Fundamental principles of particle physics

G.Ross, CERN, July05

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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

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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*

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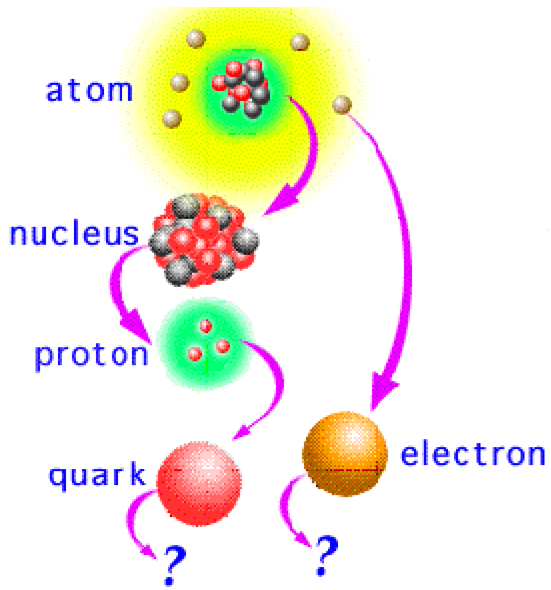
Fundamental Particles



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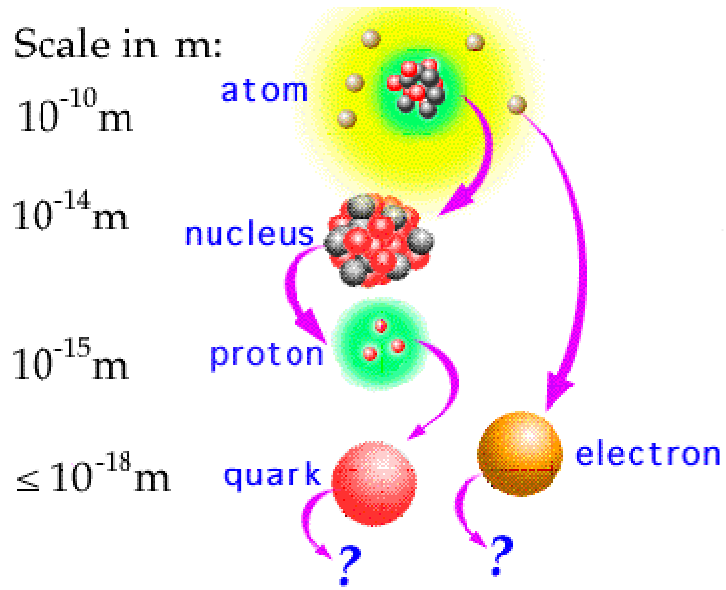

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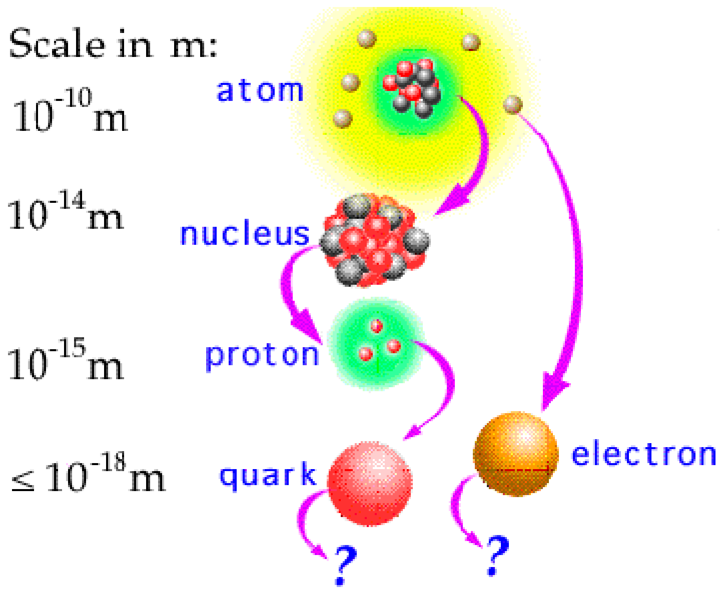
Fundamental Particles



