The Identity of the Higgs @ the LHC

Ian Low
Argonne National Lab and Northwestern U.

Work collaborated with:
Q.-H. Cao, C.B. Jackson, W.-Y. Keung, J. Lykken, R. Rattazzi, J. Shu, and A. Vichi.

What is the identity of the Higgs?

UV Identity:

- Is the Higgs fundamental or composite?
- Is the new physics at the TeV scale, if any, follows from naturalness principle?

IR Identity:

- If we observe one or more scalars, how do we know it has a VEV that breaks the electroweak symmetry?
- What's its quantum numbers and electroweak properties?

We need to answer them in order to navigate the infinite space of models!!

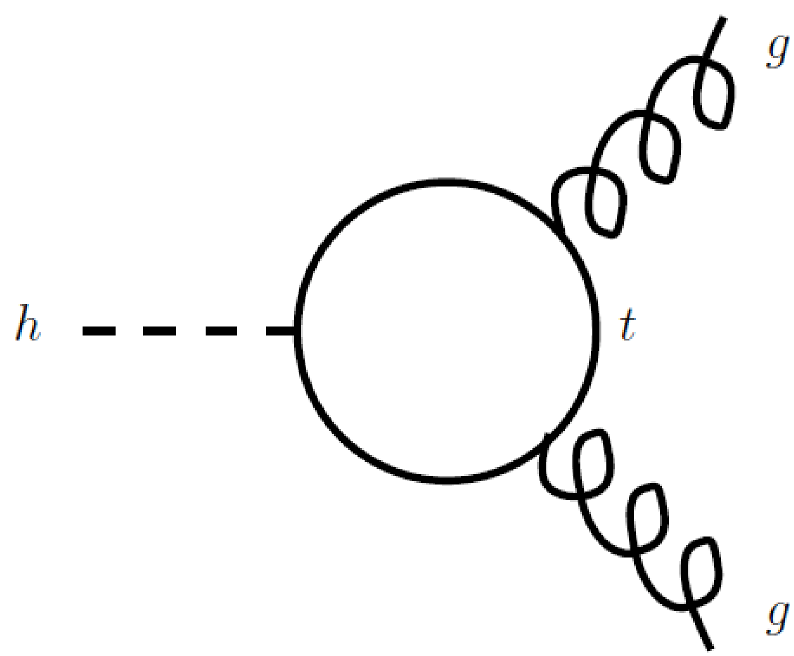
Some answers, by looking into :

- Gluon-fusion production channel:
  Compositeness and naturalness (arXiv:0907.5413)
- Decay into ZZ final states:
  Spin, CP, and origin of electroweak symmetry breaking (arXiv:0911.3398)
- Ratios of decay branching fractions into pairs of electroweak vector bosons:
  electroweak quantum numbers (arXiv:1005.0872)

At the LHC gluon fusion is the dominant production channel of the Higgs!

In the SM the dominant contribution comes from the top loop:

$$\frac{\alpha_s}{6\pi}\frac{y_t}{m_t}hG^a_{\mu\nu}G^{a\,\mu\nu} \qquad m_t = \frac{1}{\sqrt{2}}y_t v$$



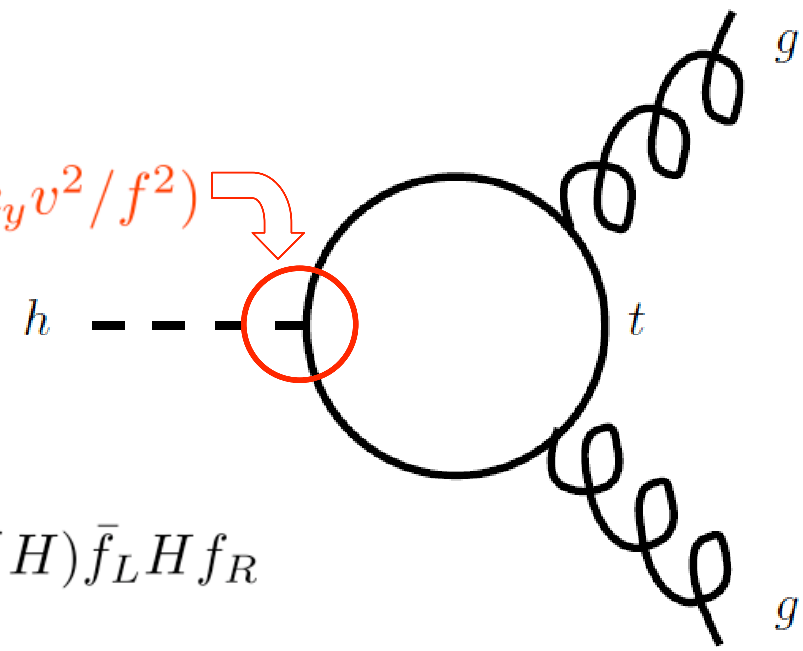
There are three ways new physics could modify the SM cross-section:

