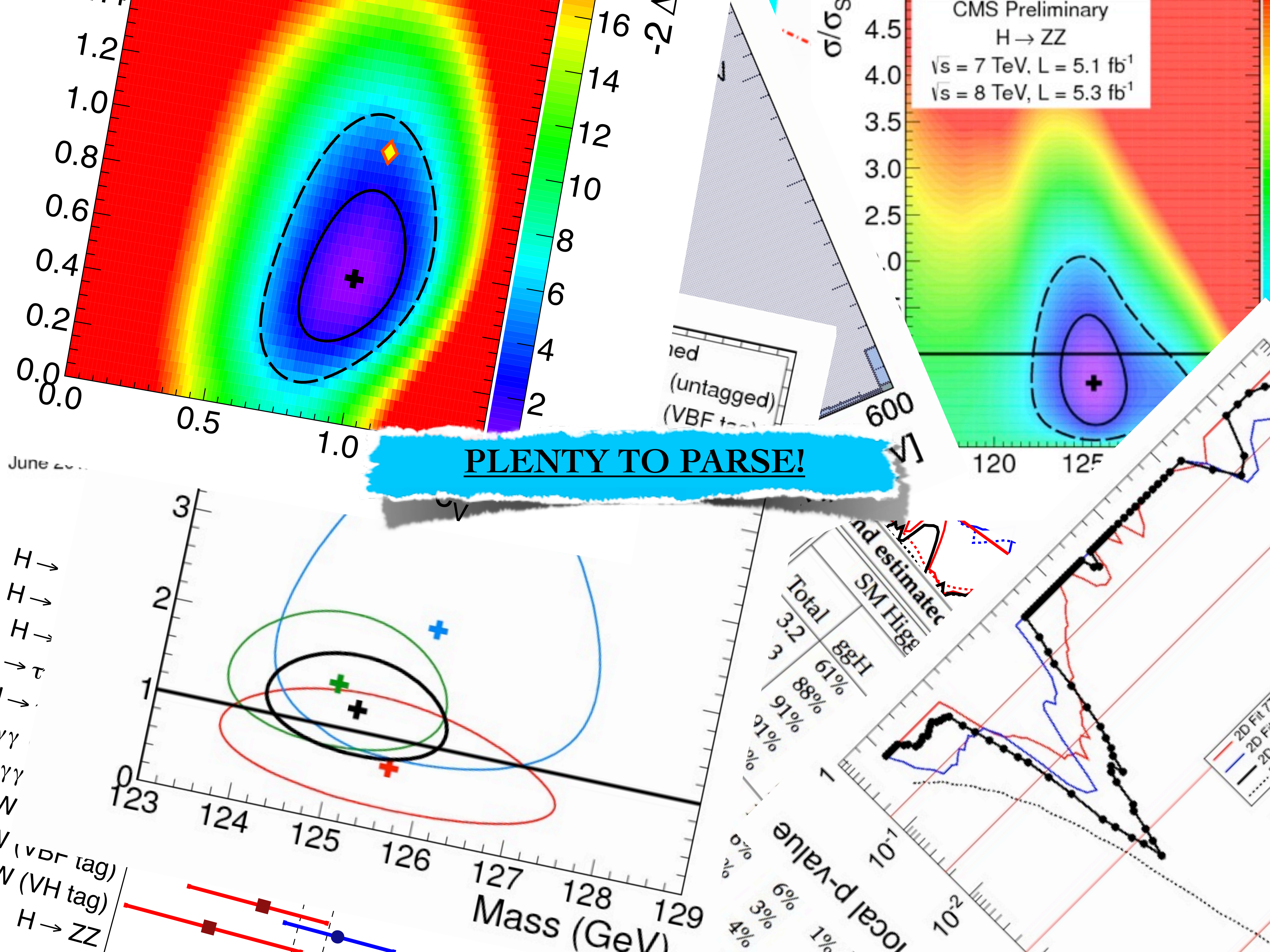
GETTING TO KNOW THE HIGGS

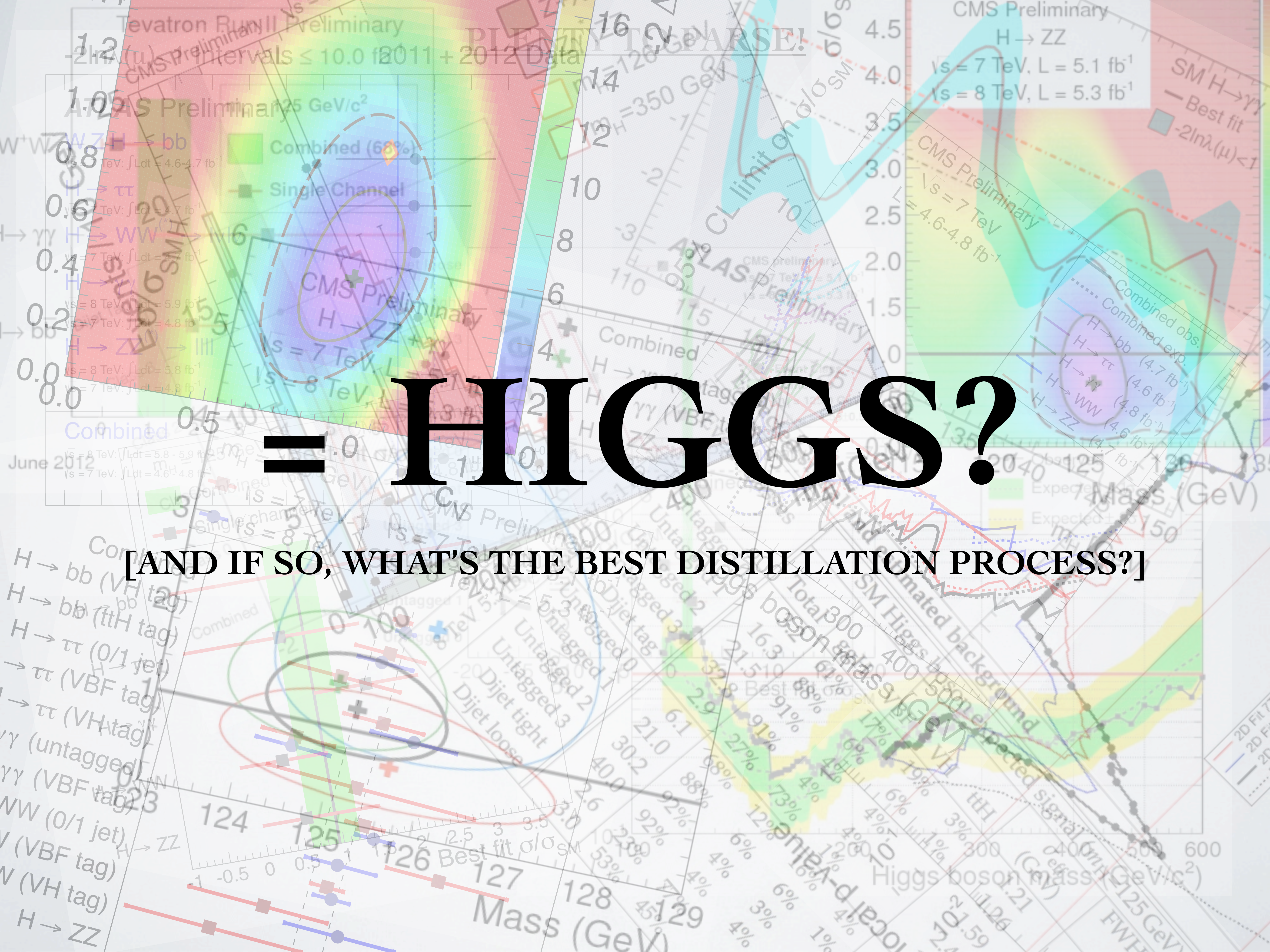
[And hoping it is a harbinger of more new physics]

Jamison Galloway
FNAL: July 19, 2012

Based on arXiv:1202.3415 with A. Azatov and R. Contino
arXiv:1206.1058 with A. Azatov, S. Chang, N. Craig

SAPIENZA
UNIVERSITÀ DI ROMA


PLENTY TO PARSE!
CMS Preliminary
H → ZZ
√s = 7 TeV, L = 5.1 fb⁻¹
√s = 8 TeV, L = 5.3 fb⁻¹
(untagged)
Total
SM Higgs
ggH
local p-value
Mass (GeV)
H → ZZ
(VH tag)



= HIGGS?

[AND IF SO, WHAT'S THE BEST DISTILLATION PROCESS?]

HIGGS HUNTERS ARE OFF THE LEASH!

HIGGS HUNTERS ARE OFF THE LEASH!

An apt metaphor:

We've been acting with a similar degree of enthusiasm...

HIGGS HUNTERS ARE OFF THE LEASH!

An apt metaphor:

We've been acting with a similar degree of enthusiasm...

...what about our degree of sophistication?

HIGGS HUNTERS ARE OFF THE LEASH!

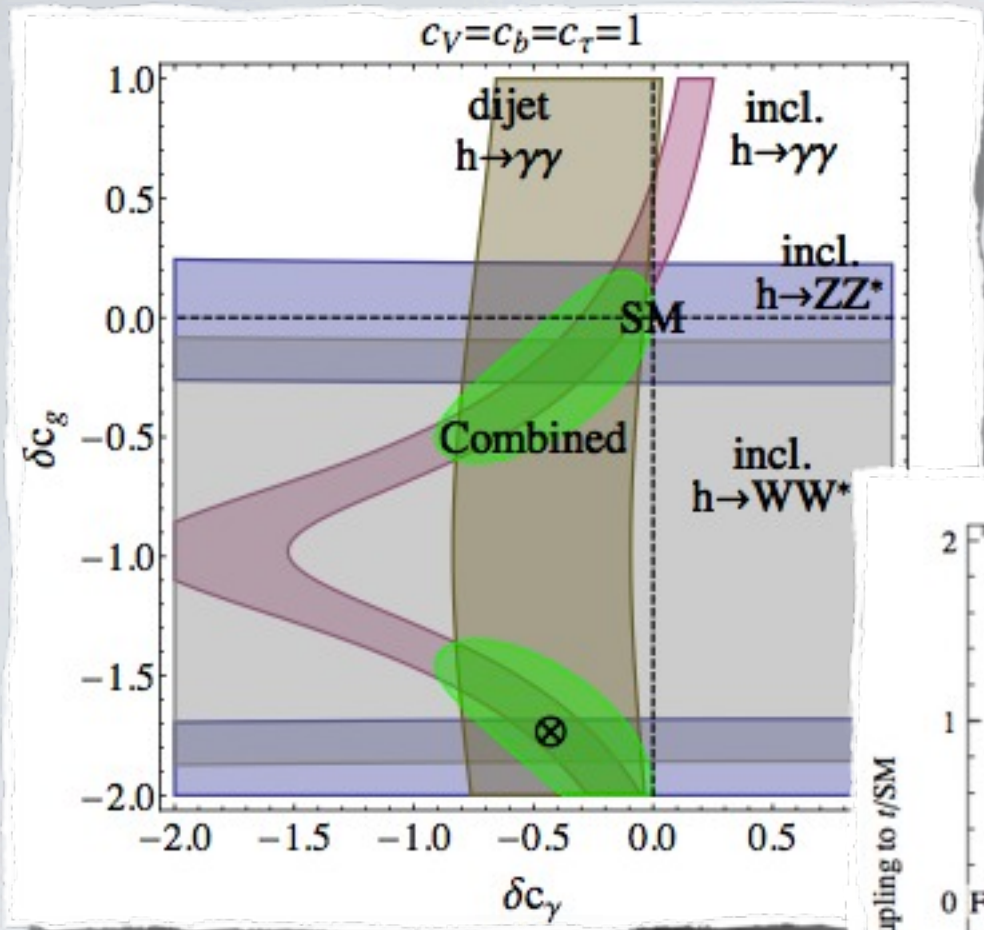
An apt metaphor:

We've been acting with a similar degree of enthusiasm...

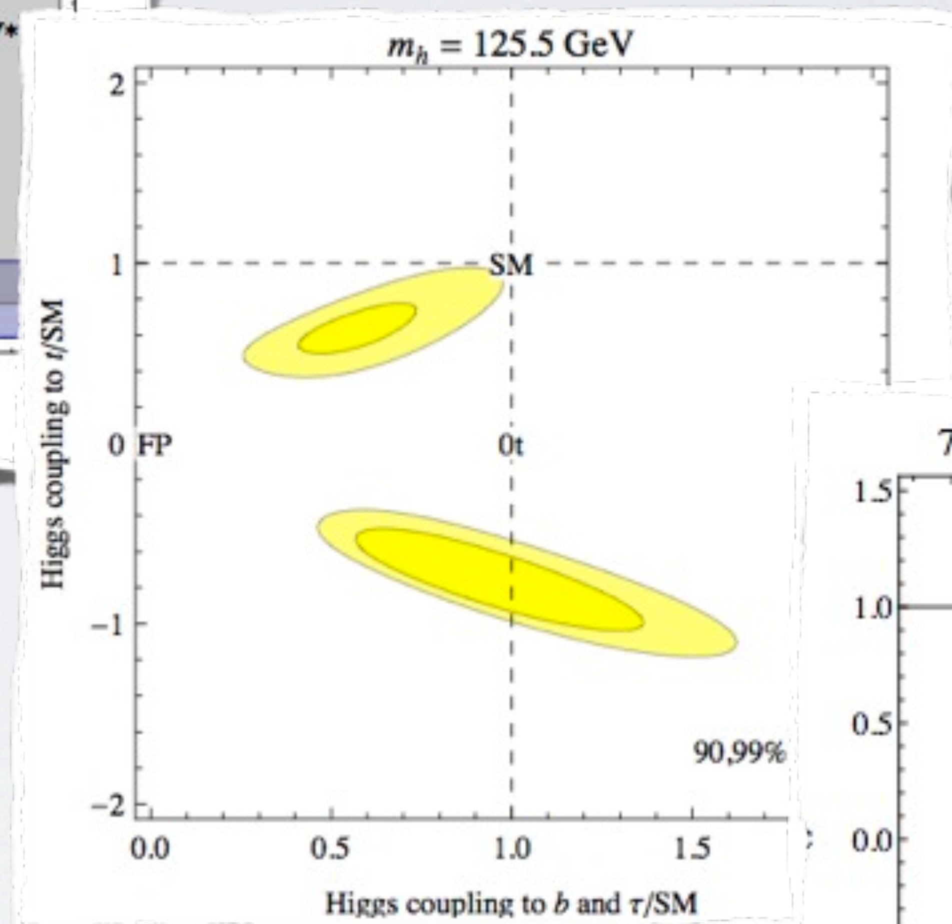
Can/should we trust collaboration outsiders?

What do the Higgs data tell us about new physics scenarios, and how firmly should we believe these conclusions?

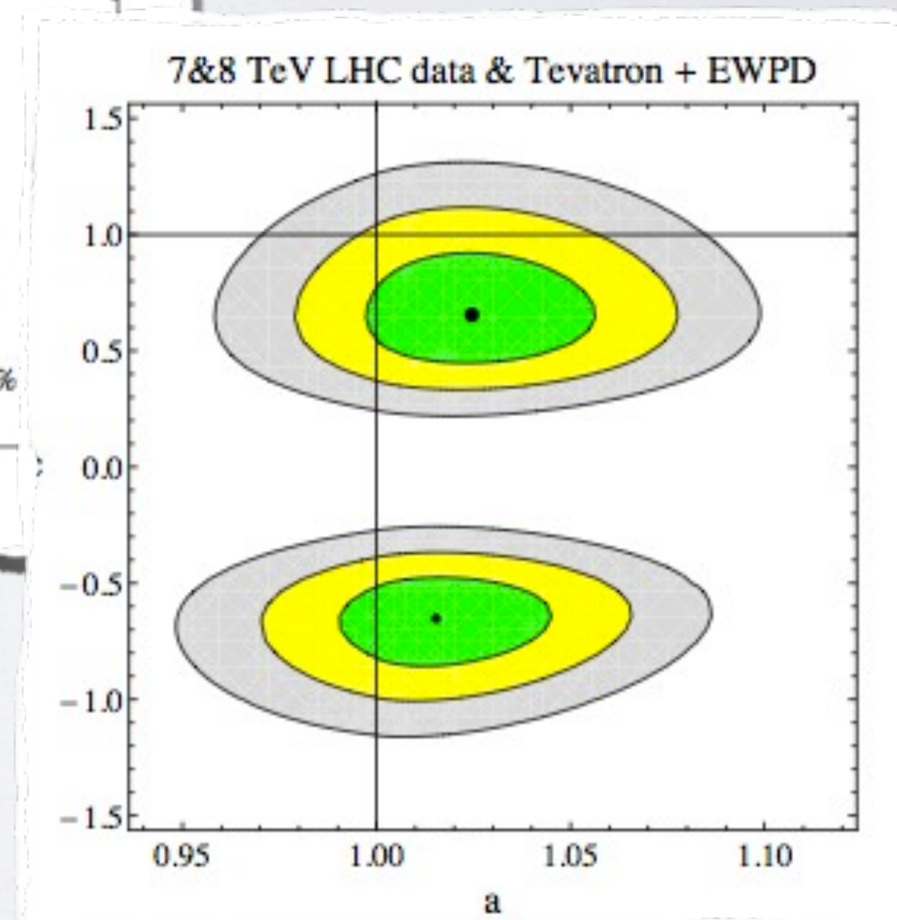
ASKED ANOTHER WAY: WHAT GOES IN TO THESE PLOTS?



(Carmi et al, 1207.1718)



(Giardino et al, 1207.1347)



(Espinosa et al, 1207.1717)

OUTLINE

1. Higgs constraints from the anxious past (February, 2012)

2. Higgs constraints from the frenzied present (July, 2012)

3. Higgs constraints as anticipatory aids and eventual consistency checks:

    a. Composite Higgs
    b. Supersymmetry
    c. Both? Other?

OUTLINE

1. Higgs constraints from the anxious past (February, 2012)

2. Higgs constraints from the frenzied present (July, 2012)

3. Higgs constraints as anticipatory aids and eventual consistency checks:

    a. Composite Higgs
    b. Supersymmetry
    c. Both? Other?

Primary focus: (simplified) METHODOLOGY
Theorists will need tools to constrain their favorite BSM scenarios...
WHICH TOOLS WORK?

