Alternative Higgs under LHC Experimental Scrutiny

NPKI workshop

Seoul, February 24-29, 2012

Christophe Grojean

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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”*

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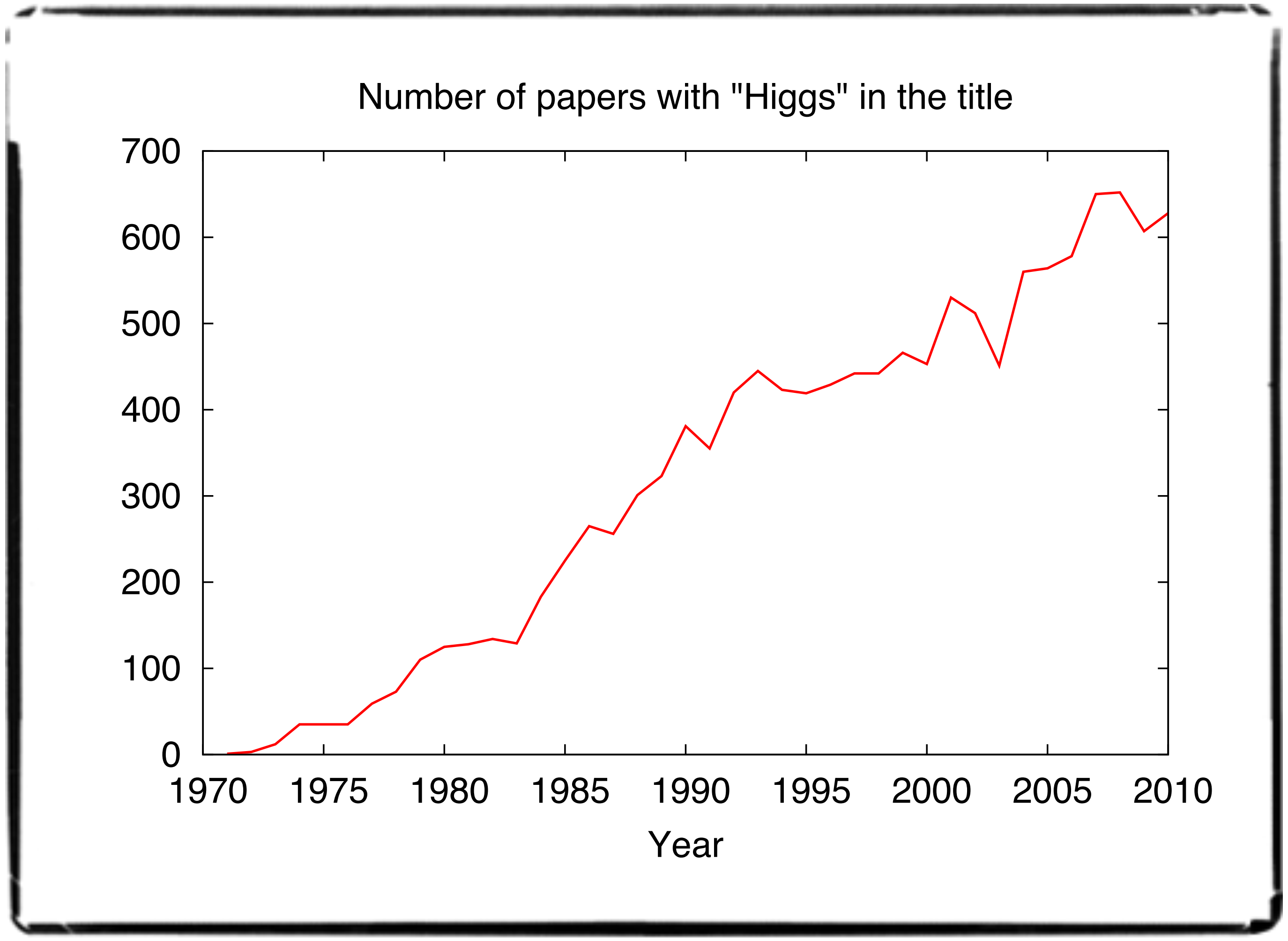

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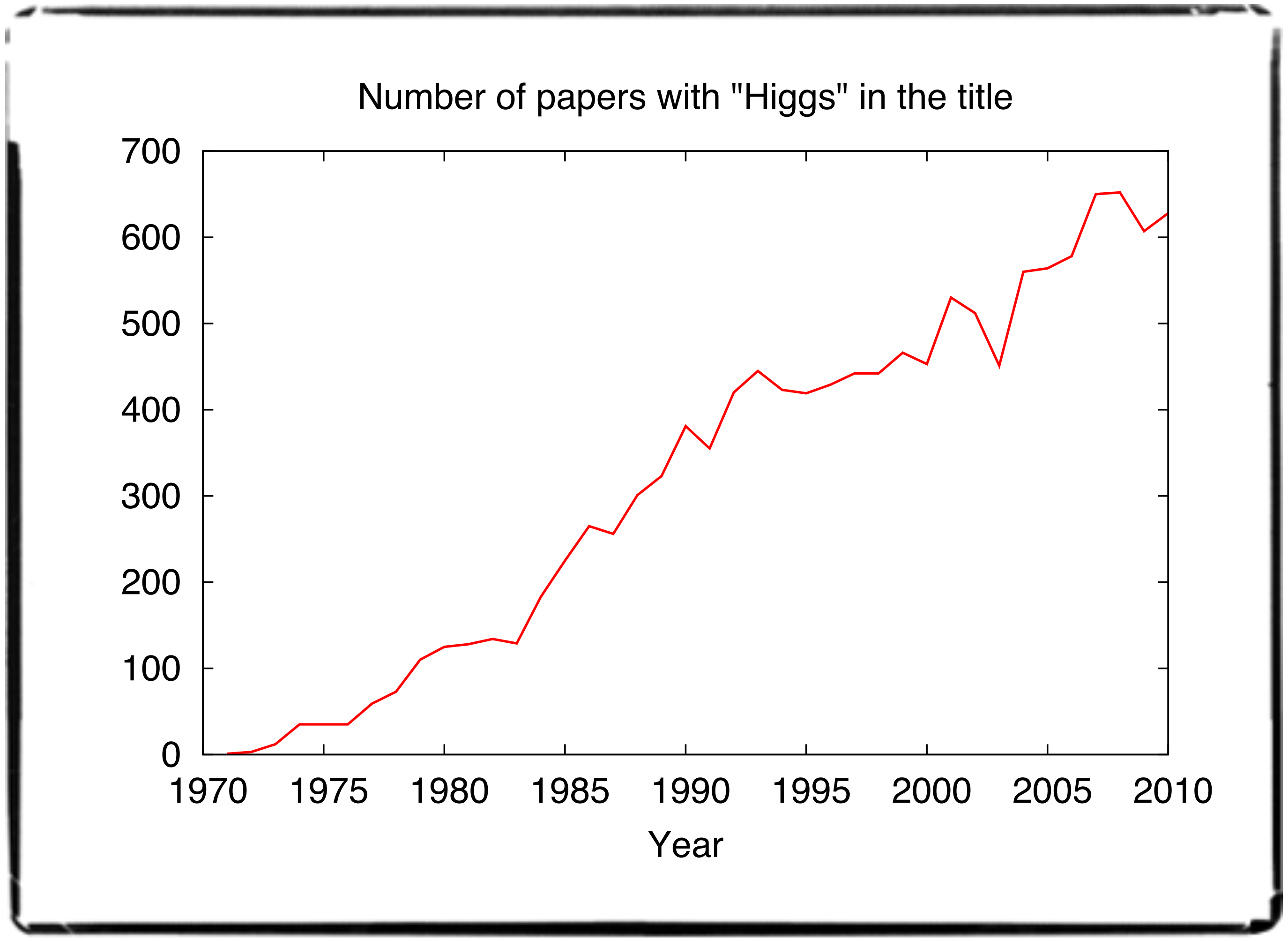

with even a bigger peak since last Dec.!

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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

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"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±, Z: 3 physical polarizations=eaten Goldstone bosons $\frac{SU(2)_L \times SU(2)_R}{SU(2)_V}$

$\Rrightarrow$ UV behavior of these Goldstone's? $\Lleftarrow$

Lee, Quigg & Thacker '77

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⇛ UV behavior of these Goldstone's? ⇚

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

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

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

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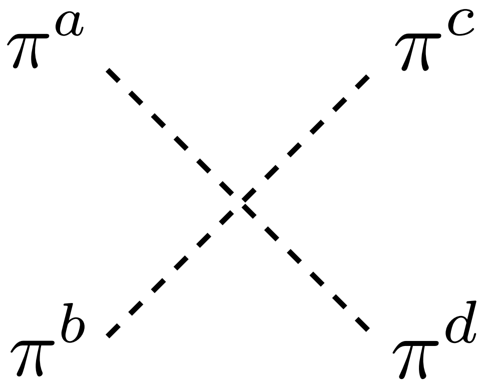
$$\boxed{\mathcal{L}_{\rm mass} = \frac{1}{2}(\partial_\mu \pi^a)^2 - \frac{1}{6v^2}\left((\pi^a \partial_\mu \pi^a)^2 - (\pi^a)^2 (\partial_\mu \pi^a)^2\right) + \ldots}$$

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

Lee, Quigg & Thacker '77

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Goldstone of SU(2)

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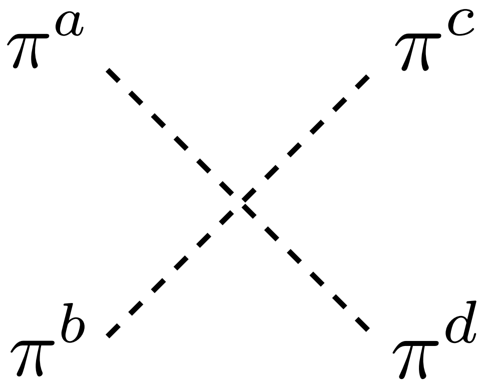

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the behavior of this amplitude is not consistent above 4πv (≈1÷3TeV)

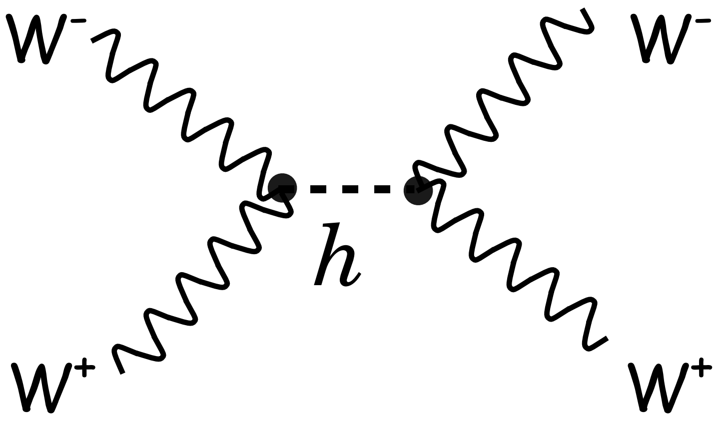
Lee, Quigg & Thacker '77

What is the SM Higgs?

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

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

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



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

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)$_L$xSU(2)$_R$/SU(2)$_V$ $D_\mu\Sigma \approx W_\mu$

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For a=1: perturbative unitarity in elastic channels WW → WW

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

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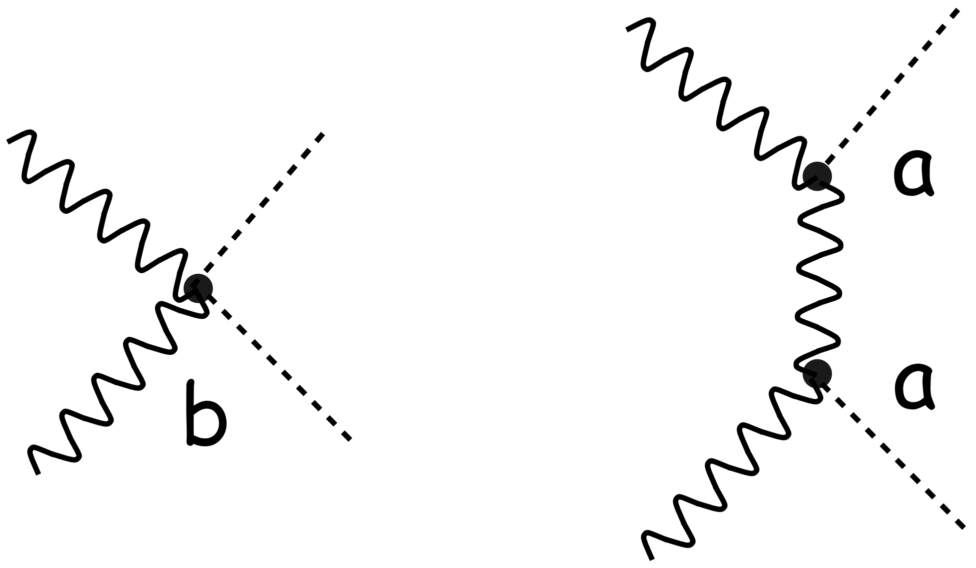

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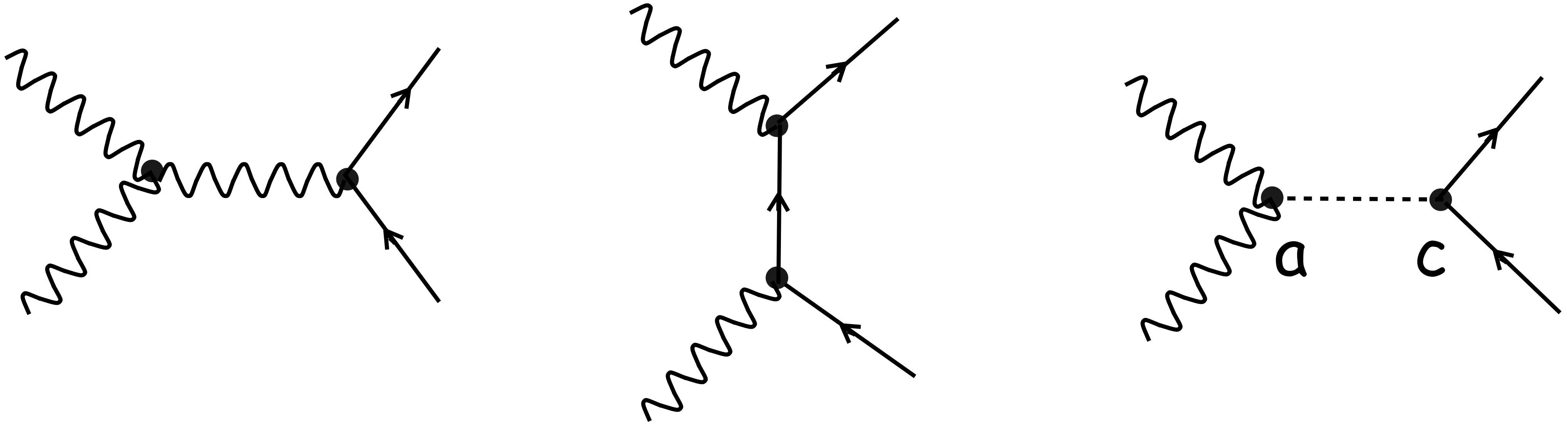

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'a=1', 'b=1' & 'c=1' define the SM Higgs

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$_L$ andZ$_L$) combine to form a linear representation of SU(2)$_L$xU(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

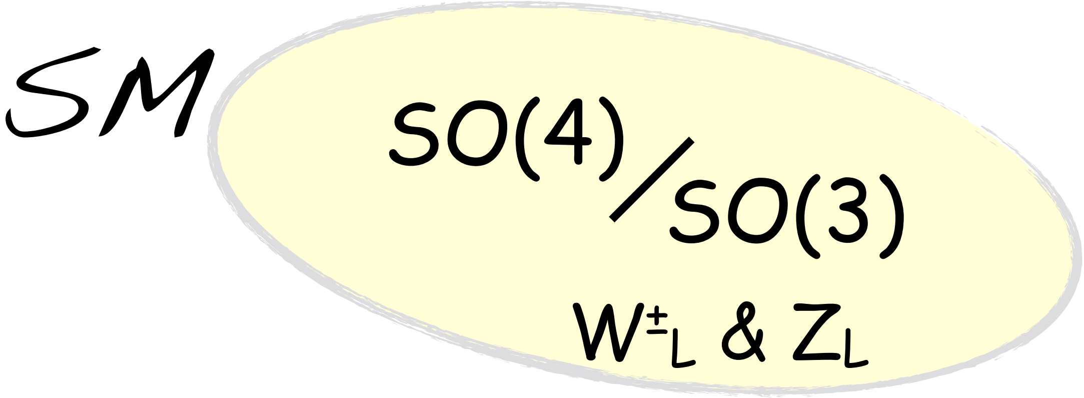
deviations of Higgs couplings originate from higher dimensional operators

$$\underbrace{\left(\partial_\mu |H|^2\right)^2 \quad |H|^2 \bar{\psi} H \psi}_{\text{relevant for composite Higgs models}} \quad \underbrace{|H|^2 B_{\mu\nu} B^{\mu\nu} \quad |H|^2 G_{\mu\nu} G^{\mu\nu}}_{\text{irrelevant for composite Higgs models}}$$

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)



$SO(4)/SO(3)$

$W^{\pm}_L$ & Z_L

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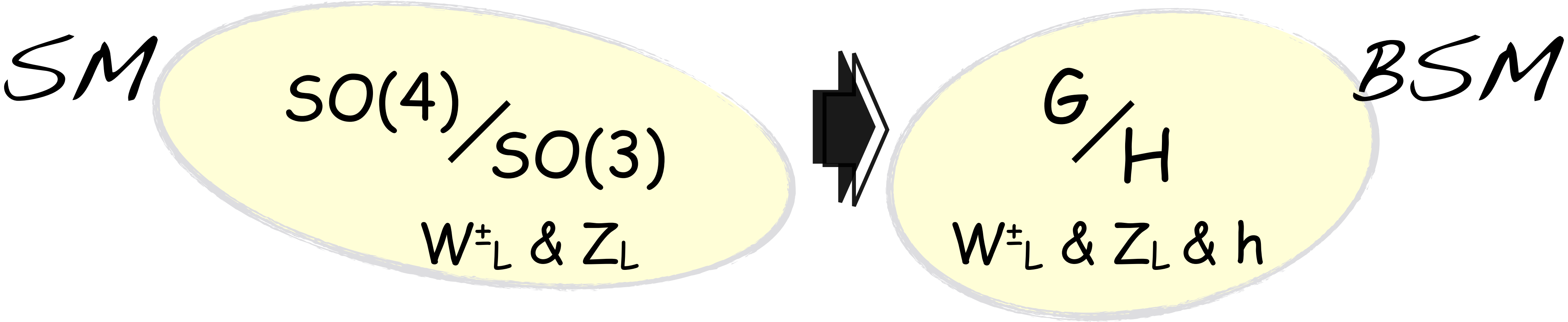

