Off-shell and Interference Theory Update

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Thanks to Stefan Liebler and Zhen Liu for contributing slides.

13th General Meeting of the LHC Higgs Cross Section Working Group

CERN

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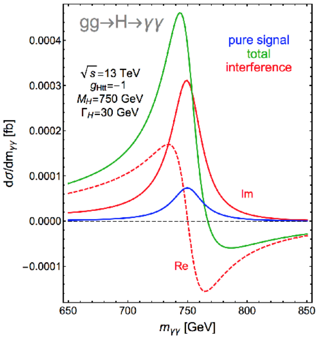
Overview

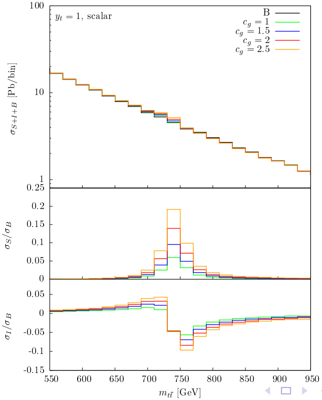
- $H \to ZZ, WW$ in ggF & VBF @ LHC: $\mathcal{O}(10\%)$ off-shell high-mass Higgs signal contribution with large Higgs(-Higgs)-continuum interference: now taken into account (rather than cut away), provides complementary physics information (similar at high-energy linear collider)
- $gg \to H \to ZZ, WW \to 4$ leptons: signal-background interference studied in detail, mature MC tools available at LO; complete NLO calculations available (2-loop multi-scale!, still some approx.), PS matching demonstrated
- First analysis of interference (& Higgs width bounds) for $pp \to H \to ZZ$ + jet
- Studies of heavy Higgs-light Higgs-background interference effects in $gg \to H \to VV$, complementary studies for VBF and linear collider
- Direct Higgs width measurement at LHC limited by mass resolution: $\Gamma_H < 600\,\Gamma_H^{SM}$
- high-mass Higgs tail not Higgs width dependent $\longrightarrow$ provides complementary constraints on Higgs couplings and Higgs width Γ_H (when combined with on-peak data)
- Assuming no E-dependence of relevant Higgs couplings, a bound on Γ_H can be obtained; optimise bound with fully differential discriminant (Matrix Element Method)
- LHC Run 1: CMS: $\Gamma_H < 5.4\,\Gamma_H^{SM}$, ATLAS: $\Gamma_H < [4.5, 7.5]\,\Gamma_H^{SM}$ (95% CL)
- $H \to \gamma\gamma$: interference-facilitated bound $\Gamma_H < 15\,\Gamma_H^{SM}$ (14 TeV, 3 ab^{-1}, 95% CL)
- LHC Run 2: improved bounds (ggF & VBF), high-mass $H \to VV$ EFT and BSM benchmark studies

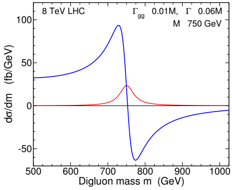
Heavy scalar (Φ) interference studies (2016)

Heavy Higgs – background – light Higgs: non-trivial interference patterns

- Signal-background interference in $gg\ (\to \Phi) \to \gamma\gamma$ ("750 GeV state") and $gg\ (\to \Phi) \to t\bar{t}$ A. Djouadi, J. Ellis, J. Quevillon arXiv:1605.00542 (left fig.)
- Signal-background interference in $gg\ (\to \Phi) \to t\bar{t}$ with higher order QCD effects (simplified model and 2HDM) B. Hespel, F. Maltoni, E. Vryonidou arXiv:1606.04149 (center fig.)
- Higgs-Singlet Model interference effects with EFT operators (Φ-SM gauge bosons) S. Dawson, I.M. Lewis arXiv:1605.04944
- Signal-background interference for a singlet spin-zero digluon resonance S.P. Martin arXiv:1606.03026 (right fig.)



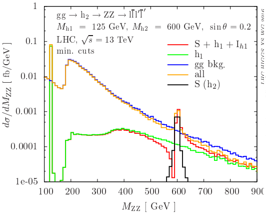


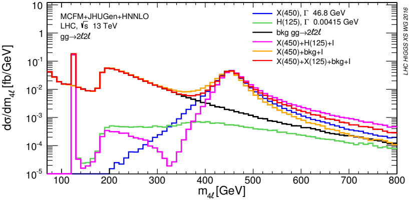


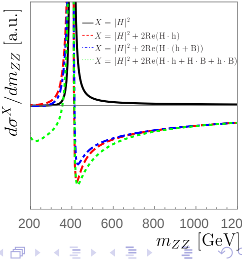
Heavy scalar interference studies (2015/16)

Heavy Higgs – background – light Higgs: non-trivial interference patterns

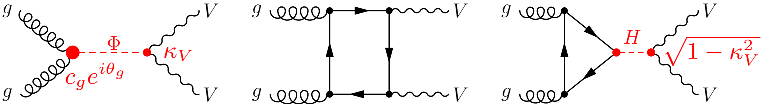
- Higgs Singlet Extension (ggF) NK, C. O'Brien arXiv:1502.04113 and YR4 (left fig.)
- Higgs Portal Scenario (ggF) C. Englert, I. Low, M. Spannowski arXiv:1502.04678
- Higgs Singlet Extension (VBF) A. Ballestrero, E. Maina arXiv:1506.02257 and YR4
- Higgs Singlet Extension (VBF) F. Campanario, M. Rauch YR4
- Generic couplings (tensor structure of HVV) Grisan, Sarica, Schulze, Xiao YR4 (center fig.)
- 2HDM: $gg(\to \{H,h\}) \to ZZ, WW$ interference effects N. Greiner, S. Liebler, G. Weiglein arXiv:1512.07232 (right fig.)
- 2HDM: $pp\ (\to \Phi) \to t\bar{t}$ @ NLO QCD W. Bernreuther, P. Galler, C. Mellein, Z.G. Si, P. Uwer arXiv:1511.05584
- Multiple heavy Higgs and BSM virtual contributions in $gg\ (\to \Phi) \to t\bar{t}$ M. Carena, Z. Liu arXiv:1608.07282





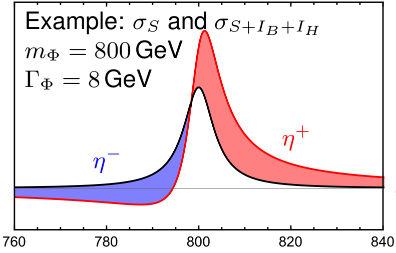


Idea: Classify relevance of interferences in the VV and HH final states:
Interferences among



Simplified approach with 5 parameters: $c_g e^{i\theta_g}, m_\Phi, \Gamma_\Phi, \kappa_V$
Similar for HH with $\lambda_{\Phi hh}$ and λ_{hhh} instead of κ_V
Quantify interference in terms of:

$$\eta = \sigma_{I_B+I_H}/\sigma_S \quad \text{with} \quad \sigma_X = \int_{m_\Phi-5\Gamma_\Phi}^{m_\Phi+5\Gamma_\Phi} dm_{VV} \frac{d\sigma^X}{dm_{VV}}$$



E.g. provide relative corrections:

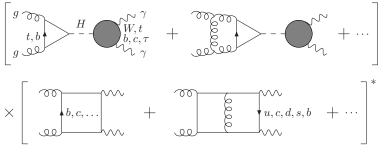
$$\eta^\mp = \begin{pmatrix} \eta^- \\ \eta^+ \\ \eta \end{pmatrix} = \begin{pmatrix} -165\% \\ +160\% \\ +38\% \end{pmatrix}$$

Make tables, figures as a function of free parameters. Provide guidance.
Check quantity $\Gamma_\Phi/m_\Phi \cdot \sigma_S/\sigma_B$.

