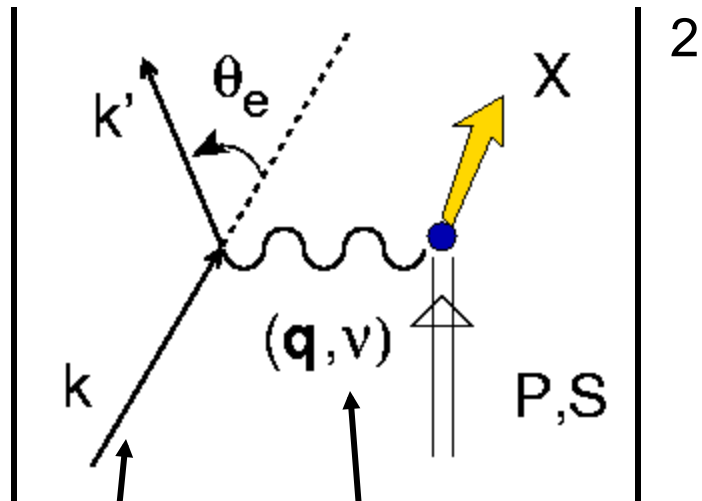


Riassunto della lezione precedente

- Calcolo sez. d' urto elementare e confronto con formula di Rosenbluth in regime DIS; funzioni di struttura e densità partoniche; relazione di Callan-Gross
- relazione di Callan-Gross e natura fermionica dei partoni
- definizioni di distribuzioni partoniche di valenza, del mare, di singoletto
- test del modello a partoni per DIS elettrone-nucleone; caratteristiche delle distribuzioni di valenza e del mare
- necessità di allargare il campo di indagine anche a DIS con (anti)neutrino; brevi cenni introduttivi al settore elettrodebole del Modello Standard; meccanismo di Goldstone e rottura spontanea di simmetria

