Interference studies in $H \to \gamma\gamma$

2212.06287, Eur.Phys.J.C 83 (2023) with P. Bargiela, F. Buccioni, F. Caola, A. Von Manteuffel, L. Tancredi

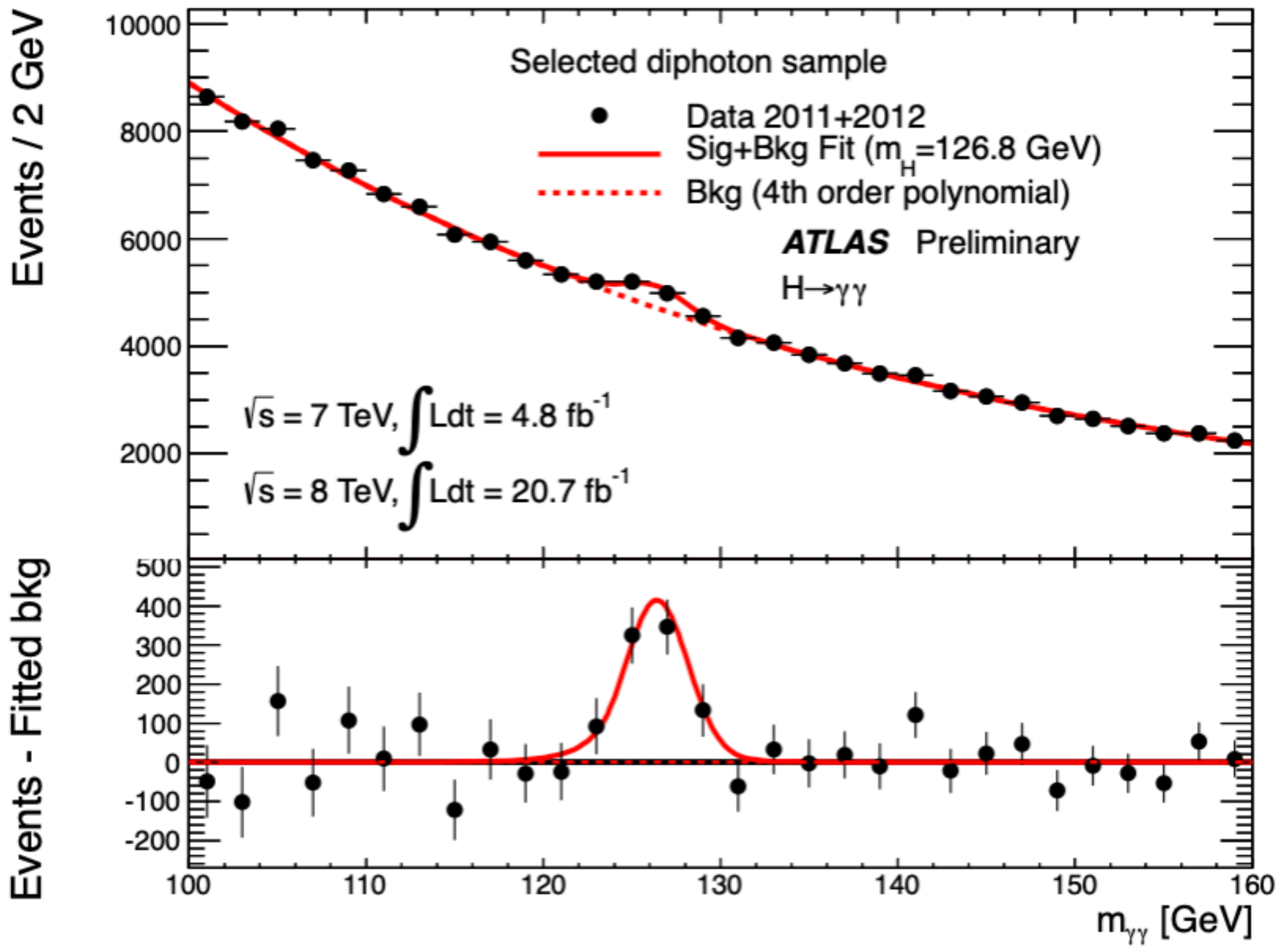
Federica Devoto

LoopFest XXI , 27/06/23

erc

UNIVERSITY OF OXFORD

We have a Higgs boson.



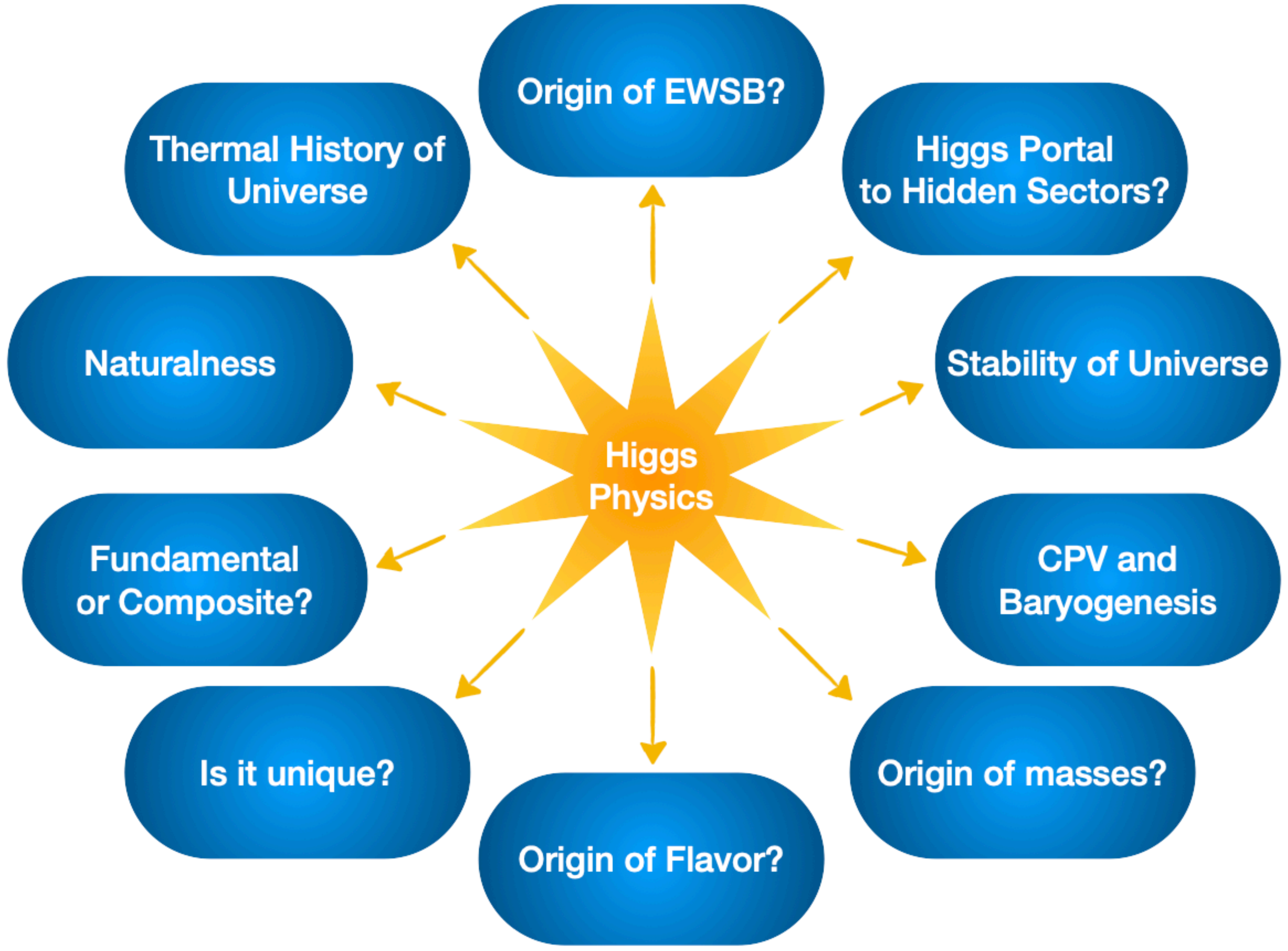


Image taken from Snowmass paper 2209.07510

- Mass
- Decay width → Focus of the talk
- CP properties
- Couplings to SM particles
- Self couplings

Caterina's talk yesterday

A measurement of the Higgs boson mass in the diphoton decay channel

The CMS Collaboration*

$$m_H = 125.78 \pm 0.26\,\text{GeV}.$$

nature physics

https://doi.org/10.103

OPEN

Measurement of the Higgs boson width and evidence of its off-shell contributions to ZZ production

