A HIGGS
-OR-
THE HIGGS

[A Bottom-Up Theory Perspective on LHC Higgs Searches]

PLHC 2012

UNIVERSITY OF BRITISH COLUMBIA

Jamison Galloway

Based on arXiv:1202.3415 with A. Azatov and R. Contino;

arXiv:1206.1058 with A. Azatov, S. Chang, and N. Craig

SAPIENZA
UNIVERSITÀ DI ROMA

Both camps weighing in...

`Experimentalists:`

Not enough data to conclude the existence or non-existence of the Higgs boson

from A. Falkowski @ Planck 2012

Both camps weighing in...

Theorists:

Come on... it's 125 GeV

from A. Falkowski @ Planck 2012

Some are already taking a bolder stance...

Higgs weights 125 GeV!
Now what?

1) Is Higgs standard? (http://arxiv.org/abs/1203.4254)
2) SM vacuum (in)stability (http://arxiv.org/abs/1205.6497)
3) Higgs & SUSY (http://arxiv.org/abs/1108.6077)

Alessandro Strumia

Talk at CERN, IFAE, Princeton and Planck2012

updated to May 31, 2012

from A. Strumia @ Planck 2012

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In any event:
THIS IS THE QUESTION!

from A. Strumia @ Planck 2012

Outline:

I. How can we tell?
(i.e. going from data to models as an outsider)

II. Contextual Answer One: Compositeness

III. Contextual Answer Two: Supersymmetry

Outline:

Primary difference between cases one and two:
flavor-universal vs. non-universal Yukawa rescalings

Outline:

Primary commonality between cases one and two: Deviations from “the-ness” imply additional low energy states associated with EWSB sector

Part One:
From Data to Models

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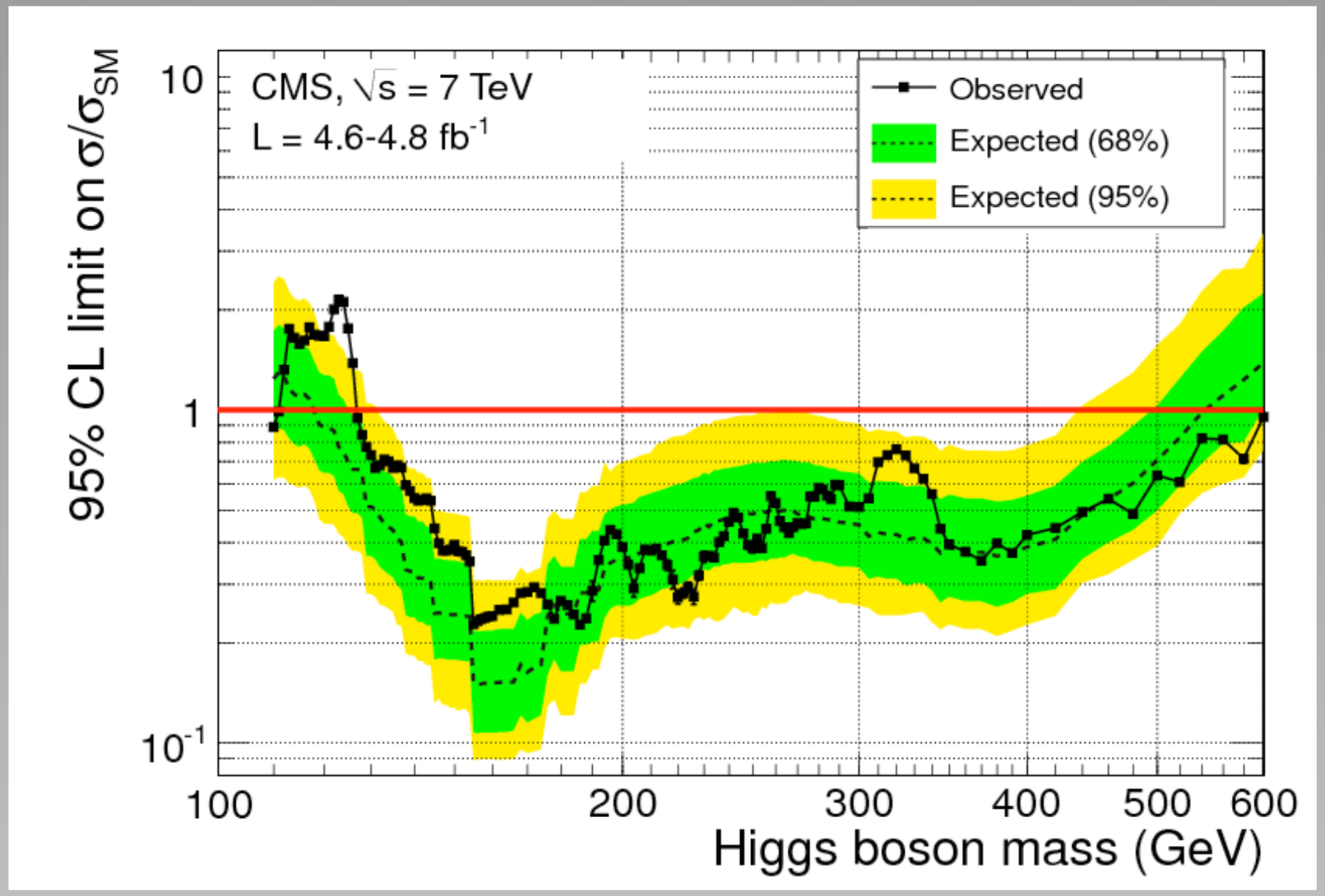
From Data to Models

Question to answer: how can we use searches -- and data presentation -- that are optimized for a SM Higgs to constrain *generic* Higgs-like parameter spaces?

Our handle: construct everything from two critical pieces of information, the expected and observed exclusion limits (from each channel/subchannel)



- We have this certainly for each channel...
- ... and each subchannel when we're lucky
- Gives necessary information over whole mass range

What do we know (thanks to the LHC)?

Answer:
We know the amount by which we can rescale production/branching -- all in the same proportions -- and still be consistent with observation.

Said another way, we know what's going on in a one-dimensional parameter space: adequate in some cases, but in several others we'd like to push this information a bit further...

How do we proceed?

Moving on: Comparison to *RECONSTRUCTED* Likelihood

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

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

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

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

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For observed exclusion, use a simple rewriting:

