Trilinear couplings in the 2HDM

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based on work with P.N. Pandita and L. Selbuz

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Scenario/Summary

- Assume rich Higgs sector is revealed at the LHC
- It may be possible to measure some trilinear couplings at the linear collider ("whoever she may be")
- The 2HDM has a rich menu of trilinear couplings
- They are considerably modified by CP violating and loop effects

Define model: 2HDM (II)

Potential:

$$V = \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$
$$+ \frac{1}{2}\left[\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\right] + \left\{\left[\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)\right](\Phi_1^\dagger\Phi_2) + \text{h.c.}\right\}$$
$$- \frac{1}{2}\left\{m_{11}^2(\Phi_1^\dagger\Phi_1) + \left[m_{12}^2(\Phi_1^\dagger\Phi_2) + \text{h.c.}\right] + m_{22}^2(\Phi_2^\dagger\Phi_2)\right\}$$

Allow CP violation:

$\lambda_5,\ \lambda_6,\ \lambda_7,\ m_{12}^2$ may be complex

Neutral sector: 3 × 3 mixing matrix $\boldsymbol{\alpha} = (\alpha_1, \alpha_2, \alpha_3)$

$$-\frac{\pi}{2} < \alpha_i \leq \frac{\pi}{2}, \quad i = 1, 2, 3$$

Often, take: $\lambda_6 = \lambda_7 = 0$

Parameters:

$$\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \mu^2, \tan\beta$$

complex

or:

$$M_1 \leq M_2 \leq M_3, M_{H^\pm}, \tan\beta, \mu^2, \alpha_1, \alpha_2, \alpha_3$$

Input parameters:

$$M_1 \leq M_2, M_{H^\pm}, \tan\beta, \mu^2, (\alpha_1, \alpha_2, \alpha_3)$$

Calculate: $M_3, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$

Conditions: $M_2 \leq M_3$

$V(\Phi_1, \Phi_2) > 0$ asymptotically

$$\Phi_i = \begin{pmatrix} \varphi_i^+ \\ \frac{1}{\sqrt{2}}(v_i + \eta_i + i\chi_i) \end{pmatrix}, \quad i = 1, 2$$

Weak basis: $\eta_1, \quad \eta_2, \quad \eta_3$

$$\eta_3 = -\sin\beta\,\chi_1 + \cos\beta\,\chi_2$$ CP odd

Mass basis: $$H_i = R_{ij}\eta_j$$

$$R = R_3\,R_2\,R_1 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha_3 & \sin\alpha_3 \\ 0 & -\sin\alpha_3 & \cos\alpha_3 \end{pmatrix} \begin{pmatrix} \cos\alpha_2 & 0 & \sin\alpha_2 \\ 0 & 1 & 0 \\ -\sin\alpha_2 & 0 & \cos\alpha_2 \end{pmatrix} \begin{pmatrix} \cos\alpha_1 & \sin\alpha_1 & 0 \\ -\sin\alpha_1 & \cos\alpha_1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} c_1\,c_2 & s_1\,c_2 & s_2 \\ -(c_1\,s_2\,s_3 + s_1\,c_3) & c_1\,c_3 - s_1\,s_2\,s_3 & c_2\,s_3 \\ -c_1\,s_2\,c_3 + s_1\,s_3 & -(c_1\,s_3 + s_1\,s_2\,c_3) & c_2\,c_3 \end{pmatrix},$$

Approach A

$\lambda_6 = \lambda_7 = 0$

Input: $M_1 \leq M_2, M_{H^\pm}, \tan\beta, \mu^2, (\alpha_1, \alpha_2, \alpha_3)$

Calculate: $M_3, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$

Approach B

Input: As above, plus:

$M_3, \quad \mathrm{Im}\,\lambda_5, \quad \mathrm{Re}\,\lambda_6, \quad \mathrm{Re}\,\lambda_7$

Calculate: As above, minus: $M_3, \quad \mathrm{Im}\,\lambda_5$

plus: $\mathrm{Im}\,\lambda_6, \quad \mathrm{Im}\,\lambda_7$

Yukawa couplings

$$H_j b\bar{b}: \qquad \frac{1}{\cos\beta}[R_{j1} - i\gamma_5 \sin\beta R_{j3}]$$

$$H_j t\bar{t}: \qquad \frac{1}{\sin\beta}[R_{j2} - i\gamma_5 \cos\beta R_{j3}]$$

$$H^+ b\bar{t}: \qquad \frac{ig}{2\sqrt{2}m_W}[m_b(1+\gamma_5)\tan\beta + m_t(1-\gamma_5)\cot\beta]$$

$$H^- t\bar{b}: \qquad \frac{ig}{2\sqrt{2}m_W}[m_b(1-\gamma_5)\tan\beta + m_t(1+\gamma_5)\cot\beta]$$

Important at low tanβ

Constraints:

- Positivity
- Perturbative unitarity (Higgs sector)
- Experimental constraints

Experimental constraints:

Independent of neutral sector	• $B \to X_s \gamma$	excludes low $M_{H^\pm}$
	• $B \to \bar{B}$ oscillations	excludes low $\tan\beta$
	• $B \to \tau\nu$	excludes high $\tan\beta$, low $M_{H^\pm}$
Depend on neutral sector	• $\Gamma_{Z \to b\bar{b}}$	excludes low $\tan\beta$
	• LEP2 non-discovery	light H decouples
	• $\Delta\rho$	spectrum compact
	• $(g\text{-}2)_\mu$	no simple characteristics

