Effect of New Physics on the Scalar Boson Properties

Benjamin Grinstein
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This talk is too long

I will skip some slides

I will just touch on others

Effect of New Physics on the Scalar Boson Properties:

or

How do we learn something about NP by measuring higgs properties

I will concentrate on:

- Modified interactions:
  - Production
  - Visible decays
- More than one scalar (of a special kind, “higgses”)

Nothing on invisible and total width (Passarino, next talk)

But what do we mean by a “higgs,”
let alone many “higgses?”

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But what do we mean by a "higgs,"
let alone many "higgses?"

Not this

What's a model independent "higgs particle?"

O(2) symmetry

Broken symmetry

Essence of higgs: hVV interaction
Except for V itself, no other field has this.

It arises from SSB: shifting $H \to H + \begin{pmatrix} 0 \\ v \end{pmatrix}$

in $(D_\mu H)^\dagger D^\mu H$

gives terms like $vhV^\mu V_\mu$

Approaches to NP analysis:

- New light particles (Total/invisible width? next talk)
- All NP states (well) above M_h

↓

Pure Pheno: modify couplings among particles, *e.g.*,

$$\mathcal{L} \sim -\frac{2m_W^2}{v} h W^\mu W_\mu \to -a\frac{2m_W^2}{v} h W^\mu W_\mu$$

↓ (more correlations, less free parameters; more sensible)

EFT:

- linearly realized EW symmetry → weakly coupled UV completion
- non-linear realization → strongly coupled UV completion

↓ (more correlations, less free parameters; more sensible ... sometimes)

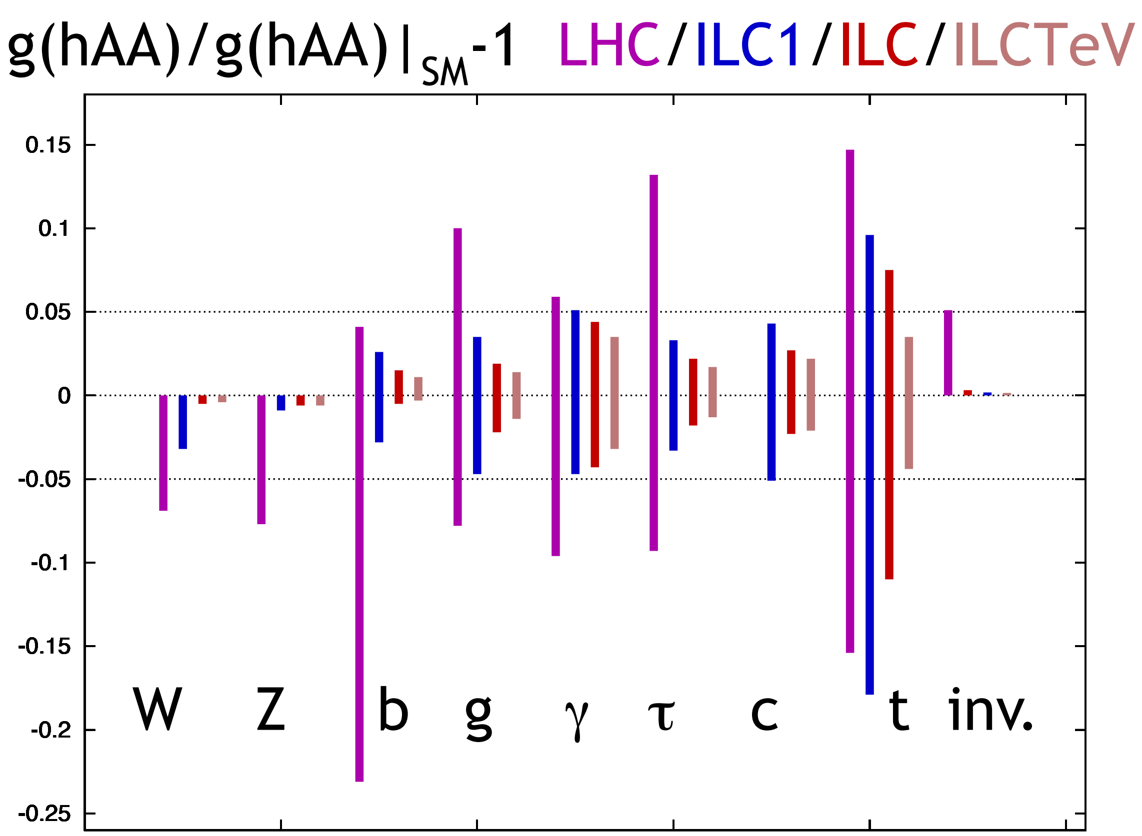
Explicit models, *e.g.*,
2HDM, pMSSM, NMSSM, ??MSSM, WTC, LLH, UED

Pure Pheno: modify couplings among particles

Convenient
Fairly general
Not Unitary ☛ will fix this later and get interesting results WAIT!
(for VVV see Shih-Chieh Hsu's talk)
Significant overlap with EFT analysis

Postpone this (for discussion of unitarity) except for:

How well can we do?



Peskin, arXiv:1207.2516

Figure 2: Comparison of the capabilities of LHC and ILC for model-independent measurements of Higgs boson couplings. The plot shows (from left to right in each set of error bars) 1 σ confidence intervals for LHC at 14 TeV with 300 fb^{-1}, for ILC at 250 GeV and 250 fb^{-1} ('ILC1'), for the full ILC program up to 500 GeV with 500 fb^{-1} ('ILC'), and for a program with 1000 fb^{-1} for an upgraded ILC at 1 TeV ('ILCTeV'). More details of the presentation are given in the caption of Fig. 1. The marked horizontal band represents a 5% deviation from the Standard Model prediction for the coupling.

BG & M. Trott, PRD76 (2007) 073002 (0704.1505)
G.F. Giudice et al, JHEP 0706 (2007) 045 (0703164)

Linear *vs* non-linear realization

Linear:

field content = SM

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\sum \mathcal{O}^{\text{dim5}} + \frac{1}{\Lambda^2}\sum \mathcal{O}^{\text{dim6}} + \cdots$$

Example: any weakly coupled theory that
(i) Contains the SM
(ii) NP decouples (masses not from EWSB)

Non-linear realization

field content = (SM − neutral CP even higgs) + neutral CP even higgs

Would-be-GBs: non-linear realization of $SU(2)_L \times U(1)_Y$
(Just like a chiral lagrangian for pions)

2×2 matrix, $\Sigma^\dagger \Sigma = 1; \qquad \Sigma \to U_L \Sigma U_R$

Add back *h* as singlet

Example: WTC with dilaton as higgs impostor

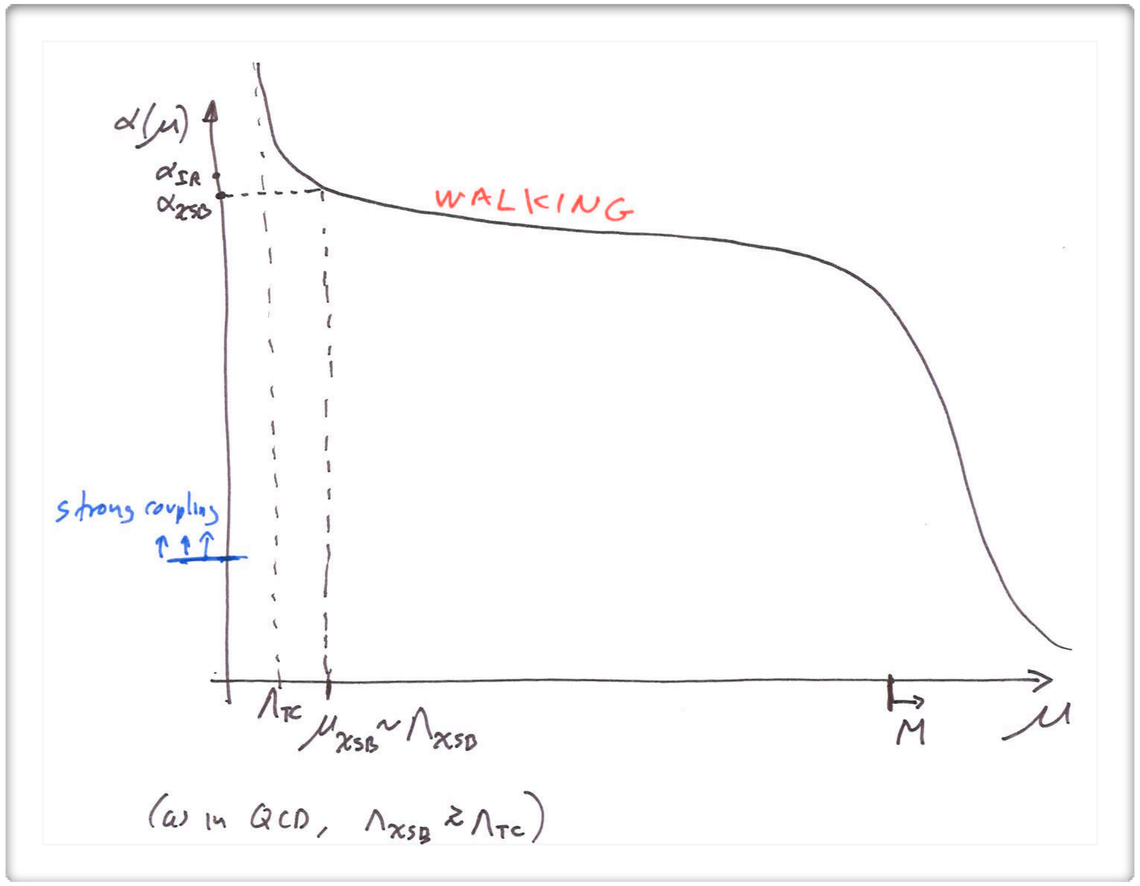
Mexican Sombrero vs Mexican Zarape

SM:

- For $M_h = 0$ the SM is scale invariant (Zarape potential)
- $\langle H \rangle = v$ breaks scale invariance spontaneously (in addition to EW symmetry)
- The GB of broken scale invariance is the "dilaton"
- The "charge" that the dilaton couples to is mass
- Just like the higgs particle!
- No surprise, because in this case IT IS the higgs

An example: WTC and a hoped for higgs impostor

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

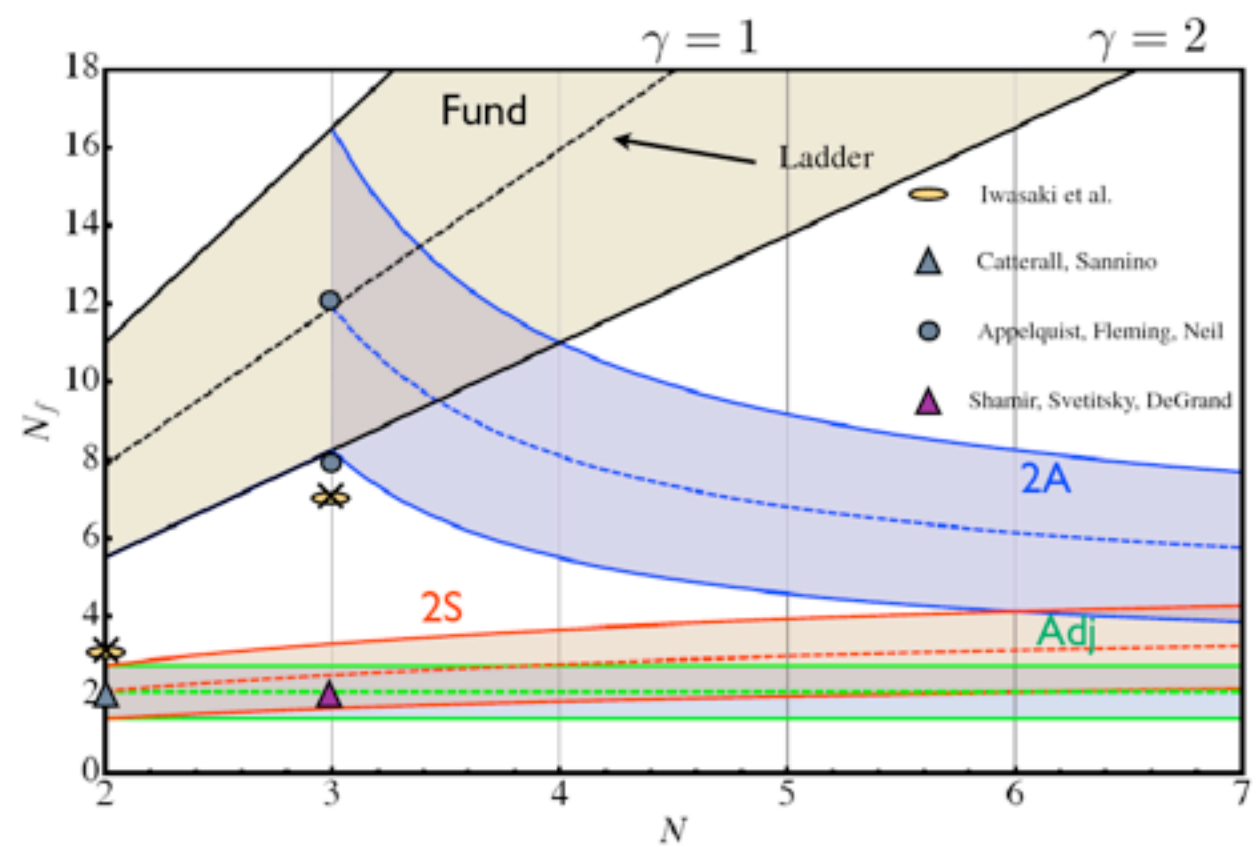


- Walking is approximate scale invariance
- Spontaneous fermion condensation by new strong interaction (TC)
- EW-symmetry broken: W/Z masses
- approx scale symmetry broken: light?? dilaton

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

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....



Conformal window caricature

Why care?

- Linear realization is more constrained
- Deviations from linear-realization correlations, smoke signals from strong-EWSB

Simple example:

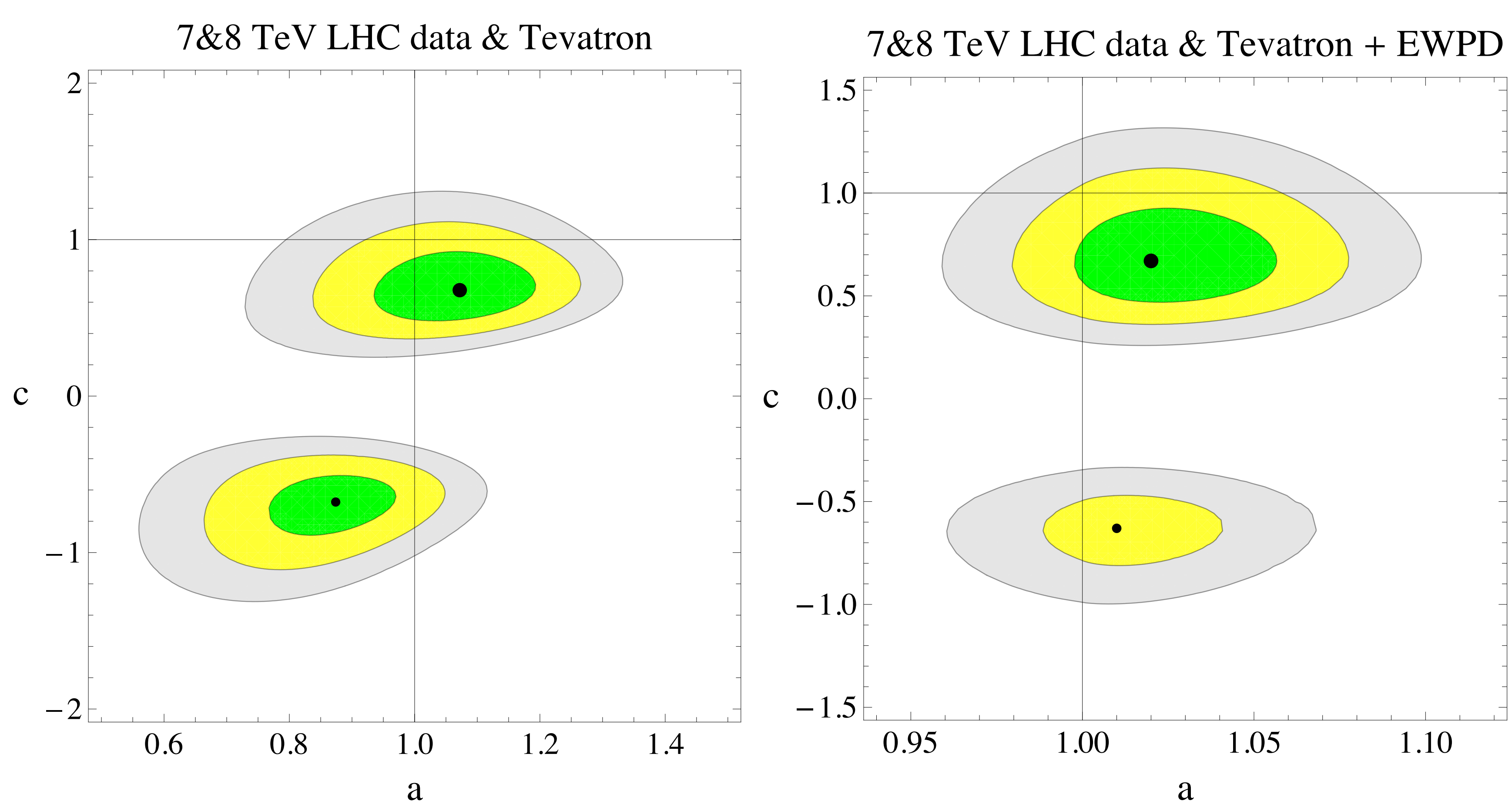
$$\mathcal{L} = \frac{1}{2}\left[1 + c_1^{eff}\frac{h}{v} + c_2^{eff}\frac{h^2}{v^2}\right]\partial^\mu h\,\partial_\mu h - \frac{1}{2}m_h^2 h^2 - \frac{v\,\lambda_3^{eff}}{3\,!}h^3 - \frac{\lambda_4^{eff}}{4\,!}h^4 + \cdots$$

Linear realization gives: $c_1^{eff} = 2c_2^{eff} \lesssim \frac{v^2}{\Lambda^2}$

Many fits done:

- Choose linear vs non-linear
- Choose a basis of operators
- Compute amplitudes (including SM) in terms of coefficients of operators
- Fit to LHC higgs data (typically chi-2, sometimes pdf); choose marginalizations

$$\mathcal{L}_{eff} = \frac{1}{2}(\partial_\mu h)^2 - V(h) + \frac{v^2}{4}\mathrm{Tr}(D_\mu\Sigma^\dagger D^\mu\Sigma)\left[1 + 2\,a\,\frac{h}{v} + b\,\frac{h^2}{v^2} + b_3\,\frac{h^3}{v^3} + \cdots\right]$$
$$-\frac{v}{\sqrt{2}}\,(\bar{u}_L^i \bar{d}_L^i)\,\Sigma\,\left[1 + c_j\,\frac{h}{v} + c_2\,\frac{h^2}{v^2} + \cdots\right]\begin{pmatrix} y_{ij}^u\,u_R^j \\ y_{ij}^d\,d_R^j \end{pmatrix} + h.c. \cdots\,,$$



