H2.1

Chenhuan Wang

a) $H^\dagger = H, \quad \vec{p} \in \mathbb{R}^3, \; m \in \mathbb{R}$

$\Rightarrow \vec{\alpha}^\dagger = \vec{\alpha}, \quad \beta^\dagger = \beta$

$tr(\alpha_i) = \sum_{n=0}^{N} (\alpha_i)_{nn}, \quad \alpha_i \in \mathbb{R}^n \times \mathbb{R}^n$

$\alpha_i^\dagger = \alpha_i \Rightarrow (\alpha_i)_{nn}^* = (\alpha_i)_{nn}, \quad \forall\, n \le N$

$A^{-1} \alpha_i A = \tilde{\alpha}_i = \begin{pmatrix} \lambda_1 & & \\ & \ddots & \\ & & \lambda_n \end{pmatrix}$

$\underbrace{A^{-1}\alpha_i A}\, \underbrace{A^{-1}\alpha_i A} = A^{-1} \alpha_i^2 A = \mathbb{1}$

$\Rightarrow \tilde{\alpha}_i^2 = \mathbb{1}$

$\Rightarrow \lambda_n^2 = 1, \quad n \le N$

(true for β)

$tr[\beta^{-1}\alpha_i \beta] = tr[\alpha_i] = -tr[\alpha_i]$

$\Rightarrow tr[\alpha_i] = 0$

$tr[\alpha_i^{-1} \beta \alpha_i] = tr[\beta] = -tr[\beta]$

$\Rightarrow tr[\beta] = 0$

$tr[A^{-1}\alpha_i A] = tr[\alpha_i] = \sum_n \lambda_n$

$\Rightarrow$ N must be even in order to have trace $\sum_n \lambda_n = 0$ to be true

if $\alpha_i \in \mathbb{R}^2 \times \mathbb{R}^2, \quad \alpha_i = \begin{pmatrix} a & c+id \\ c-id & -a \end{pmatrix}, \quad a, b, c, d \in \mathbb{R}$

hermitian, traceless

$\det(\alpha_i - \lambda \mathbb{1}) = \begin{vmatrix} a-\lambda & c+id \\ c-id & -a-\lambda \end{vmatrix} = -(a-\lambda)(a+\lambda) - (c^2+d^2)$

$= -a^2 + \lambda^2 - c^2 - d^2 \overset{!}{=} 0$

$$\Rightarrow \quad \lambda = \pm\sqrt{a^2+c^2+d^2} \overset{!}{=} \pm 1 \Rightarrow a^2 = 1-c^2-d^2$$

c and d cannot be zero at same time.

2×2 does not work

b) $\gamma^\mu = (\beta, \beta\vec{\alpha})$

$$\{\gamma^0,\gamma^0\} = \{\beta,\beta\} = \beta^2+\beta^2 = 2\mathbb{1}$$

$$\{\gamma^0,\gamma^i\} = \{\beta,\beta\alpha^i\} = \beta\beta\alpha^i + \beta\alpha^i\beta = \alpha^i - \alpha^i = 0$$

$$\begin{aligned}\{\gamma^i,\gamma^j\} &= \{\beta\alpha^i,\beta\alpha^j\} = \beta\alpha^i\beta\alpha^j + \beta\alpha^j\beta\alpha^i \\ &= -\alpha^i\alpha^j - \alpha^j\alpha^i \\ &= \begin{cases} -2\mathbb{1}, & \text{if } i=j \\ 0, & \text{if } i\neq j \end{cases} \\ &= -2\delta^{ij}\mathbb{1}\end{aligned}$$

$$\Rightarrow \{\gamma^\mu,\gamma^\nu\} = 2g^{\mu\nu}\mathbb{1}$$

c) $\{\gamma^\mu,\gamma^5\}$

$$= i\{\gamma^\mu, \gamma^0\gamma^1\gamma^2\gamma^3\}$$

$$= i\,(\underbrace{\gamma^\mu\gamma^0\gamma^1\gamma^2\gamma^3} + \gamma^0\gamma^1\gamma^2\gamma^3\gamma^\mu)$$