Trilinear couplings

$$\lambda_{ijk} = \frac{-i\,\partial^3 V}{\partial H_i \partial H_j \partial H_k}$$

Differentiate via weak fields

$$\lambda_{ijk} = \sum_{m\leq n\leq o=1,2,3}^{*} R_{i'm} R_{j'n} R_{k'o} \frac{-i\,\partial^3 V}{\partial \eta_m \partial \eta_n \partial \eta_o}$$

$$\{i', j', k'\} = \mathrm{permutation}\{i, j, k\}$$

Reference, SM: $$\lambda^{\mathrm{SM}}_{HHH} = \frac{3M_H^2}{v}$$

CP conserving limit:

6 couplings involving neutral Higgs bosons:

$$\lambda_{hhh},\ \lambda_{hhH},\ \lambda_{hHH},\ \lambda_{HHH}\ \lambda_{hAA},\ \lambda_{HAA}$$

CP non-conservation: 10 couplings

111, 112, 113, 122, 123, 133, 222, 223, 233, 333

Focus on two involving the lightest one, H_1

Study ratios wrt SM

$H_1H_1H_1$ ↔ λ_{111}

$$\xi_1 \equiv \frac{\lambda_{111}}{\lambda^{\rm SM}_{HHH}}$$

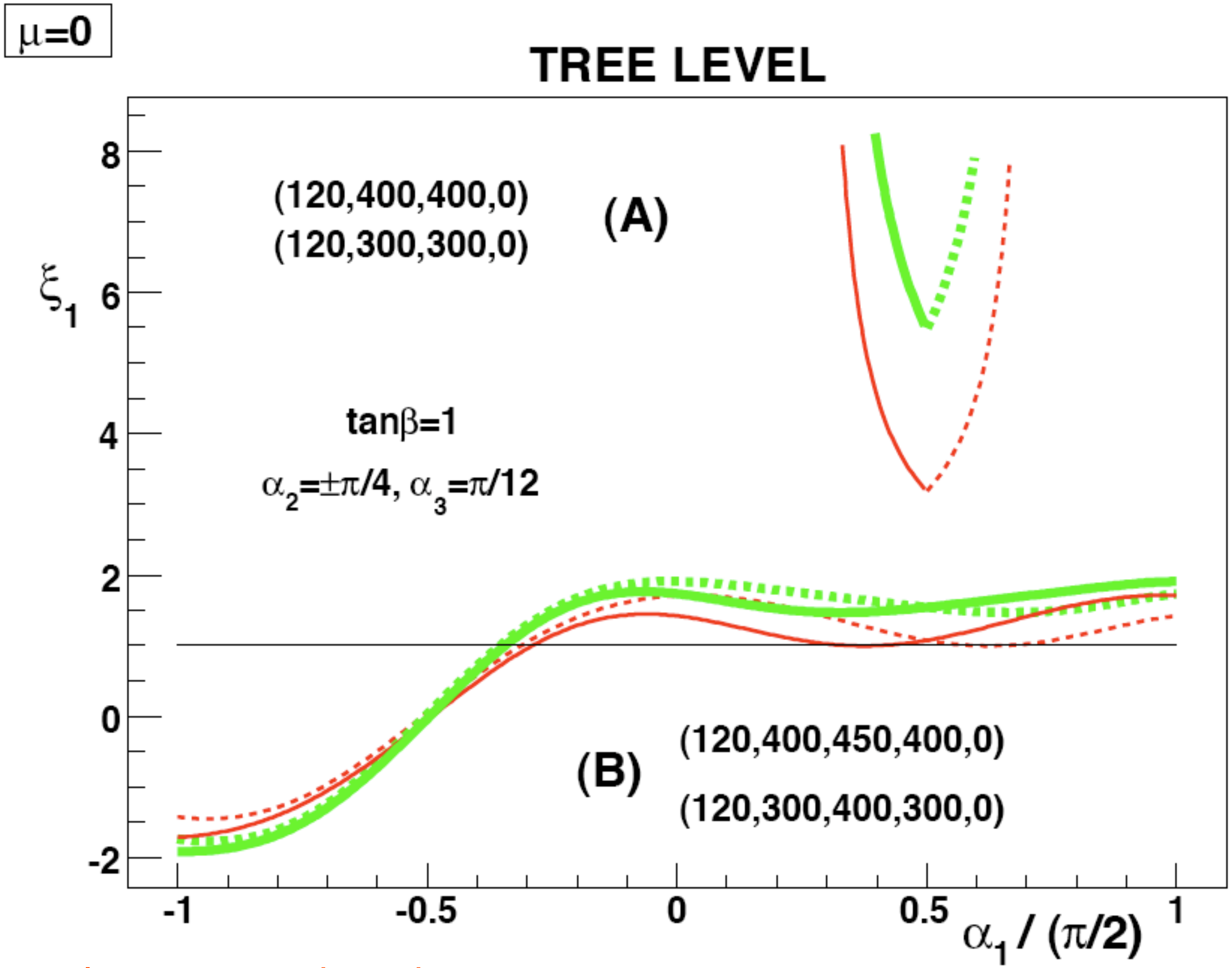
$H_1H_1H_2$ ↔ λ_{112}

$$\xi_2 \equiv \frac{\lambda_{112}}{\lambda^{\rm SM}_{HHH}}$$

average over some parameters $\boldsymbol{\alpha} = (\alpha_1, \alpha_2, \alpha_3)$

$$\langle\xi_1\rangle = \frac{\langle\lambda_{111}\rangle}{\lambda^{\rm SM}_{HHH}} \qquad \langle\xi_2\rangle = \frac{\langle\lambda_{112}\rangle}{\lambda^{\rm SM}_{HHH}}$$

