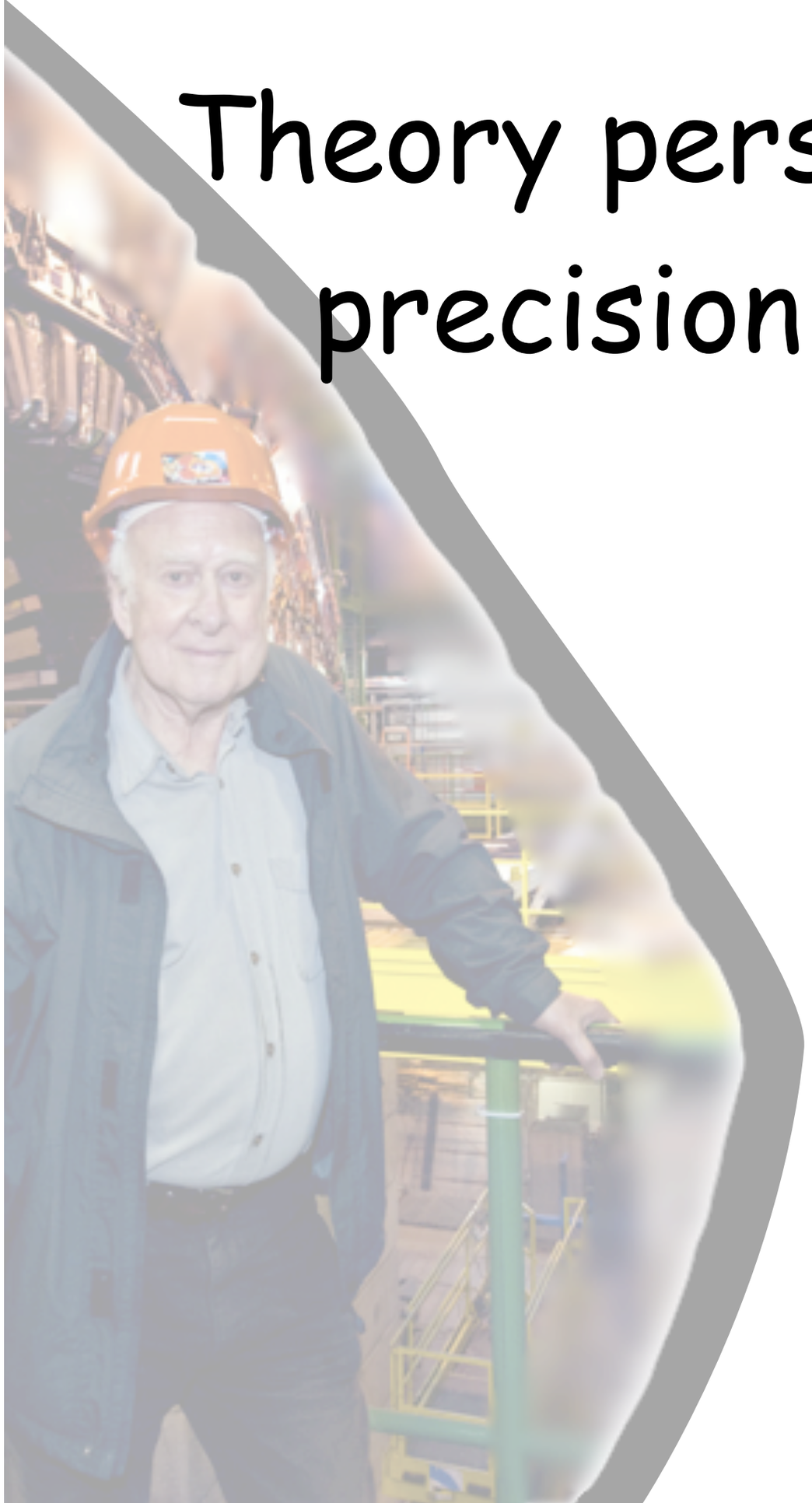
Theory perspective on precision Higgs measurements



EuCARD LEP3

CERN, 18 June 2012

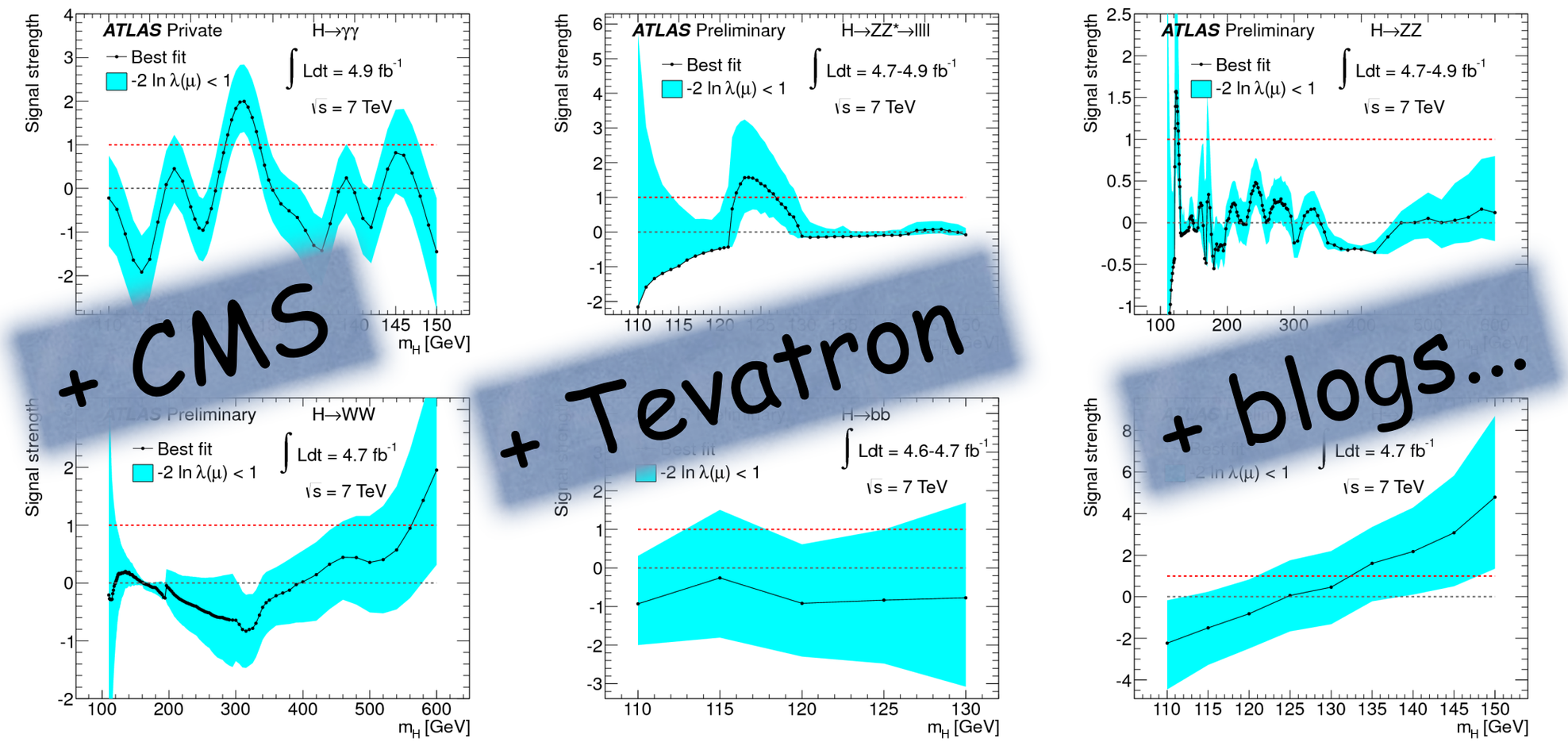
Christophe Grojean

CERN-TH

(christophe.grojean@cern.ch)

Facts that we have to live with

signal strength $$\mu_i = \frac{\sum_j \mathcal{A}_{ji}\,\sigma(j \to h) \times \mathrm{Br}(h \to i)}{\sum_j \mathcal{A}_{ji}\,\sigma(j \to h) \times \mathrm{Br}(h \to i)\,|_{\mathrm{SM}}}$$



Still not enough information:

Correlations?

Exact likelihoods?

Chiral Lagrangian for a light Higgs

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_h^2 h^2 - \frac{d_3}{6}\left(\frac{3m_h^2}{v}\right)h^3 - \frac{d_4}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 \ldots$$

$$- \left(m_W^2\, W_\mu W_\mu + \frac{1}{2}m_Z^2\, Z_\mu Z_\mu\right)\left(1 + 2a\,\frac{h}{v} + b\,\frac{h^2}{v^2} + \ldots\right)$$

$$- \sum_{\psi=u,d,l} m_{\psi^{(i)}}\, \bar{\psi}^{(i)}\psi^{(i)}\left(1 + c_\psi\frac{h}{v} + c_{2\psi}\frac{h^2}{v^2} + \ldots\right)$$

$$+ \frac{g^2}{16\pi^2}\left(c_{WW}\, W^+_{\mu\nu}W^-_{\mu\nu} + c_{ZZ}\, Z^2_{\mu\nu} + c_{Z\gamma}\, Z_{\mu\nu}\gamma_{\mu\nu}\right)\frac{h}{v} + \ldots$$

$$+ \frac{g^2}{16\pi^2}\left[\gamma^2_{\mu\nu}\left(c_{\gamma\gamma}\frac{h}{v} + \ldots\right) + G^2_{\mu\nu}\left(c_{gg}\frac{h}{v} + c_{2gg}\frac{h^2}{v^2}\ldots\right)\right]$$

$$+ \frac{g^2}{16\pi^2}\left[\frac{c_{hhgg}}{\Lambda^2}G^2_{\mu\nu}\frac{(\partial_\rho h)^2}{v^2} + \frac{c'_{hhgg}}{\Lambda^2}G_{\mu\rho}G_{\rho\nu}\frac{\partial_\mu h\partial_\nu h}{v^2} + \ldots\right]$$

$$+ \ldots$$

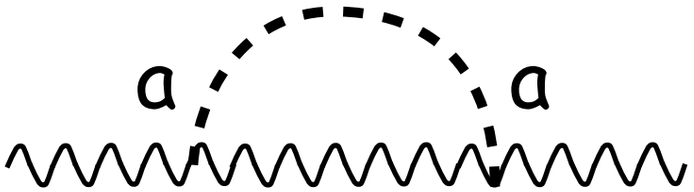
A few (reasonable) assumptions:

- ☑ spin-0 & CP-even
  - $\gamma\gamma$
  - WW & ZZ
- ☑ custodial symmetry
  - EWPD
- ☑ no Higgs FCNC
  - Flavor

Contino, Grojean, Moretti, Piccinini, Rattazzi '10 Azatov, Contino, Galloway '12

EW constraints

The parameter 'a' controls the size of the one-loop IR contribution to the LEP precision observables



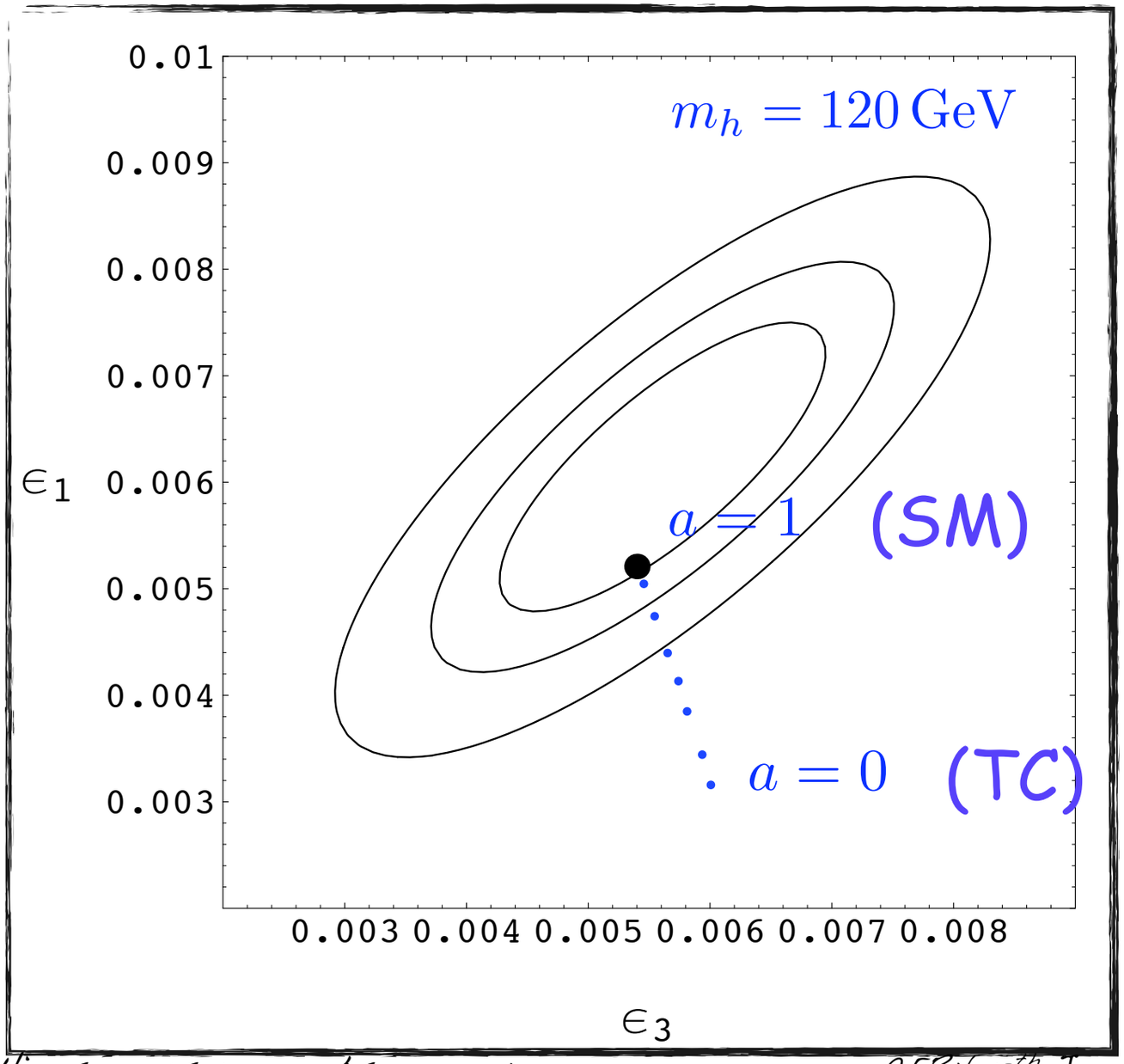
$$\epsilon_{1,3} = c_{1,3}\log(m_Z^2/\mu^2) - c_{1,3}\,a^2\log(m_h^2/\mu^2) - c_{1,3}\,\left(1-a^2\right)\log(m_\rho^2/\mu^2) + \text{finite terms}$$

