

# High Energy Physics

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

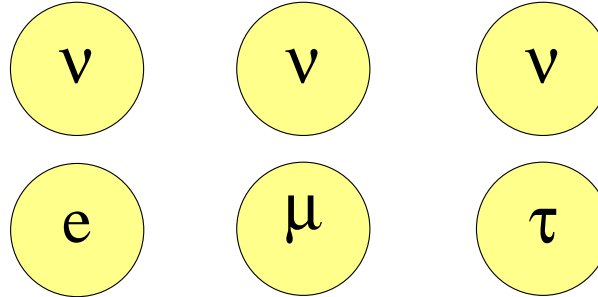
“Elementary Particle Physics”:  
emphasis on the objects of study

Fundamental Particles: **Leptons and Quarks**

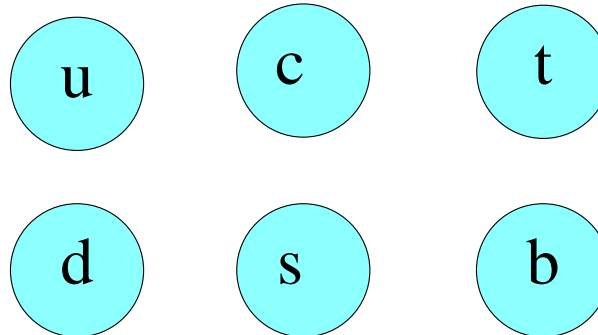
Composite Particles: **Hadrons** composed of quarks

# The Fundamental Particles: Leptons and Quarks

Leptons:



Quarks:



To date we have no indication of the existence of more than the three generations of fundamental particles.

# 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  $\mu^-$  is the  $\mu^+$

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 <sup>2</sup> )	Mean Life (ns)	Principal decay mode	% a)	I-spin b)	S c)
pion	$\pi^+$	$ud$	139.57	26	$\mu^+\nu_\mu$	99.9877	1	0
	$\pi^0$	$u\bar{u} - d\bar{d}$	134.98	$8.4 \times 10^{-8}$	$2\gamma$ $e^+e^-\gamma$	98.8 1.2	1	0
kaon	$K^+$	$u\bar{s}$	494	12	$\mu^+\nu_\mu$ $\pi^+\pi^0$ $\pi^+\pi^+\pi^-$	63.5 21.16 5.59	1/2	1
	$K^0$	$d\bar{s}$	498	0.09	$\pi^+\pi^-$	68.61	1/2	1
	$K_S^0$	d)			$\pi^0\pi^0$	31.39		
	$K_L^0$	d)		52	$\pi^\pm e^\mp \nu_e$ $3\pi^0$ $\pi^+\pi^-\pi^0$	27.18 21.13 12.55		

Notes:

a) Branching fraction %; b) isospin, a quantum number that defines the multiplicity of charge states; c)  $S = \textit{strangeness}$ , a quantum number that is conserved in strong and electromagnetic but not in weak interactions; d)  $K_S^0$  and  $K_L^0$  are superpositions of  $K^0$  and  $\bar{K}^0$ :  $K_{L,S}^0 = c_1 K^0 + c_2 \bar{K}^0$ , where  $c_{1,2} = 1 \pm \varepsilon$  with  $|\varepsilon| = (2.284 \pm 0.014) \times 10^{-3}$ ; the (small) deviation of  $|\varepsilon|$  from 1 accounts for the  $CP$  violation in the kaon system.



