CP asymmetries in Higgs decays to Z bosons at the LHC

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Outline:

- Introduction
- Total rate
- Threshold behaviour
- Angular dependence
- Asymmetries
- Conclusion

Introduction

With the discovery of a “Higgs-like” resonance at the LHC, we will need to ensure that what we have found is the SM Higgs boson.

We need to measure:

- Higgs CP and spin
- Higgs couplings to fermions and gauge bosons
- Higgs self couplings

The first 2 are intimately linked since CP and spin restrict the form of the couplings.

One possible method:

Write down the most general vertex coupling the Higgs boson to particle X and then put limits on the various coefficients.

Here we will examine the HZZ vertex

The most general vertex for a spinless particle coupling to a Z boson is

$$V^{\mu\nu}_{HZZ} = \underbrace{\frac{igm_Z}{\cos\theta_W}\left[a\, g_{\mu\nu}\right.}_{\text{SM coupling (CP even)}} + b\,\frac{p_\mu p_\nu}{m_Z^2} + c\,\epsilon_{\mu\nu\alpha\beta}\,\frac{p^\alpha k^\beta}{m_Z^2}\left.\right]$$

SM coupling
(CP even)

CP even

CP odd

Z boson momenta are q_1^μ and q_2^μ, and $p=q_1+q_2$, $k=q_1-q_2$

This can be parameterized in many different ways but all are related by redefinitions of a, b and c, which may be momenta dependent.

The SM is given by $a=1$, $b=c=0$.

a can always be chosen to be real, but b and c can be complex.

See also:

Choi, DJM, Muhlleitner, Zerwas, Phys. Lett. B 553 (2003)

Buszello, Fleck, Marquard, van der Bij, Eur. Phys. J. C 32 (2004)
Buszello, Fleck, Marquard, van der Bij, arXiv:hep-ph/040618; CPNSH report
Buszello, Marquand, arXiv:hep-ph/0603209

Biswal, Godbole, Singh, Choudhury, Phys. Rev. D 73 (2006)

The total rate

Can we distinguish the extra couplings via that total width to Z's?

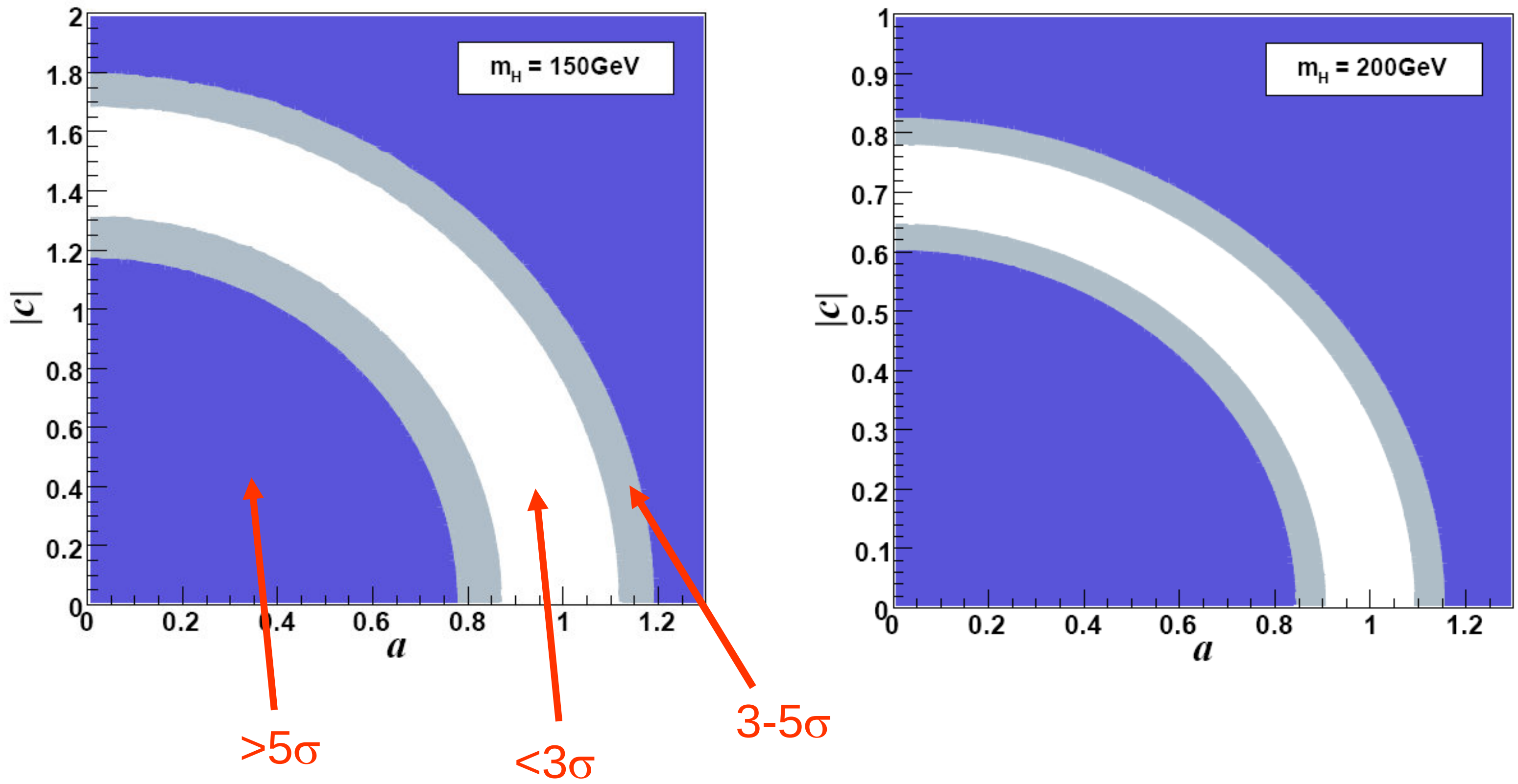
$$\Gamma_{H\to ZZ} = \frac{G_F m_H^3}{16\sqrt{2}\pi}\beta\left\{a^2\left[\beta^2+\frac{12m_1^2m_2^2}{m_H^4}\right]+|b|^2\frac{m_H^4}{m_Z^4}\frac{\beta^4}{4}+|c|^2x^2\,8\beta^2\right.$$
$$\left.+a\Re e(b)\frac{m_H^2}{m_Z^2}\beta^2\sqrt{\beta^2+4m_1^2m_2^2/m_H^4}\right\}$$

