Signals of CP Violation Beyond the MSSM in Higgs Physics

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Outline

- The Higgs sector in the MSSM and the Little Hierarchy Problem
  - Beyond the MSSM
- Additional sources of CP violation
  - CP violation beyond the MSSM
- Higgs Collider Phenomenology
- Closing Remarks

The MSSM

$$W_{MSSM} = \mu \hat{H}_u \cdot \hat{H}_d + y_u^{ij} \hat{u}_i^c \hat{H}_u \cdot \hat{Q}_{Lj} - y_d^{ij} \hat{d}_i^c \hat{H}_d \cdot \hat{Q}_{Lj} - y_\tau^{ij} \hat{e}_i^c \hat{H}_d \cdot \hat{E}_{Lj}$$

What can it do:

- It is a solution to the "Hierarchy Problem"
- Light Higgs mimics SM Higgs in production and decay
- Bound on Higgs mass at tree-level proportional to gauge couplings

$$M_{h^0} \leq M_Z \cos 2\beta$$

In the Higgs decoupling limit, the bound on the MSSM Higgs is the same as that of the SM Higgs from LEP->114 GeV

Need for large radiative corrections originating from SUSY particles... heavy stops above 1 TeV

Creates a fine tuning in the mass parameters since $m_{\tilde{t}}$ provides the cutoff for the quadratically divergent Higgs mass parameter

➡Introduces a"Little Hierarchy problem"

Beyond the MSSM

- Effective Field theory with SUSY preserving and SUSY breaking dimension 5 operators

Dine, Seiberg and Thomas;
See also:
Carena, Kong, Ponton, and Zurita;
Antoniadis, Dudas, Ghilencea, and Tziveloglou;

$$W \supset \mu \hat{H}_u \hat{H}_d + \frac{\omega}{2M}(\hat{H}_u \hat{H}_d)^2$$

NLO contributions arise from Kahler potential terms $\mathrm{O}\left(1/M^2\right)$ small for consistent effective field theory yet relevant

Beyond the MSSM

- Incorporate gauge singlets

i.e. SMSSM (Delgado, Kolda, Olson, AP 2010):

$$W_{\hat{S}} = (\lambda \hat{S} + \mu)\hat{H}_u \hat{H}_d + \frac{\mu_s}{2}\hat{S}^2$$

$$m_{h^0}^2 \simeq m_Z^2 \cos^2 2\beta + \frac{2\lambda^2 v^2}{\mu_s}(2\mu \sin 2\beta - A_\lambda \sin^2 2\beta)$$

Hunting for additional sources of CP violation

Motivations for additional sources of CP violation

Standard Model has two sources of CP violation

1. CKM matrix: Constrained by unitarity

   - probed through the K and B meson systems

2. Arising from strong dynamics: $L \supset \frac{\alpha_s}{8\pi}\Theta G\tilde{G}$

   Constrained by neutron electric dipole moment (EDM)

Problem in reproducing CP violation from the baryon asymmetry in the universe (BAU)

$$\frac{n_B}{n_\gamma} = (1.5 - 6.3) \times 10^{-10}$$

CP violation in the MSSM Higgs sector

- Radiatively induced
- Phases may occur in $\mu, A_f, m_{1/2}$
- Mixing among CP-even and CP-odd Higgs

MSSM can be used as a model for electroweak baryogenesis to generate the BAU... However

- EWBG requires a light right handed stop... (strong 1st order phase transition)
- MSSM requires a large stop
  - ➡ Fine tuning

Beyond the MSSM with CP violation

CP violating BMSSM

Effective field theory approach:

- Leading higher dimensional operators added to MSSM Higgs sector

$$W = W_{Yukawa} + \mu \hat{H}_u \hat{H}_d + \frac{w}{2M}(\hat{H}_u \hat{H}_d)^2$$

- SUSY breaking term in the Lagrangian

$$L \supset \alpha \frac{\omega m_s}{2M}(H_u H_d)^2$$

CP violating BMSSM

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$$L \supset \alpha \frac{\omega m_s}{2M}(H_u H_d)^2$$

ω **and** α **are complex order one parameters; and** m_s **is the scale of the SUSY breaking terms of the BMSSM physics**

At the renormalizable level, the tree level potential is given by:

$$
\begin{aligned}
V_{\rm ren} = V_{\rm MSSM} &+ \left(\alpha\frac{\omega m_S}{2M}(H_uH_d)^2 - \frac{\omega\mu^*}{M}(H_uH_d)(H_u^\dagger H_u + H_d^\dagger H_d) \ + \ h.c.\right) \\
&= (m_{H_u}^2 + |\mu|^2)H_u^\dagger H_u + (m_{H_d}^2 + |\mu|^2)H_d^\dagger H_d + (B\mu(H_uH_d) + h.c.) \\
&+\frac{g_2^2}{8c_W}(H_d^\dagger H_d)^2 + \frac{g_2^2}{8c_W}(H_u^\dagger H_u)^2 - \frac{g_2^2}{4c_W}(H_d^\dagger H_d)(H_u^\dagger H_u) + \frac{g_2^2}{2}(H_u^\dagger H_d)(H_d^\dagger H_u) \\
&+ \left(\alpha\frac{\omega m_S}{2M}(H_uH_d)^2 - \frac{\omega\mu^*}{M}(H_uH_d)(H_u^\dagger H_u + H_d^\dagger H_d) \ + \ h.c.\right)
\end{aligned}
$$

- Parametrize the complex coefficients as

$$\lambda_5 = |\lambda_5|e^{i\phi_5} \equiv \frac{\alpha\omega m_s}{M}$$

$$\lambda_6 = |\lambda_6|e^{i\phi_6} \equiv \frac{\omega\mu *}{M}$$

1/M operator in the Superpotential leads to additional non-renormalizable operators

$$V_6 = \frac{\lambda_8}{M^2}(H_u H_d)(H_u^\dagger H_d^\dagger)(H_u^\dagger H_u) + \frac{\lambda_8'}{M^2}(H_u H_d)(H_u^\dagger H_d^\dagger)(H_d^\dagger H_d)$$

where $\lambda_8 = |\omega|^2$

- **Crucial in bounding potential from below**
- **At the $1/M^2$, Kahler terms can be incorporated -> lead to larger Higgs masses**

Carena, Kong, Ponton and Zurita

Electroweak Symmetry Breaking:

- The Higgs fields are parametrized as follow:

$$H_u^T = e^{i\theta_u}(H_u^+, \frac{v_u + h_u + ia_u}{\sqrt{2}}) \qquad H_d^T = e^{i\theta_d}(\frac{v_d + h_d + ia_d}{\sqrt{2}}, H_d^-)$$

$$v_u = v \sin\beta$$
$$v_d = v \cos\beta$$

- Relative phase can be rotated away by a U(1) transformation and $\theta = \theta_u + \theta_d$ is physical

$$\frac{\partial V}{\partial \mathrm{Re} H_u} = \frac{\partial V}{\partial \mathrm{Re} H_d} = \frac{\partial V}{\partial \theta} = 0$$

- where the third condition leads to:

$$v^2 c_\beta s_\beta |\lambda_5| \sin(\phi_5 + 2\theta) + v^2 |\lambda_6| \sin(\phi_6 + \theta) - 2B\mu \sin\theta = 0$$