$$c_1 = +\frac{3}{16\pi^2}\frac{\alpha(m_Z)}{\cos^2\theta_W}$$

$$c_3 = -\frac{1}{12\pi}\frac{\alpha(m_Z)}{4\sin^2\theta_W}$$

$$\Delta\epsilon_{1,3} = -c_{1,3}\left(1-a^2\right)\log(m_\rho^2/m_h^2)$$

Barbieri, Bellazzini, Rychkov, Varagnolo '07

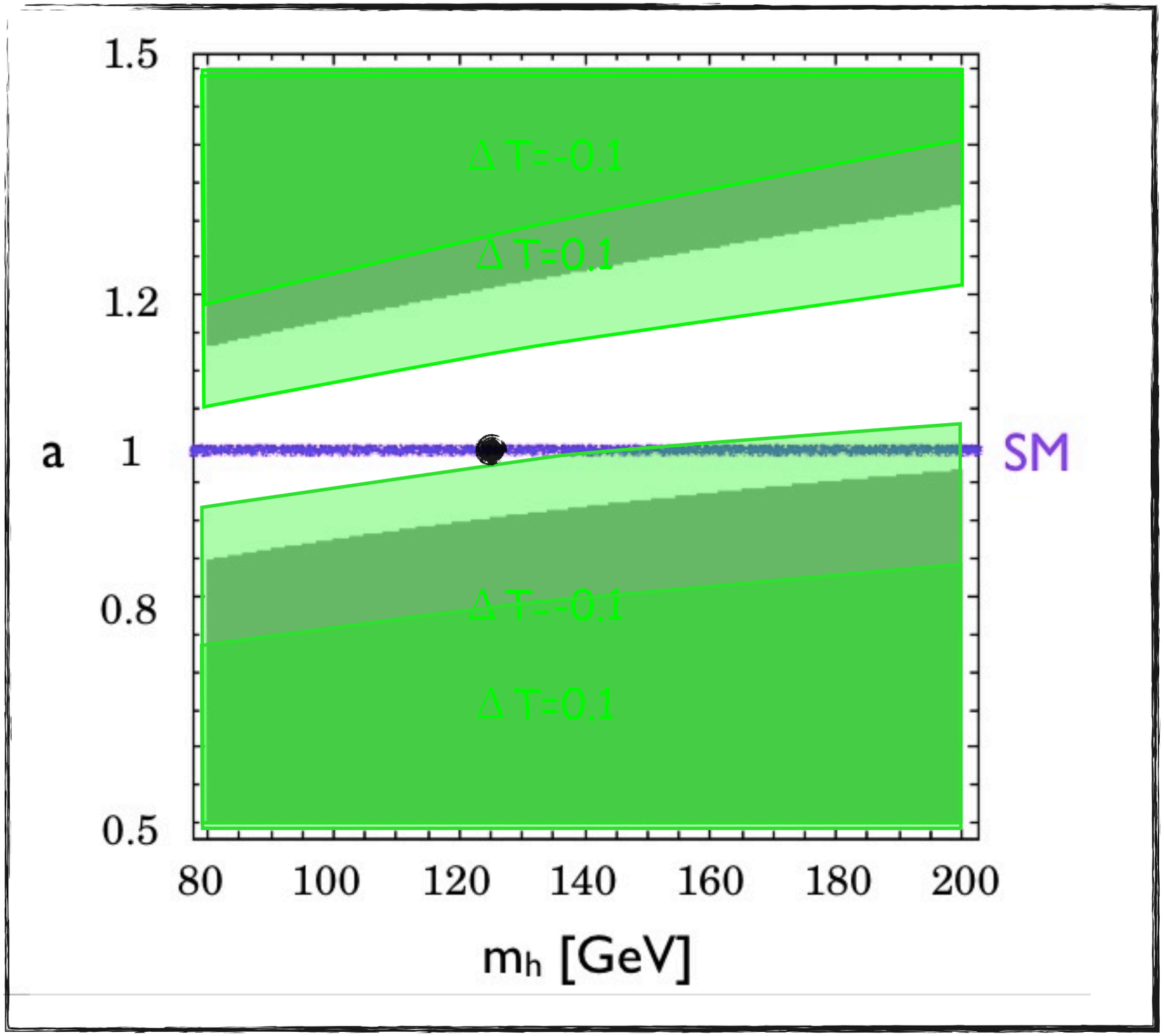


EW data constraints on 'a'

EW fit with SM degrees of freedom + (composite) Higgs

- EW data require less than 15-20% deviations in the couplings of the Higgs to gauge bosons
- EW data don't constraint the other Higgs couplings

note:
additional UV contributions to S and T can modify the preferred values of couplings



Chiral Lagrangian for a light Higgs @ LHC

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$$- \left(m_W^2\, W_\mu W_\mu + \frac{1}{2}m_Z^2\, Z_\mu Z_\mu\right)\left(1 + 2a\,\frac{h}{v} + b\,\frac{h^2}{v^2} + \ldots\right)$$

$$- \sum_{\psi=u,d,l} m_{\psi^{(i)}}\, \bar{\psi}^{(i)}\psi^{(i)}\left(1 + c_\psi\,\frac{h}{v} + \ldots\right)$$

$$+ \frac{g^2}{16\pi^2}\left[\frac{c_\gamma}{m_W^2}\, F_{\mu\nu}^2 + \frac{c_W}{m_W^2}\, W_{\mu\nu}^{+}W_{\mu\nu}^{-} + \frac{c_Z}{m_Z^2}\, Z_{\mu\nu}^2 + \ldots\right]$$

$$+ \frac{g^2}{16\pi^2}\left[\frac{c_{hhgg}}{\Lambda^2}\, G_{\mu\nu}^2\,\frac{(\partial_\rho h)^2}{v^2} + \frac{c'_{hhgg}}{\Lambda^2}\, G_{\mu\rho}G_{\rho\nu}\,\frac{\partial_\mu h\partial_\nu h}{v^2} + \ldots\right]$$

$$+ \ldots$$

still too much freedom

⇓

dynamical assumptions needed

⇓

to explore deformations of the SM

A few (reasonable) assumptions:

- ☑ spin-0 & CP-even
  - ↖ $\gamma\gamma$
  - ↖ WW & ZZ
- ☑ custodial symmetry
  - ↖ EWPD
- ☑ no Higgs FCNC
  - ↖ Flavor

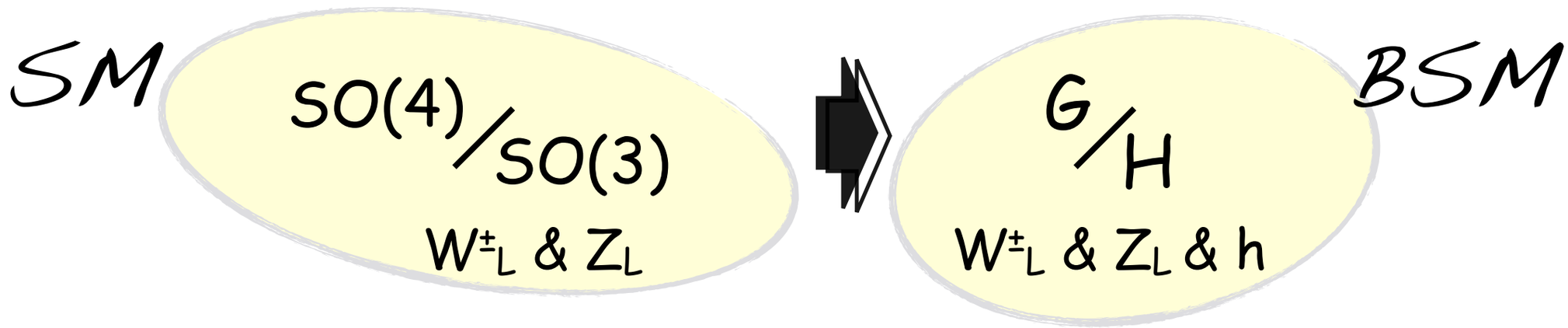
Contino, Grojean, Moretti, Piccinini, Rattazzi '10

Azatov, Contino, Galloway '12

The New Physics Mass Gap

One solution to the hierarchy pb:
Higgs transforms non-linearly under some global symmetry

Higgs=Pseudo-Goldstone boson (PGB)



Examples: SO(5)/SO(4): 4 PGBs=$W^{\pm}_L$, Z_L, h ← Minimal Composite Higgs Model

Agashe, Contino, Pomarol '04

SO(6)/SO(5): 5 PGBs=H, a ← Next MCHM

Gripaios, Pomarol, Riva, Serra '09

SU(4)/Sp(4,$\mathbb{C}$): 5 PGBs=H, s

SO(6)/SO(4)xSO(2): 8 PGBs=H_1+H_2 ← Minimal Composite Two Higgs Doublets

Mrazek, Pomarol, Rattazzi, Serra, Wulzer '11

The New Physics Mass Gap

One solution to the hierarchy pb:
Higgs transforms non-linearly under some global symmetry

Higgs=Pseudo-Goldstone boson (PGB)

SM $SO(4)/SO(3)$ $W^{\pm}_L$ & Z_L ⇒ G/H $W^{\pm}_L$ & Z_L & h BSM

How can we tell the difference with the SM Higgs?

What are the experimental constraints?

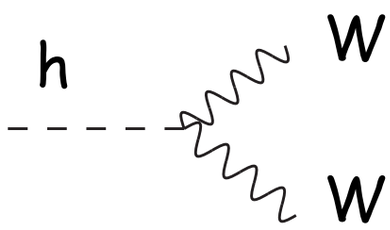
2 parameter Higgs physics @ LHC$_{2011\text{-}2012}$

$$\frac{c_H}{2f^2}\left(\partial^\mu |H|^2\right)^2$$

$$\xi = v^2/f^2$$

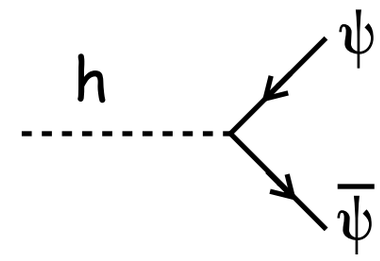
$$\frac{c_y y_\psi}{f^2}|H|^2\bar{\psi}_L H \psi_R$$

Controls the hWW, hZZ couplings



$$a\, g^{SM}_{hVV}$$

Controls the hψψ couplings



$$c\, g^{SM}_{h\psi\psi}$$

Explicit (and calculable) models built in AdS$_5$ spacetimes

Agashe, Contino, Pomarol '04

Contino, Da Rold, Pomarol '06

MCHM5

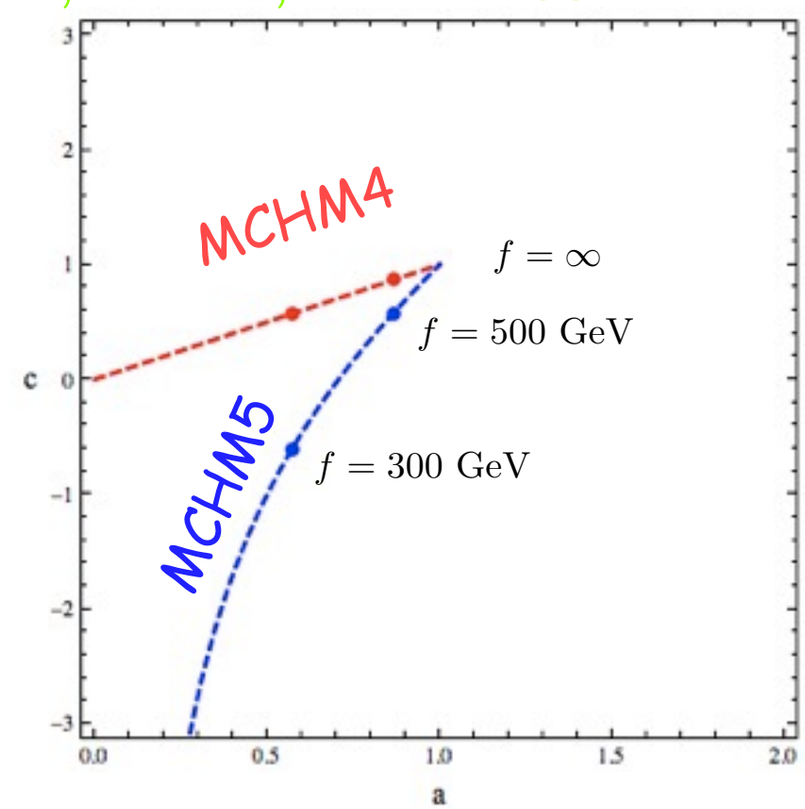
$$a = \sqrt{1-\xi} \qquad c = \frac{1-2\xi}{\sqrt{1-\xi}}$$

MCHM4

$$a = \sqrt{1-\xi} \qquad c = \sqrt{1-\xi}$$

disfavored by EW data (Zbb)

SM is recovered
as a limit when
the compositeness scale
is well above weak scale



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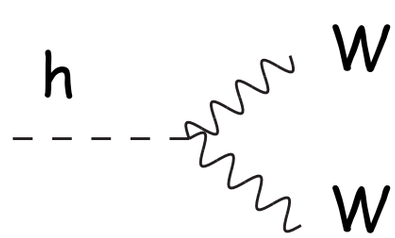
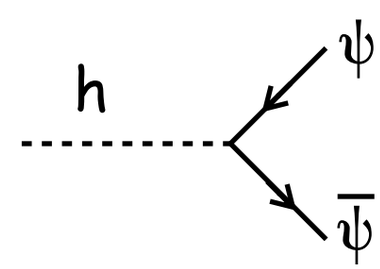


$$a\, g^{SM}_{hVV}$$

$$a = 1 - c_H\, \xi/2$$

Controls the hψψ couplings

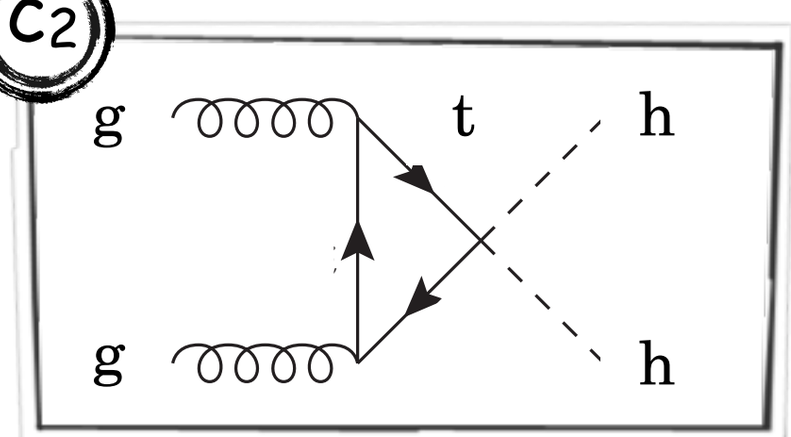


$$c\, g^{SM}_{h\psi\psi}$$

$$c = 1 - (c_H + 2c_y)\, \xi/2$$

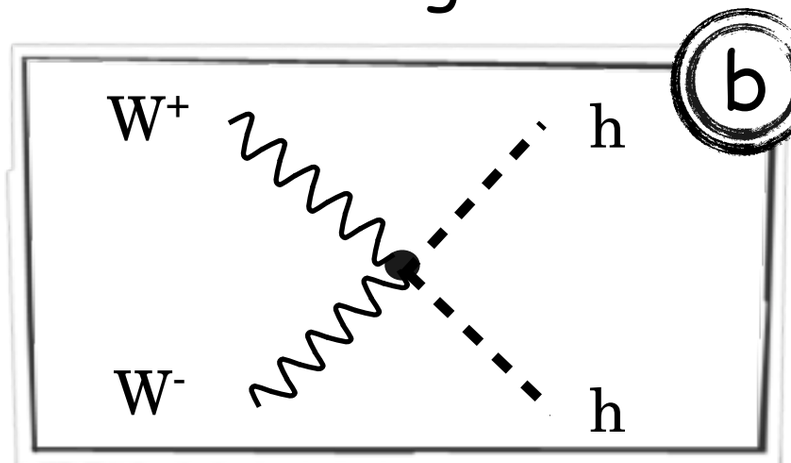
other couplings are very interesting as they are directly testing non-linearities/strong interactions of the Higgs

