Comments on Interference Effects on Di- Higgs Boson Production

Double Higgs Production at Colliders Workshop @ Fermilab

Marcela Carena

Fermilab and UChicago

Fermilab, Spetember 7, 2018

Interference Effects in Di-Higgs Production: gg → S → HH

Models with additional singlets open a door for strong first order phase transitions

Singlet extension of the SM can serve as a benchmark, challenging to test at colliders

- Consider case of Spontaneous Z_2 breaking
- Find that interference effect can enhance di-Higgs production up to 40%, improving LHC reach

$$V(s,\phi) = -\mu^2\phi^\dagger\phi - \frac{1}{2}\mu_s^2 s^2 + \lambda(\phi^\dagger\phi)^2 + \frac{\lambda_s}{4}s^4 + \frac{\lambda_{s\phi}}{2}s^2\phi^\dagger\phi,$$

spontaneous symmetry breaking defines μ^2 and μ^2_S in terms of the original quartic couplings & the vevs

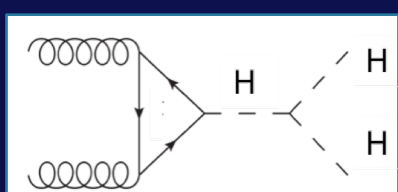
Parameters in the potential can be traded by

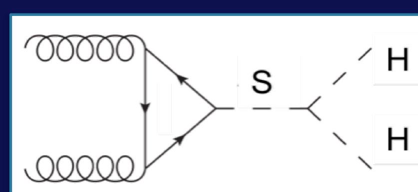
m_H =125 GeV, v=246 GeV

m_S, $\tan_\beta(=v_s/v)$, $\sin\theta$,

Besides singlet-doublet mixing governed by $\sin\theta$, di-Higgs final states are characterized by two trilinear coupling:

$$L \supset \lambda_{HHH}H^3 + \lambda_{SHH}SH^2.$$





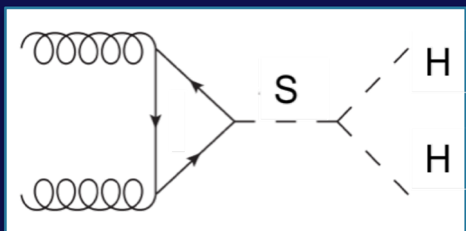
$$\lambda_{HHH} = -\frac{m_H^2}{2\tan\beta\, v}\left(\tan\beta\cos^3\theta - \sin^3\theta\right),$$

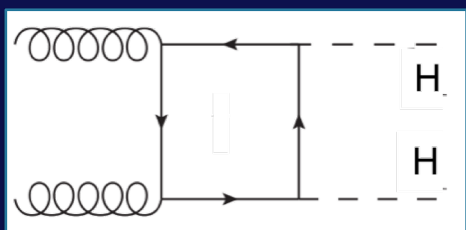
$$\lambda_{SHH} = -\frac{m_H^2}{2\tan\beta\, v}\sin 2\theta(\tan\beta\ \cos\theta + \sin\theta)(1 + \frac{m_S^2}{2m_H^2}).$$

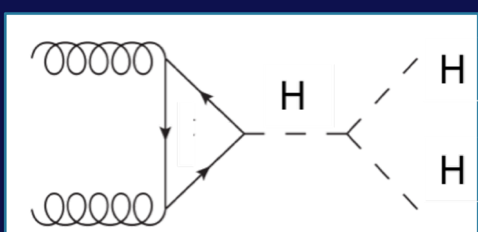
Interference Effects in Di-Higgs Production: gg → S → hh

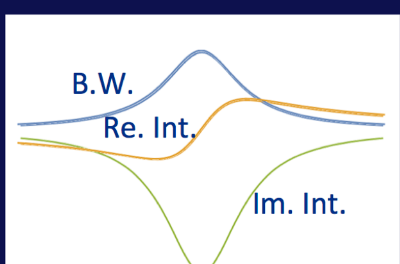
Models with additional singlets open a door for a strong first order phase transition

Singlet extension of the SM can serve as a benchmark, challenging to test at colliders









$$A^S_\Delta = A_{gg-S\to hh} = c_\Delta \frac{\hat{s}}{\hat{s} - m^2 + i\,\Gamma m}$$

$$A^H_\Box = A_{gg\to hh} = c_\Box \text{(slowing varying function of } \hat{s}\text{)}$$

$$A^H_\Delta = A_{gg\to h^*\to hh} = c'_\Delta \text{ (slowing varying function of } \hat{s}\text{)}$$

