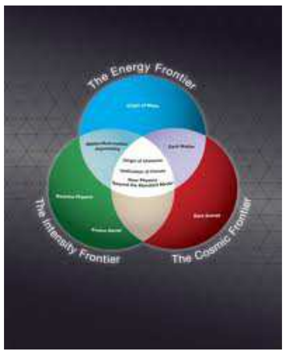
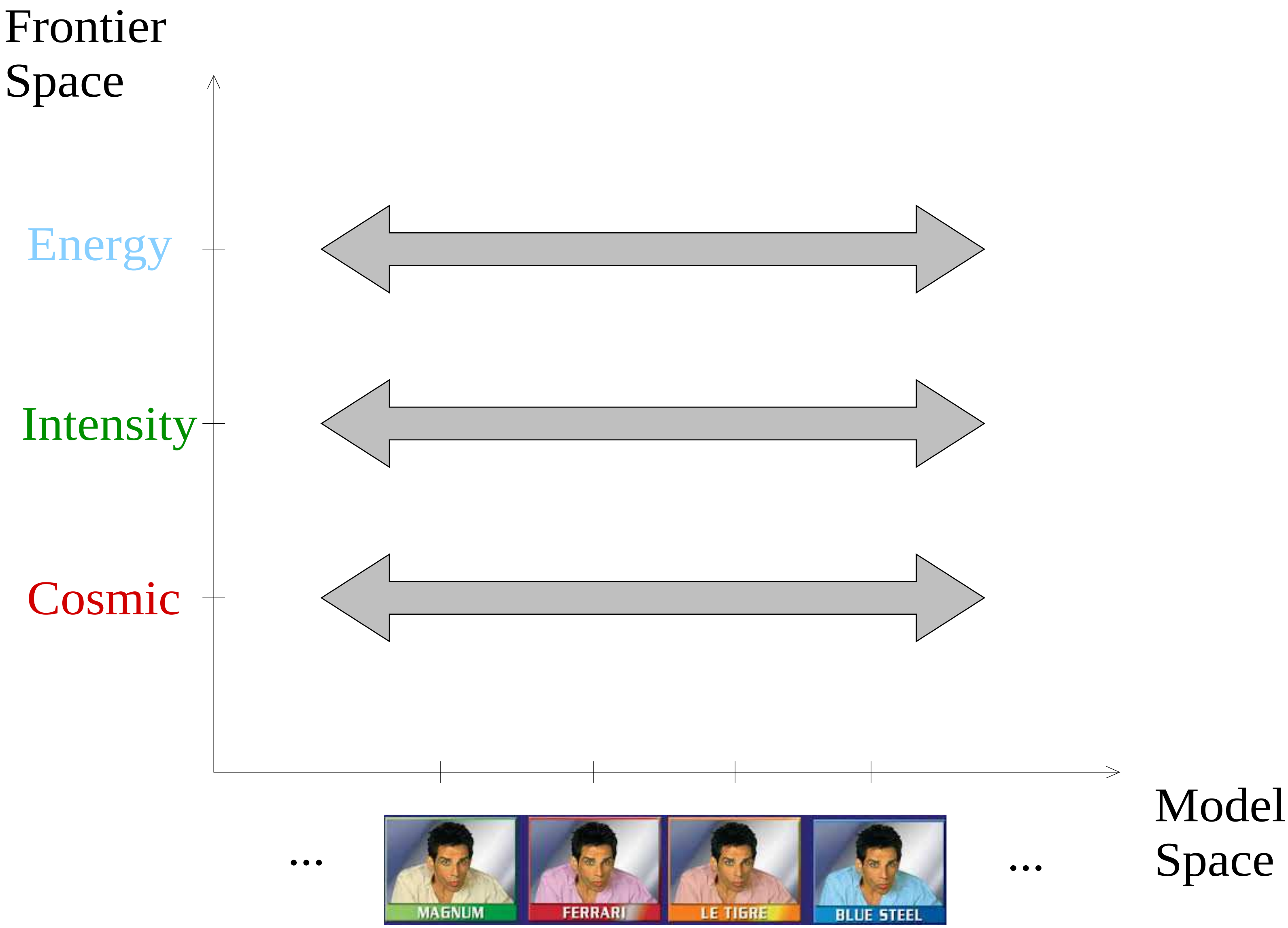
Higgs Models

David Morrissey

TRIUMF

Snowmass on the Pacific, KITP, May 29, 2013


The Energy Frontier
The Intensity Frontier
The Cosmic Frontier


Frontier Space
Energy
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Model Space
...
MAGNUM
FERRARI
LE TIGRE
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...


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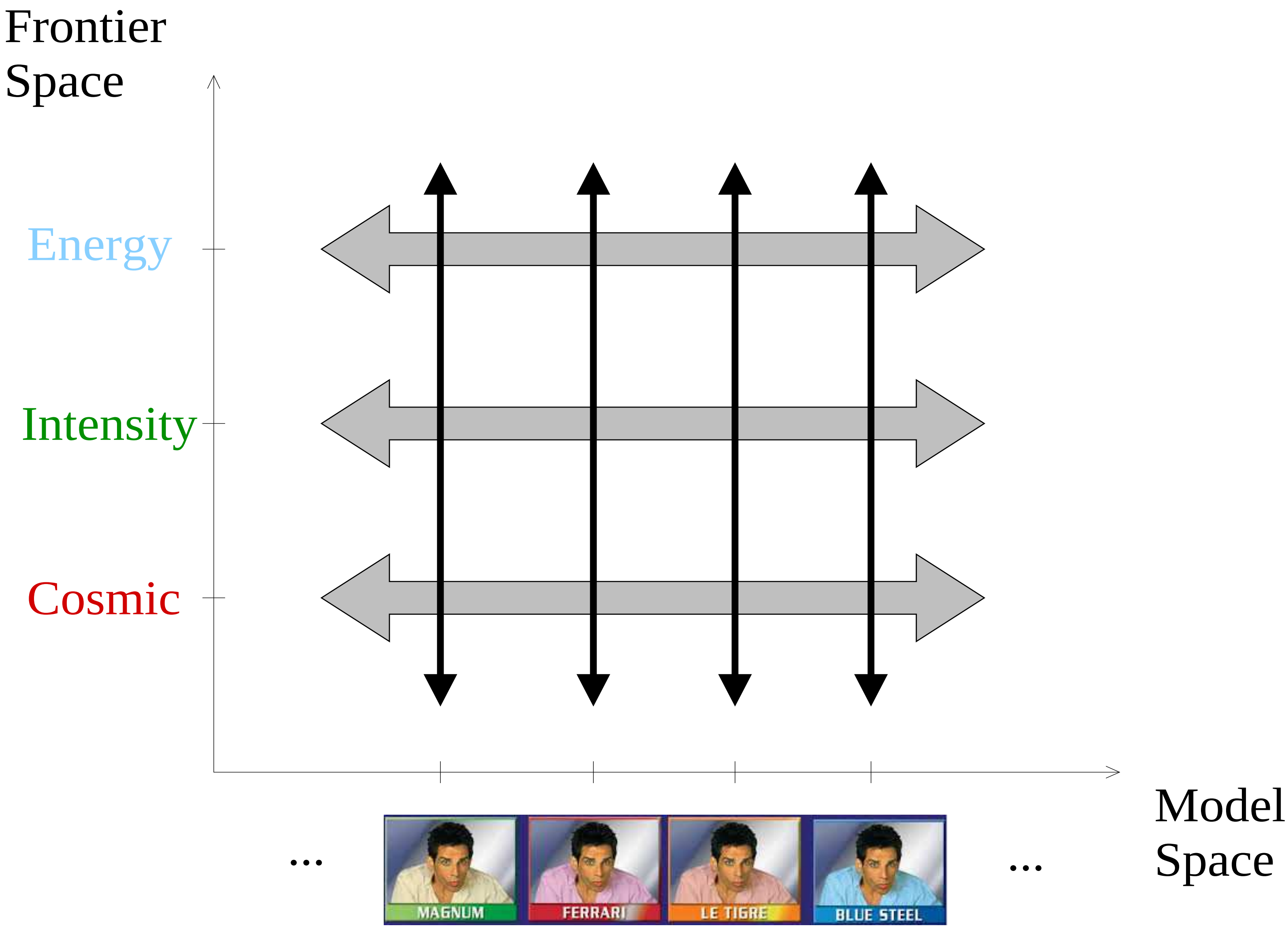
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Classifying Higgs Models

