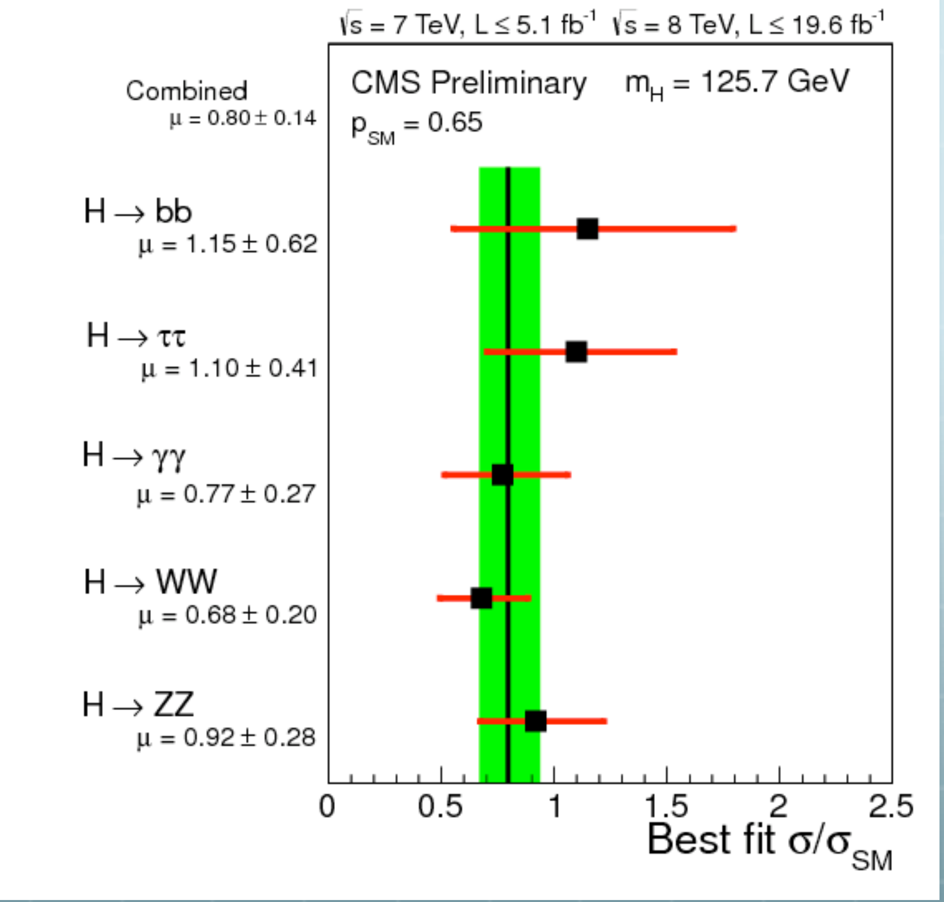
Higgs and Naturalness of EW scale

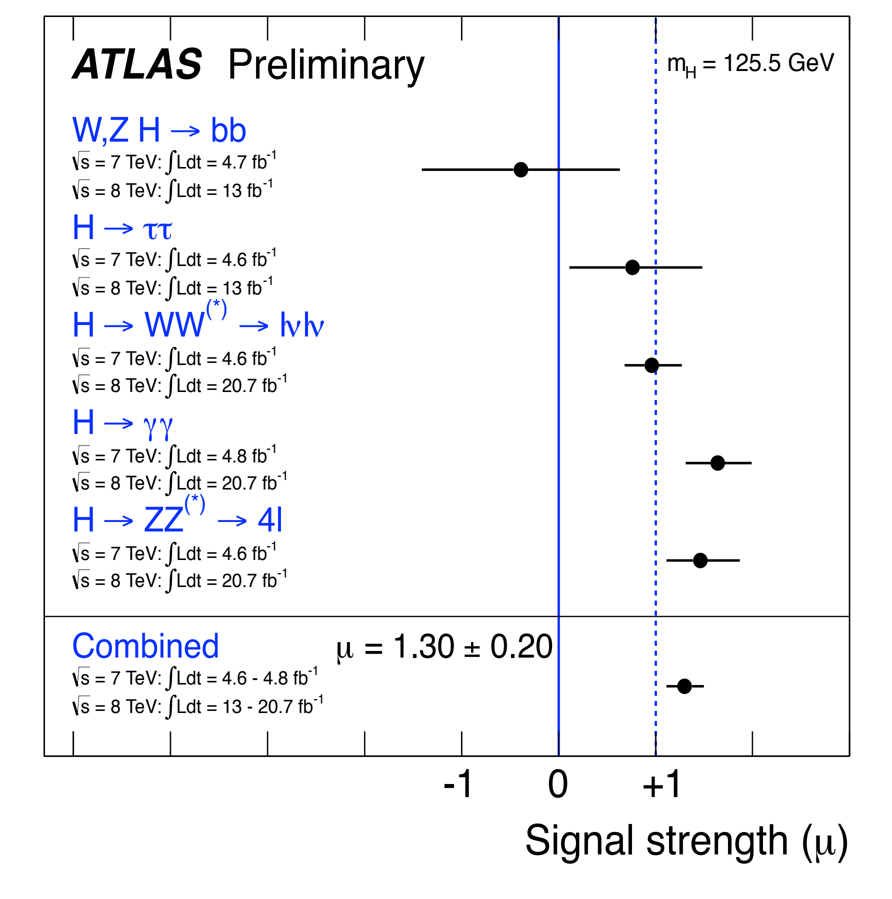
JiJi Fan
Harvard University

Kfir Blum, Raffaele D'Agnolo and JF, 1206.5303
Nima Arkani-Hamed, Kfir Blum, Raffaele D'Agnolo and JF 1207.4482
JF and Matthew Reece 1301.2597

Davis, 2013



$\sqrt{s}$ = 7 TeV, L ≤ 5.1 fb^{-1} $\sqrt{s}$ = 8 TeV, L ≤ 19.6 fb^{-1}
CMS Preliminary
m_H = 125.7 GeV
p_{SM} = 0.65
Combined
$\mu = 0.80 \pm 0.14$
$H \to bb$
$\mu = 1.15 \pm 0.62$
$H \to \tau\tau$
$\mu = 1.10 \pm 0.41$
$H \to \gamma\gamma$
$\mu = 0.77 \pm 0.27$
$H \to WW$
$\mu = 0.68 \pm 0.20$
$H \to ZZ$
$\mu = 0.92 \pm 0.28$
0 0.5 1 1.5 2 2.5
Best fit σ/σ_{SM}



