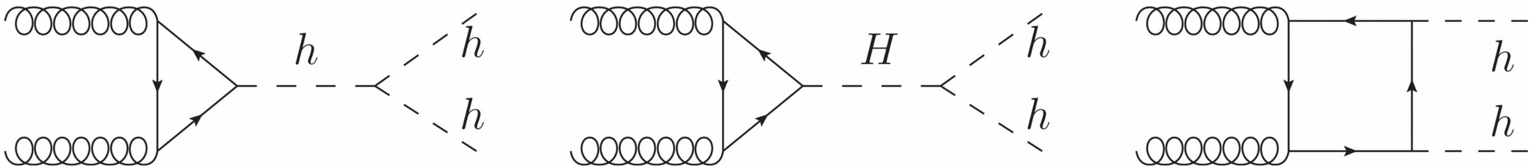
Interference Effects in Higgs Pairs

Ian Lewis
(University of Kansas)

Higgs Pairs 2022
Dubrovnik
June 1, 2022

Introduction

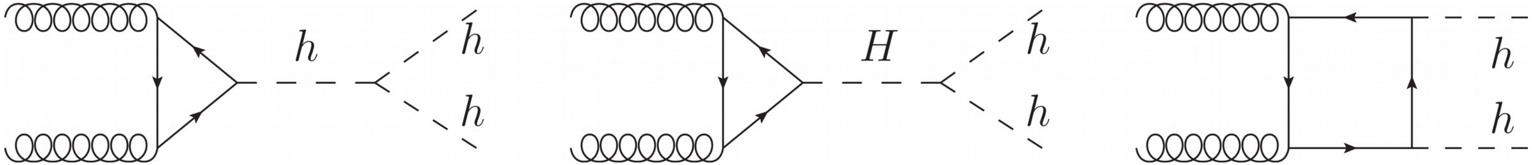


- Will cover various interference effects in resonant di-scalar production.
- Different types of interference:
  - Total interference effects.
  - "On-shell" interference effects.
  - Interference between overlapping resonances.
  - Cascade decays.
  - Contributions from new particles that do not resonantly produce di-Higgs.
- Will cover specific models for the most part.
- From different sources, so notation is not going to be consistent.

Resonance and Background Interference

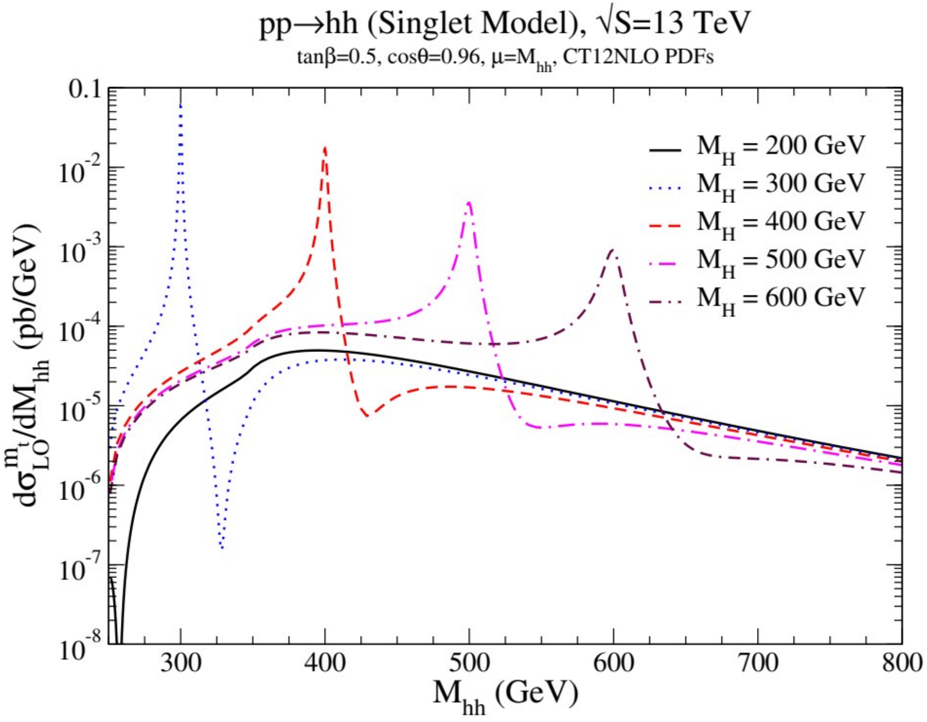
Singlet model

- Add a new scalar, S, with no charge under SM gauge group.
- Have two scalars: Higgs boson and a new singlet.
  - Obtain two mass eigenstates.
  - Singlet appears in the scalar potential, so has couplings to Di-Higgs.
  - Singlet mixes with SM-like Higgs with mixing angle θ
    - The only way it obtains couplings to other SM particles at the renormalizable level.
    - The effect is a universal suppression of SM-like Higgs couplings to SM particles.
  - Can get Di-Higgs resonances:



  - H is the heavy resonance, h is the SM-like Higgs.
  - Since it’s the simplest extension, useful model to look at Di-Higgs resonant production in.
  - “Background” will mostly be the SM-like contributions: box diagram and s-channel h.

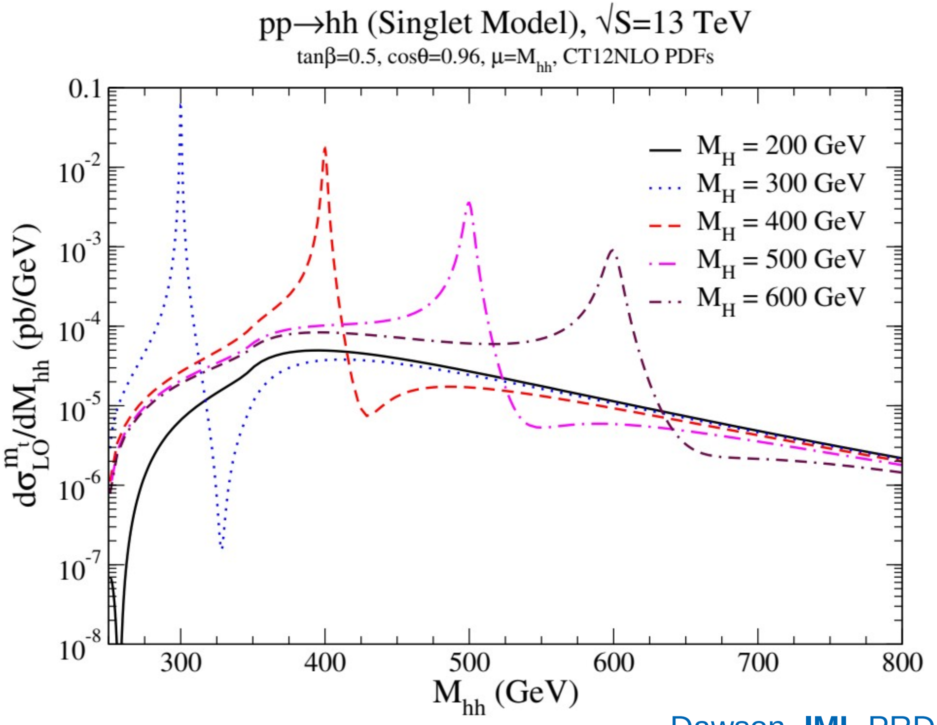
Total Interference

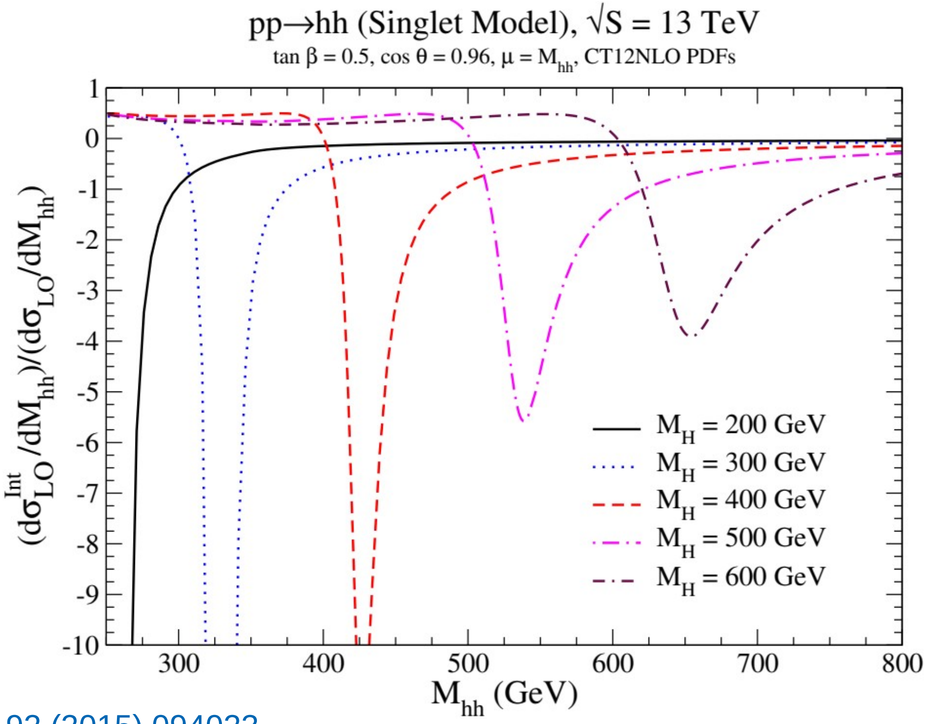


Dawson, **IML** PRD 92 (2015) 094023

- In the low energy tail, the distributions seem to converge as resonant mass gets larger.

