The SM- Like Higgs *Alignment* & the *W* Mass

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Physics Beyond the SM
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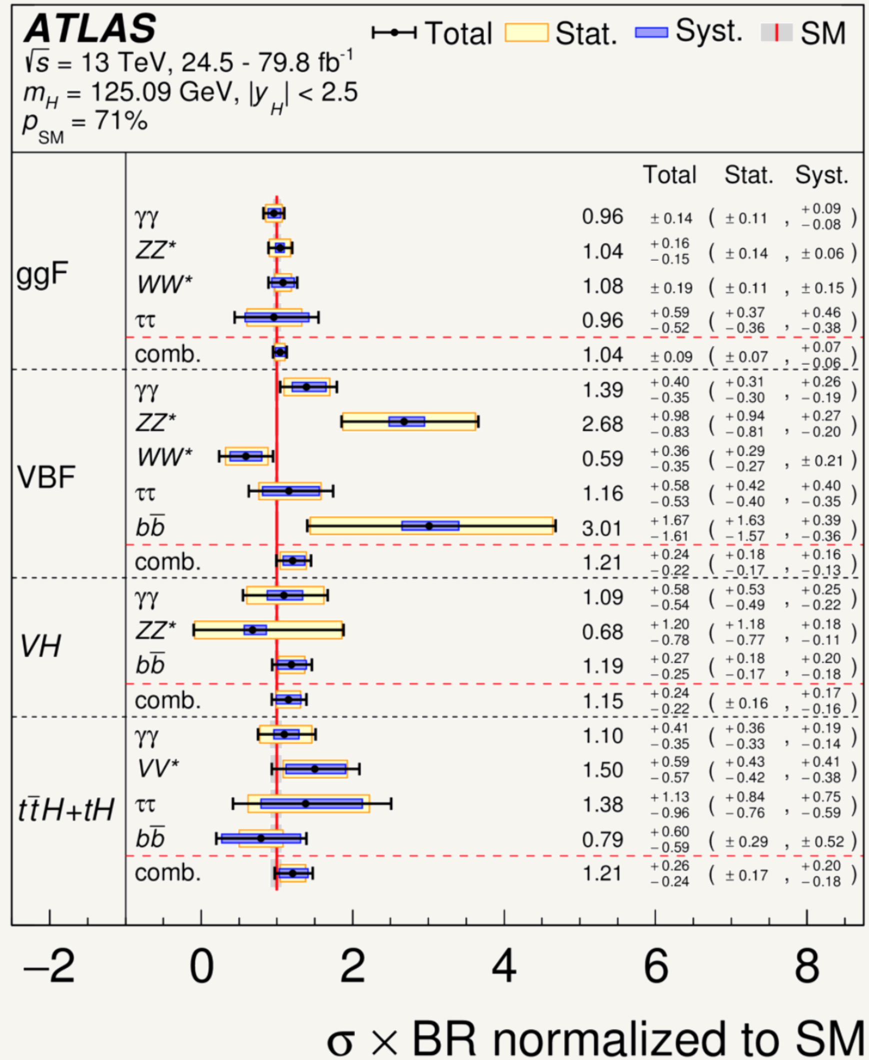
Still large uncertainties in couplings…
but compatible with SM expectations.

125 GeV SM-Like Higgs

Observed Higgs
Production x Branching Ratios
as a ratio to SM expectation



Beyond the Standard Model with the Higgs.

SM Higgs is a Doublet

- The Higgs *FIELD* is a two component weakly charged doublet.
- h is the neutral particle we think we have observed at the LHC: h_{125}
- v is the SM vev: 174 GeV.
- $G^{+/-}$ and G^0 are "eaten" by the W and Z gauge bosons to give them mass.

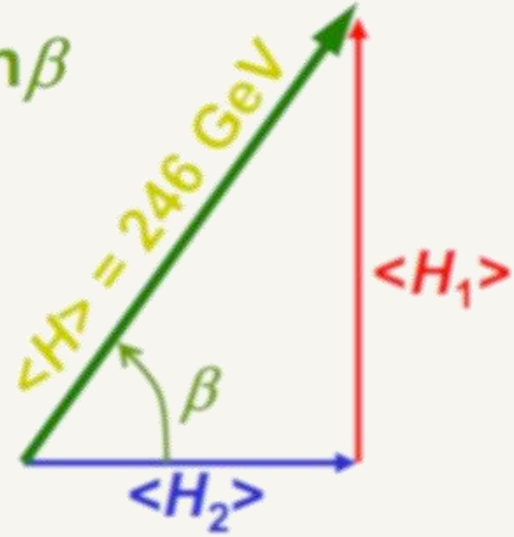
$$H_{SM} = \begin{bmatrix} G^{\pm} \\ \frac{1}{\sqrt{2}}(h + iG^0) + v \end{bmatrix}$$

What if there were more???

But we SEE a SM-like Higgs!

2 Higgs Doublet Model (2HDM).

$\langle H_1 \rangle$, $\langle H_2 \rangle$ → $\langle H \rangle$, $\tan\beta$



In SUSY Need 2 Higgs doublets:

H_u –Couples only to up-type quarks

H_d –Couples only to down-type quarks and leptons.

$$m_A \sim m_H$$

$$\tan\beta = v_u / v_d$$

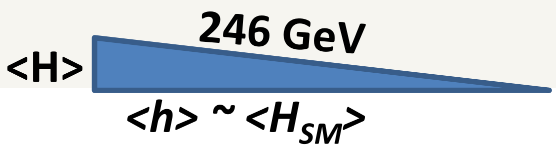
5 Physical Higgs bosons:

CP-Even: **h, H**

CP-Odd: **A**

Charged Higgs: **$H^{+,-}$**

SM-Like Higgs.



$v \sin^2 \beta$

$$H_{SM} = \sin\beta H_u + \cos\beta H_d$$
$$H_{NSM} = -\cos\beta H_u + \sin\beta H_d$$

$v \cos^2 \beta$

SM: Only 1 Higgs which then acquires a vev and leads to EWSB.

This is what we want!

Lighter (*h*) is 125 GeV SM-like Higgs.

Additional states can exist!

Additional States can be light!

Haber and Gunion, '03, *M. Carena, I. Low, N.R.S. & C. Wagner, '13, A. Delgado, G. Nardini & M. Quiros, '13, N. Craig, J. Galloway & S. Thomas,'13, P. Dev, A. Pilaftsis '14, M. Carena, H. Haber, I. Low, N.R.S. & C. Wagner '14 & '15 etc....*

$\langle H_d \rangle = v \cos\beta$

$\langle H_u \rangle = v \sin\beta$

$\Rightarrow \langle H_{SM} \rangle = v$

$\langle H_{NSM} \rangle = 0$

SM-like HIGGS

ALIGNMENT

Higgs Basis

$$H_{SM} = \sin\beta H_u + \cos\beta H_d$$
$$H_{NSM} = -\cos\beta H_u + \sin\beta H_d$$

SM-Like Higgs: h_{125}

$c_{\beta-\alpha} << 1$, $s_{\beta-\alpha} \approx 1$

$$\mathcal{V} \supset \ldots + \tfrac{1}{2} Z_1 (H_1^\dagger H_1)^2 + \ldots + \left[Z_5 (H_1^\dagger H_2)^2 + Z_6 (H_1^\dagger H_1) H_1^\dagger H_2 + \text{h.c.}\right] + \ldots$$

$$Z_1 \equiv \lambda_1 c_\beta^4 + \lambda_2 s_\beta^4 + \tfrac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5) s_{2\beta}^2 + 2 s_{2\beta}\left[c_\beta^2 \lambda_6 + s_\beta^2 \lambda_7\right],$$
$$Z_5 \equiv \tfrac{1}{4} s_{2\beta}^2 \left[\lambda_1 + \lambda_2 - 2(\lambda_3 + \lambda_4 + \lambda_5)\right] + \lambda_5 - s_{2\beta} c_{2\beta}(\lambda_6 - \lambda_7),$$
$$Z_6 \equiv -\tfrac{1}{2} s_{2\beta}\left[\lambda_1 c_\beta^2 - \lambda_2 s_\beta^2 - (\lambda_3 + \lambda_4 + \lambda_5) c_{2\beta}\right] + c_\beta c_{3\beta} \lambda_6 + s_\beta s_{3\beta} \lambda_7 .$$