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

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

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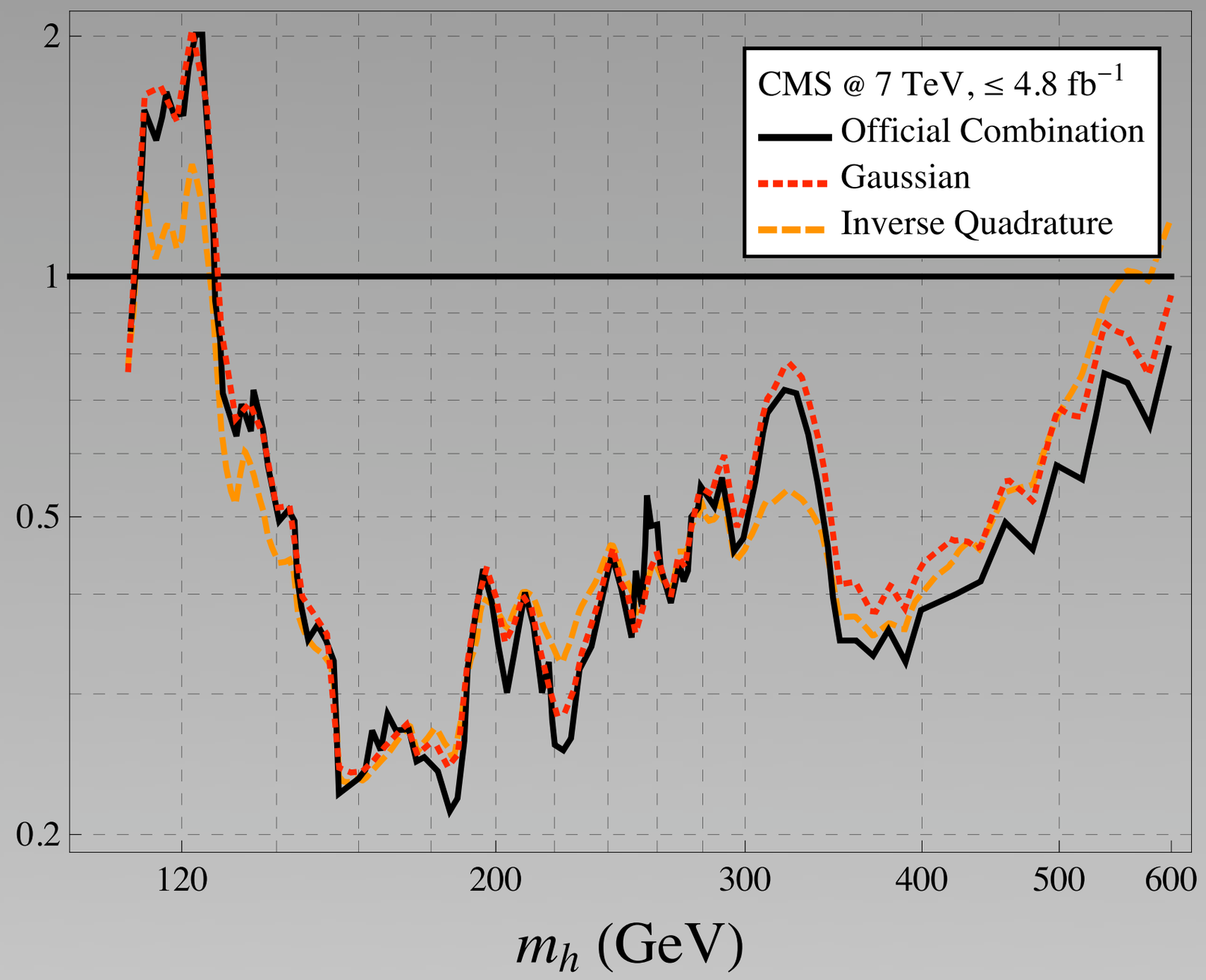
RECAP:

- Expected exclusion tells us about s/b
- Observed tells us delta, completes determination of (AL) likelihood
- Good news: can be done over whole mass range, not just at 'peaks' where information on best fit is available

How well does this method do?

One possible check: the total combination



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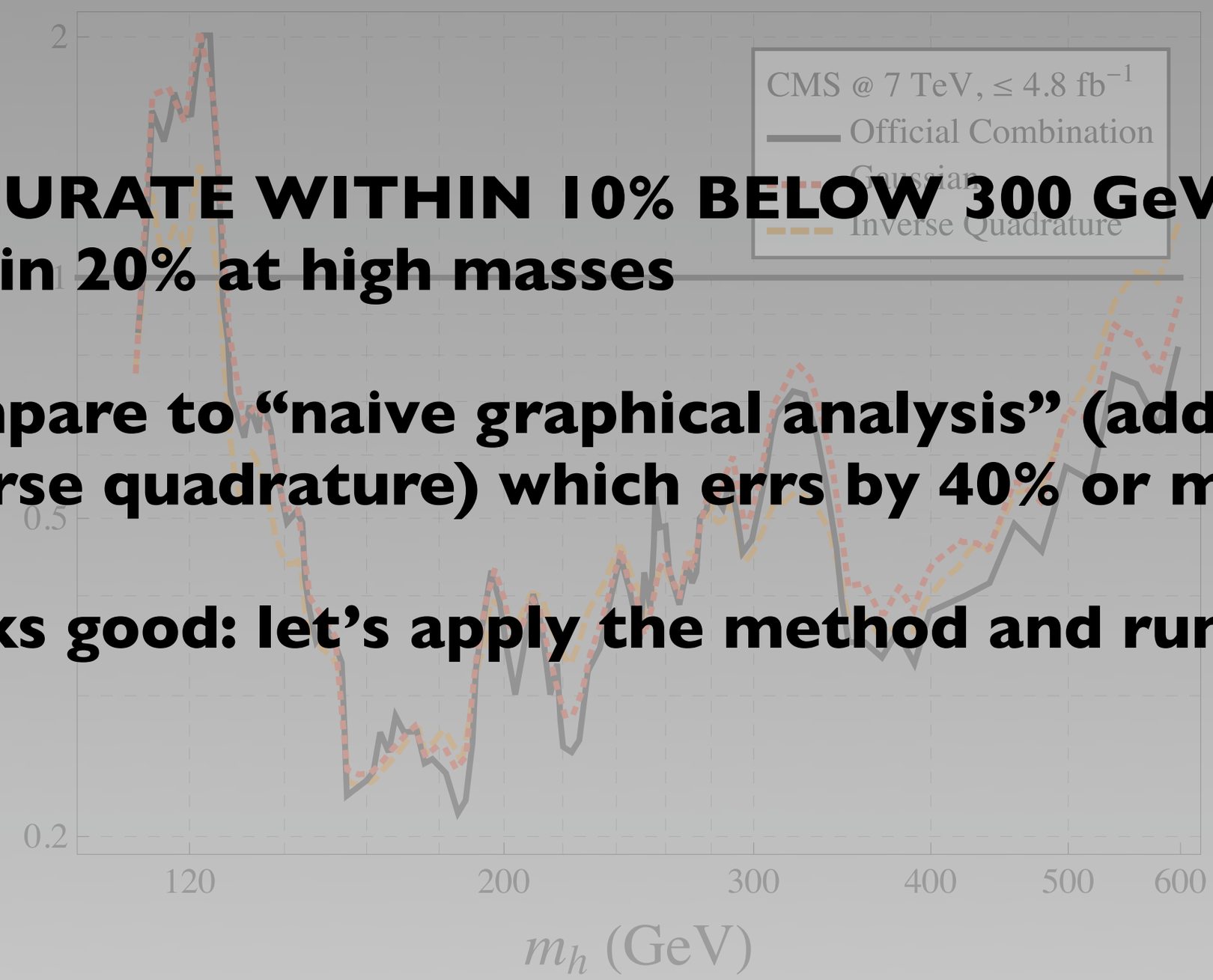

- **ACCURATE WITHIN 10% BELOW 300 GeV; within 20% at high masses**
- **Compare to "naive graphical analysis" (adding in inverse quadrature) which errs by 40% or more**
- **Looks good: let's apply the method and run with it**

Part Two:
Compositeness

Assumption here: the ‘Higgs’ emerges as a pseudo Nambu-Goldstone boson of a spontaneously broken global symmetry

The Big Picture

Setup

- Some new dynamics confines at a scale $\Lambda \sim 4\pi f$
- EW is embedded in the global symmetry such that the Higgs develops a VEV, $v = f \sin\theta$, with vacuum angle determined by symmetry-breaking spurions (top Yukawa, gauge coupling, ...)

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$$\sin\theta \to 0 \quad \Rightarrow \quad \text{SM Limit}\,(f \to \infty);$$

$$\sin\theta \to 1 \quad \Rightarrow \quad \text{Technicolor ('Higgsless') Limit}$$

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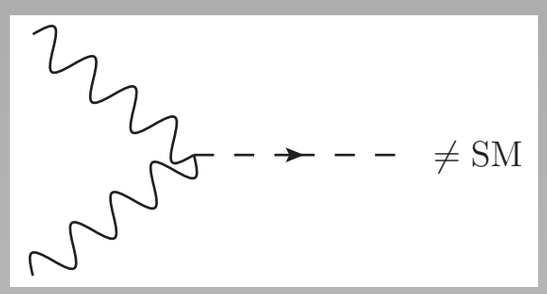
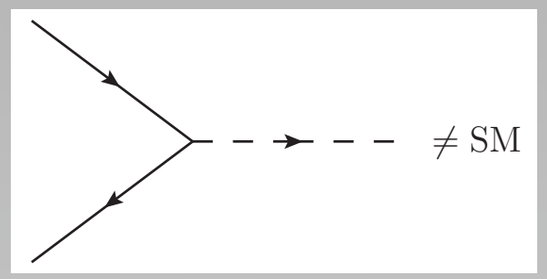
Implications: Higgs couplings interpolate between two limits



$$g_{hVV} = \sqrt{1-\xi} \times g_{hVV}^{\rm SM}; \quad \xi \equiv v^2/f^2$$



Model-dependent, e.g.

