$$i\hbar \frac{\partial}{\partial t}|\psi\rangle = H|\psi\rangle$$

↳ operatore

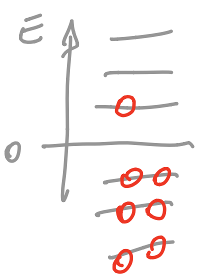
ANTIPARTICELLE

tentativi di coniugare MQ & RELSPEC

- K-G : $E<0$ vanno tenute
  $\rho<0$
  2° ordine in $\partial/\partial x_\mu$
- Dirac (spin 1/2) : $E<0$
  $\rho>0$
  1° ordine in $\partial/\partial x_\mu$

DIRAC SEA

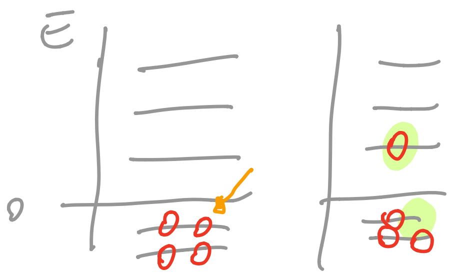
FERMIONI



- i livelli con $E<0$ sono occupati

$\gamma \to e^+ + e^-$

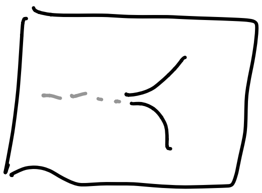
$(\gamma + N \to N + e^+ + e^-)$



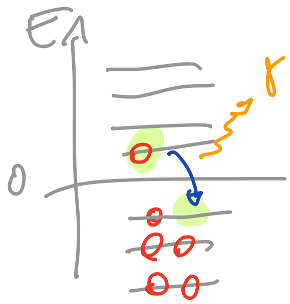
FEYNMAN-STÜCKELBERG

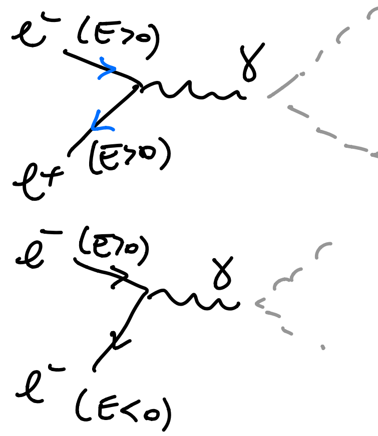
$$e^{-iEt} = e^{-i(-E)(-t)}$$

- gli elettroni ad $E<0$ sono soluzioni associate a positroni che viaggiano indietro nel tempo



$e^+ + e^- \to \gamma$





BLU = CONVENZIONE

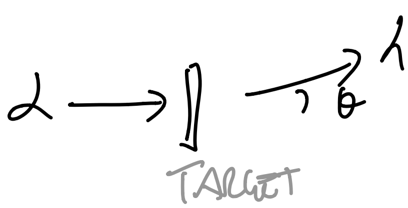
VERSO LE INTERAZIONI FORTI

Coulombiano → FORTI → DEBOLI

→ ELETTROMAGNETICHE

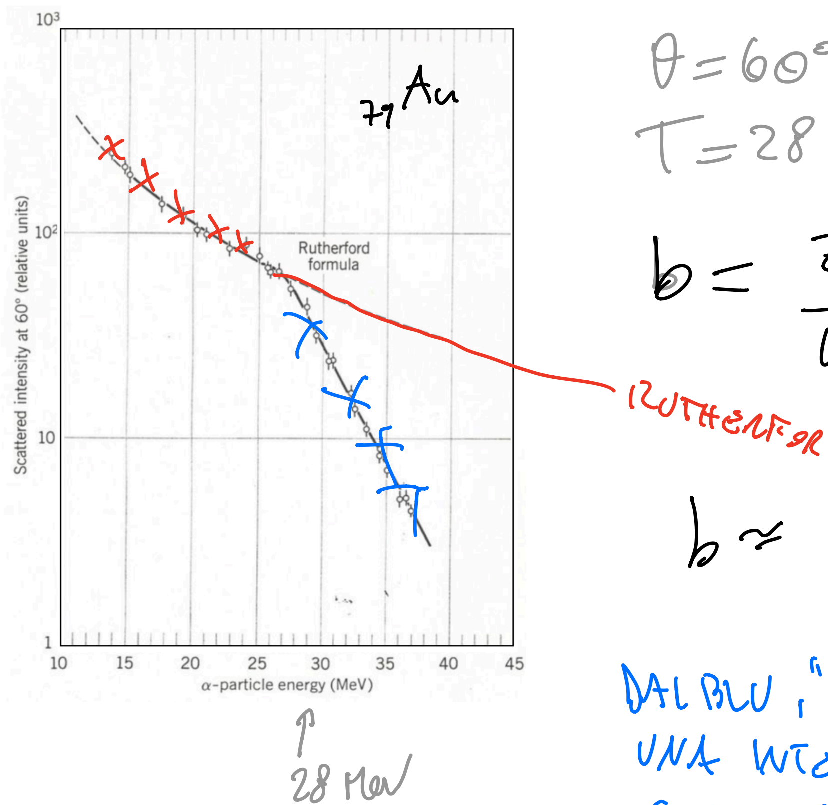
→ GRAVITAZ.