λ_i : Z_2 Quartics

(Fermion couplings defined)

$Z_1 v^2$ ~ (125 GeV)^2

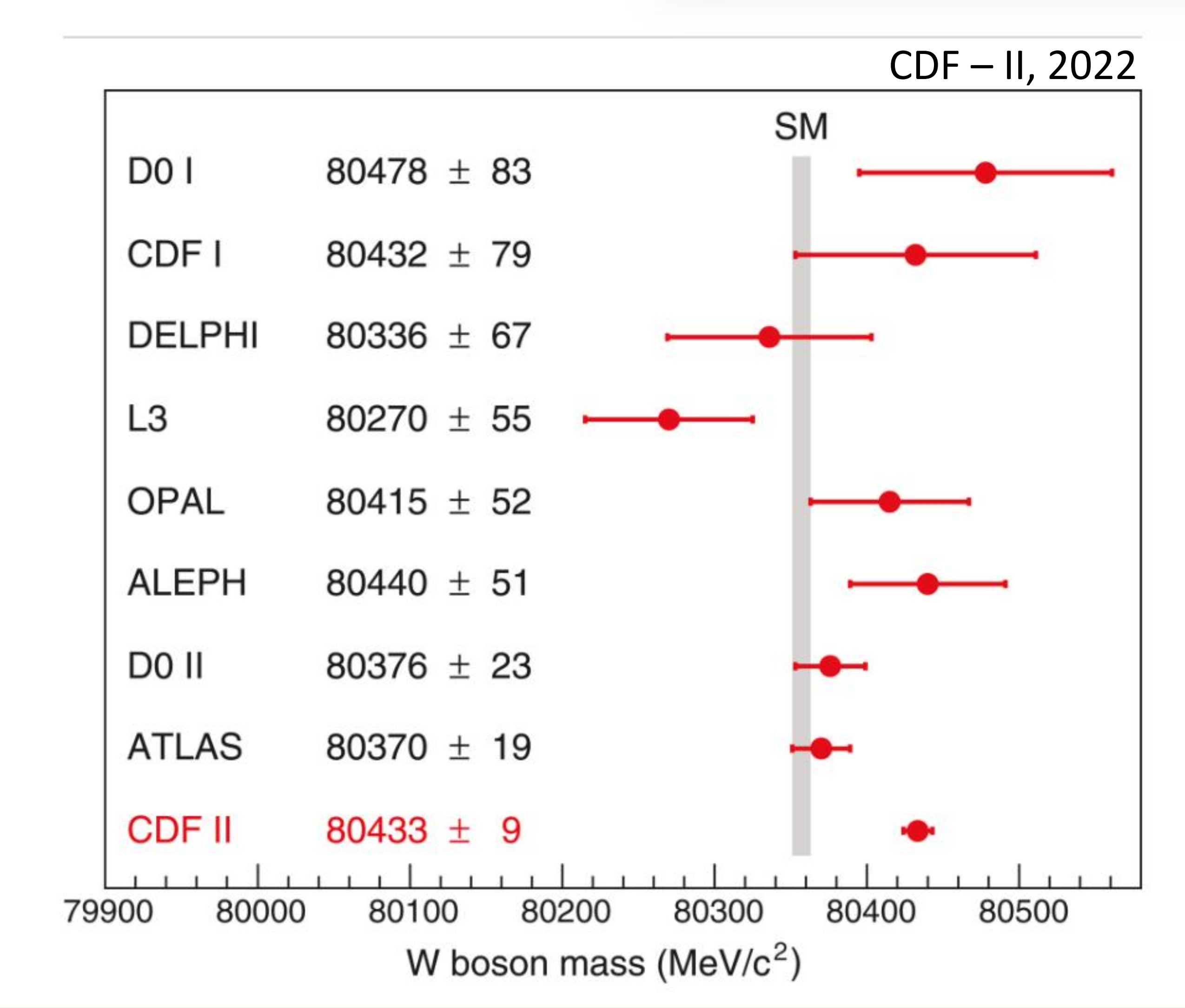
$Z_6 v^2$ controls mixing

m_A ~ mass of heavy Higgs

$$\mathcal{M}_H^2 = \begin{pmatrix} Z_1 v^2 & Z_6 v^2 \\ Z_6 v^2 & m_A^2 + Z_5 v^2 \end{pmatrix}$$

THE W MASS

Recent CDF result: 7-σ (!!!) discrepancy with the SM



W Mass

$$\rho \equiv \frac{G_F^{NC}}{G_F} = \frac{M_W^2}{M_Z^2 c_W^2} = 1 + \delta\rho \,.$$

Difference in G_F between neutral and charged processes

SM contributions (including h_{125}) calculated to 4-5 loops

Eg SM diagrams (Erler & Schott, 2019).

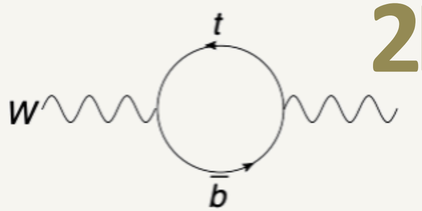
$$M_W = 80,357 \pm 4_{\text{inputs}} \pm 4_{\text{theory}} \text{ MeV}$$

SM from PDG

New CDF – II value:

$$M_W = 80,433.5 \pm 6.4_{\text{stat}} \pm 6.9_{\text{syst}} = 80,433.5 \pm 9.4 \text{ MeV}$$

2HDM Custodial Symmetry Breaking?

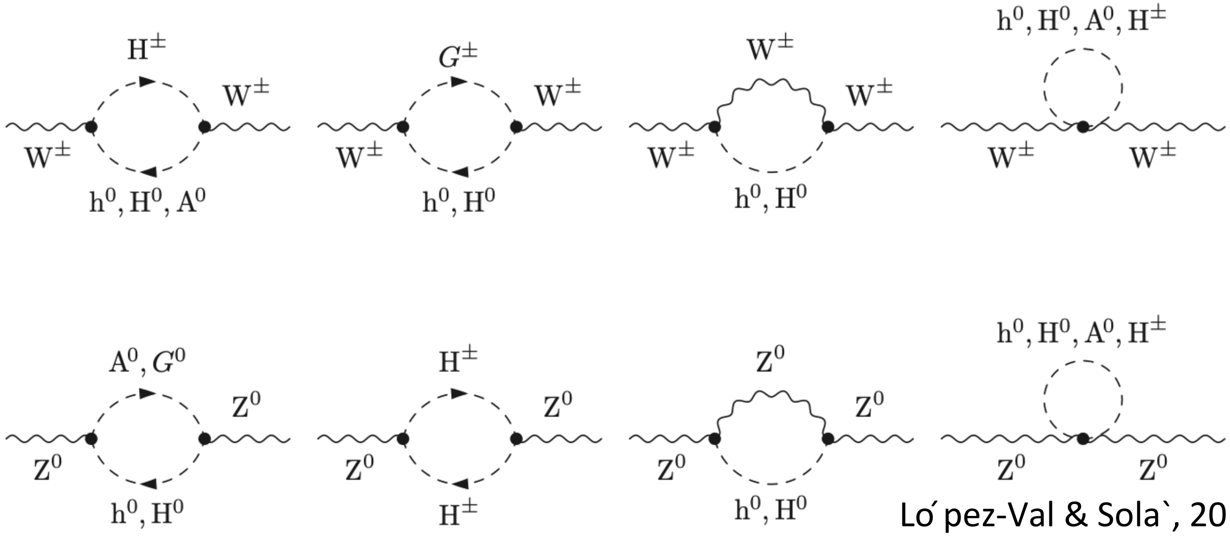


$$\delta\rho_{\rm 2HDM} = \frac{\alpha}{16\pi s_w^2 M_W^2} \left\{ \cos^2(\beta-\alpha)\left[F(M_{h^0}^2, M_{H^\pm}^2) - F(M_{h^0}^2, M_{A^0}^2)\right] \right.$$

