The Higgs Boson: A Theory Perspective

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Lecture 2

Higgs Boson Properties

What do we need to know?

To complete the Standard Model we need to verify the Higgs mechanism as the **mechanism of electroweak symmetry breaking** and as the **mechanism for giving fermions mass**.

[Personally I hope that in doing so we will find something new!]

To do this we need:

- To show the Higgs is spin 0 and CP even
- The HVV couplings
- The Hff couplings

} are proportional to their mass

- The Higgs self couplings → the "Mexican hat" 

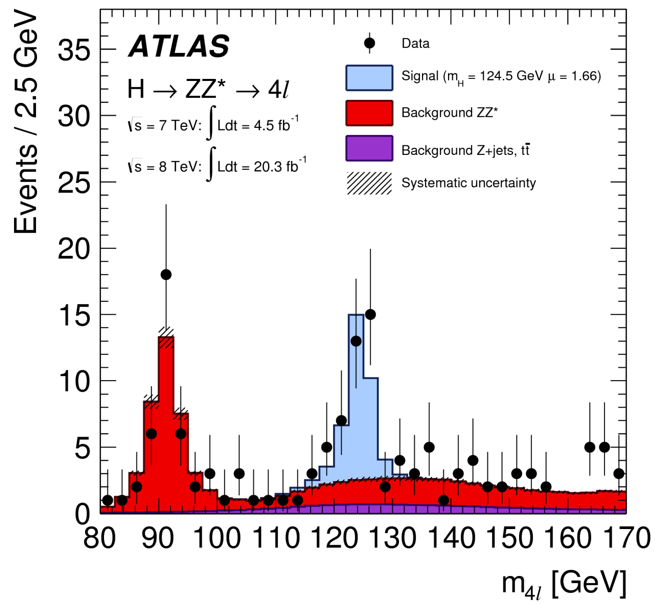
Only once we have all of these can we say that it is the SM Higgs!

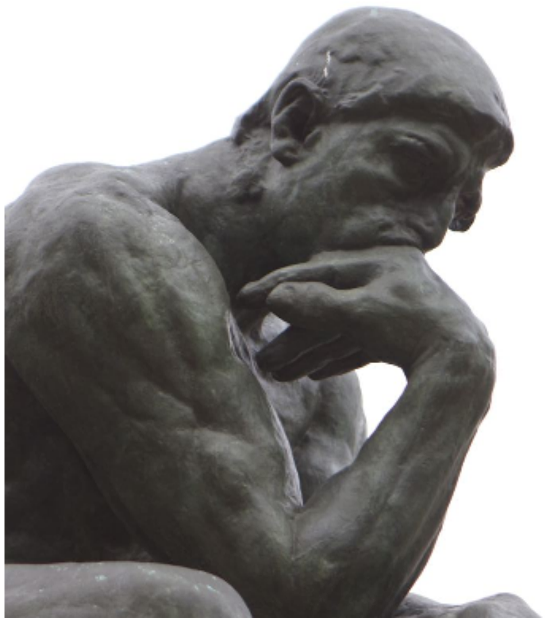
What are we allowed to assume?

We have an underlying **philosophical** dilemma.

How much theory should we assume when "**proving**" the new particle is the Standard Model Higgs boson?

For example, there is **no pseudoscalar-ZZ coupling** at tree-level in the general Two Higgs Doublet model.





Seeing $H \rightarrow ZZ^*$ only tells us that the new resonance contains CP even.

So let's make some **starting assumptions:**

There is **only one** resonance at about 125 GeV.

This resonance is **narrow**, so we can ignore the width.

Usually, deviations from the SM are only considered **separately**, so for example, the resonance will be assumed to be $J^{PC} = 0^{+}$ when examining couplings.

The underlying physics has an explicit SU(2) gauge invariance (i.e. the breaking of SU(2) is entirely dynamical and via the Higgs boson).

Higgs couplings

The Higgs couplings can be probed is several different ways. The two most popular are:

1. Introduce a **scaling factor** κ in each individual Higgs coupling and fit this to the data.

2. Consider all **higher dimensional operators** that can contain a Higgs boson and include these in the analysis with arbitrary coefficients.

Generally speaking option 2 is theoretically preferred but option 1 is easier to implement.

1. Higgs couplings via scaling factors

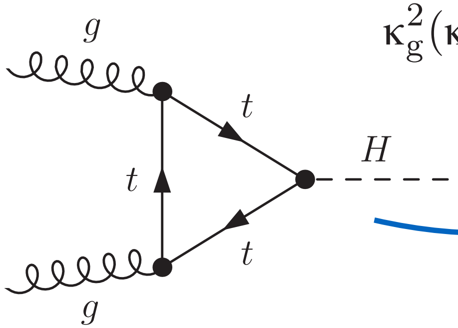
In principle, we need a scaling factor for every coupling. So we need at least:

$$\kappa_W\,,\ \kappa_Z\,,\ \kappa_b\,,\ \kappa_t\,,\ \kappa_\tau \qquad \longleftarrow \qquad \text{e.g. } \kappa_b^2 = \frac{\Gamma_{b\bar{b}}}{\Gamma_{b\bar{b}}^{\mathrm{SM}}}$$

We also have loop induced vertices, so it is also useful to have:

$$\kappa_g\,,\ \kappa_\gamma$$

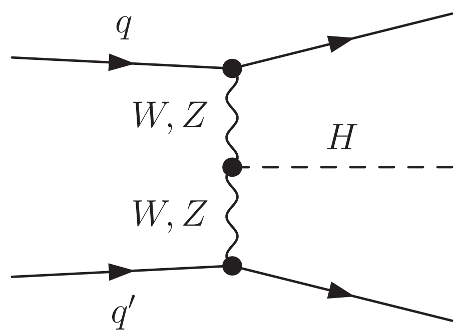
These are of course related to the previous set, e.g.



$$\kappa_g^2(\kappa_b, \kappa_t, m_H) = \frac{\kappa_t^2 \cdot \sigma_{ggH}^{tt}(m_H) + \kappa_b^2 \cdot \sigma_{ggH}^{bb}(m_H) + \kappa_t\kappa_b \cdot \sigma_{ggH}^{tb}(m_H)}{\sigma_{ggH}^{tt}(m_H) + \sigma_{ggH}^{bb}(m_H) + \sigma_{ggH}^{tb}(m_H)}$$

It is also useful to have proxy scale factors for more complicated production processes.

For example,



$$\kappa^2_{\mathrm{VBF}}(\kappa_{\mathrm{W}}, \kappa_{\mathrm{Z}}, m_{\mathrm{H}}) \quad = \quad \frac{\kappa^2_{\mathrm{W}} \cdot \sigma_{\mathrm{W}F}(m_{\mathrm{H}}) + \kappa^2_{\mathrm{Z}} \cdot \sigma_{\mathrm{Z}F}(m_{\mathrm{H}})}{\sigma_{\mathrm{W}F}(m_{\mathrm{H}}) + \sigma_{\mathrm{Z}F}(m_{\mathrm{H}})}$$

$$\left[\kappa^2_{\mathrm{VBF}} = \frac{\sigma_{\mathrm{VBF}}}{\sigma^{\mathrm{SM}}_{\mathrm{VBF}}} \right]$$

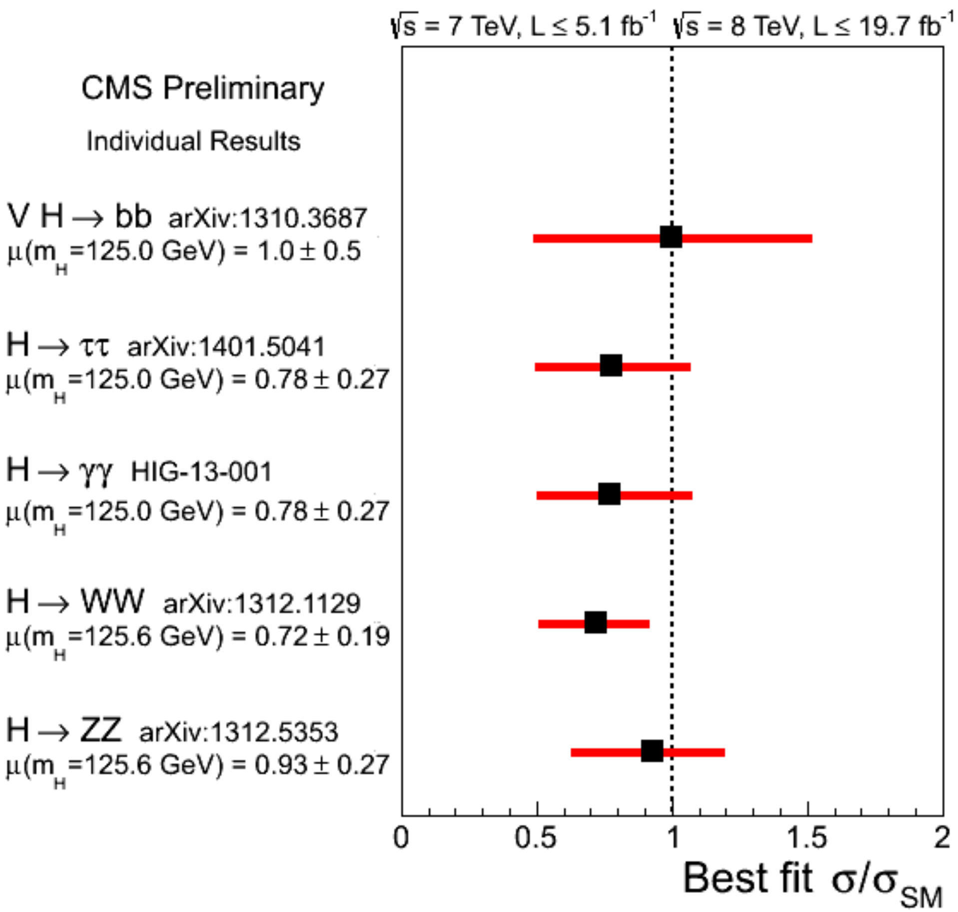
Finally, in order to account for possible invisible decays, one should also have a scale factor for the total width κ_H.

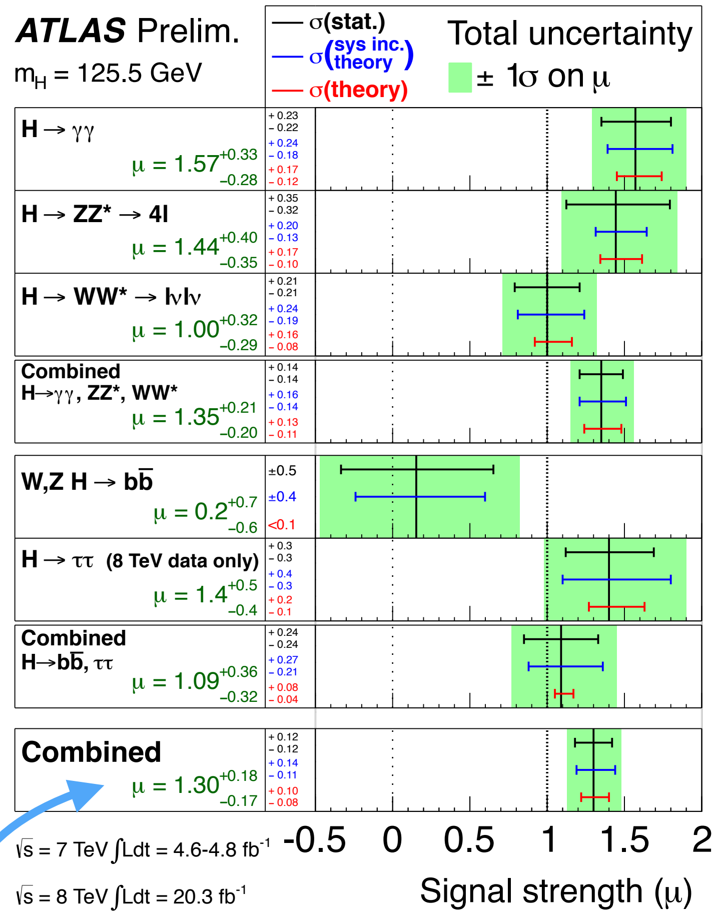
For the Standard Model we must have

$$\kappa_W = \kappa_Z = \kappa_t = \kappa_b = \kappa_\tau = 1$$

Note that checking $\kappa_{\mathrm{VBF}} = \kappa_H = 1$ is also an important check.