- $SO(5)/SO(4); \quad f \in \mathbf{4}$

$$\Rightarrow g_{hff} = \sqrt{1-\xi} \times g_{hff}^{\rm SM}$$

- $SO(5)/SO(4); \quad f \in \mathbf{5}$

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Implications: Additional new physics at low scales

Many new states could be within reach!

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

$$m_\rho \sim \frac{\Lambda}{\sqrt{N}}$$

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

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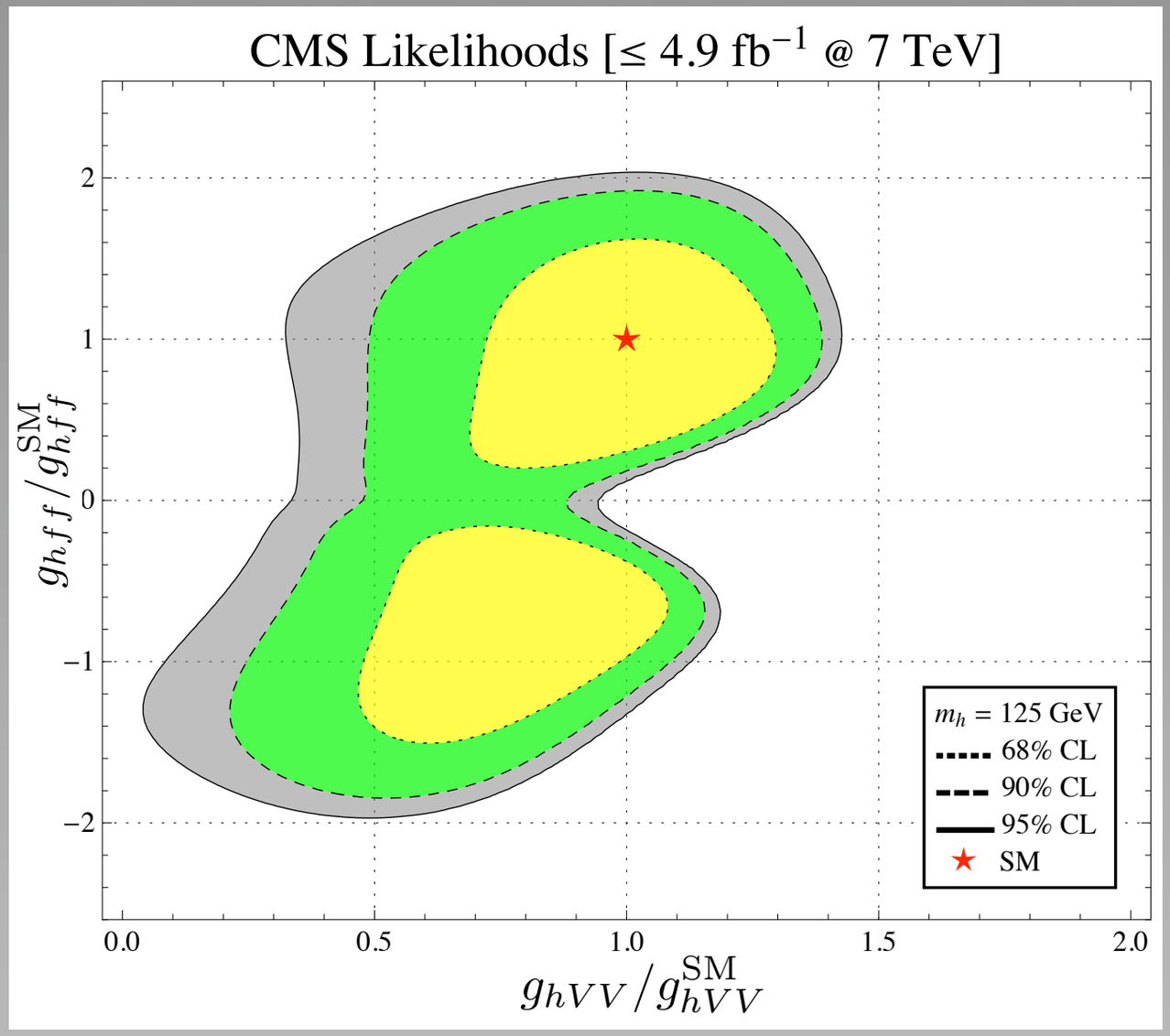
See explicitly how new physics scale depends on deviation from SM

Status report for the Higgs at 125(?)(!)



Peak likelihood falls nearly on top of SM point...

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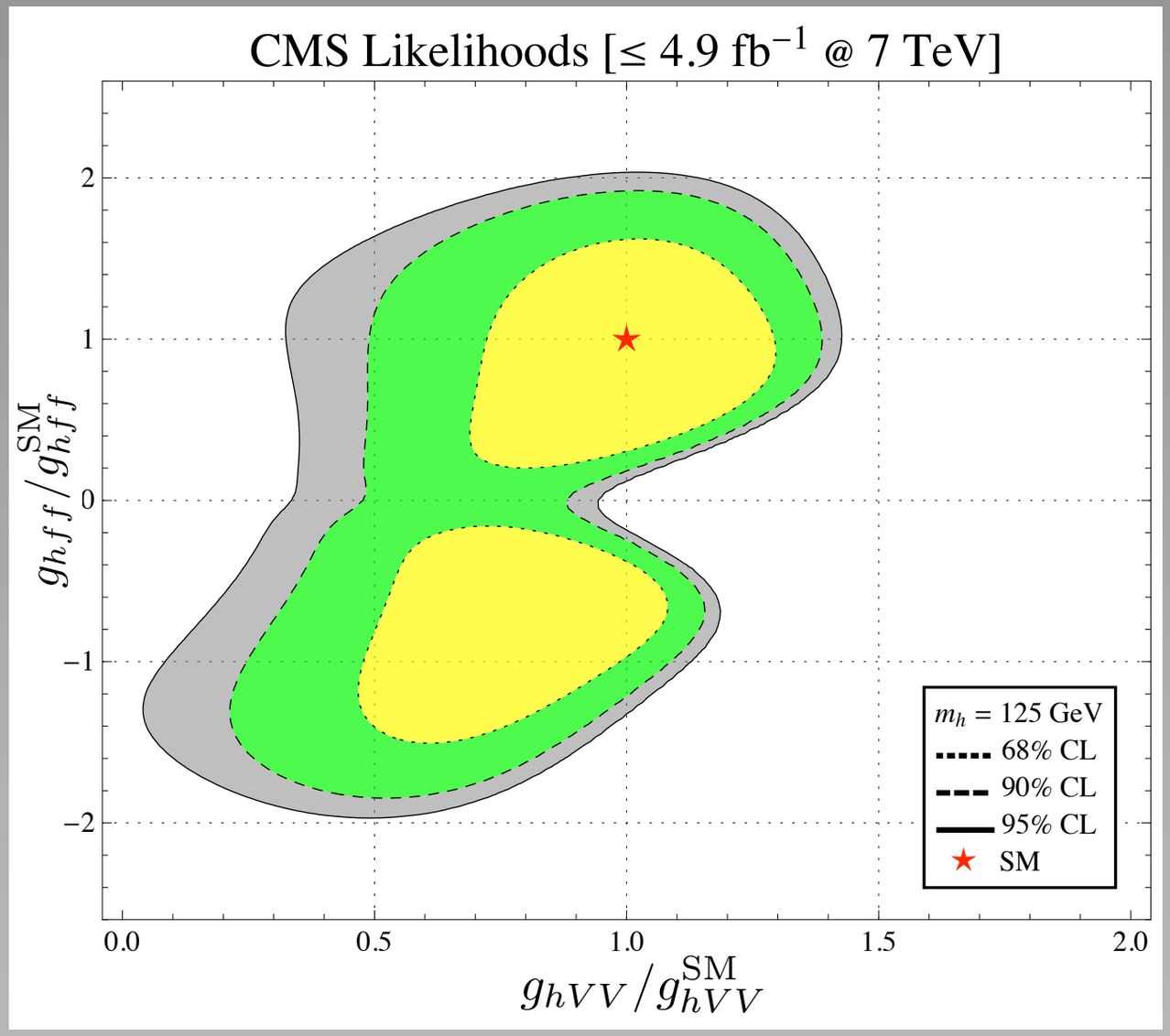

