Introdução à Física das Partículas Elementares

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(buscar: física das partículas elementares)

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Plano do Curso

14/03 Cap. 1
16/03 Cap. 1
21/03 Cap. 2
23/03 Cap. 2
28/03 Cap. 3
30/03 Cap. 3
04/04
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11/04 Cap. 4
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27/06 Cap. 11
29/06 P3
04/07 Sub

2ª Lista de exercícios

Capítulo 4: 1, 3, 6, 7, 9

Capítulo 5: 2, 3

Capítulo 6: 1, 2, 3, 4

Capítulo 7: refazer as passagens da dedução da seção de choque apresentada nas aulas

Aula 16

Capítulo 8

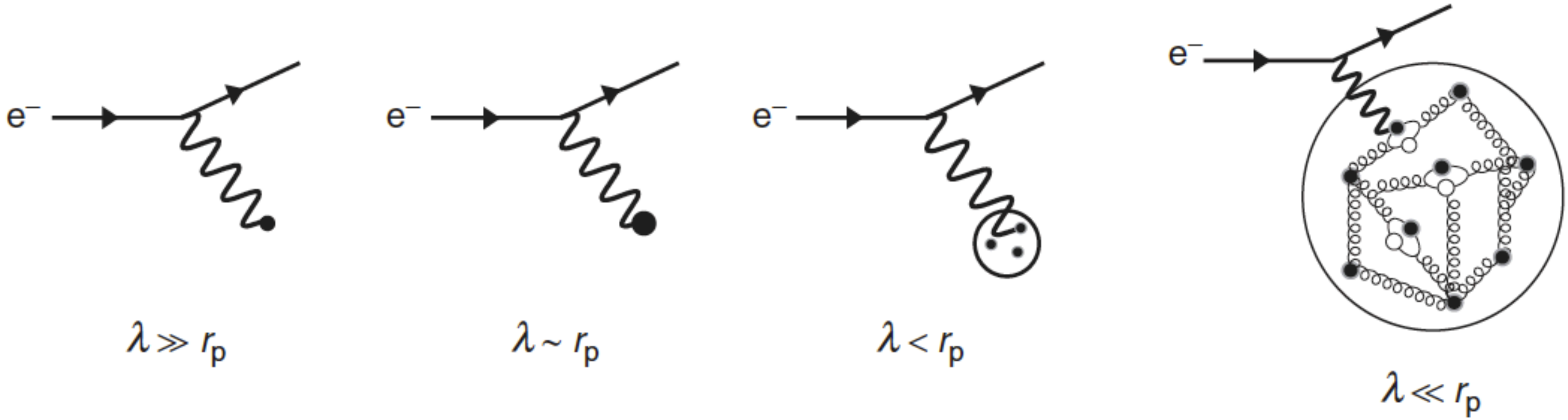
Espalhamento elétron-próton

Espalhamento Inelástico Profundo

Para descobrir do que o próton é feito !!!

A descoberta dos quarks !!!

q^μ 4-momento do fóton $\longrightarrow$ $\lambda \simeq \dfrac{1}{\sqrt{q^2}}$ comprimento de onda do fóton



Espalhamento elástico $\longrightarrow$ Espalhamento inelástico

$$e + p \to e + p \qquad\qquad e + p \to e + X$$

O próton ganha energia
e "se quebra"

$$X = \begin{cases} n + \pi^+ \\ p + \pi^+ + \pi^- \\ p + \pi^+ + \pi^- + \pi^+ + \pi^- \\ \ldots \quad \text{(profundamente inelástico)} \end{cases}$$

