

Fundamental principles of particle physics

G.Ross, CERN, July06



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Outline

- Introduction - Fundamental particles and interactions
- Symmetries I - Relativity
- Quantum field theory - Quantum Mechanics + relativity
- Theory confronts experiment - Cross sections and decay rates
- Symmetries II – Gauge symmetries, the Standard Model
- Fermions and the weak interactions



http://www.physics.ox.ac.uk/users/ross/cern_lectures.htm

Fundamental principles of particle physics

G.Ross, CERN, July05

Fundamental Interactions

	<i>Strength</i>
<i>Strong</i>	$\alpha_s = \frac{g_s^2}{4\pi\hbar c} \approx 1^\dagger$
<i>Electromagnetic</i>	$\alpha_{em} = \frac{e^2}{4\pi\hbar c} \approx \frac{1}{137}$
<i>Weak</i>	$G_F m_p^2 \approx 10^{-5}^\dagger$
<i>Gravitational</i>	$G_N m_p^2 \approx 10^{-36}$

† *Short range*

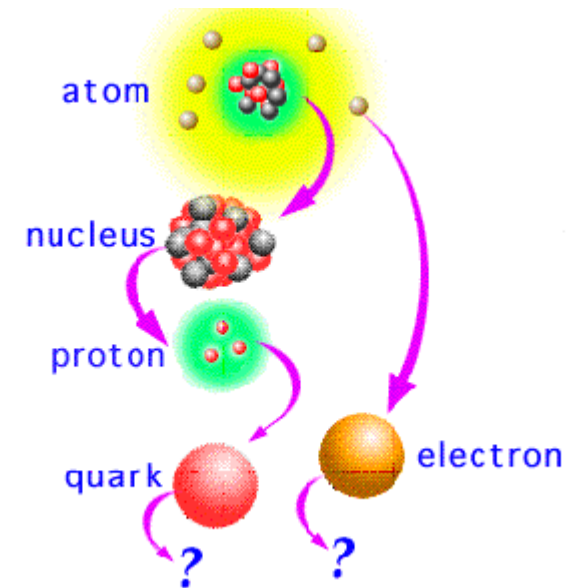
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Fundamental Particles



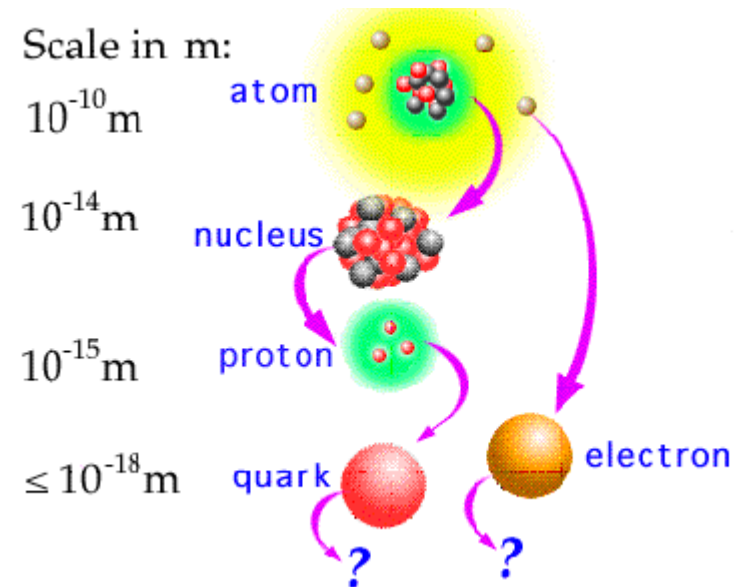
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Fundamental Particles



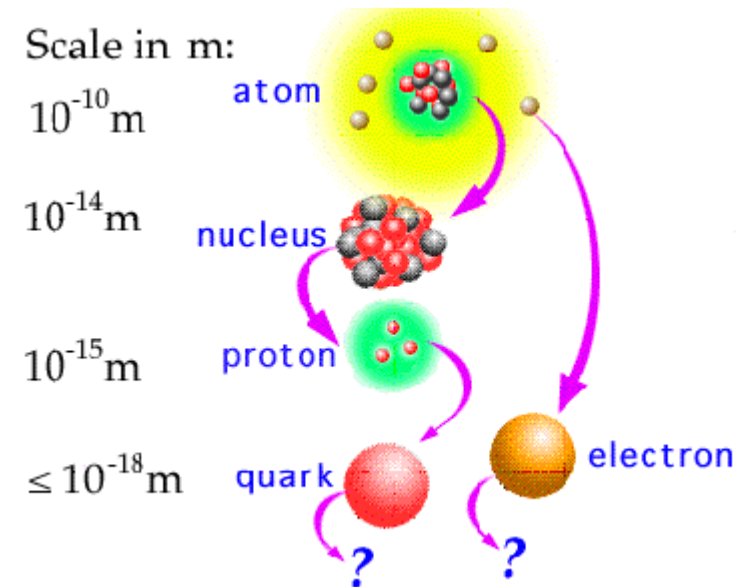
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Fundamental Particles