1. The Higgs-fermion-fermion coupling could be modified:

$$g_{hff} = g_{hff}^{(SM)} \times \left(1 - c_y \frac{v^2}{f^2}\right)$$

$f =$ (roughly) scale of new physics

$g_{hff}^{(SM)}(1 - c_y v^2/f^2)$



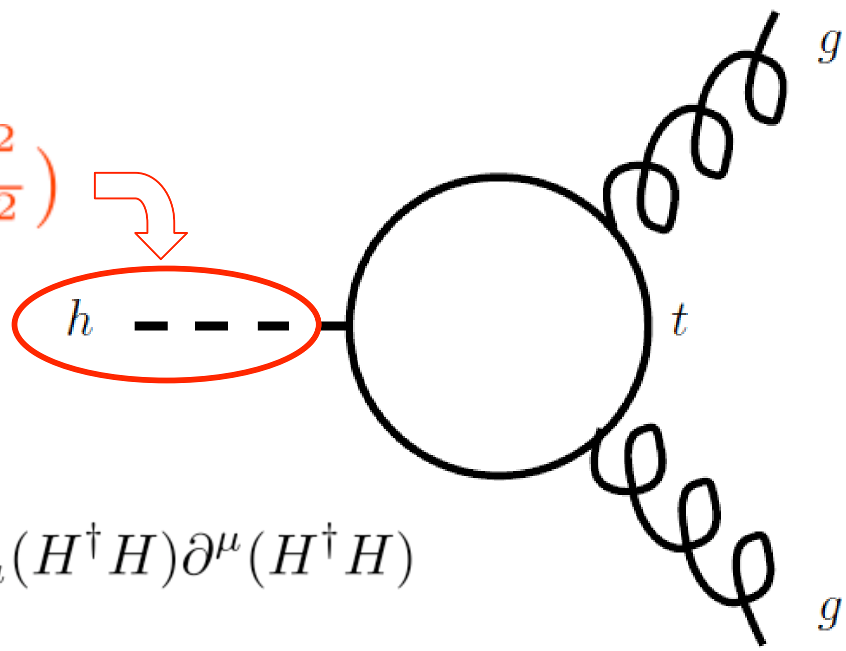
$$c_y \mathcal{O}_y \equiv \frac{c_y\, y_t}{f^2}(H^\dagger H)\bar{f}_L H f_R$$

There are three ways new physics could modify the SM cross-section:

2. The definition of the Higgs field may be modified:

$$h \to \frac{h}{\sqrt{1 + c_H v^2/f^2}} \approx h\left(1 - \frac{c_H}{2}\frac{v^2}{f^2}\right)$$

