The Higgs sector (alternatives to susy)

Implications of the Early LHC for cosmology

DESY, April 18-20, 2012

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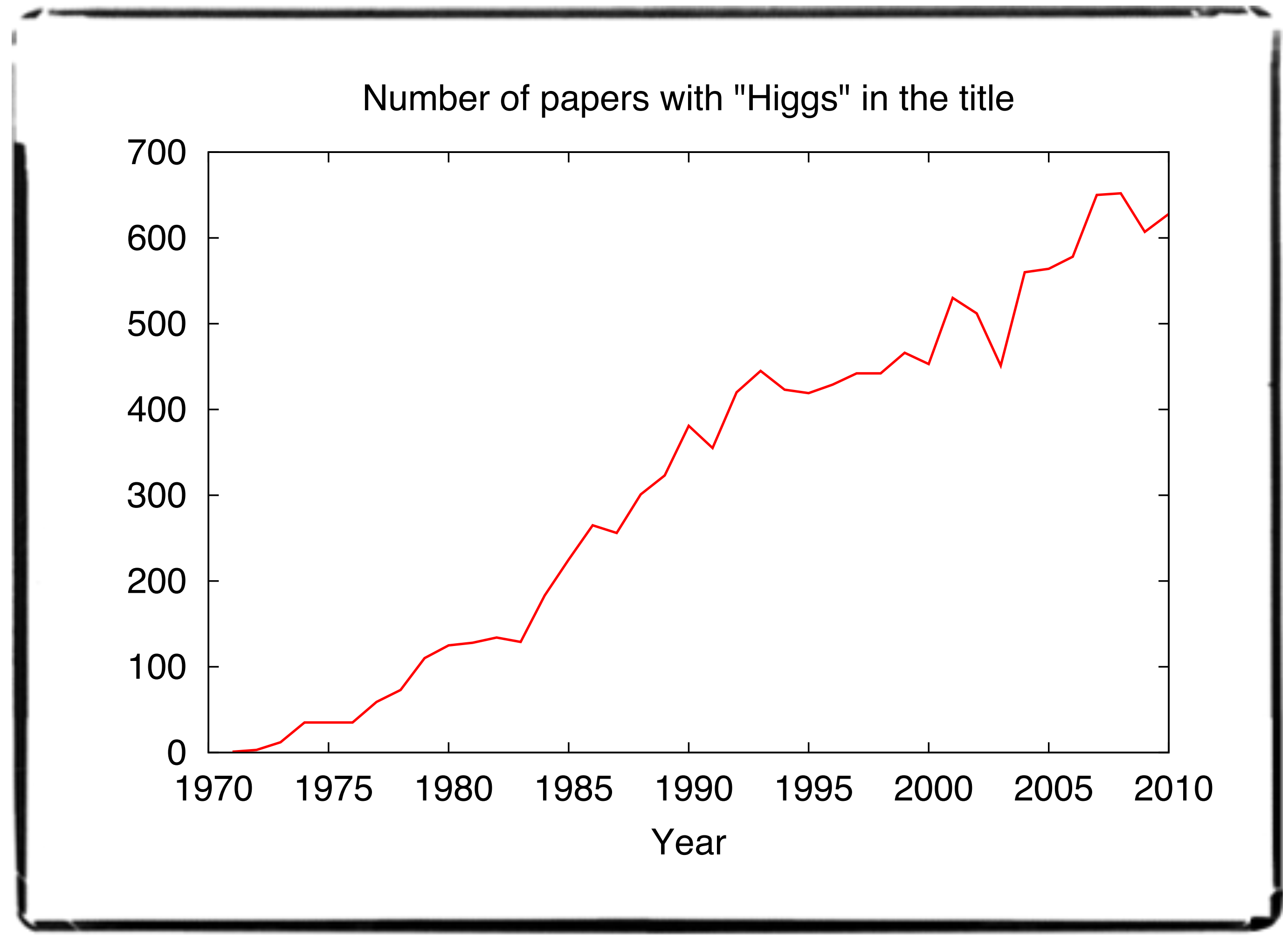
Higgs = "raison d'être" of LHC

- ≈500 physics papers over the last 5 years have an introduction starting like "*the (main) goal of the LHC is to discover the Higgs boson*"

- ≈11'000 papers in Spires contain "Higgs" in their title



with even a bigger peak since last Dec.!

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- ≈11'000 papers in Spires contain "Higgs" in their title
- ≈~~3~~x10^6 references in google (14x10^6 ≈ 1% of k€ requested by the German banks to the Greek government)
- ... no Nobel prize (so far)

Reasons of a success

- last missing piece of the SM?
- at the origin of the masses of elementary particles?
- unitarization of WW scattering amplitudes
- screening of gauge boson self-energies

"Higgs = emergency tire of the SM"

Altarelli @ Blois'10

The UV behavior of the weak Goldstone

symmetry breaking: new phase with more degrees of freedom

massive $W^{\pm}$, Z: 3 physical polarizations=eaten Goldstone bosons $\frac{SU(2)_L \times SU(2)_R}{SU(2)_V}$

$\Longrightarrow$ UV behavior of these Goldstone's? $\Longleftarrow$

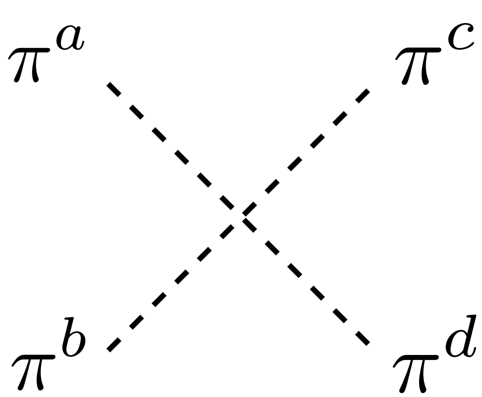
$$\mathcal{L}_{\rm mass} = m_W^2 W_\mu^+ W^{\mu\,-} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu = \frac{v^2}{4} \mathrm{Tr}\left(D_\mu \Sigma^\dagger D_\mu \Sigma\right)$$

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

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

$$\mathcal{L}_{\rm mass} = \frac{1}{2}(\partial_\mu \pi^a)^2 - \frac{1}{6v^2}\left((\pi^a \partial_\mu \pi^a)^2 - (\pi^a)^2 (\partial_\mu \pi^a)^2\right) + \dots$$

contact interaction growing with energy



$$\mathcal{A}\left(\pi^a \pi^b \to \pi^c \pi^d\right) = \mathcal{A}(s,t,u)\delta^{ab}\delta^{cd} + \mathcal{A}(t,s,u)\delta^{ac}\delta^{bd} + \mathcal{A}(u,t,s)\delta^{ad}\delta^{bc}$$

$$\mathcal{A}(s,t,u) = \frac{s}{v^2}$$ Weinberg's LET

the behavior of this amplitude is not consistent above $4\pi v$ (≈1÷3TeV)

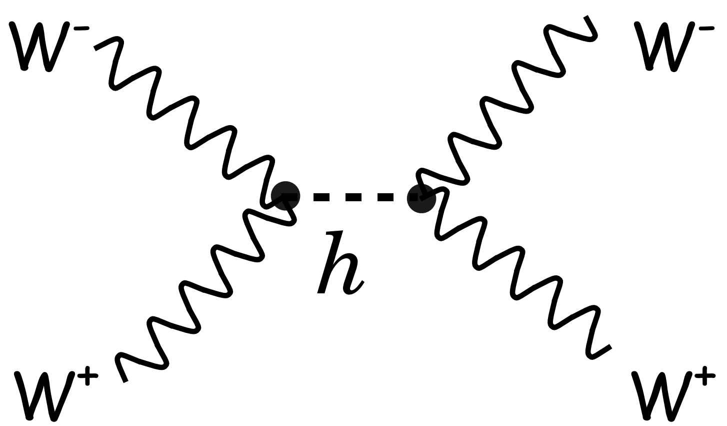
Lee, Quigg & Thacker '77

What is the SM Higgs?

A single scalar degree of freedom neutral under $SU(2)_L \times SU(2)_R / SU(2)_V$

$$\mathcal{L}_{\rm EWSB} = \frac{v^2}{4} {\rm Tr}\left(D_\mu \Sigma^\dagger D_\mu \Sigma\right) \left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right) - \lambda \bar{\psi}_L \Sigma \psi_R \left(1 + c\frac{h}{v}\right)$$

'a', 'b' and 'c' are arbitrary free couplings



$$\mathcal{A} = \frac{1}{v^2}\left(s - \frac{a^2 s^2}{s - m_h^2}\right)$$

growth cancelled for
a = 1
restoration of
perturbative unitarity

Cornwall, Levin, Tiktopoulos '73

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

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

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

$$D_\mu \Sigma \approx W_\mu$$

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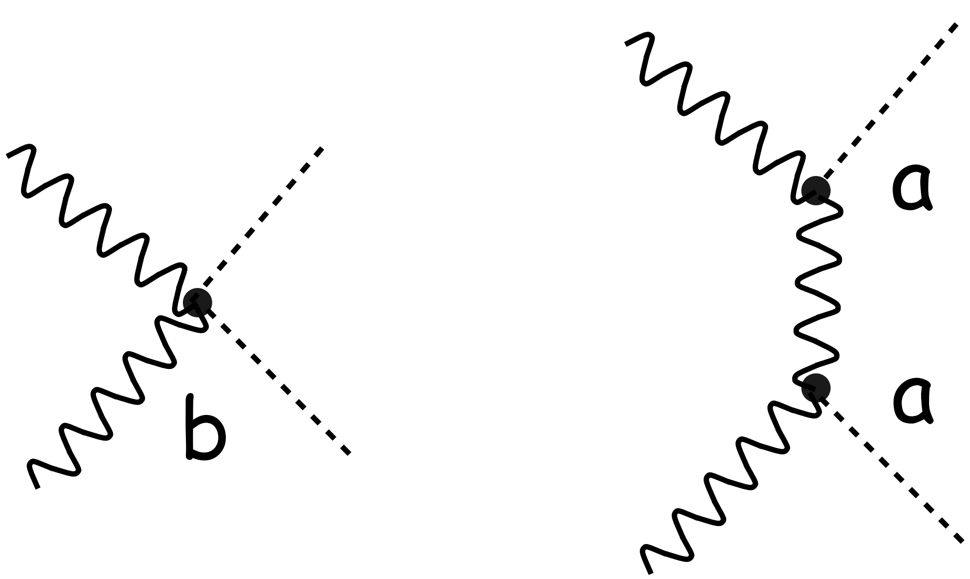
For a=1: perturbative unitarity in elastic channels WW $\to$ WW

For b = a^2: perturbative unitarity in inelastic channels WW $\to$ hh

Cornwall, Levin, Tiktopoulos '73

Contino, Grojean, Moretti, Piccinini, Rattazzi '10



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For $b = a^2$: perturbative unitarity in inelastic channels $WW \to hh$

For ac=1: perturbative unitarity in inelastic $WW \to \psi\,\psi$

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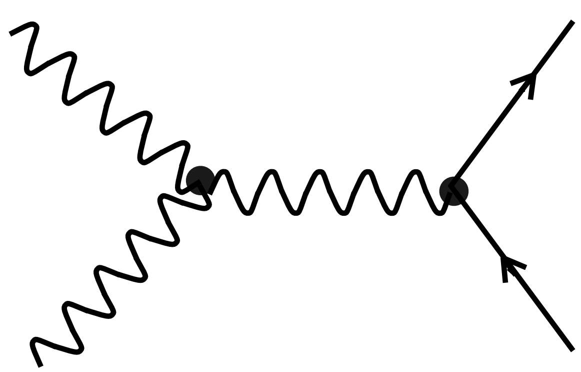

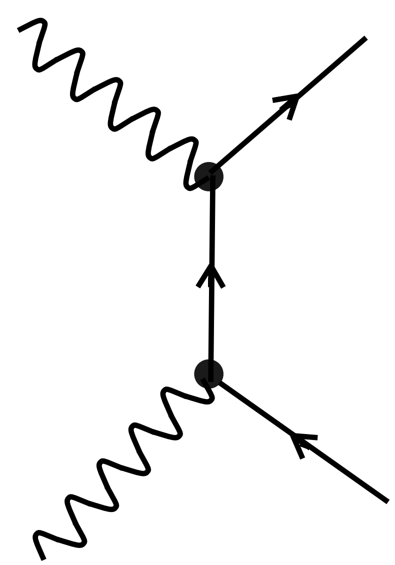

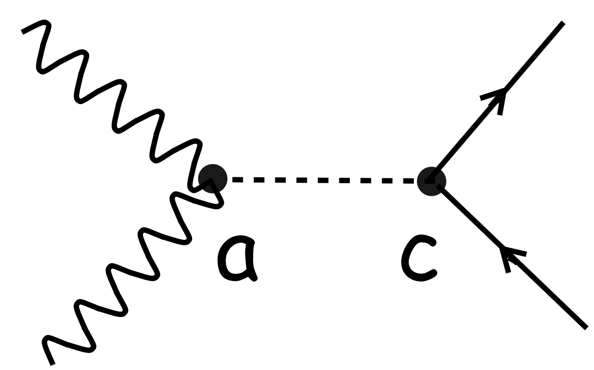

What is the SM Higgs?

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For a=1: perturbative unitarity in elastic channels WW $\to$ WW

For b = a^2: perturbative unitarity in inelastic channels WW $\to$ hh

For ac=1: perturbative unitarity in inelastic WW $\to \psi\,\psi$

'a=1', 'b=1' & 'c=1' define the SM Higgs

Higgs properties depend on a single unknown parameter (m_H)

$\mathcal{L}_{\rm EWSB}$ can be rewritten as $D_\mu H^\dagger D_\mu H$

$$H = \frac{1}{\sqrt{2}} e^{i\sigma^a \pi^a / v} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$$

h and π^a (ie W_L and Z_L) combine to form a linear representation of $SU(2)_L \times U(1)_Y$

What is a composite Higgs?

A σ particle that combines with W_L and Z_L to form a SU(2) doublet

renormalizable level = uniqueness

$SU(2)_L \times U(1)_Y$ linearly realized ⇔ Standard Model ⇔ a=b=c=1

non-renormalizable level

$SU(2)_L \times U(1)_Y$ linearly realized & a, b, c ≠ 1 ⇔ Composite Higgs

deviations of Higgs couplings originate from higher dimensional operators

$$\left(\partial_\mu |H|^2\right)^2 \quad |H|^2 \bar{\psi} H \psi \quad |H|^2 B_{\mu\nu} B^{\mu\nu} \quad |H|^2 G_{\mu\nu} G^{\mu\nu}$$

relevant for composite Higgs models

irrelevant for composite Higgs models (not for dilaton)

Higgs as a PGB: a natural extension of SM

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 ⇒ BSM: G/H — $W^\pm_L$ & Z_L & h

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

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

Mrazek, Pomarol, Rattazzi, Serra, Wulzer '11

Higgs as a PGB: a natural extension of SM

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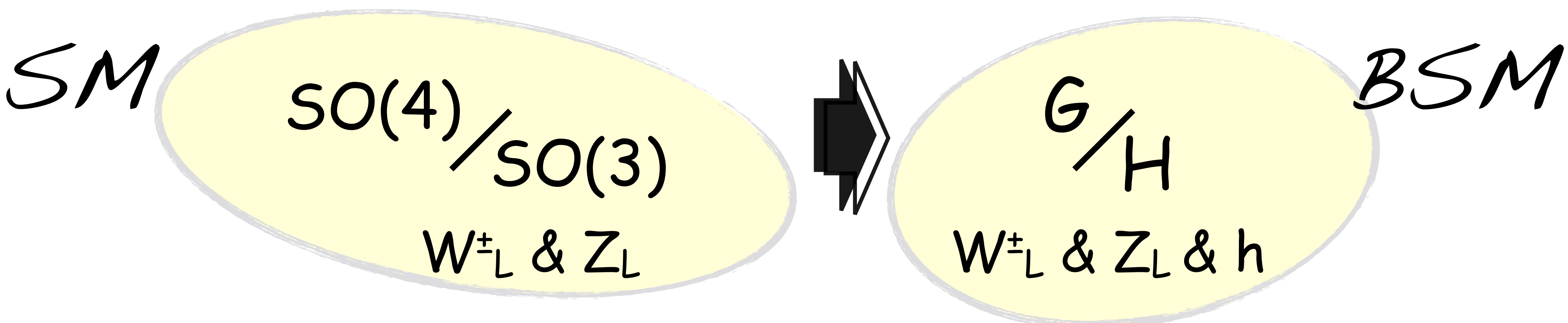


How can we tell the difference with the SM Higgs?

SILH Effective Lagrangian

(strongly-interacting light Higgs)

Giudice, Grojean, Pomarol, Rattazzi '07

- extra Higgs leg: H/f
- extra derivative: ∂/m_ρ

Genuine strong operators (sensitive to the scale f)

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

$$\frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)^2$$

custodial breaking

$$\frac{c_y y_f}{f^2}|H|^2 \bar{f}_L H f_R + \text{h.c.}$$

$$\frac{c_6 \lambda}{f^2}|H|^6$$

Form factor operators (sensitive to the scale m_ρ)

$$\frac{ic_W}{2m_\rho^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i$$

$$\frac{ic_B}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu})$$

$$\frac{ic_{HW}}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu}$$

$$\frac{ic_{HB}}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

minimal coupling: $h \to \gamma Z$

loop-suppressed strong dynamics

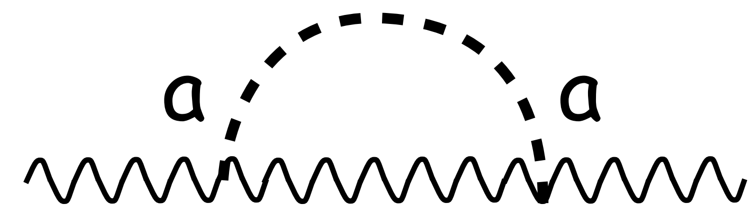
$$\frac{c_\gamma}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{g^2}{g_\rho^2} H^\dagger H B_{\mu\nu} B^{\mu\nu}$$

$$\frac{c_g}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{y_t^2}{g_\rho^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}$$

Goldstone sym.