The CMS Collaboration*

Higgs width @ hadron colliders

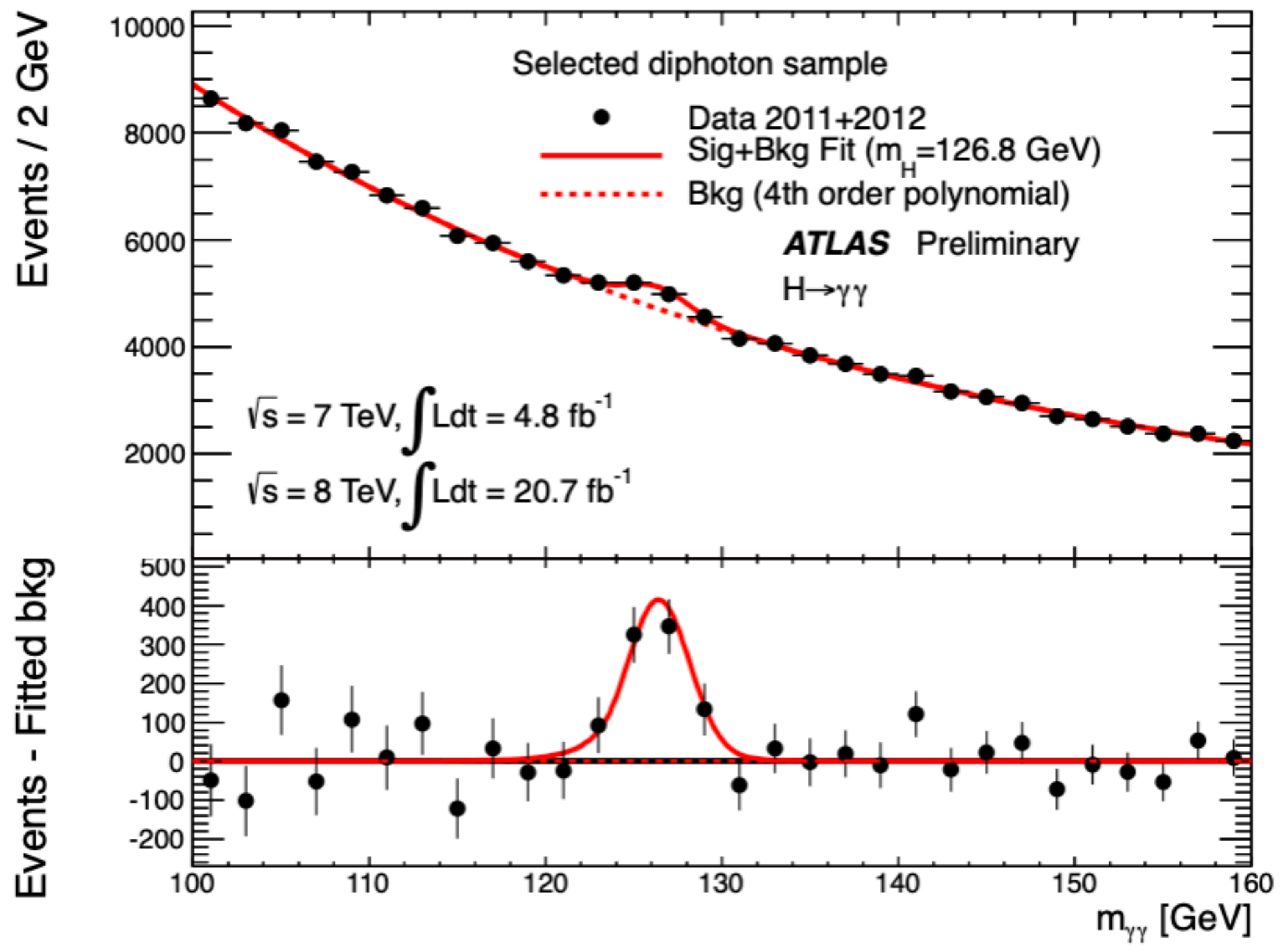
$$\boxed{\Gamma_H} = \frac{\hbar}{2\pi}\frac{1}{\boxed{\tau_H}}$$

$1.6 \times 10^{-22} s$

Too short for direct measurement

$4.1\,\mathrm{MeV}$

Too narrow for direct measurement



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

"Hope, hope, to the last!"

Charles Dickens, ~ Nicholas Nickleby

Try to place indirect bounds

On-shell cross sections

$$\sigma_{i \to H \to f} \sim \sigma_{i \to H}\, BR(H \to f) \overset{NWA}{\sim} \frac{\pi\, \lambda_i^2\, \lambda_f^2}{m_H\, \Gamma_H}$$

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

Intertwined couplings/width dependence

- On-shell → Off-shell [Caola, Melnikov '13]
- Exploit signal-background interference effects [Dixon, Li '13]

Bounding the Higgs Boson Width Through Interferometry

Lance J. Dixon[1] and Ye Li[1]
[1] *SLAC National Accelerator Laboratory, Stanford University, Stanford, CA 94309, USA*

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Bounding the Higgs Boson Width Through Interferometry

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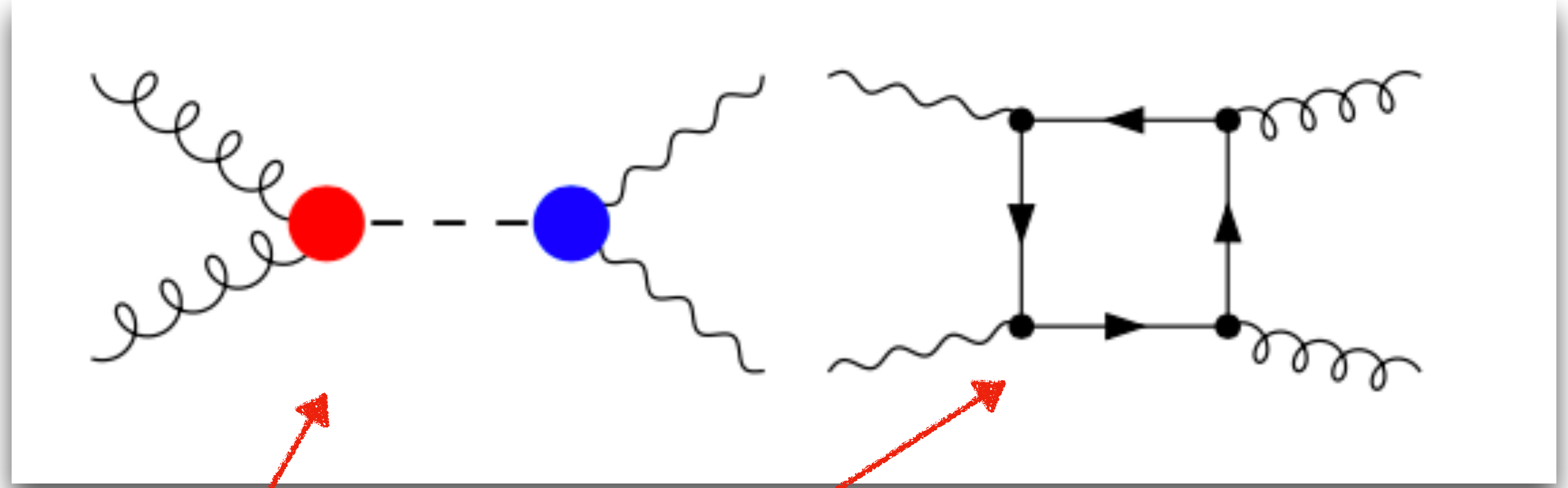
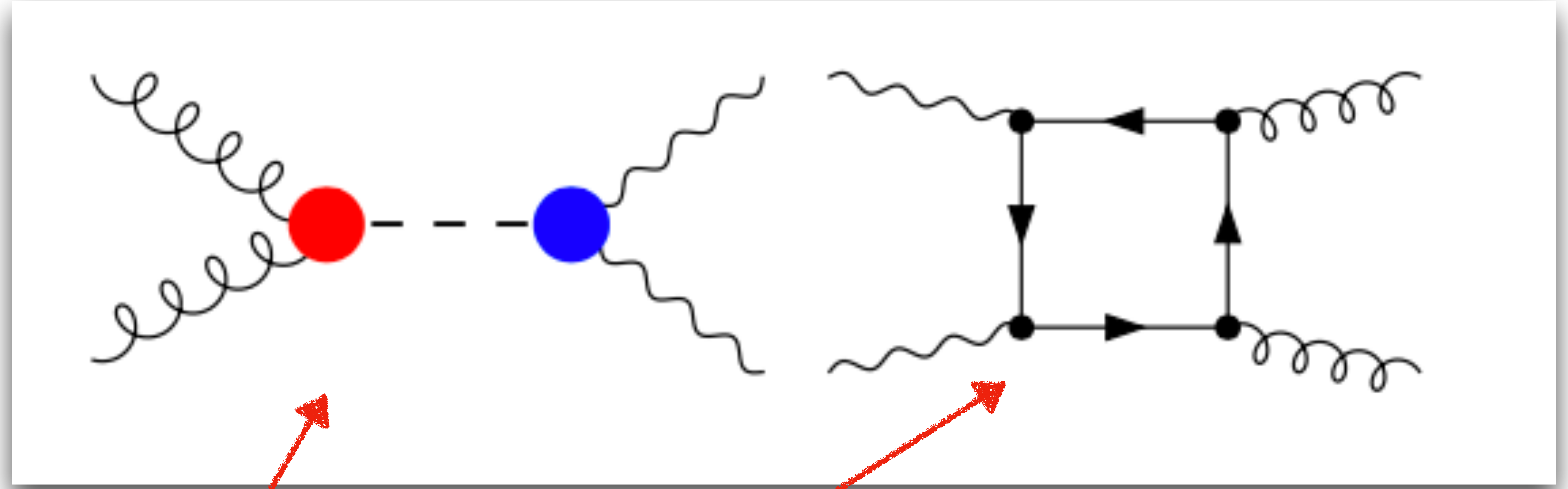
A tale of two amplitudes