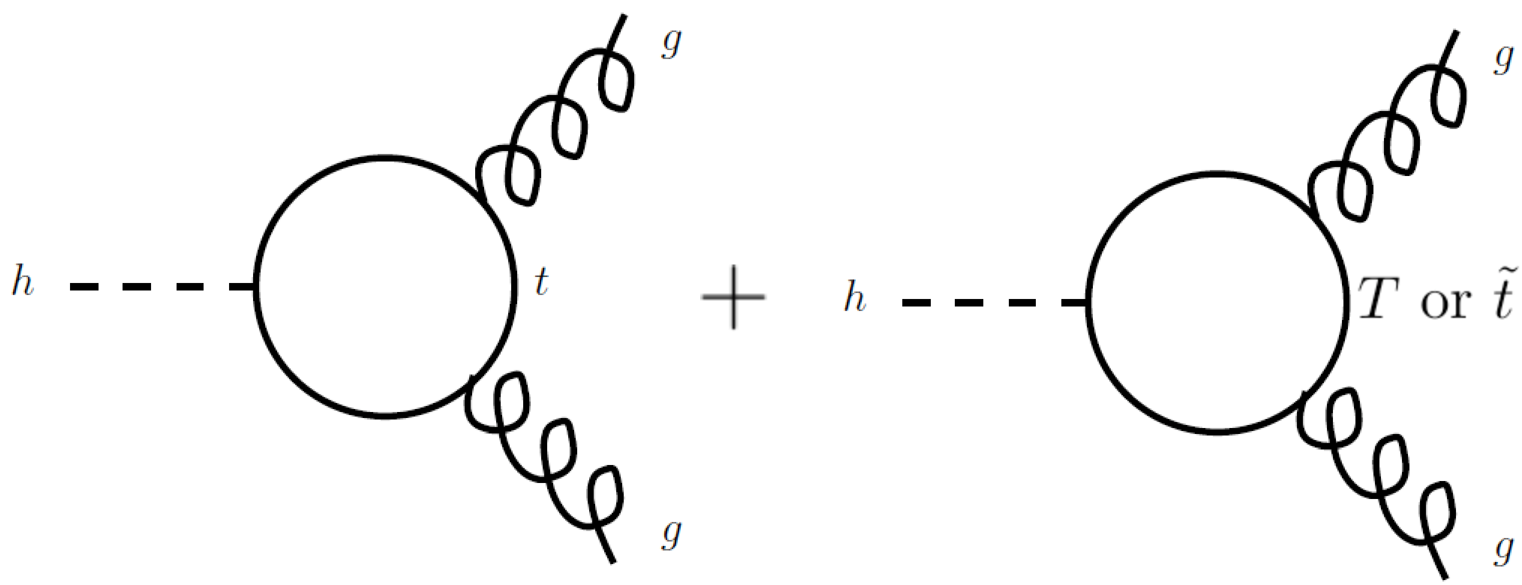
$$h(1 - \frac{c_H}{2}\frac{v^2}{f^2})$$



$$c_H \mathcal{O}_H = \frac{c_H}{2f^2}\partial_\mu(H^\dagger H)\partial^\mu(H^\dagger H)$$

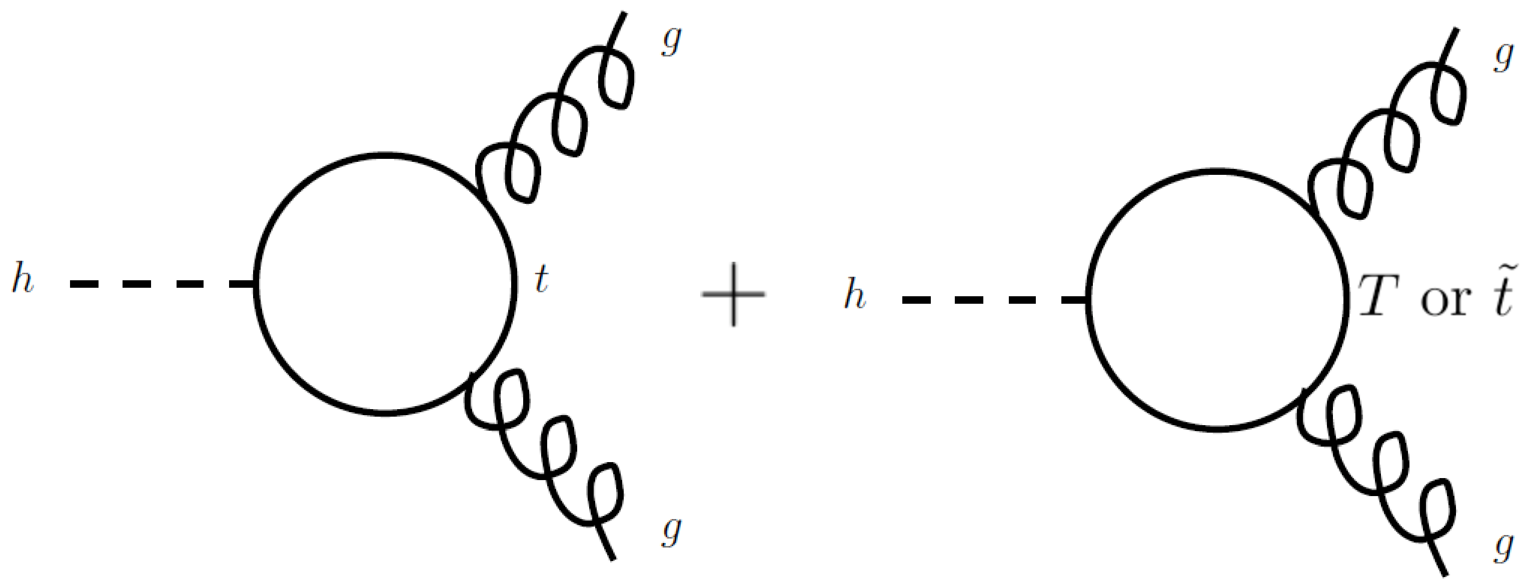
Finally, there could a new loop diagram in addition to the SM top loop:

1. For non-supersymmetric theories, it could be a new top-like fermion, the top partner.
2. For supersymmetric theories, it could be a new top-like scalar, the stop.



When the new particle in the loop is heavy, the new contribution is encoded in the parameter c_g:

$$c_g \frac{\alpha_s}{2\pi} \frac{y_t v}{m_\rho^2} h G^a_{\mu\nu} G^{a\,\mu\nu} \qquad m_\rho = m_T \text{ or } m_{\tilde{t}}$$



Summarizing these three effects, we have

$$\xi \equiv \frac{v^2}{f^2}$$

$$\Gamma(h \to gg) \;=\; \Gamma(h \to gg)_{SM}\left[1 - \xi\,\mathrm{Re}\left(c_H + 2c_y + \frac{4y_t^2 c_g}{g_\rho^2 I_g}\right)\right]$$

Quite amazingly, the sign of three parameters all go in the direction of *reducing* the production rate for composite Higgs models.