Espalhamento inelástico elétron - próton

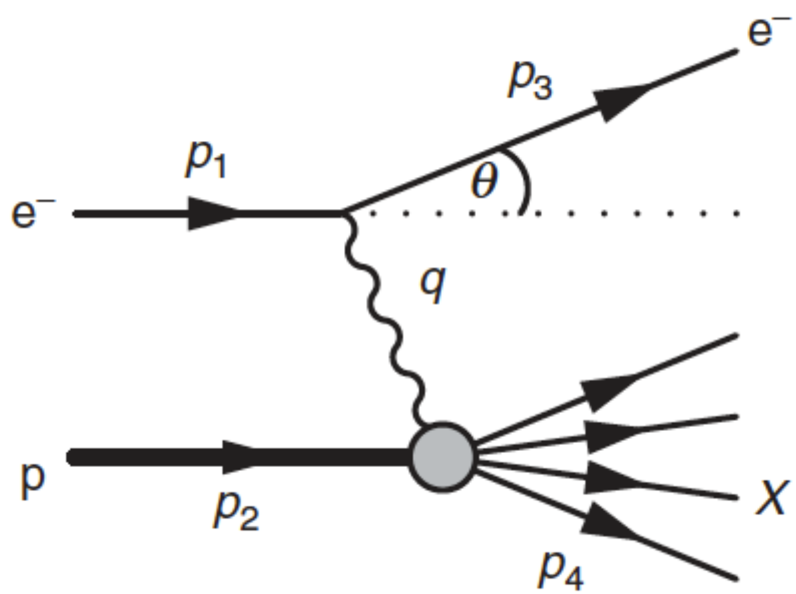
As variáveis :

$$\boxed{Q^2 = -q^2}$$

$$Q^2 = -(p_1 - p_3)^2 = -2m_e^2 + 2p_1 \cdot p_3$$

$$= \cancel{-2m_e^2} + 2E_1 E_3 - 2\mathrm{p}_1 \mathrm{p}_3 \cos\theta$$

$$Q^2 \approx 2E_1 E_3 (1 - \cos\theta) = 4E_1 E_3 \sin^2 \frac{\theta}{2}$$



W = massa do sistema X

$$\boxed{x \equiv \frac{Q^2}{2p_2 \cdot q}}$$

x de Bjorken !!!

$$W^2 \equiv p_4^2 = (q + p_2)^2 = q^2 + 2p_2 \cdot q + p_2^2$$

$$W^2 + Q^2 - m_p^2 = 2p_2 \cdot q$$

$$x = \frac{Q^2}{Q^2 + W^2 - m_p^2}$$

$$x = \frac{Q^2}{Q^2 + W^2 - m_p^2} \qquad Q^2 \geq 0 \qquad W^2 \equiv p_4^2 \geq m_p^2$$

$$\boxed{0 \leq x \leq 1}$$

"elasticidade"

$$W^2 = m_p^2 \qquad x = 1$$

espalhamento elástico

$$W^2 >> m_p^2 \qquad x << 1$$

espalhamento inelástico profundo

$$\boxed{y \equiv \frac{p_2 \cdot q}{p_2 \cdot p_1}}$$

$$p_1 = (E_1, 0, 0, E_1) \qquad p_2 = (m_p, 0, 0, 0)$$

(no Lab)

$$p_3 = (E_3, E_3 \sin\theta, 0, E_3 \cos\theta) \qquad q = (E_1 - E_3, \mathbf{p}_1 - \mathbf{p}_3)$$

$$y = \frac{m_p(E_1 - E_3)}{m_p E_1} = 1 - \frac{E_3}{E_1}$$

$$\boxed{0 \leq y \leq 1}$$

"inelasticidade"

perda fracional de energia do elétron

$$\nu \equiv \frac{p_2 \cdot q}{m_\mathrm{p}}$$

$$\nu = \frac{m_p(E_1 - E_3)}{m_p}$$

$$\nu = E_1 - E_3$$

energia perdida
pelo elétron

Espalhamento inelástico profundo elétron - próton

Espalhamento elástico: fórmula de Rosenbluth

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4E_1^2 \sin^4(\theta/2)} \frac{E_3}{E_1} \left(\frac{G_E^2 + \tau G_M^2}{(1+\tau)} \cos^2 \frac{\theta}{2} + 2\tau G_M^2 \sin^2 \frac{\theta}{2} \right)$$

$$\tau = Q^2/4m_p$$

$$\frac{E_3}{E_1} \cos^2\left(\frac{\theta}{2}\right) = 1 - y - \frac{m_p^2 y^2}{Q^2}$$