β is the usual rescaled *Z*-momentum: $\beta = \left\{\left[1-\frac{(m_1+m_2)^2}{m_H^2}\right]\left[1-\frac{(m_1-m_2)^2}{m_H^2}\right]\right\}^{1/2}$

m_1 and m_2 are the virtualities of the Z-bosons.

Examine the total number of events observed in $H \to ZZ^{(*)} \to 4$ leptons
as according to the ATLAS TDR study [Hohlfeld, ATL-PHYS-2001-004].

Deviation from the SM (with b=0)



Impossible to tell whether the difference arises from an overall factor (e.g. bigger a) or a new term in the coupling.

Can't measure the phase of c.

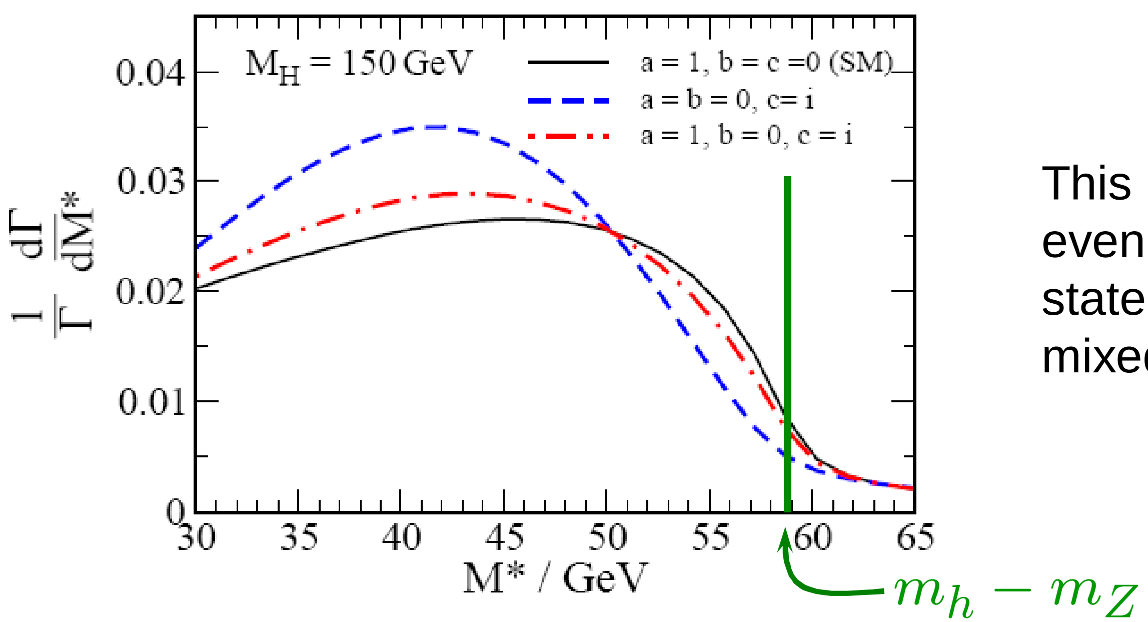
Threshold behaviour

Only one term has a linear dependence on β (this comes from the phase space)

$$\Gamma_{H\to ZZ} = \frac{G_F m_H^3}{16\sqrt{2}\pi}\beta\left\{a^2\left[\beta^2+\boxed{\frac{12m_1^2m_2^2}{m_H^4}}\right]+|b|^2\frac{m_H^4}{m_Z^4}\frac{\beta^4}{4}+|c|^2x^2\,8\beta^2 \right.$$
$$\left. +a\Re e(b)\frac{m_H^2}{m_Z^2}\beta^2\sqrt{\beta^2+4m_1^2m_2^2/m_H^4}\right\}$$

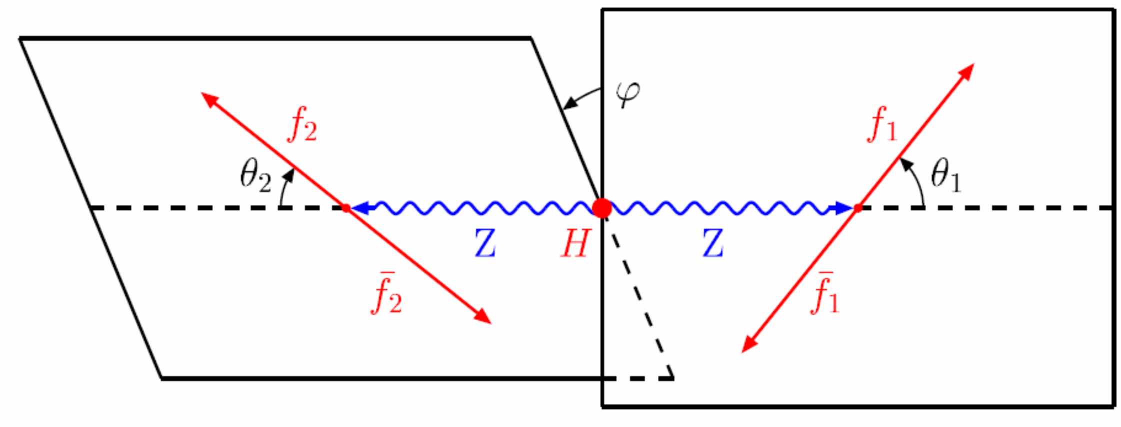
⇒ threshold dependence ($m_h<2m_Z$) can distinguish SM term from other terms

[Choi, DJM, Muhlleitner, Zerwas, Phys. Lett. B 553 (2003)]



This is good for telling a pure CP even state from a pure CP odd state, but cannot distinguish a mixed CP state.

