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

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based on [2212.06287]

In collaboration with: P. Bargiela, F. Caola, F. Devoto, A. von Manteuffel and L. Tancredi

Outline of the talk

Higgs-exploration program: focus on deacy width

Bound on Higgs-boson width from on-shell measurements: Higgs interferometry

- Mass-shift and its link to Γ_H
- Destructive interference and bounds on Γ_H

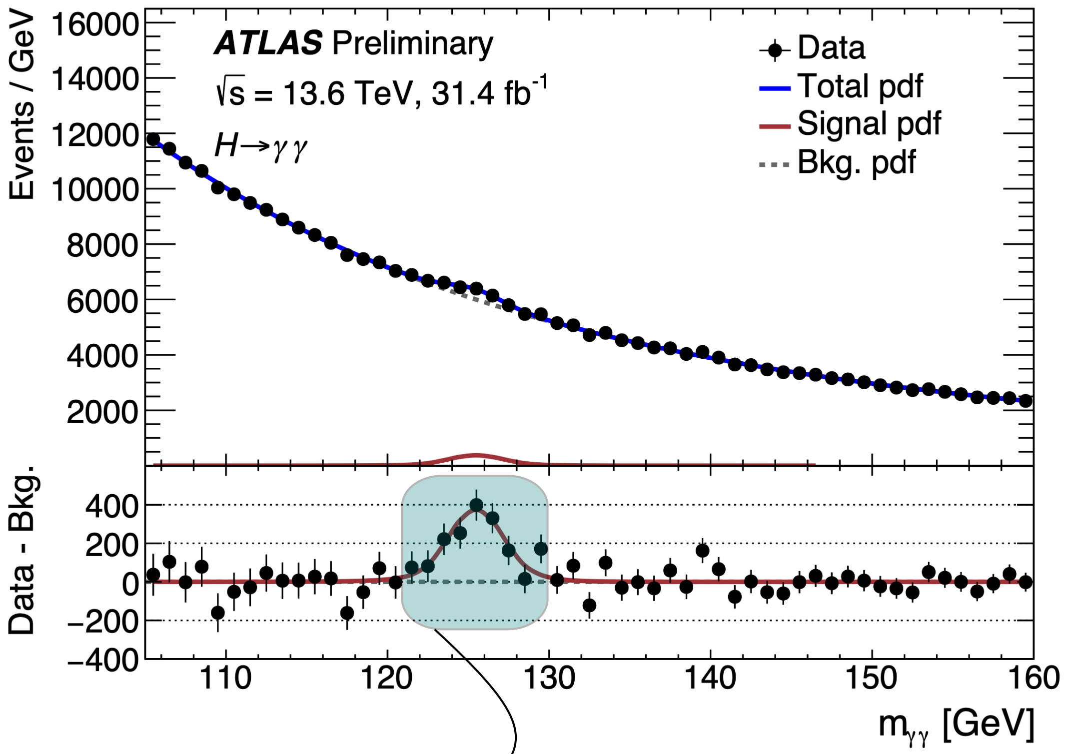
Calculation of signal-background interference in diphoton production beyond NLO QCD

- diphoton three-loop amplitudes
- Soft-virtual approximation
- updated bounds on Higgs-boson width determination

Summary and outlook

The Higgs boson: properties and couplings

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



SM prediction for $\Gamma_H \sim 4$ MeV

Dector resolution ~ few GeV

We cannot measure Γ_H at the LHC directly, we can only put bounds

This talk

- Mass
- Width
- CP properties and anomalous couplings
- Couplings to SM particles (EW sector + Yukawa)
- Higgs potential

The Higgs-boson mass the 13 TeV LHC

CMS [Phys. Lett. B 805 (2020) 135425]

$$m_H(\gamma\gamma) = 125.78 \pm 0.18\,(\text{stat}) \pm 0.18\,(\text{syst})\,\text{GeV}$$
$$m_H(4\ell) = 125.26 \pm 0.20\,(\text{stat}) \pm 0.08\,(\text{syst})\,\text{GeV}$$

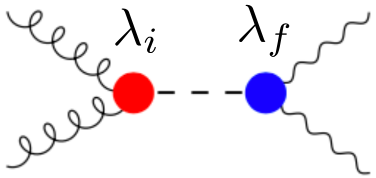
ATLAS [Phys. Lett. B 805 (2020) 135425]

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

Proposals:

- Off-shell measurements
- On-shell measurements

Bounds on Γ_H from off-shell meausurements



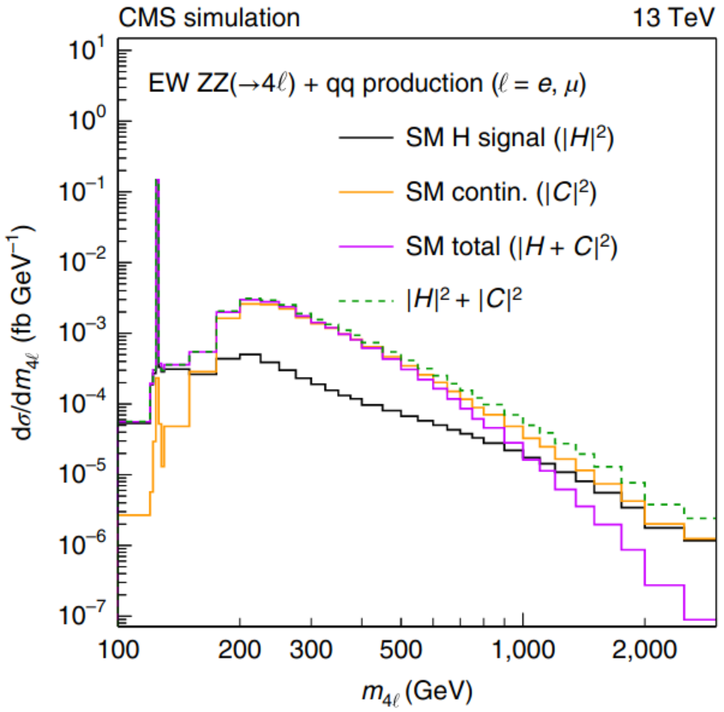
$$\sigma_{i\to H\to f} \sim \sigma_{i\to H} \times \mathrm{BR}(H\to f) \sim \frac{\lambda_i^2\lambda_f^2}{\Gamma_H m_H}$$

cross section unchanged upon rescaling

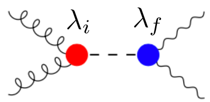
$$\begin{cases} \lambda_{i/f} = \xi\, \lambda_{i/f}^{\mathrm{SM}} \\ \Gamma_H = \xi^4\, \Gamma_H^{\mathrm{SM}} \end{cases}$$

How to lift this degeneracy?

