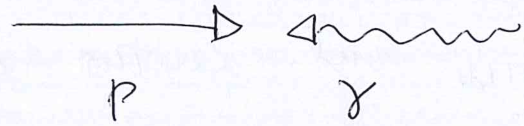
Esercizio 1

$$p + \gamma_{CMB} \longrightarrow p + \pi^0 \qquad \text{(GZK cutoff)}$$

0 numeri quantici



$E_\gamma \sim 0{,}7\ \text{meV}$

1 E_p^{th}?

$P_p = (E_p, \vec{p}_p)$

$P_\gamma = (E_\gamma, \vec{p}_\gamma)$

$$(P_\gamma + P_p)^2 = (\underbrace{P_p' + P_{\pi^0}}_{\text{ferme}})^2$$

ferme $\to \vec{p} = 0 \to E = m \Rightarrow p^2 = m^2$

$$(P_\gamma + P_p)^2 = +(m_p + m_\pi)$$

$$\vec{p}_\gamma = +E_\gamma$$

$\ominus$ p e γ opposti

$\uparrow$

$$m_p^2 + m_\pi^2 + 2m_p m_\pi = m_p^2 + 2E_p E_\gamma + 2p_p E_\gamma$$

ma $\dfrac{E_p}{m_p} \sim \dfrac{m_\pi}{E_\gamma} \gg 1 \to \boxed{p_p \approx E_p}$ $(E_p \gg m_p)$

$$\cancel{m_p^2} + m_\pi^2 + 2m_p m_\pi = \cancel{m_p^2} + 2E_p^{th}E_\gamma + 2E_p^{th}E_\gamma$$

$$4E_p^{th}(E_\gamma) = m_\pi^2 + 2m_\pi m_p \to E_p^{th} = \frac{1}{4E_\gamma}\left(m_\pi^2 + 2m_p m_\pi\right)$$

$$E_p^{th} = 0.135\ GeV \left(\frac{(2\cdot 0{,}938 + 0.135)\,GeV}{4\cdot 7\cdot 10^{-13}\,GeV} \right) =$$

$$= 0{,}19 \times 10^{18}\ eV.$$

② calcolare ϕ_{min} nel centro di massa del decadimento $\pi^0 \to \gamma\gamma$:

$$\phi_{min} = \frac{2}{\gamma} \qquad \gamma^* = \left.\frac{E^*}{m}\right|_{Tot} = \frac{E^{th} + E_\gamma}{m_p + m_\pi} \simeq \frac{E^{th}}{m_p + m_\pi}$$

$$\phi = 2\left(E^{th}/m_p + m_\pi\right)^{-1} \cong 2\times 10^{-19}\ rad$$

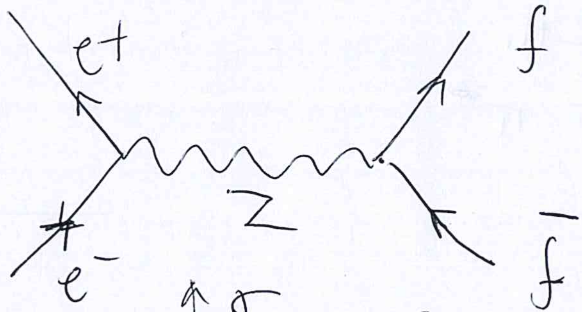
Esercizio 2

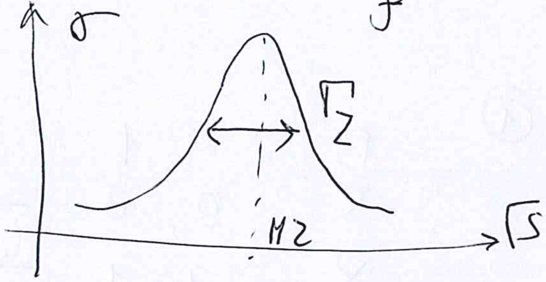
$$e^+e^- \to f\bar{f}$$

① $\Gamma_Z = 2{,}5$ GeV $\qquad \Gamma_e = \Gamma_\mu = \Gamma_\tau = 84$ MeV $= \Gamma_{ee}$

$BR(Z \to \nu\bar{\nu}) \cong 20\%$.