ATLAS Preliminary
m_H = 125.5 GeV
W,Z H → bb
$\sqrt{s}$ = 7 TeV: ∫Ldt = 4.7 fb^{-1}
$\sqrt{s}$ = 8 TeV: ∫Ldt = 13 fb^{-1}
$H \to \tau\tau$
$\sqrt{s}$ = 7 TeV: ∫Ldt = 4.6 fb^{-1}
$\sqrt{s}$ = 8 TeV: ∫Ldt = 13 fb^{-1}
$H \to WW^{(*)} \to l\nu l\nu$
$\sqrt{s}$ = 7 TeV: ∫Ldt = 4.6 fb^{-1}
$\sqrt{s}$ = 8 TeV: ∫Ldt = 20.7 fb^{-1}
$H \to \gamma\gamma$
$\sqrt{s}$ = 7 TeV: ∫Ldt = 4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV: ∫Ldt = 20.7 fb^{-1}
$H \to ZZ^{(*)} \to 4l$
$\sqrt{s}$ = 7 TeV: ∫Ldt = 4.6 fb^{-1}
$\sqrt{s}$ = 8 TeV: ∫Ldt = 20.7 fb^{-1}
Combined
$\mu = 1.30 \pm 0.20$
$\sqrt{s}$ = 7 TeV: ∫Ldt = 4.6 - 4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV: ∫Ldt = 13 - 20.7 fb^{-1}
-1 0 +1
Signal strength (μ)

The big picture

- A neutral scalar boson at ~ 125 GeV;
- Currently the data is consistent with SM Higgs;
- Still room for 30% - 50% (large) deviations in the Higgs couplings;
- Options: SM Higgs, SUSY Higgs, composite Higgs…

Outline

- Implications of Higgs mass for BSM theories: SUSY
- Higgs couplings:

how could they be modified in BSM theories?

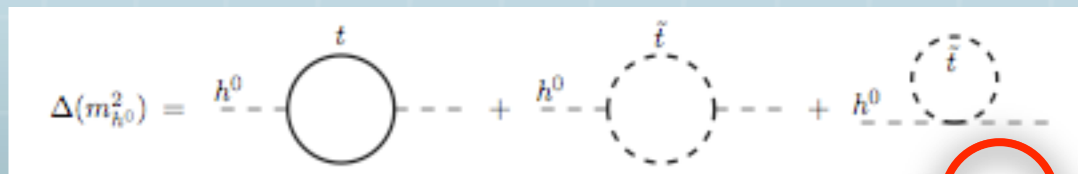
- Implications of Higgs couplings for naturalness of EW symmetry breaking
- Higgs – DM coupling
- CP violations

Higgs mass in SUSY

tree level:

$$
\begin{aligned}
V &= |F|^2 + |D|^2, \\
V &\supset \frac{1}{8}(g^2 + g'^2)(h_u^{02} + h_d^{02})^2
\end{aligned}
$$

1-loop level:



$$X_t \equiv A_t - \mu \cot\beta$$

Higgs-stop-stop trilinear coupling

$$m_h^2 = m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12 M_S^2}\right)\right)$$

