Interference effects in gluon-fusion Higgs boson production

Based on: ***Eur.Phys.J.C*** **83 (2023) 2, 174 [arXiv:2212.06287] &** ***Phys.Lett.B*** **851 (2024) 138596 [arXiv:2312.12384]**

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Federica Devoto, The 22nd Workshop of the LHC Higgs Working Group, CERN, 04/12/2025

Higgs production in gluon fusion

Dominant production mode at LHC

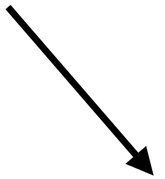
Best theory prediction, from CERN YR4 [arXiv: 1610.07922]:

$\sqrt{S}$	13 TeV
m_h	125 GeV
PDF	PDF4LHC15_nnlo_100
$\alpha_s(m_Z)$	0.118
$m_t(m_t)$	162.7 GeV ($\overline{\text{MS}}$)
$m_b(m_b)$	4.18 GeV ($\overline{\text{MS}}$)
$m_c(3GeV)$	0.986 GeV ($\overline{\text{MS}}$)
$\mu = \mu_R = \mu_F$	62.5 GeV ($= m_H/2$)

$$\sigma = 48.58\,\text{pb}^{+2.22\,\text{pb}\,(+4.56\%)}_{-3.27\,\text{pb}\,(-6.72\%)}\,(\text{theory}) \pm 1.56\,\text{pb}\,(3.20\%)\,(\text{PDF}{+}\alpha_s)\,.$$

$$\begin{aligned}
48.58\,\text{pb} = \quad & 16.00\,\text{pb} && (+32.9\%) && (\text{LO, rEFT}) \\
& +20.84\,\text{pb} && (+42.9\%) && (\text{NLO, rEFT}) \\
& -\ 2.05\,\text{pb} && (-4.2\%) && ((t,b,c),\ \text{exact NLO}) \\
& +\ 9.56\,\text{pb} && (+19.7\%) && (\text{NNLO, rEFT}) \\
& +\ 0.34\,\text{pb} && (+0.7\%) && (\text{NNLO, } 1/m_t) \\
& +\ 2.40\,\text{pb} && (+4.9\%) && (\text{EW, QCD-EW}) \\
& +\ 1.49\,\text{pb} && (+3.1\%) && (\text{N}^3\text{LO, rEFT})
\end{aligned}$$

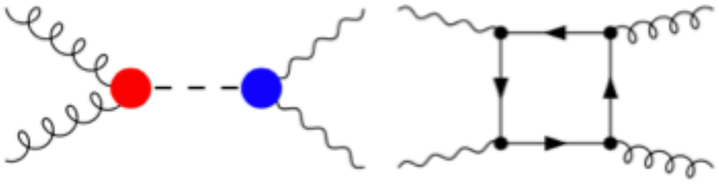
All this concerns ggF production stage of the Higgs boson, but what about the full decayed process? Other sources of uncertainties?



Signal-background interference effects

Interference effects in on-shell Higgs production

We consider $gg \to H \to V_1 V_2$ (diboson system, loop induced for now)



$$\mathcal{M}_{gg\to V_1V_2} = \frac{\mathcal{M}_{\rm sig}}{m^2_{V_1V_2} - m^2_H + i\Gamma_H m_H} + \mathcal{M}_{\rm bkg}$$

$$\left|\mathcal{M}_{gg\to V_1V_2}\right|^2 = \frac{|\mathcal{M}_{\rm sig}|^2}{(m^2_{V_1V_2} - m^2_H)^2 + \Gamma^2_H m^2_H} + |\mathcal{M}_{\rm bkg}|^2 + 2{\rm Re}\left(\frac{\mathcal{M}_{\rm sig}}{m^2_{V_1V_2} - m^2_H + i\Gamma_H m_H}\mathcal{M}^\dagger_{\rm bkg}\right)$$

$$\mathcal{M}_{\rm sig/bkg} = {\rm Re}\mathcal{M}_{\rm sig/bkg} + i\,{\rm Im}\mathcal{M}_{\rm sig/bkg}$$

$$\left|\mathcal{M}_{gg\to V_1V_2}\right|^2 = |S|^2 + |B|^2 + \frac{2m^2_{V_1V_2}}{(m^2_{V_1V_2} - m^2_H)^2 + \Gamma^2_H m^2_H}\left[(m^2_{V_1V_2} - m^2_H){\rm Re}\,I + \Gamma_H m_H {\rm Im}\,I\right]$$

