$$\overline{|\mathcal{M}|^2} = \frac{8e^4}{q^4}\left[(pp')(-kk') + (k'p)(kp') + m_e^2\, p'k' + m_\mu\, pk + 2m_e^2 m_\mu\right]$$

V ULTRARELATIVISTIČNI LIMITI

$$k = \left(\frac{E}{2}, \vec{p_i}\right),\quad k' = \left(\frac{E}{2}, \vec{p_f}\right),\quad p = \left(\frac{E}{2}, -\vec{p_i}\right),\quad p' = \left(\frac{E}{2}, -\vec{p_f}\right)$$

$$q^2 = (k'-k)^2 \underset{\text{PO KRIŽANJU}}{\longrightarrow} (p+k)^2 = E^2$$

$$\frac{d\sigma}{d\Omega} = \frac{\overline{|\mathcal{M}|^2}}{64\pi^2E^2} = \frac{8e^4\left[(1-\cos\vartheta)^2 + (1+\cos\vartheta)^2\right]\frac{E^4}{4\cdot 4}}{64\pi^2E^2\;E^4} =$$

$$\boxed{\frac{d\sigma}{d\Omega}} = \frac{e^4}{4\cdot 32\pi^2E^2}\left(2 + 2\cos^2\vartheta\right) = \frac{e^4}{4\cdot 16\pi^2E^2}\left(1+\cos^2\vartheta\right)$$

$$\sigma = \int\frac{d\sigma}{d\Omega}\,d\Omega = \frac{e^4}{4\cdot 16\pi^2E^2}\int_{-1}^{+1}\left(1+\cos^2\vartheta\right)2\pi\cdot d(\cos\vartheta) =$$

$$= \frac{e^4}{4\cdot 8\pi E^2}\left(\cos\vartheta + \frac{1}{3}\cos^3\vartheta\right)\Big|_{-1}^{+1} = \frac{e^2}{8\pi E^2}\left(2+\frac{2}{3}\right) =$$

$$\sigma = \frac{e^4}{4\cdot 3\pi E^2} = \frac{e^4}{12\pi E^2} \qquad \sigma \propto \frac{1}{E^2}$$

$$\alpha = \frac{1}{137} = \frac{e^2}{4\pi\cancel{\varepsilon_0}\hbar c}$$

$$\Rightarrow \frac{e^2}{4\pi} = \alpha\hbar c$$

$$\sigma_{e^+e^-\to\mu^+\mu^-} = \left(\frac{e^2}{4\pi}\right)^2\frac{1}{3}4\pi\,\frac{1}{E^2} =$$

$$= \alpha^2(\hbar c)^2\,\frac{4\pi}{3}\,\frac{1}{E^2}$$

$$\boxed{\sigma_{e^+e^- \to \mu^+\mu^-} = \frac{4\pi}{3}\alpha^2(\hbar c)^2 \frac{1}{E^2}}$$