Reference mass: M_1



Note: coupling may pass through zero

Limits of no CP violation

$$H_1 \text{ is odd:} \quad \alpha_2 = \pm\pi/2,$$
$$H_2 \text{ is odd:} \quad \alpha_3 = \pm\pi/2,$$
$$H_3 \text{ is odd:} \quad \alpha_2 = 0, \quad \alpha_3 = 0.$$

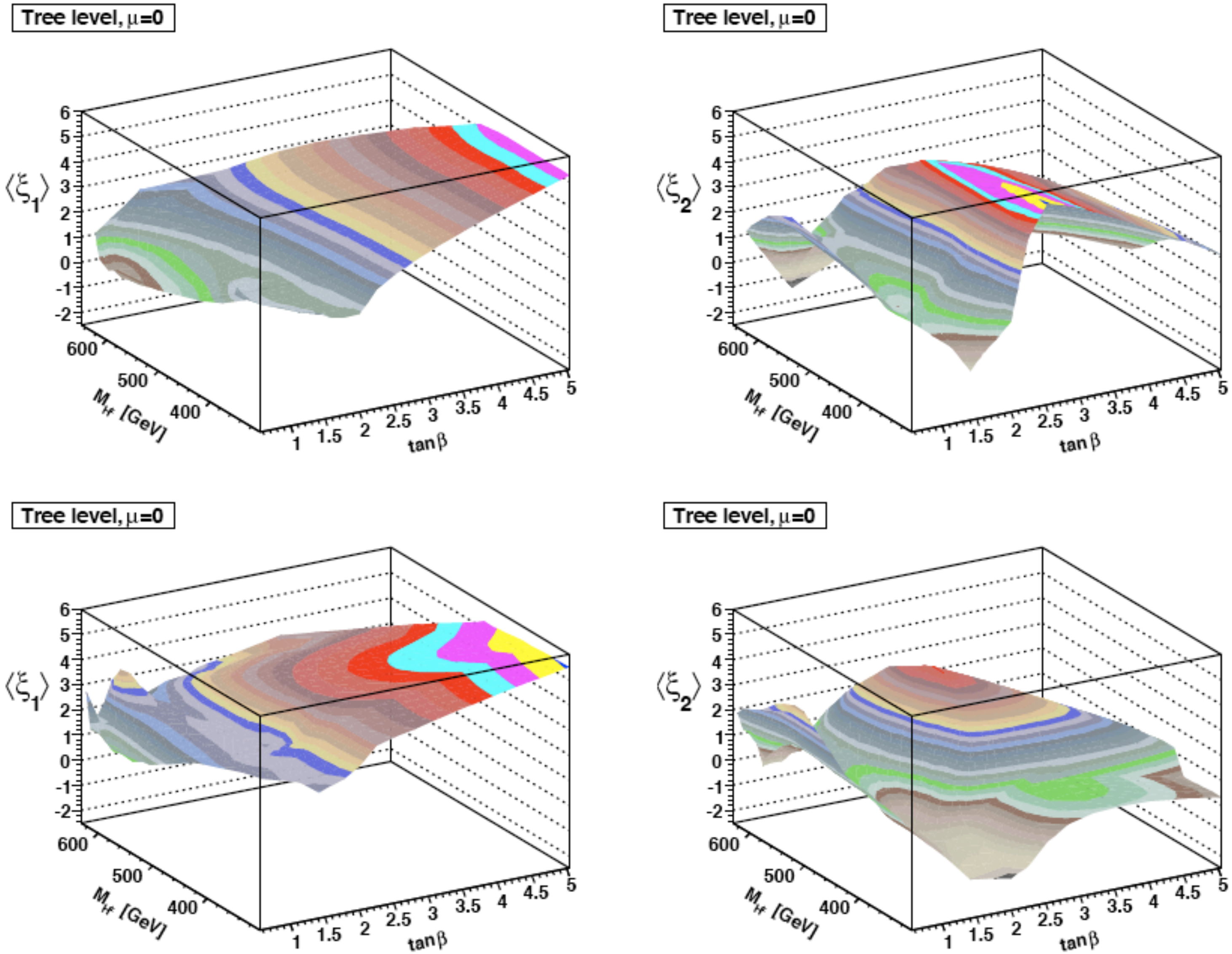
Limit of “little” CP violation:

$$|\alpha_2| \leq \alpha_0, \quad |\alpha_3| \leq \alpha_0, \quad \alpha_0 = 0.05 \times \pi/2$$

