High Energy Physics

Text: D. Griffiths: Introduction to Elementary Particles
John Wily & Sons , 2nd Edition(2008)

Reference:

F. Halzen and A.D. Martin: Quarks & Leptons John-Wiley & Sons (1984)

D.H. Perkins: Introduction to High Energy Physics
(4th Edition) Cambridge University Press (2000)

Fayyazuddin & Riazuddin: A Modern Introduction to Particle Physics
(2nd edition) World Scientific Publishing(2000)

Duncan Carlsmith: Particle Physics, Pearson Education (2013)

C H Oh

Physics Department

National University of Singapore

General Reading:

(1) Brian Greene: The Elegant Universe (1999), QC794.6 Str. Gr.

The Fabric of the Cosmos (2003); The Hidden Reality (2011)

(1) M Veltman: Facts and Mysteries in Elementary Particle Physics (WSPC, 2003)

(2) Leo Lederman: The God Particle : If the Universe is the Answer, What is the question, Boston: Houghton Mifflin (1993), QC793.Bos.L

Websites:

Update of the Particle Listings available on the Web
PDG Berkeley website: http://pdg.lbl.gov/

The Berkeley website gives access to MIRROR sites in:
Brazil, CERN, Italy, Japan, Russia, and the United Kingdom.

Also see the Particle Adventure at: http://ParticleAdventure.org

http://www-ed.fnal.gov/lml/Leon_life.html (Leo Lederman)
http://www-ed.fnal.gov/trc/projects/index_all.html

Particle Physics Labs

- **Laboratories**BNL: The Department of Energy's Brookhaven National Laboratory in Upton, Long Island.
- CERN: Originally "Conseil Européenne pour Recherches Nucléaires," now the European Laboratory for Particle Physics, in Geneva, Switzerland.
- DESY: Deutches Elektronen SYnchrotron laboratory in Hamburg, Germany.
- FNAL: The Department of Energy's Fermi National Accelerator Laboratory in Batavia, Illinois.
- KEK: Koo Energy Ken. The High Energy Research Accelerator Organization in Tsukuba, Japan.
- SLAC: The Department of Energy's Stanford Linear Accelerator Center in Palo Alto, California.

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1.1 Introduction

Elementary Particles = Basic constituents of matter.

A particle can be pointlike and wavelike.

To break matter into its smallest pieces, need high energy

$\therefore$ **Elementary particle physics = high energy physics**

Present energy achieved $\approx 1\ TeV \approx 1000\ GeV \approx 10^{12}\ eV$ (Fermilab)

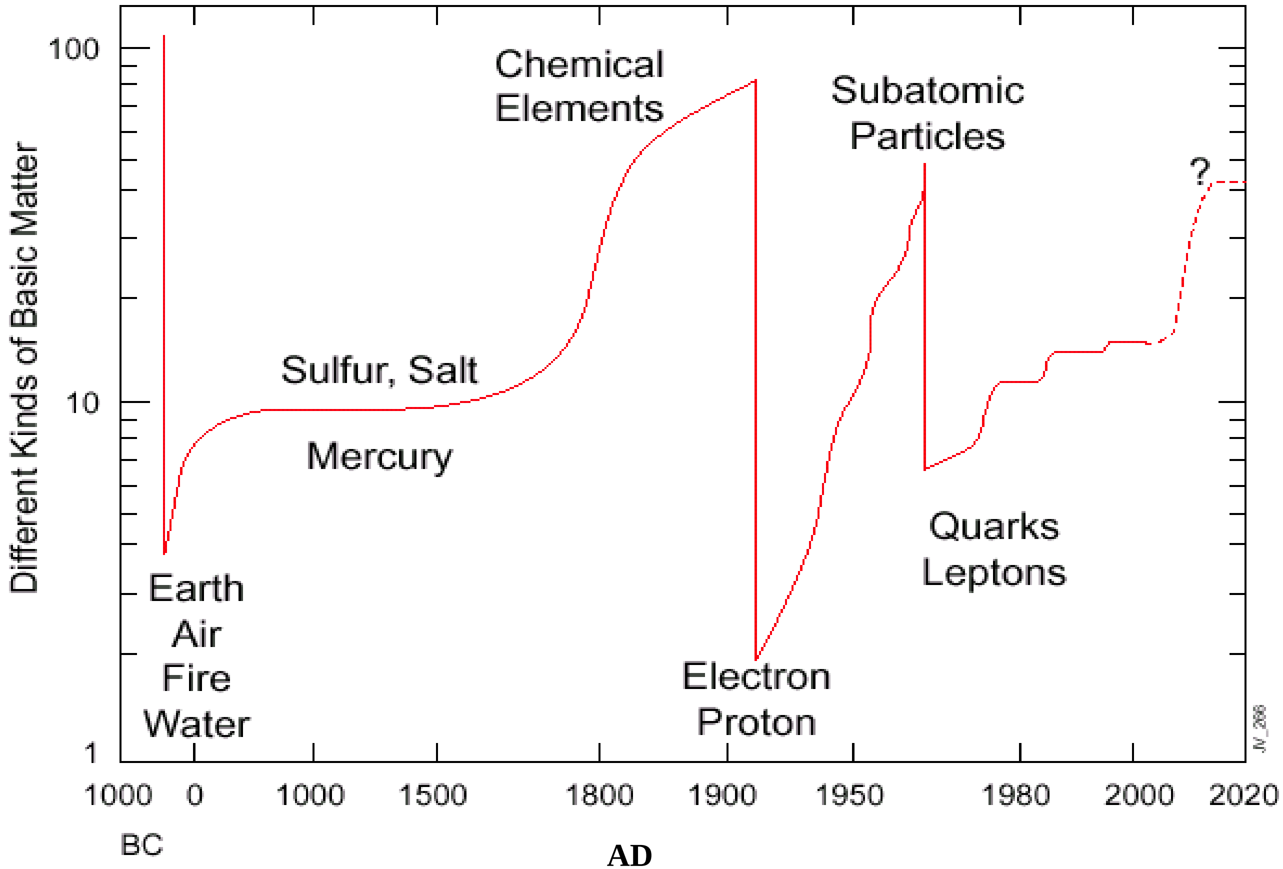
LHC (2007) proton beams $7\ TeV + 7\ TeV = 14\ TeV$

Theoretical discussion on the unification of basic forces has reached the Planck energy scale

$$\left(\frac{\hbar c}{G_N}\right)^{1/2} = 10^{-5} gm = 10^{19} GeV = 10^{28} eV$$

Close to the energy scale at which the universe is created.

History of Constituents of Matter



1.2 Particles

Leptons: Particles do not participate in strong interaction.

	Q	L_e	L_μ	L_τ
e	-1	1	0	0
ν_e	0	1	0	0
μ	-1	0	1	0
ν_μ	0	0	1	0
τ	-1	0	0	1
ν_τ	0	0	0	1

Electron pointlike up to

10^{-15} cm = 10^{-2} fm

Hadrons(strongly interacting particles)

Baryons: Half-integral spin particles (fermions) involve in all basic interactions, ***st*** (strong), ***wk*** (weak), ***em*** (electromagnetic), e g

$p, n, \Lambda, \Sigma^+, \Sigma^0, \Sigma^-, \Xi^0, \Xi^-, \Delta, \Omega^-$

Mesons: integer spin particles (bosons) involve in all basic interactions ***st, wk, em***

$\pi^+, \pi^\circ, \pi^-, k^\pm, k^\circ, \eta, \omega$

Baryons are made from three quarks q, q, q

Mesons are made from quark-antiquark $q, \bar{q}$

Three generations of quarks

	Q	U	D	C	S	T	B
u	2/3	1	0	0	0	0	0
d	-1/3	0	-1	0	0	0	0
c	2/3	0	0	1	0	0	0
s	-1/3	0	0	0	-1	0	0
t	2/3	0	0	0	0	1	0
b	-1/3	0	0	0	0	0	-1

each quark has a nonabelian charge, called colour (**source** of strong interaction); there are three different colours.

Classification symmetry group

The lepton number, like electric charge, is associated with the Abelian U(1) group.

The lepton doublet and also quark doublet are associated with the non-Abelian SU(2), originally from the isospin symmetry of proton and neutron

Baryons and Mesons are bound states of quarks.

e.g.

proton = $\boxed{u\ u\ d}$ antiproton = $\boxed{\bar{u}\ \bar{u}\ \bar{d}}$

Pion $\pi^{+} = \boxed{u\ \bar{d}}$ Pion $\pi^{-} = \boxed{\bar{u}\ d}$

Kaon $k^{+} = \boxed{u\ \bar{s}}$ Kaon $k^{-} = \boxed{\bar{u}\ s}$

$J/\psi = \boxed{c\ \bar{c}}$

Gauge field particles (force field)

Photon γ	**electromagnetic interaction**
Graviton	**gravitation**
Gluons g	**strong interaction**
Intermediate Vector bosons $W^{\pm}$ Z	**weak interaction**

Mass: $m_{W^{\pm}} \approx 82GeV/c^{2}, \quad m_{Z} \approx 92Gev/C^{2}$

1.3 Basic Interactions (forces)

Type of force:	Gravitational	Weak	Electro-magnetic	Strong
Range:	infinite	$\leq 10^{-16}$cm	infinite	$\leq 10^{-13}$cm
Strength relative to strong force at a distance 10^{-13} cm	10^{-38}	10^{-13}	10^{-2}	1
Decay time for a typical small mass hadron:		10^{-10}s	10^{-20}s	10^{-23}s
Mediator:	Graviton	W^+, W^-, Z^0	Photon γ	gluon
Mass of the mediator:	0	82 GeV/c^2 92 GeV/c^2	0	0

non-linear int.		
Theories:	**Strong interaction**	**Quantum chromodynamics QCD**
linear int.	***em* interaction**	**Quantum electrodynamics QED**
non-linear int.	***Weak* interaction**	**Weinberg – Salam model (Flavour dynamics)**
	Gravitation	**Quantum gravity (?) Einstein's general relativity**

Standard Model in particle physics

(i) Electroweak unification 1967

So called Glashow-Salam-Weinberg Model unifying weak interaction with the electromagnetic interaction. Quantum flavor dynamics

The model is based on quantum field theory. Both the particle (matter lepton) and the interaction are represented by field operators and the interaction term is of the form of current(matter) × gauge field, or $J_{\mu}^{a} \times A_{a}^{\mu}$. The symmetry group is $U(1) \times SU(2)$

(ii) The strong interaction is described by quantum chromatic dynamics (QCD) ~1973. The symmetry group is $SU(3)$. Again Both the particle (matter quarks) and the interaction are represented by field operators and the interaction term is of the form of current(matter) × gauge field, or $J_{\mu}^{a} \times A_{a}^{\mu}$.

