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

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

Federica Devoto

HP2 2022, 21/09/2022

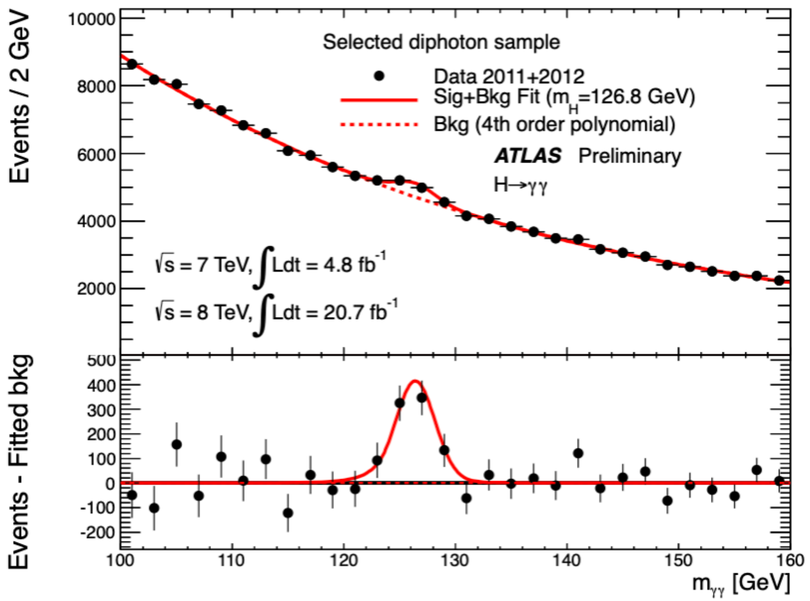
Introduction

- Higgs boson discovered at the LHC a decade ago, still ongoing remarkable theoretical and experimental efforts to determine its parameters

- Higgs width Γ_H : predicted by the Standard Model to be ~ 4 MeV

Direct sensitivity at the LHC is $\mathcal{O}(\text{GeV})$

Impossible to measure directly
Need indirect measurements/bounds



Constraints on Γ_H

$$\sigma_{i\to H\to f} \sim \sigma_{i\to H} BR(H\to f) \sim \frac{g_i^2 g_f^2}{\Gamma_H}$$

→ Cross sections are sensitive to ratios of couplings to width
Degeneracy in parameter space

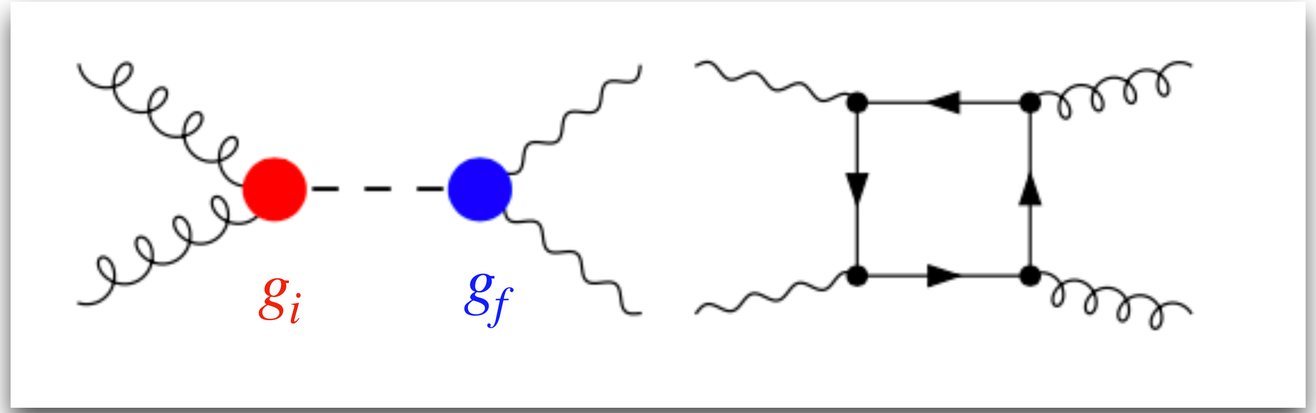
- To put indirect constraints one needs an observable with different dependence on couplings and width

- (Some) existing ideas:
  - Γ_H from off-shell cross-sections (Kauer, Passarino '13, Caola, Melnikov '13, Campbell et al '13)
  - Higgs interferometry (Martin '12; Dixon,Li '13; De Florian et al '13)

Focus of the talk

Signal-background interference in $gg \to H \to \gamma\gamma$

$$\sim \frac{g_i^2 g_f^2}{\Gamma_H}$$



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

$$\sim g_i g_f$$

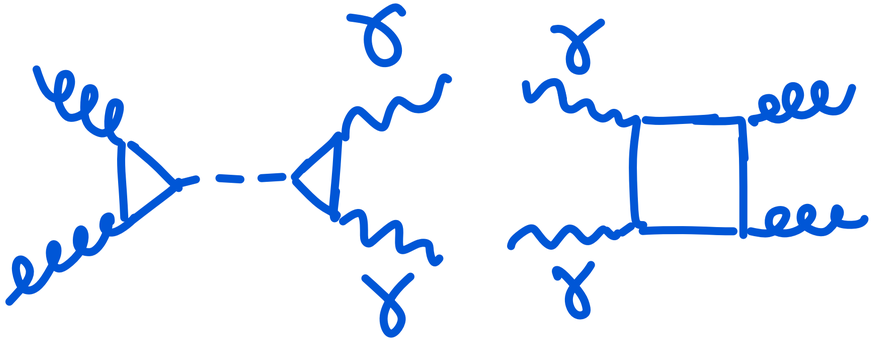
Any effect due to interference can be used to constrain Γ_H independently of couplings!

$$\mathrm{Re}\,I = \mathrm{Re}M_{bkg}\mathrm{Re}M_{sig} + \mathrm{Im}M_{bkg}\mathrm{Im}M_{sig}$$

$$\mathrm{Im}\,I = \mathrm{Re}M_{bkg}\mathrm{Im}M_{sig} - \mathrm{Im}M_{bkg}\mathrm{Re}M_{sig}$$

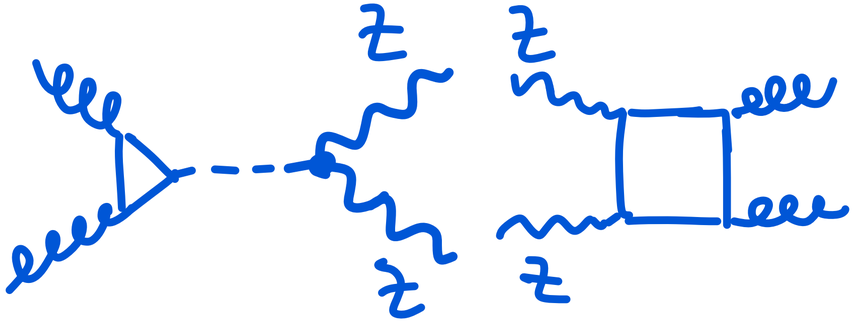
Signal-background interference: why $\gamma\gamma$?

$$|M_{gg\to\gamma\gamma}|^2 \simeq |S|^2 \left[1 + \frac{2s}{(s-m_H^2)^2 + \Gamma_H^2 m_H^2} \left((s-m_H^2)\,\mathrm{Re}\,\frac{B^*}{S} + \Gamma_H m_H\,\mathrm{Im}\,\frac{B^*}{S} \right) \right] + |B|^2$$



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

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

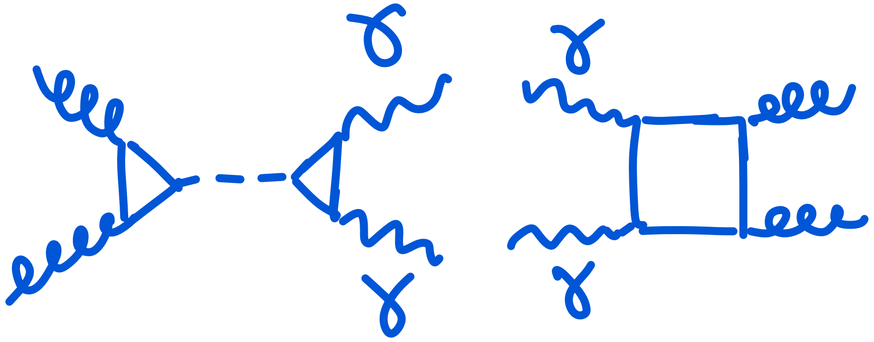


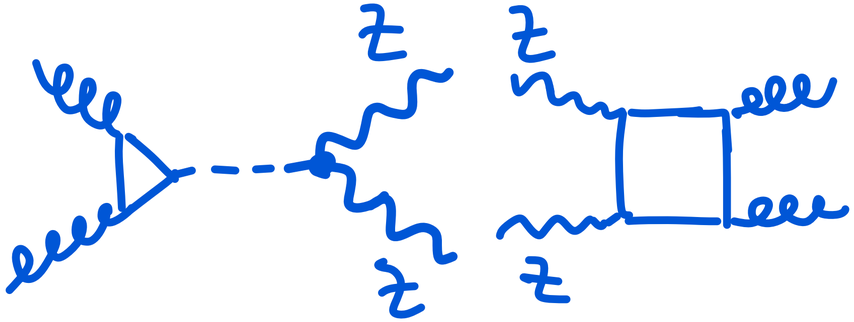
$$S_{ZZ} \sim \frac{g_s^2 e}{(4\pi)^2}$$

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

Signal-background interference: why $\gamma\gamma$?

$$|M_{gg\to\gamma\gamma}|^2 \simeq |S|^2 \left[1 + \frac{2s}{(s-m_H^2)^2 + \Gamma_H^2 m_H^2} \left((s-m_H^2)\,\mathrm{Re}\,\frac{B^*}{S} + \Gamma_H m_H\,\mathrm{Im}\,\frac{B^*}{S} \right) \right] + |B|^2$$





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

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

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

"Loop enhancement"

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

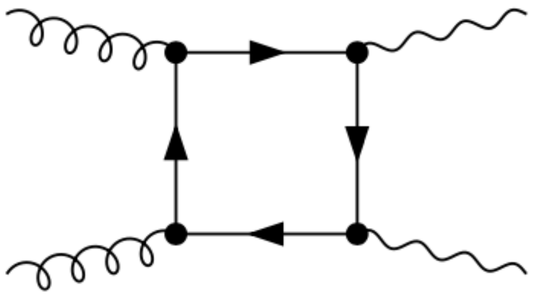
$$B_{ZZ} \sim \frac{g_s^2 e^2}{(4\pi)^2}$$

Imaginary part: a closer look

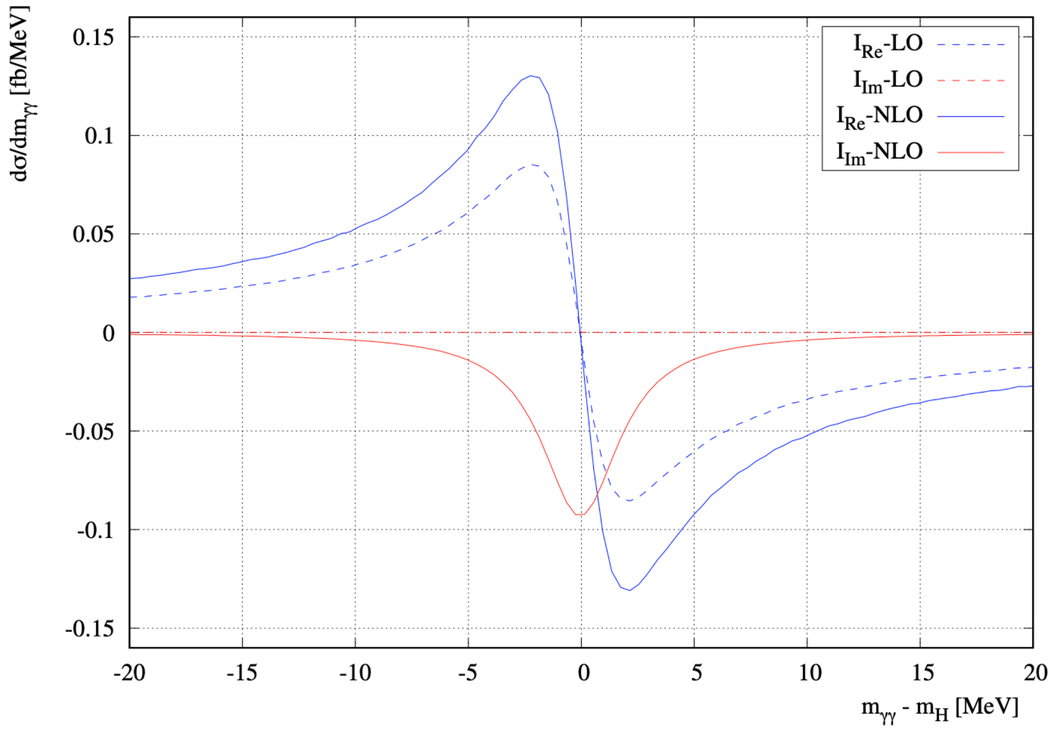
- Symmetric around the peak, contributes to cross section

- Starts contributing at NLO, background helicity amplitudes contributing to interference at LO are real

