Physics of the Higgs Boson

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Orientation: Where are we after Run 1.

i.e.

What is the status of the Higgs and BSM hopes/expectations?
No unique answer, but will give my biased theorist perspective.

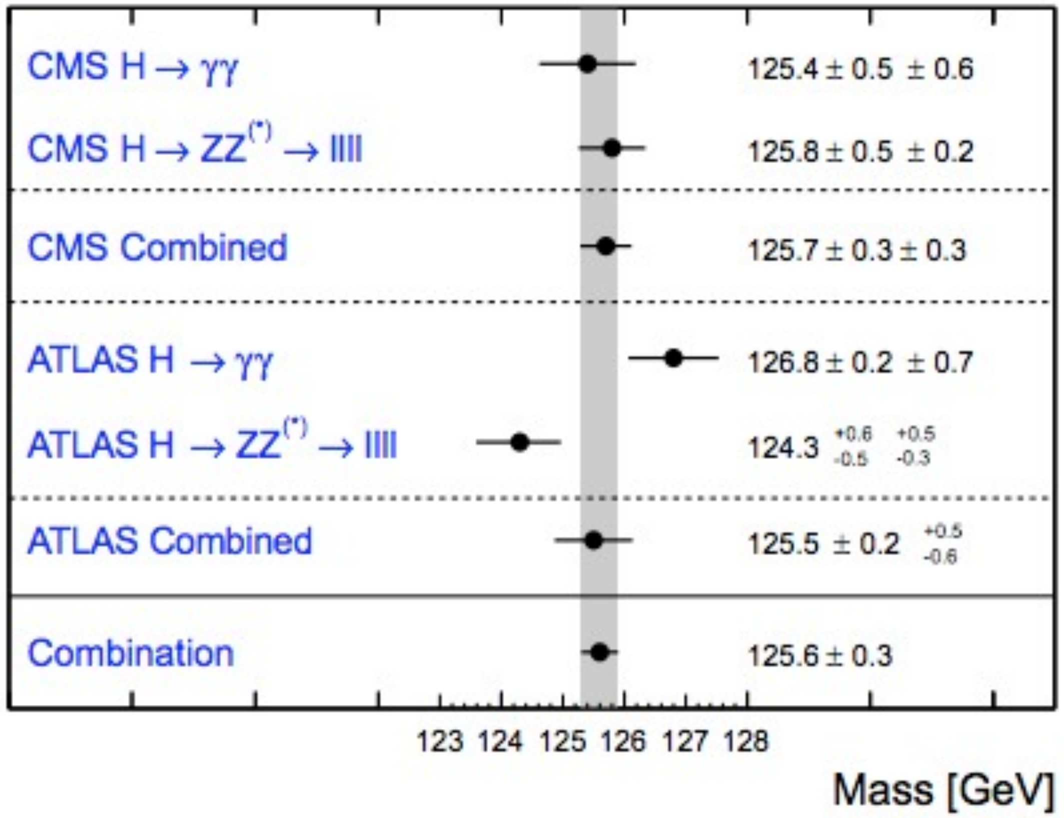
- *The Good News re Higgs.*

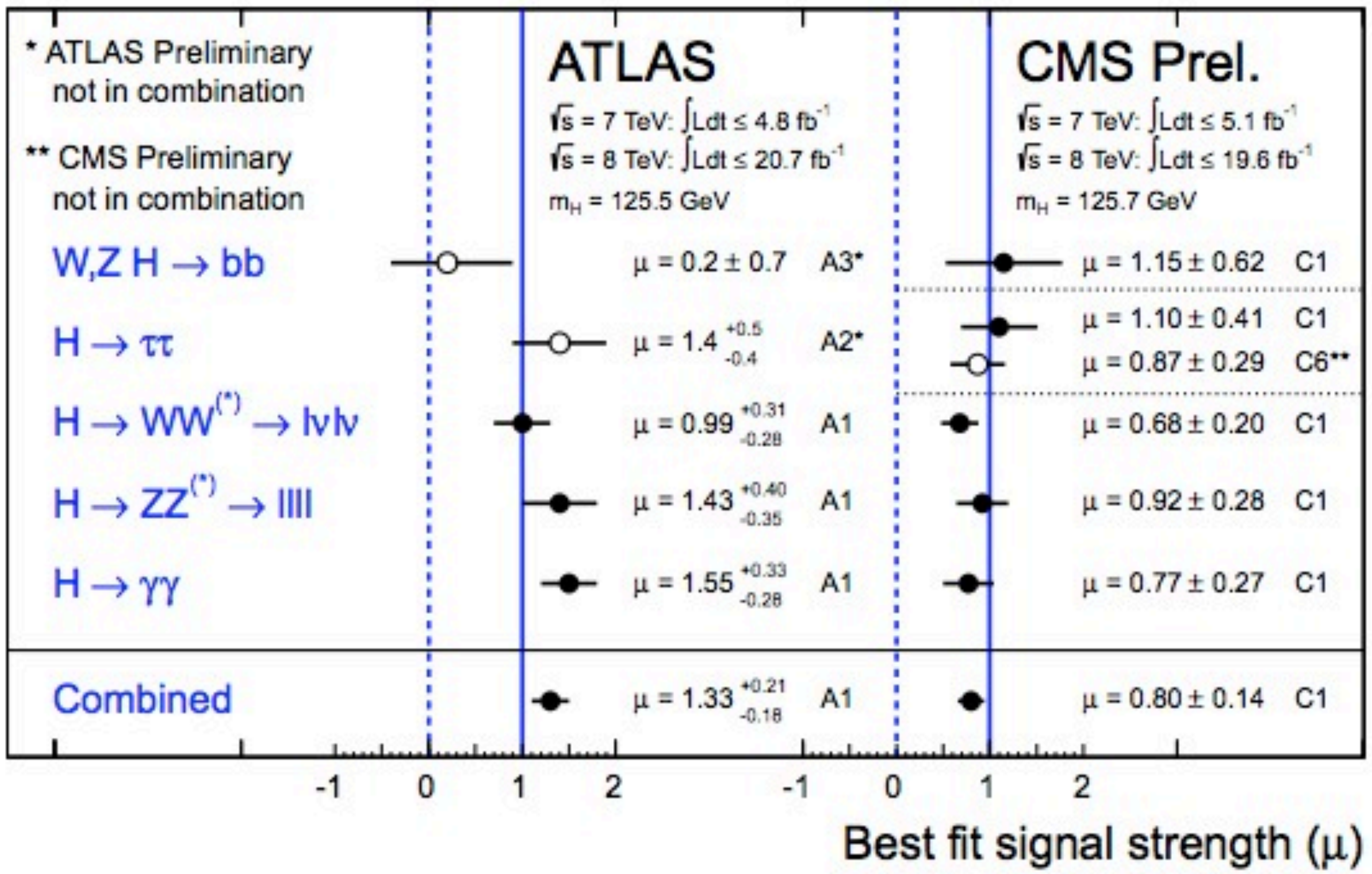
  - model independent EFT comments

- *The Bad News. (Not necessarily for LHec.)*

  - some specific model comments

The "Good News": The "Higgs like" Boson





We have found what seems to be a 0+ state, that has properties broadly consistent with the properties of the SM Higgs.

- *a new state to study*
- *it was totally obvious that some state like this should show up.*

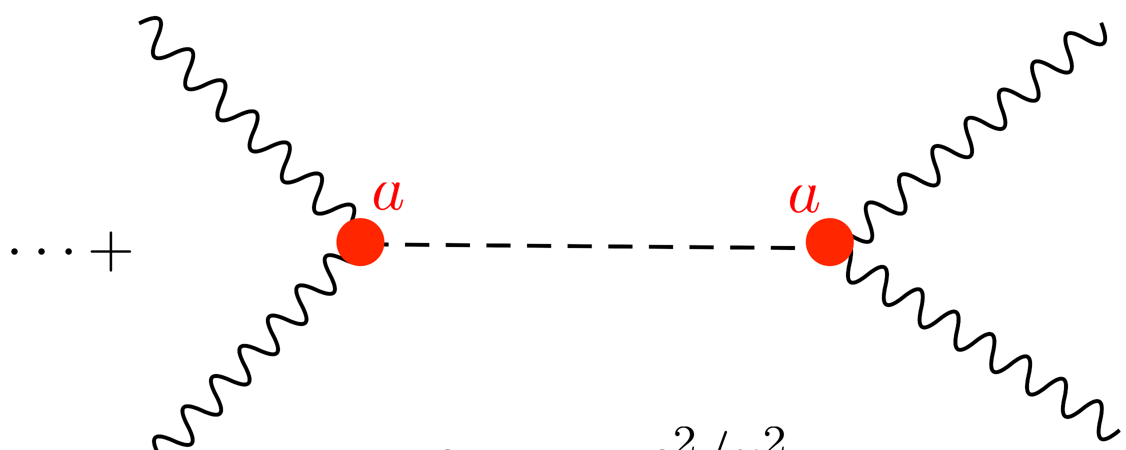
The "Good News": The "Higgs like" Boson

Why should a state like this be part of the nature of EW symmetry breaking?

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

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

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



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

0^+ *scalar is what the doctor ordered to help with unitarity problem*

Couplings within 10% of the SM, cut off scale 7 tev...

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

We see a Higgs like boson, with no other states (to date) at low scales.
That just fundamentally --- makes sense. Consistent with all sorts of precision tests.
(For energies up to a couple TeV.)

The "Good News": The "Higgs like" Boson

When things get weird is when we take the extreme limit of this basically sensible scenario, push the cut off scale to very large values $\Lambda^2 \gg m_h^2$

That fundamentally does not make sense, this is the usual hierarchy problem.

The issue is that $H^\dagger H$ *is dimension 2, and a singlet operator*