- diagramma
- calcolare $\Gamma_{\nu\bar{\nu}}$
- calcolare $\Gamma_{q\bar{q}}$
- calcolare τ_Z
- grafico





1) $\dfrac{\Gamma_{\nu\bar{\nu}}}{\Gamma_{tot}} = BR(Z \to \nu\bar{\nu}) \Rightarrow \Gamma_{\nu\bar{\nu}} = BR \times \Gamma_{tot} = 0.2 \cdot 2{,}5 =$
$\cong 500$ MeV.

② $\Gamma_{q\bar{q}} = \Gamma_Z - 3\Gamma_{ll} - \Gamma_{inv} \simeq (2{,}5 - (3 \cdot 0{,}84) - 0{,}50)\,\text{GeV} =$
$= 1744\ \text{MeV} = (2500 - 3 \cdot 84 - 500)\,\text{MeV}$

③ $\tau_Z = \dfrac{\hbar}{\Gamma_{tot}} = \dfrac{6.58 \times 10^{-16}\ \text{eV}\cdot\text{s}}{2{,}5 \times 10^{9}\ \text{eV}} \cong 2{,}6 \cdot 10^{-25}\ \text{s}.$

Esercizio 3

$$\pi^- p \to K^+ K^- n \qquad p = \text{fermi}$$

1. numeri quantici e interazione
2. decadimento di ogni particelle finale
3. $E^{th}_{\pi^-}$

1.

B	0	1		0	0	1	
S	0	0	$\to$	-1	1	0	ok forte
Q	-1	1	$\to$	1	-1	0	
L	0	0	$\to$	0	0	0	

2. $K^+ \to \pi^0 \nu_\mu \mu^+ \qquad K^+ \to \pi^- \pi^+ \pi^+$

$K^- \to \pi^- \pi^0 \qquad K^- \to \pi^0 e^- \bar{\nu}_e$

$n \to p\, e\, \bar{\nu}_e$

3. $$E^{th}_{\pi} = \frac{(m_n + 2m_K)^2 - m_\pi^2 - m_p^2}{2m_p} = \dots \text{ MeV}$$

formula:

$$E^{th}_i = \frac{\left(\sum_f m_f\right)^2 - m_i^2 - m_b^2}{2m_b}$$

Esercizio 4

Fasci incrociati di protoni frontali $\underset{p_1}{\longrightarrow} \quad \underset{p_2}{\longleftarrow}$

$E_1 = 20$ GeV $\quad E_2 = 5$ GeV $\qquad (E_1 \vec{p}_1) ; (E_2 \vec{p}_2)$

$\vec{p}_1 = -\vec{p}_2$

① $\sqrt{s}$ collisione

② β^*_{LAB} (<u>del</u> CM <u>nel</u> lab.)

③ ϕ particella prodotta a 90° dalla collisione nel lab

④ l'energia che un protone deve avere per avere la stessa $\sqrt{s}$ con targhetta fissa.

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①

$$s = (p_1 + p_2)^2 = 2m_p^2 + 2(E_1 E_2 + |\vec{p}_1||\vec{p}_2|) =$$

$$= 2m_p^2 + 2E_1E_2\left(1 + \sqrt{1-\left(\frac{m_1}{E_1}\right)^2}\sqrt{1-\left(\frac{m}{E_2}\right)^2}\right)$$

$\sqrt{s} \simeq 20$ GeV

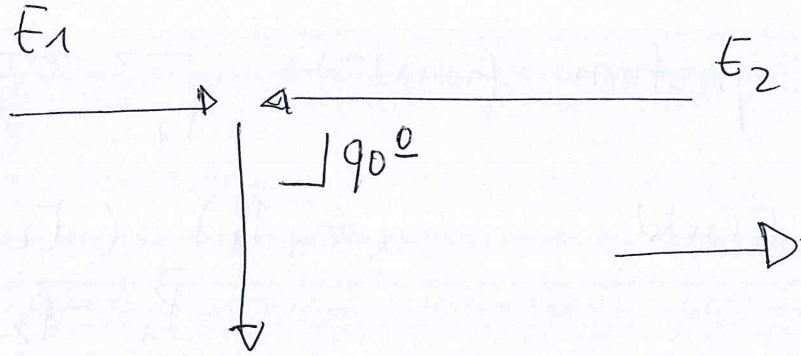
②

$$\beta_{LAB} = \frac{\vec{p}_{tot}}{E_{tot}} = \frac{\vec{p}_1 + \vec{p}_2}{E_1 + E_2} = \frac{\sqrt{E_1^2 - m_p^2} - \sqrt{E_2^2 - m_p^2}}{E_1 + E_2} = 0.6$$