$$+ \sin^2(\beta-\alpha)\left[F(M_{H^0}^2, M_{H^\pm}^2) - F(M_{H^0}^2, M_{A^0}^2)\right] + F(M_{A^0}^2, M_{H^\pm}^2)$$

$$\left. -3\cos^2(\beta-\alpha)\left[F(M_{H^0}^2, M_W^2) - F(M_{h^0}^2, M_Z^2) - F(M_{H^0}^2, M_Z^2) - F(M_{h^0}^2, M_W^2)\right] \right\},$$

$$F(x,y) = F(y,x) = \begin{cases} \frac{x+y}{2} - \frac{xy}{x-y}\log(\frac{x}{y}) & x \neq y \\ 0 & x = y \end{cases}.$$



López-Val & Solà, 2013

$\Delta\rho$ in the Alignment Limit

$$\delta\rho_{2\mathrm{HDM}} = \frac{G_F}{8\sqrt{2}\pi^2}\left\{F(M_{H^0}^2, M_{H^\pm}^2) - F(M_{H^0}^2, M_{A^0}^2) + F(M_{A^0}^2, M_{H^\pm}^2)\right\}.$$

$$\Delta M_{H^\pm H^0}^2 = M_{H^0}^2 - M_{H^\pm}^2 \quad (Z_4 + Z_5)\, v^2/2$$

$$\Delta M_{H^\pm A^0}^2 = M_{A^0}^2 - M_{H^\pm}^2 = (Z_4 - Z_5)\, v^2/2$$

$$= \frac{G_F}{8\sqrt{2}\pi^2}\frac{(Z_4^2 - Z_5^2)\, v^4}{12 M_{H^\pm}^2}\left(1 - \frac{Z_4 v^2}{4 M_{H^\pm}^2} + \frac{(Z_4^2 - Z_5^2)\, v^4}{40 M_{H^\pm}^4}\right).$$

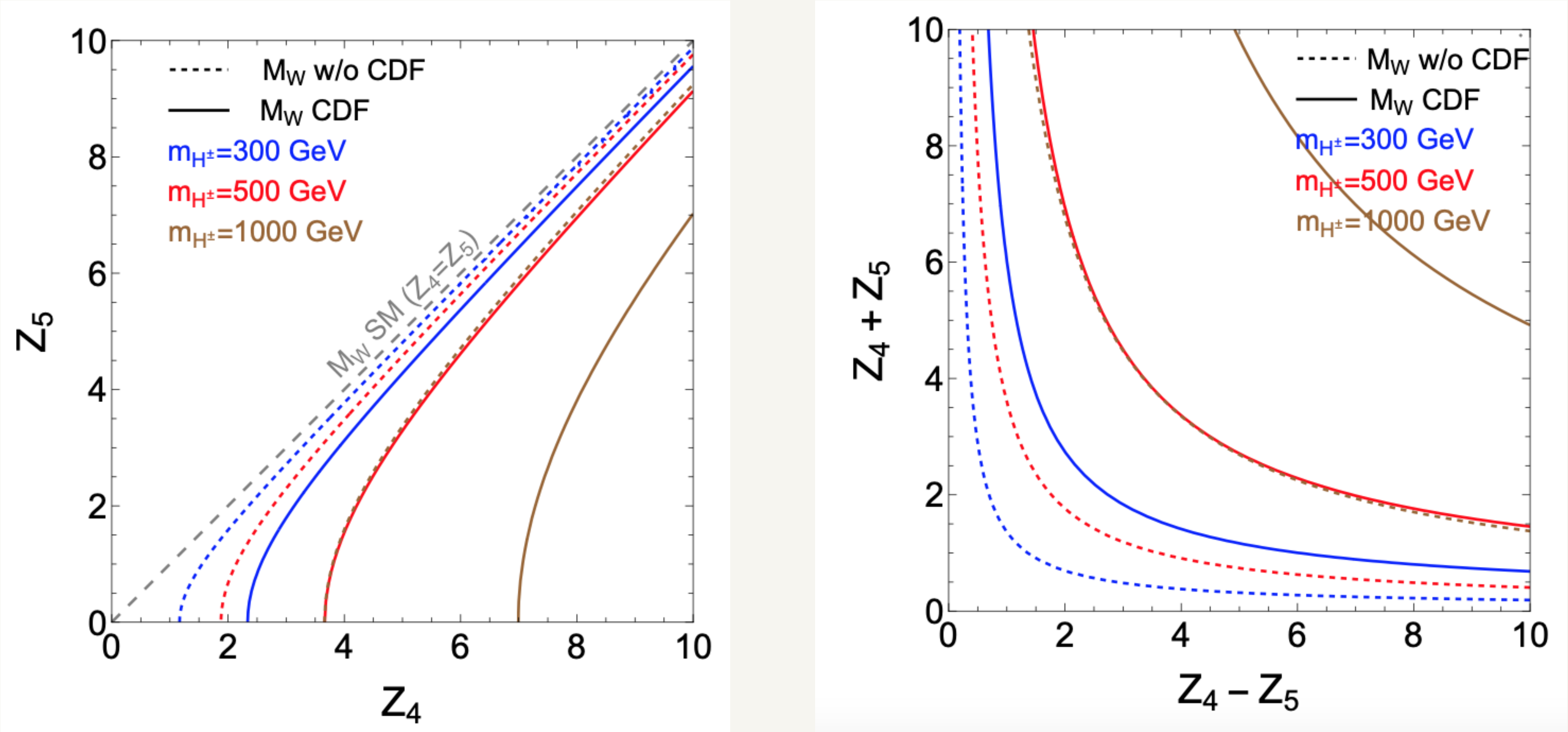
$$\mathcal{V} = Y_1 H_1^\dagger H_1 + Y_2 H_2^\dagger H_2 + \left[Y_3 H_1^\dagger H_2 + h.c.\right]$$
$$+ \frac{Z_1}{2}(H_1^\dagger H_1)^2 + \frac{Z_2}{2}(H_2^\dagger H_2)^2 + Z_3(H_1^\dagger H_1)(H_2^\dagger H_2) + Z_4(H_1^\dagger H_2)(H_2^\dagger H_1)$$
$$+ \left[\frac{Z_5}{2}(H_1^\dagger H_2)^2 + Z_6(H_1^\dagger H_1)(H_1^\dagger H_2) + Z_7(H_2^\dagger H_2)(H_1^\dagger H_2) + h.c.\right].$$