– Rutherford (1911)



$$A = \frac{e^2}{4\pi\varepsilon_0} \cdot \frac{1}{T} zZ$$

$$b = A \frac{1}{\tan\theta/2}$$



$\theta = 60°$

$T = 28$ MeV

$$b = \frac{zZe^2}{4\pi\varepsilon_0}\frac{1}{T}\frac{1}{\tan\frac{\theta}{2}}$$

$b \simeq 14$ fm

DAL BLU, "SENTIAMO" UNA INTERAZ. A CORTO RAGGIO

- 1917: scoperta il protone

$$\alpha \to {}^{14}N \to {}^{17}O + p$$

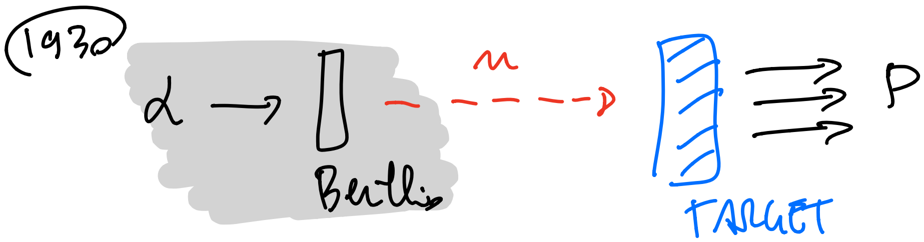
PROBLEMA:

$$m_{nuclei} > Z\, m_p$$

$\to$ c'è altro

se fossero elettroni, $T = E - m_e \simeq p$

se $p \simeq \Delta p \gtrsim \frac{\hbar}{\Delta x} = \frac{\hbar}{1\,fm} \simeq 200$ MeV

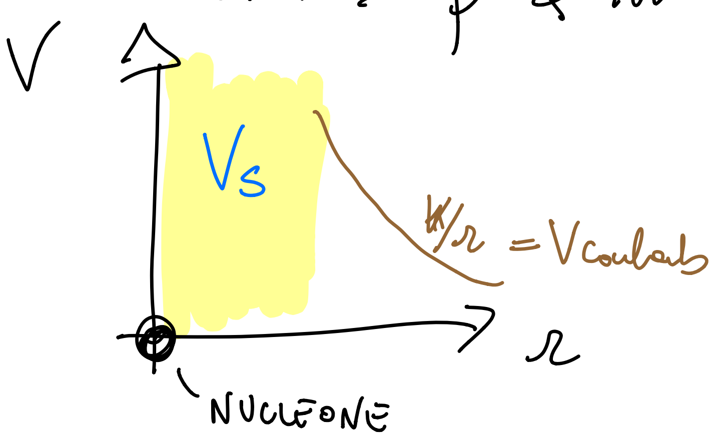


- H (paraffina) $\quad T_p \simeq 5$ MeV
- ^{14}N $\quad T_p \simeq 1$ MeV

$T^{(p)}_{MAX} = ?$ $\qquad 1 \to \boxed{2} \dashrightarrow p$

→ serve $m_n \simeq m_p$

NUCLEONI: p & n



$V_{S(TRONG)}$ breve energ a corto raggio

CAMPO EM

$$-\nabla^2 \phi = \rho/\varepsilon_0 = \frac{e}{\varepsilon_0}\,\delta^{(3)}(\vec{r})$$