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(Preliminary) Conclusions:

- Exclusive anayses suggest that couplings in this framework ~ SM
- Therefore compositeness scale would be quite high...
- ...other states from EWSB (vectors) typically heavy

Part Three:
Supersymmetry

First: U and D Yukawa Rescalings differ (Type-II 2HDM)

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

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

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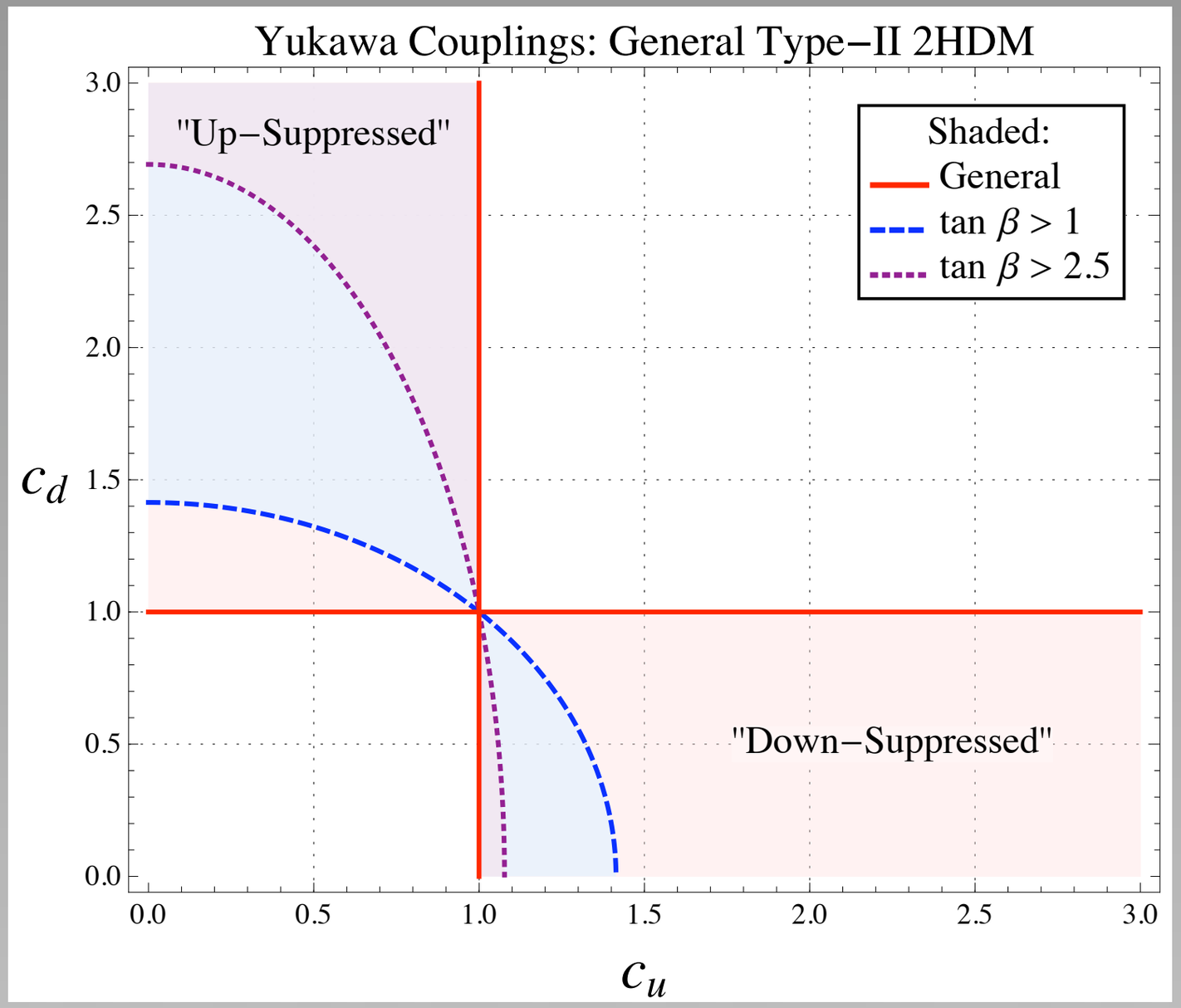
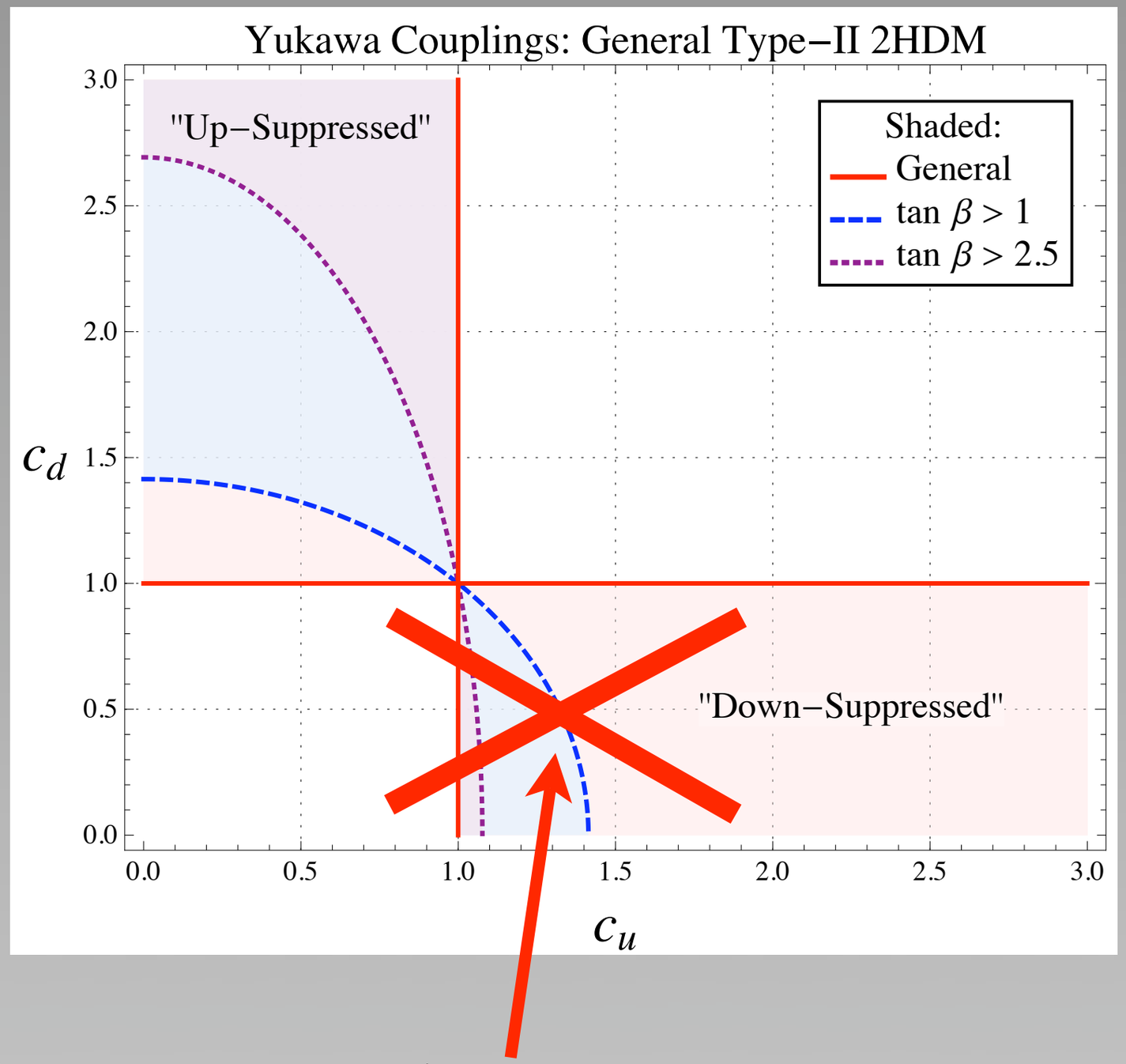
$$\left.\begin{aligned} c_u &\equiv g_{hQu^c}/\mathrm{SM} = \frac{\cos\alpha}{\sin\beta} \\ c_d &\equiv g_{hQd^c}/\mathrm{SM} = \frac{-\sin\alpha}{\cos\beta} \\ a &\equiv \mathrm{gauge}/\mathrm{SM} = \sin(\beta-\alpha) \end{aligned}\right\}$$

