Strong phase in Higgs physics

Zhen Liu (Fermilab)

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Strong phase* plays important roles in various aspects of physics

- $t\bar{t}$ heavy resonances (destructive interference with the SM background, generating dips instead of resonant bumps, M. Carena, ZL, **arXiv:1608.07282**, **JHEP**)
- Hadron physics (strong phase mapping out CPV)
- Leptogenesis (e.g., weak phase from heavy neutrino decay interferes with strong phase part, generating asymmetry)

*in contrast to weak CP phase that generates relative phase between amplitudes related by CP conjugation; strong phase is a universal phase to these CP-related amplitudes.

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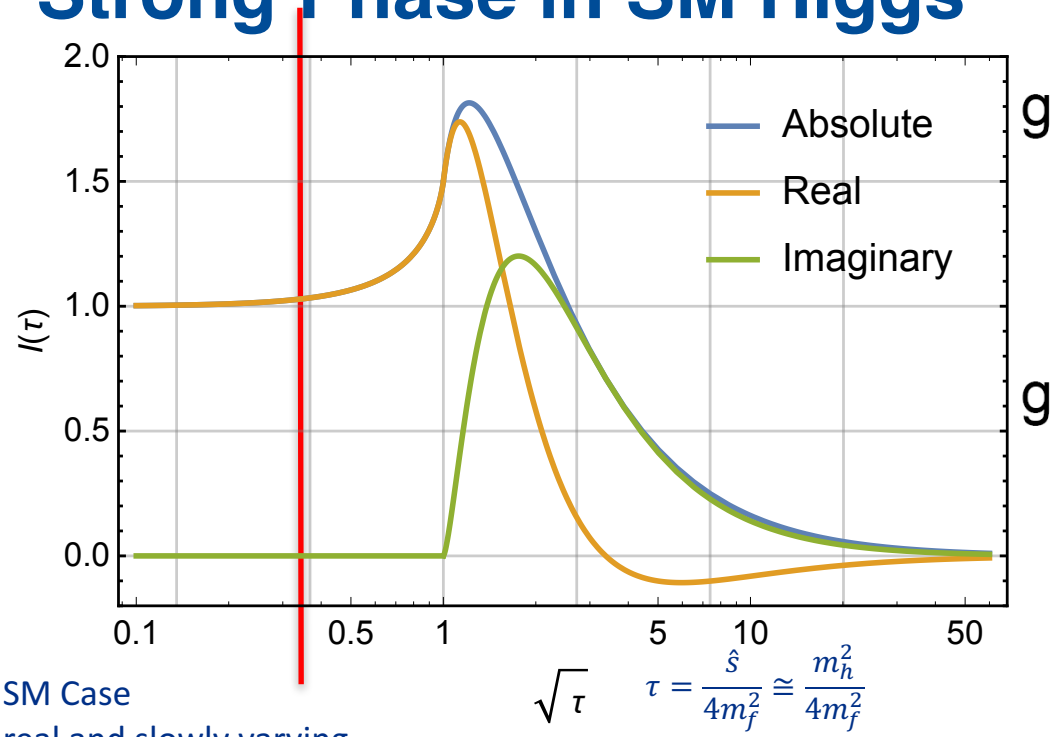
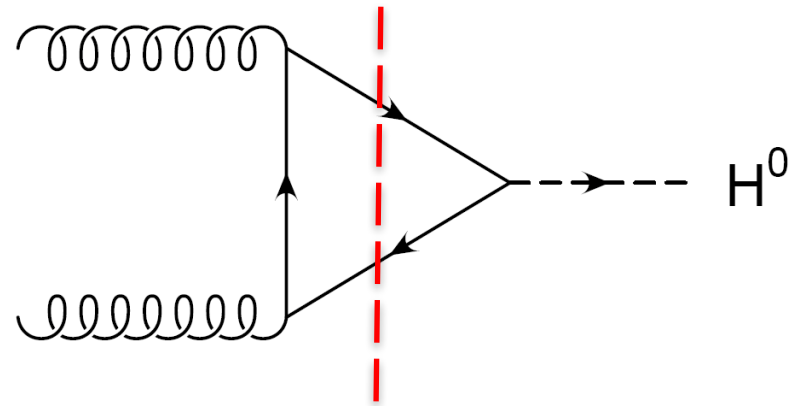
Question:
how about the strong phase in the SM Higgs?

J. Campbell, M. Carena, R. Harnik, ZL, **arXiv:1704.08259**

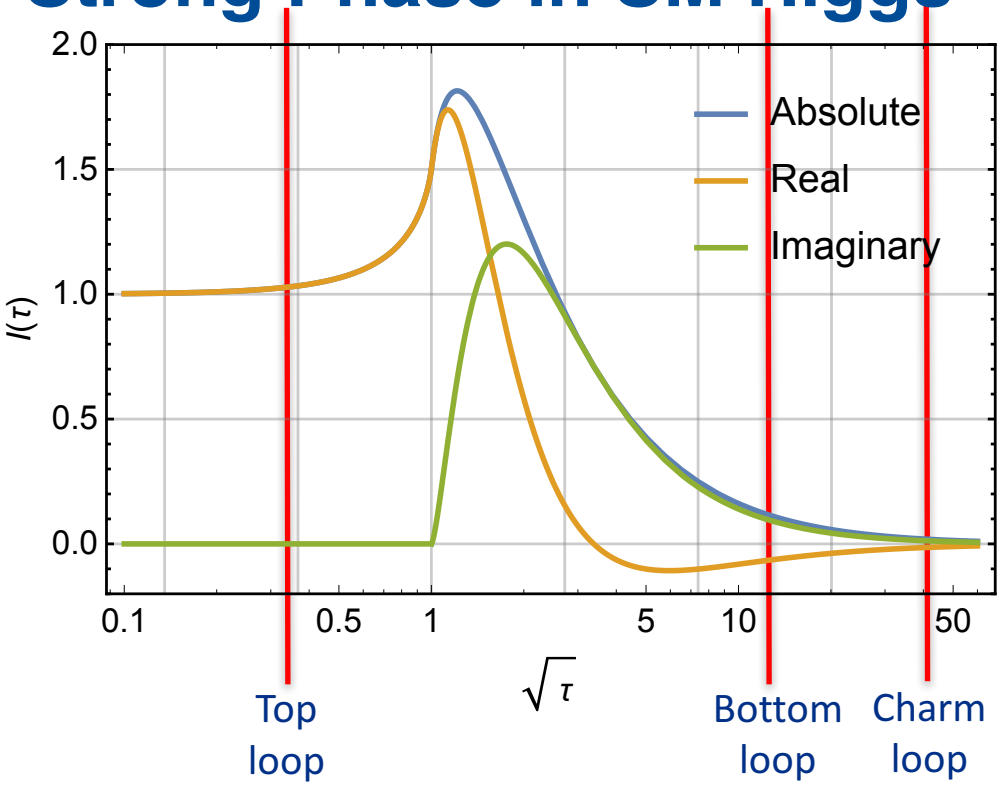
Strong Phase in SM Higgs





SM Case
real and slowly varying
``heavy (chiral) fermion
decoupling theorem'' (with
Yukawa proportional to the mass)

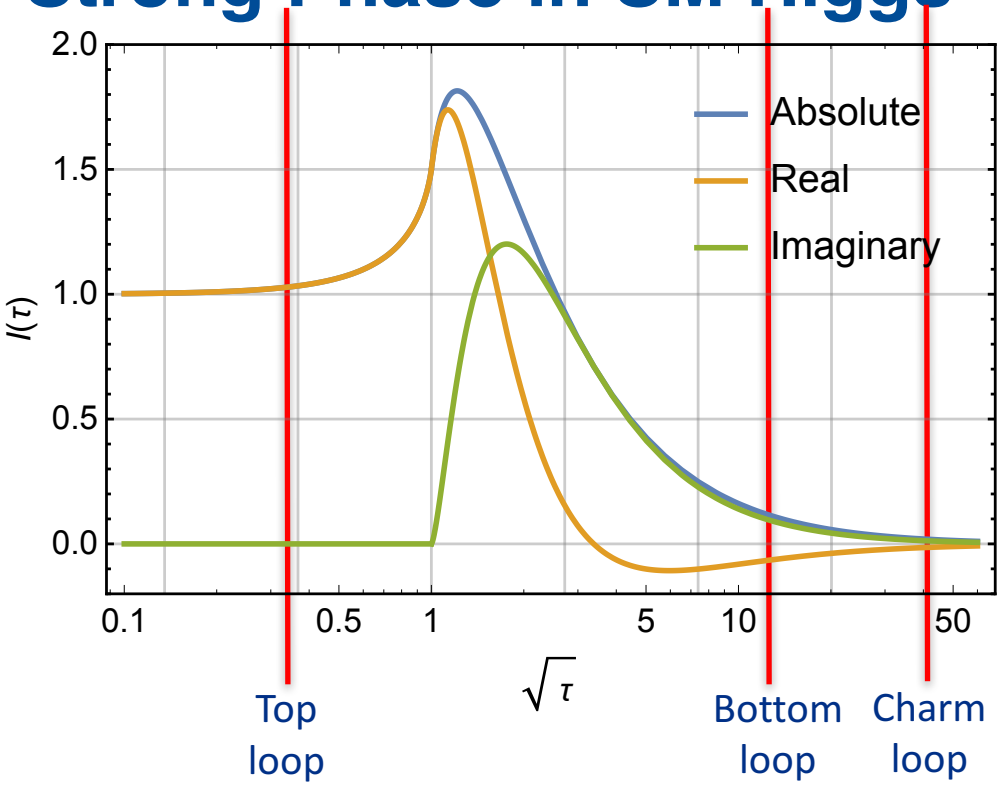
Strong Phase in SM Higgs



- 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 $-0.004 + 0.002i$

*some input parameter dependence

Strong Phase in SM Higgs



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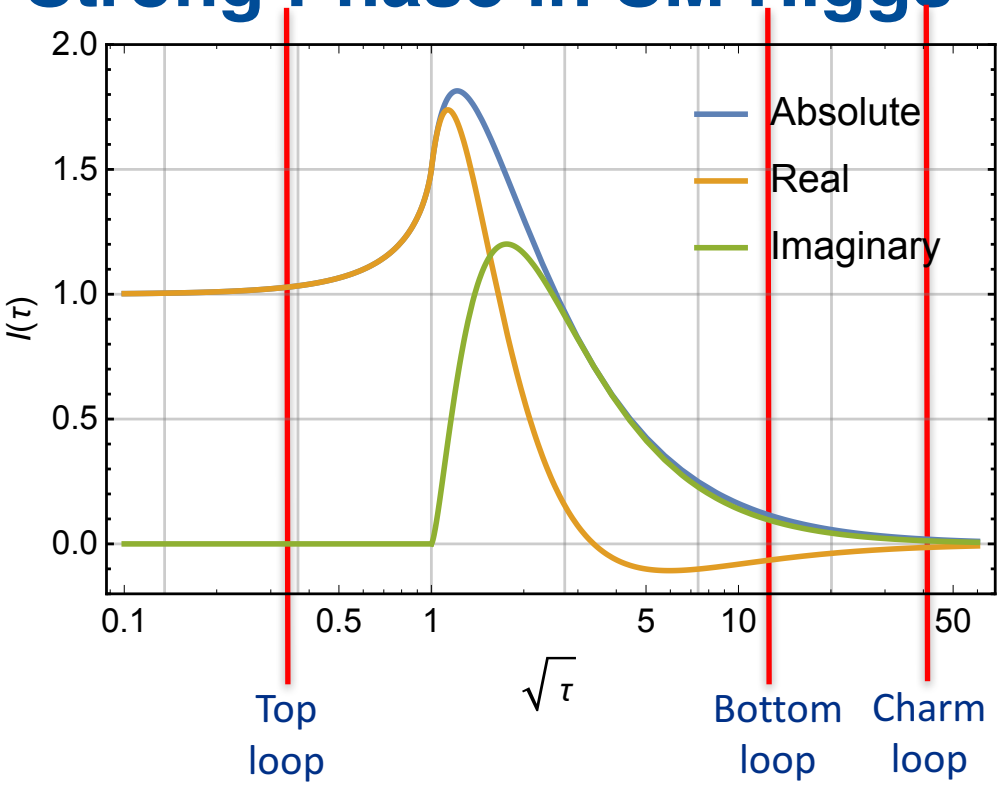
A strong phase in the gluon-gluon fusion production at hadron colliders (imaginary part)