$$\phi = \frac{e}{r}\,\frac{1}{4\pi\varepsilon_0}$$

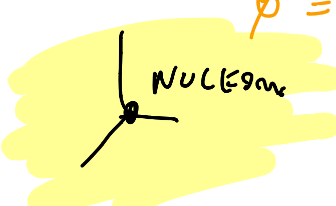
$$\partial_\mu \partial^\mu \phi = 0$$

$$\hookrightarrow \partial/\partial t\,\phi = 0$$ CAMPO STAZIONARIO

INT. FORTE

$$\left(\frac{\partial^2}{\partial t^2} - \nabla^2 + m^2\right)\phi = 0 \qquad (K-G)$$

$$\phi = \frac{1}{r}\cdot e^{-mr}$$



ϕ potenziale di Yukawa

m massa del mediatore

$$(\nabla^2 - m^2)\phi = -g\,\delta^{(3)}(\vec{r})$$

PIONE: π^0, π^+, π^-

$$\frac{\partial\phi}{\partial\theta} = \frac{\partial\phi}{\partial\varphi} = 0 \qquad \phi = \phi(r)$$

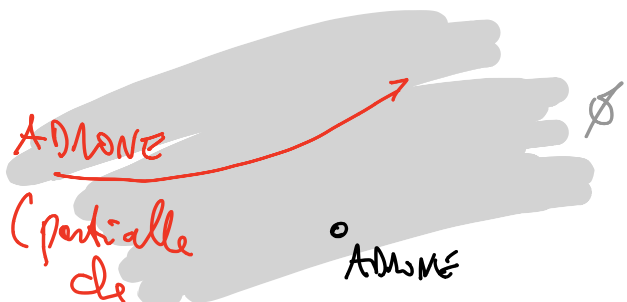
$$\nabla^2 = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \frac{\partial}{\partial r}\right) + \underline{\text{altro}}$$

devo risolvere

$$(\nabla^2 - m^2)\phi = 0$$

$$\phi \equiv \frac{C}{4\pi}\frac{e^{-mr}}{r}$$

POTENZIALE DI YUKAWA



(particella che interagisce forte)

M

$|i\rangle, |f\rangle$ onde piane

$$E_i = E_f$$

$$\vec{p}_i - \vec{p}_f \equiv \vec{p}$$

$$\psi_i = N e^{i\vec{p}_i\cdot\vec{x}}\, e^{-iE_i t}$$

$$\sigma = \frac{\Gamma_{if}}{v} \qquad (V = 1)$$

$$\Gamma_{if} = 2\pi |T_{if}|^2 \rho(E_i)$$

$$T_{if} = \langle \psi_f | \phi | \psi_i \rangle$$

$$= \frac{C}{4\pi} |N|^2 \int_0^{2\pi} d\varphi \int_0^{\pi} \sin\theta \, d\theta \int_0^{\infty} dr \, r^2$$

$$\times \frac{1}{r} e^{-mr} \cdot e^{i\vec{p}\vec{r}}$$

$$\vec{p}\vec{r} = pr\cos\theta$$

$$y \equiv \cos\theta$$

$$dy = -\sin\theta \, d\theta$$

$(|N| = 1)$

$$= -\frac{C}{4\pi} \cdot 2\pi \int_{-1}^{1} dy \int_0^{\infty} dr \, r e^{-mr} e^{ipry}$$

$$= \frac{C}{2} \int_0^{\infty} dr \cdot r e^{-mr} \left[\frac{e^{ipr} - e^{-ipr}}{ipr} \right]$$

$$= \frac{C}{2ip} \left[-\frac{1}{ip-m} - \frac{1}{ip+m} \right]$$

$$= \frac{C}{2ip} \left[\frac{-ip-m-ip+m}{-p^2-m^2} \right]$$

$$= \frac{c}{p^2+m^2}$$

$$|T_{fi}|^2 = \frac{c^2}{(p^2+m^2)^2}$$

$$\rho(E_i) = \frac{dn}{dE_f}\bigg|_{E_f=E_i} = \frac{dn}{dp_f}\left|\frac{dp_f}{dE_f}\right|$$

