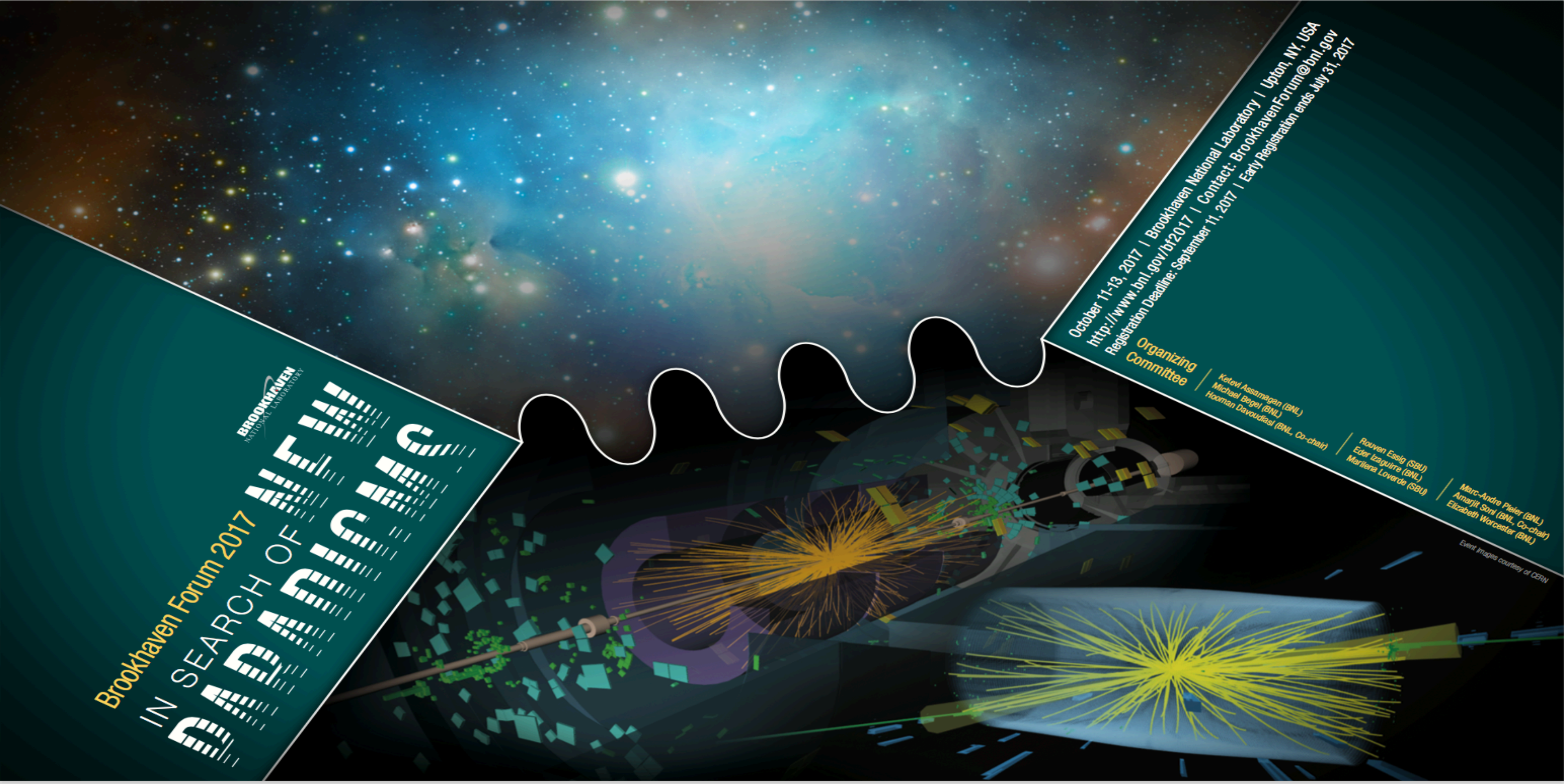

Probing Higgs Physics Through Interference Effects

Zhen Liu (Fermilab)

Brookhaven Forum 2017: In Search of New Paradigms

Oct. 12th, 2017

J. Campbell, M. Carena, R. Harnik, ZL, 1704.08259

Back to the basics of interference

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

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

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

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

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

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

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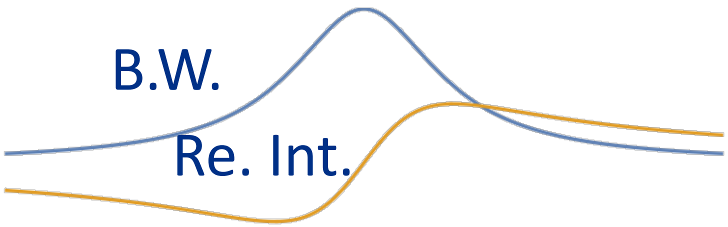

Background real

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)

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

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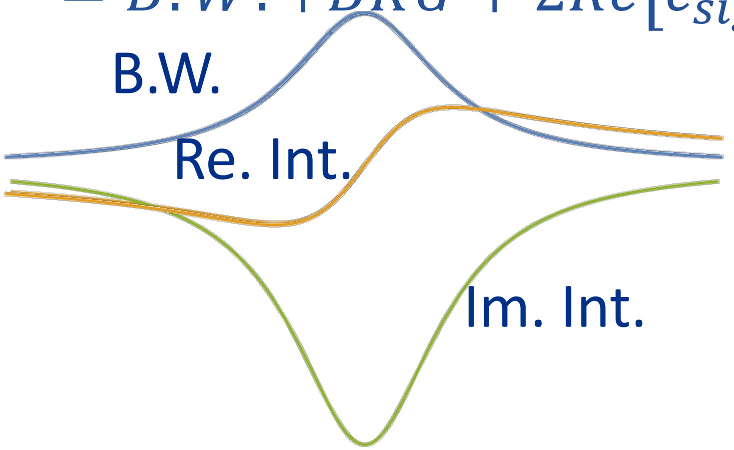

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Background real

Im. Int.– Interference from the imaginary part of propagator (rare case, changes signal rate)

