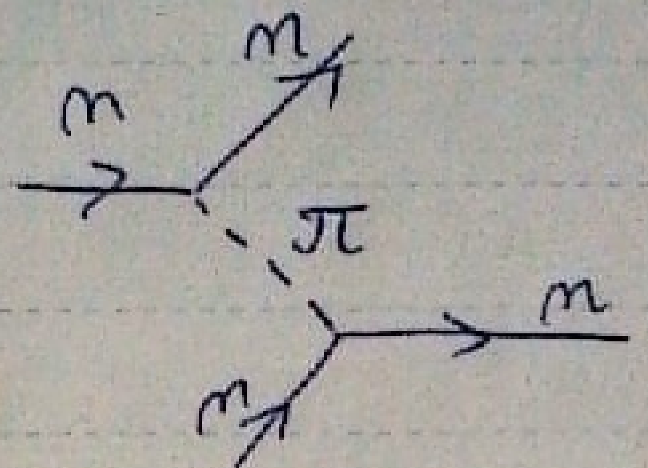
素粒子宇宙起源研究機構
Kobayashi-Maskawa Institute for the Origin of Particles and the Universe

$m \neq 0 \Rightarrow$ POTENCIAL S KONČNIM DOSEGOM

HIDEKI YUKAWA! MOČNA INTERAKCIJA (KONČNI DOSEG)

$\Rightarrow$ NOSILCI MASIVNI DELCI! DOSEG $\rightarrow$ MASA

MEZONI OCENA ~ 100 MeV

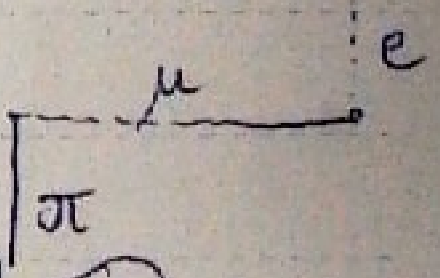


$\frac{e^{-r/R}}{r}$ YUKAWIN POTENCIAL

$$m_\pi c^2 = \frac{\hbar c}{R} \sim \frac{200 \text{ MeV fm}}{\text{nekaj fm}} \sim 100 \text{ MeV}$$

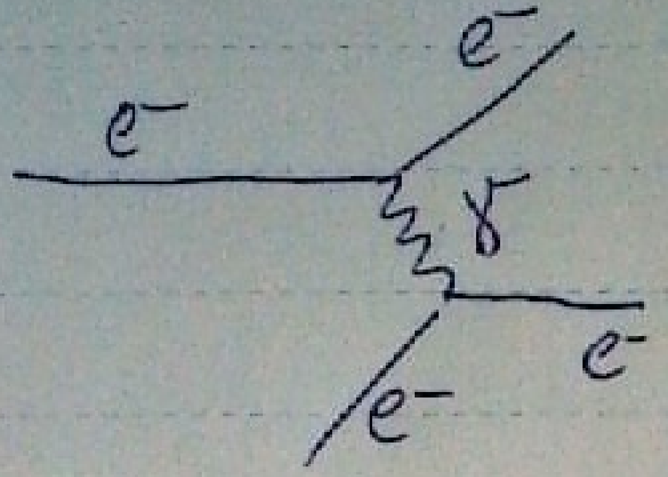
mion : $m_\mu c^2 = 104$ MeV

pion $m_\mu c^2 \sim 140$ MeV



$\pi^{\mp} \rightarrow \mu^{-} \bar{\nu}_\mu$

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



$$f = \int U(r)\, e^{+i\vec{q}\cdot\vec{r}}\, d^3 r$$

$$\text{ZA} \quad U(r) = \frac{g}{r} e^{-\frac{r}{R}}$$

$$w = \underbrace{-i\vec{q}\vec{r}}_{qr} + \frac{r}{R}$$

$$w = r\left(\frac{1}{R} - iq\right)$$

$$f = \int \frac{g}{r} e^{+i\vec{q}\vec{r}} e^{-\frac{r}{R}} \underbrace{d^3 r}_{2\pi r^2 dr} =$$

$$= g 2\pi \int_0^\infty e^{-w} \frac{w}{\left(\frac{1}{R} - iq\right)^2} dw =$$

$$= \frac{g}{\left(\frac{1}{R} - iq\right)^2} \underbrace{2\pi \int e^{-w} w\, dw}$$

$$\sigma \propto |f|^2 \propto \frac{g^2}{\left|\frac{1}{R} - iq\right|^2} = \frac{g^2}{\frac{1}{R^2} + q^2} = \frac{g^2}{\frac{m^2c^2}{\hbar^2} + q^2} =$$

$$= \frac{g^2}{m^2c^4 + q^2\hbar^2} \cdot \hbar^2 c^2$$

$$\sigma \propto \frac{g^2}{m^2c^4 + q^2\hbar^2}$$

EM: $m = 0$

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

$$\sigma \propto \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \cdot \frac{1}{q^4}$$