Strength \longleftrightarrow Size

Energy

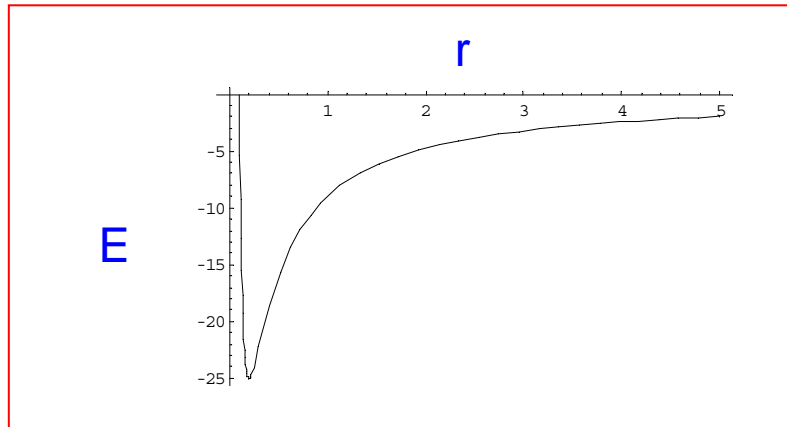
$$E = \text{PE} + \text{KE} = -\frac{e^2}{4\pi r} + \frac{p^2}{2m_e}$$

Heisenberg's

$$\Delta p \cdot \Delta r \geq \hbar \quad \Rightarrow \quad p \geq \Delta p \geq \frac{\hbar}{\Delta r} \geq \frac{\hbar}{r}$$

Uncertainty principle

$$E \approx -\frac{e^2}{4\pi r} + \frac{\hbar^2}{2m_e r^2}$$



$$\frac{\partial E}{\partial r} = 0$$

$$\Rightarrow \frac{e^2}{4\pi r^2} - \frac{\hbar^2}{m_e r^3} = 0$$

$$\alpha_{em} \equiv \frac{e^2}{4\pi\hbar c} \approx \frac{\hbar}{m_e r c}$$

Units

Length : L
Time : T
Energy : E
or Mass : m

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

$$\hbar = 10^{-34} \text{ kg m}^2/\text{sec}$$

Natural Units

Choose units such that :

$$c = 1 \quad L/T$$

$$\hbar = 1 \quad E.T \quad (\equiv M.L^2 / T)$$

1 unit left : choose

$$E = 1 \quad GeV \quad (= 10^9 \text{ electron volts} = 1.6 \cdot 10^{-10} \text{ J})$$

Natural Units

$$1 = c = 3 \cdot 10^8 \text{ m/sec} = 3 \cdot 10^{23} \text{ fm/sec}$$

$$1 = \hbar = 10^{-34} \text{ kg m}^2/\text{sec} = 10^{34} \text{ J/sec} \quad \square \quad \frac{1}{5} \text{ GeV fm} \dagger$$

energy of 1 GeV $\square 1.6 \cdot 10^{-10} \text{ J}$

...typical of elementary particles

mass of 1 GeV $\square 1.8 \cdot 10^{-27} \text{ kg}$

length of 1 GeV⁻¹ $\square 0.2 \text{ fm}$

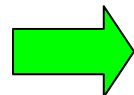
time of 1 GeV⁻¹ $\square 0.7 \cdot 10^{-24} \text{ sec}$

$$\alpha_{em} = \frac{e^2}{4\pi\hbar c} \quad \square \quad \frac{\hbar}{m_e r c} = \frac{1}{m_e r}$$

