



Unitarity bounds on multi-Higgs Models

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Valencia, July 11, 2014

1990



Nearly completed







Premature?

Surely technicolor is dead,
there IS a Higgs!

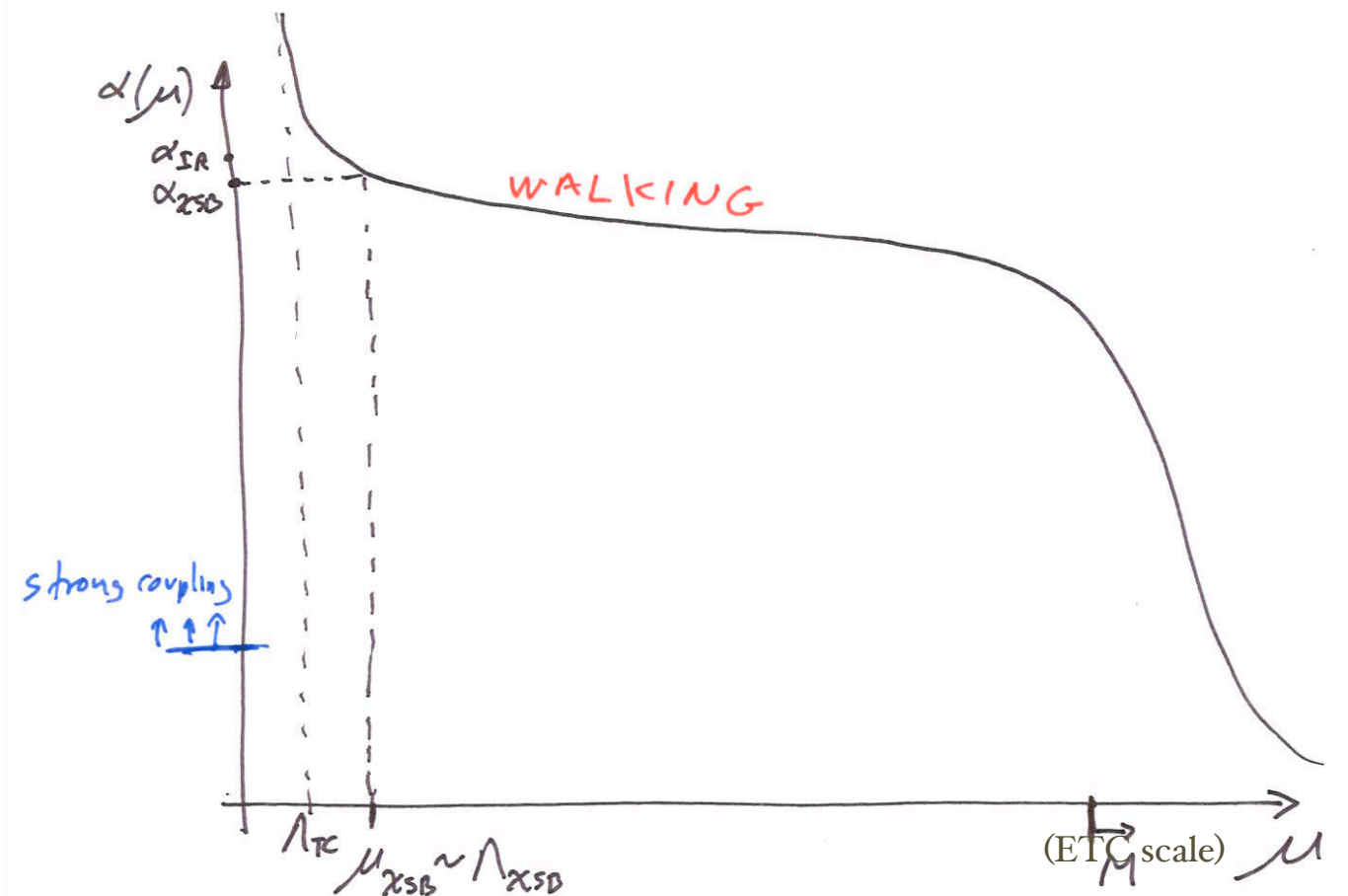
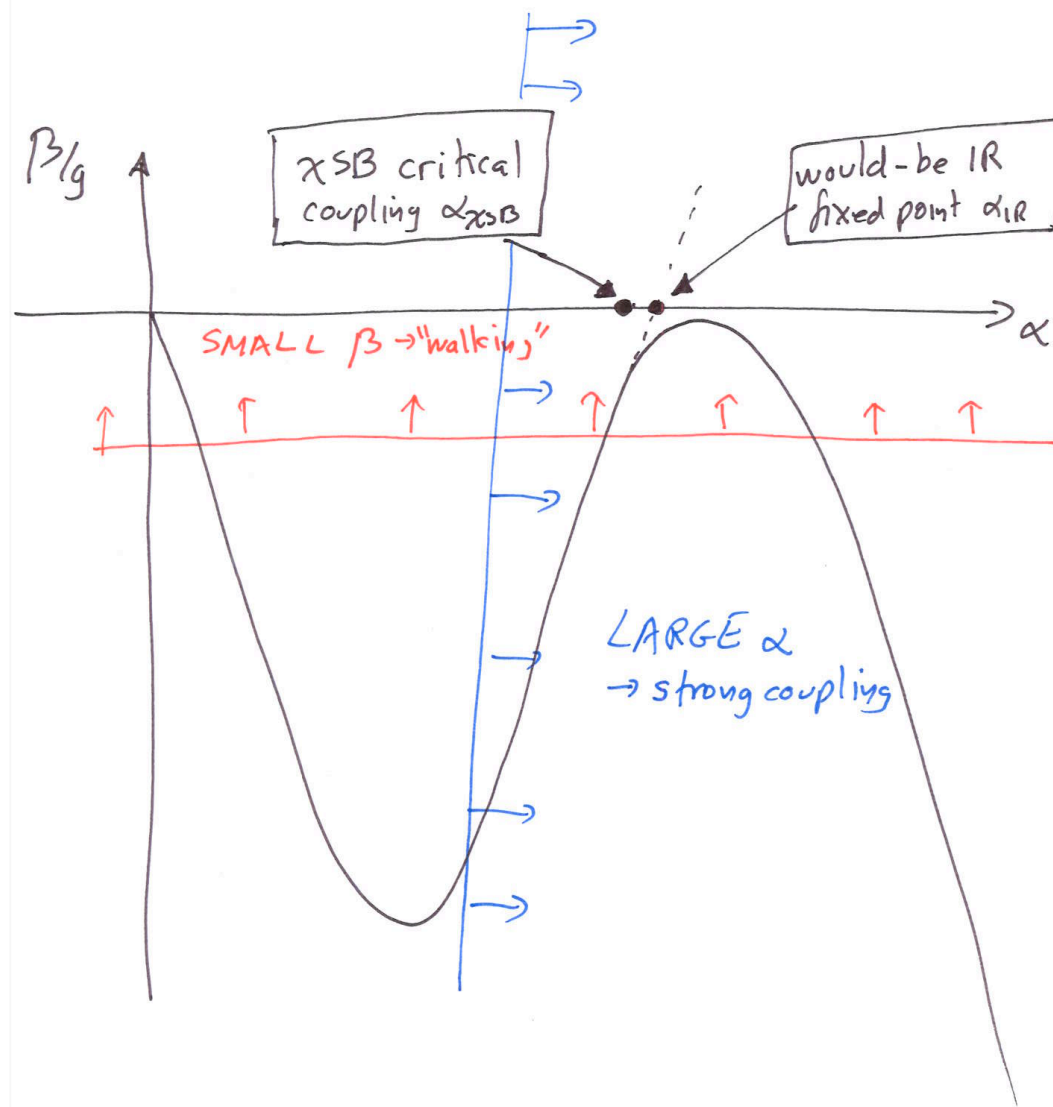


However, let's be careful

1. Need “walking” for mass/flavor problem
2. Hence, likely light dilaton
3. Dilaton “=” higgs

Note: not new. Ongoing discussion since mid 80's

See Wikipedia. Cast:
Holdom (1981),
Yamawaki, Bando and Matumoto (1981),
Appelquist, Karabali and Wijewardhana (1986)



(a) in QCD, $\Lambda_{\chi SB} \approx \Lambda_{TC}$

$$\mathcal{L}_{\text{mass}} = \frac{C(\mu)}{M^2} \langle \bar{Q}Q \rangle(\mu) \bar{q}q = \frac{C(M)}{M^2} \langle \bar{Q}Q \rangle(M) \bar{q}q = \frac{C(\Lambda)}{M^2} \langle \bar{Q}Q \rangle(\Lambda) \bar{q}q$$

$$C(\Lambda) = \left(\frac{M}{\Lambda} \right)^{\gamma_*}$$

The central observation: large coupling gives large anomalous dimension
It is argued that $\gamma_* \approx 1$

$$\mathcal{L}_{\text{mass}} = \frac{C(M)}{M\Lambda} \langle \bar{Q}Q \rangle(\Lambda) \bar{q}q \quad \Rightarrow \quad m_q \sim C(M) \frac{\Lambda^2}{M}$$

Dilaton “=” Higgs

Goldberger, BG & Skiba, PRL100 (2008) 111802
Bellazzini et al, Eur.Phys.J. C73 (2013) 2333
Chacko, Franceschini & Mishra, JHEP 1304 (2013) 015

“Higgs Impostor”

$$\mathcal{L} = \sum_i g_i(\mu) \mathcal{O}_i(x), \quad \text{with } [\mathcal{O}_i] = d_i$$

$$\partial_\mu S^\mu = T^\mu{}_\mu = \sum_i g_i(\mu)(d_i - 4)\mathcal{O}_i(x) + \sum_i \beta_i(g) \frac{\partial}{\partial g_i} \mathcal{L}$$

Dilaton as conformal compensator: $\chi(x) \rightarrow e^\lambda \chi(e^\lambda x)$ (see, eg, Coleman’s Aspects of Symmetry)

Then simply replace above $g_i(\mu) \rightarrow g_i \left(\mu \frac{\chi}{f} \right) \left(\frac{\chi}{f} \right)^{4-d_i}$

where $f = \langle \chi \rangle$ = order parameter for scale symmetry breaking

and $\chi(x) = f e^{\sigma(x)/f}$ with σ = dilaton (GB of spontaneously broken scale symmetry)

Then expanding about $\bar{\chi}(x) = \chi(x) - f$.

$$\mathcal{L}_\chi = \frac{1}{2} \partial_\mu \bar{\chi} \partial^\mu \bar{\chi} + \frac{\bar{\chi}}{f} T^\mu{}_\mu + \dots$$

EW sector: higgsless models (or strongly interacting higgs sector), below $\Lambda_{EW} \sim 4\pi v \simeq 1 \text{ TeV}$

$$\mathcal{L}_{\chi EW} = -\frac{1}{4}(B_{\mu\nu})^2 - \frac{1}{2}\text{tr}W_{\mu\nu}^2 + \frac{1}{4}v^2\text{tr}D_\mu U^\dagger D^\mu U + \dots,$$

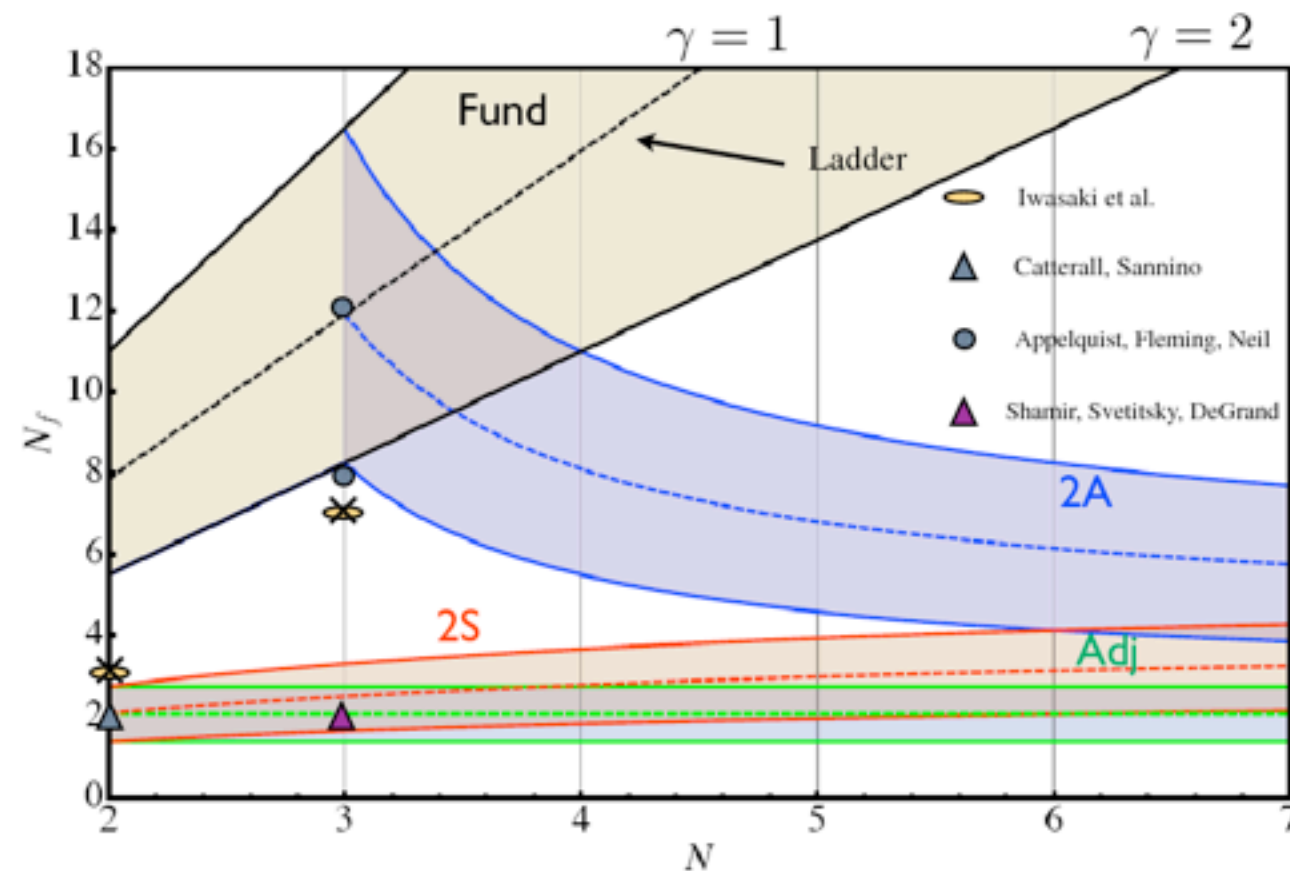
with U a unimodular 2 by 2 matrix, $D_\mu U = \partial_\mu U + ig_1 B_\mu U \frac{\tau_3}{2} - ig_2 \vec{W}_\mu \cdot \frac{\vec{\tau}}{2} U$

At tree level

$$\mathcal{L}_{\chi, SM} = \left(\frac{2\bar{\chi}}{f} + \frac{\bar{\chi}^2}{f^2} \right) \left[m_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu \right] + \frac{\bar{\chi}}{f} \sum_\psi m_\psi \bar{\psi} \psi$$

much like the SM's higgs (but f a free parameter, $f \geq v$)

Are there models like this?? That is, WTC with light dilaton? Unclear.



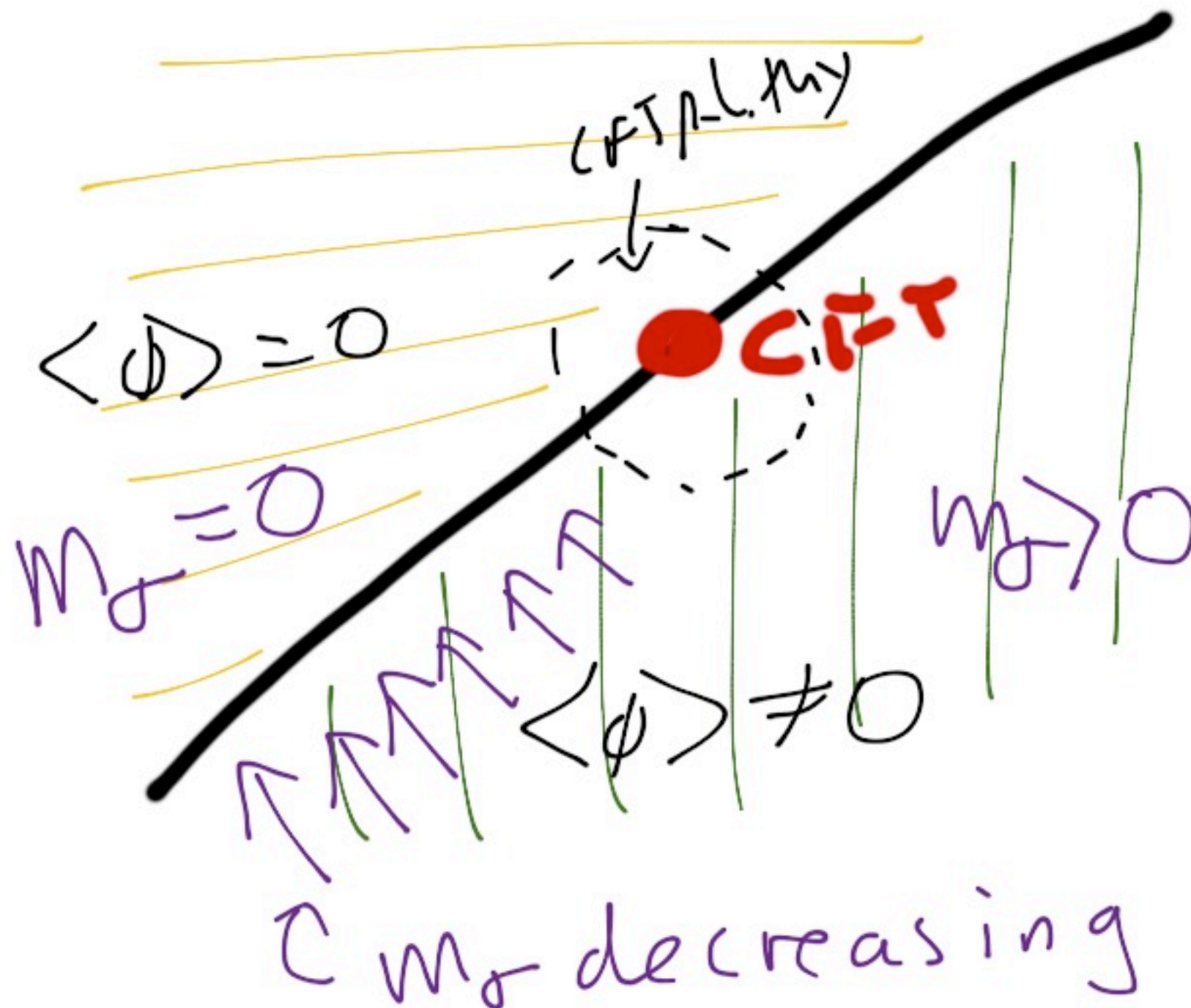
Conformal window caricature

Several groups computing on lattice:

1. Z. Fodor, K. Holland, J. Kuti, D. Nogradi, C. Schroeder and C. H. Wong,
2. T. Appelquist, R. Babich, R. C. Brower, M. I. Buchoff, M. Cheng, M. A. Clark, S. D. Cohen and G. T. Fleming
3. K. -I. Ishikawa, Y. Iwasaki, Y. Nakayama and T. Yoshie
4. L. Del Debbio, B. Lucini, C. Pica, A. Patella, A. Rago, S. Roman
- 5....

It **is** possible to construct a toy *perturbative* model with the wanted features
 (but perturbative = contains elementary scalars, mass parameter fine tuned to zero)

BG & P. Uttayarat, JHEP 1107 (2011) 038



By the way...

Recent proposals: use scale invariance to solve hierarchy problem.

R. Foot, et al, arXiv:1310.0223

M. Holthausen, et al arXiv:1310.4423

This does not work. Scale invariance broken by anomaly (except in CFTs)

The anomaly arises from divergences in QFT that must be regulated.

This leads immediately to fine tuning of scalar masses too.

