



Instituto
Balseiro

Mass: from the Higgs to Cosmology School

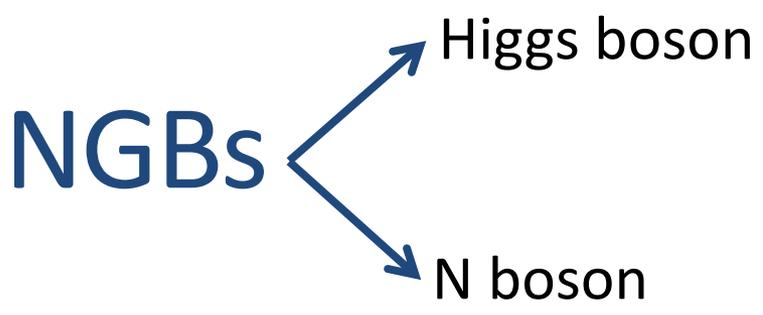
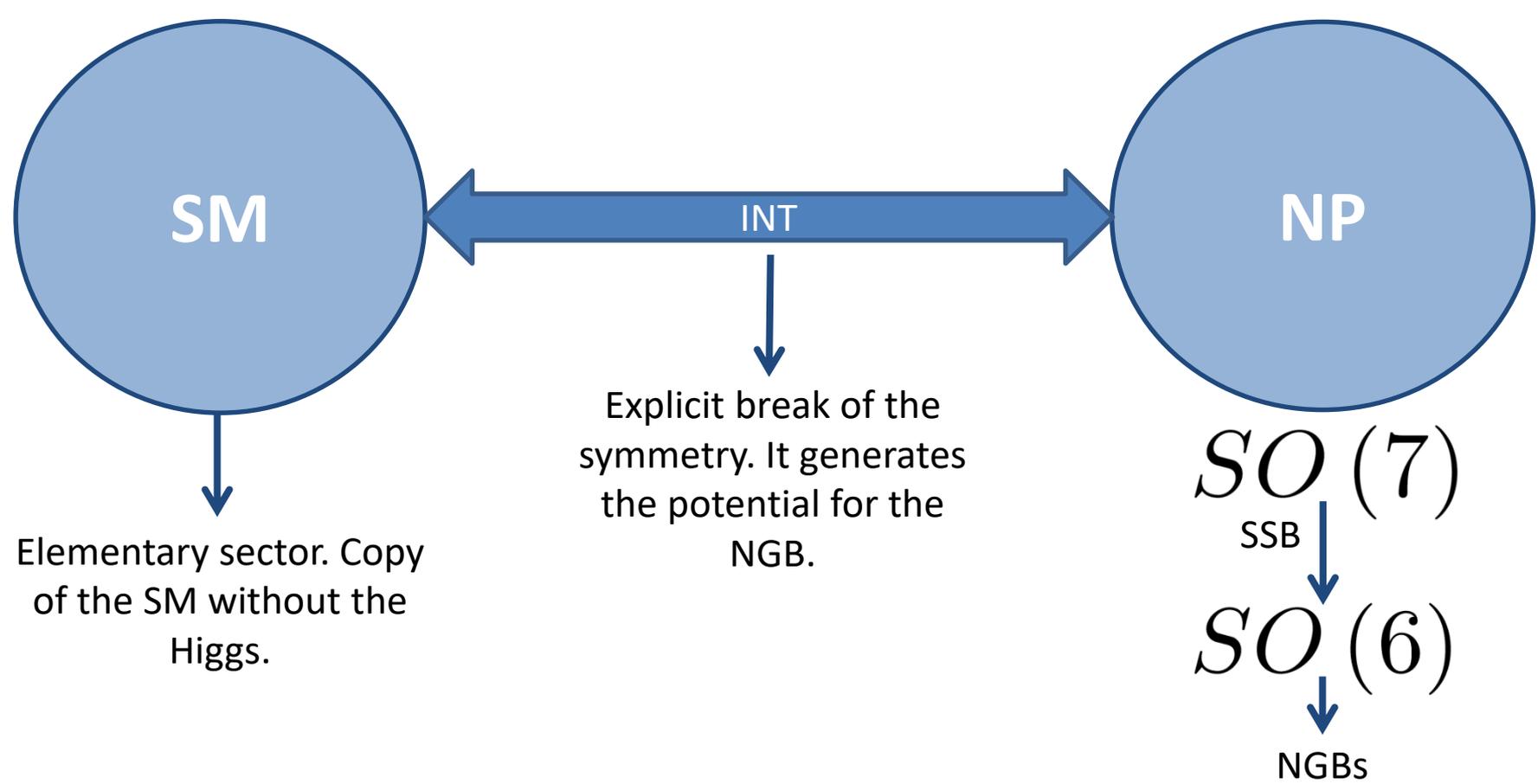
Cargèse, July 10, 2018

The $SO(7) / SO(6)$ Composite Higgs Model

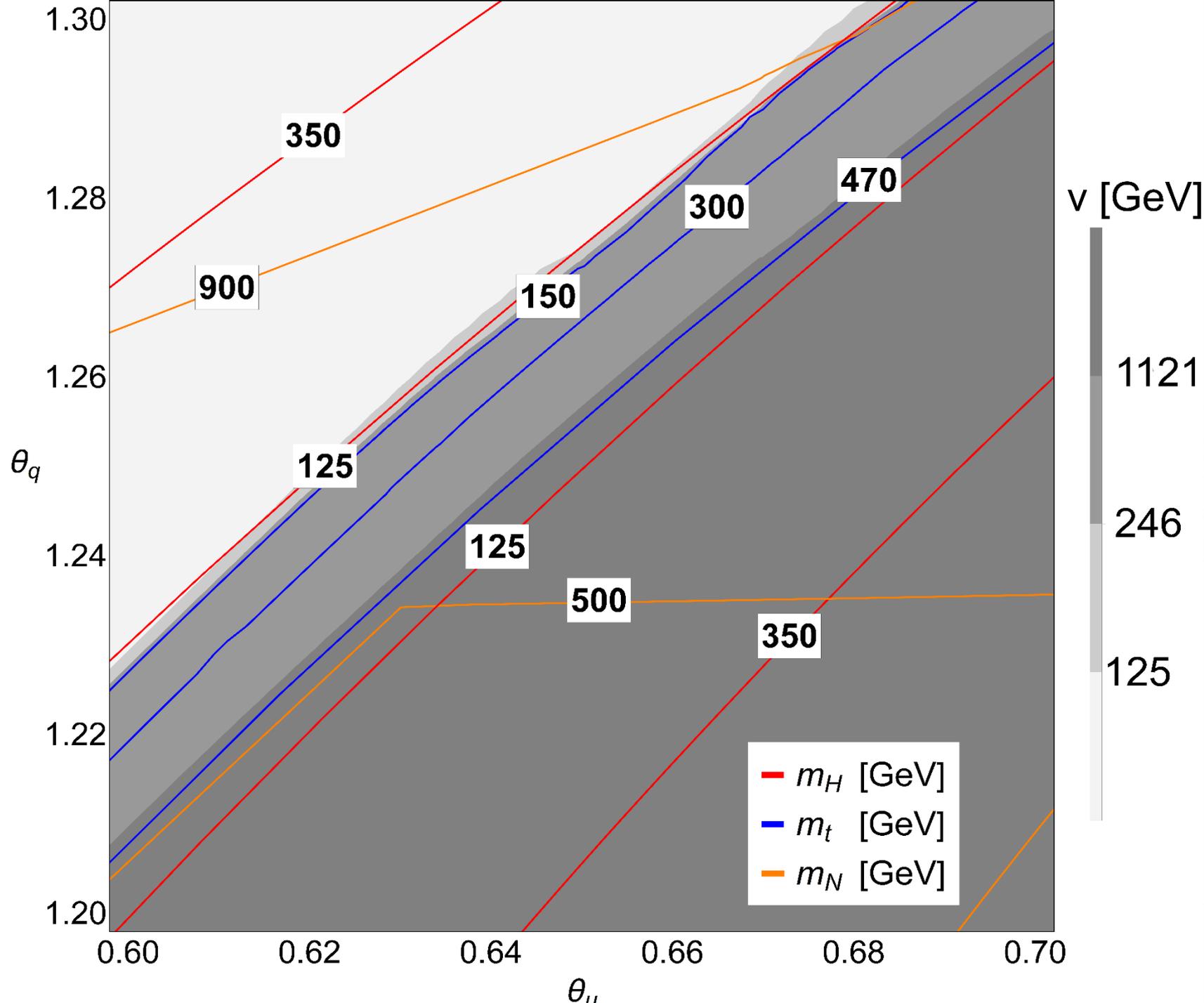
Alejo Rossia, Leandro Da Rold

CAB – IB, CNEA, CONICET & DESY

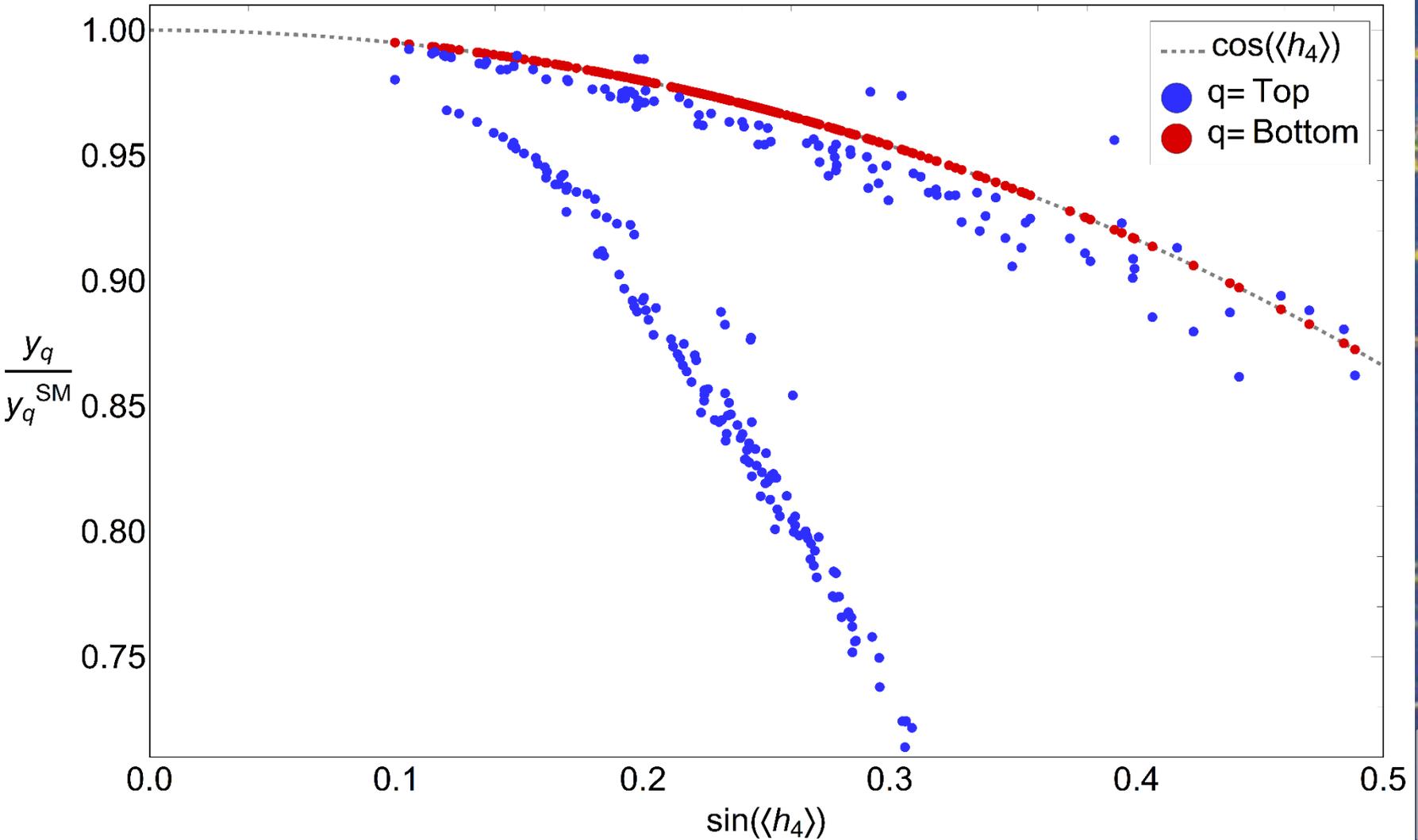




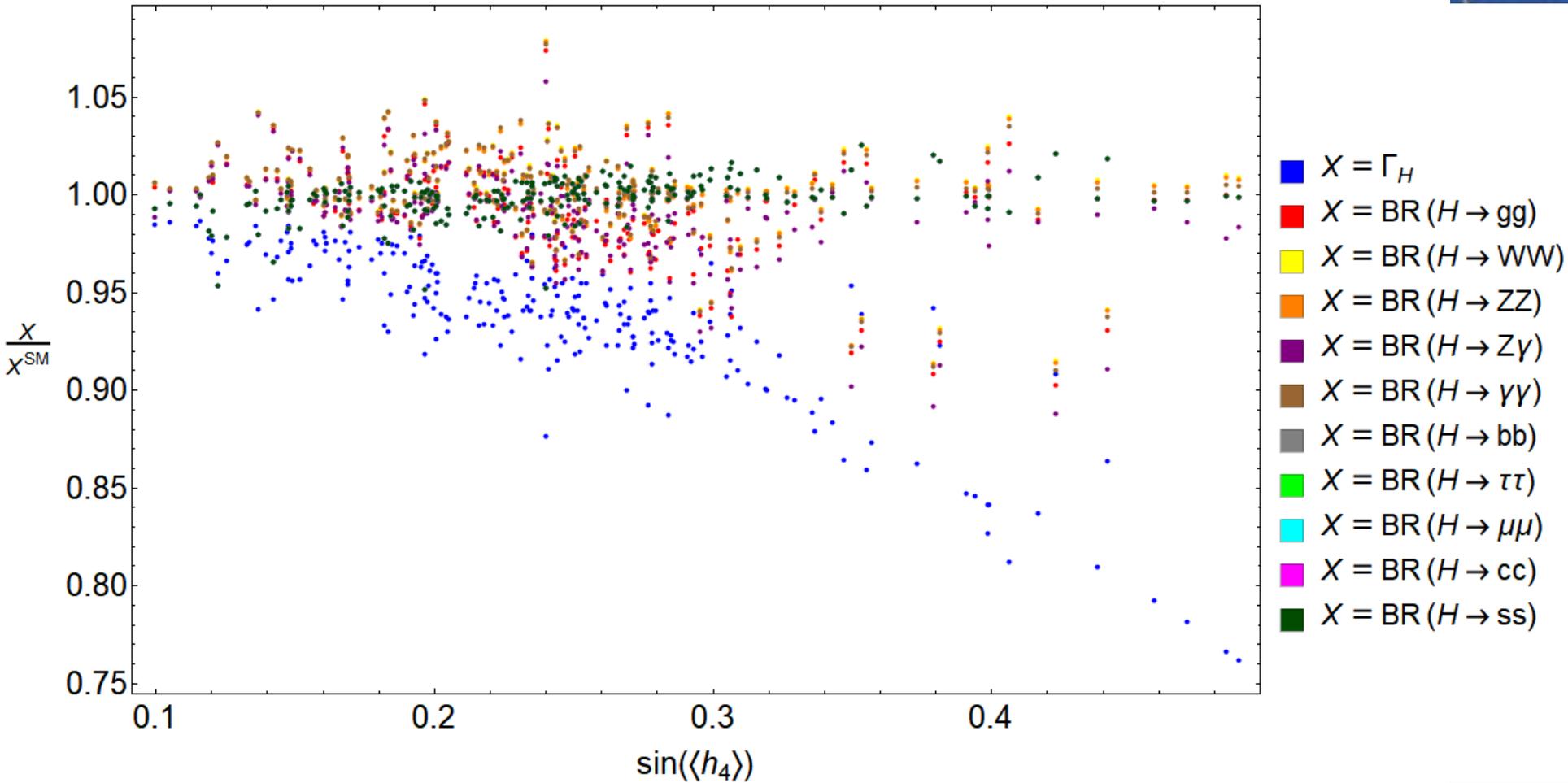
$$\left. \begin{matrix} \mathbf{2}_{\frac{1}{2}} \\ \mathbf{1}_{\frac{2}{3}} \end{matrix} \right\} SU(2)_L \times U(1)_Y$$



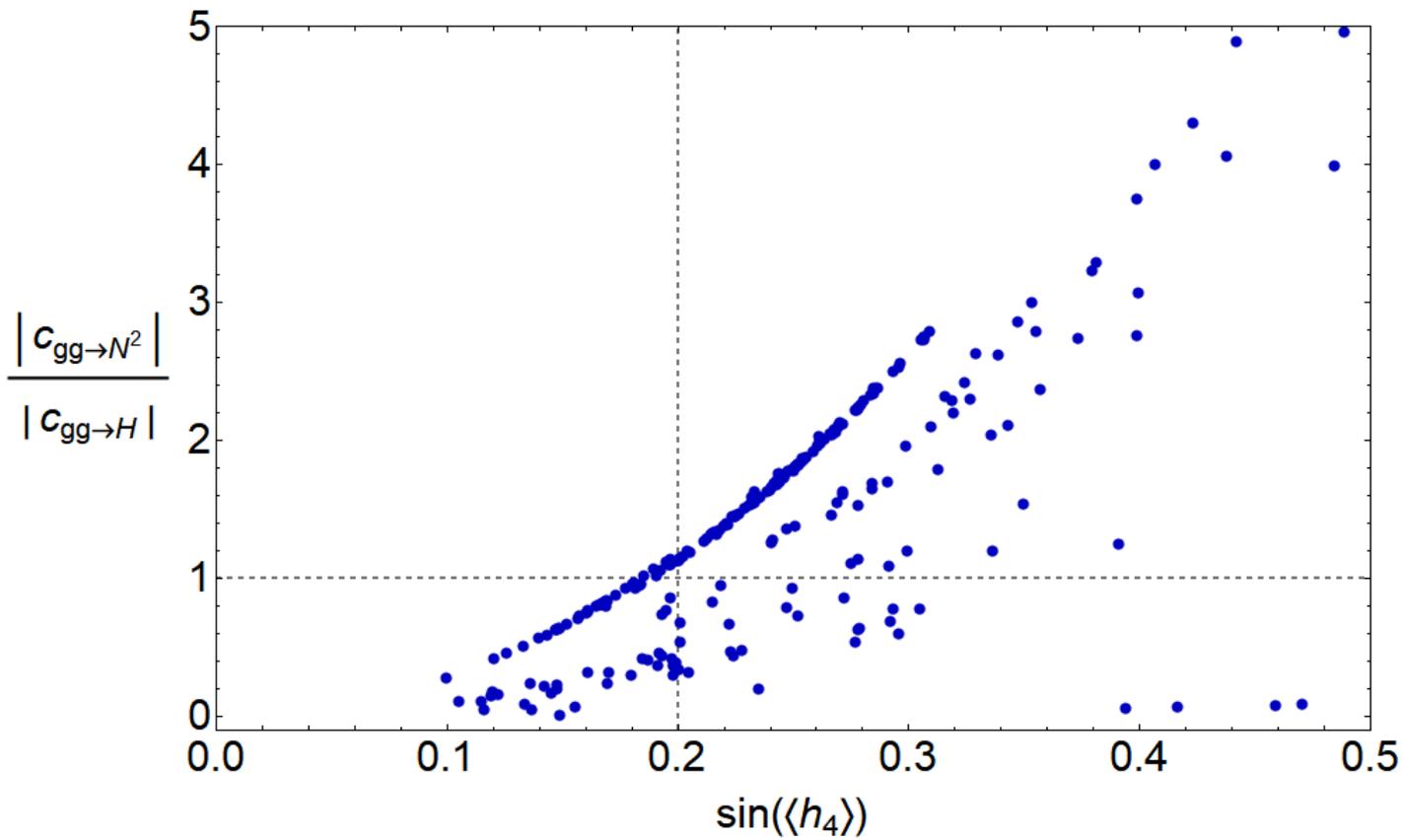
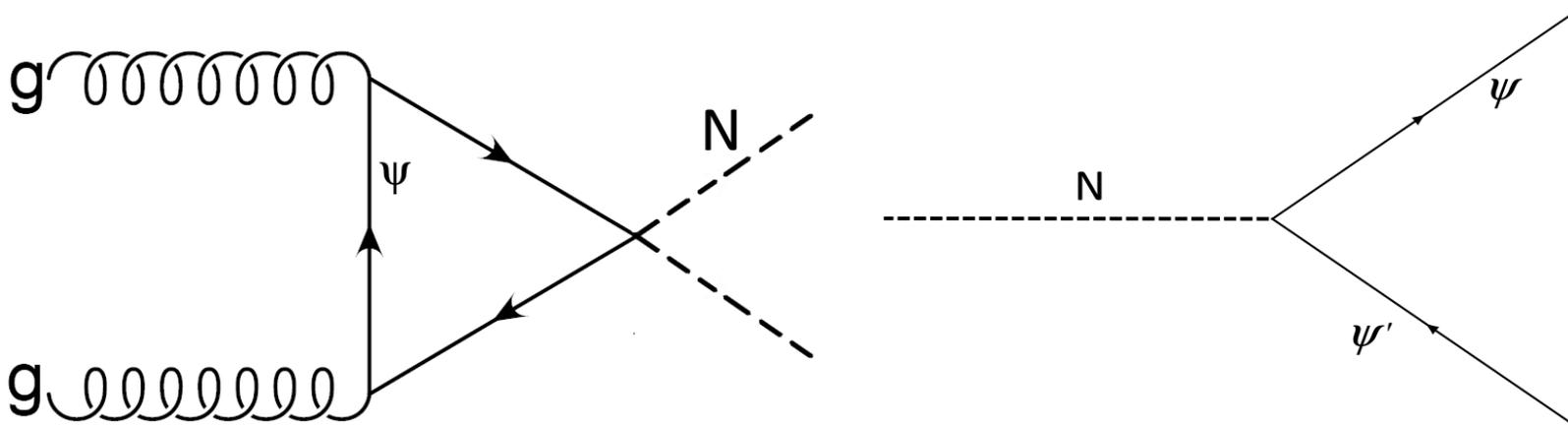
Yukawa couplings