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

Strong Phase in SM Higgs



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

How to make use in in Higgs physics?
(*neutral, spinless particle)

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

Understanding Interference and Phase

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

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

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

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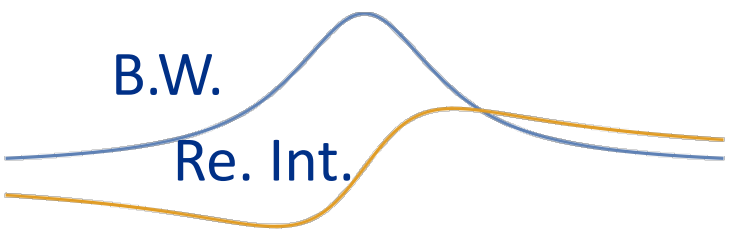

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Background real

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)

Sketching the interference

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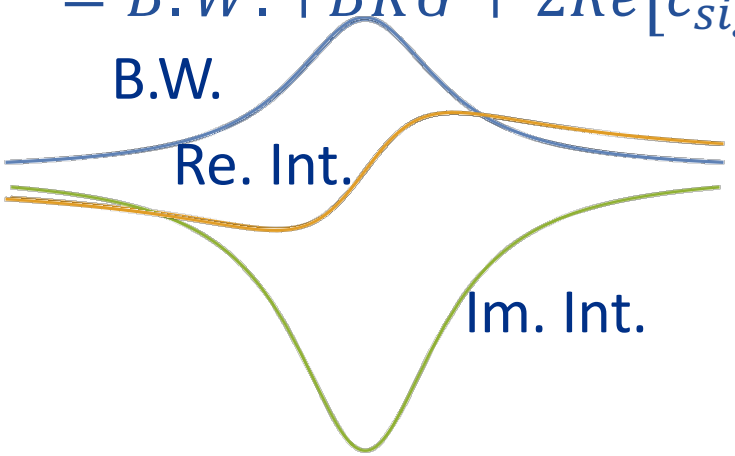

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Background real

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

Sketching the interference

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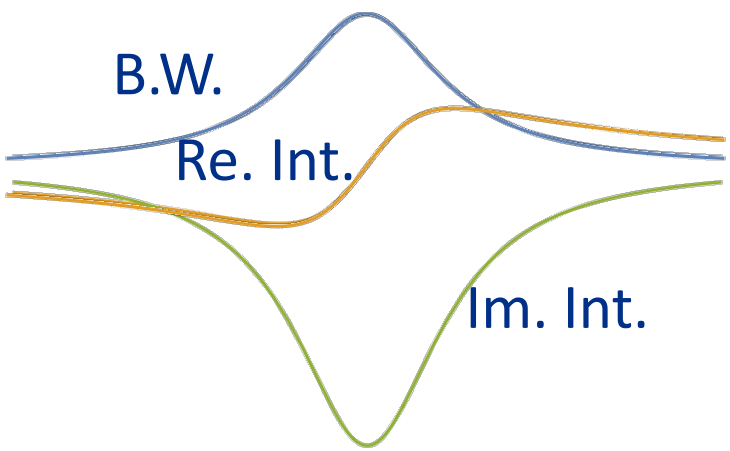


$$Im\left[c_{sig}c_{bkg}^*\right]$$
$$= \left|\mathrm{c_{sig}}\right|\left|\mathrm{c_{bkg}^*}\right|\sin(\delta_{sig} - \delta_{bkg})$$

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

Making choices of the channel to study

In the SM, there are two main loop-induced Higgs couplings (where the strong phase could be sizable):

- $Hgg: 0.042$
- $H\gamma\gamma: \pi - 0.006$
- $HZ\gamma: \sim H\gamma\gamma$

Choosing the channel to study at the LHC:

- Production and/or decay has strong phase
  - gluon-gluon-fusion production chosen;
- Signal and interfering background are comparable:
  - If background too large, hard to observe signal;
  - If background too small, interference effect would be tiny
- Preferably a channel where precision study could be performed (choose from currently observed Higgs channels)

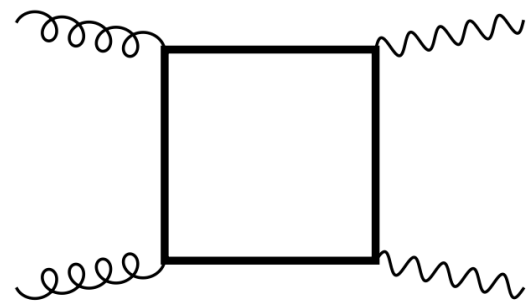
$$gg \to H \to \gamma\gamma$$

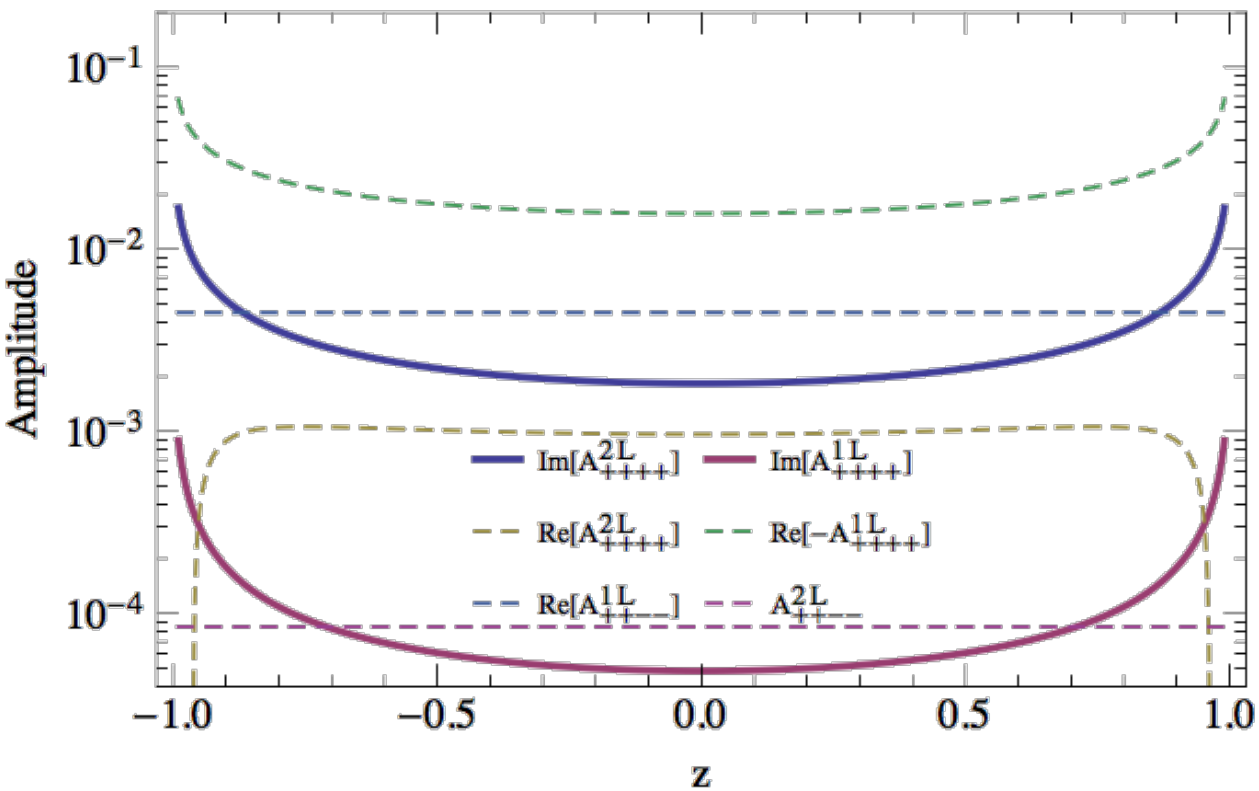
*other channels in progress

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

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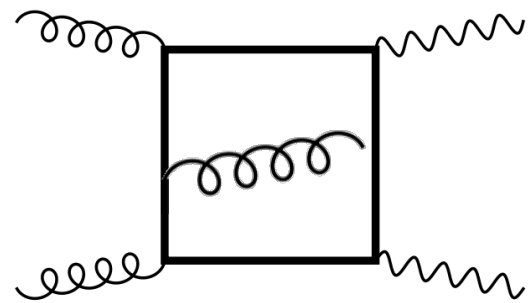
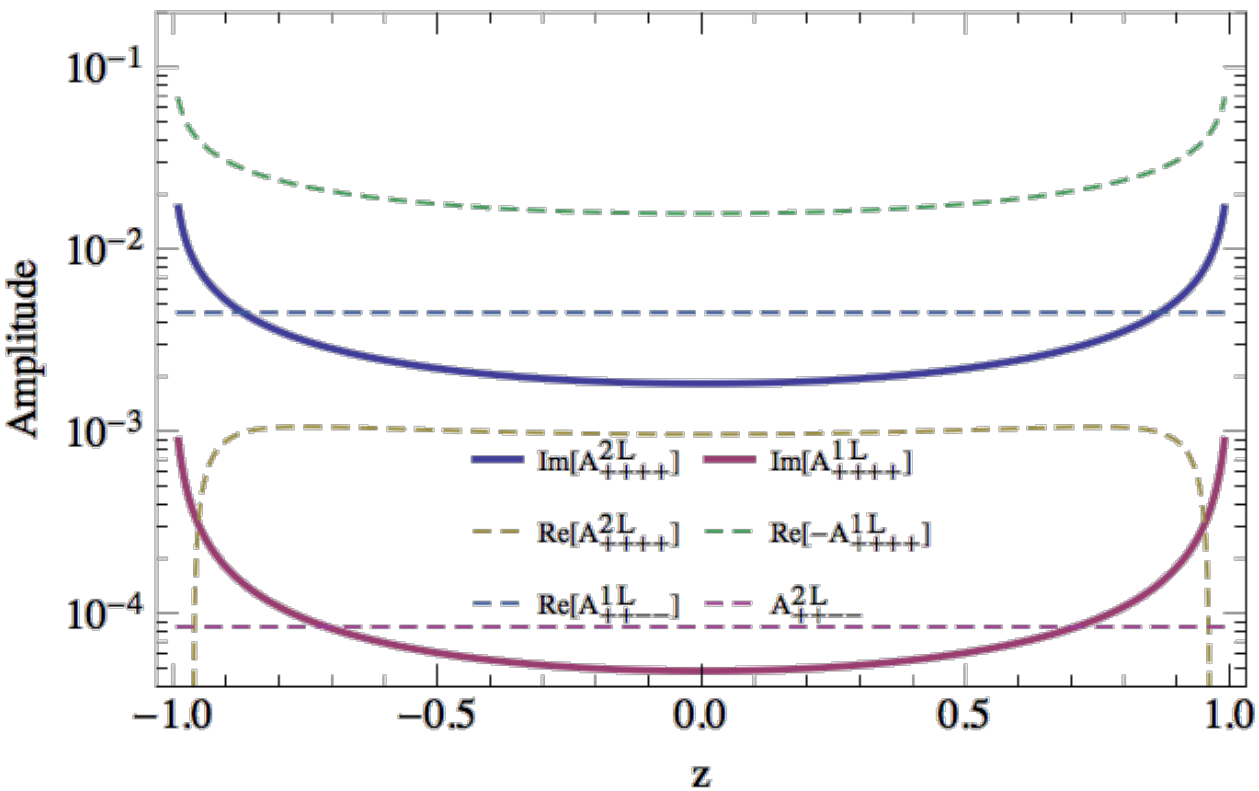
Phase from interfering background

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 IL, the imaginary part is mainly from $A_{++++} = A_{----}$ with bottom and charm contributions
- Imaginary part dominated by the 2L MHV amplitude.

