Enhanced Di-Higgs Production and the Electroweak Phase Transition

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Based on M. Carena, ZL, M. Riembau, 1801.00794

Higgs interferences

Many occasions where interference are important for Higgs physics

- Higgs total width from $\gamma\gamma$ invariant mass shift
- Higgs total width from off-shell measurement
- Double Higgs production (destructive interference between the box diagram and the trilinear Higgs diagram)
- …

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- …

**reference: M. Carena's talk Monday

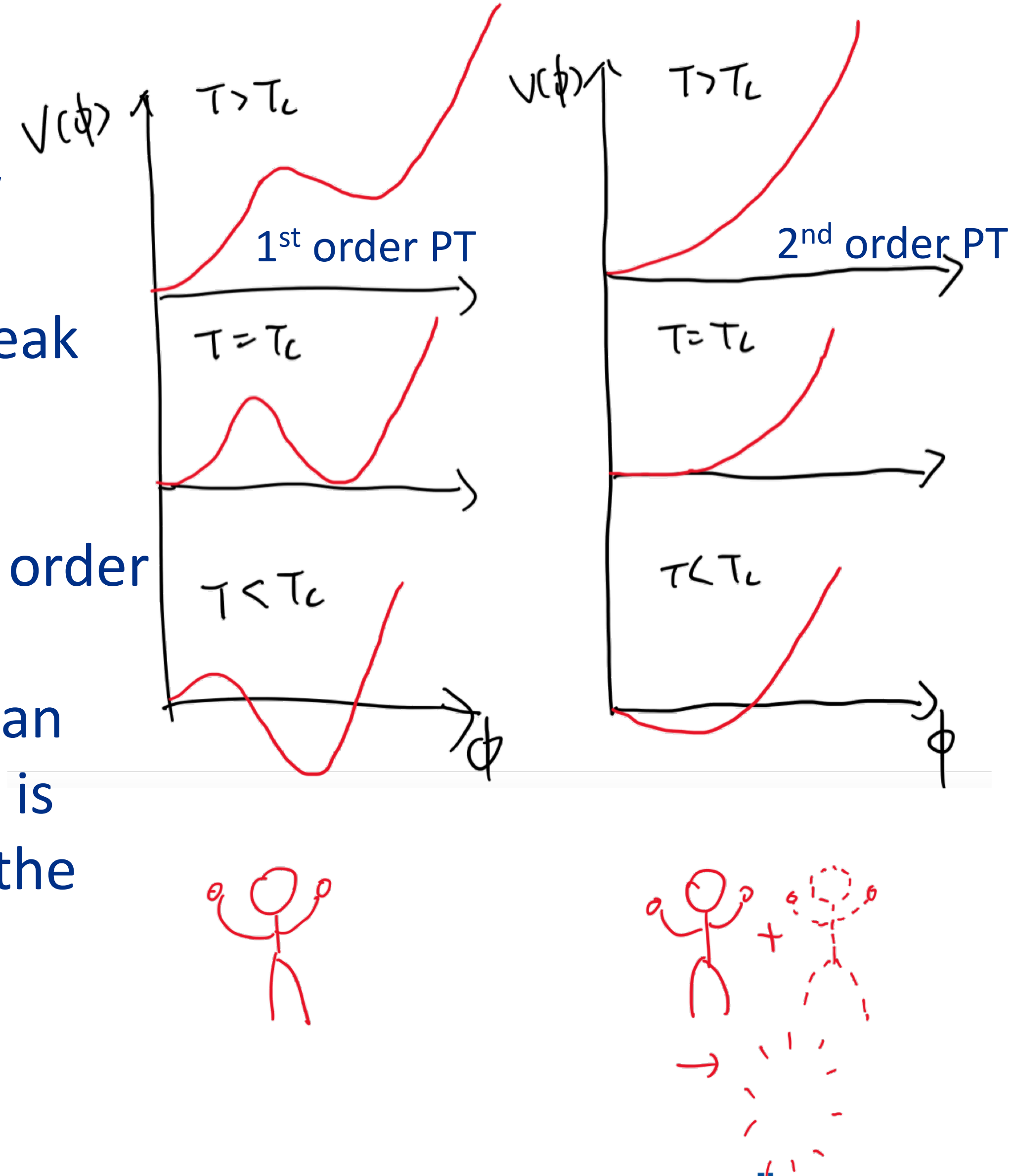
In the next hour**, I will present one example where the phase-shift by SM and new physics having important implications, **orthogonal** to above known interferences.

- $gg \to H \to \gamma\gamma$ (J. Campbell, M. Carena, R. Harnik, ZL, PRL 17')
- $\boldsymbol{gg \to S \to HH}$ **(M. Carena, ZL, M. Riembau, 18')**
- $gg \to S \to t\bar{t}$ (M. Carena, ZL, JHEP, 16')

New physics is a knob to tune the testable quantum interference effects, changing the **on-shell** behavior of the Higgs boson(s).

Higgs and electroweak phase transition

- Higgs boson discovered, now what?
- The strength of the electroweak phase transition in the SM is insufficient;
- Explore ways to enhance the order of electroweak phase;
- Singlet extension of the SM can serve as a benchmark (which is one of the hardest to test at the colliders);



What is on-shell interference? Back to the basics

$$A_{sig} = c_{sig}\frac{\hat{s}}{\hat{s}-m^2+i\,\Gamma m} = \mathrm{c}_{sig}\,\mathrm{P}(\hat{s})$$

$A_{bkg} = c_{bkg}$ (slowing varying function of $\hat{s}$)

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

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

Back to the basics of interference

$$A_{sig} = c_{sig}\frac{\hat{s}}{\hat{s} - m^2 + i\,\Gamma m} = c_{sig}\,P(\hat{s})$$

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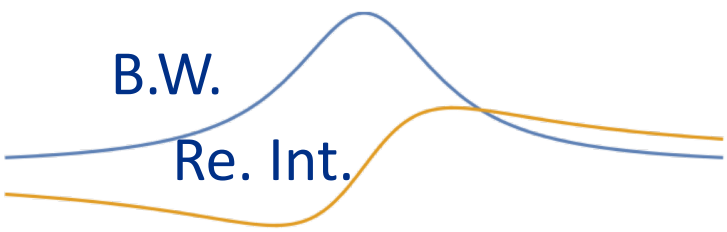

Background real

Re. Int.– Interference from the real part of the propagator

- normal interference, parton level no contribution to the rate, shift the mass peak
- When convoluting with PDF, may generate residual contribution to signal rate;
- conventional wisdom, interference only important when width is large)

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

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

Back to the basics of interference

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

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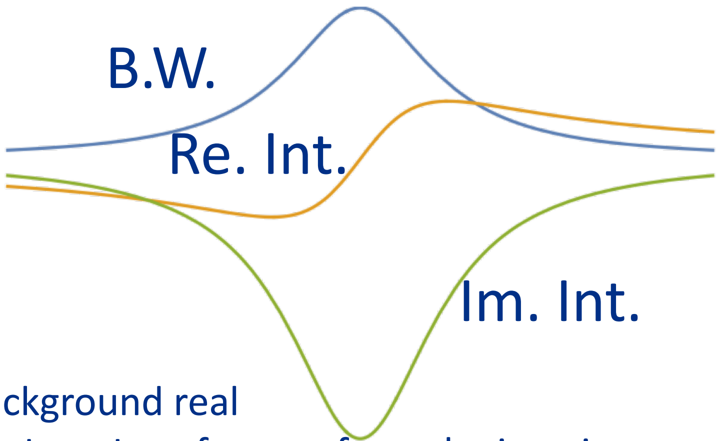
$$|A|^2 = \left|A_{sig} + A_{bkg}\right|^2 = \left|A_{sig}\right|^2 + \left|A_{bkg}\right|^2 + 2Re\left[A_{sig}A^*_{bkg}\right]$$
$$= B.W. + BKG + 2Re\left[c_{sig}c^*_{bkg}\right]Re[P(\hat{s})] + 2Im\left[c_{sig}c^*_{bkg}\right]Im[P(\hat{s})]$$



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

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

Background real

Im. Int.– Interference from the imaginary part of propagator

- rare case (at LO);
- changes signal rate;
- cannot be dropped even if the width is narrow*

*the measure of interference/resonance do not decrease, as the size of signal amplitude decrease as well

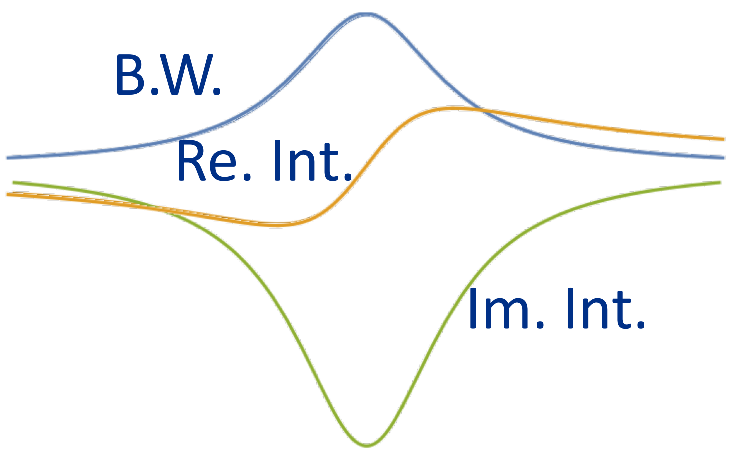
Back to the basics of interference

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

$A_{bkg} = c_{bkg}$ (slowing varying function of $\hat{s}$)

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

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



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

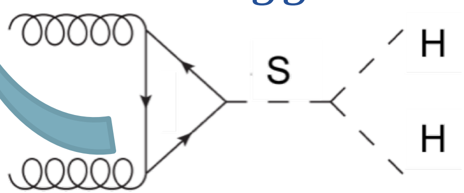
When phase $\delta_{sig} - \delta_{bkg}$ is none-zero, this new interference effect exists and cannot be neglected however narrow the resonance is!

