$$\mathcal{M}_\gamma = \frac{e^2}{3q^2}\left[\bar{v}(k)\gamma^\mu u(p)\right]\left[\bar{u}(p')\gamma_\mu v(k')\right]$$

$$4\langle|\mathcal{M}_\gamma|^2\rangle\frac{9s^2}{e^4} =$$

$$\sum_{pqrs} \bar{v}^p_a(k)\gamma^\mu_{ab}u^q_b(p)\;\bar{u}^r_c(p')\gamma_{\mu\,cd}v^s_d(k')\;\bar{v}^s_e(k')\gamma_{\rho\,ef}u^r_f(p')\;\bar{u}^q_g(p)\gamma^\rho_{gh}v^p_h(k)$$

$$= Tr\left\{(\not{k}-m)\gamma^\mu(\not{p}+m)\gamma^\rho\right\}\; Tr\left\{(\not{k}'-M)\gamma_\rho(\not{p}'+M)\gamma_\mu\right\}$$

$$Tr\left\{(\not{k}-m)\gamma^\mu(\not{p}+m)\gamma^\rho\right\} =$$

$$= Tr\left\{(\not{k}\gamma^\mu - m\gamma^\mu)(\not{p}\gamma^\rho + m\gamma^\rho)\right\} =$$

$$= Tr\left\{\not{k}\gamma^\mu\not{p}\gamma^\rho - m^2\gamma^\mu\gamma^\rho\right\} = k_\alpha p_\beta\, Tr\left\{\gamma^\alpha\gamma^\mu\gamma^\beta\gamma^\rho\right\} - 4m^2 g^{\mu\rho}$$

$$= 4\left\{k^\mu p^\rho - (k\cdot p)g^{\mu\rho} + k^\rho p^\mu - m^2 g^{\mu\rho}\right\}$$

$$= 16\left\{k^\mu p^\rho - (k\cdot p)g^{\mu\rho} + k^\rho p^\mu - m^2 g^{\mu\rho}\right\}\left\{k'_\rho p'_\mu - (k'\cdot p')g_{\rho\mu} + k'_\mu p'_\rho - M^2 g_{\mu\rho}\right\}$$

$$\overset{!}{=} 16\left\{(k\cdot p')(k'\cdot p) - \cancel{(k'\cdot p')(k\cdot p)} + (k\cdot k')(p\cdot p') - M^2(k\cdot p)\right.$$

$$- \cancel{(k\cdot p)(k'\cdot p')} + 4\cancel{(k\cdot p)(k'\cdot p')} - \cancel{(k\cdot p)(k'\cdot p')} + 4M^2(k\cdot p)$$

$$+ (k\cdot k')(p\cdot p') - \cancel{(k'\cdot p')(k\cdot p)} + (k\cdot p')(k'\cdot p) - M^2(k\cdot p)$$

$$\left. - m^2(k'\cdot p') + 4m^2(k'\cdot p') - m^2(k'\cdot p') + 4M^2m^2\right\}$$

$$= 32\left\{(k\cdot p')(k'\cdot p) + (k\cdot k')(p\cdot p') + M^2(k\cdot p) + m^2(k'\cdot p') + 2M^2m^2\right\}$$

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s}\frac{p_f}{p_i}|\mathcal{M}|^2$$

* In CMS frame

$$p = (E, 0, 0, p) \qquad p' = (E, 0, p'\sin\theta, p'\cos\theta)$$

$$k = (E, 0, 0, -p) \qquad k' = (E, 0, -p'\sin\theta, -p'\cos\theta)$$

$$(p\cdot k) = E^2 + p^2 \qquad (p'\cdot k') = E^2 + p'^2$$

$$(p \cdot p') = E^2 - pp'\cos\theta \qquad (k \cdot k') = E^2 - pp'\cos\theta =$$

$$(p \cdot k') = E^2 + pp'\cos\theta = (p' \cdot k)$$

$$p = \sqrt{E^2 - m^2}$$

$$\mathcal{M}_Z = \frac{1}{q^2 - m_Z^2}\left\{\bar v(k)\gamma^\mu(c_V - c_A\gamma^5)u(p)\right\}\left\{\bar u(p')\gamma_\mu(\tilde c_V - \tilde c_A\gamma^5)v(k')\right\}$$