Decay width and BRs



Production and decay of N

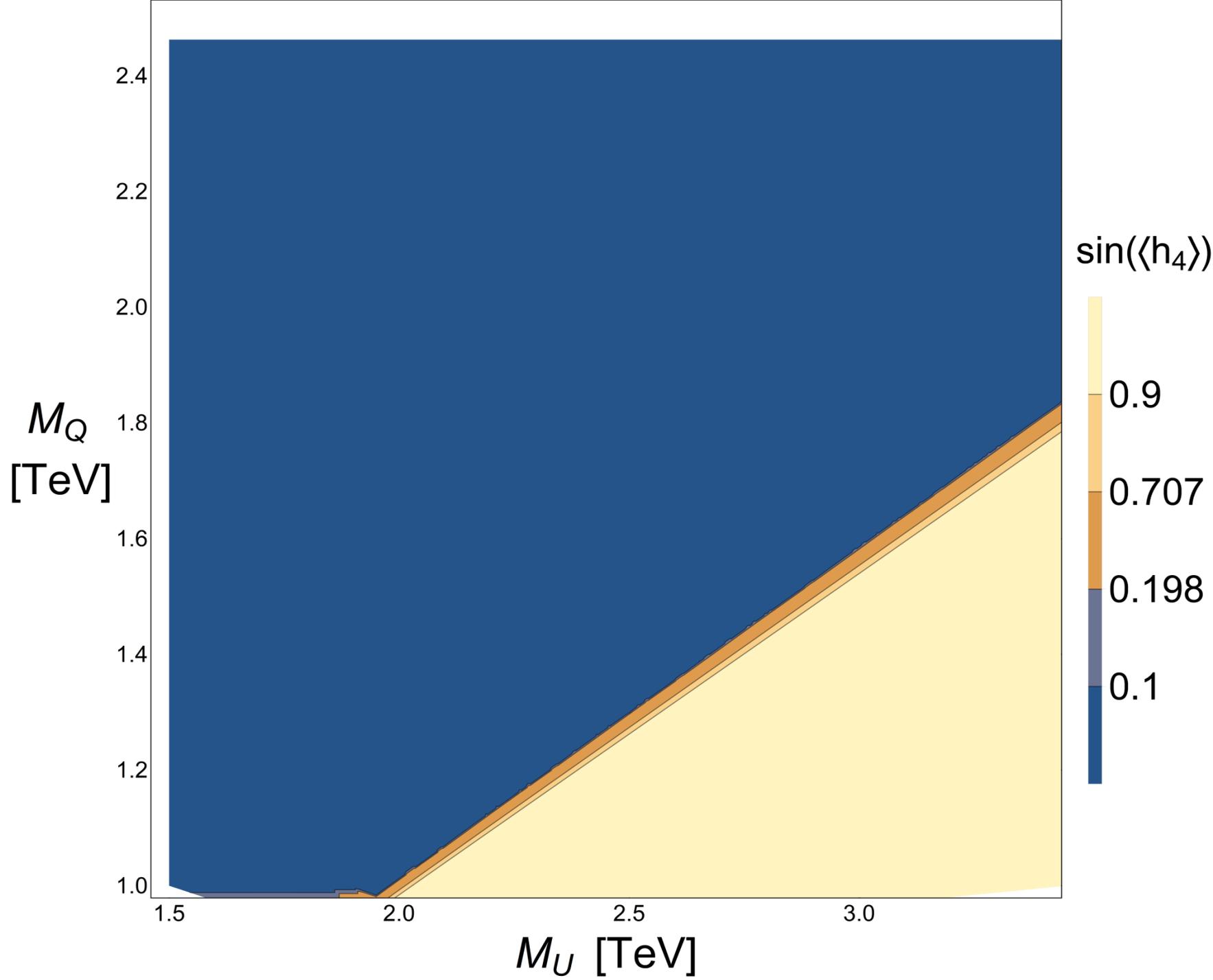


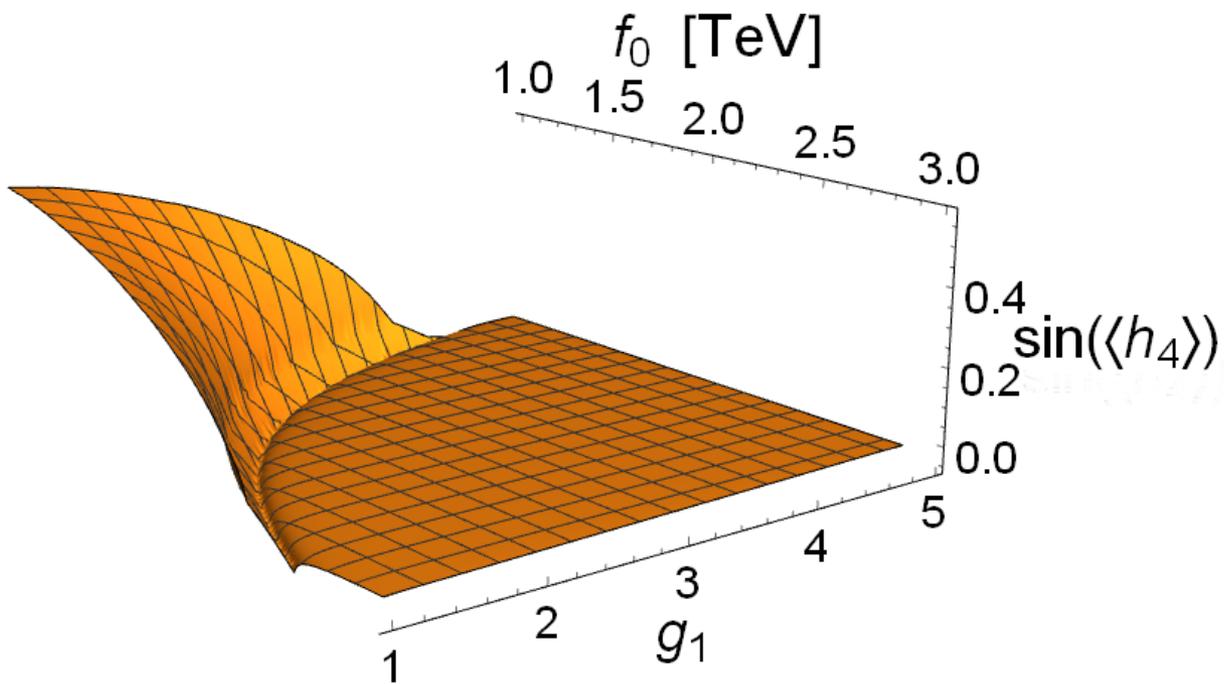
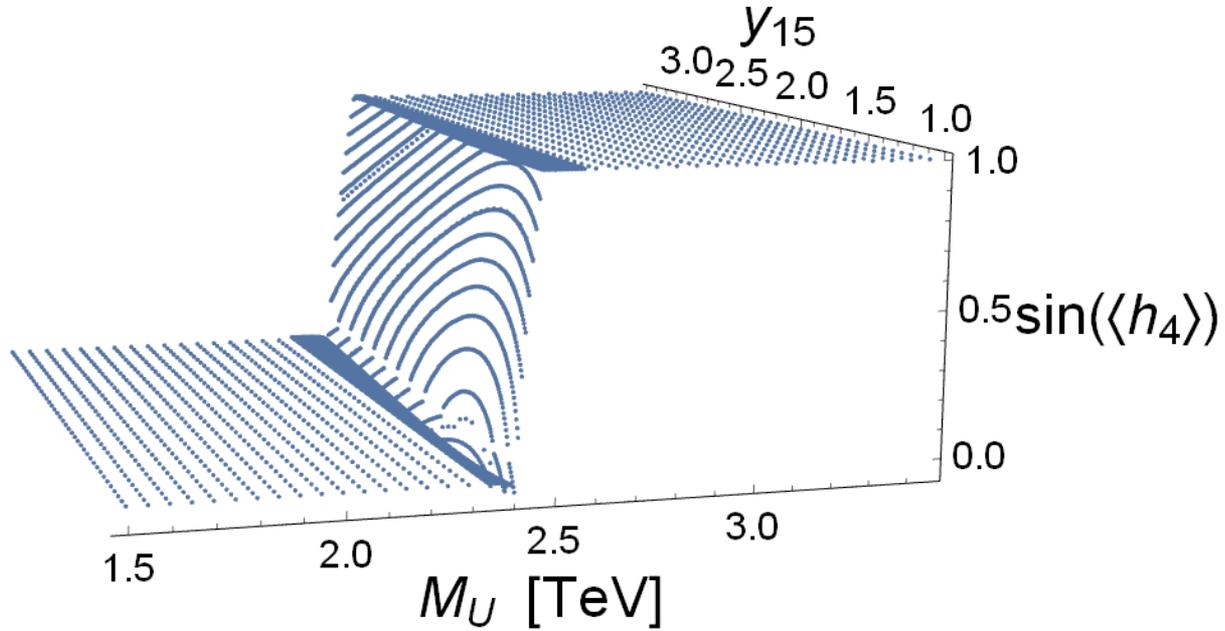
A blue-toned astronomical image of a star field. The background is a dense field of stars of various magnitudes. Several prominent stars are circled in white, and some are marked with small white crosses. Faint white lines connect some of the stars, forming a constellation pattern. The overall color palette is a range of blues, from deep navy to bright cyan.

Thank you very much!

APPENDIX







Vector bosonic resonances

m

$$\frac{f_0 g_1}{\sqrt{2}} \longrightarrow \frac{f_0 g_1}{\sqrt{2}}$$

$$A_\mu^{m_1}$$

$$f_0 \sqrt{\frac{g_{0Y}^2 + g_1^2}{2}} \longrightarrow f_0 \sqrt{\frac{g_{0Y}^2 + g_1^2}{2}} + \epsilon$$

$$A_\mu^{m_2}$$

$$f_0 \sqrt{\frac{g_0^2 + g_1^2}{2}} \longrightarrow f_0 \sqrt{\frac{g_0^2 + g_1^2}{2}} + \eta$$

$$A_\mu^{m_3}$$

$$f_0 \sqrt{\frac{g_0^2 + g_1^2}{2}} \longrightarrow f_0 \sqrt{\frac{g_0^2 + g_1^2}{2}} + \Delta$$

$$A_\mu^{m_4}$$

$$g_1 \sqrt{\frac{f_0^2 + f_1^2}{2}} \longrightarrow g_1 \sqrt{\frac{f_0^2 + f_1^2}{2}}$$

$$A_\mu^{m_5}$$

$$g_1 \sqrt{\frac{f_0^2 + f_1^2}{2}} \longrightarrow g_1 \sqrt{\frac{f_0^2 + f_1^2}{2}} + \delta$$

$$A_\mu^{m_6}$$

$$g_1 \sqrt{\frac{f_0^2 + f_1^2}{2}} \longrightarrow g_1 \sqrt{\frac{f_0^2 + f_1^2}{2}} + \alpha$$

$$A_\mu^{m_7}$$

How many NGBs?

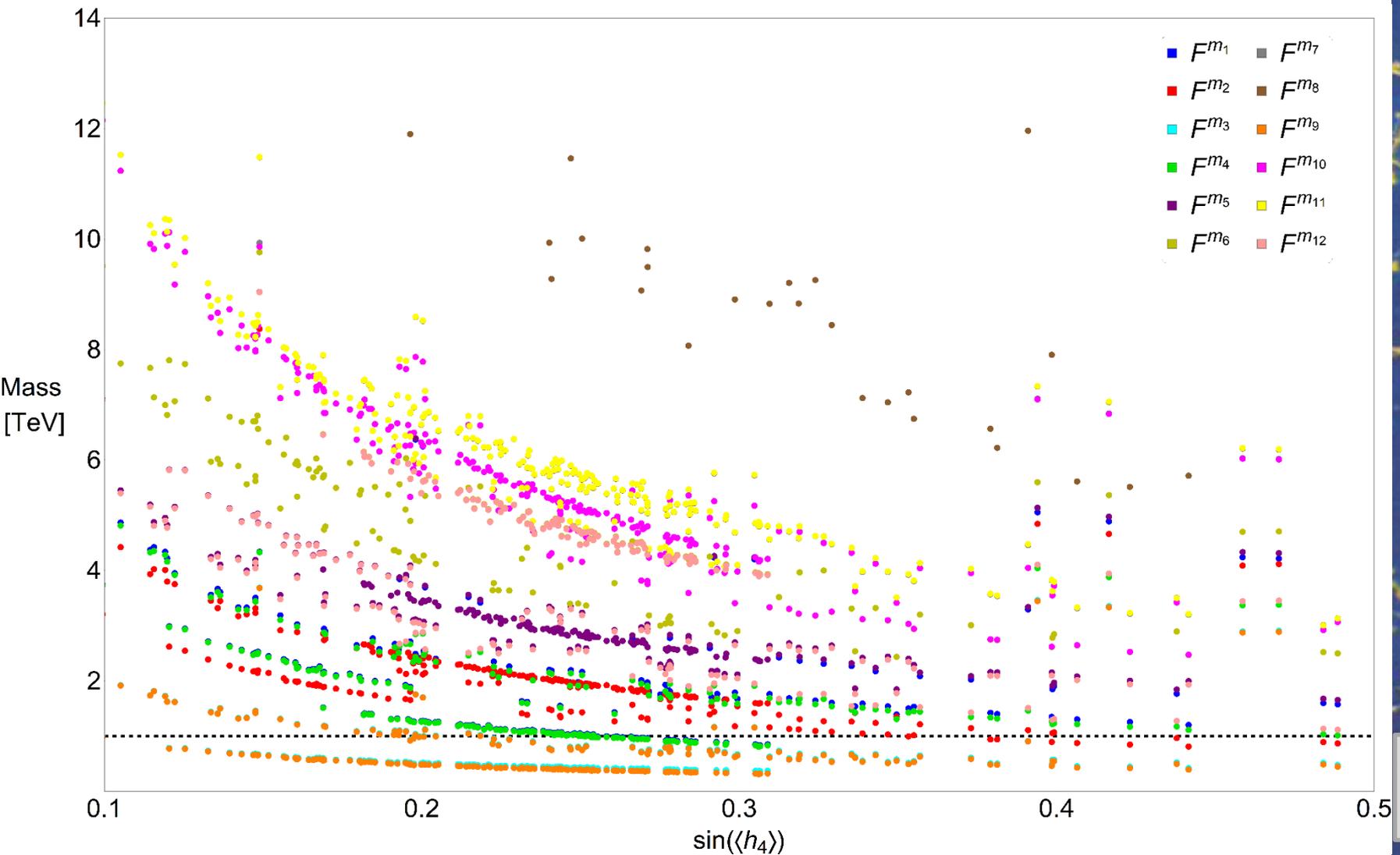
$$\underbrace{h_1, h_2, h_3, h_4}_{\text{Higgs boson}}, \underbrace{h_5, h_6}_{\text{N boson}}$$

$$SU(2)_L \times U(1)_Y$$

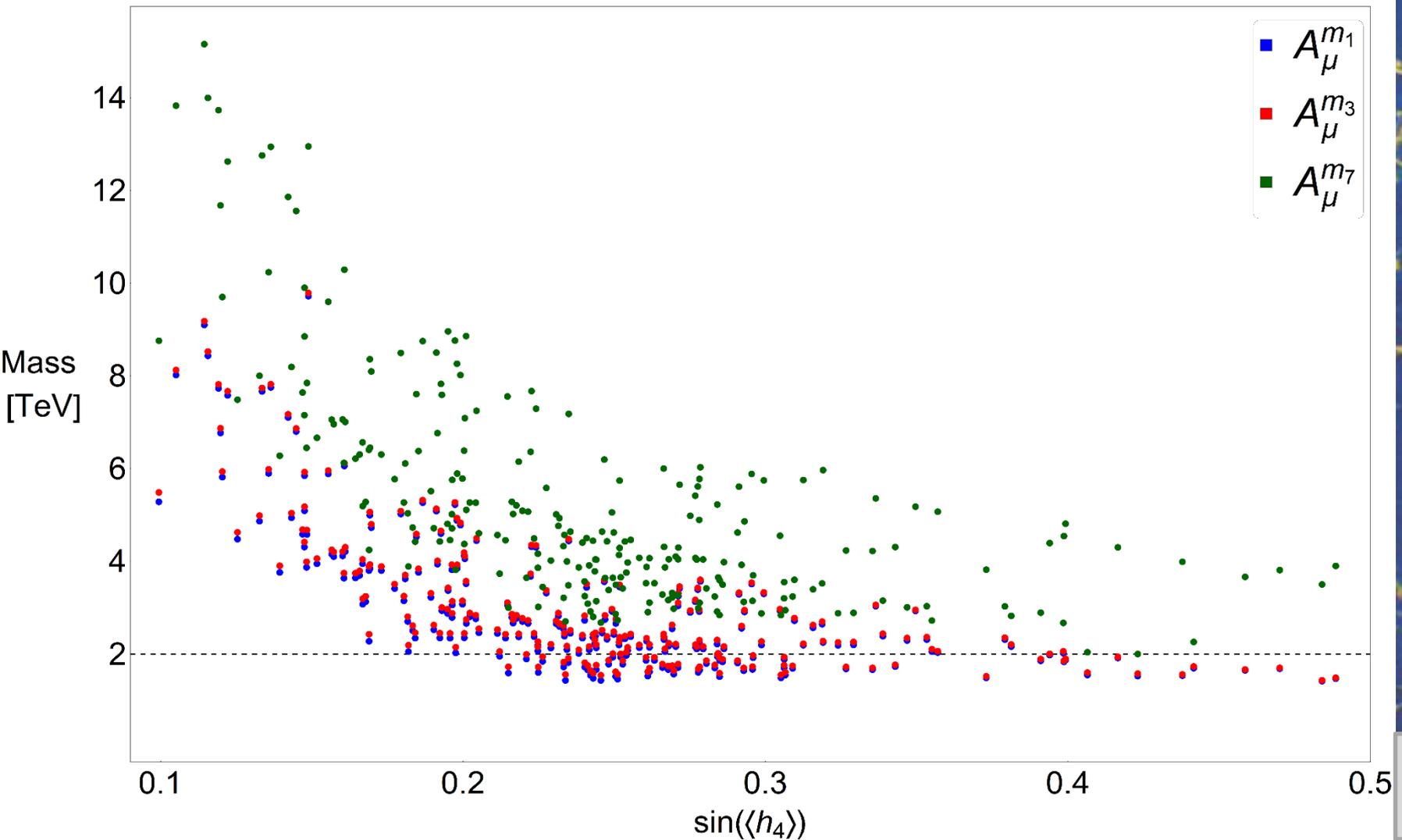
$$\mathbf{2}_{\frac{1}{2}}$$

$$\mathbf{1}_{\frac{2}{3}}$$

Fermion resonances



Vector bosonic resonances



$$m_H = \int_0^{\Lambda_{ME}} \frac{dm_H}{dE} (E, \lambda_i) dE + \int_{\Lambda_{ME}}^{\infty} \frac{dm_H}{dE} (E, \lambda_i) dE$$

$$= m_H^{ME} + m_H^{BSM},$$

$$m_H^{ME} = C \Lambda_{ME}$$

$$\mathcal{G} \sim \mathcal{G}' \times SU(3)_c$$

$$\mathcal{H} \sim \mathcal{H}' \times SU(3)_c$$

$$\mathcal{L}_{int} = f^{\frac{5}{2} - \Delta_{\mathcal{O}}} \lambda_{\psi} \bar{\psi} \mathcal{O}_{comp} + \dots$$

$$ME_{\psi} = \cos(\theta_{\psi}) \psi + \sin(\theta_{\psi}) C_{\psi}$$

$$\tan(\theta_{\psi}) = \frac{\lambda_{\psi}|_{IR}}{g^*} \quad y_{\psi} \sim y \sin(\theta_{\psi_L}) \sin(\theta_{\psi_R})$$

$$m_{\psi} \sim y \sin(\theta_{\psi_L}) \sin(\theta_{\psi_R}) v,$$

$$T^a \vec{F} = 0, \quad \hat{T}^{\hat{a}} \vec{F} \neq 0 \quad U[\Pi] = e^{i\sqrt{2}\Pi} \quad \Pi = h^{\hat{a}}(x) \hat{T}^{\hat{a}}$$

$$\vec{\Phi}(x) = U[\Pi] \vec{F} \quad U[\Pi] \rightarrow U[\Pi^{(g)}] = g \cdot U[\Pi] \cdot h^{-1}[\Pi, g]$$

$$\vec{\Phi}(x) \rightarrow \vec{\Phi}^{(g)}(x) = g \cdot \vec{\Phi}(x) \quad \mathbf{Ad}_{\mathcal{G}} = \mathbf{Ad}_{\mathcal{H}} \oplus \mathbf{r}_{\pi}$$

$$i U[\Pi]^{-1} \cdot \partial_{\mu} U[\Pi] \quad d_{\mu}^{\hat{a}} = \text{Tr} \left[i U[\Pi]^{-1} \cdot \partial_{\mu} U[\Pi] \cdot \hat{T}^{\hat{a}} \right]$$

$$d_{\mu} = d_{\mu}^{\hat{a}} \hat{T}^{\hat{a}} \rightarrow h[\Pi, g] \cdot d_{\mu} \cdot h[\Pi, g]^{-1}$$

$$\mathcal{L}_{\pi} = \frac{f^2}{4} \left| \partial_{\mu} \vec{\Phi} \right|^2$$

$$d_{\mu}^{\hat{a}} = -\frac{\sqrt{2}}{f} \partial_{\mu} \bar{h}^{\hat{a}} + \mathcal{O}(\partial\Pi/f \cdot \Pi^2/f^2)$$

$$h = \sqrt{\sum_{\hat{a}} (h^{\hat{a}})^2}$$

$$\mathcal{L}_{\pi} = \frac{f^2}{4} d_{\mu}^{\hat{a}} d_{\hat{a}}^{\mu} = \frac{1}{2} \partial_{\mu} \bar{h}^{\hat{a}} \partial^{\mu} \bar{h}^{\hat{a}} + \sum_{n=2}^{\infty} \mathcal{O}(\partial\Pi/f \cdot \Pi^n/f^n)$$