Deformation of the SM Higgs: EW constraints

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



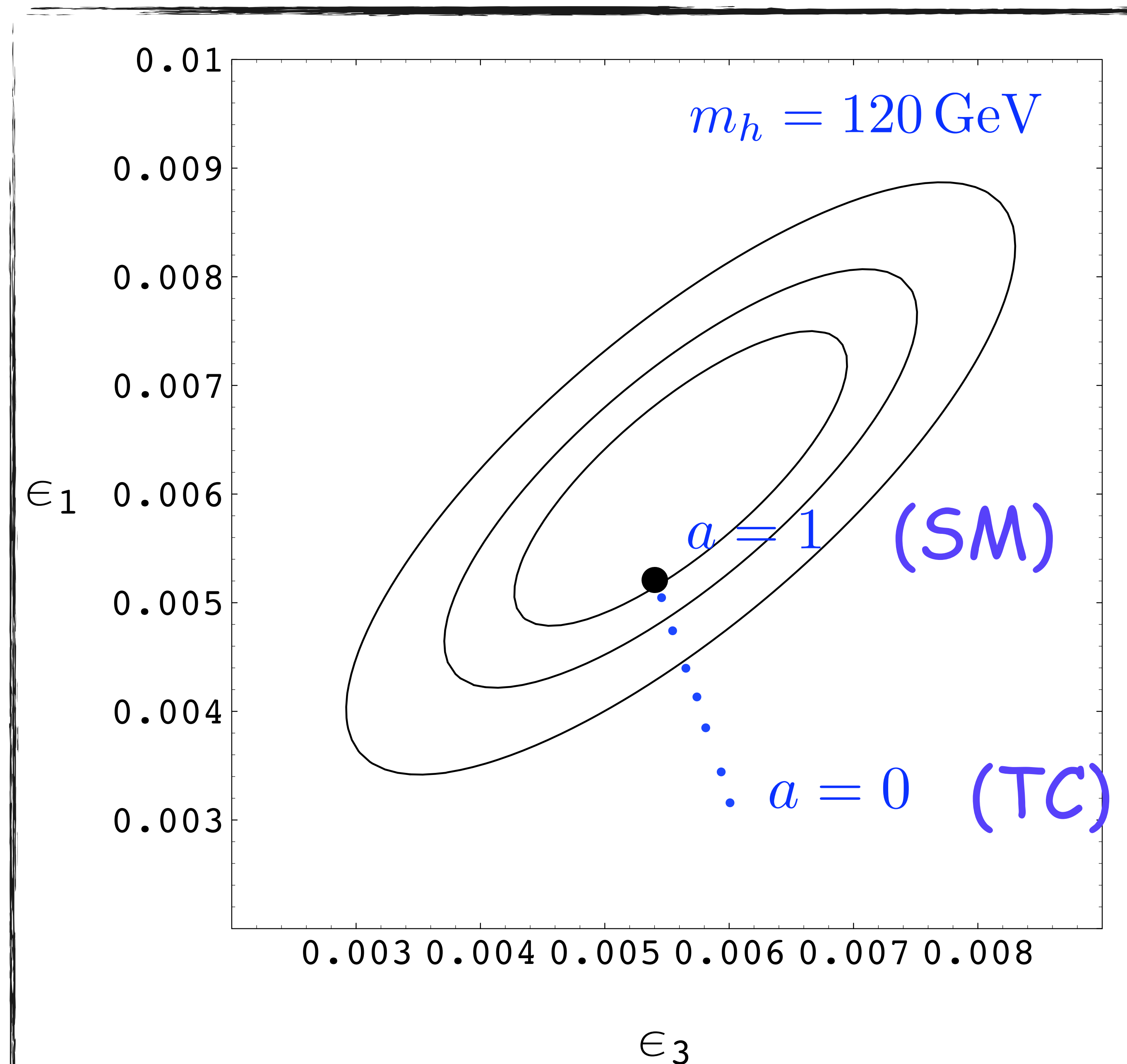
$$\epsilon_{1,3} = c_{1,3} \log(m_Z^2/\mu^2) - c_{1,3}\, a^2 \log(m_h^2/\mu^2) - c_{1,3} \left(1-a^2\right) \log(m_\rho^2/\mu^2) + \text{finite terms}$$

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

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

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

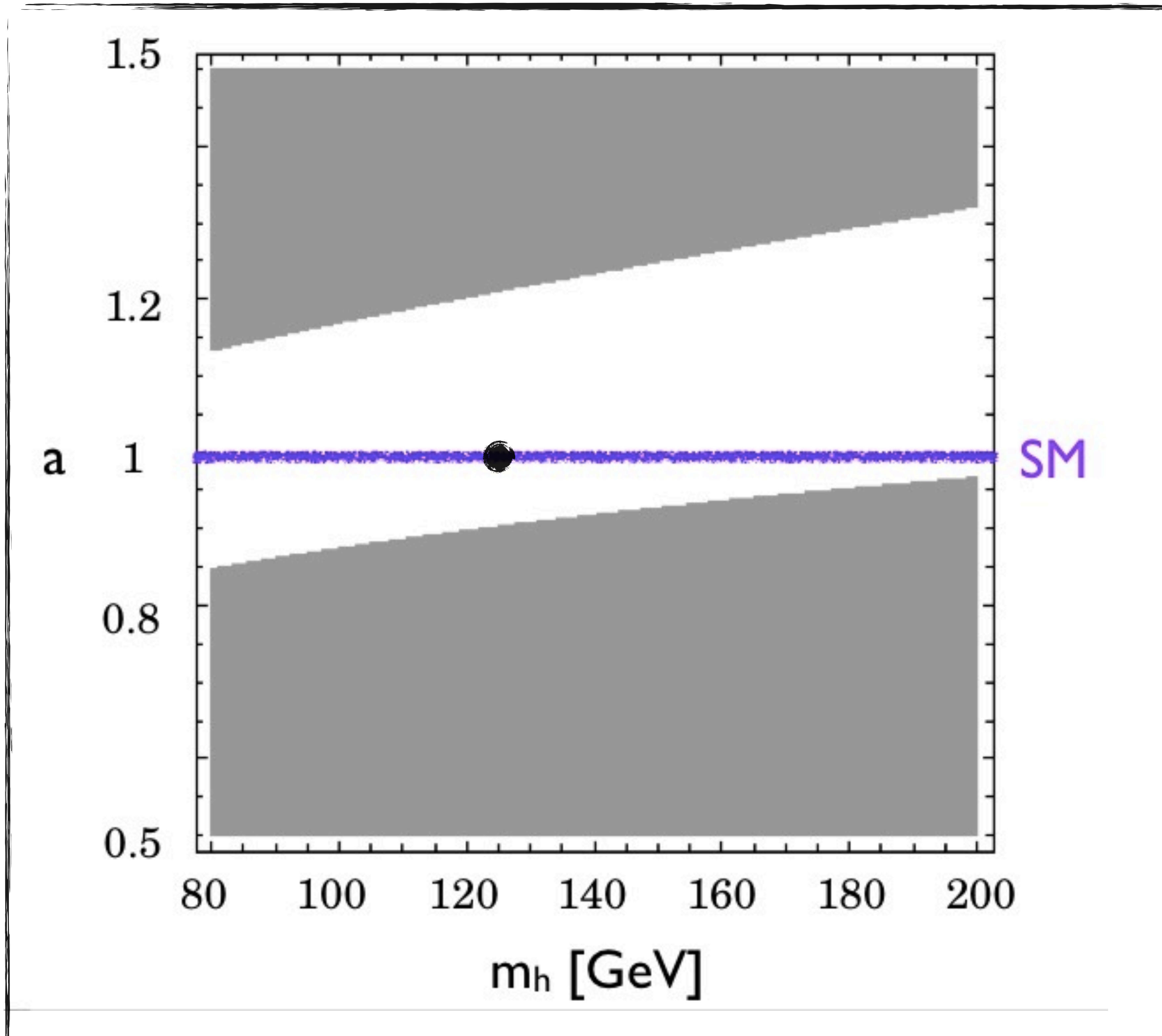
Barbieri, Bellazzini, Rychkov, Varagnolo '07



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



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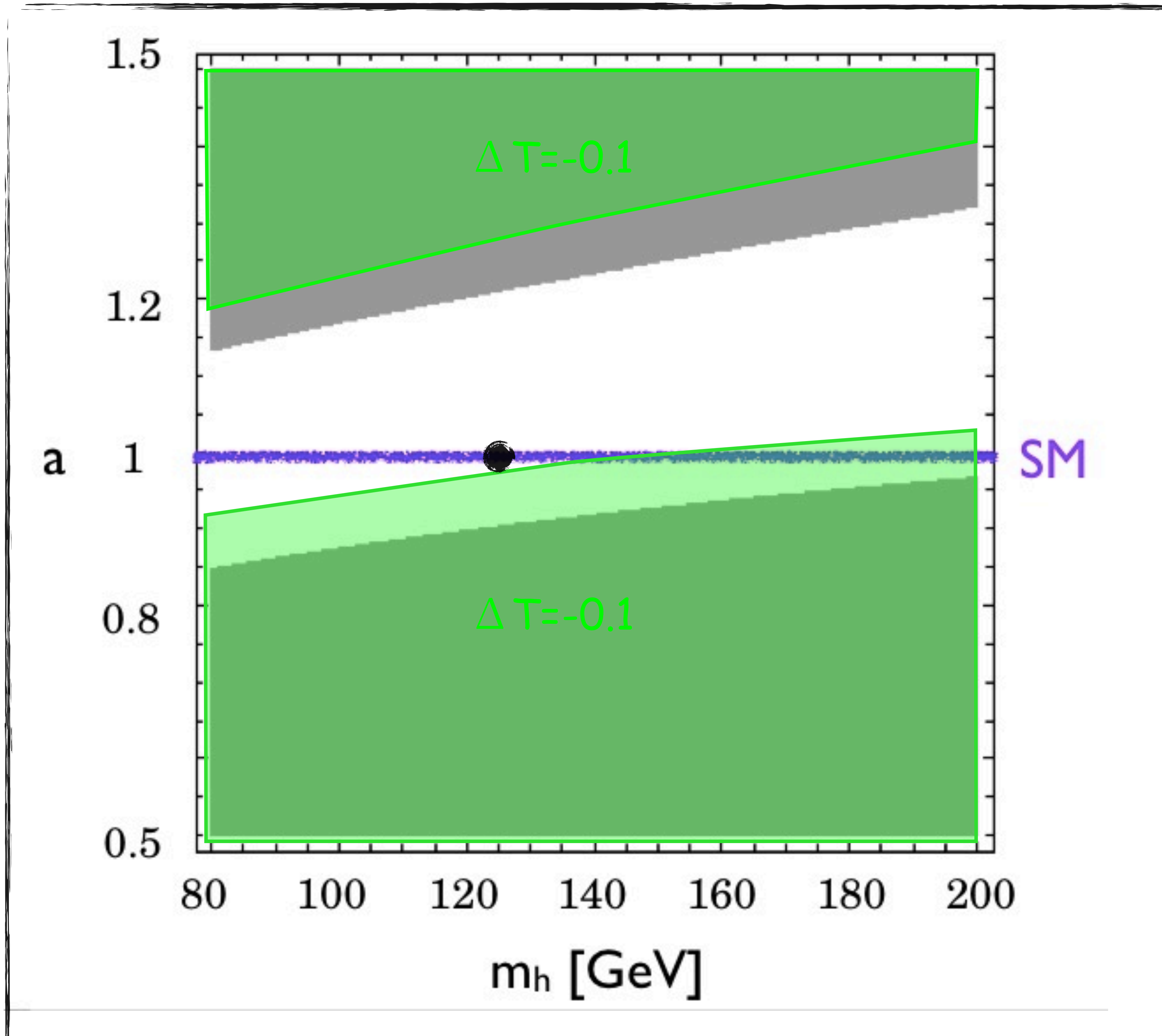


note:

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

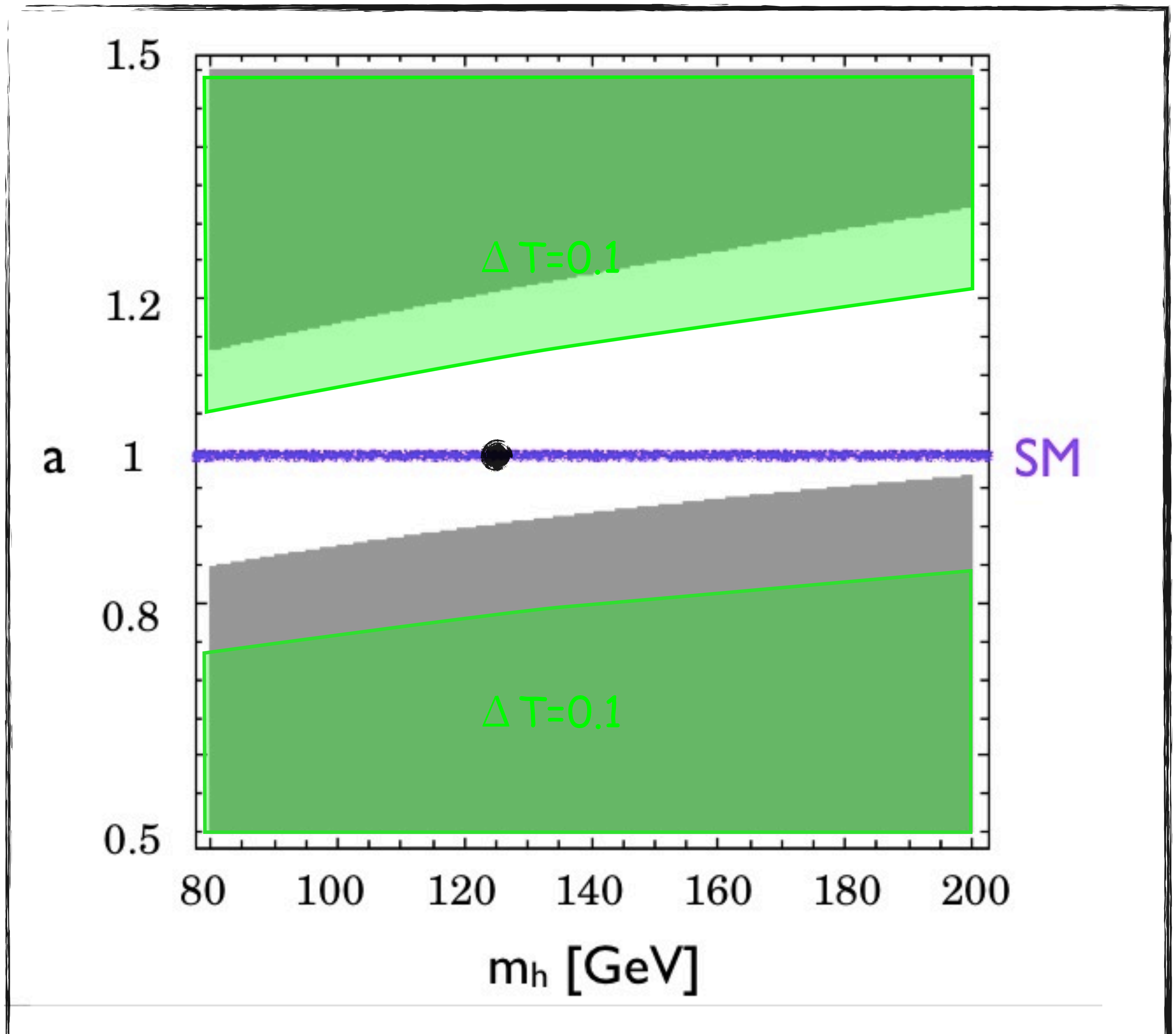
EW data constraints on 'a'

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



Flavor Constraints

$$\left(1+\frac{c_{ij}|H|^2}{f^2}\right) y_{ij}\bar{f}_{Li}H f_{Rj} = \left(1+\frac{c_{ij}v^2}{2f^2}\right)\frac{y_{ij}v}{\sqrt{2}}\bar{f}_{Li}f_{Rj}$$

$$\left(1+\frac{3c_{ij}v^2}{2f^2}\right)\frac{y_{ij}v}{\sqrt{2}}h\bar{f}_{Li}f_{Rj}$$

mass terms

Higgs fermion interactions

mass and interaction matrices are not diagonalizable simultaneously if c_{ij} are arbitrary

$\Rrightarrow$ FCNC

Composite Higgs set-up: c is flavor universal

(except may be for the top)

$\Rrightarrow$ Minimal flavor violation built in

Direct Searches

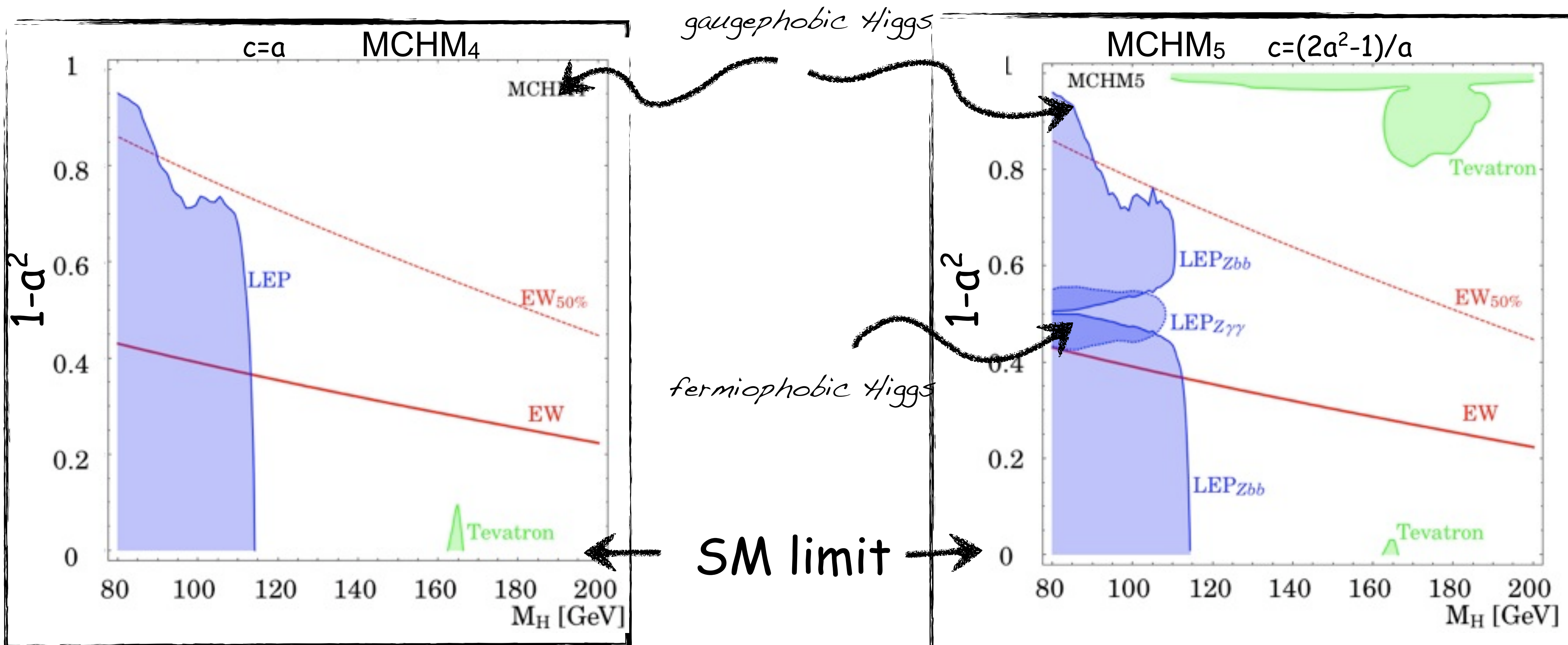
$$\mathcal{L}_{\rm EWSB} = \frac{v^2}{4}{\rm Tr}\left(D_\mu\Sigma^\dagger D_\mu\Sigma\right)\left(1+2a\frac{h}{v}+b\frac{h^2}{v^2}\right) - \lambda\bar\psi_L\Sigma\psi_R\left(1+c\frac{h}{v}\right)$$