1) Off-shell cross sections measurements [N. Kauer, G. Passarino 1206.4803] [F. Caola, K. Melnikov 1307.4935]



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



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

ATLAS [2304.01523]

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

CMS [2202.06923]

Γ_H: $3.2^{+2.4}_{-1.7}\,\mathrm{MeV}$

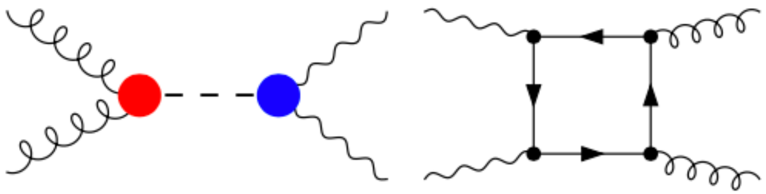
Assumption:

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

Signal-brackground interference in diphoton production

Higgs interferometry [S.P. Martin 1208.1533] [L.J. Dixon, Y. Li 1305.3854]

Consider on-shell Higgs-boson production in H -> γγ 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/Γ_H:

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

$|S|^2 \sim \lambda_i^2\lambda_f^2$, interference terms $\sim \lambda_i\lambda_f$

Idea: any effect due to Interference can be used to constrain independently Γ_H of couplings

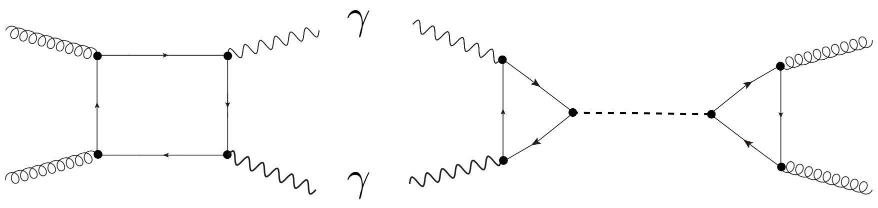
$${\rm Re}\,I = {\rm Re}\mathcal{M}_{\rm bkg}{\rm Re}\mathcal{M}_{\rm sig} + {\rm Im}\mathcal{M}_{\rm bkg}{\rm Im}\mathcal{M}_{\rm sig}$$ "real-part" of the interference

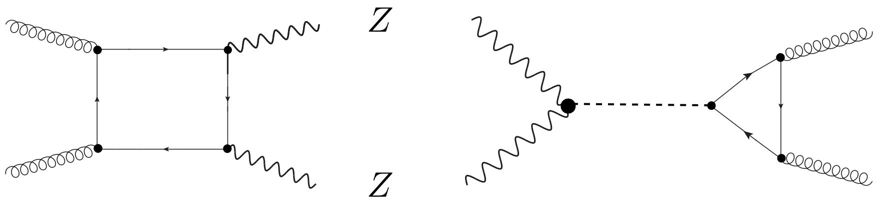
$${\rm Im}\,I = {\rm Re}\mathcal{M}_{\rm bkg}{\rm Im}\mathcal{M}_{\rm sig} - {\rm Im}\mathcal{M}_{\rm bkg}{\rm Re}\mathcal{M}_{\rm sig}$$ "imaginary-part" of the interference

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

Signal-brackground interference: why γγ?

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





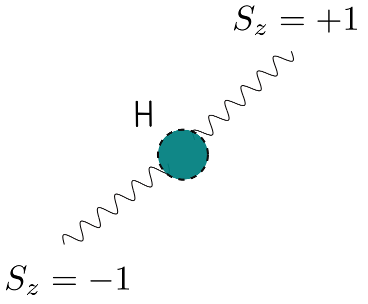
$$B_{\gamma\gamma} \sim \frac{g_s^2 e^2}{(4\pi)^2} \qquad S_{\gamma\gamma} \sim \frac{g_s^2 e^2}{(4\pi)^4} \qquad \frac{S_{\gamma\gamma}}{S_{ZZ}} \sim \frac{e}{(4\pi)^2} \qquad B_{ZZ} \sim \frac{g_s^2 e^2}{(4\pi)^2} \qquad S_{ZZ} \sim \frac{g_s^2 e}{(4\pi)^2}$$

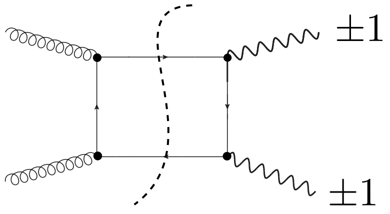
Naive power counting:

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

"Loop enhancement"

In reality, contribution to cross-section starts only at 2-loop





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

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

Real part of interference and the mass shift

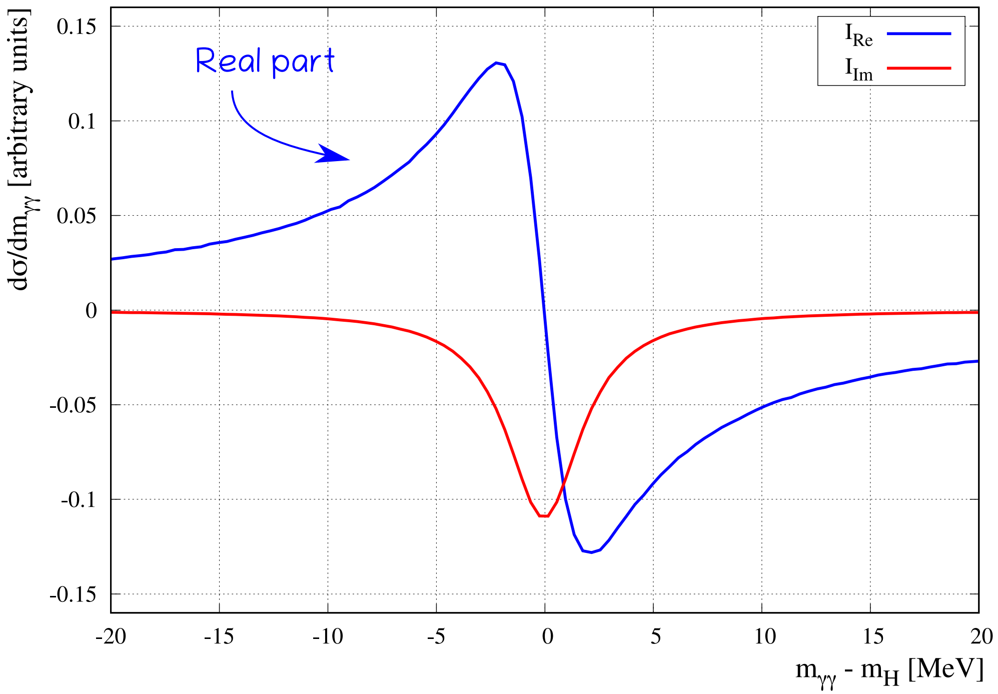
$$I_{\mathrm{Re}} \propto \frac{2m_{\gamma\gamma}^2}{(m_{\gamma\gamma}^2 - m_H^2)^2 + \Gamma_H^2 m_H^2}\,(m_{\gamma\gamma}^2 - m_H^2)\mathrm{Re}\, I$$

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

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 Γ_H?

Mass shift and bounds on Higgs width

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

Idea:

- Allow Γ_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"

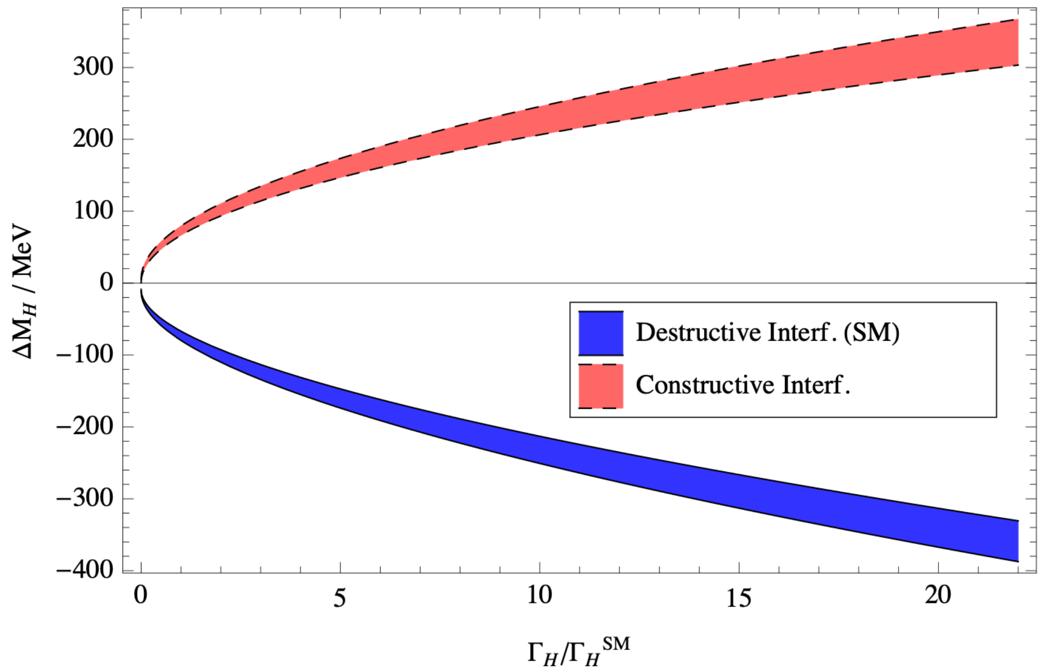
$$\lambda_{i,f} \to \xi_{i,f}\lambda_{i,f}$$