$$M_1 = 120\ \text{GeV}, \quad M_2 = 300\ \text{GeV}$$

"Little" CP violation

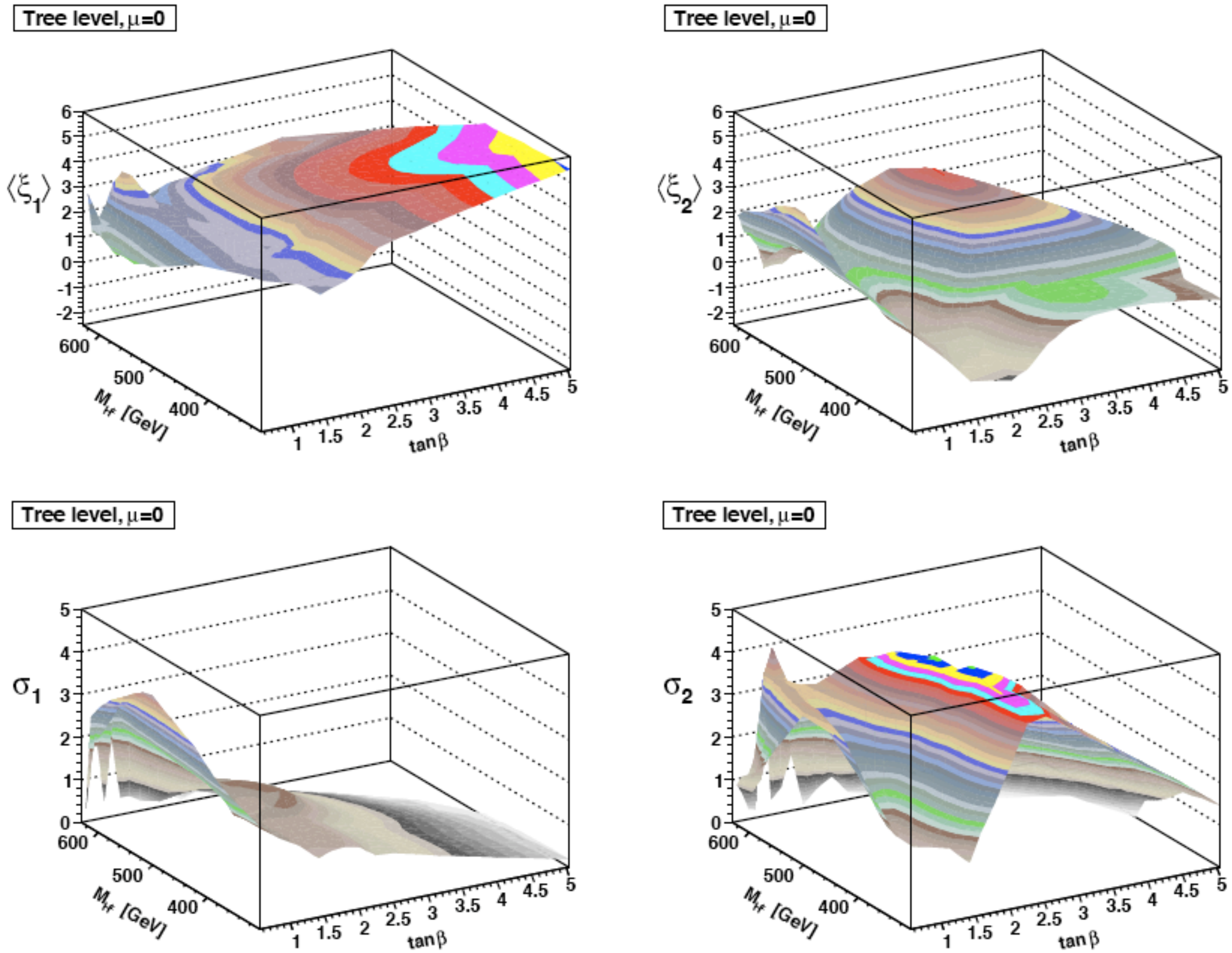
CP violation



$M_1 = 120$ GeV, $M_2 = 300$ GeV

Averages

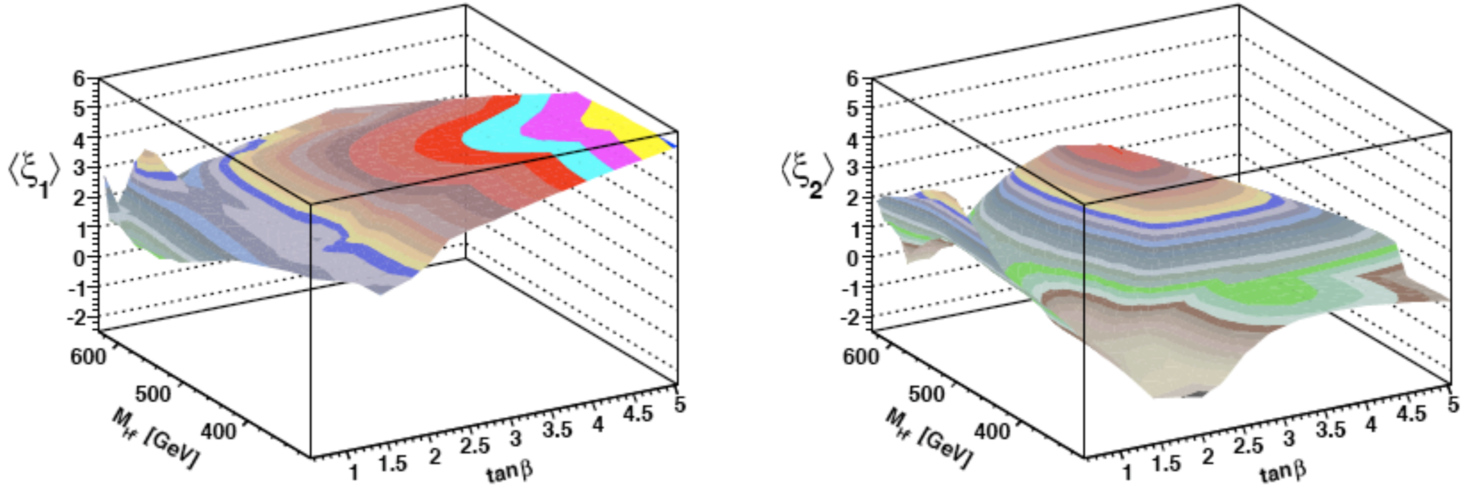
Variation



Approach A