→ Spin sums

$$4\langle|\mathcal{M}_Z|^2\rangle(s-M_Z^2)^2 =$$

$$= \sum_{pqrs}\left[\bar v^p(k)\gamma^\mu(c_V-c_A\gamma^5)u^q(p)\,\bar u^r(p')\gamma_\mu(\tilde c_V-\tilde c_A\gamma^5)v^s(k')\right]\times$$
$$\left[\bar v^p(k)\gamma^\rho(c_V-c_A\gamma^5)u^q(p)\,\bar u^r(p')\gamma_\rho(\tilde c_V-\tilde c_A\gamma^5)v^s(k')\right]^\dagger \;(*)$$

$$=\sum_{pqrs}\left\{\bar v^p_a(k)\gamma^\mu_{ab}(c_V-c_A\gamma^5)_{bc}u^q_c(p)\,\bar u^r_d(p')\gamma_{\mu\,de}(\tilde c_V-\tilde c_A\gamma^5)_{ef}v^s_f(k')\right\}\times$$
$$\left\{\bar v^s_\alpha(k')\gamma_{\rho\,\alpha\beta}(\tilde c_V-\tilde c_A\gamma^5)_{\beta\gamma}u^r_\gamma(p')\,\bar u^q_\delta(p)\gamma^\rho_{\delta\epsilon}(c_V-c_A\gamma^5)_{\epsilon\eta}v^p_\eta(k)\right\}$$

$$=\sum_p v^p_\eta(k)\bar v^p_a(k)\sum_q u^q_c(p)\bar u^q_\delta(p)\sum_r u^r_\gamma(p')\bar u^r_d(p')\sum_s v^s(k')\bar v^s_f(k')_\alpha$$
$$\gamma^\mu_{ab}(c_V-c_A\gamma^5)_{bc}\gamma_{\mu\,de}(c_V-c_A\gamma^5)_{ef}\gamma_{\rho\,\alpha\beta}(c_V+c_A\gamma^5)_{\beta\gamma}\gamma^\rho_{\delta\epsilon}(c_V+c_A\gamma^5)_{\epsilon\eta}$$

$$= \mathrm{Tr}\left\{(\not k - m)\gamma^\mu(c_V-c_A\gamma^5)(\not p+m)\gamma^\rho(c_V-c_A\gamma^5)\right\}\times$$
$$\times\,\mathrm{Tr}\left\{(\not k' - M)\gamma_\rho(\tilde c_V-\tilde c_A\gamma^5)(\not p'+M)\gamma_\mu(\tilde c_V-\tilde c_A\gamma^5)\right\}$$

- $\mathrm{Tr}\left\{(\not k - m)\gamma^\mu(c_V-c_A\gamma^5)(\not p+m)\gamma^\rho(c_V-c_A\gamma^5)\right\} =$

$$= \mathrm{Tr}\left\{(\not k\gamma^\mu - m\gamma^\mu)(c_V-c_A\gamma^5)(\not p\gamma^\rho+m\gamma^\rho)(c_V-c_A\gamma^5)\right\} =$$

$$= \mathrm{Tr}\Big\{\left[c_V\not k\gamma^\mu - c_A\not k\gamma^\mu\gamma^5 - m c_V\gamma^\mu + m c_A\gamma^\mu\gamma^5\right]\times$$
$$\times\left[c_V\not p\gamma^\rho - c_A\not p\gamma^\rho\gamma^5 + m c_V\gamma^\rho - m c_A\gamma^\rho\gamma^5\right]\Big\} =$$

$$= \mathrm{Tr}\Big\{c_V^2\not k\gamma^\mu\not p\gamma^\rho - c_A c_V\not k\gamma^\mu\not p\gamma^\rho\gamma^5 + \overset{\text{odd\#}}{\cancel{m c_V^2\not k\gamma^\mu\gamma^\rho}} + m c_V c_A\overset{\text{odd\#}}{\cancel{\not k\gamma^\mu\gamma^\rho\gamma^5}}$$
$$- c_A c_V\not k\gamma^\mu\gamma^5\not p\gamma^\rho + c_A^2\not k\gamma^\mu\gamma^5\not p\gamma^\rho\gamma^5 - m c_A c_V\overset{\text{odd\#}}{\cancel{\not k\gamma^\mu\gamma^5\gamma^\rho}} - m c_A^2\overset{\text{odd\#}}{\cancel{\not k\gamma^\mu\gamma^5\gamma^\rho\gamma^5}}$$
$$- m c_V^2\overset{\text{odd\#}}{\cancel{\gamma^\mu\not p\gamma^\rho}} + m c_A c_V\overset{\text{odd\#}}{\cancel{\gamma^\mu\not p\gamma^\rho\gamma^5}} - m^2 c_V^2\gamma^\mu\gamma^\rho - m^2 c_A c_V\gamma^\mu\gamma^\rho\gamma^5$$