In addition, the interference between SM top and a heavy top-like fermion is *destructive* if the Higgs quadratic divergence is *cancelled*, and *constructive* if it is *not cancelled*.

Gluon Fusion Rate in the Universal Extra-Dimension (UED):

The Higgs scalar is fundamental and its mass unnatural (fine-tuned). The rate is enhanced over the SM!

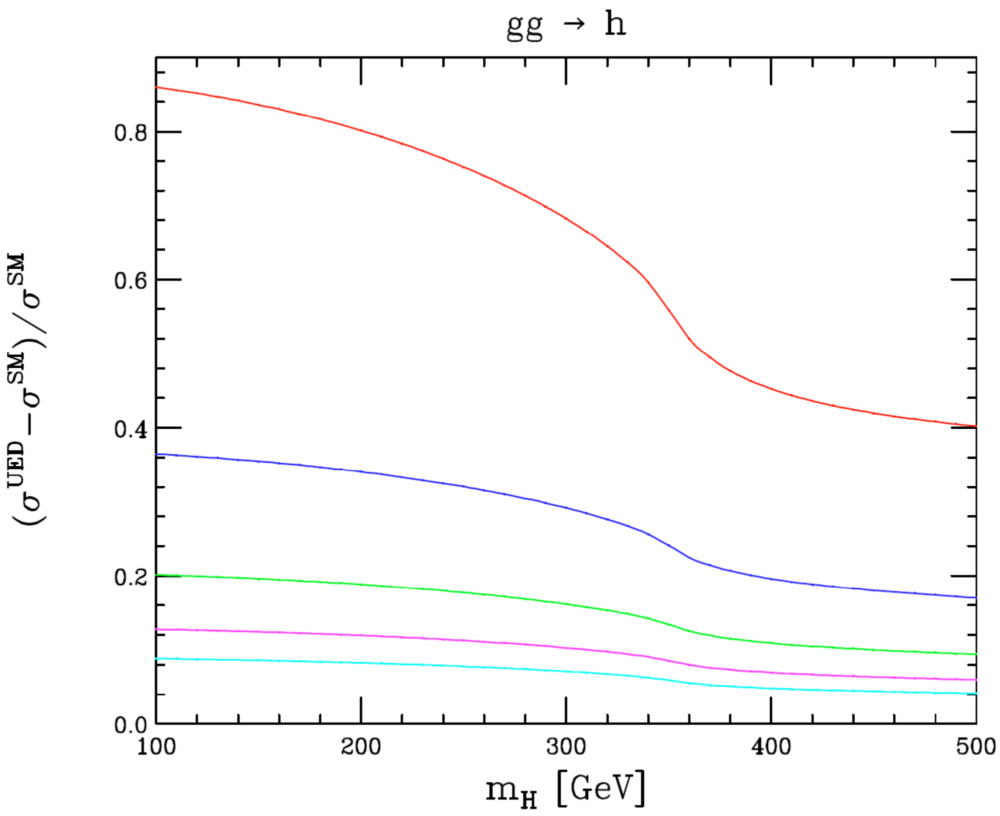
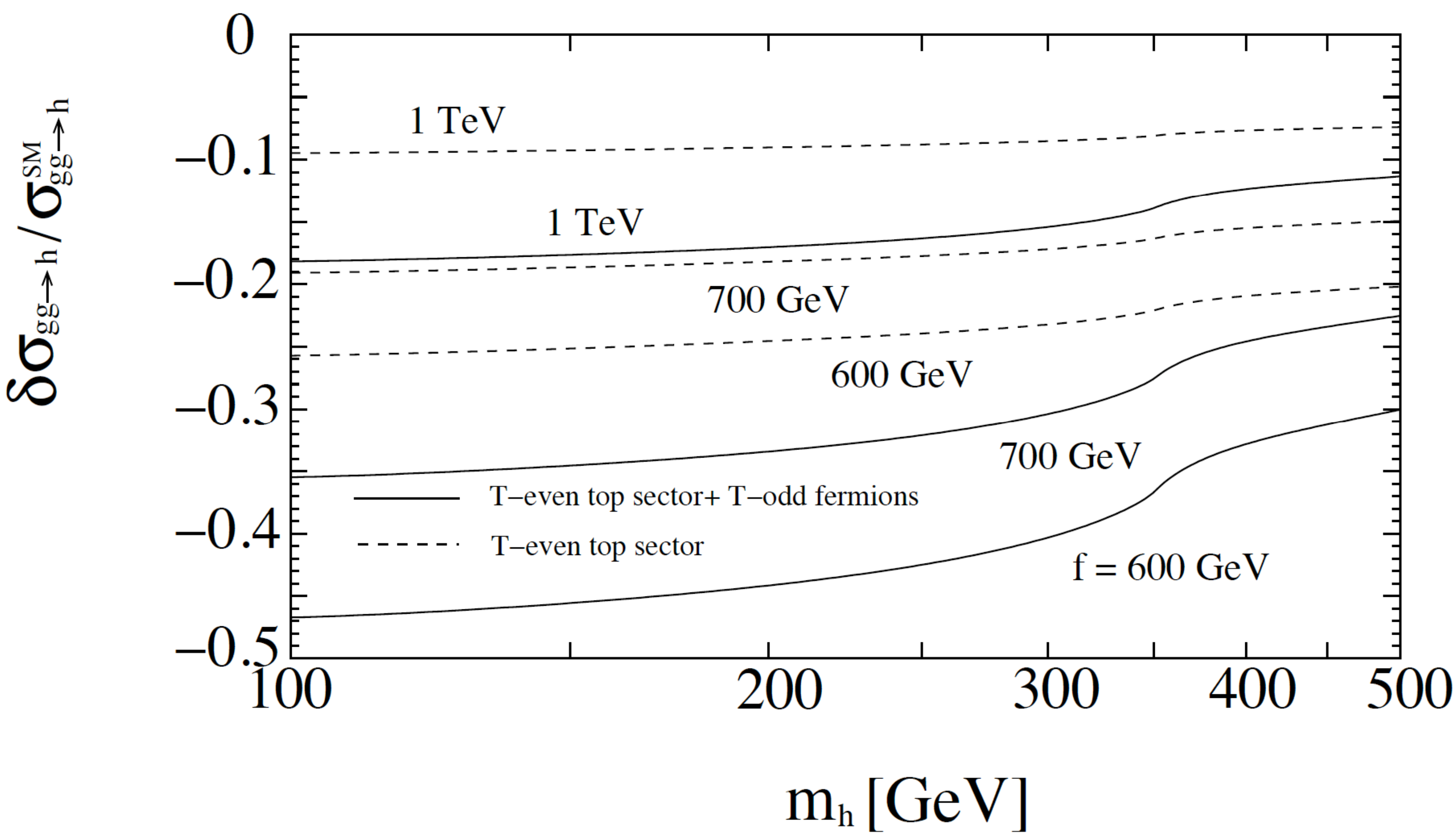