Higgs interferometry in $gg \to \gamma\gamma$

- Using interference effects in $gg \to \gamma\gamma$, LHC may bound Higgs width much better than in direct measurement [Dixon,Li] arXiv:1305.3854
- Interference has symmetric and asymmetric part around m_H
  Asymmetric part generates apparent mass shift that becomes appreciable when convoluted with detector resolution
  [Martin] arXiv:1208.1533, arXiv:1303.3342 [deFlorian et al.] arXiv:1303.1397

$$\delta\hat{\sigma}_{gg\to H\to\gamma\gamma} = -2(\hat{s}-m_H^2)\frac{\mathrm{Re}\left(\mathcal{A}_{gg\to H}\mathcal{A}_{H\to\gamma\gamma}\mathcal{A}^*_{\mathrm{cont}}\right)}{(\hat{s}-m_H^2)^2+m_H^2\Gamma_H^2} - 2m_H\Gamma_H\frac{\mathrm{Im}\left(\mathcal{A}_{gg\to H}\mathcal{A}_{H\to\gamma\gamma}\mathcal{A}^*_{\mathrm{cont}}\right)}{(\hat{s}-m_H^2)^2+m_H^2\Gamma_H^2}$$

$=$ 

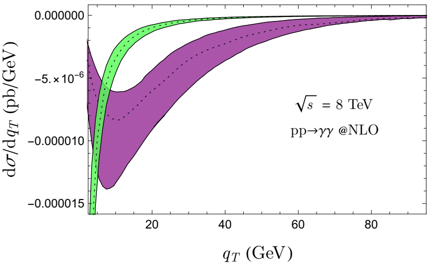
- $gg \to \gamma\gamma$ more direct than $gg \to ZZ/WW$, as it operates in neighborhood of resonance, also $gg \to ZZ/WW$ method could be invalidated by e.g. form factors [Englert,Spannowsky] arXiv:1405.0285

NLL q_T-resummation for $gg \to \gamma\gamma$ interference

[Cieri,Coradeschi,de Florian,Fidanza] arXiv:1706.07331

- NLO+NLL q_T resummation formalism, based on
  [Bozzi,Catani,de Florian,Grazzini] hep-ph/0508068
  [Catani,Cieri,de Florian,Ferrera,Grazzini] arXiv:1311.1654
- Uncertainty bands from varying $\mu_{R/F}$ and resummation scale as
  $\mu_R = 2m_H, \quad \mu_F = m_H/2, \quad \mu_{\rm res} \in [m_H/2, 2m_H]$
  $\mu_R = m_H/2, \quad \mu_F = 2m_H, \quad \mu_{\rm res} \in [m_H/2, 2m_H]$
- Setup: $\sqrt{s} = 8\mathrm{TeV}$, MSTW 2008 [MSTW] arXiv:0901.0002
  Cuts: $q_{T,\gamma 1} \geq 40\mathrm{GeV}$, $q_{T,\gamma 2} \geq 30\mathrm{GeV}$
  Smooth cone [Frixione] hep-ph/9801442 $n = 1$, $E_{\rm max} = 3\mathrm{GeV}$, $R = 0.4$

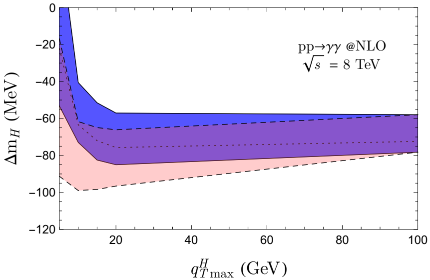
- Resummation distributes events from $q_T = 0$ to finite $q_T \to$ negative interference contribution shifted towards larger q_T
- Uncertainty more realistic due to same effect

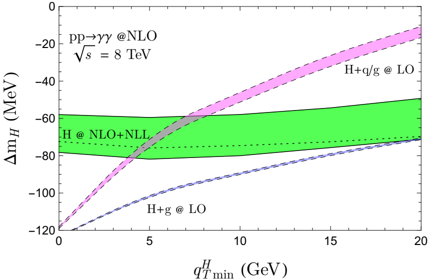


NLL q_T-resummation for $gg \to \gamma\gamma$ interference

[Cieri,Coradeschi,de Florian,Fidanza] arXiv:1706.07331

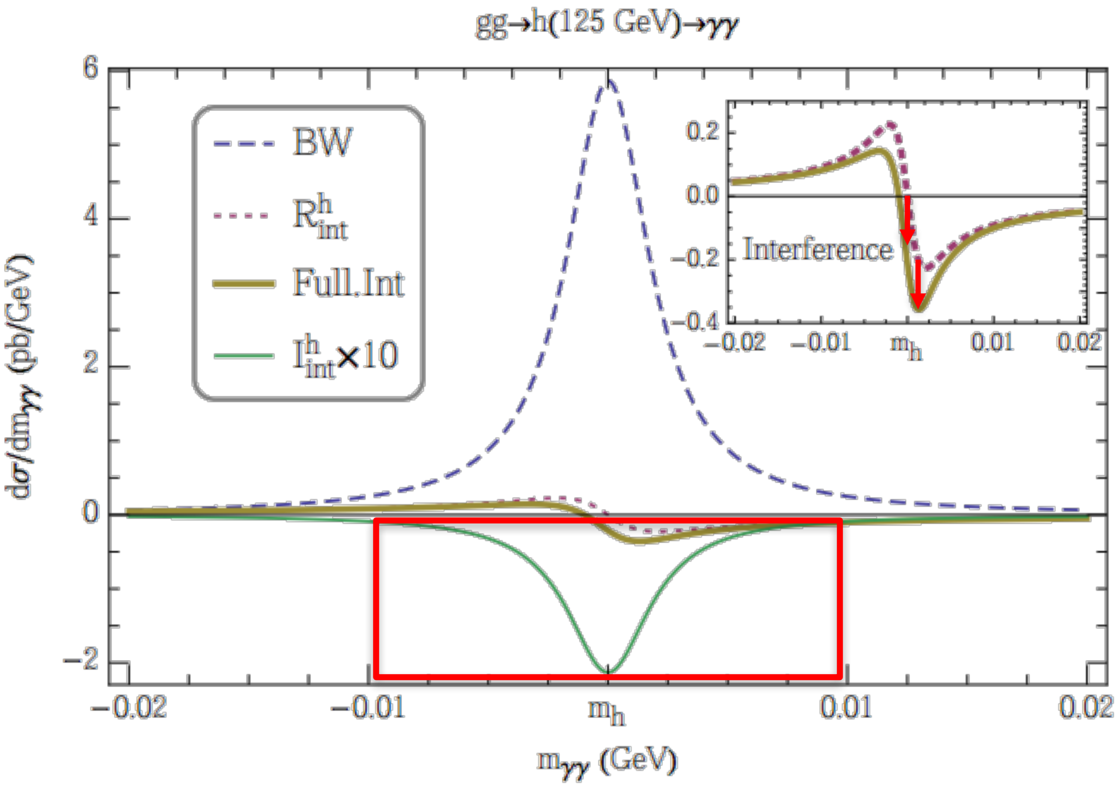
- Resummed prediction of q_T-vetoed cross section stabilises at smaller q_T than fixed-order result
- Points towards viability of measurement of mass shift in $gg \to \gamma\gamma$ alone [Dixon,Li] arXiv:1305.3854