[ATLAS-CONF-2014-009]

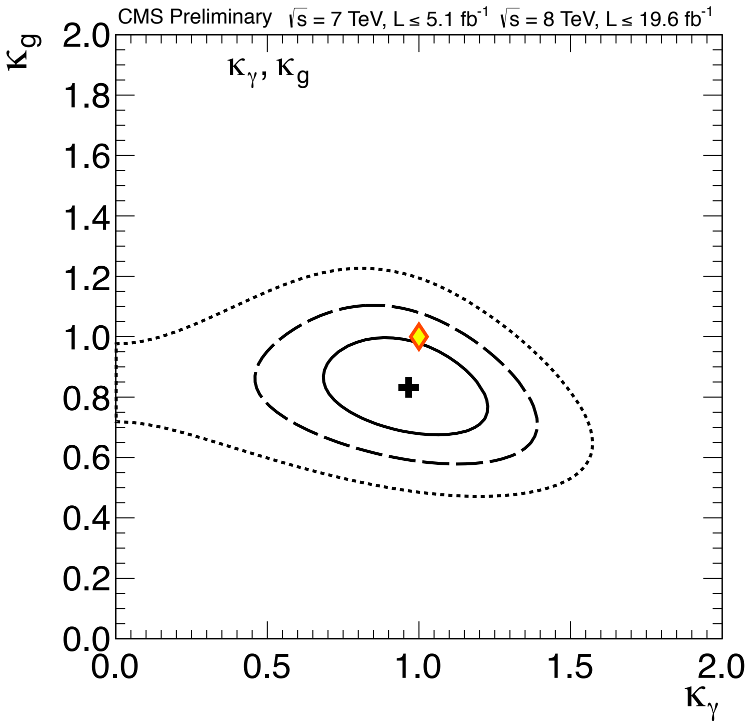


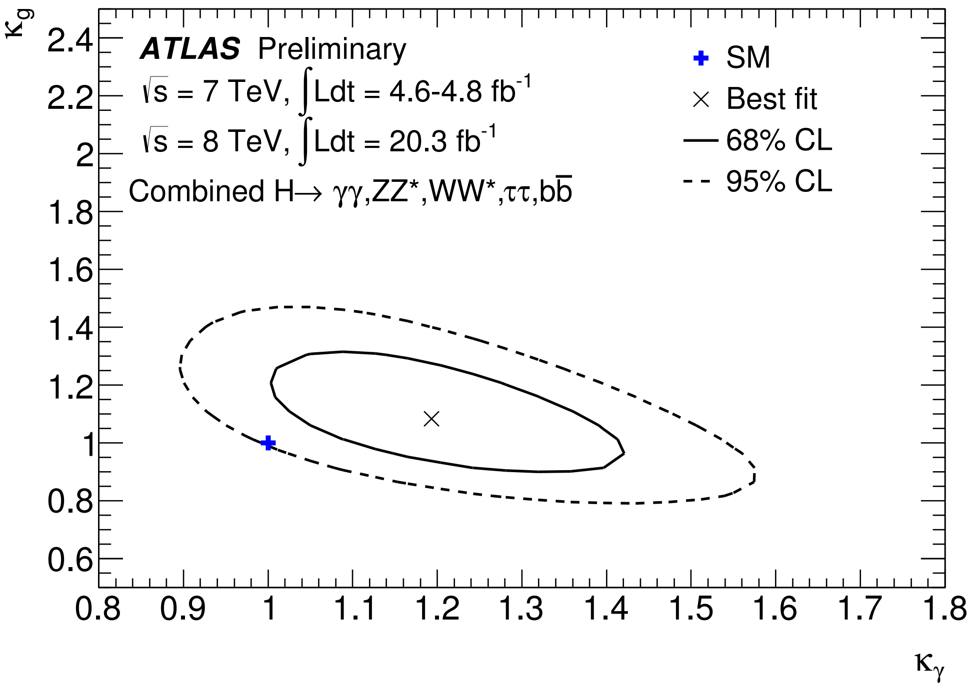


$$\mu = 1.30 \pm 0.12\,(\mathrm{stat})\ {}^{+0.14}_{-0.11}\,(\mathrm{sys})$$

combining all channels

For the loop induced vertices only (keeping the contributing proportions fixed)



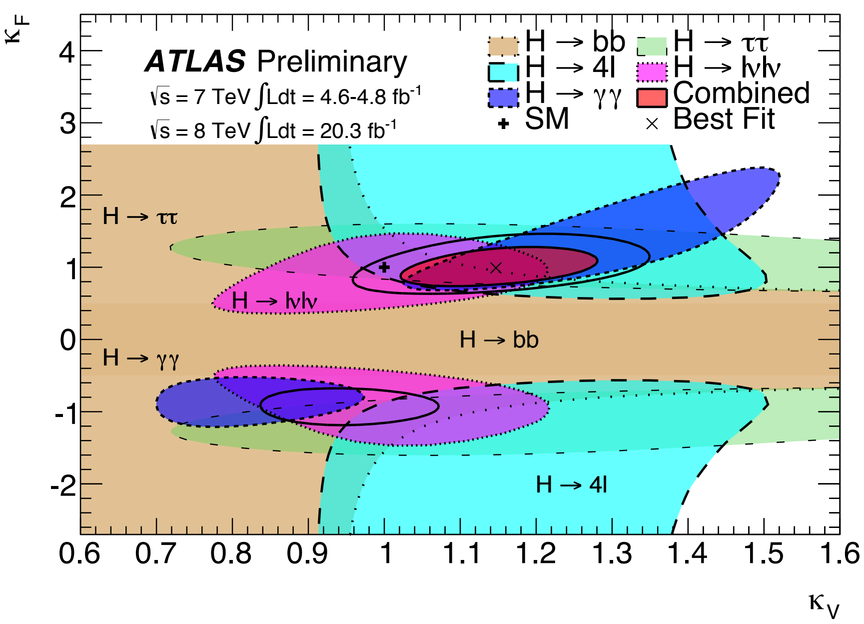


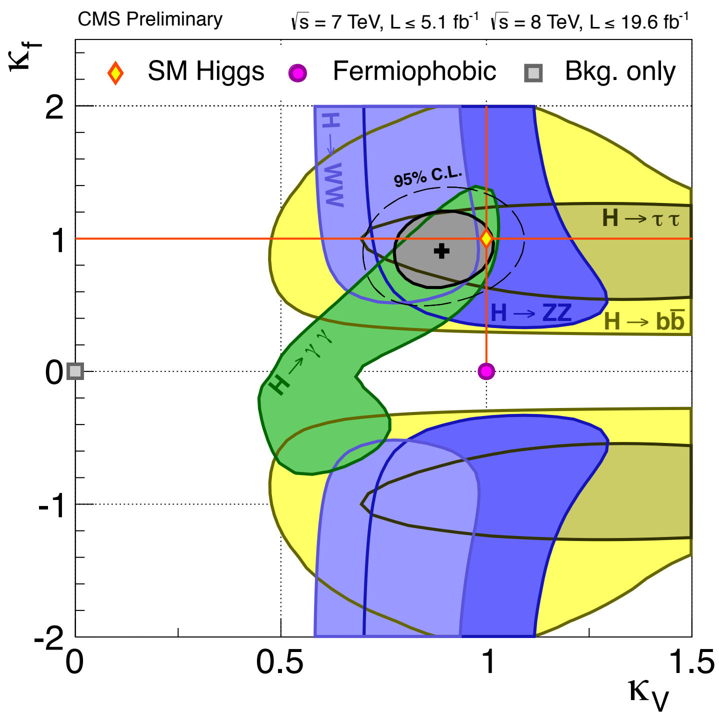
This is all very complicated and multidimensional. We can simplify things by allowing the Higgs couplings to fermions and bosons to vary only as a group.

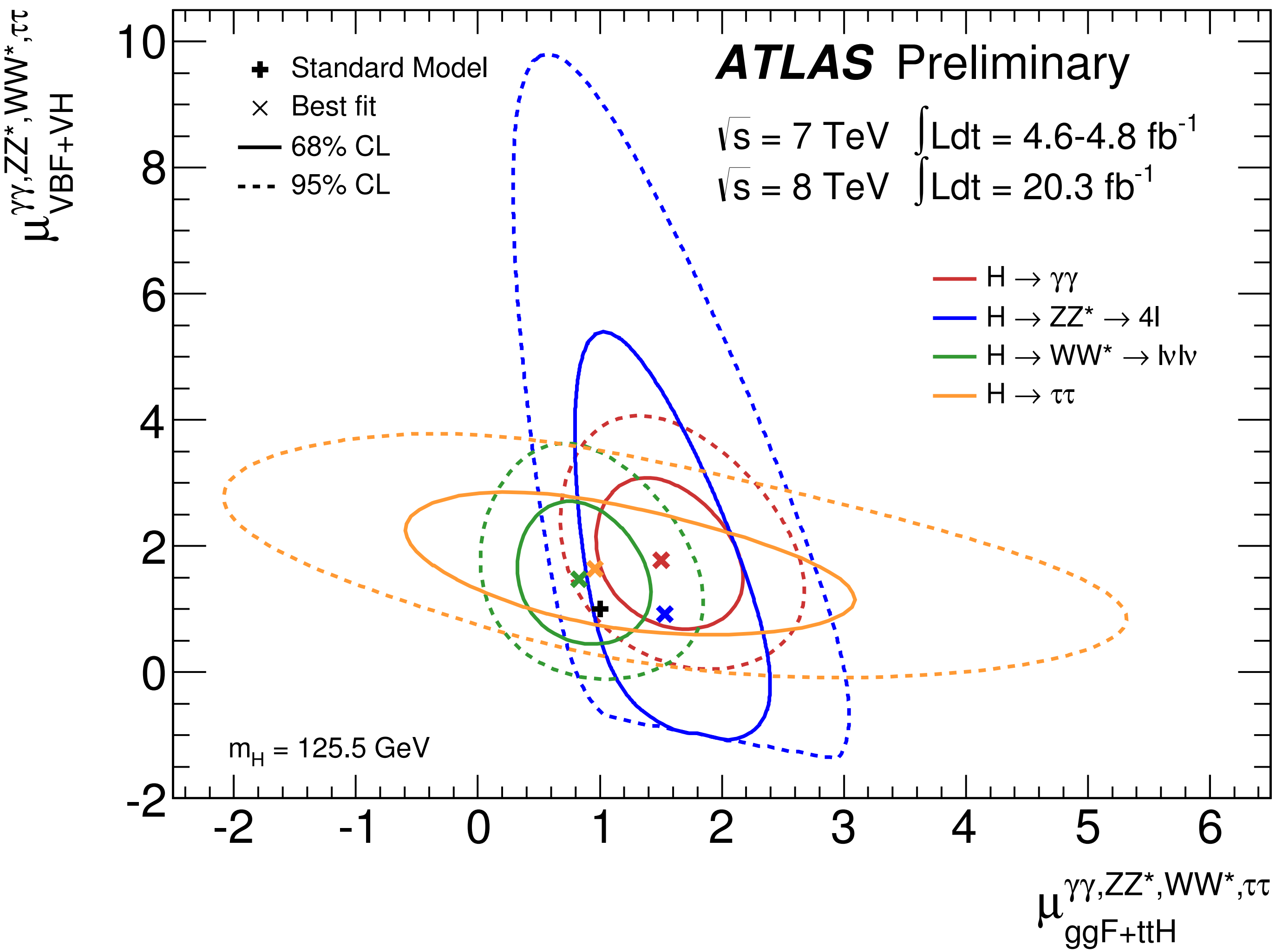
i.e. $\kappa_W = \kappa_Z \equiv \kappa_V$ and $\kappa_t = \kappa_b = \kappa_\tau \equiv \kappa_F$

This is a nice test because we have no a priori knowledge that the fermion masses and gauge boson masses should both originate from the same mechanism.