(125 GeV)^2

0 = Alignment

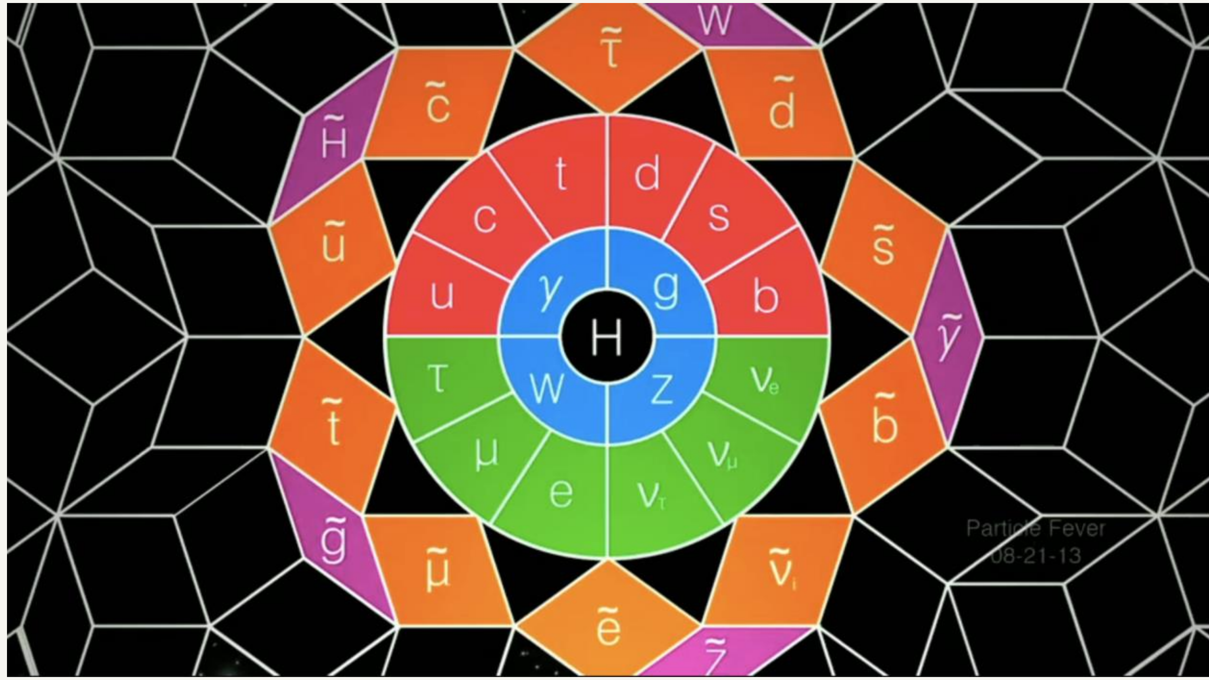
Parameters of our Ignorance

Preliminary, M. Carena, I. Low, NRS, C. Wagner, X. Wang



H_{125} mass and couplings **independent** of Heavy Higgs mass and W mass contributions.

“Particle Fever” – The movie



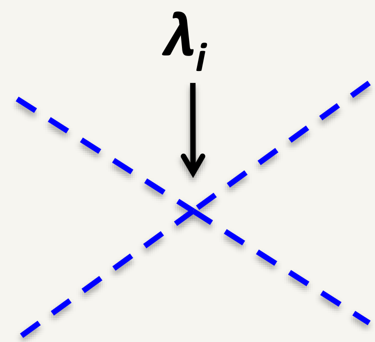
NOTORIOUS

SUPERSYMMETRY

Higgs Mass = 125 GeV.

$$V = m_{ij}^2 \Phi_i^\dagger \Phi_j + \lambda_i \Phi_j^\dagger \Phi_k \Phi_l^\dagger \Phi_m$$

H. Haber and J. Gunion, '03



Quartics without quantum corrections related only to SM couplings.

Higgs mass bounded by m_Z at tree-level.

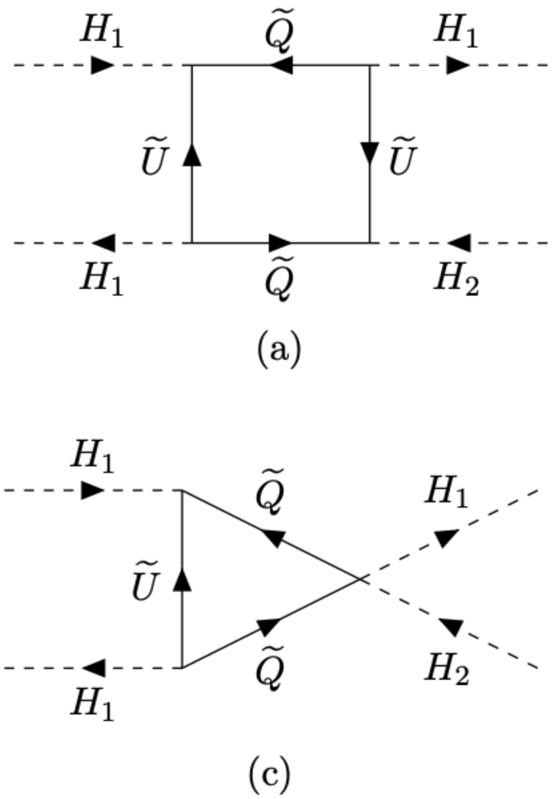
91 ≠ 125

MSSM

Need large radiative corrections.
…Stops…?

M. Carena, H. Haber, I. Low, NRS , & C. Wagner, 2014

Eg contributions to Z_6



$$\mathscr{L}_{\rm int} \supset h_t \epsilon_{ij}\left[(s_\beta X_t H_1^i + c_\beta Y_t H_2^i)\widetilde{Q}^j \widetilde{U} + {\rm h.c.}\right]$$
$$-h_t^2\left\{\left[s_\beta^2|H_1|^2 + c_\beta^2|H_2|^2 + s_\beta c_\beta(H_1^\dagger H_2 + {\rm h.c.})\right](\widetilde{Q}^\dagger\widetilde{Q} + \widetilde{U}^*\widetilde{U})\right.$$
$$\left. -s_\beta^2|\widetilde{Q}^\dagger H_1|^2 - c_\beta^2|\widetilde{Q}^\dagger H_2|^2 - s_\beta c_\beta\left[(\widetilde{Q}^\dagger H_1)(H_2^\dagger \widetilde{Q}) + {\rm h.c.}\right]\right\},$$

$$X_t \equiv A_t - \mu^*/t_\beta\,, \qquad Y_t \equiv A_t + \mu^* t_\beta\,.$$

$$Z_1 v^2 = m_Z^2 c_{2\beta}^2 + \frac{3v^2 s_\beta^4 h_t^4}{8\pi^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right],$$

$$Z_2 v^2 = m_Z^2 c_{2\beta}^2 + \frac{3v^2 c_\beta^4 h_t^4}{8\pi^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{Y_t^2}{M_S^2}\left(1 - \frac{Y_t^2}{12M_S^2}\right)\right],$$

$$Z_3 v^2 = \tfrac{1}{4}(g^2 - g'^2)v^2 + s_{2\beta}^2\left\{m_Z^2 + \frac{3v^2 h_t^4}{32\pi^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{(X_t+Y_t)^2}{4M_S^2} - \frac{X_t^2 Y_t^2}{12M_S^4}\right]\right\},$$

$$Z_4 v^2 = \tfrac{1}{2}g^2 v^2 + s_{2\beta}^2\left\{m_Z^2 + \frac{3v^2 h_t^4}{32\pi^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{(X_t+Y_t)^2}{4M_S^2} - \frac{X_t^2 Y_t^2}{12M_S^4}\right]\right\},$$

$$Z_5 v^2 = s_{2\beta}^2\left\{m_Z^2 + \frac{3v^2 h_t^4}{32\pi^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t Y_t}{M_S^2}\left(1 - \frac{X_t Y_t}{12M_S^2}\right)\right]\right\},$$

$$Z_6 v^2 = -s_{2\beta}\left\{m_Z^2 c_{2\beta} - \frac{3v^2 s_\beta^2 h_t^4}{16\pi^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t(X_t+Y_t)}{2M_S^2} - \frac{X_t^3 Y_t}{12M_S^4}\right]\right\},$$

$$Z_7 v^2 = s_{2\beta}\left\{m_Z^2 c_{2\beta} + \frac{3v^2 c_\beta^2 h_t^4}{16\pi^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{Y_t(X_t+Y_t)}{2M_S^2} - \frac{X_t Y_t^3}{12M_S^4}\right]\right\}.$$

