The Fundamental Interactions after the Higgs Discovery

A. Pich

IFIC, Univ. Valencia - CSIC

arXiv:1201.0537 (Standard Model)

arXiv:1512.08749 (Higgs Physics)

arXiv:1805.08597 (Flavour Physics)

Escuela Avanzada de Verano, México, 19-23 July 2021

Periodic Table

	1 IA	2 IIA	3 IIIA	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9 VIIIB	10 VIIIB	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	1 1.0079 **H** Hydrogen																	2 4.0025 **He** Helium
2	3 6.941 **Li** Lithium	4 9.0122 **Be** Beryllium											5 10.811 **B** Boron	6 12.011 **C** Carbon	7 14.007 **N** Nitrogen	8 15.999 **O** Oxygen	9 18.998 **F** Flourine	10 20.180 **Ne** Neon
3	11 22.990 **Na** Sodium	12 24.305 **Mg** Magnesium											13 26.982 **Al** Aluminium	14 28.086 **Si** Silicon	15 30.974 **P** Phosphorus	16 32.065 **S** Sulphur	17 35.453 **Cl** Chlorine	18 39.948 **Ar** Argon
4	19 39.098 **K** Potassium	20 40.078 **Ca** Calcium	21 44.956 **Sc** Scandium	22 47.867 **Ti** Titanium	23 50.942 **V** Vanadium	24 51.996 **Cr** Chromium	25 54.938 **Mn** Manganese	26 55.845 **Fe** Iron	27 58.933 **Co** Cobalt	28 58.693 **Ni** Nickel	29 63.546 **Cu** Copper	30 65.39 **Zn** Zinc	31 69.723 **Ga** Gallium	32 72.64 **Ge** Germanium	33 74.922 **As** Arsenic	34 78.96 **Se** Selenium	35 79.904 **Br** Bromine	36 83.8 **Kr** Krypton
5	37 85.468 **Rb** Rubidium	38 87.62 **Sr** Strontium	39 88.906 **Y** Yttrium	40 91.224 **Zr** Zirconium	41 92.906 **Nb** Niobium	42 95.94 **Mo** Molybdenum	43 96 **Tc** Technetium	44 101.07 **Ru** Ruthenium	45 102.91 **Rh** Rhodium	46 106.42 **Pd** Palladium	47 107.87 **Ag** Silver	48 112.41 **Cd** Cadmium	49 114.82 **In** Indium	50 118.71 **Sn** Tin	51 121.76 **Sb** Antimony	52 127.6 **Te** Tellurium	53 126.9 **I** Iodine	54 131.29 **Xe** Xenon
6	55 132.91 **Cs** Caesium	56 137.33 **Ba** Barium	57-71 **La-Lu** Lanthanide	72 178.49 **Hf** Halfnium	73 180.95 **Ta** Tantalum	74 183.84 **W** Tungsten	75 186.21 **Re** Rhenium	76 190.23 **Os** Osmium	77 192.22 **Ir** Iridium	78 195.08 **Pt** Platinum	79 196.97 **Au** Gold	80 200.59 **Hg** Mercury	81 204.38 **Tl** Thallium	82 207.2 **Pb** Lead	83 208.98 **Bi** Bismuth	84 209 **Po** Polonium	85 210 **At** Astatine	86 222 **Rn** Radon
7	87 223 **Fr** Francium	88 226 **Ra** Radium	89-103 **Ac-Lr** Actinide	104 261 **Rf** Rutherfordium	105 262 **Db** Dubnium	106 266 **Sg** Seaborgium	107 264 **Bh** Bohrium	108 277 **Hs** Hassium	109 268 **Mt** Meitnerium	110 281 **Ds** Darmstadtium	111 280 **Rg** Roentgenium	112 285 **Cn** Copernicium	113 284 **Nh** Nihonium	114 289 **Fl** Flerovium	115 288 **Mc** Moscovium	116 293 **Lv** Livermorium	117 292 **Ts** Tennessine	118 294 **Og** Oganesson
				57 138.91 **La** Lanthanum	58 140.12 **Ce** Cerium	59 140.91 **Pr** Praseodymium	60 144.24 **Nd** Neodymium	61 145 **Pm** Promethium	62 150.36 **Sm** Samarium	63 151.96 **Eu** Europium	64 157.25 **Gd** Gadolinium	65 158.93 **Tb** Terbium	66 162.50 **Dy** Dysprosium	67 164.93 **Ho** Holmium	68 167.26 **Er** Erbium	69 168.93 **Tm** Thulium	70 173.04 **Yb** Ytterbium	71 174.97 **Lu** Lutetium
				89 227 **Ac** Actinium	90 232.04 **Th** Thorium	91 231.04 **Pa** Protactinium	92 238.03 **U** Uranium	93 237 **Np** Neptunium	94 244 **Pu** Plutonium	95 243 **Am** Americium	96 247 **Cm** Curium	97 247 **Bk** Berkelium	98 251 **Cf** Californium	99 252 **Es** Einsteinium	100 257 **Fm** Fermium	101 258 **Md** Mendelevium	102 259 **No** Nobelium	103 262 **Lr** Lawrencium

- Alkali Metal
- Alkaline Earth Metal
- Metal
- Metalloid
- Non-metal
- Halogen
- Noble Gas
- Lanthanide/Actinide

Z mass **Symbol** Name	man made

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7	87 223 Fr Francium	88 226 Ra Radium	89-103 Ac-Lr Actinide	104 261 Rf Rutherfordium	105 262 Db Dubnium	106 266 Sg Seaborgium	107 264 Bh Bohrium	108 277 Hs Hassium	109 268 Mt Meitnerium	110 281 Ds Darmstadtium	111 R Roentg							

