HIGGS HUNTER'S DIGEST

UC DAVIS: JOINT THEORY SEMINAR

APRIL 30, 2012

Jamison Galloway

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

arXiv:1205.xxxx with A. Azatov, S. Chang, and N. Craig

SAPIENZA
UNIVERSITÀ DI ROMA

Outline

Part I: Setup

1. What do we know from the LHC?
2. How can we use this if we have BSM in mind?

Part II: Application

1. (Minimal) Composite Higgs
2. (Minimal) SUSY

Part III: Conclusions (as we go...)

1. Utility of indirect information from constraining couplings

$$\text{Naturalness} \propto (\text{couplings} \neq \text{SM})$$

2. Great opportunity for theory/experiment collaboration...
3. ...as *required* to really get the most from this machine!

PART ONE

What do we know (thanks to the LHC)?

Given background, signal, and observed events: construct likelihood:

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\begin{aligned}
P(n|n_{\rm obs}) &= \frac{n^{n_{\rm obs}} e^{-n}}{n_{\rm obs}!} \times \pi(n) \\
&\xrightarrow{\text{A.L.}} \exp\left[\frac{-(n-n_{\rm obs})^2}{2n_{\rm obs}}\right] \times \pi(n)
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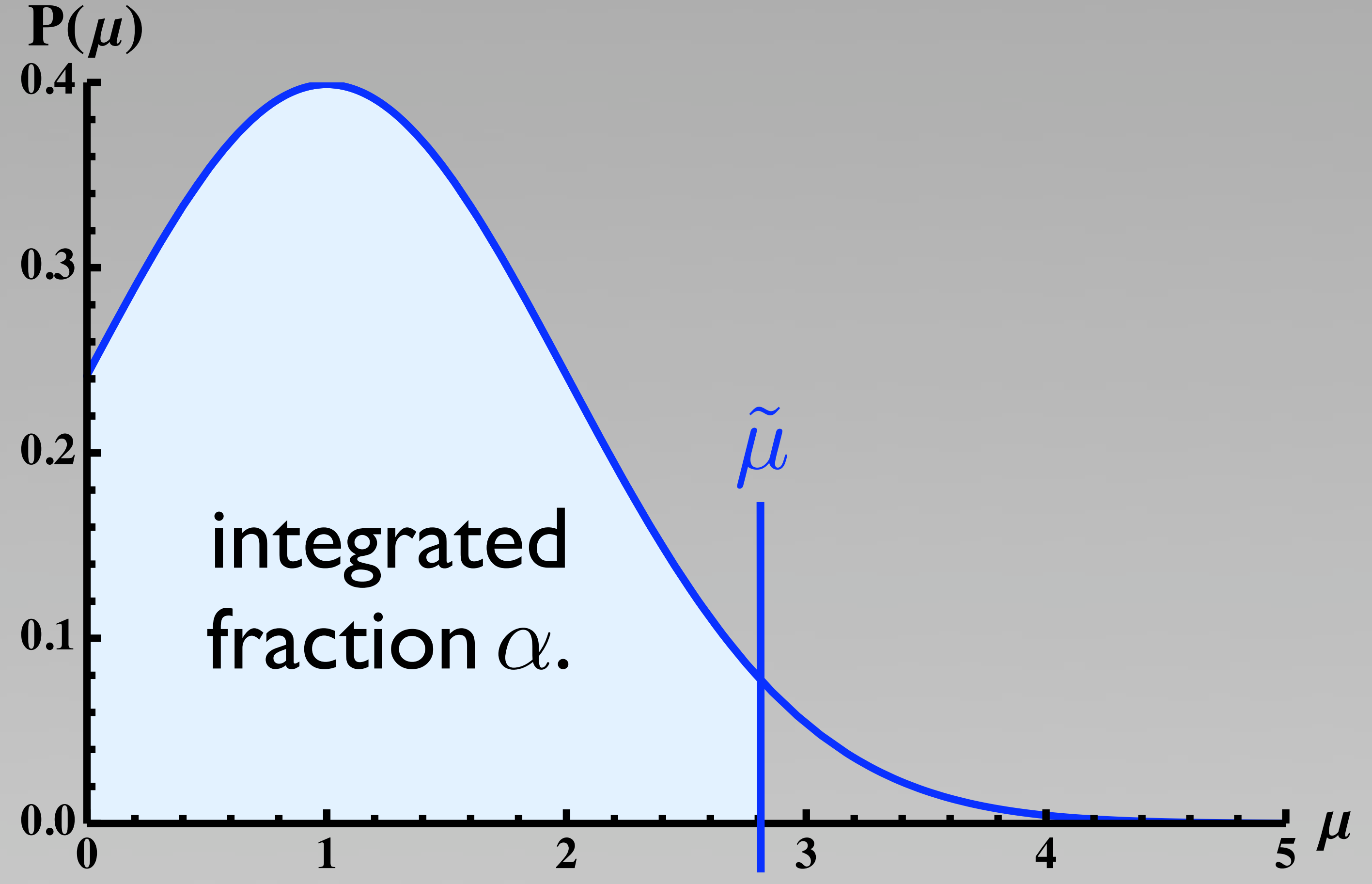

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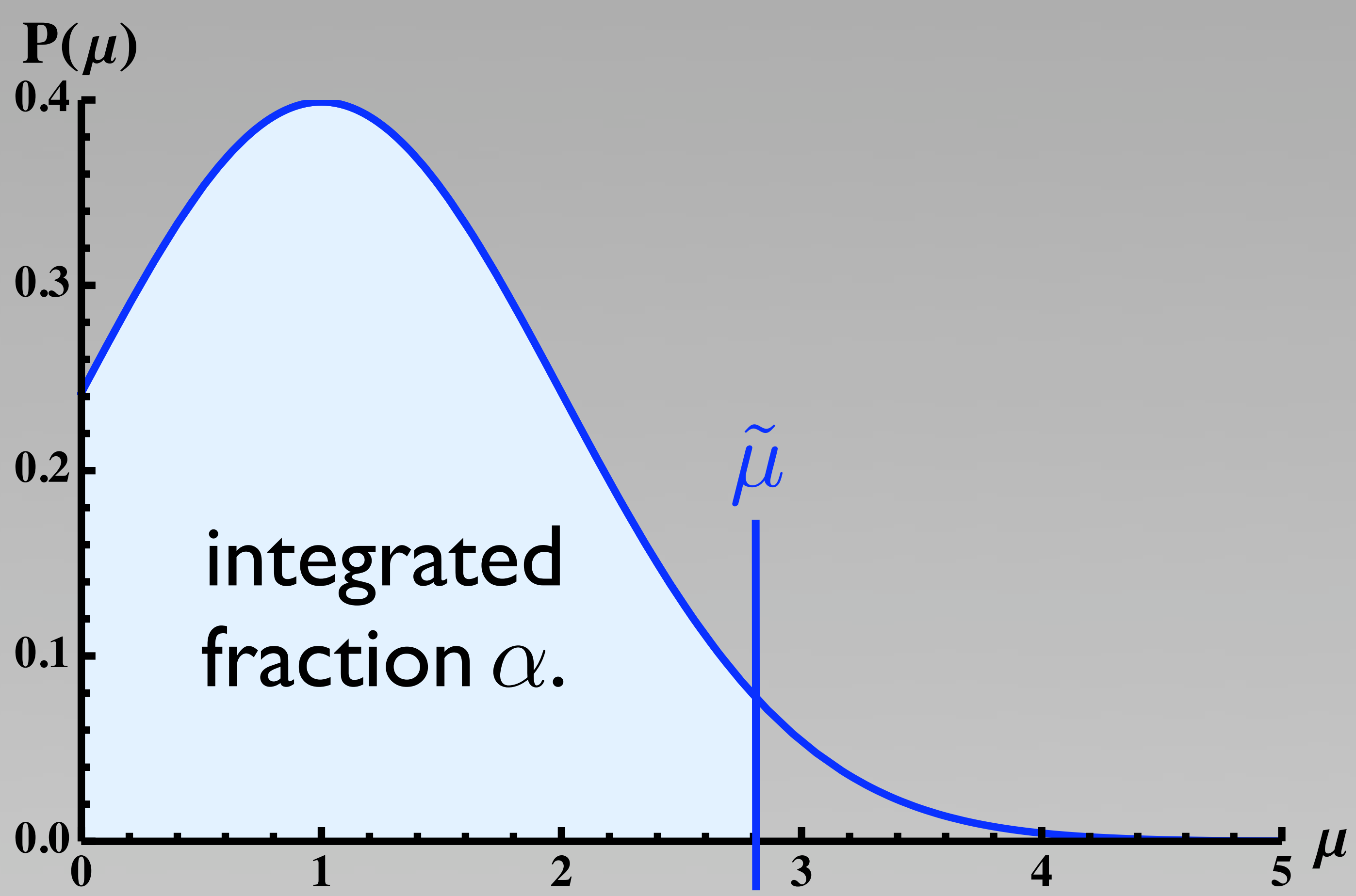

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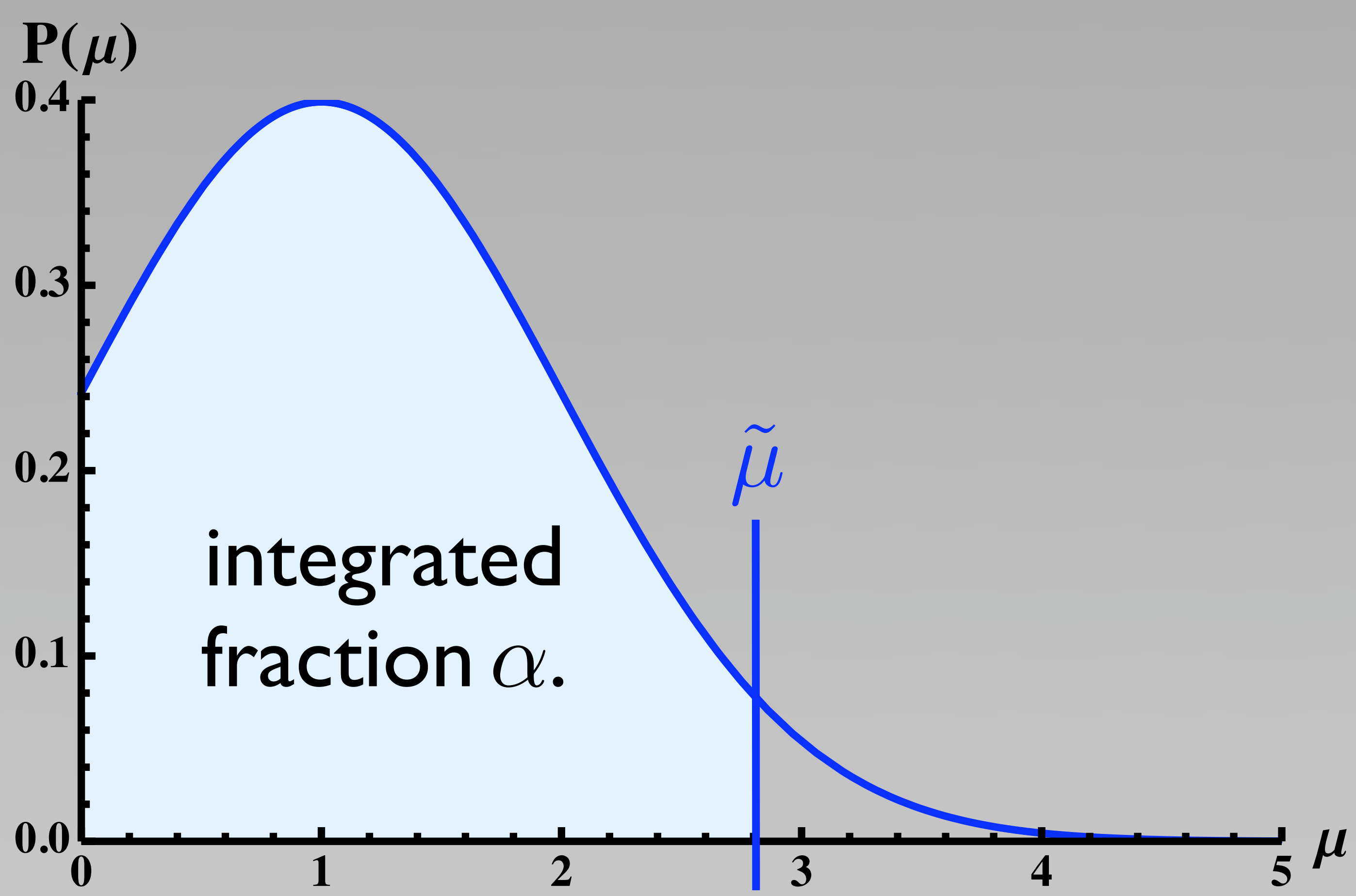

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Answer:
We know the amount by which we can rescale production/branching -- all in the same proportions -- and still be consistent with observation.

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?

PART TWO

A simplified theory input: "The non-panacean Higgs"

The theory we know has to be augmented (unitarity, renorm'ability):

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:

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

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Assumption: the (custodial singlet) 'Higgs' might not be single-handedly responsible for unitarization, etc.
OTHER NEW PHYSICS enters at potentially low scales

Cases to consider here: Compositeness, SUSY

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FOCUSING ON THESE GUYS

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First case: Composite Higgs*

*Yukawa rescaling (“c”) = flavor-universal

Moving on: Comparison to Likelihood

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... that we need to determine for ourselves at this point

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

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

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

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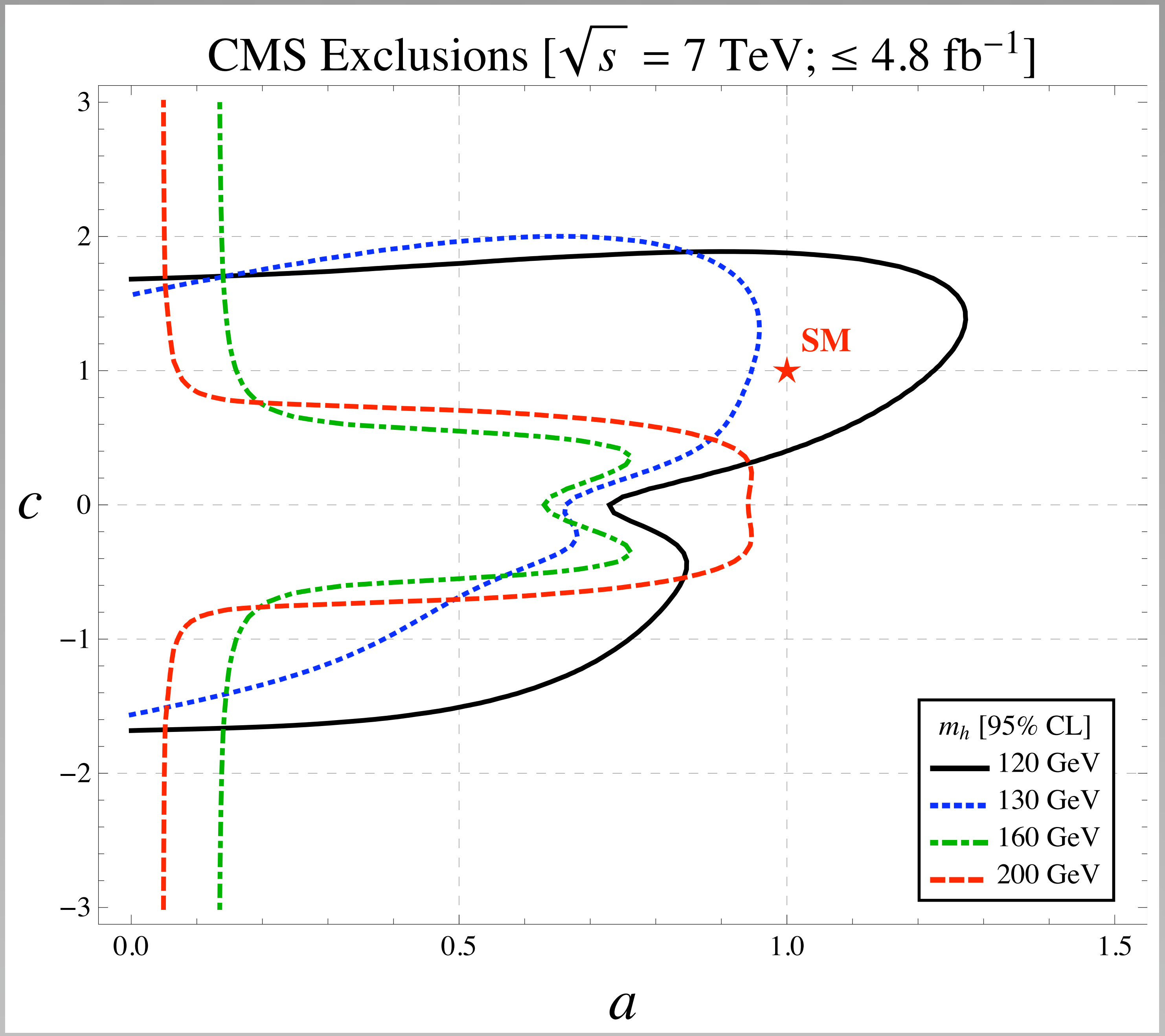
RECAP:

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

Status report for unpopular mass points



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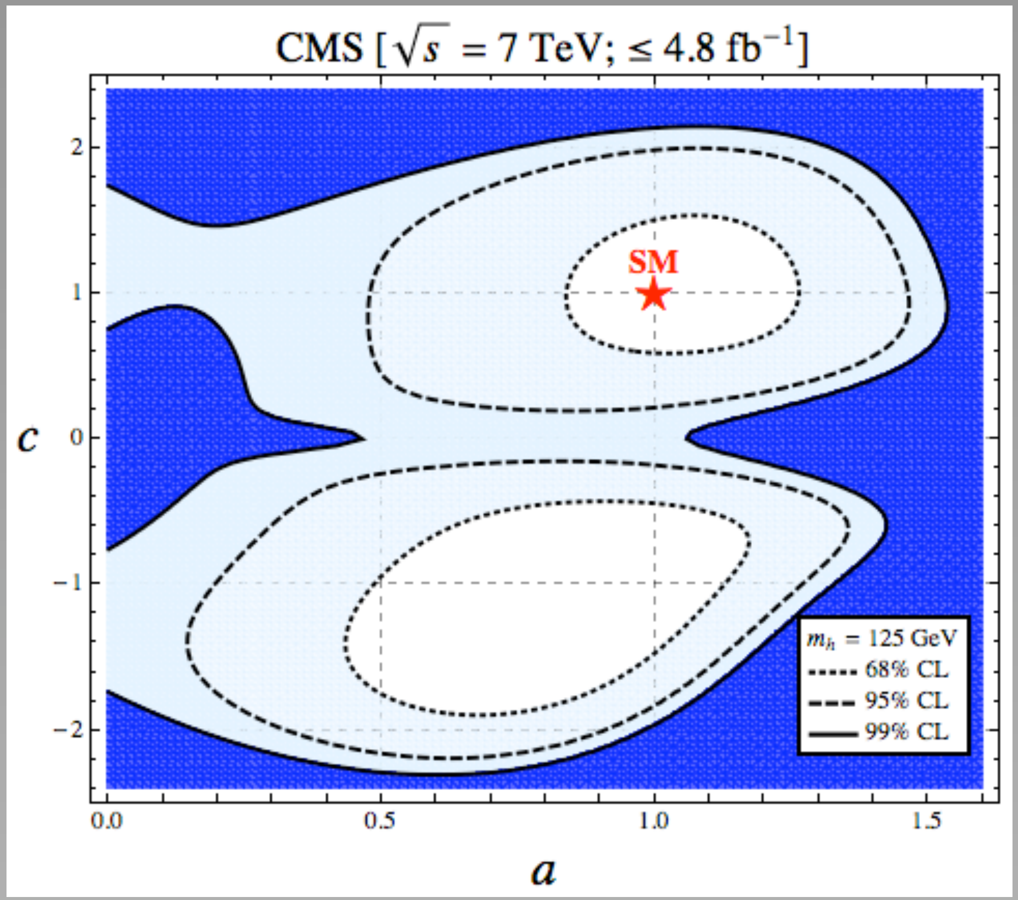

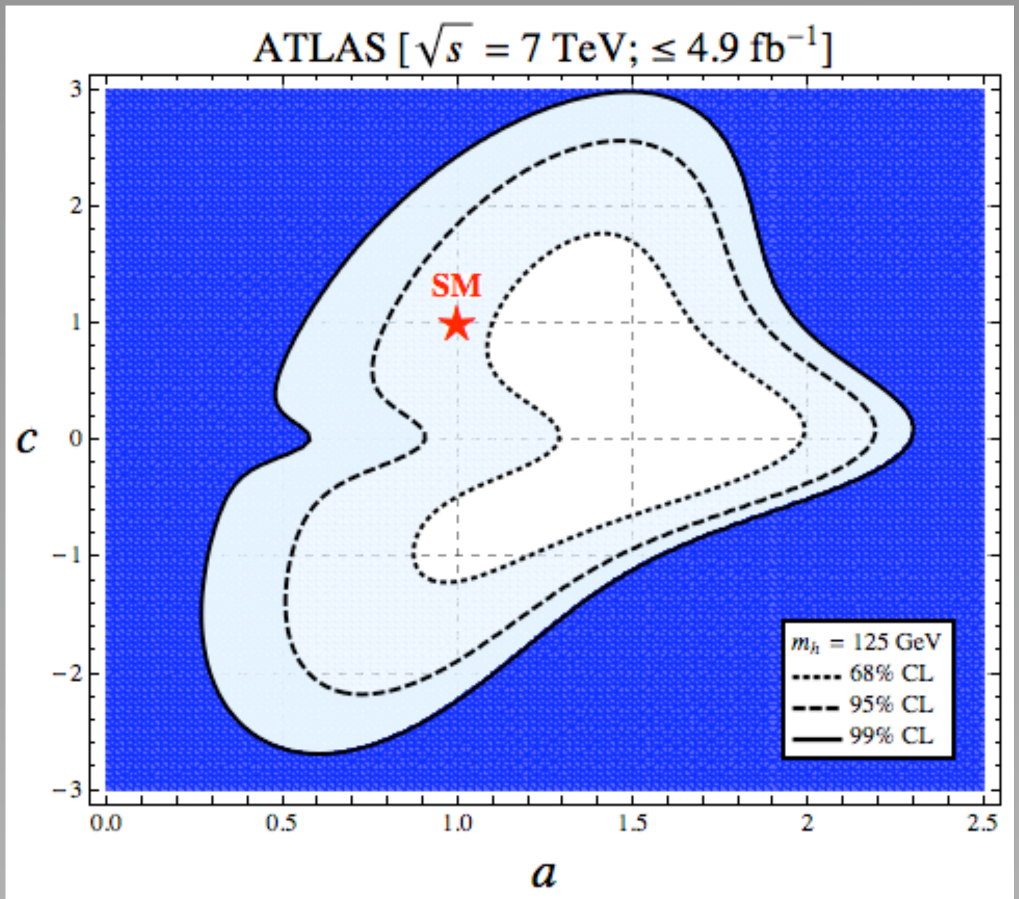

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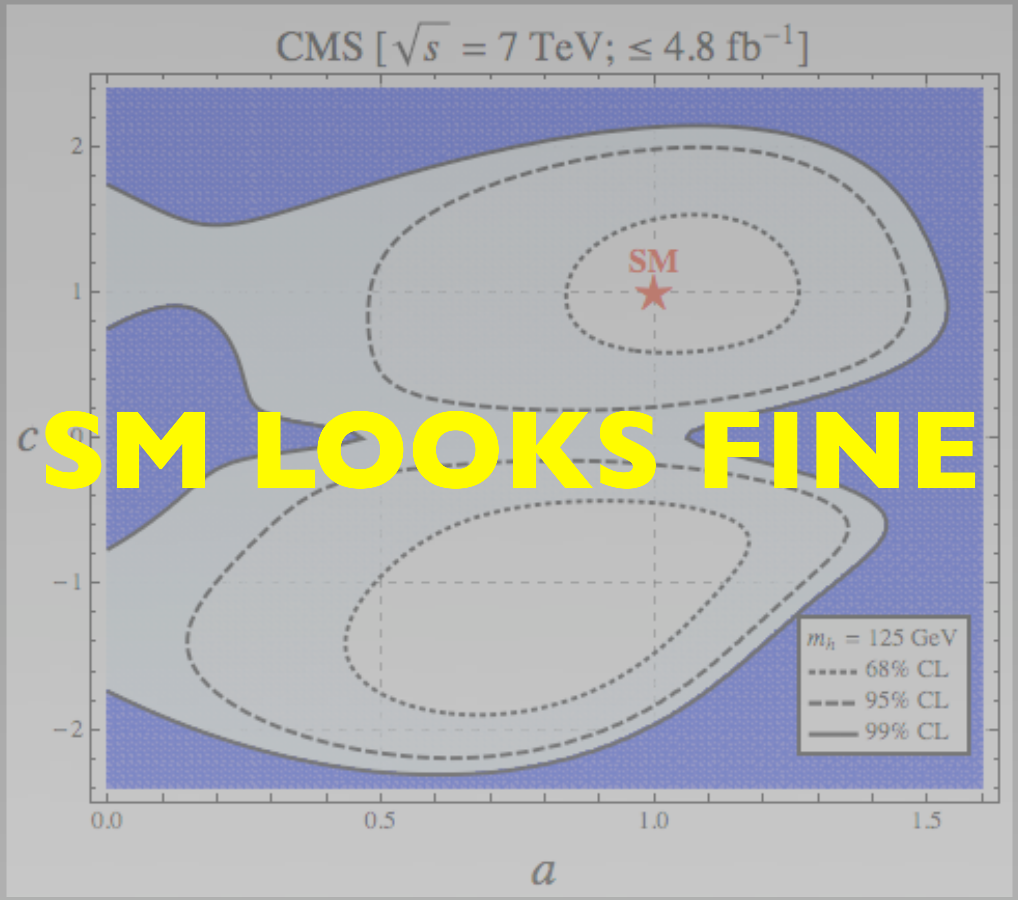

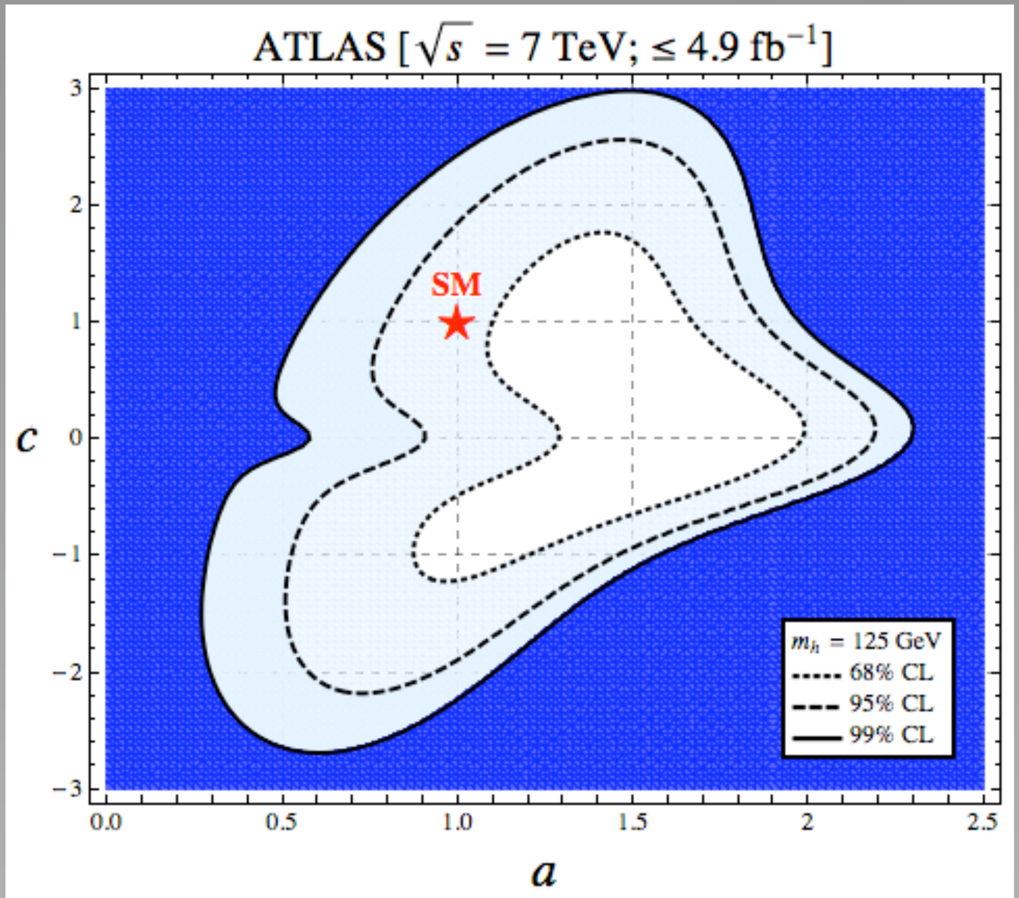

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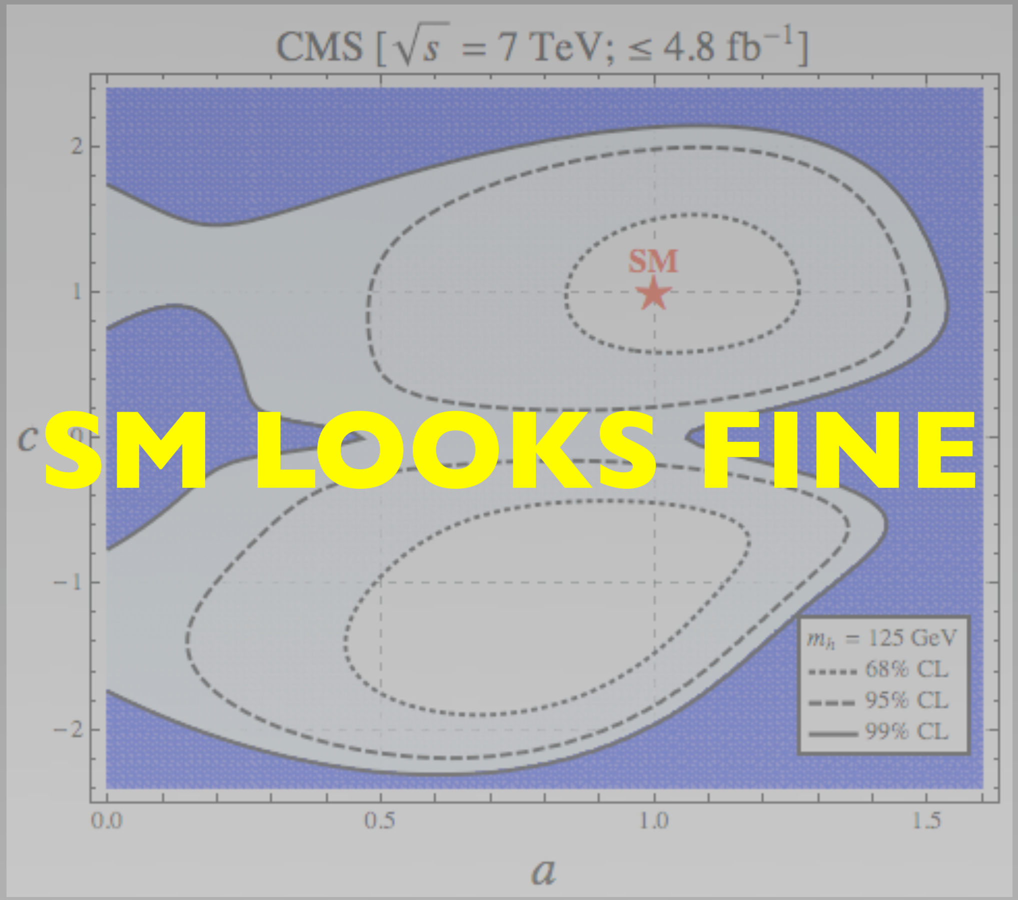

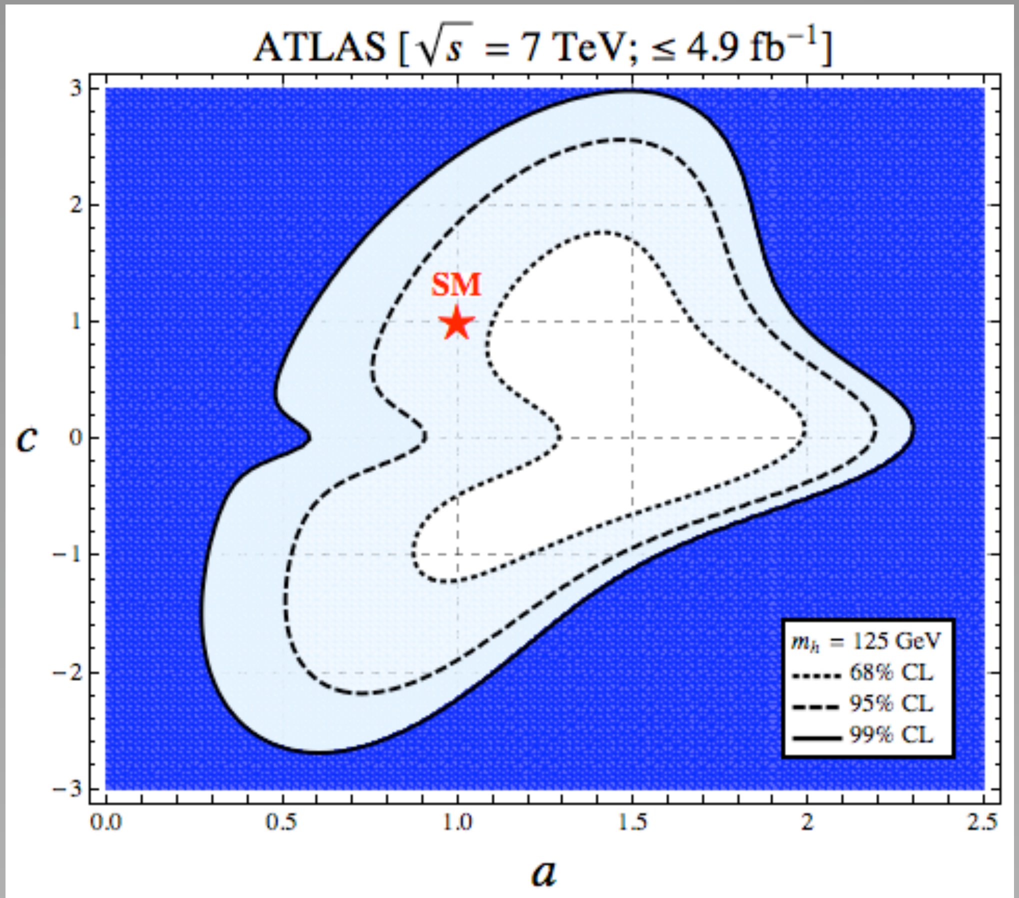

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how should we take this?

