September 14 , 2010

Introduction

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Syllabus

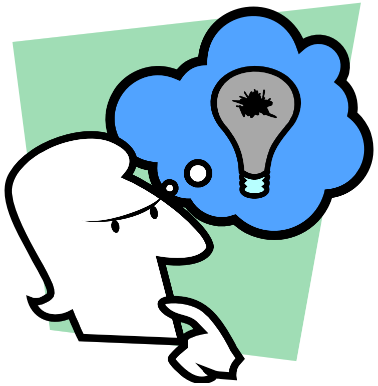
- Introduction (Chap. 1)
- Special Relativity (Chap. 2)
- Quantum Mechanics (Chap. 3)
- Detector
- Data Processing
- Feynman diagram (Chap. 4)
- QED (Chap. 5)
- QCD (Chap. 6)
- Weak interaction (Chap. 7)

People have long asked,

- What is world made of?

and

- What holds it together?



What covers in this chapter?

- History of particle physics
- Emergence of particle physics
- Classification of subatomic particles

1.1 Classification of particles

- History of particle physics

1. Discovery of the electron by J. J. Thomson -> starting point
2. Ratherford, Niels Bohr
3. Discovery of neutron by Chadwick
4. C. D. Anderson discovered the first antiparticles
5. Subsequently, so many hadrons were observed.
6. Gell-Mann proposed the quark model to classify them

Try to classify an example with set of 10 hadrons.

Introduction to the Standard Model

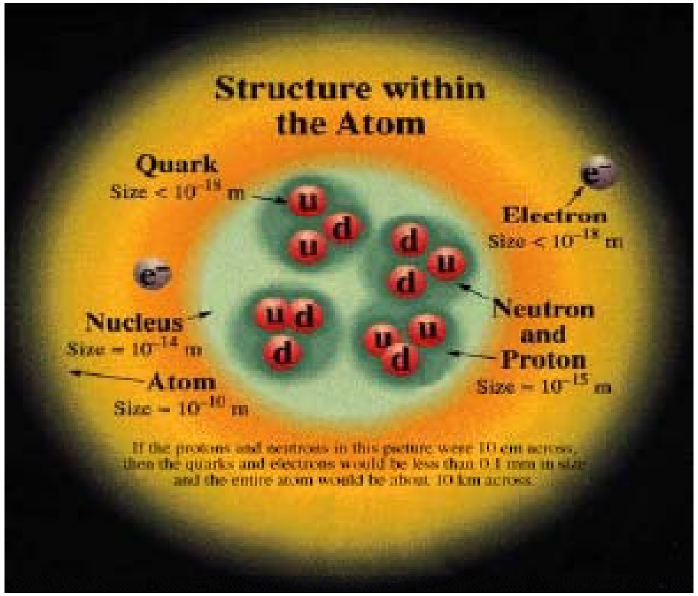
Particle Physics is the study of

- ★ **MATTER:** the fundamental constituents that make up the universe - the elementary particles
- ★ **FORCE:** the basic forces in nature i.e. the interactions between the elementary particles

Try to categorize the PARTICLES and FORCES in as simple and fundamental manner as possible.

Current understanding embodied in the STANDARD MODEL

- ★ Explains all current experimental observations.
- ★ Forces described by particle exchange.
- ★ It is not the ultimate theory - many mysteries.



The Briefest History of Particle Physics

the Greek View

- *c.* 400 B.C : Democritus : concept of matter comprised of indivisible "atoms".
- "Fundamental Elements" : air, earth, water, fire

Newton's Definition

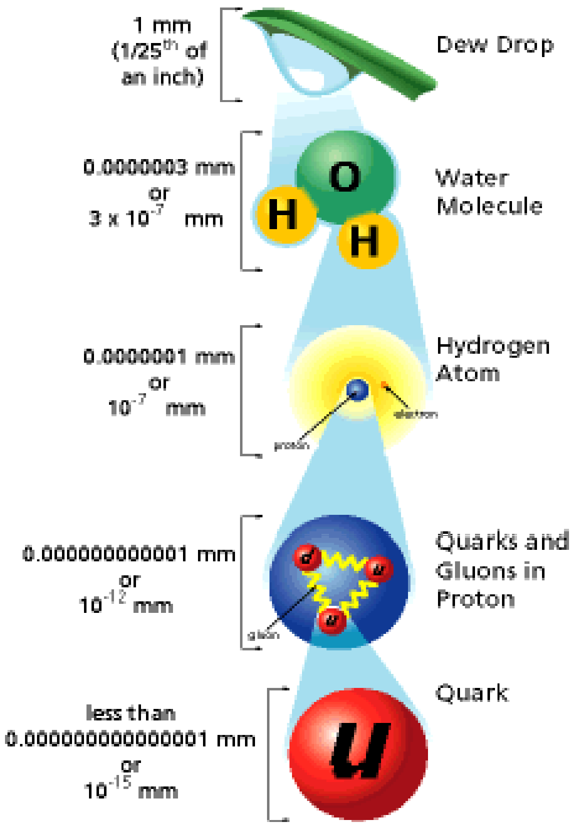
- 1704 : matter comprised of "primitive particles ... incomparably harder than any porous Bodies compounded of them, even so very hard, as never to wear out or break in pieces."
- A good definition - e.g. kinetic theory of gases.

CHEMISTRY

- Fundamental particles : "elements"
- Patterns 1869 Mendeleev's Periodic Table ➙ sub-structure
- Explained by atomic shell model

ATOMIC PHYSICS

- Bohr Model
- Fundamental particles : electrons orbiting the atomic nucleus

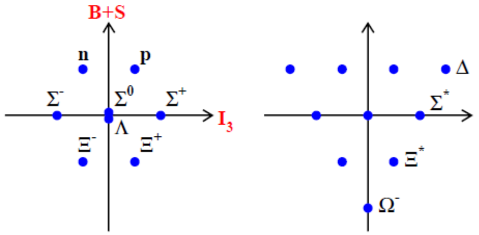


NUCLEAR PHYSICS

- ★ Patterns in nuclear structure - e.g. magic numbers in the shell model ➟ sub-structure
- ★ Fundamental particles :
  proton,neutron,electron,neutrino
- ★ Fundamental forces :
  ELECTROMAGNETIC : atomic structure
  STRONG: nuclear binding
  WEAK: β-decay $n \to p e^- \nu_e$
- ★ Nuclear physics is complicated : not dealing with fundamental particles/forces

1960s PARTICLE PHYSICS

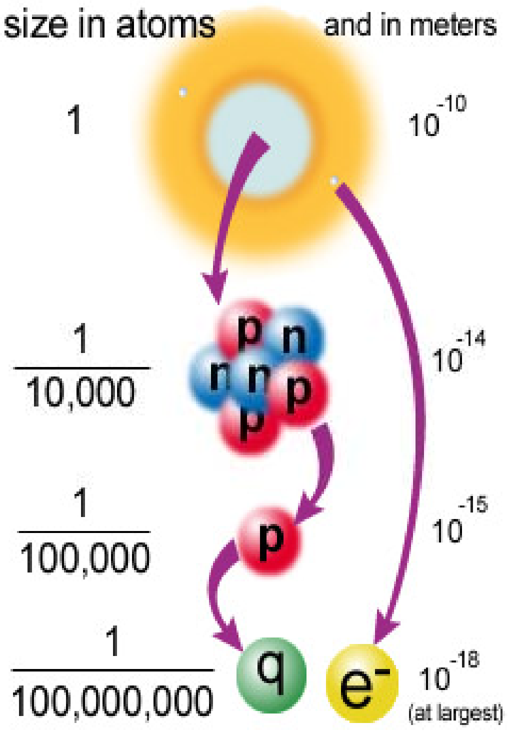
- ★ Fundamental particles ? : far too many !
  $p, n, \pi^\pm, \pi^0, \Sigma^\pm, \Lambda, \eta, \eta', K^\pm, K^0, \rho,$
  $\omega, \Omega^-, \phi, a_1, a_2, f_1, f_2, J/\psi, \Delta, \ldots$
- ★ Again Patterns emerged:



- ★ sub-structure - explained by QUARK model : u,d,c,s

TODAY

- ★ Simple/Elegant description of the fundamental particles/forces
- ★ These lectures will describe our current understanding and most recent experimental results



1.1 Classification of particles

◎There are 10 hadrons in this example.

$$H_1 \; H_2 \; H_3 \; H_4 \; H_5 \; H_6 \; H_7 \; H_8 \; H_9 \; H_{10}$$

◎First, Electric charge of each particle.

$$H_1^+ \, H_2^0 \, H_3^{++} \, H_4^+ \, H_5^0 \, H_6^- \, H_7^+ \, H_8^0 \, H_9^- \, H_{10}^0$$

1.1 Classification of particles

◎Second, the mass of each particle.

$$M_{H_1{}^{+}} \approx M_{H_2{}^{0}} \approx 940 MeV / c^2$$

$$M_{H_7{}^{+}} \approx M_{H_8{}^{0}} \approx M_{H_9{}^{-}} \approx 135 MeV / c^2$$

$$M_{H_3{}^{++}} \approx M_{H_4{}^{+}} \approx M_{H_5{}^{0}} \approx M_{H_6{}^{-}} \approx 1230 MeV / c^2$$

$$M_{H_{10}{}^{0}} \approx 550 MeV / c^2$$

1.1 Classification of particles

◎ Observing the decay modes of each hadron.