$$\sin^2\left(\frac{\theta}{2}\right) = \frac{E_1}{E_3} \frac{m_p^2}{Q^2} y^2$$

Problema 8.2

$$Q^2 \approx 2E_1 E_3 (1 - \cos\theta) = 4E_1 E_3 \sin^2 \frac{\theta}{2}$$

Pode ser reescrita em função de y

$$\frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2}{Q^4} \left[\frac{G_E^2 + \tau G_M^2}{(1+\tau)} \left(1 - y - \frac{m_p^2 y^2}{Q^2} \right) + \frac{1}{2} y^2 G_M^2 \right]$$

$$\frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2}{Q^4}\left[\frac{G_E^2 + \tau G_M^2}{(1+\tau)}\left(1 - y - \frac{m_p^2 y^2}{Q^2}\right) + \frac{1}{2} y^2 G_M^2\right]$$

Pode ser reescrita em termos de novas funções f_1 e f_2

$$\frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2}{Q^4}\left[\left(1 - y - \frac{m_p^2 y^2}{Q^2}\right) f_2(Q^2) + \frac{1}{2} y^2 f_1(Q^2)\right] \qquad x = 1$$

It can be shown that

Pode ser generalizada para o caso inelástico :

$$\frac{d^2\sigma}{dx\, dQ^2} = \frac{4\pi\alpha^2}{Q^4}\left[\left(1 - y - \frac{m_p^2 y^2}{Q^2}\right)\frac{F_2(x, Q^2)}{x} + y^2 F_1(x, Q^2)\right] \qquad x < 1$$

Funções de Estrutura

$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{4\pi\alpha^2}{Q^4}\left[\left(1 - y - \frac{m_p^2 y^2}{Q^2}\right)\frac{F_2(x,Q^2)}{x} + y^2 F_1(x,Q^2)\right]$$

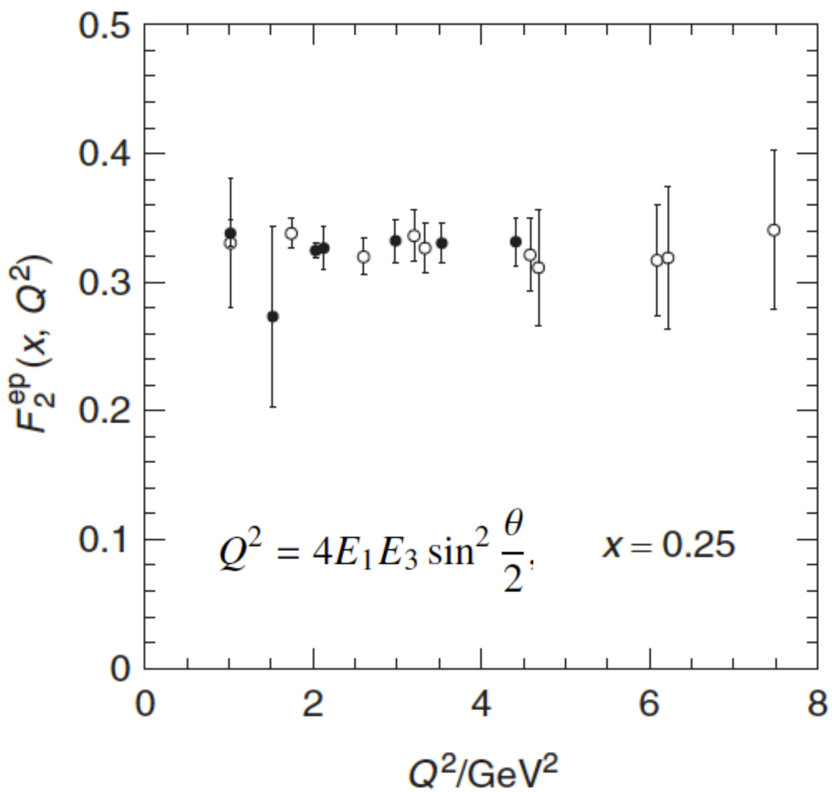
$$\left.\begin{array}{l} F_1(x,Q^2) \\ F_2(x,Q^2) \end{array}\right\}$$ Funções de Estrutura ("novos fatores de forma")

