

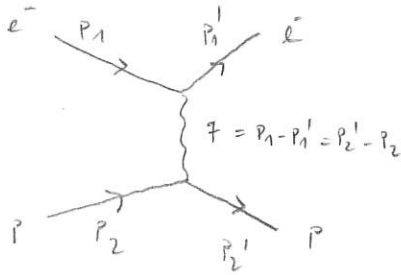
8 L'interaction forte | Structure des hadrons

Expériences pour étudier l'interaction forte avec hadrons non pas avec quarks et gluons

8.1 La diffusion ^{élastique} eN et facteurs de forme

a) Proton ponctuel

$$e^-(p_1) + p(p_2) \rightarrow e^-(p_1') + p(p_2')$$



$$p_1^2 = p_1'^2 = m^2$$

$$p_2^2 = p_2'^2 = M^2$$

$$s = (p_1 + p_2)^2 > 0$$

$$t = q^2 = (p_1 - p_1')^2$$

$|M_{fi}|^2$ de $e^+e^- \rightarrow \mu^+\mu^-$ via croisement $s \leftrightarrow t$:

$$\begin{array}{ccc} e^- & p & \rightarrow & e^- & p & \rightsquigarrow & e^- & e^+ & \rightarrow & \bar{p} & p \\ p_1 & p_2 & & p_1' & p_2' & & p_1 & -p_1' & & -p_2 & p_2' \end{array}$$

$$s = (p_1 + p_2)^2$$

$$\longrightarrow (p_1 - p_1')^2 = t \leq 0$$

$$t = (p_1 - p_1')^2$$

$$\longrightarrow (p_1 - (-p_2))^2 = s > 0$$

$$s, t \leq 0$$

$$\longrightarrow t \leq |e^+e^-|$$

Crossing - Symétrie de la matrice T:

$$\overline{|M_{fi}|^2}_{e^+p \rightarrow e^+p} = \overline{|M_{fi}|^2}_{e^+e^- \rightarrow \mu^+\mu^-} \text{ avec } s \leftrightarrow t$$

$$= 2 \frac{e^4}{t^2} [t^2 + 2st + 2(s - M^2)^2]$$

pour $s, M^2 \gg m^2 \approx 0$

(Ex. 8.1)

$$\frac{dG}{dt} e^{\vec{p} \rightarrow \vec{e}^{\vec{p}}} = \frac{1}{4\pi \lambda(s, m^2, M^2)} |\overline{M_{fi}}|^2 = \frac{2\pi \alpha^2}{(s-M^2)^2} \frac{1}{t^2} \left[t^2 + 2st + 2(s-M^2)^2 \right]$$

↑
Prop. du photon $\sim \frac{1}{q^4}$

Laboratoire:

$$P_2 = (M, \vec{0})$$

$$P_1 = (E, \vec{p}), P_1' = (E', \vec{p}') \quad ; \quad |\vec{p}| \approx E, |\vec{p}'| \approx E'$$

$$s \approx M^2 + 2ME = (P_1' + P_2)^2 = M^2 + 2P_1' \cdot P_2 \Rightarrow P_1' \cdot P_2 = \frac{s-M^2}{2} = ME$$

$$t \approx -2P_1 \cdot P_1' \approx -2EE'(1-\cos\theta) \Rightarrow P_1 \cdot P_1' = EE'(1-\cos\theta)$$

$$P_1' \cdot P_2 = P_1' (P_1' + P_2 - P_1)$$

$$\Rightarrow E'M = ME - \underbrace{EE'(1-\cos\theta)}_{= \frac{t}{2}} \Rightarrow E' \approx \frac{E}{1 + \frac{E}{M}(1-\cos\theta)} = \frac{E}{1 + \frac{2E}{M} \sin^2 \frac{\theta}{2}}$$

$$dt \quad E' = E + \frac{t}{2M} \Rightarrow dt = 2M dE' \\ 1 - \cos\theta = 2 \sin^2 \frac{\theta}{2} \Rightarrow dt = 2M \frac{dE'}{d\cos\theta} d\cos\theta$$

$$\frac{dG}{d\Omega} e^{\vec{p} \rightarrow \vec{e}^{\vec{p}}} = \frac{dt}{d\Omega} \frac{dG}{dt} \\ = \frac{E'^2}{\pi}$$

$$\frac{dG}{d\Omega} e^{\vec{p} \rightarrow \vec{e}^{\vec{p}}} \Big|_{\text{ponct.}} = \underbrace{\frac{\alpha^2}{4E^2 \sin^4 \frac{\theta}{2}}}_{\text{Rutherford}} \underbrace{\cos^2 \frac{\theta}{2} \frac{1 - \frac{t}{2M^2} \tan^2 \frac{\theta}{2}}{1 + \frac{2E}{M} \sin^2 \frac{\theta}{2}}}_{\text{Spins de } e^- \text{ et } p}$$

$$= \frac{\alpha^2}{4E^2 \sin^4 \frac{\theta}{2}} \frac{E'}{E} \left(\cos^2 \frac{\theta}{2} - \frac{t \sin^2 \frac{\theta}{2}}{2M^2} \right)$$