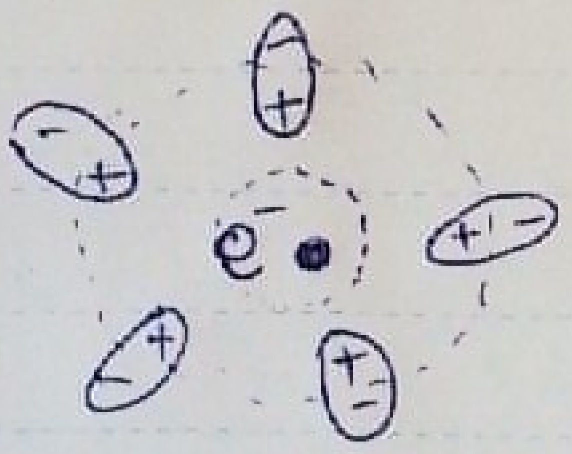
$$\sigma = \left[\frac{me}{8\pi\varepsilon_0 p^2}\right]^2 \frac{1}{\sin^4\frac{\theta}{2}} |F(q)|^2$$

POSLEDICA PRI ŠIBKI INTERAKCIJI

$m_W \sim 83\,\mathrm{GeV}/c^2$

$$\sigma_W \propto \frac{g^2}{m_W^2 c^4 + q^2\hbar^2} \xrightarrow{\hbar^2 q^2 \ll m_W^2 c^4} \frac{g^2}{m_W^2 c^4}$$

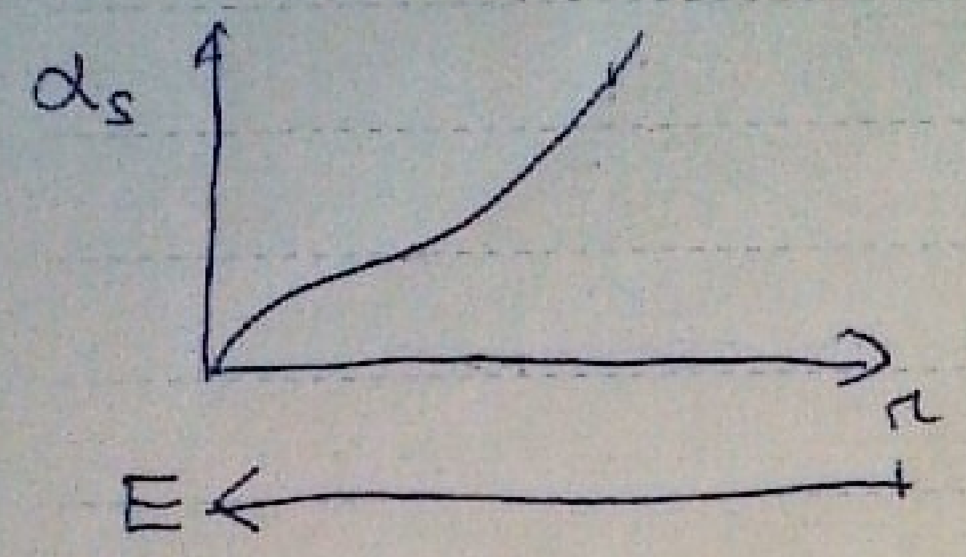
SENČENJE NABOJA IN POLARIZACIJA VAKUUMA



BLIZU e^-: VIDIM PRAVI NABOJ (GOLI)

NA VEČJI ODDALJENOSTI: NABOJ JE DEL SENČEN.

MOČNA INTERAKCIJA: ANTI-SENČENJE



1973 GROSS, POLITZER, WILCZEK

ASIMPTOTSKA SVOBODA

EM. INT.: $\alpha \approx \frac{1}{137}$ AMPLITUDA $f = \sum_{i=0}^{\infty} f_i \sim$

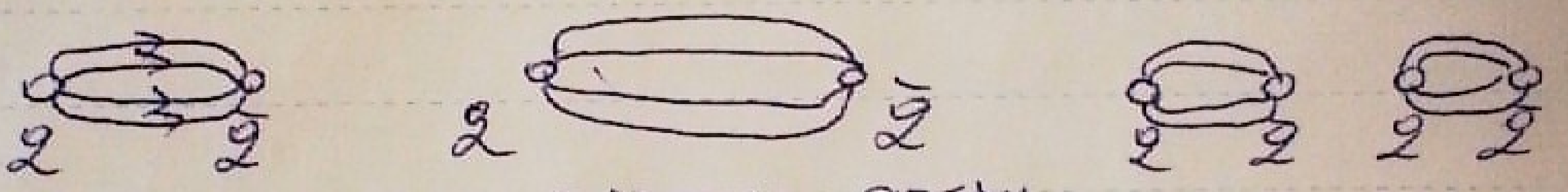
$\sim f_1 \alpha + f_2 \alpha^2 + \alpha^3$

MOČNA INT. $\alpha \sim 1$ PRI NIZKIH E

PERTURBACIJSKI RAČUN PRI NIZKIH ENERGIJAH ODPOVE

VISOKE ENERGIJE $\alpha_s \ll 1 \rightarrow$ PERTURBACIJA DELUJE!

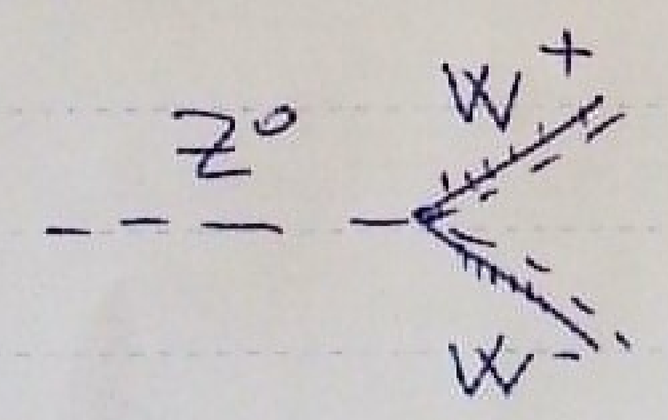
POTENCIAL MED KVARKI



ENERGIJA SISTEMA SE POVEČUJE

$\rightarrow$ PROSTIH KVARKOV NI!