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BSM

G/H

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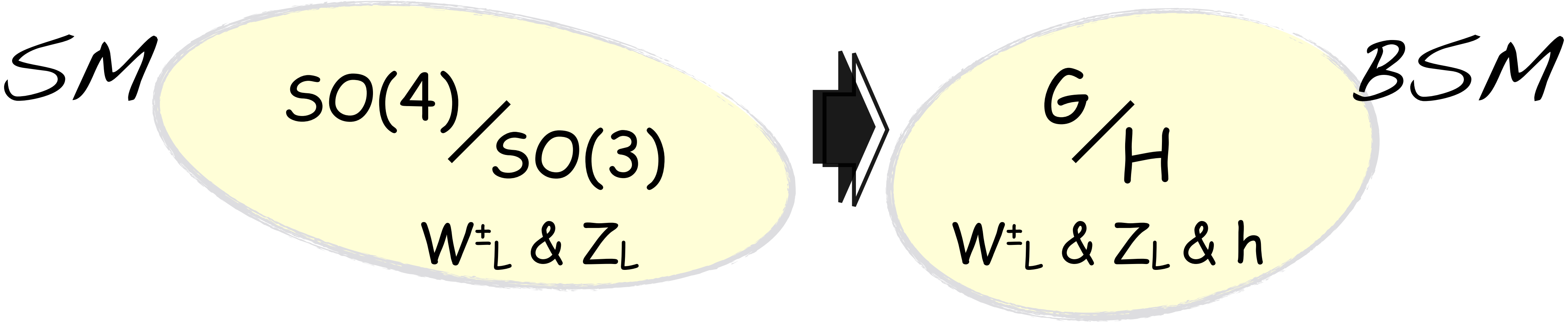

SM $SO(4)/SO(3)$ $W^{\pm}_L$ & Z_L ⇒ G/H $W^{\pm}_L$ & Z_L & h BSM

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

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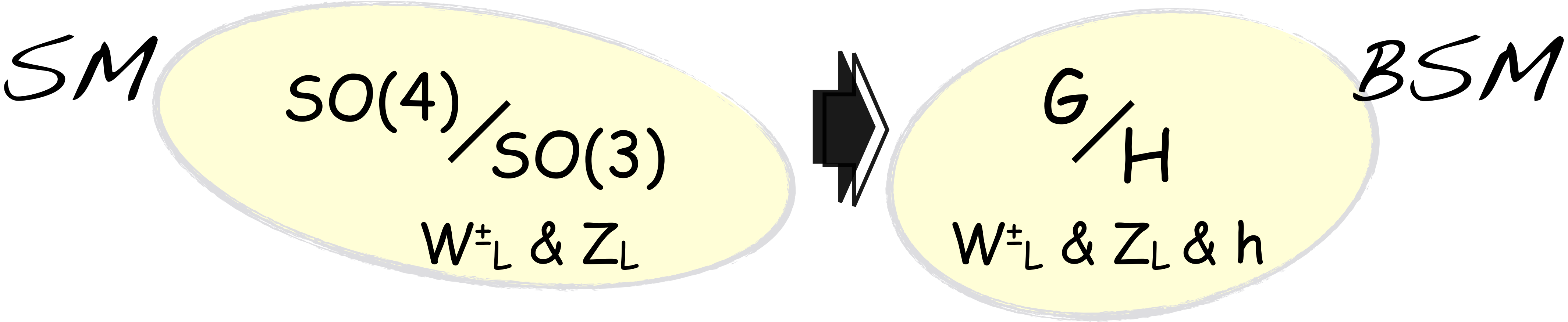

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Agashe, Contino, Pomarol '04

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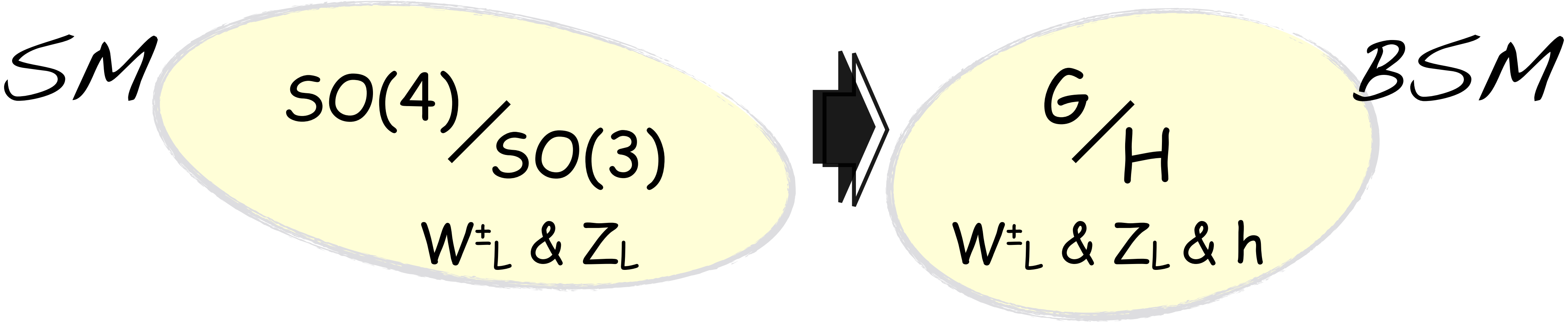

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$SO(6)/SO(5)$: 5 PGBs=H, a ← Next MCHM

Gripaios, Pomarol, Riva, Serra '09

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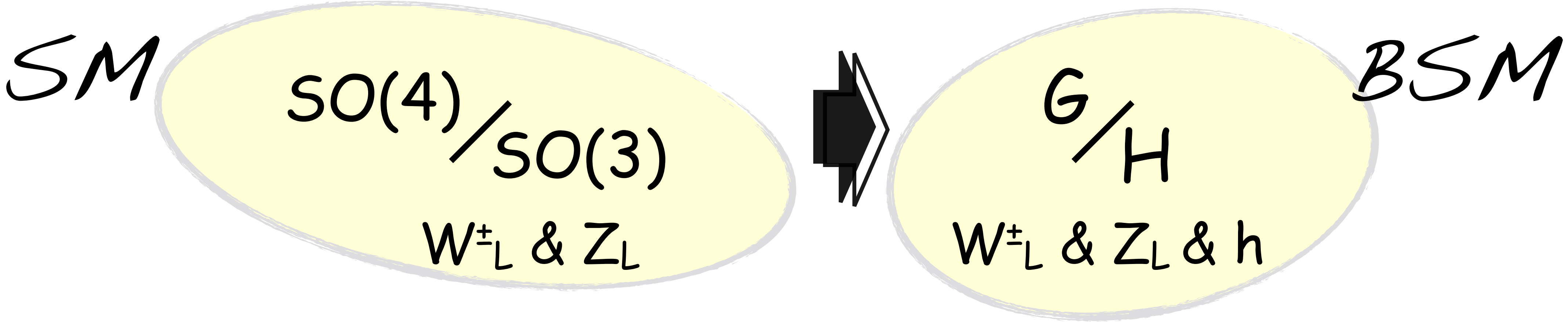

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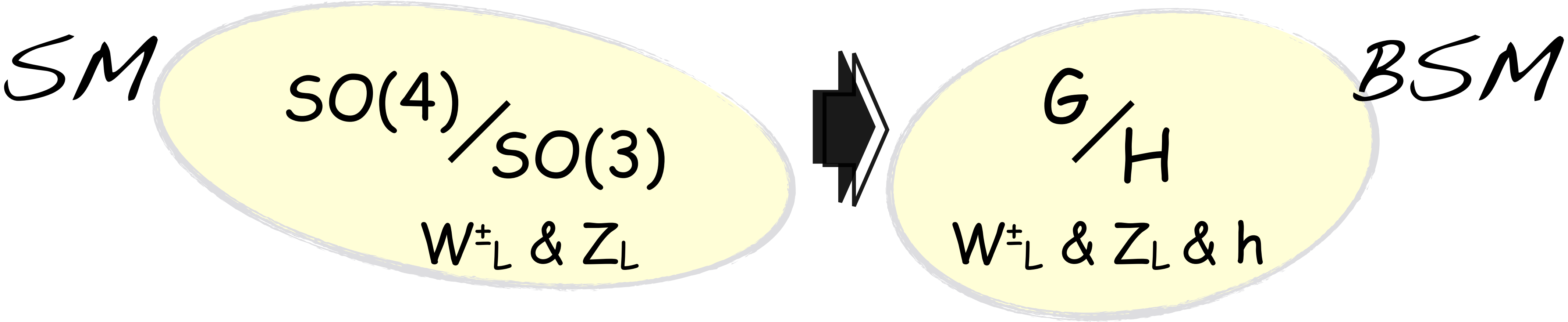

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$SU(4)/Sp(4,\mathbb{C})$: 5 PGBs=H, s

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

Mrazek, Pomarol, Rattazzi, Serra, Wulzer '11

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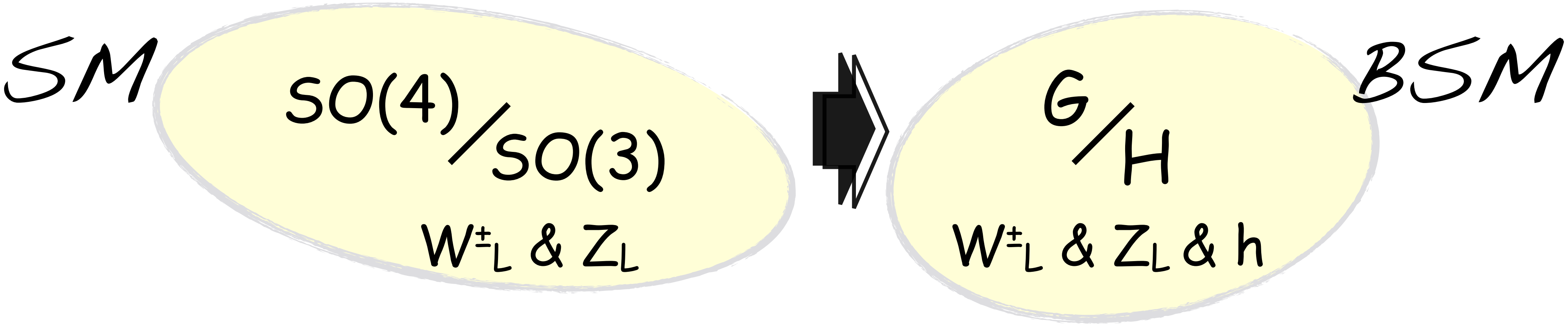

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How can we tell the difference with the SM Higgs?

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)

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

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

custodial breaking

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

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

Form factor operators (sensitive to the scale m$_\rho$)

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

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

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

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

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.

Minimal Composite Higgs Examples

The SILH Lagrangian is an expansion for small v/f
5D MCHM give a completion for large v/f

$$m_W^2 = \frac{1}{4} g^2 f^2 \sin^2 v/f \quad \Rrightarrow \quad g_{hWW} = \sqrt{1-\xi}\, g_{hWW}^{\text{SM}} \quad \Rrightarrow \quad \begin{cases} a = \sqrt{1-\xi} \\ b = 1 - 2\xi \end{cases}$$

Fermions embedded in spinorial of SO(5)

$$m_f = M \sin v/f$$

$$\Downarrow$$

$$g_{hff} = \sqrt{1-\xi}\, g_{hff}^{\text{SM}}$$

$$\Downarrow$$

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

universal shift of the couplings
no modifications of BRs

MCHM4

Fermions embedded in 5+10 of SO(5)

$$m_f = M \sin 2v/f$$

$$\Downarrow$$

$$g_{hff} = \frac{1-2\xi}{\sqrt{1-\xi}}\, g_{hff}^{\text{SM}}$$

$$\Downarrow$$

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

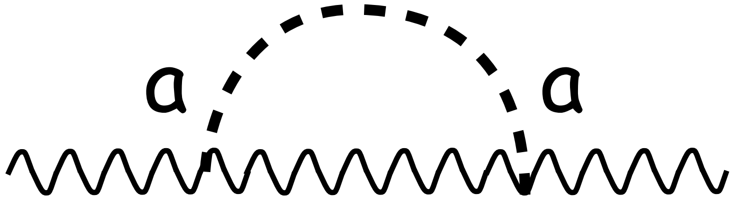
BRs now depends on v/f

MCHM5

$$\left(\xi = v^2/f^2\right)$$

Deformation of the SM Higgs: EW constraints

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



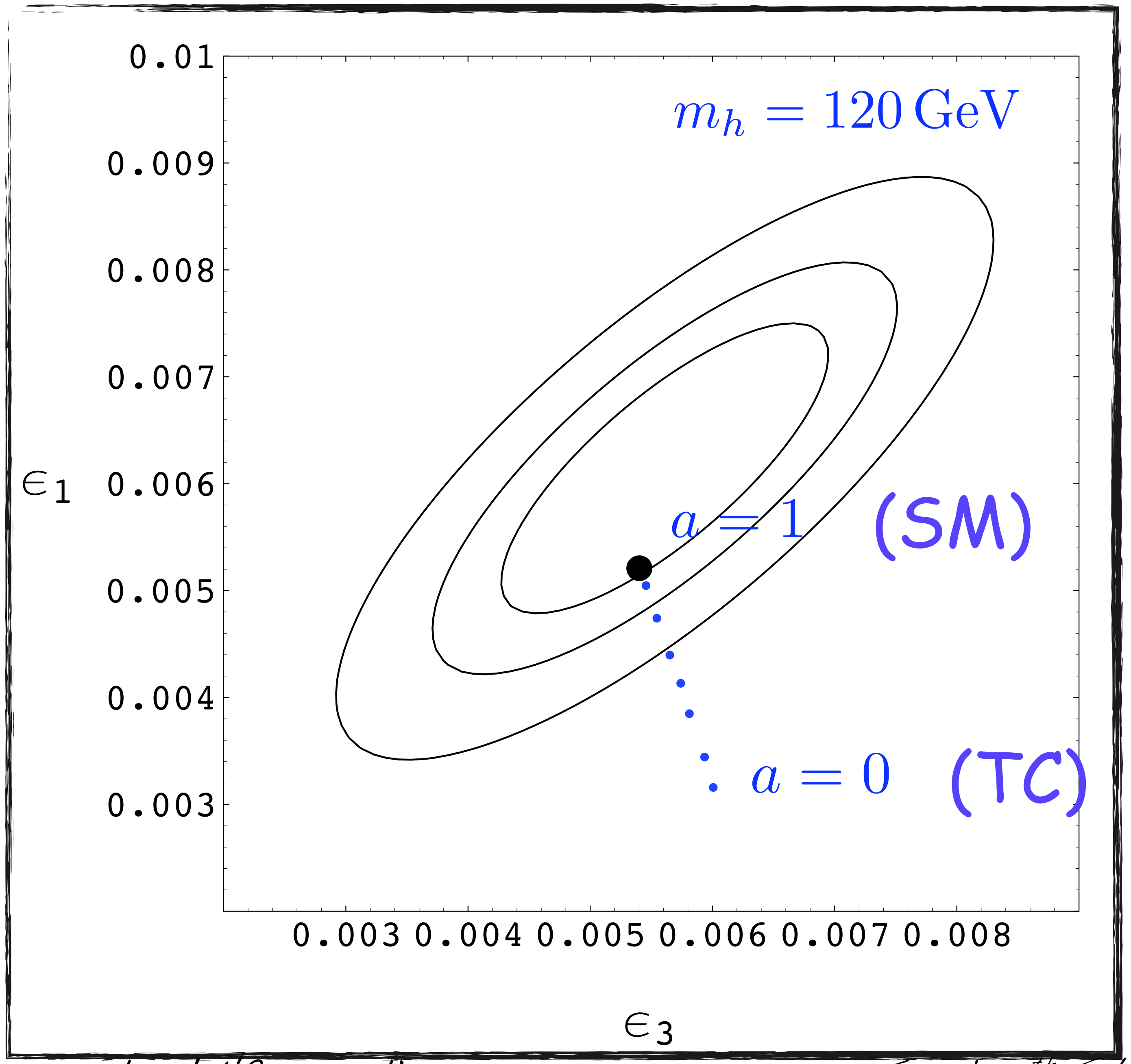
$$\epsilon_{1,3} = c_{1,3}\log(m_Z^2/\mu^2) - c_{1,3}\,a^2\log(m_h^2/\mu^2) - c_{1,3}\,\left(1-a^2\right)\log(m_\rho^2/\mu^2) + \text{finite terms}$$

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

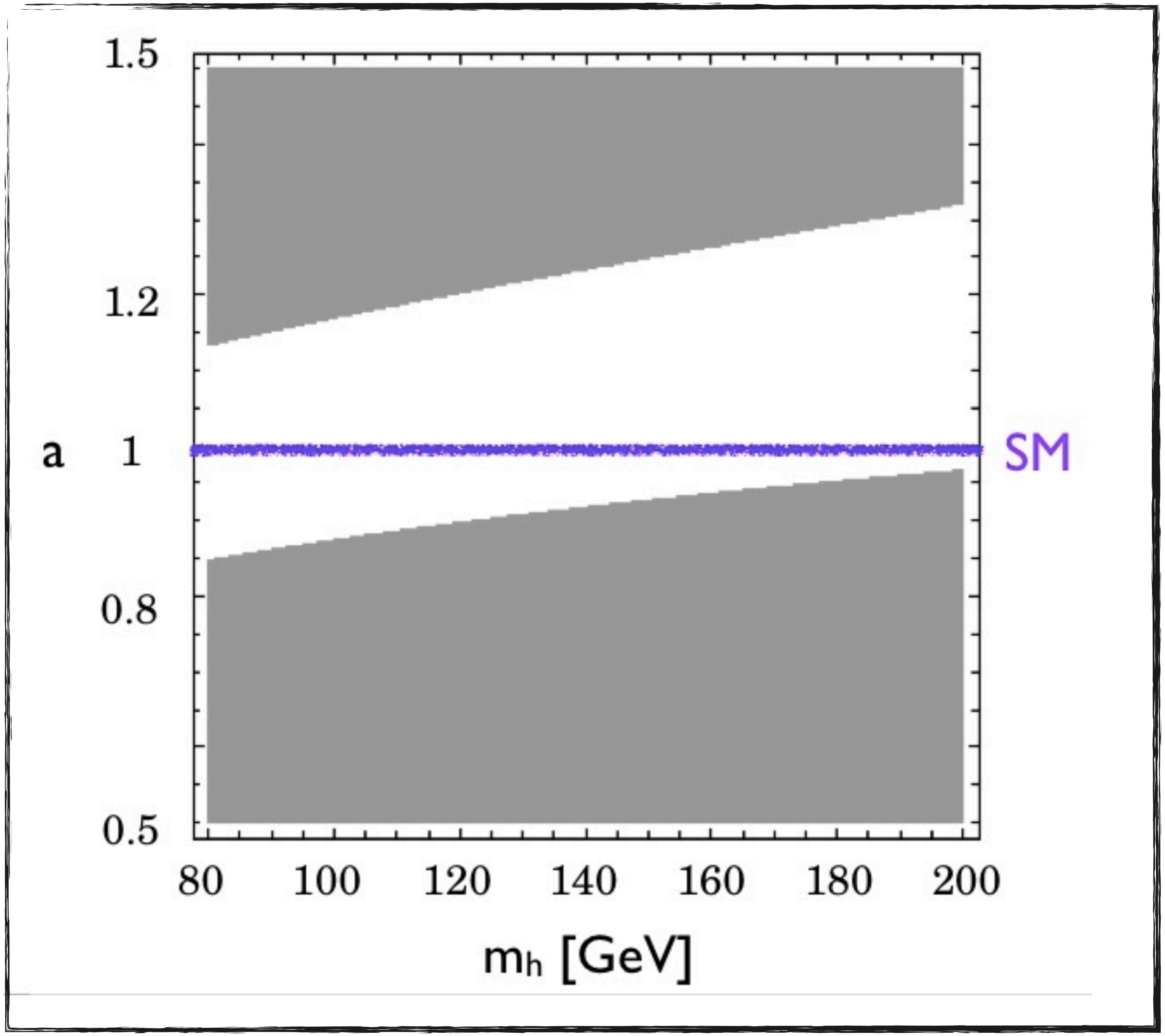
$$c_3 = -\frac{1}{12\pi}\frac{\alpha(m_Z)}{4\sin^2\theta_W}$$