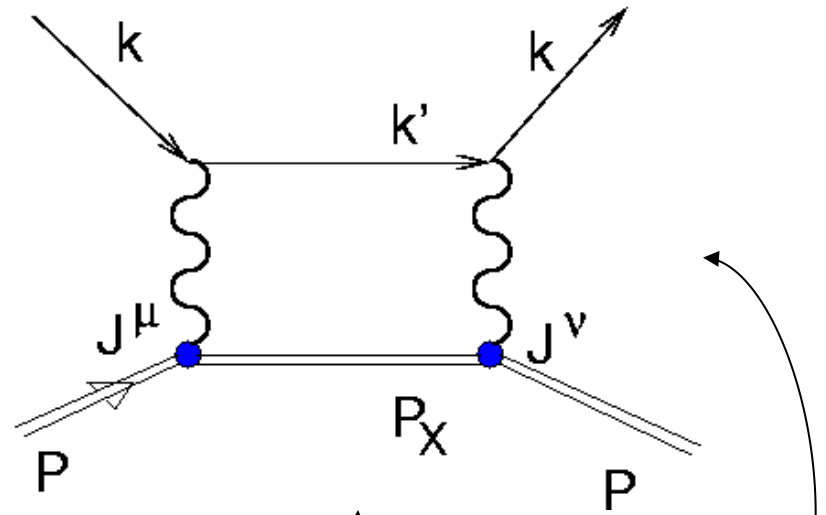
Deep Inelastic Scattering



$e^\pm, \mu^\pm,$
 $\nu_{e/\mu}, \bar{\nu}_{e/\mu}$

γ^*, W^\pm, Z^0

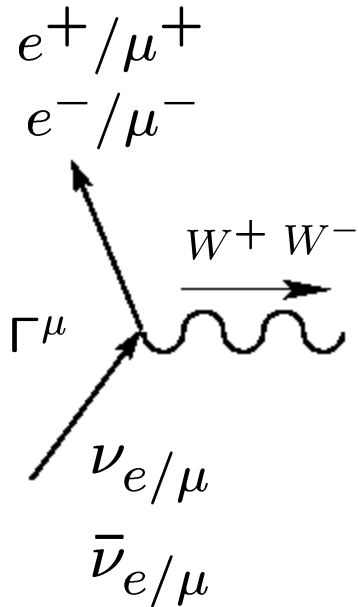
=



Tensore leptónico $L^{\mu\nu}$

Tensore adronico $W^{\mu\nu}$

Tensore leptonic



interazione e.m. (e^- / μ^- **left-handed**) \rightarrow scambio di γ

$$\Gamma^\mu = e\gamma^\mu$$

fascio di neutrini (**left-handed**) \rightarrow scambio di W^+
 (ma anche in reazioni inverse del tipo $e^+/\mu^+ \rightarrow \bar{\nu}_{e/\mu}$)

$$\Gamma^\mu = \frac{e}{2\sqrt{2}\sin\theta_W} \frac{T_3(=+1)}{2} \gamma^\mu(1 - \gamma_5) \quad \mathbf{V - A}$$

fascio di antineutrini (**right-handed**) \rightarrow scambio di W^-
 (ma anche in reazioni inverse del tipo $e^-/\mu^- \rightarrow \nu_{e/\mu}$)

$$\Gamma^\mu = \frac{e}{2\sqrt{2}\sin\theta_W} \frac{T_3(=-1)}{2} \gamma^\mu(1 + \gamma_5) \quad \mathbf{V + A}$$

$$\begin{aligned} L^{\mu\nu} &= \text{Tr} [\Gamma^\mu \not{k}' \Gamma^\nu \not{k}] \\ &= \frac{e^2}{8\sin^2\theta_W} \frac{1}{4} \left\{ \text{Tr} [\gamma^\mu \gamma^\alpha \gamma^\nu \gamma^\beta] k'_\alpha k_\beta + \text{Tr} [\gamma^\mu \gamma_5 \gamma^\alpha \gamma^\nu \gamma_5 \gamma^\beta] k'_\alpha k_\beta \right. \\ &\quad \left. \mp \text{Tr} [\gamma^\mu \gamma^\alpha \gamma^\nu \gamma_5 \gamma^\beta] k'_\alpha k_\beta \mp \text{Tr} [\gamma^\mu \gamma_5 \gamma^\alpha \gamma^\nu \gamma^\beta] k'_\alpha k_\beta \right\} \end{aligned}$$

$\swarrow \mathbf{V-V}$
 $\downarrow \mathbf{A-A}$
 $\longleftarrow \mathbf{V \mp A}$

Tensore leptónico (continua)

$$\begin{aligned}\text{Tr} [\gamma^\mu \gamma^\alpha \gamma^\nu \gamma^\beta] &= \text{Tr} [\gamma^\mu \gamma_5 \gamma^\alpha \gamma^\nu \gamma_5 \gamma^\beta] = 4(g^{\mu\alpha} g^{\nu\beta} + g^{\mu\beta} g^{\nu\alpha} - g^{\mu\nu} g^{\alpha\beta}) \\ \text{Tr} [\gamma^\mu \gamma_5 \gamma^\alpha \gamma^\nu \gamma^\beta] &= \text{Tr} [\gamma^\mu \gamma^\alpha \gamma^\nu \gamma_5 \gamma^\beta] = 4i\epsilon^{\mu\nu\alpha\beta}\end{aligned}$$

$$L^{\mu\nu} = \frac{e^2}{8 \sin^2 \theta_W} 2 \left(k'^\mu k^\nu + k'^\nu k^\mu - k \cdot k' g^{\mu\nu} \mp i\epsilon^{\mu\nu\alpha\beta} k'_\alpha k_\beta \right)$$

$$\equiv L^{\mu\nu}(S) \pm L^{\mu\nu}(A)$$


parte antisimmetrica del tensore è memoria dell'interferenza tra corrente debole vettoriale ed assiale