[CMS-HIG-13-005]



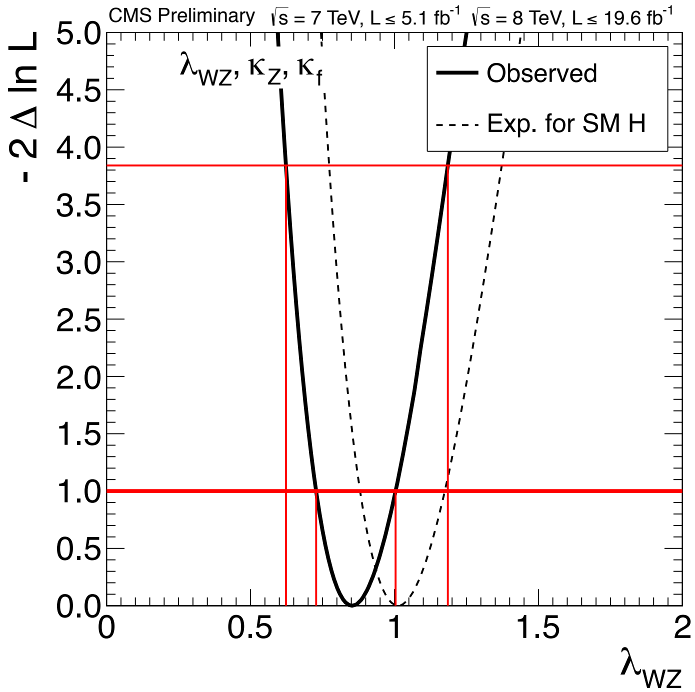


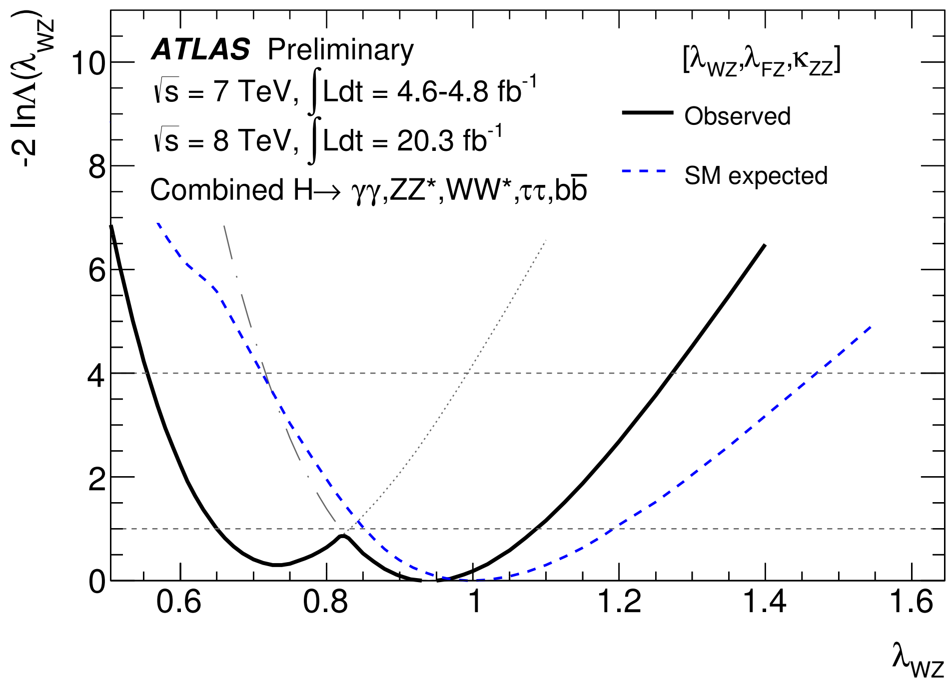


This was made using *Lilith*, Belanger et al, arXiv:122.5244, 1302.5694, 1306.2641

Finally, we can also test **custodial symmetry** by looking at the ratio

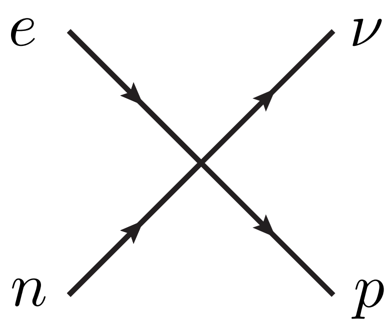
$$\lambda_{WZ} = \frac{\kappa_W}{\kappa_Z}$$





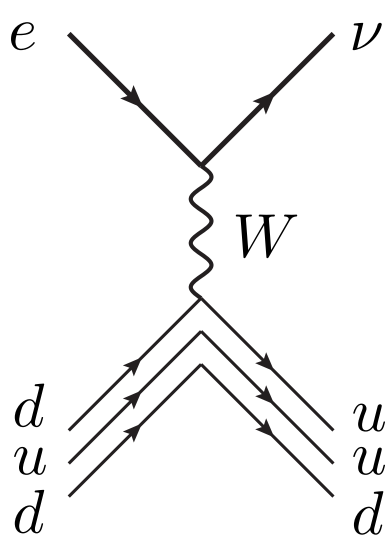
2. Higher dimensional operators

Higher dimension operators have a historical precedent: Fermi's Theory of Beta decay.



Fermi proposed that β-decay was a four fermion interaction:

$$G_F \left(\bar{\psi}_p \gamma^\mu \psi_n\right) \left(\bar{\psi}_\nu \gamma_\mu \psi_e\right)$$



Now we know it is mediated by the W boson:

$$g^2 \left(\bar{\psi}_u \gamma^\mu \psi_d\right) \frac{g_{\mu\nu}}{p^2 - M_W^2} \left(\bar{\psi}_\nu \gamma^\nu \psi_e\right)$$

This interaction returns to Fermi's when $p^2 \ll M_W^2$

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$

In the same way, new physics at the LHC that shows up in processes only involving the SM particles as external states, can be expressed as higher dimensional operators if $p^2 \ll \Lambda^2$.

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}}^{(4)} + \frac{1}{\Lambda^2} \sum_k \alpha_k \mathcal{O}_k$$

[There is a possible dimension 5 term too, which is interesting for neutrinos.]

Contains terms with dimension ≤ 4
e.g. $\mu^2 \Phi^\dagger \Phi$, $\bar{\psi} \gamma_\mu \psi B^\mu$

Dimension 6 terms

All the possible higher dimensional operators using SM fields have been listed in:

Buchmüller, Wyler (1986)

Grzadkowski et al (2010)

Higher dimensional operators [Grzadkowski et al (2010)]

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}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

+ another 25 four-fermion operators (+more if you want $\not{B}$)

Ideally, we should regard the SM + these extra operators as the "real" theory.

e.g. FeynRules

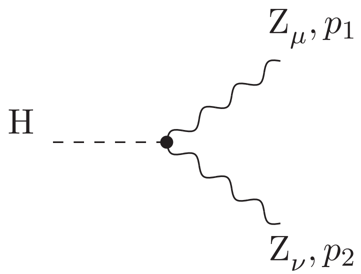
Each operator has an arbitrary **Wilson coefficient**, which should then be fitted to data.

In practice we need to worry about the details:

Best parameterisation? (Not really…)
Interference between operators.
NLO? Backgrounds?
Dimension 8 operators?

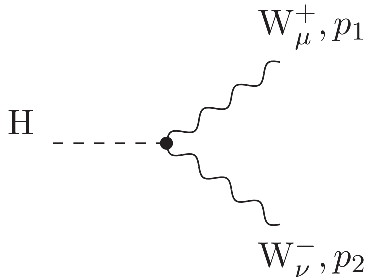
For example (taken from arXiv:1307.1347):

HZZ coupling:



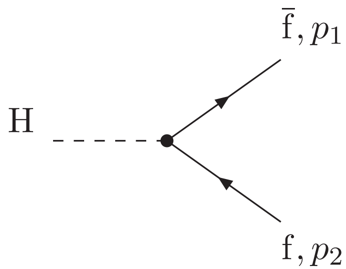
$$= \mathrm{i}g\frac{M_\mathrm{Z}}{c_\mathrm{w}}g_{\mu\nu}\left[1+\frac{1}{\sqrt{2}G_F\Lambda^2}\left(\alpha_{\Phi\mathrm{W}}+\alpha_{\Phi\Box}+\frac{1}{4}\alpha_{\Phi D}\right)\right]$$
$$+\,\mathrm{i}\frac{2g}{M_\mathrm{W}}\frac{1}{\sqrt{2}G_F\Lambda^2}\left[\alpha_{\mathrm{ZZ}}(p_{2\mu}p_{1\nu}-p_1p_2g_{\mu\nu})+\alpha_{\mathrm{Z}\widetilde{\mathrm{Z}}}\varepsilon_{\mu\nu\rho\sigma}p_1^\rho p_2^\sigma\right],$$

HWW coupling:



$$= \mathrm{i}gM_\mathrm{W}g_{\mu\nu}\left[1+\frac{1}{\sqrt{2}G_F\Lambda^2}\left(\alpha_{\Phi\mathrm{W}}+\alpha_{\Phi\Box}-\frac{1}{4}\alpha_{\Phi D}\right)\right]$$
$$+\,\mathrm{i}\frac{2g}{M_\mathrm{W}}\frac{1}{\sqrt{2}G_F\Lambda^2}\left[\alpha_{\Phi\mathrm{W}}(p_{2\mu}p_{1\nu}-p_1p_2g_{\mu\nu})+\alpha_{\Phi\widetilde{\mathrm{W}}}\varepsilon_{\mu\nu\rho\sigma}p_1^\rho p_2^\sigma\right],$$

Hff coupling:



$$= -\mathrm{i}\frac{g}{2}\frac{m_\mathrm{f}}{M_\mathrm{W}}\left[1+\frac{1}{\sqrt{2}G_F\Lambda^2}\left(\alpha_{\Phi\mathrm{W}}+\alpha_{\Phi\Box}-\frac{1}{4}\alpha_{\Phi D}-\alpha_{\mathrm{f}\phi}\right)\right],$$

Some parameterisations are better than others because the operators more directly correspond to measurable observable.

For example, [Contino et al, arXiv:1303.3876]

$$
\begin{aligned}
\Delta\mathcal{L}_{SILH} = {} & \frac{\bar{c}_H}{2v^2}\,\partial^\mu\big(H^\dagger H\big)\,\partial_\mu\big(H^\dagger H\big) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar{c}_6\,\lambda}{v^2}\left(H^\dagger H\right)^3 \\
& + \left(\left(\frac{\bar{c}_u}{v^2}\,y_u\,H^\dagger H\,\bar{q}_L H^c u_R + \frac{\bar{c}_d}{v^2}\,y_d\,H^\dagger H\,\bar{q}_L H d_R + \frac{\bar{c}_l}{v^2}\,y_l\,H^\dagger H\,\bar{L}_L H l_R\right) + h.c.\right) \\
& + \frac{i\bar{c}_W\,g}{2m_W^2}\left(H^\dagger\sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i + \frac{i\bar{c}_B\,g'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu}) \\
& + \frac{i\bar{c}_{HW}\,g}{m_W^2}\,(D^\mu H)^\dagger\sigma^i(D^\nu H)W^i_{\mu\nu} + \frac{i\bar{c}_{HB}\,g'}{m_W^2}\,(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu} \\
& + \frac{\bar{c}_\gamma\,{g'}^2}{m_W^2}\,H^\dagger H B_{\mu\nu}B^{\mu\nu} + \frac{\bar{c}_g\,g_S^2}{m_W^2}\,H^\dagger H G^a_{\mu\nu}G^{a\mu\nu}\,,
\end{aligned}
$$

At the moment, many Wilson coefficients are well constrained by electroweak precision tests.