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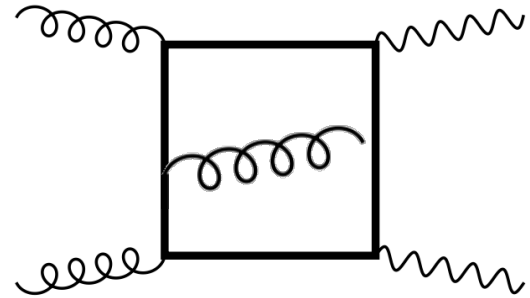

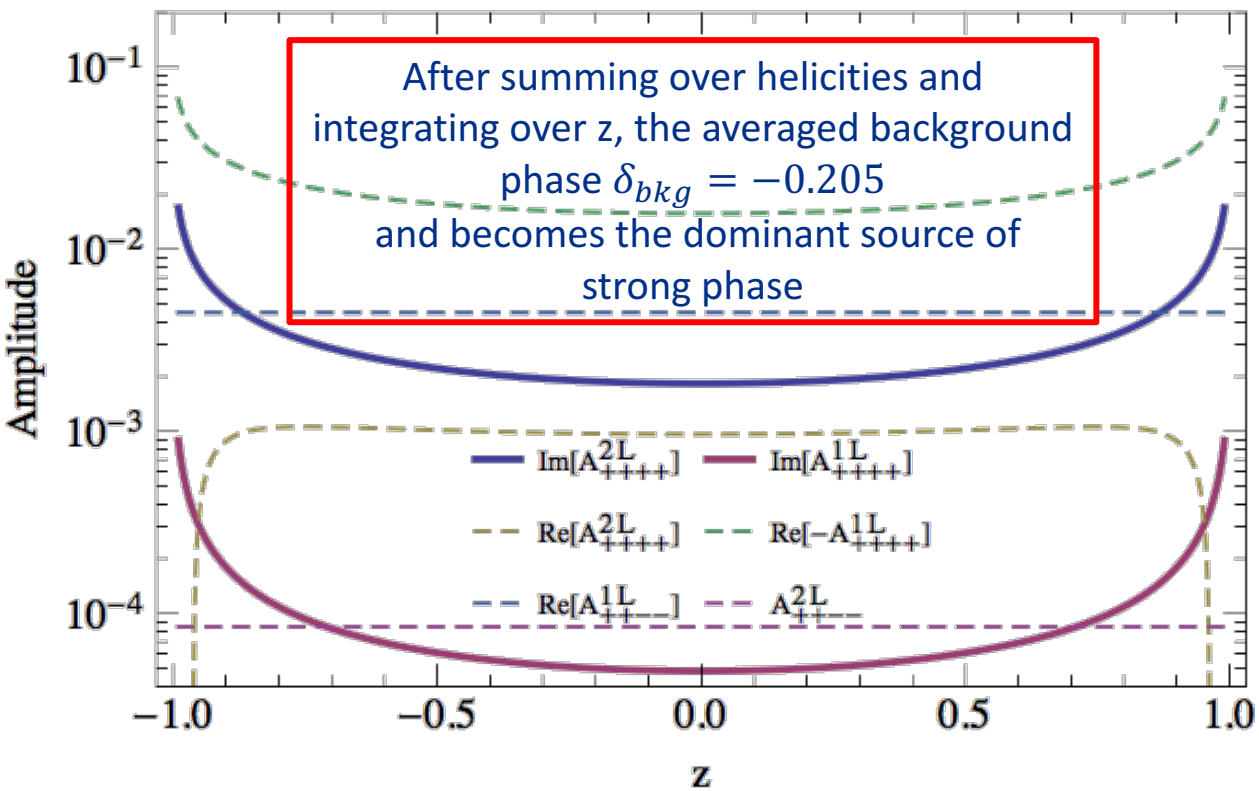

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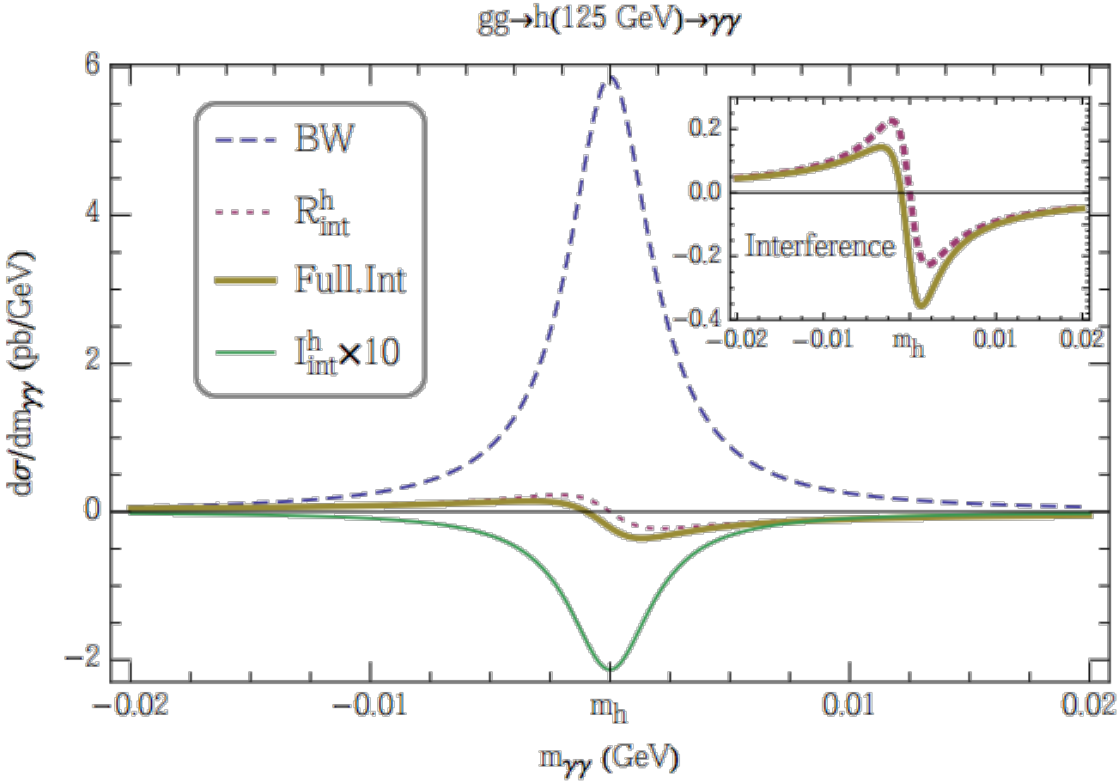
Fermilab

Strong phase and Higgs $gg \to h \to \gamma\gamma$



Define the relative strong phase $\delta = \delta_{sig} - \delta_{bkg}$, average over helicity amplitudes and polar angles, one can calculate this new interference piece between signal and background

Long been overlooked, the interference term from the strong phase does change the SM rate prediction by $\sim -2.\%$

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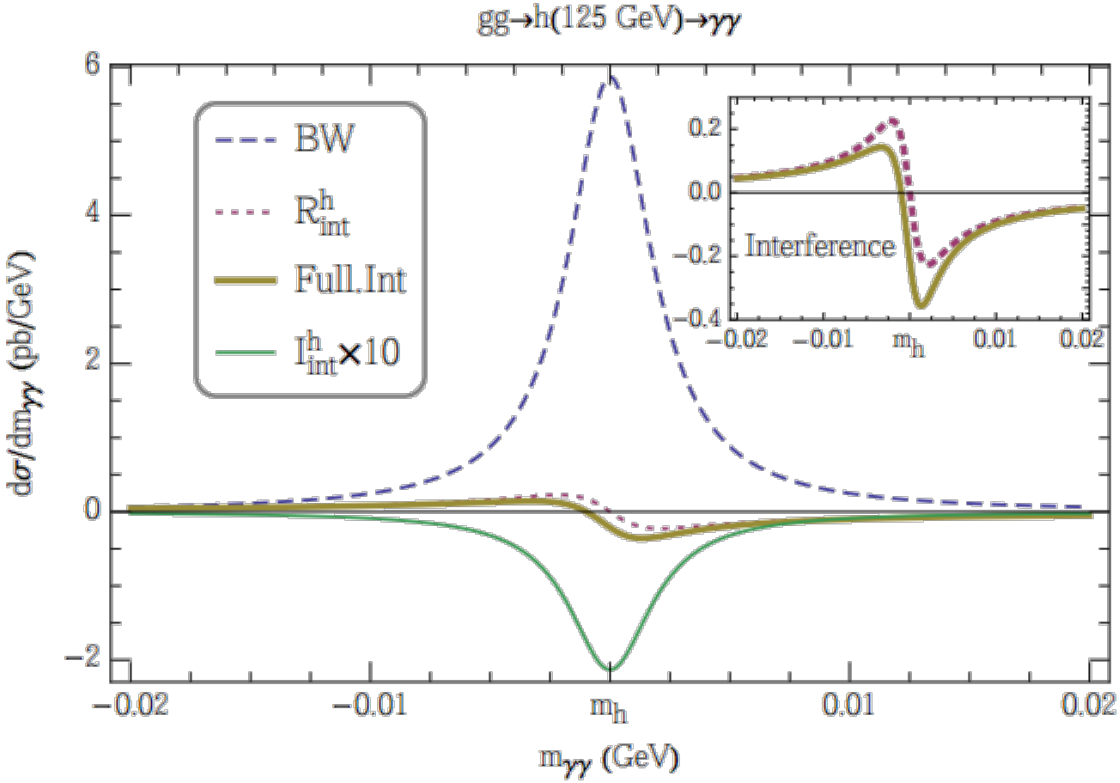

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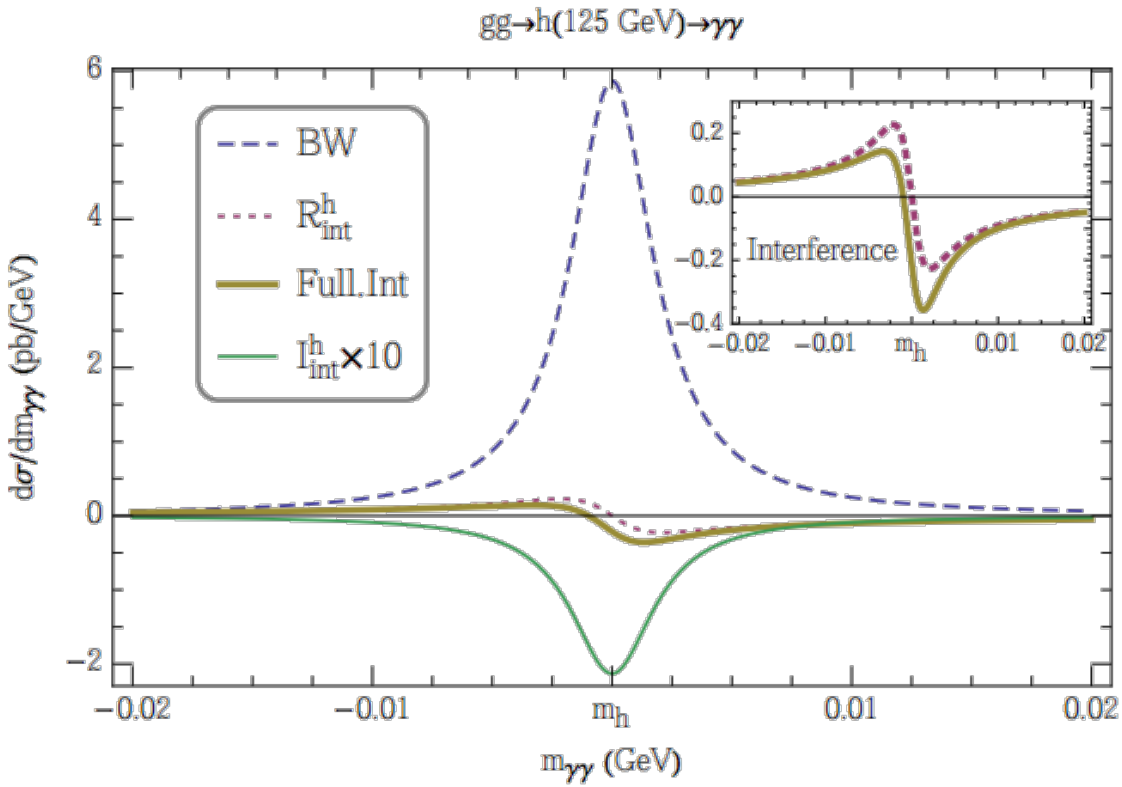
Production	Resolved scaling factor
$\sigma(ggF)$	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(\mathrm{VBF})$	$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	κ_W^2

