On-shell Interference Effect of the SM Higgs

Zhen Liu (Fermilab)

HXSWG Offshell Meeting: Off-shell/interference-enabled BSM/EFT studies

May. 24th , 2018

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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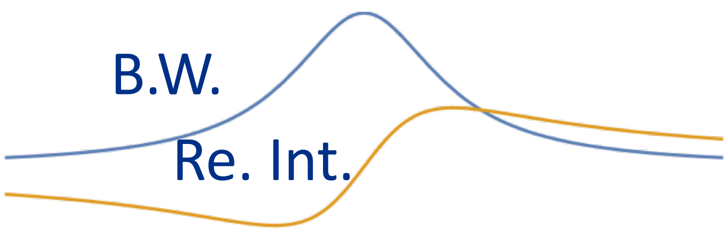

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Background real

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)

Interesting example of learning J/Psi spin

Back to the basics of interference

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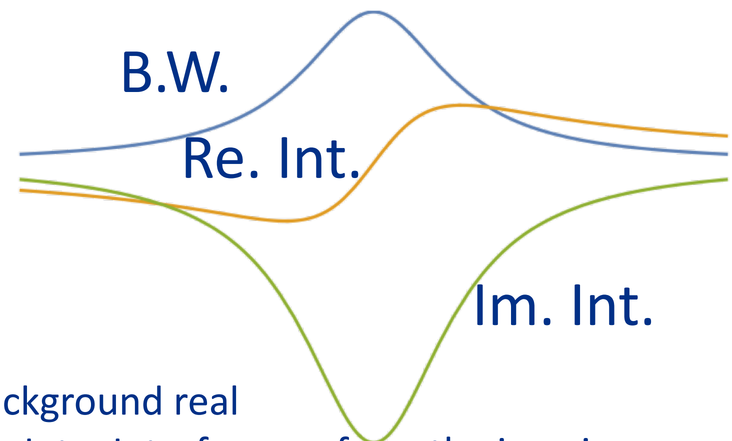

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Background real

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

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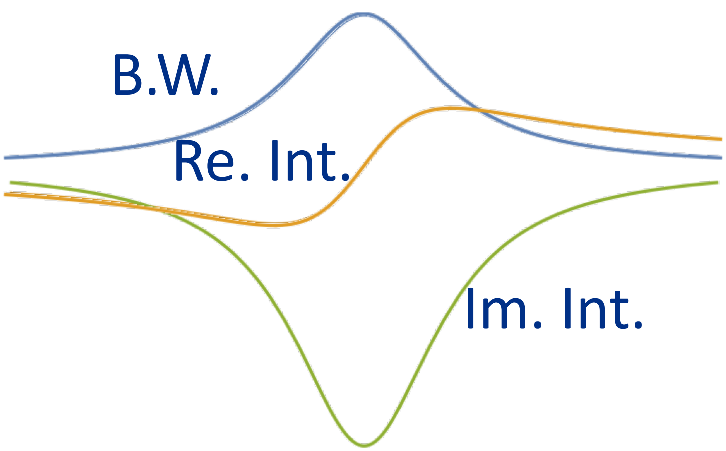

$$Im[c_{sig}c^*_{bkg}] = i|\mathrm{c_{sig}}||\mathrm{c^*_{bkg}}|\sin(\delta_{sig}-\delta_{bkg})$$

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

Strong phases

- Any ``physical phases'', the relative phase between the two interfering amplitudes would give rise to such special interference effect.
- We've exploited the physical consequences of such phase in many other places:
  1. Leptogenesis
  2. Hadron physics

  Both use strong phase to map out CPV effect

Using the hadron physics terminology:

- Weak phase (=CP phase, phase flip signs under CP)
- Strong phase (phase remains the same under CP; usually comes from loops, e.g., strong dynamics)

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

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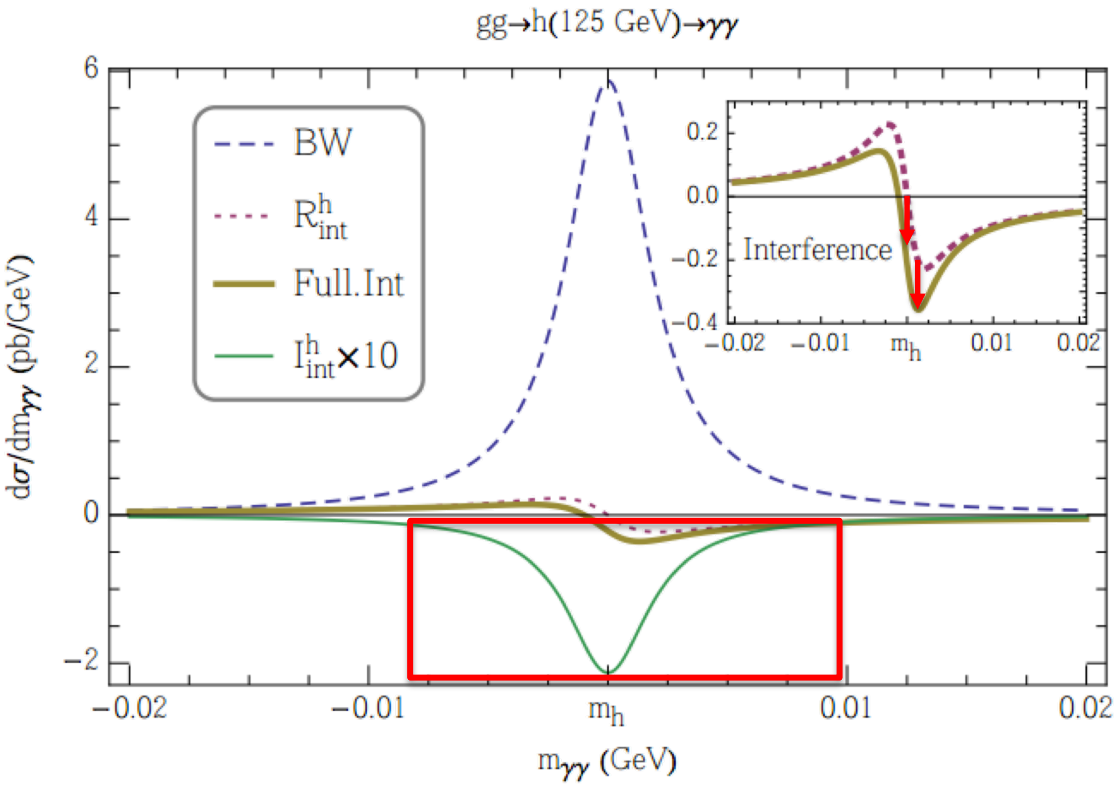
Higgs Interference