G. M. Tavares, M. Schmaltz & W. Skiba,
PPRD89 (2014) 015009

Comments:

1. The idea of a higgs impostor is falsifiable: $f \geq v$.
2. If experiment requires $f = v$ it would seem fine tuned. But in strongly coupled models there is no adjustable parameter (binary decision: works yes/no).
3. This is but one non-SUSY example of what may lay out there, solving the hierarchy problem (Little Higgs, extra-dimensions, Lee-Wick, ...)
4. There is also the (most exciting) chance we are too stupid to have guessed nature right

This is motivation for Model Independent studies of Higgs Physics

Two approaches:

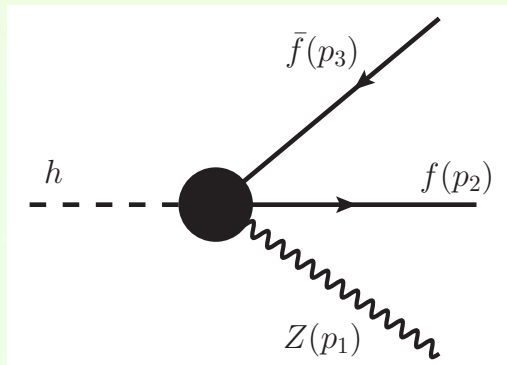
1. EFT (1 slide)
2. Sum rules, dispersion relations, etc

Higgs precision tests

2-body decays -- numbers

3-body decays -- form factors

e.g.



if, for example, model new physics by EFT

$$\mathcal{L}_{\text{NP}} = \frac{e}{s_W c_W} \left(\frac{c_{\ell Z}}{4\pi v} \bar{\ell} \sigma^{\mu\nu} \ell Z_{\mu\nu} + \bar{\ell} \gamma^\mu (c_L P_L + c_R P_R) \ell Z_\mu \right) \frac{h}{v} + \frac{\alpha}{4\pi} \left(\frac{c_{ZZ}}{s_W^2 c_W^2} Z_{\mu\nu} Z^{\mu\nu} + \frac{c_{Z\gamma}}{s_W c_W} Z_{\mu\nu} F^{\mu\nu} \right) \frac{h}{v}.$$

Isidori, Manohar & Trott Phys.Lett. B728 (2014) 131-135
BG, Murphy & Pirtskhalava, JHEP 1310 (2013) 077
Buchalla et al, Eur. Phys J. C. (2014) 74:2798
P. Artoisenet et al, JHEP 1311 (2013) 043

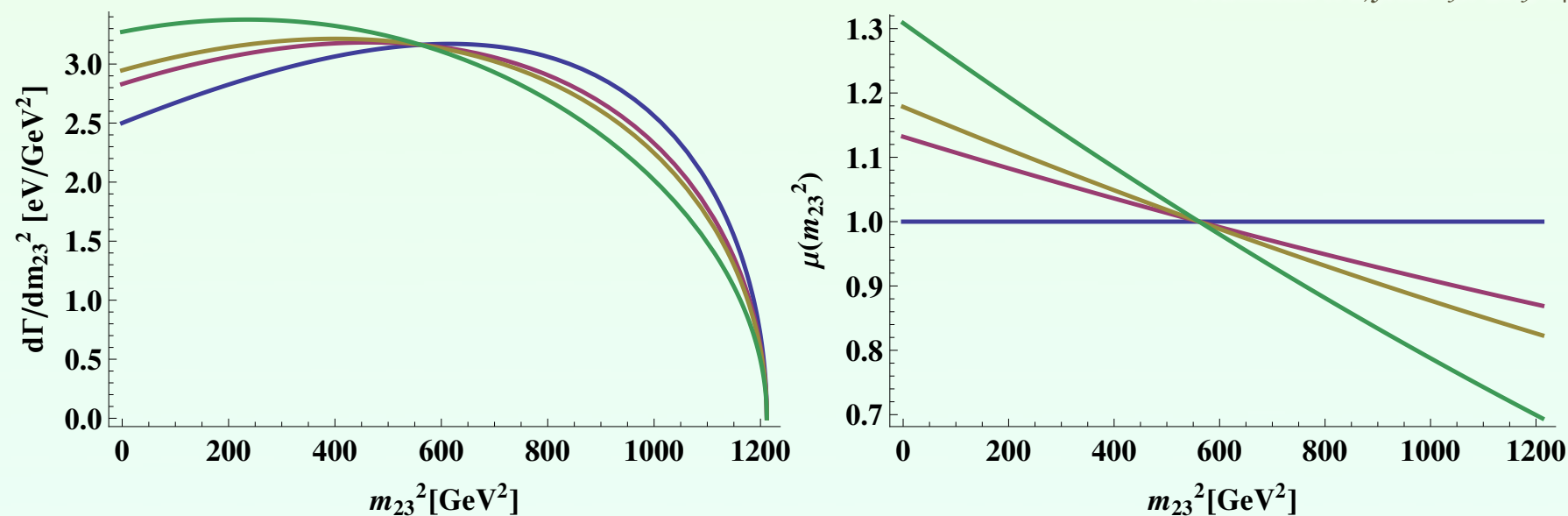


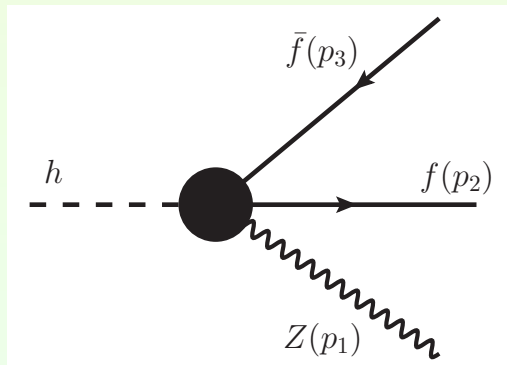
Figure 2. Contributions to $h \rightarrow Z \ell \bar{\ell}$ from $\mathcal{O}_{ZJ}$. The differential decay rate and differential signal strength as a function of m_{23}^2 are shown on the left and right respectively. The curves correspond to the SM (blue); $c_R = 0.99$, $c_L = 0$ (red); $c_L = -1.15$, $c_R = 0$ (yellow); and $c_R = -c_L = 1.07$ (green). $\mu = 1$ in each of these cases.

Higgs precision tests

2-body decays -- numbers ← Rest of this talk

3-body decays -- form factors

e.g.



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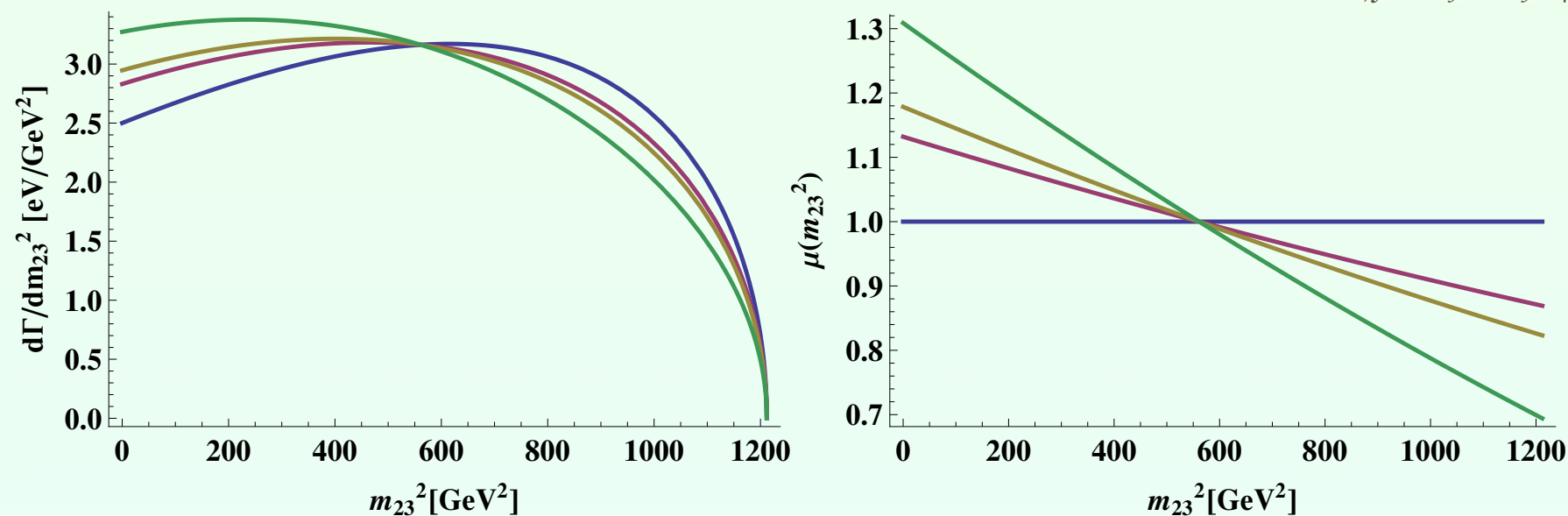


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Unitary Bounds: Introduction and Motivation



David Pirtskhalava (Pisa)



Chris Murphy (UCSD/Pisa)



Patipan Uttayarat (U Cin)

The Collaboration

JHEP 1405 (2014) 083(arXiv:1401.0070)



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BG

CMS Physics Analysis Summary

Contact: cms-pag-conveners-higgs@cern.ch

2013/07/01

Properties of the observed Higgs-like resonance decaying into two photons

The CMS Collaboration

Abstract

Analyses are reported on properties of the recently discovered Higgs-like resonance around 125 GeV in its decay to two photons. The analyses are performed using the 2011 (2012) dataset recorded by the CMS experiment at the LHC from pp collisions at a centre-of-mass energy of 7 (8) TeV. The dataset corresponds to an integrated luminosity of 5.1 (19.6) fb^{-1} . The spin analysis is evaluated on the 2012 dataset alone. An upper limit on the natural width of the observed resonance is found to be 6.9 GeV at 95% confidence level. A search has been performed for second Higgs-like states in the range $110 < m_H < 150$ GeV. Spin hypothesis tests have been performed comparing the Standard Model Higgs with a spin-2 graviton-like model with minimal couplings. The current data cannot exclude this particular model of spin-2 whilst the data are compatible with the Standard Model Higgs at the 1σ level.

CMS Physics Analysis Summary

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2013/07/01

Properties of the observed Higgs-like resonance decaying into two photons

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Nothing above 150 GeV

Tech. Rep. ATLAS-CONF-2013-067, CERN, Geneva, Jul, 2013.

Tech. Rep. CMS-PAS-HIG-12-024, CERN, Geneva, 2013

Tech. Rep. CMS-PAS-HIG-13-008, CERN, Geneva, 2013.

Tech. Rep. CMS-PAS-HIG-13-014, CERN, Geneva, 2013.

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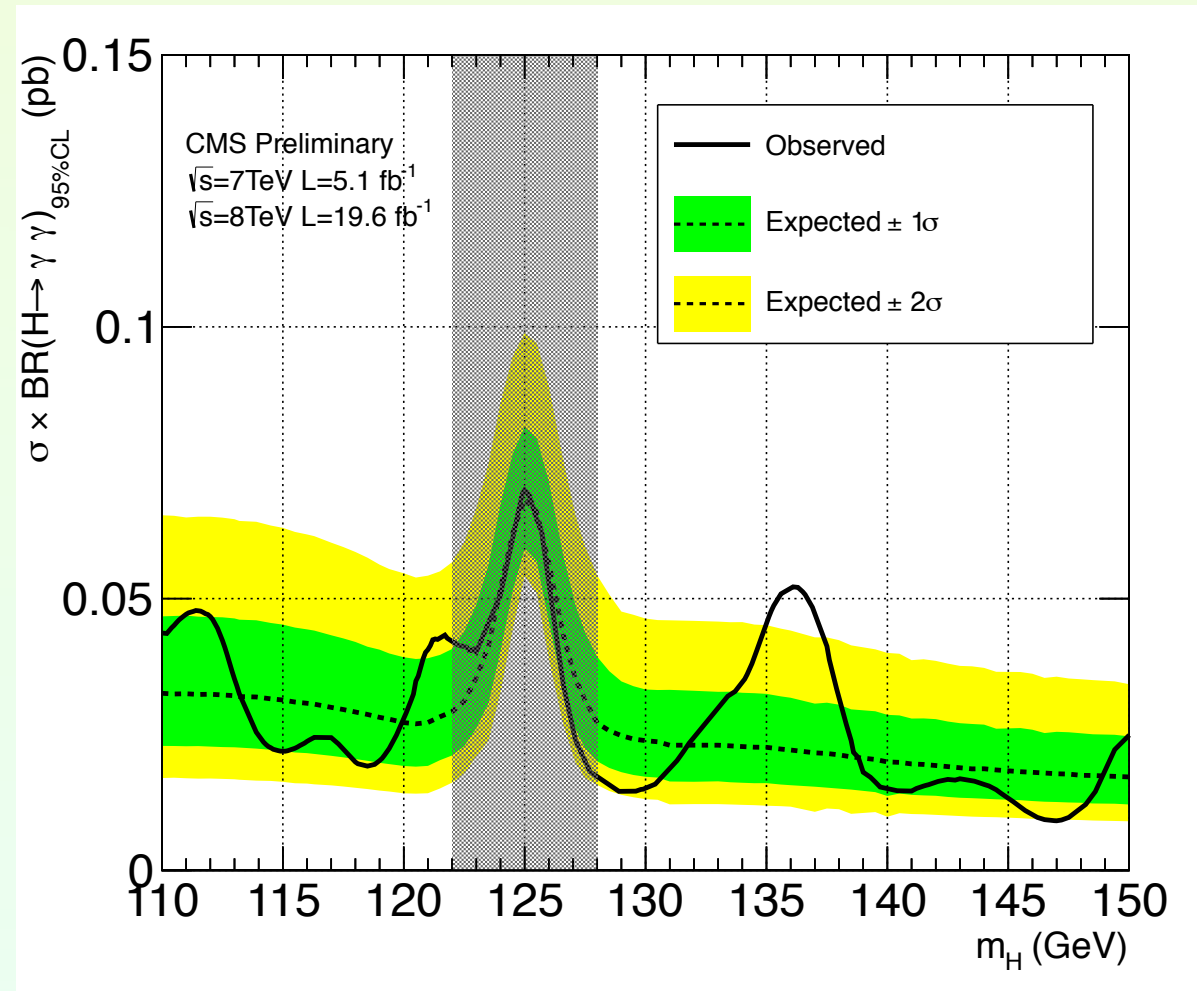


Figure 2: Exclusion limit on $\sigma \times BR$ for another Higgs state with SM couplings taking the observed state at 125 GeV as part of the background

BR = branching ratio

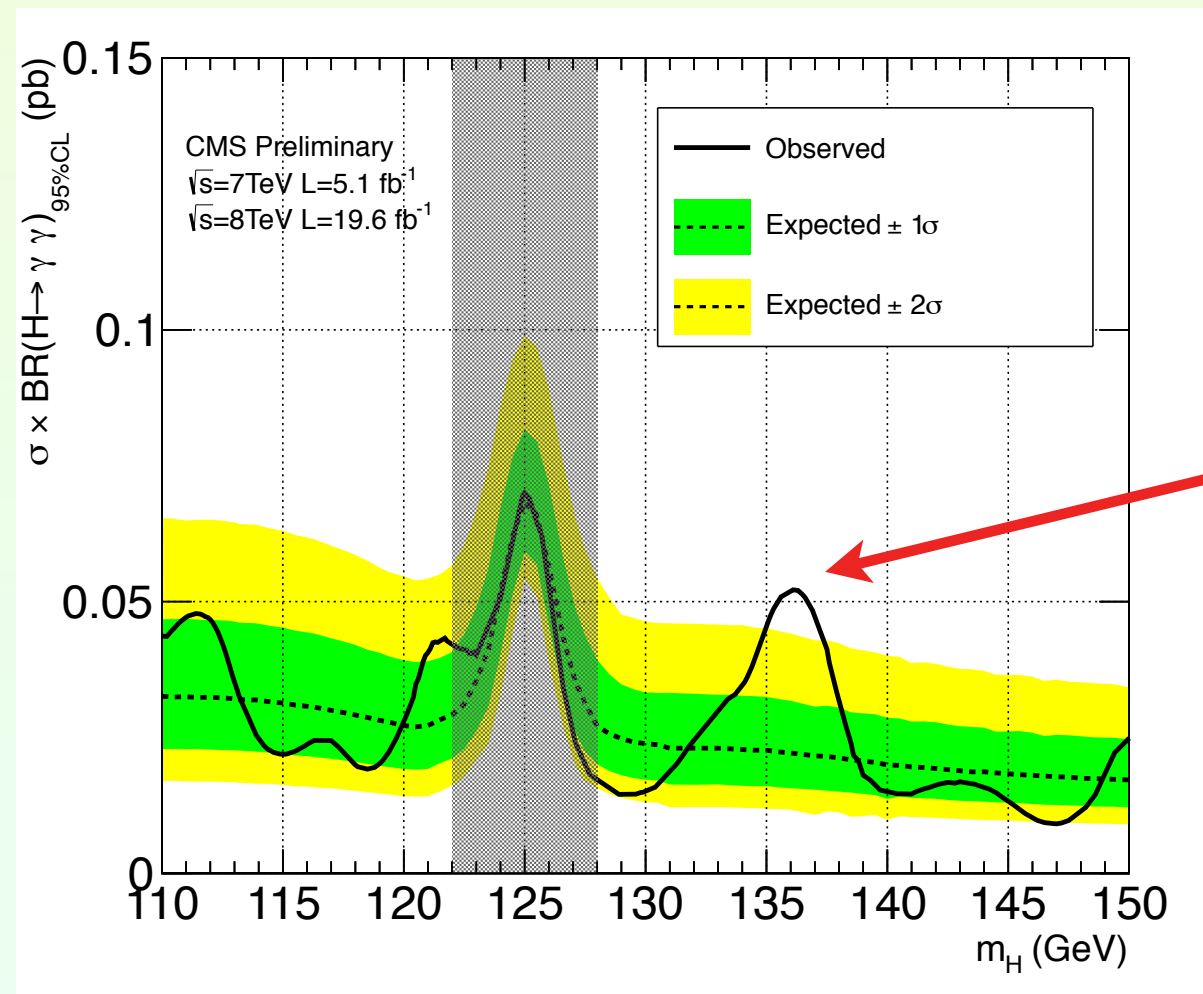


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BR = branching ratio

p -value at most significant excess, where $m_H=136.5$ GeV, is determined at 2.93σ

Even more curious/interesting

$$gg \rightarrow H + X$$

$$q\bar{q} \rightarrow q\bar{q}H + X$$

$$q\bar{q} \rightarrow W^\pm H + X$$

$$q\bar{q} \rightarrow ZH + X$$

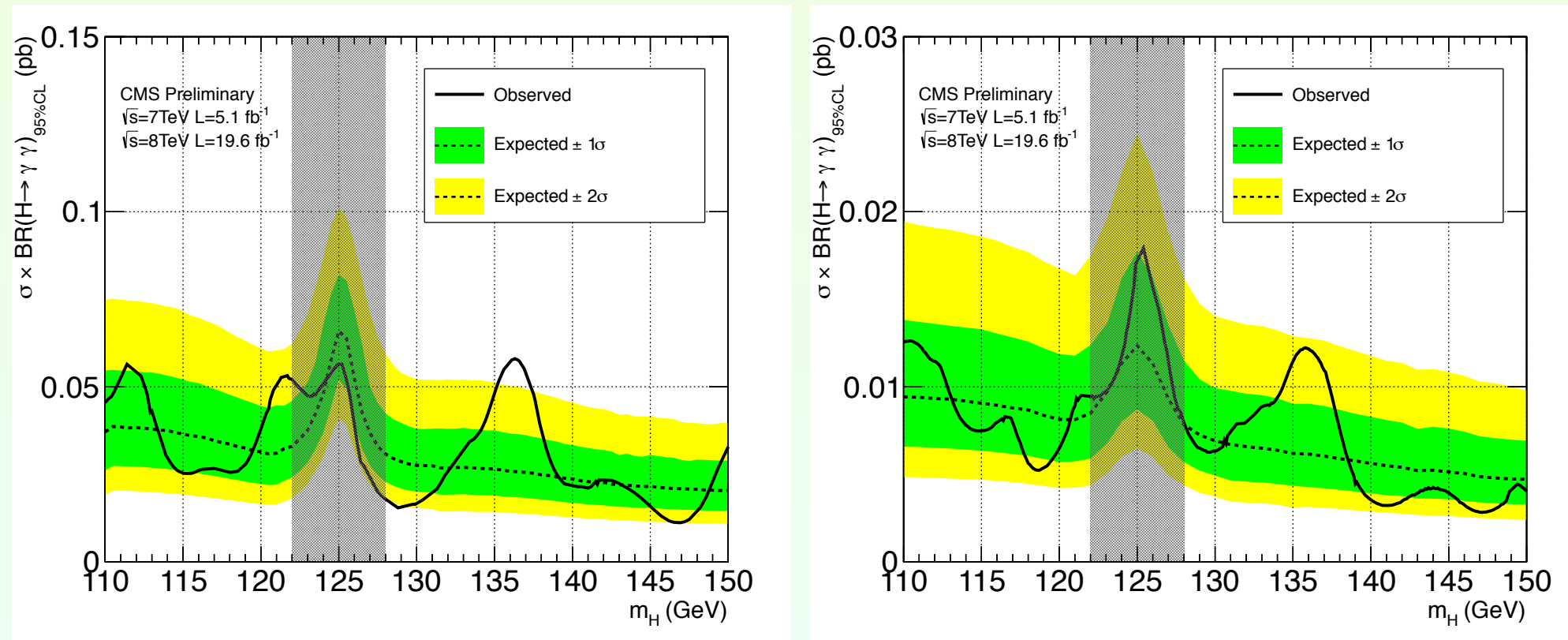
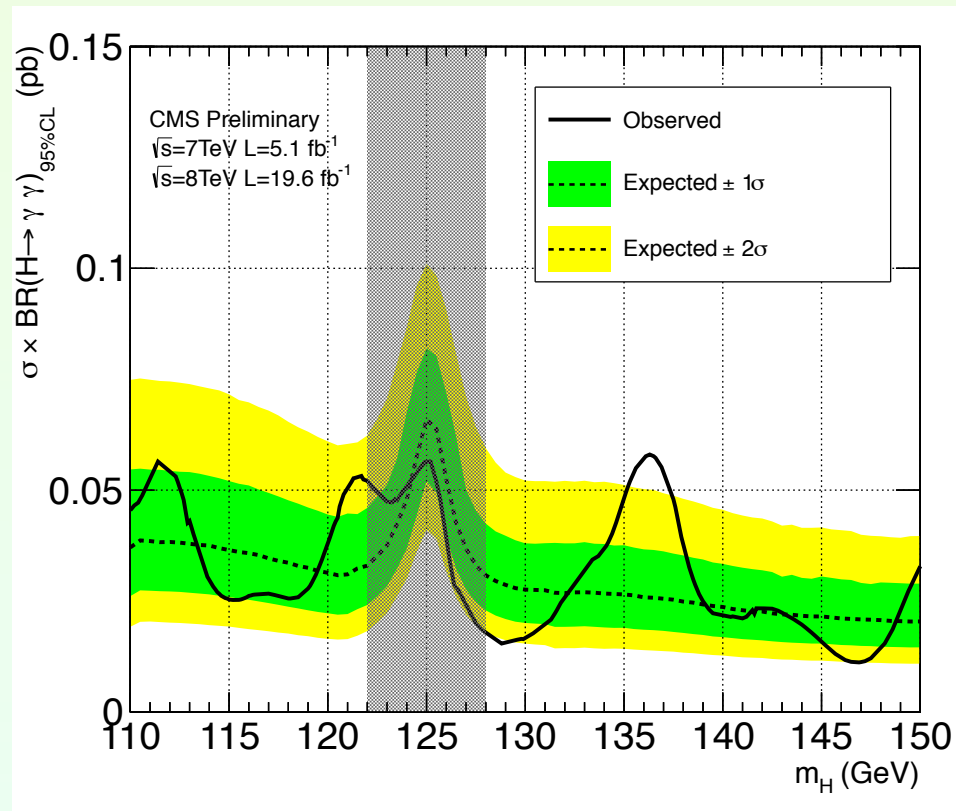


Figure 3: Exclusion limits on $\sigma \times BR$ for a second Higgs-like state produced with gluon-fusion only (left) or vector-boson-fusion and vector-boson-associated production only (right) taking the observed state at 125 GeV as part of the background.