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

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

A tale of two amplitudes



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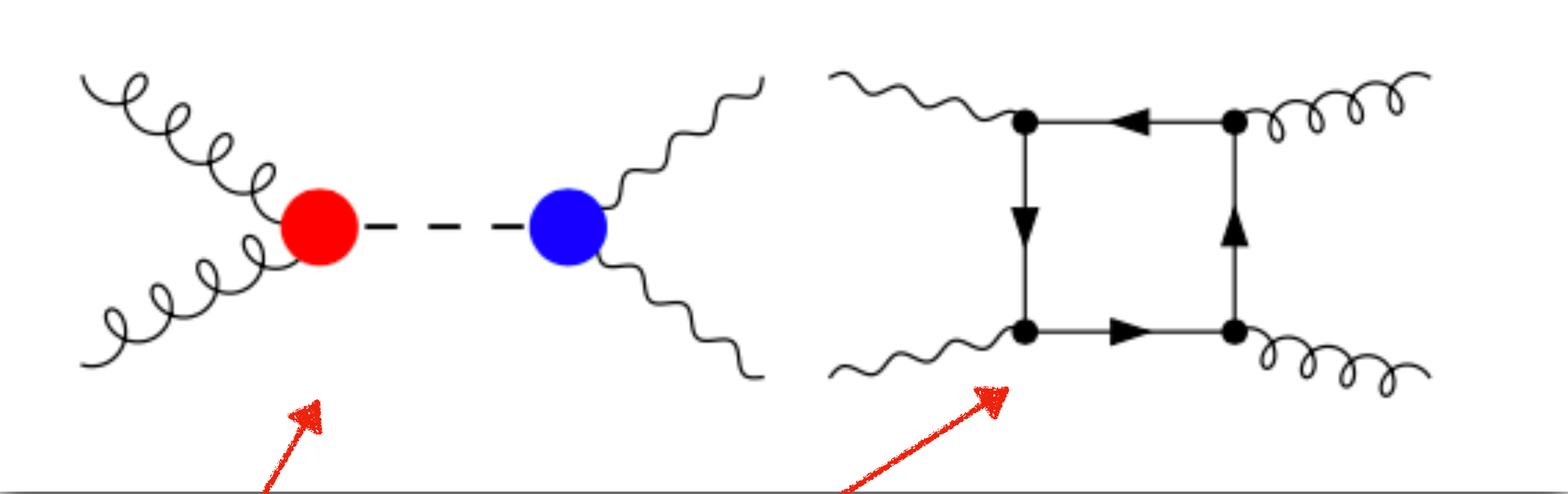

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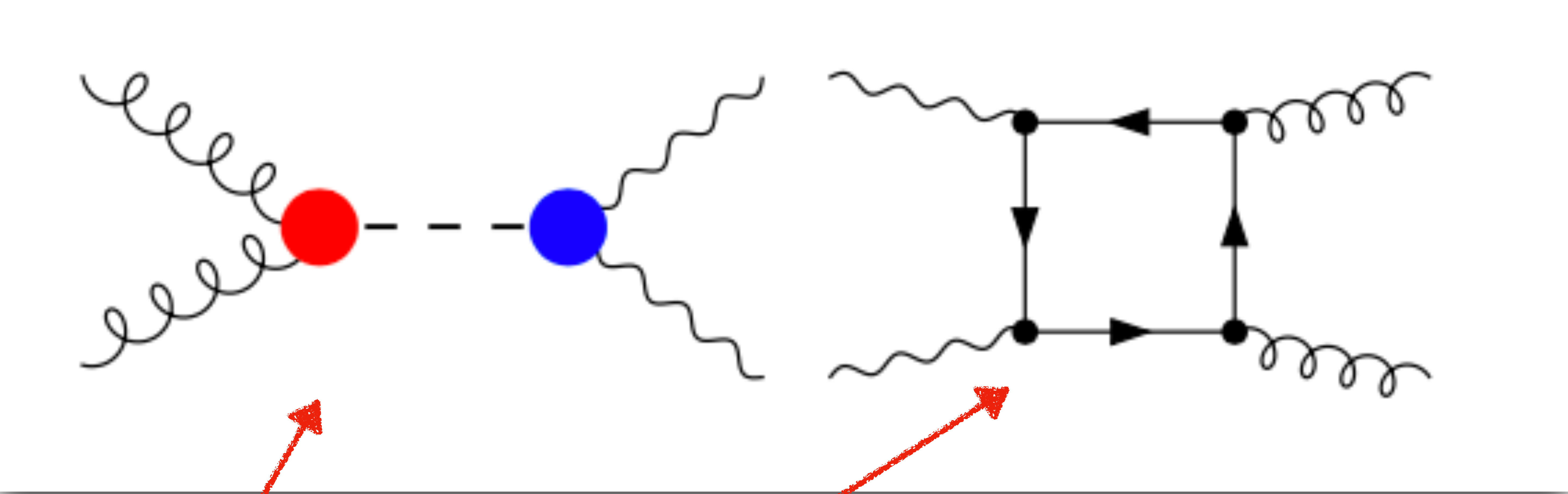

Signal-background interference

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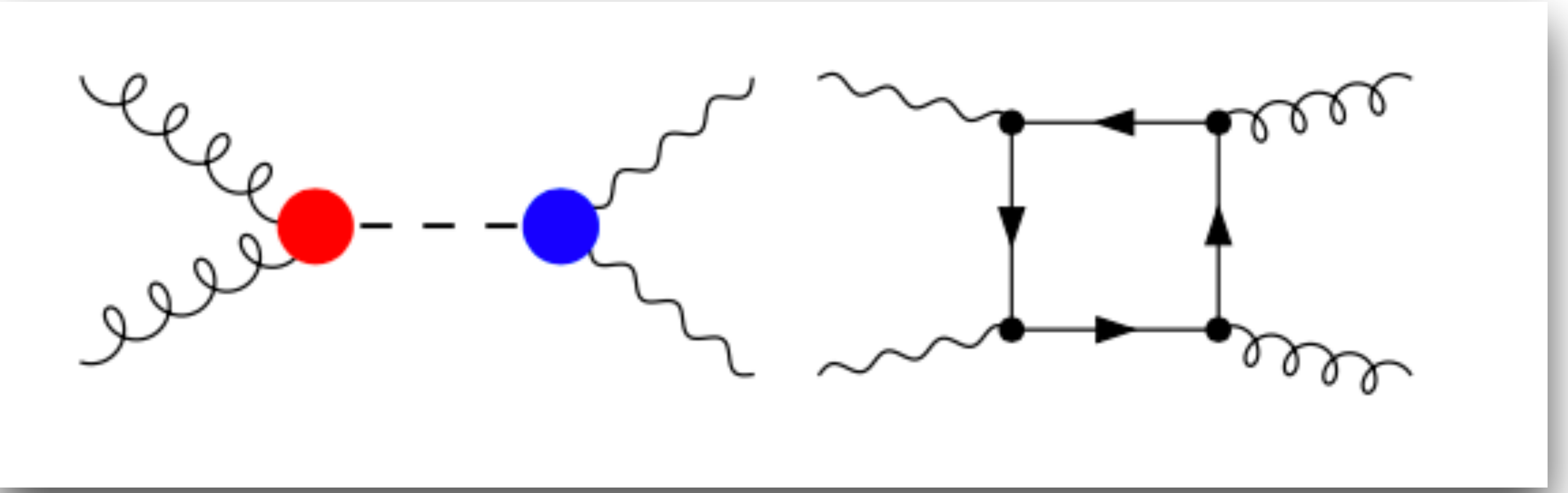

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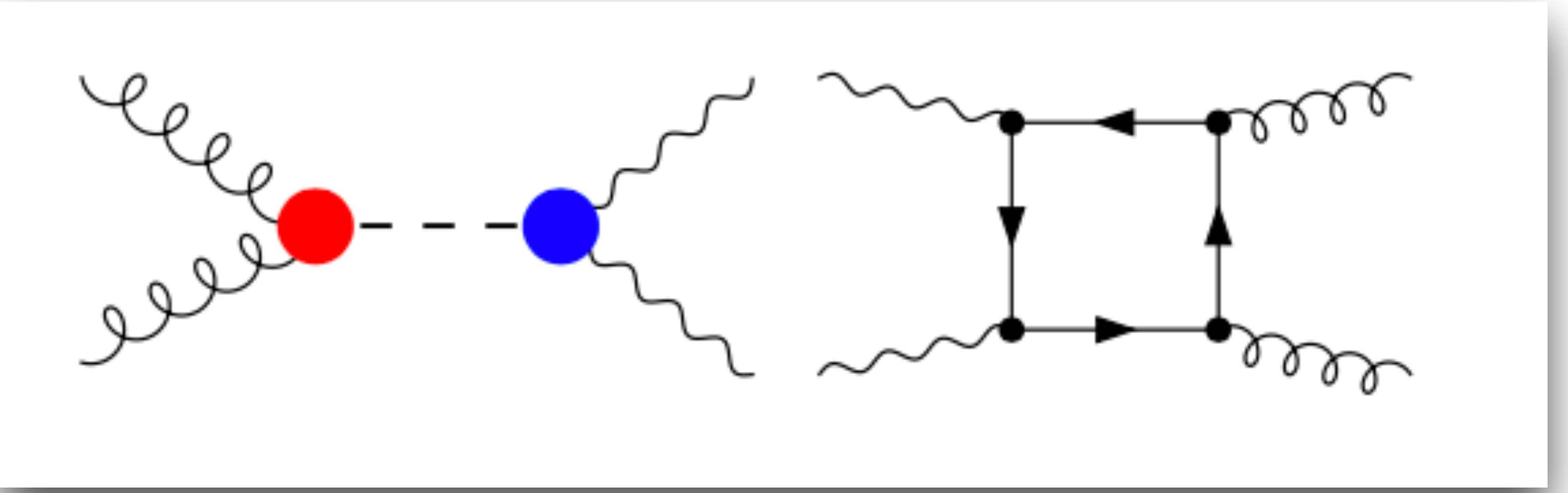