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

Strong phase and Higgs $gg \to h \to \gamma\gamma$



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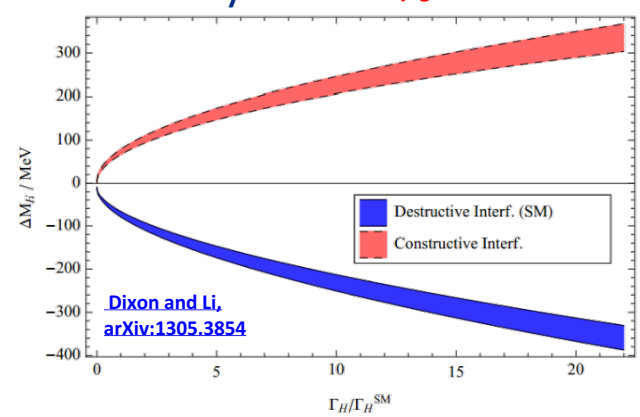

Our study is ``orthogonal'' to Dixon & Li

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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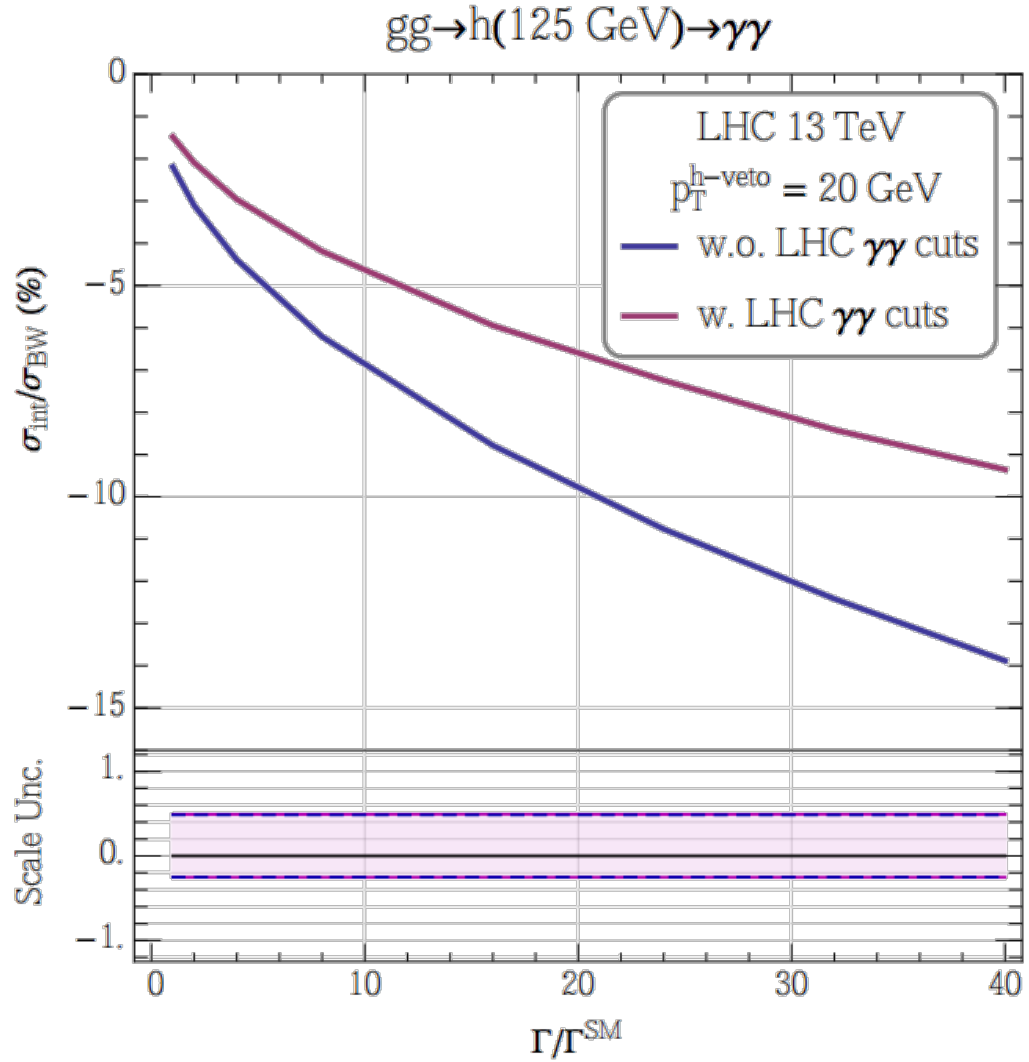

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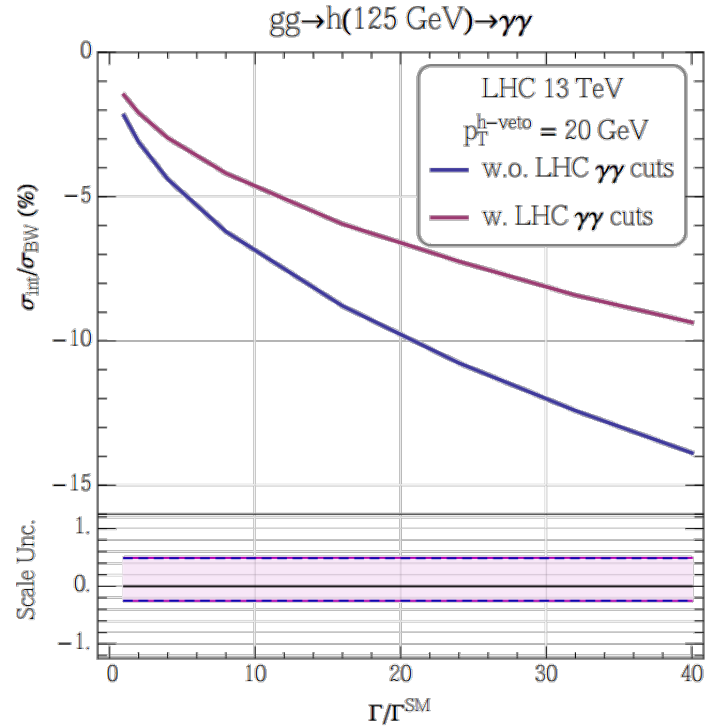

Suppose the extreme nightmare case of all observed Higgs couplings increase by factor f, and Higgs total width by factor f^4.

All on-shell cross sections same as SM predictions or measured central values.

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

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

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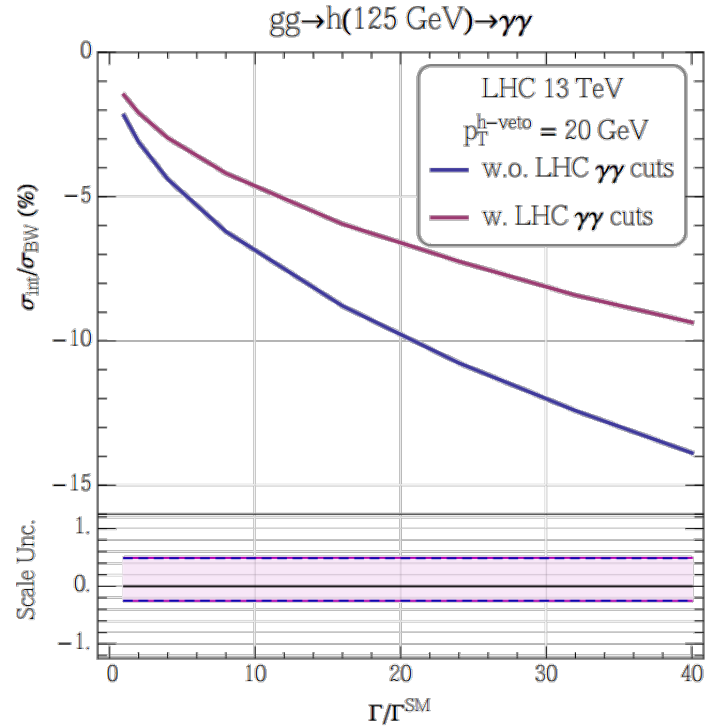

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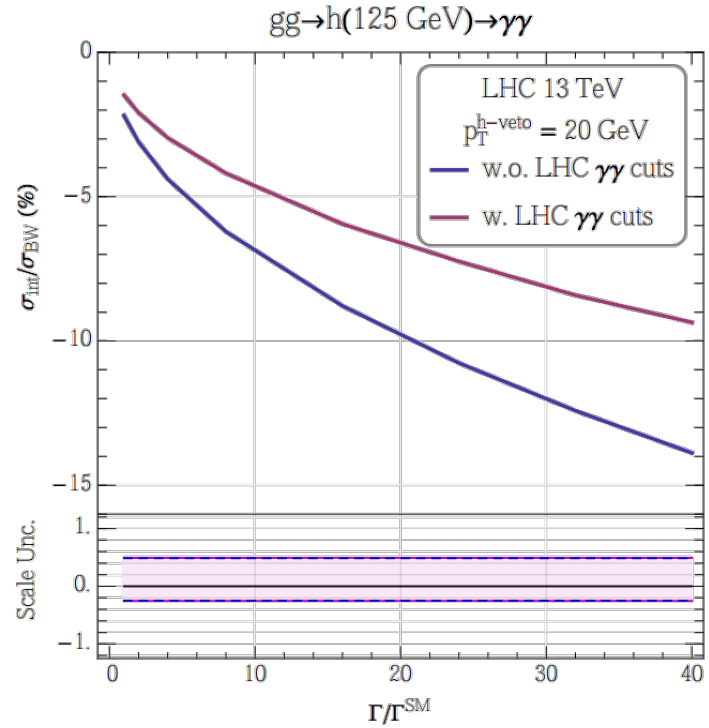

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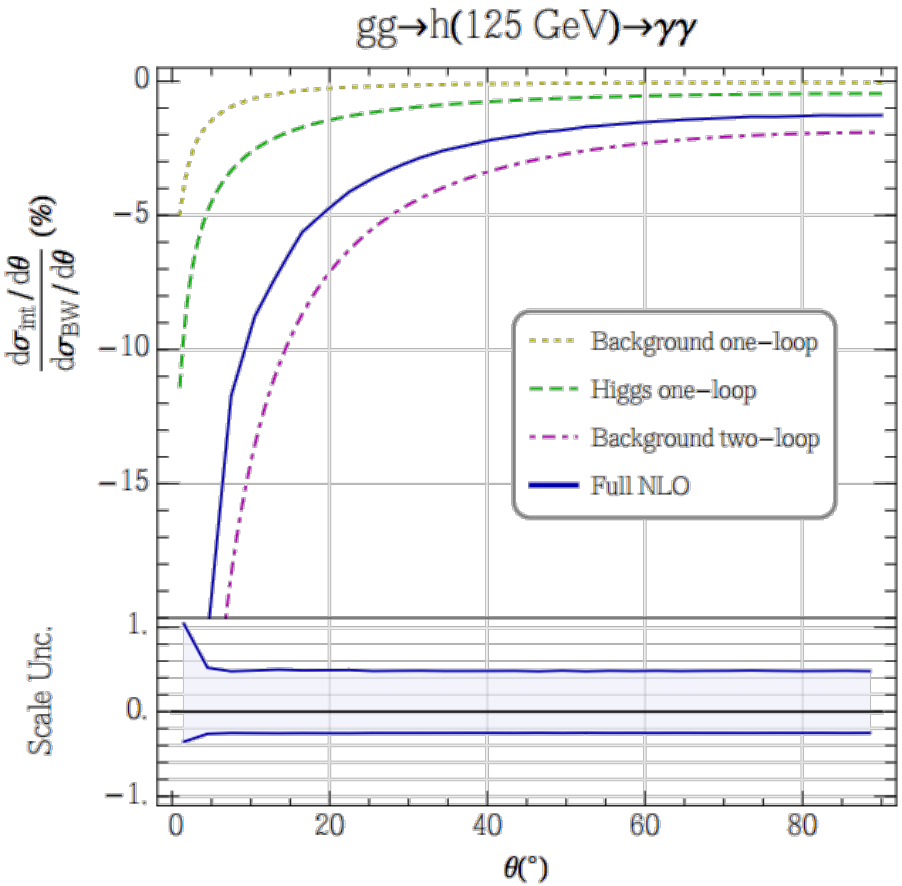
The FCC-hh will increase the precision by at least one order of magnitude, yielding a 3-σ measurement of the interference effect and bounding the Higgs width