Even more curious/interesting

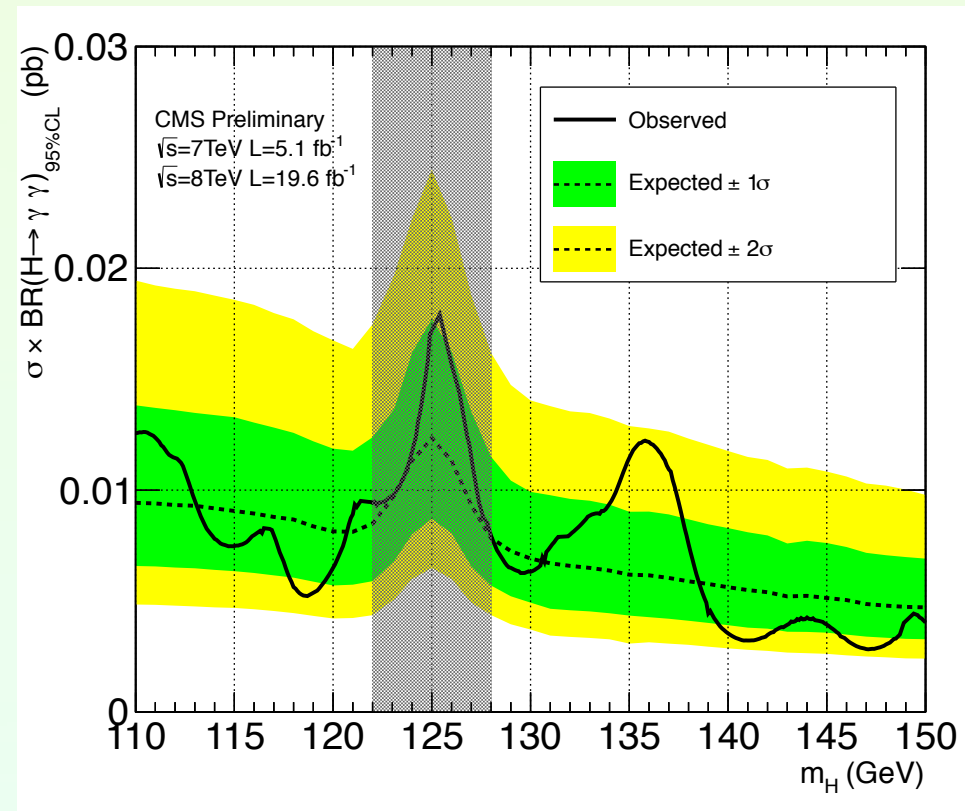
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► Both cases similarly significant: p-value 2.73σ (left) 2.15σ (right)

► Values similar to those of SM higgs; our calculation:

$$\sigma_{ggF} \times BR(h' \rightarrow \gamma\gamma) = 0.036 \pm 0.013 \text{ pb},$$

$$\sigma_{VBF+Vh'} \times BR(h' \rightarrow \gamma\gamma) = 0.007 \pm 0.003 \text{ pb}.$$



$$\mu \equiv (\sigma \times Br)/(\sigma_{SM} \times Br_{SM}),$$

“signal strength”

$$\mu_{ggF} = 1.1 \pm 0.4$$

$$\mu_{VBF} = 1.6 \pm 0.7$$



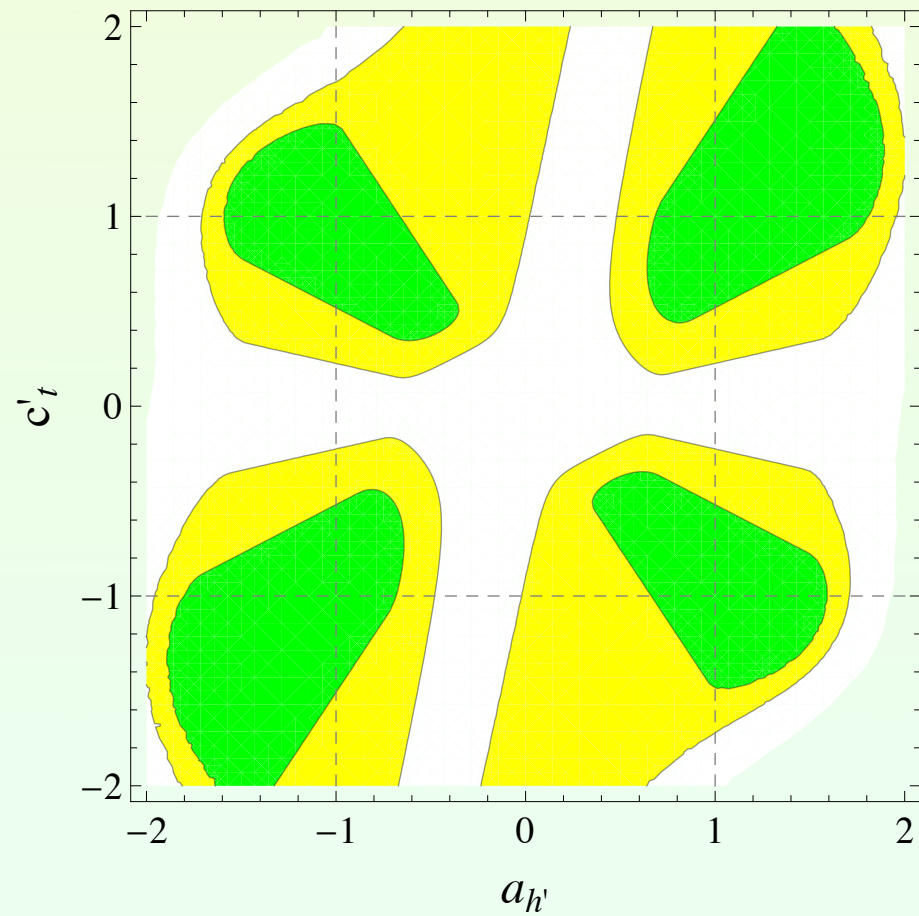
danger, I may get burned

- ⌘ ATLAS has not reported a deviation in this mass range
- ⌘ 2.93σ means nothing ...
- ⌘ But, hypothetically ... Ergo, our interest plus it gives us a playground

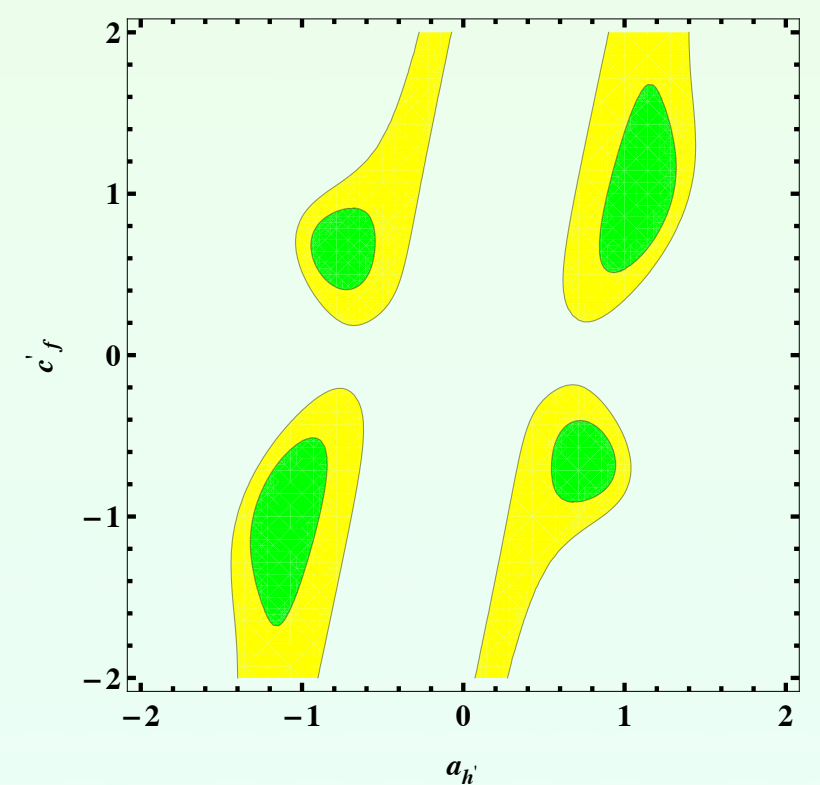
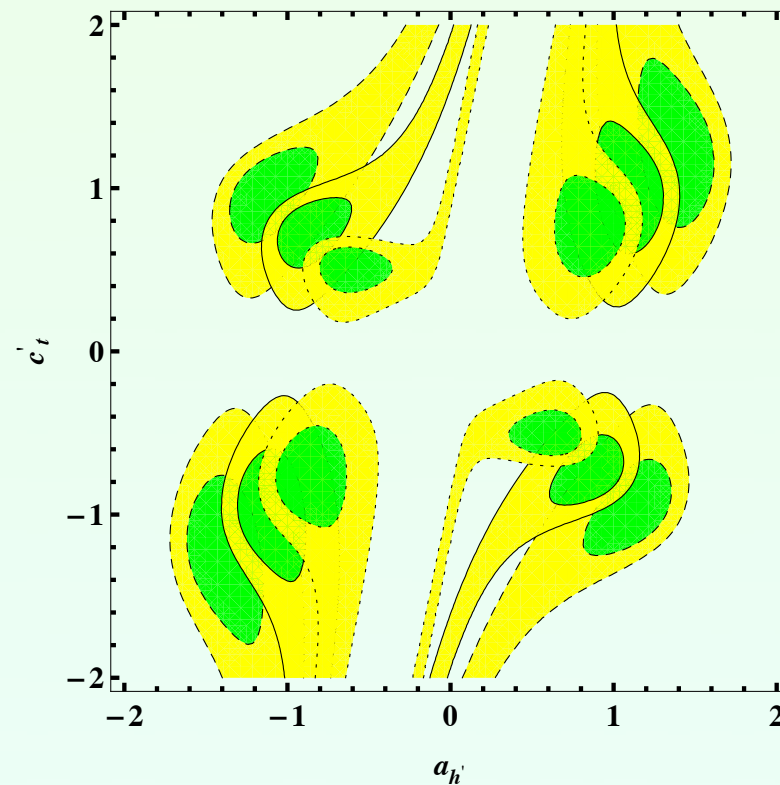
$$\mathcal{L}_{h'} \supset -\frac{2m_W^2}{v_{EW}} a_{h'} W^\mu W_\mu h' - \frac{m_Z^2}{v_{EW}} a_{h'} Z^\mu Z_\mu h' - \sum_i \frac{m_{f_i}}{v_{EW}} c'_{f_i} \bar{f}_i f_i h'$$

parametrization
of couplings of
new higgs h'

$$v_{EW} = (\sqrt{2}G_F)^{-1/2} \approx 246 \text{ GeV}$$



fit to data; 68% CL - green,
95% CL - yellow
Fermion couplings free,
save for $|c| < 3$

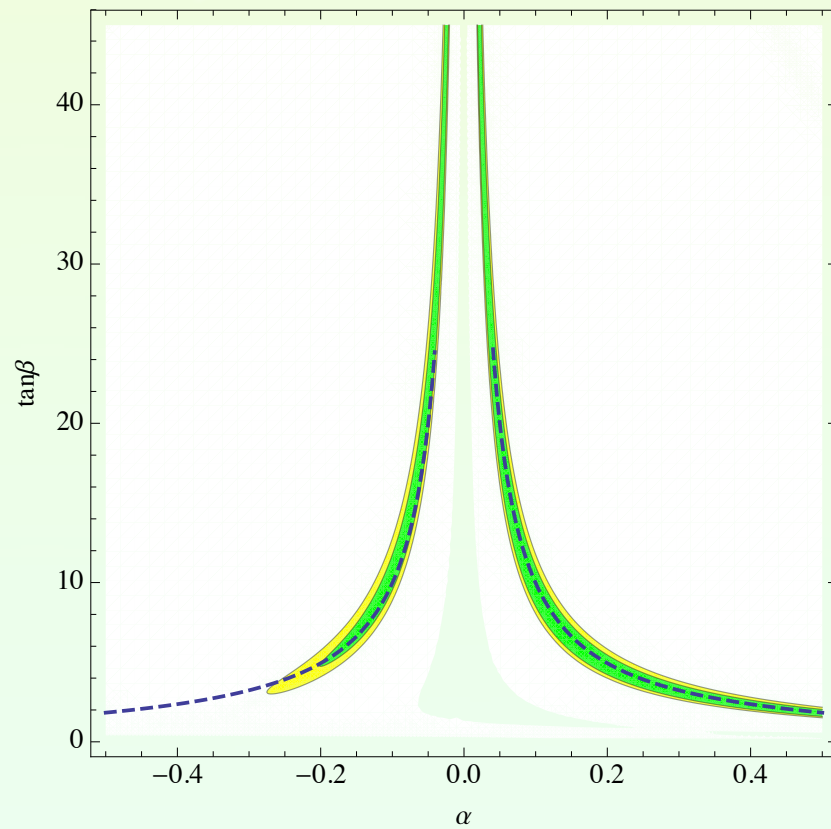


Left: common h' coupling to all fermions except top Contours with
points, solid dashes correspond to $c'_{f \neq t} = \{0, 1, 2\}$, respectively.
Right: universal fermion coupling modifier, $c'_f = c'_t$

Consider 2HDM first (two higgs doublet models)

BG & Uttayarat, JHEP 1306 (2013) 094, Erratum-ibid. 1309 (2013) 110 e-Print: arXiv:1304.0028

Fit to 125 GeV resonance data



Dotted line is decoupling limit, $\alpha + \beta = \pm \pi / 2$, for which couplings are SM-similar (modulo sign change in d-s-b-Yukawa).

H. Cheon and S. K. Kang, arXiv:1207.1083.
Y. Bai et al arXiv:1210.4922.
W. Altmannshofer et al, arXiv:1210.2465.
A. Drozd, et al, arXiv:1211.3580.
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C.-Y. Chen and S. Dawson, arXiv:1301.0309.
A. Goudelis, et al, arXiv:1303.3010.

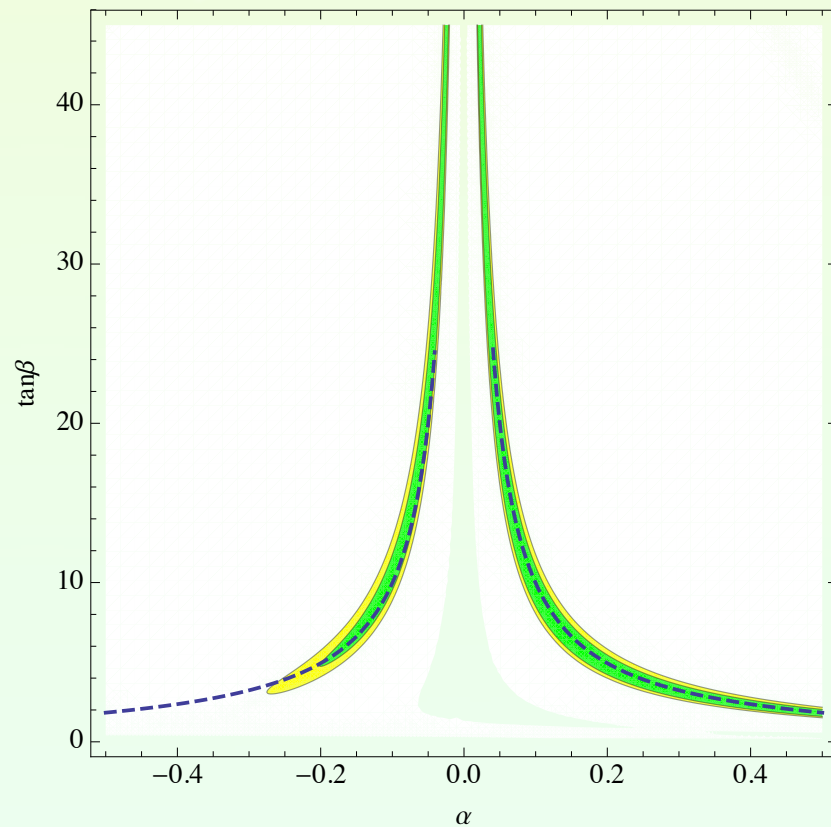
$$\tan \beta = v_2 / v_1 \quad \begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix} = \begin{pmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

$$\begin{aligned} \mathcal{L}_{yuk} = & -\frac{M_u}{v} \left(\frac{\cos \alpha}{\sin \beta} \right) \bar{u} u h - \frac{M_d}{v} \left(\frac{\sin \alpha}{\cos \beta} \right) \bar{d} d h - \frac{M_e}{v} \left(\frac{\sin \alpha}{\cos \beta} \right) \bar{e} e h \\ & + \frac{M_u}{v} \left(\frac{\sin \alpha}{\sin \beta} \right) \bar{u} u H - \frac{M_d}{v} \left(\frac{\cos \alpha}{\cos \beta} \right) \bar{d} d H - \frac{M_e}{v} \left(\frac{\cos \alpha}{\cos \beta} \right) \bar{e} e H \\ & + \frac{2M_W^2}{v} W_\mu^+ W^{-\mu} h \sin(\alpha + \beta) + \frac{M_Z^2}{v} Z_\mu Z^\mu h \sin(\alpha + \beta) \\ & + \frac{2M_W^2}{v} W_\mu^+ W^{-\mu} H \cos(\alpha + \beta) + \frac{M_Z^2}{v} Z_\mu Z^\mu H \cos(\alpha + \beta). \end{aligned}$$

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ZERO, if $\alpha + \beta = \pm \pi / 2$

Questions

Theoretical bounds on higgsless models:

J. Distler, B. Grinstein, R. A. Porto, and I. Z. Rothstein, Phys.Rev.Lett. 98 (2007) 041601, arXiv:hep-ph/0604255 [hep-ph].

and with one higgs:

I. Low, R. Rattazzi, and A. Vichi, JHEP 1004 (2010) 126, arXiv:0907.5413 [hep-ph].

- Can we accommodate this in 3HDM? 4HDM? or simply nHDM
- other models?
- model independent analysis?

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NOTE: What do we mean by a “higgs-boson” if we presume a model independent analysis?

Answer: any particle that couples linearly to a pair of electroweak vector mesons

Answers

nHDM

N doublets H_i all with $Y=1/2$, with expectation value $v_i/\sqrt{2}$, neutral CP-even component $\tilde{h}_i$.

$$\mathcal{L} = \cdots + \frac{1}{4}g^2 W_\mu^+ W_\nu^- \eta^{\mu\nu} \sum_{i=1}^N (v_i + \tilde{h}_i)^2.$$

$$\frac{1}{2}g^2(v_1, \dots, v_N) \equiv gM_W \vec{\tilde{a}} = gM_W(\tilde{a}_1, \dots, \tilde{a}_N) \quad \text{characterizes couplings to } WW/ZZ$$

of fields $\vec{\tilde{h}} = (\tilde{h}_1, \dots, \tilde{h}_N)$

W mass: $|\vec{\tilde{a}}|^2 = 1.$

Mass eigenstates (physical states): $\vec{\tilde{h}} = R\vec{h}$

their couplings $\vec{\tilde{a}} = R^T \vec{a}.$

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$$\sum_{i>1} a_i^2 = 1 - a_1^2.$$



Other models: Generalization

Field H_i in $(2n_i + 1)$ rep of $SU(2)$, with VEV in component with $T^3 = m_i$

$$\mathcal{L} = \cdots + \frac{1}{4}g^2 W_\mu^+ W_\nu^- \eta^{\mu\nu} \sum_{i=1}^N C_i (v_i + \tilde{h}_i)^2, \quad C_i = C(n_i, m_i) = 2[n_i(n_i + 1) - m_i^2].$$

couplings: $\vec{\tilde{a}} = \frac{g}{2M_W} (C_1 v_1, \dots, C_N v_N) \quad \vec{a} = R^T \vec{\tilde{a}},$

$$\sum_{i=1}^N \frac{\tilde{a}_i^2}{C_i} = 1, \quad \Rightarrow \quad a^T R^T C^{-1} R a = 1,$$

Ah, freedom!

However, only reps with $n=1/2$ may couple directly to quarks.