$$= \frac{p^2\, dp_f\, d\Omega}{(2\pi)^3\, dp_f}\left|\frac{dp_f}{dE_f}\right|$$

$$E_f = p_f^2/2M$$

$$p_f = \sqrt{2ME_f}$$

$$\frac{dp_f}{dE_f} = \frac{\sqrt{2M}}{\sqrt{4E_f}} = \sqrt{\frac{M}{2E_f}}$$

$$\rho(E_i) = \sqrt{\frac{M}{2E_f}} \cdot \frac{d\Omega}{(2\pi)^3} p_f^2$$

$$= M\sqrt{2ME_f}\,\frac{d\Omega}{(2\pi)^3}$$

$$\Gamma_{fi} = 2\pi\,|T_{fi}|^2\,\rho(E_i)$$

$$\phi = v = \frac{p_f}{M} = \frac{\sqrt{2ME_f}}{M}$$

$$d\sigma = 2\pi\cdot|T_{fi}|^2\cdot M\sqrt{2ME_f}\,\frac{d\Omega}{(2\pi)^3}$$

$$\frac{M}{\sqrt{2ME_f}}$$

$$\sigma = \int d\Omega\,\text{“}d\sigma\text{”} =$$

$$= \frac{c^2}{\pi}\left(\frac{M}{(p^2+m^2)^2}\right)^2$$

se p è basso

$$\sigma \simeq \frac{c^2}{\pi}\left(\frac{M}{m^2}\right)^2$$

$$\equiv 4\pi a^2$$

- vogliamo stimare m del mediatore di Yukawa (PIONE)

- vogliamo stimare c

$$4\pi a^2 = \frac{c^2}{\pi}\left(\frac{M}{m^2}\right)^2$$

$$\rightarrow a = \frac{1}{2\pi} c\left(\frac{M}{m^2}\right)$$

Stimo m

$$e^{-mr} \equiv e^{-r/\lambda}$$

$$\lambda \simeq 1\,\text{fm} \longrightarrow m \simeq 200\,\text{MeV}$$

$$\frac{1}{1\,\text{fm}} \Rightarrow \frac{197\,\text{MeV}\cdot\text{fm}}{1\,\text{fm}}$$

- $a \simeq \lambda \sim 1\,\text{fm}$

$$M \simeq 1\,\text{GeV} \quad (\sim m_p, m_n)$$

$$C \simeq O(1)$$

per campo EM:

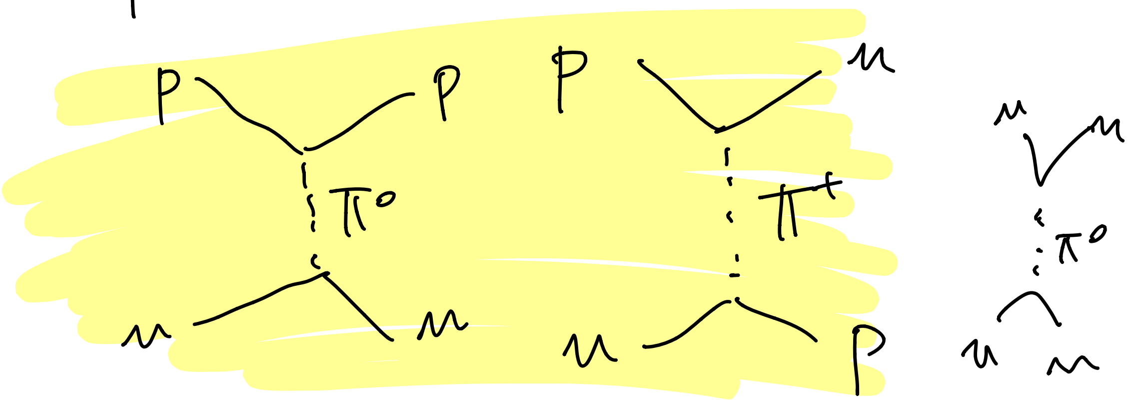
$$V = \frac{e^2}{4\pi\varepsilon_0 r}$$

$$C_{EM} = \frac{e^2}{\varepsilon_0} = 4\pi\alpha \simeq 0.1$$

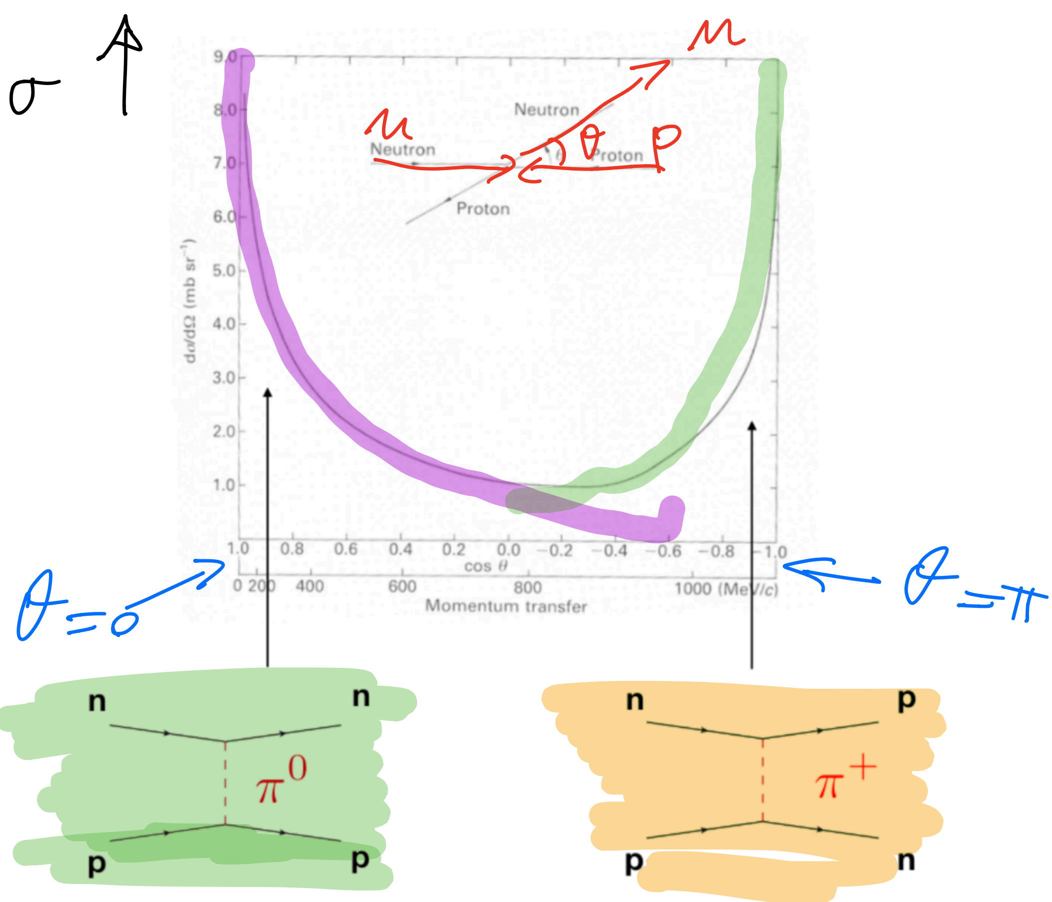
$$C \gg C_{EM}!$$

(è FORTE)