(iii) The standard model is based on the gauge group is $U(1) \times SU(2) \times SU(3)$. Strictly not a complete unification because it consists of 3 separate gauge group. Ideally unification should be based on one single gauge group.

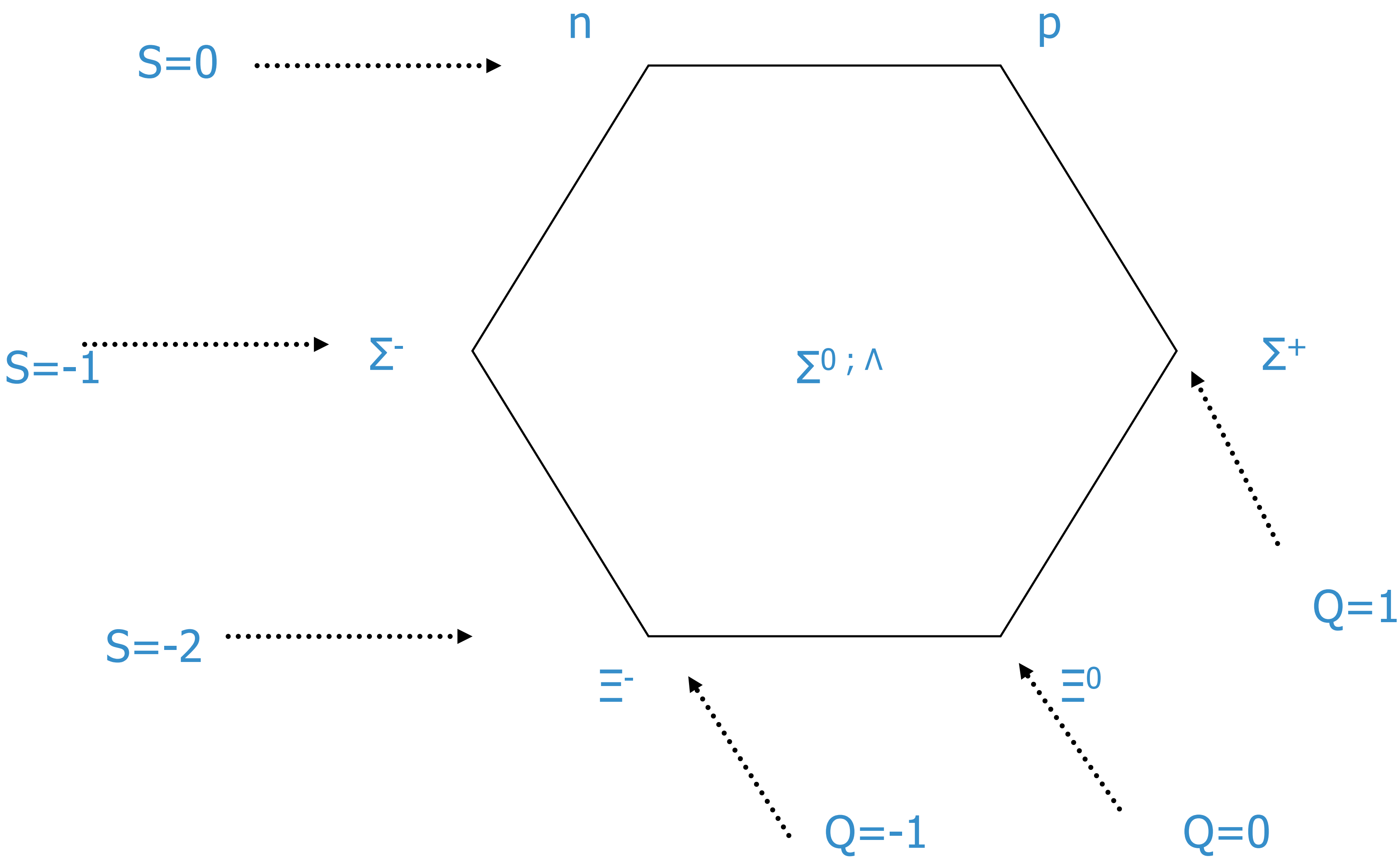
THE EIGHTFOLD WAY

(1961)

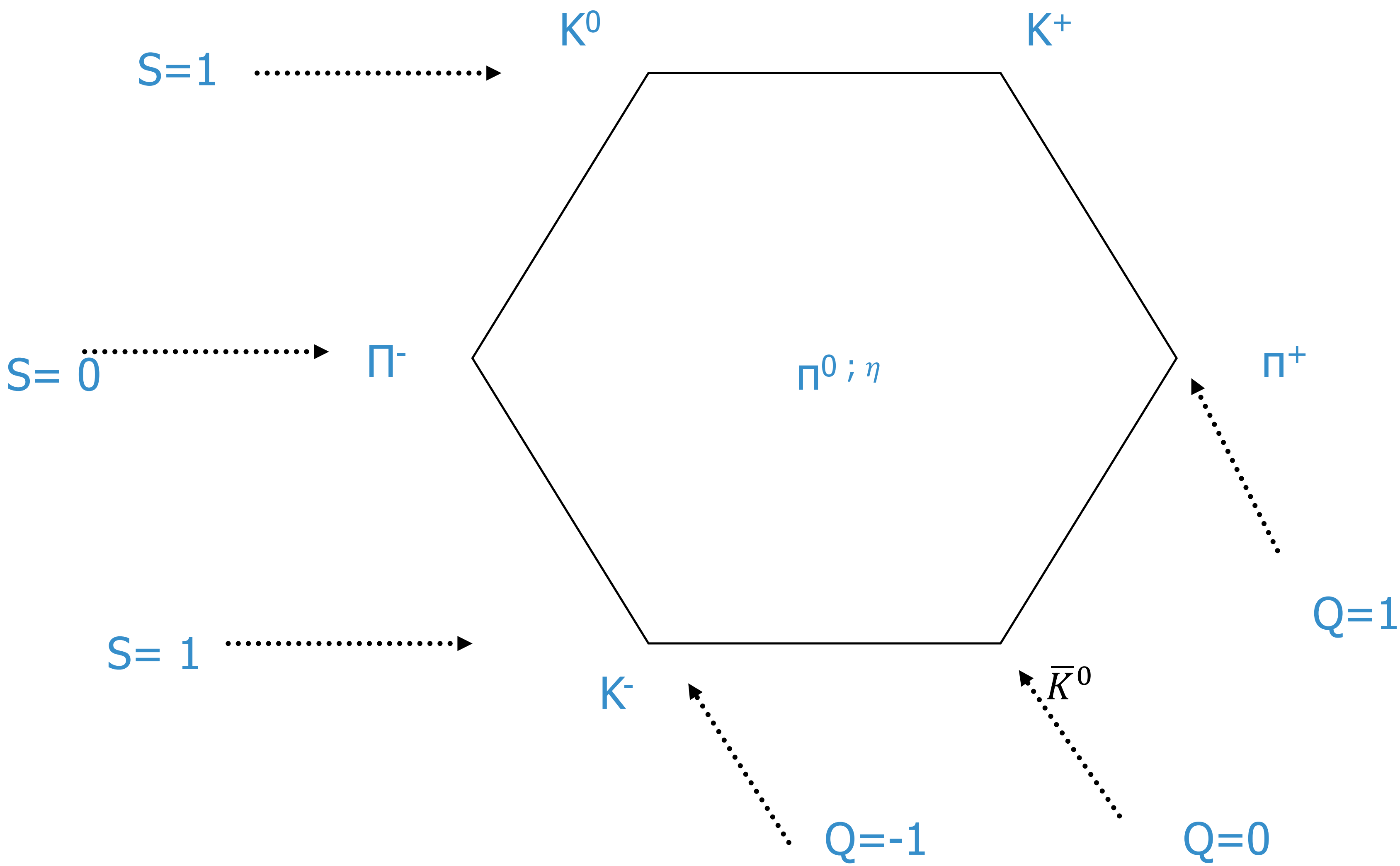
Classify hadrons (baryons and mesons) according to multiplets (singlets, octets, decuplets) of the unitary group SU(3), so called unitary symmetry.

This scheme is an extension of the isospin classification, SU(2). E.g. proton and neutron form an isodoublet.

