Summary of L1 2025. 1. 16 L2

Basic constituent of matter

particle-like duality wave-like

photos of q-bit, q-trit (trinity)

Particle-like →

leptons
(No strong interaction)

hadrons

baryons
spin $\frac{1}{2}, \frac{3}{2} \cdots$
3 quarks

mesons
spin 0, 1, 2, ...
quark-antiquark pair

3 generations (families)

| | | | |
|---|---|---|---|
| $e$ | $\nu_e$ | $u$ | $d$ |
| $\mu$ | $\nu_\mu$ | $s$ | $c$ |
| $\tau$ | $\nu_\tau$ | $t$ | $b$ |

Properties of particles : quantum numbers

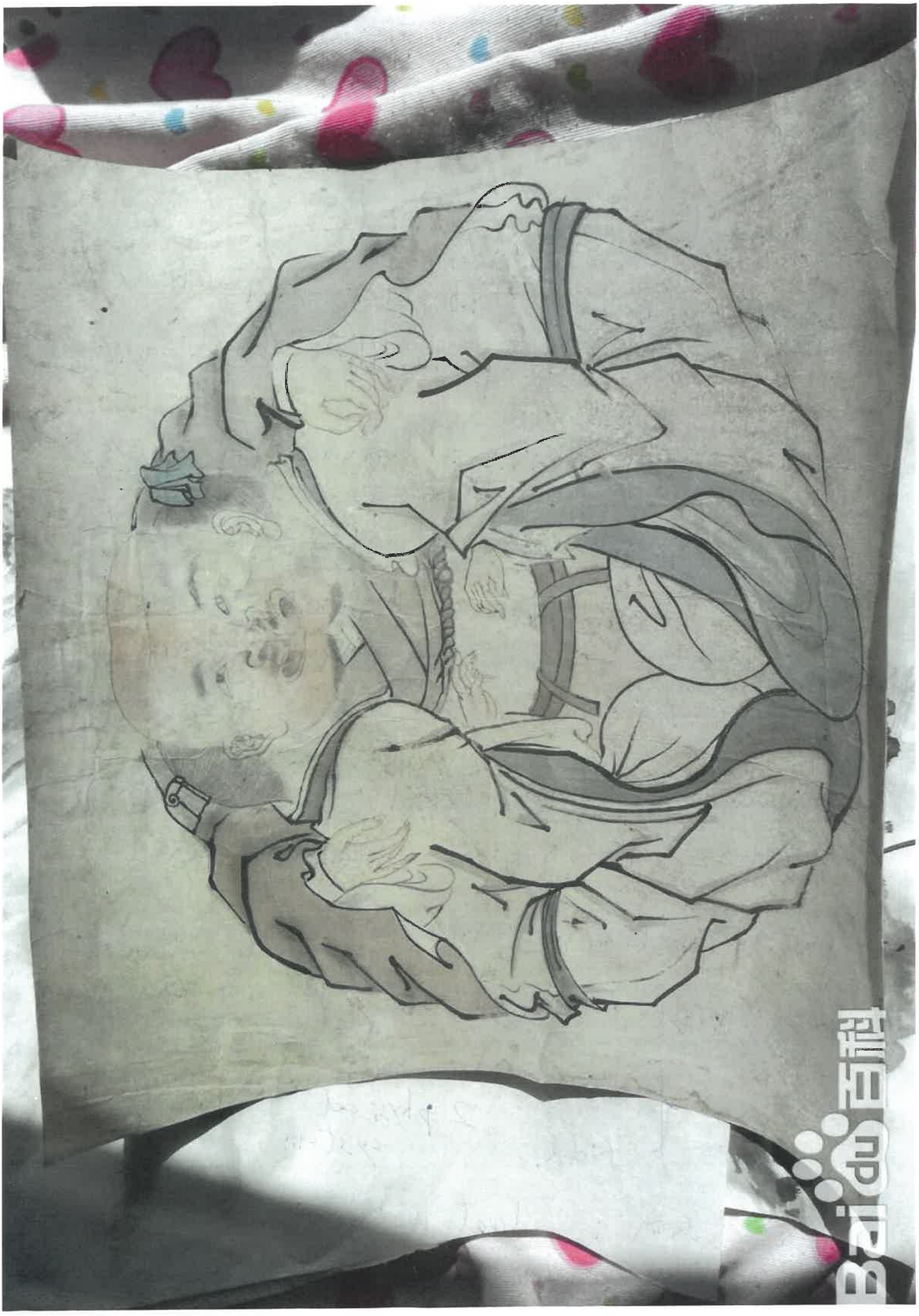
# Two things in one?