Total Interference



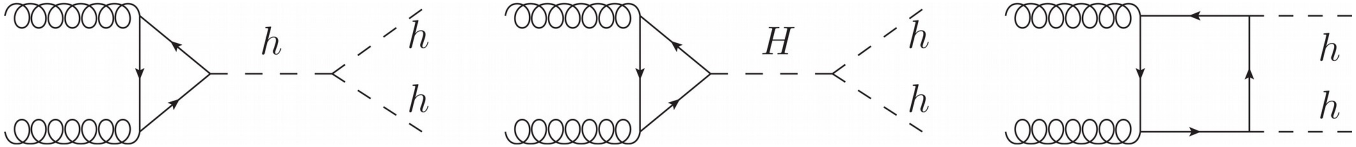


Dawson, **IML** PRD 92 (2015) 094023

- Define interference by subtracting off resonance, and SM-like contributions:

$$\frac{d\sigma_{LO}^{Int}}{dM_{hh}} = \frac{d\sigma_{LO}}{dM_{hh}} - \left(\frac{d\sigma_{LO}^{H}}{dM_{hh}} + \frac{d\sigma_{LO}^{h+Box}}{dM_{hh}} \right)$$

Total Interference Details



- Cross section:

$$\frac{d\hat{\sigma}^{m_t}_{LO}}{dt} = \frac{\alpha_s^2(\mu_R)}{2^{15}\pi^3 v^4}\left(\frac{|\, F_1(s,t,u,m_t^2)\,|^2 + |\, F_2(s,t,u,m_t^2)\,|^2}{s^2}\right)$$

$$\begin{aligned}
F_1(s,t,u,m_t^2) &\equiv F_1^{tri}(s,t,u,m_t^2) + F_1^{box}(s,t,u,m_t^2)\\
F_1^{tri}(s,t,u,m_t^2) &= -s\left(\frac{\cos\theta\lambda_{111}v}{s-m_h^2+im_h\Gamma_h} + \frac{\sin\theta\lambda_{211}v}{s-M_H^2+iM_H\Gamma_H}\right)F_\triangle(s,m_t^2)\\
F_1^{box}(s,t,u,m_t^2) &= s\cos^2\theta F_\square(s,t,u,m_t^2)\\
F_2(s,t,u,m_t^2) &= s\cos^2\theta G_\square(s,t,u,m_t^2)\,.
\end{aligned}$$

- In limit $m_h^2, s \ll M_H^2 \quad \lambda_{211} \propto M_H^2$

$$\begin{aligned}
F_1 \to\; & -s\left(\frac{\cos\theta\lambda_{111}v}{s-m_h^2+im_h\Gamma_h} + \frac{\sin\theta\sin 2\theta}{2}(\cos\theta+\sin\theta\tan\beta)\right)F_\triangle(s,m_t^2)\\
& + s\cos^2\theta F_\square(s,t,u,m_t^2).
\end{aligned}$$

Total Interference Details

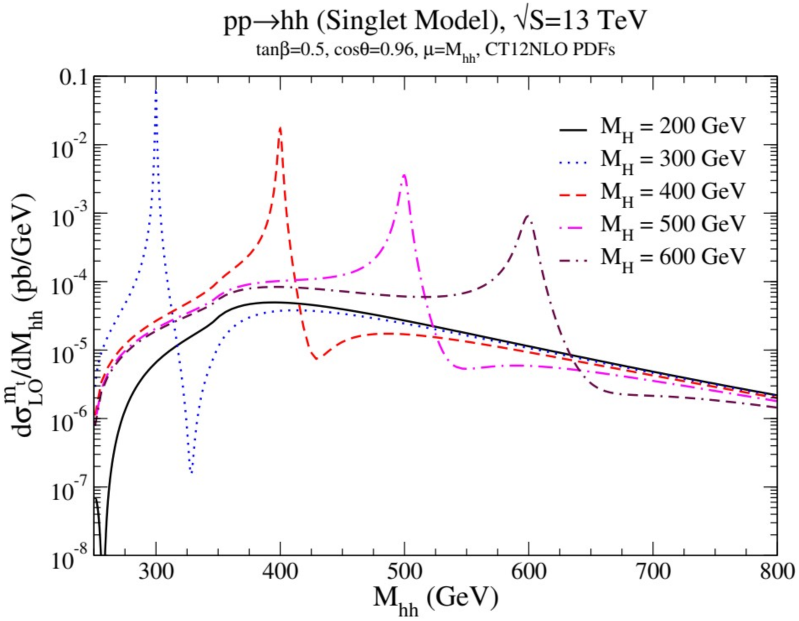
$$\frac{d\hat{\sigma}_{LO}^{m_t}}{dt} = \frac{\alpha_s^2(\mu_R)}{2^{15}\pi^3 v^4}\left(\frac{|\,F_1(s,t,u,m_t^2)\,|^2 + |\,F_2(s,t,u,m_t^2)\,|^2}{s^2}\right)$$

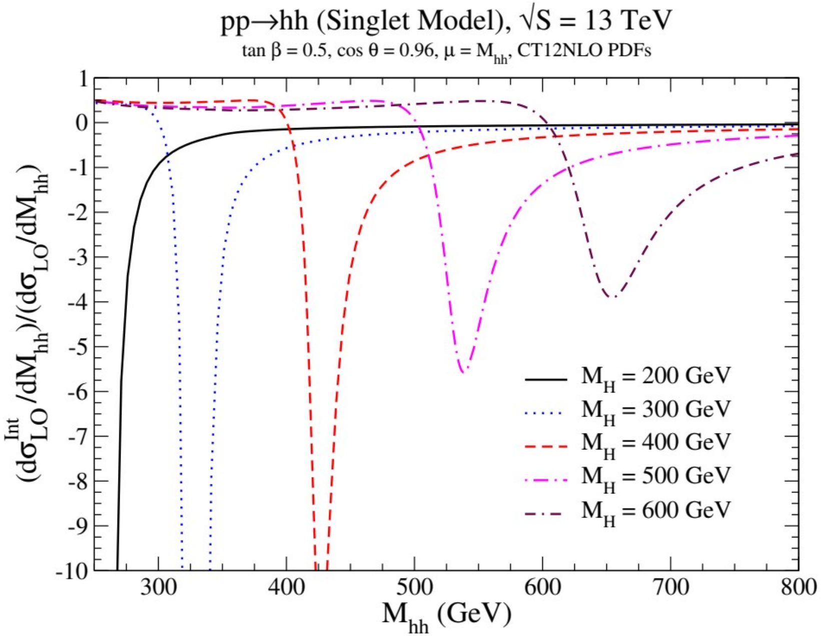
$$F_1 \rightarrow -s\left(\frac{\cos\theta\lambda_{111}v}{s-m_h^2+im_h\Gamma_h} + \frac{\sin\theta\sin 2\theta}{2}(\cos\theta+\sin\theta\tan\beta)\right)F_\triangle(s,m_t^2)$$
$$+s\cos^2\theta F_\Box(s,t,u,m_t^2).$$

- The point:
  - Low invariant mass independent of explicit dependence on heavy resonance mass.
  - For higher resonance masses, “low invariant mass” has larger contribution to total cross section due to longer low energy tail.
  - Interference contribution to total cross section will increase.

Ian Lewis
(University of Kansas)

Total Interference

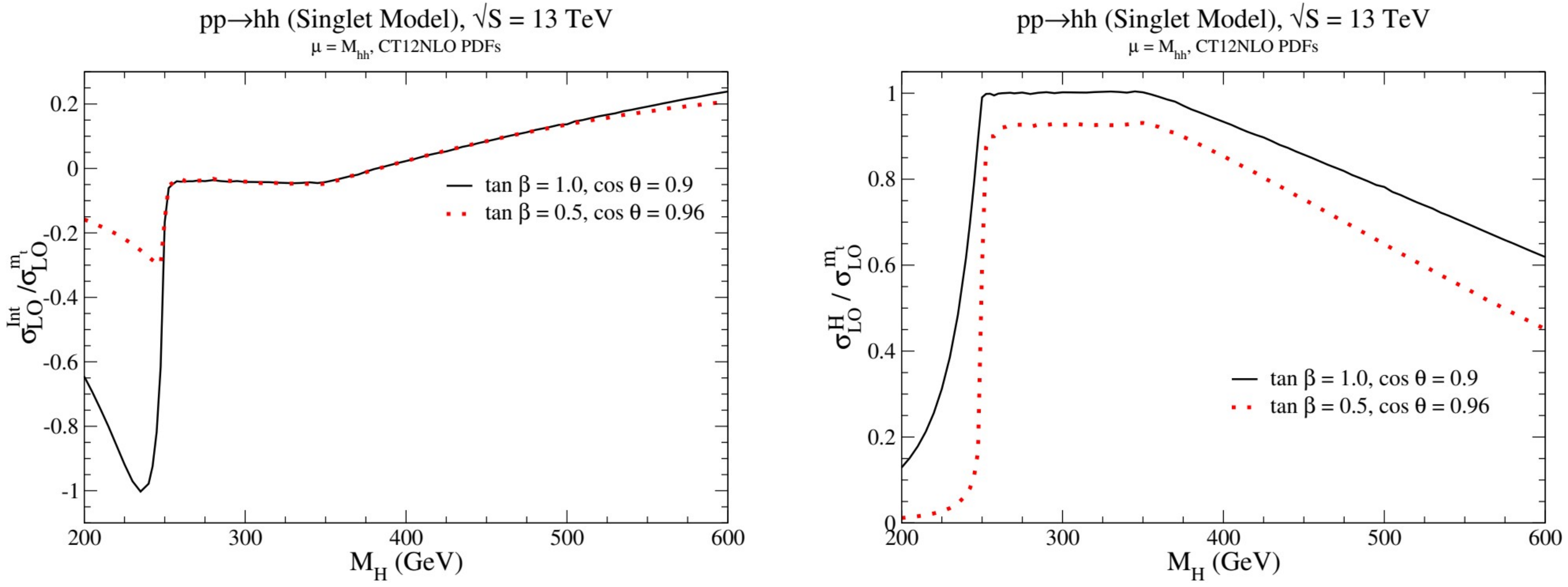




Dawson, **IML** PRD 92 (2015) 094023

- Can clearly see at invariant masses much below resonance mass all distributions are the same.

