Fundamental principles of particle physics

G.Ross, CERN, July09

Fundamental principles of particle physics

G.Ross, CERN, July09

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, July09

Fundamental Interactions

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

† *Short range*

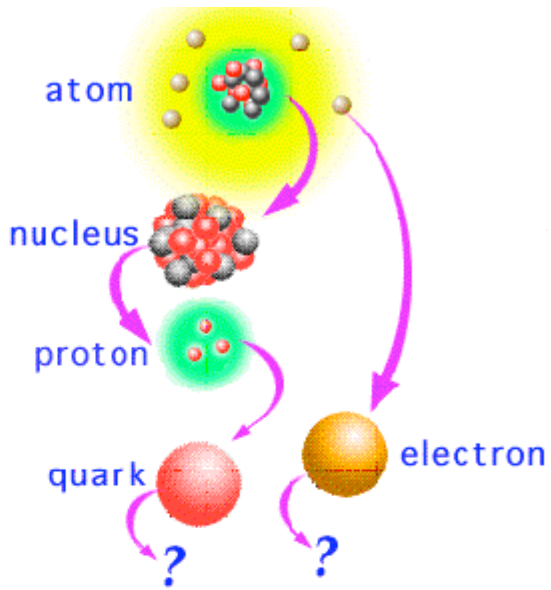
Fundamental principles of particle physics

G.Ross, CERN, July09

Fundamental Interactions

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

Fundamental Particles



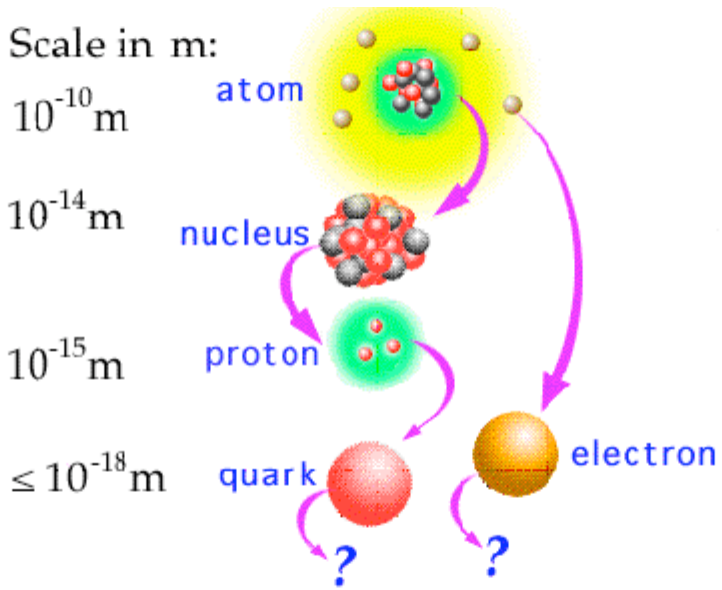
Fundamental principles of particle physics

G.Ross, CERN, July09

Fundamental Interactions

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

Fundamental Particles



Strength ↔ Size

Energy

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

Energy

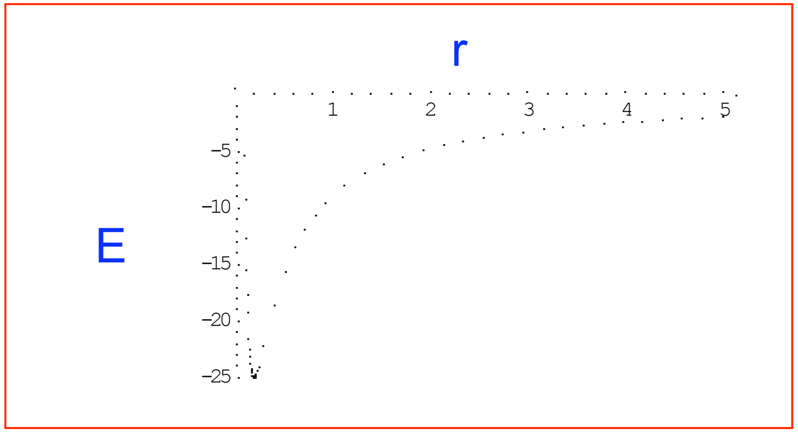
$$E = \mathrm{PE} + \mathrm{KE} = -\frac{e^2}{4\pi r} + \frac{p^2}{2m_e}$$

Heisenberg's

Uncertainty principle

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

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



Energy

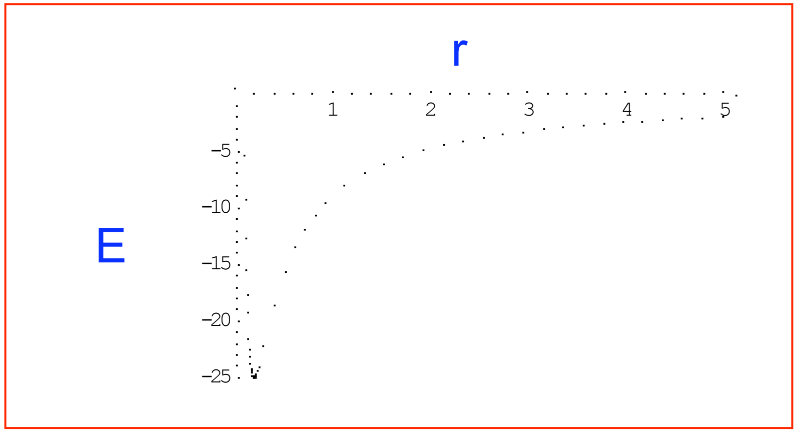
$$E = \mathrm{PE} + \mathrm{KE} = -\frac{\mathrm{e}^2}{4\pi \mathrm{r}} + \frac{p^2}{2m_e}$$