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

Barbieri, Bellazzini, Rychkov, Varagnolo '07



EW data constraints on 'a'



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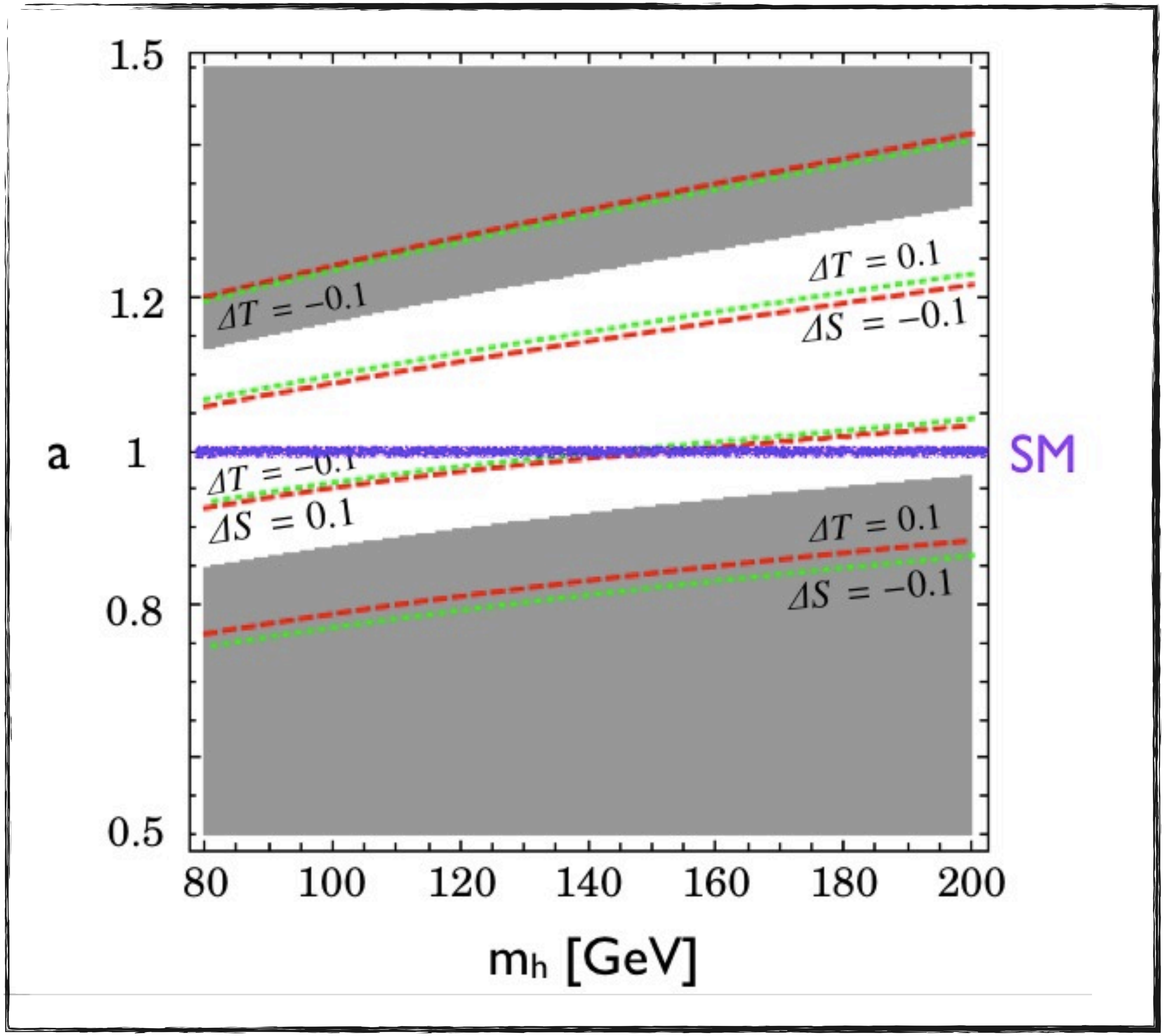


Flavor Constraints

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

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

mass terms

Higgs fermion interactions

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

⇛ FCNC

Composite Higgs set-up: c is flavor universal

(except may be for the top)

⇛ Minimal flavor violation built in

Deformation of the SM Higgs: current constraints

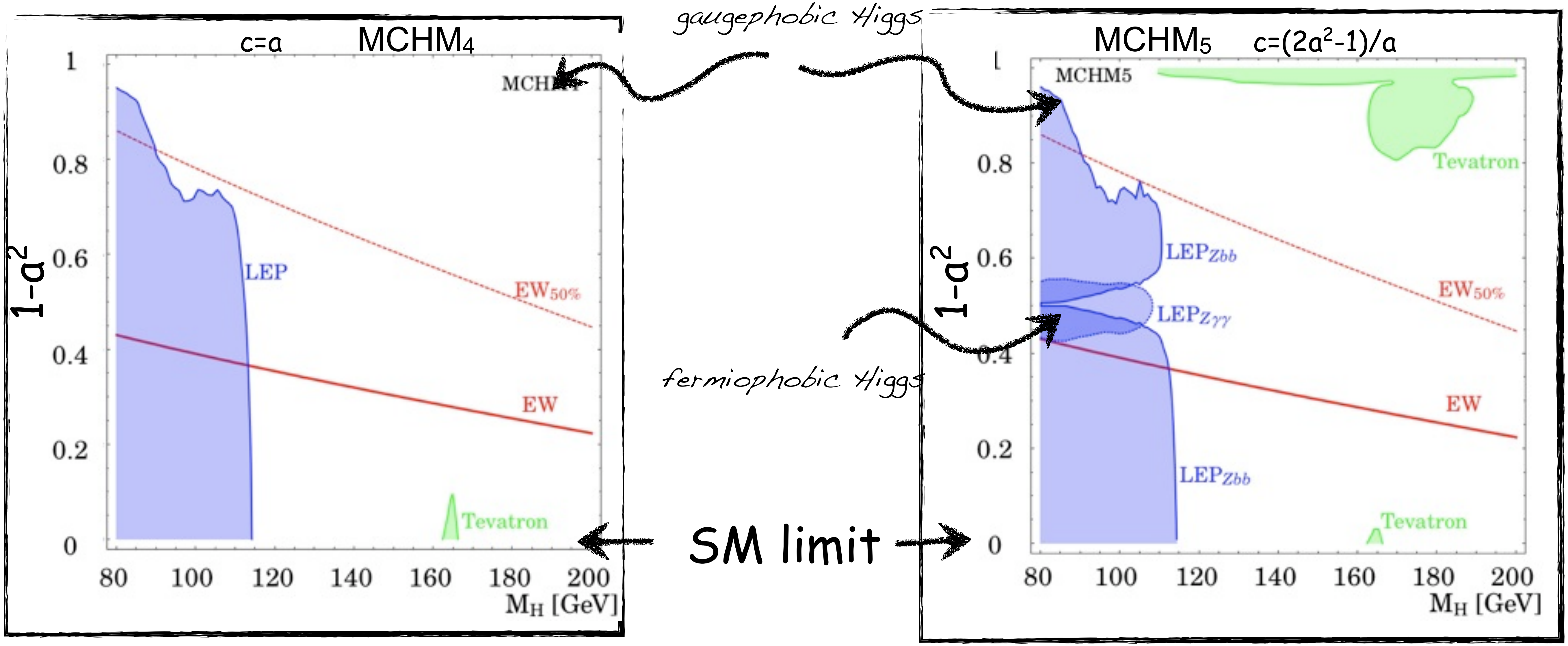
$$\mathcal{L}_{\rm EWSB} = \frac{v^2}{4}\mathrm{Tr}\left(D_\mu\Sigma^\dagger D_\mu\Sigma\right)\left(1+2a\frac{h}{v}+b\frac{h^2}{v^2}\right) - \lambda\bar{\psi}_L\Sigma\psi_R\left(1+c\frac{h}{v}\right)$$

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

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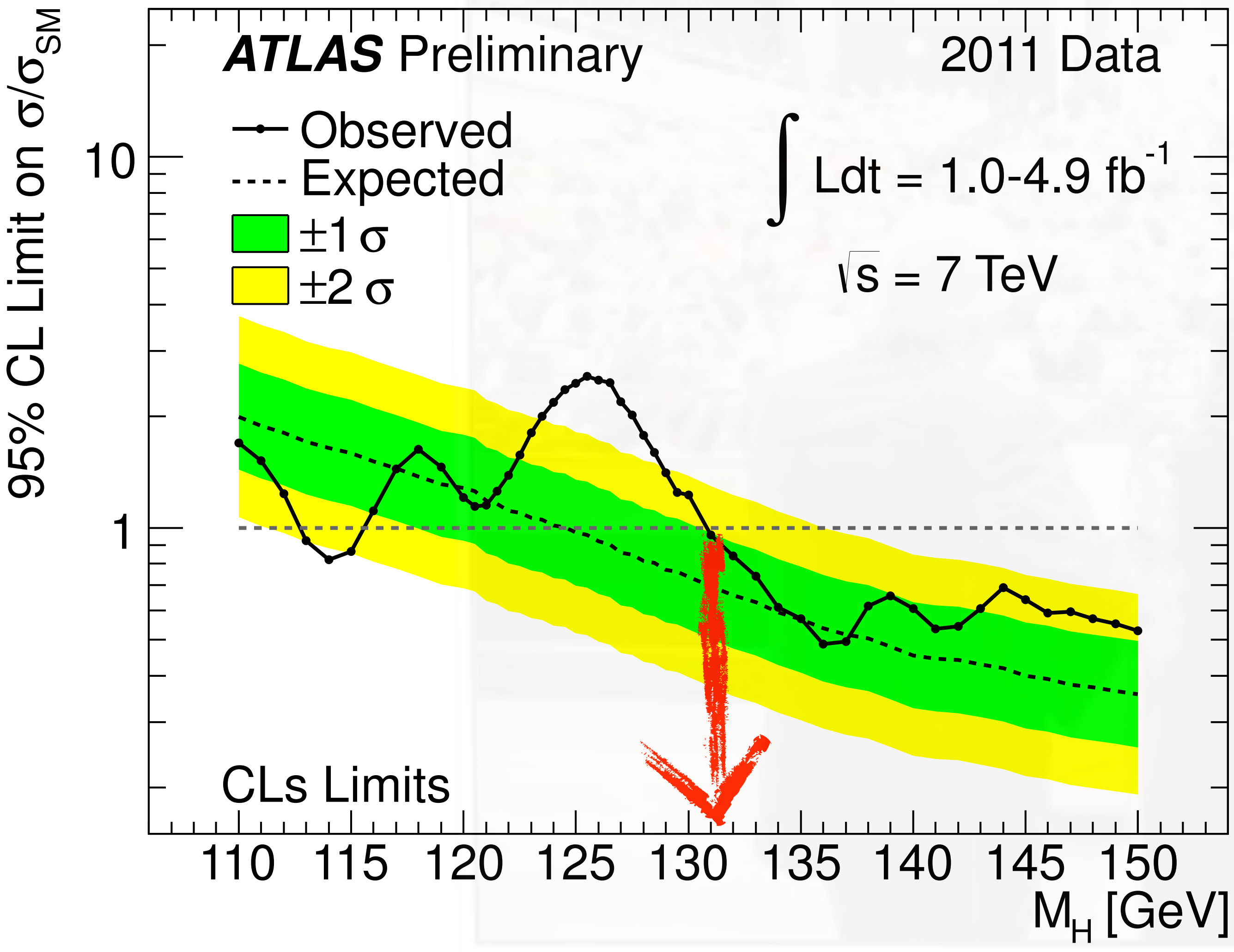
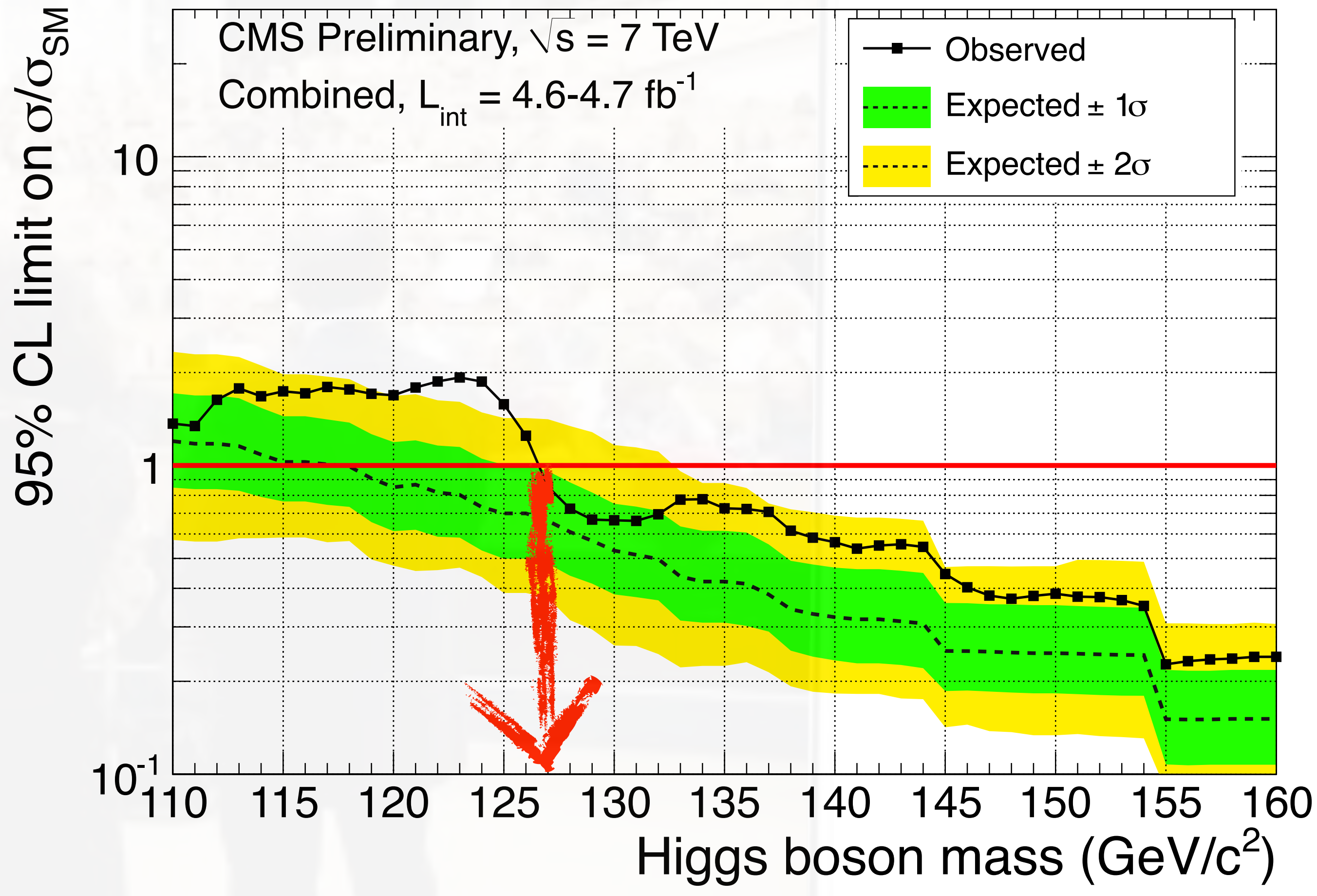
ATLAS-CONF-2011-163



≈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

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⇓ ⇓ ⇓

simple rescaling of SM searches

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⤋ ⤋ ⤋

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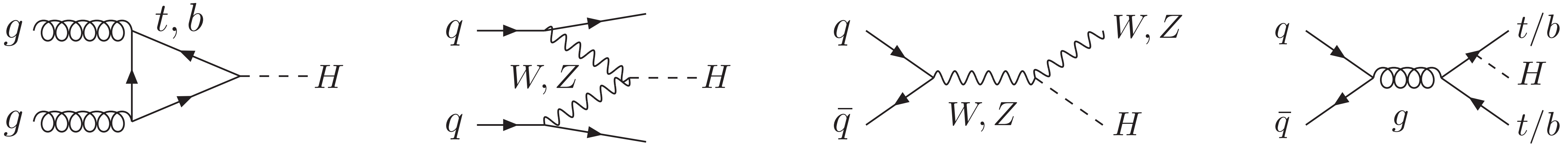


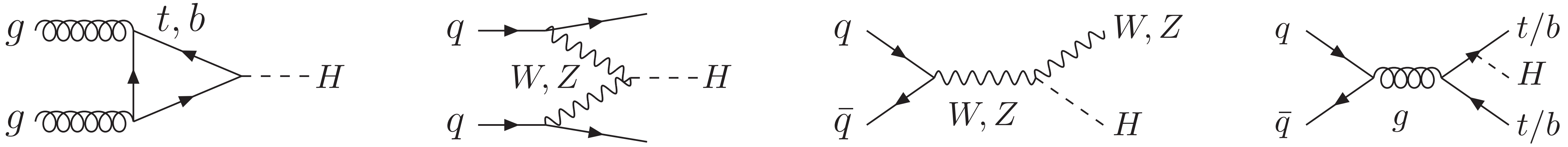
$\frac{\sigma_{NLO}}{\sigma^{SM}_{NLO}}$	c^2	a^2	a^2	c^2

Rescaling Higgs Searches

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

⇓ ⇓ ⇓

simple rescaling of SM searches



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

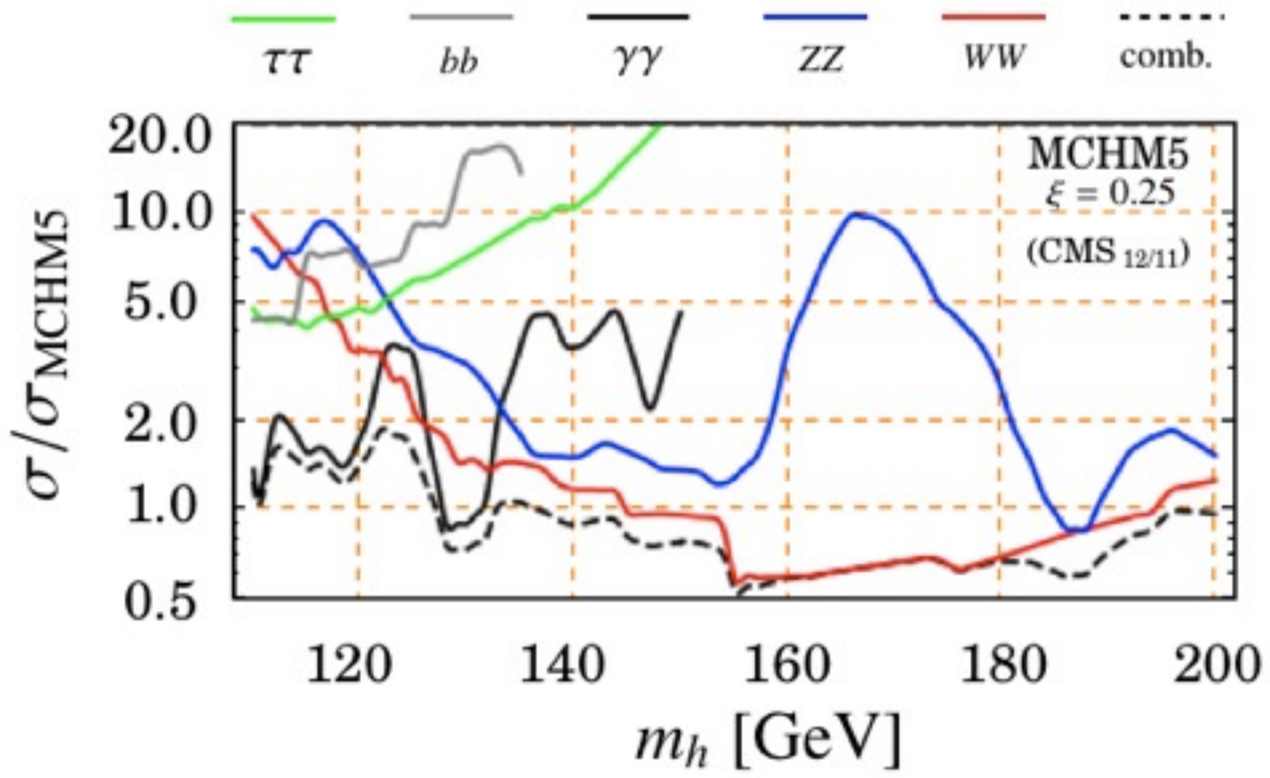
$$\Gamma(H \to f\bar{f}) = c^2\, \Gamma^{SM}(H \to f\bar{f})\,,$$