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

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

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

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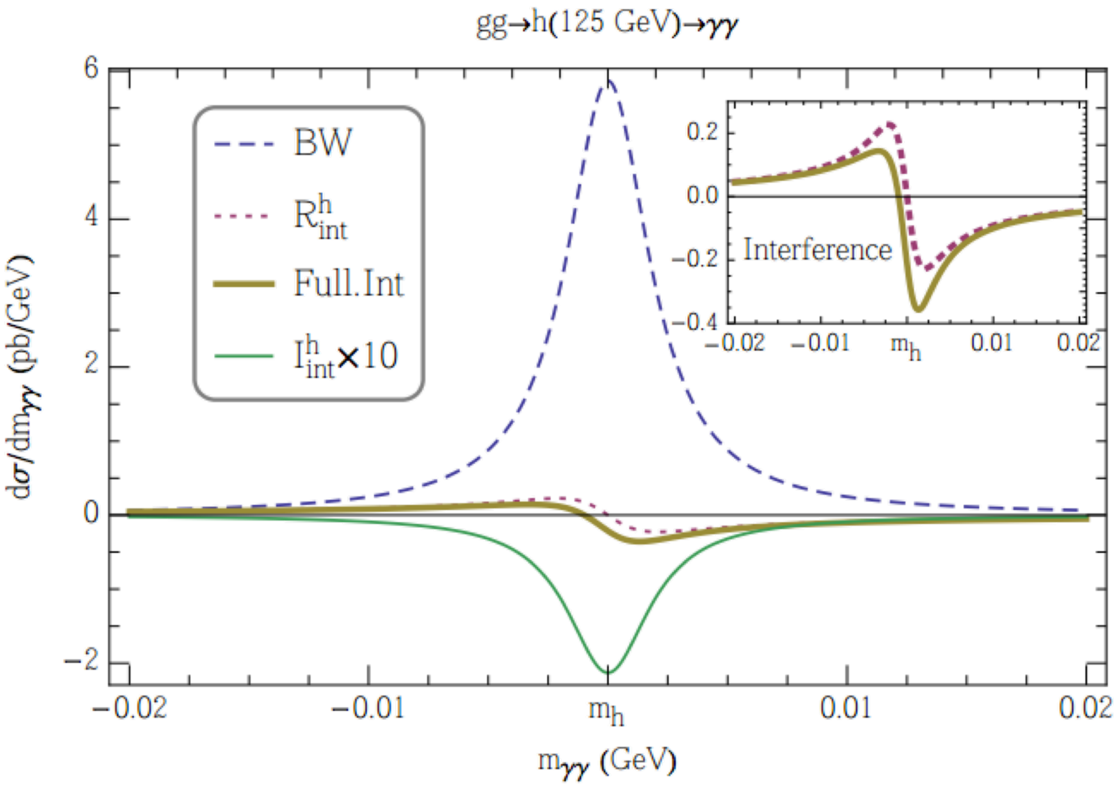

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The interference term from the strong phase does change the SM rate prediction by $\sim -2.\%$

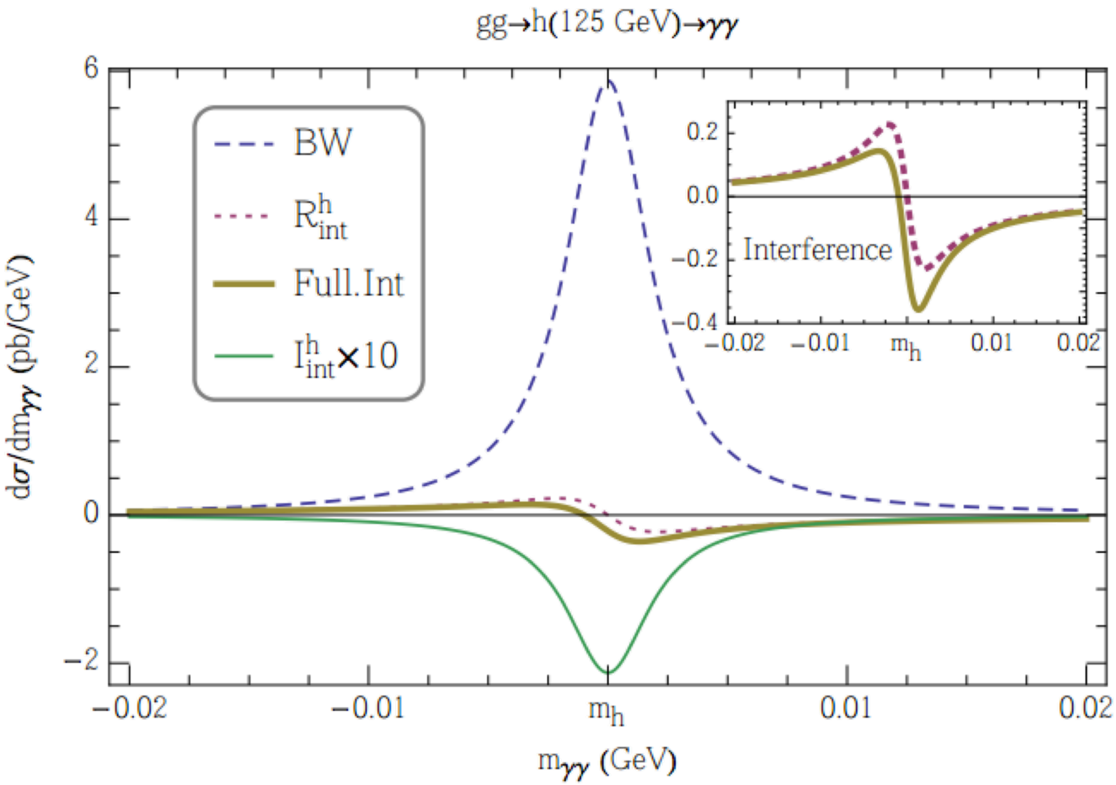
Production	Resolved scaling factor
$\sigma(ggF)$	$1.06\cdot\kappa_t^2+0.01\cdot\kappa_b^2-0.07\cdot\kappa_t\kappa_b$
$\sigma(\mathrm{VBF})$	$0.74\cdot\kappa_W^2+0.26\cdot\kappa_Z^2$
$\sigma(WH)$	κ_W^2

ATLAS and CMS legacy combination paper, JHEP

- The size of this effect is relevant
- 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