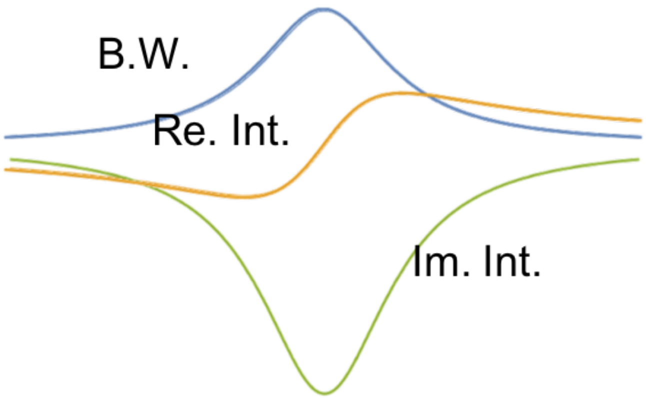
Back to the basics of interference

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

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

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





Back to the basics of interference

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

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

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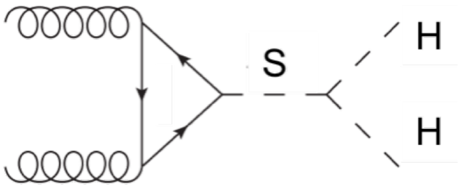
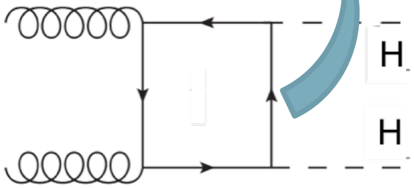
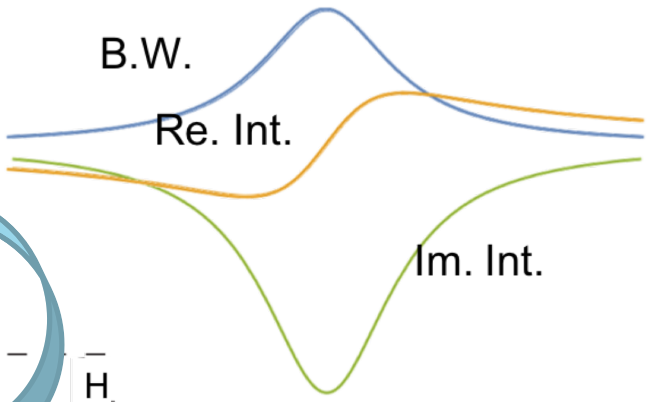
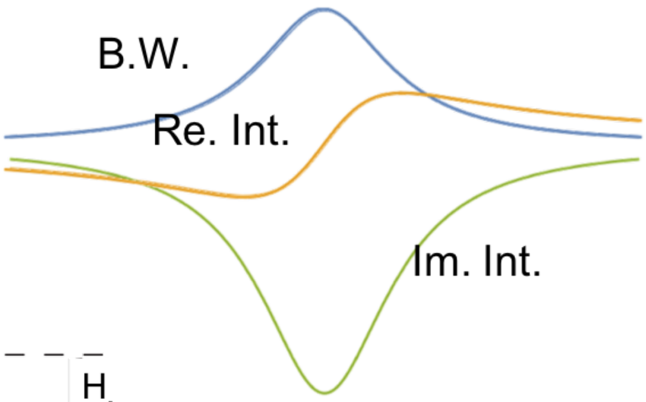






Back to the basics of interference



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

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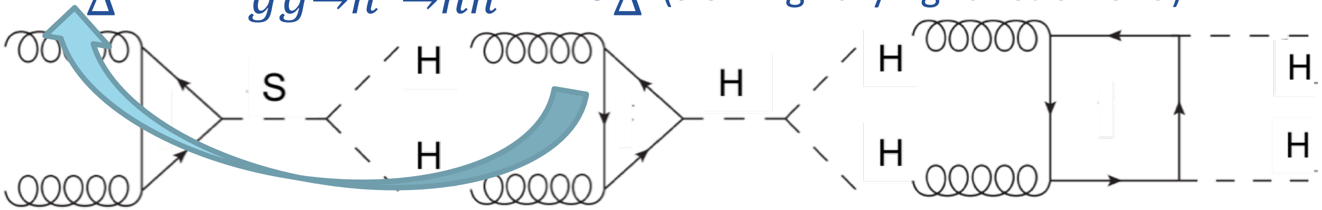

Back to the basics of interference

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

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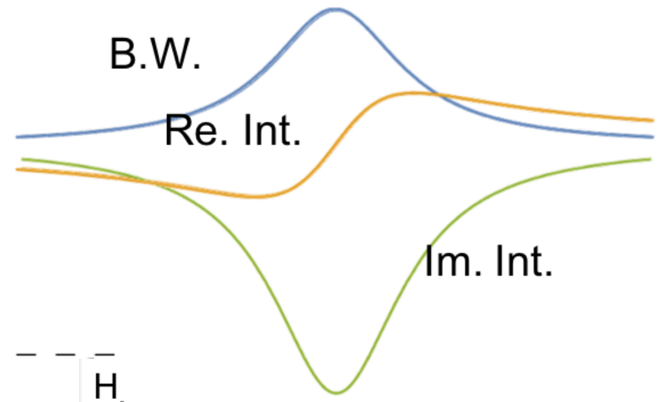
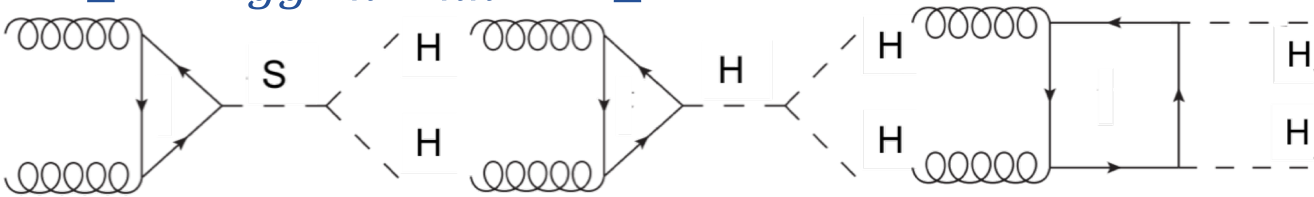
$A^H_\Delta = A_{gg\to h^*\to hh} = c'_\Delta$ (slowing varying function of $\hat{s}$)





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
$A^S_\triangleright$-$A^H_\Box$	$\mathcal{R}_{int}$	$\cos(\delta_\triangleright - \delta_\Box)$	$\lambda_{SHH}\cos^2\theta\sin\theta$	$+/-$
	$\mathcal{I}_{int}$	$\sin(\delta_\triangleright - \delta_\Box)$	$\lambda_{SHH}\cos^2\theta\sin\theta$	$+$

