Pion-nucleon scattering amplitude

$$S = :\exp\left[\int \left(\phi_{in} \overleftrightarrow{K} \frac{\delta}{\delta J} + \bar{\psi}_{in} \overrightarrow{D} \frac{\delta}{\delta \bar{\eta}} - \frac{\delta}{\delta \eta} \overleftarrow{\bar{D}} \psi_{in}\right) dx\right]: Z[J,\eta,\bar{\eta}]|_0$$

其中 $D = i\gamma^\mu \partial_\mu - m \quad \bar{D} = -i\gamma^\mu \overleftarrow{\partial}_\mu - m$

$$\mathcal{L}_{int} = ig\underset{\sim}{\bar{\psi}\gamma_5\vec{\tau}\psi} \cdot \underline{\vec{\phi}}$$

定义

$$\phi^{\mp} = \frac{1}{\sqrt{2}}(\phi_1 \pm i\phi_2), \quad \phi^0 = \phi_3$$

$$\mathcal{L}_{int} = i\sqrt{2}g(\bar{p}\gamma_5 n\phi^+ + \bar{n}\gamma_5 p\phi^-) + ig(\bar{p}\gamma_5 p - \bar{n}\gamma_5 n)\phi^0$$

$\pi^+ \quad p$

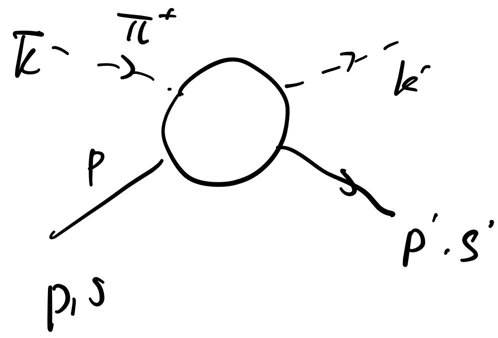
$$\mathcal{L}_{int} = i\sqrt{2}g(\bar{p}\gamma_5 n\phi^+ + \bar{n}\gamma_5 p\phi^-)$$

$$\mathcal{L} = \mathcal{L}_0 + \mathcal{L}_{int} = \bar{\psi}\gamma^\mu\partial_\mu\psi + m\bar{\psi}\psi + \frac{1}{2}\partial^\mu\vec{\phi}\partial_\mu\vec{\phi} - \frac{1}{2}m^2\vec{\phi}^2 + i\sqrt{2}g(\bar{p}\gamma_5 n\phi^+ + \bar{n}\gamma_5 p\phi^-)$$

$$Z[J,\eta,\bar{\eta}] = \frac{\exp\left\{i\int\left(i\sqrt{2}g\frac{\delta}{\delta\eta(z)}\gamma_5\frac{\delta}{\delta\bar{\eta}(z)}\frac{\delta}{\delta J(z)}\right)dz\right\}Z_0[J,\eta,\bar{\eta}]}{[\cdots]|_{J=\eta=\bar{\eta}=0}}$$

$$= \frac{\int D\phi D\eta D\bar{\eta}\exp\left[i\int\left(\bar{\psi}S^{-1}\psi - \frac{1}{2}\phi K\phi + \bar{\eta}\psi + \bar{\psi}\eta + J\phi\right)dx\right]}{[\cdots]|_{J=\eta=\bar{\eta}=0}}$$

$$= \exp\left\{-i\int\left[\frac{1}{2}J(x)\Delta_F(x-y)J(y) + \bar{\eta}(x)S(x-y)\eta(y)\right]dxdy\right.$$



$$S_{fi} = \langle p', s'; k' | S | p, s; k \rangle$$

$$S = :\exp\left[\int \left(\phi_{in} \overrightarrow{K} \frac{\delta}{\delta J} + \bar{\psi}_{in} \overrightarrow{D} \frac{\delta}{\delta \bar{\eta}} - \frac{\delta}{\delta \eta} \overleftarrow{\bar{D}} \psi_{in} \right) dx \right]: Z[J, \eta, \bar{\eta}]\Big|_0$$

$$|p, s; k\rangle = b_s^\dagger(p) a^\dagger(k) |0\rangle$$
$$\langle p', s'; k' | = \langle 0 | b_{s'}(p') a(k')$$

