Introdução à Física das Partículas Elementares

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(buscar: física das partículas elementares)

Fernando S Navarra

navarra@if.usp.br

Guilherme Germano

guilherme.germano@usp.br

Plano do Curso

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Aula 6

Capítulo 3

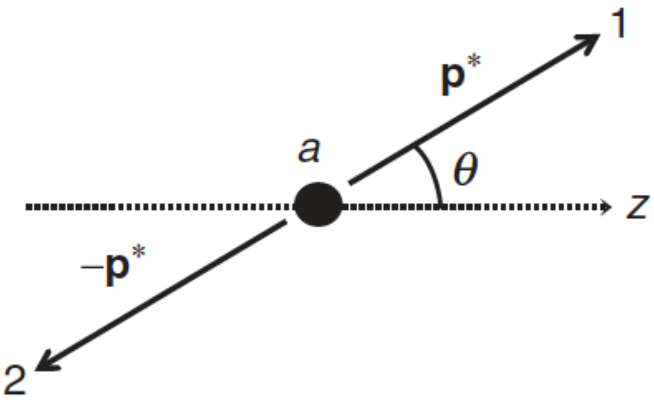
Seção de choque de interação

Decaimento em dois corpos

$a \to 1 + 2$ visto no sistema do centro de massa

$E_a = m_a$

$\mathbf{p}_a = \mathbf{0}$



$$\Gamma_{fi} = \frac{(2\pi)^4}{2E_a} \int |\mathcal{M}_{fi}|^2 \delta(E_a - E_1 - E_2)\delta^3(\mathbf{p}_a - \mathbf{p}_1 - \mathbf{p}_2) \frac{d^3\mathbf{p}_1}{(2\pi)^3 2E_1} \frac{d^3\mathbf{p}_2}{(2\pi)^3 2E_2}$$

$$\Gamma_{fi} = \frac{p^*}{32\pi^2 m_a^2} \int |\mathcal{M}_{fi}|^2 \, d\Omega$$

No centro de massa !

$$p^* = \frac{1}{2m_a}\sqrt{\left[(m_a^2 - (m_1 + m_2)^2\right]\left[m_a^2 - (m_1 - m_2)^2\right]}.$$

Seção de Choque

$$a + b \to 1 + 2$$

Fórmula geral

$$\sigma = \frac{(2\pi)^{-2}}{4E_aE_b(v_a+v_b)}\int |\mathcal{M}_{fi}|^2 \delta(E_a+E_b-E_1-E_2)\delta^3(\mathbf{p}_a+\mathbf{p}_b-\mathbf{p}_1-\mathbf{p}_2)\frac{d^3\mathbf{p}_1}{2E_1}\frac{d^3\mathbf{p}_2}{2E_2}$$

Trabalhando com 4-vetores, espaço de fase, integrais, etc...

Espalhamento no Sistema do Centro de Massa

A seção de choque pode ser calculada em qualquer sistema de referência

$$a + b \rightarrow 1 + 2$$

No CM: $\mathbf{p}_a = -\mathbf{p}_b = \mathbf{p}_i^*$ $\quad \mathbf{p}_1 = -\mathbf{p}_2 = \mathbf{p}_f^*$ $\quad \sqrt{s} = (E_a^* + E_b^*)$

$$\sigma = \frac{(2\pi)^{-2}}{4\,E_a E_b(\mathrm{v}_a + \mathrm{v}_b)} \int |\mathcal{M}_{fi}|^2 \delta(E_a + E_b - E_1 - E_2)\delta^3(\mathbf{p}_a + \mathbf{p}_b - \mathbf{p}_1 - \mathbf{p}_2)\frac{\mathrm{d}^3\mathbf{p}_1}{2E_1}\frac{\mathrm{d}^3\mathbf{p}_2}{2E_2}$$

$$4E_a^*E_b^*(\mathrm{v}_a^* + \mathrm{v}_b^*) = 4E_a^*E_b^*\left(\frac{\mathrm{p}_i^*}{E_a^*} + \frac{\mathrm{p}_i^*}{E_b^*}\right) = 4\mathrm{p}_i^*(E_a^* + E_b^*) \quad = 4\mathrm{p}_i^*\sqrt{s}.$$

