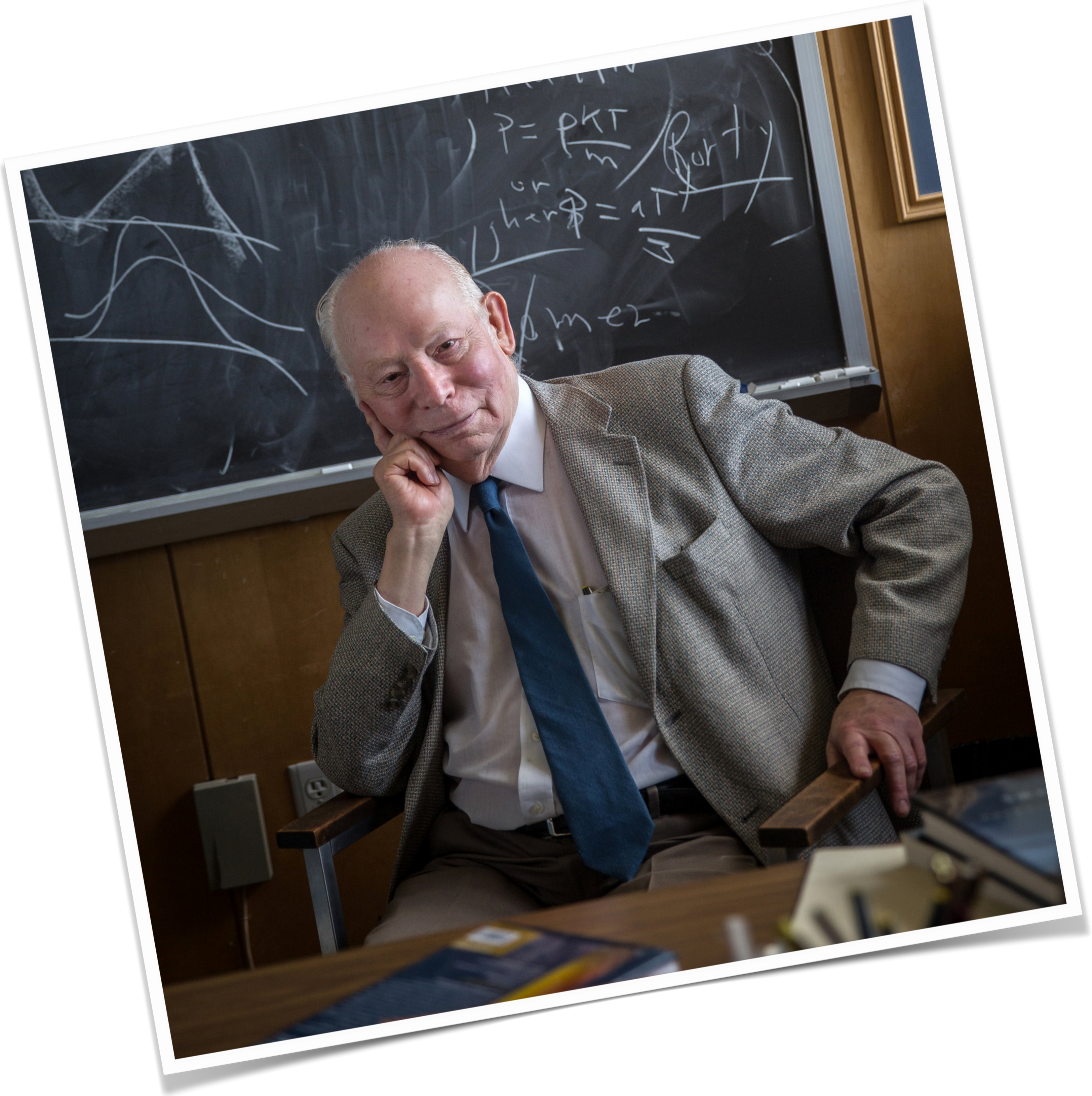




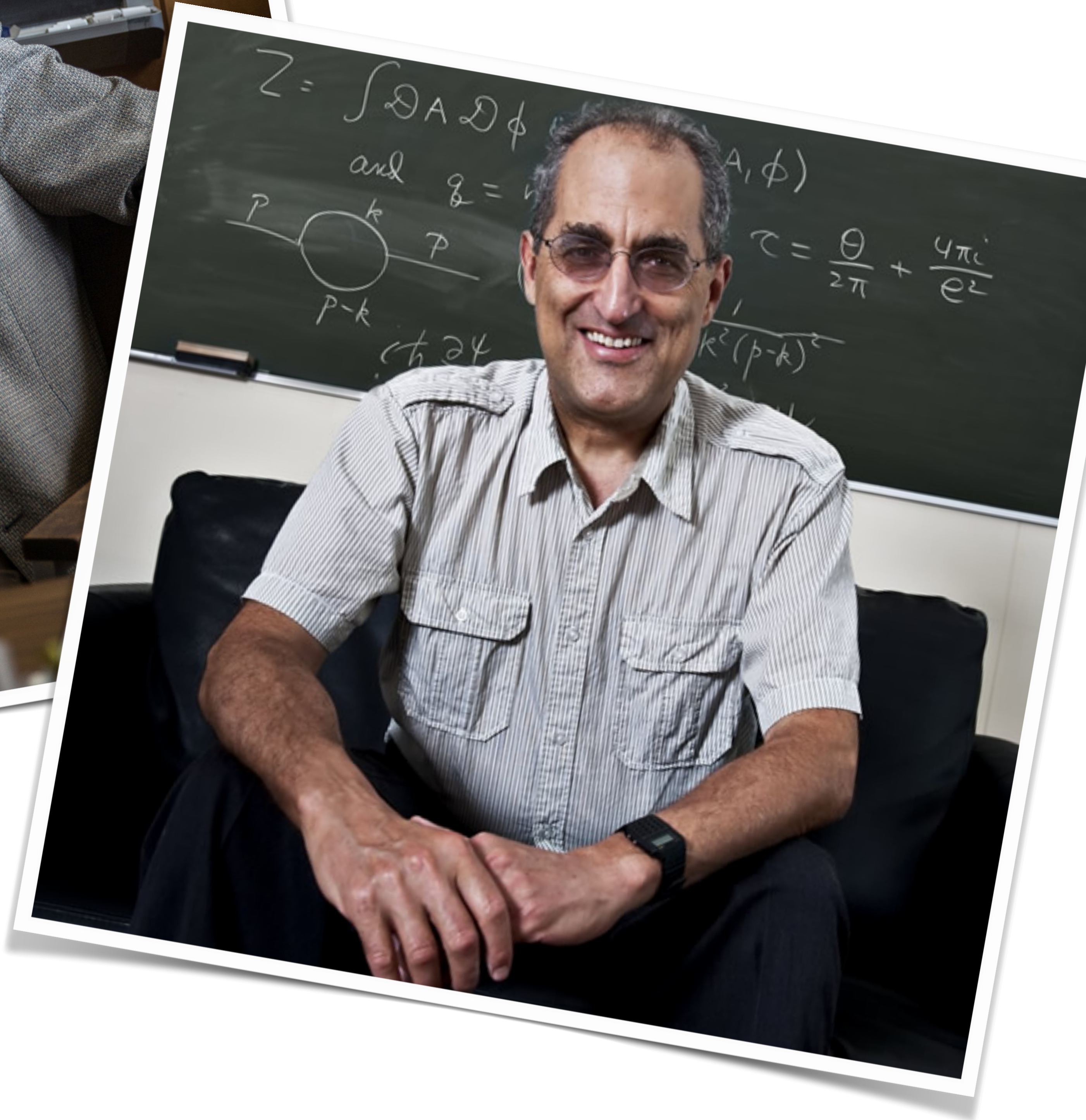
Teorema 2: Weinberg-Witten



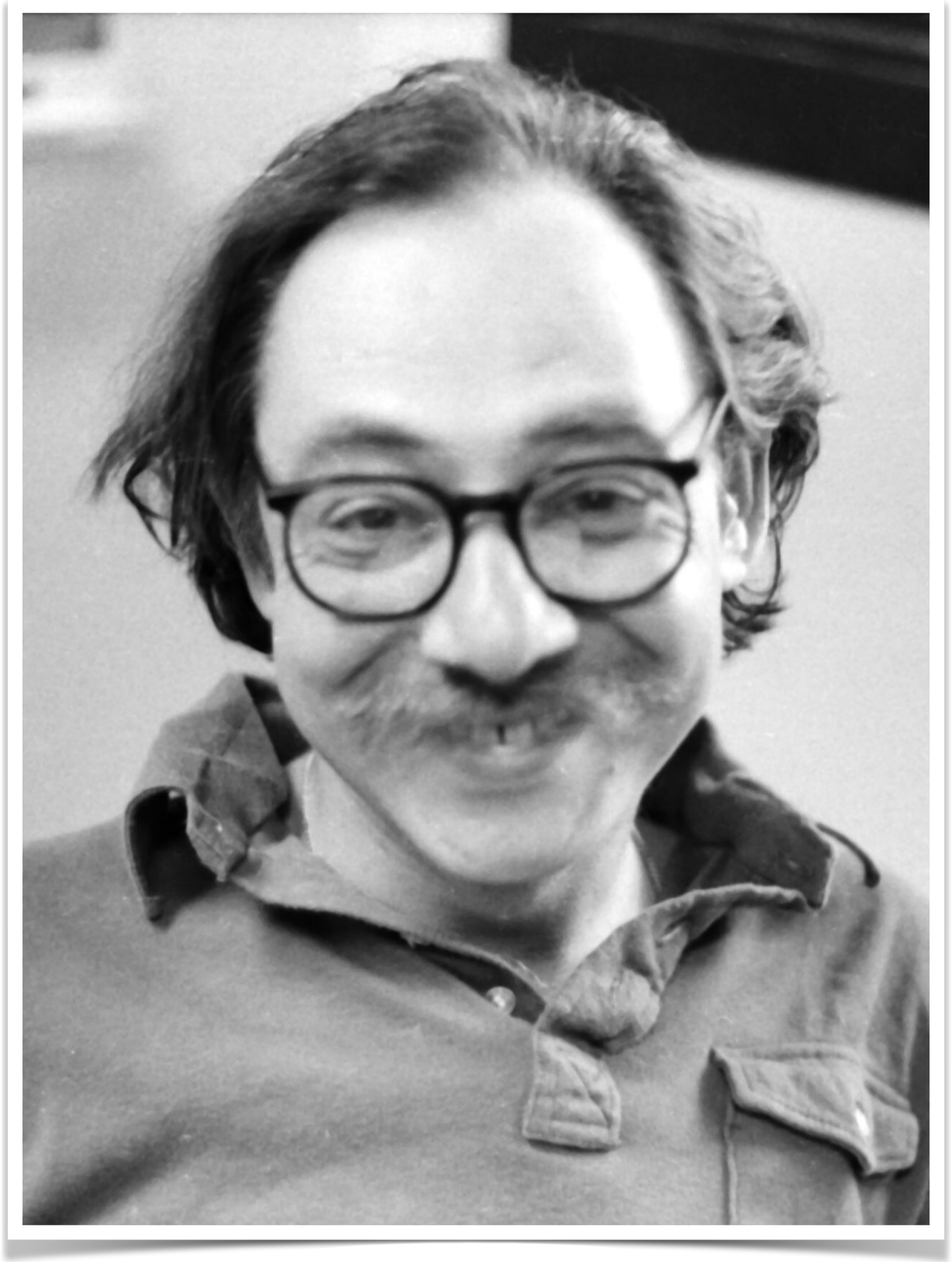
Teorema 2: Weinberg-Witten



Teorema 2: Weinberg-Witten