Propagatore del bosone vettore

si approssima con $\left(-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\right) \frac{1}{q^2 - M_W^2} \sim -\frac{g^{\mu\nu}}{q^2 - M_W^2}$

perché $\frac{q^\mu q^\nu}{q^2} \sim \left(\frac{m_e}{M_W}\right)^2 \sim 0$

Tensore adronico

- 2 vettori indipendenti P, q
- base tensoriale: $b_1=g^{\mu\nu}$, $b_2=q^\mu q^\nu$, $b_3=P^\mu P^\nu$,
 $b_4=(P^\mu q^\nu + P^\nu q^\mu)$, $b_5=(P^\mu q^\nu - P^\nu q^\mu)$,
 $b_6= \varepsilon_{\mu\nu\rho\sigma} q^\rho P^\sigma$
- tensore adronico $W^{\mu\nu} = \sum_i c_i (q^2, P \cdot q) b_i$
- Hermiticity $\rightarrow c_i$ sono reali
- invarianza per time-reversal $\rightarrow c_5 = 0$
- corrente debole non conservata: $q_\mu W^{\mu\nu} \neq 0 \rightarrow c_6 \neq 0$
- c_1 e c_3 dipendenti da c_2 e c_4

$$W^{\mu\nu} = \left(-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2} \right) q^2 c_2(q^2, P \cdot q) + \frac{\tilde{P}^\mu \tilde{P}^\nu}{M^2} \left(-\frac{M^2 q^2}{P \cdot q} \right) c_4(q^2, P \cdot q) + i \varepsilon^{\mu\nu\rho\sigma} \frac{P_\rho q_\sigma}{M^2} c_6(q^2, P \cdot q)$$

\downarrow \swarrow \searrow
 W_3 W_1 W_2
 $W^{(A)}_{\mu\nu}$ $\underbrace{\hspace{10em}}_{W^{(S)}_{\mu\nu}}$

violazione di parità

Ampiezza di scattering

$$\begin{aligned}
 L_{\mu\nu} &= L_{\mu\nu}^{(S)} \pm L_{\mu\nu}^{(A)} \\
 W^{\mu\nu} &= W^{(S)\mu\nu} + W^{(A)\mu\nu}
 \end{aligned}
 \longrightarrow
 \begin{aligned}
 L_{\mu\nu} W^{\mu\nu} &= L_{\mu\nu}^{(S)} W^{(S)\mu\nu} \\
 &\pm L_{\mu\nu}^{(A)} W^{(A)\mu\nu}
 \end{aligned}$$

$$L_{\mu\nu} W^{\mu\nu} \stackrel{TRF}{\propto} \frac{e^4}{64 \sin^4 \theta_W} 4EE' \cos^2 \frac{\theta_e}{2}$$



$$\times \left[W_2 + 2W_1 \tan^2 \frac{\theta_e}{2} \pm \frac{E + E'}{M} W_3 \tan^2 \frac{\theta_e}{2} \right]$$



interferenza **VA** → antisimmetria tra leptoni / antileptoni

Sezione d' urto

$$\begin{aligned} \frac{d\sigma^{\nu/\bar{\nu}}}{dE'd\Omega} &= \frac{\alpha^2}{64 \sin^4 \theta_W} \frac{E'}{E} \frac{1}{(Q^2 + M_W^2)^2} L_{\mu\nu} W^{\mu\nu} \\ &= \frac{\alpha^2}{64 \sin^4 \theta_W} \frac{E'}{E} \frac{1}{(Q^2 + M_W^2)^2} 4EE' \cos^2 \frac{\theta_e}{2} \\ &\quad \times \left[W_2 + 2W_1 \tan^2 \frac{\theta_e}{2} \pm \frac{E + E'}{M} W_3 \tan^2 \frac{\theta_e}{2} \right] \end{aligned}$$

$$= \frac{G_F^2}{8\pi^2} \left(\frac{M_W^2}{Q^2 + M_W^2} \right)^2 E'^2 \cos^2 \frac{\theta_e}{2}$$