Strength ⟷ Size

Energy

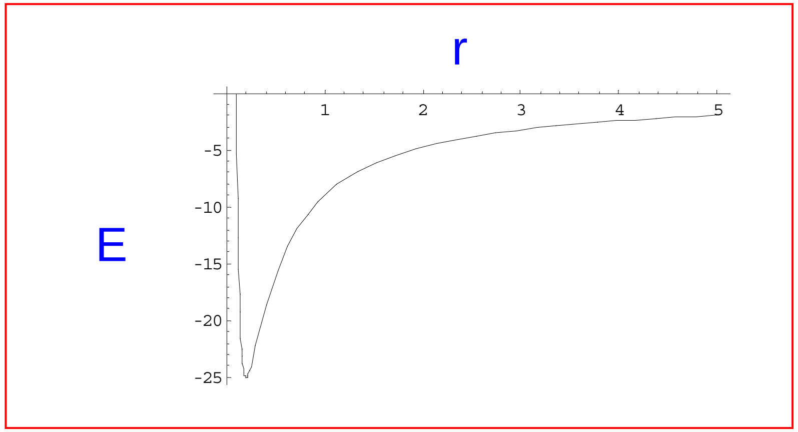
$$E = \mathrm{PE} + \mathrm{KE} = -\frac{\mathrm{e}^2}{4\pi \mathrm{r}} + \frac{p^2}{2m_e}$$

Heisenberg's

Uncertainty principle

$$\Delta \mathrm{p}.\Delta \mathrm{r} \geq \hbar$$

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



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

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

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

Units

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

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

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

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

Natural Units

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

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

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

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

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

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

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

Dimensionless- same in any units

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

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

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

Fundamental Interactions and sizes

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

Atomic binding :

$$r_{atom} \sim 10^{-10}\,m \sim 10^{5}\,fm$$
$$m_e \sim 0.5\,10^{-3}\,GeV$$
$$\alpha_{em} = \frac{e^2}{4\pi} \approx 10^{-2}$$

Nuclear binding :

$$r_{nucleus} \sim 10^{-15}\,m \sim 1\,fm$$
$$m_p \sim 1\,GeV$$
$$\alpha_{strong} = \frac{g^2}{4\pi} \approx 1$$

	Strength
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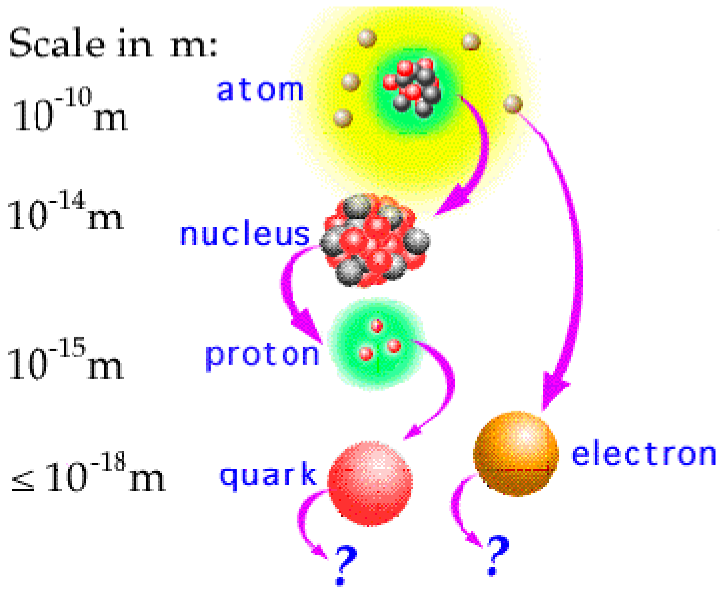
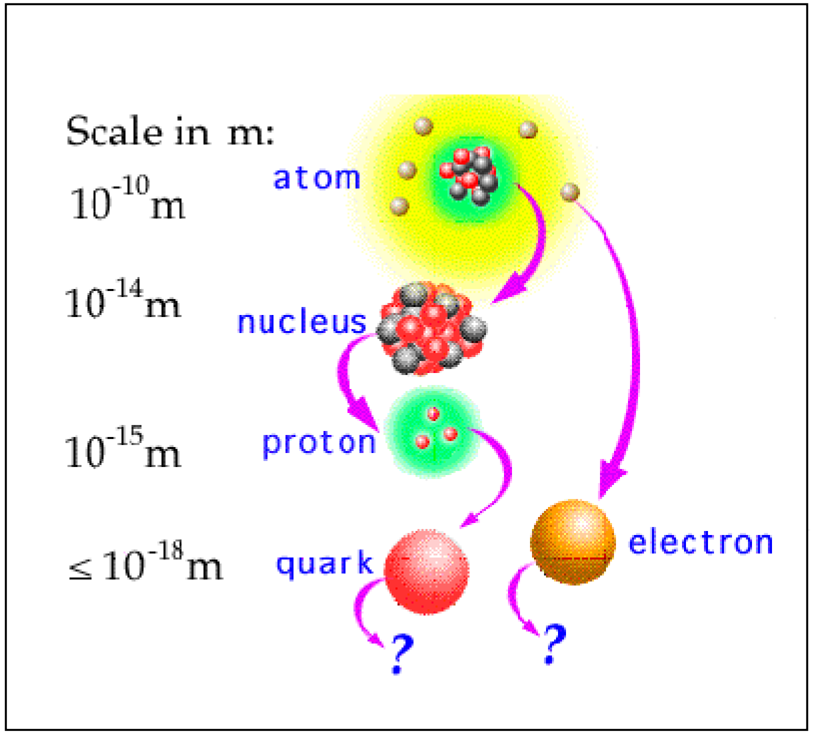