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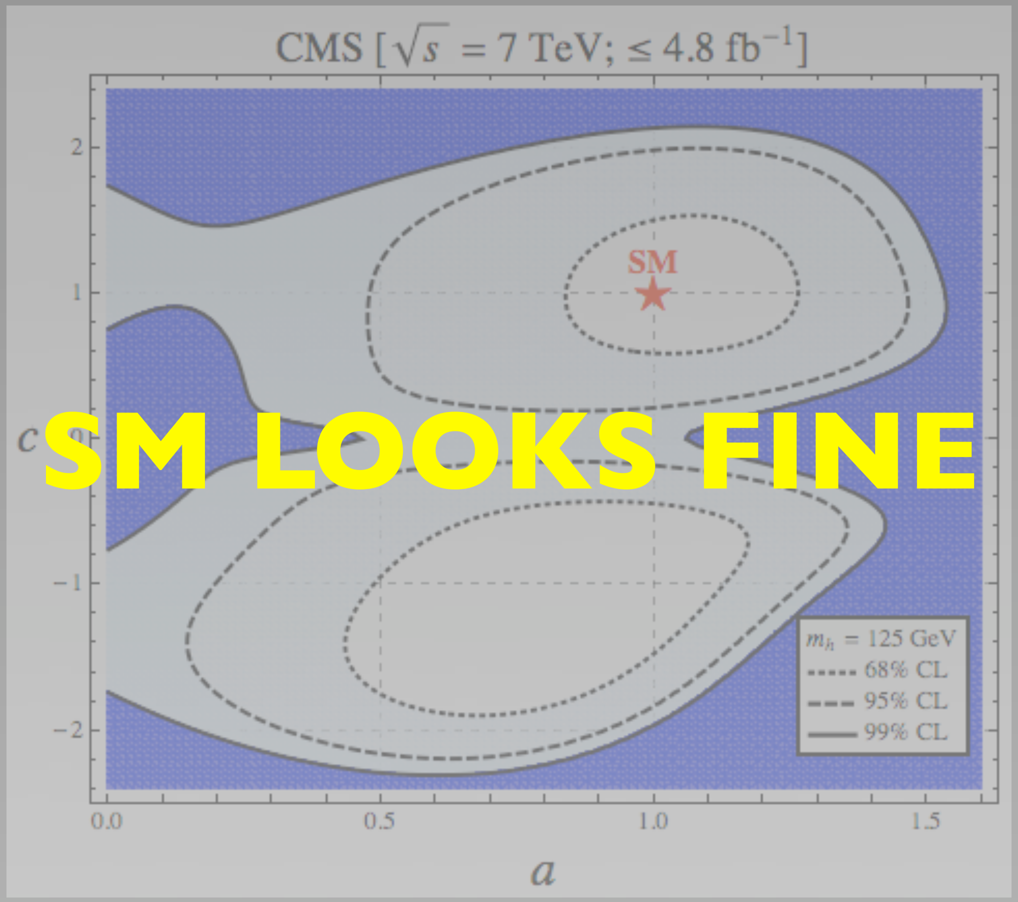

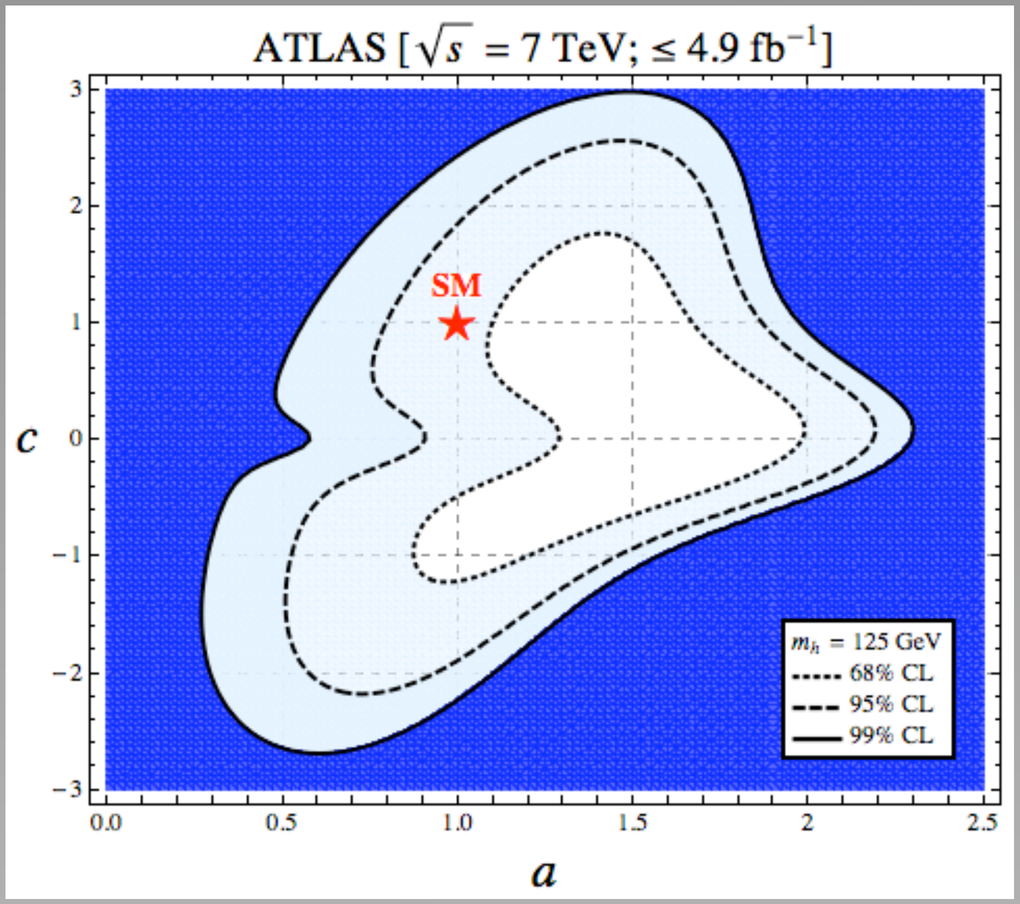

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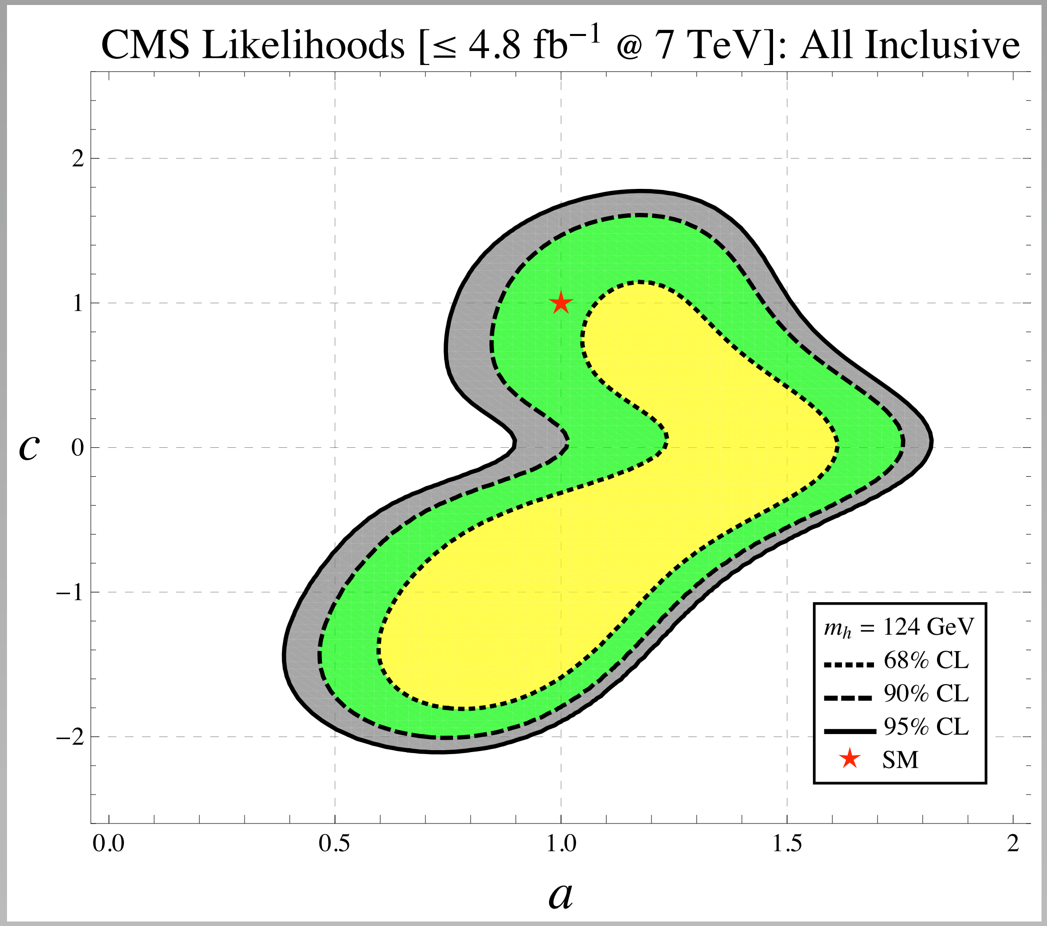
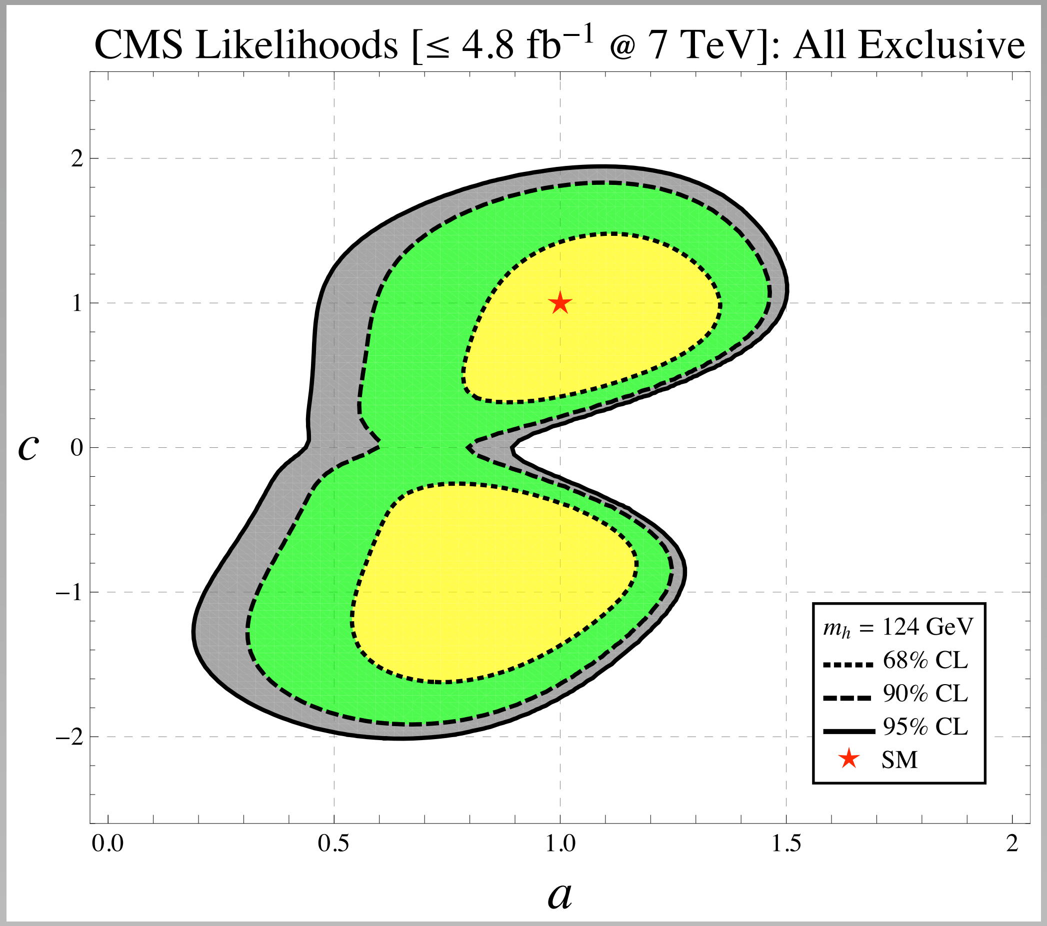
NOT VERY SERIOUSLY
stay tuned...

Take Caution: Need Exclusive Searching and Reporting

ALL INCLUSIVE vs. ALL EXCLUSIVE subchannels:





Second case: SUSY

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

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Holomorphy

Anomaly-cancellation

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

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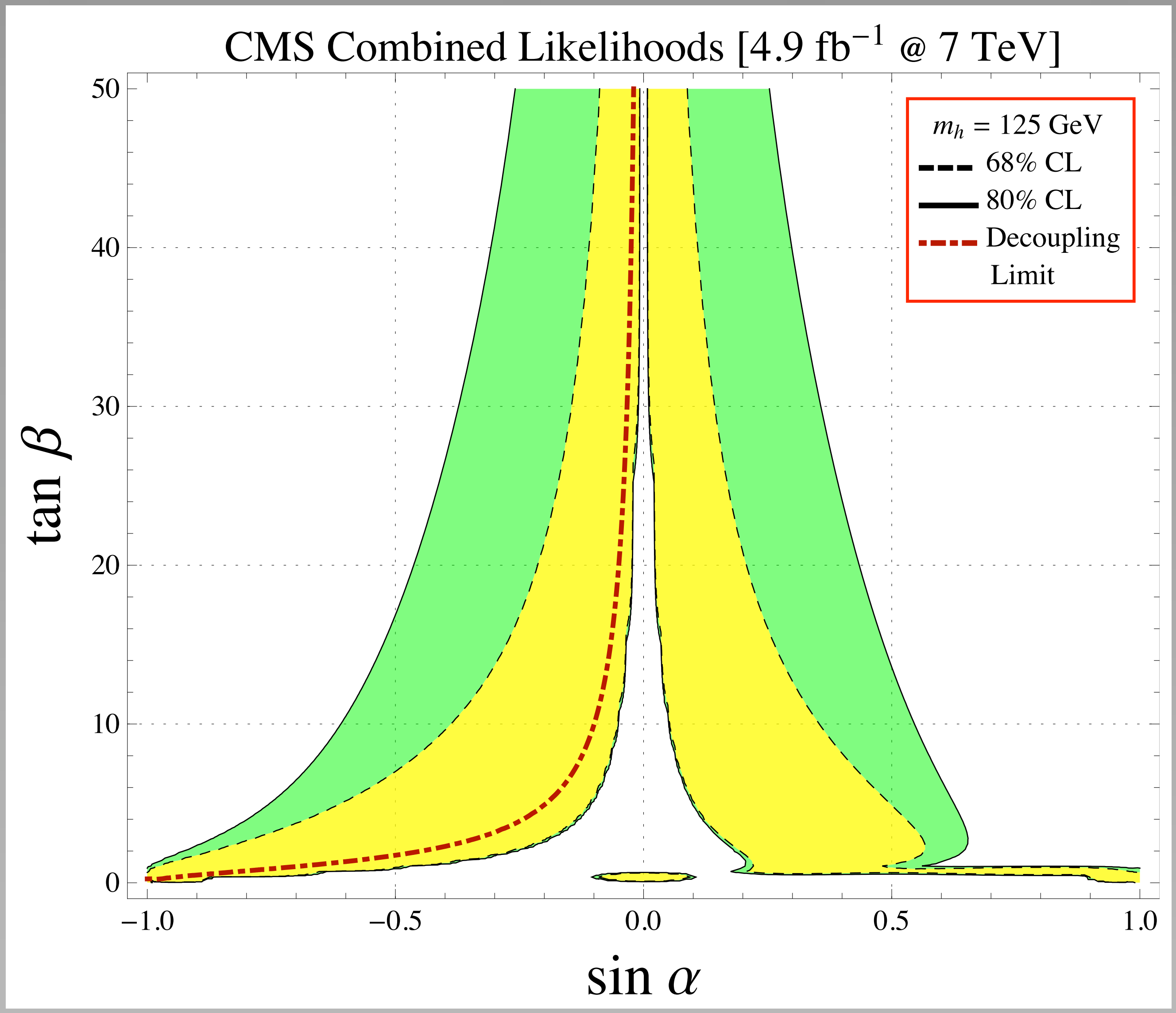
What is the data telling us about this space?