Limite DIS :
scaling in
dσ elastica

$$\begin{aligned} W_1 &\rightarrow \frac{F_1}{M} \\ W_2 &\rightarrow \frac{F_2}{\nu} \\ W_3 &\rightarrow \frac{F_3}{\nu} \end{aligned}$$

$$\times \left[\frac{F_2}{\nu} + 2\frac{F_1}{M} \tan^2 \frac{\theta_e}{2} \pm \frac{E + E'}{M\nu} F_3 \tan^2 \frac{\theta_e}{2} \right]$$

$$G_F = \frac{e^2}{4\sqrt{2}M_W^2 \sin^2 \theta_W}$$



Vertice elettrodebole elementare in correnti cariche

$$D_f = d, s, b$$

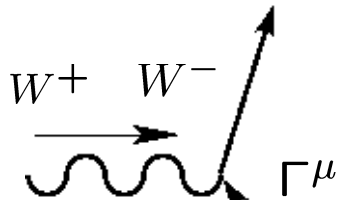
$$\bar{U}_{\bar{f}} = \bar{u}, \bar{c}, \bar{t}$$

$$U_f = u, c, t$$

$$\bar{D}_{\bar{f}} = \bar{d}, \bar{s}, \bar{b}$$

interazione e.m. \rightarrow scambio di γ

$$\Gamma^\mu = e\gamma^\mu$$

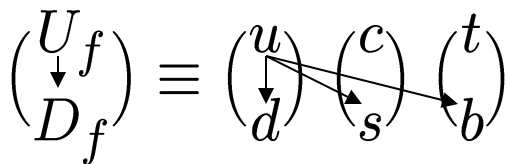


quark (**left-handed**)

$$\Gamma^\mu = \frac{e}{2\sqrt{2}\sin\theta_W} \frac{T_3(=+1)}{2} \gamma^\mu (1 - \gamma_5) \sum_{f'} V_{ff'}$$

antiquark (**right-handed**)

$$\Gamma^\mu = \frac{e}{2\sqrt{2}\sin\theta_W} \frac{T_3(=-1)}{2} \gamma^\mu (1 + \gamma_5) \sum_{\bar{f}'} V_{\bar{f}\bar{f}'}$$



$$V_{U_f D_f} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \in SU_f(3)$$

$$\sim \begin{pmatrix} \cos\theta_C & \sin\theta_C & 0 \\ -\sin\theta_C & \cos\theta_C & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\sum_{f'} |V_{U_f D_{f'}}|^2 = 1$$

Tensore adronico elementare

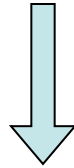
$$\begin{aligned}
 2mW^{\text{el}\mu\nu} &= \frac{1}{2\pi} \int \frac{d\mathbf{p}'}{(2\pi)^3 2p'^0} (2\pi)^4 \delta(p' - p - q) H^{\text{el}\mu\nu} \\
 &= \frac{1}{2M\nu} \delta(x - x_B) H^{\text{el}\mu\nu}
 \end{aligned}$$

$$\begin{aligned}
 H^{\text{el}\mu\nu} &= \frac{e_f^2}{4} \text{Tr} [(x \not{P} + \not{q} + m) \gamma^\mu (1 \mp \gamma_5) (x \not{P} + m) \gamma^\nu (1 \mp \gamma_5)] \\
 &\quad \times \sum_{f'} \left| V_{U_f D_{f'}} \right|^2 \\
 &= H^{\text{el}(S)\mu\nu} \pm H^{\text{el}(A)\mu\nu}
 \end{aligned}$$

$$\text{Poi} \quad L_{\mu\nu} H^{\text{el}\mu\nu} = L_{\mu\nu}^{(S)} H^{\text{el}(S)\mu\nu} \pm L_{\mu\nu}^{(A)} H^{\text{el}(A)\mu\nu}$$