Elementary particles



Leptons :

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

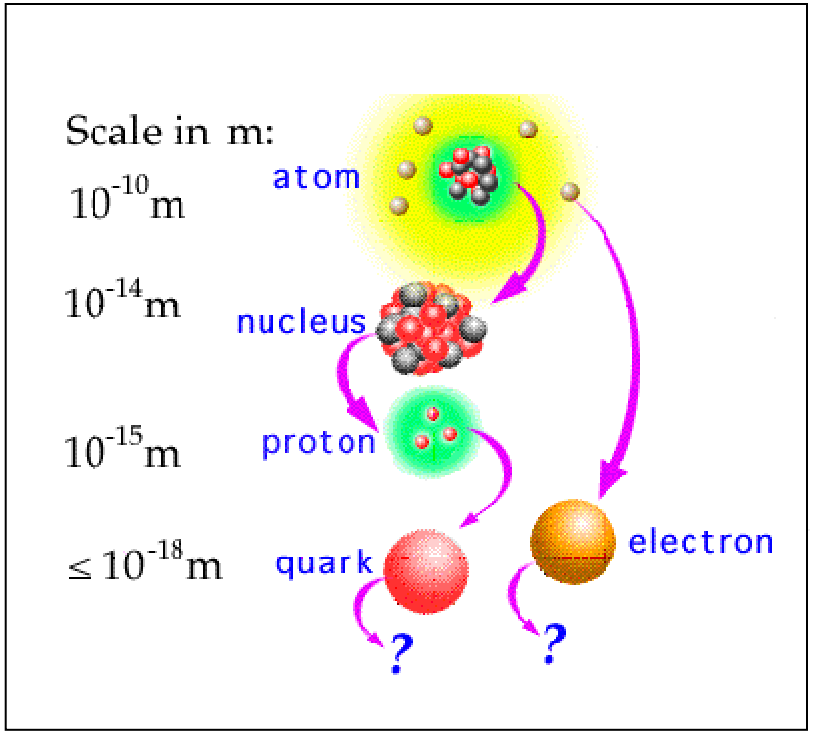
$$\nu_e, \quad \nu_\mu, \quad \nu_\tau$$

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 :