$$+ m c_A c_V \cancel{\gamma^\mu \gamma^5 \not p \gamma^\rho} + m c_A^2 \cancel{\gamma^\mu\gamma^5 \not p \gamma^\rho}\gamma^5 + m^2 c_A c_V \gamma^\mu\gamma^5\gamma^\rho - m^2 c_A^2 \gamma^\mu\gamma^5\gamma^\rho\gamma^5 \Big\}$$

$$= \mathrm{Tr}\Big\{ c_V^2 \not k \gamma^\mu \not p \gamma^\rho - c_A c_V \not k\gamma^\mu\not p\gamma^\rho\gamma^5 - c_A c_V \not k \gamma^\mu\gamma^5\not p\gamma^\rho + \underbrace{c_A^2 \not k\gamma^\mu\gamma^5\not p\gamma^\rho\gamma^5}_{\substack{c_A^2 \not k\gamma^\mu\not p\gamma^5\gamma^\rho\gamma^5 \\ -c_A^2\not k\gamma^\mu\not p\gamma^\rho}}$$

$\{\gamma^5,\gamma^\mu\}=0,\ (\gamma^5)^2=\mathbb{1},\ \mathrm{Tr}(\gamma^\alpha\gamma^\beta\gamma^5)=0$

$$-m^2 c_V^2 \gamma^\mu\gamma^\rho + m^2 c_A c_V \overset{\mathrm{Tr}=0}{\cancel{\gamma^\mu\gamma^\rho\gamma^5}} - m^2 c_A c_V \overset{\mathrm{Tr}=0}{\cancel{\gamma^\mu\gamma^5\gamma^\rho}} \underbrace{- m^2 c_A^2 \gamma^\mu\gamma^5\gamma^\rho\gamma^5}_{+m^2c_A^2\gamma^\mu\gamma^\rho} \Big\}$$

$$= \mathrm{Tr}\Big\{c_V^2 \not k\gamma^\mu\not p\gamma^\rho - c_A c_V \not k\gamma^\mu\not p\gamma^\rho\gamma^5 - \underbrace{c_Ac_V\not k\gamma^\mu\gamma^5\not p\gamma^\rho}_{\substack{+c_Ac_V\not k\gamma^\mu\not p\gamma^5\gamma^\rho \\ -c_Ac_V\not k\gamma^\mu\not p\gamma^\rho\gamma^5}} + c_A^2\not k\gamma^\mu\not p\gamma^\rho$$

$$-m^2c_V^2\gamma^\mu\gamma^\rho - m^2c_A^2\gamma^\mu\gamma^\rho\Big\}$$

$$= \mathrm{Tr}\Big\{(\not k\gamma^\mu\not p\gamma^\rho)(c_V^2+c_A^2) - m^2\gamma^\mu\gamma^\rho(c_V^2-c_A^2) - 2c_Ac_V\not k\gamma^\mu\not p\gamma^\rho\gamma^5\Big\}$$

$$\mathrm{Tr}(\gamma^\alpha\gamma^\beta\gamma^\gamma\gamma^\delta) = 4(g^{\alpha\beta}g^{\gamma\delta} - g^{\alpha\gamma}g^{\beta\delta}+g^{\alpha\delta}g^{\beta\gamma})$$

$$= (c_V^2 - c_A^2) k_\alpha p_\beta \underbrace{\mathrm{Tr}\{\gamma^\alpha\gamma^\mu\gamma^\beta\gamma^\rho\}}_{4(g^{\alpha\mu}g^{\beta\rho} - g^{\alpha\beta}g^{\mu\rho}+g^{\alpha\rho}g^{\mu\beta})} - 4m^2(c_V^2-c_A^2)g^{\mu\rho} - 2c_Ac_V \mathrm{Tr}\{\not k\gamma^\mu\not p\gamma^\rho\gamma^5\}$$

$$= 4\Big\{(c_V^2+c_A^2)[k^\mu p^\rho - (k\cdot p)g^{\mu\rho} + k^\rho p^\mu] - m^2(c_V^2-c_A^2)g^{\mu\rho}$$

$$- 2i c_Ac_V k_\alpha p_\beta \underbrace{\epsilon^{\alpha\mu\beta\rho}}_{\text{antisymmetric in } \mu\rho}\Big\}$$