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

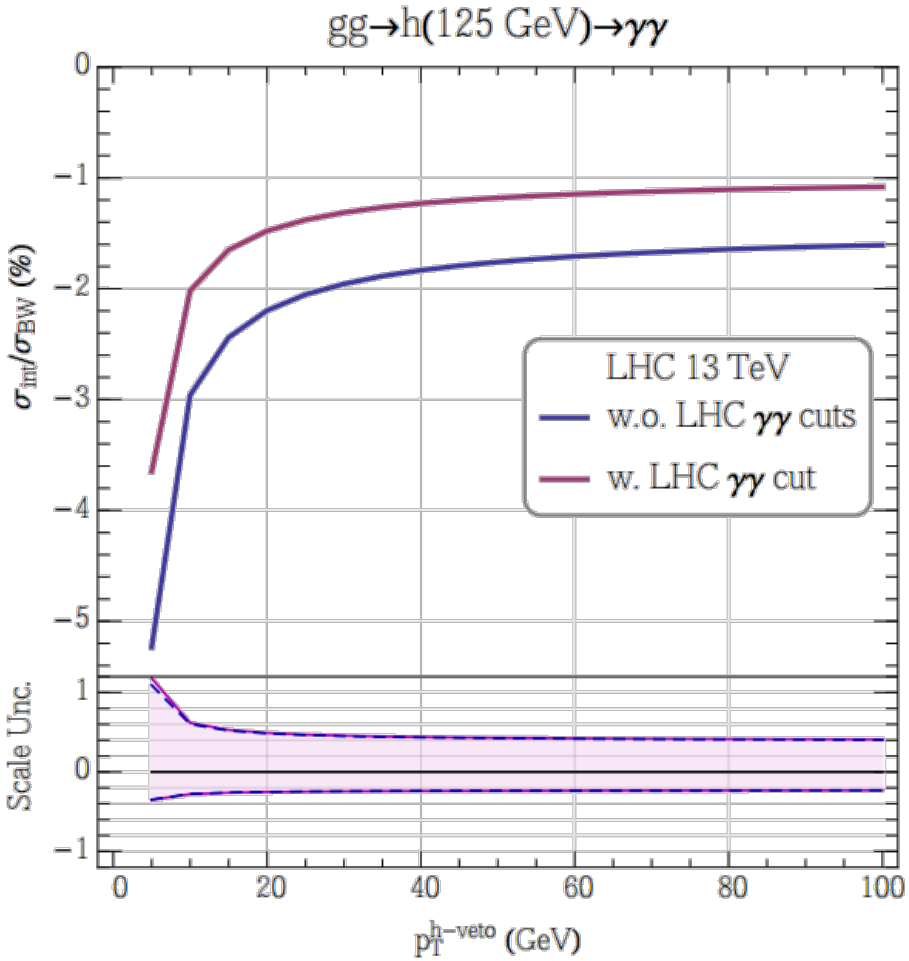
Kinematic features of the interference effect



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 2L 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



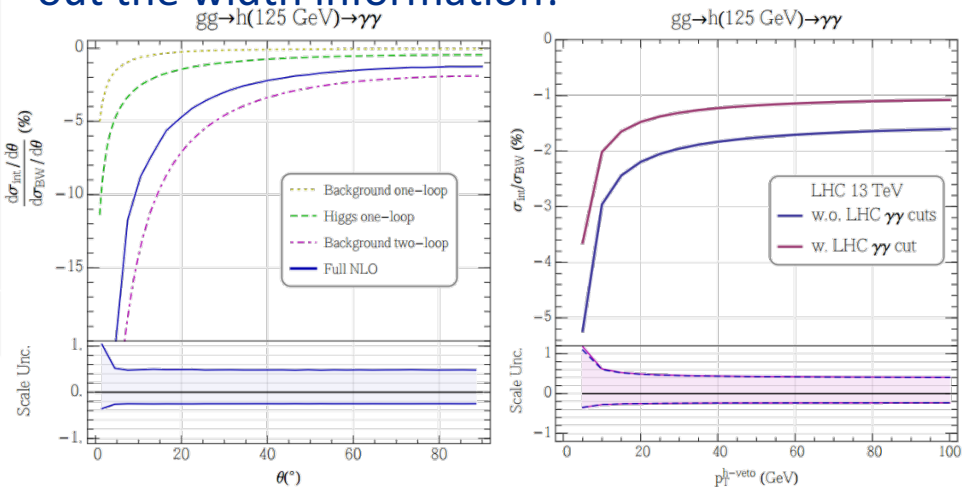
pT-veto distribution:

Consequently, one can also use jet-veto distribution to see the difference;
Larger veto-pT, smaller relative size

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 it can help mapping out the width information!



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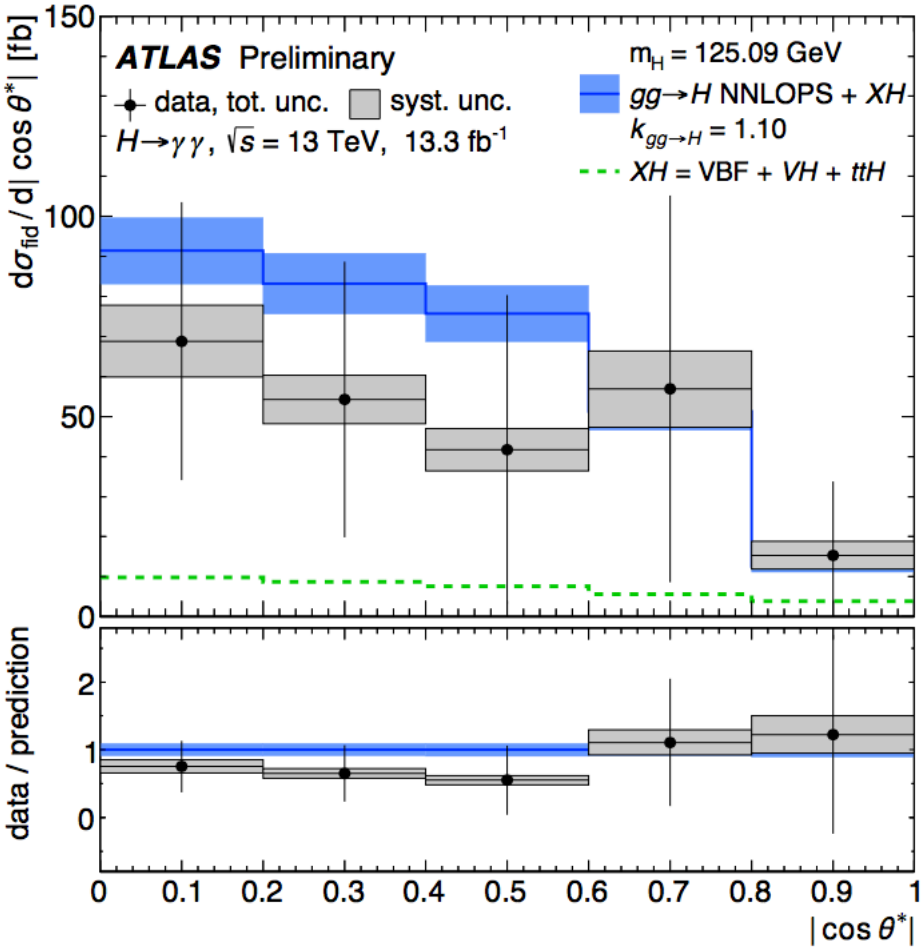
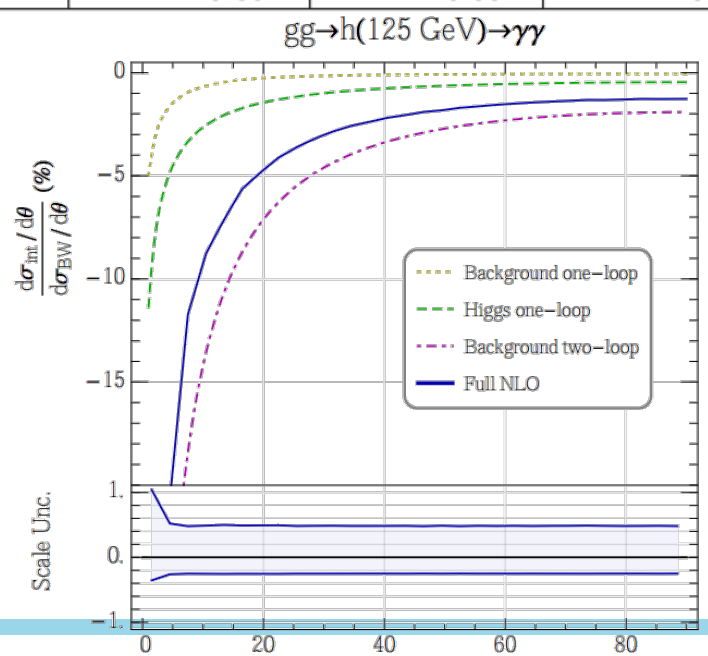
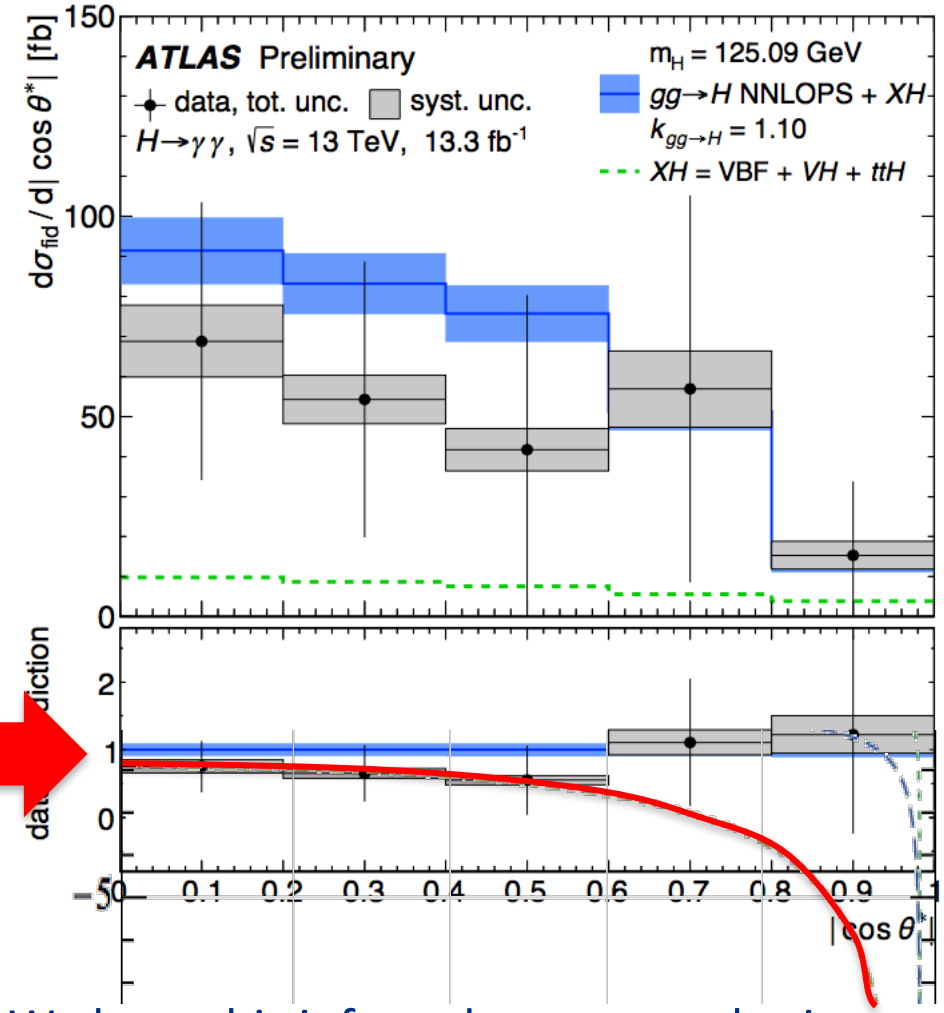


Kinematic features of the interference effect

$\lvert\cos\theta\rvert$	$-\sigma_{\rm int}/\sigma_{\rm BW}$ (%) 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	$1.52^{+0.60}_{-0.35}$	$2.20^{+1.06}_{-0.55}$	$1.48^{+0.73}_{-0.38}$





We have this info and gave new physics information from it!