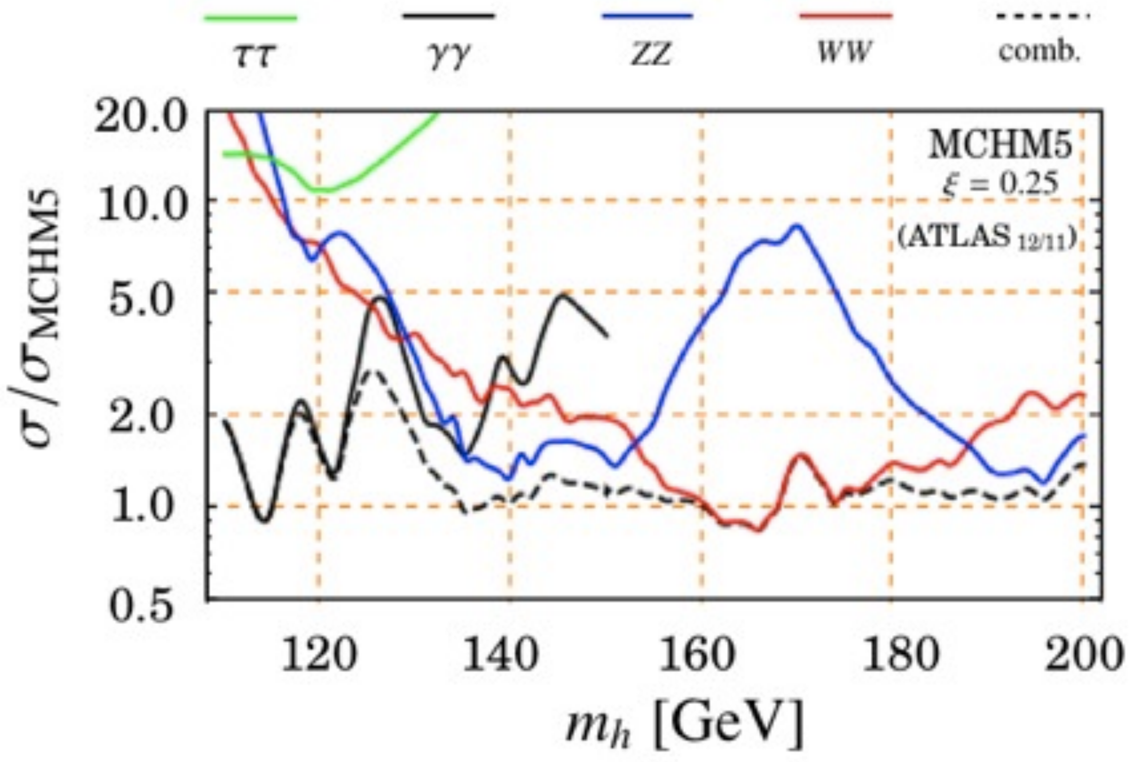
$$\Gamma(H \to VV) = a^2\, \Gamma^{SM}(H \to VV)\,,$$

$$\Gamma(H \to gg) = c^2\, \Gamma^{SM}(H \to gg)\,,$$

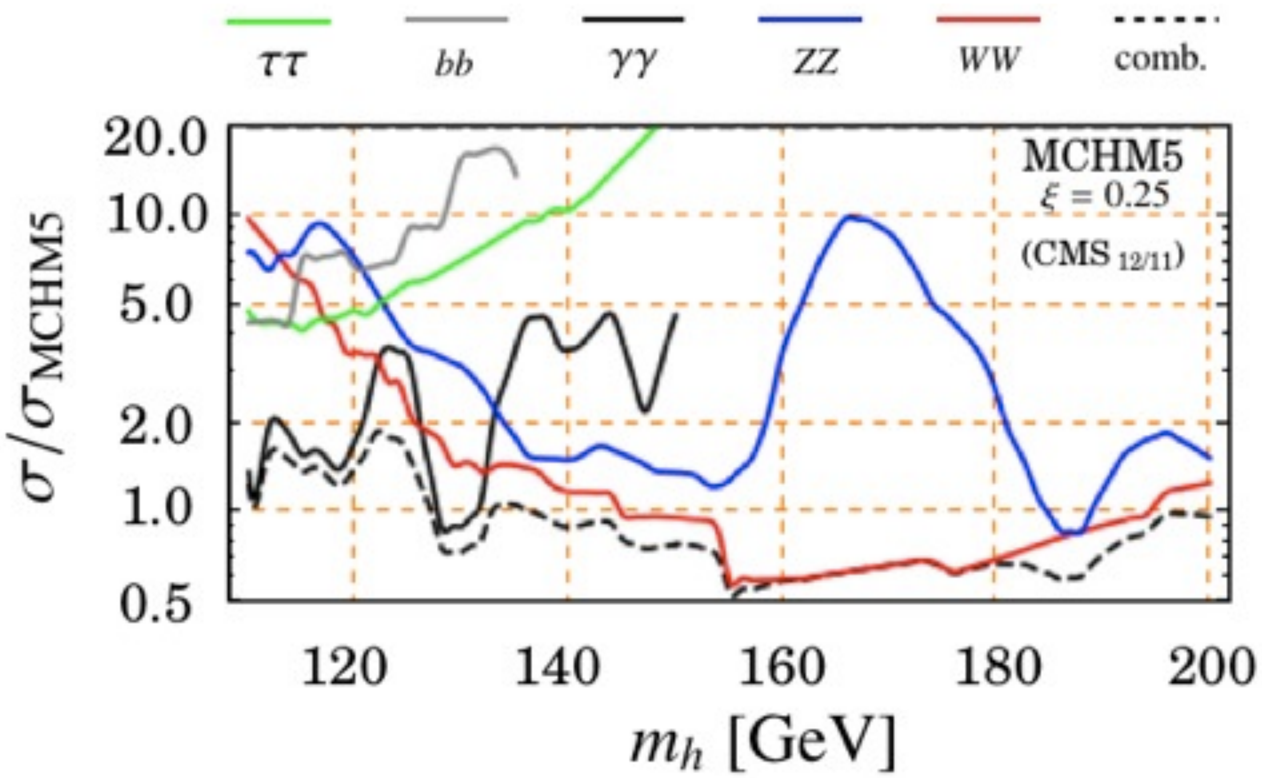
$$\Gamma(H \to \gamma\gamma) = \frac{\left(cI_\gamma + aJ_\gamma\right)^2}{(I_\gamma + J_\gamma)^2} \Gamma^{SM}(H \to \gamma\gamma)\,,$$

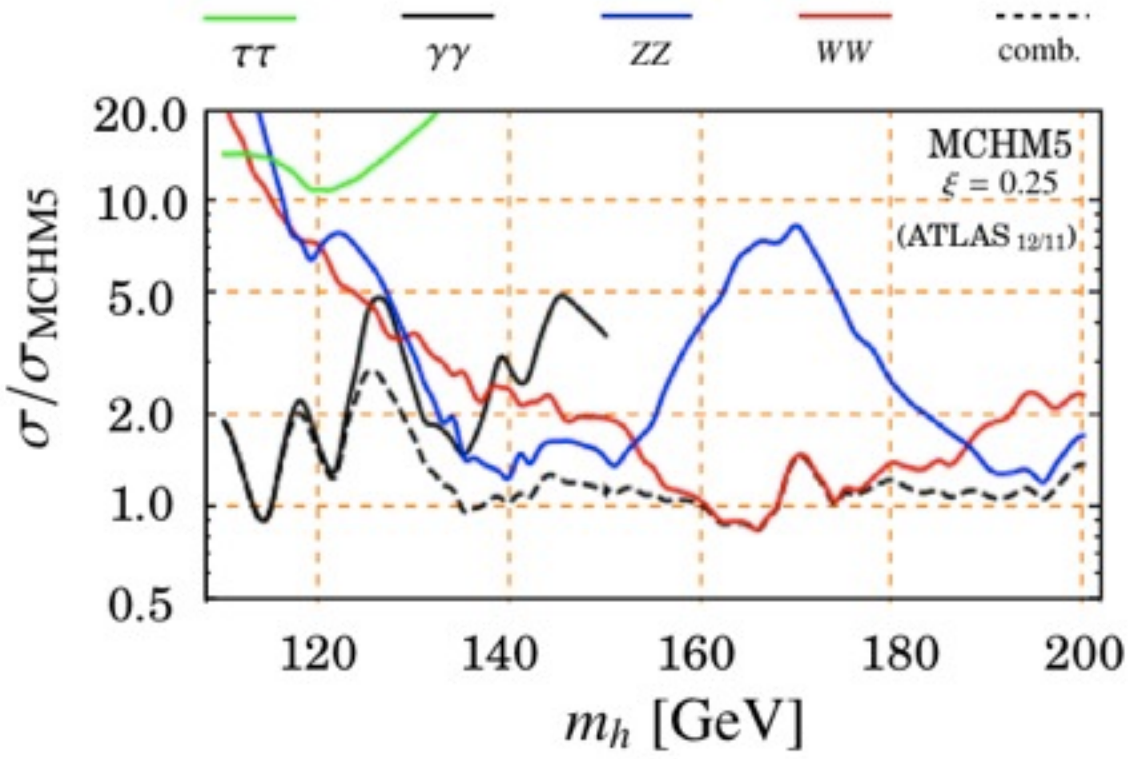
Rescaling Higgs Searches





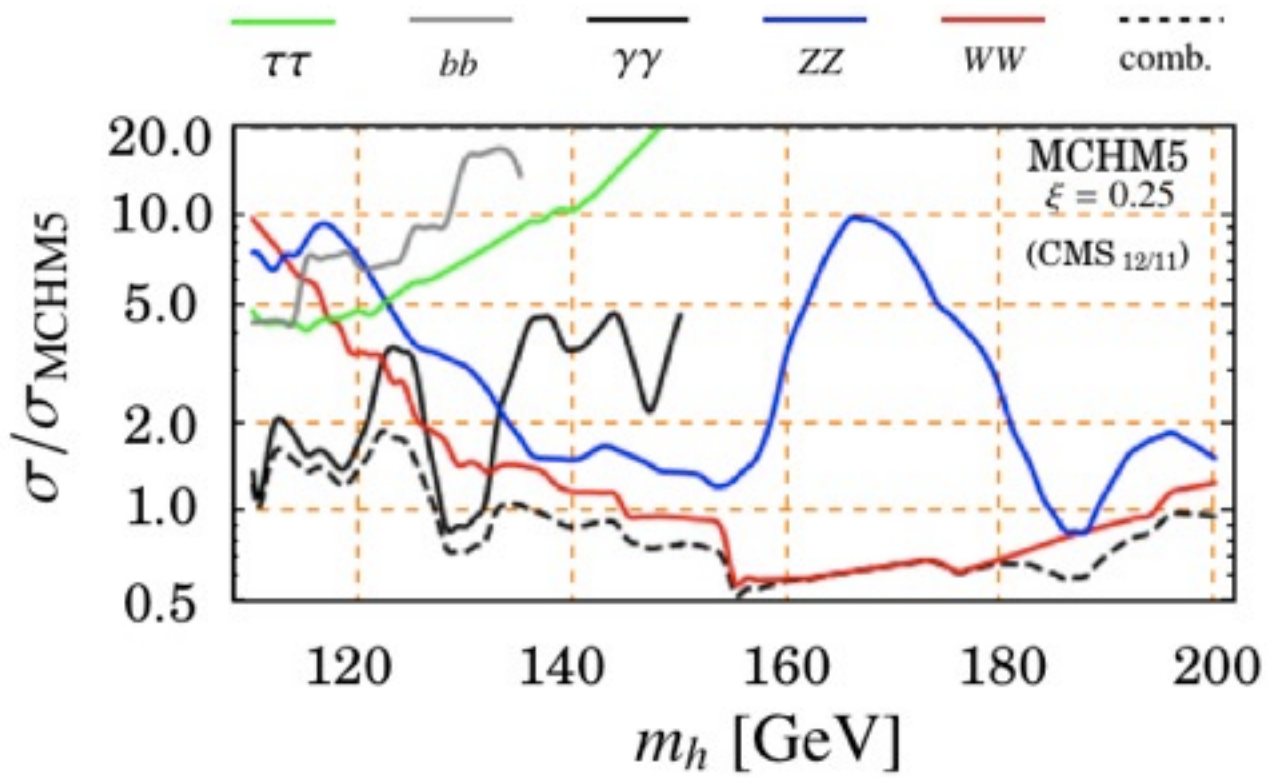
Rescaling Higgs Searches

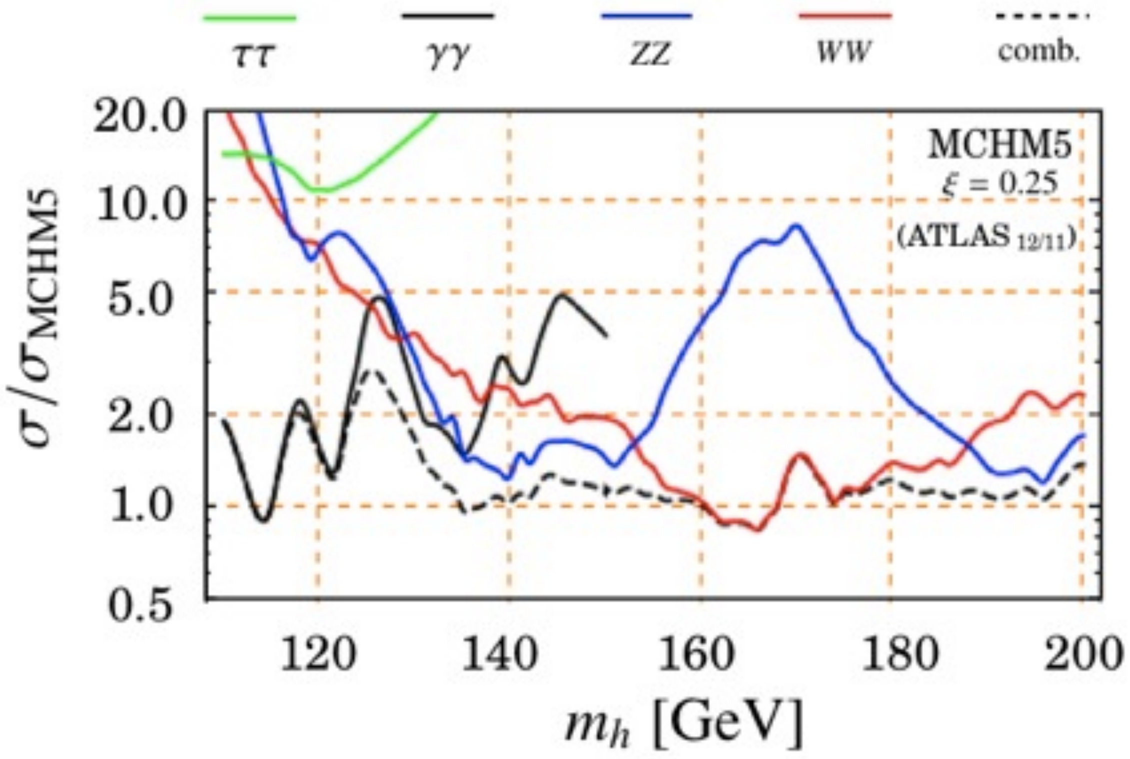




each search channel is rescaled individually

Rescaling Higgs Searches





each search channel is rescaled individually

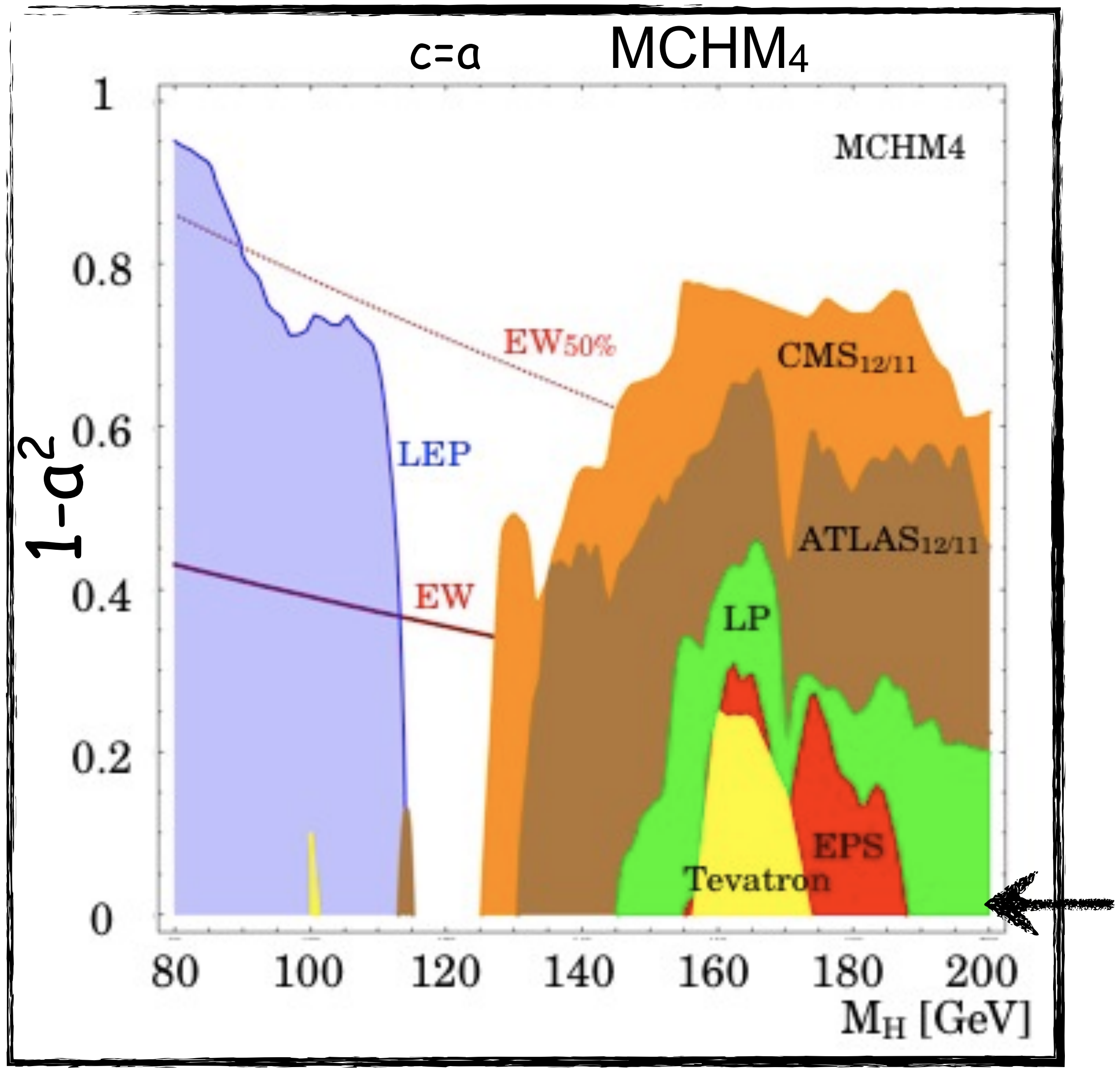
all the channels are then added in quadrature