- Resummed prediction of q_T-region above veto stable at small q_T
- Again brought about by redistribution of events from $q_T = 0$ to finite q_T

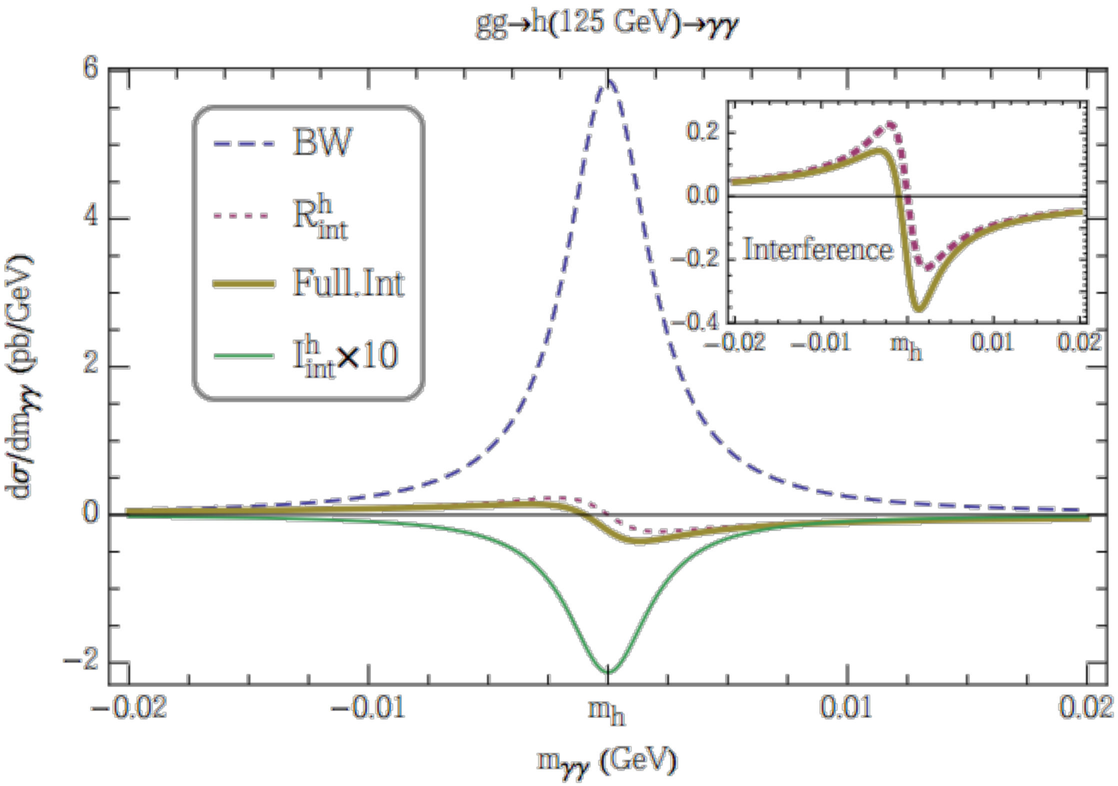
Diphoton SM Higgs decay: Strong phase J. Campbell, M. Carena, R. Harnik, Z. Liu (arXiv:1704.08259)



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
- This effect cannot be factorized into production times decay branching fractions, the framework fails to capture this;

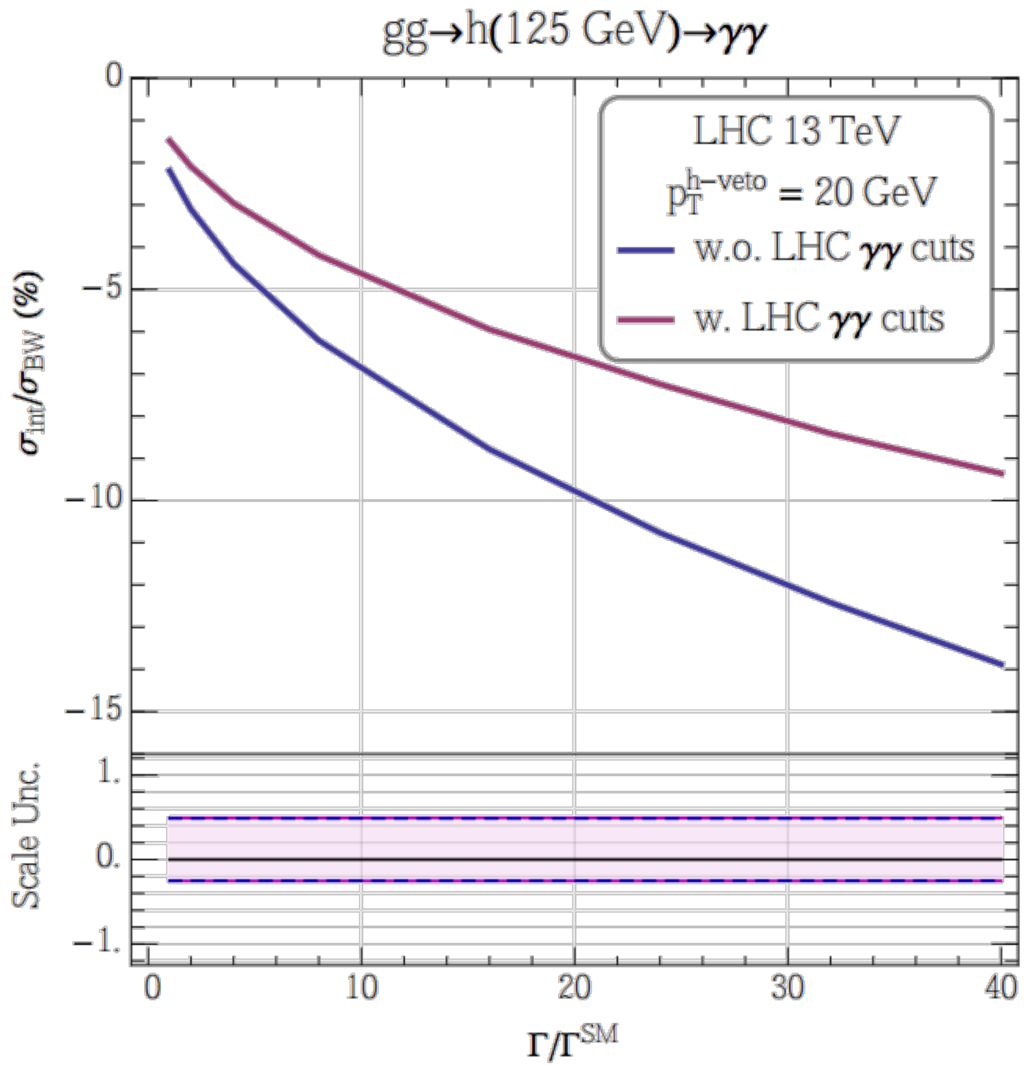
*This agrees with Dixon and Siu's calculation in 03