Figure 1: The fractional deviation of the $gg \to h$ production rate in the UED model as a function of m_H; from top to bottom, the results are for $m_1 = 500, 750, 1000, 1250, 1500$ GeV.

F. Petriello, hep-ph/0204067

Gluon Fusion Rate in the littlest Higgs with T-parity (LHT):

The Higgs is a composite scalar like the pion and the rate is reduced!



Chuan-Ren Chen et al, hep-ph/0602211

- We found the gluon fusion production rate is a unique handle into the compositeness of the Higgs boson as well as the naturalness of the mass.
- Composite Higgs models generally have a reduced gluon fusion rate.
- Unnatural models tend to have an enhanced production rate.

So this is an important number to measure precisely!

- Higgs -> ZZ ->4l is the gold-plated mode for the Higgs discovery when the mass is *not* too light.

- There have been studies using the angular correlations to determine the spin and CP property of the resonance.

I wish to emphasize the usefulness of two observables:

the total width and ϕ, the azimuthal angle between the two decay planes of the Z.

A scalar decaying into ZZ

- The Higgs mechanism predicts

$$|D_\mu H|^2 = \left| \left(\partial_\mu - ig\frac{\sigma^a}{2} W_\mu^a - ig'\frac{1}{2} B_\mu \right) H \right|^2$$

$$\Rightarrow \quad \left(1 + \frac{h}{v}\right)^2 m_V^2 V_\mu V^\mu \qquad g_{hVV} = -2i\frac{m_V^2}{v} g_{\mu\nu}$$

- But there are still two other possible couplings of a scalar with two Z bosons:

$$\mathcal{L}_{eff} = \frac{1}{2} m_S\, S \left(c_1 Z^\nu Z_\nu + \frac{1}{2}\frac{c_2}{m_S^2} Z^{\mu\nu} Z_{\mu\nu} + \frac{1}{4}\frac{c_3}{m_S^2} \epsilon_{\mu\nu\rho\sigma} Z^{\mu\nu} Z^{\rho\sigma} \right)$$

Higgs mechanism predicts only this term!

- We computed the azimuthal angular distribution

$$\frac{d\Gamma}{\Gamma d\phi} = \frac{1}{N}\left\{\frac{8}{9}\cos(2\phi+2\delta) + \frac{\pi^2}{2}\frac{M_L}{M_T}\left(\frac{g_R^2-g_L^2}{g_R^2+g_L^2}\right)^2\cos(\phi+\delta) + \frac{16}{9}\left(\frac{M_L^2}{M_T^2}+2\right)\right\}.$$

Negligible (~0.06) in the SM!

$\delta = 0$ for vanishing c_3. (CP-even scalar!)

$\delta = \pi/2$ for vanishing c_1 and c_2. (CP-odd scalar!)

