# Signal-background interference effects in Higgs-mediated diphoton production beyond NLO

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based on [2212.06287]

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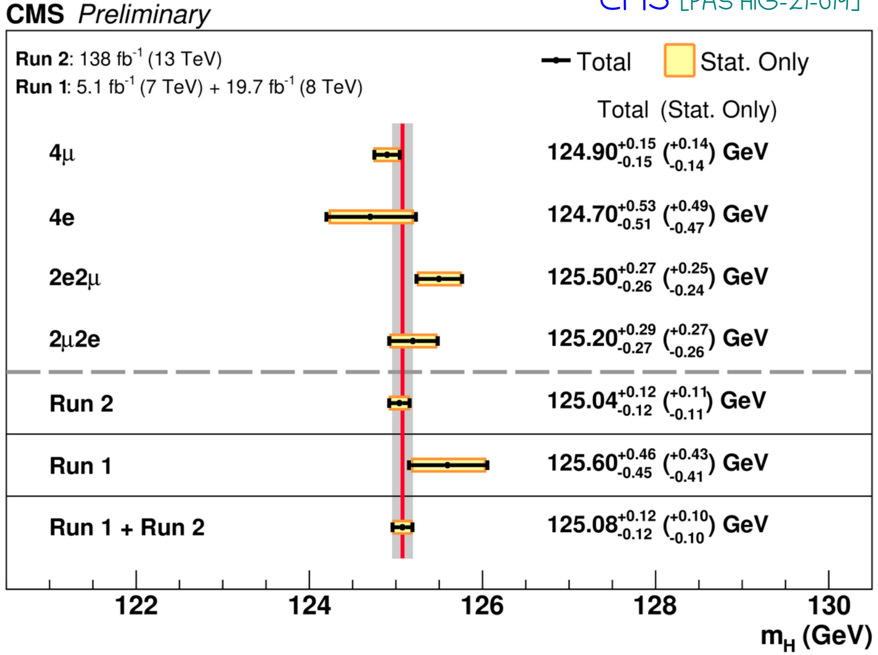
# A decade (+1) of Higgs boson studies

- Mass

Combination of Run 1 + 2

CMS [PAS HIG-21-019]

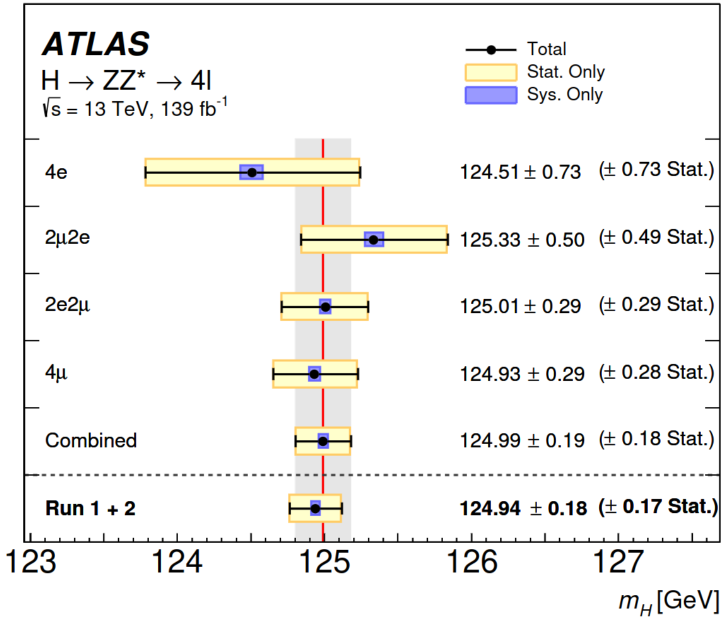



CMS
$$m_H(4\ell) = 125.08 \pm 0.10(\text{stat}) \pm 0.07(\text{syst.})$$

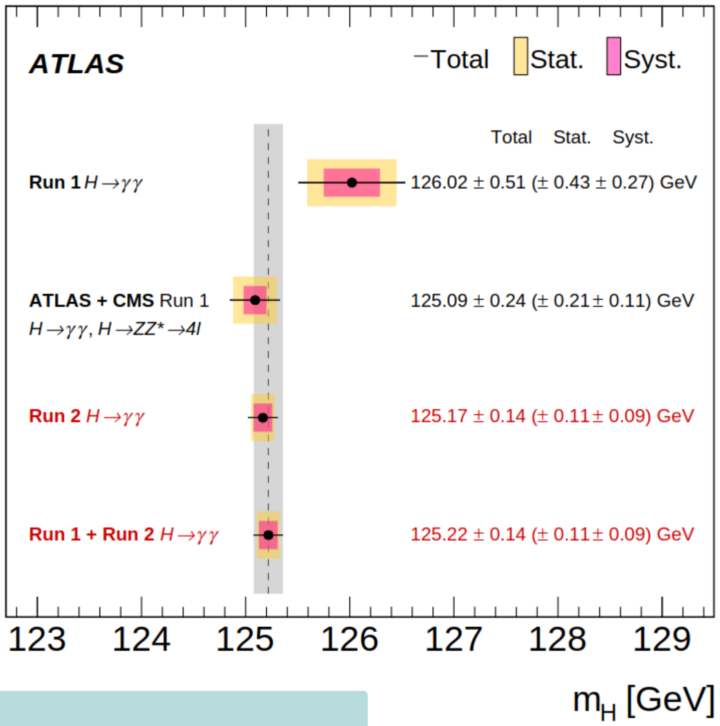
CMS [Phys. Lett. B 805 (2020) 135425]
$$m_H(\gamma\gamma) = 125.78 \pm 0.18\,(\text{stat}) \;\pm 0.18\,(\text{syst})\,\text{GeV}$$

ATLAS
$$m_H(4\ell) = 124.99 \pm 0.18\,(\text{stat}) \;\pm 0.04\,(\text{syst})\,\text{GeV}$$

[2207.00320]




[2308.07216]




ATLAS
$$m_H(\gamma\gamma) = 125.22 \pm 0.11\,(\text{stat.}) \pm 0.09\,(\text{syst.})\;\text{GeV}$$

# The Higgs boson width

SM prediction for $\Gamma_H \sim 4.1$ MeV

Any coupling of the Higgs boson to BSM particles would modify $\Gamma_H$

Proposal:
measure $\Gamma_H$ in a model-independent fashion at future H factories, i.e.
$e^- e^+ \to ZH$ [Fujii et al 1710.07621]

For $\sqrt{s}$ = 250, Z @ Energy = 110 GeV tags the presence of an H boson

$$\sigma(e^+e^- \to Zh)/BR(h \to ZZ^*)$$

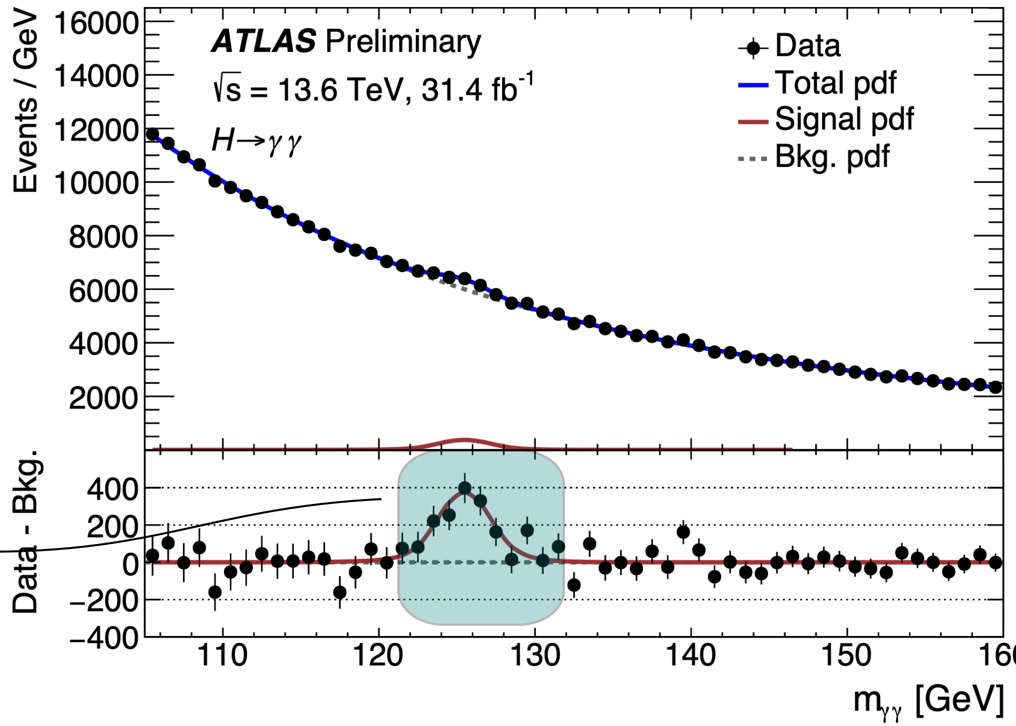
yields $\Gamma_H$

we can only put indirect bounds

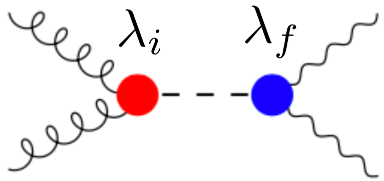
We cannot measure $\Gamma_H$ at the LHC directly from signal line-shape

Dector resolution:
1-2 GeV

ATLAS "rediscovers" the Higgs @ 13.6 TeV (23.05.23)




Issues with on-shell XS:




$$\sigma_{i\to H\to f} \sim \sigma_{i\to H} \times \mathrm{BR}(H \to f) \sim \frac{\lambda_i^2 \lambda_f^2}{\Gamma_H m_H}$$

cross section unchanged upon rescaling

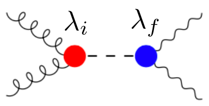
$$\begin{cases} \lambda_{i/f} = \xi\, \lambda_{i/f}^{\mathrm{SM}} \\ \Gamma_H = \xi^4\, \Gamma_H^{\mathrm{SM}} \end{cases}$$

How to lift this degeneracy?

