What the Fit is that Boson?

Michael Trott, CERN

Papers discussed:

Espinosa, Muhlleitner, Grojean, Trott arXiv:1202.3697

Espinosa, Muhlleitner, Grojean, Trott arXiv: 1205.6790

Espinosa, Muhlleitner, Grojean, Trott arXiv:1207.1717

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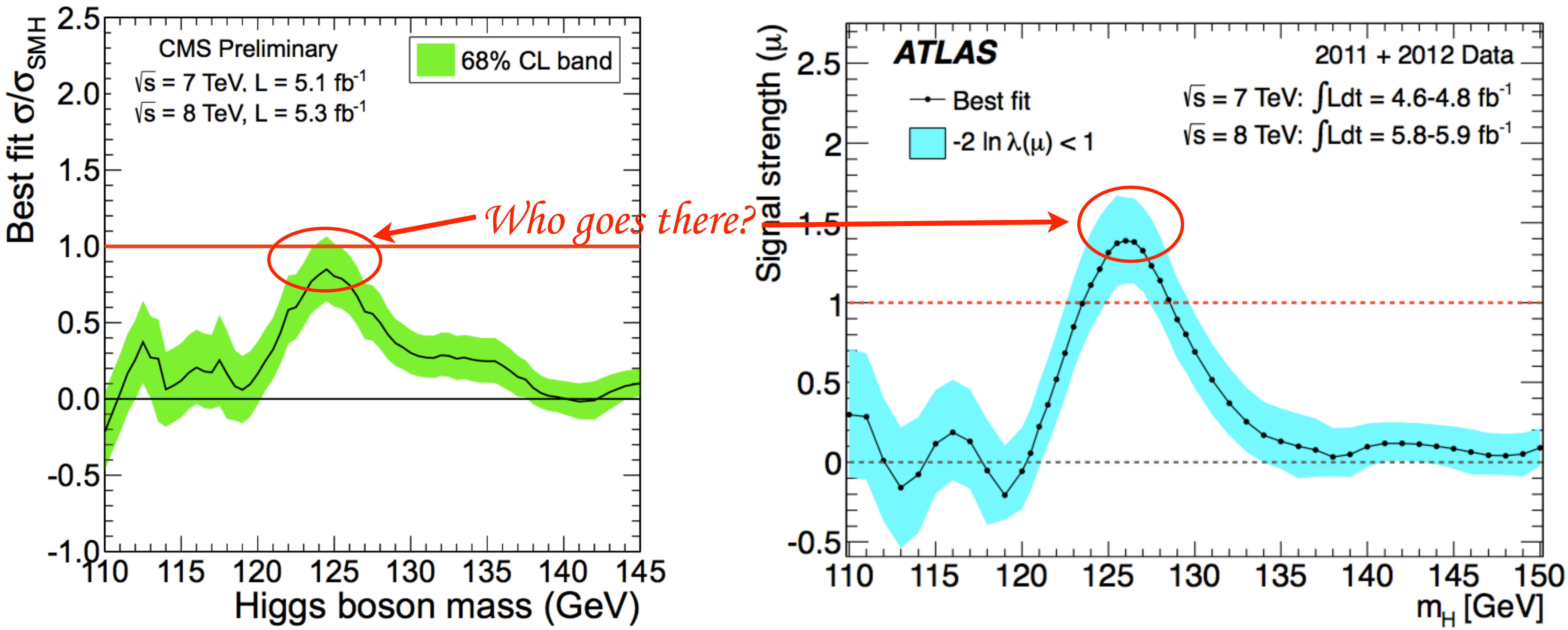
Content (for ref):

Basic fit EFT, limits, χ^2, 7 TeV data

Invisible width fits, PDF developments

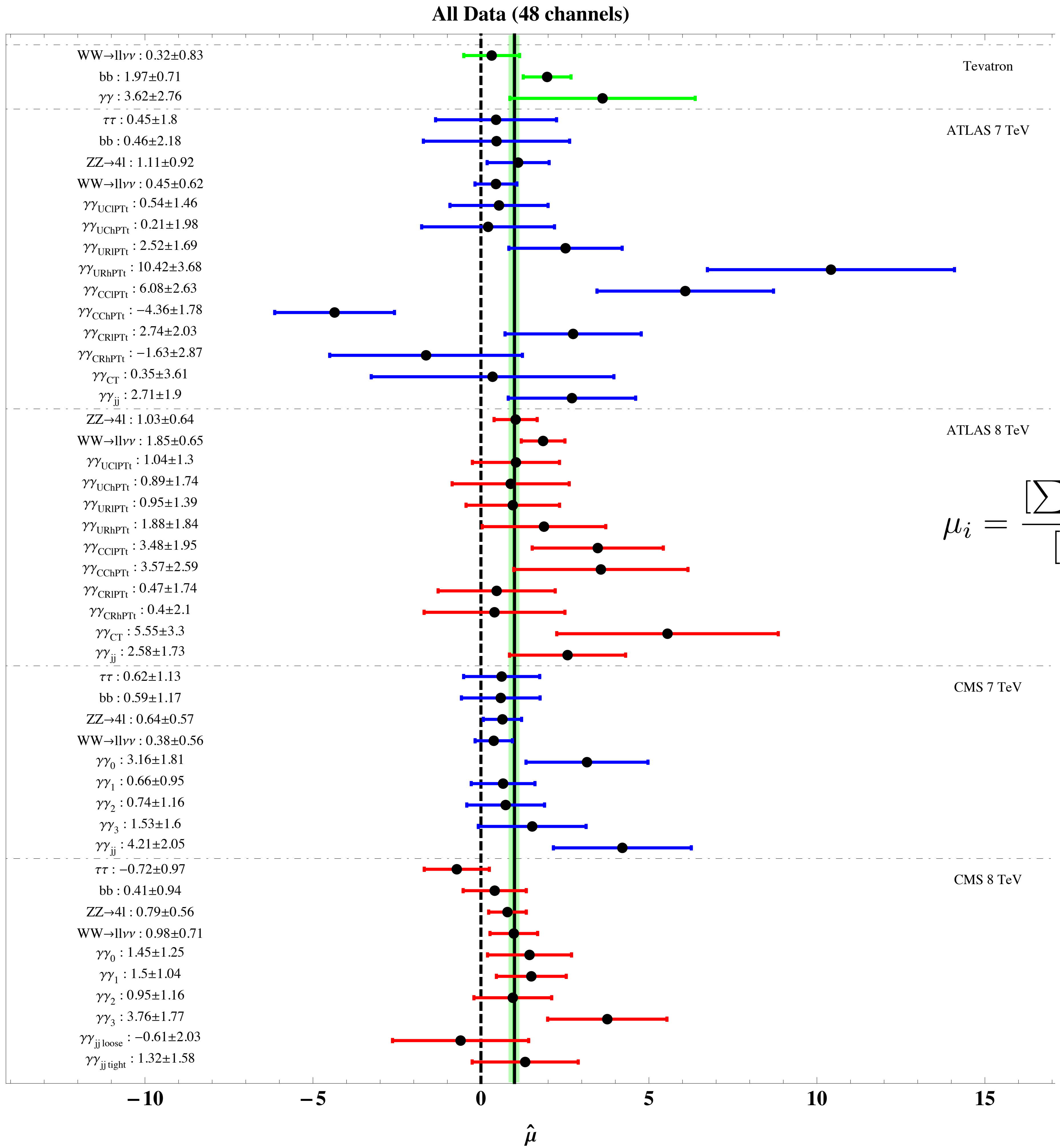
"Tension", ICHEP data (updates)

Discovery Physics!



"As a layman, I would say: I think we have it." - the D.G.

Depends on what the meaning of the word ~~is~~ it is.



"IT".

Signal Strengths.

$$\mu_i = \frac{[\sum_j \sigma_{j\to h} \times \mathrm{Br}(h \to i)]_{observed}}{[\sum_j \sigma_{j\to h} \times \mathrm{Br}(h \to i)]_{SM}} ,$$

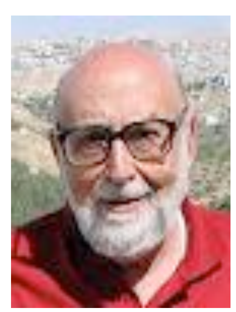
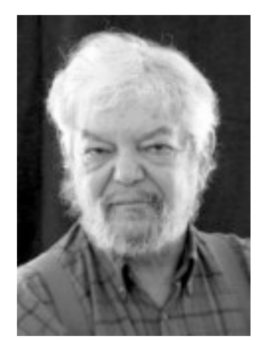
WHAT IS "IT"?

Experimental profile still being resolved

WHAT IS "IT"?

Experimental profile still being resolved

Is it a SM "Higgs"?

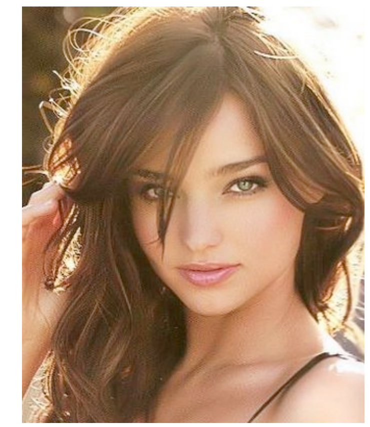
      

Best of luck sorting the credit out nobel committee!

WHAT IS "IT"?

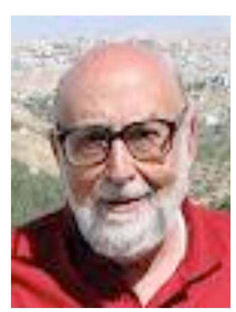
Experimental profile still being resolved

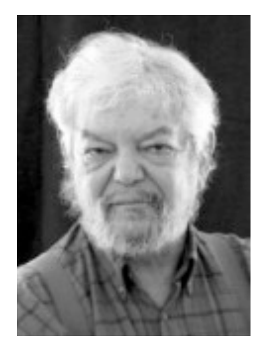
A beautiful alternative theory?



Is it a SM "Higgs"?



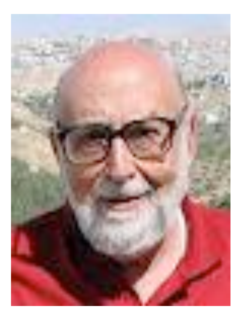


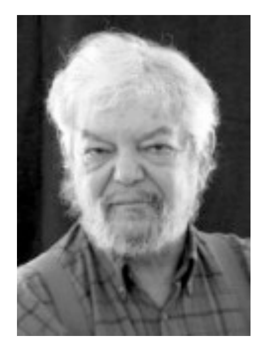

WHAT IS "IT"?