First look: *The* space of the MSSM Higgs



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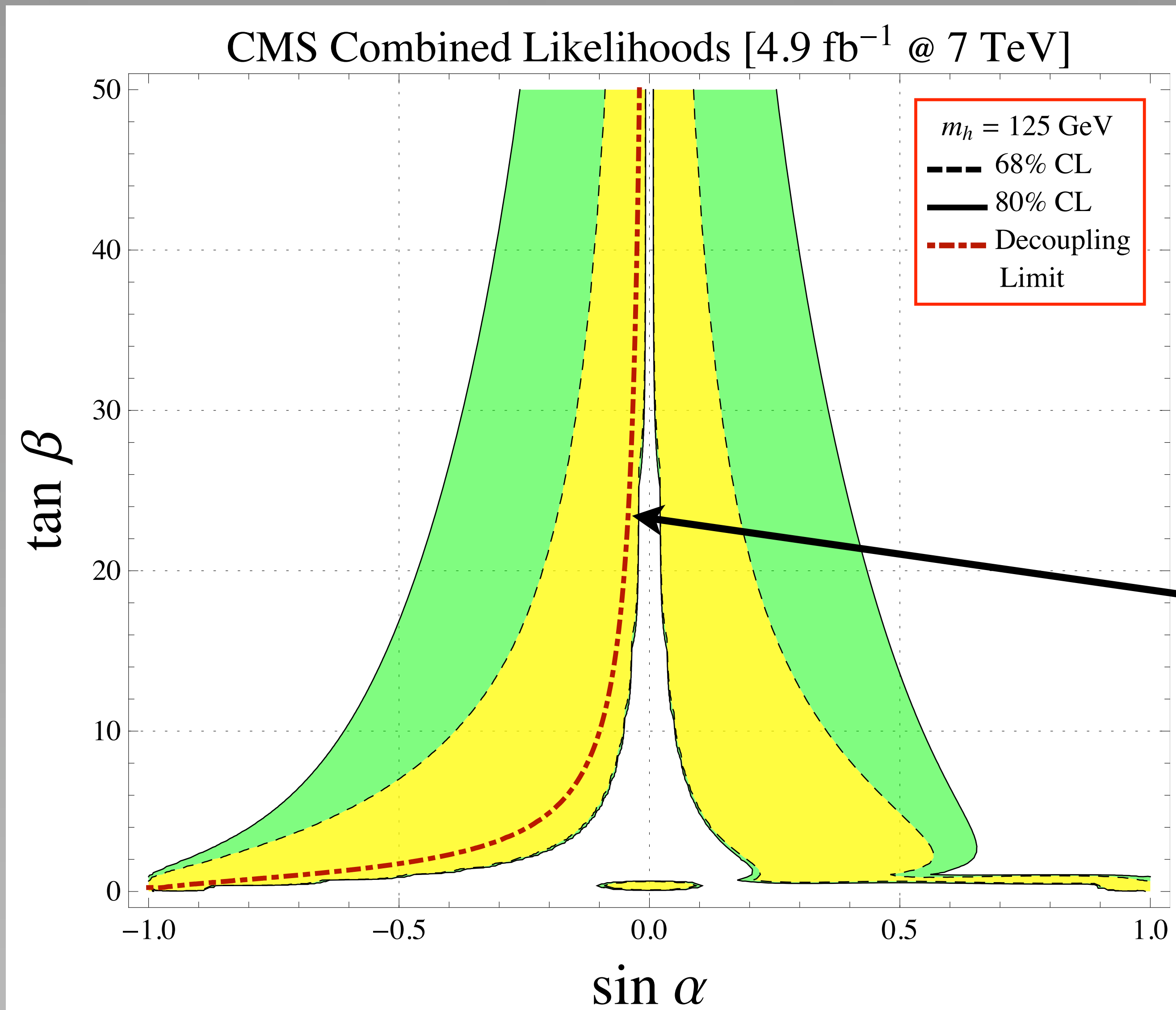

Decoupling:

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

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

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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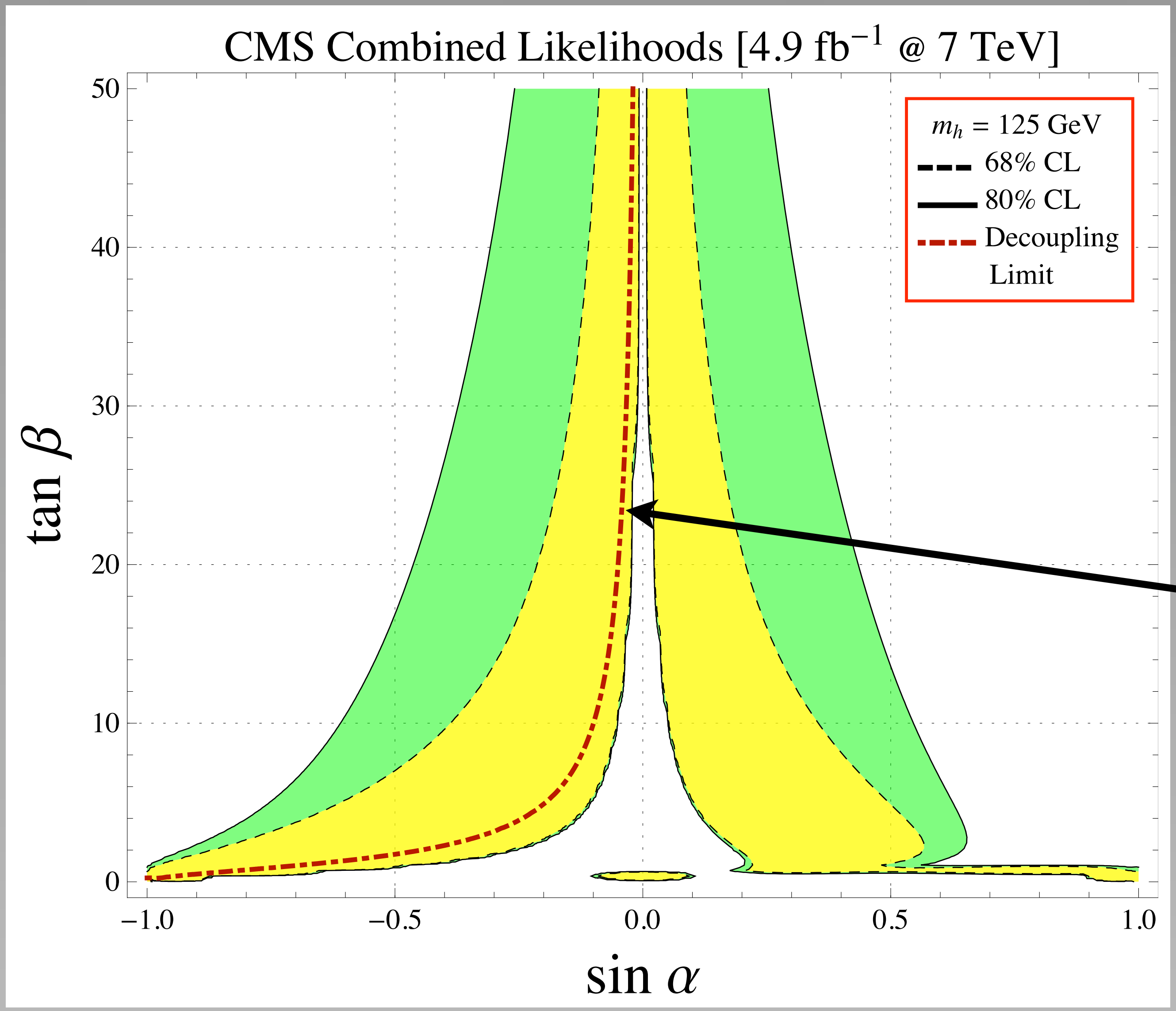

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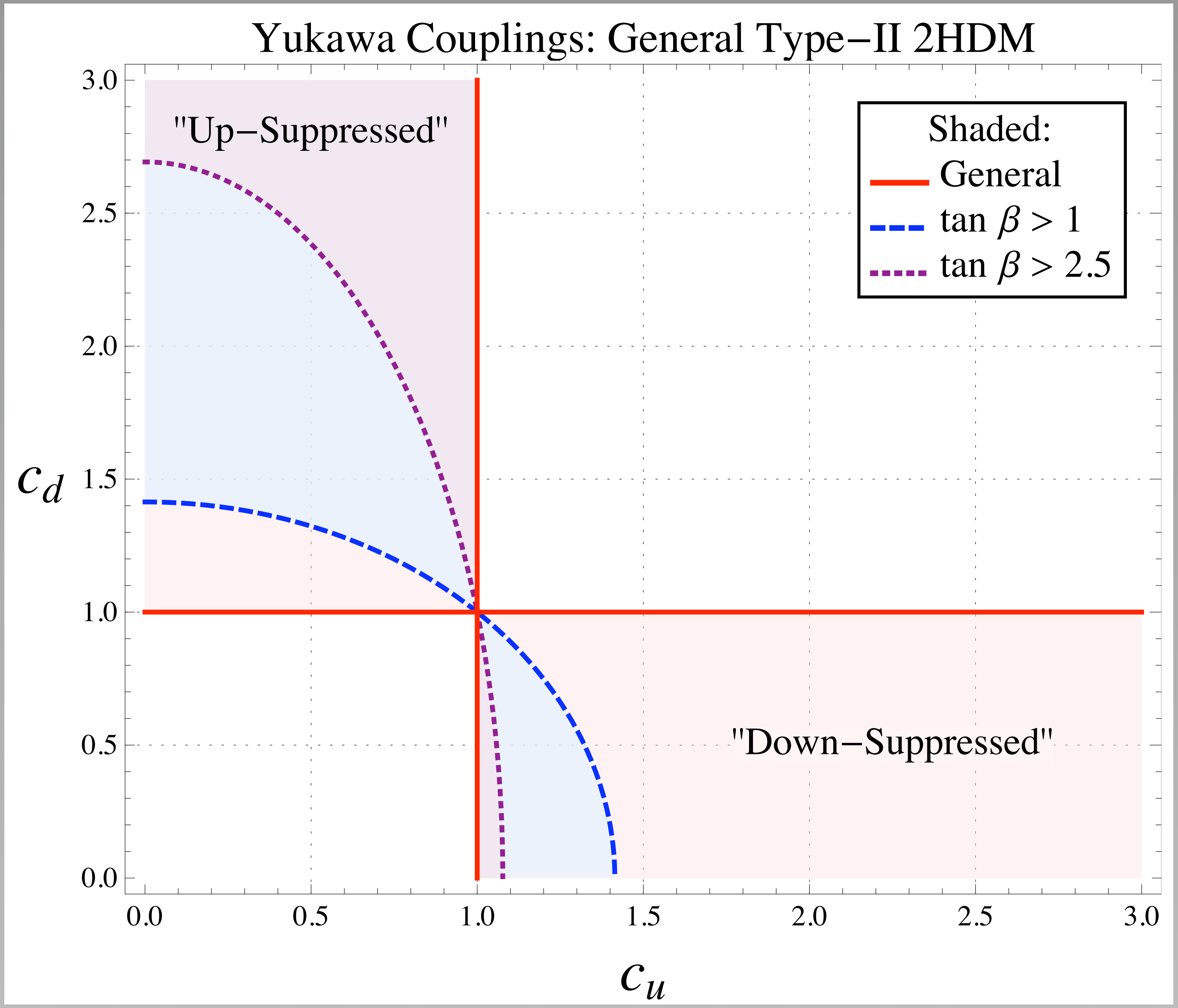
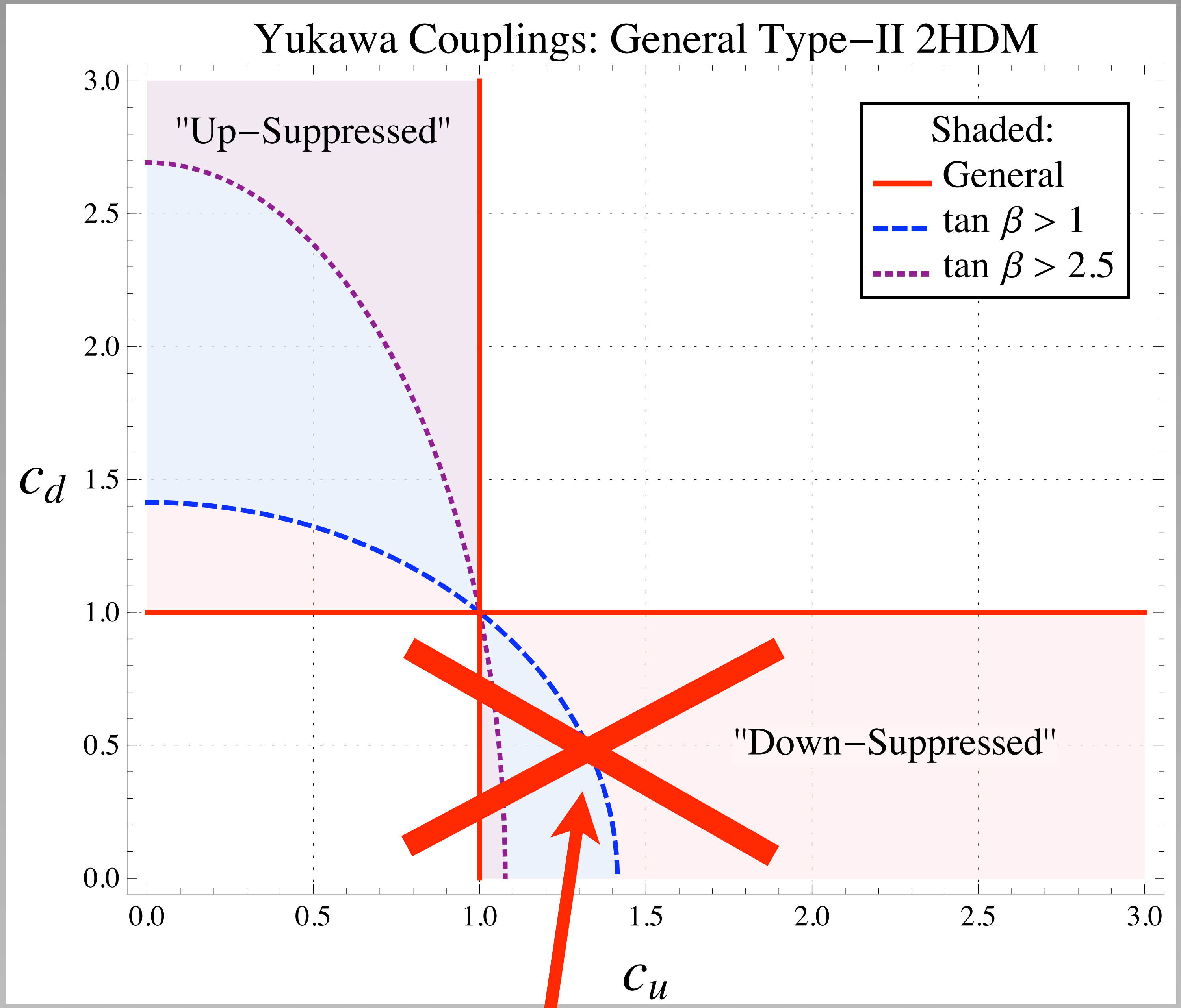
- Peak likelihood lies very close to the deoupling limit contour
- Consistency of this requires ALL couplings to revert to SM
- To check this, we can examine a 3D space...

FIRST: What does the accessible space of Yukawas look like?