Back to the basics of interference

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

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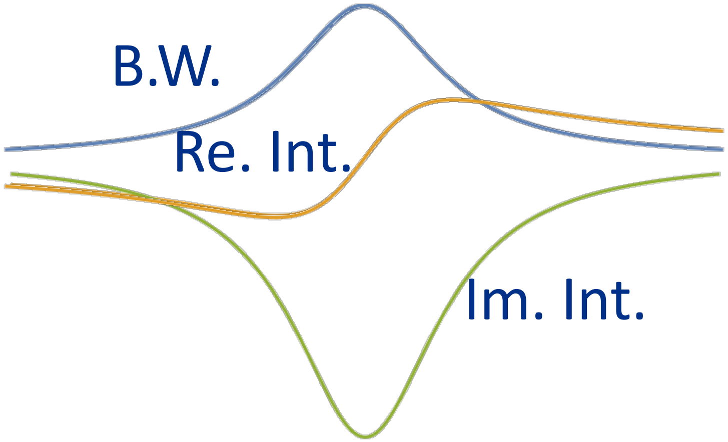
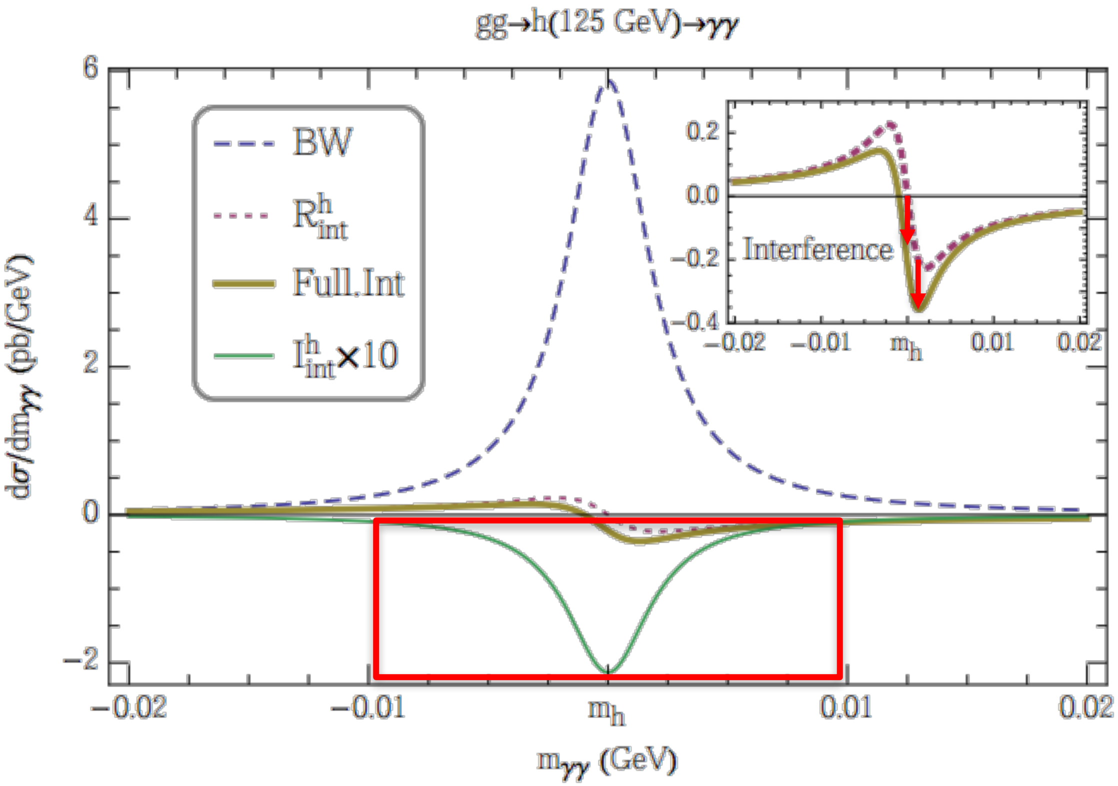


$$Im\left[c_{sig}c_{bkg}^*\right] = \left|\mathrm{c_{sig}}\right|\left|\mathrm{c_{bkg}^*}\right|\sin(\delta_{sig} - \delta_{bkg})$$

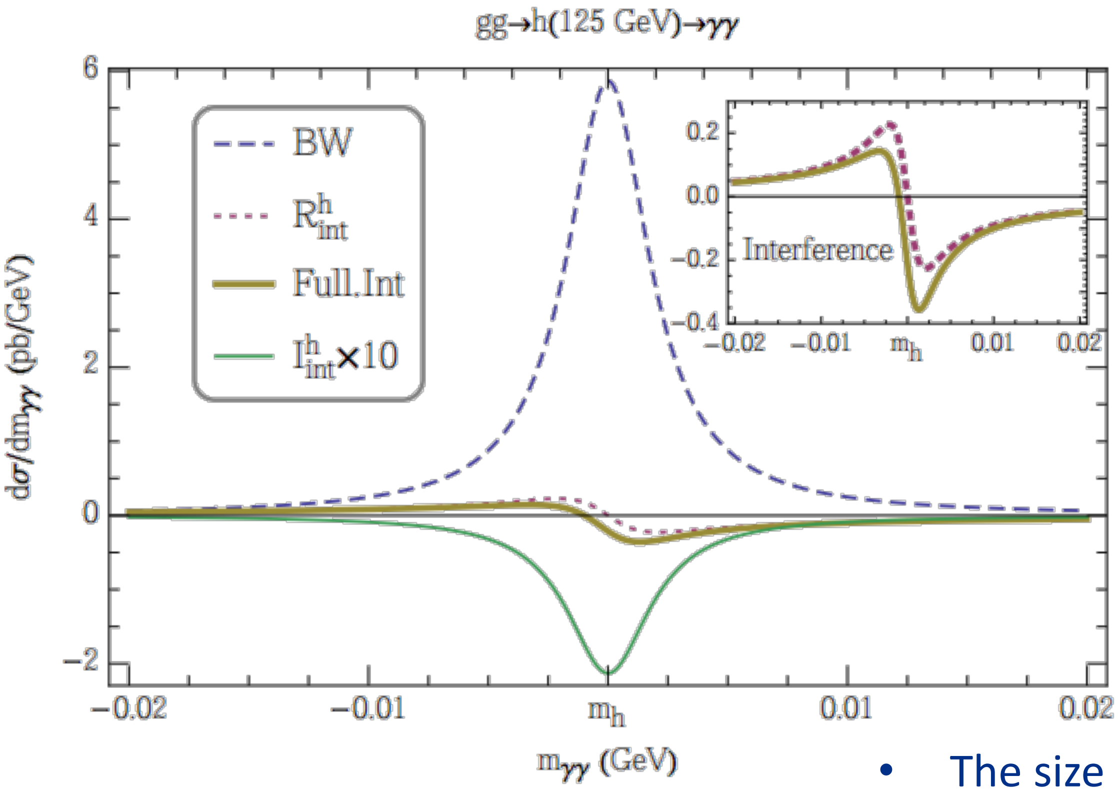
When phase $\delta_{sig} - \delta_{bkg}$ is none-zero, this new interference effect exists and cannot be neglected however narrow the resonance is!