Heisenberg's

Uncertainty principle

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

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



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

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

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

Units

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

$$c = 3.10^8 \text{ m/sec}$$

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

Units

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

$$c = 3.10^8 \text{ m/sec}$$

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

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

Natural Units

$$1 = c = 3.10^{8}\ \text{m/sec} = 3.10^{23}\ \text{fm/sec}$$

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

Natural Units

$$1 = c = 3.10^8 \text{ m/sec} = 3.10^{23} \text{ fm/sec}$$

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

energy of $1\,GeV \simeq 1.6\ 10^{-10}\ J$	*...typical of elementary particles*
mass of $1\,GeV \simeq 1.8\ 10^{-27}\ kg$	
length of $1\,GeV^{-1} \simeq 0.2\ fm$	
time of $1\,GeV^{-1} \simeq 0.7\,10^{-24}$ sec	

Natural Units

$$1 = c = 3.10^{8} \text{ m/sec} = 3.10^{23} \text{ fm/sec}$$

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

energy of $1\, GeV \simeq 1.6\ 10^{-10}\ J$ ...*typical of elementary particles*

mass of $1\, GeV \simeq 1.8\ 10^{-27}\ kg$

length of $1\, GeV^{-1} \simeq 0.2\ fm$

time of $1\, GeV^{-1} \simeq 0.7\, 10^{-24}$ sec

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

Dimensionless- same in any units

Natural Units

$$1 = c = 3.10^{8}\ \text{m/sec} = 3.10^{23}\ \text{fm/sec}$$

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

energy of $1\,GeV \simeq 1.6\ 10^{-10}\ J$ ...*typical of elementary particles*

mass of $1\,GeV \simeq 1.8\ 10^{-27}\ kg$

length of $1\,GeV^{-1} \simeq 0.2\ fm$

time of $1\,GeV^{-1} \simeq 0.7\,10^{-24}\ \text{sec}$

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

Dimensionless- same in any units

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

$m_e \simeq 0.5\,10^{-3}\ GeV\ ^{\dagger}$

$\Rightarrow$

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

Fundamental Interactions and sizes

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

Atomic binding :

$$r_{atom} \sim 10^{-10}\, m \simeq 10^{5}\ fm$$

$$m_e \simeq 0.5\, 10^{-3}\ GeV$$

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

Fundamental Interactions and sizes

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

Atomic binding :

$$r_{atom} \sim 10^{-10}\, m \simeq 10^{5}\, fm$$

$$m_e \simeq 0.5\, 10^{-3}\ GeV$$

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

Nuclear binding :

$$r_{nucleus} \sim 10^{-15}\, m \simeq 1\, fm$$

$$m_p \simeq 1\, GeV$$

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

Fundamental Interactions and sizes

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

Atomic binding :

$$r_{atom} \sim 10^{-10}\,m \simeq 10^{5}\,fm$$
$$m_e \simeq 0.5\,10^{-3}\,GeV$$

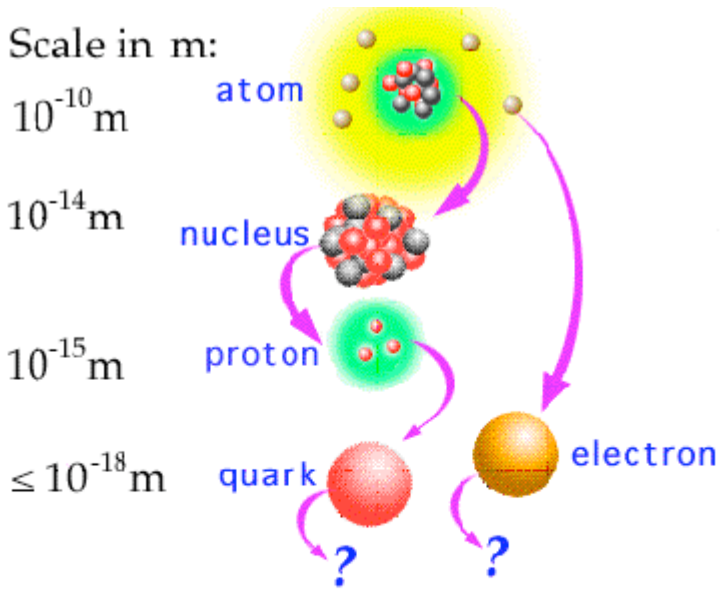
$$\alpha_{em} = \frac{e^2}{4\pi} \approx 10^{-2}$$

Nuclear binding :