Inter. Term.		rel. phase	proportionality	Inter. Sign
$A^H_\triangleright$-$A^H_\Box$	$\mathcal{R}_{int}$	$\cos(\delta_\triangleright - \delta_\Box)$	$\cos^3\theta\lambda_{HHH}$	$-$
	$\mathcal{I}_{int}$	$\sin(\delta_\triangleright - \delta_\Box)$	0^*	0
$A^S_\triangleright$-$A^H_\triangleright$	$\mathcal{R}_{int}$	1	$\lambda_{SHH}\lambda_{HHH}\cos\theta\ \sin\theta$	$-/+$
	$\mathcal{I}_{int}$	0	$\lambda_{SHH}\lambda_{HHH}\cos\theta\ \sin\theta$	0
$A^S_\triangleright$-$A^H_\Box$	$\mathcal{R}_{int}$	$\cos(\delta_\triangleright - \delta_\Box)$	$\lambda_{SHH}\cos^2\theta\sin\theta$	$+/-$
	$\mathcal{I}_{int}$	$\sin(\delta_\triangleright - \delta_\Box)$	$\lambda_{SHH}\cos^2\theta\sin\theta$	$+$

M.C. Z. Liu and M. Riembau. ‘18

Di-Higgs Production and Interference effects

$A_{sig} = c_{sig} \frac{\hat{s}}{\hat{s} - m^2 + i\,\Gamma m} = c_{sig}\,\mathrm{P}(\hat{s})$ $A_{bkg} = c_{bkg}$ (slowing varying function of $\hat{s}$)

$$|A|^2 = \left|A_{sig} + A_{bkg}\right|^2 = \left|A_{sig}\right|^2 + \left|A_{bkg}\right|^2 + 2Re\left[A_{sig}A^*_{bkg}\right]$$
$$= B.W. + BKG + 2Re\left[c_{sig}c^*_{bkg}\right]\boldsymbol{Re}[\boldsymbol{P}(\hat{\boldsymbol{s}})] + 2Im\left[c_{sig}c^*_{bkg}\right]\boldsymbol{Im}[\boldsymbol{P}(\hat{\boldsymbol{s}})]$$

R_{int}

$$\boldsymbol{Re}[\boldsymbol{P}(\hat{\boldsymbol{s}})] = \frac{\hat{s}(\hat{s} - m^2)}{(\hat{s} - m^2)^2 + \Gamma^2 m^2}$$

$$\boldsymbol{Im}[\boldsymbol{P}(\hat{\boldsymbol{s}})] = \frac{-i\,\hat{s}\,\Gamma m}{(\hat{s} - m^2)^2 + \Gamma^2 m^2}$$

- Background real
- Re. Int.– from the real part of the propagator:

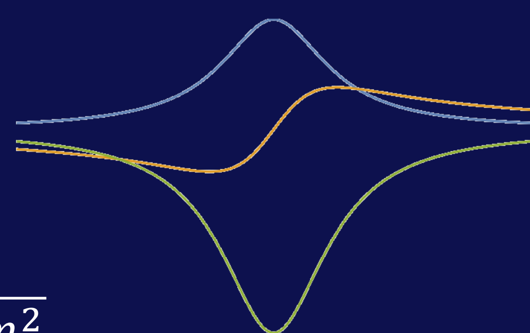
at parton level no contribution to the rate
➔ shift the mass peak. [When convoluting with PDF, may generate residual contribution to signal rate]

Di-Higgs Production and Interference effects

$A_{sig} = c_{sig} \frac{\hat{s}}{\hat{s} - m^2 + i\,\Gamma m} = c_{sig}\, P(\hat{s})$ $\qquad A_{bkg} = c_{bkg}$ (slowing varying function of $\hat{s}$)

$$|A|^2 = \left|A_{sig} + A_{bkg}\right|^2 = \left|A_{sig}\right|^2 + \left|A_{bkg}\right|^2 + 2Re\left[A_{sig} A_{bkg}^*\right]$$

$$= B.W. + BKG + 2Re\left[c_{sig} c_{bkg}^*\right] \boldsymbol{Re}[\boldsymbol{P}(\hat{\boldsymbol{s}})] + \underbrace{2Im\left[c_{sig} c_{bkg}^*\right] \boldsymbol{Im}[\boldsymbol{P}(\hat{\boldsymbol{s}})]}_{I_{int}}$$



I_{in}

$$\boldsymbol{Re}[\boldsymbol{P}(\hat{\boldsymbol{s}})] = \frac{\hat{s}(\hat{s} - m^2)}{(\hat{s} - m^2)^2 + \Gamma^2 m^2}$$

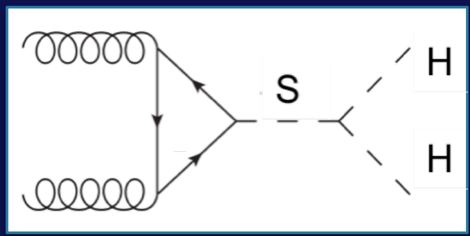
$$\boldsymbol{Im}[\boldsymbol{P}(\hat{\boldsymbol{s}})] = \frac{-i\,\hat{s}\,\Gamma m}{(\hat{s} - m^2)^2 + \Gamma^2 m^2}$$