- Higgs = scalar fields H contributing to EWSB

  = scalar particles h derived (in part) from them

- An imperfect BSM classification:

  I. new heavy states couple to H $(M > m_h/2)$

  II. new light states couple to H $(M < m_h/2)$

  III. not all of EWSB is contained in h

Case I

New Heavy States Coupling to H

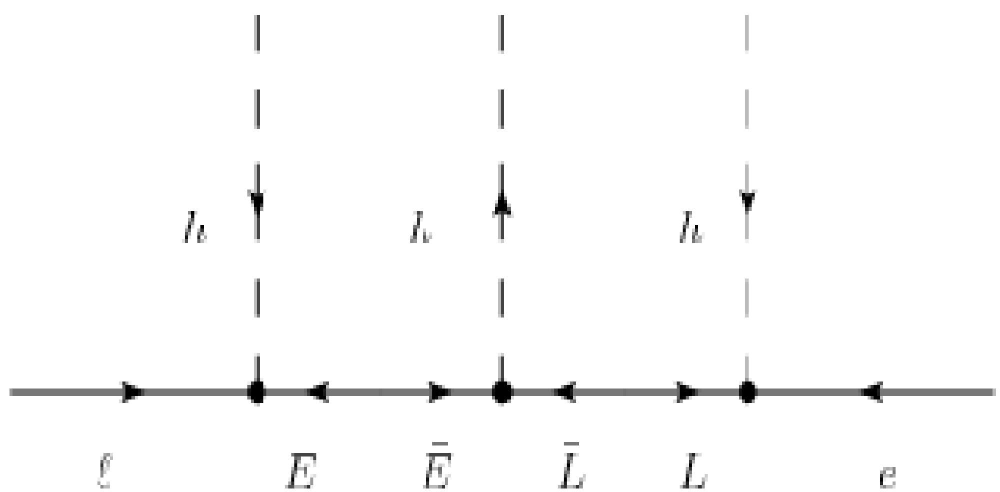
e.g. I.1: Vector-Like Fermions

$$-\mathcal{L} \supset MFF^c + yHFF' + y'HFf + \ldots$$

- $f =$ SM fermion, $F =$ exotic vector-like fermion.
- F from Little Higgs, custodial RS, SUSY, A_b^{FB} fixes . . .
- $y' \neq 0 \Rightarrow$ mixing with SM fermions, $(V_{CKM}^{SM})^{-1} \neq (V_{CKM}^{SM})^{\dagger}$.
- $y' = 0 \Rightarrow F \leftrightarrow -F$ symmetry is possible, dark matter.

  (Also permits F to be Majorana.)

- Integrating out F, F^c can generate: [e.g. Kearney, Pierce, Weiner '12]
  - $|H|^2 F_{\mu\nu}F^{\mu\nu}$, $|H|^2 G^a_{\mu\nu}G^{a\,\mu\nu}$: shifts $\Gamma(h \to \gamma\gamma)$, $\sigma(gg \to h)$.
  - $|H^\dagger D_\mu H|^2$: contributes to precision electroweak.
  - $\frac{\lambda_{ij}}{M^2}\,\bar{f}_i f_j\, H(H^\dagger H)$: changes Higgs-fermion couplings.