- Previous studies only focus on c_1 but not c_2!

We see the cos(2ϕ) dependence, signaling a spin-0 resonance. (Again cos(ϕ) component is tiny!) For spin-1 it should be cos(ϕ).

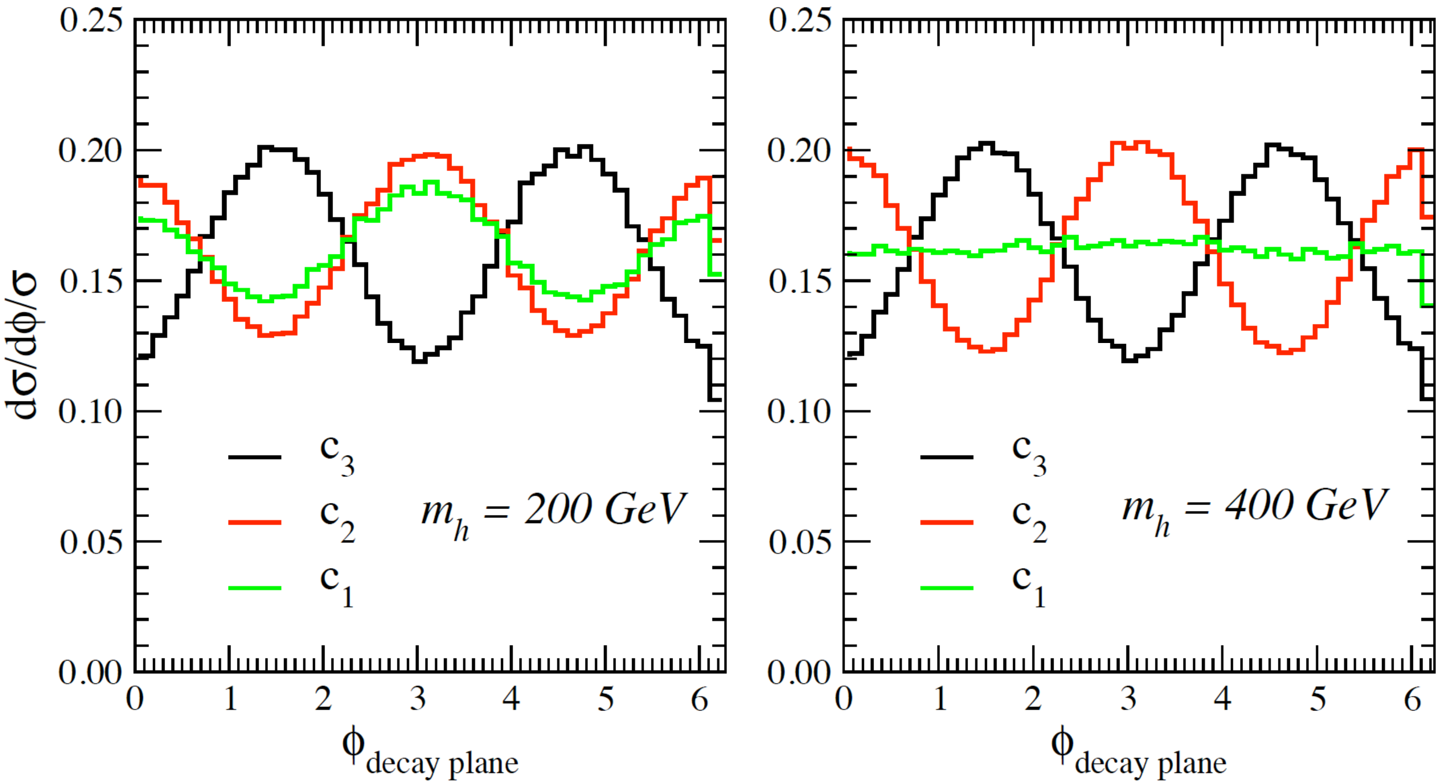


FIG. 4: *The normalized azimuthal angular distributions for 200 and 400 GeV scalar masses, turning on one operator at a time.*

Notice c_1 and c_2 will be difficult to tell unless the Higgs is heavy.