PART ONE

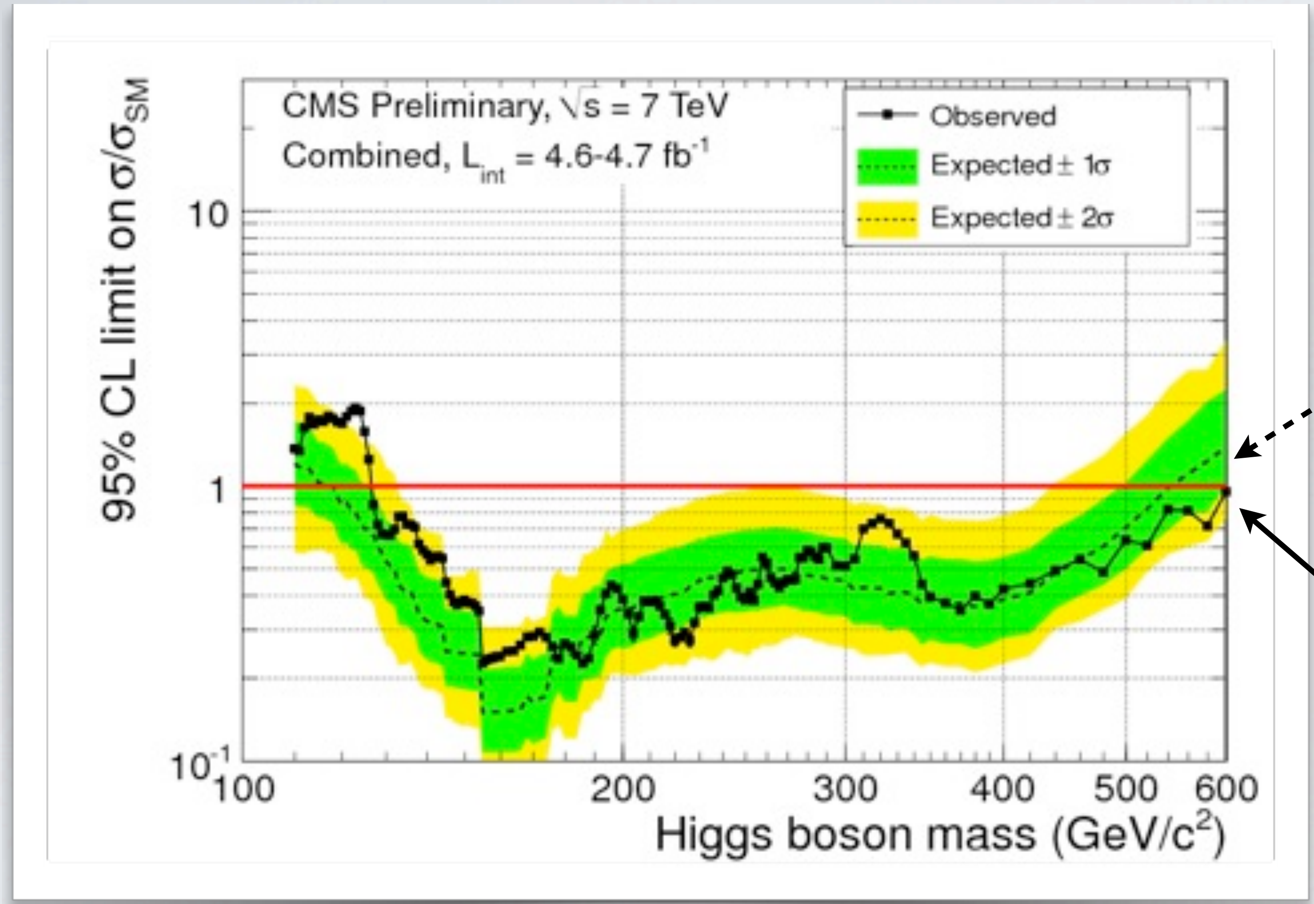
Prehistory

PART ONE

(Pre*Higgs*tory)

PRE-HIGGS: WHAT WERE WE LEARNING FROM THE LHC?

Answer: Exclusion limits (of course)



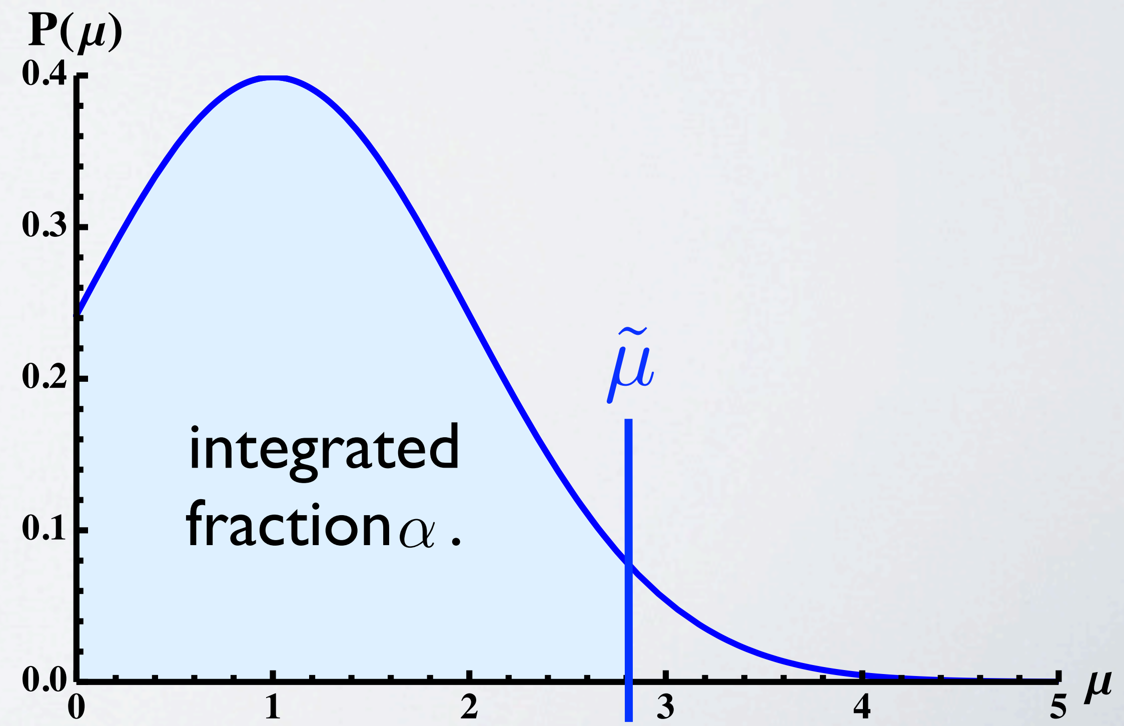
with data like this very kindly provided for each search channel over their entire mass range.

Expected:

$$\alpha = \int_0^{\tilde{\mu}^{(\alpha)}_{\rm exp}} d\mu\, P(n_B + \mu n_S | n_{\rm obs} = n_B)$$

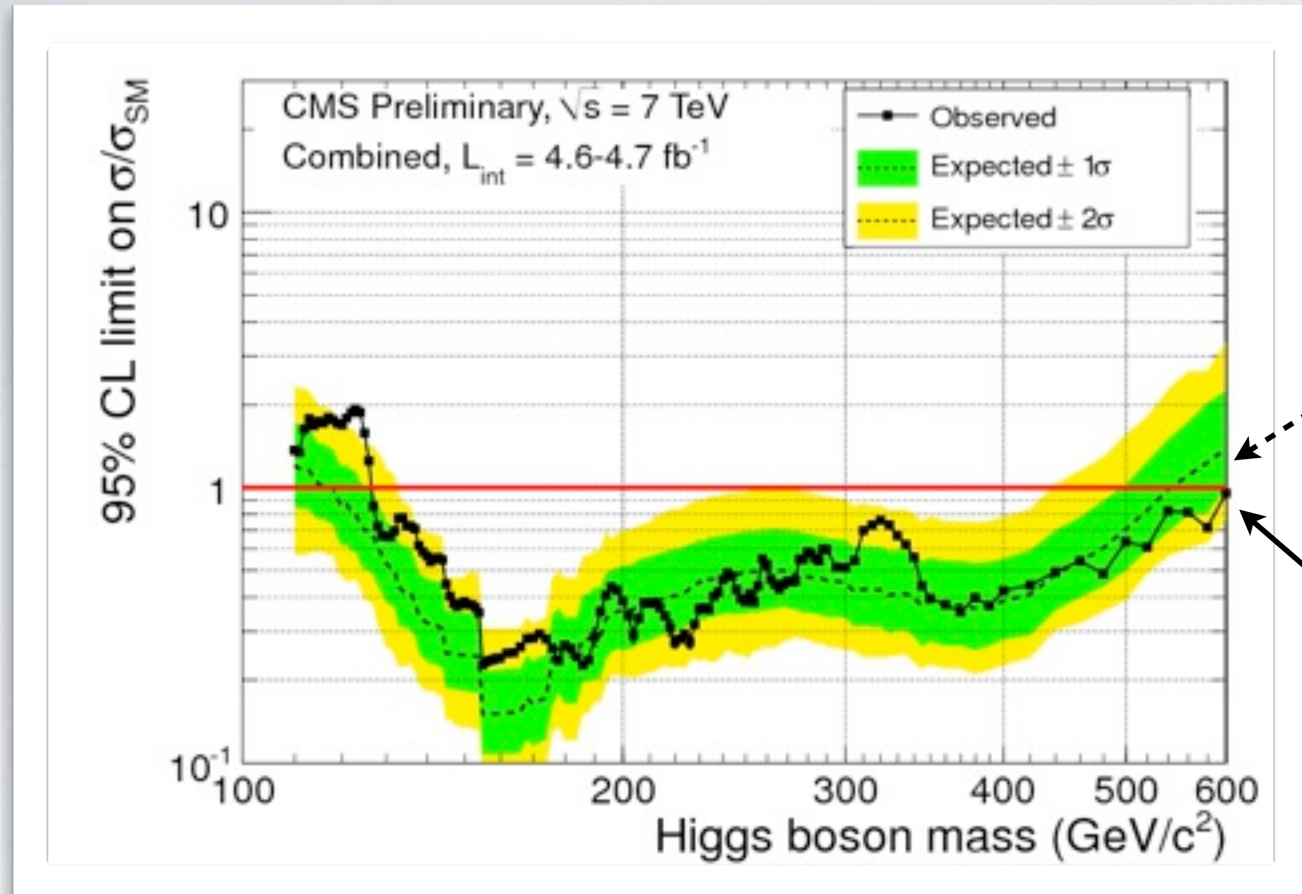
Observed:

$$\alpha = \int_0^{\tilde{\mu}^{(\alpha)}_{\rm obs}} d\mu\, P(n_B + \mu n_S | n_{\rm obs})$$



PRE-HIGGS: WHAT WERE WE LEARNING FROM THE LHC?

Answer: Exclusion limits (of course)



with data like this very kindly provided for each search channel over their entire mass range.

Expected:

$$\alpha = \int_0^{\tilde{\mu}^{(\alpha)}_{\rm exp}} d\mu\, P(n_B + \mu n_S | n_{\rm obs} = n_B)$$

Observed:

$$\alpha = \int_0^{\tilde{\mu}^{(\alpha)}_{\rm obs}} d\mu\, P(n_B + \mu n_S | n_{\rm obs})$$

Already this is enough to start constraining *generic* spaces, not *just* SM-like (far from obvious)

INTERLUDE: DEFINING "GENERIC"?

The 'substandard model' has to be augmented

Three massive vectors, triplet of approximate SU(2)

$$\begin{aligned} U &= \exp\left[2i\tau_a\pi_a(x)/v\right] \\ &\mapsto LUR^\dagger \end{aligned}$$

described at leading order:

$$\begin{aligned} \Delta\mathcal{L} &= \frac{v^2}{4}\mathrm{tr}\left[(D_\mu U)^\dagger(D^\mu U)\right] \\ &\quad -\frac{v}{\sqrt{2}}\,\psi_i^c\,U^\dagger \times \lambda_{ij}\psi_j + \mathrm{h.c.} \end{aligned}$$

INTERLUDE: DEFINING "GENERIC"?

The 'substandard model' has to be augmented

Three massive vectors, triplet of approximate SU(2)

$$\begin{aligned} U &= \exp\left[2i\tau_a\pi_a(x)/v\right] \\ &\mapsto LUR^\dagger \end{aligned}$$

described at leading order:

$$\begin{aligned} \Delta\mathcal{L} &= \frac{v^2}{4}\mathrm{tr}\left[(D_\mu U)^\dagger(D^\mu U)\right] \times \left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \ldots\right) \\ &\quad -\frac{v}{\sqrt{2}}\,\psi_i^c\,U^\dagger \times \lambda_{ij}\psi_j + \mathrm{h.c.} \times \left(1 + c\frac{h}{v} + \ldots\right) \end{aligned}$$

Assumption: the (custodial singlet) 'Higgs' might not be single-handedly responsible for unitarization, etc.

more specifically: non-linearities may persist...
OTHER NEW PHYSICS enters at potentially low scales

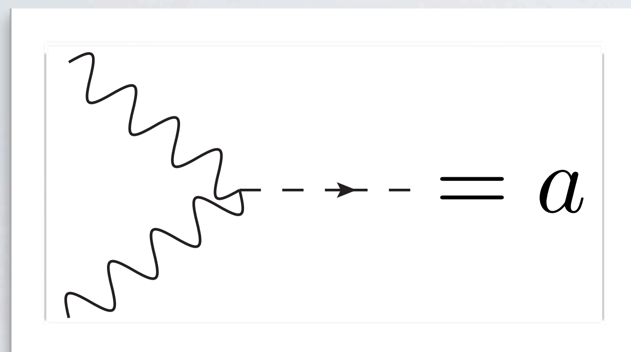
The 'substandard model' has to be augmented

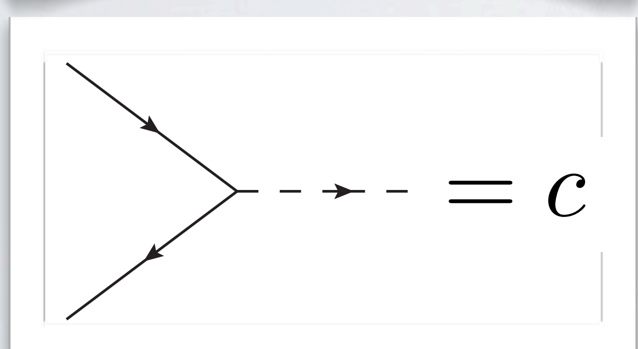
Three massive vectors, triplet of approximate SU(2)

$$\begin{aligned} U &= \exp\left[2i\tau_a\pi_a(x)/v\right] \\ &\mapsto LUR^\dagger \end{aligned}$$

described at leading order:

$$\begin{aligned} \Delta\mathcal{L} &= \frac{v^2}{4}\mathrm{tr}\left[(D_\mu U)^\dagger(D^\mu U)\right] \times \left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \ldots\right) \\ &\quad - \frac{v}{\sqrt{2}}\,\psi_i^c\,U^\dagger \times \lambda_{ij}\psi_j + \mathrm{h.c.} \times \left(1 + c\frac{h}{v} + \ldots\right) \end{aligned}$$





FOCUSING ON THESE GUYS

Case studies to come: (minimal) compositeness and SUSY

INTERLUDE: DEFINING "GENERIC"?

The 'substandard model' has to be augmented

Three massive vectors, triplet of approximate SU(2)

$$
\begin{aligned}
U &= \exp\left[2i\tau_a\pi_a(x)/v\right] \\
&\mapsto LUR^\dagger
\end{aligned}
$$

described at leading order:

$$
\begin{aligned}
\Delta\mathcal{L} &= \frac{v^2}{4}\mathrm{tr}\left[(D_\mu U)^\dagger(D^\mu U)\right] \times \left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \ldots\right) \\
&\quad - \frac{v}{\sqrt{2}}\,\psi_i^c\,U^\dagger \times \lambda_{ij}\psi_j + \mathrm{h.c.} \times \left(1 + c\frac{h}{v} + \ldots\right)
\end{aligned}
$$

WHY?

I. Naturalness $\propto$ (Couplings' deviation from SM)

II. Highly relevant for constraining 'typical' BSM @ early LHC

III. Consistency check if other low-mass EWSB states appear

(RE)CONSTRUCTING LIKELIHOODS IN THE B.H. ERA

(Three variables, only two constraints: we need to be slightly clever)

Assume asymptotic limit, i.e. Poisson $\longrightarrow$ Gaussian:

$$P(n_B + \mu n_S | n_{\rm obs}) = \pi(\mu) \times \exp\left[\frac{-(n_B + \mu n_S - n_{\rm obs})^2}{2 n_{\rm obs}}\right]$$

$$\Rightarrow \tilde{\mu}^{95\%}_{\rm exp} = 1.96 \times \frac{\sqrt{n_B}}{n_S}$$

(RE)CONSTRUCTING LIKELIHOODS IN THE B.H. ERA

(Three variables, only two constraints: we need to be slightly clever)

Assume asymptotic limit, i.e. Poisson ⟶ Gaussian:

$$P(n_B + \mu n_S | n_{\rm obs}) = \pi(\mu) \times \exp\left[\frac{-(n_B + \mu n_S - n_{\rm obs})^2}{2 n_{\rm obs}}\right]$$

$$\Rightarrow \tilde{\mu}^{95\%}_{\rm exp} = 1.96 \times \frac{\sqrt{n_B}}{n_S}$$

For observed exclusion, use a simple rewriting:

$$P(n_B + \mu n_S | n_{\rm obs}) = \pi(\mu) \times \exp\left[-\frac{1}{2}\left(\mu \frac{n_S}{\sqrt{n_B}} \frac{\sqrt{n_B}}{\sqrt{n_{\rm obs}}} + \delta\right)^2\right]; \quad \delta \equiv \frac{n_B - n_{\rm obs}}{\sqrt{n_{\rm obs}}}$$

(RE)CONSTRUCTING LIKELIHOODS IN THE B.H. ERA

(Three variables, only two constraints: we need to be slightly clever)

Assume asymptotic limit, i.e. Poisson $\longrightarrow$ Gaussian:

$$P(n_B + \mu n_S | n_{\rm obs}) = \pi(\mu) \times \exp\left[\frac{-(n_B + \mu n_S - n_{\rm obs})^2}{2 n_{\rm obs}}\right]$$

$$\Rightarrow \tilde{\mu}^{95\%}_{\rm exp} = 1.96 \times \frac{\sqrt{n_B}}{n_S}$$

For observed exclusion, use a simple rewriting:

$$P(n_B + \mu n_S | n_{\rm obs}) = \pi(\mu) \times \exp\left[-\frac{1}{2}\left(\mu \frac{n_S}{\sqrt{n_B}} \frac{\sqrt{n_B}}{\sqrt{n_{\rm obs}}} + \delta\right)^2\right]; \quad \delta \equiv \frac{n_B - n_{\rm obs}}{\sqrt{n_{\rm obs}}}$$

Now make the assumption $\frac{n_{\rm obs} - n_B}{n_{\rm obs}} \ll 1$

(RE)CONSTRUCTING LIKELIHOODS IN THE B.H. ERA

(Three variables, only two constraints: we need to be slightly clever)

Assume asymptotic limit, i.e. Poisson $\longrightarrow$ Gaussian:

$$P(n_B + \mu n_S | n_{\rm obs}) = \pi(\mu) \times \exp\left[\frac{-(n_B + \mu n_S - n_{\rm obs})^2}{2 n_{\rm obs}}\right]$$

$$\Rightarrow \tilde{\mu}^{95\%}_{\rm exp} = 1.96 \times \frac{\sqrt{n_B}}{n_S}$$

For observed exclusion, use a simple rewriting:

$$P(n_B + \mu n_S | n_{\rm obs}) = \pi(\mu) \times \exp\left[-\frac{1}{2}\left(\mu \frac{n_S}{\sqrt{n_B}} \frac{\sqrt{n_B}}{\sqrt{n_{\rm obs}}} + \delta\right)^2\right]; \quad \delta \equiv \frac{n_B - n_{\rm obs}}{\sqrt{n_{\rm obs}}}$$

Now make the assumption $\dfrac{n_{\rm obs} - n_B}{n_{\rm obs}} \ll 1$

(RE)CONSTRUCTING LIKELIHOODS IN THE B.H. ERA

(Three variables, only two constraints: we need to be slightly clever)