Total Interference



Dawson, **IML** PRD 92 (2015) 094023

- Contribution of interference to total cross section quite significant for very heavy resonances.
- Contribution from the actual resonance decreases with mass.

On-Shell Interference

- Previous effects coming from integrating over lower energy tails.
  - Most effect coming from far off-shell production.
- Can we cut around resonance mass and remove these interference effects?
- Parameterize resonance contribution:

$$A_{res} = a_{res} \frac{\hat{s}}{\hat{s} - m^2 + i\Gamma m}$$

- Interference between resonance and non-resonance:

$$|\mathcal{M}|^2_{int} = 2\,\mathrm{Re}(A_{res} \times A^*_{nr}) = 2\,(\mathcal{I}_{int} + \mathcal{R}_{int})$$

  - Contribution from imaginary part of resonant propagator (finite width effect)

$$\mathcal{I}_{int} \equiv |A_{nr}||a_{res}| \frac{\hat{s}\Gamma m}{(\hat{s} - m^2)^2 + \Gamma^2 m^2} \sin(\delta_{res} - \delta_{nr}),$$

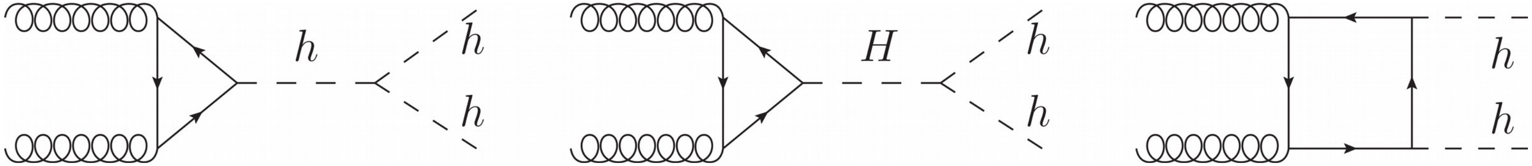
  - Contribution from real part of resonant propagator

$$\mathcal{R}_{int} \equiv |A_{nr}||a_{res}| \frac{\hat{s}(\hat{s} - m^2)}{(\hat{s} - m^2)^2 + \Gamma^2 m^2} \cos(\delta_{res} - \delta_{nr})$$

- δ_{res} δ_{nr} are complex phase other than the width.

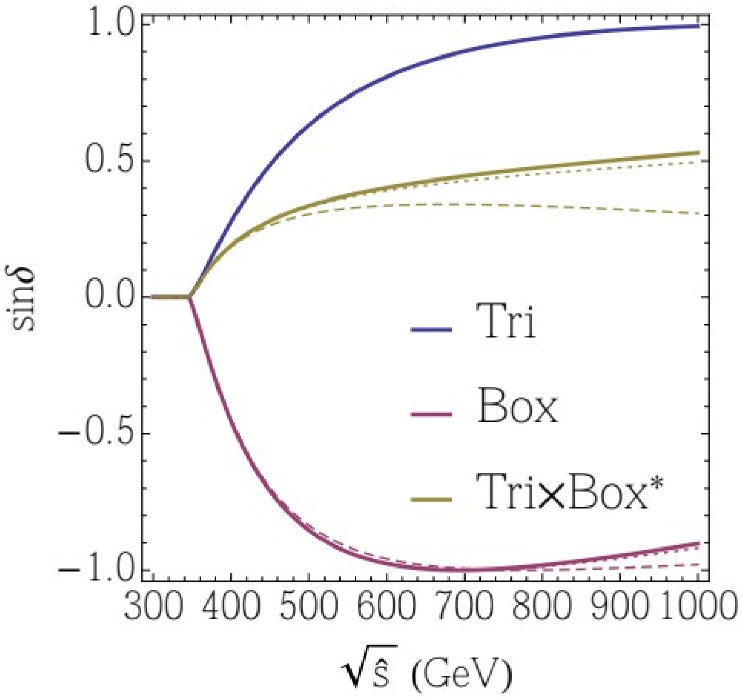
Carena, Liu, Riembau, PRD97 (2018) 095032

On-shell Interference



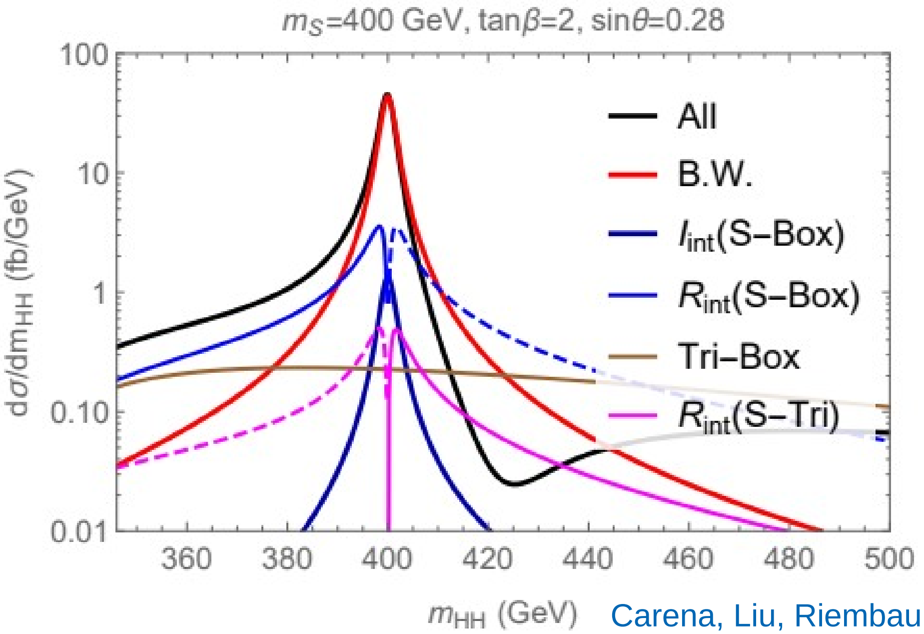
- Triangle and box diagrams have different phase after top threshold
- Interference from imaginary part of resonance propagator and box diagram can contribute when resonance on-shell:

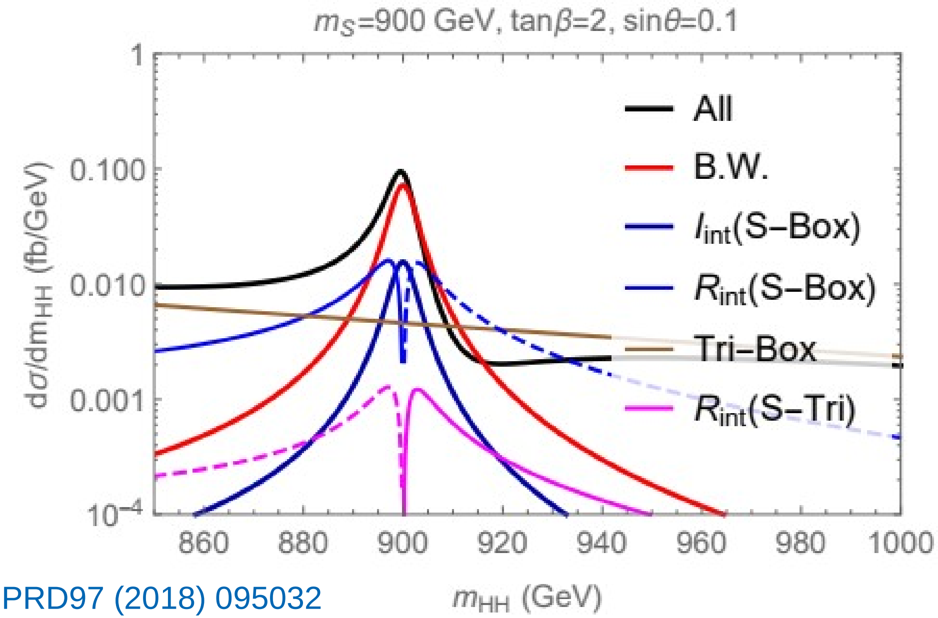
$$\mathcal{I}_{int} \equiv |A_{nr}||a_{res}| \frac{\hat{s}\Gamma m}{(\hat{s}-m^2)^2+\Gamma^2 m^2} \sin(\delta_{res}-\delta_{nr}),$$