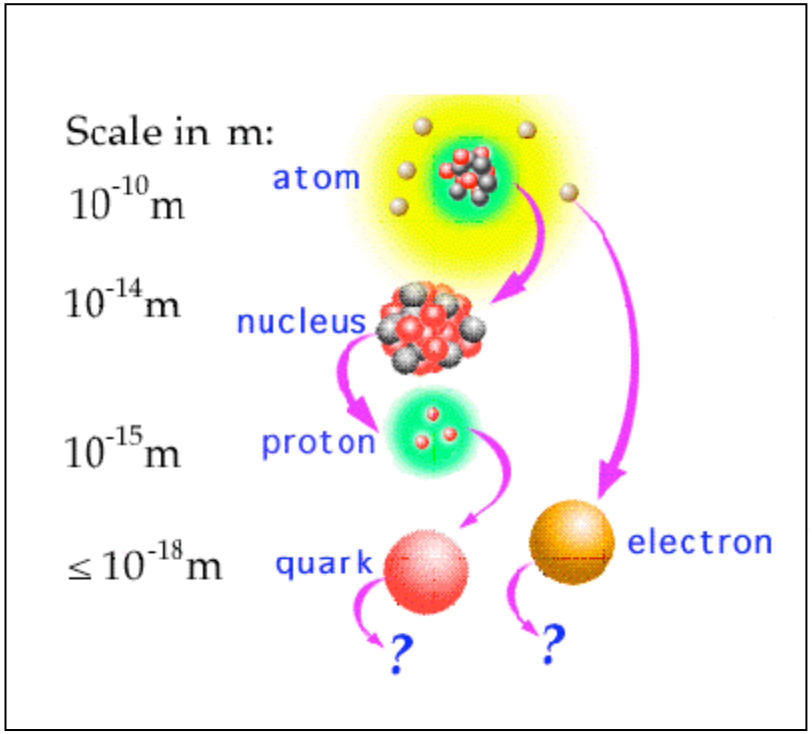
$$r_{nucleus} \sim 10^{-15}\,m \simeq 1\,fm$$
$$m_p \simeq 1\,GeV$$

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

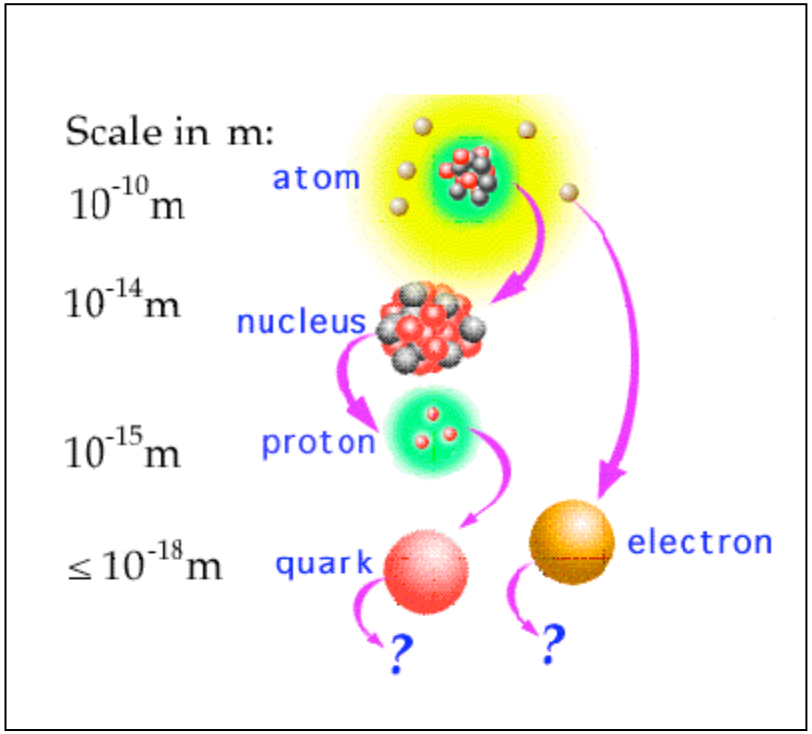
	Strength
Strong	$\alpha_s = \frac{g_s^2}{4\pi\hbar c} \sim 1$
Electromagnetic	$\alpha_{em} = \frac{e^2}{4\pi\hbar c} \sim \frac{1}{137}$
Weak	$G_F m_p^2 \sim 10^{-5}$
Gravitational	$G_N m_p^2 \sim 10^{-36}$



Elementary particles



Elementary particles



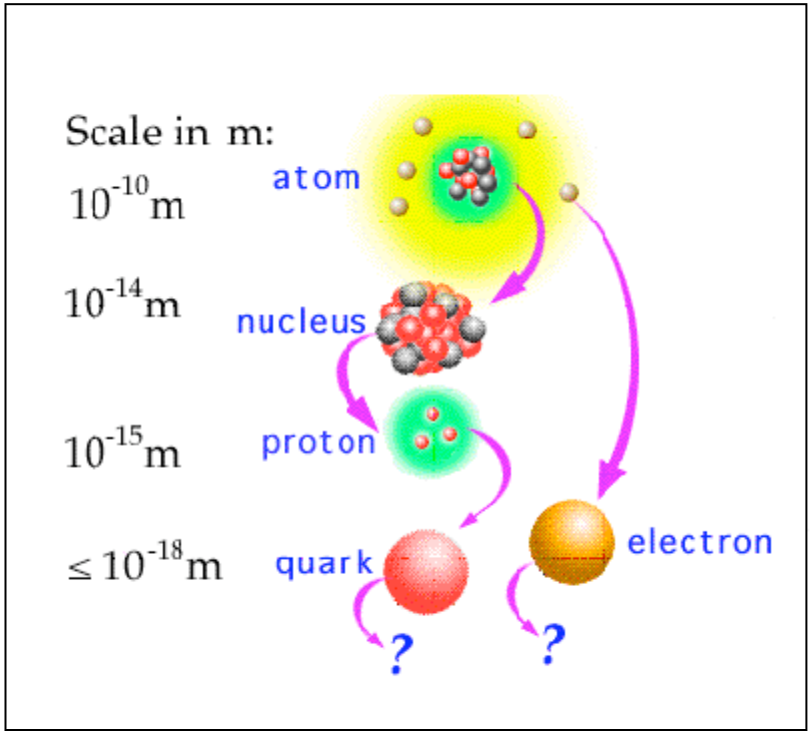
Leptons :