$$\begin{aligned}&= \gamma^0(-\gamma^\mu + 2g^{\mu 0}\mathbb{1})\gamma^1\gamma^2\gamma^3 \\ &= -\gamma^0\gamma^\mu\gamma^1\gamma^2\gamma^3 + 2g^{\mu 0}\gamma^0\gamma^1\gamma^2\gamma^3 \\ &= -\gamma^0\gamma^1(-\gamma^\mu + 2g^{\mu 1})\gamma^2\gamma^3 + 2g^{\mu 0}\gamma^0\gamma^1\gamma^2\gamma^3 \\ &= \gamma^0\gamma^1\gamma^\mu\gamma^2\gamma^3 - 2g^{\mu 1}\gamma^0\gamma^1\gamma^2\gamma^3 + 2g^{\mu 0}\gamma^0\gamma^1\gamma^2\gamma^3 \\ &\;\vdots \\ &= \gamma^0\gamma^1\gamma^2\gamma^3\gamma^\mu + 2(g^{\mu 0} - g^{\mu 1} + g^{\mu 2} - g^{\mu 3})\gamma^0\gamma^1\gamma^2\gamma^3\end{aligned}$$

$$= 2 \gamma^5 (\gamma^\mu + g^{\mu 0} \mathbb{1} - g^{\mu 1} \mathbb{1} + g^{\mu 2} \mathbb{1} - g^{\mu 3} \mathbb{1})$$

?

- $(\gamma^0)^2 = \beta^2 = \mathbb{1}$
- $(\gamma^i)^2 = (\beta \alpha^i)^2 = \beta \alpha^i \beta \alpha^i = - {\alpha^i}^2 = - \mathbb{1}$
- $(\gamma^5)^2 = - \gamma^0 \gamma^1 \gamma^2 \gamma^3 \gamma^0 \gamma^1 \gamma^2 \gamma^3$

$$= (\gamma^0)^2 \gamma^1 \gamma^2 \gamma^3 \gamma^1 \gamma^2 \gamma^3$$
$$= (\gamma^0)^2 (\gamma^1)^2 \gamma^2 \gamma^3 \gamma^2 \gamma^3$$
$$= - (\gamma^0) (\gamma^1)^2 (\gamma^2)^2 (\gamma^3)^2$$
$$= \mathbb{1}$$

- $(\gamma^\mu)^\dagger = [(\beta, \beta \vec{\alpha})^\mu]^\dagger$

$$\begin{cases} \mu = 0, & \beta^\dagger = \beta\beta\beta = \beta \\ \mu = i, & (\beta \alpha^i)^\dagger = (\alpha^i)^\dagger \beta^\dagger = \alpha^i \beta = \beta \beta \alpha^i \beta = \beta \gamma^i \beta \end{cases}$$

$$= \gamma^0 \gamma^\mu \gamma^0$$

- $(\gamma^5)^\dagger = -i \gamma^{3\dagger} \gamma^{2\dagger} \gamma^{1\dagger} \gamma^{0\dagger}$

$$= -i \beta \gamma^3 \gamma^2 \gamma^1 \gamma^0 \beta$$
$$= i \beta^2 \gamma^3 \gamma^2 \gamma^1 \gamma^0$$
$$= -i \gamma^0 \gamma^3 \gamma^2 \gamma^1$$

$$= -i\, \gamma^0 \gamma^1 \gamma^3 \gamma^2$$
$$= i\, \gamma^0 \gamma^1 \gamma^2 \gamma^3$$
$$= \gamma^5$$

d) $\mathrm{Tr}[\gamma^\mu \gamma^\nu] = \frac{1}{2} \mathrm{tr}[\{\gamma^\mu, \gamma^\nu\}] = \frac{1}{2} 2 \cdot 4 g^{\mu\nu} = 4 g^{\mu\nu}$