$${\rm Re}\,I = {\rm Re}\mathcal{M}_{\rm bkg}{\rm Re}\mathcal{M}_{\rm sig} + {\rm Im}\mathcal{M}_{\rm bkg}{\rm Im}\mathcal{M}_{\rm sig}$$

$${\rm Im}\,I = {\rm Re}\mathcal{M}_{\rm bkg}{\rm Im}\mathcal{M}_{\rm sig} - {\rm Im}\mathcal{M}_{\rm bkg}{\rm Re}\mathcal{M}_{\rm sig}$$

"Real part" of interference

"Imaginary part" of interference

Interference effects: real vs imaginary parts

“Real”

$$I_{\mathrm{Re}} \propto \frac{2m^2_{V_1V_2}}{(m^2_{V_1V_2} - m^2_H)^2 + \Gamma^2_H m^2_H} \, (m^2_{V_1V_2} - m^2_H) \, \mathrm{Re}\, I$$

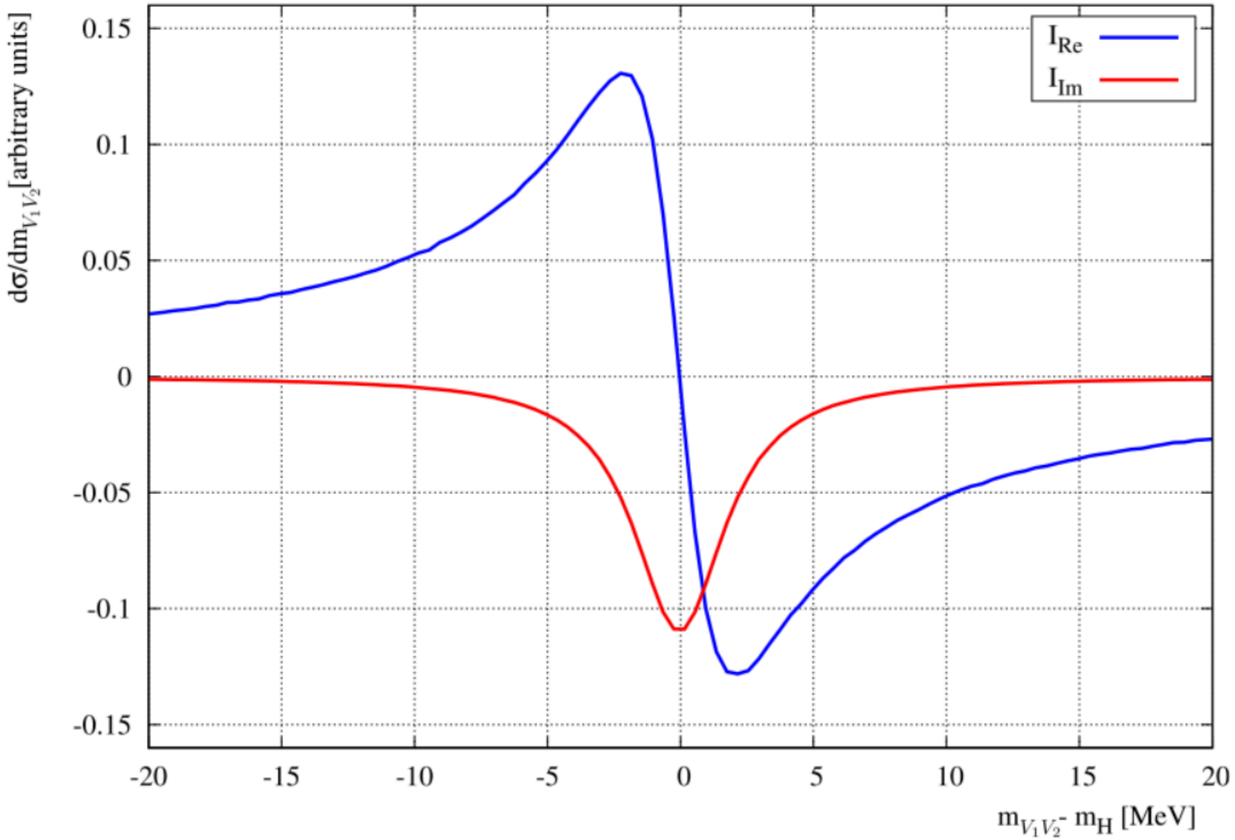
Antisymmetric around Higgs peak, does not contribute to the cross section; shifts events off the peak