57 138.91 La Lanthanum	58 140.12 Ce Cerium	59 140.91 Pr Praseodymium	60 144.24 Nd Neodymium	61 145 Pm Promethium	62 150.36 Sm Samarium	63 151.96 Eu Europium	64 G Gadol
89 227 Ac Actinium	90 232.04 Th Thorium	91 231.04 Pa Protactinium	92 238.03 U Uranium	93 237 Np Neptunium	94 244 Pu Plutonium	95 243 Am Americium	96 C Cur

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Z mass
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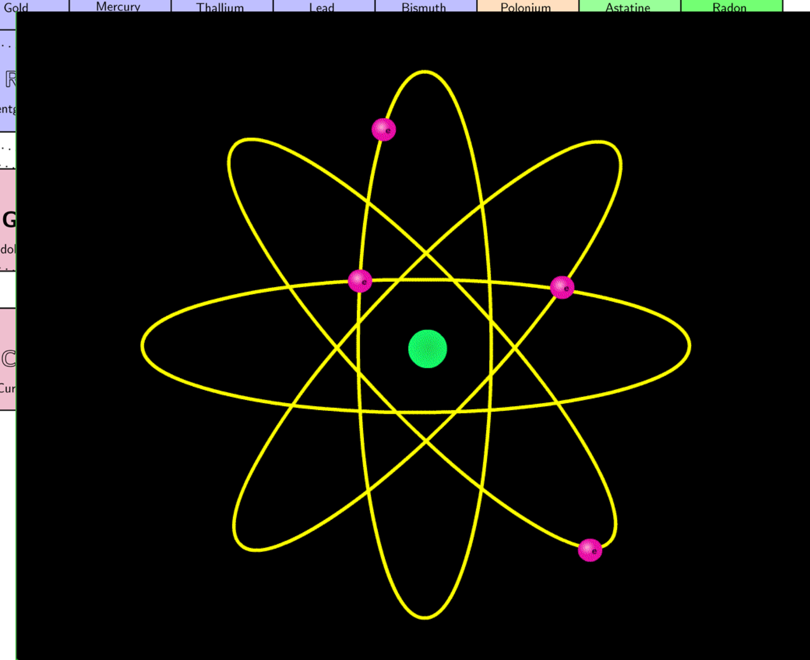
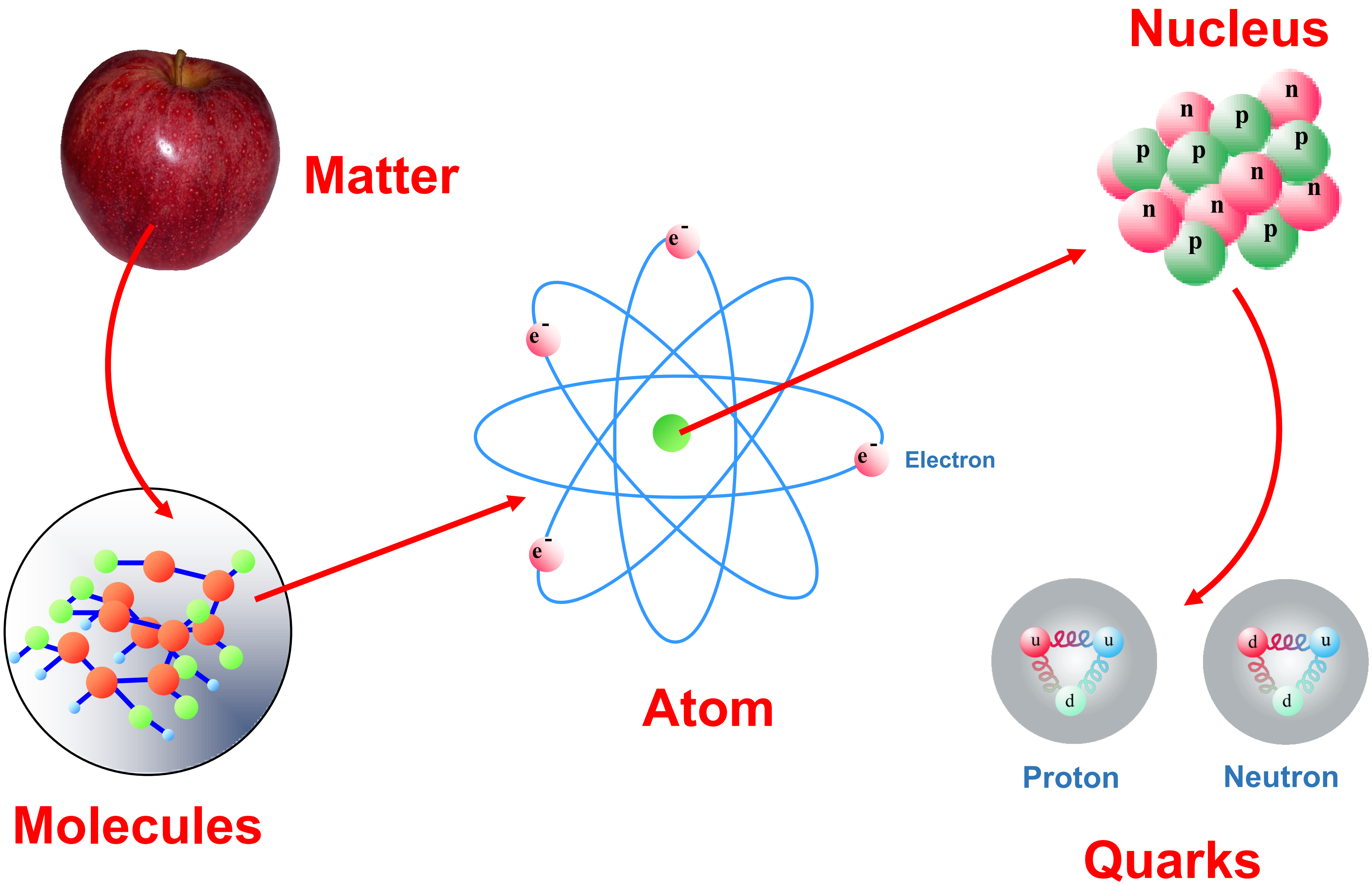