ŠIBKA INTERAKCIJA



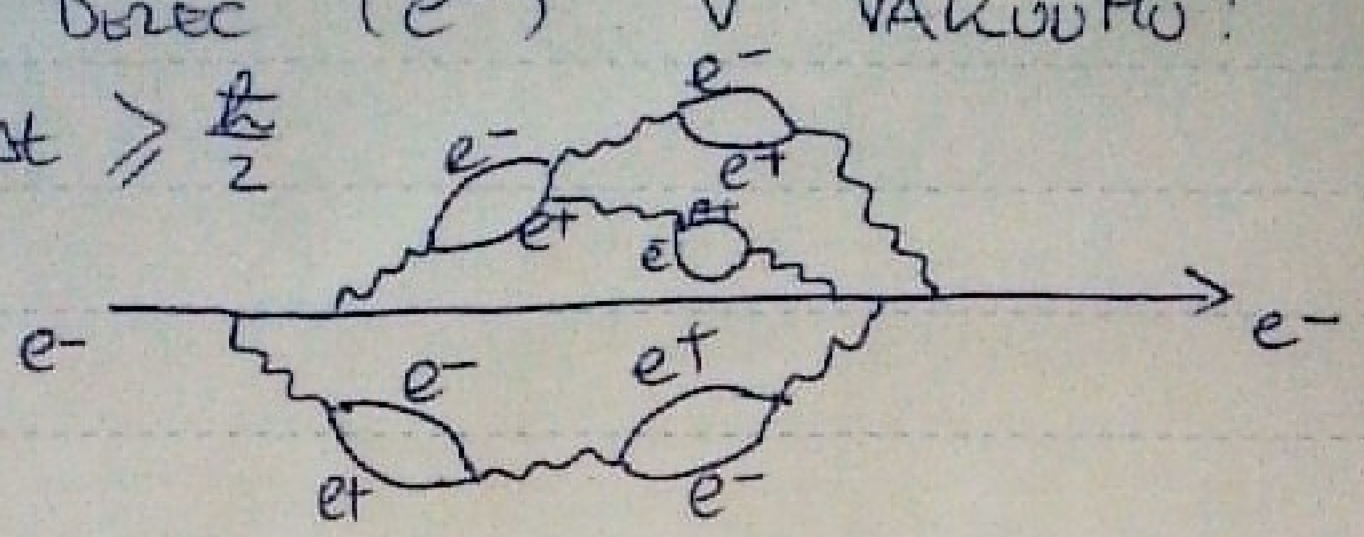
α_W z RAZDALJO RASTE

z ENERGIJO PADA

SKLOPITVENE KONSTANTE NISO ZARES KONSTANTE, AMPAK SO ODVISNE OD ENERGIJE, PRI KATERI POTEKA PROCES.

OSNOVNI DELEC (e^-) V VAKUUMU:

$\Delta E \Delta t \geq \frac{\hbar}{2}$



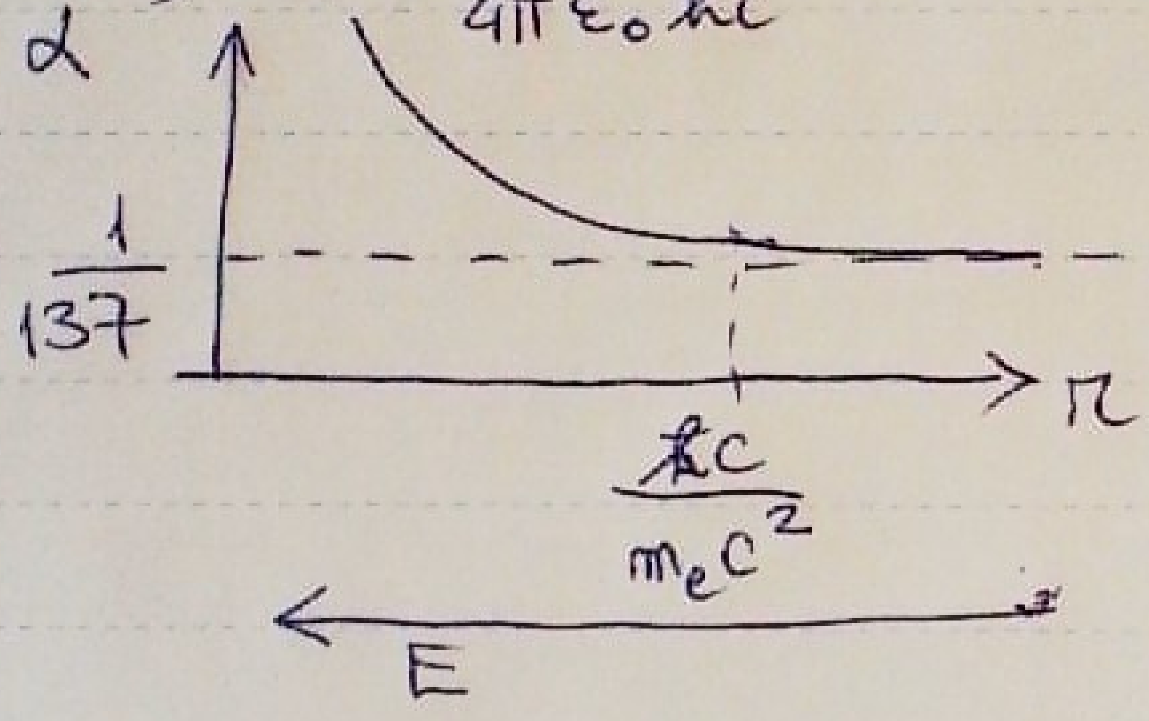
$$\Delta t \sim \frac{\hbar}{\Delta E} \sim \frac{\hbar}{m_e c^2} \qquad c\Delta t \sim \frac{\hbar c}{m_e c^2} = \frac{200\ \text{MeV fm}}{0{,}5\ \text{MeV}}$$