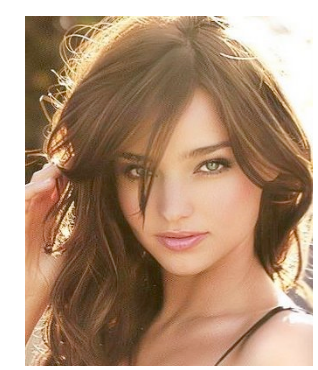
Experimental profile still being resolved

Is it a SM "Higgs" and the impact of NP?





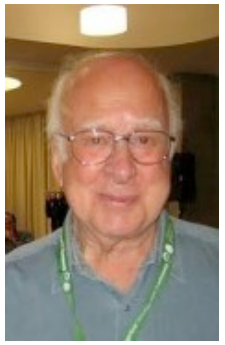
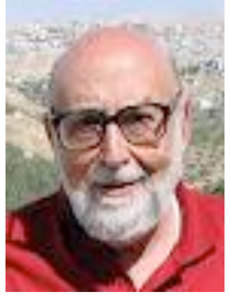


WHAT IS "IT"?

Experimental profile still being resolved

Have to assume something. - I assume a scalar field -
Consider more exotic possibilities AFTER
broad scalar EFT attempts fail.

Is it a SM "Higgs" and the impact of NP?

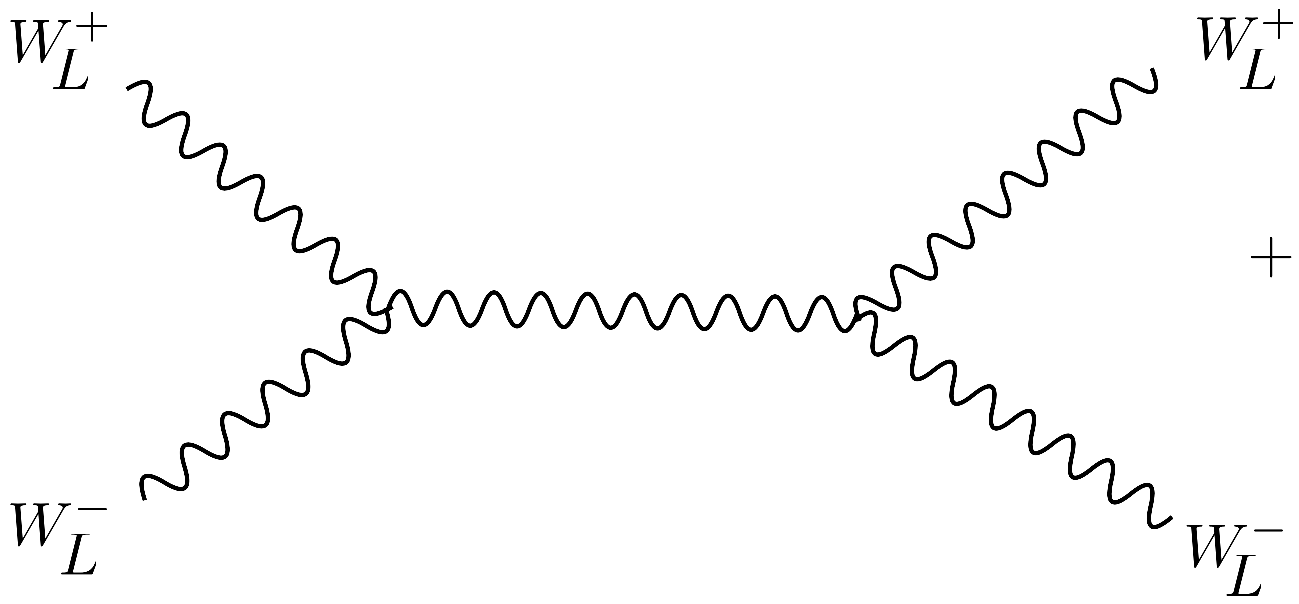
       

Consistency Problems requiring some New Physics

A scalar field is already strongly implied by the problem to solve.
The massive W,Z indicate that there is a consistency issue at high energies:

$$\mathcal{L}_{eff} = m_W^2\, W^+ W^- + \frac{m_Z^2}{2}\, Z\, Z + \cdots$$

The extra polarization mode causes the inconsistency:



$$+\cdots \qquad A \propto \frac{s}{v^2}$$

Consistency Problems requiring some New Physics

A scalar field is already strongly implied by the problem to solve.
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$$\mathcal{L}_{eff} = m_W^2\, W^+\, W^- + \frac{m_Z^2}{2}\, Z\, Z + \cdots \qquad W_L^+\, W_L^- \to W_L^+\, W_L^- : \quad A \propto \frac{s}{v^2}$$

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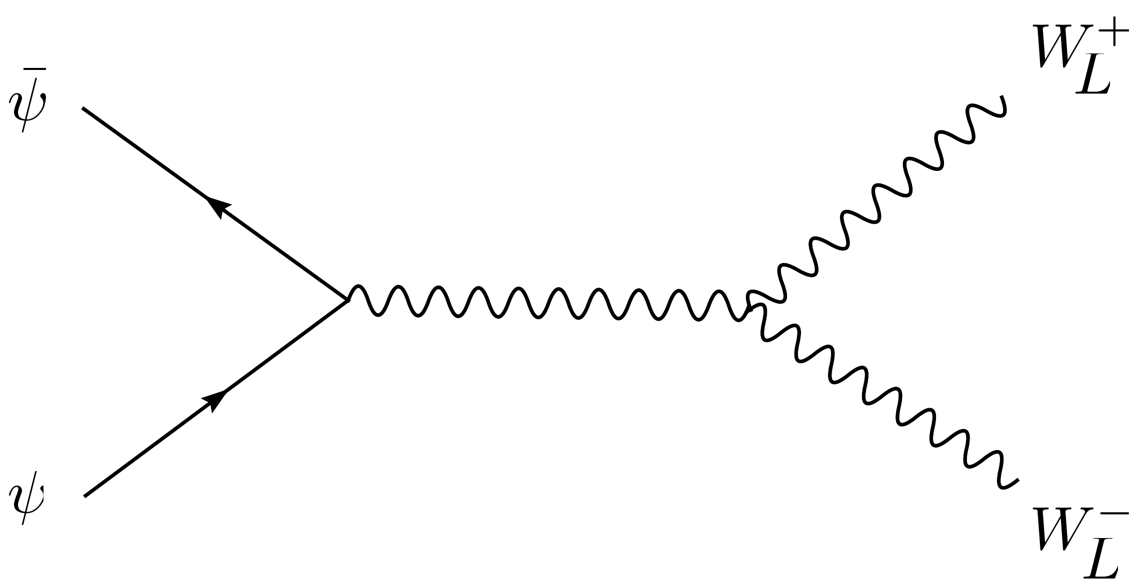

$$+ \cdots \quad A \propto \frac{s}{v^2}$$

Consistency Problems requiring some New Physics

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$$\mathcal{L}_{eff} = m_W^2 \, W^+ \, W^- + \frac{m_Z^2}{2} \, Z \, Z + \cdots$$

$$W_L^+ \, W_L^- \to W_L^+ \, W_L^- : \quad A \propto \frac{s}{v^2}$$

$$\psi \, \bar{\psi} \to W_L^+ \, W_L^- : \; A \propto \frac{s}{v^2}$$

The way to think of the theory we have actually been probing till now is:

$$\mathcal{L} = m_W^2 W \, W + \frac{m_z^2}{2} \, Z \, Z = \frac{v^2}{4} \mathrm{Tr} \left(D^\mu \Sigma^\dagger D_\mu \, \Sigma \right)$$

Goldstones of broken $\mathrm{SU}_L(2) \times \mathrm{SU}_R(2)/\mathrm{SU}_V(2)$ *give mass the to W and Z*

grouped in the nonlinear chiral EW Lagrangian as $\Sigma = \exp(i \, \sigma_a \, \pi^a / v)$

Consistency Problems requiring some New Physics

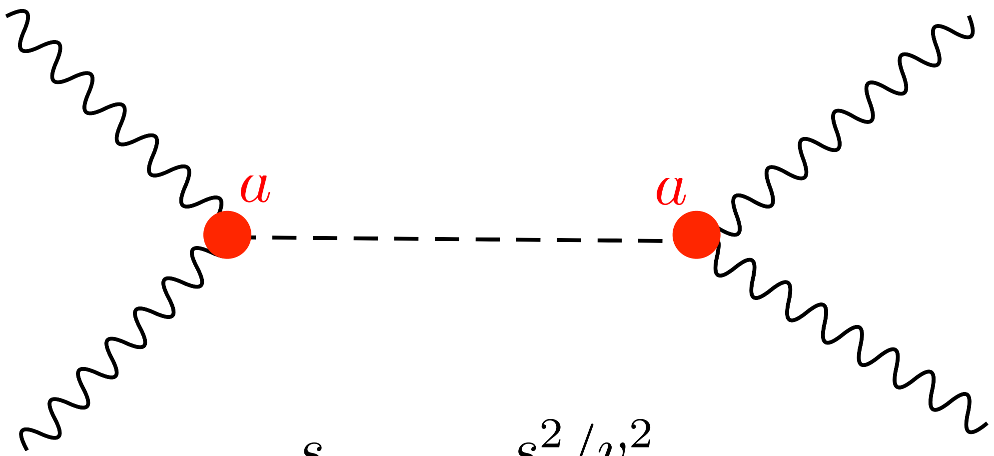
A scalar field is already strongly implied by the problem to solve.
The massive W,Z indicate that there is a consistency issue at high energies:

$$\mathcal{L}_{eff} = m_W^2\, W^+\, W^- + \frac{m_Z^2}{2}\, Z\, Z + \cdots$$

$$W_L^+\, W_L^- \rightarrow W_L^+\, W_L^- : \quad A \propto \frac{s}{v^2}$$

$$\psi\, \bar{\psi} \rightarrow W_L^+\, W_L^- : \; A \propto \frac{s}{v^2}$$

$$\cdots +$$



$$\mathcal{A} = \frac{s}{v^2} - a^2 \frac{s^2/v^2}{s - m_h^2}$$

Cut off scale of the EFT: $\Lambda = 4\, v\, \pi$ ..raised to... $\Lambda = 4\, v\, \pi/\sqrt{|1-a^2|}$

Fairly suggestive that a scalar field of some form will be involved in the UV completion.