Assume asymptotic limit, i.e. Poisson ⟶ Gaussian:

$$P(n_B + \mu n_S | n_{\rm obs}) = \pi(\mu) \times \exp\left[\frac{-(n_B + \mu n_S - n_{\rm obs})^2}{2 n_{\rm obs}}\right]$$

$$\Rightarrow \tilde{\mu}^{95\%}_{\rm exp} = 1.96 \times \frac{\sqrt{n_B}}{n_S}$$

For observed exclusion, use a simple rewriting:

$$P(n_B + \mu n_S | n_{\rm obs}) = \pi(\mu) \times \exp\left[-\frac{1}{2}\left(\mu \frac{n_S}{\sqrt{n_B}} \frac{\sqrt{n_B}}{\sqrt{n_{\rm obs}}} + \delta\right)^2\right]; \quad \delta \equiv \frac{n_B - n_{\rm obs}}{\sqrt{n_{\rm obs}}}$$

Now make the assumption $\dfrac{n_{\rm obs} - n_B}{n_{\rm obs}} \ll 1$

(RE)CONSTRUCTING LIKELIHOODS IN THE B.H. ERA

$$P(\mu) = N \times \exp\left[-\frac{1}{2}\left(\frac{1.96 \times \mu}{\tilde{\mu}^{(95\%)}_{\mathrm{exp}}} + \delta\right)^2\right]$$

(RE)CONSTRUCTING LIKELIHOODS IN THE B.H. ERA

$$P(\mu) = N \times \exp\left[-\frac{1}{2}\left(\frac{1.96 \times \mu}{\tilde{\mu}^{(95\%)}_{\rm exp}} + \delta\right)^2\right]$$

Solve for remaining parameter using observed exclusion limit:

$$0.95 = \int_0^{\tilde{\mu}^{(95\%)}_{\rm obs}} d\mu \, P(\mu)$$

(RE)CONSTRUCTING LIKELIHOODS IN THE B.H. ERA

$$P(\mu) = N \times \exp\left[-\frac{1}{2}\left(\frac{1.96 \times \mu}{\tilde{\mu}_{\rm exp}^{(95\%)}} + \delta\right)^2\right]$$

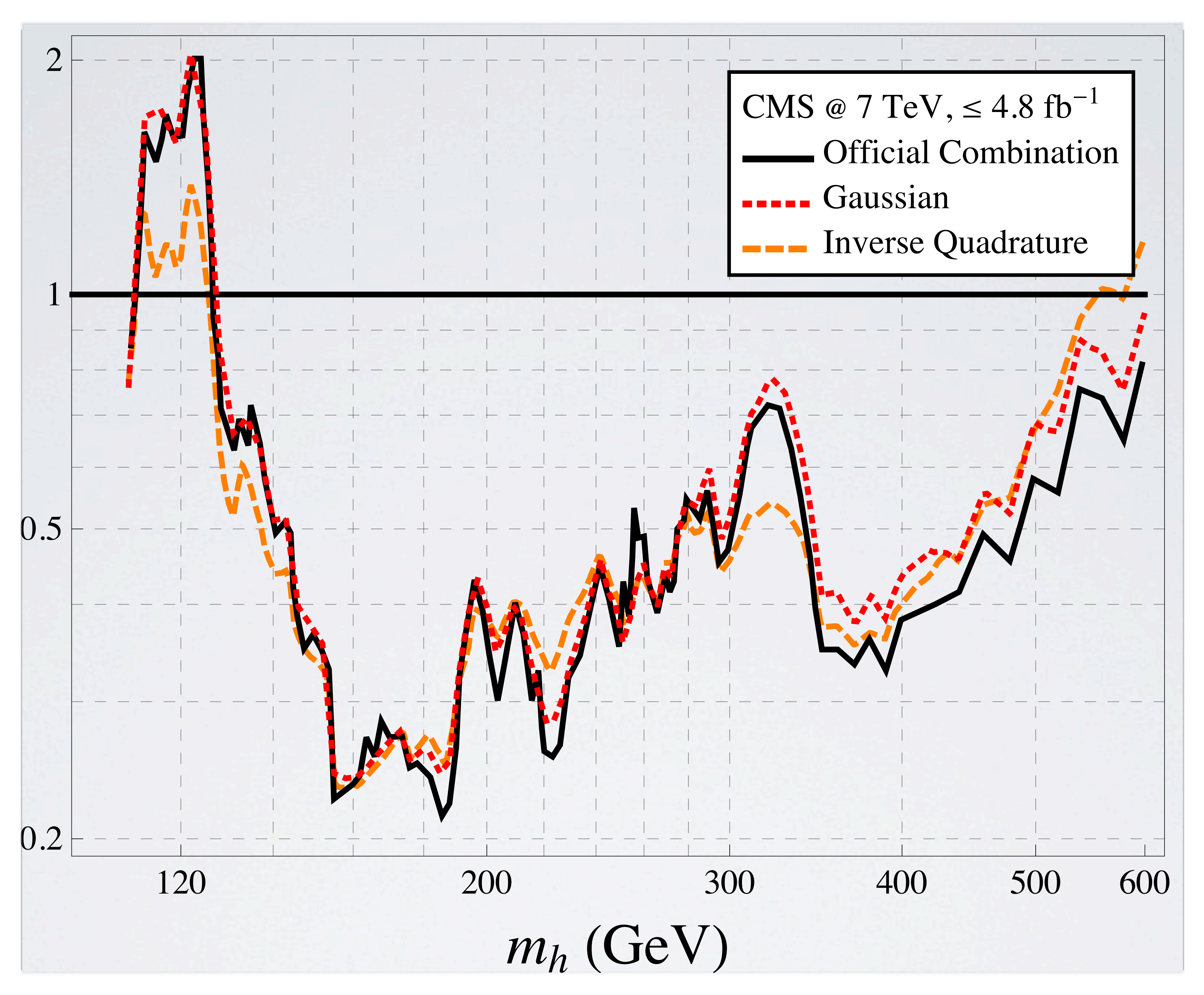
Solve for remaining parameter using observed exclusion limit:

$$0.95 = \int_0^{\tilde{\mu}_{\rm obs}^{(95\%)}} d\mu\, P(\mu)$$

RECAP:

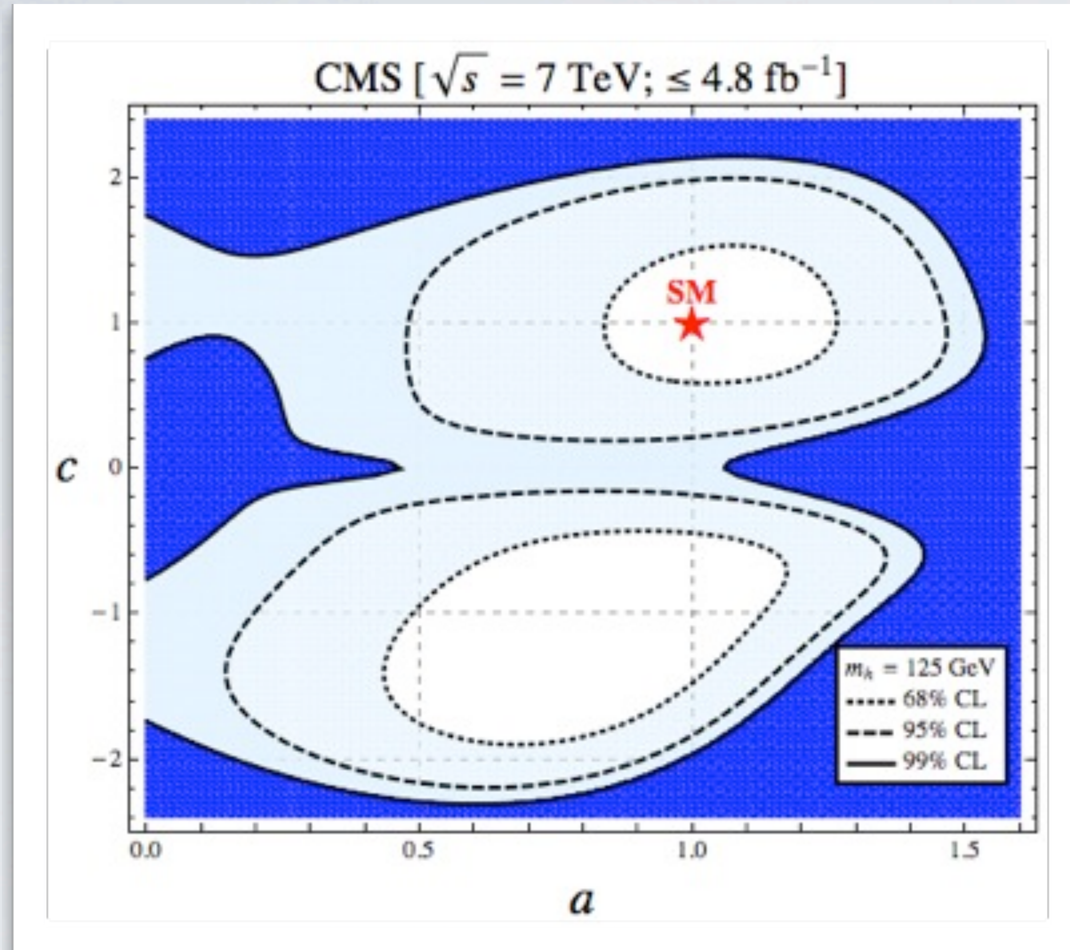
- Expected exclusion tells us about s/b
- Observed tells us delta, completes determination of (AL) likelihood
- Can be done over whole mass range, not just at ‘peaks’ with fits

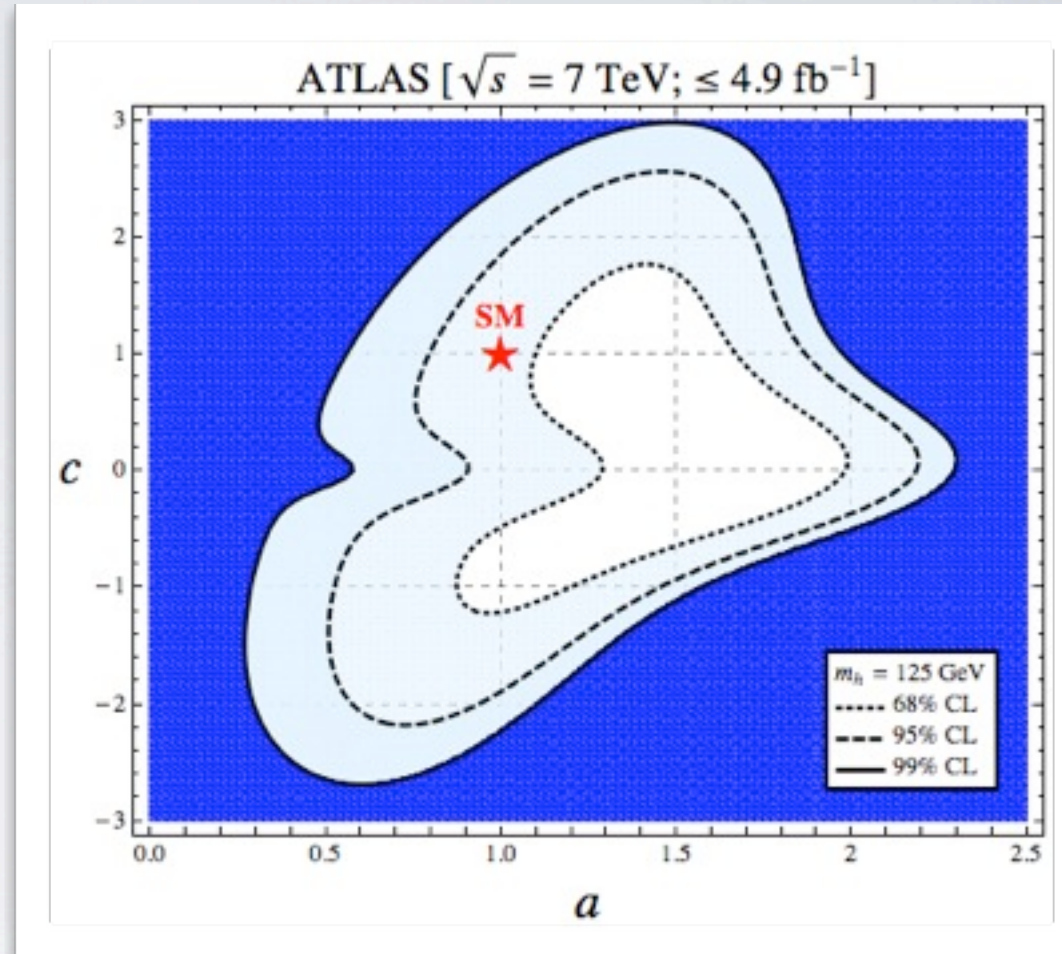
SANITY CHECK



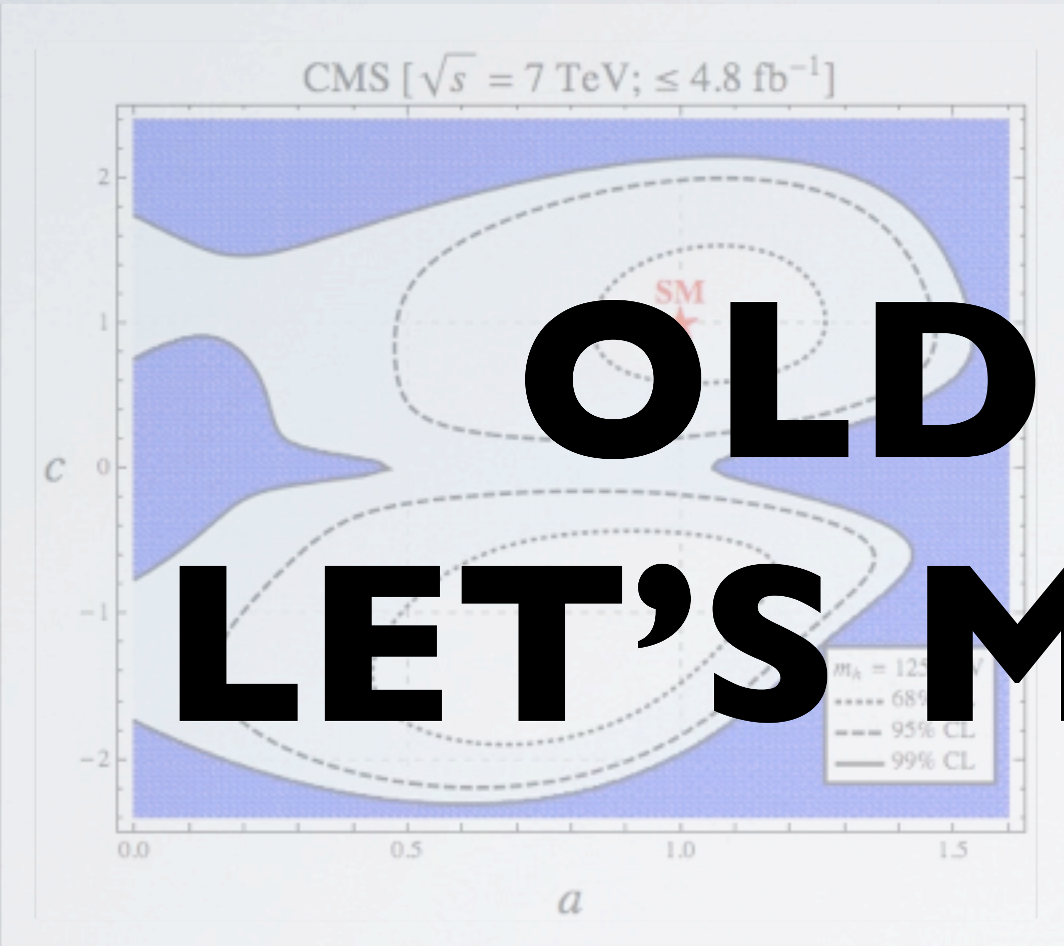
Provided we know exclusive breakdowns (i.e. have an idea of production mechanism) we can map multi-dimensional spaces to these likelihoods

USING 'RECONSTRUCTED' LIKELIHOODS





USING ‘RECONSTRUCTED’ LIKELIHOODS



OLD NEWS
LET’S MOVE ON*

* Though method still of use in cases where best fits are unavailable

PART TWO

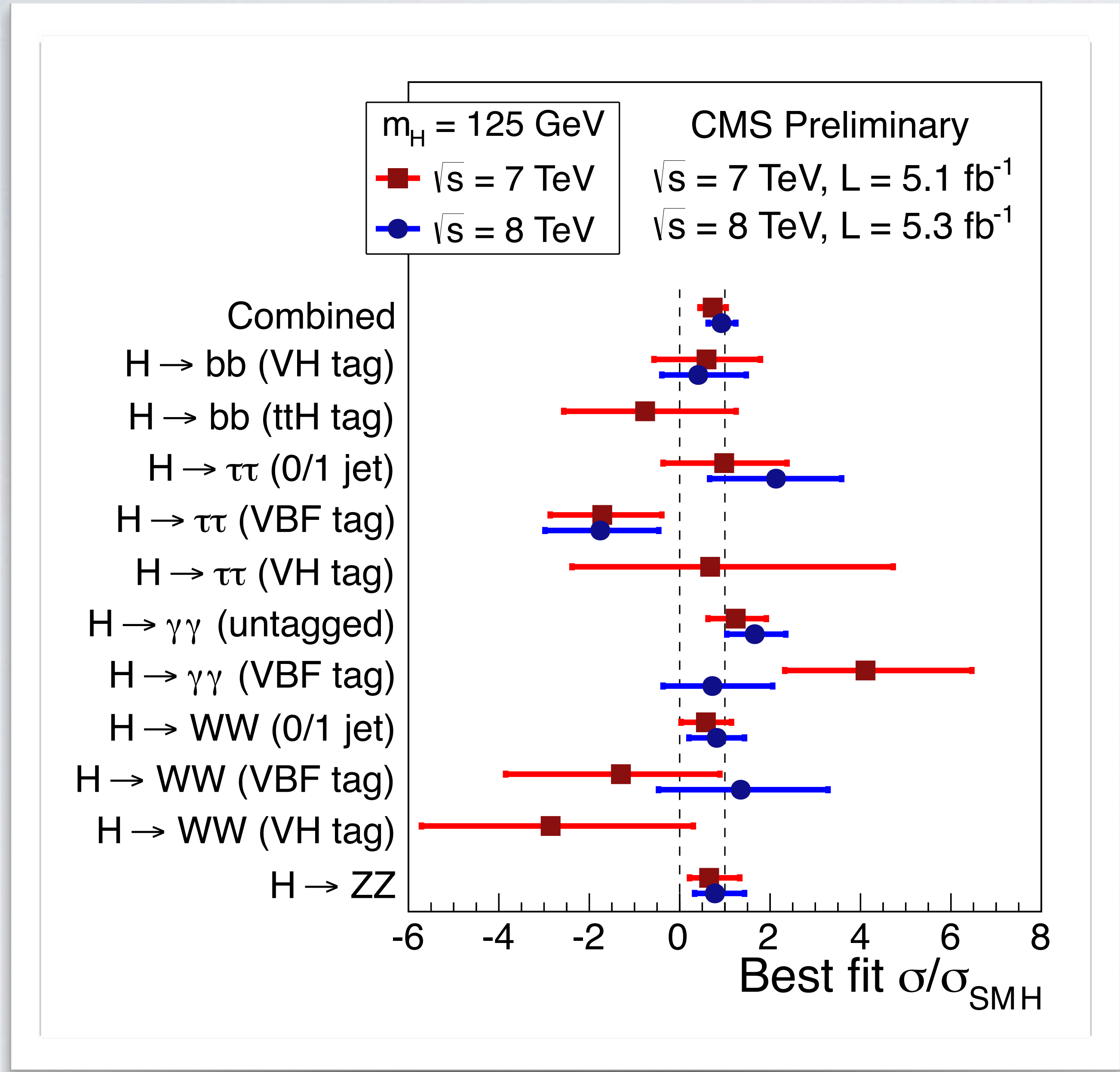
The Higgs Era

WHAT ARE WE LEARNING *NOW* FROM THE LHC?