Im. Int.–from the imaginary part of propagator

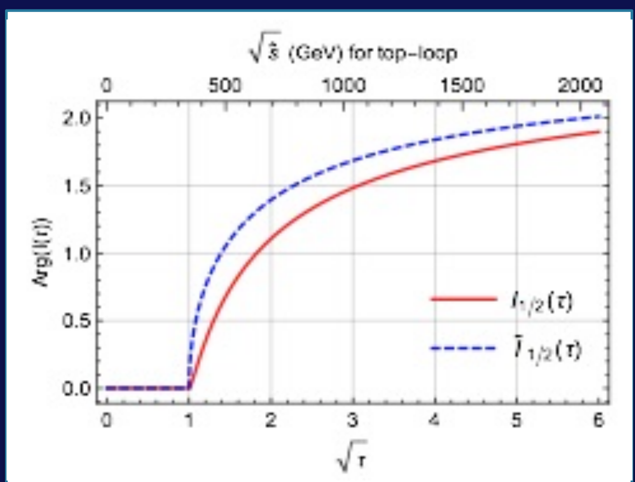
$$Im\left[c_{sig} c_{bkg}^*\right] = |c_{sig}||c_{bkg}^*| \sin(\delta_{sig} - \delta_{bkg})$$

When phase $\delta_{sig} - \delta_{bkg}$ (strong phase) is none-zero, there is a new interference effect that cannot be neglected

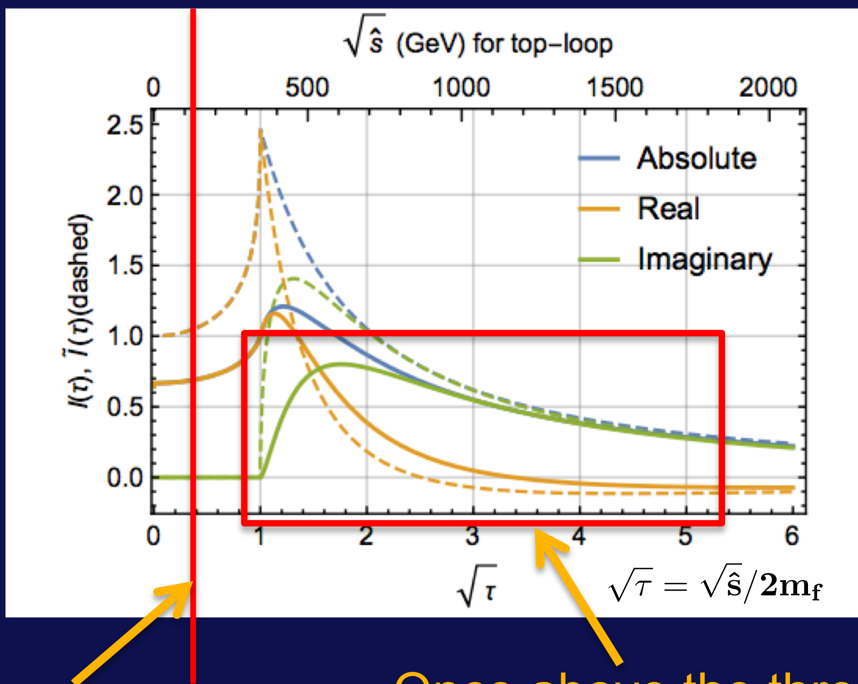
Imaginary parts contributing to the Interference effects



Phase of the loop function



Triangle loop function



SM Higgs
real & slowly varying

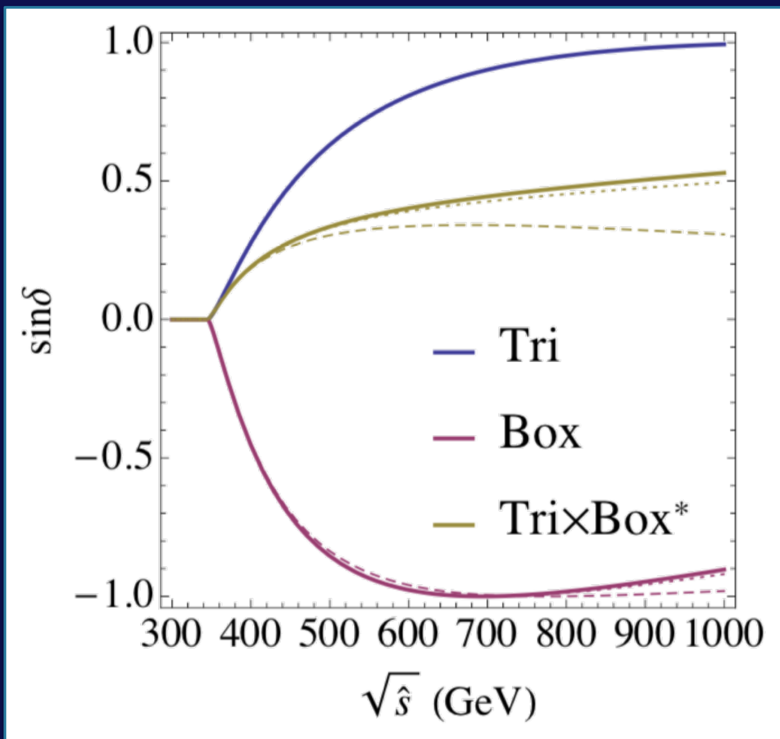
Once above the threshold, imaginary piece increases and real piece decreases.