Pode ser escrita como:

$$\sigma = \frac{1}{(2\pi)^2}\frac{1}{4\mathrm{p}_i^*\sqrt{s}} \int |\mathcal{M}_{fi}|^2 \delta\left(\sqrt{s} - E_1 - E_2\right)\delta^3(\mathbf{p}_1 + \mathbf{p}_2)\frac{\mathrm{d}^3\mathbf{p}_1}{2E_1}\frac{\mathrm{d}^3\mathbf{p}_2}{2E_2}$$

$$\sigma = \frac{1}{(2\pi)^2} \frac{1}{4p_i^* \sqrt{s}} \int |\mathcal{M}_{fi}|^2 \delta\left(\sqrt{s} - E_1 - E_2\right) \delta^3(\mathbf{p}_1 + \mathbf{p}_2) \frac{d^3\mathbf{p}_1}{2E_1} \frac{d^3\mathbf{p}_2}{2E_2}$$

Vamos usar da aula passada e lembrar que $m_a = \sqrt{s}$

$$\int |\mathcal{M}_{fi}|^2 \delta(m_a - E_1 - E_2) \delta^3(\mathbf{p}_1 + \mathbf{p}_2) \frac{d^3\mathbf{p}_1}{2E_1} \frac{d^3\mathbf{p}_2}{2E_2} = \frac{p^*}{4m_a} \int |\mathcal{M}_{fi}|^2 d\Omega$$

$$\sigma = \frac{1}{16\pi^2 p_i^* \sqrt{s}} \times \frac{p_f^*}{4\sqrt{s}} \int |\mathcal{M}_{fi}|^2 d\Omega^*$$

$$\sigma = \frac{1}{64\pi^2 s} \frac{p_f^*}{p_i^*} \int |\mathcal{M}_{fi}|^2 d\Omega^*$$

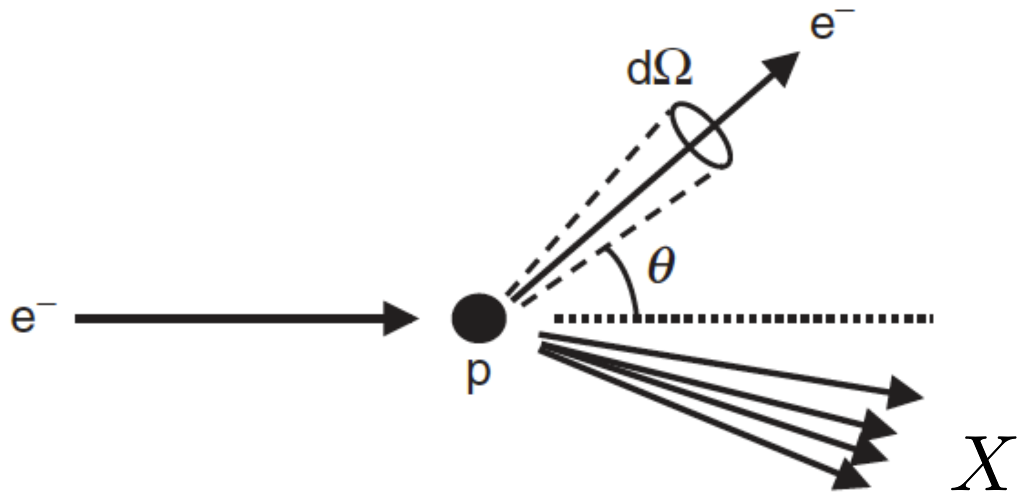
Seção de Choque Diferencial

$$e^- p \to e^- p$$

(esp. elástico)

$$e^- p \to eX$$

(esp. inelástico)



$$d\Omega = d(\cos\theta)d\phi$$

Seção de choque diferencial :