For example, [Contino et al, arXiv:1303.3876] again

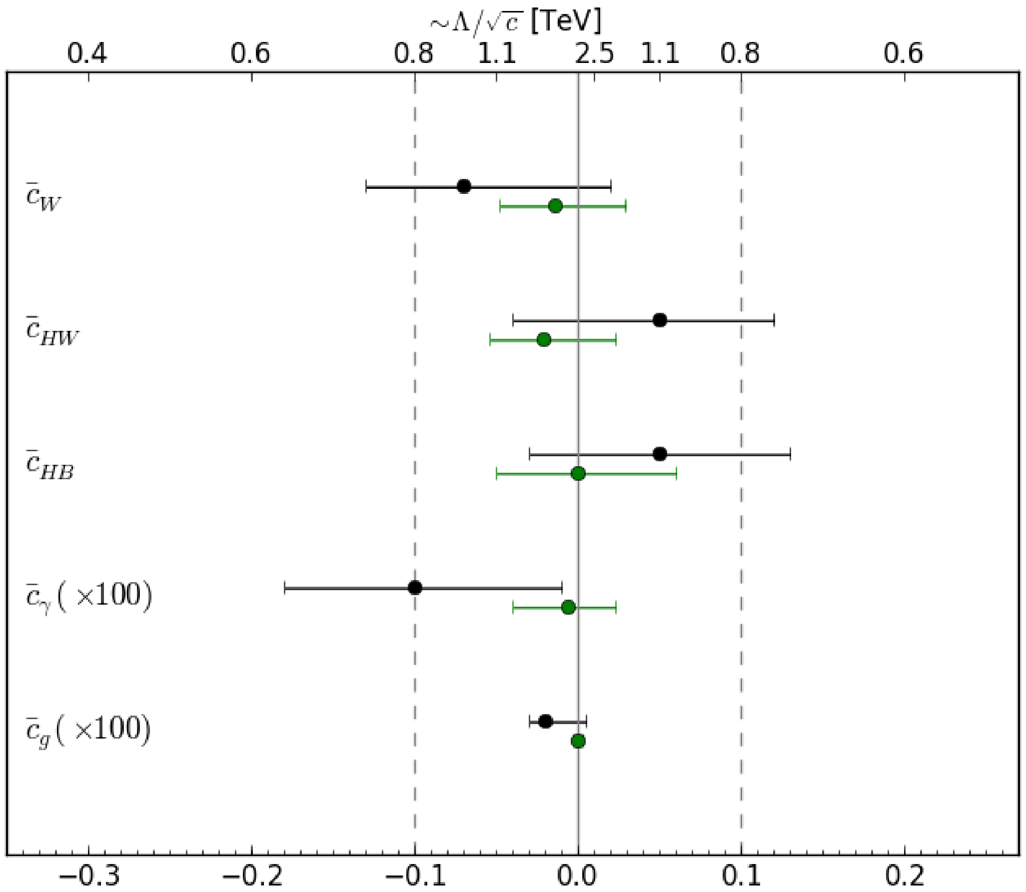
$$\frac{i\bar{c}_W\, g}{2m_W^2}\left(H^\dagger\sigma^i \overleftrightarrow{D}^{\mu} H\right)\left(D^\nu W_{\mu\nu}\right)^i \quad\Longrightarrow\quad \frac{\Gamma(h\to W^{(*)}W^*)}{\Gamma(h\to W^{(*)}W^*)_{SM}} \simeq 1+2.2\,\bar{c}_W$$

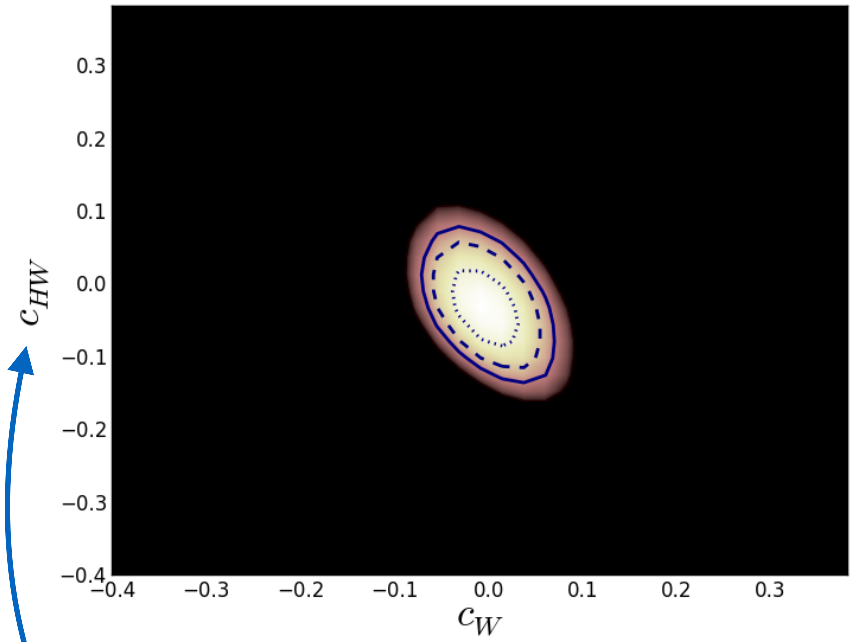
But $\bar{c}_W$ contributes to the S parameter, so

$$-1.4\times 10^{-3} < \bar{c}_W(m_Z)+\bar{c}_B(m_Z) < 1.9\times 10^{-3}$$

…although we should of course still check it!

Ellis, Sanz, You, arXiv: 1404.3667





$$\frac{2ig\ \bar{c}_{HW}}{m_W^2}\left[D^\mu\Phi^\dagger T_{2k} D^\nu \Phi\right] W_{\mu\nu}^k$$

See also: Elias-Miró et al, arXiv:1308.1879; Pomerol and Riva, arXiv:1308.2803

Higgs boson spin and CP

The Standard Model Higgs boson is peculiar because it is the only fundamental scalar in the model.

We need to test: $J^{PC} = 0^{+}$

Spin: Spin 0 — At the moment we can't really "measure" the spin of the Higgs - we can only rule out other hypotheses.

Spin 2 — KK graviton?

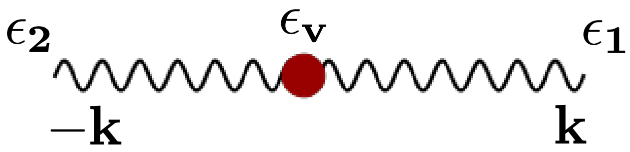
Spin 1 — Ruled out by the Landau-Yang Theorem, but we should still check spin 1 anyway!

CP: Even once we "know" it is spin 0, is it a **scalar or a pseudoscalar**?

Spin 1: The Landau-Yang Theorem

The discovery channel $H \to \gamma\gamma$ already tells us the the Higgs is **not** spin 1.

Imaging a vector decaying to two photons:



There are 3 possible vertex structures:

$$\epsilon_{\mathbf{1}} \times \epsilon_{\mathbf{2}} \cdot \epsilon_{\mathbf{v}} \; F_1(k^2)$$

$$\epsilon_{\mathbf{1}} \times \epsilon_{\mathbf{2}} \cdot \mathbf{k} \; \epsilon_{\mathbf{v}} \cdot \mathbf{k} \; F_2(k^2)$$

$$\epsilon_{\mathbf{1}} \cdot \epsilon_{\mathbf{2}} \; \epsilon_{\mathbf{v}} \cdot \mathbf{k} \; F_3(k^2)$$

But **Bose** tells us that $\mathcal{M}(\epsilon_{\mathbf{1}}, \epsilon_{\mathbf{2}}, \mathbf{k}) = \mathcal{M}(\epsilon_{\mathbf{2}}, \epsilon_{\mathbf{1}}, -\mathbf{k})$ so all these terms must be zero!

Methodology

As with the cross-sections, there are two ways of testing the other hypotheses.

Anomalous couplings

$$i g_W M_W \left[g^{\mu\nu} + \frac{4c_1}{\Lambda_1^2} \left(p^\mu q^\nu - g^{\mu\nu} p \cdot q \right) + \frac{8c_2}{\Lambda_2^2} \epsilon^{\mu\nu\rho\sigma} p_\rho q_\sigma \right]$$

HWW vertex

$\longleftrightarrow$

Higher dimensional operators

$$g_W^2 \frac{c_1}{2\Lambda_1^2} \Phi^\dagger \Phi W_{\mu\nu} W^{\mu\nu}$$

$$g_W^2 \frac{c_1}{2\Lambda_2^2} \Phi^\dagger \Phi \tilde{W}_{\mu\nu} W^{\mu\nu}$$

Beware: If one uses anomalous couplings without linking them to higher dimensional operators then we cannot be certain that the coefficients (here c_1 and c_2) are constant.

Spin 2

Could the new resonance be spin 2?

This is difficult to test because we have no real model for a spin 2 boson. a graviton would be massless, so it could not be that.

So far, ATLAS and CMS have only tested **"graviton-like"** hypotheses.

They use $H \to \gamma\gamma$, $H \to WW^*$ and $H \to ZZ^*$ simulating a $J^{PC}=2^+$ state using JHUGen [Gao et al (2010)]

[Gao et al (2010)]

$$A(X \to VV) = \Lambda^{-1}\Big[2g_1^{(2)} t_{\mu\nu} f^{*1,\mu\alpha} f^{*2,\nu\alpha} + 2g_2^{(2)} t_{\mu\nu}\frac{q_\alpha q_\beta}{\Lambda^2} f^{*1,\mu\alpha} f^{*2,\nu,\beta}$$
$$+g_3^{(2)}\frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu}(f^{*1,\mu\nu} f^{*2}_{\mu\alpha} + f^{*2,\mu\nu} f^{*1}_{\mu\alpha}) + g_4^{(2)}\frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} f^{*(2)}_{\alpha\beta}$$
$$+m_V^2\left(2g_5^{(2)} t_{\mu\nu}\epsilon_1^{*\mu}\epsilon_2^{*\nu} + 2g_6^{(2)}\frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu}\left(\epsilon_1^{*\nu}\epsilon_2^{*\alpha} - \epsilon_1^{*\alpha}\epsilon_2^{*\nu}\right) + g_7^{(2)}\frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu}\epsilon_1^*\epsilon_2^*\right)$$
$$+g_8^{(2)}\frac{\tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta}\tilde{f}^{*(2)}_{\alpha\beta} + g_9^{(2)} t_{\mu\alpha}\tilde{q}^\alpha \epsilon_{\mu\nu\rho\sigma}\epsilon_1^{*\nu}\epsilon_2^{*\rho} q^\sigma + \frac{g_{10}^{(2)} t_{\mu\alpha}\tilde{q}^\alpha}{\Lambda^2}\epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma\left(\epsilon_1^{*\nu}(q\epsilon_2^*) + \epsilon_2^{*\nu}(q\epsilon_1^*)\right)\Big]$$

$$f^{(i),\mu\nu} = \epsilon_i^\mu q_i^\nu - \epsilon_i^\nu q_i^\mu$$

$$1/2\ \epsilon_{\mu\nu\alpha\beta} f^{(i),\alpha\beta} = \epsilon_{\mu\nu\alpha\beta}\epsilon_i^\alpha q_i^\beta$$