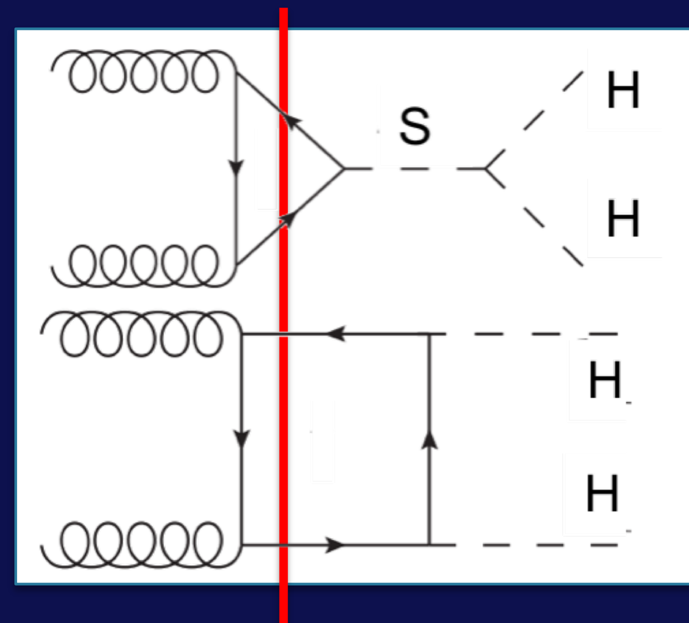
Background real

Real Interference from the real part of the propagator and real part of loop function (shifts the mass peak; no contribution to the signal rate besides residual effect of PDF's)

Im. Interference from the imaginary part of propagator with imaginary part of loop function (rare case, changes signal rate)

Strong phase in the loop functions

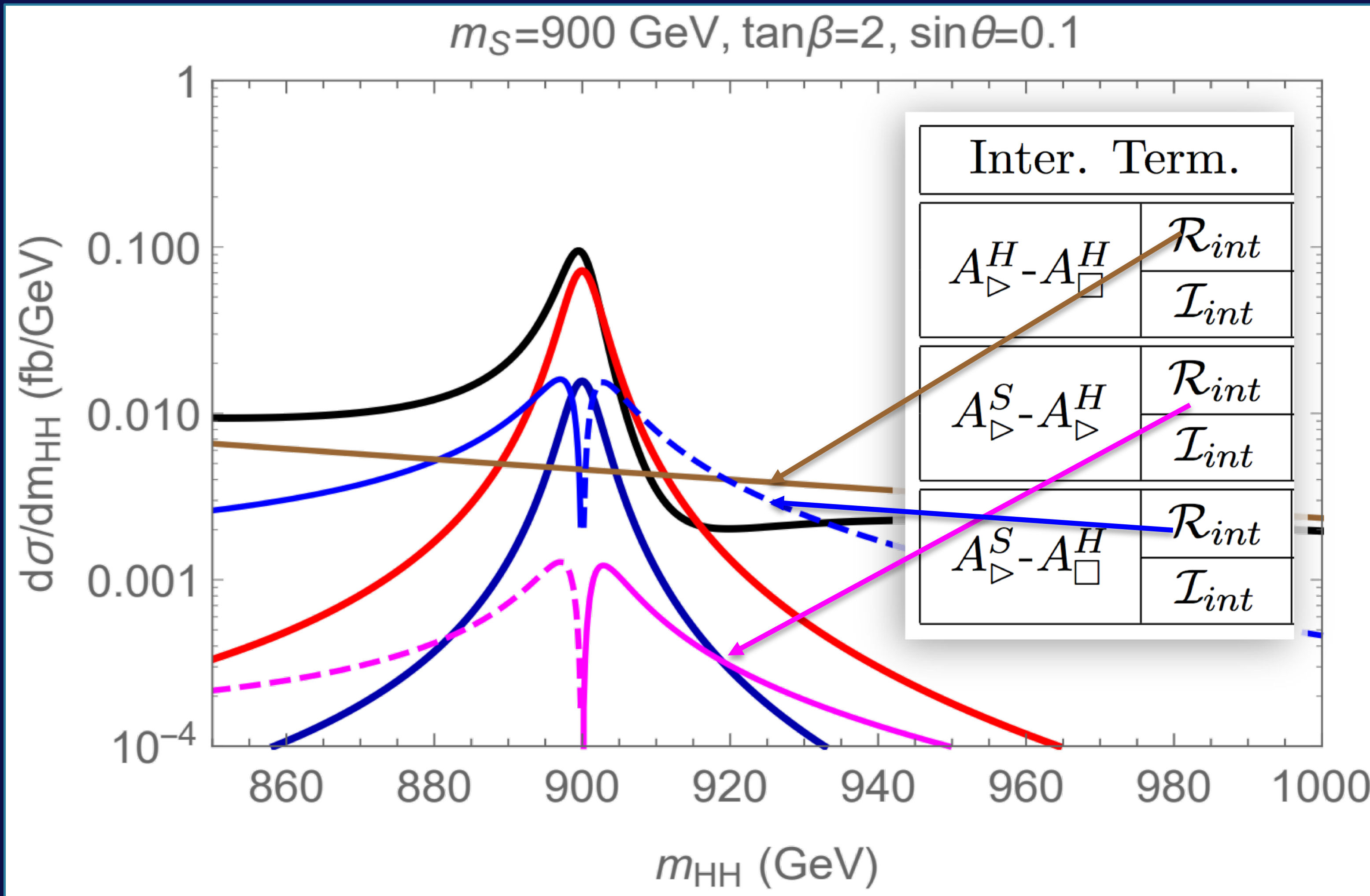




The solid, dotted, and dashed curves correspond to scattering angles of 0, 0.5 and 1, respectively