c_2



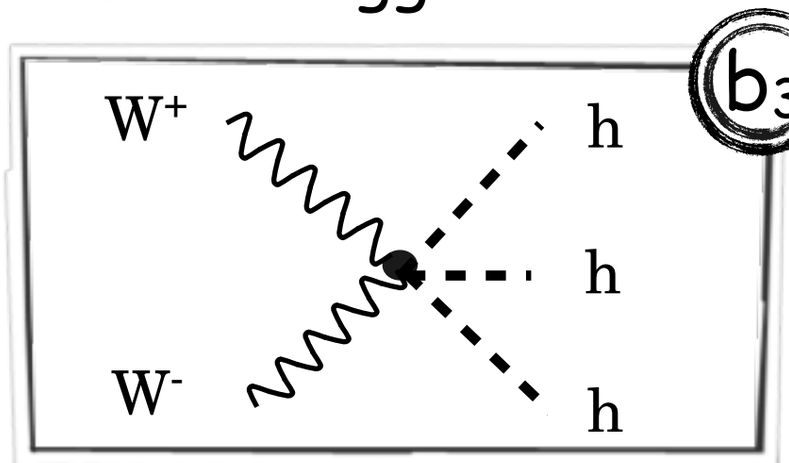
Grôber, Mûhlleitner '10
Contino et al '12
Gillioz et al 'to appear

b



Contino, Grojean,
Moretti, Piccinini, Rattazzi '10

b_3



Contino, Grojean, Pappadopoulo,
Rattazzi, Thamm 'to appear

but they are not on agenda of the current LHC run

2 parameter Higgs physics @ LHC$_{2011\text{-}2012}$

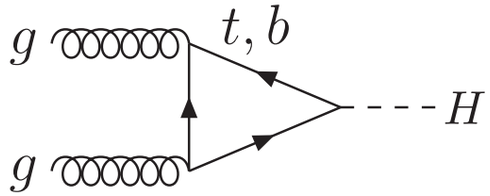
- Higgs couplings modified w.r.t. SM but same kinematics

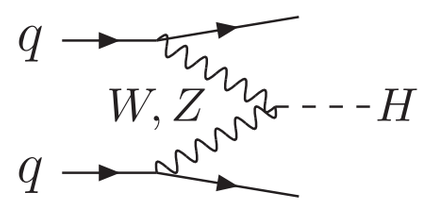
  (particular to single Higgs process - with more than one Higgs, sensitive to derivative couplings)

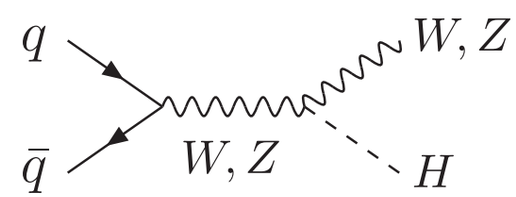
- Background processes unaffected

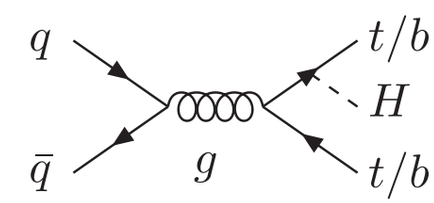
$\Downarrow$ $\Downarrow$ $\Downarrow$

simple rescaling of SM searches









$\frac{\sigma_{NLO}}{\sigma_{NLO}^{SM}}$ c^2 a^2 a^2 c^2

The QCD NLO rescale trivially in the flavor universal limit. Not the EW NLO

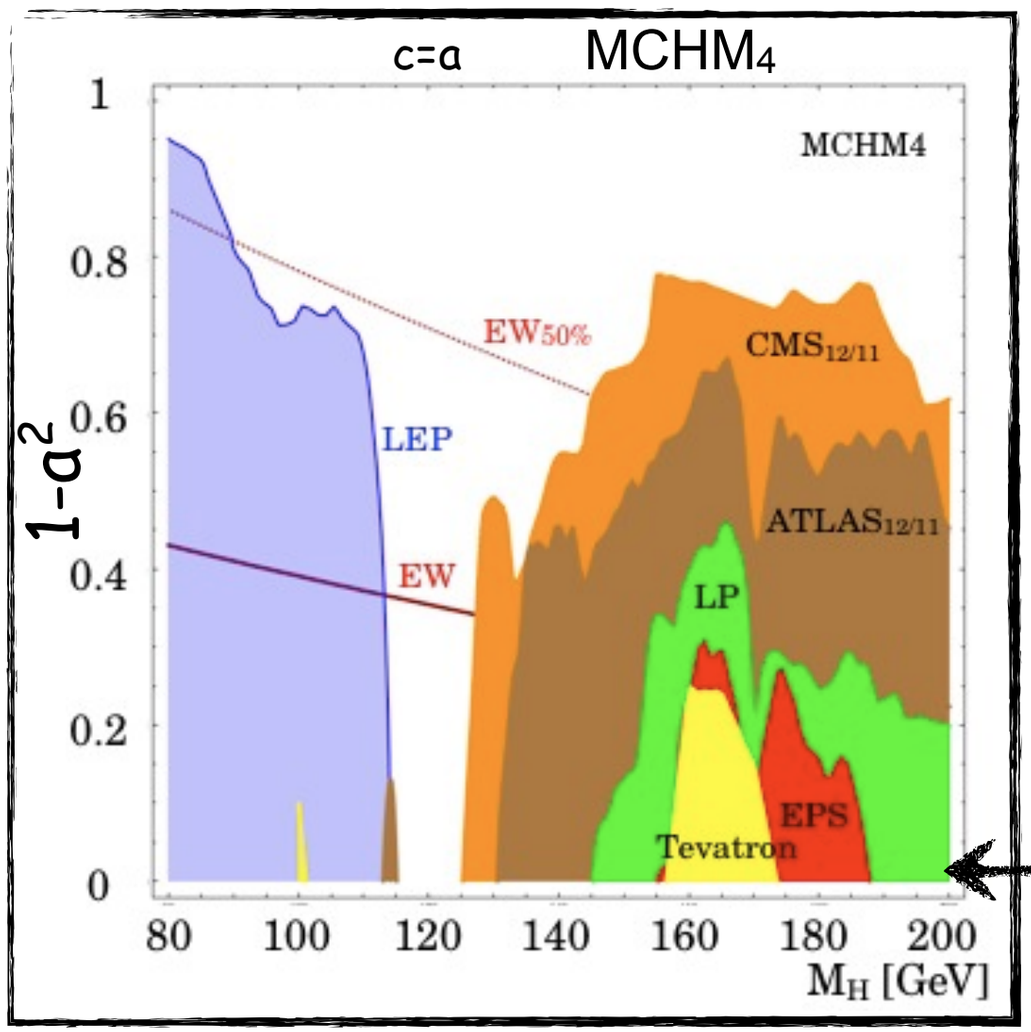
$$\Gamma(H \to f\bar{f}) = c^2\, \Gamma^{SM}(H \to f\bar{f})\,,$$
$$\Gamma(H \to VV) = a^2\, \Gamma^{SM}(H \to VV)\,,$$
$$\Gamma(H \to gg) = c^2\, \Gamma^{SM}(H \to gg)\,,$$
$$\Gamma(H \to \gamma\gamma) = \frac{(cI_\gamma + aJ_\gamma)^2}{(I_\gamma + J_\gamma)^2}\Gamma^{SM}(H \to \gamma\gamma)\,,$$

$\simeq (1.26\,a - 0.26\,c)^2$ for m_h=125GeV

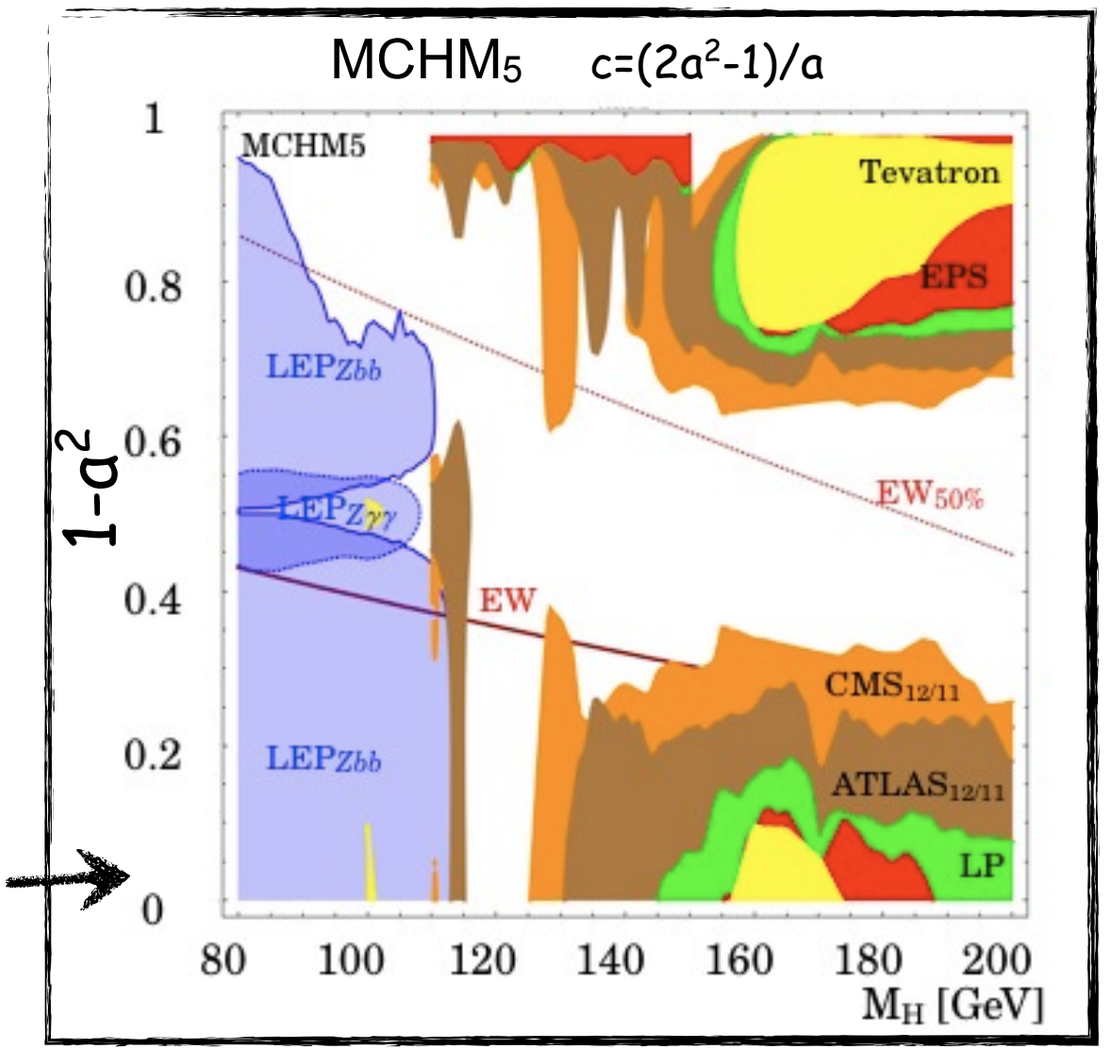
Deformation of the SM Higgs: current constraints

the SM exclusion bounds are easily rescaled in the (m_H,a) plane

Espinosa, Grojean, Muehlleitner '11



SM limits



the LHC can do much more than simply excluding the SM Higgs

for similar analysis, see also Azatov, Contino, Galloway '12

Model independent χ^2 fit to LHC excess @ 125

Espinosa, Grojean, Muhlleitner, Trott '12

Atlas 95%CL exclusion

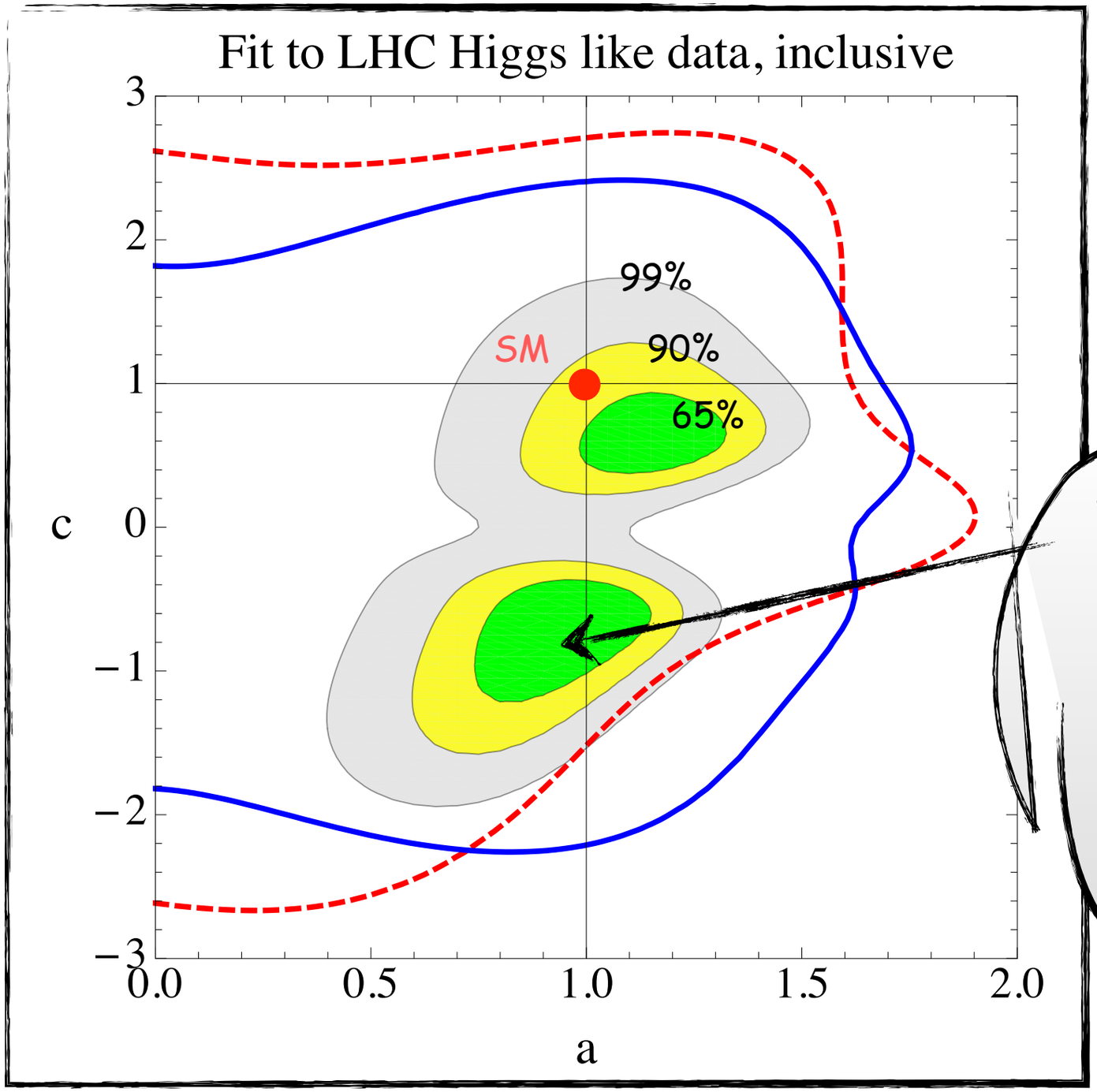
CMS 95%CL exclusion

SM 82%CL away from best fit point

Two minima:

(a,c)=(1.13,0.58)
χ^2=2.86

(a,c)=(0.96,-0.64)
χ^2=1.96



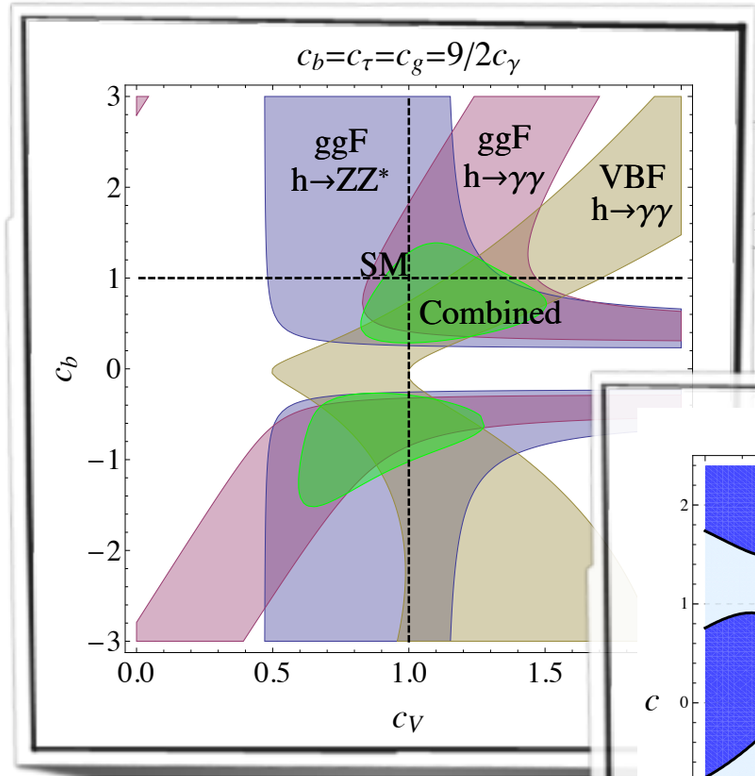
note: a fermiophobic Higgs is disfavored by data (mostly VBF channels)

"disfermiophilia"

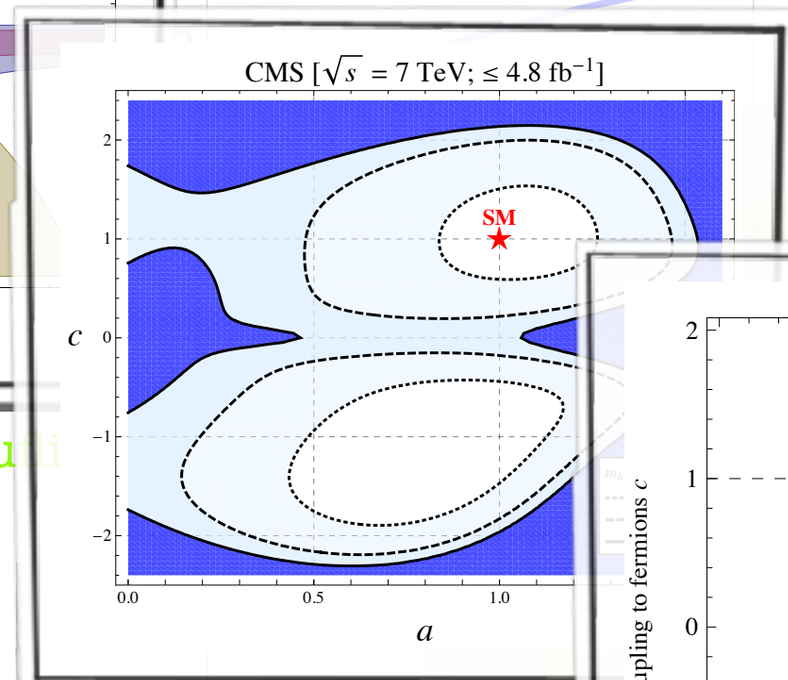
the current data prefers "negative" coupling to fermions
≈
positive interference between top and W in $\gamma\gamma$ channel

Model independent χ^2 fit to LHC excess @ 125

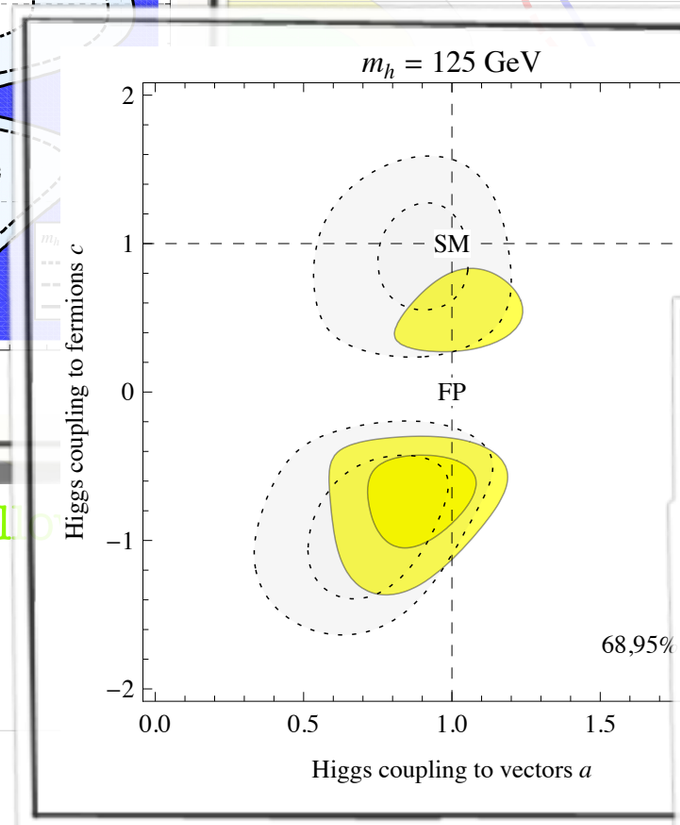
Espinosa, Grojean, Muhlleitner, Trott '12



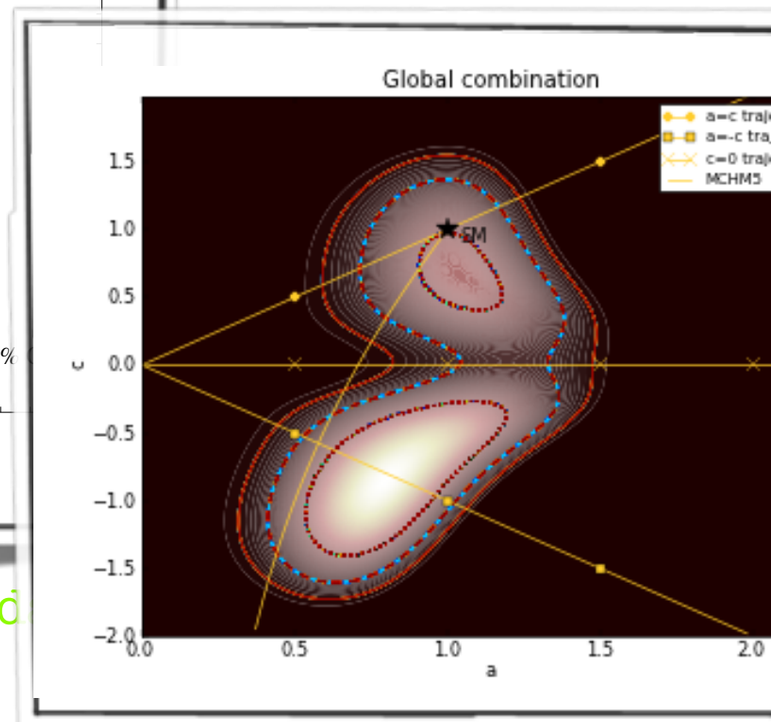
Carni, Falkowski, Ku
Volansky '12



Azatov, Contino, Gall
'12



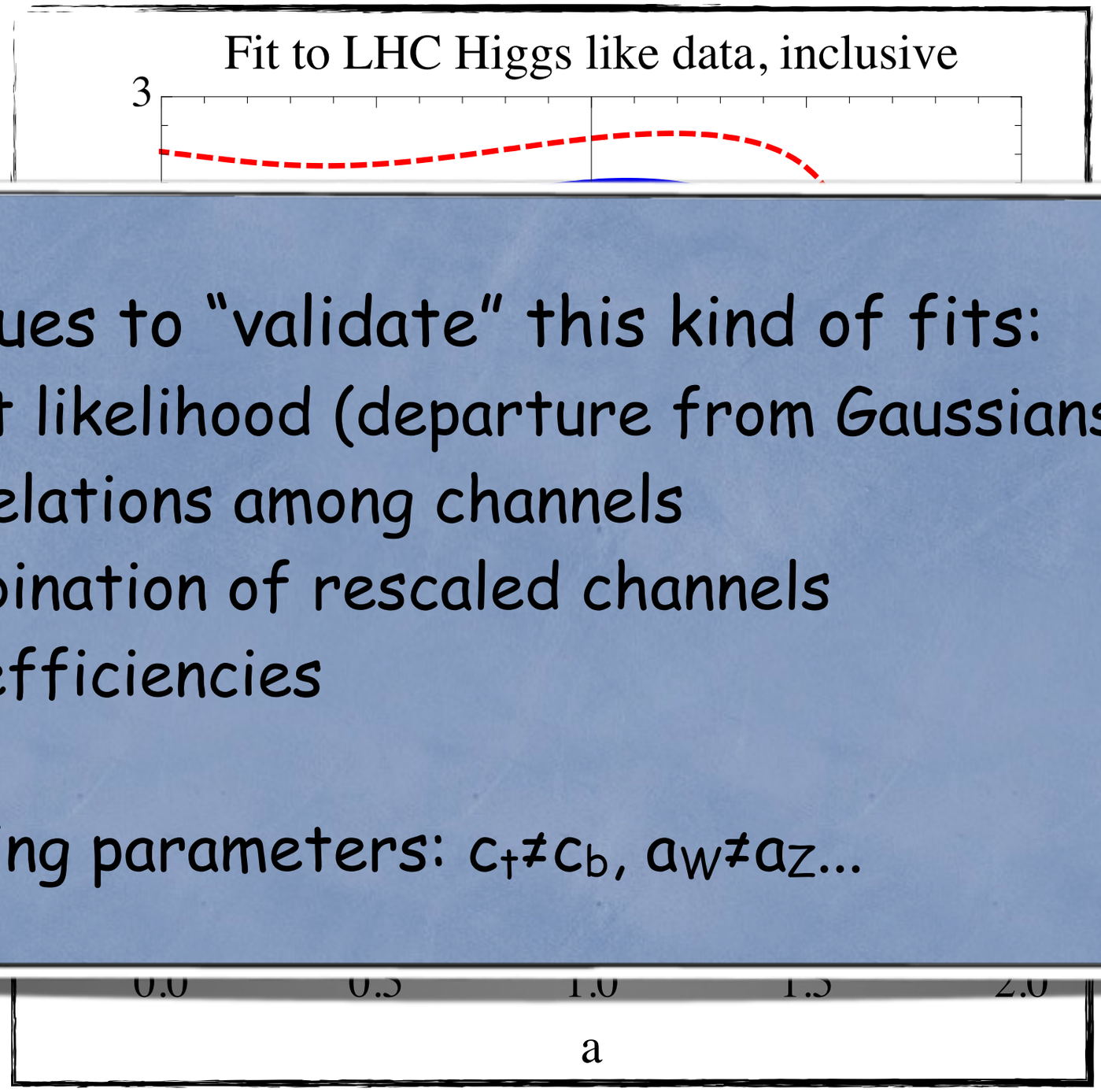
Giardino, Kannike, Raid
Strumia '12



Ellis, You '12

Model independent χ^2 fit to LHC excess @ 125

Espinosa, Grojean, Muhlleitner, Trott '12



Atlas 95%CL exclusion

CMS

note: a fermiophobic Higgs is disfavored by

many issues to "validate" this kind of fits:

1. exact likelihood (departure from Gaussians...)
2. correlations among channels
3. combination of rescaled channels
4. cut efficiencies
5. ...
6. missing parameters: $c_t \neq c_b$, $a_W \neq a_Z$...

(a,c)=(0.96,-0.64)

χ^2=1.96

for similar analyses, see also

Azatov, Contino, Galloway '12

Carni, Falkowski, Kuflik, Volansky '12

Model independent χ^2 fit to (Moriond) LHC data

Espinosa, Grojean, Muhlleitner, Trott '12

Atlas 95%CL exclusion

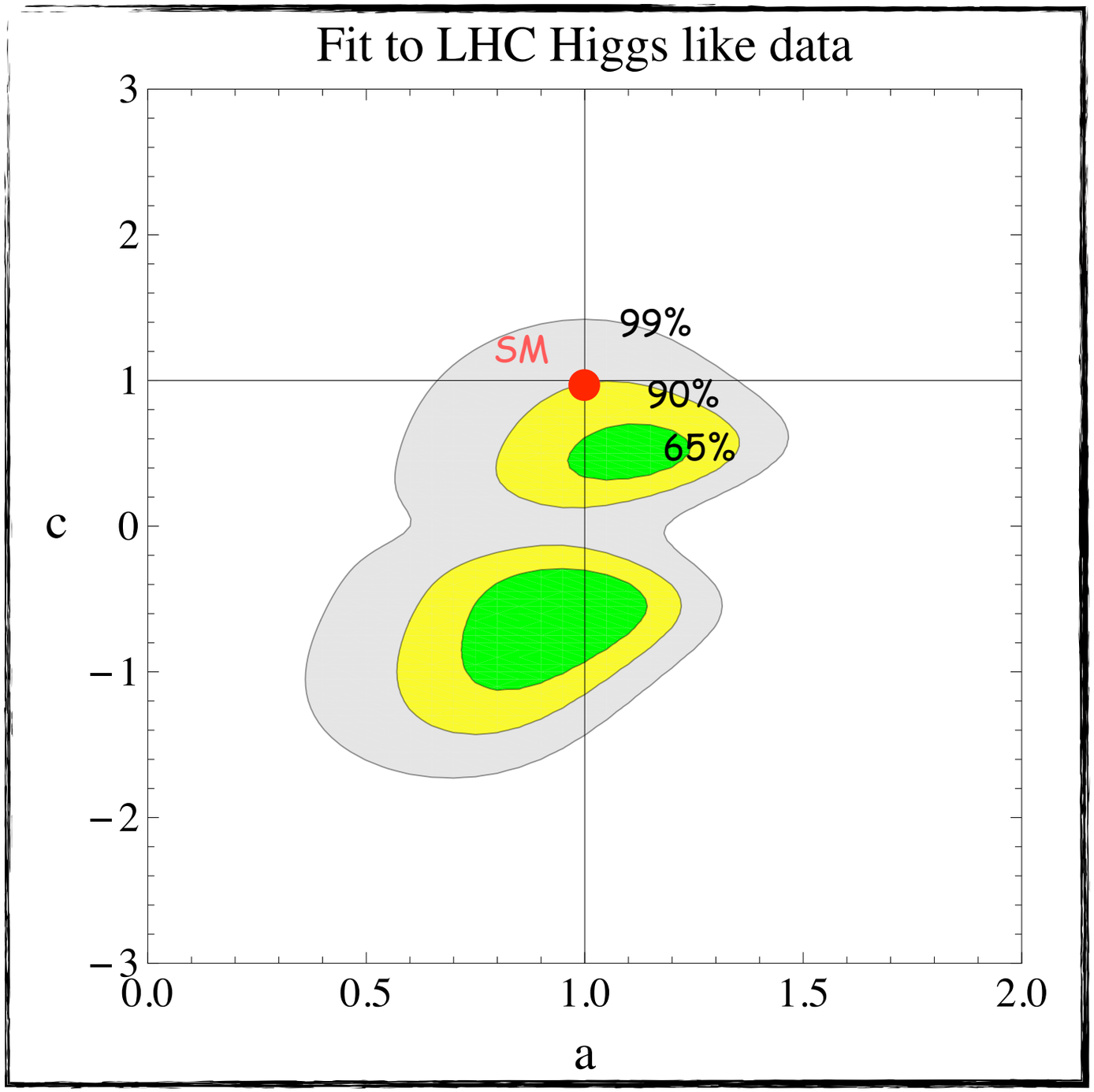
CMS 95%CL exclusion

SM 88%CL away from best fit point (~2σ)