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

$$\nu_e, \quad \nu_\mu, \quad \nu_\tau$$

Elementary particles

Isador Rabi 1937 “Who ordered the muon?”



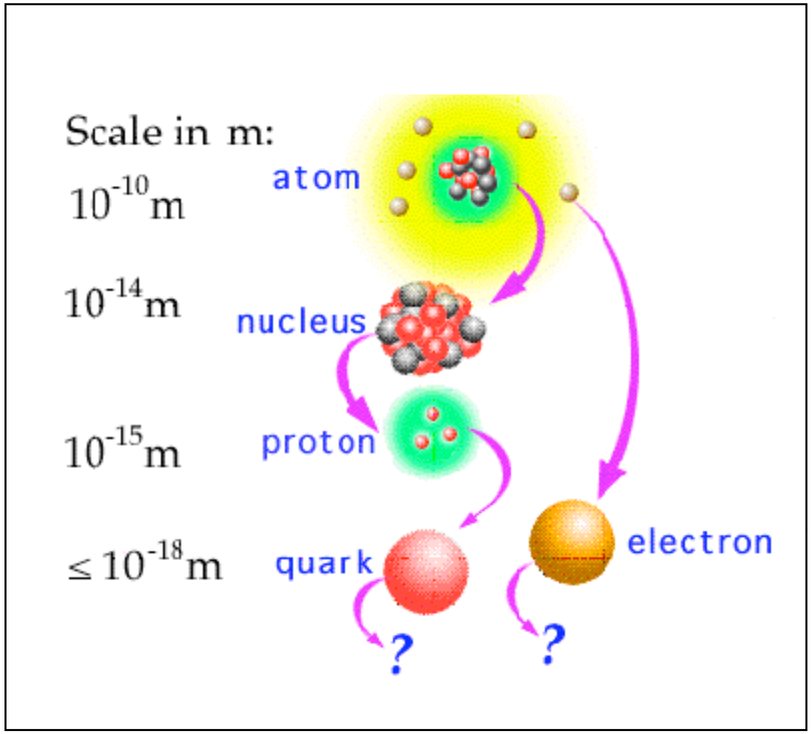
Leptons :

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

$$\nu_e, \quad \nu_\mu, \quad \nu_\tau$$

Elementary particles

Isador Rabi 1937 "Who ordered the muon?"



Leptons :

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

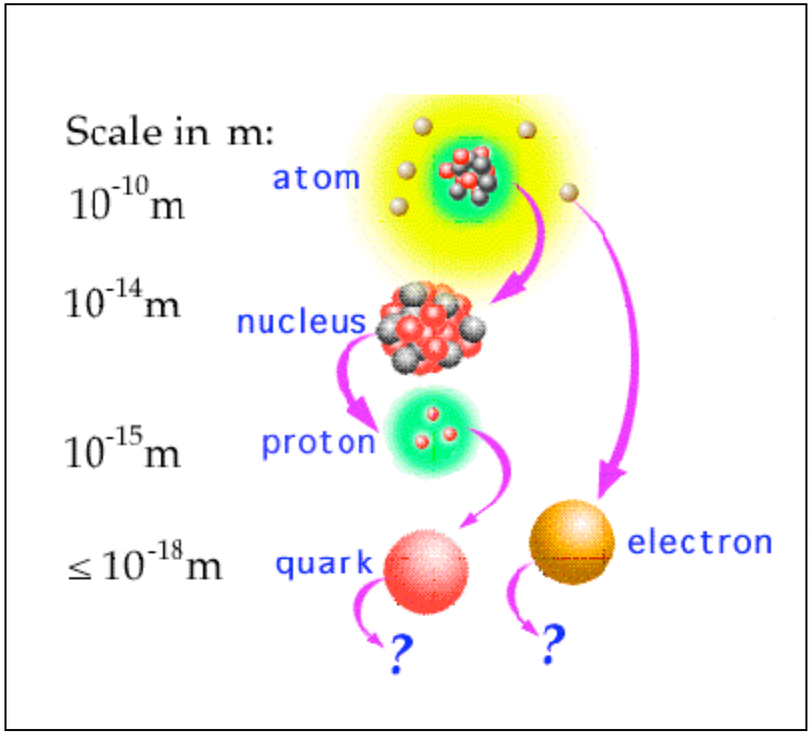
$$\nu_e, \quad \nu_\mu, \quad \nu_\tau$$

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^{-}

$\nu_e, \quad \nu_\mu, \quad \nu_\tau$

Quarks :