Leading order contributions

Preliminary, M. Carena, I. Low, NRS, C. Wagner, X. Wang

Relevant for W mass (too small!!):

$$(Z_4 - Z_5)v^2 = \tfrac{1}{2}g^2 v^2 + s_{2\beta}^2 \frac{3v^2 h_t^4}{32\pi^2}\frac{(X_t - Y_t)^2}{4M_S^2} = \tfrac{1}{2}g^2 v^2 + \frac{3v^2 h_t^4}{32\pi^2}\frac{\mu^2}{M_S^2}$$

Direct Stops and W Mass

Preliminary, M. Carena, I. Low, NRS, C. Wagner, X. Wang

$$m^2_{\tilde{t}_{1,2}} = M_S^2 + m_t^2 \pm m_t X_t.$$

$$\delta\rho_{\tilde{t}} = \frac{3G_F}{4\sqrt{2}\pi^2}\left(c_t^2 F(M^2_{\tilde{t}_1}, M^2_{\tilde{b}_1}) + s_t^2 F(M^2_{\tilde{t}_2}, m^2_{\tilde{b}_1}) - s_t^2 c_t^2 F(M^2_{\tilde{t}_1}, M^2_{\tilde{t}_2})\right)$$

$$(\delta M_W)_{\tilde{t}} = \frac{G_F}{8\sqrt{2}\pi^2}\frac{m_t^4}{M_S^2}\frac{c_w^2}{c_w^2 - s_w^2}\left(1 - \frac{X_t^2}{2M_S^2} + \frac{X_t^4}{10M_S^4}\right) M_W.$$

$$(\delta M_W)_{\tilde{t}} \sim 9\ \mathrm{MeV}\frac{1}{M_S^2[\mathrm{TeV}^2]}\left(1 - \frac{X_t^2}{2M_S^2} + \frac{X_t^4}{10M_S^4}\right)$$

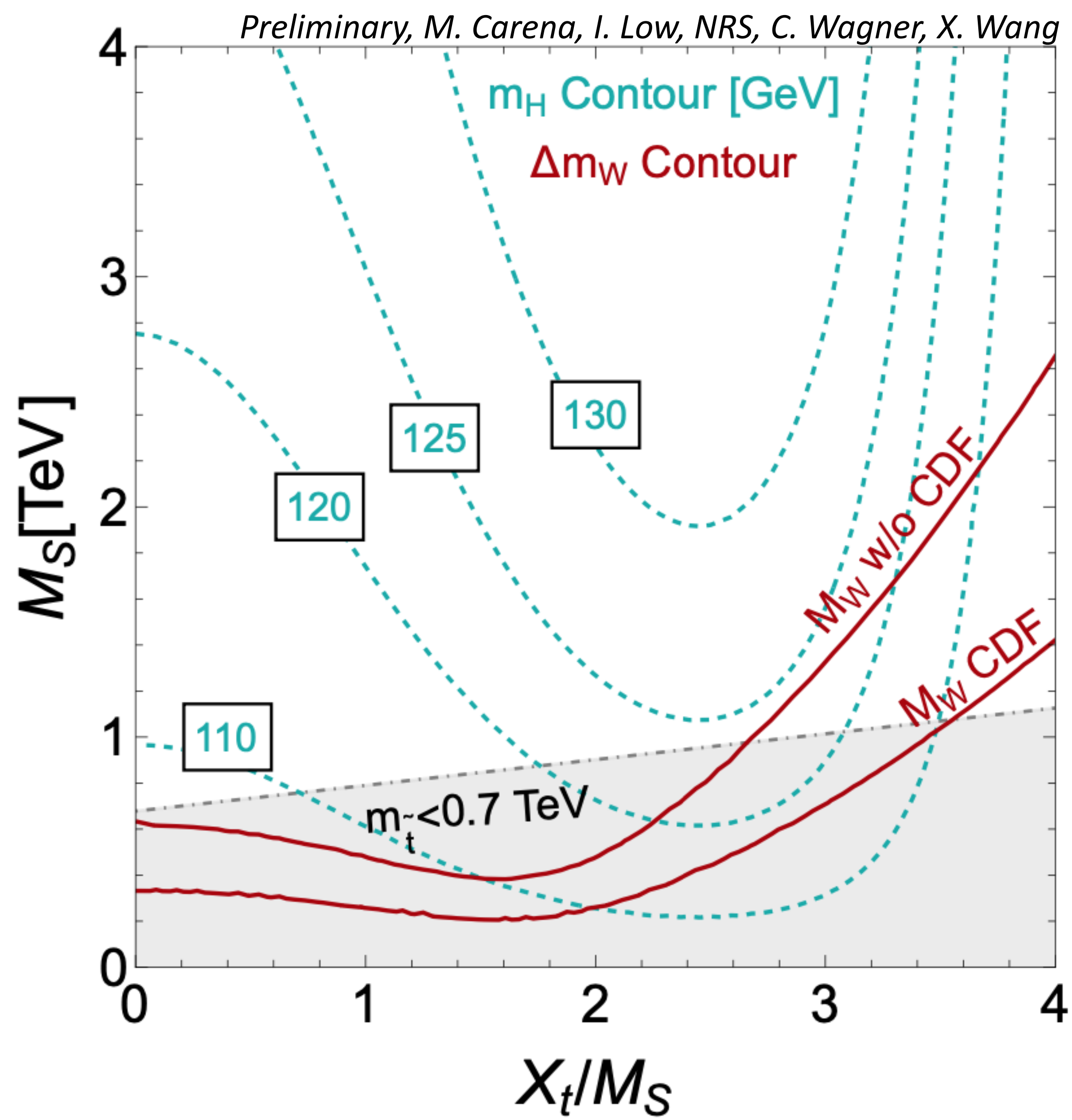
Ignoring botttom mass dependent corrections to sbottom sector and degenerate soft masses

$$M_W = 80,357 \pm 4_{\text{inputs}} \pm 4_{\text{theory}}\ \mathrm{MeV}$$

SM from PDG

~ 76 MeV

$$M_W = 80,433.5 \pm 6.4_{\text{stat}} \pm 6.9_{\text{syst}} = 80,433.5 \pm 9.4\ \mathrm{MeV}$$



m_w inconsistent with m_{h125}!