The Baryon Octet



The Meson Octet



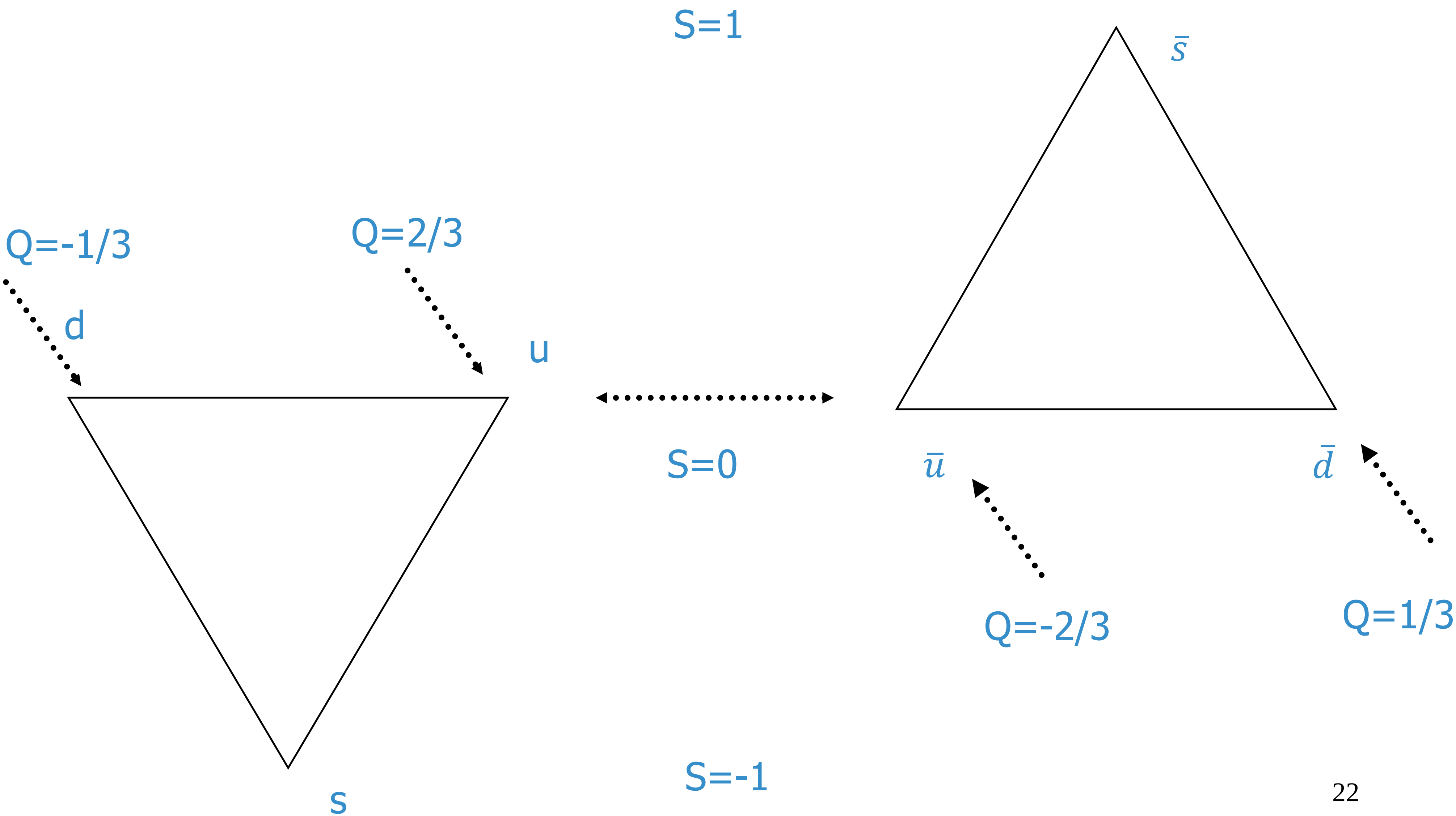
SU(3) Octet and Nonet

An SU(3) octet consists of 2 isodoublets, 1 isotriplet, and 1 isosinglet. These isomultiplets refer to SU(2).

An nonet consists of an SU(3) octet and an SU(3) singlet.

An nonet is a SU(3) reducible representation, and is equivalent to an irreducible SU(3) octet representation and an irreducible SU(3) singlet representation.

The Quark Model (1964)



1.4 Theoretical Framework

1.4.1 Quantum field theories

To every elementary particle, we associate a field operator $\psi(\underline{x})$, $x^0 = ct$, $\underset{\sim}{x} = (x^1, x^2, x^3)$, $\psi(\underline{x})$ acts on state vectors of a Hilbert space. The field operator $\psi(\underline{x})$ obeys equation of motion. For free particles, equations of motion are known. Usually can obtain equation of motion from action S

$$S = \int d^4x \;\mathscr{L}$$ $\mathscr{L} =$ Lagrangian density.

For particles in interaction, interaction terms are usually derived from a symmetry principle, called principle of local gauge invariance.

Two types of interaction terms:

$\overline{\psi}(\underline{x})\psi(\underline{x})\varphi(\underline{x})$ Yukawa exchange of pi meson

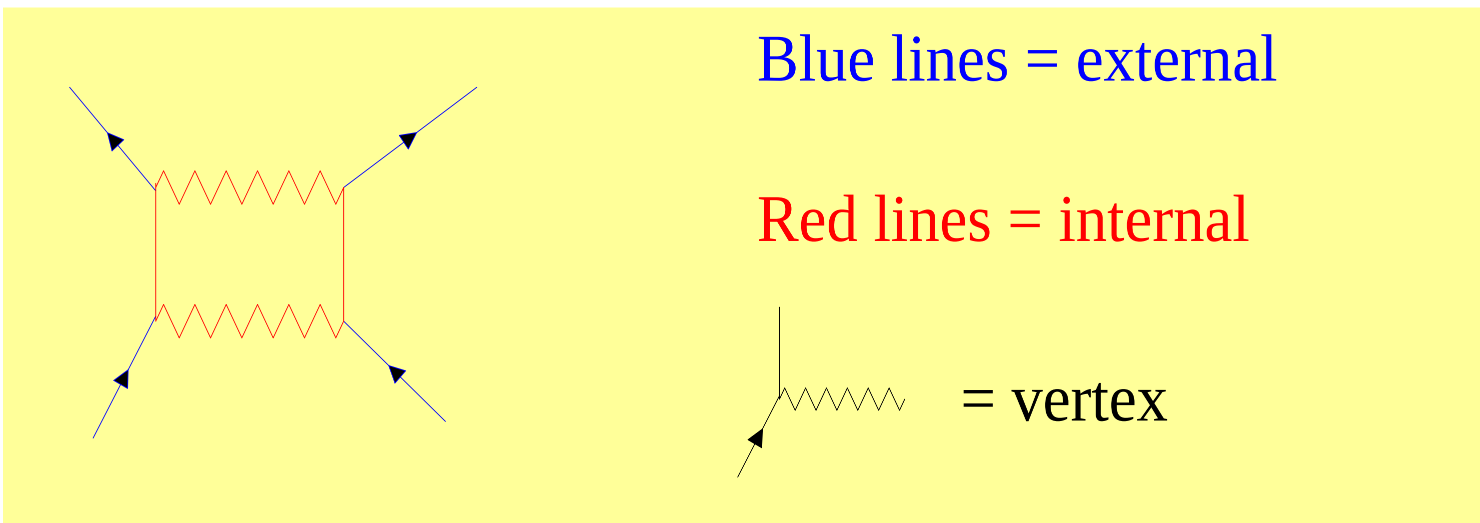
$\overline{\psi}(\underline{x})\gamma^{\mu}\psi(\underline{x})A_{\mu}(\underline{x})$ Gauge field theories

In quantum theory, exp (-i*S*) determines the physics, S= action.

1.4.2 Feynman diagram

1. A Feynman diagram consists of external lines (lines which enter or leave the diagram) and internal lines (lines start and end in the diagram). External lines represent physical particles (observable). Internal lines represent virtual particles (A virtual particle is just like a physical particle except its mass can assume any value i.e. not on mass-shell). Vertices represent interactions. 4-momentum p^μ must be conserved at each vertex; in fact all conservation laws.

e.g.



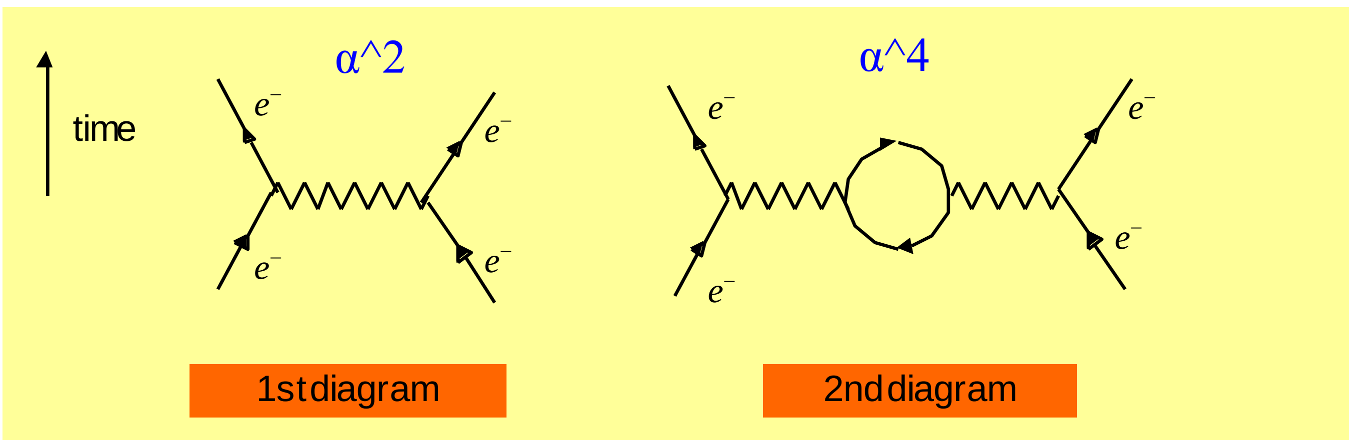
2. The diagram is symbolic, the lines do not represent particle trajectories.