Nonlinear Chiral EW Lagrangian + scalar

Leading terms in the EFT, there is a systematic derivative expansion to exploit:

$$
\begin{aligned}
\mathcal{L} &= \frac{1}{2}(\partial_\mu h)^2 - V(h) + \frac{v^2}{4}\mathrm{Tr}(D_\mu \Sigma^\dagger \, D^\mu \Sigma)\left[1 + 2\, a_{W,Z}\,\frac{h}{v} + b_{Z,W}\,\frac{h^2}{v^2} + b_{3,Z,W}\,\frac{h^3}{v^3} + \cdots\right], \\
&\quad - \frac{v}{\sqrt{2}}\,(\bar{u}_L^i \bar{d}_L^i)\,\Sigma\left[1 + c_i^{u,d}\,\frac{h}{v} + c_{2,j}^{u,d}\,\frac{h^2}{v^2} + \cdots\right]\begin{pmatrix} y_{ij}^u \, u_R^j \\ y_{ij}^d \, d_R^j \end{pmatrix} + h.c., \\
V(h) &= \frac{1}{2}\, m_h^2 \, h^2 + \frac{d_3}{6}\left(\frac{3\, m_h^2}{v}\right) h^3 + \frac{d_4}{24}\left(\frac{3 m_h^2}{v^2}\right) h^4 + \cdots \,.
\end{aligned}
$$

Also higher dimensional operators: (hats -dual fields)

$$
\begin{aligned}
\mathcal{L}_{HD}^5 &= -\frac{c_g\, g_3^2}{32\,\pi^2\, v}\, h\, G_{\mu\,\nu}^A G^{A\,\mu\,\nu} - \frac{c_W\, g_2^2}{32\,\pi^2\, v}\, h\, W_{\mu\,\nu}^a W^{a\,\mu\,\nu} - \frac{c_B\, g_1^2}{32\,\pi^2\, v}\, h\, B_{\mu\,\nu} B^{\mu\,\nu} \\
&\quad - \frac{\hat{c}_g\, g_3^2}{32\,\pi^2\, v}\, h\, \hat{G}_{\mu\,\nu}^A G^{A\,\mu\,\nu} - \frac{\hat{c}_W\, g_2^2}{32\,\pi^2\, v}\, h\, \hat{W}_{\mu\,\nu}^a W^{a\,\mu\,\nu} - \frac{\hat{c}_B\, g_1^2}{32\,\pi^2\, v}\, h\, \hat{B}_{\mu\,\nu} B^{\mu\,\nu} + \mathcal{O}(h^2)
\end{aligned}
$$

Also higher dimensional derivative operators in the chiral EFT...

TOO MANY DAMN PARAMETERS!

Nonlinear Chiral EW Lagrangian + scalar

EFT gives model independence & is a systematically improvable Lagrangian approach . ALSO LETS ONE USE SYMMETRY TO REDUCE PARAMETERS.

Assuming custodial sym and consistent with MFV:

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

Also higher dimensional operators: - assuming no large BSM CP violation

$$\mathcal{L}_{HD}^5 = -\frac{c_g\, g_3^2}{32\,\pi^2\, v}\, h\, G_{\mu\nu}^A G^{A\,\mu\nu} - \frac{c_W\, g_2^2}{32\,\pi^2\, v}\, h\, W_{\mu\nu}^a W^{a\,\mu\nu} - \frac{c_B\, g_1^2}{32\,\pi^2\, v}\, h\, B_{\mu\nu} B^{\mu\nu}$$

Reasonable coupling space, can draw physical conclusions for sym theories with current data. Still have degeneracies. **ONLY THE START OF THIS PROGRAM.**

Fit Methodology:

It is just a damn χ^2 *!* *-many charitable and friendly physicists.*

We advocate fitting to the signal strength parameters for fits. Not constructing a private likelihood from CLs limits, or making up signal strengths from CLs limits to avoid distorting the fit space (this is industry standard -- now):

$$\mu_i = \frac{[\sum_j \sigma_{j\to h} \times \mathrm{Br}(h \to i)]_{observed}}{[\sum_j \sigma_{j\to h} \times \mathrm{Br}(h \to i)]_{SM}}\,, \qquad \chi^2(\mu_i) = \sum_{i=1}^{N_{ch}} \frac{(\mu_i - \hat{\mu}_i)^2}{\sigma_i^2}$$

The equation above is more properly a matrix equation with a correlation coefficient matrix.

Correlations are neglected as they are unsupplied -- somewhat unknown apparently.

We <u>do not</u> make up our own correlations. Currently they are (far subdominant), but soon they will matter. (End of year perhaps?)

Please think about them experimentalists!