Larger X_t -> Unstable Vacuum

Light stops LHC constraints

Light stops:
h_{125} gluon fusion + γγ rate

$$(\delta M_W)_{\tilde{t}} \lesssim 30 \text{ MeV}.$$

(~ 76 MeV)

SOMETHING ELSE …

Something else: Z_3 NMSSM Higgs Sector

$$W = \lambda S H_u H_d + \frac{\kappa}{3} S^3$$

$$-\mathcal{L}_{\text{soft}} = \lambda A_\lambda S H_u H_d + \frac{1}{3}\kappa A_\kappa S^3$$

$A_\lambda \leftrightarrow m_A$

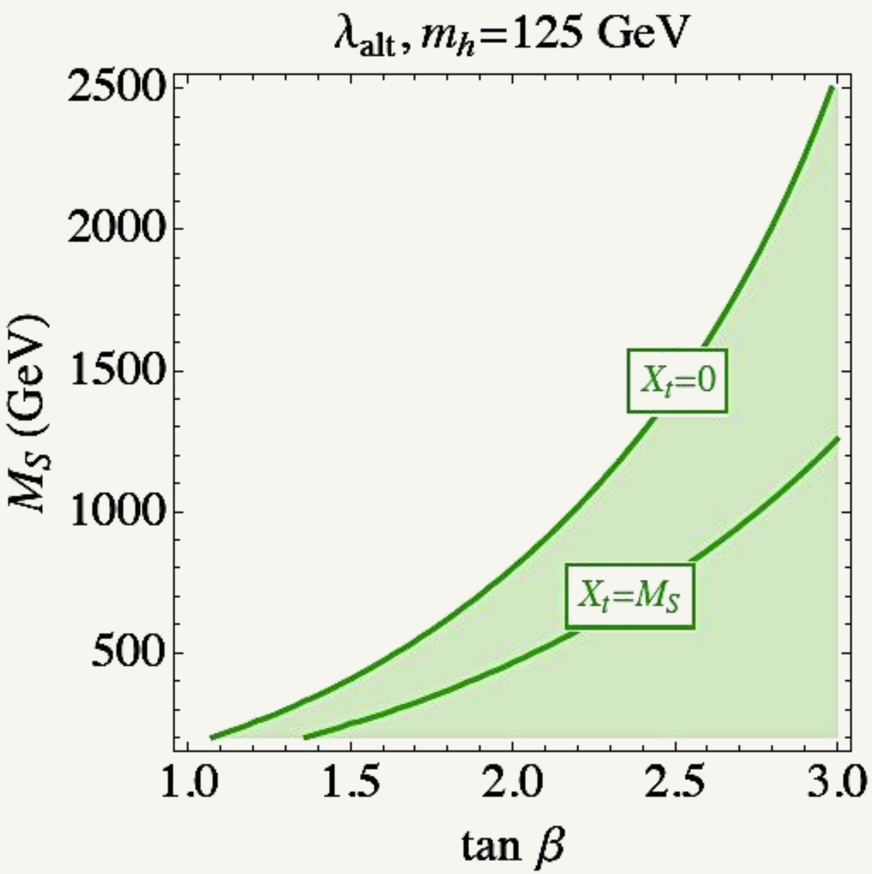
$A_\kappa \leftrightarrow m_a / m_{hS}$

- **2 Doublets (H_u, H_d) + Singlet (S)**
- Singlet couples only to Higgs Sector.
- vevs: (H_u, $H_{d,}$, S) =(v_u, v_d, v_S =μ/ λ)

- **3 CP-Even Higgs bosons:**
  - Mixing between all three (H_u, H_d and S).
- **2 CP-Odd Higgs bosons:**
  - Mixtures of "MSSM" m_A and singlet.
- **Charged Higgs bosons**

- **Singlino** mass: 2 κ μ/λ

M. Carena, H. Haber, I. Low, N.R.S., C. Wagner, '15



Alignment (No-Mixing):

$$m_h^2 \simeq \lambda^2 \frac{v^2}{2} \sin^2 2\beta + M_Z^2 \cos^2 2\beta + \Delta_{\tilde{t}}$$

$$\Delta_{\tilde{t}} = -\cos 2\beta (m_h^2 - M_Z^2)$$

Well Known

- 125 GeV Higgs
  - Tree-level contribution to Higgs mass from λ.
  - λ ~ 0.65-0.7
- Low tanβ
- Light Stops

NMSSM:

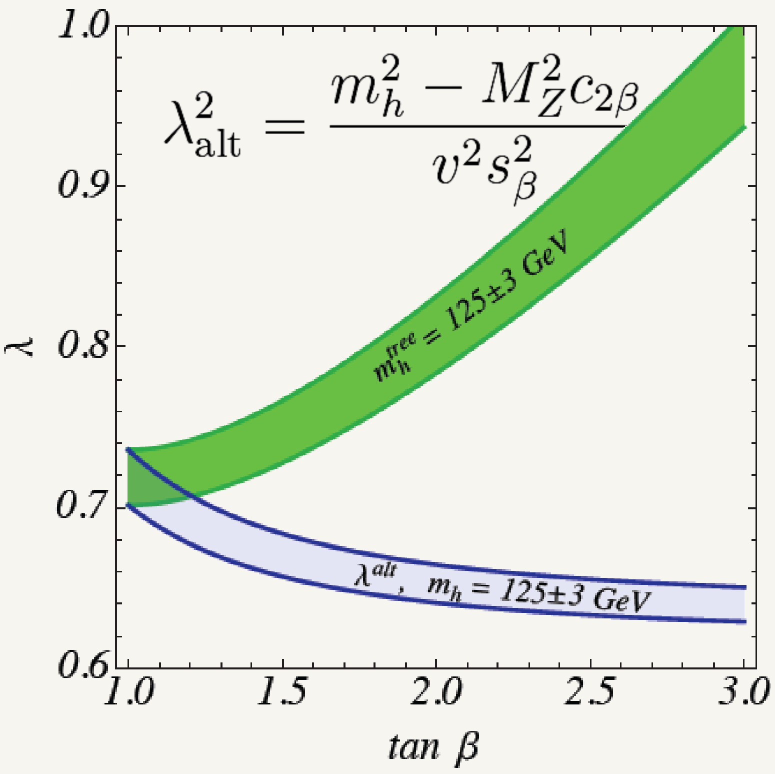
125 GeV Higgs Naturally!

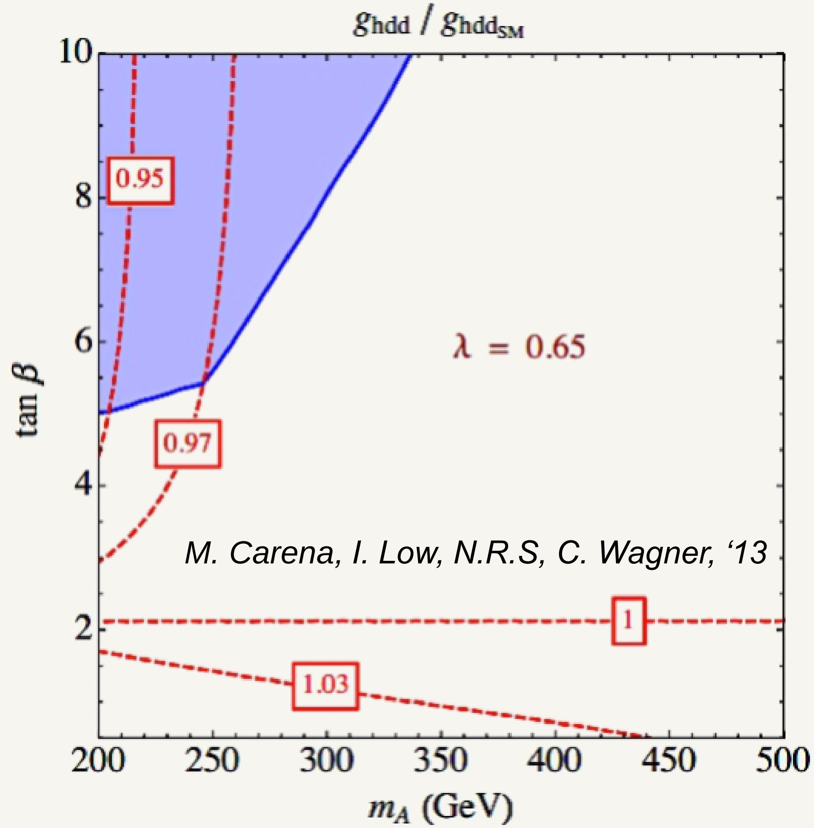
- Perturbative up to GUT scale.
  - $\lambda_{max} \sim 0.7$, $\kappa_{max} \sim \lambda/2$

Not so well known:

- Excellent Alignment (very little mixing)

M. Carena, H. Haber, I. Low, N.R.S., C. Wagner, '15





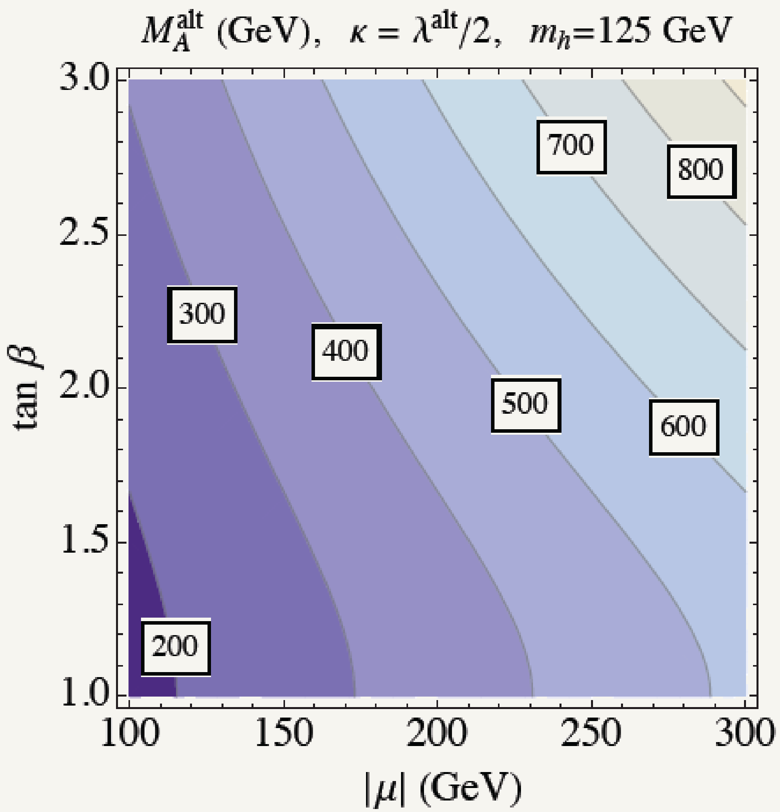
M. Carena, I. Low, N.R.S, C. Wagner, '13

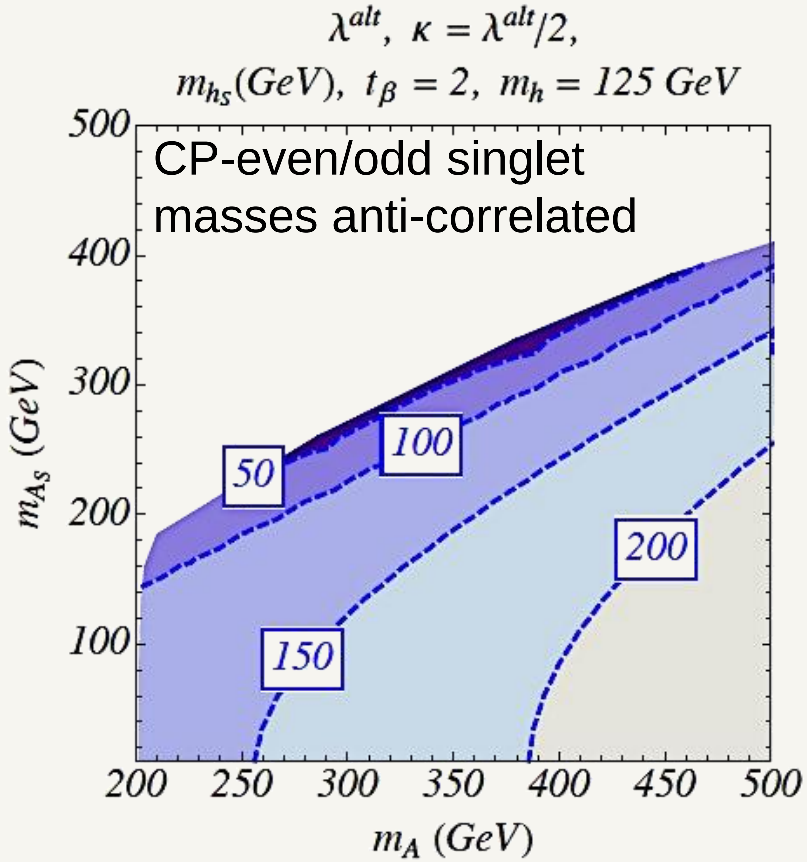
Originate dynamically from Higgs compositeness at the GUT scale?

N. Coyle, C. Wagner, '19

SM-Like Higgs Naturally!

M. Carena, H. Haber, I. Low, N.R.S., C. Wagner, ’15





$$1 - \frac{m_A^2}{4\mu^2} s_{2\beta}^2 - \frac{\kappa}{2\lambda} s_{2\beta} = 0$$