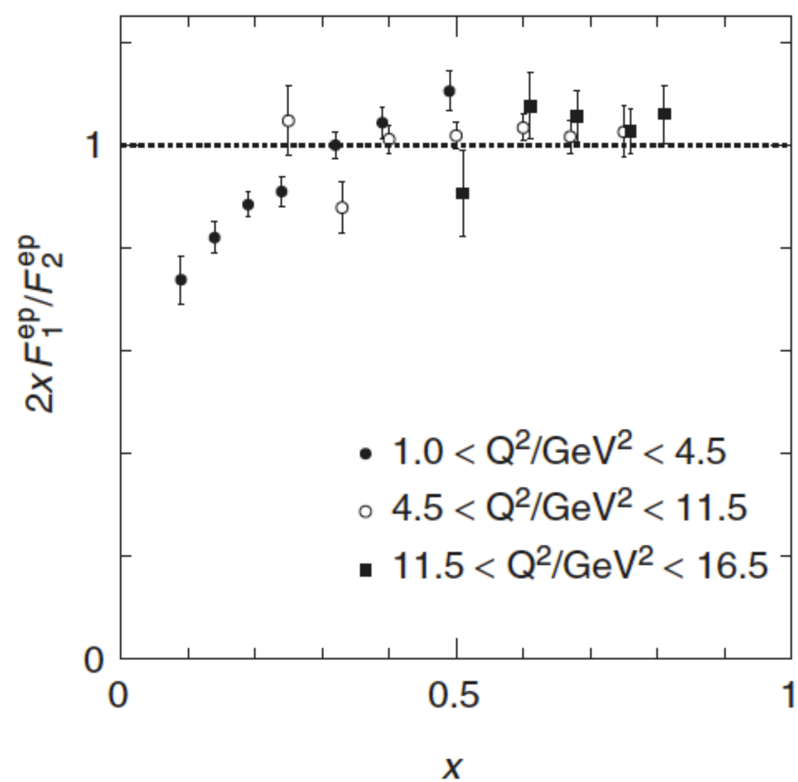
No DIS $Q^2 \gg m_p^2 y^2$

$$\boxed{\frac{d^2\sigma}{dx\,dQ^2} \approx \frac{4\pi\alpha^2}{Q^4}\left[(1 - y)\frac{F_2(x,Q^2)}{x} + y^2 F_1(x,Q^2)\right]}$$

$$Q^2 = 4E_1E_3\sin^2\frac{\theta}{2}, \qquad x = \frac{Q^2}{2m_p(E_1 - E_3)} \qquad y = 1 - \frac{E_3}{E_1}$$

Os resultados experimentais SLAC (1968) :