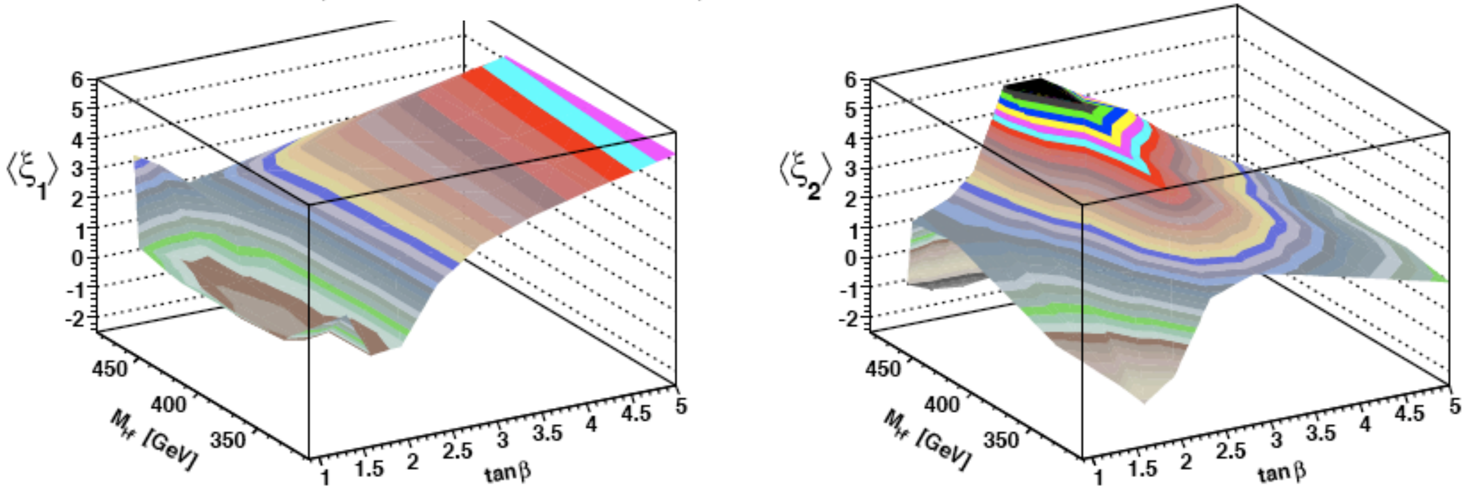
$M_1 = 120$ GeV, $\quad M_2 = 300$ GeV

Tree level, μ=0



Approach B

$M_1 = 120$ GeV, $\quad M_2 = 300$ GeV, $\quad M_3 = 400$ GeV

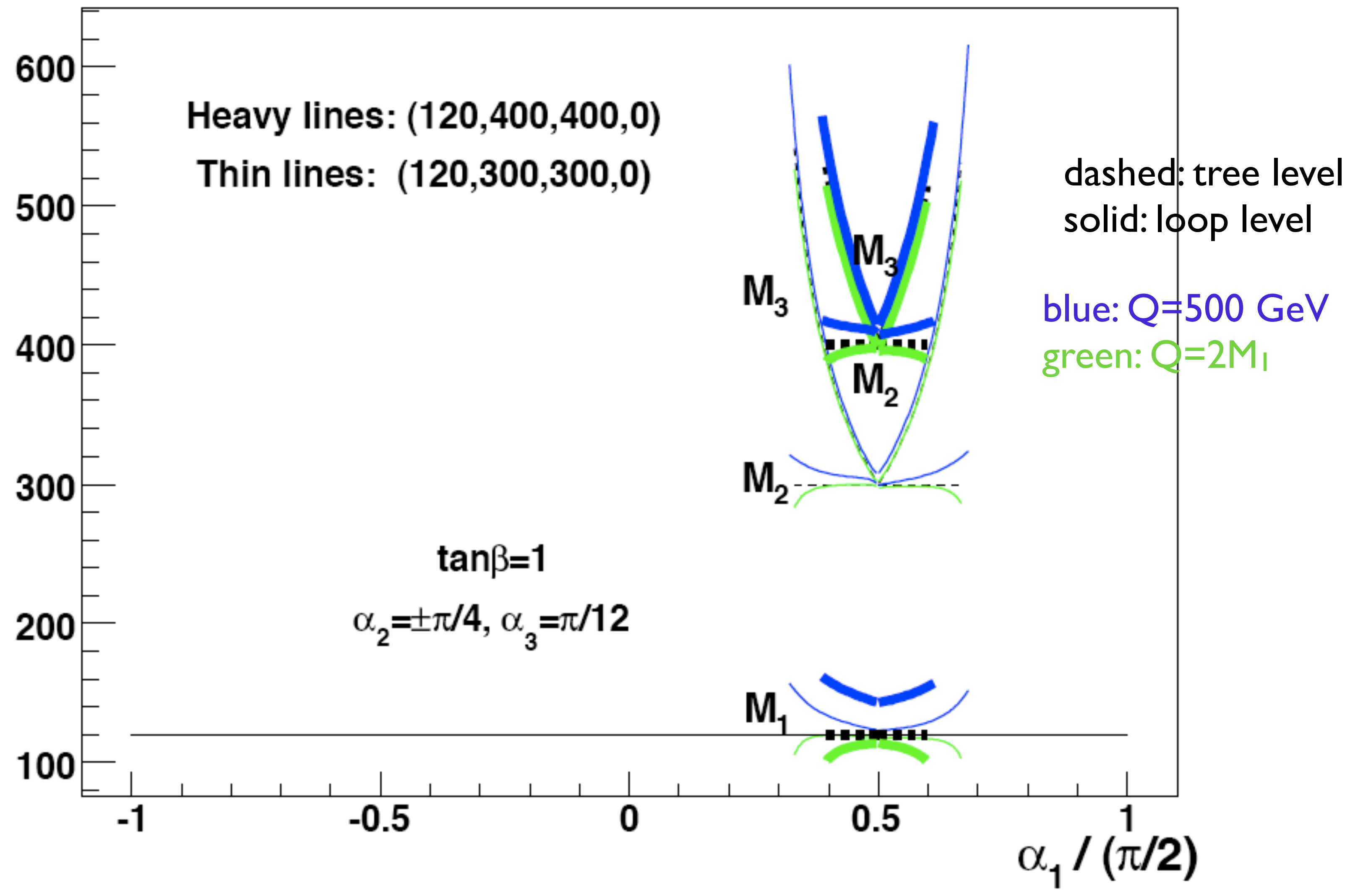


Loop corrections, Coleman-Weinberg:

$$\Delta V = \frac{1}{64\pi^2}\left[\sum_{\text{bosons}} M^4 \left(\log\frac{M^2}{Q^2} - \frac{3}{2}\right) - \sum_{\text{fermions}} M^4 \left(\log\frac{M^2}{Q^2} - \frac{3}{2}\right)\right],$$

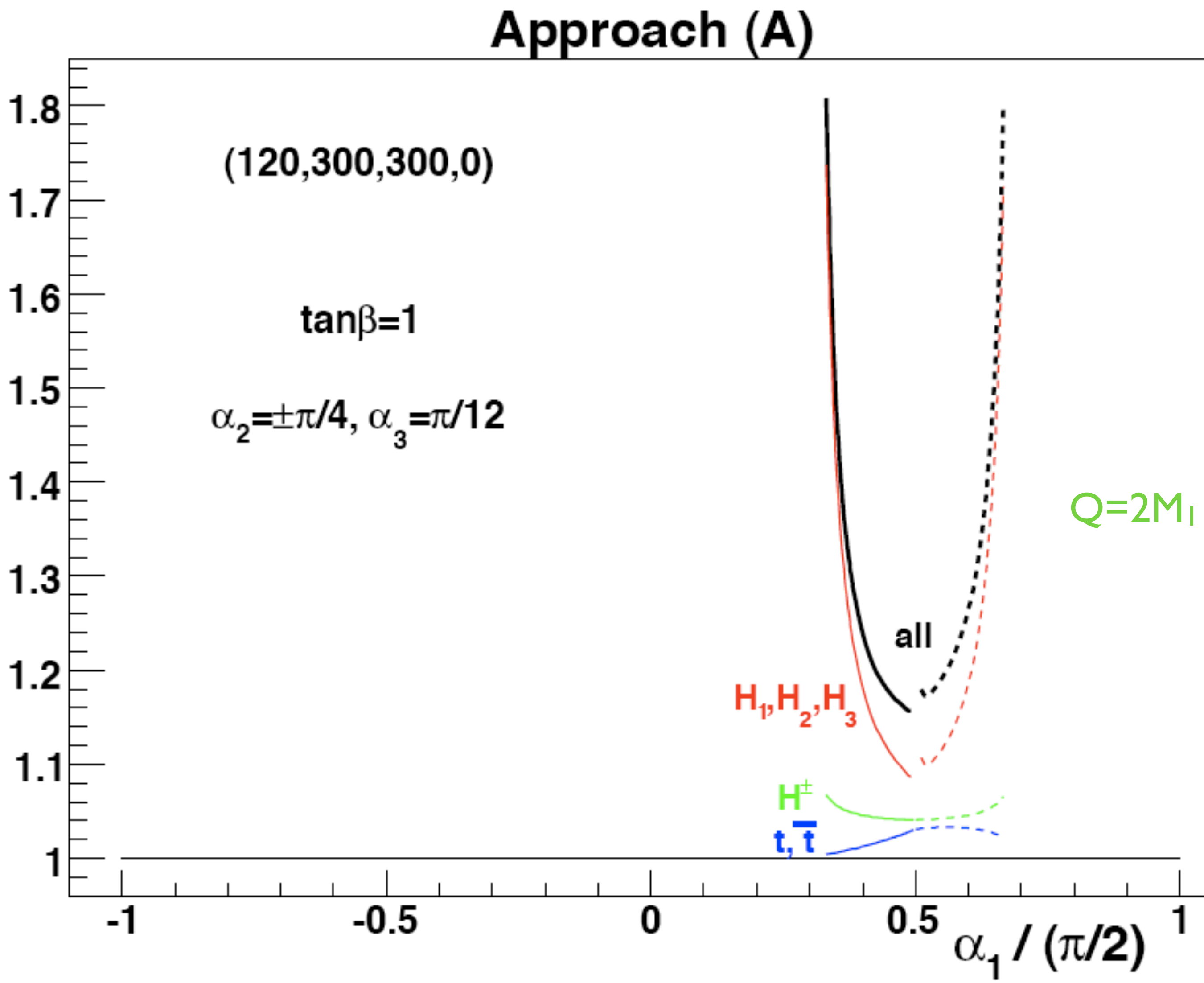
First, quick look at mass corrections...