Carena, Liu, Riembau, PRD97 (2018) 095032

On-Shell Interference



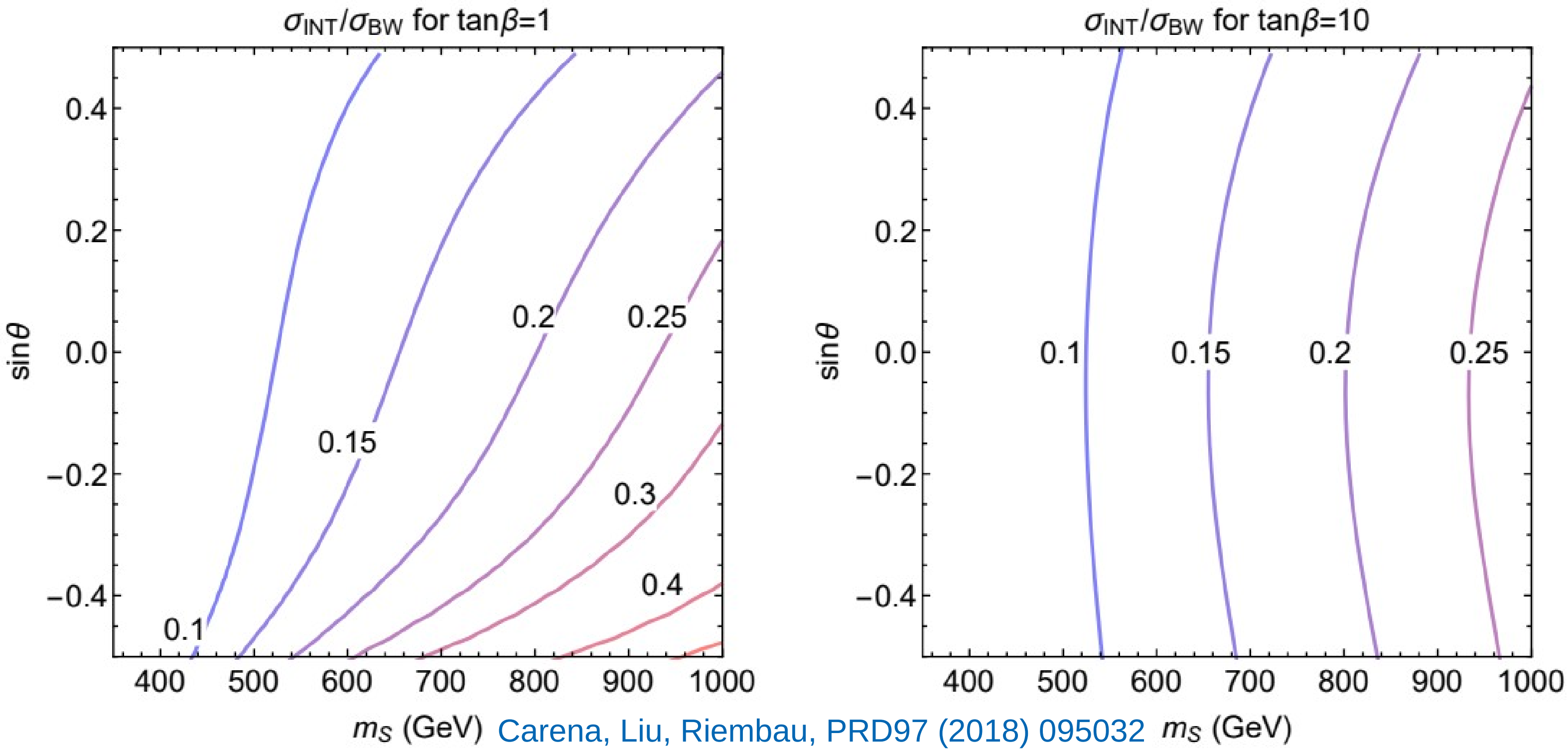


Carena, Liu, Riembau, PRD97 (2018) 095032

- Dashed lines: negative contribution to cross section.
- Inteference with real part of propagator flips sign across resonance.
- Interference with imaginary part of propagator behaves is similar to Breit-Wigner resonance.
- B.W. = Breit-Wigner.

$$\mathcal{I}_{int} \equiv |A_{nr}||a_{res}|\frac{\hat{s}\Gamma m}{(\hat{s}-m^2)^2+\Gamma^2 m^2}\sin(\delta_{res}-\delta_{nr}), \quad \mathcal{R}_{int} \equiv |A_{nr}||a_{res}|\frac{\hat{s}(\hat{s}-m^2)}{(\hat{s}-m^2)^2+\Gamma^2 m^2}\cos(\delta_{res}-\delta_{nr})$$

On-Shell Interference

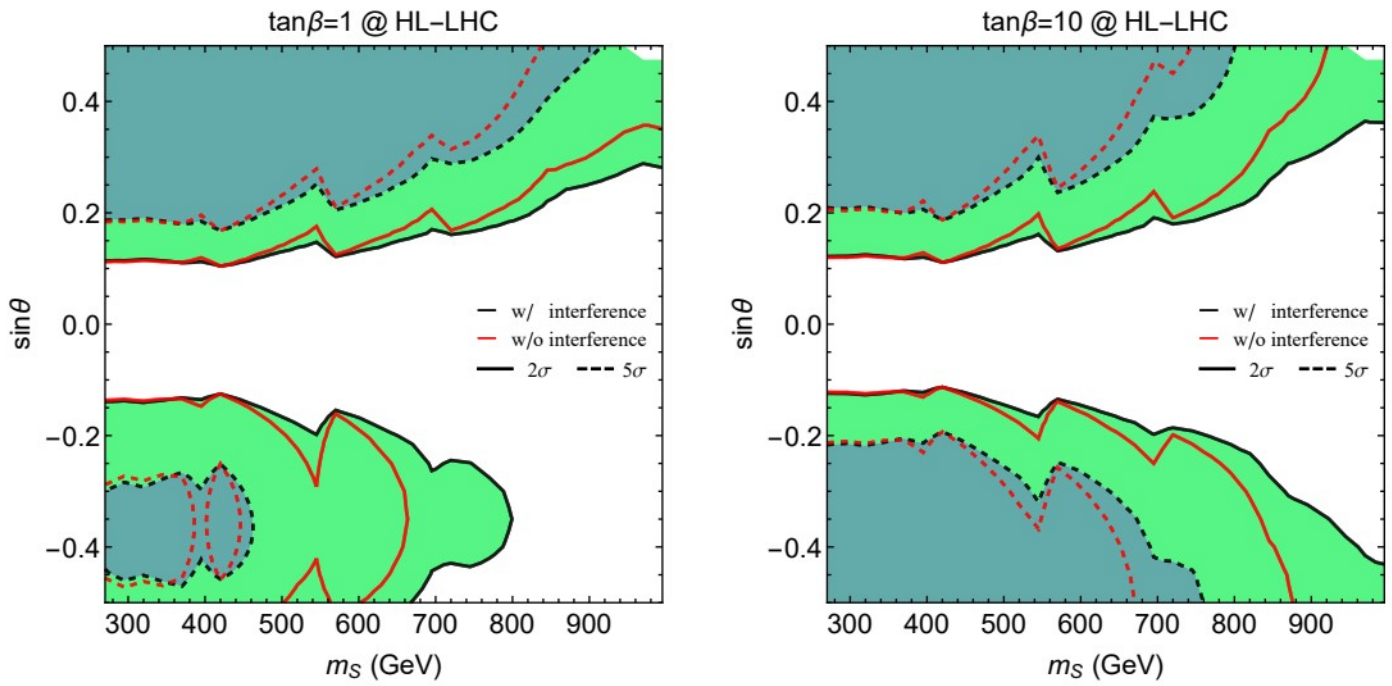


Carena, Liu, Riembau, PRD97 (2018) 095032

- Size of interference effects on the mass peak can be significant at high resonance masses.
- Current constraints from precision Higgs measurements: $|\sin\theta|<0.2$

Adhikari, Lane, **IML**, Sullivan arXiv:2203.07455

On-Shell Interference



Carena, Liu, Riembau, PRD97 (2018) 095032

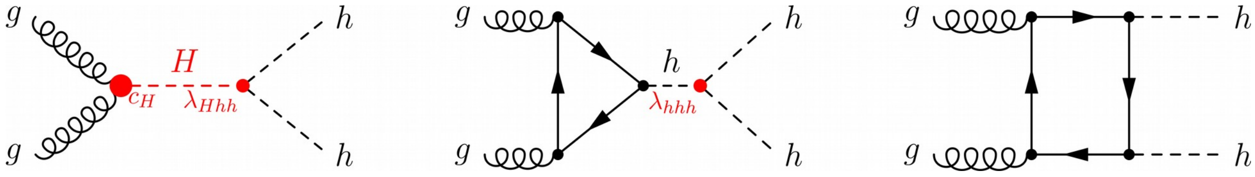
- Current constraints from precision Higgs measurements: $|\sin\theta| < 0.2$ Adhikari, Lane, **IML**, Sullivan arXiv:2203.07455

Quantifying Overall Interference

- Parameterize interaction of new resonance as effective interaction:

$$L \supset \frac{\alpha_s}{12\pi v} c_H \, H G^a_{\mu\nu} G^{a,\mu\nu}$$

  - $c_\varphi = |c_\varphi| e^{i\theta_\varphi}$ is allowed to be complex to account for possible phases from thresholds in loops.