Higgs Interference



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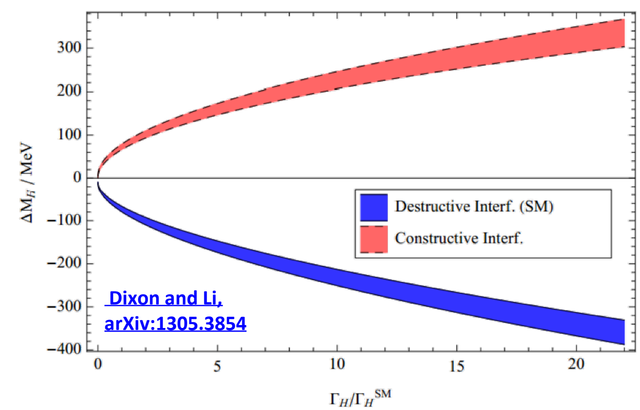
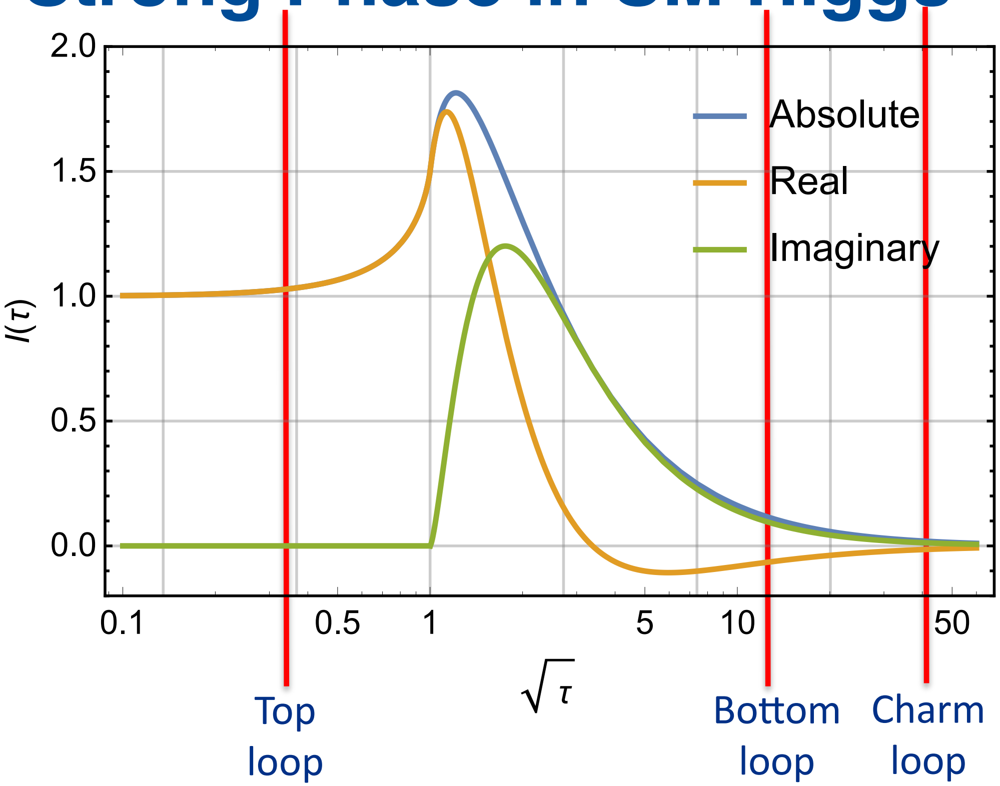
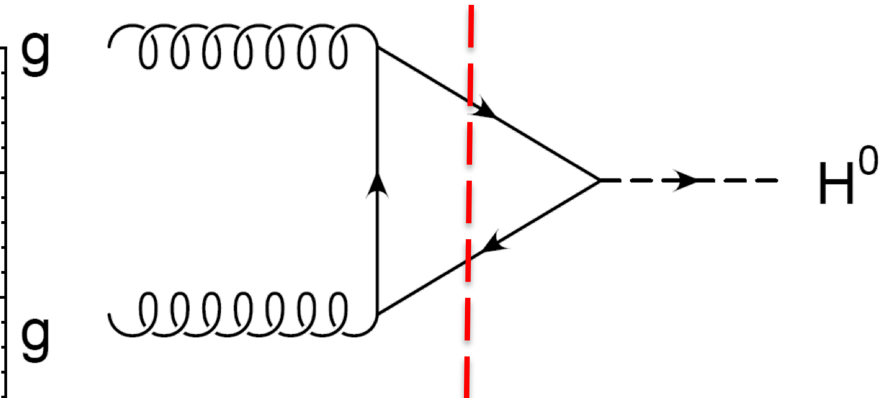


Strong Phase in SM Higgs





- 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 $-0.004 + 0.002i$

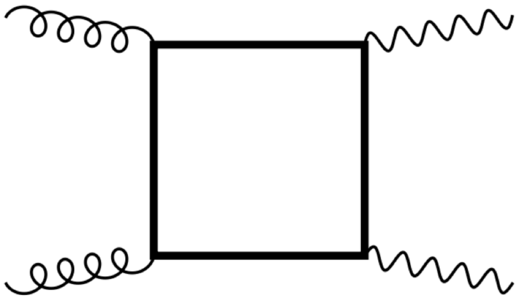
A strong phase in the gluon-gluon fusion production at hadron colliders (imaginary part)

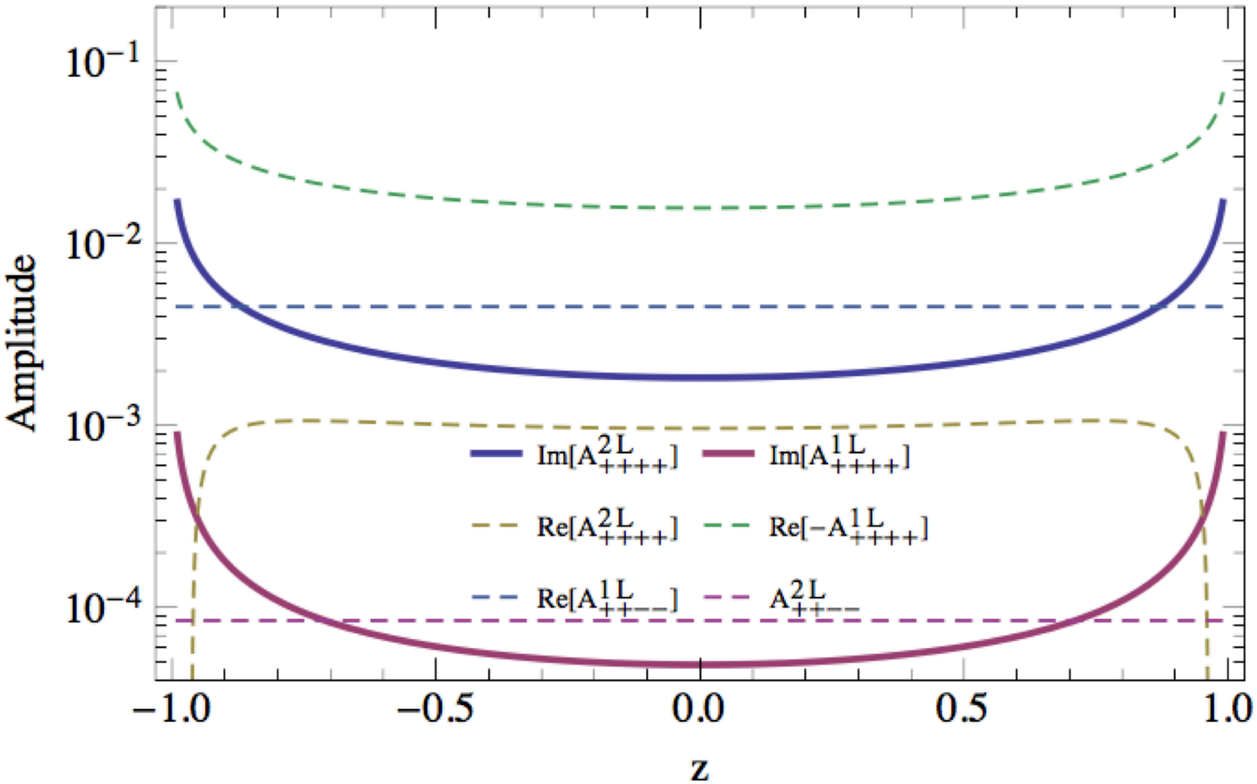
Phase in gluon-gluon-fusion $\mathbf{0.042}$