$$S_{fi} = \langle 0 | b_{s'}(p') a(k') \left[1 + :\int \left(\phi_{in} \overrightarrow{K} \frac{\delta}{\delta J} + \bar{\psi}_{in} \overrightarrow{D} \frac{\delta}{\delta \bar{\eta}} - \frac{\delta}{\delta \eta} \overleftarrow{\bar{D}} \psi_{in}\, dx \right): + \cdots \right] Z\Big|_0$$
$$\times\, b_s^\dagger(p) a^\dagger(k) |0\rangle$$

$$b_s(p)|0\rangle = a(k)|0\rangle$$

代入ϕ_{in} $\quad \phi$

$$\langle 0 | a(k') \int dx \frac{d^3 q}{[(2\pi)^3 2\omega_q]^{1/2}} \left[f_q(x) a(q) + f_q^*(x) a^\dagger(q) \right] a^\dagger(k) |0\rangle \overrightarrow{K} \frac{\delta}{\delta J}$$

$$= \Big\{ \langle 0 | a(k') \int dx \frac{d^3 q}{[(2\pi)^3 2\omega_q]^{1/2}} f_q(x) [a(q), a^\dagger(k)] |0\rangle$$
$$+ \langle 0 | \int dx \frac{d^3 q}{[(2\pi)^3 2\omega_q]^{1/2}} f_q^*(x) [a(k'), a^\dagger(q)] a^\dagger(k) |0\rangle \Big\} \overrightarrow{K} \frac{\delta}{\delta J}$$
$$= 0$$

$$\frac{1}{2}\left(\overrightarrow{K} [\delta/\delta J]\right)^2$$

$$\langle 0 | a(k') \int dx_1 dx_2 \frac{d^3 q}{[(2\pi)^3 2\omega_q]^{1/2}} \frac{d^3 q'}{[(2\pi)^3 2\omega_{q'}]^{1/2}} \Big[f_q(x_1) f_{q'}(x_2) a(q) a(q')$$
$$+ f_q(x_1) f_{q'}^*(x_2) a^\dagger(q') a(q) + f_q^*(x_1) f_{q'}(x_2) a^\dagger(q) a(q')$$

$$+ f_q^*(x_1) f_{q'}^*(x_2) a^+(q) a^+(q')] a^+(k)|0\rangle$$

$$\langle 0| a(k') a^+(q') a(q) a^+(k)|0\rangle = \langle 0|[a(k'), a^+(q')][a(q), a^+(k)]|0\rangle$$
$$= (2\pi)^6 4 \omega_{k'} \omega_k \delta^3(k'-q') \delta^3(q-k)$$
$$\langle 0| a(k') a^+(q) a(q') a^+(k)|0\rangle = (2\pi)^6 4 \omega_{k'} \omega_k \delta^3(k'-q) \delta^3(k-q')$$

$$\int dx_1 dx_2 \frac{d^3q\, d^3q'}{[4\omega_q \omega_{q'}]^{1/2}} 4\omega_k \omega_{k'} \frac{1}{[4\omega_q \omega_{q'}]} [e^{-i(qx_1 - q'x_2)} \times \delta^3(k'-q') \delta^3(q-k) + e^{i(qx_1 - q'x_2)}$$
$$\delta^3(k'-q) \delta^3(k-q')]$$

$$= \int dx_1 dx_2 (e^{-ikx_1} e^{ik'x_2} + e^{ik'x_1} e^{-ikx_2})$$

$$\frac{1}{2} K_{x_1} \frac{\delta}{\delta J(x_1)} K_{x_2} \frac{\delta}{\delta J(x_2)} Z[J, \eta, \bar{\eta}] \Big|_{J=\eta=\bar{\eta}=0} \quad \text{2 3 項}$$

$$\int dx_1 dx_2\, e^{-ik'x_2} \frac{1}{2} K_{x_2} \frac{\delta}{\delta J(x_1)} \frac{\delta}{\delta J(x_2)} Z[J, \eta, \bar{\eta}] \Big|_{J=\eta=\bar{\eta}=0} \overleftarrow{K}_{x_1} e^{-ikx_1}$$

$$\int dx_3 dx_4 \langle 0| b_{s'}(p') : \left[\bar{\psi}(x_4) D_{x_4} \frac{\delta}{\delta \bar{\eta}(x_4)} - \psi(x_4) \frac{\delta}{\delta \eta(x_4)} \bar{D}_{x_4} \right]$$
$$\times \left[\bar{\psi}(x_3) D_{x_3} \frac{\delta}{\delta \bar{\eta}(x_3)} - \psi(x_3) \frac{\delta}{\delta \eta(x_3)} \bar{D}_{x_3} \right] b_s^+(p)|0\rangle$$