$u, \quad c, \quad t$
$u, \quad c, \quad t$
$u, \quad c, \quad t$

$d, \quad s, \quad b$
$d, \quad s, \quad b$
$d, \quad s, \quad b$

Hadrons : 3 strong "colour" charges

Elementary forces

Exchange forces

Electromagnetism

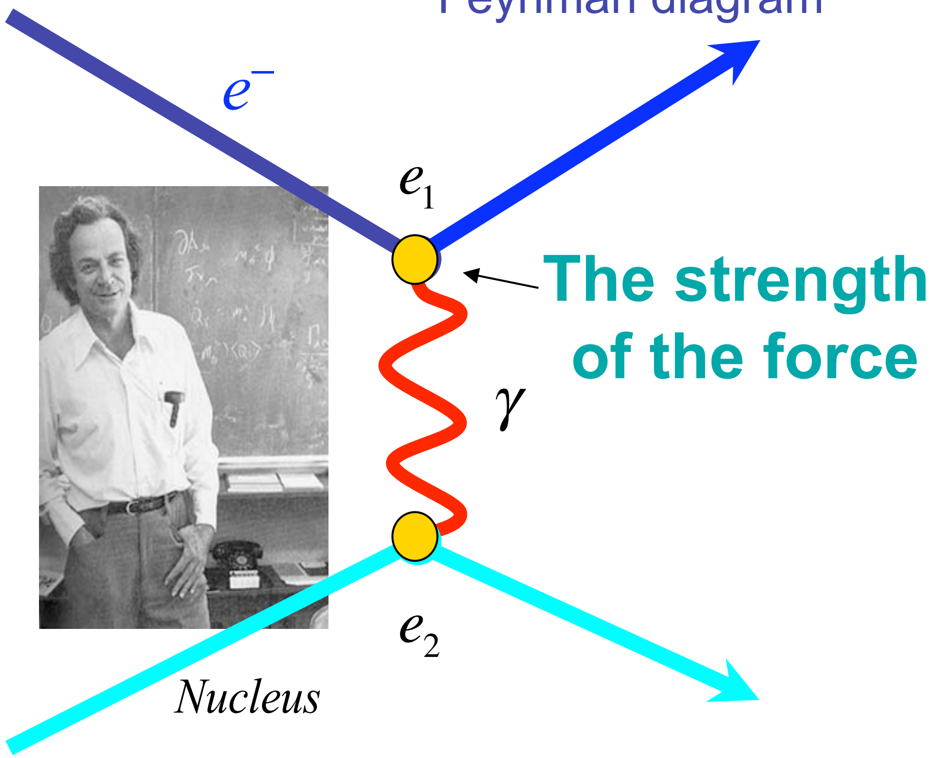
$$V_{em}(r) = \frac{e_1 e_2}{4\pi} \frac{1}{r}$$