$$v = f \sin(\langle h \rangle)$$

$$\frac{v^2}{f^2} = \sin^2(\langle h \rangle) \ll 1$$

$$\mathcal{L} = \mathcal{L}_0 + \mathcal{L}_1 + \mathcal{L}_{Mezcla}$$

$$\mathcal{L}_{bos} = -\frac{1}{4g_0^2} F_{\mu\nu}^{0,A} F_A^{0,\mu\nu} + \frac{f_0^2}{4} \text{Tr} |D_\mu \Omega|^2 + \frac{f_1^2}{4} |D_\mu \vec{\Phi}_1|^2 - \frac{1}{4g_1^2} F_{\mu\nu}^{1,A} F_A^{1,\mu\nu}$$

$$\mathcal{L}_{bos} \supset \frac{f_0^2}{4} |A_\mu^{0,a} - A_\mu^{1,a}|^2 + \frac{f_0^2}{4} |A_\mu^{1,\hat{a}}|^2 + \frac{f_1^2}{4} |A_\mu^{1,\hat{a}}|^2$$

$$\mathcal{L}_{0,ferm} = \bar{q}_L i \not{\partial} q_L + \bar{t}_R i \not{\partial} t_R$$

$$\mathcal{L}_{1,ferm} = \bar{Q} i \not{\partial} Q - \bar{Q}_L M_Q Q_R + \bar{T} i \not{\partial} T - \bar{T}_L M_U T_R + h.c.$$

$$+ f_1 y_{15} P_{21 \rightarrow 15} \left(\overline{U [\Pi_{21}]_{21}^\dagger} Q_L \right) P_{35 \rightarrow 15} \left(U [\Pi_{35}]_{35}^\dagger T_R \right) + h.c.$$

$$\mathcal{L}_{Mezcla,ferm} = f_0 \lambda_q \bar{Q}_L Q_R + f_0 \lambda_u \bar{T}_R T_L + h.c.$$

$$\tan(\theta_{u,q}) = \frac{\lambda_{u,q} f_0}{M_{U,Q}}$$

$$V_{eff}^\psi = A_\psi \int \ln \left[\frac{\det [K(p_E, \phi_c)]}{\det [K(p_E, 0)]} \right] \frac{d^4 p_E}{(2\pi)^4}$$

$$\Omega \rightarrow g_0 \Omega g_1^\dagger$$

$$D_\mu \bar{h}_1^{\hat{a}} = \partial_\mu \bar{h}_1^{\hat{a}} - i (A_\mu^{1,A} T^A \bar{h}_1)^{\hat{a}}$$

$$\vec{\Phi} = \Omega U \vec{F} = U_T \vec{F}$$

$$D_\mu \Omega = \partial_\mu \Omega - i A_\mu^{0,A} T^A \Omega + i A_\mu^{1,A} \Omega T^A$$

$$U_T = e^{i\sqrt{2}h^{\hat{a}}\hat{T}^{\hat{a}}}$$

$$U^\dagger [\Pi_{\mathbf{r}_Q}] Q \rightarrow h [\Pi_{\mathbf{r}_Q}, g] \cdot U^\dagger [\Pi_{\mathbf{r}_Q}] Q$$

$$\mathcal{L}_{eff}^1 = Z_{q_L} \overline{Q}_L \not{p} Q_L + Z_{t_R} \overline{\mathcal{T}}_R \not{p} \mathcal{T}_R$$

$$\begin{aligned} \mathcal{L}_{eff}^2 = & \sum_{i=1}^{d_Q} \mathcal{S}_{\mathbf{r}_Q^i}^q(p^2) P_{\mathbf{r}_Q \rightarrow \mathbf{r}_Q^i} \left(\overline{U^\dagger Q_L} \right) \not{p} P_{\mathbf{r}_Q \rightarrow \mathbf{r}_Q^i} (U^\dagger Q_L) \\ & + \sum_{i=1}^{d_T} \mathcal{S}_{\mathbf{r}_T^i}^u(p^2) P_{\mathbf{r}_T \rightarrow \mathbf{r}_T^i} \left(\overline{U^\dagger \mathcal{T}_R} \right) \not{p} P_{\mathbf{r}_T \rightarrow \mathbf{r}_T^i} (U^\dagger \mathcal{T}_R) \end{aligned}$$

$$\mathcal{L}_{eff}^3 = \mathcal{M}_t(p^2) P_{\mathbf{r}_Q \rightarrow \mathbf{r}_c} \left(\overline{U^\dagger Q_L} \right) P_{\mathbf{r}_T \rightarrow \mathbf{r}_c} (U^\dagger \mathcal{T}_R) + h.c.$$

$$\mathcal{L}_{eff}^4 = Z_W A_\mu^{0,A} P_T^{\mu\nu} p^2 A_\nu^{0,A}$$

$$\mathcal{L}_{eff}^5 = \sum_{r=\text{Adj}[\mathcal{H}], \mathbf{r}\pi} g_r(p^2) P_T^{\mu\nu} P_{\text{Adj}[\mathcal{G}] \rightarrow r} (U^\dagger A_\mu^0) P_{\text{Adj}[\mathcal{G}] \rightarrow r} (U^\dagger A_\nu^0)$$

$$\mathcal{L}_{eff}^6 = \frac{f^2}{4} \left| D_\mu \vec{\Phi} \right|^2 \quad \mathcal{L}_{eff} = \sum_{i=1}^6 \mathcal{L}_{eff}^i$$

$$\mathcal{L}_{eff}^1 = Z_{q_L} \bar{q}_L \not{p} q_L + Z_{t_R} \bar{t}_R \not{p} t_R \quad \mathcal{L}_{eff}^2 = \bar{q}_L \not{p} \bar{\pi}_{q_L} q_L + \bar{t}_R \not{p} \pi_{t_R} t_R$$

$$\bar{\pi}_{q_L} = \begin{pmatrix} \pi_{t_L} & \pi_{tb_L} \\ \pi_{tb_L}^* & \pi_{b_L} \end{pmatrix} \quad \mathcal{L}_{eff}^3 = \bar{q}_L M_{q_L t_R} t_R + h.c. \quad M_{q_L t_R} = \begin{pmatrix} M_{t_{L/R}} \\ M_{b_{L} t_R} \end{pmatrix}$$

$$\mathcal{L}_{eff} \supset \tilde{b}_\mu \left(Z_B p^2 + \frac{1}{2} \Lambda_B \right) P_T^{\mu\nu} \tilde{b}_\nu + \sum_{i=1}^3 \tilde{w}_\mu^i \left(Z_W p^2 + \frac{1}{2} \Lambda_i \right) P_T^{\mu\nu} \tilde{w}_\nu^i$$

$$\mathcal{L}_{eff} \supset \frac{1}{2} \sum_{i=1}^3 \tilde{w}_\mu^i \Omega_i P_T^{\mu\nu} \tilde{b}_\nu$$

$$\mathcal{A}_{\mathcal{F}} \mathcal{F} = \begin{pmatrix} \tilde{Z}_{t_L} & \not{p} \pi_{tb_L} & M_{t_{L/R}} \\ \not{p} \pi_{tb_L}^* & \tilde{Z}_{b_L} & M_{b_{L}t_R} \\ M_{t_{L/R}}^* & M_{b_{L}t_R}^* & \tilde{Z}_{t_R} \end{pmatrix} \begin{pmatrix} t_L \\ b_L \\ t_R \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}$$

$$\mathcal{A}_{\mathcal{B}} \mathcal{B} = \begin{pmatrix} 2Z_W p^2 + \Lambda_1 & 0 & 0 & \frac{1}{2}\Omega_1 \\ 0 & 2Z_W p^2 + \Lambda_2 & 0 & \frac{1}{2}\Omega_2 \\ 0 & 0 & 2Z_W p^2 + \Lambda_3 & \frac{1}{2}\Omega_3 \\ \frac{1}{2}\Omega_1 & \frac{1}{2}\Omega_2 & \frac{1}{2}\Omega_3 & 2Z_B p^2 + \Lambda_B \end{pmatrix} \begin{pmatrix} \tilde{w}_{\nu,T}^1 \\ \tilde{w}_{\nu,T}^2 \\ \tilde{w}_{\nu,T}^3 \\ \tilde{b}_{\nu,T} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

$$V_{CW} = \int \left(-2N_c \ln \left[\frac{\det [\mathcal{A}_{\mathcal{F}}]}{\det [\mathcal{A}_{\mathcal{F}}|_{h=0}]} \right] + \frac{3}{2} \ln \left[\frac{\det [\mathcal{A}_{\mathcal{B}}]}{\det [\mathcal{A}_{\mathcal{B}}|_{h=0}]} \right] \right) \frac{d^4 p}{(2\pi)^4}$$

$$\mathbf{21}_{SO(7)} \sim \mathbf{15}_{SO(6)} \oplus \mathbf{6}_{SO(6)}$$

$$\mathbf{6}_{SO(6)} \sim (\mathbf{2}, \mathbf{2})_0 \oplus (\mathbf{1}, \mathbf{1})_{\frac{1}{\sqrt{2}}} \oplus (\mathbf{1}, \mathbf{1})_{-\frac{1}{\sqrt{2}}}$$

$$\Pi = i h_1 T_{12} + i h_2 T_{10} + i h_3 T_{19} + i h_4 T_6 + i h_5 T_4 + i h_6 T_{15}$$

$$\sqrt{2}\Pi_7 = \begin{pmatrix} 0 & 0 & 0 & 0 & i h_1 & 0 & 0 \\ 0 & 0 & 0 & 0 & i h_2 & 0 & 0 \\ 0 & 0 & 0 & 0 & i h_3 & 0 & 0 \\ 0 & 0 & 0 & 0 & i h_4 & 0 & 0 \\ -i h_1 & -i h_2 & -i h_3 & -i h_4 & 0 & i h_5 & i h_6 \\ 0 & 0 & 0 & 0 & -i h_5 & 0 & 0 \\ 0 & 0 & 0 & 0 & -i h_6 & 0 & 0 \end{pmatrix}$$

$$\begin{aligned} (\sqrt{2}\Pi)^{2n} &= (\Gamma^2)^{n-1} 2\Pi^2 \\ (\sqrt{2}\Pi)^{2n+1} &= (\Gamma^2)^n \sqrt{2}\Pi, \end{aligned}$$

$$\Gamma^2 = \sum_{i=1}^6 h_i^2$$

$$U = e^{i\sqrt{2}\Pi} = \mathbb{I} + \frac{i}{\Gamma} \sin[\Gamma] \sqrt{2}\Pi + \frac{2}{\Gamma^2} (\cos[\Gamma] - 1) \Pi^2$$

$$\mathbf{35}_{SO(7)} = \mathbf{15}_{SO(6)} \oplus \mathbf{10}_{SO(6)} \oplus \overline{\mathbf{10}}_{SO(6)}$$

$$\mathbf{21}_{SO(7)} = (\mathbf{3}, \mathbf{1})_0 \oplus (\mathbf{1}, \mathbf{3})_0 \oplus (\mathbf{1}, \mathbf{1})_0 \oplus (\mathbf{2}, \mathbf{2})_{\frac{1}{\sqrt{2}}}$$

$$\oplus (\mathbf{2}, \mathbf{2})_{-\frac{1}{\sqrt{2}}} \oplus (\mathbf{2}, \mathbf{2})_0 \oplus (\mathbf{1}, \mathbf{1})_{\frac{1}{\sqrt{2}}} \oplus (\mathbf{1}, \mathbf{1})_{-\frac{1}{\sqrt{2}}}$$

$$t_R = \mathcal{T}_{R,(0,0)}^{el} \frac{1}{\sqrt{2}}$$

$$\tilde{w}_\mu^\pm = A_{\mu,(\pm 1,0)_0}^0 \quad \tan(\theta_Y) = \frac{2}{3}\sqrt{2} \quad \tilde{b}_\mu = \cos(\theta_Y) A_{\mu,(0,0)_0}^0 + \sin(\theta_Y) A_{\mu,(\tilde{0},\tilde{0})_{\bar{0}}}^0$$

$$\tilde{w}_\mu^0 = A_{\mu,(0,0)_0}^0$$

$$\tan(\omega) = \frac{g_0 Y}{g_1} \quad B_{\mu,ME} = \cos(\omega) \tilde{b}_\mu + \sin(\omega) (\cos(\theta_Y) A_\mu^{1;20} + \sin(\theta_Y) A_\mu^{1;15})$$

$$\tan(\varphi) = \frac{g_0}{g_1}$$

$$\mathcal{L}_{bos} \supset A^+ M_1^2 A^- \quad M_1^2 = \begin{pmatrix} \frac{f_0^2 g_0^2}{2} & 0 & -\frac{1}{2} f_0^2 g_0 g_1 & 0 \\ 0 & \frac{1}{2} g_1^2 \kappa & -\frac{i f_1^2 g_1^2 \sin(2\langle h_4 \rangle)}{4\sqrt{2}} & -\frac{f_1^2 g_1^2 \sin(2\langle h_4 \rangle)}{4\sqrt{2}} \\ -\frac{1}{2} f_0^2 g_0 g_1 & \frac{i f_1^2 g_1^2 \sin(2\langle h_4 \rangle)}{4\sqrt{2}} & \frac{1}{4} g_1^2 \varepsilon & -\frac{1}{4} i f_1^2 g_1^2 \sin^2(\langle h_4 \rangle) \\ 0 & -\frac{f_1^2 g_1^2 \sin(2\langle h_4 \rangle)}{4\sqrt{2}} & \frac{1}{4} i f_1^2 g_1^2 \sin^2(\langle h_4 \rangle) & \frac{1}{4} g_1^2 \varepsilon \end{pmatrix}$$

$$\kappa = f_0^2 + f_1^2 \cos^2(\langle h_4 \rangle),$$

$$\varepsilon = 2f_0^2 + f_1^2 \sin^2(\langle h_4 \rangle). \quad D_\mu \supset -i (g_0 A_\mu^{0;17} T_{L,0}^3 \oplus g_1 A_\mu^{1;17} T_{L,1}^3)$$

$$D_\mu \supset -i (g_0 \cos(\varphi) W_{\mu,ME}^3 T_{L,0}^3 \oplus g_1 \sin(\varphi) W_{\mu,ME}^3 T_{L,1}^3)$$

$$g_0 \cos(\varphi) = g_1 \sin(\varphi) = \frac{g_0 g_1}{\sqrt{g_0^2 + g_1^2}} \quad T_{L,0+1}^3 = T_{L,0}^3 \oplus T_{L,1}^3$$

$$D_\mu \supset -i \frac{g_0 g_1}{\sqrt{g_0^2 + g_1^2}} W_{\mu,ME}^3 T_{L,0+1}^3 \quad \mathcal{L}_{ferm} = -\overline{F}_L M_{LR} F_R - \overline{F}_R M_{RL} F_L$$

$$F_{L,R} = \begin{pmatrix} Q_{L,R} \\ T_{L,R} \\ t_{L,R} \end{pmatrix} \quad M_{LR} = \begin{pmatrix} M_Q \mathbb{1}_{21} & -Y_u & 0 \\ 0 & M_U \mathbb{1}_{35} & -\lambda_u^* f_0 \\ \lambda_q f_0 & 0 & 0 \end{pmatrix}$$

$$\Psi_{1,L} = -\bar{T}_L,$$

$$y_t \sim y_{15} \tan(\theta_q) \tan(\theta_u),$$

$$\Psi_{1,R} = -\cos(\theta_u) \bar{T}_R + \sin(\theta_u) t_R$$

$$m_t \sim y_{15} \tan(\theta_q) \tan(\theta_u) v.$$

$$S_6^q(p^2) = \frac{f_0^2 |\lambda_q|^2}{M_Q^2 - p^2},$$

$$S_{15}^q(p^2) = \frac{f_0^2 |\lambda_q|^2 \beta(M_U)}{\omega},$$

$$S_{10}^u(p^2) = \frac{f_0^2 |\lambda_u|^2}{M_U^2 - p^2}, \quad S_{10}^u(p^2) = \frac{f_0^2 |\lambda_u|^2}{M_U^2 - p^2}, \quad S_{15}^u(p^2) = \frac{f_0^2 |\lambda_u|^2 \beta(M_Q)}{\omega},$$

$$\mathcal{M}_u(p^2) = \frac{f_0^2 f_1 y_{15} \lambda_u^* \lambda_q M_Q M_U}{\omega},$$

$$\omega = (M_Q^2 - p^2)(M_U^2 - p^2) - p^2 f_1^2 |y_{15}|^2, \quad g_6(p^2) = \frac{f_0^2 (f_1^2 g_1^2 - 2p^2)}{2(f_0^2 + f_1^2) g_1^2 - 4p^2}$$

$$\beta(x) = f_1^2 |y_{15}|^2 + x^2 - p^2.$$

$$g_{15}(p^2) = -\frac{f_0^2 p^2}{f_0^2 g_1^2 - 2p^2},$$

$$P_{21 \rightarrow 15} \left(\overline{U^\dagger Q_L^{el}} \right) \not{p} P_{35 \rightarrow 15} (U^\dagger \mathcal{T}_R^{el}) = \frac{\sin(\Gamma)}{2\Gamma} \left[\overline{t_L} \not{p} t_R (h_4 + i h_3) + \overline{b_L} \not{p} t_R (i h_1 - h_2) \right]$$

$$\Lambda_i = g_6 (p^2) H^2 \frac{\sin^2(\Gamma)}{2\Gamma^2} + g_{15} (p^2) \frac{1}{4\Gamma^2} (H^2 \cos(2\Gamma) + 3\Gamma^2 + N^2)$$

$$\pi_{tbL} = 0$$

$$M_{bLtR} = 0$$

$$\Omega_{1,2} = 0,$$

$$V_{CW} = \int_0^\infty \mathcal{V}(p_E, h_4, h_5, h_6) dp_E$$

$$\mathcal{V}(p_E, h_4, h_5, h_6) \approx \frac{1}{p_E^3} A + \mathcal{O}\left(\frac{1}{p_E^4}\right) \text{ si } p_E \rightarrow \infty$$

$$\mathcal{V}(p_E, h_4, h_5, h_6) \approx p_E^3 B + \mathcal{O}(p_E^5) \text{ si } p_E \rightarrow 0,$$

$$V_{CW} = m_1^2 H^2 + m_2^2 N^2 + \lambda_1 H^4 + \lambda_2 H^2 N^2 + \lambda_3 N^4,$$

$$\langle H \rangle^2 = \frac{m_2^2 \lambda_2 - 2m_1^2 \lambda_3}{4\lambda_1 \lambda_3 - \lambda_2^2}$$

$$\langle N \rangle^2 = \frac{m_1^2 \lambda_2 - 2m_2^2 \lambda_1}{4\lambda_1 \lambda_3 - \lambda_2^2}$$

$$V_{CW} = a_1 \left(\frac{1 + \cos(\Gamma)}{2} \right)^2 + a_2 \sin^2(\Gamma) + a_3 \left(\frac{2\Gamma^2 - H^2}{\Gamma^2} \right) \sin^2(\Gamma) \\ + 3 \frac{\sin^2[\Gamma]}{68 \Gamma^2} (51a_4 H^2 + a_5 (9H^2 + 16N^2)),$$

$$\langle H \rangle = \arccos \left[\frac{a_2 - a_1}{a_1 - a_2 + 4a_3 + 4a_4 + 204a_5 + 36a_6} \right]$$

$$M^2 = \text{diag} \left[\frac{1}{2} (a_1) \langle H \rangle^2; (2a_3 - 102a_4 + 14a_5) - \frac{2}{3} (a_3 - 51a_4 + 7a_5) \langle H \rangle^2; \right. \\ \left. (2a_3 - 102a_4 + 14a_5) - \frac{2}{3} (a_3 - 51a_4 + 7a_5) \langle H \rangle^2 \right].$$

$$V_{CW} = m_1^2 H^2 + m_2^2 N^2 + \lambda_1 H^4 + (\lambda_1 + \lambda_3) H^2 N^2 + \lambda_3 N^4. \quad \langle H \rangle^2 = -\frac{m_1^2}{2\lambda_1}.$$

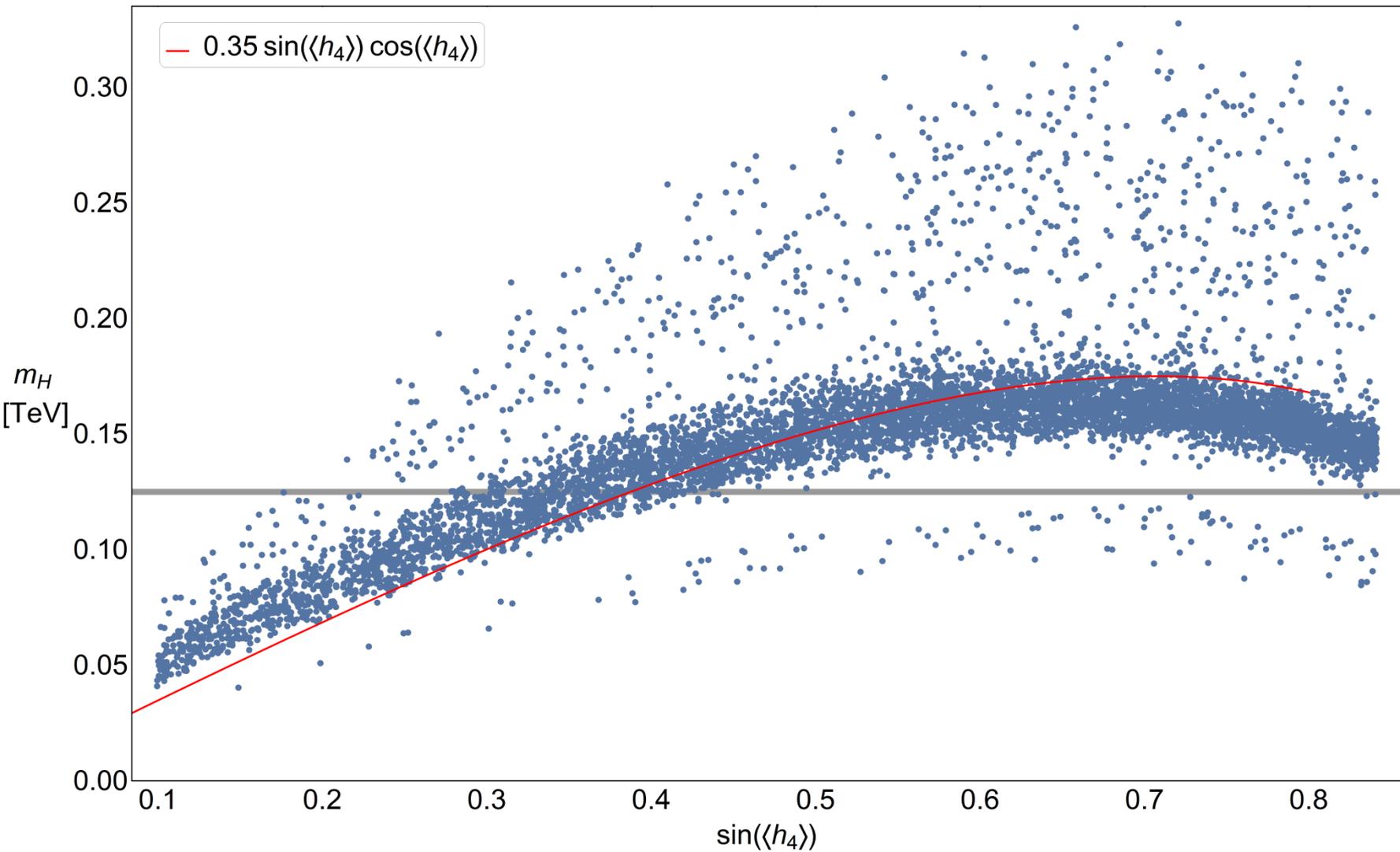
$$M^2 = \begin{pmatrix} 8\lambda_1 \langle H \rangle^2 & 0 & 0 \\ 0 & 2m_2^2 + 2(\lambda_1 + \lambda_3) \langle H \rangle^2 & 0 \\ 0 & 0 & 2m_2^2 + 2(\lambda_1 + \lambda_3) \langle H \rangle^2 \end{pmatrix}$$