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

Negligible for small deviation from SM prediction

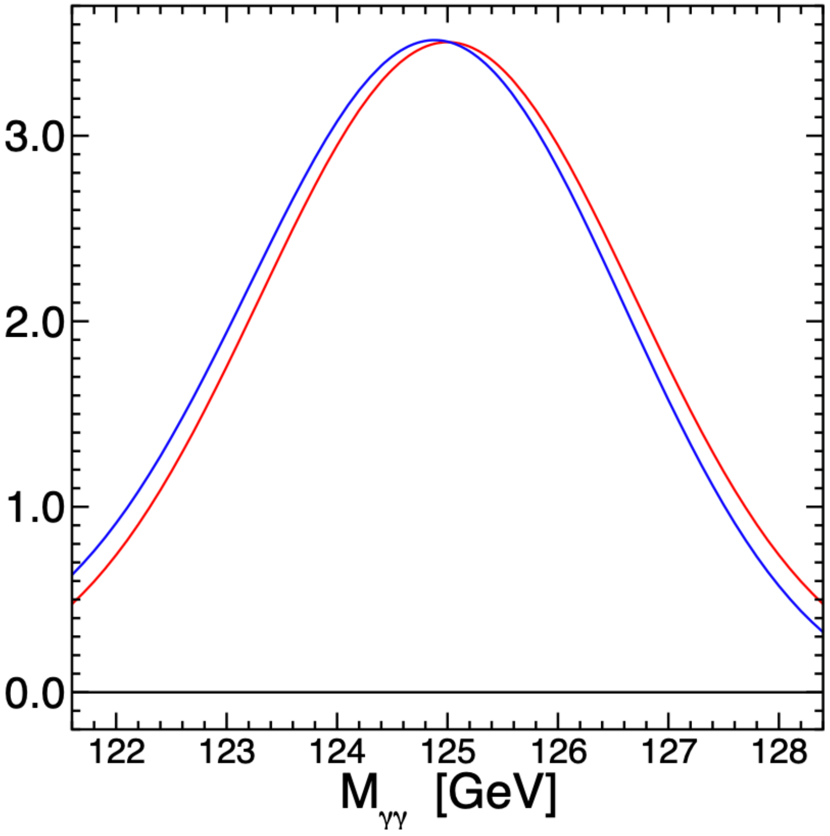
Interference effect on cross section is small wrt integrated signal

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



Theory estimation of the mass shift

[S.P. Martin 1208.1533]



Gaussian likelihood fit [Dixon, Li 1305.3854]

Extract mean value at fixed std. deviation

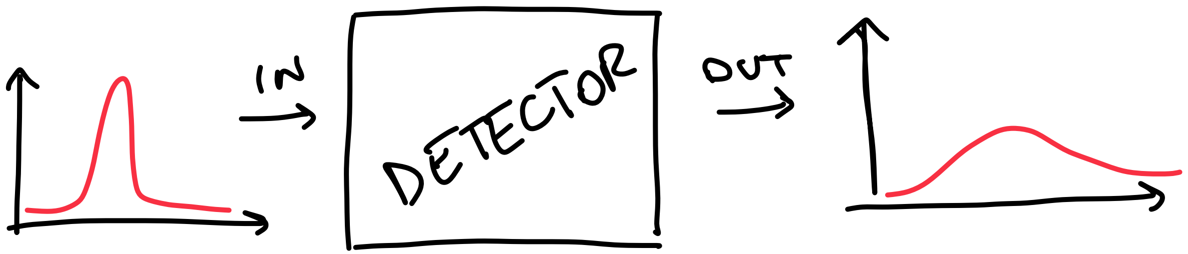
First moment of
invariant mass distribution [S.P. Martin 1208.1533]

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

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

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

Smearing effect from detector resolution



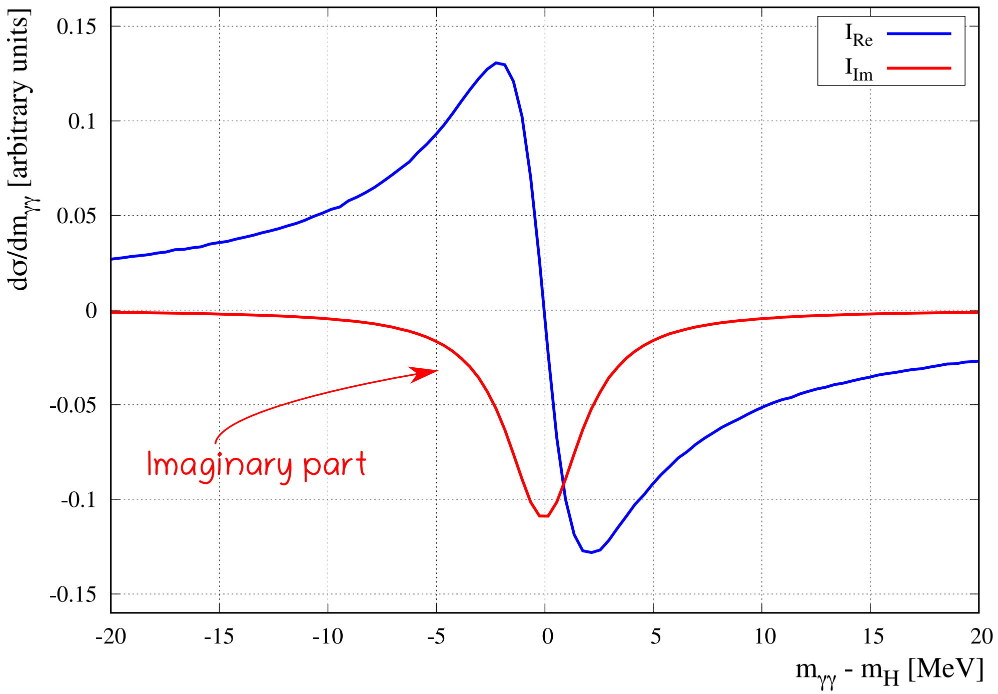
Theory approach:
Simulate detector resolution via Gaussian smearing.
Mass-shift O(100 MeV)

Realistic detector resolution: Mass-shift ~ 35 MeV
[ATL-PHYS-PUB-2016-009]

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 Γ_H?