generically one can construct $(\mathcal{L}_{other\, stuff})\, H^\dagger H$

$$\delta m_h^2 = \frac{3 m_{F,B}^2}{8\,\pi^2}\, \lambda_{F,B} (-1)^{2S} \, \log \frac{\mu^2}{Q^2}$$

where $M_{F,B} \propto \Lambda$ *. This is the issue, quadratic divergences matter to the degree they capture this simple point about threshold corrections in dim reg.*

The "Good News": The "Higgs like" Boson

Light ($m_s \ll \Lambda$) fundamental scalars are difficult to understand.

There is a cut off scale.

Why:

- the SM does not explain the matter-antimatter asy
- no clearly consistent inflaton candidate in the SM (we can talk about Higgs inflation later)
- no successful explanation of galactic rotation curves, cosmo fits of various scales (i.e dark matter).

If these problems are solved in a manner that introduces a new scale, their is an issue to resolve.

The standard moves:

- New symmetry group, that cancels the threshold correction
- New strong interaction, and the Higgs is a "light sigma or pion"
- reinterpret the scales (extra dimensions)

The "Good News": The "Higgs like" Boson

A solution to the known problems that involves a new scale shifts the expected couplings. For example, in the case of a goldstone Higgs, one expects

1303.3876

Higgs couplings	$\Delta\mathcal{L}_{SILH}$	MCHM4	MCHM5
c_W	$1 - \bar{c}_H/2$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$
c_Z	$1 - \bar{c}_H/2 - 2\bar{c}_T$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$
$c_\psi\ \ (\psi = u, d, l)$	$1 - (\bar{c}_H/2 + \bar{c}_\psi)$	$\sqrt{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$
c_3	$1 + \bar{c}_6 - 3\bar{c}_H/2$	$\sqrt{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$
c_{gg}	$8\,(\alpha_s/\alpha_2)\,\bar{c}_g$	0	0
$c_{\gamma\gamma}$	$8\sin^2\theta_W\,\bar{c}_\gamma$	0	0