$u, \quad c, \quad t$

$u, \quad c, \quad t$

$u, \quad c, \quad t$

$d, \quad s, \quad b$

$d, \quad s, \quad b$

$d, \quad s, \quad b$

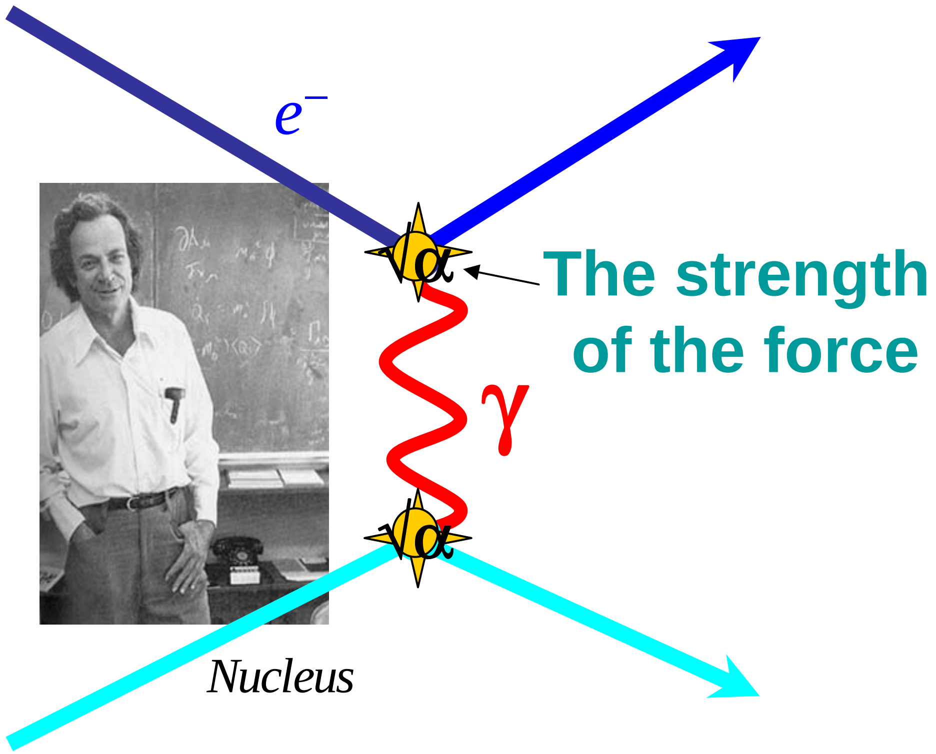
Hadrons : 3 strong "colour" charges

Elementary forces

Exchange forces

Electromagnetism

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



Experiments conducted in momentum space :

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

Exchange forces

Electromagnetism

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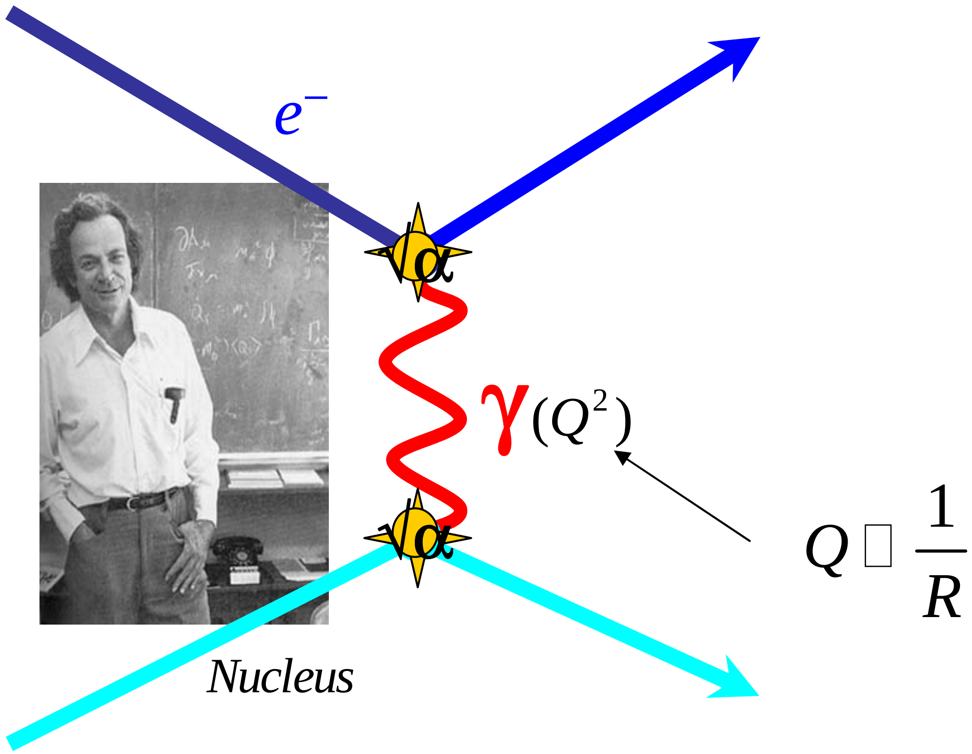


Experiments conducted in momentum space :

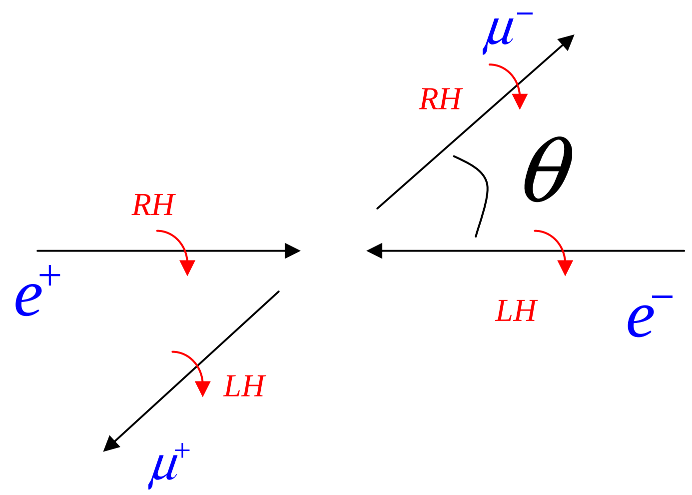
$$V_{em}(|\mathbf{q}|) \sim \int V_{em}(|\mathbf{r}|) e^{-i\mathbf{k}.\mathbf{r}} d^3\mathbf{r} \sim \frac{\alpha}{|\mathbf{k}|^2}$$

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

"virtual photon"