(*) Cross term: $4 c_A c_V \tilde c_A \tilde c_V k_\alpha p_\beta p'^\sigma k'^\tau \underbrace{\epsilon^{\alpha\mu\beta\rho}\epsilon_{\sigma\mu\tau\rho}}$

$$= 8 c_Ac_V\tilde c_A\tilde c_V\{(k\cdot p')(k'\cdot p) - (p\cdot p')(k\cdot k')\} \qquad \epsilon^{\rho\mu\beta\alpha}\epsilon_{\rho\mu\tau\sigma} = -2(\delta^\beta_\tau\delta^\alpha_\sigma - \delta^\beta_\sigma\delta^\alpha_\tau)$$

$$\Rightarrow \cancel{4}\langle|\mathcal M_Z|^2\rangle (s-M_Z^2)^2 =$$

$$\cancel{16}\,4 \Big\{\overbrace{(c_V^2+c_A^2)}^{\equiv\Sigma}\overbrace{[k^\mu p^\rho - (k\cdot p)g^{\mu\rho}+k^\rho p^\mu]}^{\text{Fully symmetric in }\mu\rho} - m^2\overbrace{(c_V^2-c_A^2)}^{\equiv\Delta}g^{\mu\rho}\Big\}\times$$

$$\times\Big\{\overbrace{(\tilde c_V^2+\tilde c_A^2)}^{\equiv\tilde\Sigma}[k'_\mu p'_\rho - (k'\cdot p')g_{\mu\rho} + k'_\rho p'_\mu] - M^2\overbrace{(\tilde c_V^2-\tilde c_A^2)}^{\equiv\tilde\Delta}g_{\mu\rho}\Big\}=$$

$$= 4 \Big\{ \Sigma\tilde{\Sigma} \left(k^\mu p^\rho - (k\cdot p) g^{\mu\rho} + k^\rho p^\mu\right)\left(k'_\mu p'_\rho - (k'\cdot p') g_{\mu\rho} + k'_\rho p'_\mu\right) +$$

$$+ \Sigma\tilde{\Delta} M^2 (\underbrace{k\cdot p - 4 k\cdot p + k\cdot p}_{-2 k\cdot p}) + 2\Delta\tilde{\Sigma} m^2 (k'\cdot p')$$

$$+ \Delta\tilde{\Delta}\, 4 m^2 M^2 \Big\}$$

$$\rightsquigarrow \left(k^\mu p^\rho - (k\cdot p) g^{\mu\rho} + k^\rho p^\mu\right)\left(k'_\mu p'_\rho - (k'\cdot p') g_{\mu\rho} + k'_\rho p'_\mu\right)$$

$$= \Big\{ (k\cdot k')(p\cdot p') - \cancel{(k'\cdot p')(k\cdot p)} + (k'\cdot p)(k\cdot p')$$

$$- \cancel{(k\cdot p)(k'\cdot p')} + 4\cancel{(k\cdot p)(k'\cdot p')} - \cancel{(k\cdot p)(k'\cdot p')}$$

$$+ (k\cdot p')(k'\cdot p) - \cancel{(k'\cdot p')(k\cdot p)} + (k\cdot k')(p\cdot p') \Big\}$$

$$= 2(k\cdot k')(p\cdot p') + 2(k\cdot p')(k'\cdot p)$$

$$\Rightarrow \langle |\mathcal{M}_Z|^2 \rangle (s - m_Z^2) =$$

$$= 8 \Big\{ \Sigma\tilde{\Sigma} \left[(k\cdot k')(p\cdot p') + (k\cdot p')(k'\cdot p) \right] - M^2 \tilde{\Delta} \Sigma (k\cdot p) + m^2 \Delta \tilde{\Sigma} (k'\cdot p')$$

$$+ 2\Delta\tilde{\Delta} m^2 M^2 - 4 c_A c_V \tilde{c}_A \tilde{c}_V \left[(k\cdot p')(k'\cdot p) - (p\cdot p')(k\cdot k') \right] \Big\}$$

(*) $$\left[\bar{v}(k) \gamma^\mu (c_V - c_A \gamma^5) u(p) \right]^\dagger =$$

$$= u(p)^\dagger (c_V - c_A\gamma^5)^\dagger (\gamma^\mu)^\dagger (\gamma^0)^\dagger v(k)$$

$$= u(p)^\dagger (c_V - c_A\gamma^5) (\gamma^\mu)^\dagger \gamma^0 v(k)$$

[illegible]