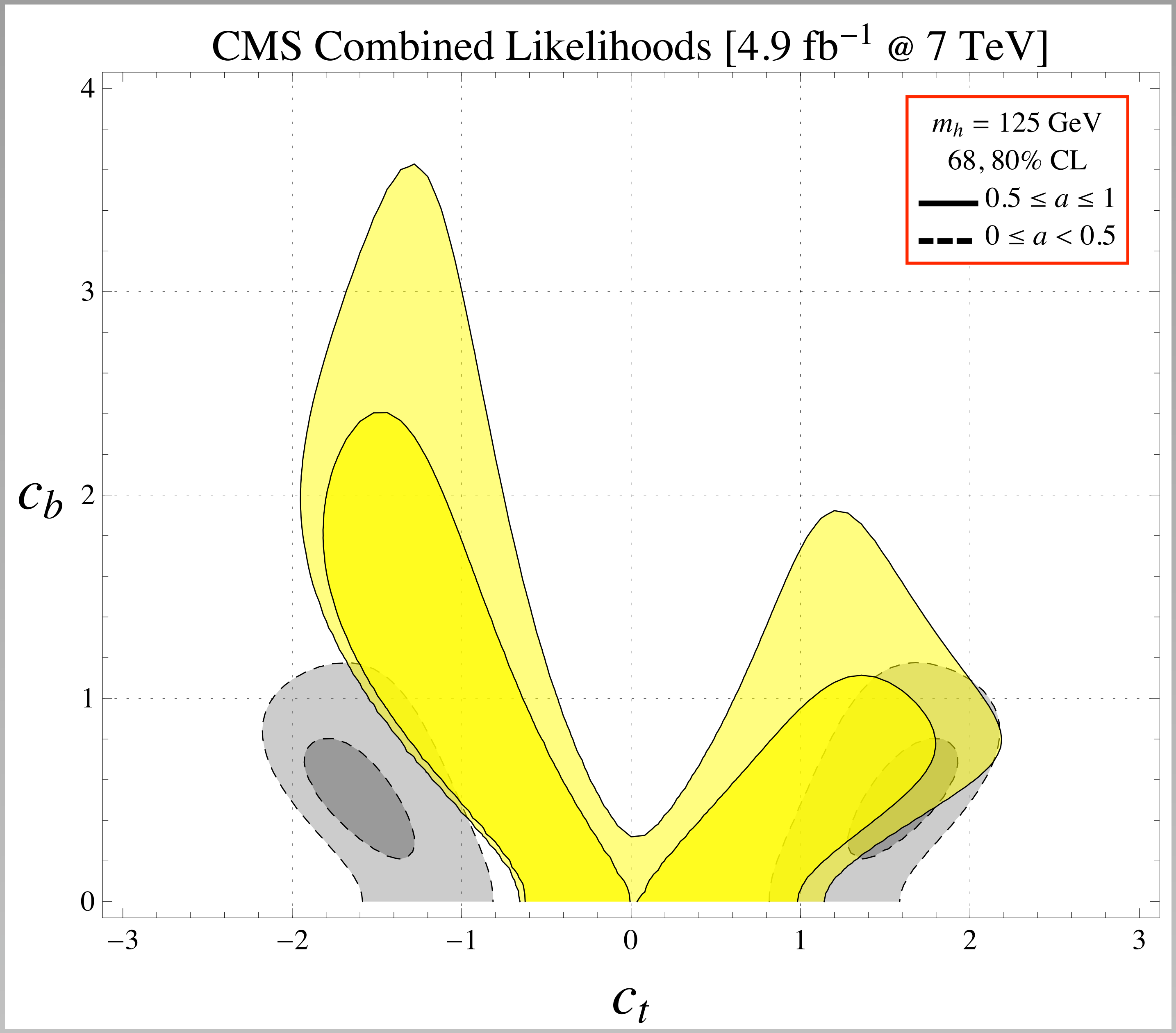
And for the MSSM?



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:



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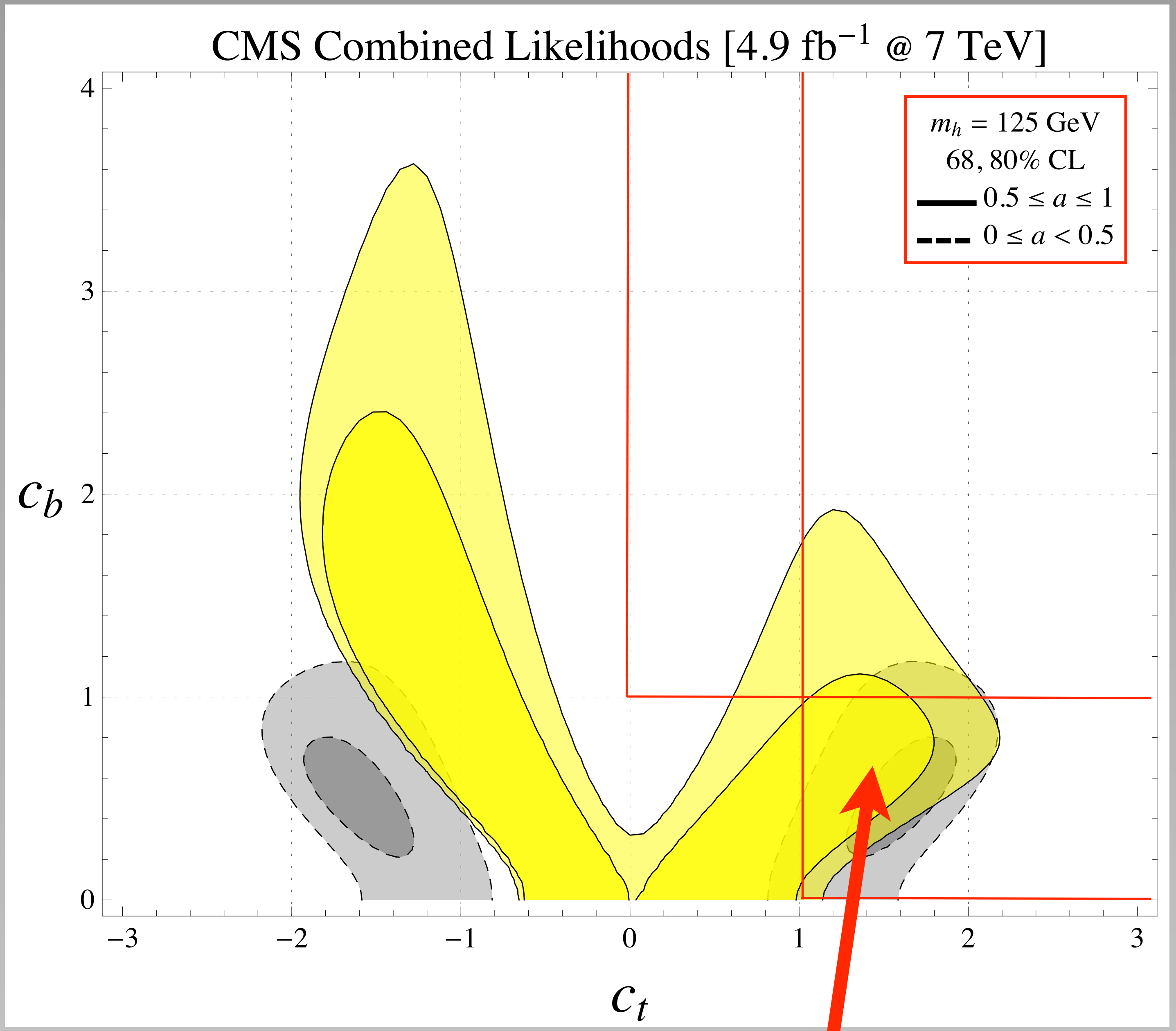

While gauge coupling currently prefers decoupling (couplings = SM), fermions seem to sing a slightly different tune: inaccessible for MSSM!

How does the MSSM fare?

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

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

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

i.e. big quantum-level correction to $\lambda_{2,3}$ when $\tan\beta > 1$

Natural thing to consider: new non-minimal dynamics -- new fields or compositeness...

Down-Suppression from New Perturbative Dynamics

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

I. Singlets (e.g. NMSSM)

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

III. Triplets

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Tadpoles $\Rightarrow \beta$

Masses $\Rightarrow \alpha$

INDEPENDENT ANGLES!

III. Triplets

Down-Suppression from New Perturbative Dynamics

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

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Conclusions

I. (preliminary) Composite Higgs: Fairly SM-like couplings indicate strong dynamics at a high scale (so for instance would need large N for light resonances)

II. (preliminary) SUSY: Some hints of non-minimality so far; non-SM couplings indicate that some new states could show up soon...

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

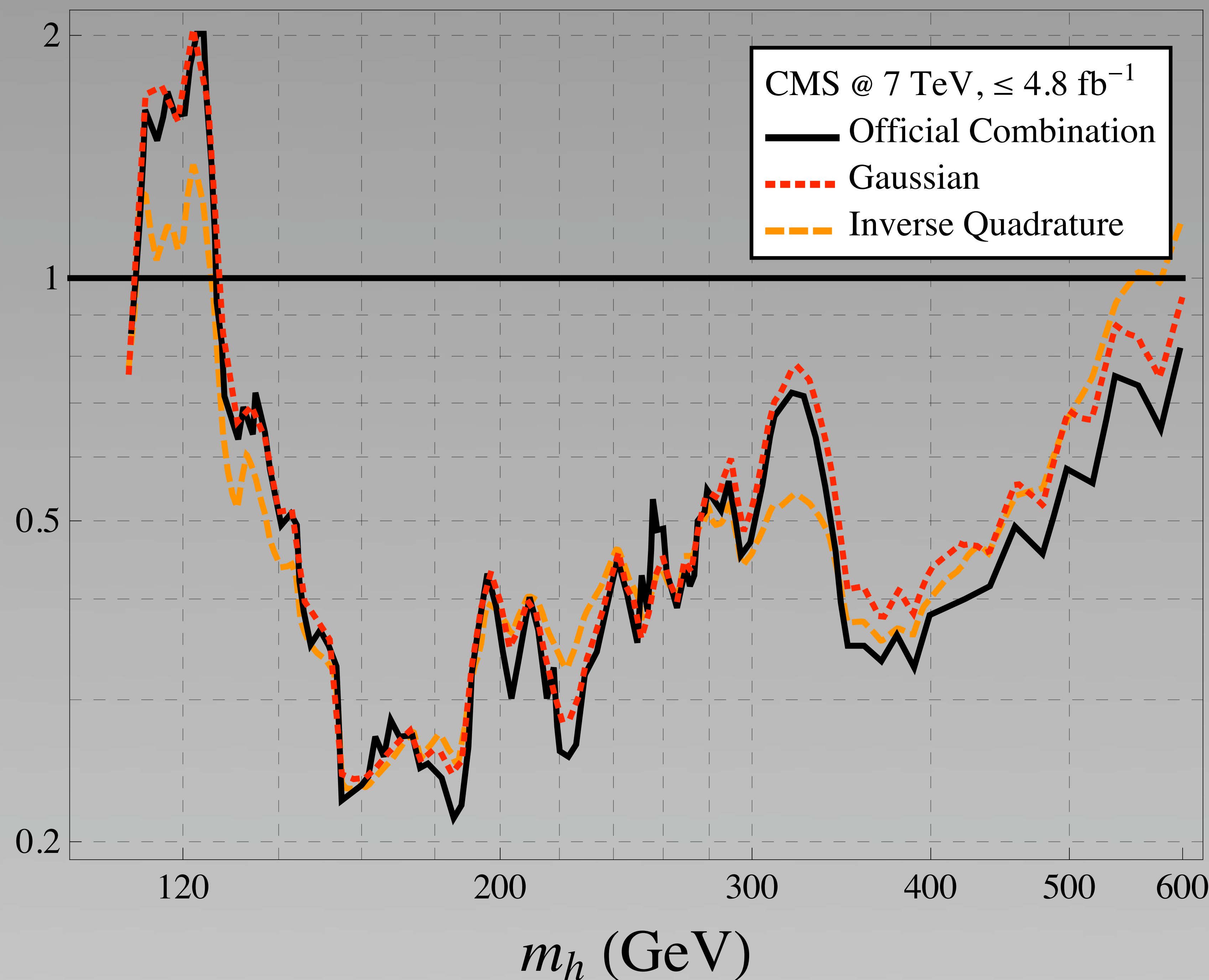
If spectra make headlines, couplings will be the fact checkers:

Each piece of the puzzle is important for consistency of the emerging picture; ultimately more data are needed, but we should be well-prepared to fully analyze every bit that we can!

Backups

How well does this method do?

One possible check: the total combination



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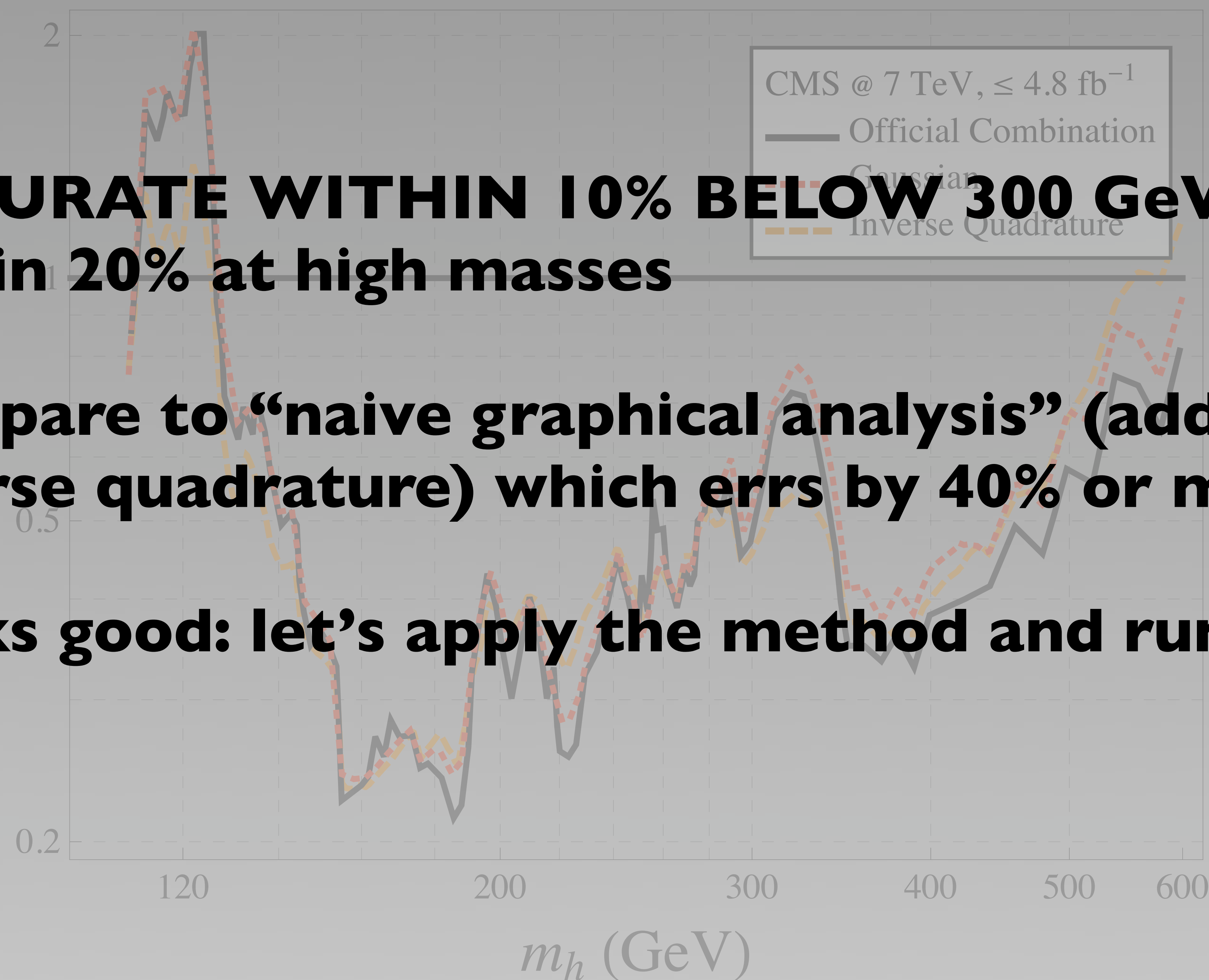

- **ACCURATE WITHIN 10% BELOW 300 GeV; within 20% at high masses**
- **Compare to "naive graphical analysis" (adding in inverse quadrature) which errs by 40% or more**
- **Looks good: let's apply the method and run with it**

<u>Before moving on:</u>
<u>A closer look at "signal strength modifier"</u>

We want to compare number of *observed* signal events in SM units:

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$$\Rightarrow \mu = \frac{\sum_p \sigma_p^{(i)} \times \zeta_{p,i} \times \mathrm{BR}(h \to i)}{\left[\sum_p \sigma_p^{(i)} \times \zeta_{p,i} \times \mathrm{BR}(h \to i)\right]_{\mathrm{SM}}}$$

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Efficiencies not always provided, so unknown to theorists

Best we can do: *assume* that $\zeta_{p,i} = \zeta_i \ \forall \ p$.†

† Safely justified for SM and SM-like ($a = c$), but not in general.