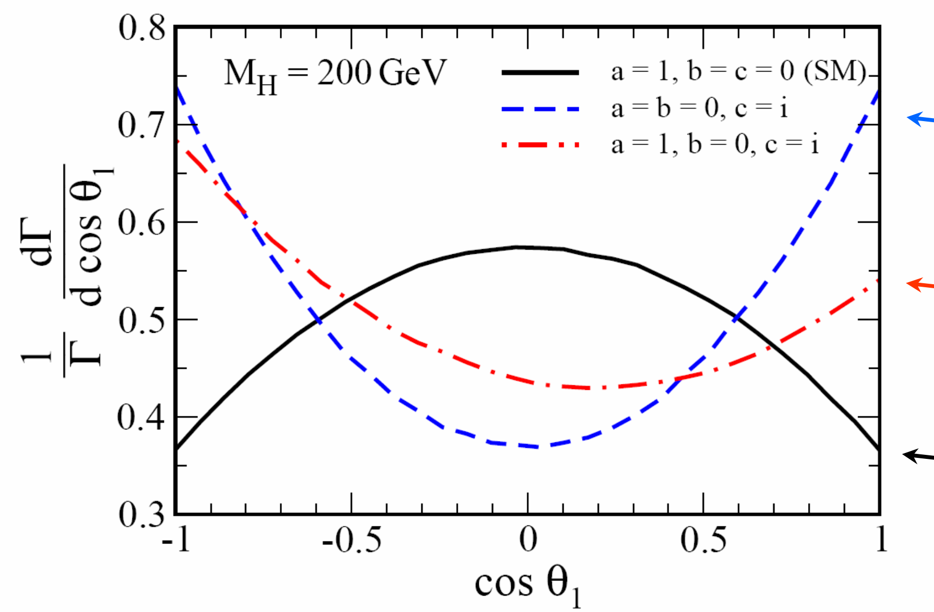
Angle distributions



It is much better to use the dependence on the angles between the two planes and/or the angles of the leptons in the Z rest frames.

Distributions are very different for different CP

Allows investigation of CP violation via asymmetries

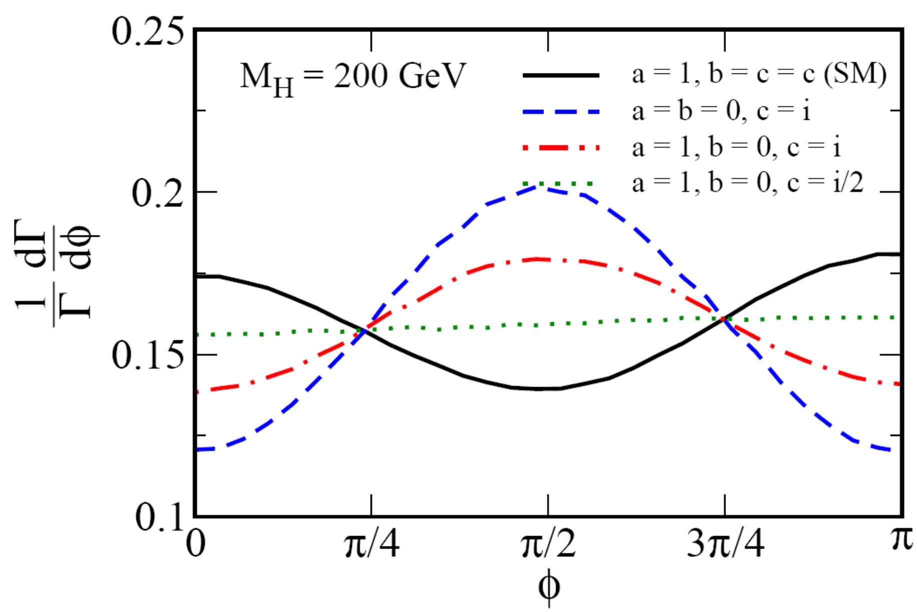


CP odd

Mixed CP

SM

Notice the asymmetry for the CP mixed state



Asymmetries

We can construct asymmetries which vanish when CP is conserved:

e.g. $O_1 = \cos\theta_1$

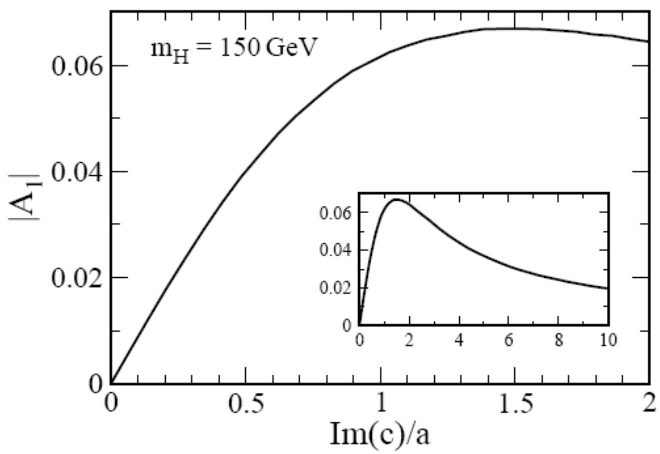
$$\mathcal{A}_1 = \frac{\Gamma(\cos\theta_1 > 0) - \Gamma(\cos\theta_1 < 0)}{\Gamma(\cos\theta_1 > 0) + \Gamma(\cos\theta_1 < 0)}$$

