I. Introduction

1. Building blocks of matter and their interactions
2. Experimental tools
3. Natural units

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1. Building blocks of matter and their interactions

1.1 Leptons and Quarks

Point-like, spin ½ , elementary building blocks of matter

	Flavor-Generation	$Q\,[e]$
Leptons	$\begin{pmatrix}\nu_e\\ e\end{pmatrix}\quad\begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix}\quad\begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix}$	$\begin{pmatrix}0\\ -1\end{pmatrix}$
Quarks	$\begin{pmatrix}u\\ d\end{pmatrix}\quad\begin{pmatrix}c\\ s\end{pmatrix}\quad\begin{pmatrix}t\\ b\end{pmatrix}$	$\begin{pmatrix}+2/3\\ -1/3\end{pmatrix}$

Anti-particles with opposite charge to each lepton/quark

Lepton Properties

- All leptons exist as free particles
- Lepton number conservation

$$\begin{array}{cccc} & \pi^+ & \rightarrow \mu^+ & \nu_\mu \\ L_\mu = 0 & & \rightarrow -1 & 1 \end{array}$$

In the standard model lepton flavor conservation is a consequence of vanishing neutrino masses.

Lepton flavor violation also for charged leptons ?

	mass·c^2	lifetime	Lepton number
e^-	511 keV	∞	L_e=1
μ^-	106 MeV	2.2 μs	L_μ=1
τ^-	1.78 GeV	0.3 ps	L_τ=1
ν_e	< 3 eV	∞	L_e=1
ν_μ	<190 keV	∞	L_μ=1
ν_τ	<18.2 MeV	∞	L_τ=1

In the Standard Model neutrinos are assumed to be massless. Recently clear evidence for neutrino oscillations have been observed: explained with non-zero masses. Mass difference are very small: $m_\nu < 3$ eV for all Neutrinos

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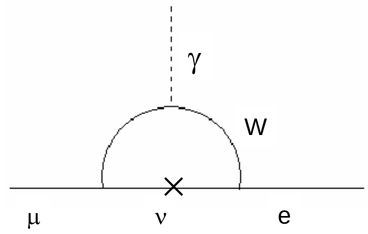
Impressive limits for lepton flavor violation:

$$BR_{\mu\rightarrow e\gamma} = \frac{\Gamma(\mu \rightarrow e\gamma)}{\Gamma(\mu \rightarrow e\bar{\nu}_e\nu_\mu)} < 1.2\cdot 10^{-11}$$

$$BR_{\mu\rightarrow e} = \frac{\Gamma(\mu^- + (Z,A) \rightarrow e + (Z,A))}{\Gamma(\mu^-(Z,A) \rightarrow \nu_\mu + (Z-1,Z))} < 8\cdot 10^{-13}$$ Muon capture

proposed: MEG $BR_{\mu\rightarrow e\gamma} < 5\cdot 10^{-14}$ proposed: MECO $BR_{\mu\rightarrow e} < 8\cdot 10^{-17}$ (Al)

Standard model process:



Effect of neutrino mass is “GIM suppressed” by a factor of $(\Delta m_\nu^2/M_W^2)^2 \sim 10^{-50}$ and hence unobservable

SUSY-GUT scenarios predict larger BR for LFV decays.

Quark Properties

- Quarks are confined in hadrons: mesons ($q\bar{q}$) or baryons (qqq)
- Quark masses cannot be measured directly
- Constituent quark masses: determination from observed hadron mass spectra + assumed binding potential

  For the light quarks (u,d,s,) the masses are estimates of the "current masses" which appear in the QCD Lagrangian
- Quarks carry color charge

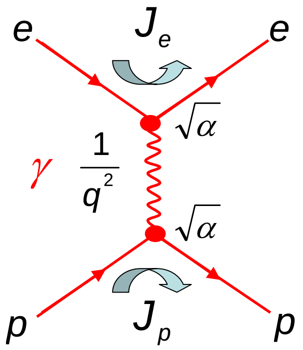
	quark mass·c^2	Flavour number
u, d	2 - 8 MeV	I=±1/2
s	80 - 130 MeV	S=-1
c	1.15 - 1.35 GeV	C=+1
b	4.6 – 4.9 GeV	B=-1
t	~175 GeV	T=+1

1.2 Fundamental interactions

IA	Mediator boson	strength
Strong	Gluon g	1
Elektro-magnetic	Photon	$\sim 10^{-2}$
weak	$W^{\pm}$ Z^0	$\sim 10^{-5}$
Gravitation	Graviton	$\sim 10^{-39}$