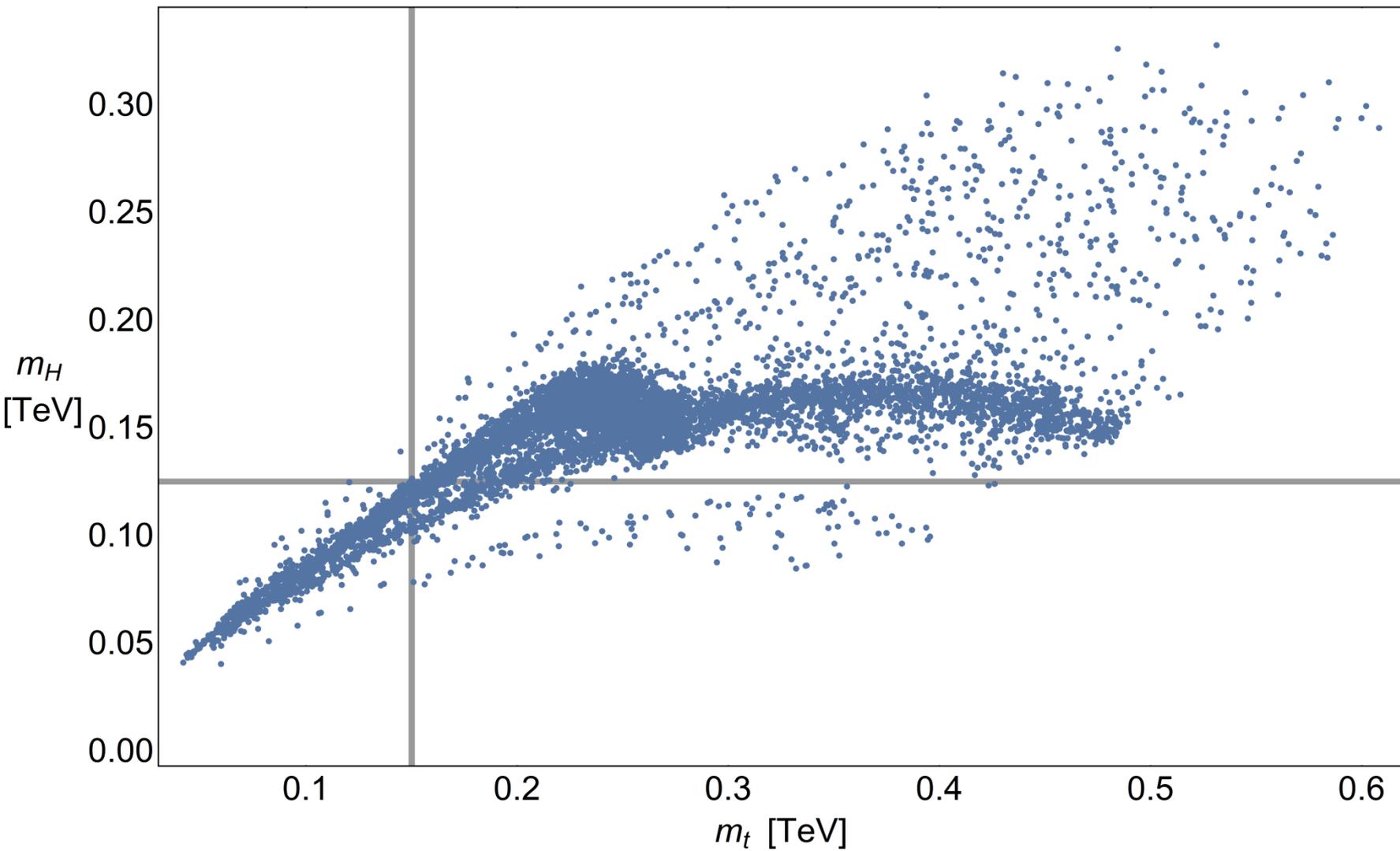
$$m_H \sim \sin(\langle h_4 \rangle) \cos(\langle h_4 \rangle)$$

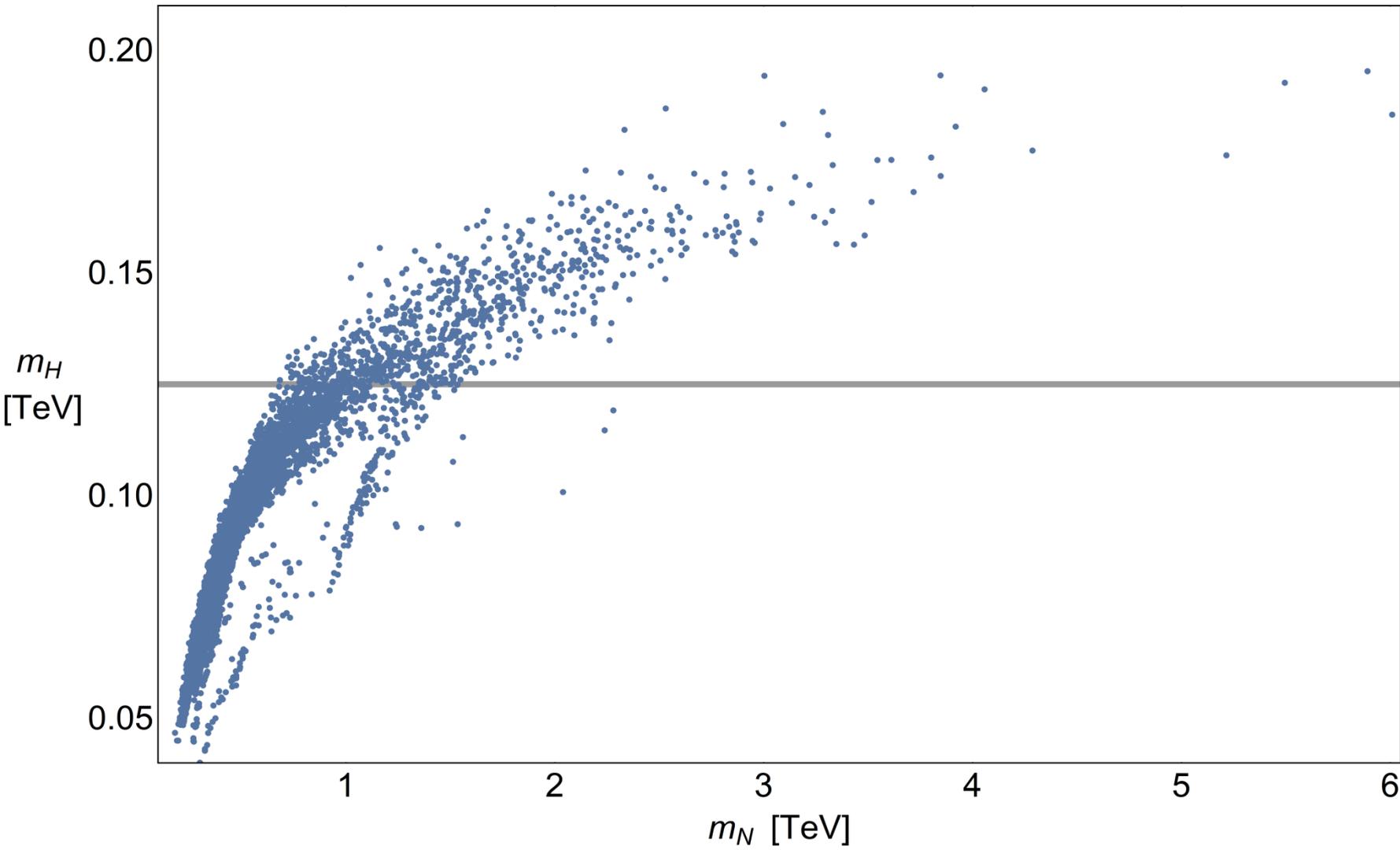
Parámetro	Valor
f_0	1,4701 TeV
f_1	2,3437 TeV
M_U	2,4410 TeV
M_Q	1,2631 TeV

Parámetro	Valor
θ_u	0,788399
θ_q	1,37272
y_{15}	2,51821
g_1	1,95045

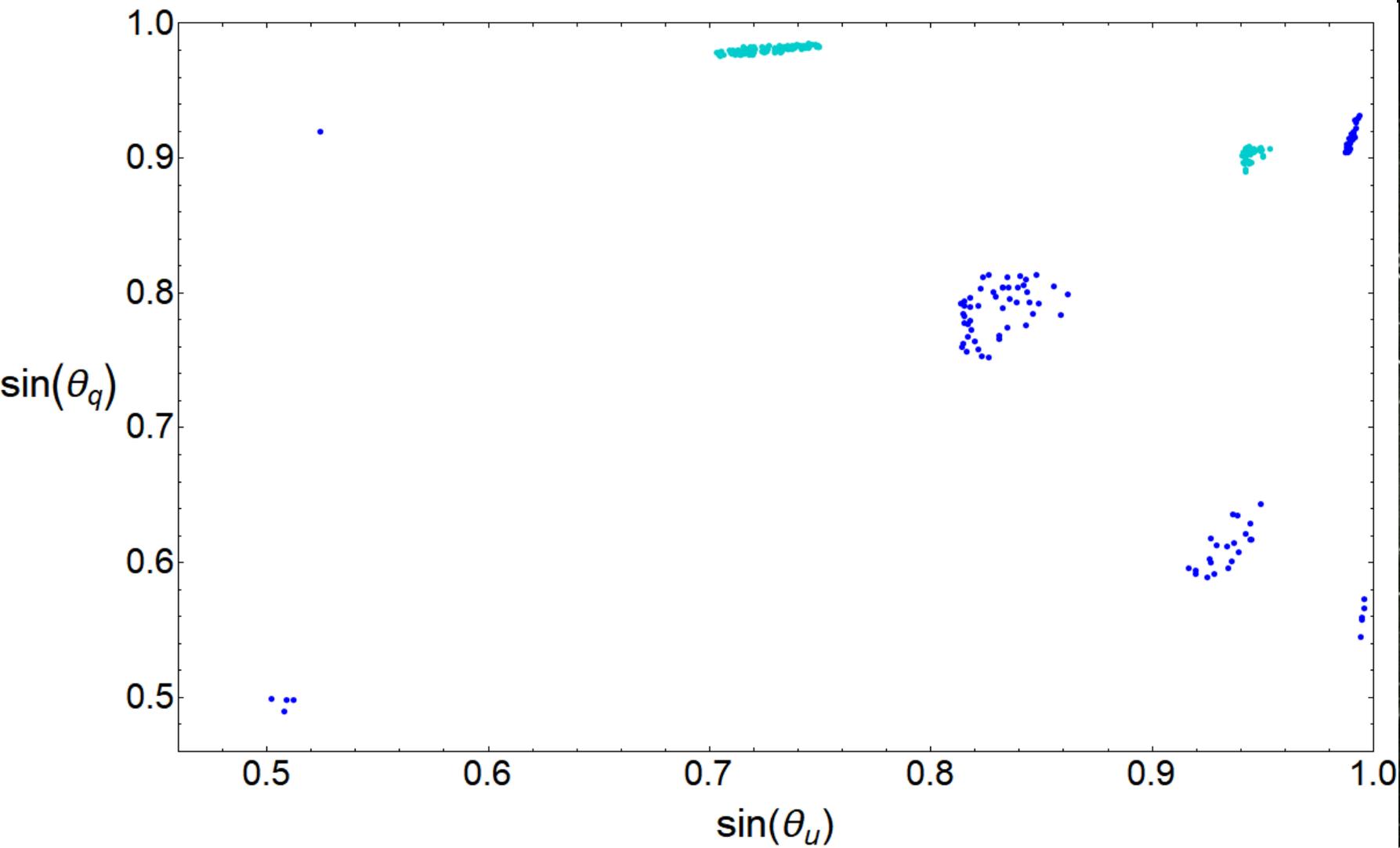
Tabla 4.1: Valores de los parámetros para el punto del espacio de parámetros alrededor del cual se hizo un escaneo sistemático.

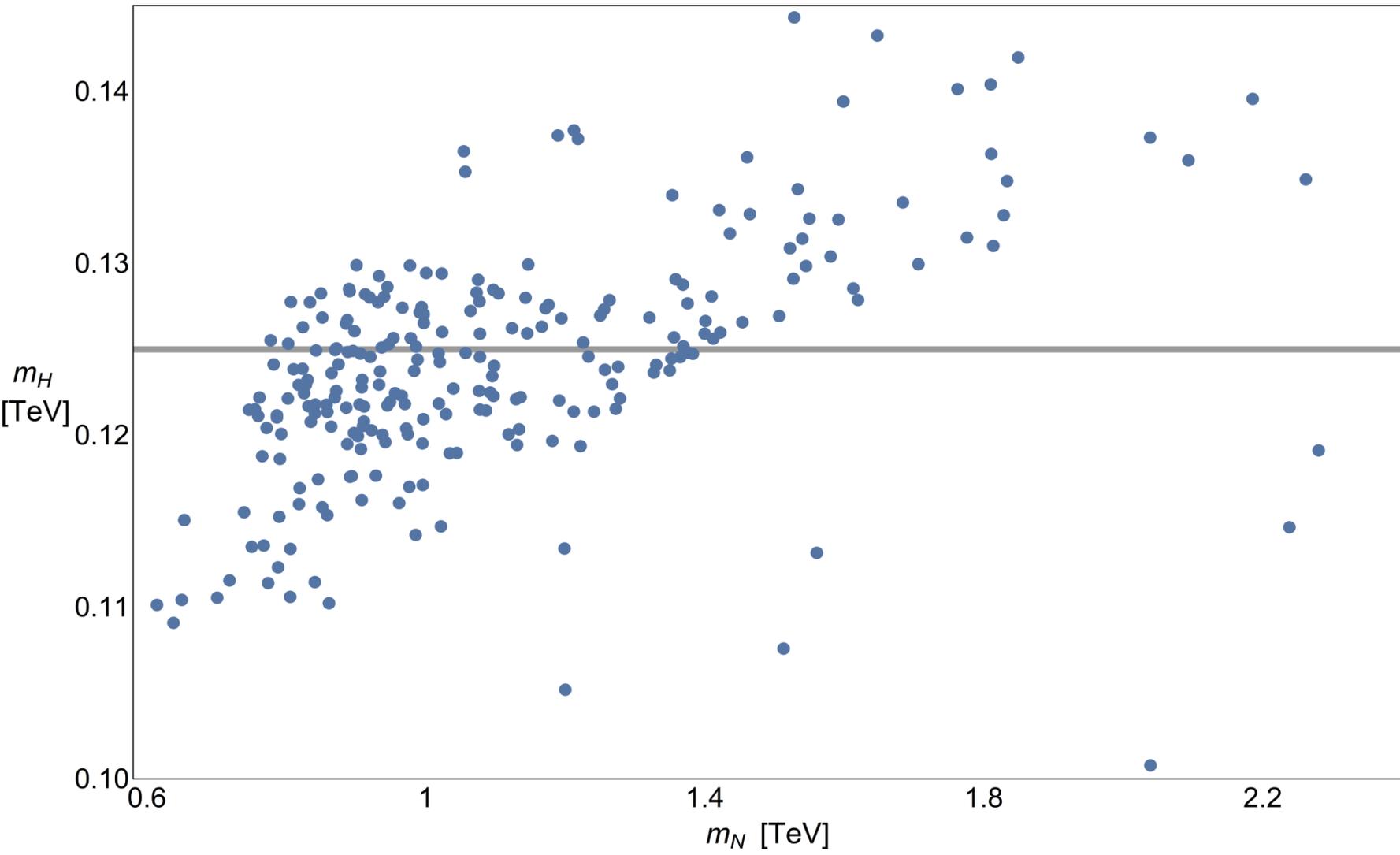


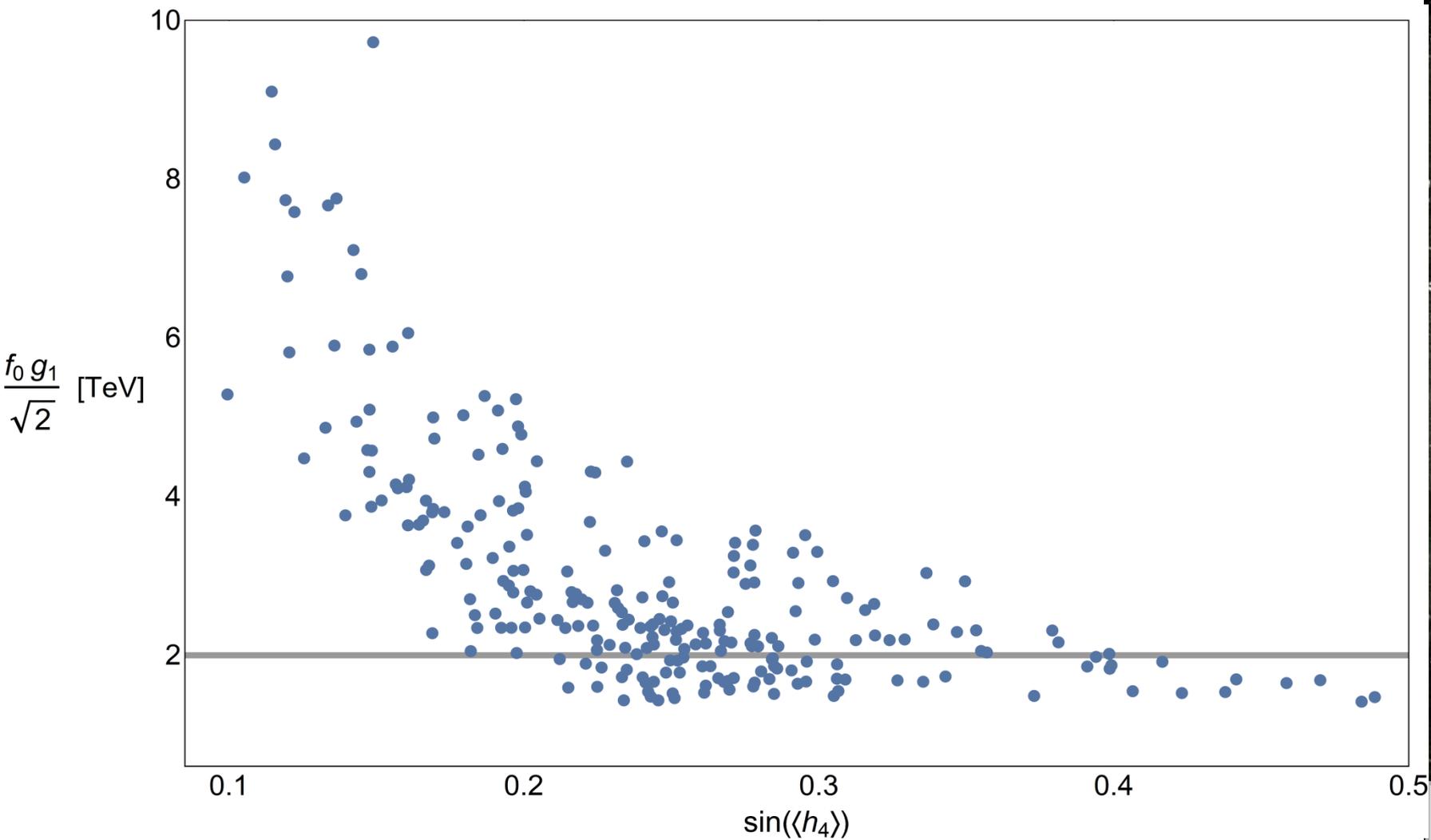




$$v = 246 \text{ GeV}$$

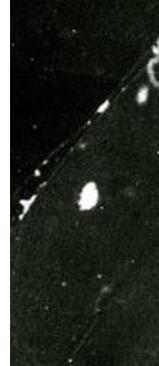
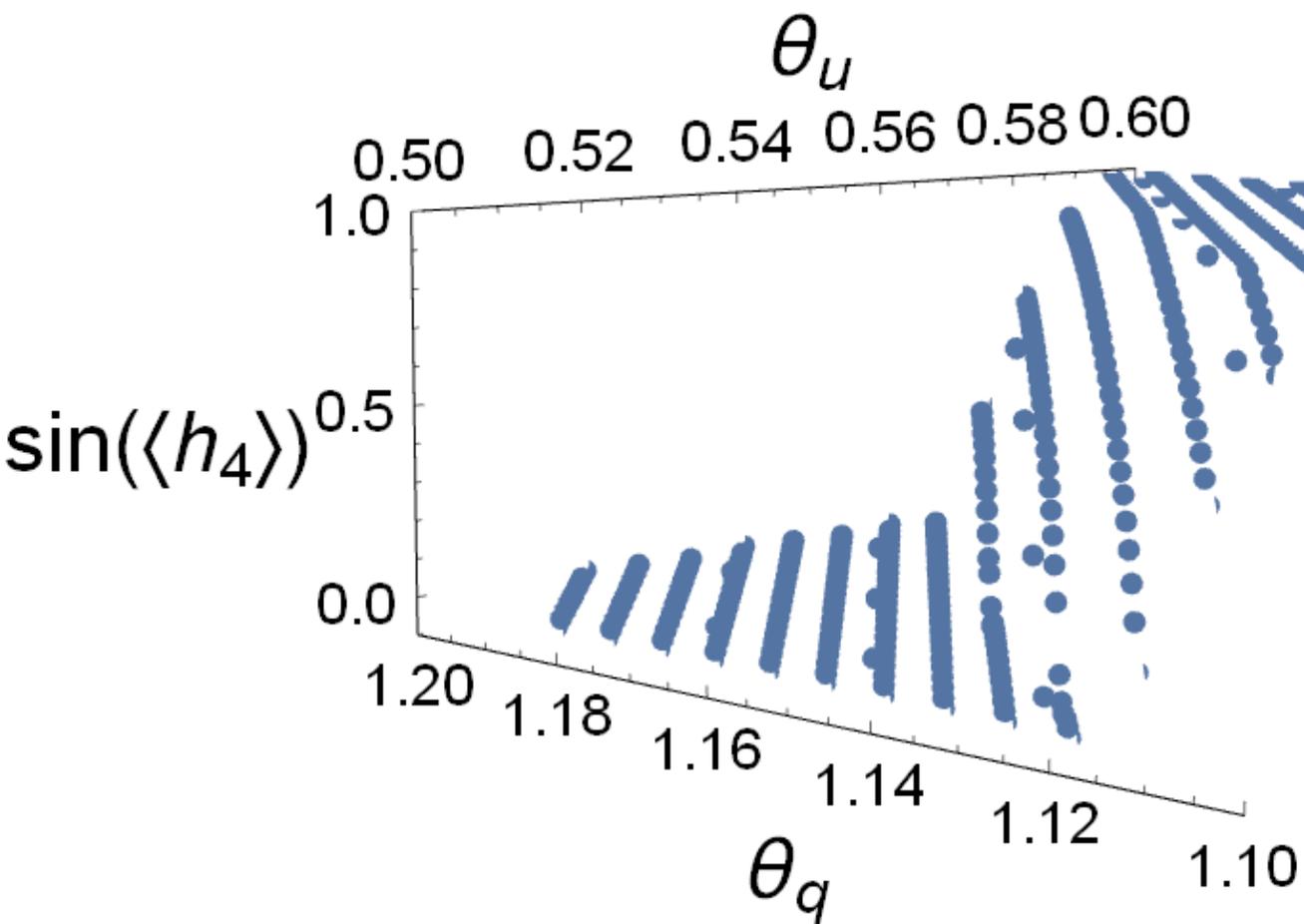