$$= \frac{1}{\tilde{\Gamma}} \int d^2\mathcal{P}\, \beta\, \{-3\, a\Im m(c)\, x\, \eta_1\, \gamma_b\}$$

x and γ_b are kinematic factors

vanishes if a=0 or c=0

suppressed by factor $\eta = \frac{2va}{v^2+a^2}$



This is the perfect theoretical asymmetry:

$$A_1^{\text{theory}} = \frac{N^{\text{asym}}}{N_S}$$

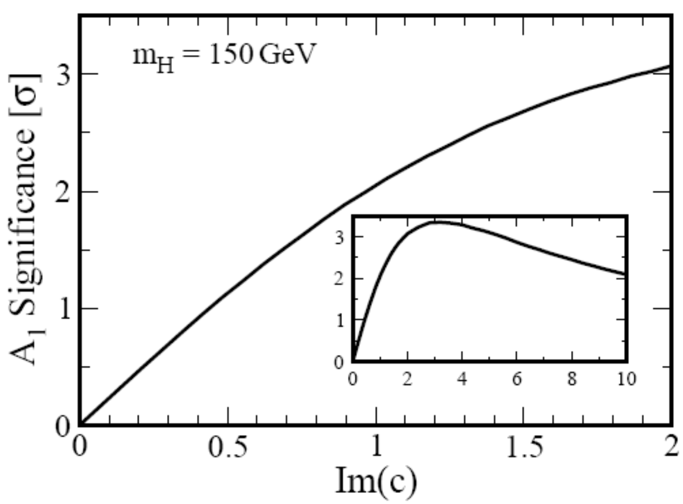
Calculate significance using number of events from ATLAS TDR study:

$$A_1^{\text{measured}} = \frac{N^{\text{asym}}}{N_S+N_B} = A_1^{\text{theory}} \frac{N_S}{N_S+N_B}$$

Background contaminates normalization, and background fluctuations may mimic an asymmetry.

Statistical fluctuation $= \frac{1}{\sqrt{N_S+N_B}}$

Significance = $A_1^{\text{measured}} \sqrt{N_S + N_B} = A_1^{\text{theory}} \frac{N_S}{\sqrt{N_S+N_B}}$



Use event sample before 'vigourous' cuts

Not very good significance

$$
\begin{aligned}
\frac{d^3\Gamma}{dc_{\theta_1}\,dc_{\theta_2}d\phi} \;\sim\;& a^2\left[s^2_{\theta_1}s^2_{\theta_2}+\frac{1}{2\gamma_a}s_{2\theta_1}s_{2\theta_2}c_\phi+\frac{1}{2\gamma_a^2}\left[(1+c^2_{\theta_1})(1+c^2_{\theta_2})+s^2_{\theta_1}s^2_{\theta_2}c_{2\phi}\right]\right.\\
&\left.\quad -\frac{2\eta_1\eta_2}{\gamma_a}\left(s_{\theta_1}s_{\theta_2}c_\phi+\frac{1}{\gamma_a}c_{\theta_1}c_{\theta_2}\right)\right]\\
&+\;|b|^2\frac{\gamma_b^4}{\gamma_a^2}\,x^2\,s^2_{\theta_1}s^2_{\theta_2}\\
&+\;|c|^2\frac{\gamma_b^2}{\gamma_a^2}\,4x^2\left[1+c^2_{\theta_1}c^2_{\theta_2}-\frac{1}{2}s^2_{\theta_1}s^2_{\theta_2}(1+c_{2\phi})-2\eta_1\eta_2c_{\theta_1}c_{\theta_2}\right]\\
&-\;2a\Im m(b)\frac{\gamma_b^2}{\gamma_a^2}\,x\,s_{\theta_1}s_{\theta_2}s_\phi\left[\eta_2c_{\theta_1}-\eta_1c_{\theta_2}\right]\\
&-\;2a\Re e(b)\frac{\gamma_b^2}{\gamma_a^2}\,x\left[-\gamma_as^2_{\theta_1}s^2_{\theta_2}-\frac{1}{4}s_{2\theta_1}s_{2\theta_2}c_\phi+\eta_1\eta_2s_{\theta_1}s_{\theta_2}c_\phi\right]\\
&-\;2a\Im m(c)\frac{\gamma_b}{\gamma_a}\,2x\left[s_{\theta_1}s_{\theta_2}c_\phi(\eta_1c_{\theta_2}-\eta_2c_{\theta_1})\right.\\
&\qquad\qquad\left.+\frac{1}{\gamma_a}\left(\eta_1c_{\theta_1}(1+c^2_{\theta_2})-\eta_2c_{\theta_2}(1+c^2_{\theta_1})\right)\right]\\
&-\;2a\Re e(c)\frac{\gamma_b}{\gamma_a}\,2x\,s_{\theta_1}s_{\theta_2}s_\phi\left[c_{\theta_1}c_{\theta_2}+\frac{s_{\theta_1}s_{\theta_2}c_\phi}{\gamma_a}-\eta_1\eta_2\right]\\
&-\;2\Im m(b^*c)\frac{\gamma_b^3}{\gamma_a^2}\,2x^2\,s_{\theta_1}s_{\theta_2}c_\phi\left[\eta_1c_{\theta_2}-\eta_2c_{\theta_1}\right]\\
&-\;2\Re e(b^*c)\frac{\gamma_b^3}{\gamma_a^2}\,2x^2\,s_{\theta_1}s_{\theta_2}s_\phi\left[c_{\theta_1}c_{\theta_2}-\eta_1\eta_2\right]\;.
\end{aligned}
$$