Two minima:

(a,c)=(1.18,0.55)
χ^2=7.5

(a,c)=(0.99,-0.64)
χ^2=6.3



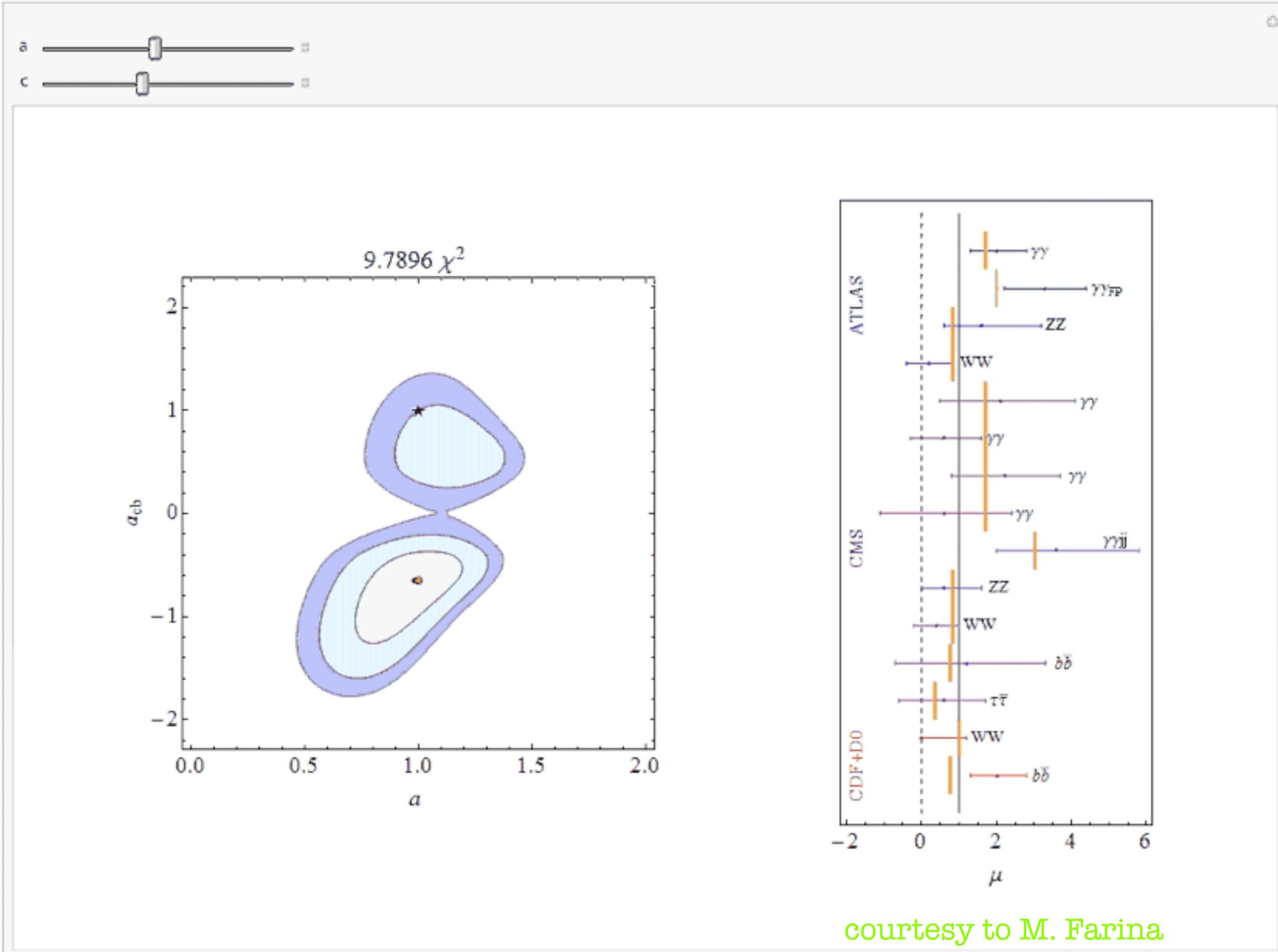
note: a fermiophobic Higgs is disfavored by data (mostly VBF channels) at 97%CL

for similar analyses, see also

Azatov, Contino, Galloway '12

Carni, Falkowski, Kuflik, Volansky '12

Model independent χ^2 fit to LHC data



courtesy to M. Farina

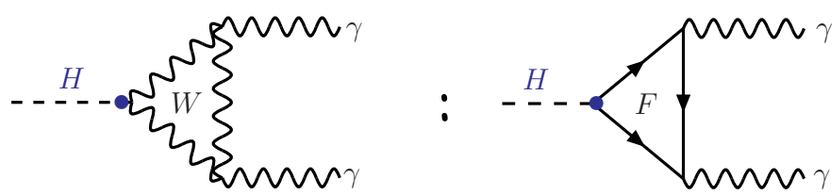
Fermiophilia or Disfermiophilia?

difficult!

Farina, Grojean, Maltoni, Salvioni, Thamm 'in progress

difference is physically relevant only in the presence of strong interference with single $h\psi\psi$ coupling

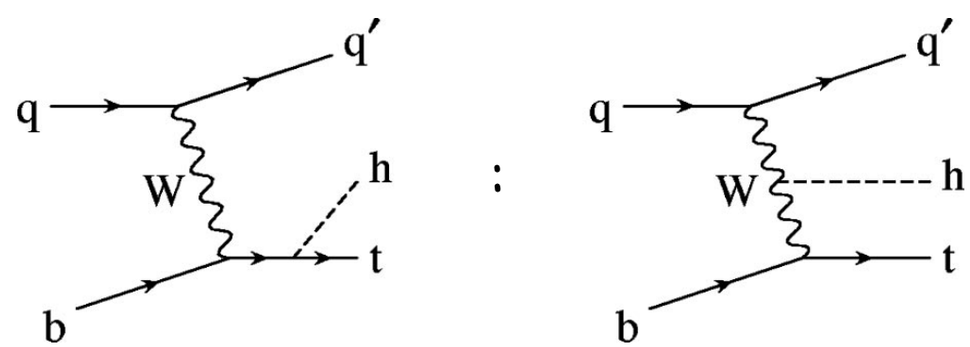
$h \to \gamma\gamma$



@m_H=125GeV $\quad \dfrac{|\mathcal{A}_W - \mathcal{A}_t|^2}{|\mathcal{A}_W + \mathcal{A}_t|^2} \approx 2.3$

rare decay and one needs some largish luminosity to be sensitive to the sign of c

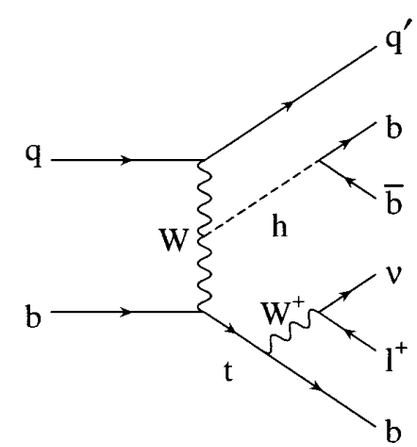
$qb \to q'th$



@m_H=125GeV $\quad \dfrac{|\mathcal{A}_W - \mathcal{A}_t|^2}{|\mathcal{A}_W + \mathcal{A}_t|^2} \approx 13$

Maltoni, Stelzer, Willenbrock '01

look at final state: $3\,b + 1\,\text{fwd jet} + l^{\pm} + \not{p}^T$.



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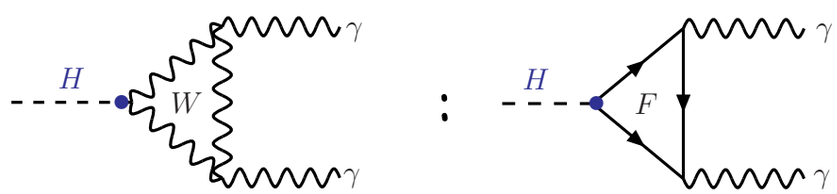

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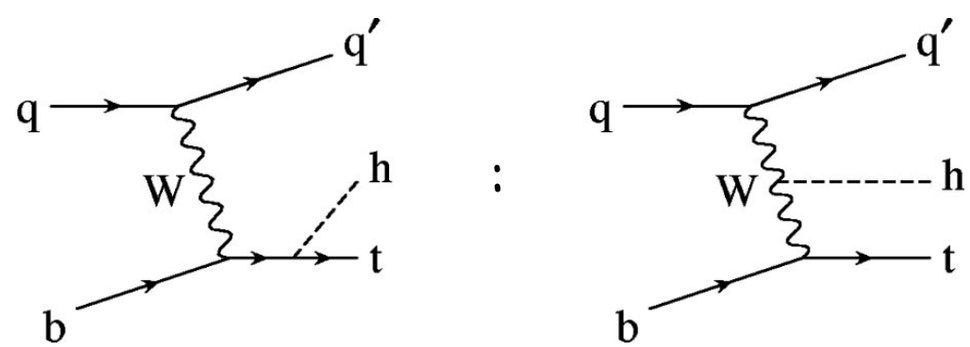
rare decay and one needs some largish luminosity to be sensitive to the sign of c

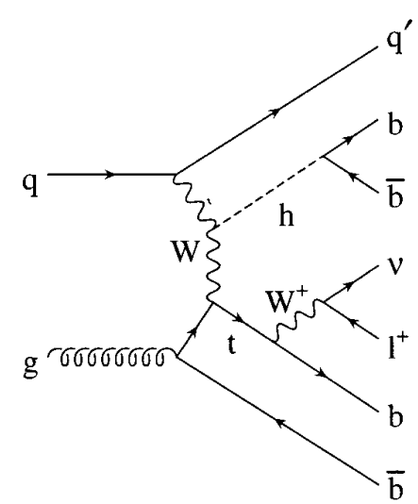
$qb \to q'th$



@m_H=125GeV $\quad \dfrac{|\mathcal{A}_W - \mathcal{A}_t|^2}{|\mathcal{A}_W + \mathcal{A}_t|^2} \approx 13$

Maltoni, Stelzer, Willenbrock '01

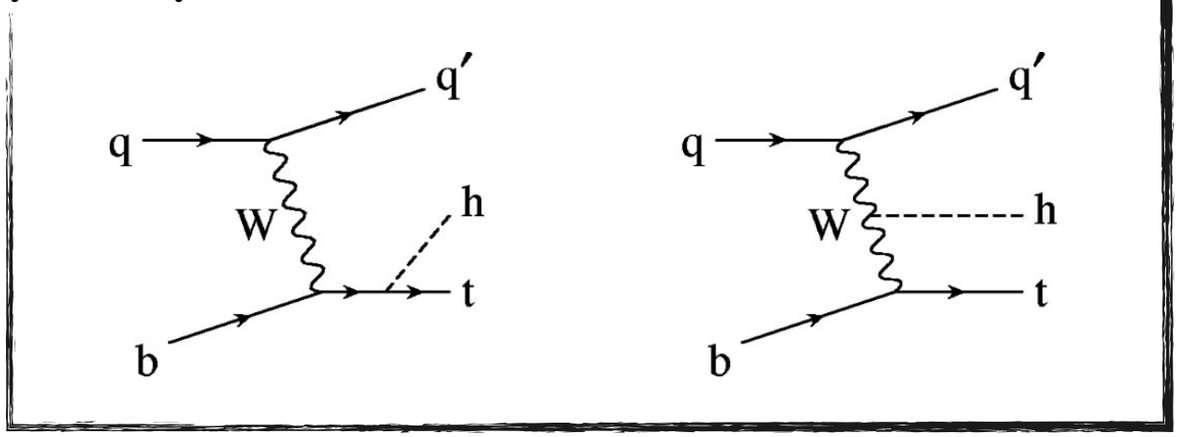
look at final state: $4\,b + 1\,\text{fwd jet} + l^{\pm} + \not{p}^T$.



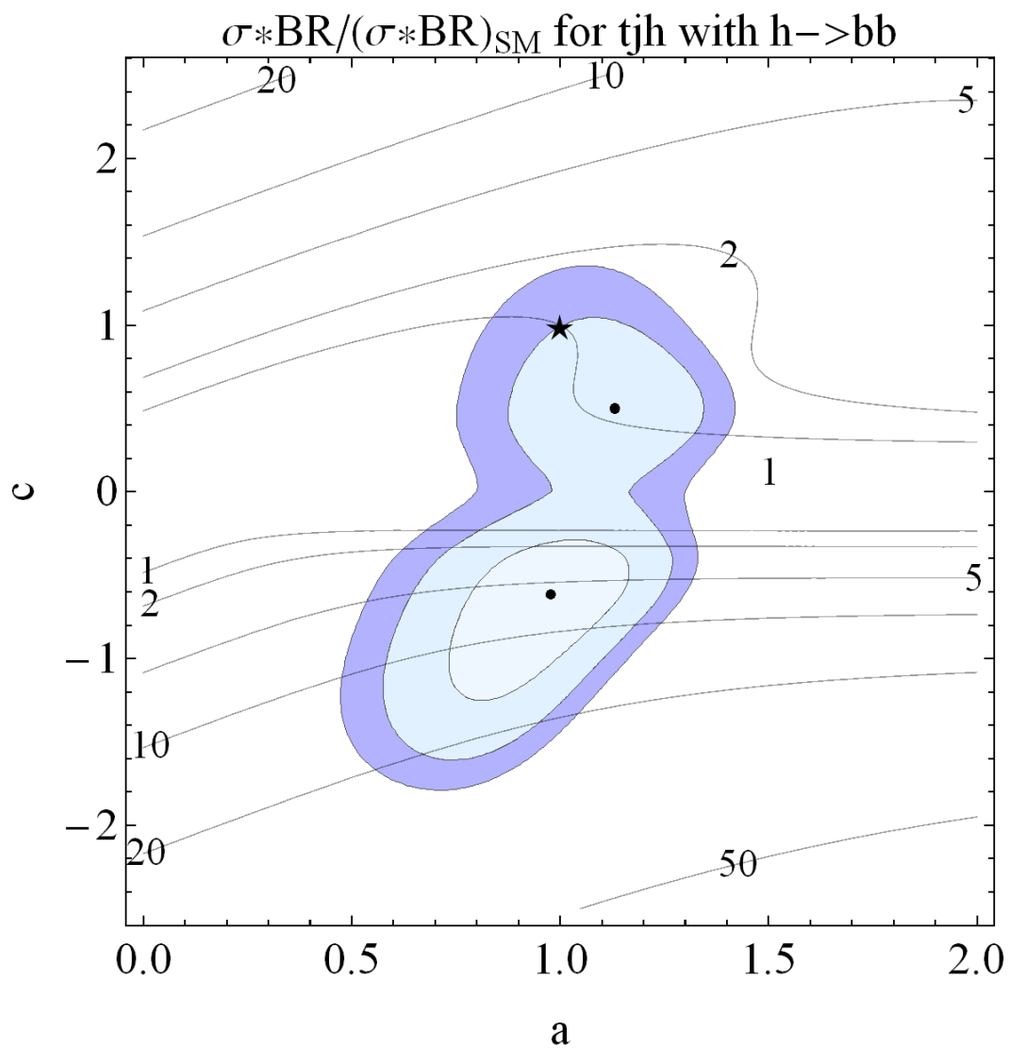
Fermiophilia or Disfermiophilia?