- Pour e^- avec $\frac{E}{M} \ll 1$ ($\Rightarrow \frac{t}{M^2} \ll 1$):

$$\frac{dG}{d\Omega} e^{\vec{p} \rightarrow \vec{e}^{\vec{p}}} \approx \frac{dG}{d\Omega}^{\text{Mott}} = \frac{\alpha^2}{4E^2 \sin^4 \frac{\theta}{2}} \cos^2 \frac{\theta}{2}$$

- Pour $\frac{E}{M} \ll 1$ et $\cos^2 \frac{\theta}{2} \approx 1$ ($\theta \approx 0$)

$$\frac{dG}{d\Omega} e^{\vec{p} \rightarrow \vec{e}^{\vec{p}}} \approx \frac{dG}{d\Omega}^{\text{Rutherford}} = \frac{\alpha^2}{4E^2 \sin^4 \frac{\theta}{2}}$$

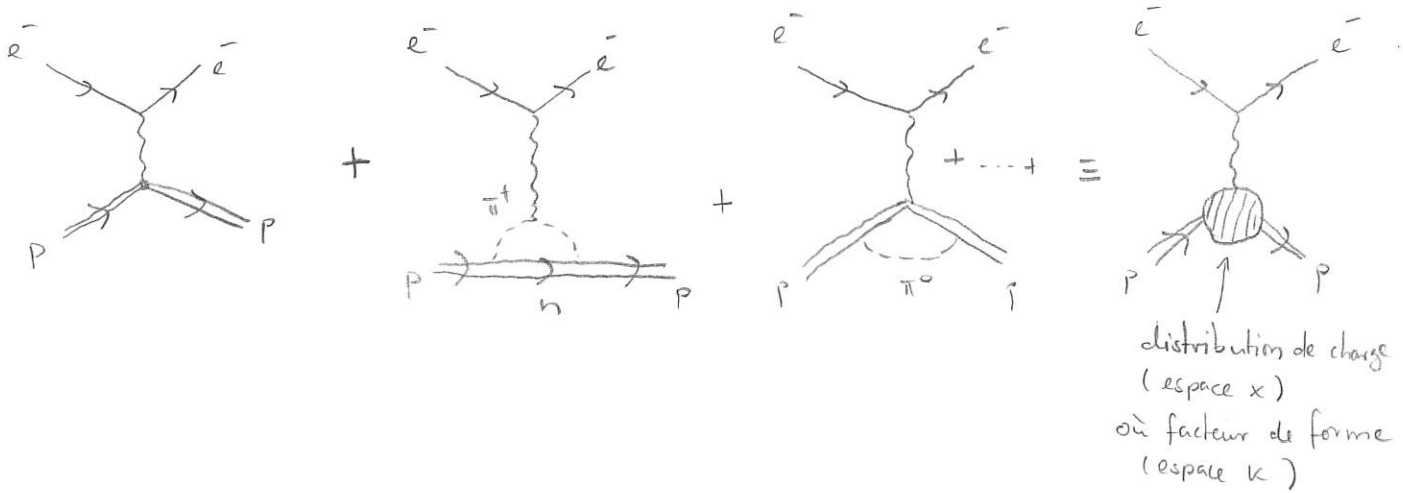


b) Proton étendu

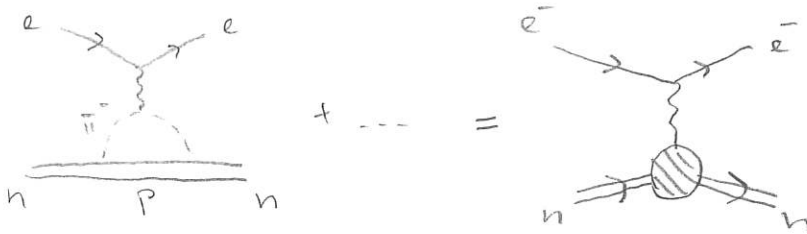
Exp.: Le proton n'est pas ponctuel pour $E > O(100 \text{ MeV})$!