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

This rate change as a new probe of Higgs total width

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

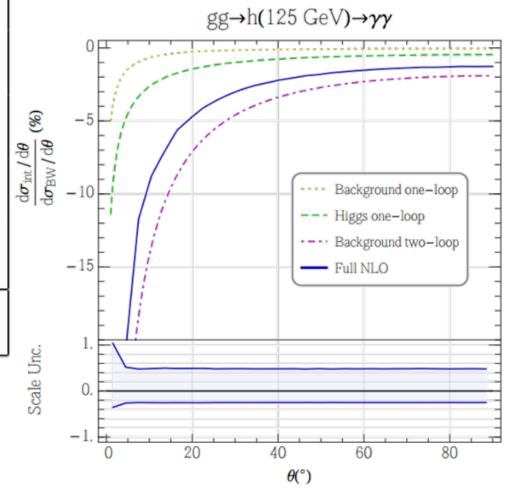
- Unique piece that does not depend on total width;
- Similar to off-shell ZZ/WW measurement;
- Negligible dependence on coupling at different scales.

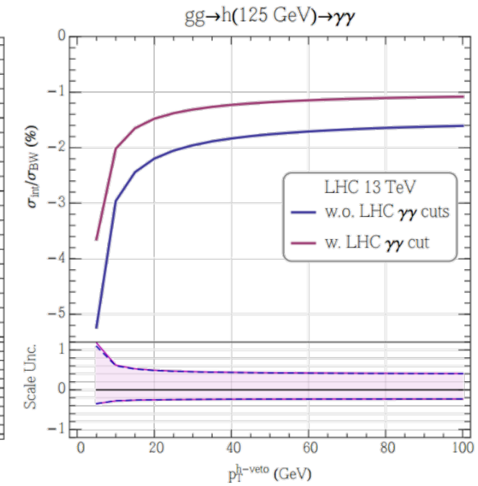


Kinematic features of the interference effect

$\lvert\cos\theta\rvert$	$-\sigma_{\rm int}/\sigma_{\rm BW}$ (%)		
	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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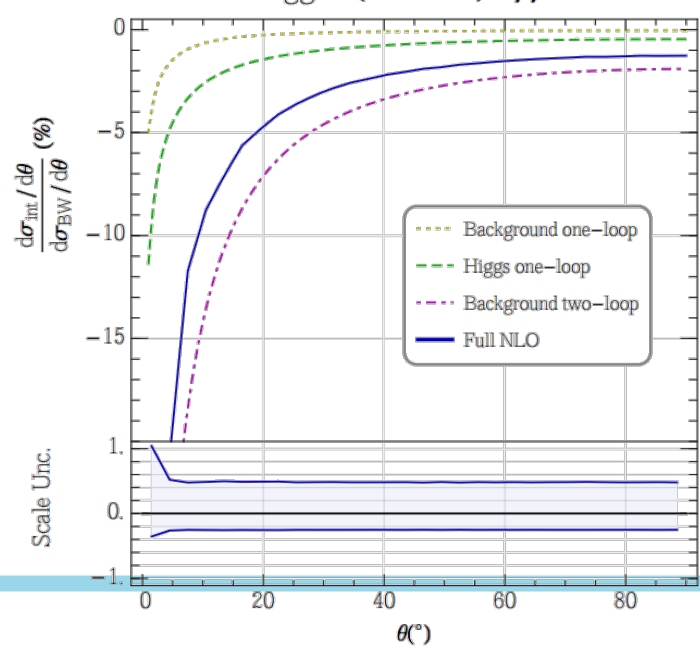
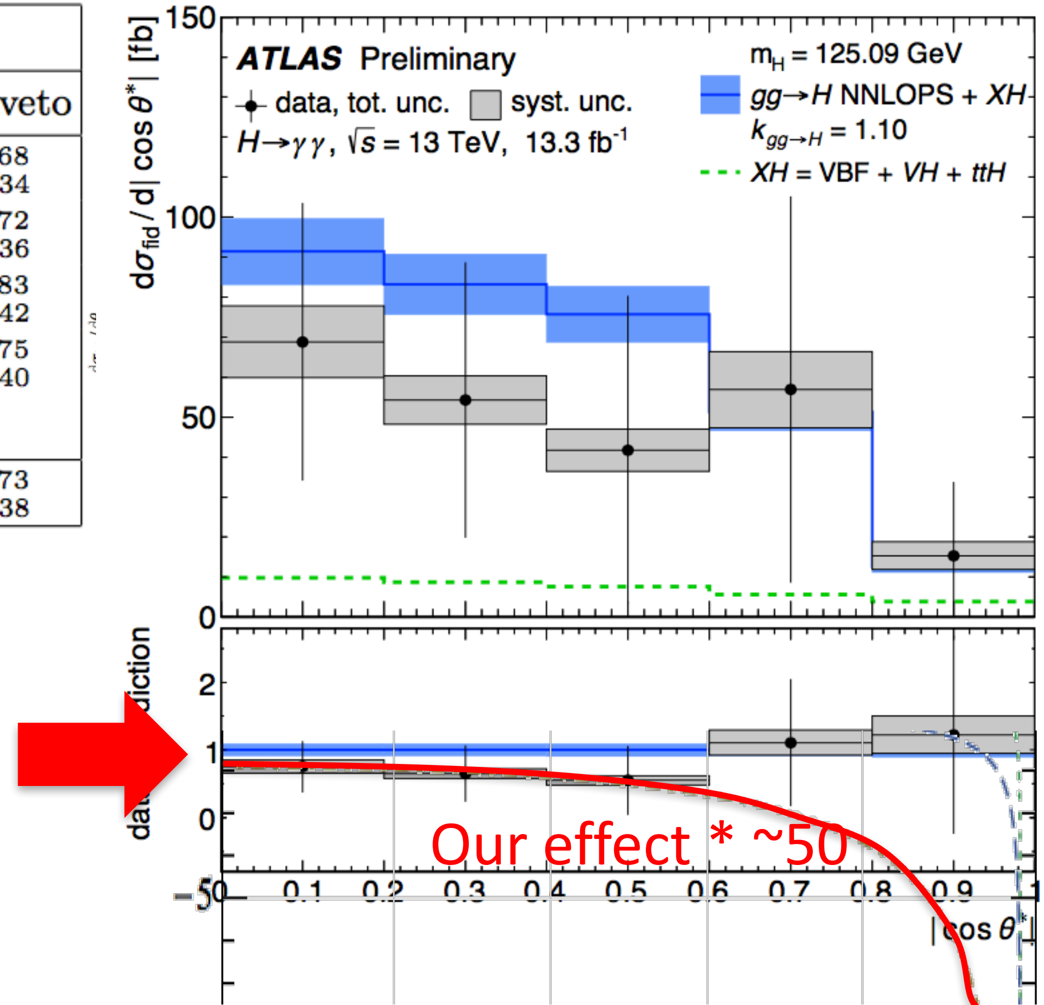