# Bounds on $\Gamma_H$ from off-shell meausurements

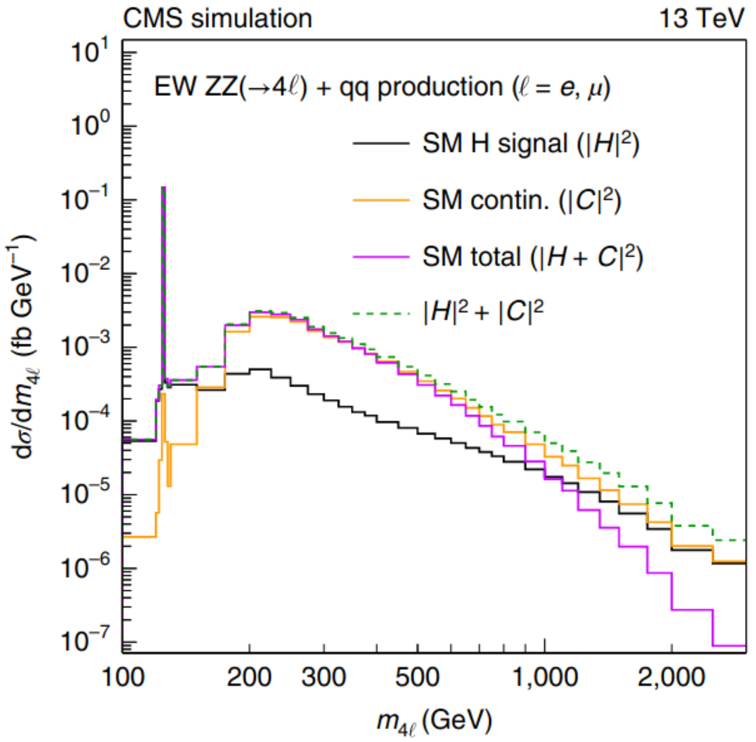
Off-shell cross sections measurements [N. Kauer, G. Passarino 1206.4803] [F. Caola, K. Melnikov 1307.4935] [J.M. Campbell, R.K.Ellis, C.Williams 1311.3589]

$$\sigma \propto \int \left| \right|^2 \sim \int \frac{\lambda_i^2 \lambda_f^2}{(m_{VV}^2 - m_H^2)^2 + \Gamma_H^2 m_H^2} \xrightarrow{m_{VV} \gg m_H} \int \frac{\lambda_i^2 \lambda_f^2}{m_{VV}^4} \sim \frac{\lambda_i^2 \lambda_f^2}{m_{VV}^2}$$




on-shell

$$\frac{\lambda_i^2 \lambda_f^2}{\Gamma_H m_H}$$




$$\sigma_{X-shell} = \mu_{X-shell}\sigma_{X-shell}^{SM}$$

$$(\lambda_i^{SM}\lambda_f^{SM})^2\, \mu_{off-shell} = (\lambda_i\lambda_f)^2$$

$$\frac{(\lambda_i^{SM}\lambda_f^{SM})^2}{\Gamma_H^{SM}}\mu_{on-shell} = \frac{(\lambda_i\lambda_f)^2}{\Gamma_H}$$

$$\frac{\Gamma_H}{\Gamma_H^{SM}} = \frac{\mu_{off-shell}}{\mu_{on-shell}}$$

ATLAS [2304.01523]

$\Gamma_H$: $4.5^{+3.3}_{-2.5}$ MeV + upper limit 10.5 MeV

CMS [2202.06923 ]

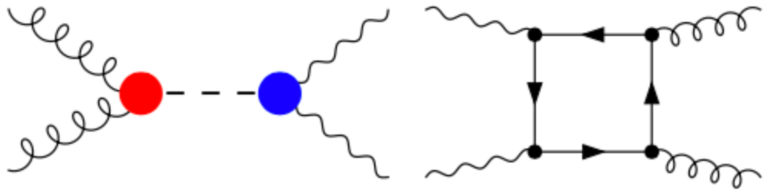
$\Gamma_H$: $3.2^{+2.4}_{-1.7}$ MeV

Assumption:

couplings in the off-shell region are the same as in the on-shell region

# Signal-background interference in diphoton production

Consider on-shell Higgs-boson production in $H \to \gamma\gamma$ decay channel



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

Interference lifts degeneracy on couplings/$\Gamma_H$:

$$\left|\mathcal{M}_{gg\to\gamma\gamma}\right|^2 = \frac{|\mathcal{M}_{\rm sig}|^2}{(m_{\gamma\gamma}^2 - m_H^2)^2 + \Gamma_H^2 m_H^2} + |\mathcal{M}_{\rm bkg}|^2 + 2{\rm Re}\left(\frac{\mathcal{M}_{\rm sig}}{m_{\gamma\gamma}^2 - m_H^2 + i\Gamma_H m_H}\mathcal{M}_{\rm bkg}^\dagger\right)$$

$\sim \lambda_i^2\lambda_f^2$ $\qquad$ $\sim \lambda_i\lambda_f$

Idea:
any effect due to Interference can be used to constrain
independently $\Gamma_H$ of couplings

What are suitable "observables"?
How to harness interference effects?

# Signal-background interference in diphoton production

Consider real and imaginary parts of amplitudes independently

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

What are suitable "observables"?
How to harness interference effects?

The interference can be then organised as

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

"real-part" of the interference

"imaginary-part" of the interference

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

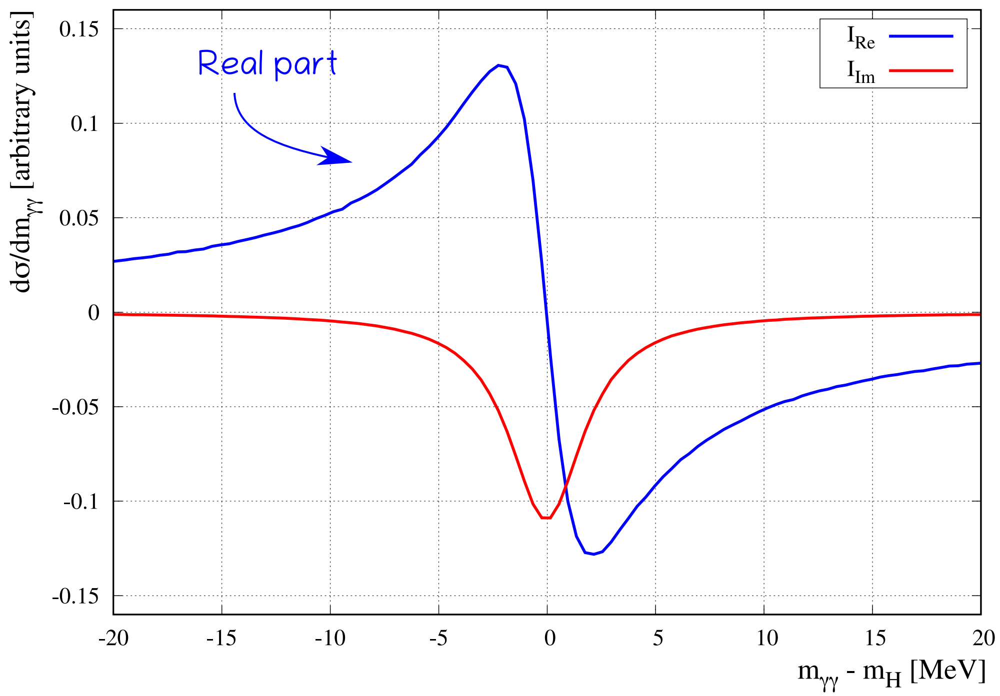
$$\mathrm{Im}\,I = \mathrm{Re}\mathcal{M}_{\mathrm{bkg}}\mathrm{Im}\mathcal{M}_{\mathrm{sig}} - \mathrm{Im}\mathcal{M}_{\mathrm{bkg}}\mathrm{Re}\mathcal{M}_{\mathrm{sig}}$$

The real and imaginary have very different behaviours and properties

# Real part of the interference and the mass shift

$$I_{\mathrm{Re}} \propto \frac{2m_{\gamma\gamma}^2}{(m_{\gamma\gamma}^2 - m_H^2)^2 + \Gamma_H^2 m_H^2} (m_{\gamma\gamma}^2 - m_H^2)\mathrm{Re}\, I$$

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




Real part

- Antisymmetric around the peak, does not contribute to the cross section
- unbalance of events around the Higgs peak: excess below the peak

apparent mass shift [S.P. Martin 1208.1533]

First pointed out in the context of precision Higgs boson mass measurements

Expected mass-shift @LO O(100 MeV) [S.P. Martin 1208.1533]

The mass shift is a direct consequence of signal-background interference.

How can one exploit this to put bounds on $\Gamma_H$?