$$H_4^+ \rightarrow H_1^+ \gamma$$

$$H_4^+ \rightarrow H_1^+ H_8^0$$

$$H_4^+ \rightarrow H_2^0 H_7^+$$

1.1 Classification of particles

Information which can be obtained by observing the decay

1. *Conservation of total charges.*
2. *Conservation of total energies before and after the decay.*

$$H_4^+ \rightarrow H_1^+ \gamma$$

$$H_4^+ \rightarrow H_1^+ H_8^0$$

$$H_4^+ \rightarrow H_2^0 H_7^+$$

1.1 Classification of particles

3. The stronger the interaction is, the more quickly the decay take place

The typical electromagnetic decay time -> $10^{-19} s$

The hadronic decay time -> $10^{-23} s$

There is deeper physics behind the dynamics

The stronger the interaction is, the more quantum numbers are conserved

1.1 Classification of particles

*Classification of the 10 hadrons by **I** values – **I** means isospin*

$$(H_1^{+}, H_2^{0}); I = \frac{1}{2}, 2I + 1 = 2$$

$$(H_3^{++}, H_4^{+}, H_5^{0}, H_6^{-}); I = \frac{3}{2}, 2I + 1 = 4$$

$$(H_7^{+}, H_8^{0}, H_9^{-}); I = 1, 2I + 1 = 3$$

$$(H_{10}^{0}); I = 0, 2I + 1 = 1$$

The photon doesn’t have a unique **I** values

1.1 Classification of particles

$$H_4^{+} \rightarrow H_1^{+} \quad \gamma$$

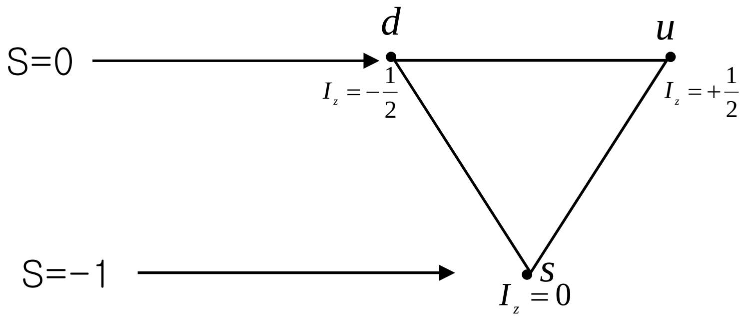
$$I = \frac{3}{2} \quad \frac{1}{2} \quad (0\, or\, 1)$$

$$H_4^{+} \rightarrow H_1^{+} H_8^{0} \quad H_2^{0} H_7^{+}$$

$$I = \frac{3}{2} \quad \frac{1}{2} 1 \quad \frac{1}{2} 1$$

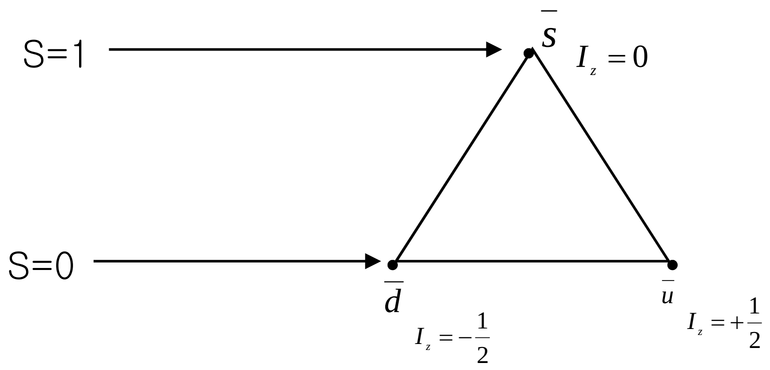
1.2 Quark Model and Fundamental interaction

$Q(quark)$



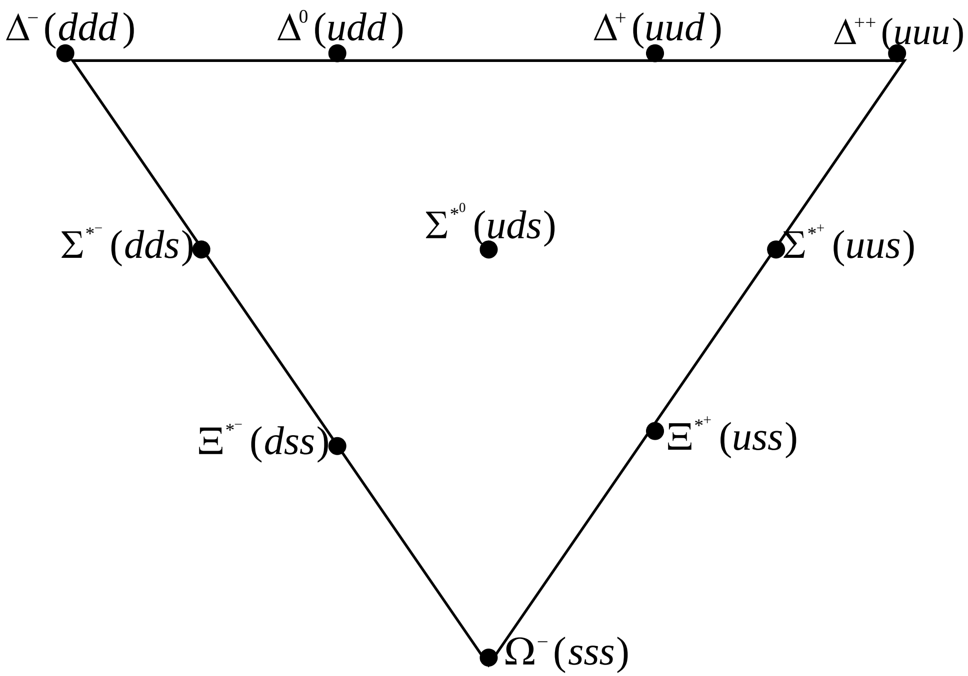
(Triplet)

$\overline{Q}(Anti-quark)$



(Anti- Triplet)

1.2 Quark Model and Fundamental interaction



1.2 Quark Model and Fundamental interaction

When Gell-Mann proposed the quark model, Ω^- was not yet observed.

$$M_{\Delta}(S=0) \approx 1232\, Mev/c^2$$

$$M_{\Sigma^*}(S=-1) \approx 1385\, Mev/c^2$$

$$M_{\Xi^*}(S=-2) \approx 1533\, Mev/c^2$$

$$\downarrow$$

$$M_{\Omega}(S=-3)??$$

1.2 Quark Model and Fundamental interaction

We can guess its mass by observing the mass gap between two adjacent strangeness.

$$M_{\Omega}(S=-3)-M_{\Xi^*}(S=-2)\approx 150Mev/c^2$$

$$\downarrow$$

The estimated mass of Ω^- was about $1683\mathrm{MeV/c}^2$

Baryon Decuplet

Baryon Decuplet (J=3/2)

Expect 10 states.

Prediction of the Ω⁻ (mass =1672 MeV/c², S

Use bubble chamber to find the event.

1969 Nobel Prize to Gell-Mann!

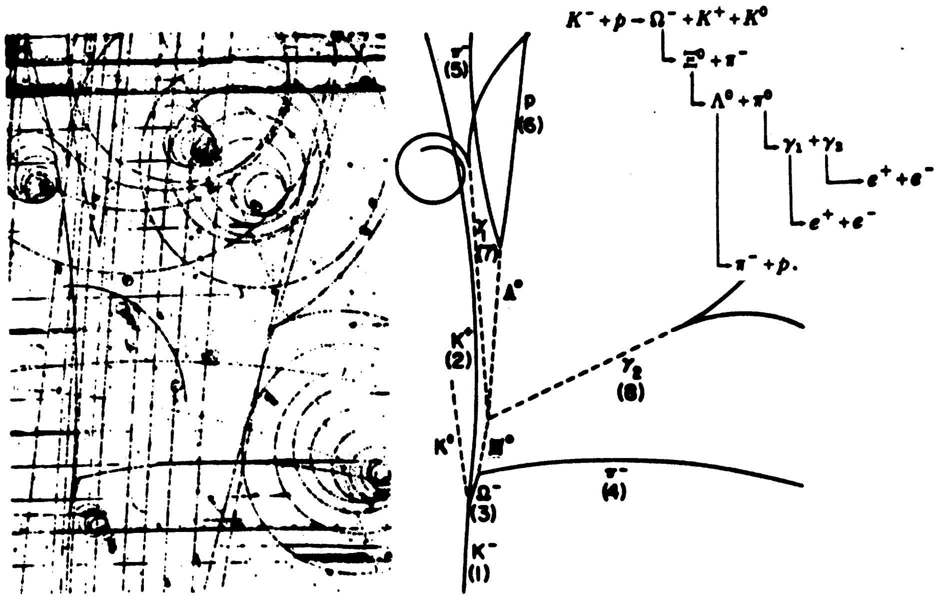
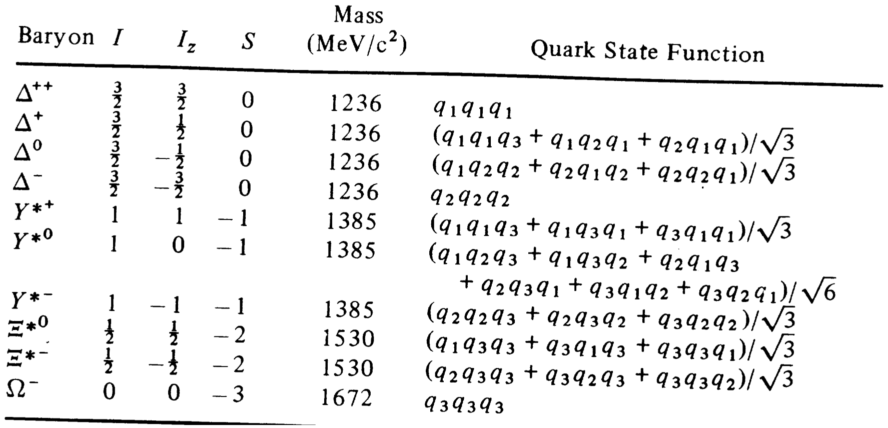


FIG. 2. Photograph and line diagram of event showing decay of Ω^-.

> “Observation of a hyperon with strangeness minus 3”
> PRL V12, 1964.