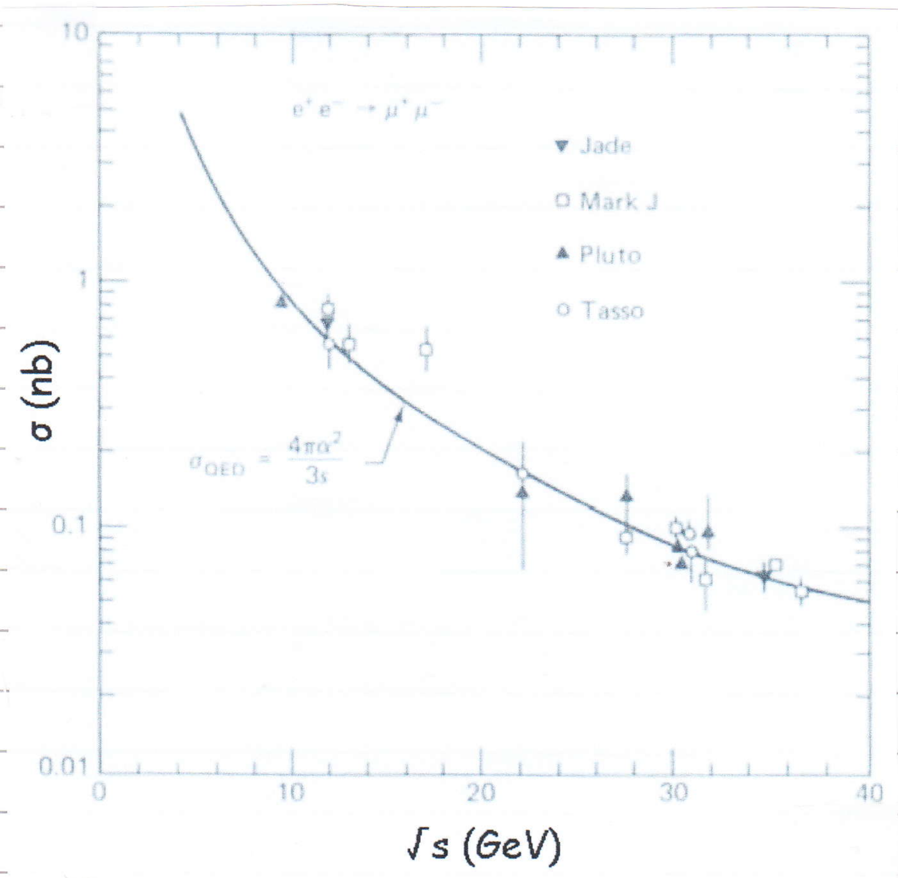
σ pri $E = \boxed{10\ \text{GeV}}$

$$\sigma = \frac{4\pi\ (0{,}2)^2\ (\text{GeV})^2\ \text{fm}^2}{3\ 10^2 (\text{GeV})^2\ (137)^2} =$$

$$= \frac{4\pi\ 0{,}04}{3\ 10^2\ 10^2\ 137^2}\ \text{b}$$

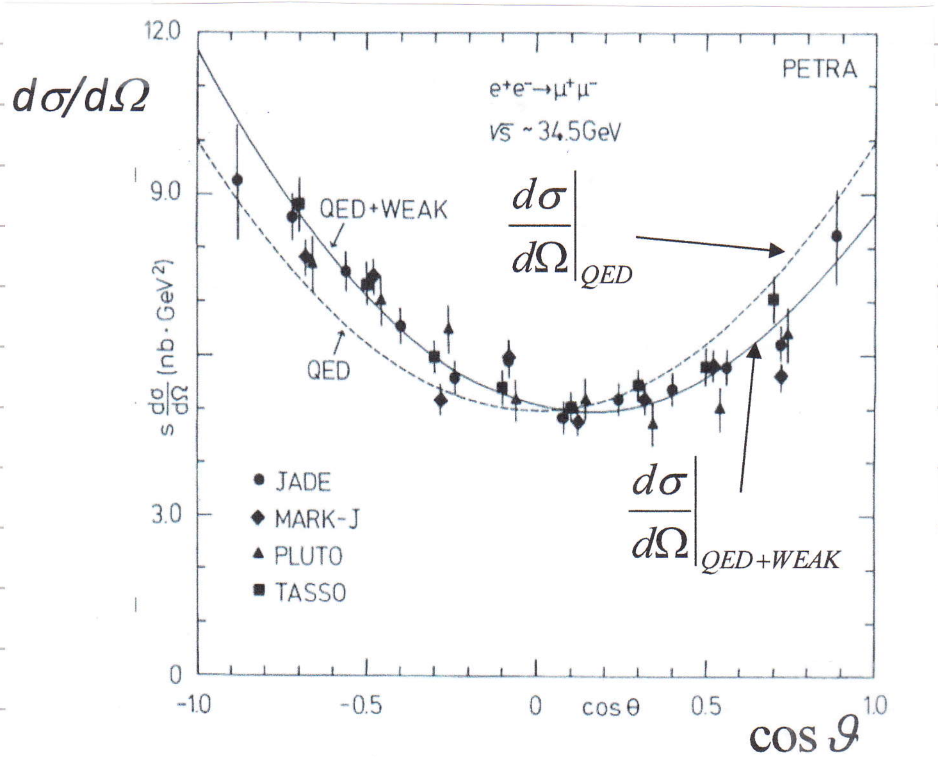
$1\text{b} = (10\ \text{fm})^2$

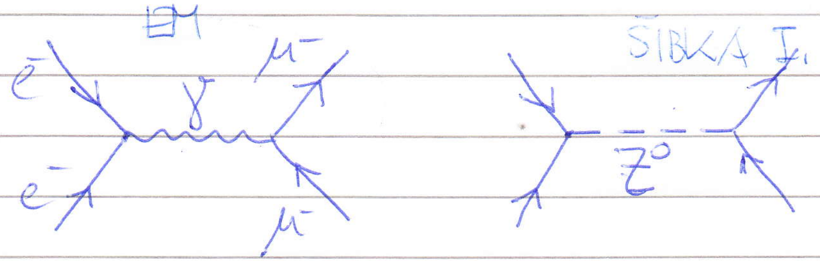
$$\sim 9\ 10^{-10}\ \text{b} = \boxed{0{,}9\ \text{nb}}$$