Dimensionless-
same in any units

$$r_{atom} \quad \square \quad 10^{-10} \text{ m} \quad \square \quad 10^5 \text{ fm}$$

$$m_e \quad \square \quad 0.5 \cdot 10^{-3} \text{ GeV} \quad \dagger$$



$$\alpha_{em} = \frac{e^2}{4\pi} \quad \square \quad 10^{-2}$$

Fundamental Interactions and sizes

$$\alpha = \frac{1}{m r}$$

Atomic binding :

$$r_{atom} \approx 10^{-10} m \approx 10^5 fm$$

$$m_e \approx 0.5 \cdot 10^{-3} GeV$$

$$\alpha_{em} = \frac{e^2}{4\pi} \approx 10^{-2}$$

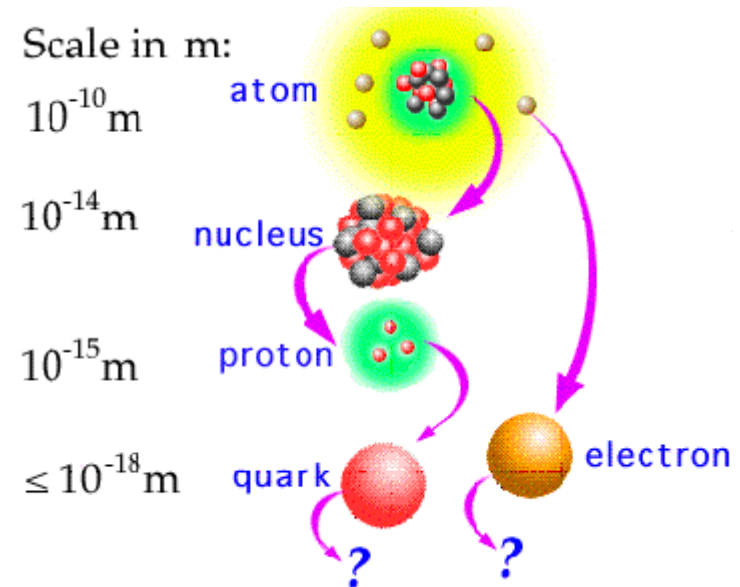
Nuclear binding :

$$r_{nucleus} \approx 10^{-15} m \approx 1 fm$$

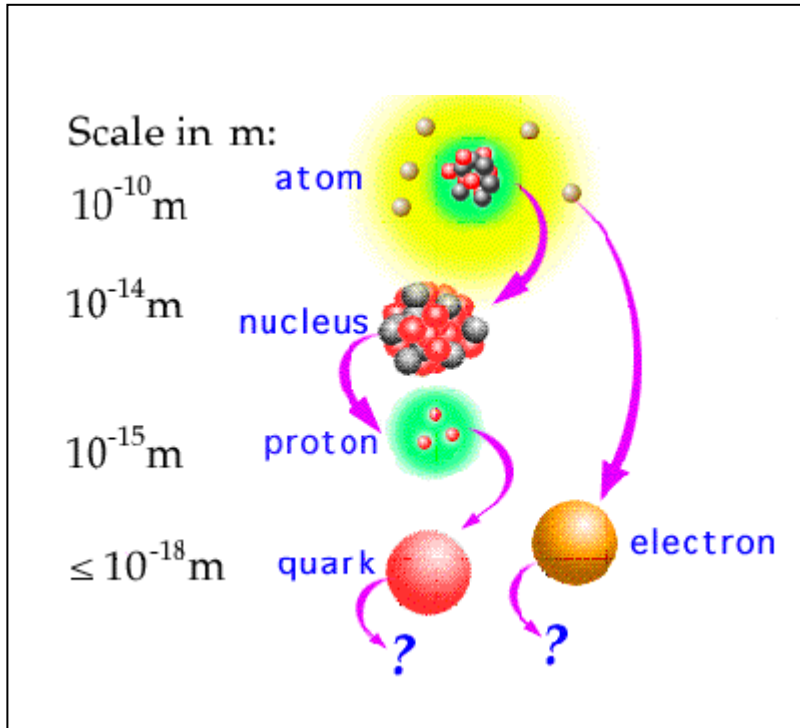
$$m_p \approx 1 GeV$$

$$\alpha_{strong} = \frac{g^2}{4\pi} \approx 1$$

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Elementary particles



Leptons :