3. Each Feynman diagram stands for a complex number (scattering amplitude) which can be computed from Feynman's rules. The sum total of all Feynman diagrams with the same external lines represents a physical process.

There are infinitely many Feynman diagrams for a particular physical process. Each vertex in the diagram introduces a factor $\sqrt{\alpha}$ (coupling constant).

For QED $\alpha_e = \dfrac{1}{137}$, thus higher order diagrams with many vertices will contribute less to the process.

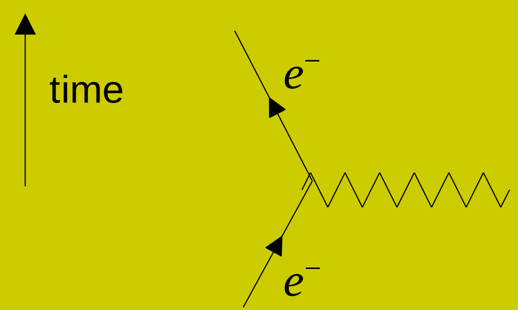
e.g. Electron-electron scattering $e^- e^- \to e^- e^-$



The 2nd diagram (1-loop) contributes less than the first diagram (tree).

4. At each vertex, the energy- momentum p^{μ} must be conserved.

e.g. $e^- \to e^- + \gamma$ **violates energy conservation**

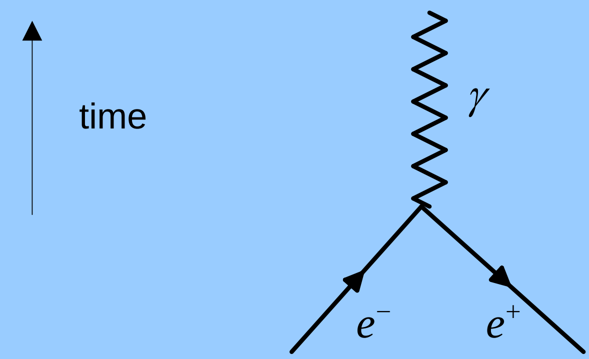


In ***cm*** frame, the e^- is initially at rest The energy of the emitted electron and photon is

$(\gamma m_e c^2 + \hbar\omega) > m_e c^2$ (energy of e^- at rest)

$$\gamma = \frac{1}{\sqrt{1-\beta^2}}, \quad \beta = \frac{v}{c}$$

$e^- + e^+ \to \gamma$ violates conservation of momentum 3-momentum



In ***cm*** frame total momentum of e^- and e^+ (positron) = 0, but total momentum after annihilation = momentum of γ (photon) $\neq$ 0.
cm =center of momentum

5. Each virtual particle (internal line) is represented by the "propagator" (a function describes the propagation of the virtual particle).The virtual particles are responsible for the description of force fields through which interacting particles affect on another.

(a) QED

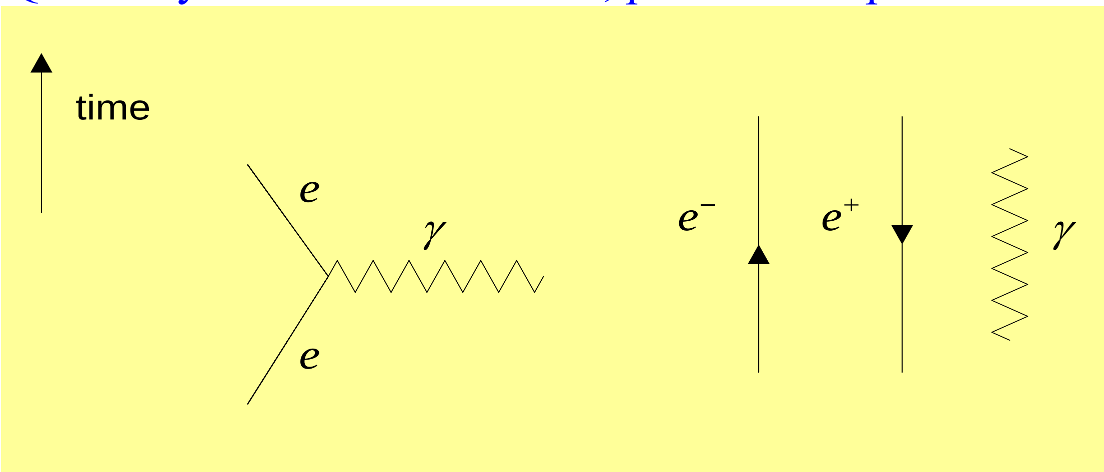
Coupling constant $\alpha_e = \dfrac{q_e^2}{4\pi\varepsilon_0 \hbar c} = \dfrac{1}{137}$

$q_e = 1.602 \text{ x } 10^{-19}$ Coul, $\hbar = 1.055 \text{ x } 10^{-34}$ Joule-Sec

$c = 2.998 \text{ x } 10^{8}$ m/s, $\dfrac{1}{4\pi\varepsilon_0} = 8.9875 \text{ x } 10^{9}$

All ***em*** phenomena are ultimately reducible to following elementary process (primitive vertex)

QED only consists of electrons, positrons or photons



QED Lagrangian (not needed for now, will see again in C7)

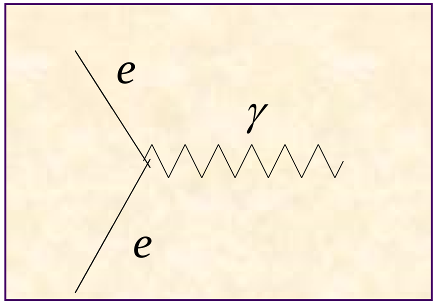
$$L = \bar{\psi}\gamma^{\mu}D_{\mu}\psi + m\bar{\psi}\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$
$$= \bar{\psi}\gamma^{\mu}\partial_{\mu}\psi + m\bar{\psi}\psi - ie\bar{\psi}\gamma^{\mu}\psi A_{\mu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

Interaction vertex $\bar{\psi}\gamma^{\mu}\psi A_{\mu} = j^{\mu}A_{\mu}$

and $F_{\mu\nu} = \partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu}$

All ***em*** processes can be described by patching together two or more of the primitive vertices.

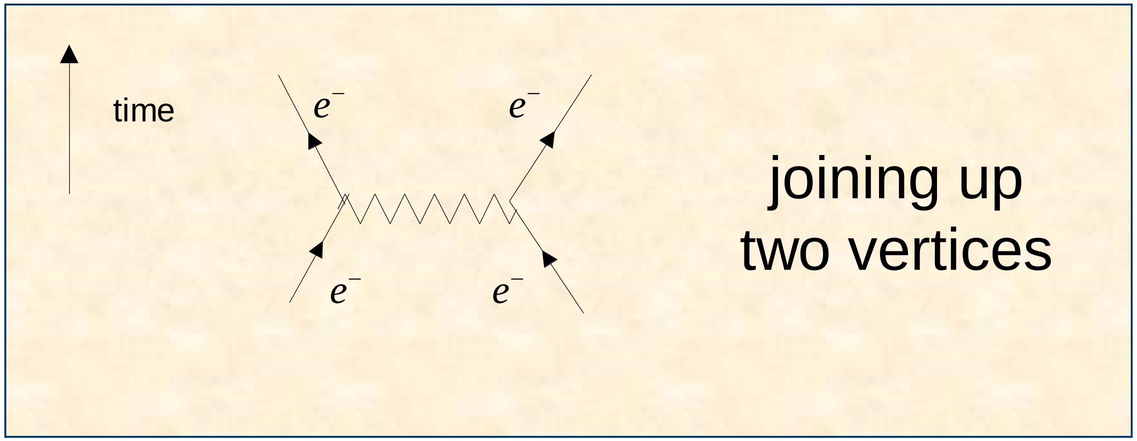
Note: The primitive QED vertex



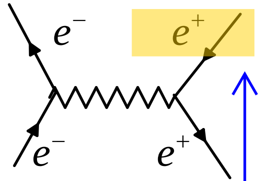
by itself does not represent a possible physical process as it violates the conservation of energy.

Some examples of electromagnetic interaction

1. Møller Scattering $e^- e^- \to e^- e^-$

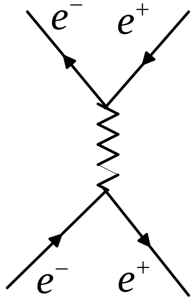


2. Bhabha Scattering $e^- e^+ \to e^- e^+$



e^- gives up a virtual photon which is absorbed by the position e^+

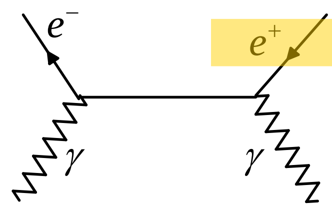
Particle line running backward in time (as indicated by the arrow) is interpreted as the corresponding antiparticle running forward.