“Imaginary”

$$I_{\mathrm{Im}} \propto \frac{2m^2_{V_1V_2}}{(m^2_{V_1V_2} - m^2_H)^2 + \Gamma^2_H m^2_H} \, \Gamma_H m_H \, \mathrm{Im}\, I$$

Symmetric around Higgs peak, contributes to the cross section

How much?



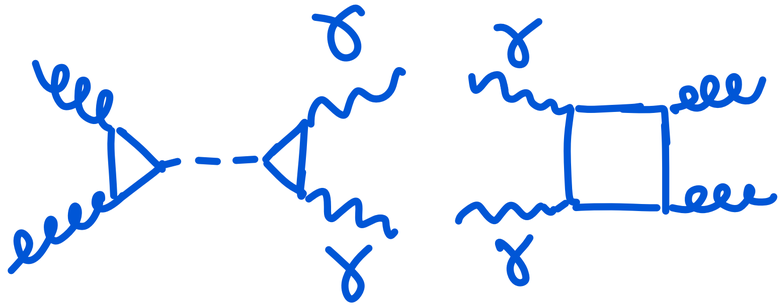
Both are interesting effects and can be exploited in different ways

Interference effects: why loop-induced decay?

Example with $\gamma\gamma$ (same holds for $Z\gamma$)

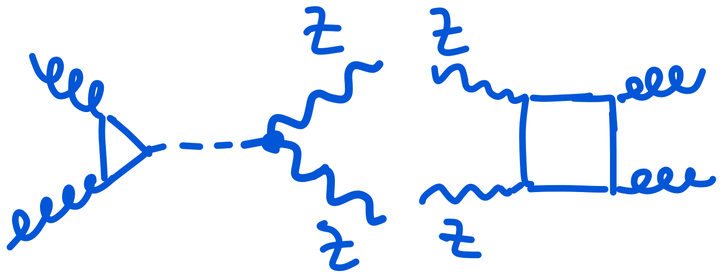
$$\left|\mathcal{M}_{gg\to VV}\right|^2 = |S|^2 \left[1 + \frac{2m_{VV}^2}{(m_{VV}^2 - m_H^2)^2 + \Gamma_H^2 m_H^2}\left((m_{VV}^2 - m_H^2)\mathrm{Re}\frac{B^\dagger}{S} + \Gamma_H m_H \mathrm{Im}\frac{B^\dagger}{S}\right)\right] + |B|^2$$

Diphoton: 3-loops



$$S_{\gamma Z} \sim \lambda_i \lambda_f \qquad B_{\gamma Z} \sim \frac{g_s^2 e^2}{(4\pi)^2}$$

ZZ: 2-loops



$$S_{ZZ} \sim \lambda_i \frac{e^2 v}{2 c_w^2 s_w^2} \qquad B_{ZZ} \sim \frac{g_s^2 e^2}{(4\pi)^2}$$