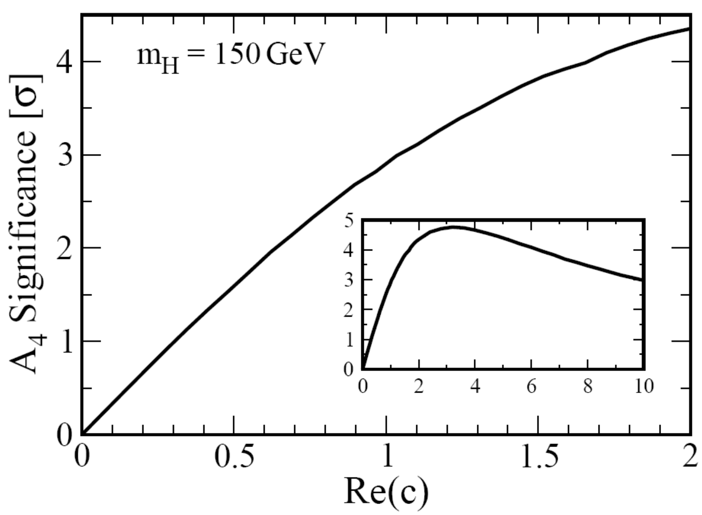
poor significance caused by η

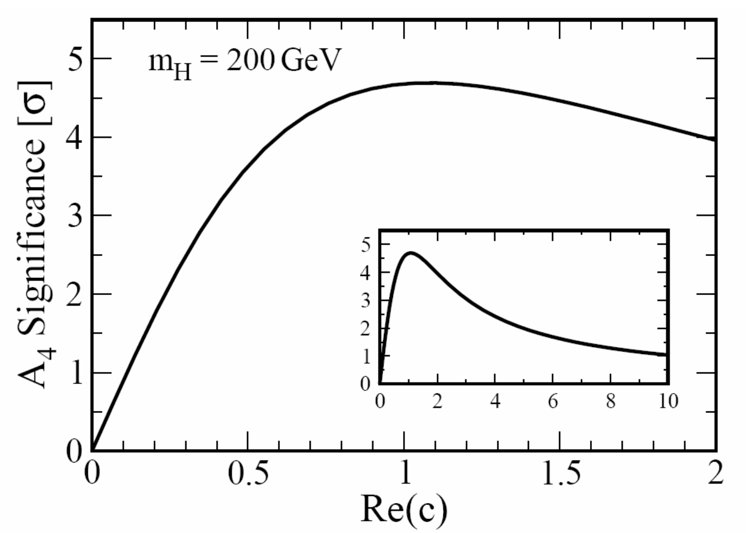
some other terms have no such supression