Averaging over helicity amplitudes and polar angles, one can calculate this new interference piece between signal and background:

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

The interference term from the strong phase does change the SM rate prediction by $\sim -2.\%$



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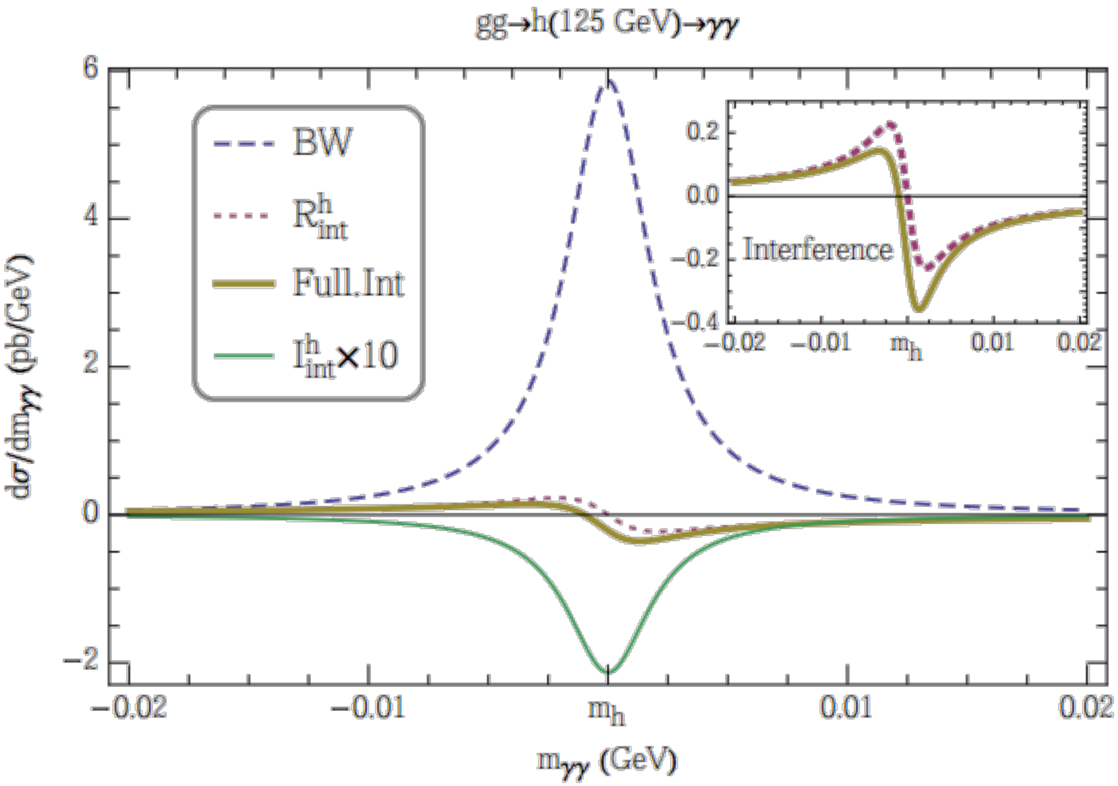
Production	Resolved scaling factor
$\sigma(ggF)$	$1.06\cdot\kappa_t^2+0.01\cdot\kappa_b^2-0.07\cdot\kappa_t\kappa_b$
$\sigma(VBF)$	$0.74\cdot\kappa_W^2+0.26\cdot\kappa_Z^2$
$\sigma(WH)$	κ_W^2

ATLAS and CMS legacy combination paper, JHEP

- The size of this effect is relevant
- **Taking ratios of cross sections of $\frac{\sigma(gg\to h\to\gamma\gamma)}{\sigma(gg\to h\to 4l)}$ can have PDF, scale, lumi uncertainties cancelled, reaching 1%~4% level at HL-LHC**
- This effect cannot be factorized into production times decay branching fractions, the framework fails to capture this;

*This agrees with Dixon and Siu's partial calculation in 03



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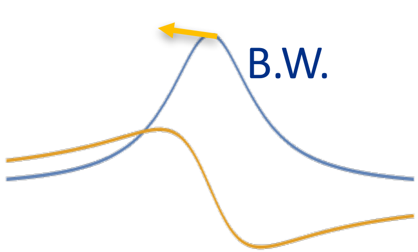
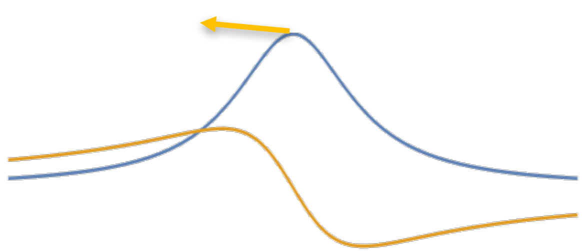
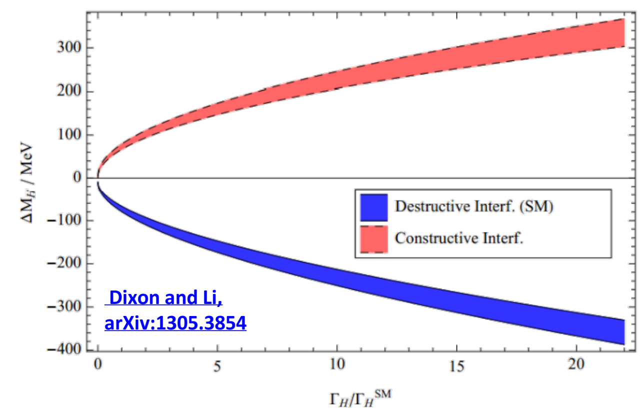
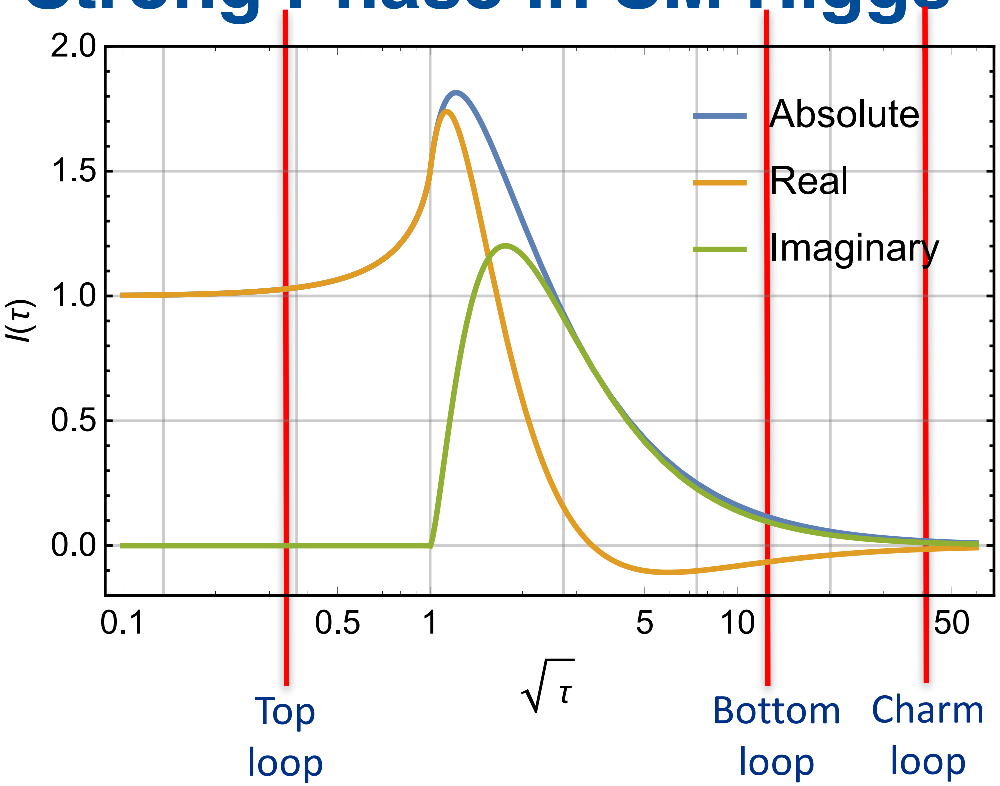