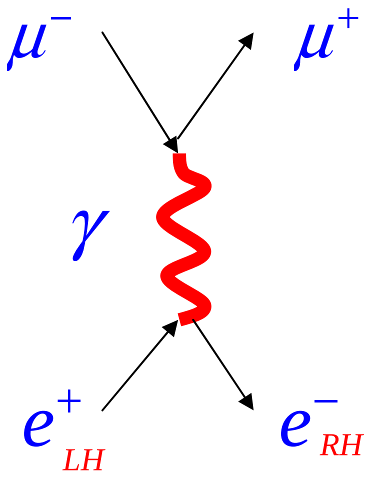
Application to a scattering processes

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



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

Feynman diagram



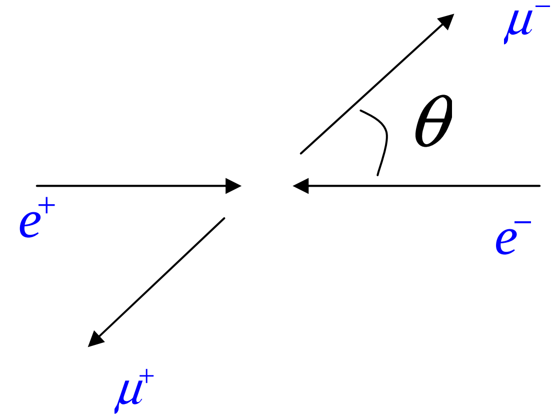
QM : Transition amplitude <final state$|H_I|$initial state>

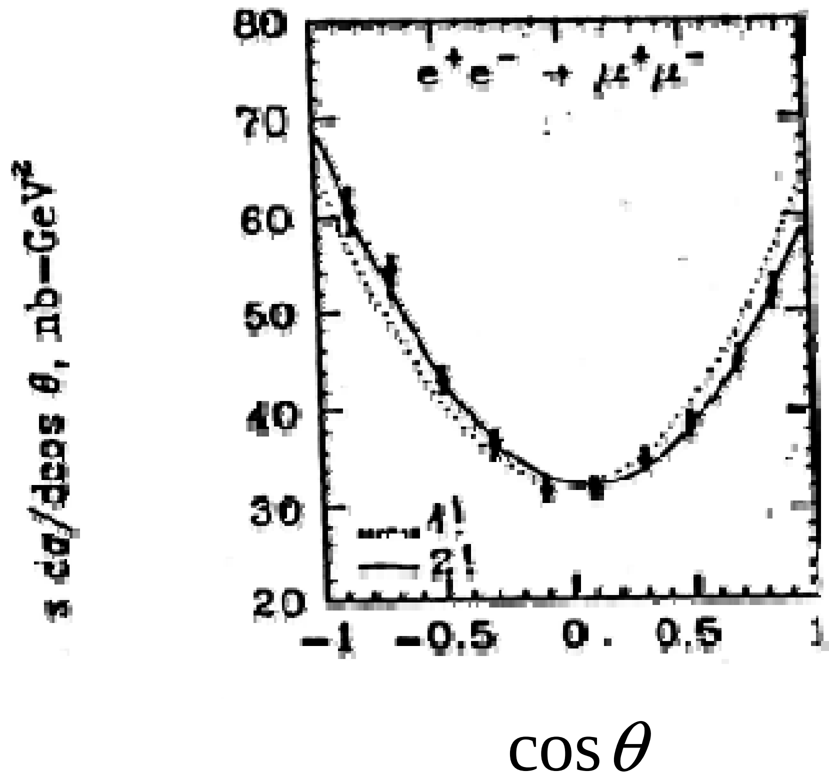
$$M \propto <\mu^+\mu^- | H_I | \gamma >^\alpha < \gamma | H_I | e^+e^- >_\alpha$$