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

$$= u(p)^\dagger \gamma^0 (c_V + c_A \gamma^5) \gamma^\mu v(k)$$

$$\stackrel{!}{=} \bar{u}(p) \gamma^\mu (c_V - c_A \gamma^5) v(k)$$

$$\mathcal{M}_h = \frac{-g_w^2}{4m_w^2} \frac{m_\mu m_b}{s - m_h^2} \bar{v}(k) u(p) \bar{u}(p') v(k')$$

$$4 \langle |\mathcal{M}_h|^2 \rangle =$$

$$\underbrace{\left(\frac{g_w^2}{4m_w^2} \frac{m_\mu m_b}{s - m_h^2}\right)^2}_{K_H} \sum_{pqrs} \bar{v}_a^p(k) \overset{\mathbb{1}_{ab}}{\,} u_b^q(p) \bar{u}_c^r(p') \overset{\mathbb{1}_{cd}}{\,} v_d^s(k') \bar{v}_e^s(k') \overset{\mathbb{1}_{ef}}{\,} u_f^r(p') \bar{u}_g^q(p) \overset{\mathbb{1}_{gh}}{\,} v_h^p(k)$$

$$= K_H^2 \sum_p v_h^p(k) \bar{v}_a^p(k) \sum_q u_b^q(p) \bar{u}_g^q(p) \sum_r u_f^r(p') \bar{u}_c^r(p') \sum_s v_d^s(k') \bar{v}_e^s(k')$$

$$= K_H^2 (\not{k} - m)_{ha} \mathbb{1}_{ab} (\not{p} + m)_{bg} \mathbb{1}_{gh} (\not{p}' + M)_{fc} \mathbb{1}_{cd} (\not{k}' - M)_{de} \mathbb{1}_{ef}$$

$$= K_H^2 \operatorname{Tr}\{(\not{k} - m)(\not{p} + m)\} \operatorname{Tr}\{(\not{p}' + M)(\not{k}' - M)\}$$

$$\operatorname{Tr}\{(\not{k} - m)(\not{p} + m)\} = \operatorname{Tr}\{\not{k}\not{p} - m\not{k} - m\not{p} - m^2\} = 4\{(k \cdot p) - m^2\}$$

$$= 16 K_H [(k \cdot p) - m^2][(k' \cdot p') - M^2]$$

$$= 16 K_H [(k \cdot p)(k' \cdot p') - M^2(k \cdot p) - m^2(k' \cdot p') + M^2 m^2]$$

→ w/ Mandelstam variables

$$(k \cdot p) = \frac{s}{2} - m^2 \qquad (k' \cdot p') = \frac{s}{2} - M^2$$

$$\Rightarrow = 16 K_H \left\{ \left(\frac{s}{2} - m^2\right)\left(\frac{s}{2} - M^2\right) - M^2\left(\frac{s}{2} - m^2\right) - m^2\left(\frac{s}{2} - M^2\right) + M^2 m^2 \right]$$

$$= 16 K_H \left\{ \frac{s^2}{4} - \frac{M^2}{2} s - \frac{m^2}{2} s + M^2 m^2 - M^2 \frac{s}{2} + M^2 m^2 - \frac{m^2}{2} s + M^2 m^2 + M^2 m^2 \right]$$

$$= 16 K_H \left\{ \frac{s^2}{4} - s(M^2 + m^2) + 4 M^2 m^2 \right\}$$

$$\mathcal{M}_Z = \frac{1}{s-m_Z^2}\left\{\bar v(k)\gamma^\mu(c_v - c_A\gamma^5)u(p)\right\}\left\{\bar u(p')\gamma_\mu(c_v-c_A\gamma^5)v(k')\right\}$$

$$\mathcal{M}_\gamma = \frac{e^2}{3s}\left\{\bar v(k)\gamma^\rho u(p)\right\}\left\{\bar u(p')\gamma_\rho v(k')\right\}$$

$$\to 4\langle \mathcal{M}_Z \mathcal{M}_\gamma^* \rangle 3s(s-m_Z^2) =$$

$$\sum_{pqrs}\left\{\bar v^p(k)\gamma^\mu(c_v-c_A\gamma^5)u^q(p)\right\}\left\{\bar u^r(p')\gamma_\mu(c_v-c_A\gamma^5)v^s(k')\right\}$$
$$\left\{\left[\bar v^p(k)\gamma^\rho u^q(p)\right]\left[\bar u^r(p')\gamma_\rho v^s(k')\right]\right\}^\dagger =$$