$\mathrm{Tr}[\gamma^\mu \gamma^\nu \gamma^\rho \gamma^\sigma]$
$$= \mathrm{Tr}[\gamma^\nu \gamma^\rho \gamma^\sigma \gamma^\mu]$$
$$= \mathrm{Tr}[\gamma^\nu \gamma^\rho (-\gamma^\mu \gamma^\sigma + 2 g^{\sigma\mu} \mathbb{1})]$$
$$= -\mathrm{Tr}[\gamma^\nu \gamma^\rho \gamma^\mu \gamma^\sigma] + 8 g^{\sigma\mu} g^{\nu\rho}$$
$$= -\mathrm{Tr}[\gamma^\nu (-\gamma^\mu \gamma^\rho + 2 g^{\rho\mu} \mathbb{1}) \gamma^\sigma] + 8 g^{\sigma\mu} g^{\nu\rho}$$
$$= +\mathrm{Tr}[\gamma^\nu \gamma^\mu \gamma^\rho \gamma^\sigma] + 8(-g^{\nu\sigma} g^{\rho\mu} + g^{\sigma\mu} g^{\nu\rho})$$
$$= +\mathrm{Tr}[(-\gamma^\mu \gamma^\nu + 2 g^{\mu\nu} \mathbb{1}) \gamma^\rho \gamma^\sigma] + \ldots$$
$$= -\mathrm{Tr}[\gamma^\mu \gamma^\nu \gamma^\rho \gamma^\sigma] + 8(g^{\mu\nu} g^{\rho\sigma} - g^{\nu\sigma} g^{\rho\mu} + g^{\sigma\mu} g^{\nu\rho})$$

$$\Rightarrow \mathrm{Tr}[\gamma^\mu \gamma^\nu \gamma^\rho \gamma^\sigma] = 4(g^{\mu\nu} g^{\rho\sigma} - g^{\mu\rho} g^{\nu\sigma} + g^{\mu\sigma} g^{\nu\rho})$$

$\mathrm{Tr}[\gamma^{\mu_1} \ldots \gamma^{\mu_n}] = 0, \quad \forall\, n \in 2\mathbb{Z}+1$

$$LHS = \mathrm{Tr}[\gamma^5 \gamma^5 \gamma^{\mu_1} \ldots \gamma^{\mu_n}]$$
$$= \mathrm{Tr}[\gamma^5 \gamma^{\mu_1} \ldots \gamma^{\mu_n} \gamma^5]$$
$$= (-1)^n \mathrm{Tr}[(\gamma^5)^2 \gamma^{\mu_1} \ldots \gamma^{\mu_n}]$$
$$\Rightarrow \mathrm{Tr}[\ldots] = 0$$

$$\mathrm{Tr}[\gamma^5] = \mathrm{Tr}[\gamma^5 \gamma^0 \gamma^0]$$
$$= -\mathrm{Tr}[\gamma^0 \gamma^5 \gamma^0] \qquad \Rightarrow \mathrm{Tr}[\gamma^5] = 0$$
$$= -\mathrm{Tr}[\gamma^5]$$

$$\mathrm{Tr}[\gamma^\mu \gamma^\nu \gamma^5] = \mathrm{Tr}[\gamma^\mu \gamma^\nu \gamma^5 \gamma^0 \gamma^0]$$
$$= -\mathrm{Tr}[\gamma^\mu \gamma^\nu \gamma^0 \gamma^5 \gamma^0]$$
$$= -\mathrm{Tr}[\gamma^0 \gamma^\mu \gamma^\nu \gamma^0 \gamma^5]$$