Caveat: bottom quark mass would give an imaginary part
Small effect



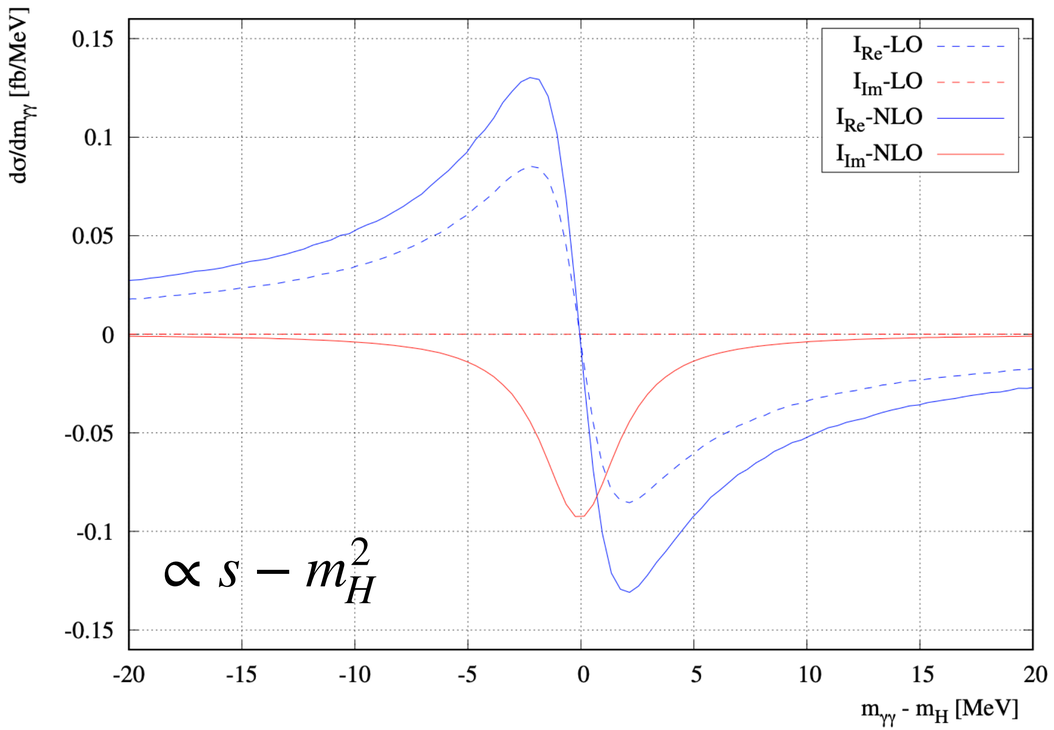
$$\mathrm{Im}\, I = \mathrm{Re}M_{bkg}\mathrm{Im}M_{sig} - \mathrm{Im}M_{bkg}\mathrm{Re}M_{sig}$$



Real part: a closer look

$$\mathrm{Re}\, I = \mathrm{Re} M_{bkg} \mathrm{Re} M_{sig} + \mathrm{Im} M_{bkg} \mathrm{Im} M_{sig}$$

- Antisymmetric around the peak, does not contribute to cross section
- Interesting physical effects, e.g. apparent mass shift [Martin '12]
- excess of events below $m_{\gamma\gamma} = 125\,\mathrm{GeV}$ rather than above



Mass-shift estimate: theory

- How can we estimate it from a theory side?

First moment method

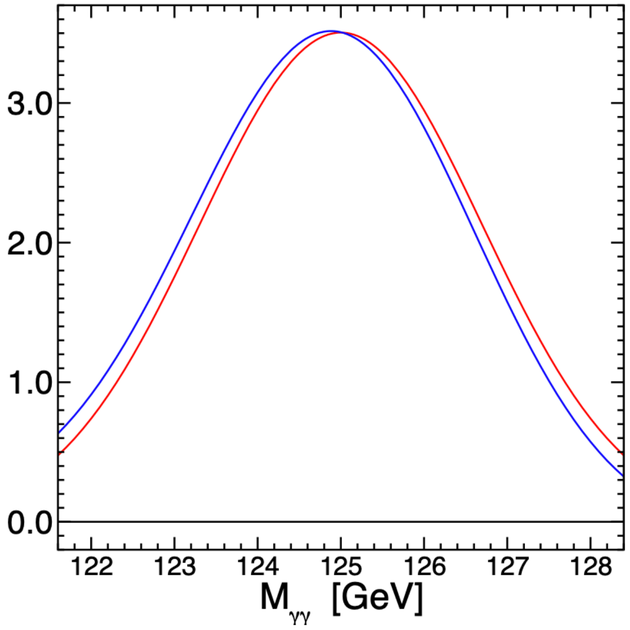
$$\langle M_{\gamma\gamma}\rangle_\delta = \frac{1}{\sigma_0}\int_{M_{\gamma\gamma}-\delta}^{M_{\gamma\gamma}+\delta} dM_{\gamma\gamma}\frac{d\sigma}{dM_{\gamma\gamma}}M_{\gamma\gamma}$$

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

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

Likelihood analysis, e.g. gaussian fit

[Dixon, Li '13]



[Martin '12]

Expected shift @LO
$\mathcal{O}(100)$ MeV

Mass-shift estimate: experiments

Mass-shift estimate: experiments

More realistic ways to measure it in experiments?

Mass-shift estimate: experiments

More realistic ways to measure it in experiments?

Compare measures in $\gamma\gamma$ vs ZZ channels

Mass-shift estimate: experiments

$p_{T,H}$ dependent measurements

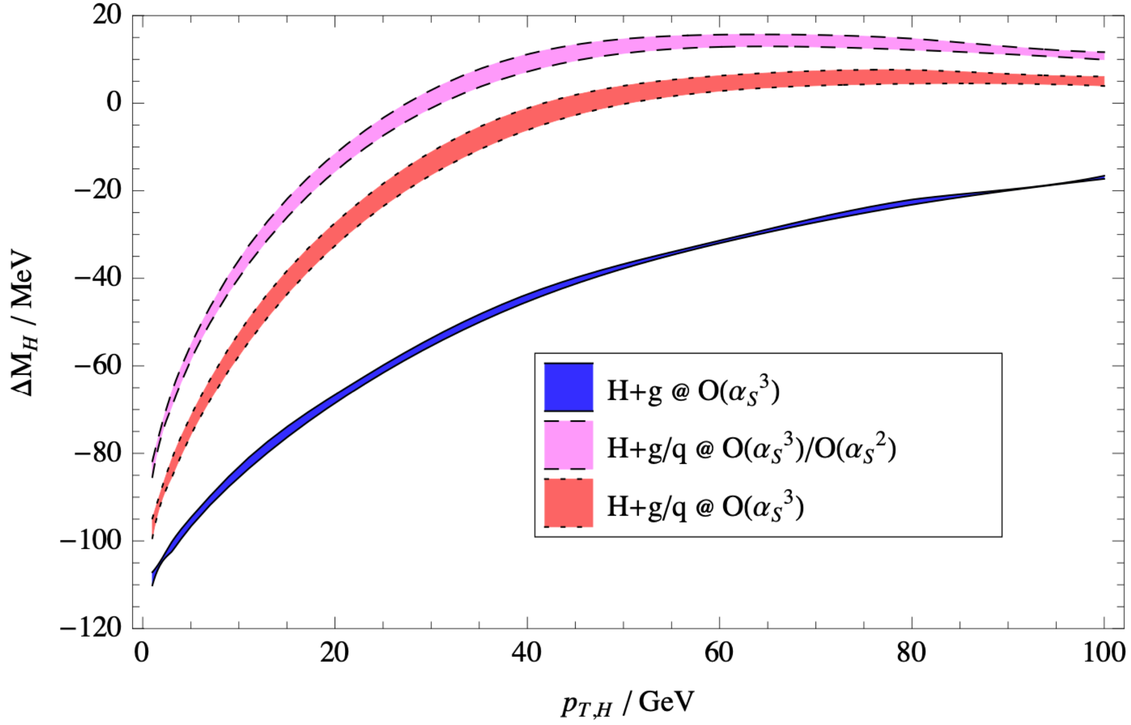
More realistic ways to measure it in experiments?

Compare measures in $\gamma\gamma$ vs ZZ channels

Mass-shift estimate: experiments

$p_{T,H}$ dependent measurements

More realistic ways to measure it in experiments?

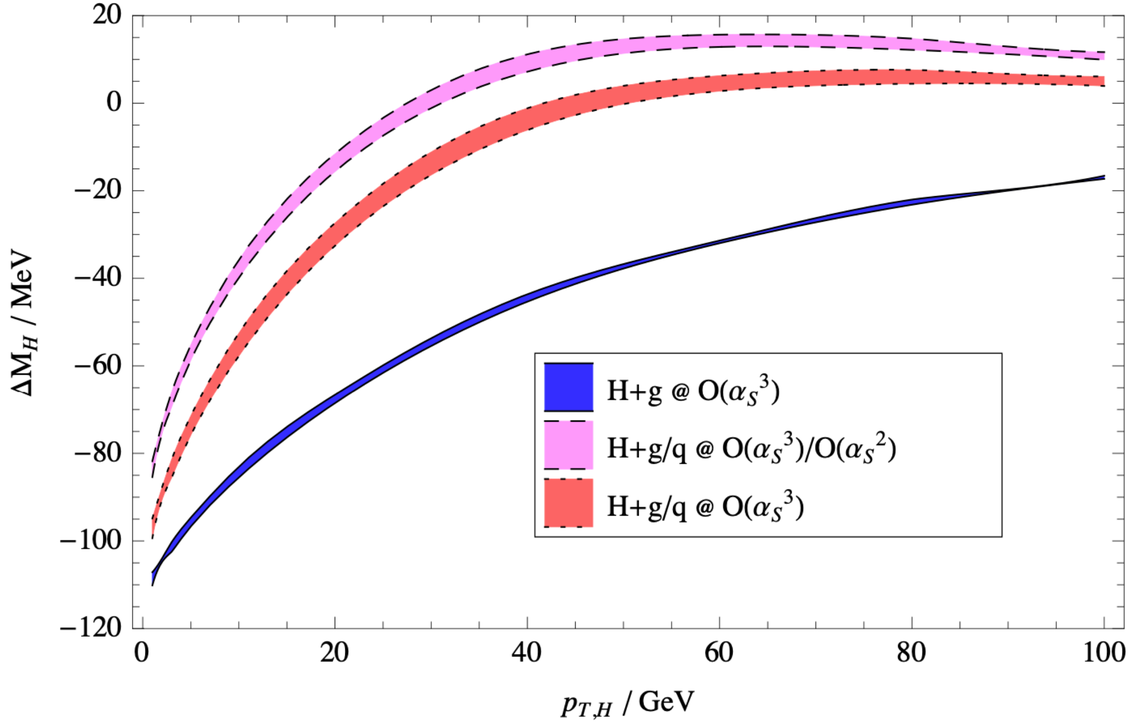


Compare measures in $\gamma\gamma$ vs ZZ channels

Mass-shift estimate: experiments

$p_{T,H}$ dependent measurements

More realistic ways to measure it in experiments?



[Dixon, Li '13]

Compare measures in $\gamma\gamma$ vs ZZ channels

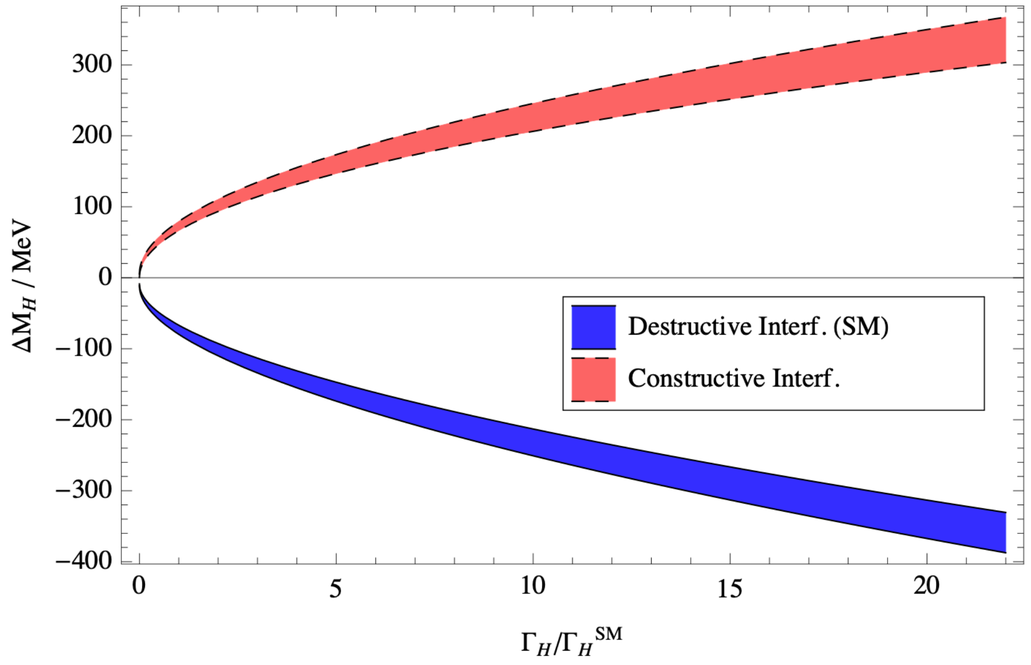
Mass shift and Higgs width

- Allow Higgs width to differ from SM prediction
- Higgs couplings need to change accordingly to maintain roughly SM yield (LHC measurements)

$g_i \longrightarrow \lambda_i g_i$

$g_f \longrightarrow \lambda_f g_f$

$$\frac{(\lambda_i \lambda_f)^2 S}{m_H \Gamma_H} + \lambda_i \lambda_f I \sim \frac{S}{m_H \Gamma_{H,SM}} + I$$



[Dixon, Li '13]

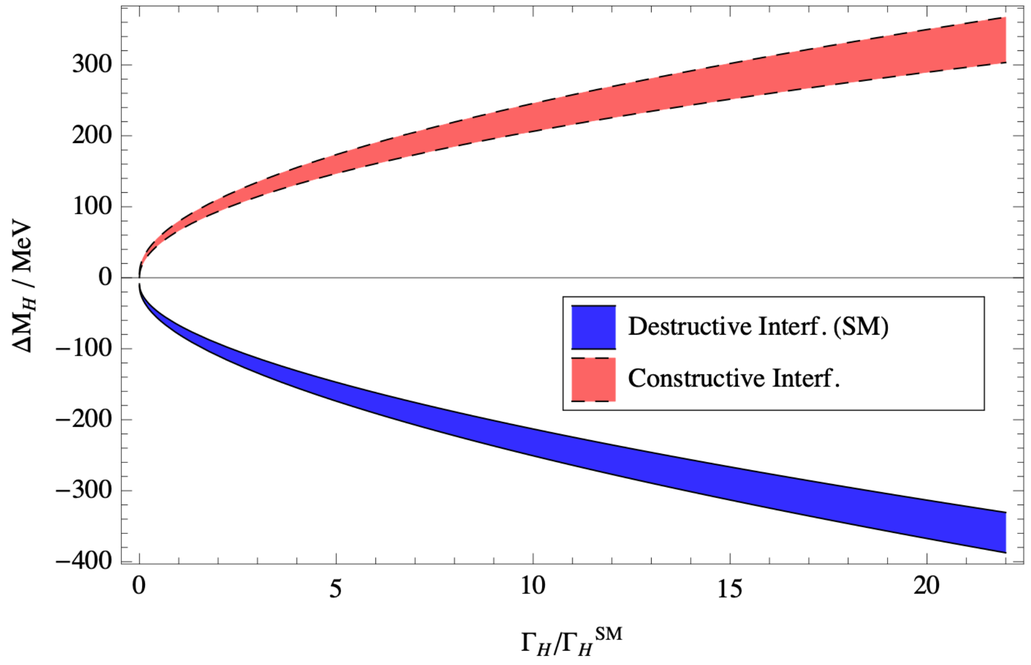
Mass shift and Higgs width

- Allow Higgs width to differ from SM prediction
- Higgs couplings need to change accordingly to maintain roughly SM yield (LHC measurements)

