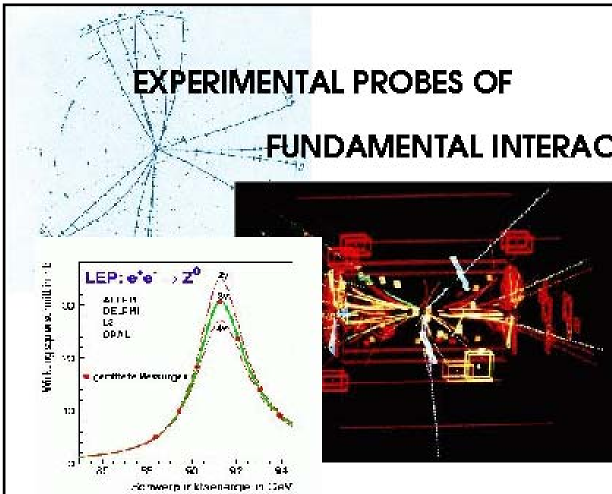
EXPERIMENTAL PROBES OF FUNDAMENTAL INTERACTIONS



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Outline

I. Introduction

II. Pre-requisite

III. QED for “pedestrians”

IV. e^+e^- annihilation experiments below the Z resonance

V. Experimental studies of QCD

VI. Probing the weak interaction

VII. Electro-weak unification: Phenomenological approach to the SM

VIII. Experimental test of the Standard Model (SM)

IX. Flavor oscillations

X. The quest for new physics at current and future accelerators

Literature

- D.H.Perkins: Introduction to High Energy Physics, Cambridge University Press.
- D.Griffith: Introduction to Elementary Particles, John Wiley.
- F.Halzen, A.Martin: Quarks and Leptons, John Wiley.
- P.Renton: Introduction to the Physics of Quarks and Leptons, Cambridge University Press.
- E.Leader und E.Predazzi: An Introduction to Gauge Theories and Modern Particle Physics, Vol. 1+2, Cambridge Mongraphs.
- Particle Data Group: Review pf Particle Physics, 2004.
- Original literature
- Web links

I. Introduction

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

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	$\begin{pmatrix}\nu_e \\ e\end{pmatrix}$	$\begin{pmatrix}\nu_\mu \\ \mu\end{pmatrix}$	$\begin{pmatrix}\nu_\tau \\ \tau\end{pmatrix}$	$\begin{pmatrix}0 \\ -1\end{pmatrix}$
Quarks	$\begin{pmatrix}u \\ d\end{pmatrix}$	$\begin{pmatrix}c \\ s\end{pmatrix}$	$\begin{pmatrix}t \\ b\end{pmatrix}$	$\begin{pmatrix}+2/3 \\ -1/3\end{pmatrix}$

Anti-particles with opposite charge to each lepton/quark

Lepton Properties

- All leptons exist as free particles
- Lepton number conservation

$$\pi^+ \rightarrow \mu^+ \; \nu_\mu$$
$$L_\mu = 0 \rightarrow -1 \quad 1$$

Searches for lepton flavor violation
$BR(\mu^+ \rightarrow e^+\gamma) < 10^{-11}$

⇧

Lepton number conservation strictly true only w/o oscillation

	mass·c²	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

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

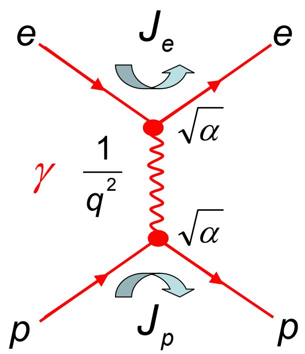
	quark mass·c^2	Flavour number
u, d	2 - 8 MeV	I=±1/2
s	80 - 130 MeV	S=-1
c	1.15 - 1.35 GeV	C=+1
b	4.6 – 4.9 GeV	B=-1
t	~175 GeV	T=+1

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:

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

(Rutherford formula)

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

$\hbar = c = 1$

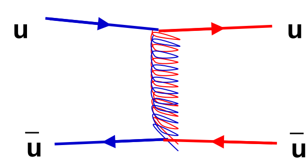
b.) Strong interaction

Color charges and gluons.