$$e^{-}, \mu^{-}, \tau^{-}$$

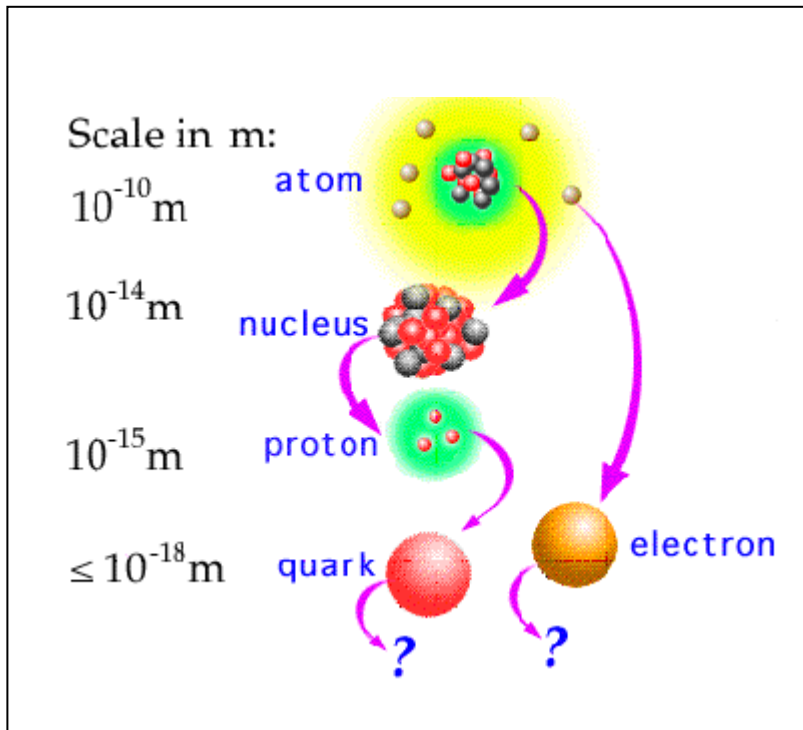
$$\nu_e, \nu_{\mu}, \nu_{\tau}$$

Quarks :

$$u^{2/3}, c^{2/3}, t^{2/3}$$

$$d^{-1/3}, s^{-1/3}, b^{-1/3}$$

Elementary particles



Leptons :

e^- , μ^- , τ^-

ν_e , ν_μ , ν_τ

Quarks :

u , c , t

u , c , t

u , c , t

d , s , b

d , s , b

d , s , b

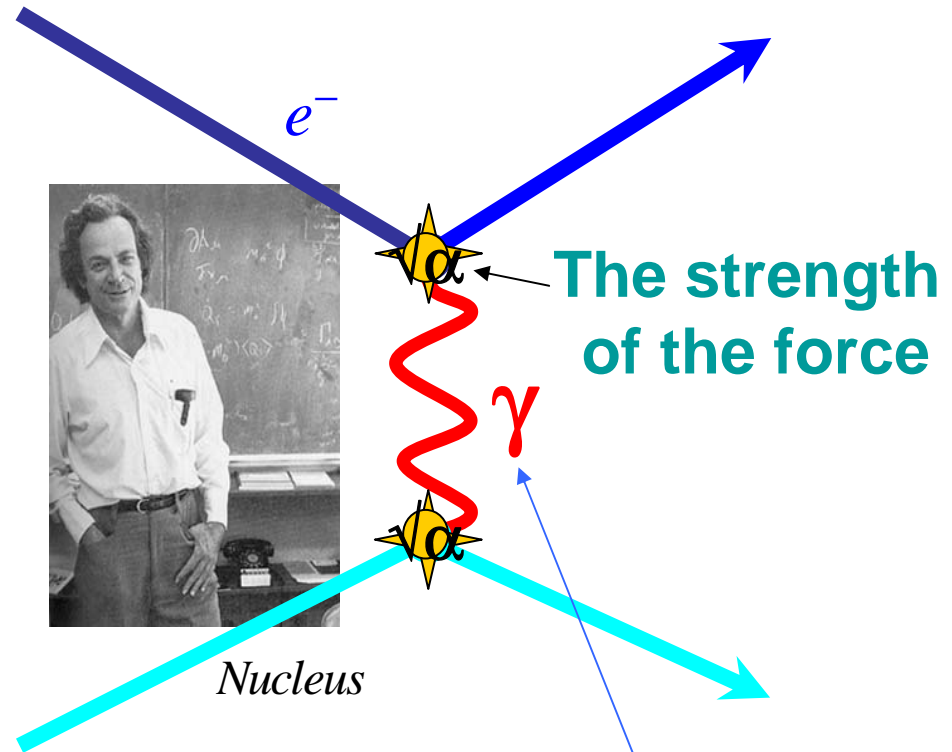
Hadrons : 3 strong “colour” charges

Elementary forces

Exchange forces

Electromagnetism

$$V_{em}(\mathbf{r}) = \frac{e_1 e_2}{4\pi} \frac{1}{r}$$



Experiments conducted in momentum space :