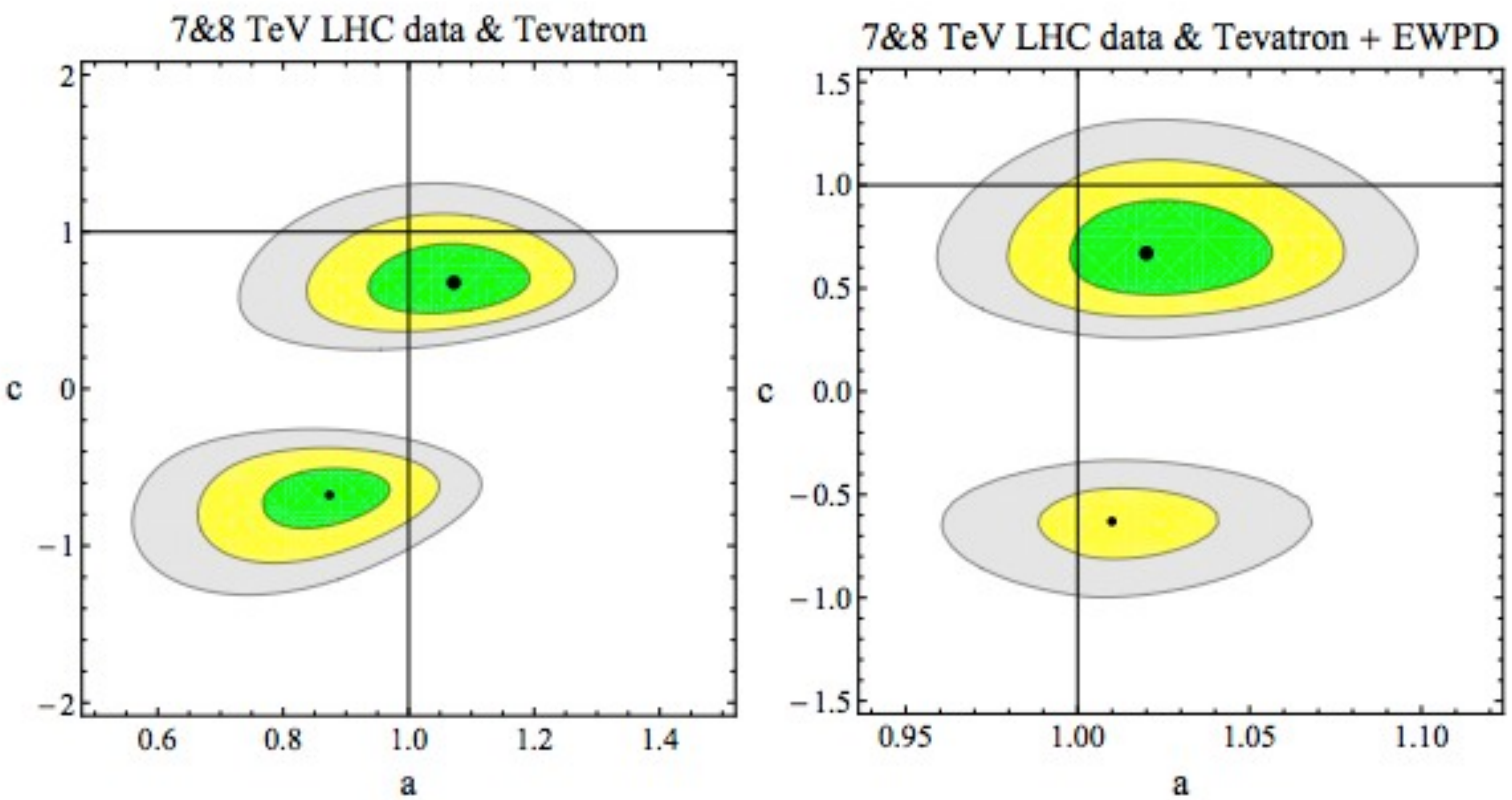
However, we already knew that these shifts were implied to be small.

The "Bad News":

For example, EWPD strongly constrains anomalous couplings of the scalar to the vector bosons

$$\Delta S \approx \frac{-(1-a^2)}{6\pi} \log\left(\frac{m_h}{\Lambda}\right), \qquad \Delta T \approx \frac{3(1-a^2)}{8\pi \cos^2\theta_W} \log\left(\frac{m_h}{\Lambda}\right)$$

$$S = 0.00 \pm 0.10, \qquad T = 0.02 \pm 0.11, \qquad U = 0.03 \pm 0.09\ ,$$



EWPD implies:

$$v^2/f^2 \lesssim 0.1$$

1207.1717 trott et al.

Which is extremely challenging for composite models to accommodate.

Monday, January 20, 14

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1303.3876

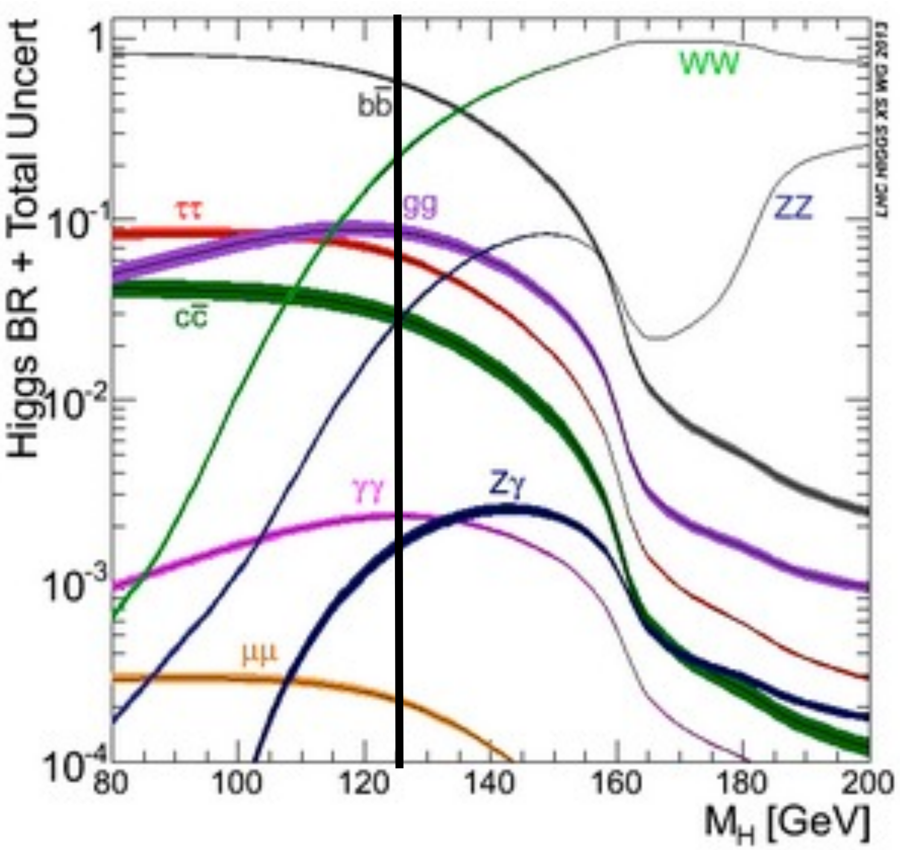
go as $v^2/f^2 \lesssim 0.1$

bad news for compositeness (minus sign even worse)

However, we already knew that these shifts were implied to be small.