$$\frac{d\sigma^{exp}}{dt} \sim t^{-4} \quad \text{pour } -t \gtrsim 0.1 \text{ GeV}^2, \quad s = \text{fixe} \quad (\rightarrow \text{Hofstadter})$$

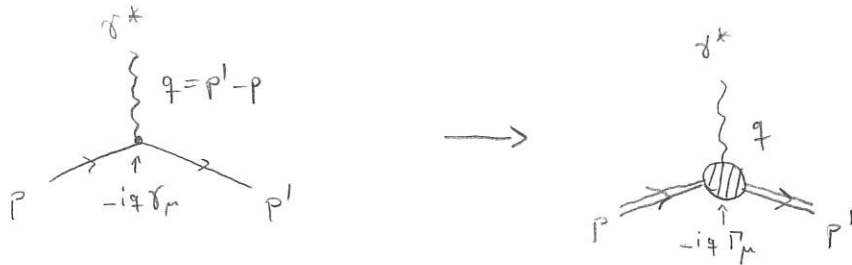
Interaction forte \rightarrow Objets étendus



Neutrons:



Expression générale covariante :



$$-e \bar{u}(p') \delta_{\mu} u(p)$$

\uparrow
($q = +e$)

$$-e \bar{u}(p') \Gamma_{\mu}(q^2) u(p) \Leftrightarrow \hat{j}_{\mu}^A(x) = \langle p' | \hat{j}_{\mu}^A(x) | p \rangle$$

$$= \underbrace{q \bar{u}(p') \Gamma_{\mu}^A u(p)}_{\hat{j}_{\mu}^A(0)} e^{i(p'-p)x}$$

où $\hat{j}_{\mu}^A(x) = q : \hat{\psi}(x) \delta^{\mu} \hat{\psi}(x) :$

$\bar{u} \delta_{\mu} u$ est un 4-vecteur ; Γ_{μ} tel que $\bar{u} \Gamma_{\mu} u$ 4-vecteur

\rightarrow covariantes bilinéaires

$$\Gamma_\mu = A(q^2) \not{q}_\mu + B(q^2) \not{P}_\mu + C(q^2) \gamma_\mu + D(q^2) i\sigma_{\mu\nu} q^\nu + E(q^2) i\sigma_{\mu\nu} P^\nu$$

$$q_\mu = p'_\mu - p_\mu, \quad P_\mu = p'_\mu + p_\mu, \quad \sigma_{\mu\nu} = \frac{i}{2} [\gamma_\mu, \gamma_\nu]$$

$$p^2 = p'^2 = M^2, \quad P^2 = 2M^2 + 2p \cdot p', \quad t = q^2 = 2M^2 - 2p \cdot p'$$

Equation de Dirac et conservation du courant

~~Dirac Gleichung und Stromerhaltung~~ $\partial_\mu j^\mu = 0$

Ansatz:

$$\Gamma_\mu = A_1 \not{P}_\mu + A_2 \not{P}'_\mu + A_3 \not{q}_\mu + A_4 \sigma_{\mu\nu} P^\nu + A_5 \sigma_{\mu\nu} P'^\nu$$

$$= A \not{q}_\mu + B \not{P}_\mu + \dots$$

$$A \neq B = A_2, \quad B - A = A_1, \dots$$

$\bar{u} \Gamma^\mu u$: Skalar $\Rightarrow \bar{u} \Gamma^\mu u p_\mu$ 4-Vektor

$\bar{u} \gamma_\mu u$: 4-Vektor

$\bar{u} \Gamma^\mu_\nu u$: Tensor $\Rightarrow \bar{u} \Gamma^\mu_\nu u p^\nu = 4$ -Vektor

u. s. w.

$\Rightarrow \exists 2$ ~~lin. indep.~~
 (Übungen) \rightarrow Ex. 8.2)
 fonctions lin. indep.

$$\bar{u}(p') \Gamma_\mu u(p) = \bar{u}(p') \left[F_1(q^2) \gamma_\mu + F_2(q^2) i\sigma_{\mu\nu} q^\nu \right] u(p)$$