Exchange forces

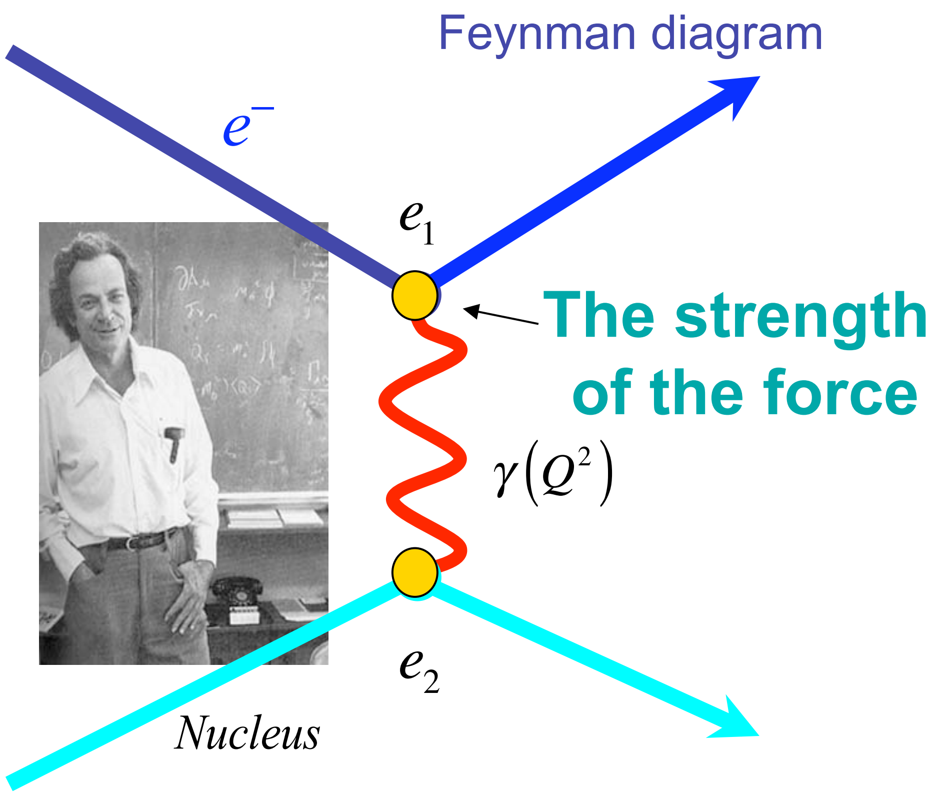
Electromagnetism

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

Feynman diagram



Exchange forces



Electromagnetism

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

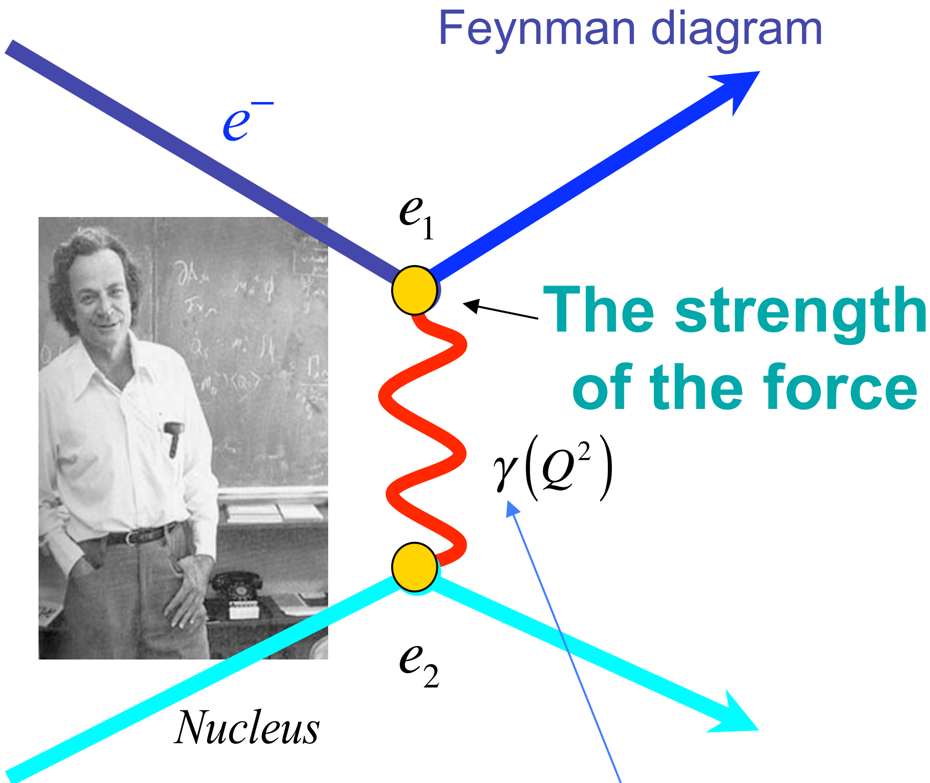
Experiments conducted in momentum space :

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

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

$$\text{"}\textit{virtual photon}\text{"}$$

Exchange forces



Electromagnetism

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

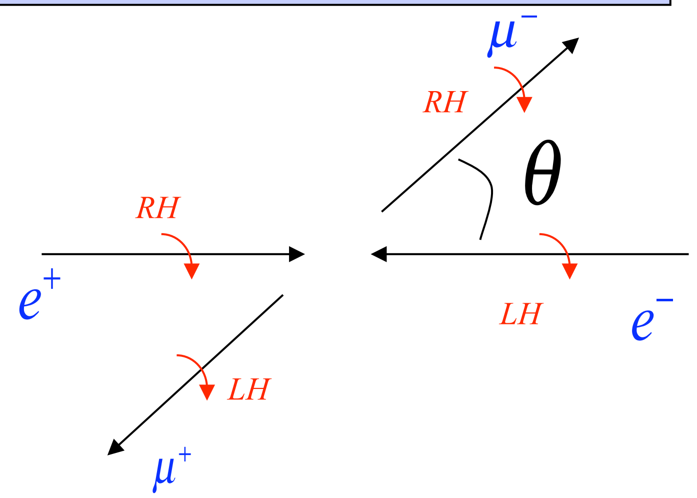
Experiments conducted in momentum space :

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

Photon "propagator"

Application to a scattering processes

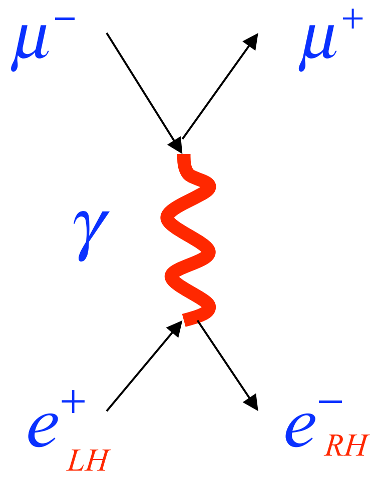
$$e^+e^- \rightarrow \mu^+\mu^-$$



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

Feynman diagram

QM : Transition amplitude $\langle \text{final state} | H_I | \text{initial state} \rangle$