Back to the basics of interference

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

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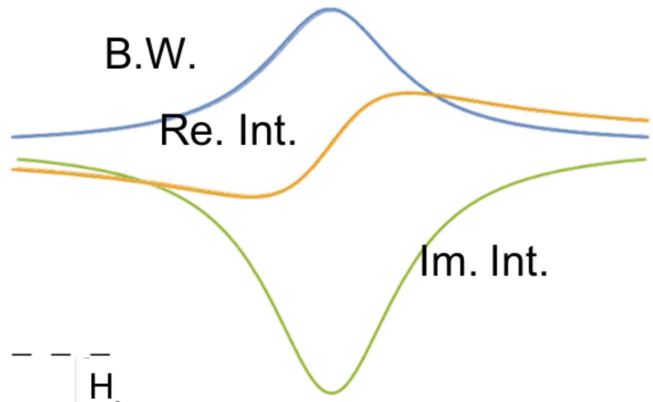
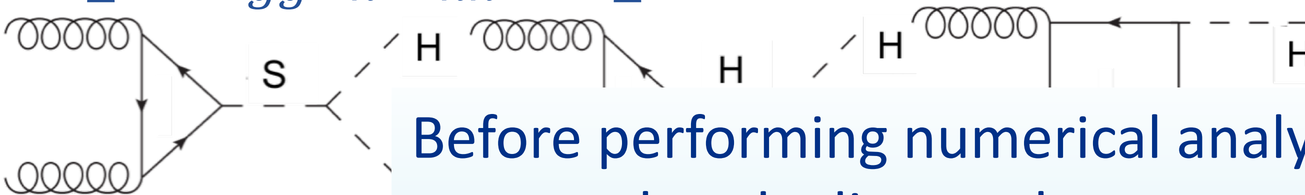
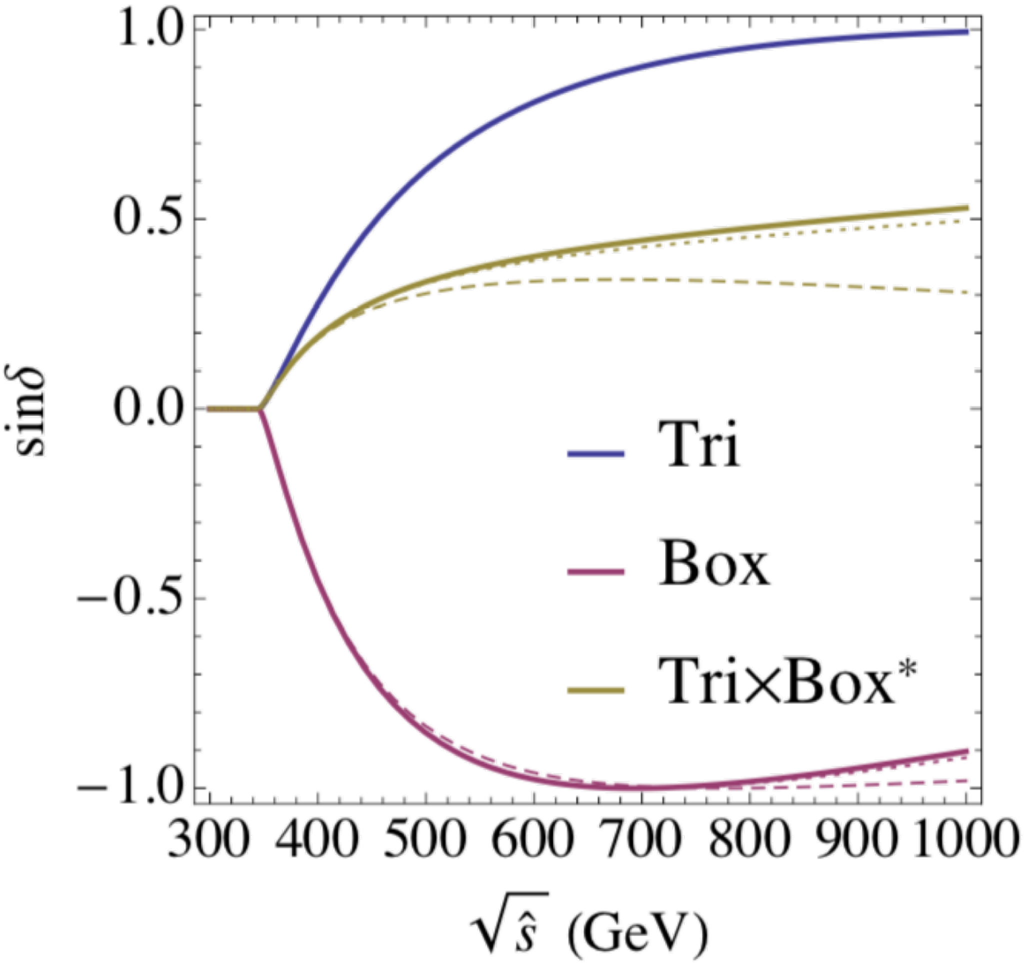


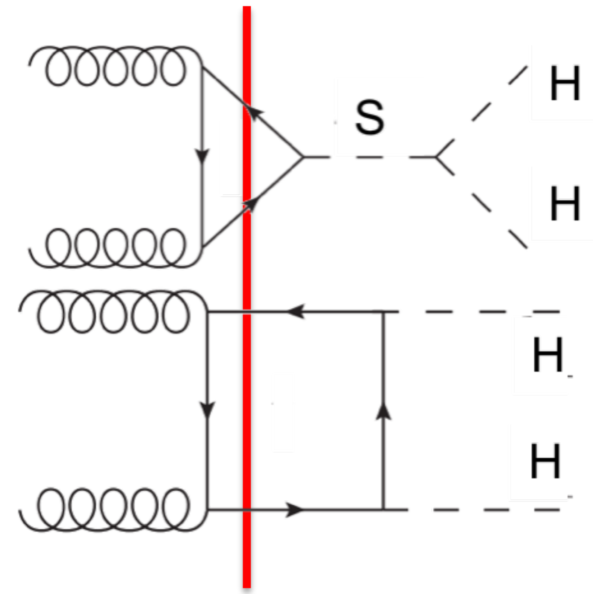


Before performing numerical analysis, we can already discuss the patterns of interference effect.
The unique I_{int} only shows up in one particular interference term,
in contrast to the R_{int} part that has been studied at various places.

Inter. Term.				Inter. Sign
$A^H_\triangleright$-$A^H_\square$	$\mathcal{R}_{int}$			$-$
	$\mathcal{I}_{int}$			0
$A^S_\triangleright$-$A^H_\triangleright$	$\mathcal{R}_{int}$			$-/+$
	$\mathcal{I}_{int}$			0
$A^S_\triangleright$-$A^H_\square$	$\mathcal{R}_{int}$	$\cos(\delta_\triangleright - \delta_\square)$	$\lambda_{SHH}\cos^2\theta\sin\theta$	$+/-$
	$\mathcal{I}_{int}$	$\sin(\delta_\triangleright - \delta_\square)$	$\lambda_{SHH}\cos^2\theta\sin\theta$	$+$

Strong Phases



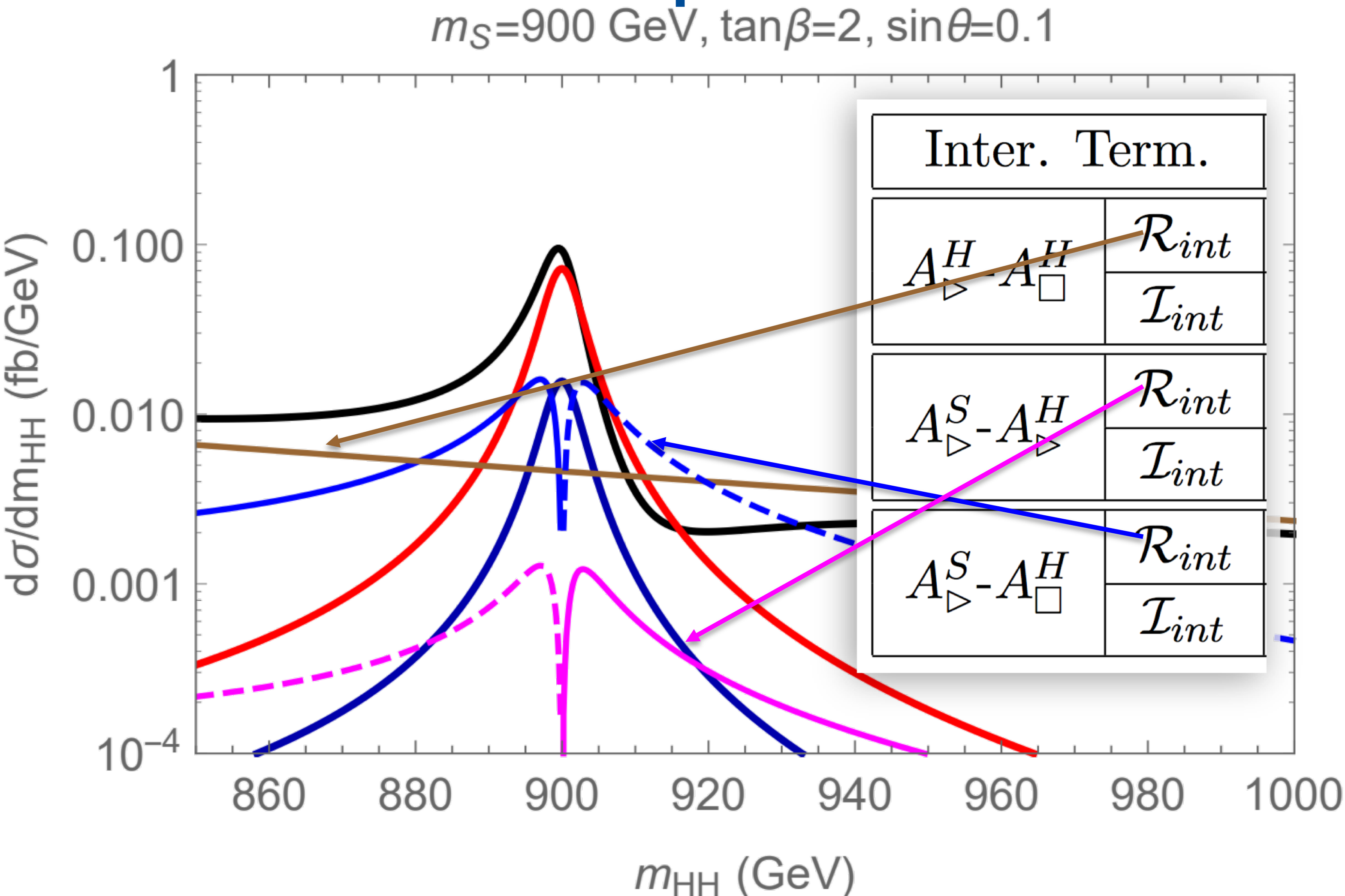


A strong phase in the gluon-gluon fusion production at hadron colliders (imaginary part)