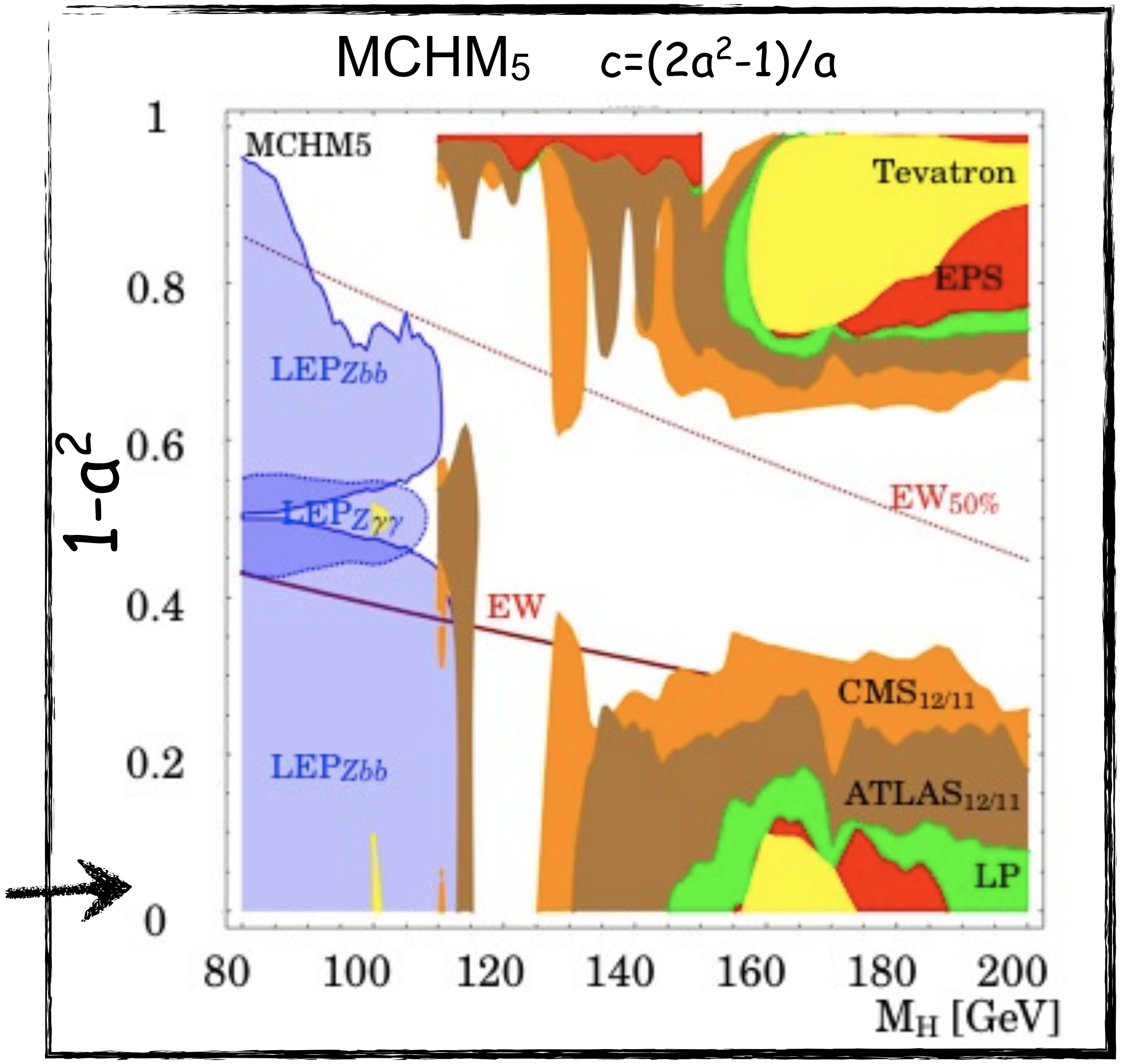
$$\frac{1}{\mu^2_{\text{comb}}} = \sum_{\text{i}} \frac{1}{\mu_i^2}$$

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 →

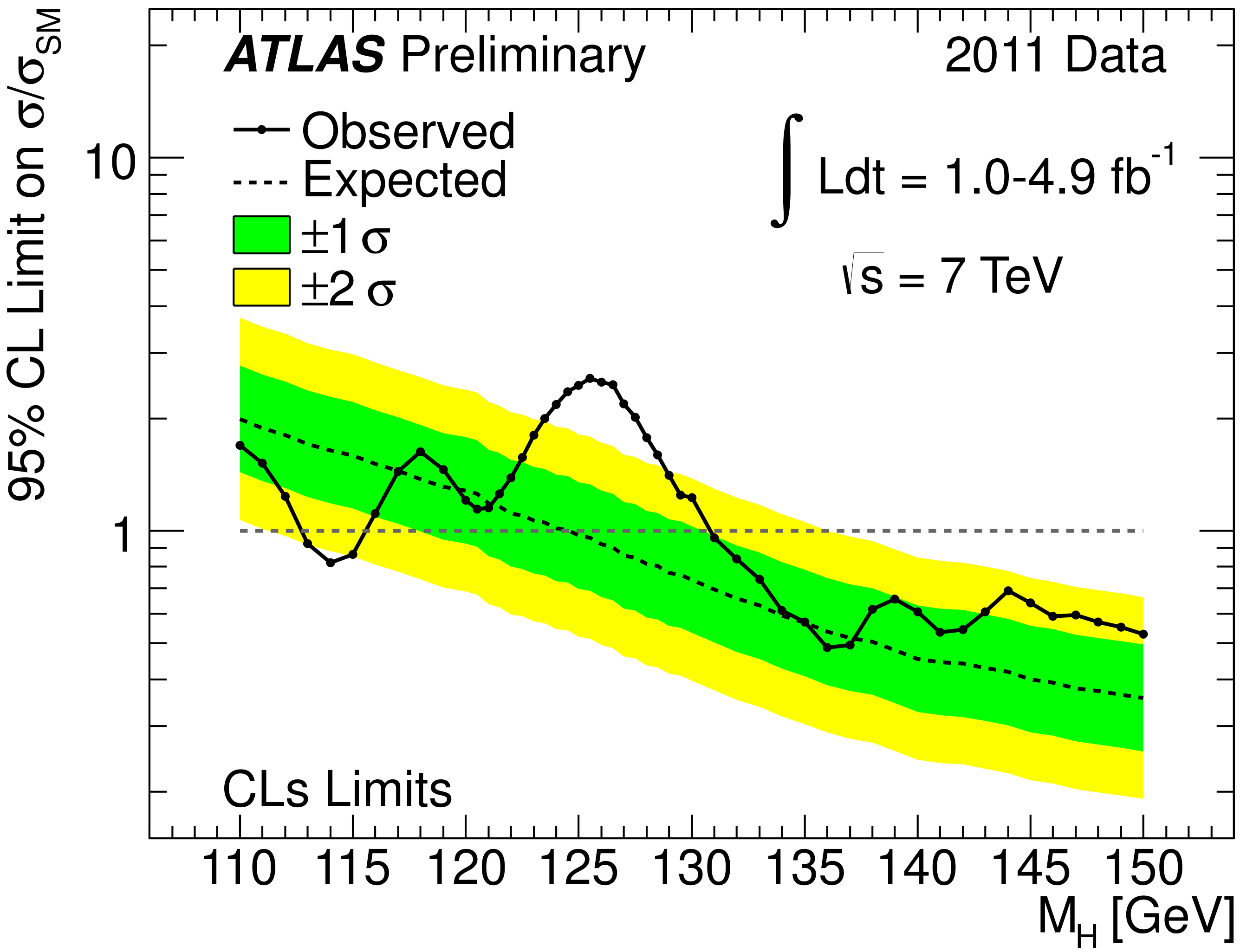
LHC tsunami!