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This *can* be related purely to theory, but it's only approximate

EFFICIENCIES NEEDED

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

Five channels for a light Higgs:

$$1.\ WW \quad 2.\ \gamma\gamma \quad 3.\ ZZ \quad 4.\ \tau\tau \quad 5.\ bb$$

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$$\left.\begin{array}{ll} 1,2. & \text{Zero Jet, same/opposite flavor lepton} \\ 3,4. & \text{One Jet, same/opposite flavor lepton} \end{array}\right\} \longleftarrow \text{Inclusive}$$

$$\begin{array}{ll} 5. & \text{Two Jets} \end{array} \qquad \longleftarrow \text{VBF}$$

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$$\left.\begin{array}{ll} 1. & \text{Both in barrel, } \min(R9) > 0.94 \\ 2. & \text{Both in barrel, } \min(R9) < 0.94 \\ 3. & \geq \text{One in endcap, } \min(R9) > 0.94 \\ 4. & \geq \text{One in endcap, } \min(R9) < 0.94 \end{array}\right\} \longleftarrow \text{Inclusive}$$

$$\begin{array}{ll} 5. & \text{Dijet tag} \end{array} \qquad \longleftarrow \text{VBF}$$

Photon candidates with high values of R_9 are mostly unconverted and have less background than those with lower values. Photon candidates in the barrel have less background than those in the endcap. For this reason it has been found useful to divide photon candidates into four categories and apply a different selection in each category, using more stringent requirements in categories with higher background and worse resolution.

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Five channels for a light Higgs:

$$1.\ WW \quad 2.\ \gamma\gamma \quad 3.\ ZZ \quad 4.\ \tau\tau \quad 5.\ bb$$

Inclusive

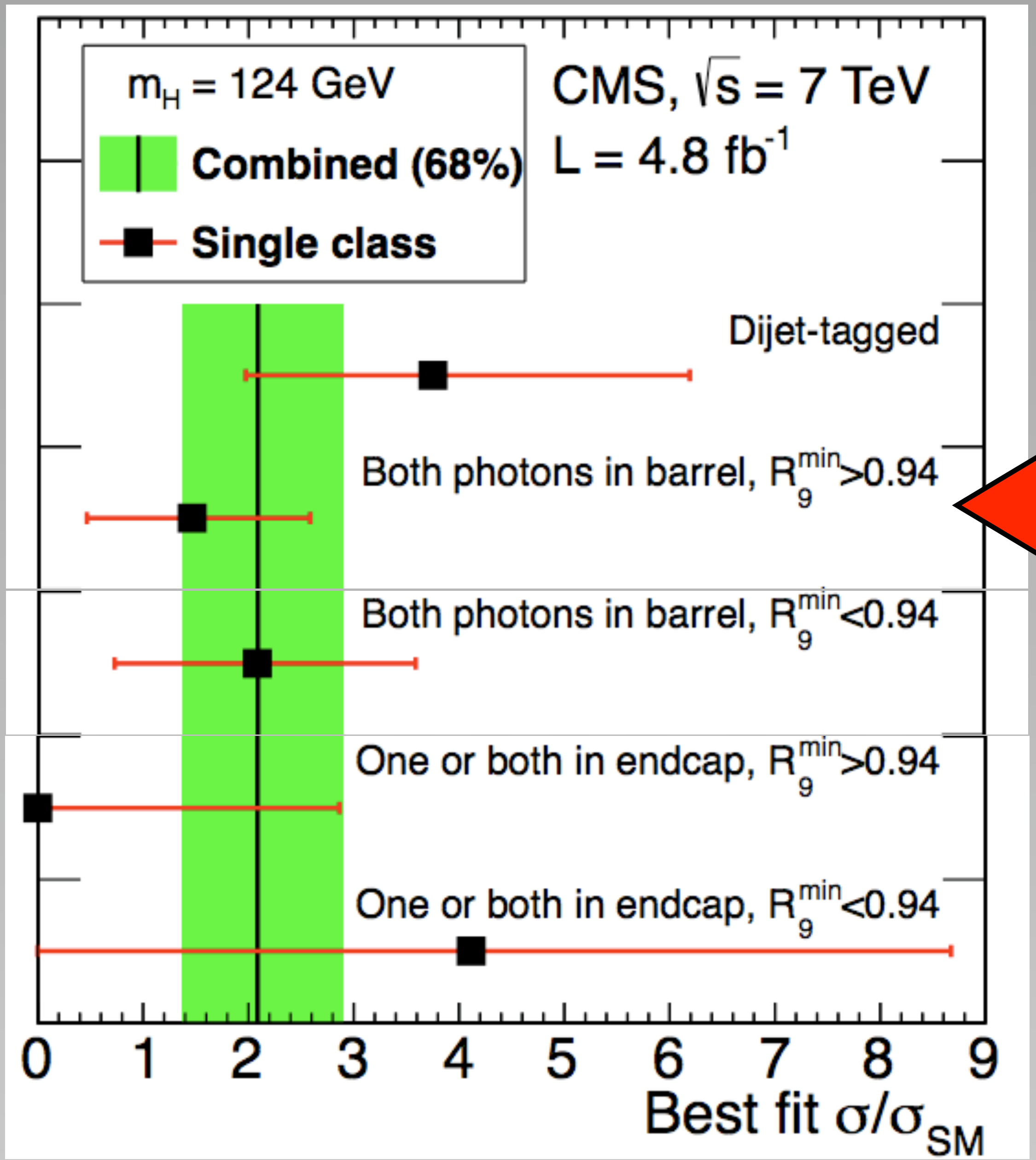
VBF + GF + “Boosted”
(combined limit given; event numbers for one mass)

Associated Production

Take Caution: Need Exclusive Searching and Reporting

About the displayed CMS results:

- o All WW subchannels treated individually
- o Others (except bb) treated inclusively
- o Can do better for gamma gamma exactly at peak



Different method:
Fit each band with
appropriate distribution
(approx. Gaussian)

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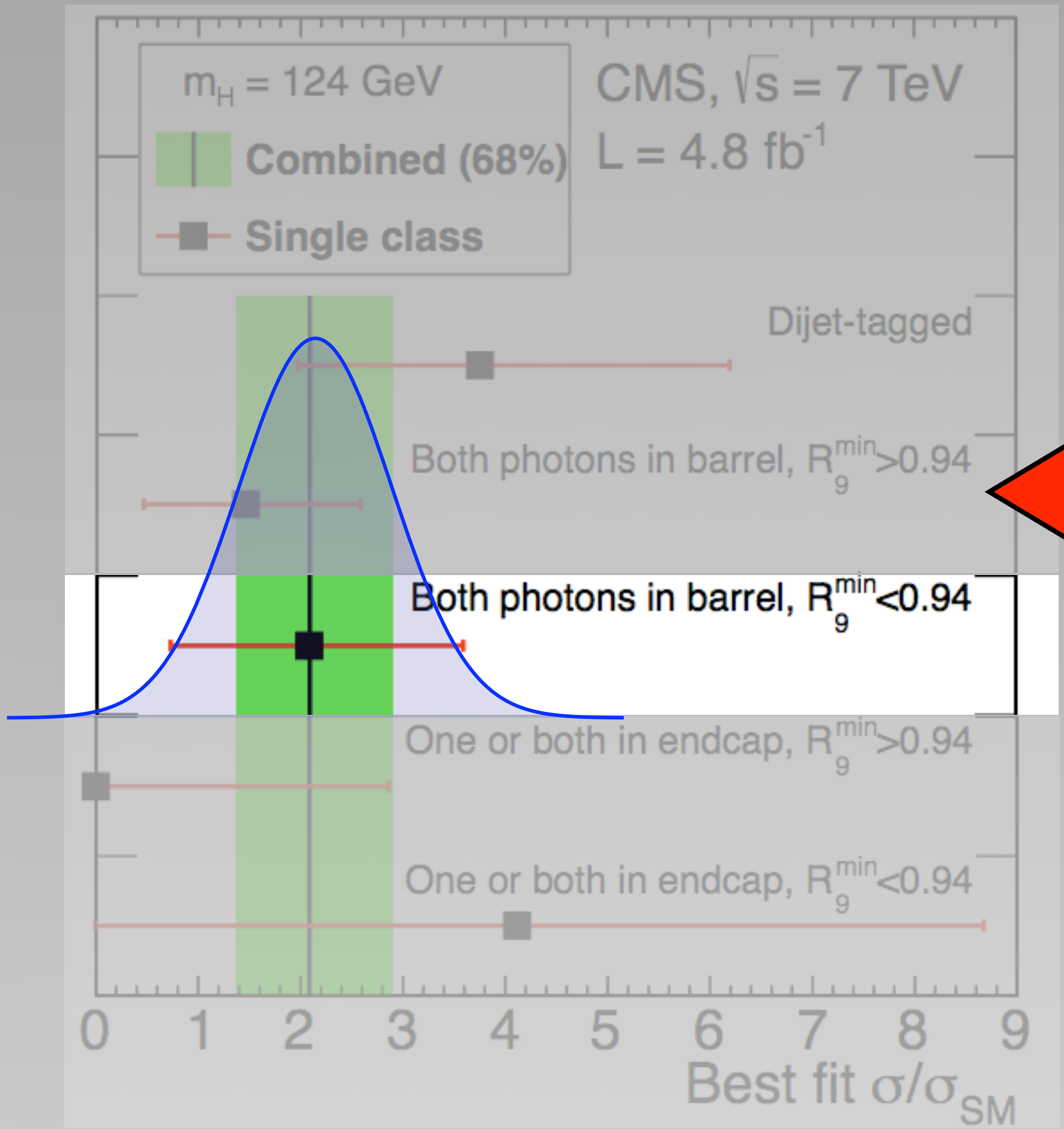

e.g. ...

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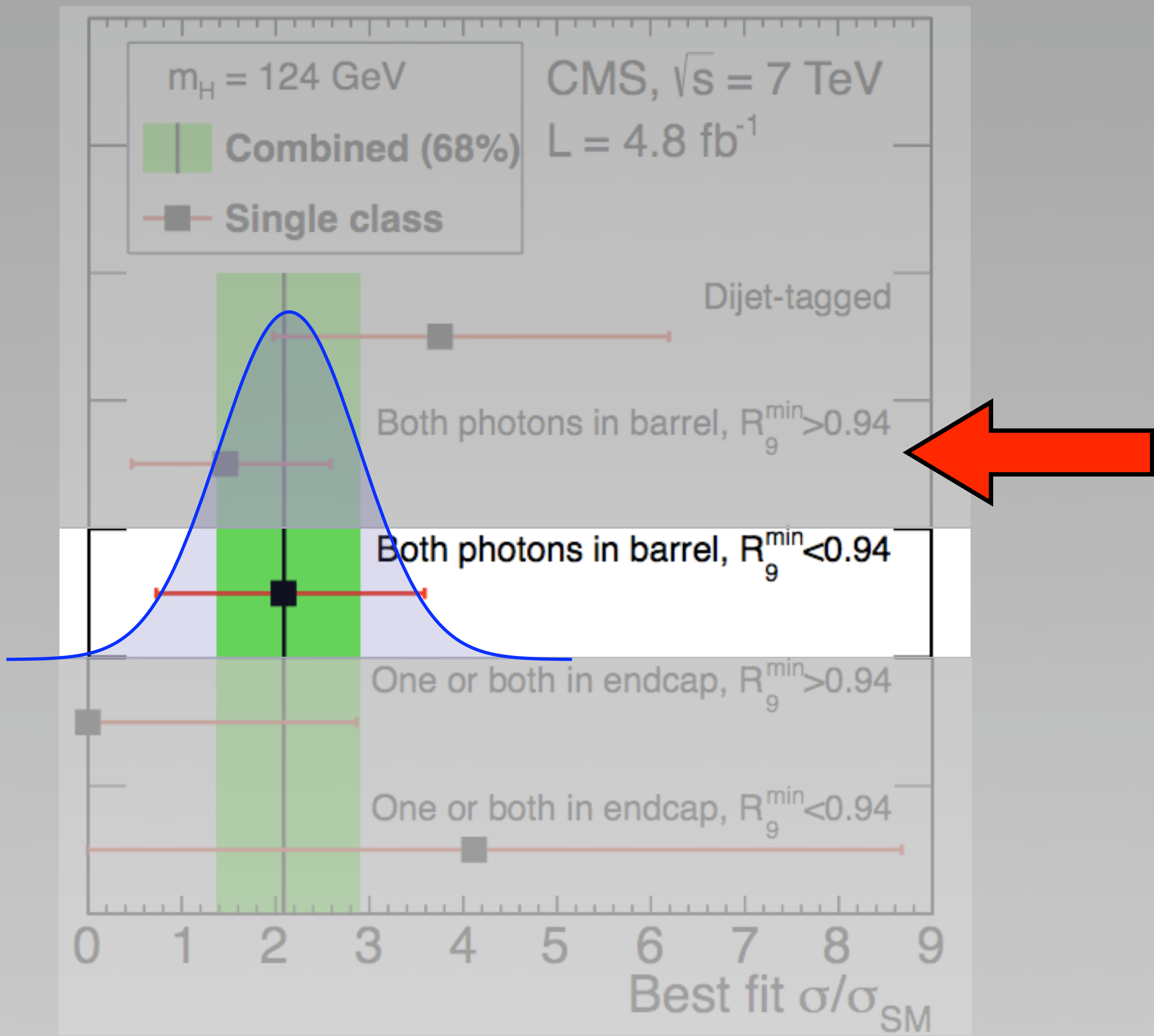
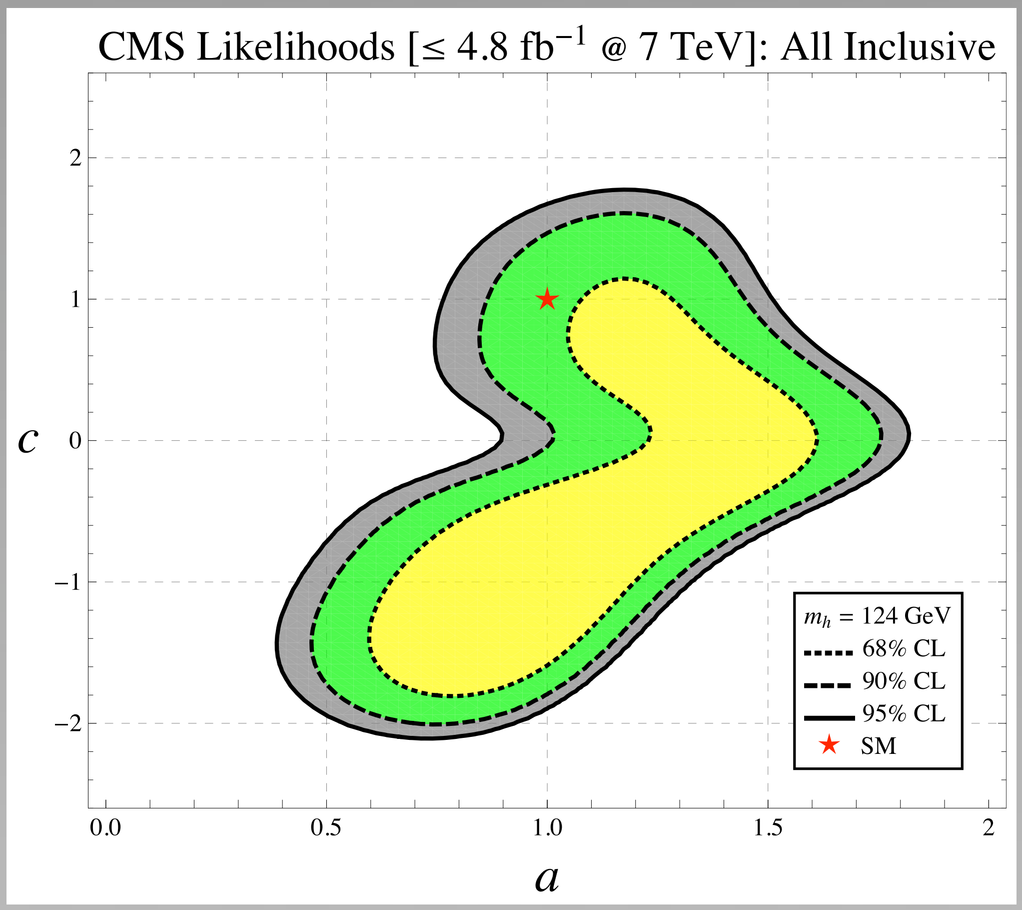
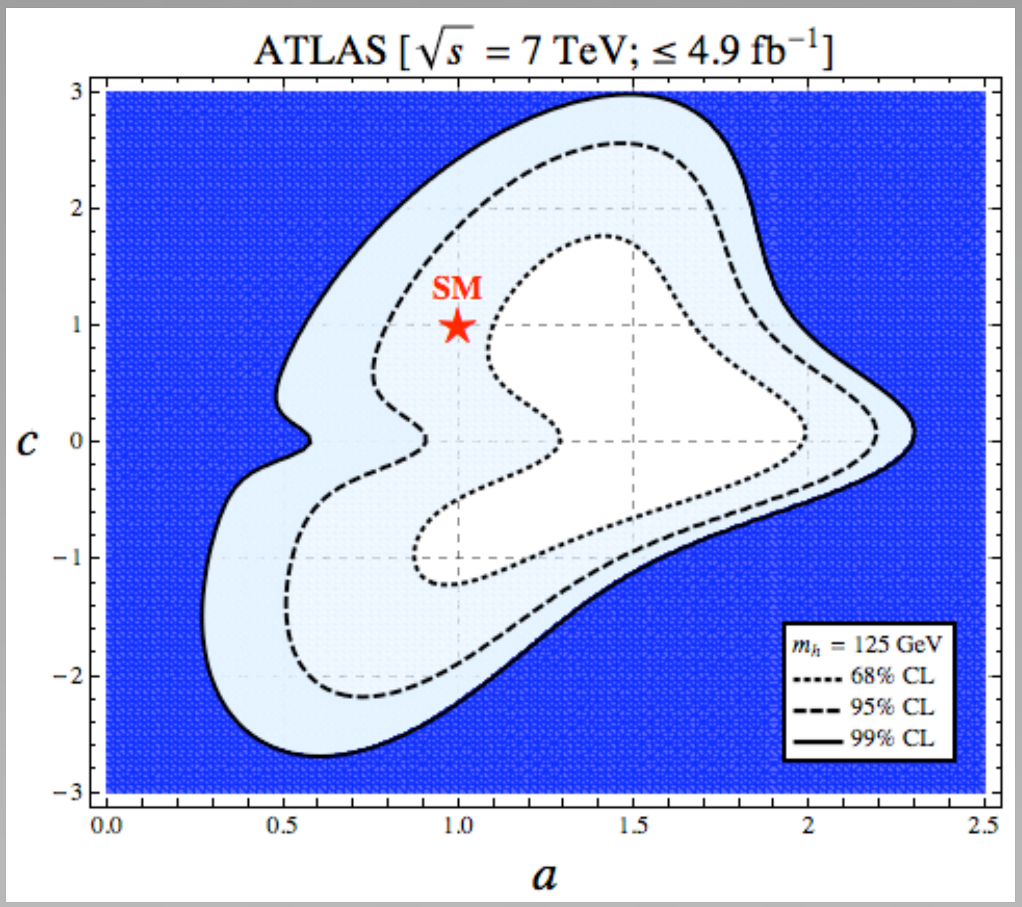