Solid/Dotted/Dashed, scattering angle of 0/0.5/1;

- Blue: the phase of the triangle diagram;
- Magenta: the phase of the box diagram;
- Yellow: the relative phase between them;

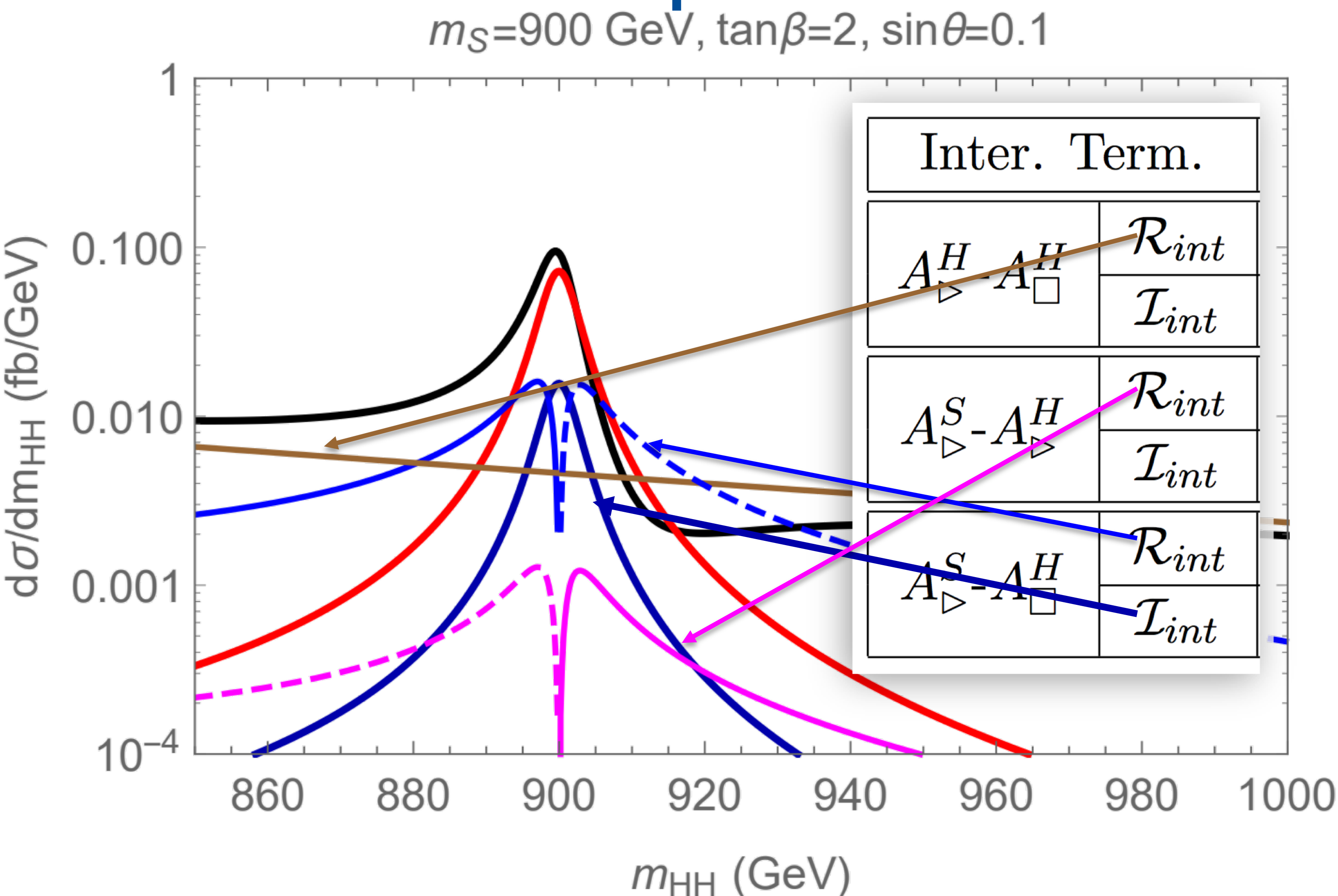
Interference Line shape



Logarithmic to see other components;

Dashed represent destructive interference;

Interference Line shape

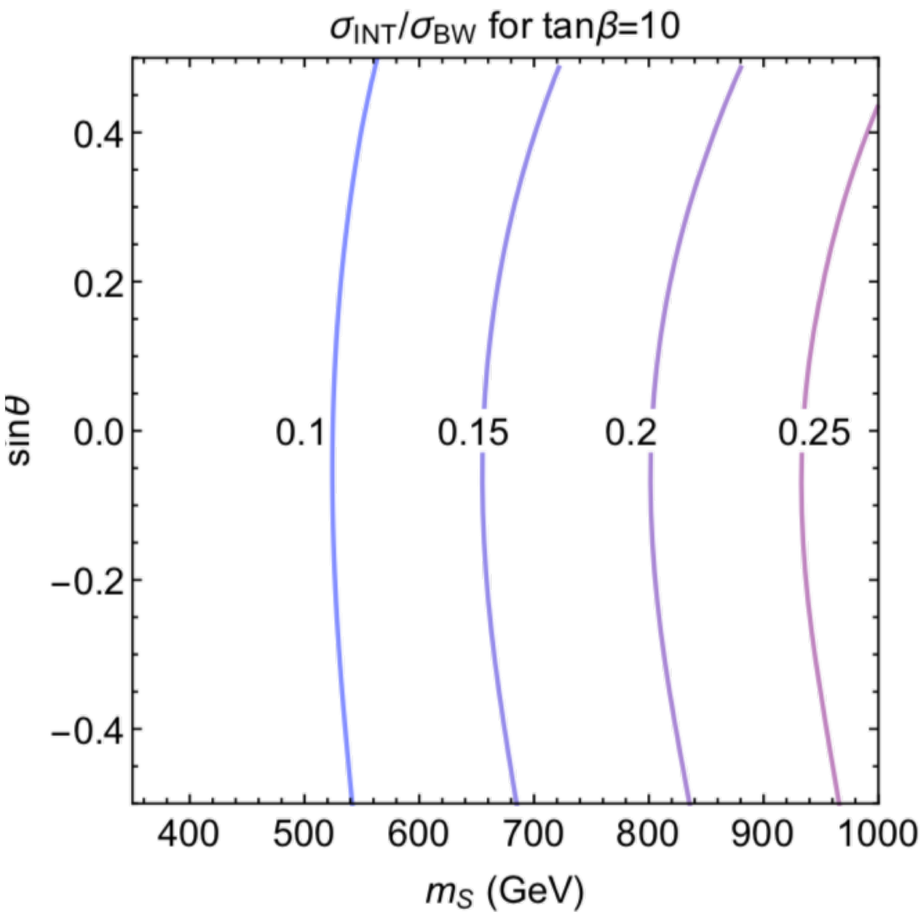


Logarithmic to see other components;

Dashed represent destructive interference;