$$\tilde{q} = q_1 - q_2$$

$$t_{\mu\nu} q^\nu = 0$$

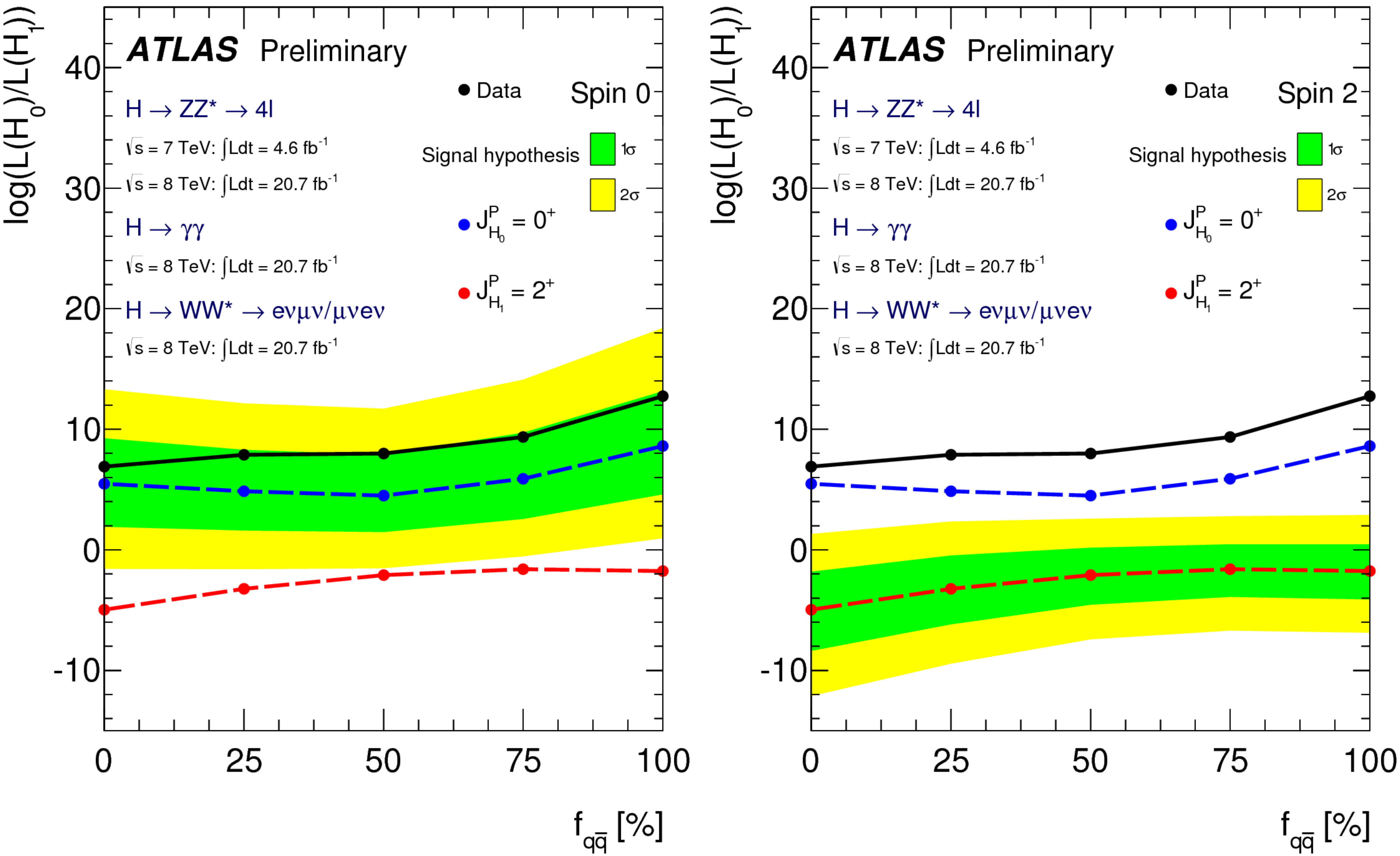
symmetric, traceless

"**Graviton-like**" means taking

$$g_1^{(2)} = g_5^{(2)} = 1$$

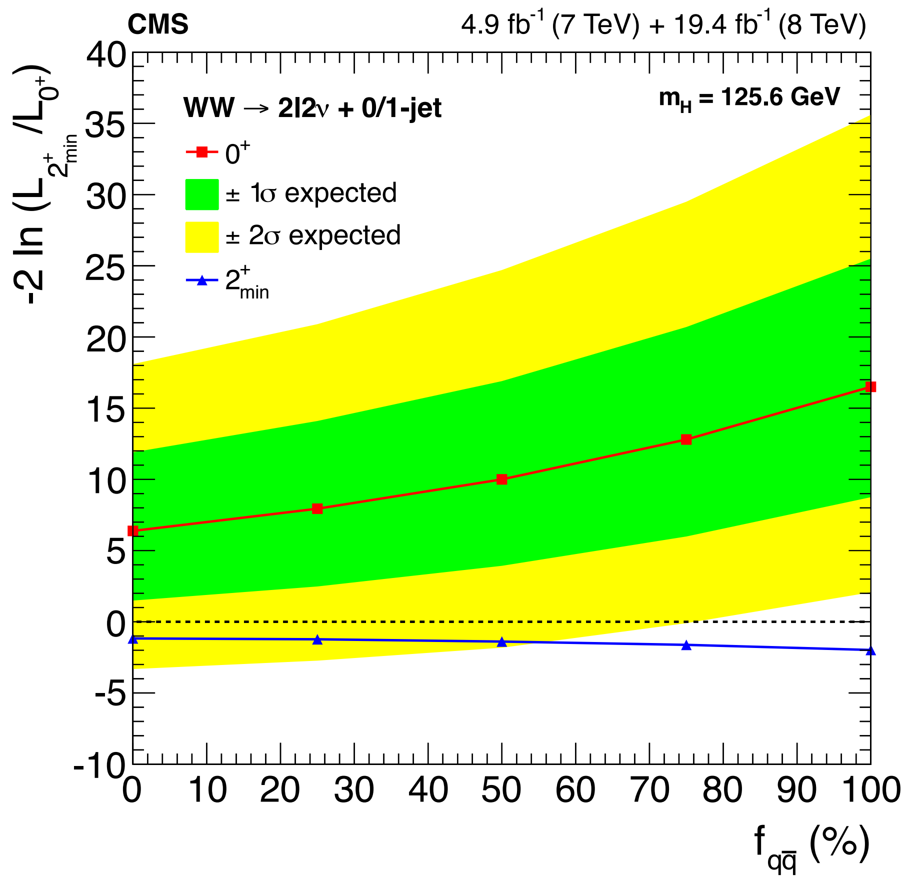
and setting the other couplings to zero.

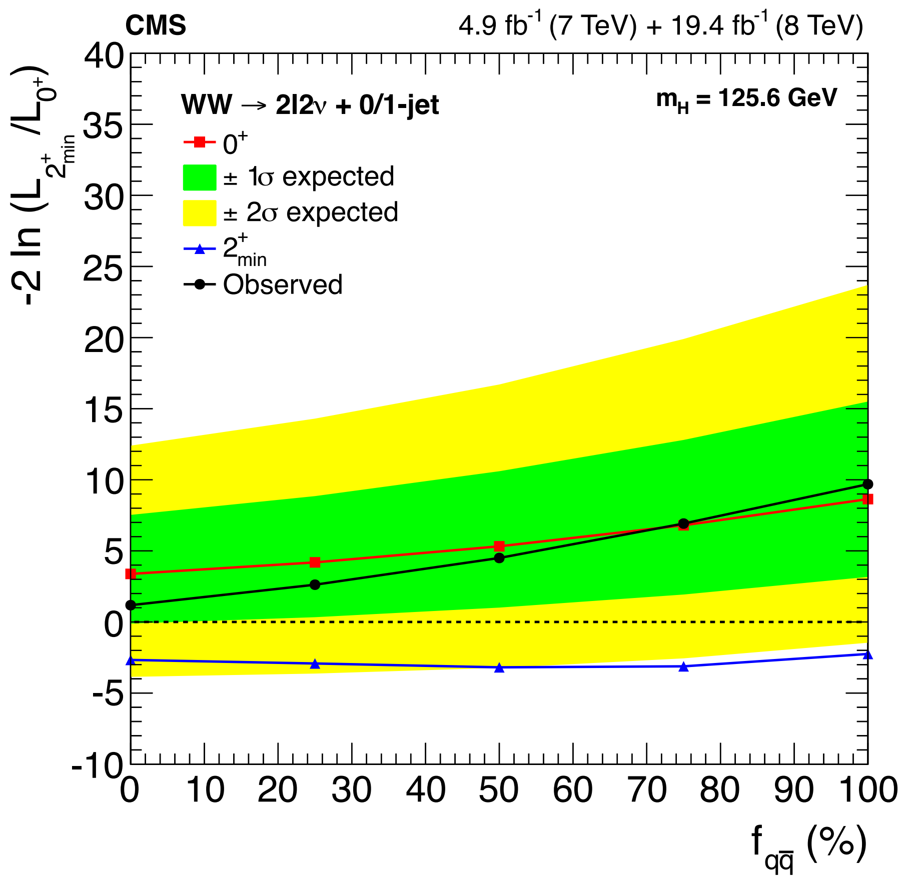
$H \to ZZ$



(Boosted Decision Trees)

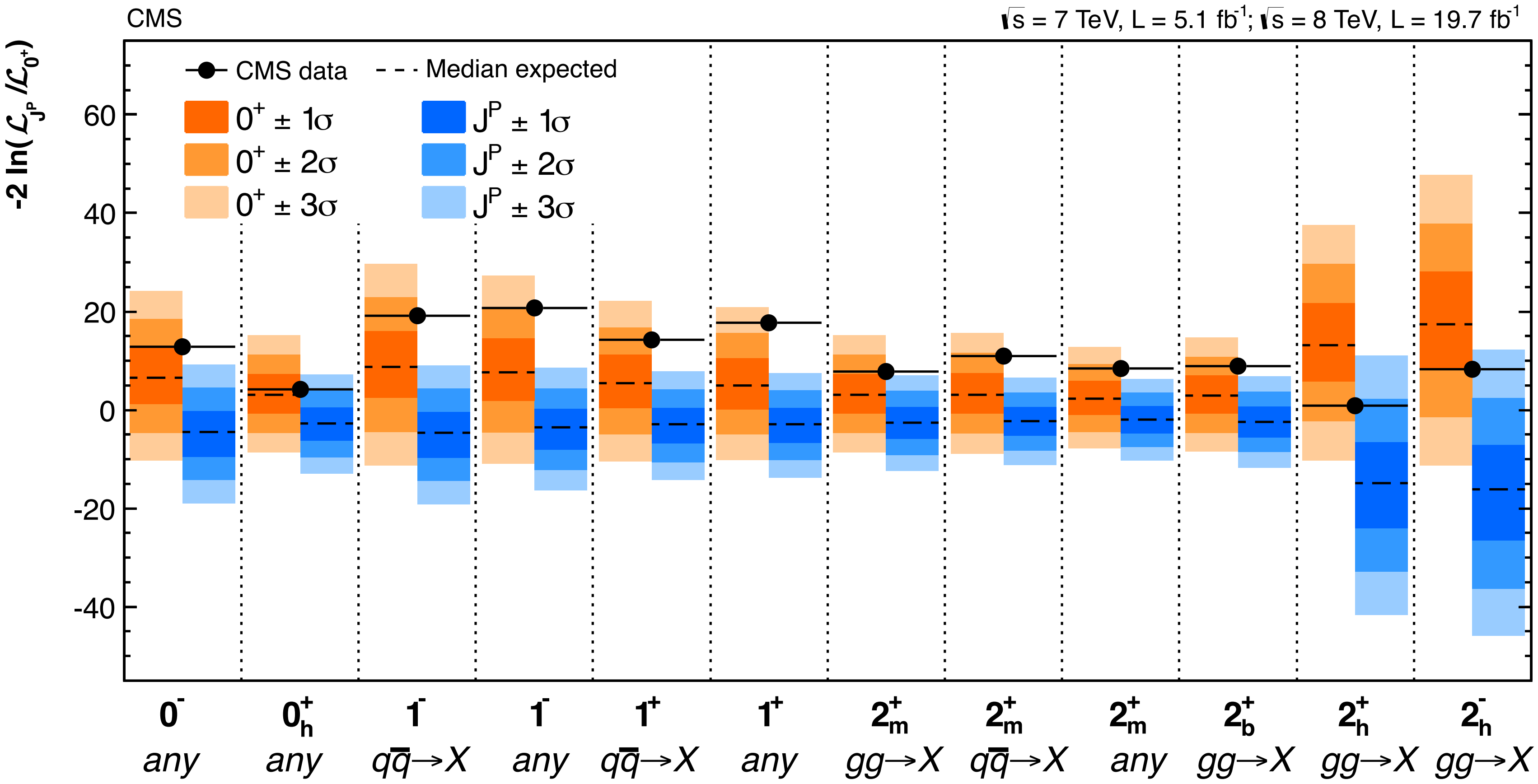
$H \to WW$





$$\sigma/\sigma_{\rm SM} = 1$$

CMS-HIG-13-002 $H \to ZZ$



Spin 2 and higher

An alternative formulation of the 2^+ tensor structure is:

$$c_1\,(g^{\mu\beta_1} g^{\nu\beta_2} + g^{\mu\beta_2} g^{\nu\beta_1})$$

“graviton-like”

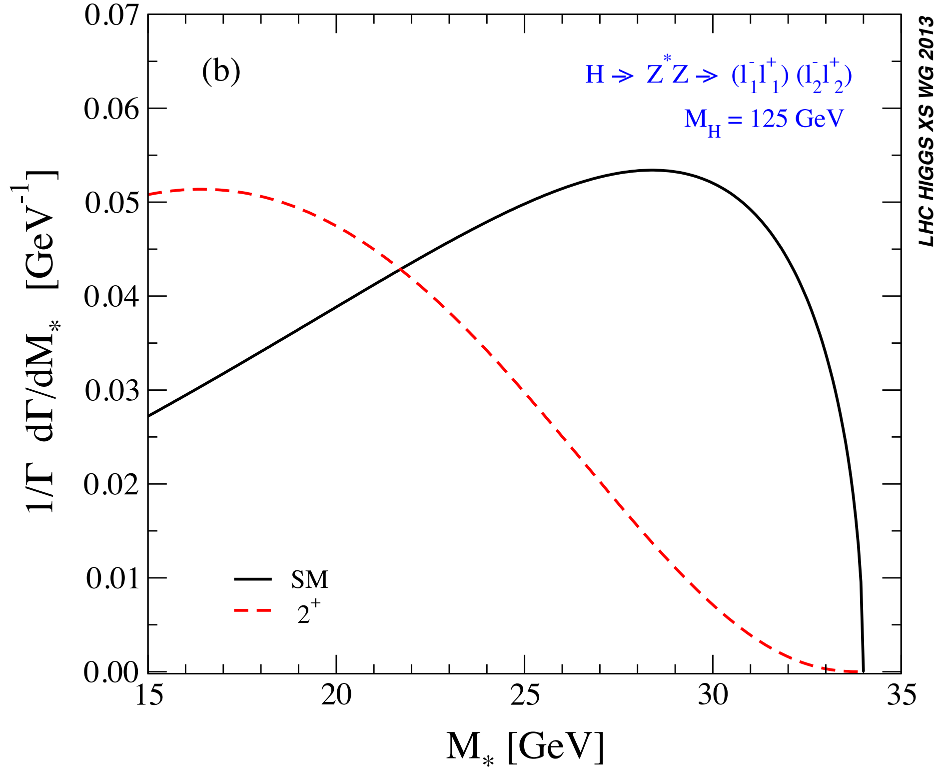
$$+c_2\, g^{\mu\nu}\, k^{\beta_1} k^{\beta_2}$$

$$+c_3\,[(g^{\mu\beta_1}\, p^{\nu} - g^{\nu\beta_1}\, p^{\mu}) k^{\beta_2}$$

$$+(\beta_1 \leftrightarrow \beta_2)]$$

$$+c_4\, p^{\mu} p^{\nu} k^{\beta_1} k^{\beta_2}$$

All the other terms contain extra momenta so will have a slower threshold rise.



This is also true for all terms when J>2…
and for a pseudoscalar…

[Choi et al (2003)]

Spin 0 and CP

Once we are sure that the Higgs is spin 0, we have to ask what is its CP?

For HVV there are really only two extra (non-SM, dim 6) operators.

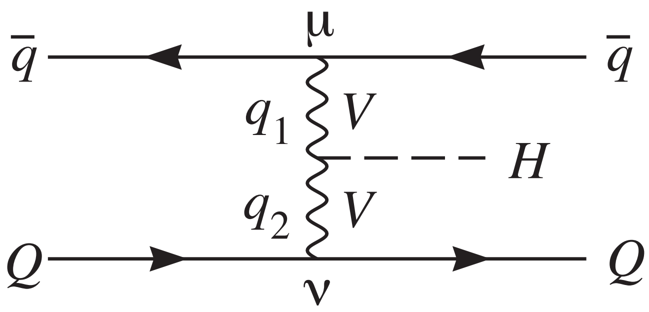
$$g_W^2 \frac{c_1}{2\Lambda_1^2} \Phi^\dagger \Phi W_{\mu\nu} W^{\mu\nu} \qquad g_W^2 \frac{c_1}{2\Lambda_2^2} \Phi^\dagger \Phi \tilde{W}_{\mu\nu} W^{\mu\nu}$$

CP even CP odd

In principle, the Higgs could be a combination of all 3 and be CP violating, but so far we have only tested these individually (i.e. assuming CP conservation)

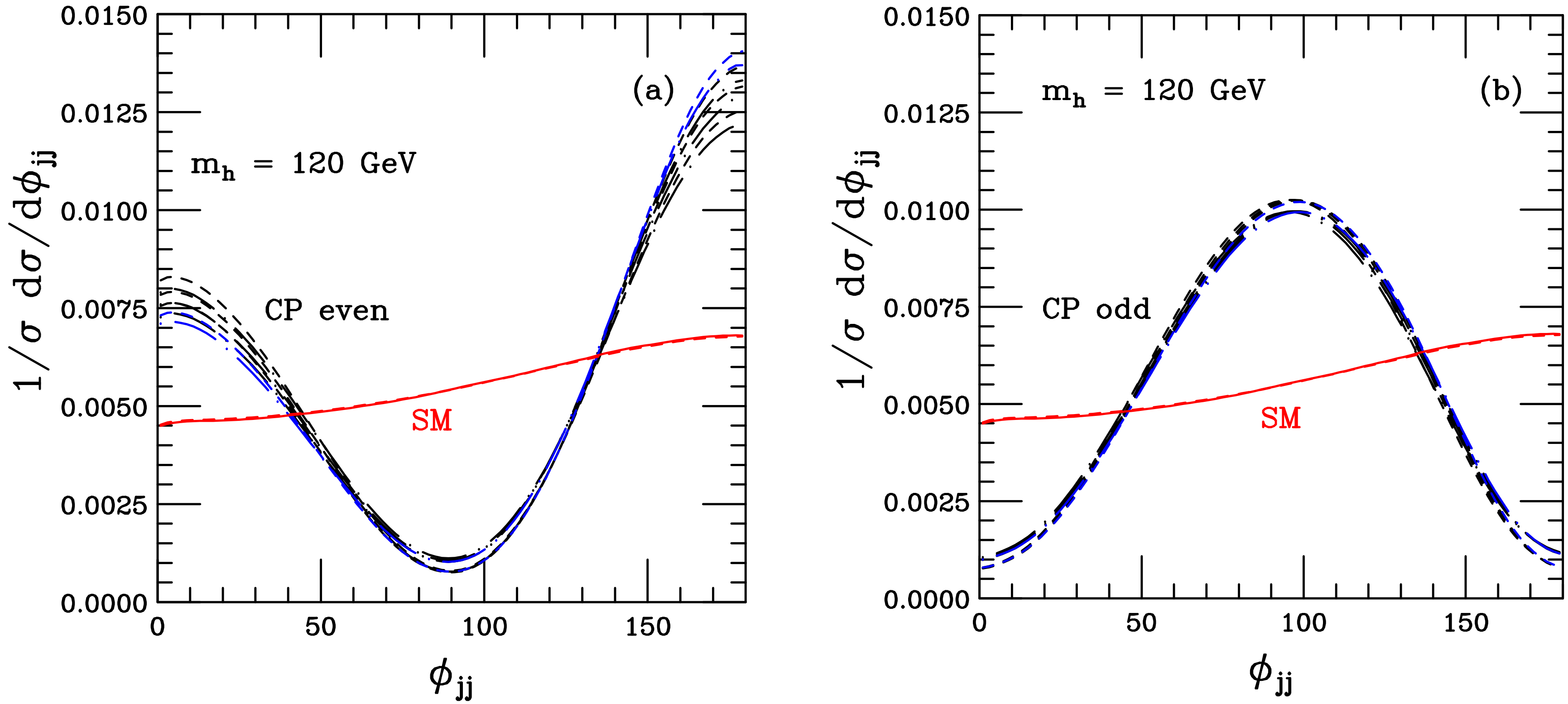
As with spin, we can distinguish these by looking at shapes of distributions.