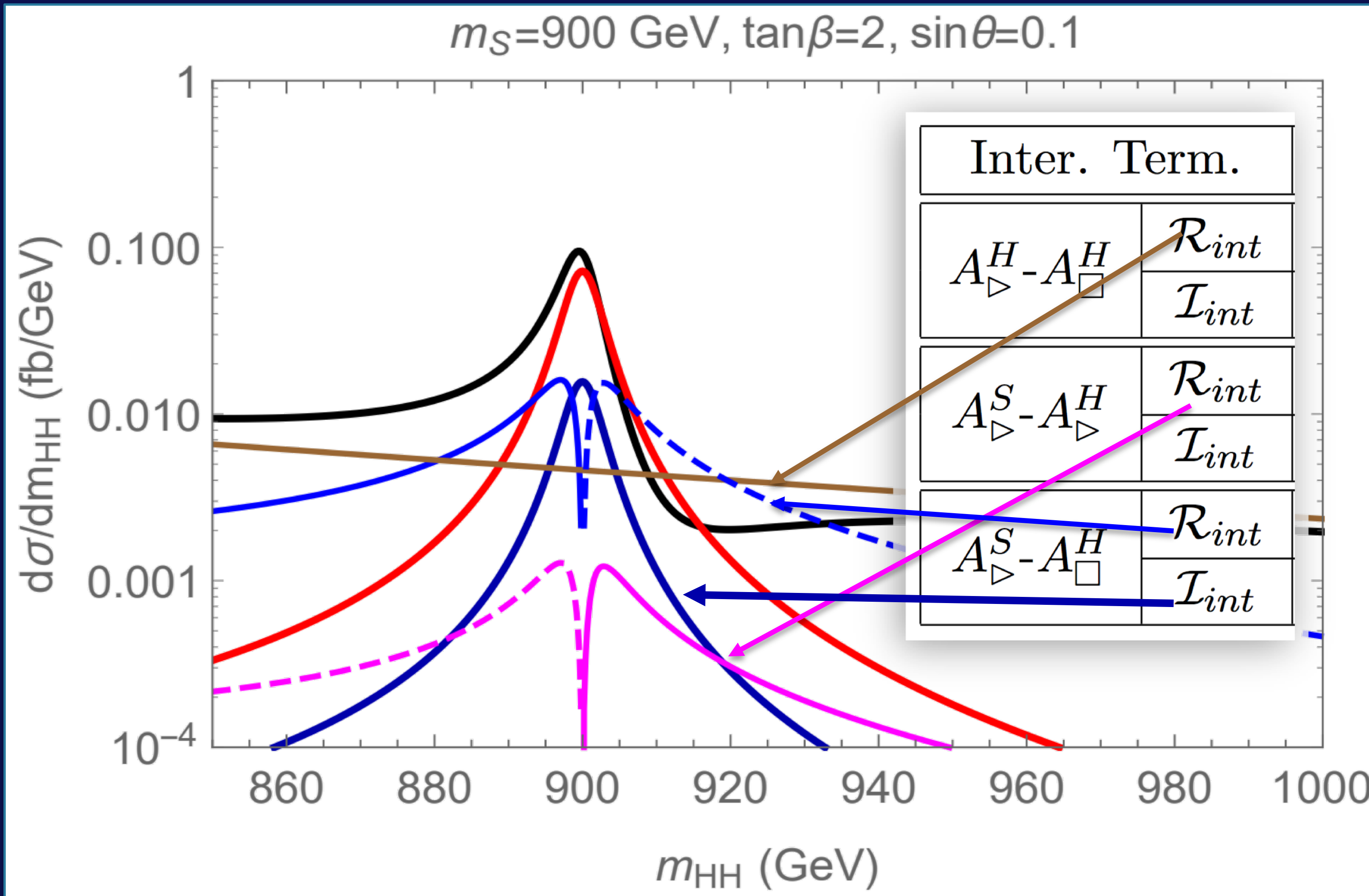
Relative strong phase (yellow curve) allows for a non-vanishing interference effect between the singlet resonance diagram and the SM box diagram.

