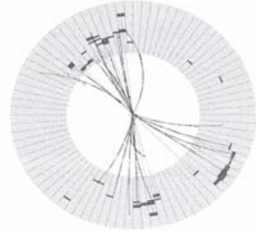
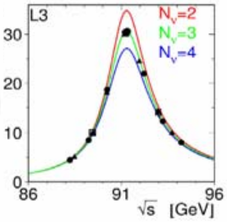
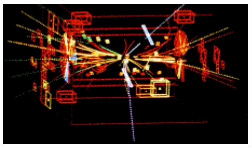






Advanced Particle Physics

Date: Wed, 9:15 - 11:00
Fri, 9:15 – 11:00
Venue: HS1 INF227
Lecturer: V. Lendermann / U. Uwer

http://www.physi.uni-heidelberg.de/~uwer/lectures/ParticlePhysics/

Advanced Particle Physics

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

- F.Halzen, A.Martin: Quarks and Leptons, John Wiley.
- C.Berger: Elementarteilchenphysik, Springer.
- D.H.Perkins: Introduction to High Energy Physics, Cambridge University Press.
- D.Griffith: Introduction to Elementary Particles, John Wiley.
- Particle Data Group: Review of Particle Physics, 2006.
- Original literature
- Web links

I. Introduction

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

What you already know from „Physik 5“

1. Building blocks of matter and their interactions

1.1 Leptons and Quarks

Point-like, spin ½ , elementary building blocks of matter
$< 10^{-18}$ m

	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

$$\begin{array}{lccc} & \pi^+ & \to & \mu^+ \quad \nu_\mu \\ L_\mu = & 0 & \to & -1 \quad\; 1 \end{array}$$

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

Lepton flavor violation also for charged leptons ?

		mass·c²	lifetime	Lepton number
	e^-	511 keV	∞	$L_e=1$
	μ^-	106 MeV	2.2 μs	$L_\mu=1$
1975	τ^-	1.78 GeV	0.3 ps	$L_\tau=1$
	ν_e	< 3 eV	∞	$L_e=1$
	ν_μ	<190 keV	∞	$L_\mu=1$
2000	ν_τ	<18.2 MeV	∞	$L_\tau=1$

Direct measurements

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

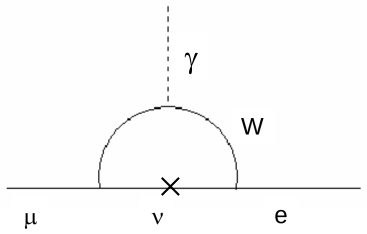
Impressive limits for lepton flavor violation:

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

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

proposed: MEG $BR_{\mu\to e\gamma}<5\cdot 10^{-14}$ proposed: MECO $BR_{\mu\to e}<8\cdot 10^{-17}$ (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: mass is well defined only for free particles
- Heavy quarks: 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	Flavor number
u, d	~5 and ~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

1995

Questions:

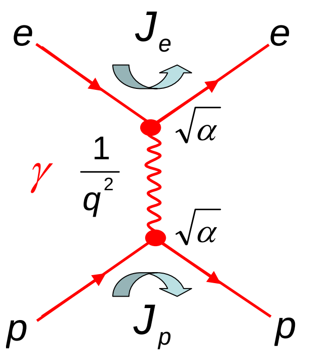
- Why 3 generations ?
- Mass hierarchy ?
- Charges = 0, 1/3e, 2/3e or e ?

1.2 Fundamental interactions

IA	Mediator boson	strength
Strong	Gluon g	1
Elektro-magnetic	Photon	$\sim 10^{-2}$
weak	$W^{\pm}$ Z^0	$\sim 10^{-6}$
Gravitation	Graviton	$\sim 10^{-39}$

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

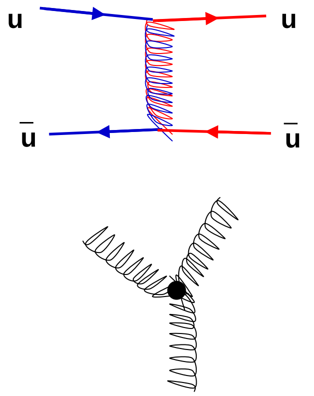
$$\alpha = \alpha_{QED} = \frac{e^2}{4\pi\varepsilon_0\hbar c} \underset{\hbar = c = 1}{\uparrow}{=} \frac{e^2}{4\pi}$$

b.) Strong interaction

Color charges and gluons.

