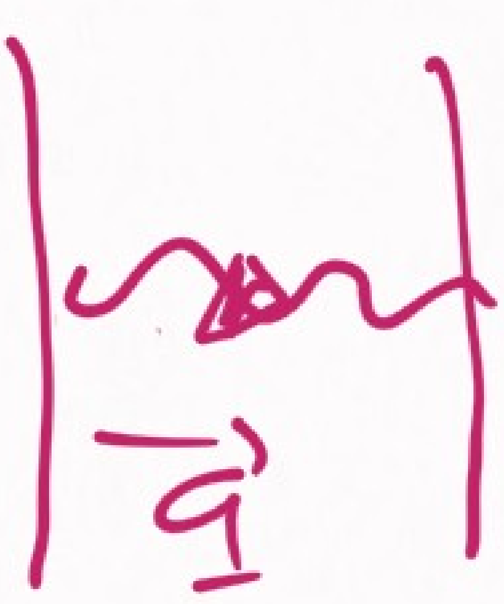
Nuclear Physics (5)

More about the origin & nature of nuclear forces

RECAP: Yukawa's idea

Exchange of a virtual pion → origin of nuclear forces

Identical to photon exchange & the Coulomb force



$$= \frac{e^2}{|\vec{q}|^2}$$

[Yukawa's idea can be improved!]

Improvements over Yukawa:

1) more pions
2) other light bosons

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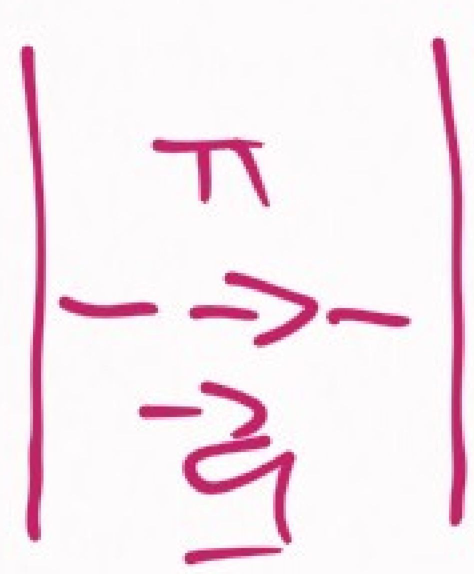
1) more pions



← one-pion exchange (OPE)

⇓

two-pion exchange (TPE)

box — crossed box — football — triangle

two-pion exchange:

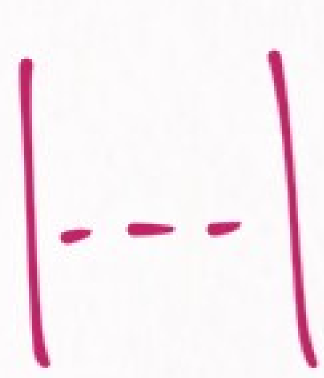
1.a) Seminal pion theories

1950's → full of infinities

Why? Wrong understanding of:

- pion dynamics
- renormalization

(重正化)

[Outcome:]  → right result

 → wrong result

Failure of pion theories

→ one-boson exchange (OBE) model

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1. b) Modern pion theories

Original pion theories

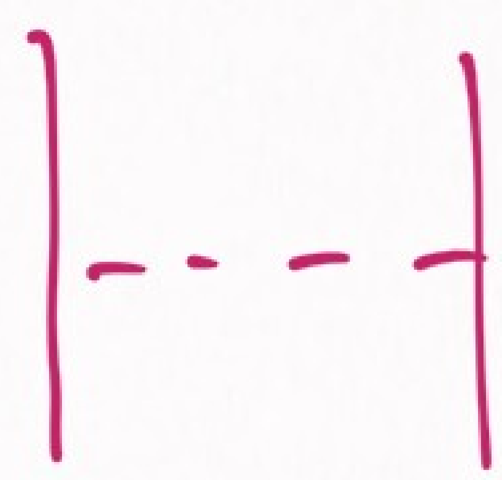
$$\mathcal{L} = g_\pi \bar{\psi}_N \gamma^5 \vec{\tau} \cdot \vec{\phi} \, \psi_N$$

($\bar{\psi}_N \ldots \psi_N$): Nucleon field

($\vec{\phi}$): Pion field

→ Simplest Pseudoscalar Theory (Ockam's razor)