$F_1(q^2)$: ~~Dirac Formfaktor~~

Facteur de forme de Dirac

du nucléon

$F_2(q^2)$: ~~Pauli Formfaktor~~

~~des nucléons~~

Fact. de forme de Pauli

Décomposition du courant de Gordon
 ~~Gordon Zerlegung d. Stromes~~



$$\bar{u}(p') \gamma_\mu u(p) = \bar{u}(p') \frac{1}{2M} \left[(p+p')_\mu + i\sigma_{\mu\nu} (p'-p)^\nu \right] u(p)$$

kein Operator (Quasimfeld)
 \downarrow Matrixelement

Ex. Ansatz: Kovariantenzerlegung
 (\rightarrow Übungen)
 direkt nachrechnen
 Kovariantenzerlegung (2)

$$\bar{u}(p') \Gamma_\mu u(p) = \bar{u}(p') \left[(F_1 + 2MF_2) \gamma_\mu - F_2 (p+p')_\mu \right] u(p)$$

mit ~~avec~~

$$j_\mu = j_\mu^+ \Rightarrow F_i = F_i^*, \quad F_i \text{ réel } (q^2 < 0)$$

$$\int \underbrace{F \bar{u} \gamma_\mu u}_{\in \mathbb{C}} = \left(F \bar{u} \gamma_\mu u \right)^* = F^* u^\dagger \gamma_\mu^+ \gamma_0^+ u$$

$$= F^* u^\dagger \gamma_0 \gamma_\mu \gamma_0 u$$

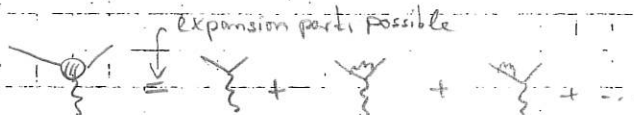
$$\gamma_0^+ = \gamma_0, \quad \gamma_r^+ = \gamma_0 \gamma_r \gamma_0$$

$$\gamma_0 \gamma_\mu^+ \gamma_0 = \gamma_\mu$$

$$= \bar{\gamma}_\mu$$

$$= F^* \bar{u} \gamma_\mu u \quad \sim \quad \underline{F = F^*}$$

Rem.: De même en QED



sauf que F_1, F_2 calculable pert. $F_1(q^2) = 1 + O(\alpha)$

$$F_2(q^2) = O(\alpha)$$

$\bar{u}(p') \Gamma_\mu u(p)$ statt $\bar{u} \gamma_\mu u$:

$$\frac{d\sigma}{dt} = \frac{2\pi\alpha^2}{(s-M^2)^2 t^2} [2st + 2(s-M^2)^2] \left\{ F_1^2 - t F_2^2 + \frac{t^2}{2[st + (s-M^2)^2]} (F_1 + 2M F_2)^2 \right\}$$

Formule de Rosenbluth - ~~Formule~~

Systeme du laboratoire:

~~Laborsystem:~~

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_{\text{Mott}}}{d\Omega} \underbrace{\left(\frac{1}{1 + \frac{2E}{M} \sin^2 \frac{\theta}{2}} \right)}_{\text{Interferenzterm } F_1 F_2 \text{ im Vergleich zu } G_E^2} \left\{ F_1^2 - t F_2^2 - \frac{t}{2M^2} (F_1 + 2M F_2)^2 \tan^2 \frac{\theta}{2} \right\}$$

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_M}{d\Omega} \left\{ \frac{G_E^2}{1 - q^2/4M^2} - \frac{q^2}{4M^2} \left(\frac{1}{1 - q^2/4M^2} + 2 \tan^2 \frac{\theta}{2} \right) G_M^2 \right\}$$

avec ~~avec~~

$$G_E(q^2) = F_1(q^2) + \frac{q^2}{2M} F_2(q^2), \quad G_M = F_1(q^2) + 2M F_2(q^2)$$

~~elektrische Formfaktor~~

Facteur de forme électrique

($|q^2| \ll M^2$: G_E est la transformée de la distribution de charge)

~~magnétique Formfaktor~~

Facteur de forme magnétique

~~(Sachs Formfaktor)~~

(Fourier de la distri. du moment magnétique)

termes d'interférence

mesure simple

~~interférence terme~~ $G_E G_M \Rightarrow$ ~~simple~~ simple ~~mesure~~ mesure ~~de~~ de G_E, G_M

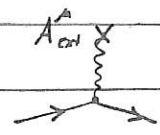
~~via~~

$$\frac{d\sigma}{d\Omega} / \frac{d\sigma_M}{d\Omega}$$

vs. $\tan^2 \frac{\theta}{2}$

Droite de Rosenbluth

$\bar{u} \Gamma_\mu u$: $q^2=0$ nicht-relativist. (Limes) WW eines Nukleons mit externem Feld A_{ext}^μ ($|p'| \ll M$)