$g_i \longrightarrow \lambda_i g_i$

$g_f \longrightarrow \lambda_f g_f$

$$\frac{(\lambda_i \lambda_f)^2 S}{m_H \Gamma_H} + \lambda_i \lambda_f I \sim \frac{S}{m_H \Gamma_{H,SM}} + \cancel{I}$$



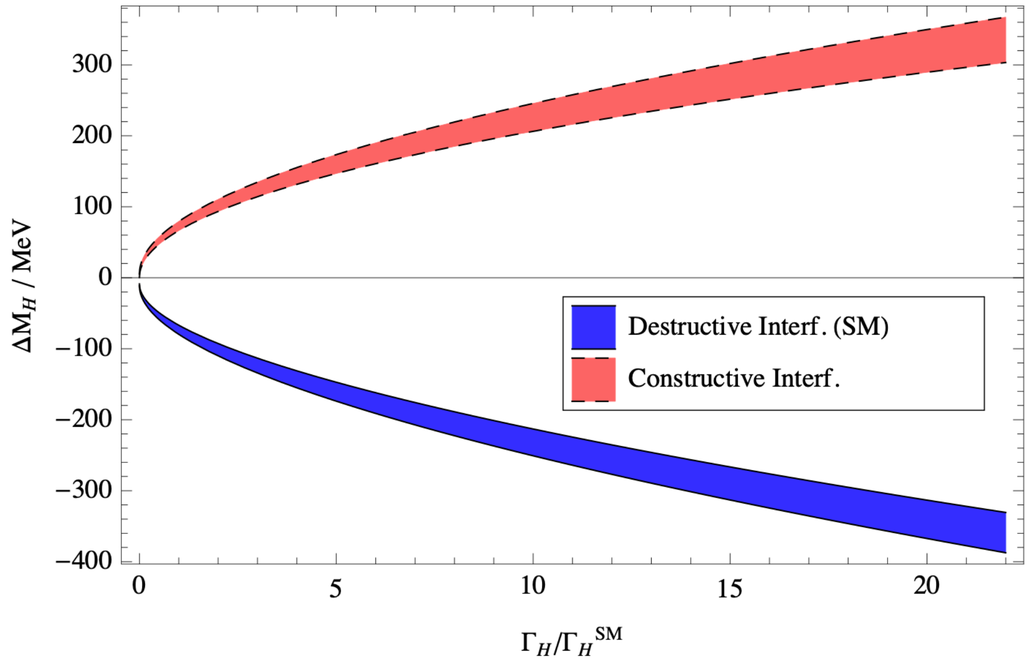
[Dixon, Li '13]

Mass shift and Higgs width

- Allow Higgs width to differ from SM prediction
- Higgs couplings need to change accordingly to maintain roughly SM yield (LHC measurements)

$g_i \longrightarrow \lambda_i g_i$

$g_f \longrightarrow \lambda_f g_f$



[Dixon, Li '13]

$$\frac{(\lambda_i\lambda_f)^2 S}{m_H\Gamma_H} + \lambda_i\lambda_f I \sim \frac{S}{m_H\Gamma_{H,SM}} + \cancel{I}$$

Mass shift and Higgs width

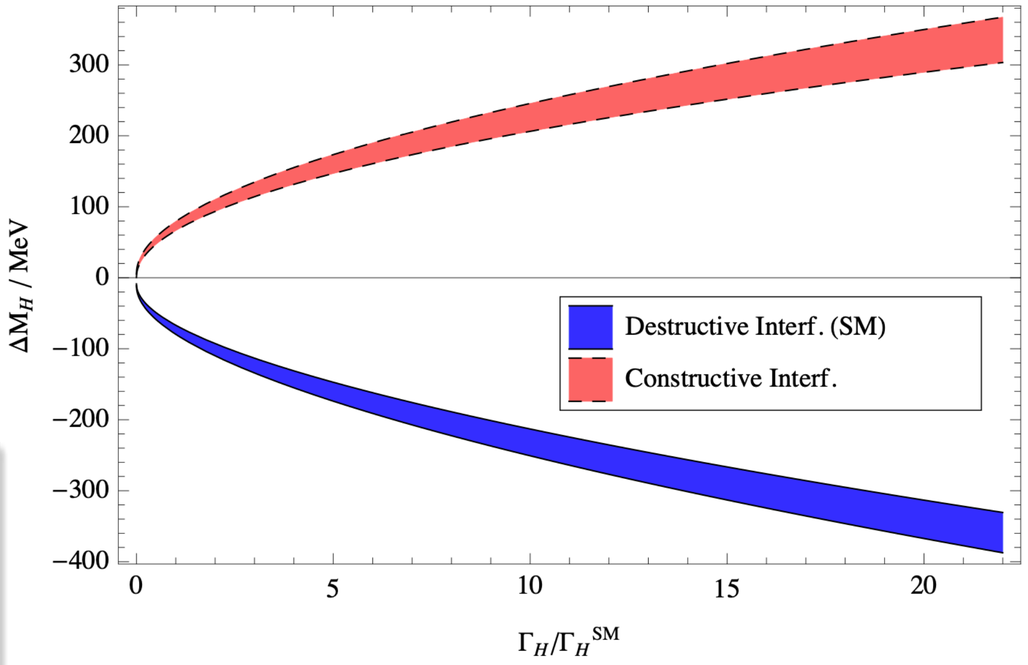
- Allow Higgs width to differ from SM prediction
- Higgs couplings need to change accordingly to maintain roughly SM yield (LHC measurements)

$g_i \longrightarrow \lambda_i g_i$

$g_f \longrightarrow \lambda_f g_f$

$$\frac{(\lambda_i \lambda_f)^2 S}{m_H \Gamma_H} + \lambda_i \lambda_f I \sim \frac{S}{m_H \Gamma_{H,SM}} + \cancel{I}$$

Interference effect on cross section is small w.r.t integrated signal: I $\sim 1\,\%$ of S



[Dixon, Li '13]

Mass shift and Higgs width

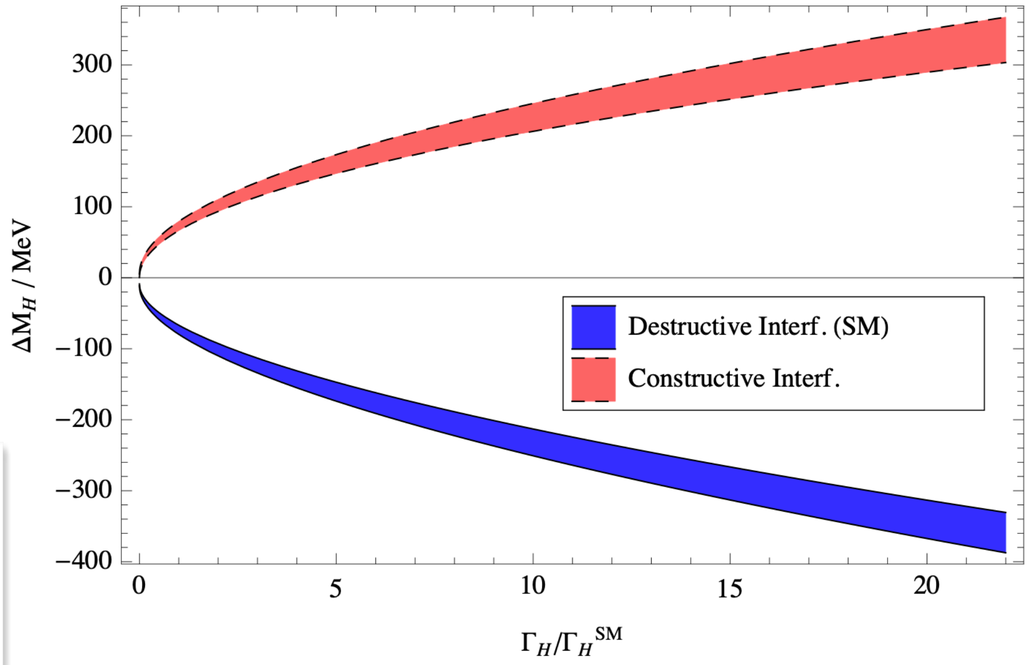
- Allow Higgs width to differ from SM prediction
- Higgs couplings need to change accordingly to maintain roughly SM yield (LHC measurements)

$g_i \longrightarrow \lambda_i g_i$

$g_f \longrightarrow \lambda_f g_f$

$$\frac{(\lambda_i \lambda_f)^2 S}{m_H \Gamma_H} + \lambda_{i,f} I \sim \frac{S}{m_H \Gamma_{H,SM}} + \cancel{I}$$

Interference effect on cross section is small w.r.t integrated signal: I $\sim 1\,\%$ of S



[Dixon, Li '13]

Mass shift and Higgs width

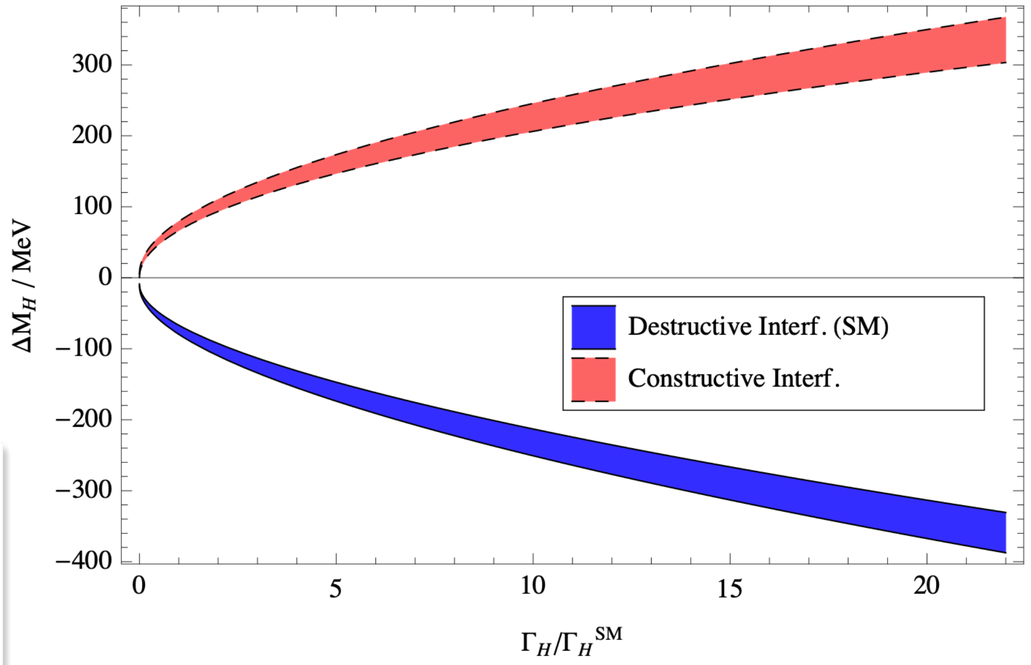
- Allow Higgs width to differ from SM prediction
- Higgs couplings need to change accordingly to maintain roughly SM yield (LHC measurements)

$g_i \longrightarrow \lambda_i g_i$

$g_f \longrightarrow \lambda_f g_f$

$$\frac{(\lambda_i \lambda_f)^2 S}{m_H \Gamma_H} + \lambda_{i,f} I \sim \frac{S}{m_H \Gamma_{H,SM}} + \cancel{I}$$

Interference effect on cross section is small w.r.t integrated signal: I $\sim 1\,\%$ of S



[Dixon, Li '13]

Mass shift and Higgs width

- Allow Higgs width to differ from SM prediction
- Higgs couplings need to change accordingly to maintain roughly SM yield (LHC measurements)

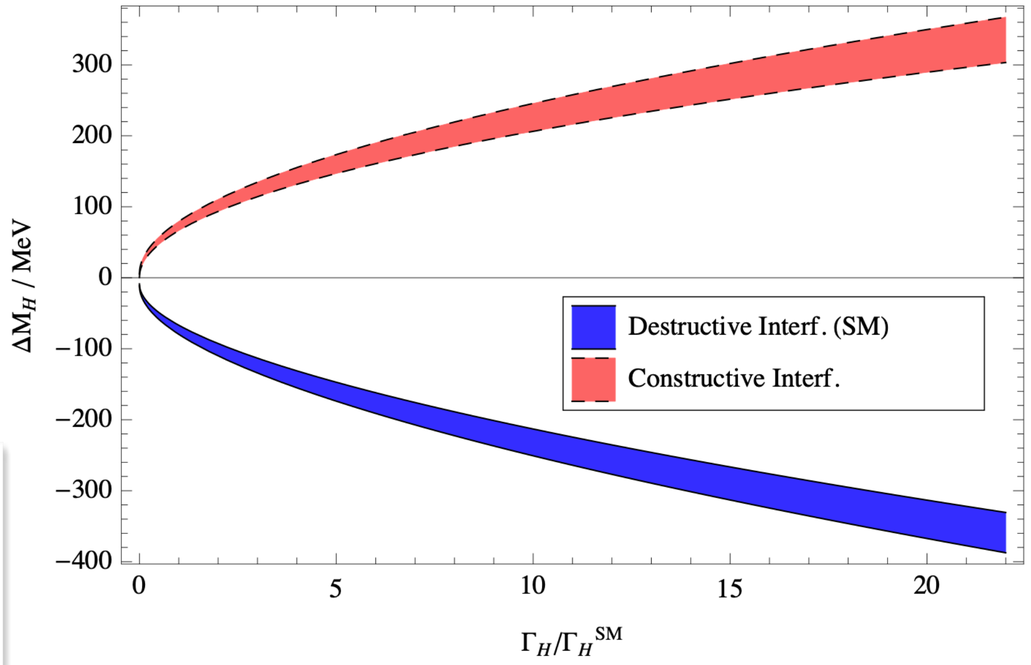
$g_i \longrightarrow \lambda_i g_i$

$g_f \longrightarrow \lambda_f g_f$

Also negligible for reasonable values of Higgs width

Interference effect on cross section is small w.r.t integrated signal: I $\sim 1\,\%$ of S

$$\frac{(\lambda_i \lambda_f)^2 S}{m_H \Gamma_H} + \lambda_i \lambda_f I \sim \frac{S}{m_H \Gamma_{H,SM}} + \cancel{I}$$