SM 'a=1', 'b=1' & 'c=1'

Current EW data constrain only 'a'

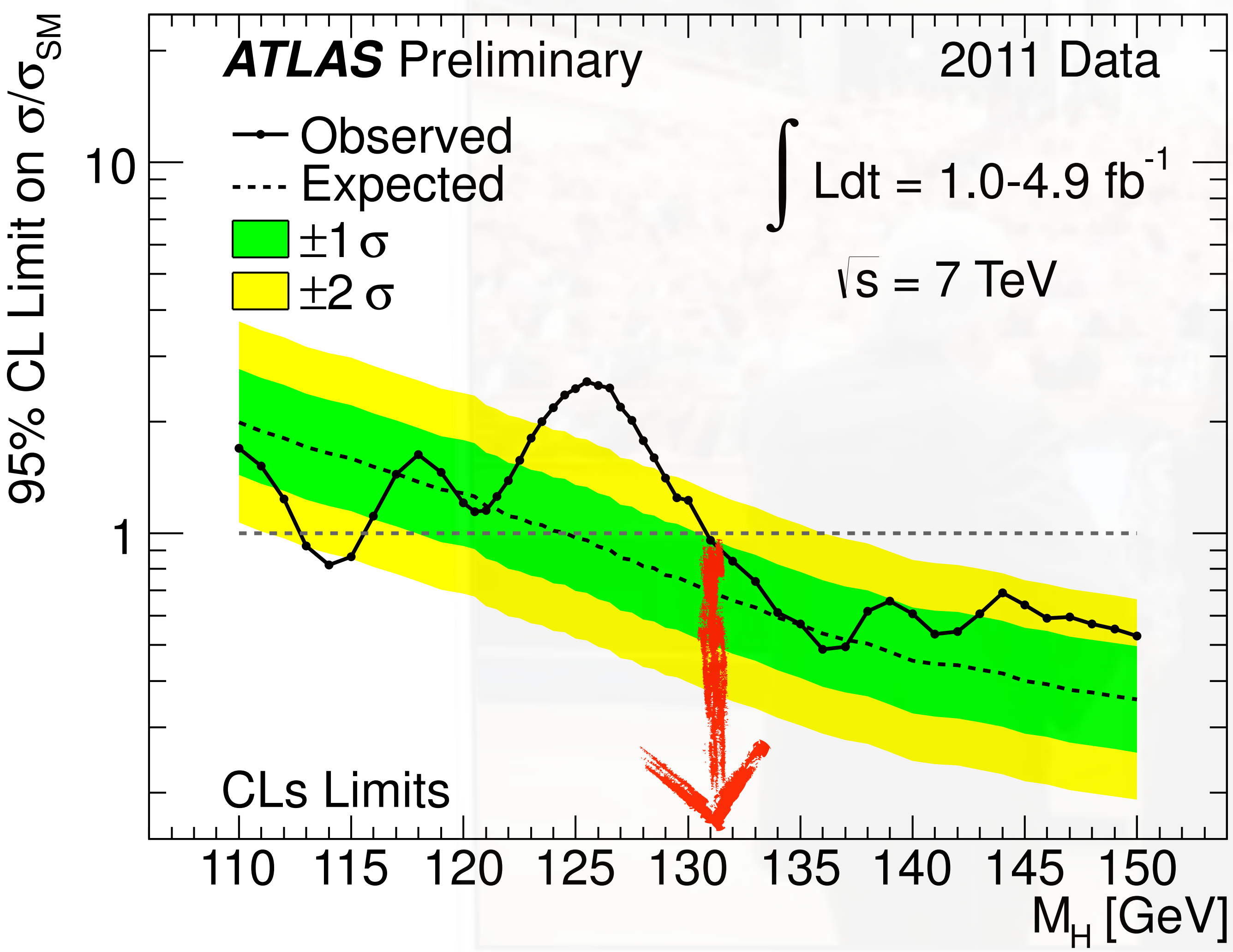
Direct searches constrain also 'c'

Espinosa, Grojean, Muehlleitner '10



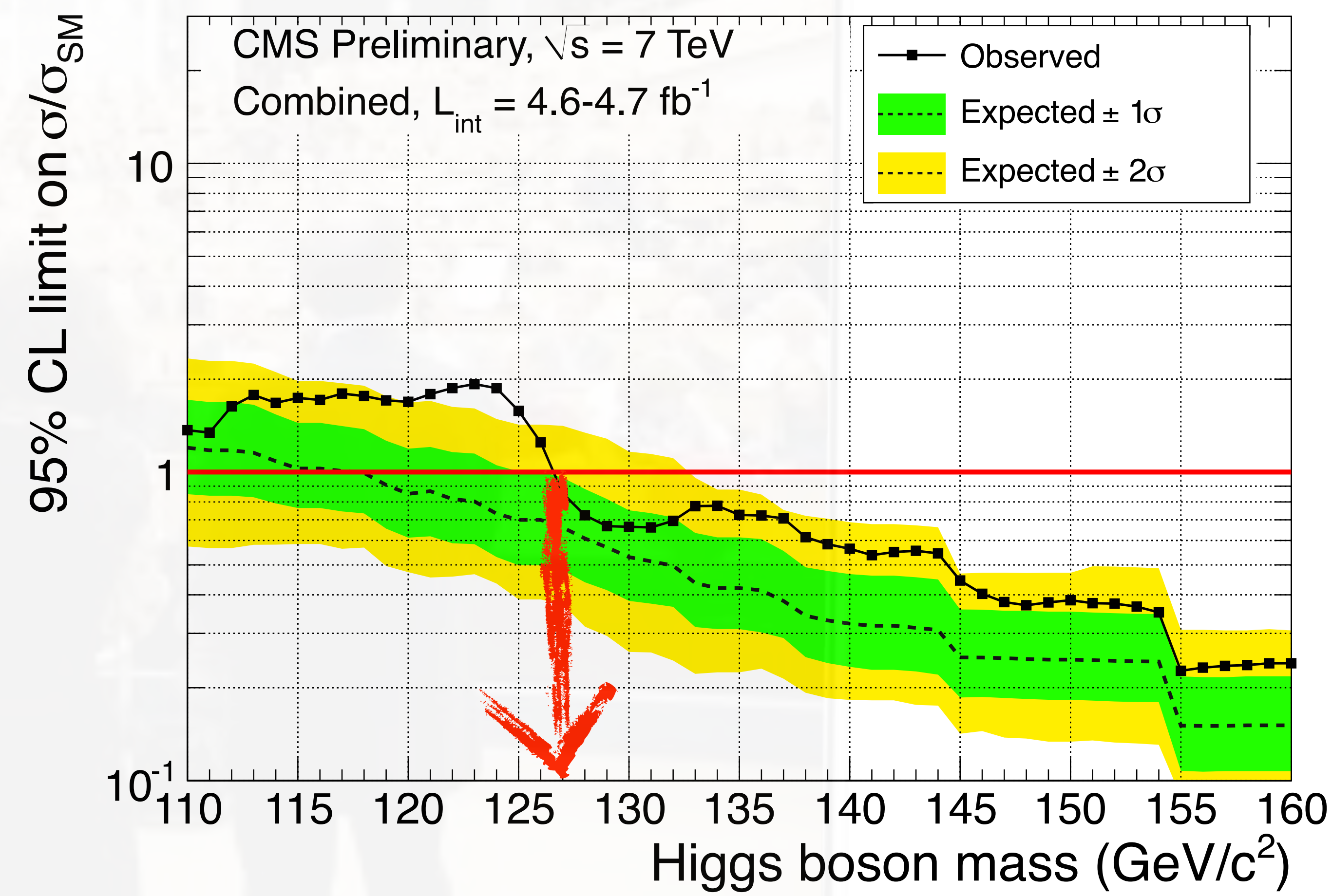
Higgs bounds: news from last December

ATLAS-CONF-2011-163



≈131 GeV

CMS PAS HIG-11-032



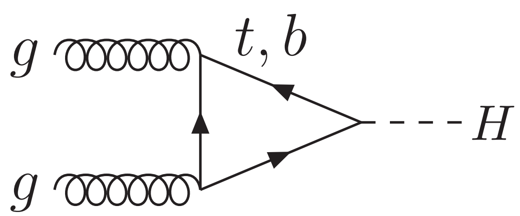
≈127 GeV

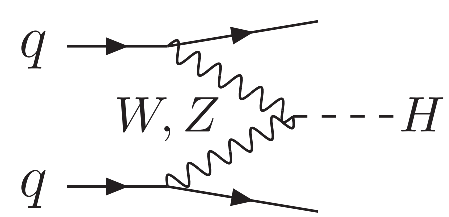
Rescaling Higgs Searches

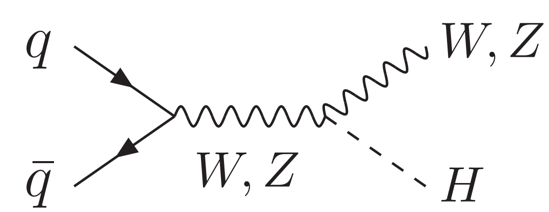
- Higgs couplings modified w.r.t. SM but same kinematics
- Background processes unaffected

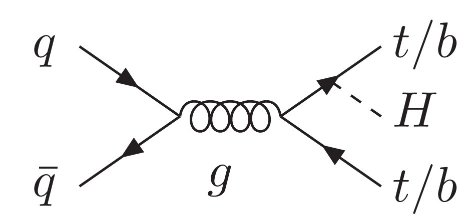
$\Downarrow \qquad \Downarrow \qquad \Downarrow$

simple rescaling of SM searches







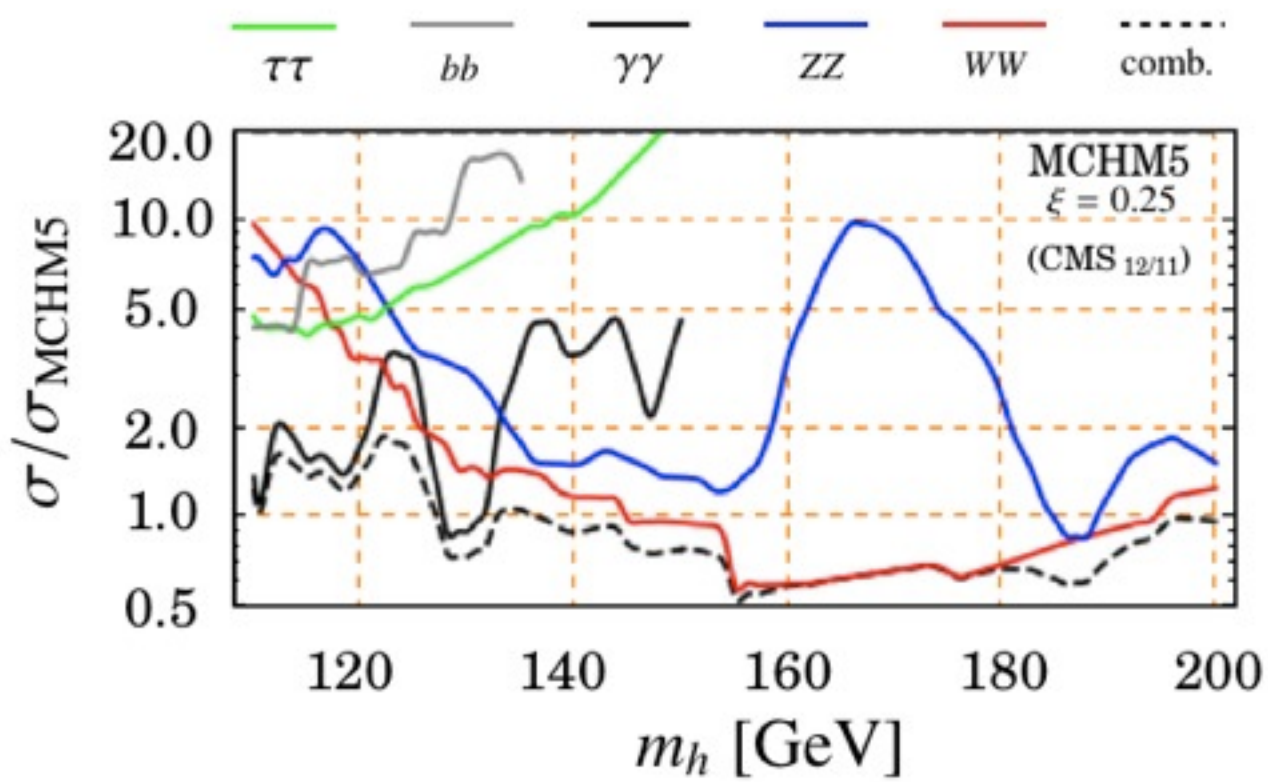


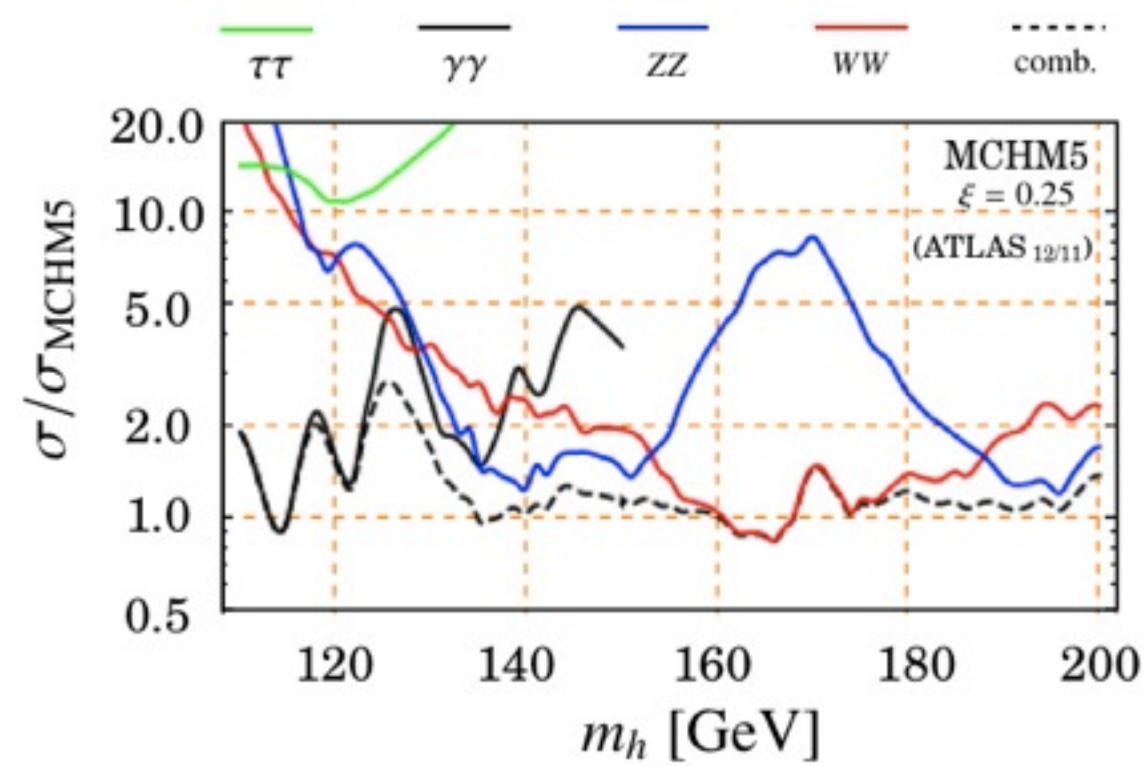
$\dfrac{\sigma_{NLO}}{\sigma^{SM}_{NLO}}$	c^2	a^2	a^2	c^2