~~$$S_{fi} = -i \int d^4x \langle p' | j_{\text{em}}^\mu | p \rangle A_{\mu}^{\text{ext}}(x)$$~~

~~$$= -i \int d^4x \mathcal{H}'(x) = -i \int dt H'(t)$$~~

~~$$\mathcal{H}' = -\mathcal{L}'$$~~

~~$$H = \int d^3x A_{\text{ext}}^\mu(x) \langle p' | e j_\mu(x) | p \rangle$$~~

~~$$e e^{i(p'-p) \cdot x} \langle p' | j_\mu(0) | p \rangle = e e^{i(E'-E)t - i(\vec{p}'-\vec{p}) \cdot \vec{x}} \langle \dots \rangle$$~~

~~Autre convention: $F_2 \rightarrow F_2 + \frac{2k}{2M}$
 $F_2 = F_1 - \text{mom}$
Comme magn
Absolut
extremel~~

Limit $q^2 \rightarrow 0$: * large longueur d'onde des photons

* la structure du proton n'est pas résolue

On voit une particule de charge e et d'un moment magnétique

$$g = 2(1 + \mu)$$

$$\Rightarrow \mu = \frac{g-2}{2}$$

2 ?

$$\downarrow \frac{e}{2M} (1 + \mu)$$

↑
mom. magn. anomal

$$\Rightarrow F_1^p(0) = 1 \quad ; \quad F_1^n(0) = 0 \quad \text{charge des nucléons}$$

$$F_2^p(0) = \frac{\mu_p}{2M} \quad , \quad \mu_p \approx 1,79$$

$$F_2^n(0) = \frac{\mu_n}{2M} \quad , \quad \mu_n \approx -1,91$$

(→ Ex. 8.3 (8.4))

Autre convention:

$$F_2 \rightarrow \tilde{F}_2 = F_2 \left(\frac{M}{2M}\right)^{-1} \Rightarrow \tilde{F}_2(0) = 1$$

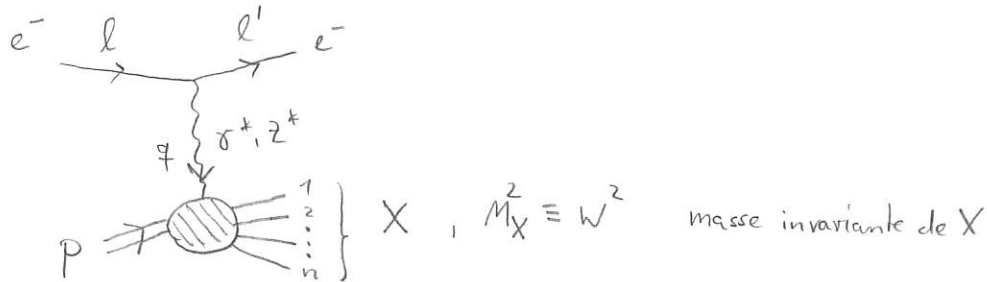
[Next time: Add VN scattering]

8.2 La diffusion inélastique $eN \rightarrow eX$

Considérons : $e^- N \rightarrow e^- X$ ou $\bar{\nu} N \rightarrow \bar{\nu} X$

non pas $\nu N \rightarrow \mu^- X$, $\bar{\nu} N \rightarrow \mu^+ X$, $e^- N \rightarrow \nu_e X$

$\nu N \rightarrow \nu N$, $\bar{\nu} N \rightarrow \bar{\nu} N$ \leftrightarrow aussi violation de la parité



X : système hadronique quelconque (exp. pas analysé)

$$p^2 = M^2 \gg l^2 = l'^2 \simeq 0$$

2 variables lin. indép. $\leftrightarrow E', \theta$

$$Q^2 = -q^2 = -(l-l')^2 \geq 0$$

$$v = \frac{P \cdot q}{M} = \underset{\text{Lab.}}{E - E'} \quad \text{"transfert d'énergie"}$$