The original pion theories work perfectly for:



but fail miserably for:

Why? → Because of a special type of symmetry called

CHIRAL SYMMETRY

↳ Explains why $m_\pi \ll M_N$

(140 MeV ≪ 940 MeV)

Chiral Pion Theories:

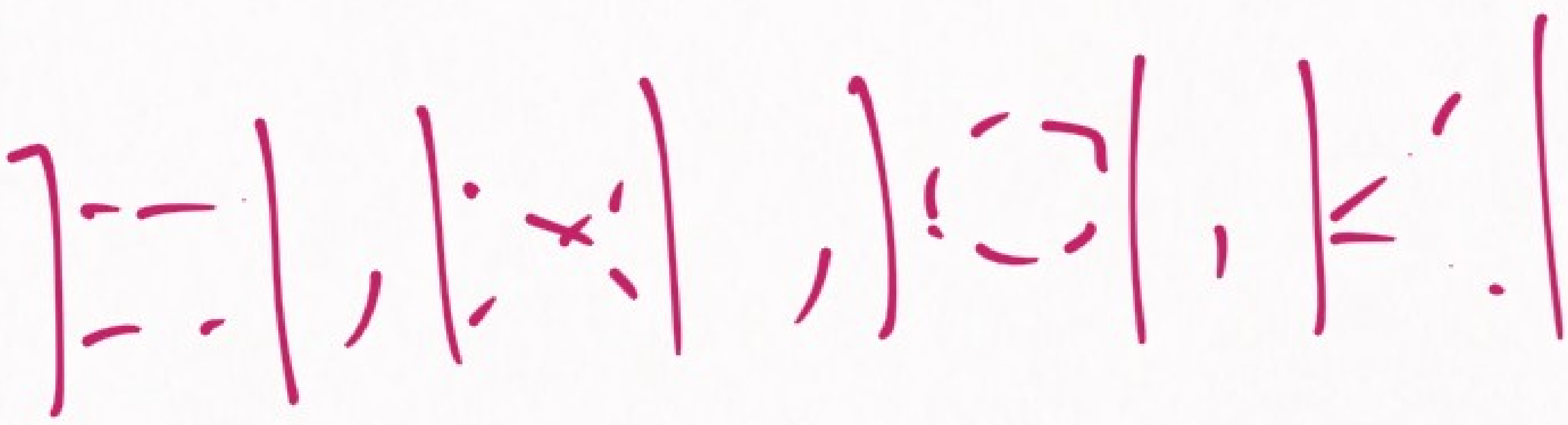
$$\mathcal{L} = \frac{g}{2f_\pi} \bar{\psi}_N \gamma^5 \gamma^\mu \partial_\mu (\vec{\tau} \cdot \vec{\phi}) \psi_N$$

→ CRUCIAL DIFFERENCE

We call this: DERIVATIVE INTERACTION

CONSEQUENCES:

 → no change

 → change

now we obtain the correct form

2) Other light bosons

50's → failure of pion theories

$\Downarrow$

Let's try another idea

- π : 0^- $\Rightarrow$ we can consider other bosons

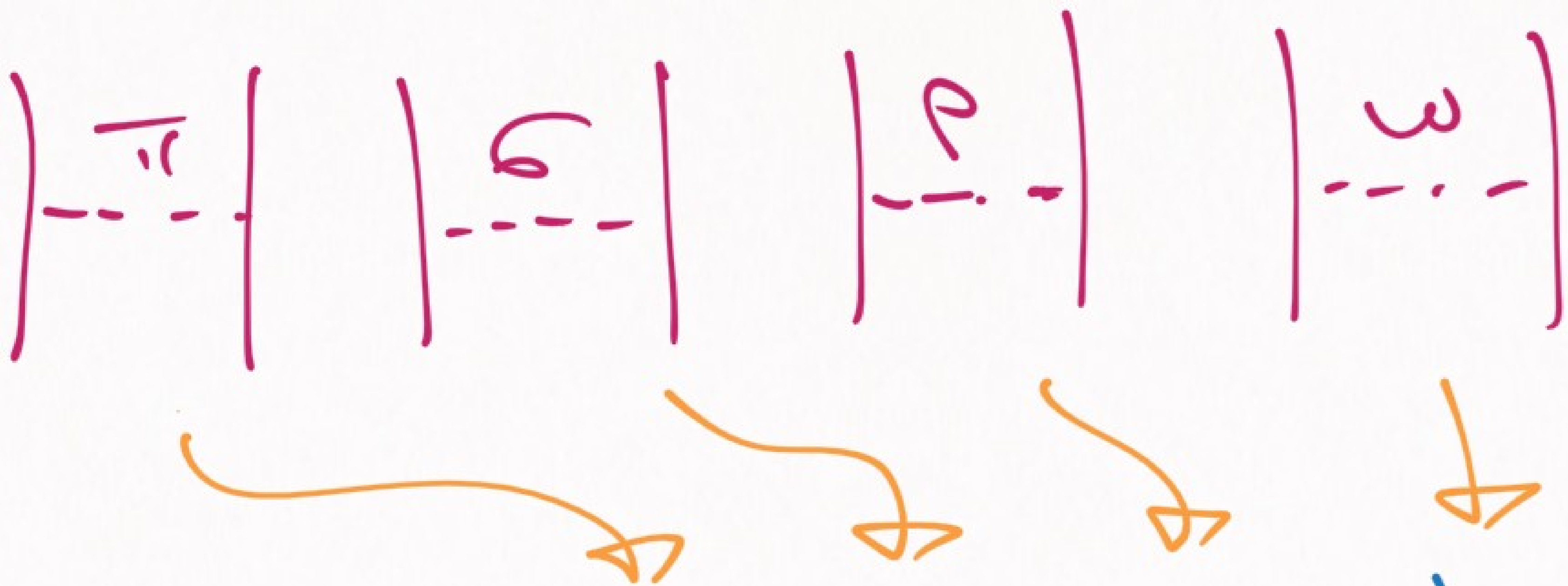
$m_\pi = 140\ \text{MeV}$

- σ : 0^+
- ρ : 1^-
- ω : 1^-

$m_\sigma = 600\ \text{MeV}$

$m_\rho \simeq 770\ \text{MeV}$

$m_\omega \simeq 780\ \text{MeV}$



$$V_{NN}(\vec{r}) = V_\pi + V_\sigma + V_\rho + V_\omega$$

→ this is incredibly simple (and we saw how to compute each piece of the potential in the previous lesson)

→ **OBE model**

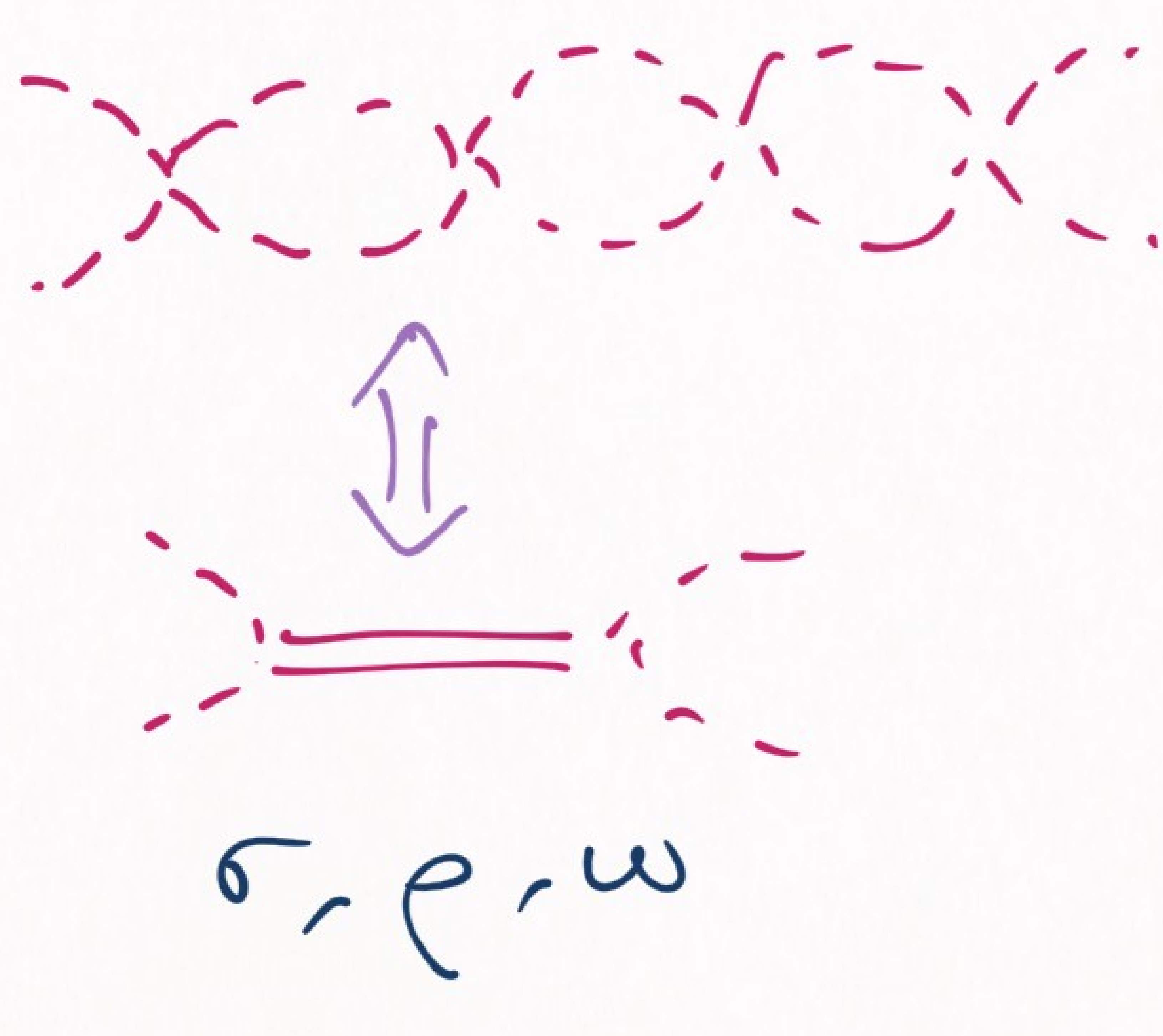
OBE → motivation:

multipion exchanges:

a) correlated

b) ~~uncorrelated~~ > not important

hypothesis:



But... motivation not important

Why? OBE → phenomenological model

?

meaning: it works (more or less)

but we do not worry about

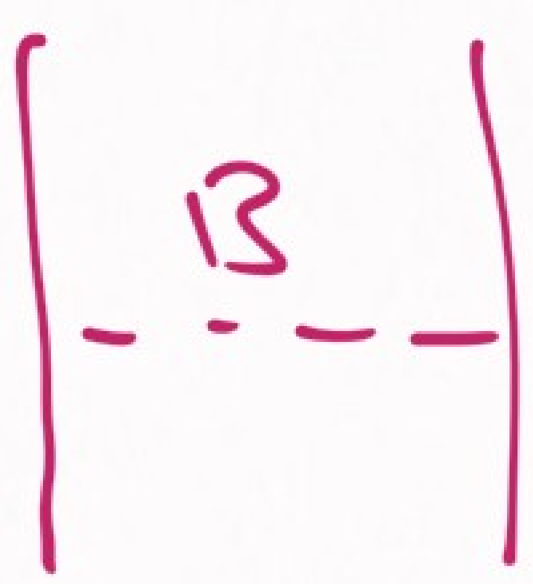
it's theoretical basis

→ [we just use it because

it's convenient]