Interference Line shape



Logarithmic to see other components;
Dashed represent destructive interference;
Dark blue, unique on-shell constructive interference

Interference Line shape

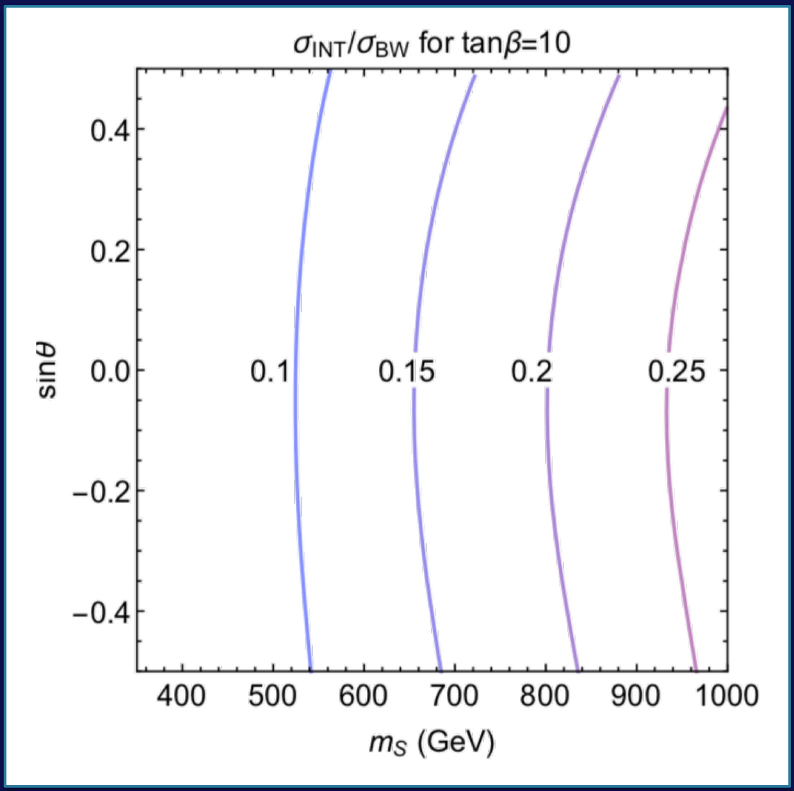


Logarithmic to see other components;

Dashed represent destructive interference;