Vector Boson Fusion

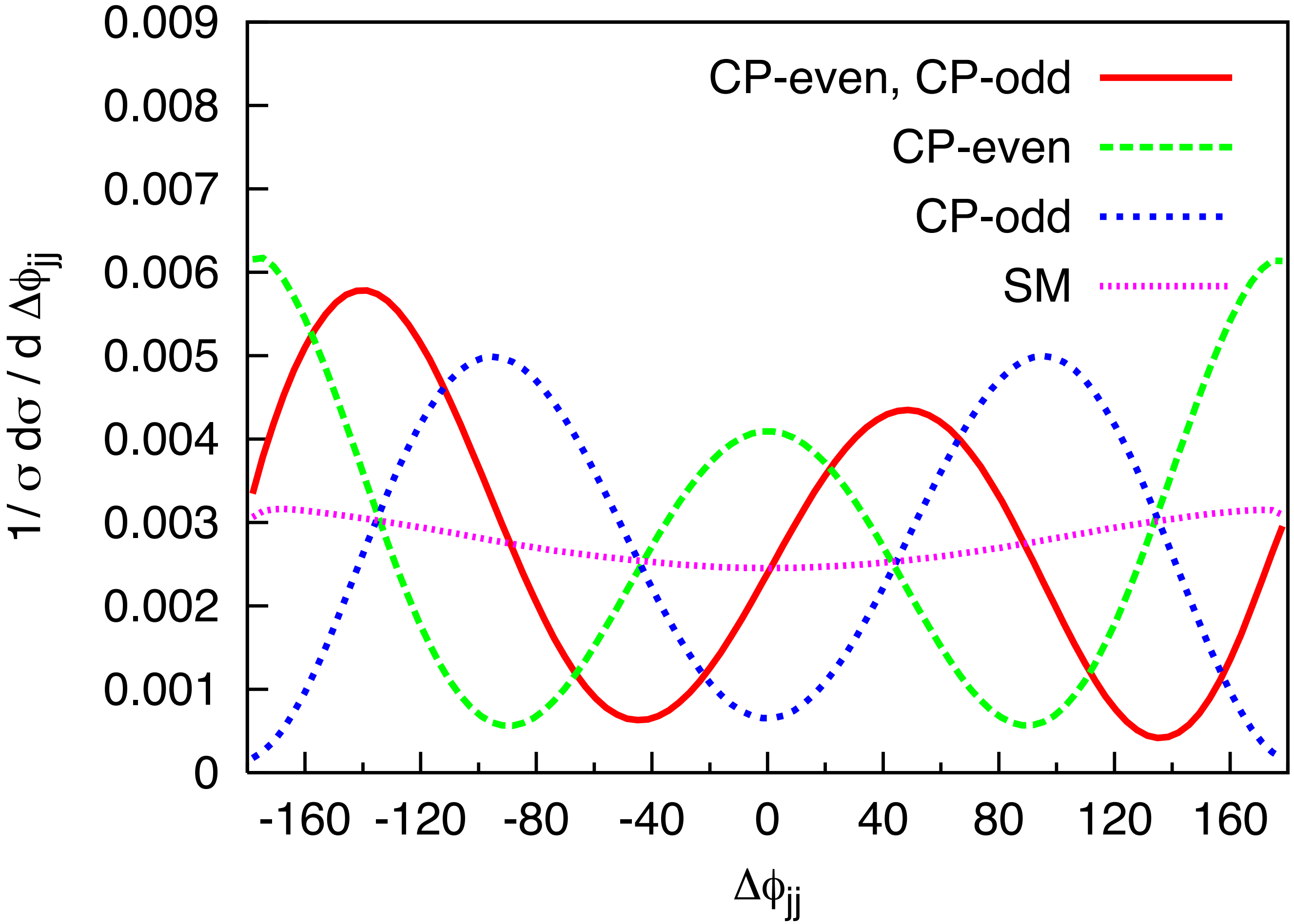


The azimuthal angle between tagging jets is a good discriminant.

[Plehn et al (2001)]

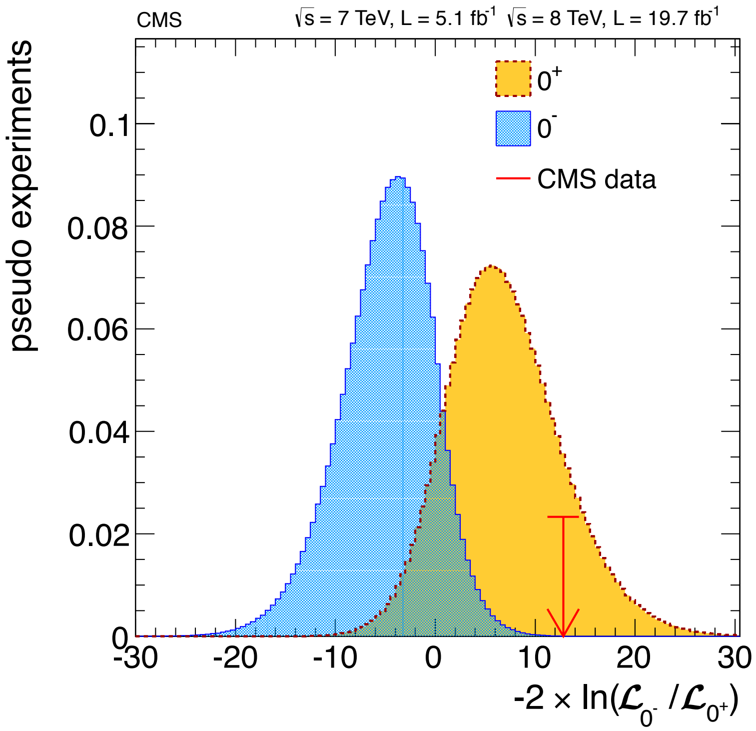


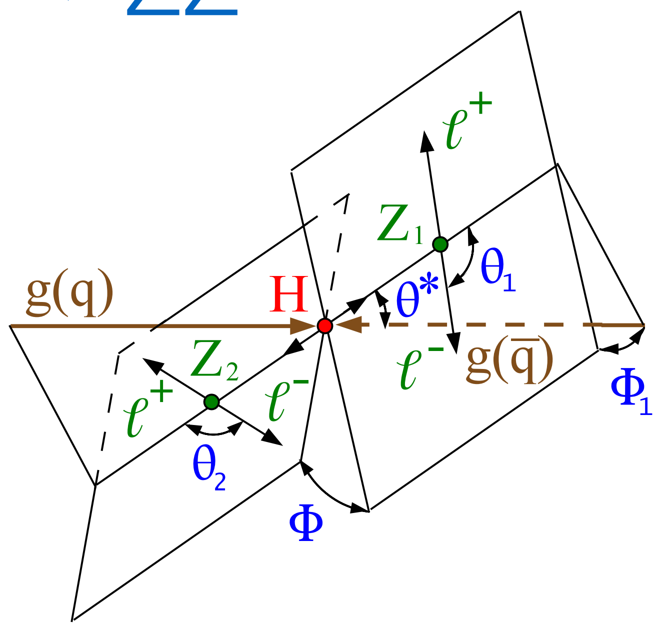
And it can also distinguish CP even/odd mixtures.



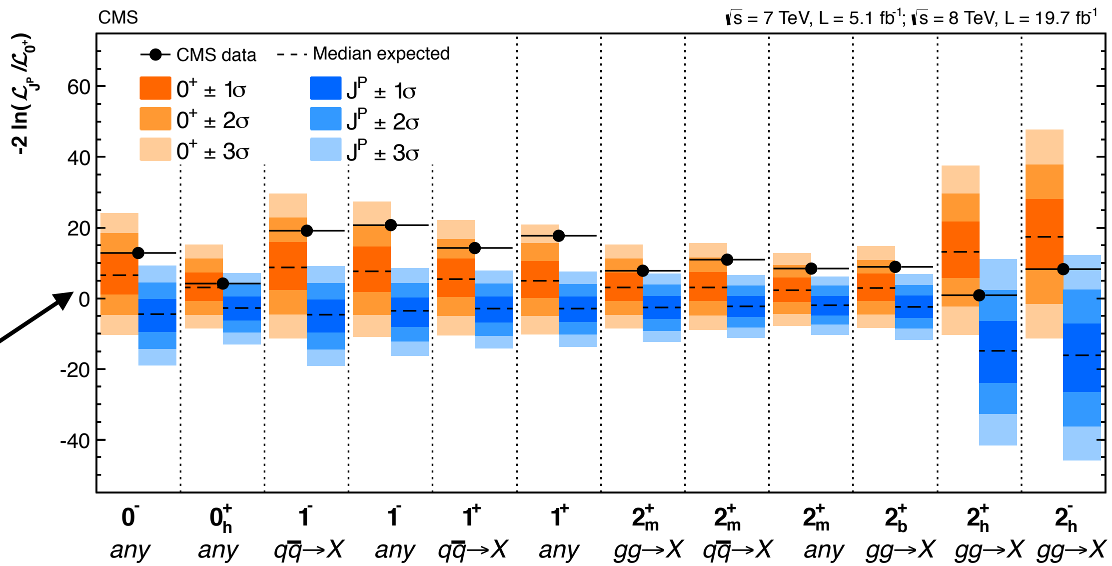
But no experimental results for VBF yet…

CMS H → ZZ





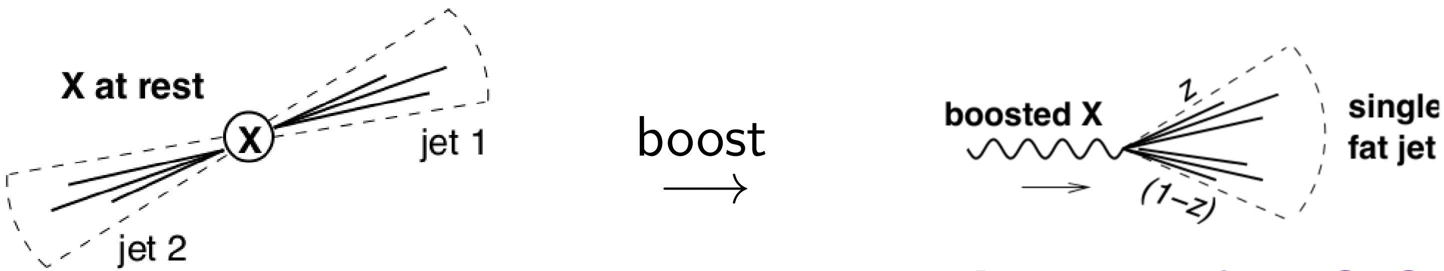
Pure 0^- is now disfavoured at more than 3σ.



CMS-HIG-13-002

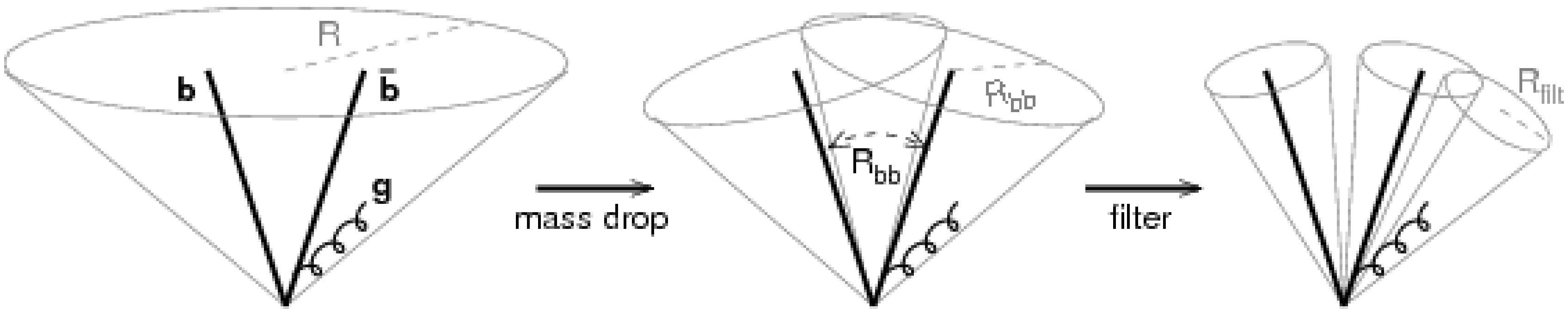
Boosted Higgs

$H \to \tau\tau$ is very small but we can use $H \to b\bar{b}$ if we use boosted events and jet substructure techniques [Butterworth et al (2008)].