- Forces are mediated by virtual field quanta (bosons)
- Virtual bosons transfer energy and momentum for which in general $m_{Boson}^2 \neq E^2 - p^2$ (off mass-shell)

a.) Electro-magnetic interaction



ep scattering:

$$M_{fi} \sim J_e \cdot \sqrt{\alpha} \cdot \frac{1}{q^2} \cdot \sqrt{\alpha} \cdot J_p \sim \frac{\alpha}{q^2}$$

Diff. cross section:

$$d\sigma \sim \left|M_{fi}\right|^2 \sim \frac{\alpha^2}{q^4}$$

(Rutherford formula)

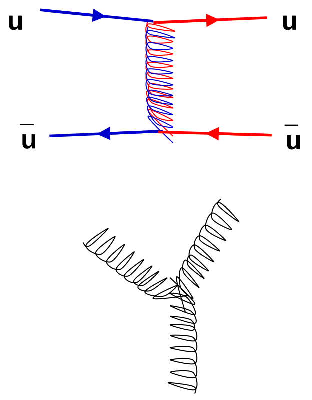
$$\alpha = \alpha_{QED} = \frac{e^2}{4\pi\varepsilon_0\hbar c} \underset{\substack{\uparrow \\ \hbar = c = 1}}{=} \frac{e^2}{4\pi}$$

b.) Strong interaction

Color charges and gluons.

- Quarks and anti-quarks carry 3 color different (anti) charges
- Interaction is mediated by 8 massless colored gluons (spin 1)
- Color symmetry is exact: strong interaction only depends on color and is independent of quark flavor
- Color charge of gluons ⇒ gluon-gluon coupling: triple gluon vertex

q: r g b **$\bar{q}$: $\bar{r}$ $\bar{g}$ $\bar{b}$**



How strong is “strong” ?

Use decay times of the following kinematically similar Σ decays:

Σ decays	Q-value	Decay time	IA
$\Sigma^0(1192, \lvert uds\rangle) \to \Lambda\gamma$	74 MeV	10^{-19} s	e.m.
$\Sigma^+(1189, \lvert uus\rangle) \to p\pi^0$	189 MeV	10^{-10} s	weak
$\Sigma^0(1385, \lvert uds\rangle) \to \Lambda\pi^0$	208 MeV	10^{-23} s	strong

For the decay times one finds

$$\tau = \frac{\hbar}{\Gamma} \sim \frac{1}{\lvert M_{fi}\rvert^2} \sim \frac{1}{\alpha_{IA}^2}$$

α_{IA} = effective coupling of decay process

Neglecting kinematics:

$$\frac{\tau(\Sigma \to \Lambda\gamma)}{\tau(\Sigma \to \Lambda\pi^0)} \approx \frac{\alpha_s^2}{\alpha_{em}^2} \approx 10^{-4}$$

with $\alpha_{em} = \frac{1}{137} \Rightarrow \alpha_s \approx 1$

c.) Weak interaction

Mediated by massive bosons:

$$M_W \approx 80\,GeV/c^2$$
$$M_Z \approx 91\,GeV/c^2$$

$$M_{fi} \sim g_w \cdot \frac{1}{q^2 - M_W^2} \cdot g_w$$

for Σ decay: $q^2 << M_W^2$: $M_{fi} \sim \frac{g_w^2}{M_W^2} \sim G_F \approx 10^{-5}\,\text{GeV}^{-2}$ $\Leftrightarrow \alpha_w$ is small

(massive propagator leads to suppression)

Estimate the strength from $\Sigma \to$ **p** π^0 decay

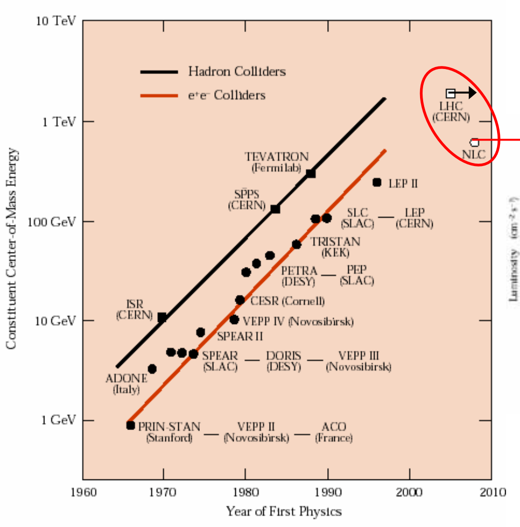
$$\frac{\tau(\Sigma \to \Lambda\gamma)}{\tau(\Sigma \to p\pi^0)} \approx \frac{\alpha_w^2}{\alpha_{em}^2}$$

$$\Rightarrow \frac{\alpha_w}{\alpha_{em}} \approx 10^{-5} \ldots 10^{-4}$$

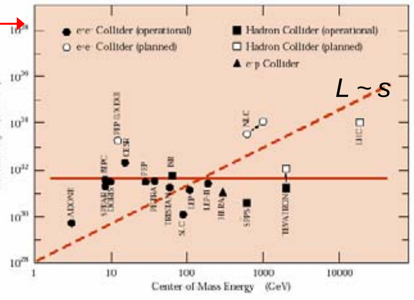
“effective weak coupling”