# Mass shift and bounds on Higgs width

Exploit linear dependence of interference on couplings to put bounds on $\Gamma_H$ [Dixon, Li 1305.3854]

Idea:

- Allow $\Gamma_H$ to differ from SM prediction
- Higgs coupling change accordingly in order to maintain roughly SM yield (good agreement with SM prediction)

  Usual "flat direction in parameter space"

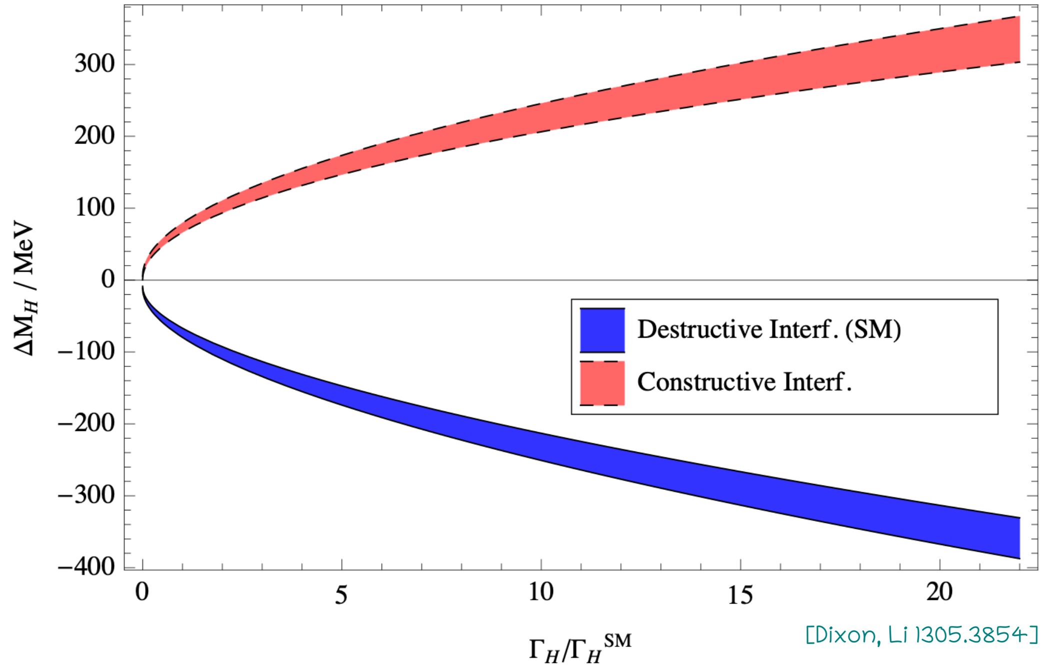
$$\lambda_{i,f} \to \xi_{i,f}\lambda_{i,f}$$

$$\frac{(\xi_i\xi_f)^2 S}{m_H\Gamma_H} + \xi_i\xi_f I \sim \frac{S}{m_H\Gamma_H^{SM}} + I$$

Negligible for small deviation from SM prediction

Interference effect on cross section is small wrt integrated signal

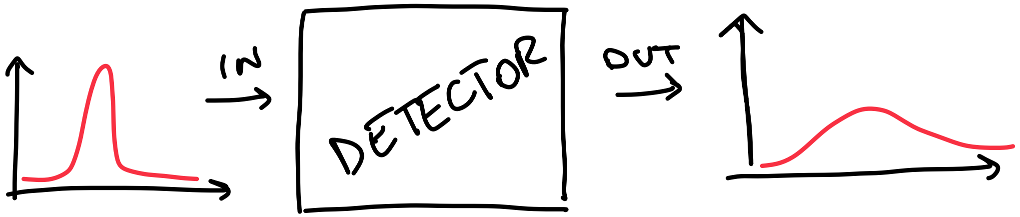
$$\Delta M_{\gamma\gamma} \propto \xi_i\xi_f \propto \sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}}$$



[Dixon, Li 1305.3854]

# Estimates of the mass-shift: theory vs experiments

Smearing effect from detector resolution




Experiments:

Realistic detector resolution [ATL-PHYS-PUB-2016-009]

Mass-shift ~ 35 MeV

Theory simulation: NLO QCD + NLL (Sherpa) @ 7 TeV LHC

Theory approach:

Simulate detector resolution via Gaussian smearing.

Mass-shift O(100 MeV)

ATLAS [2308.07216]

| Source | Impact [MeV] |
|---|---|
| Photon energy scale | 83 |
| $Z \to e^+e^-$ calibration | 59 |
| $E_T$-dependent electron energy scale | 44 |
| $e^\pm \to \gamma$ extrapolation | 30 |
| Conversion modelling | 24 |
| Signal–background interference | 26 |
| Resolution | 15 |
| Background model | 14 |
| Selection of the diphoton production vertex | 5 |
| Signal model | 1 |
| Total | 90 |

In $\gamma\gamma$ analysis, interference treated as a systematic. NLO accuracy

ATLAS PUB Note
CMS PAS Note
ATL-PHYS-PUB-2022-018
CMS PAS FTR-22-001
17th March 2022

**Snowmass White Paper Contribution: Physics with the Phase-2 ATLAS and CMS Detectors**

(syst) GeV. The result of the likelihood scan is presented in Figure 2. The projected precision of 0.07 GeV on the $m_H$ measurement in the diphoton decay channel is better by nearly a factor of 3 compared to the current measurement [29] with the 2016 dataset. In addition to the factor of ≈10 increase in luminosity, the

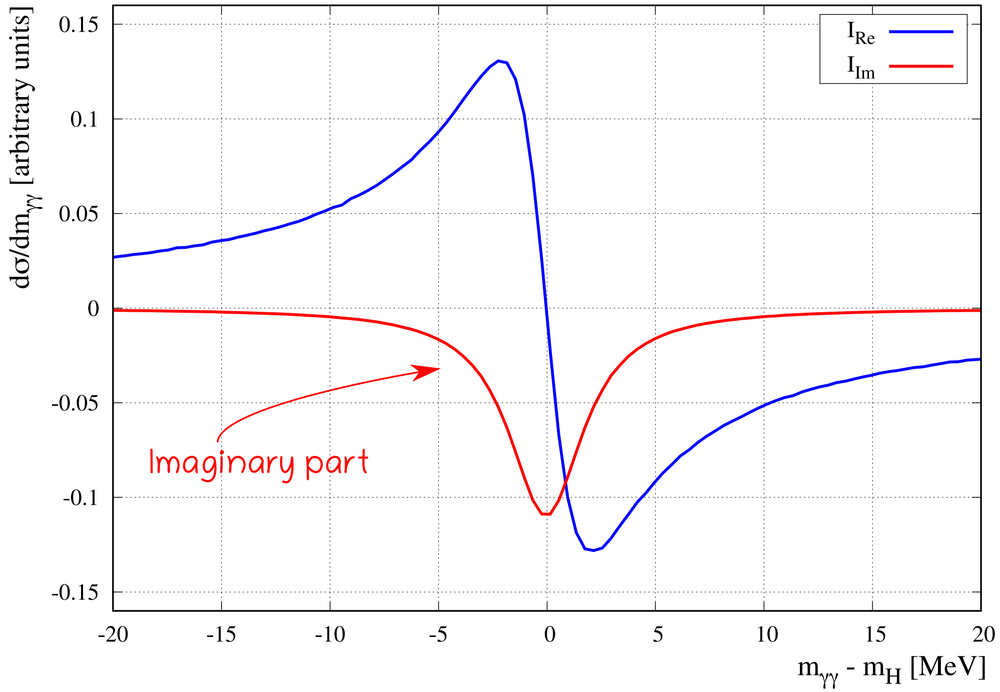
Very exciting projections

Interest from two main collaborations in performing a new analysis @ 13 TeV

# Imaginary part and the destructive interference

$$I_{\rm Im} \propto \frac{2m_{\gamma\gamma}^2}{(m_{\gamma\gamma}^2 - m_H^2)^2 + \Gamma_H^2 m_H^2}\,\Gamma_H m_H {\rm Im}\, I$$

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




Imaginary part

- Symmetric around the peak, contributes to the cross section
- Relative phase of sig-bkg amplitudes is such that the interference is destructive

Expected impact on on-shell cross-section O(1%)

When uncertainty on Higgs cross-section measurements fall below 2% interference effects will become relevant

How can one exploit the contribution from the destructive interference to put bounds on $\Gamma_H$?

# Bounds on Higgs-boson width from XS measurements

On-shell rate and the Higgs boson total width [Campbell, Carena, Harnik, Liu 1704.08259]

$$I_{\rm Im} \propto \frac{2m_{\gamma\gamma}^2}{(m_{\gamma\gamma}^2 - m_H^2)^2 + \Gamma_H^2 m_H^2}\,\Gamma_H m_H \,{\rm Im}\, I \quad \xrightarrow{\text{NWA}} \quad \sigma_{int} \propto \frac{\pi}{\Gamma_H m_H} \times \lambda_i \lambda_f \Gamma_H m_H$$

Linearly dependent on couplings

independent of width

Consider a simultaneous modification of couplings and width along the flat direction in parameter space

$$\lambda_{i,f} = \xi \lambda_{i,f}^{\rm SM}$$

$$\Gamma_H = \xi^4 \Gamma_H^{\rm SM}$$

$$\xi^2 = \sqrt{\frac{\Gamma_H}{\Gamma_H^{\rm SM}}}$$

$$\sigma_{sig} = \sigma_{sig}^{\rm SM} \qquad \sigma_{int} = \xi^2 \sigma_{int}^{\rm SM} = \sqrt{\frac{\Gamma_H}{\Gamma_H^{\rm SM}}}\,\sigma_{int}^{\rm SM}$$

@LO: -0.5 %

@NLO: -1.2 %

@NNLO: (this talk)