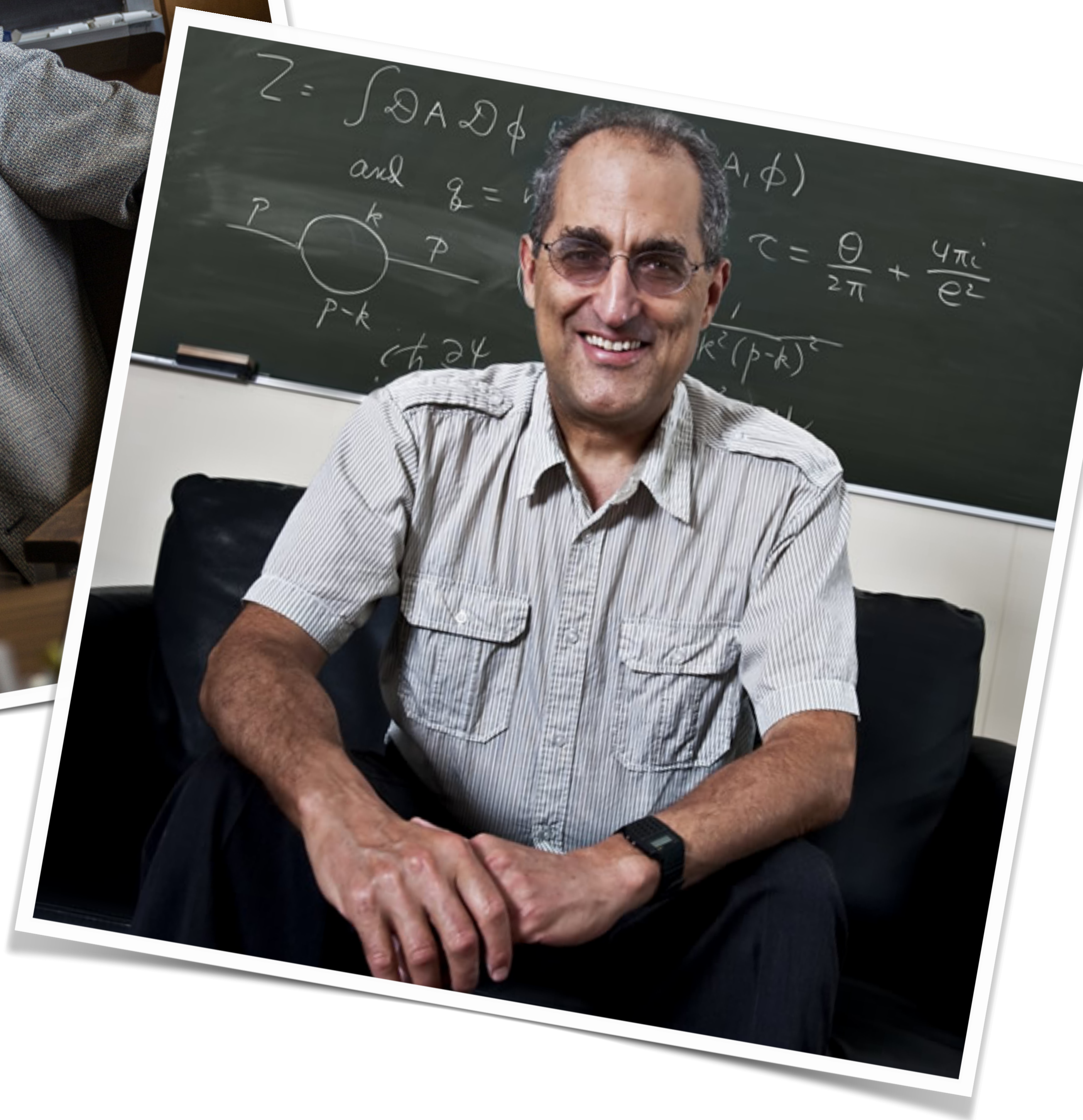
Teorema 2: Weinberg-Witten



S. Coleman

Teorema 2: Weinberg-Witten

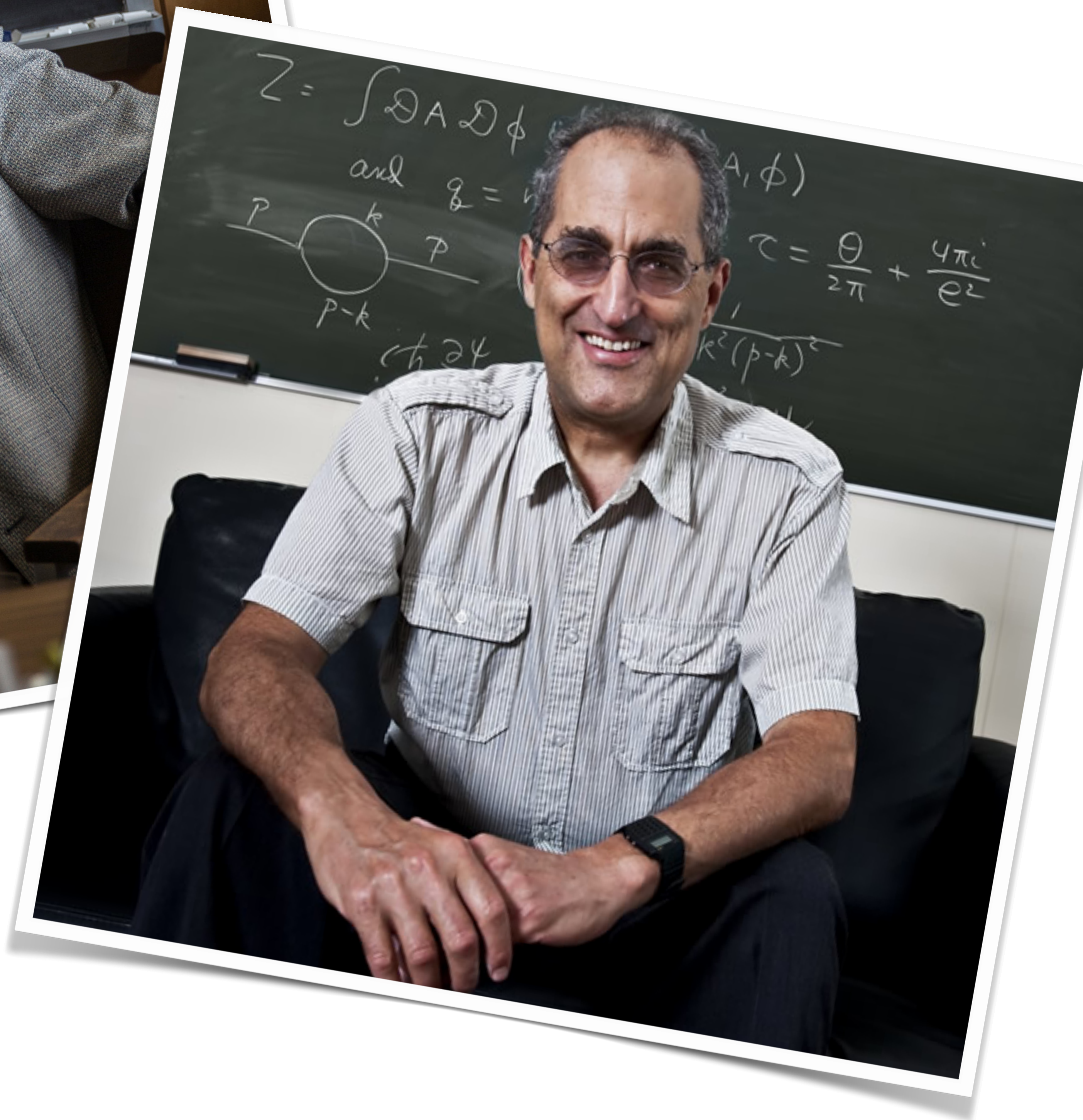
Sean $|p, \pm j\rangle$ y $|p', \pm j\rangle$ dos estados de una partícula sin masa, de espín j.