$$= -\mathrm{Tr}[\gamma^\mu \gamma^\nu \gamma^5]$$

$$\Rightarrow \mathrm{Tr}[\gamma^\mu \gamma^\nu \gamma^5] = 0$$

$$\gamma^5 = i\gamma^0\gamma^1\gamma^2\gamma^3 = \frac{i}{4!}\,\varepsilon_{\mu\nu\alpha\beta}\,\gamma^\mu\gamma^\nu\gamma^\alpha\gamma^\beta$$

$$\mathrm{Tr}[\gamma^\mu\gamma^\nu\gamma^\rho\gamma^\sigma\gamma^5]$$

if any two of μ, ν, ρ, σ are same $\longrightarrow \mathrm{Tr}[\gamma^\mu\gamma^\nu\gamma^5] = 0$

$$\Rightarrow \mathrm{Tr}[\gamma^\mu\gamma^\nu\gamma^\rho\gamma^\sigma\gamma^5] \propto \epsilon^{\mu\nu\rho\sigma}$$

To get the proportional constant, set $\mu=0,\ \nu=1,\ \rho=2,\ \sigma=3$

$$\Rightarrow \mathrm{Tr}[\gamma^0\gamma^1\gamma^2\gamma^3\gamma^5] = -i\,\mathrm{Tr}[(\gamma^5)^2] = -i\,\mathrm{Tr}[\mathbb{1}] = -4i$$

$$\Rightarrow \mathrm{Tr}[\gamma^\mu\gamma^\nu\gamma^\rho\gamma^\sigma\gamma^5] = -4i\,\epsilon^{\mu\nu\rho\sigma}$$

e)

$$\begin{aligned}
\gamma^\mu\gamma_\mu &= \gamma^\mu\gamma^\nu g_{\mu\nu} \\
&= \tfrac{1}{2}(\gamma^\mu\gamma^\nu g_{\mu\nu} + \gamma^\mu\gamma^\nu g_{\mu\nu}) \\
&= \tfrac{1}{2}(\gamma^\mu\gamma^\nu g_{\mu\nu} + \gamma^\nu\gamma^\mu \underbrace{g_{\nu\mu}}_{= g_{\mu\nu}}) \\
&= \tfrac{1}{2}\{\gamma^\mu, \gamma^\nu\} g_{\mu\nu} \\
&= \tfrac{1}{2}\cdot 2 g^{\mu\nu}\mathbb{1}\, g_{\mu\nu} \\
&= 4\mathbb{1}
\end{aligned}$$

$$\begin{aligned}
\gamma^\mu\gamma^\nu\gamma_\mu &= (-\gamma^\nu\gamma^\mu + 2g^{\mu\nu}\mathbb{1})\gamma_\mu \\
&= -\gamma^\nu\cdot 4\mathbb{1} + 2g^{\mu\nu}\mathbb{1}\gamma_\mu \\
&= -4\gamma^\nu + 2\gamma^\nu \\
&= -2\gamma^\nu
\end{aligned}$$

$$\begin{aligned}
\gamma^\mu\gamma^\nu\gamma^\rho\gamma_\mu &= (-\gamma^\nu\gamma^\mu + 2g^{\mu\nu}\mathbb{1})\gamma^\rho\gamma_\mu \\
&= -\gamma^\nu(-2\gamma^\rho) + 2\gamma^\rho\gamma^\nu \\
&= 2\gamma^\nu\gamma^\rho + 2\gamma^\rho\gamma^\nu \\
&= 2\{\gamma^\nu, \gamma^\rho\} = 4g^{\rho\nu}\mathbb{1}
\end{aligned}$$

$$\gamma^\mu \gamma^\nu \gamma^\rho \gamma^\sigma \gamma_\mu = (-\gamma^\nu \gamma^\mu + 2 g^{\mu\nu} \mathbb{1}) \gamma^\rho \gamma^\sigma \gamma_\mu$$

$$= -\gamma^\nu \cdot 4 g^{\rho\sigma} \mathbb{1} + 2 \gamma^\rho \gamma^\sigma \gamma^\nu$$