[Dixon, Li '13]

Mass shift and Higgs width

- Allow Higgs width to differ from SM prediction
- Higgs couplings need to change accordingly to maintain roughly SM yield (LHC measurements)

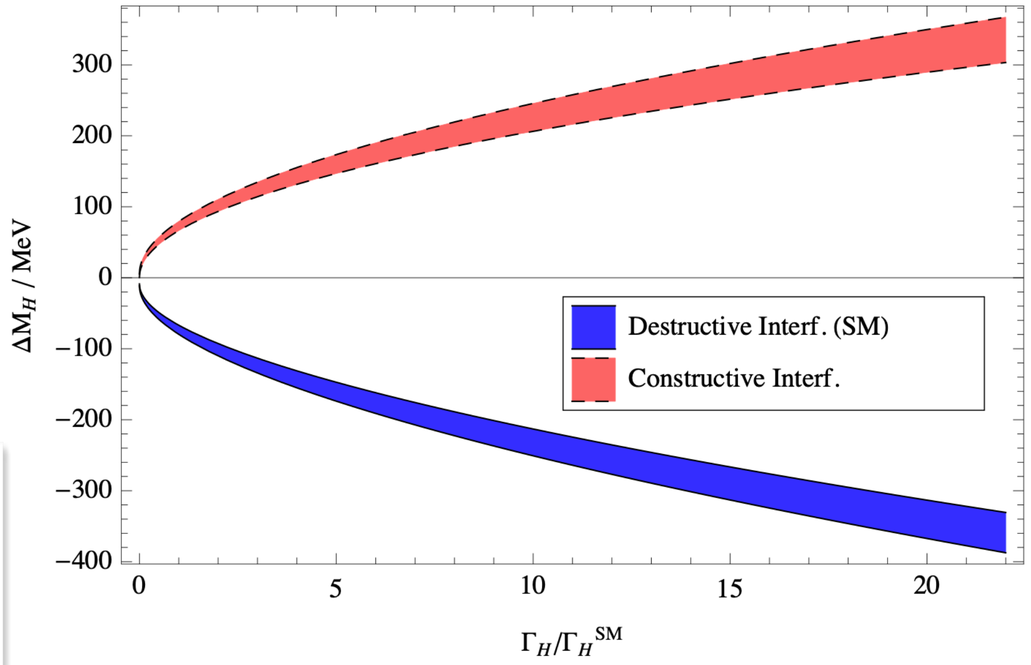
$g_i \longrightarrow \lambda_i g_i$

$g_f \longrightarrow \lambda_f g_f$

Also negligible for reasonable values of Higgs width

Interference effect on cross section is small w.r.t integrated signal: I $\sim 1\,\%$ of S

$$\frac{(\lambda_i\lambda_f)^2 S}{m_H \Gamma_H} + \lambda_i\lambda_f I \sim \frac{S}{m_H \Gamma_{H,SM}} + \cancel{I}$$



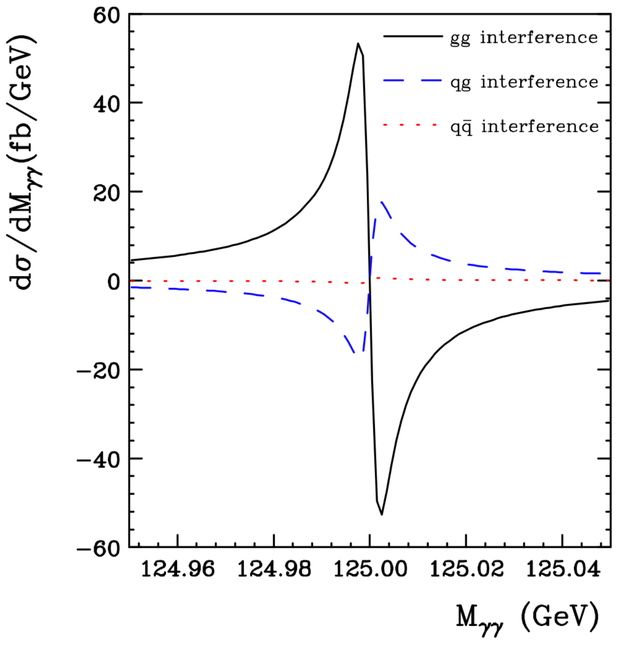
[Dixon, Li '13]

$$\lambda_i\lambda_f \propto \Delta M_{\gamma\gamma} \propto \sqrt{\Gamma_H}$$

Interference effects: state of the art

- Interference effects analysis in $\gamma\gamma$ channel performed up to next-to-leading order [Dixon,Li '13]

- Other channels also included: i.e. $qg \to \gamma\gamma q$ (about three times smaller than gg but opposite sign), $q\bar{q} \to \gamma\gamma g$ (same sign as qg, negligible contribution)



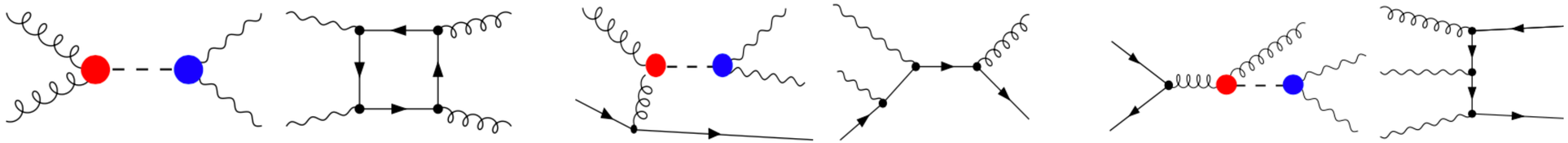
- NLO analysis decreases mass shift to $\sim 70\,\mathrm{MeV}$

$\mathcal{O}(40\%)$ decrease w.r.t LO!

- Calls for a higher order analysis!

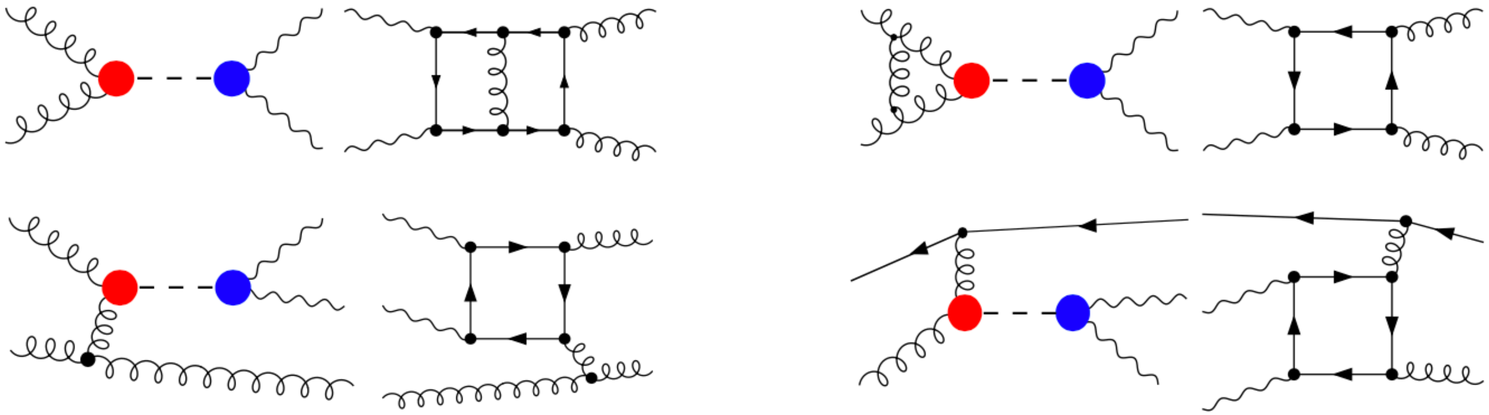
[De Florian et al, '12]

LO(gg) LO(qg) LO(q$\bar{q}$)



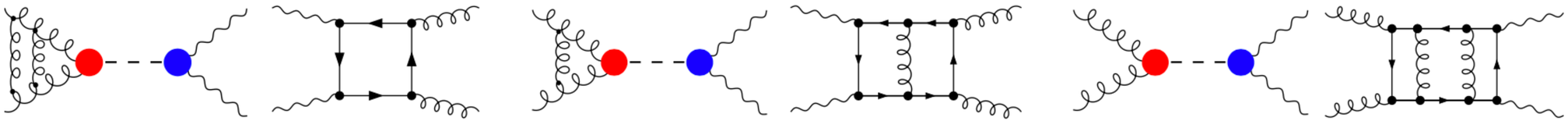
$\mathcal{O}(\alpha_s^2)$

NLO(gg)



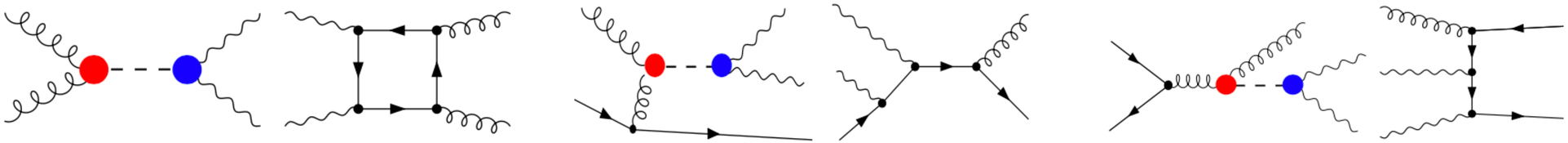
$\mathcal{O}(\alpha_s^3)$

NNLO(gg)



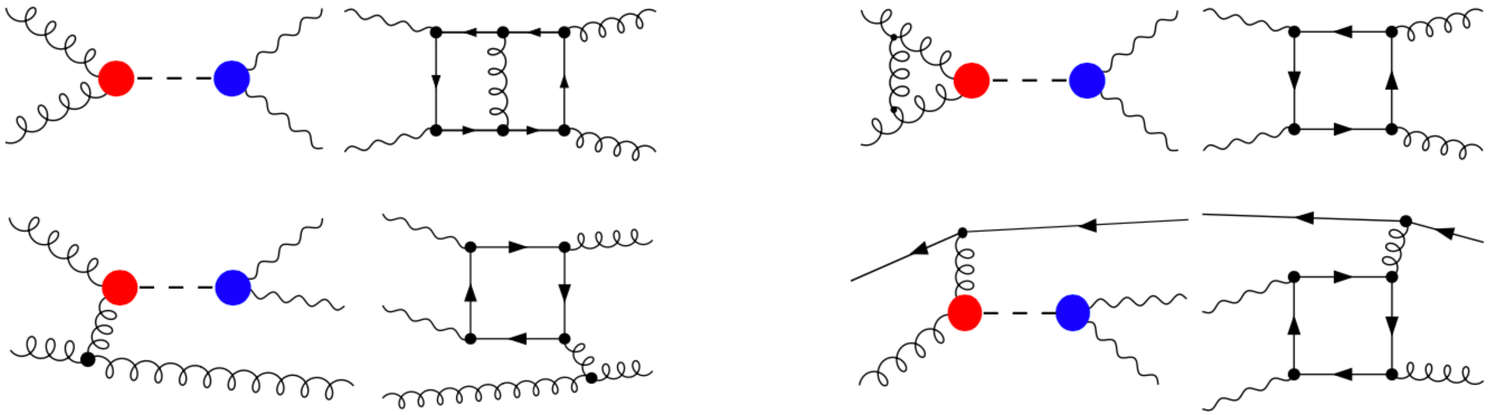
$\mathcal{O}(\alpha_s^4)$

LO(gg) LO(qg) LO(q$\bar{q}$)



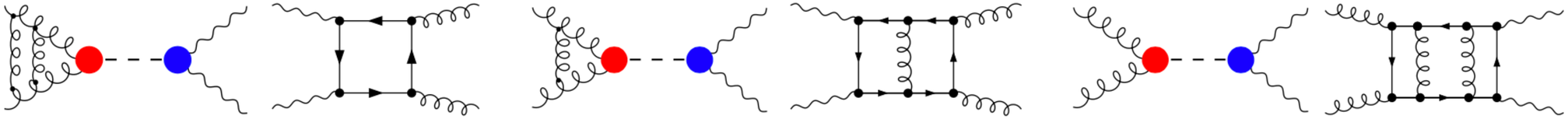
$\mathcal{O}(\alpha_s^2)$

NLO(gg)



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

NNLO(gg)

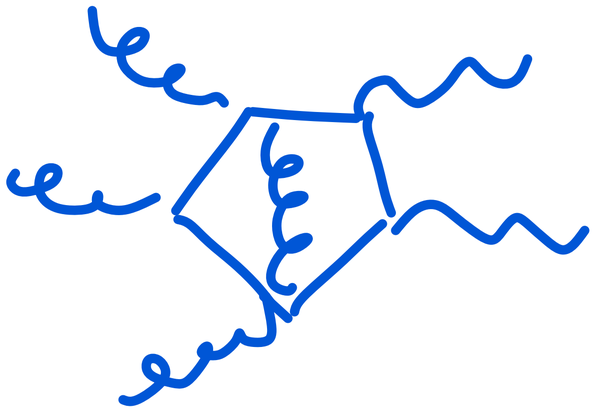


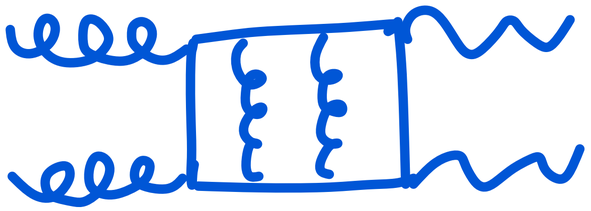
$\mathcal{O}(\alpha_s^4)$

Interference beyond NLO: ingredients

- Subtraction @ NNLO for color singlet production ✓
- 5-points two loop amplitudes for background process [Badger et al, '21] [Agarwal et al, '21] ✓
- Three-loop amplitudes for background process ✓

  [Bargiela,Caola,von Manteuffel,Tancredi, '22]





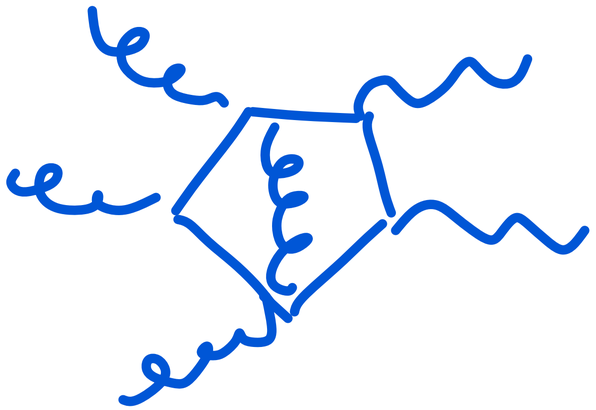
In principle: everything is there… in practice: potential technical difficulties
(e.g. evaluation of complicated amplitudes in extreme kinematic configurations, involved subtraction structure etc.)