Funzioni di struttura

$$\frac{d\sigma}{dE'd\Omega}(P, q) = \sum_{f, \bar{f}} \int_0^1 dx \frac{d\sigma^{\text{el}}}{dE'd\Omega}(xP, q) \phi_f(x)$$



$$F_2(x_B) = x_B \sum_f e_f^2 \left[\phi_f(x_B) + \bar{\phi}_f(x_B) \right]$$

$$2x_B F_1(x_B) = F_2(x_B)$$

$$F_3(x_B) = \sum_f e_f^2 \left[\phi_f(x_B) - \bar{\phi}_f(x_B) \right]$$

non-singlet flavor

asimmetria **right-/left-** handed (V/A)

sensibile al flavor

$SU_f(3) \rightarrow 12$ incognite : $u_p, d_p, s_p, \bar{u}_p, \bar{d}_p, \bar{s}_p$
 $u_n, d_n, s_n, \bar{u}_n, \bar{d}_n, \bar{s}_n$

8 misure possibili : $F_2^{W^+p}, F_2^{W^-p}, F_3^{W^+p}, F_3^{W^-p}$
 $F_2^{W^+n}, F_2^{W^-n}, F_3^{W^+n}, F_3^{W^-n}$

invarianza di isospin : $u_p \equiv d_n$ $d_p \equiv u_n$
(2 relazioni)

simmetria di isospin del “mare” : $\bar{u} = \bar{d}$
(2 relazioni)

Sistema determinato: da DIS (anti)neutrino – Nucleone si possono estrarre le distribuzioni degli (anti)quark per i tre flavor

Esempio : $\nu_{e/\mu} + p \rightarrow e^-/\mu^- + X$

$$J_{W^+}^\mu \propto \bar{u} \gamma^\mu (1 - \gamma_5) [d \cos \theta_C + s \sin \theta_C] + \bar{c} \gamma^\mu (1 - \gamma_5) [s \cos \theta_C - d \sin \theta_C] + \text{antiquarks} \dots$$

$$\frac{F_2(x_B)}{x_B} = 2F_1(x_B) \sim 2 \left[\frac{1}{9} d(x_B) + \frac{1}{9} s(x_B) + \frac{4}{9} \bar{u}(x_B) + \frac{4}{9} \bar{c}(x_B) \right] + \dots$$

$$F_3(x_B) \sim 2 \left[\frac{1}{9} d(x_B) + \frac{1}{9} s(x_B) - \frac{4}{9} \bar{u}(x_B) - \frac{4}{9} \bar{c}(x_B) \right] + \dots$$

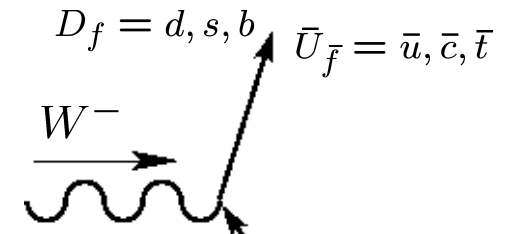
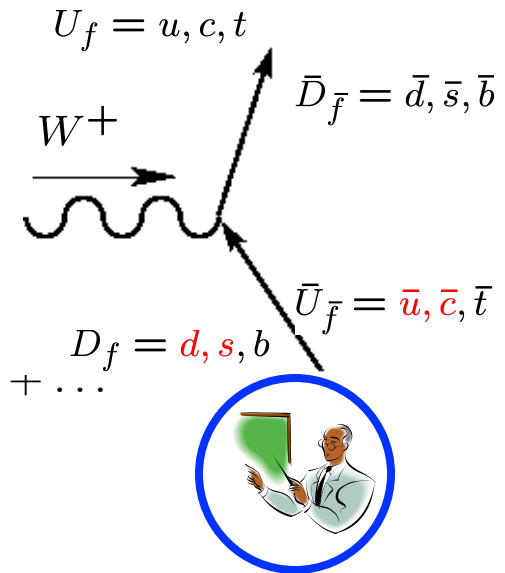
$\bar{\nu}_{e/\mu} + p \rightarrow e^+/\mu^+ + X$