We at least have many experimental handles

Precision measurements of the SM Higgs are likely to be a key component in unraveling (a) underlying theory of EWSB. More good news:



Rich spectrum of final states to study couplings structure and search for clues of underlying theory.

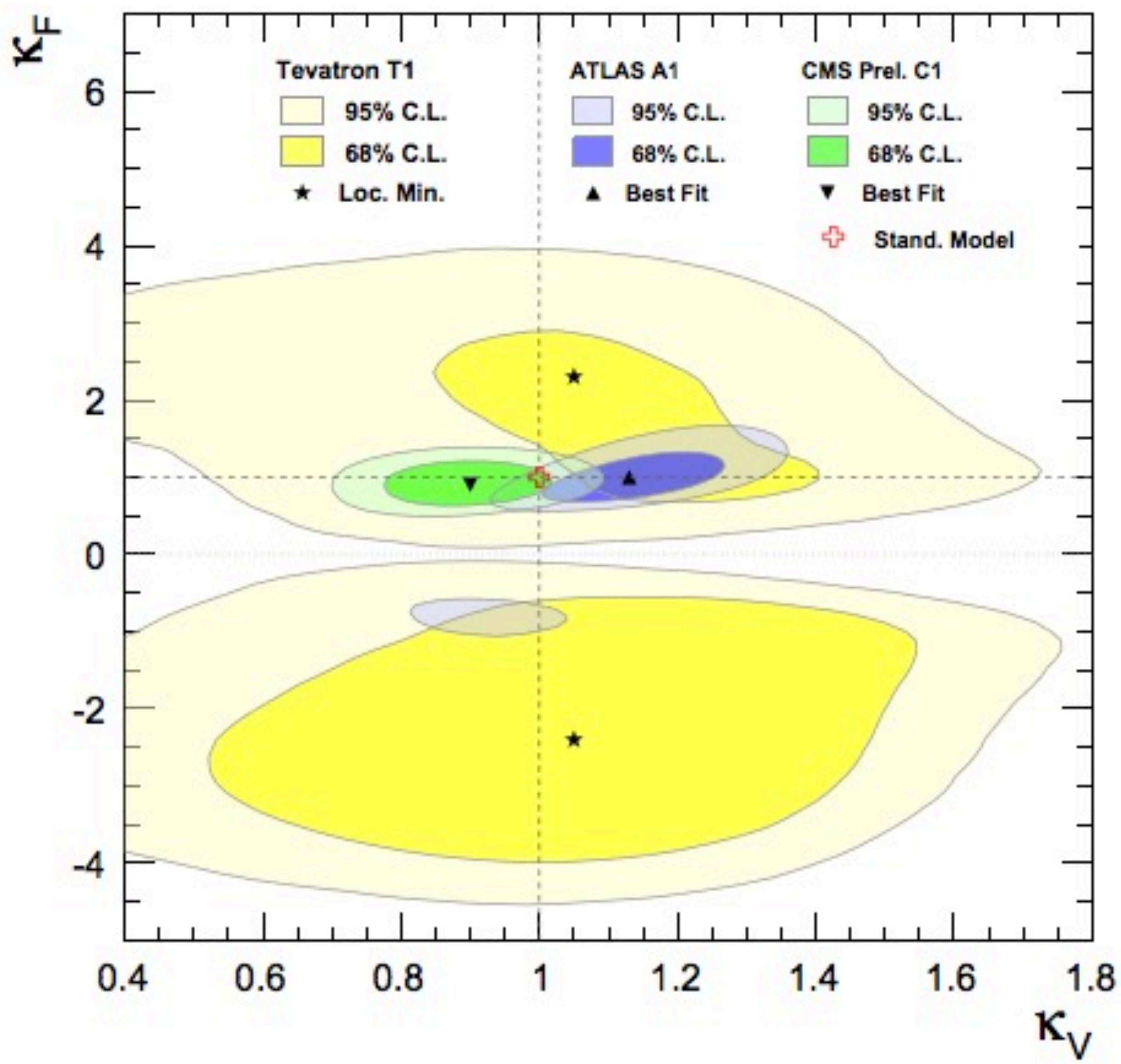
About 200,000 higgs events at 7 teV (trivial $\sigma \int \mathcal{L}\, dt$ *)*

About 900,000 higgs events at 8 teV

A challenge is studying the rich spectrum of production and decay channels at LHC and disentangling possible NP effects from SM uncertainty.

The "Good News": The "Higgs like" Boson

Even now, using symmetry to leverage the data, we can ask specific questions.