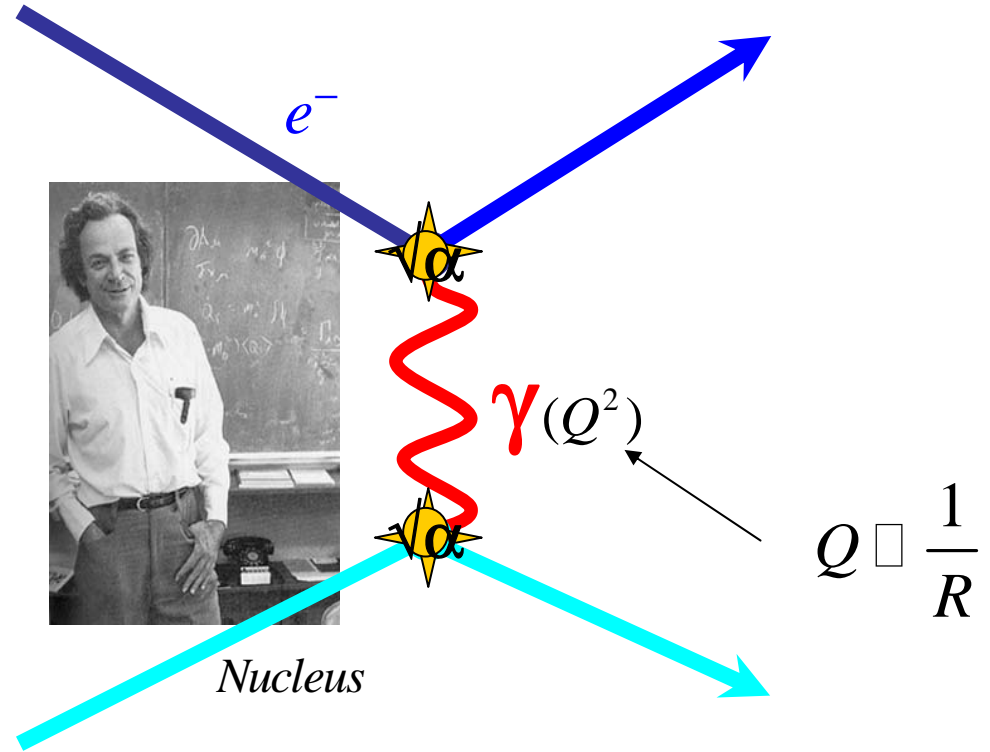
$$V_{em}(|\mathbf{q}|) \propto \int V_{em}(|\mathbf{r}|) e^{-i\mathbf{k}\cdot\mathbf{r}} d^3\mathbf{r} \propto \frac{\alpha}{|\mathbf{k}|^2}$$

Photon "propagator"

Exchange forces

Electromagnetism

$$V_{em}(\mathbf{r}) = \frac{e_1 e_2}{4\pi} \frac{1}{r}$$



Experiments conducted in momentum space :

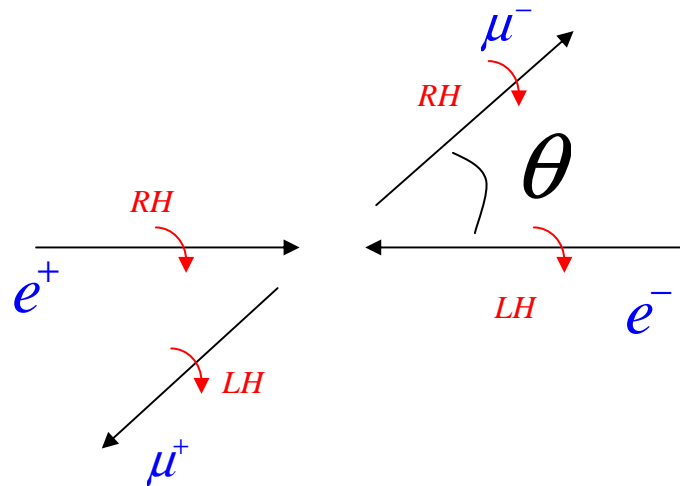
$$V_{em}(|\mathbf{q}|) = \int V_{em}(|\mathbf{r}|) e^{-i\mathbf{k}\cdot\mathbf{r}} d^3\mathbf{r} = \frac{\alpha}{|\mathbf{k}|^2}$$

$$Q^2 \equiv -\mathbf{k}^2$$

"virtual photon"