The obvious point: we're no longer working with only exclusion data. What tools can we test and use now?

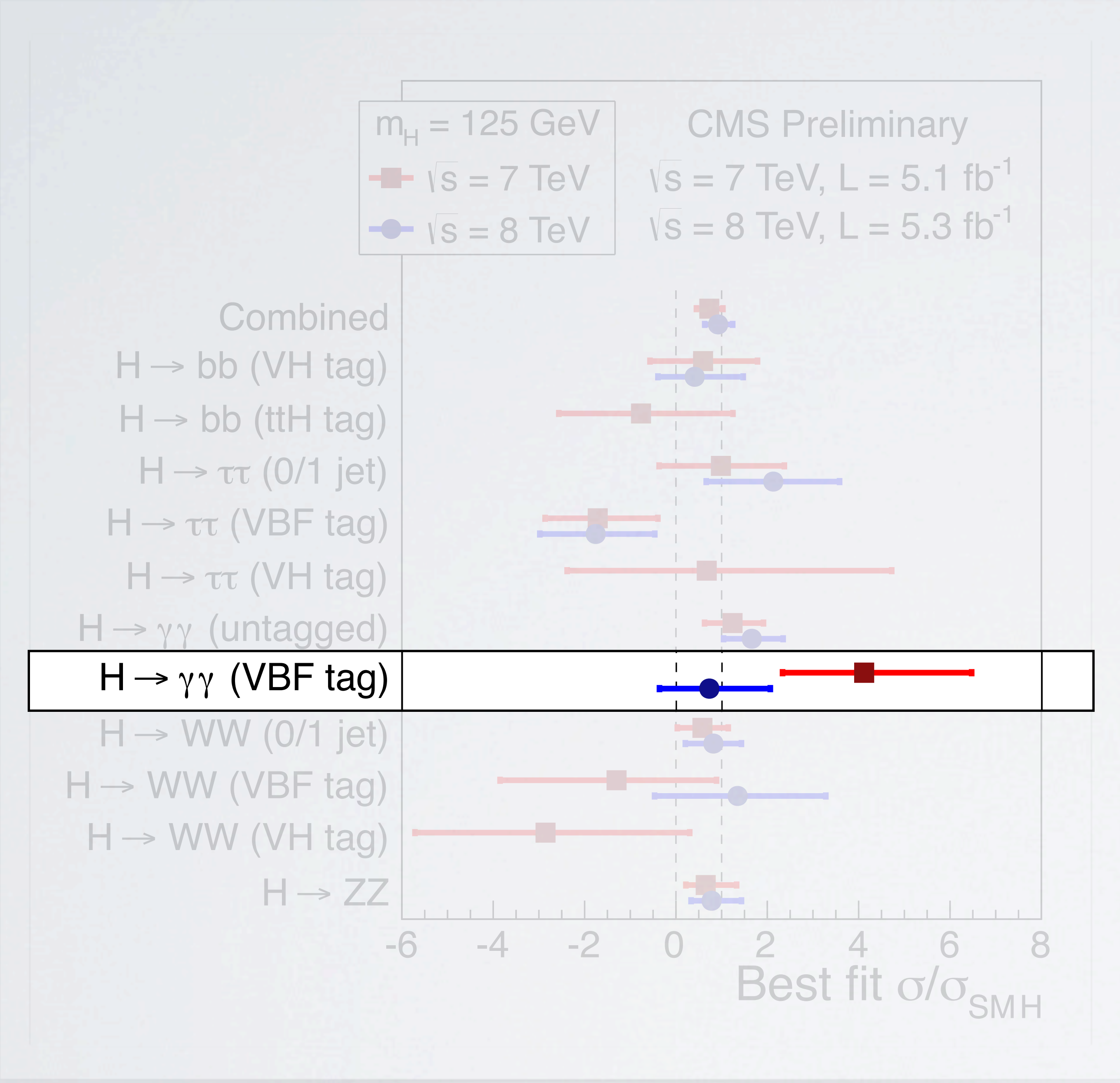
WHAT ARE WE LEARNING *NOW* FROM THE LHC?

No likelihoods directly (yet), but we have de facto *snapshots* of them:



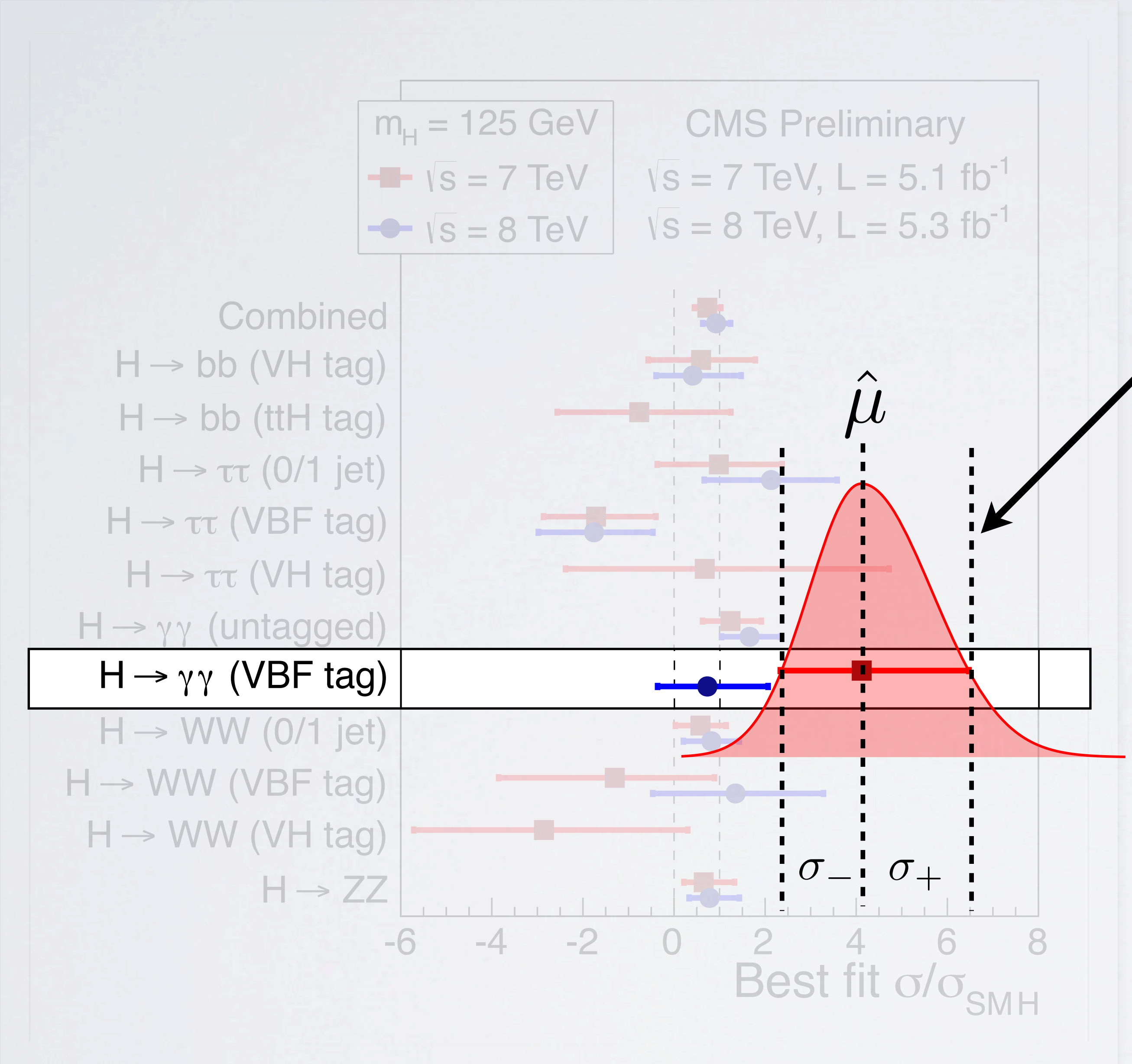
WHAT ARE WE LEARNING *NOW* FROM THE LHC?

No likelihoods directly (yet), but we have de facto *snapshots* of them:



WHAT ARE WE LEARNING *NOW* FROM THE LHC?

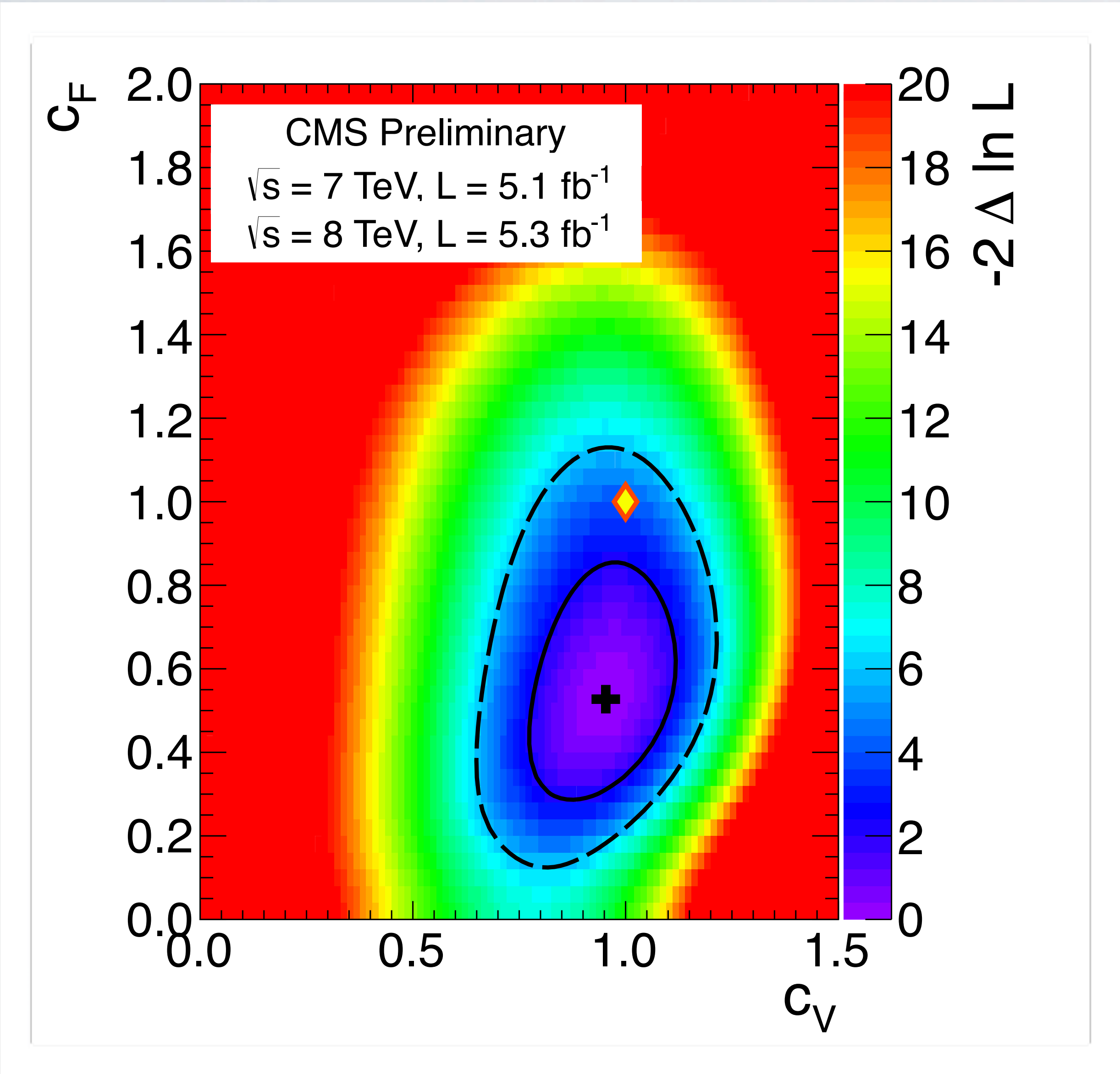
No likelihoods directly (yet), but we have de facto *snapshots* of them:

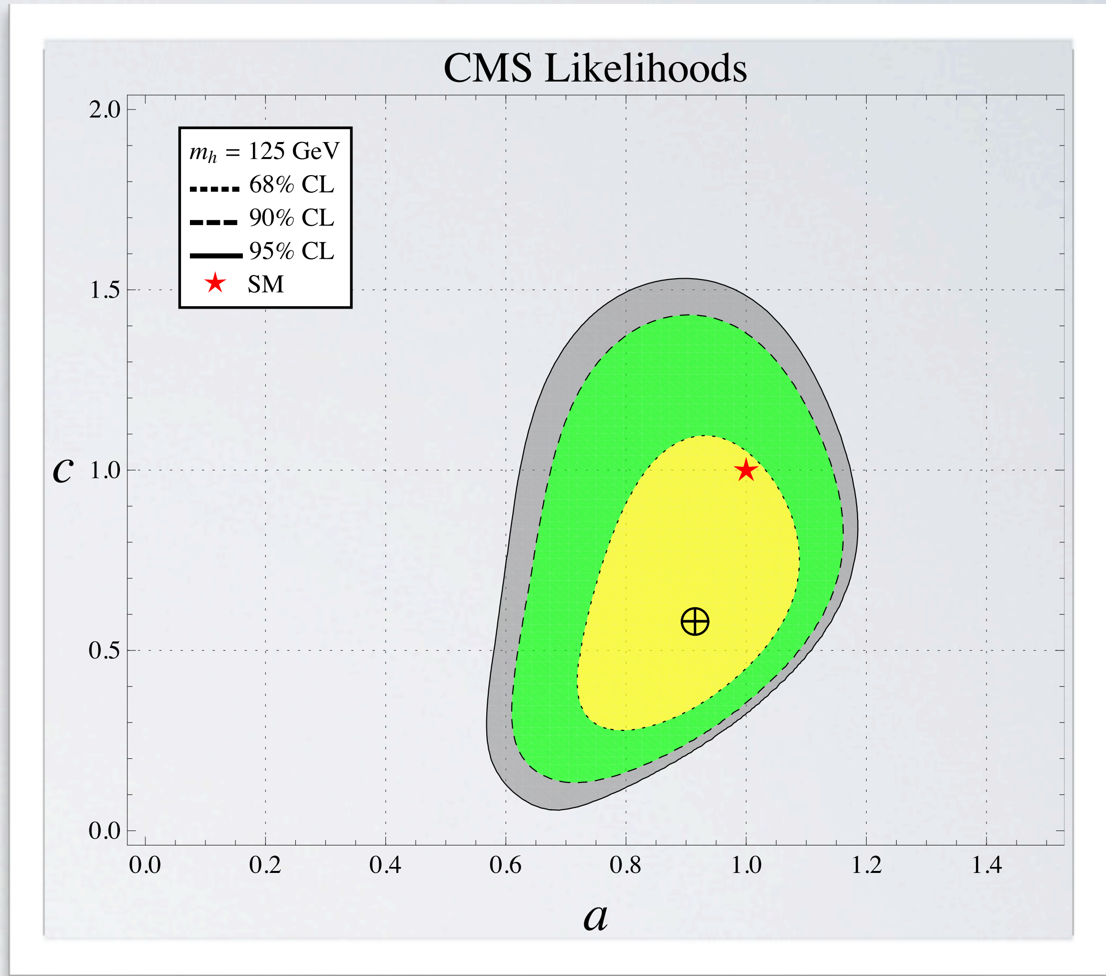


Fit approximately with two-sided Gaussian (typically broader than true likelihood, so errs on the conservative side)

$$P^i_\pm(\mu) = \pi(\mu) \times \exp \frac{-(\mu - \hat{\mu}^i_\pm)^2}{2(\sigma^i_\pm)^2}$$