Table 14-4 The quark model content of the baryon decuplet: $q_1 = p$, $q_2 = n$, $q_3 = \lambda$ (Taken from Ref. 14LIC)



Baryon	I	I_z	S	Mass (MeV/c²)	Quark State Function
Δ^{++}	$\frac{3}{2}$	$\frac{3}{2}$	0	1236	$q_1q_1q_1$
Δ^{+}	$\frac{3}{2}$	$\frac{1}{2}$	0	1236	$(q_1q_1q_3 + q_1q_2q_1 + q_2q_1q_1)/\sqrt{3}$
Δ^{0}	$\frac{3}{2}$	$-\frac{1}{2}$	0	1236	$(q_1q_2q_2 + q_2q_1q_2 + q_2q_2q_1)/\sqrt{3}$
Δ^{-}	$\frac{3}{2}$	$-\frac{3}{2}$	0	1236	$q_2q_2q_2$
Y^{*+}	1	1	−1	1385	$(q_1q_1q_3 + q_1q_3q_1 + q_3q_1q_1)/\sqrt{3}$
Y^{*0}	1	0	−1	1385	$(q_1q_2q_3 + q_1q_3q_2 + q_2q_1q_3 + q_2q_3q_1 + q_3q_1q_2 + q_3q_2q_1)/\sqrt{6}$
Y^{*-}	1	−1	−1	1385	$(q_2q_2q_3 + q_2q_3q_2 + q_3q_2q_2)/\sqrt{3}$
Ξ^{*0}	$\frac{1}{2}$	$\frac{1}{2}$	−2	1530	$(q_1q_3q_3 + q_3q_1q_3 + q_3q_3q_1)/\sqrt{3}$
Ξ^{*-}	$\frac{1}{2}$	$-\frac{1}{2}$	−2	1530	$(q_2q_3q_3 + q_3q_2q_3 + q_3q_3q_2)/\sqrt{3}$
Ω^{-}	0	0	−3	1672	$q_3q_3q_3$

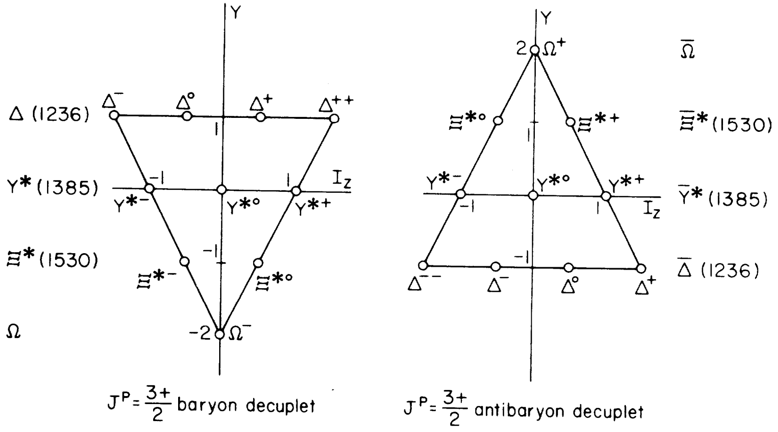
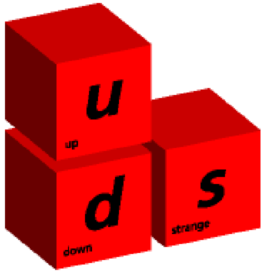


Fig. 14-3 The $SU(3)$ decuplet classification of the $J = \frac{3}{2}$ baryon and antibaryon multiplets.



1.2 Quark Model and Fundamental interaction

There were a couple of problems in accepting Gell-Mann's quark model.

First, other combinations of quarks such as two quarks were not observed and there is no evidence for the existence of quark.

Second, problem of Pauli's exclusion principle.

$$\Delta^{++}(S_z = \frac{3}{2}) = (u^{\uparrow}u^{\uparrow}u^{\uparrow}) \times (L = 0 \ \ symmetric \ \ orbital)$$

1.2 Quark Model and Fundamental interaction

<u>The postulate</u>

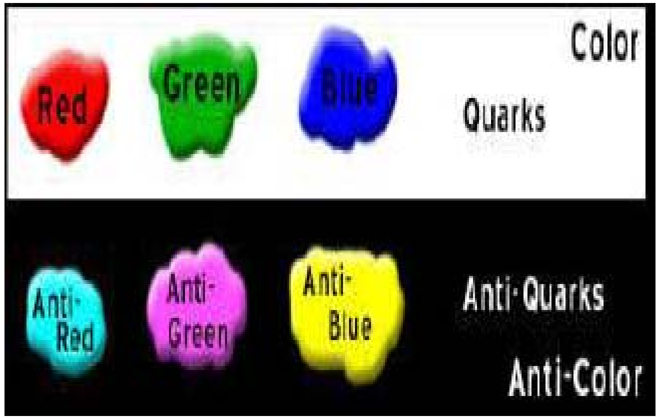
1. Quarks carry three different "color charges".
2. Only color-neutral objects can be observed in nature.

Suppose three colors are r, y, and g. ↓

$$r + y + g = 0$$

$$r + \bar{r} = 0$$
$$y + \bar{y} = 0$$
$$g + \bar{g} = 0$$

→ $\bar{r}, \bar{y}, \bar{g}$ means anticolor.



1.2 Quark Model and Fundamental interaction

All other combinations would fail to cancel the color charges each other

$$\Delta^{++}(S_z = \frac{3}{2}) = (u_r{}^{\uparrow} u_y{}^{\uparrow} u_g{}^{\uparrow}) \times (L = 0\ \ symmetric\ \ orbital)$$

↓

The problem of Pauli's exclusion principle is also naturally solved

1.2 Quark Model and Fundamental interaction

So, why can only color-neutral objects be observed in nature?

Maybe the answer will be provided by QCD(quantum chromodynamics)

Nowadays, people have established the standard model of elementary particle physics assuming the six quarks (u, d, s, c, b, t) and the six leptons $(e, \nu_e, \mu, \nu_\mu, \tau, \nu_\tau)$

Modern Particle Physics

Our current theory is embodied in the

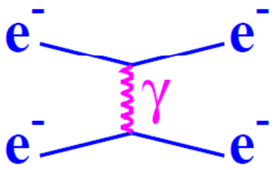
Standard Model

which accurately describes all data.

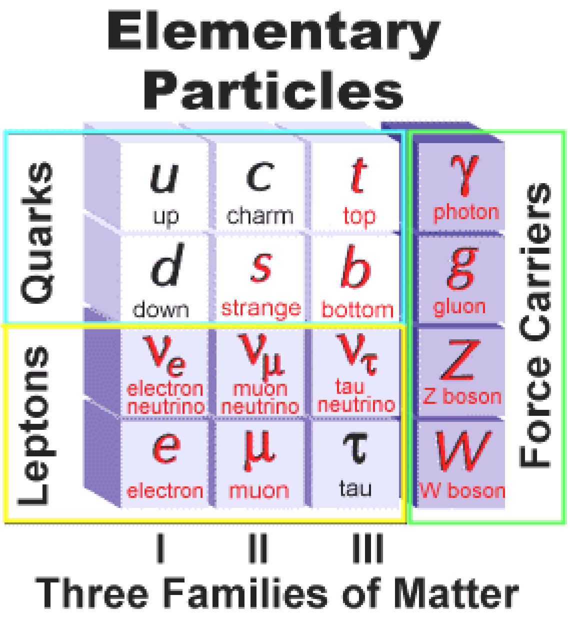
MATTER: made of spin-$\frac{1}{2}$ FERMIONS of which there are two types.

- ★ LEPTONS: e.g. e$^-$, ν_e
- ★ QUARKS: e.g. up quark and down quark
  proton - (u,u,d)
- ★ + ANTIMATTER: e.g. positron e$^+$,
  anti-proton - $(\bar{\mathrm{u}},\bar{\mathrm{u}},\bar{\mathrm{d}})$

FORCES: forces between quarks and leptons mediated by the exchange of spin-1 bosons - the GAUGE BOSONS.



Electromagnetic	Photon	γ
Strong	Gluon	g
Weak	W and Z	$W^{\pm}, Z^0$
Gravity	Graviton	G



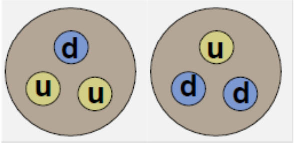
Matter: 1^{st} Generation

Almost all phenomena you will have encountered can be described by the interactions of FOUR spin-half particles : “the First Generation”

particle	symbol	type	charge
Electron	e^-	lepton	-1
Neutrino	ν_e	lepton	0
Up Quark	u	quark	+2/3
Down Quark	d	quark	-1/3

The proton and the neutron are the lowest energy states of a combination of three quarks:

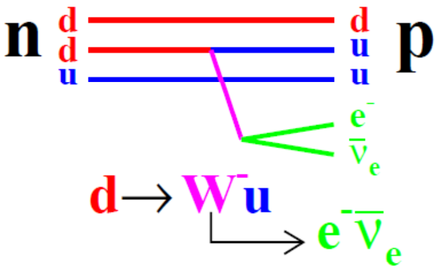
- ★ Proton = (uud)
- ★ Neutron = (udd)

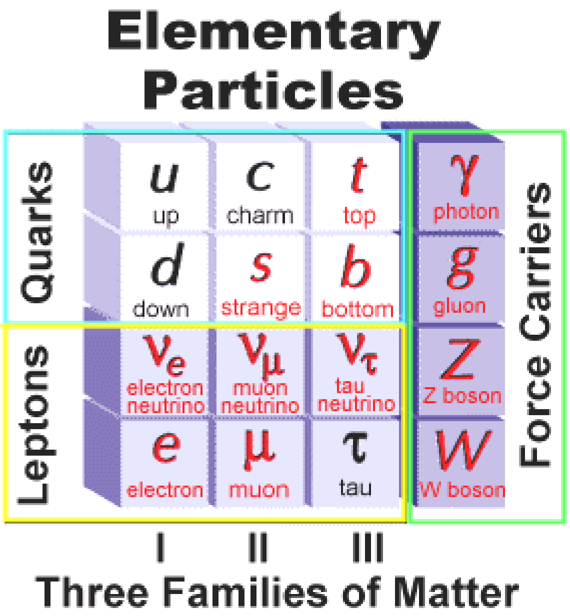


e.g. beta-decay viewed in the quark picture

$$n \rightarrow p + e^- + \overline{\nu}_e$$

$$d \rightarrow u + e^- + \overline{\nu}_e$$





GENERATIONS

- ★ Nature is not quite that simple.
- ★ There are 3 GENERATIONS of fundamental fermions.

First Generation		Second Generation		Third Generation	
Electron	e^-	Muon	μ^-	Tau	τ^-
Electron Neutrino	ν_e	Muon Neutrino	ν_μ	Tau Neutrino	ν_τ
Up Quark	u	Charm Quark	c	Top Quark	t
Down Quark	d	Strange Quark	s	Bottom Quark	b

- ★ Each generation e.g. (μ^-, ν_μ, c, s) is an exact copy of (e^-, ν_e, u, d).
- ★ The only difference is the mass of the particles - with first generation the lightest and third generation heaviest.
- ★ Clear symmetry - origin of 3 generations is NOT UNDERSTOOD

The LEPTONS

PARTICLES which do not interact via the STRONG interaction - “colour charge” = 0.

- ★ spin 1/2 fermions
- ★ 6 distinct FLAVOURS of leptons
- ★ 3 charged leptons : e^-,μ^-,τ^-

  Muon (μ^-) - heavier version of the electron ($m_\mu/m_e \approx 207$)
- ★ 3 neutral leptons : neutrinos

Gen.	flavour		q	Approx. Mass
1^{st}	Electron	e^-	-1	0.511 MeV/c^2
1^{st}	Electron neutrino	ν_e	0	massless ?
2^{nd}	Muon	μ^-	-1	105.7 MeV/c^2
2^{nd}	Muon neutrino	ν_μ	0	massless ?
3^{rd}	Tau	τ^-	-1	1777.0 MeV/c^2
3^{rd}	Tau neutrino	ν_τ	0	massless ?