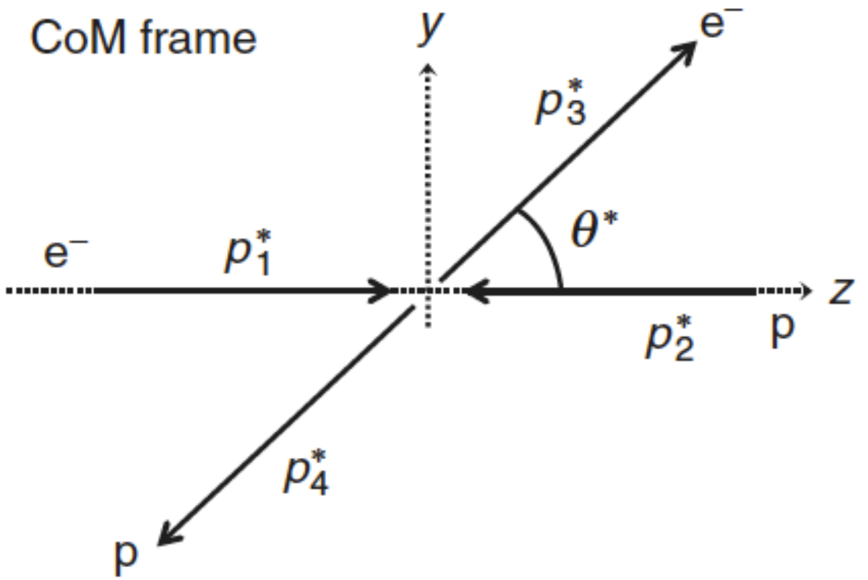
$$\frac{d\sigma}{d\Omega} = \frac{\text{number of particles scattered into } d\Omega \text{ per unit time per target particle}}{\text{incident flux}}$$

Seção de choque total :

$$\sigma = \int \frac{d\sigma}{d\Omega} d\Omega$$

Sistema do Centro de Massa

$$\sigma = \frac{1}{64\pi^2 s}\frac{p_f^*}{p_i^*}\int |\mathcal{M}_{fi}|^2 d\Omega^*$$



"Desintegrando" a equação acima:

$$d\sigma = \frac{1}{64\pi^2 s}\frac{p_f^*}{p_i^*}|\mathcal{M}_{fi}|^2 d\Omega^*$$

$$\frac{d\sigma}{d\Omega^*} = \frac{1}{64\pi^2 s}\frac{p_f^*}{p_i^*}|\mathcal{M}_{fi}|^2$$

$$p_i^{*2} = \frac{1}{4s}[s-(m_1+m_2)^2][s-(m_1-m_2)^2]$$

Vamos reescrever em termos da variável t : $t = p_1 - p_3$

$$t = (p_1^* - p_3^*)^2 = p_1^{*2} + p_3^{*2} - 2p_1^* \cdot p_3^* \quad = m_1^2 + m_3^2 - 2(E_1^* E_3^* - \mathbf{p}_1^* \cdot \mathbf{p}_3^*)$$

$$= m_1^2 + m_3^2 - 2E_1^* E_3^* + 2\mathrm{p}_1^* \mathrm{p}_3^* \cos\theta^*$$

$$\mathrm{d}t = 2\mathrm{p}_1^* \mathrm{p}_3^* \, \mathrm{d}(\cos\theta^*) \longrightarrow d(cos\theta^*) = dt/(2p_1^* p_3^*)$$

$$\mathrm{d}\Omega^* \equiv \mathrm{d}(\cos\theta^*)\, \mathrm{d}\phi^* = \frac{\mathrm{d}t\, \mathrm{d}\phi^*}{2\mathrm{p}_1^* \mathrm{p}_3^*} = \frac{dt d\phi^*}{2p_i^* p_f^*} \qquad (p_1^* = p_i^*\ ,\ p_3^* = p_f^*)$$