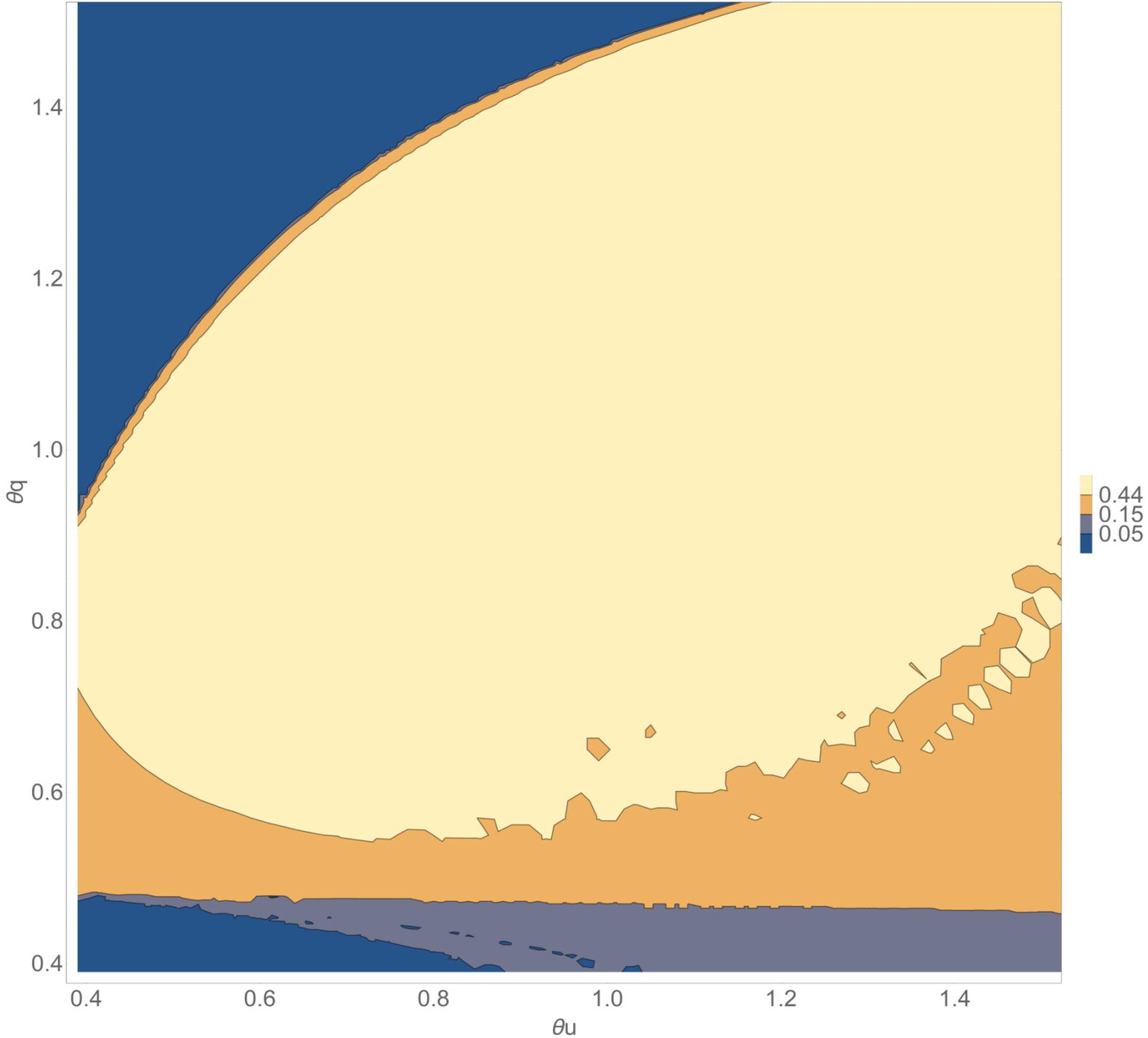


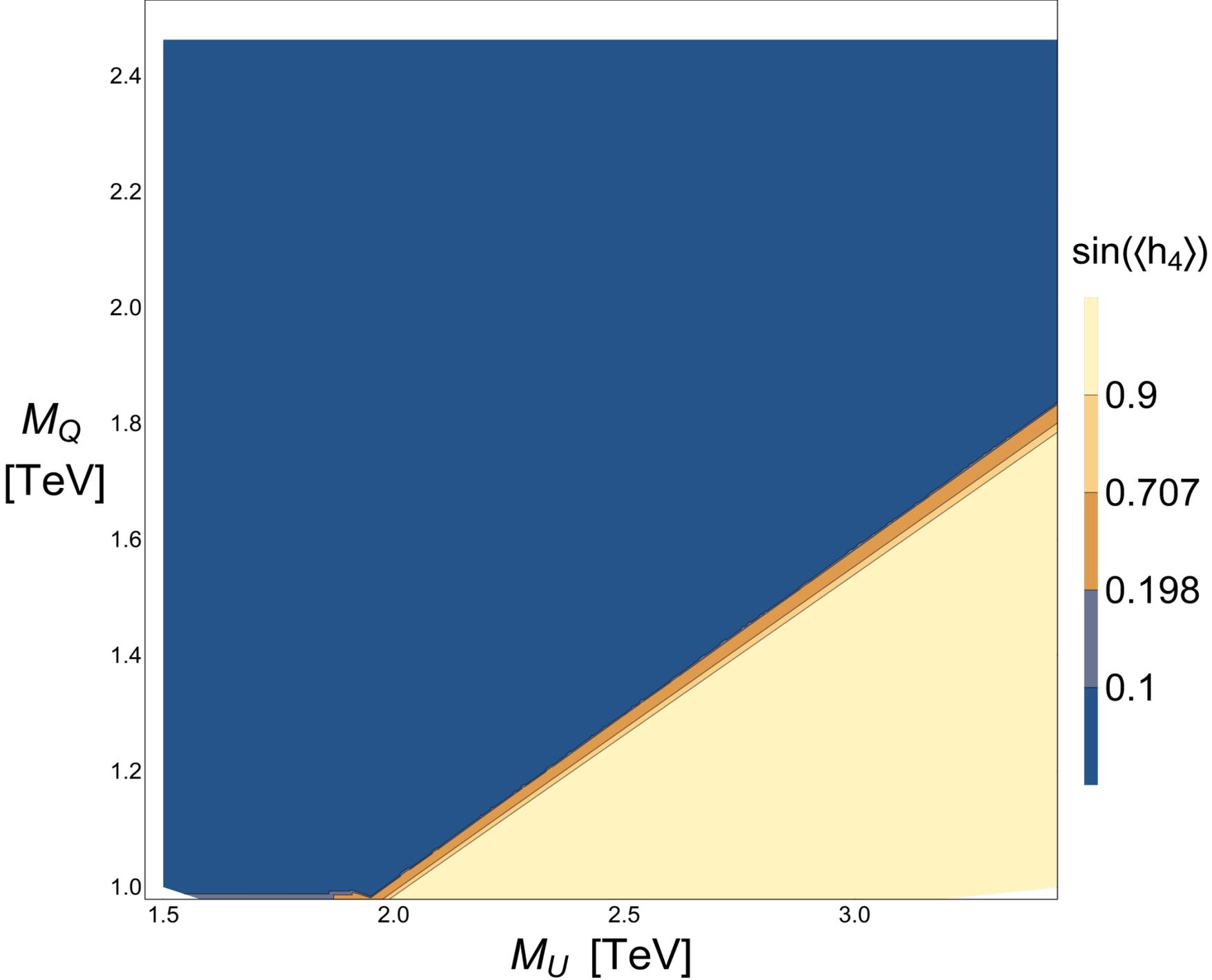


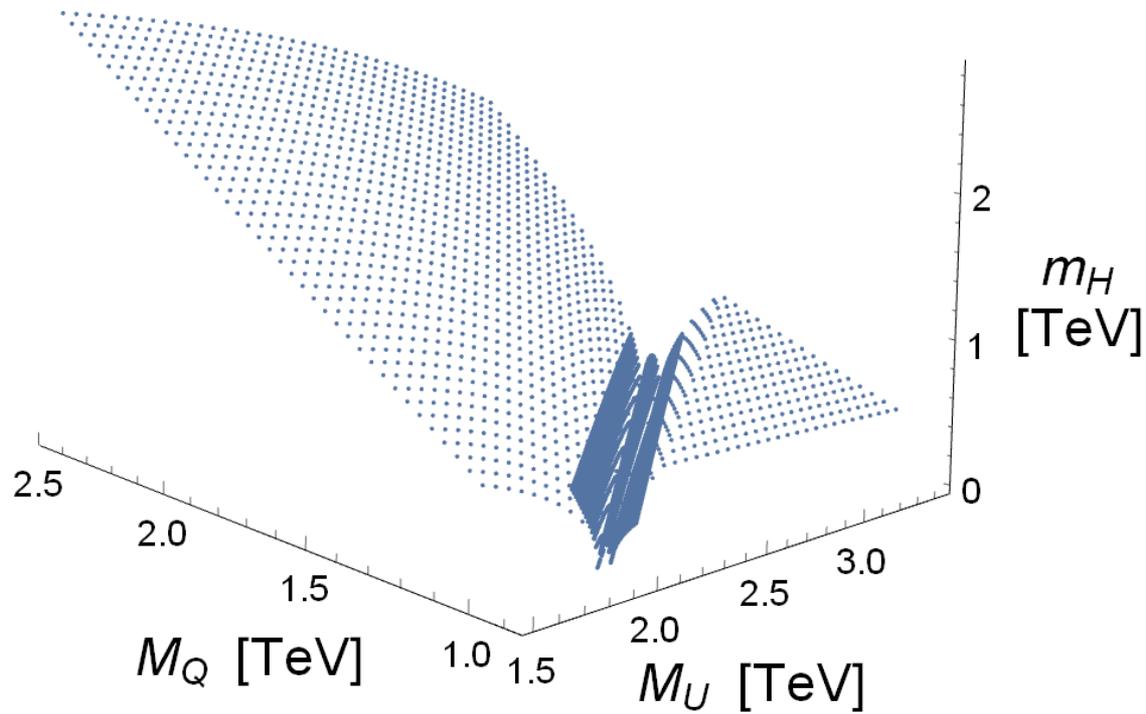
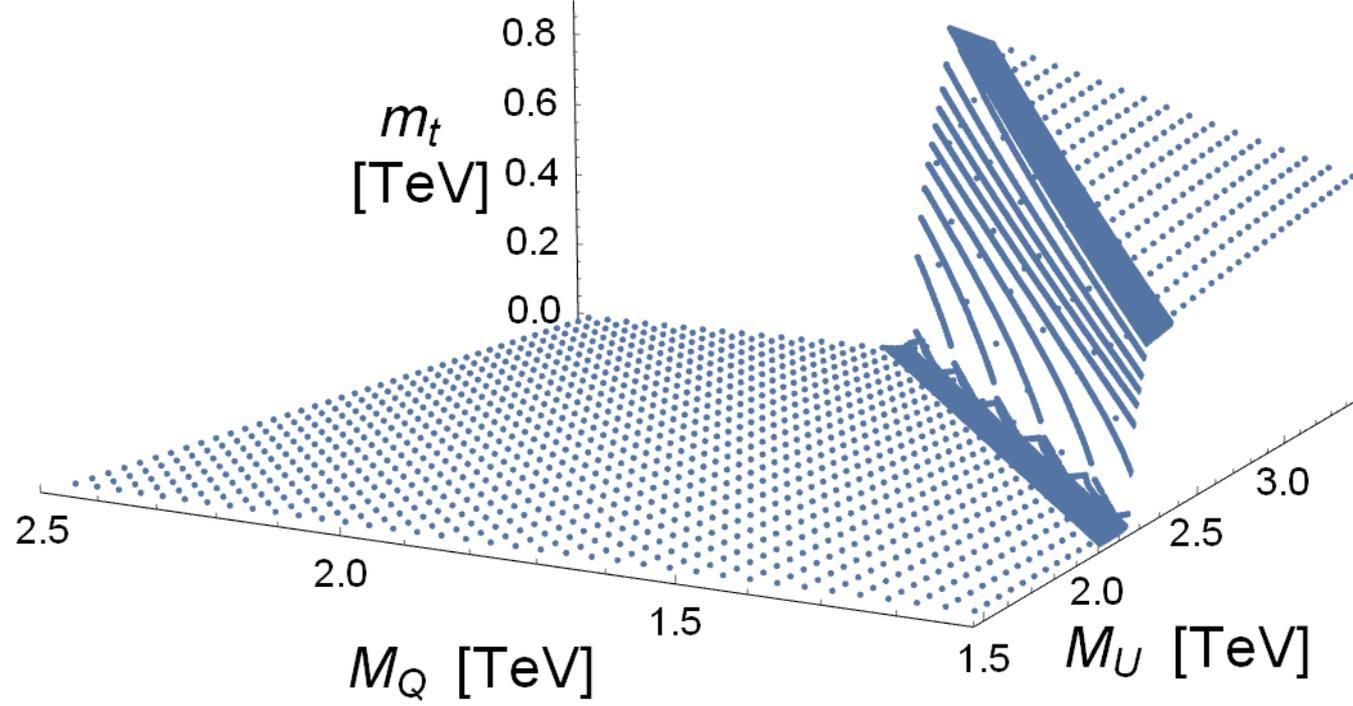
Parámetro	Valor
f_0	1,4701 TeV
f_1	2,3437 TeV
M_U	2,4410 TeV
M_Q	1,2631 TeV

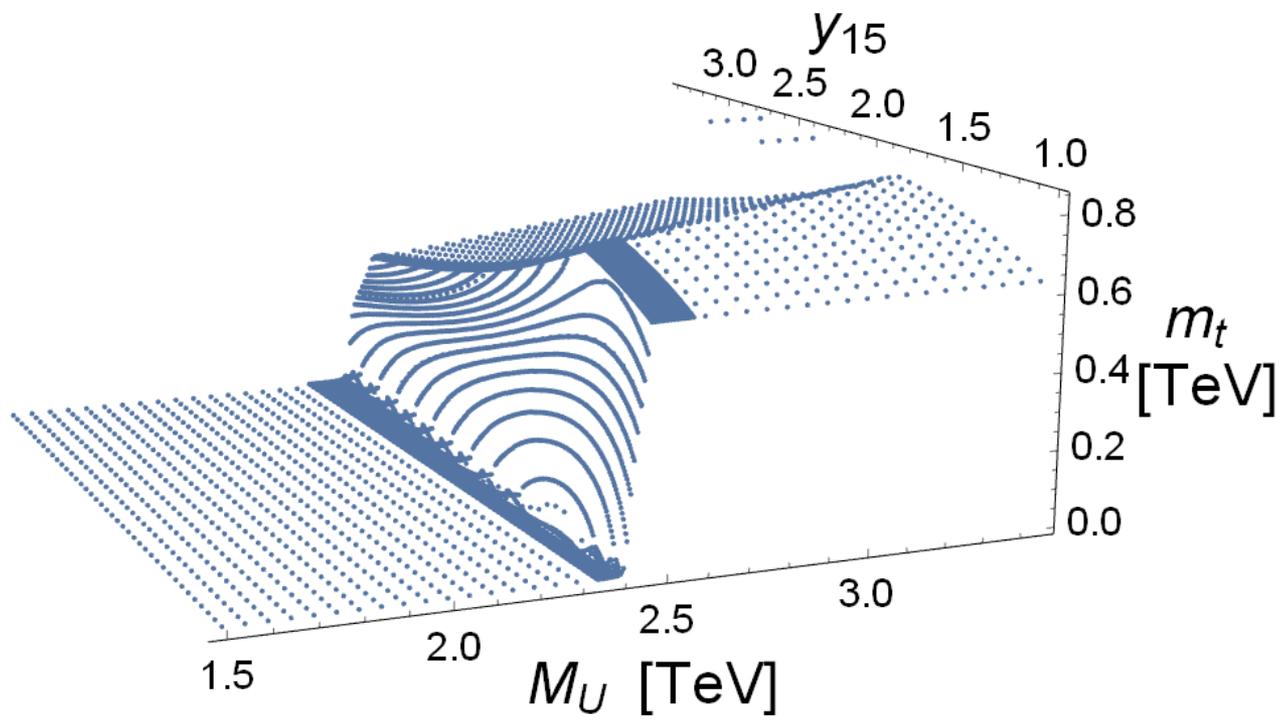
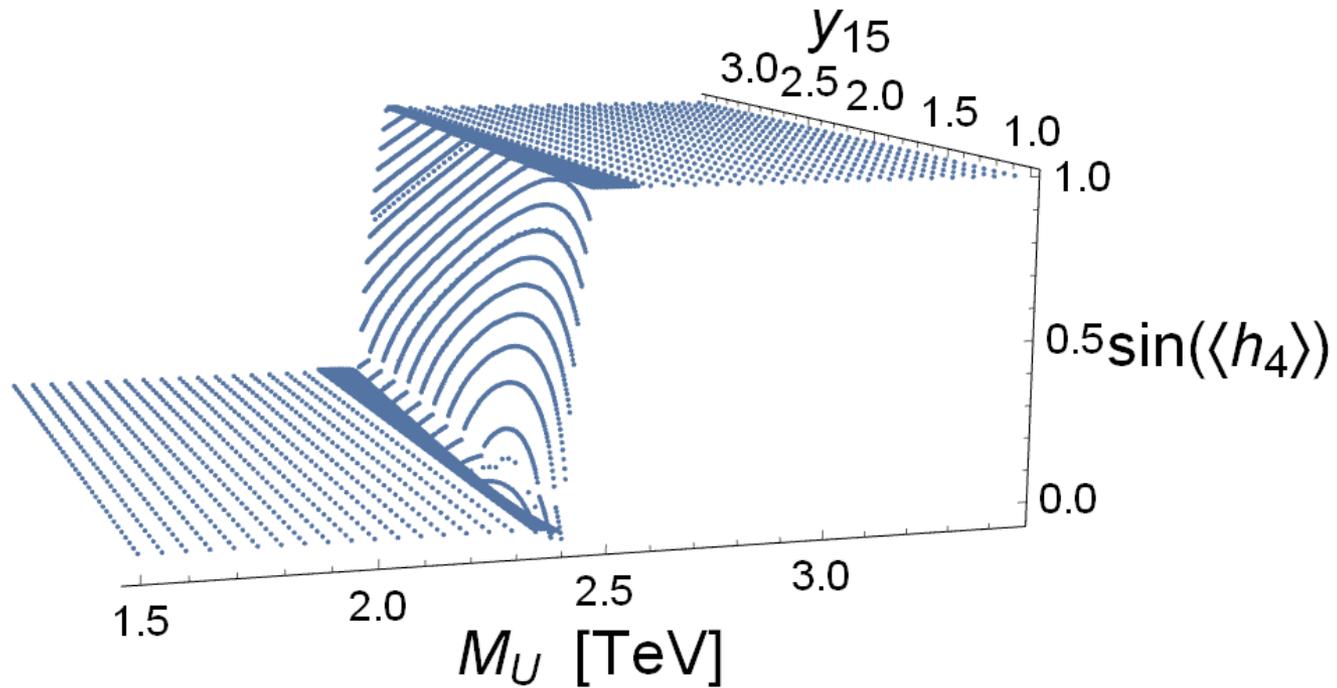
Parámetro	Valor
θ_u	0,788399
θ_q	1,37272
y_{15}	2,51821
g_1	1,95045