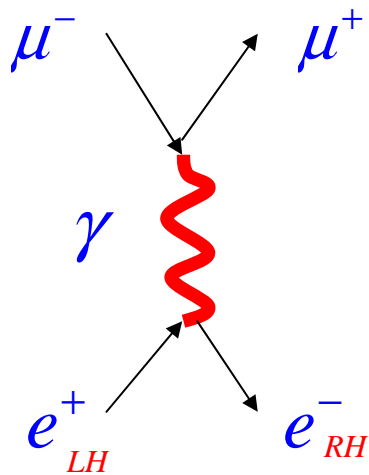
Application to a scattering processes

$$e^+ e^- \rightarrow \mu^+ \mu^-$$



$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 E_{CM}^2} |M|^2$$

Feynman diagram



QM : Transition amplitude

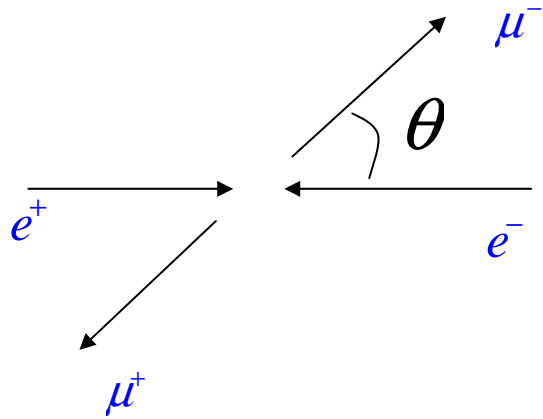
$\langle \text{final state} | H_I | \text{initial state} \rangle$

$$M \propto \langle \mu^+ \mu^- | H_I | \gamma \rangle^\alpha \langle \gamma | H_I | e^+ e^- \rangle_\alpha$$

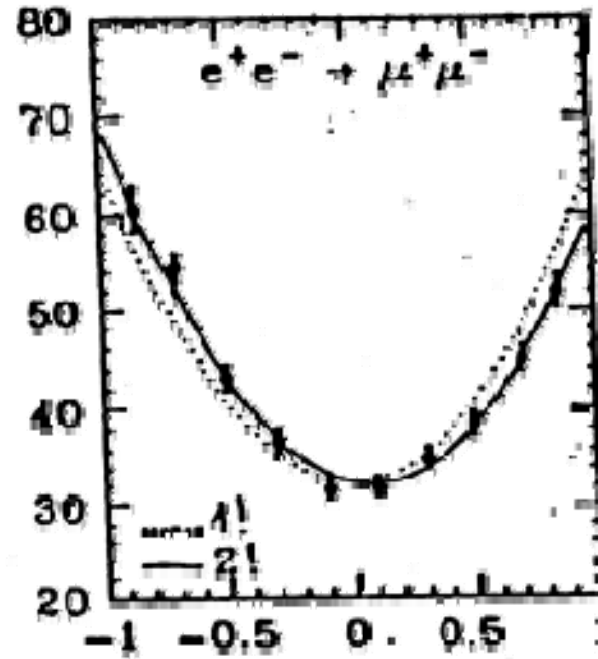
$$\langle \gamma | H_I | e^+ e^- \rangle^\alpha \propto e(0, 1, i, 0)$$

$$\langle \mu^+ \mu^- | H_I | \gamma \rangle^\alpha \propto e(0, \cos \theta, i, \sin \theta)$$

$$M(RL \rightarrow RL) = e^2 (1 + \cos \theta)$$



$\frac{d\sigma}{d\cos\theta}, \text{ nb-GeV}^2$



$\cos\theta$

$$\frac{d\sigma}{d\Omega} \Big|_{\text{unpolarised}} = \frac{\alpha^2}{4E_{CM}^2} (1 + \cos^2\theta)$$