E.M. interaction

Z = # electrons

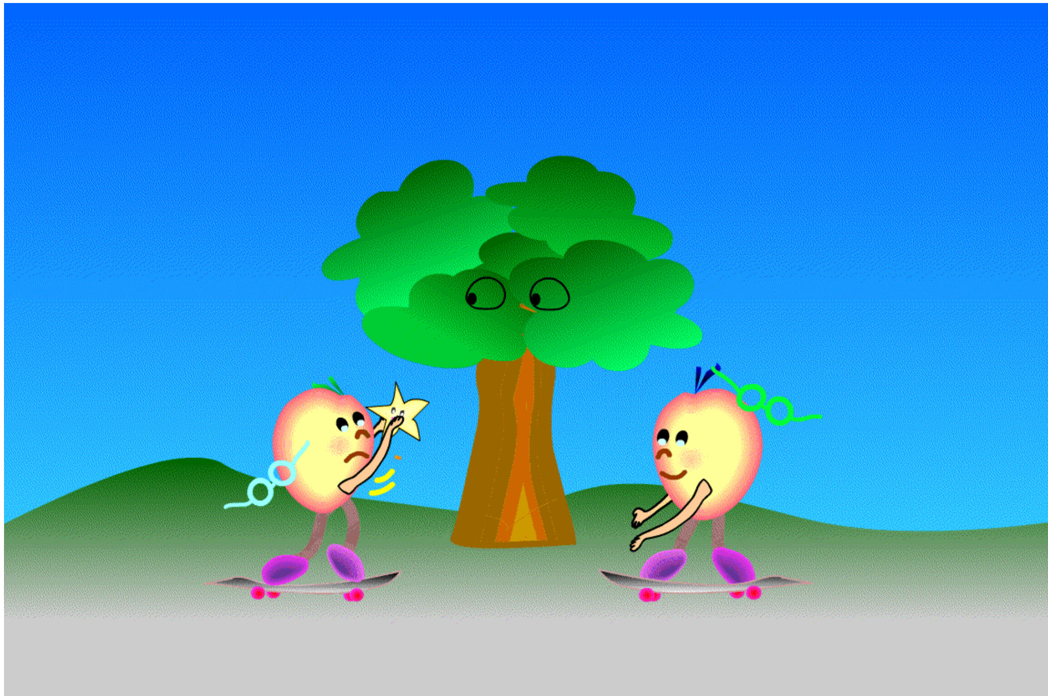


$$Q_u = +\frac{2}{3} \quad , \quad Q_d = -\frac{1}{3}$$

Fundamental Interactions

Type	Intensity	Intermediate Particle	Physical System
Strong	≈ 1	Gluons (m = 0)	Atomic Nucleus
Electromagnetic	$\approx 10^{-3}$	Photon (m = 0)	Atom
Weak	$\approx 10^{-5}$	$W^{\pm}$, Z ($M \neq 0$)	Radioactivity β
Gravitation	$\approx 10^{-38}$	Graviton ?	Massive Bodies

The exchange of particles generates the interaction



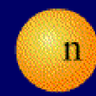
RADIOACTIVITY

$${}^{14}_{6}C \to {}^{14}_{7}N + e^{-} + \overline{\nu}_e$$

(β decay)

$$n \to p + e^{-} + \overline{\nu}_e$$

$$"\, p \to n + e^{+} + \nu_e \,"$$

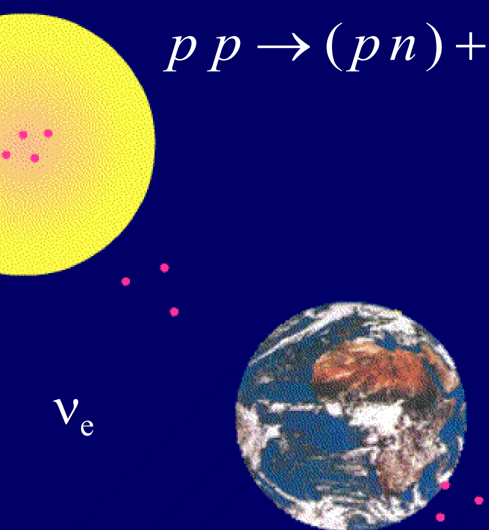


$$Q_{\nu_e} = Q_{\bar{\nu}_e} = 0$$

$$m_{\nu_e} = m_{\bar{\nu}_e} \approx 0$$

$\nu_e \equiv$ Neutrino ; $\overline{\nu}_e \equiv$ Anti-Neutrino

$$p\, p \to (p\, n) + e^{+} + \nu_e$$



Weak Interaction

$$W^{\pm},\; Z^{0}$$

$$M_W \sim M_Z \approx 100\; m_p$$

NEUTRINOS

ν_e

- Interact very weakly
- Very abundant in the Universe
- Each second your body is crossed by

$\sim 10^{14}\ \nu_e$ coming from the Sun

$$p\,p \to d\ e^+ \nu_e \ , \ \ldots$$

NEUTRINOS

Each second your body is crossed by

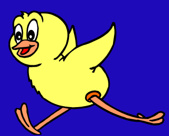
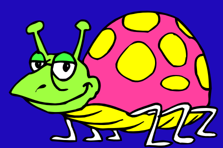
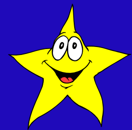
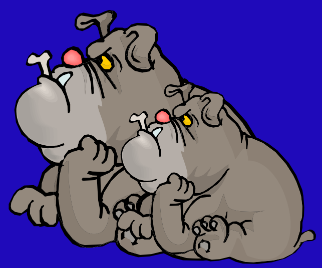
$\sim 10^{14}\ \nu_e$ coming from the Sun

$$p\,p \rightarrow d\, e^{+} \nu_e \ , \ \ldots$$

They also come from below!