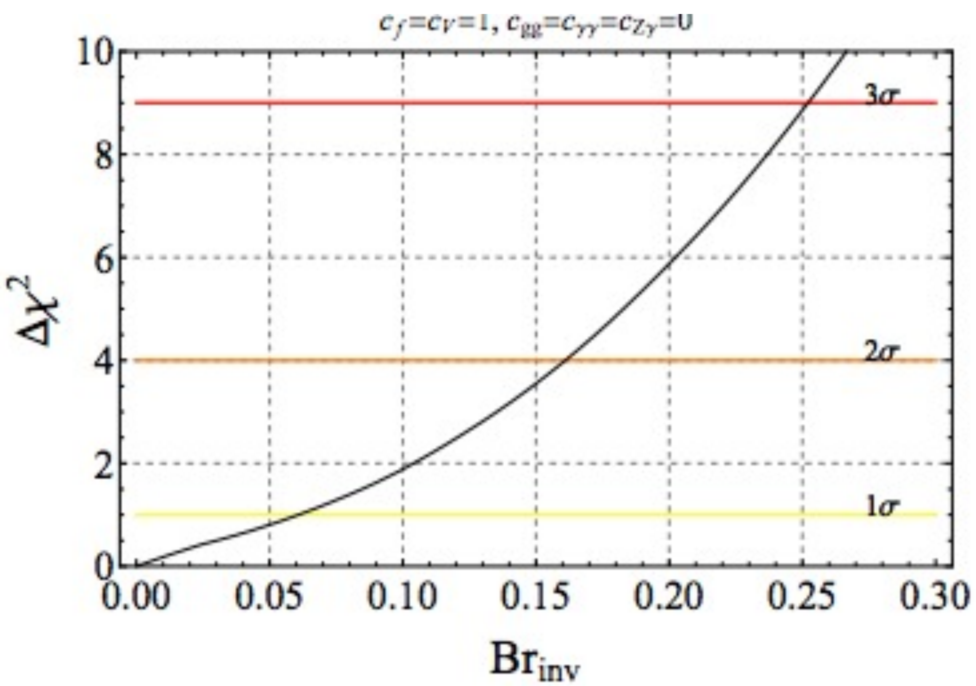
From the PDG: .

Based on: **Carmi,Falkowski,Kuflik,Volansky arXiv:1202.3144**
Azatov,Contino,Galloway arXiv:1202.3415
Espinosa,Grojean,Muhlleitner,Trott arXiv:1202.3697

This is not a most general model independent operator analysis.

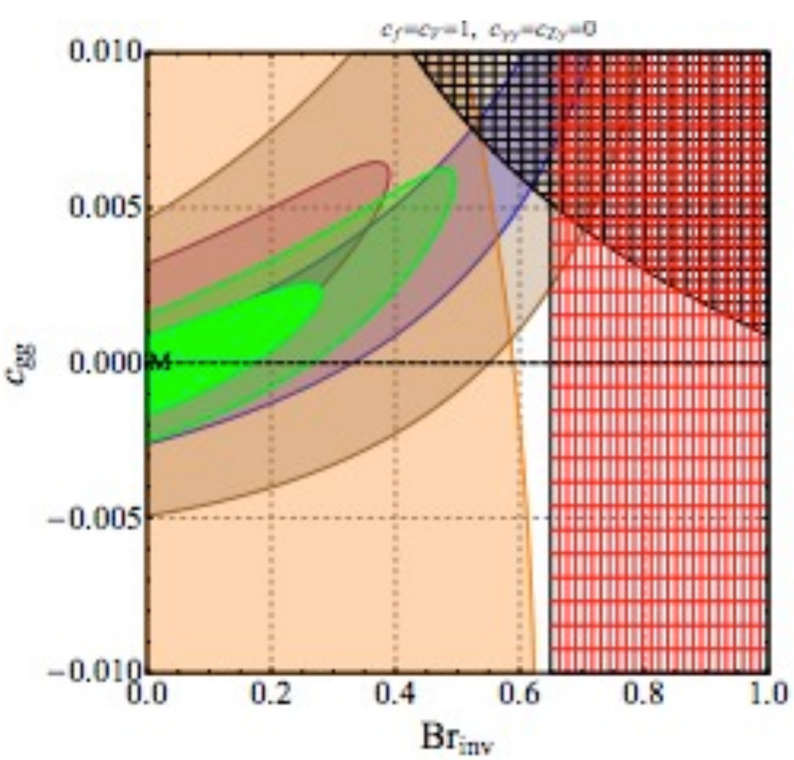
The “Good News”: The “Higgs like” Boson

But, allowing for the current degeneracies significantly reduces the strength of current conclusions.



Fit to just the invisible width in Falkowski 1311.1113 (methodology of arXiv:1205.6790 Espinosa,Mulleitner,Grojean,Trott)

Fit to just the invisible width in Falkowski et al. 1303.1812 with cgg floating.



Similar degeneracy for hbb coupling as both (largely) shift total width.

The "Good News": The "Higgs like" Boson

In the absence of any explicit new states, or overwhelming theory prejudice, the goal is to systematically study the SM EFT for hints of NP, using all possible future facilities to maximize physics conclusions.

It doesn't matter how beautiful your theory is,
it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong.

R.P Feynman

The "Good News": The "Higgs like" Boson

In the absence of any explicit new states, or overwhelming theory prejudice, the goal is to systematically study the SM EFT for hints of NP, using all possible future facilities to maximize physics conclusions.

What is the SM EFT? A linear realization of gauge symmetry and the new state is a 0+ scalar:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}^{(6)},$$

$$\mathcal{L}_{\rm SM} = -\frac{1}{4}G^A_{\mu\nu}G^{A\mu\nu} - \frac{1}{4}W^I_{\mu\nu}W^{I\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + (D_\mu H^\dagger)(D^\mu H) + \sum_{\psi=q,u,d,l,e} \overline{\psi}\, i\not{D}\, \psi$$
$$- \lambda\left(H^\dagger H - \frac{1}{2}v^2\right)^2 - \left[H^{\dagger j}\overline{d}\, Y_d\, q_j + \widetilde{H}^{\dagger j}\overline{u}\, Y_u\, q_j + H^{\dagger j}\overline{e}\, Y_e\, l_j + \text{h.c.}\right]$$

$\mathcal{L}^{(6)} = \sum_i C_i\, Q_i$. where their are 59 operators (or 2499 parameters) to experimentally constrain. Lots to do!

Specifics of the linear SM EFT.

Initial work in the 80's: Leung, Love, Rao in 1984, 1986: Buchmuller and Wyler

1008.4884 Grzadkowski, Iskrzynski, Misiak,Rosiek
operator basis FULLY reduced by SM EOM.

over 20 years?!
700 citations?
...for shame...

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC}\widetilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar l_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\,\widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\,\widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\,\widetilde B_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar q_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\,\widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

6 dual operators

28 non dual operators

25 four fermi ops

59 operators

Specifics of the linear SM EFT.

Four fermion operators: 1008.4884 This seems fearsome. Lets add to the fear.