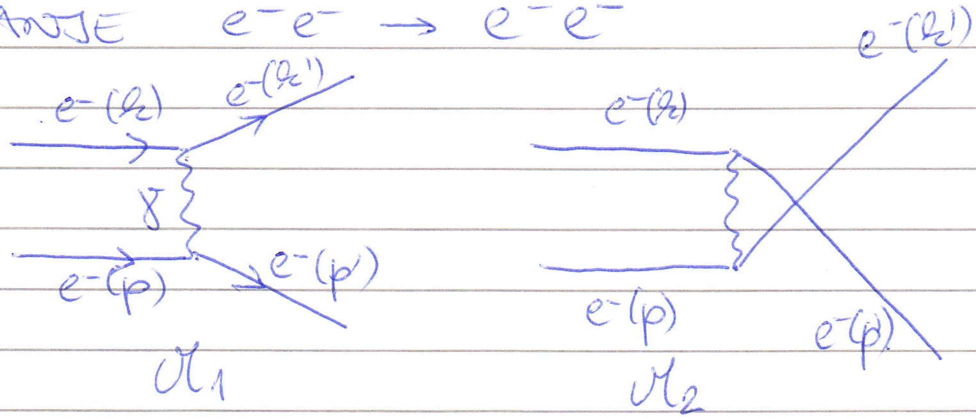
$E^2 = s$

$$\left(\frac{d\sigma}{d\Omega}\right)_{e^+e^- \to \mu^+\mu^-} = \frac{e^4}{4\cdot 16\pi^2 E^2}\left(1+\cos^2\vartheta\right) = \frac{\alpha^2(\hbar c)^2}{4E^2}\left(1+\cos^2\vartheta\right)$$





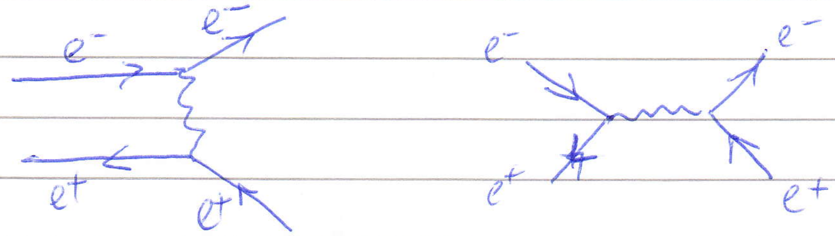
SIPANJE $e^-e^- \to e^-e^-$



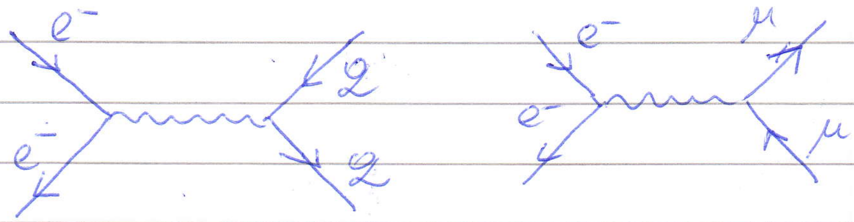
$$\mathcal{M} = \mathcal{M}_1 + \mathcal{M}_2 \qquad \mathcal{M}_1 \propto \left[\bar{u}(k')\gamma^\kappa u(k)\right]\left[\bar{u}(p')\gamma_\kappa u(p)\right]$$

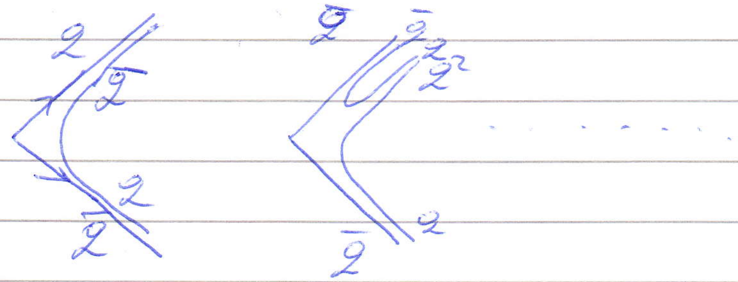
$$\mathcal{M}_2 \propto \left[\bar{u}(p')\gamma^\kappa u(k)\right]\left[\bar{u}(k')\gamma_\kappa u(p)\right]$$