$$\gtrsim (85\mathrm{GeV})^2$$

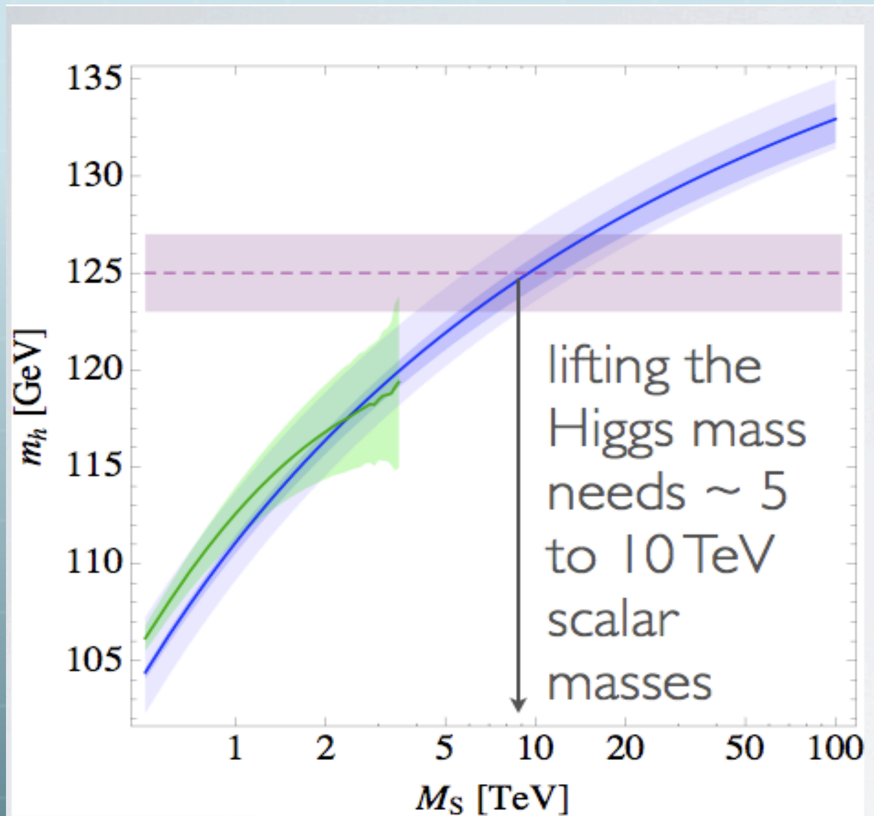
< (90 GeV)²

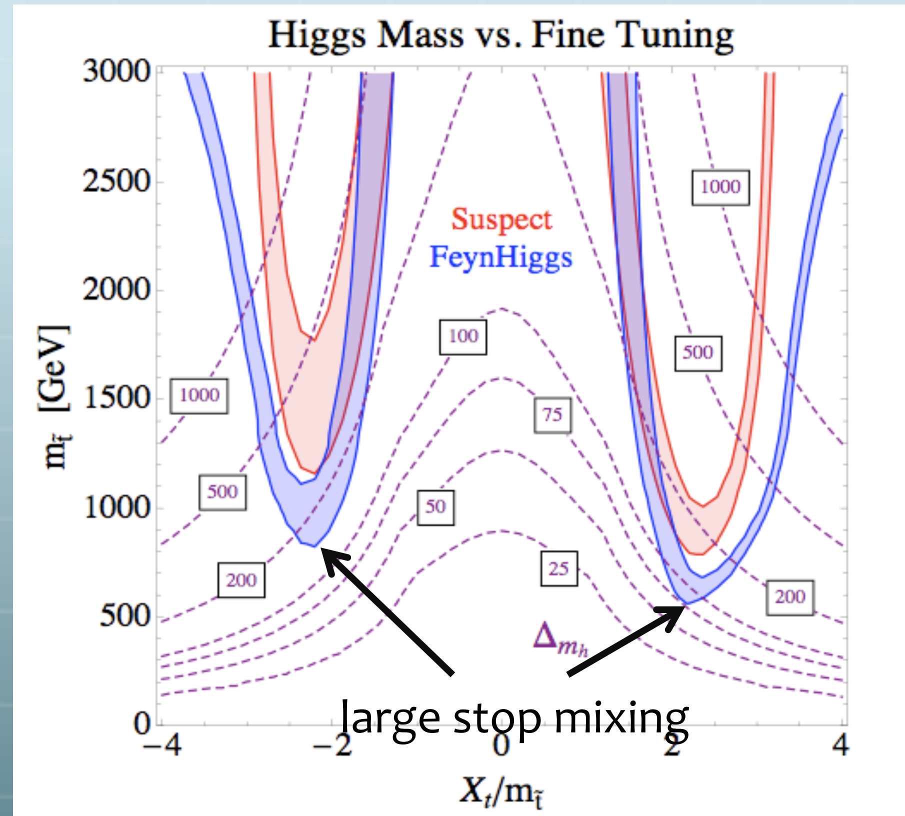
$$M_S \equiv \left(m_{\tilde{t}_1} m_{\tilde{t}_2}\right)^{1/2}$$

Higgs mass in SUSY

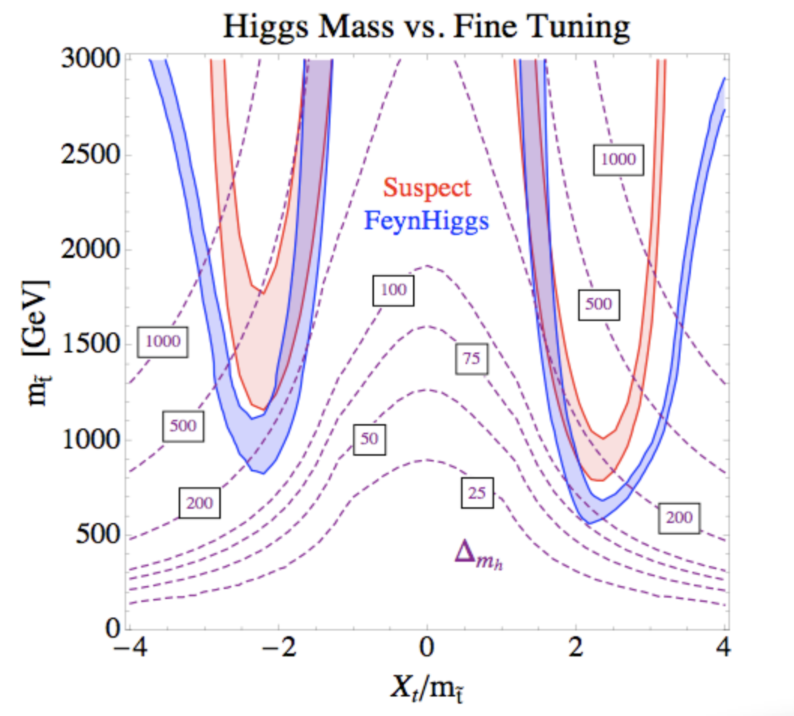
$$X_t \equiv A_t - \mu \cot\beta$$

$$m_h^2 = m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12 M_S^2}\right)\right)$$





Draper, Meade, Reece, Shih; Hall, Pinner, Ruderman, 2011; among many others



In MSSM, to get the Higgs mass to be 125 GeV, a large quantum correction must be introduced with multi-TeV SUSY breaking parameters;

the fine-tuning is worse than a few percent.
MSSM is tuned!!

$$|X_t| \gtrsim 1000 \text{ GeV}, \quad M_S \gtrsim 500 \text{ GeV}.$$

$$m_h^2 = m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right)$$

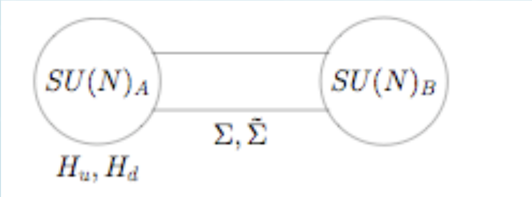
$$\gtrsim (85\text{GeV})^2$$

Barbieri, Giudice, 1988; Kitano, Murayama 2006

SUSY breaking mediation scale

$$(\Delta_Z^{-1})_{\tilde t} = \left|\frac{2\delta m_{H_u}^2}{m_h^2}\right|, \qquad \delta m_{H_u}^2|_{stop} = -\frac{3}{8\pi^2} y_t^2 \left(m_{Q_3}^2 + m_{u3}^2 + A_t^2\right) \log\left(\frac{\Lambda}{\text{TeV}}\right).$$

- **Beyond MSSM, one could add new tree level interactions to raise the Higgs mass and mitigates fine-tuning**
- **Non-decoupling D-term models**



Batra, Delgado, Kaplan and Tait 2004; Maloney, Pierce, Wacker 2004

- **F-term models**

$$W = SH_uH_d + f(S)$$

NMSSM, fat Higgs, λSUSY…

Outline

- Implications of Higgs mass for BSM theories: SUSY
- Higgs couplings:

How could they be modified?