$$\sim 400\ \text{fm}$$

OD $\sim 10^3$ fm SE VREDNOST NABOJA NE BO SPREMINJALA. $e(r) = e_0 = +1{,}6 \cdot 10^{-19}$ As

→ POLARIZACIJA VAKUUMA.

$\Rightarrow \alpha = \frac{e^2}{4\pi\varepsilon_0 \hbar c}$ JE FUNKCIJA RAZDALJE

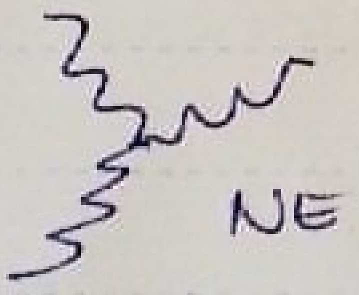


$\cancel{ee}\ \alpha(r) \to \alpha(E)$

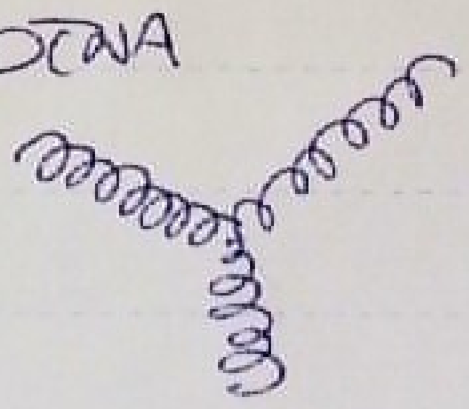
$\Delta p \Delta x \geq \frac{\hbar}{2}$