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

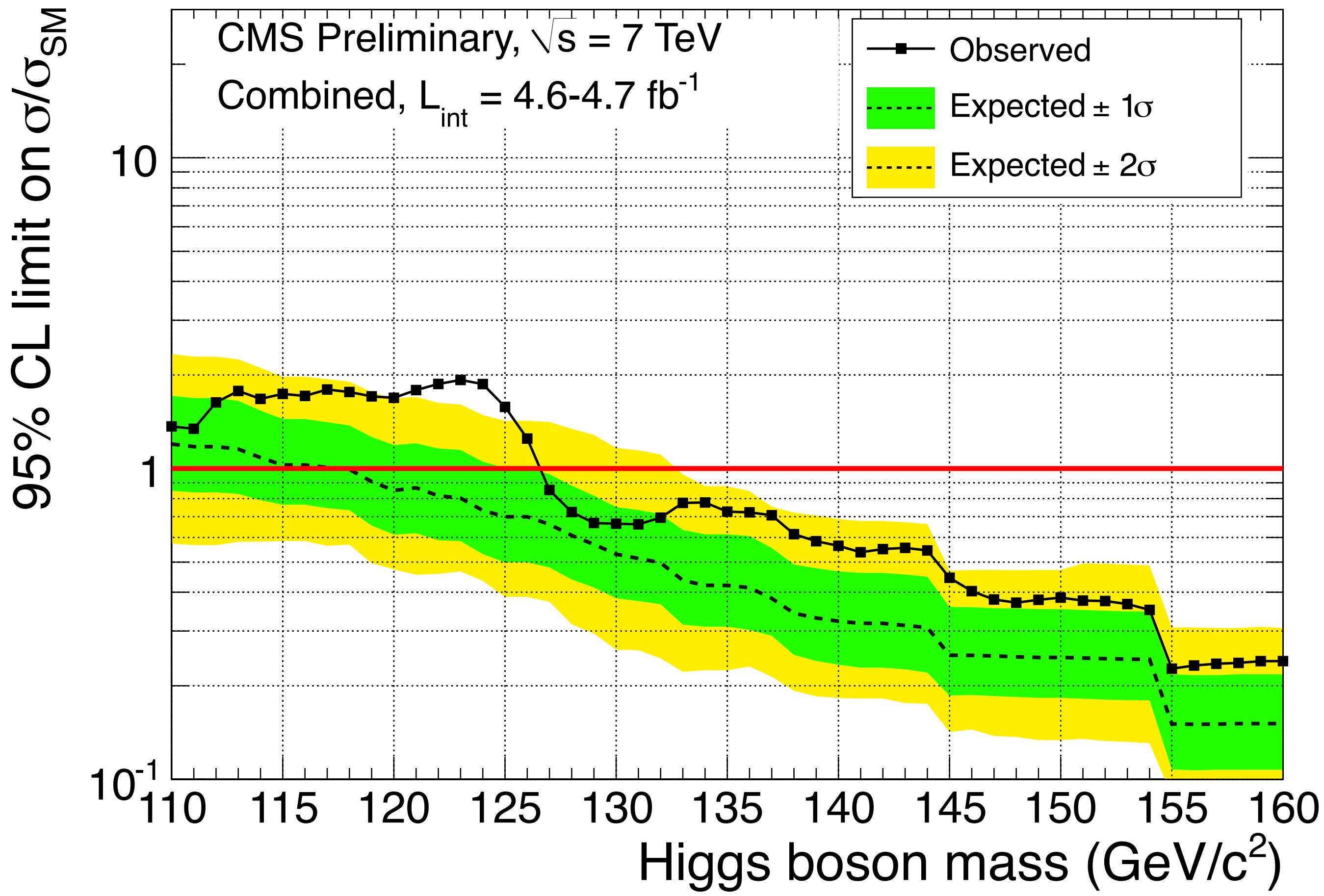
Higgs bounds: news from last December

Higgs bounds: news from last December

ATLAS-CONF-2011-163

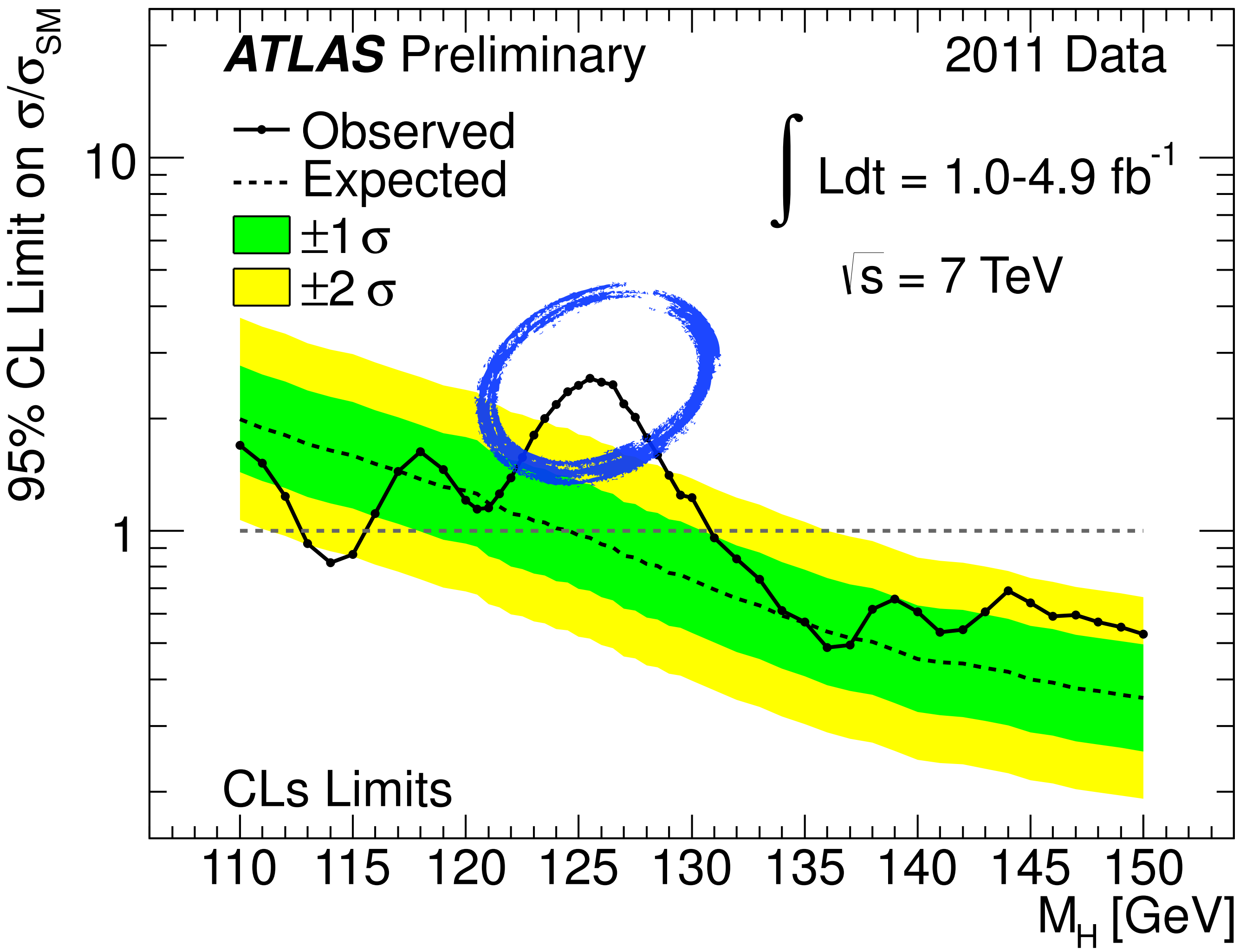


CMS PAS HIG-11-032

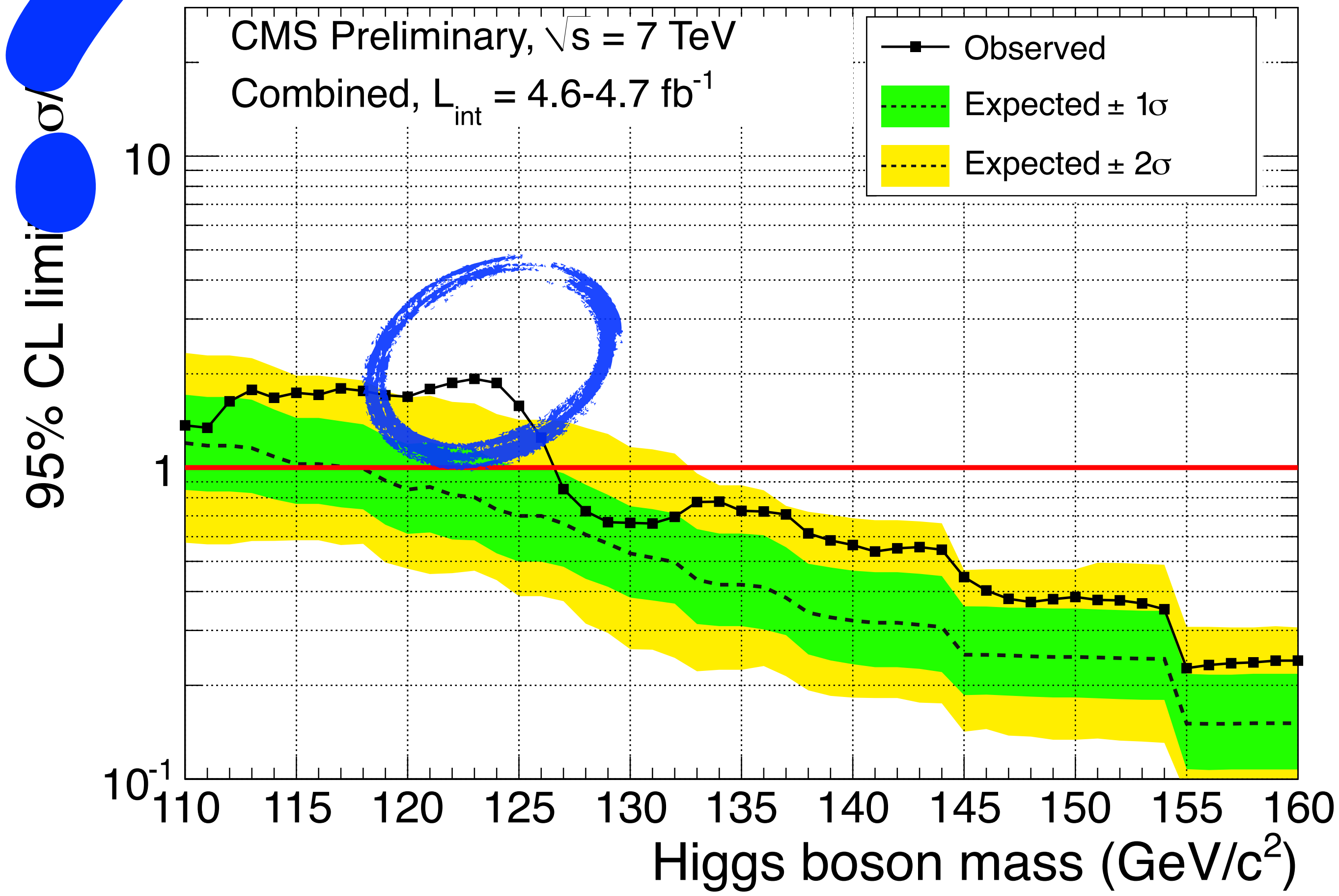


Higgs bounds: news from last December

ATLAS-CONF-2011-163



CMS PAS HIG-11-032



Higgs bounds: news from last December

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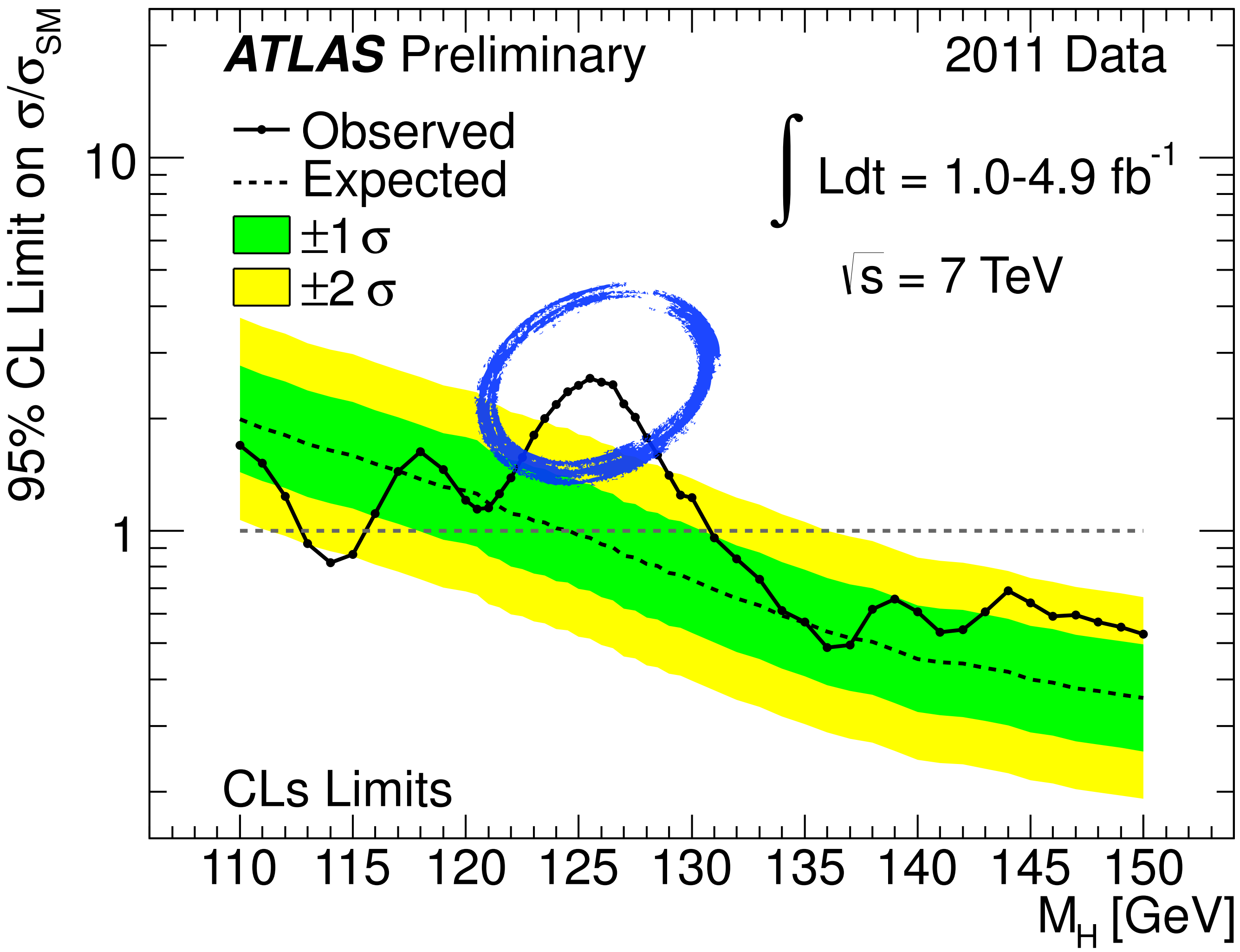

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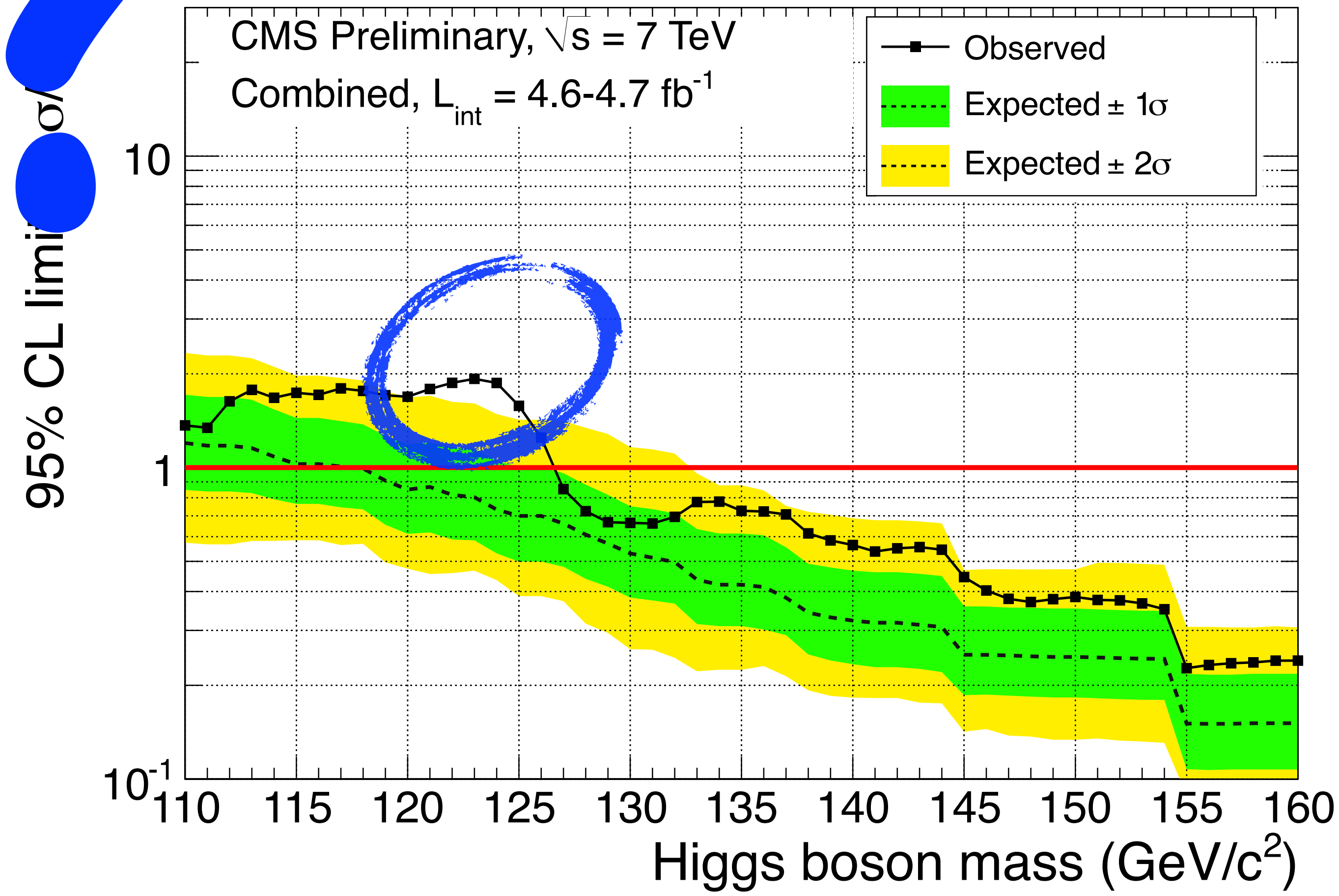
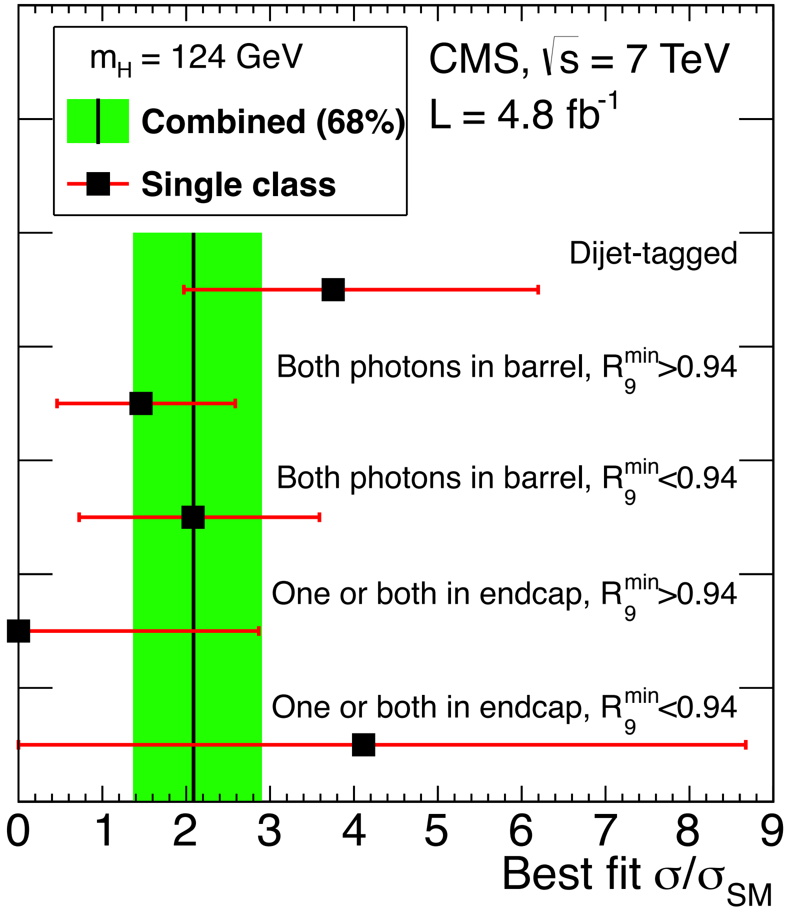
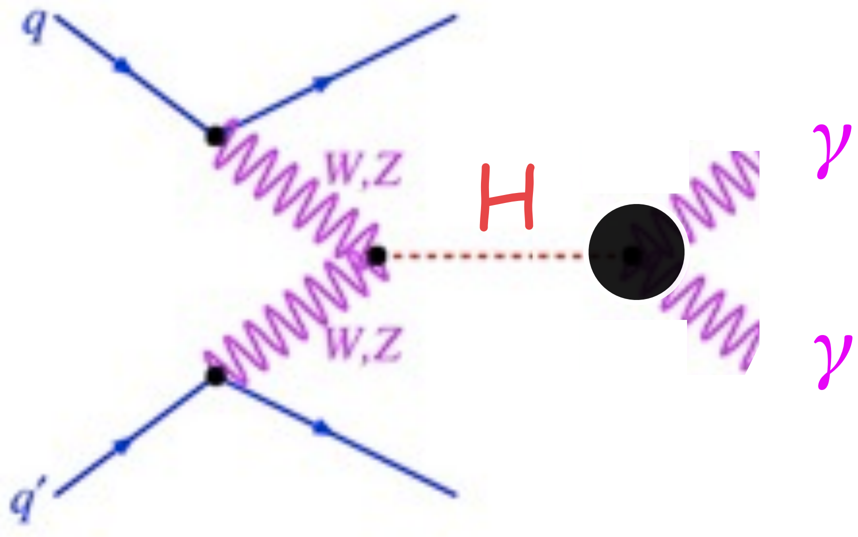


a 120-130 GeV higgs is very interesting (from the exp. point of view)
since many competing decay channels

News from two weeks ago

CMS PAS HIG-11-033





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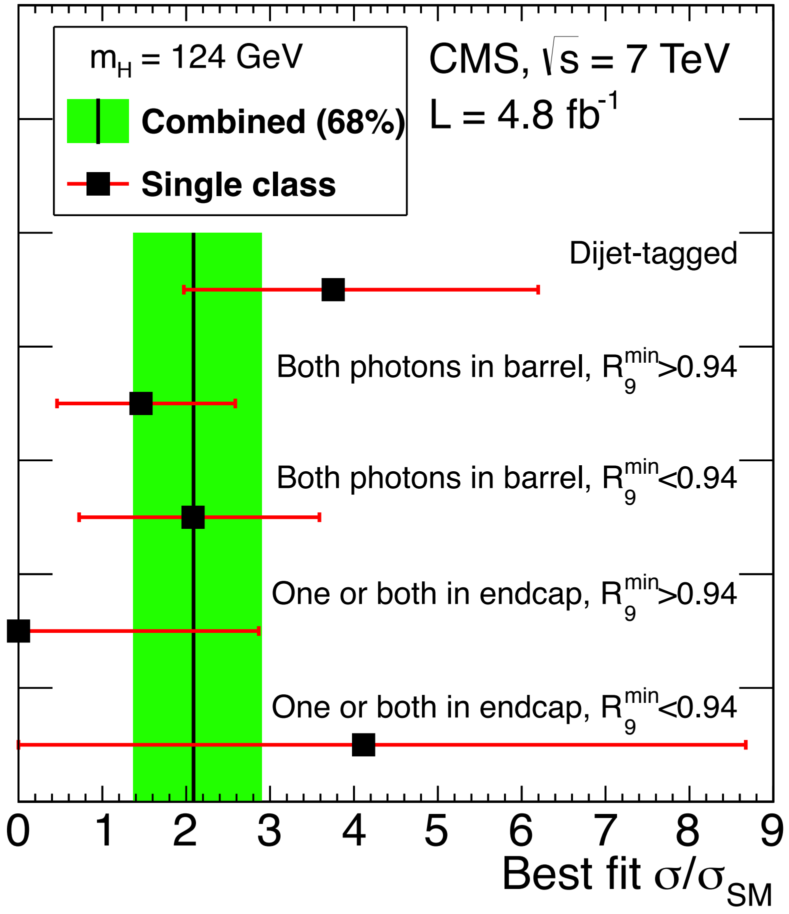
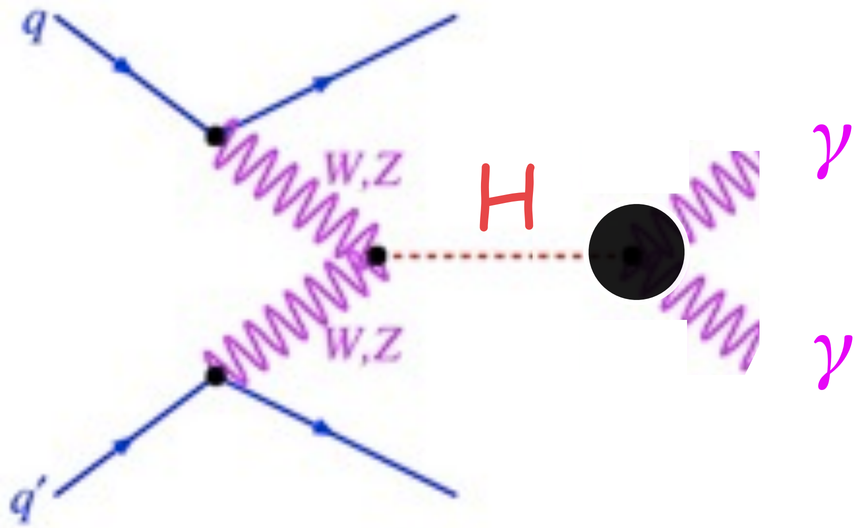


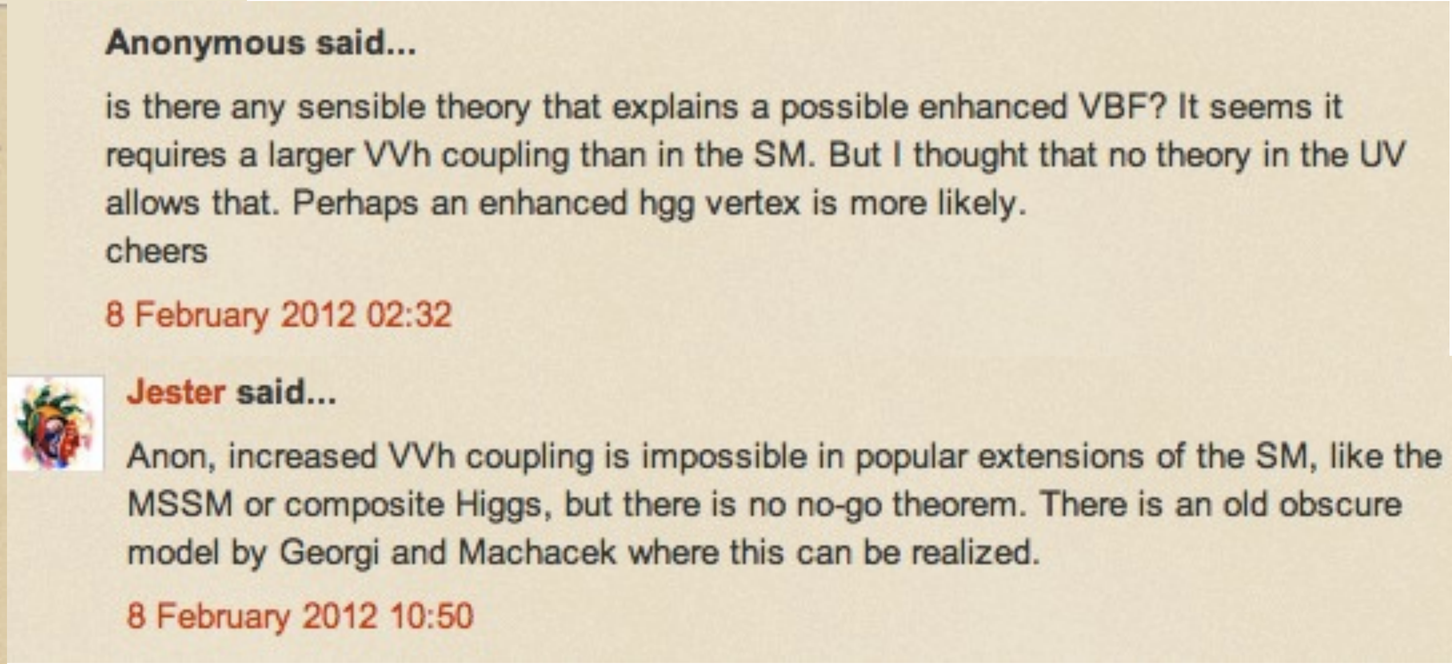


Résonances

Particle Physics Blog

Wednesday, 8 February 2012

Higgs: stronger and more exciting



Anonymous said...

is there any sensible theory that explains a possible enhanced VBF? It seems it requires a larger VVh coupling than in the SM. But I thought that no theory in the UV allows that. Perhaps an enhanced hgg vertex is more likely.
cheers

8 February 2012 02:32

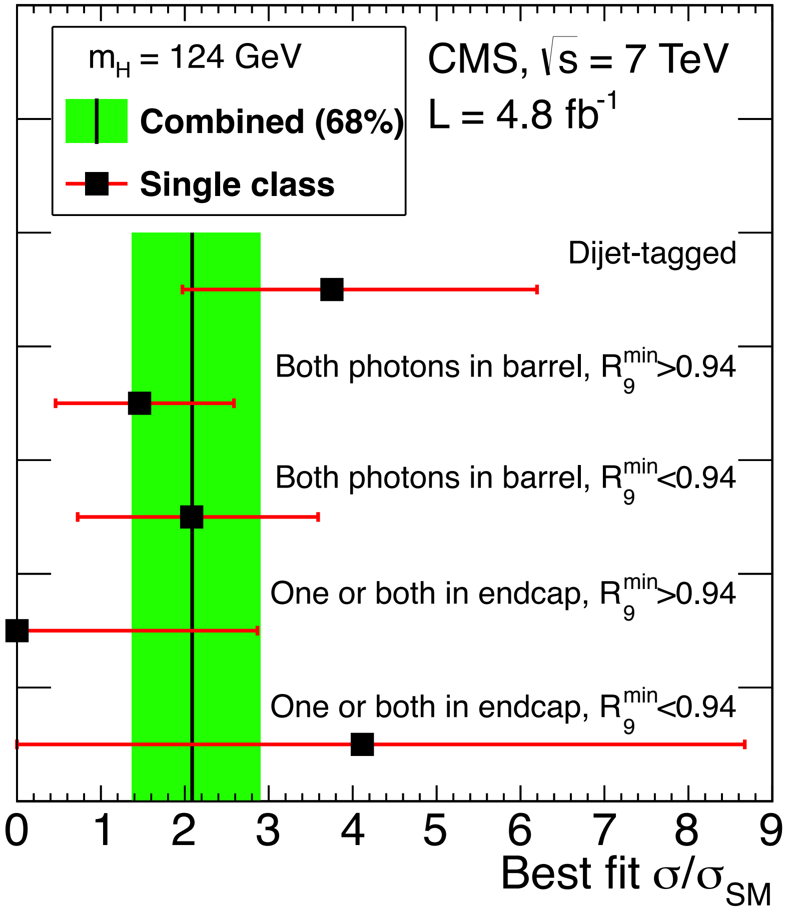
Jester said...