$P = (M, \vec{0})$

Commun: variables sans dimension

$$x := \frac{Q^2}{2P \cdot q} = \frac{Q^2}{2Mv} \quad , \quad 0 \leq x \leq 1 \quad \text{Bjorken } x$$

$$y := \frac{P \cdot q}{P \cdot l} = \underset{\text{Lab.}}{v} \frac{1}{E} = \frac{E - E'}{E} \quad , \quad 0 \leq y \leq 1 \quad \text{Paramètre d'inélasticité}$$

le plus souvent utilisé : x, Q^2

Relation entre Q^2, x, y :

$$Q^2 = (2p \cdot l) \left(\frac{Q^2}{2P \cdot q} \right) \left(\frac{P \cdot q}{P \cdot l} \right) = S \times y \quad ; \quad S = 2p \cdot l = (p+l)^2 - p^2 - l^2$$

$$= 2ME \times y$$

Masse invariante de X:

$$\begin{aligned}
 W^2 &= (p+q)^2 = M^2 + 2p \cdot q + q^2 \\
 &= M^2 + \frac{Q^2}{x} - Q^2 \\
 &= M^2 + \frac{Q^2}{x} (1-x)
 \end{aligned}$$

diffusion élastique: $W^2 = M^2 = p^2 \Leftrightarrow x = 1$

inélastique: $W \geq M + m_\pi$ } • résonances discrètes: $W^2 = M_\Delta^2, M_{N^*}^2, \dots$
 $\frac{M_R^2 - M^2 + Q^2}{Q^2} = \frac{1}{x} \equiv \omega$

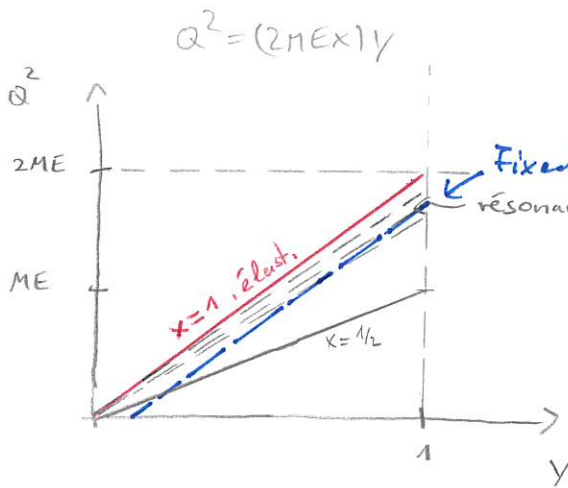
• continuum

diffusion profondément inélastique:

Q^2, W large

in praxi: $Q^2 \geq 1 \dots 2 \text{ GeV}^2 \Leftrightarrow x > x_{\min}, y > y_{\min}$

$W \geq 2 \text{ GeV} \Leftrightarrow x < x_{\max}, y > y_{\min}$



$Q^2 = (2MEx)y$ with $x = \frac{Q^2}{Q^2 + M_R^2 - M^2}$
 $\Rightarrow Q^2 = M^2 - M_R^2 + \sqrt{2ME} y$
 parallel to elastic curve

$$Q^2 = 2ME x \gamma \quad ; \quad x = x(Q^2) : \quad W^2 \stackrel{!}{=} M_R^2 = M^2 + \frac{Q^2}{x} (1-x)$$

$$\Rightarrow x = \frac{Q^2}{Q^2 + M_R^2 - M^2}$$

$$Q^2 = 2ME \frac{Q^2}{Q^2 + M_R^2 - M^2} \gamma$$

$$c=1 \quad Q^2 + M_R^2 - M^2 = 2ME \gamma$$

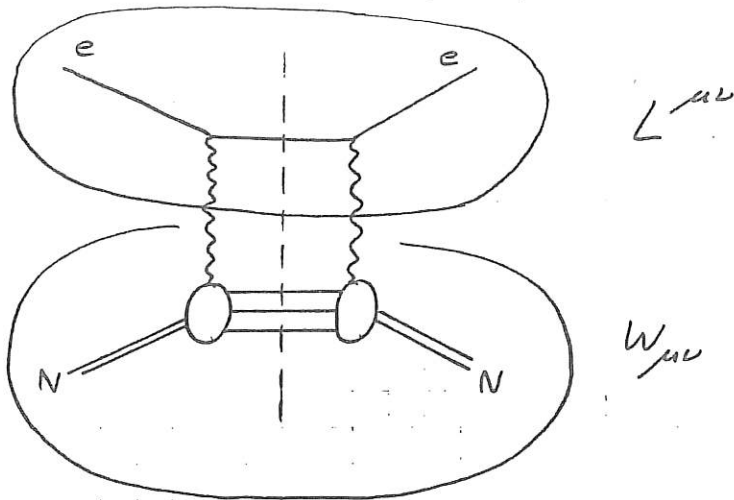
$$c=1 \quad Q^2 = M^2 - M_R^2 + \underbrace{2ME \gamma}_{\text{parallel to elastic curve}}$$