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

Rescaling Higgs Searches

Espinosa, Grojean, Muehlleitner '10





each search channel is rescaled individually

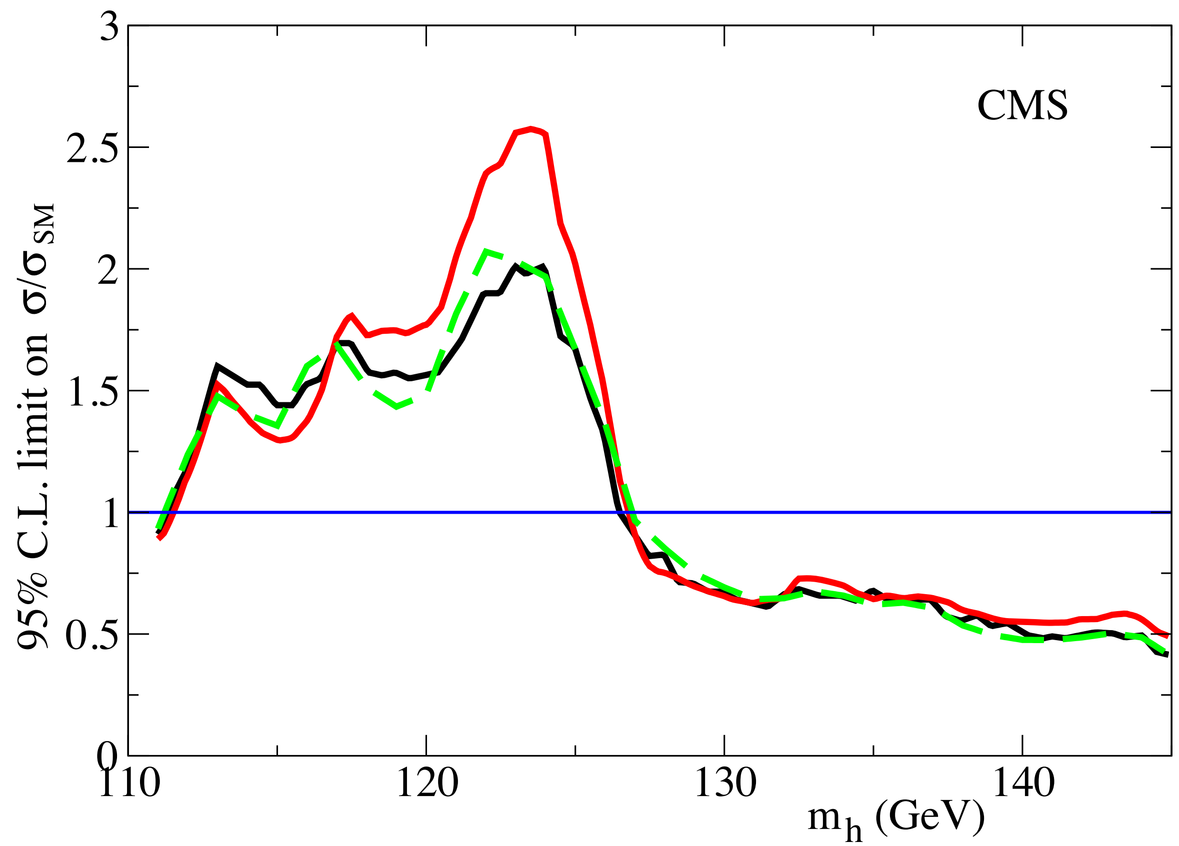
all the channels are then combined

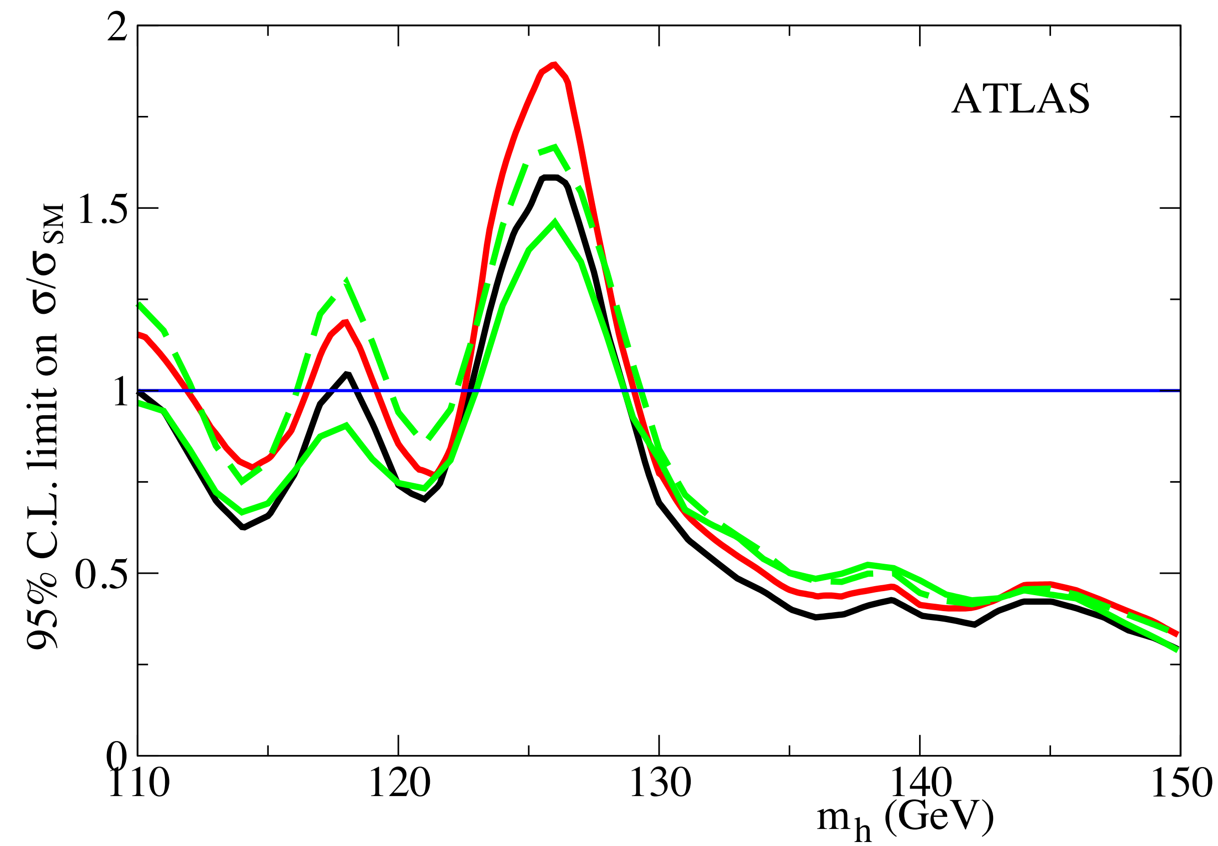
Rescaling Higgs Searches

Espinosa, Grojean, Muehlleitner '10
Espinosa, Grojean, Muhlleitner, Trott '12

How robust is our TH combination?

Let's look at the SM (a=c=1)





official

improved combination
in quadrature

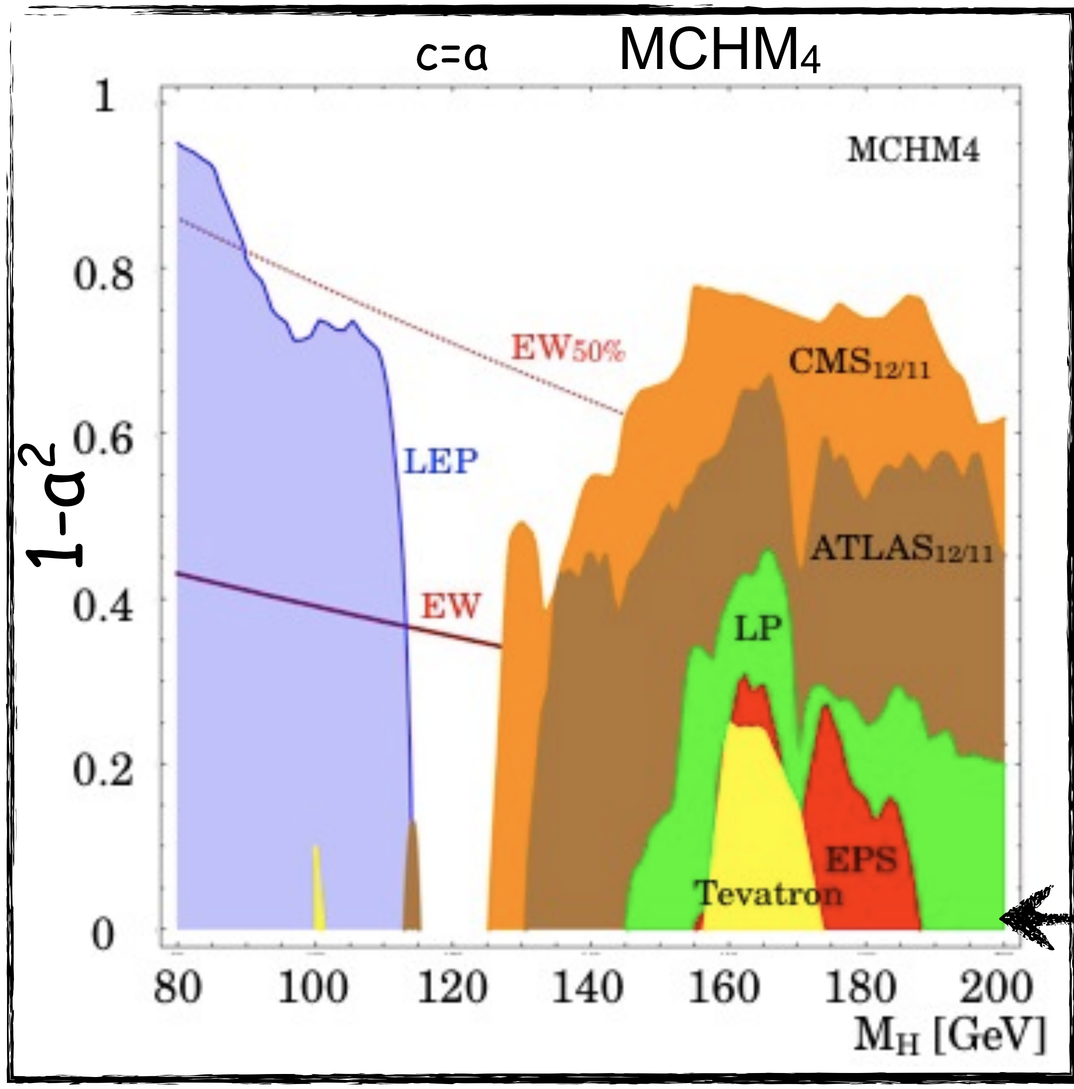
improved combination
with reconstructed likelihood

See also Azatov, Contino, Galloway '12

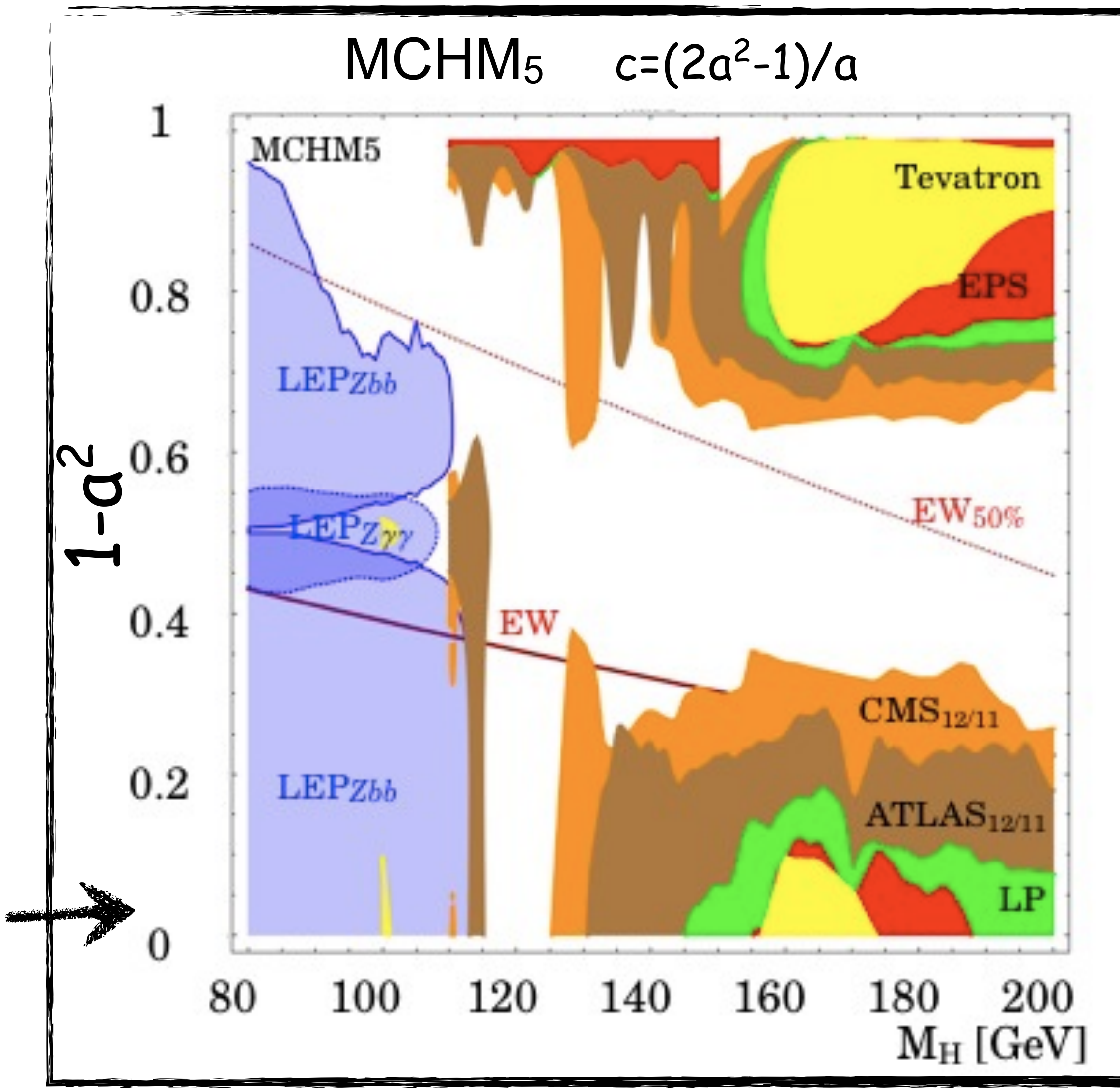
Deformation of the SM Higgs: current constraints

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

Espinosa, Grojean, Muehlleitner '11



SM limits

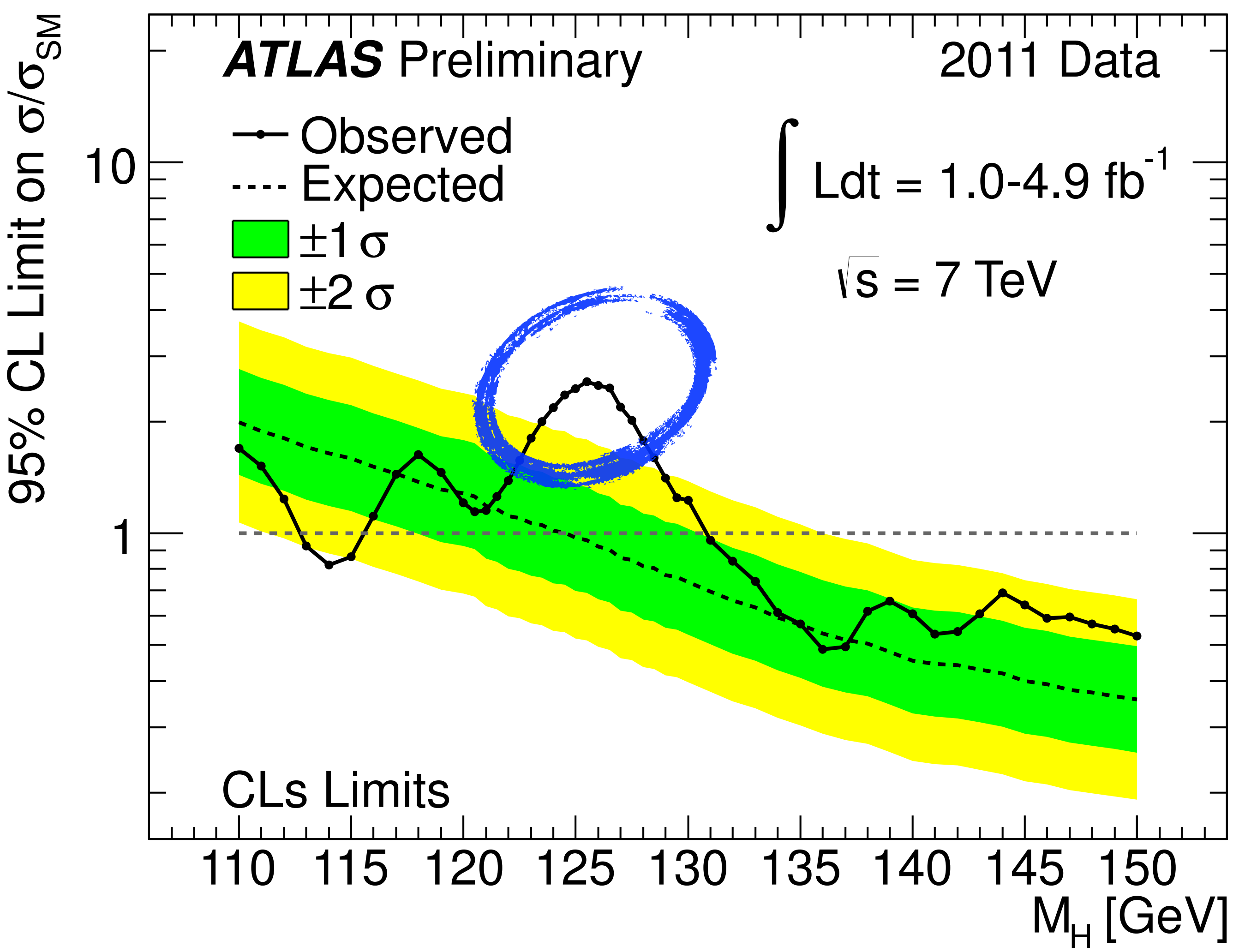


LHC tsunami!