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

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

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





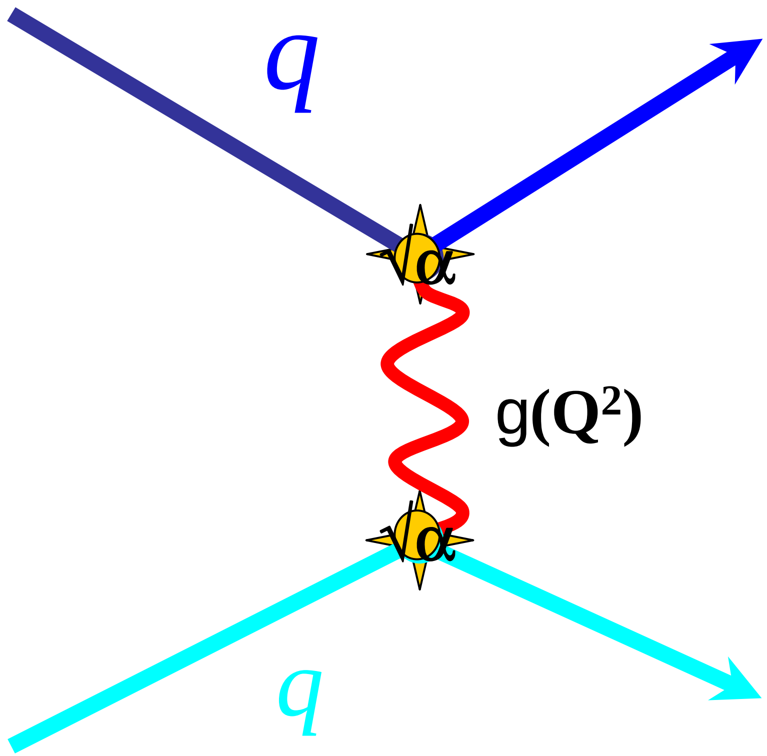
$$\left.\frac{d\sigma}{d\Omega}\right|_{unpolarised} = \frac{\alpha^2}{4E_{CM}^2}\left(1+\cos^2\theta\right)$$

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

Exchange forces

Strong interactions

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



In momentum space :

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

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

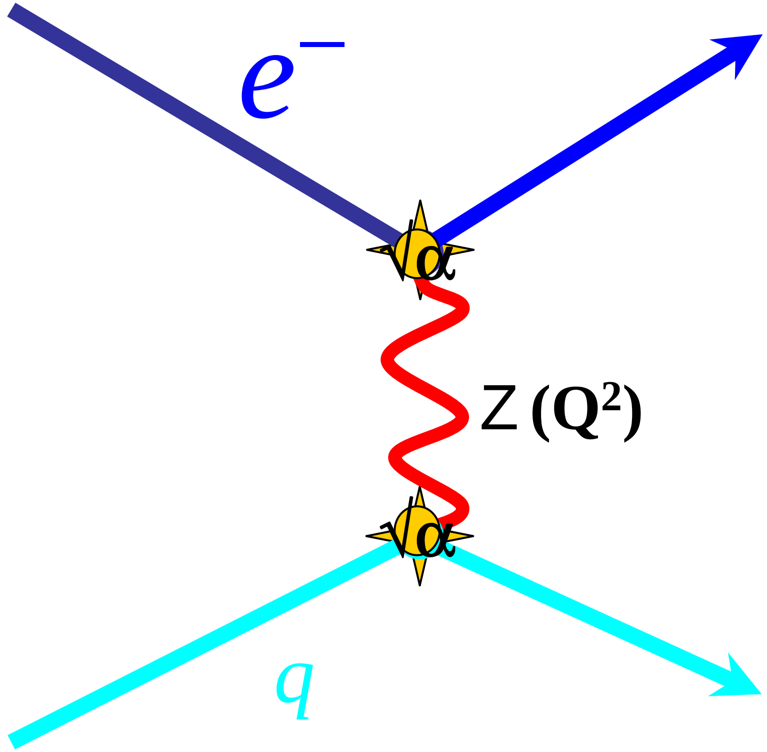
$$\text{"}\textit{virtual gluon}\text{"}$$

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 :

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

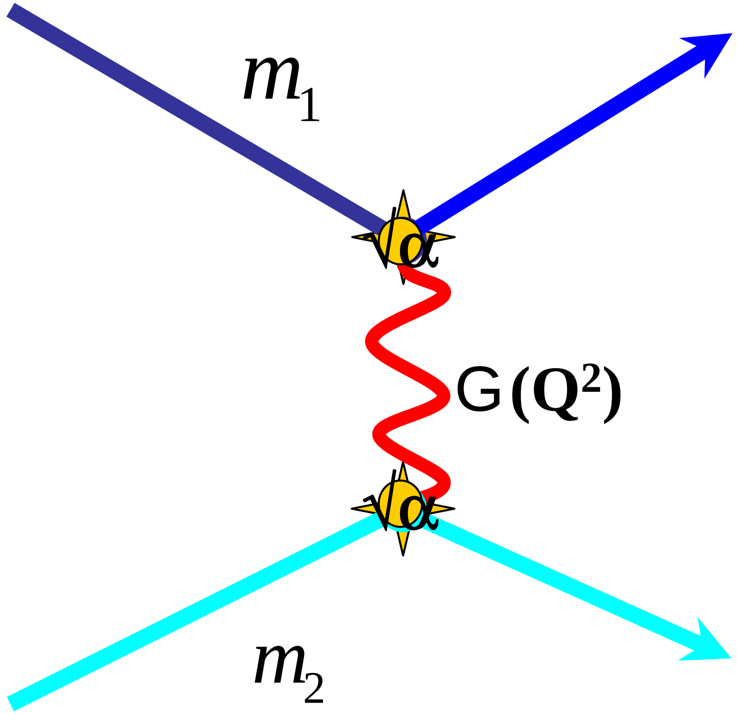
"virtual Z boson"