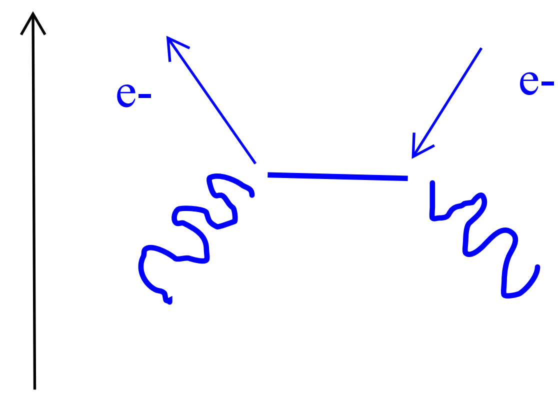


$e^+ e^-$ annihilate to produce a virtual photon γ which then pair – produces $e^+ e^-$

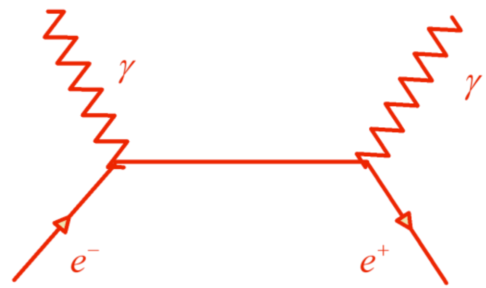
Dr. Oh's convention writes the positron even though his arrow already indicates positron

3. Pair Production $\gamma\gamma \to e^+ e^-$

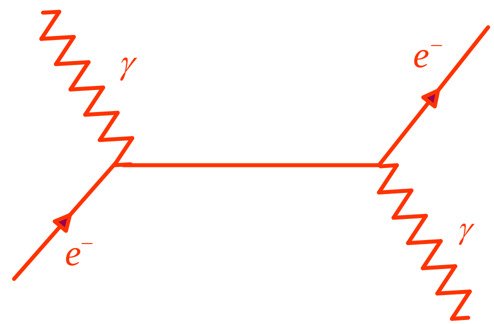




4. Pair Annihilation $e^+e^- \to \gamma\gamma$

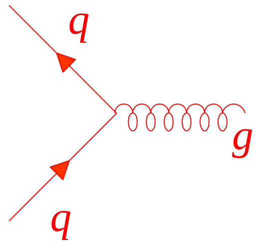


5. Compton Scattering $e^-\gamma \to e^-\gamma$

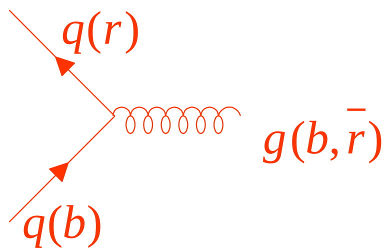


(b) **QCD**

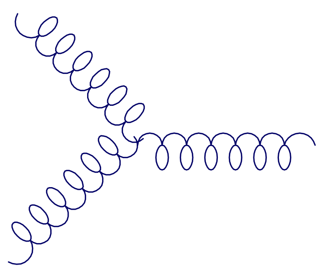
Only quarks and gluons involve basic vertices: Quark-gluon vertex $q \to q + g$



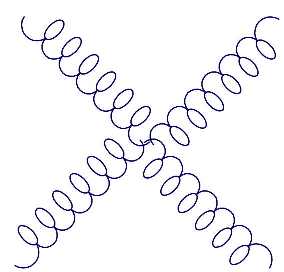
More exactly



Gluon vertices

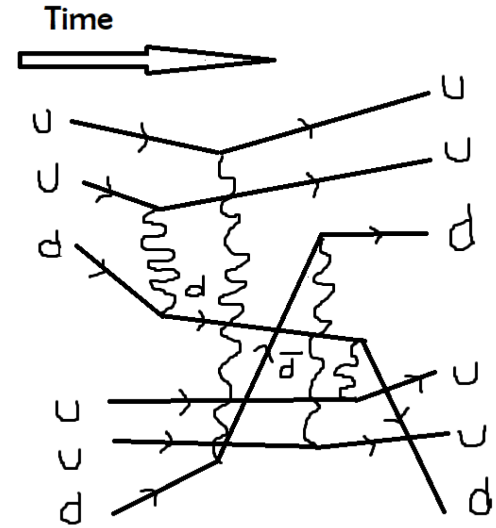


Glueballs



no expt evidence of glueballs yet

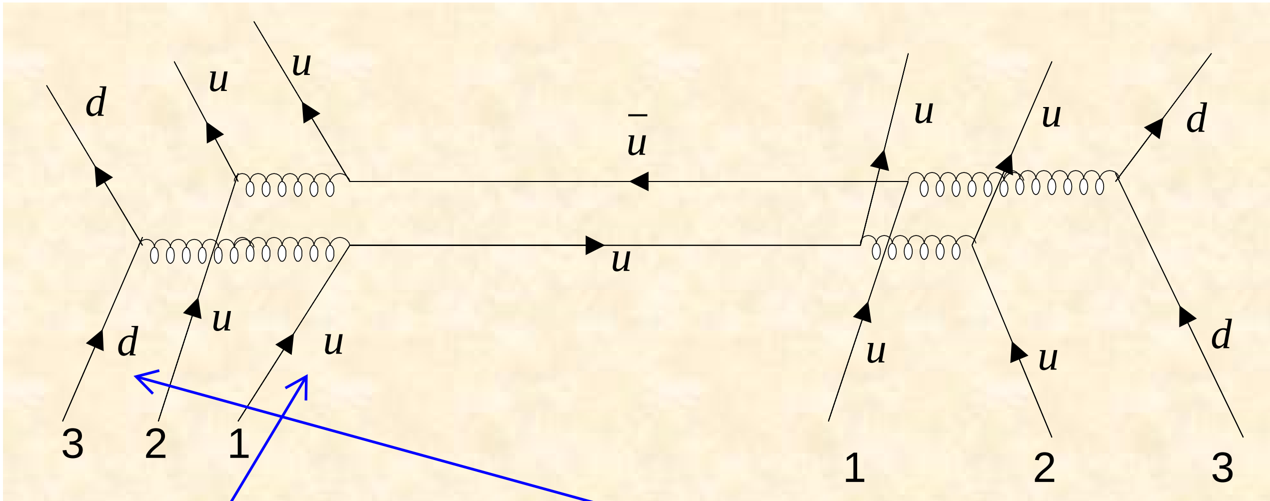
Interaction between two proton



Nucleons (proton or neutron) interact by exchange of π mesons.

e.g.

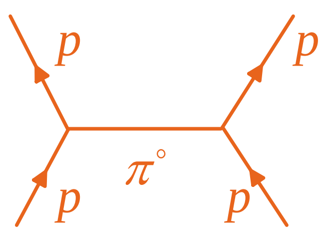
Gauge-field int.



exchange d quark instead

First *u* quark of LH p interacts with *d* and then propagates to the RH p to become the *u* of the RH p and also interacts with the second *u* of the RH p.

Similarly the first *u* of RH p interacts with the *d* and goes to become a *u* of the LH p and also interacts with the second *u* of the LH p.



Yukawa int.

$$\pi^\circ = (u\bar{u} - d\bar{d})/\sqrt{2}$$

As int. energy increases, strong force decreases;
smaller coupling constant -> less likely for process to occur

The coupling constant α_s decreases as interaction energy increases (short-range), known as asymptotic freedom.

$$\alpha_{s\,eff} = \frac{\alpha_s}{\varepsilon} \qquad \varepsilon = \text{dielectric constant}$$

If coupling constant is large, cannot use perturbation theory
If Int Energy ~ 0, α becomes large but always finite (aka Landau pole or Moscow Zero)

For QCD α_s increases as interaction energy decreases (long range)

$$\alpha_s(m_Z) = 0.112, \qquad m_Z = 91GeV/c^2$$
$$\alpha_s(m_\psi) = 0.2, \qquad m_\psi = 3.1GeV/c^2$$
$$\alpha_s(200MeV) \approx 1$$

known as infrared slavery.

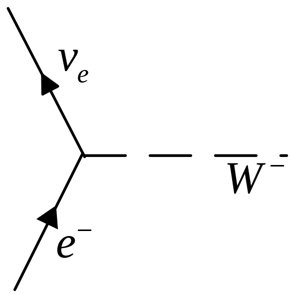
(c) **Weak Interaction**

sometimes called Quantum Flavour Dynamics

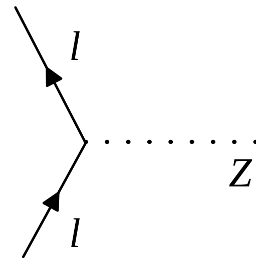
Two kinds, charged and neutral vertices

Leptons: primitive vertices connect members of the <u>same</u> generation
Lepton number is separately conserved for each Lepton generation, that is, L_e, L_μ, L_τ separately conserved.