$:\bar{\psi}(x_4)\bar{\psi}(x_3):$ $\quad$ $:\psi(x_4)\psi(x_3):$ $\quad$ vanish

$:\bar{\psi}(x_4)\psi(x_3):$

$$-\langle 0| b_{s'}(p') \int \frac{d^3q\, d^3q'}{(2\pi)^6} \frac{m^2}{q_0' q_0} \sum_{\alpha \alpha'} : [b_\alpha^+(q) \bar{u}^\alpha(q) e^{iqx_4} + d_\alpha(q) \bar{v}^\alpha(q) e^{-iqx_4}$$
$$\times (b_{\alpha'}(q') u^{\alpha'}(q') e^{-iq'x_3} + d_{\alpha'}^+(q') v^{\alpha'}(q') e^{iq'x_3}] : b_s^+(p)$$
$$|0\rangle$$

$$= -\int \frac{d^3q\, d^3q'}{(2\pi)^6} \frac{m^2}{q q_0} \sum_{\alpha\alpha'} \langle 0| b_{s'}(p') b_\alpha^+(q) b_{\alpha'}(q') b_s^+(p)|0\rangle \times \bar{u}^\alpha(q) u^{\alpha'}(q') e^{iqx_4}$$
$$e^{-iq'x_3}$$

$$= -\bar{u}^{s'}(p') u^s(p) e^{ip'x_4} e^{-ipx_3}$$

$:\psi(x_4)\bar\psi(x_3):$

$\frac{1}{2}D_{x_4}(\delta/\delta\bar\eta(x_4))(\delta/\delta\eta(x_3))\bar D_{x_3}$ $\qquad$ $\frac{1}{2}(\delta/\delta\eta(x_4))\bar D_{x_4} D_{x_3}(\delta/\delta\bar\eta(x_3))$

$\delta/\delta\eta$, $\delta/\delta\bar\eta$

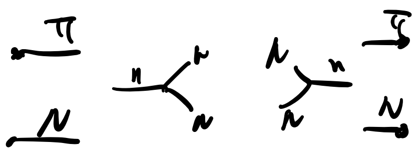
$$\int dx_3 dx_4\, e^{ip'x_4}\bar u^{s'}(p')D_{x_4}\frac{\delta}{\delta\eta(x_3)}\frac{\delta}{\delta\eta(x_4)} Z[J,\eta,\bar\eta]\Big|_{J=\eta=\bar\eta=0}\overleftarrow{\bar D}_{x_3}\, u^s(p)e^{-ipx_3}$$

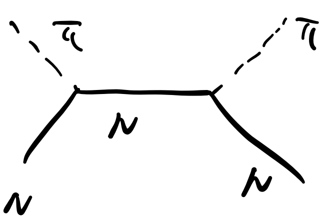
$$S_{fi}=\int dx_1\cdots dx_4\, e^{ik'x_2}e^{ip'x_4}\bar u^{s'}(p')\overrightarrow{K}_{x_2}\overrightarrow{D}_{x_4}\underline{\tau(x_1,\dots,x_4)}\overleftarrow{\bar D}_{x_2}\overleftarrow{\bar K}_{x_1}\, u^s(p)e^{-ipx_3}e^{-ikx_1}$$

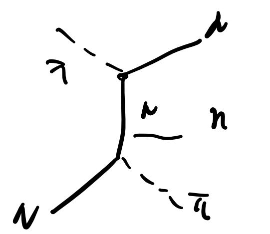
$$\tau(x_1,x_2,x_3,x_4)=\frac{\delta}{\delta J(x_1)}\frac{\delta}{\delta J(x_2)}\frac{\delta}{\delta\eta(x_3)}\frac{\delta}{\delta\bar\eta(x_4)}Z[J,\eta,\bar\eta]\Big|_{J=\eta=\bar\eta=0}$$