Section effluence:

~~allg.~~ Wirkungsquerschnitt:

$$d\sigma \sim \frac{e^4}{(q^2)^2} \underbrace{L^{\mu\nu}}_{\text{Leptonische (QED)}} \underbrace{W_{\mu\nu}}_{\text{Hadronische (QCD)}} 4\pi M$$

Konvention



avec ~~mit~~

$$L^{\mu\nu} = \frac{1}{2} \sum_{s_1, s_2} [\bar{u}(l') \gamma^\mu u(l) \bar{u}(l) \gamma^\nu u(l')] \\ = \frac{1}{2} \text{Tr} (\gamma^\mu (\not{l} + m) \gamma^\nu (\not{l}' + m))$$

$$= 2 (l^\mu l'^\nu + l^\nu l'^\mu - g^{\mu\nu} (l \cdot l' - m^2))$$

"trivial", ~~bekannt~~ ^{connu} ~~de la~~ ~~QED~~

$$W_{\mu\nu} = \frac{1}{4\pi M} \sum_X (2\pi)^4 \delta(p + q - p_X) \langle p | j_\mu^{em+}(0) | X \rangle \langle X | j_\nu^{em}(0) | p \rangle$$

$$\sum_X \equiv \frac{1}{2} \sum_{S_p} \sum_N \left(\sum_{S_p'} \int \frac{d^3 p_n}{(2\pi)^3 2p_n^0} \dots \right)$$

$$\frac{1}{2} \sum_{S_p} \sum_{S_p'} \langle p | j_\mu^{em+}(0) | p \rangle \langle p | j_\nu^{em}(0) | p \rangle \equiv \Theta_{\mu\nu}$$

$$\leadsto W_{\mu\nu} = \frac{1}{4\pi M} \int d^4 z e^{iqz} \langle p | j_\mu^{em+}(z) j_\nu^{em}(0) | p \rangle$$

~~(Spinnentwicklung weiter)~~

$$\equiv \underbrace{\left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2} \right)}_{-\hat{g}_{\mu\nu}} W_1(x, Q^2) + \frac{1}{M^2} \underbrace{\left(p_\mu - \frac{p \cdot q}{q^2} q_\mu \right)}_{p_\mu^+ - \frac{p \cdot q}{q^2} q_\mu^+} \underbrace{\left(p_\nu - \frac{p \cdot q}{q^2} q_\nu \right)}_{p_\nu^+ - \frac{p \cdot q}{q^2} q_\nu^+} W_2(x, Q^2)$$

paramétrisiert Unwissenheit über Hadronen

Paramétrisation de notre ignorance des hadrons
 Forme générale covariante + conservation du courant
~~allg.~~ lorentzkovariante Form, die Stromerhaltung erfüllt

(wie bei elast. Formfaktoren) (\Rightarrow facteurs de forme)

$$q^\mu W_{\mu\nu} = q^\nu W_{\mu\nu} = 0$$

Rem. Bemerkung: ^{pour} falls $\nu N \rightarrow \mu^- X$, $\nu N \rightarrow \nu X$

dann \exists ^{fonction de structure supplémentaire} ~~weiterer Formfaktor~~:

$$W_{\mu\nu} = \dots - \frac{i}{2M^2} \underbrace{\epsilon_{\mu\nu\alpha\beta} p^\alpha q^\beta}_{\text{Pseudotensor}} W_3(x, Q^2)$$

Section efficace différentielle \rightarrow ^{Violation de la parité} ~~Paritätsverletzung~~

Diff. Wirkungsquerschnitt:

~~$$d\sigma = \frac{1}{4F} \left\{ \frac{e^4}{q^4} L^{\mu\nu} W_{\mu\nu} 4\pi M \right\} \frac{d^3 l'}{2E'(2\pi)^3}$$~~

~~$$\text{avec } F = 4\sqrt{(lp)^2 - m^2 M^2} \quad \text{Möller-Fluß}$$~~

Lab.:

$$\frac{d^2\sigma}{dE'd\Omega'} = \frac{4\alpha^2 E'^2}{Q^4} \left[2W_1 \sin^2 \frac{\theta}{2} + W_2 \cos^2 \frac{\theta}{2} \right]$$