- Minimization conditions do not necessarily lead to a unique solution
- Second mimima along D-flat direction
- Metastability

Spectrum at tree-level

In the absence of CP violation we have:

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} h_u \\ h_d \end{pmatrix} , \quad \begin{pmatrix} G \\ A \end{pmatrix} = \begin{pmatrix} s_\beta & -c_\beta \\ c_\beta & s_\beta \end{pmatrix} \begin{pmatrix} a_u \\ a_d \end{pmatrix}$$

- **CP violation leads to scalar-pseudoscalar mixing:**

$$M_H^2 = \begin{pmatrix} M_h^2 & 0 & M_{hA}^2 \\ 0 & M_H^2 & M_{HA}^2 \\ M_{hA}^2 & M_{HA}^2 & M_A^2 \end{pmatrix}$$

$$M_{hA}^2 = -\frac{v^2}{2} \left(c_{\beta+\alpha} |\lambda_5| \sin(\phi_5 + 2\theta) - 2 s_{\beta-\alpha} |\lambda_6| \sin(\phi_6 + \theta) \right)$$

$$M_{HA}^2 = -\frac{v^2}{2} \left(s_{\beta+\alpha} |\lambda_5| \sin(\phi_5 + 2\theta) - 2 c_{\beta-\alpha} |\lambda_6| \sin(\phi_6 + \theta) \right)$$

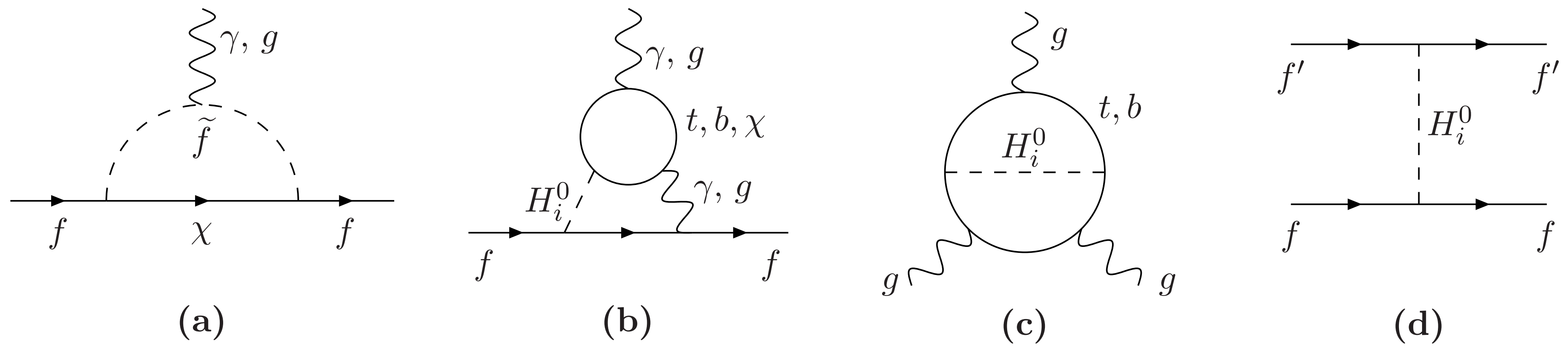
Spectrum at tree-level

$$M_H^2 = \begin{pmatrix} M_h^2 & 0 & M_{hA}^2 \\ 0 & M_H^2 & M_{HA}^2 \\ M_{hA}^2 & M_{HA}^2 & M_A^2 \end{pmatrix}$$

- The mass matrix is diagonalized by an orthogonal matrix O_{ij} such that

$$O^T M_H^2 O = \mathrm{diag}(M_{H_1}^2, M_{H_2}^2, M_{H_3}^2)$$

Constraints arising from EDM's



- Highly sensitive probes of CP violation
- Lead to tight constraints on new sources of CP violation

at 95% C.L:

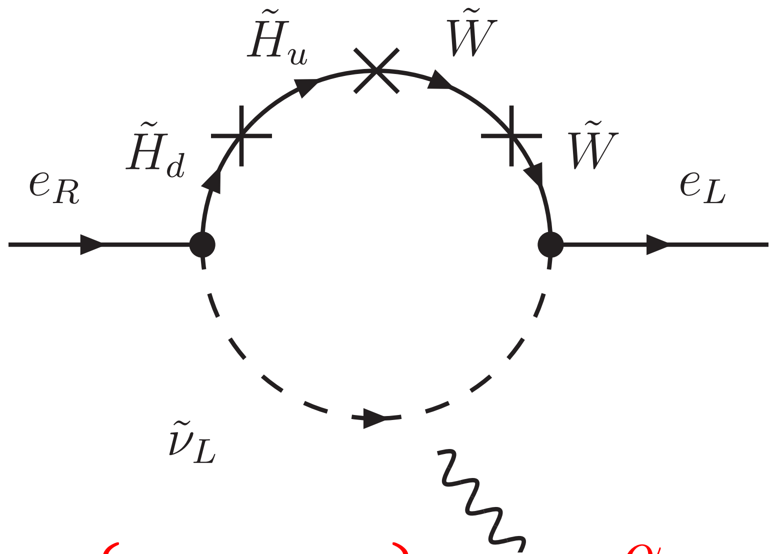
$$|d_n| < 3.5 \times 10^{-26} ecm$$

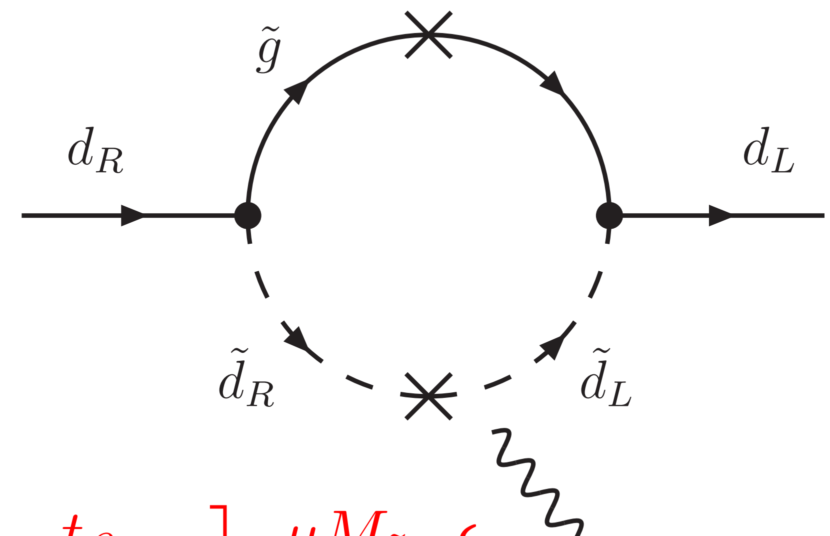
$$|d_{Tl}| < 1.1 \times 10^{-24} ecm$$

$$|d_{Hg}| < 2.9 \times 10^{-29} ecm$$

Constraints arising from EDM's

- One loop EDMs mainly induced by phase of the Higgs vev





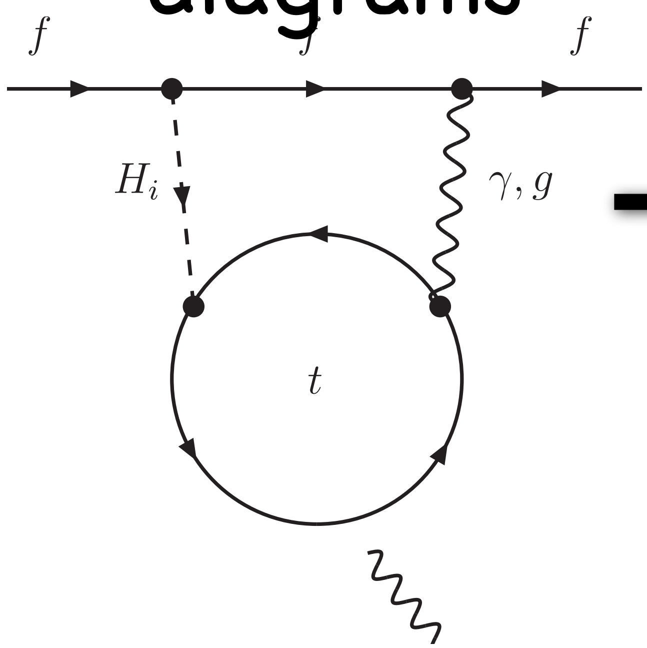
$$\left\{ d_d^{\tilde{g}}/e \ , \ \tilde{d}_d^{\tilde{g}} \right\} \simeq \frac{\alpha_s}{4\pi} m_d \, \mathrm{Im}\left[e^{i\theta} \frac{t_\beta}{1+\epsilon_d t_\beta} \right] \frac{\mu M_{\tilde{g}}}{\tilde{m}^4} \left\{ f_d(x_g) \ , \ \tilde{f}_d(x_g) \right\}$$

$$d_e^{\tilde{H}}/e \simeq \frac{\alpha_2}{4\pi} m_e \, \mathrm{Im}\left[e^{i\theta} \frac{t_\beta}{1+\epsilon_\ell t_\beta} \right] \frac{\mu M_2}{\tilde{m}^4} f_e(x_\mu, x_2)$$

- ϵ terms due to $\tan\beta$ resummation from non-holomorphic corrections to down quark and electron Yukawa couplings
- One loop contributions are $\tan\beta$ enhanced

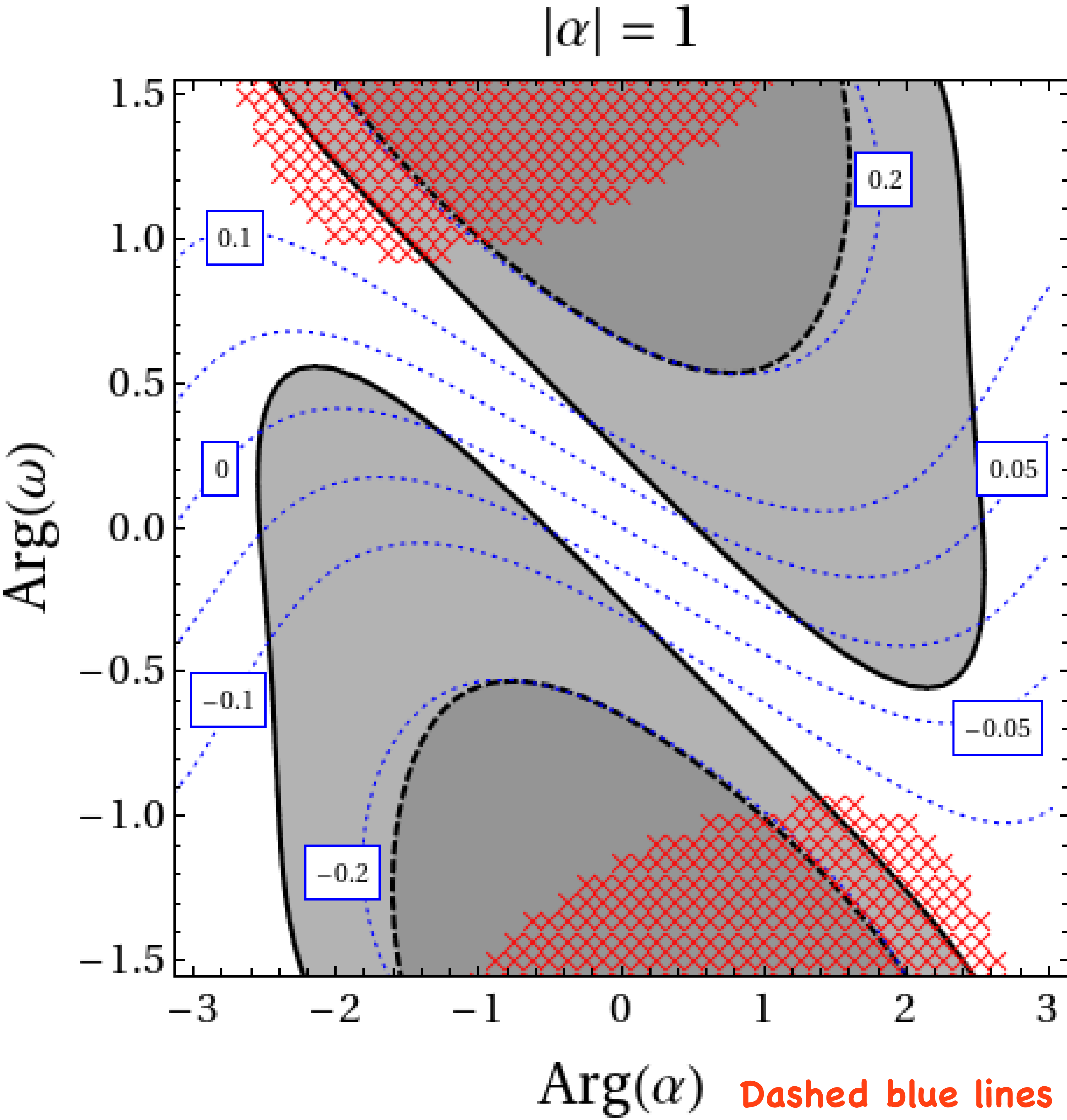
Constraints arising from EDM's

- Two-loop contributions are due to Bar-Zee diagrams



$$d_e^{(2)t}/e = \frac{\alpha_2 \alpha_{em}}{16\pi^2}\frac{4}{3} m_e \,\mathrm{Re}\left[\frac{\tan\beta}{1+\epsilon_\ell t_\beta}\right]\frac{m_t^2}{M_W^2}$$
$$\times \sum_{i=1}^{3}\frac{1}{M_{H_i}^2} O_{3i}\left(\frac{s_\alpha}{s_\beta}O_{2i}+\frac{c_\alpha}{s_\beta}O_{1i}\right) f\left(\frac{m_t^2}{M_{H_i}^2}\right)$$

- Sensitive to mixing between scalar and pseudoscalar Higgs through O_{ij}
- Two-loop contributions can be as large as 1-loop contributions for relatively light Higgs masses