$e^-e^- \to e^-e^-$ → s križanjem → $e^-e^+ \to e^-e^+$



SIPANJE $e^+e^- \to q\bar{q}$





$$\sigma_{e^+e^-\to\mu^+\mu^-} \propto e^4 = \underset{e}{\underset{\uparrow}{e^2}} \cdot \underset{\mu}{\underset{\uparrow}{e^2}}$$

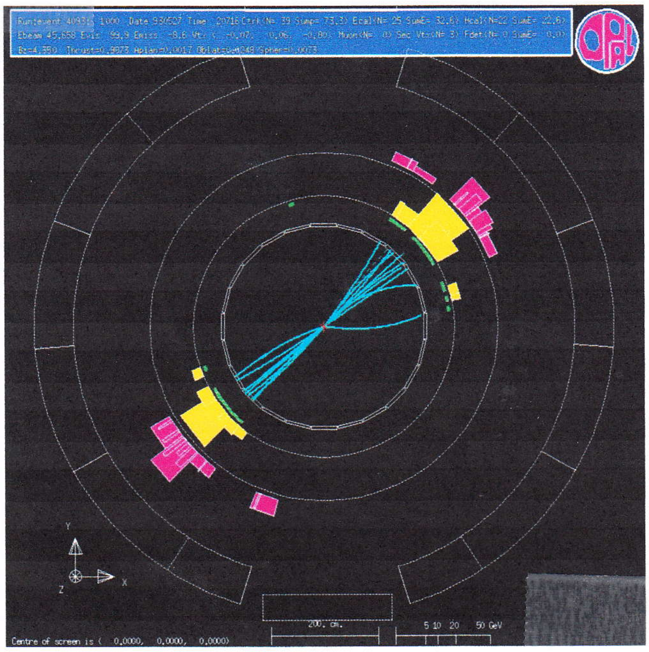
$$\sigma_{e^+e^-\to q\bar{q}} \propto \underset{e}{\underset{\uparrow}{e^2}} \cdot \underset{q}{\underset{\uparrow}{e_q^2}} \qquad e_q^2 = \frac{1}{9}, \frac{4}{9}$$

$$\frac{\sigma_{e^+e^-\to q\bar{q}_i}}{\sigma_{e^+e^-\to\mu^+\mu^-}} = 3\,\frac{e_e^2 \cdot e_{q_i}^2}{e_e^2 \cdot e_\mu^2} = 3Q_{q_i}^2$$

3: 3 BARVE

$$Q_{q_i} = \frac{e_{q_i}}{e_0}$$

$$\sigma(e^+e^- \to \text{hadroni}) = \sum_{q=u,d,s,c} \sigma(e^+e^- \to q\bar{q})$$