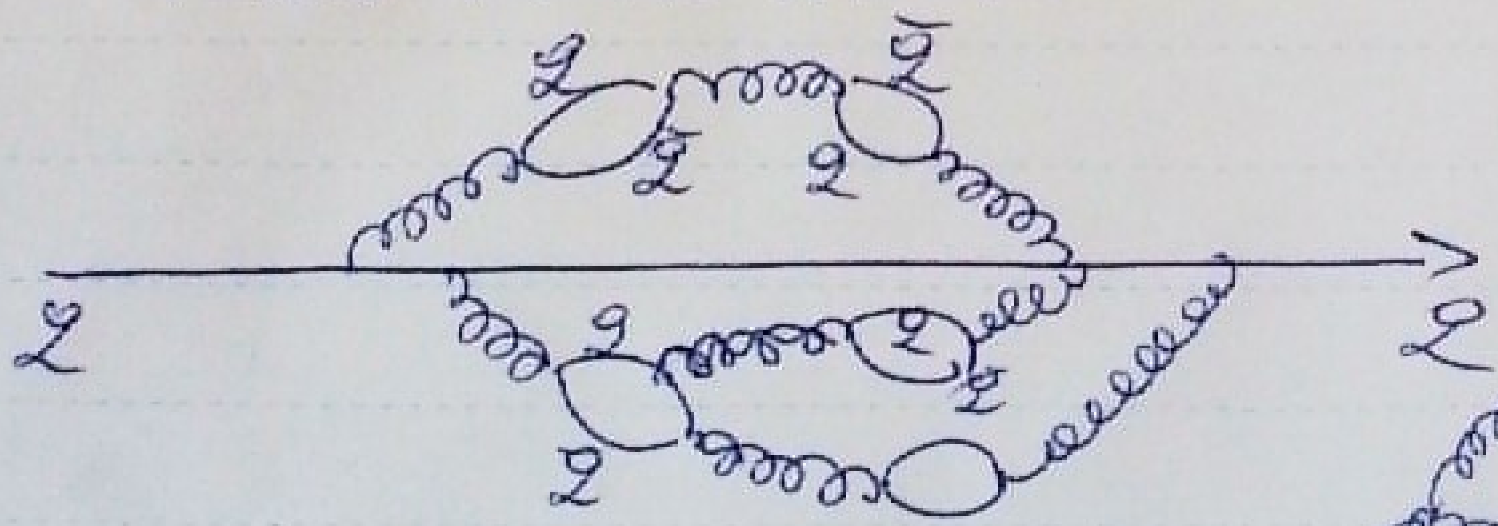
$E\, r \sim \hbar$

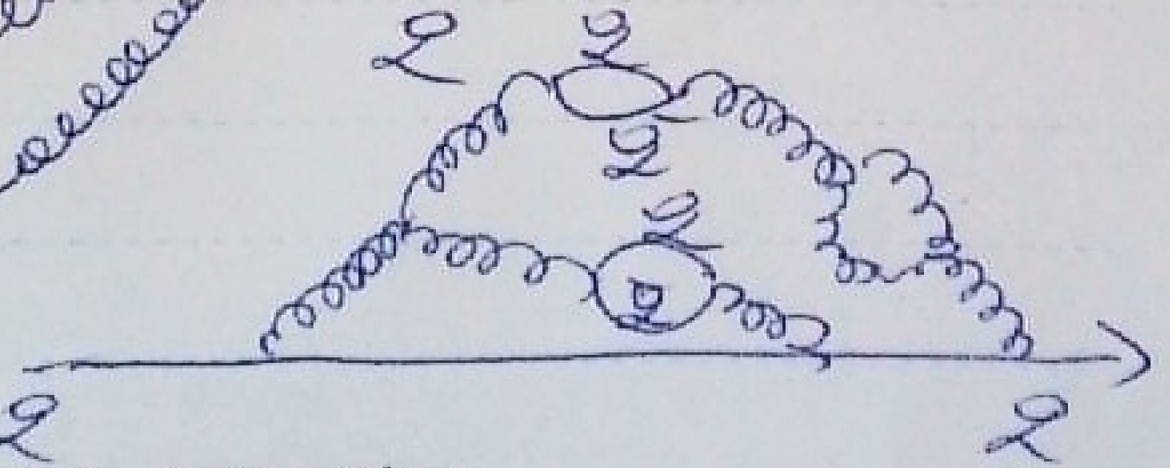
α_S, α_W: ODVISNOST OD ENERGIJE DRUGAČNA

EM  NE GRE!