$$F_1(x, Q^2) \rightarrow F_1(x)$$

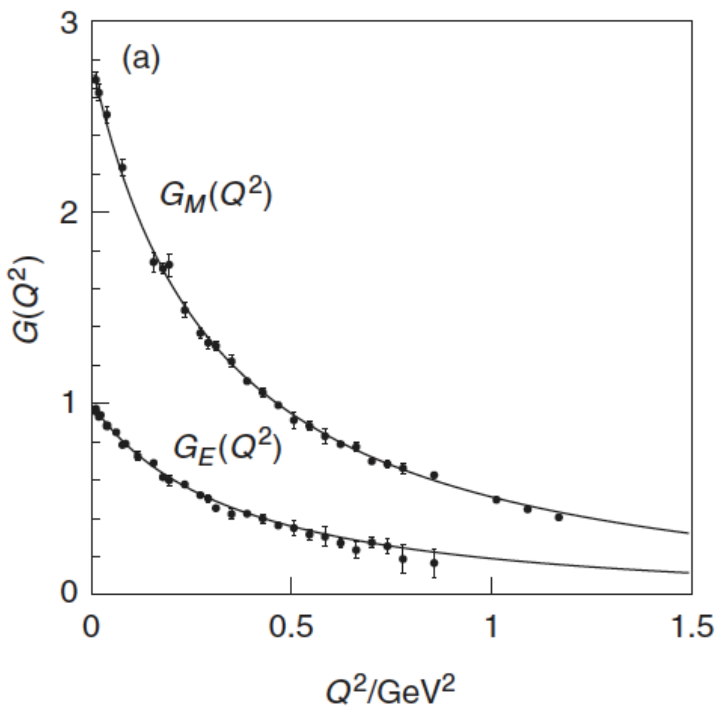
$$F_2(x, Q^2) \rightarrow F_2(x)$$

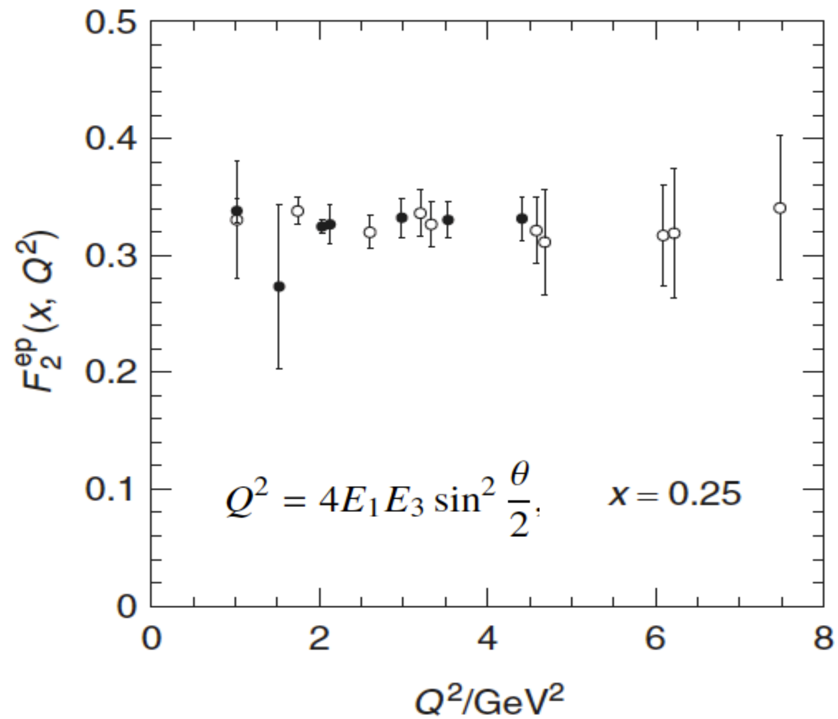
"Bjorken scaling"