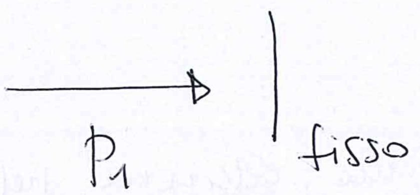
③

$$tg\,\theta = \frac{\sin\theta}{\gamma\cos\theta + \beta\gamma} = \frac{\sin \pi/2}{\gamma\cos\pi/2 + \beta\gamma} = \frac{1}{\beta\gamma} = 1.32$$

$\theta = \arctg(1.32)$



4



$$\sqrt{s} = \sqrt{2m_p^2 + 2m_p E_f}$$

$(E_1, \vec{P}_1)$ $(E_f, 0)$

$$2m_p^2 + 2m_p E_f = s$$

$$E_f = \frac{s - 2m_p^2}{2m_p} = 211 \text{ GeV}$$

mi servono 211 GeV
per fare $\sqrt{s}$ di 20 GeV su bersaglio fisso
rispetto a collisioni frontali dove mi basta $E \cong 20$ GeV

usando: (*) $\downarrow$ 7 bis

$$\begin{cases} M = E_1 + E_2 = \sqrt{m_1^2 + p^2} + \sqrt{m_2^2 + p_2^2} \\ \vec{p}_1 = -\vec{p}_2 \rightarrow |p_1| = |p_2| = p. \end{cases}$$

$$M^2 = m_1^2 + m_2^2 + p^2 + p^2 + 2\sqrt{m_1^2 + p^2}\sqrt{m_2^2 + p^2}$$

$$M^2 - m_1^2 - m_2^2 = 2\left(p^2 + \sqrt{}\sqrt{}\right) = 2\left(p^2 + E_1 E_2\right)$$

$$\frac{M^2 - m_1^2 - m_2^2}{2} = p^2 + E_1(M - E_1) = p^2 + E_1 M - E_1^2 =$$

$$= -m_1^2 + E_1 M$$

$$E_1 = \frac{M^2 + m_1^2 - m_2^2}{2M}.$$

Esercizio 6. (8)

$\nu_e n \to e^- \pi^0 p$ debole

$K^- n \to \Lambda \pi^- \pi^0$ forte

$p p \to \Sigma^+ p \pi^+ \pi^- K^0$ forte

$p \bar{p} \to \Sigma^- \Sigma^+$ $\cancel{B}$ $\cancel{S}$

$\pi^- p \to \Sigma^- K^+ \pi^+$ $\cancel{Q}$

$\Xi^0 \to \Lambda \pi^+$ $\cancel{Q}, \cancel{S}$

$n \to p e^- \bar{\nu}_e$ debole

$\pi^0 \to \mu^- e^+$ $\cancel{L}_\mu$ $\cancel{L}_e$

$K^+ \to \pi^0 e^+ \nu_e$ debole

$\Sigma^- \to \Xi^0 e^- \bar{\nu}_e$ $\cancel{M}$, $\cancel{S}$

NB: $S_s = -1$ $S_{\bar{s}} = 1$

$S_\Lambda = -1$ $S_{\Sigma^+} = -1$ $S_{K^0} = 1$ $S_{\Sigma^0} = -1$

$S_{\Sigma^-} = -1$ $S_{\Xi^0} = -2$ $S_{K^-} = -1$ $S_{K^+} = 1$

Esercizio 5 7

$$\gamma\, p \to \Lambda\, K^+$$

① numeri quantici
② quark composition
③ E^{th}_γ
④ decadimenti Λ, K^+
⑤ E, p della particella negativa del decadimento della Λ.

$\Lambda \to \pi^- p$
$K^+ \to \mu^+ \nu_\mu \pi^0$

①

B	0	1	1	0
S	0	0	1	-1
Q	0	1	0	1
L	0	0	0	0

forte.

② $\gamma + uud \to uds + u\bar{s}$

③ $$E_\gamma^{th} = \frac{(m_K + m_\Lambda)^2 - m_p^2}{2 m_p} = 1987 \text{ MeV}$$

④ $$E^*_\pi = \frac{m_\Lambda^2 - m_p^2 + m_\pi^2}{2 m_\Lambda} \sim 3\,\text{GeV} \quad p^*_\pi = \sqrt{E^{2*}_\pi - m_\pi^2} = 215 \text{ MeV}$$

decadimento
... [illegible]