High Energy Physics

Lectures by W.B. von Schlippe
given at Moscow State University, October – November 2005

Lecture 1: Overview of the current state of HEP

Science is built up of facts, as a house is built of stones; but an accumulation of facts is no more a science than a heap of stones is a house.

Henri Poincaré (1854 – 1912)
in "*Science and Hypothesis*" (1905)

Two Names for our Subject:

"High Energy Physics": emphasis on methods

- Accelerators
- Detectors

"Elementary Particle Physics":
emphasis on the objects of study

Fundamental Particles: Leptons and Quarks

Composite Particles: Hadrons composed of quarks

The Fundamental Particles: Leptons and Quarks

				Charge/e
Leptons:	ν_e	ν_μ	ν_τ	0
	e^-	μ^-	τ^-	-1
Quarks:	u	c	t	2/3
	d	s	b	-1/3

To date there is no indication of the existence of more generations of fundamental fermions

Antimatter

Every particle has an antiparticle

The antiparticle of the electron e^- is the positron e^+

When a particle collides with its antiparticle, they can annihilate into a pair of photons:

$$e^+e^- \rightarrow 2\gamma$$

The antiparticle of the μ^- is the μ^+

The antiparticle of the proton p is the antiproton $\bar{p}$

More on Antimatter

The anti *u* quark is denoted $\bar{u}$

Similarly the anti *d* quark *etc*.: $\bar{d}$

Also the antineutrino: $\bar{\nu}$

The complete list of fundamental particles consists of leptons, quarks, antileptons and antiquarks.

Hadrons

Hadrons are composite particles

They consist either of a quark and an antiquark

these are called mesons

Example: *pi* meson: $\pi^{+} = u\bar{d}$

or they consist of three quarks

these are called baryons

Example: proton: $p = uud$

More than 200 hadrons are known

some of these are shown in the following tables:

Table 1: **Light Mesons**

Particle	Symbol	Constit. quarks	Mass (MeV/c^2)	Mean Life (ns)	Principal decay mode	% a)	I-spin b)	S c)
pion	π^+	ud	139.57	26	$\mu^+\nu_\mu$	99.9877	1	0
	π^0	$u\bar{u} - d\bar{d}$	134.98	8.4×10^{-8}	2γ	98.8	1	0
					$e^+e^-\gamma$	1.2		
kaon	K^+	$u\bar{s}$	494	12	$\mu^+\nu_\mu$	63.4	1/2	1
					$\pi^+\pi^0$	21.1		
					$\pi^+\pi^+\pi^-$	5.6		
	K^0	$d\bar{s}$	498				1/2	1
	K^0_S	d)		0.09	$\pi^+\pi^-$	69		
					$\pi^0\pi^0$	31		
	K^0_L	d)		52	$\pi^\pm e^\mp \nu_e$	39		
					$\pi^\pm \mu^\mp \nu_\mu$	27		
					$3\pi^0$	21		
					$\pi^+\pi^-\pi^0$	12.6		

Notes:

a) Branching fraction %; b) isospin, a quantum number that defines the multiplicity of charge states; c) S = *strangeness*, a quantum number that is conserved in strong and electromagnetic but not in weak interactions. d) K^0_S and K^0_L are superpositions of K^0 and $\bar{K}^0$: $K^0_{L,S} = p\,K^0 \pm q\,\bar{K}^0$, $p \neq q$, $|p|^2 + |q|^2 = 1$.

Table 2: **Heavy Mesons**

Particle	Symbol	Constit. quarks	Mass (MeV/c^2)	Mean Life (ps)	Principal decay modes	% a)	I-spin
D meson	D^+	cd	1869.0	1	e^+X	17.2	1/2
					K^-X	24.2	
					K^+X	5.8	
					$K^0X + \bar{K}^0Y$	59	
	D^0	$c\bar{u}$	1864.5	0.4	K^-X	53	1/2
					$K^0X + \bar{K}^0Y$	42	
					e^+X	6.75	
					μ^+X	6.6	
					K^+X	3.4	
	D_s^+	$c\bar{s}$	1968.6	0.5	$K^0X + K^0Y$	39	0
					K^+X	20	
					K^-X	13	
B meson	B^+	ub	5279.0	1.65	$\ell^+\nu_\ell X$	10.2	1/2
	B^0	$d\bar{b}$	5279.4	1.548	K^+X	78	1/2
	B_s^0	$s\bar{b}$	5369.6	1.493	D_s^-X	92	0
	B_c^+	$c\bar{b}$	6400.0	0.46			0

Notes:

In addition to the heavy mesons shown there are families of mesons with *hidden charm* $c\bar{c}$ (charmonium) and with *hidden bottomness* $b\bar{b}$, also *heavy meson resonances* D^* *etc.*, which will be discussed elsewhere.