- ★ + antimatter partners, e^+, $\overline{\nu}_e$

Neutrinos

stable and (almost ?) massless:

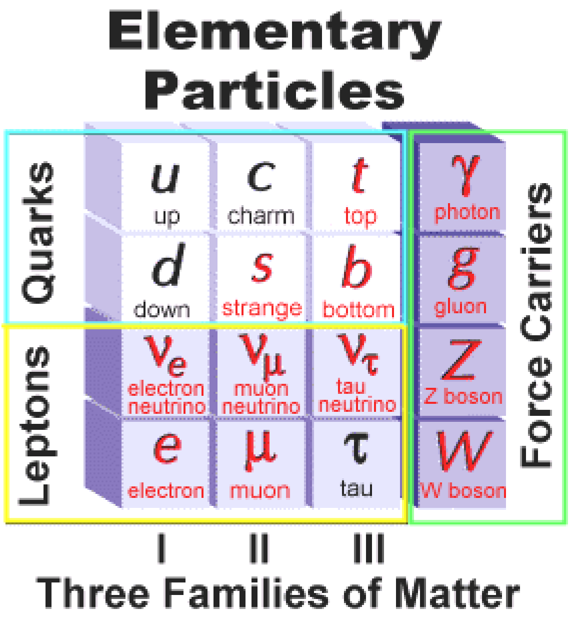
ν_e Mass < 3 eV$/c^2$

ν_μ Mass < 0.19 MeV$/c^2$

ν_τ Mass < 18.2 MeV$/c^2$

★ Charged leptons only experience the ELECTROMAGNETIC and WEAK and forces.

★ Neutrinos only experience the WEAK force.



The Quarks

- ★ spin 1/2 fermions
- ★ fractional charge
- ★ 6 distinct FLAVOURS of quarks

Generation	flavour		charge	Approx. Mass
1^{st}	down	d	-1/3	0.35 GeV/c^2
1^{st}	up	u	+2/3	0.35 GeV/c^2
2^{nd}	strange	s	-1/3	0.5 GeV/c^2
2^{nd}	charm	c	+2/3	1.5 GeV/c^2
3^{rd}	bottom	b	-1/3	4.5 GeV/c^2
3^{rd}	top	t	+2/3	175 GeV/c^2

Mass quoted in units of GeV/c^2. To be compared with $M_{\rm proton}$ = 0.938 GeV/c^2.

- ★ Quarks come in 3 "COLOURS"

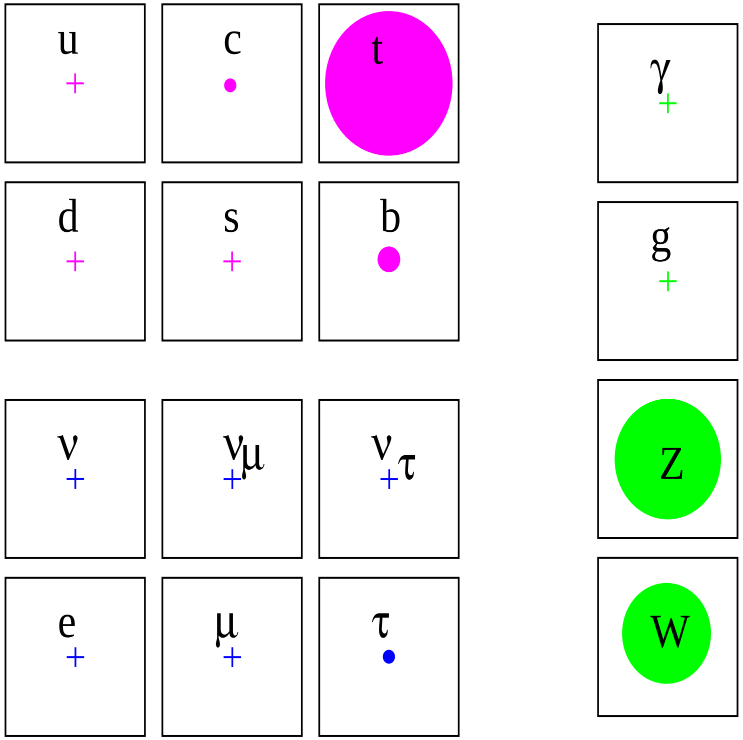
  "RED", "GREEN", "BLUE"

COLOUR is a label for the charge of the strong interaction. Unlike the electric charge of an electron ($-e$), the strong charge comes in three "orthogonal colours" RGB.

- ★ quarks confined within *HADRONS*

  e.g. p $\equiv$ (uud), $\pi^+ \equiv$ (u$\overline{\rm d}$)

- ★ Quarks experience the ALL forces: ELECTROMAGNETIC, STRONG and WEAK (and of course gravity).

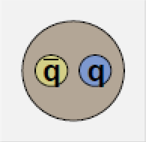


+ = "too small to show"

HADRONS

- ★ single free QUARKS are NEVER observed
- ★ quarks always CONFINED in HADRONS
  i.e. ONLY see bound states of $(q\overline{q})$ or (qqq).
- ★ HADRONS = $\{$ MESONS,BARYONS $\}$

MESONS = $q\overline{q}$



A meson is a bound state of a QUARK and an ANTI-QUARK

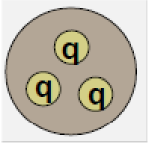
- All have INTEGER spin 0,1,2,...
- e.g. $\pi^+ \equiv u\overline{d}$

  charge, $Q_{\pi^+} = Q_u + Q_{\overline{d}} = \frac{2}{3} + \frac{1}{3} = +1$

  π^+ is the ground state (L=0) of $u\overline{d}$

  there are other states, e.g. ρ^+, ...

BARYONS=qqq

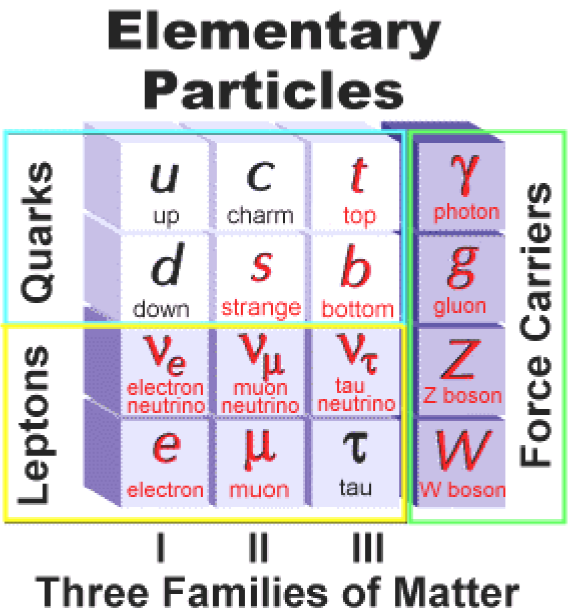


- All have half-INTEGER spin $\frac{1}{2}, \frac{3}{2}$,...
  e.g. $p \equiv (uud)$

  e.g. $n \equiv (udd)$
- Plus ANTI-BARYONS= $\overline{q}\,\overline{q}\,\overline{q}$
  e.g. anti-proton $\overline{p} \equiv (\overline{u}\overline{u}\overline{d})$

  e.g. anti-neutron $\overline{n} \equiv (\overline{u}\overline{d}\overline{d})$

★ Composite ⇒ relatively complicated



Forces

Consider ELECTROMAGNETISM and scattering of electrons from a proton:

Classical Picture

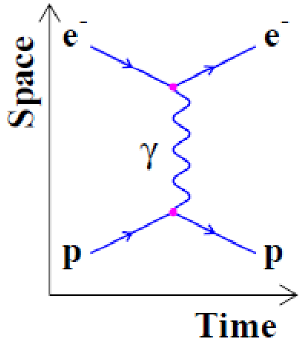
Electrons scatter in the static potential of the proton:

$$V(r) \propto -\frac{1}{r}$$

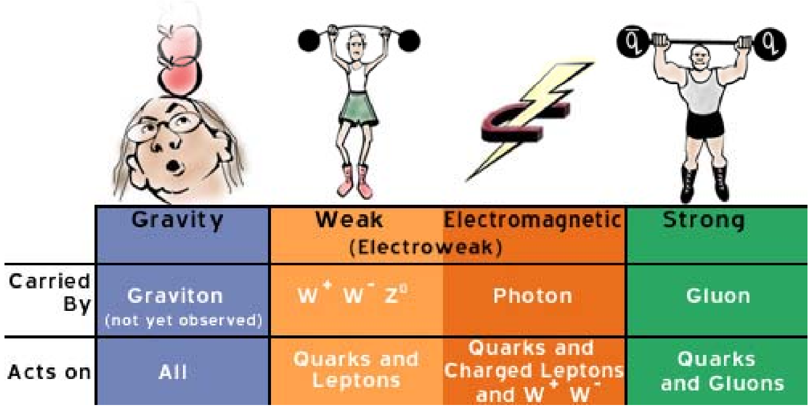
NEWTON : "...that one body can act upon another at a distance, through a vacuum, without the mediation of anything else,..., is to me a great absurdity"

Modern Picture

Particles interact via the exchange of particles GAUGE BOSONS. The PHOTON is the gauge bosons of electromagnetic force.



Early next week we'll learn how to calculate Quantum Mechanical amplitudes for scattering via Gauge Boson Exchange.