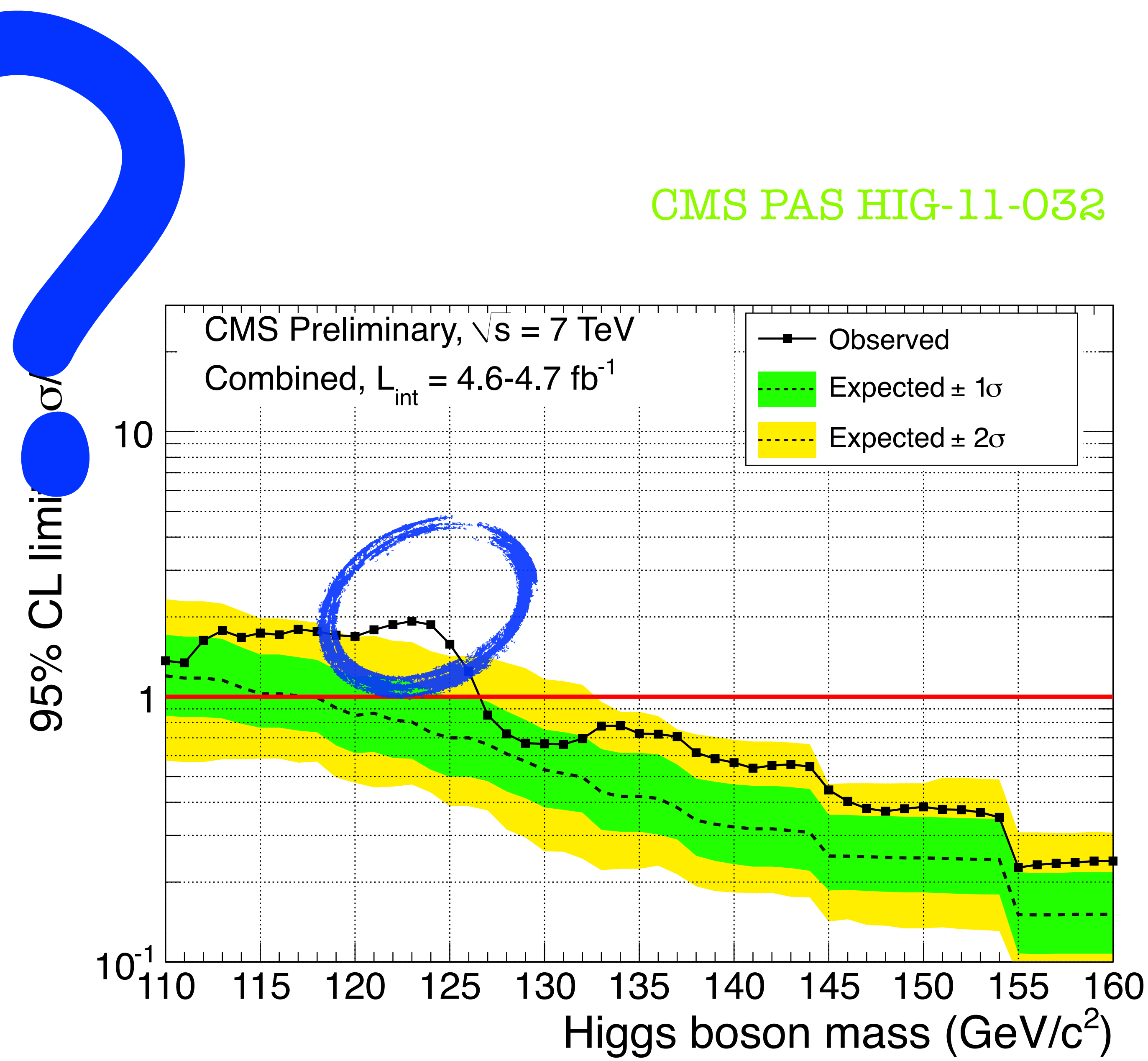
the LHC can do much more than simply excluding the SM Higgs

Higgs bounds: news from last December

ATLAS-CONF-2011-163



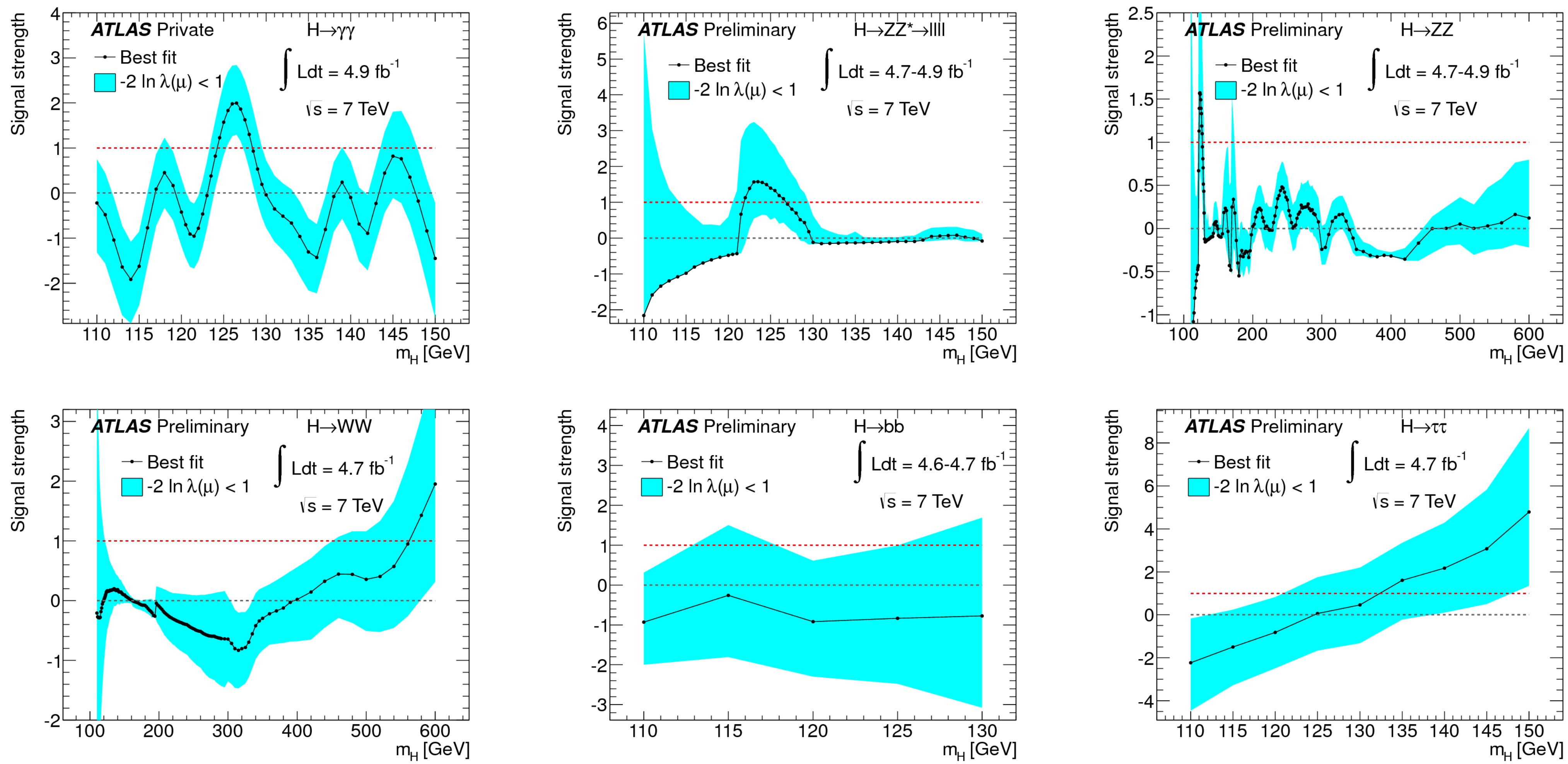
CMS PAS HIG-11-032



a 120-130 GeV higgs is very interesting (from the exp. point of view) since many competing decay channels

Various Search Channels

signal strength $$\mu = \frac{\sigma \times BR}{(\sigma \times BR)_{\rm SM}}$$



Various Search Channels

signal strength $$\mu = \frac{\sigma \times BR}{(\sigma \times BR)_{\rm SM}}$$

Channel [Exp]	m_h[GeV] (Local Significance)	μ (μ_L)	Scaling to SM
$pp \to \gamma\,\gamma$ [ATLAS]	126.5 ± 0.7 $(2.8\,\sigma)$ [26]	$2^{+0.9}_{-0.7}$ [27] (2.6)	$\sim c^2\,{\rm Br}_{\gamma\,\gamma}[a,c]$
$pp \to Z\,Z^\star \to \ell^+\,\ell^-\,\ell^+\,\ell^-$ [ATLAS]	$126 \pm \sim 2\%$ $(2.1\,\sigma)$ [26]	$1.2^{+1.2}_{-0.8}$ [27] (4.9)	$\sim c^2\,{\rm Br}_{ZZ}[a,c]$
$pp \to W\,W^\star \to \ell^+\,\nu\,\ell^-\,\bar\nu$ [ATLAS]	$126 \pm \sim 20\%$ $(1.4\,\sigma)$ [26]	$1.2^{+0.8}_{-0.8}$ [27] (3.4)	$\sim c^2\,{\rm Br}_{WW}[a,c]$
$pp \to \gamma\,\gamma\,j\,j$ [CMS]	$124 \pm 3\%$ [10, 11]	$3.7^{+2.5}_{-1.8}$ [11]	$\sim a^2\,{\rm Br}_{\gamma\gamma}[a,c]$
$pp \to \gamma\,\gamma[{\rm CMS, b}, R_9^{\rm min} > 0.94]$	$124 \pm 3\%$ [10, 11]	$1.5^{+1.1}_{-1.0}$ [11]	$\sim c^2\,{\rm Br}_{\gamma\,\gamma}[a,c]$
$pp \to \gamma\,\gamma[{\rm CMS, b}, R_9^{\rm min} < 0.94]$	$124 \pm 3\%$ [10, 11]	$2.1^{+1.5}_{-1.4}$ [11]	$\sim c^2\,{\rm Br}_{\gamma\,\gamma}[a,c]$
$pp \to \gamma\,\gamma[{\rm CMS, e}, R_9^{\rm min} > 0.94]$	$124 \pm 3\%$ [10, 11]	$0.0^{+2.9}$ [11]	$\sim c^2\,{\rm Br}_{\gamma\,\gamma}[a,c]$
$pp \to \gamma\,\gamma[{\rm CMS, e}, R_9^{\rm min} < 0.94]$	$124 \pm 3\%$ [10, 11]	$4.1^{+4.6}_{-4.1}$ [11]	$\sim c^2\,{\rm Br}_{\gamma\,\gamma}[a,c]$
$pp \to Z\,Z^\star \to \ell^+\,\ell^-\,\ell^+\,\ell^-$ [CMS]	$126 \pm 2\%$ $(1.5\,\sigma)$ [11, 28]	$0.5^{+1.0}_{-0.7}$ [10] (2.7)	$\sim c^2\,{\rm Br}_{ZZ}[a,c]$
$pp \to W\,W^\star \to \ell^+\,\nu\,\ell^-\,\bar\nu$ [CMS]	$126 \pm 20\%$ [10, 29]	$0.7^{+0.4}_{-0.6}$ [10] (1.8)	$\sim c^2\,{\rm Br}_{WW}[a,c]$
$pp \to b\,\bar b$ [CMS]	$124 \pm 10\%$ [10]	$1.2^{+1.4}_{-1.7}$ [10] (4.1)	$\sim a^2\,{\rm Br}_{b\bar b}[a,c]$
$pp \to \tau\,\bar\tau$ [CMS]	$124 \pm 20\%$[10]	$0.8^{+1.2}_{-1.7}$ [10] (3.3)	$\sim c^2\,{\rm Br}_{\tau\bar\tau}[a,c]$

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Various Search Channels (after Moriond)

signal strength $$\mu = \frac{\sigma \times BR}{(\sigma \times BR)_{\mathrm{SM}}}$$

Channel [Exp]	$\mu_{119.5}$ ($\mu^L_{119.5}$)	μ_{124} (μ^L_{124})	μ_{125} (μ^L_{125})
$pp \to \gamma\,\gamma$ [ATLAS]	$0.0^{+0.6}_{-0.8}$ (1.5)	$0.8^{+0.8}_{-0.7}$ (2.6)	$1.6^{+0.9}_{-0.8}$ (3.9)
$pp \to Z\,Z^\star \to \ell^+\,\ell^-\,\ell^+\,\ell^-$ [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)
$pp \to \gamma\,\gamma$ [CMS]	$-1.1^{+0.6}_{-0.6}$ (1.3)	$1.5^{+0.7}_{-0.7}$ (3.5)	$1.6^{+0.7}_{-0.6}$ (3.0)
$pp \to Z\,Z^\star \to \ell^+\,\ell^-\,\ell^+\,\ell^-$ [CMS]	$2.0^{+1.6}_{-1.1}$ (5.2)	$0.5^{+1.1}_{-0.7}$ (2.7)	$0.6^{+0.9}_{-0.6}$ (2.5)
$pp \to W\,W^\star \to \ell^+\,\nu\,\ell^-\,\bar\nu$ [CMS]	$0.9^{+0.8}_{-0.7}$ (2.5)	$0.6^{+0.7}_{-0.7}$ (1.8)	$0.4^{+0.6}_{-0.6}$ (1.5)
$pp \to b\,\bar b$ [CMS]	$0.4^{+1.8}_{-1.6}$ (4.1)	$1.2^{+1.9}_{-1.8}$ (5.0)	$1.2^{+2.1}_{-1.7}$ (5.2)
$pp \to \tau\,\bar\tau$ [CMS]	$0.2^{+0.9}_{-1.1}$ (3.6)	$0.4^{+1.0}_{-1.2}$ (3.9)	$0.6^{+1.1}_{-1.2}$ (4.1)
$pp \to \tau\,\bar\tau$ [ATLAS]	$-0.9^{+1.7}_{-1.7}$ (2.9)	$-0.1^{+1.7}_{-1.8}$ (3.4)	$0.1^{+1.7}_{-1.8}$ (3.5)
$p\bar p \to b\,\bar b$ [CDF&DØ]	$1.5^{+0.6}_{-0.5}$ (2.5)	$1.9^{+0.8}_{-0.6}$ (3.1)	$2.0^{+0.8}_{-0.7}$ (3.2)

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Model independent fit to LHC data

Espinosa, Grojean, Muhlleitner, Trott '12

Atlas 95%CL exclusion

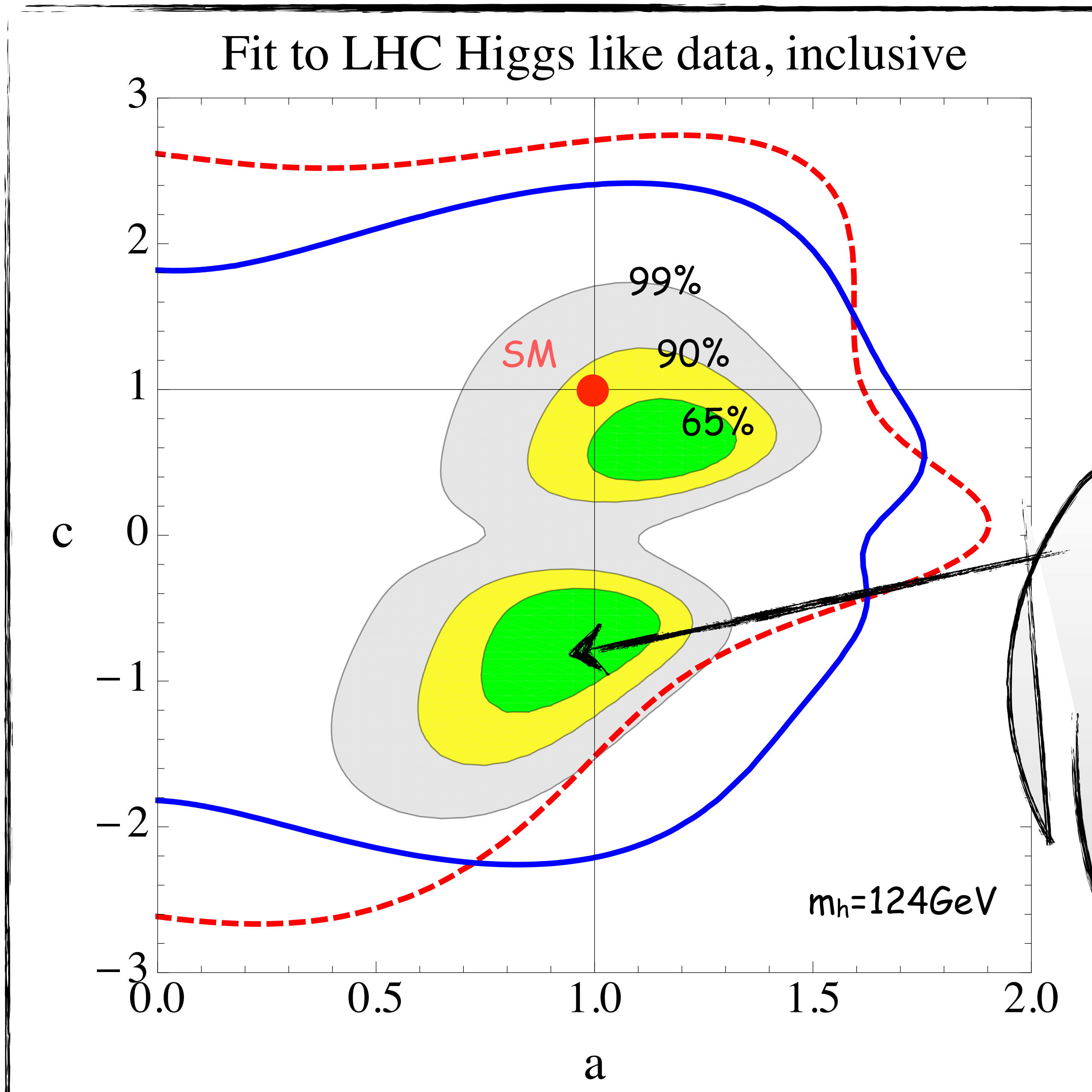
CMS 95%CL exclusion

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

for similar analyses, see also
Azatov, Contino, Galloway '12
Carni, Falkowski, Kuflik, Volansky '12

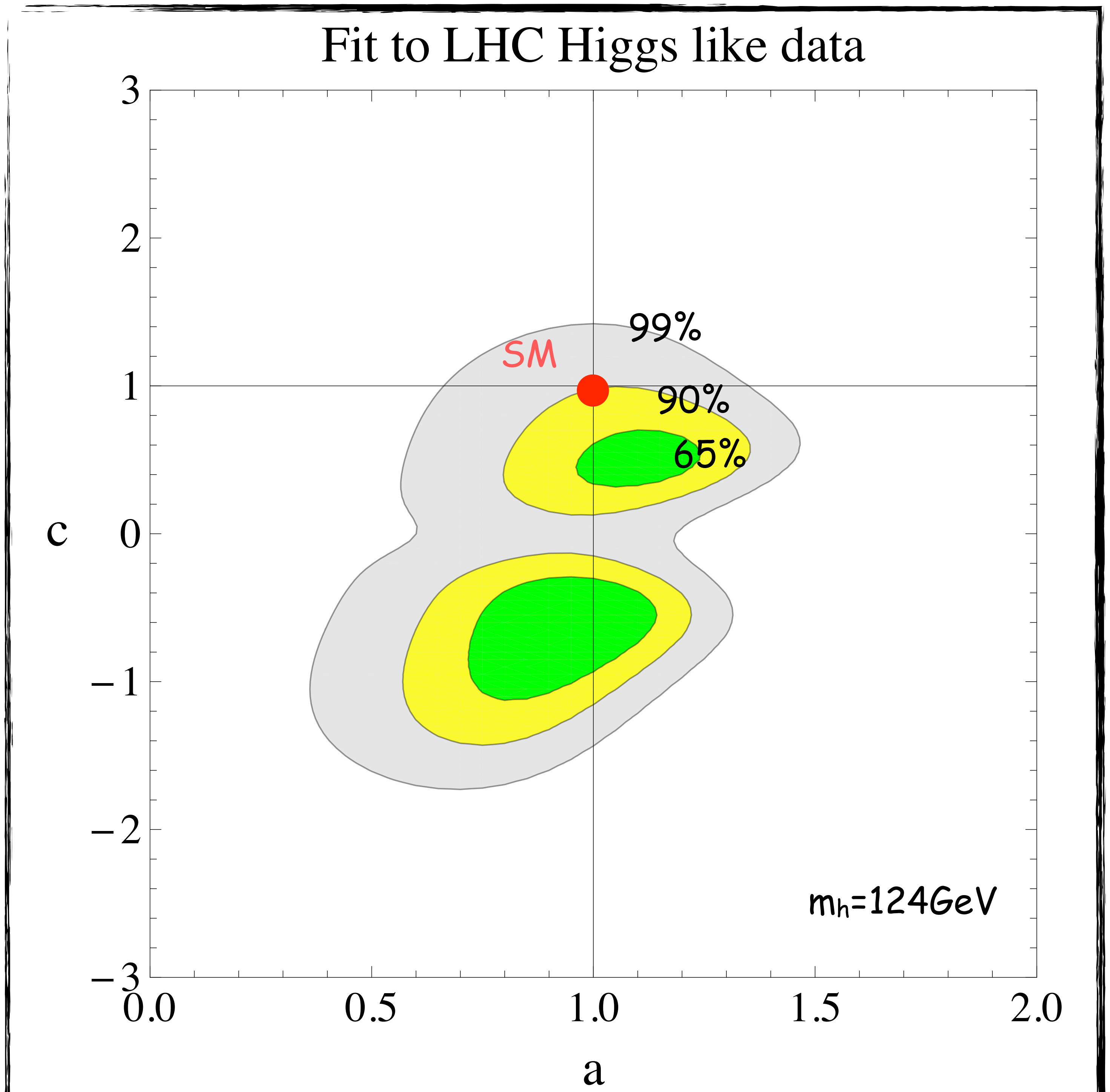
Model independent fit to (Moriond) LHC data