## What do you see?

a) An old woman smiling

b) A young lady with her head turned

?



Wave-like → force field
(Gauge field) Interactions

photon $\gamma$ spin 1 electromagnetic field

gluon $g$ spin 1 strong force

$W^{\pm}$, Z spin 1 weak force

Graviton spin 2 gravitional force

Theory QED QCD

Electroweak model

General Relativity

=

1950' ~ hundred of elementary particles

classification as a first step of understanding

Chemical elements (atoms)

Mendeleev periodic Table

An excellent classification scheme

1960' classification of elementary

particles into multiplets:

singlet, octet, decuplet

Eight-fold way classification

SU(3) unitary group

very successful

SU(3) classification scheme can

be understood in terms of

quark model.

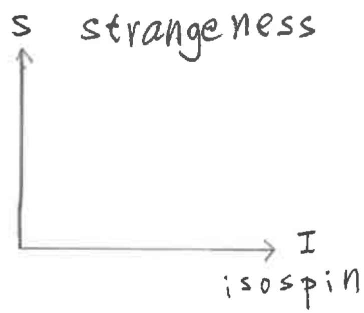
# THE EIGHTFOLD WAY

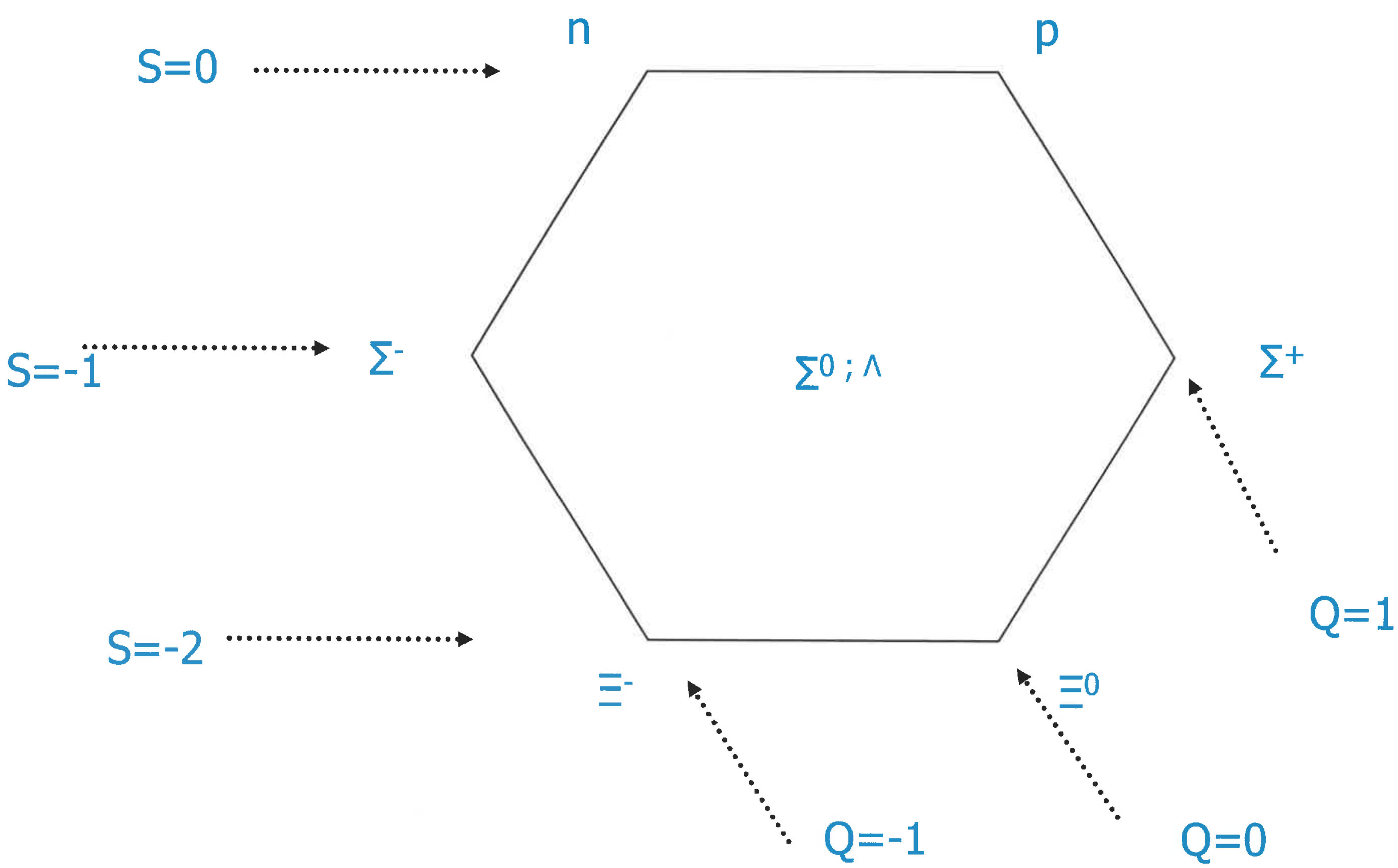
# (1961)