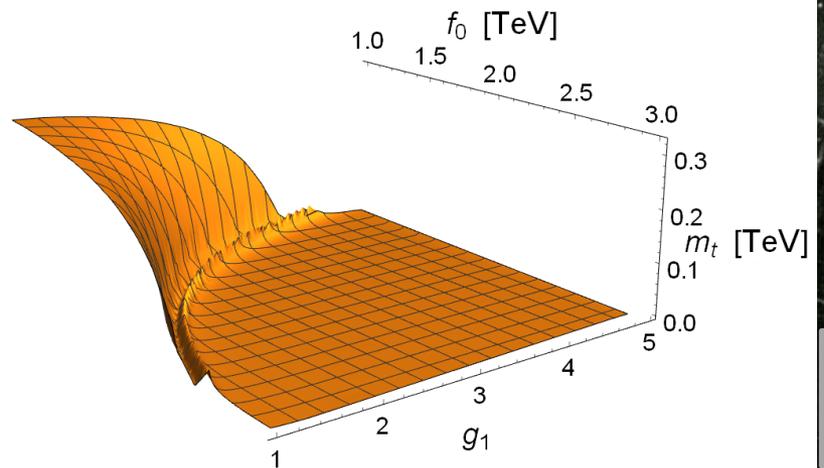
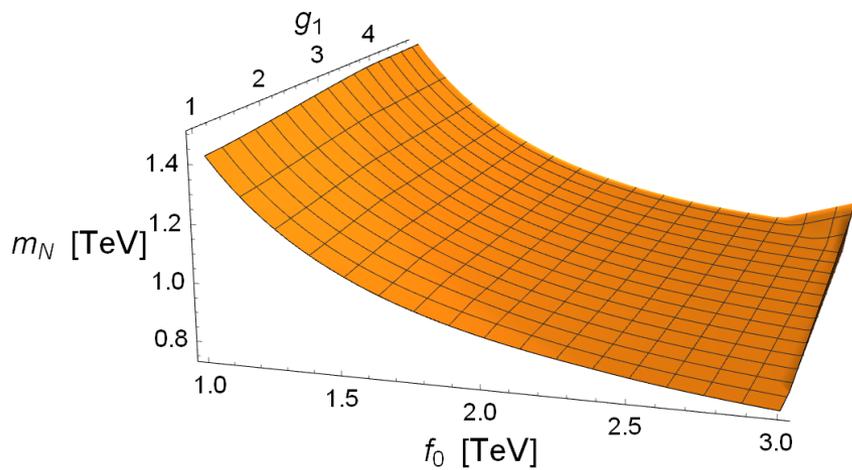
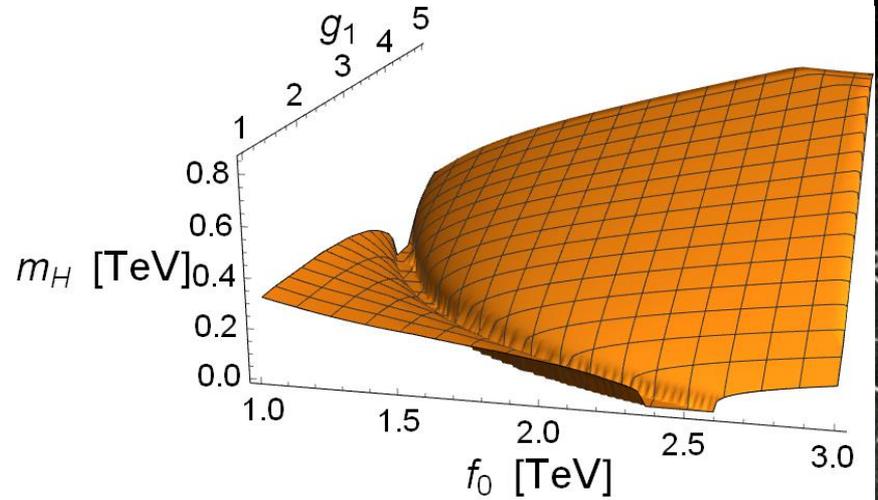
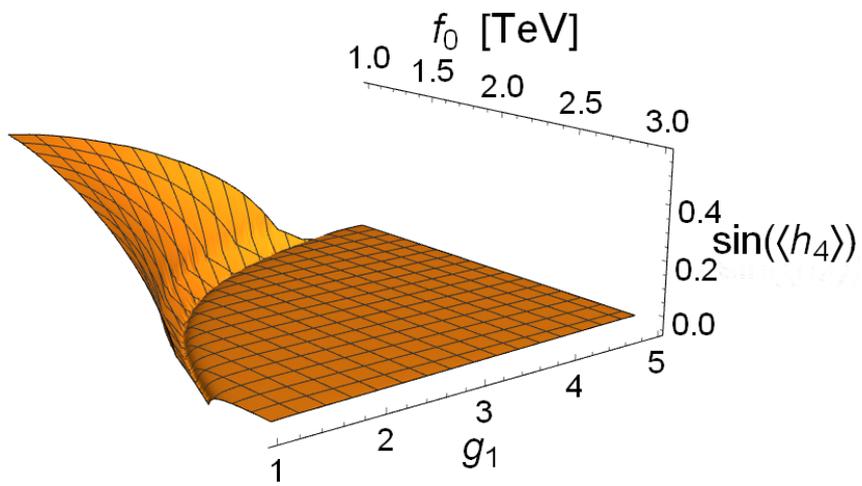


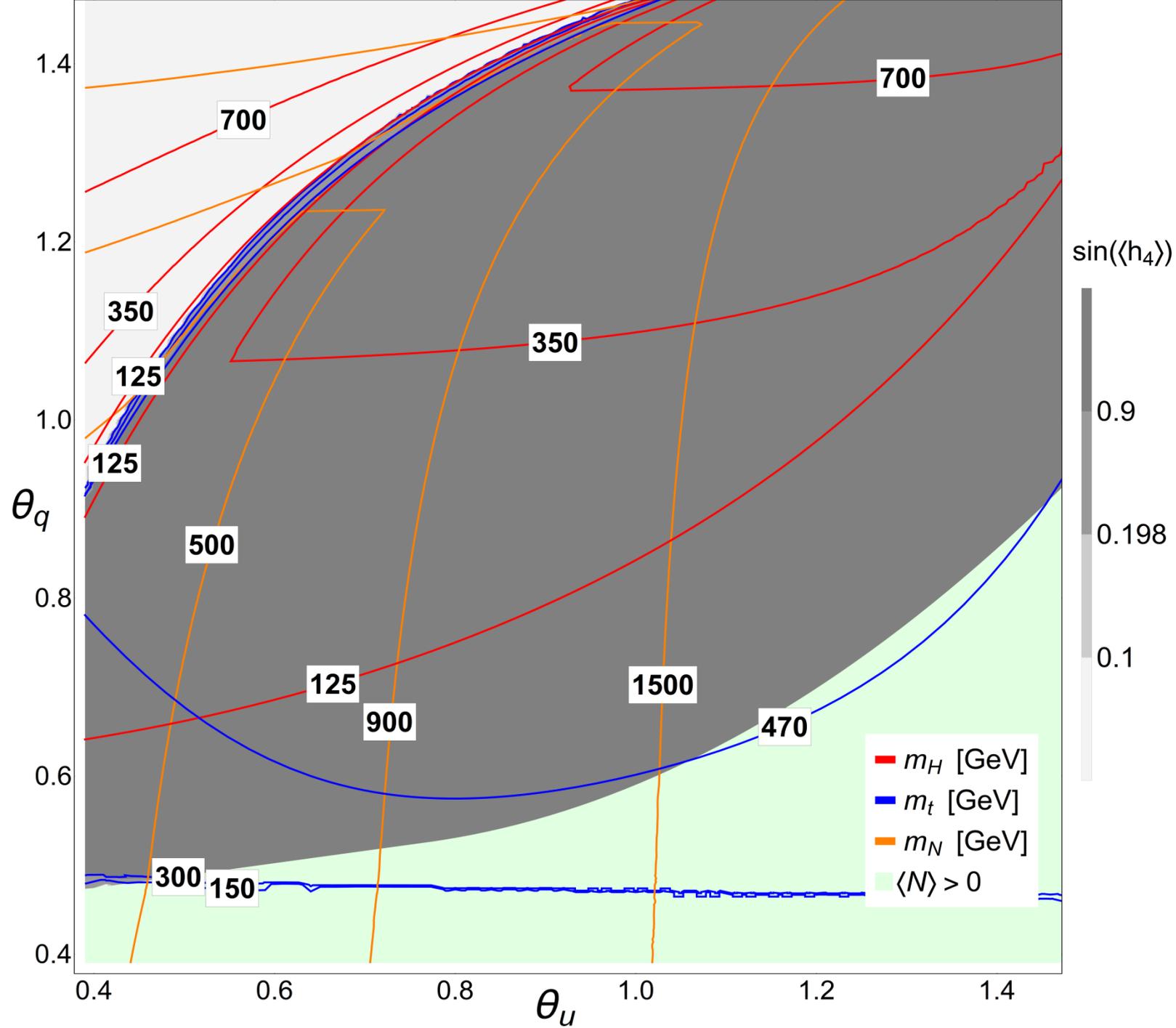


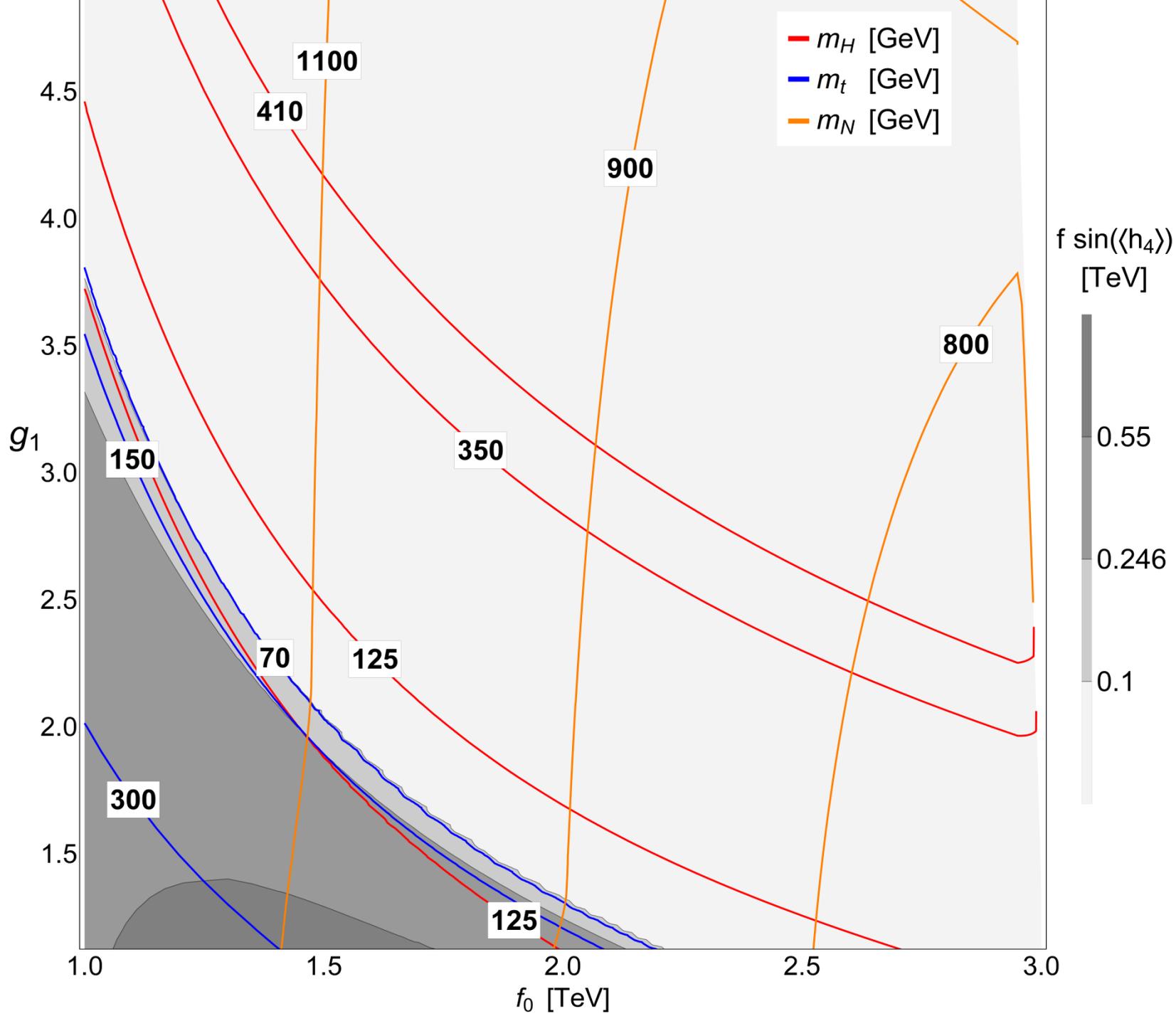












$$\det [\mathcal{A}_{\mathcal{F}}] = \left(\tilde{Z}_{t_L} \tilde{Z}_{t_R} - |M_{t_{L/R}}|^2 \right) \tilde{Z}_{b_L}$$

$$\det [\mathcal{A}_{\mathcal{F}}] = \left(\tilde{Z}_{t_L} \tilde{Z}_{t_R} - |M_{t_{L/R}}|^2 \right) \left(\tilde{Z}_{b_L} \tilde{Z}_{b_R} - |M_{b_{L/R}}|^2 \right)$$

$$m_W \cong \frac{f_0 f_1}{\sqrt{f_0^2 + f_1^2}} \frac{g_0 g_1}{\sqrt{g_0^2 + g_1^2}} \frac{\sin(\langle h_4 \rangle)}{2} = \frac{gv}{2}$$

$$m_W^2 = a_1 \sin^2(\langle h_4 \rangle) + a_2 \sin^4(\langle h_4 \rangle)$$

$$\begin{aligned} \mathcal{L}_{eff} \Big|_{p=0} &\supset \frac{v^2}{4} \left(\frac{9}{34} g_{0Y}^2 \tilde{b}_\mu \tilde{b}^\mu - \frac{3}{\sqrt{17}} g_0 g_{0Y} \tilde{b}_\mu \tilde{w}_3^\mu + \frac{g_0^2}{2} \tilde{w}_3^\mu \tilde{w}_\mu^3 \right) \\ &= \frac{1}{2} \frac{v^2}{4} (g^2 + g'^2) \left(\frac{g'}{\sqrt{g'^2 + g^2}} \tilde{b}_\mu \tilde{b}^\mu - \frac{g}{\sqrt{g'^2 + g^2}} \tilde{w}_3^\mu \tilde{w}_\mu^3 \right)^2 \end{aligned}$$

$$\mathcal{L}_{eff,bos} \supset \frac{1}{2} \left(\tilde{b}_\mu, \tilde{w}_\mu^3 \right) \mathcal{X} \left(\tilde{b}^\mu, \tilde{w}_3^\mu \right)^T$$

Identificación	Masa	$ Q_{EM} $	Número de grados de libertad reales
$A_\mu^{m_1}$	$\frac{f_0 g_1}{\sqrt{2}}$	0	1
		$\frac{1}{3}$	2
		$\frac{2}{3}$	4
		1	2
		$\frac{5}{3}$	2
$A_\mu^{m_2}$	$f_0 \sqrt{\frac{g_{0Y}^2 + g_1^2}{2}} + \epsilon$	0	1
$A_\mu^{m_3}$	$f_0 \sqrt{\frac{g_0^2 + g_1^2}{2}} + \eta$	1	2
$A_\mu^{m_4}$	$f_0 \sqrt{\frac{g_0^2 + g_1^2}{2}} + \Delta$	0	1
$A_\mu^{m_5}$	$g_1 \sqrt{\frac{f_0^2 + f_1^2}{2}}$	$\frac{2}{3}$	2
		0	1
$A_\mu^{m_6}$	$g_1 \sqrt{\frac{f_0^2 + f_1^2}{2}} + \delta$	1	2
$A_\mu^{m_7}$	$g_1 \sqrt{\frac{f_0^2 + f_1^2}{2}} + \alpha$	0	1

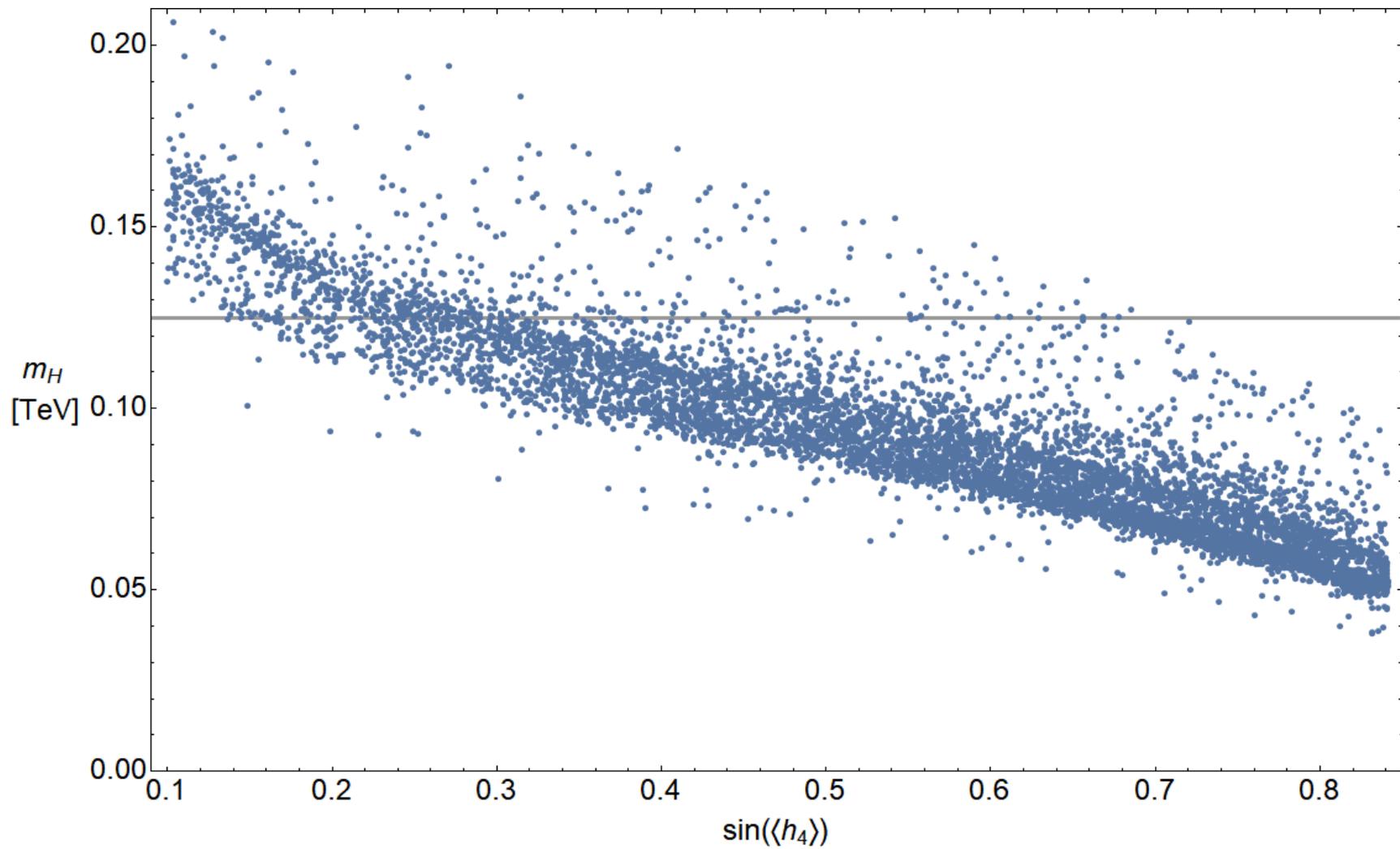
Identificación	Masa	Corrección por mezcla promedio
$A_\mu^{m_2}$	$f_0 \sqrt{\frac{g_{0Y}^2 + g_1^2}{2}} + \epsilon$	-0,03 %
$A_\mu^{m_3}$	$f_0 \sqrt{\frac{g_0^2 + g_1^2}{2}} + \eta$	-0,09 %
$A_\mu^{m_4}$	$f_0 \sqrt{\frac{g_0^2 + g_1^2}{2}} + \Delta$	-0,08 %
$A_\mu^{m_6}$	$\sqrt{\frac{f_0^2 + f_1^2}{2}} g_1 + \delta$	0,01 %
$A_\mu^{m_7}$	$\sqrt{\frac{f_0^2 + f_1^2}{2}} g_1 + \alpha$	0,02 %

Name	Q_{EM}	Number of Dirac fermions
F^{m_1}	0	2
	± 1	2
	$-\frac{2}{3}$	1
F^{m_2}	0	4
	$\pm \frac{1}{3}$	4
	$\frac{2}{3}$	1
	$-\frac{2}{3}$	2
	± 1	4
	$\pm \frac{5}{3}$	4
F^{m_3}	$\frac{2}{3}$	1
F^{m_4}	$\frac{2}{3}$	1
F^{m_5}	$\frac{2}{3}$	1
F^{m_6}	$\frac{2}{3}$	1

Name	Q_{EM}	Number of Dirac fermions
F^{m_7}	$\frac{2}{3}$	1
F^{m_8}	$\frac{2}{3}$	1
F^{m_9}	0	3
	$\frac{1}{3}$	1
	$-\frac{2}{3}$	2
	± 1	4
	$\pm \frac{5}{3}$	2
$F^{m_{10}}$	0	3
	$\frac{1}{3}$	1
	$-\frac{2}{3}$	2
	± 1	4
	$\pm \frac{5}{3}$	2
$F^{m_{11}}$	$-\frac{1}{3}$	1
$F^{m_{12}}$	$-\frac{1}{3}$	1