Espinosa et al 1207.1717

And many more:

Espinosa et al, 1205.6790
Espinosa et al, 1207.1717 (previous slide)
Corbett et al, 1207.1344 (next slide)
...
BG et al, 1305.6938 →
Artoisenet et al, 1306.6464
Banerjee et al, 1308.4860
Boos et al, 1309.5410
Dawson et al, 1310.8361
Brivio et al, 1311.1823
C. Englert et al, 1403.7191
Ellis et al, 1404.3667
Alloul et al, 1405.1617
Brivio et al, 1405.5412
...

a_{WB}	a_h	a^s_{hl}	a^t_{hl}	a^s_{hq}	a^t_{hq}	a_{hu}	a_{hd}	a_{he}	a_W
4.6 ± 7.5	$0.0 \pm 26.$	2.8 ± 6.7	$0.9 \pm 21.$	-0.9 ± 2.2	$0.9 \pm 21.$	-3.6 ± 8.9	1.7 ± 4.4	$5.6 \pm 13.$	$-3.9 \pm 32.$

$$\Delta\mathcal{L}_{\rm eff} = \sum_i a_i O_i,$$

$$O_{WB} = H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}, \quad O_h = |H^\dagger D_\mu H|^2,$$

$$O^s_{hl} = H^\dagger i D_\mu H \bar{l} \gamma^\mu l + \text{h.c.}, \quad O^t_{hl} = H^\dagger \sigma^a i D_\mu H \bar{l} \sigma^a \gamma^\mu l + \text{h.c.},$$

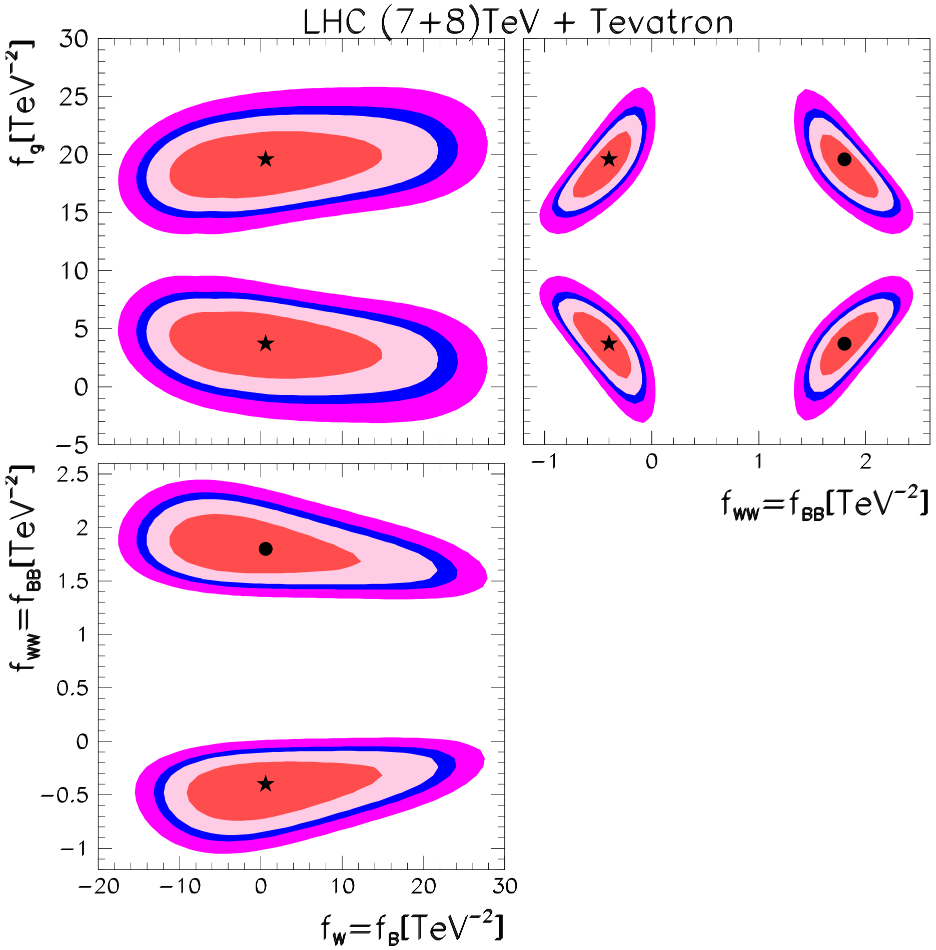
$$O^s_{hq} = H^\dagger i D_\mu H \bar{q} \gamma^\mu q + \text{h.c.}, \quad O^t_{hq} = H^\dagger \sigma^a i D_\mu H \bar{q} \sigma^a \gamma^\mu q + \text{h.c.},$$

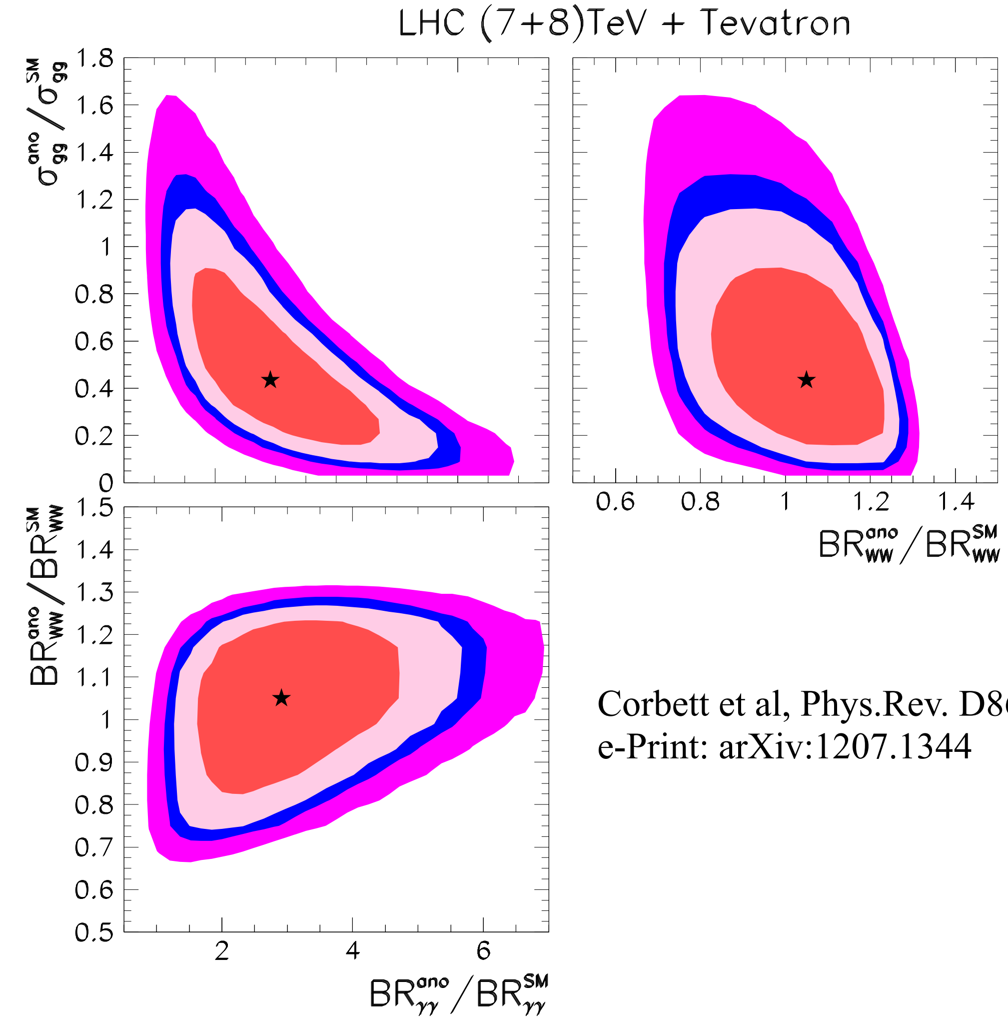
$$O_{hu} = H^\dagger i D_\mu H \bar{u} \gamma^\mu u + \text{h.c.}, \quad O_{hd} = H^\dagger i D_\mu H \bar{d} \gamma^\mu d + \text{h.c.},$$

$$O_{he} = H^\dagger i D_\mu H \bar{e} \gamma^\mu e + \text{h.c.} \quad \text{and} \quad O_W = \epsilon^{abc} W^{a\nu}_\mu W^{b\lambda}_\nu W^{b\mu}_\lambda.$$

Incidentally, *S, T, U*, very poorly bound in global fit

One more example, for good measure.





Corbett et al, Phys.Rev. D86 (2012) 075013
e-Print: arXiv:1207.1344

Linear realization. Correlations (incomplete list):

$$g_{Hgg} = \frac{f_{GG}v}{\Lambda^2} \equiv -\frac{\alpha_s}{8\pi}\frac{f_g v}{\Lambda^2} ,$$

$$g_{H\gamma\gamma} = -\left(\frac{gM_W}{\Lambda^2}\right)\frac{s^2(f_{BB}+f_{WW}-f_{BW})}{2} ,$$

$$g^{(1)}_{HZ\gamma} = \left(\frac{gM_W}{\Lambda^2}\right)\frac{s(f_W-f_B)}{2c} ,$$

$$g^{(2)}_{HZ\gamma} = \left(\frac{gM_W}{\Lambda^2}\right)\frac{s[2s^2 f_{BB}-2c^2 f_{WW}+(c^2-s^2)f_{BW}]}{2c} ,$$

$$g^{(1)}_{HZZ} = \left(\frac{gM_W}{\Lambda^2}\right)\frac{c^2 f_W+s^2 f_B}{2c^2} ,$$

$$g^{(2)}_{HZZ} = -\left(\frac{gM_W}{\Lambda^2}\right)\frac{s^4 f_{BB}+c^4 f_{WW}+c^2 s^2 f_{BW}}{2c^2} ,$$

$$g^{(3)}_{HZZ} = \left(\frac{gM_W v^2}{\Lambda^2}\right)\frac{f_{\Phi,1}-f_{\Phi,2}}{4c^2} ,$$

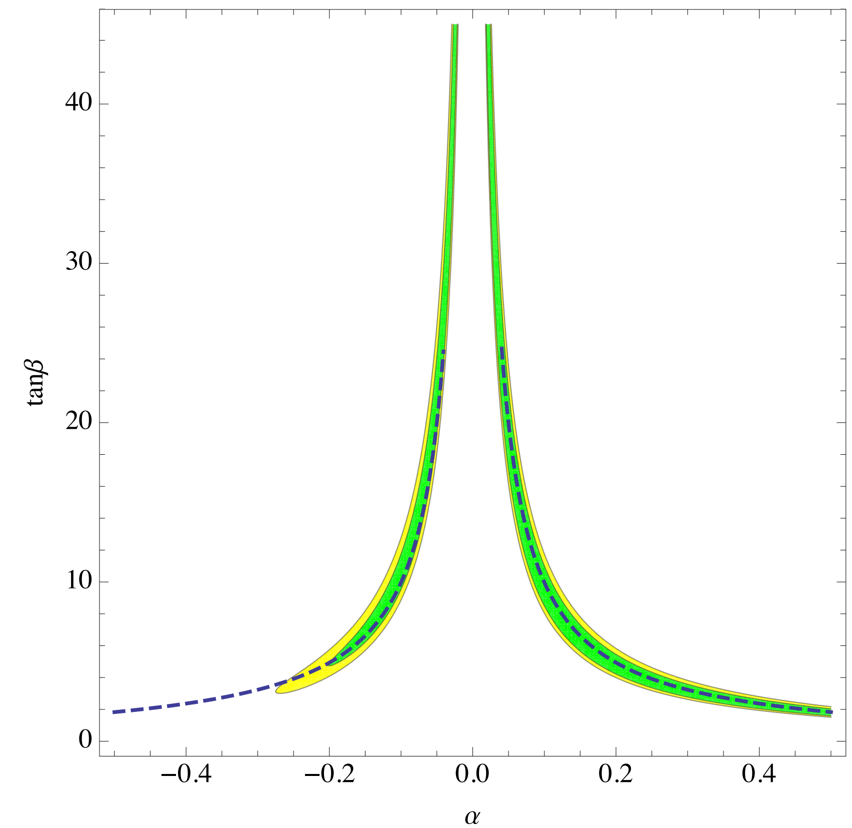
$$g^{(1)}_{HWW} = \left(\frac{gM_W}{\Lambda^2}\right)\frac{f_W}{2} ,$$

$$g^{(2)}_{HWW} = -\left(\frac{gM_W}{\Lambda^2}\right)f_{WW} ,$$

$$g^{(3)}_{HWW} = -\left(\frac{gM_W v^2}{\Lambda^2}\right)\frac{f_{\Phi,1}+2f_{\Phi,2}}{4} ,$$

UV completion: Explicit Models

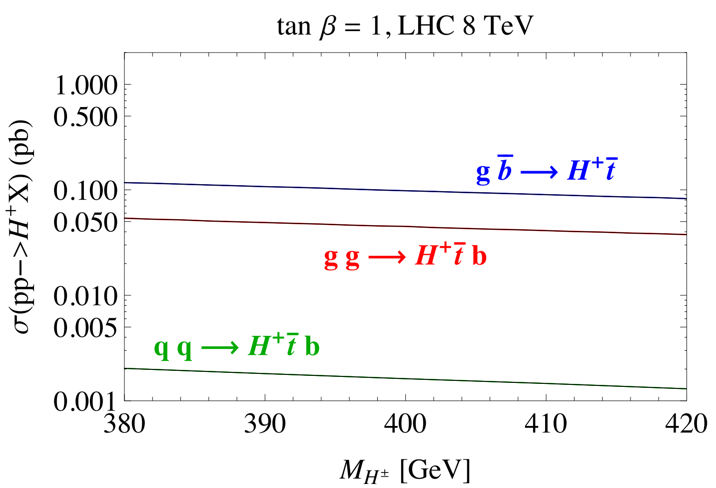
2HDM typeII BG&Uttayarat, 1304.0028

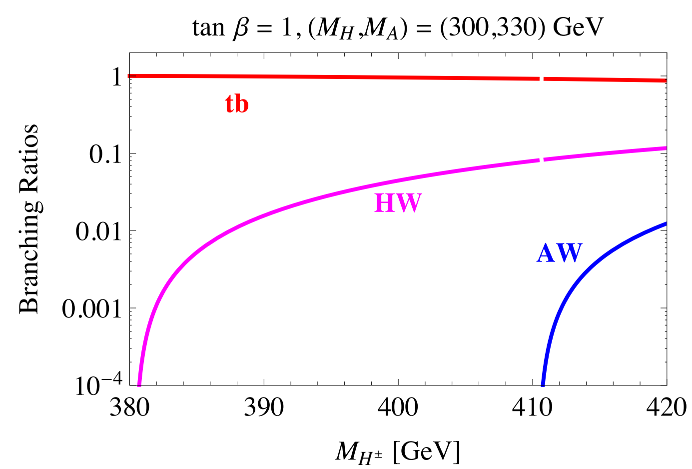


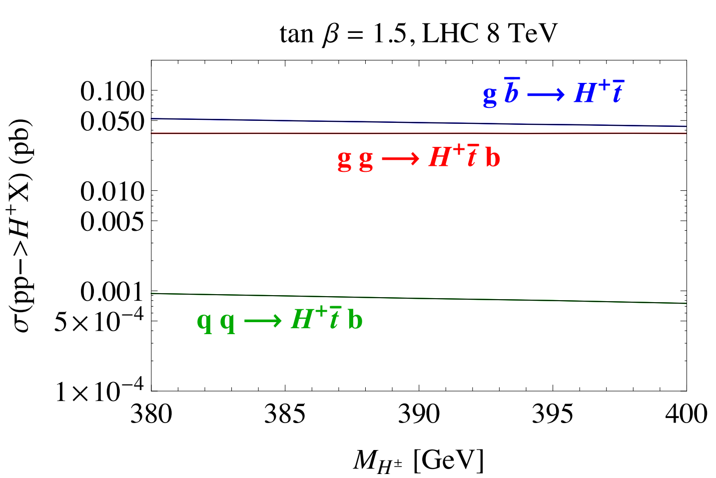
Less free parameters = More correlations

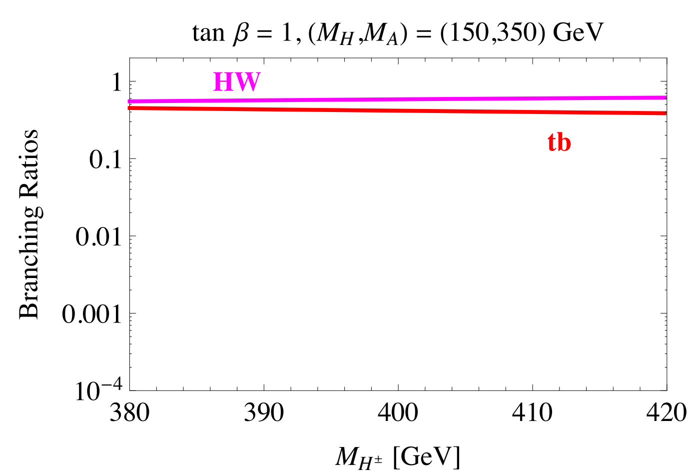
Same strategy:
Compute amplitudes
Global fit

But now
Infer properties of NP





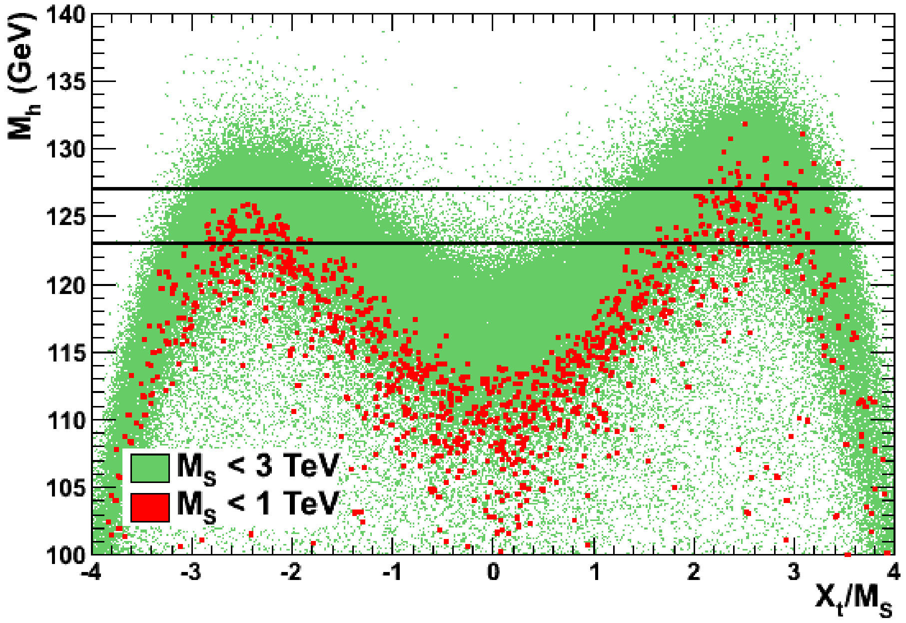


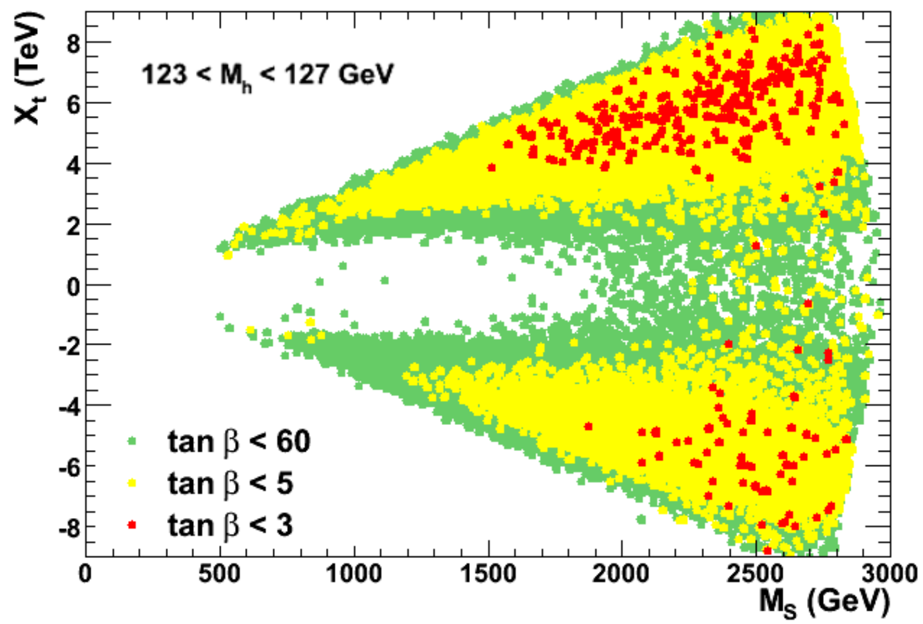


Saturday: BSM session...