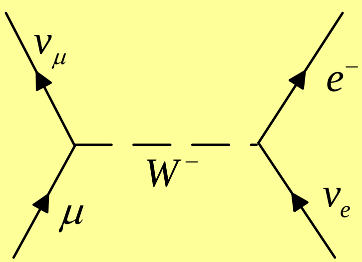
Charged vertex



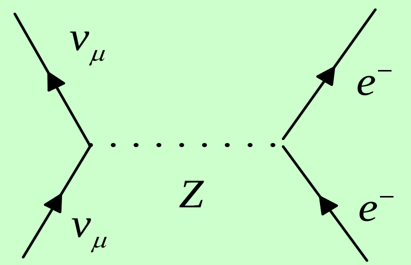
Neutral vertex



e.g.



$$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$$



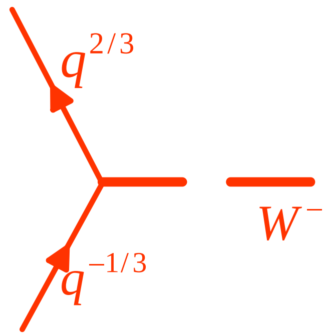
$$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$$

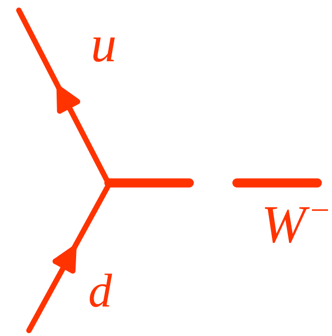
Quarks

Sidenote: Recall that weak int. doesn't conserve parity

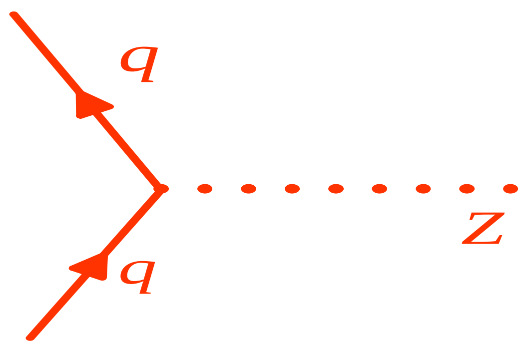
Flavour not conserved in weak interaction .

Charged Vertex.





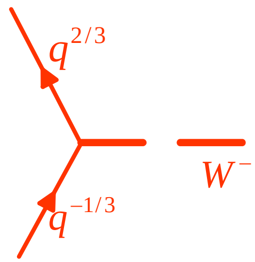
Neutral vertex

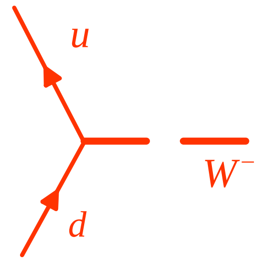


Quarks

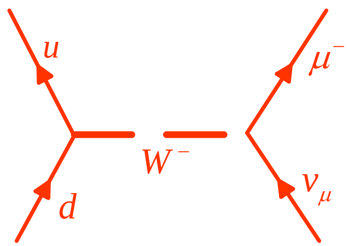
Flavour not conserved in weak interaction

Charged Vertex.





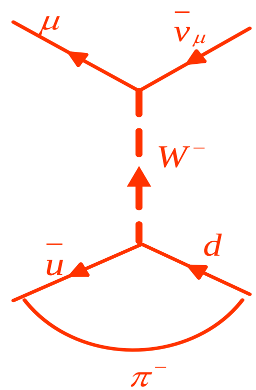
Semileptonic process $d + \nu_\mu \to u + \mu^-$



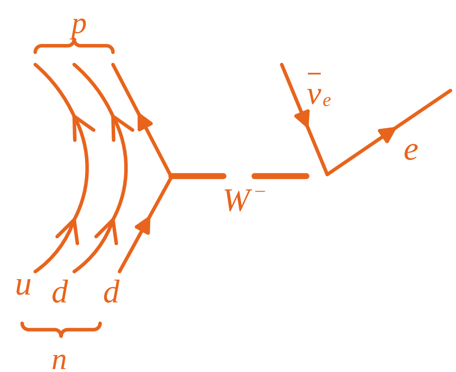
Not observable due to quark confinement

But can be observed in

Decay of $\pi^- \to \mu^- + \bar{\nu}_\mu$

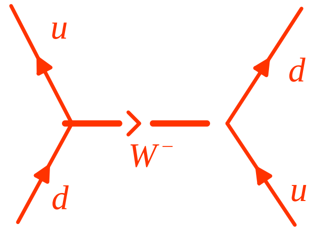


and neutron decay $n \to p + e^- + \bar{\nu}_e$



Two quarks *u, d* in neutron *n* not participating are called spectator quarks.

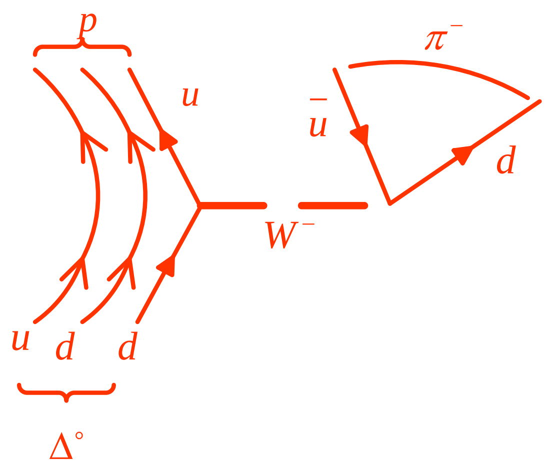
Hadronic decays



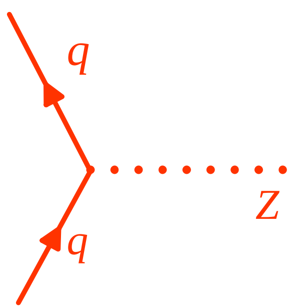
observed in

$\Delta^\circ(udd)$

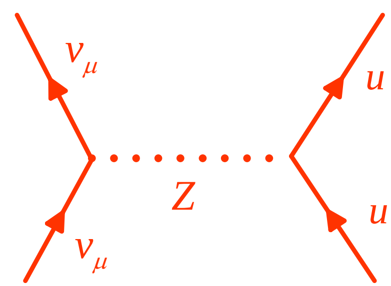
$\Delta^\circ \to p + \pi^-$



Neutral vertex



e.g.

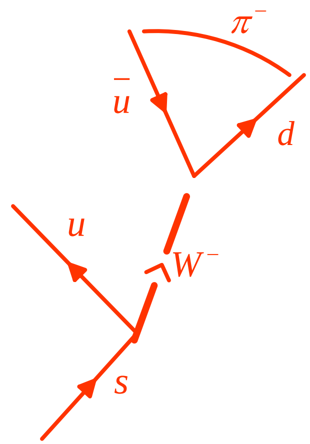


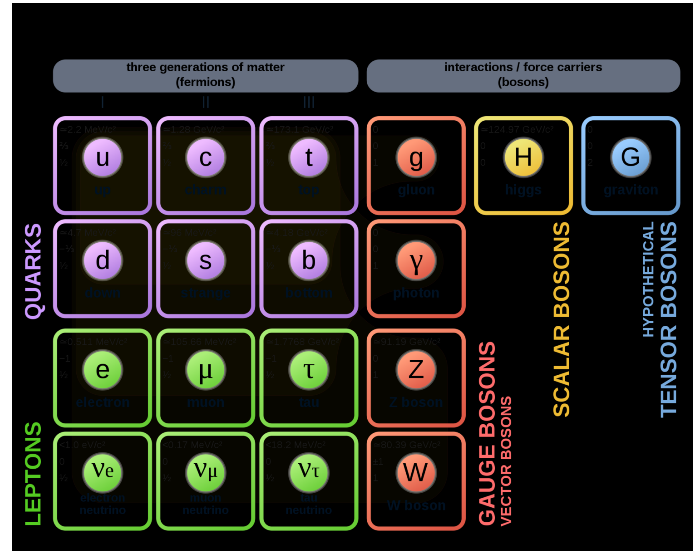
observed in

$\nu_\mu + p \to \nu_\mu + p$

Decays of quark by weak interaction can involve members of different generations

e.g. a strange quark can decay into an u-quark (flavor is not conserved)





The weak force not just couples members of the same generation

$$\binom{u}{d} \ or \ \binom{c}{s} \ or \ \binom{t}{b}$$

but **couples also members of different generations**

$$\begin{pmatrix} u \\ d' \end{pmatrix} \ or \ \begin{pmatrix} c \\ s' \end{pmatrix} \ or \ \begin{pmatrix} t \\ b' \end{pmatrix}$$

where

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

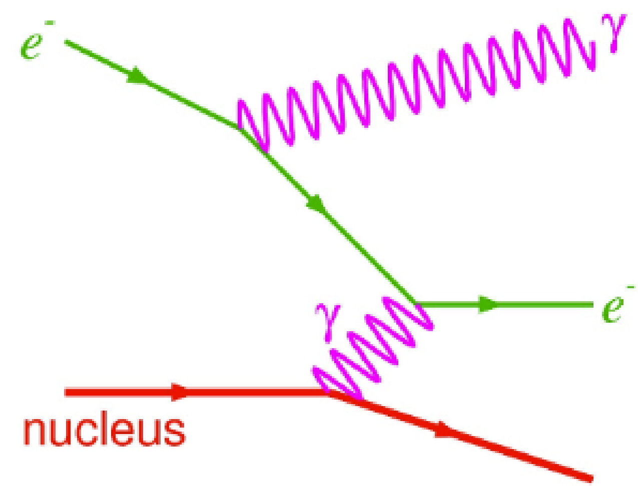
Kobayashi –Maskawa matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 0.9747-0.9759, & 0.218-0.224, & 0.001-0.007 \\ 0.218-0.224, & 0.9734-0.9752, & 0.030-0.058 \\ 0.003-0.019, & 0.029-0.058, & 0.9983-0.9996 \end{pmatrix}$$