Identificación	Masa
F^{m_1}	M_Q
F^{m_2}	M_U
F^{m_9}	$\sqrt{\frac{M_U^2 + M_Q^2 + f_1^2 y_{15}^2 - \sqrt{(M_U^2 + M_Q^2 + f_1^2 y_{15}^2)^2 - 4M_Q^2 M_U^2}}{2}}$
$F^{m_{10}}$	$\sqrt{\frac{M_U^2 + M_Q^2 + f_1^2 y_{15}^2 + \sqrt{(M_U^2 + M_Q^2 + f_1^2 y_{15}^2)^2 - 4M_Q^2 M_U^2}}{2}}$

$$y_t = \left. \frac{\partial m_t}{\partial \bar{h}_4} \right|_{\langle \bar{h}_4 \rangle} \quad y_t^{ME} = \frac{m_t}{v} \quad g_{WW h} = \left. \frac{\partial m_W^2}{\partial \bar{h}_4} \right|_{\langle \bar{h}_4 \rangle} \quad g_{WW hh} = \left. \frac{\partial^2 m_W^2}{\partial \bar{h}_4^2} \right|_{\langle \bar{h}_4 \rangle}$$



$$g_{WW_h}^{ME} = g m_W g_{WWhh}^{ME} = \frac{g^2}{2}$$

$$\frac{g_{WW_h}}{g_{WW_h}^{ME}} \cong \cos(\langle h_4 \rangle) \left(1 + \frac{3}{4} \frac{g^4}{g_0^2 g_1^4} \frac{f^2 v^2}{f_0^4 f_1^2} (f_1^2 g_1^2 + f_0^2 (g_0^2 + 2g_1^2)) + \mathcal{O}(\sin^3(\langle h_4 \rangle)) \right)$$

$$\frac{g_{WWhh}}{g_{WWhh}^{ME}} \cong \cos(2\langle h_4 \rangle) + \sin^2(\langle h_4 \rangle) (4 \cos^2(\langle h_4 \rangle) - 1) \frac{g^2}{f_0^2 + f_1^2} \left[f_1^2 + \frac{f^2}{g_1^2} \right]$$

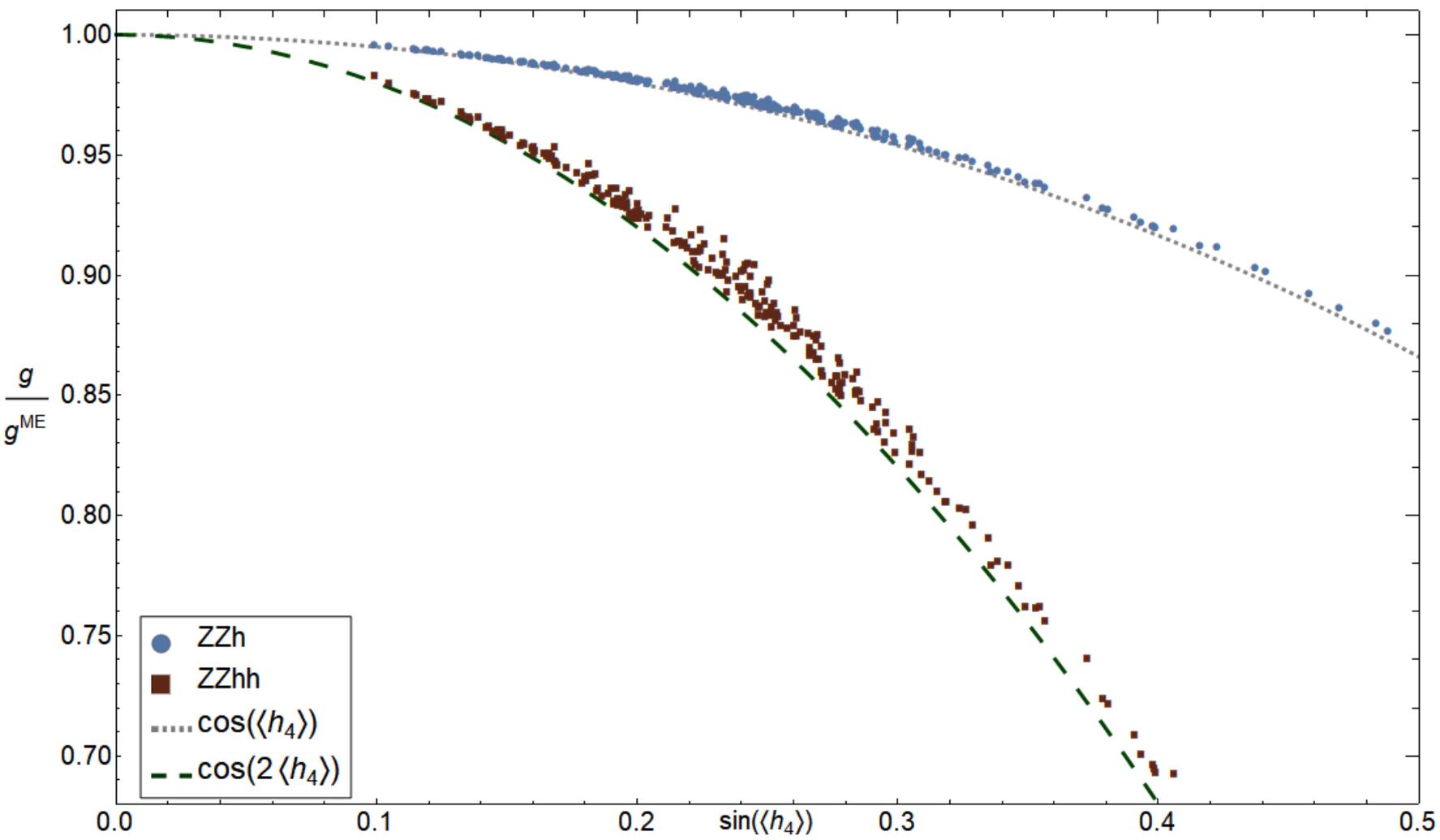
$$g_{ZZh} = \frac{1}{2} \frac{\partial m_Z^2}{\partial \bar{h}_4} \Big|_{\langle \bar{h}_4 \rangle} \quad g_{ZZhh} = \frac{1}{4} \frac{\partial^2 m_Z^2}{\partial \bar{h}_4^2} \Big|_{\langle \bar{h}_4 \rangle} \quad g_{ZZh}^{ME} = \frac{m_Z^2}{v} g_{ZZhh}^{ME} = \frac{m_Z^2}{2v^2}$$

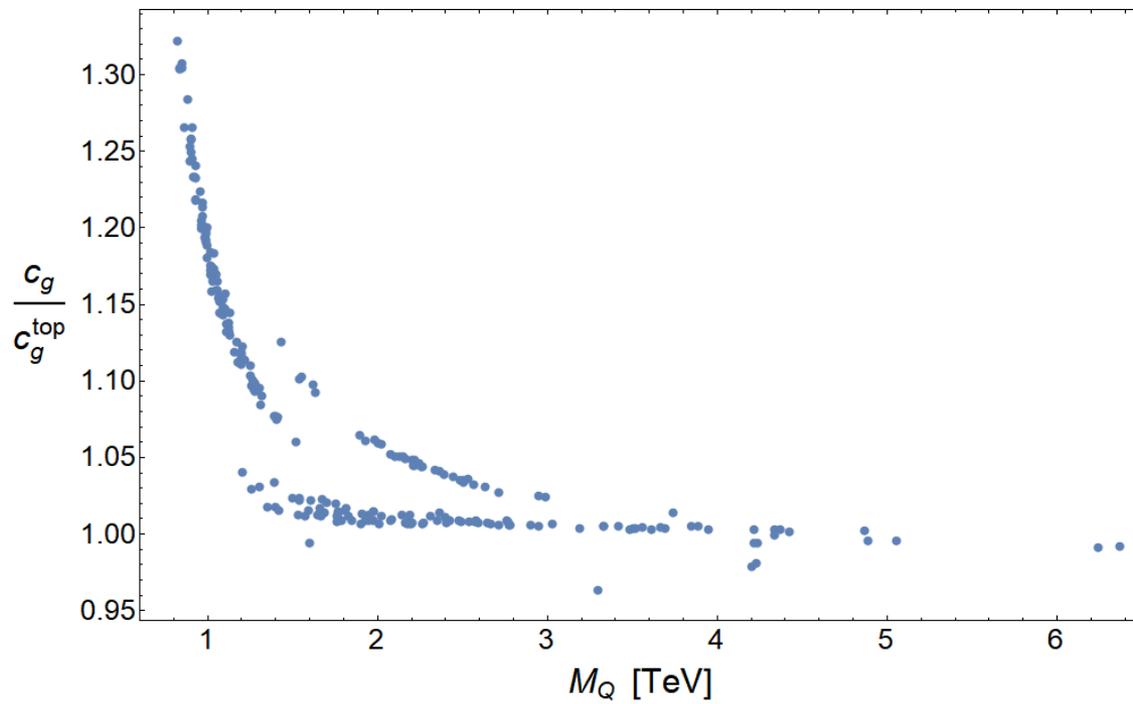
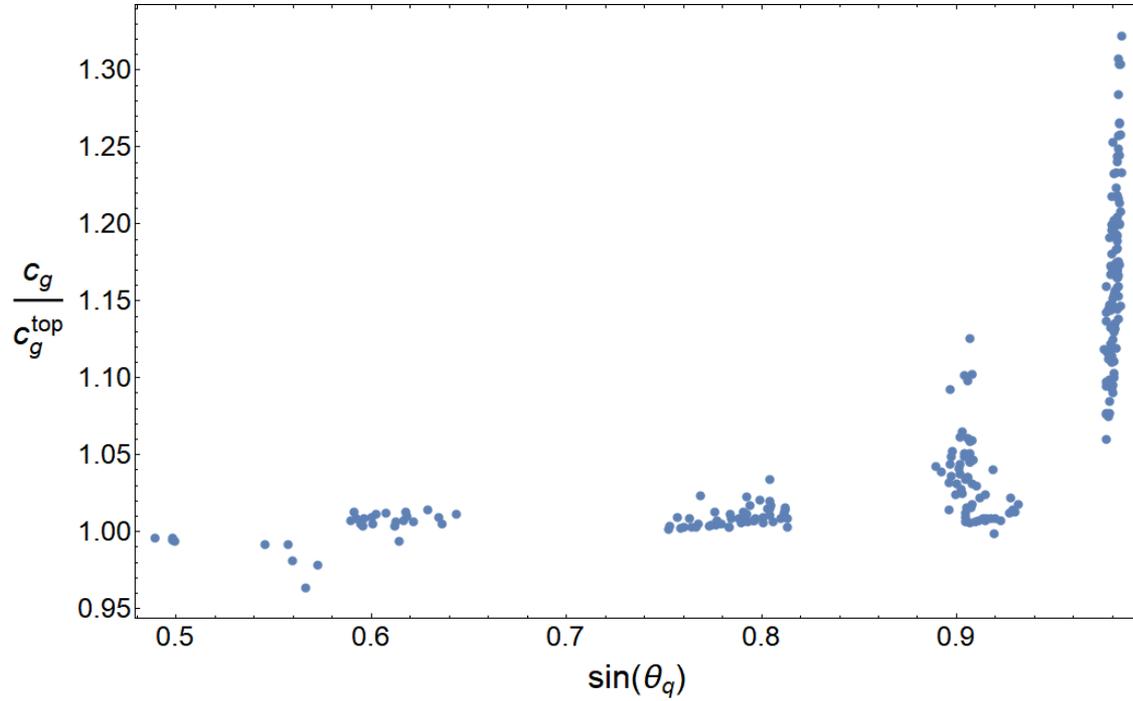
$$c_g = \sum_n \frac{y_n}{m_n} A_{1/2} \left(\frac{m_h^2}{4m_n^2} \right) \lim_{x \rightarrow 0^+} A_{1/2}(x) = \frac{4}{3} A_{1/2} \left(\frac{m_h^2}{4m_n^2} \right) \cong \frac{4}{3}$$

$$c_g^{ME} = \frac{y_t^{ME}}{m_t} A_{1/2} \left(\frac{m_h^2}{4m_t^2} \right) = \frac{1}{v} A_{1/2} \left(\frac{m_h^2}{4m_t^2} \right) \quad c_g \cong \frac{4}{3} \text{Tr}(M_{ferm}^{-1} Y_{ferm}) = \frac{4 \cot(\langle h_4 \rangle)}{f}$$

$$c_g \cong \frac{4}{3} \left(\text{Tr}(M_{ferm}^{-1} Y_{ferm}) - \frac{y_t}{m_t} \right) + \frac{y_t}{m_t} A_{1/2} \left(\frac{m_h^2}{4m_t^2} \right)$$

$$\frac{4 \cot(\langle h_4 \rangle)}{3 f} = \frac{4}{3v} \cos(\langle h_4 \rangle) \approx \cos(\langle h_4 \rangle) c_g^{ME}$$





$$c_{\gamma\gamma hF} = 3 \sum_n Q_{EM}^2 \frac{y_n}{m_n} A_{1/2} \left(\frac{m_h^2}{4m_n^2} \right) \quad c_{\gamma\gamma hF}^{ME} = \left(\frac{2}{3} \right)^2 \frac{3}{v} A_{1/2} \left(\frac{m_h^2}{4m_t^2} \right)$$

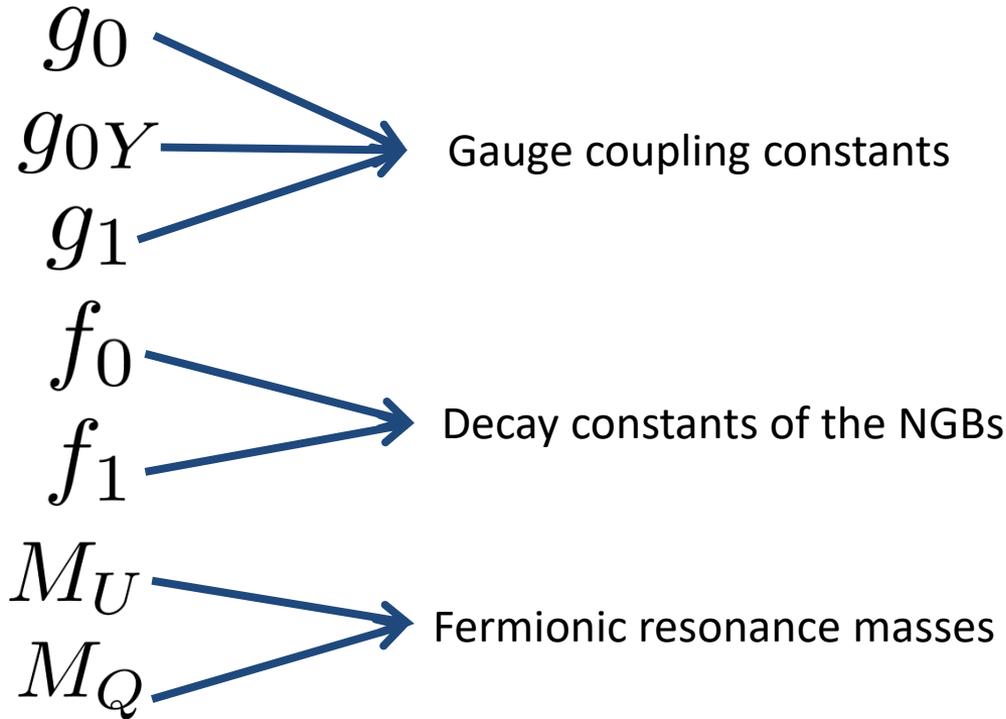
$$c_{\gamma\gamma hW} = \sum_n Q_{EM}^2 \frac{g_{W^{(n)}W^{(n)}h}}{m_n^2} A_1 \left(\frac{m_h^2}{4m_n^2} \right)$$

$$G_{W^{(q)}W^{(q)}h} = \frac{\partial M_q^2}{\partial \bar{h}_4}$$

$$c_{\gamma\gamma hW} \propto \sum_n Q_{EM}^2 \frac{g_{W^{(n)}W^{(n)}h}}{m_n^2} = \sum_q q^2 \text{Tr} [G_{W^{(q)}W^{(q)}h} M_q^{-2}]$$

$$c_{\gamma\gamma hW} \cong -7 \text{Tr} [G_{W^{(n)}W^{(n)}h} M_n^{-2}] = c_{\gamma\gamma hW}^{ME} \cos(\langle h_4 \rangle)$$

$$\mathcal{L} = \mathcal{L}_0 + \mathcal{L}_1 + \mathcal{L}_{Mezcla}$$

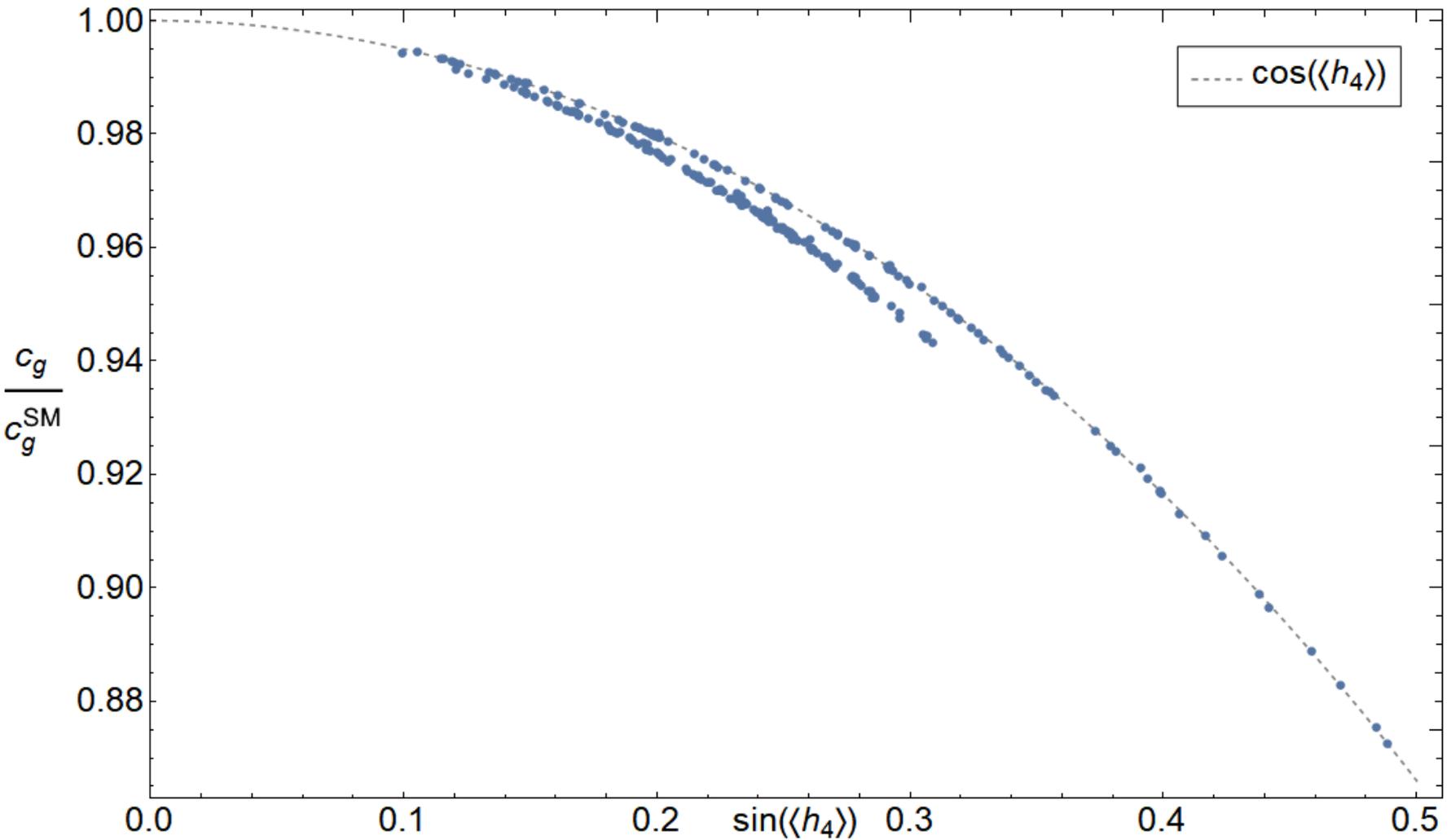


$$f_1 y_{15} P_{\mathbf{21} \rightarrow \mathbf{15}} \left(\overline{U [\Pi_{\mathbf{21}}]_{\mathbf{21}}^\dagger Q_L} \right) P_{\mathbf{35} \rightarrow \mathbf{15}} \left(U [\Pi_{\mathbf{35}}]_{\mathbf{35}}^\dagger T_R \right) + h.c.$$