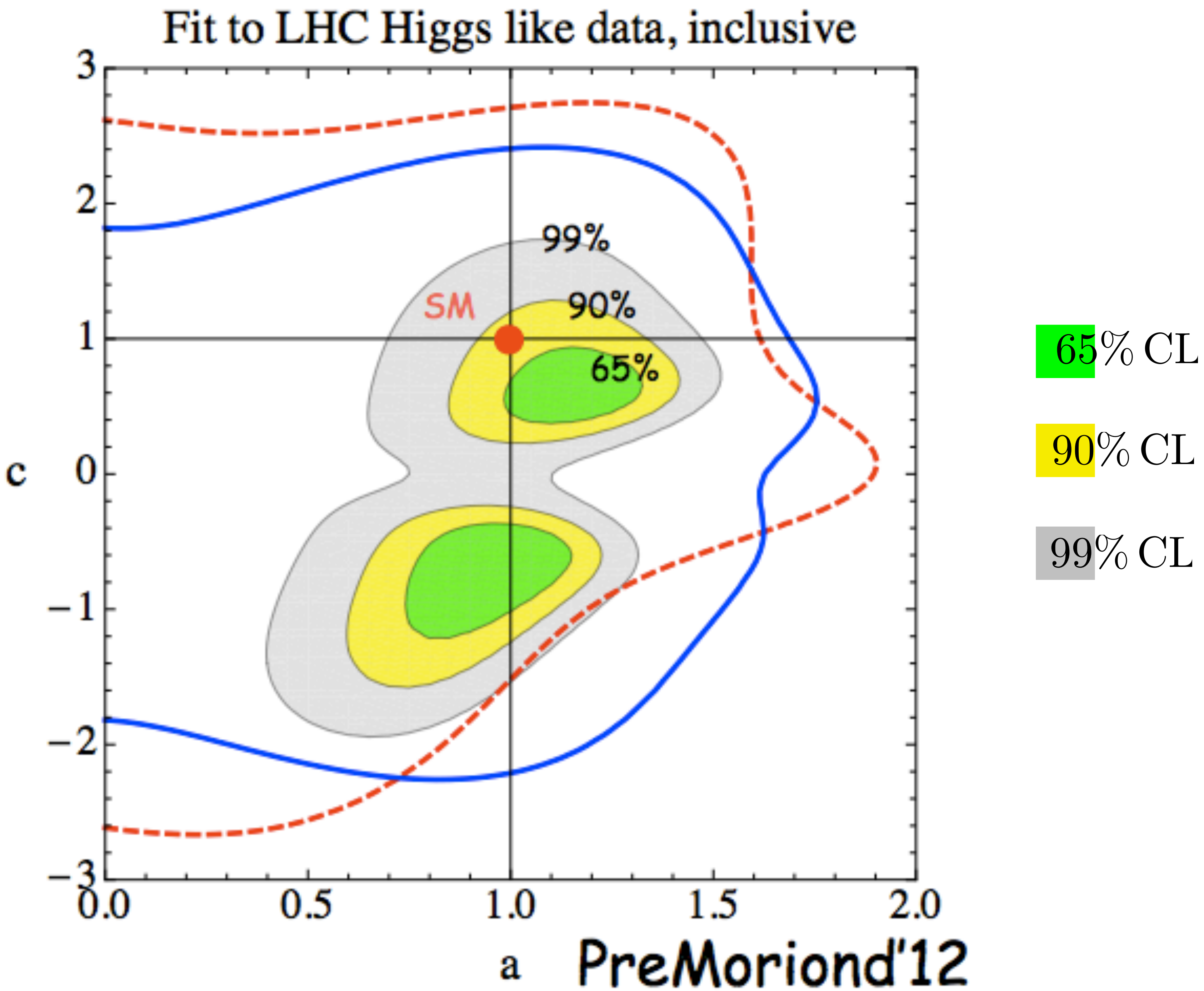
History of a discovery in Fit space

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



Espinosa,Grojean,Muhlleitner,Trott
JHEP 1205 (2012) 097 arxiv:1202.3697

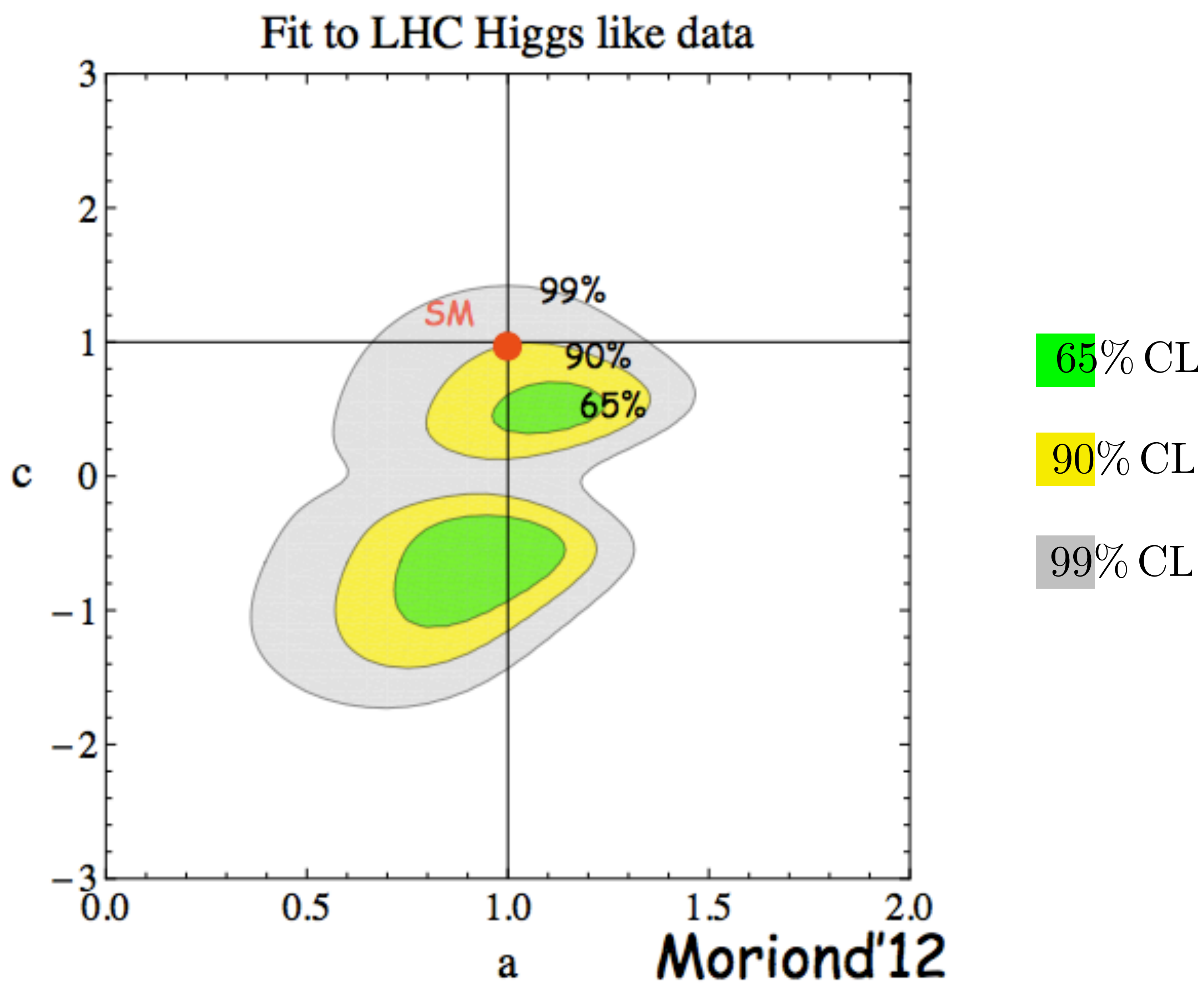
History of a discovery in Fit space

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



Atlas 95%CL exclusion

CMS 95%CL exclusion

Tevatron 95%CL exclusion

combined 95%CL exclusion

Espinosa,Grojean,Muhlleitner,Trott
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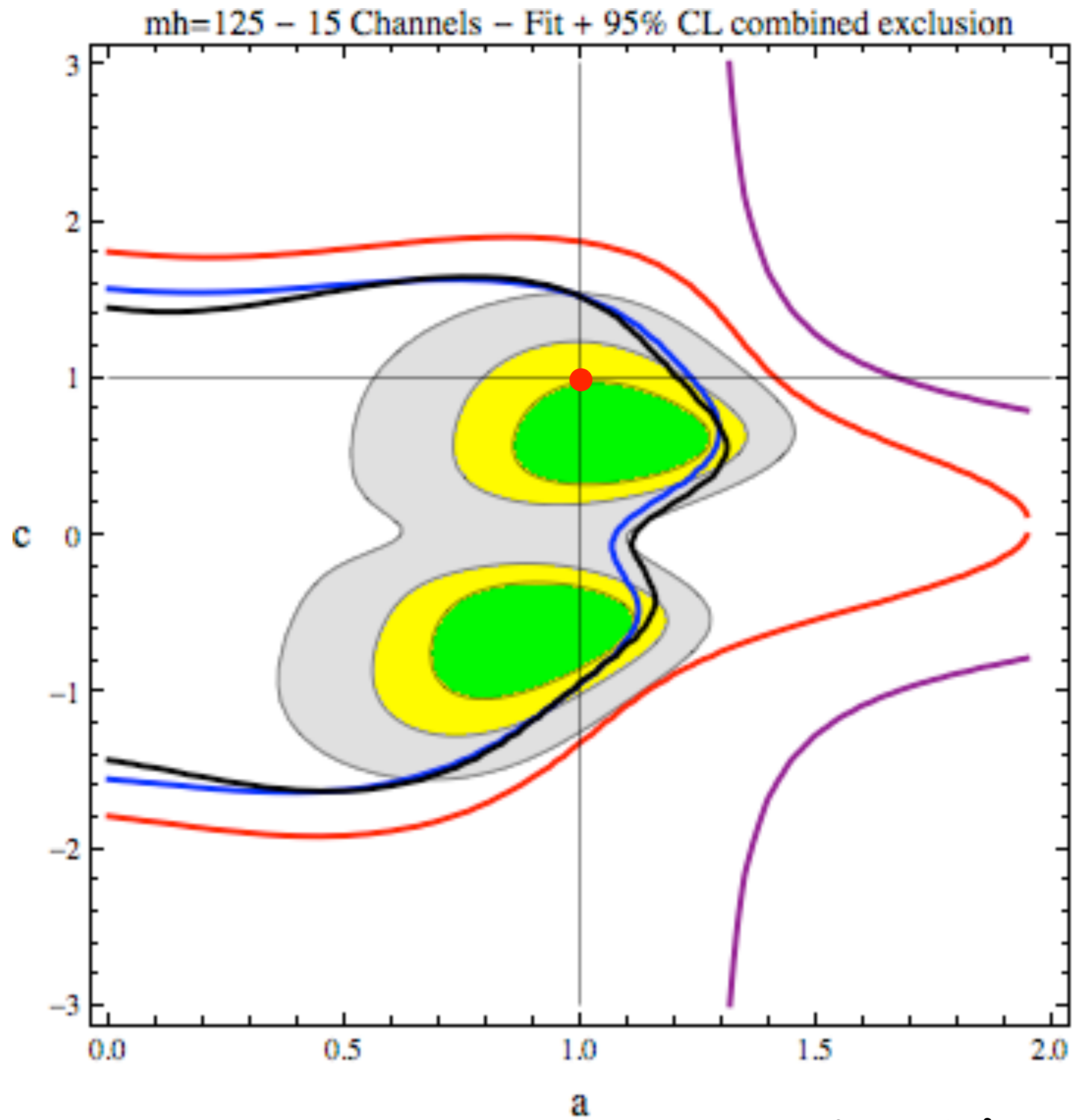
History of a discovery in Fit space



65% CL

90% CL

99% CL

Atlas 95%CL exclusion

CMS 95%CL exclusion

Tevatron 95%CL exclusion

combined 95%CL exclusion

Post-Moriond/Pre-ICHEP

Espinosa,Grojean,Muhlleitner,Trott
JHEP 1205 (2012) 097 arxiv:1202.3697

History of a discovery in Fit space

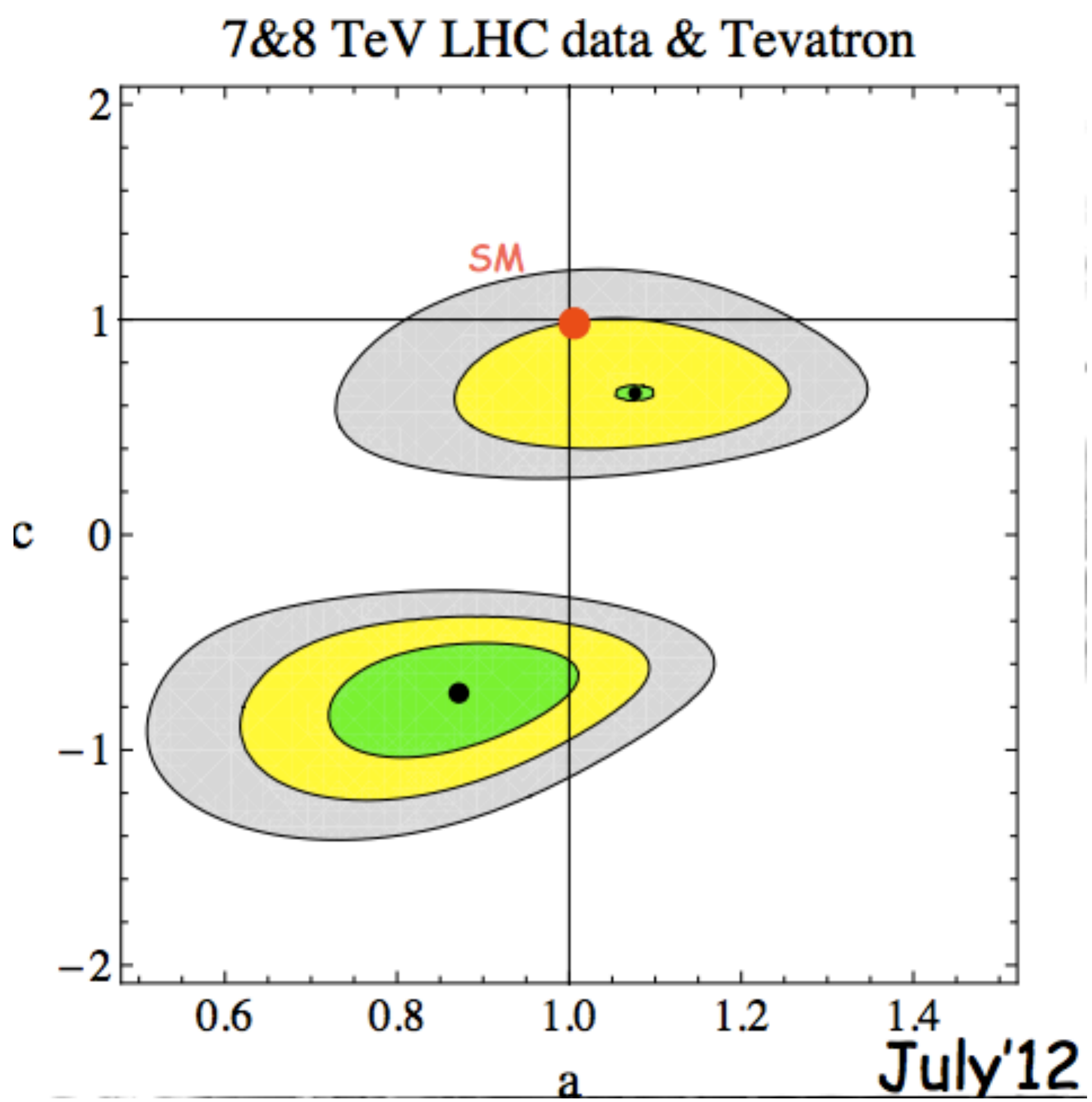
SM 93%CL
away from
best fit point
(~1.8σ)

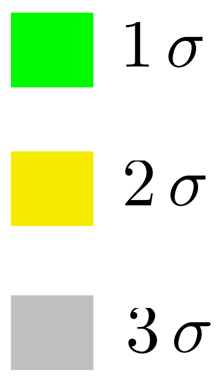
Two minima:

(a,c)=(0.86,-0.64)
χ^2=41

(a,c)=(1.05,0.63)
χ^2=41.4

Notice scale change, errors coming down!





Need to rescale 7, 8 TeV data independently.

Data released day of largely 7+8 TeV combinations.

Data day of discovery (released).