For example, if we assume only H_1 is a doublet

$$\mathcal{L}_f = \tilde{H}_1 \bar{q}_L \lambda_U u_R + H_1 \bar{q}_L \lambda_D d_R + H_1 \bar{\ell}_L \lambda_E e_R,$$

$$\Rightarrow \text{neutral component couplings: } \mathcal{L}_f = \frac{1}{v_1} R_{1i} h_i (\bar{u} m_U u + \bar{d} m_D d + \bar{e} m_E e)$$

$R^T R = 1$ gives: $\sum_{i>1} R_{1i}^2 = 1 - R_{11}^2$, Eureka: competition between couplings to VV and ff

digression: VEVs for fields with $n > 1/2$

$$\delta\rho = \frac{M_W^2 - M_3^2}{M_3^2}, \quad M_3 = M_Z \cos \theta_W$$

Explicitly (to lowest order)

$$\delta\rho = \frac{\sum_i v_i^2 [n_i(n_i + 1) - 3m_i^2]}{\sum_i 2v_i^2 m_i^2},$$

Vanishes if $n_i = |m_i| = \frac{1}{2}$ (doublets)

$n_i = 3, |m_i| = 2$ (septets)

$n_i = 48, |m_i| = 28$ ($g_i n_i/4\pi > 1$, perturbation theory to hell, Landau pole in you face)

$n_i = \frac{361}{2}, |m_i| = \frac{209}{2}$

Vanishes also if cancellation between positive and negative terms

Example: *Georgi-Machacek model*: several fields, all with same VEV, all with $n = 1$ (triplets), so that $n(n+1) = 2$

With 3 triplets, one with $m = 0$: $3(2) - 2(3 \times 1^2) = 0$

H. Georgi and M. Machacek, Nucl.Phys. B262 (1985) 463.

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Will use these as examples

Vanishes also if cancellation between positive and negative terms
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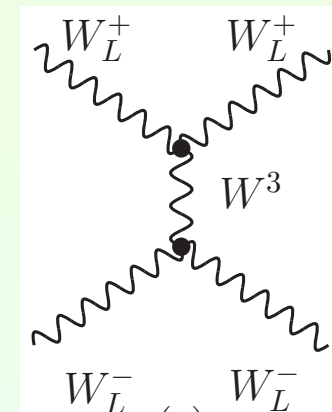
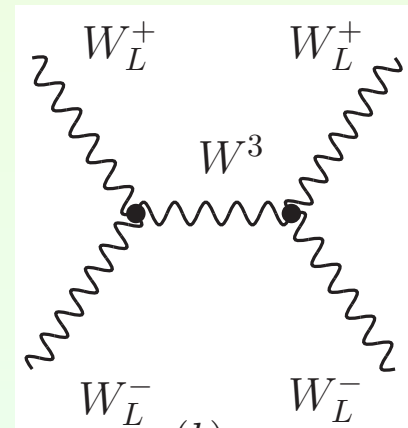
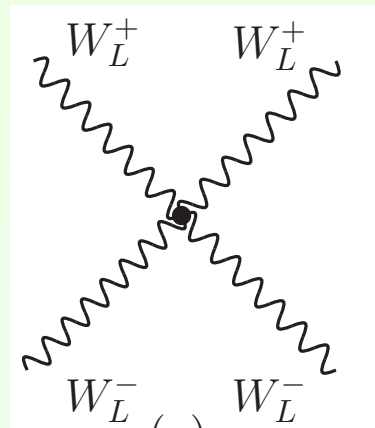
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More General: Unitarity Bounds

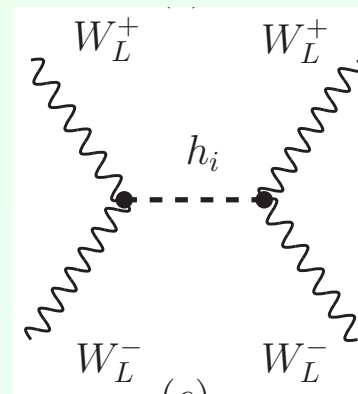
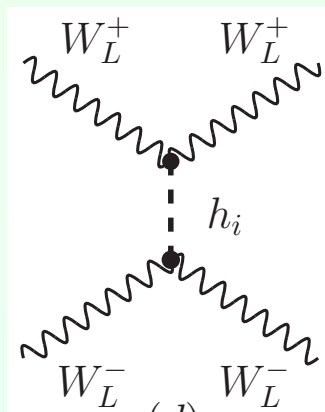
B. W. Lee, C. Quigg, and H. Thacker, Phys.Rev. D16 (1977) 1519.
J.F. Gunion, H.E. Haber, J. Wudka. Phys.Rev. D43 (1991) 904-912

$s = (p_1 + p_2)^2$ partial amplitude growth with energy, s

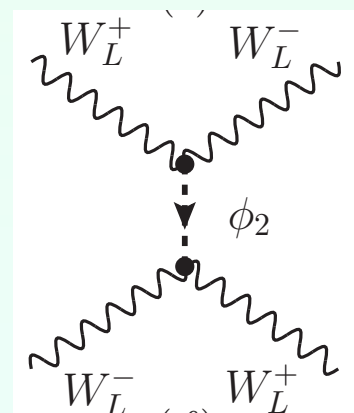
partial amplitudes $a_{J=0,1,2}$



$s^2, s, 1, \dots$



$s, 1, \dots$



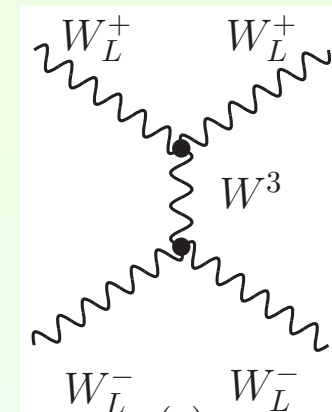
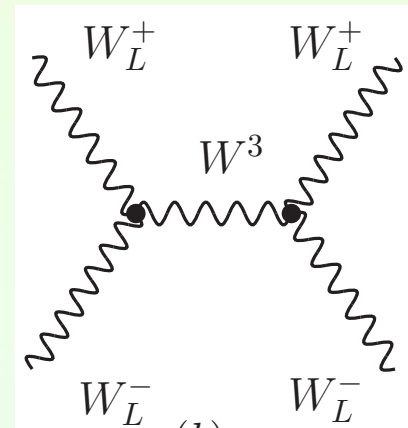
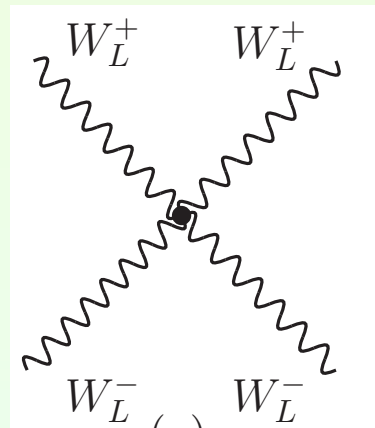
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More General: Unitarity Bounds

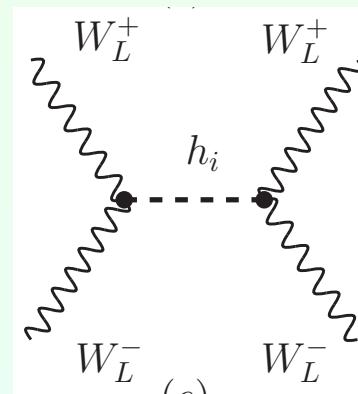
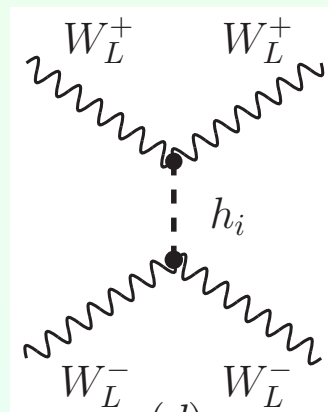
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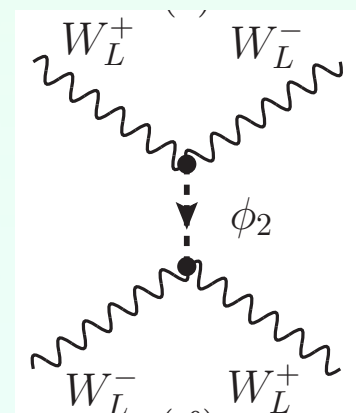
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$$\begin{array}{c} \triangle \\ s^2, \quad s, \quad 1, \dots \\ \boxed{=0 \text{ automatic,} \\ \text{gauge inv}} \end{array}$$



$$s, \quad 1, \dots$$



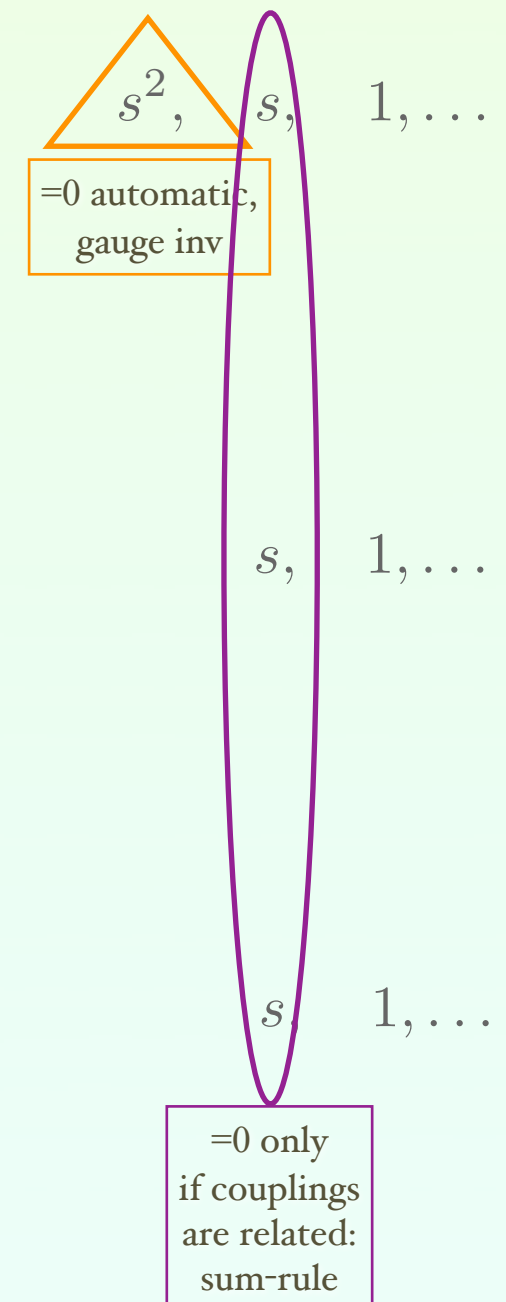
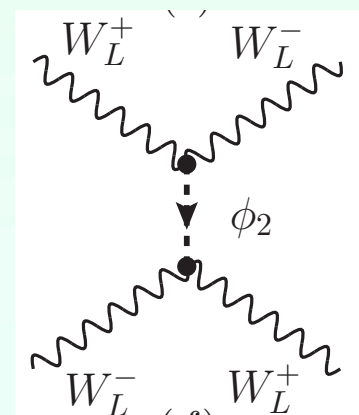
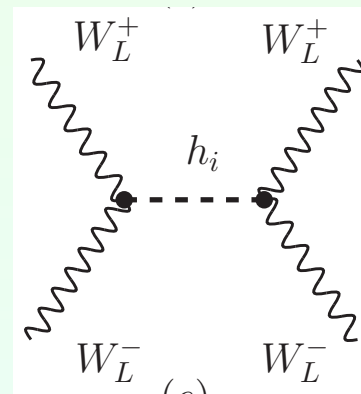
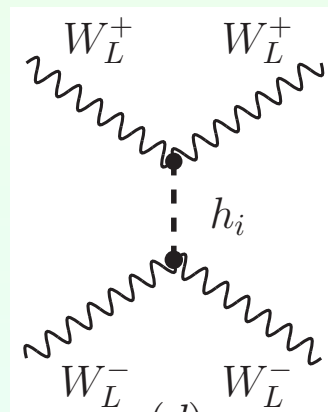
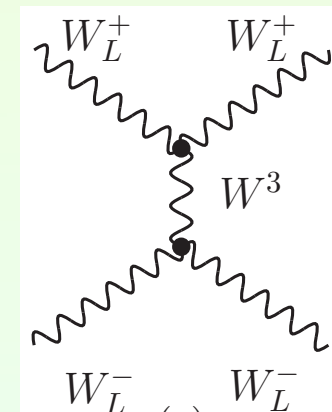
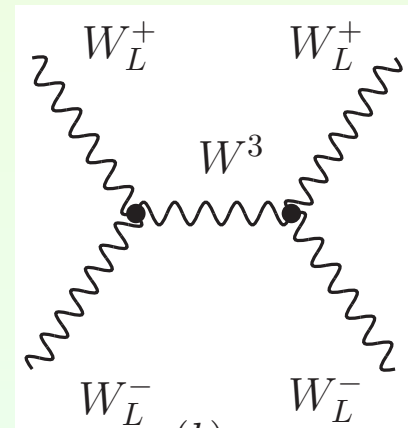
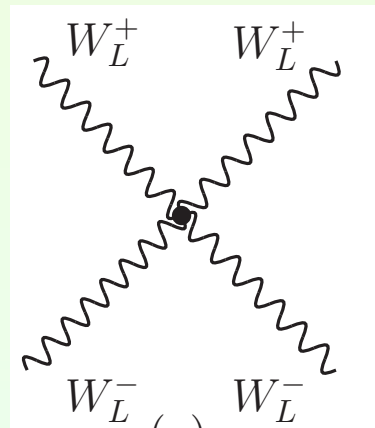
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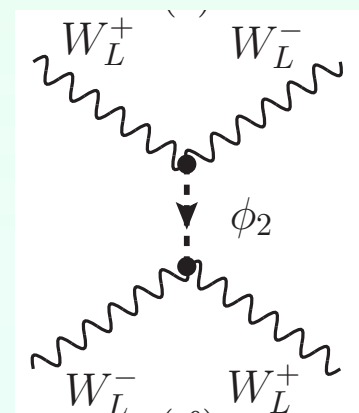
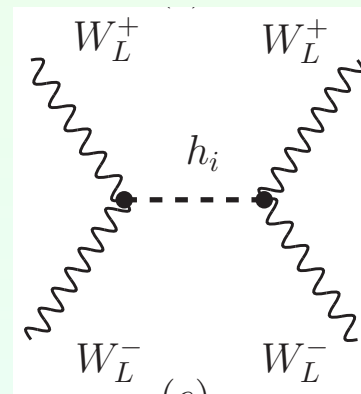
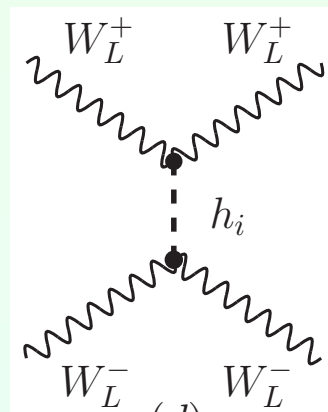
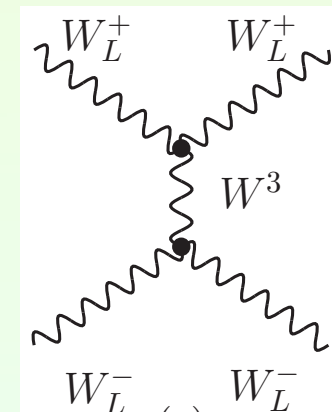
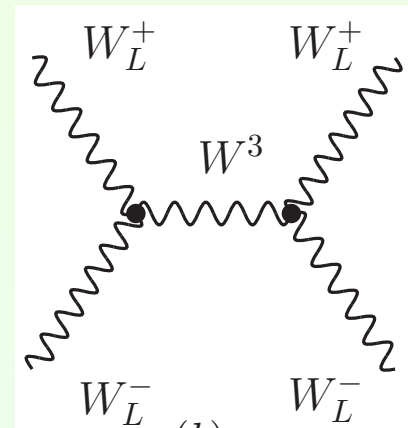
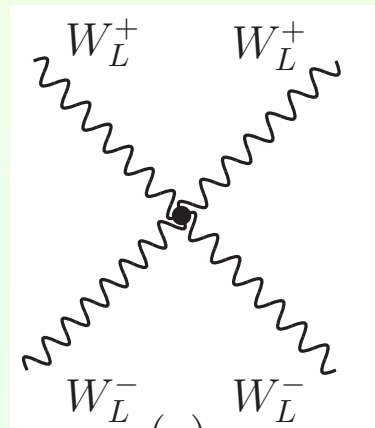


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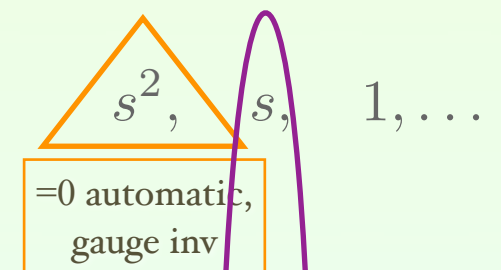
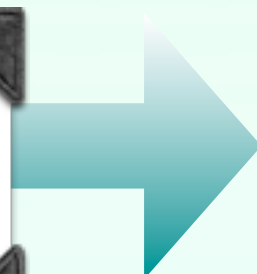
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Generally
requires doubly
charged higgs!



$s, 1, \dots$

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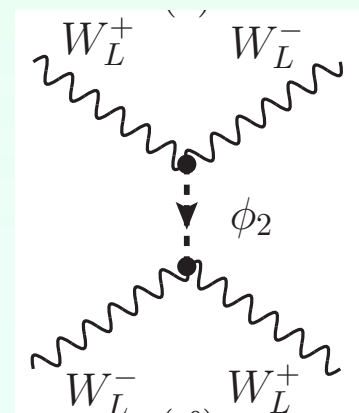
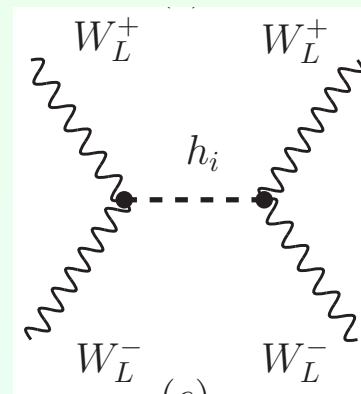
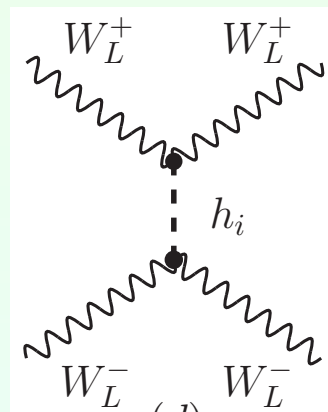
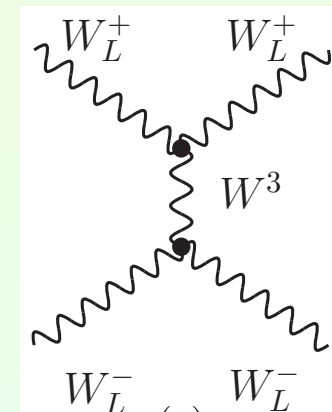
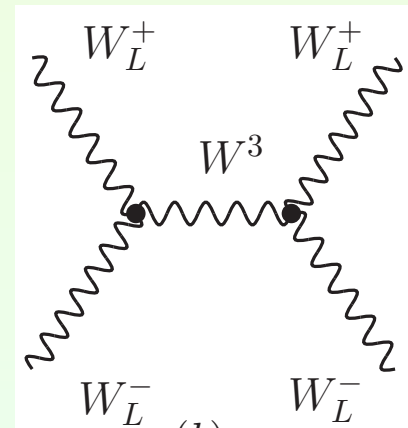
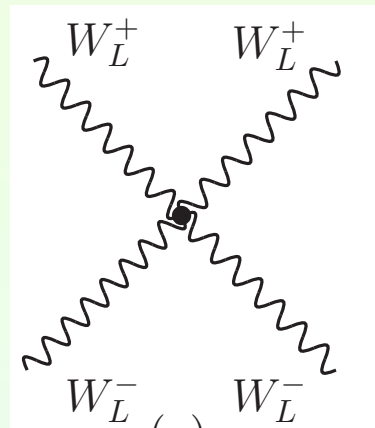
=0 only
if couplings
are related:
sum-rule

More General: Unitarity Bounds

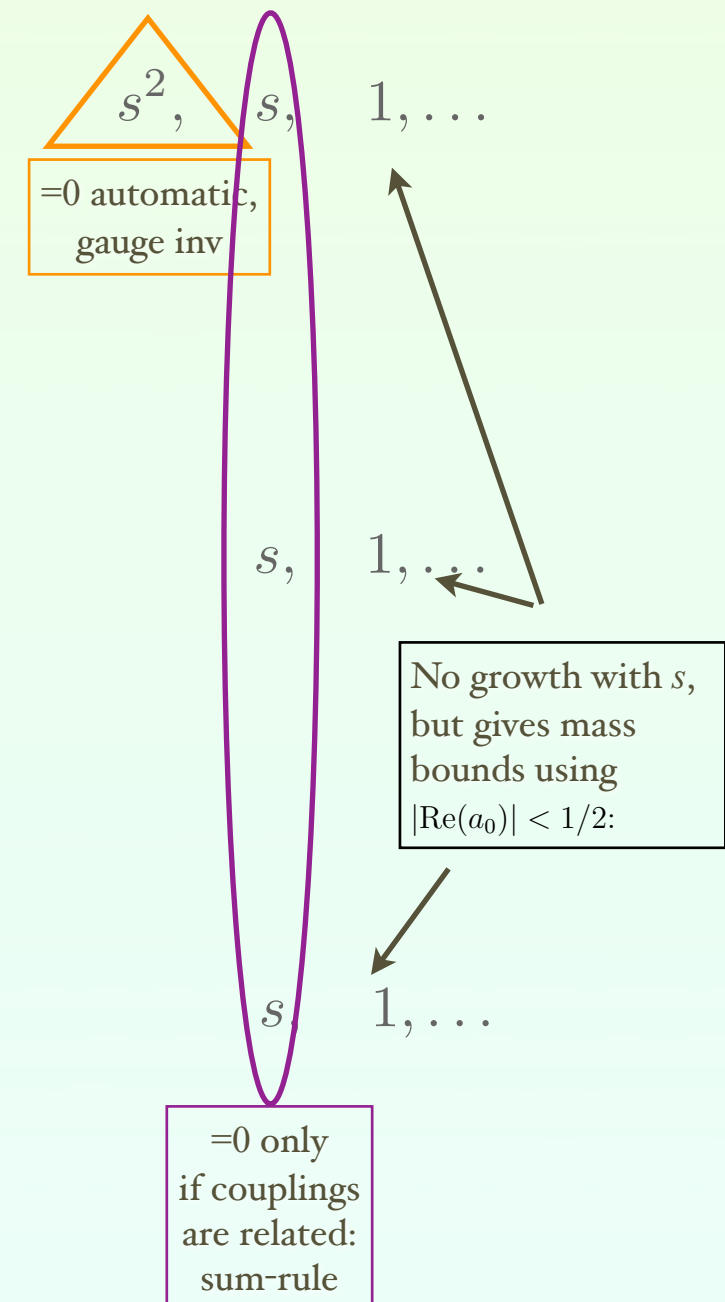
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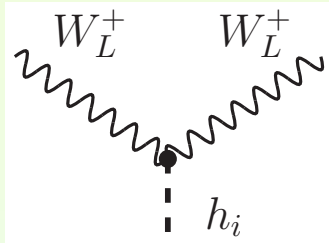
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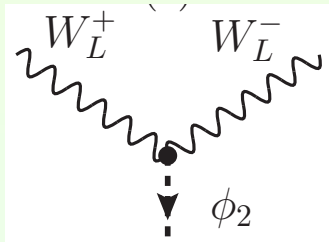
Generally requires doubly charged higgs!