ϕ^4 $\quad i\bar\psi\gamma_5\psi\phi$

$(\pi N)\to(\pi N)$





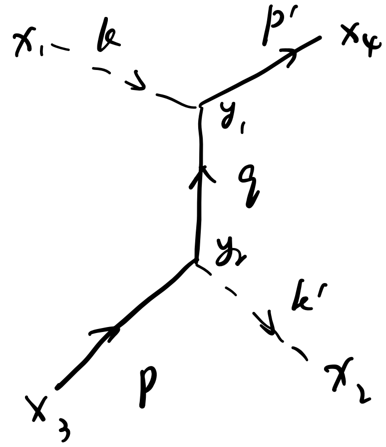


$\sqrt{2}\,g$ $\qquad i\gamma_5$

$\langle\phi_{out}|S|\phi_{in}\rangle$

$$\tau(x_1,x_2,x_3,x_4)=2g^2\int dy_1 dy_2\, i\Delta_F(x_2-y_2)\,iS(x_4-y_1)\,i\gamma_5 \times iS(y_1-y_2)\,i\gamma_5\, iS(y_2-x_3)\,i\Delta_F(x_1-y_1)$$

N^{++}



$$\begin{cases} K_x \Delta_F(x-y) = (\Box_x + m^2)\Delta_F(x-y) = -\delta^4(x-y) \\ D_x S(x-y) = (i\gamma\cdot\partial_x - M) S(x-y) = \delta^4(x-y) \\ S(x-y)\overleftarrow{D}_x = S(x-y)(-i\gamma\overleftarrow{\partial}_x - M) = \delta^4(x-y) \end{cases}$$

$$S_{fi} = -2ig\int dx_1 \cdots dx_4\, dy_1 dy_2\, e^{ik'x_2} e^{ip'x_4} \bar{u}^{s'}(p') \delta^4(x_2-y_2)$$
$$\times \delta^4(x_4-y_1)\gamma_5 S(y_1-y_2)\gamma_5 \delta^4(y_2-x_3)\, \delta^4(y_1-x_1) u^s(p) e^{-ipx_3} e^{-ikx_1}$$

$$= -2ig^2\int dy_1 dy_2\, e^{i(p'-k)y_1} e^{i(k'-p)y_2}\, \bar{u}^{s'}(p')\gamma_5 S(y_1-y_2)\gamma_5 u^s(p)$$

$S(x)$ $\Delta_F(x)$

$$S(y_1-y_2) = \frac{1}{(2\pi)^4}\int dq\, \frac{\gamma^\mu q_\mu + M}{q^2-m^2} e^{-iq(y_1-y_2)}$$

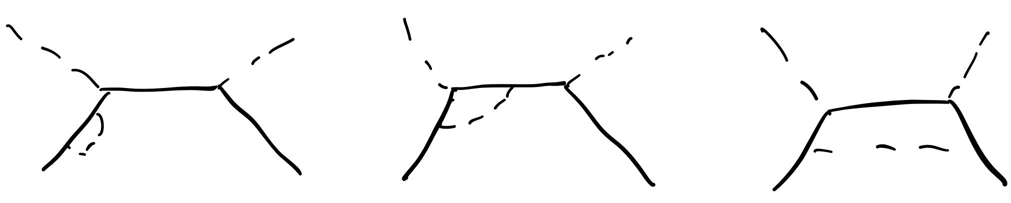
$$\int dy_1\, dy_2\, e^{i(p'-k)y_1} e^{i(k'-p)} e^{-iq(y_1-y_2)} = (2\pi)^8 \delta^4(p'-k-q)\,\delta^4(k'-p+q)$$
$$= (2\pi)^8 \delta^4(q-p+k')\,\delta^4(p'+k'-p-k)$$
$$= (2\pi)^8 \delta^4(q-p+k')\,\delta^4(P_f-P_i)$$