classify hadrons
(baryons, mesons)
according to the
multiplets (singlet,
octet, decuplet) of
SU(3) group, so
called unitary symmetry.

Extension of isospin scheme SU(2)

# The Baryon Octet

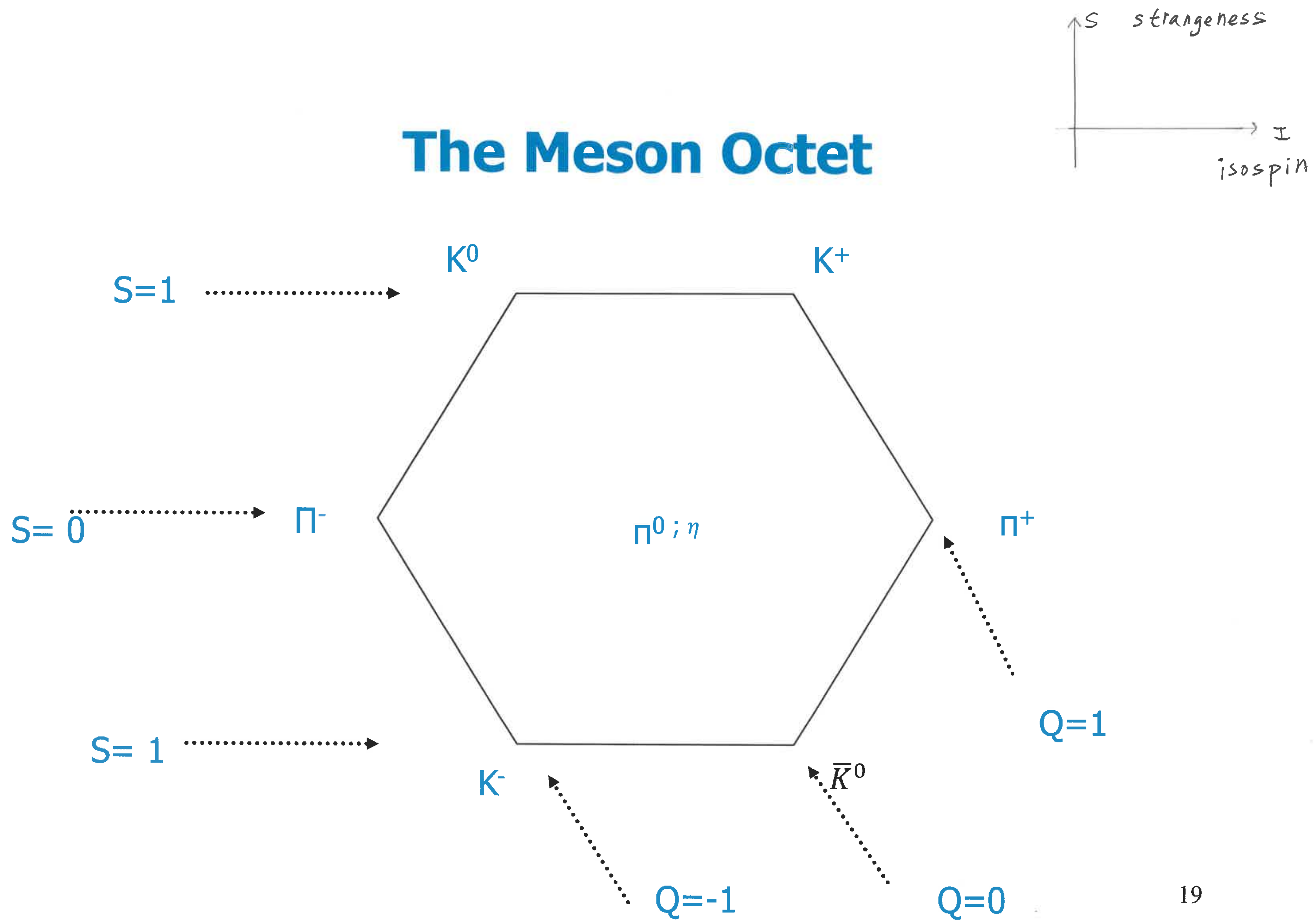


Classify hadrons (baryons and mesons) according to multiplets (singlets, octets, decuplets) of the unitary group SU(3), so called unitary symmetry.