FOTONI NIMAJO NABOJA

MOČNA  GLUONI IMAJO NABOJ

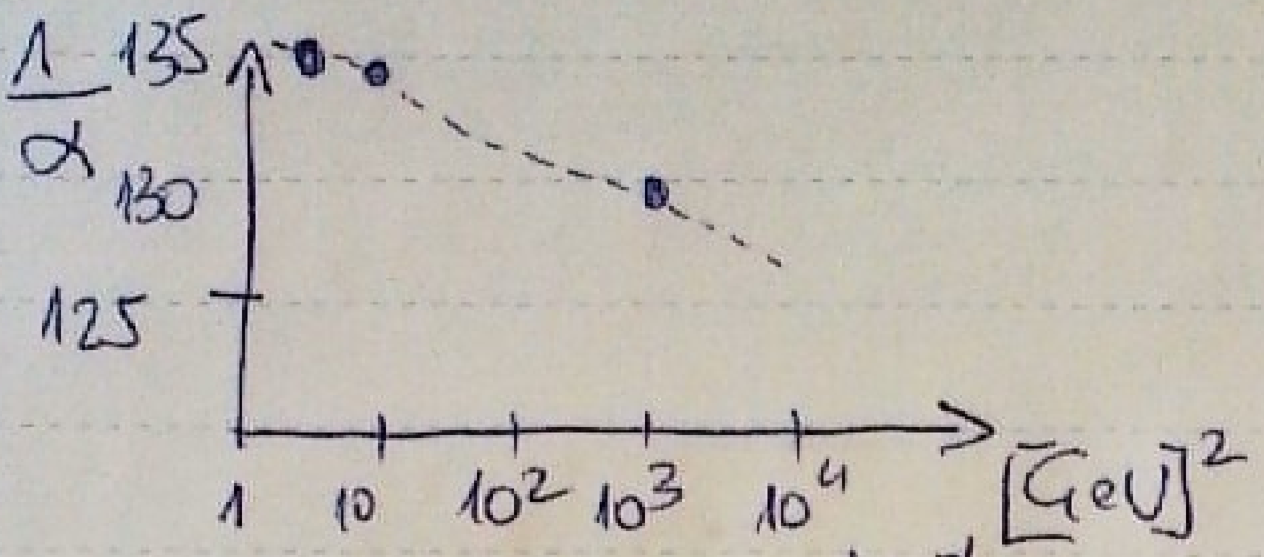


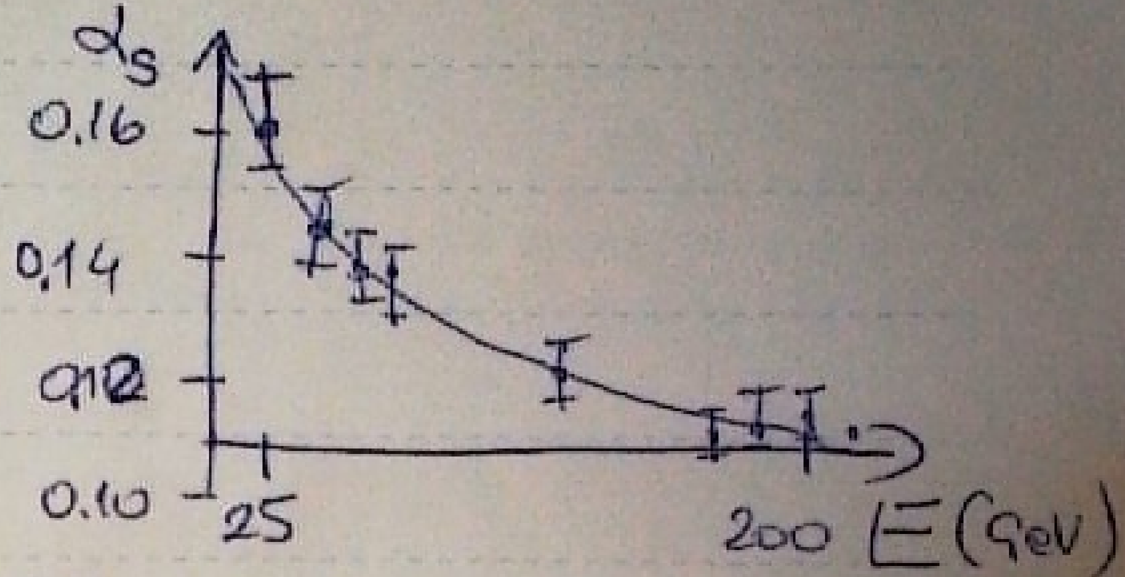


VELIKOST $\alpha_s, \alpha_1, \alpha_W$ PRI ~ 100 GeV

$\alpha \sim \frac{1}{128}$ PRI 100 GeV , $\frac{1}{137}$ PRI ~ 1 MeV

$\alpha_s \sim 20\,\alpha$ PRI 100 GeV

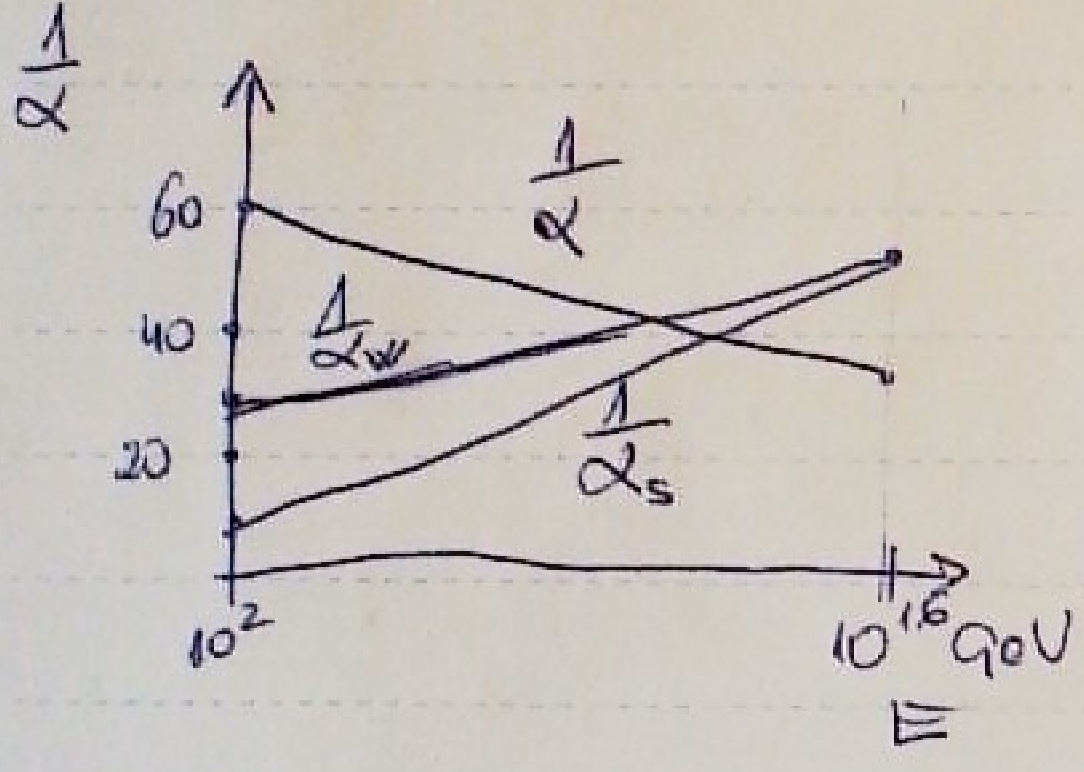


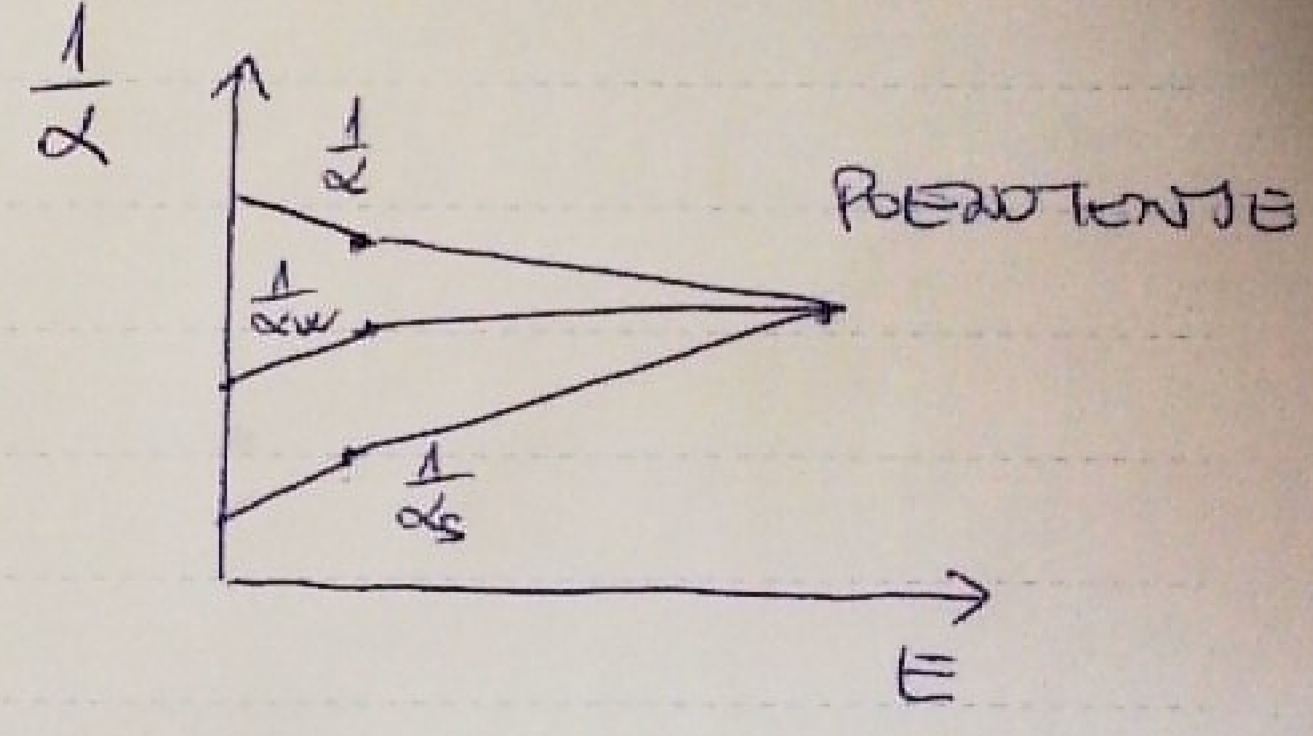


$|Q^2|$ = ČETVEREC PRENOSA GIBAL. KOLIČINE

$(p_f^4 - p_i^4)$

$\alpha_W \sim \alpha \qquad G \propto \frac{g^2}{m_W^2 c^4}$ PRI NIZKIH ENERGIJAH





SUPERSIMETRIČNI PARTNERJI OBIČAJNIH DELCEV SPIN $\frac{1}{2}$ → 0

e^- SELEKTRON

SIMETRIJE IN OHRANITVENI ZAKONI

OPAZLJIVKE, KI SE OHRANJAJO

STANJE $|\psi(t)\rangle$, ob $t=0$: $|\psi(t=0)\rangle$

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

$$|\psi(t)\rangle = e^{-\frac{i\hat{H}t}{\hbar}}|\psi(0)\rangle$$

$$|\psi(t)\rangle = \hat{U}(t)|\psi(0)\rangle \qquad \hat{U} = e^{-\frac{i\hat{H}t}{\hbar}}$$