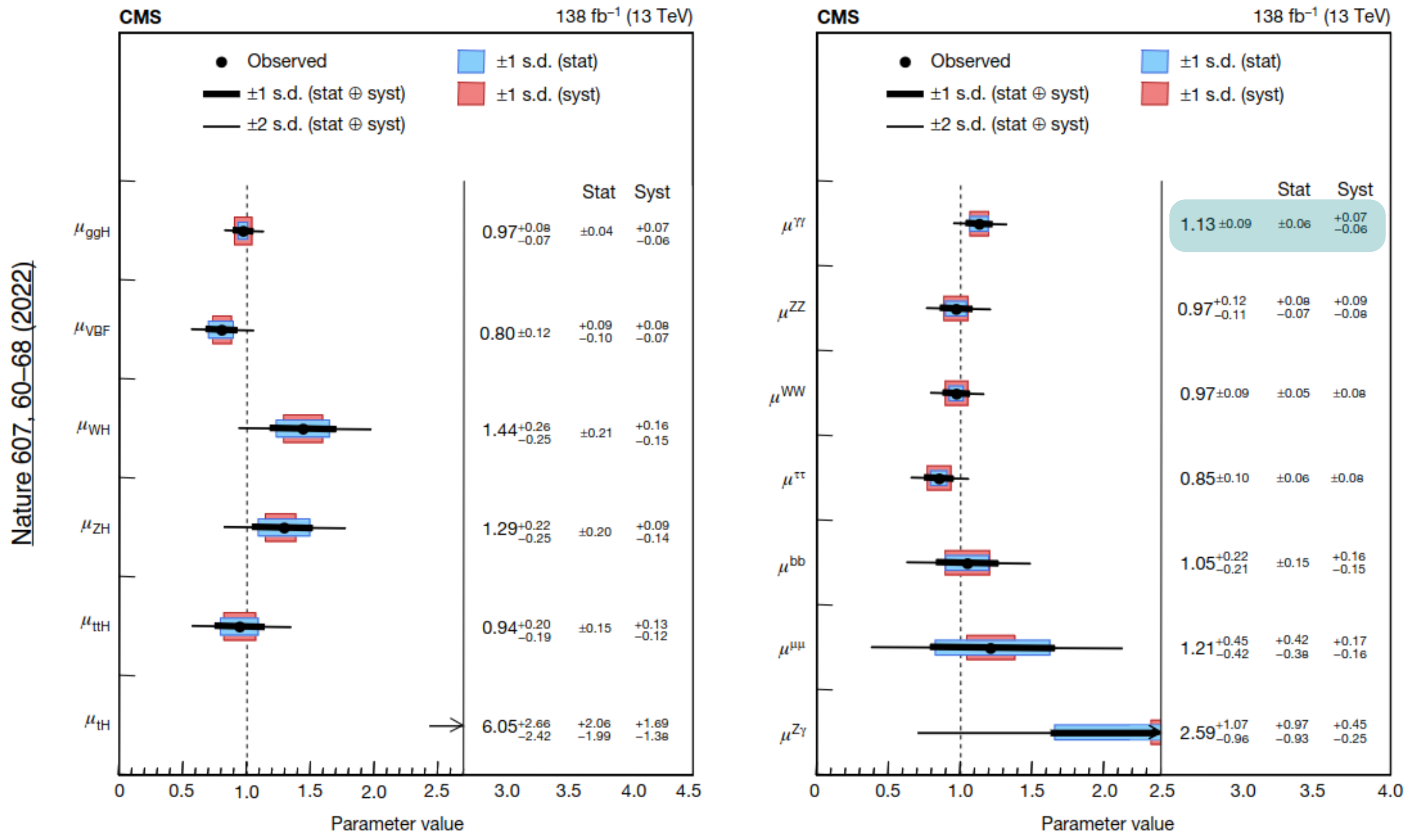
$$\sigma_{\rm on-shell} = \sigma_{sig}^{\rm SM} + \sigma_{int} = \sigma_{sig}\left(1 + \sqrt{\frac{\Gamma_H}{\Gamma_H^{\rm SM}}}\,\frac{\sigma_{int}^{\rm SM}}{\sigma_{sig}^{\rm SM}}\right)$$

Theory prediction

$$\Gamma_H < \left(\frac{\sigma_{sig}^{\rm SM}}{\sigma_{int}^{\rm SM}}\,\delta_{\rm XS}^{\rm exp}\right)^2 \Gamma_H^{\rm SM}$$

# Combined cross sections measurements

CMS combination




[Slide from S.J. Dittmer@Higgs 2022]

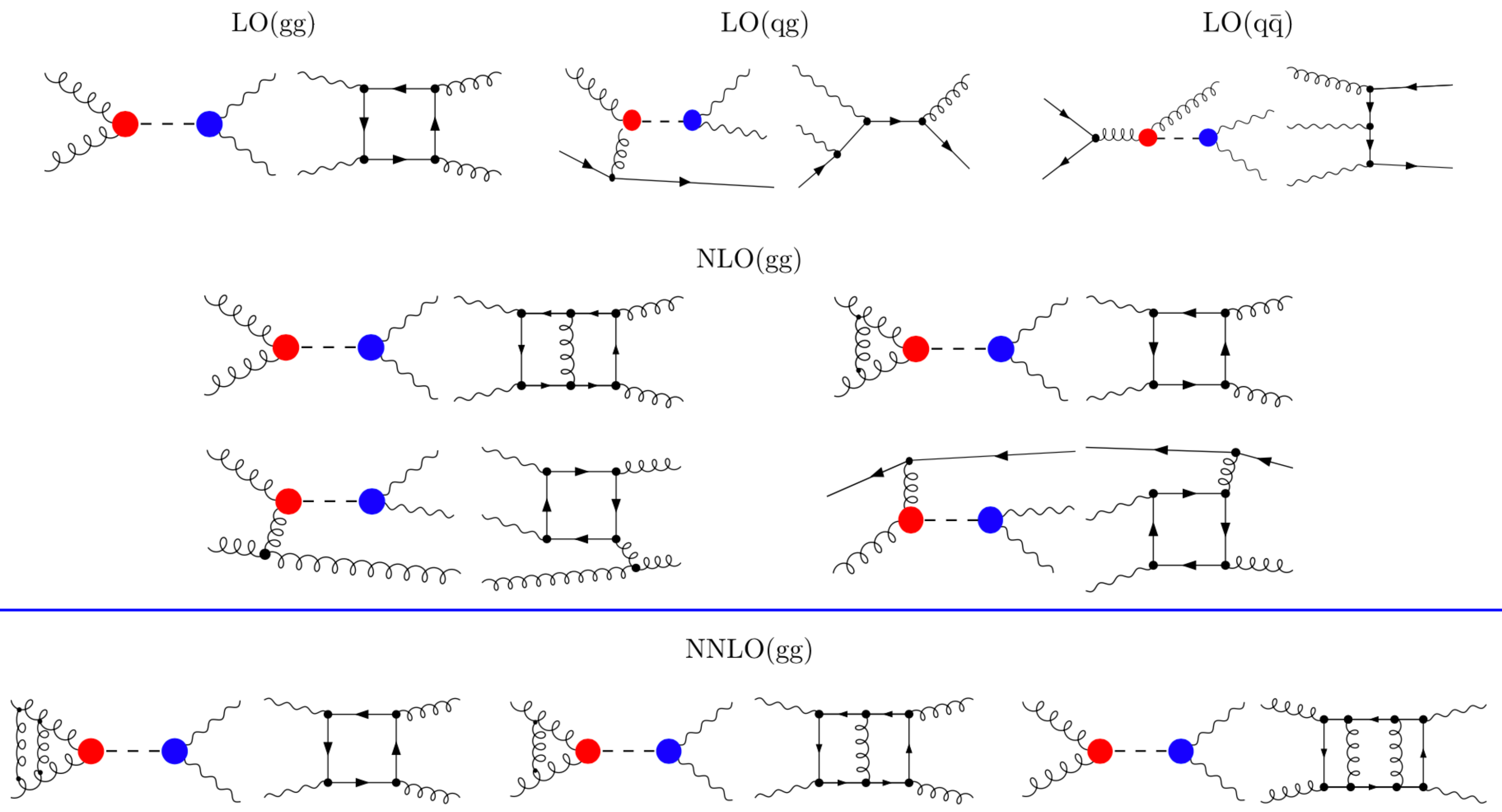
Estimates on bounds:

Assuming $\sigma_{int}/\sigma_{sig} \sim -1.5\%$

Uncertainty on $\gamma\gamma$ XS ~ 9%

$\Gamma_H < 30/40 \times \Gamma_H^{SM}$

# Signal-background interference beyond NLO




$\mathcal{O}(\alpha_s^2)$

$\mathcal{O}(\alpha_s^3)$

$\mathcal{O}(\alpha_s^4)$

This talk

# Setup of the calculation @NNLO$_{SV}$

$\sqrt{s} = 13.6\,\text{TeV}$

PDF set: NNLO31_nnlo_as_0118

Choice of scale: $\mu_F = \mu_R = m_{\gamma\gamma}/2$

Fiducial cuts:

- $p_{T,\gamma_{1,2}} > 20\,\text{GeV}$
- $|\eta_\gamma| < 2.5$
- $p_{T,\gamma_1} p_{T,\gamma_2} > (35\,\text{GeV})^2$
- $\Delta R_{\gamma_{1,2}} > 0.4$

Effectively play a role @NLO (treated exactly)

Choice of product cuts reduces sensitivity to IR physics effects [Salam, Slade 2106.08329]

We note that it plays a major role in the reliability of the soft-virtual approximation.