- Implications of Higgs couplings for naturalness of EW symmetry breaking
- Higgs – DM coupling
- CP violations

Higgs couplings

- Radiative effect: hgg, hγγ couplings

  Low energy Higgs theorem: hgg, hγγ couplings are related to beta function coefficients (Shifman et.al)

Gauge theory

$$\mathcal{L} = -\frac{1}{4g^2} G^a_{\mu\nu} G^{a\mu\nu}$$

Run the gauge coupling from Λ to μ with an intermediate scale M, at which the beta function coef. changes from b to b+Δb

$$\frac{1}{g^2(\mu)} = \frac{1}{g^2(\Lambda)} + \frac{b}{8\pi^2}\log\frac{\Lambda}{\mu} + \frac{\Delta b}{8\pi^2}\log\frac{\Lambda}{M}$$

- **Suppose the intermediate mass threshold M is a function of the Higgs field M=M(h(x)) , one can extract from the gauge kinetic term the Higgs coupling**

$$\mathcal{L} = -\frac{1}{4g^2} G^a_{\mu\nu} G^{a\mu\nu} \qquad \frac{1}{g^2(\mu)} = \frac{1}{g^2(\Lambda)} + \frac{b}{8\pi^2} \log\frac{\Lambda}{\mu} + \frac{\Delta b}{8\pi^2} \log\frac{\Lambda}{M}$$

$M(h)|_{\langle h\rangle=v}$

$$\frac{\Delta b}{32\pi^2} \frac{h}{v} G^a_{\mu\nu} G^{a\mu\nu} \frac{\partial \log M(v)}{\partial \log v}$$

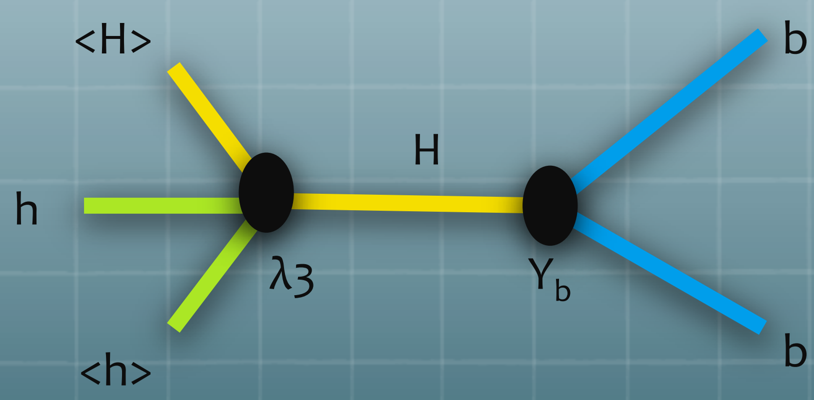
Any heavy matter with mass proportional to the Higgs VEV contribute with the same sign, whether it is a fermion or a scalar
Low energy Higgs theorem captures the leading log correction from new heavy mass threshold; there is finite mass correction, which is small

- **Mixing effect: h mixing with other scalars; new fermions mixing with the SM fermions** Gunion, Haber 2002

- **Example: type II 2HDM (where the second Higgs is heavy and large tan beta)**

$$\tan\beta = \frac{\langle H_2 \rangle}{\langle H_1 \rangle}$$

$$\begin{aligned}
-\mathcal{L} &= H_1^\dagger \mathcal{D}^2 H_1 + H_2^\dagger \mathcal{D}^2 H_2 + m_1^2 |H_1|^2 + m_2^2 |H_2|^2 \\
&+ \frac{\lambda_1}{2}|H_1|^4 + \frac{\lambda_2}{2}|H_2|^4 + \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 |H_1 \sigma_2 H_2|^2 \\
&+ \left\{ \frac{\lambda_5}{2}(H_1^\dagger H_2)^2 + (H_1^\dagger H_2)\left(m_{12}^2 + \lambda_6 |H_1|^2 + \lambda_7 |H_2|^2\right) \right. \\
&+ \left. Y_t H_2 \epsilon \bar{t}_R Q_{L3} + \left(Y_b H_1^\dagger - Y_b \Delta_b H_2^\dagger\right) \bar{b}_R Q_{L3} + \left(Y_\tau H_1^\dagger - Y_\tau \Delta_\tau H_2^\dagger\right) \bar{\tau}_R L_3 + h.c. \right\}
\end{aligned}$$



$$
\begin{aligned}
-\mathcal{L} &= H_1^\dagger \mathcal{D}^2 H_1 + H_2^\dagger \mathcal{D}^2 H_2 + m_1^2 |H_1|^2 + m_2^2 |H_2|^2 \\
&+ \frac{\lambda_1}{2}|H_1|^4 + \frac{\lambda_2}{2}|H_2|^4 + \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 |H_1 \sigma_2 H_2|^2 \\
&+ \left\{ \frac{\lambda_5}{2}(H_1^\dagger H_2)^2 + (H_1^\dagger H_2)\left(m_{12}^2 + \lambda_6 |H_1|^2 + \lambda_7 |H_2|^2\right) \right. \\
&+ \left. Y_t H_2 \epsilon \bar{t}_R Q_{L3} + \left(Y_b H_1^\dagger - Y_b \Delta_b H_2^\dagger\right) \bar{b}_R Q_{L3} + \left(Y_\tau H_1^\dagger - Y_\tau \Delta_\tau H_2^\dagger\right) \bar{\tau}_R L_3 + h.c. \right\}
\end{aligned}
$$

$$
r_b = \left(1 - \frac{m_h^2}{m_H^2}\right)^{-1} \left(1 - \frac{1}{1+\Delta_b \tan\beta}\left(\frac{\lambda_{35} v^2}{m_H^2 - m_h^2} - \frac{\lambda_7 v^2}{m_H^2}\tan\beta + \frac{m_h^2}{m_H^2}\Delta_b \tan\beta\right)\right) \times \left\{1 + \mathcal{O}\left(\frac{1}{\tan^2\beta}\right)\right\},
$$

$$
r_b = \frac{g_{hb\bar{b}}}{SM}
$$

dominant piece in many models

breaks PQ; can be subdominant

$$
\lambda_{35} = \lambda_3 + \lambda_5
$$

small if the potential is mostly type II 2HDM

Modification of hbbar coupling will change the rates of other channels simultaneously; e.g, a reduction of hbbar coupling will enhance diphoton and diboson rates simultaneously!

Outline

- Implications of Higgs mass for BSM theories: SUSY
- Higgs couplings:

How could they be modified?