MSSM briefly (extra singlet versions, like NMSSM, discussed by Kiwoon Choi)

$$M_h^2 \stackrel{M_A \gg M_Z}{\rightarrow} M_Z^2 \cos^2 2\beta + \frac{3\bar{m}_t^4}{2\pi^2 v^2 \sin^2\beta}\left[\log\frac{M_S^2}{\bar{m}_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12 M_S^2}\right)\right]$$





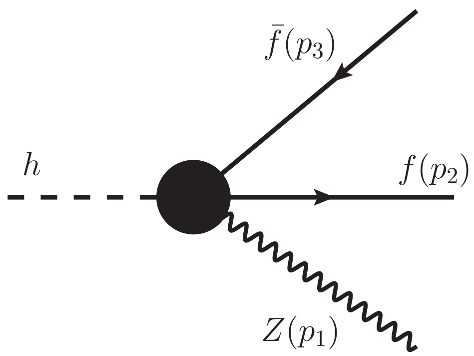
Arbey et al, 1112.3028, idem 1207.1348, idem 1211.4004
See also: Espinnosa et al 1207.7355, Cheung et al 1310.3937, Djouadi 1311.0720,
.... many more

Higgs precision tests

2-body decays -- numbers

3-body decays -- form factors

e.g.



if, for example, model new physics by EFT

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

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

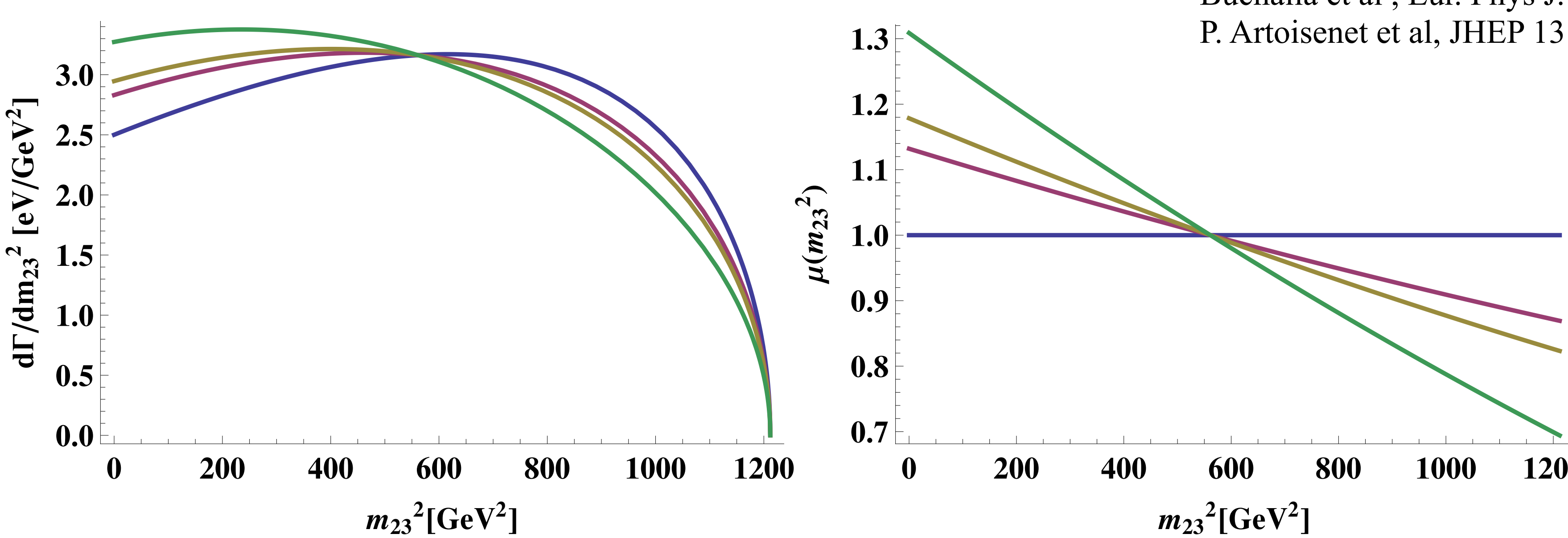


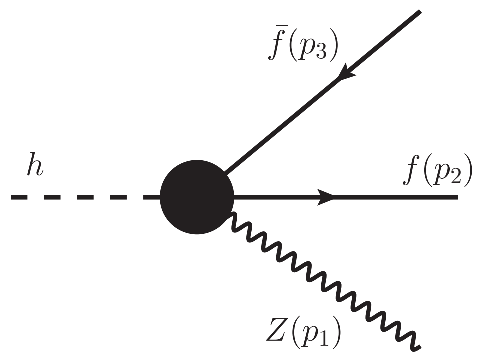
Figure 2. Contributions to $h \to Z\ell\bar{\ell}$ from $\mathcal{O}_{ZJ}$. The differential decay rate and differential signal strength as a function of m_{23}^2 are shown on the left and right respectively. The curves correspond to the SM (blue); $c_R = 0.99$, $c_L = 0$ (red); $c_L = -1.15$, $c_R =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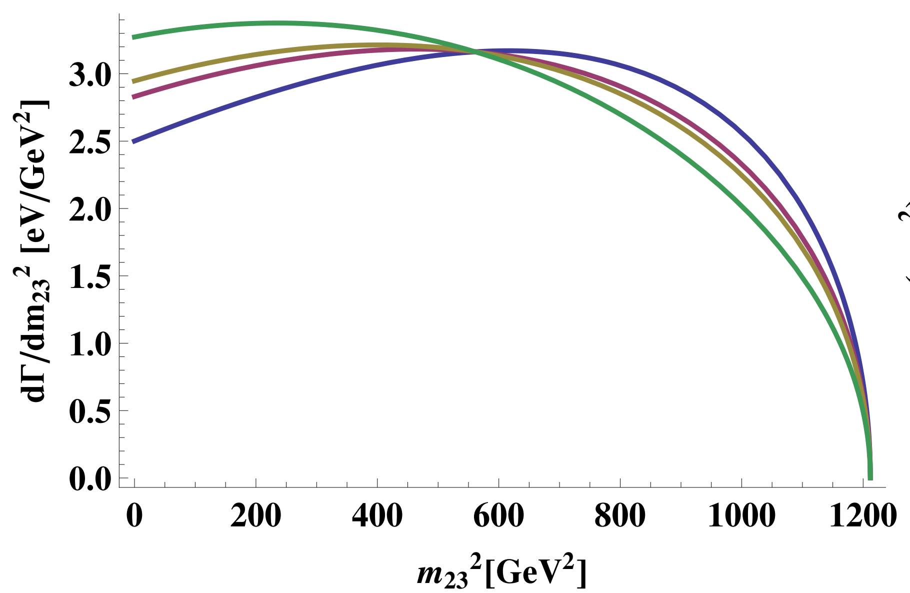

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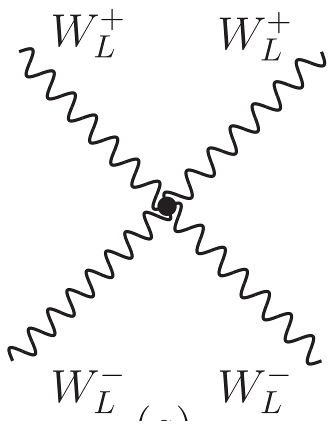
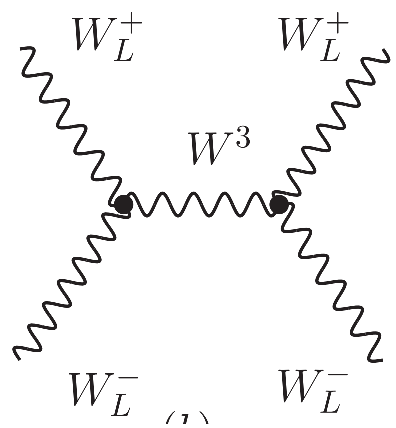
Unitarity Bounds

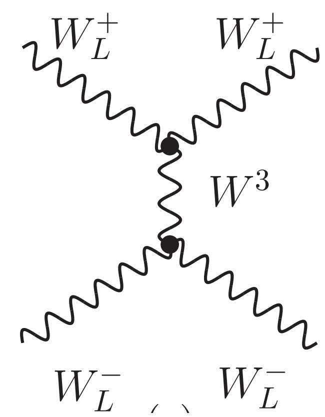
B. W. Lee, C. Quigg, and H. Thacker, PRD16 (1977) 1519.
J.F. Gunion, H.E. Haber, J. Wudka. PRD43 (1991) 904-912
BG, C. W. Murphy, D. Pirtskhalava & P. Uttayarat, JHEP 1405 (2014) 083

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

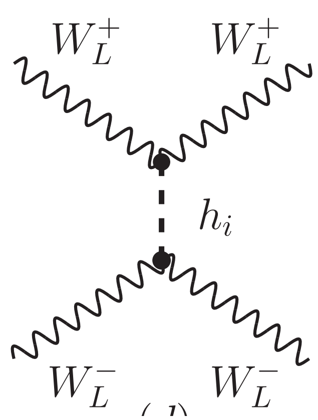
<u>partial amplitudes $a_{J=0,1,2}$</u>

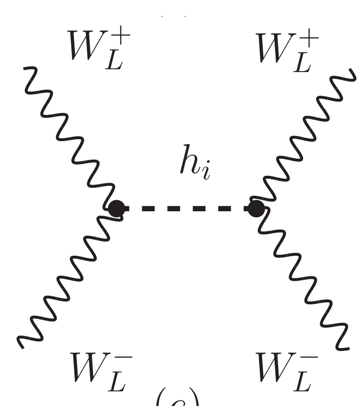






$s^2, \quad s, \quad 1, \ldots$





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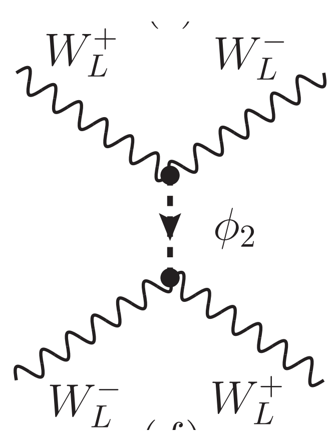

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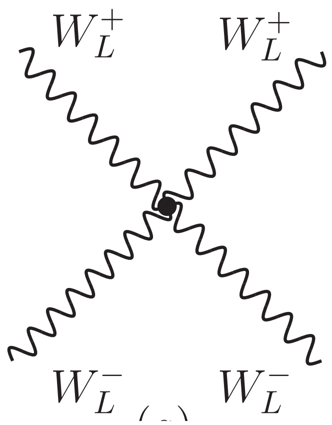
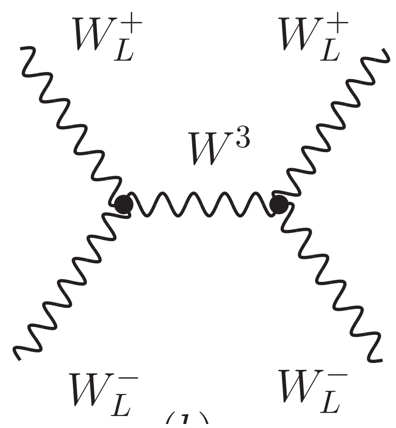
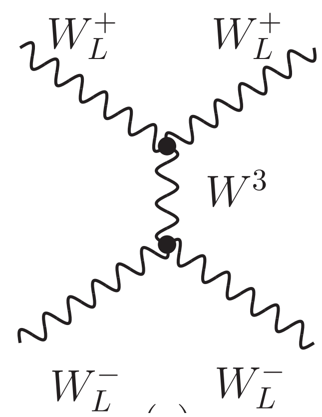
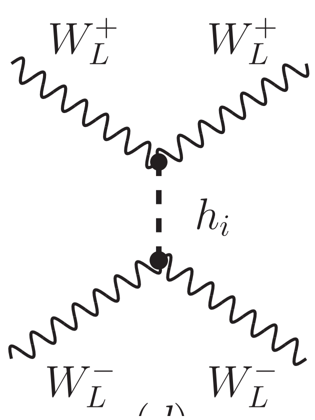


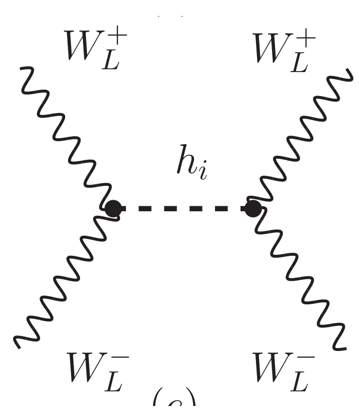




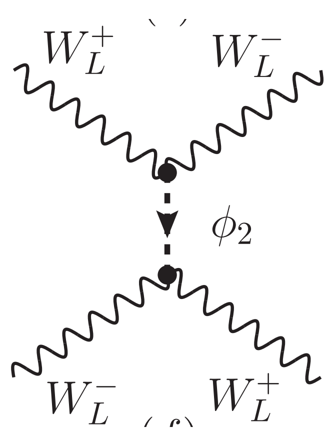
s^2, s, $1, \ldots$

=0 automatic, gauge inv





s, $1, \ldots$



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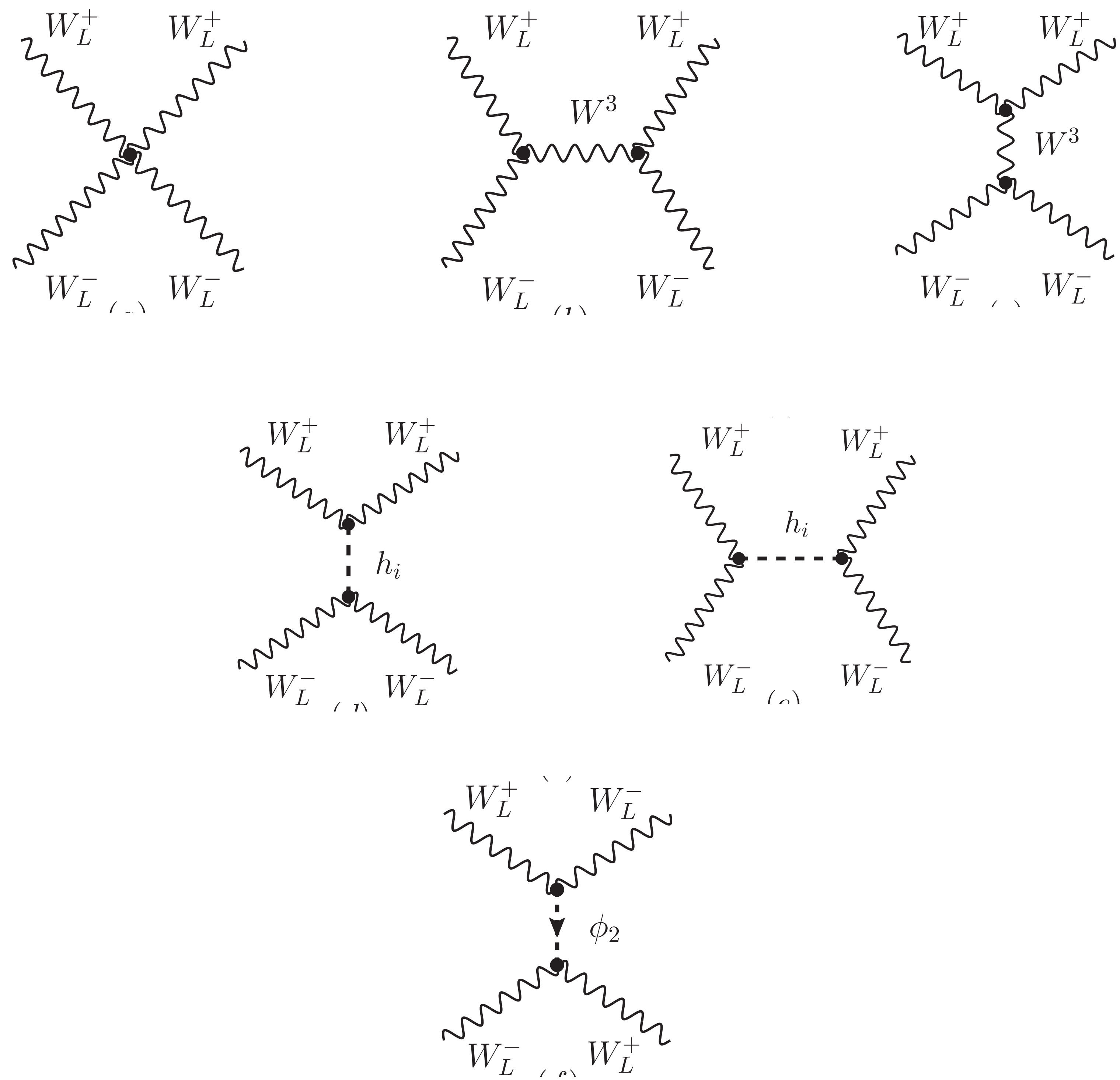


$s^2,$ $s,$ $1, \ldots$

=0 automatic, gauge inv

$s,$ $1, \ldots$

$s,$ $1, \ldots$

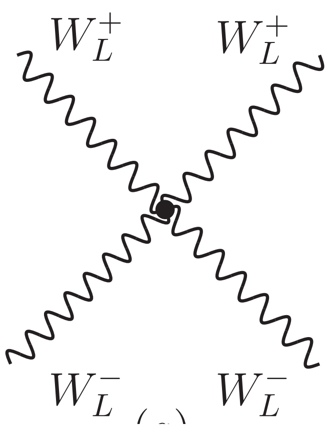
=0 only if couplings are related: sum-rule