$$J_{W^-}^\mu \propto [\bar{d} \cos \theta_C + \bar{s} \sin \theta_C] \gamma^\mu (1 - \gamma_5) u + [\bar{s} \cos \theta_C - \bar{d} \sin \theta_C] \gamma^\mu (1 - \gamma_5) c + (\bar{u}) \gamma^\mu (1 + \gamma_5) [\bar{d} \cos \theta_C + \bar{s} \sin \theta_C] \dots$$

$$[V^{-1} = V^\dagger]$$

$$\frac{F_2(x_B)}{x_B} = 2F_1(x_B) \sim 2 \left[\frac{1}{9} \bar{d}(x_B) + \frac{1}{9} \bar{s}(x_B) + \frac{4}{9} u(x_B) + \frac{4}{9} c(x_B) \right] + \dots$$

$$F_3(x_B) \sim 2 \left[-\frac{1}{9} \bar{d}(x_B) - \frac{1}{9} \bar{s}(x_B) + \frac{4}{9} u(x_B) + \frac{4}{9} c(x_B) \right] + \dots$$



$$U_f = u, c, t \quad \bar{D}_f = \bar{d}, \bar{s}, \bar{b}$$

Verifiche sperimentali

1) (anti)neutrino DIS su nuclei isoscalari ($Z=N \rightarrow n^{\circ} u = n^{\circ} d$ quarks)

$$\frac{\sigma(\nu A)}{\sigma(\bar{\nu} A)} \sim 3$$

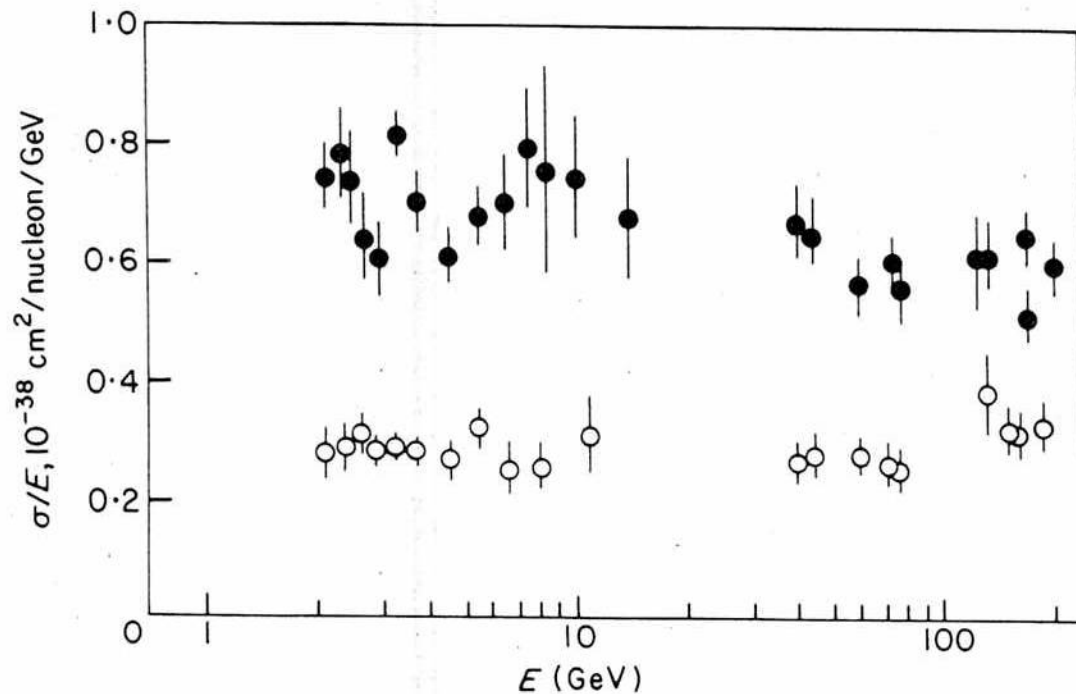


FIG. 11.12. $\sigma^{\bar{\nu}}/E$ and σ^{ν}/E for $E \leq 200$ GeV.