2. Experimental tools

2.1 Particle accelerators



Cross sections $\sigma \sim \frac{1}{s}$



From W.K.H.Panofsky: The evolution of particle accelerators and colliders

Large Hadron Collider

Momentum at collision	**7**	**TeV/c**
Momentum at injection	450	GeV/c
Dipole field at 7 TeV	8.33	Tesla
Circumference	26658	m

High beam energy in LEP tunnel
superconducting NbTi magnets at 1.9 K

Luminosity	**10^{34}**	**$cm^{-2}s^{-1}$**
Number of bunches	2808	
Particles per bunch	$1.1 \cdot 10^{11}$	
DC beam current	0.56	A
Stored energy per beam	**350**	**MJ**

Normalised emittance	**3.75**	**µm**
Beam size at IP / 7 TeV	15.9	µm
Beam size in arcs (rms)	300	µm

High luminosity at 7 TeV
very high energy stored in the beam

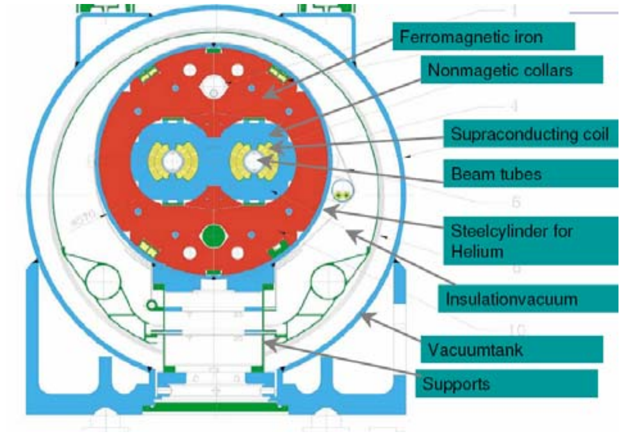
beam power concentrated in small area

Arcs: Counter-rotating proton beams in two-in-one magnets

Magnet coil inner diameter	**56**	**mm**
Distance between beams	194	mm

Limited investment
small aperture for beams

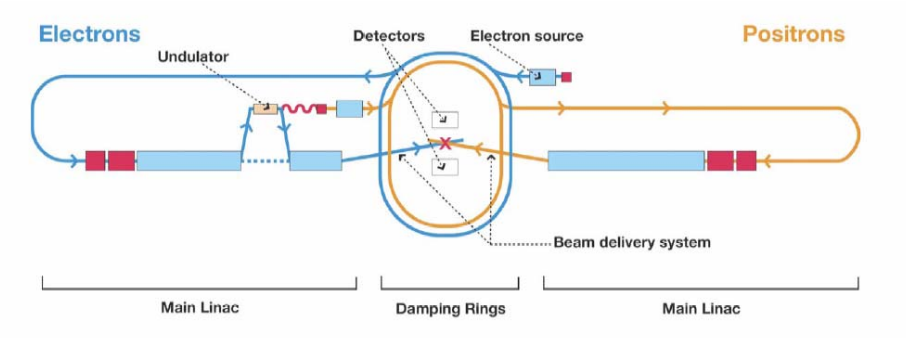
LHC Dipole Magnet



Dipole current: 12 KA (super-conducting, T=1.9 k), B = 8.3 T

Energy stored in 1 dipole: 7.6 MJ in all 1232 dipoles: 9.4 GJ

International Linear Collider



← 30 km →

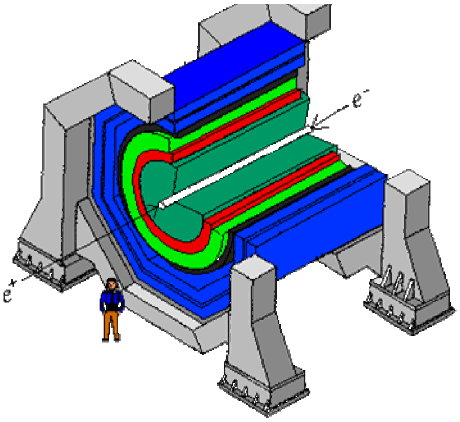
Center of mass energy: √s=500 … 1 TeV Field gradients: ~35 MV/m