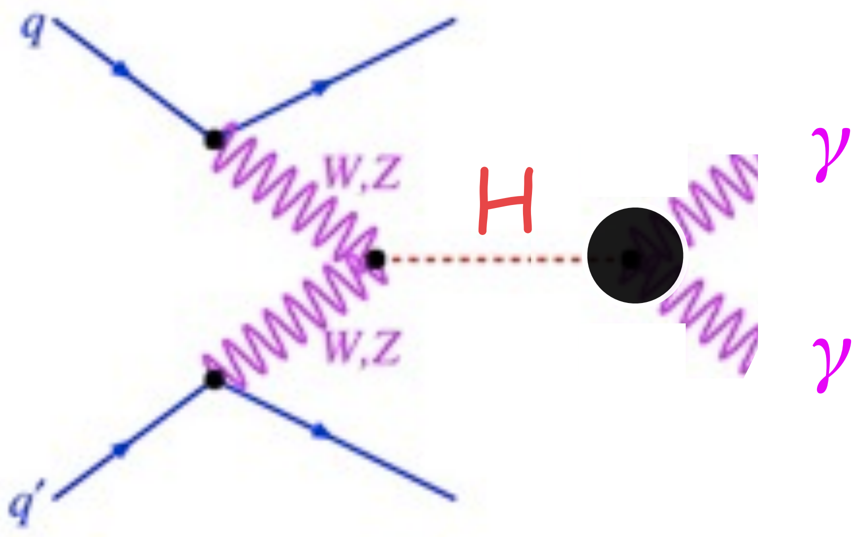
Anon, increased VVh coupling is impossible in popular extensions of the SM, like the MSSM or composite Higgs, but there is no no-go theorem. There is an old obscure model by Georgi and Machacek where this can be realized.

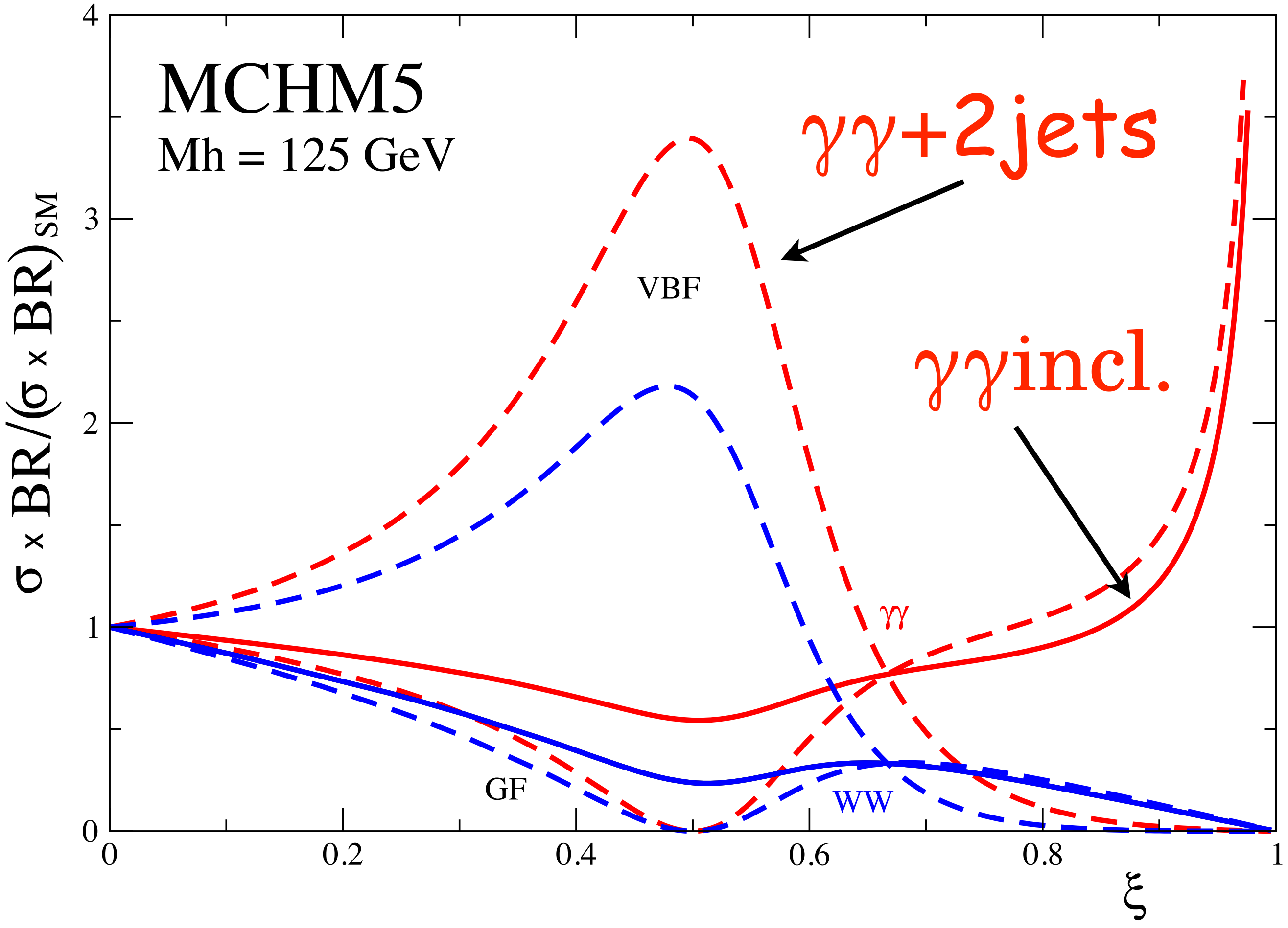
8 February 2012 10:50

News from two weeks ago

CMS PAS HIG-11-033







Espinosa, Grojean, Muhlleitner, Trott '12

All channels together

Channel [Exp]	m_h[GeV] (Local Significance)	$\mu = \sigma/\sigma_{SM}$ (μ_L)	Scaling to SM
$pp \to \gamma\,\gamma$ [ATLAS]	126.5 ± 0.7 ($2.8\,\sigma$) [22]	$2^{+0.9}_{-0.7}$ [23] (2.6)	$\sim c^2\,\mathrm{Br}_{\gamma\,\gamma}[a,c]$
$pp \to Z\,Z^\star \to \ell^+\,\ell^-\,\ell^+\,\ell^-$ [ATLAS]	$126 \pm \sim 2\%$ ($2.1\,\sigma$) [22]	$1.2^{+1.2}_{-0.8}$ [23] (4.9)	$\sim c^2\,\mathrm{Br}_{ZZ}[a,c]$
$pp \to W\,W^\star \to \ell^+\,\nu\,\ell^-\,\bar\nu$ [ATLAS]	$126 \pm \sim 20\%$ ($1.4\,\sigma$) [22]	$1.2^{+0.8}_{-0.8}$ [23] (3.4)	$\sim c^2\,\mathrm{Br}_{WW}[a,c]$
$pp \to \gamma\,\gamma\,j\,j$ [CMS]	$124 \pm 3\%$ [10, 11]	$3.7^{+2.5}_{-1.8}$ [11]	$\sim a^2\,\mathrm{Br}_{\gamma\gamma}[a,c]$
$pp \to \gamma\,\gamma[\mathrm{CMS, b}, R_9^{\mathrm{min}} > 0.94]$	$124 \pm 3\%$ [10, 11]	$1.5^{+1.1}_{-1.0}$ [11]	$\sim c^2\,\mathrm{Br}_{\gamma\,\gamma}[a,c]$
$pp \to \gamma\,\gamma[\mathrm{CMS, b}, R_9^{\mathrm{min}} < 0.94]$	$124 \pm 3\%$ [10, 11]	$2.1^{+1.5}_{-1.4}$ [11]	$\sim c^2\,\mathrm{Br}_{\gamma\,\gamma}[a,c]$
$pp \to \gamma\,\gamma[\mathrm{CMS, e}, R_9^{\mathrm{min}} > 0.94]$	$124 \pm 3\%$ [10, 11]	$0.0^{+2.9}$ [11]	$\sim c^2\,\mathrm{Br}_{\gamma\,\gamma}[a,c]$
$pp \to \gamma\,\gamma[\mathrm{CMS, e}, R_9^{\mathrm{min}} < 0.94]$	$124 \pm 3\%$ [10, 11]	$4.1^{+4.6}_{-4.1}$ [11]	$\sim c^2\,\mathrm{Br}_{\gamma\,\gamma}[a,c]$
$pp \to Z\,Z^\star \to \ell^+\,\ell^-\,\ell^+\,\ell^-$ [CMS]	$126 \pm 2\%$ ($1.5\,\sigma$) [11, 24]	$0.5^{+1.0}_{-0.7}$ [10] (2.7)	$\sim c^2\,\mathrm{Br}_{ZZ}[a,c]$
$pp \to W\,W^\star \to \ell^+\,\nu\,\ell^-\,\bar\nu$ [CMS]	$126 \pm 20\%$ [10, 25]	$0.7^{+0.4}_{-0.6}$ [10] (1.8)	$\sim c^2\,\mathrm{Br}_{WW}[a,c]$
$pp \to b\,\bar b$ [CMS]	$124 \pm 10\%$ [10]	$1.2^{+1.4}_{-1.7}$ [10] (4.1)	$\sim c^2\,\mathrm{Br}_{b\bar b}[a,c]$
$pp \to \tau\,\bar\tau$ [CMS]	$124 \pm 20\%$[10]	$0.8^{+1.2}_{-1.7}$ [10] (3.3)	$\sim c^2\,\mathrm{Br}_{\tau\bar\tau}[a,c]$

in the presence of
excess, the combined
limit is stronger than the
combined quadrature

$$\sum_i \frac{(\mu_L - \hat\mu)^2}{(\mu_L^i - \hat\mu)^2} - \sum_i \frac{\hat\mu^2}{(\mu_L^i - \hat\mu)^2} = 1$$

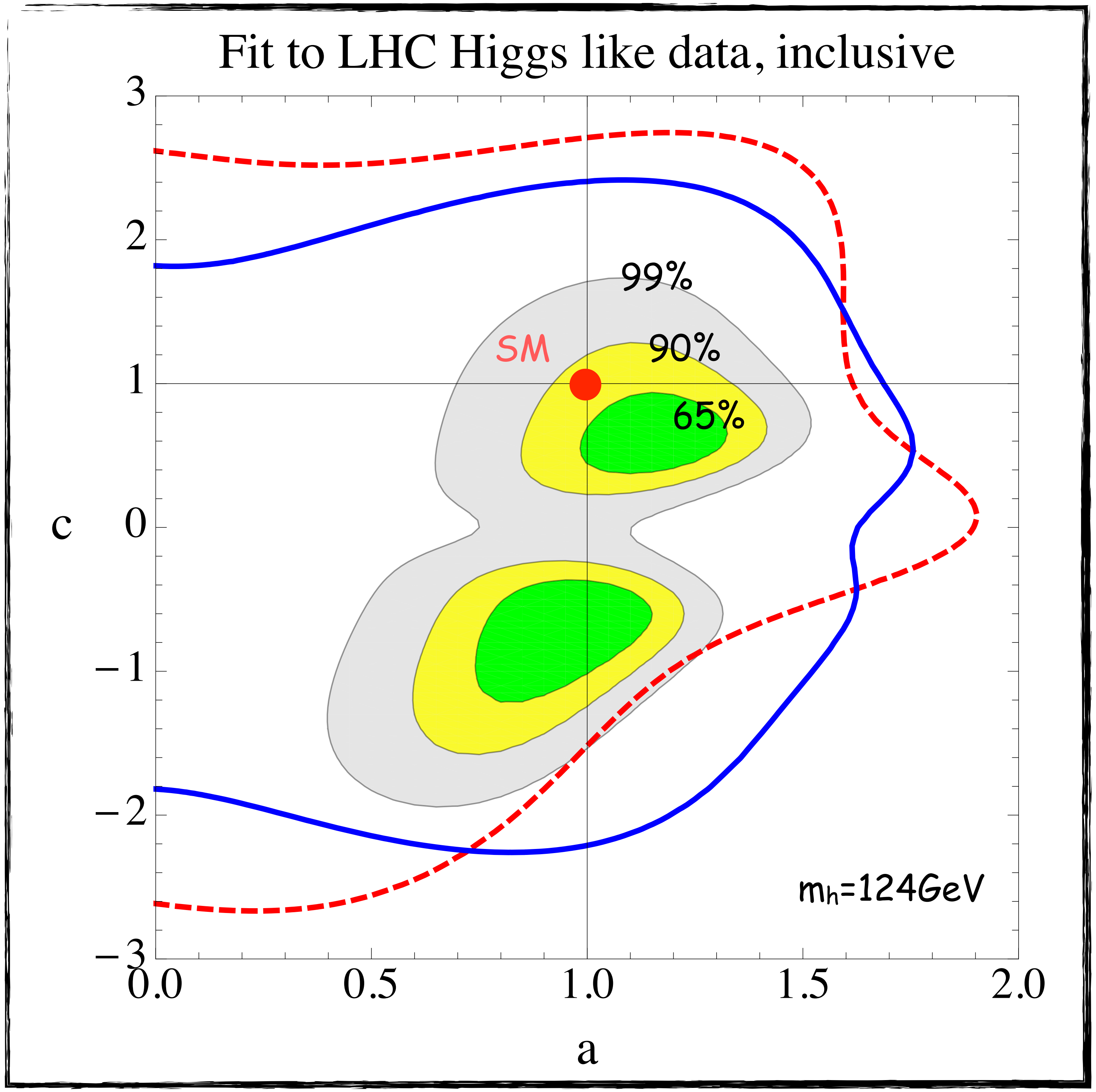
Espinosa, Grojean, Muhlleitner, Trott '12

Model independent fit to LHC data

Espinosa, Grojean, Muhlleitner, Trott '12

Atlas 95%CL exclusion

CMS 95%CL exclusion



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

Two minima:

(a,c)=(1.13,0.58)
χ^2=2.86

(a,c)=(0.96,-0.64)
χ^2=1.96

for similar analyses, see also

Azatov, Contino, Galloway '12

Carni, Falkowski, Kuflik, Volansky '12

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- - - -

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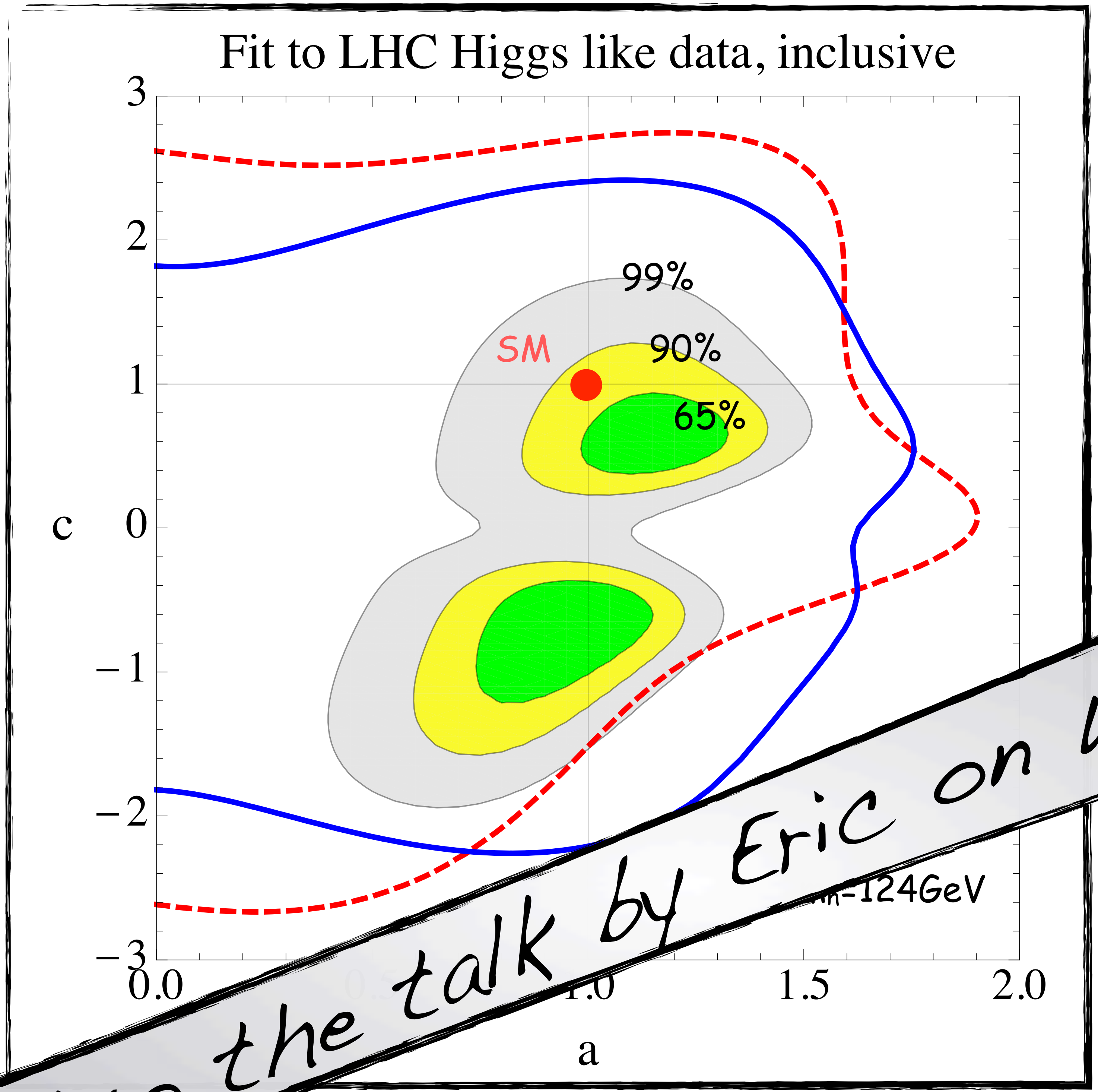