V_{ud} = coupling of u to d

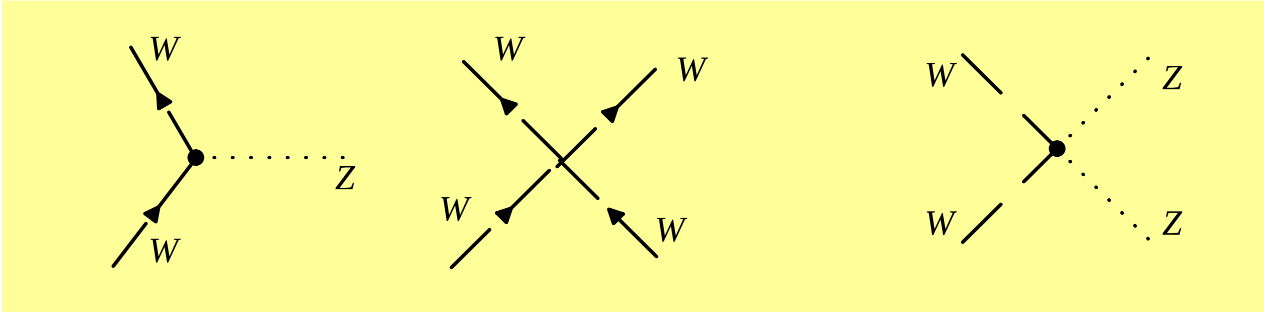
V_{us} = coupling of u to s

Feynmann Diagram for Bresstraulung radiation

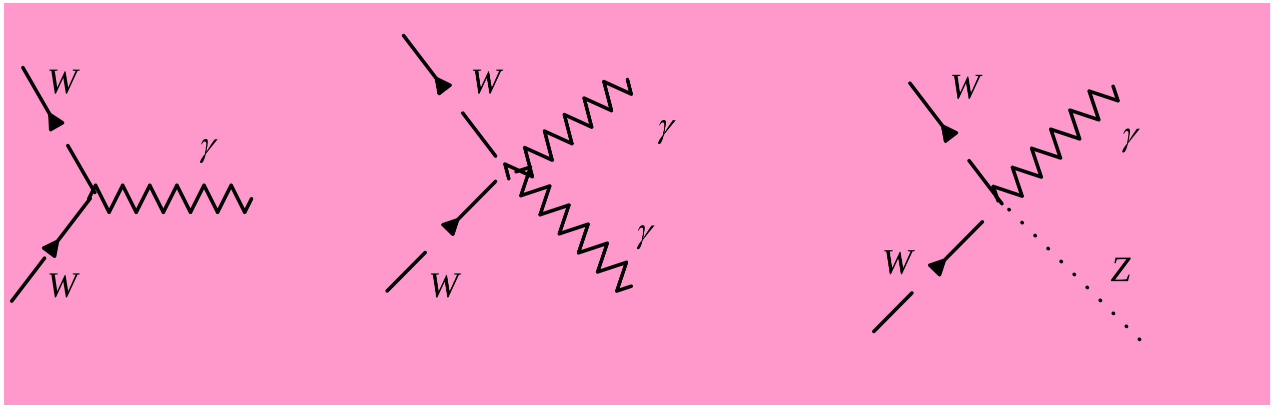


(d) ***wk*** and ***em*** couplings of $W^{\pm}$ and Z

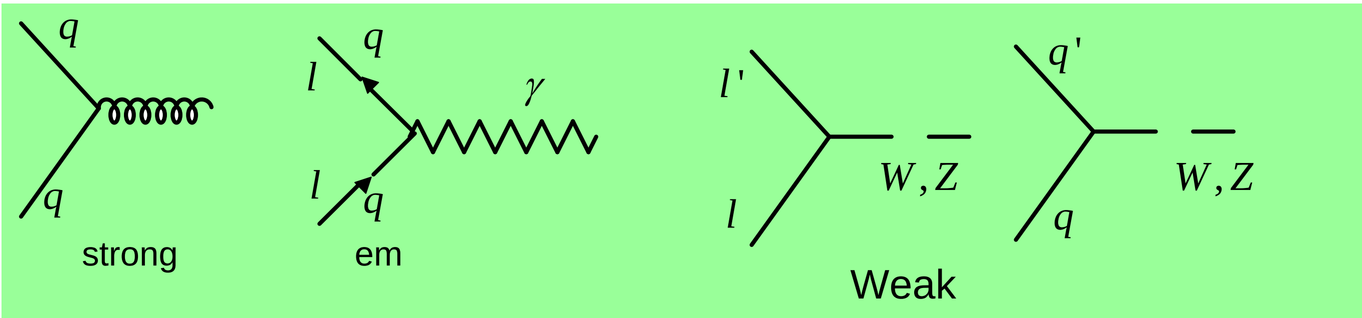
Weak couplings



Couplings involve photon γ



Summary



1.5 Decay & Conservation Laws

1.5.1

(a) Every particle decays into lighter particles unless prevented by some conservation law

#1

Stable particles : e^- (lightest lepton, conservation of lepton number),

#2

p (lightest baryon, conservation of baryon number), neutrinos, photons (massless particles)

(b) Most particles exhibit several different decay modes
e.g.

		Branching ratio
$K^+ \rightarrow$	$\mu^+ + \nu_\mu$	64%
	$\pi^+ + \pi^\circ$	21%
	$\pi^+ + \pi^+ + \pi^-$	6%
	$\pi^+ + \nu_e + \pi^\circ$	5%

Each unstable species has a characteristic mean life time τ

e.g.

$$\tau_\mu = 2.2 \times 10^{-6}\ s$$
$$\tau_{\pi^+} = 2.6 \times 10^{-8}\ s$$
$$\tau_{\pi^\circ} = 8.3\ \times\ 10^{-17} s$$

Note: $I = I_0\ e^{-t/\tau}$,

τ = time taken for ***I*** to decrease from I_0 to $I_0\ e^{-1}$

$t_{1/2}$ = time taken for ***I*** to reduce to $\frac{1}{2} I_o$,

$$\frac{1}{2} I_o = I_o\ e^{-(t_{1/2}/\tau)} \Rightarrow ln2 = (t_{1/2}/\tau)$$

(c) Three Fundamental Decays:

Strong decay e.g. $\Delta^{++} \rightarrow p + \pi^{+}$ $\tau = 10^{-23} s$

em decay e.g. $\pi^{\circ} \rightarrow \gamma + \gamma$ $\tau = 10^{-16} s$

wk decay e.g. $\Sigma^{-} \rightarrow n + e^{-} + \bar{\nu}_e$ $\tau \sim 10^{-13} s$

Neutron decay $n \rightarrow p + e^{-} + \bar{\nu}_e$ $(\tau = 15 \min)$

$(d \rightarrow u + e^{-} + \bar{\nu}_e)$

(d) Kinematic Effect: the larger the mass difference between the original particle and the decay products, the more rapidly the decay occurs.

This is also known as phase space factor. It accounts for the enormous range of mean life time τ in ***wk*** decays.

1.5.2 CONSERVATION LAWS

(i) Spacetime symmetry

Homogeneity of space time $\rightarrow$ laws of physics are invariant under time and space translations $\rightarrow$

Conservation of spatial momentum $\underset{\sim}{p}$, Conservation of energy $E/c = p^0$

Isotropy of space time $\rightarrow$ laws of physics are invariant under rotations in space time.

In particular laws of physics are invariant under rotations in space $\rightarrow$
Conservation of angular momentum.
Invariant under rotation in space and time (Lorentz transformation), Lorentz Symmetry

Discrete Symmetry
Space inversion $\rightarrow$ conservation of parity
Time inversion T, no quantum number associated.
T represented by anti-unitary operator.

$T^{+} = T^{-1}$ (unitary)
$T(c_1|\psi_1\rangle + c_2|\psi_2\rangle) = c_1^* T|\psi_1\rangle + c_2^* T|\psi_2\rangle$ (antilinear)
and c_1^* is the complex conjugate of c_i, i=1, 2

(ii) Internal Symmetry

(1) $U(1)$ symmetry

A physical state of a physical system is represented by a vector $|\psi\rangle$ in Hilbert space up to a phase factor (assume normalization)

i.e. if $|\psi\rangle$ represents a physical state

then $e^{i\alpha}|\psi\rangle$ represents the same physical state, where α=constant, phase whereas exp($i\,\alpha$) is known as phase factor.

$\left\{e^{i\alpha_1}, e^{i\alpha_2}...\right\}$ form a group, an Abelian group *U(1)*

Conservations of electric charge, baryon number and lepton number are due to the *U(1)* phase invariance.

For the electric charge case, can also let phase α be dependent on spacetime point x^u, namely $\alpha = \alpha(\underline{x})$ and one gets local gauge invariance

(2) The QCD Lagrangian is invariant under local *SU(3)* transformations. i.e. QCD has a local *SU(3)* symmetry. An *SU(3)* transformation is represented by a unitary 3 x 3 matrix with determinant=1.

SU(3) = special unitary group in three dimensions

(3) Approximate conservation of flavour. Quark flavour is conserved at a strong or electromagnetic vertex, but <u>not</u> at a weak vertex.

Symmetry (invariance): a physical or mathematical feature of the system that is preserved or unchanged under some operation. (e.g. isospin transformation of proton to neutron)

Global symmetry: symmetry across all particles
Gauge symmetry: localized symmetry for specific particles

OZI (Okubo, Zweig and Iizuka) rule
Some <u>strong</u> decays are suppressed

e.g.