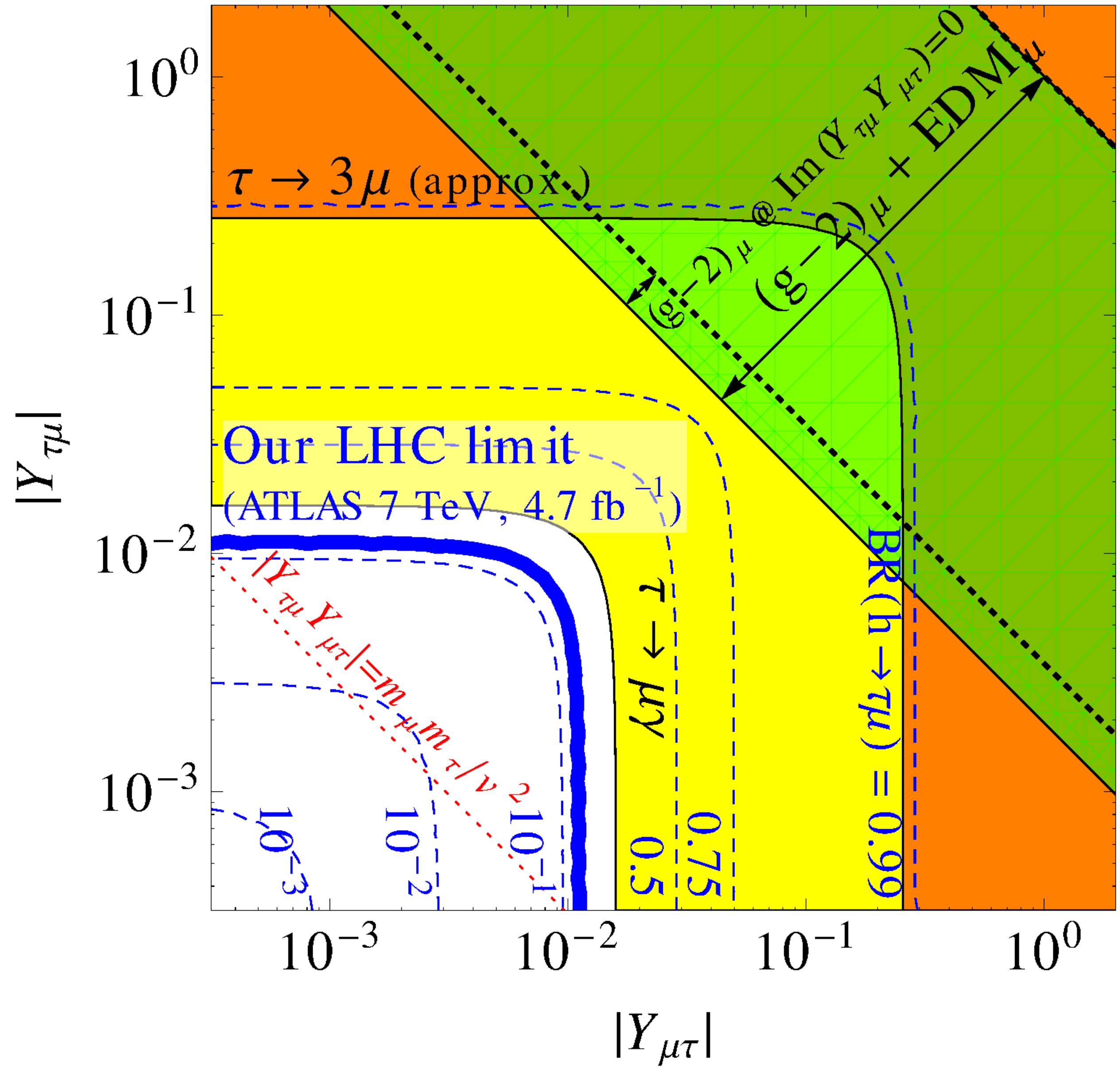
- Modified Higgs-fermion couplings from $\frac{\lambda_{ij}}{M^2}\,\bar{f}_i f_j\, H(H^\dagger H)$:

$$m_{ij} = \left(y_{ij} + \lambda_{ij}\frac{v^2}{M^2}\right) v$$

$$g_{ij}^{(hff)} = y_{ij} + 3\lambda_{ij}\frac{v^2}{M^2}$$

- Effects:
  - Diagonal – changes $\Gamma(h \to ff)$ [Kearney *et al* '12]
  - Off-diagonal – flavor-change in Higgs [Harnik,Kopp,Zupan '12]
  - Non-trivial phases – EDMs via Higgs [McKeen,Pospelov,Ritz '12]

- Leptonic FV *vs.* BR($h \to \tau\mu$): [Harnik,Kopp,Zupan '12]



e.g. I.2: Higgs Portal

$$-\mathcal{L} \supset M_X^2|X|^2 + Q_X|X|^2|H|^2$$

$$m_X = \sqrt{M_X^2 + Q_X v^2/2}$$

- X is a boson that does not get a VEV, $m_X > m_h/2$.
- Modified $\Gamma(h \to \gamma\gamma)$ and $\sigma(gg \to h)$ if X has SM charge.

  Other production and decay modes are less affected.

  [e.g. Batell,Gori,Wang '11, Kunal,Vega-Morales,Yu '12; Chang,Ng,Wu '12]

- X also modifies the electroweak phase transition.

  In the early Universe at temperature T:

$$V_{eff}(\varphi, T) \simeq -(\mu^2 - \xi\, T^2)\, \varphi^2 - \frac{T}{4\pi}\left[m_X^2(\varphi, T)\right]^{3/2} + \frac{\lambda}{4}\varphi^4 \; ,$$

  where

$$m_X^2(\varphi, T) \simeq Q_X\, \varphi^2 + \underbrace{M_X^2 + \xi\, T^2}_{\delta m^2} .$$

- Large Q_X, $\delta m^2 \to 0$ yields a strongly first-order transition.

$$\text{Phase Transition Strength} \sim \frac{\text{“}\langle\varphi_c\rangle\text{”}}{T_c} \propto \frac{Q_X^{3/2}}{\lambda}$$

- A strong PT is needed for electroweak baryogenesis and can generate gravity waves.

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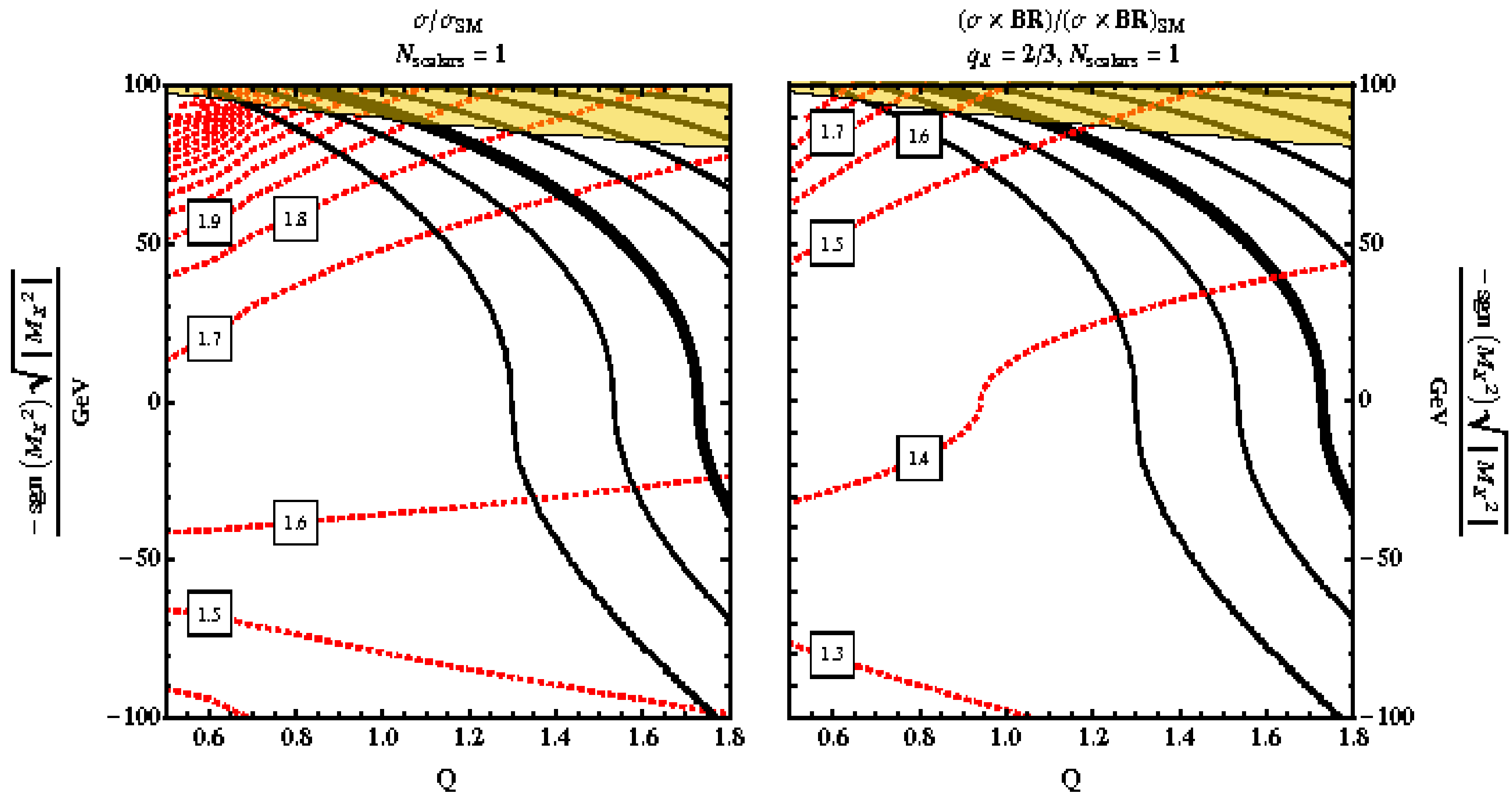
- For $X = (3, 1, 2/3)$,