Table 3: **Baryons**

Particle	Symbol	Constit. quarks	Mass (MeV/c^2)	Mean Life (ps)	Principal decay mode	% a)	I-spin	S
proton	p	uud	938.272	stable			1/2	0
neutron	n	udd	939.535	886×10^{12}	$pe^-\bar{\nu}_e$	100	1/2	0
Λ hyperon	Λ	uds	1115.68	26.32	$p\pi^-$	63.9	0	-1
					$n\pi^0$	35.8		
Σ hyperon	Σ^+	uus	1189.37	8.02	$p\pi^0$	51.57	1	-1
					$n\pi^+$	48.31		
	Σ^0	uds	1192.64	7×10^{-8}	$\Lambda\gamma$	100	1	-1
	Σ^-	dds	1197.45	14.8	$n\pi^-$	99.85	1	-1
Ξ baryon	Ξ^0	uss	1314.83	29.0	$\Lambda\pi^0$	99.51	1/2	-2
	Ξ^-	dss	1321.31	16.4	$\Lambda\pi^-$	99.89	1/2	-2
Ω baryon	Ω^-	sss	1672.45	8.21	ΛK^-	67.8	0	-3
					$\Xi^0\pi^-$	23.6		
					$\Xi^-\pi^0$	8.6		

Notes:

a) Branching fraction %; 1.) S = *strangeness*, a quantum number that is conserved in strong and electromagnetic but not in weak interactions;