Espinosa, Grojean, Muhlleitner, Trott '12

Atlas 95%CL exclusion

CMS 95%CL exclusion

SM 94%CL away from best fit point



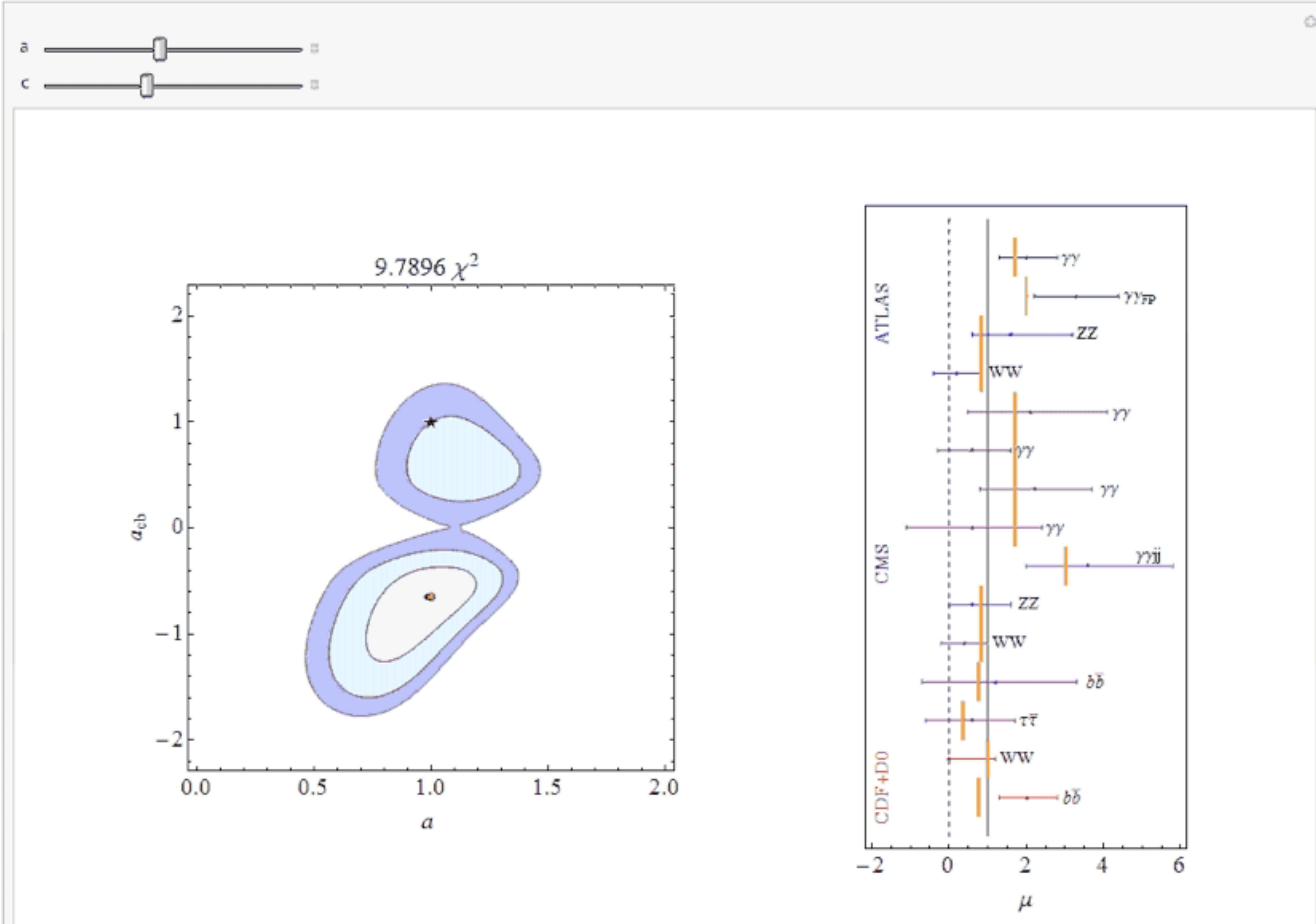
note: a fermiophobic Higgs is disfavored by data (mostly VBF channels) at 96%CL

for similar analyses, see also

Azatov, Contino, Galloway '12

Carni, Falkowski, Kuflik, Volansky '12

Model independent fit to LHC data

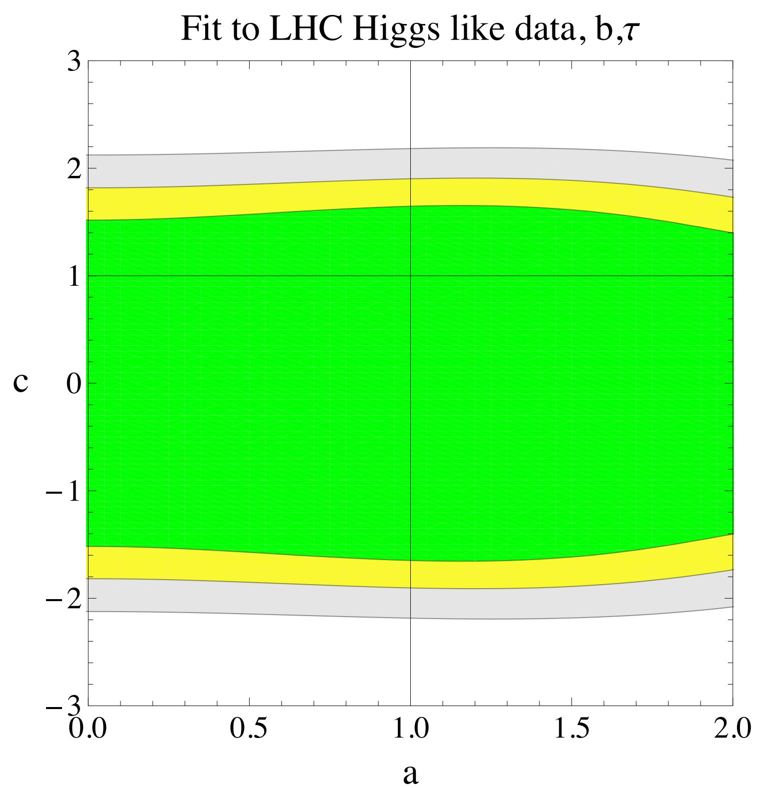


courtesy to M. Farina

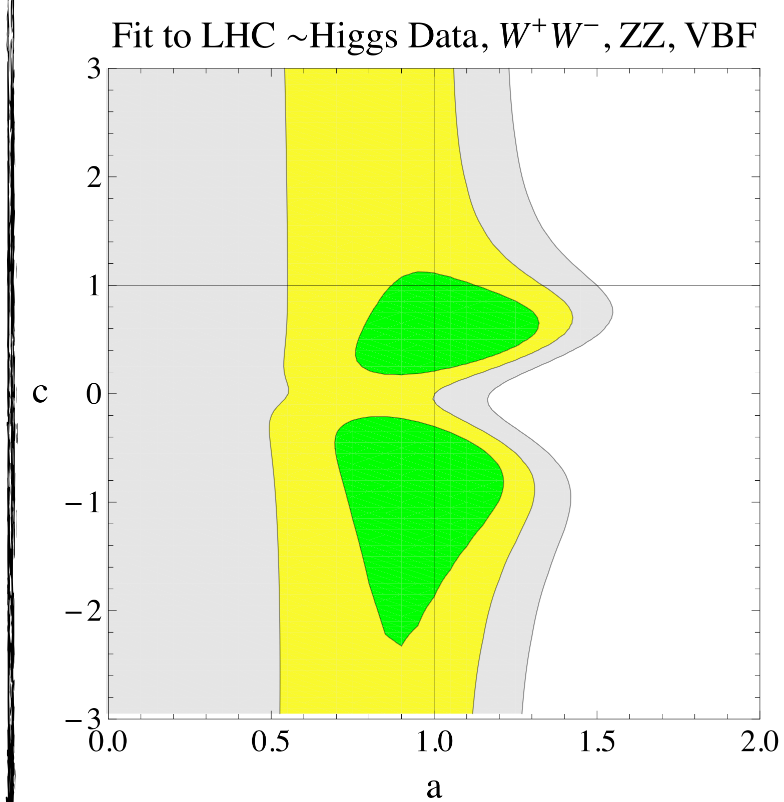
Which are the channels driving the fit?

Espinosa, Grojean, Muhlleitner, Trott '12

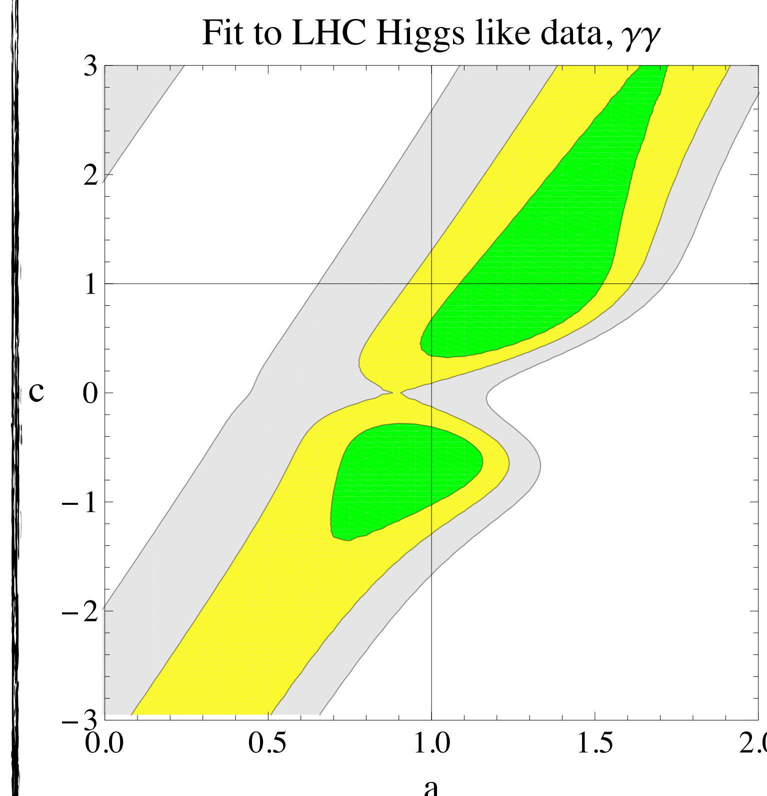
fermion couplings



gauge couplings



both couplings



almost
no constraints at the moment

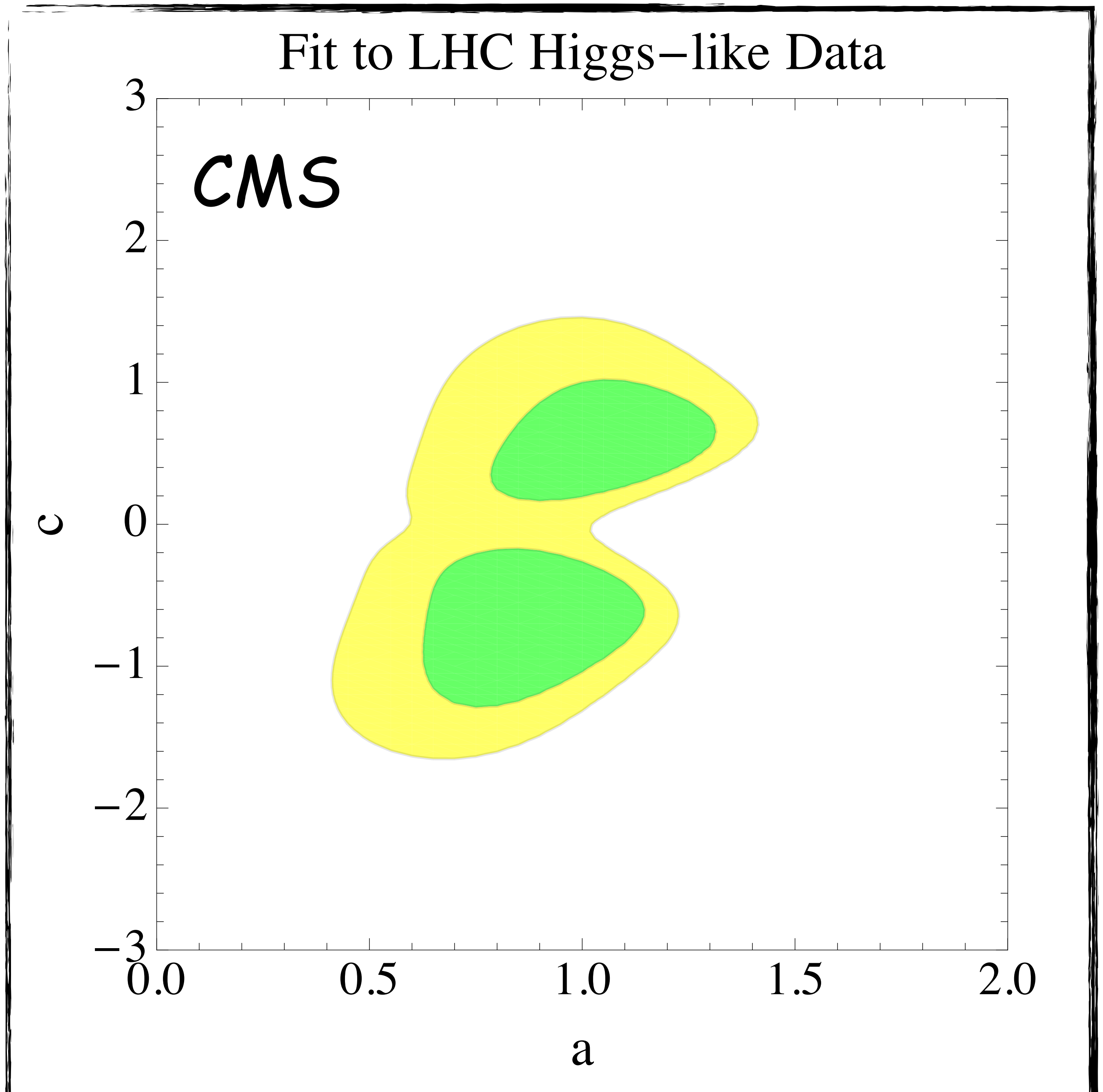
almost
(a,c)↔(a,-c) symmetric

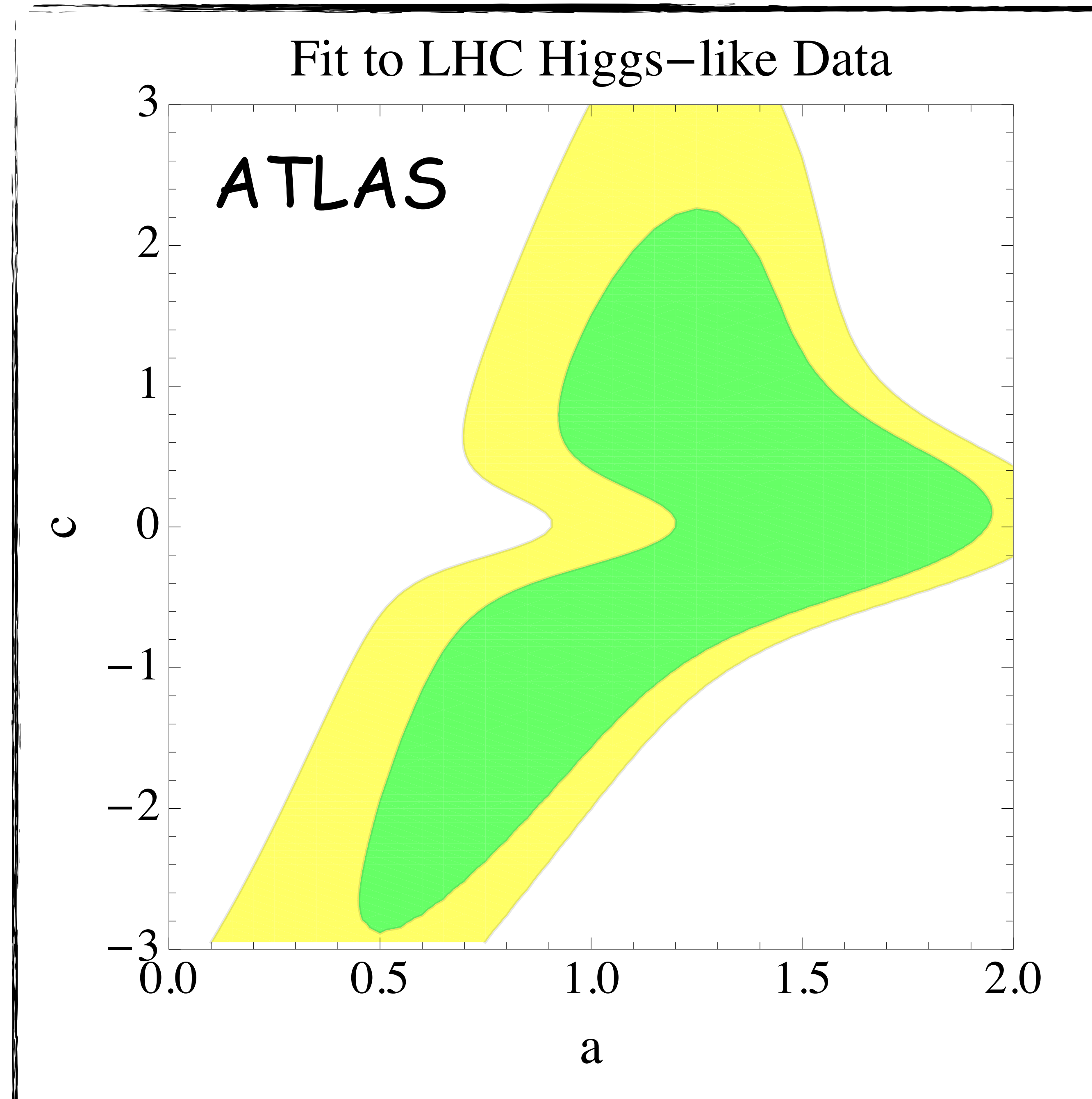
large a are disfavored

most constraining

note: even if $\Gamma(h\to\gamma\gamma)$ is not really modified (no operator $|H|^2 B_{\mu\nu}B^{\mu\nu}$), $BR_{\gamma\gamma}$ has strong dependence on 'a' and 'c'