[Cohen,DM,Pierce '12]

- Strong tension with measured Higgs rates for $\varphi_c/T_c > 1$.

[Curtin,Jaiswal,Meade '12]

e.g. I.3: Supersymmetry ($m_A \gg m_Z$)

$$-\mathcal{L} \supset Q_i|\tilde{f}_i|^2|H|^2 + (g_j H\psi_j\psi'_j + h.c.) + (a_k H\tilde{f}_k\tilde{f}'_k + h.c.)$$

- higgs portal + vector (Majorana) fermions + scalar trilinear
- Loops of $\tilde{t}_{1,2}$, $\tilde{b}_{1,2}$, $\tilde{\tau}_{1,2}$, $\chi_i^{\pm}$ can all be important.
- Effects can be limited by direct searches for these states.

e.g. I.4: A General Approach

- Parametrize heavy stuff in terms of effective operators:

  [*e.g.* Giudice,Grojean,Pomarol,Rattazzi '07]

$$-\mathcal{L} \supset \frac{c_f y_f}{M^2}|H|^2 \bar{f}_L f_R H + \frac{\tilde{c}_g \alpha_s}{4\pi}\frac{1}{M^2}|H|^2 G^a_{\mu\nu} G^{a\,\mu\nu} + \ldots$$

- M = mass of new physics.

  Corrections to SM observables go like v^2/M^2.

- Works well for composite Higgs, Little Higgs, . . .

  (Tree-level electroweak deviations force $M \gg v$.)

Case II

New Light Stuff Coupling to H

Higgs and Light Stuff

- $m_X < m_h/2$:

$$h \to XX \qquad (X = \text{fermion or boson})$$

followed by

$$X \to \begin{cases} \text{stable} & ; \quad \text{invisible} \\ SM + \ldots & ; \quad \text{exotic} \end{cases}$$

- Small Γ_h^{SM} means exotic decays can have significant BR.

e.g. II.1: $h \to inv$

- Direct LHC searches constrain invisible decays:

$$BR(h \to inv) < \left\{ \text{0.65} \quad ; \quad \text{[ATLAS '13], from } Zh \to \ell\ell \not{E}_T \right.$$

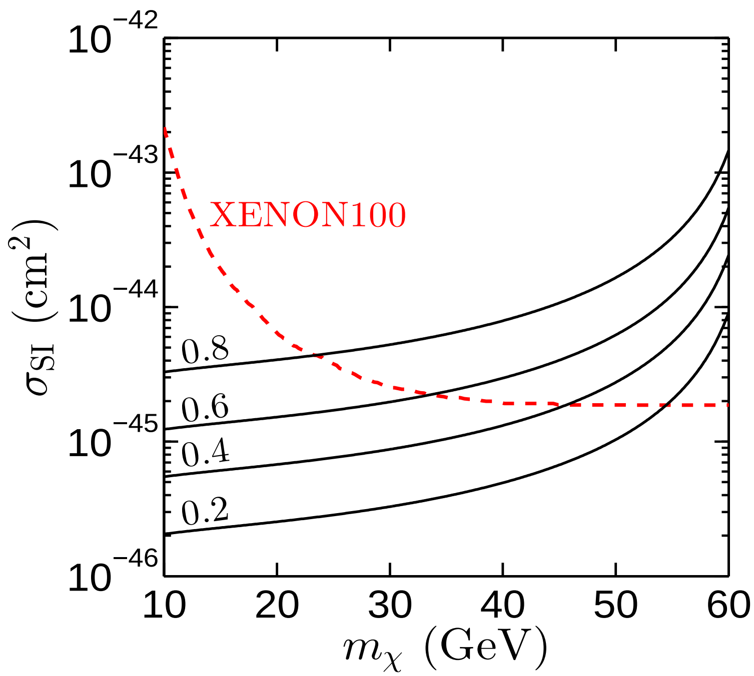
- For SM-like production, measured rates limit

$$BR(h \to inv) < \begin{cases} 0.20 & ; \quad \text{[Bélanger } et\ al. \text{ '13]} \\ 0.19 & ; \quad \text{[Giardino } et\ al. \text{ '13]} \\ 0.13 & ; \quad \text{[Ellis+You '13]} \\ 0.52 & ; \quad \text{[Djouadi+Moreau '13]} \end{cases}$$

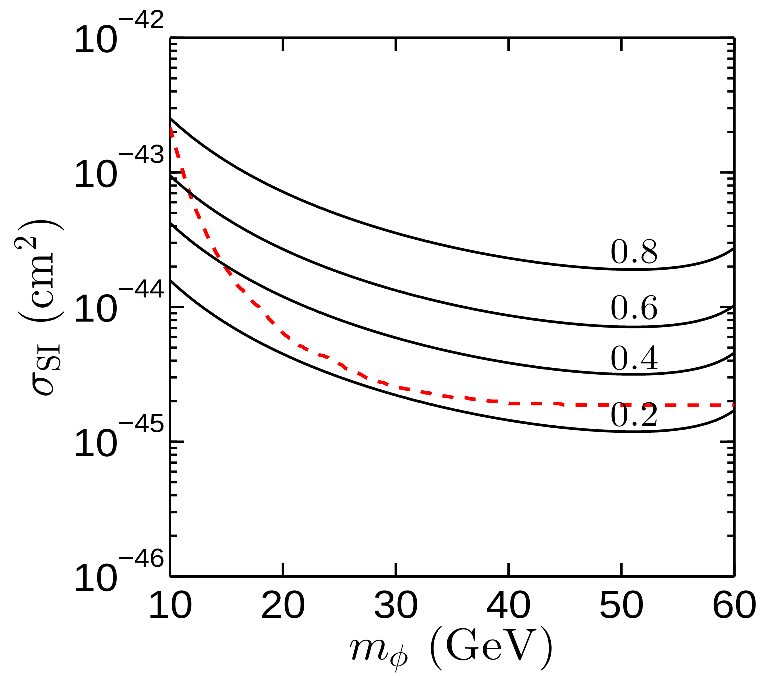
- This also applies to any exotic decay not contributing to standard Higgs search channels.