$$\alpha = \frac{e^2}{4\pi} = \frac{1}{137}$$

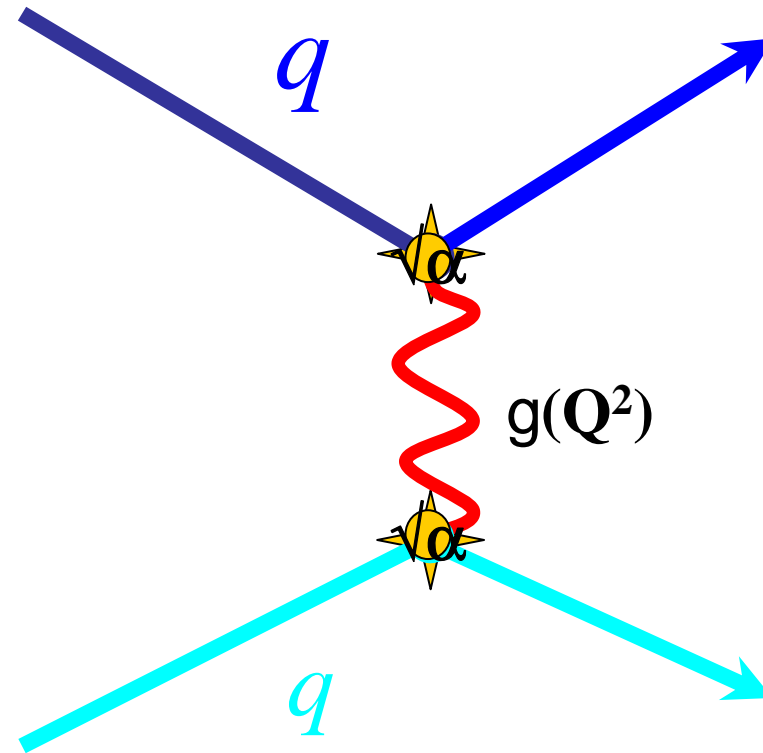
Exchange forces

Strong interactions

$$V_{strong}(r) = \frac{g_s^2}{4\pi} \frac{1}{r}$$

In momentum space :

$$V_s(|\mathbf{q}|) \propto \int V_s(|\mathbf{r}|) e^{-i\mathbf{k}\cdot\mathbf{r}} d^3\mathbf{r} \propto \frac{\alpha_s}{|\mathbf{k}|^2}$$



$$Q^2 \equiv -\mathbf{k}^2$$

"virtual gluon"

Exchange forces

Weak force

$$V_{weak}(r) = \frac{g_1 g_2}{4\pi} \frac{1}{r} e^{-M_Z r}$$

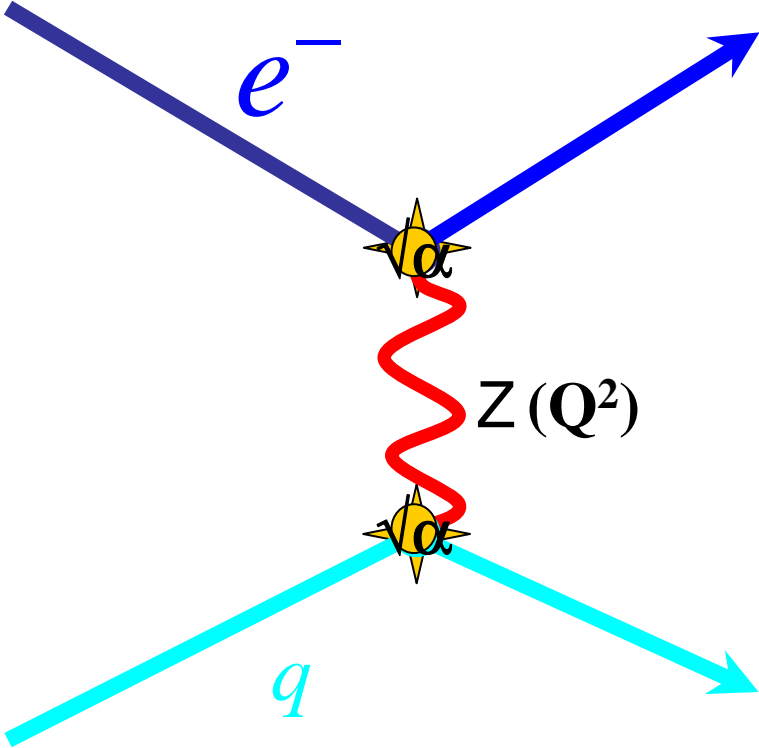
Yukawa interaction

In momentum space :

$$V_{weak}(|\mathbf{k}|) \propto \int V_{weak}(|\mathbf{r}|) e^{-i\mathbf{k}\cdot\mathbf{r}} d^3\mathbf{r} \propto \frac{\alpha_{weak}}{|\mathbf{k}|^2 + M_Z^2}$$

"virtual Z boson"