ν_e

Matter (Fermions , $J = \frac{1}{2}$) — Forces

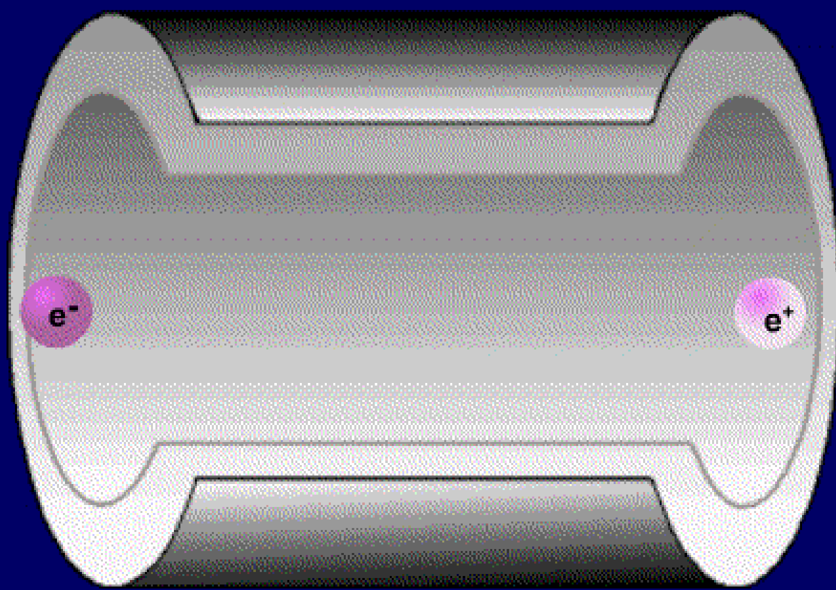
Quarks		Leptons		Bosons
$Q = 2/3$	$Q = -1/3$	$Q = 0$	$Q = -1$	$J = 1$
 up (u)	 down (d)	 neutrino e (ν_e)	 electron (e)	 photon
				 gluons
				 Z^0 $W^\pm$

Quantum Mechanics + Relativity → Antiparticles

(Dirac)

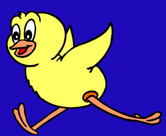
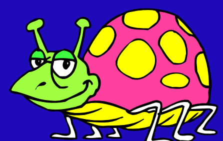
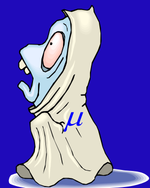
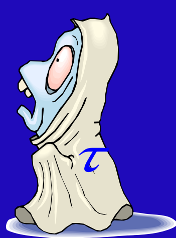
ANTIMATTER

u	d	ν_e	e^-
$\bar{u}$	$\bar{d}$	$\bar{\nu}_e$	e^+



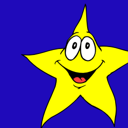
$$E = m c^2$$

Matter (Fermions , J = ½) Forces

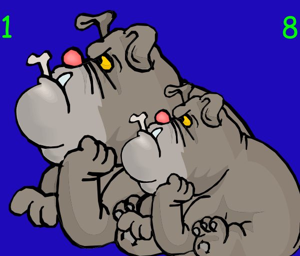
Quarks		Leptons	
Q = 2/3	Q = -1/3	Q = 0	Q = -1
0.003  up (u)	0.005  down (d)	< 0.000002  neutrino e (ν_e)	0.0005  electron (e)
1.3  charm (c)	0.1  strange (s)	< 0.000002  neutrino μ (ν_μ)	0.105  muon (μ)
173  top (t)	4.2  beauty (b)	< 0.000002  neutrino τ (ν_τ)	1.777  tau (τ)

Bosons

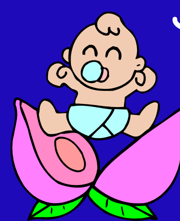
J = 1

0 
Photon

0 
gluons

91 80 
Z^0 $W^\pm$

J = 0

125 
Higgs

STANDARD MODEL

Quantum Mechanics $(\hbar)$ + Special Relativity (c)

➡ **Quantum Field Theory**

- **Quantum Electrodynamics (QED)**

  Electricity + Magnetism + Light: γ

- **Quantum Chromodynamics (QCD)**

  Strong interaction: 8 Gluons

- **Electroweak Theory** $SU(2)_L \otimes U(1)_Y$

  QED + Weak Interactión: $\gamma,\ Z,\ W^{\pm}$

Quantum Mechanics Wave Equations $(\hbar = c = 1)$

- **Non Relativistic:** **Schrödinger equation**

$$E = i\,\frac{\partial}{\partial t} \quad ; \quad \vec{p} = -i\,\vec{\nabla} \qquad\qquad E = \frac{\vec{p}^{\,2}}{2m} \quad \Longrightarrow \quad \boxed{i\,\frac{\partial}{\partial t}\Psi \;=\; -\frac{\vec{\nabla}^2}{2m}\Psi}$$

- **Relativistic:** **Klein-Gordon equation**

$$p^\mu \equiv (E, \vec{p}) = i\,\partial^\mu = i\,g^{\mu\nu}\,\frac{\partial}{\partial x^\nu} \qquad\qquad E^2 = \vec{p}^{\,2} + m^2 \quad \Longrightarrow \quad \boxed{(\Box + m^2)\,\phi \;=\; 0}$$

$$\Box \;\equiv\; \partial^\mu \partial_\mu \;=\; g^{\mu\nu}\,\partial_\mu \partial_\nu \;=\; \frac{\partial^2}{\partial t^2} - \vec{\nabla}^2$$