- Implications of Higgs couplings for naturalness of EW symmetry breaking
- Higgs – DM coupling
- CP violations

Natural SUSY

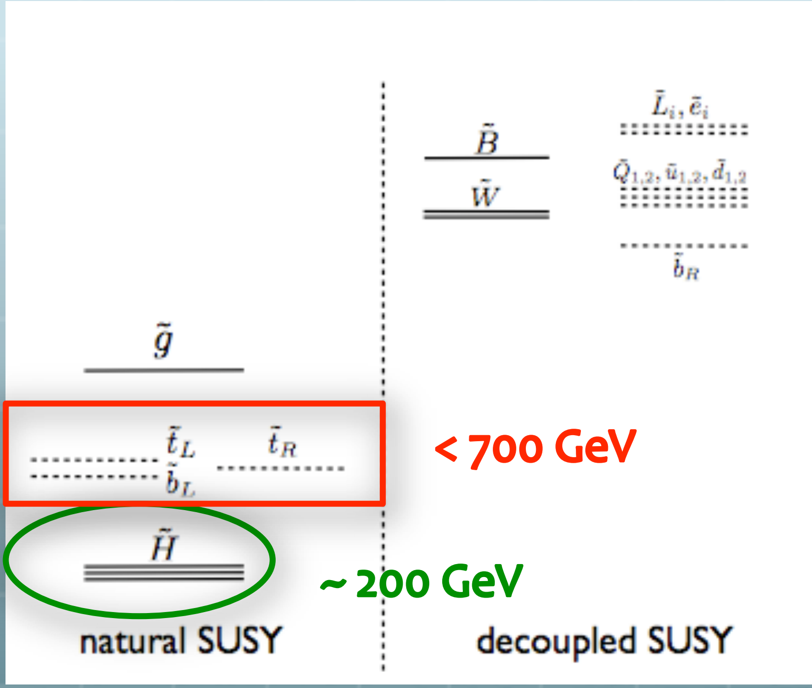
- Concrete questions: What are the predications of minimal natural and unnatural beyond SM theories? How large deviations in Higgs couplings they could obtain?

- Minimal natural SUSY:

- Beyond MSSM

interactions to raise the

Higgs mass



Assuming that Higgs sector is approximately 2HDM in the low energy, then all Higgs couplings are described by 4 parameters in natural scenario

$$\tan\beta, \quad r_b, \quad \left(0.6 < r_G^{\tilde{t}} < 1.6\right), \quad \left(0.7 < r_\gamma^{\tilde{\chi}^\pm} < 1.1\right)$$

suppress hbb coupling;
radiative effects from stops and charginos

$$\mu_{\gamma\gamma;GF} < 4.7 \text{ to } 6.2$$

$$\frac{\mu_{\gamma\gamma;GF}}{\mu_{WW,ZZ;GF}} < 1.4$$

radiative effects from stops and charginos

$$\frac{\mu_{\gamma\gamma;VBF}}{\mu_{\gamma\gamma;GF}} < 1.5$$

radiative effects from stops

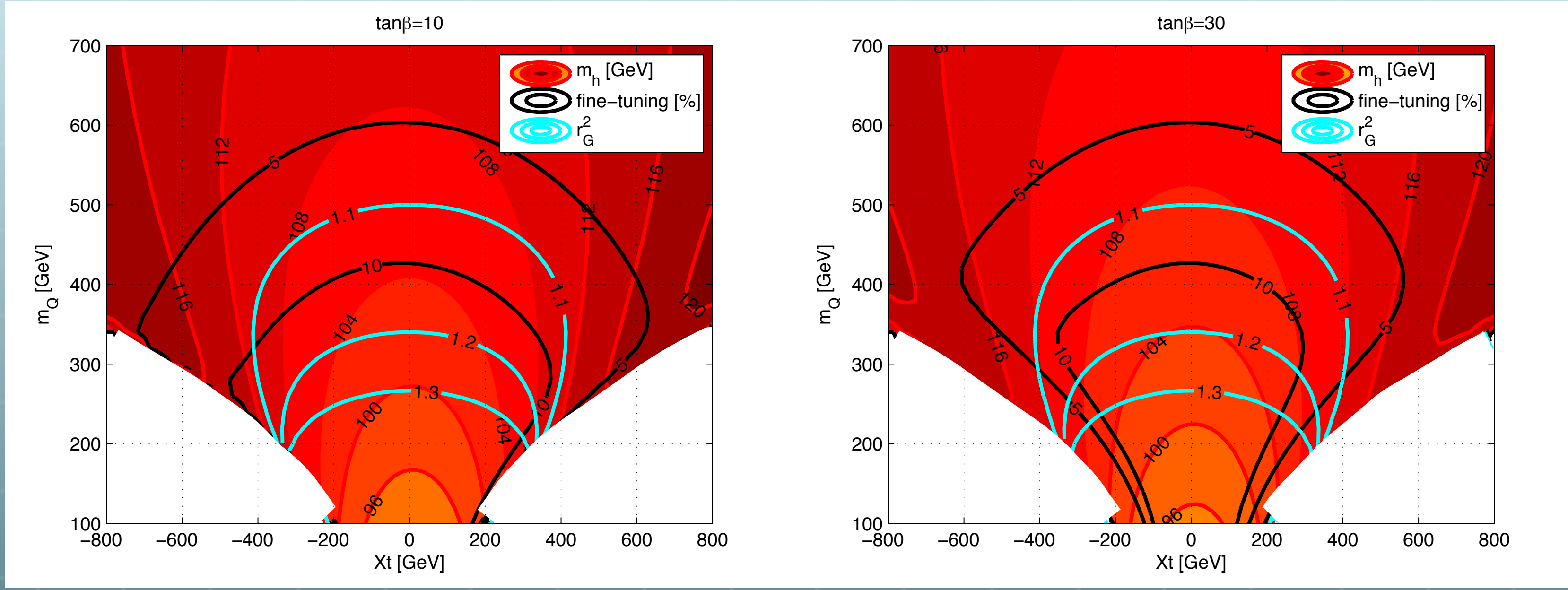
$$\mu_{bb;AP} < 1.5$$

enhance hbb coupling

Radiative effect: stop/chargino $\left(0.6 < r_G^{\tilde{t}} < 1.6\right)$

$$r_G^{\tilde{t}} \approx \frac{1}{4}\left(\frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{m_t^2}{m_{\tilde{t}_2}^2} - \frac{m_t^2 X_t^2}{m_{\tilde{t}_1}^2\, m_{\tilde{t}_2}^2}\right), \quad \text{stop contribution},$$

$$r_G^{\tilde{t}} \approx -3.65 r_\gamma^{\tilde{t}}$$



Large stop mixing and fine tuning in B to X_s γ

$$BR(B \to X_s\gamma)^{\text{exp}} = (3.52 \pm 0.25) \times 10^{-4}.$$

$$BR(B \to X_s\gamma)^{\text{SM}} = (2.98 \pm 0.26) \times 10^{-4}.$$

$$\mathcal{O}_7 = \frac{e}{16\pi^2} m_b \left(\bar{s}_L \sigma_{\mu\nu} b_R\right) F^{\mu\nu}, \quad \mathcal{O}_8 = \frac{g}{16\pi^2} m_b \left(\bar{s}_L \sigma_{\mu\nu} T^a b_R\right) G^{a\mu\nu}.$$

$$C_{7,8} \approx \frac{m_t^2 A_t \mu}{m_{\tilde{t}}^4} \mathcal{F}_{7,8}\left(\frac{m_{\tilde{t}_1}^2}{|\mu|^2}, \frac{m_{\tilde{t}_2}^2}{|\mu|^2}\right) \tan\beta,$$