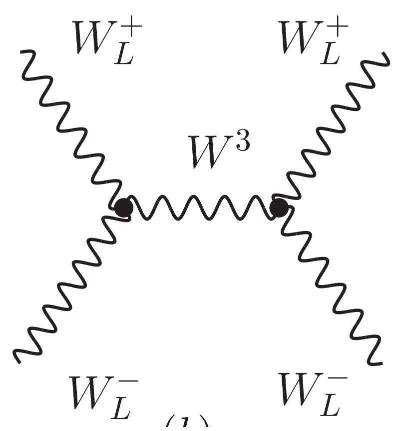
Unitarity Bounds

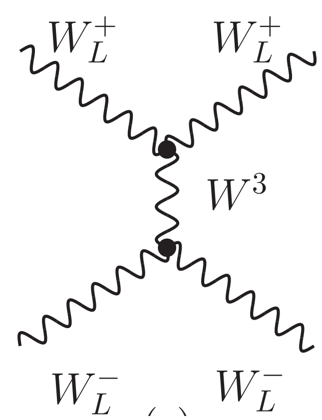
B. W. Lee, C. Quigg, and H. Thacker, PRD16 (1977) 1519.
J.F. Gunion, H.E. Haber, J. Wudka. PRD43 (1991) 904-912
BG, C. W. Murphy, D. Pirtskhalava & P. Uttayarat, JHEP 1405 (2014) 083

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

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

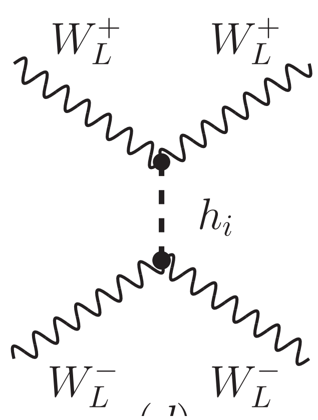


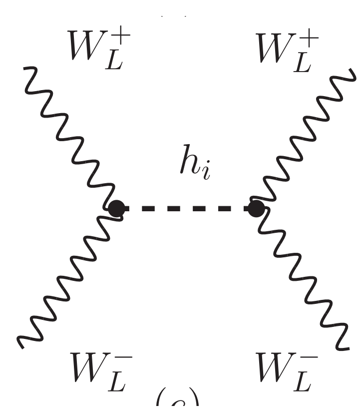




s^2, s, $1, \ldots$

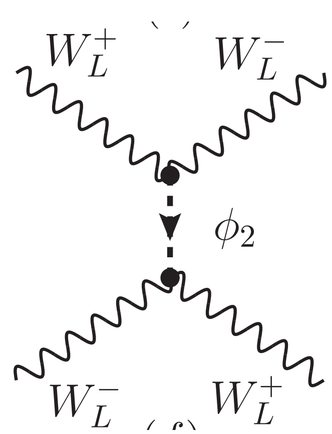
=0 automatic, gauge inv





s, $1, \ldots$

¡Generally requires doubly charged higgs!



s, $1, \ldots$

=0 only if couplings are related: sum-rule

Unitarity Bounds

B. W. Lee, C. Quigg, and H. Thacker, PRD16 (1977) 1519.
J.F. Gunion, H.E. Haber, J. Wudka. PRD43 (1991) 904-912
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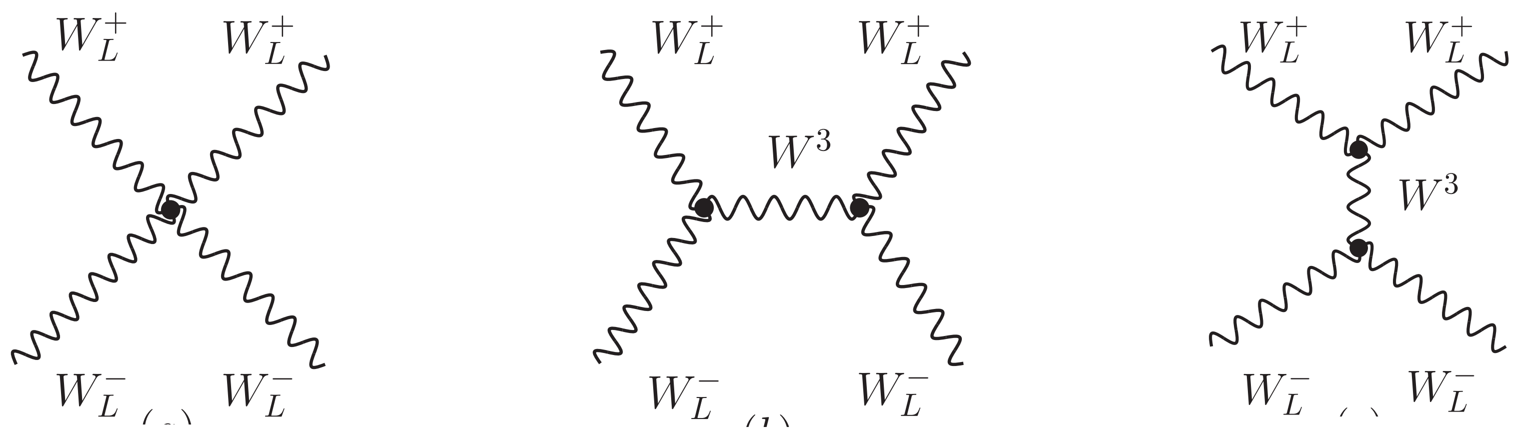

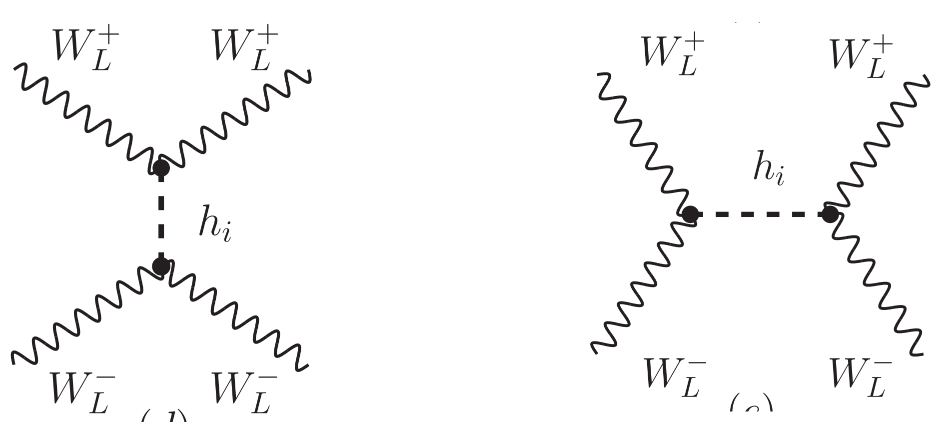

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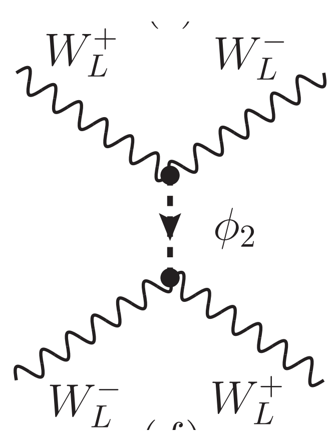


<u>partial amplitudes $a_{J=0,1,2}$</u>

s^2, s, $1, \ldots$

=0 automatic, gauge inv

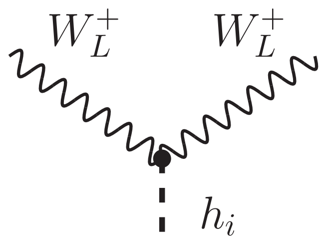
s, $1, \ldots$

No growth with s, but gives mass bounds using $|\mathrm{Re}(a_0)| < 1/2$:

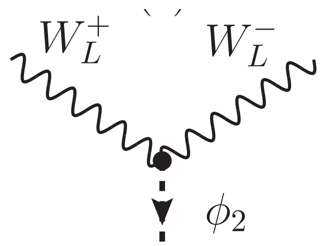
s, $1, \ldots$

=0 only if couplings are related: sum-rule

$W_L^+ W_L^- \to W_L^+ W_L^-$



$= igM_W a_i$



$= igM_W b_r$

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

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

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

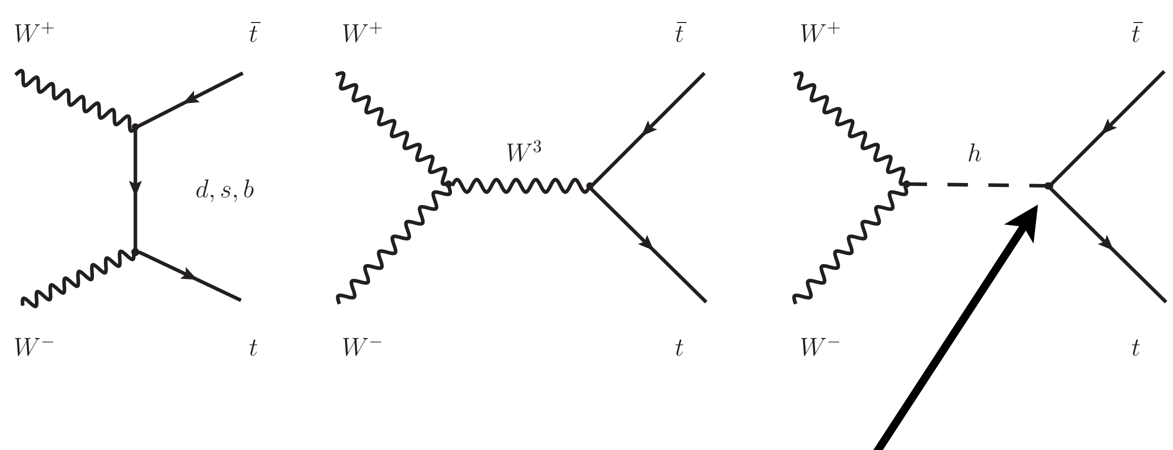
$Z_L Z_L \to W_L^+ W_L^-$

$$ZZh_i \to \tfrac{1}{2} g M_W d_i \qquad ZW^- h_r^+ \to g M_W f_r$$

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

$W_L^+ W_L^- \to t\bar{t}$



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

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

+ analogous results for other quarks and leptons

Examples - Applications

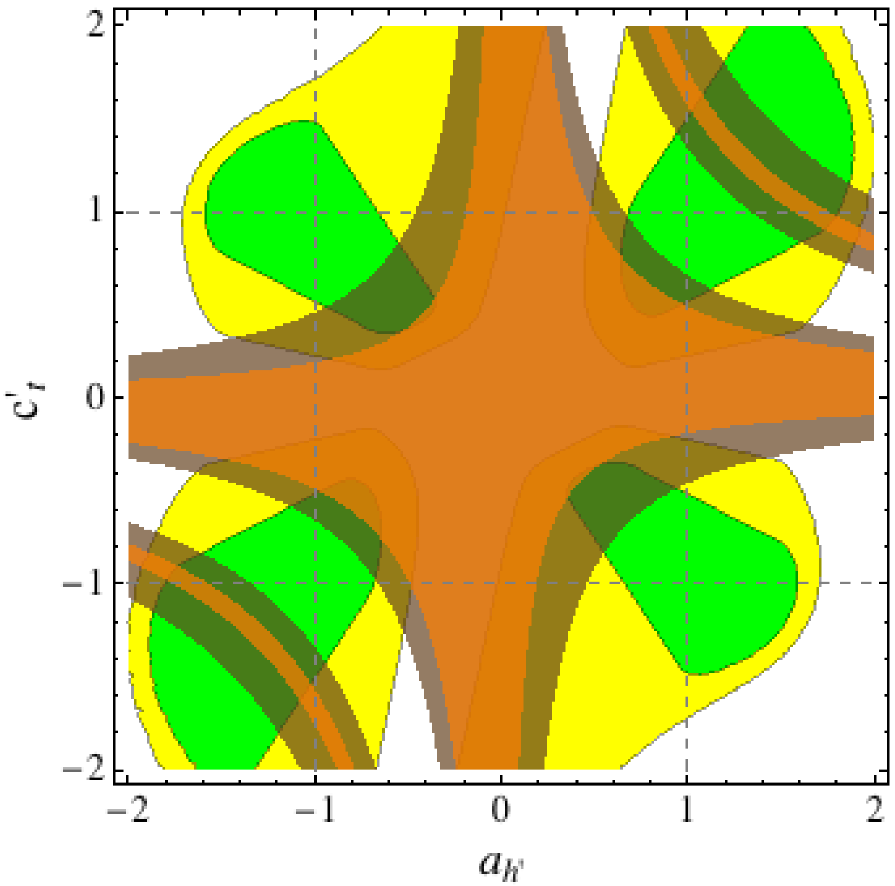
Idea: use 125 Higgs data and see what's left in the sum rule

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

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

This graph is independent of the mass of h'

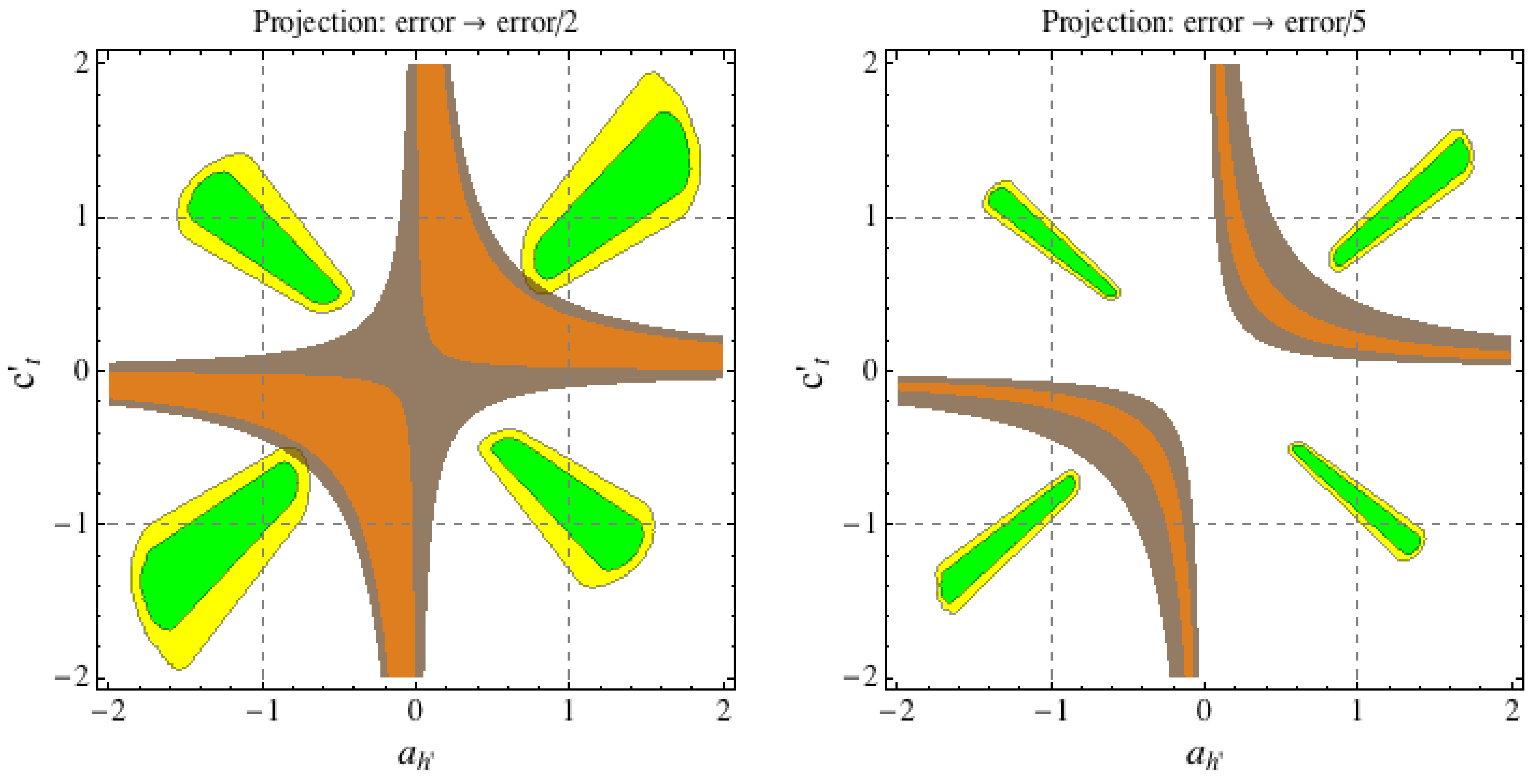
Superimposed on the CMS 135 GeV "bump," just for comparison, graph (brown) does not depend on it.



ALLOWED REGION:
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 et al, arXiv:1311.7208 [hep-ph].

$$\mathcal{L}_{int} = g M_W b W^-_\mu W^{\mu -} h^{++} \text{ -}$$

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

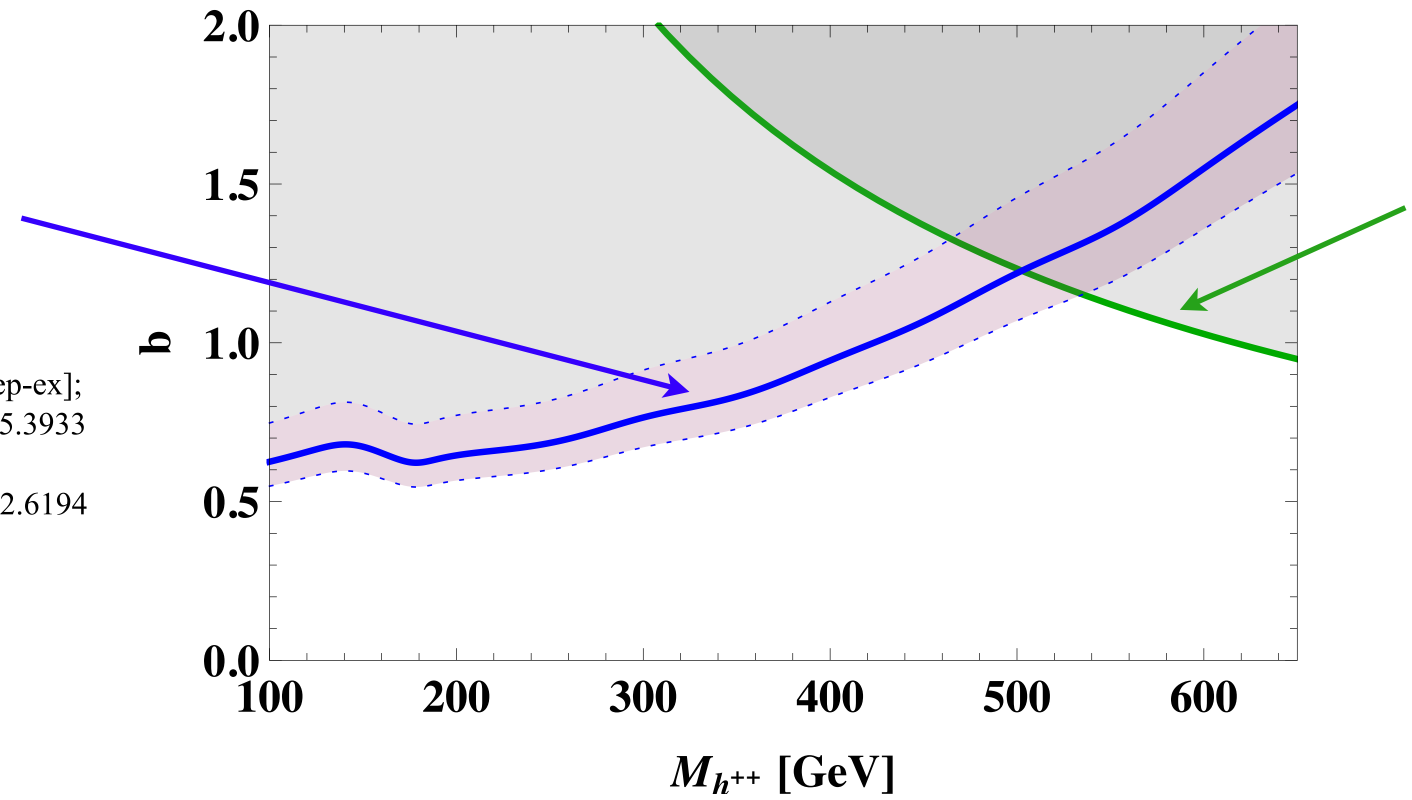
since $\Gamma(h^{++} \to h^+h^+)$ is model dependent

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].