Total likelihood given by product of all

Take Caution: Need Exclusive Searching and Reporting

Side-by-side comparison of INCLUSIVE results:

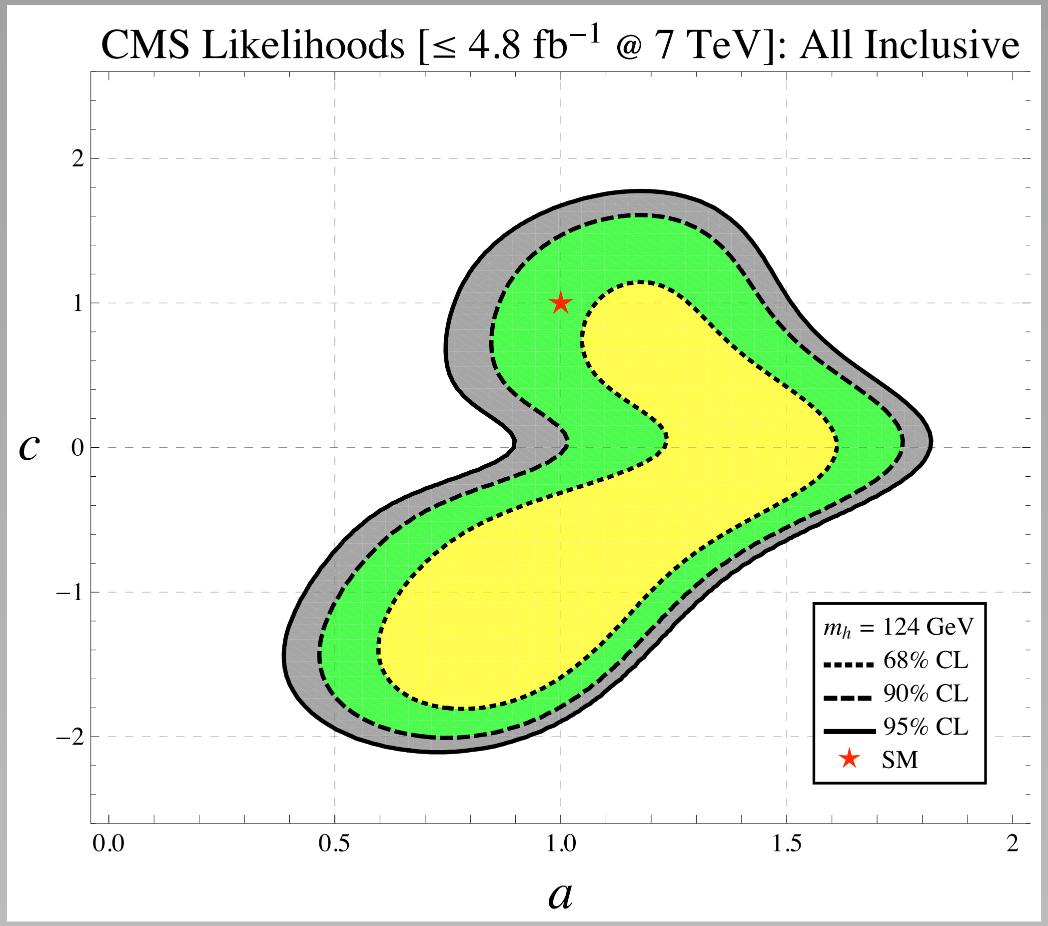


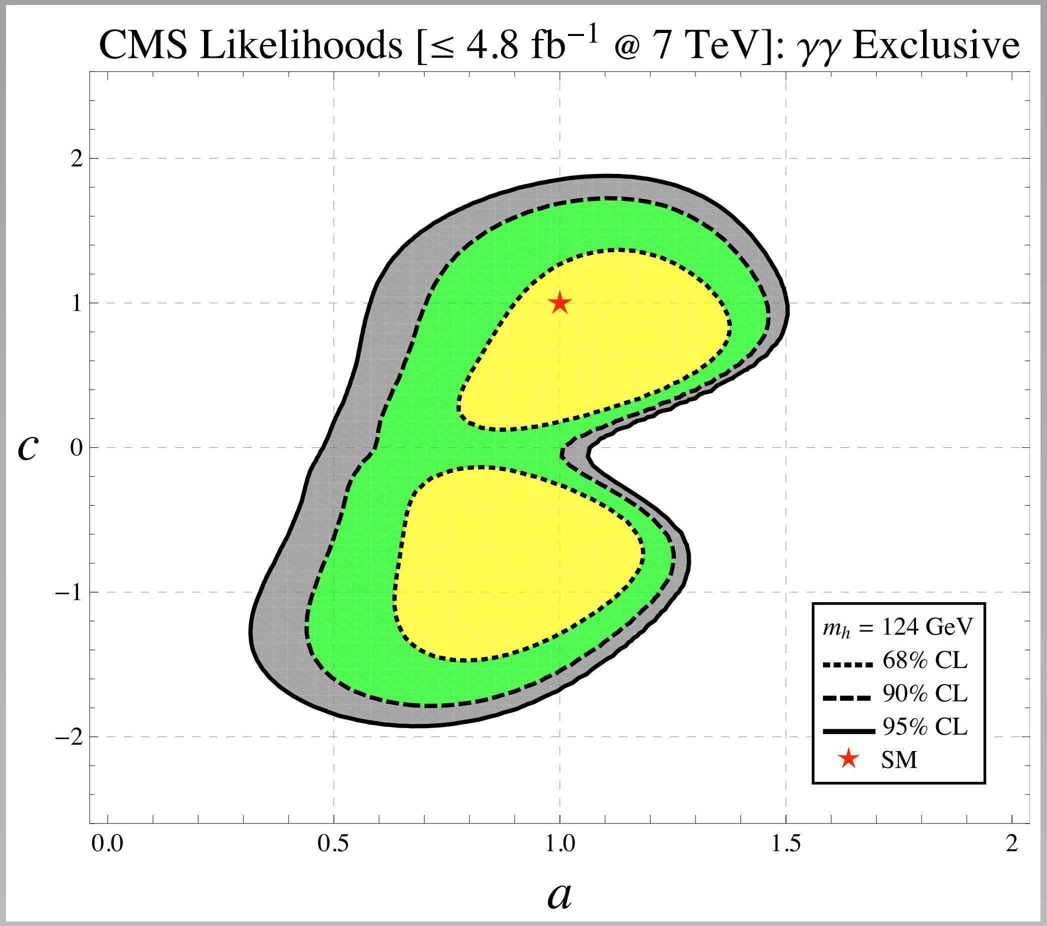


(There *are* real differences, but we see a distinctive -- qualitative -- similarity here)

Final Point: The Need for Exclusive Searching and Reporting

Now treat gamma gamma subchannels:





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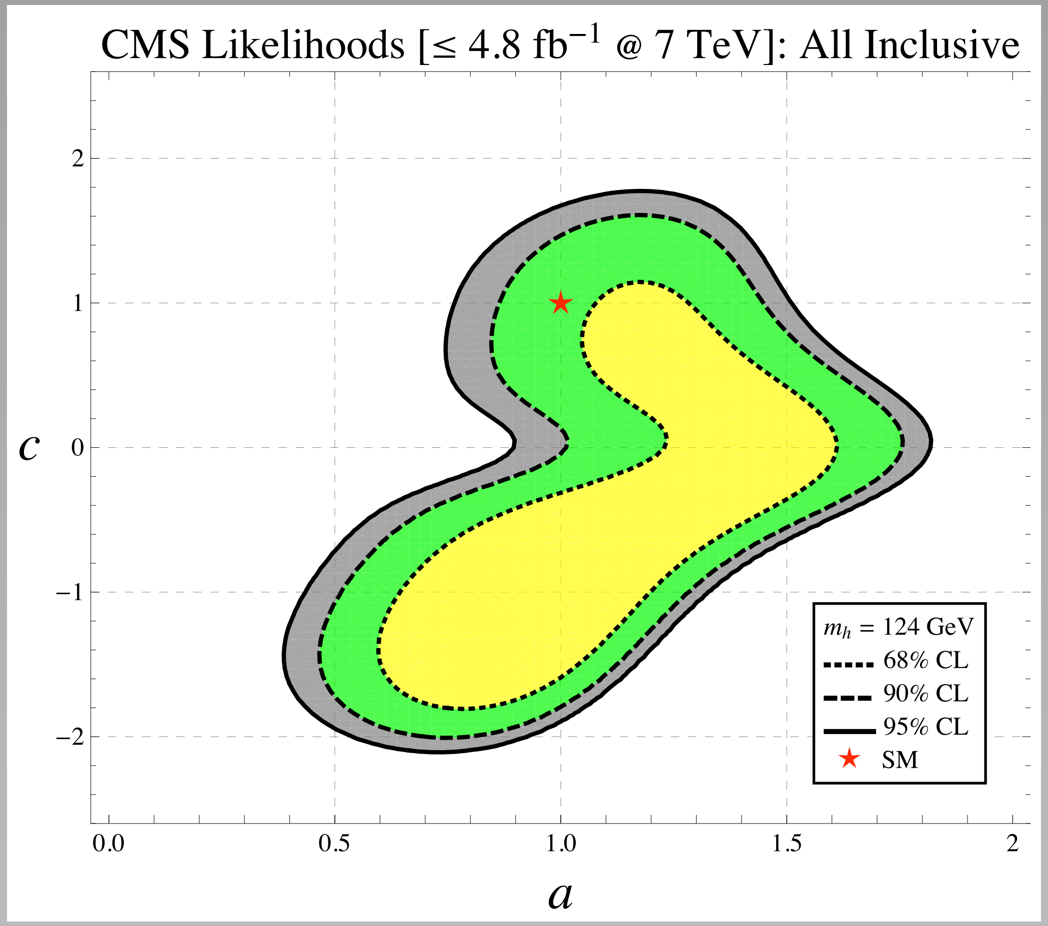

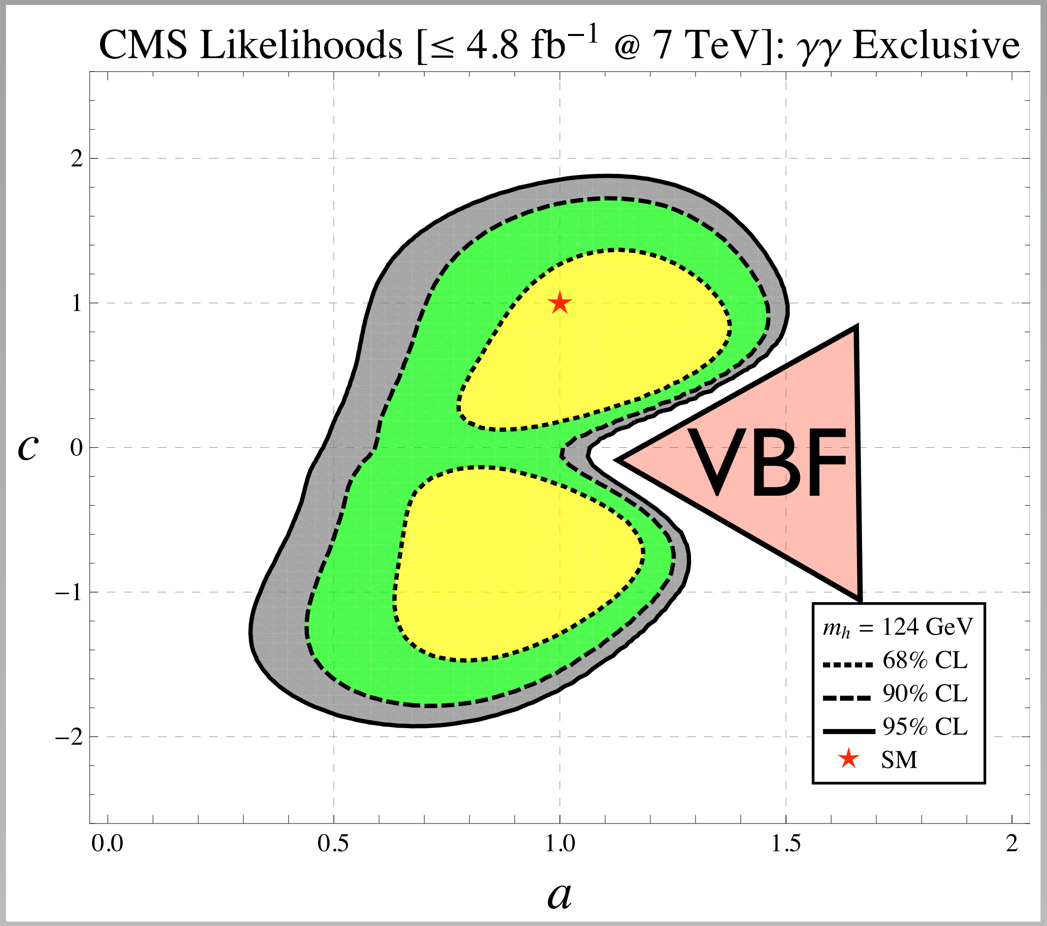

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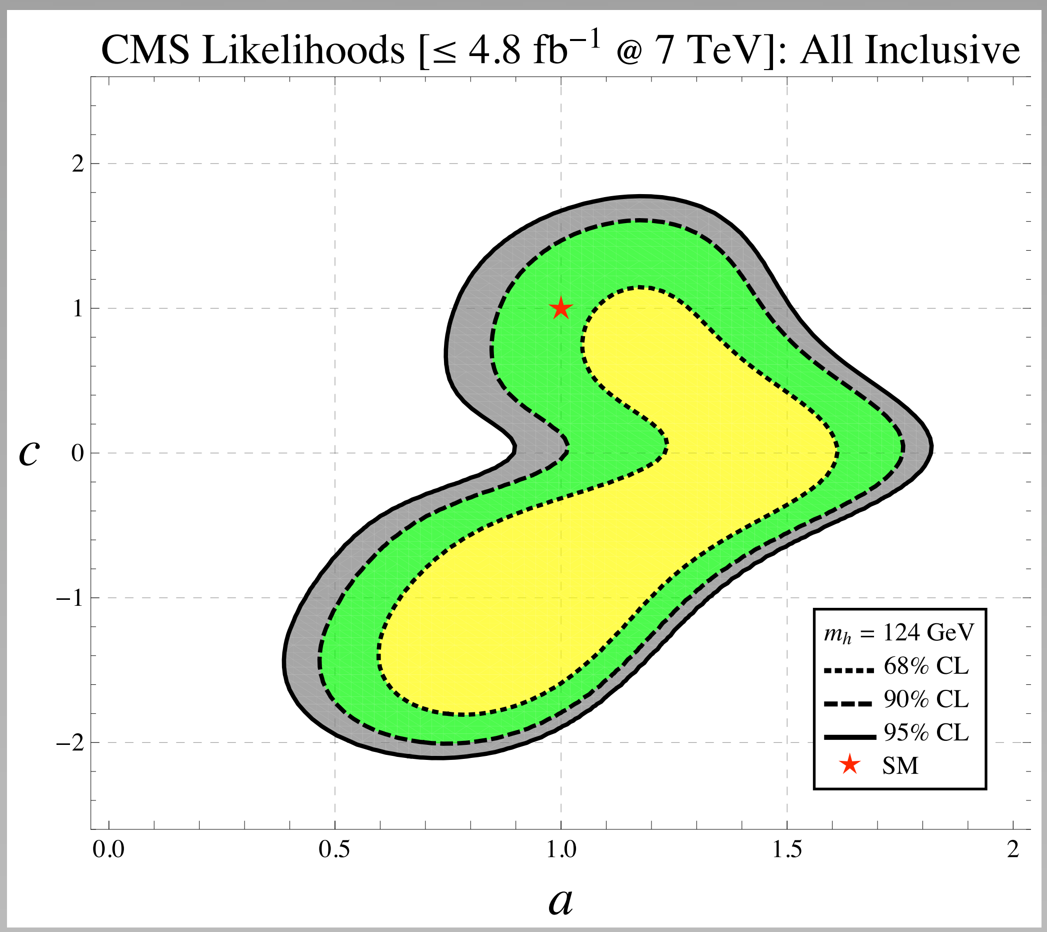