What is the data telling us about this space?

First: what does the accessible space of Yukawas look like?



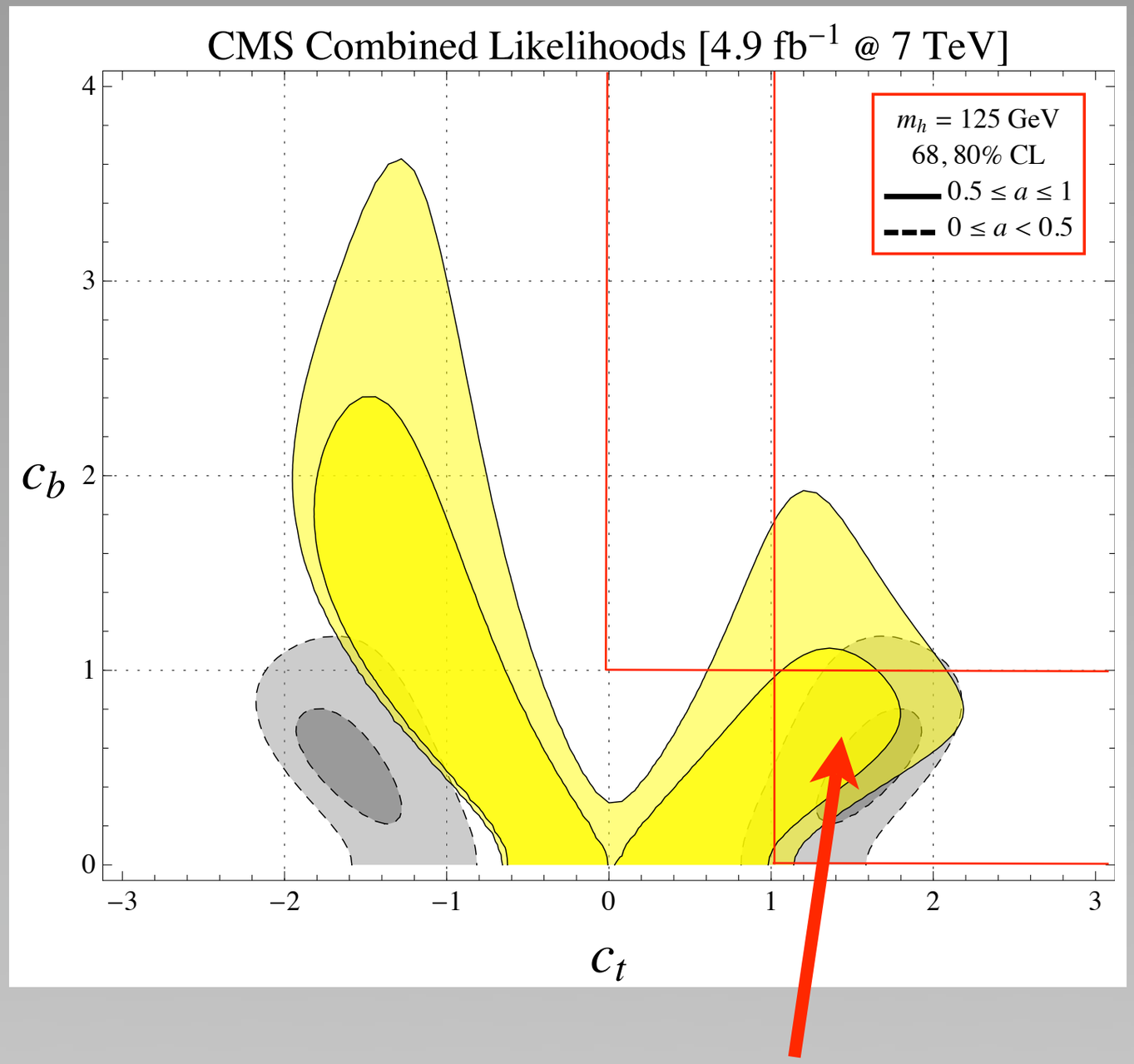
And for the MSSM?



The *very constrained* quartic structure of the MSSM (all coming from D terms) forbids it from entering the down-suppressed region whenever tan beta > 1.

Status...

We can construct the likelihood in the full 3D space, then project the gauge direction onto the 2D Yukawa plane:



While gauge coupling currently prefers decoupling (couplings = SM), other channels slide shallowly into a region inaccessible for MSSM!

How does the (loop-level) MSSM fare?

$$\Delta V_{\text{generic}} = \lambda_1 |H_u|^4 + \lambda_2 |H_d|^4 - 2\lambda_3 |H_u|^2 |H_d|^2$$
$$(+ \text{ non-minimal terms})$$

MSSM for neutral CP-even fields: $\lambda_{1,2,3} = \frac{1}{8}(g^2 + g'^2)$

with potentially lifesaving quantum corrections to λ_1, but for "down-suppression" we need

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

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Two potential strikes against minimality:

- Higgs mass;
- Higgs couplings.