Summary and outlook

We uniquely explore the physics consequences of this strong phase in Higgs physics

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

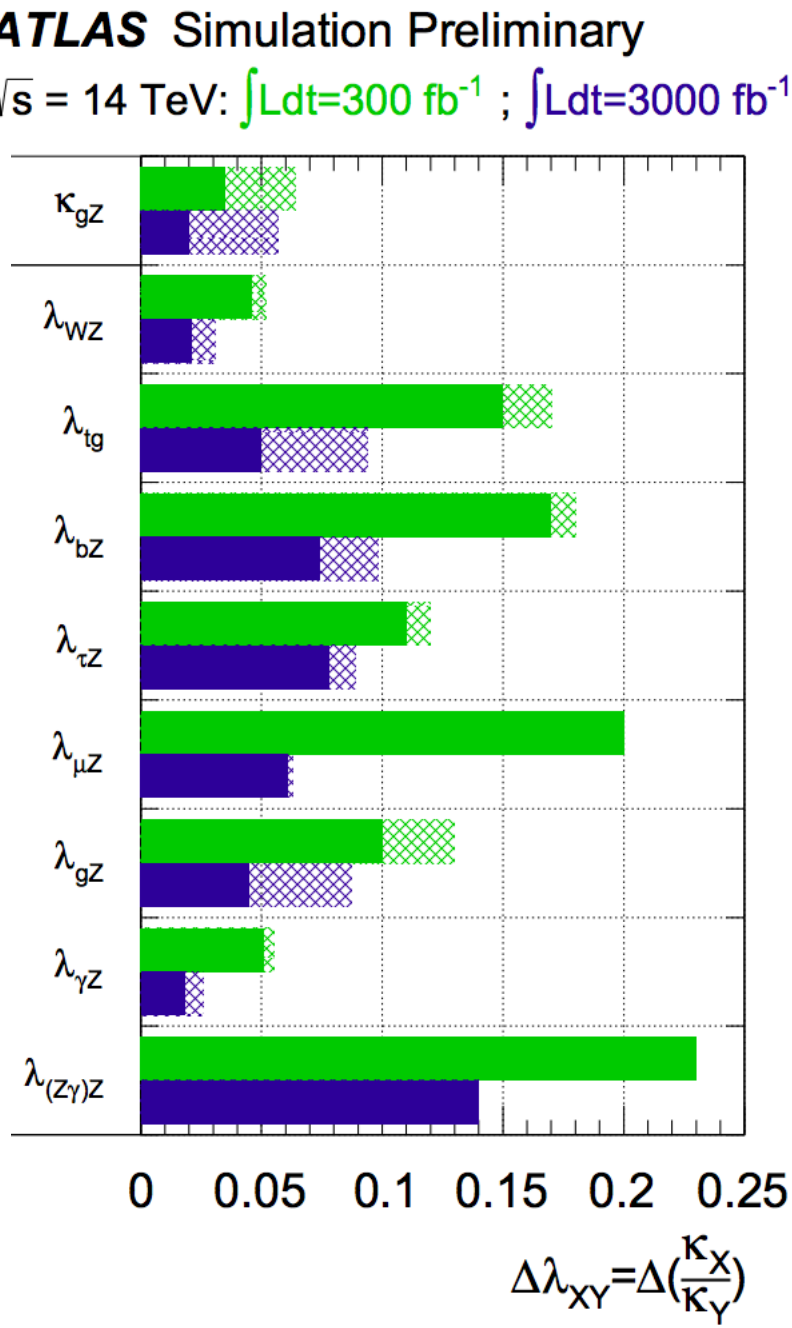
There are interesting kinematical distributions for the process can be utilized to map out the interference effect

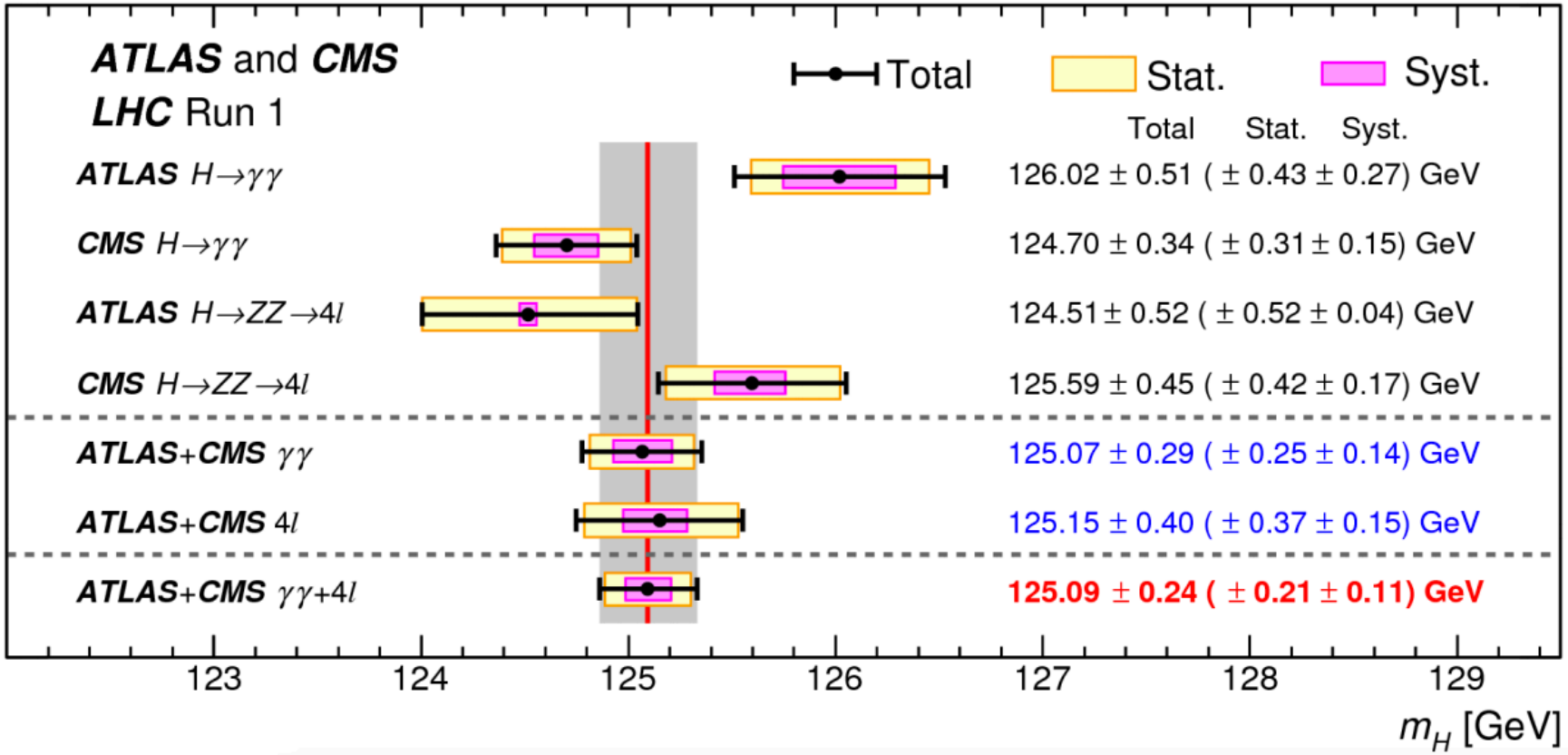
There are many more other interesting channels and physics to explore using this interference effect.