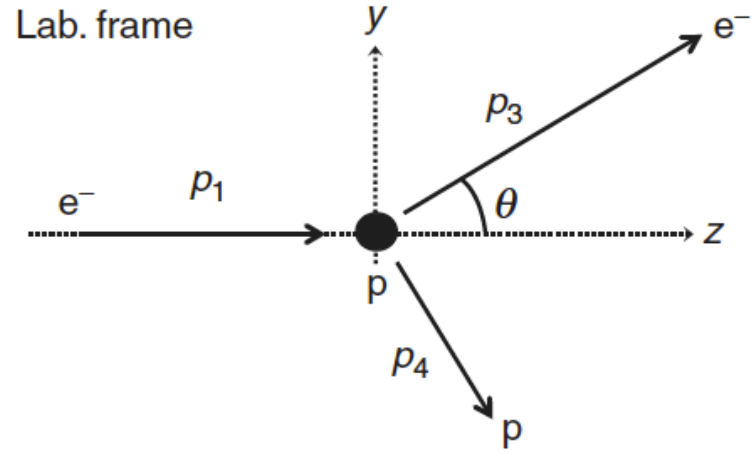
$$\mathrm{d}\sigma = \frac{1}{64\pi^2 s} \frac{\mathrm{p}_f^*}{\mathrm{p}_i^*} |\mathcal{M}_{fi}|^2 \mathrm{d}\Omega^* \longrightarrow \mathrm{d}\sigma = \frac{1}{128\pi^2 s\, \mathrm{p}_i^{*2}} |\mathcal{M}_{fi}|^2 \mathrm{d}\phi^* \mathrm{d}t$$

Assumindo simetria azimutal integramos em $\mathrm{d}\phi^* \longrightarrow 2\pi$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t} = \frac{1}{64\pi s\, \mathrm{p}_i^{*2}} |\mathcal{M}_{fi}|^2.$$

Sistema do Laboratório

$$p_1 \approx (E_1, 0, 0, E_1),$$
$$p_2 = (m_\mathrm{p}, 0, 0, 0),$$
$$p_3 \approx (E_3, 0, E_3 \sin\theta, E_3 \cos\theta)$$
$$p_4 = (E_4, \mathbf{p}_4).$$



$$\frac{d\sigma}{dt} = \frac{1}{64\pi s\, \mathrm{p}_i^{*2}} |\mathcal{M}_{fi}|^2.$$

$$\mathrm{p}_i^{*2} = \frac{1}{4s}[s - (m_1 + m_2)^2][s - (m_1 - m_2)^2]$$

$$m_p >> m_e \qquad m_2 >> m_1 \quad \longrightarrow \quad \mathrm{p}_i^{*2} \approx \frac{(s - m_\mathrm{p}^2)^2}{4s},$$

$$s = (p_1 + p_2)^2 = p_1^2 + p_2^2 + 2p_1 \cdot p_2$$
$$= m_\mathrm{p}^2 + 2E_1 m_\mathrm{p}, \quad \longrightarrow \quad \mathrm{p}_i^{*2} = \frac{E_1^2 m_\mathrm{p}^2}{s}$$

$$t = (p_1 - p_3)^2 = p_1^2 + p_3^2 - 2p_1.p_3 \simeq -2\,(E_1 E_3 - E_1 E_3\, cos\theta)$$