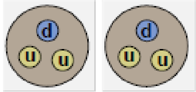


	Gravity	Weak	Electromagnetic	Strong
		(Electroweak)		
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons

All (known) particle interactions can be explained by 4 fundamental forces:

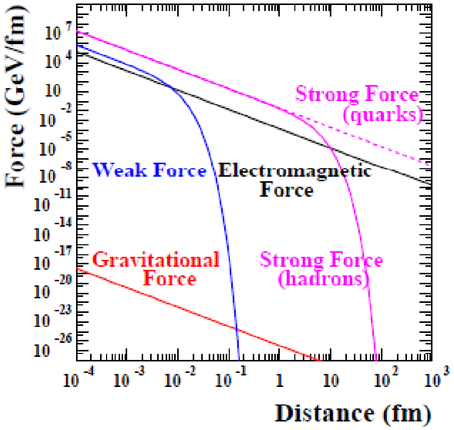
Electromagnetic, Strong, Weak, Gravity

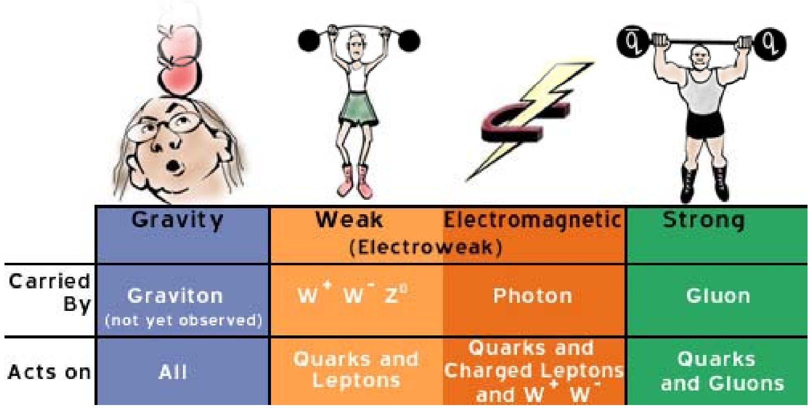
Relative strengths of the forces between two protons just in contact (10^{-15} m):



Strong	1
Electromagnetic	10^{-2}
Weak	10^{-7}
Gravity	10^{-39}

At very small distances (high energies) - **UNIFICATION**





	Gravity	Weak	Electromagnetic	Strong
		(Electroweak)		
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons

The Gauge Bosons

- ★ GAUGE BOSONS mediate the fundamental forces
- ★ Spin-1 particles (i.e. VECTOR BOSONS)
- ★ The manner in which the GAUGE BOSONS interact with the LEPTONS and QUARKS determines the nature of the fundamental forces.

Force	Boson	Mass (GeV/c^2)	Range (m)
Electromagnetic	Photon	massless	∞
Weak	$W^{\pm}, Z$	80/90	10^{-17}
Strong	Gluon	massless	$\infty/10^{-15}$

Practical Particle Physics

OR How do we study the particles and forces ?

- **Static Properties:**
  - Mass
  - Spin, Parity : J^P e.g. 1^-
  - Magnetic Moments (see Quark Model handout)

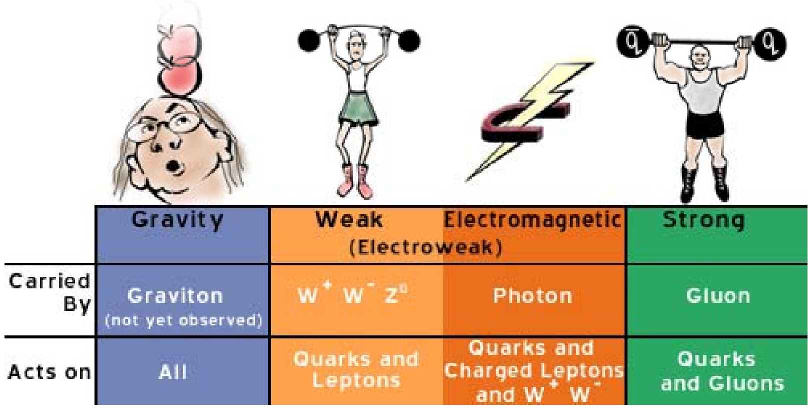
- **Particle Decays :**
  - Allowed/Forbidden decays $\rightarrow$ conservation laws
  - Particle lifetimes

Force	Typical Lifetime
STRONG	10^{-23} s
E-M	10^{-20} s
WEAK	10^{-8} s

- **Accelerator physics - particle scattering:**
  - Direct production of new massive particles in Matter/Antimatter ANNIHILATION
  - Study of particle interaction cross sections

FORCE	Typical Cross section
STRONG	10 mb
E-M	10^{-2} mb
WEAK	10^{-13} mb

Scattering and Annihilation in Quantum Electrodynamics are the main topics of the next two lectures. Particle decay will be covered later in the course.



	Gravity	Weak	Electromagnetic	Strong
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Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons

NATURAL UNITS

SI UNITS: kg m s $[M]\,[L]\,[T]$

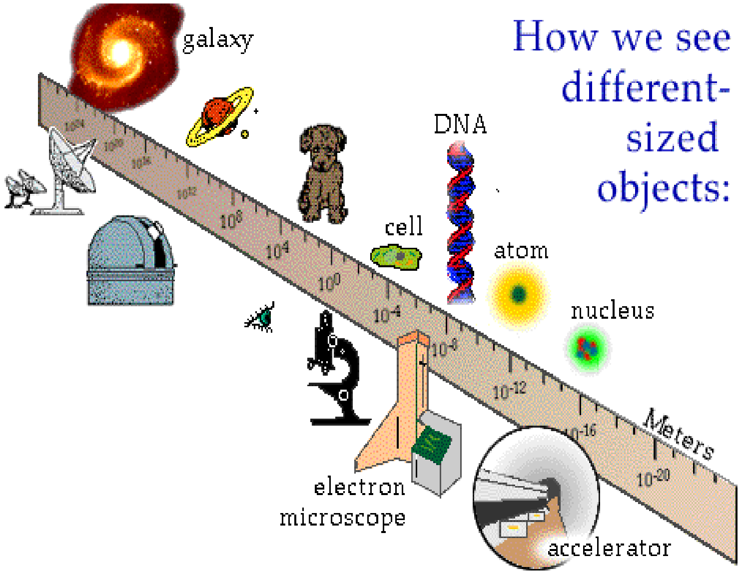
- ★ For everyday physics SI units are a natural choice : M(Widdecombe)~ 250 kg
- ★ Not so good for particle physics: $M_{\text{proton}} \sim 10^{-27}$ kg
- ★ use a different basis - NATURAL UNITS
- ★ based on language of particle physics, *i.e.* Quantum Mechanics and Relativity
  - unit of action in QM $\hbar$ (Js)
  - velocity of light c (ms^{-2})
- ★ Unit of energy : GeV = 10^9 eV= 1.6×10^{-10} J

Natural Units

GeV ħ c

Units become

Energy	GeV	**Time**	(GeV/$\hbar$)$^{-1}$
Momentum	GeV/c	**Length**	(GeV/$\hbar$c)$^{-1}$
Mass	GeV/c^2	**Area**	(GeV/$\hbar$c)$^{-2}$



Simplify (!) by choosing

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

All quantities expressed in powers of GeV

Energy	GeV	Time	GeV^{-1}
Momentum	GeV	Length	GeV^{-1}
Mass	GeV	Area	GeV^{-2}

★ **Convert back to S.I. units by reintroducing 'missing' factors of $\hbar$ and c**

EXAMPLE: $\mathrm{Area} = 1\,\mathrm{GeV}^{-2}$

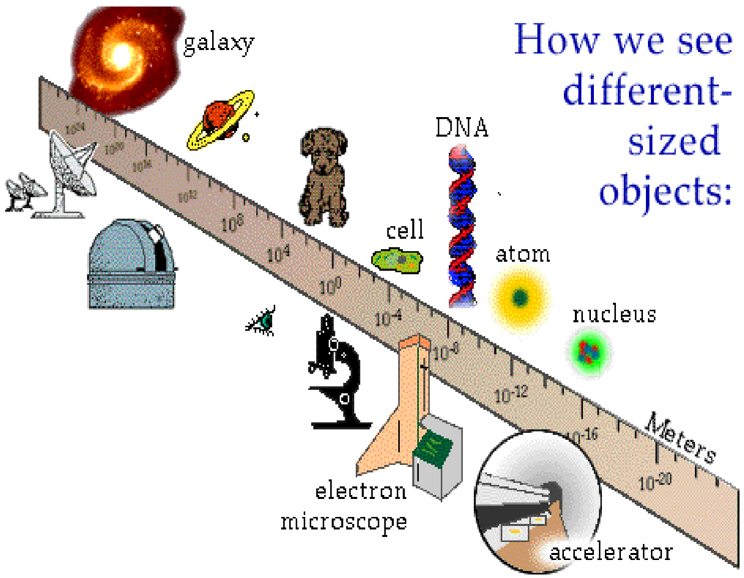
$$\begin{aligned}
[\mathrm{L}]^2 &= [\mathrm{E}]^{-2}[\hbar]^n[c]^m \\
[\mathrm{L}]^2 &= [\mathrm{E}]^{-2}[\mathrm{E}]^n[\mathrm{T}]^n[\mathrm{L}]^m[\mathrm{T}]^{-m} \\
\therefore n = 2 \quad &\text{and} \quad m = 2 \\
\rightarrow \mathrm{Area(S.I.)} &= 1\,\mathrm{GeV}^{-2} \times \hbar^2 c^2 \\
&= 3.8 \times 10^{-32}\ m^2 \\
&= 0.38\ mb
\end{aligned}$$

Heaviside-Lorentz units $\epsilon_0 = \mu_0 = \hbar = c = 1$

Fine structure constant α:

$$\alpha = \frac{e^2}{4\pi\epsilon_0 \hbar c} \approx \frac{1}{137}$$

becomes $$\alpha = \frac{e^2}{4\pi} \approx \frac{1}{137}$$



Summary

FERMIONS : spin $\frac{1}{2}$

leptons

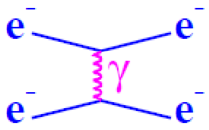
$$\begin{pmatrix} e^- \\ \nu_e \end{pmatrix} \quad \begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix} \quad \begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix} \qquad \begin{matrix} \text{Charge} \\ -1 \\ 0 \end{matrix}$$

quarks e.g. proton (uud)

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix} \qquad \begin{matrix} +\frac{2}{3} \\ -\frac{1}{3} \end{matrix}$$

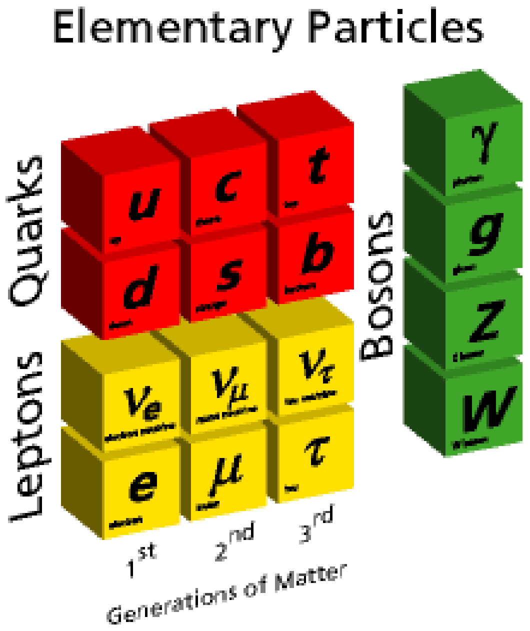
+ anti-particles

Fermion interactions = exchange of spin 1 bosons



BOSONS : spin 1

		Mass	Force
Photon	γ	0	Electromagnetic
W-boson	$W^\pm$	91.2 GeV	Weak (CC)
Z-boson	Z^0	80.3 GeV	Weak (NC)
Gluon	g	0	Strong (QCD)