$h_{125} = H_{SM}$

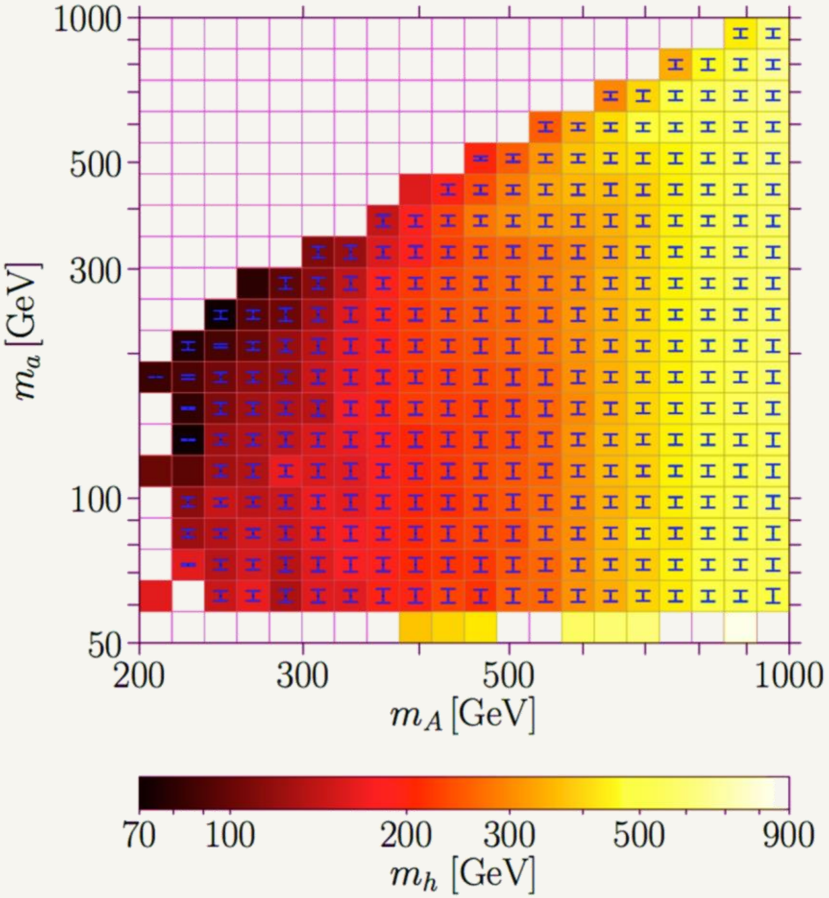
LIGHT SPECTRUM

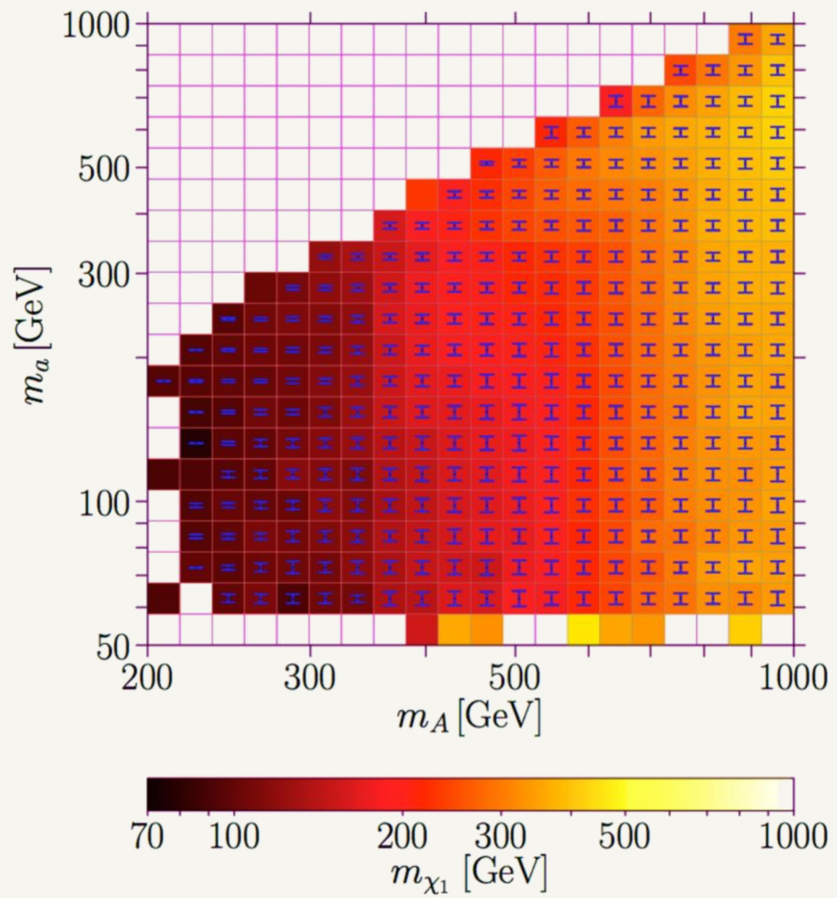
Singlino: **2 κ μ/λ ~ < μ**

Singlet Alignment

SM - like h_{125}: Mass Correlations!

S. Baum, N.R.S, K. Freese, '19





NMSSMTools scan with consistent h_{125} pheno

W Mass and Alignment – ☹

Preliminary, M. Carena, I. Low, NRS, C. Wagner, X. Wang

$g_{hbb}/g_{hbb}^{SM} < 10\%$

$$\lambda^2 < \frac{0.1 m_H^2 + 2m_h^2 + 2M_Z^2}{v^2}.$$

$$\Delta M_W \sim 1.2\ 10^6 \frac{\lambda^4}{m_H^2[\mathrm{GeV}^2]}\ \mathrm{MeV}.$$

$\lambda > \sim 1$

$m_H \sim$ Few hundred GeV

$$\Delta M_W < 3.2\ 10^{-6} m_H^2[\mathrm{GeV}^2]\left(1 + \frac{4.8 \times 10^5}{m_H^2[\mathrm{GeV}^2]}\right)^2\ \mathrm{MeV}$$

$m_H >> m_{h125}$

TOO SMALL!!

Singlet Decoupling – Threshold Effects

Preliminary, M. Carena, I. Low, NRS, C. Wagner, X. Wang

Tadpole terms for Singlet: in scalar potential (ξ_S) and Superpotential (ξ_F)

$$m_S^2 \simeq -\frac{\xi_S}{< S >} = -\frac{\xi_S \lambda}{\mu}$$

$$m_{h_S}^2 = m_S^2 + 2\xi_F \kappa, \qquad m_{A_S}^2 = m_S^2 - 2\xi_F \kappa,$$

Decoupling singlets: Replace singlet fields by their equation of motion:

Corrections to the effective **quartic couplings at low energies**

$$\delta Z_4 \simeq -\lambda^2 \left(\frac{A_\lambda^2}{2m_{h_S}^2} + \frac{A_\lambda^2}{2m_{A_S}^2} \right)$$

$$\delta Z_5 \simeq -\lambda^2 \left(\frac{A_\lambda^2}{2m_{h_S}^2} - \frac{A_\lambda^2}{2m_{A_S}^2} \right)$$

$$\delta Z_6 \simeq \lambda^2 \frac{A_\lambda^2}{t_\beta m_{h_S}^2} - \lambda^2 \frac{\mu A_\lambda}{m_{h_S}^2}$$

W Mass and Alignment – ☺

Preliminary, M. Carena, I. Low, NRS, C. Wagner, X. Wang

$g_{hbb}/g_{hbb}^{SM} < 10\%$

$$\lambda^2 < 0.1 \frac{m_H^2}{v^2}\left(1+\frac{4.8\times 10^5}{m_H^2[\mathrm{GeV}^2]}\right)\times\left(1-\frac{A_\lambda^2 - A_\lambda \mu t_\beta}{m_{h_S}^2}\right)^{-1}$$

$$\left[\mu\left(A_\lambda + \frac{\kappa}{\lambda}\mu\right) + \lambda\xi_F\right] t_\beta \simeq M_A^2$$

Relationship of A_λ and m_A in the presence of tadpoles.

$$\Delta M_W < 3.2\ 10^{-6}\ m_H^2[\mathrm{GeV}^2]\left(1+\frac{4.8\times 10^5}{m_H^2[\mathrm{GeV}^2]}\right)^2 \frac{\left(1-\frac{A_\lambda^2}{m_{h_S}^2}\right)\left(1-\frac{A_\lambda^2}{m_{A_s}^2}\right)}{\left(1-\frac{A_\lambda^2 - A_\lambda\mu t_\beta}{m_{h_S}^2}\right)^2}$$

For eg:

m_H ~ 500 GeV, A_λ ~ μ tb, A_λ/m_S large,

+ Stop contributions!

Thank You!

SM works beautifully…

But **MANY** puzzles remain.

UV physics? **BREAK** the SM!
May be systematics, but may be hints for BSM physics!

What are the right questions?

???

Data + Theory: Where to look next!

Absence of Evidence != Evidence of Absence
Data driven age: Collider + Precision + Astrophysical Probes

~~"May we live in interesting times."~~

BACK UP SLIDES

- Interaction basis: (H_u, H_d, S)
  - H_u: Couples only to up-type fermions
  - H_d: Couples only to down-type fermions
  - S: Only couples to Higgs

$\langle H_u \rangle = v_u$
$\langle H_d \rangle = v_d$
$t_\beta = v_u/v_d$
$\langle S \rangle = \mu/\lambda$

CP-Even Higgs Bases

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- "Extended" Higgs basis: (H_{NSM}, H_{SM}, S)
  - H_{NSM}: (down, up, V) = $(y_d\, t_\beta, y_u/\, t_\beta, 0)$
  - H_{SM}: (down, up, V) = (y_d, y_u, g_{hVV})

Only SM state couples to WW or ZZ!!

$\langle H_{NSM} \rangle = 0$
$\langle H_{SM} \rangle = v$

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- Mass basis: (H^3, H^2, H^1)

$$H^i = S^i_{NSM}\, H_{NSM} + S^i_{SM}\, H_{SM} + S^i_S\, H_S$$

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- Mass basis: $(H_3, H_2, H_1) \longrightarrow$ (H, h125, h)

$$H_i = S_i^{NSM}\, H_{NSM} + S_i^{SM}\, H^{SM} + S_i^{S}\, H_S$$

CP-odd mix similarly:
$A_i = P_i^{NSM}\, A_{NSM} + P_i^{S}\, A_S$

CP-Even Higgs Bases