We have this info and can extract new physics information from it!

Summary and outlook $gg \to h \to \gamma\gamma$

We uniquely explore the physics consequences of the 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.

Matrix element–parton shower matching/merging

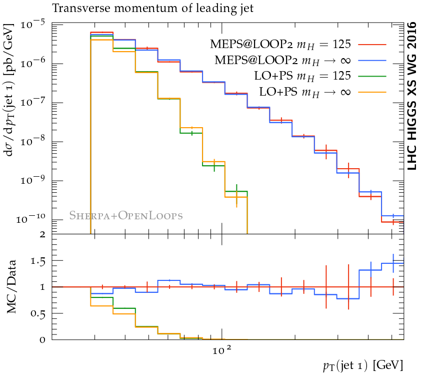
[LO(+partons)]+PS versus LO+PS

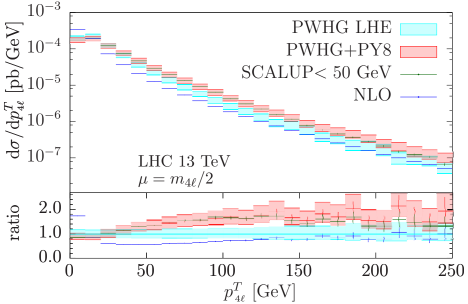
SHERPA+OPENLOOPS: $gg\ (\to H) \to Y$ vs. in addition $gg \to Yg$ and $qg \to Yq$ ($Y \equiv \ell\bar{\nu}_\ell \bar{\ell}' \nu_{\ell'}$, quark-loop amplitudes) merged with PS; harder p_T spectrum, overall: 10% effect from multi-jet merging Höche, Krauss, Pozzorini, Siegert arXiv:1309.0500 and YR4 (left fig.)

NLO+PS versus NLO

$gg \to ZZ \to 2\ell 2\ell'$ (without Higgs), PS effects for trans. mom. obs. ($p_{T,4\ell}, p_{T,j_1}$), but not for incl. obs. ($M_{4\ell}, \Delta\phi_{\ell\ell}$) S. Alioli, F. Caola, G. Luisoni, R. Röntsch arXiv:1609.09719 (right fig.)

$gg\ (\to H) \to \gamma\gamma$ including interference available in SHERPA: fixed order and matched to PS (MC@NLO) S. Höche et al., ATLAS studies C. Becot, L. Fayard, et al. ATL-PHYS-PUB-2016-009





Implementing loop-induced @ NLO in MC tools

Automated loop-induced @ LO

- MG5_aMC (OLP MadLoop): Hirschi, Mattelaer arXiv:1507.00020
- similar capability in Sherpa+OpenLoops (e.g. arXiv:1309.0500) and GoSam (e.g. arXiv:1512.07232, arXiv:1602.05141)
- ...

Implementing loop-induced @ NLO in MC tools

- POWHEG: Alioli, Caola, Luisoni, Röntsch arXiv:1609.09719
- MG5_aMC: in progress
  Hirschi, Mattelaer, Vryonidou, NK, Shivaji, Mandal, ...
  Method 1: reweighting (arXiv:1607.00763)
  Method 2: direct integration in MadFKS
  Feasibility study for $gg \to (\gamma \to e^+e^-)(\gamma \to \mu^+\mu^-)$ completed
- Sherpa: in progress Kuttimalai, ... (Catani-Seymour)
- Herwig7+GoSam: in progress
- ...