Our fiducial setup different from [Dixon, Li '13] so direct comparison not immediate

However, @(N)LO we have validated our calculation against the literature [Dixon, Li '13]

For a fair comparison, also the signal treated in soft-virtual approximation @NNLO

naive soft-virtual does poorly @NNLO: several recipes to tweak and improve it

NNLO$_{SV}$': we follow the strategy in [Ball, Bonvini, Forte, Marzani, Ridolfi 1303.3590]

$$\mathcal{D}_i(z) \to \mathcal{D}_i(z) + (2-3z+2z^2)\frac{\ln^i \frac{1-z}{\sqrt{z}}}{1-z} - \frac{\ln^i(1-z)}{1-z}$$

# Results for the integrated cross-section

LO results:

- bottom mass in both signal and background amplitudes:

  $\sigma_{int}$ = -0.11 fb

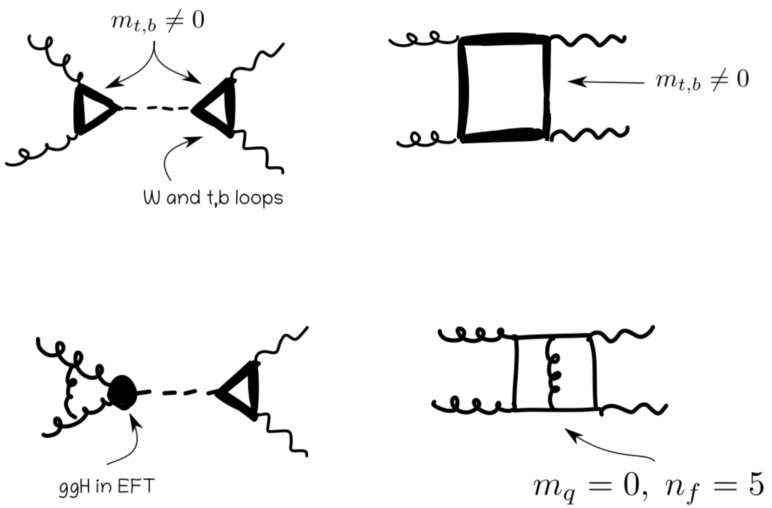
- bottom mass in background amplitudes only:

  $\sigma_{int}$ = -0.02 fb

- bottom mass in signal amplitudes only:

  $\sigma_{int}$ = -0.09 fb

LO ~ 6 smaller than dNLO correction




dNLO correction:

- massless background amplitudes

  $\sigma_{int}$ = -0.62 fb

it is safe to discard mass effects beyond LO

$$\sigma_S^{\mathrm{NNLOsv}'} = 72.21^{+8\%}_{-8\%}\ \mathrm{fb}$$

$$\sigma_I^{\mathrm{NNLOsv}} = -1.21^{+7\%}_{-10\%}\ \mathrm{fb}$$

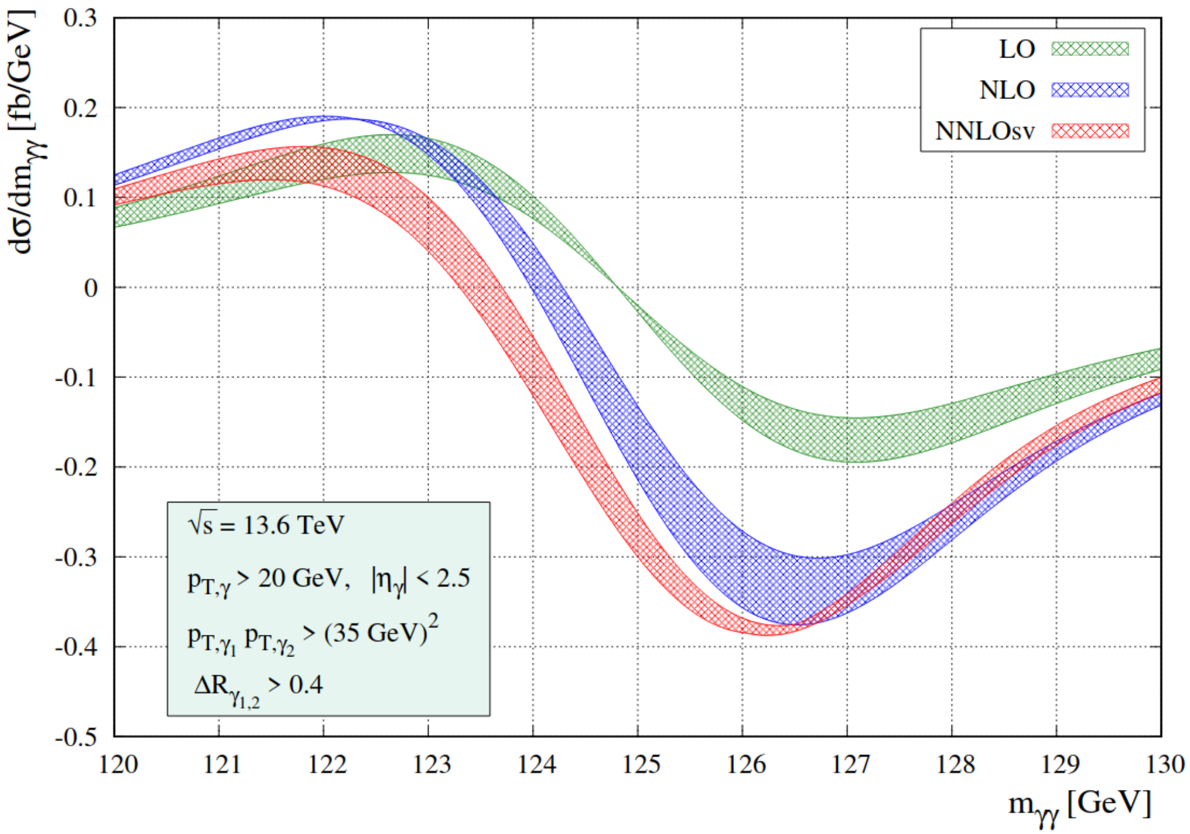
dNNLO$_{SV}$ correction:

- massless background amplitudes

  $\sigma_{int}$ = -0.48 fb

Sizeable effect @ NNLO$_{SV}$ comparable to NLO contribution

# Interference @NNLOsv




Signal-background interference contribution to the diphoton invariant mass distribution after Gaussian smearing. Bands represent the envelope given by scale variations.