CMS vs ATLAS





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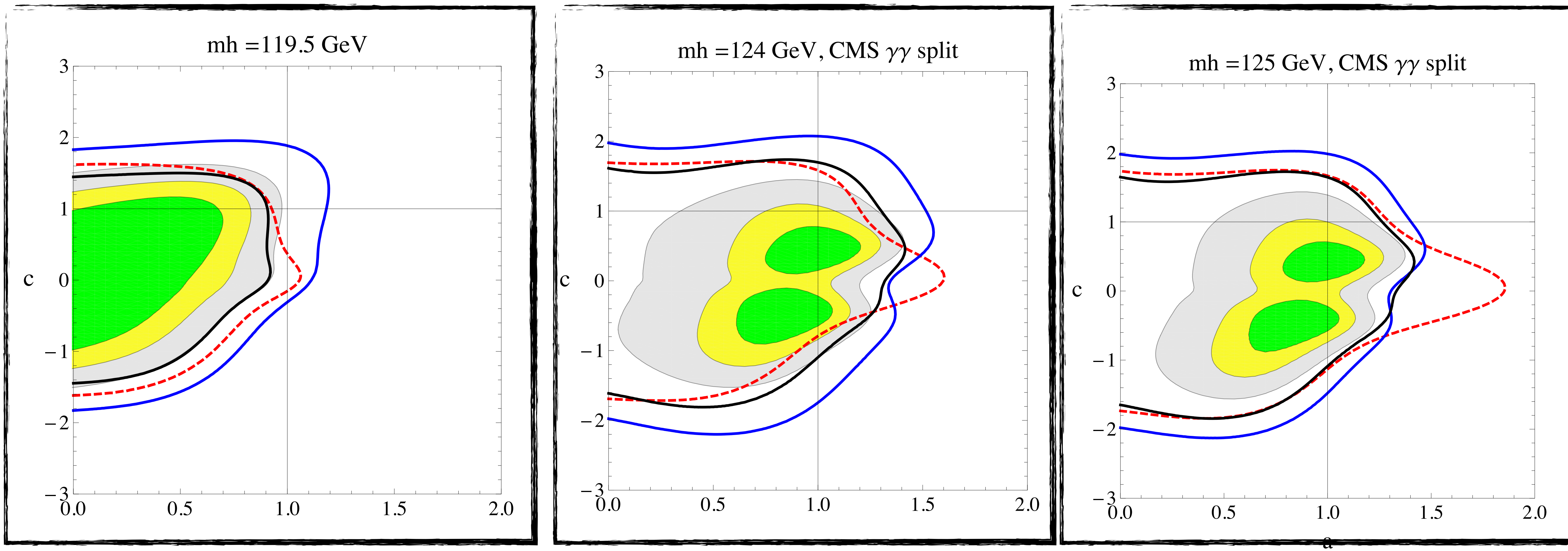
Which Higgs mass?



$(119.5, 0.28, 0.49, 9.8)$ $(124, 0.87, -0.43, 4.1)$ $(125, 0.87, -0.42, 4.6)$

(m_h, a, c, χ^2)

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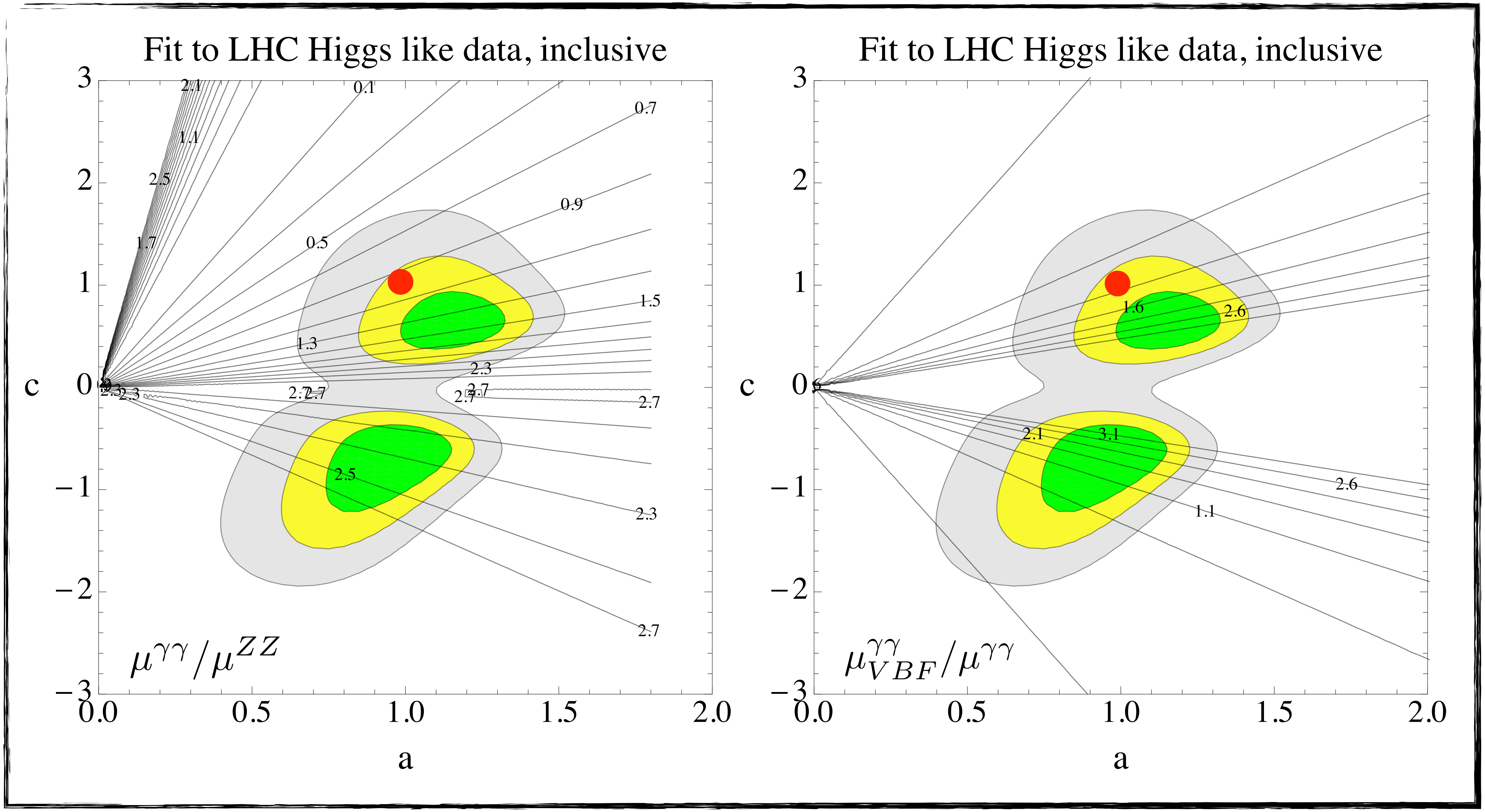
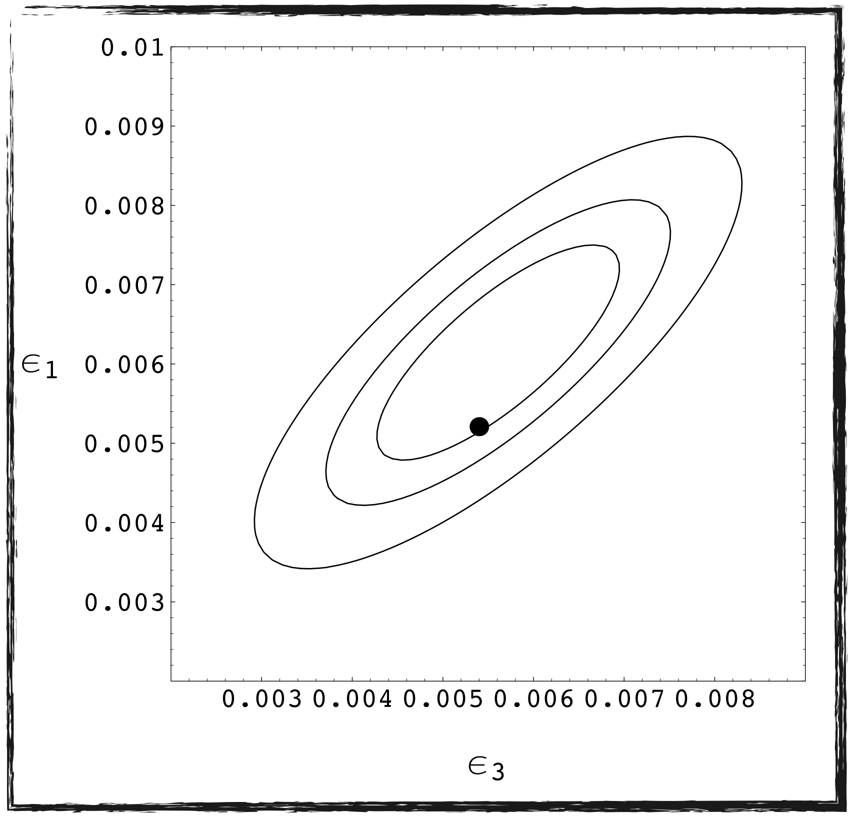
How to distinguish the two minima

the (a,c)↔(a,-c) symmetry is broken in the $\gamma\gamma$ channel



Espinosa, Grojean, Muhlleitner, Trott '12

A tension between LHC and EW data



EW fit strongly suggests custodial symmetry

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

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

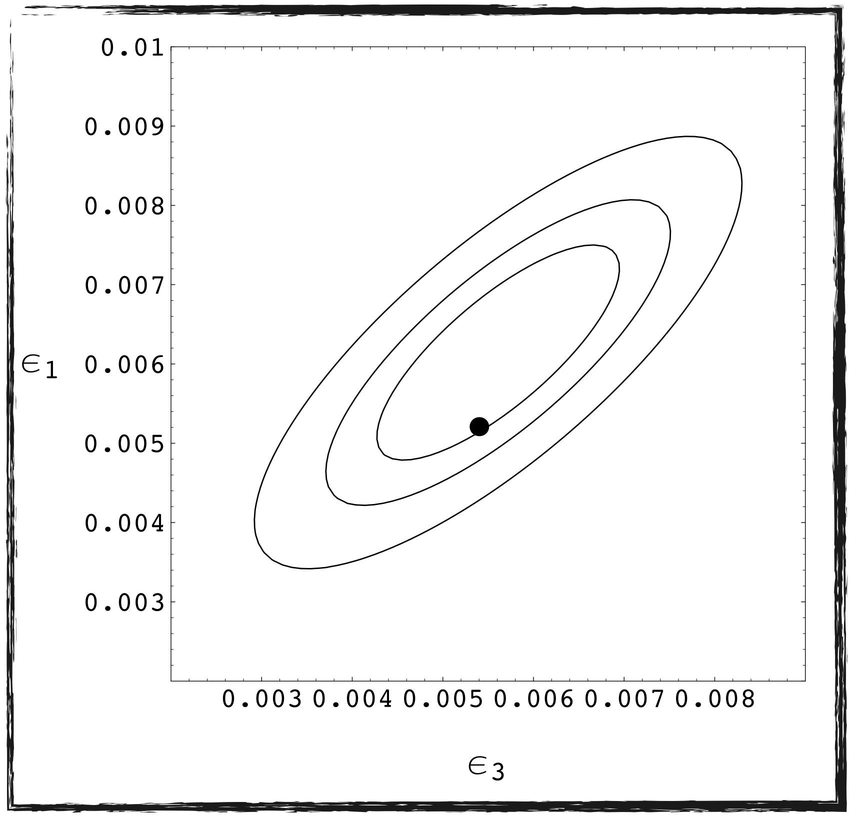
$$\frac{v^2}{4} \mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma \right) \Rrightarrow \rho = 1 \;\; \text{ie} \;\; \epsilon_1 = \hat{T} = 0$$

✓

$$\frac{v^2}{4} \mathrm{Tr}^2\left(\Sigma^\dagger D_\mu \Sigma \sigma^3 \right) \quad \Rrightarrow \quad \rho = 2 \quad \text{ie} \quad \epsilon_1 = \hat{T} = 1$$

strongly disfavored

A tension between LHC and EW data



EW fit strongly suggests custodial symmetry

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

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

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

✓

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

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?

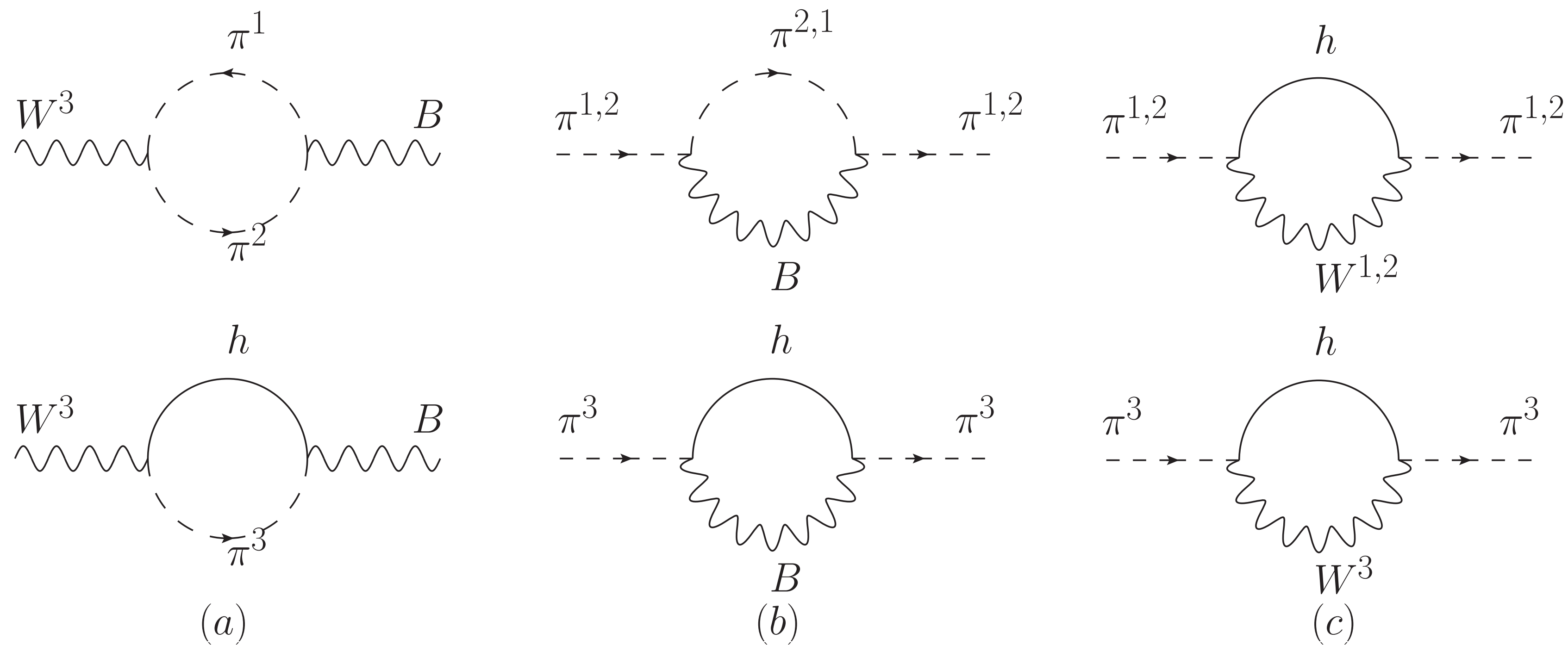
DisZphilia or how to live with custodial breaking

Farina, Grojean, Salvioni 'to appear

$$\mathcal{L}_{cb} = -\frac{v^2}{8}\left(\mathrm{Tr}\left[\Sigma^\dagger D_\mu \Sigma\, \sigma^3\right]\right)^2 \left(0 + 2a_{cb}\frac{h}{v} + \cdots\right)$$

no custodial breaking in the vacuum

custodial breaking Higgs interactions



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

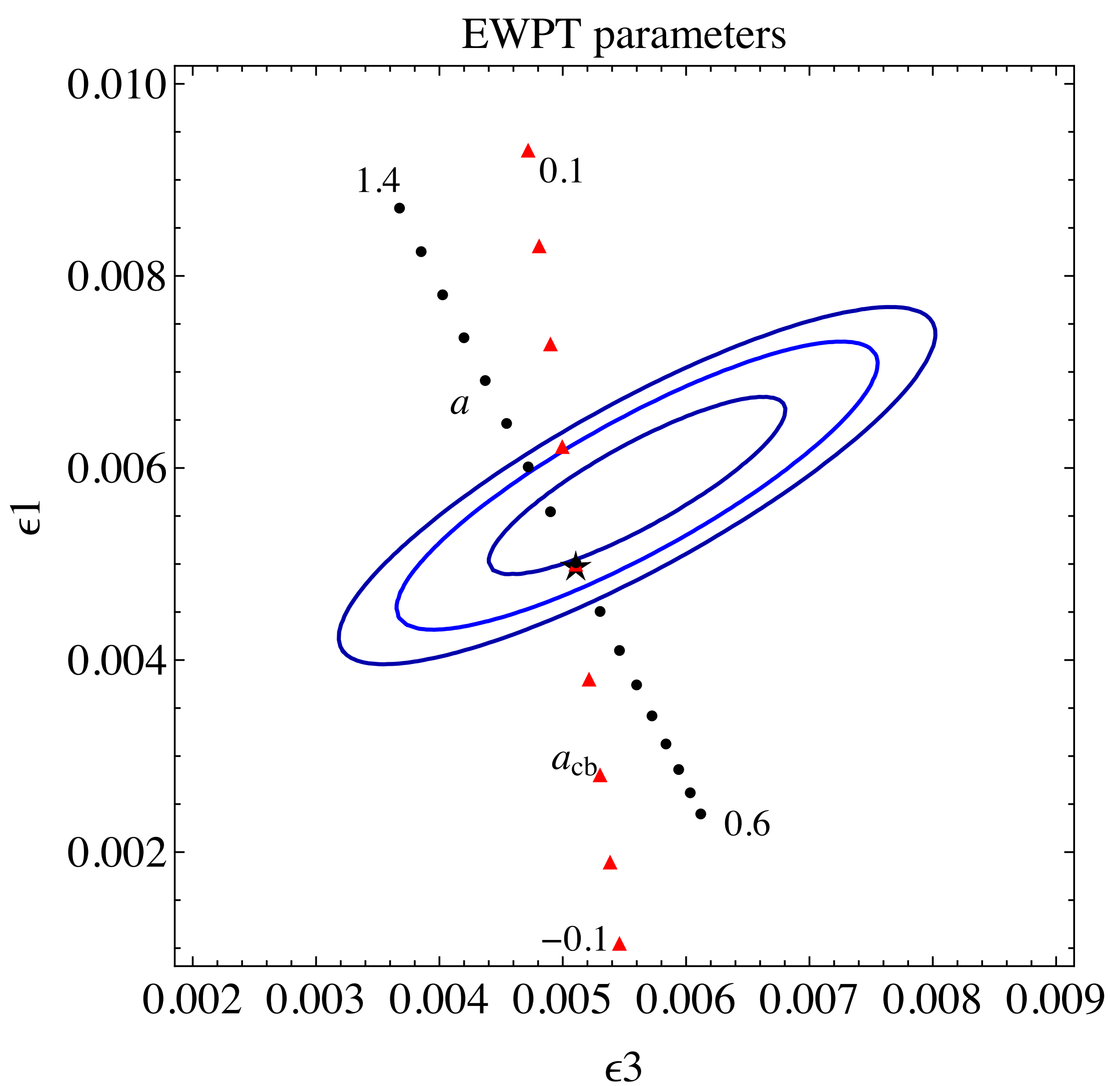
$$\Delta\epsilon_3 = +\frac{1}{48\pi}\frac{\alpha(m_Z)}{\sin^2\theta_W}\left[1-(a+a_{cb})^2\right]\log\left(\frac{\Lambda^2}{m_h^2}\right).$$