Teorema 2: Weinberg-Witten

Sean $|p, \pm j\rangle$ **y** $|p', \pm j\rangle$ dos estados de una partícula sin masa, de espín j. Sean

$$\langle p', \pm j | \, j^{\mu} \, | p, \pm j\rangle \text{ y } \langle p', \pm j | \, T^{\mu\nu} \, | p, \pm j\rangle$$



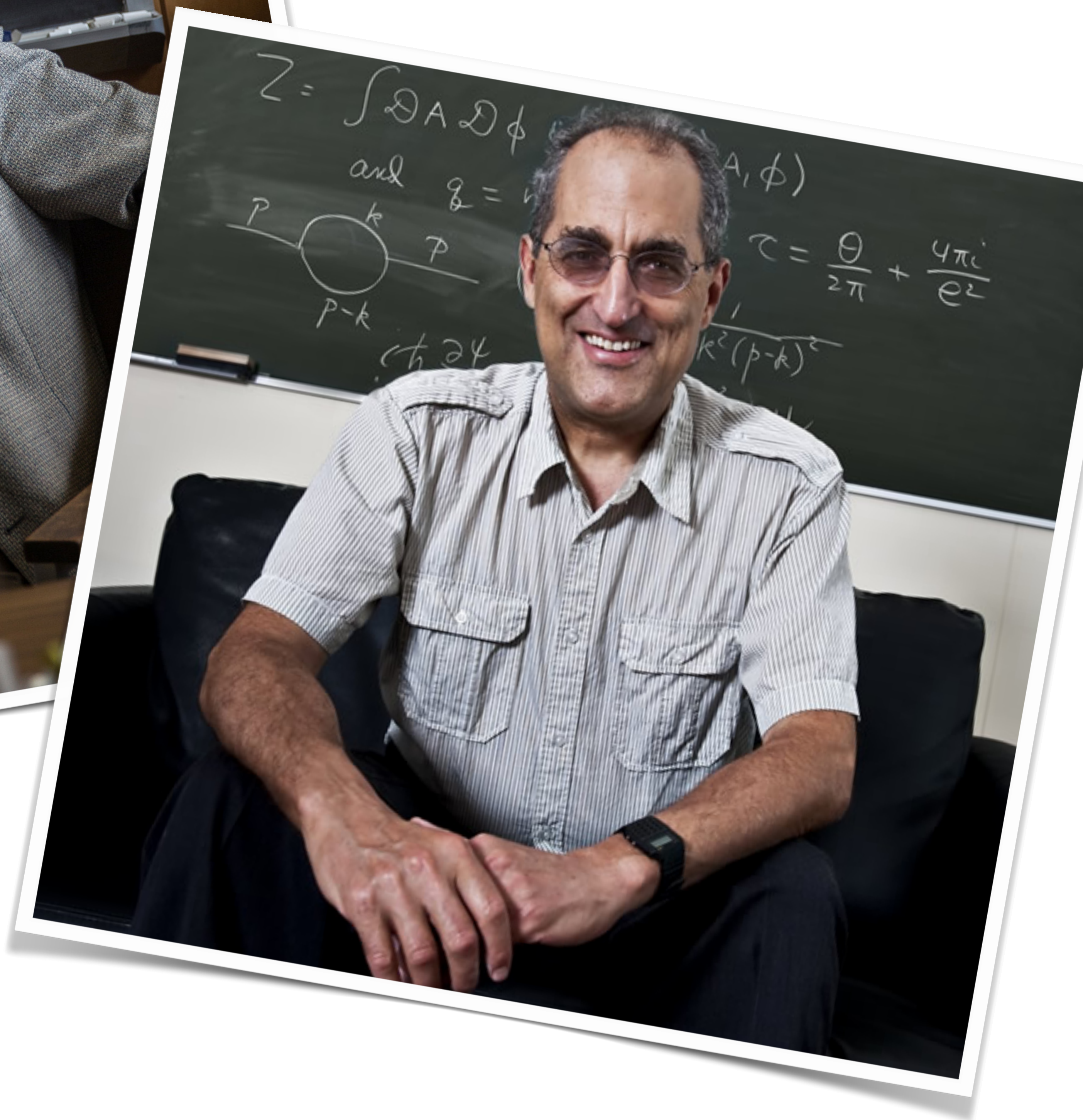
Teorema 2: Weinberg-Witten

Sean $|p, \pm j\rangle$ **y** $|p', \pm j\rangle$ dos estados de una partícula sin masa, de espín j. Sean

$$\langle p', \pm j | \, j^{\mu} \, | p, \pm j \rangle \quad \text{y} \quad \langle p', \pm j | \, T^{\mu\nu} \, | p, \pm j \rangle$$

Cumpliéndose

$$\partial_{\mu} \langle j^{\mu} \rangle = 0 \quad \text{y} \quad \partial_{\mu} \langle T^{\mu\nu} \rangle = 0$$



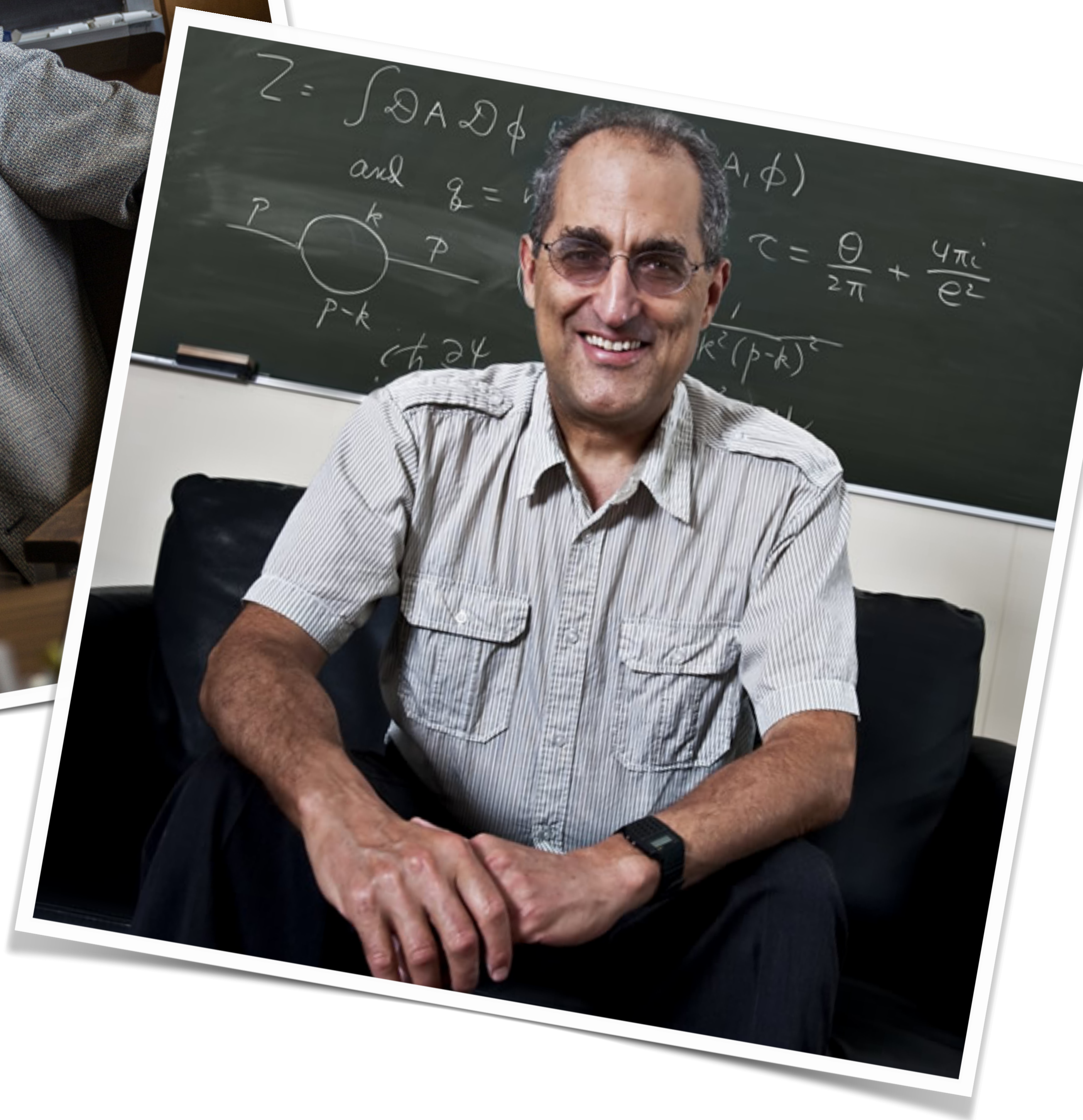
Teorema 2: Weinberg-Witten

Caso j>1/2

Si asumimos que las partículas sin masa tienen una carga conservada no nula

$$Q = \int d^3x j^0$$

Tal que $Q\,|\,p\rangle = q\,|\,p\rangle$.