- For X = dark matter, the hXX coupling also mediates DM scattering with nuclei via h.

- Higgs rate bounds on $h \to inv$ are competitive with DM direct detection: [Bélanger *et al.* '13]



Majorana fermion



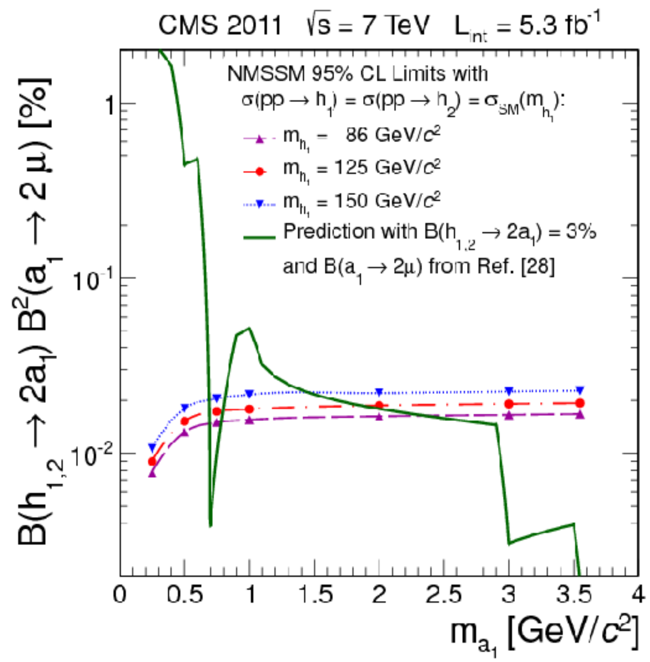
real scalar

e.g. II.2: $h \to aa$ $(a = pNGB)$

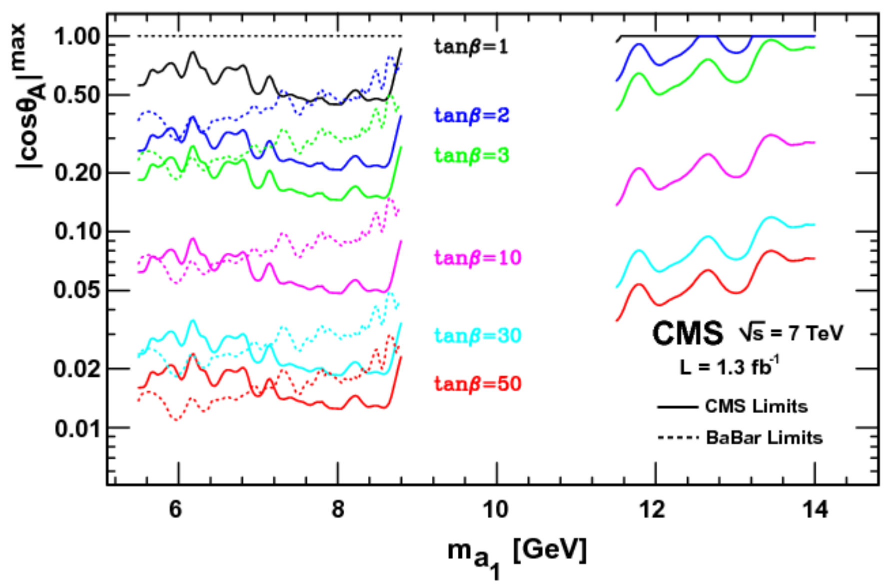
$$-\mathcal{L} \supset \underbrace{\epsilon\,|H|^2|S|^2}_{\text{H portal},\,\epsilon \ll 1} + \underbrace{\lambda_S(|S|^2 - v_S^2)^2}_{\langle S\rangle \simeq v_S} + \underbrace{\left(\frac{\kappa}{3} v_S S^3 + \dots\right)}_{U(1)_S \text{ breaking},\,\kappa \ll 1}$$

- $\epsilon \neq 0$ implies $h \to aa$ will occur
- $a \to b\bar{b},\ \tau\bar{\tau},\ \mu\bar{\mu},\ \dots$ by mixing with stuff (*e.g.* A in 2HDM)
- Can arise in limits of the NMSSM. [Dermíšek+Gunion '05]

- CMS $h \to aa,\ a \to \mu\mu$:



- Limits from $\Upsilon \to \gamma\, a$ (BaBar) and $pp \to a \to \mu\mu$ (CMS):



e.g. II.3: $h \to \chi_1^0 \chi_1^0$ in SUSY

$$\chi_1^0 \to \begin{cases} \text{stable} & ; \text{ invisible [e.g. Dreiner et al. '12]} \\ \gamma\tilde{G} & ; \ \gamma\gamma + \not{E}_T \text{ [Mason et al. '09]} \\ Z_x\chi^x & ; \text{ lepton jets} + \not{E}_T \text{ [Falkowski et al. '10]} \\ \ldots & \end{cases}$$

- New light states can be probed at the intensity frontier:
  - direct detection of dark matter
  - $p \to \tilde{G}K^+$ via $U^cD^cD^c$ [Choi,Chun,Lee '97]
  - Z_x and χ^x in fixed-target experiments [*e.g.* Bjorken *et al.* '09]

Case III

Not all EWSB is in h

$h \neq$ EWSB

- SM:
  - EWSB from only $\langle H \rangle = v \neq 0$
  - $H \to (v + h/\sqrt{2} + \text{NGBs})$ yields one physical state
- BSM:
  - EWSB can come from multiple H fields (or more)
  - multiple h particles can share this EWSB
  - h can contain some non-EWSB field (*e.g.* singlet)
- A zoo of possibilities . . .

e.g. III.1: 2HDM

- $H_1,\ H_2 = (1, 2, -1/2)$ scalar doublets
- No tree-level FCNC: each fermion type $(u,\ d,\ e)$ only gets mass from one of the doublets.

$$\mathrm{I}\ :\ H_2\{u,d,e\},\ H_1\{\} \qquad \mathrm{II}:\ H_2\{u\},\ H_1\{d,e\}$$

$$\mathrm{III}:\ H_2\{u,d\},\ H_1\{e\}, \qquad \mathrm{IV}:\ H_2\{u,e\},\ H_1\{d\}$$