However… different considerations for $\gamma\gamma$ vs $Z\gamma$

$$\lambda_i \sim \frac{\alpha_s}{4\pi}\frac{m_H^2}{v}$$

$$\lambda_f \sim \frac{\alpha_w}{4\pi}\frac{m_H^2}{v}$$

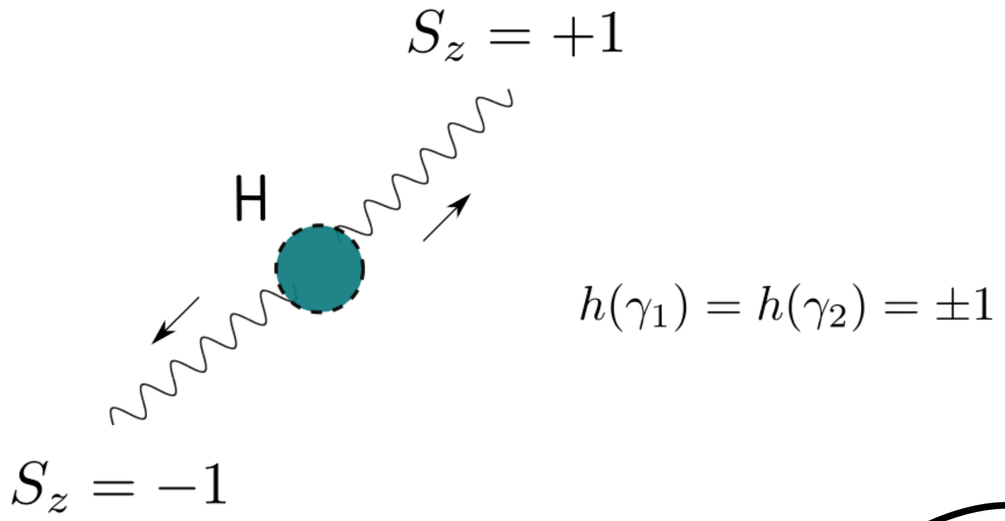
$$\frac{S_{\gamma\gamma}}{S_{ZZ}} \sim \left(\frac{c_w s_w m_H}{2\pi v}\right)^2 \sim 10^{-3}$$

$$\frac{\sigma_{int,\gamma\gamma}}{\sigma_H} \sim \frac{2\Gamma_H}{m_H}\frac{(4\pi v)^2}{m_H^2} \sim 4\,\%$$

"Loop enhancement"

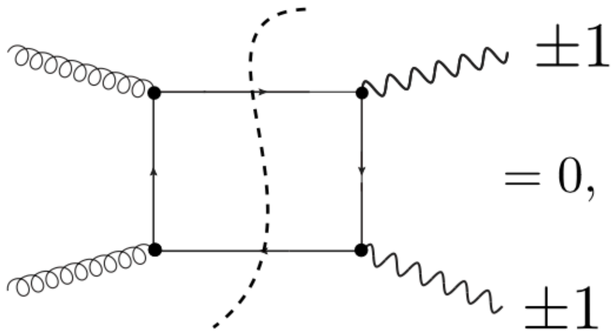
Interference effects: $\gamma\gamma$ vs $Z\gamma$

Diphoton:



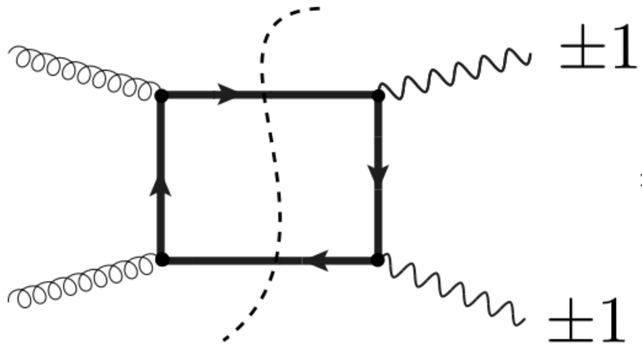
$$h(\gamma_1) = h(\gamma_2) = \pm 1$$

Im(A) ~



$= 0, \quad \text{for} \quad m_q = 0$

Im(A) ~



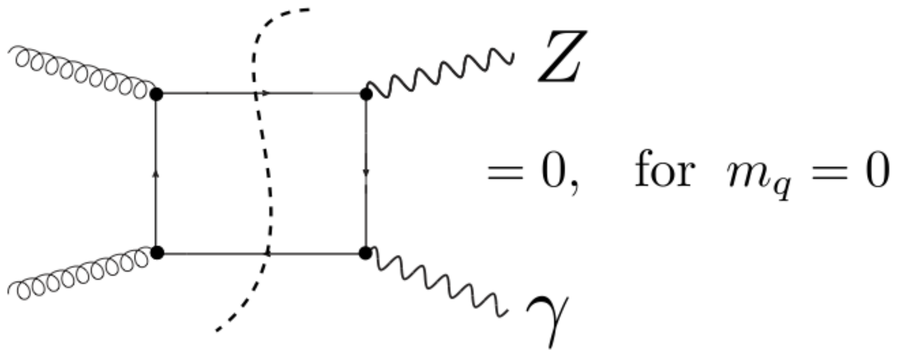
$\neq 0, \quad \text{for} \quad s > 4m_q^2$