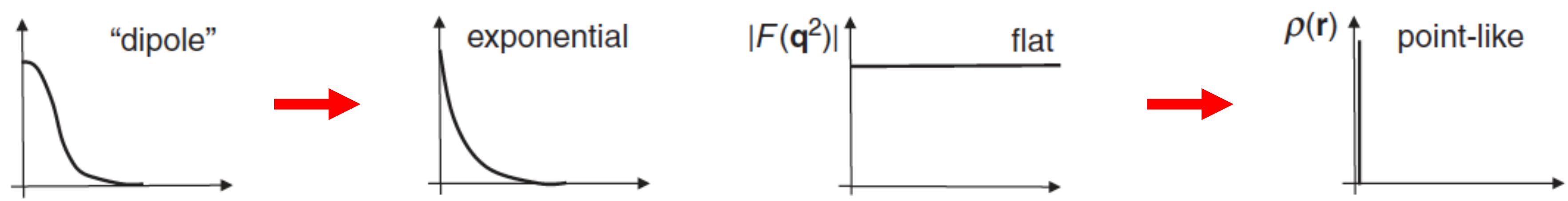
$$F_2(x) = 2xF_1(x).$$

Relação de
Callan - Gross

Vamos lembrar do caso elástico



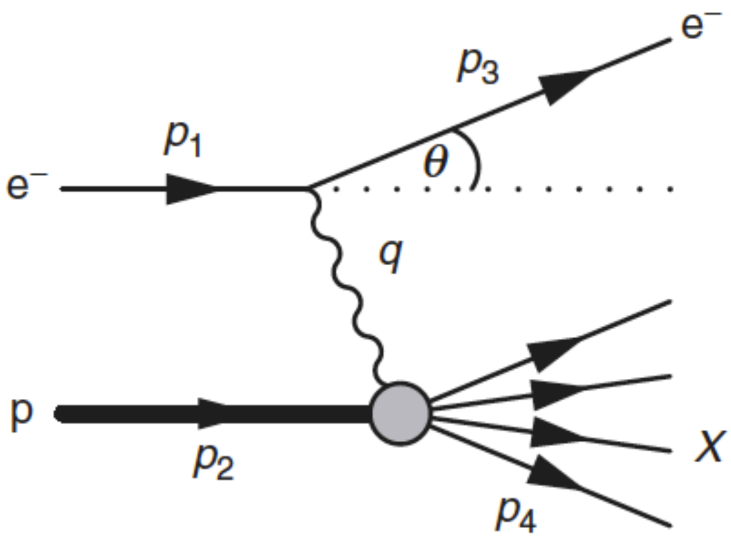


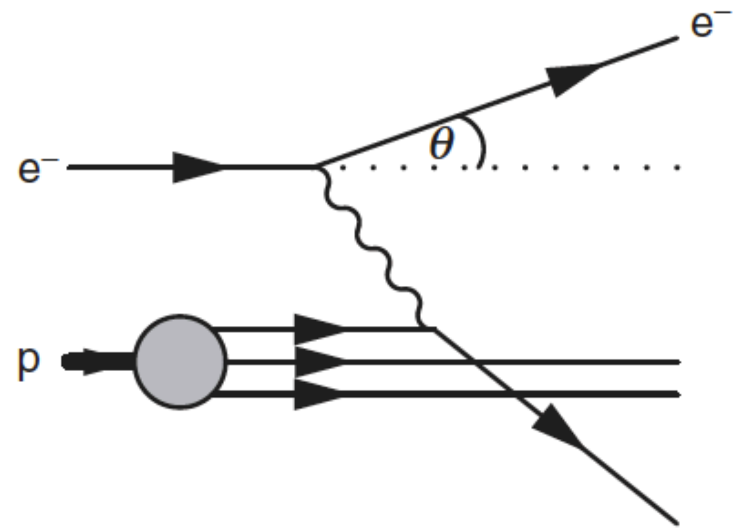


O elétron bateu em alguma coisa puntiforme !

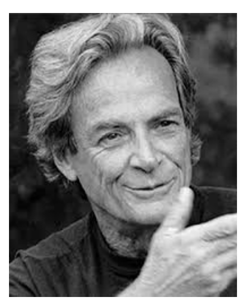
Como entender estes resultados ?

Supondo que o espalhamento elétron-próton inelástico é na verdade a soma de espalhamentos elásticos do elétron com partículas puntiformes de spin 1/2





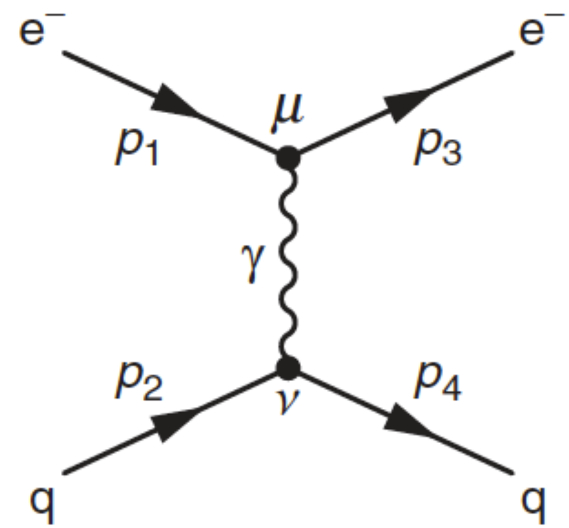
James Bjorken



Richard Feynman

A descoberta dos quarks !!!

Espalhamento elétron-quark



$$\overline{u}(p_3)[ie\gamma^{\mu}]u(p_1)$$

$$-ig_{\mu\nu}/q^2$$

$$\overline{u}(p_4)[-iQ_{\mathrm{q}}e\gamma^{\nu}]u(p_2)$$

$$\mathcal{M}_{fi} = \frac{Q_{\mathrm{q}}e^2}{q^2}\left[\overline{u}(p_3)\gamma^{\mu}u(p_1)\right]g_{\mu\nu}\left[\overline{u}(p_4)\gamma^{\nu}u(p_2)\right]$$

Vamos desprezar as massas do elétron e do quark.