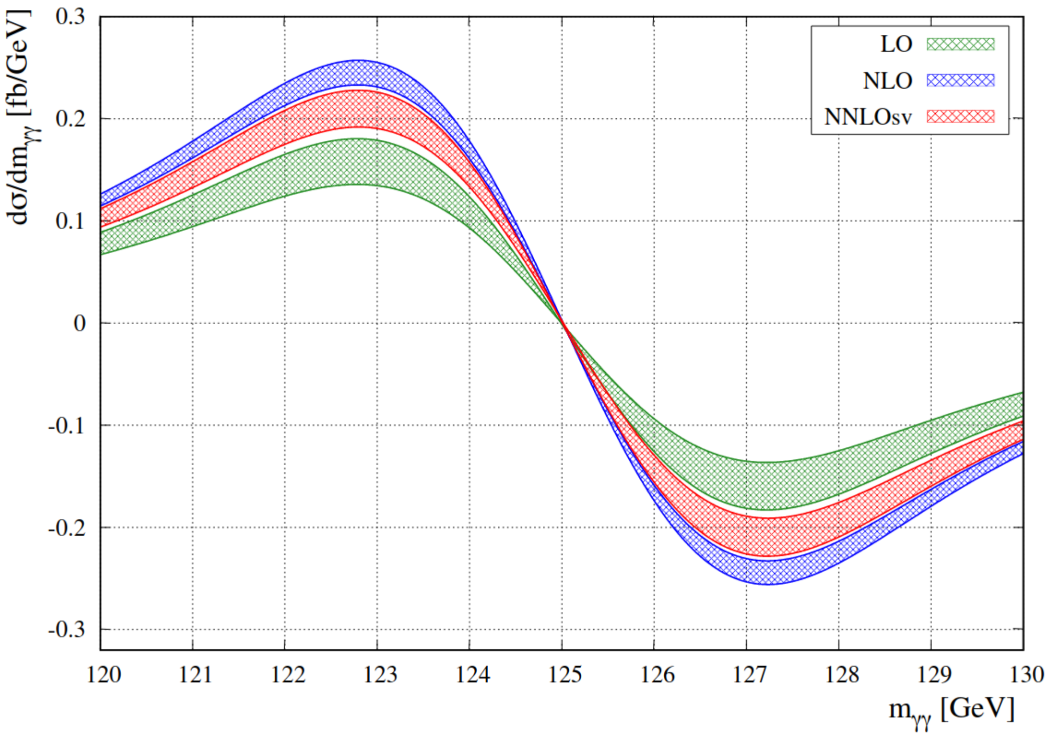
$\sigma$ = 1.7 GeV

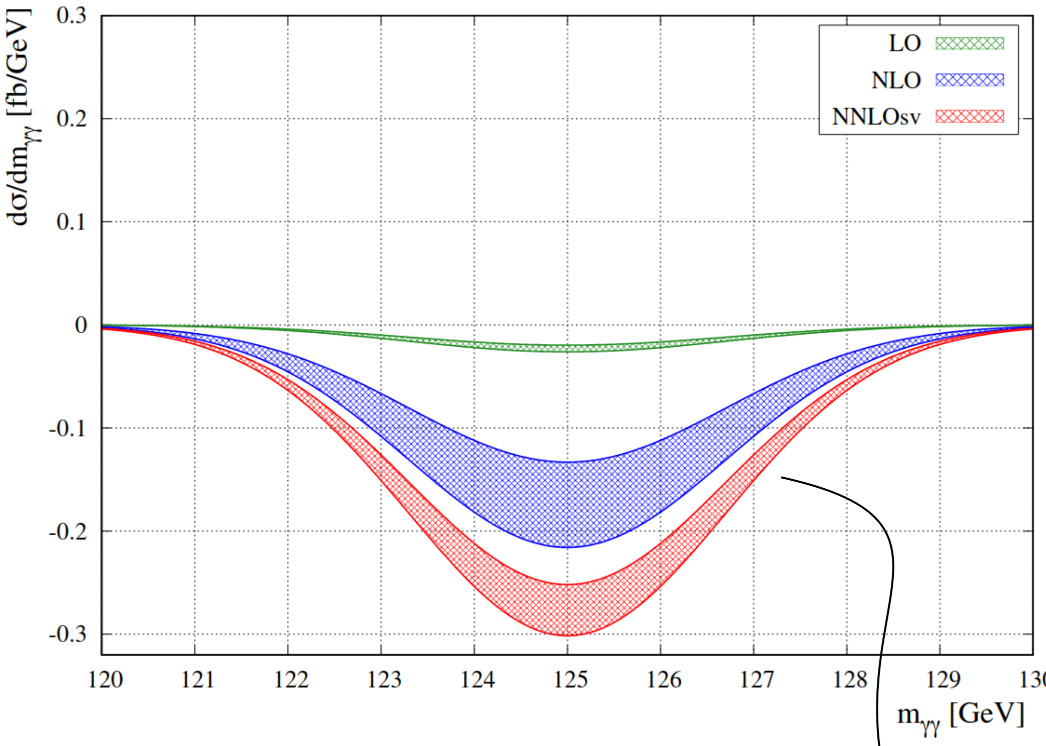
- NNLOsv corrections not captured by NLO scale variations
- NLO → NNLO, curve is shifted further down

  asymmetry effect weakened: mass-shift reduced
- Recall the interference is the sum of two contributions with very different behaviours: real + imaginary
  - real part responsible for the shape
  - imaginary part responsible for "shift to the left and down"

# Real and imaginary parts of interference @NNLO$_{SV}$

Real part of the interference




Imaginary part of the interference

Shapes and scale variations well behaved for Re and Im separately

"convergence" upon including higher-order effects

Destructive interference ~ -1.7% of signal cross-section in chosen setup

$$\sigma_I^{\mathrm{NNLOsv}} = -1.21^{+7\%}_{-10\%}\ \mathrm{fb}$$

# Impact of $NNLO_{SV}$ corrections on the mass-shift

| $\Delta m_{\gamma\gamma}$ [MeV] | 7 TeV | 8 TeV | 13.6 TeV |
|---|---|---|---|
| LO | $-77.2^{+0.8\%}_{-1.0\%}$ | $-79.5^{+0.6\%}_{-0.8\%}$ | $-83.1^{+0\%}_{-0.3\%}$ |
| NLO | $-56.2^{+13\%}_{-15\%}$ | $-56.8^{+13\%}_{-14\%}$ | $-55.2^{+12\%}_{-12\%}$ |
| NNLOsv | $-46.3^{+15\%}_{-17\%}$ | $-47.0^{+14\%}_{-16\%}$ | $-46.0^{+11\%}_{-12\%}$ |
| NNLOsv′ | $-39.5^{+20\%}_{-24\%}$ | $-39.7^{+19\%}_{-22\%}$ | $-39.4^{+16\%}_{-17\%}$ |

-34% (LO → NLO)

-28% (NLO → NNLOsv′)

Mass-shift at different proton-proton collider energies via Gaussian fit method

| $\Delta m_{\gamma\gamma}$ [MeV] | 7 TeV | 8 TeV | 13.6 TeV |
|---|---|---|---|
| LO | $-113.4^{+0.8\%}_{-1.0\%}$ | $-116.7^{+0.6\%}_{-0.8\%}$ | $-122.1^{+0.1\%}_{-0.3\%}$ |
| NLO | $-82.6^{+13\%}_{-15\%}$ | $-82.8^{+12\%}_{-14\%}$ | $-81.2^{+12\%}_{-12\%}$ |
| NNLOsv | $-68.1^{+15\%}_{-17\%}$ | $-68.4^{+13\%}_{-15\%}$ | $-67.7^{+11\%}_{-12\%}$ |
| NNLOsv′ | $-58.1^{+20\%}_{-23\%}$ | $-59.2^{+18\%}_{-21\%}$ | $-58.0^{+16\%}_{-17\%}$ |

-34% (LO → NLO)

-28% (NLO → NNLOsv′)

Mass-shift at different proton-proton collider energies via first-moment method

$$\Delta m_{(N)NLO} = \Delta m_{\mathrm{LO}} K_{\mathrm{(N)NLO}}$$

| $\Delta m_{\gamma\gamma}$ [MeV] | First moment | Gaussian Fit |
|---|---|---|
| $K_{\mathrm{NLO}}$ | 0.665 | 0.664 |
| $K_{\mathrm{NNLOsv}}$ | 0.554 | 0.554 |
| $K_{\mathrm{NNLOsv'}}$ | 0.475 | 0.474 |

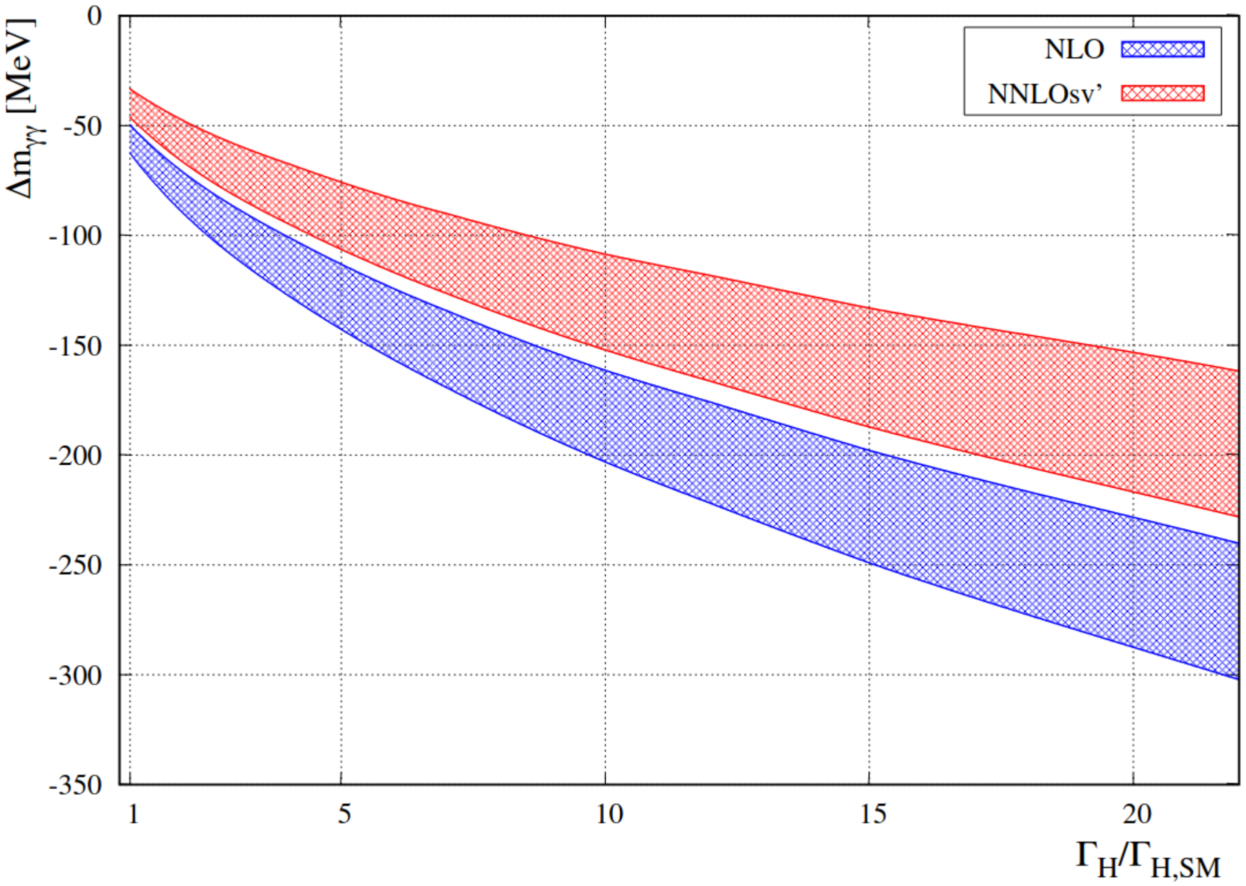
- Mass-shift via Gaussian fit and first moment: "different observables"

Different predictions in two methods

- However, K-factors are insensitive to the method used

# Bounds on Higgs width from mass shift

Updated bounds on $\Gamma_H$ from $NNLO_{SV}$ corrections:




- Functional dependence ~ square root
- NNLO curve lies above the NLO one, thus looser bounds on $\Gamma_H$
- competing effects from Re and Im parts of interference
- If uncertainty on the mass shift reaches:

  ~ 150 MeV → $\Gamma_H < (10\text{-}20)\ \Gamma_{H,SM}$
  ~ 75 MeV → $\Gamma_H < (3\text{-}5)\ \Gamma_{H,SM}$

- To be compared with XS based method:

  ~ 9% uncertainty on XS → $\Gamma_H < (28\text{-}30)\ \Gamma_{H,SM}$
  ~ 4.5% uncertainty on XS → $\Gamma_H < 7\ \Gamma_{H,SM}$

# Some remarks/comments on XS

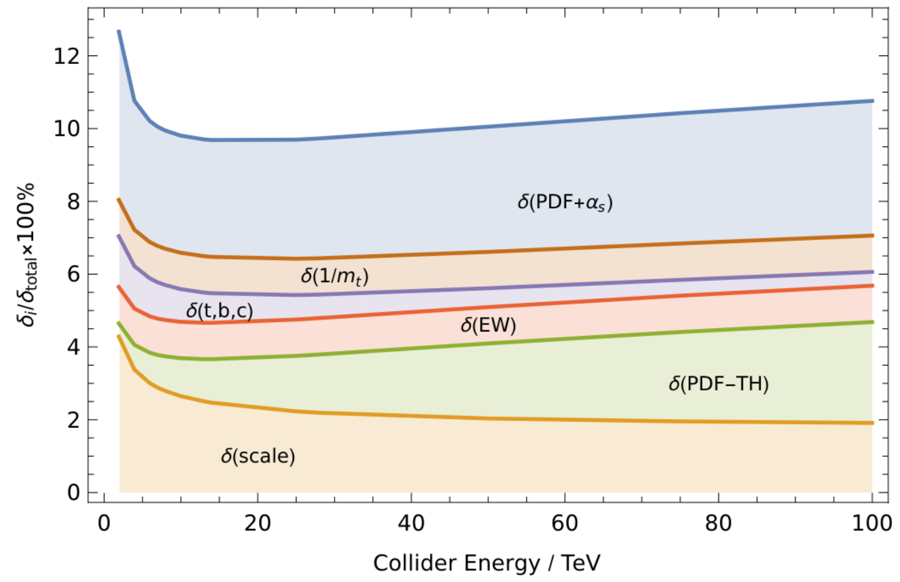
cross section for $gg \to H$ [Yellow Report 4]

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

| $\delta$(scale) | $\delta$(trunc) | $\delta$(PDF-TH) | $\delta$(EW) | $\delta(t,b,c)$ | $\delta(1/m_t)$ |
|---|---|---|---|---|---|
| $^{+0.10}_{-1.15}$ pb | $\pm0.18$ pb | $\pm0.56$ pb | $\pm0.49$ pb | $\pm0.40$ pb | $\pm0.49$ pb |
| $^{+0.21\%}_{-2.37\%}$ | $\pm0.37\%$ | $\pm1.16\%$ | $\pm1\%$ | $\pm0.83\%$ | $\pm1\%$ |

After YR4 (2018) most of these have been addressed/lifted

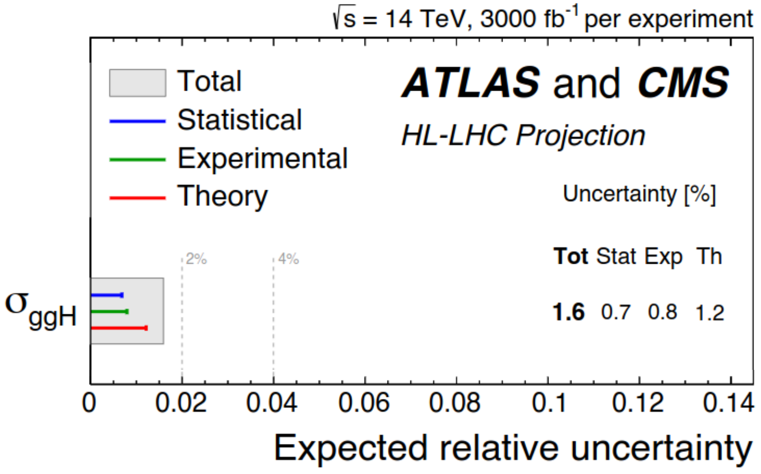
[Dulat, Lazopoulos, Mistlberger 1802.00827]




Interference effects:

destructive ~ -2% effect on XS in $H \to \gamma\gamma$

- fairly enough neglected so far!
- deserves more attention and care for future XS studies/survey




[ATL-PHYS-PUB-2022-018]

# Summary and outlook

- Currents bounds on Higgs-boson width extremely close to SM value: mild assumptions in off-shell meausrements

- Alternative proposal: on-shell meausrements in diphoton production. Important complementary information

- We reviewed the diphoton signal-background interferometry framework: access to Higgs-boson width

- First studies beyond NLO accuracy thanks to advance in multi-loop calculations:
  - enhanced effect on destructive interference at XS level ⟶ large contribution from 3-loop $gg\gamma\gamma$ amplitude
  - although mass shift extraction dependent on methodology, K-factors are universal
  - looser bounds on $\Gamma_H$ via mass-shift study: assuming 150 MeV error on mass-shift, $\Gamma_H$ < (10-20)$\Gamma_{H,SM}$
  - improved bounds on $\Gamma_H$ via integrated XS: with current 9% error on $\gamma\gamma$ XS, $\Gamma_H$ < (28-30)$\Gamma_{H,SM}$

Outlook:

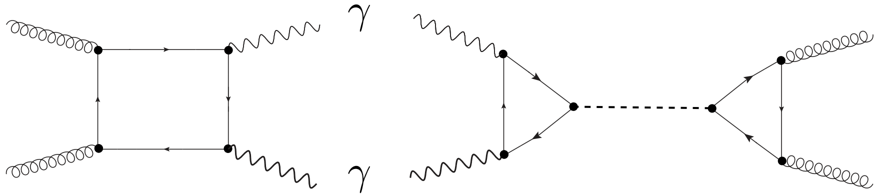
- Exact NNLO calculation + pT resummation: improved modeling of $p_{T,\gamma\gamma}$ in sig/bkg interference (only described @LO as of today). Work in progress

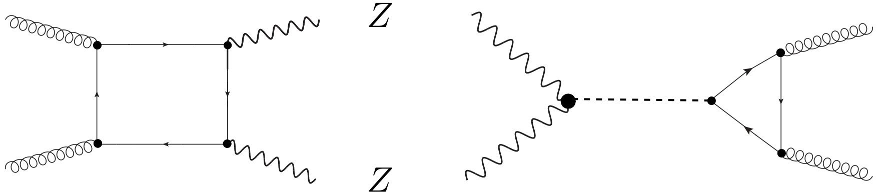
  $p_{T,\gamma\gamma}$ dependence can be used to define signal and control regions to extract the mass shift

# Backup

# Signal-background interference: why γγ?

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




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

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

Naive power counting/dim analysis:

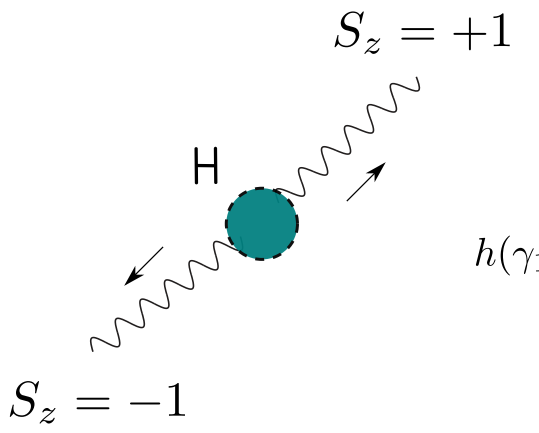
$$\frac{\sigma_{int,\gamma\gamma}}{\sigma_H} \sim 2\frac{\Gamma_H}{m_H}\frac{(4\pi v)^2}{m_H^2} \sim 0.1$$

"Loop enhancement"

# Spin and mass effects

$$\frac{\sigma_{int,\gamma\gamma}}{\sigma_H} \sim 2\frac{\Gamma_H}{m_H}\frac{(4\pi v)^2}{m_H^2} \sim 0.1$$

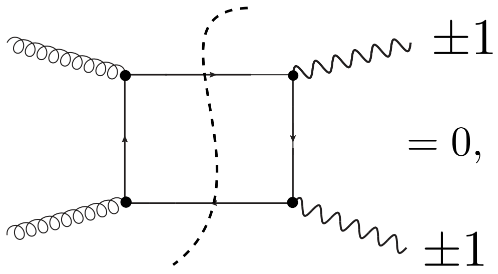
"Loop enhancement"




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

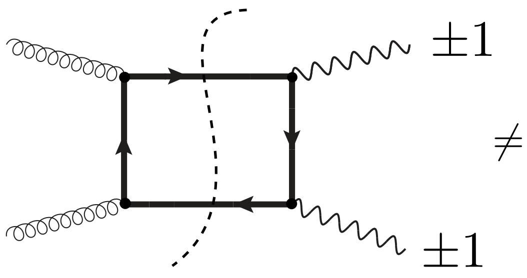
Effectively, contribution to cross-section starts only at 2-loop