Bounds on Higgs-boson width from XS measurements

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

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

Linearly dependent on couplings

independent of width

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

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

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

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

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

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

Theory prediction

@LO: -0.5 %

@NLO: -1.2 %

@NNLO: (this talk)

Estimates on bounds:

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

Uncertainty on γγ XS ~ 9% [ATL+CMS Nature 607, 60-68 (2022)]

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

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]

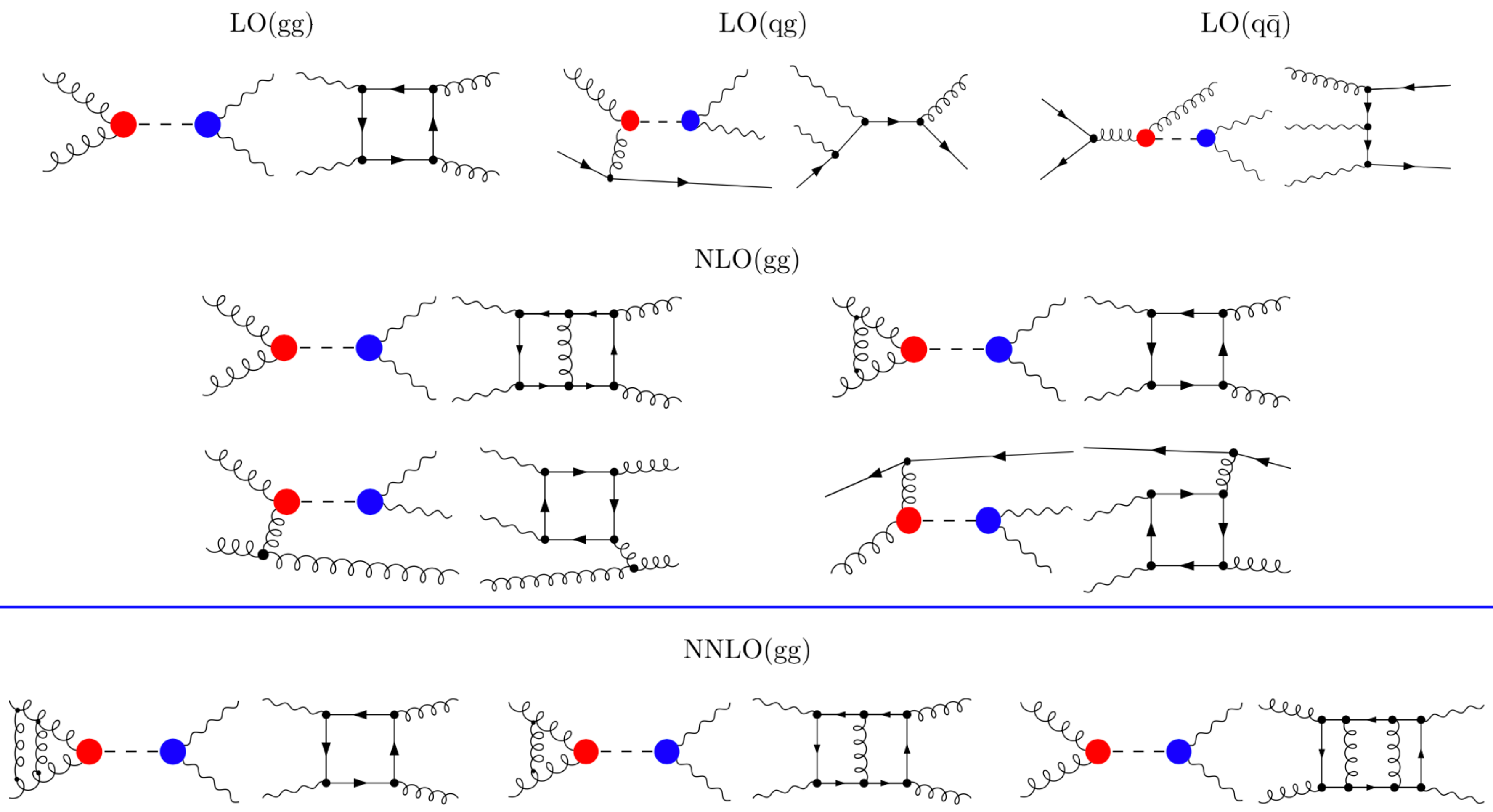
- Interference at NLO [Dixon and Siu hep-ph/0302233] and proposal to use mass-shift to put bounds on Γ_H [Dixon, Li 1305.3854]: mass-shift goes from ~ 120 MeV @LO to ~70 MeV @NLO

- 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 σ_{int} would necessitate a three-loop calculation of a 2 → 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

Signal-background interference beyond NLO



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

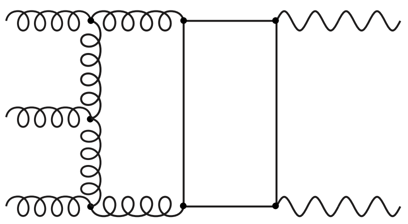
$\mathcal{O}(\alpha_s^3)$

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

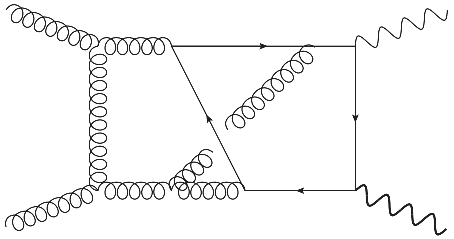
This talk

Interference@NNLO: ingredients

- Subtraction scheme for NNLO QCD corrections to colour singlet
- 5-point two-loop amplitudes for background process [B. Agarwal, FB, A. von Manteuffel, L. Tancredi] [S. Badger et al]
- Three-loop amplitudes for background process [P. Bargiela, F. Caola, A. von Manteuffel, L. Tancredi]



Everything ready to be deployed for full NNLO analysis



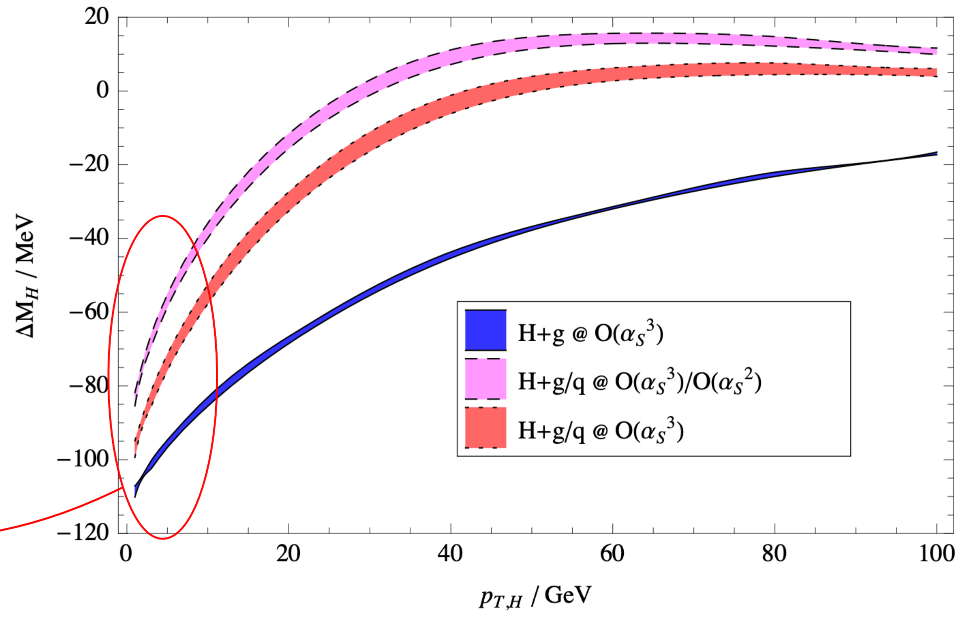
However:

Technically involved and non-trivial, mostly due to
evaluation of loop amplitudes in unresolved kinematic configurations

Strategy:
capture main effects beyond NLO
through appropriate approximation:

Soft-virtual approximation

Mass-shift enhanced
at small value of Higgs p_T



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:

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

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

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

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 ($c_0^{(n)}$, $c_k^{(n)}$)