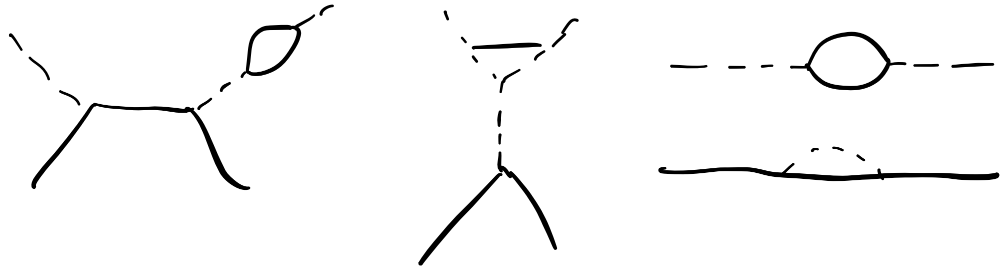
$p-k' \Leftrightarrow p'-k$

$$S_{fi} = -i\delta^4(P_f-P_i)\, 2g^2 (2\pi)^4\, \bar{u}^{s'}(p')\gamma_5 \frac{\gamma(p-k')+M}{(p-k')^2-M^2}\gamma_5 u^s(p)$$

$$= i\delta^4(P_f-P_i)\, 2g^2(2\pi)^4\, \bar{u}^{s'}(p')\, \gamma\cdot k' u^s(p) \frac{1}{2pk'-m^2}$$

1. n阶 → n个顶点





2. 入射 spinor: $u(p)$ ($v(p)$ 反粒子), 出射 spinor: $\bar{u}(p)$

3. 对于顶点, 标量 int: ig 赝标量 int: $i\gamma_5 g$ 乘以 $(2\pi)^4\delta^4$

4. spinor prop: $\frac{i}{(2\pi)^4}\frac{i}{(\gamma\cdot p-m)}d^4p$

5. (pseudo) scalar prop: $\frac{i}{(2\pi)^4}\frac{i}{p^2-m^2}d^4p$

6. 积分 (内部动量)

Scattering cross-section

Lorentz invariant M

$$\langle p_1', p_2', \cdots, | S-1 | p_1, p_2, \cdots \rangle$$
$$= (2\pi)^4\delta^4(p_f - p_i)\, iM(p_1', p_2', \cdots p_1, p_2, \cdots)$$

p_1 p_2

$$|i\rangle = \int \frac{d^3k_1}{(2\pi)^3 2k_1^0}\frac{d^3k_2}{(2\pi)^3 2k_2^0} f(k_1)\, g(k_2)\, |k_1, k_2\rangle$$

$k_1 \simeq p_1$, $k_2 \simeq p_2$

$$|f\rangle = |p_1', p_2'\rangle$$

$$\int d\tilde{k}_1 d\tilde{k}_2 f(k_1) g(k_2) \langle p_1' p_2' | S-1 | k_1 k_2 \rangle$$

$$= (2\pi)^4 i \int d\tilde{k}_1 d\tilde{k}_2 f(k_1) g(k_2) \delta(p_1'+p_2'-k_1-k_2) M(p_1', p_2', k_1 k_2)$$

$$W = (2\pi)^8 \int d\tilde{k}_1 d\tilde{k}_2 d\tilde{q}_1 d\tilde{q}_2 f(k_1) g(k_2) f^*(q_1) g^*(q_2)$$
$$\underline{\delta(p_1'+p_2'-k_1-k_2)\,\delta(p_1'+p_2'-q_1-q_2)}\, M(p_1', p_2', k_1, k_2) M^*(p_1', p_2', q_1 q_2)$$

$$\delta(k_1+k_2-q_1-q_2) \qquad M(p_1', p_2', p_1, p_2)$$

$$\hat{f}(x) = \int d\tilde{q}\, e^{iqx} f(q) \qquad d\tilde{q} = \frac{d^3 q}{(2\pi)^3 2q_0}$$

$$|\hat{f}(x)|^2 = \int d\tilde{k}_1 d\tilde{q}_1 e^{i(k_1-q_1)x} f(k_1) f^*(q_1)$$

$$|\hat{g}(x)|^2 = \int d\tilde{k}_2 d\tilde{q}_2 e^{i(k_2-q_2)x} g(k_2) g^*(q_2)$$