- Define signal, background, and interference:
  - $\frac{d\sigma_S}{dm_{hh}}$ is resonant signal
  - $\frac{d\sigma_B}{dm_{hh}}$ is SM-like contributions
  - $\frac{d\sigma_I}{dm_{hh}}$ is the interference

Bagnaschi, Carvalho, Gröber, Liebler, Quevillon
arXiv:1803.10379, Rev.Phys. 5 (2020) 100045

- Perform a scan:

$$|c_H| \in [0.001, 5], \quad \theta_H \in \{0, \frac{\pi}{4}, \frac{\pi}{2}\}, \quad m_H \in [0.3, 1.4]\,\text{TeV}, \quad \Gamma_H/m_H \in [10^{-4}, 0.2]. \qquad \lambda_{hhh} \in (0,1,2)\lambda_{hhh}^{SM}$$

Bagnaschi, Carvalho, Gröber, Liebler, Quevillon
arXiv:1803.10379, Rev.Phys. 5 (2020) 100045

Quantifying Interference

- Define parameters for ratio of interference to total cross section.

$$\eta = \int_{m_H-10\Gamma_H}^{m_H+10\Gamma_H} dm_{hh}\left(\frac{d\sigma_S}{dm_{hh}}+\frac{d\sigma_I}{dm_{hh}}\right)\Big/\int_{m_H-10\Gamma_H}^{m_H+10\Gamma_H} dm_{hh}\left(\frac{d\sigma_S}{dm_{hh}}\right),$$

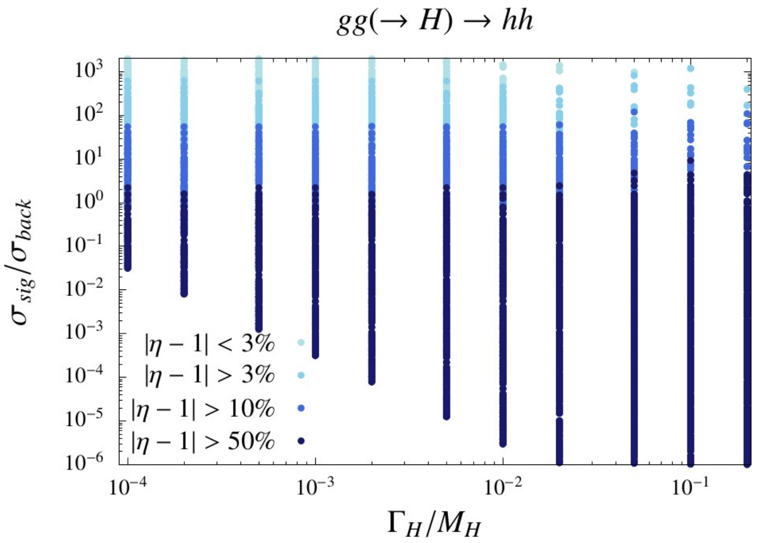
$$\eta_- = \int_{m_H-10\Gamma_H}^{m_{hh}^I} dm_{hh}\left(\frac{d\sigma_S}{dm_{hh}}+\frac{d\sigma_I}{dm_{hh}}\right)\Big/\int_{m_H-10\Gamma_H}^{m_{hh}^I} dm_{hh}\left(\frac{d\sigma_S}{dm_{hh}}\right),$$

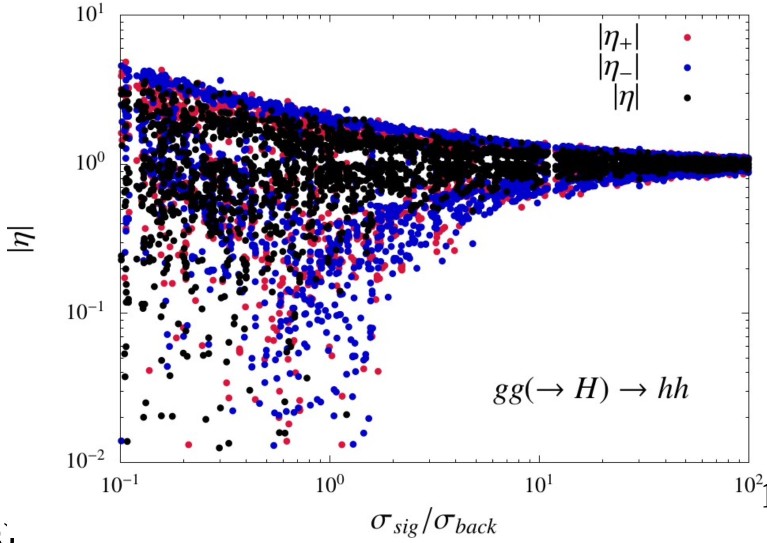
$$\eta_+ = \int_{m_{hh}^I}^{m_H+10\Gamma_H} dm_{hh}\left(\frac{d\sigma_S}{dm_{hh}}+\frac{d\sigma_I}{dm_{hh}}\right)\Big/\int_{m_{hh}^I}^{m_H+10\Gamma_H} dm_{hh}\left(\frac{d\sigma_S}{dm_{hh}}\right).$$

- Define signal and background in resonant region:

$$\sigma_{sig} = \int_{m_H-10\Gamma_H}^{m_H+10\Gamma_H} dm_{hh}\frac{d\sigma_S}{dm_{hh}} \quad \sigma_{back} = \int_{m_H-10\Gamma_H}^{m_H+10\Gamma_H} dm_{hh}\frac{d\sigma_B}{dm_{hh}}$$

- Relative size of interference mostly dependent on relative size of signal and background.
  - Previous shown finite width effects on resonance were order 10% corrections.
  - This study also showed that when signal/background is around 10, interference can enhance the signal by around 50%





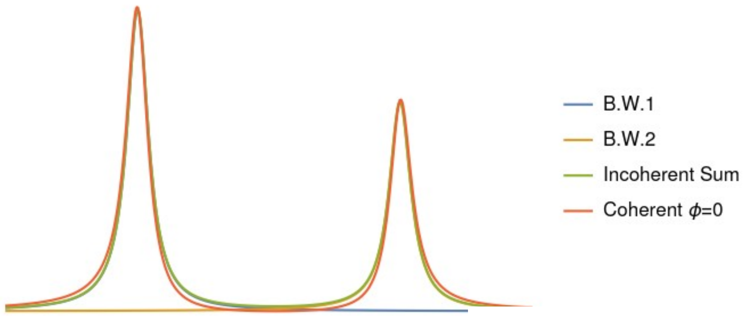
Overlapping resonances

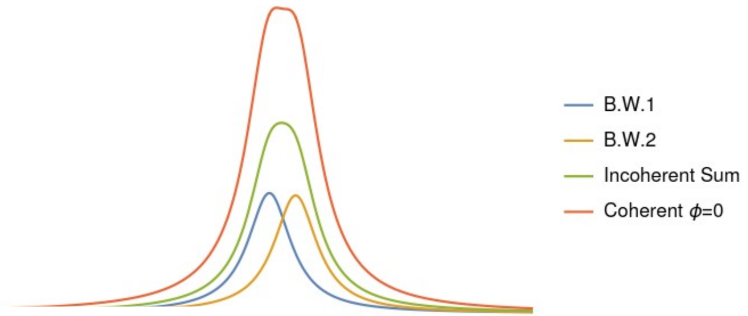
Two Overlapping Resonances

- "Signal-signal" interference can be quite important as well.
- Parameterize two resonances as Breit-Wigners with a relative phase (purely illustrative, very simplified):

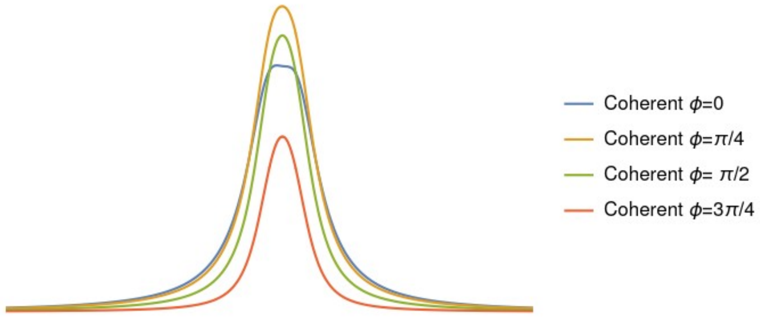
$$\frac{1}{s-m_1^2+i\Gamma_1 m_1}+\frac{e^{i\phi}}{s-m_2^2+i\Gamma_2 m_2}$$

  - Comparing well-separated and overlapping:





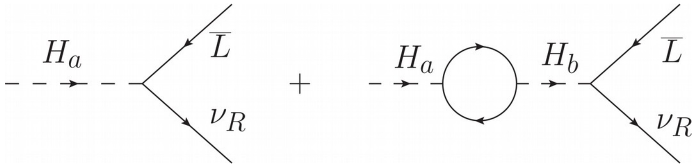
  - Changing the relative phase:



Real Model: Baryogenesis From Higgs Decays

Davoudiasl, **IML**, Sullivan, PRD101 (2020) 055010, PRD104 (2021) 015024

- Consider 3HDM model with two heavy doublets.
- Asymmetry decay of a heavy doublet into leptons can create a lepton asymmetry that becomes a baryon asymmetry:



- Asymmetry parameter that governs the magnitude of the baryon asymmetry generated:

$$\varepsilon_a = \frac{1}{8\pi}\frac{(m_b^2 - m_a^2)m_a^2}{(m_b^2 - m_a^2)^2 + m_b^2\Gamma_b^2}\frac{\sum_{f=q} N_{c,f}\mathrm{Im}\left(\mathrm{Tr}_\nu^{ba}\mathrm{Tr}_f^{ba*}\right)}{\sum_{f=q} N_{c,f}\mathrm{Tr}_f^{aa}}$$

- All else being equal, expanding about a small width, this expression is maximized when

$$\frac{m_a}{m_b} = \pm\frac{\Gamma_b}{2m_b}$$

- That is, to generate the baryon asymmetry with TeV or 10s of TeV scale Higgses, this model would prefer degenerate Higgs doublets.
- There are two heavy neutral CP even states, two neutral CP odd states, and four charged states.
- With this degeneracy, interference effects can be important.