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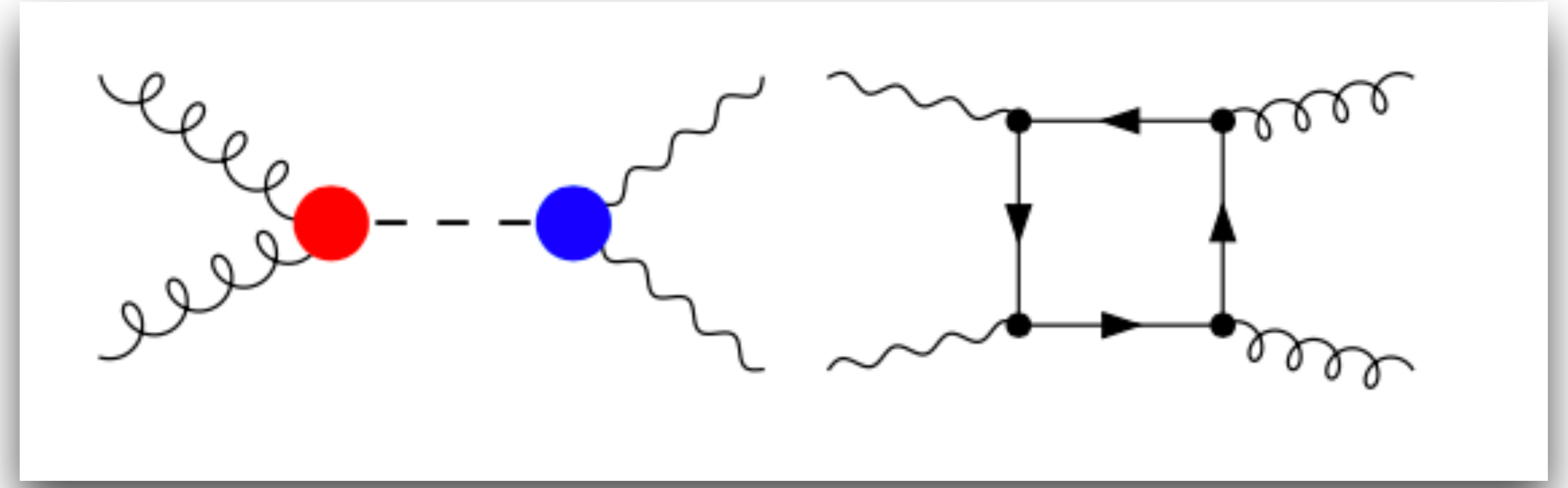

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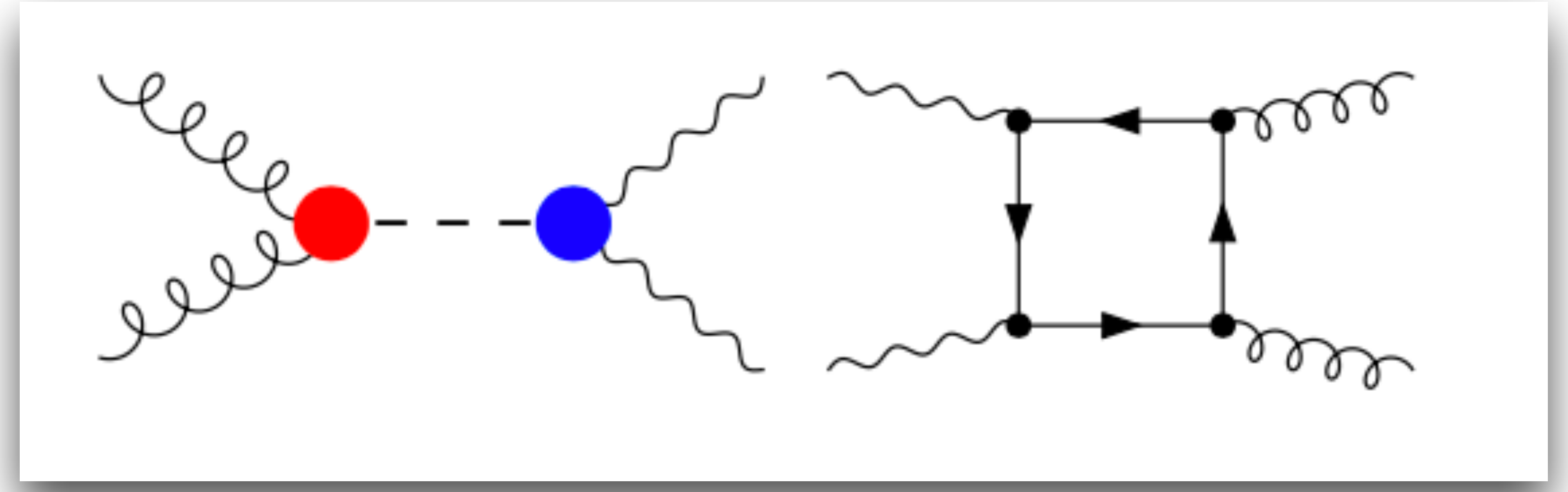

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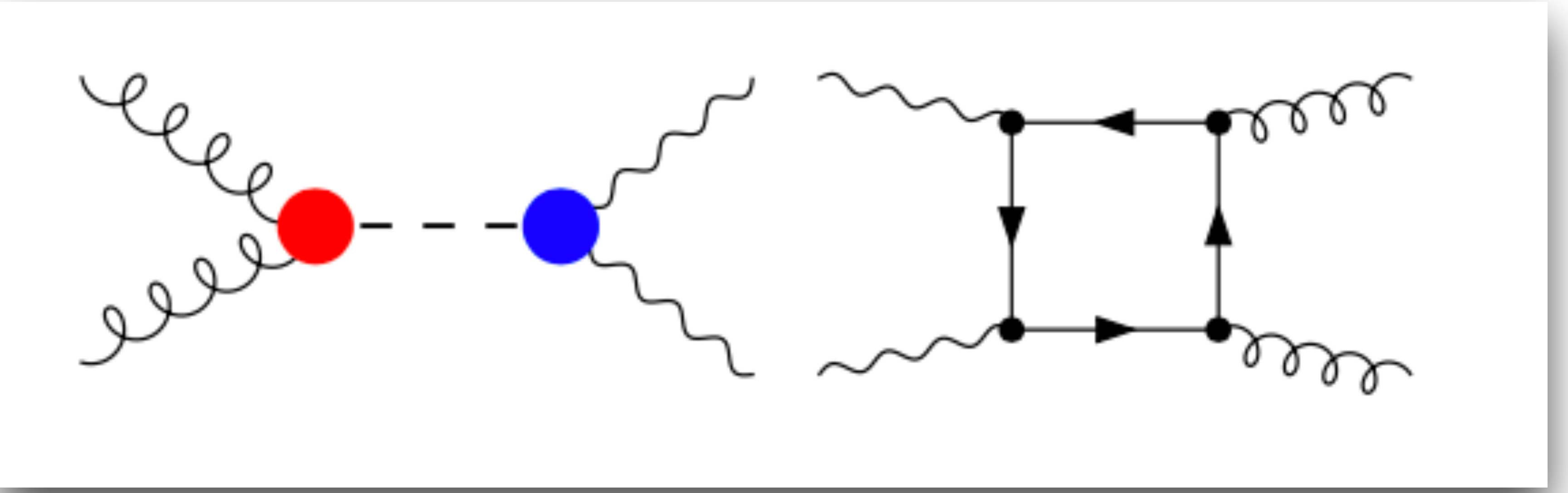

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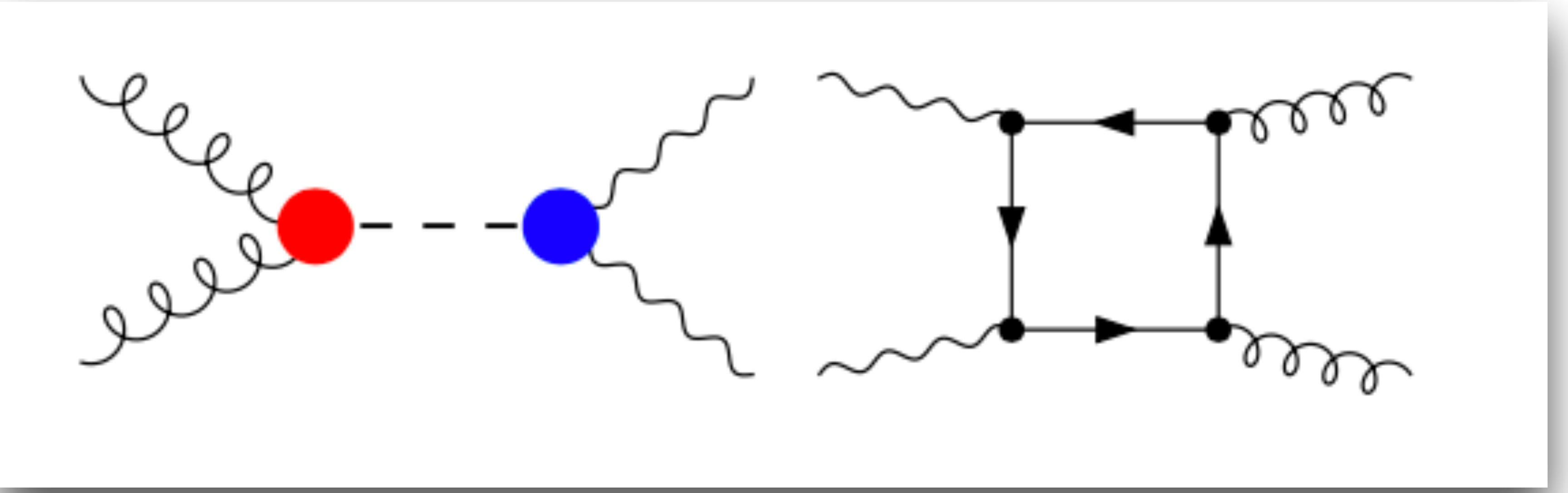

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$$I_{\mathrm{Re}} \propto \frac{2}{(m_{\gamma\gamma}^2 - m_H^2)^2 + \Gamma_H^2 m_H^2}\left(m_{\gamma\gamma}^2 - m_H^2\right) \times \times \left[\mathrm{Re}\mathcal{M}_{\mathrm{bkg}}\mathrm{Re}\mathcal{M}_{\mathrm{sig}} + \mathrm{Im}\mathcal{M}_{\mathrm{bkg}}\mathrm{Im}\mathcal{M}_{\mathrm{sig}}\right],$$