$$= \cancel{-4 \gamma^\nu g^{\rho\sigma}} + 2 (-\gamma^\sigma \gamma^\rho + \cancel{2 g^{\rho\sigma} \mathbb{1}}) \gamma^\nu$$

$$= -2 \gamma^\sigma \gamma^\rho \gamma^\nu$$

H2.2 $$\mathcal{L} = \frac{1}{2} \partial^\mu \phi \partial_\mu \phi - \frac{m_\phi^2}{2} \phi^2 - V(\phi) - \bar{\psi} (i \partial_\mu \gamma^\mu - m_\psi) \psi - g \bar{\psi} \psi \phi$$

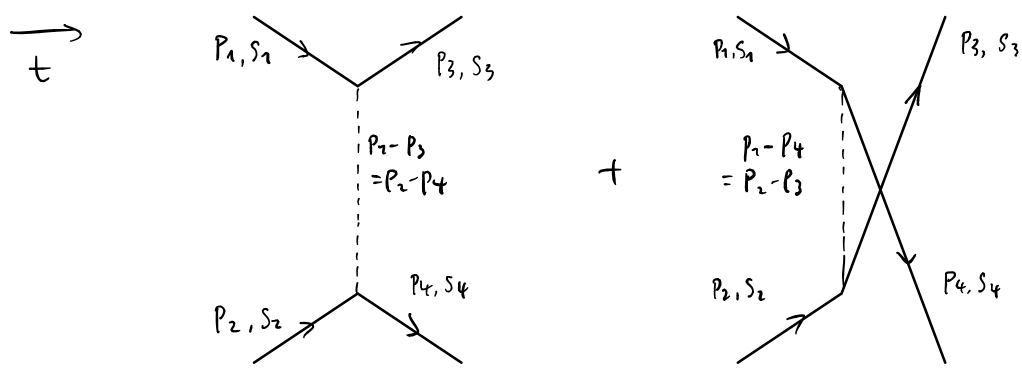
a) $2[\psi] + 1 = d = 4$

$\Rightarrow [\psi] = \frac{3}{2}$

$2[\psi] + [\phi] + [g] = d = 4$

$\Rightarrow [g] = 4 - 3 - 1 = 0$

b) $\psi(p_1, s_1)\, \psi(p_2, s_2) \longrightarrow \psi(p_3, s_3)\, \psi(p_4, s_4)$



$$\mathcal{M}_a = \bar{u}^{s_3}(p_3)(-ig) u^{s_1}(p_1) \frac{i}{(p_1 - p_3)^2 - m_\phi^2} \times \bar{u}^{s_4}(p_4)(-ig) u^{s_2}(p_2)$$

$$= \frac{-ig^2}{t - m_\phi^2} \bar{u}^{s_3}(p_3) u^{s_1}(p_1) \bar{u}^{s_4}(p_4) u^{s_2}(p_2)$$

$$\mathcal{M}_b = \bar{u}^{s_4}(p_4)(-ig) u^{s_1}(p_1) \frac{i}{(p_1 - p_4)^2 - m_\phi^2} \times \bar{u}^{s_3}(p_3)(-ig) u^{s_2}(p_2)$$

$$= \frac{-ig^2}{u - m_\phi^2} \bar{u}^{s_4}(p_4) u^{s_1}(p_1) \bar{u}^{s_3}(p_3) u^{s_2}(p_2)$$

c) $\left(\bar{u}(p_a)^{s_a}\, u(p_b)^{s_b}\right)^*$

$= \left(\bar{u}(p_a)^{s_a}\, u(p_b)^{s_b}\right)^\dagger$

$= u^\dagger(p_b)^{s_b}\, (\gamma^0)^\dagger\, u(p_a)^{s_a}$, $(\gamma^\mu)^\dagger = \gamma^0\gamma^\mu\gamma^0$, $(\gamma^0)^2 = \mathbb{1}$