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{dt}\frac{dt}{d\Omega} = \frac{1}{2\pi}\frac{dt}{d(\cos\theta)}\frac{d\sigma}{dt}$$

$$E_4 = E_1 + m_p - E_3$$

$$t = (p_1 - p_3)^2 \approx -2E_1E_3(1-\cos\theta)$$

$$t = (p_2 - p_4)^2 = 2m_p^2 - 2p_2 \cdot p_4 = 2m_p^2 - 2m_p E_4 \quad = -2m_p(E_1 - E_3)$$

$$E_3 = \frac{E_1 m_p}{m_p + E_1 - E_1\cos\theta} \quad \longrightarrow \quad \frac{dE_3}{d(\cos\theta)} = \frac{E_1^2 m_p}{(m_p + E_1 - E_1\cos\theta)^2} = \frac{E_3^2}{m_p}$$

$$dt = 2\,m_p\,dE_3$$

$$\frac{d\sigma}{dt} = \frac{1}{64\pi s\, p_i^{*2}}|\mathcal{M}_{fi}|^2$$

$$\frac{dt}{d(\cos\theta)} = 2m_p\frac{dE_3}{d(\cos\theta)}$$

$$\frac{dt}{d(\cos\theta)} = 2E_3^2 \quad \longrightarrow \quad \frac{d\sigma}{d\Omega} = \frac{1}{2\pi}2E_3^2\frac{d\sigma}{dt} \quad = \frac{E_3^2}{64\pi^2 s\, p_i^{*2}}|\mathcal{M}_{fi}|^2$$

$$\frac{d\sigma}{d\Omega} = \frac{1}{2\pi} 2E_3^2 \frac{d\sigma}{dt} = \frac{E_3^2}{64\pi^2 s\, p_i^{*2}} |\mathcal{M}_{fi}|^2$$

$$p_i^{*2} = \frac{E_1^2 m_p^2}{s}$$

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2} \left(\frac{E_3}{m_p E_1} \right)^2 |\mathcal{M}_{fi}|^2$$

$$E_3 = \frac{E_1 m_p}{m_p + E_1 - E_1 \cos\theta}$$

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2} \left(\frac{1}{m_p + E_1 - E_1 \cos\theta} \right)^2 |\mathcal{M}_{fi}|^2$$

Exercícios

2.8) $P^{\mu} = \sum_i p_i^{\mu}$ $\qquad P^{\mu} P_{\mu}$ é invariante $\qquad P^{\mu} P_{\mu} = P'^{\mu} P'_{\mu}$

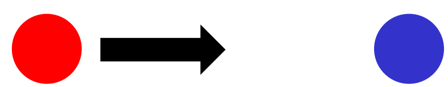
Lab $\qquad$ CM

Conservação de energia e momento : $P_a^{\mu} = P_d^{\mu} \qquad P_a'^{\mu} = P_d'^{\mu}$

$$P_a^{\mu} P_{\mu\,a} = P_d^{\mu} P_{\mu\,d}$$

Antes no Lab = Depois no CM : $\boxed{P_a^{\mu} P_{\mu\,a} = P_d'^{\mu} P'_{\mu\,d}}$

Antes no Lab:

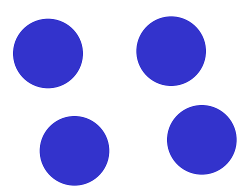


$(E, \vec{p}) \qquad (m, 0)$

$$P^{\mu} = (E + m, \vec{p})$$

$$P^{\mu} P_{\mu} = (E + m)^2 - p^2$$

Depois no CM:

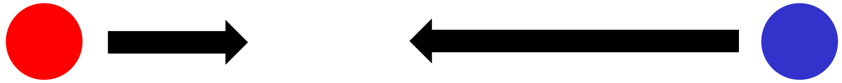


$$P'^{\mu} = (4\,m, 0)$$

$$P'^{\mu} P'_{\mu} = 16\,m^2$$

$(E + m)^2 - p^2 = 16\,m^2 \qquad E^2 = p^2 + m^2 \qquad \boxed{E = 7\,m}$

2.13)



Elétron Próton

$$E_e^2 = p_e^2 + m_e^2$$

$$E_p^2 = p_p^2 + m_p^2$$

$$p_e^\mu = (E_e, \vec{p}_e) \qquad p_p^\mu = (E_p, \vec{p}_p)$$

$$P^\mu = p_e^\mu + p_p^\mu \quad = (E_e, \vec{p}_e) + (E_p, \vec{p}_p) \quad = (E_e + E_p, \vec{p}_e + \vec{p}_p)$$