Bottom quark mass effects, suppressed ~ $\mathcal{O}\left(\frac{m_q^2}{s}\right)$

"Helicity selection" for $\gamma\gamma$ makes interference negligible at LO

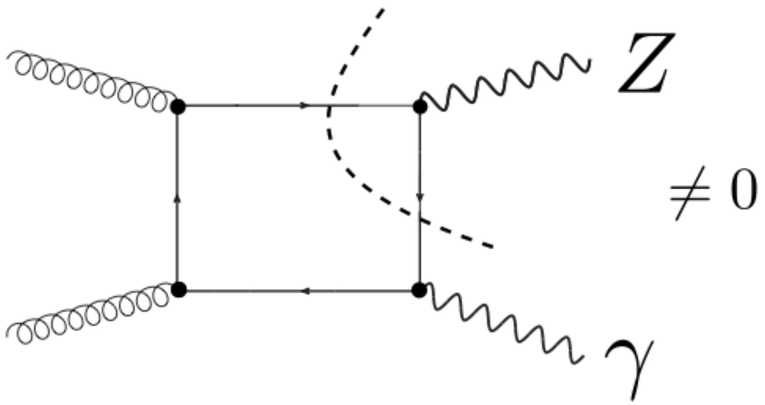
Interference effects: $\gamma\gamma$ vs $Z\gamma$

$Z\gamma$: here helicity selection does not occur (only gg)



$= 0, \quad \text{for} \quad m_q = 0$

Im(A) ~

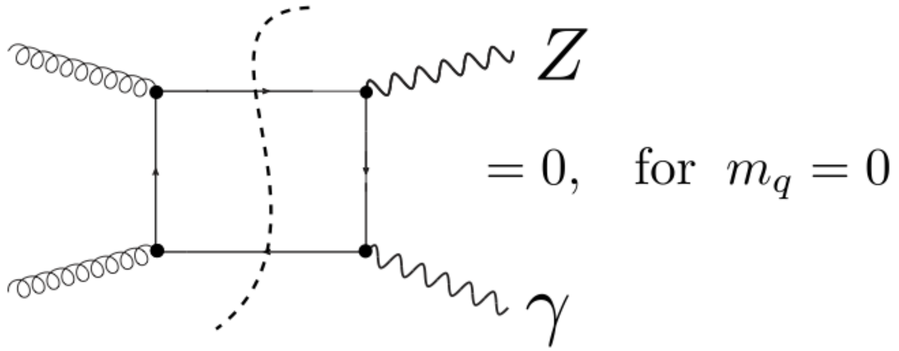


$\neq 0$

Non-vanishing cut, interference contribution already at LO

Interference effects: $\gamma\gamma$ vs $Z\gamma$

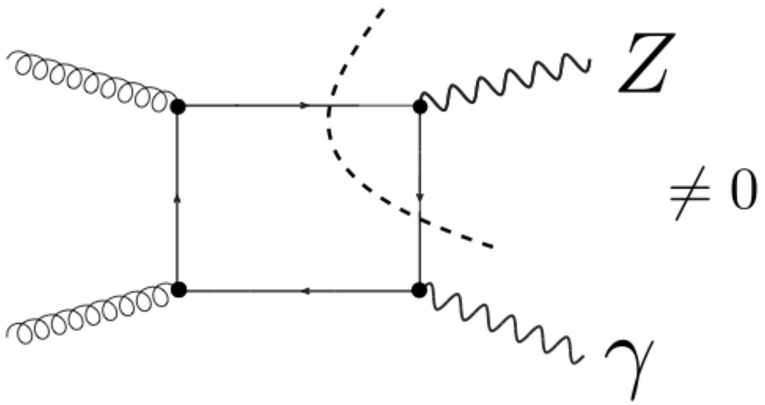
$Z\gamma$: here helicity selection does not occur (only gg)



$= 0, \quad \text{for} \quad m_q = 0$

What is the actual impact on the XS in the two different channels?