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

Exchange forces

Gravitational force

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

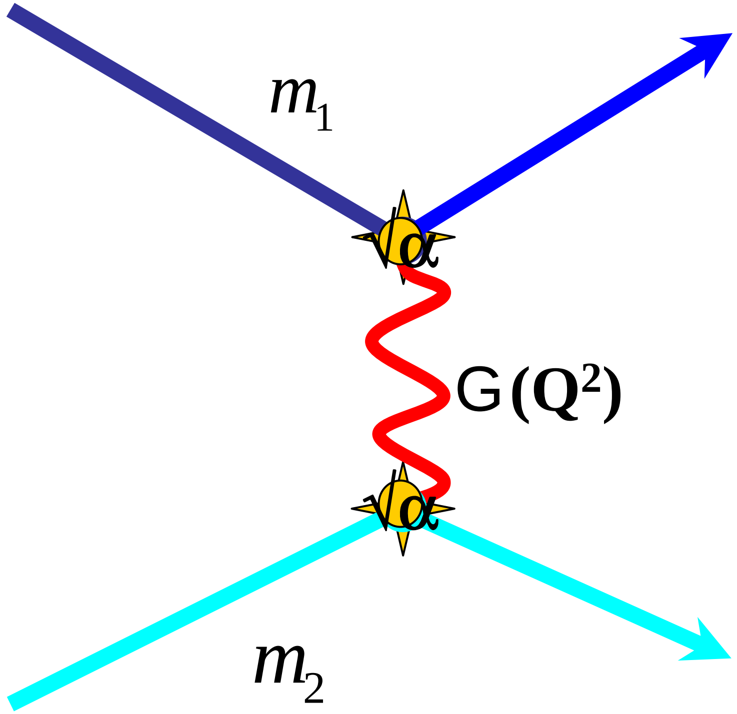


"virtual graviton"

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*:

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

$length = 10^{-33}\ cm$

or maybe M_{Planck} *not fundamental* !