- Physical states: $h^0,\ H^0,\ A^0,\ H^\pm$ (no CPV)

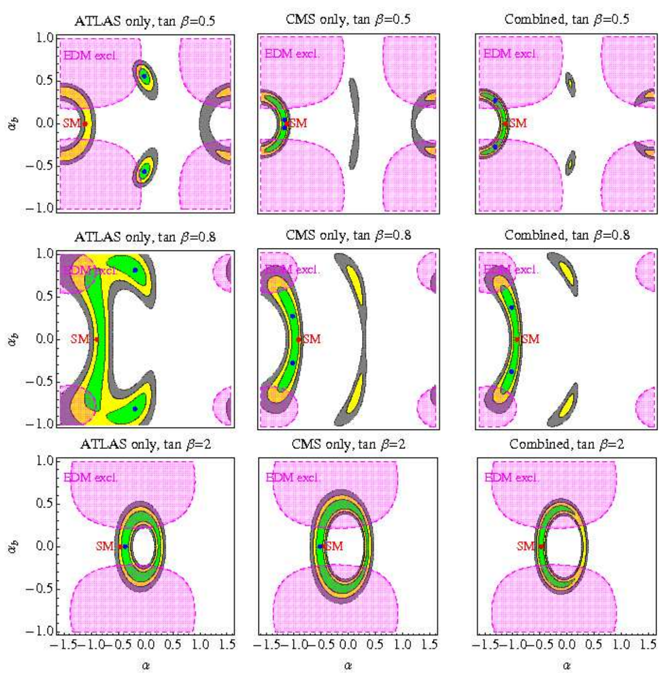
$$(174\,\mathrm{GeV})^2 = v_1^2 + v_2^2\ , \qquad \tan\beta = v_2/v_1\ ,$$

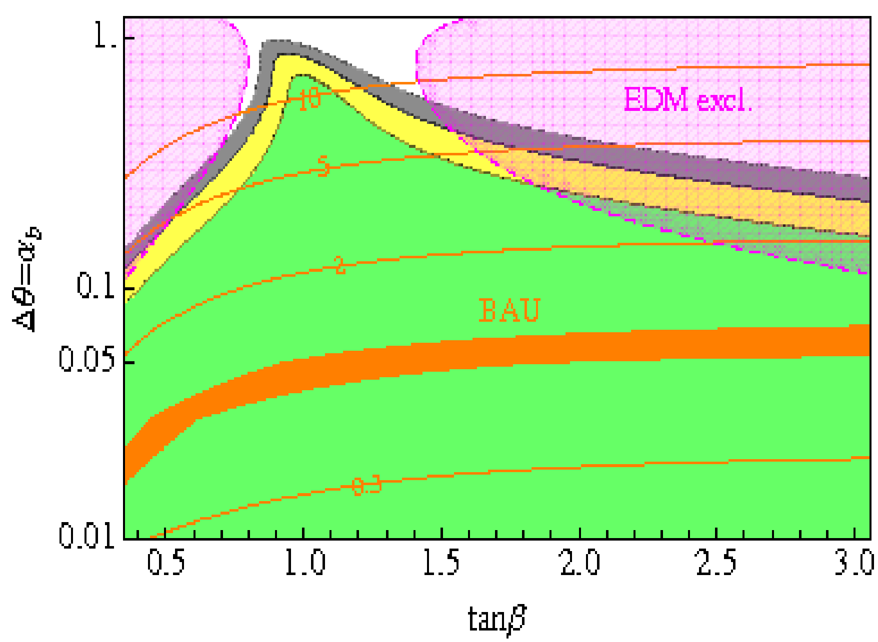
$$\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \end{pmatrix}$$

- A general 2HDM can have CP violation too!

  $\Rightarrow H_1^0, H_2^0, A^0$ all mix to give h_1, h_2, h_3

- Effects: [Shu+Zhang '13; Tulin+Winslow '11; Cline+Trott '11; CPSuperH]
  - modified Higgs couplings (*e.g.* hGG and $hG\tilde{G}$)
  - electric dipole moments (EDM)
  - CP violation during the electroweak phase transition





e.g. III.2: 2.5HDM

- 2.5HDM = singlet plus two doublets*
- $\langle H_1^0 \rangle = v_1$, $\langle H_2^0 \rangle = v_2$, $\langle S \rangle = v_S$, everything mixes
- States: h_1, h_2, h_3, A_1, A_2, $H^{\pm}$.

  Mostly-singlet states can be very light.
- NMSSM is a popular example.

* A singlet is half a doublet.

e.g. III.3: 1.25HDM

- 1.25HDM = real singlet plus complex doublet*

- $\langle H^0 \rangle = v$, $\langle \phi \rangle = v_\phi$

- States: h_1, h_2.

- Important example: $\phi =$ dilaton in RS-like theories.

  [*e.g.* Csaki,Hubisz,Lee '07; Toharia '08]

$$-\mathcal{L} \supset \frac{1}{\Lambda} \phi \, T_\mu{}^\mu \; .$$

* A real singlet is one quarter of a complex doublet.

Summary

Some Questions

1. How does the sensitivity of the LHC (and beyond) to Higgs deviations compare to the reach for heavy new physics that could give rise to them?

2. Should we forego writing down specific theories and just do fits to higher-dimensional operators?

3. Are there potentially observable rare Higgs decay modes that are not picked up by current or planned analyses?

4. Have the correlations with the intensity and cosmic frontiers been fully explored?

5. Do we pay enough attention to flavor and CP?

Extra Slides

SM Higgs

- $H = (1, 2, -1/2)$

- Couplings:

$$\mathcal{L} \supset |D_\mu H|^2 - \left(-\mu^2|H|^2 + \frac{\lambda}{4}|H|^4\right)$$
$$-y_u\,\tilde{H}\bar{Q}_L u_R - y_d\,H\bar{Q}_L d_R - y_e\,H\bar{L}_L e_R + h.c.$$

with

$$H \to v + h/\sqrt{2} + \text{gauge stuff}\ .$$

- Masses:

$$m_f = y_f\,v\ , \qquad m_V = \frac{1}{\sqrt{2}} g_V v\ .$$

MSSM (Minimal Supersymmetric) Higgs

- $H_u = (1, 2, \frac{1}{2})$, $H_d = (1, 2, -\frac{1}{2})$ for holomorphy, anomalies
- Couplings:

$$W = \mu H_u \cdot H_d + y_u \, H_u \cdot Q U^c - y_d \, H_d \cdot Q D^c - y_e \, H_d \cdot L E^c$$

$$V = V_F + V_D + V_{soft}$$

- Constrained Type II 2HDM.

  States: h^0, H^0, A^0, $H^\pm$.