Natural to consider non-minimal dynamics (left as an exercise*)

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*But the answer is in the back of the book (backup slides)

(Way too early for any) Conclusions

I. Composite Higgs: Fairly SM-like couplings indicate strong dynamics preferred at a high scale, if at all

II. SUSY: Hints of non-minimality in some channels so far; non-SM couplings indicate that some new states could show up soon

III. Generally: Couplings provide crucial indirect *hints* and *consistency checks* for BSM physics...

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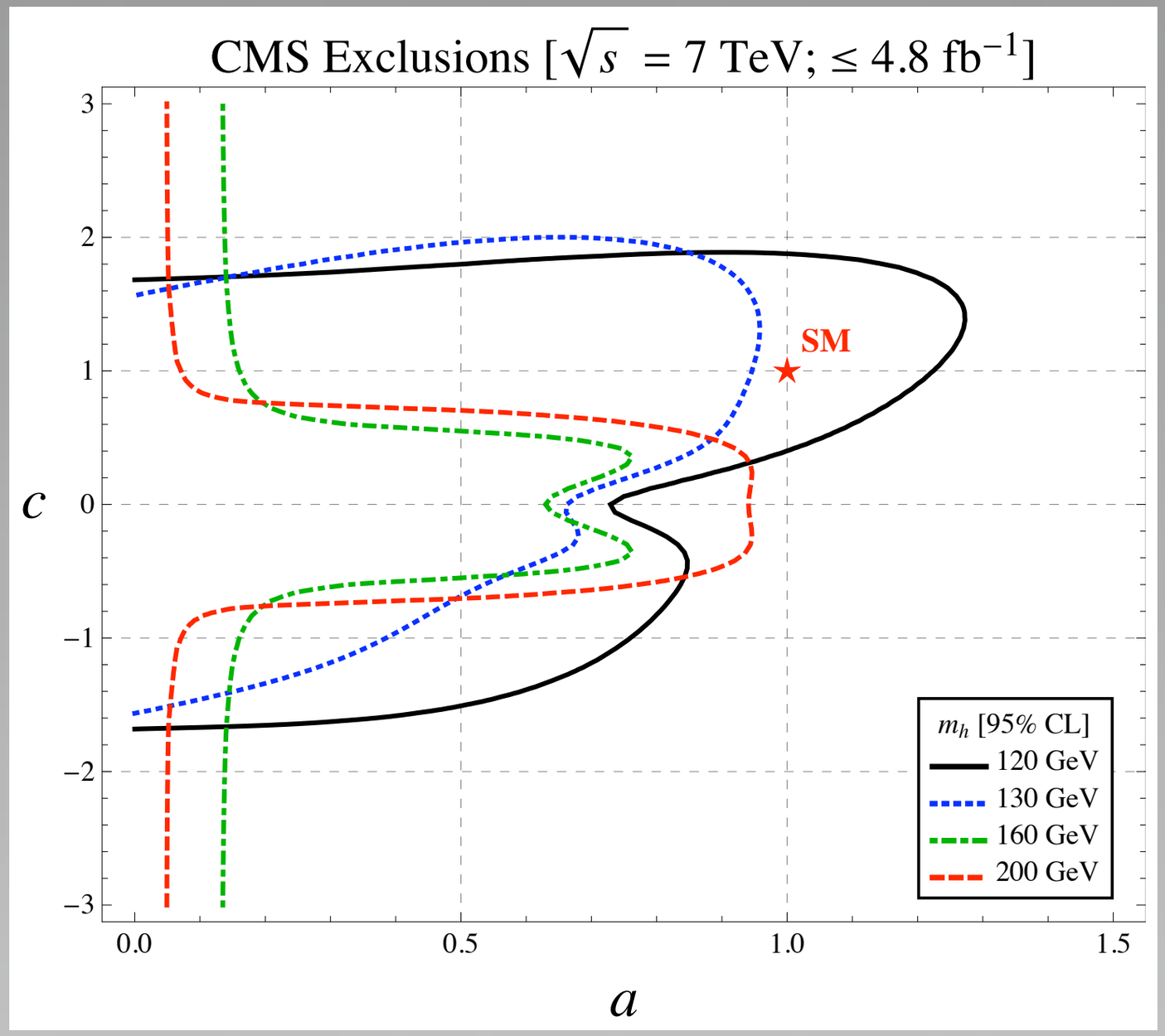
III. Generally: Couplings provide crucial indirect *hints* and *consistency checks* for BSM physics...

Spectra may make headlines, but couplings serve as fact-checkers. Establishing consistency of new physics requires collaboration between theorists and experimentalists; let's be ready for it!