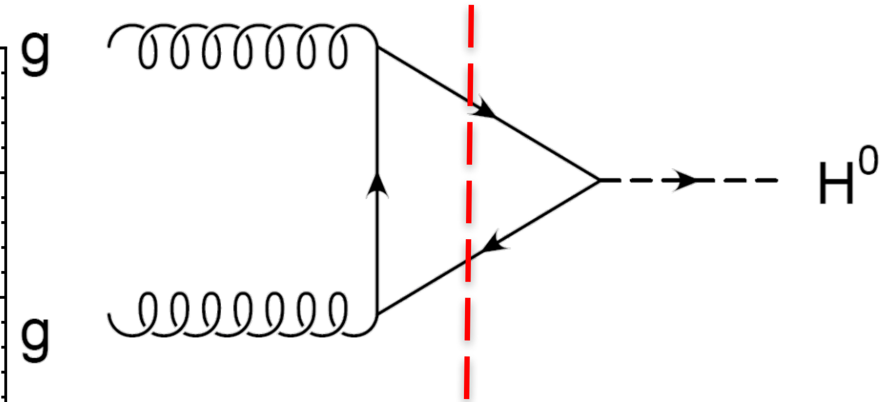




Our study is ``orthogonal'' to Dixon & Li 13'

Strong Phase in SM Higgs





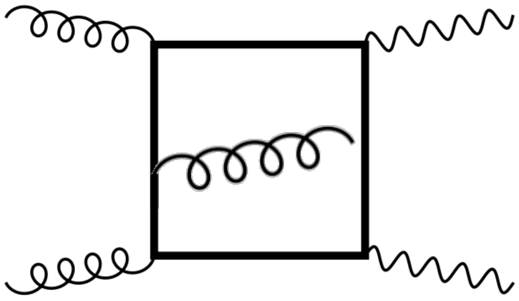
- All quark contributions normalized the same way, the plot represents the relative contributions
- Numerically:
  - t-loop $+1.034$
  - b-loop $-0.035 + 0.039i$
  - c-loop $-0.004 + 0.002i$

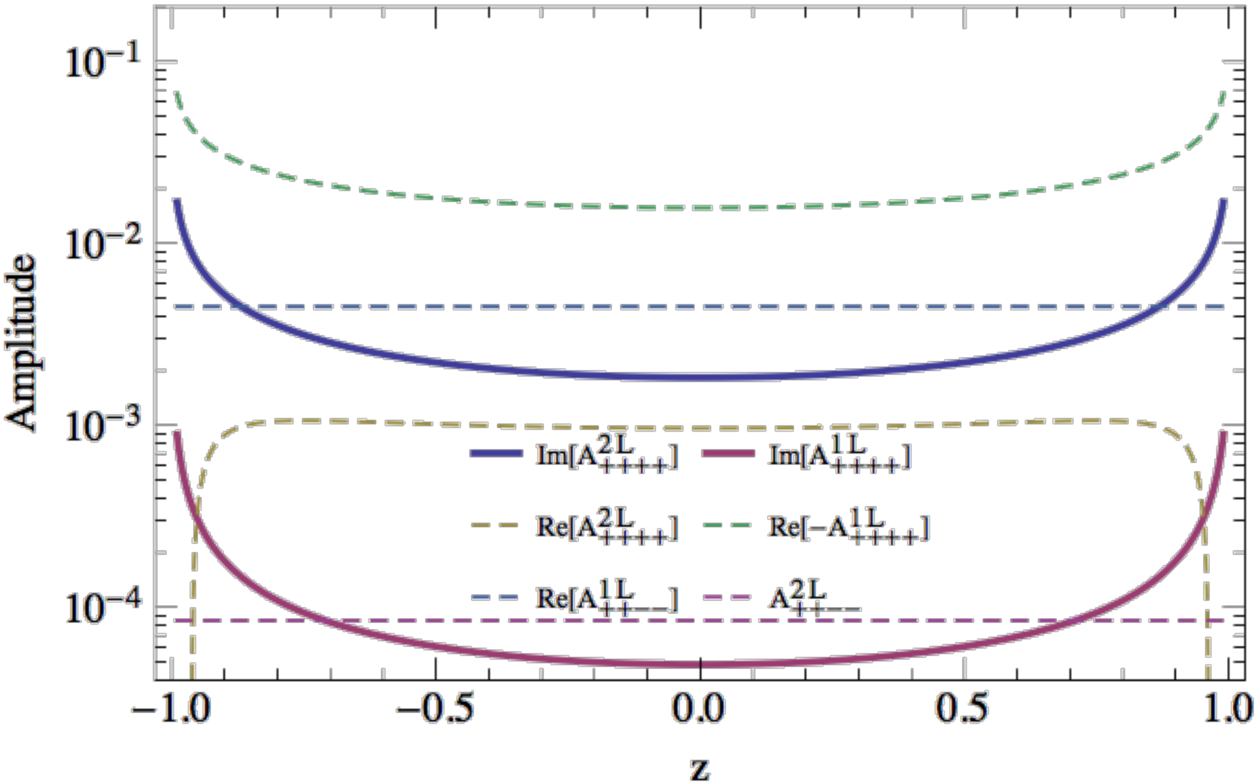
A strong phase in the gluon-gluon fusion production at hadron colliders (imaginary part)

Phase in gluon-gluon-fusion $\mathbf{0.042}$

Phase from interfering background

Interfering background are from SM box diagram of $gg \to \gamma\gamma$
There is also a strong phase in the background:





- Angular dependence
- a smaller but negative phase w.r.t to the signal
- At l-loop, the imaginary part is mainly from $A_{++++} = A_{----}$ with bottom and charm contributions
- Imaginary part dominated by the 2-loop MHV amplitude.