Teorema 2: Weinberg-Witten

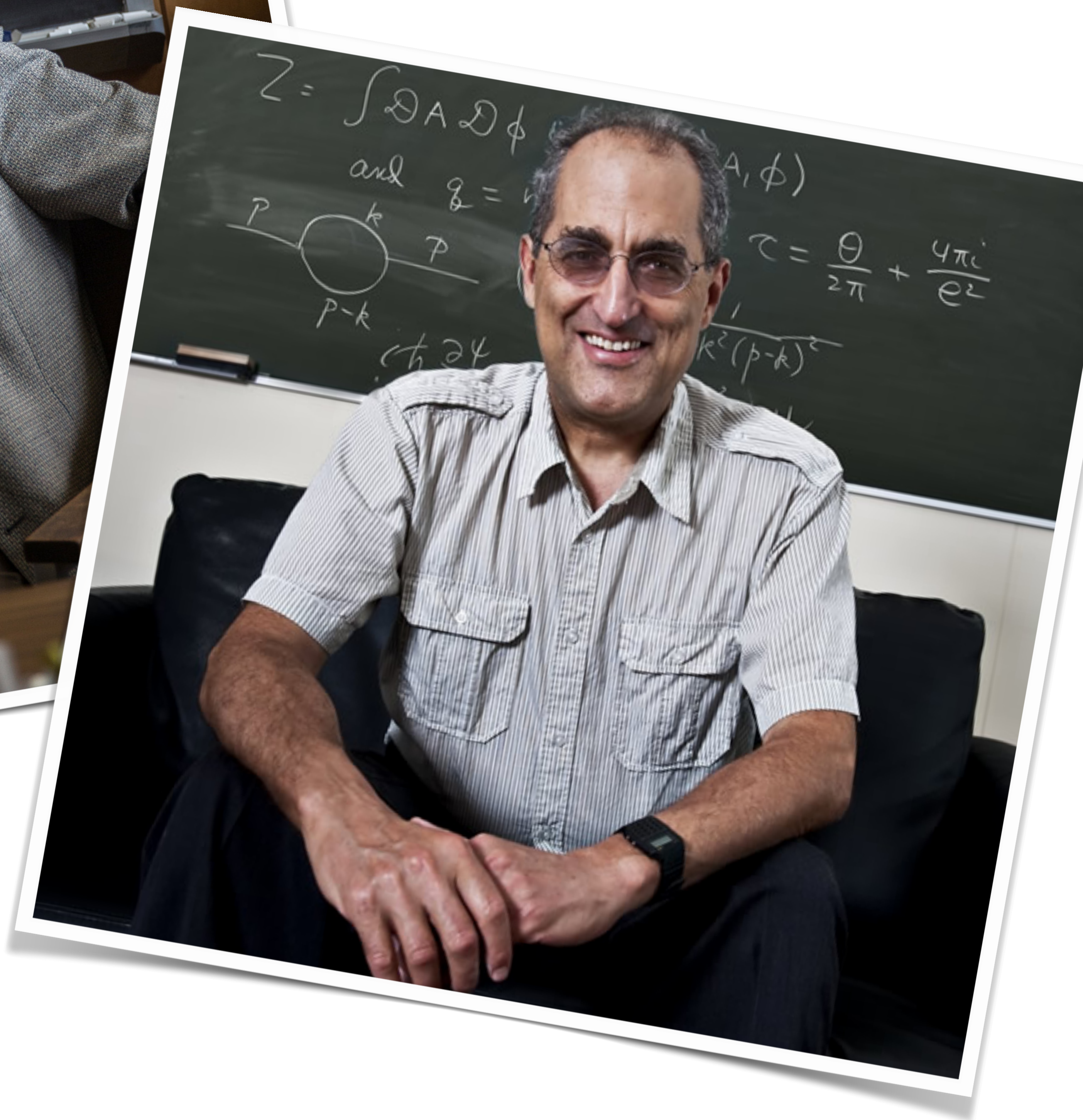
Caso j>1/2

Si asumimos que las partículas sin masa tienen una carga conservada no nula

$$Q = \int d^3x j^0$$

Tal que $Q\,|p\rangle = q\,|p\rangle$. Si $q \neq 0$

$$\langle p' \big|\, Q\,|p\rangle = q\delta^3\left(\boldsymbol{p}' - \boldsymbol{p}\right)$$



Teorema 2: Weinberg-Witten

Caso j>1/2

Tambien podemos calcular

$$\langle p' | Q | p \rangle = \int d^3x \langle p' | j^0(t, \boldsymbol{x}) | p \rangle = \int d^3x \langle p' | e^{i\boldsymbol{P}\cdot\boldsymbol{x}} j^0(t,0) e^{-i\boldsymbol{P}\cdot\boldsymbol{x}} | p \rangle$$

$$= \int d^3x e^{i(\boldsymbol{p}' - \boldsymbol{p})\cdot\boldsymbol{x}} \langle p' | j^0(t,0) | p \rangle = (2\pi)^3 \delta^3 \left(\boldsymbol{p}' - \boldsymbol{p}\right) \langle p' | j^0(t,0) | p \rangle$$

Teorema 2: Weinberg-Witten

Caso j>1/2

Tambien podemos calcular

$$\langle p' | \, Q \, | p \rangle = \int d^3x \, \langle p' | \, j^0(t,\boldsymbol{x}) \, | p \rangle = \int d^3x \, \langle p' | \, e^{i\boldsymbol{P}\cdot\boldsymbol{x}} j^0(t,0) e^{-i\boldsymbol{P}\cdot\boldsymbol{x}} \, | p \rangle$$

$$= \int d^3x e^{i(\boldsymbol{p}'-\boldsymbol{p})\cdot\boldsymbol{x}} \langle p' | \, j^0(t,0) \, | p \rangle = (2\pi)^3 \delta^3 \left(\boldsymbol{p}' - \boldsymbol{p}\right) \langle p' | \, j^0(t,0) \, | p \rangle$$

Comparando estos resultados

Teorema 2: Weinberg-Witten

Caso j>1/2

Tambien podemos calcular

$$\langle p' | Q | p \rangle = \int d^3x \langle p' | j^0(t, \boldsymbol{x}) | p \rangle = \int d^3x \langle p' | e^{i\boldsymbol{P}\cdot\boldsymbol{x}} j^0(t,0) e^{-i\boldsymbol{P}\cdot\boldsymbol{x}} | p \rangle$$

$$= \int d^3x e^{i(\boldsymbol{p}' - \boldsymbol{p})\cdot\boldsymbol{x}} \langle p' | j^0(t,0) | p \rangle = (2\pi)^3 \delta^3 \left(\boldsymbol{p}' - \boldsymbol{p}\right) \langle p' | j^0(t,0) | p \rangle$$

Comparando estos resultados

$$\lim_{p' \to p} \langle p' | j^0(t,0) | p \rangle = \frac{q}{(2\pi)^3}$$

Teorema 2: Weinberg-Witten

Caso j>1/2

Tambien podemos calcular

$$\langle p'|\, Q\,|p\rangle = \int d^3x\, \langle p'|\, j^0(t,\boldsymbol{x})\,|p\rangle = \int d^3x\, \langle p'|\, e^{i\boldsymbol{P}\cdot\boldsymbol{x}} j^0(t,0) e^{-i\boldsymbol{P}\cdot\boldsymbol{x}}\,|p\rangle$$

$$= \int d^3x e^{i(\boldsymbol{p}'-\boldsymbol{p})\cdot\boldsymbol{x}} \langle p'|\, j^0(t,0)\,|p\rangle = (2\pi)^3 \delta^3\left(\boldsymbol{p}'-\boldsymbol{p}\right) \langle p'|\, j^0(t,0)\,|p\rangle$$

Comparando estos resultados

$$\lim_{p'\to p} \langle p'|\, j^0(t,0)\,|p\rangle = \frac{q}{(2\pi)^3} \quad \Longrightarrow \quad \lim_{p'\to p} \langle p'|\, j^\mu(t,0)\,|p\rangle = \frac{q p^\mu}{E(2\pi)^3} \neq 0$$

Covarianza de Lorentz

Teorema 2: Weinberg-Witten

Caso j>1/2

Tambien podemos calcular

$$\langle p' | \, Q \, | p \rangle = \int d^3x \, \langle p' | \, j^0(t, \boldsymbol{x}) \, | p \rangle = \int d^3x \, \langle p' | \, e^{i\boldsymbol{P}\cdot\boldsymbol{x}} j^0(t,0) e^{-i\boldsymbol{P}\cdot\boldsymbol{x}} \, | p \rangle$$

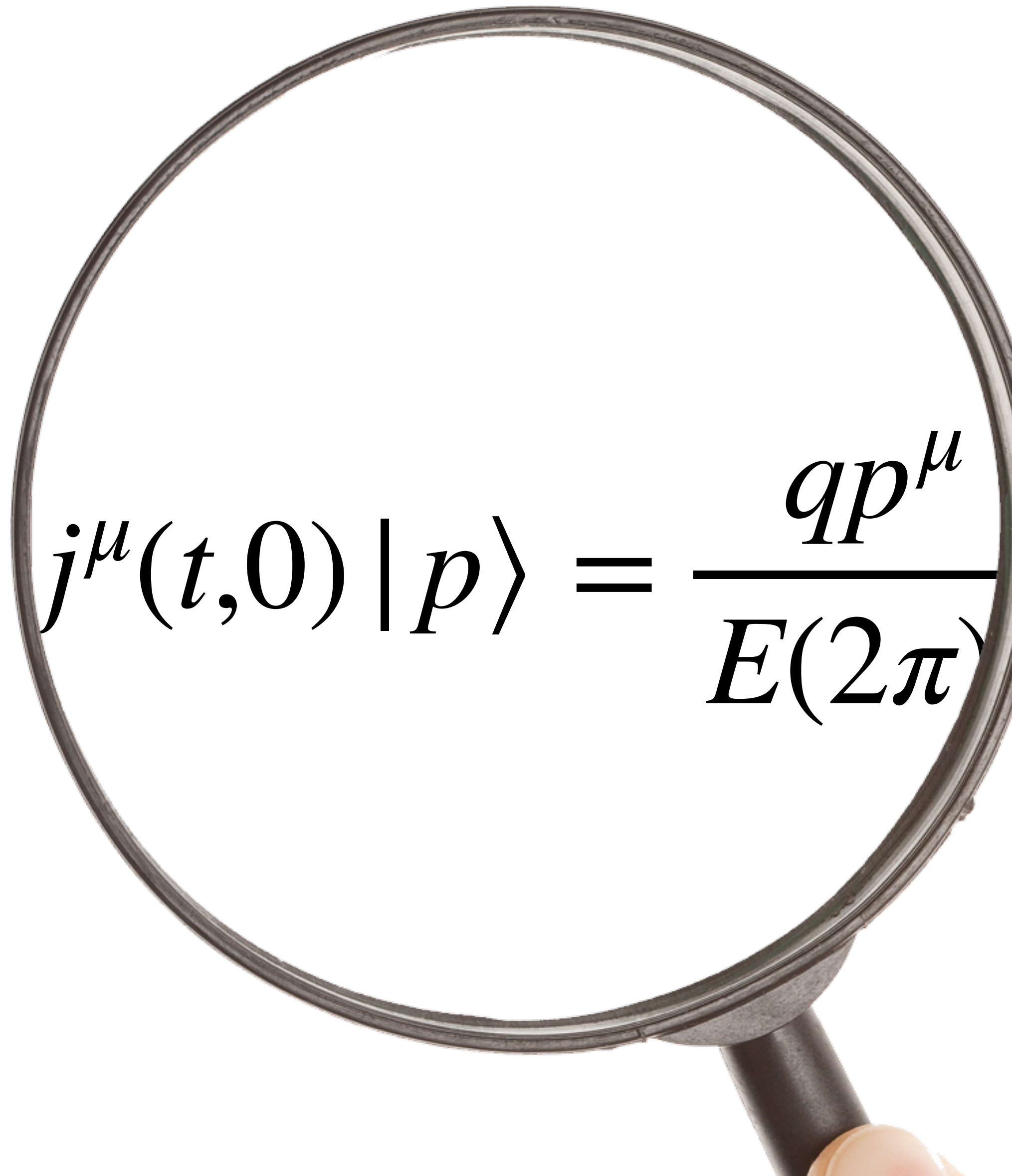
$$= \int d^3x e^{i(\boldsymbol{p}' - \boldsymbol{p})\cdot\boldsymbol{x}} \langle p' | \, j^0(t,0) \, | p \rangle = (2\pi)^3 \delta^3 \left(\boldsymbol{p}' - \boldsymbol{p}\right) \langle p' | \, j^0(t,0) \, | p \rangle$$