$\tan\beta = 2$

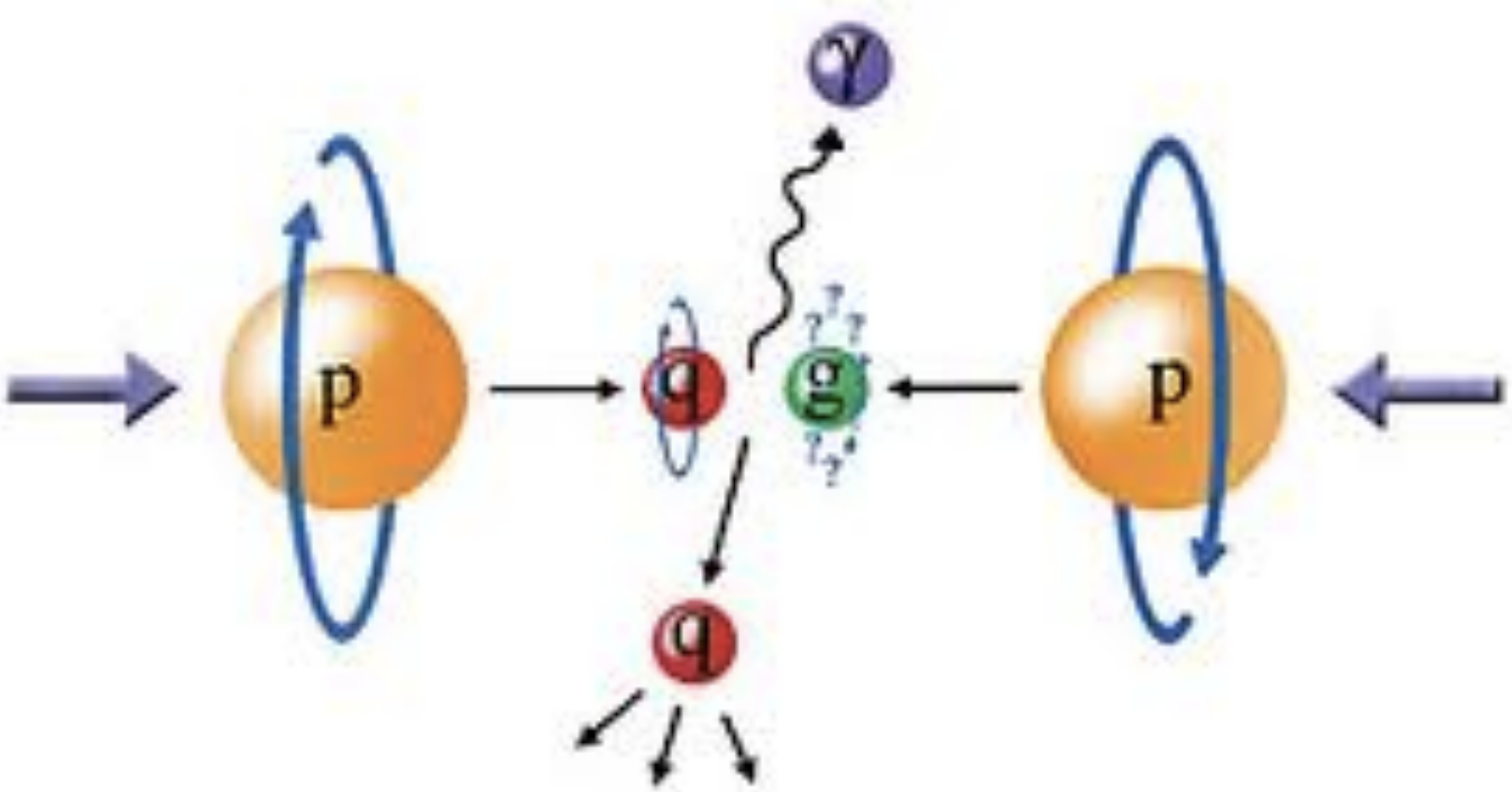
$\omega = 1$

$\mu = m_s = 150\ 150$

$M_{H+} = 200$ GeV

$M = 1.5$ TeV

Dashed blue lines correspond to different values of the phase of the Higgs vev



Higgs Collider Phenomenology

LEP and Tevatron Bounds

- Worked with effective couplings normalized to SM

$$\xi^2_{\gamma\gamma H_i} = \frac{\Gamma\left(H_i \to \gamma\gamma\right)_{LO}}{\Gamma\left(H_i \to \gamma\gamma\right)^{SM}_{LO}}$$

$$\xi^2_{ggH_i} = \frac{\Gamma\left(H_i \to gg\right)_{LO}}{\Gamma\left(H_i \to gg\right)^{SM}_{LO}} \approx \frac{\sigma\left(gg \to H_i\right)}{\sigma\left(gg \to H_i\right)^{SM}}$$

5-20%

- Compatibility with LEP and Tevatron searches is checked using Higgsbounds

Bechtle, Brein, Heinemeyer, Werglein, Williams

- **Incorporating also latest Tevatron exclusion** T. Aaltonen et al. 2011

Parameter Scan:

- Excluded by EDMs
- Excluded by LEP
- Excluded by Tevatron
- Allowed

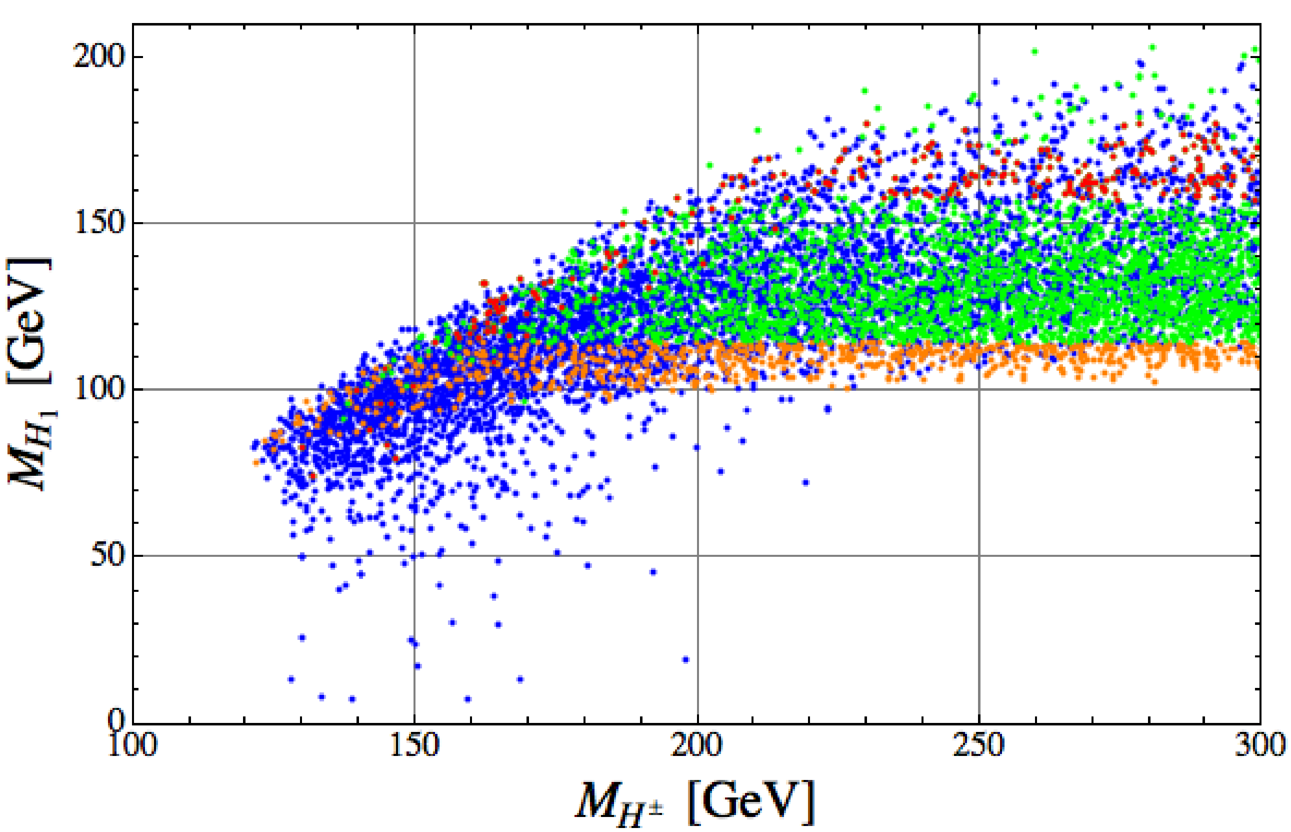
$$Arg(\alpha) \in [0, 2\pi]$$

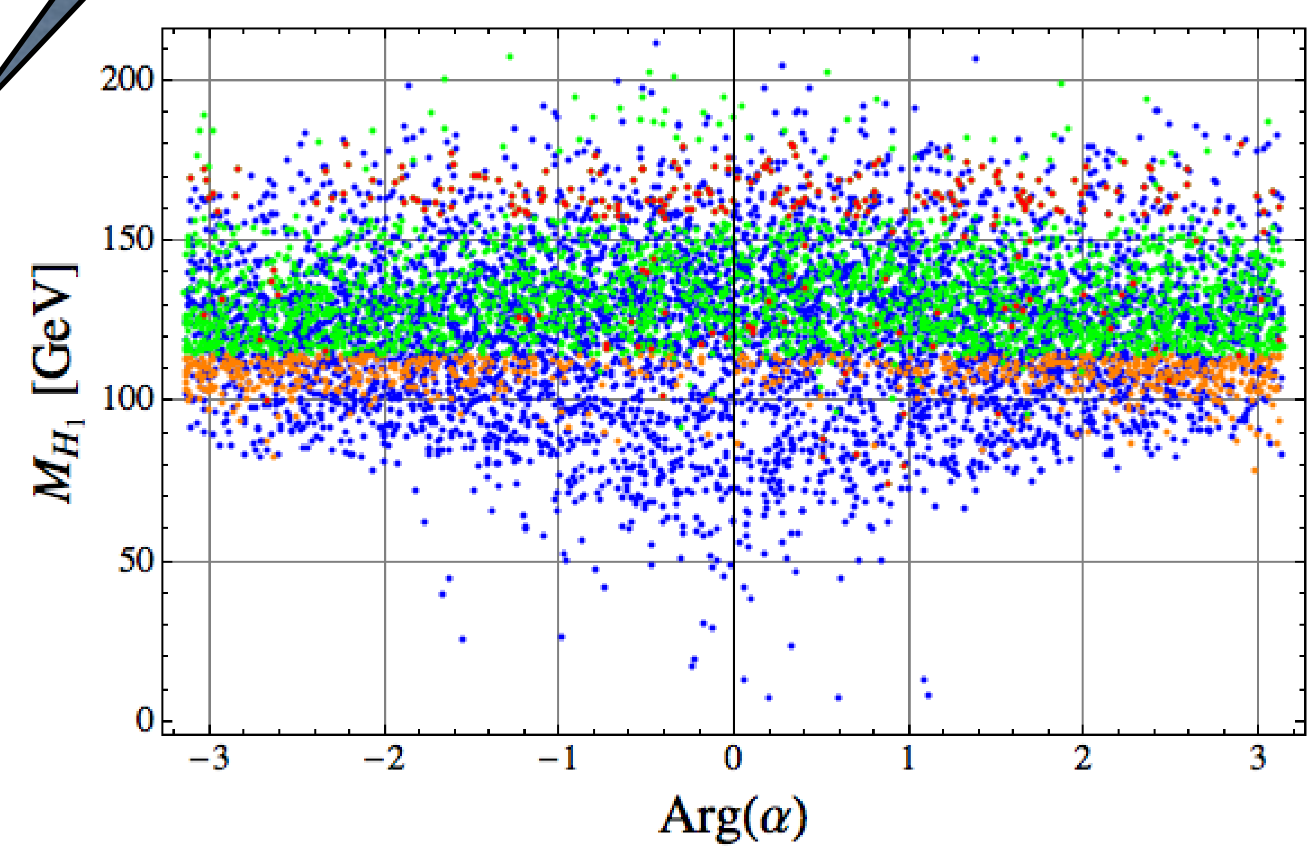
$$\omega = (0.5 \to 2.)e^{-\frac{i}{5} Arg(\alpha)}$$