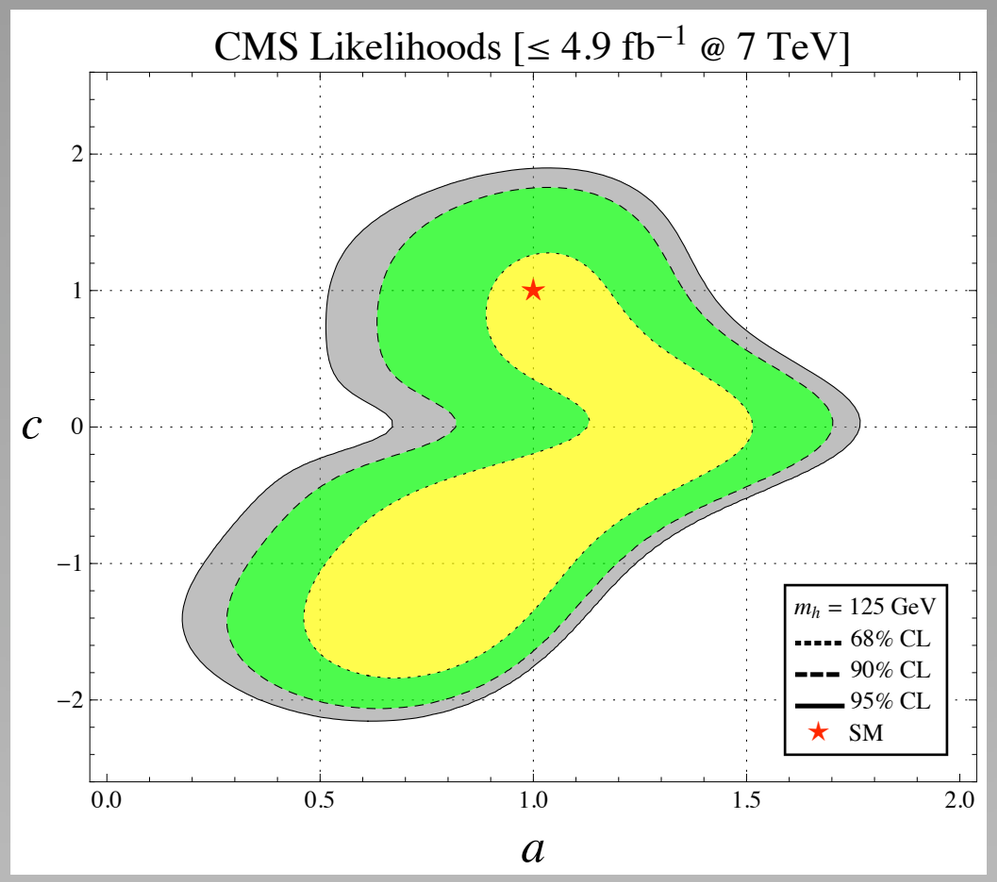
Backups

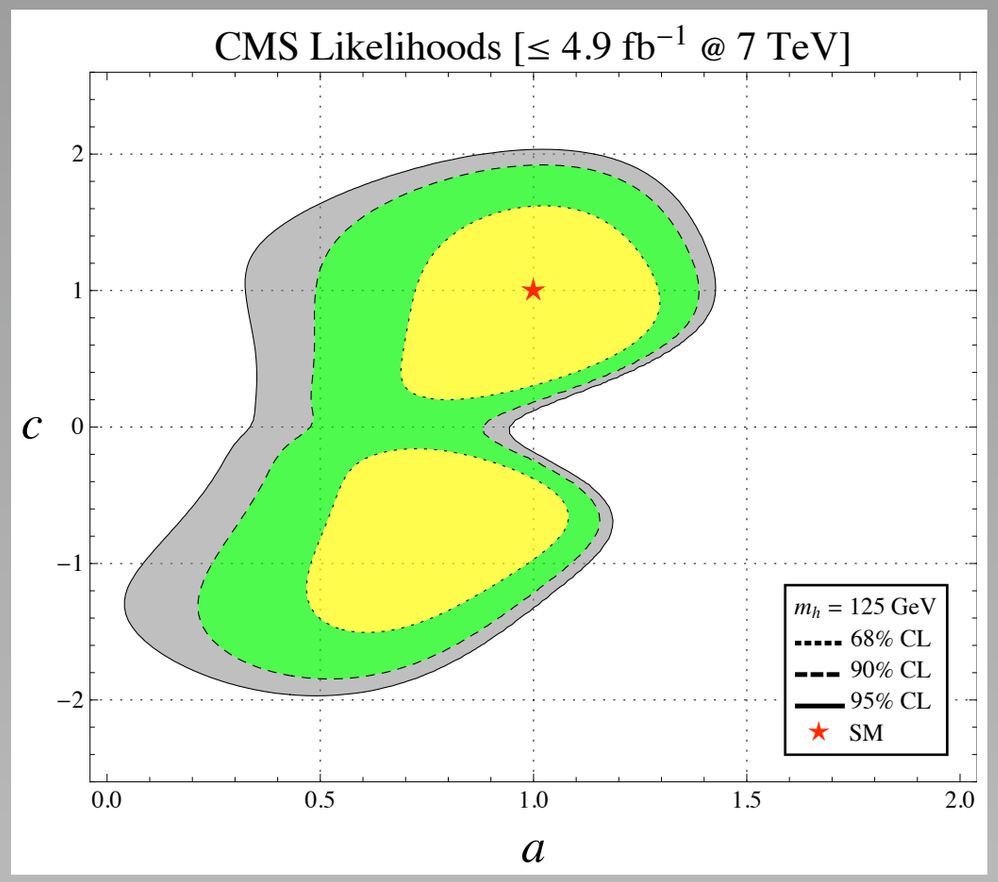
Status report for unpopular mass points



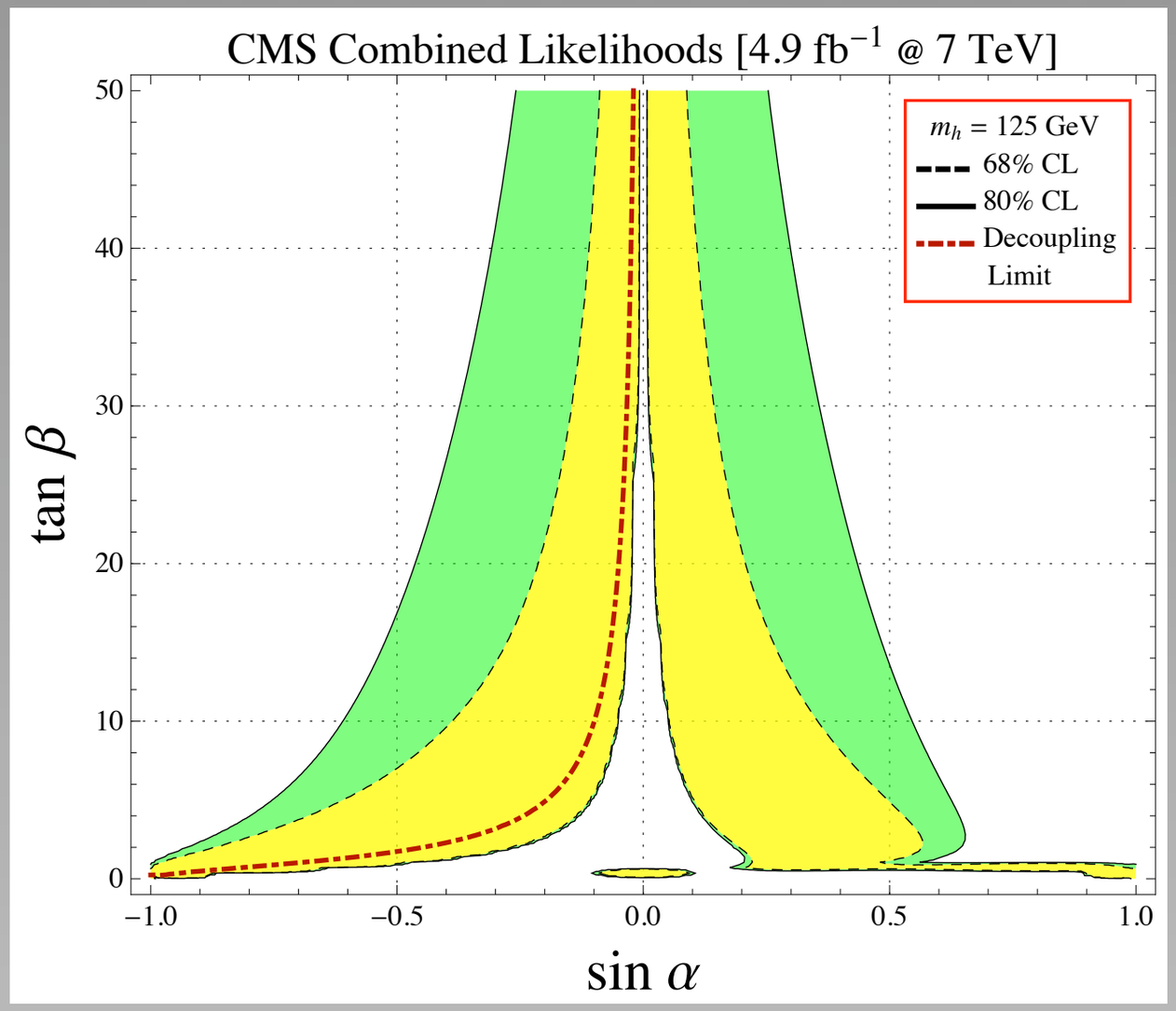
A Cautionary tale: Need Exclusive Searching and Reporting

ALL INCLUSIVE vs. ALL EXCLUSIVE subchannels:





The space of the MSSM Higgs



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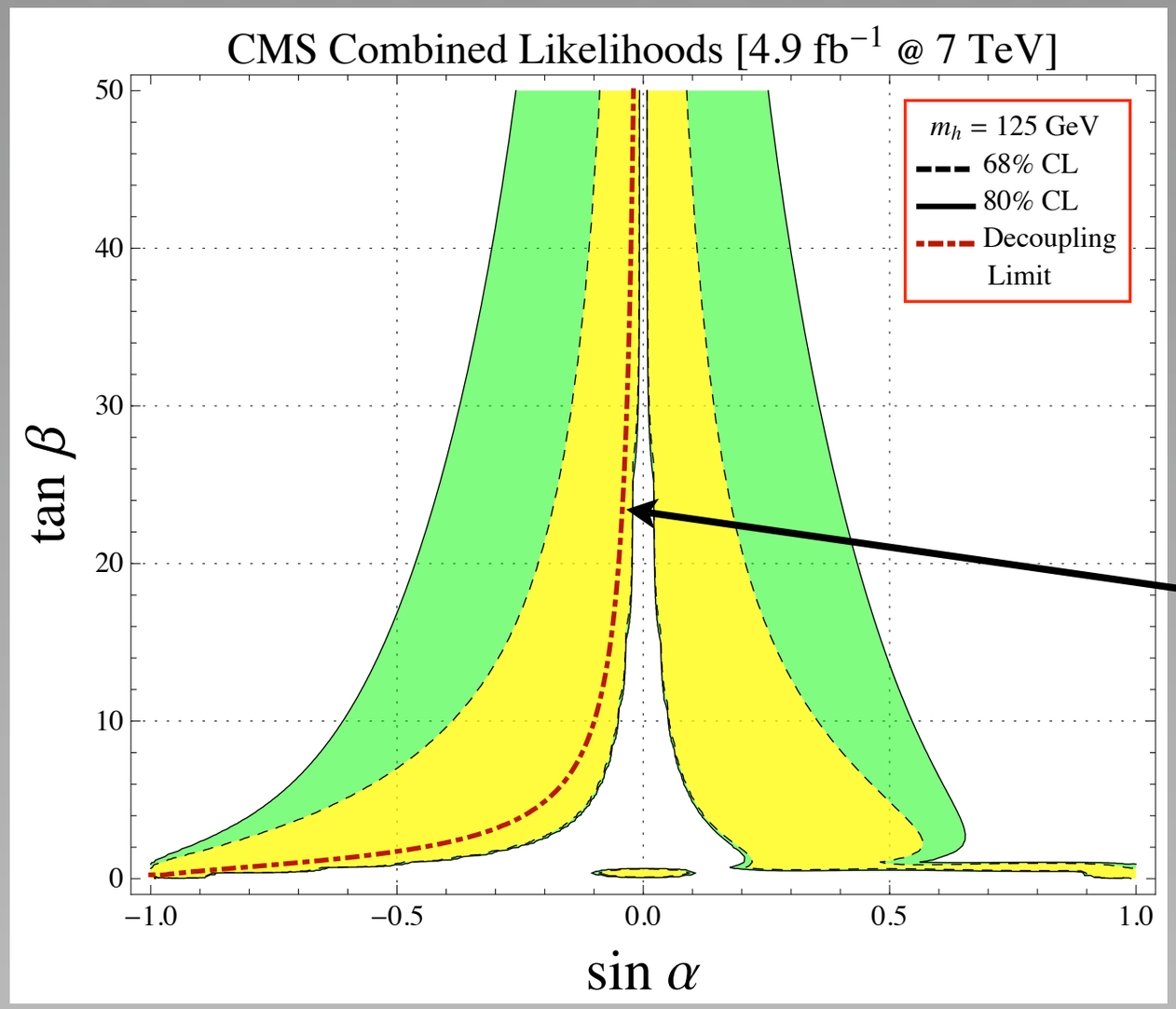