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

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

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

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 Σ→ **p** π^0 decay

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

“effective weak coupling”

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

Questions:

- Electromagnetic and weak forces can be unified:
  - What about strong force ?
  - What about gravitation ?
- Unification scales are very different ?

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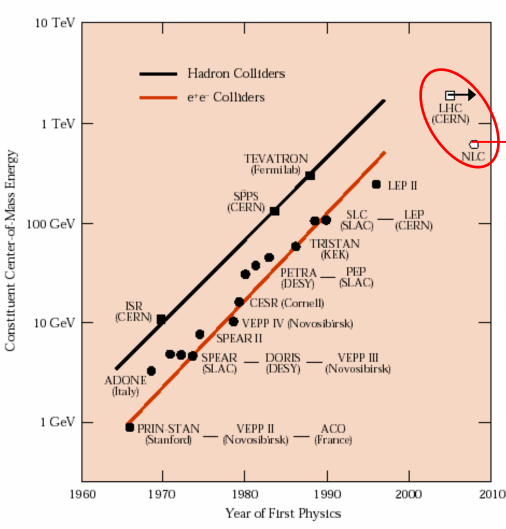
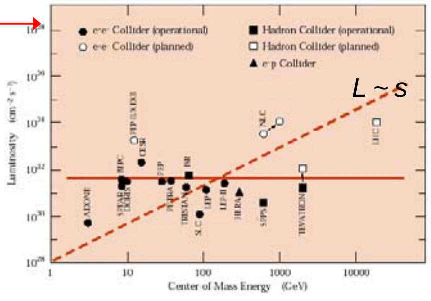
2. Experimental tools

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

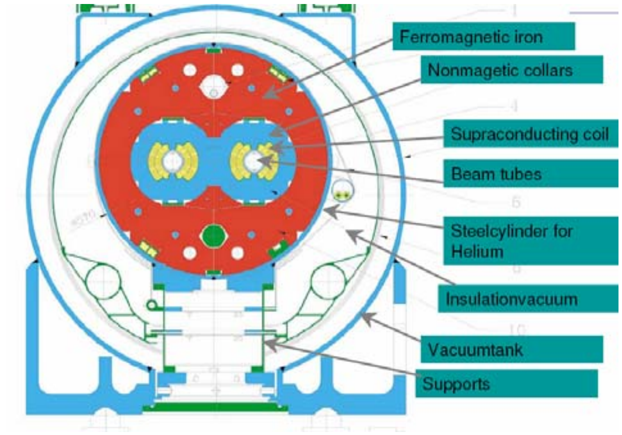
beam power concentrated in small area

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

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

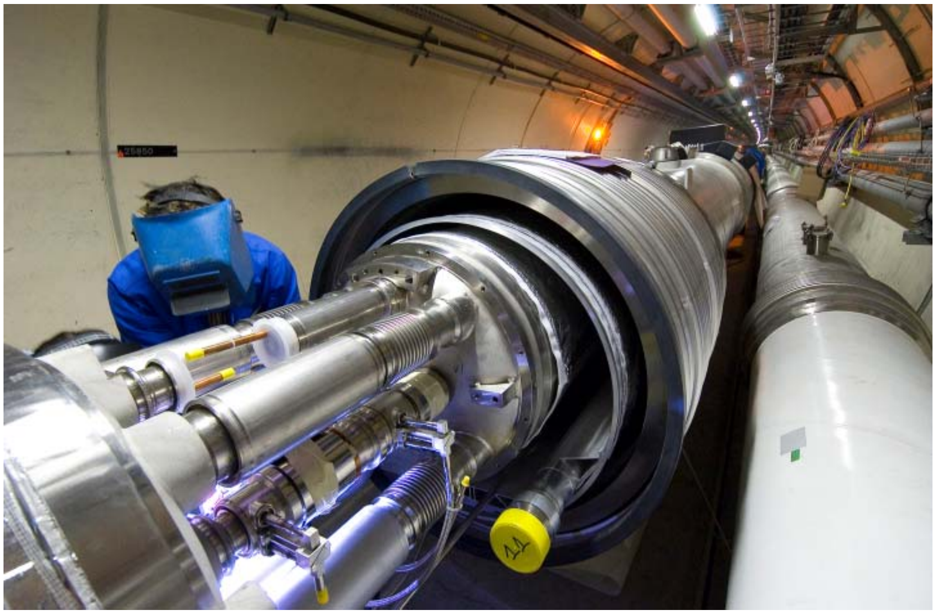
Limited investment
small aperture for beams