OPOMBA: ČE $|\psi(t)\rangle$ LASTNA F.: $\hat{H}|\psi\rangle = E|\psi\rangle$

$$e^{-\frac{i\hat{H}t}{\hbar}}|\psi(0)\rangle = \left(1 \mp \frac{i\hat{H}t}{\hbar} + \dots\right)|\psi(0)\rangle = \left(1 \mp \frac{iEt}{\hbar} + \dots\right)|\psi(0)\rangle = e^{-\frac{iEt}{\hbar}}|\psi(0)\rangle$$

OPAZLJIVKA x, KI SE NAJ OHRANJA

$$\langle\psi(t)|x|\psi(t)\rangle = \langle\psi(0)|\hat{U}^+ x \hat{U}(t)|\psi(0)\rangle = \langle\psi(0)|x_0|\psi(0)\rangle$$

$$\hat{U}^+ x \hat{U} = x_0$$

$\hat{U}$ UNITAREN $\quad \hat{U}^+\hat{U} = I \Rightarrow x = \hat{U} x_0 \hat{U}^+$

$$\frac{\partial x}{\partial t} = \frac{\partial \hat{U}}{\partial t} x_0 U^+ + \hat{U} x_0 \frac{\partial U^+}{\partial t}$$

$$\frac{\partial \hat{U}}{\partial t} = -\frac{i\hat{H}}{\hbar}\hat{U} \qquad \frac{\partial \hat{U}^+}{\partial t} = \frac{i\hat{H}}{\hbar}\hat{U}^+$$

$$\frac{\partial x}{\partial t} = -\frac{i\hat{H}}{\hbar}\underbrace{\hat{U} x_0 \hat{U}^+}_{x} + \hat{U} x_0 \underbrace{\,}_{\hat{U}^+ U} i\frac{\hat{H}}{\hbar} U^+ = 0$$