$$\langle|\mathcal{M}_{fi}|^2\rangle = 2Q_{\mathrm{q}}^2e^4\left(\frac{s^2+u^2}{t^2}\right) = 2Q_{\mathrm{q}}^2e^4\frac{(p_1.p_2)^2+(p_1.p_4)^2}{(p_1.p_3)^2}$$

$$s = p_1 + p_2 \qquad t = p_1 - p_3 \qquad u = p_1 - p_4$$

Lembramos que :

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

$$\langle |\mathcal{M}_{fi}|^2 \rangle = 2Q_q^2 e^4 \left(\frac{s^2 + u^2}{t^2} \right)$$

$$t = q^2$$

$$\frac{d\sigma}{dq^2} = \frac{1}{64\pi s\, p_i^{*2}} \langle |\mathcal{M}_{fi}|^2 \rangle = \frac{Q_q^2 e^4}{32\pi s\, p_i^{*2}} \left(\frac{s^2 + u^2}{t^2} \right)$$

$$p_i^* = \sqrt{s}/2$$

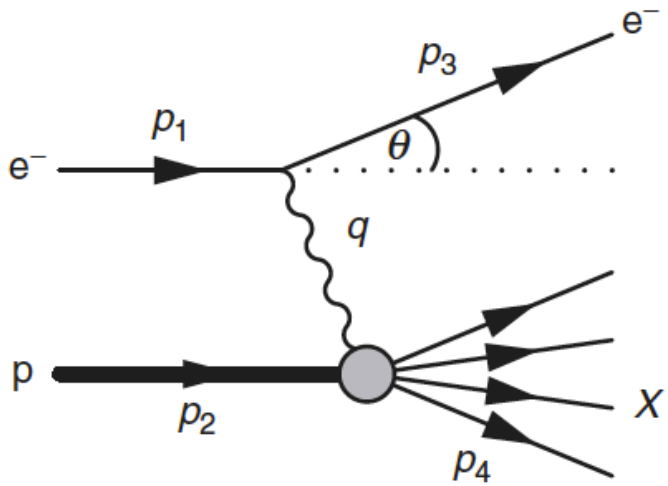
$$\frac{d\sigma}{dq^2} = \frac{Q_q^2 e^4}{8\pi q^4} \left(\frac{s^2 + u^2}{s^2} \right) = \frac{Q_q^2 e^4}{8\pi q^4} \left[1 + \left(\frac{u}{s} \right)^2 \right]$$

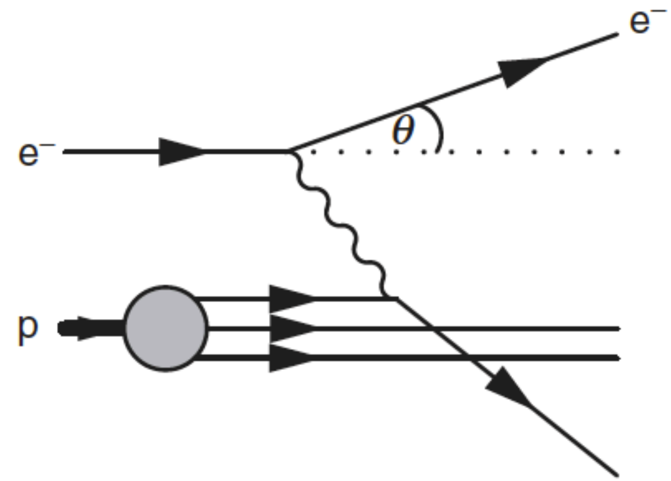
$$u \approx -s - t = -s - q^2$$

$$\frac{d\sigma}{dq^2} = \frac{2\pi\alpha^2 Q_q^2}{q^4} \left[1 + \left(1 + \frac{q^2}{s} \right)^2 \right]$$

(volta em 3 slides...)