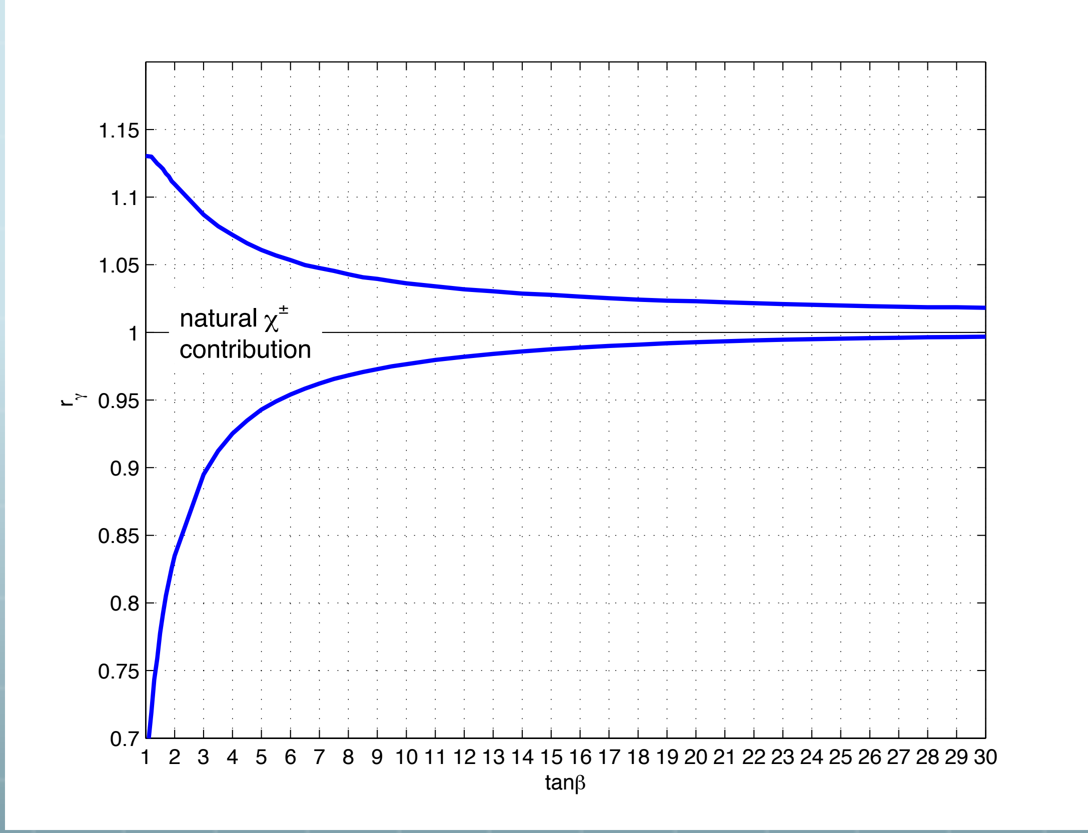
Fine tuning associated with accidental cancelation

$$\mathcal{O}_{bs\gamma} = \frac{BR(B \to X_s\gamma)^{\text{exp}}}{BR(B \to X_s\gamma)^{\text{SM}}} - 1 = 0.18 \pm 0.13.$$

$$\left[\Delta^{(P)}_{\mathcal{O}_{bs\gamma}}\right]^{-1} = \left|\frac{\mathcal{O}_{bs\gamma}}{\sigma_{\mathcal{O}_{bs\gamma}}} \frac{\partial \log \mathcal{O}_{bs\gamma}}{\partial \log P}\right| = \left|\frac{P}{0.3} \frac{\partial \mathcal{O}_{bs\gamma}}{\partial P}\right|,$$

uncertainty

chargino: Higgs diphoton coupling $0.7 < r_{\gamma}^{\tilde{\chi}^{\pm}} < 1.1$



$$\mathcal{L}_M = -\left(\psi^{+Q} \; \chi^{+Q}\right) \begin{pmatrix} m_\psi & \frac{yv}{\sqrt{2}} \\ \frac{y^c v}{\sqrt{2}} & m_\chi \end{pmatrix} \begin{pmatrix} \psi^{-Q} \\ \chi^{-Q} \end{pmatrix} + cc, \qquad y, y^c \longrightarrow g$$

Higgs mixing effect: type II 2HDM

$$r_b = \left(1 - \frac{m_h^2}{m_H^2}\right)^{-1} \left(1 - \frac{1}{1+\Delta_b \tan\beta}\left(\frac{\lambda_{35} v^2}{m_H^2 - m_h^2} - \frac{\lambda_7 v^2}{m_H^2}\tan\beta + \frac{m_h^2}{m_H^2}\Delta_b \tan\beta\right)\right) \times \left\{1 + \mathcal{O}\left(\frac{1}{\tan^2\beta}\right)\right\},$$

- **MSSM** $\lambda_{35} = -\frac{g^2 + g'^2}{4} \approx -0.14, \quad \lambda_5 = \lambda_6 = \lambda_7 = 0, \quad \Delta_b = \Delta_\tau = 0.$
- **Non-decoupling D-term (H_u , H_d are in vector-like representation of the new gauge group)**

$$V_D = \sum_G \frac{g_G^2}{2}\left(1 + \frac{g_A^2}{g_B^2}\frac{M_s^2}{M_V^2 + M_s^2}\right)\left(H_u^\dagger T_G^a H_u + H_d^\dagger T_G^a H_d\right)^2 \supset \frac{g^2(1+\Delta) + g'^2(1+\Delta')}{8}\left(|h_u^0|^2 - |h_d^0|^2\right)^2.$$

$$\lambda_{35} = \lambda_{35}^{\rm MSSM}\left(1 + \frac{g^2\Delta + g'^2\Delta'}{g^2 + g'^2}\right)$$

hbbar coupling is enhanced

Higgs mixing effect: type II 2HDM

$$r_b = \left(1 - \frac{m_h^2}{m_H^2}\right)^{-1} \left(1 - \frac{1}{1+\Delta_b \tan\beta}\left(\frac{\lambda_{35} v^2}{m_H^2 - m_h^2} - \frac{\lambda_7 v^2}{m_H^2}\tan\beta + \frac{m_h^2}{m_H^2}\Delta_b \tan\beta\right)\right) \times \left\{1 + \mathcal{O}\left(\frac{1}{\tan^2\beta}\right)\right\},$$