Im(A) ~



$\neq 0$

Non-vanishing cut, interference contribution already at LO

Interference effects: diphoton channel

NLO QCD analyses: Dixon, Siu [hep-ph/0302233]; Dixon, Li [1305.3854]; Coradeschi et al. [1504.05215], Cieri et al. [1706.07331]

NNLO QCD in soft-virtual approximation: Bargiela et al. [2212.06287]

Setup:

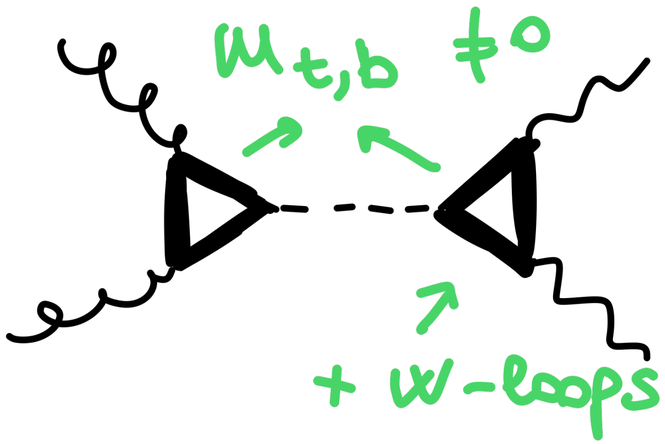
- PDF set: NNPDF31_nnlo_as_0118
- Dynamic scale: $\mu_F = \mu_R \equiv \mu = \dfrac{m_{\gamma\gamma}}{2}$
- Fiducial cuts:
  - $p_{T\,\gamma_{1,2}} > 20\,\mathrm{GeV}$
  - $|\eta_\gamma| < 2.5$
  - $p_{T\,\gamma_1} p_{T\,\gamma_2} > (35\,\mathrm{GeV})^2$
  - $\Delta R_{\gamma_{1,2}} > 0.4$

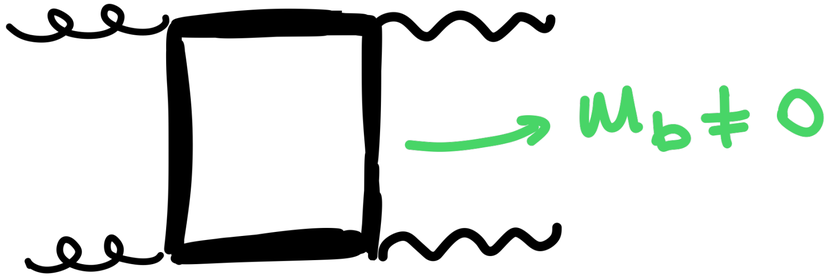
[Salam, Slade 2106.08329]

Interference effects: diphoton channel beyond NLO

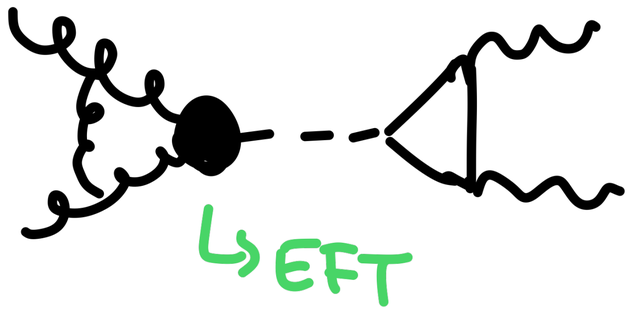
NNLO QCD in soft-virtual approximation: Bargiela et al. [2212.06287]

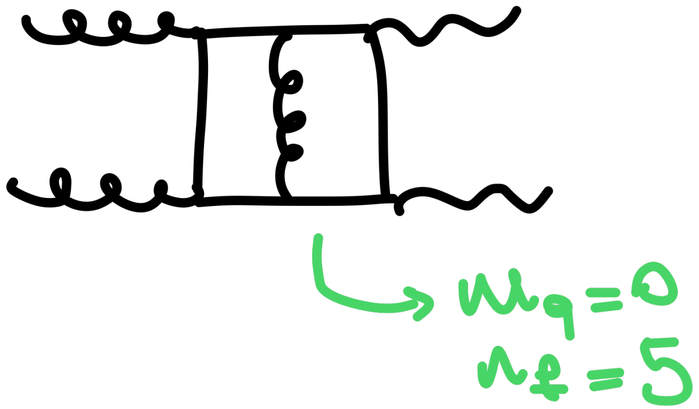
LO





N(N)LO





Interference effects: diphoton channel beyond NLO

NNLO QCD in soft-virtual approximation: Bargiela et al. [2212.06287]