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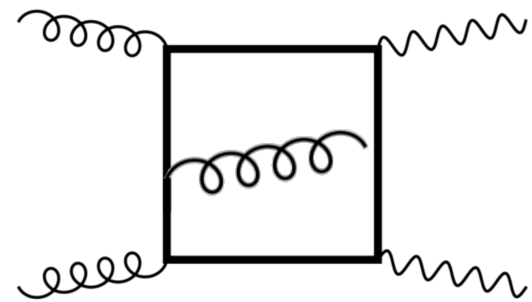

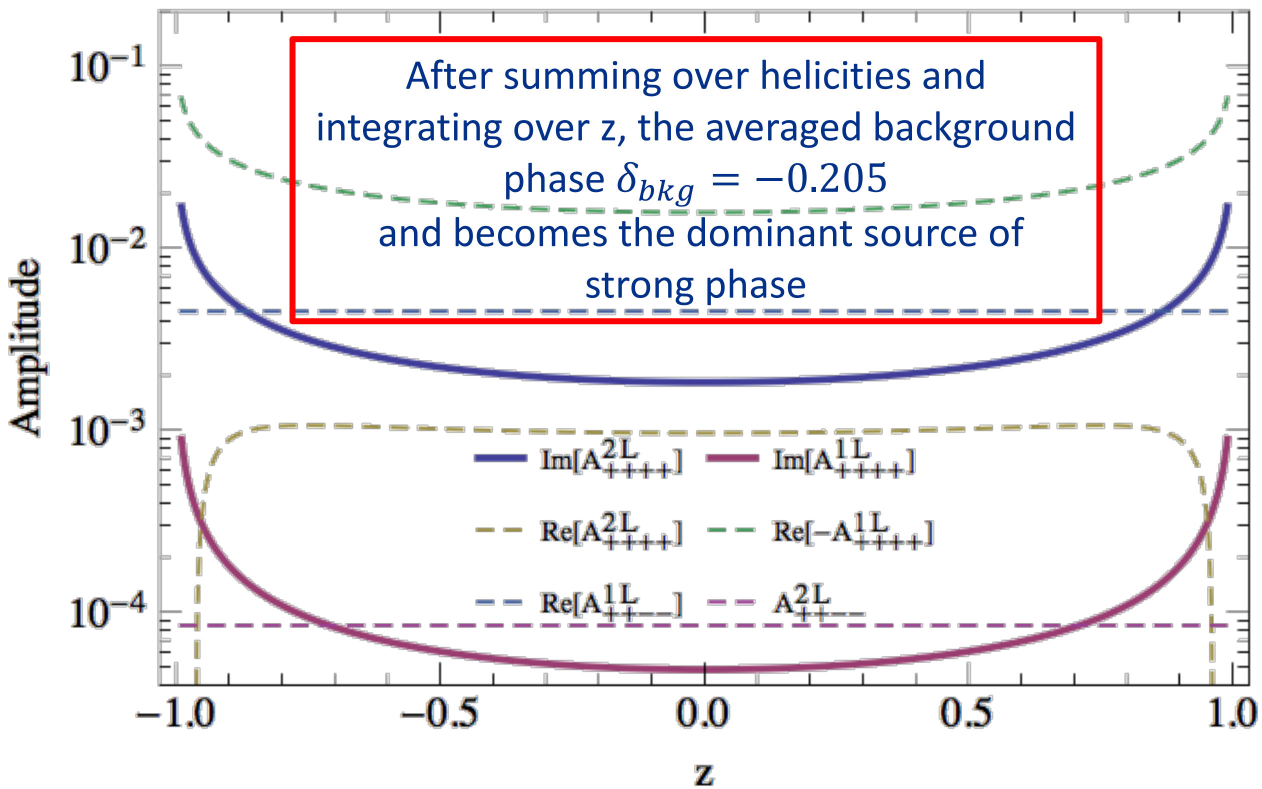

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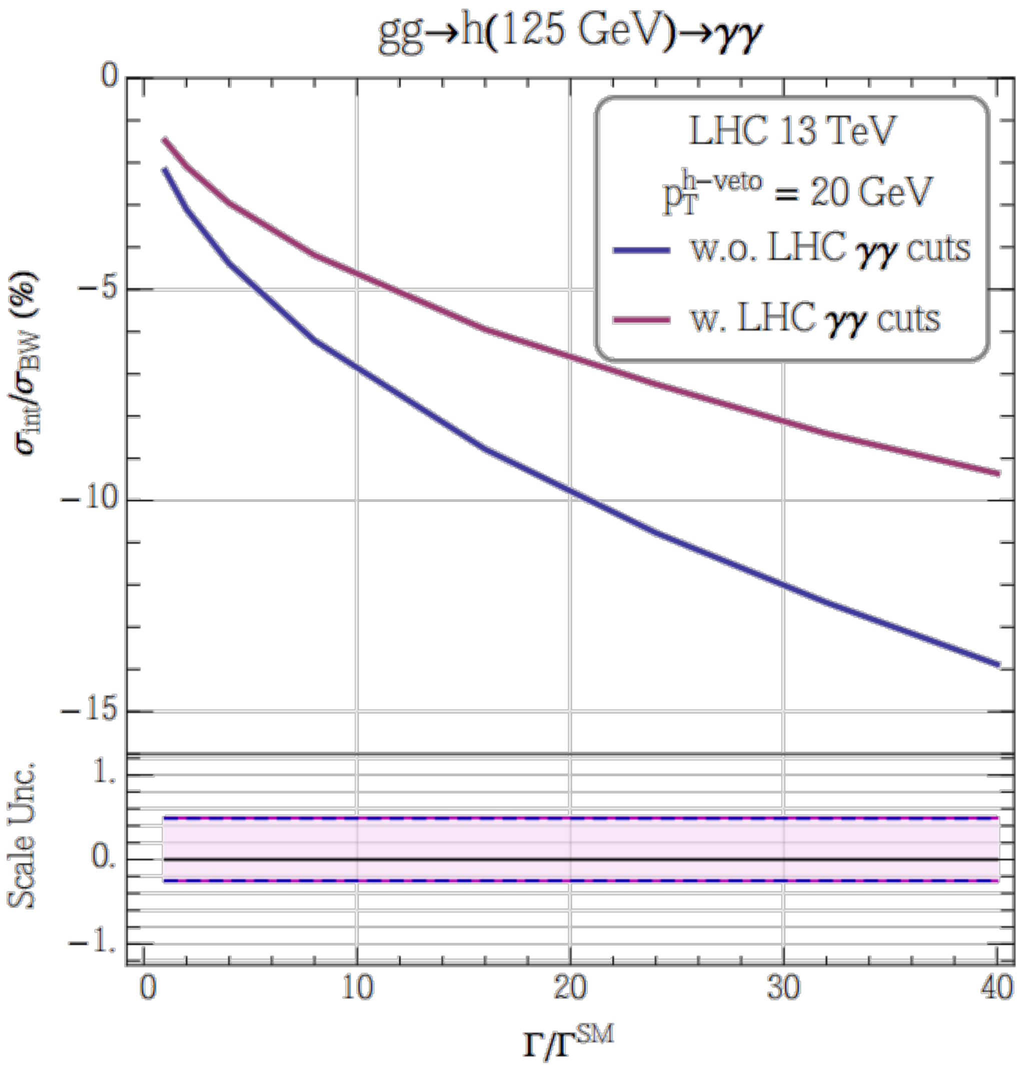
Strong phase and Higgs $gg \to h \to \gamma\gamma$ (BSM)