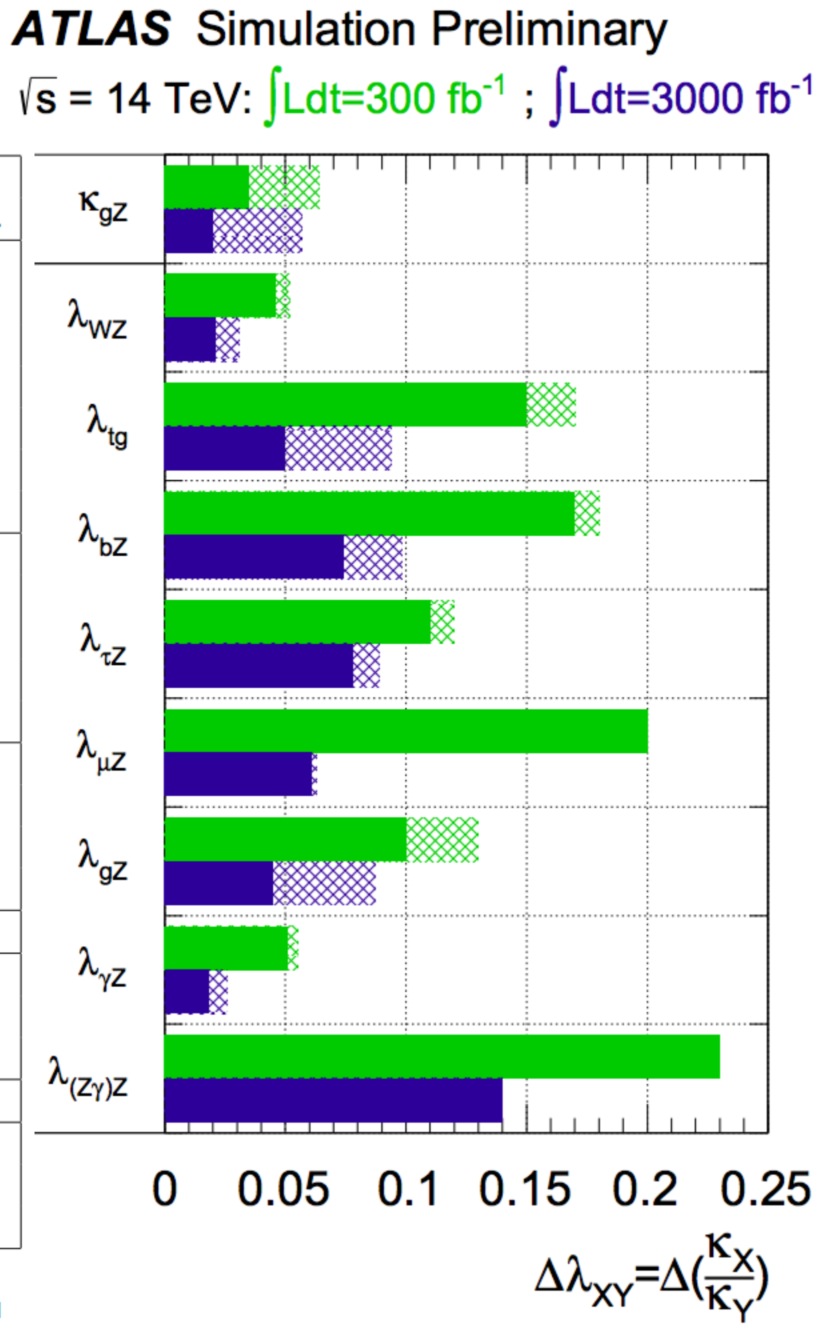
Future directions and discussion points

- Tools: high-mass NLO $gg \to VV$ (exact?) matched/merged with PS
  $\to$ public event generators for experimental studies
  (HERWIG7, MG5_AMC, POWHEG, SHERPA, ...)
- Comparing NLO+PS with (merged) LO+PS predictions
- qg effects at NLO (overlap with $pp \to VV$ @ N^{3}LO)
- finite top mass corrections
- EW corrections
- Improved precision in $H \to \gamma\gamma$ interference studies
- BSM/EFT constraints and interference studies

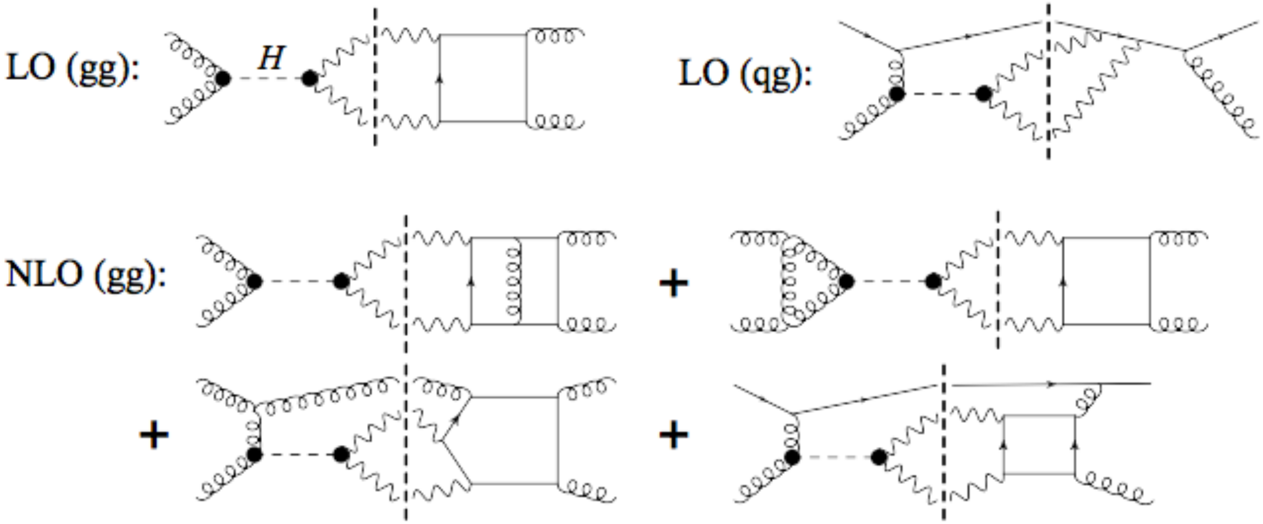
Backup Slides

1.ATL-PHYS-PUB-2014-016

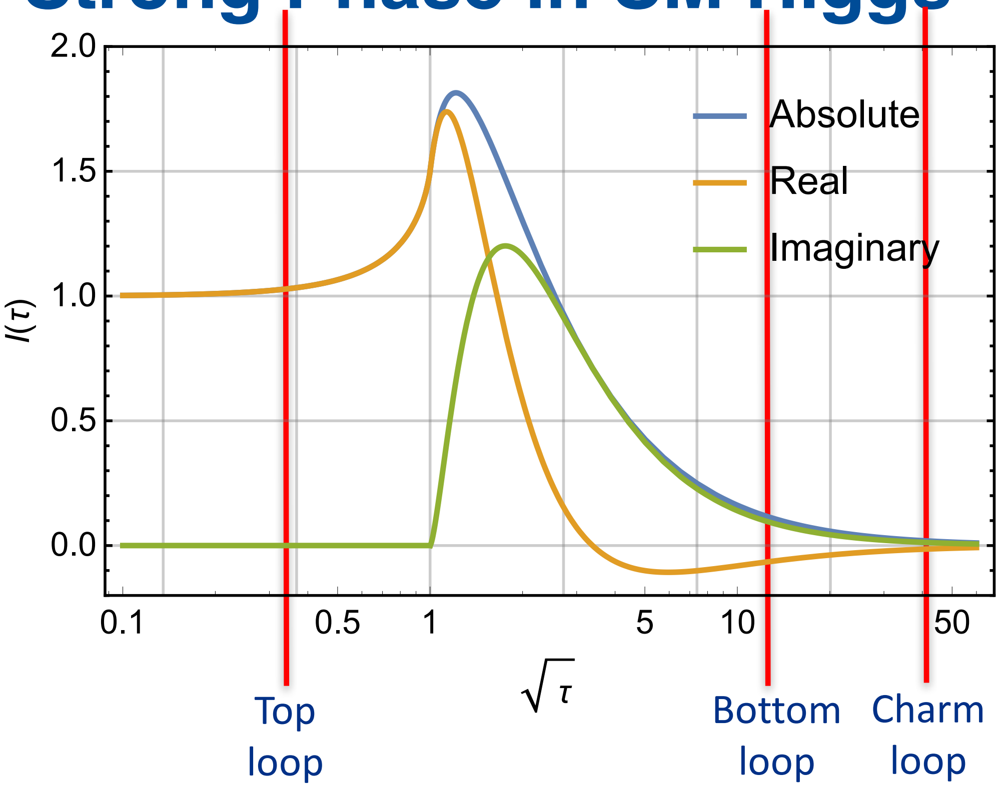
$\Delta\mu/\mu$	300 fb^{-1}		3000 fb^{-1}	
	All unc.	No theory unc.	All unc.	No theory unc.
$H \to \gamma\gamma$ (comb.)	0.13	0.09	0.09	0.04
(0j)	0.19	0.12	0.16	0.05
(1j)	0.27	0.14	0.23	0.05
(VBF-like)	0.47	0.43	0.22	0.15
(WH-like)	0.48	0.48	0.19	0.17
(ZH-like)	0.85	0.85	0.28	0.27
(ttH-like)	0.38	0.36	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