- **F-term models (Additional d.o.f could be integrated out, e.g. , λSUSY Hall, Pinner, Ruderman, 2011)**

$$V = V^{\rm MSSM} + |\lambda|^2 |H_u H_d|^2.$$

$$\lambda_{35} = \lambda_{35}^{\rm MSSM} + |\lambda|^2$$

hbbar coupling is suppressed

Caution: F-term models are more complicated: NMSSM with light singlet

Minimal BSM unnatural theory

- **Any fine-tuning should serve an ``environmental" purpose.**
- **Minimal beyond SM unnatural theory: SM+fermions**
- **Additional scalars or gauge bosons would introduce fine-tunings that do not have an ``anthropic" reason.**

- **Unnatural SUSY: all squarks and gluino are heavy;**

a few 10 TeV - 100 TeV —— $\tilde{q}$

A few TeV —— $\tilde{g}$

Split SUSY: Wells; Arkani-Hamed, Dimopoulos; Giudice and Romanino 2004

- **Example: Split SUSY that preserve two merits of natural SUSY: DM candidate (probably with a non-thermal history); gauge coupling unification**

- **In split SUSY, low energy effective theory does not contain new bosonic d.o.f up to a much higher scale >> 10 TeV**

Before Moroind 2013, there is a small tension between Higgs diphoton rate and split scenario

- **To get a diphoton enhancement >~ 1.5, one needs to have a light charged state with mass below 150 GeV and a very low cutoff below 10 TeV.**
- **This light charged state, if exists, is within reach of LHC 8 TeV running; at worst, 14 TeV running.**
- **Scalar degrees of freedom must kick in below or about 10 TeV to cure the theory**

Arkani-Hamed, Blum, D'Agnolo and JF 1207.4482

- Split SUSY or in general, theory with low-energy effective description containing only fermions + Higgs up to 10 TeV predicts the diphoton enhancement has to disappear!
- Alternatively, diphoton enhancement, if true, will rule out split SUSY and its variants
- Now diphoton enhancement is diminished given CMS' data

Outline

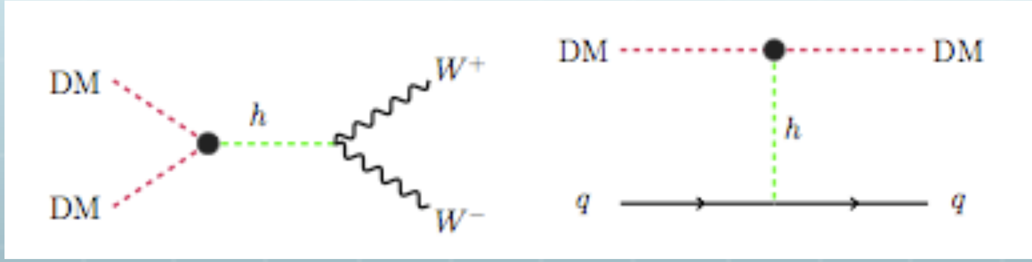
- Implications of Higgs mass for BSM theories: SUSY
- Higgs couplings:

how could they be modified in BSM theories?

- Implications of Higgs couplings for naturalness of EW symmetry breaking
- Higgs – DM coupling
- CP violations

Continuum constraint on induced Higgs-DM coupling: E.g., scalar DM model

$$\begin{aligned}\langle\sigma v\rangle &= \sum_{i=W,Z} n_i \frac{|\lambda_{\phi H}|^2}{2\pi m_\phi^2}\sqrt{1-\frac{m_i^2}{m_\phi^2}}\frac{m_i^4}{\left(4m_\phi^2-m_h^2\right)^2}\left(2+\frac{(2m_\phi^2-m_i^2)^2}{m_i^4}\right)\\ &= \left|\frac{\lambda_{\phi H}}{0.028}\right|^2 3\times10^{-26}\mathrm{cm}^3\mathrm{s}^{-1},\end{aligned}$$



Direct detection constraint

$$\begin{aligned}\sigma_{SI} &= \frac{|\lambda_{\phi H}|^2 m_n^4 f^2}{\pi m_h^4 m_\phi^2}\\ &= \left(\frac{\lambda_{\phi H}}{0.05}\right)^2 5\times10^{-45}\mathrm{cm}^2,\end{aligned}$$

Indirect detection and direct detection could probe DM-higgs coupling at the same level

- If the new physics that modifies Higgs couplings have order-one CP phases, EDM experiments could be more sensitive than measurements of Higgs coupling;
- I will use Higgs diphoton coupling as an illustrating example

Correlation between CP-even and CP-odd observables

A CP-odd version of low-energy theorem:

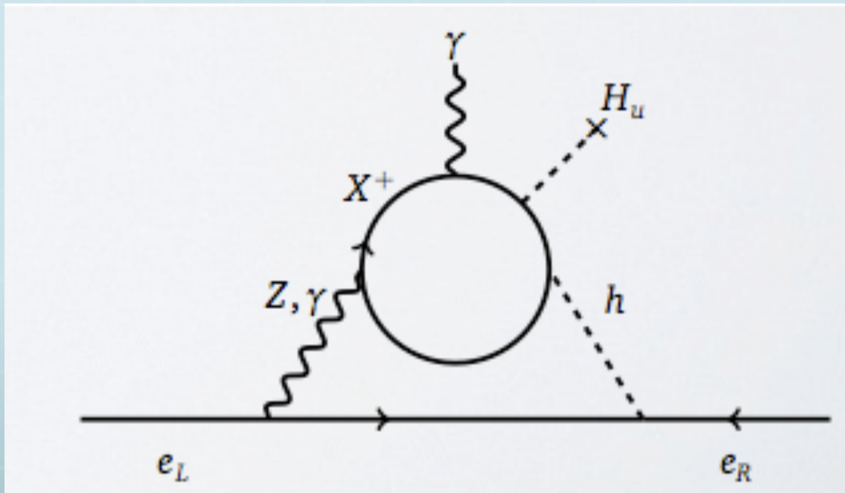
$$\frac{\alpha}{4\pi}\arg\det\mathcal{M}F_{\mu\nu}\tilde{F}^{\mu\nu} \to \frac{\alpha}{4\pi}\frac{\partial\arg\det\mathcal{M}}{\partial v}hF_{\mu\nu}\tilde{F}^{\mu\nu}$$