- **Spin $\frac{1}{2}$:** $$\boxed{(i\,\gamma^\mu \partial_\mu - m)\,\psi \;=\; 0}$$ **Dirac equation**

$$-(i\,\gamma^\nu \partial_\nu + m)\,[(i\,\gamma^\mu \partial_\mu - m)\,\psi] = 0 \;\equiv\; (\Box + m^2)\,\psi \quad \Longrightarrow \quad \{\gamma^\mu, \gamma^\nu\} = 2 g^{\mu\nu}$$

Spin matrices $(D = 4)$

Dirac Algebra

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

$$\gamma^0 = \begin{pmatrix} I_2 & 0 \\ 0 & -I_2 \end{pmatrix} \quad ; \quad \vec{\gamma} = \begin{pmatrix} 0 & \vec{\sigma} \\ -\vec{\sigma} & 0 \end{pmatrix}$$

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

$$\{\sigma^i, \sigma^j\} = 2\delta^{ij} \quad ; \quad [\sigma^i, \sigma^j] = 2i\varepsilon^{ijk}\sigma^k$$

$$\psi = \begin{pmatrix} \varphi \\ \chi \end{pmatrix}$$ **Particle** / **Antiparticle** } **Spinors**

Chirality Projectors:

$$\gamma_5 \equiv i\gamma^0\gamma^1\gamma^2\gamma^3 = \begin{pmatrix} 0 & I_2 \\ I_2 & 0 \end{pmatrix} \quad ; \quad (\gamma_5)^2 = I_4$$

$$P_R \equiv \frac{1+\gamma_5}{2} \quad ; \quad P_L \equiv \frac{1-\gamma_5}{2}$$

$$\mathrm{P}_R^2 = \mathrm{P}_R \quad ; \quad \mathrm{P}_L^2 = \mathrm{P}_L \quad ; \quad \mathrm{P}_R\,\mathrm{P}_L = \mathrm{P}_L\,\mathrm{P}_R = 0$$

$$\psi = (P_R + P_L)\,\psi \equiv \psi_R + \psi_L$$

Chirality (~ helicity) components

Lagrangian Formalism

$$S = \int d^4x \;\; \mathcal{L}(\phi, \partial_\mu \phi)$$

$$\boxed{\delta S = 0 \quad \longrightarrow \quad \frac{\partial \mathcal{L}}{\partial \phi} - \partial^\mu \left(\frac{\partial \mathcal{L}}{\partial(\partial^\mu \phi)} \right) = 0}$$

Eq. Motion

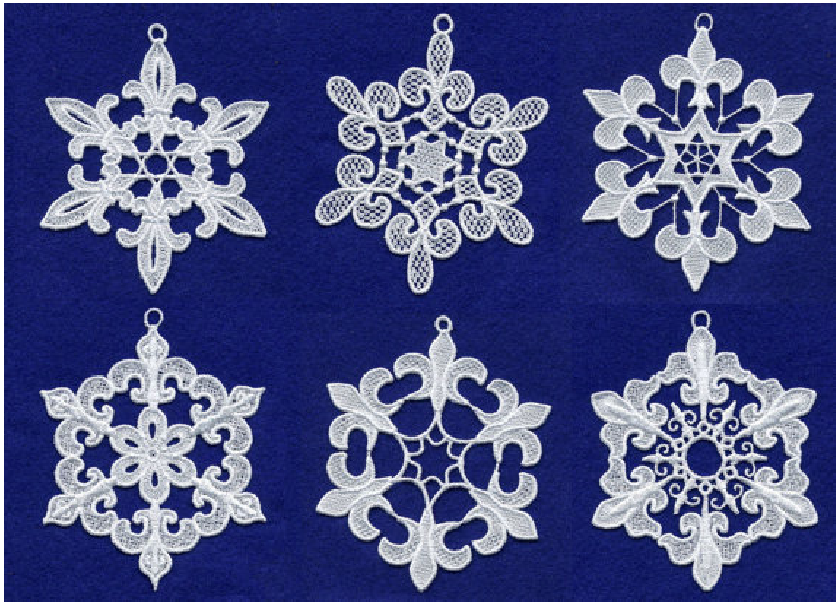
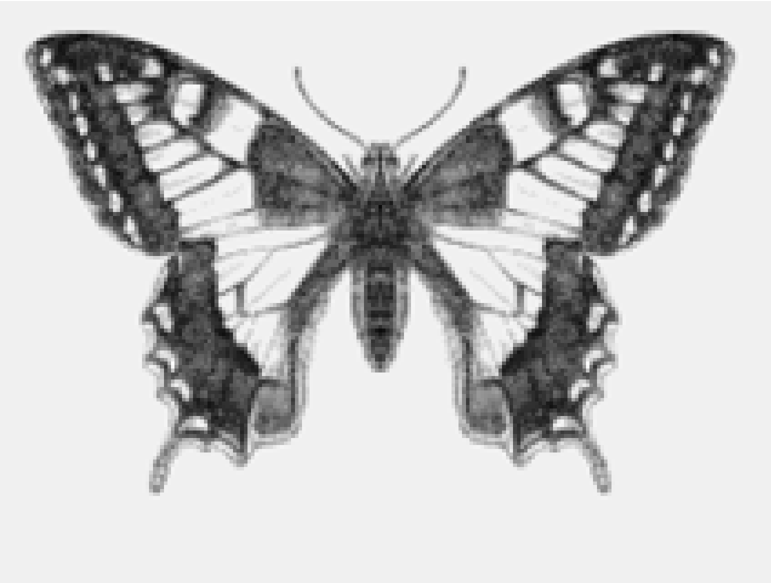
Klein-Gordon: (spin 0)

$$\mathcal{L} = \partial^\mu \phi^* \partial_\mu \phi - m^2 \phi^* \phi \quad \longrightarrow \quad (\Box + m^2)\, \phi = 0$$