Farina, Grojean, Maltoni, Salvioni, Thamm 'in progress

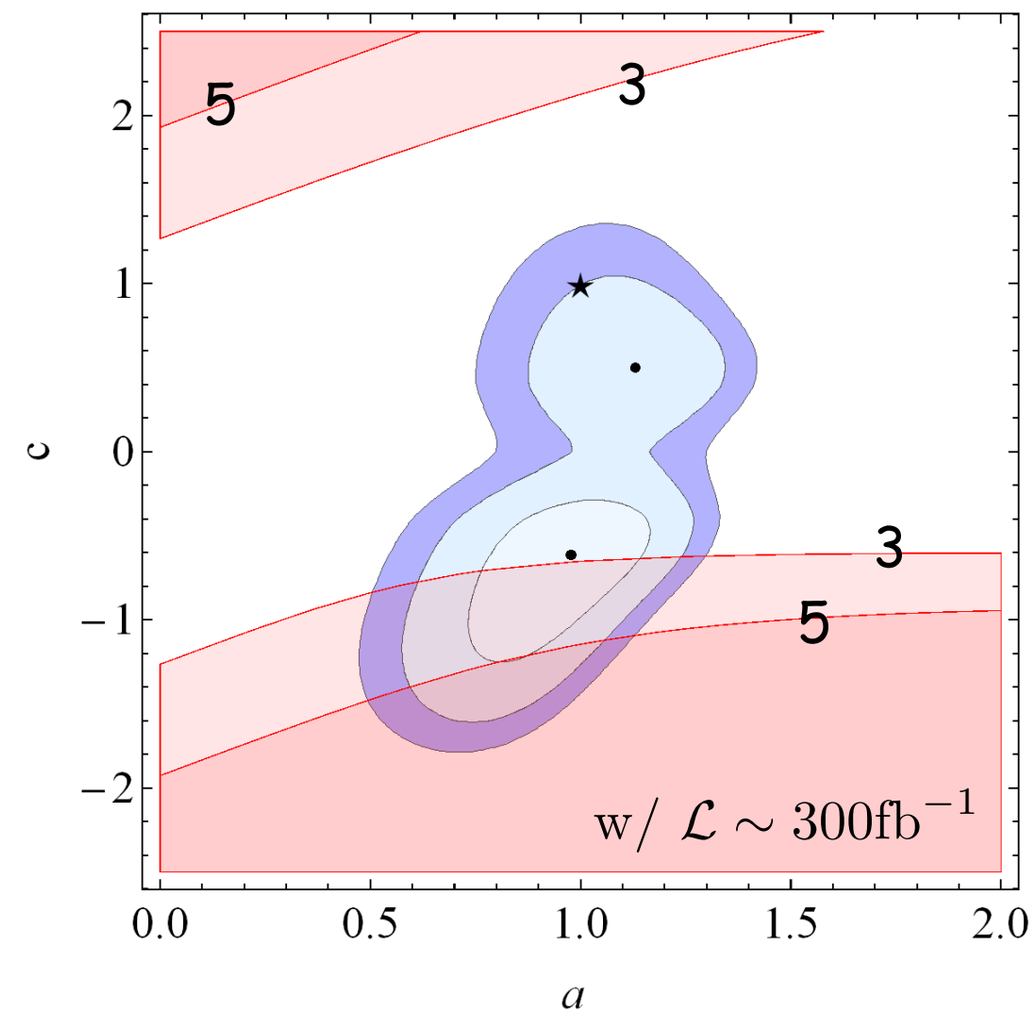
qb→q'th



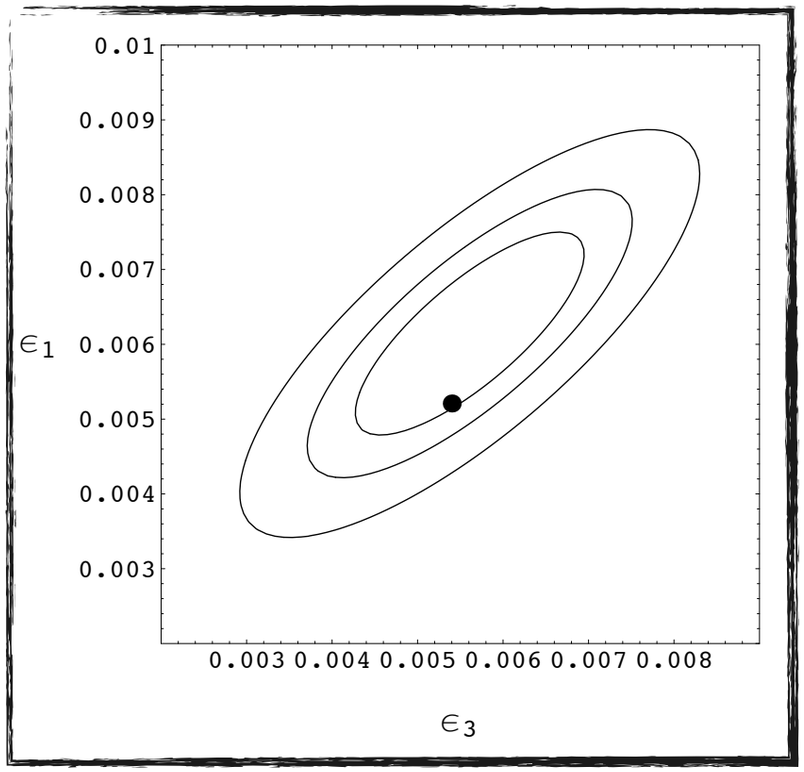
the sign ambiguity will remain with us for a long time!



$$S/\sqrt{S+B}$$



A tension between LHC and EW data?



EW fit strongly suggests custodial symmetry

$$\Sigma = e^{i\sigma^a \pi^a / v}$$

Goldstone of $SU(2)_L \times SU(2)_R / SU(2)_V$

$$\frac{v^2}{4} \mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right) \Rightarrow \rho = 1 \text{ ie } \epsilon_1 = \hat{T} = 0$$

✓

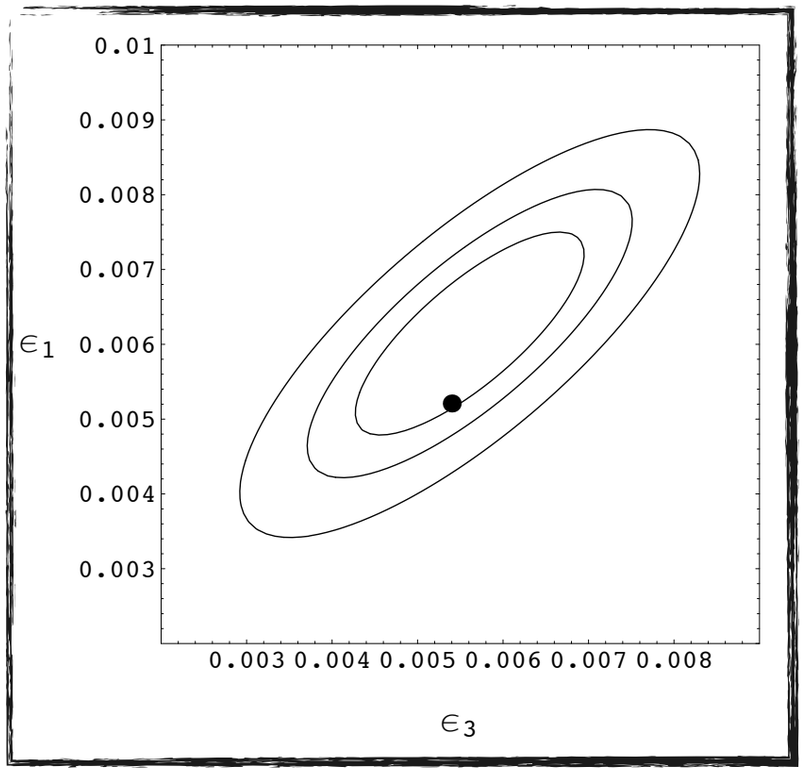
also $\Rightarrow$ $\mu_{ZZ} = \mu_{WW}$

$$\left(\mu_i = \frac{\sum_j \mathcal{A}_{ji}\, \sigma(j \to h) \times \mathrm{Br}(h \to i)}{\sum_j \mathcal{A}_{ji}\, \sigma(j \to h) \times \mathrm{Br}(h \to i)\, |_{\mathrm{SM}}} \right)$$

$$\frac{v^2}{8} \mathrm{Tr}^2\left(\Sigma^\dagger D_\mu \Sigma \sigma^3\right) \Rightarrow \rho = 2 \text{ ie } \epsilon_1 = \hat{T} = 1$$

strongly disfavored

A tension between LHC and EW data?



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✓

also $\Rightarrow$ $\mu_{ZZ} = \mu_{WW}$ ✗

but

Channel [Exp]	$\mu_{119.5}$ ($\mu^L_{119.5}$)	μ_{124} (μ^L_{124})	μ_{125} (μ^L_{125})
$pp \to Z\,Z^\star \to \ell^+\,\ell^-\,\ell^+\,\ell^-$ [ATLAS]	$-0.5^{+0.5??}$ (5.1)	$1.6^{+1.4}_{-0.8}$ (4.7)	$1.4^{+1.3}_{-0.8}$ (4.1)
$pp \to W\,W^\star \to \ell^+\,\nu\,\ell^-\,\bar{\nu}$ [ATLAS]	$0.0^{+1.2}_{-1.3}$ (2.4)	$0.1^{+0.7}_{-0.7}$ (1.6)	$0.1^{+0.7}_{-0.6}$ (1.4)

1. has LHC identified a violation of the custodial symmetry?
2. if yes, how to reconcile LHC data with EW data?

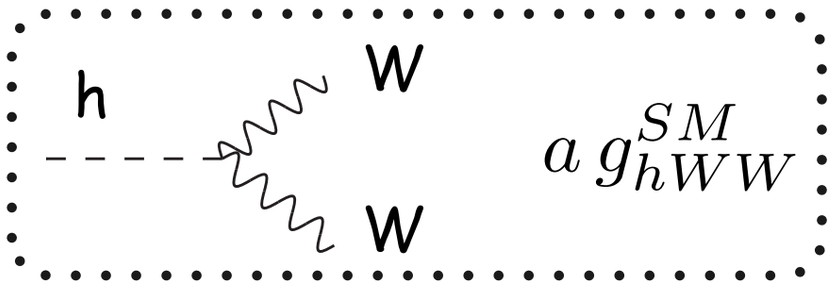
$$\frac{v^2}{8} \mathrm{Tr}^2\left(\Sigma^\dagger D_\mu \Sigma \sigma^3\right) \Rightarrow \rho = 2 \quad \text{ie} \quad \epsilon_1 = \hat{T} = 1$$

strongly disfavored

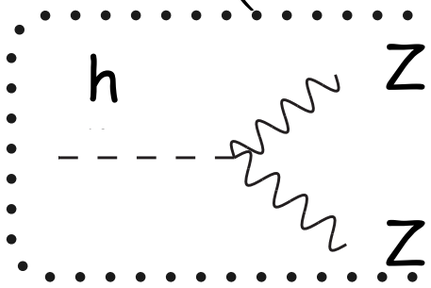
DisZphilia or how to live with custodial breaking

Farina, Grojean, Salvioni '12

$$\mathcal{L}_{cb} = -\frac{v^2}{8}\left(\mathrm{Tr}\left[\Sigma^\dagger D_\mu \Sigma\, \sigma^3\right]\right)^2 \left(t_{cb} + 2a_{cb}\frac{h}{v} + \cdots\right)$$

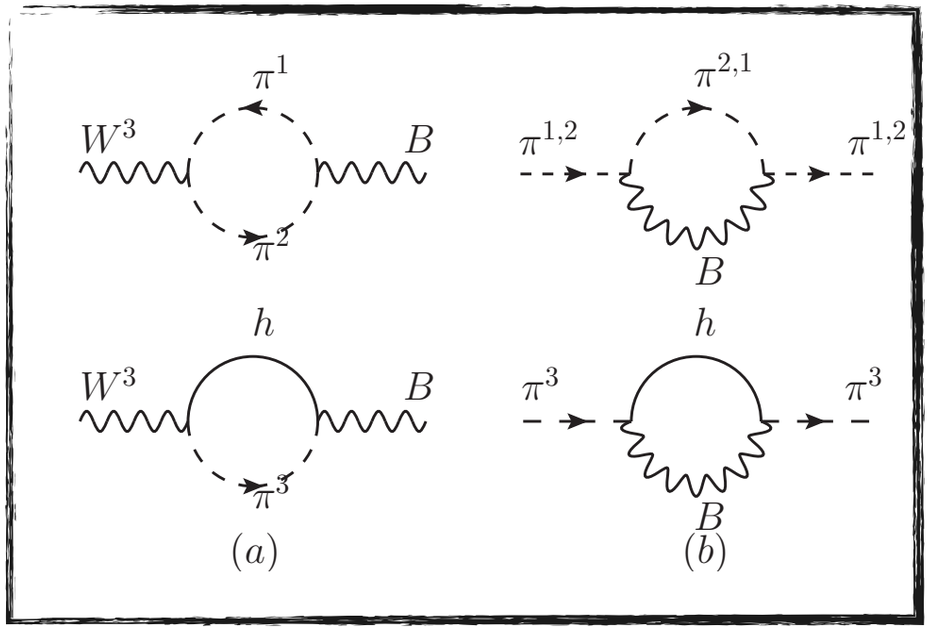


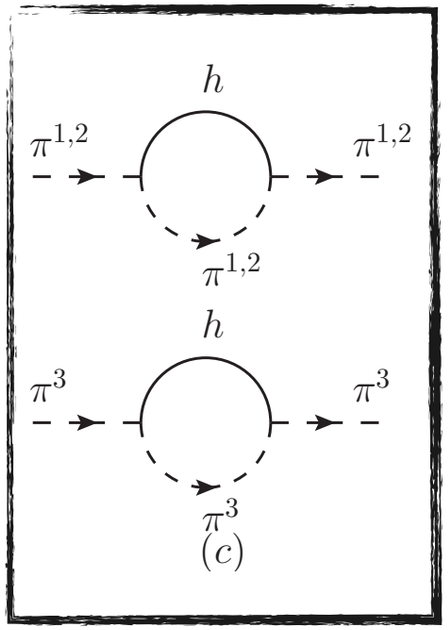
$a\, g^{SM}_{hWW}$



$(a + a_{cb})\, g^{SM}_{hZZ}$

EWPT





Log(Λ) UV sensitivity

Λ^2 UV sensitivity

$$\Delta\epsilon_1 = -\frac{3}{16\pi}\frac{\alpha(m_Z)}{\cos^2\theta_W}\left[1-(a+a_{cb})^2 + \left(\frac{g}{g'}\right)^2 (a^2-(a+a_{cb})^2)\right]\log\left(\frac{\Lambda^2}{m_h^2}\right)$$

$$\Delta\epsilon_3 = +\frac{1}{48\pi}\frac{\alpha(m_Z)}{\sin^2\theta_W}\left[1-(a+a_{cb})^2\right]\log\left(\frac{\Lambda^2}{m_h^2}\right).$$

$$\Delta\epsilon_1 = \left((a+a_{cb})^2 - a^2\right)\frac{\Lambda^2}{16\pi^2 v^2}$$