$$=\sum_{pqrs}\left\{\bar v^p_a(k)\left(\gamma^\mu(c_v-c_A\gamma^5)\right)_{ab}u^q_b(p)\right\}\left\{\bar u^r_c(p')\left(\gamma_\mu(\tilde c_v-\tilde c_A\gamma^5)\right)_{cd}v^s_d(k')\right\}$$
$$\times\left\{\bar v^s_e(k')\gamma_{\rho\,ef}u^r_f(p')\;\bar u^q_g(p)\gamma^\rho_{gh}v^p_h(k)\right\}$$

$$= (\not k - m)_{ha}(\not p + m)_{bg}(\not k' - M)_{de}(\not p' + M)_{fc}$$
$$\left(\gamma^\mu(c_v-c_A\gamma^5)\right)_{ab}\left(\gamma_\mu(\tilde c_v-\tilde c_A\gamma^5)\right)_{cd}\gamma_{\rho\,ef}\gamma^\rho_{gh}$$

$$= \mathrm{Tr}\left\{(\not k - m)\gamma^\mu(c_v-c_A\gamma^5)(\not p+m)\gamma^\rho\right\}\times$$
$$\times\,\mathrm{Tr}\left\{(\not k'-M)\gamma_\rho(\not p'+M)\gamma_\mu(\tilde c_v-\tilde c_A\gamma^5)\right\}$$

- $$\mathrm{Tr}\left\{(\not k \pm m)\gamma^\mu(c_v-c_A\gamma^5)(\not p \mp m)\gamma^\rho\right\} =$$

$$= \mathrm{Tr}\left\{(c_v\not k\gamma^\mu \pm m c_v\gamma^\mu - c_A\not k\gamma^\mu\gamma^5 \mp m c_A\gamma^\mu\gamma^5)(\not p\gamma^\rho \mp m\gamma^\rho)\right\}$$

$$= \mathrm{Tr}\Big\{c_v\not k\gamma^\mu\not p\gamma^\rho - \underbrace{\cancel{m c_v\gamma^\mu\not p\gamma^\rho}}_{\text{odd}} - c_A\not k\gamma^\mu\gamma^5\not p\gamma^\rho + \underbrace{\cancel{m c_A\gamma^\mu\gamma^5\not p\gamma^\rho}}_{\text{odd}}$$
$$+ \underbrace{\cancel{m c_v\not k\gamma^\mu\gamma^\rho}}_{\text{odd}} - m^2 c_v\gamma^\mu\gamma^\rho - \underbrace{\cancel{m c_A\not k\gamma^\mu\gamma^5\gamma^\rho}}_{\text{odd}} + \underbrace{\cancel{m^2 c_A\gamma^\mu\gamma^5\gamma^\rho}}_{=0}\Big\}$$

$$= \mathrm{Tr}\Big\{\underbrace{c_v\not k\gamma^\mu\not p\gamma^\rho}_{c_v k_\epsilon p_\tau \gamma^{\epsilon\mu\tau\rho}} - c_A\underbrace{\underbrace{\not k\gamma^\mu\gamma^5\not p\gamma^\rho}_{k_\alpha p_\beta \gamma^\alpha\gamma^\mu\gamma^5\gamma^\beta\gamma^\rho}}_{-i4k_\alpha p_\beta\epsilon^{\alpha\mu\beta\rho}} - m^2 c_v\underbrace{\gamma^\mu\gamma^\rho}_{4g^{\mu\rho}}\Big\}$$

$$= c_V\, 4\, k_\epsilon p_\tau \left(g^{\epsilon\mu} g^{\tau\rho} - g^{\epsilon\tau} g^{\mu\rho} + g^{\epsilon\rho} g^{\mu\tau} \right) - i 4 c_A k_\alpha p_\beta \epsilon^{\alpha\mu\beta\rho} - 4 m^2 C_V g^{\mu\rho}$$

$$= 4 \left\{ c_V \left[k^\mu p^\rho - (k\cdot p) g^{\mu\rho} + k^\rho p^\mu \right] - c_A i k_\alpha p_\beta \epsilon^{\alpha\mu\beta\rho} - c_V m^2 g^{\mu\rho} \right\}$$

- $\mathrm{Tr}\left\{ (\not{k}' - M) \gamma_\rho (\not{p}' + M) \gamma_\mu (\tilde{c}_V - \tilde{c}_A \gamma^5) \right\}$