Laboratório $P^\mu = (E_e + E_p, \vec{p}_e + \vec{p}_p)$ $P^\mu P_\mu$ invariante

Centro de massa $P'^\mu = ({E'}_e + {E'}_p, 0)$ $P'^\mu {P'}_\mu$ invariante

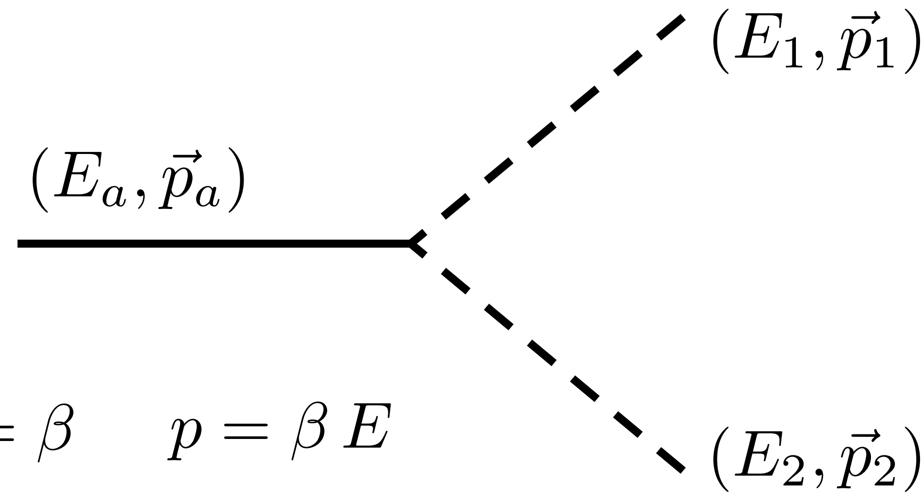
$$P'^\mu {P'}_\mu = P^\mu P_\mu \qquad (E_e + E_p)^2 - (\vec{p}_e + \vec{p}_p)^2 = (E'_e + E'_p)^2 = s$$

$$E_e^2 + E_p^2 + 2E_e E_p - p_e^2 - p_p^2 - 2\vec{p}_e.\vec{p}_p = s \qquad p_e\, p_p \cos\theta = -p_e\, p_p$$

$$s = m_e^2 + m_p^2 + 2E_e\, E_p + 2p_e\, p_p \qquad s \simeq 4\, E_e\, E_p$$

$$\boxed{\sqrt{s} \simeq 306 \text{ GeV}}$$

2.6) $a \rightarrow 1 + 2$



$$\left.\begin{array}{l} p = m\,v\,\gamma \\ E = m\,c^2\,\gamma \end{array}\right\} \quad \frac{p}{E} = \frac{v}{c^2} = \frac{\beta}{c} = \beta \qquad p = \beta\,E$$

$$(E_a, \vec{p}_a) = (E_1 + E_2, \vec{p}_1 + \vec{p}_2)$$ Conservação de E e p

$$E_a^2 - p_a^2 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p})^2$$ Fizemos $P^\mu P_\mu$

$$m_a^2 = \cancel{p_1^2} + m_1^2 + \cancel{p_2^2} + m_2^2 + 2\,E_1 E_2 - \cancel{p_1^2} - \cancel{p_2^2} - 2\vec{p}_1.\vec{p}_2$$

$$m_a^2 = m_1^2 + m_2^2 + 2\,E_1\,E_2 - 2p_1\,p_2\,cos\,\theta$$

$$\boxed{m_a^2 = m_1^2 + m_2^2 + 2\,E_1\,E_2(1 - 2\beta_1\,\beta_2\,cos\,\theta)}$$

FIM

Roy Lichtenstein


POP!