$$M \in [1, 3] \text{ TeV}$$

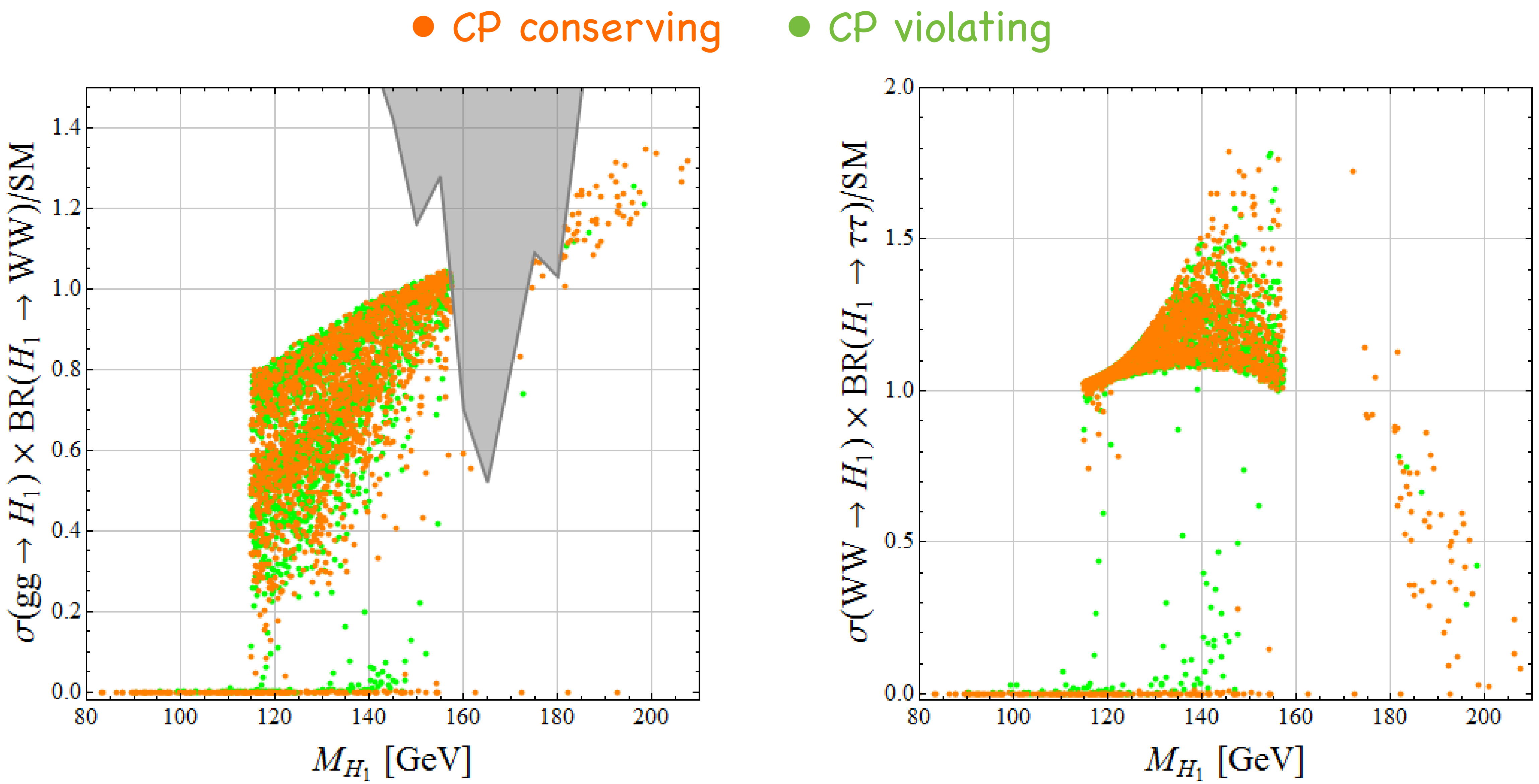
$$M_{H^\pm} \leq 350 \text{ GeV}$$

$$\tan\beta = 2\ , m_s = \mu = 150 \text{ GeV}, m_{\tilde{q}} = 800 \text{ GeV}$$





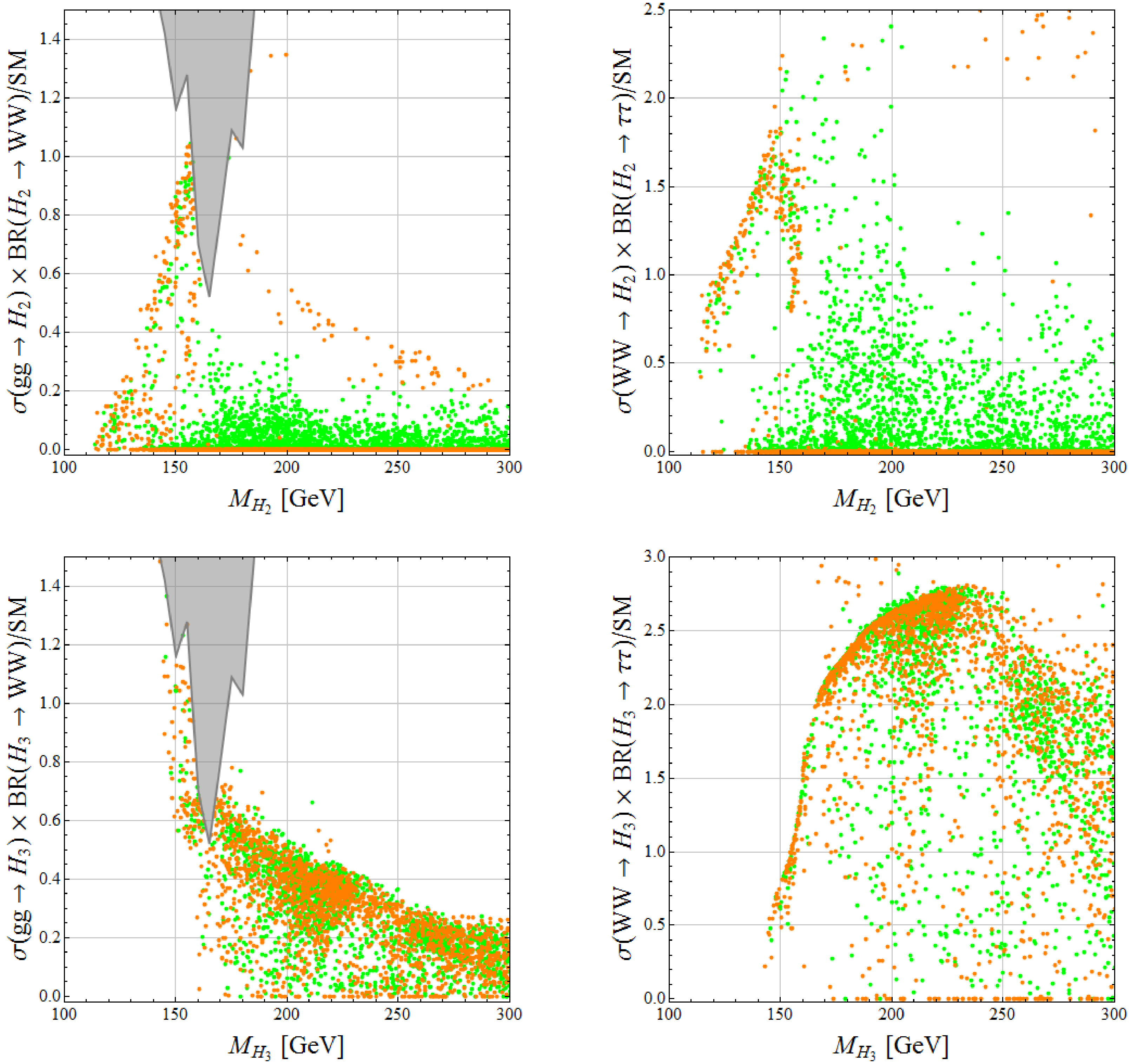
Generic features of the Parameter Scan



- WW channel promising in both scenarios
- For masses below 140 GeV, $\sigma\,(gg \to H_1) \cdot BR\,(H_1 \to WW)$ suppressed compared to SM, but may be possible to probe at Tevatron and LHC
- The $\tau\tau$ channel is slightly enhanced for wide range of masses... LHC not yet sensitive

Generic features of the Parameter Scan

● CP conserving ● CP violating



- Heavier Higgs boson can be discovered in the WW channel

- Absence of a pure pseudoscalar… mixing even leads to sizable enhancement in the WW production cross section

- $\tau\tau$ channel enhanced with respect to SM for masses above 150 GeV where $\sigma\,(WW \to H_{2,3}) \cdot BR(H_{2,3} \to \tau\tau)$ are too small to allow for detection

CP violating scenarios: Benchmark points

Scenario A:

Scenario III	H_1	H_2	H_3
M_{H_i} [GeV]	145	169	198
$\xi^2_{ZZH_i}$	0.94	0.02	0.04
$\xi^2_{ggH_i}$	0.68	0.59	0.53
$\mathrm{BR}(H_i \to bb)$	42% (23%)	59% (0.8%)	15% (0.2%)
$\mathrm{BR}(H_i \to WW)$	45% (60%)	31% (97%)	62% (74%)
$\mathrm{BR}(H_i \to ZZ)$	6% (8%)	0.7% (2.4%)	20% (26%)
$\mathrm{BR}(H_i \to \gamma\gamma) \times 10^4$	15 (17)	0.8 (1.6)	0.2 (0.5)

	Sc. III
$\|\alpha\|$	1
$\|\omega\|$	1.5
$\mathrm{Arg}(\alpha)$	$\pi/3$
$\mathrm{Arg}(\omega)$	$-\pi/15$
$\tan\beta$	2
$M_{H^\pm}$ [GeV]	190
M [TeV]	2.5
μ [GeV]	150
m_S [GeV]	150