Phase from interfering background

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

The overall sizes of different helicity amplitudes are



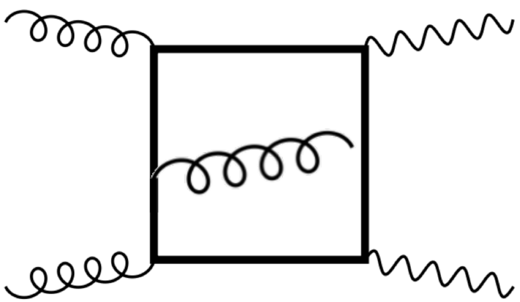


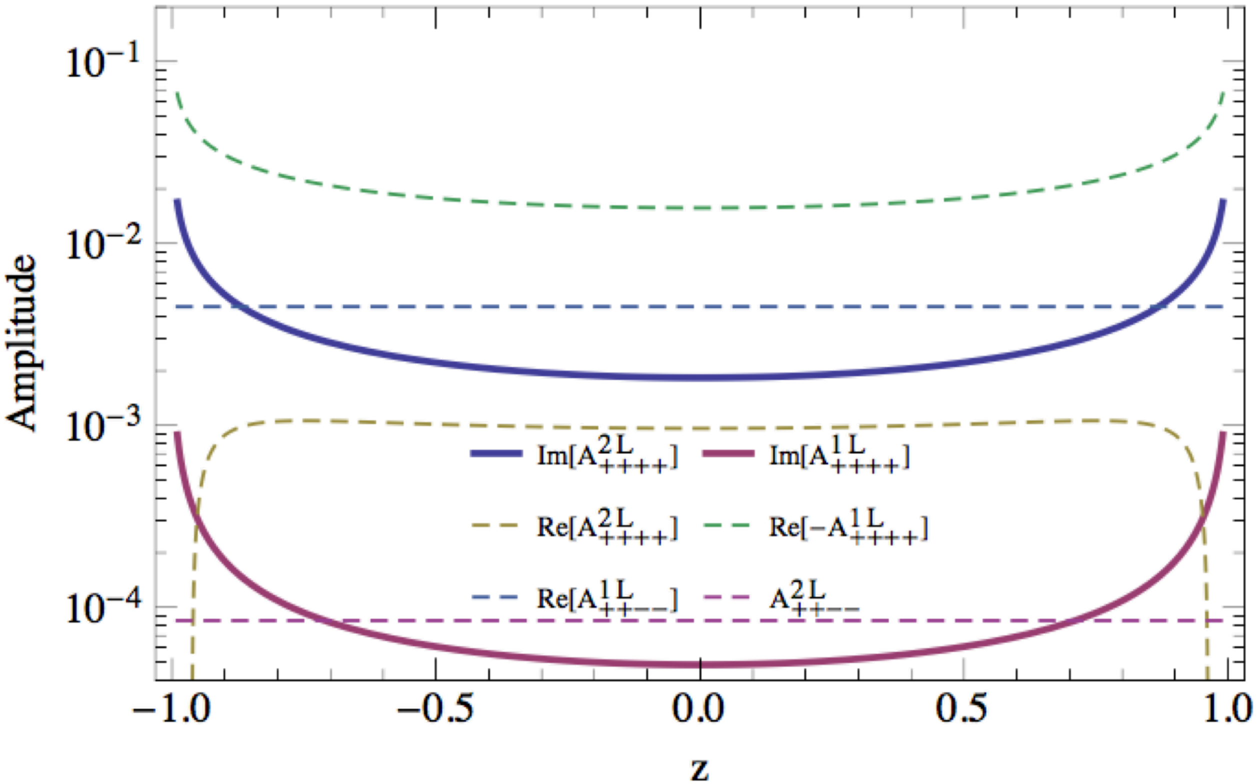
- $A_{++++} = A_{----}$ dominants, $A_{++--} = A_{--++}$ much smaller
- Light quark dominants
- Angular dependence

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
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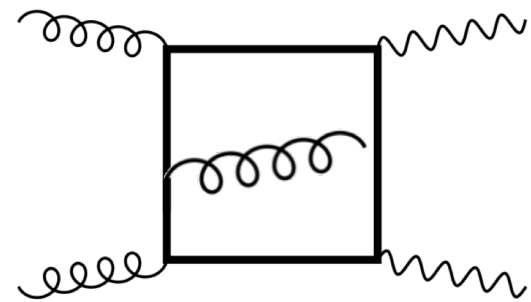