Atlas 95%CL exclusion

CMS 95%CL exclusion

Tevatron 95%CL exclusion

combined 95%CL exclusion

Espinosa,Grojean,Muhlleitner,Trott
JHEP 1205 (2012) 097 arxiv:1207.1717

History of a discovery in Fit space

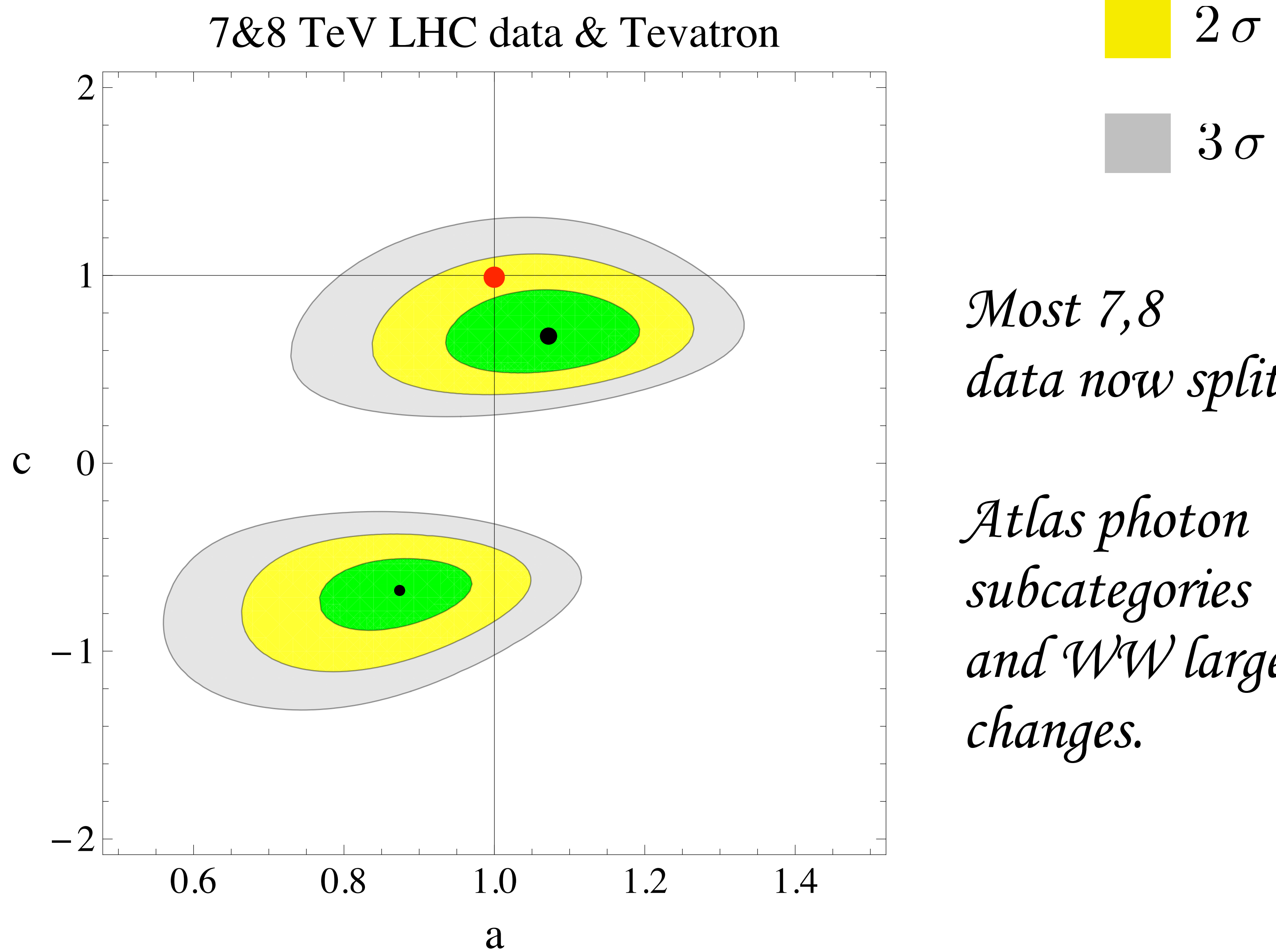
Notice scale change, errors coming down!

SM *88* %CL
away from
best fit point

Two minima:

(a,c)=(*1.07, 0.68*)
χ^2= *43.6*

(a,c)=(*0.87,-0.68*)
χ^2= *44.3*



Most 7,8 data now split.

Atlas photon subcategories and WW largest changes.

Atlas 95%CL exclusion

CMS 95%CL exclusion

Tevatron 95%CL exclusion

combined 95%CL exclusion

Post ICHEP Data - up to date.

Espinosa,Grojean,Muhlleitner,Trott
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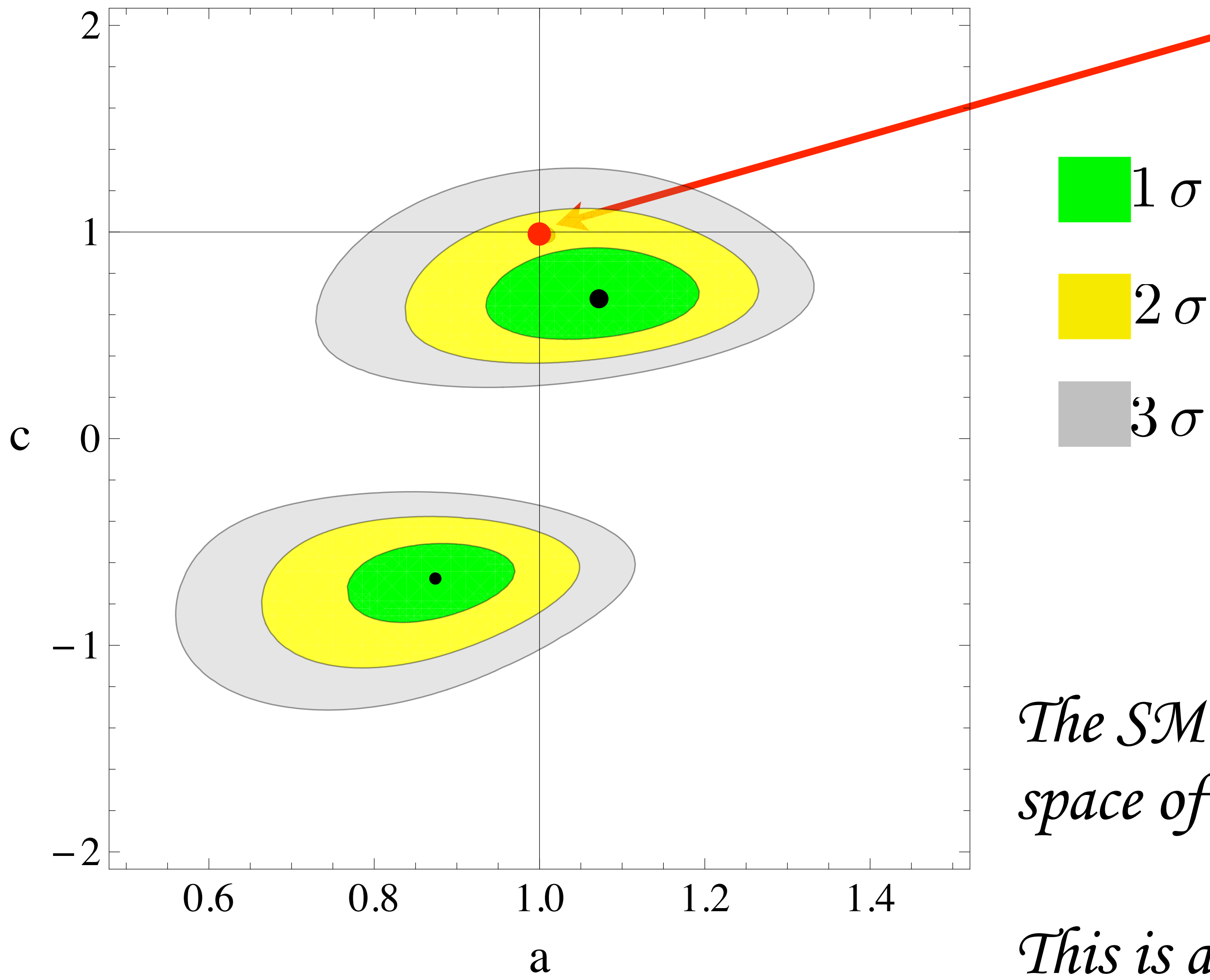
<u>*Point of the symmetric a,c fits*</u>

7&8 TeV LHC data & Tevatron



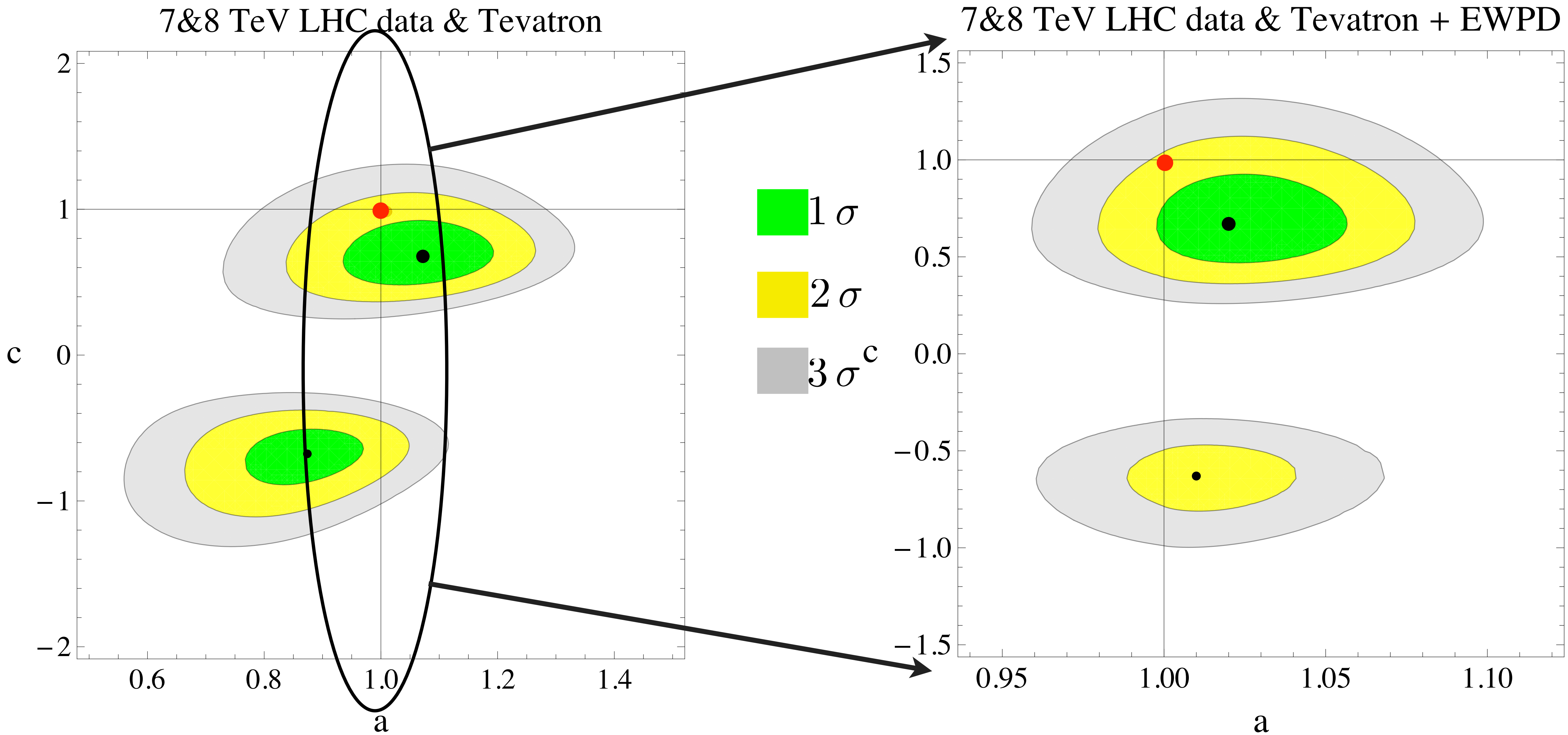
GWS is here, is the data there as well?