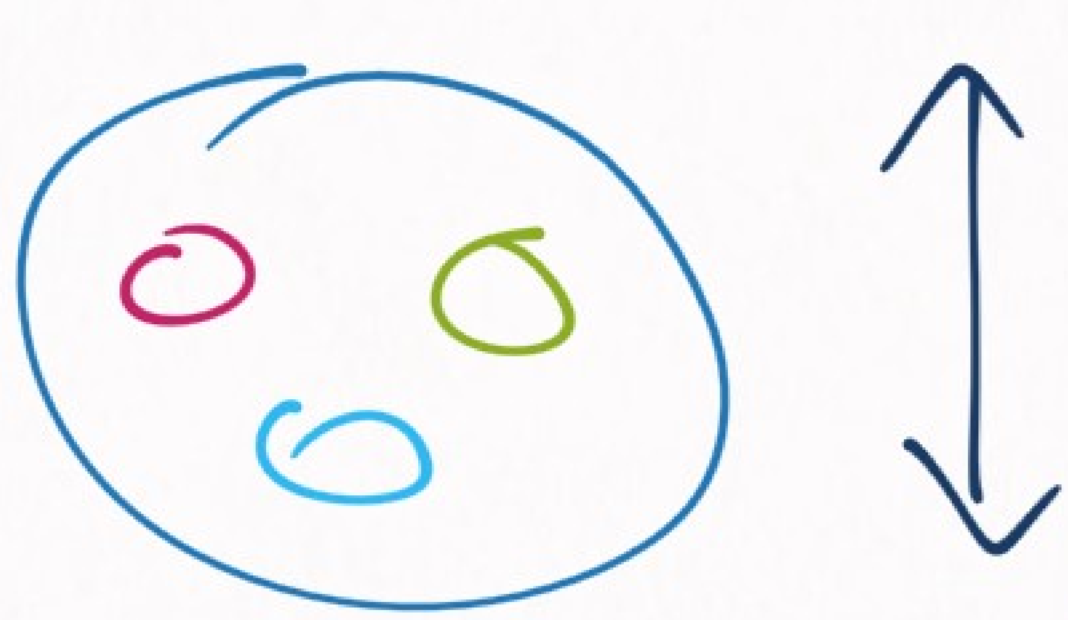
OBE ⇒ THEORETICAL PROBLEMS

1) range of σ, ρ, ω
similar nucleon size



$\sim \frac{e^{-m_B r}}{r} \Rightarrow \frac{1}{m_B}$ range

$\sigma, \rho, \omega \Rightarrow \frac{1}{m_B} \sim 0.3\ \text{fm}$

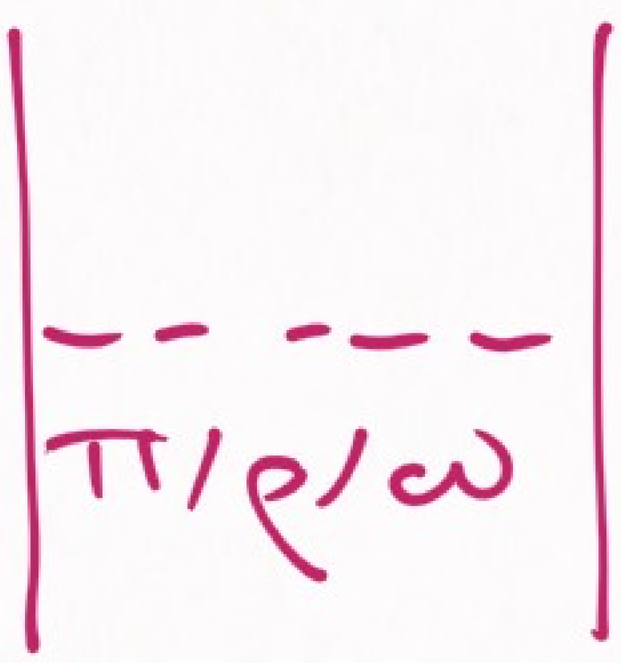


$\sim 1\ \text{fm}$

neutron/proton

There's a problem

2) singular potentials



$$\sim \frac{e^{-mr}}{r}\left(1+\frac{3}{mr}+\frac{3}{(mr)^2}\right)$$

$$\sim \frac{1}{r^3} \text{ for } mr \ll 1$$

↓

singular potential:

→ if attractive,
no fundamental state

↳ a serious problem
(till recently, when we
finally understood them)

RECAP: old pion theories

(diverge)

↓

OBE model

(finite nucleon size,
singular potentials)