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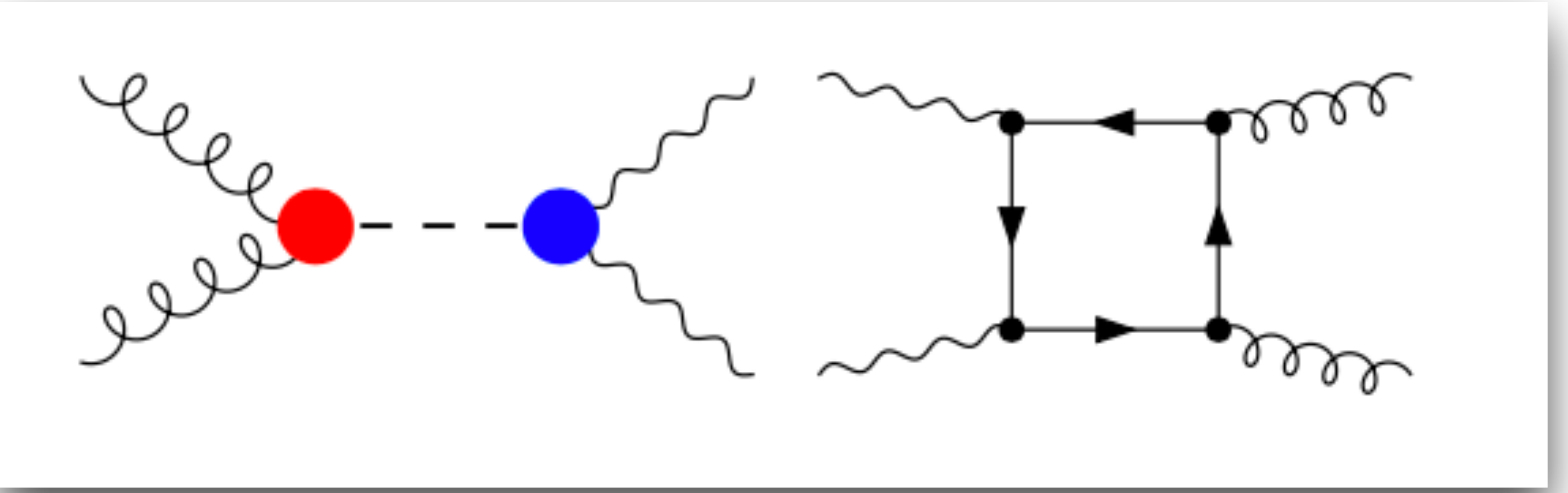

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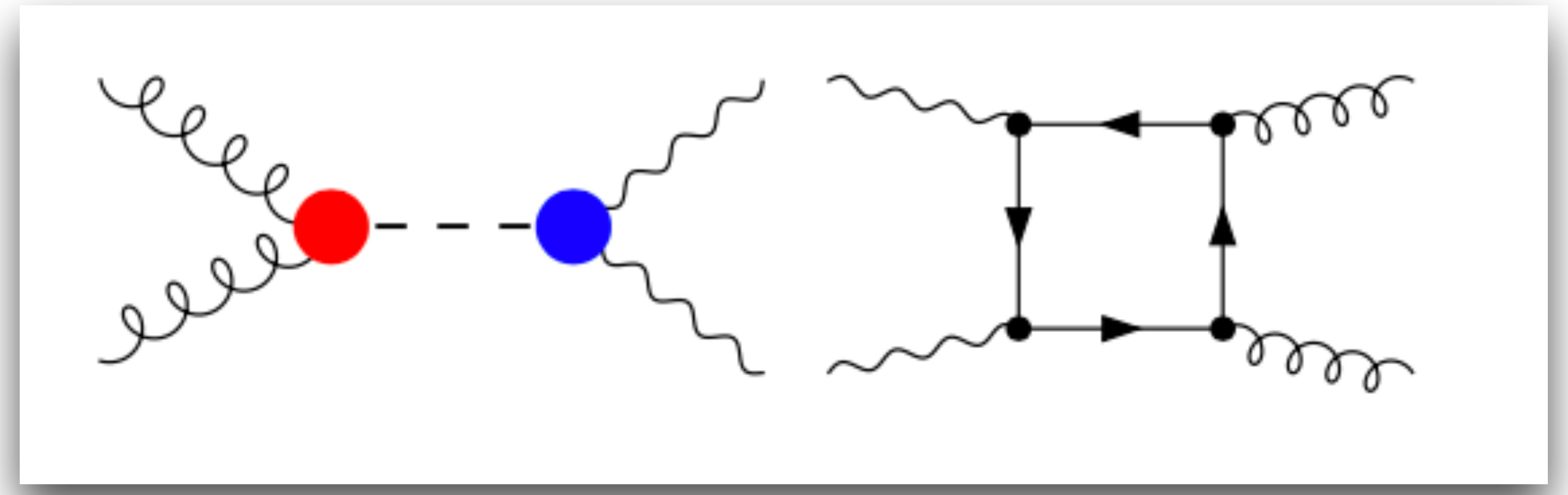

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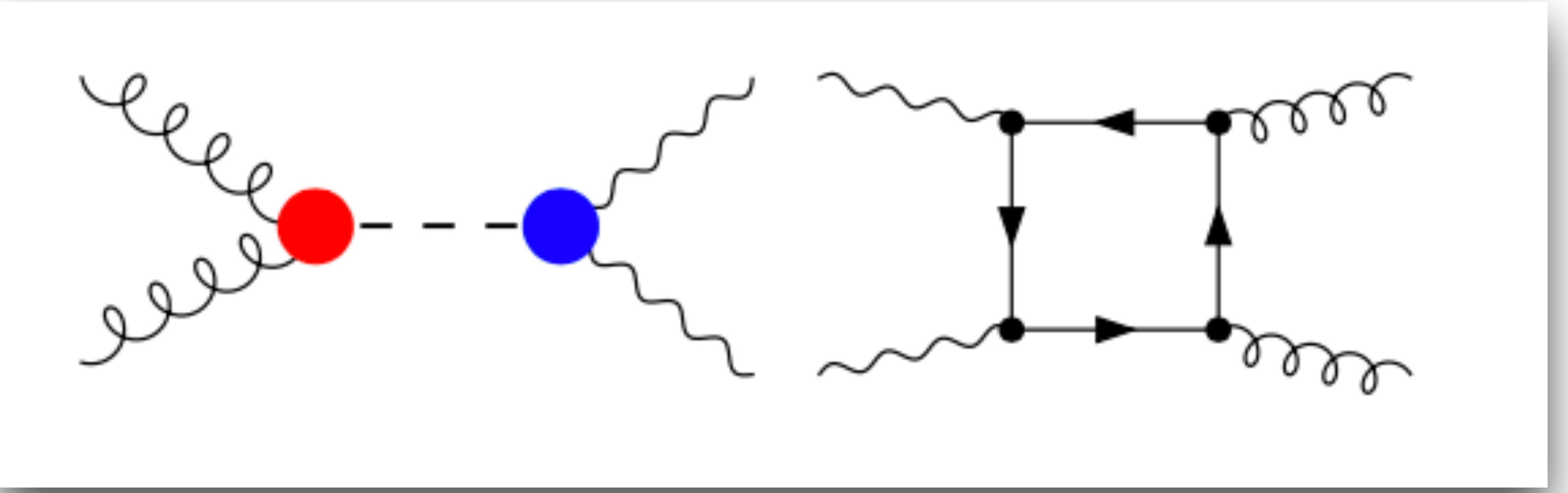

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“Real part”

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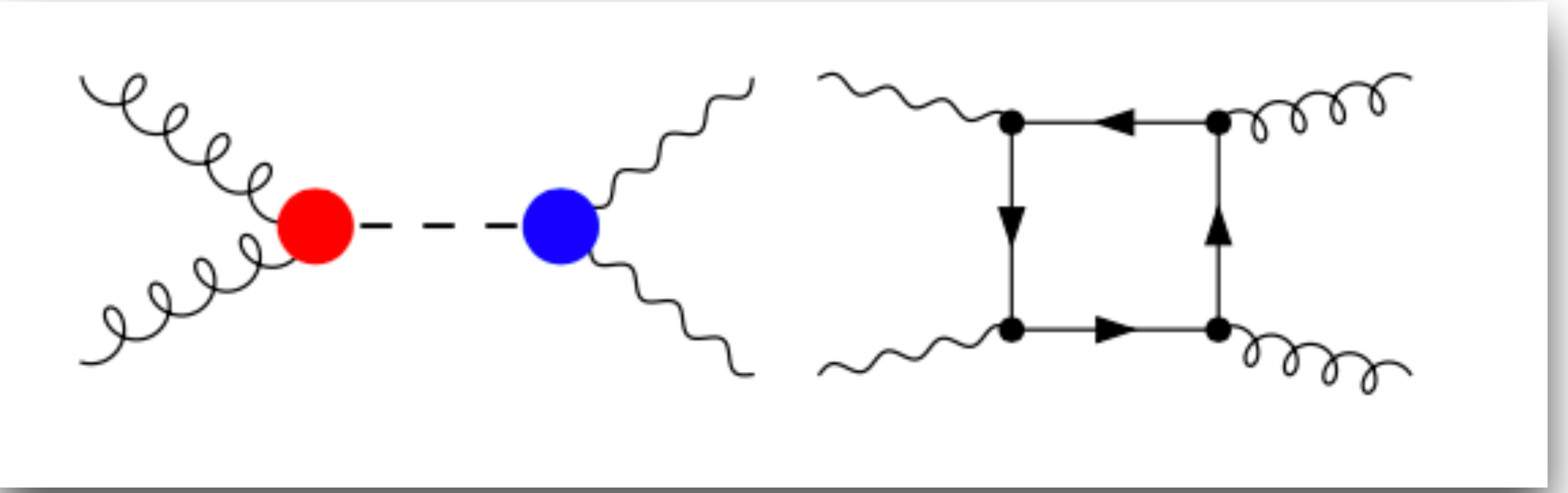