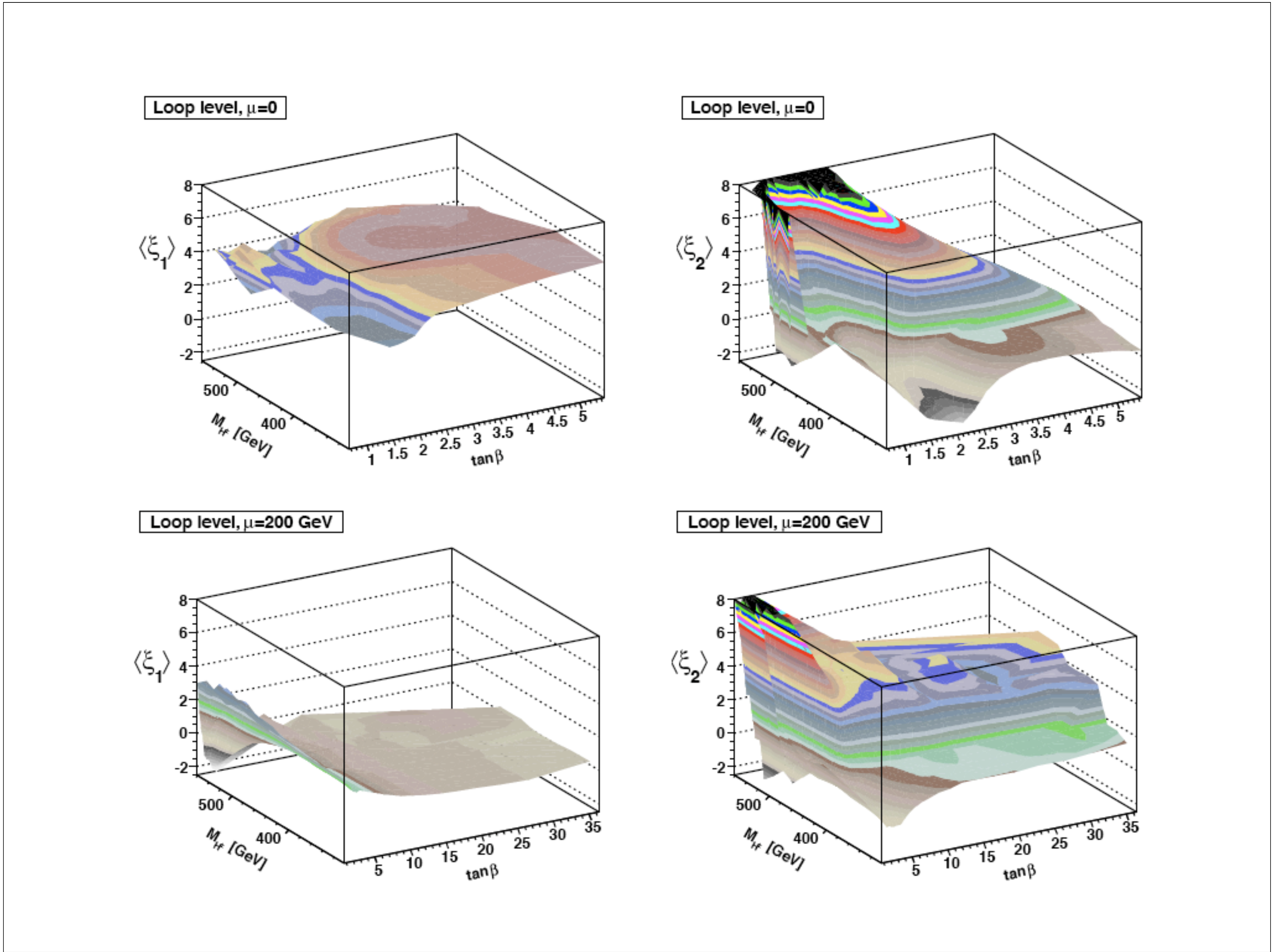
Approach (A)



Heavy lines: (120,400,400,0)
Thin lines: (120,300,300,0)
tanβ=1
α2=±π/4, α3=π/12
M3
M3
M2
M2
M1
600
500
400
300
200
100
-1
-0.5
0
0.5
1
α1 / (π/2)
dashed: tree level
solid: loop level
blue: Q=500 GeV
green: Q=2M1

Ratio: loop/tree




Loop level, μ=0
⟨ξ1⟩
M_H [GeV]
tanβ
Loop level, μ=0
⟨ξ2⟩
M_H [GeV]
tanβ
Loop level, μ=200 GeV
⟨ξ1⟩
M_H [GeV]
tanβ
Loop level, μ=200 GeV
⟨ξ2⟩
M_H [GeV]
tanβ

Decoupling?