Fonctions de structure F_i sans dimension:

dimensionslose Strukturfunktionen F_i :

$$F_1(x, Q^2) = M W_1(x, Q^2)$$

$$F_2(x, Q^2) = \nu W_2(x, Q^2)$$

$$F_3(x, Q^2) = \nu W_3(x, Q^2)$$

$$4\sqrt{(lp)^2 - m^2 M^2} = 2\sqrt{\lambda} = 2(S - M^2)$$

$$\lambda \equiv \lambda(s, m^2, M^2)$$

$$\frac{d^3 l'}{12\pi^3 2E'} = \frac{1}{20\pi^2} ME' dx dy$$

$$= \frac{S - M^2}{4\pi^2} y dx dy$$

$$\Rightarrow \frac{d^2\sigma}{dx dy} = \frac{4\pi\alpha^2 S}{Q^4} \left((1-y)F_2 + xy^2 F_1 + \mathcal{O}\left(\frac{M}{E}\right) \right) = \frac{2ME}{E'} \pi y \frac{d^2\sigma}{dE'd\Omega'}$$

~~$$Q^2 := -q^2 = -(k-a)^2 = 2kk' \quad , \quad S = (k+p)^2 = 2kp = \frac{4p^2}{y} = \frac{-q^2}{xy} = \frac{Q^2}{xy}$$~~

~~$$\Rightarrow \parallel Q^2 = Sxy \parallel$$~~

~~Naive Partonmodell: $F_1(x) = \frac{1}{x} F_2(x)$ \leftarrow Gitter-Gross-Relation~~

~~$$\Rightarrow \frac{d^2\sigma}{dx dy} = \frac{4\pi\alpha^2 S}{Q^4} \left\{ (1-y)F_2 + \frac{y^2}{x} F_2 \right\} = \frac{2\pi\alpha^2}{Sx^2 y^2} \left\{ 1 + (1+y)^2 \right\} F_2(x)$$~~

~~$$\frac{d^2\sigma}{dx dy} = \frac{4\pi\alpha^2}{x^2 y^2 S} \left\{ (1-y)F_2 + xy^2 F_1 + (y - \frac{y^2}{x}) F_3 \right\}$$~~

Discussion:

* voir sec. 16 booklet

a) $dG \sim L_{\mu\nu} W_{\mu\nu}^{BB'}$ $Q^2 \geq M_Z^2$: Test du MS F_i^{NC}

Par ex.: $\delta\delta, \delta z + z\delta, z z$ $\rightarrow F_i^{\delta\delta}, F_i^{\delta z}, F_i^{zz}$

$WW \rightarrow F_i^{WW} = F_i^{CC}$

$WW, WW' + W'W, W'W'$



b) $W_{\mu\nu} = -g_{\mu\nu} F_1(x, Q^2) + \frac{P_\mu^\perp P_\nu^\perp}{P \cdot q} F_2(x, Q^2)$ Résonances, élastique:

$-i \epsilon_{\mu\nu\alpha\beta} \frac{q^\alpha P^\beta}{2P \cdot q} F_3(x, Q^2)$ \leftarrow violation de Parité

$+ \text{Spin-dep. } [g_1(x, Q^2), \dots, g_5(x, Q^2)]$ (échange W^\pm, Z)

(\exists aussi F_4, F_5 : négligé car $\propto m_e^2/s$ dans dG)

c) Projecteurs: $P_i^{\mu\nu} W_{\mu\nu} = F_i$, $P_i^{\mu\nu} = a g^{\mu\nu} + b P_\perp^\mu P_\perp^\nu + c i \epsilon^{\mu\nu\alpha\beta} q_\alpha P_\beta$

$\rightarrow 2 \times F_1 \equiv F_T$  $\propto F_T$  $\propto F_L$

$F_2 = F_L + F_T$

d) Calculer $F_i(x, Q^2)$ dans le modèle des partons (plus tard)

$F_2(x, Q^2) = x \left(\frac{4}{9} (u + \bar{u}) + \frac{1}{9} (d + \bar{d} + s + \bar{s}) + \frac{4}{9} (c + \bar{c}) \right) \neq O(\alpha_s)$

$\uparrow \quad \uparrow$
PDFs

e) F_2^P mesuré avec précision énorme à HERA @ DESY Hambourg (exp. H1, ZEUS)

$F_2^P(x, Q^2)$ vs Q^2 ; $Q^2 = Sxy \rightarrow$ petit $x \hat{=}$ petit Q^2

pas calculable \uparrow prediction

\rightarrow violation d'échelle : $F_2 \searrow Q^2$ pour $x \gtrsim 0.2$

\uparrow prediction de la QCD $F_2 \approx \text{const}$ pour $x \approx 0.1, 0.2$ (scaling)

$F_2 \nearrow Q^2$ pour $x \lesssim 0.1$