Dirac: (spin $\frac{1}{2}$) $\qquad \bar{\psi} \equiv \psi^\dagger \gamma^0$

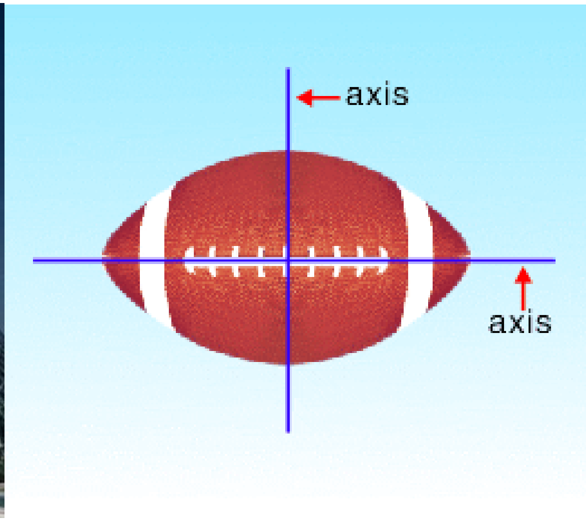
$$\mathcal{L} = \bar{\psi}\, (i\gamma^\mu \partial_\mu - m)\, \psi \quad \longrightarrow \quad (i\,\gamma^\mu \partial_\mu - m)\, \psi = 0$$

Fields create, annihilate and propagate (anti)particles

SYMMETRIES





Free Dirac Fermion: $\mathcal{L} = \bar{\psi}\,(i\gamma^\mu\partial_\mu - m)\,\psi$

Phase Invariance: $\psi \;\to\; \psi' = \mathrm{e}^{iQ\theta}\,\psi \quad ; \quad \bar{\psi} \;\to\; \bar{\psi}' = \mathrm{e}^{-iQ\theta}\,\bar{\psi}$

Absolute phases are not observable in Quantum Mechanics

GAUGE PRINCIPLE: $\theta = \theta(x)$

Phase Invariance should hold LOCALLY

BUT $\partial_\mu\psi \;\to\; \mathrm{e}^{iQ\theta}\,(\partial_\mu + i\,Q\,\partial_\mu\theta)\,\psi$

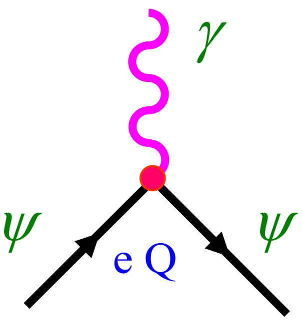
SOLUTION: Covariant Derivative

$$D_\mu\psi \equiv (\partial_\mu + i\,e\,Q\,A_\mu)\,\psi \;\to\; \mathrm{e}^{iQ\theta}\,D_\mu\psi$$

One needs a spin-1 (gauge) field A_μ **satisfying** $A_\mu \;\to\; A_\mu - \frac{1}{e}\,\partial_\mu\theta$

Quantum Electrodynamics (QED)

$$\boxed{\begin{aligned}\mathcal{L} &= \bar{\psi}\,(i\,\gamma^{\mu} D_{\mu} - m)\,\psi \\ &= \bar{\psi}\,(i\,\gamma^{\mu}\partial_{\mu} - m)\,\psi \;-\; e\,Q\,A_{\mu}\;(\bar{\psi}\,\gamma^{\mu}\psi)\end{aligned}}$$



Kinetic term: $F^{\mu\nu} \equiv \partial^{\mu} A^{\nu} - \partial^{\nu} A^{\mu}$

$$\boxed{\mathcal{L}_K = -\frac{1}{4}\,F_{\mu\nu}F^{\mu\nu}} \;\Rightarrow\; \partial_{\mu}F^{\mu\nu} = e\,Q\,(\bar{\psi}\,\gamma^{\nu}\,\psi) \equiv J^{\nu}$$

Maxwell

Mass term: $[\,\text{exp:} \quad \mathrm{m}_{\gamma} < 1 \times 10^{-18}\ \mathrm{eV}\,]$

$$\mathcal{L}_M = \frac{1}{2}\,m_{\gamma}^2\;A^{\mu}A_{\mu}$$

Not Gauge Invariant ⇒ $m_{\gamma} = 0$

Gauge Symmetry ⇒ QED Dynamics

GAUGE THEORIES

The symmetries determine the interactions

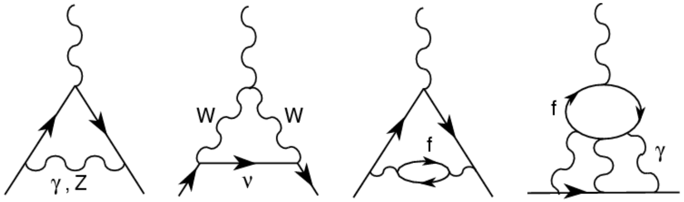
(locally in each space-time point)

- **Electrodynamics:** 1 parameter $\alpha \equiv \frac{e^2}{4\pi}$ (interaction strength)

  Phase symmetry ➡ QED ➡ Maxwell Eqs.