Remember: synchrotron radiation for circular machines

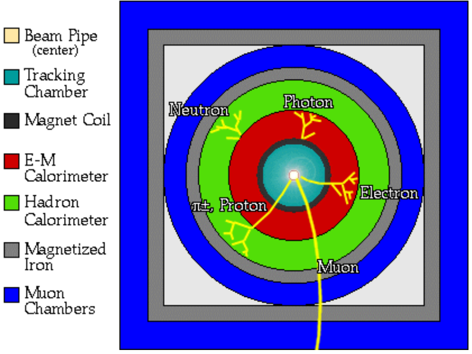
$$P = \frac{2\alpha}{3R^2}\beta^4\gamma^4 \xrightarrow{\beta\approx1} = \frac{2\alpha}{3R^2}\left(\frac{E}{m}\right)^4$$

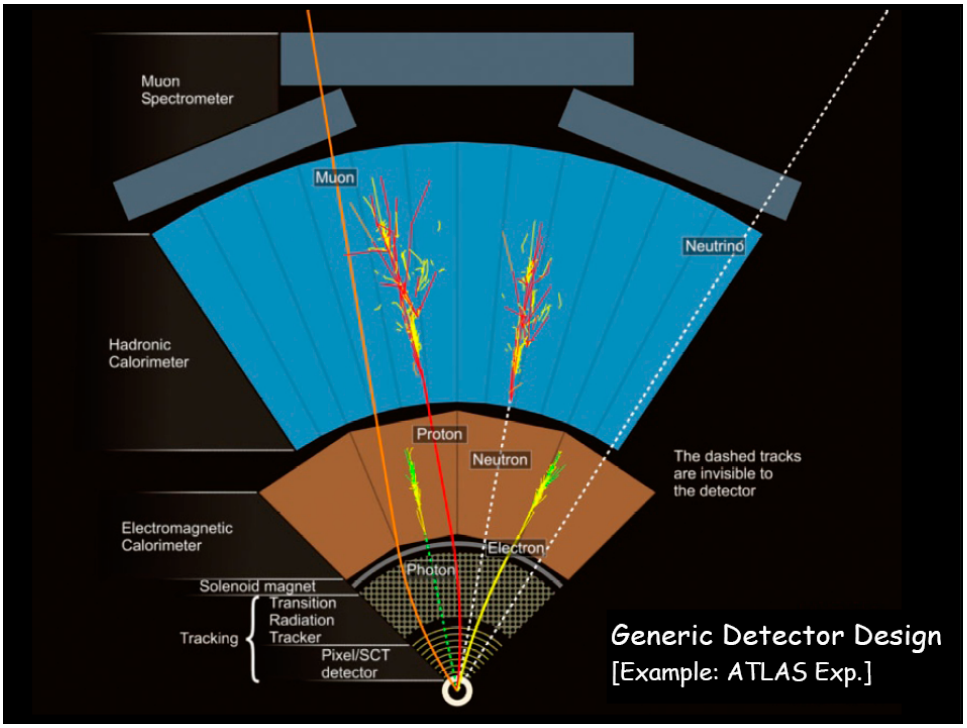
2.2 Particle detectors

Prototype of a modern compact particle detector



A detector cross-section, showing particle paths





Generic Detector Design
[Example: ATLAS Exp.]

3. Natural units

$$\boxed{\hbar = c = 1}$$

With this choice one has the freedom to choose the unit of one other physical quantity. Typically: **[E] = GeV**

⇒ Units of all other quantities are defined

Quantity	HEP unit	$\longrightarrow$	SI unit
Energy	GeV		$1.6 \cdot 10^{-10}\,J$
Mass	GeV	$\times 1/c^2$	$1.78 \cdot 10^{-27}\,kg$
Time	GeV^{-1}	$\times \hbar$	$6.58 \cdot 10^{-25}\ s$
Length	GeV^{-1}	$\times \hbar c$	$0.197\ fm$
Area	GeV^{-2}	$\times (\hbar c)^2$	$0.389\ mb$
Charge e	$\sqrt{4\pi\alpha}$	$\times (\hbar c \varepsilon_0)^{1/2}$	$1.6 \cdot 10^{-19}\,C$
Temp Tk	GeV	$\times 1/k$	$1.16 \cdot 10^{16}\,K$

Heaviside Lorentz Units: $\varepsilon_0 = \mu_0 = 1$

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

useful const.: $\hbar c = 197\ \text{MeV} \cdot \text{fm}$

$(\hbar c)^2 = 0.389\ \text{GeV}^2\text{mb}$