2. ČLEN $\quad x\hat{U} i\frac{\hat{H}}{\hbar}\hat{U}^+ =$

$$\hat{U}\hat{H}\hat{U}^+ = e^{-\frac{i\hat{H}t}{\hbar}}\hat{H}e^{+\frac{i\hat{H}t}{\hbar}} =$$

$$\left(1 - \frac{i\hat{H}}{\hbar}t + \frac{(iHt)^2}{2\hbar^2} - \right)\hat{H}\left(1 + \frac{i\hat{H}}{\hbar}t + \frac{(it\hat{H})^2}{2\hbar^2}\right) =$$

$$= \hat{U}\hat{U}^+\hat{H} = \hat{H}$$

$$\frac{\partial x}{\partial t} = -i\frac{\hat{H}}{\hbar}x + \frac{ixH}{\hbar} = -\frac{i}{\hbar}[\hat{H}, x] = 0$$

x KOMUTIRA S $\hat{H} \Longrightarrow$ PRIČAKOVANA VRED. x

KONSTANTA $\rightarrow$ SE OHRANJA

PRIMER: 3. KOMPONENTA VRTILNE KOLIČINE

ct. $[\hat{H}, \hat{J}_z] = 0$ $\Rightarrow$ PRIČAKOVANA VREDNOST J_z SE OHRANJA

→ POSLEDICA: TRETJA KOMPONENTA VRTILNE KOLIČINE JE POVEZANA Z OPERATORJEM, KI ZAVRTI KOORDINATNI SISTEM OKOLI OSI Z

$$e^{\frac{iJ_z}{\hbar}\varphi}$$

$$\left(1 + i\frac{J_z}{\hbar}\varphi\right)\psi(x, y, z)$$

DN: IZPELJITE TO, ZAČNITE Z INFINITEZIMALNO ROTACIJO $\varphi \ll 1$

OHRANITEV BARIONSKEGA IN LEPTONSKEGA ŠTEVILA

B: BARIONSKO ŠTEVILO. VSI BARIONI IMAJO B=1
ANTI-BARIONI B=-1

p	uud	$B=1$
n	udd	1
lambda Λ	uds	1
$\bar{p}$	$\bar{u}\bar{u}\bar{d}$	-1
$\bar{\Lambda}$	$\bar{u}\bar{d}\bar{s}$	-1
π^+	$u\bar{d}$	0

$$p\,p \rightarrow p\,p\,p\,\bar{p}$$
B: +1 +1 → +1 +1 +1 −1

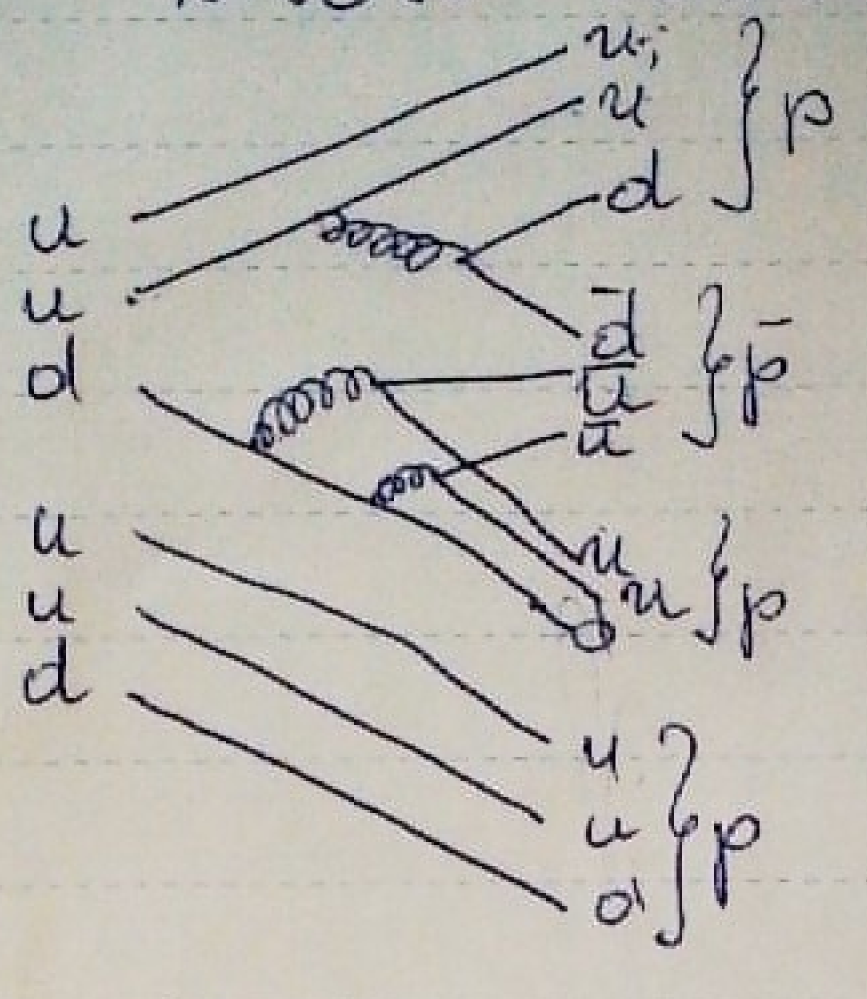
BARIONSKO ŠTEVILO SE OHRANJA
OK, DOVOLJEN

$$p\,p \not\rightarrow p\,\bar{p}\,\pi^+\pi^+$$
B: +1 +1 → +1 −1 0 0

NE GRE, B SE NE OHRANJA

OHRANITEV B NA NIVOJU KVARKOV

$pp \to ppp\bar{p}$



KVARKI $B = +\frac{1}{3}$

ANTIKVARKI $= -\frac{1}{3}$