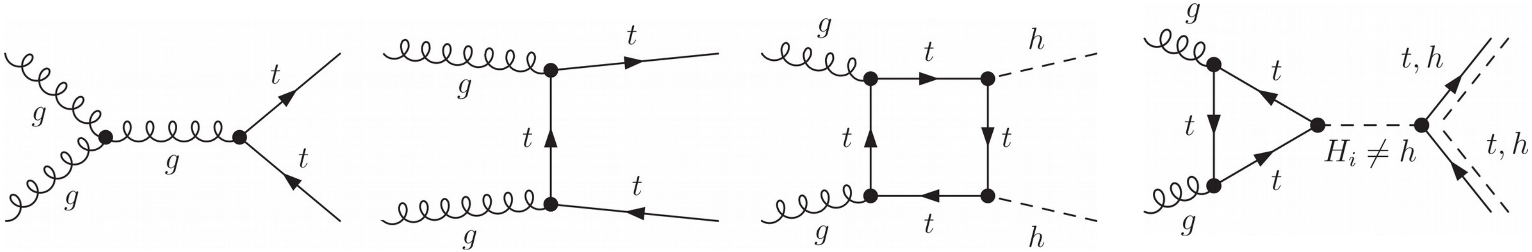
Real Model: C2HDM

Basler, Dawson, Englert, Mühlleitner, PRD101 (2020) 015019

- In real 2HDM, have two heavy neutral CP eigenstates, H and A.
  - EW precision prefers components of Higgs double to be somewhat degenerate in mass
- In complex 2HDM, H and A can mix because CP is violated.
  - Now the resonance can interfere:

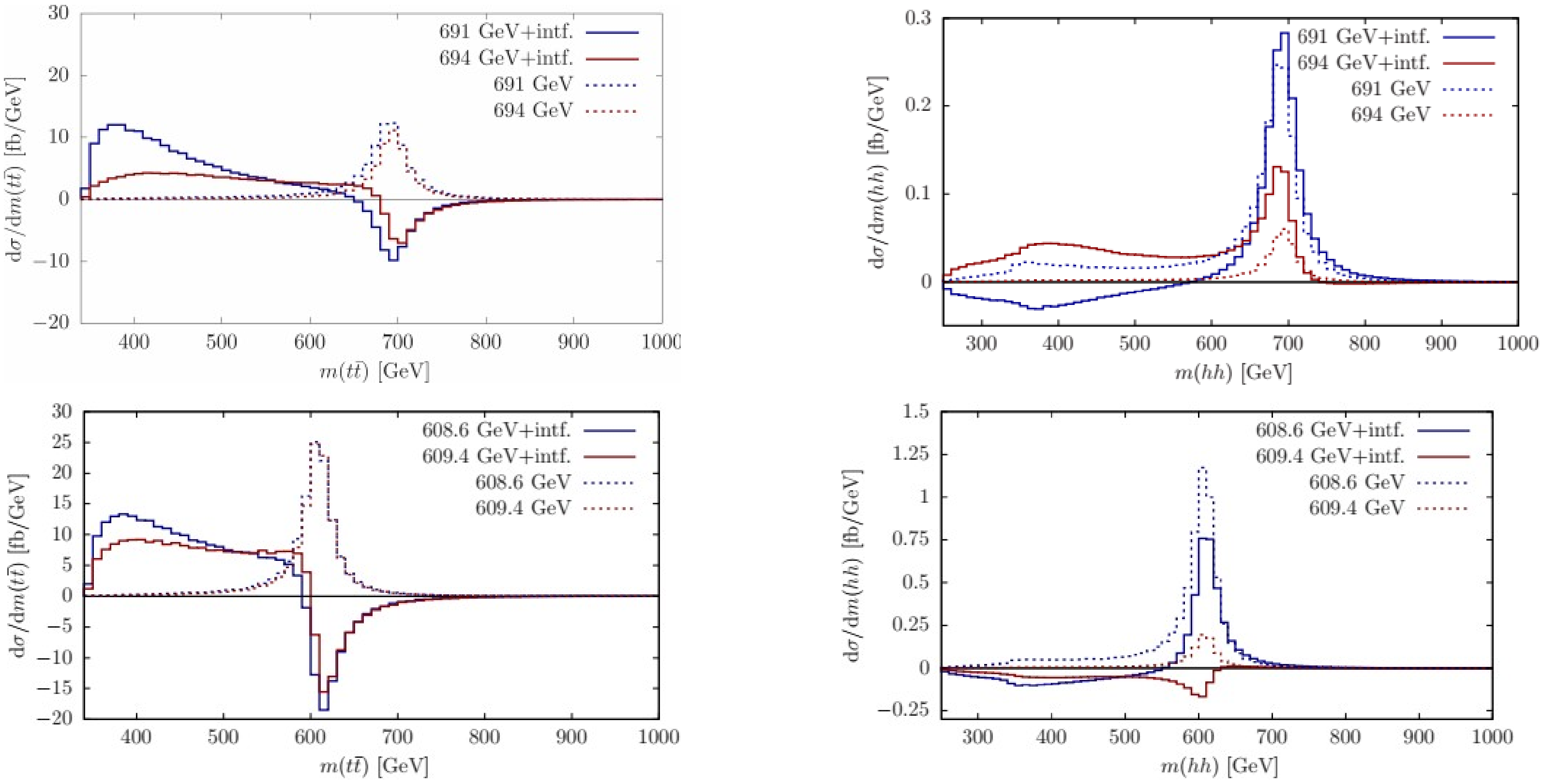
- Results presented were showing that interference in Di-Higgs could help resolve destructive interference between resonance and the continuum background in $t\bar{t}$ pair production, when there are complex phase between signal and background:

Gaemers, Hoogeveen, PLB146 (1984) 347; Dicus, Stange, Willenbrock, PLB333 (1994) 126; Jung, Song, Yoon, PRD92 (2015) 055009; Carena, Liu, JHEP11 (2016) 159; etc. etc.



C2HDM

Basler, Dawson, Englert, Mühlleitner, PRD101 (2020) 015019



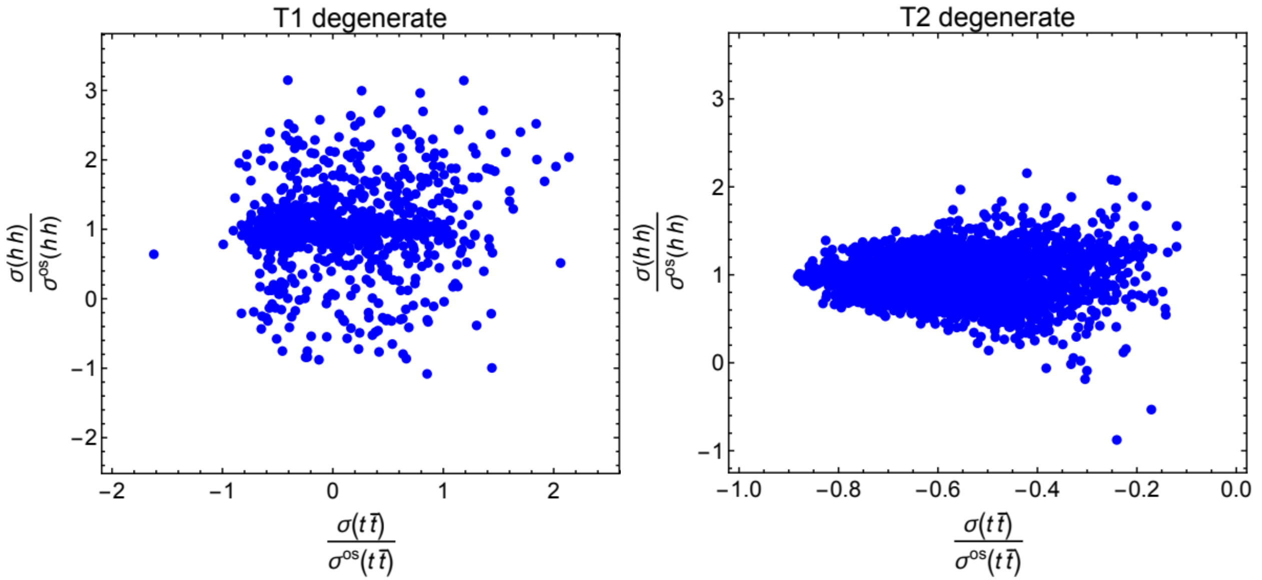
- Signal-signal interference effects may enhance Di-Higgs resonant signal when $t\bar{t}$ is suppressed.
- Even when Di-Higgs is suppressed, effect may not be as large as in $t\bar{t}$

C2HDM

- Degenerate = masses within 10% of each other
- Scan parameters:

	t_β	$\alpha_{1,2,3}$	$\mathrm{Re}(m_{12}^2)$ [TeV^2]	$m_{H^\pm}$ [TeV]	$m_{H_{i,j\neq h}}$ [TeV]
min	0.8	$-\frac{\pi}{2}$	0	0.15/0.59	0.125
max	20	$\frac{\pi}{2}$	0.5	1.5	1.5

TABLE II: C2HDM scan: All parameters are varied independently between the given minimum and maximum values. The two minimum values of the charged Higgs mass range refer to the scan in the C2HDM T1 and T2, respectively. For more details, see text.