$$(2\pi)^4 \delta(k_1+k_2-q_1-q_2) = \int e^{i(k_1+k_2-q_1-q_2)} d^4x$$

$$W = \int d^4x\, |\hat{f}(x)|^2 |\hat{g}(x)|^2 (2\pi)^4 \delta(p_1'+p_2'-p_1-p_2) |M(p_1', p_2', p_1, p_2)|^2$$

$$\frac{dW}{dV dt} = |\hat{f}(x)|^2 |\hat{g}(x)|^2 (2\pi)^4 \delta(p_1'+p_2'-p_1-p_2) |M(p_1' p_2' p_1 p_2)|^2$$

$$|\hat{f}(x)|^2 2p_1^0 \qquad |\hat{g}(x)|^2 2p_2^0$$

$p_2^0 = m_2$ inc flux $= 2|\vec{p}_1| |\hat{f}(x)|^2$

tar density $= 2m_2 |\hat{g}(x)|^2$

$\frac{dW}{dt\,dV} = (\text{inc flux}) \times (\text{tar density}) \times d\sigma$

$$d\sigma = (2\pi)^4 \delta^4(p_1' + p_2' - p_1 - p_2) \frac{1}{4m_1|p_1|} |M|^2$$

$m_2|p_1|$

$B = [(p_1 \cdot p_2)^2 - m_1^2 m_2^2]^{1/2} = m_2|p_1|$ 实验室系

$$d\sigma = \frac{(2\pi)^4}{4B} \frac{d^3p_1'}{(2\pi)^3 2(p_1')_0} \frac{d^3p_2'}{(2\pi)^3 2(p_2')_0} \delta^4(p_f - p_i)|M|^2$$

s_1, s_2 (spin)

$$|M|^2 \to \frac{1}{(2s_1+1)(2s_2+1)} \sum_{s_1, s_2} |M_{fi}|^2$$

$p_0/m \qquad |\hat{g}(x)|^2$

$\frac{d^3p}{(2\pi)^3 2p_0} \qquad \left(\frac{m}{p_0}\right)\left[\frac{d^3p}{(2\pi)^3}\right]$

$$d\sigma = \frac{1}{(2\pi)^2} \frac{d^3p_1'}{2E_1'} \frac{d^3p_2'}{E_2/M} \cdot \frac{M}{2B} \delta^4(p_f - p_i) \frac{1}{S}\sum_{spin} |M_{fi}|^2$$

$$= \frac{1}{32\pi^2} \frac{d^3p_1}{E_1'} \frac{d^3p_2}{E_2'} \frac{M^2}{B} \delta(E_1' + E_2' - E_i)\, \delta^3(p_1' + p_2' - p_i) \sum_{spin} |M_{fi}|^2$$

F_{cms}: $\vec{p}_1' = -\vec{p}_2' = \vec{p}_f$

$$I = \int \frac{d^3p_1'}{E_1'} \frac{d^3p_2'}{E_2'} \delta(E_1' + E_2' - E_i)\, \delta^3(p_1' + p_2' - p_i)$$

$$= \int \frac{d^3p_f}{E_1' E_2'} \delta(E_1' + E_2' - E_i) = \int \frac{p_f^2\, dp_f\, d\Omega_f}{E_1' E_2'} \delta(E_1' + E_2' - E_i)$$

$\delta(f(x)) = \frac{\delta(x - x_0)}{|f'(x_0)|} \qquad f(x_0) =$

$$I = \frac{p_f}{E_i}\int d\Omega_f$$

$$\frac{d\sigma}{d\Omega} = \frac{1}{32\pi^2}\frac{M^2 p_f}{B E_i}\sum_{spin}|M_{fi}|^2$$

$$B = p_f(E_1' + E_2') = p_f W$$ ，W为系统能量

$$\frac{d\sigma}{d\Omega} = \frac{1}{32\pi^2}\left(\frac{M}{W}\right)^2\sum_{spin}|M_{fi}|^2$$

$$M_{fi} = 2g^2\,\bar{u}^{s'}(p')\,\gamma k'\,u^s(p)\,\frac{1}{2p\cdot k - m^2}$$