$p + n \to p + n$


p
p
n
n
π⁰
p
n
π⁺
n
p
n
n
π⁰
n
n

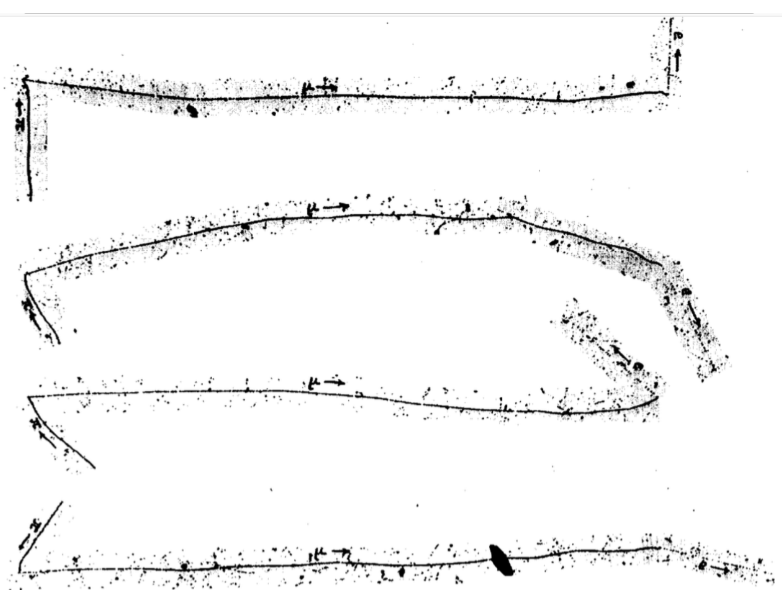
$\to t$

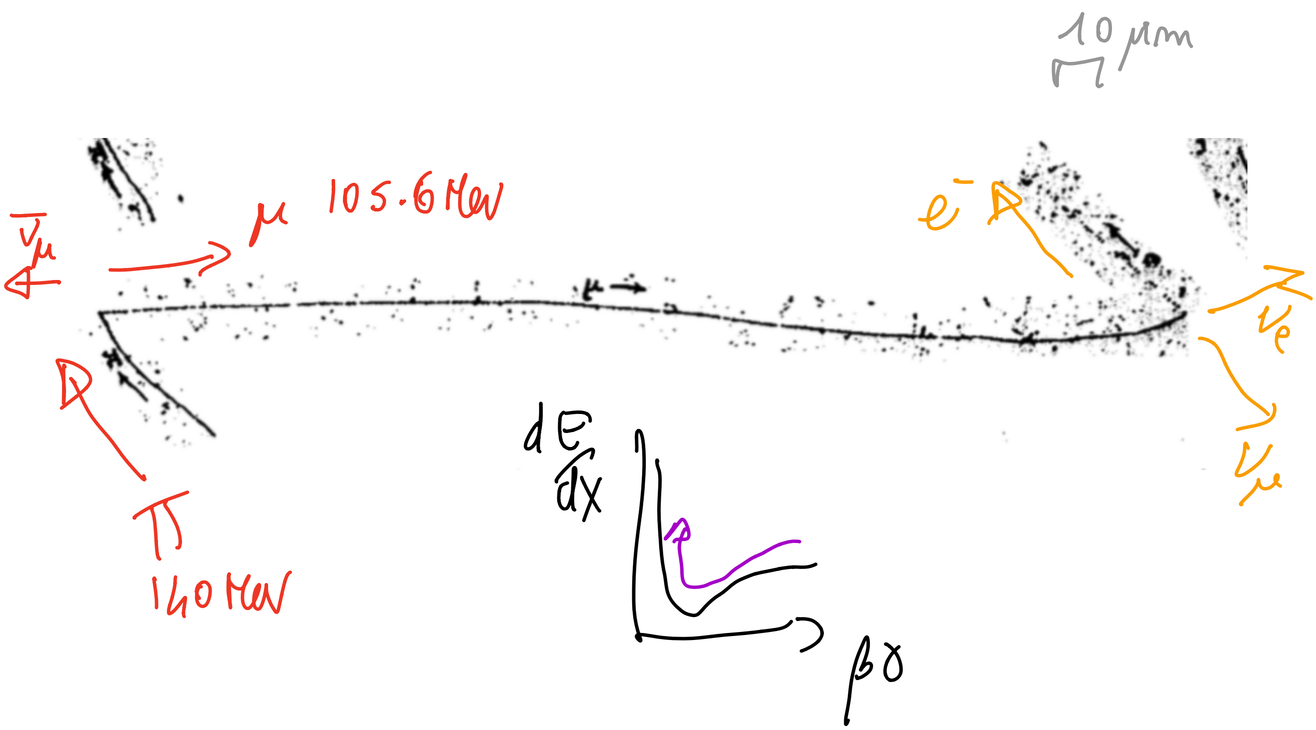

σ
n
Neutron
Neutron
θ
Proton
p
Proton
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
dσ/dΩ (mb sr⁻¹)
1.0 0.8 0.6 0.4 0.2 0.0 −0.2 −0.4 −0.6 −0.8 −1.0
cos θ
0 200 400 600 800 1000 (MeV/c)
Momentum transfer
θ = 0
θ = π
n
n
π⁰
p
p
n
p
π⁺
p
n

Si è scoperto il PIONE
o mesone, π^+ π^-
π^0

$m_{\pi^\pm} \simeq 140$ MeV

$m_{\pi^0} \simeq 135$ MeV





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

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

$\hookrightarrow_{1949}$ π^- (π^+, π^0) particelle di Yukawa

MESONI

$$\mu^- = ?????$$

- storicamente: MESONE $\quad m \in [m_e, m_p]$
- MESONE stato legato $q \; \bar{q}$ QUARK (FERMIONI)

- BARIONI qqq
- 4, 5 quark