Dark blue, unique on-shell constructive interference

Relevance of the on-shell interference

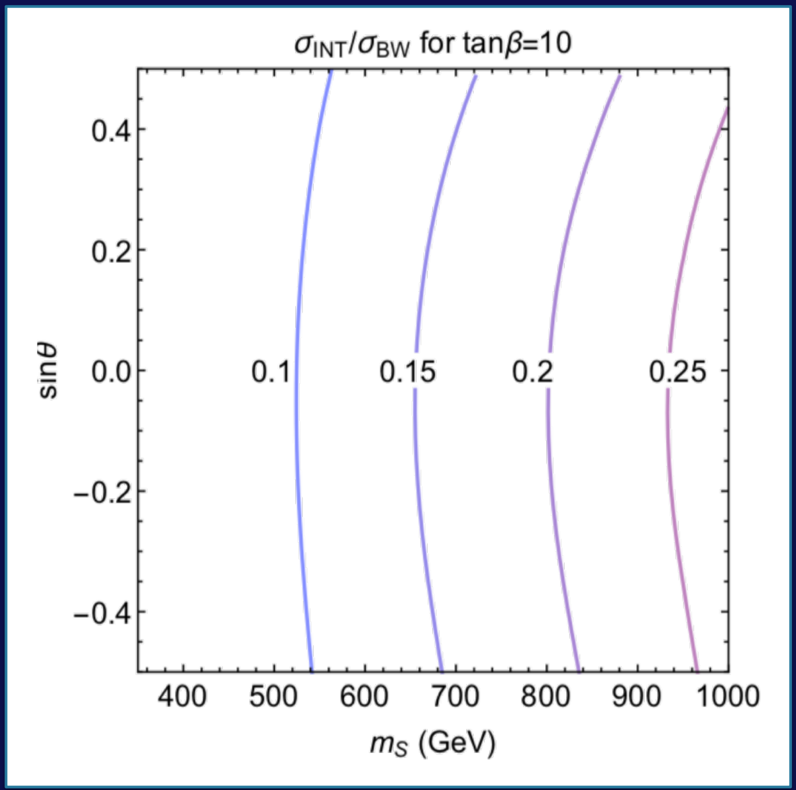


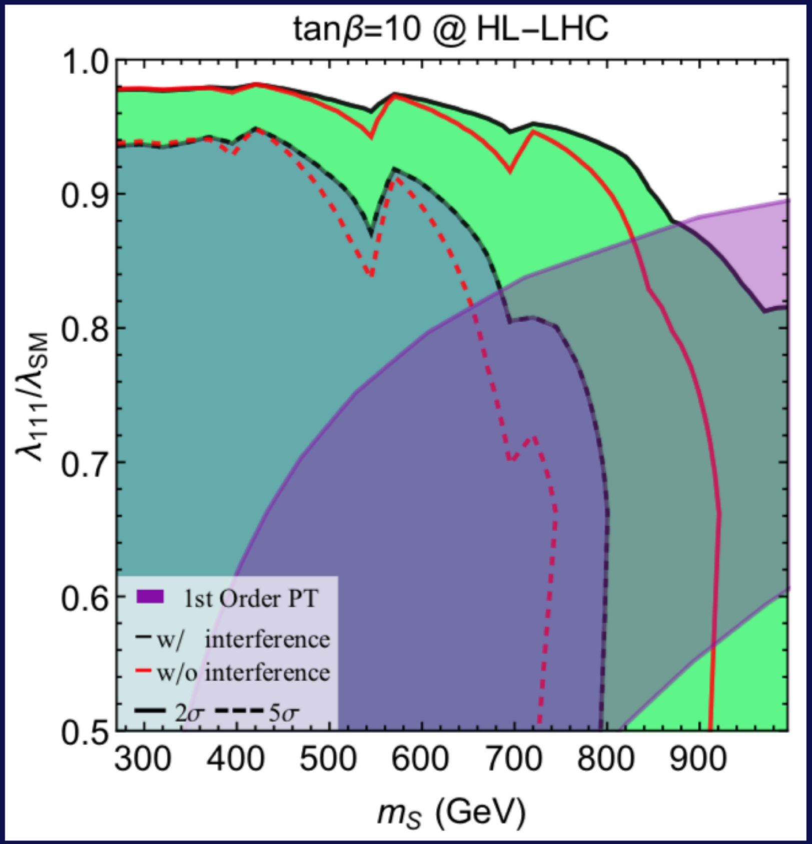
Relative size of the on-shell interference effect w.r.t. the resonant BW signal, averaged over scattering angle [-0.5,0.5]

For different parameters, it could be up to 40% below 1 TeV or increase even further for heavier singlet masses.

Interference effect could play an important role in the pheno and further determination of model parameters if the heavy scalar is discovered.

Relevance of the on-shell interference





Based on the pp → HH→ bbγγ, analysis [arXiv:1502.00539] we perform a differential analysis of the lineshapes:

M.C. Z. Liu and M. Riembau. ‘18

- Black/red lines, w/wo interference effect;
- Purple shaded region, 1st Order Phase Transition (FOPT) through an EFT analysis
- Correct inclusion of the interference effect extends the sensitivity in FOPT region

Di-Higgs Production as a signal of Enhanced Yukawa couplings

Bauer, MC, Carmona (1801.00363)

Correlation between enhanced Higgs-fermion couplings and di-Higgs production in 2HDM w/ flavour symmetry (2HDFM)

$$\mathcal{L}_Y^{\rm I} \ni y_{ij}^u \left(\frac{\phi_1\phi_2}{\Lambda^2}\right)^{n_{u_{ij}}} \bar{Q}_i\phi_1\, u_j + y_{ij}^d \left(\frac{\phi_1^\dagger\phi_2^\dagger}{\Lambda^2}\right)^{n_{d_{ij}}} \bar{Q}_i\tilde{\phi}_1\, d_j + y_{ij}^\ell \left(\frac{\phi_1^\dagger\phi_2^\dagger}{\Lambda^2}\right)^{n_{\ell_{ij}}} \bar{L}_i\tilde{\phi}_1\, \ell_j + h.c.\,,$$

$$g_{\varphi f_{L_i} f_{R_i}} = \kappa_{f_i}^{\varphi}\frac{m_{f_i}}{v} = \left(g_{f_i}^{\varphi}(\alpha,\beta) + n_{f_i}\, f^{\varphi}(\alpha,\beta)\right)\frac{m_{f_i}}{v}$$

$$g_{Hhh} = \frac{c_{\beta-\alpha}}{v}\left[\left(1-f^h(\alpha,\beta)s_{\beta-\alpha}\right)\left(3M_A^2-2m_h^2-M_H^2\right)-M_A^2\right]$$

$$g_{hhh} = -\frac{3}{v}\left[f^h(\alpha,\beta)c_{\beta-\alpha}^2(m_h^2-M_A^2)+m_h^2 s_{\beta-\alpha}\right]$$

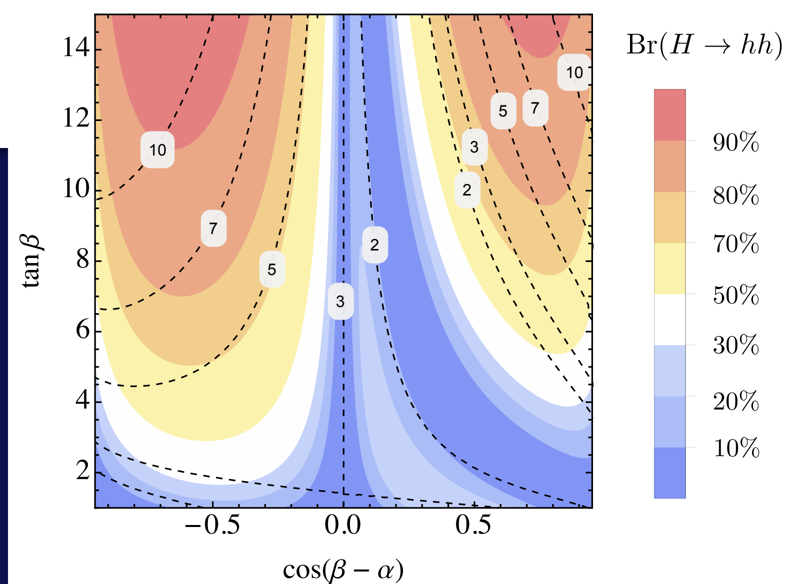


FIG. 1: The color coding shows the dependence of Br$(H\to hh)$ on $c_{\beta-\alpha}$ and t_β for $M_H = M_{H^\pm} = 550$ GeV, $M_A = 450$ GeV. The dashed contours correspond to constant $|\kappa_f^h|$ for $n_f = 1$.