$\leftarrow$ cyclic

$$= \mathrm{Tr}\left\{ (\not{p}' + M) \gamma_\mu (\tilde{c}_V - \tilde{c}_A \gamma^5) (\not{k}' - M) \gamma_\rho \right\}$$

$$= 4 \left\{ \tilde{c}_V \left[p'_\mu k'_\rho - (k'\cdot p') g_{\mu\rho} + p'_\rho k'_\mu \right] - i \tilde{c}_A p'^\sigma k'^\tau \epsilon_{\sigma\mu\tau\rho} - \tilde{c}_V M^2 g_{\mu\rho} \right\}$$

$$\Rightarrow \langle \mathcal{M}_Z \mathcal{M}_\gamma^* \rangle\, 3s(s - m_Z^2) =$$

$$4 \left\{ \tilde{c}_V \left[p'_\mu k'_\rho - (k'\cdot p') g_{\mu\rho} + p'_\rho k'_\mu \right] - i \tilde{c}_A p'^\sigma k'^\tau \epsilon_{\sigma\mu\tau\rho} - \tilde{c}_V M^2 g_{\mu\rho} \right\} \times$$

$$\left\{ c_V \left[k^\mu p^\rho - (k\cdot p) g^{\mu\rho} + k^\rho p^\mu \right] - c_A i k_\alpha p_\beta \epsilon^{\alpha\mu\beta\rho} - c_V m^2 g^{\mu\rho} \right\}$$

$$= 4 \Big\{ 2 c_V \tilde{c}_V \left[(p'\cdot k)(p\cdot k') + (p'\cdot p)(k'\cdot k) \right] - 2 c_V \tilde{c}_V m^2 (k'\cdot p')$$

$$- c_A \tilde{c}_A k_\alpha p_\beta p'^\sigma k'^\tau \underbrace{\epsilon^{\alpha\mu\beta\rho} \epsilon_{\sigma\mu\tau\rho}}_{-\epsilon^{\alpha\mu\beta\rho}\epsilon_{\rho\mu\tau\sigma}} - 2 c_V \tilde{c}_V M^2 (k\cdot p) + 4 c_V \tilde{c}_V m^2 M^2 \Big\}$$

$$\epsilon^{\rho\mu\beta\alpha} \epsilon_{\rho\mu\tau\sigma} = -2 \left(\delta^\beta_\tau \delta^\alpha_\sigma - \delta^\beta_\sigma \delta^\alpha_\tau \right)$$

$$= 4 \Big\{ 2 c_V \tilde{c}_V \left[(p'\cdot k)(p\cdot k') + (p'\cdot p)(k'\cdot k) \right] - 2 c_V \tilde{c}_V \left[m^2 (k'\cdot p') + M^2 (k\cdot p) \right]$$

$$+ 2 c_A \tilde{c}_A \left[(p\cdot k')(p'\cdot k) - (p\cdot p')(k\cdot k') \right] + 4 c_V \tilde{c}_V m^2 M^2 \Big\}$$

$$= 4 \Big\{ 2 c_V \tilde{c}_V \left[\frac{(m^2 + M^2 - u)^2}{4} + \frac{(m^2 + M^2 - t)^2}{4} - m^2 \left(\frac{s}{2} - M^2 \right) - M^2 \left(\frac{s}{2} - m^2 \right) \right]$$

$$+ 2 c_A \tilde{c}_A \left[\frac{(m^2 + M^2 - u)^2}{4} + \frac{(m^2 + M^2 - t)^2}{4} \right] \Big\}$$

$$\mathcal{M}_H = -\frac{g^2}{4m_W^2}\,\frac{mM}{s-m_H^2}\;\bar v(k)\,u(p)\,\bar u(p')\,v(k')$$

$$\mathcal{M}_\gamma = \frac{e^2}{3q^2}\left[\bar v(k)\,\gamma^\mu\,u(p)\right]\left[\bar u(p')\,\gamma_\mu\,v(k')\right]$$

$$4\,\langle \mathcal{M}_\gamma \mathcal{M}_H^* \rangle\;\frac{12\,m_W^2\,s(s-m_H^2)}{e^2g^2\,mM}\,(-1) =$$

$$\sum_{pqrs} \bar v^p_a(k)\,\gamma^\mu_{ab}\,u^q_b(p)\,\bar u^r_c(p')\,\gamma_{\mu\,cd}\,v^s_d(k')\;\bar v^s_e(k')\,\mathbb{1}_{ef}\,u^r_f(p')\,\bar u^q_g(p)\,\mathbb{1}_{gh}\,v^p_h(k)$$

$$= \mathrm{Tr}\left\{(\not k - m)\,\gamma^\mu\,(\not p + m)\right\}\;\mathrm{Tr}\left\{(\not p' + M)\,\gamma_\mu\,(\not k' - M)\right\}$$