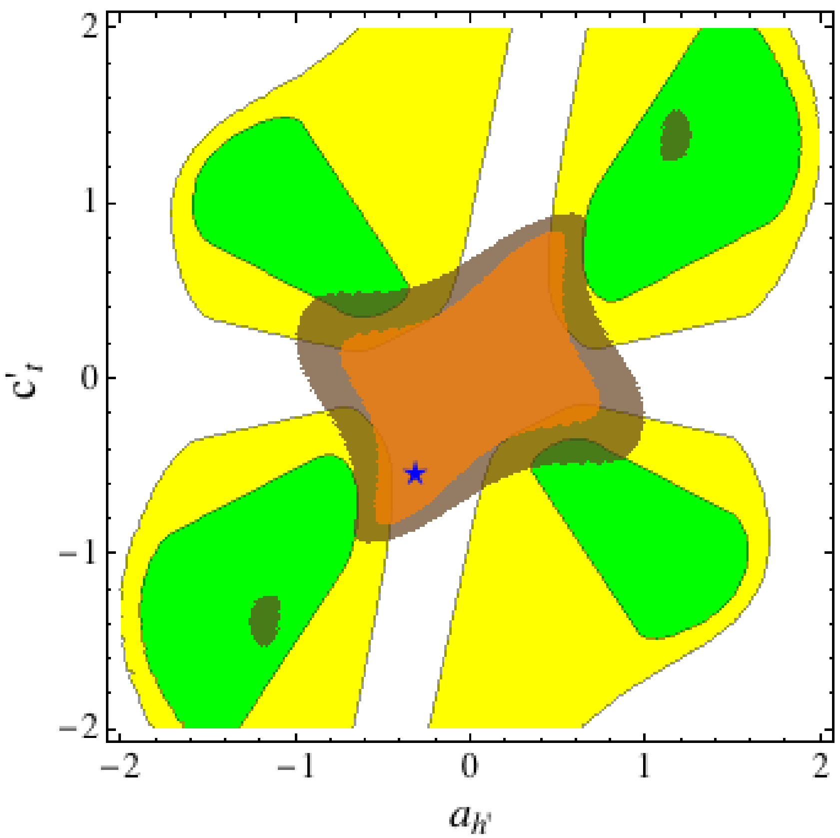


unitarity bound

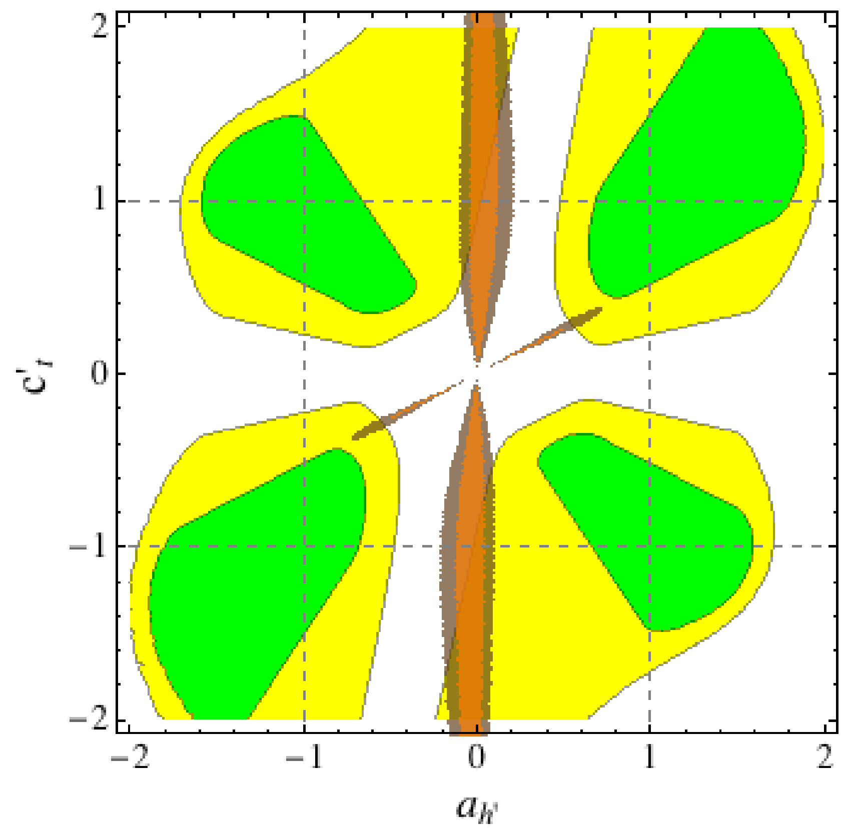
Explicit models, briefly

Correlations: reduced allowed region, nothing to do with sum rule (unitary sum rule automatic)
Mass Bounds: useful even for explicit models !!

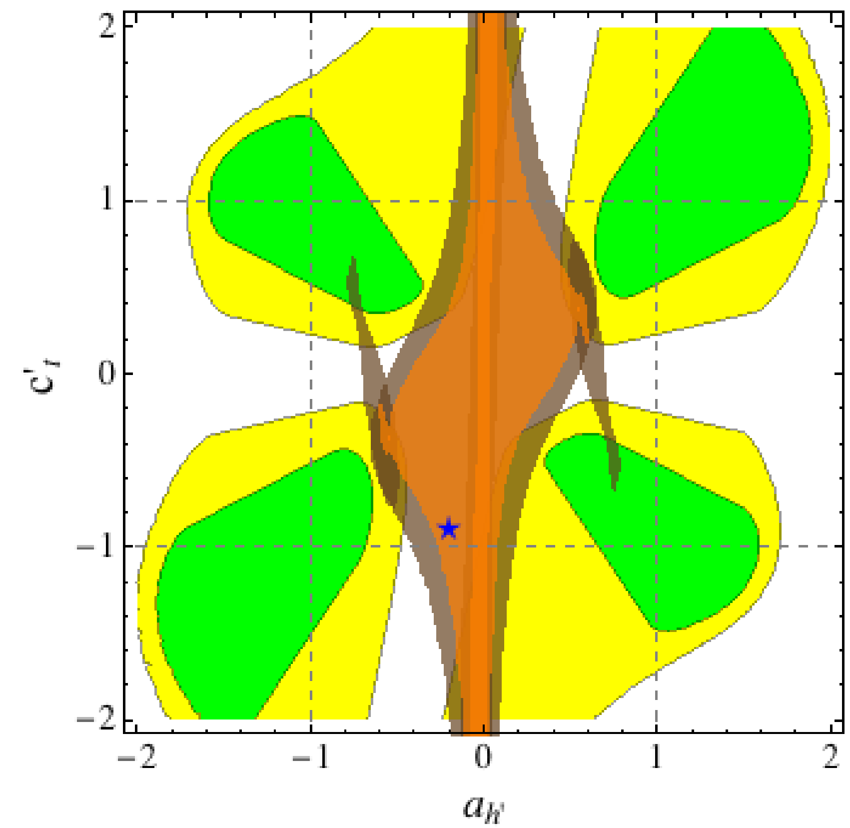
Georgi-Machacek



2HDM-II

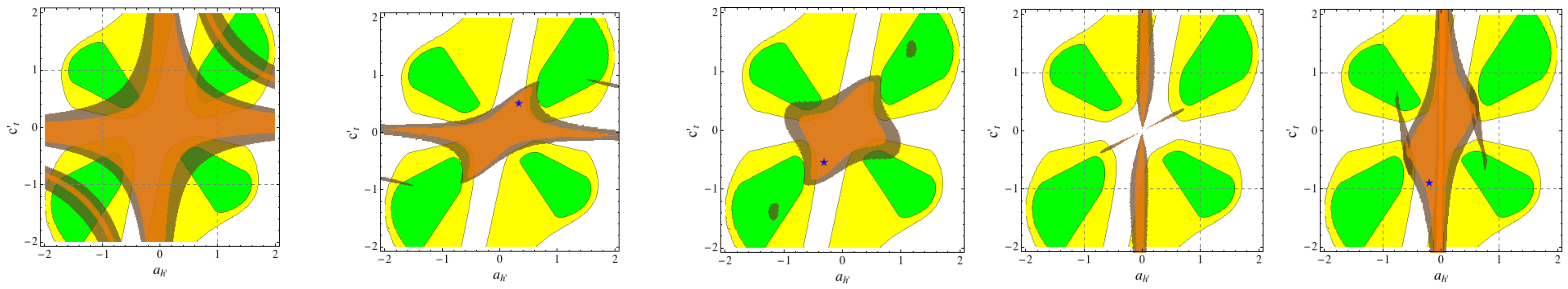


2HDM-III



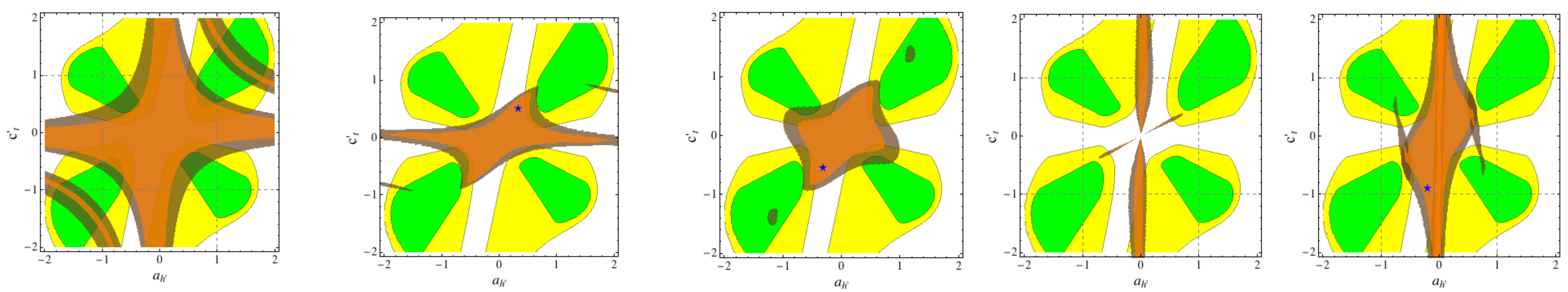
simetria "custodial" en modelo GM:
C.-W. Chiang and K. Yagyu, JHEP 1301 (2013) 026, arXiv:1211.2658 [hep-ph].

Conclusions/Summary



Conclusions/Summary

- Should be open to possibilities (beyond SUSY, *e.g.*, higgs impostor)



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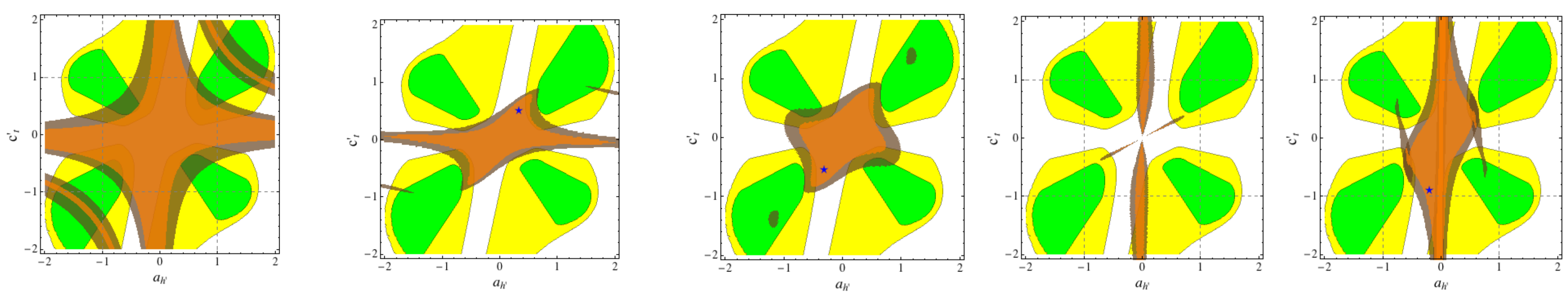

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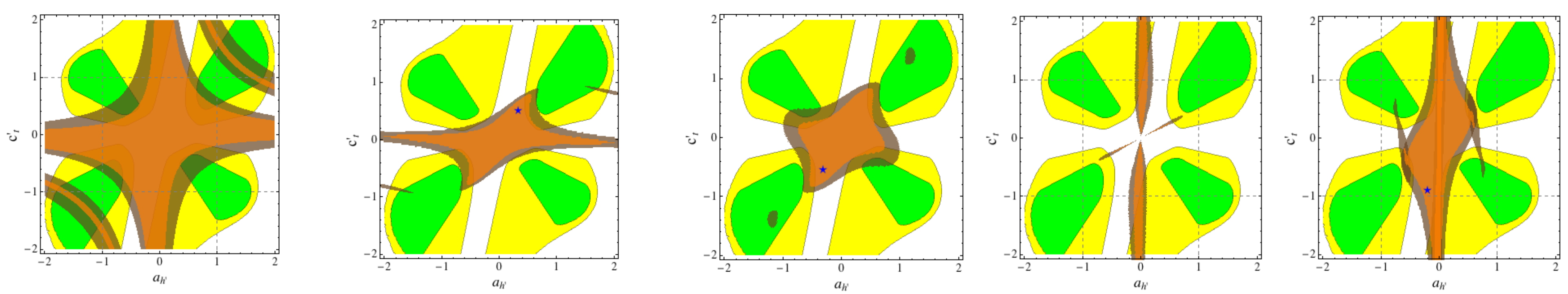

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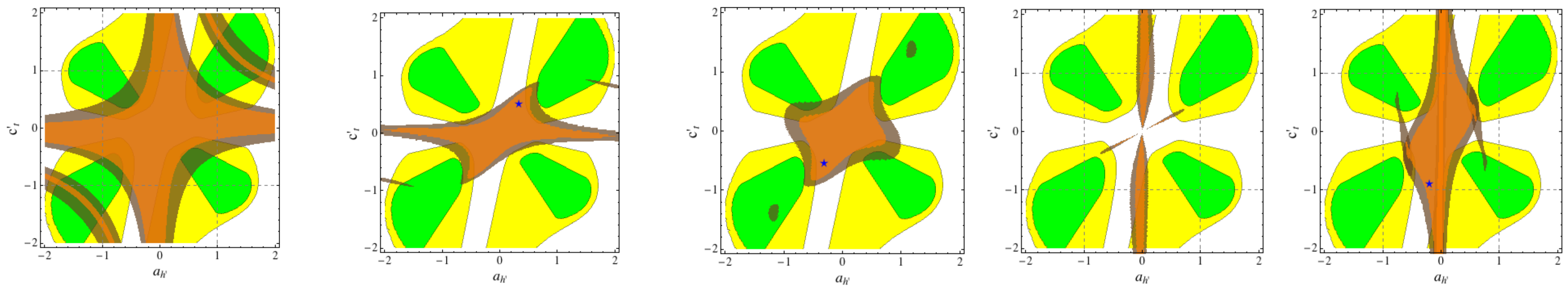

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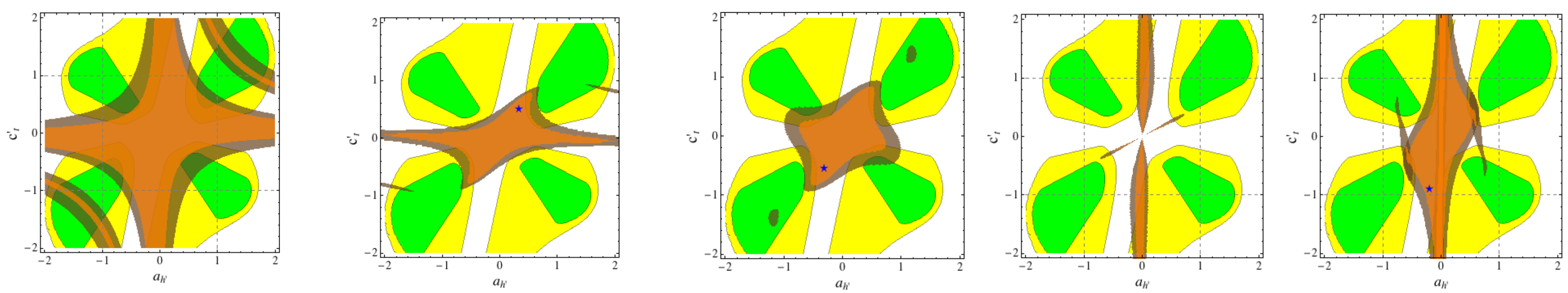

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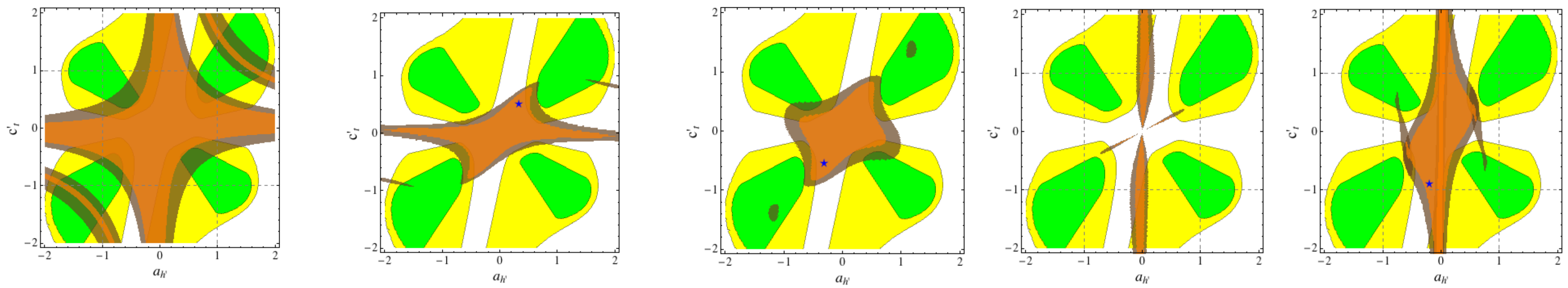
- Unitarity bounds: complimentary to high energy collider data
- Unitarity bounds (but not sum-rules) contain new useful information for specific models.