Dark blue, unique on-shell constructive interference

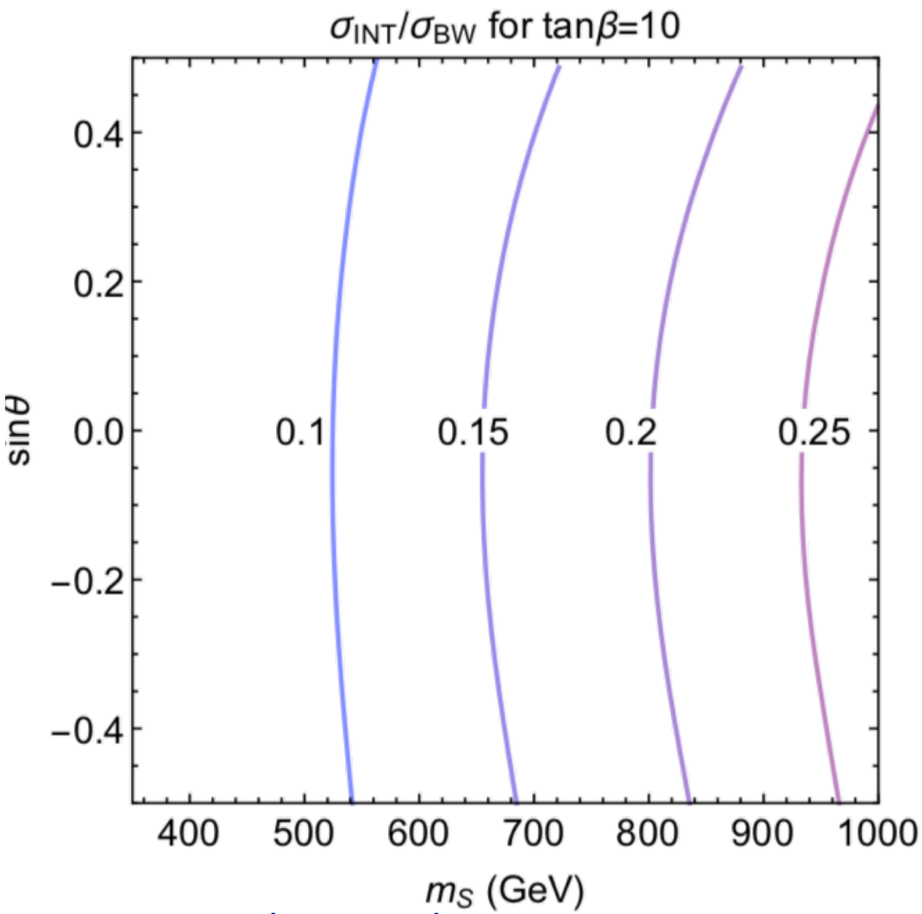
Size of the on-shell interference

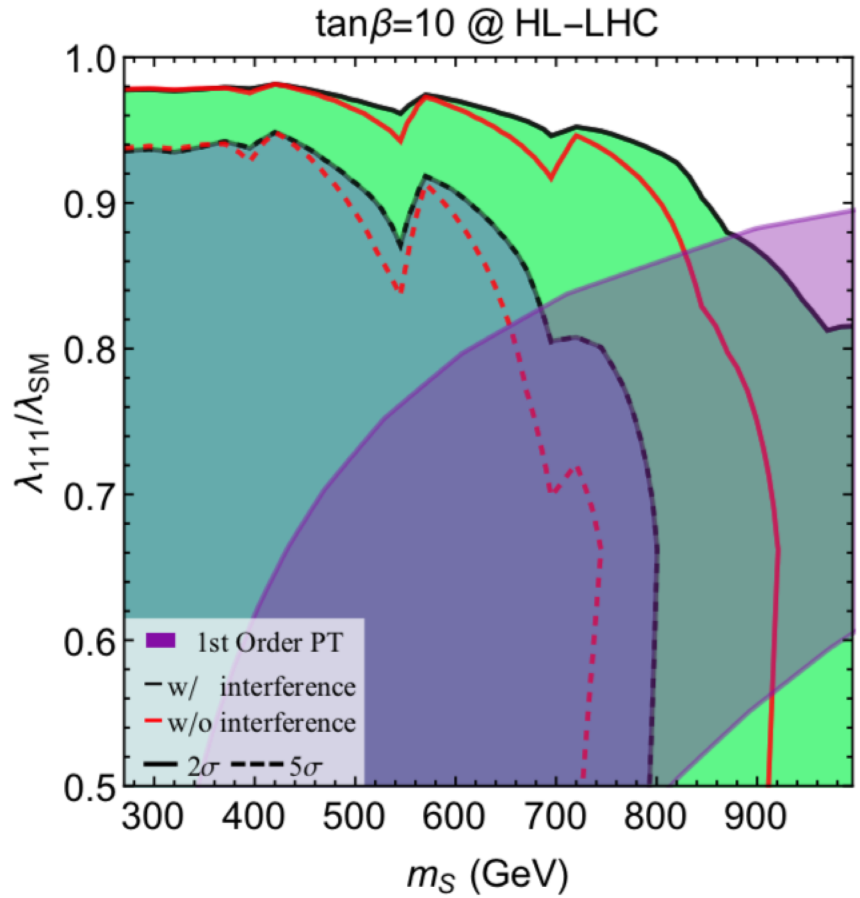


The size of the on-shell interference effect w.r.t. the resonant signal.

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

Interference Lineshape





Using the bb\gamma\gamma analysis, we perform a differential analysis of the lineshapes:

- Black/red lines, w/wo interference effect;
- Purple shaded region, 1st Order Phase transition through an EFT analysis;
- The correct inclusion of the interference effect extend our sensitivity in the 1st order PT

Interferences in $gg \to S \to HH$

- Singlet extension of the SM can serve as a paramount physics target to be tested at colliders that enhances the electroweak phase transition to first order;
- We uniquely explore the physics consequences of the novel on-shell interference effect in this process.
- Correctly taking into account this effect can enhance the signal strength sizably and differential lineshape analysis shows that the inclusion of interference effect will enhance the sensitivity to this model.
- The interference effect is relevant where a first order electroweak phase transition is enabled in this model through a simplified EFT analysis.

Outlook

Higgs interference carries great physics importance:

- **Making correct SM predictions;**
- **Being Sensitive to BSM effects;**
- **Special kinematic features to map out interferences;**

Phase might be another important expansion parameter when performing the calculations for SM/BSM physics where interferences could be important.

Interference effect is important for many BSM bump hunting, especially for the case of better and better limits (as the relative strength of the interference pieces increases relatively to the B.W. piece).

A bit of details

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

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

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

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

$$m_H = 125\ \text{GeV}, \quad v = 246\ \text{GeV}$$

and the three "physical" parameters,

$$\mu^2 = v^2\left(\lambda + \frac{1}{2}\tan^2\beta\lambda_{s\phi}\right), \qquad \mu_s^2 = v^2\left(\tan^2\beta\lambda_s + \frac{1}{2}\lambda_{s\phi}\right)$$

$$m_S, \quad \tan\beta(\equiv \frac{v_s}{v}), \text{ and } \sin\theta,$$

$$\begin{pmatrix} h \\ s \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} H \\ S \end{pmatrix}$$

$$\mu^2 = \frac{1}{4}\left(2m_H^2\cos^2\theta + 2m_S^2\sin^2\theta + (m_S^2 - m_H^2)\tan\beta\sin 2\theta\right)$$

$$\mu_s^2 = \frac{1}{4}\left(2m_H^2\sin^2\theta + 2m_S^2\cos^2\theta + (m_S^2 - m_H^2)\cot\beta\sin 2\theta\right)$$

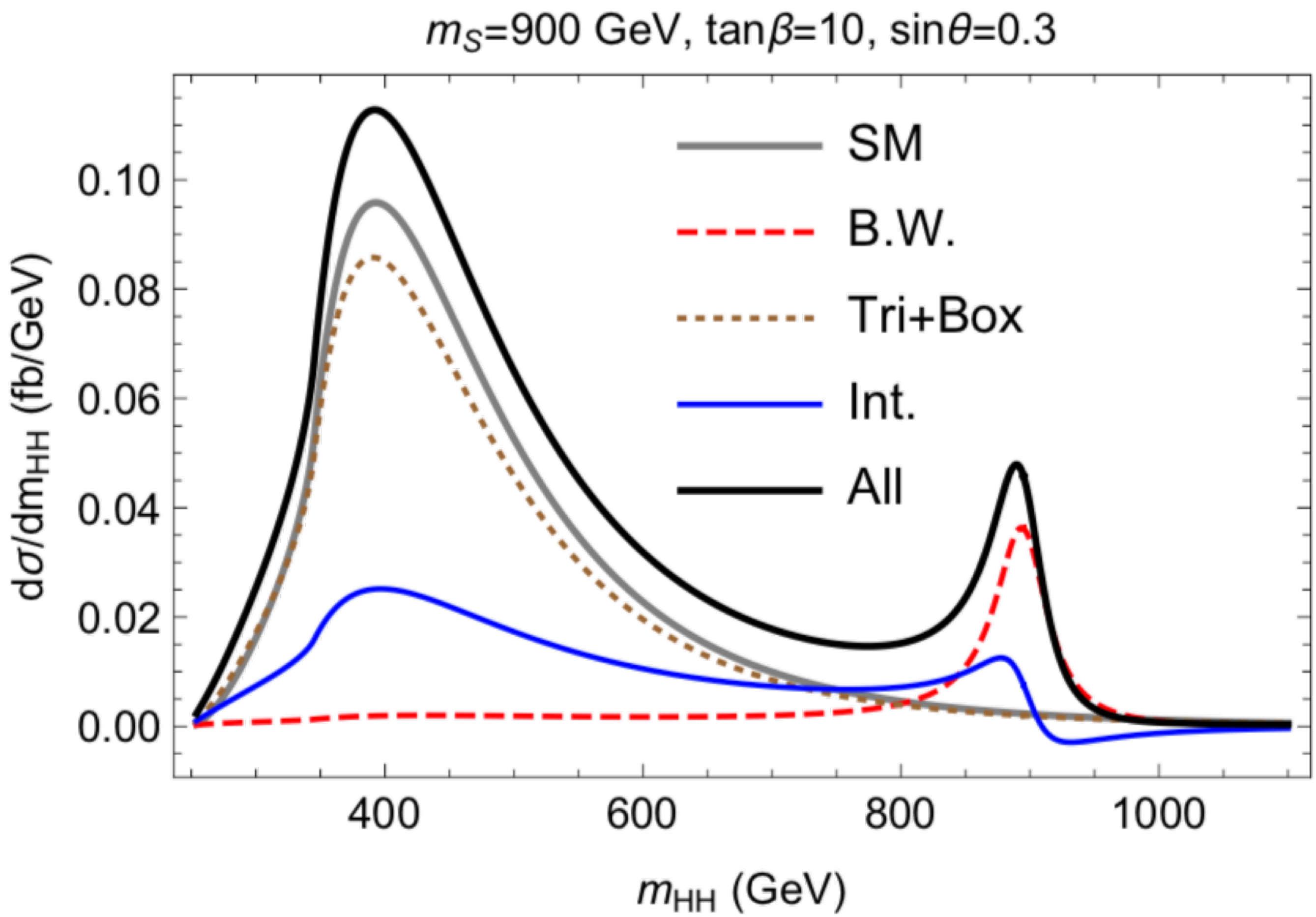
$$\lambda = \frac{m_H^2\cos^2\theta + m_S^2\sin^2\theta}{2v^2}$$