LEP

e^-e^+ v tunelu LHC

$E \sim 90$ GeV

$e^+e^- \to q\bar{q}$

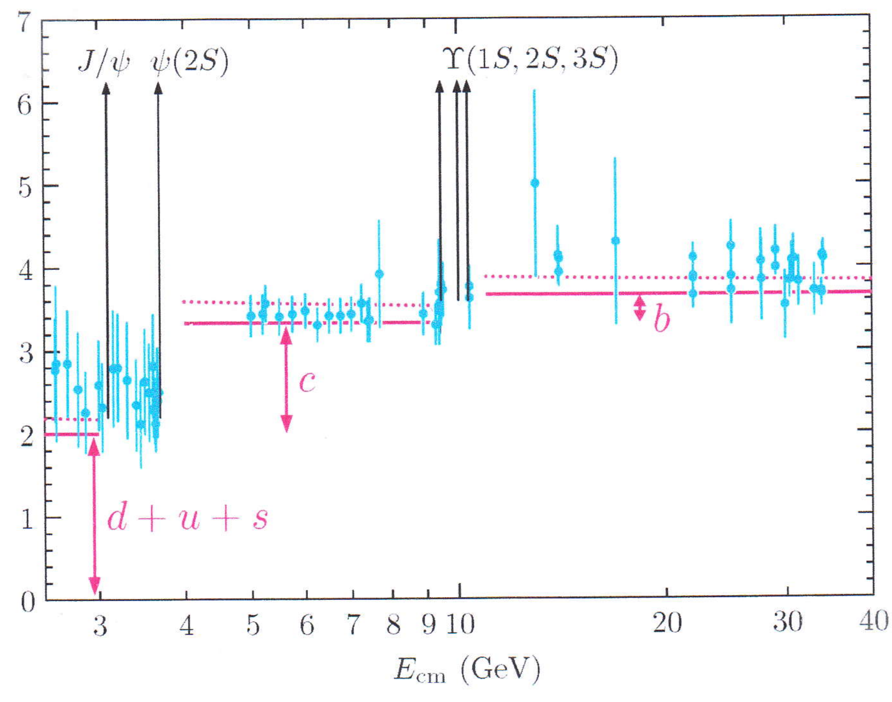
JET

$$R = \frac{\sigma(e^+e^- \to \text{hadroni})}{\sigma(e^+e^- \to \mu^+\mu^-)} = 3 \sum_i Q_{q_i}^2$$

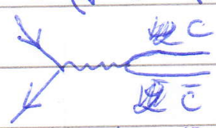
$$E < 3\ \text{GeV}: \quad R = 3\left(\overset{u}{\frac{4}{9}} + \overset{d}{\frac{1}{9}} + \overset{s}{\frac{1}{3}}\right) = 2$$

$$4\ \text{GeV} < E < \sim 9\ \text{GeV}: \quad R = 3\left(\frac{4}{9} + \frac{1}{9} + \frac{1}{9} + \frac{4}{9}\right) = \frac{10}{3} = 3\tfrac{1}{3}$$

$$E > 10\ \text{GeV}: \quad R = 3\tfrac{2}{3}$$

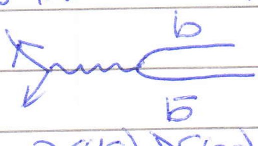


$3\ \text{GeV} < E < 4\ \text{GeV}$



$J/\psi, \psi(2S)$

$9\ \text{GeV} < E < 10\ \text{GeV}$

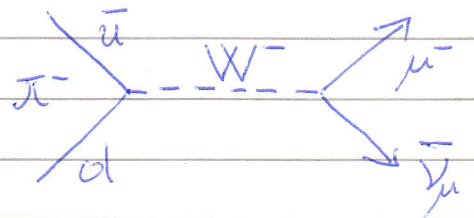


$\Upsilon(1S), \Upsilon(2S), \Upsilon(3S), \Upsilon(4S)$

ŠIBKA INTERAKCIJA

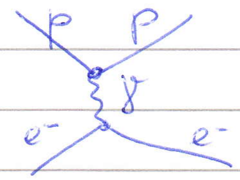
$\tau(\pi^-) = 2{,}6 \cdot 10^{-8}\,s$ $\quad \tau(\pi^0) = 8{,}4 \cdot 10^{-17}\,s$

ŠIBKA $\quad$ EM $\quad \pi^0 \to \gamma\gamma$



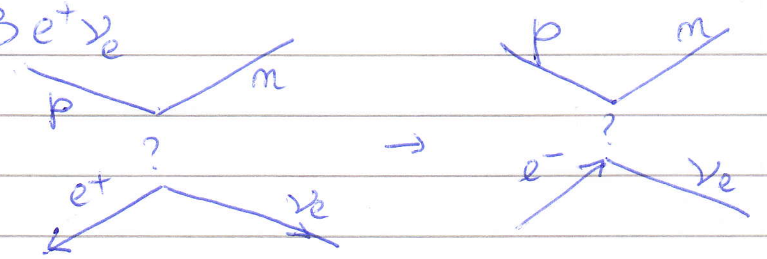
$\pi^- \to \mu^- \bar{\nu}_\mu$

FERMI 1932 – ANALOGIJA Z E.M. INTERAKCIJO



$$-i\mathcal{M} = e^2 [\bar{u}_p \gamma^\mu u_p] \left(-\frac{g_{\mu\nu}}{q^2}\right) [\bar{u}_e \gamma^\nu u_e]$$

$^{10}C \to {}^{10}B\, e^+ \nu_e$



$$-i\mathcal{M} = \frac{G_F}{\sqrt{2}} [\bar{u}_n \gamma^\mu u_p][\bar{u}_\nu \gamma_\mu u_e]$$