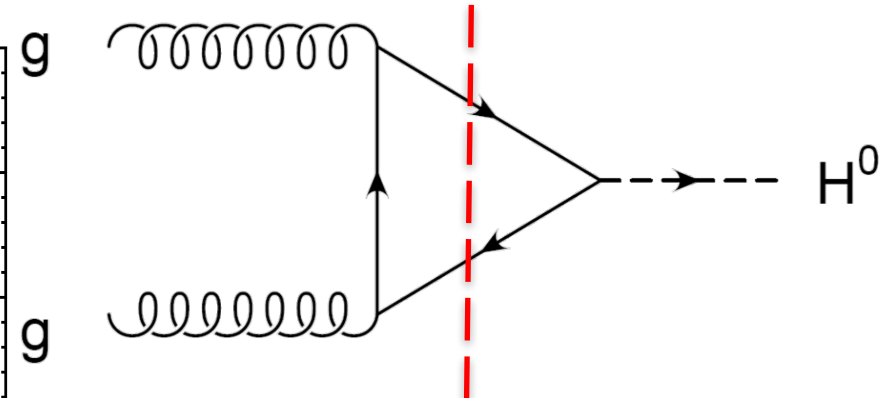


Dots represent point-like interaction, where the phase is ignored at NLO.



Strong Phase in SM Higgs





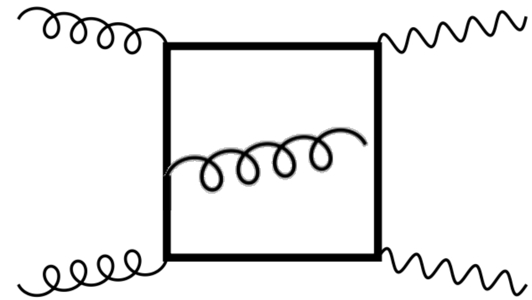
- All quark contributions normalized the same way, the plot represents the relative contributions
- Numerically:
  - t-loop $+1.034$
  - b-loop $-0.035+0.039i$
  - c-loop $-0.004+0.002i$

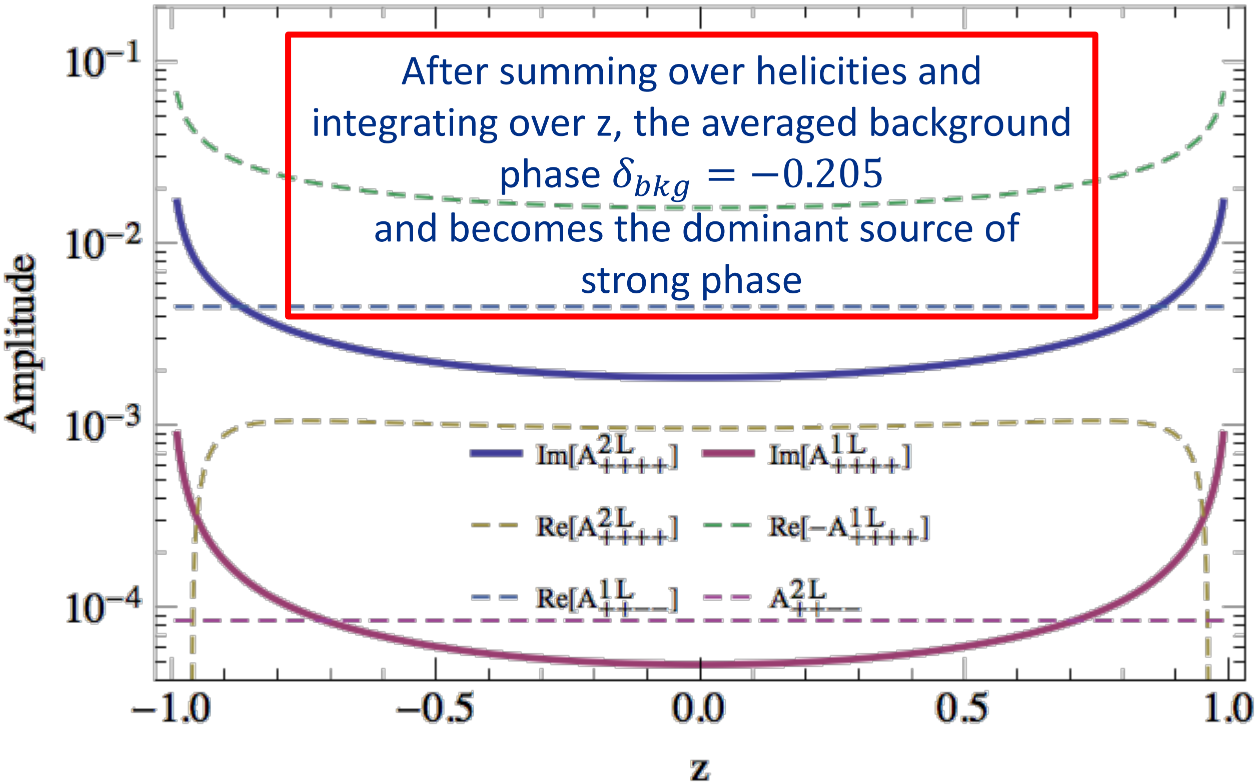
A strong phase in the gluon-gluon fusion production at hadron colliders (imaginary part)