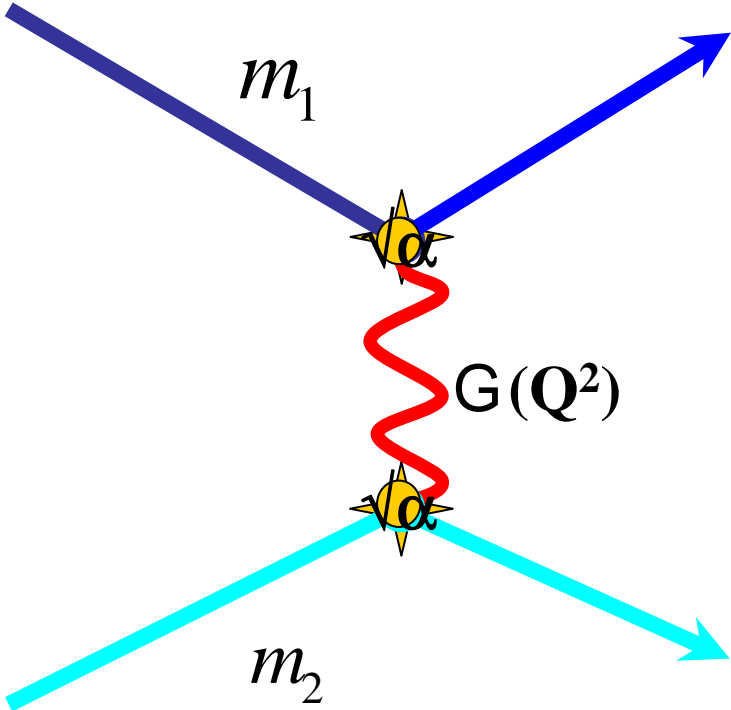
$$G_F \propto \frac{1}{M_Z^2}$$



Exchange forces

Gravitational force

$$V_{gravity}(r) = G_N \frac{m_1 m_2}{r}$$

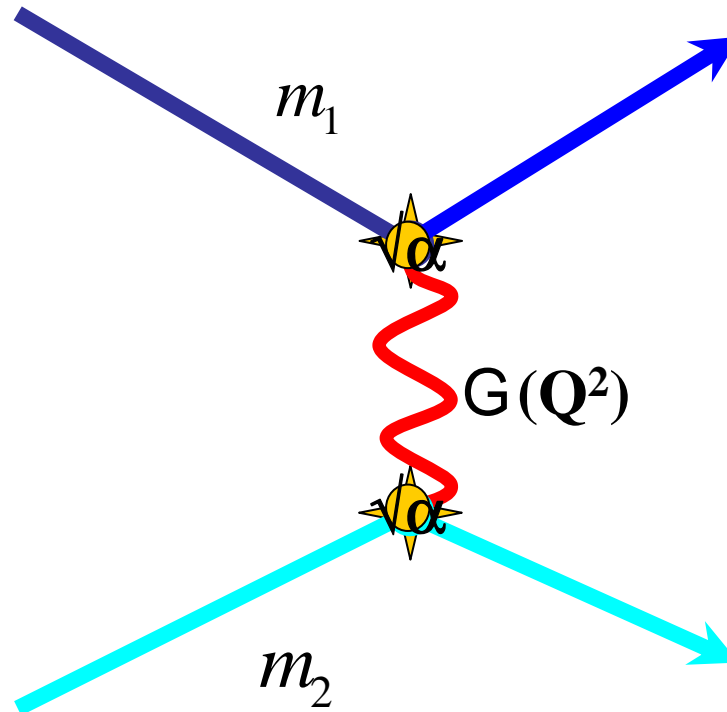


"virtual graviton"

Exchange forces

Gravitational force

$$V_{gravity}(r) = G_N \frac{m_1 m_2}{r}$$



$G_N = 6.6 \cdot 10^{-11} \text{ m}^3 / \text{kg} \cdot \text{sec}^2$...could provide *fundamental* scale:

mass = $(\hbar c / G_N)^{1/2} = 1.2 \cdot 10^{19} \text{ GeV} \equiv M_{Planck}$

length = $10^{-33} \text{ cm} \equiv l_{Planck}$

or maybe M_{Planck} *not fundamental!*

THE PERIODIC TABLE

Leptons		Quarks (each in 3 "colors")	
e 0.511 MeV	ν_e < 0.000003	d 7	u 3
μ 106	ν_μ < 0.2	s 120	c 1200
τ 1777	ν_τ < 20	b 4300	t 175,000
-1	0	-1/3	2/3

← charge

Particles like
the electron
(fermions, spin 1/2)

Particles like
the photon
(bosons, spin 1)

γ 0	photon	"electromagnetism"
g 0	gluon (8 "colors")	"strong interaction"
W^\pm 80,420	Z^0 91,188	"weak interaction"