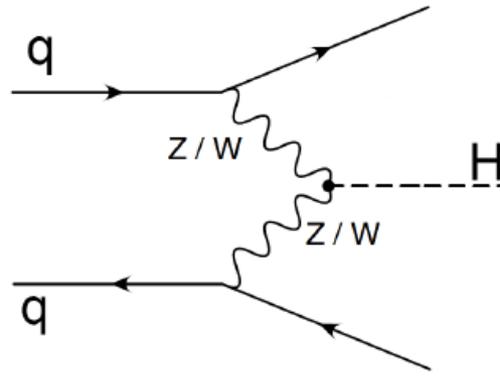
$$\mathcal{L}_{Mezcla, ferm} = f_0 \lambda_q \overline{Q}_L Q_R + f_0 \lambda_u \overline{T}_R T_L + h.c.$$

$$\tan(\theta_{u,q}) = \frac{\lambda_{u,q} f_0}{M_{U,Q}}$$

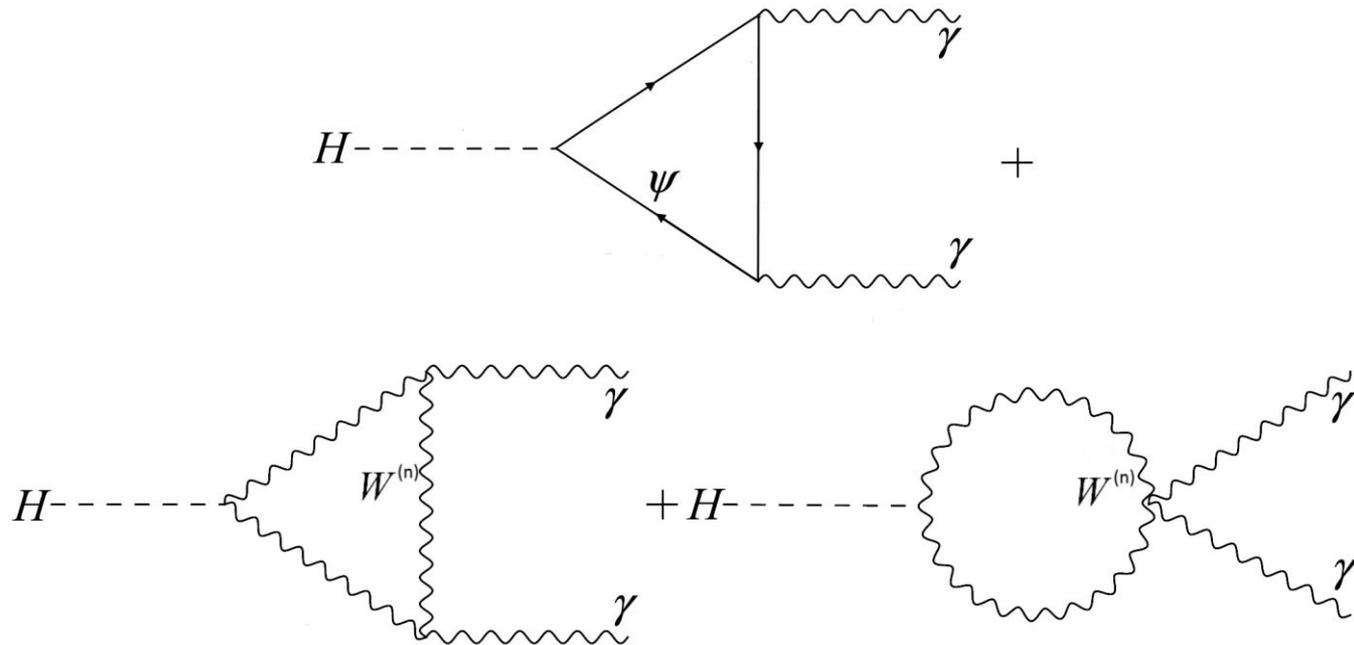
ttH and gluon fusion

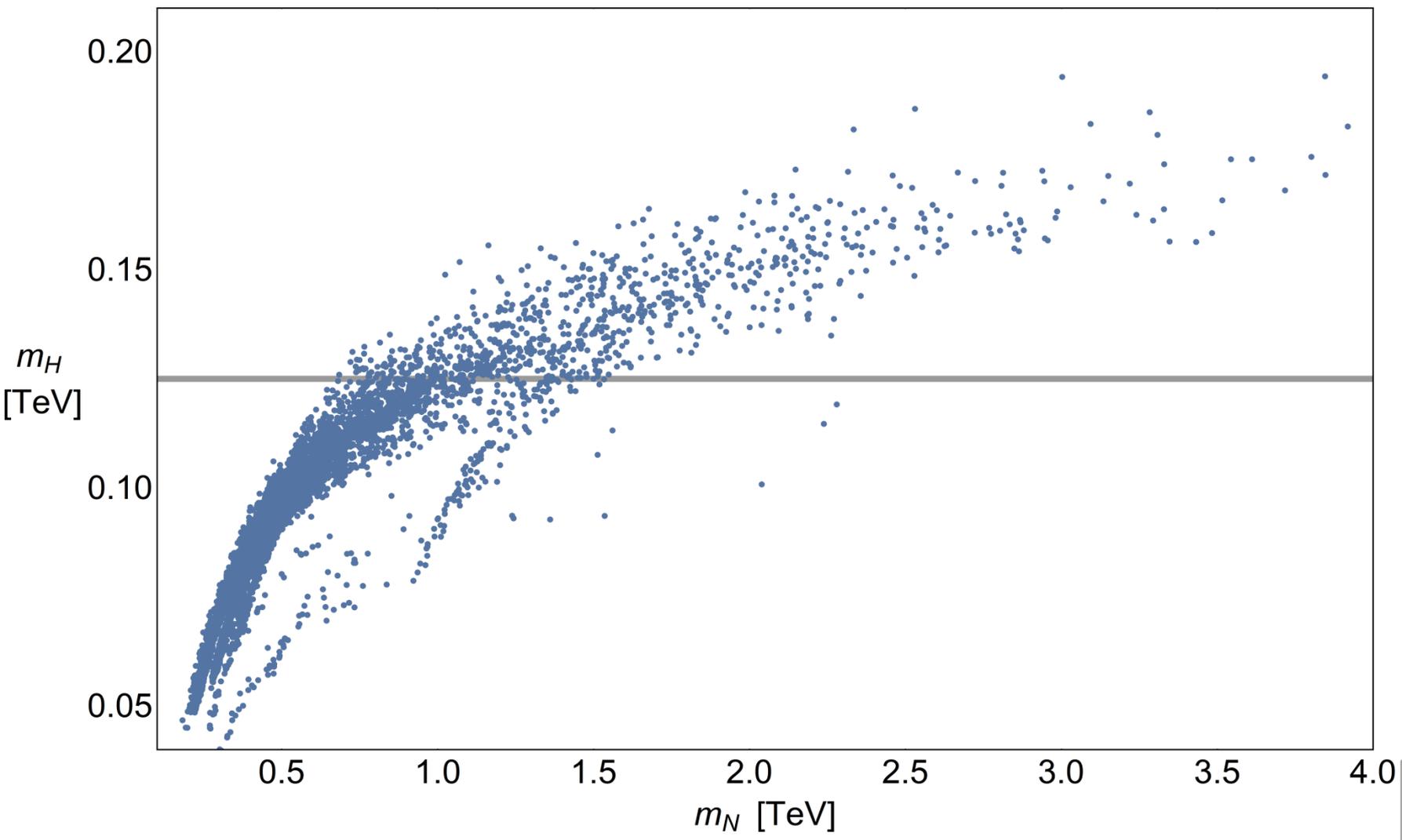


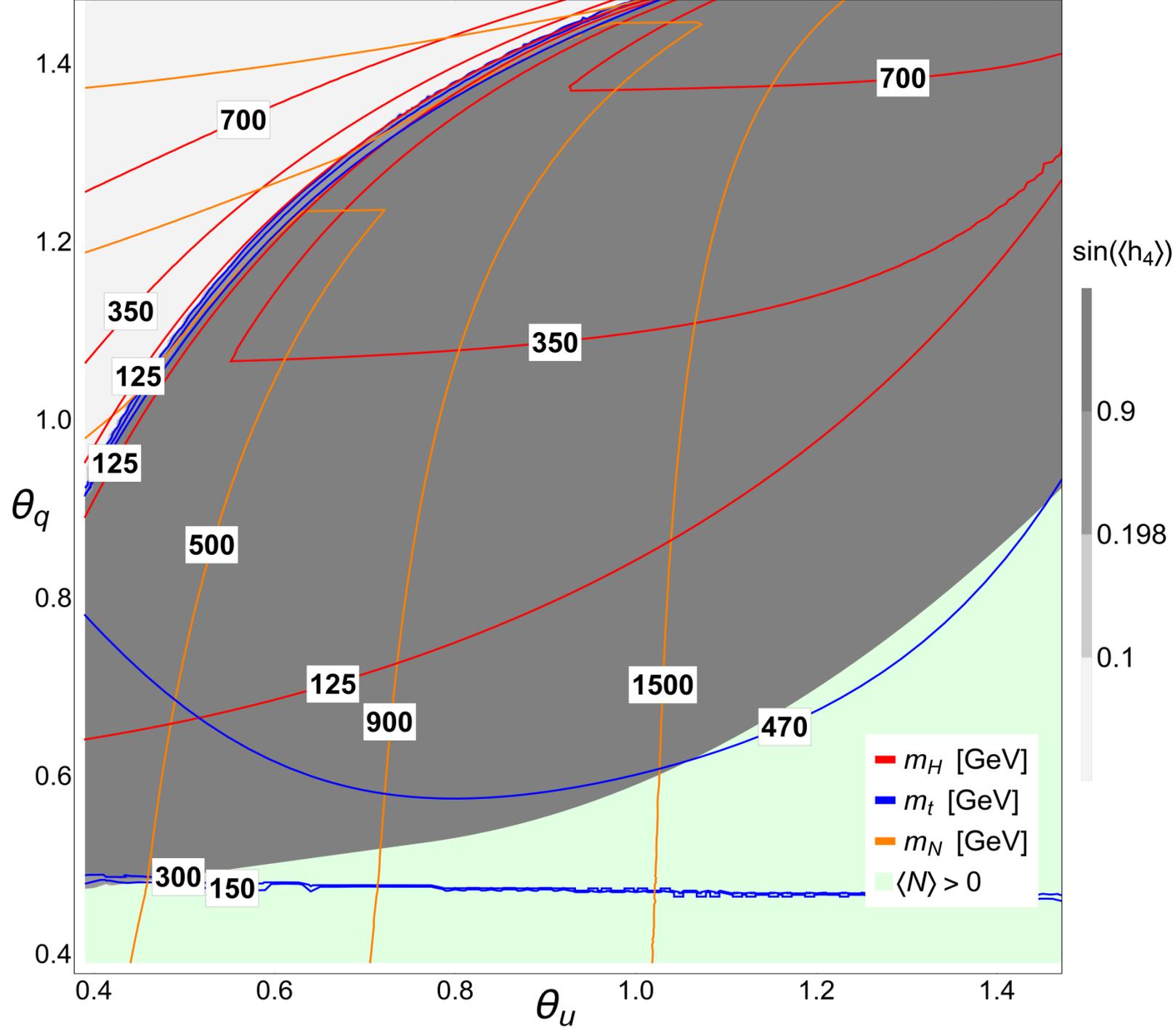
Vector boson fusion

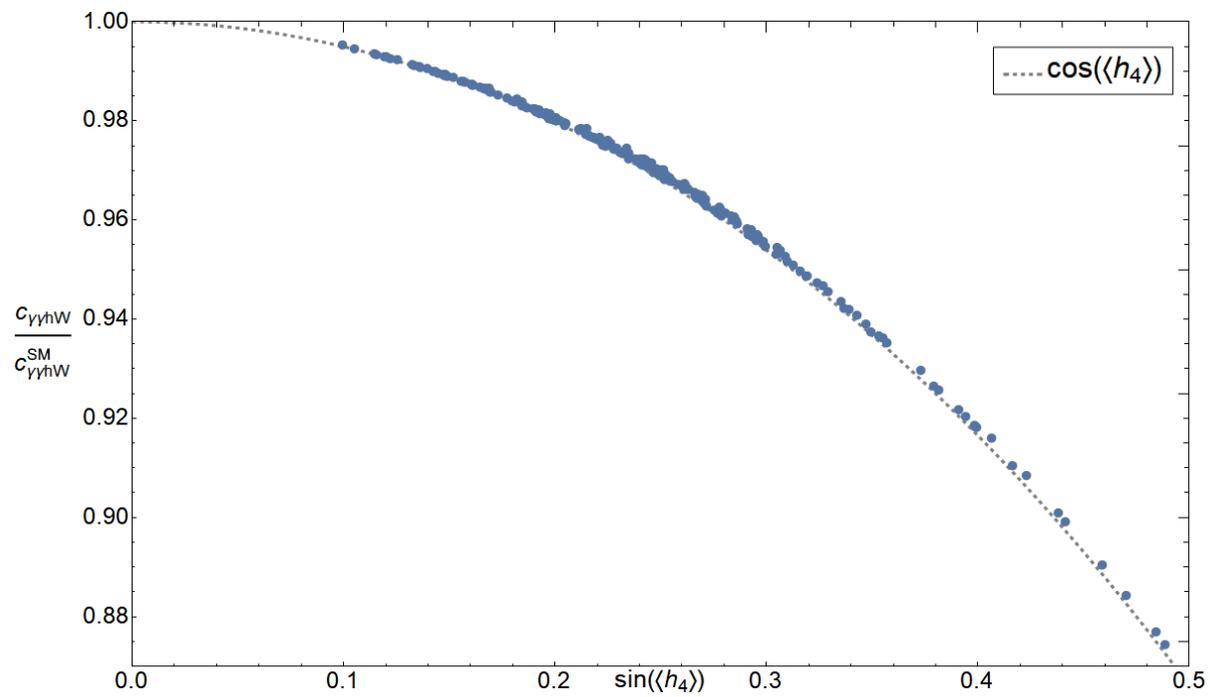
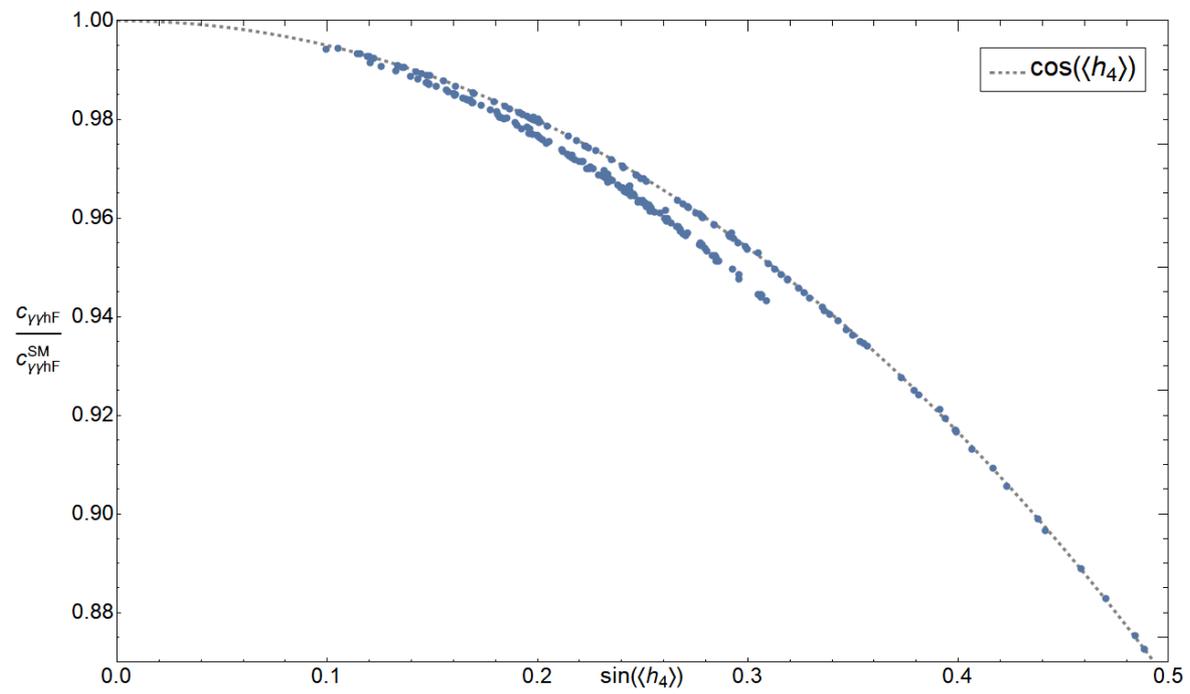


Decay to photons

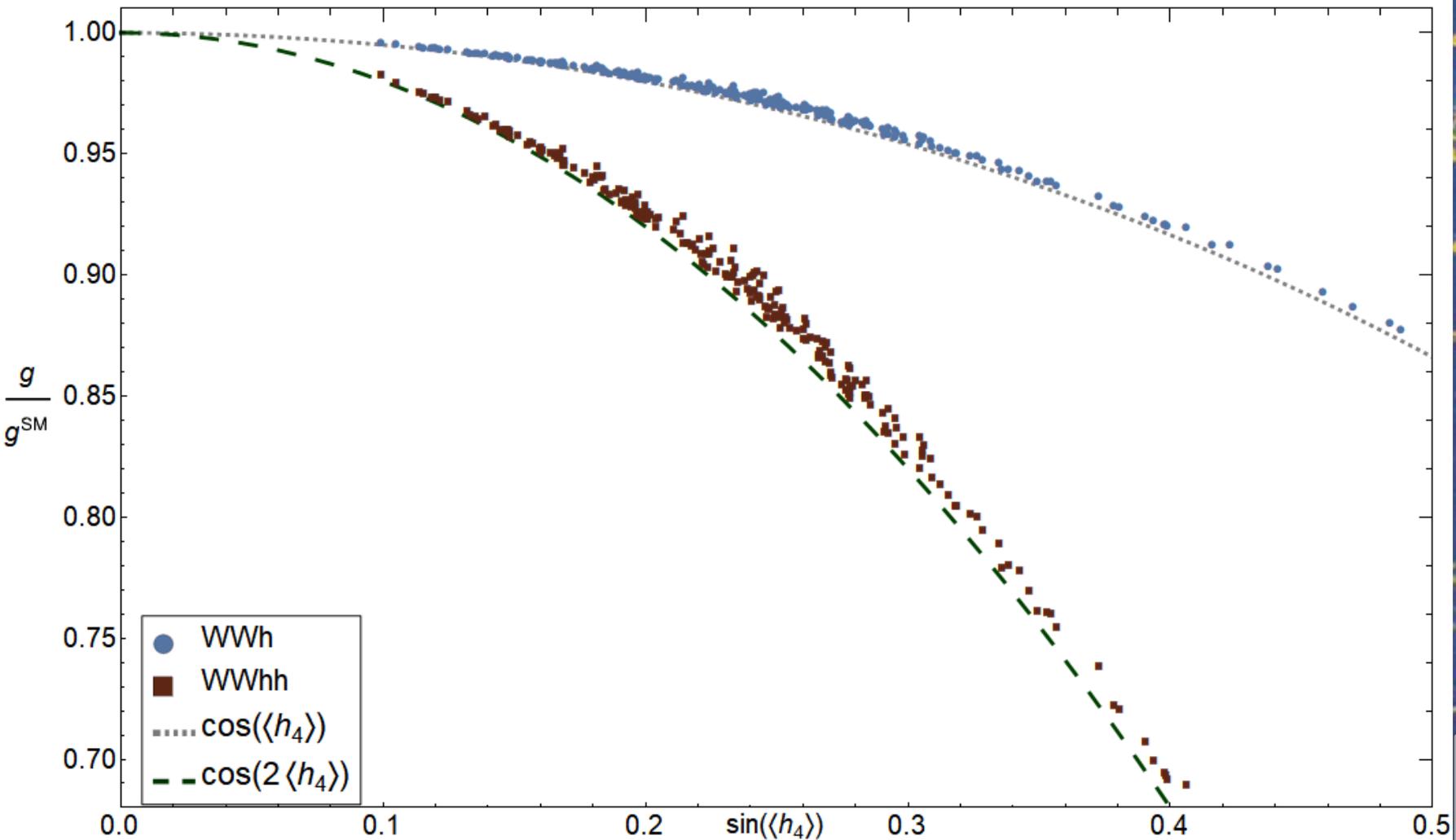


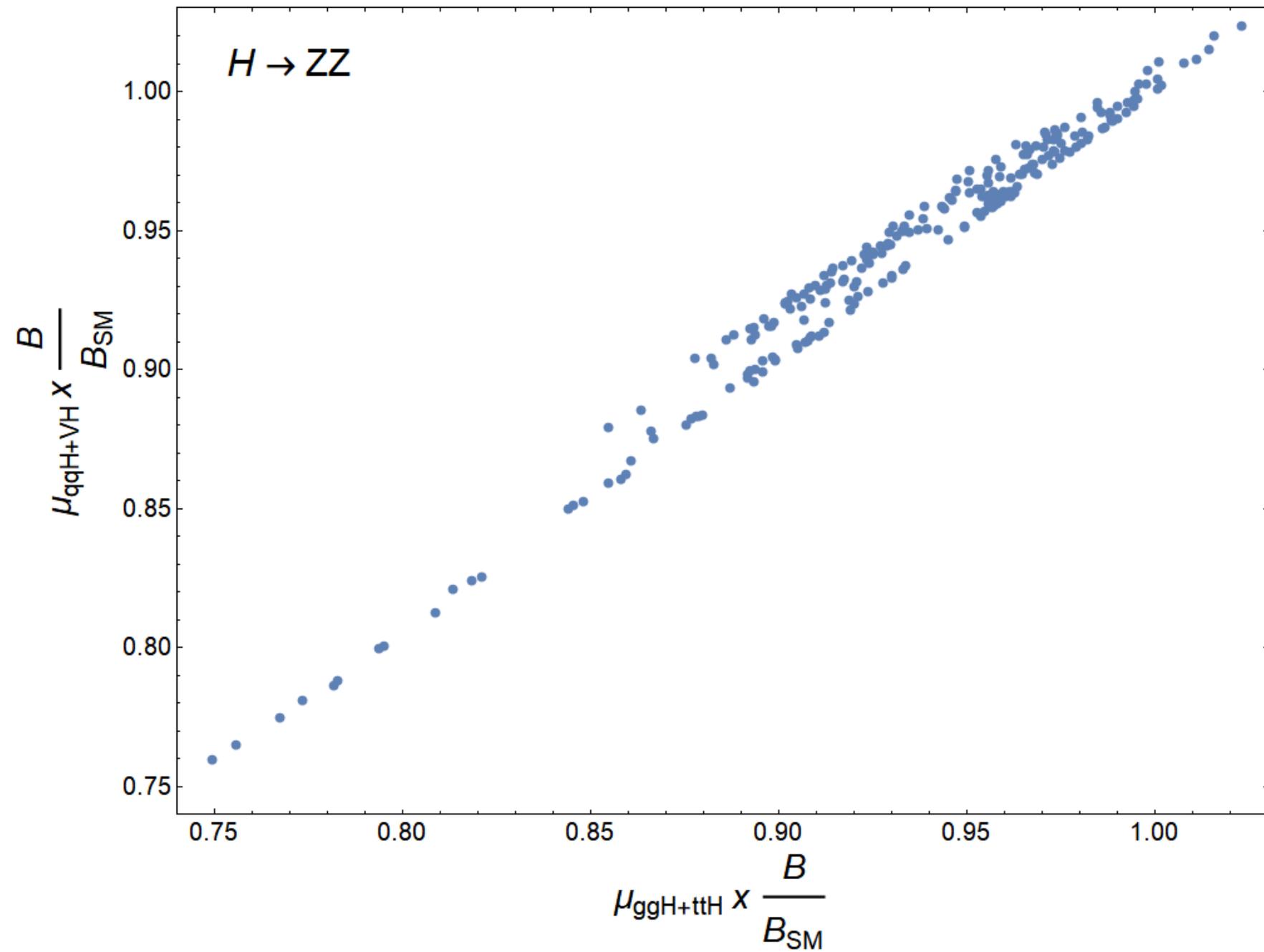






Couplings between H and W/Z





N boson stability