Di-Higgs Production as a signal of Enhanced Yukawa couplings

Bauer, MC, Carmona (1801.00363)

Correlation between enhanced Higgs-fermion couplings and di-Higgs production in 2HDM w/ flavour symmetry

Visible in resonant & non-resonant, dedicated LHC searches

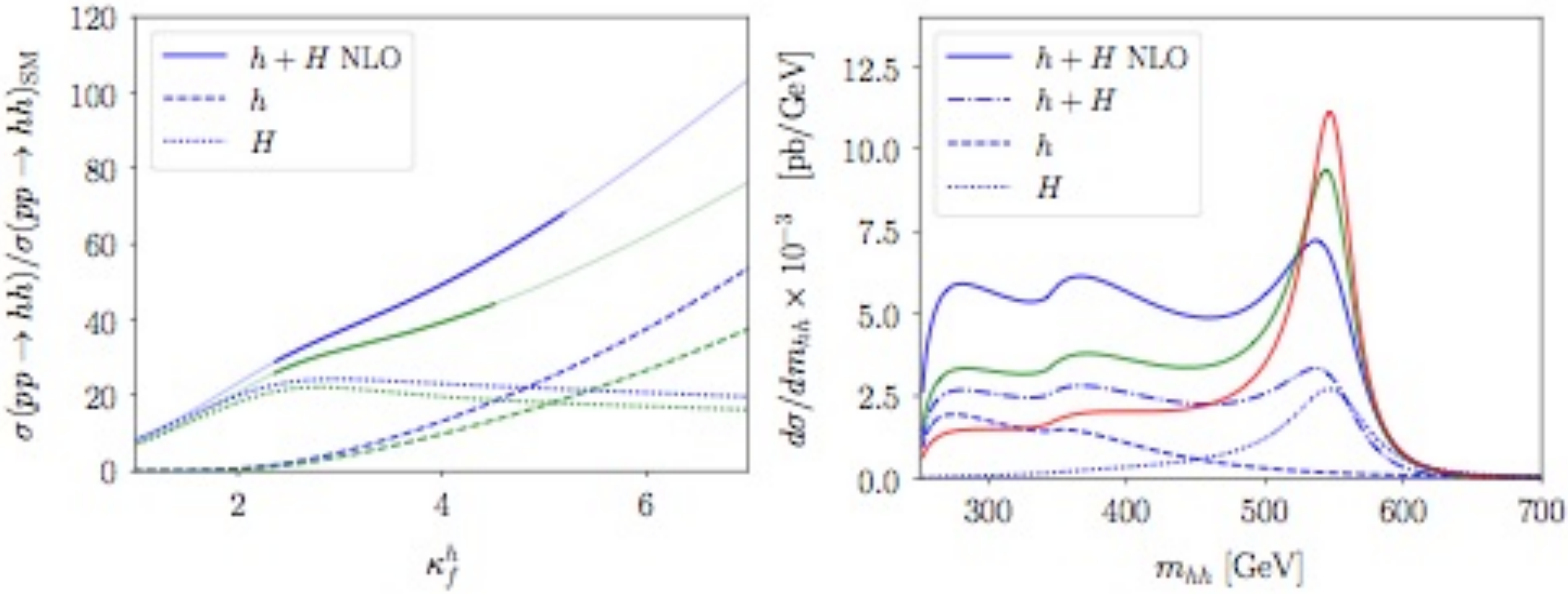


FIG. 2: Left: Cross section for Higgs pair production in units of the SM prediction as a function of κ_f^h for $c_{\beta-\alpha} = -0.45$ (-0.4) and $M_H = M_{H^\pm} = 550$ GeV, $M_A = 450$ GeV in blue (green) at $\sqrt{s} = 13$ TeV. Right: Invariant mass distribution for the different contributions to the signal with $c_{\beta-\alpha} = -0.45$ and $\kappa_f^h = 5$ (blue), $\kappa_f^h = 4$ (green) and $\kappa_f^h = 3$ (red) at $\sqrt{s} = 13$ TeV, respectively. Solid (dot-dashed) lines correspond to the NLO (LO) calculation for the sum of the resonant and non-resonant production, while dotted (dashed) lines correspond to the pure resonant (non-resonant) contributions.

Outlook

The 125 GeV Higgs precision measurements call for a significant degree of alignment, with important implications for additional Higgs bosons searches

Phase shift between SM and new physics can have important implications

- Enhance LHC sensitivity to simple models with a strong first order phase transition

Also relevant for

- 2HDFMs with enhanced light quark Higgs couplings
- Novel on-shell info on Higgs total width
- Performing scalar resonant searches above the top threshold