Anomalous Magnetic Moment

$$\mu_l \equiv g_l \, \frac{e}{2\, m_l} \qquad\qquad a_l \equiv \frac{1}{2}\,(g_l - 2)$$



$$\alpha^{-1}_{\mathrm{Rb2020}} = 137.035\,999\,206\;(11) \quad \Rightarrow \quad \begin{aligned} a_e^{\mathrm{th}} &= 0.001\,159\,652\,180\,252\;\;(95) \\ a_e^{\mathrm{exp}} &= 0.001\,159\,652\,180\,91\;\;(26) \end{aligned}$$

- **Electroweak Theory:** 2 parameters $\alpha,\ \theta_W$
- **Quantum Chromodynamics:** 1 parameter α_s

Quantum Chromodynamics (QCD)

Free Quarks: $N_C = 3$ colours

$$\mathcal{L} = \bar{\mathbf{q}}\,[\,i\gamma^\mu\partial_\mu - m\,]\,\mathbf{q} \qquad\qquad \mathbf{q} \equiv \begin{pmatrix} q \\ q \\ q \end{pmatrix}$$

SU(3)$_C$ Colour Symmetry:

$$\mathbf{q} \to \mathbf{U}\,\mathbf{q} = \exp\left\{ i\,\frac{\lambda^a}{2}\,\theta_a \right\}\mathbf{q}$$

$$[\lambda^a, \lambda^b] = 2i\, f^{abc}\, \lambda^c$$

Gauge Principle: **Local Symmetry** $\theta_a = \theta_a(x)$

$$\mathbf{D^\mu q} \equiv (\mathbf{I}_3\,\partial^\mu + i\,g_s\,\mathbf{G}^\mu)\,\mathbf{q} \quad\to\quad \mathbf{U}\;\mathbf{D^\mu q}$$

$$\mathbf{D}^\mu \to \mathbf{U}\;\mathbf{D}^\mu\;\mathbf{U}^\dagger \qquad\qquad \mathbf{G}^\mu \to \mathbf{U}\,\mathbf{G}^\mu\,\mathbf{U}^\dagger + \frac{i}{g_s}\,(\partial^\mu\mathbf{U})\;\mathbf{U}^\dagger$$

$$[\mathbf{G}^\mu]_{\alpha\beta} \equiv \frac{1}{2}\,(\lambda^a)_{\alpha\beta}\;G^\mu_a(x)$$

8 Gluon Fields

Kinetic Term:

$$\mathbf{G}^{\mu\nu} \equiv -\frac{i}{g_s}\,[\mathbf{D}^\mu, \mathbf{D}^\nu] = \partial^\mu \mathbf{G}^\nu - \partial^\nu \mathbf{G}^\mu + i\, g_s\,[\mathbf{G}^\mu, \mathbf{G}^\nu] \quad \rightarrow \quad \mathbf{U}\ \mathbf{G}^{\mu\nu}\ \mathbf{U}^\dagger$$

$$\mathbf{G}^{\mu\nu} \equiv \frac{\lambda^a}{2} G_a^{\mu\nu} \quad ; \quad G_a^{\mu\nu} = \partial^\mu G_a^\nu - \partial^\nu G_a^\mu - g_s\, f^{abc}\, G_b^\mu\, G_c^\nu$$

$$\boxed{\mathcal{L}_K = -\frac{1}{2}\,\mathrm{Tr}\,(\mathbf{G}^{\mu\nu}\mathbf{G}_{\mu\nu}) = -\frac{1}{4}\, G_a^{\mu\nu}\, G^a_{\mu\nu}}$$

Mass Term:

$$\mathcal{L}_M = \frac{1}{2}\, m_G^2\ G_a^\mu\ G^a_\mu$$

Not Gauge Invariant ➡ $m_G = 0$

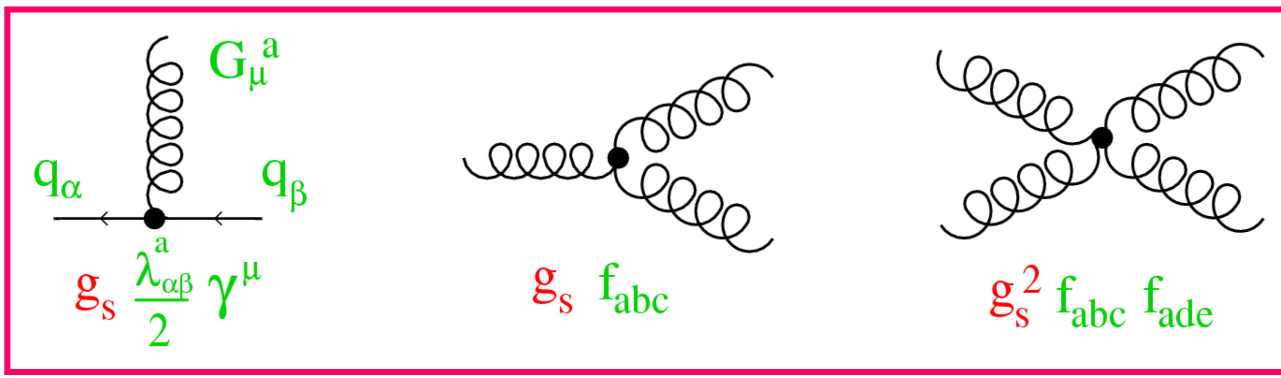
Massless Gluons

$$\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{2}\,\mathrm{Tr}\,(\mathbf{G}^{\mu\nu}\,\mathbf{G}_{\mu\nu}) + \bar{\mathbf{q}}\,[\,i\,\gamma^{\mu}\,\mathbf{D}_{\mu} - m_q\,]\,\mathbf{q}$$

$$= -\frac{1}{4}\left(\partial^{\mu}G^{\nu}_{a} - \partial^{\nu}G^{\mu}_{a}\right)\left(\partial_{\mu}G^{a}_{\nu} - \partial_{\nu}G^{a}_{\mu}\right) + \sum_{q}\bar{q}_{\alpha}\,[\,i\,\gamma^{\mu}\partial_{\mu} - m_q\,]\,q_{\alpha}$$