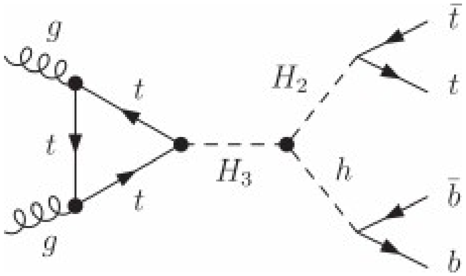
Basler, Dawson, Englert, Mühlleitner, PRD101 (2020) 015019

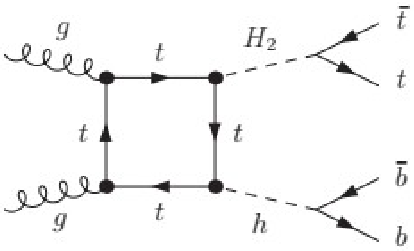
Interference in cascade decays

Interference in Cascade Decays

Atkinson, Englert, Sylianou, PLB821 (2021) 136618

- Signal:



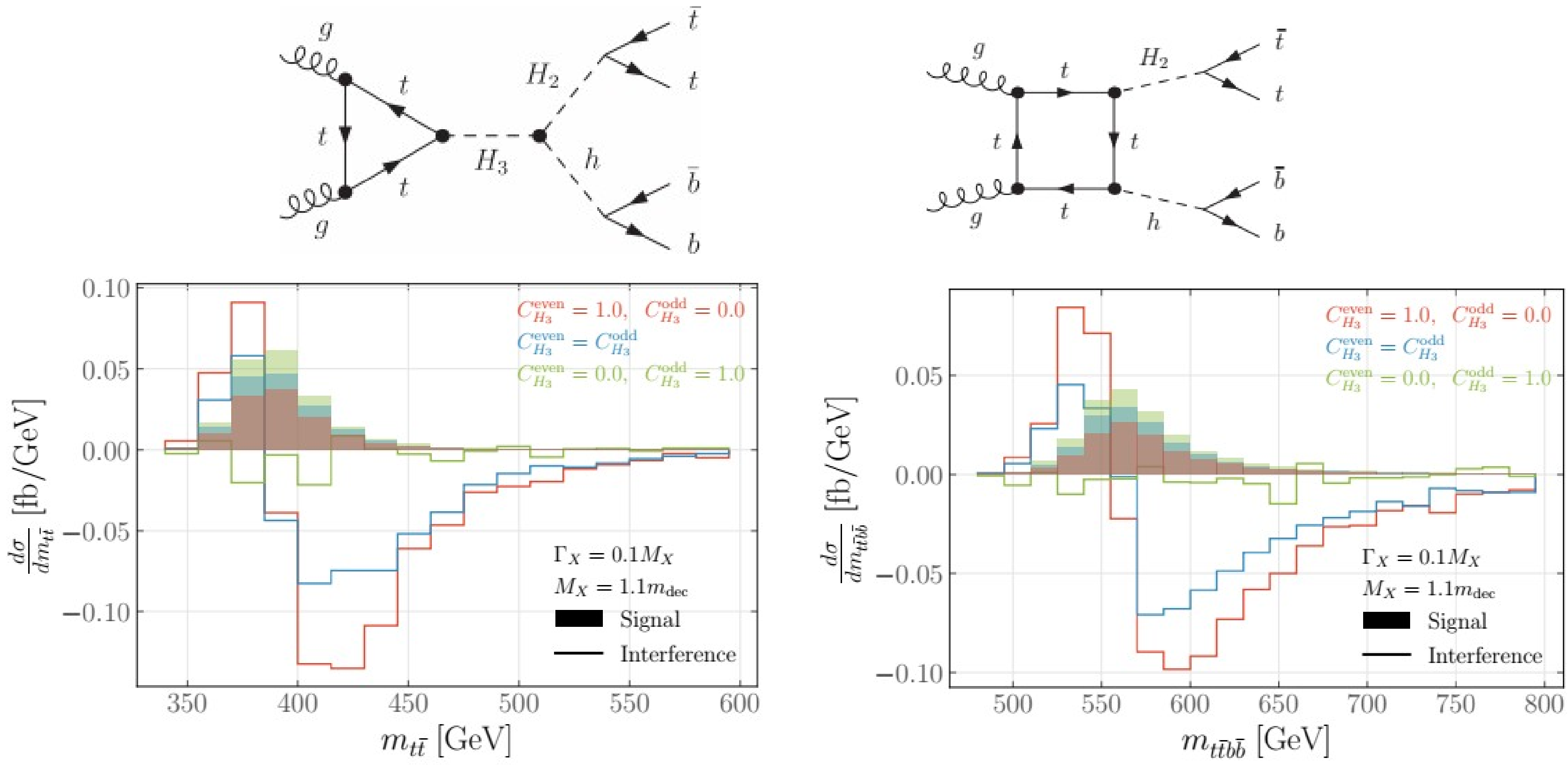


- Very simplified model can in principle get sizeable interference with SM backgrounds:

$$
\begin{aligned}
\mathcal{L} = \mathcal{L}_{\rm SM} + \\
\sum_{i=2,3} \frac{H_i}{v} \left[C^{\rm even}_{H_i} \frac{g_s^2}{16\pi^2} G^a_{\mu\nu} G^{a\mu\nu} + C^{\rm odd}_{H_i} \frac{g_s^2}{16\pi^2} G^a_{\mu\nu} \widetilde{G}^{a\mu\nu} \right] \\
- \frac{\lambda_{H_2hh}}{2} H_2 h^2 - \frac{\lambda_{H_3hh}}{2} H_3 h^2 - \lambda_{H_3H_2h} H_3 H_2 h \\
- y^E_{H_3} \frac{m_t}{v} H_3 \bar{t}_L t_R - y^E_{H_2} \frac{m_t}{v} H_2 \bar{t}_L t_R + \text{h.c.} \\
- i y^O_{H_3} \frac{m_t}{v} H_3 \bar{t}_L t_R - i y^O_{H_2} \frac{m_t}{v} H_2 \bar{t}_L t_R + \text{h.c.}\ .
\end{aligned}
$$

Interference in Cascade Decays

Atkinson, Englert, Sylianou, PLB821 (2021) 136618

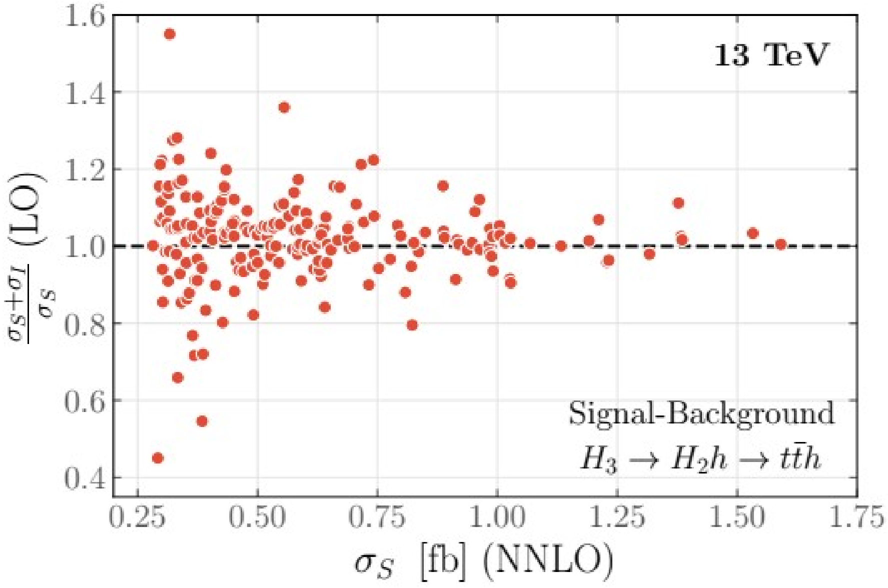


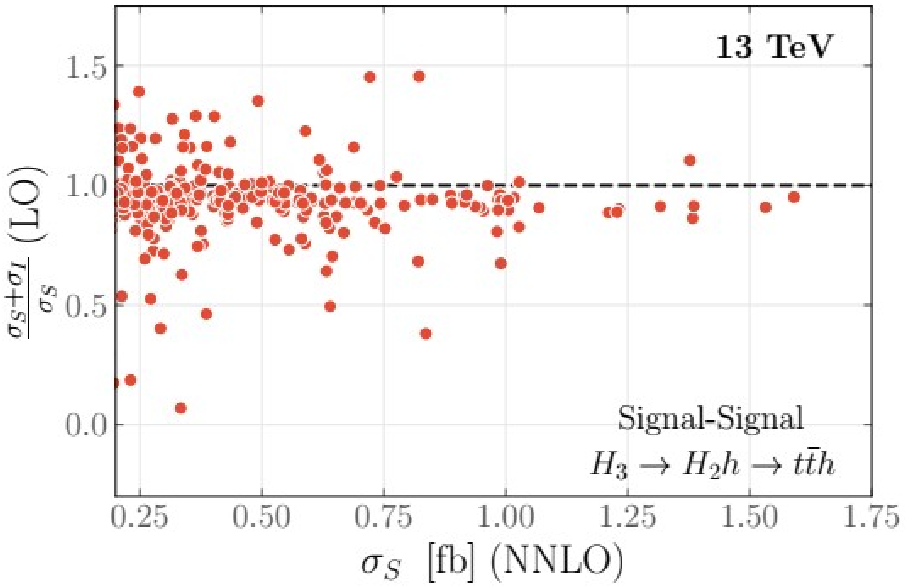
- In very simplified model can get strong effects.
- Look at real simplified model: SM extended by two real singlets.

Two Singlet Scalar Model

Atkinson, Englert, Sylianou, PLB821 (2021) 136618

- Add two real singlet scalars to SM.
  - Give each a separate Z_2. Barger et al PRD79 (2009) 015018; Costa, Mühlleitner, Sampaio, Santos JHEP 06 (2016) 034; Robens, Stefaniak, Wittbrodt, EPJC (2020) 80, etc.
- Performed a scan requiring agreement with Higgs precision measurements, EW precision:
  - Considering a mass window of 15% around the resonance mass.