UPDATED SANITY CHECK

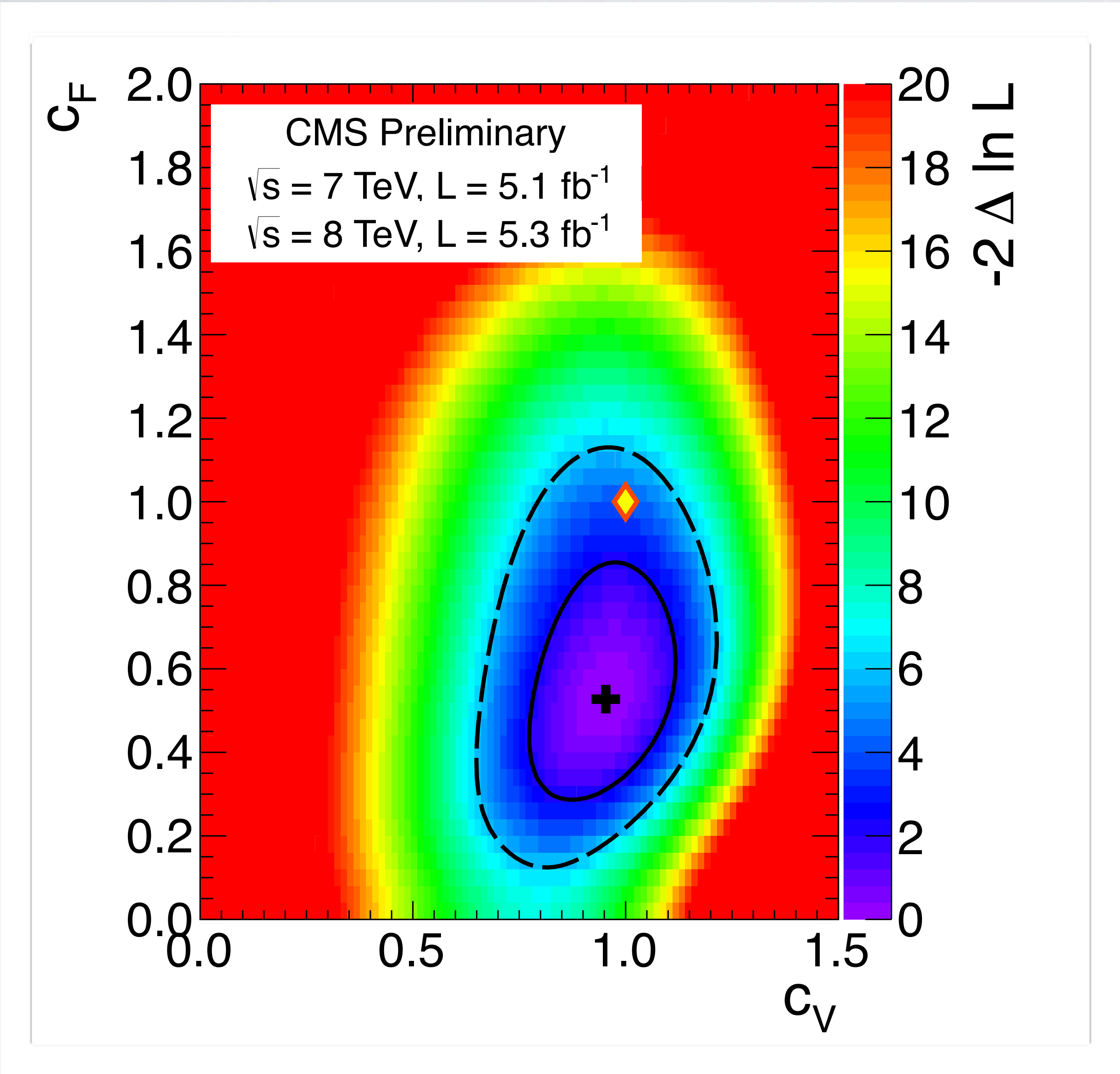


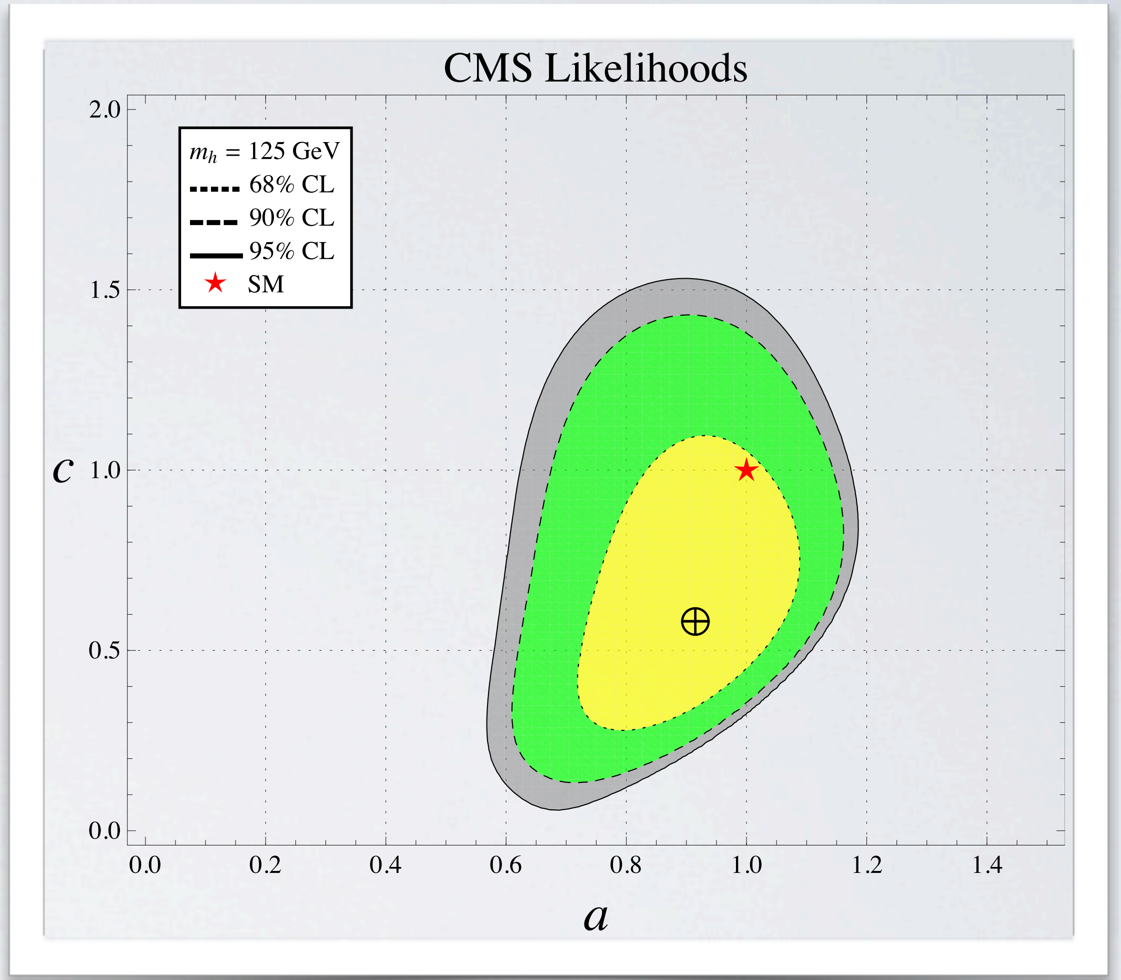


To notice:

- Best fit well captured (as should be anticipated)
- Errs on the conservative side (as advertised) by <1sigma or so

UPDATED SANITY CHECK

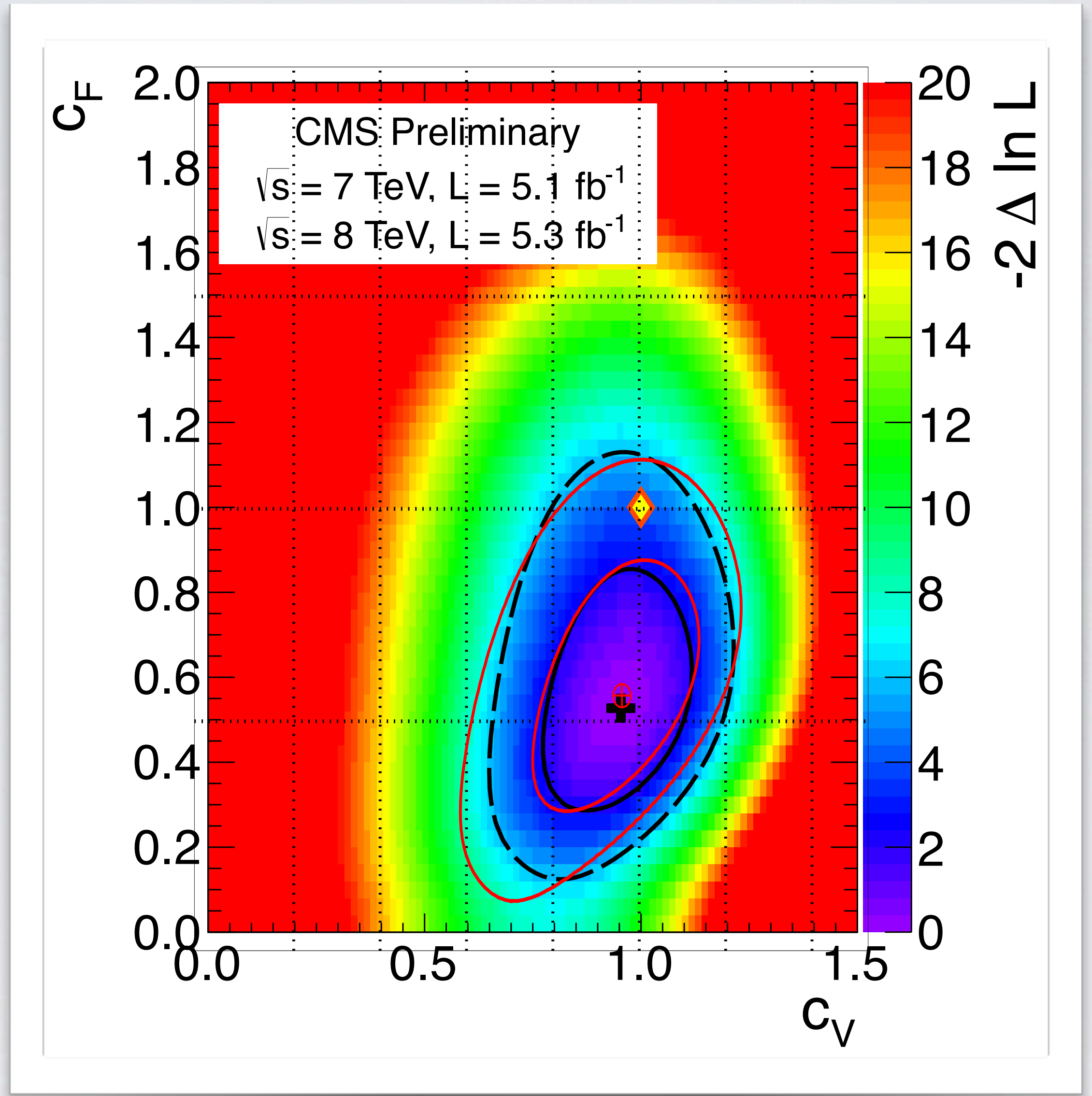




The moral: if it's excluded by simplified methods,
the pros can probably wipe it out definitively.

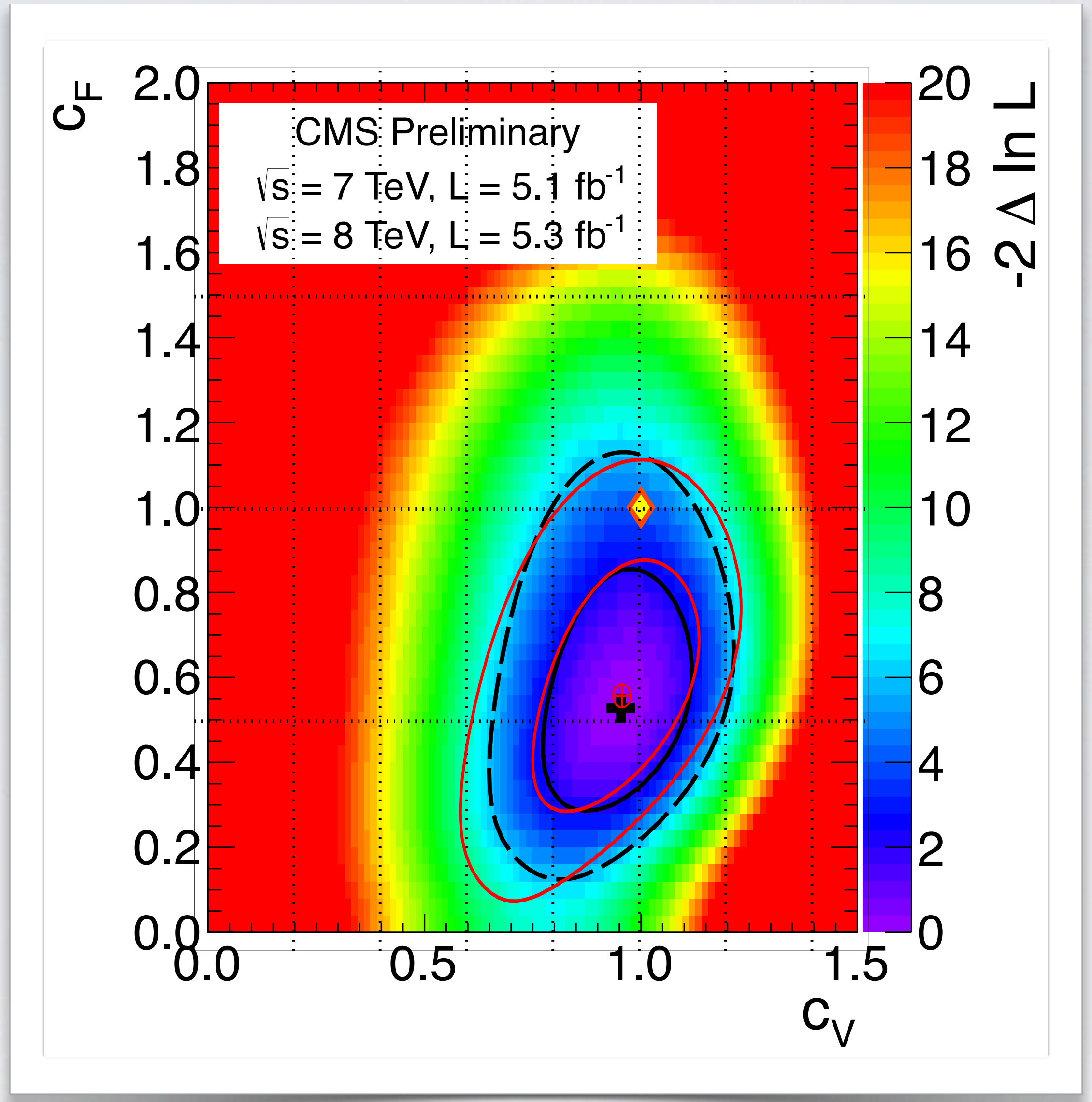
INCIDENTAL: CAN WE (THEORISTS) DO BETTER?

[yes]



INCIDENTAL: CAN WE (THEORISTS) DO BETTER?

[yes]



$$P(\mu) = \int d\theta_B \int d\theta_S \frac{(\theta_B + \mu\theta_S)^{n_{\rm obs}}}{n_{\rm obs}!} e^{(\theta_B+\mu\theta_S)} f(\theta_B) f(\theta_S)$$

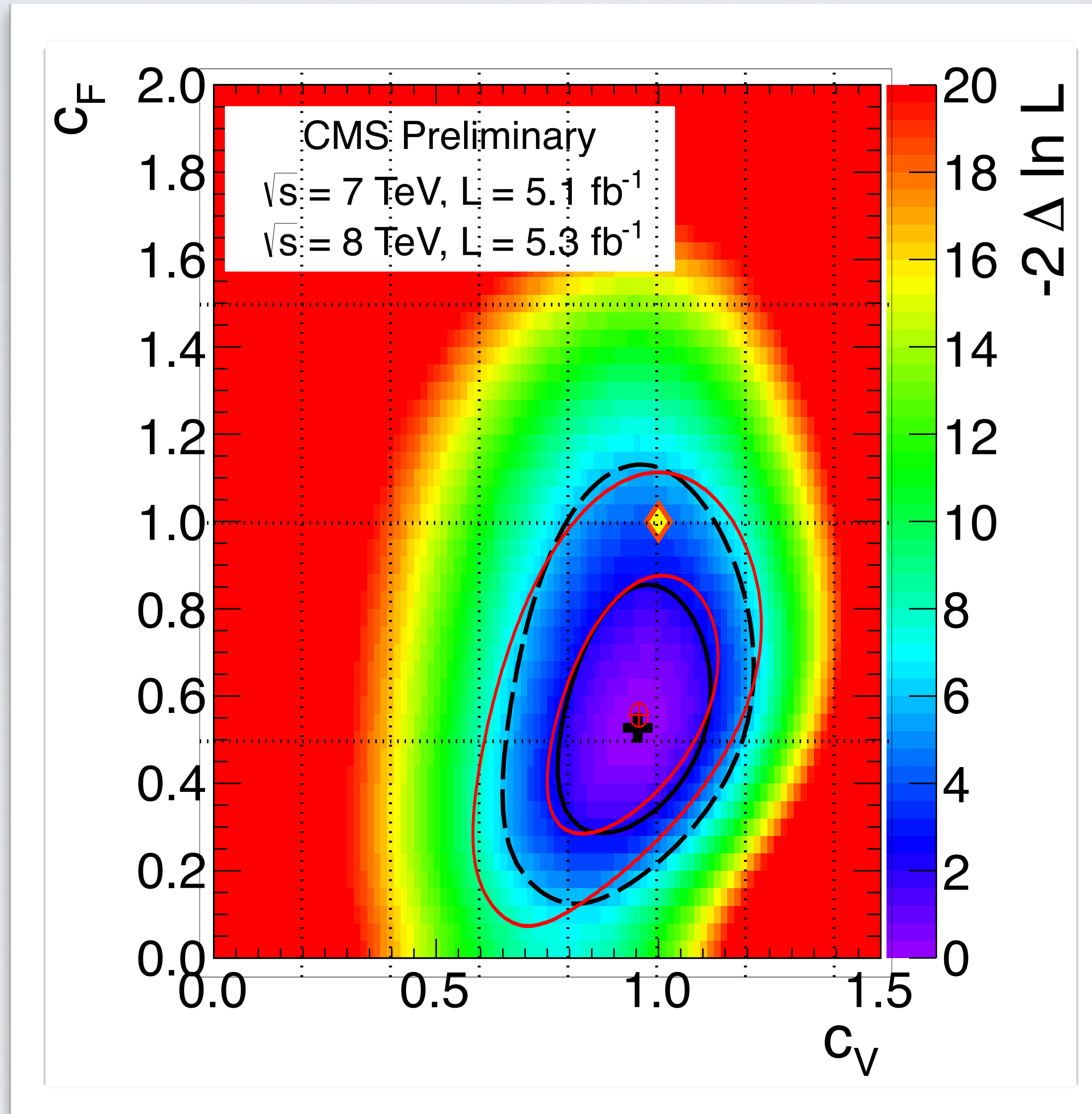
e.g. $f(\theta_B) = \exp \frac{(\theta_B - n_B)^2}{2\sigma_B^2}$

central values and

uncertainties *needed*

INCIDENTAL: CAN WE (THEORISTS) DO BETTER?

[yes]



Not to mention EFFICIENCIES

$$P(\mu) = \int d\theta_B \int d\theta_S \frac{(\theta_B + \mu\theta_S)^{n_{\rm obs}}}{n_{\rm obs}!} e^{(\theta_B+\mu\theta_S)} f(\theta_B) f(\theta_S)$$

e.g. $f(\theta_B) = \exp - \frac{(\theta_B - n_B)^2}{2\sigma_B^2}$

central values and uncertainties *needed*

INCIDENTAL: CAN WE (THEORISTS) DO BETTER?