$$\cdot \underline{W_L^+ W_L^- \rightarrow W_L^+ W_L^-}$$



$$= igM_W a_i$$



$$= igM_W b_r$$

sum rule:

$$\sum_i a_i^2 - 4 \sum_r b_r^2 = 4 - 3(M_3/M_W)^2$$

unitarity bound:

$$\sum_i (a_i M_i^0)^2 + 2 \sum_r (b_r M_r^{++})^2 \leq \frac{2\pi\sqrt{2}}{G_F} \approx 0.5 \text{ TeV}^2$$

Comments:

A. Falkowski et al, JHEP 1204 (2012) 073 arXiv:1202.1532

If $|a_1| > 1$ a doubly charged higgs must exist

The 125GeV higgs contribution to the bound is negligible

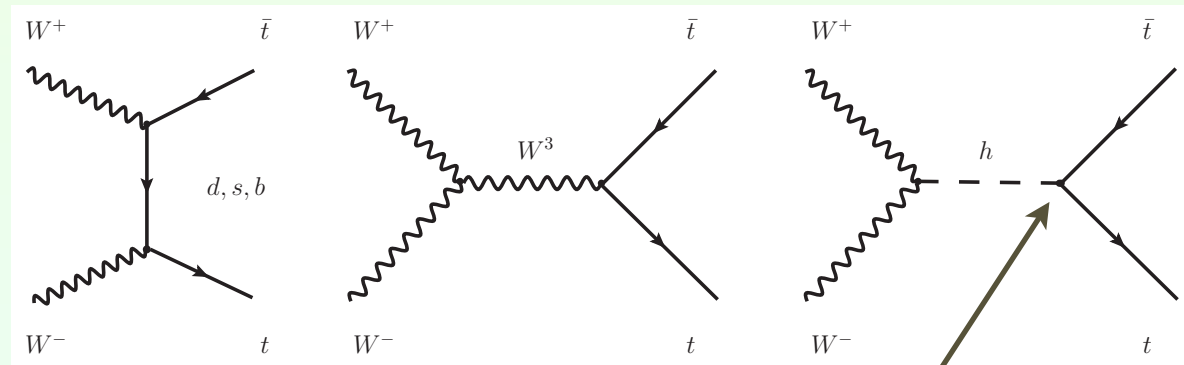
$$\underline{Z_L Z_L \rightarrow W_L^+ W_L^-}$$

$$ZZh_i \rightarrow \frac{1}{2}gM_W d_i \quad ZW^- h_r^+ \rightarrow gM_W f_r$$

sum rule: $\cos^2 \theta_W M_Z^4 / M_W^4 + \sum_r f_r^2 - \sum_i a_i d_i = 0$

Unitarity bound: $\sum_i a_i d_i (M_i^0)^2 + 2 \sum_r f_r^2 (M_r^+)^2 < \frac{4\pi\sqrt{2}}{\cos^2 \theta_W G_F} \approx 1.3 \text{ TeV}^2$

$$\underline{W_L^+ W_L^- \rightarrow t\bar{t}}$$



$$\lambda_i = (gm_t / \sqrt{2}M_W) c_{ti}$$

sum rule: $\sum_i a_i c_{ti} = 1.$ unitarity bound:

+ analogous results for other quarks and leptons

Examples - Applications

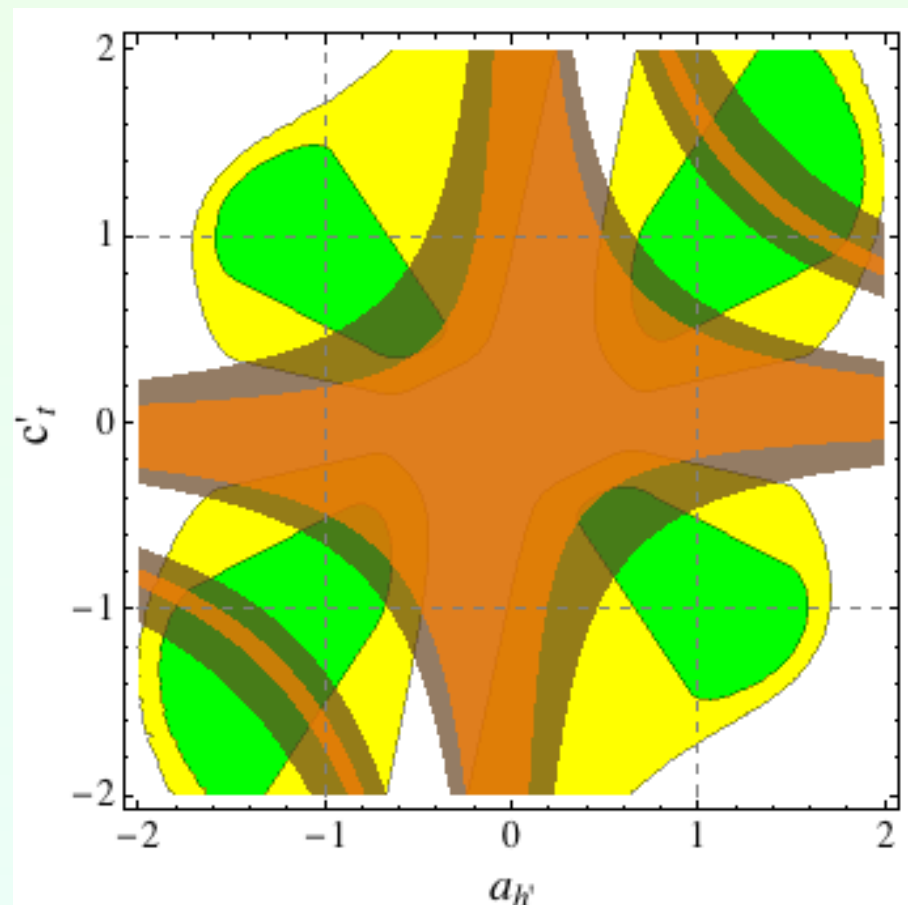
Idea: use 125 Higgs data and see what's left in the sum rule

I. **Neutral Higgs:** Suppose there are two neutral higgs:

$$\sum_i a_i c_{ti} = 1. \quad \Rightarrow \quad a_{h'} c'_t = 1 - a_h c_t.$$

This graph is independent
of the mass of h'

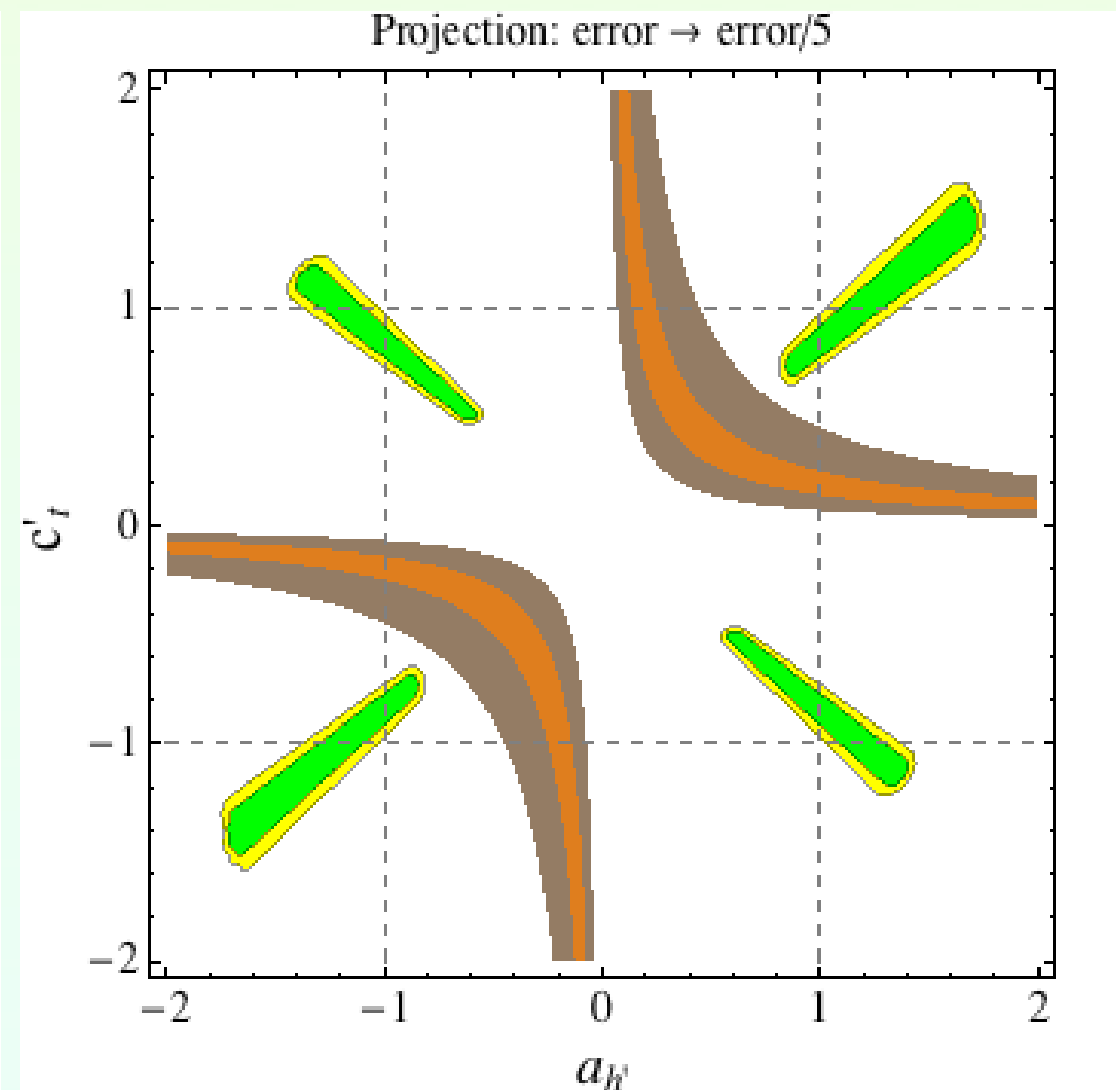
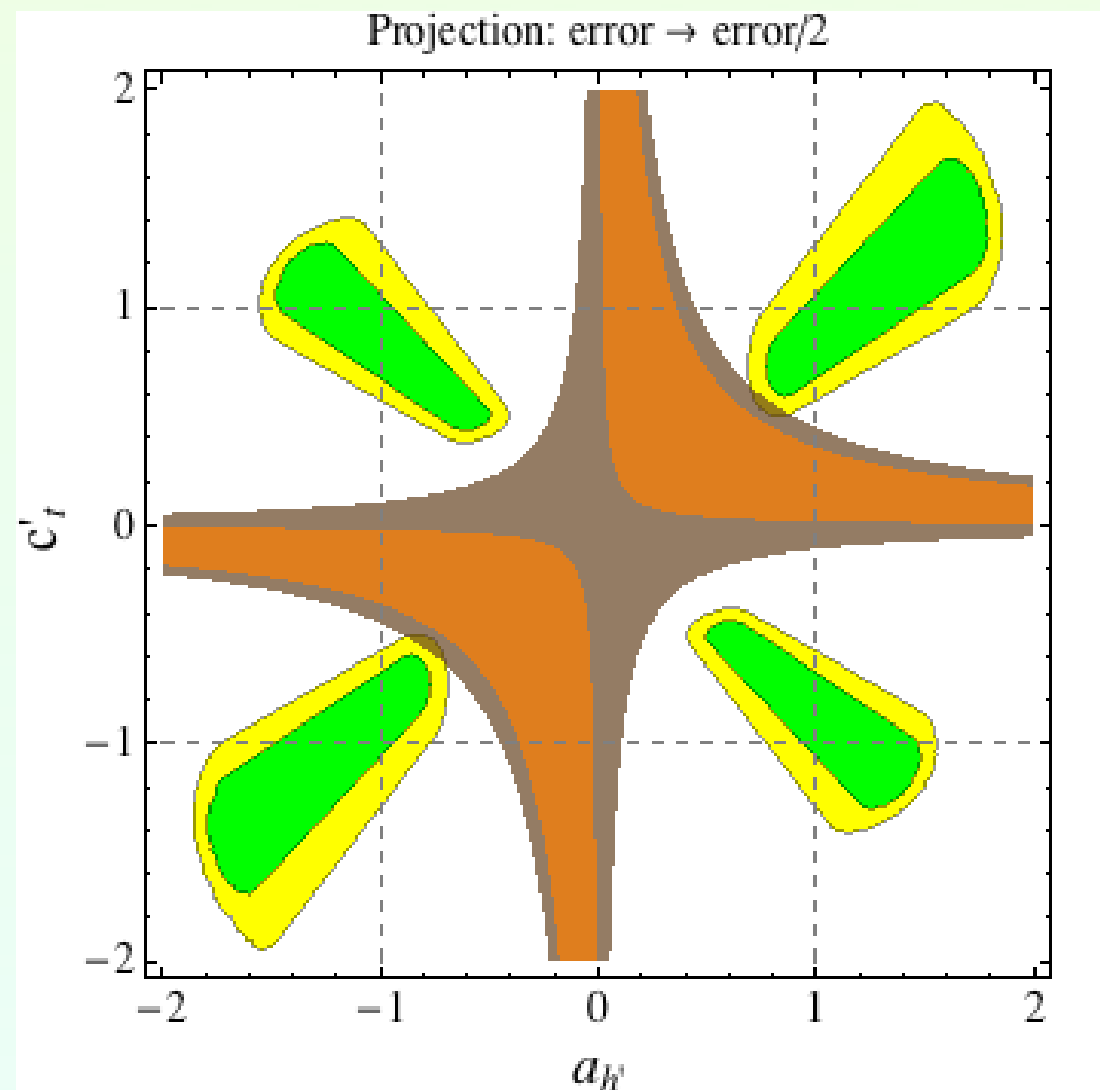
Superimposed on the CMS
135 GeV resonance,
just for comparison,
graph (brown) does not
depend on it.



68%: light brown
95%: dark brown

Peek into the future: what does higher precision buy you?

Same central values, reduce error by factor of 2 or 5



2. Doubly-charged Higgs: Suppose there is one, with coupling

E. J. Chun and P. Sharma, arXiv:1309.6888 [hep-ph].
 F. del Aguila and M. Chala, arXiv:1311.1510 [hep-ph].
 R. Dermisek, J. P. Hall, E. Lunghi, and S. Shin, arXiv:1311.7208 [hep-ph].

$$\mathcal{L}_{int} = gM_W b W_\mu^- W^{\mu-} h^{++} +$$

Suppose, in addition $\text{Br}(h^{++} \rightarrow W^+W^+) = 100\%$,

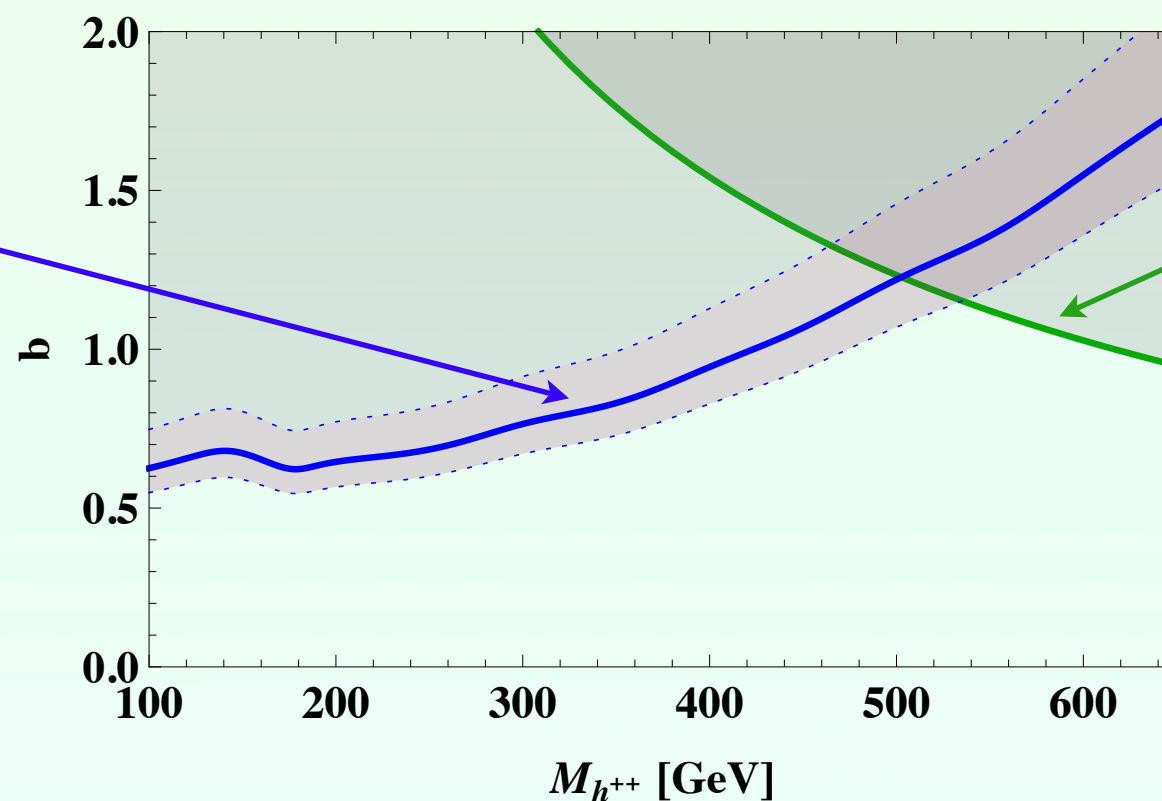
since $\Gamma(h^{++} \rightarrow h^+h^+)$ is model dependent

LHC production: vector boson fusion, and in association with vector boson.

Signal: same sign di-leptons plus jets.

our analysis of
CMS data

CMS Collaboration arXiv:1311.6736 [hep-ex];
 idem JHEP 1208 (2012) 110, arXiv:1205.3933 [hep-ex].
 idem JHEP 1303 (2013) 037, arXiv:1212.6194 [hep-ex].

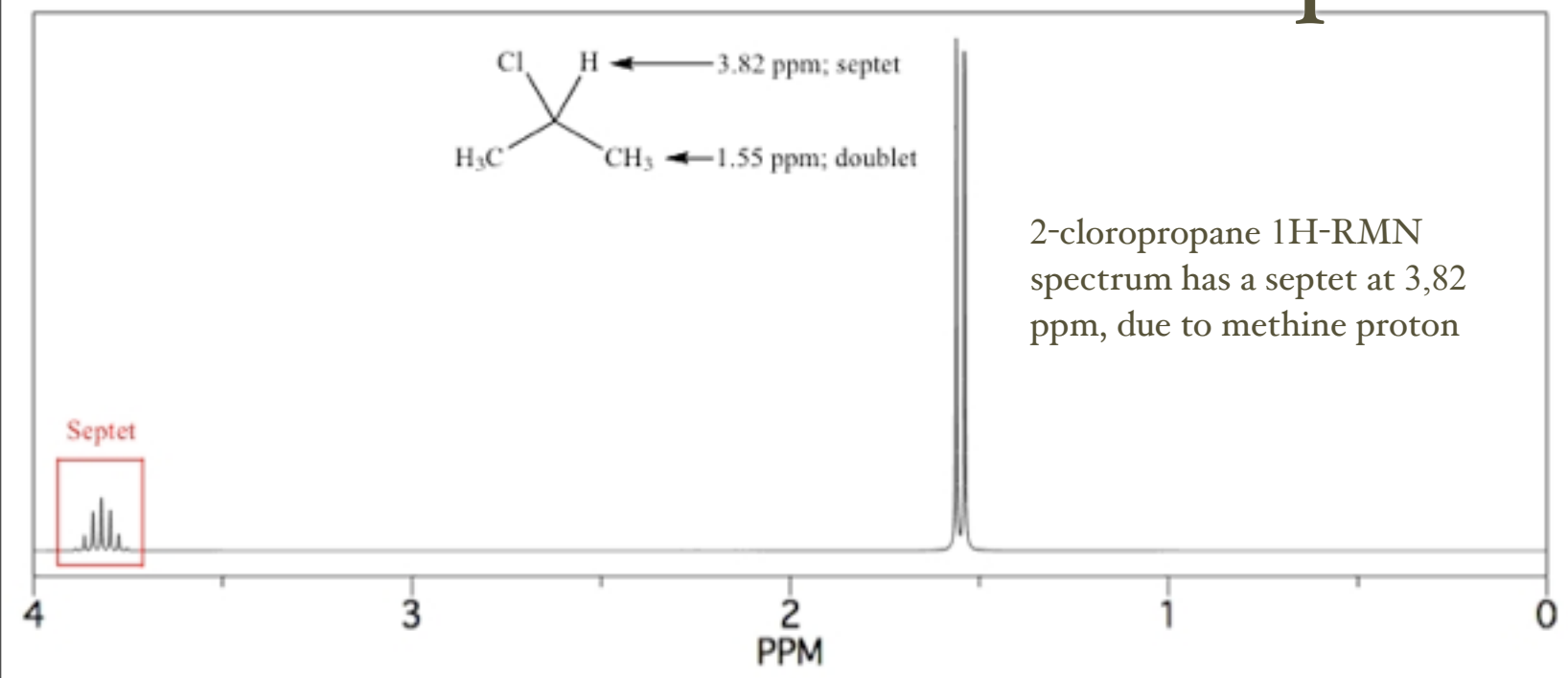


Examples - Specific Models

- Sum rules: automatically satisfied (in models based on unitary QFT)
- Models give correlations among effective parameters (a, b, c, d, f).
Fit to 125-higgs gives more severe limits than sum rules.
- Unitarity bounds: new information