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Two minima:

$(a,c)=(1.13,0.58)$
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$(a,c)=(0.96,-0.64)$
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See also the talk by Eric on Wednesday

for similar analyses, see also

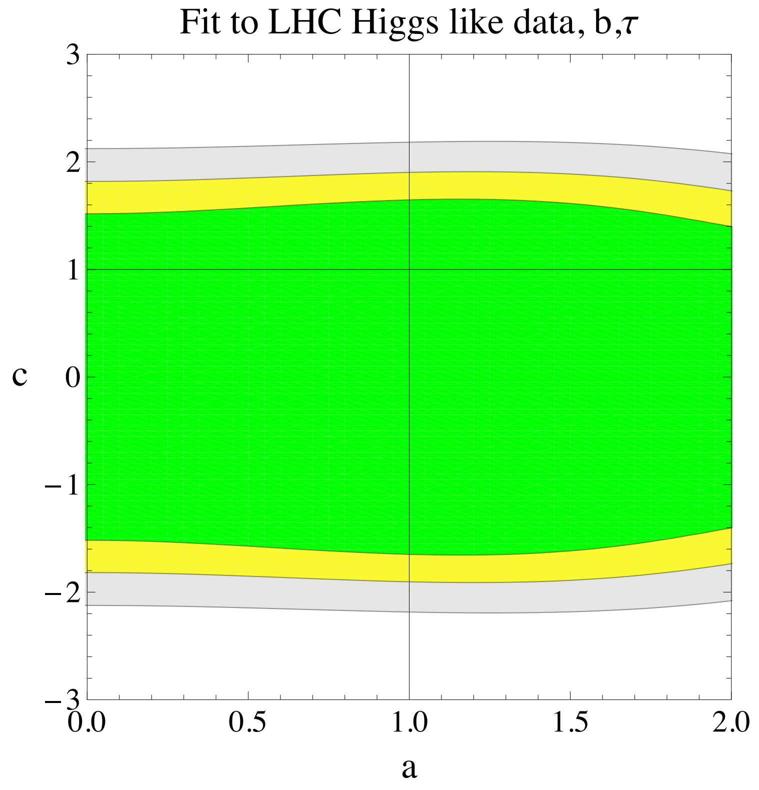
Azatov, Contino, Galloway '12

Carni, Falkowski, Kuflik, Volansky '12

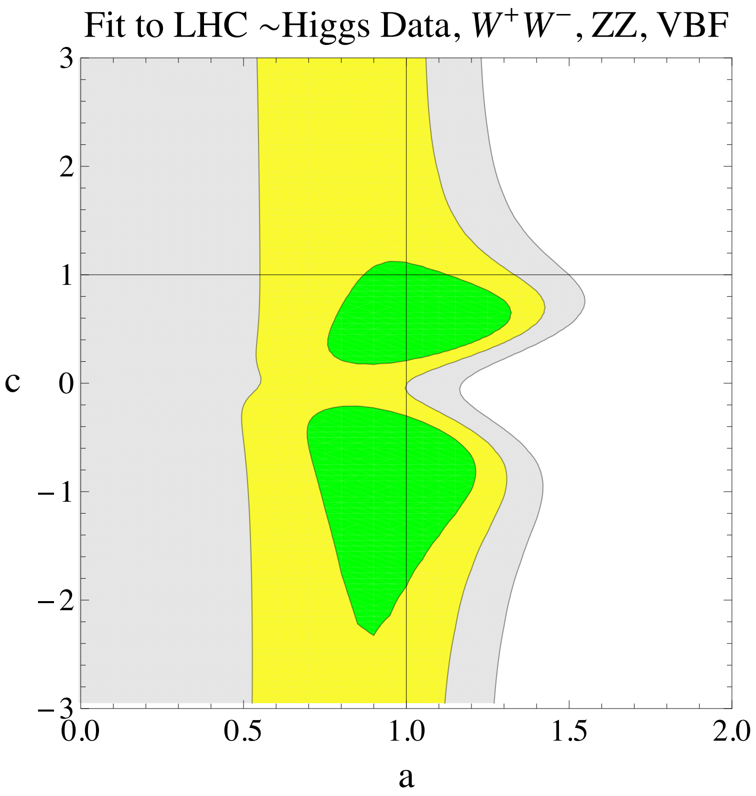
Which are the channels driving the fit?

Espinosa, Grojean, Muhlleitner, Trott '12

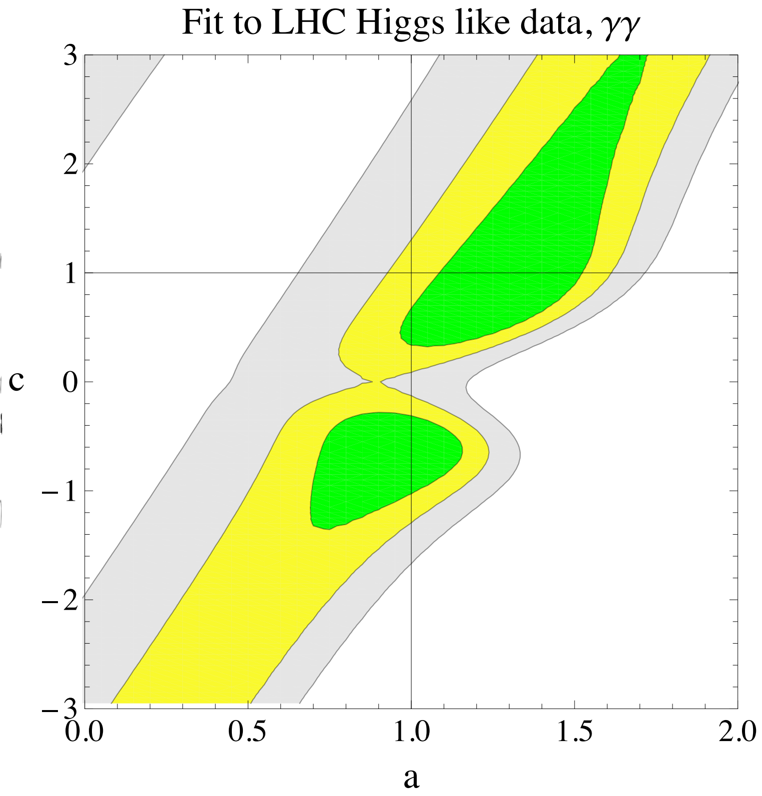
fermion couplings



gauge couplings



both couplings



almost
no constraints at the moment

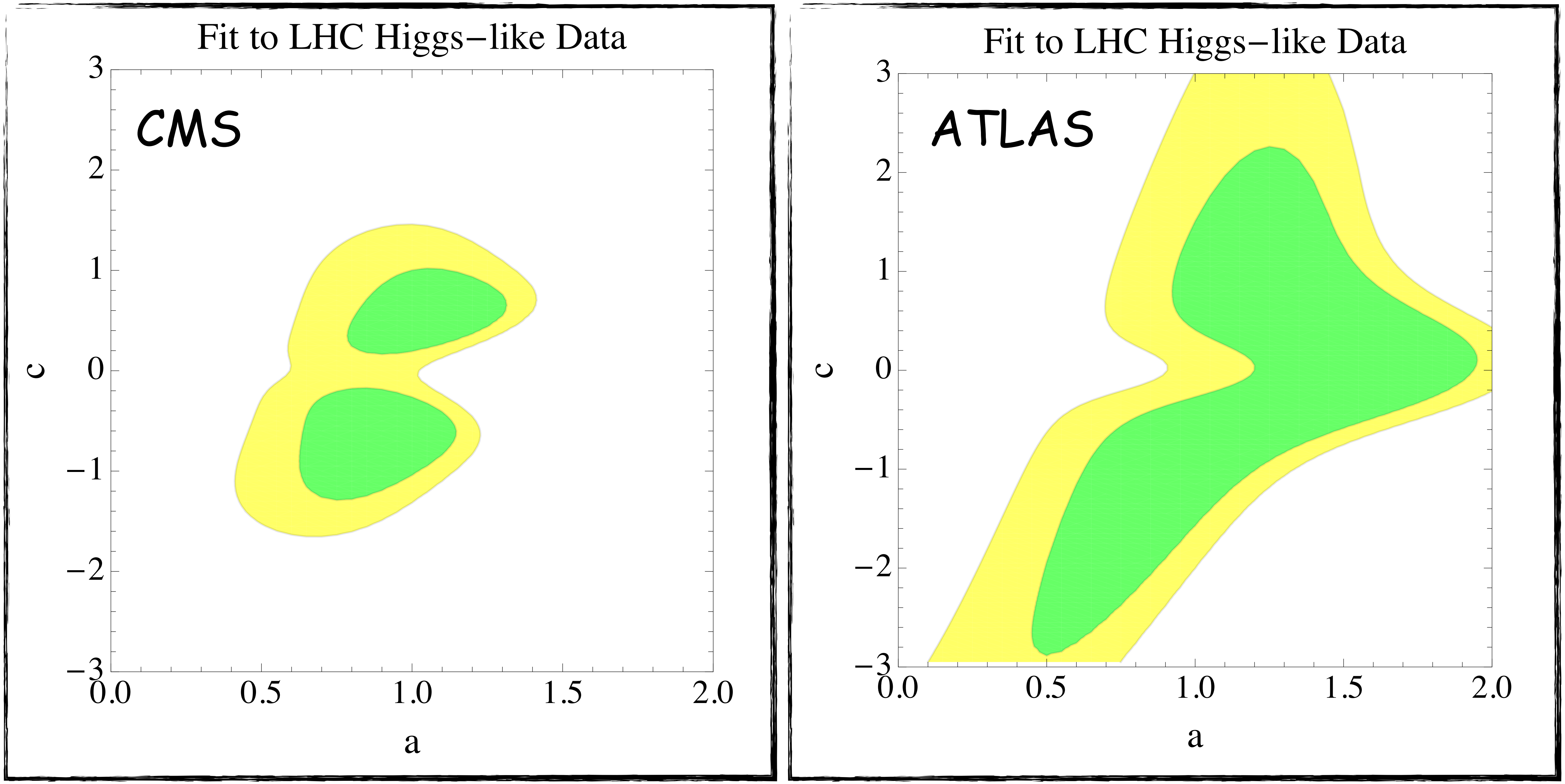
almost
(a,c)↔(a,-c) symmetric

large a are disfavored

most constraining

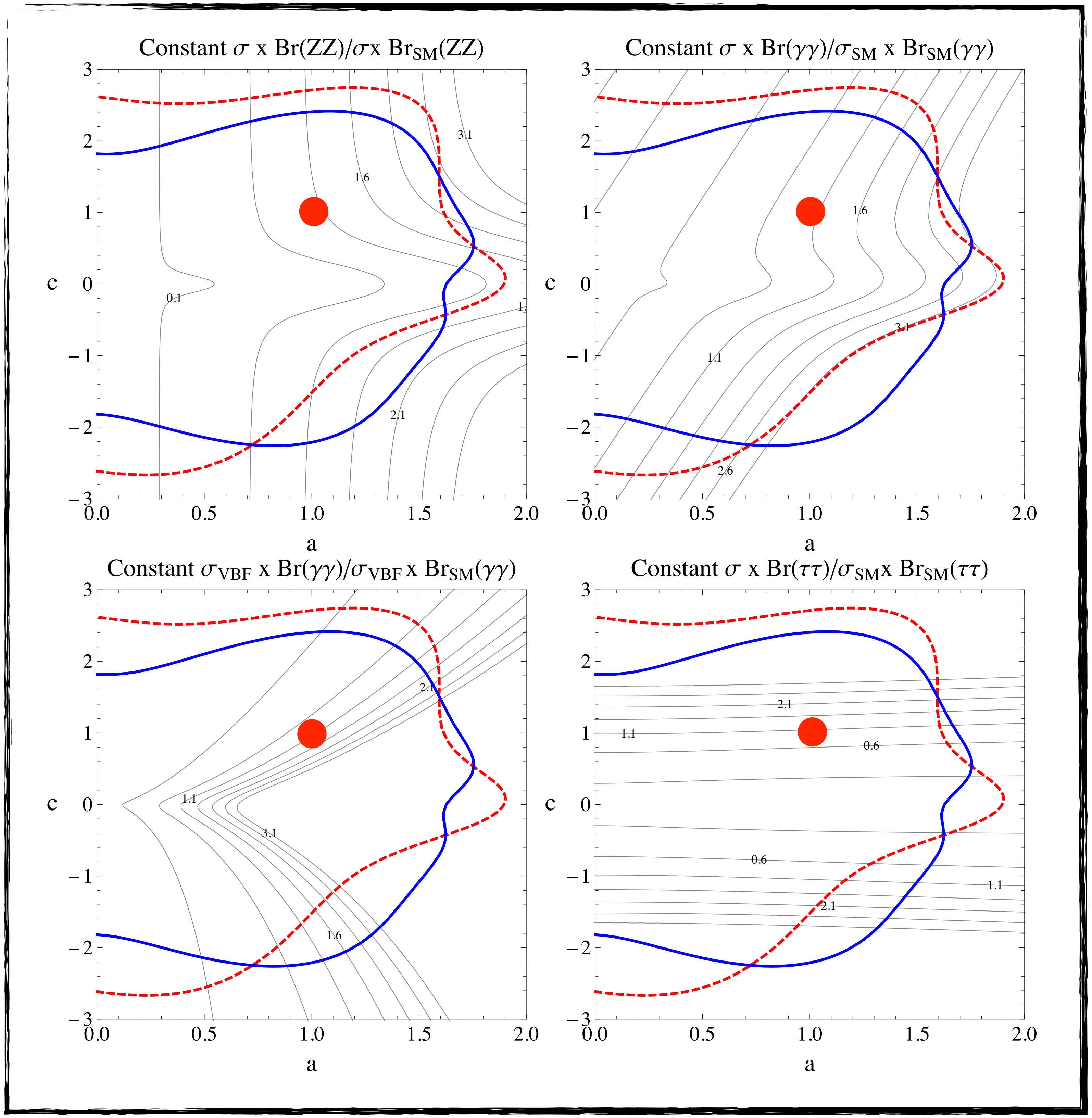
note: even if $\Gamma(\mathrm{h}\to\gamma\gamma)$ is not really modified (no operator $|H|^2 B_{\mu\nu} B^{\mu\nu}$), $\mathrm{BR}_{\gamma\gamma}$ has strong dependence on 'a' and 'c'

Which are the channels driving the fit?



Espinosa, Grojean, Muhlleitner, Trott '12

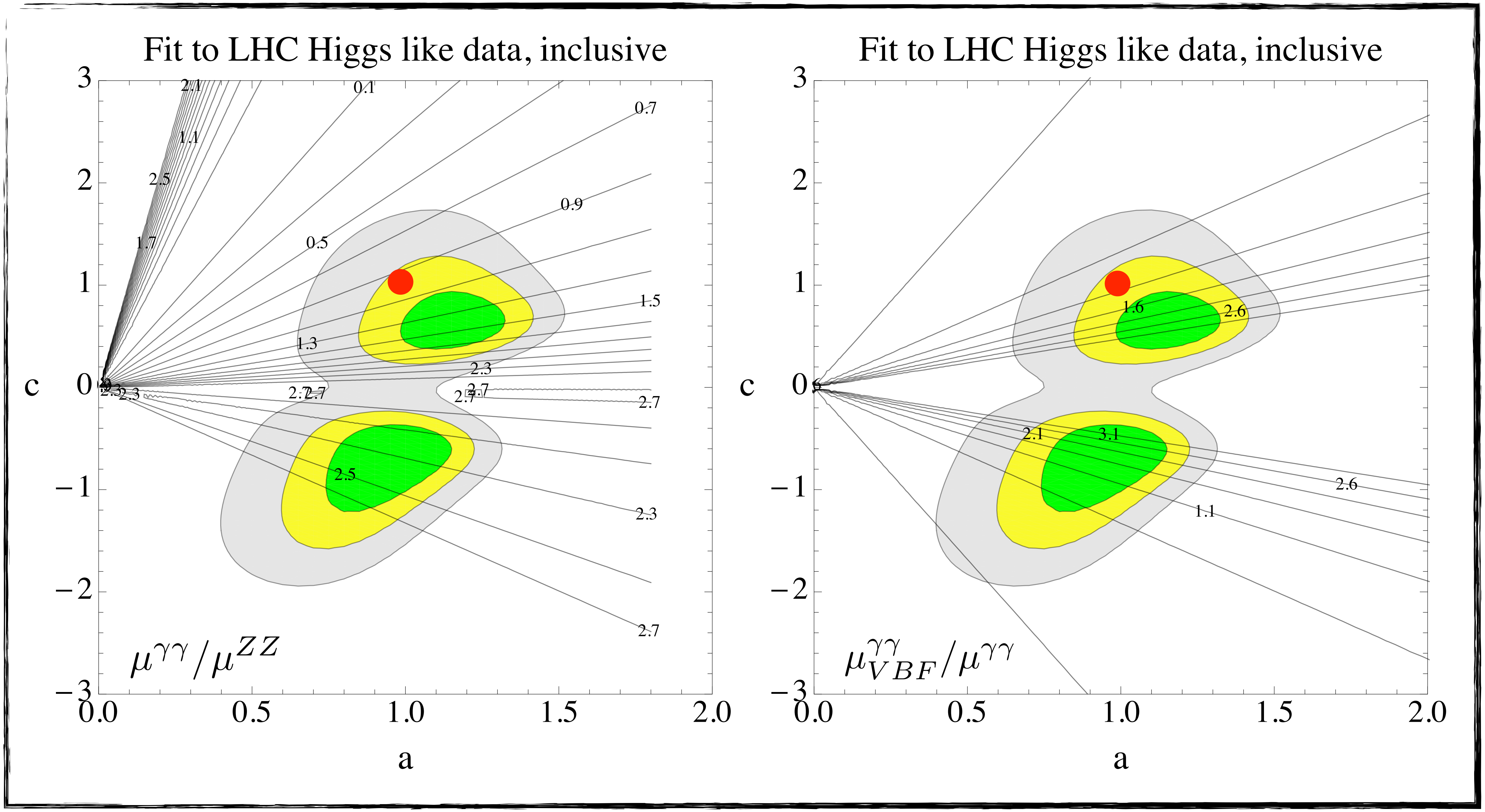
What to see at LHC @ 8 TeV?



Espinosa, Grojean, Muhlleitner, Trott ’12

How to distinguish the two minima

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



Fit to LHC Higgs like data, inclusive

Fit to LHC Higgs like data, inclusive

Espinosa, Grojean, Muhlleitner, Trott '12

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!

An Emergency Tire Even Beyond the SM

"Higgs = emergency tire of the SM"

Altarelli @ Blois'10

An Emergency Tire Even Beyond the SM

“Higgs = emergency tire of the SM”

Altarelli @ Blois’10

[picture courtesy to Andreas Weiler]