$8:(\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$

$8:(\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}R)(\bar{R}L)+\text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8:(\bar{L}R)(\bar{L}R)+\text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$

for ng generations the total number of dim 6 CP even + CP odd parameters is

$$\left[107n_g^4+2n_g^3+135n_g^2+60\right]/4$$

Specifics of the linear SM EFT.

Four fermion operators with leptons and quark fields:

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$8:(\bar{R}R)(\bar{R}R)$	
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Number of 4 fermion parameters with lepton-quark: $13\,n_g^4$ *or* 1053 *of* 2499

Specifics of the linear SM EFT.

Four fermion operators with leptons and quark fields are directly induced in some models (by lepto-quarks for example).

Also, if you have a rich NP sector, and describe it in the minimal EFT basis, effects are shuffled around. The EOM

Gauge field EOM: $[D^\alpha, G_{\alpha\beta}]^A = g_3 j^A_\beta, \qquad [D^\alpha, W_{\alpha\beta}]^I = g_2 j^I_\beta, \qquad D^\alpha B_{\alpha\beta} = g_1 j_\beta,$

$$j^A_\beta = \sum_{\psi=u,d,q} \overline{\psi}\, T^A \gamma_\beta \psi\,,$$

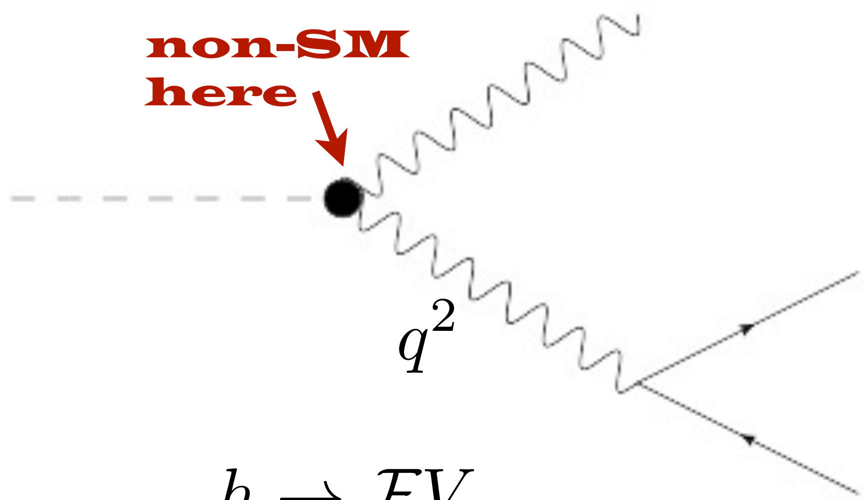
$$j^I_\beta = \frac{1}{2}\overline{q}\,\tau^I \gamma_\beta q + \frac{1}{2}\overline{l}\,\tau^I \gamma_\beta l + \frac{1}{2} H^\dagger\, i \overleftrightarrow{D}^I_\beta H\,,$$

$$j_\beta = \sum_{\psi=u,d,q,e,l} \overline{\psi}\, \mathsf{y}_i \gamma_\beta \psi + \frac{1}{2} H^\dagger\, i \overleftrightarrow{D}_\beta H\,,$$

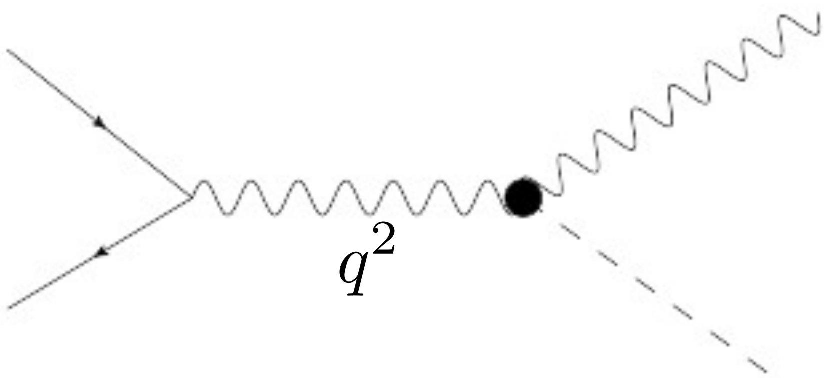
Footprint of gauge field modifications in the contact operators, need as much information as possible to unravel any future deviations.

Important future sources of information - DISTRIBUTIONS.

We also need to test the derivative expansion the h is embedded in to sub leading order. Consider the following processes with non-SM interactions involving the "h":