The SM is a specific point in the coupling space of the EFT.

This is a direct (minimal) way to test - is it the SM Higgs with no other NP.

<u>*Of course the conclusions are changed if you fit with a different theory.*</u>

Add in EWPD to the Fit



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Notice "a" scale changed significantly

Here we use the log dependence on a not 1 in EWPD determined in

Barbieri, Bellazzini, Rychkov, Varagnolo **arXiv:0706.0432**

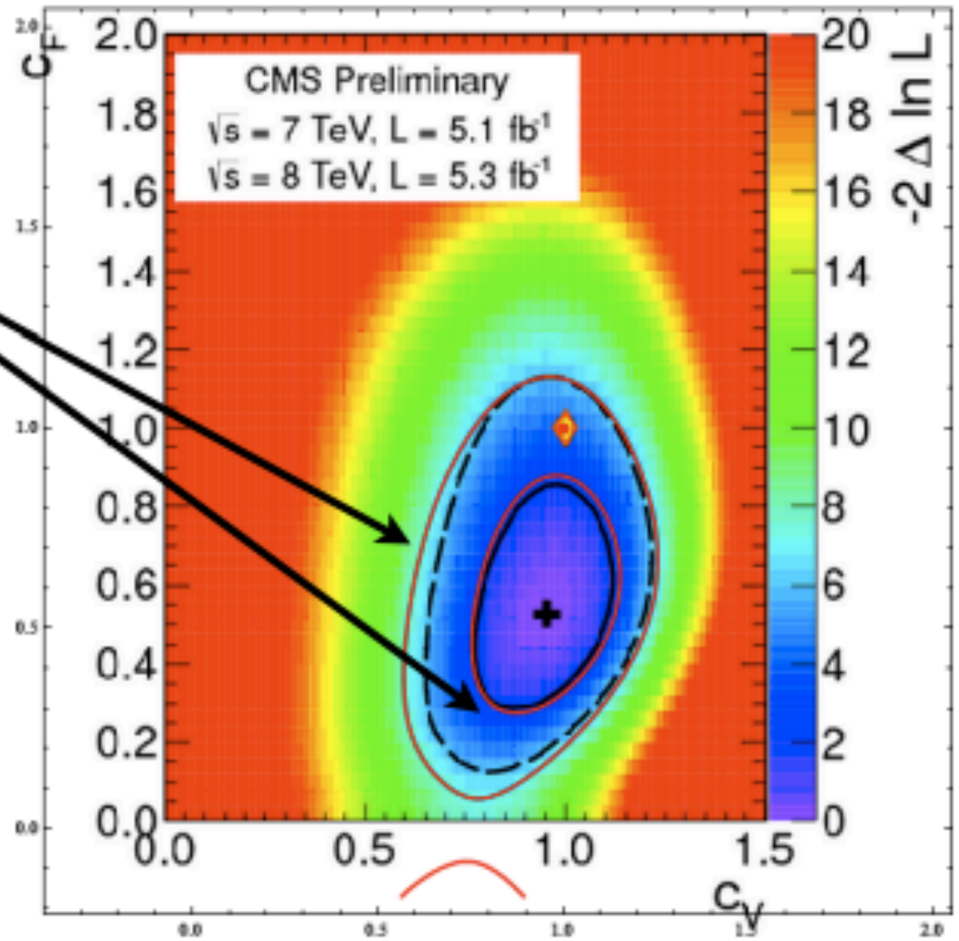
Can you trust a theorist to do this?

Comparison with CMS "official" fit

CMS imposed a prior c > 0
(it doesn't affect χ^2, but it modifies $\Delta\chi^2$)

Your χ^2 is too damn good !
-our friendly competition

Our contours



This means that:

a) We are not badly screwing up.

b) correlations do not matter (now)

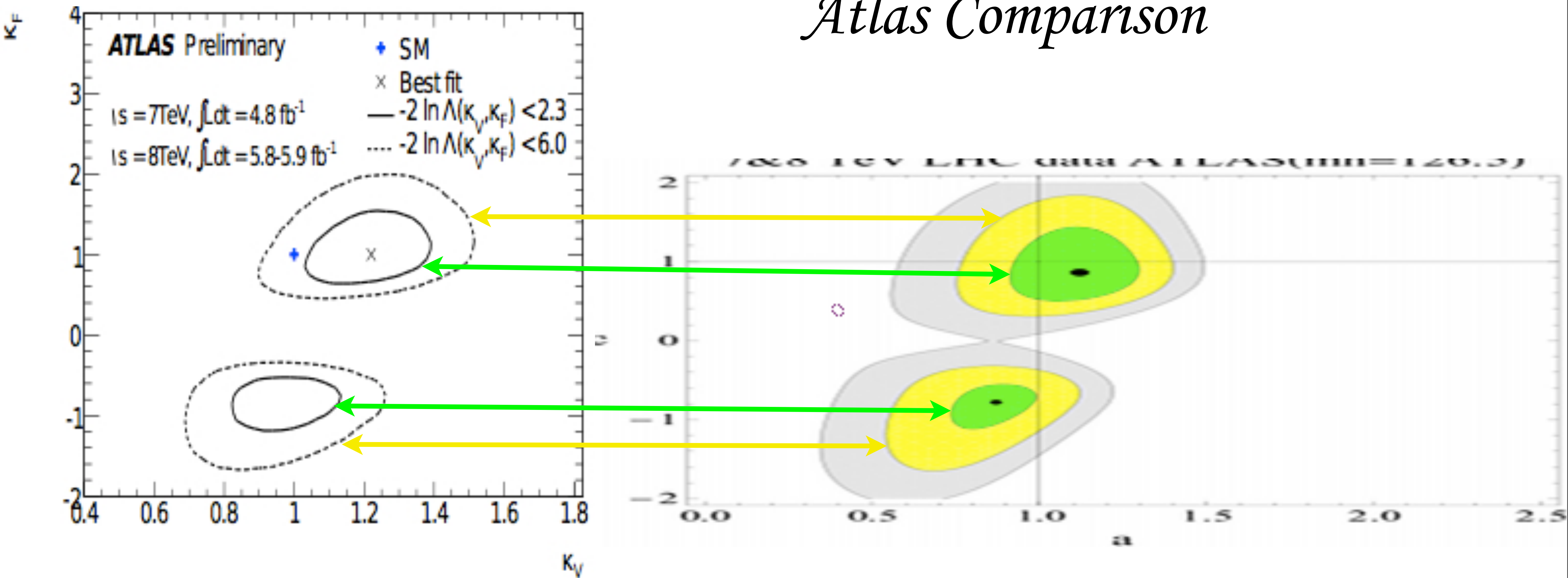
or

b) they do matter but CMS is as lost on estimating them correctly as we are.

Conclusion: You can trust some theorists to do this (for now).

More Movement by Atlas and CMS in this direction

Atlas Comparison



The contours of comparison are pretty good! However, more of a shift than CMS.

1) WW (0,1,2 jet) sub-channel treatment, they have more info, can use the sub-channels.

2) gamma gamma correlations might matter here due to the way the data was sliced up

Need more info from ATLAS for a more direct comparison.

What is the right approach to use?

It is obvious that we will be doing Higgs Effective Field theory for LHC and linear colliders. But WHICH EFT to use?

1) Assume that the scalar is embedded in an $SU_L(2)$ doublet?

If yes most relevant to study the effects of these operators:

$$\begin{aligned}\mathcal{L}^6_{HD} = &-\frac{c_g\, g_3^2}{\Lambda^2}\,(\phi^\dagger\,\phi)\, G^A_{\mu\,\nu} G^{A\,\mu\,\nu} - \frac{c_W\, g_2^2}{\Lambda^2}\,(\phi^\dagger\,\phi)\, W^a_{\mu\,\nu} W^{a\,\mu\,\nu} - \frac{c_B\, g_1^2}{\Lambda^2}\,(\phi^\dagger\,\phi)\, B_{\mu\,\nu} B^{\mu\,\nu} \\ &-\frac{\hat{c}_g\, g_3^2}{\Lambda^2}\,(\phi^\dagger\,\phi)\, \hat{G}^A_{\mu\,\nu} G^{A\,\mu\,\nu} - \frac{\hat{c}_W\, g_2^2}{\Lambda^2}\,(\phi^\dagger\,\phi)\, \hat{W}^a_{\mu\,\nu} W^{a\,\mu\,\nu} - \frac{\hat{c}_B\, g_1^2}{\Lambda^2}\,(\phi^\dagger\,\phi)\, \hat{B}_{\mu\,\nu} B^{\mu\,\nu}\end{aligned}$$

A complaint here is that one assumes the SM (+ NP) when trying to prove the SM.

What is the right approach to use?

It is obvious that we will be doing Higgs Effective Field theory for LHC and linear colliders. But WHICH EFT to use?