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

# The Meson Octet



# SU(3) Octet and Nonet

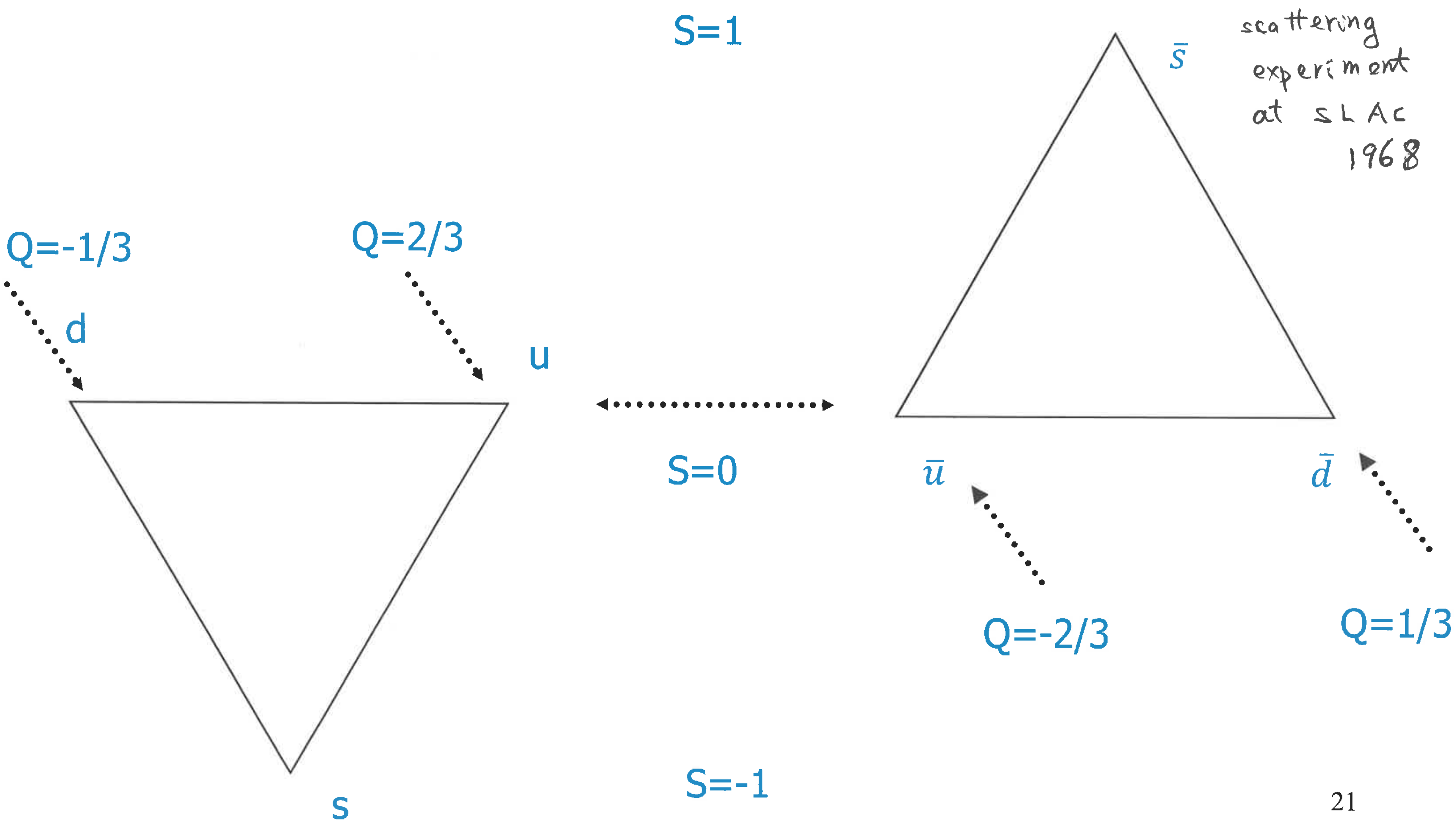
An SU(3) octet consists of 2 isodoublets, 1 isotriplet, and 1 isosinglet. These isomultiplets refer to SU(2).

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)

Quarks indirectly detected in the deep inelastic $e^- p$ scattering experiment at SLAC 1968



# 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**

$S = \int d^4x \; \mathcal{L}$ $\mathcal{L}$= 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:**