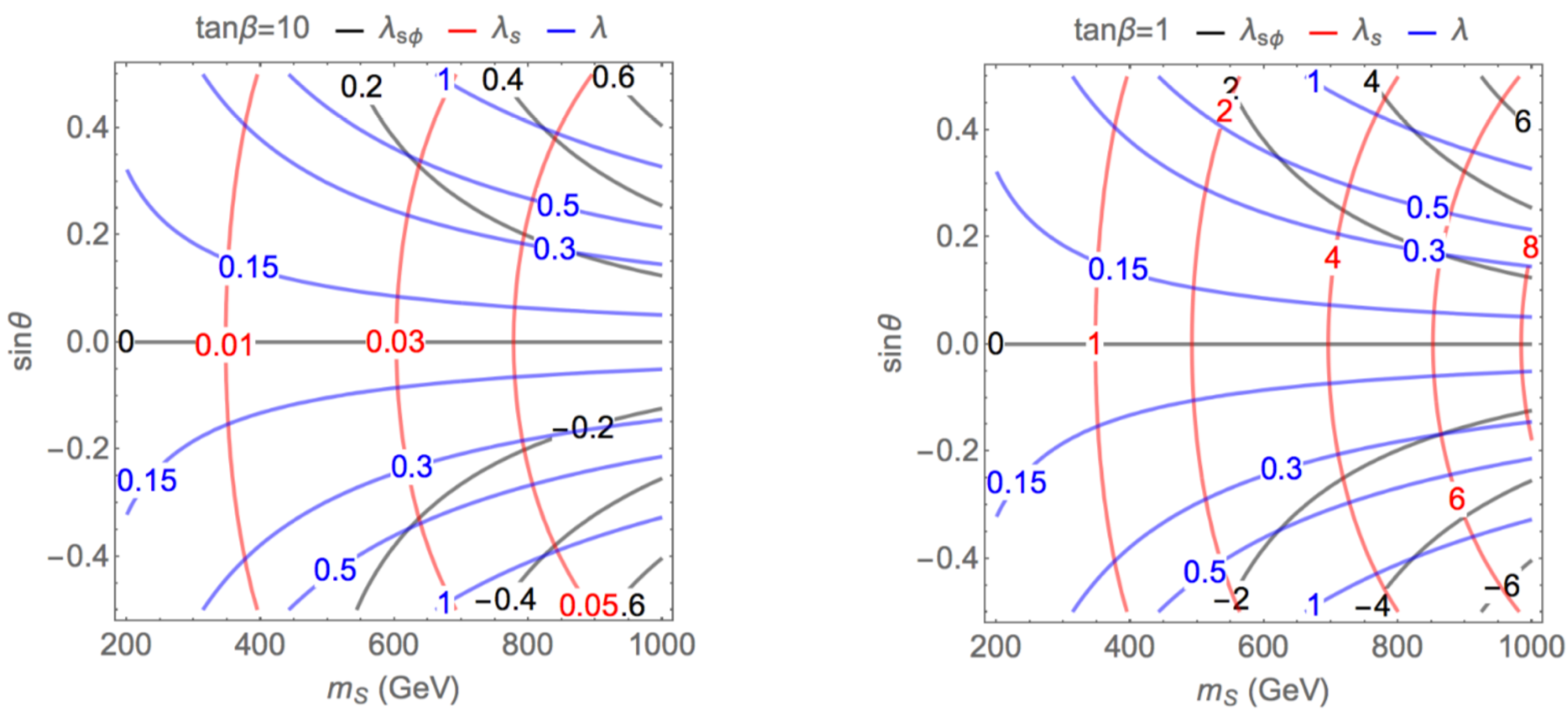
$$\lambda_s = \frac{m_H^2\sin^2\theta + m_S^2\cos^2\theta}{2\tan^2\beta\ v^2}$$

$$\lambda_{s\phi} = \frac{\left(m_S^2 - m_H^2\right)\sin 2\theta}{2\tan\beta\ v^2}.$$

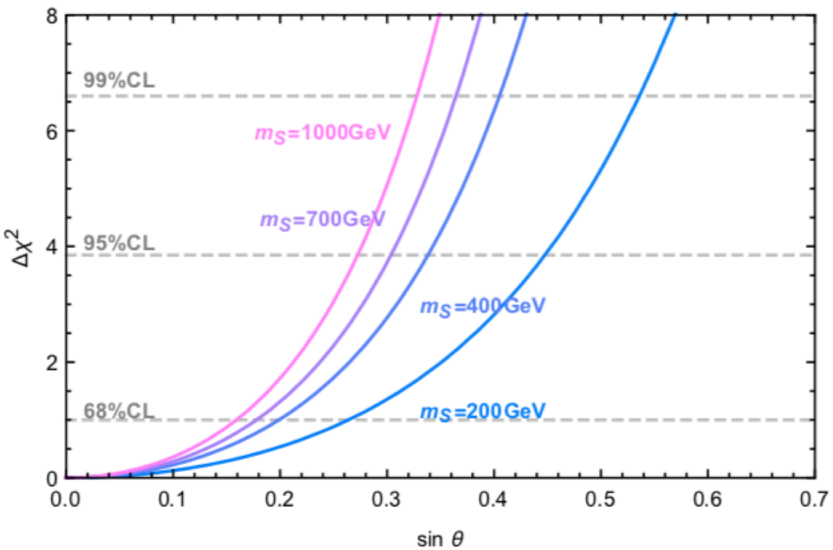
$\phi^T = (G^+, \frac{1}{\sqrt{2}}(h + iG^0 + v))$, where $G^{\pm,0}$ are the Goldstone modes.