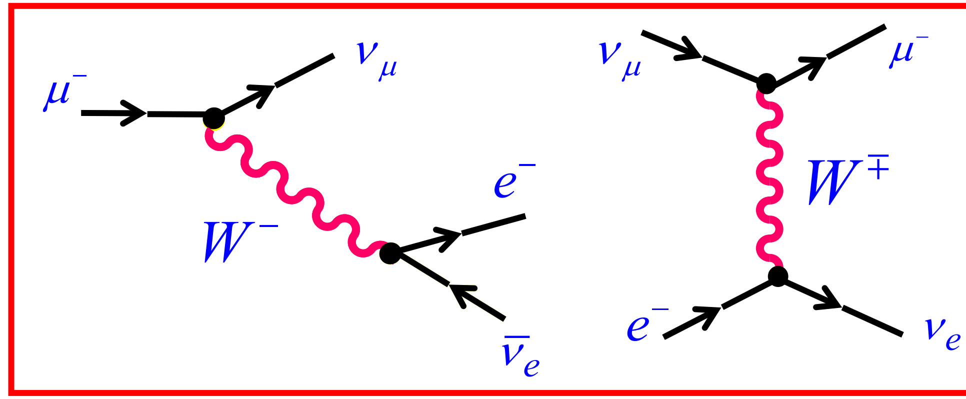
$$-\ \frac{1}{2}\sum_{q} g_s\,[\bar{q}_{\alpha}\,(\lambda^{a})_{\alpha\beta}\,\gamma^{\mu}q_{\beta}]\,G^{a}_{\mu}$$

$$+\ \frac{1}{2}\,g_s\,f_{abc}\,(\partial_{\mu}G^{a}_{\nu} - \partial_{\nu}G^{a}_{\mu})\,G^{\mu}_{b}\,G^{\nu}_{c} \ -\ \frac{1}{4}\,g_s^{2}\,f_{abc}\,f_{ade}\,G^{\mu}_{b}\,G^{\nu}_{c}\,G^{d}_{\mu}\,G^{e}_{\nu}$$

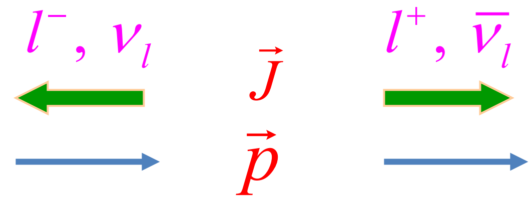


- **Gluon Self – interactions: G^3 , G^4**
- **Universal Coupling g_s** **(No Colour Charges)**

Experimental Facts on Weak Transitions



- **Left-handed leptons (Right-handed antileptons)**



- **Doublet partners:** $l_L^- \Leftrightarrow (\nu_l)_L \quad , \quad d_L \Leftrightarrow u_L$

$$\nu_\mu X \to \mu^- X' \quad ; \quad \nu_\mu X \not\to e^- X' \quad ; \quad d \to u\, e^- \bar{\nu}_e \quad ; \quad u \to d\, e^+ \nu_e$$

- **Three families:** $\begin{bmatrix} \nu_e & u \\ e^- & d' \end{bmatrix} \quad , \quad \begin{bmatrix} \nu_\mu & c \\ \mu^- & s' \end{bmatrix} \quad , \quad \begin{bmatrix} \nu_\tau & t \\ \tau^- & b' \end{bmatrix}$

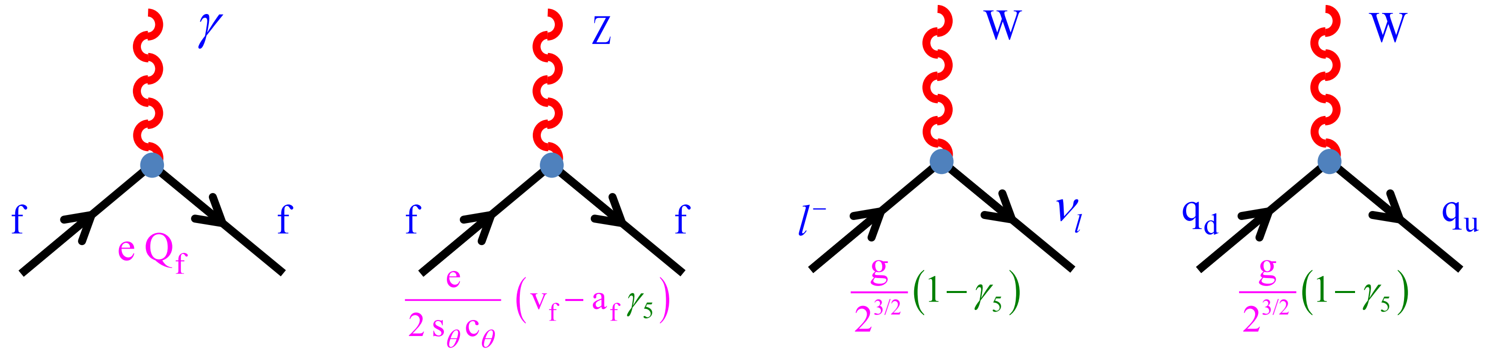
Family Structure

$$\boxed{\begin{bmatrix} \nu_l & q_u \\ l^- & q_d \end{bmatrix} \equiv \left\{ \begin{pmatrix} \nu_l \\ l^- \end{pmatrix}_L , \ (\nu_l)_R \ , \ l_R^- \right\} \quad ; \quad \left\{ \begin{pmatrix} q_u \\ q_d \end{pmatrix}_L , \ (q_u)_R \ , \ (q_d)_R \right\}}$$

$SU(2)_L \otimes U(1)_Y$ Electroweak Gauge Theory

3 + 1 gauge bosons: $W^{\pm}$, Z , γ ; **2 gauge couplings:** g , g'

Fermion Interactions



$$g\ \sin\theta_W = g'\cos\theta_W = e \qquad , \qquad v_f = T_3^f = \pm\frac{1}{2} \qquad , \qquad a_f = T_3^f\left(1-4\,|Q_f|\,\sin^2\theta_W\right)$$

Gauge Self-Interactions