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

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

PDF set: NNLO31_nnlo_as_0118

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

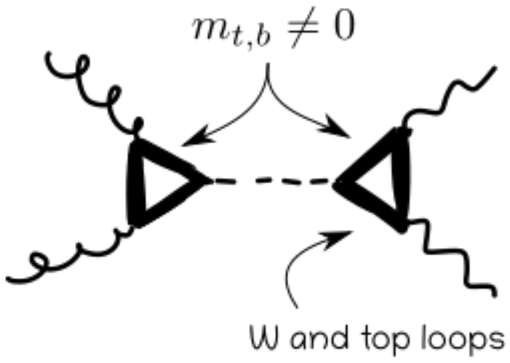
Fiducial cuts:

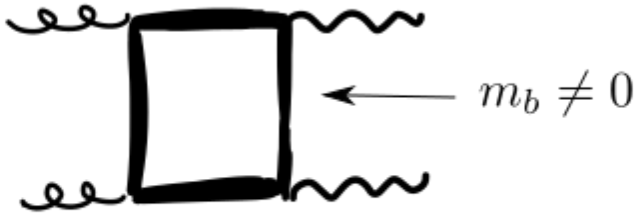
- $p_{T,\gamma_{1,2}} > 20\,\mathrm{GeV}$
- $|\eta_\gamma| < 2.5$
- $p_{T,\gamma_1} p_{T,\gamma_2} > (35\,\mathrm{GeV})^2$
- $\Delta R_{\gamma_{1,2}} > 0.4$

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

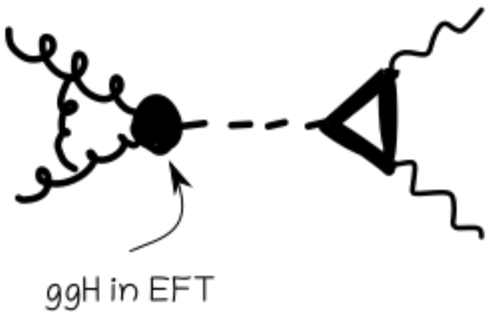
We note that it plays a relevant role in the reliability of the soft-virtual approximation.

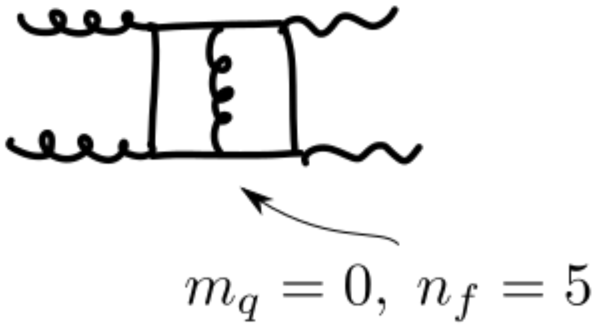
- @LO:





- @NLO and NNLOsv:





Results for integrated cross-section

LO results:

- bottom mass in both signal and background amplitudes:

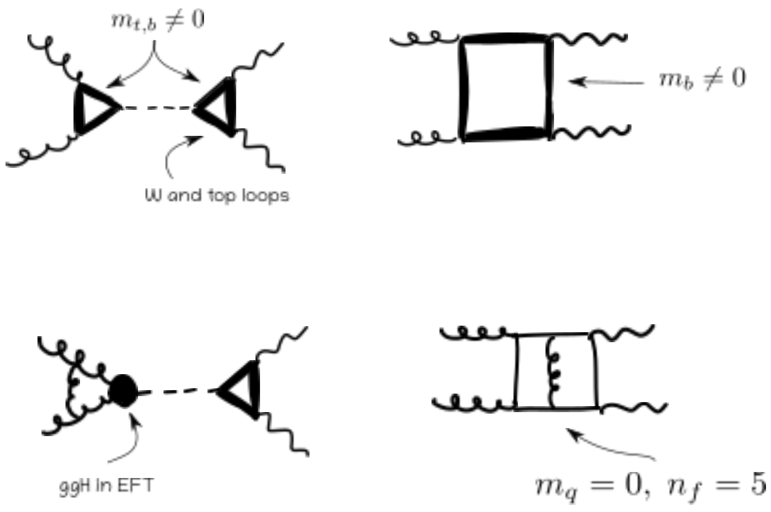
  σ_{int} = -0.11 fb

- bottom mass in background amplitudes only:

  σ_{int} = -0.02 fb

- bottom mass in signal amplitudes only:

  σ_{int} = -0.09 fb



LO ~ 6 smaller
than dNLO correction

dNLO correction:

- massless background amplitudes

  σ_{int} = -0.62 fb

it is safe to discard
mass effects beyond LO

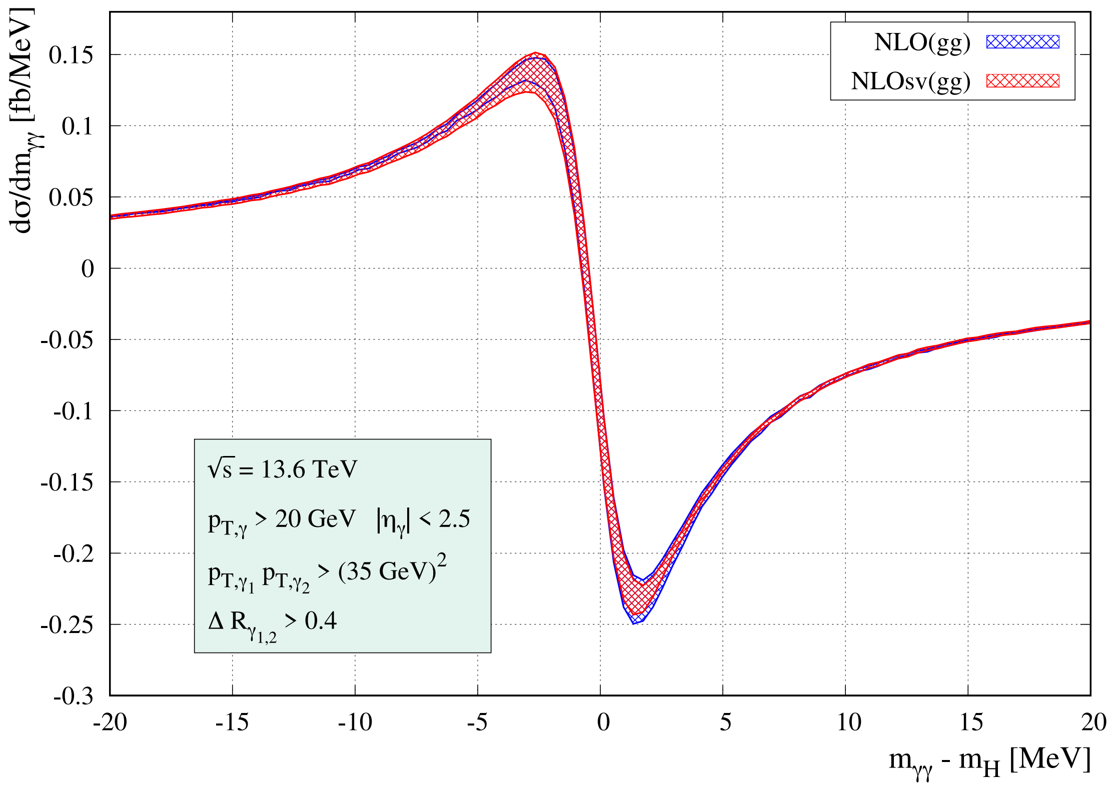
dNNLO$_{SV}$ correction:

- massless background amplitudes

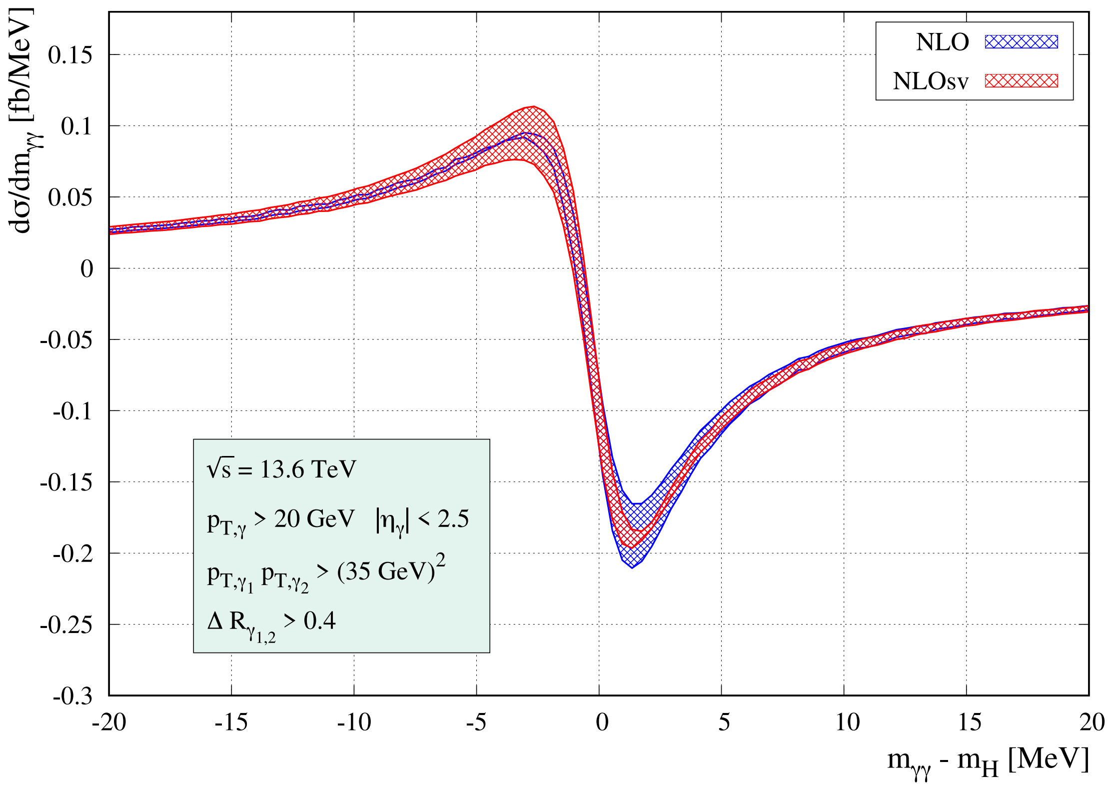
  σ_{int} = -0.48 fb

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

Validation of Soft-virtual approximation @NLO



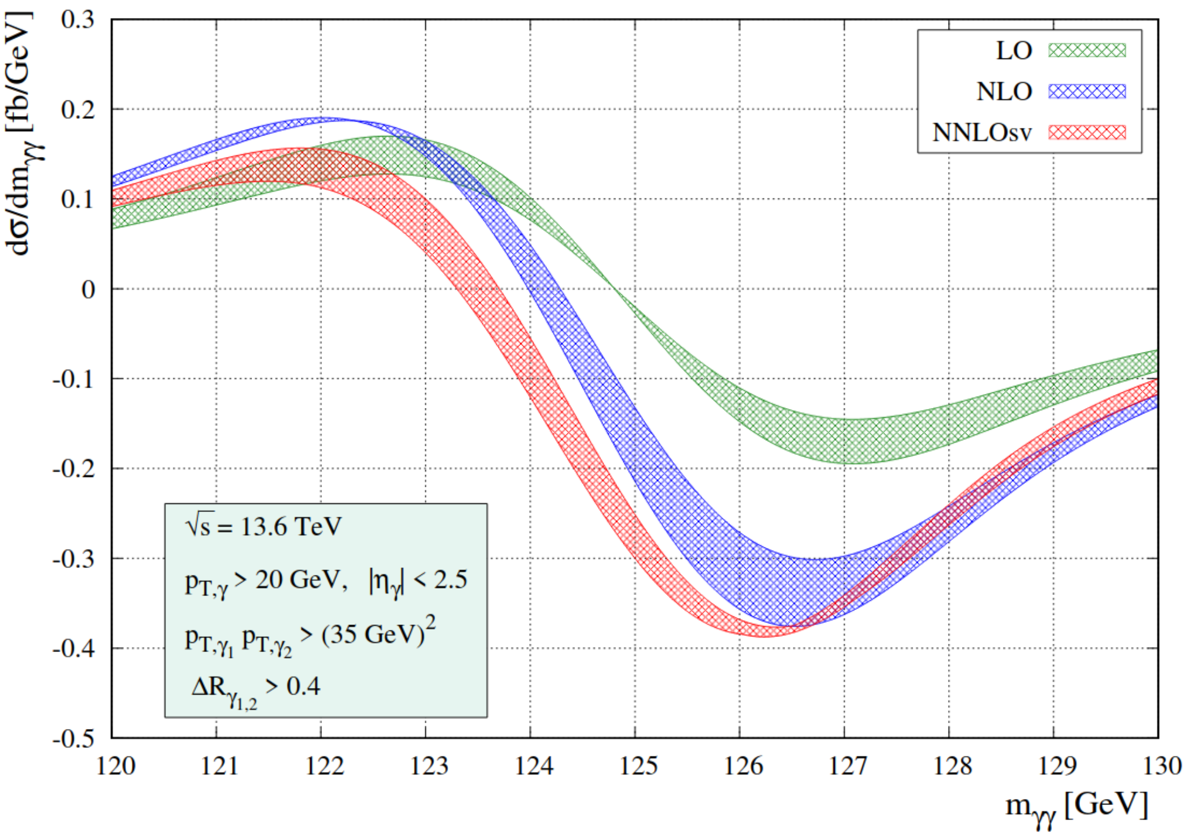
gg partonic channel only



all partonic channels

Mass shift @NLO: exact vs sv approx: 5% difference ⟶ well below the NLO correction and within scale uncertainty