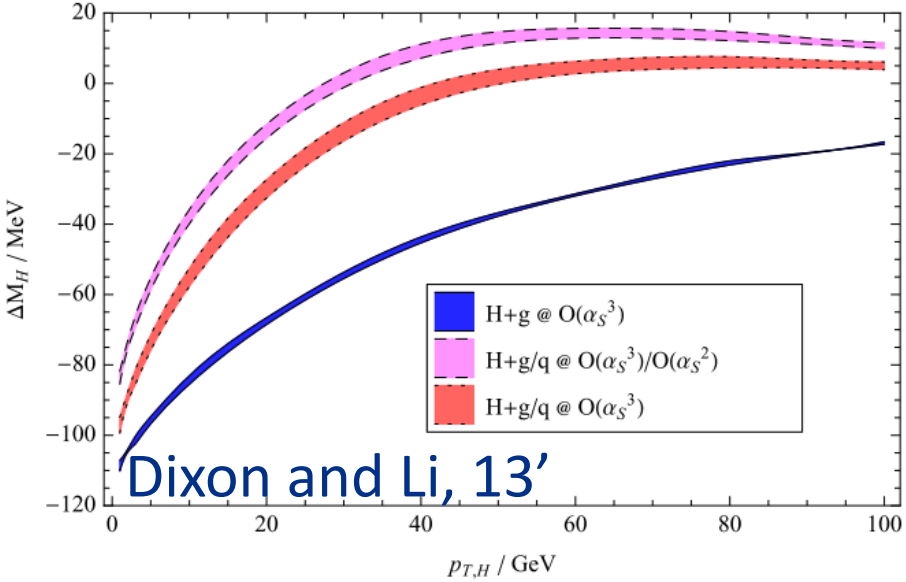
Backup

1.ATL-PHYS-PUB-2014-016

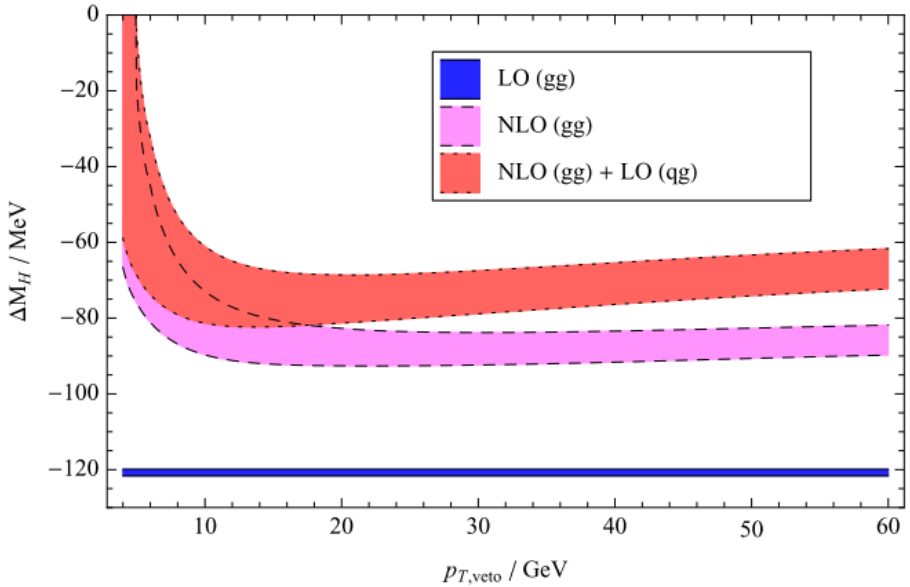
$\Delta\mu/\mu$	300 fb^{-1}		3000 fb^{-1}	
	All unc.	No theory unc.	All unc.	No theory unc.
$H \to \gamma\gamma$ (comb.)	0.13	0.09	0.09	0.04
(0j)	0.19	0.12	0.16	0.05
(1j)	0.27	0.14	0.23	0.05
(VBF-like)	0.47	0.43	0.22	0.15
(WH-like)	0.48	0.48	0.19	0.17
(ZH-like)	0.85	0.85	0.28	0.27
(ttH-like)	0.38	0.36	0.17	0.12
$H \to ZZ$ (comb.)	0.11	0.07	0.09	0.04
(VH-like)	0.35	0.34	0.13	0.12
(ttH-like)	0.49	0.48	0.20	0.16
(VBF-like)	0.36	0.33	0.21	0.16
(ggF-like)	0.12	0.07	0.11	0.04
$H \to WW$ (comb.)	0.13	0.08	0.11	0.05
(0j)	0.18	0.09	0.16	0.05
(1j)	0.30	0.18	0.26	0.10
(VBF-like)	0.21	0.20	0.15	0.09
$H \to Z\gamma$ (incl.)	0.46	0.44	0.30	0.27
$H \to b\bar{b}$ (comb.)	0.26	0.26	0.14	0.12
(WH-like)	0.57	0.56	0.37	0.36
(ZH-like)	0.29	0.29	0.14	0.13
$H \to \tau\tau$ (VBF-like)	0.21	0.18	0.19	0.15
$H \to \mu\mu$ (comb.)	0.39	0.38	0.16	0.12
(incl.)	0.47	0.45	0.18	0.14
(ttH-like)	0.74	0.72	0.27	0.23

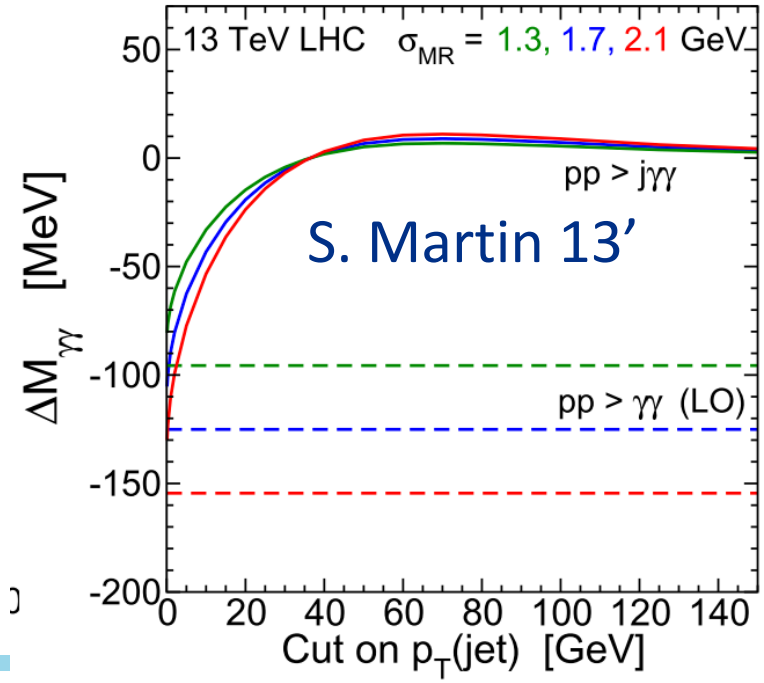



ATLAS and CMS
LHC Run 1
Total
Stat.
Syst.
Total Stat. Syst.
ATLAS H→γγ
126.02 ± 0.51 (± 0.43 ± 0.27) GeV
CMS H→γγ
124.70 ± 0.34 (± 0.31 ± 0.15) GeV
ATLAS H→ZZ→4l
124.51 ± 0.52 (± 0.52 ± 0.04) GeV
CMS H→ZZ→4l
125.59 ± 0.45 (± 0.42 ± 0.17) GeV
ATLAS+CMS γγ
125.07 ± 0.29 (± 0.25 ± 0.14) GeV
ATLAS+CMS 4l
125.15 ± 0.40 (± 0.37 ± 0.15) GeV
ATLAS+CMS γγ+4l
125.09 ± 0.24 (± 0.21 ± 0.11) GeV
123
124
125
126
127
128
129
m_H [GeV]



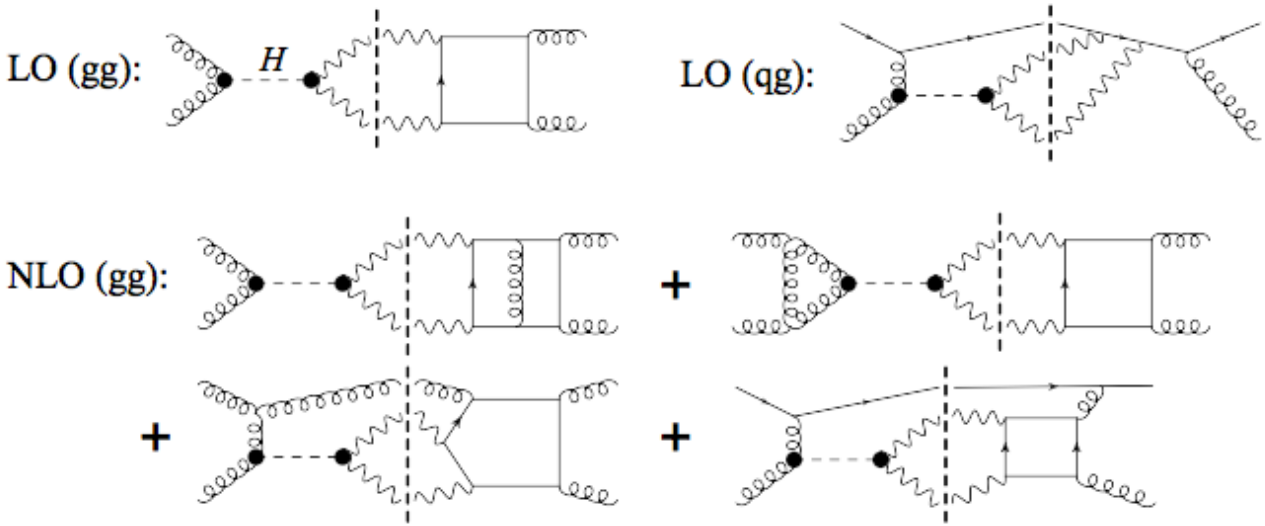
Dixon and Li, 13'



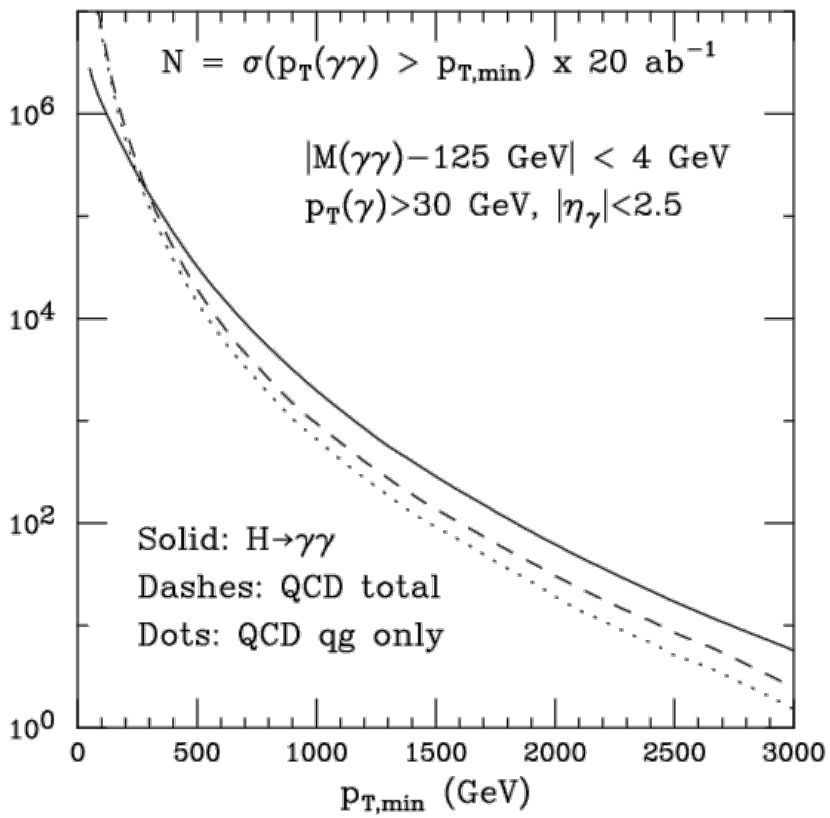


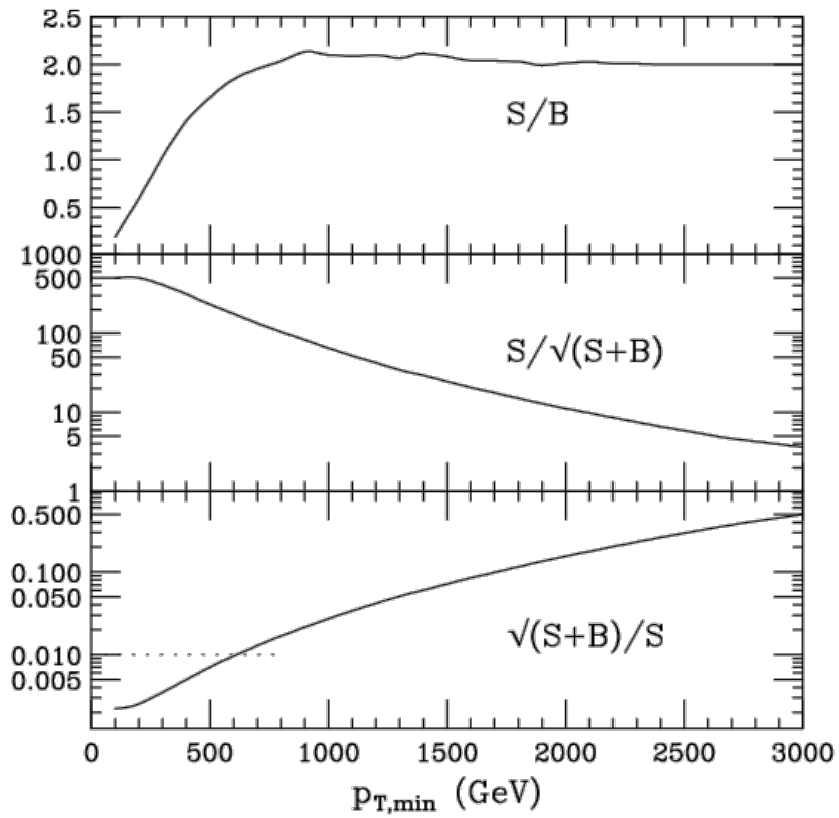
S. Martin 13'

Dots represent point-like interaction, where the phase is ignored.