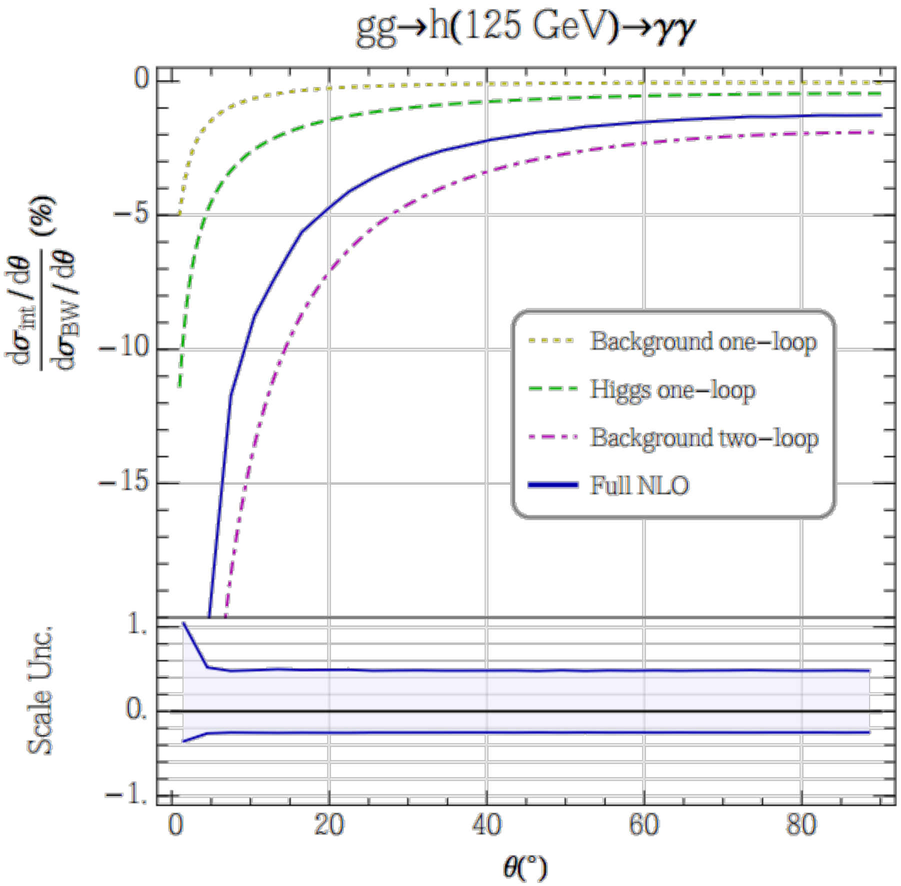
This rate change as a new probe of Higgs total width

$$\sigma(gg \to h \to \gamma\gamma) \propto \frac{g_{ggh}^2 g_{\gamma\gamma h}^2}{\Gamma_{tot}} - (\sim 2.\%) g_{ggh} g_{\gamma\gamma h}$$

- Unique piece that does not depend on total width;
- Similar to off-shell ZZ/WW measurement;
- **Negligible dependence on coupling at different scales (unlike the off-shell measurements).**



Kinematic features of the interference effect



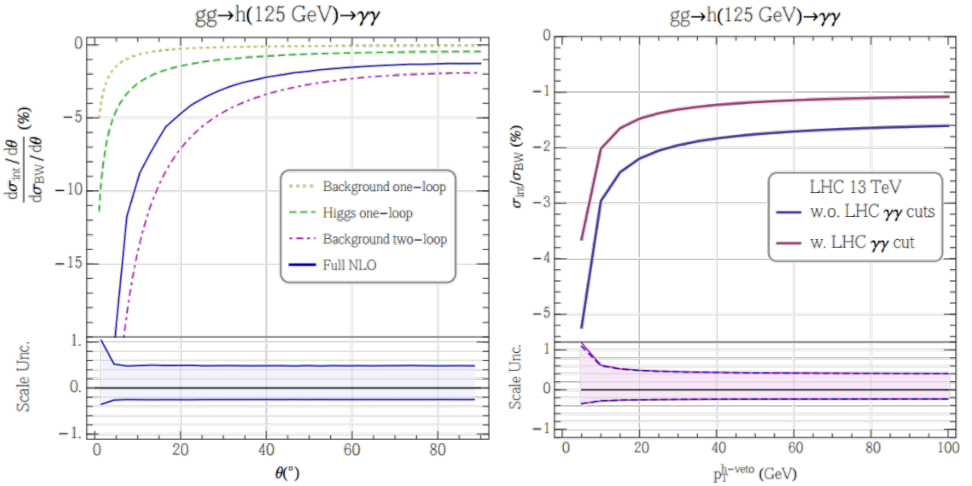
Angular distribution:

- Interference effects larger in the forward direction, driven by background amplitude kinematics;
- Interference effects ~0.5% at LO
- Interference effects increases to ~2% at NLO, driven by the 2-loop MHV amplitude's large imaginary part
- Fully inclusive cross section has larger B.W. cross section while the interference effect does not increase much, resulting in a smaller relative correction.

Kinematic features of the interference effect

$\lvert\cos\theta\rvert$	$-\sigma_{\rm int}/\sigma_{\rm BW}$ (%)		
	no cuts	p_T^h veto	$\gamma\gamma$ cuts+veto
0.0–0.2	$0.87^{+0.34}_{-0.20}$	$1.28^{+0.62}_{-0.32}$	$1.34^{+0.68}_{-0.34}$
0.2–0.4	$0.91^{+0.36}_{-0.21}$	$1.35^{+0.65}_{-0.34}$	$1.41^{+0.72}_{-0.36}$
0.4–0.6	$1.04^{+0.41}_{-0.24}$	$1.53^{+0.74}_{-0.38}$	$1.62^{+0.83}_{-0.42}$
0.6–0.8	$1.37^{+0.53}_{-0.31}$	$1.99^{+0.96}_{-0.50}$	$1.65^{+0.75}_{-0.40}$
0.8–1.0	$3.55^{+1.45}_{-0.82}$	$4.85^{+2.37}_{-1.23}$	–
0.0–1.0	$1.52^{+0.60}_{-0.35}$	$2.20^{+1.06}_{-0.55}$	$1.48^{+0.73}_{-0.38}$

Differential distributions help map out the interference effect, and further the width information!