$$\mathrm{Tr}\left\{(\not k\gamma^\mu \overset{+}{-} m\gamma^\mu)(\not p \overset{-}{+} m)\right\} = \mathrm{Tr}\left\{\cancel{\not k\gamma^\mu\not p} \overset{-}{+} m\not k\gamma^\mu \overset{+}{-} m\not p\gamma^\mu \overset{-}{+} \cancel{m^2\gamma^\mu}\right\}$$

$$= 4m\,(k^\mu - p^\mu) \qquad\qquad 4M\,(k'_\mu - p'_\mu)$$

$$= 16\,Mm\,(k^\mu - p^\mu)(k'_\mu - p'_\mu) = 16Mm\left[(k\cdot k') - (k\cdot p') - (p\cdot k') + (p\cdot p')\right]$$

$$= 16\,Mm\,[u - t]$$

$$\mathcal{M}_Z = \frac{1}{s-m_Z^2}\left[\bar v(k)\gamma^\mu(c_V - c_A\gamma^5)u(p)\right]\left[\bar u(p')(c_V - c_A\gamma^5)v(k')\right]$$

$$\mathcal{M}_H = -\frac{g^2}{4m_W^2}\,\frac{mM}{s-m_h^2}\,\bar v(k)u(p)\,\bar u(p')v(k')$$

$$\langle \mathcal{M}_Z\mathcal{M}_H^*\rangle\,\frac{(s-m_h^2)(s-m_Z^2)4m_W^2}{g^2 mM}(-1) =$$

$$= \sum_{pqrs} \bar v^p_a(k)\gamma^\mu(c_V-c_A\gamma^5)_{ab}\,u^q_b(p)\,\bar u^r_c(p')\gamma_\mu(c_V-c_A\gamma^5)_{cd}\,v^s_d(k')$$

$$\bar v^s_\alpha(k')\,\mathbb{1}_{\alpha\beta}\,u^r_\beta(p')\,\bar u^q_\gamma(p)\,\mathbb{1}_{\gamma\delta}\,v^p_\delta(k) =$$

$$= \mathrm{Tr}\{(\not k - m)\gamma^\mu(c_V-c_A\gamma^5)(\not p+m)\}\,\mathrm{Tr}\{(\not p'+M)\gamma_\mu(\tilde c_V-\tilde c_A\gamma^5)(\not k'-M)\}$$

$$\cdot\ \mathrm{Tr}\{(\not k\pm m)\gamma^\mu(c_V-c_A\gamma^5)(\not p\mp m)\} =$$

$$= \mathrm{Tr}\{(\not k\gamma^\mu \pm m\gamma^\mu)(c_V\not p \mp mc_V - c_A\gamma^5\not p \pm mc_A\gamma^5)\} =$$

$$= \mathrm{Tr}\{\underbrace{\cancel{c_V\not k\gamma^\mu\not p}}_{\text{odd}} \mp mc_V\overbrace{\not k\gamma^\mu}^{k_\alpha\gamma^\alpha\gamma^\mu \to k_\alpha g^{\alpha\mu}} - \underbrace{\cancel{c_A\not k\gamma^\mu\gamma^5\not p}}_{\text{odd}} - \cancel{mc_A\not k\gamma^\mu\gamma^5}\quad \mathrm{tr}(\gamma^\mu\gamma^\nu\gamma^5)=0$$

$$\pm mc_V\gamma^\mu\not p - \underbrace{\cancel{m^2c_V\gamma^\mu}}_{\text{odd}} + \cancel{mc_A\gamma^\mu\gamma^5\not p} + \cancel{m^2c_A\gamma^\mu\gamma^5}\}$$

$$= 4mc_Vk^\mu - 4mc_Vp^\mu = 4mc_V(k^\mu - p^\mu)$$

$$\cdot\ \mathrm{Tr}\{(\not p'+M)\gamma_\mu(\tilde c_V-\tilde c_A\gamma^5)(\not k'-M)\} = -4M\tilde c_V(p'_\mu - k'_\mu) = 4M\tilde c_V(k'_\mu - p'_\mu)$$

$$= 16Mm\,c_V\tilde c_V(k^\mu - p^\mu)(k'_\mu - p'_\mu)$$

$$= 16Mm\,c_V\tilde c_V\left[(k\cdot k') - (k\cdot p') - (k'\cdot p) + (p\cdot p')\right]$$

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$$= 16Mm\,c_V\tilde c_V\left[\cancel{m^2+M^2} - t - \cancel{m^2-M^2} + u\right]$$

$$= 16Mm\,c_V\tilde c_V\left[u-t\right]$$