- Quarks and anti-quarks carry 3 color different (anti) charges

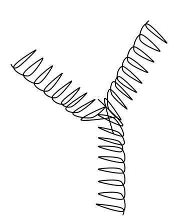
q: r g b **$\bar{q}$: $\bar{r}$ $\bar{g}$ $\bar{b}$**

- 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



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

(massive propagator leads to suppression)

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

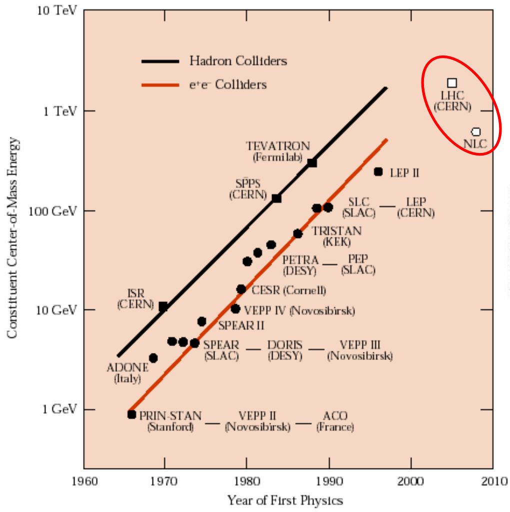
$$\frac{\tau(\Sigma \to \Lambda\gamma)}{\tau(\Sigma \to p\pi^0)} \approx \frac{\alpha_w^2}{\alpha_{em}^2}$$

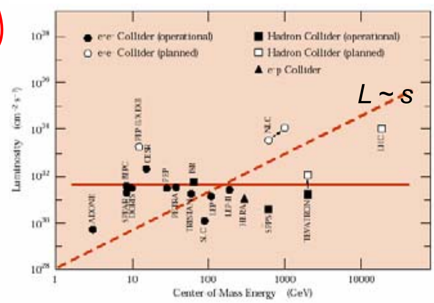
$$\Rightarrow \frac{\alpha_w}{\alpha_{em}} \approx 10^{-5} \ldots 10^{-4}$$

"effective weak coupling" ← α_w

2. Experimental tools

2.1 Particle accelerators

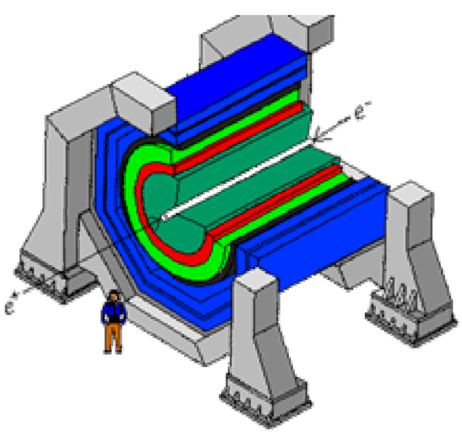


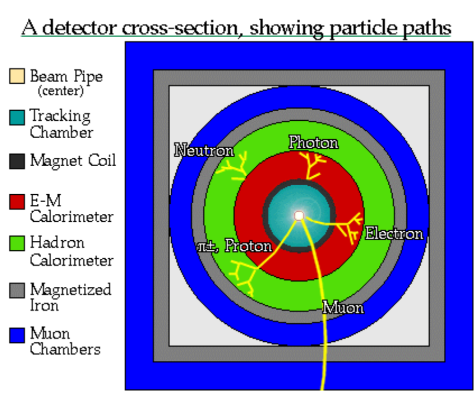


From W.K.H.Panofsky: The evolution of particle accelerators and colliders

2.2 Particle detectors

Prototype of a modern compact particle detector





3. Natural units

$$\hbar = c = 1$$

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

$\Rightarrow$ Units of all other quantities are defined

Quantity	HEP unit	$\longrightarrow$	SI unit
Energy	GeV		$1.6 \cdot 10^{-10}\,J$
Mass	GeV	$\times 1/c^2$	$1.78 \cdot 10^{-27}\,kg$
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.: $\hbar c = 197\ \text{MeV} \cdot \text{fm}$

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