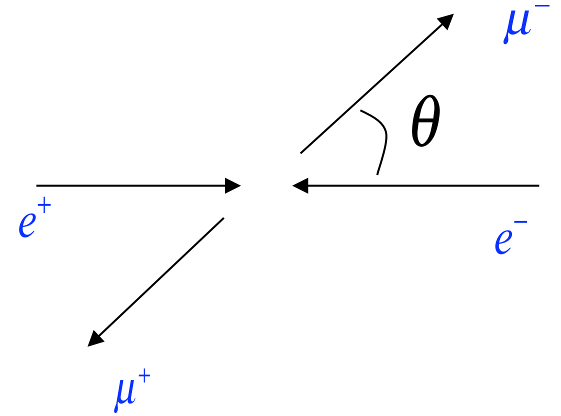


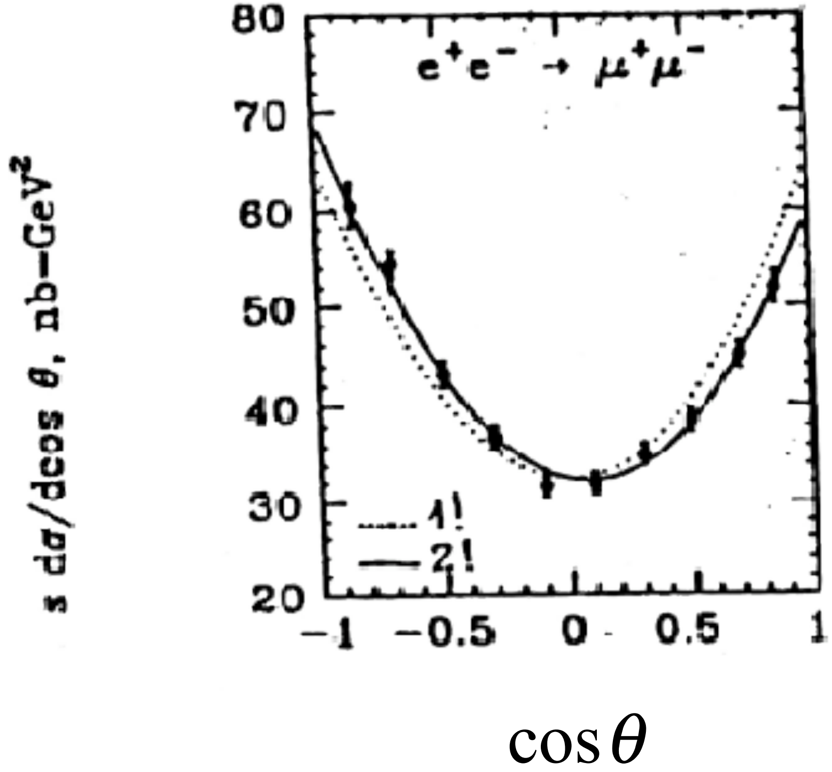
$$M \propto \langle \mu^+\mu^- | H_I | \gamma \rangle^\alpha \langle \gamma | H_I | e^+e^- \rangle_\alpha$$

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

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

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





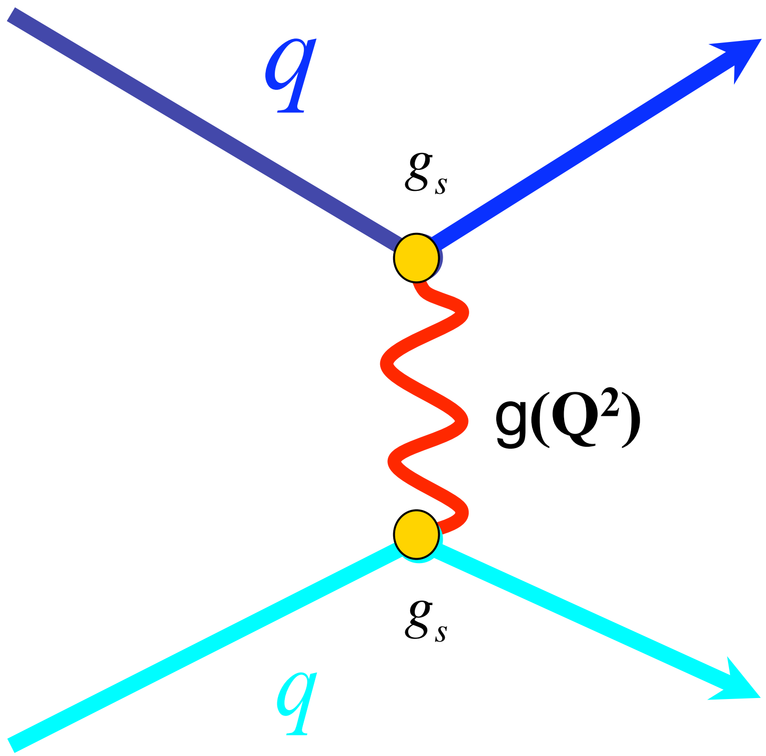
$$\frac{d\sigma}{d\Omega}\Big|_{unpolarised} = \frac{\alpha^2}{4E_{CM}^2}\left(1+\cos^2\theta\right)$$

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

Exchange forces

Strong interactions

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



In momentum space :