Interference Lineshape

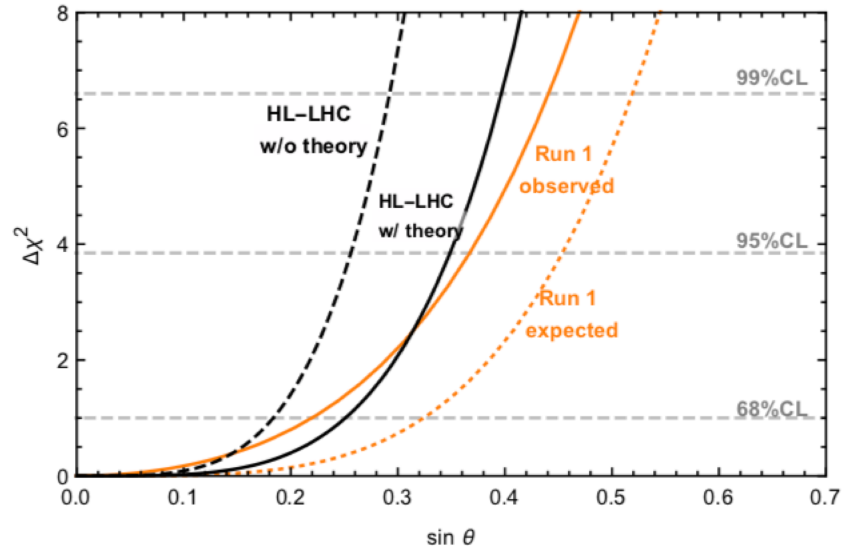




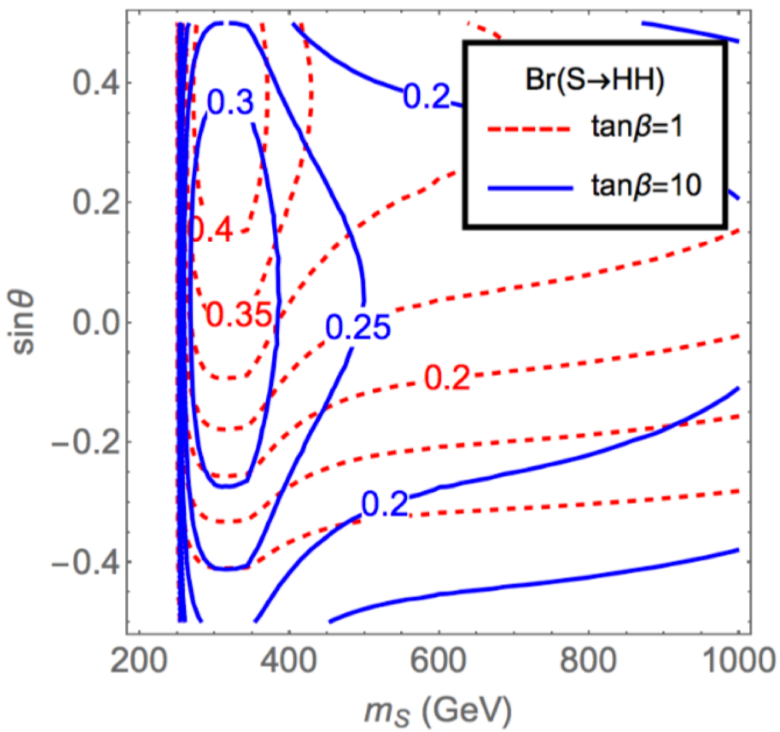
tanβ=10 — $\lambda_{s\phi}$ — λ_s — λ
sinθ
m_S (GeV)
tanβ=1 — $\lambda_{s\phi}$ — λ_s — λ
sinθ
m_S (GeV)

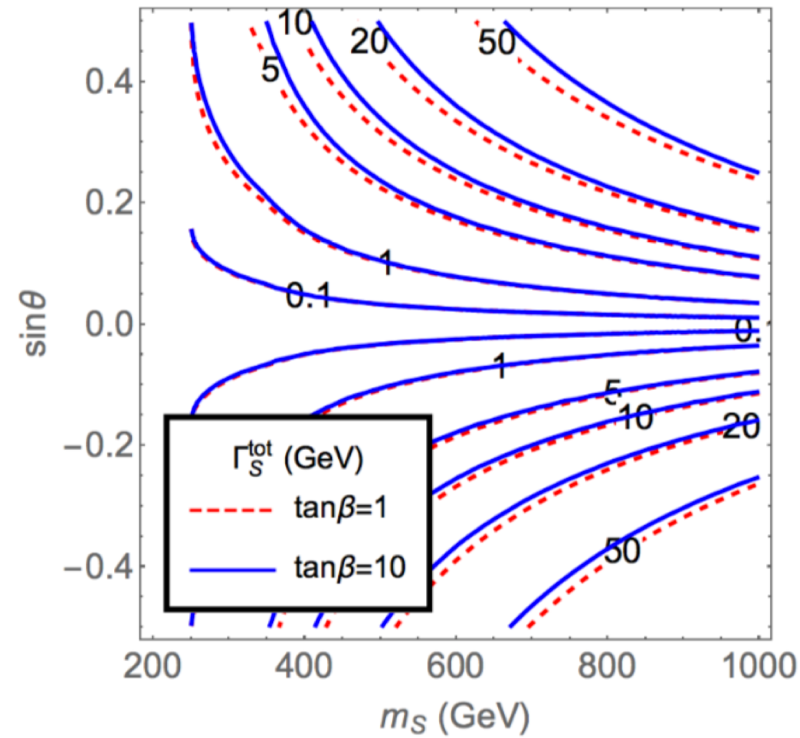


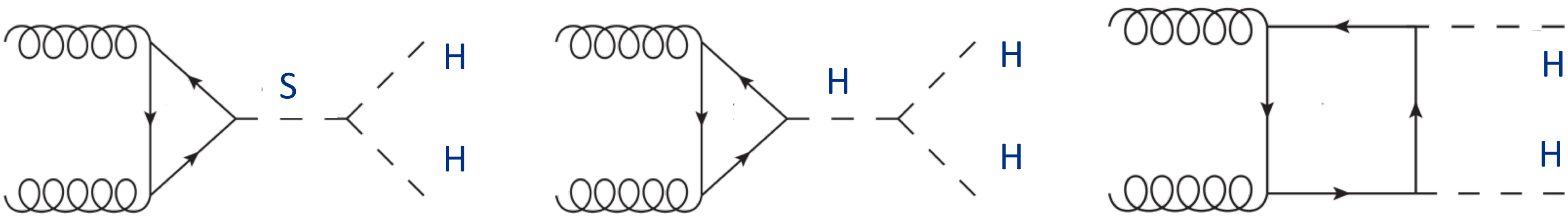
99%CL
95%CL
68%CL
m_S=1000GeV
m_S=700GeV
m_S=400GeV
m_S=200GeV
$\Delta\chi^2$
sin θ



99%CL
95%CL
68%CL
HL–LHC
w/o theory
HL–LHC
w/ theory
Run 1
observed
Run 1
expected
$\Delta\chi^2$
sin θ

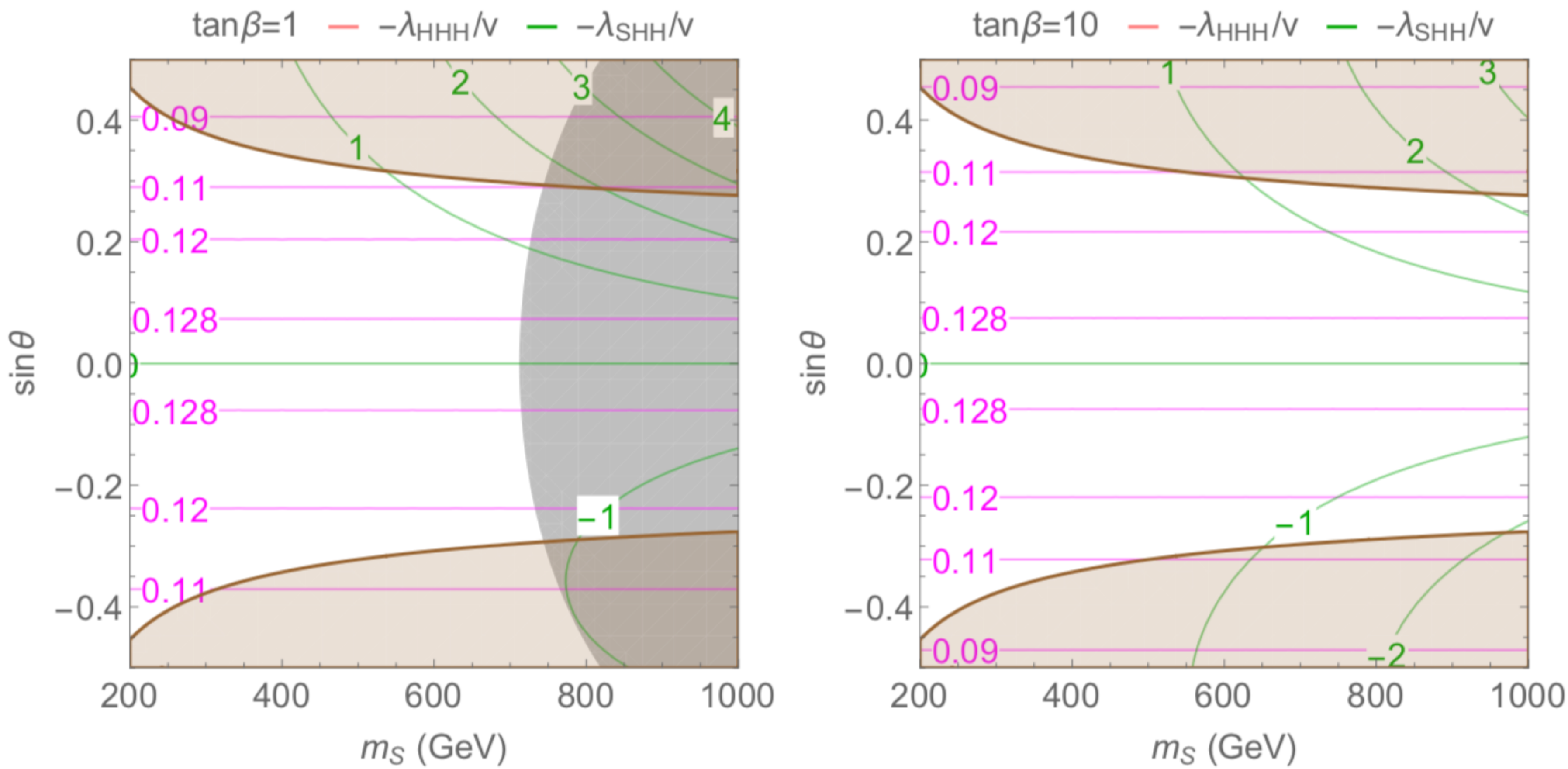

Br(S→HH)
tanβ=1
tanβ=10
0.3
0.2
0.4
0.35
0.25
0.2
0.2
0.4
0.2
0.0
−0.2
−0.4
sinθ
200
400
600
800
1000
m_S (GeV)