Models	126 GeV Fit		126 & 136 GeV Fit	
	χ^2/N	N	χ^2/N	N
Model independent	0.38	14	0.44	12
Douplet-septet	0.34	16	0.73	18
Georgi-Machacek	0.34	16	0.56	18
2HDM-II	0.36	16	0.61	18
2HDM-III	0.38	14	0.67	16

doublet-septet model



higgs++ interaction:

$$\mathcal{L}_{int} \supset \sqrt{15} \frac{M_W^2}{v_{EW}} \cos \beta (W_\mu^- W^{-\mu} h^{++} + W_\mu^+ W^{+\mu} (h^{++})^*)$$

neutral higgs interaction:

$$\mathcal{L}_{int} \supset \frac{2}{v_{EW}} \left(M_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu \right) ((s_\beta c_\alpha - 4c_\beta s_\alpha)h + (s_\beta s_\alpha + 4c_\beta c_\alpha)h'),$$

$$\begin{pmatrix} h_2^0 \\ h_7^0 \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} h \\ h' \end{pmatrix} \quad \tan \beta = v_1/(4v_2).$$

Yukawa interaction:

$$\mathcal{L} \supset \left(\frac{\cos \alpha}{\sin \beta} h + \frac{\sin \alpha}{\sin \beta} h' \right) \sum_i \frac{m_{f,i}}{v_{EW}} \bar{f}_i f_i,$$

Correlations:

$$a_h = \sin \beta \cos \alpha - 4 \cos \beta \sin \alpha, \quad a_{h'} = \sin \beta \sin \alpha + 4 \cos \beta \cos \alpha, \quad b = \frac{\sqrt{15}}{2} \cos \beta,$$

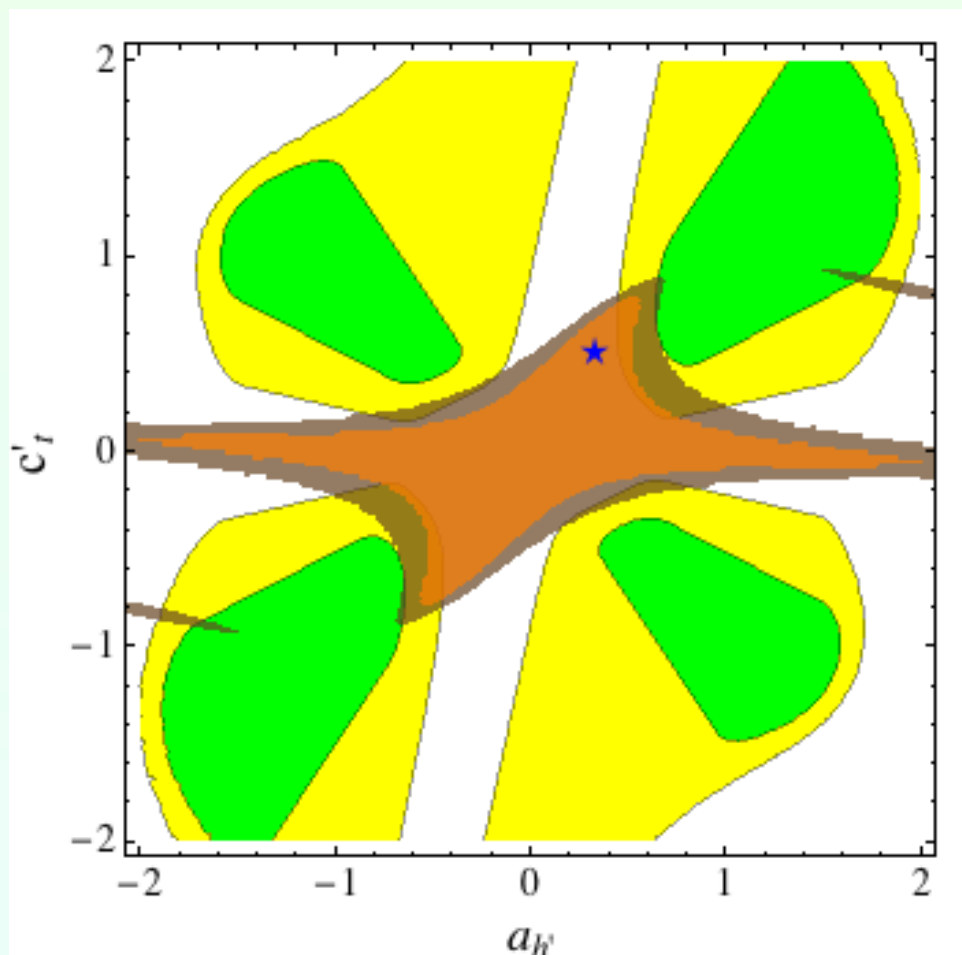
$$c_f = \cos \alpha / \sin \beta, \quad c'_f = \sin \alpha / \sin \beta.$$

higgs+ & higgs++:

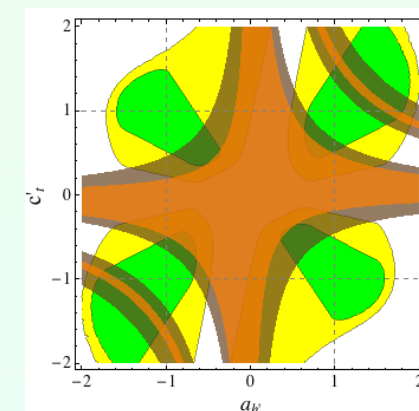
$$a_h = \frac{M_W^2}{M_Z^2} d_h : \quad f_h = -\frac{M_Z}{M_W} \frac{c_\beta (5\sqrt{3}s_\beta c_\gamma + 3\sqrt{5}s_\gamma)}{\sqrt{3 + 5s_\beta^2}},$$

$$a_{h'} = \frac{M_W^2}{M_Z^2} d_{h'} \quad f_{h'} = \frac{M_Z}{M_W} \frac{c_\beta (3\sqrt{5}c_\gamma - 5\sqrt{3}s_\beta s_\gamma)}{\sqrt{3 + 5s_\beta^2}}.$$

Fit (to 125 GeV higgs):

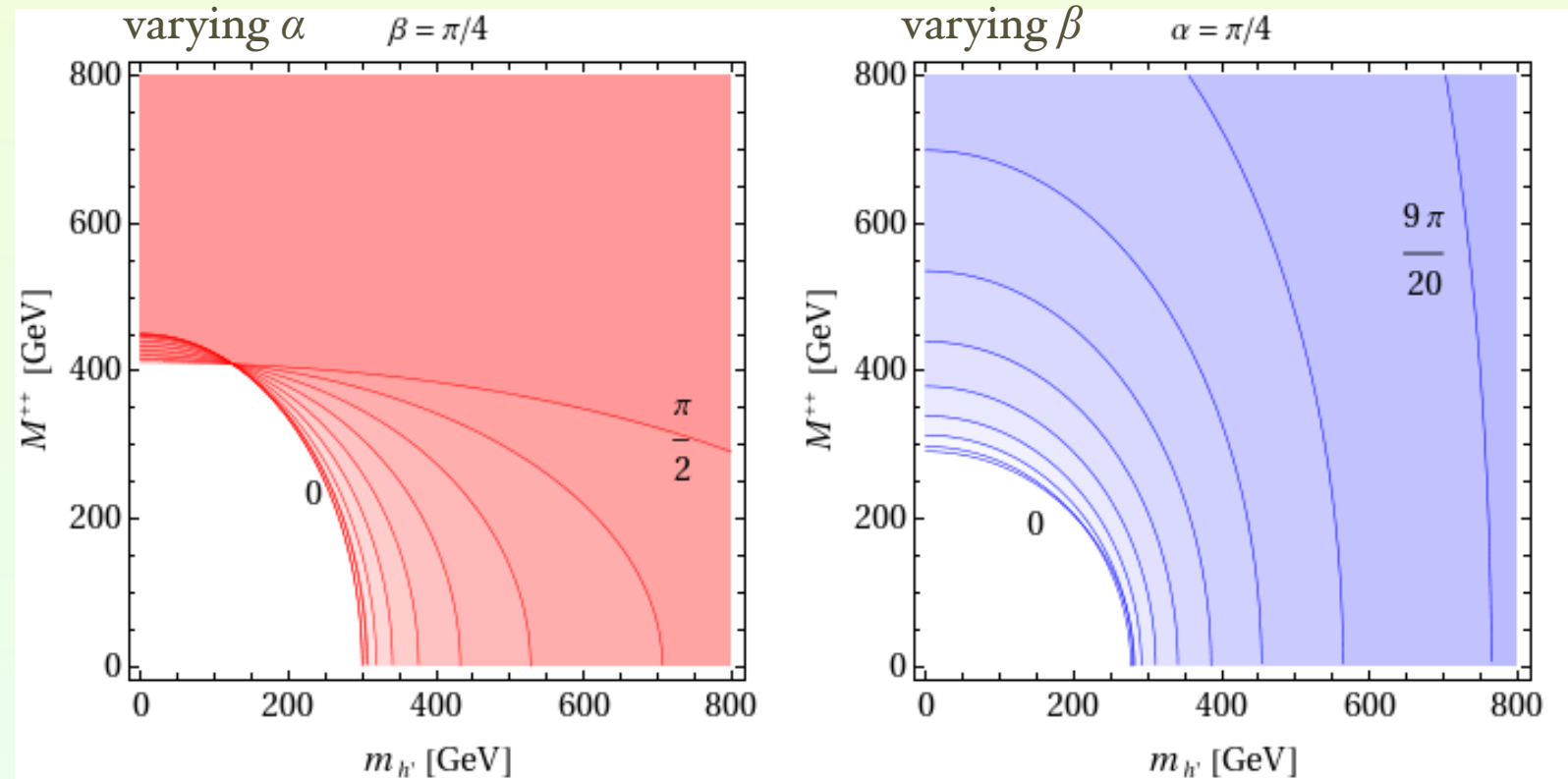


compare: indep de modelo



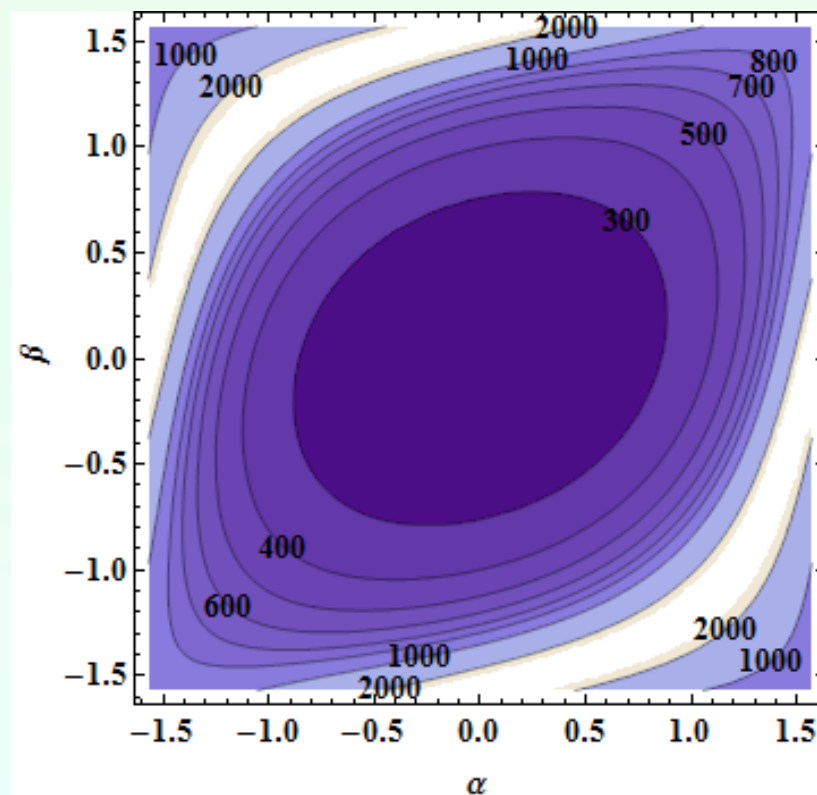
★ best fit value

Unitarity bounds: Higgs⁺⁺ mass *vs* mass of 2nd neutral Higgs



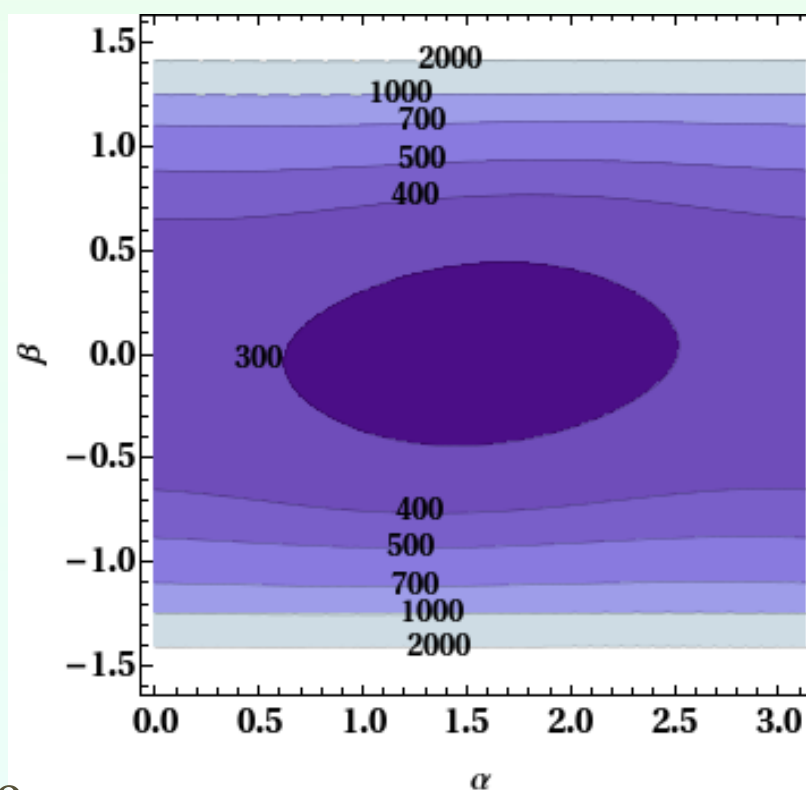
Unitarity bounds: contours of the higgs mass bound in the α vs β plane

h' mass
using
 $M^{++} = 0$

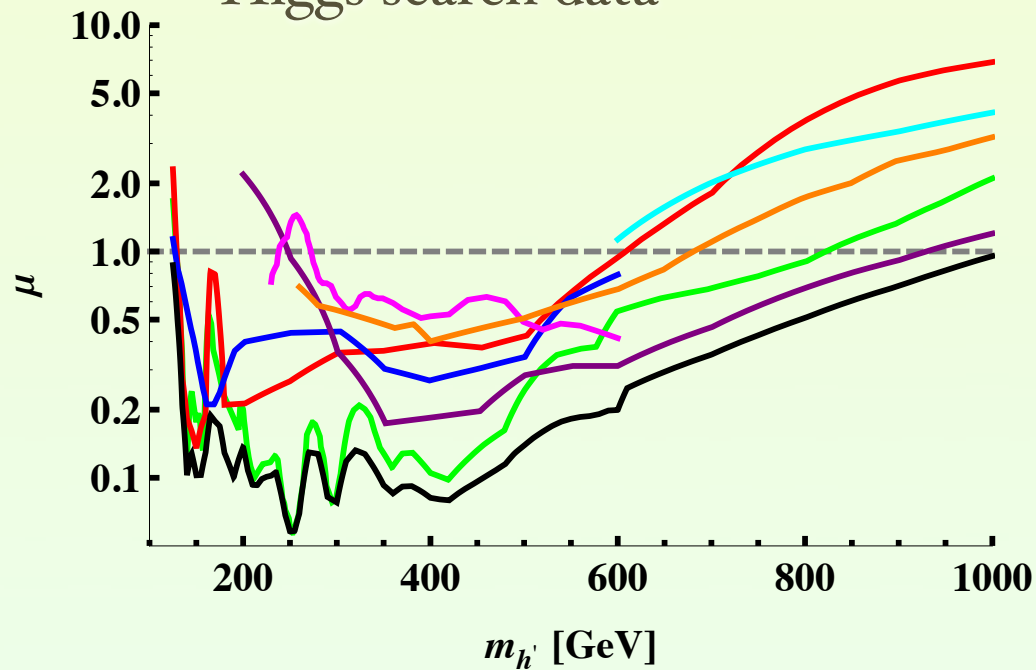


39

M^{++}
using
 $m_{h'} = 0$



Higgs search data

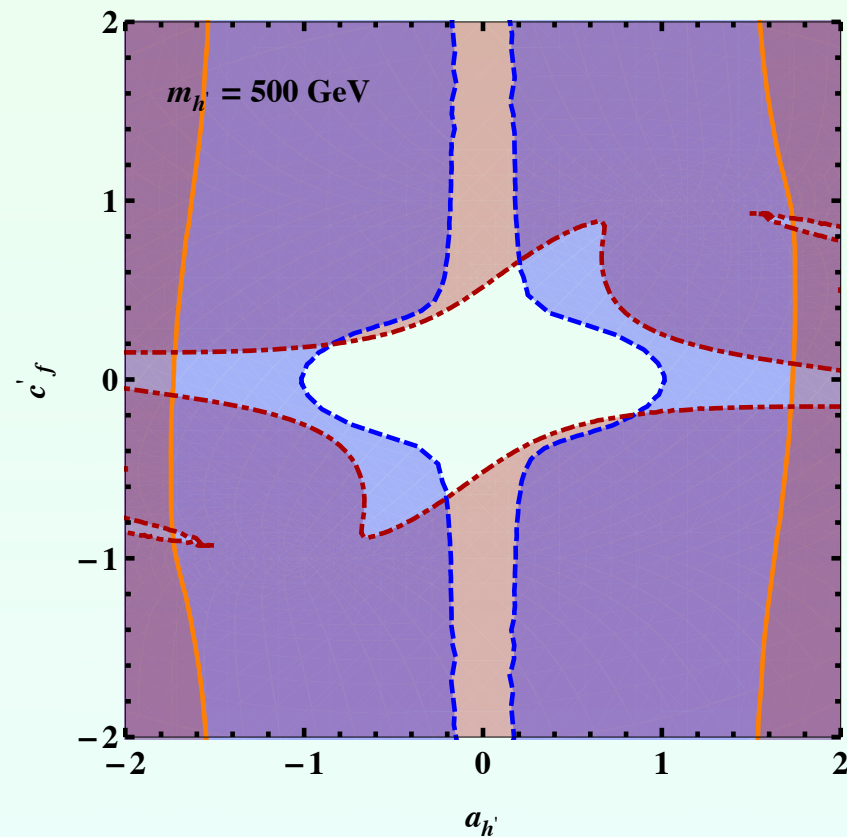


Collaboration	Channel	$\sqrt{s}$ [TeV]	$\mathcal{L}$ [fb $^{-1}$]	Range $m_{h'}$ probed [GeV]
ATLAS [3]	$h' \rightarrow ZZ \rightarrow 4\ell$	8	20.7	110 – 1000
ATLAS [4]	$h' \rightarrow WW \rightarrow 2(\ell\nu)$	8	20.7	260 – 1000
CMS [5]	$h' \rightarrow ZZ \rightarrow 2\ell 2q$	7 + 8	5.3 + 19.6	230 – 600
CMS [6]	$h' \rightarrow ZZ \rightarrow 4\ell$	7 + 8	5.1 + 19.6	100 – 1000
CMS [7]	$h' \rightarrow WW \rightarrow 2(\ell\nu)$	7 + 8	4.9 + 19.5	100 – 600
CMS [8]	$h' \rightarrow WW \rightarrow \ell\nu qq'$	8	19.3	600 – 1000
CMS [9]	$h' \rightarrow ZZ \rightarrow 2\ell 2\nu$	7 + 8	5.0 + 19.6	200 – 1000

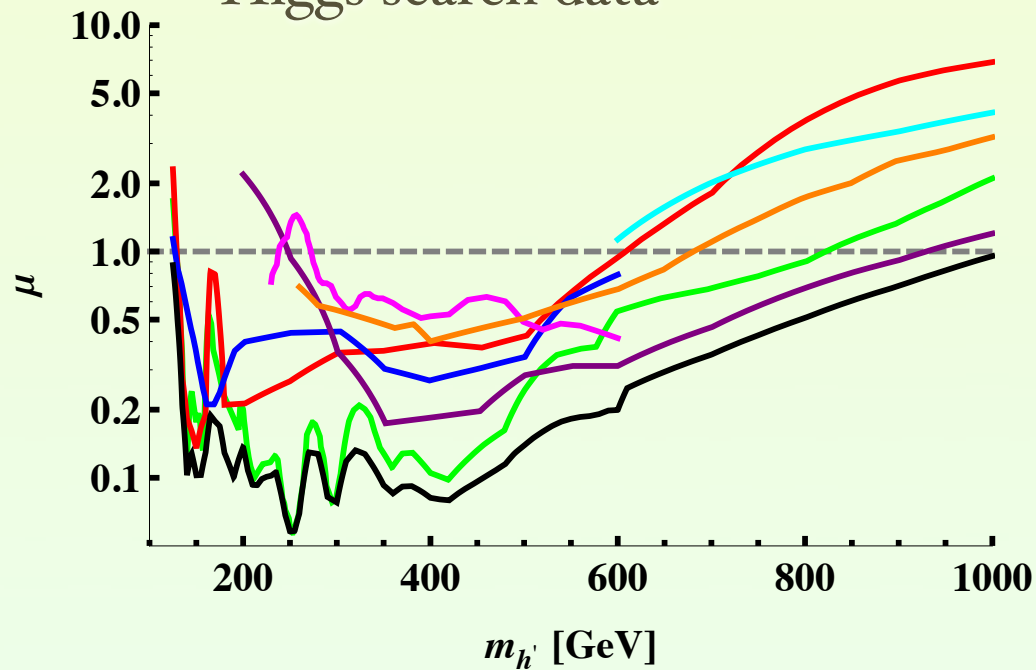
([x] are the references listed in 1401.0070)

in terms of SM cross sections and Br's:

$$\mu(h' \rightarrow WW + ZZ) = \frac{c_f'^2 \sigma_{ggF+t\bar{t}h'} + a_{h'}^2 \sigma_{VBF+Vh'}}{\sigma_{ggF+t\bar{t}h'} + \sigma_{VBF+Vh'}} \frac{a_{h'}^2}{c_f'^2 Br_{f\bar{f}} + a_{h'}^2 Br_{VV} + c_f'^2 Br_{gg}},$$