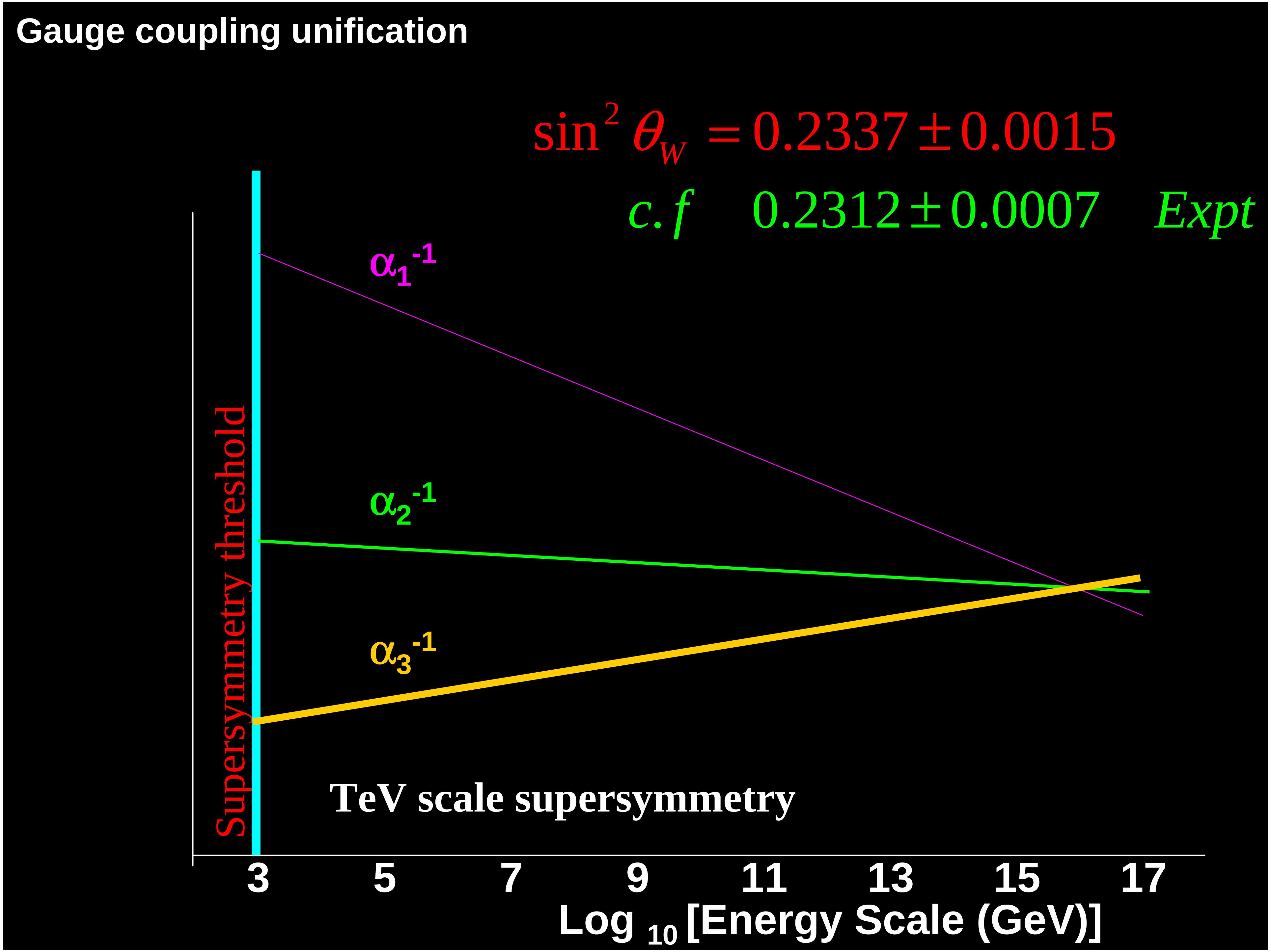
THE PERIODIC TABLE

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

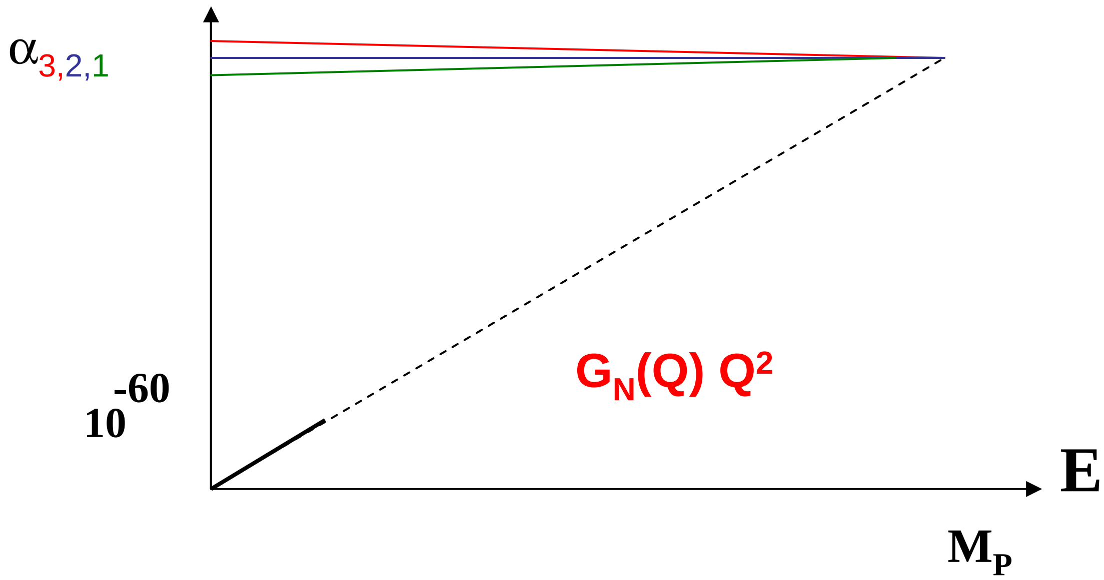
Leptons		Quarks (each in 3 "colors")		
e 0.511 MeV	ν_e < 0.000003	d 7	u 3	
μ 106	ν_μ < 0.2	s 120	c 1200	
τ 1777	ν_τ < 20	b 4300	t 175,000	
-1	0	$-1/3$	$2/3$	← charge

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"



Gauge coupling unification
$\sin^2\theta_W = 0.2337 \pm 0.0015$
$c.f \quad 0.2312 \pm 0.0007 \quad Expt$
α_1^{-1}
α_2^{-1}
α_3^{-1}
Supersymmetry threshold
TeV scale supersymmetry
3
5
7
9
11
13
15
17
Log 10 [Energy Scale (GeV)]



$\alpha_{3,2,1}$
10^{-60}
$G_N(Q)\,Q^2$
E
M_P