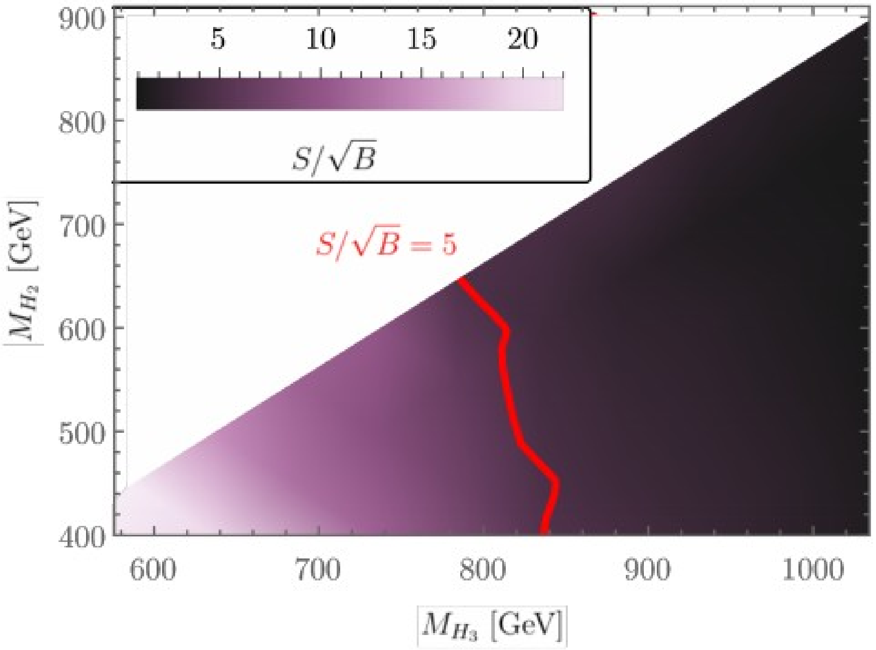


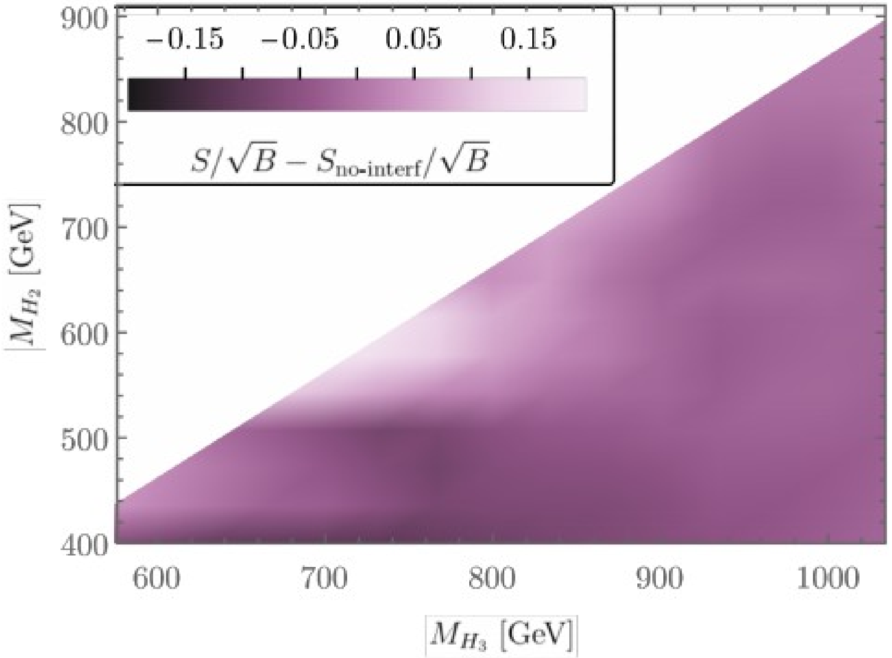


Two Singlet Model

Atkinson, Englert, Sylianou, PLB821 (2021) 136618

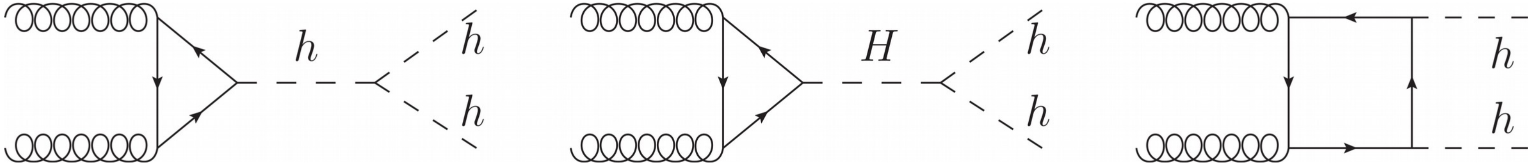
- Impact on significances:
  - Set branching ratios $\mathrm{BR}(H_3 \to H_2 h) \sim 0.5$ and $\mathrm{BR}(H_2 \to t\bar{t}) \sim 1$
  - LEFT: total signal
  - RIGHT: subtracting off non-interfering signal prediction:





Non-Resonant Considerations

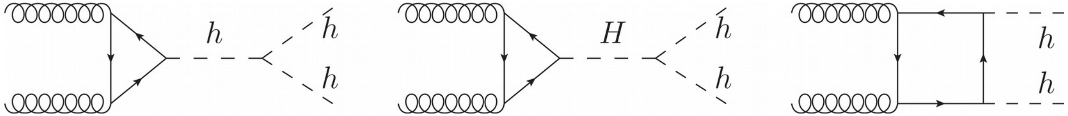
Non-resonant contributions in Singlet Model



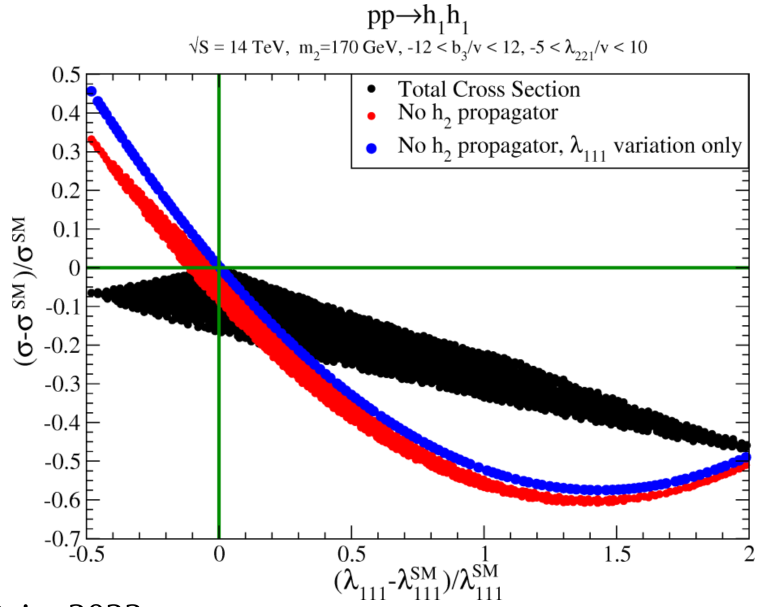
- The new scalar does not have to be above the Di-Higgs threshold.
  - Perfectly well-allowed.
  - Can still motivate by things like electroweak phase transition.
- It will still contribute to the non-resonant Di-Higgs production.
  - This is not captured by varying the Higgs trilinear, Higgs-top Yukawa, or the Higgs-gluon interactions.
- The addition of these diagrams to the non-resonant production can have significant impact in our interpretation of Di-Higgs production rates.
- See also H. Alhazmi’s talk tomorrow afternoon.

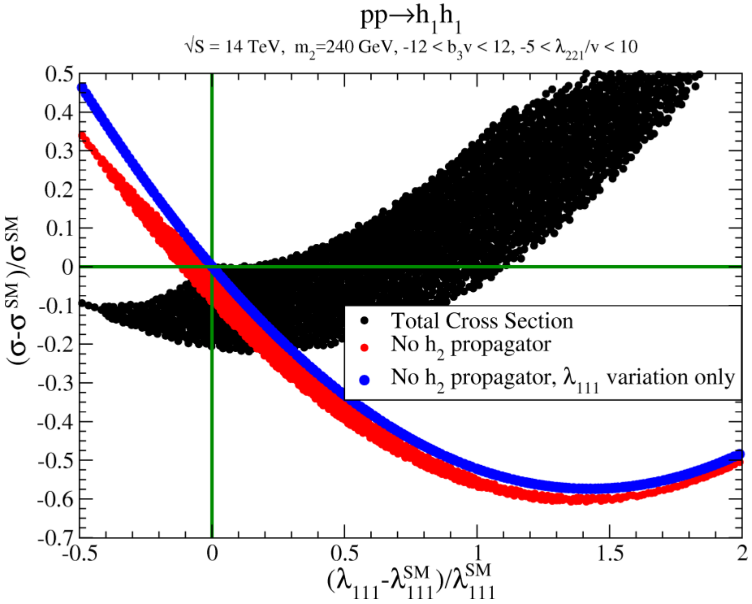
Cross Section vs. Higgs Trilinear

- Variations within the model:
  - Blue: only SM-like Higgs trilinear
  - Red: SM-like Higgs trilinear and top Yukawa
  - Black: all contributions
- The new diagram weakens the correlation between cross section and Higgs trilinear.



Chen, Kozaczuk, **IML** JHEP 08 (2017) 096





Summary

- Interference effects in di-scalar production can be interesting in many scenarios.
- Considered interference effects in many scenarios, in mostly model specific variations.
  - Di-Higgs production with one resonance:
    - Single singlet scalar.
    - Interference effects off the mass peak are significant.
    - Finite width effects on the mass peak can be significant.
  - Di-Higgs production with two resonances:
    - Complex 2HDM.
    - Interference between overlapping resonances can significantly increase signal cross sections
  - Cascade/asymmetric decays:
    - In principle can have large interference effects, but in the specific model was less important.
  - Di-Higgs with new s-channel propagator below threshold:
    - Can have significant impacts on the correlation between total non-resonant Di-Higgs rate and the Higgs trilinear.

Thank You