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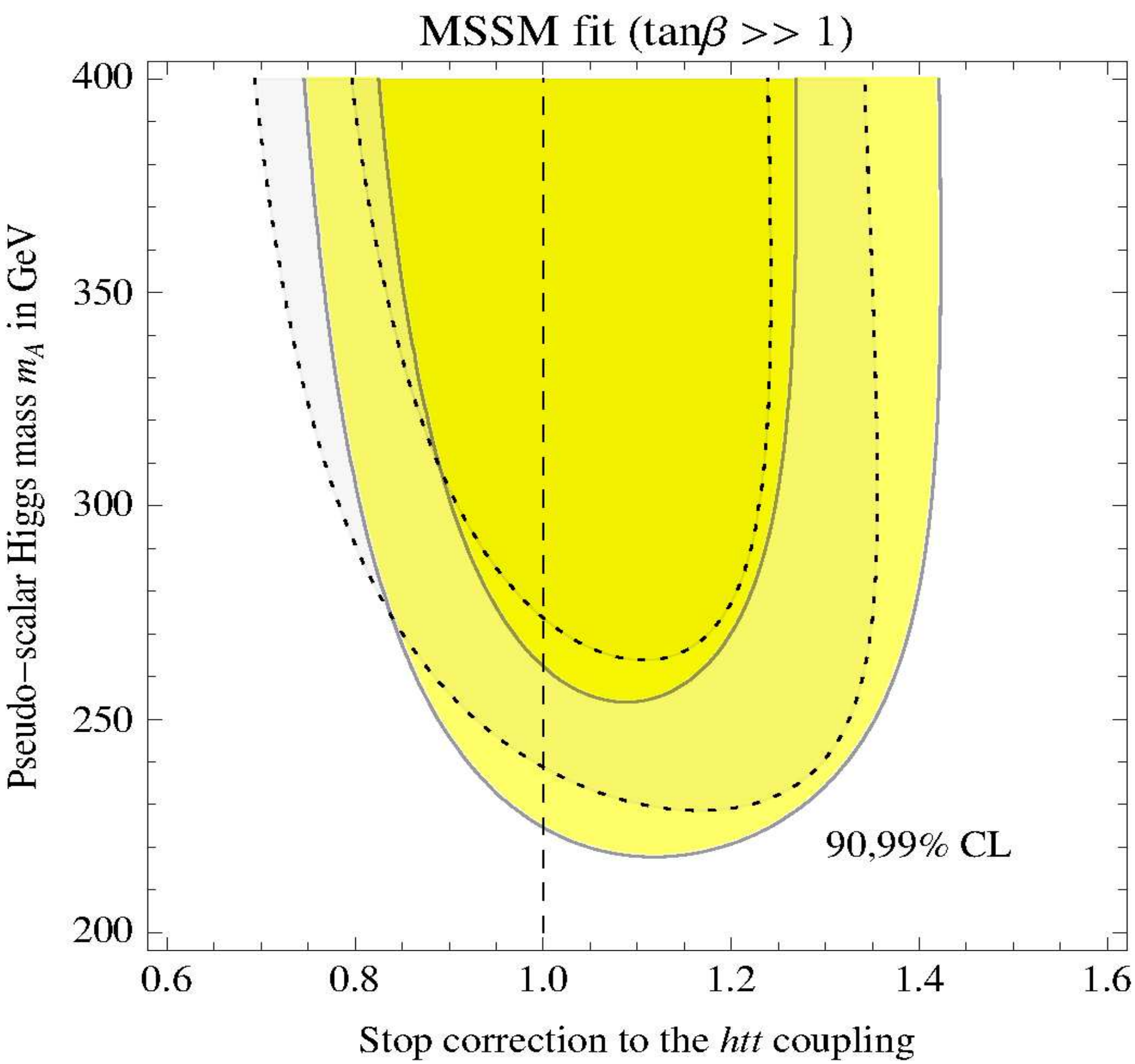
- Fits to data: [Giardino *et al.* '13]



NMSSM (Next-to-Minimal Supsersymmetric) Higgs

- NMSSM = MSSM + singlet chiral superfield
- Interactions:

$$W = W'_{MSSM} + \lambda\, S\, H_u \cdot H_d + w(S) \ .$$

- States: h_1^0, h_2^0, h_3^0, A_1^0, A_2^0, $H^\pm$.

Composite/Little Higgs

- New paradigm at scale $f \gg v$. (*e.g.* strong coupling, XD)
- One (or more) Higgs doublet emerges as a pseudo-NGB.

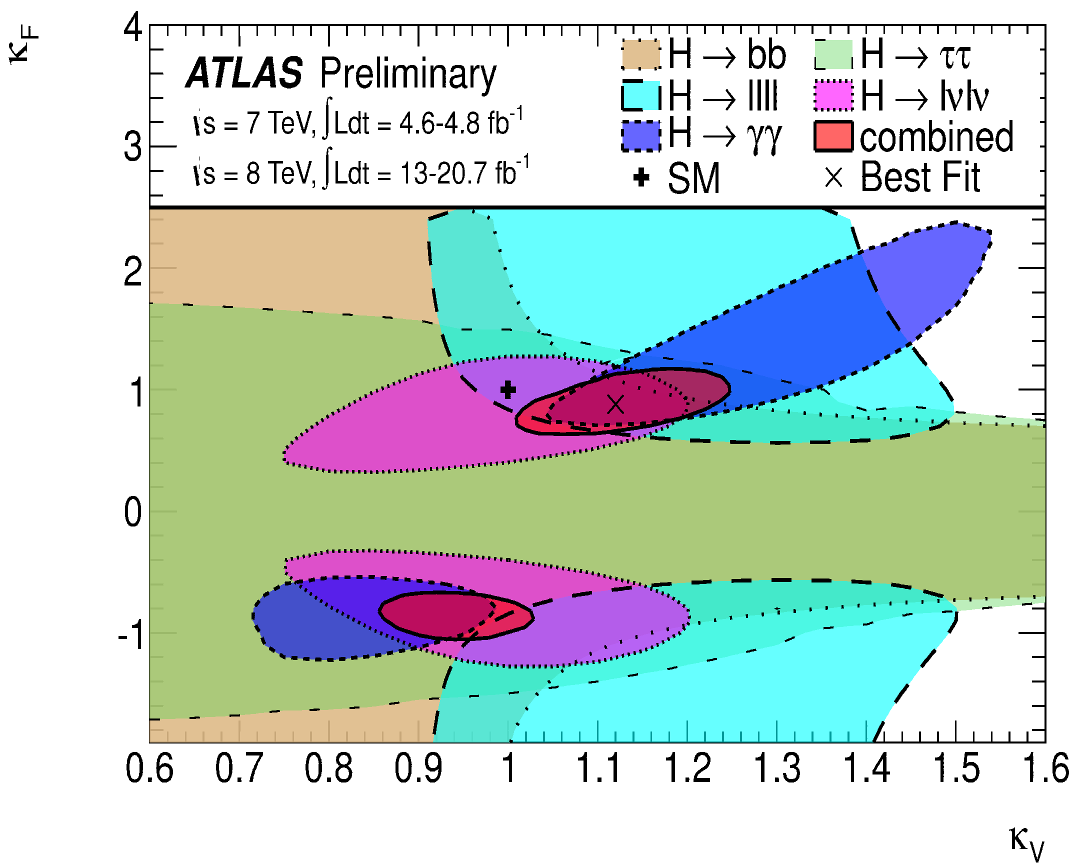
  Vector-like top partners generic too.
- Integrate out new physics at f, run to m_h: [Giudice *et al.* '07]