For example, $O_4 = \sin 2\phi$ probes $\Re$e(c)

$$\mathcal{A}_4 = \frac{1}{\tilde{\Gamma}} \int d^2\mathcal{P} \left[\frac{-2}{\pi}\right] a\Re e(c) x \gamma_b$$

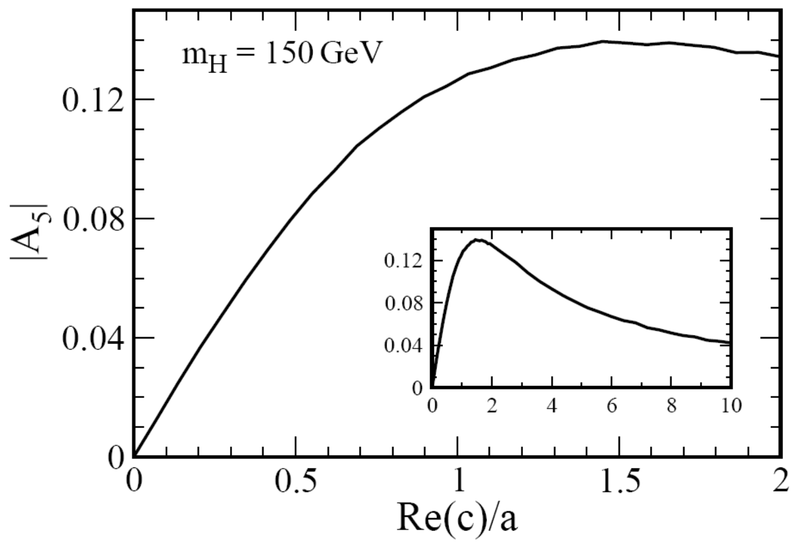
Provides bigger asymmetries and better exclusion 

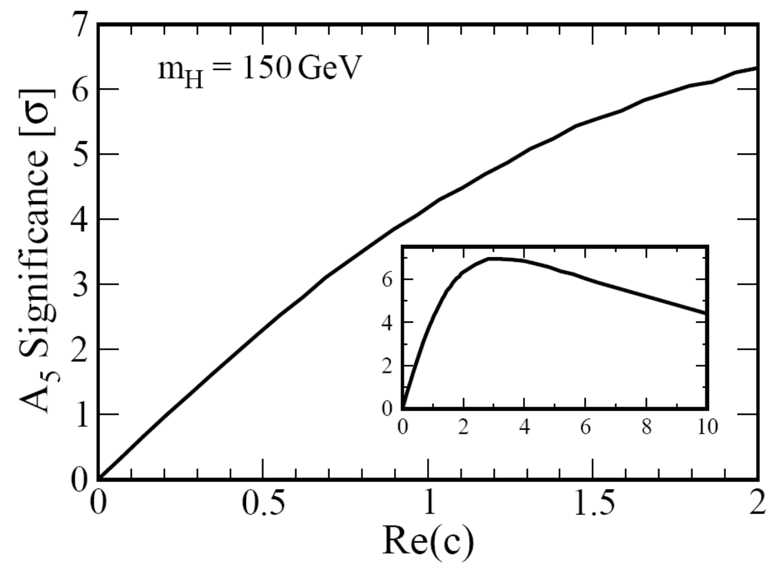




Complicated asymmetries which pick up multiple contributions do best.

e.g. $O_5 = \sin\phi\,[\cos\phi + \cot\theta_1 \cot\theta_2]$ probes $\Re$e(c)





$m_H = 150$ GeV
- Evidence (3σ) of CP violation for $\Re e(c) \gtrsim 0.66$
- Discovery (5σ) of CP violation for $\Re e(c) \gtrsim 1.28$

$m_H = 200$ GeV
- Evidence (3σ) of CP violation for $\Re e(c) \gtrsim 0.24$
- Discovery (5σ) of CP violation for $\Re e(c) \gtrsim 0.54$

Conclusions

- It is important to probe the structure of Higgs vertices at the LHC.
- We have investigated the HZZ vertex.
- The total rate does not probe CP-violation (but is still interesting)
- Asymmetries must be used to definitively study CP violation.
- Many asymmetries are small due to vector-axial interference, but can construct some which have reasonable sensitivity to new couplings.
- Can potentially provide exclusion limits on these couplings at the LHC.