Interference @NNLOsv



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

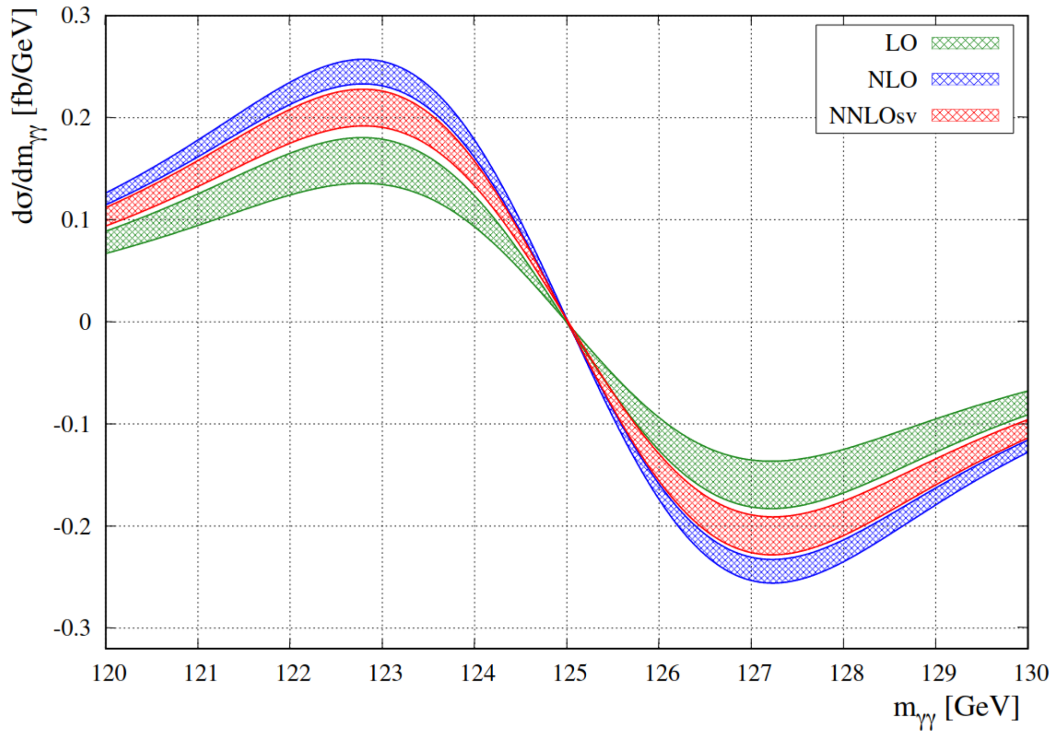
σ = 1.7 GeV

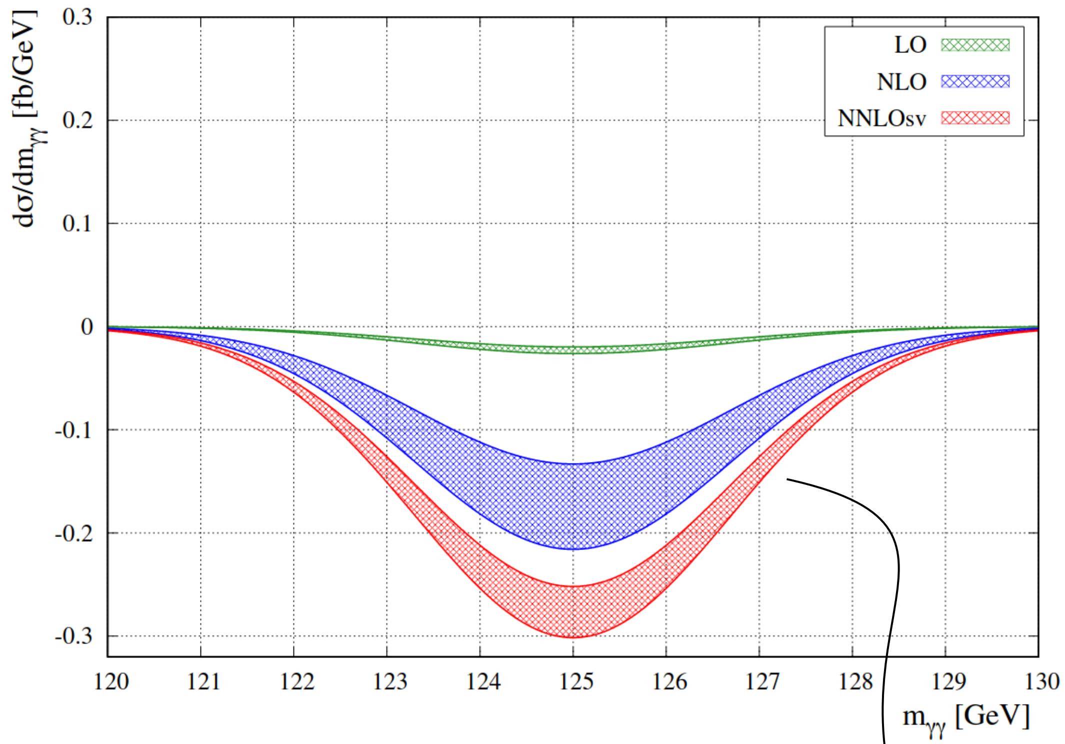
- NNLOsv corrections not captured by NLO scale variations
- NLO -> NNLO, curve is shifted further down

  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

$$\sigma_S^{\rm NNLO} = 72.12^{+8\%}_{-8\%}\ {\rm fb} \qquad \sigma_I^{\rm NNLOsv} = -1.21^{+7\%}_{-10\%}\ {\rm fb}$$

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%

-28%

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%

-28%

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

Soft-virtual "improved" approximation for Higgs XS based on [R.D. Ball, Bonvini, Forte, Marzani, Ridolfi 1303.3590]

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

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

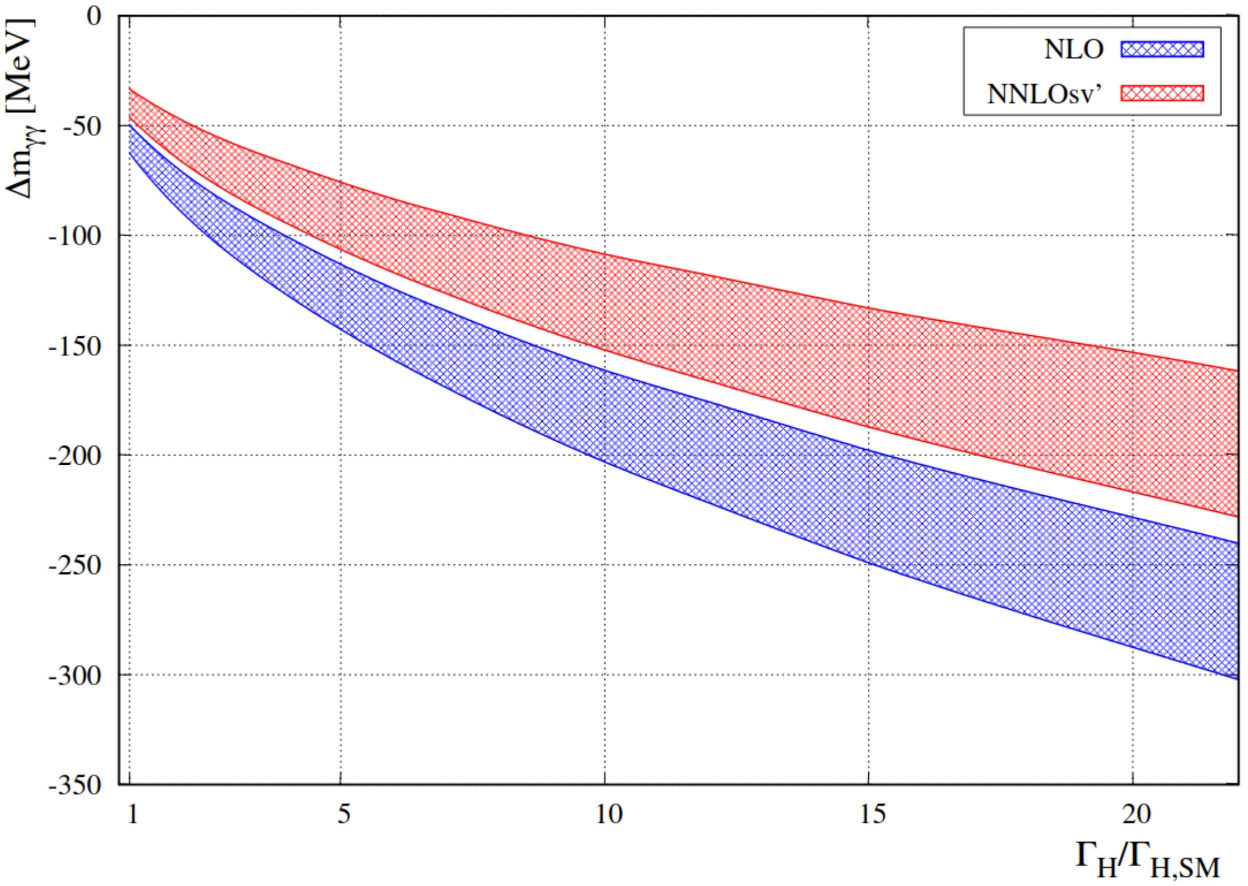
- Mass-shift via Gaussian fit and first moment: "different observables"