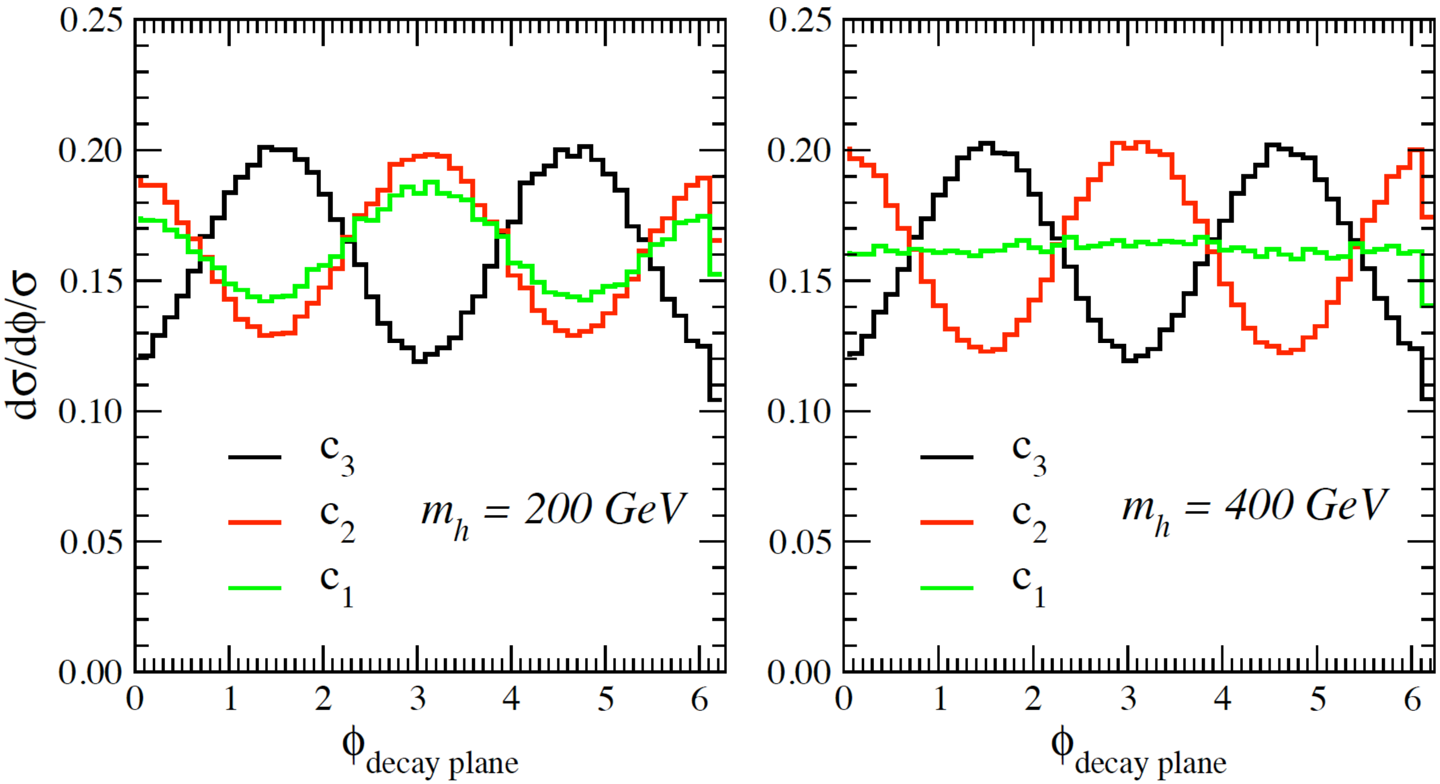


FIG. 4: *The normalized azimuthal angular distributions for 200 and 400 GeV scalar masses, turning on one operator at a time.*

- Another handle makes use of the crucial observation that the two non-Higgs operators

$$S \times \left(\frac{1}{2} \frac{c_2}{m_S^2} Z_{\mu\nu} Z^{\mu\nu} + \frac{1}{4} \frac{c_3}{m_S^2} \epsilon_{\mu\nu\rho\sigma} Z^{\mu\nu} Z^{\rho\sigma} \right)$$

are both loop-induced:

$$c_2 \sim \mathcal{O}\left(\frac{1}{16\pi^2}\right) \qquad c_3 \sim \mathcal{O}\left(\frac{1}{16\pi^2}\right)$$

$$\Gamma(S \to ZZ) \approx \text{loop-induced for both } c_2 \text{ and } c_3$$

- Thus in order to have a sizable branching ratio, the total width must be also loop-induced and order-of-magnitude smaller than that of the SM Higgs:

$$\Gamma_{total} \ll \Gamma_{total}^{(SM)}$$

Otherwise we simply would not observe the resonance in the ZZ channel due to the suppression in the branching ratio with around 30 fb of data!!

A non-Higgs like scalar would have a very narrow resonance, which is buried under the energy resolution of the detector!