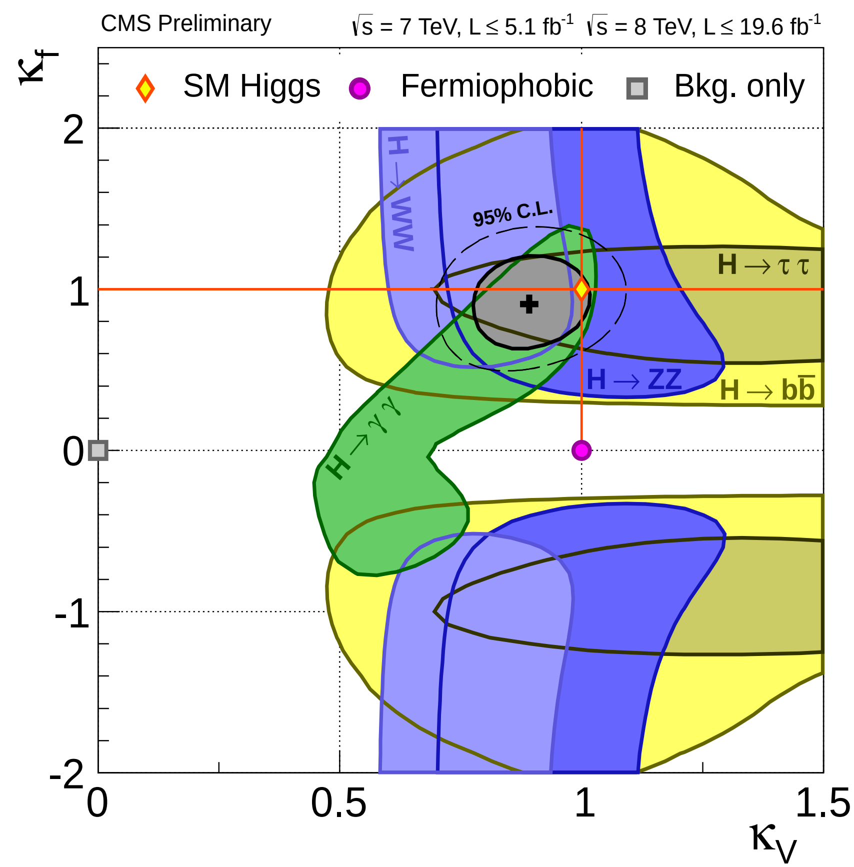
$$-\mathcal{L}_{eff} \supset \frac{c_f y_f}{f^2}|H|^2 \bar{F}_L f_R H + \frac{\tilde{c}_g \alpha_s}{4\pi}\frac{1}{f^2}|H|^2 G^a_{\mu\nu}G^{a\,\mu\nu} + \ldots$$

$$\to \kappa_f \frac{m_f}{v} h\bar{f}f + \kappa_g \frac{\alpha_s}{12\pi\, v} hG^a_{\mu\nu}G^{a\,\mu\nu} - \kappa_V \frac{m_V^2}{v} hV_\mu V^\mu + \ldots$$

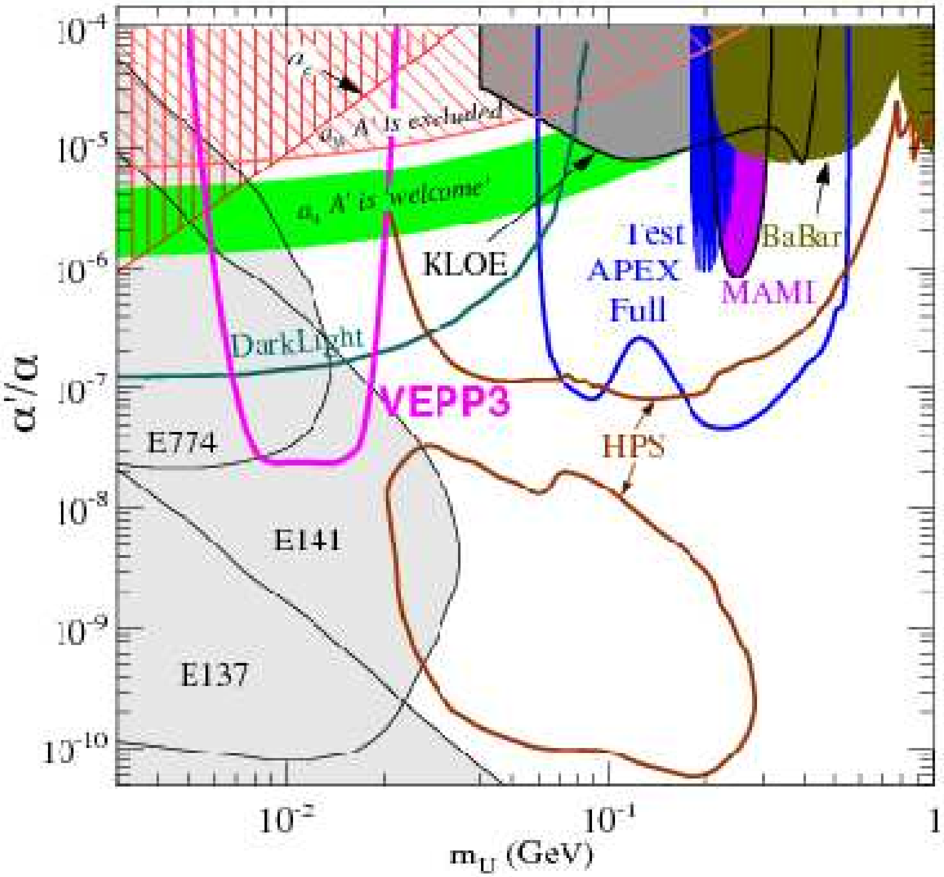
- $\kappa_i \to 1$ in the SM ($f/v \to \infty$).

- Fits to data: [ATLAS '13; CMS '13]





Searches for a Dark Photon: [e.g. Bjorken,Essig,Schuster,Toro '09]



[Kahn+Thaler '12]