Comparando estos resultados

$$\lim_{p' \to p} \langle p' | \, j^0(t,0) \, | p \rangle = \frac{q}{(2\pi)^3}$$

Covarianza de Lorentz

$$\lim_{p' \to p} \langle p' | \, j^\mu(t,0) \, | p \rangle = \frac{q p^\mu}{E(2\pi)^3} \neq 0$$



Teorema 2: Weinberg-Witten

Caso j>1/2

Tambien podemos calcular

$$\langle p' | Q | p \rangle = \int d^3x \langle p' | j^0(t, \boldsymbol{x}) | p \rangle = \int d^3x \langle p' | e^{i\boldsymbol{P}\cdot\boldsymbol{x}} j^0(t,0) e^{-i\boldsymbol{P}\cdot\boldsymbol{x}} | p \rangle$$

$$= \int d^3x e^{i(\boldsymbol{p}'-\boldsymbol{p})\cdot\boldsymbol{x}} \langle p' | j^0(t,0) | p \rangle = (2\pi)^3 \delta^3 \left(\boldsymbol{p}' - \boldsymbol{p}\right) \langle p' | j^0(t,0) | p \rangle$$

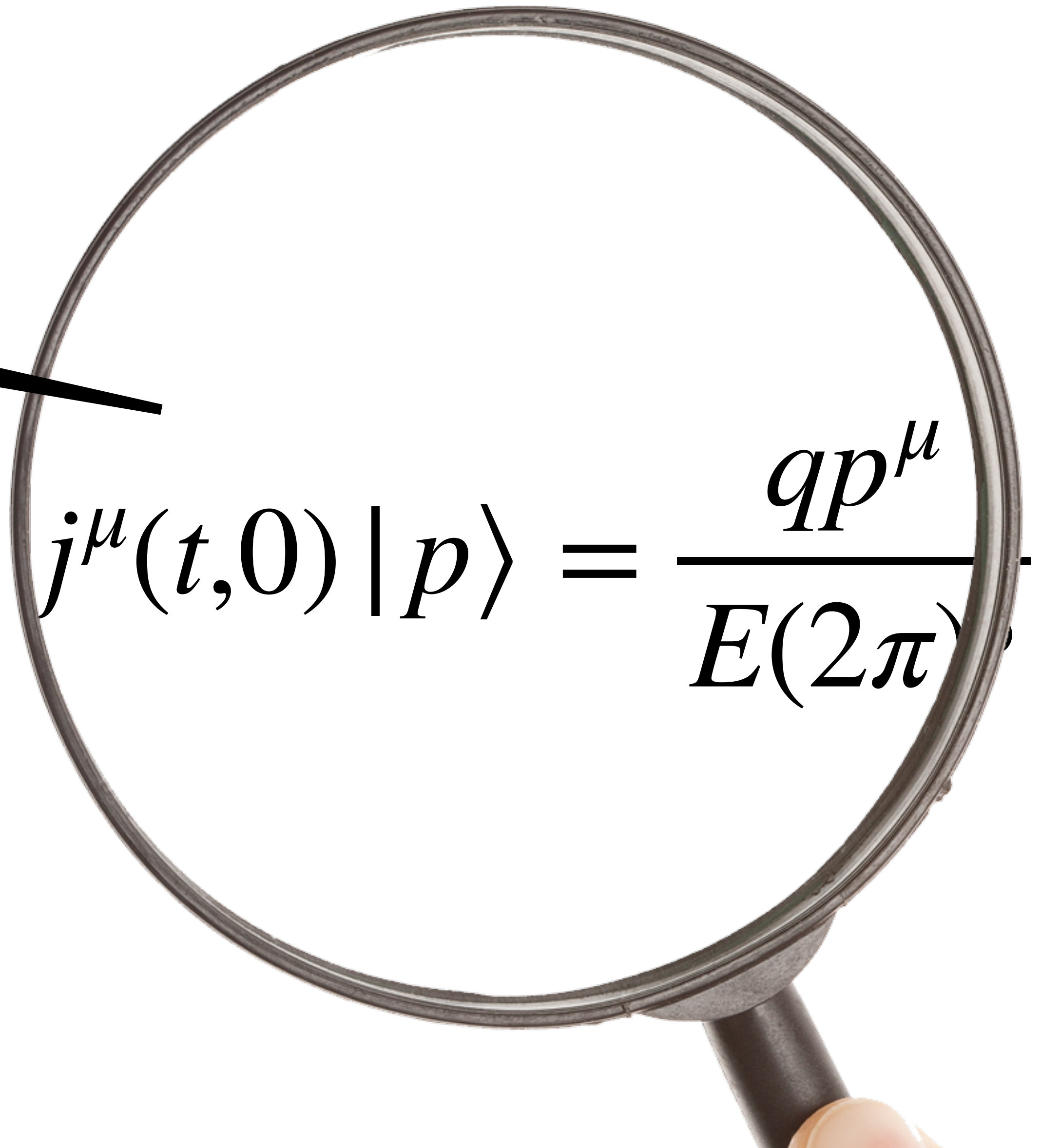
Comparando estos resultados

Implica conservación de la corriente

$$\lim_{p'\to p} \langle p' | j^0(t,0) | p \rangle = \frac{q}{(2\pi)^3}$$

Covarianza de Lorentz

$$\lim_{p'\to p} \langle p' | j^\mu(t,0) | p \rangle = \frac{q p^\mu}{E(2\pi)^3} \neq 0$$



Teorema 2: Weinberg-Witten

Caso j>1/2

Para *light-like* partículas

Teorema 2: Weinberg-Witten

Caso j>1/2

Para *light-like* partículas

$$\left(p' + p\right)^2 = 2\left(p' \cdot p\right) = 2\left(\left|\boldsymbol{p}'\right| |\boldsymbol{p}| - \boldsymbol{p}' \cdot \boldsymbol{p}\right) = 2\left|\boldsymbol{p}'\right| |\boldsymbol{p}| (1 - \cos\theta) \geq 0$$

Teorema 2: Weinberg-Witten

Caso j>1/2

Para *light-like* partículas

$$(p' + p)^2 = 2\,(p' \cdot p) = 2\left(\left|\boldsymbol{p}'\right|\,|\boldsymbol{p}\,| - \boldsymbol{p}' \cdot \boldsymbol{p}\right) = 2\left|\boldsymbol{p}'\right|\,|\boldsymbol{p}\,|(1 - \cos\theta) \geq 0$$

Si $\theta \neq 0$, entonces $(p' + p)$ es *time-like*

Teorema 2: Weinberg-Witten

Caso j>1/2

Para *light-like* partículas

$$(p' + p)^2 = 2\,(p' \cdot p) = 2\left(\left|\boldsymbol{p}'\right|\,|\boldsymbol{p}\,| - \boldsymbol{p}' \cdot \boldsymbol{p}\right) = 2\left|\boldsymbol{p}'\right|\,|\boldsymbol{p}\,|(1 - \cos\theta) \geq 0$$

Si $\theta \neq 0$, entonces $(p' + p)$ es *time-like*. Por lo tanto, podemos escoger un S.R. donde las componentes espaciales sean nulas

Teorema 2: Weinberg-Witten

Caso j>1/2

Para *light-like* partículas

$$(p' + p)^2 = 2\,(p' \cdot p) = 2\left(\left|\boldsymbol{p}'\right|\,|\boldsymbol{p}\,| - \boldsymbol{p}' \cdot \boldsymbol{p}\right) = 2\,\left|\boldsymbol{p}'\right|\,|\boldsymbol{p}\,|(1 - \cos\theta) \geq 0$$

Si $\theta \neq 0$, entonces $(p' + p)$ es *time-like*. Por lo tanto, podemos escoger un S.R. donde las componentes espaciales sean nulas

$$p = (\,|\boldsymbol{p}\,|, \boldsymbol{p}); \quad p' = (\,|\boldsymbol{p}\,|, -\boldsymbol{p})$$

Teorema 2: Weinberg-Witten

Caso j>1/2

Para *light-like* partículas

$$\left(p' + p\right)^2 = 2\left(p' \cdot p\right) = 2\left(\left|\boldsymbol{p}'\right| |\boldsymbol{p}| - \boldsymbol{p}' \cdot \boldsymbol{p}\right) = 2\left|\boldsymbol{p}'\right| |\boldsymbol{p}| (1 - \cos\theta) \geq 0$$

Si $\theta \neq 0$, entonces $(p' + p)$ es *time-like*. Por lo tanto, podemos escoger un S.R. donde las componentes espaciales sean nulas

$$p = (|\boldsymbol{p}|, \boldsymbol{p}); \quad p' = (|\boldsymbol{p}|, -\boldsymbol{p})$$

Ambas partículas se propagan en direcciones contrarias con la misma energía.