$h \to \mathcal{F} V$



$\mathcal{F} \to h V$

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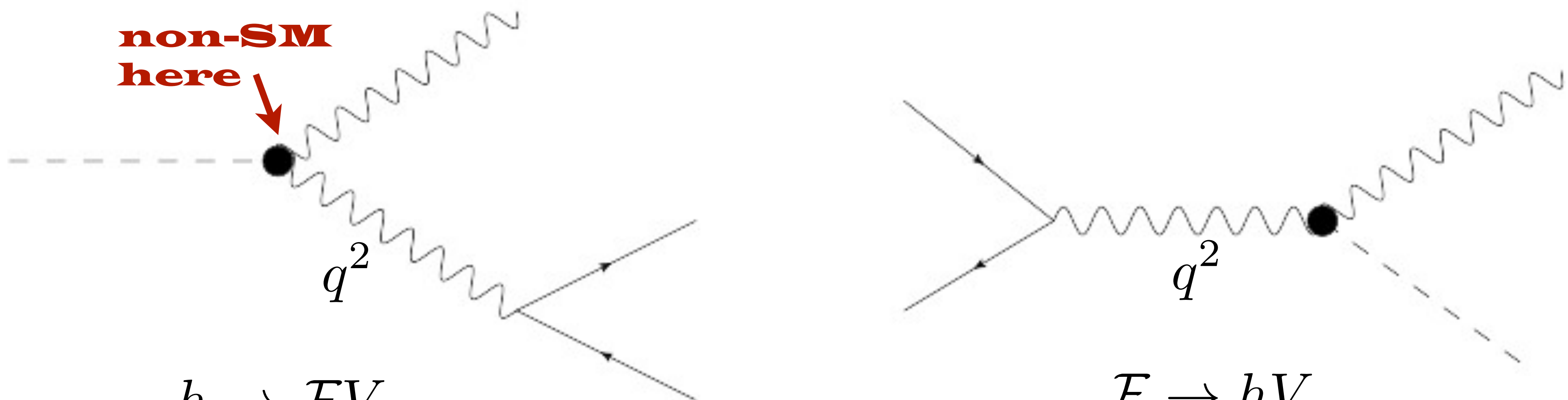
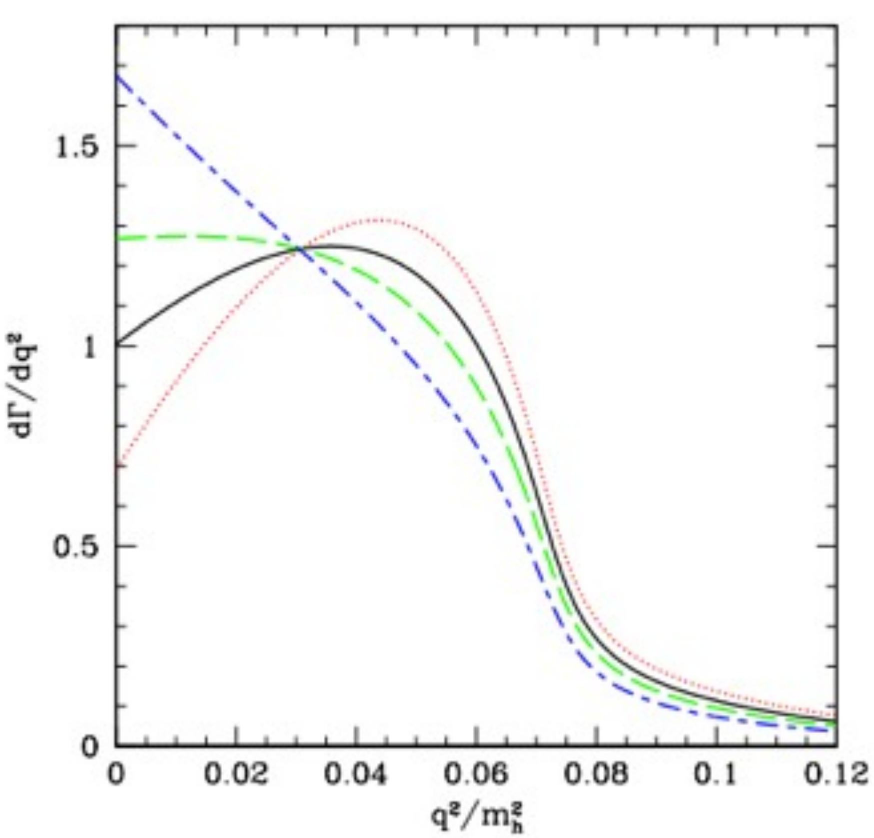


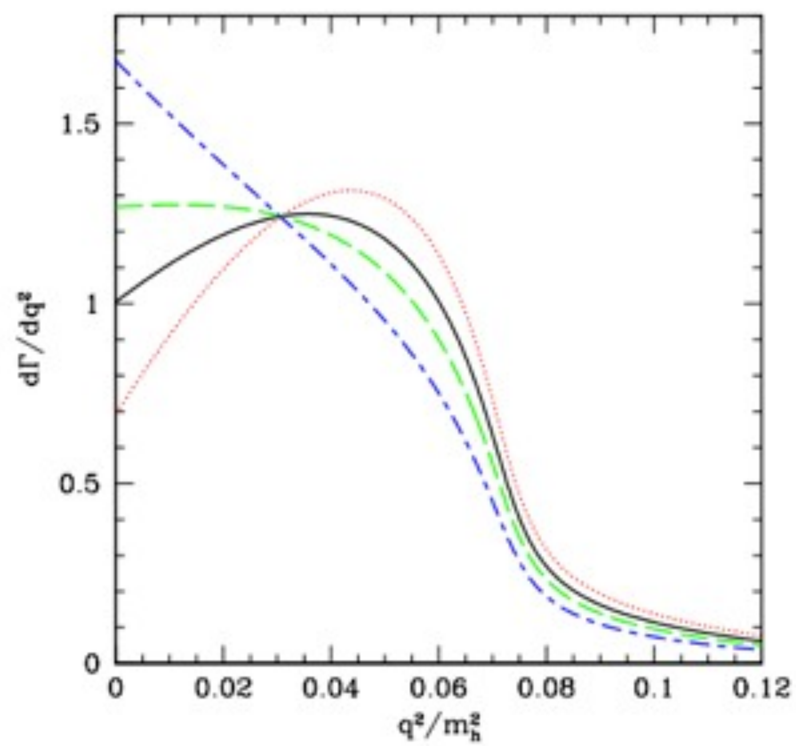
$h \to \mathcal{F} V$ $\mathcal{F} \to h V$



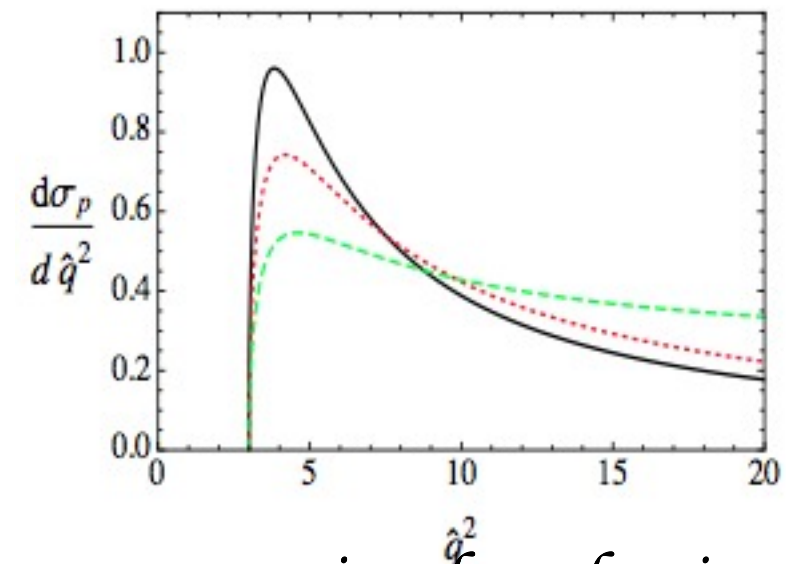
shifted to minimal bi-lepton distribution (V reconstructed)

Total signal strength the same, shape variations possible in q^2 spec. Photon pole neglected here, it is an important modification at low q^2.