+ added run at 13 TeV for YR5 contribution

Signal exact NNLO (obtained via NNLOJET [2503.22804]), interference in NNLO soft-virtual

Order	σ_{sig} [fb]	σ_{int} [fb]	δ_{int} [%]
$\sqrt{s} = 7$ TeV			
LO	$9.018^{+2.01}_{-1.66}$	$-0.033^{-0.010}_{+0.007}$	−0.36
NLO	$20.73^{+4.67}_{-3.42}$	$-0.26^{-0.10}_{+0.07}$	−1.23
NNLO*	$25.93^{+2.20}_{-2.49}$	$-0.44^{-0.05}_{+0.06}$	−1.70
$\sqrt{s} = 8$ TeV			
LO	$11.19^{+2.41}_{-1.95}$	$-0.042^{-0.012}_{+0.009}$	−0.38
NLO	$25.94^{+5.70}_{-4.17}$	$-0.32^{-0.11}_{+0.08}$	−1.2
NNLO*	$32.73^{+2.92}_{-3.14}$	$-0.55^{-0.06}_{+0.07}$	−1.68

$\sqrt{s} = 13$ TeV			
LO	$23.00^{+3.59}_{-3.19}$	$-0.100^{-0.021}_{+0.017}$	−0.43
NLO	$55.04^{+11.0}_{-8.04}$	$-0.67^{-0.19}_{+0.14}$	−1.22
NNLO*	$69.99^{+6.40}_{-6.29}$	$-1.12^{-0.08}_{+0.12}$	−1.61
$\sqrt{s} = 13.6$ TeV			
LO	$24.47^{+3.70}_{-3.32}$	$-0.109^{-0.022}_{+0.180}$	−0.44
NLO	$58.77^{+11.7}_{-8.51}$	$-0.73^{-0.20}_{+0.15}$	−1.24
NNLO*	$74.71^{+6.75}_{-6.73}$	$-1.21^{-0.08}_{+0.13}$	−1.62

$Z\gamma$ decay channel

Much less studied than diphoton

First evidence by ATLAS and CMS in [2309.03501]

Signal yield $\mu = 2.2 \pm 0.7$ x SM rate

Tension significantly reduced in most recent ATLAS analysis [ATLAS-CONF-2025-007]

Signal yield $\mu = 1.3^{+0.6}_{-0.5}$ x SM rate

Consistent with SM

Even if this is not a “precision channel” (yet), interesting to ask impact of interference effects also in this case

Interference effects: $Z(\rightarrow e^+e^-)\gamma$ decay channel

NLO analysis in soft-virtual approximation, F.Buccioni et al. [2312.12384]

Setup:

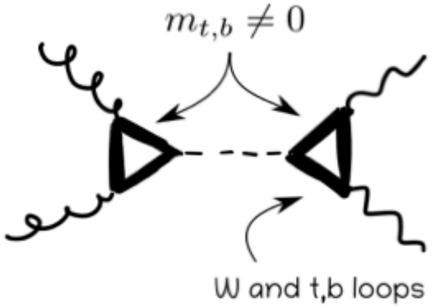
- PDF set: NNPDF31_nlo_as_0118
- Dynamic scale: $\mu_F = \mu_R \equiv \mu = \dfrac{m_H}{2}$
- Fiducial cuts:
  - $50\ \text{GeV} < m_{ll} < 101\ \text{GeV}$
  - $p_{T,i} > 10\ \text{GeV} \qquad i \in \{\gamma, e^-, e^+\}$
  - $|y_\gamma| < 2.37 \quad |y_{e^\pm}| < 2.47$

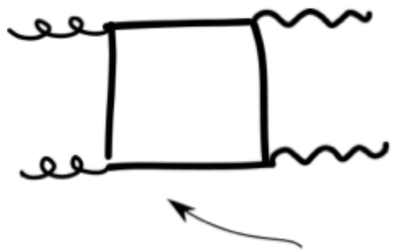
Inspired by ATLAS [2005.05382]