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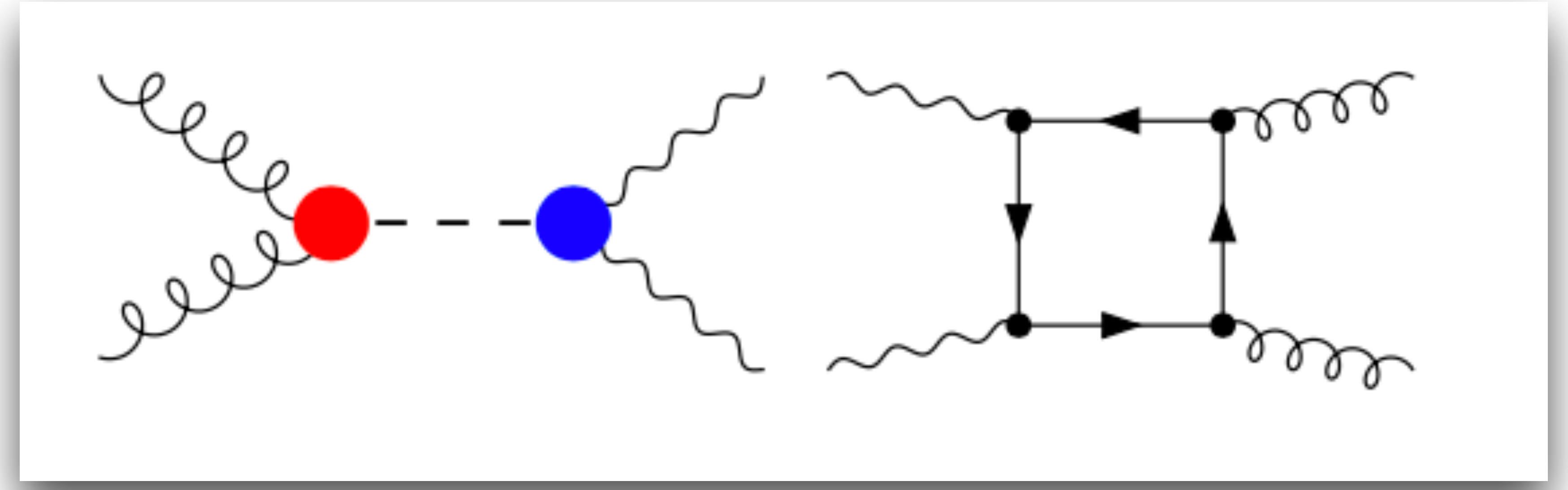

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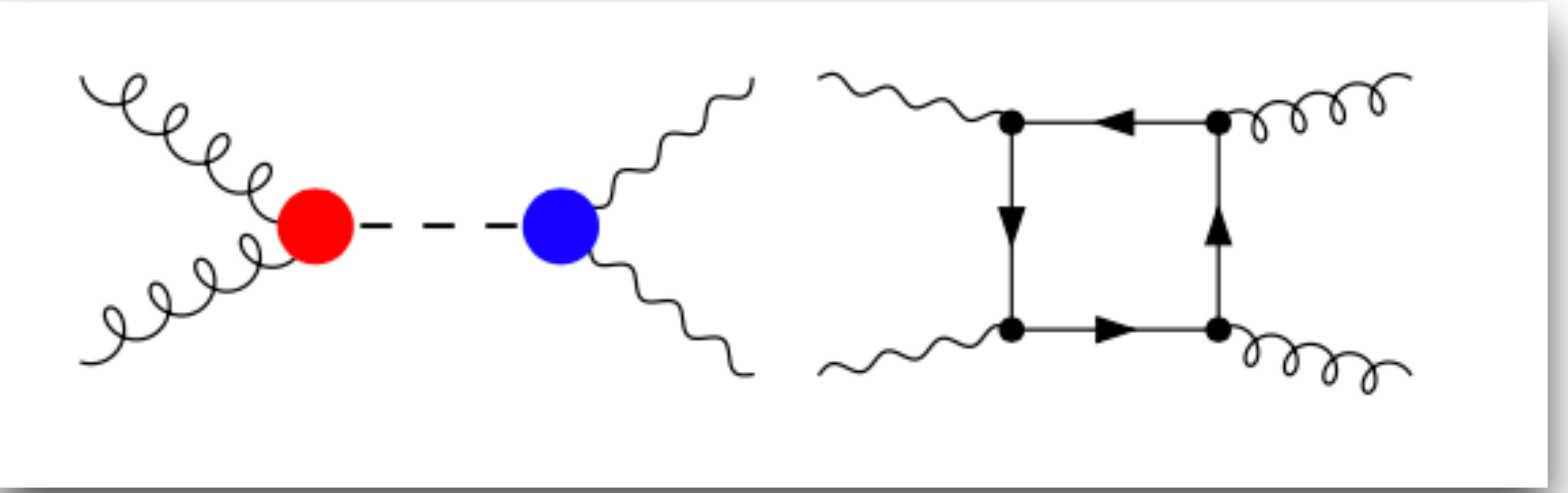
"Imaginary part"

Main message: these two contributions can be exploited to set bounds on the Higgs width due to their different dependence on width and couplings



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

$$I_{\rm Re} + I_{\rm Im}$$

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"Imaginary part"

"Imaginary part" of interference

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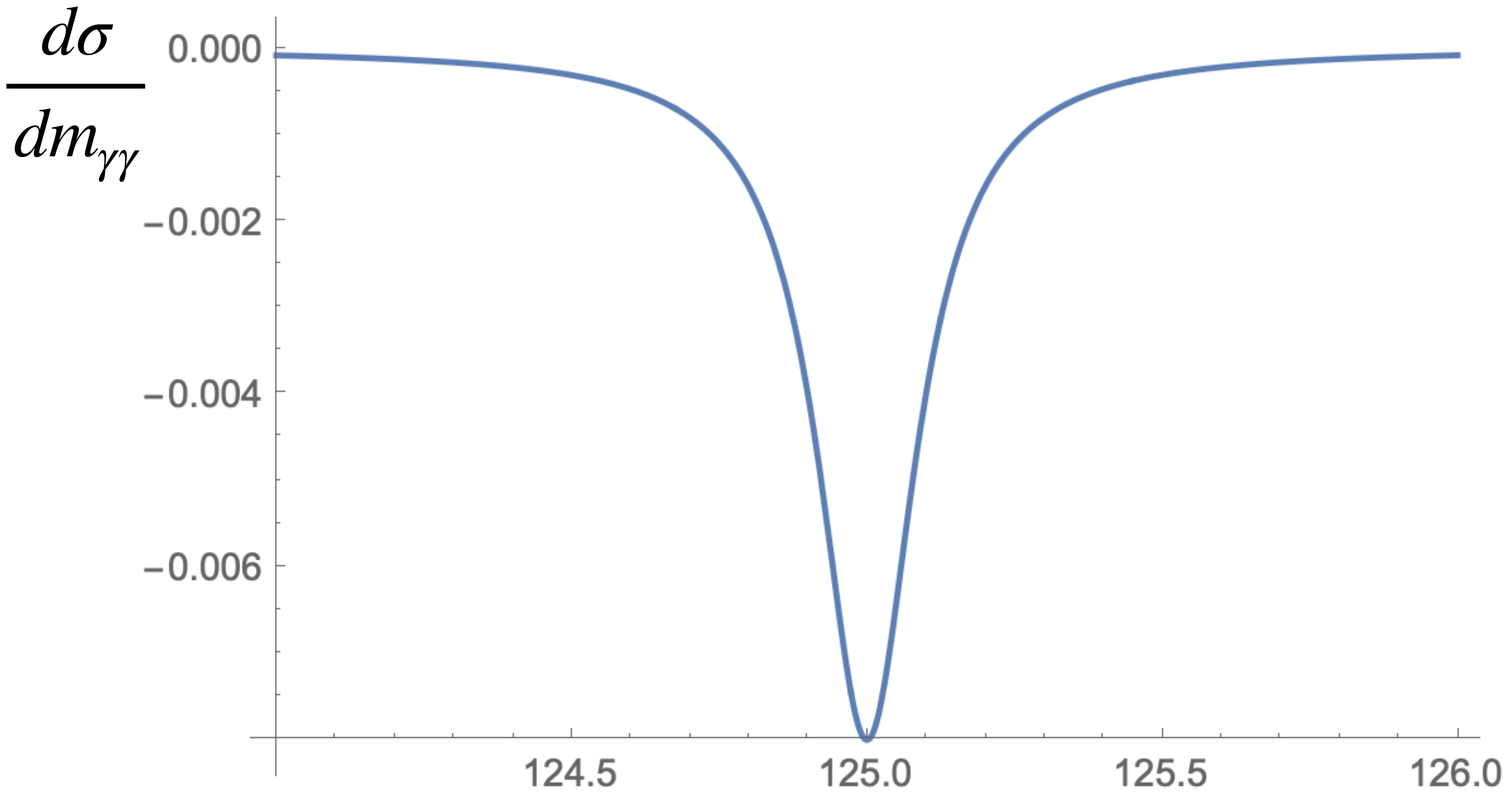

- Symmetric around the peak, contributes to cross section

- One expects a non negligible effect due to loop enhancement in diphoton channel, but it starts to contribute at NLO if one neglects bottom quark mass