$\bar{\psi}(\underline{x})\psi(\underline{x})\varphi(\underline{x})$ Yukawa

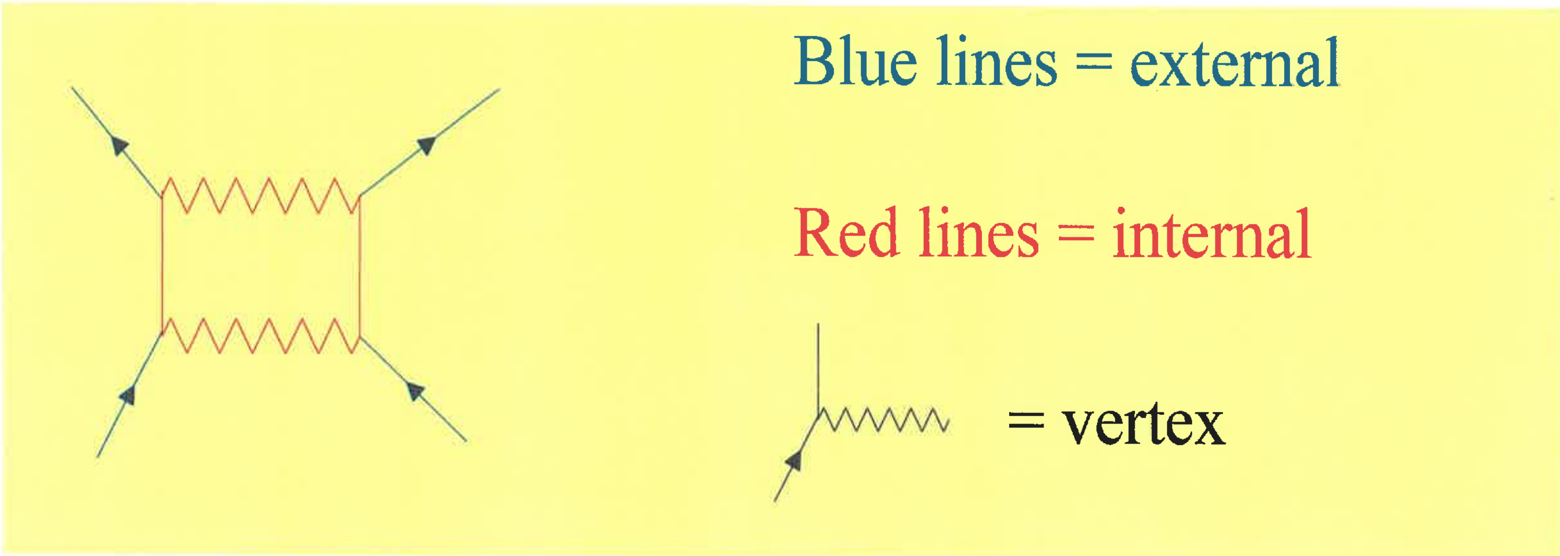
$\underbrace{\bar{\psi}(\underline{x})\gamma^{\mu}\psi(\underline{x})}_{= j^{\mu}(\underline{x})}A_{\mu}(\underline{x})$ Gauge field theories

**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 $p^\mu$ must be conserved at each vertex; in fact all conservation laws.

e.g.