$= \bar{u}(p_b)^{s_b}\, u(p_a)^{s_a}$

wo $\frac{1}{2}$?

d) $\overline{|\mathcal{M}|^2} = \frac{1}{2}\sum_{s_1=1,2}\frac{1}{2}\sum_{s_2=1,2}\sum_{s_3=1,2}\sum_{s_4=1,2}|\mathcal{M}|^2$

$= \frac{1}{4}\sum_{s_1,s_2,s_3,s_4}|\mathcal{M}_a+\mathcal{M}_b|^2$

$= \frac{1}{4}\sum\left[\mathcal{M}_a\mathcal{M}_a^* + \mathcal{M}_b\mathcal{M}_b^* + 2\,\mathrm{Re}(\mathcal{M}_a\mathcal{M}_b^*)\right]$

1st term $= \frac{1}{4}\frac{g^4}{(t-m_\phi^2)^2}\sum_s \bar{u}^{s_3}(p_3)\,u^{s_1}(p_1)\,\bar{u}^{s_4}(p_4)\,u^{s_2}(p_2)\,\bar{u}^{s_2}(p_2)\,u^{s_4}(p_4)\,\bar{u}^{s_1}(p_2)\,u^{s_3}(p_3)$

$= \frac{g^4}{4(t-m_\phi^2)^2}\sum_s tr\left[\underbrace{u^1\bar{u}^4\overbrace{u^2\bar{u}^2}^{A}u^4\bar{u}^1\overbrace{u^3\bar{u}^3}^{B}}\right]$

$= u^1\bar{u}^4 A\, u^4\bar{u}^1 B$

$= \underbrace{u^1_\alpha\,\bar{u}^4_\beta\, A_{\beta\gamma}\, u^4_\gamma\,\bar{u}^1_\sigma\, B_{\sigma\lambda}}$

$= tr(\not{p}_1+m_\psi)_{\alpha\sigma}\, A_{\beta\gamma}\,(\not{p}_4+m_\psi)_{\gamma\beta}\, B_{\sigma\lambda}$

$= tr(\not{p}_1+m_\psi)(\not{p}_3+m_\psi)(\not{p}_2+m_\psi)(\not{p}_4+m_\psi)$

$= \frac{g^4}{4(t-m_\phi^2)^2}\, tr\left[(\not{p}_1+m_\psi)(\not{p}_3+m_\psi)(\not{p}_2+m_\psi)(\not{p}_4+m_\psi)\right]$

Similarly

2nd term $= \frac{g^4}{4(u-m_\phi^2)^2}\, tr\left[(\not{p}_1+m_\psi)(\not{p}_4+m_\psi)(\not{p}_2+m_\psi)(\not{p}_3+m_\psi)\right]$

3rd term $= \frac{g^4}{2(t-m_\phi^2)(u-m_\phi^2)}\sum_s \bar{u}^{s_3}(p_3)\,u^{s_1}(p_1)\,\bar{u}^{s_4}(p_4)\,u^{s_2}(p_2)\,\bar{u}^{s_2}(p_2)\,u^{s_3}(p_4)\,\bar{u}^{s_1}(p_2)\,u^{s_4}(p_3)$

$$= \frac{g^4}{2(t-m_\phi^2)(u-m_\phi^2)} \, tr\left[(\not{p}_2 + m_\psi)(\not{p}_3 + m_\psi)(\not{p}_1 + m_\psi)(\not{p}_4 + m_\psi)\right]$$

c) $tr[(\not{p}_1 + m_\psi)(\not{p}_3 + m_\psi)(\not{p}_2 + m_\psi)(\not{p}_4 + m_\psi)]$