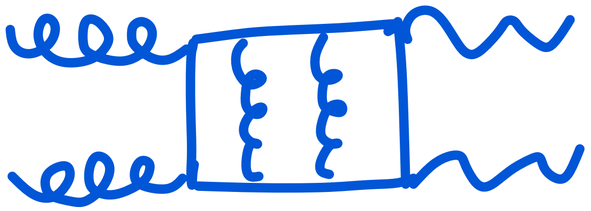
Interference is enhanced at low $p_{T,H}$,
bulk of the contribution coming from the virtuals

Interference beyond NLO: ingredients

- Subtraction @ NNLO for color singlet production ✓
- 5-points two loop amplitudes for background process [Badger et al, '21] [Agarwal et al, '21] ✓
- Three-loop amplitudes for background process ✓

  [Bargiela,Caola,von Manteuffel,Tancredi, '22]





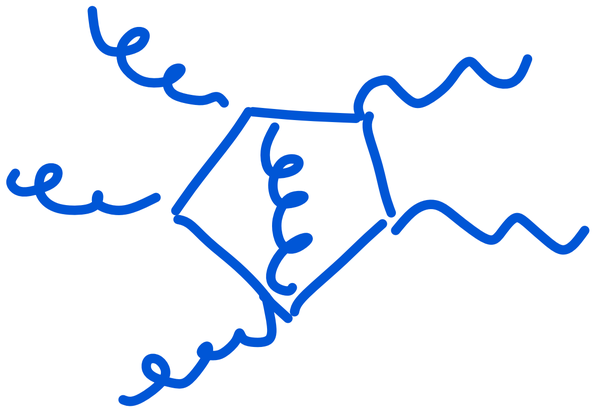
In principle: everything is there… in practice: potential technical difficulties
(e.g. evaluation of complicated amplitudes in extreme kinematic configurations, involved subtraction structure etc.)

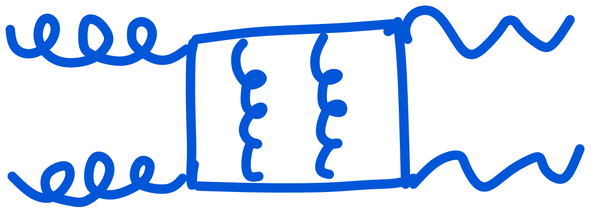
Interference is enhanced at low $p_{T,H}$,
bulk of the contribution coming from the virtuals →

Interference beyond NLO: ingredients

- Subtraction @ NNLO for color singlet production ✓
- 5-points two loop amplitudes for background process [Badger et al, '21] [Agarwal et al, '21] ✓
- Three-loop amplitudes for background process ✓

  [Bargiela,Caola,von Manteuffel,Tancredi, '22]





In principle: everything is there… in practice: potential technical difficulties
(e.g. evaluation of complicated amplitudes in extreme kinematic configurations, involved subtraction structure etc.)

Interference is enhanced at low $p_{T,H}$,
bulk of the contribution coming from the virtuals → **Soft-virtual approximation**

Soft-virtual approximation in a nutshell

$$Q^2 \frac{d\sigma}{dQ^2}(s_H, Q^2) = \sum_{a,b} \int_0^1 dx_1\, dx_2\, f_{a/h_1}(x_1, \mu_F^2)\, f_{b/h_2}(x_2, \mu_F^2) \int_0^1 dz\, \delta\left(z - \frac{\tau}{x_1 x_2}\right) \times \hat{\sigma}_0\, z\, G_{ab}(z; \alpha_S(\mu_R^2), Q^2/\mu_R^2; Q^2/\mu_F^2)\,,$$

$$\tau = \frac{Q^2}{s_H}$$

$$\mathcal{D}_n(z) = \left[\frac{\ln^n(1-z)}{1-z}\right]_+$$

$$G(z, \alpha_s) = \delta(1-z) + \frac{\alpha_s}{2\pi}\left[8 C_A \mathcal{D}_1(z) + \left(\frac{2\pi^2}{3} C_A + c_1\right)\delta(1-z)\right]$$

Universal structure

Process-dependent, from virtual contributions

- Evaluation of soft contributions only, neglect hard emissions
- Works best near partonic threshold, i.e. $z \to 1$ → soft limit
- Gluon PDFs fall off fast at large partonic x: center-of-mass energy tends to be close to invariant mass of the system ➡ only soft extra radiation allowed

Setup

- $\sqrt{s} = 13.6\,\mathrm{TeV}$
- 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 '21]

Setup

- $\sqrt{s} = 13.6\,\mathrm{TeV}$
- PDF set: NNPDF31_nnlo_as_0118
- Dynamic scale: $\mu_F = \mu_R \equiv \mu = \dfrac{m_{\gamma\gamma}}{2}$
- Fiducial cuts:
  - $p_{T\,\gamma_{1,2}} > 20\,\mathrm{GeV}$
  - $|\eta_\gamma| < 2.5$
  - $\boxed{p_{T\,\gamma_1} p_{T\,\gamma_2} > (35\,\mathrm{GeV})^2}$
  - $\Delta R_{\gamma_{1,2}} > 0.4$

[Salam, Slade '21]

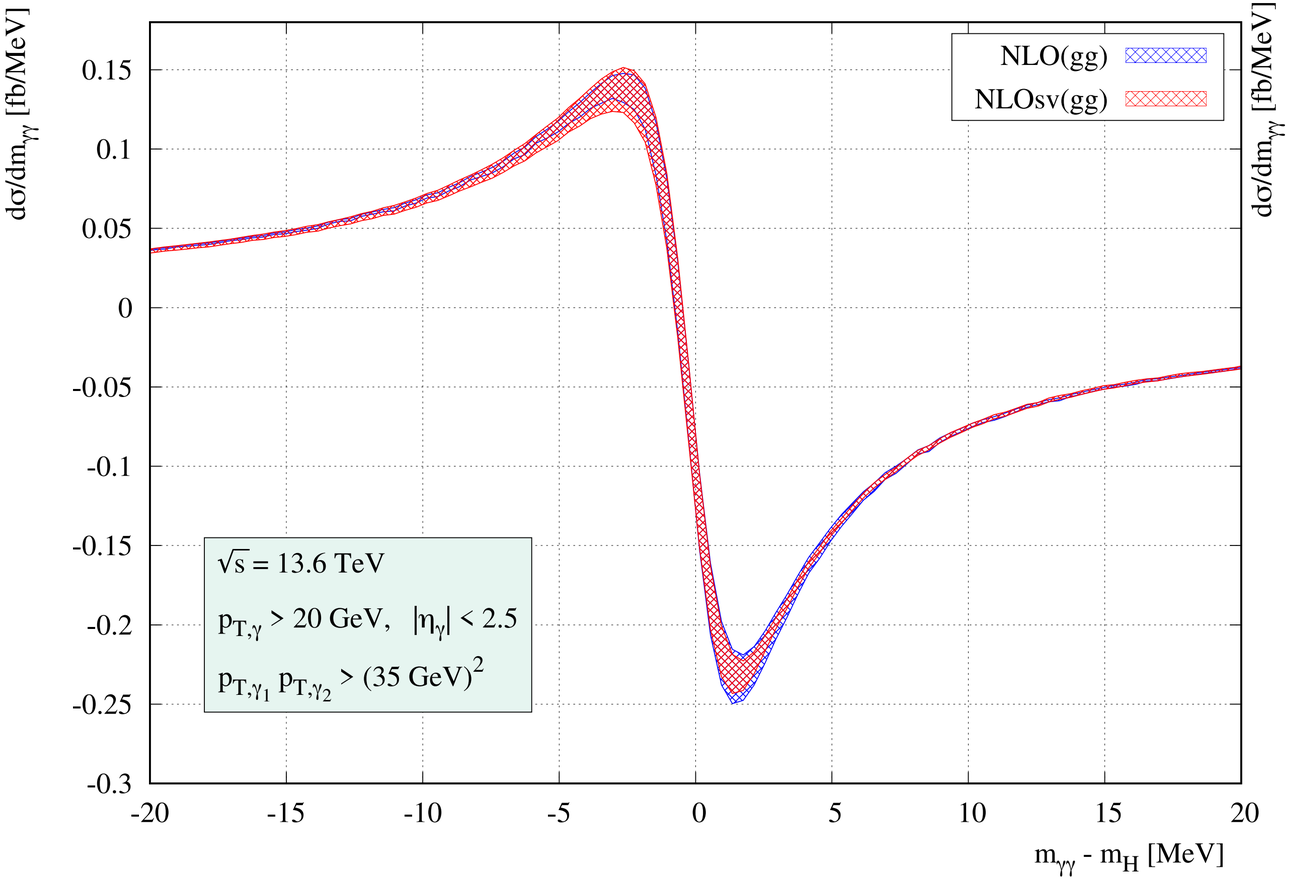
Setup

- $\sqrt{s} = 13.6\,\mathrm{TeV}$
- PDF set: NNPDF31_nnlo_as_0118
- Dynamic scale: $\mu_F = \mu_R \equiv \mu = \dfrac{m_{\gamma\gamma}}{2}$
- Fiducial cuts:
  - $p_{T\,\gamma_{1,2}} > 20\,\mathrm{GeV}$
  - $|\eta_\gamma| < 2.5$
  - $\boxed{p_{T\,\gamma_1} p_{T\,\gamma_2} > (35\,\mathrm{GeV})^2}$
  - $\Delta R_{\gamma_{1,2}} > 0.4$

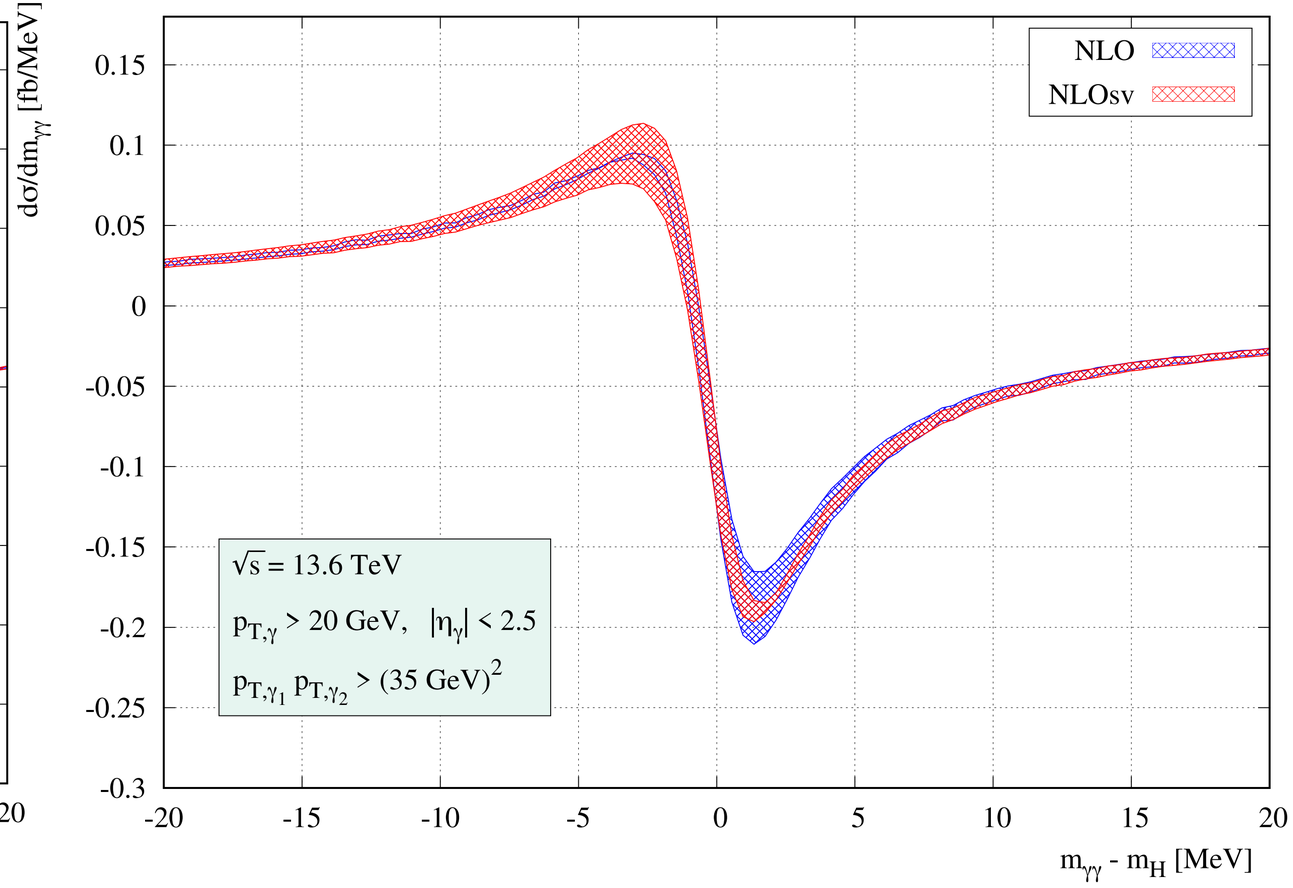
Signal-background interference receives large corrections
"Usual" cuts plagued by unphysical sensitivity to IR physics

[Salam, Slade '21]