[yes]

Expected signal and estimated background

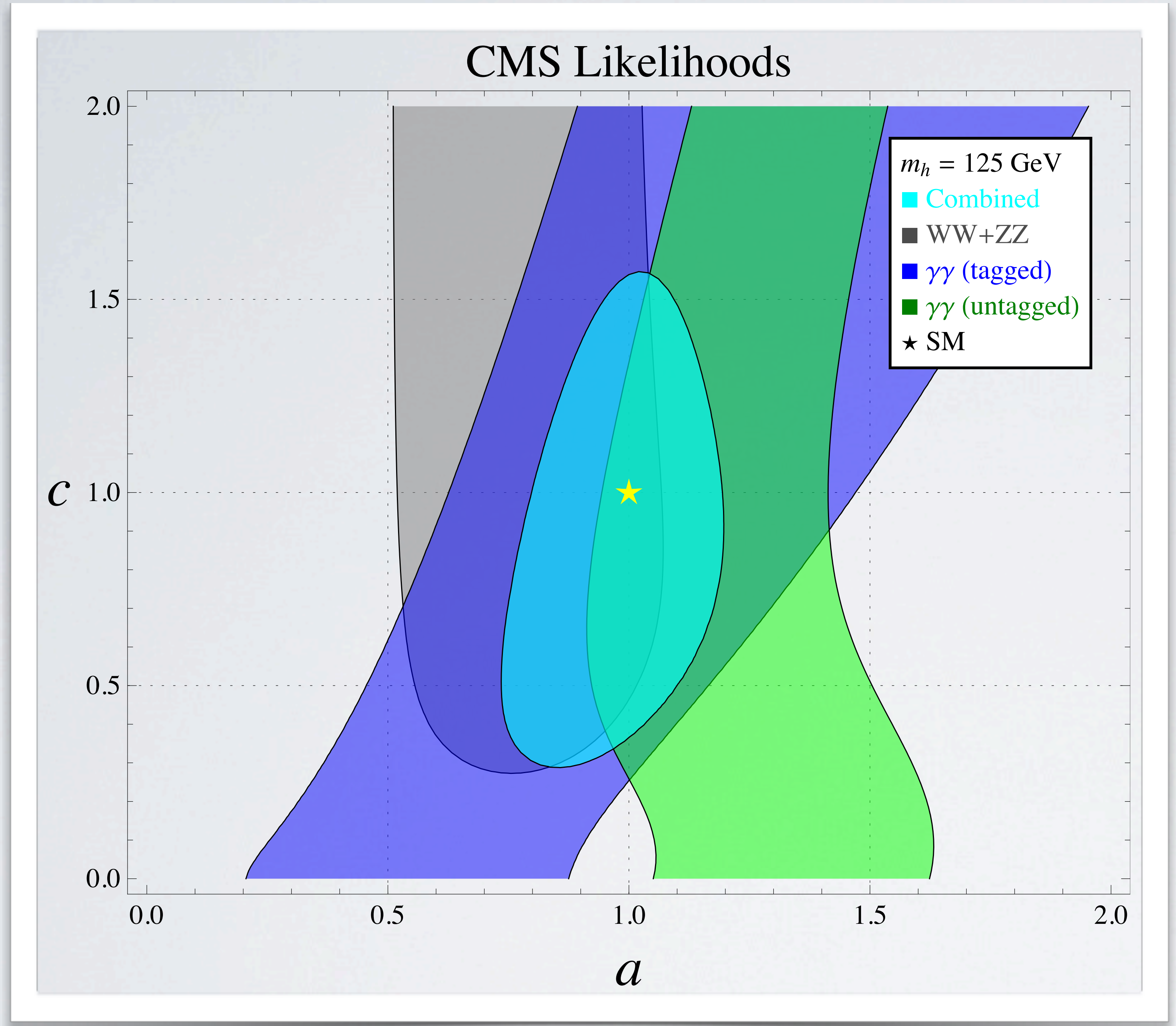
Event classes		SM Higgs boson expected signal (m_H=125 GeV) Total	ggH	VBF	VH	ttH	σ_{eff} (GeV)	FWHM/2.35 (GeV)	Background $m_{\gamma\gamma}$ = 125 GeV (ev./GeV)
7 TeV 5.1 fb^{-1}	Untagged 0	3.2	61%	17%	19%	3%	1.21	1.14	3.3 ± 0.4
	Untagged 1	16.3	88%	6%	6%	1%	1.26	1.08	37.5 ± 1.3
	Untagged 2	21.5	91%	4%	4%	–	1.59	1.32	74.8 ± 1.9
	Untagged 3	32.8	91%	4%	4%	–	2.47	2.07	193.6 ± 3.0
	Dijet tag	2.9	27%	73%	1%	–	1.73	1.37	1.7 ± 0.2
8 TeV 5.3 fb^{-1}	Untagged 0	6.1	68%	12%	16%	4%	1.38	1.23	7.4 ± 0.6
	Untagged 1	21.0	88%	6%	6%	1%	1.53	1.31	54.7 ± 1.5
	Untagged 2	30.2	92%	4%	3%	–	1.94	1.55	115.2 ± 2.3
	Untagged 3	40.0	92%	4%	4%	–	2.86	2.35	256.5 ± 3.4
	Dijet tight	2.6	23%	77%	–	–	2.06	1.57	1.3 ± 0.2
	Dijet loose	3.0	53%	45%	2%	–	1.95	1.48	3.7 ± 0.4

IDEAL PRESENTATION: GAMMA GAMMA @ CMS

[this is the sort of stuff we need to bug collaborations about]

ANOTHER INCIDENTAL: WHO'S RUNNING THE SHOW?

[and where do the tensions lie?]



Who does what (generically)?

- o VV final states
  => vertical bands
- o Diphoton states
  => diagonal bands
- o Fermionic final states
  => horizontal bands

Eventually chopping up these channels to be as exclusive as possible is what we'll need to really probe the SM-ness of the Higgs

PART THREE

What does it all mean?

(application to models - i.e. finally getting to some physics)

3A. COMPOSITE (GOLDSTONE) HIGGS

[Simple principles exemplified with a simple model]

	$SU(2)_{\text{CH}}$	$SU(2)_W$	$U(1)_Y$
ψ	$\square$	$\square$	0
χ	$\square$	1	$1/2$
χ'	$\square$	1	$-1/2$

"CH" group is SU(4)-invariant:

$$\Psi = (\psi_1 \ \psi_2 \ \chi \ \chi')^T$$

Vacuum is Sp(4)-invariant:

$$\Phi^{AB} = \langle \Psi^A \Psi^B \rangle$$
$$= -\Phi^{BA}$$

3A. COMPOSITE (GOLDSTONE) HIGGS

[Simple principles exemplified with a simple model]

	$SU(2)_{\text{CH}}$	$SU(2)_W$	$U(1)_Y$
ψ	$\square$	$\square$	0
χ	$\square$	1	$1/2$
χ'	$\square$	1	$-1/2$

"CH" group is SU(4)-invariant:

$$\Psi = (\psi_1 \ \psi_2 \ \chi \ \chi')^T$$

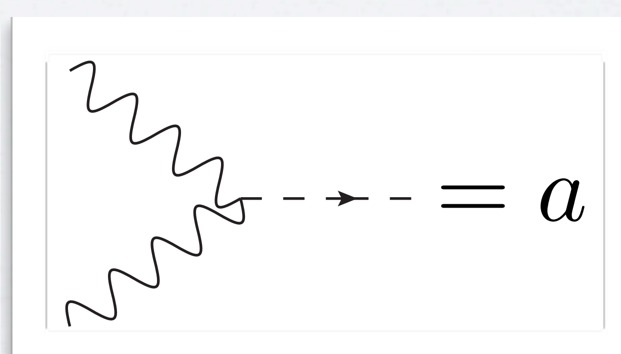
Vacuum is Sp(4)-invariant:

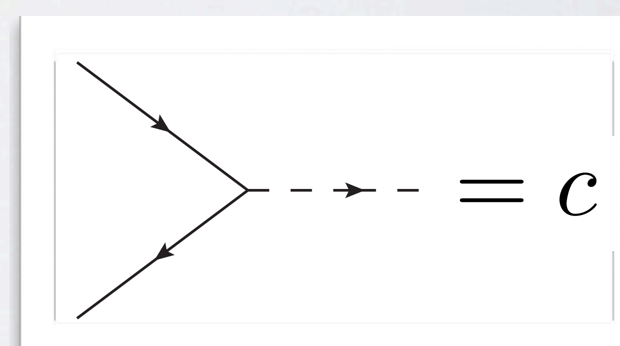
$$\Phi^{AB} = \langle \Psi^A \Psi^B \rangle = -\Phi^{BA}$$

Vacuum alignment angle (determined by UV dynamics) represents how the gauged global symmetry is embedded relative to the unbroken Sp(4)

$$\Phi_{\text{EW}} = \begin{pmatrix} \epsilon & 0 \\ 0 & \epsilon \end{pmatrix} \quad \longleftarrow \theta \longrightarrow \quad \Phi_{\text{TC}} = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

One of the five Goldstones acts like a Higgs:





$$a = c = \cos\theta \equiv \sqrt{1 - v^2/f^2}$$

3A. COMPOSITE (GOLDSTONE) HIGGS

[Simple principles exemplified with a simple model]

	$SU(2)_{\rm CH}$	$SU(2)_W$	$U(1)_Y$
ψ	$\square$	$\square$	0
χ	$\square$	1	$1/2$
χ'	$\square$	1	$-1/2$

"CH" group is SU(4)-invariant:

$$\Psi = (\psi_1 \; \psi_2 \; \chi \; \chi')^T$$

Vacuum is Sp(4)-invariant:

$$\Phi^{AB} = \langle \Psi^A \Psi^B \rangle = -\Phi^{BA}$$

Many new states could be within reach!

- Non-minimal symmetry structure => additional scalars (PNGBs)
- Vector mesons (analogue of $\rho_{\rm QCD}$)

$$m_\rho \sim \frac{\Lambda}{\sqrt{N}} \sim \frac{4\pi v}{\sqrt{N}} \times \sqrt{\frac{1}{1-(g_{hVV}/g_{hVV}^{\rm SM})^2}}$$

3A. COMPOSITE (GOLDSTONE) HIGGS

[More minimal models: Four Goldstones+Custodial symmetry]

- SO(5)/SO(4) with SM fermions in spinor ("MCHM4"):

$$a = c = \sqrt{1 - v^2/f^2}$$

- SO(5)/SO(4) with SM fermions in fundamental ("MCHM5"):

$$a = \sqrt{1 - v^2/f^2}$$

$$c = \frac{1 - 2v^2/f^2}{\sqrt{1 - v^2/f^2}}$$

3A. COMPOSITE (GOLDSTONE) HIGGS

[More minimal models: Four Goldstones+Custodial symmetry]

- SO(5)/SO(4) with SM fermions in spinor ("MCHM4"):

$$a = c = \sqrt{1 - v^2/f^2}$$

- SO(5)/SO(4) with SM fermions in fundamental ("MCHM5"):

$$a = \sqrt{1 - v^2/f^2}$$

$$c = \frac{1 - 2v^2/f^2}{\sqrt{1 - v^2/f^2}}$$

Realizes a fermiophobic limit;
studies exist, more ongoing...

3A. COMPOSITE (GOLDSTONE) HIGGS

[More minimal models: Four Goldstones+Custodial symmetry]

- SO(5)/SO(4) with SM fermions in spinor ("MCHM4"):

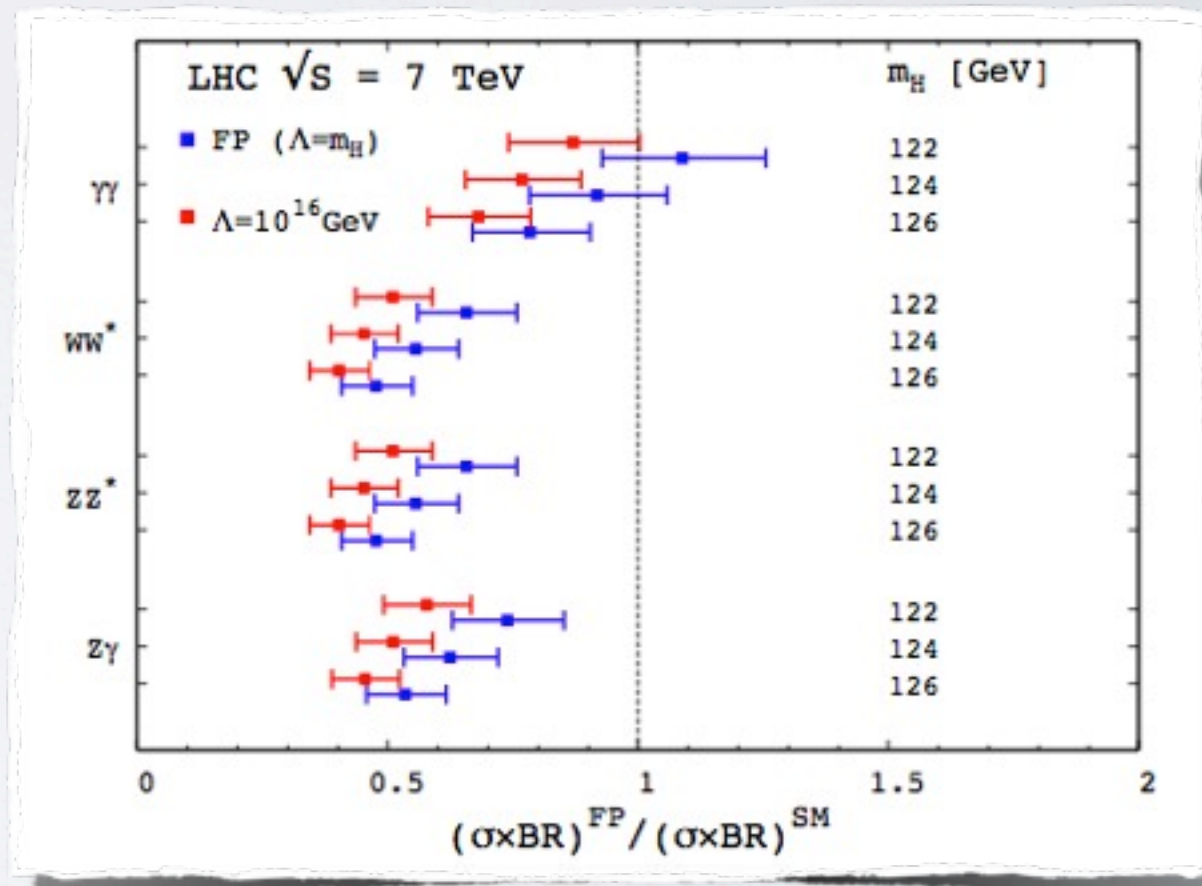
$$a = c = \sqrt{1 - v^2/f^2}$$

- SO(5)/SO(4) with SM fermions in fundamental ("MCHM5"):

$$a = \sqrt{1 - v^2/f^2}$$

$$c = \frac{1 - 2v^2/f^2}{\sqrt{1 - v^2/f^2}}$$

Realizes a fermiophobic limit; studies exist, more ongoing...



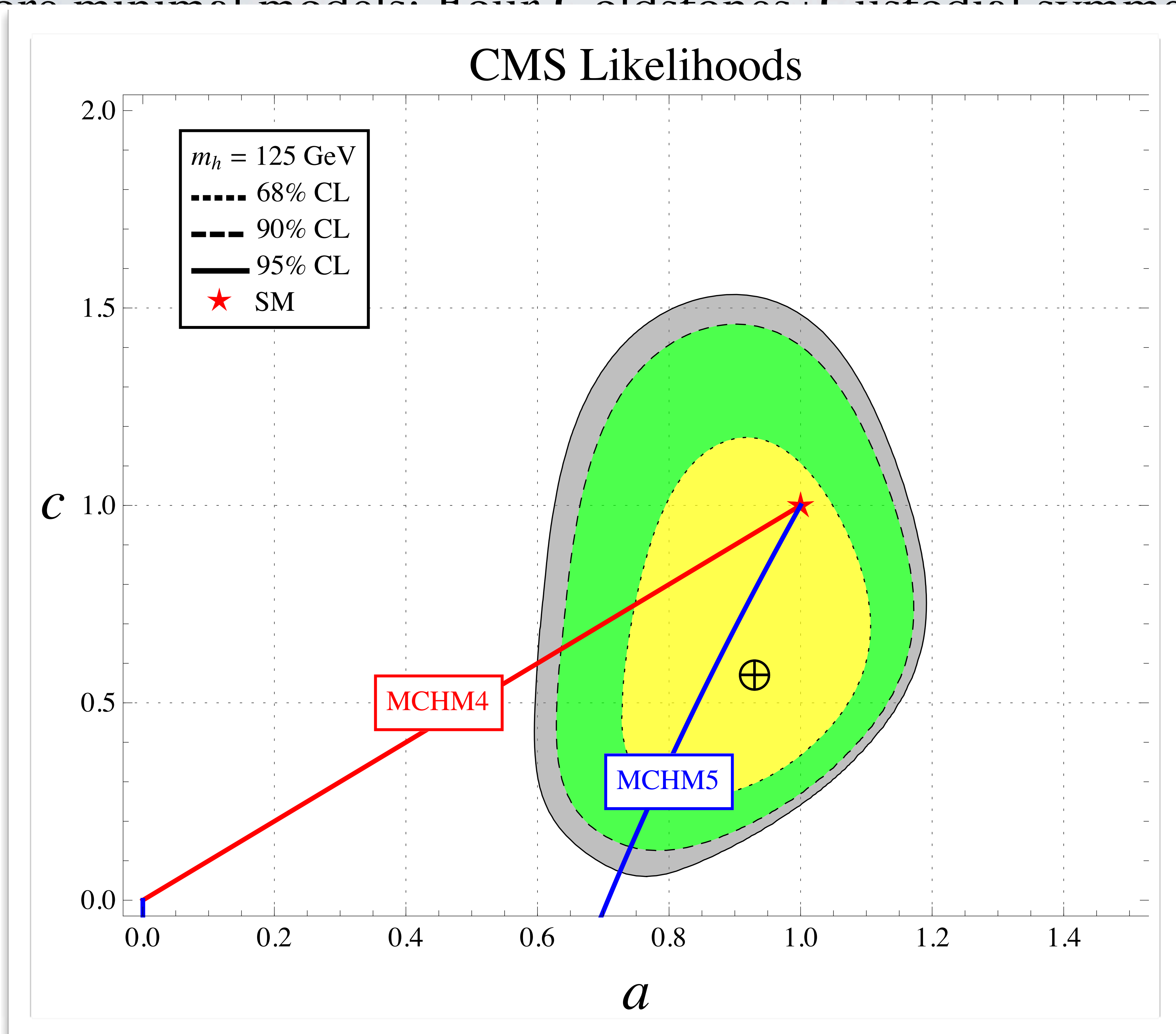
(Gabrielli et al, 1202.1796)

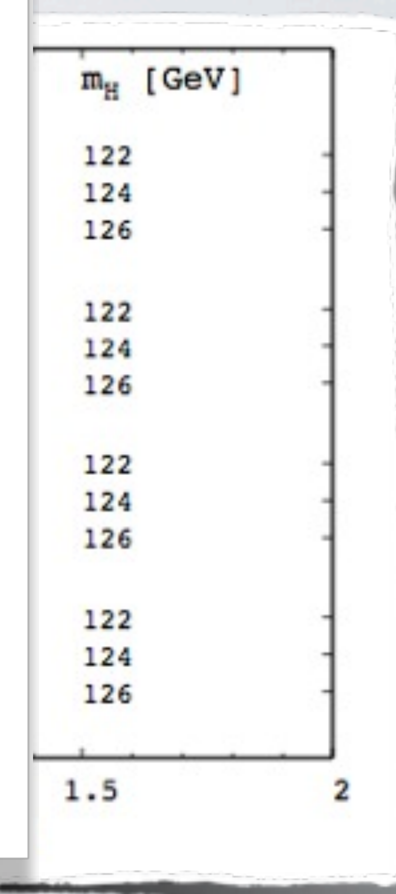
3A. COMPOSITE (GOLDSTONE) HIGGS

[Mo... ...try]

* SC

* SC ... I5"):





Rea
stud

(Gabrielli et al, 1202.1796)

[And now for something completely different]

3B. SUPERSYMMETRY

Conventions: $H_u = 2_{1/2},\ H_d = 2_{-1/2},\ \langle \mathrm{Re} H_u^0 \rangle / \langle \mathrm{Re} H_d^0 \rangle \equiv \tan\beta$

$$\begin{pmatrix} h \\ H \end{pmatrix} = \sqrt{2} \begin{pmatrix} -\sin\alpha & \cos\alpha \\ \cos\alpha & \sin\alpha \end{pmatrix} \begin{pmatrix} \mathrm{Re} H_d^0 \\ \mathrm{Re} H_u^0 \end{pmatrix}$$

Implications: (Again) Additional new physics at low scales

$$\sum_i g^2_{VVh_i} = g^2_{VVh_{\mathrm{SM}}}; \quad \text{e.g.} \quad \frac{g^2_{VVh}}{g^2_{VVh_{\mathrm{SM}}}} + \frac{g^2_{VVH}}{g^2_{VVh_{\mathrm{SM}}}} = 1$$

3B. SUPERSYMMETRY

Conventions: $H_u = 2_{1/2},\ H_d = 2_{-1/2},\ \langle \mathrm{Re} H_u^0 \rangle / \langle \mathrm{Re} H_d^0 \rangle \equiv \tan\beta$

$$\begin{pmatrix} h \\ H \end{pmatrix} = \sqrt{2} \begin{pmatrix} -\sin\alpha & \cos\alpha \\ \cos\alpha & \sin\alpha \end{pmatrix} \begin{pmatrix} \mathrm{Re} H_d^0 \\ \mathrm{Re} H_u^0 \end{pmatrix}$$

Implications: (Again) Additional new physics at low scales

$$\sum_i g_{VVh_i}^2 = g_{VVh_{\mathrm{SM}}}^2; \quad \text{e.g.} \quad \frac{g_{VVh}^2}{g_{VVh_{\mathrm{SM}}}^2} + \frac{g_{VVH}^2}{g_{VVh_{\mathrm{SM}}}^2} = 1$$

Heavy Higgs in the low-energy spectrum $\Rightarrow$ Deviations from SM couplings

3B. SUPERSYMMETRY

Conventions: $H_u = 2_{1/2},\ H_d = 2_{-1/2},\ \langle \mathrm{Re} H_u^0 \rangle / \langle \mathrm{Re} H_d^0 \rangle \equiv \tan\beta$

$$\begin{pmatrix} h \\ H \end{pmatrix} = \sqrt{2} \begin{pmatrix} -\sin\alpha & \cos\alpha \\ \cos\alpha & \sin\alpha \end{pmatrix} \begin{pmatrix} \mathrm{Re} H_d^0 \\ \mathrm{Re} H_u^0 \end{pmatrix}$$

Implications: (Again) Additional new physics at low scales

$$\sum_i g^2_{VVh_i} = g^2_{VVh_{\rm SM}}; \quad \text{e.g.} \quad \frac{g^2_{VVh}}{g^2_{VVh_{\rm SM}}} + \frac{g^2_{VVH}}{g^2_{VVh_{\rm SM}}} = 1$$

Heavy Higgs in the low-energy spectrum $\Rightarrow$ Deviations from SM couplings

$$\left.\begin{aligned} c_u &\equiv g_{hQu^c}/\mathrm{SM} = \frac{\cos\alpha}{\sin\beta} \\ c_d &\equiv g_{hQd^c}/\mathrm{SM} = \frac{-\sin\alpha}{\cos\beta} \\ a &\equiv \mathrm{gauge}/\mathrm{SM} = \sin(\beta-\alpha) \end{aligned}\right\}$$

What is the data telling us about this space, which is dictated strongly by the (constrained) quartics?