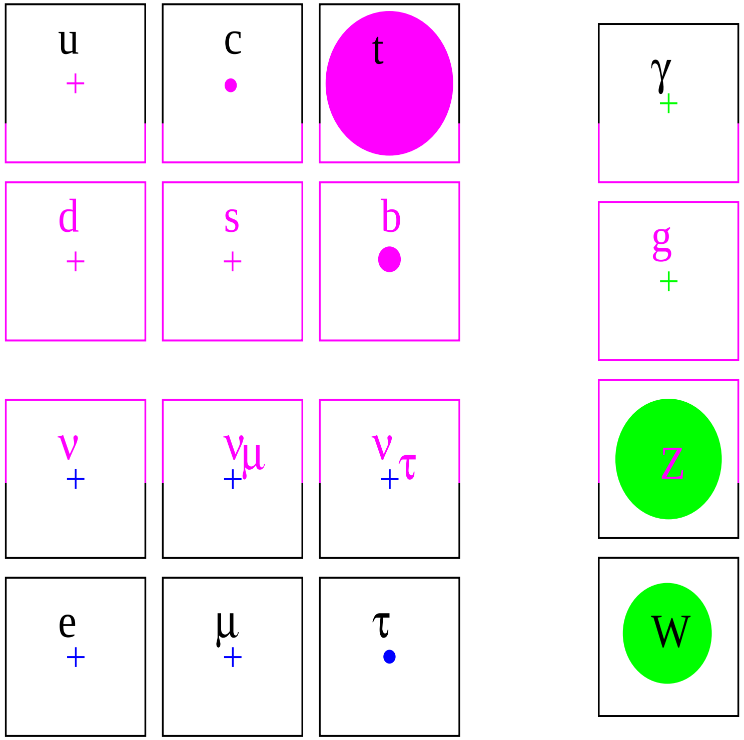
References

- Seok Hoon Yun
- M.A. Thompson
- …

Thank you.

Back-up

Standard Model



\+ = "too small to show"

- t, b, c are heavier than other quarks
  - heavy flavor quarks
- W, Z, top are stand out from the rest.

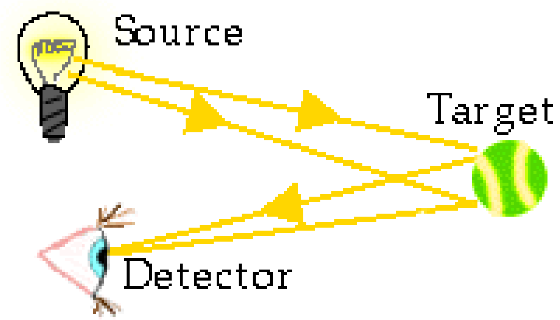
Matter

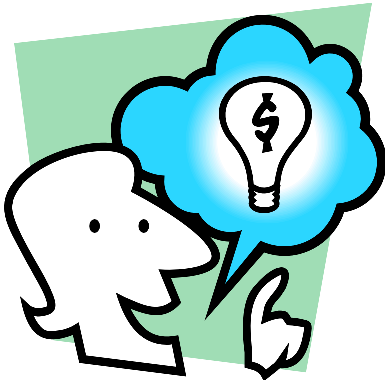
- Hadron (Quark) - size
  - Baryon (qqq): proton, neutron
  - Meson (q qbar): pion, kaon

- Lepton – no size
  - Point particle

How to know any of this? (Testing Theory)

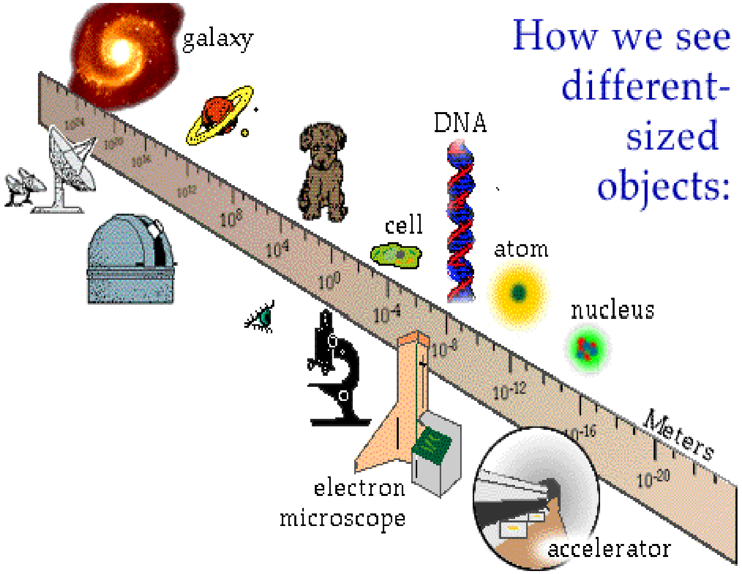
- Example
  - Light bulb (Source)
  - Tennis ball (target)
  - Eye (detector)





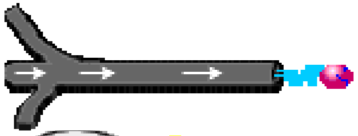
How to detect?

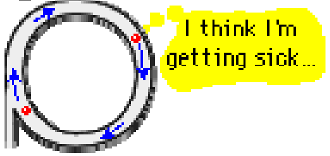
- Accelerators solve two problems:
  - High energy gives small wavelength to detect small particles. (Lambda = h /p)
  - The high energy create the massive particles that the physicist want to study.(E=mc^2)



Accelerator design

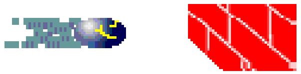
- Shapes
  - Linacs (SLAC)
  - Synchrotrons (Fermilab)





- Collision types
  - Fixed target (E687, FOCUS)
  - Colliding beams (CDF, Belle, BTeV)

  => CM = 1TeV+1TeV => 2TeV

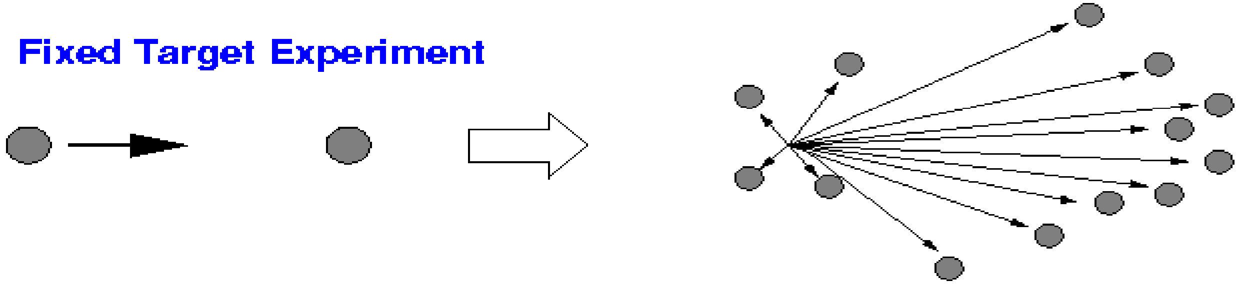


High Energy Experiment

To see subatomic particles, incident beam wavelength should
less than the size of each particle.

$\lambda = h / p$ (h:Planck constant p:Incident particle momentum)

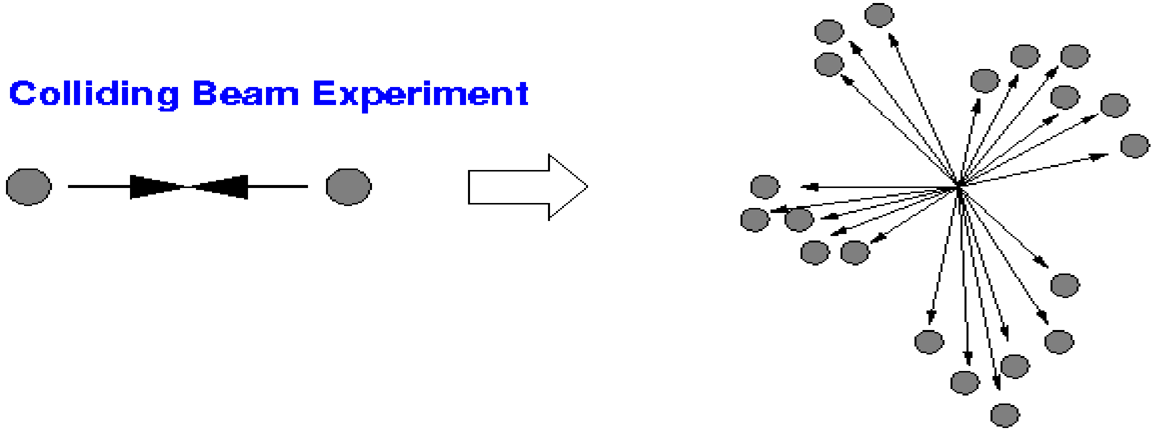
Fixed Target Experiment



Before collision

After collision

Colliding Beam Experiment



Fixed target vs Colliding beams

(total energy)^2-(total momentum)^2 = invariant in all frames of reference

Assume that 800GeV(E_{beam}) proton collides in a fixed target(proton).