Validation of SV: interference

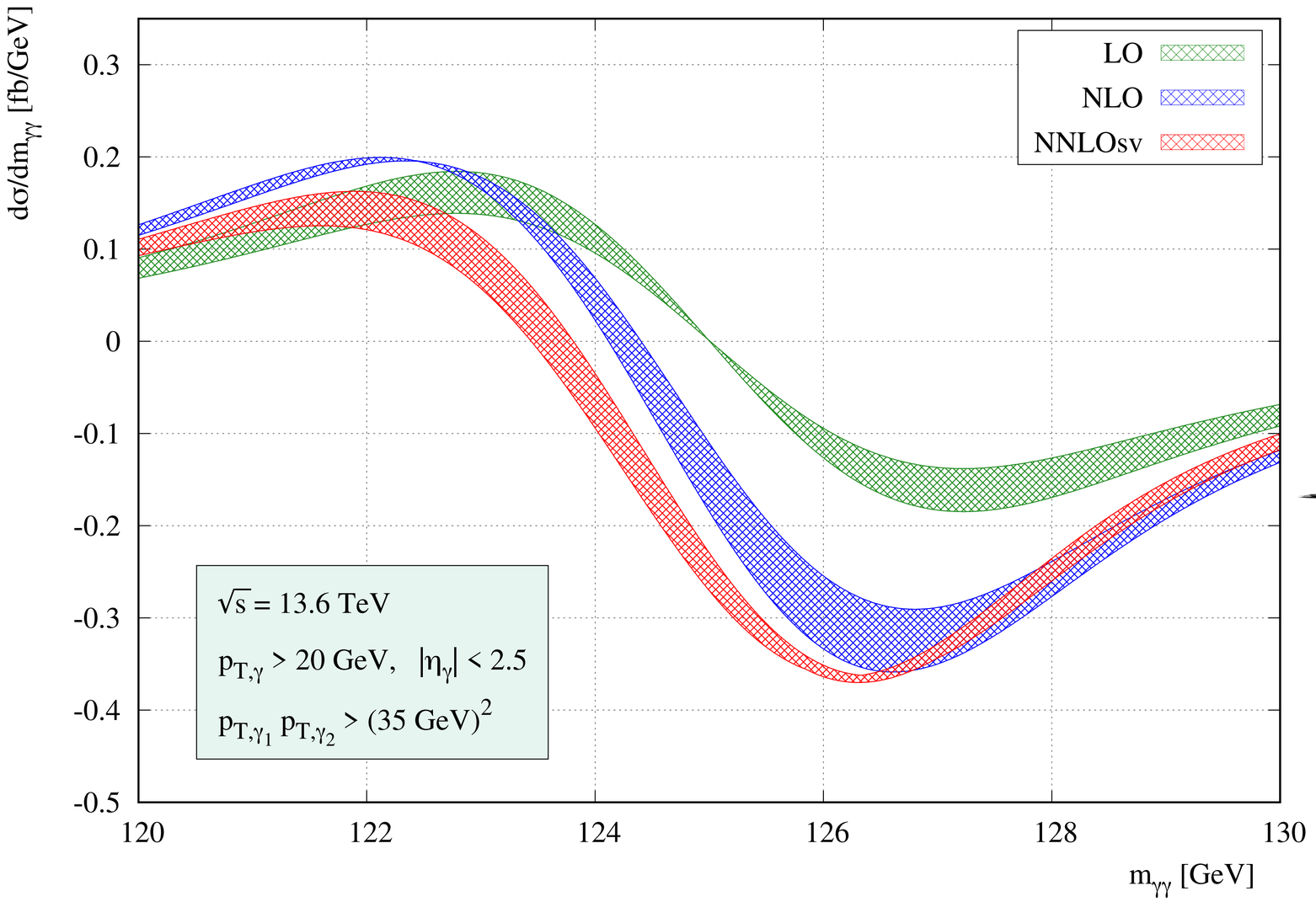


gg only



all channels

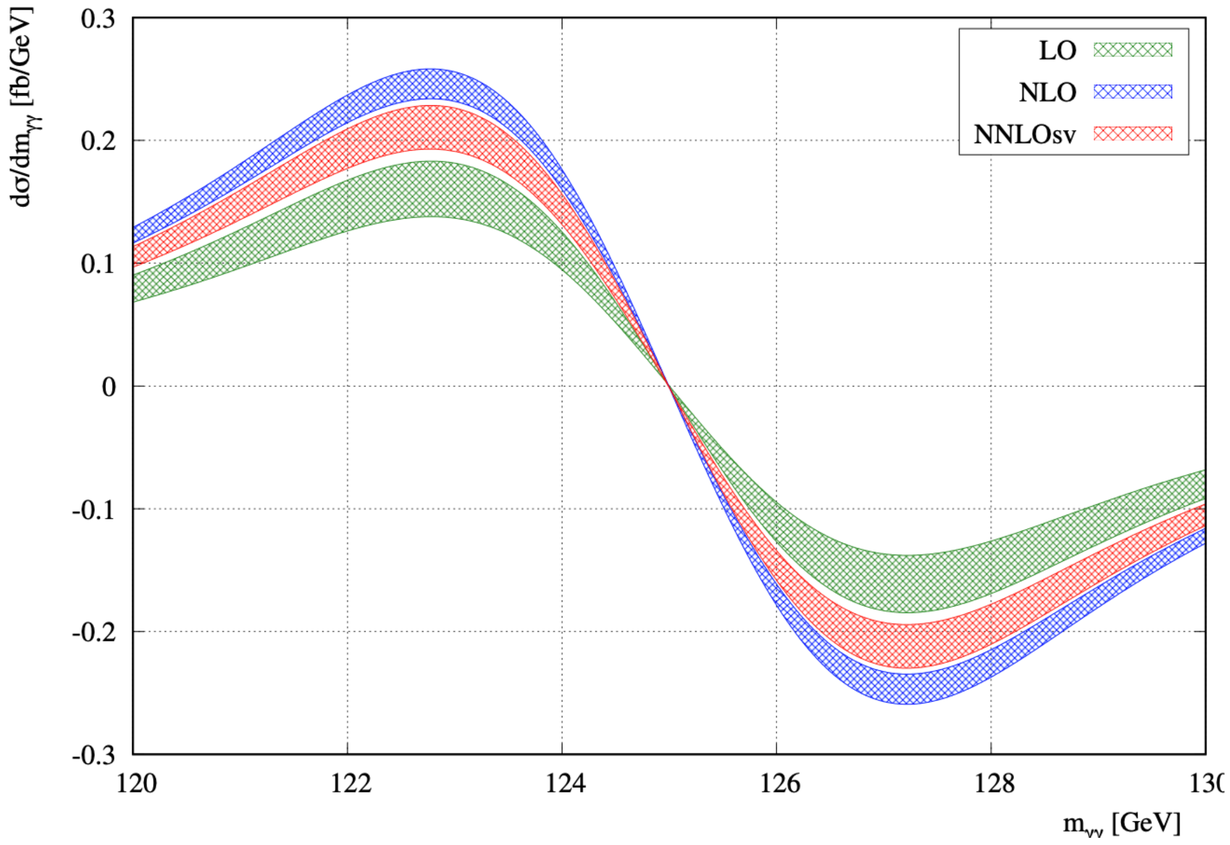
Results: Interference @NNLOsv

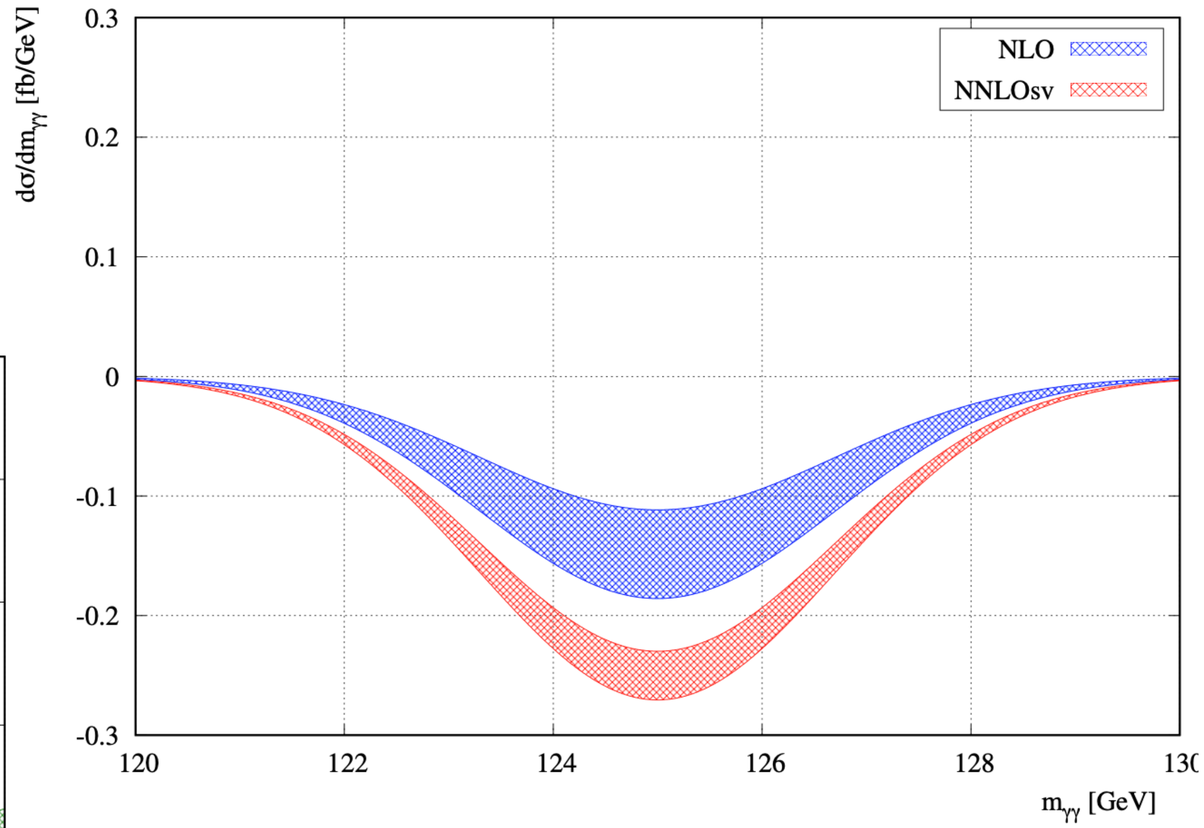


- imaginary parts of two and three loop amplitudes shift distribution to the left
- NNLO corrections not captured by the NLO uncertainty bands

Gaussian smearing with standard deviation $\sigma = 1.7\,\text{GeV}$ to simulate detector resolution

Real part of interference





Imaginary part of interference

Destructive interference @ NNLOsv ~ -1.5 %

Results: Mass shift @NNLO soft-virtual

ΔM [MeV]	7 TeV	8 TeV	13.6 TeV
LO	$-111.0^{+0.7\%}_{-0.9\%}$	$-114.1^{+0.5\%}_{-0.7\%}$	$-123.2^{+0.1\%}_{-0.2\%}$
NLO	$-82.0^{+13\%}_{-15\%}$	$-82.3^{+12\%}_{-14\%}$	$-81.5^{+12\%}_{-12\%}$
NNLOsv	$-67.7^{+22\%}_{-26\%}$	$-68.2^{+20\%}_{-24\%}$	$-67.9^{+17\%}_{-20\%}$

First moment method

$$\Delta M_{(N)NLO} = \Delta M_{\rm LO}\, K_{(N)NLO}$$

Results: Mass shift @NNLO soft-virtual

ΔM [MeV]	7 TeV	8 TeV	13.6 TeV
LO	$-111.0^{+0.7\%}_{-0.9\%}$	$-114.1^{+0.5\%}_{-0.7\%}$	$-123.2^{+0.1\%}_{-0.2\%}$
NLO	$-82.0^{+13\%}_{-15\%}$	$-82.3^{+12\%}_{-14\%}$	$-81.5^{+12\%}_{-12\%}$
NNLOsv	$-67.7^{+22\%}_{-26\%}$	$-68.2^{+20\%}_{-24\%}$	$-67.9^{+17\%}_{-20\%}$

First moment method

ΔM [MeV]	7 TeV	8 TeV	13.6 TeV
LO	$-75.6^{+0.7\%}_{-0.9\%}$	$-77.7^{+0.5\%}_{-0.7\%}$	$-83.8_{-0.2\%}$
NLO	$-55.8^{+13\%}_{-15\%}$	$-56.0^{+13\%}_{-14\%}$	$-55.4^{+12\%}_{-12\%}$
NNLOsv	$-46.1^{+22\%}_{-26\%}$	$-46.4^{+20\%}_{-24\%}$	$-46.2^{+17\%}_{-20\%}$

$$\Delta M_{(N)NLO} = \Delta M_{\rm LO}\, K_{(N)NLO}$$

Results: Mass shift @NNLO soft-virtual

ΔM [MeV]	7 TeV	8 TeV	13.6 TeV
LO	$-111.0^{+0.7\%}_{-0.9\%}$	$-114.1^{+0.5\%}_{-0.7\%}$	$-123.2^{+0.1\%}_{-0.2\%}$
NLO	$-82.0^{+13\%}_{-15\%}$	$-82.3^{+12\%}_{-14\%}$	$-81.5^{+12\%}_{-12\%}$
NNLOsv	$-67.7^{+22\%}_{-26\%}$	$-68.2^{+20\%}_{-24\%}$	$-67.9^{+17\%}_{-20\%}$

First moment method

ΔM [MeV]	7 TeV	8 TeV	13.6 TeV
LO	$-75.6^{+0.7\%}_{-0.9\%}$	$-77.7^{+0.5\%}_{-0.7\%}$	$-83.8_{-0.2\%}$
NLO	$-55.8^{+13\%}_{-15\%}$	$-56.0^{+13\%}_{-14\%}$	$-55.4^{+12\%}_{-12\%}$
NNLOsv	$-46.1^{+22\%}_{-26\%}$	$-46.4^{+20\%}_{-24\%}$	$-46.2^{+17\%}_{-20\%}$