“Imaginary part” of interference

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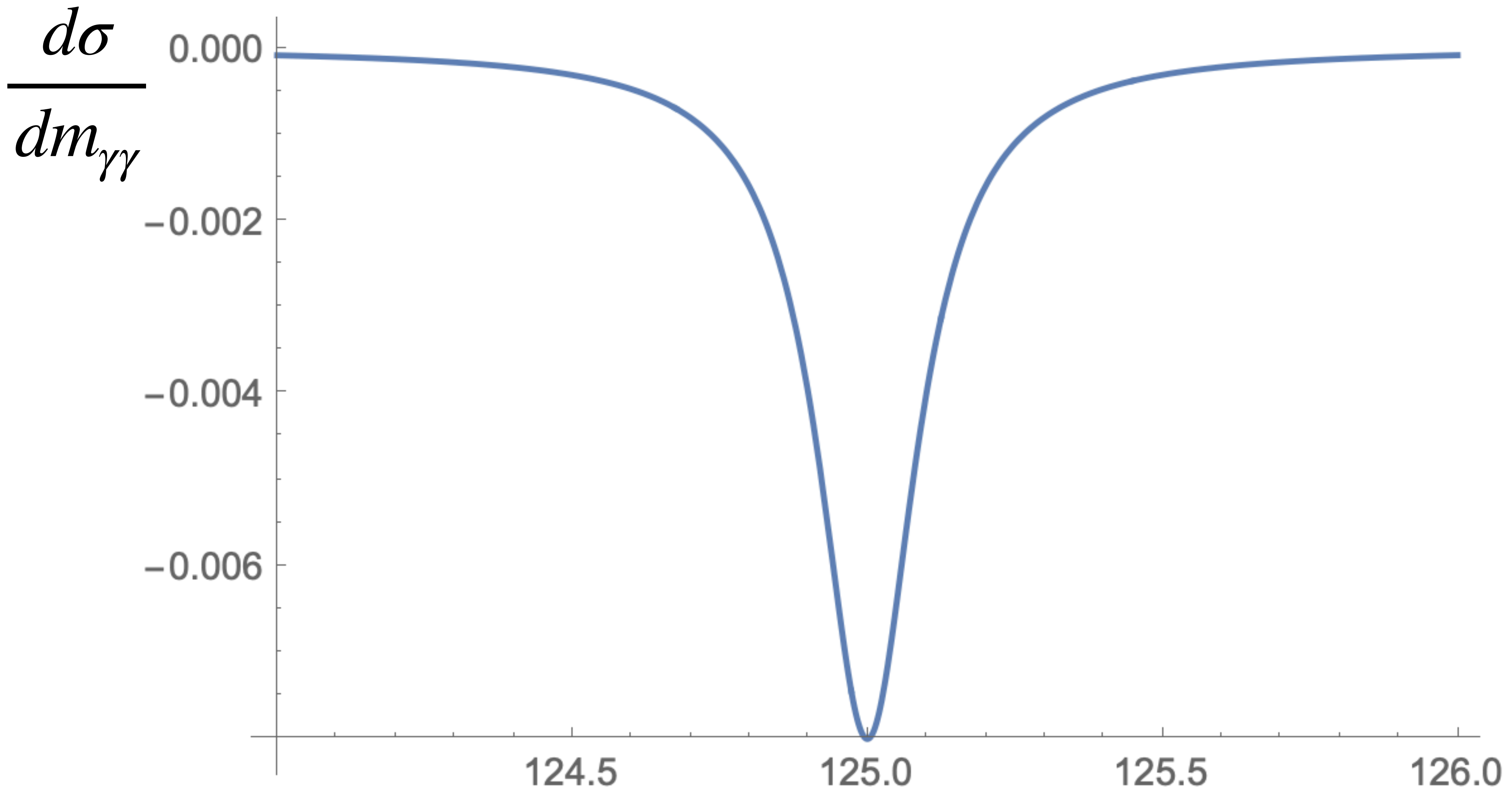

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Why?

"Imaginary part" of interference

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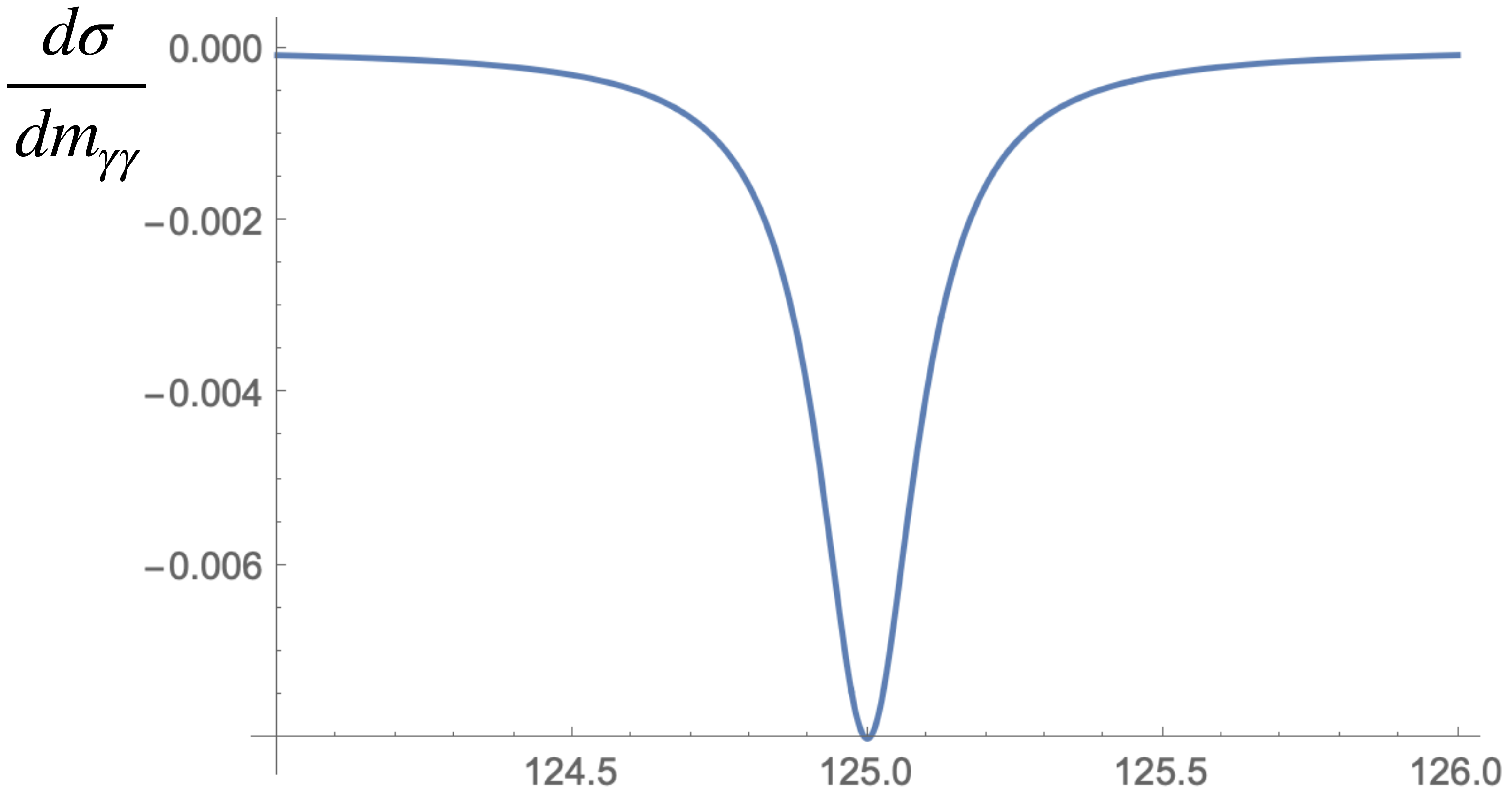

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Why?

Scalar nature of the Higgs boson

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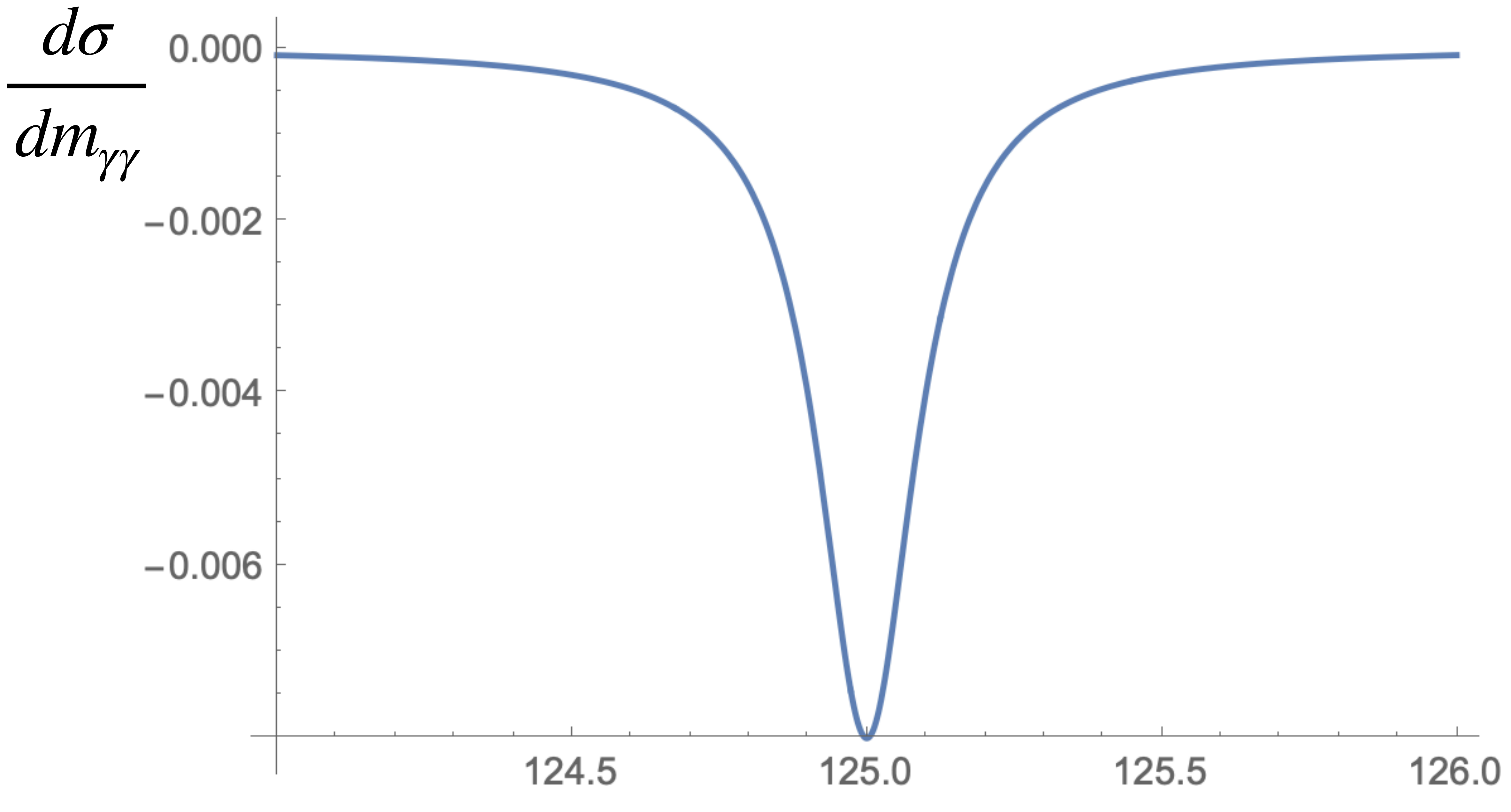