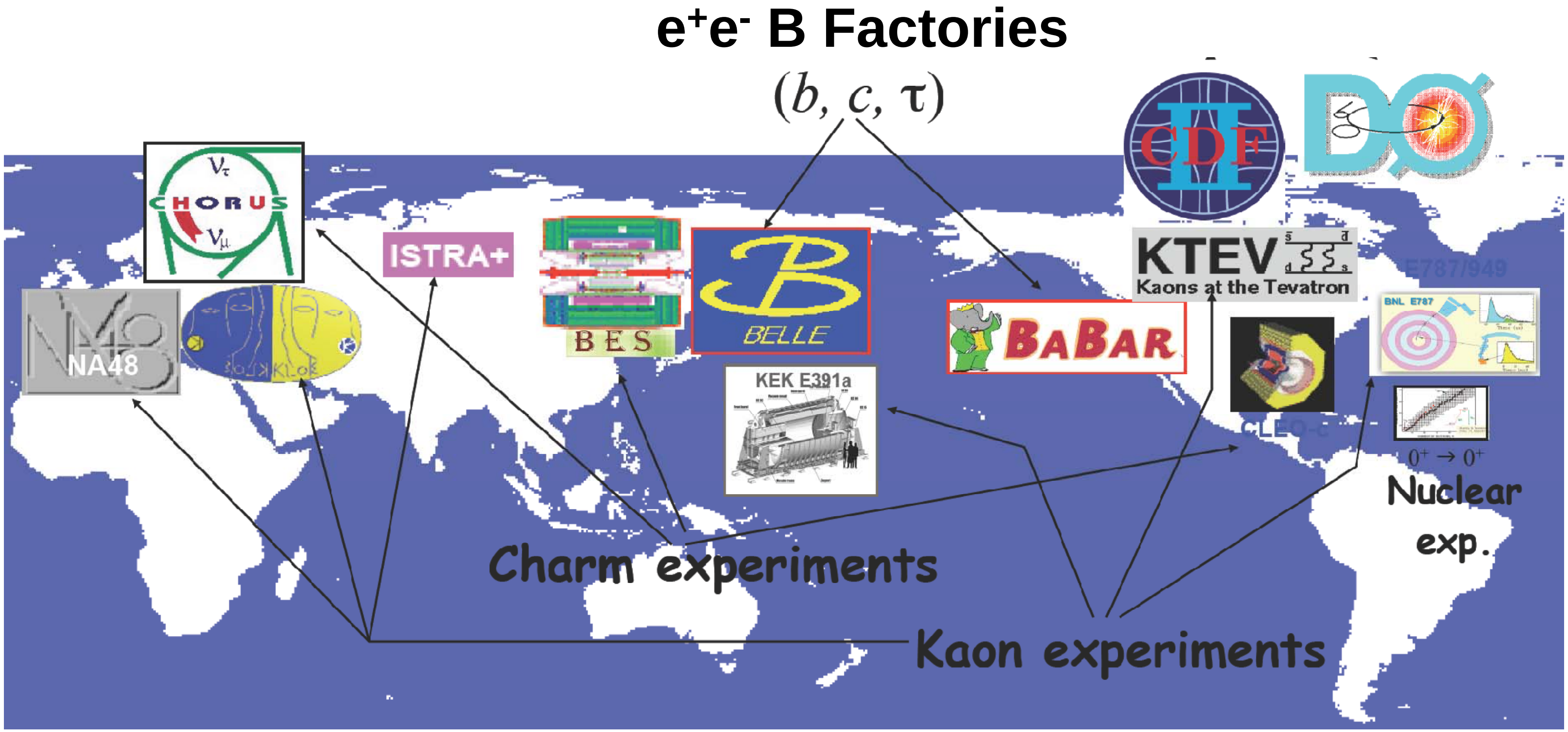
	Center of mom. frame	**Laboraroty frame**
Total energy:	E_{CM}	$E_{beam}+m_p$
Total momentum:	0	P_{beam}
Invariant:	E_{CM}^2	$(E_{beam}+m_p)^2-P_{beam}^2$

$$E = [\, 2(m_p^2+E_{beam}m_p)\,]^{1/2} = 38.8\text{GeV}$$

We are enough to 19.4GeV+19.4GeV proton beams in collider !!!

Question: What's the advantage of a fixed target experiment?

Experiments related to CKM parameters



e^+e^- B Factories

(b, c, τ)

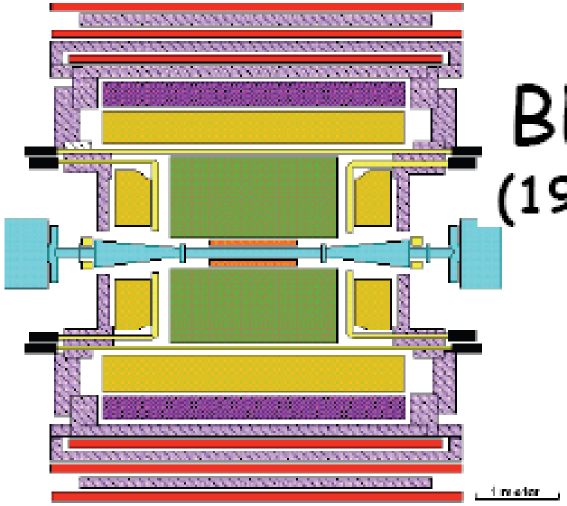
Charm experiments

Kaon experiments

Nuclear exp.

Talk by Elisabetta Barberio

전자-양전자 충돌 가속기 실험

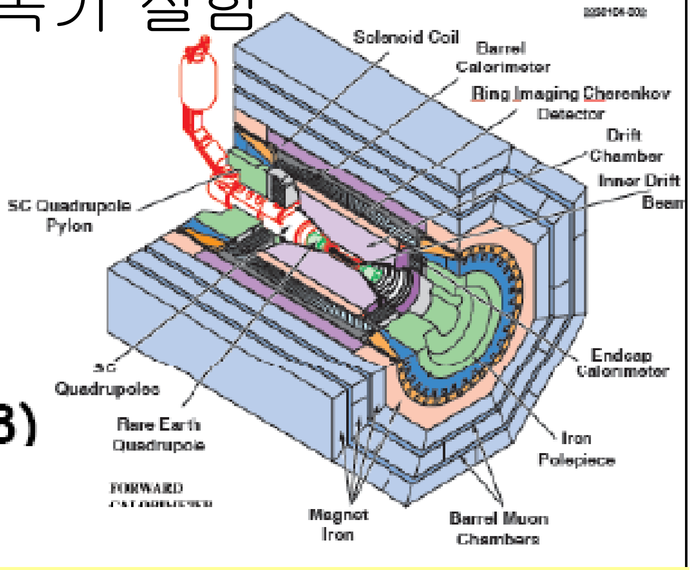


BESII

(1996 - 2004)

CLEOc

(2003 - 2008)

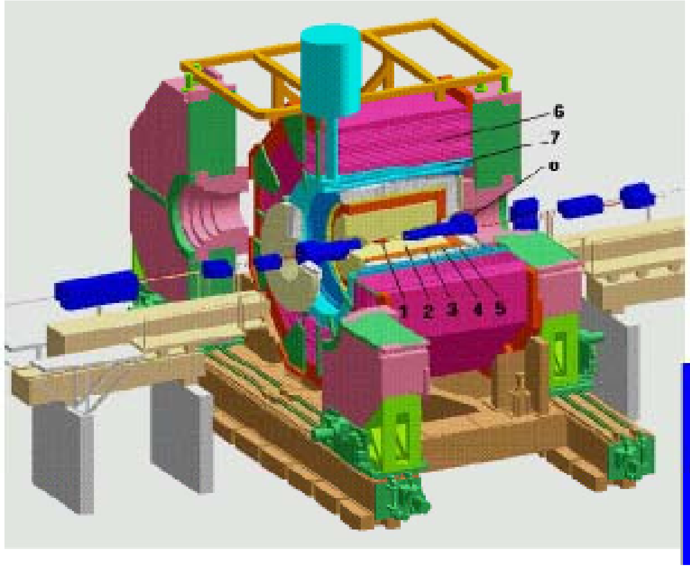


e^+e^-

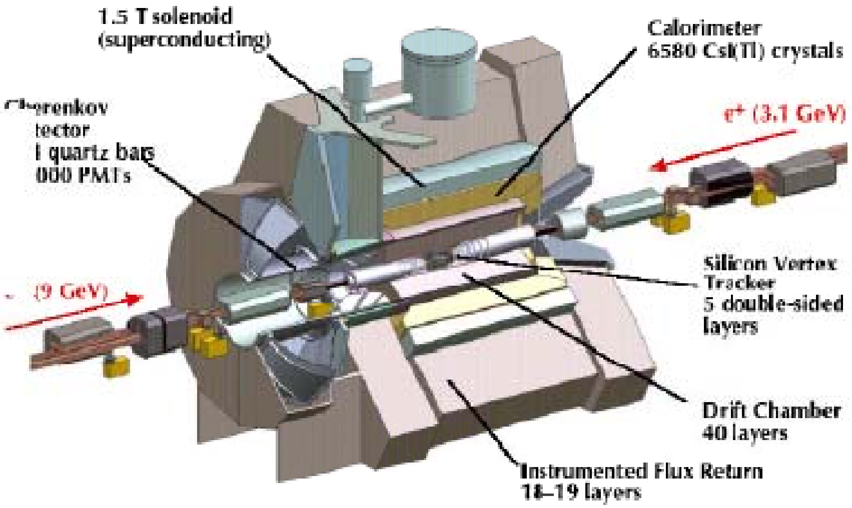
Excellent photon resolution.

BABAR (1998 - 2008)

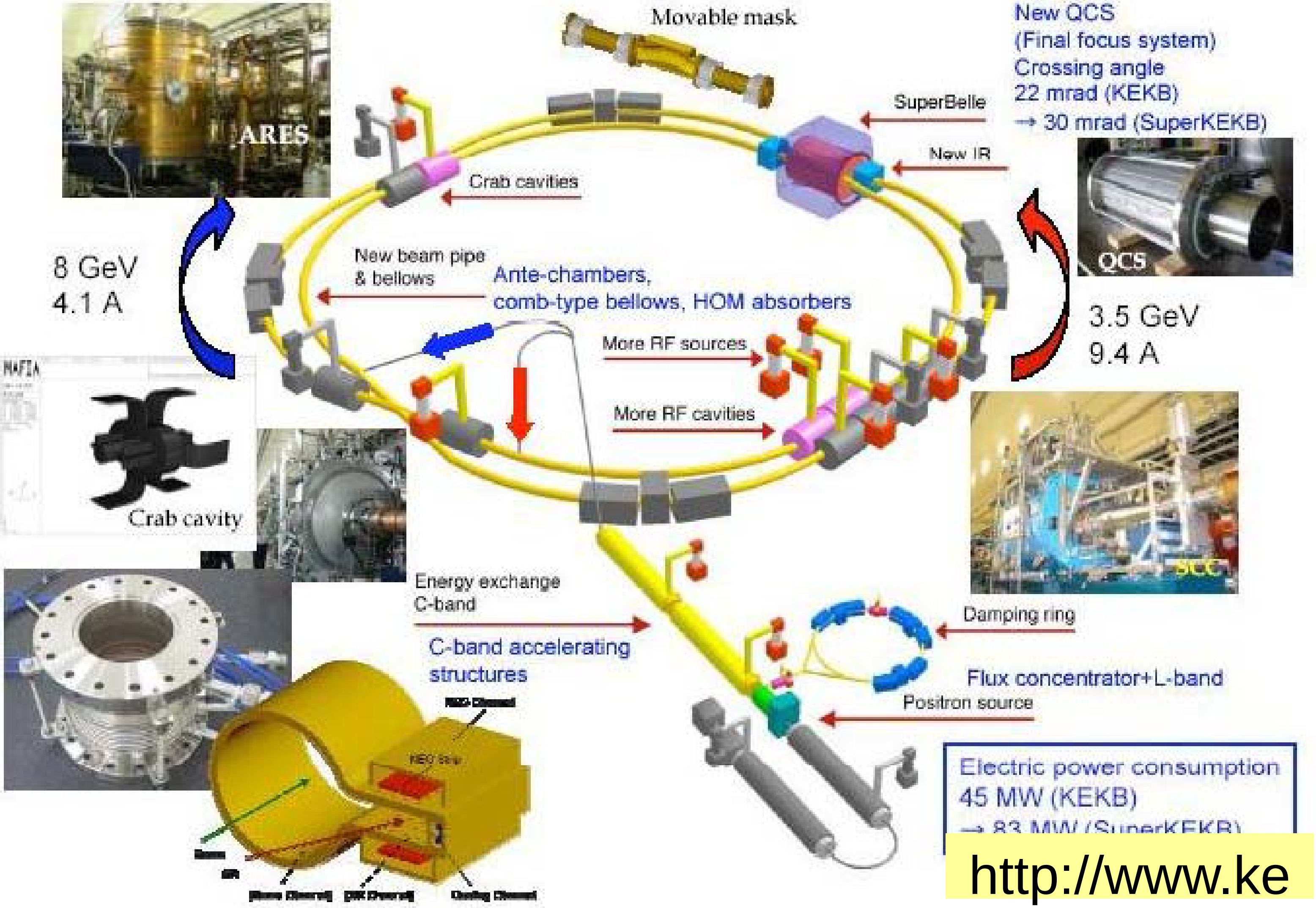
Belle (1998 -)