G_F = FERMIJEVA SKLOPITVENA KONSTANTA

1950. LETA $\quad$ "Θ^+/τ^+" UGANKA ! "Θ^+" $\to \pi^+\pi^0$, "τ^+" $\to \pi^+\pi^+\pi^-$

$\Theta^+ \equiv \tau^+ \equiv K^+$ IZ EKSPERIMENTOV

PARNOST PIONA : $P = -1$

K^+ RAZPADE ENKRAT V STANJE S $P = (-1)^2 = +1$

ENKRAT PA V $P = (-1)^3 = -1$

E.M. IN MOČNA INT. OHRANJATA PARNOST

$P_i = P_f$

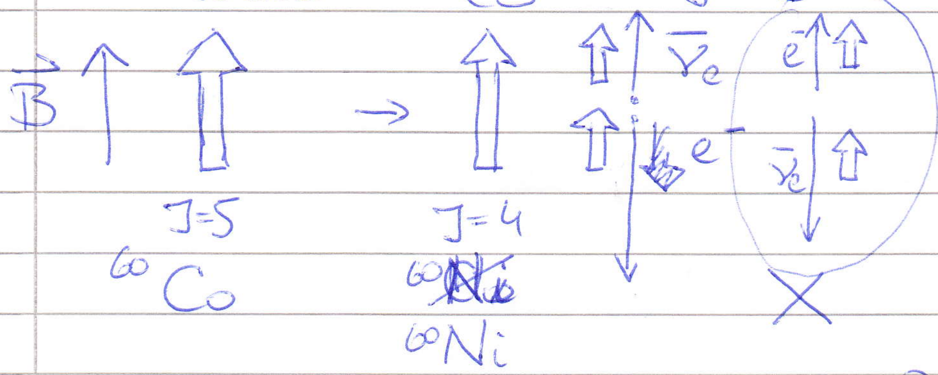
1956 T.D. LEE $\quad$ CHEN-NING YANG

$\to$ ŠIBKA INTERAKCIJA NE OHRANJA PARNOSTI

CHIEN SHIUNG WU

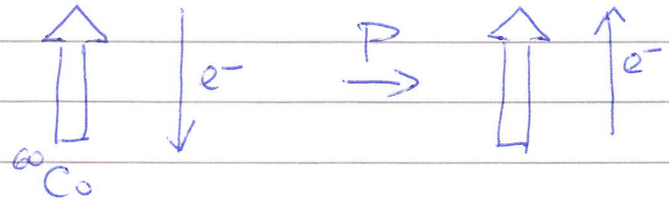
$\boxed{\text{EKSPERIMENT S } {}^{60}Co}$