Testing the derivative expansion? - use DISTRIBUTIONS.



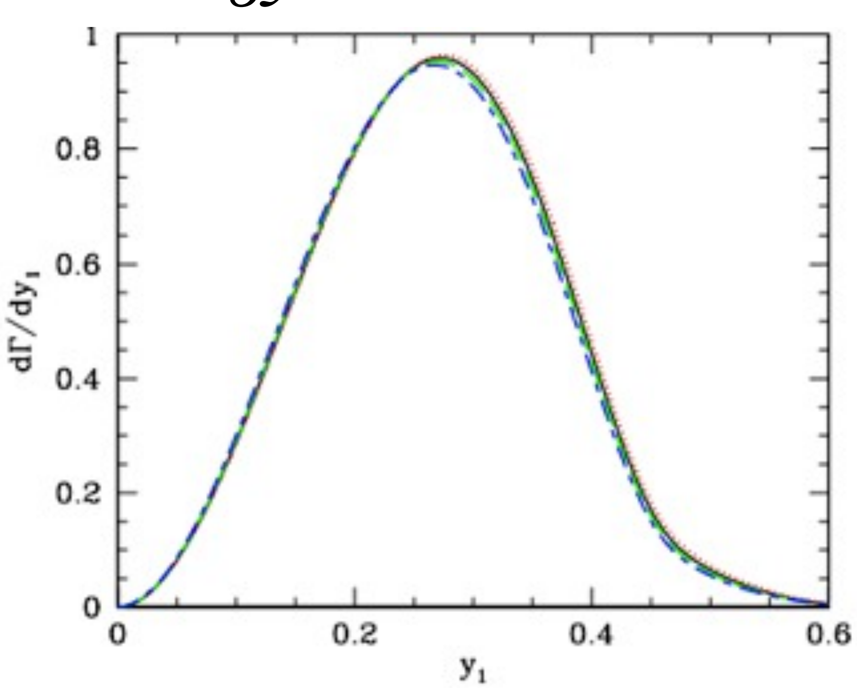
If this deviates more than expected in linear realization, nonlinear smoking gun

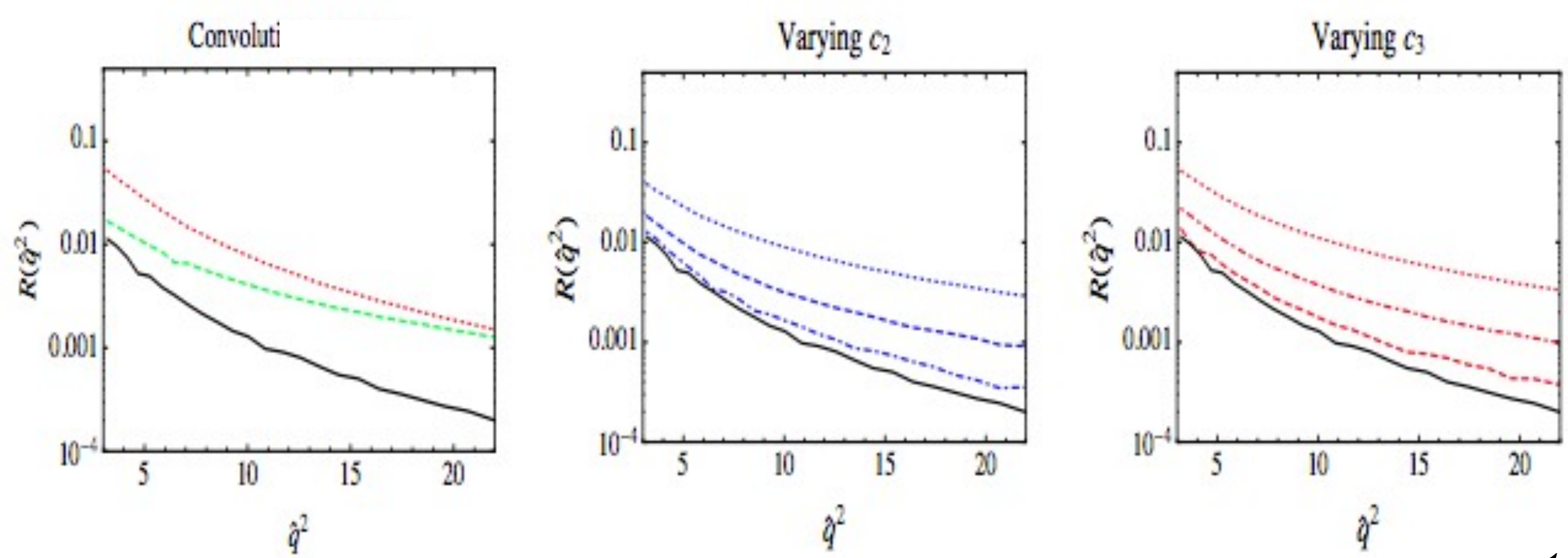


associated production

q^2 bi-lepton and lepton energy distribution

PDF's in associated production reduce discriminatory power - need PDFs as precisely as possible





Summary

- *It makes perfect sense to find a "Higgs like" boson with couplings roughly consistent with the SM values. And an associated high cut off scale.*
- *It makes no sense to find a "Higgs like" boson with couplings that are exactly equal to SM values.*
- *We need to study the couplings of the "Higgs like" boson as precisely as possible in the SM EFT, and all posssible processes in this EFT to uncover any pattern of deviations in the absence of explicit new states.*
- *Lepton quark interactions are an important source of information, 1053 of 2499 parameters characterizing deviations are present in these interactions (not just about lepto-quarks)*
- *In studying the derivative expansion the "Higgs like" boson is embedded in, we will be probing less inclusive signals, the differential distributions. And the deviations should be small! We need the SM errors on PDFs as small as possible to probe for small shape variations.*