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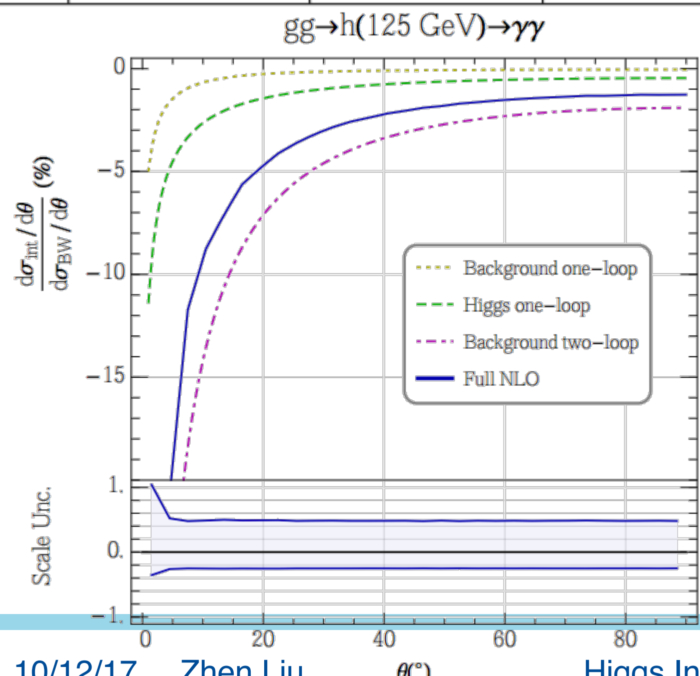

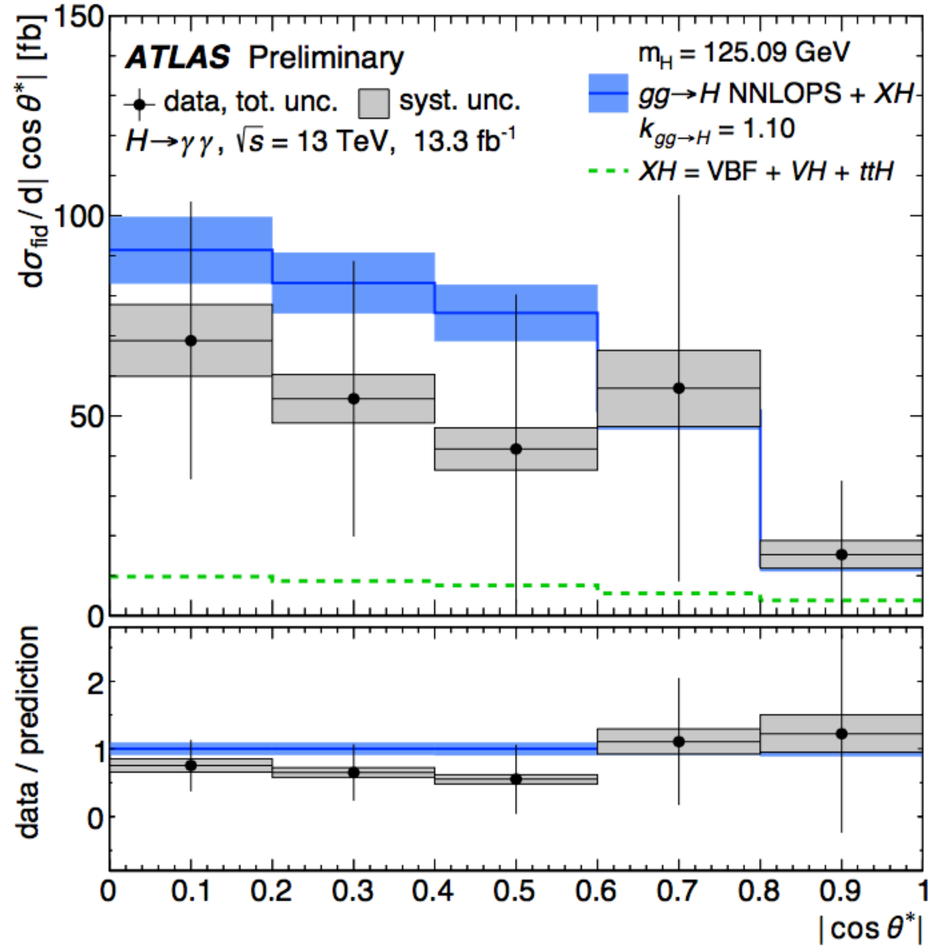

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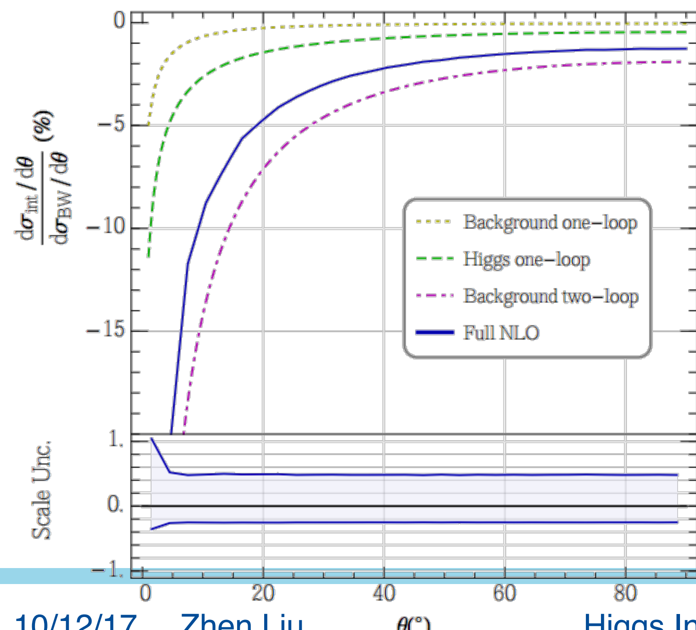
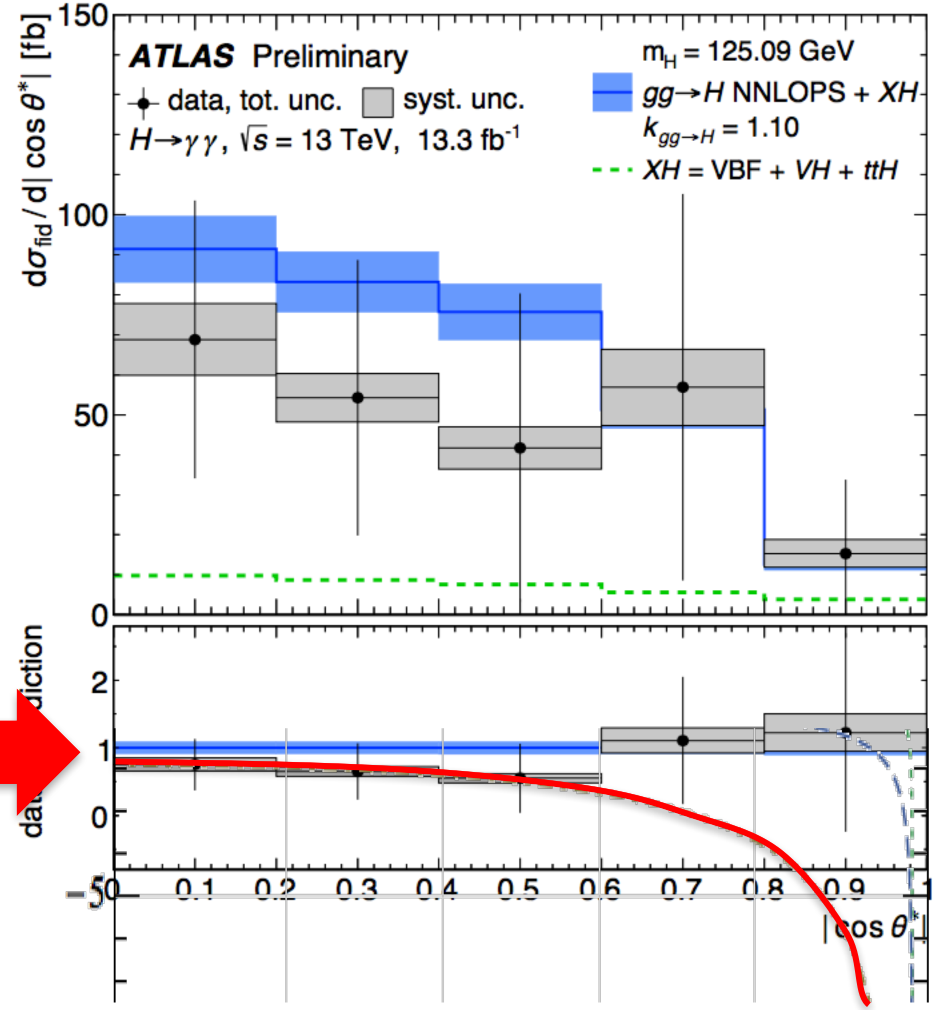
$gg\to h(125\ {\rm GeV})\to\gamma\gamma$