3B. SUPERSYMMETRY

Simple question of increasing relevance

Can we use the quartic structure and consequent information about couplings, comparing directly to data to tell us about feasibility and consistency of particular SUSY scenarios?*

*Assuming $m_{\text{SUSY}} > m_h$

3B. SUPERSYMMETRY

Simple question of increasing relevance

$$\mathrm{DATA} \overset{?}{\Leftrightarrow} \{\tan\beta, \lambda_i\}$$

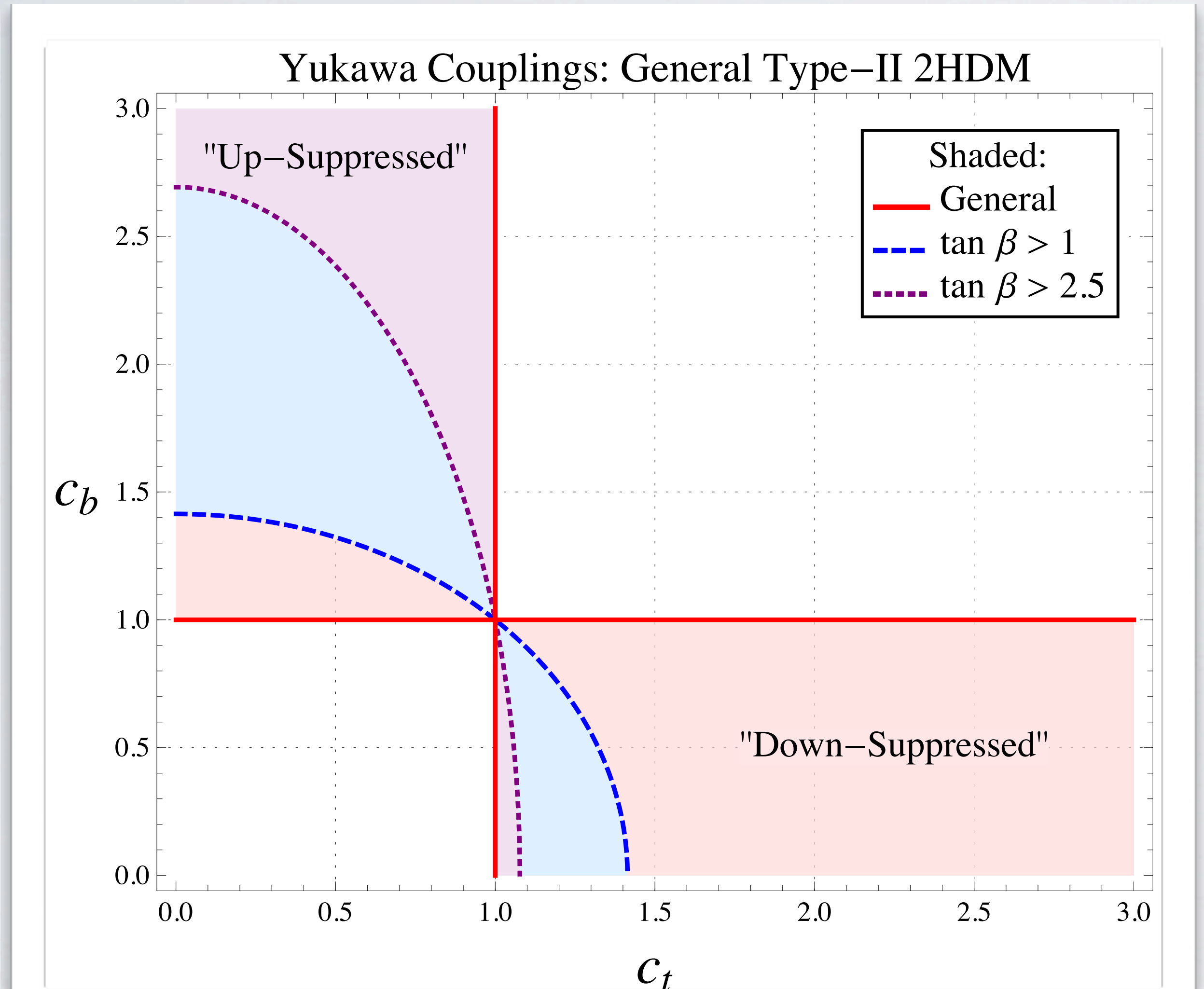
Can we use the quartic structure and consequent information about couplings, comparing directly to data to tell us about feasibility and consistency of particular SUSY scenarios?*

TYPE-II 2HDM, THE GENERAL CASE

With all quartics turned on, and treated generically:

$$\Delta V = \lambda_1 \left|H_u^0\right|^4 + \lambda_2 \left|H_d^0\right|^4 - 2\lambda_3 \left|H_u^0\right|^2 \left|H_d^0\right|^2 + \left[\lambda_4 \left|H_u^0\right|^2 H_u^0 H_d^0 + \lambda_5 \left|H_d^0\right|^2 H_u^0 H_d^0 + \lambda_6 (H_u^0 H_d^0)^2 + \text{c.c.}\right]$$

These feed into mass matrices, thus into couplings



Two distinct regions accessible in the up-down Yukawa plane

The lower region (suppressed down-type) requires some fancy footwork

$$\lambda_1 \sin^2\beta - \lambda_2 \cos^2\beta - \cos(2\beta)\lambda_3 + \frac{\sin 3\beta}{2\cos\beta}\lambda_4 + \frac{\cos 3\beta}{2\sin\beta}\lambda_5 < 0$$

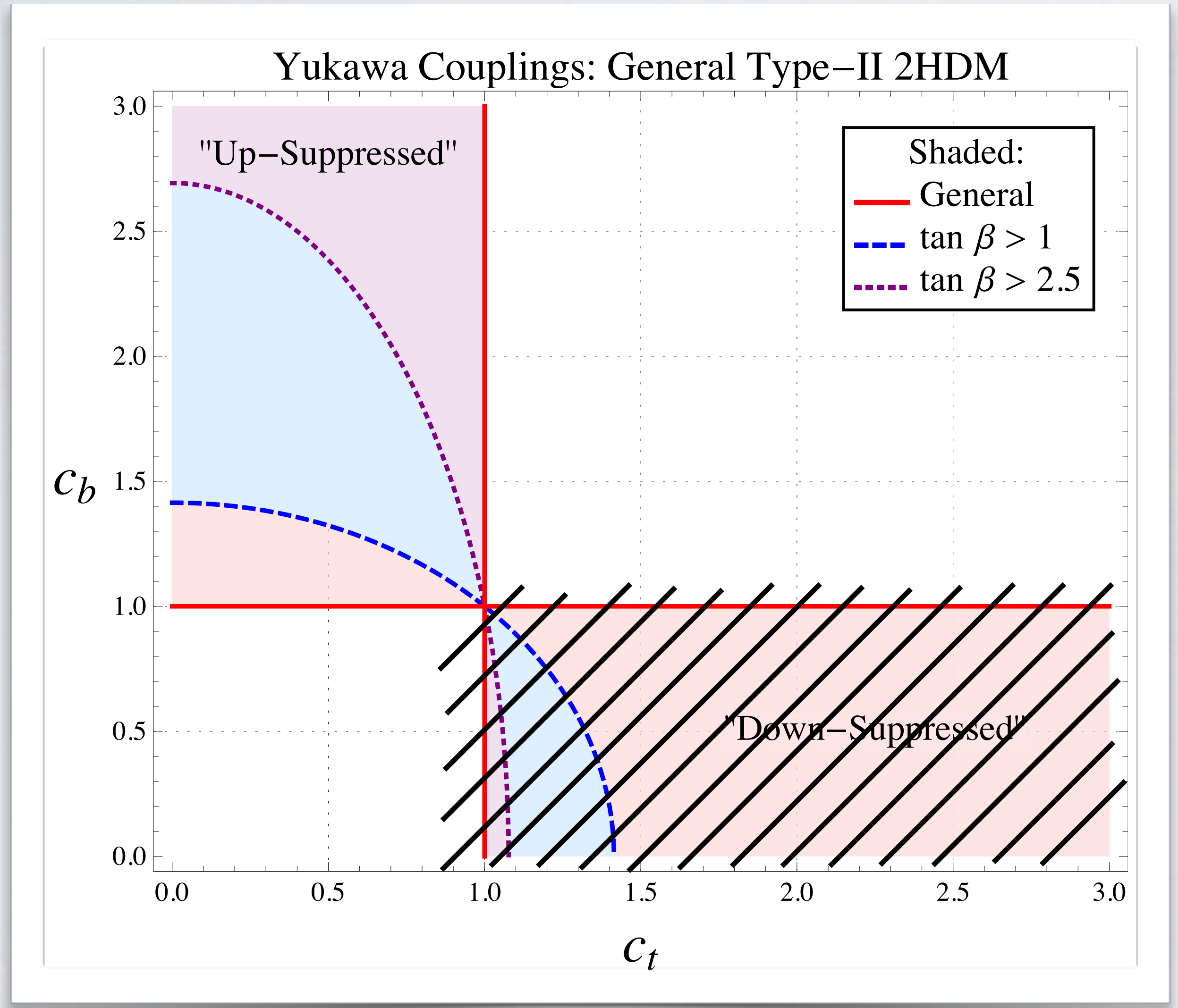
(cf. Azatov et al, 1206.1058)

TYPE-II 2HDM, THE GENERAL CASE

With all quartics turned on, and treated generically:

$$\Delta V = \lambda_1 \left|H_u^0\right|^4 + \lambda_2 \left|H_d^0\right|^4 - 2\lambda_3 \left|H_u^0\right|^2 \left|H_d^0\right|^2 + \left[\lambda_4 \left|H_u^0\right|^2 H_u^0 H_d^0 + \lambda_5 \left|H_d^0\right|^2 H_u^0 H_d^0 + \lambda_6 (H_u^0 H_d^0)^2 + \text{c.c.}\right]$$

These feed into mass matrices, thus into couplings



Two distinct regions accessible in the up-down Yukawa plane

e.g. unbroken MSSM:

$$(\lambda_1 + \lambda_3) \times v_u^2 < (\lambda_2 + \lambda_3) \times v_d^2$$

CONCLUSION: bottom is typically *enhanced* in MSSM (assuming $\delta\lambda_1$ large)

WHAT'S IN THE DATA?

	$R(a,c)$	$\hat{\mu}\vert_{\mathrm{CMS}}$
$\gamma\gamma + 2j$	$a^2 r_{\gamma\gamma}$	~ 2
$\gamma\gamma$	$c^2 r_{\gamma\gamma}$	~ 1.5
$WW + 2j$	a^4	~ 0
VV	$a^2 c^2$	~ 1

$$r_{\gamma\gamma} \simeq (1.26a - 0.26c)^2$$

WHAT'S IN THE DATA?

	$R(a,c)$	$\hat{\mu}\vert_{\text{CMS}}$
$\gamma\gamma + 2j$	$a^2 r_{\gamma\gamma}$	~ 2
$\gamma\gamma$	$c^2 r_{\gamma\gamma}$	~ 1.5
$WW + 2j$	a^4	~ 0
VV	$a^2 c^2$	~ 1

$$r_{\gamma\gamma} \simeq (1.26a - 0.26c)^2$$

Some tension between channels most sensitive to the vector coupling; let's take this at face value and run with it...

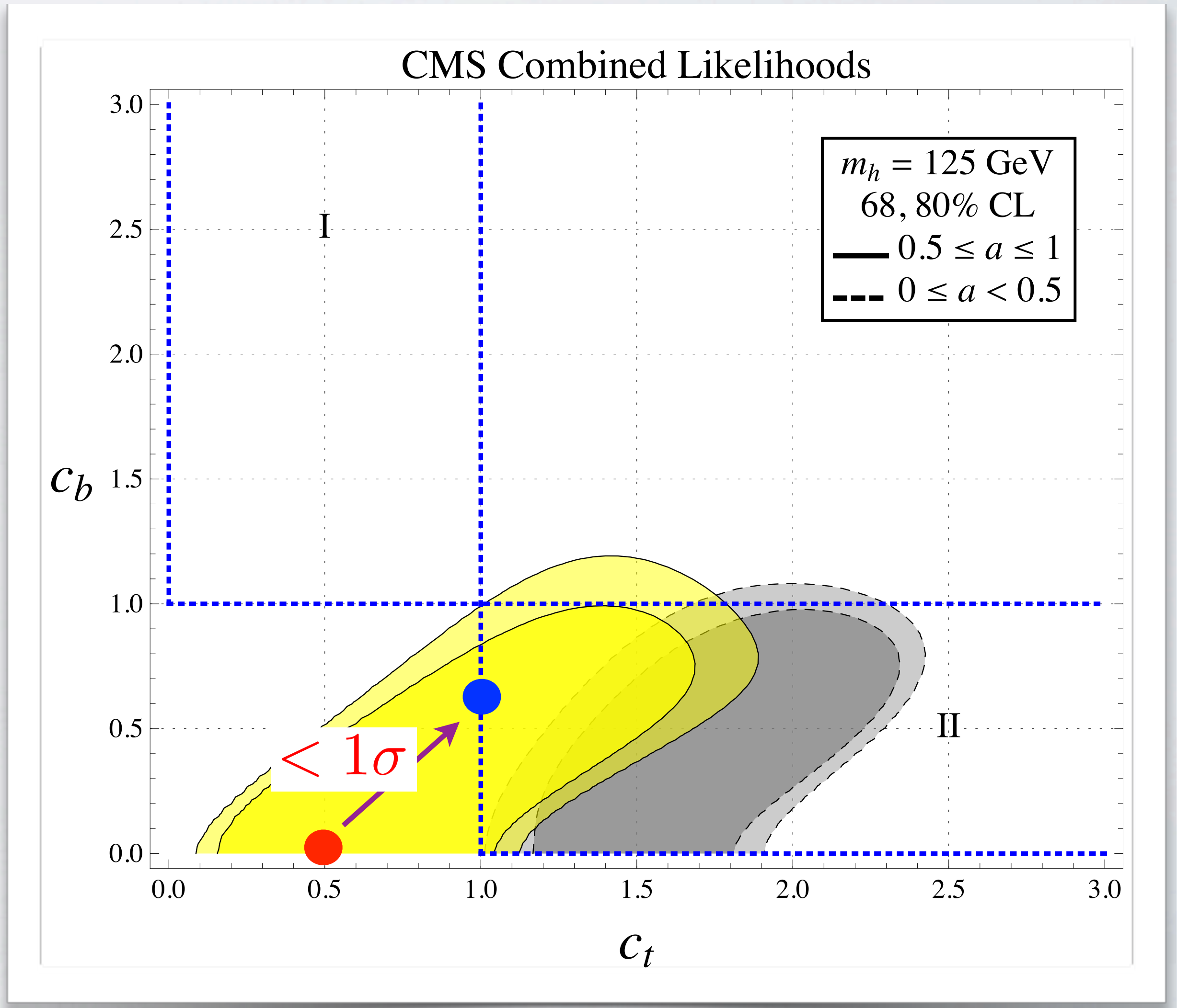
WHAT'S IN THE DATA?

	$R(a,c)$	$\hat{\mu}\vert_{\text{CMS}}$
$\gamma\gamma + 2j$	$a^2 r_{\gamma\gamma}$	~ 2
$\gamma\gamma$	$c^2 r_{\gamma\gamma}$	~ 1.5
$WW + 2j$	a^4	~ 0
VV	$a^2 c^2$	~ 1

$$r_{\gamma\gamma} \simeq (1.26a - 0.26c)^2$$

Some tension between channels most sensitive to the vector coupling; let's take this at face value and run with it...

Seen in a slightly different way:



Global: $(a \sim 0.7,\ c_b \sim 0,\ c_t \sim 0.5)$

Type-II: $(a \sim 0.7,\ c_b \sim 0.7,\ c_t \sim 1)$

(Assuming no new large contributions in $hGG, h\gamma\gamma$; some clear caveats)

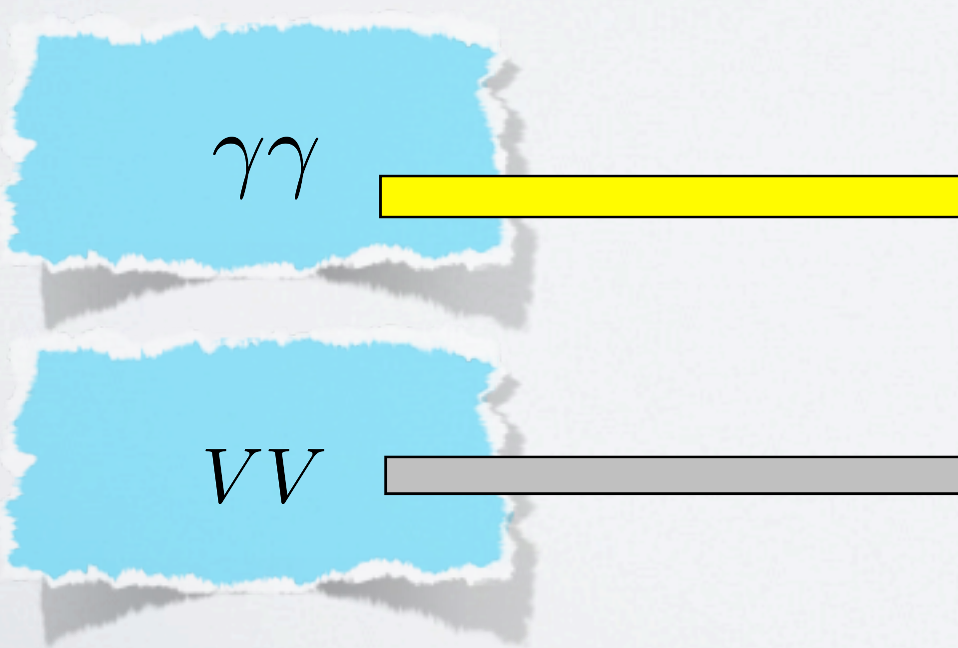
WHAT'S IN THE DATA?