LHC Dipole Magnet

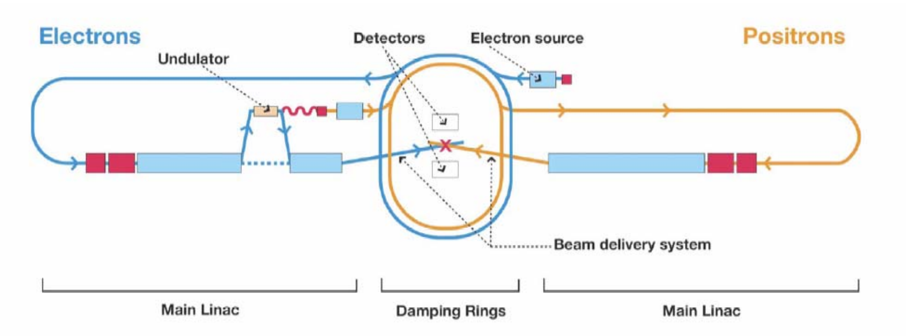


Dipole current: 12 KA (super-conducting, T=1.9 k), B = 8.3 T

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



International Linear Collider



30 km

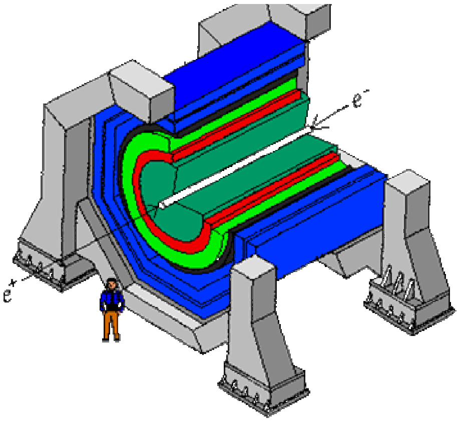
Center of mass energy: √s=500 … 1 TeV Field gradients: ~35 MV/m

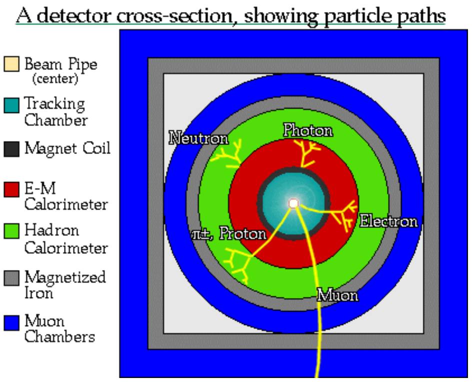
Remember: synchrotron radiation for circular machines

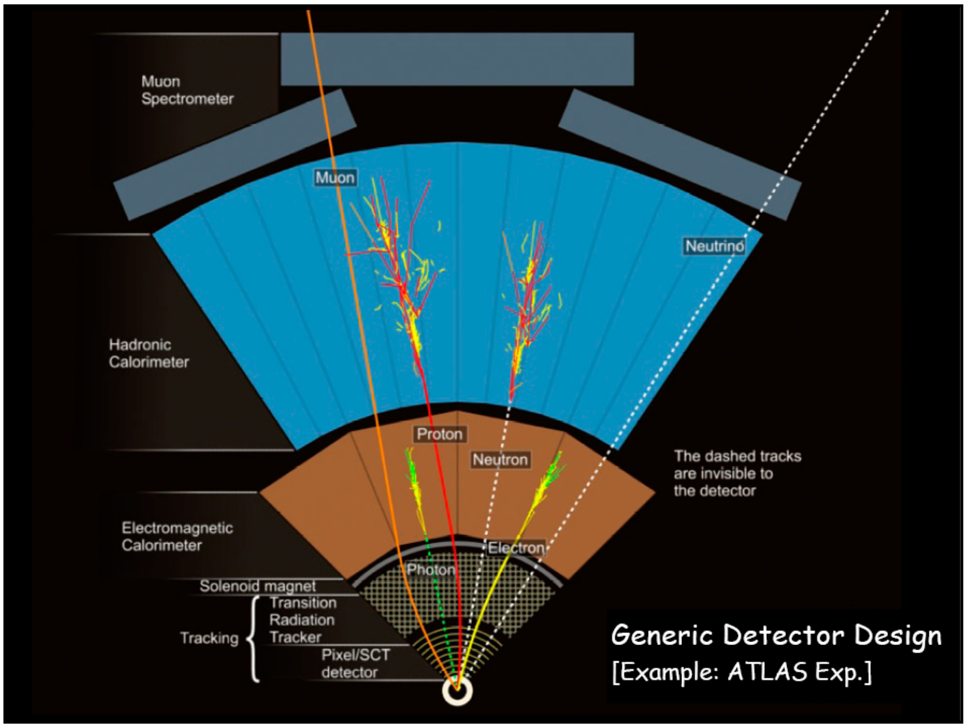
$$P = \frac{2\alpha}{3R^2}\beta^4\gamma^4 \xrightarrow{\beta\approx1} = \frac{2\alpha}{3R^2}\left(\frac{E}{m}\right)^4$$