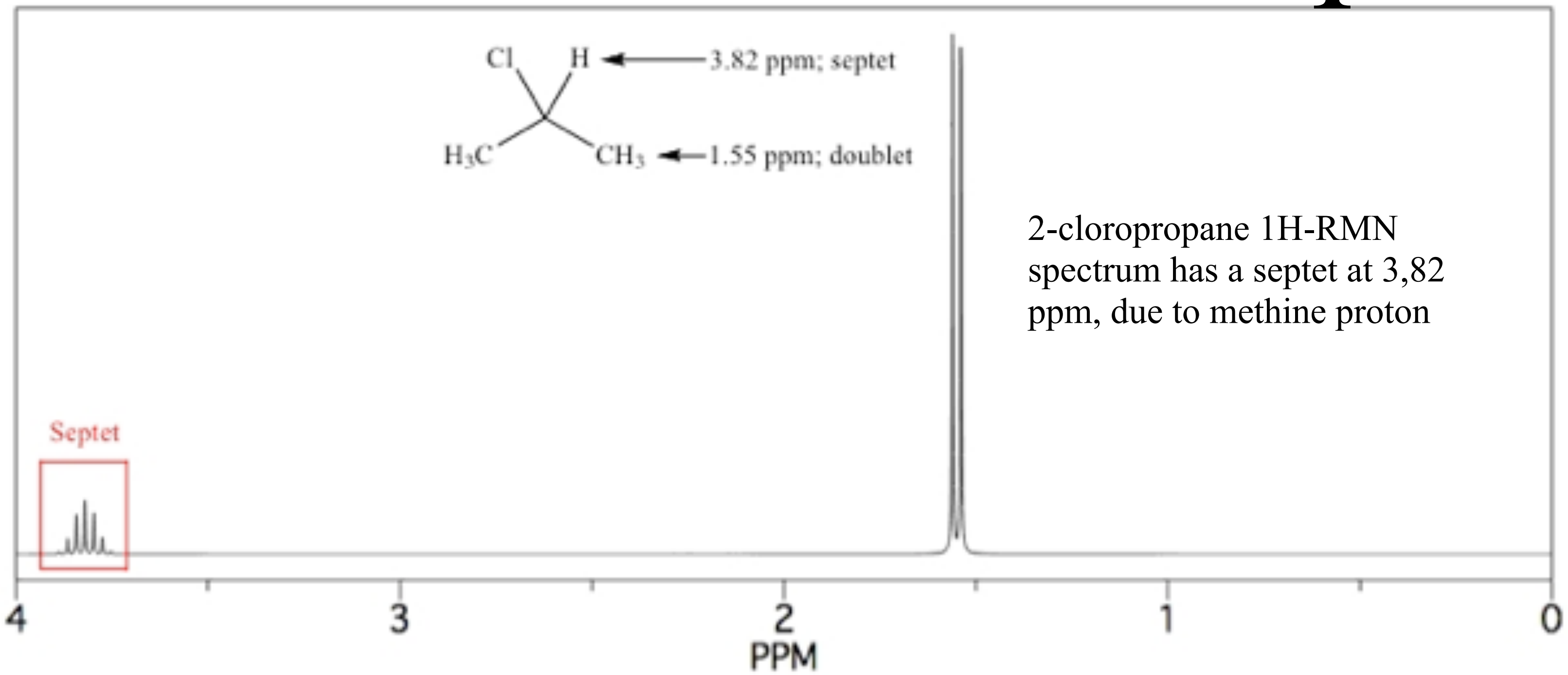


Examples - Specific Models: as time permits...

- 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



EWPD: scalar VEV
No tree level contribution to $\delta\rho$
for SU(2) doublet
OR for SU(2) spin-3 (7-plet)
if Y=2 (vev on neutral entry)

higgs++ interaction:

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

neutral higgs interatcion:

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

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

Yukawa interaction:

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

Correlations:

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

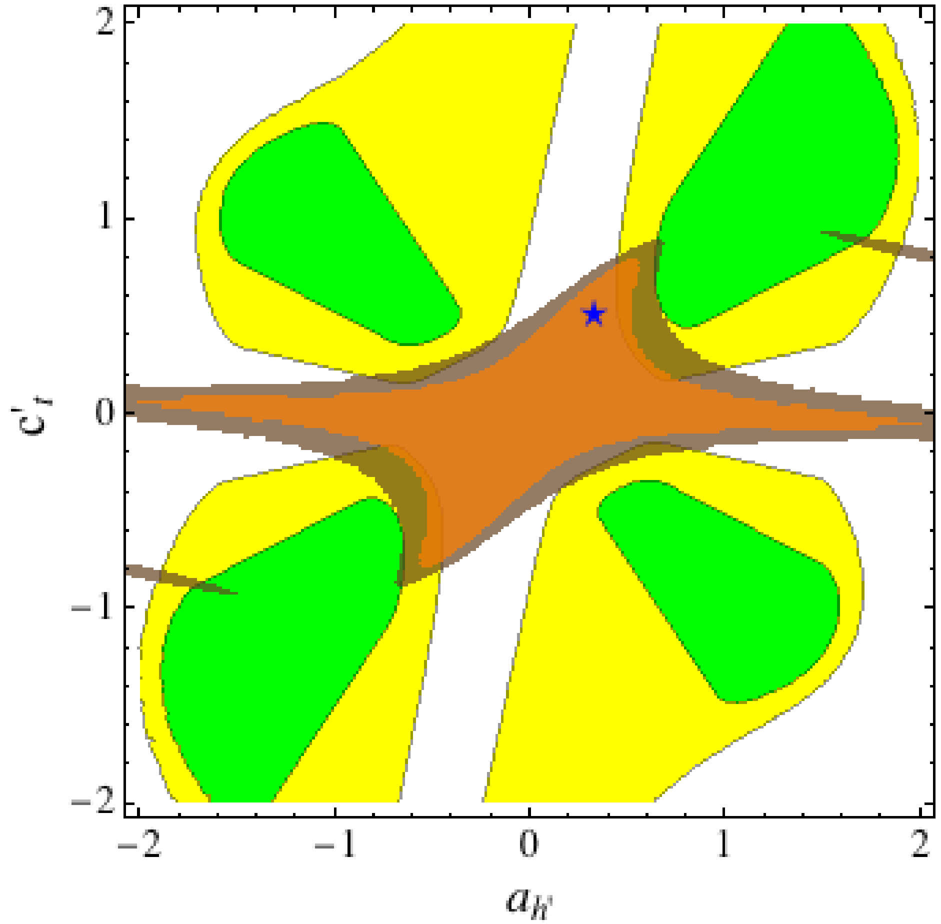
$$c_f = \cos\alpha/\sin\beta, \quad c'_f = \sin\alpha/\sin\beta.$$

higgs+ & higgs++:

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

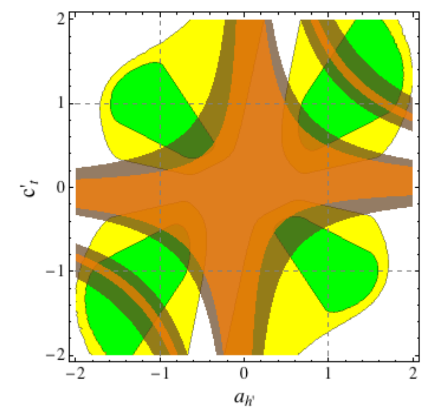
$$a_{h'} = \frac{M_W^2}{M_Z^2}d_{h'} \qquad f_{h'} = \frac{M_Z}{M_W}\frac{c_\beta(3\sqrt{5}c_\gamma - 5\sqrt{3}s_\beta s_\gamma)}{\sqrt{3+5s_\beta^2}}.$$

Fit (to 125 GeV higgs):

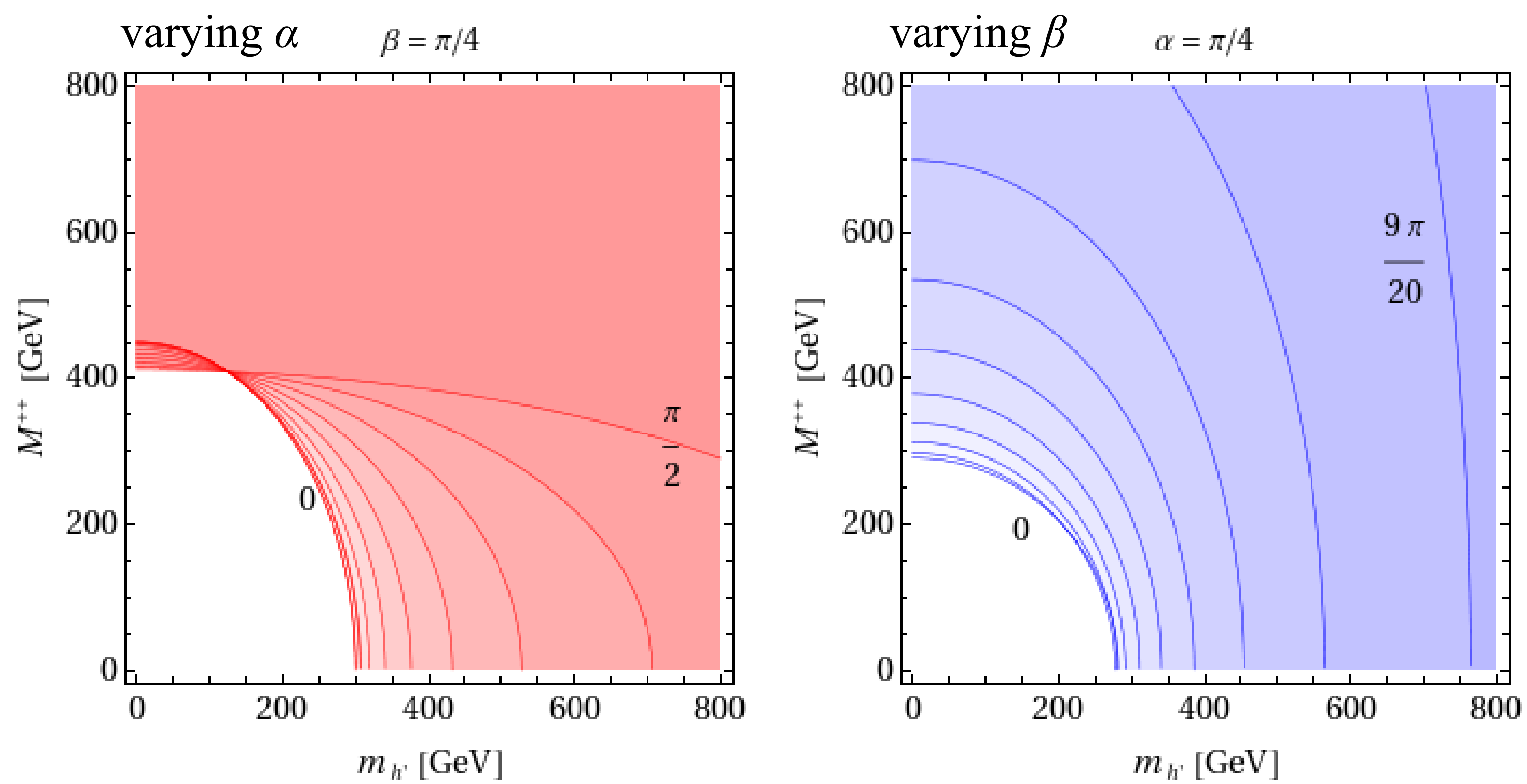


★best fit value

compare: indep de modelo

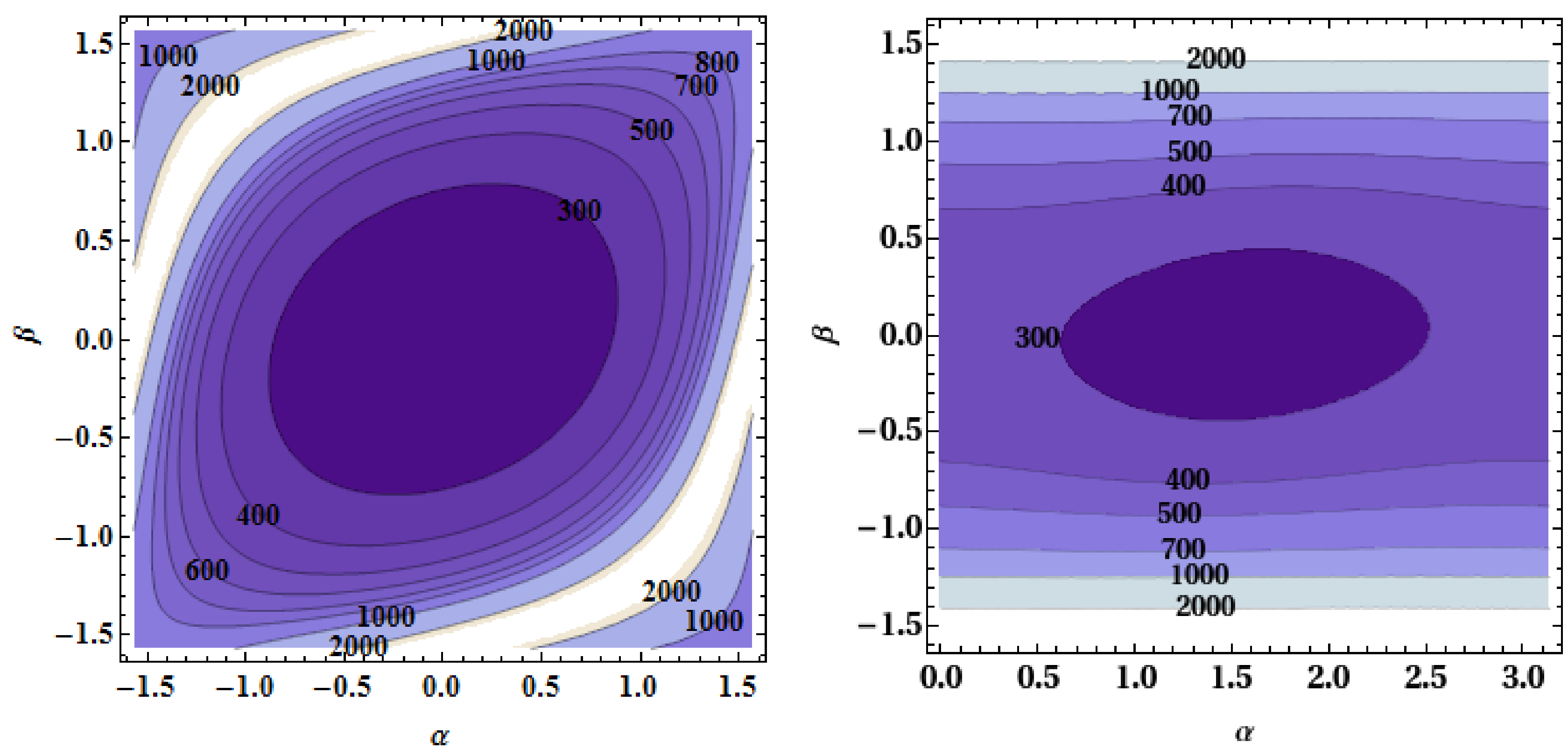


Unitarity bounds: Higgs++ mass *vs* mass of 2nd neutral Higgs



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

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



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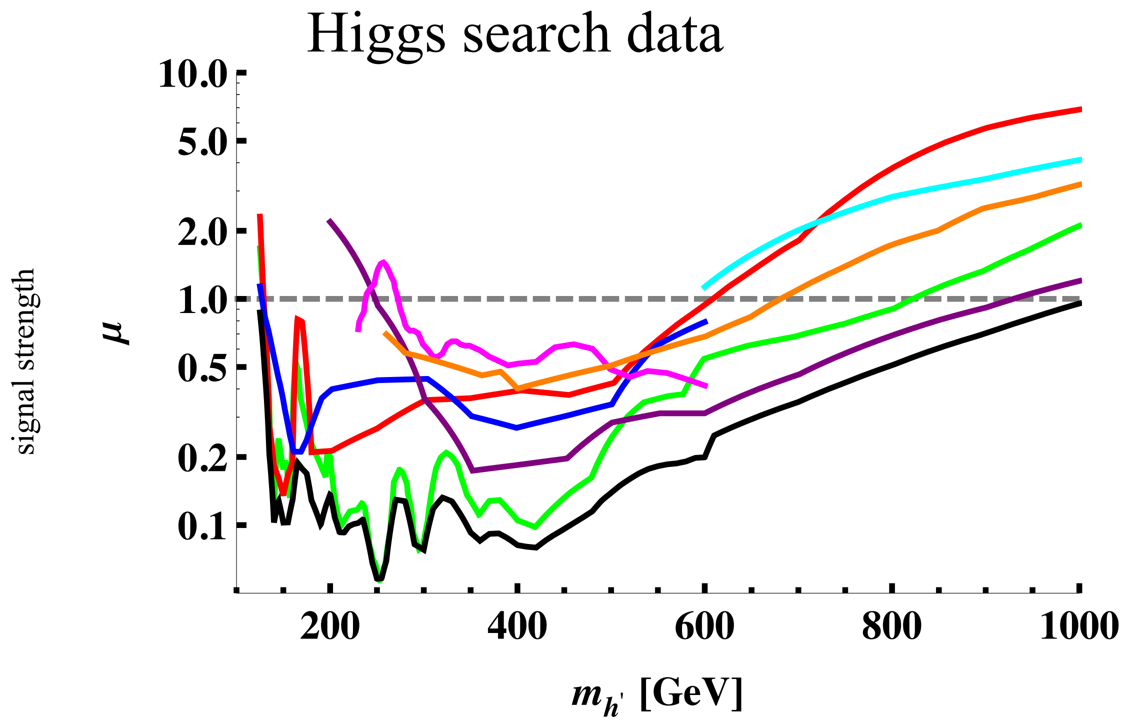
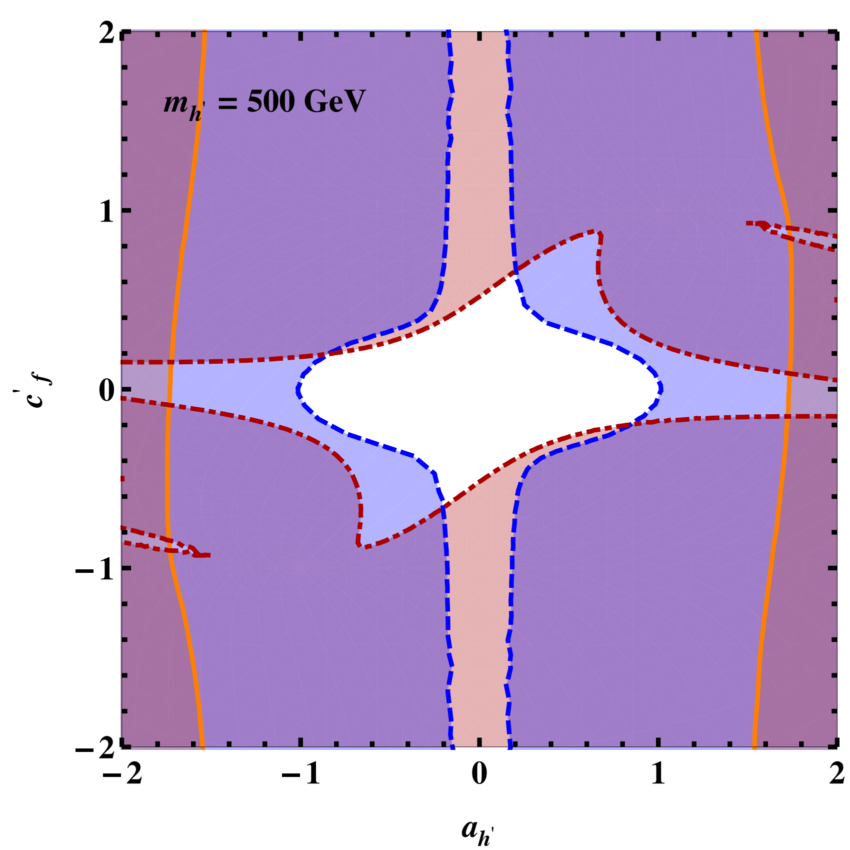