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

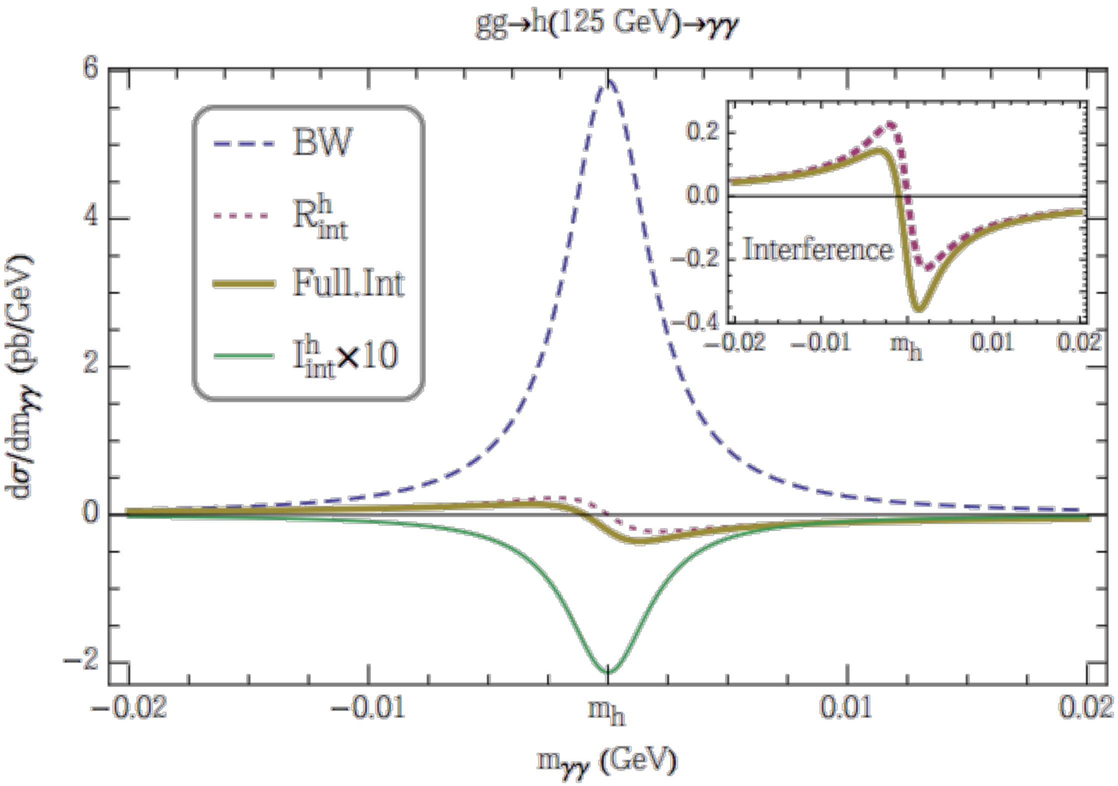
Phase from interfering background

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





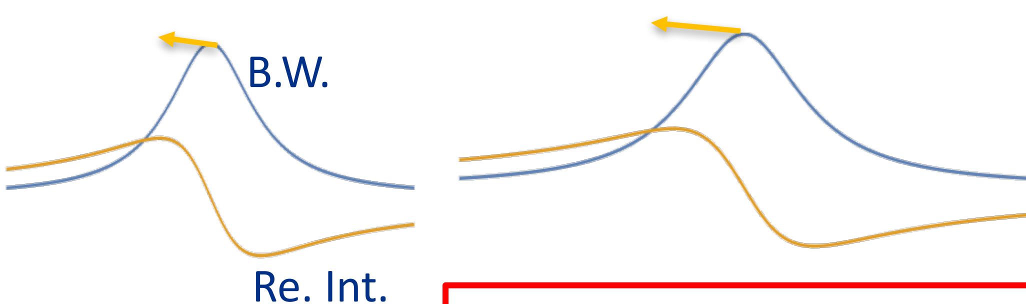
- Angular dependence
- a smaller but negative phase w.r.t to the signal
- At l-loop, the imaginary part is mainly from $A_{++++} = A_{----}$ with bottom and charm contributions
- Imaginary part dominated by the 2-loop MHV amplitude.

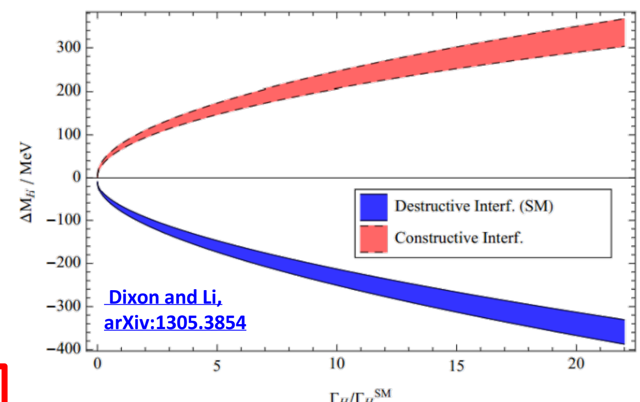


Averaging over helicity amplitudes and polar angles, one can calculate this new interference piece between signal and background:

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

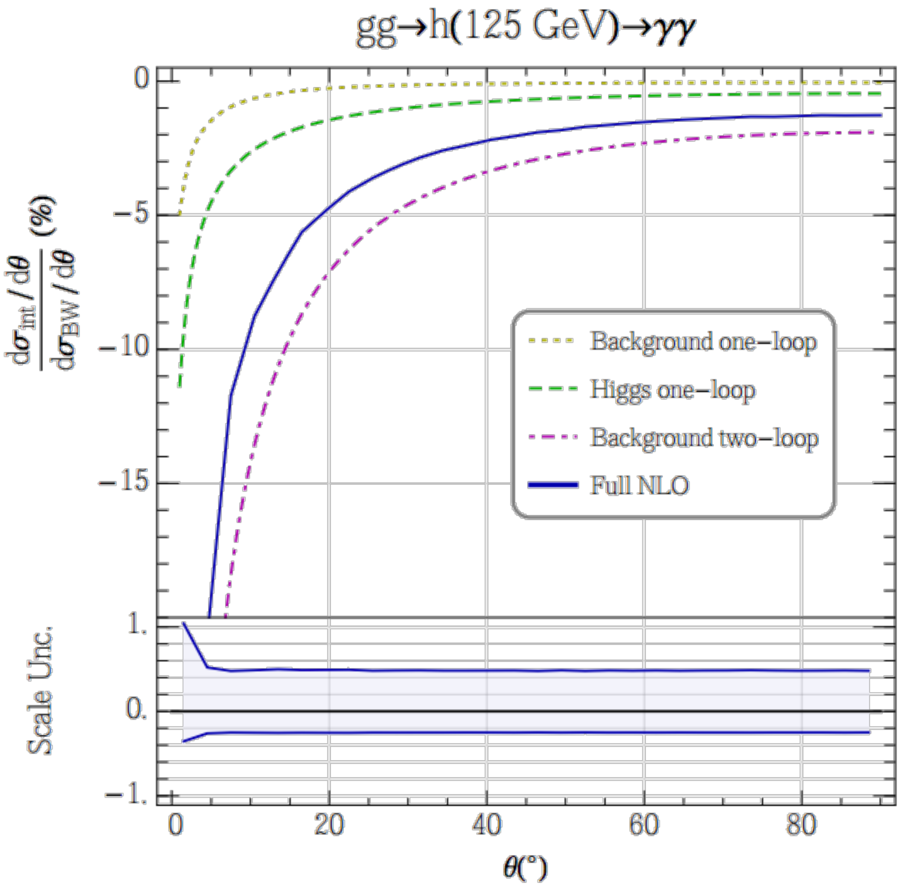
The interference term from the strong phase does change the SM rate prediction by $\sim -2.\%$





Our study is ``orthogonal'' to Dixon & Li 13', S. Martin 12, 13'

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.