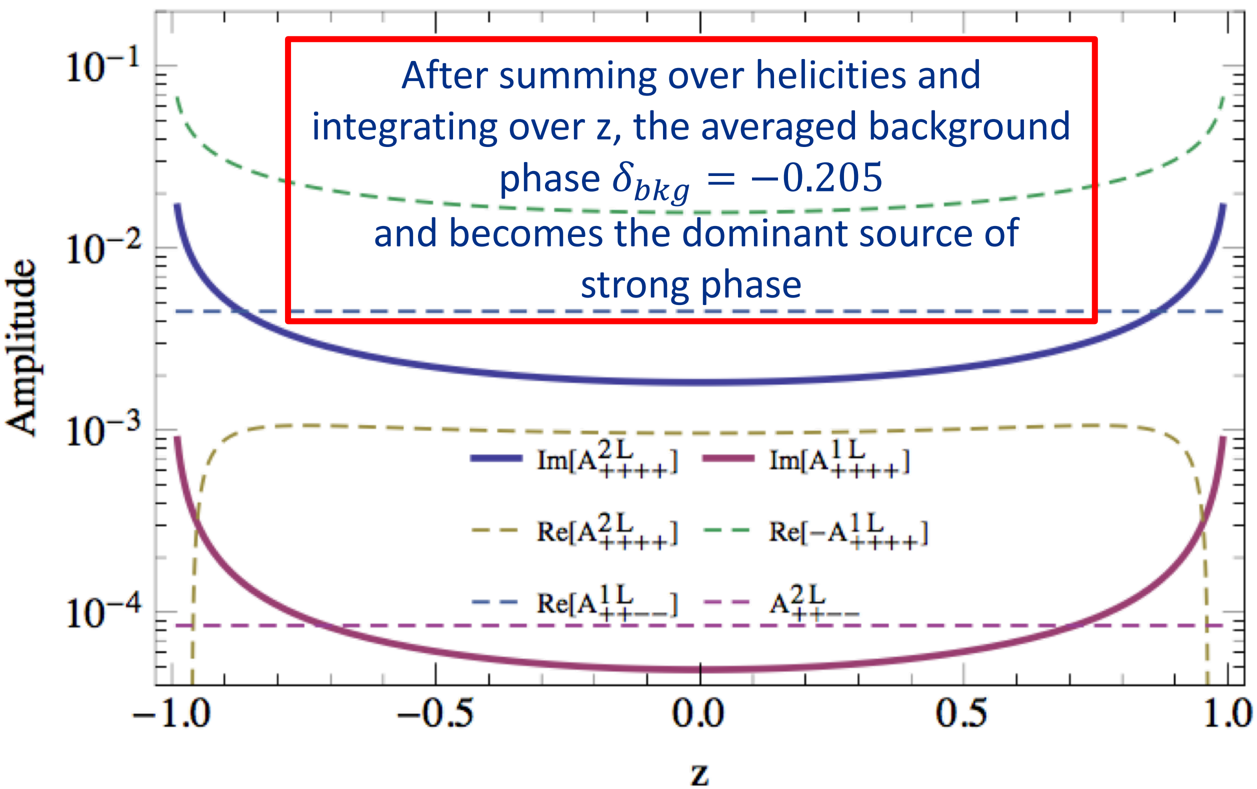

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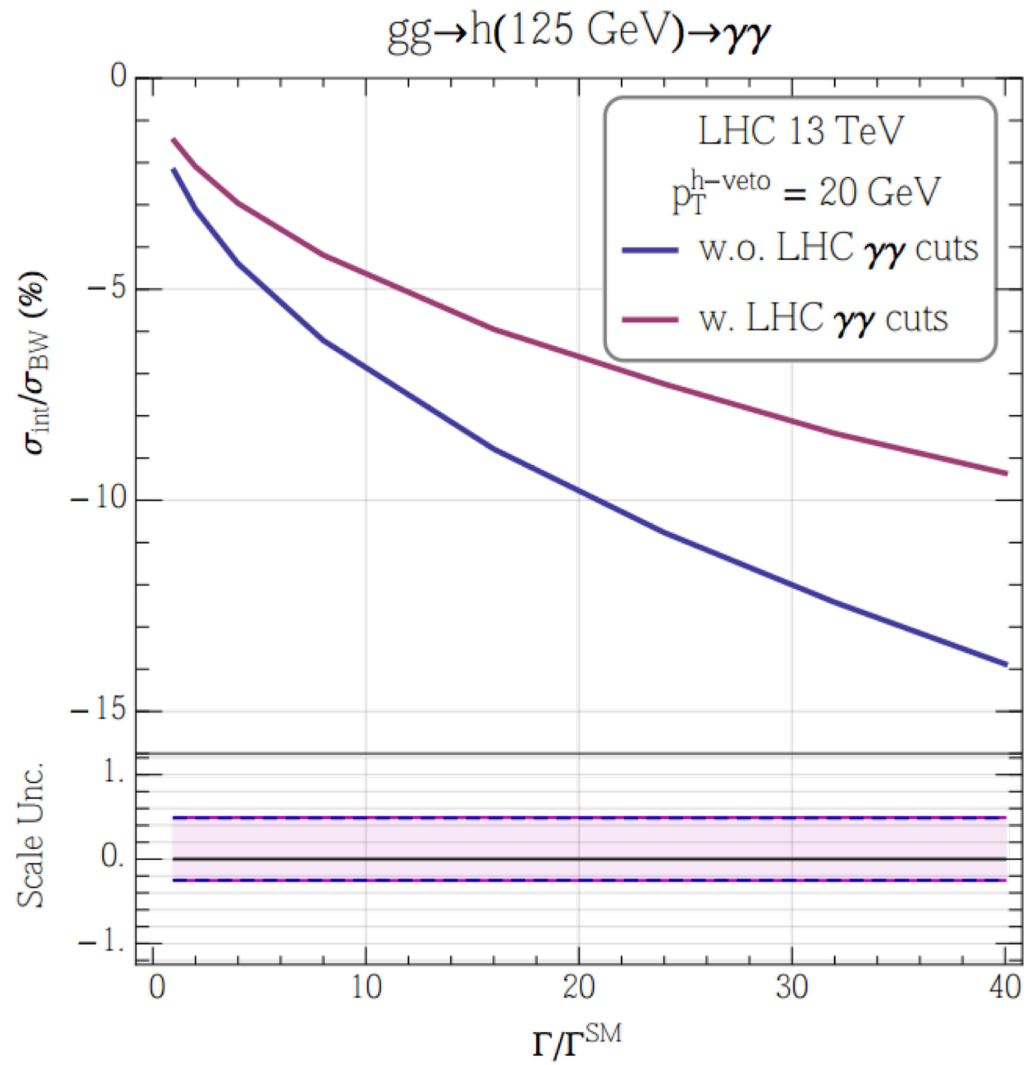
Strong phase and Higgs $gg \to h \to \gamma\gamma$ (BSM)

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 measurement;
- Negligible dependence on coupling at different scales.



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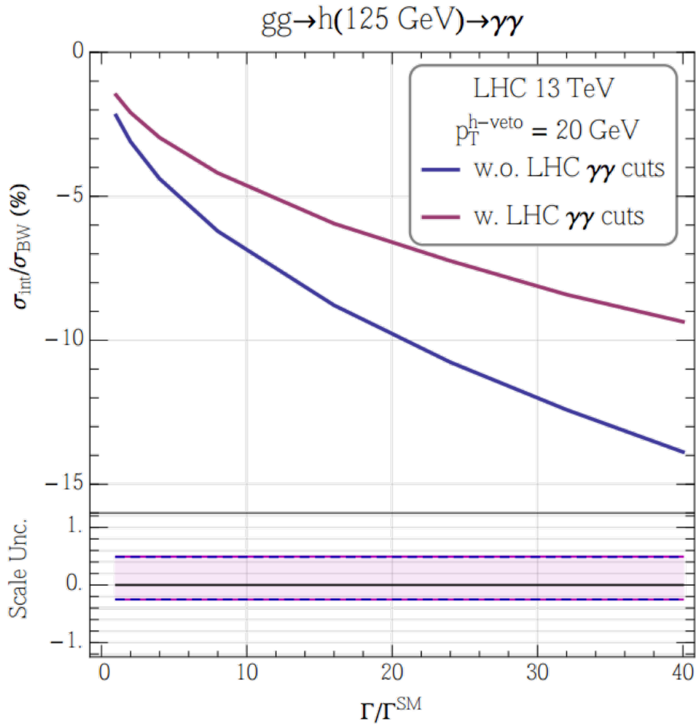

Suppose the extreme nightmare case of all observed Higgs couplings increase by factor f, and Higgs total width by factor f^4.

All on-shell cross sections remains the same as SM predictions.