2) Do not assume that the scalar is embedded in an $SU_L(2)$ *doublet.*

Can still have $SU_L(2) \times U(1)$ *just realized non-linearly. Use the EW chiral lagrangian + scalar EFT. This is more general . The SM as a subclass of this general EFT.*

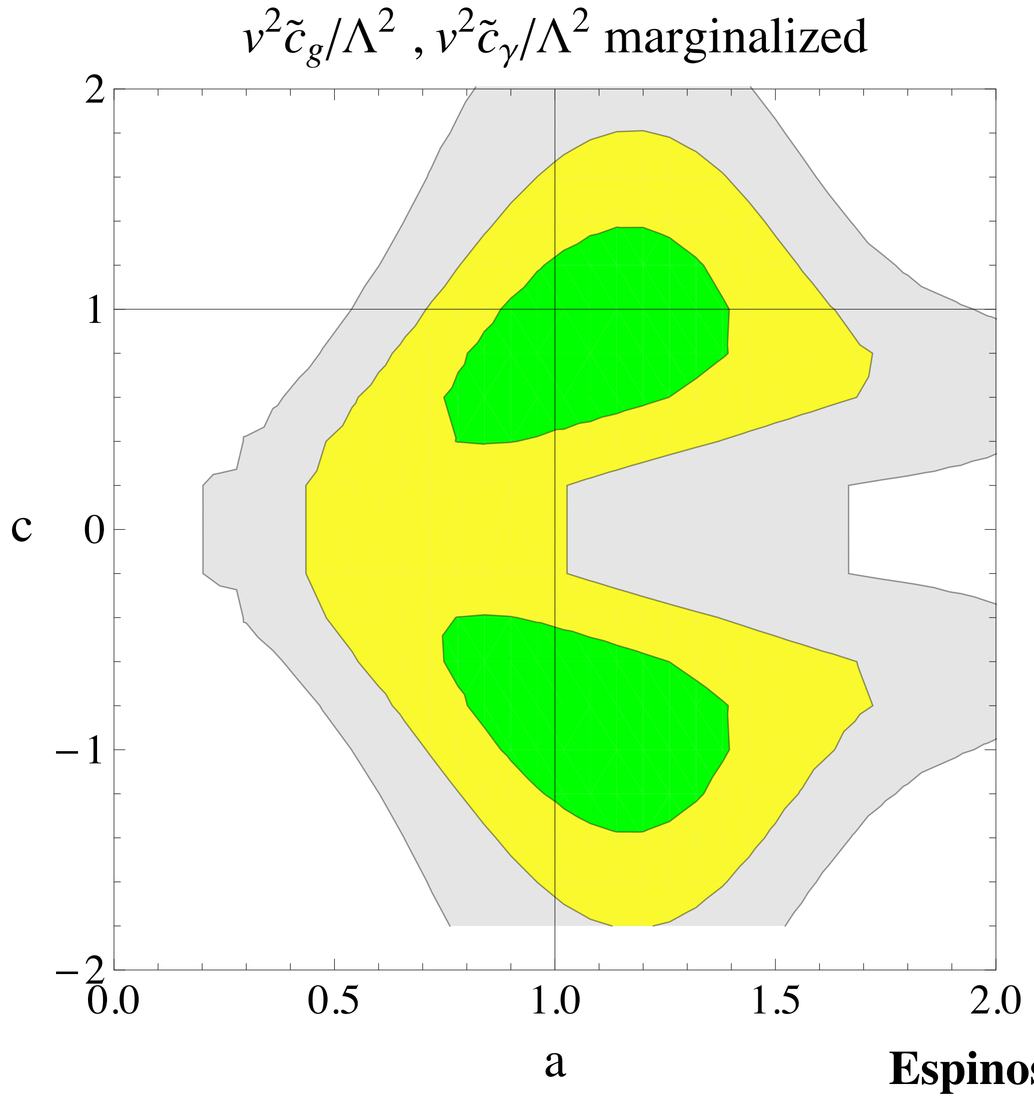
$$
\begin{aligned}
\mathcal{L}^5_{HD} \quad = \quad & -\frac{c_g\, g_3^2}{32\,\pi^2\, v}\, h\, G^A_{\mu\,\nu} G^{A\,\mu\,\nu} - \frac{c_W\, g_2^2}{32\,\pi^2\, v}\, h\, W^a_{\mu\,\nu} W^{a\,\mu\,\nu} - \frac{c_B\, g_1^2}{32\,\pi^2\, v}\, h\, B_{\mu\,\nu} B^{\mu\,\nu} \\
& -\frac{\hat{c}_g\, g_3^2}{32\,\pi^2\, v}\, h\, \hat{G}^A_{\mu\,\nu} G^{A\,\mu\,\nu} - \frac{\hat{c}_W\, g_2^2}{32\,\pi^2\, v}\, h\, \hat{W}^a_{\mu\,\nu} W^{a\,\mu\,\nu} - \frac{\hat{c}_B\, g_1^2}{32\,\pi^2\, v}\, h\, \hat{B}_{\mu\,\nu} B^{\mu\,\nu} + \mathcal{O}(h^2)
\end{aligned}
$$

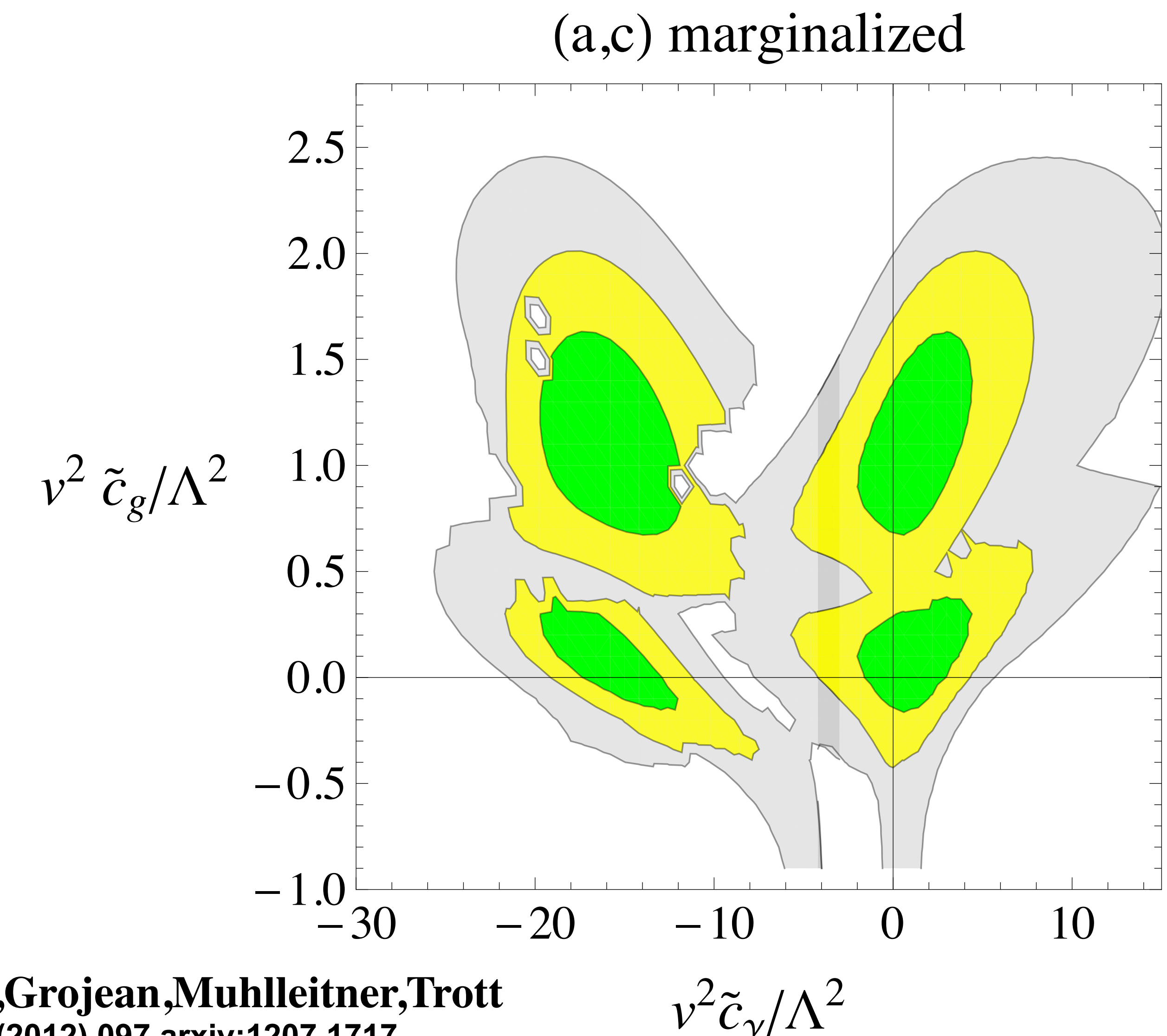
There are also higher order terms in the EW chiral Lagrangian + scalar EFT:

$$
c_W \left(W^-_\nu\, D_\mu\, W^{+\mu\,\nu} + W^+_\nu\, D_\mu\, W^{-\mu\,\nu}\right) \frac{h}{v} + c_Z\, Z_\nu \partial_\mu Z^{\mu\,\nu} \frac{h}{v} +
$$

The momentum dependence is different, precision studies of distributions at linear colliders are of interest if these terms are non zero.

Marginalization Games





Espinosa,Grojean,Muhlleitner,Trott
JHEP 1205 (2012) 097 arxiv:1207.1717

Very interesting that the SM higgs hypothesis test is improved in the context of NP in this way. Need more data.