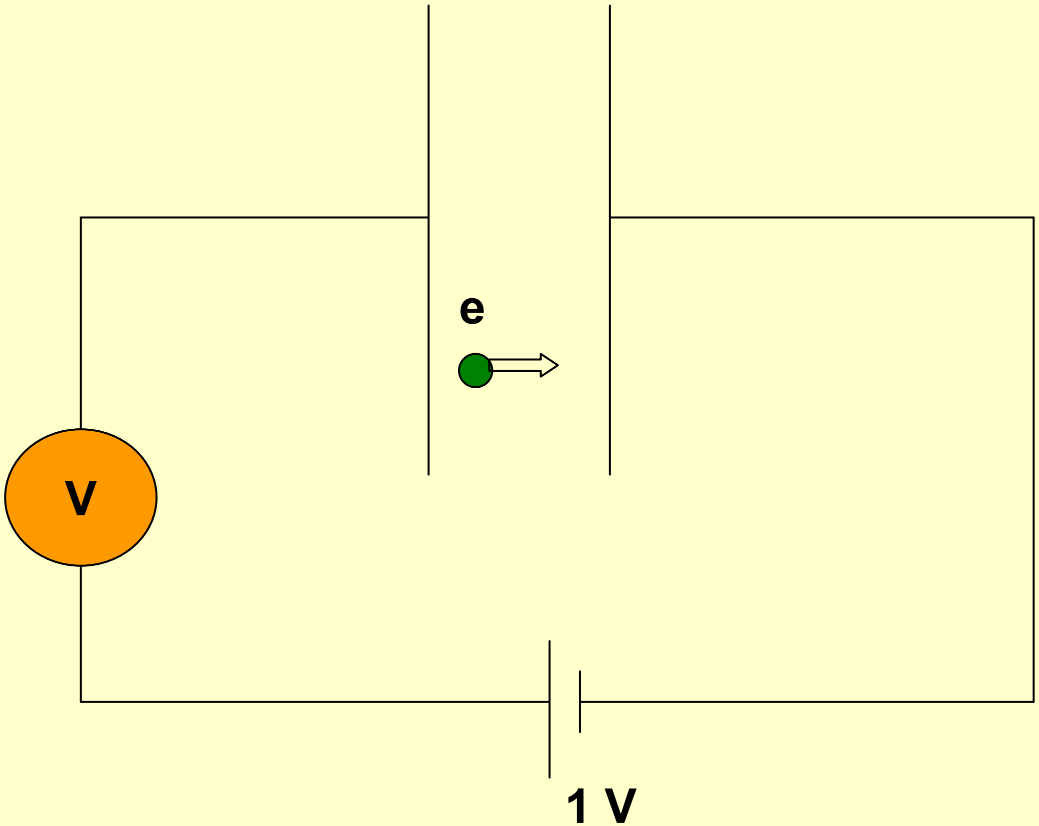
Hierarchy of sizes and masses

	size	mass		charge
	m	kg	MeV/c^2	$e^{**)}$
Everyday objects	1	1 - 100		0
Atom	10^{-10}	2 - 200 x 10^{-27}		0
Nucleus	few x 10^{-15}	2 - 200 x 10^{-27}		Z
Proton	~10^{-15}	≈ 1.7 x 10^{-27}	938.272	1
Neutron	~10^{-15}	≈ 1.7 x 10^{-27}	939.535	0
Electron	<10^{-16} *)	≈ 9 x 10^{-31}	0.511	-1

*) experimental limit

**) 1 e = 1.602 x 10^{-19} C

Units: definition of electron-Volt (eV)



The electron e acquires a K.E. of 1 eV in falling through a p.d. of 1 V

Mass – Energy Equivalence (*Einstein*):

$$E = mc^2$$

Which explains the use of the unit of mass: MeV/c^2

More on Units: *multiples of the basic units*

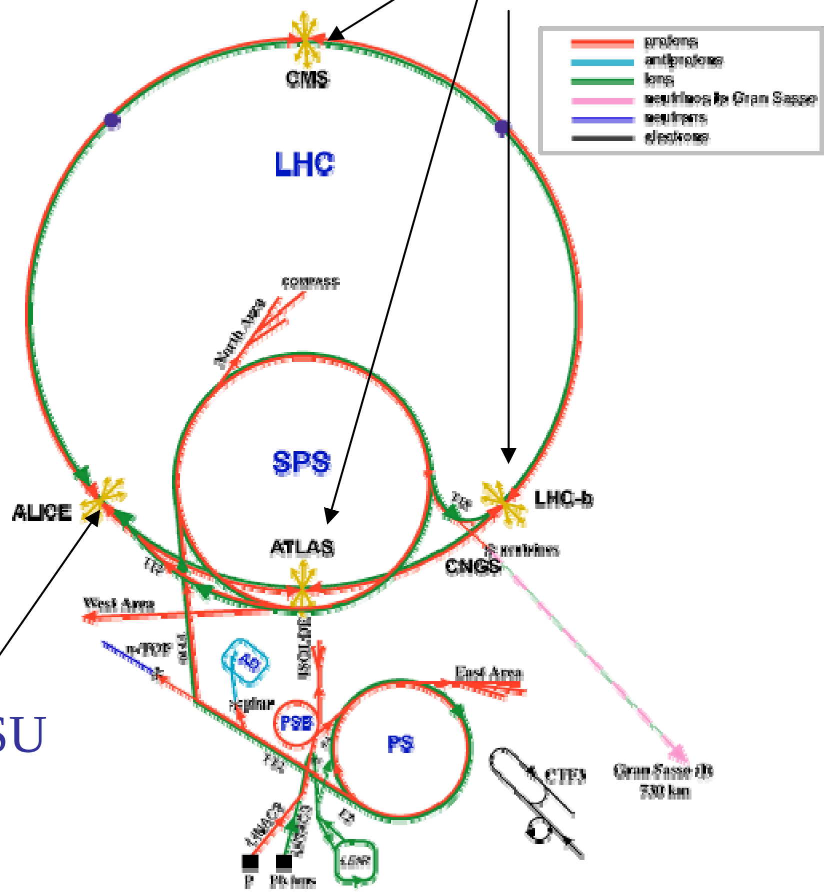
Name	Symbol	Factor
femto	f	10^{-15}
pico	p	10^{-12}
nano	n	10^{-9}
micro	μ	10^{-6}
milli	m	10^{-3}
kilo	k	10^{3}
Mega	M	10^{6}
Giga	G	10^{9}
Terra	T	10^{12}

Remember the masses of a few of the most frequently encountered particles (only approximate values are shown to make it easier to remember):

Particle	Mass (MeV/c^2)
electron, e	0.5
muon, μ	106
pion, π	140
proton, p	938.3
neutron, n	939.6

The CERN Accelerator Complex

PNPI



SPbSU

PS: proton synchrotron (1959 -)
SPS: Super PS (1976 -)
SppS: super antiproton-proton
synchrotron (1981 – 1990)
LHC: Large Hadron Collider
planned start of operation
2007

Experimental groups from
SPbSU and PNPI

take part in experiments
ALICE, ATLAS, CMS and
LHC-b.