However, the process $gg \to h \to \gamma\gamma$ will be altered by

$$-(\sim 2\% \times f^2)$$

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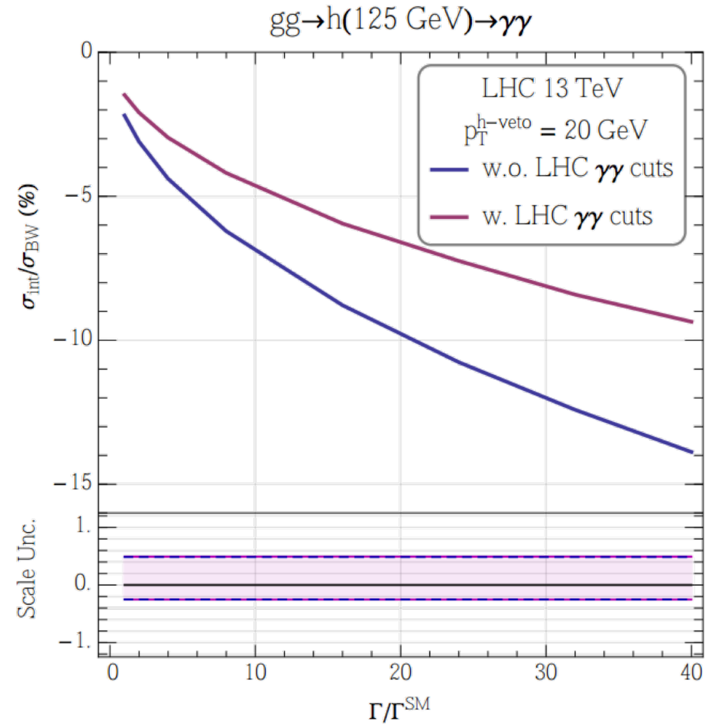

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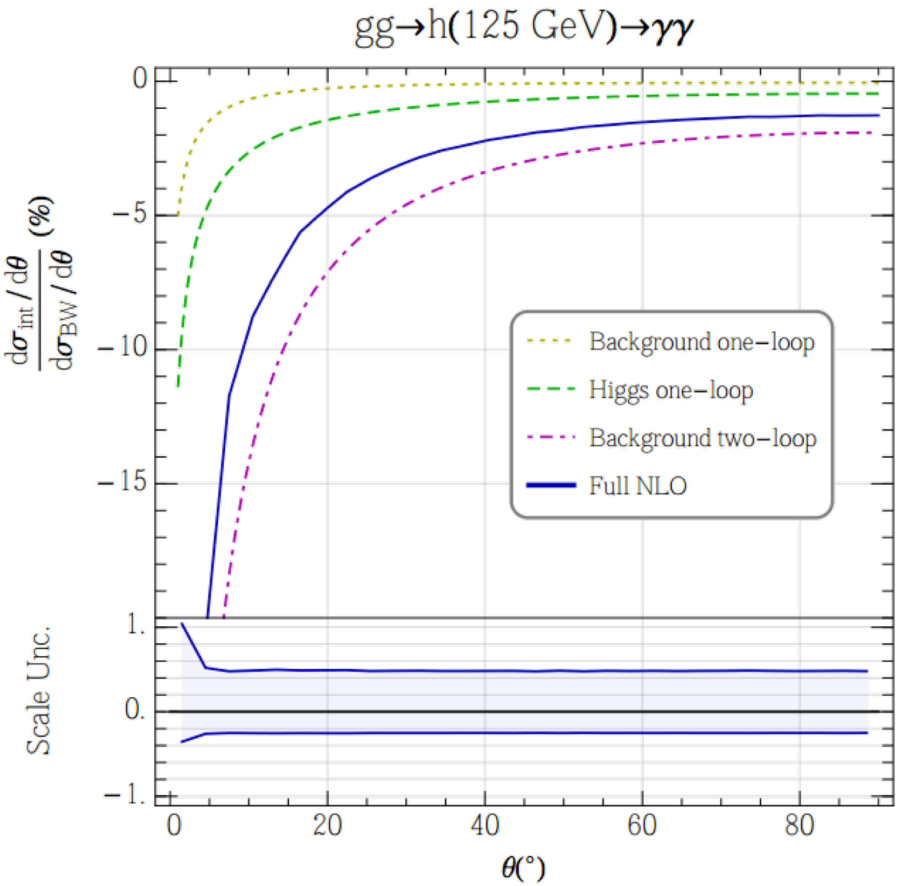
Suppose HL-LHC will measure this effect (e.g., the ratio of $\sigma_{\gamma\gamma}/\sigma_{4l}$) to 4%, it will constraint Higgs total width to ~13 times SM value

Kinematic features of the interference effect



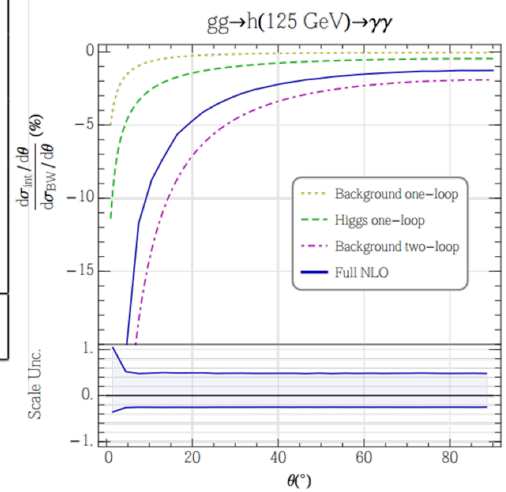
Angular distribution:

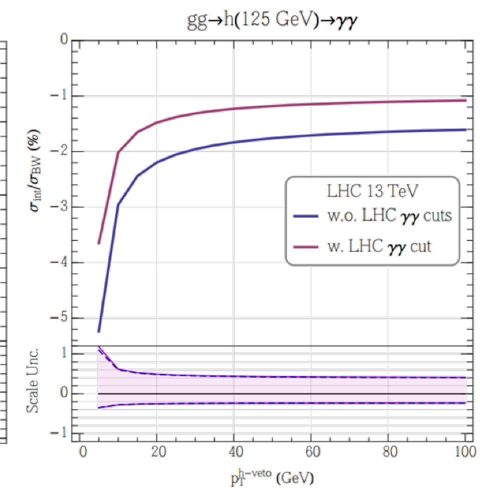
- Interference effects larger in the forward direction, driven by background amplitude kinematics;
- Interference effects ~0.5% at LO
- Interference effects increases to ~2% at NLO, driven by the 2-loop MHV amplitude's large imaginary part
- Fully inclusive cross section has larger B.W. cross section 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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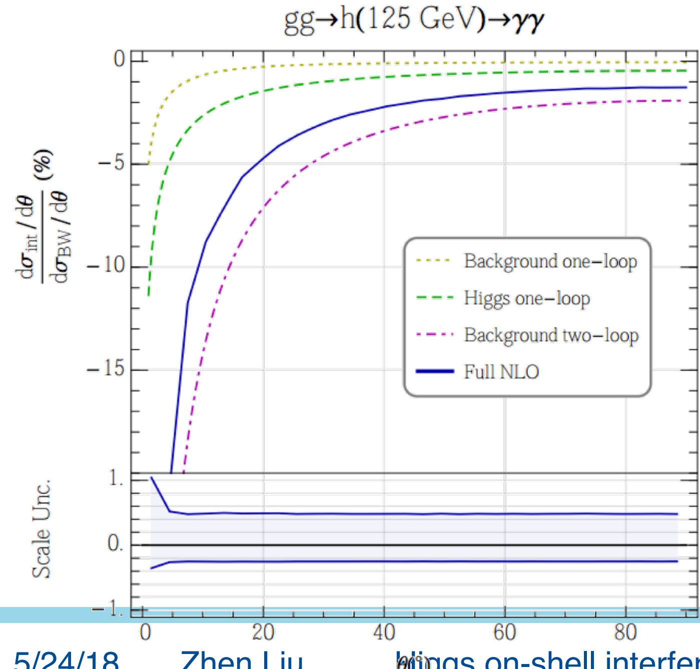
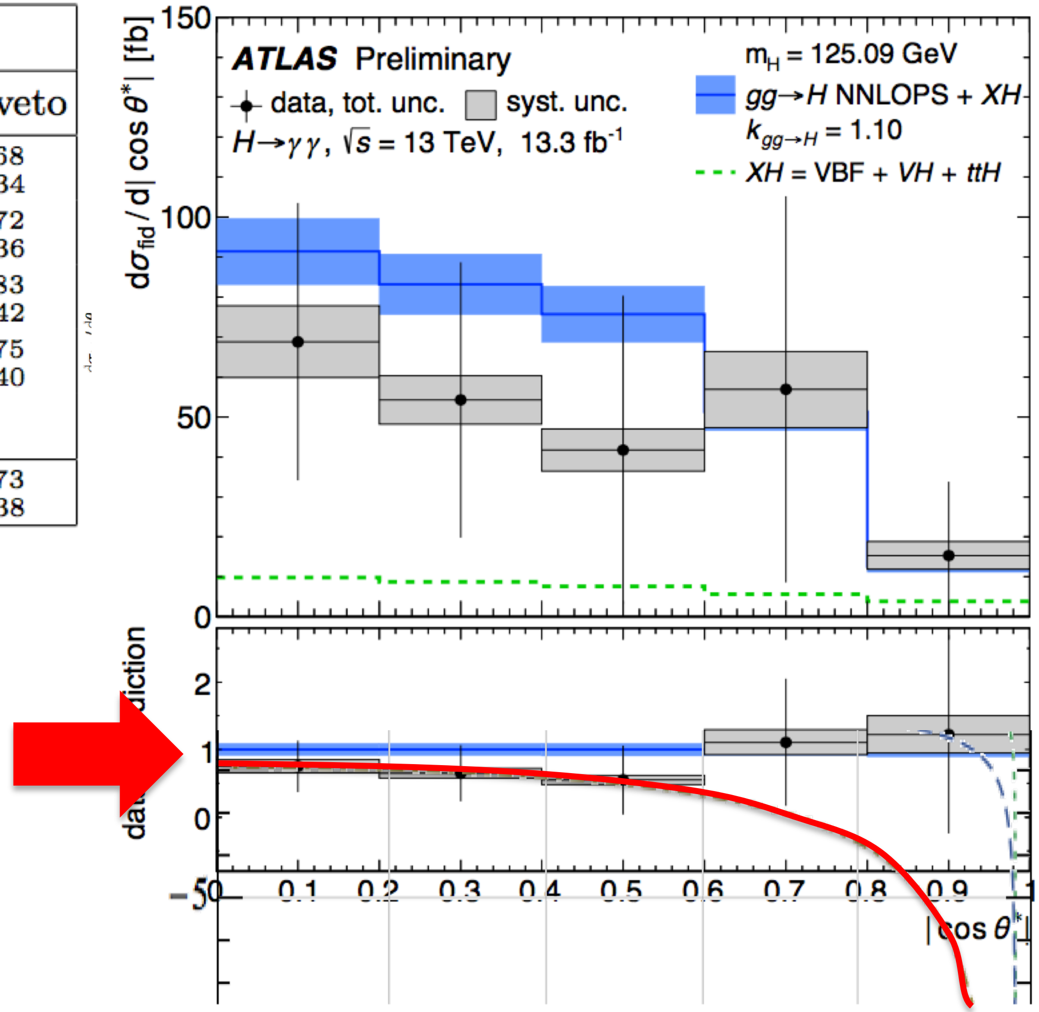




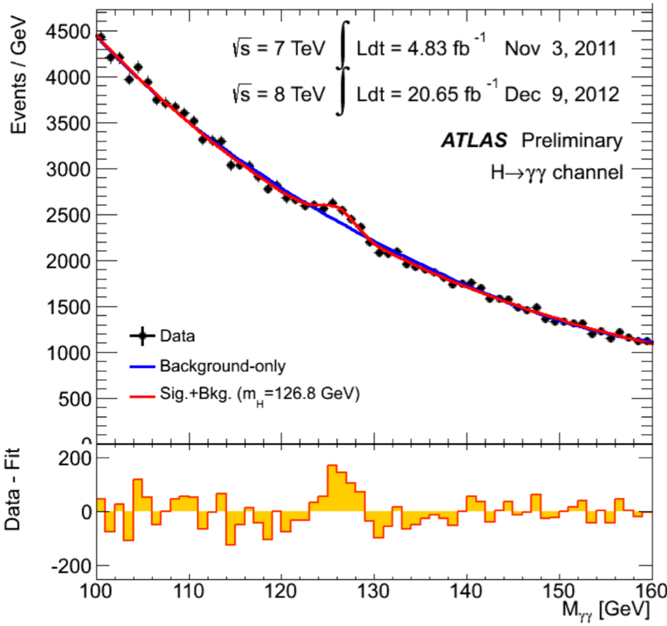
Summary and outlook

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.



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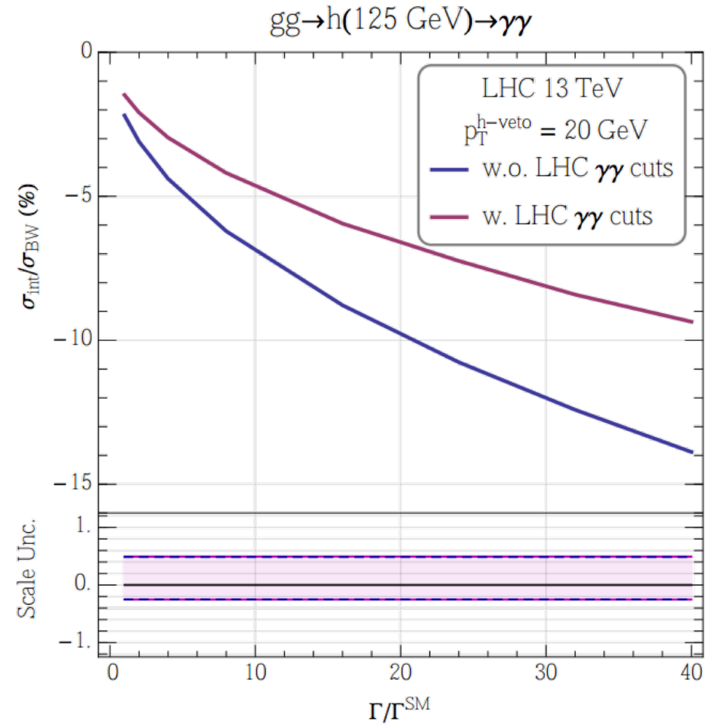