Teorema 2: Weinberg-Witten

Caso j>1/2

En este S.R. consideramos la rotación de las partículas por un ángulo ϕ

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Donde $\Lambda(\phi)^{\mu}_{\nu}$ es la transformación de Lorentz correspondiente a una rotación por un ángulo ϕ.

Teorema 2: Weinberg-Witten

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Teorema 2: Weinberg-Witten

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Teorema 2: Weinberg-Witten

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Y concluimos también que los elementos de la matriz deben ser nulos para $j > 1/2$. En particular en el limite $p' \to p$

$$\lim_{p' \to p} \langle p' \Big| j^{\mu}(t,0)\,|\,p\rangle = 0 \qquad \text{para} \qquad j > 1/2$$

Teorema 2: Weinberg-Witten

Caso j>1/2

Esto nos lleva a una contradicción

$$\lim_{p'\to p} \langle p' \big| \, j^{\mu}(t,0) \, | \, p \rangle = \frac{qp^{\mu}}{E(2\pi)^3} \neq 0$$

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→ **Una partícula sin masa de spin $j > 1/2$, no puede llevar una carga inducida por un vector de corriente conservada.**

Teorema 2: Weinberg-Witten

Caso j>1

Por argumentos similares llegamos primero a

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$$\lim_{p' \to p} \langle p' \big| \, T^{\mu\nu}(t,0) \, | \, p \rangle = \frac{p^{\mu} p^{\nu}}{E(2\pi)^3} \neq 0$$

Teorema 2: Weinberg-Witten

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Teorema 2: Weinberg-Witten

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Por covarianza relativista

$$e^{\pm 2i\phi j} \langle p', \pm j \big| \, T^{\mu\nu}(t,0) \, | \, p, \pm j \rangle = \Lambda(\phi)^\mu_\rho \Lambda(\phi)^\nu_\sigma \langle p', \pm j \big| \, T^{\rho\sigma}(t,0) \, | \, p, \pm j \rangle$$

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Una partícula sin masa de spin $j > 1$, no puede llevar una carga inducida por un vector de corriente conservada.

Teorema 2: Weinberg-Witten

Evidentemente

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Teorema 2: Weinberg-Witten

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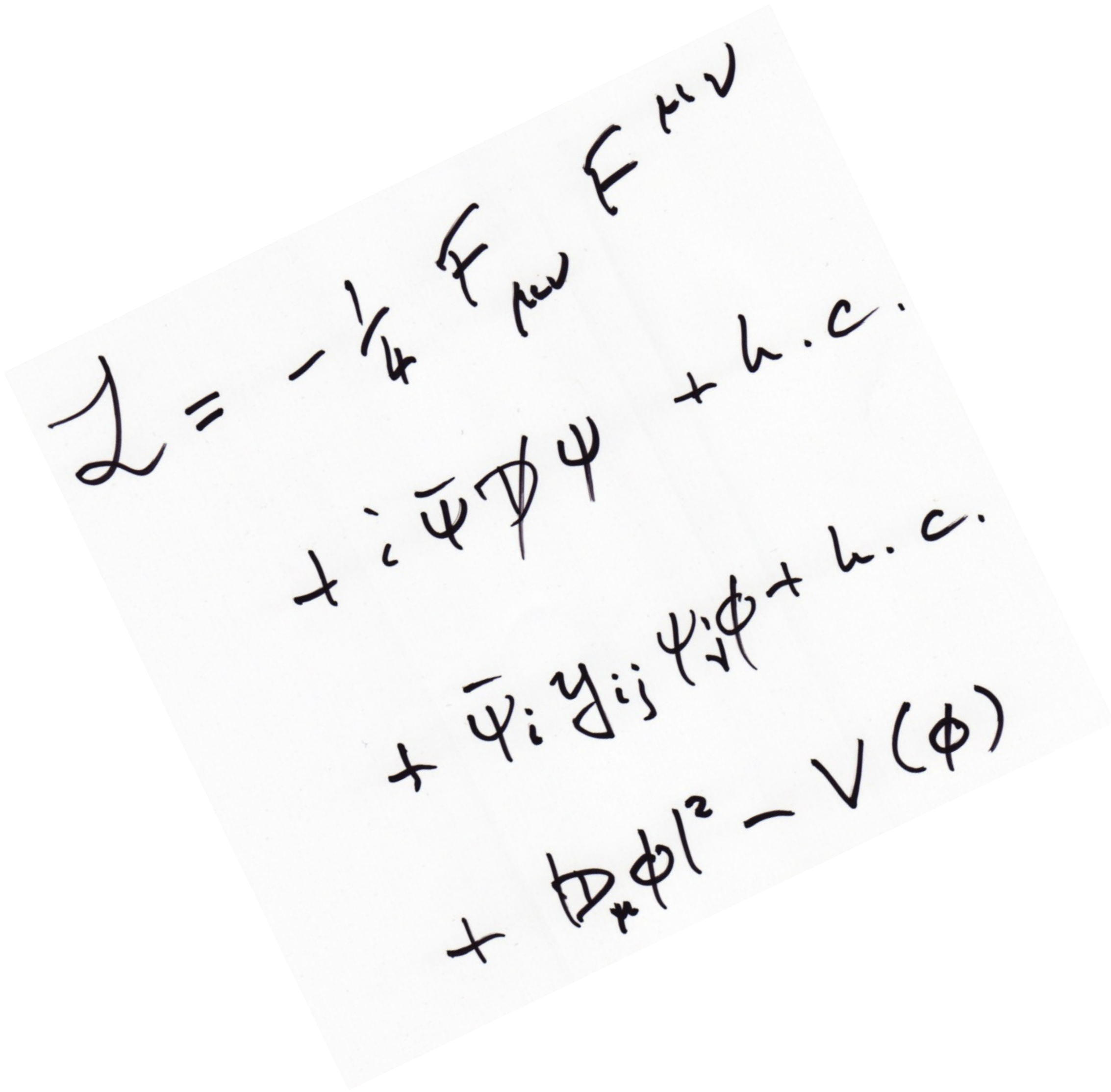
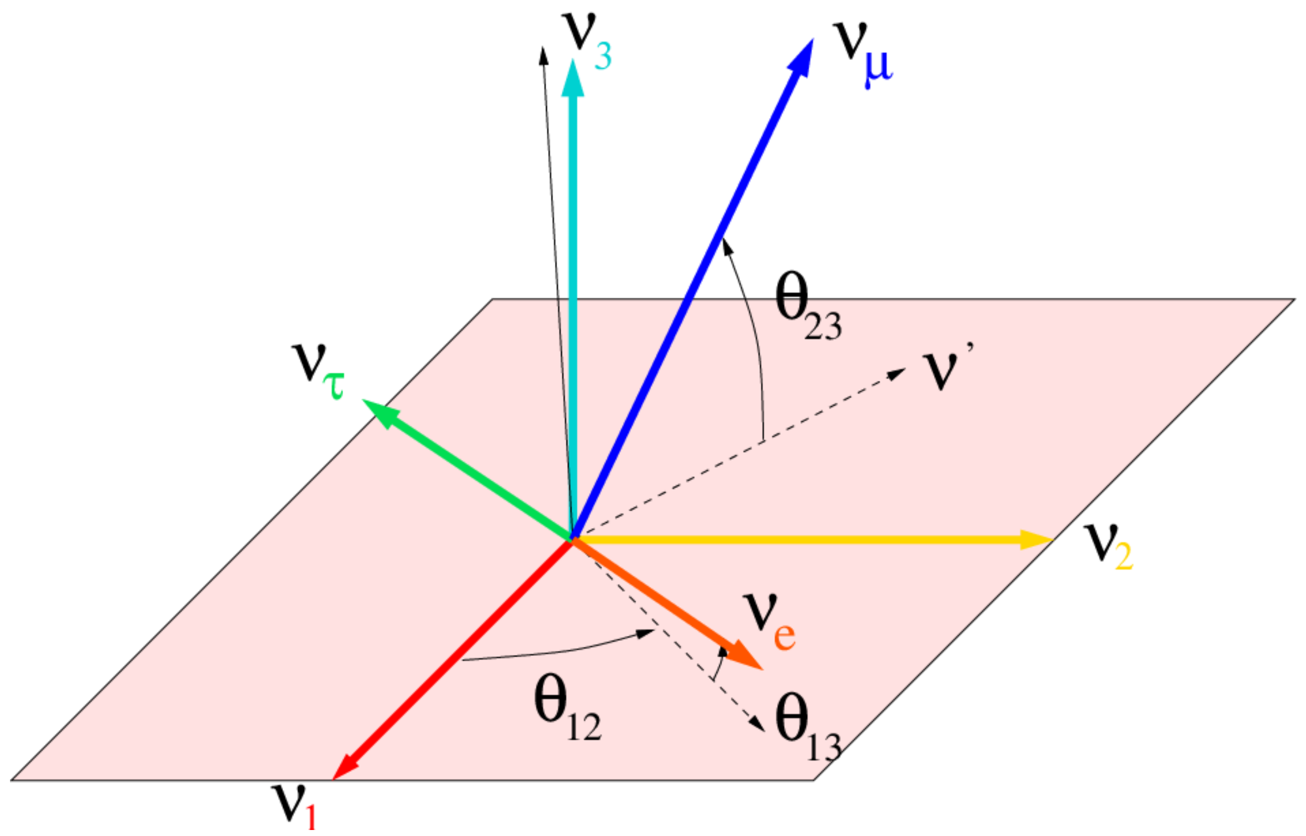
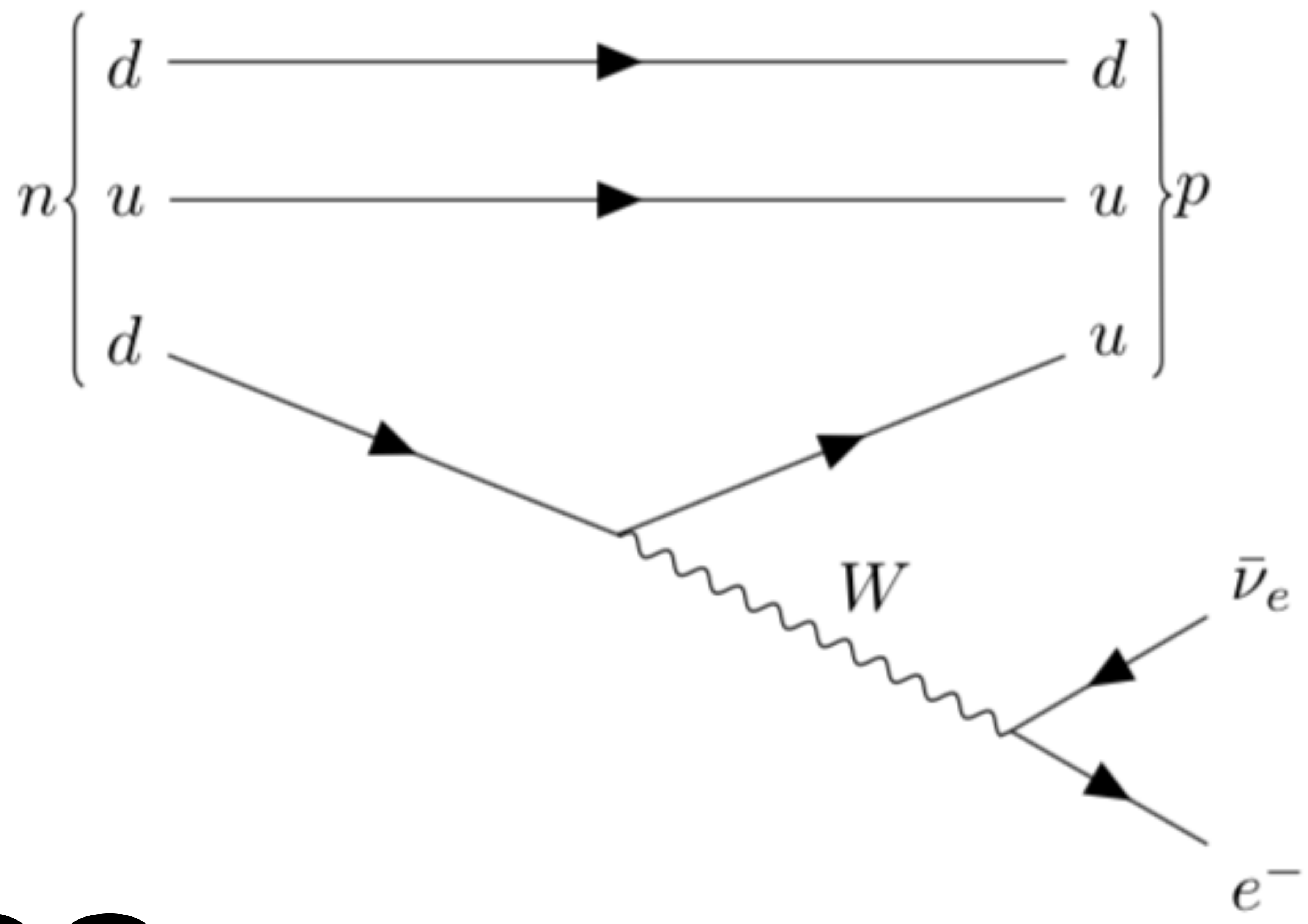
→ El teorema no se aplica a los fotones, ya que estos no llevan carga