$$= tr[\not{p}_1 \not{p}_3 \not{p}_2 \not{p}_4 + m_\psi^2 (\not{p}_1\not{p}_3 + \not{p}_1\not{p}_2 + \not{p}_1\not{p}_4 + \not{p}_3\not{p}_2 + \not{p}_3\not{p}_4 + \not{p}_2\not{p}_4)]$$

$$= 4\left[(p_1\cdot p_3)(p_2\cdot p_4) + (p_1\cdot p_2)(p_3\cdot p_4) + (p_1\cdot p_4)(p_3\cdot p_2)\right]$$

$$+ 4m_\psi^2 [(p_1\cdot p_3) + (p_1\cdot p_2) + (p_1\cdot p_4) + (p_3\cdot p_2) + (p_3\cdot p_4) + (p_2\cdot p_4)]$$

$$= p_1(p_1+p_2) \qquad\qquad = p_2(p_1+p_2)$$

$$= m_\psi^2 + (p_1\cdot p_2) \qquad\qquad = (p_1\cdot p_2) + m_\psi^2$$

$$p_1 + p_2 = p_3 + p_4 \iff (p_1\cdot p_2) = (p_3\cdot p_4)$$

$$= 4\left((p_1\cdot p_2)^2 + (p_1\cdot p_3)(p_2\cdot p_4) + (p_1\cdot p_4)(p_2\cdot p_3) + m_\psi^2(m_\psi^2 + 4(p_1\cdot p_2))\right)$$

$$s = (p_1+p_2)^2 \iff s - 2m_\psi^2 = 2(p_1\cdot p_2) \;;\; t - 2m_\psi^2 = -2(p_1\cdot p_3) \;; \cdots$$

$$= 4\left[\left(\tfrac{1}{2}s - m_\psi^2\right)^2 + \left(-\tfrac{1}{2}t + m_\psi^2\right)^2 + \left(-\tfrac{1}{2}u + m_\psi^2\right)^2 + m_\psi^2(m_\psi^2 + 2(s - 2m_\psi^2))\right]$$

$$= (s-2m_\psi^2)^2 + (t-2m_\psi^2)^2 + (u-2m_\psi^2)^2 + 4m_\psi^2(m_\psi^2 + 2s - 4m_\psi^2)$$

$$= \underline{s^2 + u^2 + t^2} - 4m_\psi^2 s + \cancel{4m_\psi^4} - 4m_\psi^2 t + \cancel{4m_\psi^4} - 4m_\psi^2 u + \cancel{4m_\psi^4}$$

$$+ 8m_\psi^2 s - \cancel{12m_\psi^4}$$

$$= s^2 + u^2 + t^2 + 4m_\psi^2(s - t - u)$$

$tr[(\not{p}_1 + m_\psi)(\not{p}_4 + m_\psi)(\not{p}_2 + m_\psi)(\not{p}_3 + m_\psi)]$

$$= \cdots = 4\left((p_1\cdot p_2)^2 + (p_1\cdot p_4)(p_2\cdot p_3) + (p_1\cdot p_3)(p_2\cdot p_4) + m_\psi^2(m_\psi^2 + 4(p_1\cdot p_2))\right)$$

$$= s^2 + u^2 + t^2 + 4m_\psi^2(s - t - u)$$

$$= tr[(\not{p}_2 + m_\psi)(\not{p}_3 + m_\psi)(\not{p}_1 + m_\psi)(\not{p}_4 + m_\psi)]$$

$$\Rightarrow \overline{|\mathcal{M}|^2} = \underbrace{g^4 \left\{ \left[\frac{1}{4(t-m_\phi^2)^2} + \frac{1}{4(u-m_\phi^2)^2} + \frac{1}{2(t-m_\phi^2)(u-m_\phi^2)} \right] \left(s^2 + t^2 + u^2 + 4m_\psi^2 (s-t-u) \right) \right.}\left. \right\}$$

$$\Rightarrow \frac{d\sigma}{dt} = \frac{1}{16\pi s^2} \left(\quad - \quad - \; - \quad \right)$$