Decoupling:

$$H^0, H^\pm, A^0 \to \infty;$$

$$\Rightarrow a, c_u, c_d \to 1$$

Supported here by couplings, but also by Higgs mass!

$$m_h \to m_Z \text{ as } m_{A^0} \to \infty$$

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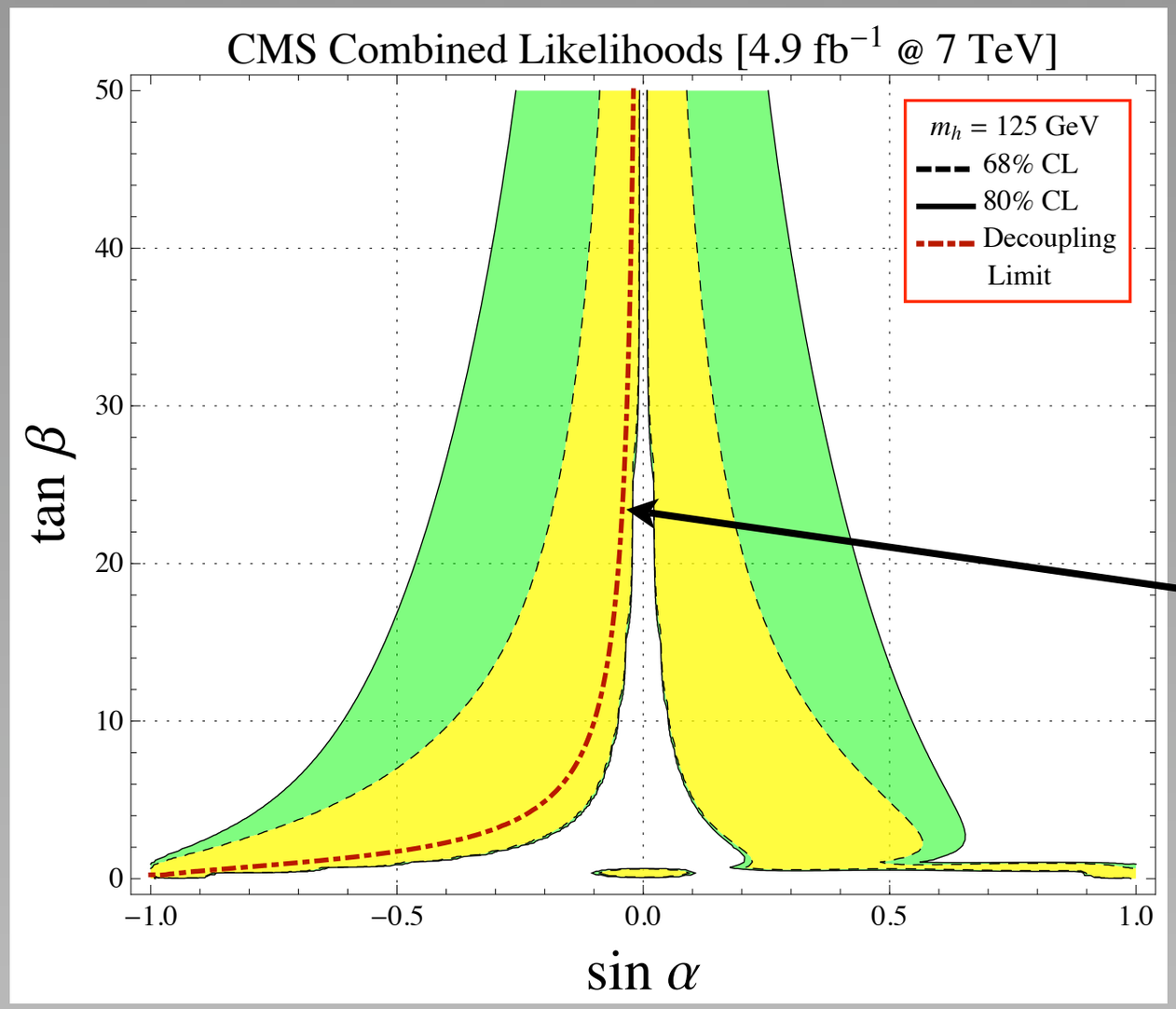

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- Peak likelihood lies close to the deoupling limit contour
- Consistency of this requires ALL couplings to revert to SM
- To check this, we can examine a 3D space...

Down-Suppression from New Perturbative Dynamics

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

I. Singlets (e.g. NMSSM)

II. Doublets (Superconformal TC = "The Seiberg Higgs")

III. Triplets

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$$\left.\begin{array}{c} \Delta W = \lambda_u H_u \mathcal{O}_d + \lambda_d H_d \mathcal{O}_u \\ \Rightarrow \Delta\mathcal{L} \sim \dfrac{\lambda_{u,d}\Lambda^3}{16\pi^2} H_{u,d};\ v_{u,d} \sim \dfrac{\lambda_{u,d}\Lambda^3}{16\pi^2 m_{H_{u,d}}^2} \end{array}\right\} \begin{array}{c} \text{Tadpoles} \Rightarrow \beta \\ \text{Masses} \Rightarrow \alpha \\ \text{INDEPENDENT} \\ \text{ANGLES!} \end{array}$$

III. Triplets

Down-Suppression from New Perturbative Dynamics

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

I. Singlets (e.g. NMSSM)

$$\Delta W = \lambda S H_u H_d + \kappa S^3 \quad \Rightarrow \quad \delta\lambda_3 = -|\lambda|^2$$

II. Doublets (Superconformal TC = "The Seiberg Higgs")

$$\left.\begin{array}{c} \Delta W = \lambda_u H_u \mathcal{O}_d + \lambda_d H_d \mathcal{O}_u \\ \Rightarrow \Delta\mathcal{L} \sim \dfrac{\lambda_{u,d}\Lambda^3}{16\pi^2} H_{u,d};\ v_{u,d} \sim \dfrac{\lambda_{u,d}\Lambda^3}{16\pi^2 m^2_{H_{u,d}}} \end{array}\right\} \begin{array}{c} \text{Tadpoles} \Rightarrow \beta \\ \text{Masses} \Rightarrow \alpha \\ \text{INDEPENDENT} \\ \text{ANGLES!} \end{array}$$

III. Triplets

$$\Delta W = \lambda_T T H_u H_u + \lambda_{\bar{T}} \bar{T} H_d H_d \quad \Rightarrow \quad \delta\lambda_{1,2} = \left|\lambda_{T,\bar{T}}\right|^2$$

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