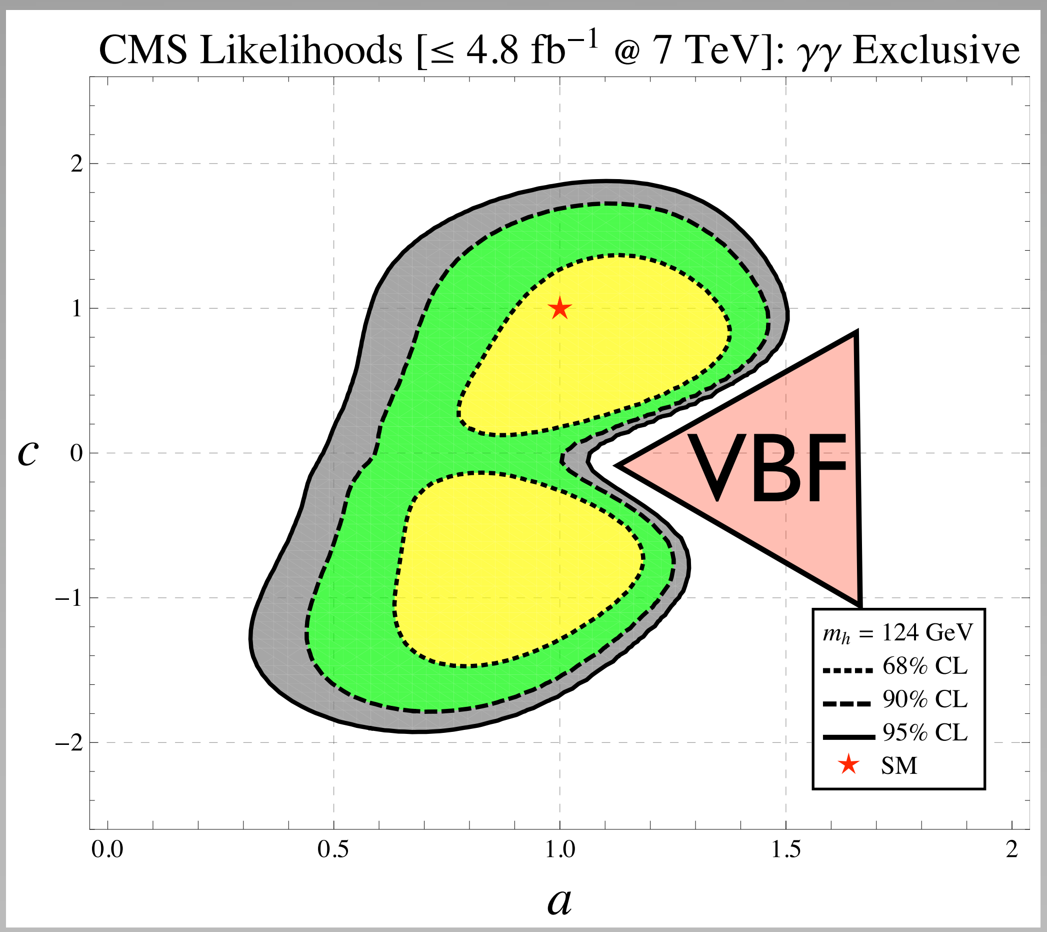

near $c = 0$ line, $R \sim a^2$ → Excess in dijet fit with gauge coupling

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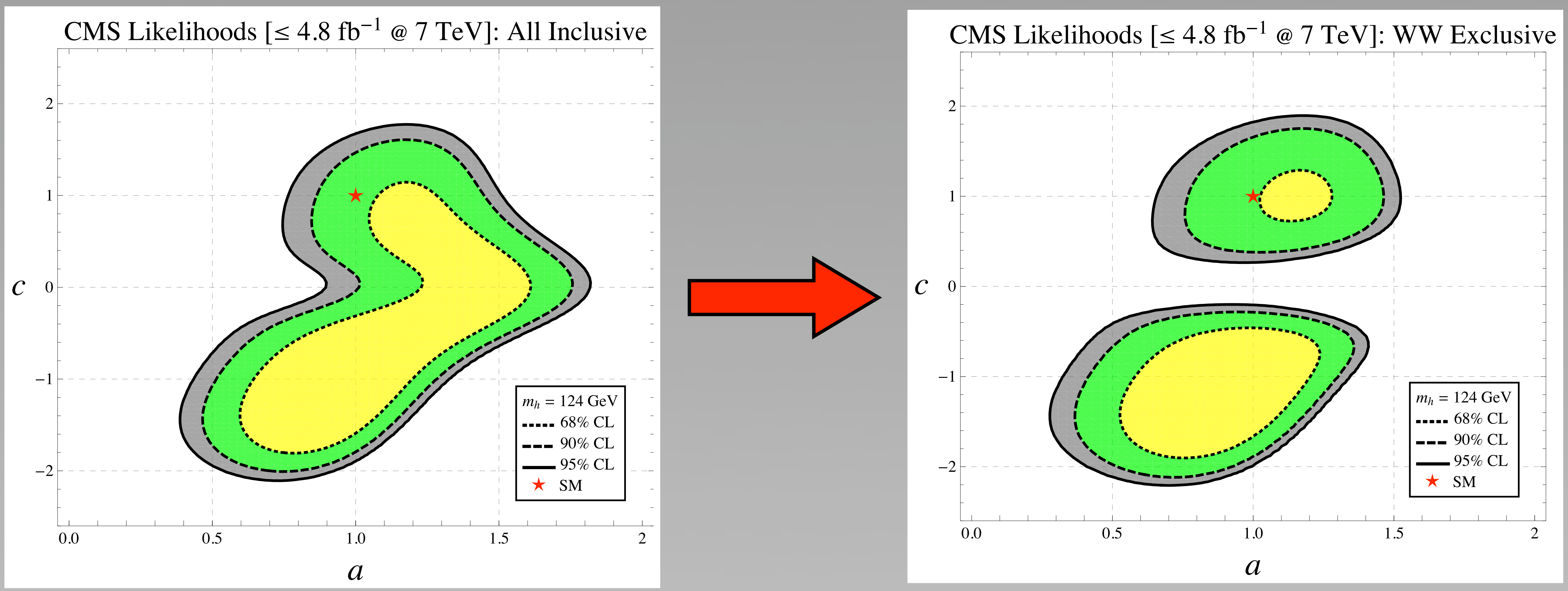
WW subchannels:



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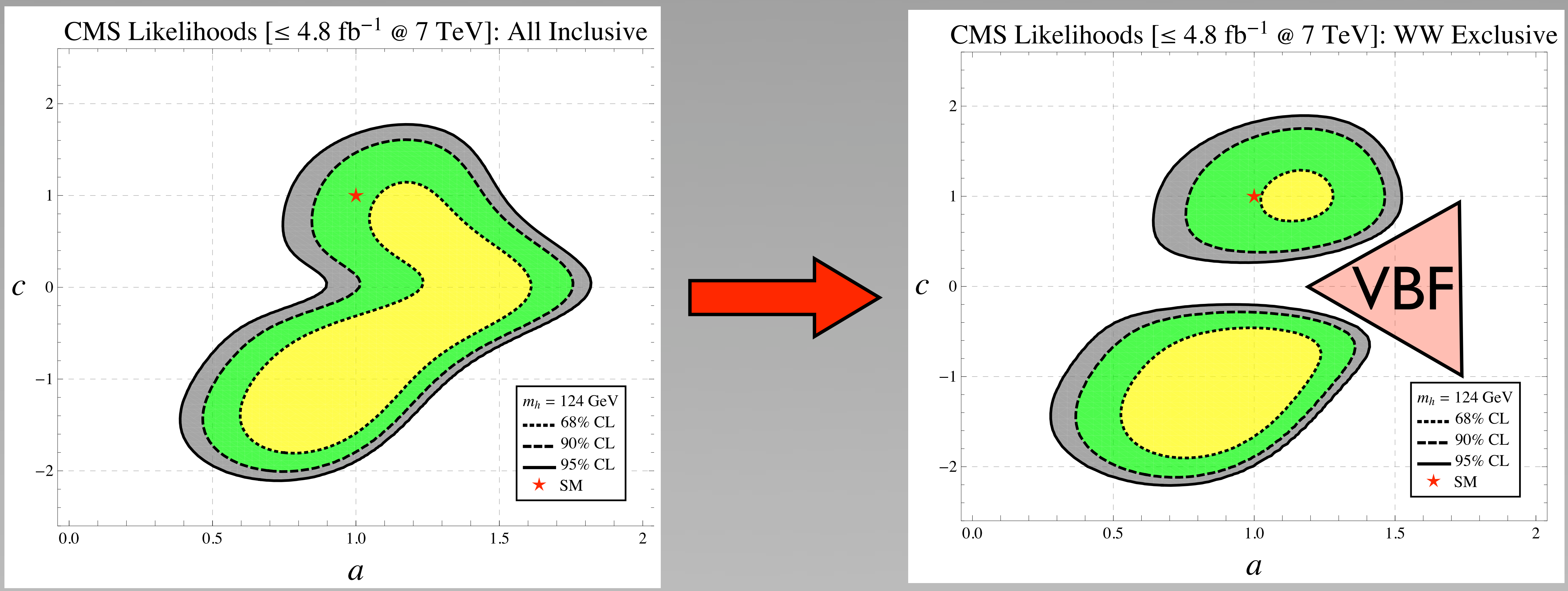

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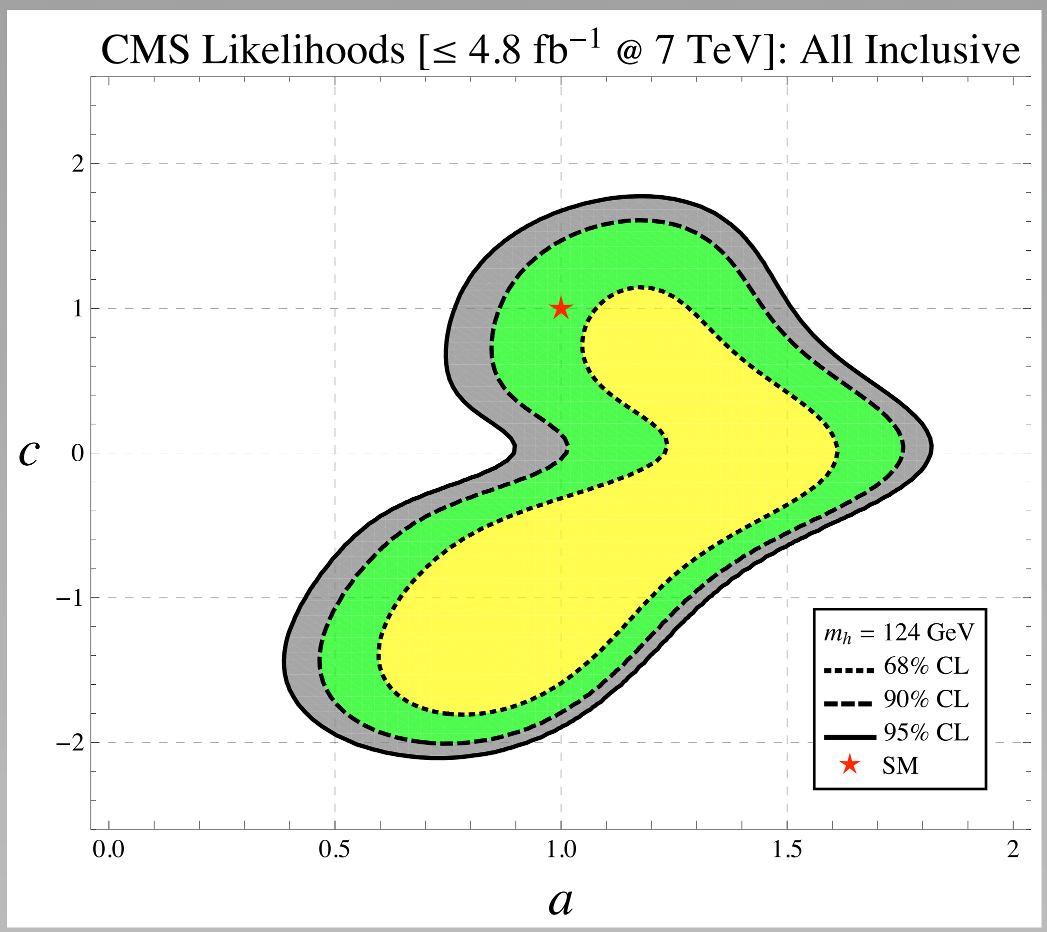

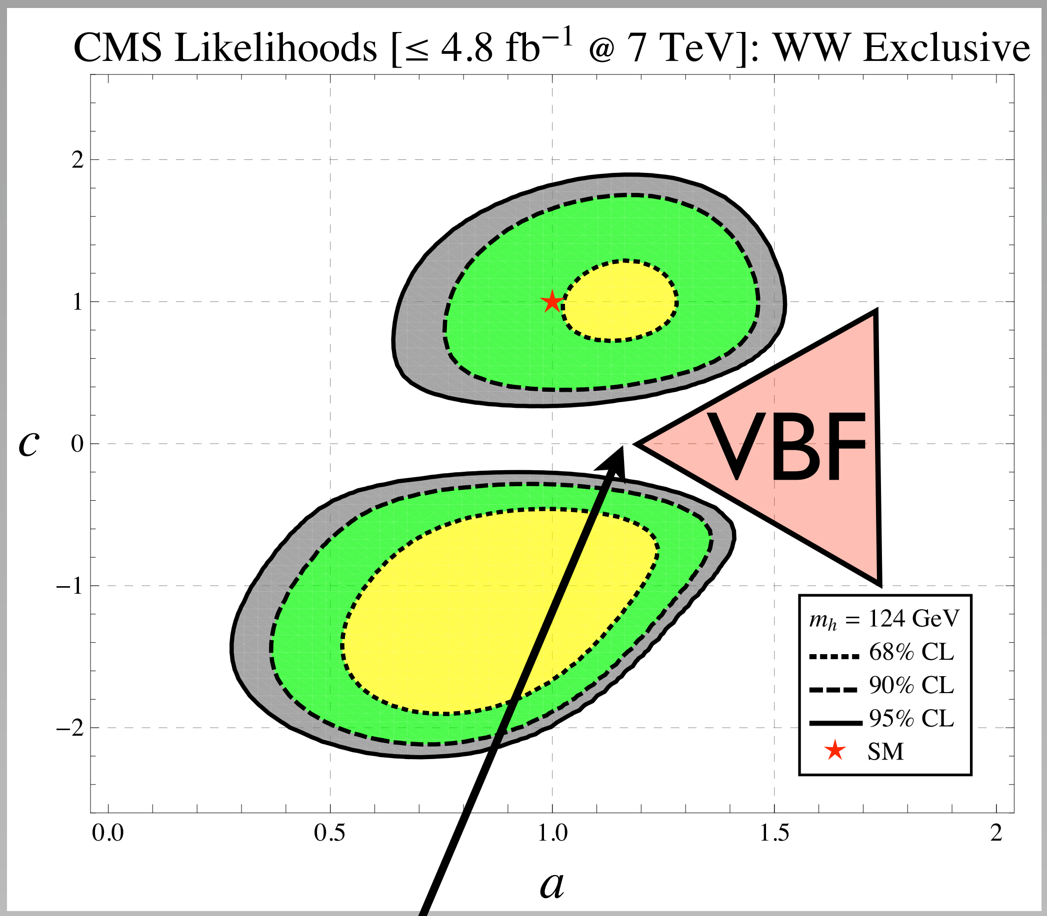

Note VBF cuts deeper in this case: signal deficit in this subchannel BG ~ 11, obs. ~ 8