Quarks e Partons

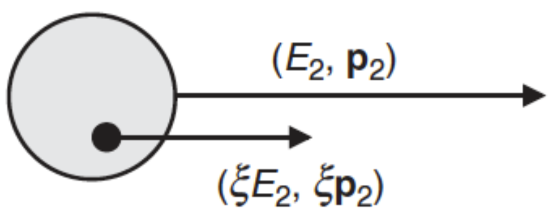




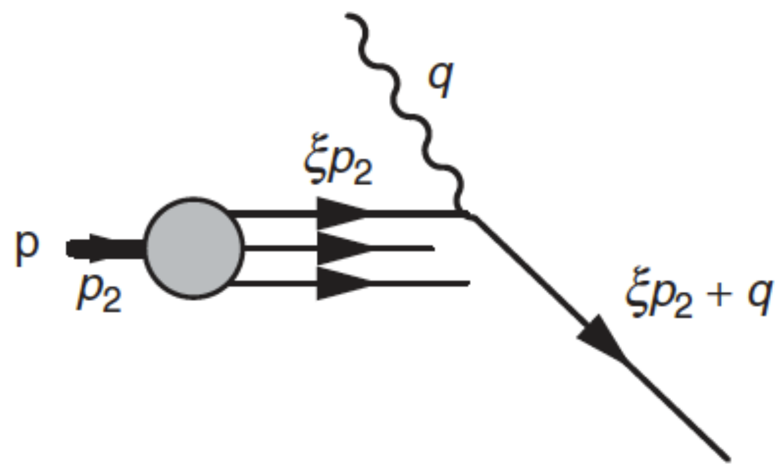
$$p_2 = (E_2, 0, 0, E_2)$$

$$p_q = \xi p_2 = (\xi E_2, 0, 0, \xi E_2)$$

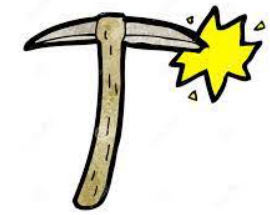
ξ é a fração do 4-momento do próton carregada pelo quark



$$0 \leq \xi \leq 1$$



Variáveis dos quarks



$$(\xi p_2 + q)^2 = \xi^2 \cancel{p_2^2} + 2\xi p_2 \cdot q + q^2 = \cancel{m_q^2}$$

$$\xi^2 p_2^2 = m_q^2 \qquad q^2 + 2\xi p_2 \cdot q = 0$$

$$\xi = \frac{-q^2}{2p_2 \cdot q} = \frac{Q^2}{2p_2 \cdot q} \equiv x$$

$$s = (p_1 + p_2)^2 \approx 2p_1 \cdot p_2 \qquad p_q = xp_2$$

$$s_q = xs,$$

$$s_q = (p_1 + xp_2)^2 \approx 2xp_1 \cdot p_2 = xs$$

$$y_q = y$$

Para o próton : $y = \dfrac{p_2 \cdot q}{p_2 \cdot p_1} \qquad x = \dfrac{Q^2}{2p_2 \cdot q}$

$$x_q = 1$$

Para o quark : $y_q = \dfrac{p_q \cdot q}{p_q \cdot p_1} = \dfrac{xp_2 \cdot q}{xp_2 \cdot p_1} = y$

quark sofre espalhamento elástico !

Seção de choque elétron-quark

$$\frac{\mathrm{d}\sigma}{\mathrm{d}q^2} = \frac{2\pi\alpha^2 Q_\mathrm{q}^2}{q^4}\left[1 + \left(1 + \frac{q^2}{s}\right)^2\right] \rightarrow \frac{\mathrm{d}\sigma}{\mathrm{d}q^2} = \frac{2\pi\alpha^2 Q_\mathrm{q}^2}{q^4}\left[1 + \left(1 + \frac{q^2}{s_\mathrm{q}}\right)^2\right]$$

$$Q^2 = (s - m_\mathrm{p}^2)xy. \qquad (8.8)$$

$$q^2 = -Q^2 = -(s_q - \cancel{m_\mathrm{q}^2})x_q y_q \rightarrow \frac{q^2}{s_\mathrm{q}} = -x_\mathrm{q} y_\mathrm{q} = -y$$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}q^2} = \frac{2\pi\alpha^2 Q_q^2}{q^4}\left[1 + (1 - y)^2\right] \qquad \frac{\mathrm{d}\sigma}{\mathrm{d}Q^2} = \frac{4\pi\alpha^2 Q_\mathrm{q}^2}{Q^4}\left[(1 - y) + \frac{y^2}{2}\right]$$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