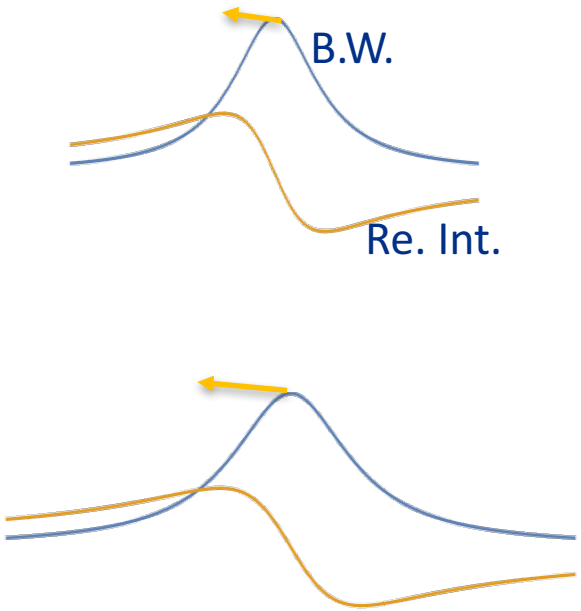
FCC-hh

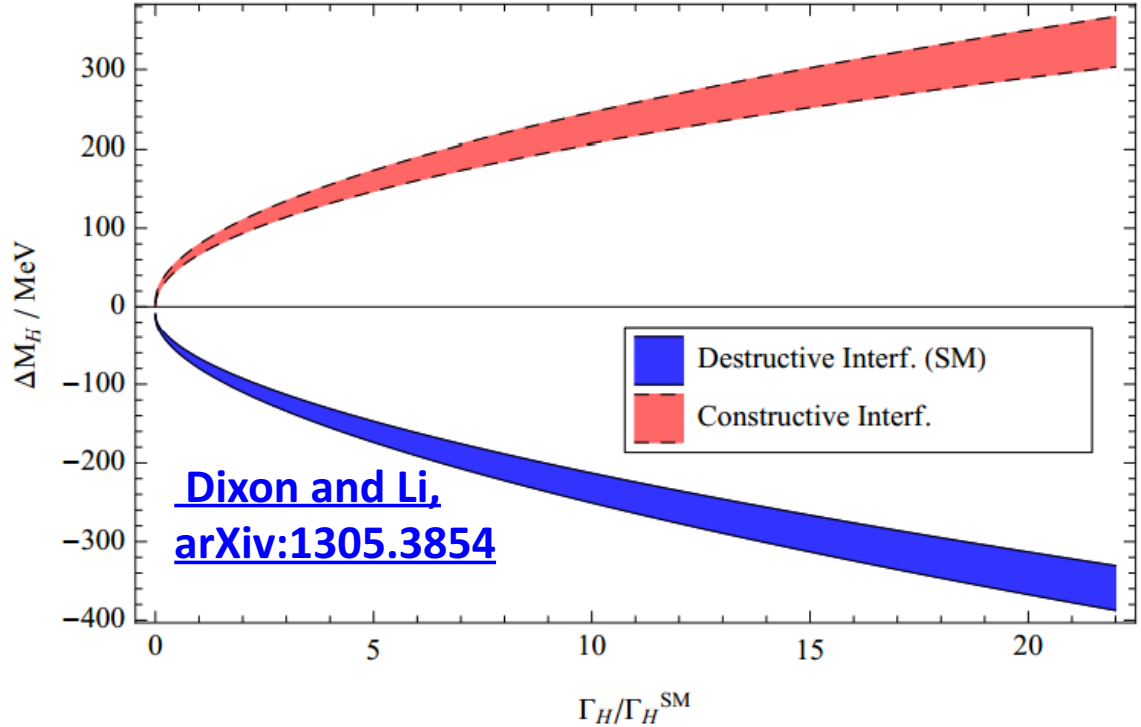




	N_{100}	N_{100}/N_8	N_{100}/N_{14}
$gg \to H$	16×10^9	4×10^4	110
VBF	1.6×10^9	5×10^4	120
WH	3.2×10^8	2×10^4	65
ZH	2.2×10^8	3×10^4	85
$t\bar{t}H$	7.6×10^8	3×10^5	420

Higgs interferences (shifting diphoton)





Interference with the irreducible background shifts the invariant mass peak.

By comparing with the 4l invariant mass (where little interference due to the smallness of the irreducible background), ideally, one can see the shift in the invariant mass of the final states.

Higgs interferences (on-shell and off-shell)

All on-shell cross sections for the narrow Higgs can be parametrized as (NWA):

$$\sigma(i \to h \to f) \propto \frac{g_i^2 g_f^2}{f_{\Gamma_{tot}}}$$

Treating all couplings and total width as free parameters, there will always be a flat/runaway direction allowing increasing all parameters universally.

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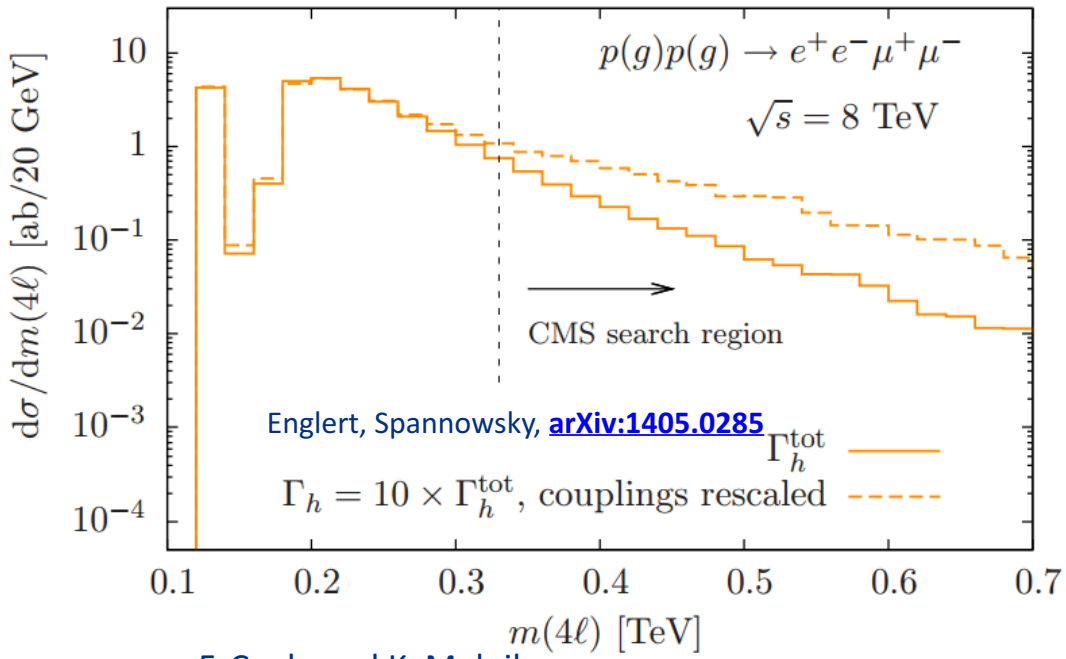
Cross sections:

On-shell: $\frac{g_{ggh}^2 g_{ZZh}^2}{\Gamma_{tot}}$

Off-shell: $g_{ggh}^2 g_{ZZh}^2$

Higgs interferences (on-shell and off-shell)



Englert, Spannowsky, arXiv:1405.0285

F. Caola and K. Melnikov arXiv:1307.4935

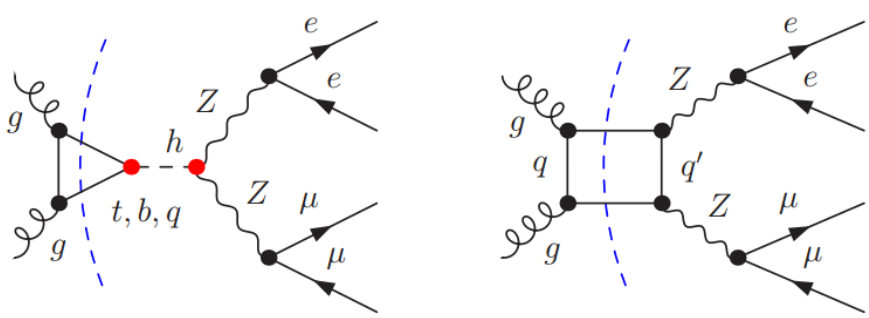
And N. Kauer and G.Passarino arXiv:1206.4803 estimated an "eventual" reach of ~10 SM width;

CMS with current data ~5.4 SM width;

Cross sections:

On-shell: $\frac{g_{ggh}^2 g_{ZZh}^2}{\Gamma_{tot}}$

Off-shell: $g_{ggh}^2 g_{ZZh}^2$



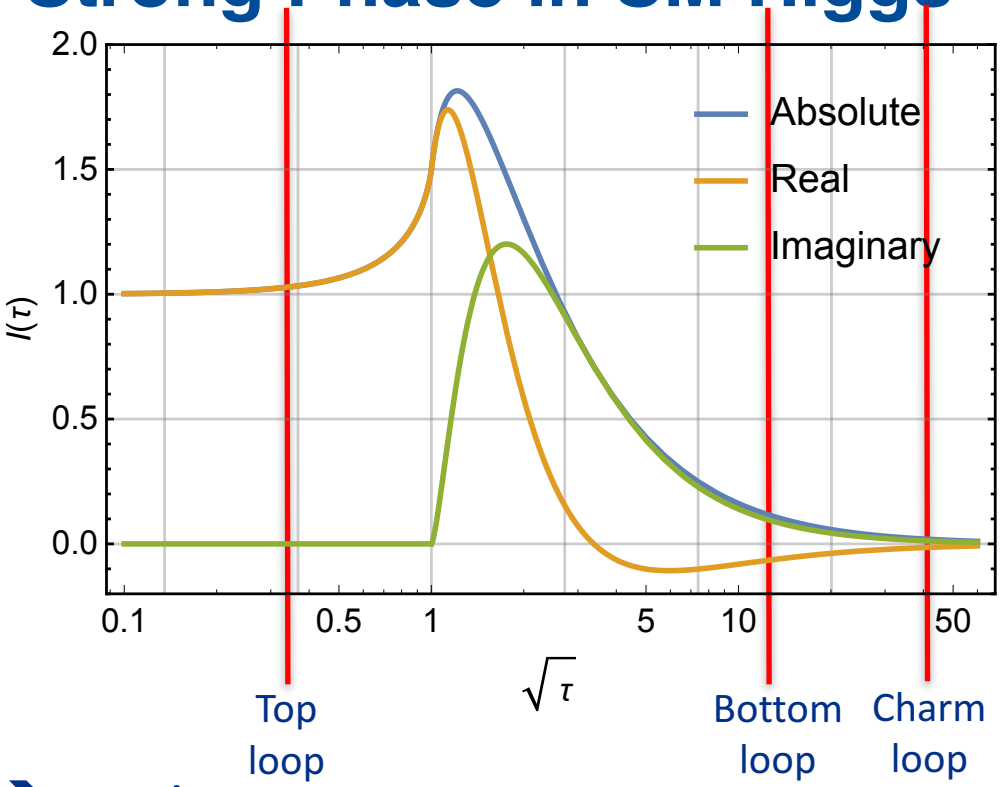
Fermilab

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)
- Higgs diphoton CPV effects from converted photon and its interference with $h \to ZZ^* \to 4e$ (Chen, Harnik and Vegas-Morales, **arXiv:1404.1336**, **arXiv:1503.05855**, **etc.**)
- ...

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 $-0.004 + 0.002i$

$$\frac{\sigma_{\rm BW}}{\sigma_{\rm BW}^{\rm SM}} = 1.078\kappa_t^2 - 0.074\kappa_t\kappa_b - 0.008\kappa_t\kappa_c + 0.003\kappa_b^2 + O(< 0.001; \kappa_t, \kappa_b, \kappa_c).$$

➔two important consequences

- Destructive interference between the top-loop and light quarks for gluon-gluon fusion (real part)

*some input parameter dependence
HXWG recommends:
$\sigma(gg \to h) \propto 1.06\kappa_t^2 - 0.07\kappa_t\kappa_b + 0.01\kappa_b^2$

Sketching the interference

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:

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