Table 2: **Heavy Mesons**

Particle	Symbol	Constit. quarks	Mass (MeV/c <sup>2</sup> )	Mean Life (ps)	Principal decay modes	% a)	I-spin
<i>D</i> meson	$D^+$	$cd$	1869.0	1	$e^+X$ $K^-X$ $K^+X$ $K^0X + \bar{K}^0Y$	17.2 24.2 5.8 59	1/2
	$D^0$	$c\bar{u}$	1864.5	0.4	$K^-X$ $K^0X + \bar{K}^0Y$ $e^+X$ $\mu^+X$ $K^+X$	53 42 6.75 6.6 3.4	1/2
	$D_s^+$	$c\bar{s}$	1968.6	0.5	$K^0X + \bar{K}^0Y$ $K^+X$ $K^-X$	39 20 13	0
<i>B</i> 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 <sup>2</sup> )	Mean Life (ps)	Principal decay mode	% a)	I-spin	S
proton	p	<i>uud</i>	938.272	stable			1/2	0
neutron	n	<i>udd</i>	939.535	$886 \times 10^{12}$	$pe^- \bar{\nu}_e$	100	1/2	0
$\Lambda$ hyperon	$\Lambda$	<i>uds</i>	1115.68	26.32	$p\pi^-$ $n\pi^0$	63.9 35.8	0	-1
$\Sigma$ hyperon	$\Sigma^+$	<i>uus</i>	1189.37	8.02	$p\pi^0$ $n\pi^+$	51.57 48.31	1	-1
	$\Sigma^0$	<i>uds</i>	1192.64	$7 \times 10^{-8}$	$\Lambda\gamma$	100	1	-1
	$\Sigma^-$	<i>dds</i>	1197.45	14.8	$n\pi^-$	99.85	1	-1
$\Xi$ baryon	$\Xi^0$	<i>uss</i>	1314.83	29.0	$\Lambda\pi^0$	99.51	1/2	-2
	$\Xi^-$	<i>dss</i>	1321.31	16.4	$\Lambda\pi^-$	99.89	1/2	-2
$\Omega$ baryon	$\Omega^-$	<i>sss</i>	1672.45	8.21	$\Lambda K^-$ $\Xi^0\pi^-$ $\Xi^-\pi^0$	67.8 23.6 8.6	0	-3

Notes:

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

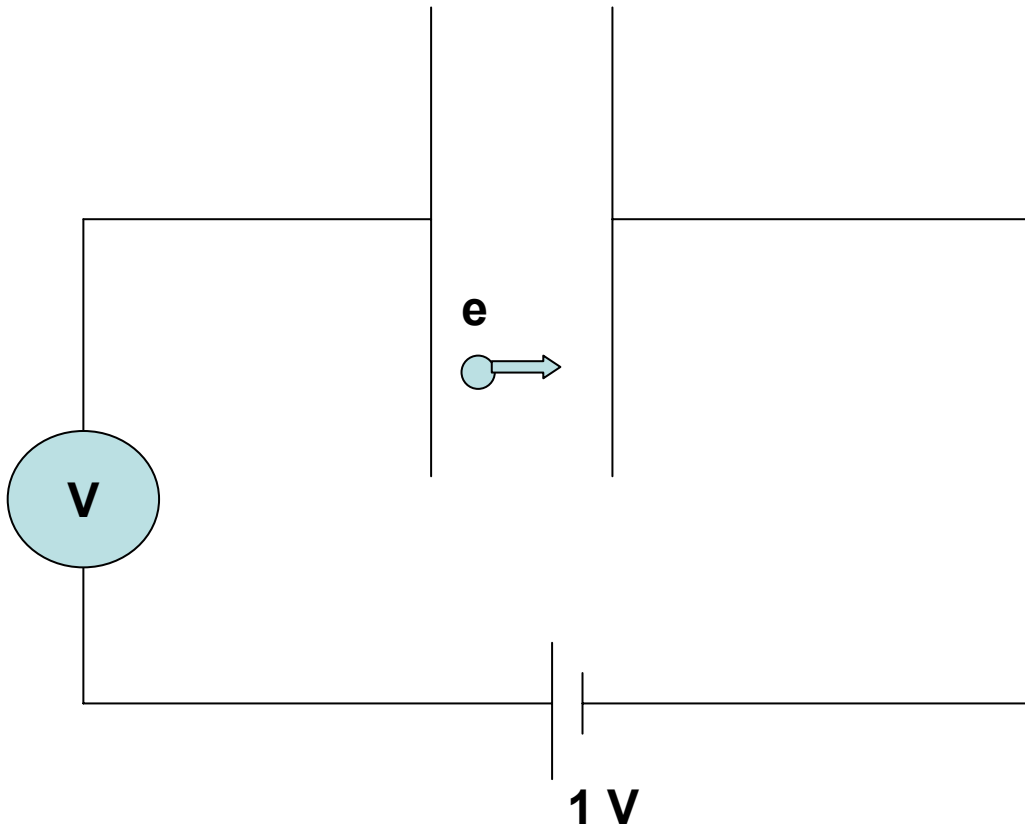
# Hierarchy of sizes and masses

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

\*) experimental limit

\*\*\*) 1 e = 1.602 x 10<sup>-19</sup> 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<sup>2</sup>

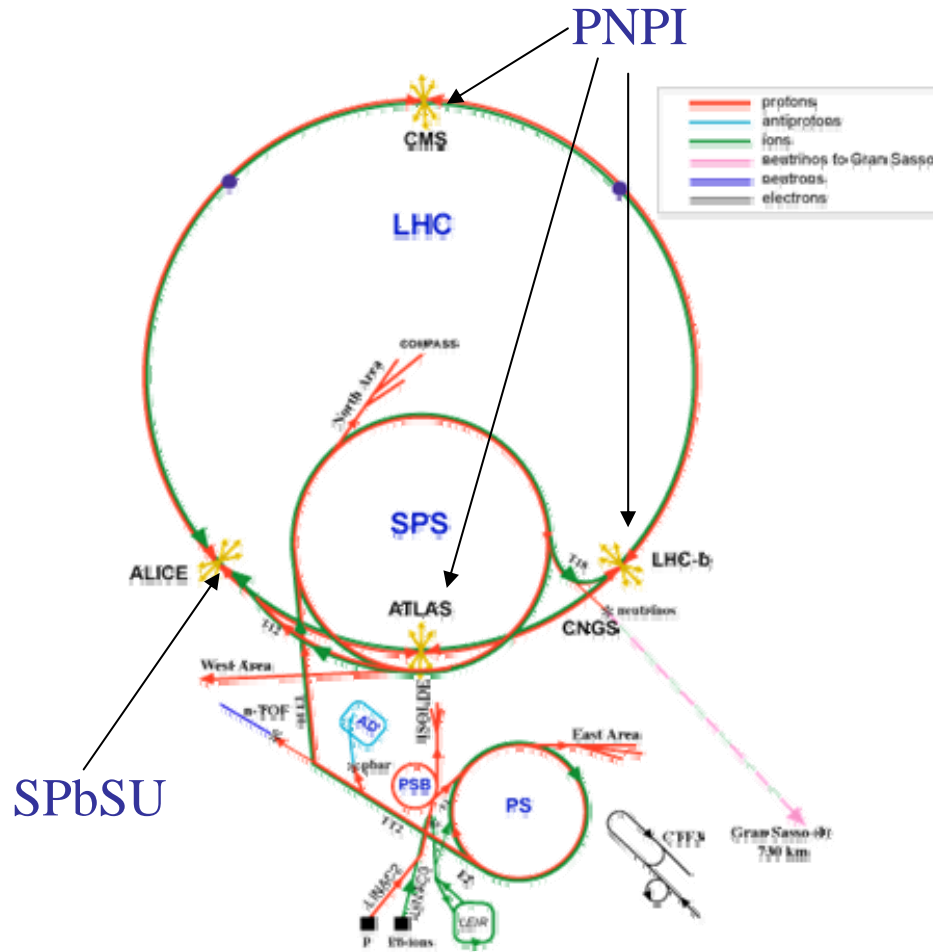
More on Units: *multiples of the basic units*

Name	Symbol	Factor
femto	f	$10^{-15}$
pico	p	$10^{-12}$
nano	n	$10^{-9}$
micro	$\mu$	$10^{-6}$
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 <sup>2</sup> )
electron, e	0.5
muon, $\mu$	106
pion, $\pi$	140
proton, p	938.3
neutron, n	939.6

# The CERN Accelerator Complex



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.