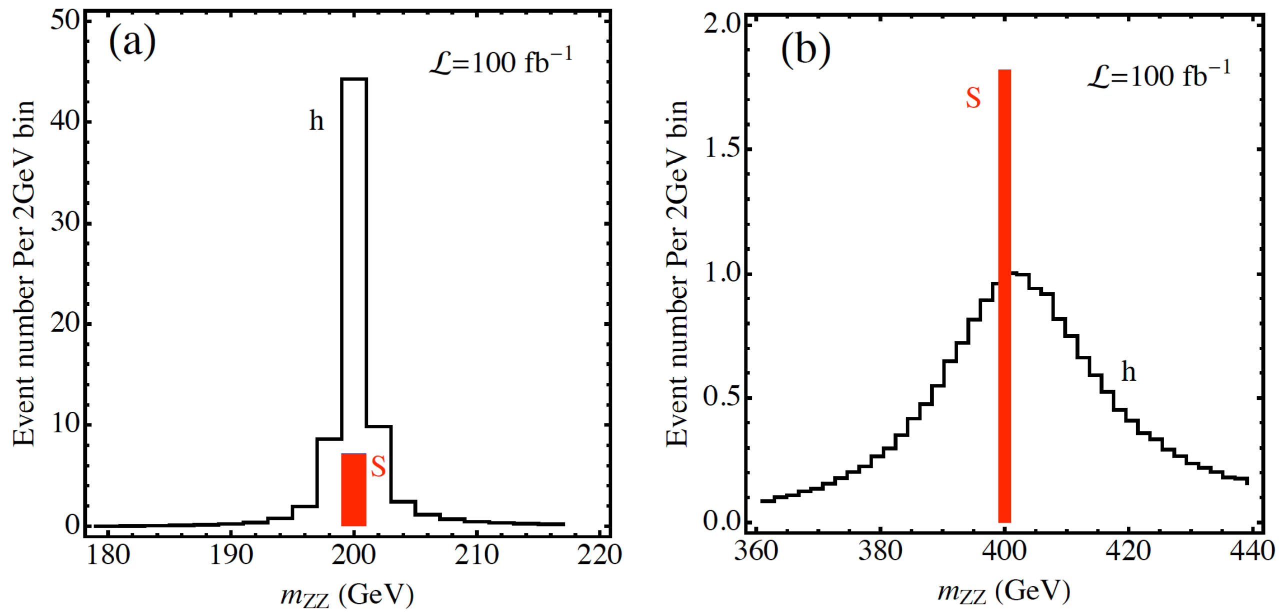


FIG. 3: *The ZZ invariant mass distribution for a SM Higgs boson and a scalar S decaying through loop-induced effects, using a 2 GeV bin size. The narrow width of S is below the detector resolution, resulting in a concentration of all events in just one bin. In the plot we assume the event rate of $gg \to S \to ZZ \to 4\ell$ is only 10% of rate for the SM Higgs boson.*

- If a resonance is observed in the ZZ final states, the azimuthal angular distribution would provide crucial information on the spin and CP property of the resonance.

- The width of the resonance provides a smoking-gun signal on the Higgs nature of the resonance ---- whether the scalar gives rise to masses to W/Z bosons through the Higgs mechanism!

Electroweak properties of a scalar resonance:

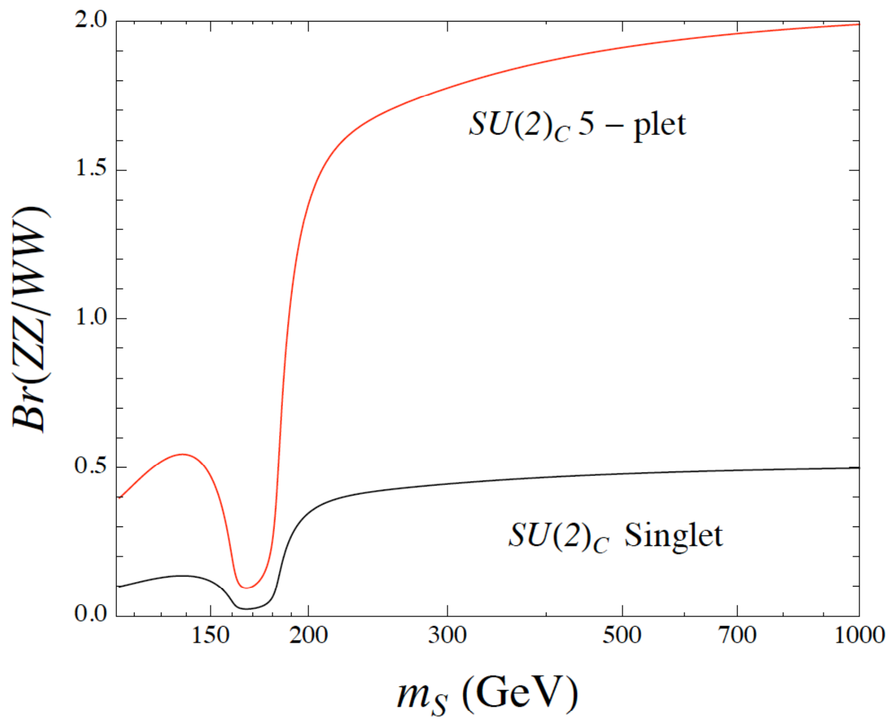


FIG. 1: *Ratio of branching fractions into WW and ZZ, $Br(ZZ/WW)$, for an $SU(2)_C$ singlet and a 5-plet, as a function of the scalar mass.*