DisZphilia or how to live with custodial breaking

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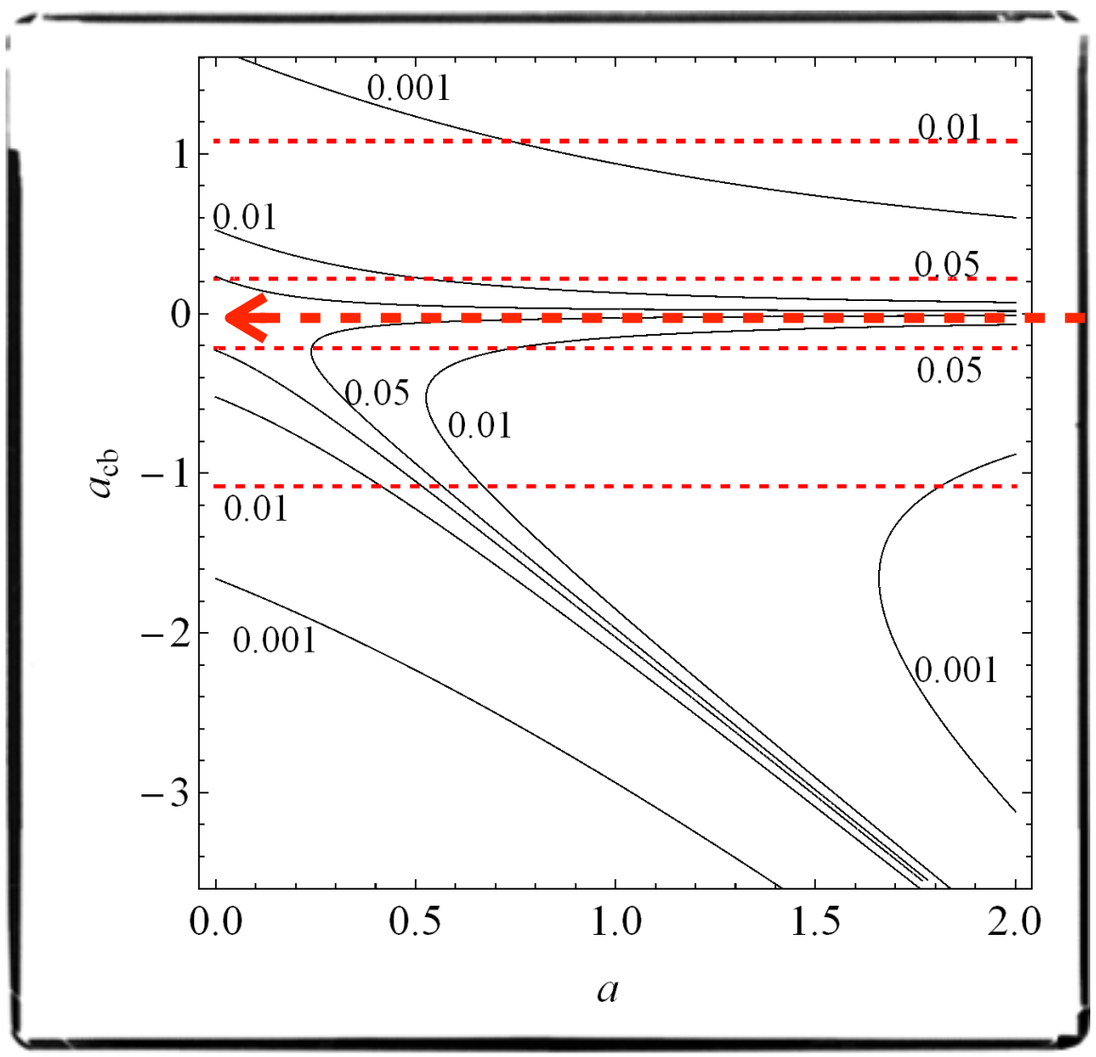
$$\mathcal{L}_{cb} = -\frac{v^2}{8}\left(\mathrm{Tr}\left[\Sigma^\dagger D_\mu \Sigma\, \sigma^3\right]\right)^2 \left(t_{cb} + 2a_{cb}\frac{h}{v} + \cdots\right)$$

EWPT highly model-dependent

tuning between tree-level and loop contributions?

new light states?



Amount of fine-tuning in EWPT

custodial invariance

Λ^2 UV sensitivity

ie

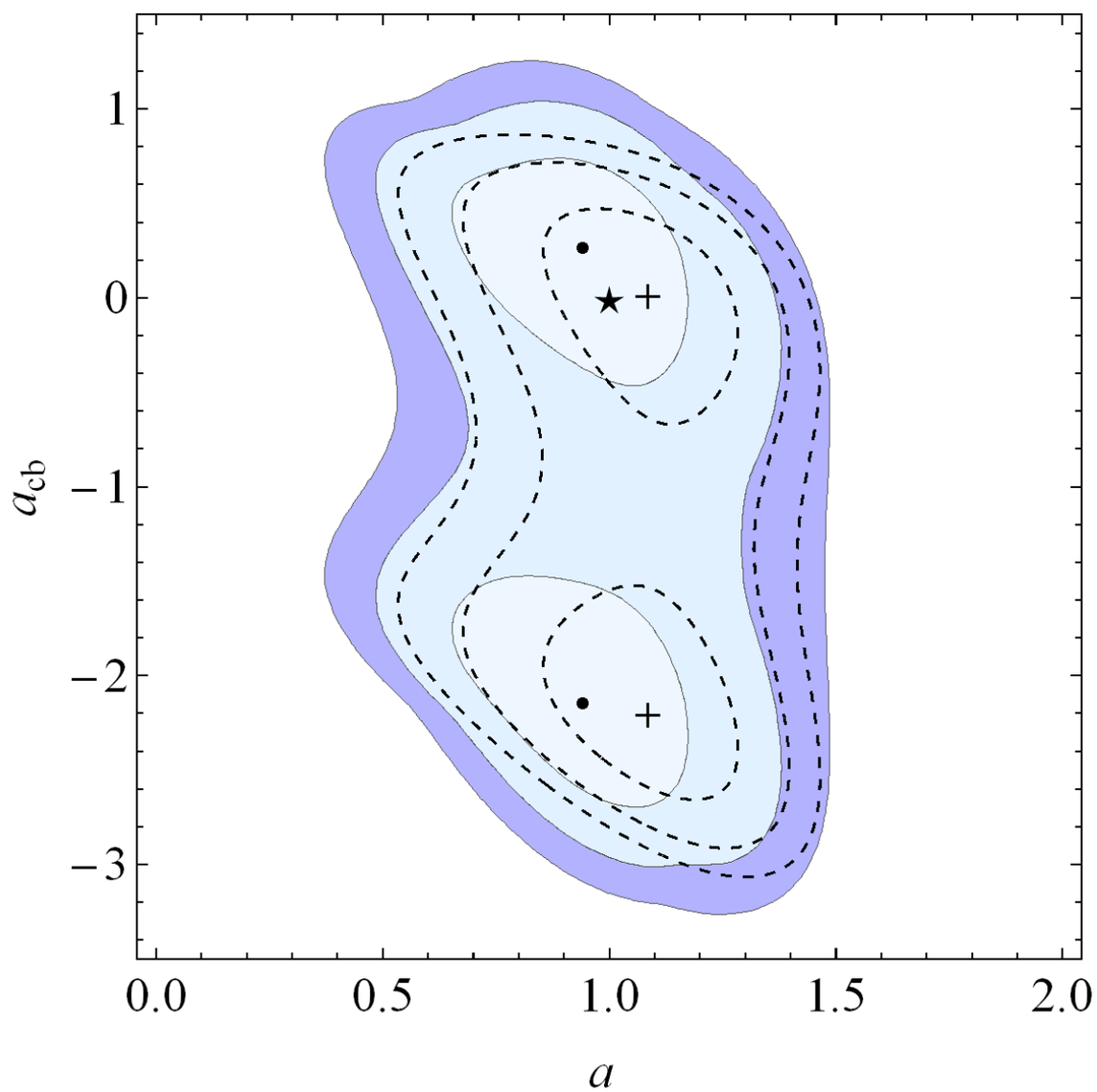
could be as bad as the hierarchy problem

DisZphilia or how to live with custodial breaking

Farina, Grojean, Salvioni '12

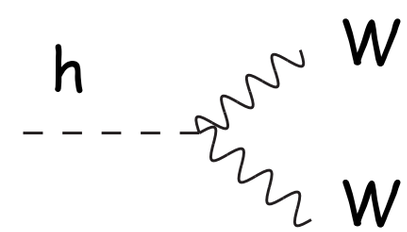
$$\mathcal{L}_{cb} = -\frac{v^2}{8}\left(\mathrm{Tr}\left[\Sigma^\dagger D_\mu \Sigma\, \sigma^3\right]\right)^2 \left(t_{cb} + 2a_{cb}\frac{h}{v} + \cdots\right)$$

Fit to LHC data

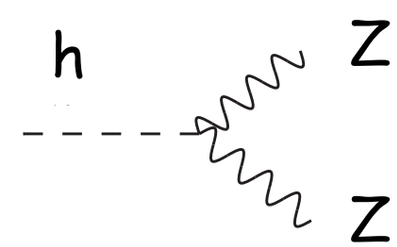


---------- c = 1

———— marginalization over c



$$a\, g^{SM}_{hWW}$$



$$(a + a_{cb})\, g^{SM}_{hZZ}$$

LHC data are symmetric under

$$(a + a_{cb}) \leftrightarrow -(a + a_{cb})$$

i.e.

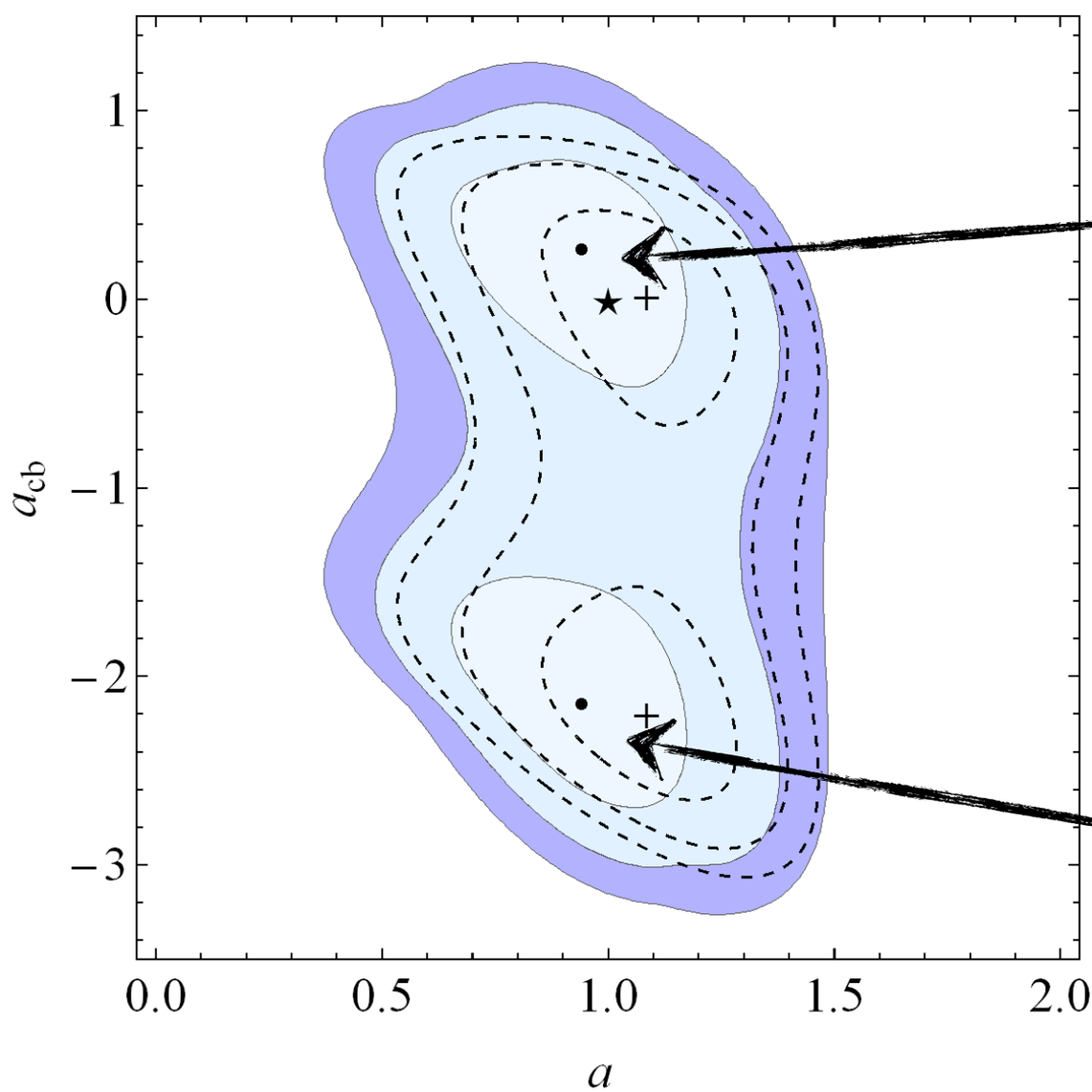
$$(a, a_{cb}) \leftrightarrow (a, -(2a + a_{cb}))$$

DisZphilia or how to live with custodial breaking

Farina, Grojean, Salvioni '12

$$\mathcal{L}_{cb} = -\frac{v^2}{8}\left(\mathrm{Tr}\left[\Sigma^\dagger D_\mu \Sigma\, \sigma^3\right]\right)^2 \left(t_{cb} + 2a_{cb}\frac{h}{v} + \cdots\right)$$

Fit to LHC data



---------- c = 1

———— marginalization over c

$$2\,\frac{h}{v}\left(m_W^2 W_\mu^+ W_\mu^- + \frac{1}{2} m_Z^2 Z_\mu Z_\mu\right)$$

the two solutions can only be distinguished in the presence of interference with a single hZZ vertex

$$2\,\frac{h}{v}\left(m_W^2 W_\mu^+ W_\mu^- - \frac{1}{2} m_Z^2 Z_\mu Z_\mu\right)$$