Dati dell' esp. Gargamelle
Perkins, Contemp. Phys. **16** 173 (75)

Interpretazione in QPM

$$\frac{d\sigma^{\nu/\bar{\nu}}}{dE'd\Omega} = \frac{G_F^2}{8\pi^2} \left(\frac{M_W^2}{Q^2 + M_W^2} \right)^2 E'^2 \cos^2 \frac{\theta}{2} \left[\frac{F_2}{\nu} + 2 \frac{F_1}{M} \tan^2 \frac{\theta}{2} \pm \frac{E + E'}{M\nu} F_3 \tan^2 \frac{\theta}{2} \right]$$



$$\frac{d\sigma^{\nu/\bar{\nu}}}{dx_B dy} = \frac{dE'd\Omega}{dx_B dy} \frac{d\sigma}{dE'd\Omega} = \frac{\pi 2 M \nu}{E'} \frac{d\sigma}{dE'd\Omega}$$



$$\begin{aligned} \frac{d\sigma^{\nu/\bar{\nu}}}{dx_B dy} &= \frac{G_F^2}{4\pi} \left(\frac{M_W^2}{Q^2 + M_W^2} \right)^2 M E \left[F_1 x_B y^2 + F_2 \left(1 - y - \frac{M x_B y}{2E} \right) \pm x_B \left(y - \frac{y^2}{2} \right) F_3 \right] \\ &\sim \frac{G_F^2}{4\pi} \left(\frac{M_W^2}{Q^2 + M_W^2} \right)^2 M E \left[F_2 \left(1 - y + \frac{y^2}{2} \right) \pm x_B \left(y - \frac{y^2}{2} \right) F_3 \right] \end{aligned}$$

Interpretazione (continua)

$$\text{approssimazioni : } \bar{u} = \bar{d} = \bar{c} = \bar{s} = \bar{t} = \bar{b} = t = b = 0 \\ s \sim c \sim K$$

$$\frac{d\sigma^{\nu A}}{dx_B dy} = N^{\nu A} \left[\left(1 - y + \frac{y^2}{2} - \frac{M_A x_B y}{2E} \right) F_2 + \left(y - \frac{y^2}{2} \right) x_B F_3 \right] \\ \sim N^{\nu A} 2x_B (d + K) \quad F_2 = x_B F_3 = 2x_B (d + s)$$



$$\frac{d\sigma^{\bar{\nu} A}}{dx_B dy} = N^{\bar{\nu} A} \left[\left(1 - y + \frac{y^2}{2} - \frac{M_A x_B y}{2E} \right) F_2 - \left(y - \frac{y^2}{2} \right) x_B F_3 \right] \\ \sim N^{\bar{\nu} A} 2x_B (u + K) (1 - y)^2 \quad F_2 = x_B F_3 = 2x_B (u + c)$$



Interpretazione (continua)



$$\frac{\sigma^{\nu A}}{\sigma^{\bar{\nu} A}} = \frac{\int_0^1 dx dy d\sigma^{\nu A}}{\int_0^1 dx dy d\sigma^{\bar{\nu} A}} = \frac{N^{\nu A} \int_0^1 dx 2x(d + K)}{N^{\bar{\nu} A} \int_0^1 dx 2x(u + K)} \frac{1}{3} \sim 3$$

$$N^{\nu A} \equiv N^{\bar{\nu} A} = \frac{G_F^2}{4\pi} \left(\frac{M_W^2}{Q^2 + M_W^2} \right)^2 ME$$

nuclei isoscalari $\rightarrow n_u = n_d$

$N = \{ \text{partoni a spin } \frac{1}{2} \text{ con stessa interazione elettrodebole dei leptoni; antipartoni soppressi} \}$

N.B. deviazioni dovute a $s \neq c \neq K$ e per contributo di antiquarks