Different predictions in two methods

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

Bounds on Higgs width from mass shift

Updated bounds on Γ_H from $NNLO_{SV}$ corrections:



- Functional dependence ~ square root
- NNLO curve lies above the NLO one, thus looser bounds on Γ_H
- competing effects from Re and Im parts of interference
- If uncertainty on the mass shift reaches ~ 150 MeV: $\Gamma_H < (10\text{-}20)\ \Gamma_{H,SM}$
- To be compared with XS based method, i.e. 9% uncertainty on XS: $\Gamma_H < (28\text{-}30)\ \Gamma_{H,SM}$

Summary and outlook

- Currents bounds on Higgs-boson width extremely close to SM value: mild assumptions on off-shell meauserements
- Alternative proposal: on-shell meauserements 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 → First pheno application of a 3-loop QCD amplitude
  - although mass shift extraction dependent on methodology, K-factors are universal
  - looser bounds on Γ_H via mass-shift study: assuming 150 MeV error on mass-shift, $\Gamma_H < (10\text{-}20)\Gamma_{H,SM}$
  - improved bounds on Γ_H via integrated XS: with current 9% error on $\gamma\gamma$ XS, $\Gamma_H < (28\text{-}30)\Gamma_{H,SM}$

Outlook:

- Exact NNLO calculation: 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
- Understand how to improve SV approximation for continuum background process

  Next-to-leading power corrections (?) for loop-induced processes

Backup

Proposals to extract mass-shift in experiments

1) ZZ vs γγ

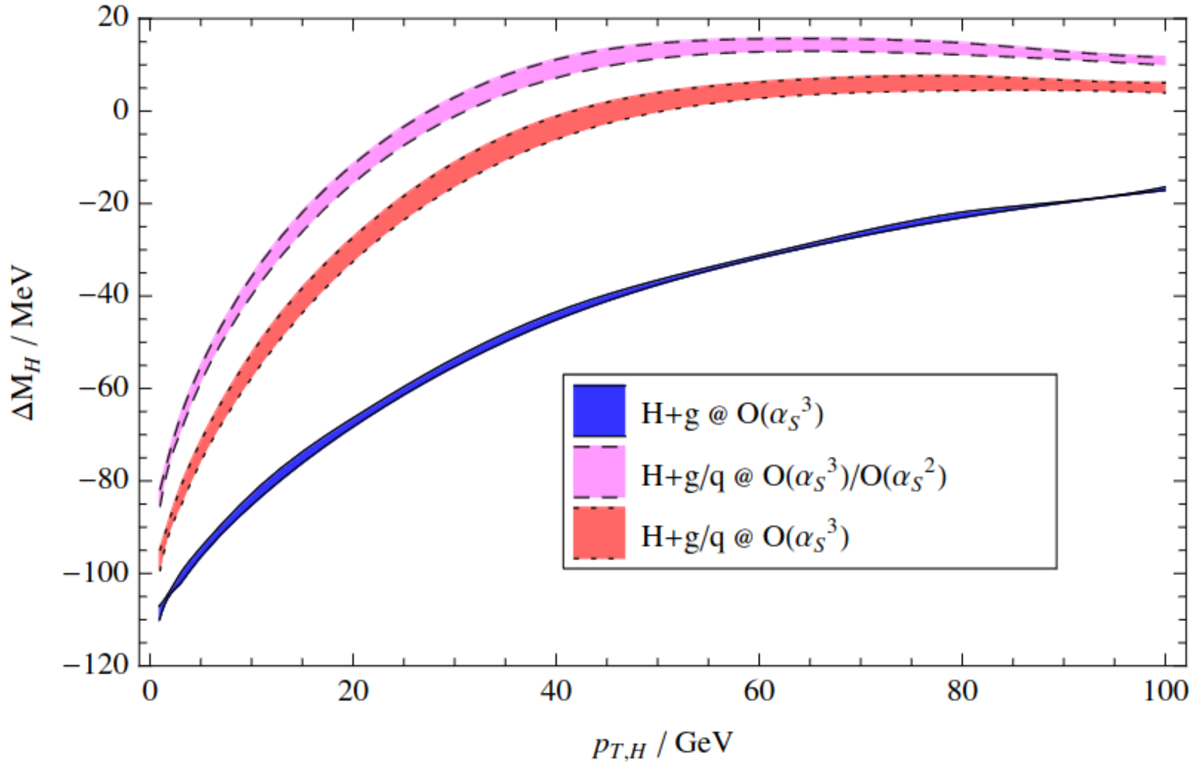
One could exploit the existing measurements of the Higgs mass in the ZZ and γγ channels and get an estimate on the mass shift

This would give a first limit on the Higgs width

2) $p_{T\gamma\gamma}$ meausrements

Exploit strong $p_{T\gamma\gamma}$ dependence of mass-shift.

Define a small and a large bin and take difference



Asymmetric cuts and NLO_{SV}

Cuts:

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

$|\eta_\gamma| < 2.5$

Isolation (discard events if):

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

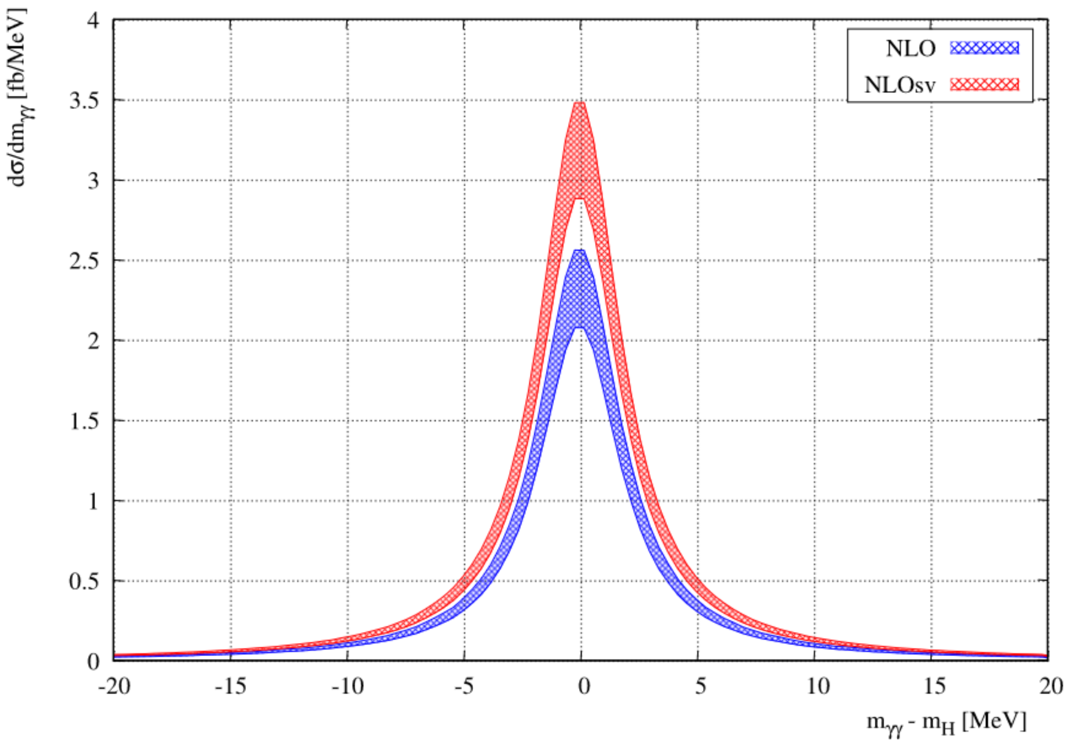
$\Delta R_{\gamma j} < 0.4$

Jet veto (reject if):

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

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

Signal process



Interference process