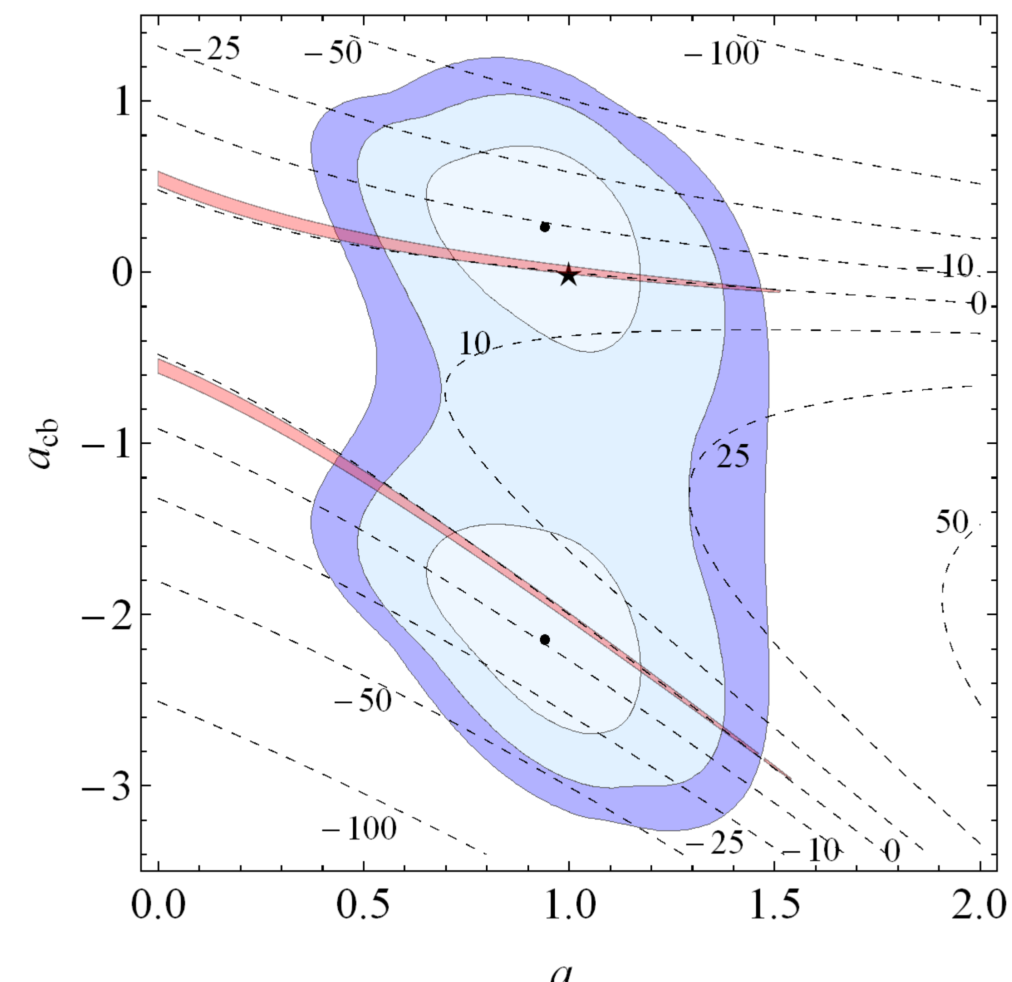
Note: quadratic custodial breaking couplings will give Λ^2 UV sensitivity in ϵ_1

DisZphilia or how to live with custodial breaking

Farina, Grojean, Salvioni 'to appear

$$\mathcal{L}_{cb} = -\frac{v^2}{8}\left(\mathrm{Tr}\left[\Sigma^\dagger D_\mu \Sigma\, \sigma^3\right]\right)^2 \left(0 + 2a_{cb}\frac{h}{v} + \cdots\right)$$





'a_{cb}' allows for larger range of values for 'a'

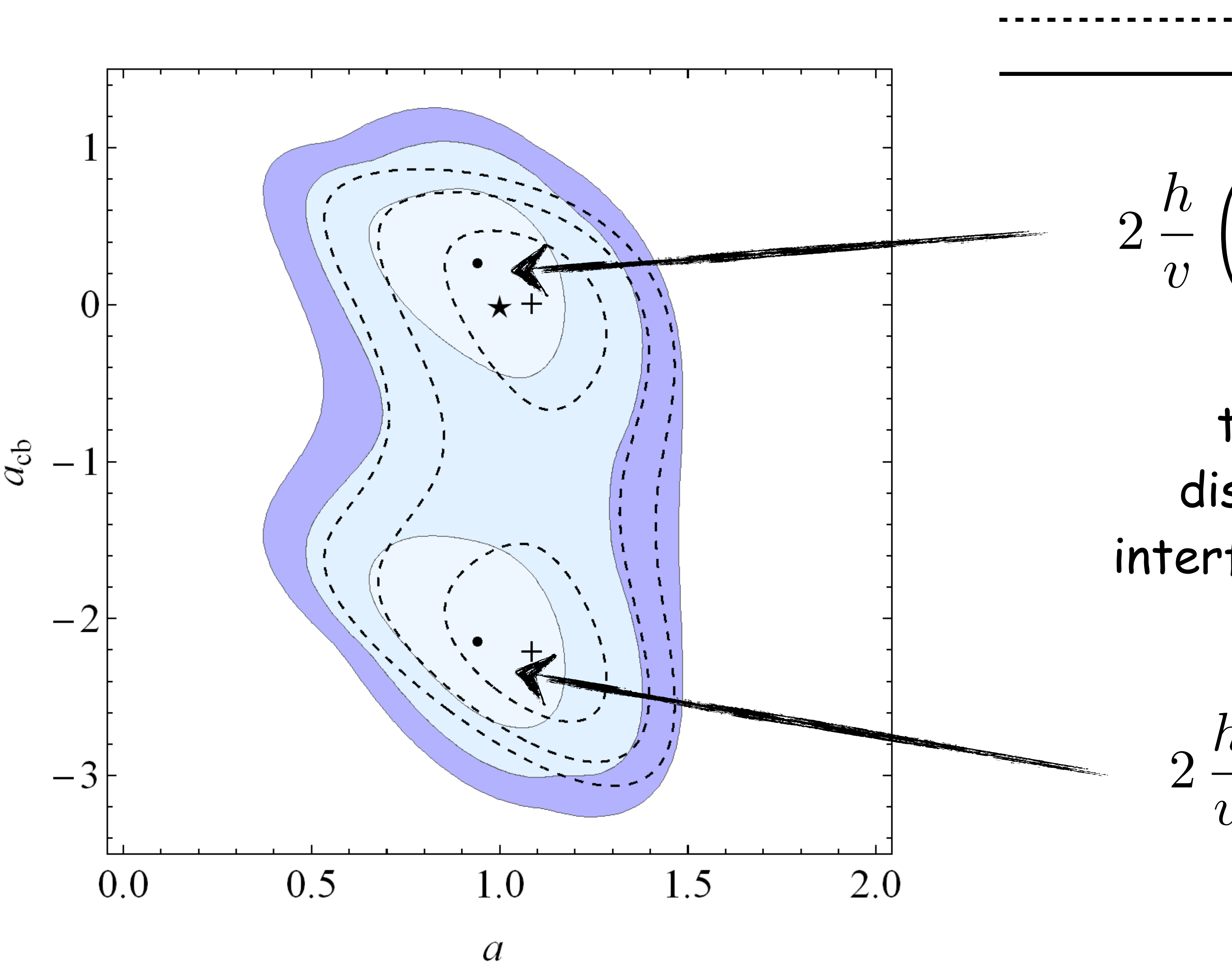
$a_{cb}=0$: $0.95 \lesssim a \lesssim 1.1$

$a_{cb}\neq 0$: $0.4 \lesssim a \lesssim 1.5$

DisZphilia or how to live with custodial breaking

Farina, Grojean, Salvioni 'to appear

$$\mathcal{L}_{cb} = -\frac{v^2}{8}\ \left(\mathrm{Tr}\left[\Sigma^\dagger D_\mu \Sigma\, \sigma^3\right]\right)^2 \left(0 + 2a_{cb}\frac{h}{v} + \cdots\right)$$



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

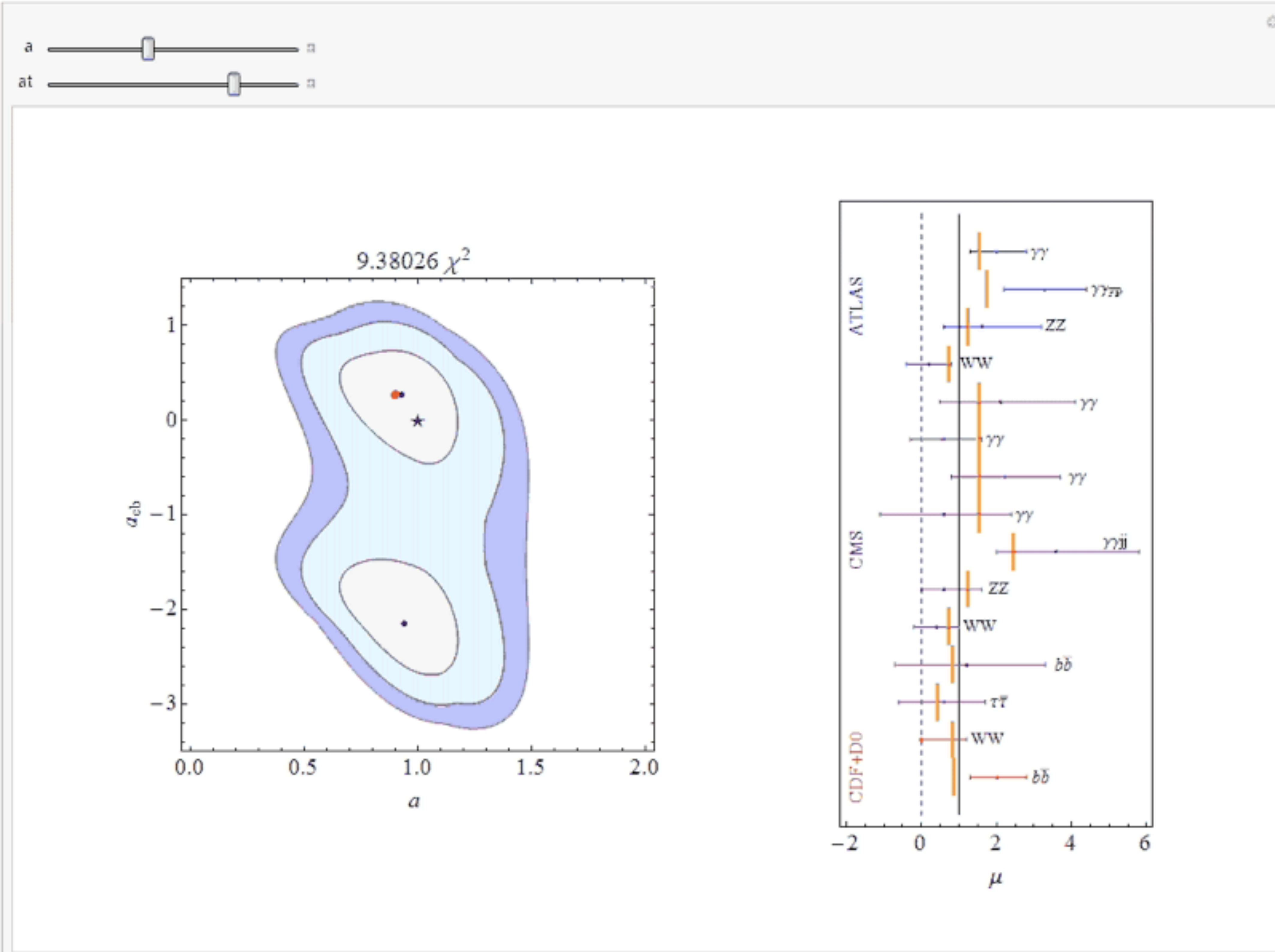
the two solutions can only be distinguished in the presence of interference with a single hZZ vertex

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

"disZphilia"

DisZphilia or how to live with custodial breaking

Farina, Grojean, Salvioni 'to appear

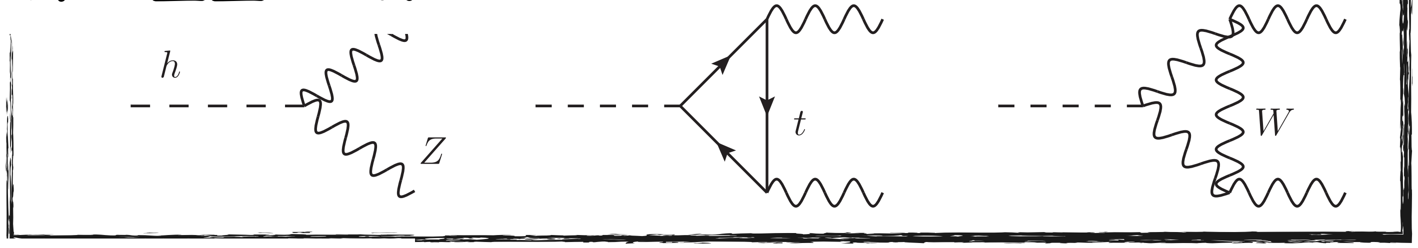
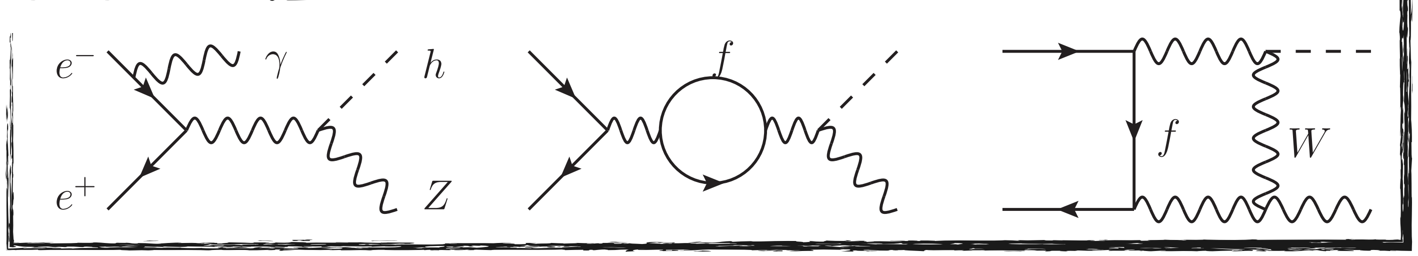
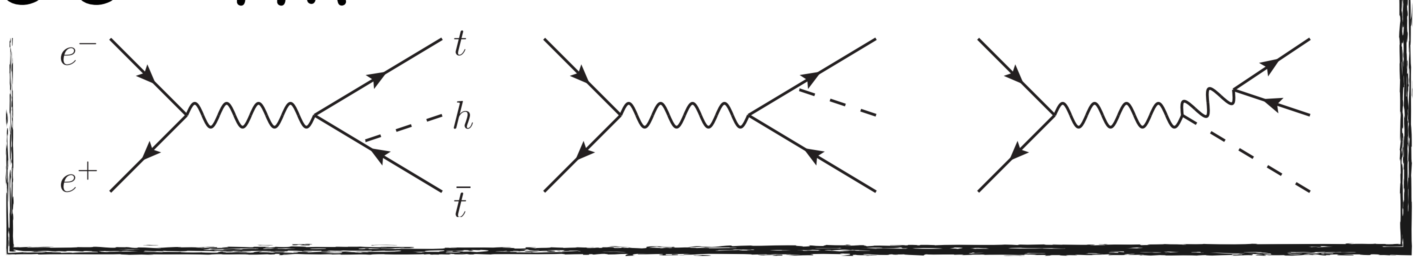
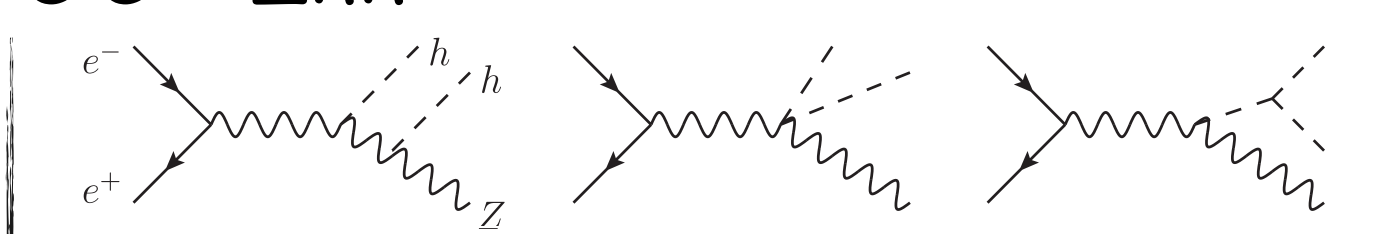


Zphilia or DisZphilia?

difficult!

Farina, Grojean, Salvioni 'to appear

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

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

Conclusions

EW interactions need Goldstone bosons to provide mass to W, Z

⇓ ⇓ ⇓ ⇓ ⇓ ⇓

EW interactions also need a UV moderator/new physics
to unitarize WW scattering amplitude

We'll need another Gargamelle experiment
to discover the still missing neutral current of the SM: the Higgs

weak NC ⇔ gauge principle

Higgs NC ⇔ ?

Strong EWSB w/o an elementary Higgs can be very similar to SM

it might take a long time to decipher the true dynamics of EWSB!