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

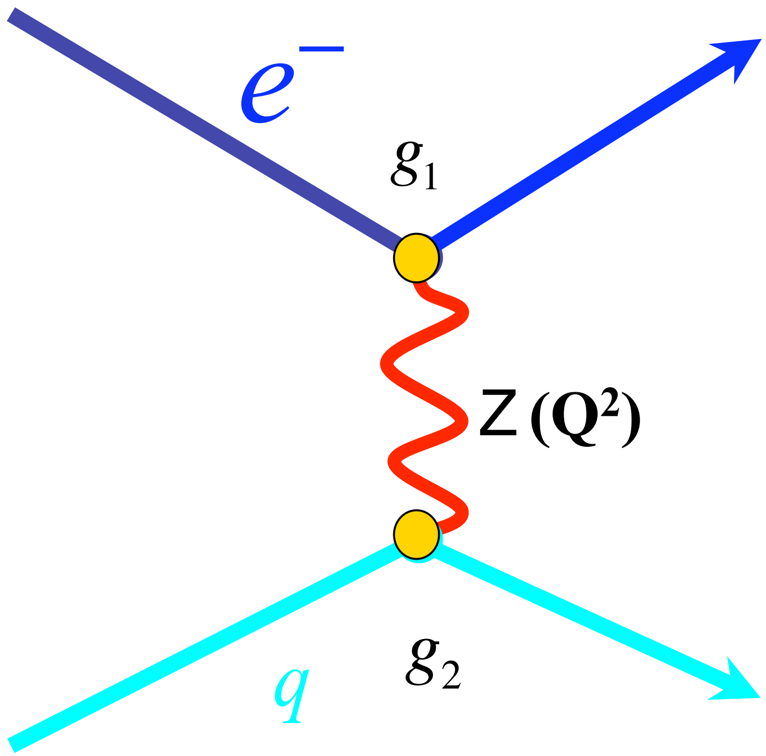
$$Q^2 \equiv -\mathbf{k}^2$$

"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 :

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

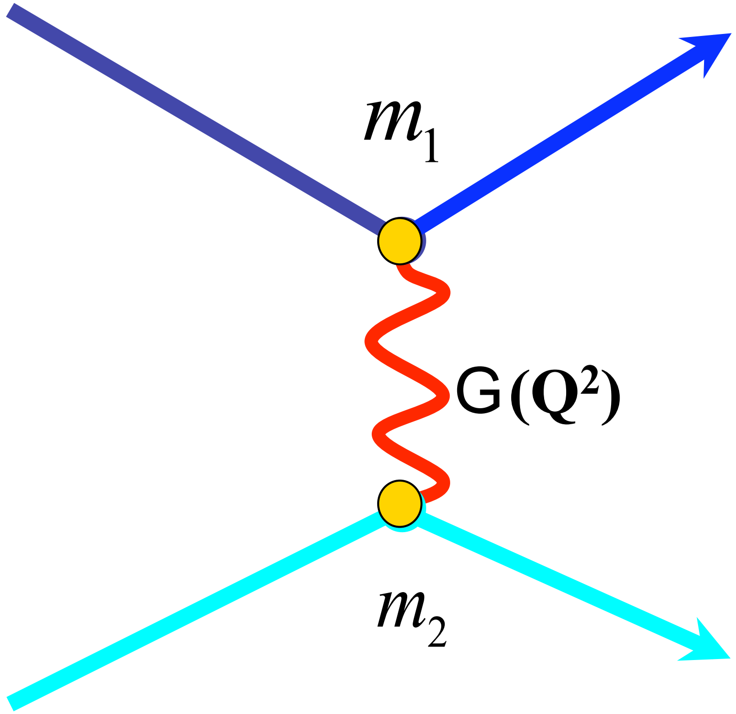
"virtual Z boson"

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

Exchange forces

Gravitational force

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

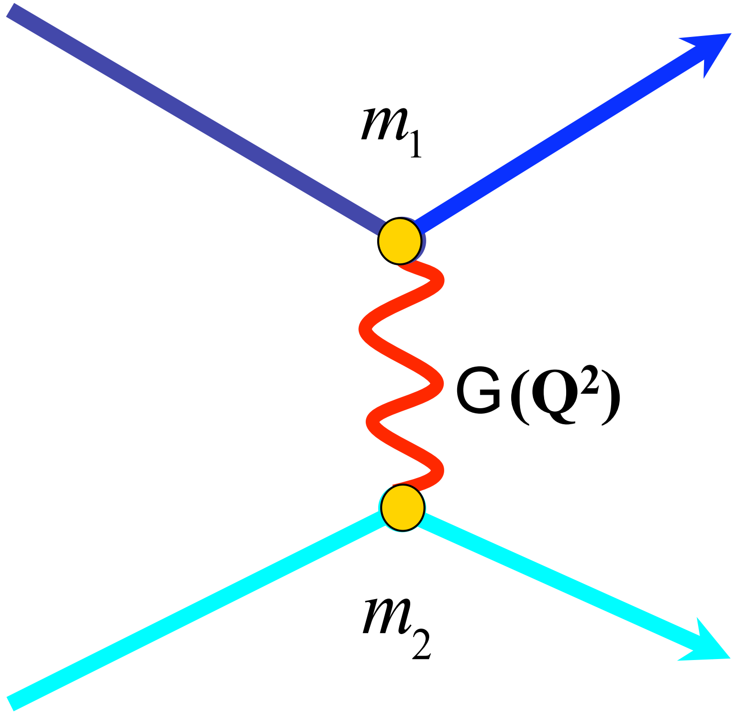


"*virtual graviton*"

Exchange forces

Gravitational force

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



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

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

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

or maybe M_{Planck} *not fundamental!*

THE PERIODIC TABLE

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

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 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"

References useful for future lectures:

Halzen & Martin, ‘Quarks & leptons’, Wiley, 1984

Aitchison & Hey, ‘Gauge Theories in Particle Physics’, Taylor and Francis, 2005

[Peskin & Schroeder, ‘Quantum Field Theory’, Addison-Wesley, 1995]