Interference effects: $Z(\rightarrow e^+e^-)\gamma$ decay channel

NLO analysis in soft-virtual approximation

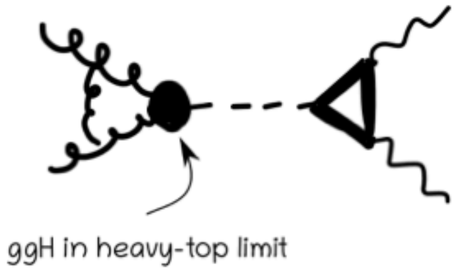
LO:

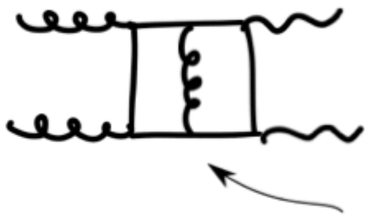




$m_q = 0,\ n_f = 5$

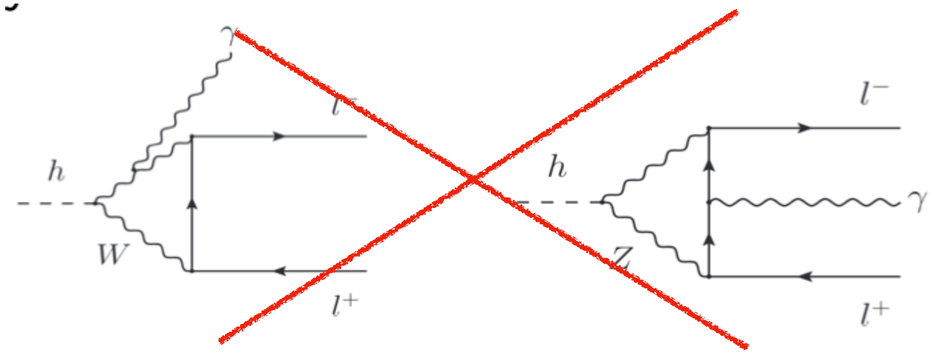
NLO$_{sv}$:



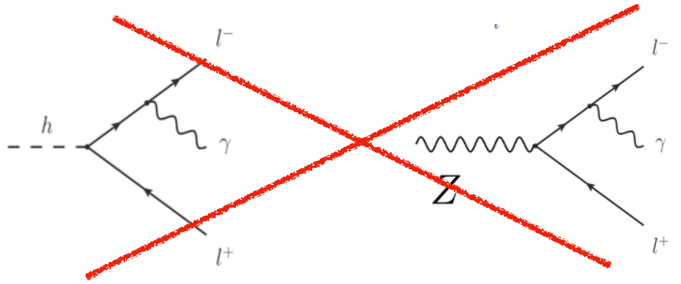


$m_q = 0,\ n_f = 5$

Pole approximation (resonant Z), ensured by leptons cuts



Neglect photon radiation off leptons



Small Yukawa

Suppressed by Higgs resonance region

Interference effects: $Z(\to e^+e^-)\gamma$ decay channel

F.Buccioni et al. [2312.12384] + added results at 13 TeV for YR5 contribution

Exact NLO for signal, soft-virtual for interference

Order	σ_{sig} [fb]	σ_{int} [fb]	δ_{int} [%]
	$\sqrt{s} = 13$ TeV		
LO	$0.484^{+0.075}_{-0.067}$	$-0.0215^{-0.003}_{+0.003}$	−4.4
NLO*	$1.13^{+0.23}_{-0.16}$	$-0.0363^{-0.006}_{+0.005}$	−3.2
	$\sqrt{s} = 13.6$ TeV		
LO	$0.514^{+0.078}_{-0.070}$	$-0.0228^{-0.003}_{-0.003}$	−4.4
NLO*	$1.21^{+0.24}_{-0.17}$	$-0.0386^{-0.006}_{+0.005}$	−3.2

Interference non-zero already at LO (as discussed earlier); close to “naive” estimate

Summary

- Controlling theory uncertainty on ggF Higgs production mode remains a central task, espacially moving towards HL-LHC
- So far, production and decay treated separately; now we are after %-level precision, interference effects play a role
- This is especially true in the well-studied diphoton channel, whereas in Z-photon we still lack statistics
- Interference impacts the total XS at ~1.7% in the diphoton channel, and ~3% in the $Z\gamma$ channel; their impact can now be incorporated with other more traditional sources of uncertainty in ggF

Thank you!