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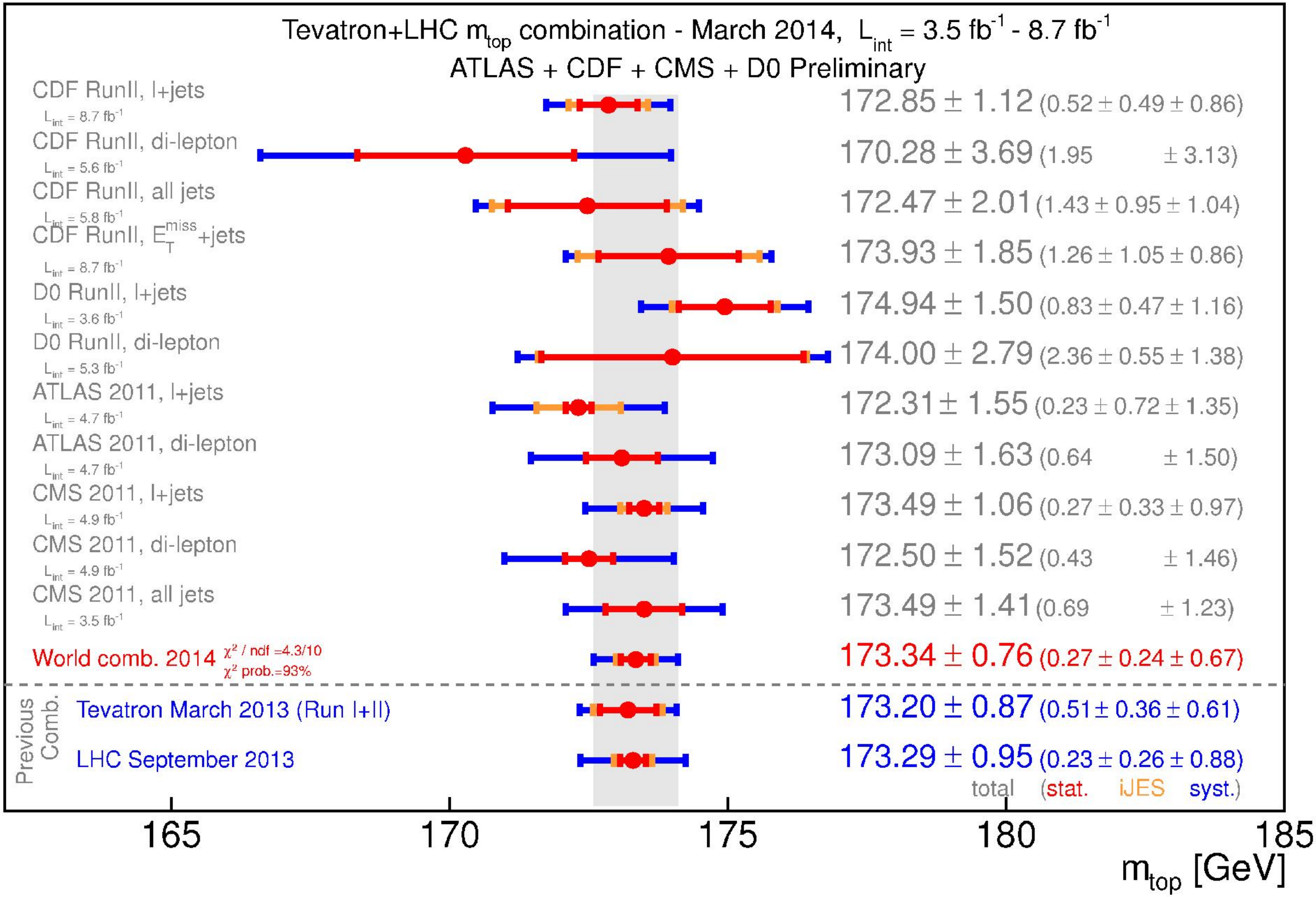
Suppose HL-LHC will measure this effect (e.g., the ratio of $\sigma_{\gamma\gamma}/\sigma_{4l}$) to 4%, it will constraint Higgs total width to ~13 times SM value;

The FCC-hh will increase the precision by at least one order of magnitude, yielding a 3-σ measurement of the interference effect and bounding the Higgs width

$$0.5 < \Gamma/\Gamma_{SM} < 1.6$$



Tevatron+LHC m_top combination - March 2014, L_int = 3.5 fb^-1 - 8.7 fb^-1
ATLAS + CDF + CMS + D0 Preliminary
CDF RunII, l+jets
L_int = 8.7 fb^-1
172.85 ± 1.12 (0.52 ± 0.49 ± 0.86)
CDF RunII, di-lepton
L_int = 5.6 fb^-1
170.28 ± 3.69 (1.95 ± 3.13)
CDF RunII, all jets
L_int = 5.8 fb^-1
172.47 ± 2.01 (1.43 ± 0.95 ± 1.04)
CDF RunII, E_T^miss+jets
L_int = 8.7 fb^-1
173.93 ± 1.85 (1.26 ± 1.05 ± 0.86)
D0 RunII, l+jets
L_int = 3.6 fb^-1
174.94 ± 1.50 (0.83 ± 0.47 ± 1.16)
D0 RunII, di-lepton
L_int = 5.3 fb^-1
174.00 ± 2.79 (2.36 ± 0.55 ± 1.38)
ATLAS 2011, l+jets
L_int = 4.7 fb^-1
172.31 ± 1.55 (0.23 ± 0.72 ± 1.35)
ATLAS 2011, di-lepton
L_int = 4.7 fb^-1
173.09 ± 1.63 (0.64 ± 1.50)
CMS 2011, l+jets
L_int = 4.9 fb^-1
173.49 ± 1.06 (0.27 ± 0.33 ± 0.97)
CMS 2011, di-lepton
L_int = 4.9 fb^-1
172.50 ± 1.52 (0.43 ± 1.46)
CMS 2011, all jets
L_int = 3.5 fb^-1
173.49 ± 1.41 (0.69 ± 1.23)
World comb. 2014 χ² / ndf =4.3/10 χ² prob.=93%
173.34 ± 0.76 (0.27 ± 0.24 ± 0.67)
Previous Comb.
Tevatron March 2013 (Run I+II)
173.20 ± 0.87 (0.51 ± 0.36 ± 0.61)
LHC September 2013
173.29 ± 0.95 (0.23 ± 0.26 ± 0.88)
total (stat. iJES syst.)
165
170
175
180
185
m_top [GeV]