→ Tampoco a $W^{\pm}$ ni al Z, pues estos son masivos

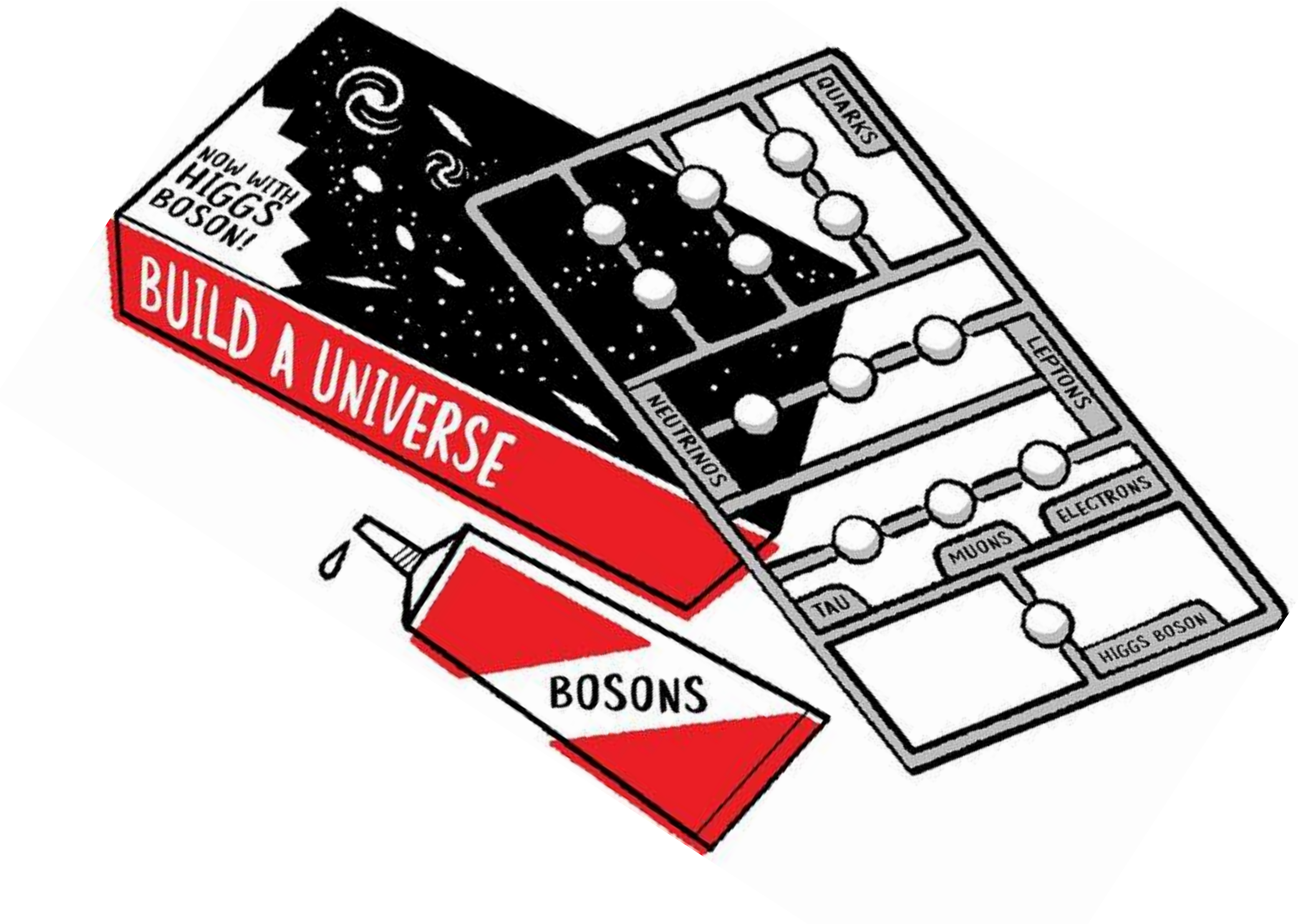
Porque son permitidos los gluones y los gravitones?