- All three neutral Higgs bosons have masses above 145 GeV with significant branching ratios into WW
- This scenario cannot be achieved in the MSSM

CP violating scenarios: Benchmark points

Scenario A:

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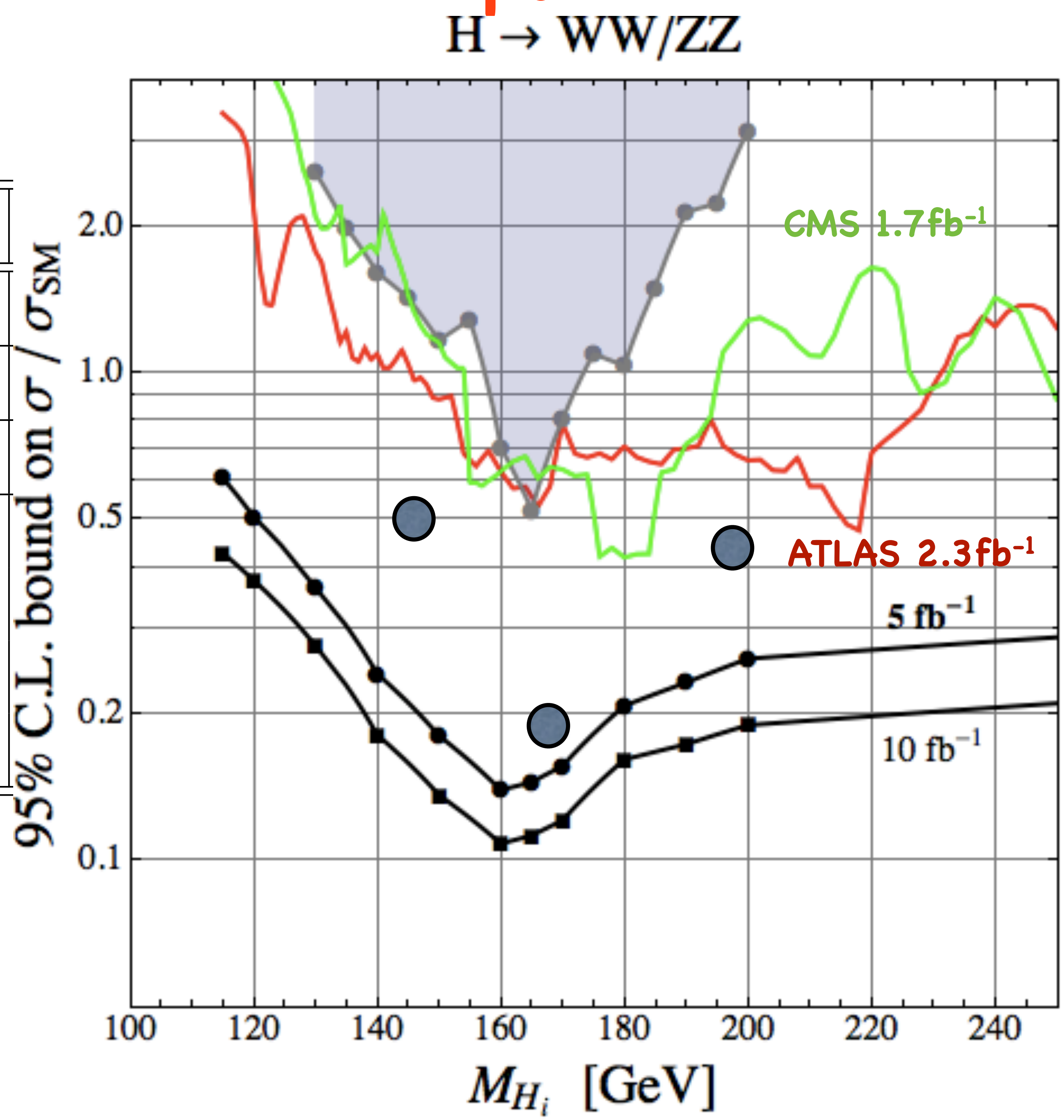

- Scenario testable with $5\mathrm{fb}^{-1}$ of data at the LHC

CP violating scenarios: Benchmark points

Scenario B:

Scenario II	H_1	H_2	H_3
M_{H_i} [GeV]	147	150	162
$\xi^2_{ZZH_i}$	0.62	0.32	0.06
$\xi^2_{ggH_i}$	0.41	0.53	0.39
$\mathrm{BR}(H_i \to bb)$	69% (22%)	72% (16%)	65% (2%)
$\mathrm{BR}(H_i \to WW)$	20% (63%)	17% (69%)	26% (94%)
$\mathrm{BR}(H_i \to ZZ)$	3% (8%)	2% (8%)	1% (3%)
$\mathrm{BR}(H_i \to \gamma\gamma) \times 10^4$	6 (16)	3 (13)	0.5 (4)

	Sc. II
$\lvert\alpha\rvert$	0.8
$\lvert\omega\rvert$	1.6
$\mathrm{Arg}(\alpha)$	$-2\pi/3$
$\mathrm{Arg}(\omega)$	$\pi/20$
$\tan\beta$	3
$M_{H^\pm}$ [GeV]	166
M [TeV]	2
μ [GeV]	140
m_S [GeV]	100

- All three neutral Higgs bosons have masses between 145 and 160 GeV decaying dominantly to $b\bar{b}$
- Strongly suppressed cross sections in the channel $gg \to H_i \to \gamma\gamma$
- Associated production with Higgs decays to $\tau\tau$ larger than SM but difficult to probe given the large Higgs masses

CP violating scenarios: Benchmark points

Scenario B:

Scenario II	H_1	
M_{H_i} [GeV]	147	
$\xi^2_{ZZH_i}$	0.62	
$\xi^2_{ggH_i}$	0.41	
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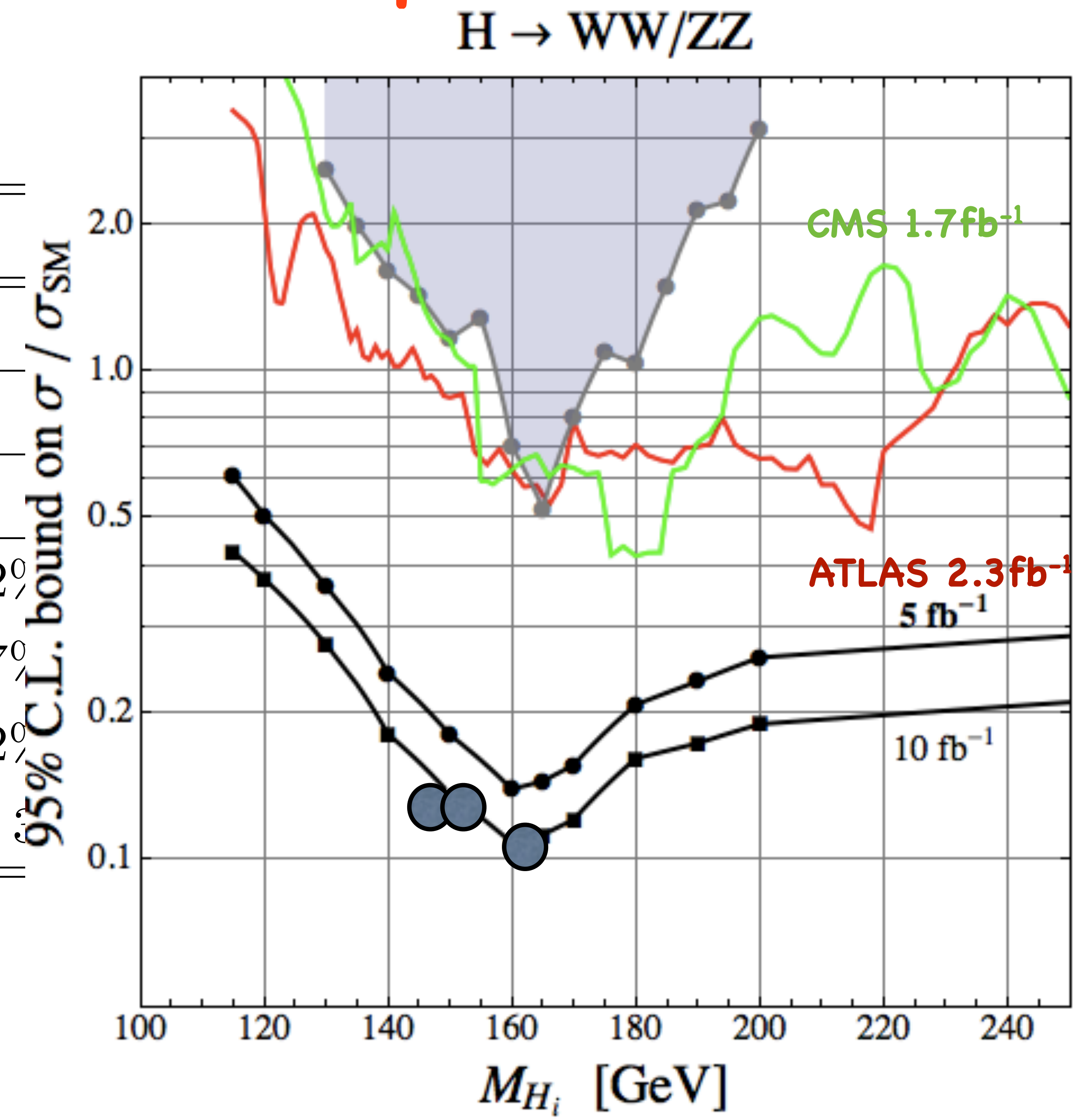
$\mathrm{BR}(H_i \to ZZ)$	3% (8%)	2%
$\mathrm{BR}(H_i \to \gamma\gamma) \times 10^4$	6 (16)	

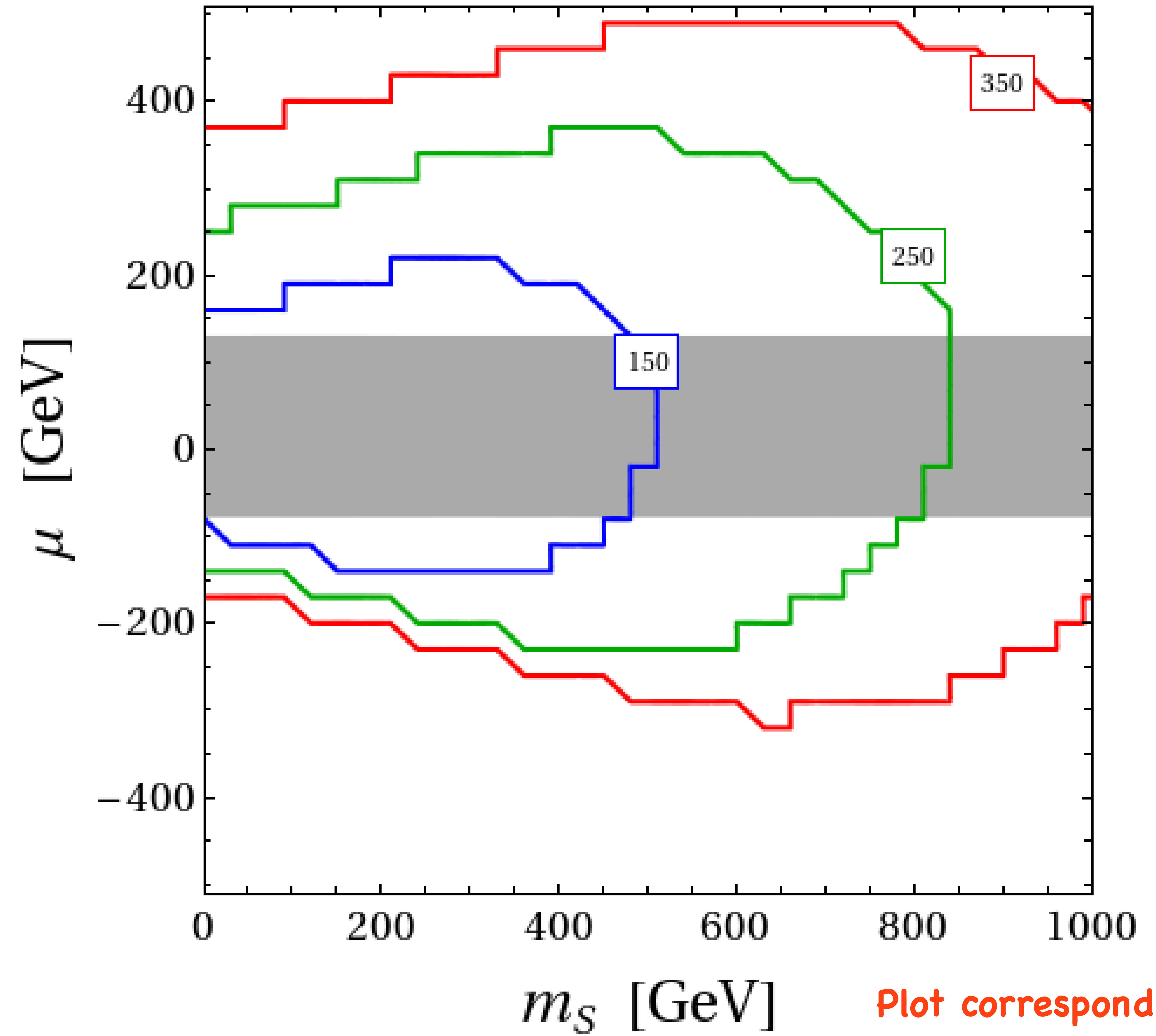


- Might be probed with 5fb^{-1} of data given lack of mass resolution... All three Higgs bosons appear as one

Closing Remarks

- Introduced two new dimension 5 operators to the MSSM and study their implications as a possible source of CP violation
  - Low $\tan\beta$ favorable with EDM constraints
  - Sizable couplings of Higgs bosons with weak gauge bosons
- BMSSM with CP violation leads to interesting signals in Higgs collider physics that will be probed very soon
  - Three Higgs bosons with significant branching ratios into WW
  - Three heavy Higgs bosons decaying primarily into $b\bar{b}$

Back-up Slides



$M = 2$ TeV

$\tan\beta = 2$

$|\alpha| = |\omega| = 1$

Plot corresponding to values for the charged Higgs mass of 150, 250 and 350 GeV