Gaussian fit method

$$\Delta M_{(N)NLO} = \Delta M_{\rm LO}\, K_{(N)NLO}$$

Results: Mass shift @NNLO soft-virtual

ΔM [MeV]	7 TeV	8 TeV	13.6 TeV
LO	$-111.0^{+0.7\%}_{-0.9\%}$	$-114.1^{+0.5\%}_{-0.7\%}$	$-123.2^{+0.1\%}_{-0.2\%}$
NLO	$-82.0^{+13\%}_{-15\%}$	$-82.3^{+12\%}_{-14\%}$	$-81.5^{+12\%}_{-12\%}$
NNLOsv	$-67.7^{+22\%}_{-26\%}$	$-68.2^{+20\%}_{-24\%}$	$-67.9^{+17\%}_{-20\%}$

$\sim 34\,\%$

First moment method

ΔM [MeV]	7 TeV	8 TeV	13.6 TeV
LO	$-75.6^{+0.7\%}_{-0.9\%}$	$-77.7^{+0.5\%}_{-0.7\%}$	$-83.8_{-0.2\%}$
NLO	$-55.8^{+13\%}_{-15\%}$	$-56.0^{+13\%}_{-14\%}$	$-55.4^{+12\%}_{-12\%}$
NNLOsv	$-46.1^{+22\%}_{-26\%}$	$-46.4^{+20\%}_{-24\%}$	$-46.2^{+17\%}_{-20\%}$

Gaussian fit method

$$\Delta M_{(N)NLO} = \Delta M_{\rm LO}\, K_{(N)NLO}$$

Results: Mass shift @NNLO soft-virtual

ΔM [MeV]	7 TeV	8 TeV	13.6 TeV
LO	$-111.0^{+0.7\%}_{-0.9\%}$	$-114.1^{+0.5\%}_{-0.7\%}$	$-123.2^{+0.1\%}_{-0.2\%}$
NLO	$-82.0^{+13\%}_{-15\%}$	$-82.3^{+12\%}_{-14\%}$	$-81.5^{+12\%}_{-12\%}$
NNLOsv	$-67.7^{+22\%}_{-26\%}$	$-68.2^{+20\%}_{-24\%}$	$-67.9^{+17\%}_{-20\%}$

First moment method

$\sim 34\,\%$

$\sim 17\,\%$

ΔM [MeV]	7 TeV	8 TeV	13.6 TeV
LO	$-75.6^{+0.7\%}_{-0.9\%}$	$-77.7^{+0.5\%}_{-0.7\%}$	$-83.8_{-0.2\%}$
NLO	$-55.8^{+13\%}_{-15\%}$	$-56.0^{+13\%}_{-14\%}$	$-55.4^{+12\%}_{-12\%}$
NNLOsv	$-46.1^{+22\%}_{-26\%}$	$-46.4^{+20\%}_{-24\%}$	$-46.2^{+17\%}_{-20\%}$

Gaussian fit method

$$\Delta M_{(N)NLO} = \Delta M_{\rm LO}\, K_{(N)NLO}$$

Results: Mass shift @NNLO soft-virtual

ΔM [MeV]	7 TeV	8 TeV	13.6 TeV
LO	$-111.0^{+0.7\%}_{-0.9\%}$	$-114.1^{+0.5\%}_{-0.7\%}$	$-123.2^{+0.1\%}_{-0.2\%}$
NLO	$-82.0^{+13\%}_{-15\%}$	$-82.3^{+12\%}_{-14\%}$	$-81.5^{+12\%}_{-12\%}$
NNLOsv	$-67.7^{+22\%}_{-26\%}$	$-68.2^{+20\%}_{-24\%}$	$-67.9^{+17\%}_{-20\%}$

First moment method

$\sim 34\,\%$

$\sim 17\,\%$

Starting to converge..

ΔM [MeV]	7 TeV	8 TeV	13.6 TeV
LO	$-75.6^{+0.7\%}_{-0.9\%}$	$-77.7^{+0.5\%}_{-0.7\%}$	$-83.8_{-0.2\%}$
NLO	$-55.8^{+13\%}_{-15\%}$	$-56.0^{+13\%}_{-14\%}$	$-55.4^{+12\%}_{-12\%}$
NNLOsv	$-46.1^{+22\%}_{-26\%}$	$-46.4^{+20\%}_{-24\%}$	$-46.2^{+17\%}_{-20\%}$

Gaussian fit method

$$\Delta M_{(N)NLO} = \Delta M_{\rm LO}\, K_{(N)NLO}$$

Results: Mass shift @NNLO soft-virtual

ΔM [MeV]	7 TeV	8 TeV	13.6 TeV
LO	$-111.0^{+0.7\%}_{-0.9\%}$	$-114.1^{+0.5\%}_{-0.7\%}$	$-123.2^{+0.1\%}_{-0.2\%}$
NLO	$-82.0^{+13\%}_{-15\%}$	$-82.3^{+12\%}_{-14\%}$	$-81.5^{+12\%}_{-12\%}$
NNLOsv	$-67.7^{+22\%}_{-26\%}$	$-68.2^{+20\%}_{-24\%}$	$-67.9^{+17\%}_{-20\%}$

First moment method

$\sim 34\,\%$

$\sim 17\,\%$

Starting to converge..

ΔM [MeV]	7 TeV	8 TeV	13.6 TeV
LO	$-75.6^{+0.7\%}_{-0.9\%}$	$-77.7^{+0.5\%}_{-0.7\%}$	$-83.8_{-0.2\%}$
NLO	$-55.8^{+13\%}_{-15\%}$	$-56.0^{+13\%}_{-14\%}$	$-55.4^{+12\%}_{-12\%}$
NNLOsv	$-46.1^{+22\%}_{-26\%}$	$-46.4^{+20\%}_{-24\%}$	$-46.2^{+17\%}_{-20\%}$

Gaussian fit method

ΔM [MeV]	First moment	Gaussian Fit
$K_{\rm NLO}$	0.662	0.662
$K_{\rm NNLOsv}$	0.551	0.552

$$\Delta M_{(N)NLO} = \Delta M_{\rm LO}\, K_{(N)NLO}$$

Results: Mass shift @NNLO soft-virtual

ΔM [MeV]	7 TeV	8 TeV	13.6 TeV
LO	$-111.0^{+0.7\%}_{-0.9\%}$	$-114.1^{+0.5\%}_{-0.7\%}$	$-123.2^{+0.1\%}_{-0.2\%}$
NLO	$-82.0^{+13\%}_{-15\%}$	$-82.3^{+12\%}_{-14\%}$	$-81.5^{+12\%}_{-12\%}$
NNLOsv	$-67.7^{+22\%}_{-26\%}$	$-68.2^{+20\%}_{-24\%}$	$-67.9^{+17\%}_{-20\%}$

First moment method

$\sim 34\,\%$

$\sim 17\,\%$

Starting to converge..

ΔM [MeV]	7 TeV	8 TeV	13.6 TeV
LO	$-75.6^{+0.7\%}_{-0.9\%}$	$-77.7^{+0.5\%}_{-0.7\%}$	$-83.8_{-0.2\%}$
NLO	$-55.8^{+13\%}_{-15\%}$	$-56.0^{+13\%}_{-14\%}$	$-55.4^{+12\%}_{-12\%}$
NNLOsv	$-46.1^{+22\%}_{-26\%}$	$-46.4^{+20\%}_{-24\%}$	$-46.2^{+17\%}_{-20\%}$

Gaussian fit method

ΔM [MeV]	First moment	Gaussian Fit
$K_{\rm NLO}$	0.662	0.662
$K_{\rm NNLOsv}$	0.551	0.552

$$\Delta M_{(N)NLO} = \Delta M_{\rm LO}\, K_{(N)NLO}$$

Results: Mass shift @NNLO soft-virtual

ΔM [MeV]	7 TeV	8 TeV	13.6 TeV
LO	$-111.0^{+0.7\%}_{-0.9\%}$	$-114.1^{+0.5\%}_{-0.7\%}$	$-123.2^{+0.1\%}_{-0.2\%}$
NLO	$-82.0^{+13\%}_{-15\%}$	$-82.3^{+12\%}_{-14\%}$	$-81.5^{+12\%}_{-12\%}$
NNLOsv	$-67.7^{+22\%}_{-26\%}$	$-68.2^{+20\%}_{-24\%}$	$-67.9^{+17\%}_{-20\%}$

First moment method

$\sim 34\,\%$

$\sim 17\,\%$

Starting to converge..

K-factors are insensitive to method used to extract mass-shift!

ΔM [MeV]	7 TeV	8 TeV	13.6 TeV
LO	$-75.6^{+0.7\%}_{-0.9\%}$	$-77.7^{+0.5\%}_{-0.7\%}$	$-83.8_{-0.2\%}$
NLO	$-55.8^{+13\%}_{-15\%}$	$-56.0^{+13\%}_{-14\%}$	$-55.4^{+12\%}_{-12\%}$
NNLOsv	$-46.1^{+22\%}_{-26\%}$	$-46.4^{+20\%}_{-24\%}$	$-46.2^{+17\%}_{-20\%}$

Gaussian fit method

ΔM [MeV]	First moment	Gaussian Fit
$K_{\rm NLO}$	0.662	0.662
$K_{\rm NNLOsv}$	0.551	0.552

$$\Delta M_{(N)NLO} = \Delta M_{\rm LO}\, K_{(N)NLO}$$

Conclusions and outlooks

- Mass-shift can be used to put bounds on the Higgs width
- We extended the existing analysis beyond NLO and included NNLO corrections in the soft-virtual approximation
- The NLO mass-shift is enhanced at low values of Higgs p_T , we expect the bulk of contribution coming from this region -> SV good approximation
- $K_{NNLOsv} = 0.55$
- Study of Higgs p_T distribution beyond LO in $gg \to H \to \gamma\gamma j$ would enable p_T dependent mass shift extraction (future work!)
- Ultimate goal is the exact calculation: would enable to perform a full analysis of interference effects

Thank you for your attention!

Back up slides

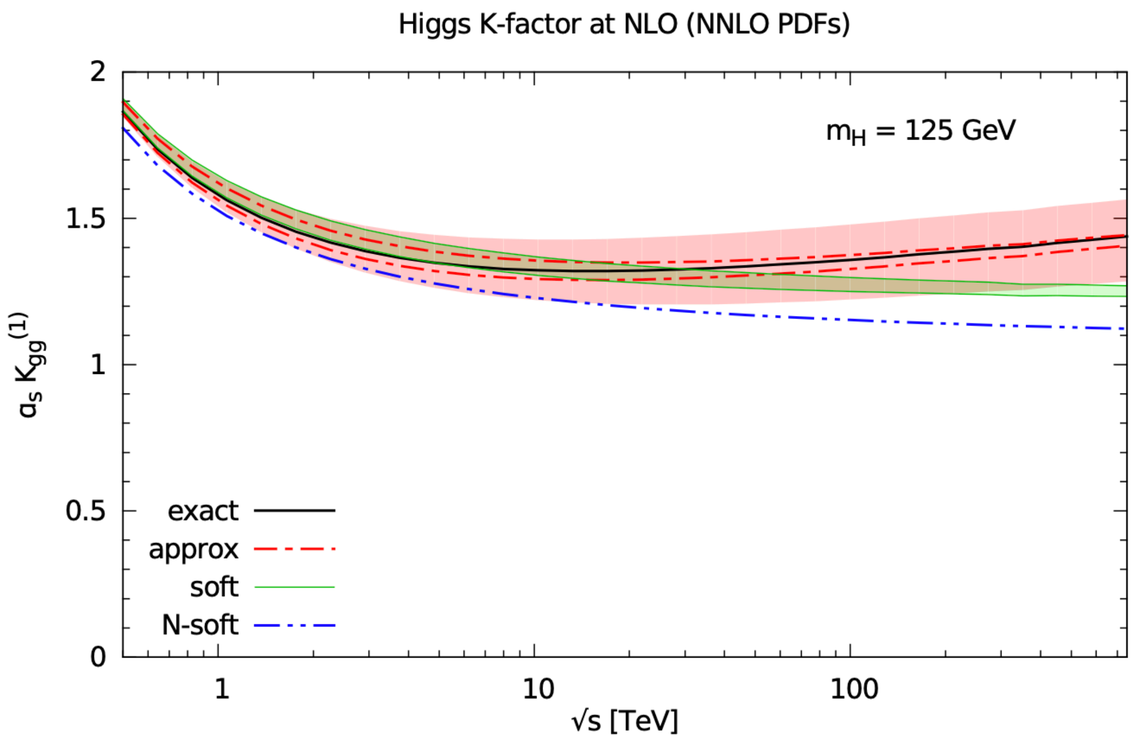
Validation of SV: signal

- Exact calculation available up to N3LO both inclusive [Anastasiou et al '15] and differential [Chen et al '21]
- Soft-virtual (SV) approximation studied extensively in the Higgs sector
- Known how to "tweak" it, i.e. retain subleading terms (which would naively vanish at threshold $z \to 1$)

We will use a "soft-collinear" approximation for the signal:

$$\mathscr{D}_i(z) \to \mathscr{D}_i(z) + \delta\mathscr{D}_i(z)$$

$$\delta\mathscr{D}_i(z) = (2 - 3z + 2z^2)\frac{\log^i((1-z)/\sqrt{z})}{1-z} - \frac{\log^i(1-z)}{1-z}$$



[Ball,Bonvini,Forte,Marzani,Ridolfi '14]

"NNLOsv'"