Definition from (CP-conserving) MSSM:

- W. Hollik and S. Penaranda, EPJC 23 (2002) 163
- A. Dobado, M.J. Herrero + above, PRD 66 (2002) 095016

Trilinear coupling can be expressed in terms of masses, as in the SM at tree level, but masses are loop corrected

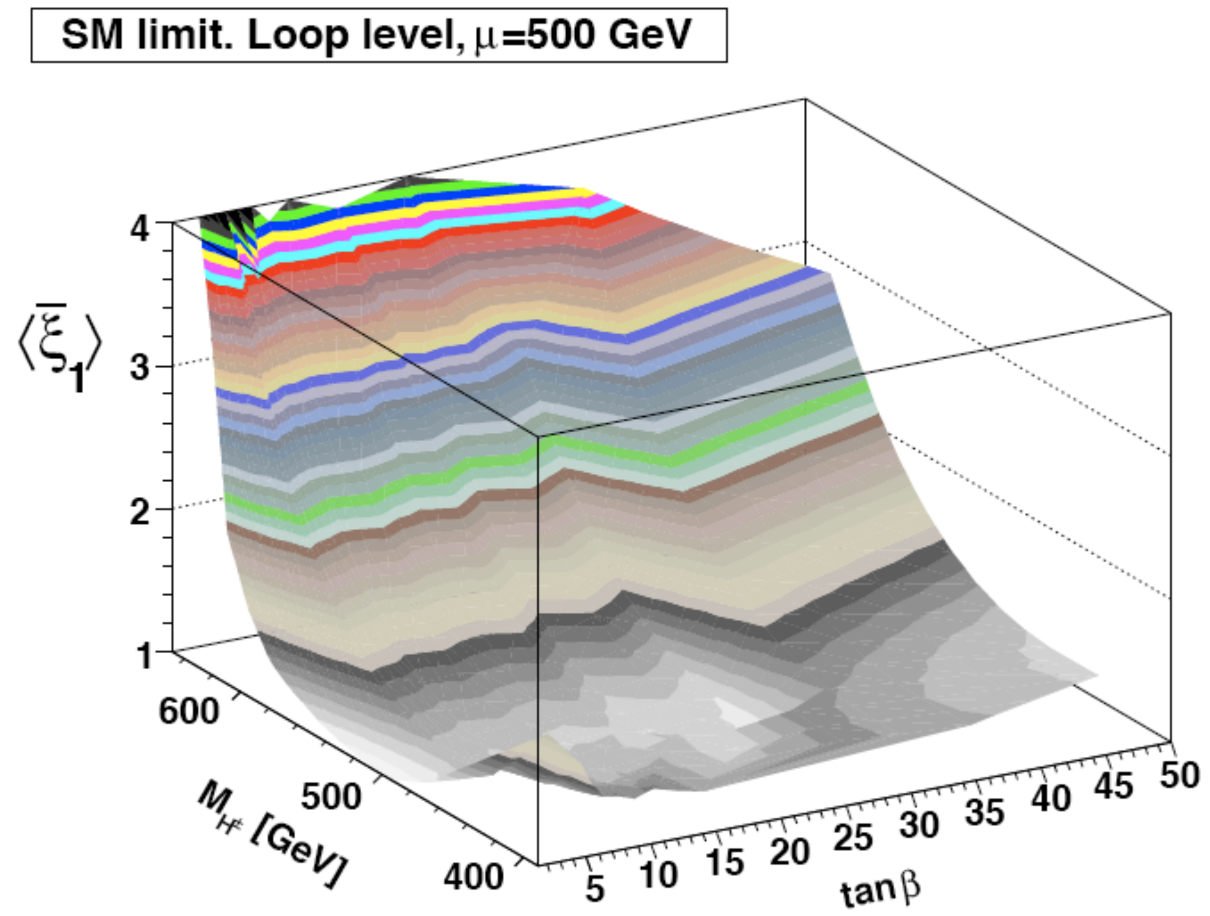
Study:

$$\langle \bar{\xi}_1 \rangle = \frac{\langle \lambda_{111}^{\mathrm{full}} \rangle}{\langle \lambda_{111}^{\mathrm{SM}} \rangle}$$

SM-like limit

SM-like limit:

- $\lambda_6 = \lambda_7 = 0$
- $|\alpha_2| \leq \alpha_0, \quad |\alpha_3| \leq \alpha_0, \quad \alpha_0 = 0.025 \times \pi/2$
  "minimal CP violation"
- $\lambda_{111}^{\mathrm{SM}}$ includes only loop corrections due to $t\bar{t}$ and H_1, as would be the case in the SM.
- $\lambda_{111}^{\mathrm{full}}$ includes all one-loop corrections to the Higgs coupling in the two Higgs doublet model, i.e., also those due to H_2, H_3 and $H^{\pm}$.



$\langle\bar{\xi}_1\rangle \simeq 1$

Decoupling breaks down for high values of $M_{H\pm}$

Summary

- Trilinear couplings are in the 2HDM typically larger than in the SM
- They vary a lot as one scans across parameter space, even for fixed masses M_1 and M_2
- Decoupling in limited region of parameter space