$J/\psi = c\bar{c}$ bound state of charmed quarks has anomalously long lifetime

$\sim 10^{-20}$sec
(Strong decay $\sim 10^{-23}$sec)

φ Meson $(s\bar{s})$, $I^G(J^{pc}) = 0^-(1^{--})$

mass = 1020 *MeV*, Full width $\Gamma = 4MeV$, $(\tau\Gamma = \hbar)$ τ=1.6 x 10^{-22}s

Decay modes

K^+K^-	50%
$K_l^0 K_s^0$	34%
$\rho\pi$	13%
$\pi^+\pi^-\pi^o$	2%
$\eta\gamma$	1%

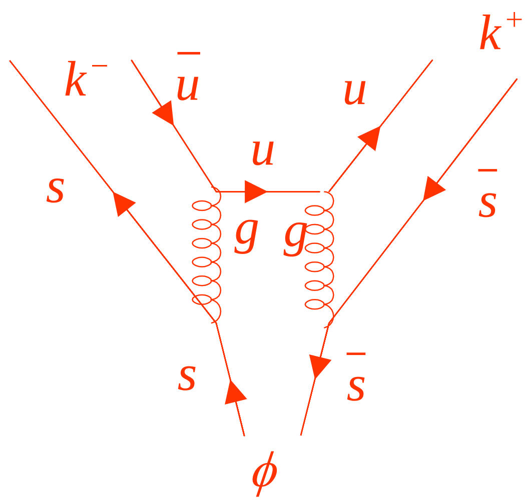
Clearly, ϕ meson decays more often into K^+K^-

$\phi \rightarrow K^+ + K^-$ mass of $(K^+ + K^-) = 990$ MeV/c^2

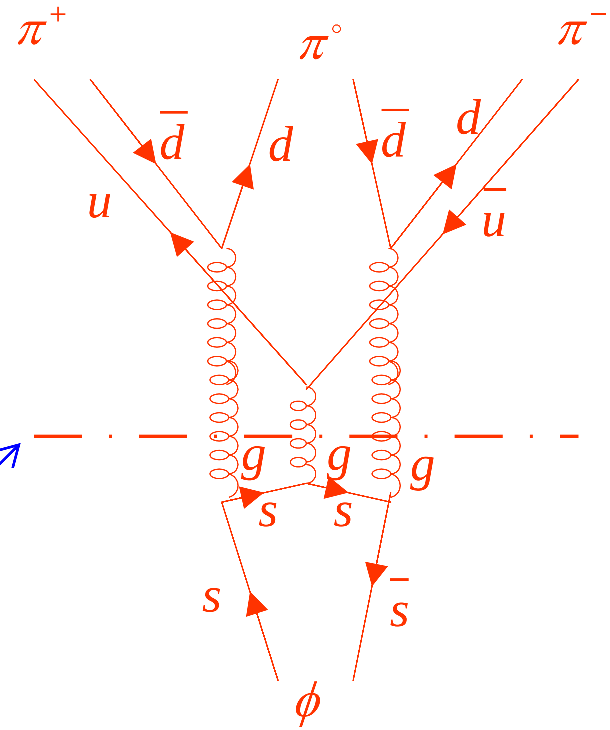
than into $3\pi^{'}$s

$\phi \rightarrow \pi^+ + \pi^- + \pi^0$ mass of $(\pi^+ + \pi^- + \pi^0) = 415 MeV/c^2$

OZI Allowed



OZI Suppressed



OZI rule:

If the diagram can be cut in two by slicing only gluon lines (and not cutting open any external lines), the process is suppressed.

Qualitatively OZI rule is related to the asymptotic freedom.

In an OZI suppressed diagram the gluons have higher energy than those in the OZI - allowed diagram. (More gluons imply higher energy, higher energy so strong interaction coupling constant is smaller, meaning process less likely to occur).

$$J/\psi I^G(J^p) = 0^-(1^-)$$

mass = 3100 MeV/c^2, Γ=0.093 MeV

Decay modes

e^+e^-	6.0%
$\mu^+\mu^-$	6.0%
hadrons	88%

$J/\psi \to 3\pi$ OZI - suppressed

$J/\psi \to D^+ + D^-(D^\circ + \overline{D}^\circ)$ charmed nonstrange Mesons

mass of D ≈ 1869 MeV/c^2 . D^+ (c $\bar{d}$); D^0 (c $\bar{u}$)

Kinematically forbidden since a pair of two charmed D mesons has larger total mass than the J particle. **Hence this J particle has a longer life time than the ϕ meson.**

Planck Scale

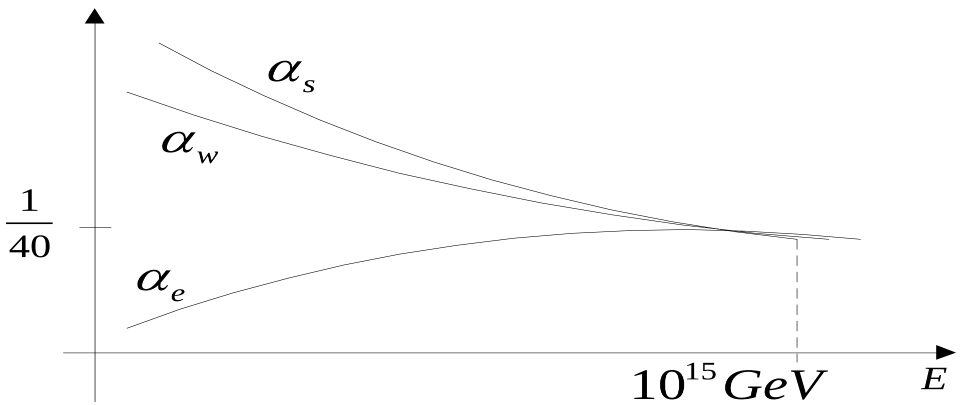
Strong coupling constant α_s decreases at short distances (very high energy collisions)

Weak coupling α_w also decreases but at a slower rate.

Electromagnetic coupling constant α_e increases as energy increases

[Note: the relative weakness of the weak force is due to the large mass of $W^{\pm}$, Z; its intrinsic strength is greater than that of the ***em*** force.]

From the present functional form of the running coupling constants, $\alpha_{s,}$ $\alpha_{w,}$ and α_e converge at around 10^{15} *GeV* (Planck energy scale).



$$At\ 10^{-19}\,m,$$

$$\alpha_s = \frac{1}{10}$$

$$\alpha_w = \frac{1}{27}$$

$$\alpha_e = \frac{1}{129}$$

$g\bar{\psi}\gamma^{\mu}T^{a}\psi A_{\mu}^{a}$

Our Universe according to Wilkison Microwave Anistropy Probe (WMAP) 2003

- Age: 13.7 billion years
- Shape: Flat
- Age when first light appeared:200 Million years
- Contents: 4% ordinary matter, 23% dark matter, nature unknown; 73% dark energy, nature unknown
- Hubble constant (expansion rate):71km/sec/megaparsec

To see a World in a Grain of Sand

And a Heaven in A Wild Flower

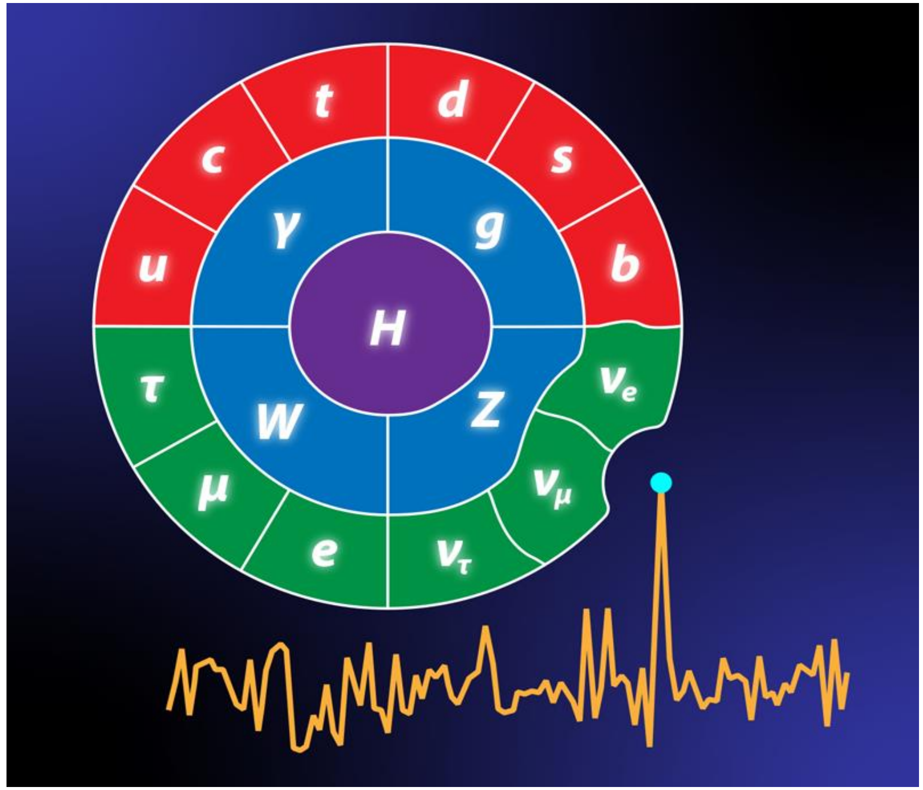
Hold Infinity in the palm of your hand

And Eternity in an hour

W. Blake (1757-1827)

M.C. Escher

(Dutch graphic artist,
1898- 1972)



APS/**Alan Stonebraker**

The colored circle represents the standard model of particle physics, which describes the Higgs boson (purple), the force-carrying particles (blue), the quarks (red), and the leptons (green). Particle physicists hope that an anomaly (shown as a data peak) will pierce through the standard model's long-standing dominance, so that a new, more comprehensive theory can develop.