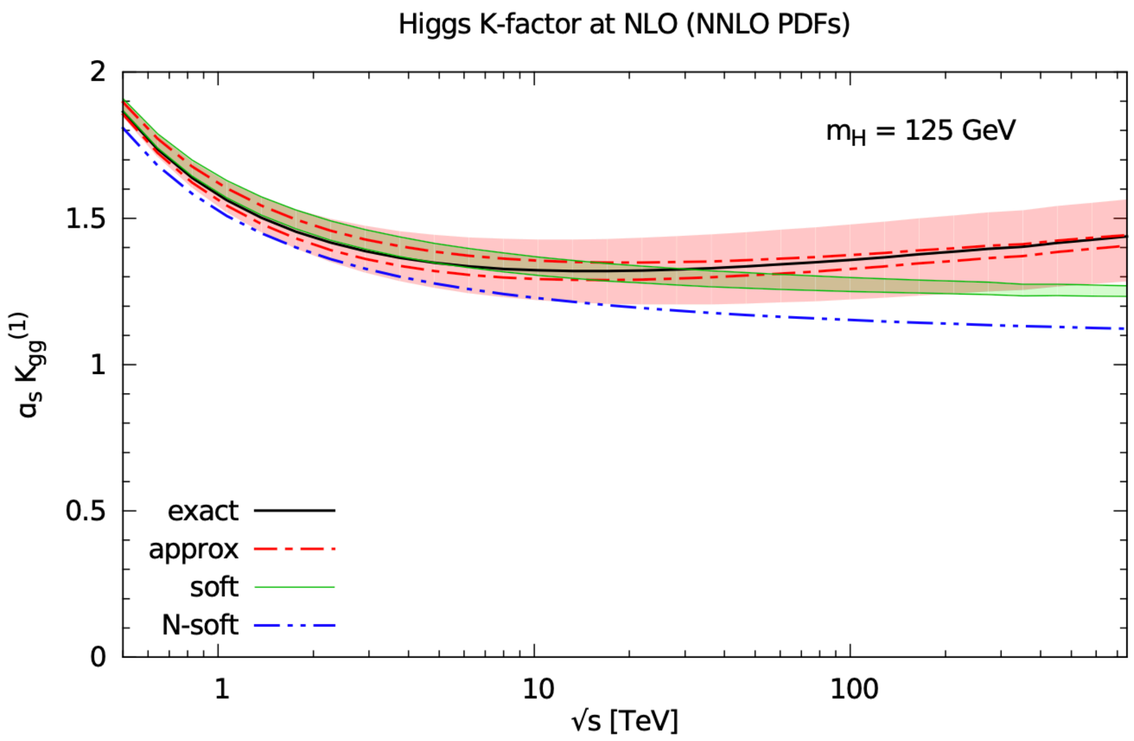
Validation of SV: signal

- Exact calculation available up to N3LO both inclusive [Anastasiou et al '15] and differential [Chen et al '21]
- Soft-virtual (SV) approximation studied extensively in the Higgs sector
- Known how to "tweak" it, i.e. retain subleading terms (which would naively vanish at threshold $z \to 1$)

We will use a "soft-collinear" approximation for the signal:

$$\mathscr{D}_i(z) \to \mathscr{D}_i(z) + \delta\mathscr{D}_i(z)$$

$$\delta\mathscr{D}_i(z) = (2 - 3z + 2z^2)\frac{\log^i((1-z)/\sqrt{z})}{1-z} - \frac{\log^i(1-z)}{1-z}$$



[Ball,Bonvini,Forte,Marzani,Ridolfi '14]

"NNLOsv'"

Validation of SV: signal

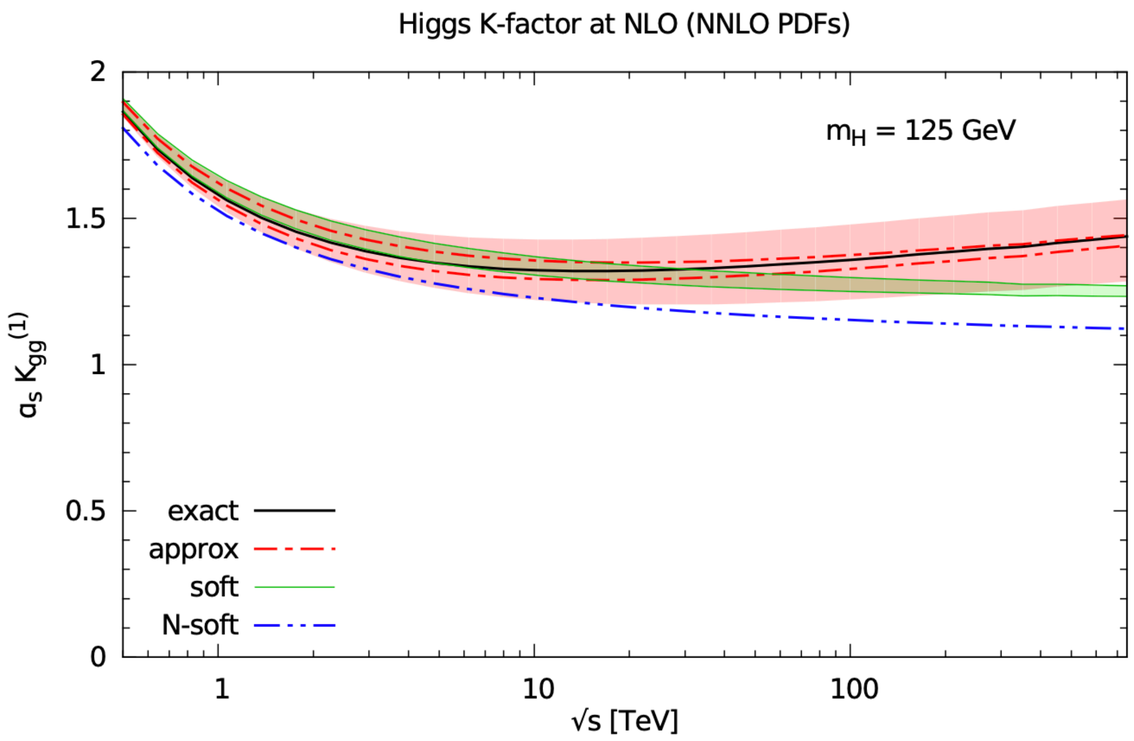
- Exact calculation available up to N3LO both inclusive [Anastasiou et al '15] and differential [Chen et al '21]
- Soft-virtual (SV) approximation studied extensively in the Higgs sector
- Known how to "tweak" it, i.e. retain subleading terms (which would naively vanish at threshold $z \to 1$)

We will use a "soft-collinear" approximation for the signal:

$$\mathscr{D}_i(z) \to \mathscr{D}_i(z) + \delta\mathscr{D}_i(z)$$

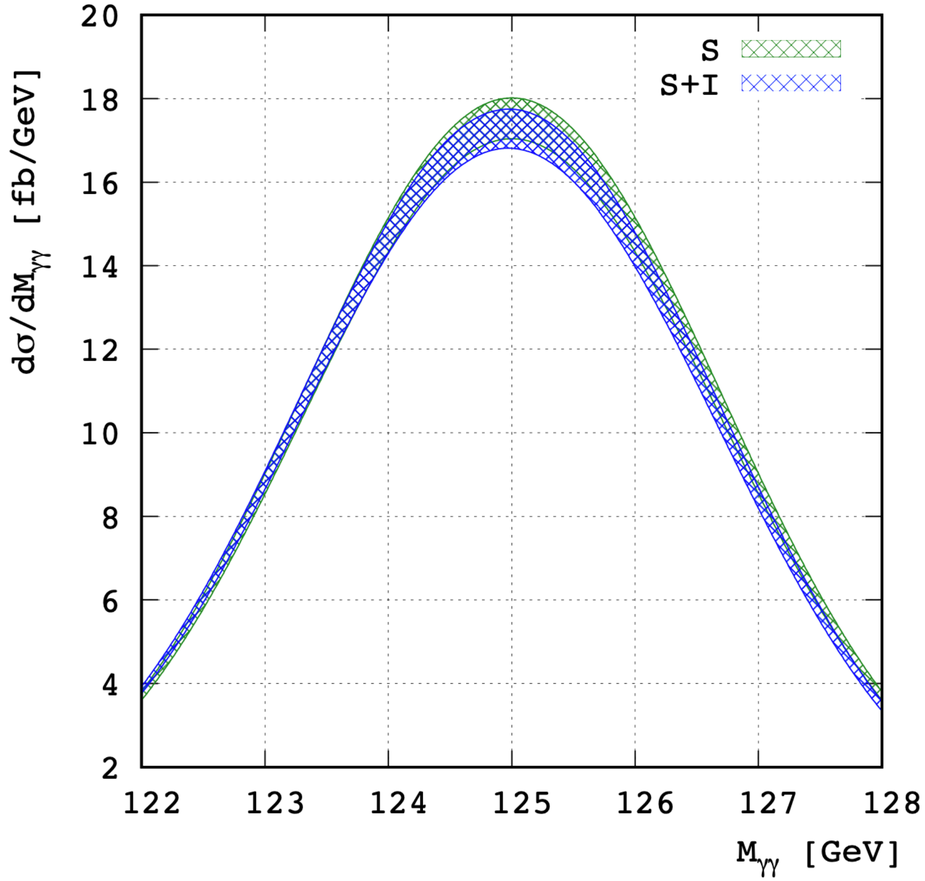
$$\delta\mathscr{D}_i(z) = (2 - 3z + 2z^2)\frac{\log^i((1-z)/\sqrt{z})}{1-z} - \frac{\log^i(1-z)}{1-z}$$

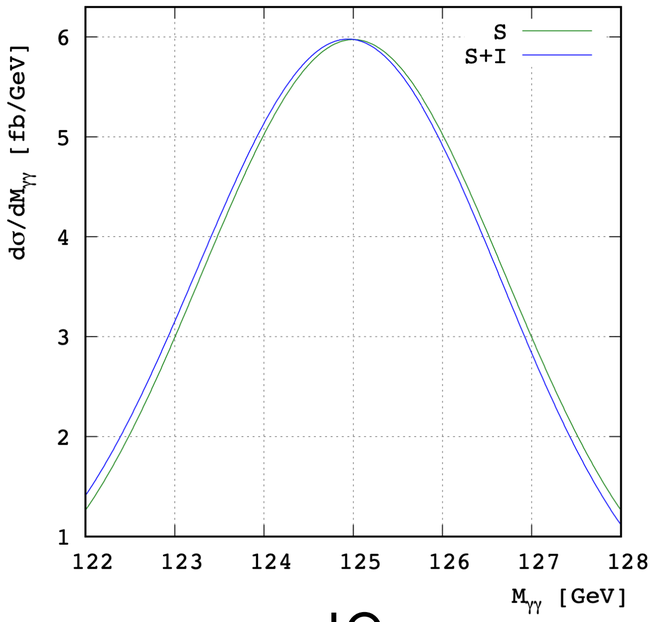
"NNLOsv'"



[Ball,Bonvini,Forte,Marzani,Ridolfi '14]

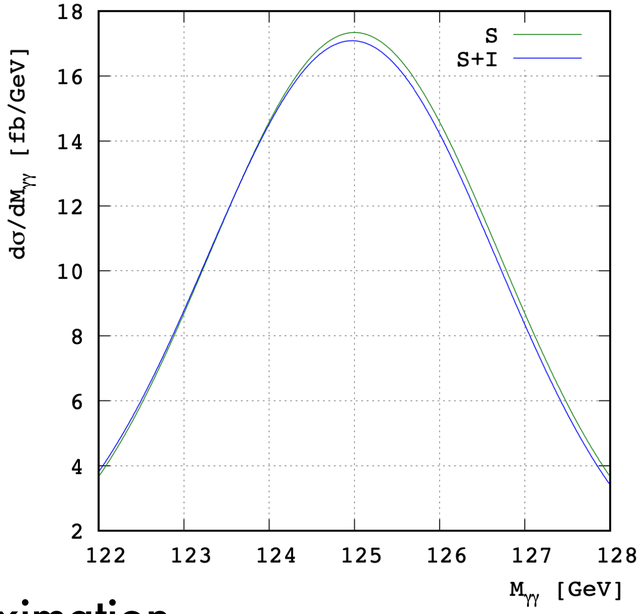
Results: Mass shift @NNLO soft-virtual





LO

NNLOsv′



NNLOsv′: - interference in SV approximation
- signal in SV "improved" approximation

ΔM [MeV]	7 TeV	8 TeV	13.6 TeV
LO	$-75.6^{+0.7\%}_{-0.9\%}$	$-77.7^{+0.5\%}_{-0.7\%}$	$-83.8_{-0.2\%}$
NLO	$-55.8^{+13\%}_{-15\%}$	$-56.0^{+13\%}_{-14\%}$	$-55.4^{+12\%}_{-12\%}$
NNLOsv	$-46.1^{+22\%}_{-26\%}$	$-46.4^{+20\%}_{-24\%}$	$-46.2^{+17\%}_{-20\%}$
NNLOsv$'$	$-39.4^{+13\%}_{-20\%}$	$-39.7^{+11\%}_{-19\%}$	$-39.6^{+7.8\%}_{-14\%}$

ΔM [MeV]	7 TeV	8 TeV	13.6 TeV
LO	$-111.0^{+0.7\%}_{-0.9\%}$	$-114.1^{+0.5\%}_{-0.7\%}$	$-123.2^{+0.1\%}_{-0.2\%}$
NLO	$-82.0^{+13\%}_{-15\%}$	$-82.3^{+12\%}_{-14\%}$	$-81.5^{+12\%}_{-12\%}$
NNLOsv	$-67.7^{+22\%}_{-26\%}$	$-68.2^{+20\%}_{-24\%}$	$-67.9^{+17\%}_{-20\%}$
NNLOsv$'$	$-57.9^{+12\%}_{-20\%}$	$-58.4^{+11\%}_{-18\%}$	$-58.2^{+7.8\%}_{-14\%}$

First moment method

ΔM [MeV]	7 TeV	8 TeV	13.6 TeV
LO	$-75.6^{+0.7\%}_{-0.9\%}$	$-77.7^{+0.5\%}_{-0.7\%}$	$-83.8_{-0.2\%}$
NLO	$-55.8^{+13\%}_{-15\%}$	$-56.0^{+13\%}_{-14\%}$	$-55.4^{+12\%}_{-12\%}$
NNLOsv	$-46.1^{+22\%}_{-26\%}$	$-46.4^{+20\%}_{-24\%}$	$-46.2^{+17\%}_{-20\%}$
NNLOsv$'$	$-39.4^{+13\%}_{-20\%}$	$-39.7^{+11\%}_{-19\%}$	$-39.6^{+7.8\%}_{-14\%}$

Gaussian fit method

ΔM [MeV]	7 TeV	8 TeV	13.6 TeV
LO	$-111.0^{+0.7\%}_{-0.9\%}$	$-114.1^{+0.5\%}_{-0.7\%}$	$-123.2^{+0.1\%}_{-0.2\%}$
NLO	$-82.0^{+13\%}_{-15\%}$	$-82.3^{+12\%}_{-14\%}$	$-81.5^{+12\%}_{-12\%}$
NNLOsv	$-67.7^{+22\%}_{-26\%}$	$-68.2^{+20\%}_{-24\%}$	$-67.9^{+17\%}_{-20\%}$
NNLOsv$'$	$-57.9^{+12\%}_{-20\%}$	$-58.4^{+11\%}_{-18\%}$	$-58.2^{+7.8\%}_{-14\%}$

First moment method