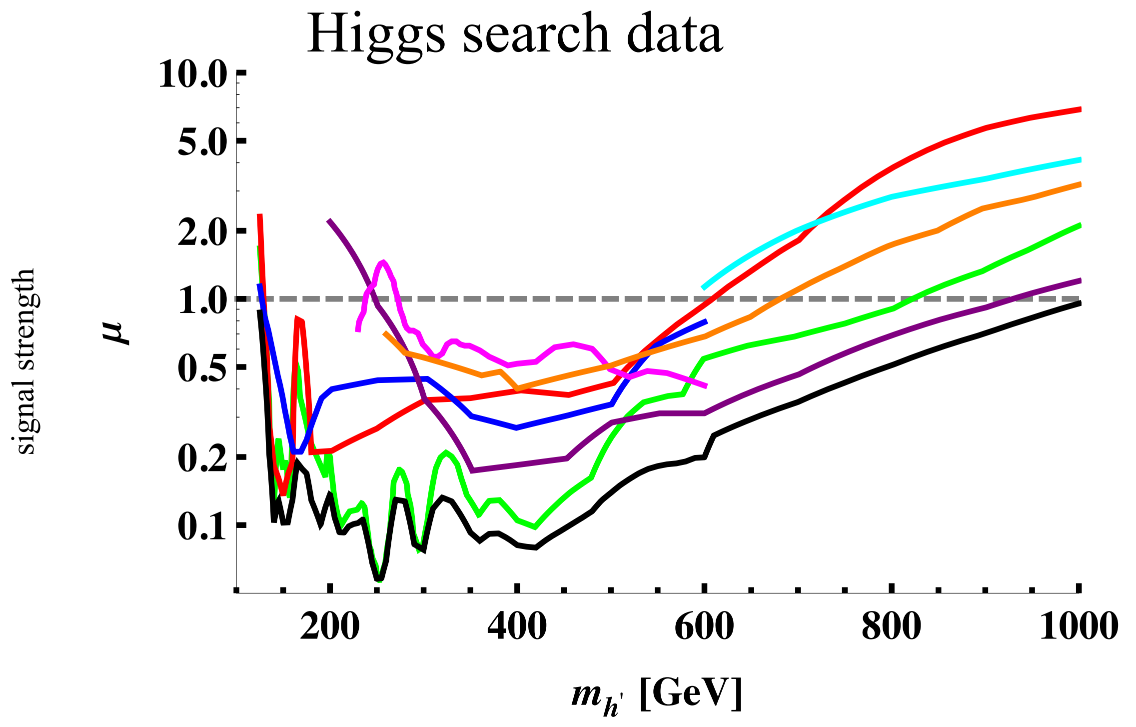
Collaboration	Channel	$\sqrt{s}$ [TeV]	$\mathcal{L}$ [fb^{-1}]	Range $m_{h'}$ probed [GeV]
ATLAS [3]	$h' \to ZZ \to 4\ell$	8	20.7	110 – 1000
ATLAS [4]	$h' \to WW \to 2(\ell\nu)$	8	20.7	260 – 1000
CMS [5]	$h' \to ZZ \to 2\ell 2q$	7 + 8	5.3 + 19.6	230 – 600
CMS [6]	$h' \to ZZ \to 4\ell$	7 + 8	5.1 + 19.6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

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





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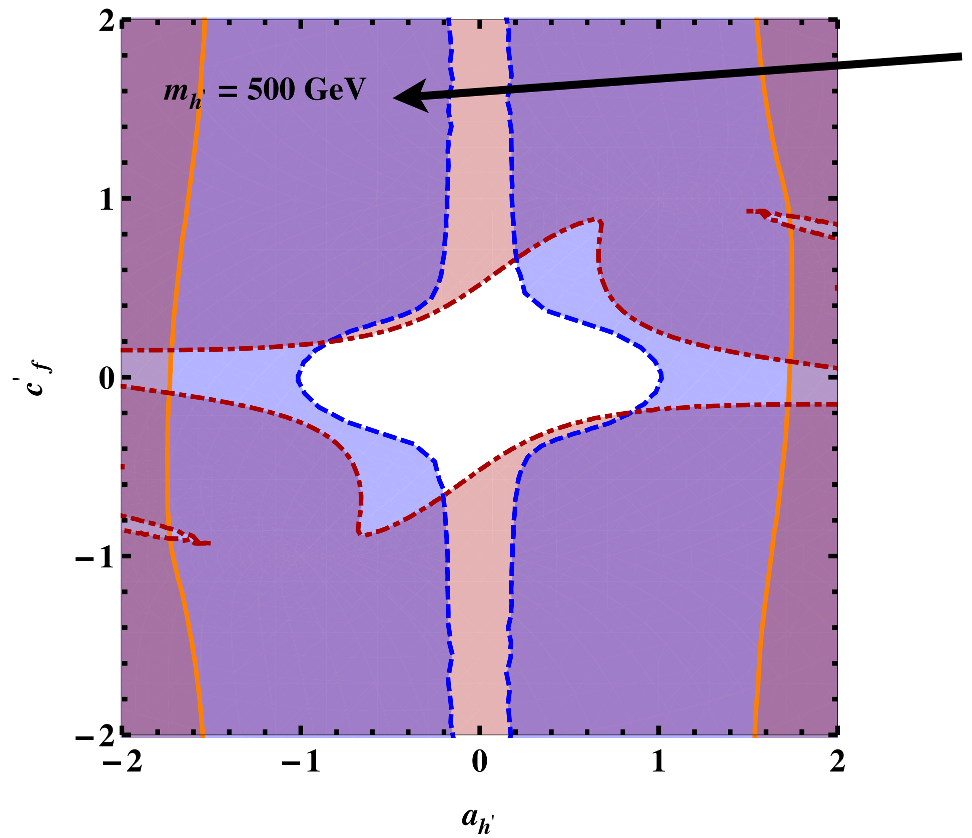
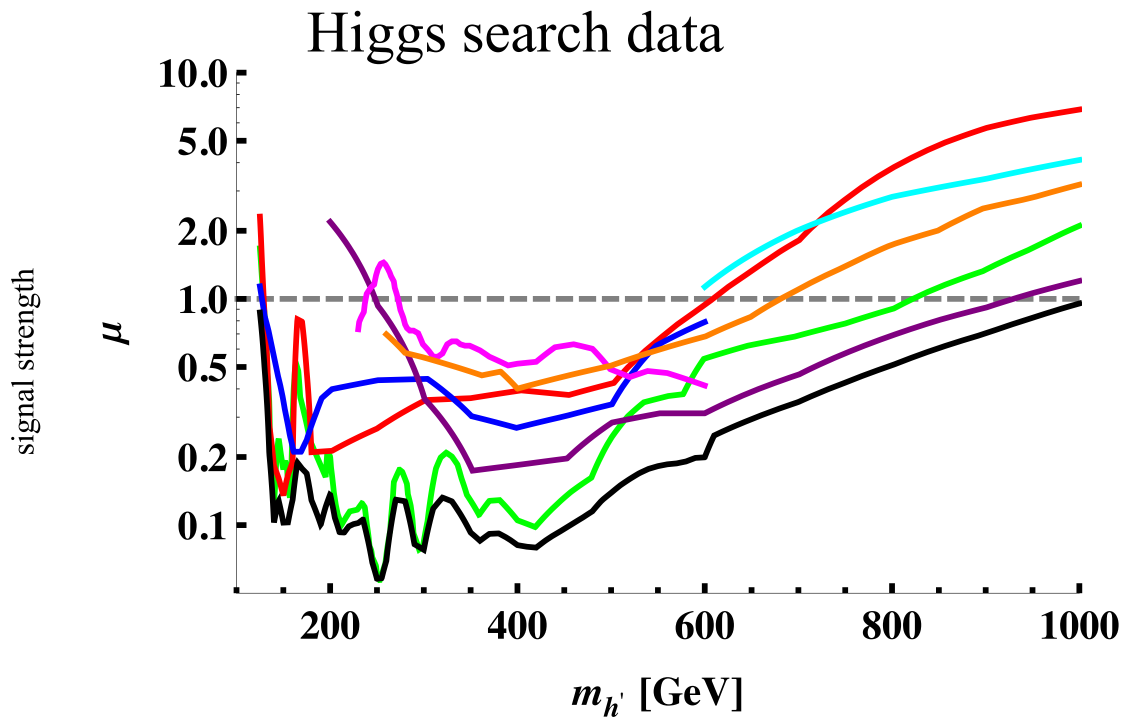


1. Choose a mass for this study



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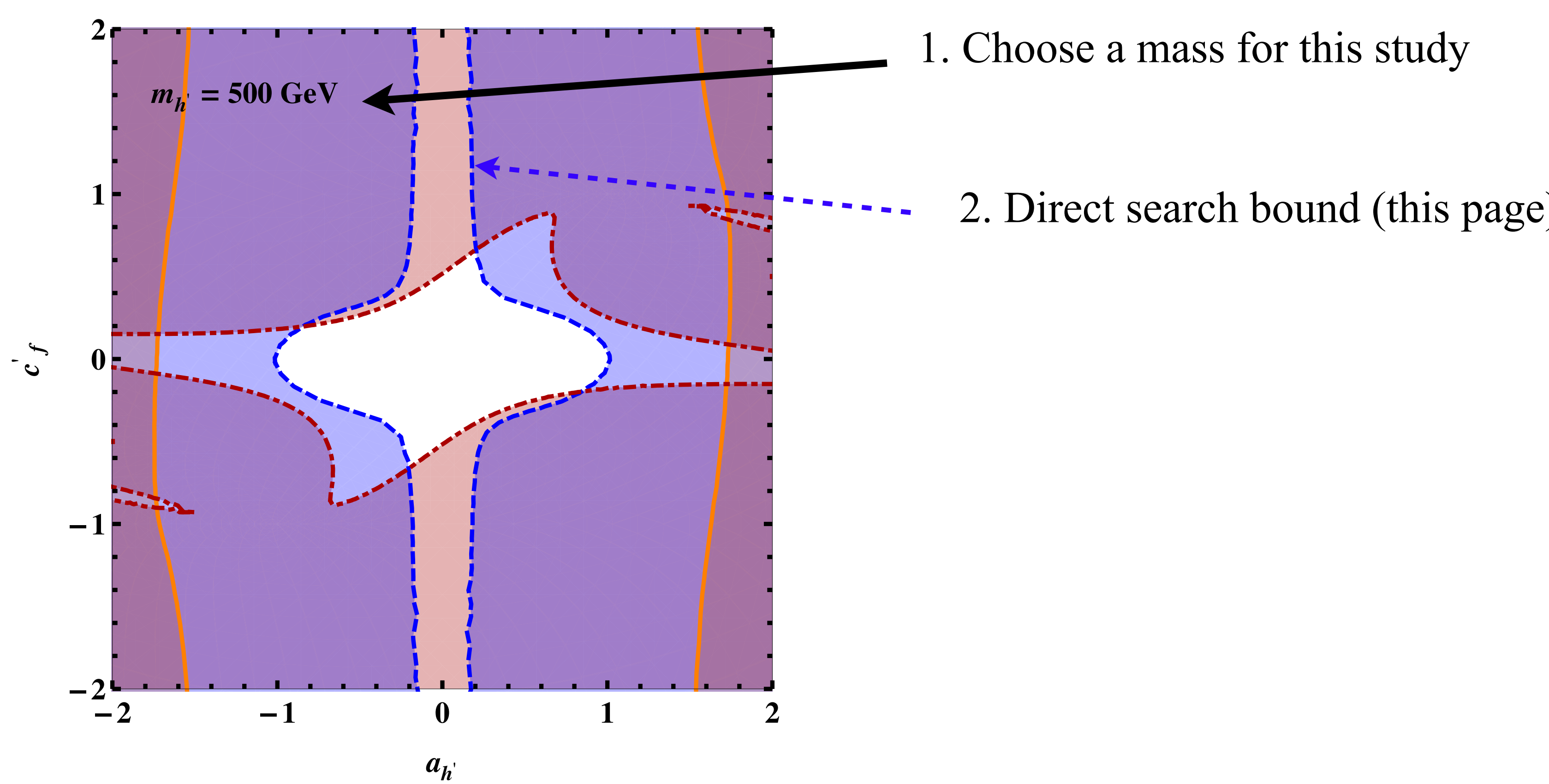

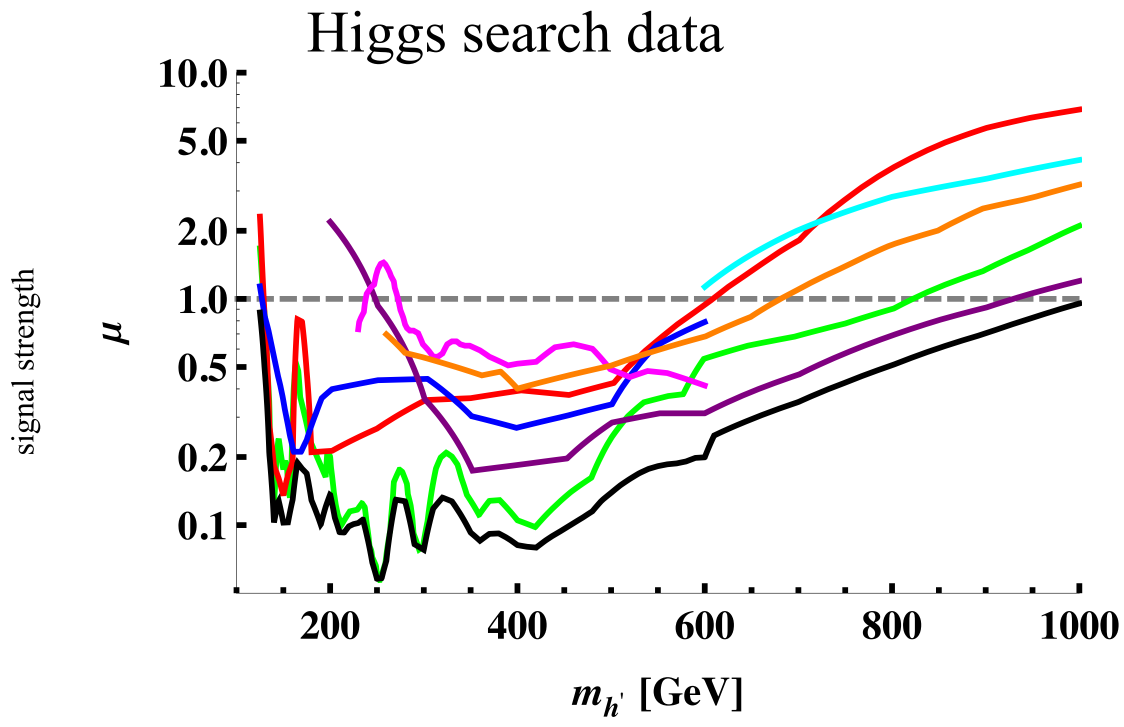

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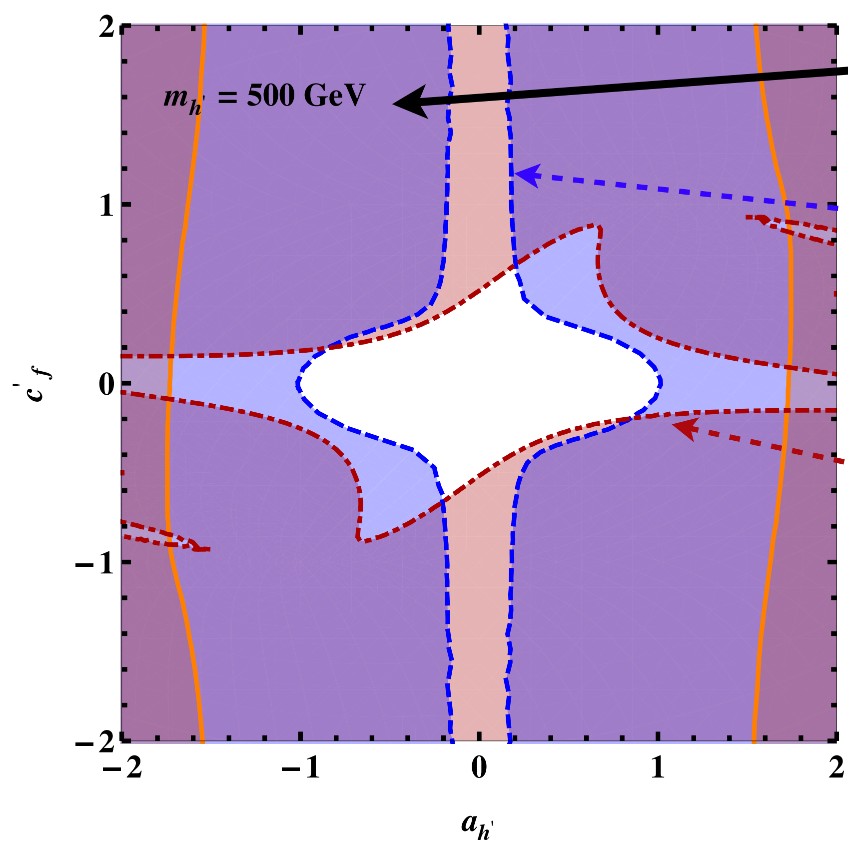
ATLAS [3]	$h' \to ZZ \to 4\ell$	8	20.7	110 – 1000
ATLAS [4]	$h' \to WW \to 2(\ell\nu)$	8	20.7	260 – 1000
CMS [5]	$h' \to ZZ \to 2\ell 2q$	7 + 8	5.3 + 19.6	230 – 600
CMS [6]	$h' \to ZZ \to 4\ell$	7 + 8	5.1 + 19.6	100 – 1000
CMS [7]	$h' \to WW \to 2(\ell\nu)$	7 + 8	4.9 + 19.5	100 – 600
CMS [8]	$h' \to WW \to \ell\nu qq'$	8	19.3	600 – 1000
CMS [9]	$h' \to ZZ \to 2\ell 2\nu$	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:

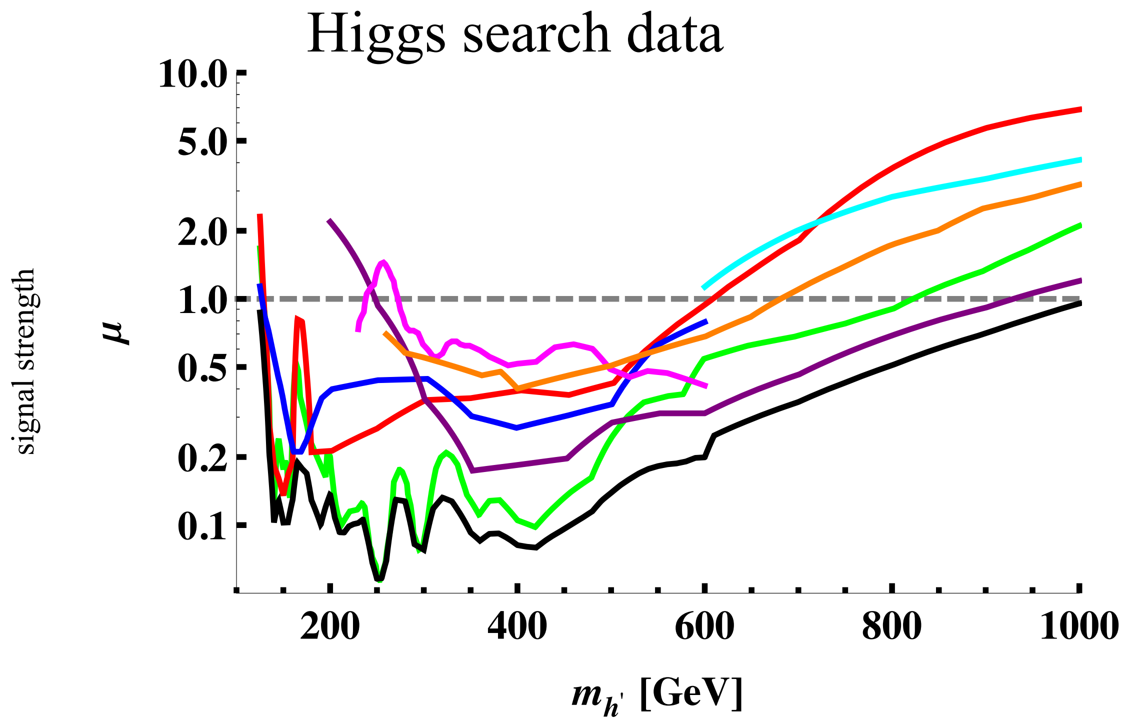
$$\mu(h' \to WW + ZZ) = \frac{c_f'^2 \sigma_{ggF+t\bar{t}h'} + a_{h'}^2 \sigma_{VBF+Vh'}}{\sigma_{ggF+t\bar{t}h'} + \sigma_{VBF+Vh'}} \frac{a_{h'}^2}{c_f'^2 Br_{f\bar{f}} + a_{h'}^2 Br_{VV} + c_f'^2 Br_{gg}},$$



1. Choose a mass for this study

2. Direct search bound (this page)

3. Fit to 125 GeV resonance (previous pages)



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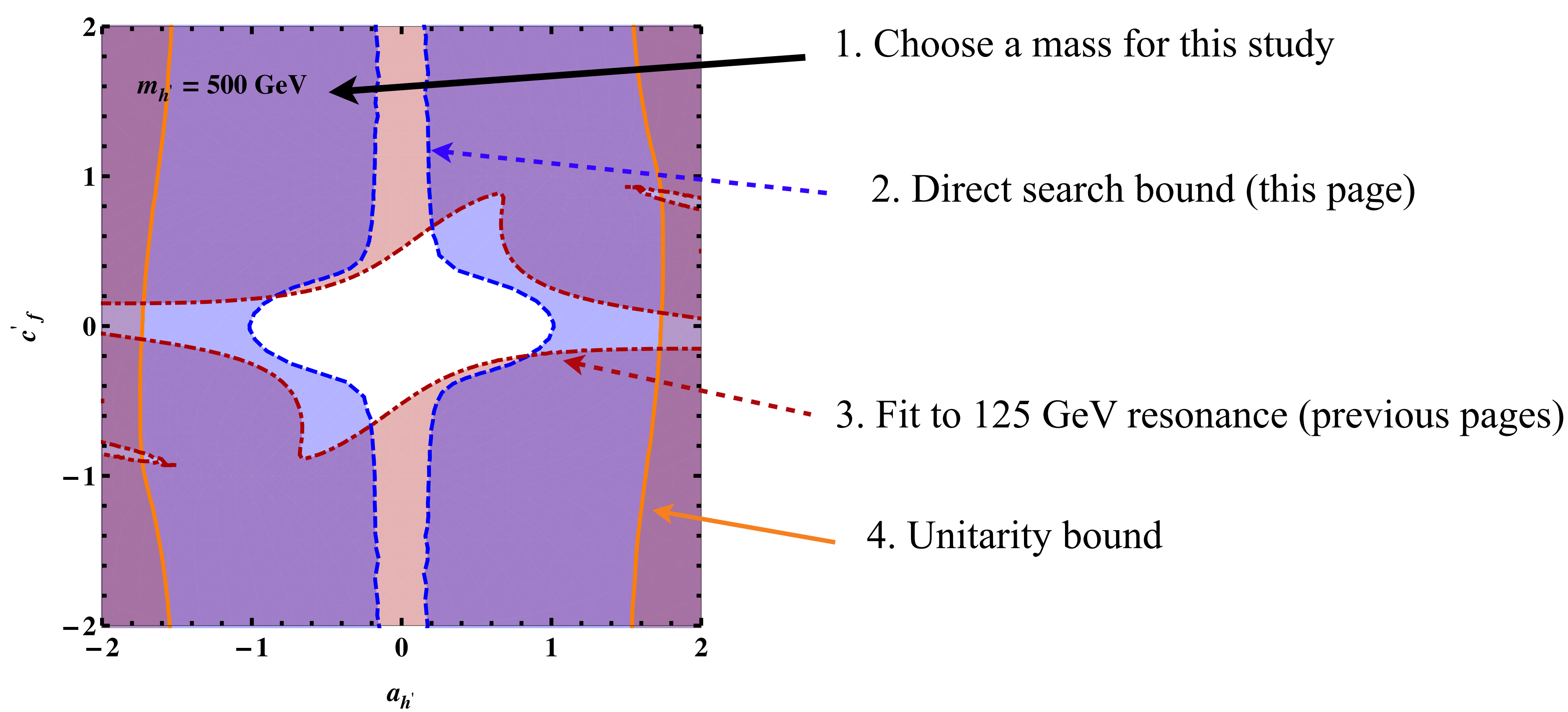
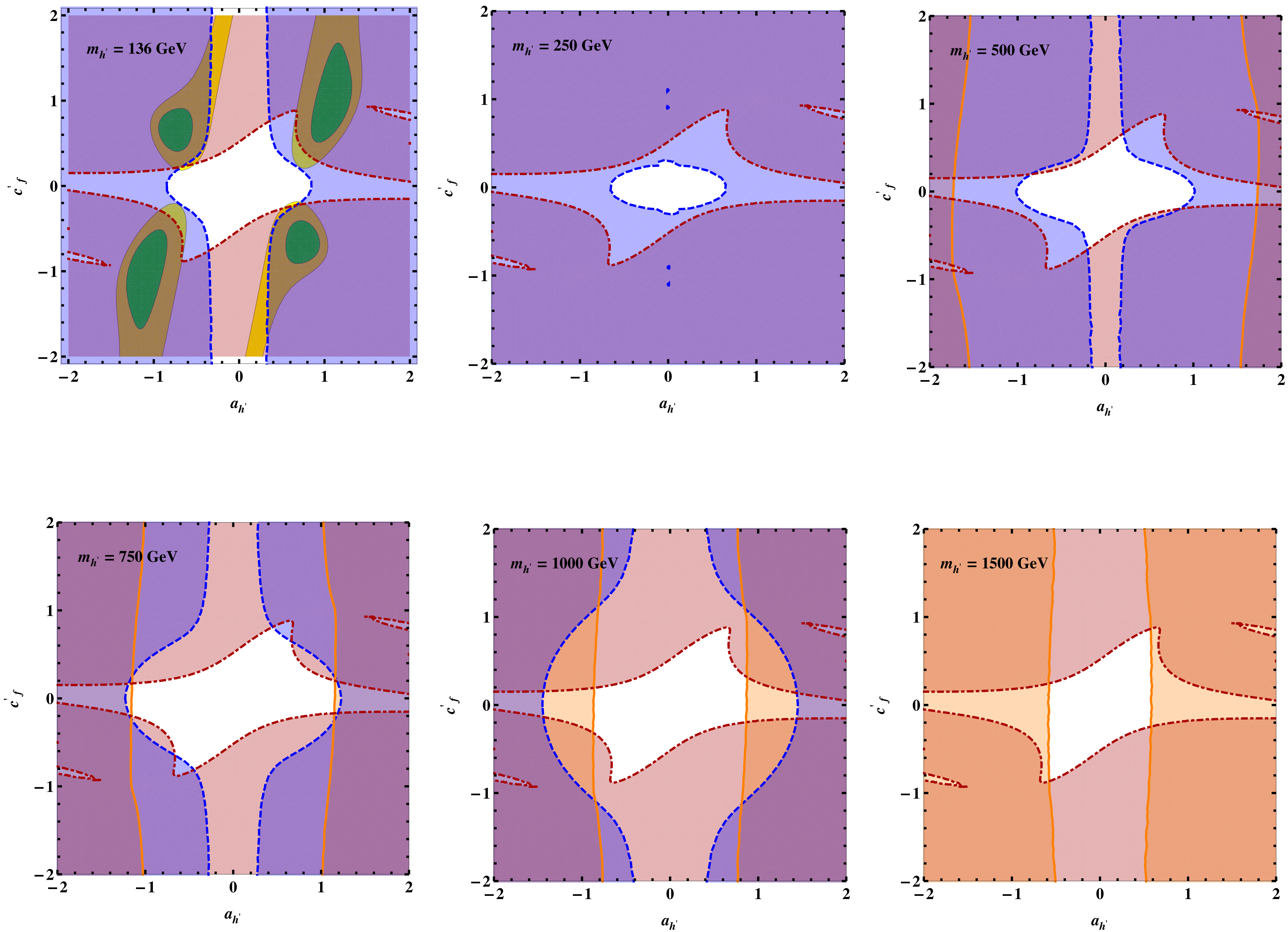


Compare mass bounds: LHC vs unitarity tournament



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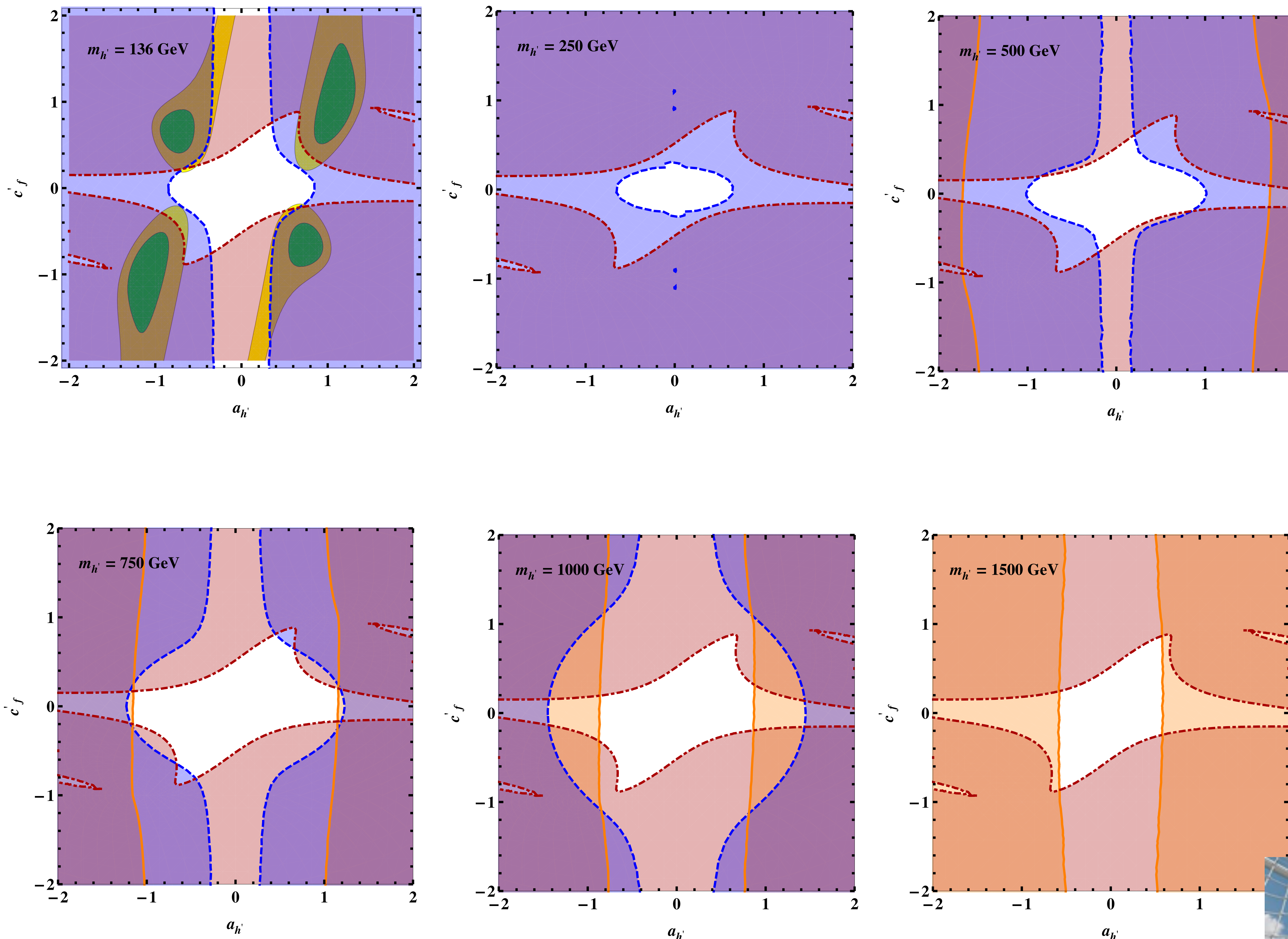
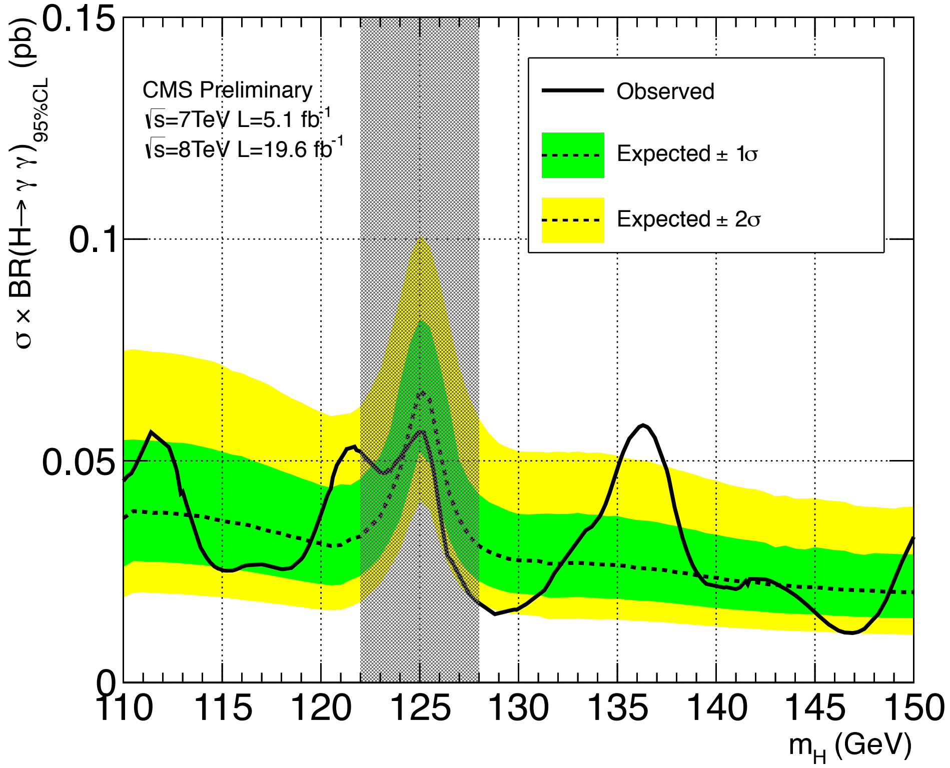


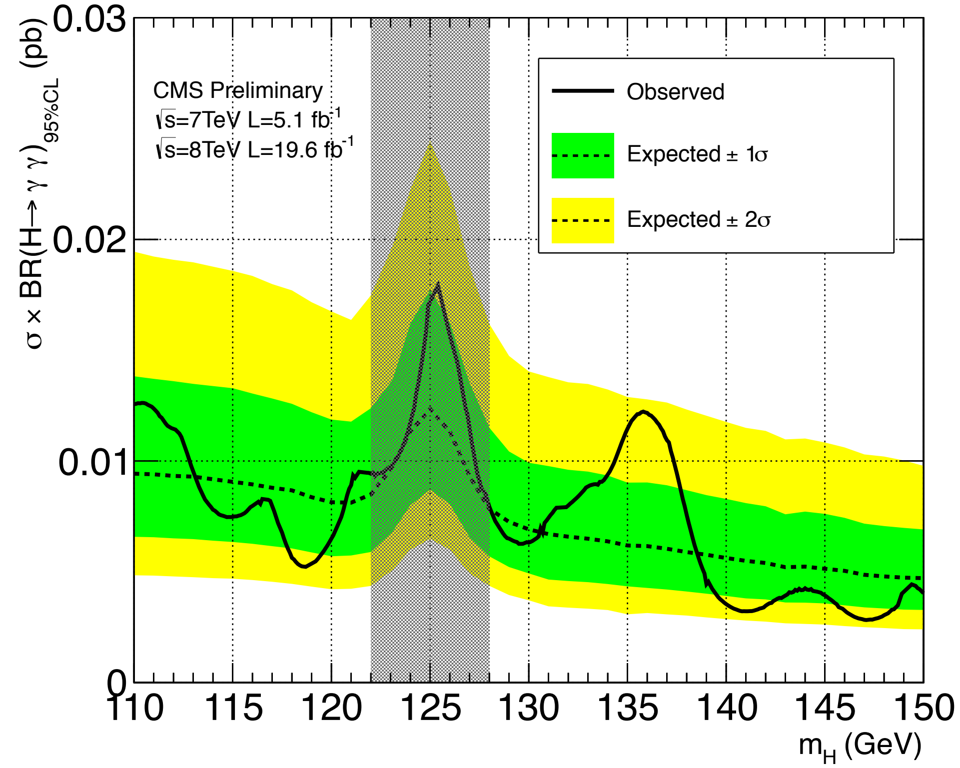
score

CMS PAS HIG-13-016:

$$gg \to H + X$$

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





- Both cases similarly significant: p-value 2.73σ (left) 2.15σ (right)
- Values similar to those of SM higgs; our calculation:

$$\sigma_{ggF} \times BR(h' \to \gamma\gamma) = 0.036 \pm 0.013 \text{ pb},$$
$$\sigma_{VBF+Vh'} \times BR(h' \to \gamma\gamma) = 0.007 \pm 0.003 \text{ pb}.$$

$$\Rightarrow$$

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

"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 little-to-nothing …
- Take this as a playground to develop methods and ideas