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Summary and outlook

We uniquely explore the physics consequences of the strong phase in Higgs physics. The effect of strong phase is robust in other than BSM physics, such as hadron physics and leptogenesis.

We choose the $gg \to h \to \gamma\gamma$ as one example and found the inclusion of this strong phase reduce the signal rate by ~2.% (at NLO, need higher order calculation); an important ingredient should be included in all LHC Higgs precision programs (global fit, etc.).

This effect could be used as probes to BSM physics, providing information on

- Higgs light quark Yukawas
- Higgs total width
- CPV effect

There are interesting kinematical distributions for the process can be utilized to map out the interference effect.
There are many more BSM process where this on-shell interference effects are important, e.g., heavy Higgs to ttbar(M. Carena, ZL, **1608.07282**), $J/\psi + \gamma$(on-going), etc.

Discussion

A theorist's perspective

Sketching the interference w CPV effect

Remark on strong v.s. weak phase

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

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

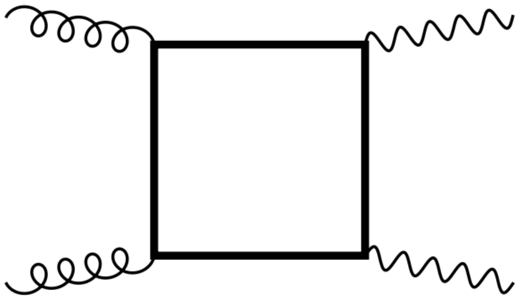
For neutral process, without construction of CP-order observables, the rate will be affected in a factorized way:

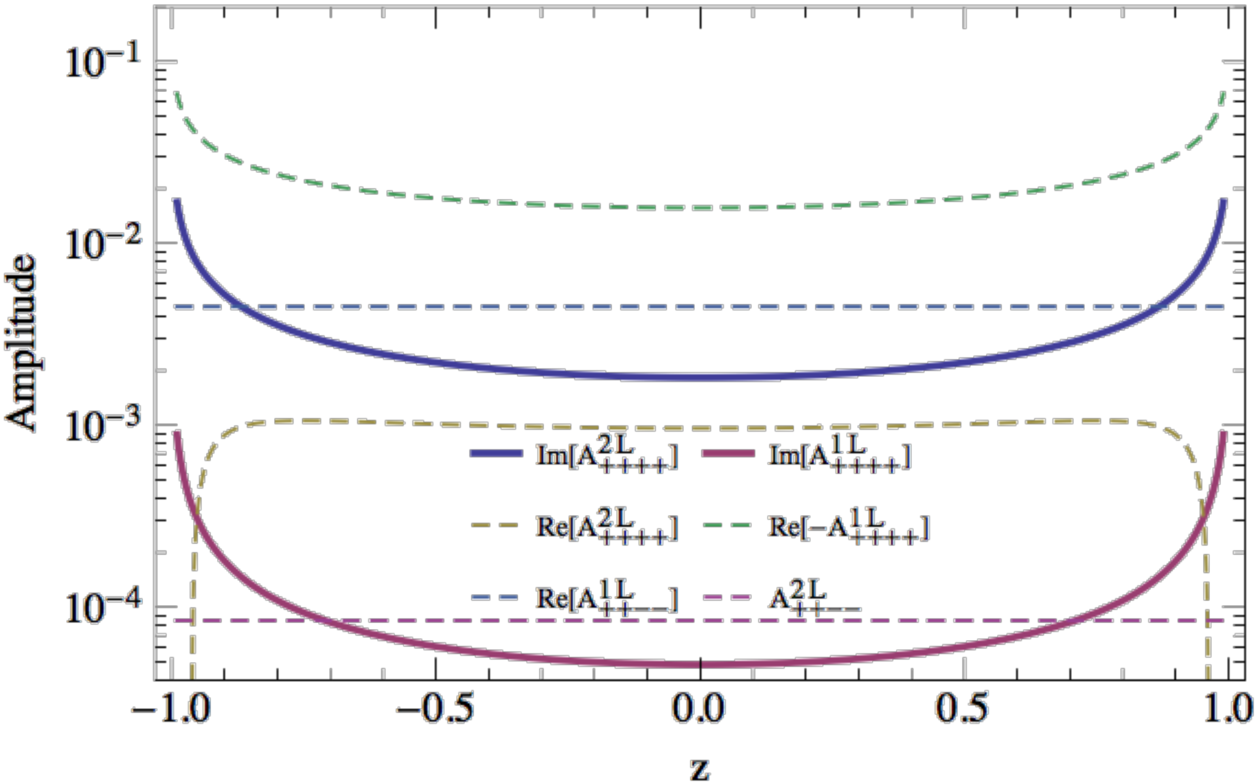
$$2Im\left[(c_{sig}^+ + c_{sig}^-)c_{bkg}\right]Im[P(\hat{s})]$$
$$= 2\left|c_{sig}^+\right|Im[P(\hat{s})]\left\{\sin\left(\delta_{sig}+\frac{\theta_{CP}}{2}-\delta_{bkg}\right)+\sin\left(\delta_{sig}-\frac{\theta_{CP}}{2}-\delta_{bkg}\right)\right\} = 4\left|c_{sig}^+\right|Im[P(\hat{s})]\sin\left(\delta_{sig}-\delta_{bkg}\right)\cos\left(\frac{\theta_{CP}}{2}\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

Phase from interfering background

Interfering background are from SM box diagram of $gg \to \gamma\gamma$

The overall sizes of different helicity amplitudes are





- $A_{++++} = A_{----}$ dominants, $A_{++--} = A_{--++}$ much smaller
- Light quark dominants
- Angular dependence