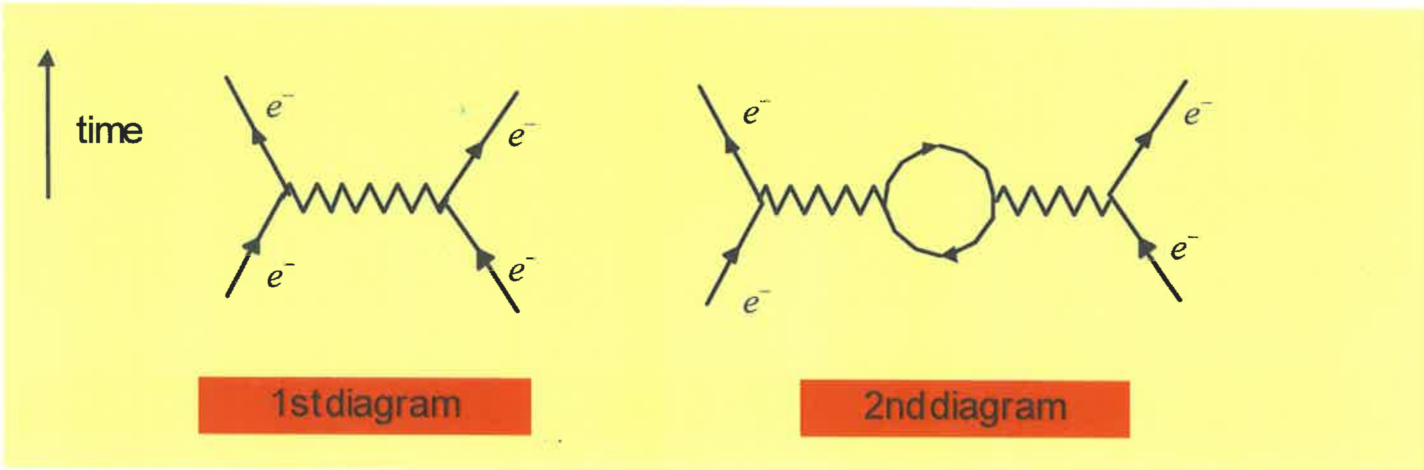

2. The diagram is symbolic, the lines do not represent particle trajectories.

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

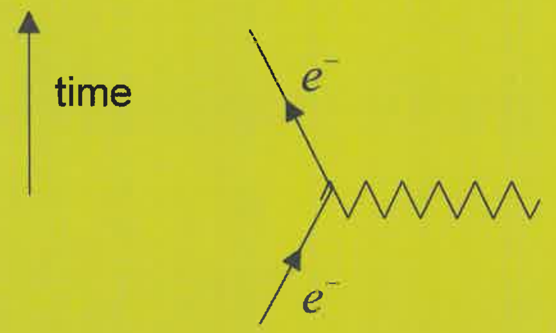
e.g. Electron-electron scattering $e^- e^- \to e^- e^-$




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

## 4. At each vertex, the energy- momentum $p^\mu$ must be conserved.

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

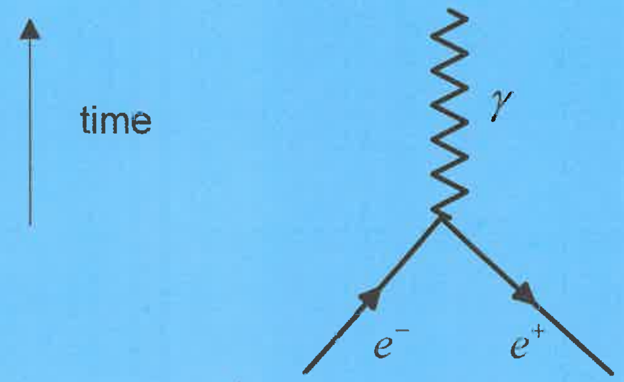



In ***cm*** frame, the $e^-$ is initially at rest The energy of the emitted electron and photon is