Higgs CP-violating decay (Voloshin 1208.4303); and CP-odd TGCs; more importantly, it results in EDM through the RGE mixing:

$$\frac{c}{\Lambda^2}H^\dagger HF_{\mu\nu}\tilde{F}^{\mu\nu} \text{ and } d_f LH\sigma_{\mu\nu}\bar{e}\tilde{F}^{\mu\nu}$$

$$\frac{d_f}{e} = -\frac{Q_f m_f c}{4\pi^2\Lambda^2}\log\frac{\Lambda^2}{m_h^2}$$

Bar-Zee type diagram



$$\mathcal{L}_M = -\left(\psi^{+Q}\ \chi^{+Q}\right)\begin{pmatrix} m_\psi & \frac{yv}{\sqrt{2}} \\ \frac{y^c v}{\sqrt{2}} & m_\chi \end{pmatrix}\begin{pmatrix}\psi^{-Q} \\ \chi^{-Q}\end{pmatrix} + cc,$$

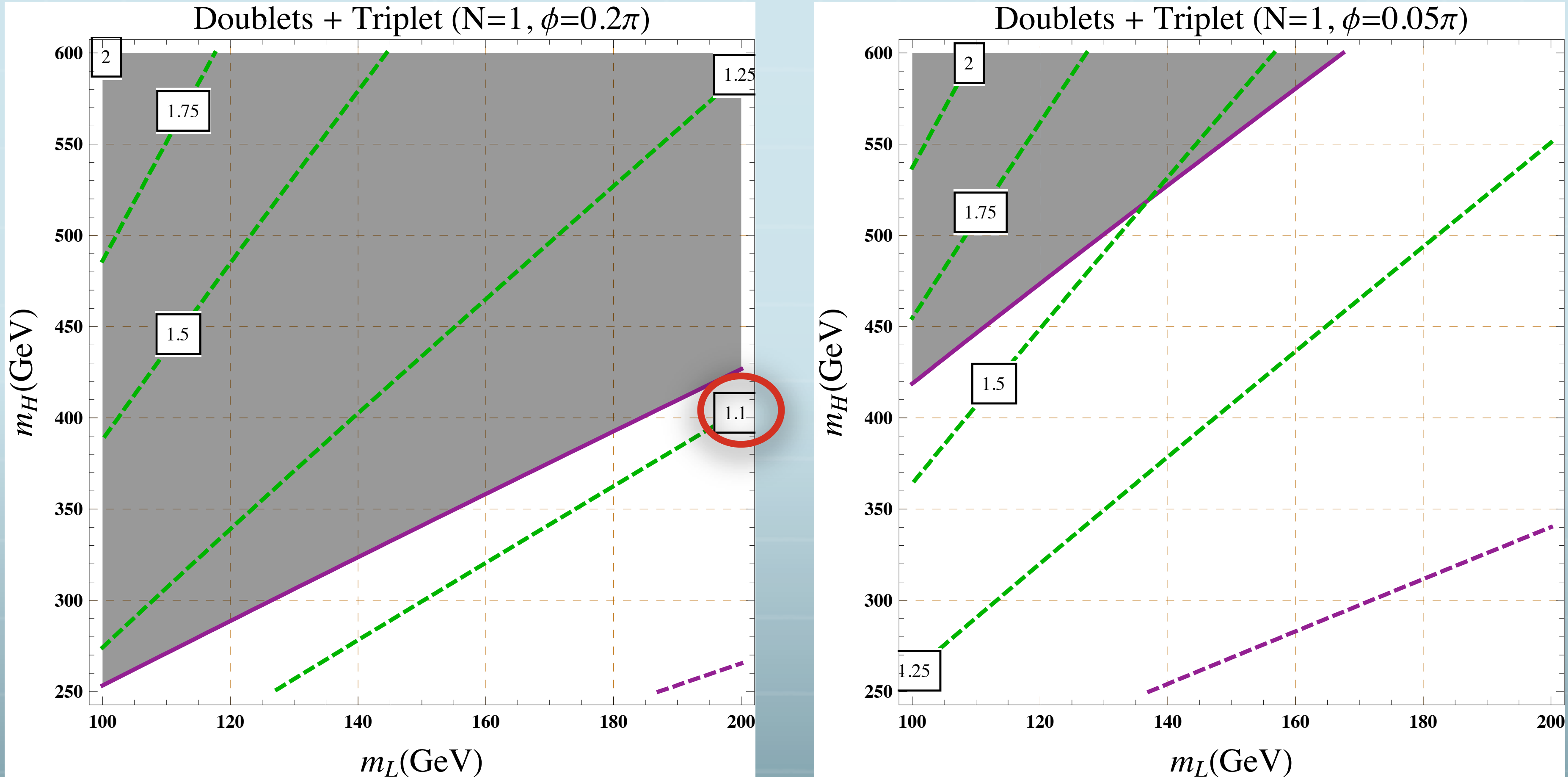
$$\phi = \arg\left(m_\psi^* m_\chi^* y y^c\right)$$

$$\frac{c}{\Lambda^2} H^\dagger H F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$c = \frac{\alpha}{4\pi} y y^c \sin\phi; \Lambda^2 = m_\psi m_\chi$$

$$\frac{d_e}{e} < 10^{-27}\,\mathrm{cm} \to \Lambda \geq 700\mathrm{GeV}\sqrt{\frac{yy^c\sin\phi}{1}}$$

In split context:
Arkani-Hamed, Dimopoulous, Giudice, Romanino; ...
Recently, McKeen, Pospelov and Ritz 1208.4597;
Fan and Reece 1301.2597;



Solid purple: $d_e/e = 1.05\ 10^{-27}$ cm;
dashed purple: $d_e/e = 10^{-28}$ cm

For order one phase, EDM bounds the diphoton rate to be <~ 1.1 SM value;

To evade current EDM and have diphoton enhancement ~ 1.5, the physical CP phase has to be small <~ 0.1; -> Higgs CP problem!
(An order one phase will be ruled out unless a few percent tuning is evoked)

In general, given new physics that modifies Higgs physics could be associated with order one CP phase, EDM experiments could indirectly constrain the size of Higgs coupling modifications.

The ACME collaboration (Yale-Harvard group) will potentially improve the bound by an order of magnitude in a few years or measure it!

Conclusion

- Higgs couplings would be a powerful indirect probe of beyond SM physics!
- Higgs coupling modifications in both natural SUSY and unnatural SUSY could be small
- EDM experiments could be an important constraint on Higgs physics as well!

Thank you!