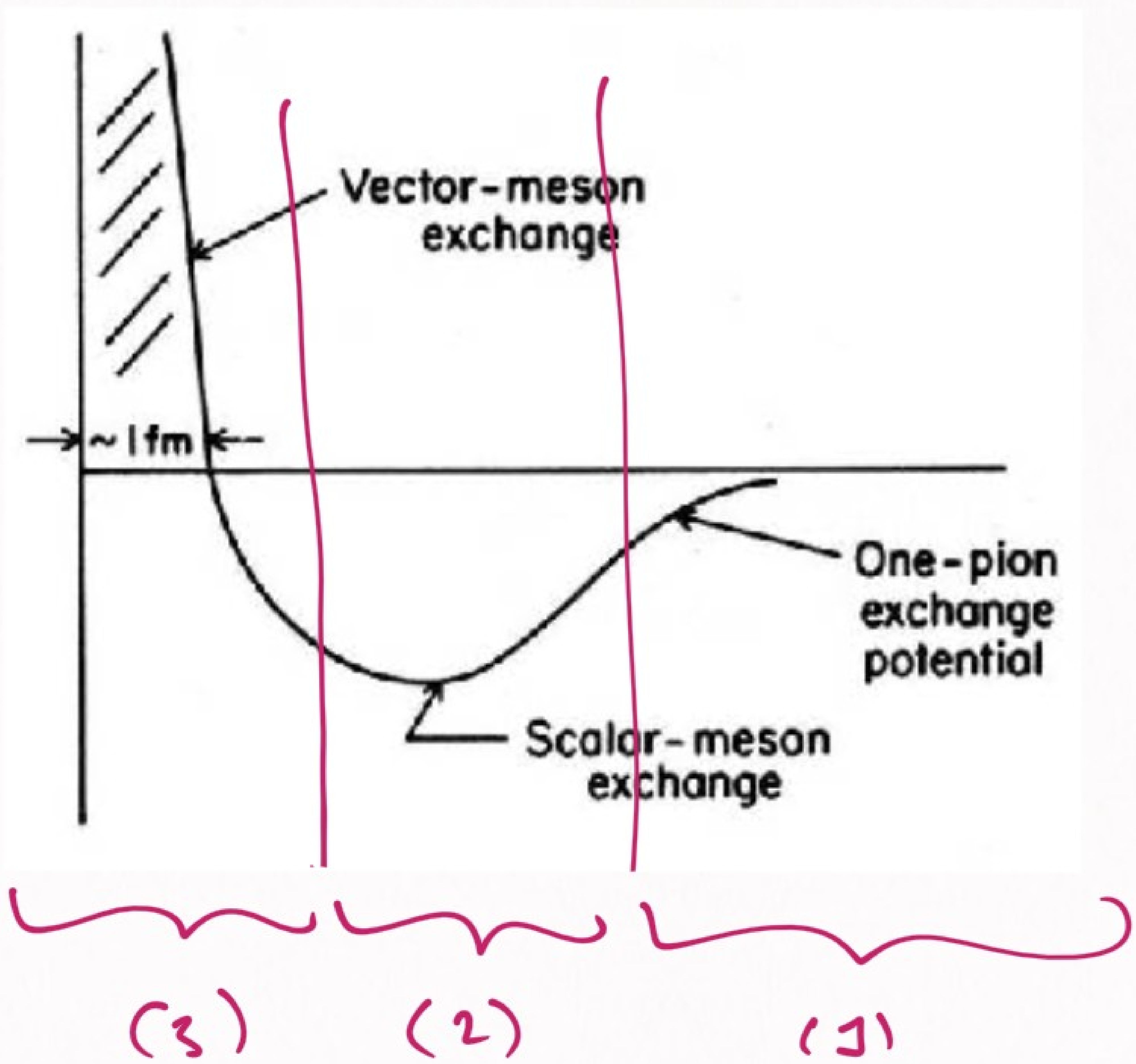
↓

modern pion theories

(chiral symmetry,
renormalization)

Now let's explore other ideas

Taketani, Nakamura, Sasaki (TNS)



(1) Classical Zone ($r \geq 2$ fm)

→ OPE (One pion exchange)

(2) Dynamical Zone (1–2 fm)

→ TPE, σ

(3) Phenomenological Zone ($r < 1$ fm)