Im(A) ~




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

Im(A) ~



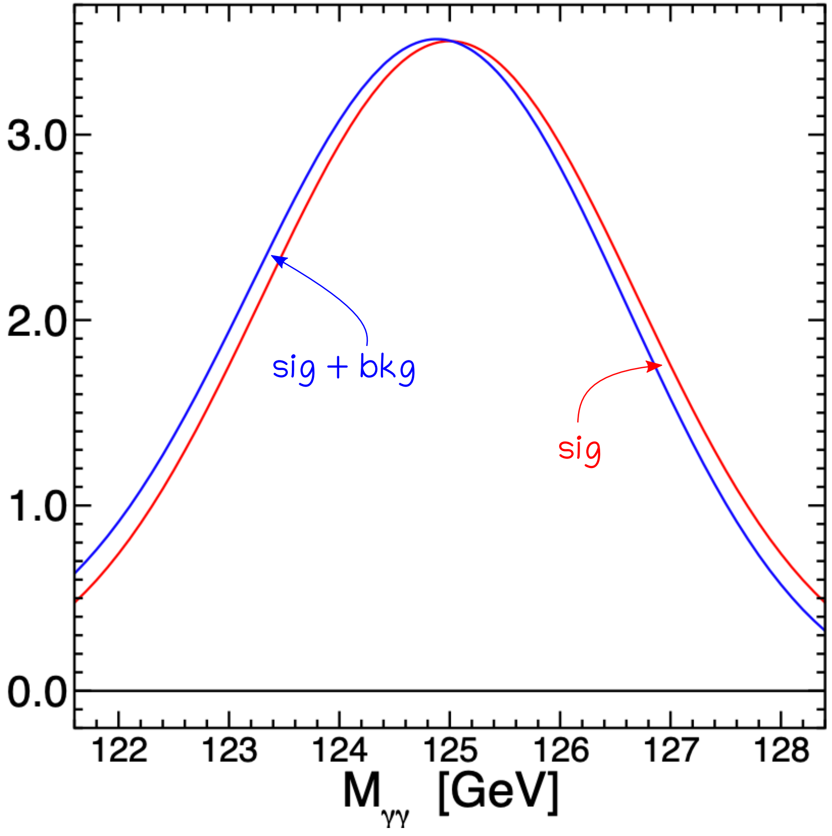

$\neq 0, \quad \text{for} \;\; s > 4m_q^2$

bottom effects ~ mass suppressed, $O(m_q^2/s)$

Realistically, impact on cross-section ~ 1%

we will see: well below NLO effects

# Theory estimates of the mass shift




1) First moment of invariant mass distribution [S.P. Martin 1208.1533]

$$\sigma_0 = \int_{M_{\gamma\gamma}-\delta}^{M_{\gamma\gamma}+\delta} dM_{\gamma\gamma} \frac{d\sigma}{dM_{\gamma\gamma}}$$

$$\langle M_{\gamma\gamma}\rangle_\delta = \frac{1}{\sigma_0}\int_{M_{\gamma\gamma}-\delta}^{M_{\gamma\gamma}+\delta} dM_{\gamma\gamma} \frac{d\sigma}{dM_{\gamma\gamma}} M_{\gamma\gamma}$$

$$\Delta M_{\gamma\gamma} = \langle M_{\gamma\gamma}\rangle_{sig+int} - \langle M_{\gamma\gamma}\rangle_{sig}$$

These two are in spirit different objects/observables

2) Gaussian likelihood fit [Dixon, Li 1305.3854]

Extract mean value at fixed std. deviation

$$0 = \delta\langle t\rangle \propto \int dM \frac{\frac{d\tilde\sigma}{dM} - \frac{d\sigma}{dM}}{\frac{d\tilde\sigma}{dM}} \delta \frac{d\tilde\sigma}{dM} \approx \int dM \frac{\frac{d\tilde\sigma}{dM} - \frac{d\sigma}{dM}}{\frac{d\sigma}{dM}} \delta \frac{d\tilde\sigma}{dM} = \delta\left[\int dM \frac{\left(\frac{d\tilde\sigma}{dM} - \frac{d\sigma}{dM}\right)^2}{2\frac{d\sigma}{dM}}\right]$$

# State of the art of interference effects in diphoton production

- Leading-order analysis including gg channel only. Mass-shift estimated via first moment ~ 150 MeV [S.P. Martin 1208.1533]

- Inclusion of other partonic channels: qg and qq give an effect of ~30 MeV, opposite sign wrt gg channel, qg mainly responsible [D. de Florian, N. Fidanza, R. J. Hernandez-Pinto, J. Mazzitelli, Y. Rotstein Habarnau, F. R.Sborlini 1303.1397]

- Interference at NLO [Dixon and Siu hep-ph/0302233] and proposal to use mass-shift to put bounds on $\Gamma_H$ [Dixon, Li 1305.3854]: mass-shift goes from ~ 120 MeV @LO to ~70 MeV @NLO

- Analysis at NLO focussed on integrated on-shell cross sections [Campbell, Caren, Harnik, Liu 1704.08259]: destructive interference contributing only at NLO (thus effectively LO). NNLO corrections could follow "Higgs-signal" pattern and increase with higher-order corrections

> even in our NLO calculation. A reduction of the uncertainty in $\sigma_{\text{int}}$ would necessitate a three-loop calculation of a $2 \to 2$ scattering process, which is currently not tractable. However, on the time-scale over which the experimental precision could probe deviations at this level, i.e. the HL-LHC, there will surely be progress in this direction.
>
> [Campbell, Caren, Harnik, Liu 1704.08259]

Call for a study at NNLO of signal-background interference effects

# Soft-virtual approximation in a nutshell

Soft-virtual (SV) @NNLO: consider only soft emissions, discard hard real contributions

The SV approximation and various improvements of it extensively adopted for Higgs predictions (colour singlet in general)

Several proposals on how to account for subleading terms

Important: process largely dominated by gg-fusion

The only process-dependent part is encoded in purely virtual contributions

Differential hadronic cross-section:

$$\mathrm{d}\sigma(\tau, y, \theta_i) = \int \mathrm{d}\xi_1 \mathrm{d}\xi_2 f_g(\xi_1, \mu_F) f_g(\xi_2, \mu_F) \delta(\tau - \xi_1 \xi_2 z) \mathrm{d}\hat{\sigma}\left(z, \hat{y}, \hat{\theta}_i, \alpha_s, Q^2\right)$$

Soft limit of the partonic cross section, i.e. z→1:

$$\mathrm{d}\hat{\sigma}\left(z, \hat{y}, \hat{\theta}_i, \alpha_s, Q^2\right) \simeq \mathrm{d}\hat{\sigma}_{\mathrm{Born}}\, z\, G\left(z, \alpha_s, Q^2\right) \qquad G(z, \alpha_s) = \delta(1-z) + \sum_{n=1}^{\infty} \left(\frac{\alpha_s}{2\pi}\right)^n G^{(n)}(z)$$

In soft-virtual approximation:

$$G^{(n)}(z) = c_0^{(n)} \delta(1-z) + \sum_{k=1}^{2n-1} c_k^{(n)} \mathcal{D}_k(z)$$

process-dependent part

# Asymmetric cuts and NLO$_{SV}$

Cuts:

$p_{T,\gamma}^{\text{hard/soft}} > 40, 30\,\text{GeV}$

$|\eta_\gamma| < 2.5$

Isolation (discard events if):

$p_{T,j} > 3\,\text{GeV}$

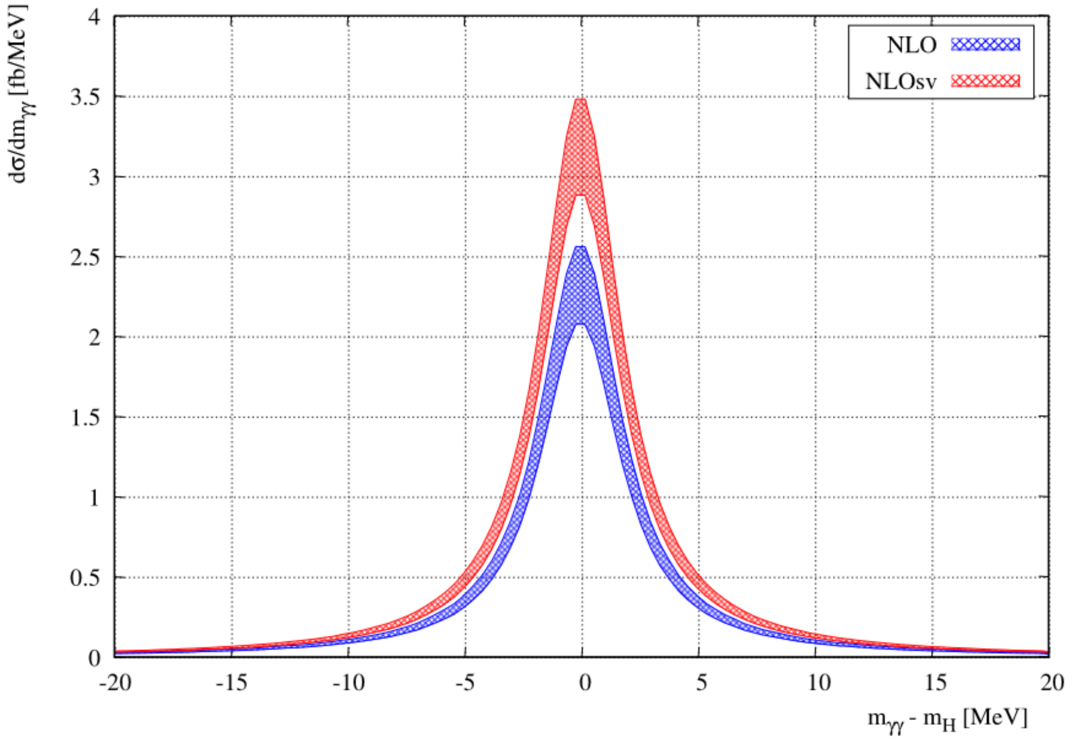
$\Delta R_{\gamma j} < 0.4$

Jet veto (reject if):

$p_{T,j} > 20\text{GeV}$

$|\eta_{T,j}| > 3$

Signal process




Interference process