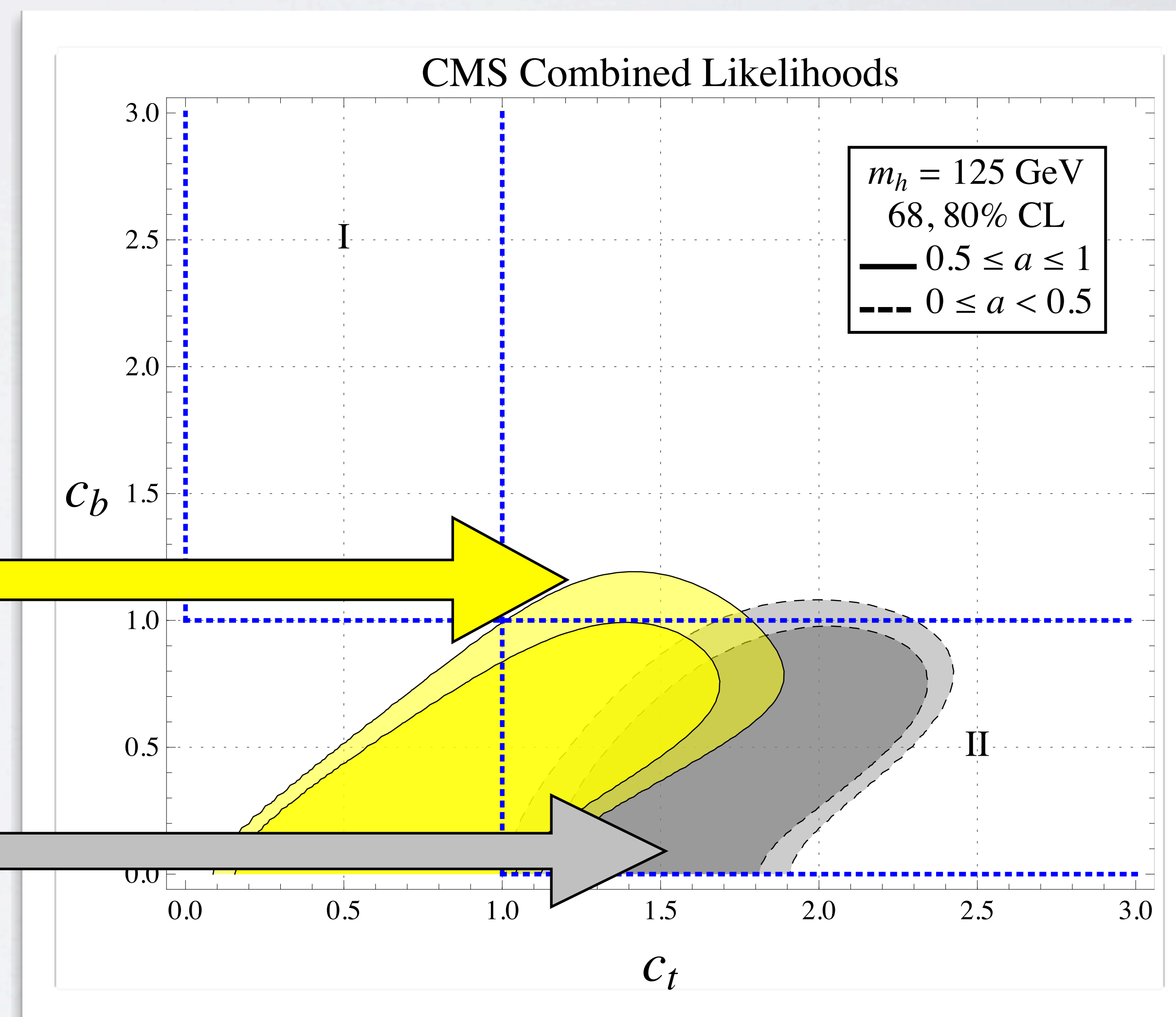
	$R(a,c)$	$\hat{\mu}\vert_{\text{CMS}}$
$\gamma\gamma + 2j$	$a^2 r_{\gamma\gamma}$	~ 2
$\gamma\gamma$	$c^2 r_{\gamma\gamma}$	~ 1.5
$WW + 2j$	a^4	~ 0
VV	$a^2 c^2$	~ 1

Some tension between channels most sensitive to the vector coupling; let's take this at face value and run with it...

$$r_{\gamma\gamma} \simeq (1.26a - 0.26c)^2$$

Seen in a slightly different way:





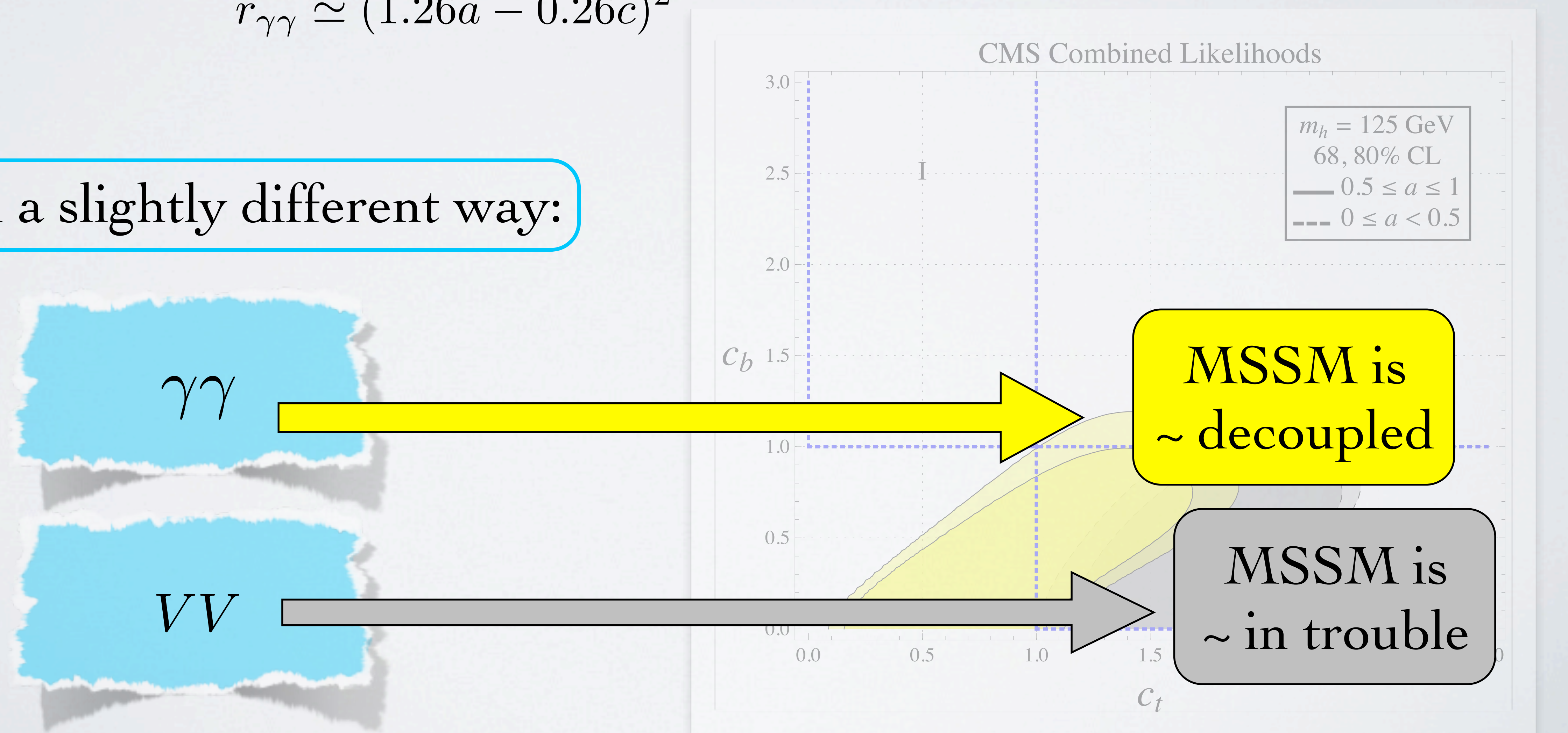
WHAT'S IN THE DATA?

	$R(a,c)$	$\hat{\mu}\vert_{\text{CMS}}$
$\gamma\gamma + 2j$	$a^2 r_{\gamma\gamma}$	~ 2
$\gamma\gamma$	$c^2 r_{\gamma\gamma}$	~ 1.5
$WW + 2j$	a^4	~ 0
VV	$a^2 c^2$	~ 1

Some tension between channels most sensitive to the vector coupling; let's take this at face value and run with it...

$$r_{\gamma\gamma} \simeq (1.26a - 0.26c)^2$$

Seen in a slightly different way:



WHAT'S IN THE DATA?

	$R(a,c)$	$\hat{\mu}\vert_{\text{CMS}}$
$\gamma\gamma + 2j$	$a^2 r_{\gamma\gamma}$	~ 2
$\gamma\gamma$	$c^2 r_{\gamma\gamma}$	~ 1.5
$WW + 2j$	a^4	~ 0
VV	$a^2 c^2$	~ 1

Some tension between channels most sensitive to the vector coupling; let's take this at face value and run with it...

$$r_{\gamma\gamma} \simeq (1.26a - 0.26c)^2$$

...What if down suppression persists?

ESCAPE HATCHES IN THE (X)MSSM

[eXtra stuff]

Recall the general potential:

$$\Delta V = \lambda_1 \left|H_u^0\right|^4 + \lambda_2 \left|H_d^0\right|^4 - 2\lambda_3 \left|H_u^0\right|^2 \left|H_d^0\right|^2 + \left[\lambda_4 \left|H_u^0\right|^2 H_u^0 H_d^0 + \lambda_5 \left|H_d^0\right|^2 H_u^0 H_d^0 + \lambda_6 (H_u^0 H_d^0)^2 + \text{c.c.}\right]$$

With bottom suppression at largish tan beta possible when

$$\lambda_1 + \lambda_3 - \frac{\lambda_4}{2} \tan\beta \lesssim 0$$

MSSM

e.g. effects from stops:

$$\delta\lambda_1 = \frac{3y_t^4}{16\pi^2}\left[\left(\frac{A_t}{m_{\tilde{t}}}\right)^2 - \frac{1}{12}\left(\frac{A_t}{m_{\tilde{t}}}\right)^4\right]$$

$$\delta\lambda_3 = \frac{3y_t^4\mu^2}{64\pi^2 m_{\tilde{t}}^2}\left[\left(\frac{A_t}{m_{\tilde{t}}}\right)^2 - 2\right]$$

$$\delta\lambda_4 = \frac{y_t^4\mu}{32\pi^2 m_{\tilde{t}}}\left[\left(\frac{A_t}{m_{\tilde{t}}}\right)^3 - \frac{6A_t}{m_{\tilde{t}}}\right]$$

(cf. Carena et al, hep-ph/9504316)

Possibilities remain (e.g. staus)...

(cf. Carena et al, 1112.3336 & 1205.5842)

NMSSM, etc.

$$W = \lambda S H_u H_d + f(S)$$

$$\Rightarrow \delta\lambda_3 = -|\lambda|^2/2$$

(cf. lots of stuff...)

inequality can be turned around, provided coupling is largish:

$$\lambda \gtrsim 0.6$$

approaching Fat Higgs territory, especially in the presence of non-light stops; again possibilities remain...

DEMOTING THE QUARTICS

[Possible escape hatch in case a b-suppressed balance is struck]

Can we arrange something simpler than usual? One possibility:

$$\Delta\mathcal{L} \sim \Lambda^3 H - m^2 H^2$$

DEMOTING THE QUARTICS

[Possible escape hatch in case a b-suppressed balance is struck]

Can we arrange something simpler than usual? One possibility:

$$\Delta\mathcal{L} \sim \Lambda^3 H - m^2 H^2$$

Umm...

DEMOTING THE QUARTICS

[Possible escape hatch in case a b-suppressed balance is struck]

Can we arrange something simpler than usual? One possibility:

$$\Delta\mathcal{L} \sim \Lambda^3 H - m^2 H^2$$

Umm...

But this comes from something we know well: Higgs from a "magnetic sector"

(cf. Craig et al, 1106.2164; Azatov et al, 1106.3346; Gherghetta et al, 1107.4697; Heckman et al, 1108.3849...)

	$SU(2)$	$SU(2)_i$
Q_i	$\square$	$\square$
H_{ij}	1	$(\square, \square)$

$$\Delta W = \lambda HQQ$$

- Minimal confining gauge group
- $i = 1, \ldots, 4$; $1 \to L$, $2 \to R$
- 2N flavors: self-dual, strong F.P.

- Assume no SUSY mass for $Q_{1,2}$
- $\not{\text{SUSY}} \Rightarrow$ confines @ $\Lambda_{\text{M}} \lesssim \Lambda_{\text{SUSY}}$

$$\Rightarrow \Delta V = m^2_{H_{u,d}} |H_{u,d}|^2 + \left(c \frac{\lambda_{u,d} \Lambda^3_{\text{M}}}{16\pi^2} H_{u,d} + \text{h.c.} \right) + \ldots$$

DEMOTING THE QUARTICS

[Possible escape hatch in case a b-suppressed balance is struck]

Can we arrange something simpler than usual? One possibility:

$$\Delta\mathcal{L} \sim \Lambda^3 H - m^2 H^2$$

Umm...

But this comes from something we know well: Higgs from a "magnetic sector"

(cf. Craig et al, 1106.2164; Azatov et al, 1106.3346; Gherghetta et al, 1107.4697; Heckman et al, 1108.3849...)

	$SU(2)$	$SU(2)_i$
Q_i	$\square$	$\square$
H_{ij}	1	$(\square, \square)$

$$\Delta W = \lambda H Q Q$$

- Minimal confining gauge group
- $i = 1, \ldots, 4$; $1 \to L$, $2 \to R$
- 2N flavors: self-dual, strong F.P.

- Assume no SUSY mass for $Q_{1,2}$
- $\not{\text{SUSY}} \Rightarrow$ confines @ $\Lambda_{\text{M}} \lesssim \Lambda_{\text{SUSY}}$

$$\Delta V = m^2_{H_{u,d}} |H_{u,d}|^2 + \left(c \frac{\lambda_{u,d}\Lambda^3_{\text{M}}}{16\pi^2} H_{u,d} + \text{h.c.} \right) + \ldots$$

$m^2_{H_{u,d}} > 0$

$$v = c\frac{\lambda\Lambda^3_{\text{M}}}{16\pi^2 m^2} > f_{\text{M}}$$

$\lambda \Rightarrow \tan\beta$

$m \Rightarrow \text{mass}, \alpha$

DEMOTING THE QUARTICS

$$\Delta V = m^2_{H_{u,d}} |H_{u,d}|^2 + \left(c \frac{\lambda_{u,d} \Lambda^3_{\mathrm{M}}}{16\pi^2} H_{u,d} + \text{h.c.} \right) + \ldots$$

> 0

$$v = c \frac{\lambda \Lambda^3_{\mathrm{M}}}{16\pi^2 m^2} > f_{\mathrm{M}}$$

$\lambda \Rightarrow \tan\beta$

$m \Rightarrow$ mass, α

α and β fully independent!

Lots of breathing room w.r.t. mass *and* angles;
nothing all that exotic after all
[Schematically $\Delta W = \lambda_u H_u \mathcal{O}_d + \lambda_d H_d \mathcal{O}_u$]

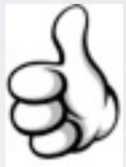
IMPLICATIONS

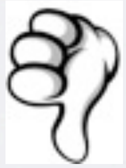
1. We don't even *need* the quartics
   $\Rightarrow$ Nothing fancy (no tuning) needed in order to attain $m_h \gg m_Z$

   $\Rightarrow$ Nothing fancy (large A terms, mixings, ...) for $c_b \to 0$ as $\tan\beta \to \infty$

2. The magnetic sector contains lightish scalars. Minimally $[SU(2)^2/SU(2)]$:

$$m^2_{\vec{\pi}} \sim (\lambda_u v_u + \lambda_d v_d)\Lambda_{\rm M} \left\{ \begin{array}{l} \text{e.g.} \quad \Lambda_{\rm M} = \text{TeV},\ \text{large}\ \tan\beta,\ m_h = 125\,\text{GeV} \\ \qquad \Rightarrow m_\pi \sim 350\,\text{GeV},\ \lambda_u v_u/\Lambda_{\rm M} \simeq 0.1 \\ \text{Decays to heavy SM states: } \pi^0 \to t\bar{t},\ Zh^0 \end{array} \right.$$

3. Theoretical aspects:
   > Naturalness fully restored (frees up Higgs, stops as well) 

   > Unification certainly not automatic, but *can* be done 

   > Dark matter: nothing to add. 

(THE ONLY SAFE) CONCLUSION:

At this point,
THERE IS STILL PLENTY IN PLAY

and THINGS WILL REMAIN IN FLUX

SPECULATION:

THERE IS SOMETHING FUNNY GOING ON WITH FERMION COUPLINGS:

both 2D and 3D fits show preference for substantial suppression...

- Composite Higgs: Flavor-universal suppression by order 50%

$\Rightarrow$ SM Fermions in a 5 of SO(5)? Light custodians?

- SUSY: A potentially relevant portion of Yukawa space can be reopened by careful conspiracy among (x)MSSM parameters

$$\Delta W = \lambda S H_u H_d, \ \lambda H \mathcal{O}, \ \lambda T H_u H_u, \ \ldots$$

(singlets) (doublets) (triplets)

- In any case, much more information is needed...

- Might be anticipating new physics, but will certainly serve as a useful consistency check. What message will the Higgs hunters return with????

SPECULATION:

THERE IS SOMETHING FUNNY GOING ON WITH FERMION COUPLINGS:

both 2D and 3D fits show preference for substantial suppression...

- o Composite Higgs: Flavor-universal suppression by order 50%

$\Rightarrow$ SM Fermions in a 5 of SO(5)? Light custodians?

- o SUSY: A potentially relevant portion of Yukawa space can be reopened by careful conspiracy among (x)MSSM parameters

$$\Delta W = \lambda S H_u H_d, \ \lambda H \mathcal{O}, \ \lambda T H_u H_u, \ \ldots$$

(singlets) (doublets) (triplets)

- o In any case, much more information is needed...

- o Might be anticipating new physics, but will certainly serve as a useful consistency check. What message will the Higgs hunters return with????

SPECULATION:

THERE IS SOMETHING FUNNY GOING ON WITH FERMION COUPLINGS:

- o Composite F

- o SUSY: A po
  reopened by

- o In any case,

- o Might be anticipating new physics, but will certainly serve as a useful consistency check. What message will the Higgs hunters return with????