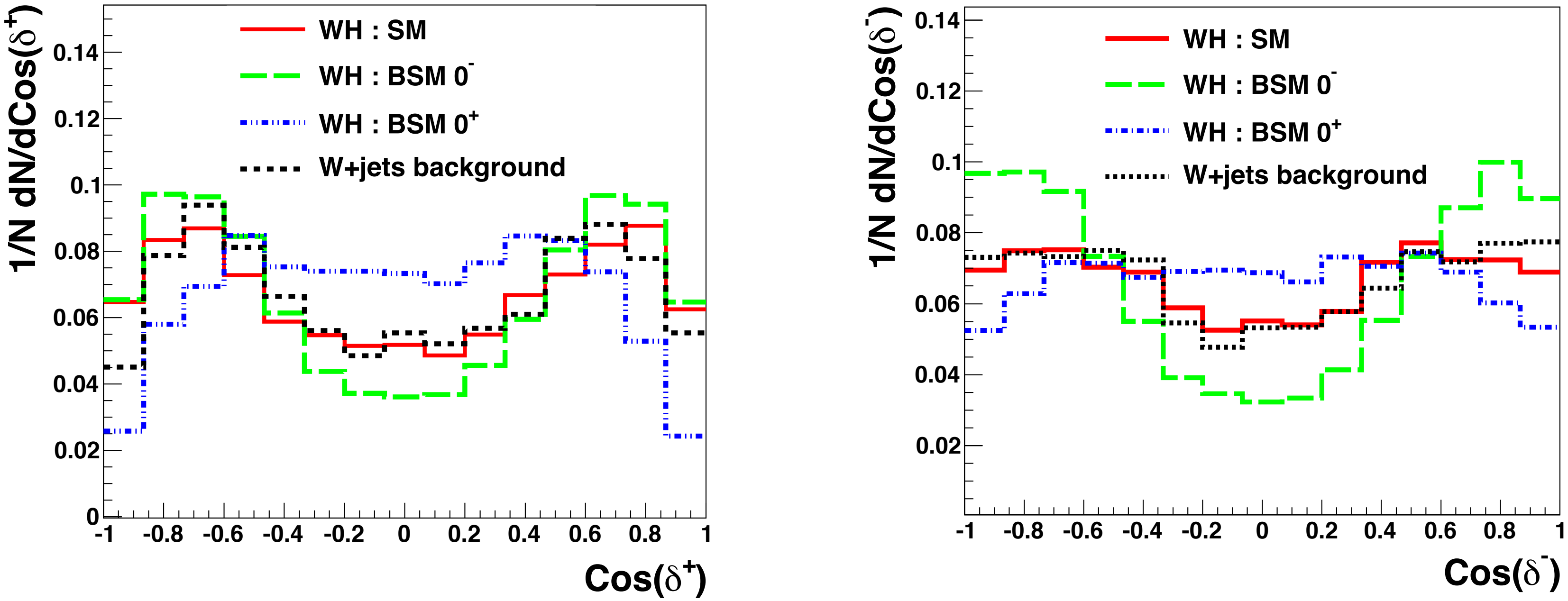
[Diagrams from G. Salam]

If the Higgs is boosted, the daughter b-jets look like one fat jet.



If we can reconstruct the b-jets and therefore the Higgs we can use angular distributions to determine the Spin and CP.

Example: $pp \to HW,\ H \to b\bar{b}$ [Godbole et al, arXiv:1306.2573]



There are lots of other good theory analyses of Higgs spin/CP and/or couplings. Apologies if I have missed your favourite!

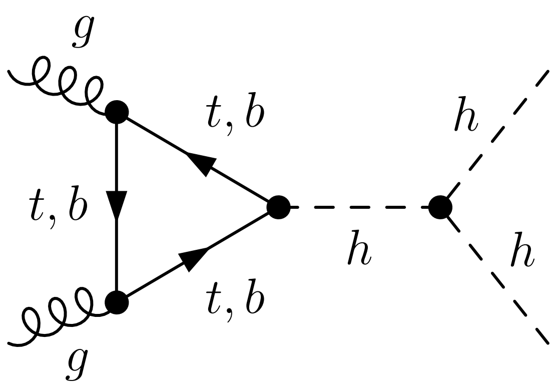
Higgs Self Couplings

$$V(\Phi^\dagger\Phi) = \mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2 = \frac{1}{2}m_h^2 h^2 + \sqrt{\frac{\lambda}{2}}m_h h^3 + \frac{\lambda}{4}h^4$$

The self couplings all involve either 3 or 4 Higgs bosons, so unless we plan on building a Higgs collider, we need to produce **multiple Higgs bosons in the final state**.

This is extremely challenging, but it may be possible to measure the **triple Higgs coupling** at the LHC, and should be possible at the ILC.

The **four Higgs vertex** looks out of reach for the foreseeable future.

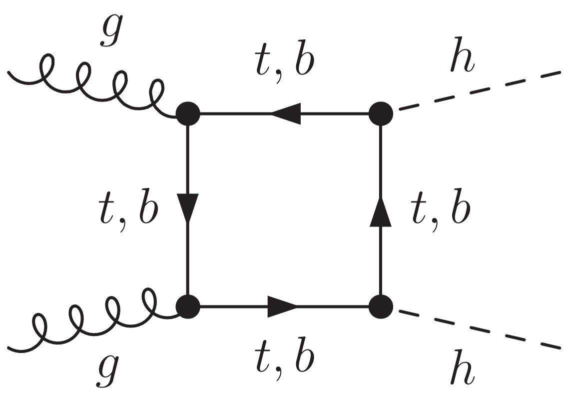


There have been a few (theory) analyses over the years including (but not limited to):

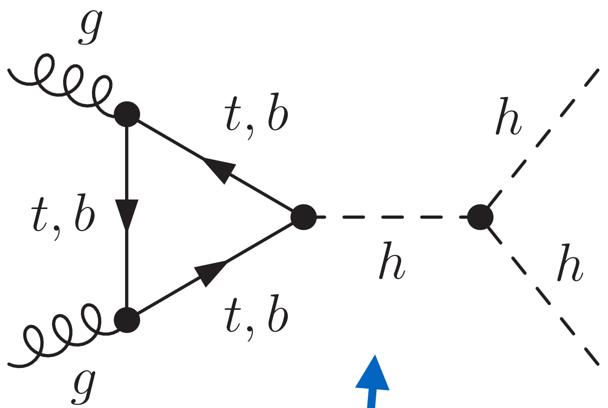
Glover, van der Bij (1988)
Plehn, Spira, Zerwas (1996)
Dawson, Dittmaier, Spira (1998)
Baur, Plehn, Rainwater (2002)
Binoth, Karg, Kauer, Ruckl (2006)

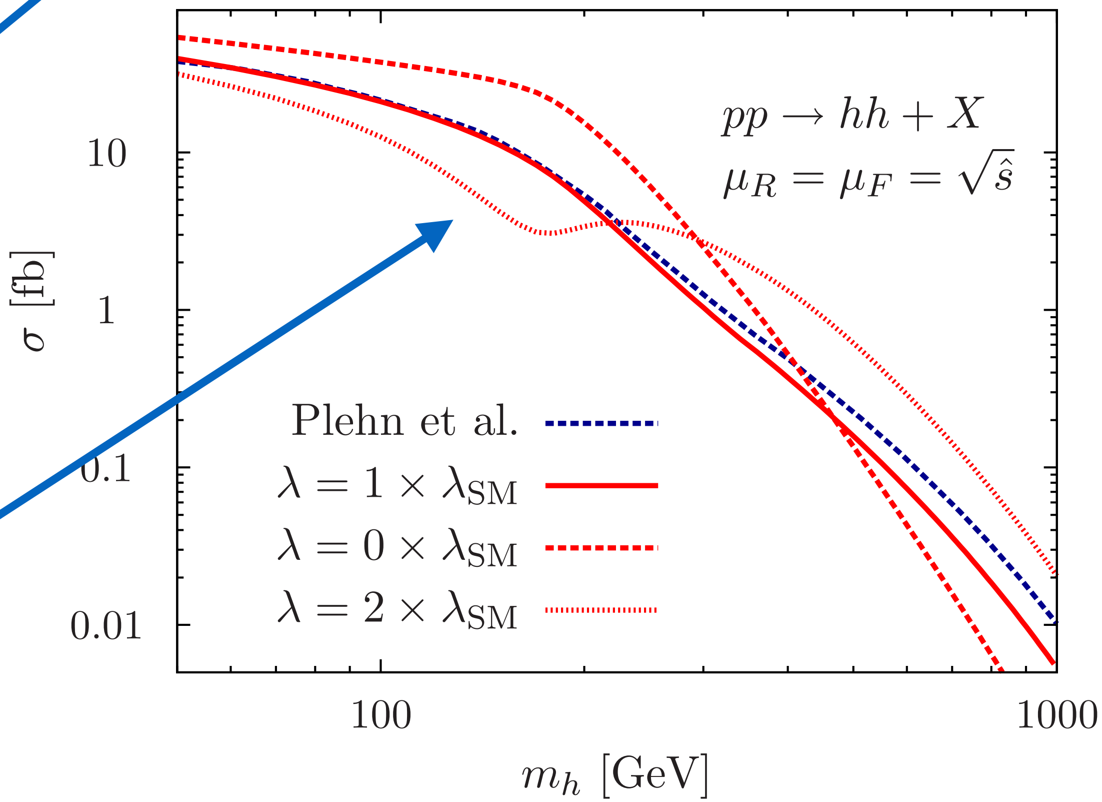
Used $hh \to b\bar{b}\gamma\gamma$

More recently Dolan, Englert, Spannowsky (2012) pointed out that the maximum sensitivity for the triangle graph in $gg \to hh$ is when the Higgs are rather boosted, allowing us to use **jet substructure**.

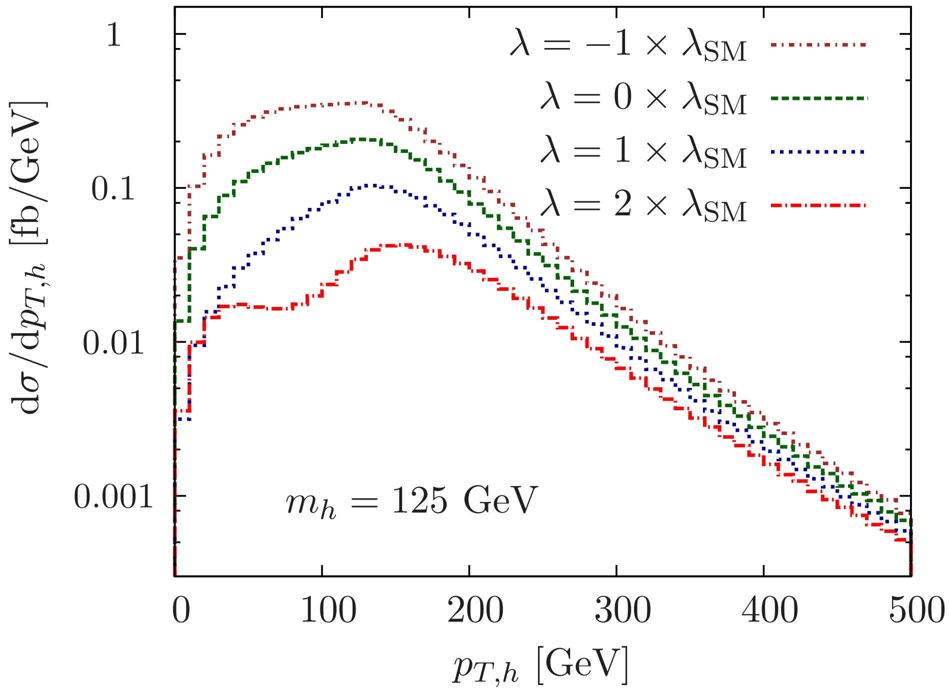


These graphs have the same initial and final state, so will **interfere** (usually destructively).





This graph is **enhanced** at $s \approx 4m_t^2$ due to the top loop



Of course this is still challenging to see, but since the Higgs are rather boosted, it may be possible to use $hh \to b\bar{b}b\bar{b}$ and **jet substructure techniques**.

For extended Higgs sectors, there will be many more opportunities due to heavy Higgs decaying to lighter ones, e.g. $H \to hh$.

Summary and Conclusions

Now that we have discovered the Higgs boson, the next step is to check its **properties**.

We need to measure its **spin, CP and couplings**.

We can measure its couplings either by fitting **scale factors** to the production channels, or by testing for higher dimensional operators.

So far, all Higgs production and decay is **consistent with the SM**.

We have similarly tested various spin/CP hypothesis and there is **good evidence that the resonance is indeed 0^+**, though care must be taken to rule out all possible spin 2 structures and CP even/odd mixtures.

Higgs self couplings will be challenging but preliminary measurements of the triple Higgs coupling may be made in $gg \to hh \to b\bar{b}\gamma\gamma$ or in $gg \to hh \to b\bar{b}b\bar{b}$ using jet substructure.