Higgs search data

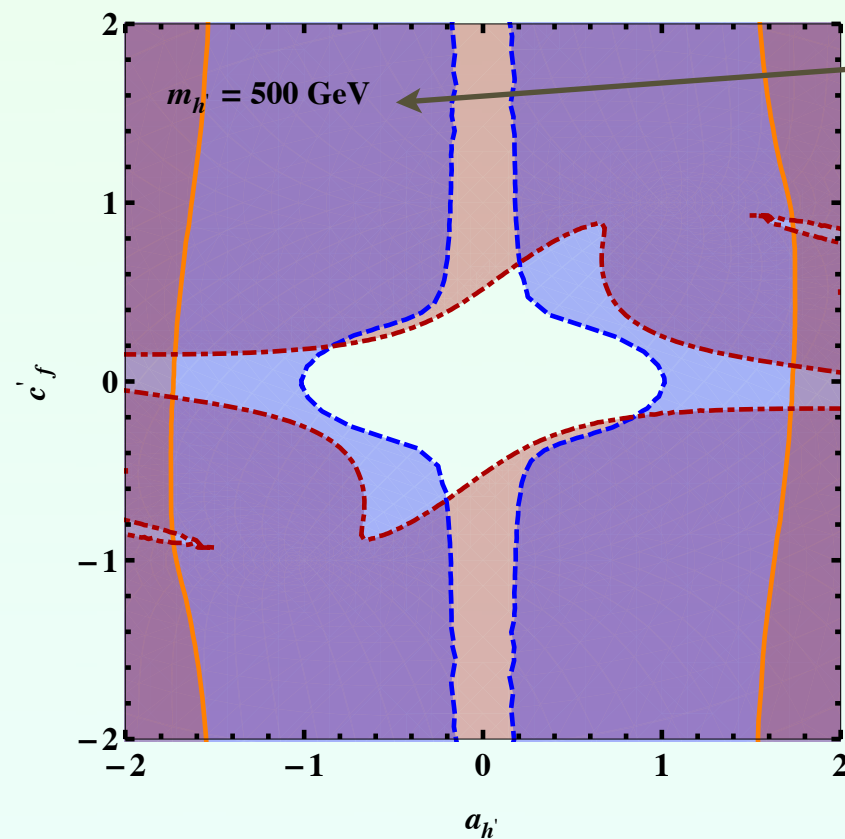


Collaboration	Channel	$\sqrt{s}$ [TeV]	$\mathcal{L}$ [fb $^{-1}$]	Range $m_{h'}$ probed [GeV]
ATLAS [3]	$h' \rightarrow ZZ \rightarrow 4\ell$	8	20.7	110 – 1000
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([x] are the references listed in 1401.0070)

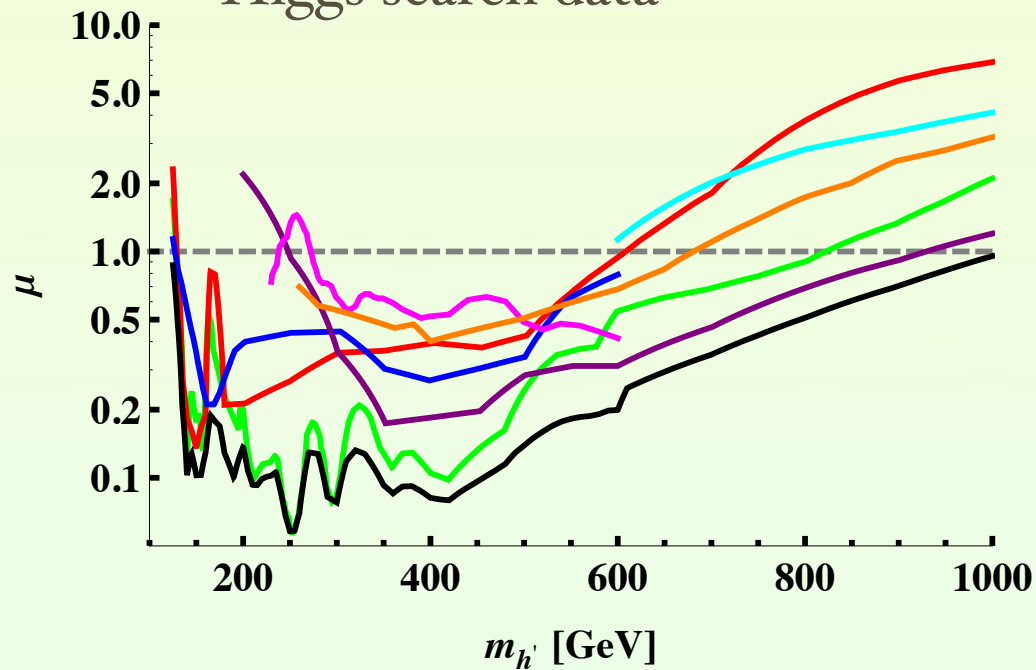
in terms of SM cross sections and Br's:

$$\mu(h' \rightarrow WW + ZZ) = \frac{c_f'^2 \sigma_{ggF+t\bar{t}h'} + a_{h'}^2 \sigma_{VBF+Vh'}}{\sigma_{ggF+t\bar{t}h'} + \sigma_{VBF+Vh'}} \frac{a_{h'}^2}{c_f'^2 Br_{f\bar{f}} + a_{h'}^2 Br_{VV} + c_f'^2 Br_{gg}},$$



1. Choose a mass for this study

Higgs search data

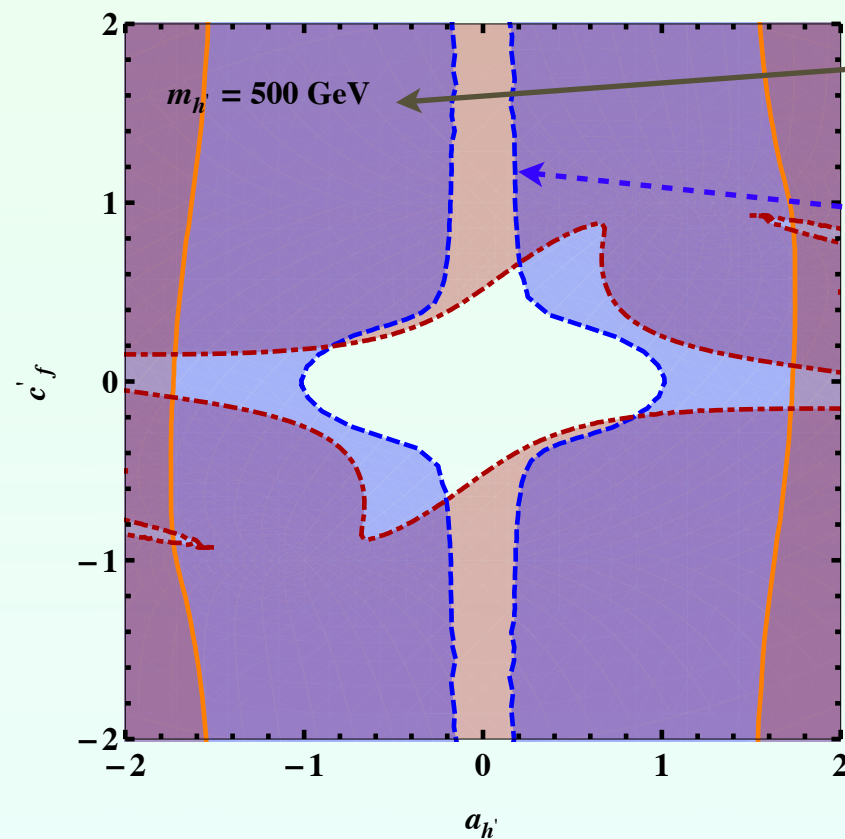


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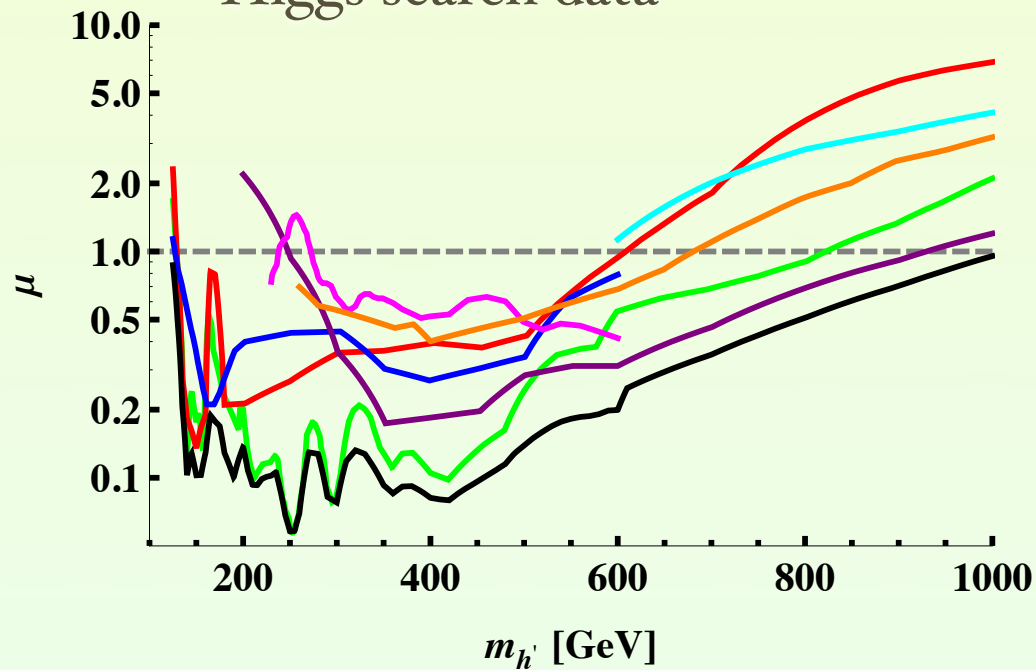
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1. Choose a mass for this study

2. Direct search bound (this page)

Higgs search data

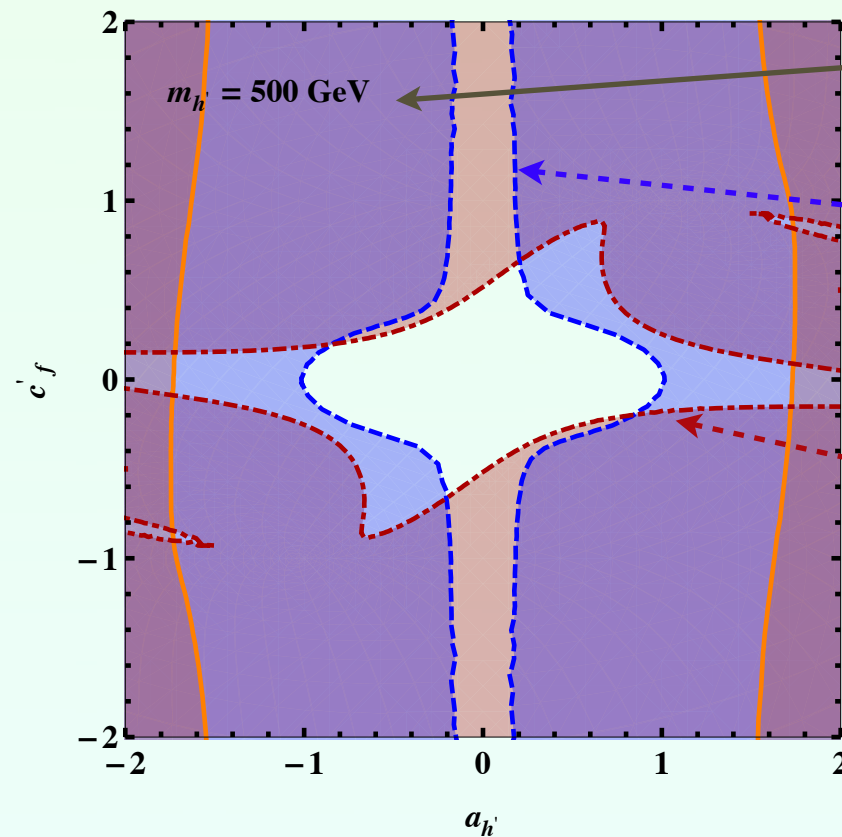


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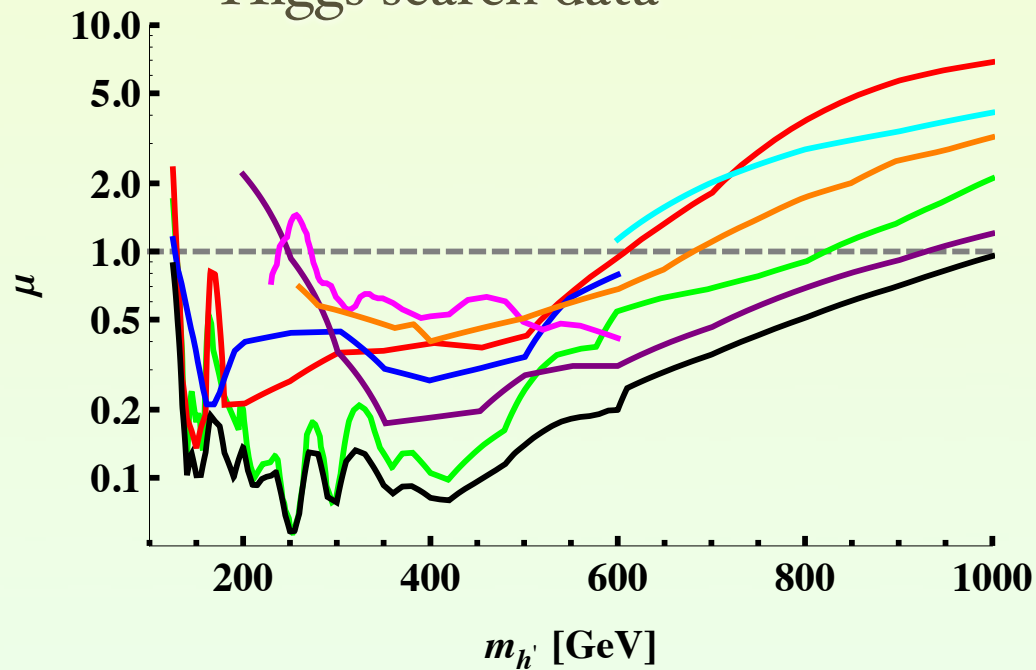


1. Choose a mass for this study

2. Direct search bound (this page)

3. Fit to 125 GeV resonance (previous pages)

Higgs search data

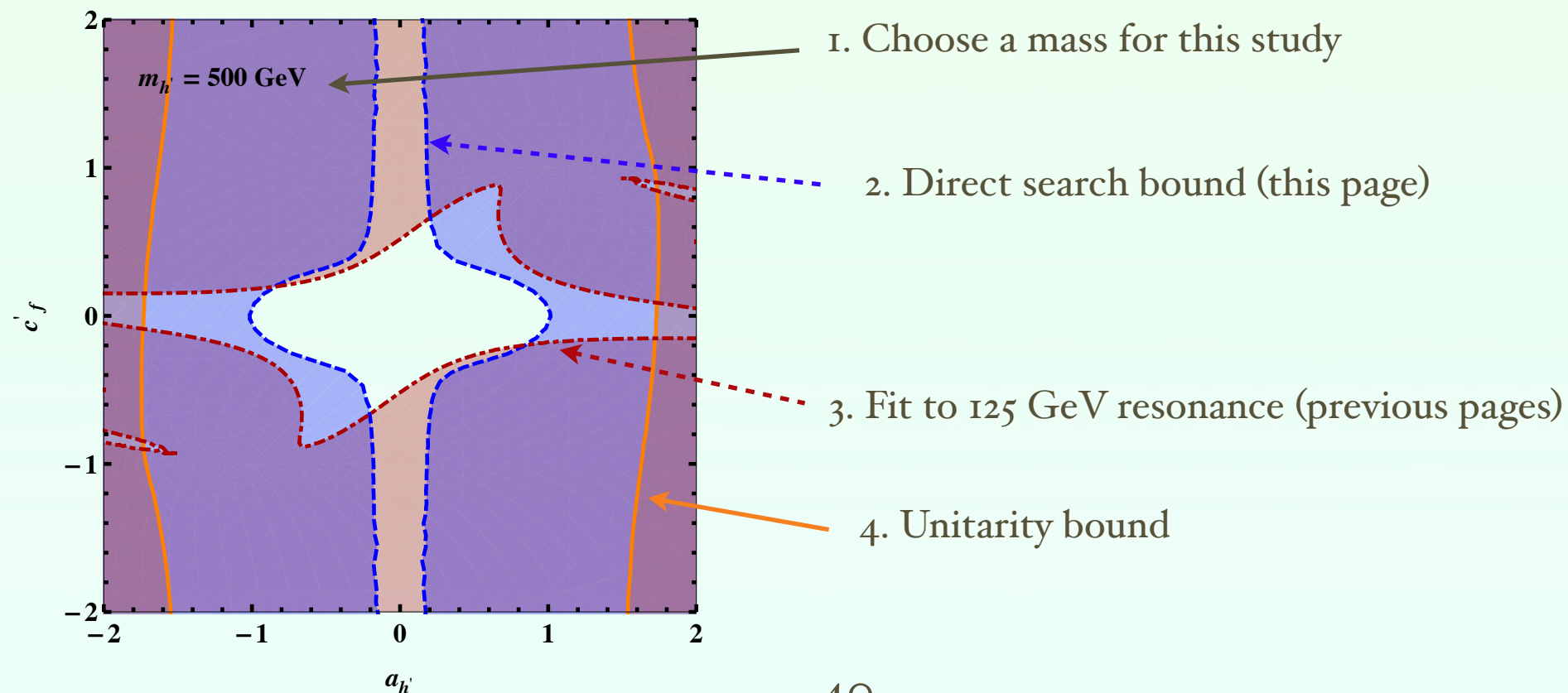


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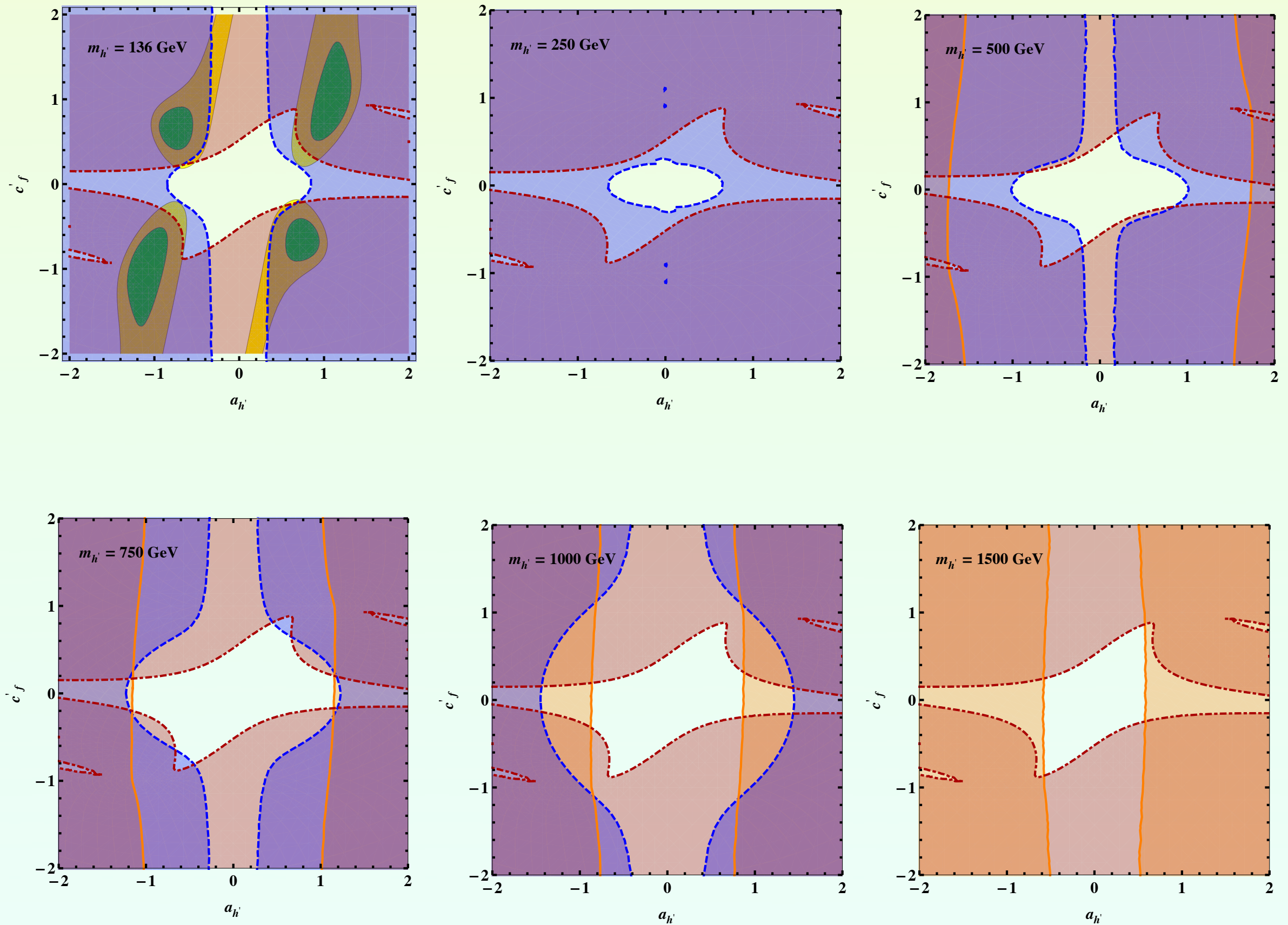
([x] are the references listed in 1401.0070)

in terms of SM cross sections and Br's:

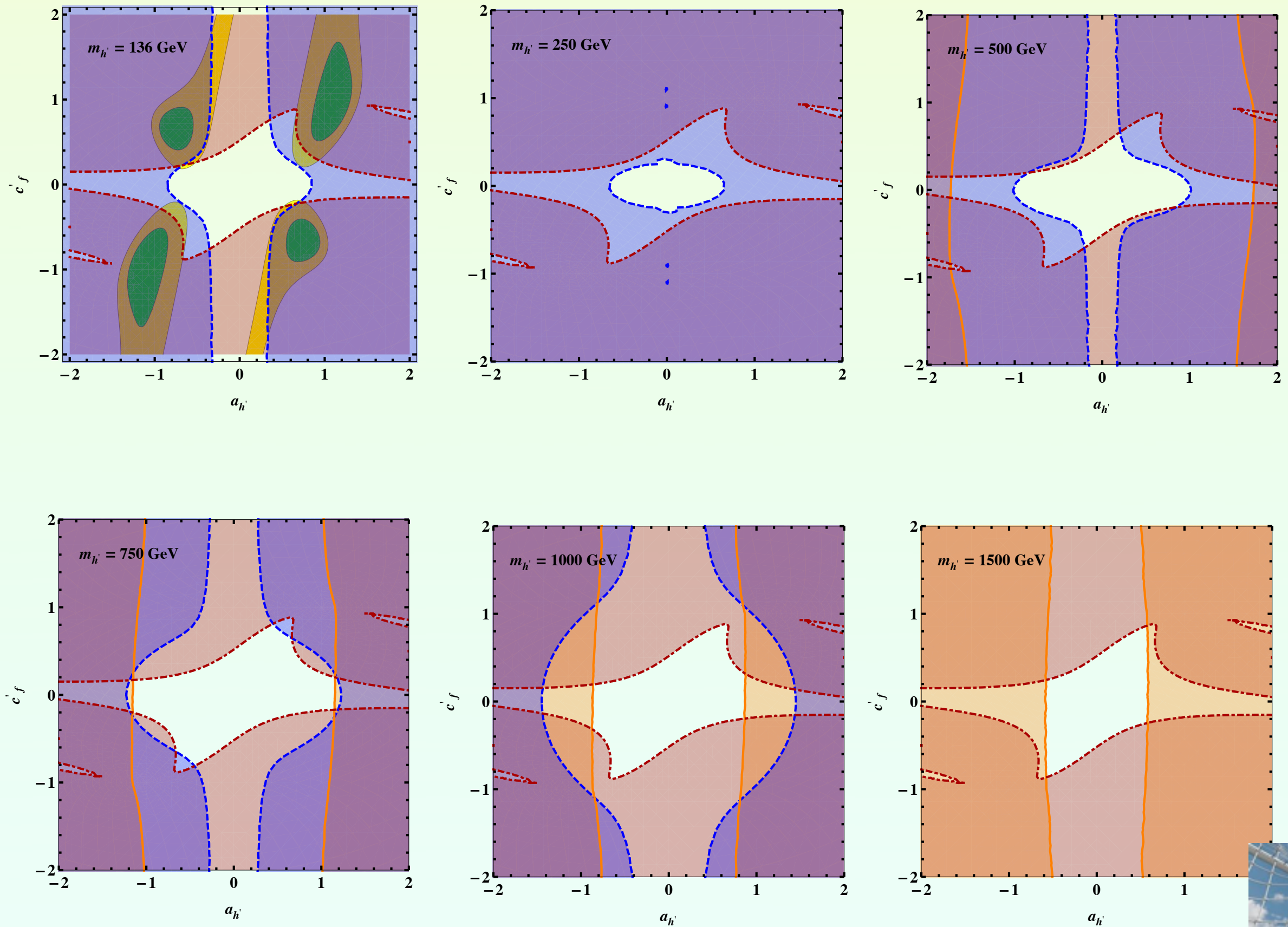
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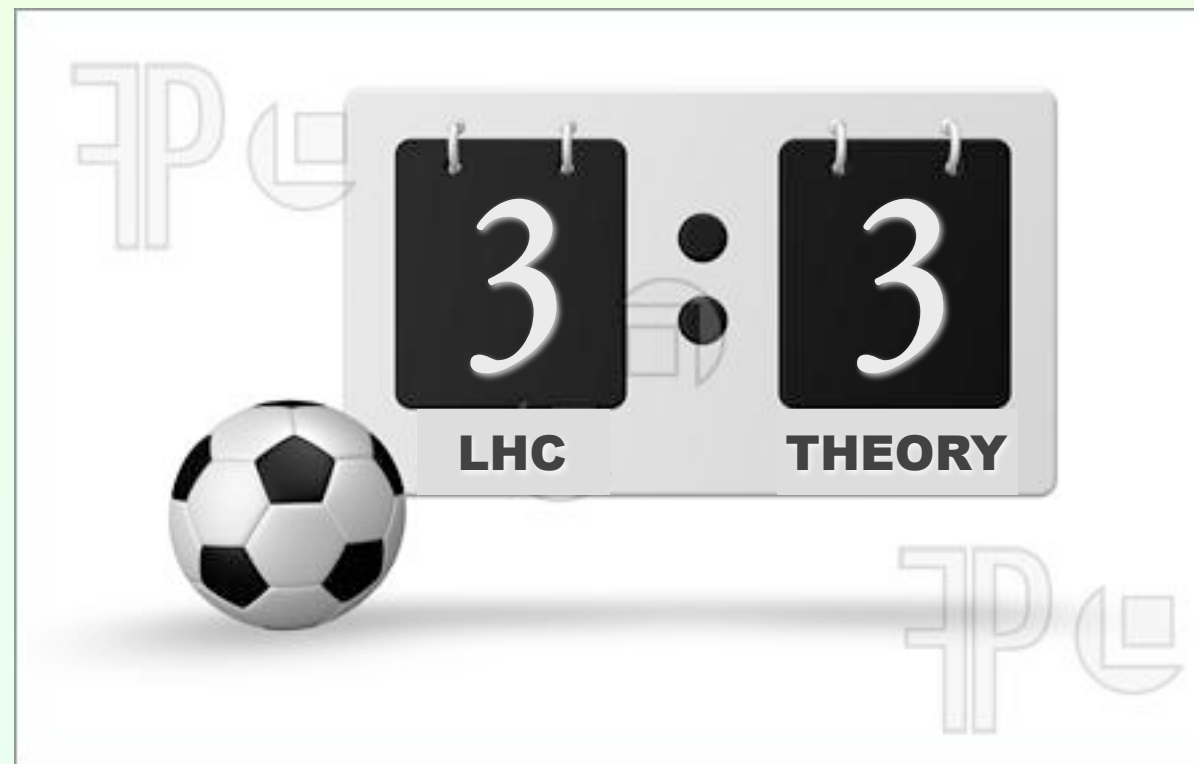
Compare mass bounds: LHC vs unitarity tournament



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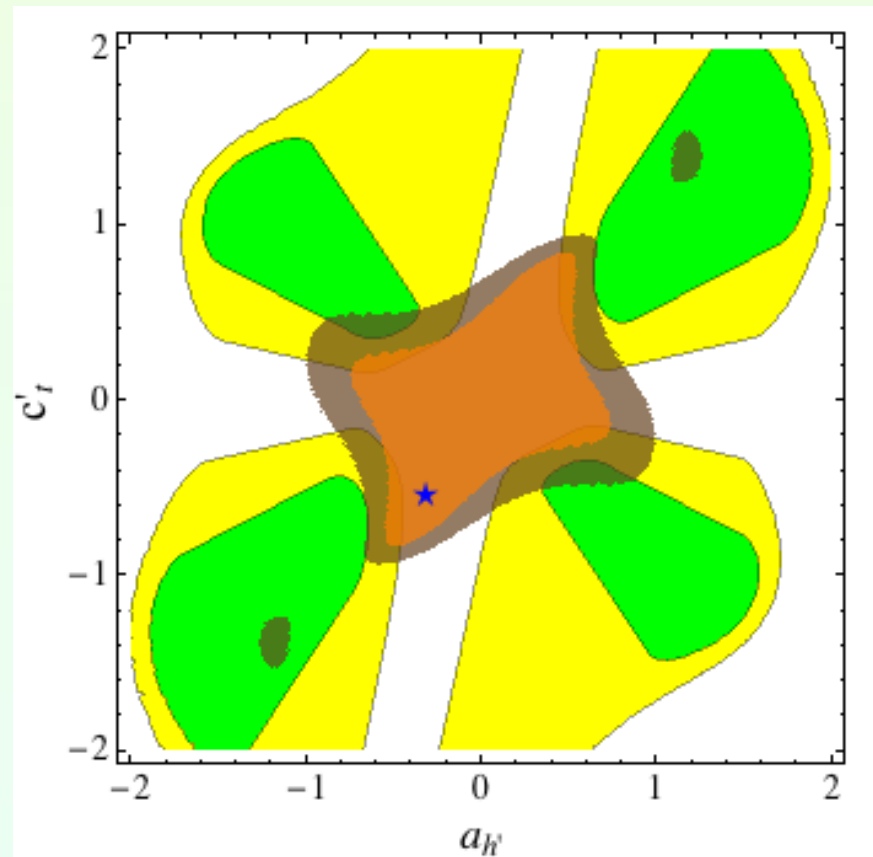


score

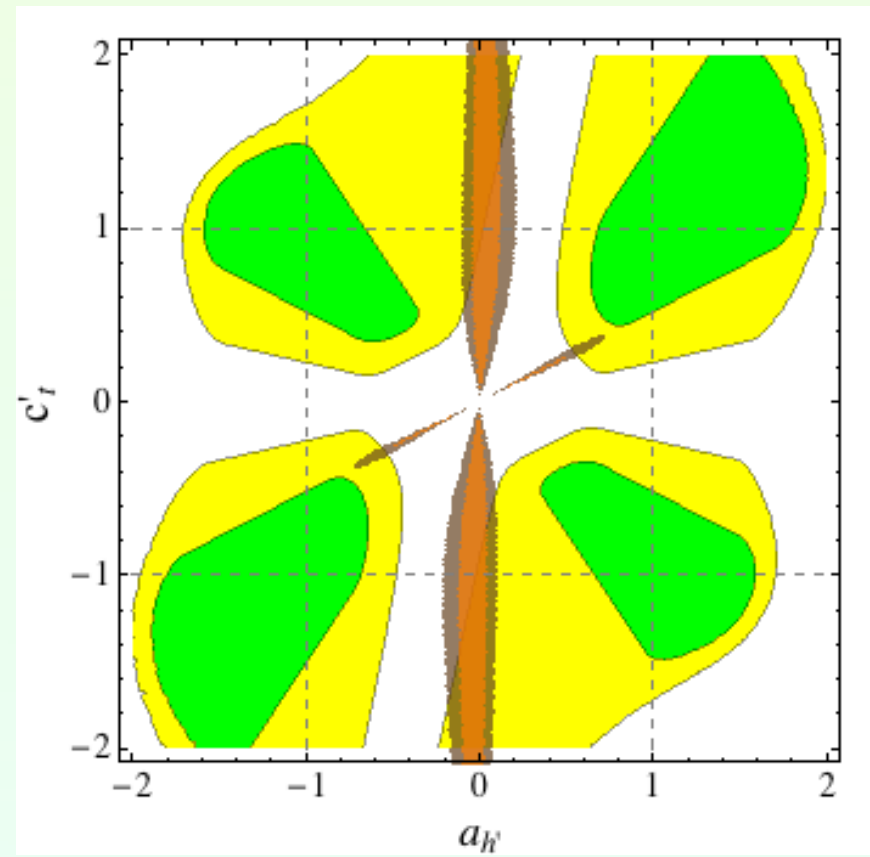


Other models, briefly

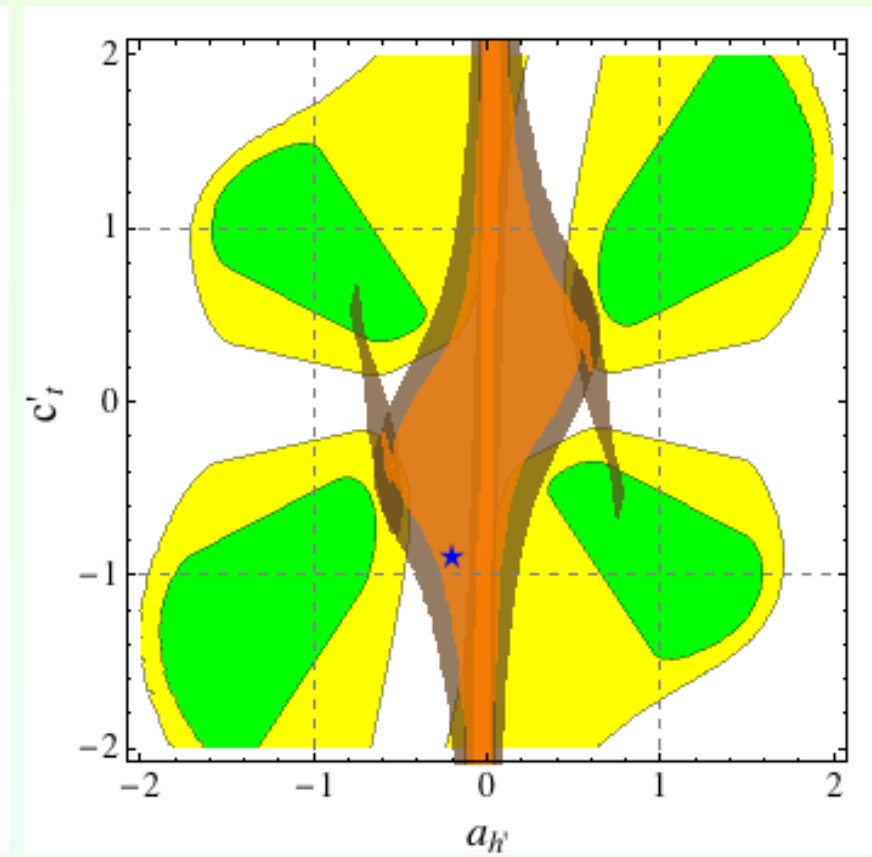
Georgi-Machacek



2HDM-II

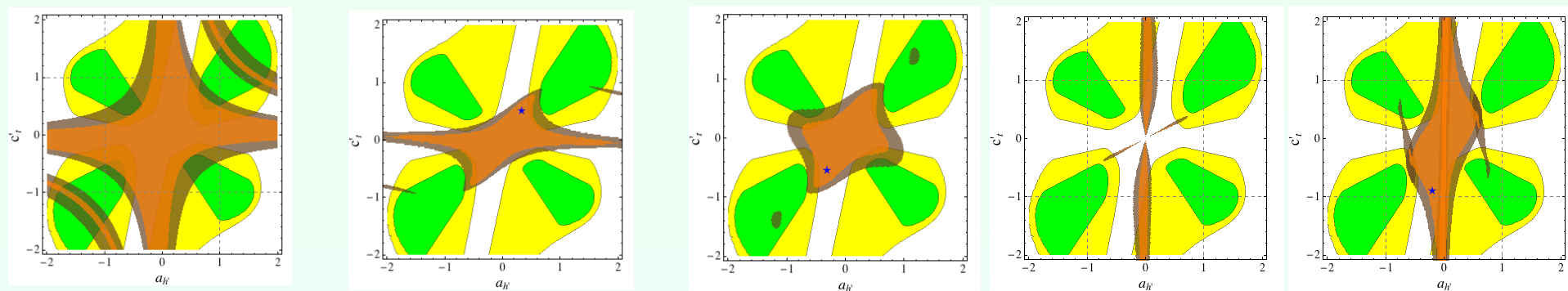


2HDM-III



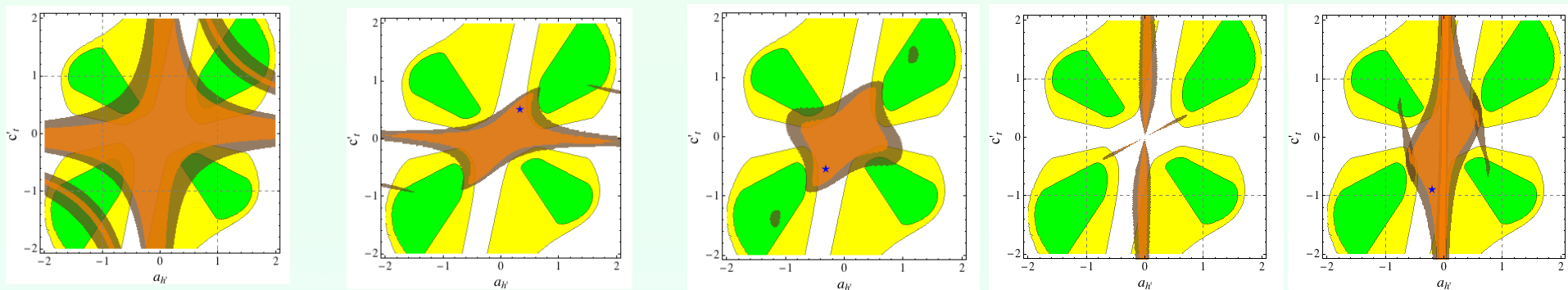
custodial “symmetry” in GM model::
C.-W. Chiang and K. Yagyu, JHEP 1301 (2013) 026, arXiv:1211.2658 [hep-ph].

Conclusions/Summary



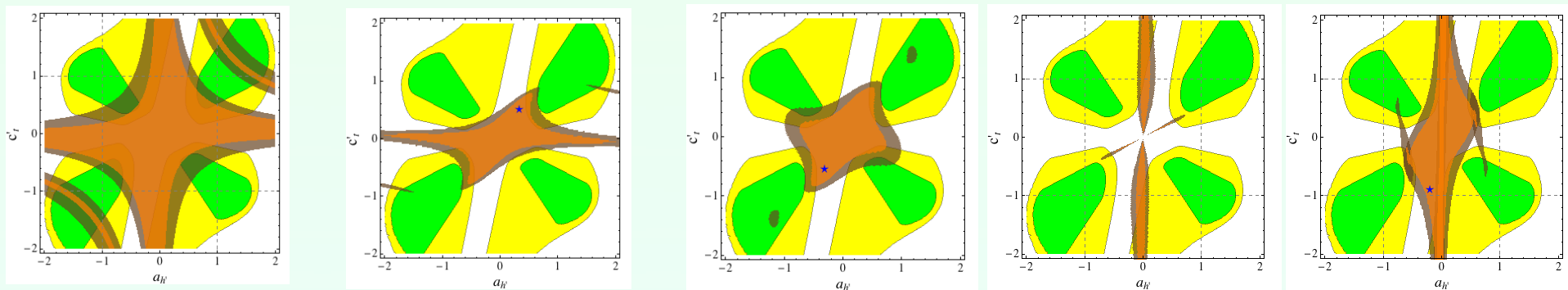
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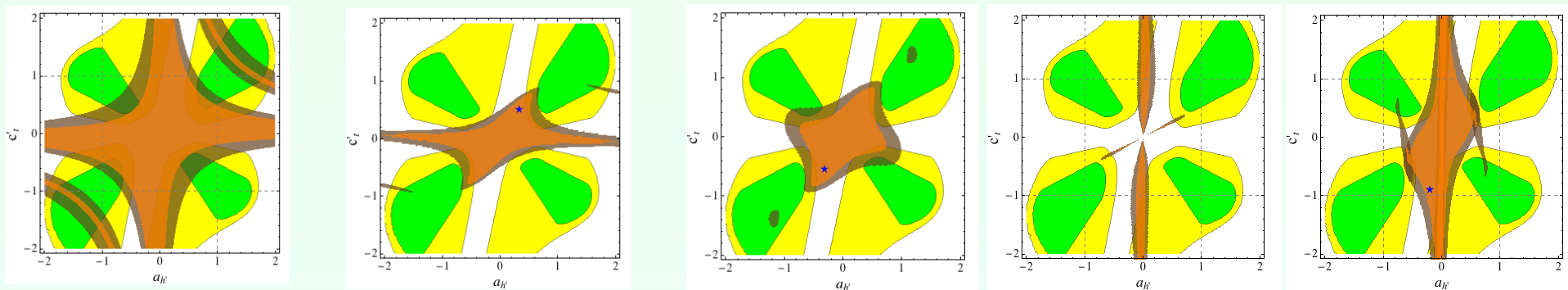
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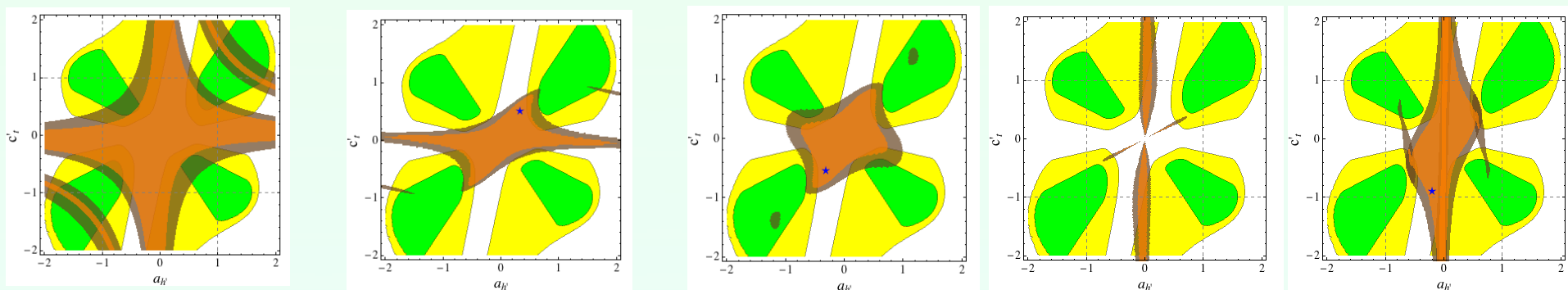
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- Unitarity bounds: complimentary to high energy collider data
- Unitarity bounds (but not sum-rules) contain new useful information for specific models.