→ multipion, ρ, ω, weird things

TNS → interesting idea

↓

very modern approach

↓

long / medium / short distances

↓ well known ↓ poorly known

↓

SCALE SEPARATION

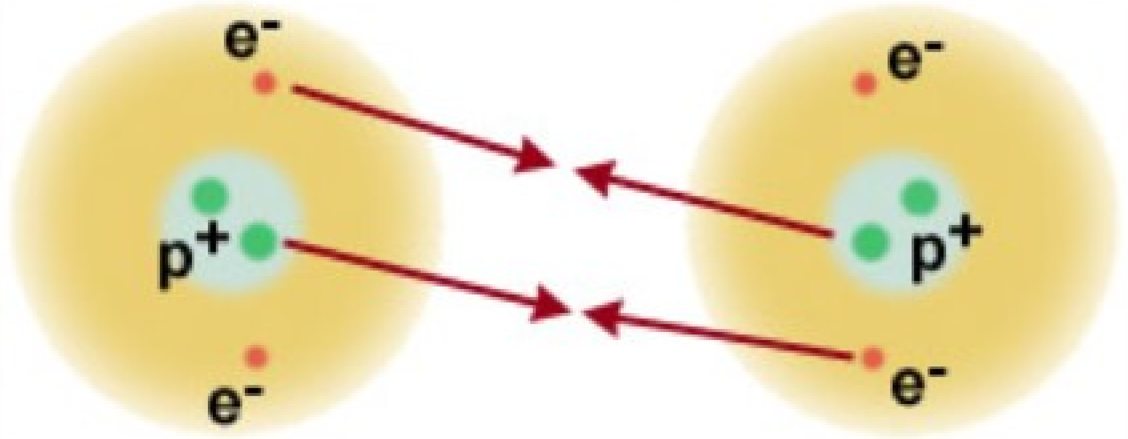
↓

distinguish between knowns & unknowns

Another idea :

NUCLEAR FORCES ARE RESIDUAL FORCES

Residual forces



Residual E-M force in action: the atoms are electrically neutral, but the electrons in one are attracted to the protons in another, and vice versa!

↙

atoms → electrically neutral

but electrons & protons inside can interact

⇓

RESULT: RESIDUAL FORCE

RESIDUAL FORCES

Example → van der Waals

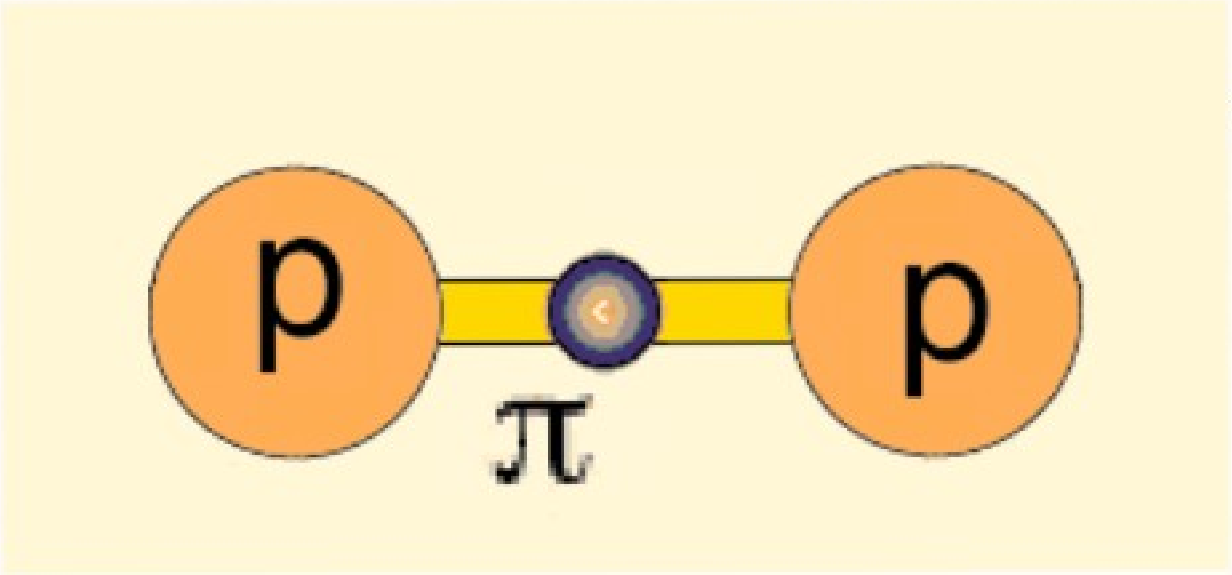
$$V(r) = -\frac{C_6}{r^6} - \frac{C_8}{r^8} - \dots$$

Residual

(while Coulomb is fundamental)