Γ_S^{tot} (GeV)
tanβ=1
tanβ=10
10
20
50
5
1
0.1
1
5
10
20
50
0.4
0.2
0.0
−0.2
−0.4
sinθ
200
400
600
800
1000
m_S (GeV)

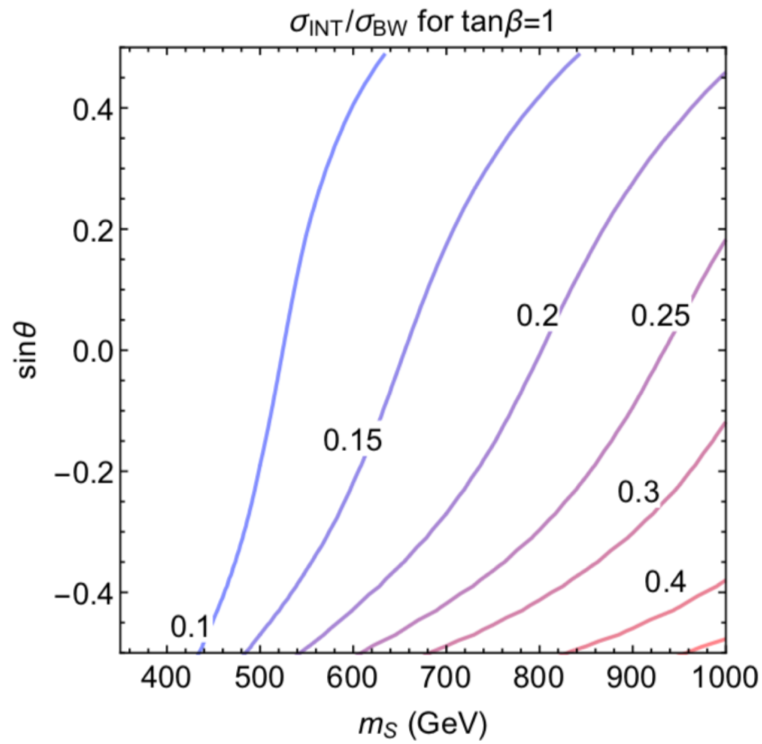

S
H
H
H
H
H
H
H

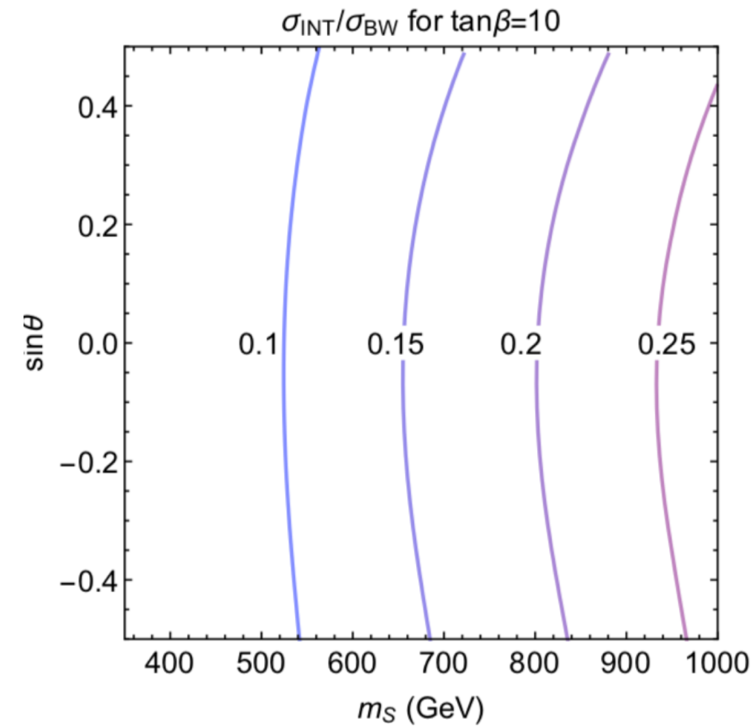
# of events expected	HL-LHC 13 TeV @ 3 ab^{-1}		HE-LHC 27 TeV @ 10 ab^{-1}	
bins (GeV)	SM HH	SM BKG	SM HH	SM BKG
250-400	2.1	12.0	33.2	186.4
400-550	6.3	15.9	110.9	278.8
550-700	2.9	5.2	58.4	105.6
700-850	1.0	2.0	23.4	46.7
850-1000	0.3	1.4	8.9	38.8
1000-1200	0.2	0.7	4.7	20.4
1200-1400	–	–	1.9	8.0
1400-1600	–	–	0.8	3.5
1600-1800	–	–	0.4	1.7
1800-2000	–	–	0.2	0.9

S



tanβ=1
−λHHH/v
−λSHH/v
0.09
0.11
0.12
0.128
0.128
0.12
0.11
1
2
3
4
−1
0
0.4
0.2
0.0
−0.2
−0.4
sinθ
200
400
600
800
1000
mS (GeV)
tanβ=10
−λHHH/v
−λSHH/v
0.09
0.11
0.12
0.128
0.128
0.12
0.11
0.09
1
2
3
−1
−2
0.4
0.2
0.0
−0.2
−0.4
sinθ
200
400
600
800
1000
mS (GeV)


σ_{INT}/σ_{BW} for tanβ=1
$\sin\theta$
m_S (GeV)
0.1
0.15
0.2
0.25
0.3
0.4

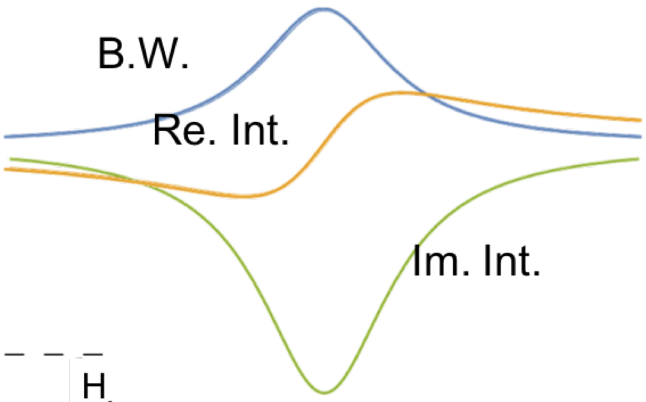

σ_{INT}/σ_{BW} for tanβ=10
$\sin\theta$
m_S (GeV)
0.1
0.15
0.2
0.25

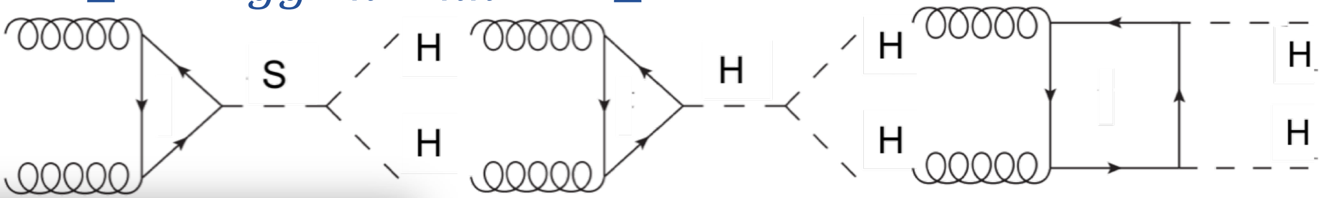
Back to the basics of interference

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

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

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





Inter. Term.		Inter. Sign
$A^H_\triangleright$-$A^H_\Box$	$\mathcal{R}_{int}$	$-$
	$\mathcal{I}_{int}$	0
$A^S_\triangleright$-$A^H_\triangleright$	$\mathcal{R}_{int}$	$-/+$
	$\mathcal{I}_{int}$	0
$A^S_\triangleright$-$A^H_\Box$	$\mathcal{R}_{int}$	$+/-$
	$\mathcal{I}_{int}$	$+$

Sketching the interference w CPV effect

Remark on strong v.s. weak phase

$$A_+ = |A_+| e^{i(\delta + \theta_{CP}/2)}$$
$$A_- = |A_+| e^{i(\delta - \theta_{CP}/2)}$$

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

For neutral process, without construction of CP-odd observables, the rate will be affected in a factorized way:

$$2Im\left[\left(c^+_{sig} + c^-_{sig}\right) c_{bkg}\right] Im[P(\hat{s})]$$
$$= 2\left|c^+_{sig}\right| Im[P(\hat{s})] \left\{\sin\left(\delta_{sig} + \frac{\theta_{CP}}{2} - \delta_{bkg}\right) + \sin\left(\delta_{sig} - \frac{\theta_{CP}}{2} - \delta_{bkg}\right)\right\} = 4\left|c^+_{sig}\right| Im[P(\hat{s})] \sin\left(\delta_{sig} - \delta_{bkg}\right) \cos\left(\frac{\theta_{CP}}{2}\right)$$