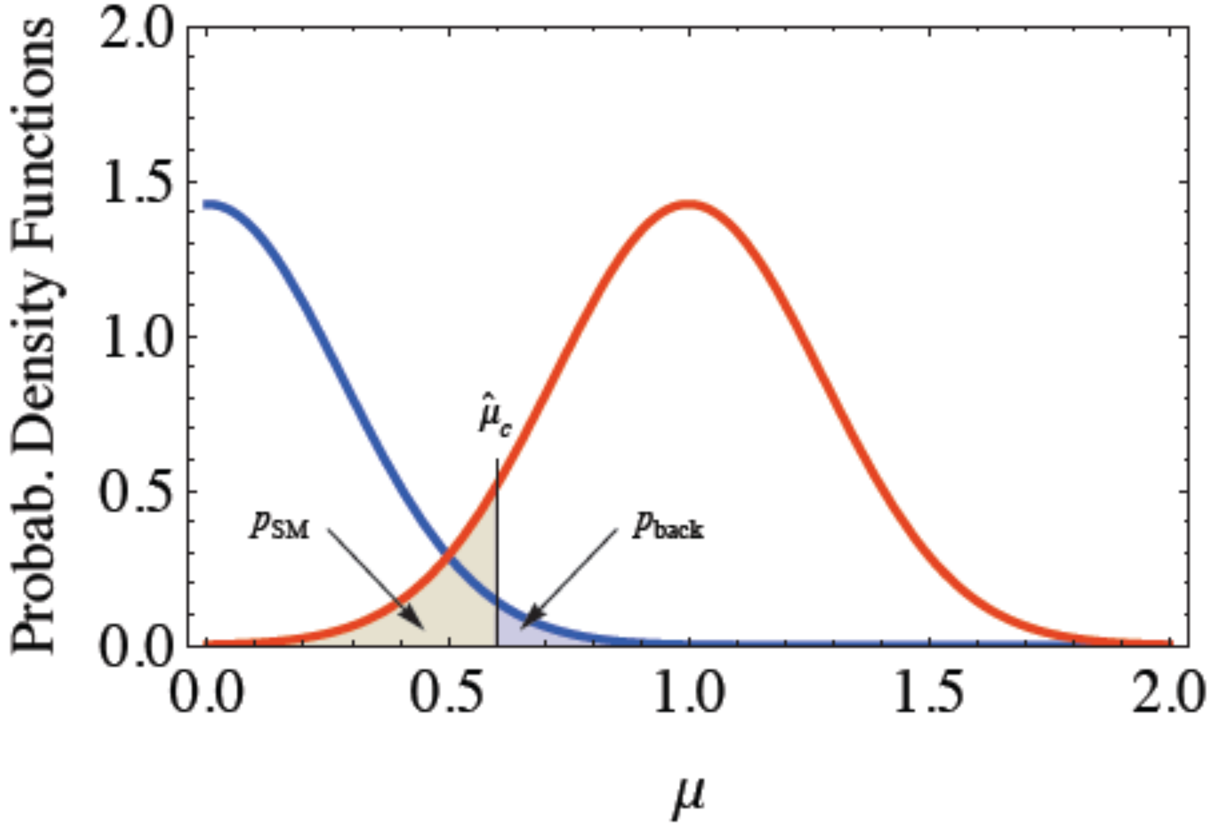
A way of seeing that the existence of the $\gamma\,\gamma$ "excess" depends upon the Yukawa couplings being SM - like. Need more data.

see also **Rauch, Plehn arxiv:1207.6108**

Branching Ratio Invisible

The invisible branching ratio is great as it is a universal shift on signal strengths.

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



In terms of the gaussian combination variables

$$\frac{1}{\sigma_c^2} = \sum_i^{N_{ch}} \frac{1}{\sigma_i^2}, \qquad \frac{\hat{\mu}_c}{\sigma_c^2} = \sum_i^{N_{ch}} \frac{\hat{\mu}_i}{\sigma_i^2} \, .$$

The invisible branching ratio is expressed as: $\mathrm{Br}_{inv} = 1 - \hat{\mu}_c.$

One can fit to it using the SUPPLIED COMBINED SIGNAL STRENGTHS

Branching Ratio Invisible

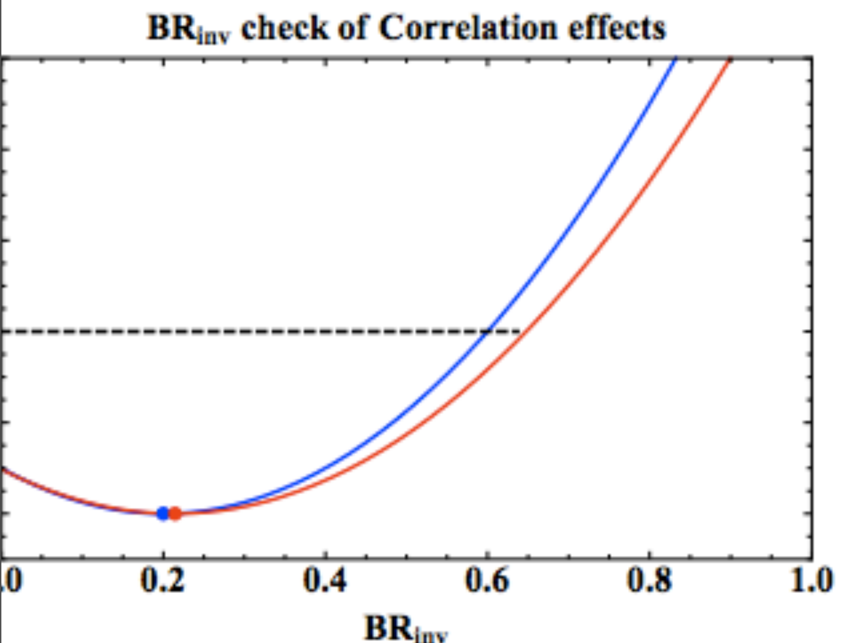
Supplied combined signal strengths:

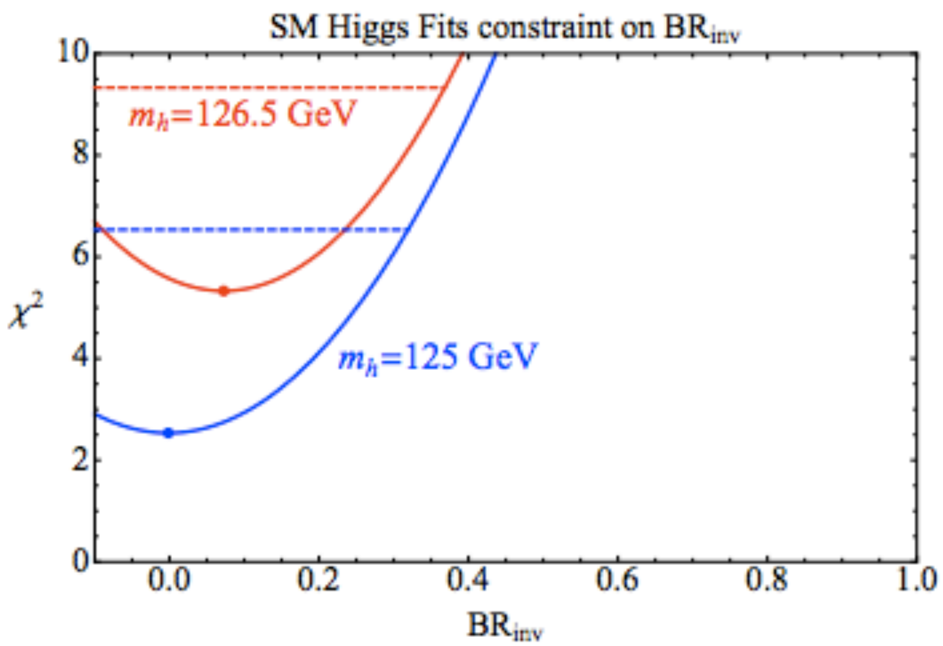
Experiments	$\hat{\mu}_c,\ m_h = 124$	$\sigma_c,\ m_h = 124$	$\hat{\mu}_c,\ m_h = 125$	$\sigma_c,\ m_h = 125$
CMS [22]	0.98	0.32	0.94	0.32
ATLAS [22]	0.61	0.38	0.81	0.38
CDF&DØ [24]	1.31	0.62	1.28	0.62

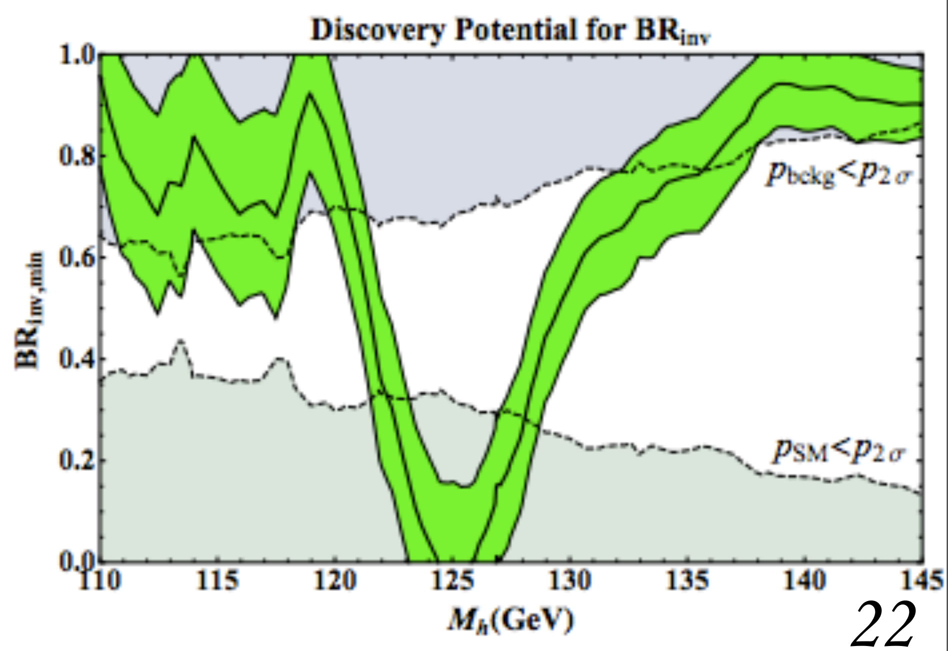
7 tev

Experiments	$\hat{\mu}_c,\ m_h = 125$	$\sigma_c,\ m_h = 125$	$\hat{\mu}_c,\ m_h = 126.5$	$\sigma_c,\ m_h = 126.5$
CMS [7&8 TeV] [1]	0.80	0.20	0.67	0.19
ATLAS [7&8 TeV] [1]	1.12	0.27	1.24	0.26
ATLAS [7&8 TeV] (& μ_{WW}) [56]	1.32	0.29	1.37	0.27
CDF&DØ [44]	1.35	0.59	1.38	0.60

Now







Conclusions

So, what exactly is "IT"? We don't know yet. However.

Global fits to signal strengths are a powerful tool to understand "it".
Using symmetry one can gain a lot more from the signal strength data in an EFT approach.

Have shown how one can study the boson in this context, and how the profile has evolved over time. The SM higgs hypothesis consistency with the data has been relatively stable with about a 2 sigma deviation present in the (a,c) space test.

Global fits to Higgs properties are a powerful tool for constraining new physics. Showed an application to an invisible branching ratio. This will matter in the LHC run for dark matter direct detection, limits are approaching the interesting BR range rather fast!

Global data studies are very powerful and are scaling amazingly fast!

Constraints are scaling!