$(\gamma m_e c^2 + \hbar\omega) > m_e c^2$ (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 $\gamma$ (photon) $\neq$ 0.

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.

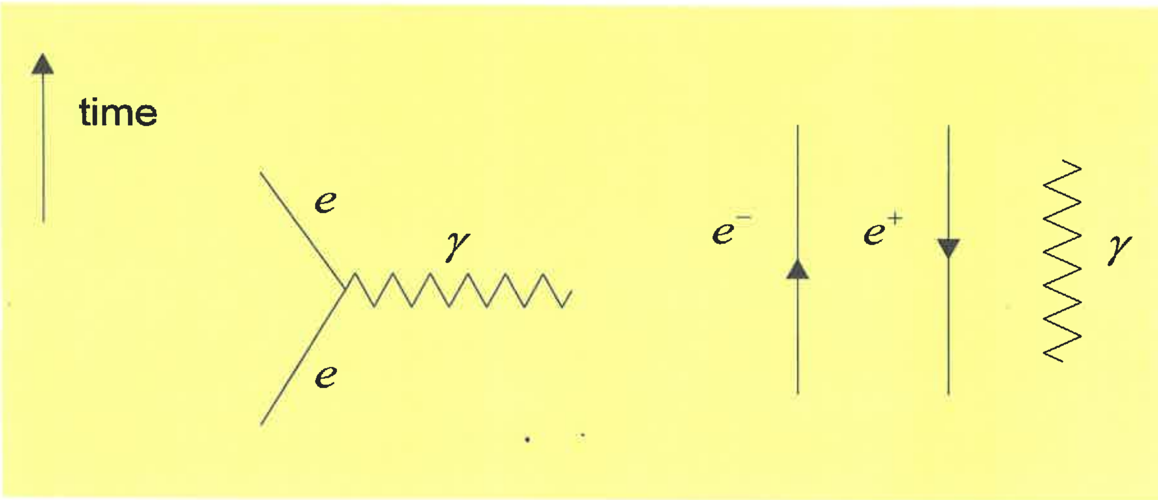
### (a) QED

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

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

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

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




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

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

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