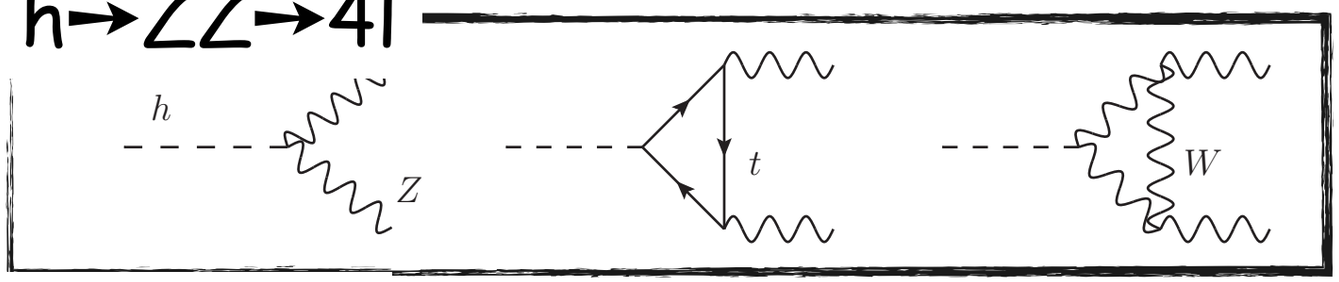
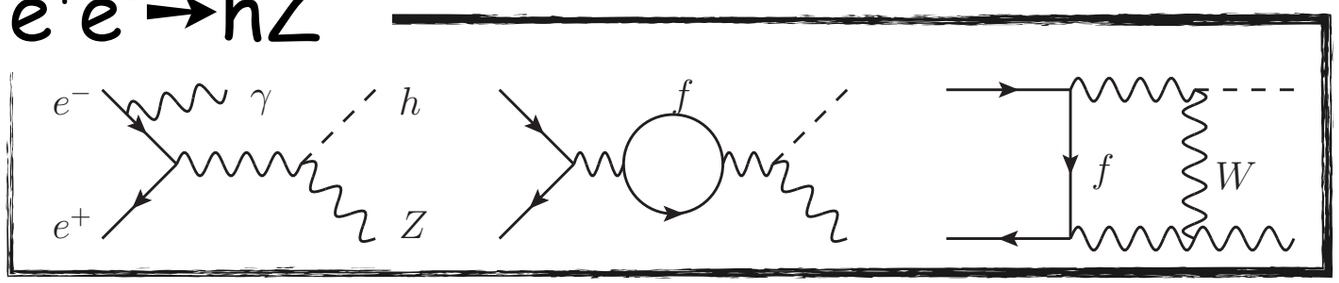
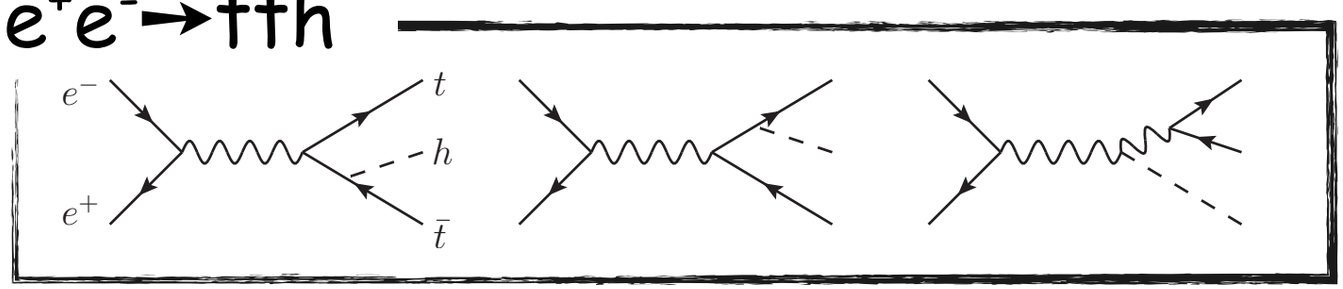
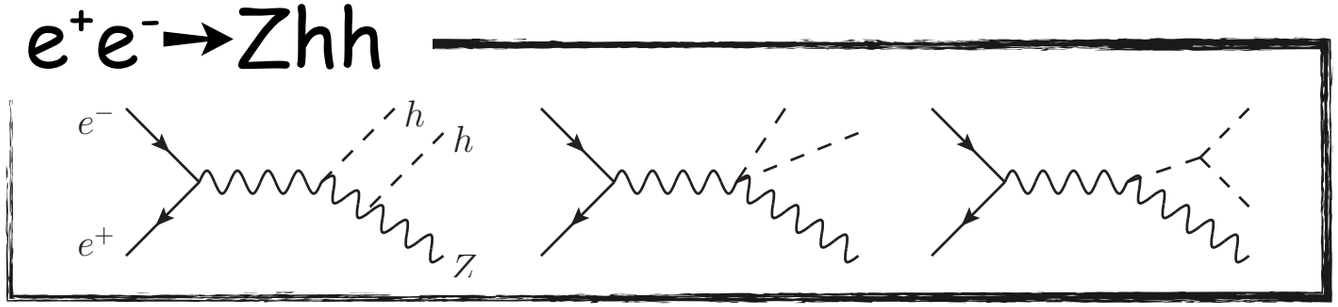
"disZphilia"

Zphilia or DisZphilia?

difficult!

Farina, Grojean, Salvioni '12

difference is physically relevant only in the presence of interference with single hZZ coupling

		TH prediction	ILC ($\sqrt{s}$=800GeV and 1ab^{-1})	
h→ZZ→4l		$\Delta = \left\lvert \frac{\Gamma_Z^+ - \Gamma_Z^-}{\Gamma_Z^+ + \Gamma_Z^-} \right\rvert = \delta \approx 1\%$	≈1%	☠
e^+e^-→hZ		$\Delta = \left\lvert \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \right\rvert \approx 15\%$	≈5%	☺
e^+e^-→tth		$\Delta = \left\lvert \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \right\rvert \lesssim 4\%$	≈10%	☠
e^+e^-→Zhh		$\Delta = \left\lvert \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \right\rvert \approx 50\%$	≈10%	☺

Signs of New Particles?

Espinosa, Grojean, Muhlleitner, Trott '12

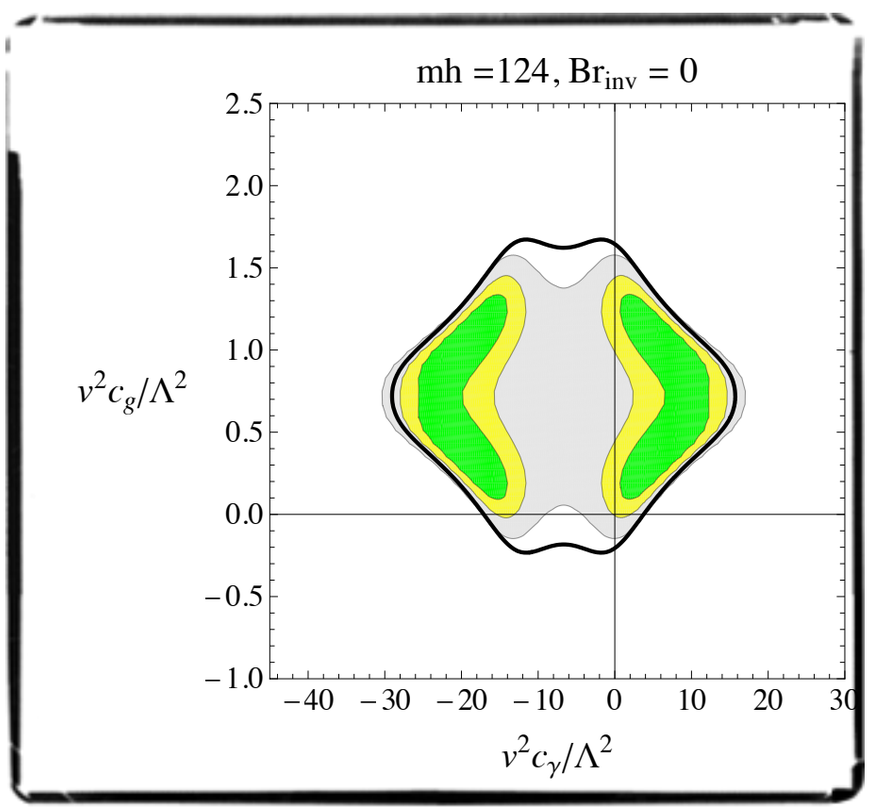
The Higgs can couple to new particles

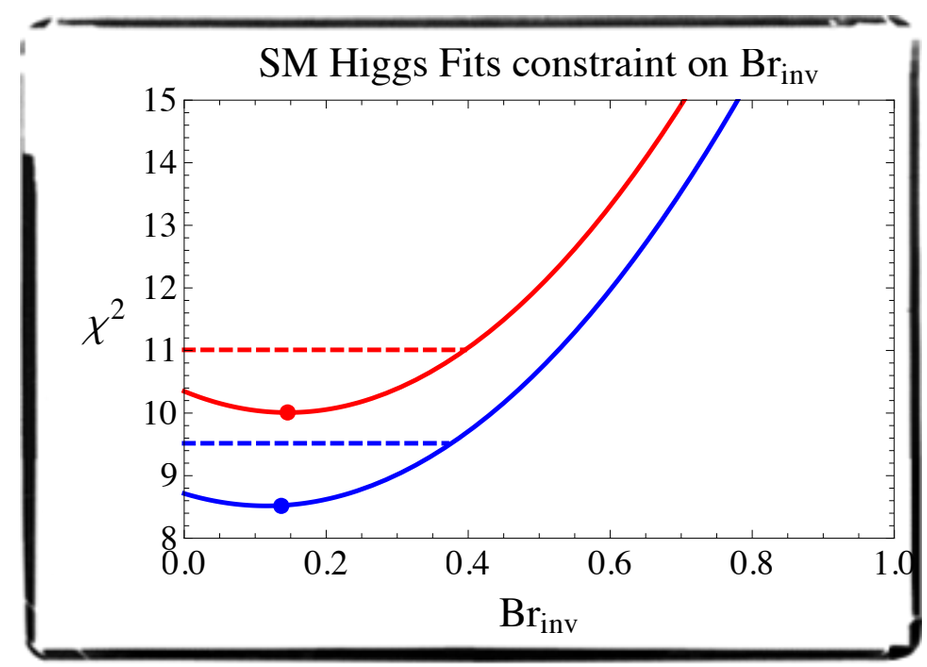
charged under SM gauge group

neutral under SM gauge group

$$\mathcal{L} = -\frac{\tilde{c}_\gamma e^2}{32\pi^2\Lambda^2} H^\dagger H\, F_{\mu\nu}F^{\mu\nu} - \frac{\tilde{c}_g g_s^2}{32\pi^2\Lambda^2} H^\dagger H\, G^a_{\mu\nu}G^{a\,\mu\nu}$$

$$\mathrm{Br}(h\to f) \equiv \frac{\Gamma(h\to f)}{\Gamma_{\rm SM}+\Gamma_{inv}} = (1-\mathrm{Br}_{inv})\times \mathrm{Br}_{SM}(h\to f)$$



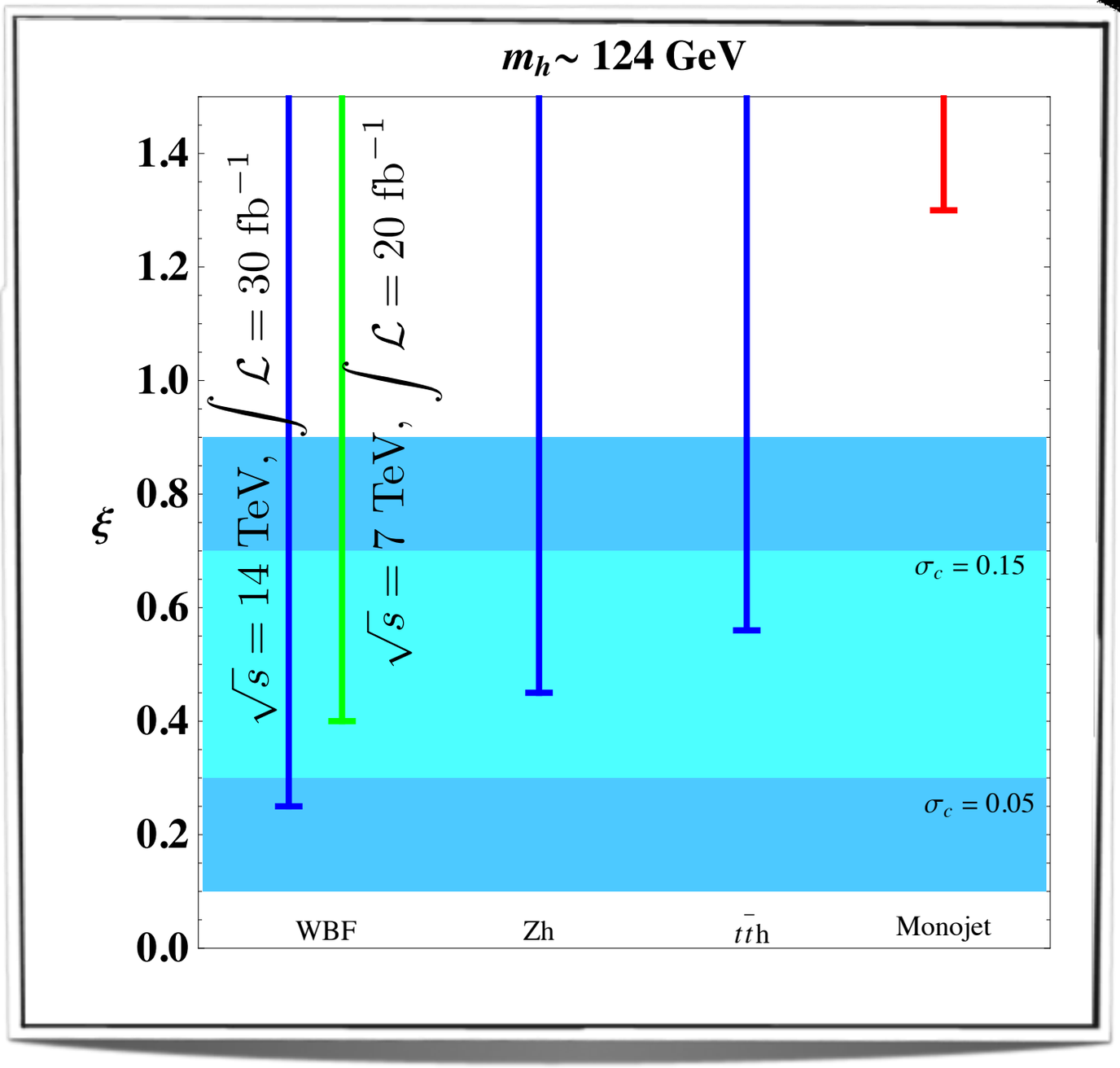


Search for Invisible Decays with Visible Channels

Espinosa, Grojean, Muhlleitner, Trott '12

direct (vertical) vs indirect (horizontal) searches

Values of
$\xi = \sigma/\sigma_{SM} BR(h \to inv)$
for which a 95%CL limit can be imposed



The Question of the next Decade(s)

What is really this Higgs boson that might have been discovered at ~ 125GeV?

"Higgs = emergency tire of the SM"

Altarelli @ Blois'10

[picture courtesy to Andreas Weiler]