— ⊗ —

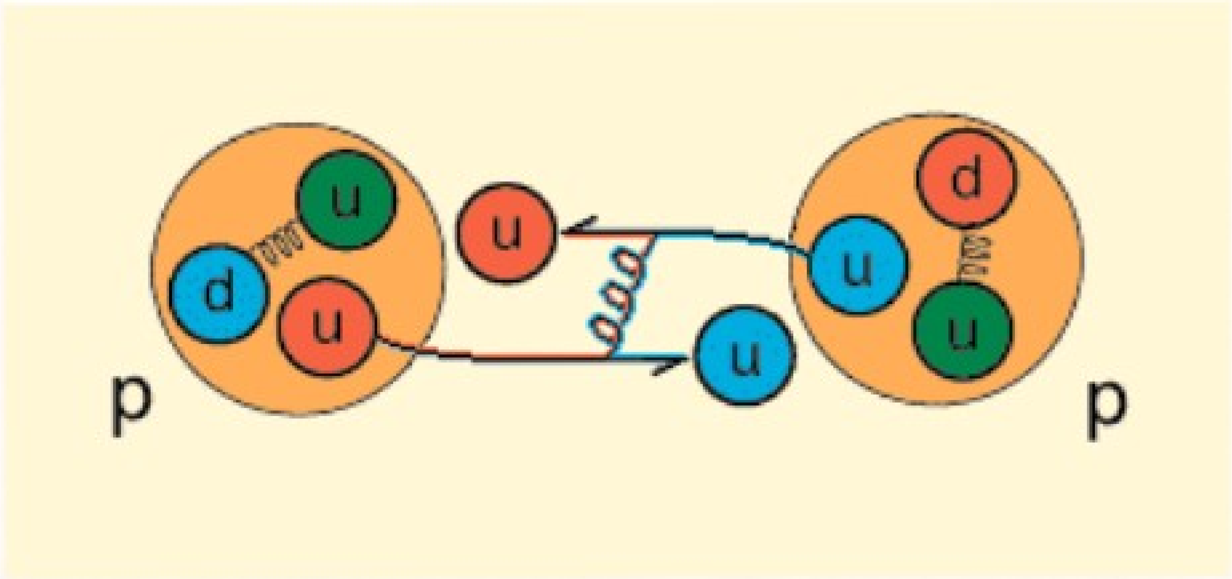
Example → nuclear forces

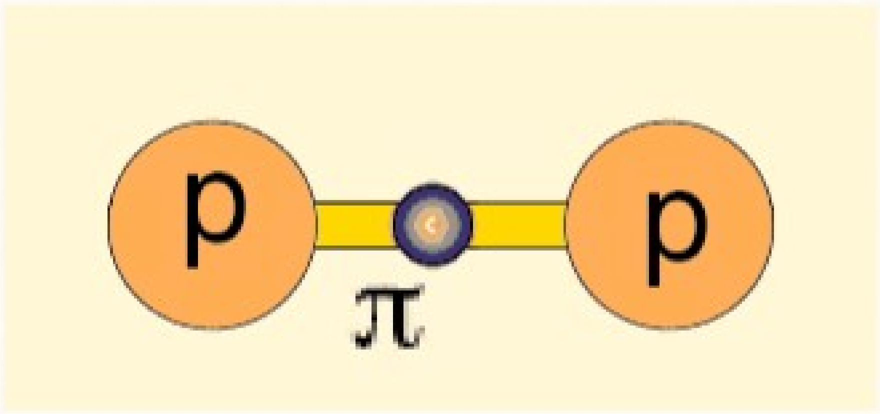


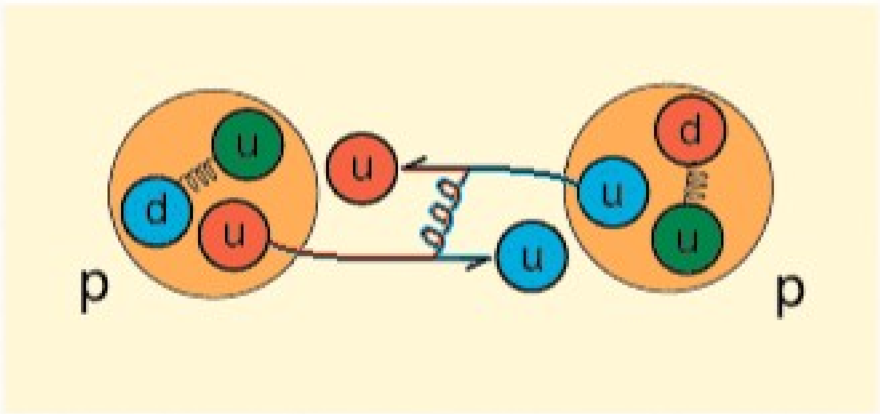
→ protons, neutrons, pions

↓

compound







→ **BASIC IDEA**

Explain nuclear forces in terms of its components

NEXT LECTURE

We will check the components of neutrons, protons, pions

→ quarks & gluons