JEDRO ^{60}Co : $J = 5$ $\qquad {}^{60}Co \to {}^{60}Ni\, e^- \bar{\nu}_e$

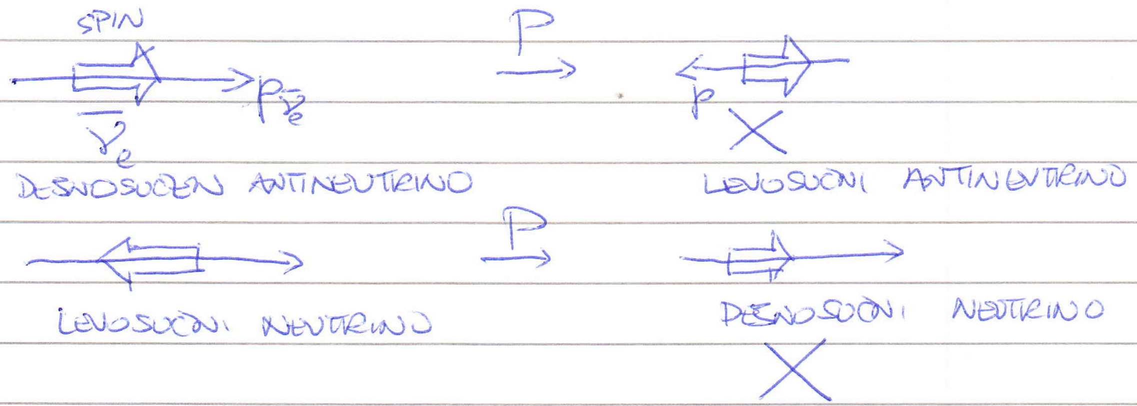


^{60}Co V MOČNEM POLJU B, MERIMO SMER ELEKTRONOV

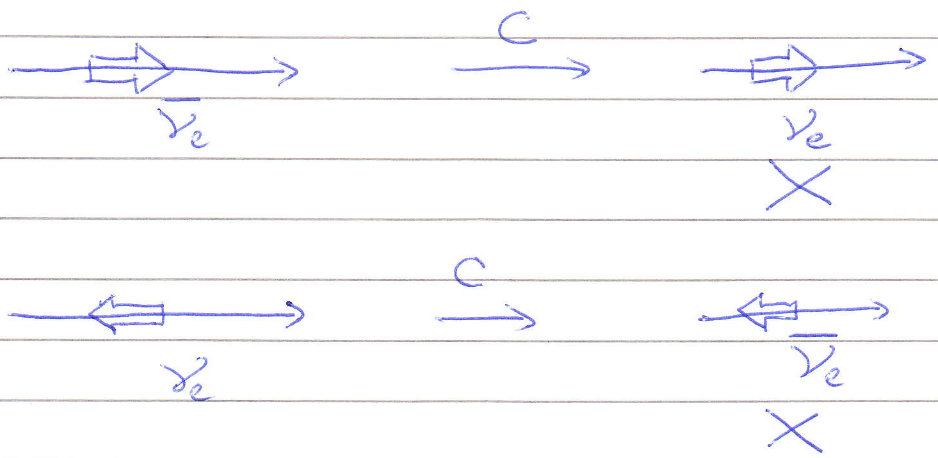
$P: \vec{r} \to -\vec{r} : \vec{p} \to -\vec{p}, \; \vec{L} \to \vec{L}, \; \vec{J} \to \vec{J}$



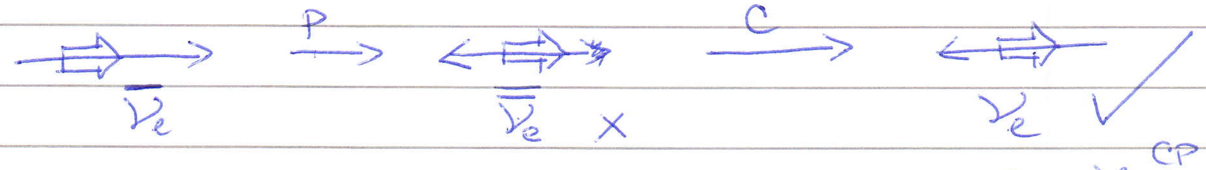
$\Rightarrow$ PARNOST JE KRŠENA PRI ŠIBKI INTERAKCIJI



KRŠENA JE TUDI PARNOST C : DELEC $\to$ ANTIDELEC



P, C KRŠENI, OHRANJA SE PA CP

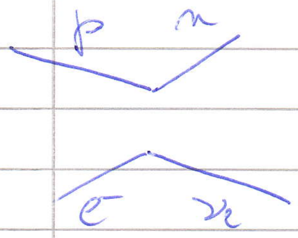


DN $\nu_e \xrightarrow{CP}$?

1964 FITCH, CRONIN RAZPADI K^0 : CP SE NE OHRANJA

KAKO NAPISATI $\mathcal{M}$, DA BO AVTOMATSKO ZA TO POSKRBLJENO? (UPOŠTEVANO)

NEOHRANITEV P



$$-i\mathcal{M} = \frac{G_F}{\sqrt{2}}\left[\bar{u}_p \gamma^\mu (1-\gamma^5) u_p\right]\left[\bar{u}_\nu \gamma_\mu (1-\gamma^5) u_e\right]$$

$$\gamma^5 = \gamma^0\gamma^1\gamma^2\gamma^3 = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \qquad \text{"}1\text{"} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

$$\gamma^{5\dagger} = \gamma^5 \; ; \; (\gamma^5)^2 = 1 \; ; \; \gamma^5\gamma^\mu + \gamma^\mu\gamma^5 = 0$$

$\frac{1}{2}(1-\gamma^5)u = u_L$ LEVOROČNI BISPINOR

$\frac{1}{2}(1+\gamma^5)u = u_R$ DESNOROČNI

$$u_L + u_R = u$$

$$\gamma^5 u_L = \gamma^5 \frac{1}{2}(1-\gamma^5)u = \frac{1}{2}(\gamma^5 - 1)u = -\frac{1}{2}(1-\gamma^5)u = -u_L$$