2.2 Particle detectors

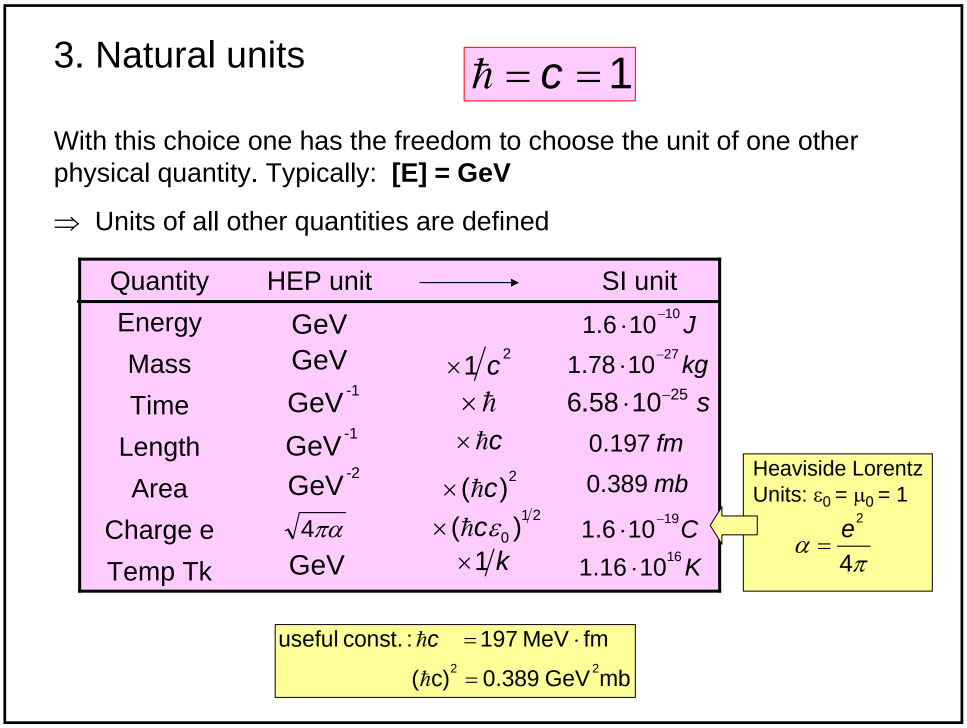
Prototype of a modern compact particle detector







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**

$\Rightarrow$ Units of all other quantities are defined

Quantity	HEP unit	$\longrightarrow$	SI unit
Energy	GeV		$1.6\cdot10^{-10}\,J$
Mass	GeV	$\times 1/c^2$	$1.78\cdot10^{-27}\,kg$
Time	GeV^{-1}	$\times\hbar$	$6.58\cdot10^{-25}\,s$
Length	GeV^{-1}	$\times\hbar c$	$0.197\,fm$
Area	GeV^{-2}	$\times(\hbar c)^2$	$0.389\,mb$
Charge e	$\sqrt{4\pi\alpha}$	$\times(\hbar c\varepsilon_0)^{1/2}$	$1.6\cdot10^{-19}\,C$
Temp Tk	GeV	$\times 1/k$	$1.16\cdot10^{16}\,K$

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

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

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

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