The BaBar Detector



Super Belle (2012~



Movable mask

New QCS
(Final focus system)
Crossing angle
22 mrad (KEKB)
→ 30 mrad (SuperKEKB)

SuperBelle

New IR

Crab cavities

8 GeV
4.1 A

3.5 GeV
9.4 A

New beam pipe
& bellows

Ante-chambers,
comb-type bellows, HOM absorbers

More RF sources

More RF cavities

Energy exchange
C-band

C-band accelerating
structures

Damping ring

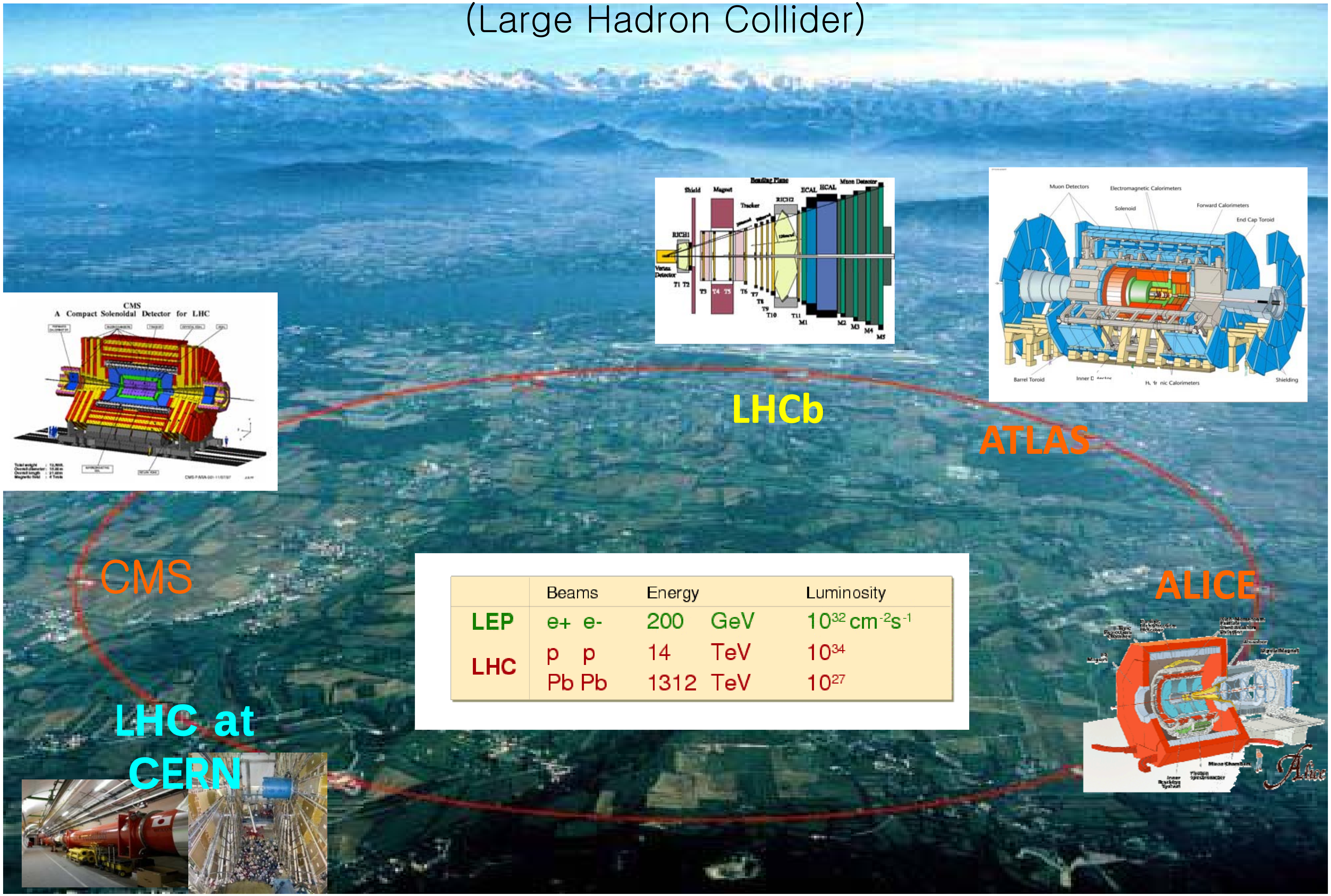
Flux concentrator+L-band

Positron source

Electric power consumption
45 MW (KEKB)
→ 83 MW (SuperKEKB)

http://www.ke

양성자-양성자 충돌 가속기 실험 (Large Hadron Collider)



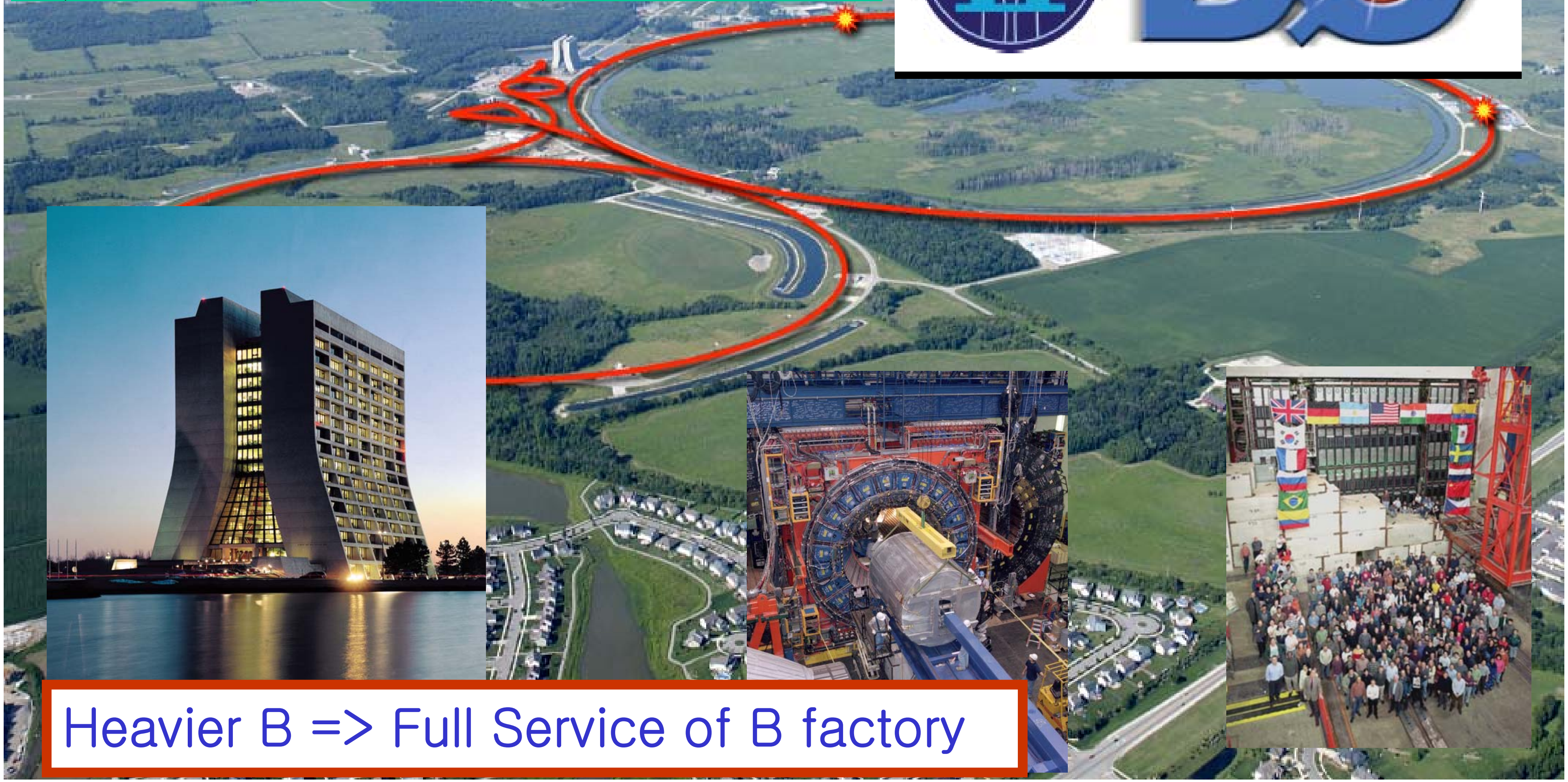
	Beams	Energy		Luminosity
LEP	e+ e-	200	GeV	10^{32} cm^{-2}s^{-1}
LHC	p p	14	TeV	10^{34}
	Pb Pb	1312	TeV	10^{27}

양성자-반양성자 충돌 가속기 실험 (Tevatron)

$\sigma(p\bar{p} \to b\bar{b}) \approx 150\,\mu b$ at 2 TeV (~ 15 kHz!)

$\sigma(e\bar{e} \to b\bar{b}) \approx 7nb$ at Z^0

$\sigma(e\bar{e} \to B\bar{B}) \approx 1nb$ at $\Upsilon(4S)$



Heavier B => Full Service of B factory