Conclusiones



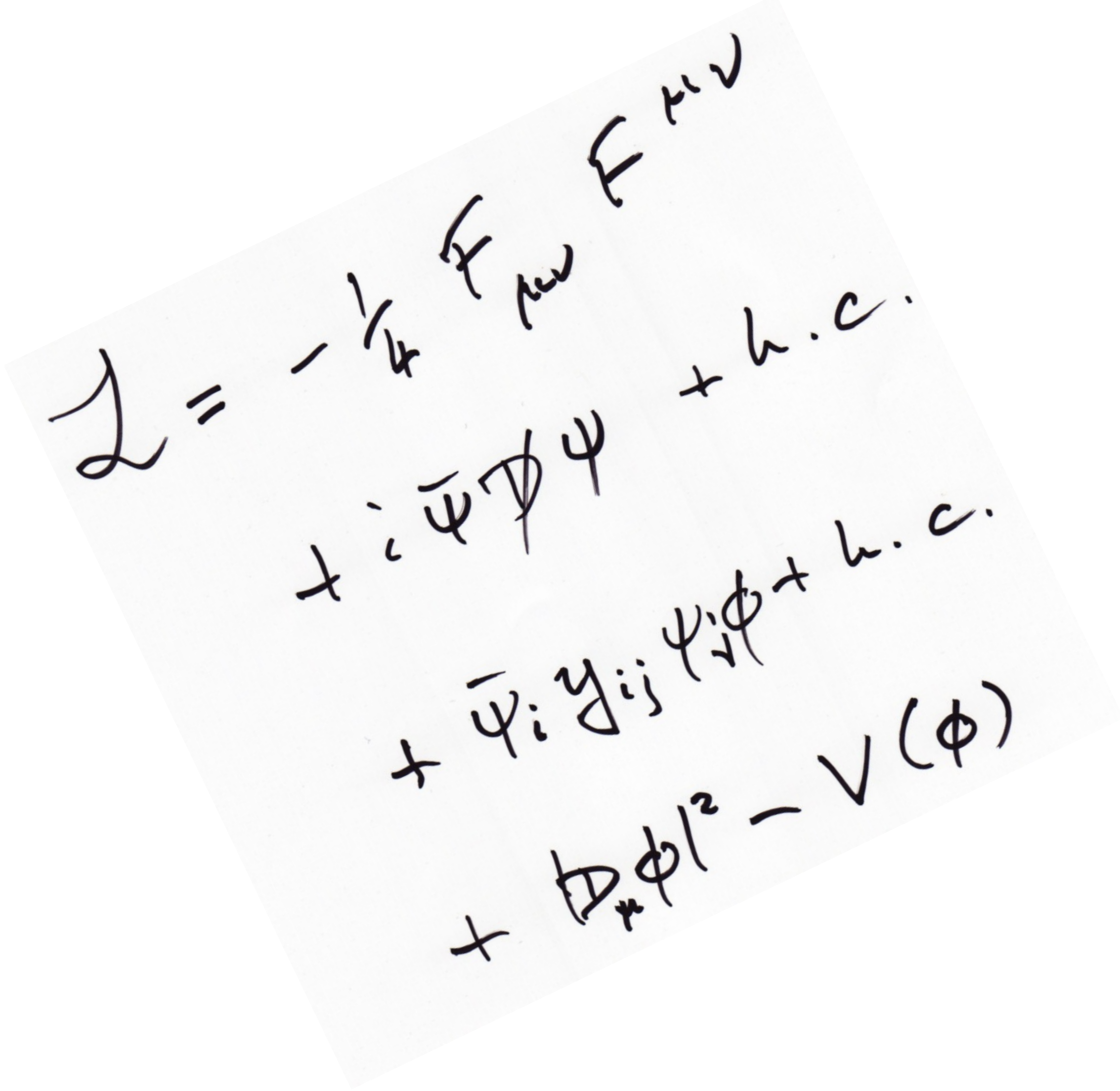
Conclusiones

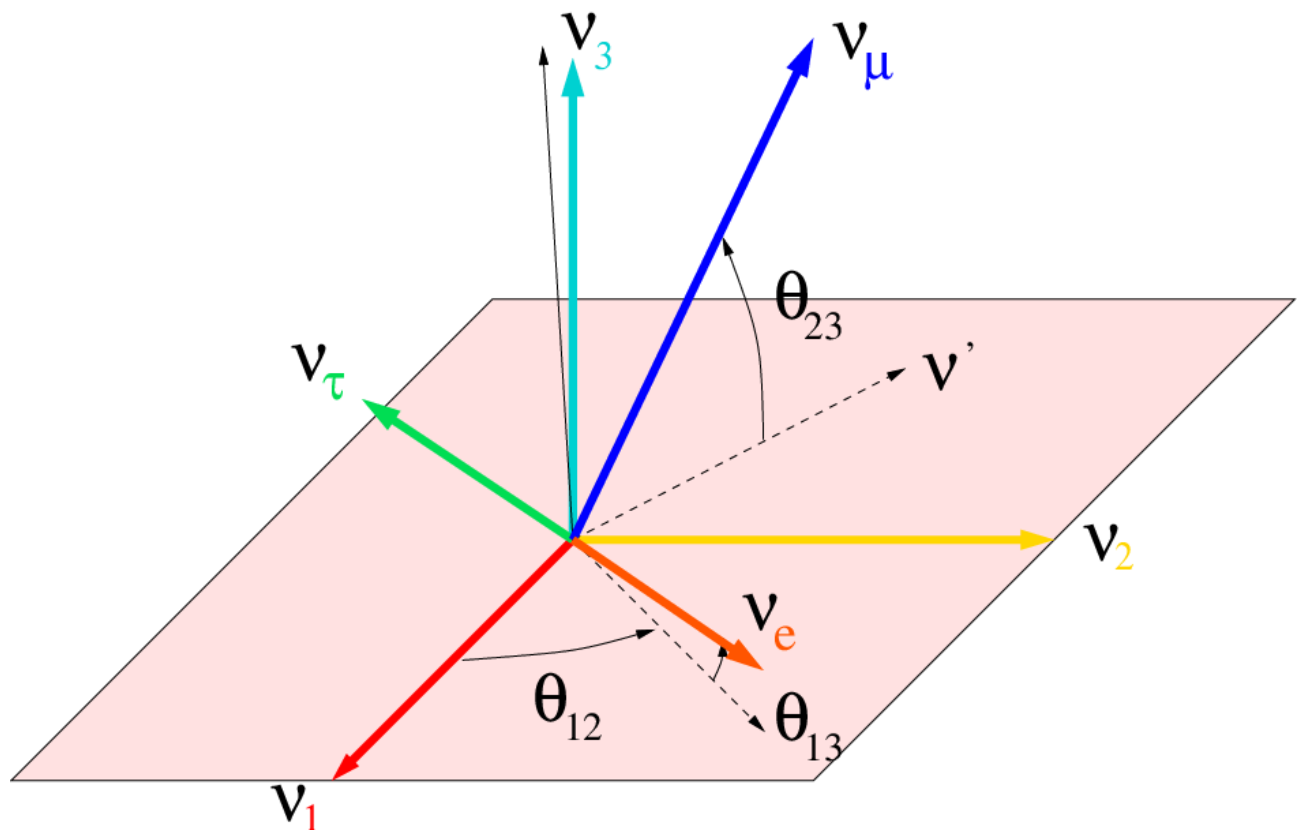
Los teoremas presentados buscan

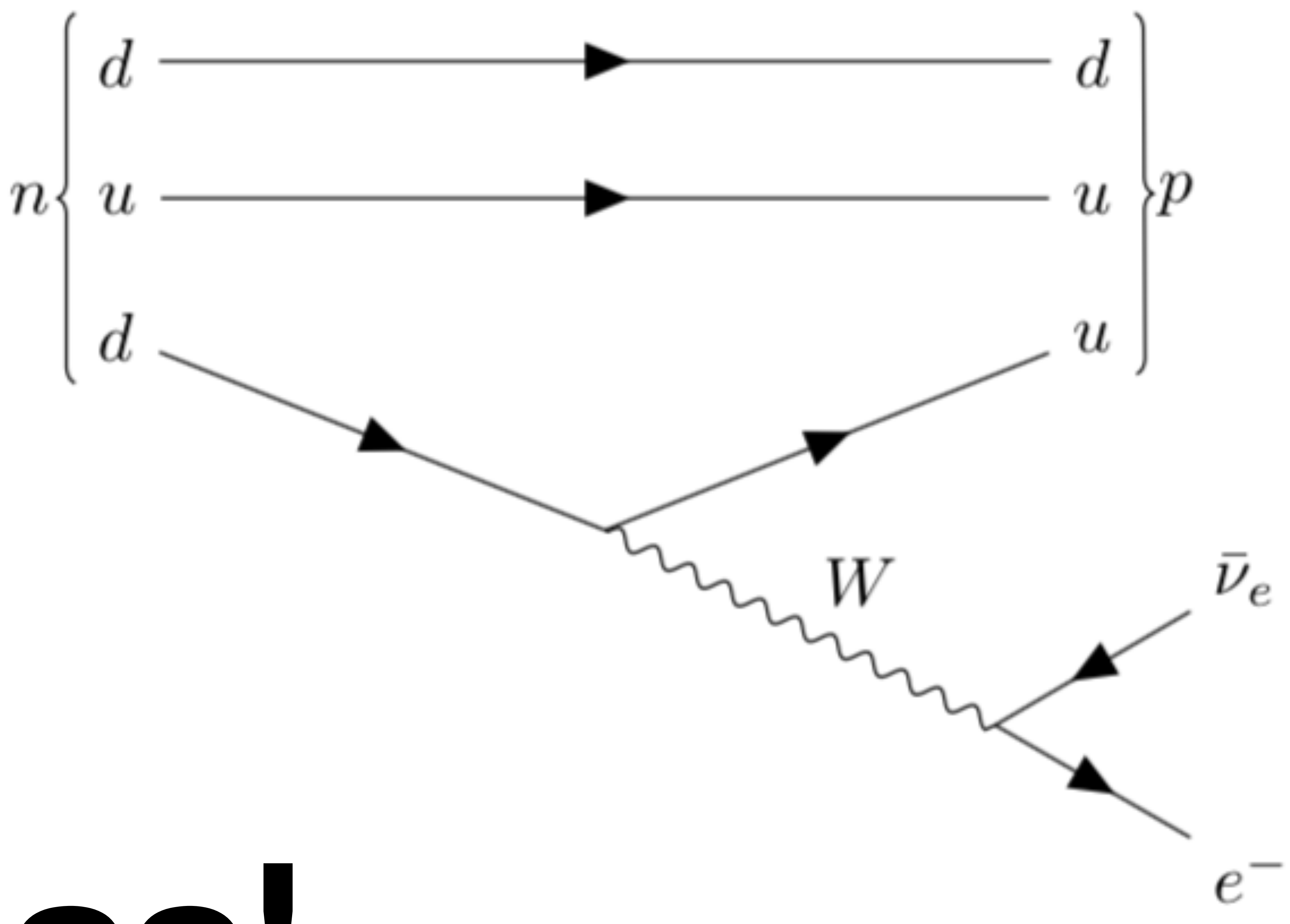
- Dictar el camino permitido o no en la construcción de modelos BSM
- Conocerlos permite ver que la construcción de modelos es un asunto delicado y bastante complicado
- En caso de no respetarlos, buscar una forma *ingeniosa* de evitarlos

“Si no quiebras algo, no generalizas.”

T. Sallis







Muchas gracias!