$$\gamma^5 u_R = +u_R$$

LEVOROČNI BISPINOR

$$u_L = \frac{1}{2}(1-\gamma^5)u = \frac{N}{2}\begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix}\begin{bmatrix} \chi \\ \frac{\vec{\sigma}\cdot\vec{p}}{E+m}\chi \end{bmatrix} = \frac{N}{2}\begin{bmatrix} \chi - \frac{\vec{\sigma}\cdot\vec{p}}{E+m}\chi \\ -\left(\chi - \frac{\vec{\sigma}\cdot\vec{p}}{E+m}\chi\right) \end{bmatrix}$$

za $E \gg m$ $\frac{\vec{p}}{E+m} \to \hat{p}$ ENOTSKI VEKTOR

$$\to = \frac{N}{2}\begin{bmatrix} \chi - \vec{\sigma}\cdot\hat{p}\chi \\ -(\chi - \vec{\sigma}\cdot\hat{p}\chi) \end{bmatrix}$$

SUČNOST u_L !

OPERATOR $\vec{\Sigma}\cdot\hat{p}$ $\qquad \vec{\Sigma}\cdot\hat{p}\, u_L = \begin{bmatrix} \vec{\sigma}\cdot\hat{p} & 0 \\ 0 & \vec{\sigma}\cdot\hat{p} \end{bmatrix} u_L =$

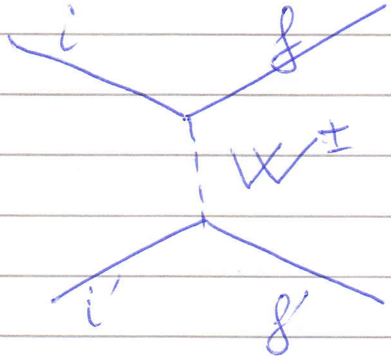
$$= \frac{N}{2}\begin{bmatrix} \vec{\sigma}\cdot\hat{p}\chi - (\vec{\sigma}\cdot\hat{p})^2\chi \\ -(\vec{\sigma}\cdot\hat{p}\chi - (\vec{\sigma}\cdot\hat{p})^2\chi) \end{bmatrix} = \frac{N}{2}\begin{bmatrix} \vec{\sigma}\cdot\hat{p}\chi - \chi \\ -\vec{\sigma}\cdot\hat{p}\chi + \chi \end{bmatrix} = -u_L$$

$\boxed{\text{LEVOSUČEN}}$

$\vec{\Sigma}\hat{p}\, u_R = + u_R$ ZA ULTRARELATIVISTIČNE DELCE

V ULTRAREL. LIMITI: ROČNOST $\equiv$ SUČNOST

KONČNA OBLIKA MATRIČNEGA ELEMENTA ZA ŠIBEK PROCES



$$-i\mathcal{M} = \left[\frac{g_W}{\sqrt{2}}\bar{u}_f \gamma^\kappa (1-\gamma^5) u_i\right]\left(-\frac{g_{\kappa\nu}}{M_W^2 - q^2}\right)$$
$$\left[\frac{g_W}{\sqrt{2}}\bar{u}_{f'} \gamma^\nu (1-\gamma^5) u_{i'}\right]$$

RAZPADI $q^2 \ll M_W^2$ $\quad \frac{G_F}{\sqrt{2}} = \frac{g_W^2}{2 M_W^2} \Rightarrow \boxed{G_F = \frac{g_W^2}{\sqrt{2} M_W^2}}$

$(\text{MeV})^2 \quad (83\,\text{GeV})^2$

A. SALAM, S. GLASHOW, S. WEINBERG

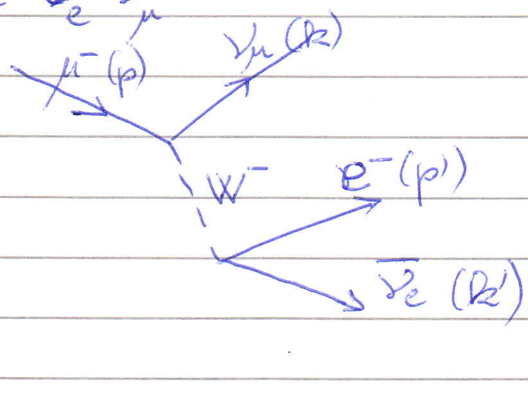
→ ELEKTROŠIBKA INTERAKCIJA

→ STANDARDNI MODEL

ENA OD NAPOVEDI: NEVTRALNI ŠIBKI TOKOVI Z^0

PRIMER ŠIBKEGA PROCESA PRI OSNOVNIH DELCIH

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



$\equiv$