$$\sum_{spin}|\bar{u}' A u|^2 \qquad u' = u^{s'}(p') \qquad A$$

$$(\bar{u}' A u)^* = u'^T \gamma^{0*} A^* u^*$$
$$= u^\dagger A^\dagger \gamma^{0T} u'$$
$$= \bar{u}\bar{A}u'$$

$$\sum_\alpha u_i^\alpha(p)\,\overline{u}_j^\alpha(p) = \left(\frac{\gamma\cdot p + M}{2M}\right)_{ij}$$

$$\mathrm{Tr}(\gamma\cdot a)(\gamma\cdot b) = 4a\cdot b$$

$$\mathrm{Tr}(\gamma\cdot a)(\gamma\cdot b)(\gamma\cdot c)(\gamma\cdot d) = -\mathrm{Tr}(\gamma\cdot b)(\gamma\cdot a)(\gamma\cdot c)(\gamma\cdot d) + 2a\cdot b\,\mathrm{Tr}(\gamma\cdot c)(\gamma\cdot d)$$

$$\sum_{spin}|M_{fi}|^2 = 4g^4\left(\frac{1}{2p\cdot k' - m^2}\right)^2\frac{1}{4M^2}\mathrm{Tr}\{(\gamma\cdot p' + M)\gamma\cdot k'(\gamma\cdot p + M)\gamma\cdot k'\}$$

$$= \frac{g^4}{M^2}\left(\frac{1}{2p\cdot k' - m^2}\right)^2 4\{2(p\cdot k')(p'\cdot k') + m^2[M^2 - (p\cdot p')]\}$$

$$|\vec{p}| = |\vec{p}'| = |\vec{k}| = |\vec{k}'| = q$$

$$p = ((q^2+M^2)^{1/2}, \vec{q}), \quad k = ((q^2+m^2)^{1/2}, -\vec{q})$$

$$p' = ((q^2+M^2)^{1/2}, \vec{q}), \quad k' = ((q^2+m^2)^{1/2}, -\vec{q})$$

Low energy, $m, M \gg q$ $\quad p\cdot k' \simeq Mm \quad p'\cdot k' \simeq Mm \quad p\cdot p' \simeq M^2$

$$\sum_{\text{spin}} |M_{fi}|^2 \approx \frac{8g^4}{(2M-m)^2}$$

$$W \approx M+m$$

$$\frac{d\sigma}{d\Omega} = \frac{g^4}{4\pi^2}\left(\frac{M}{M+m}\right)^2 \frac{1}{(2M-m)^2} \approx \frac{g^4}{16\pi}\frac{1}{M^2}$$

Yukawa potential:

$$V = \frac{g e^{-\eta r}}{r} \qquad \eta = \chi^{-1} \qquad \text{pion Compton 波长}$$

$1.4\times10^{-15}\,m$

$r = \underline{2.8\times10^{-15}\,m}$ $\quad$ 20 MeV $\quad$ 0.5 MeV

$$\frac{g^2}{e^2} \approx 40$$

$$\frac{g^2}{\hbar c} \approx 40 \times \frac{e^2}{\hbar c} \approx 0.3$$

$$\begin{aligned}
\sigma &= 4\pi\left(\frac{d\sigma}{d\Omega}\right) \\
&= 4\pi\left(\frac{g^2}{4\pi}\right)^2 \frac{1}{M^2} \\
&= \frac{1}{4\pi}\left(\frac{g^2}{\hbar c}\right)^2\left(\frac{\hbar}{Mc}\right)^2 \\
&\simeq 120\,\mu b
\end{aligned}$$

$1b = 10^{-28}\,m^2$

$$\mathcal{L}_{int} = \frac{f}{m}\bar{\psi}\gamma_5\gamma^\mu\vec{\tau}\psi\cdot\partial_\mu\vec{\phi}$$

$\frac{f^2}{4\pi} = 0.08$ $\quad$ f 偏移值

Schweber, Bethe & de Hoffmann

$g = \left(\frac{2M}{m}\right) f$ （M 核子质量）

$\frac{g^2}{4\pi} \approx 15$ $\sigma = 4\pi \frac{d\sigma}{d\Omega} = 486$