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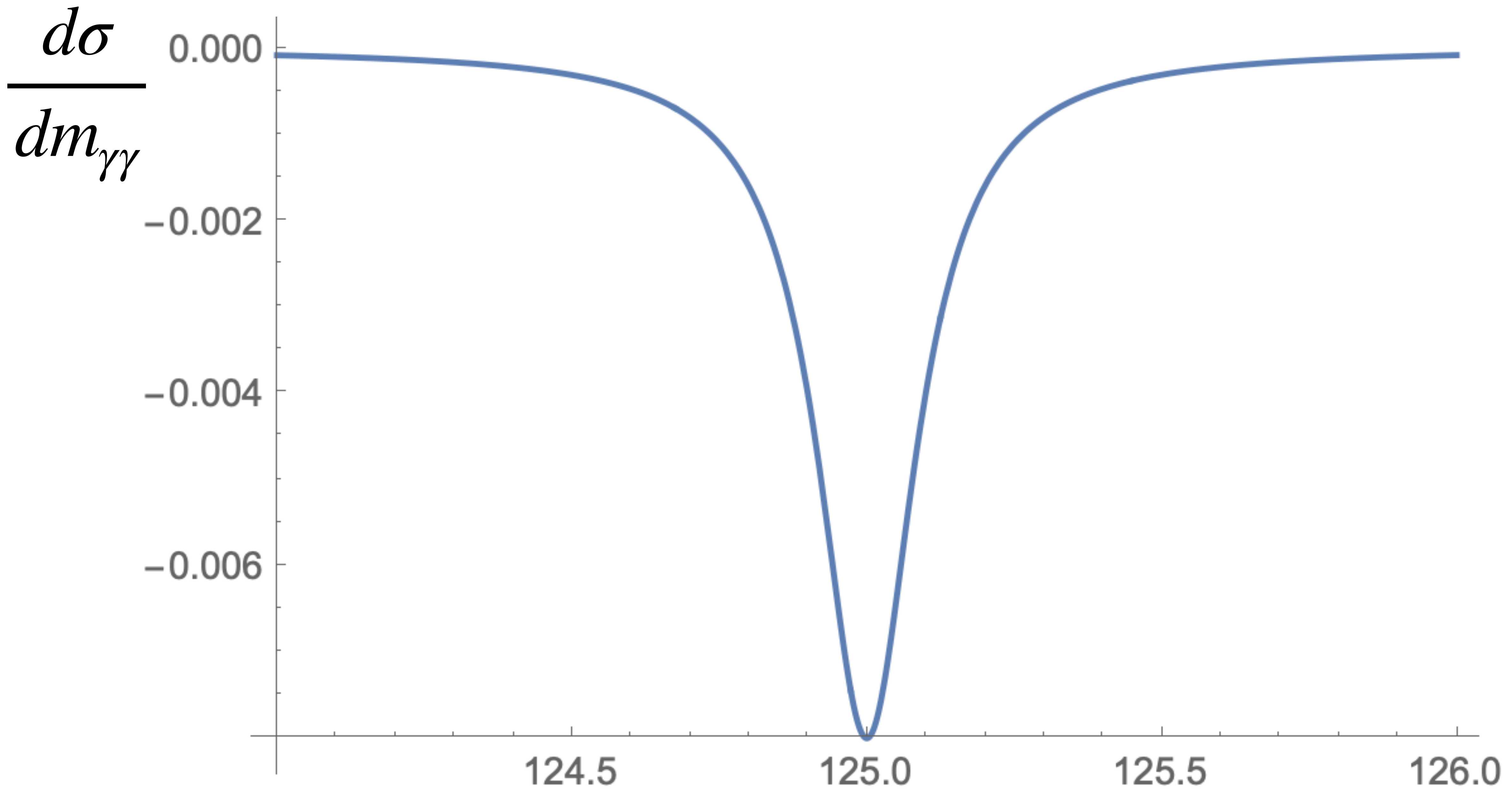

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Why?

Scalar nature of the Higgs boson + Missing cut in background amplitudes

“Real part” of interference

$$I_{\rm Re} \propto \frac{2}{(m_{\gamma\gamma}^2 - m_H^2)^2 + \Gamma_H^2 m_H^2} \left(m_{\gamma\gamma}^2 - m_H^2\right) \times$$
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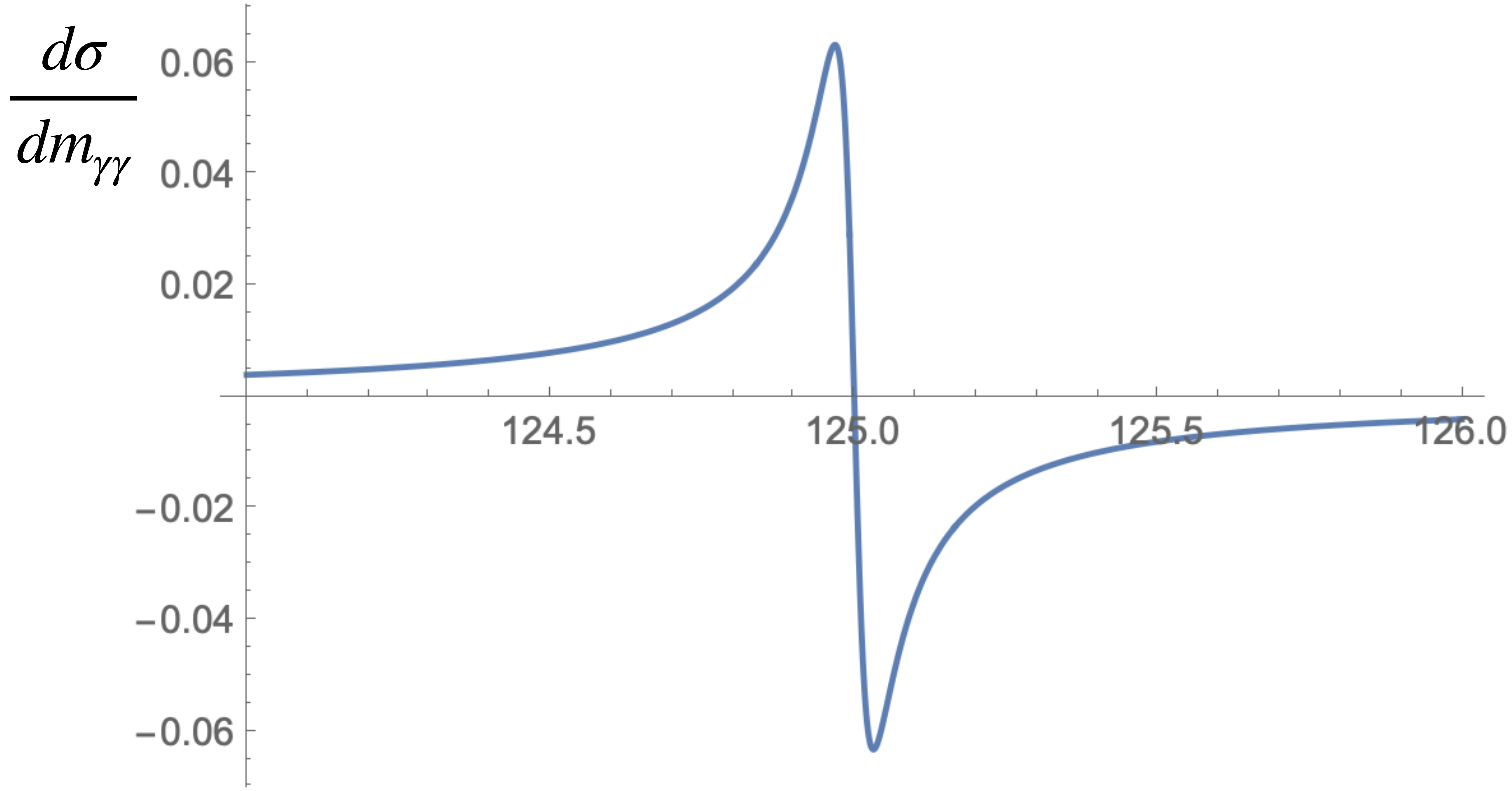

- Antisymmetric around the peak, does not contribute to cross section
- excess of events below $m_{\gamma\gamma} = 125\,\mathrm{GeV}$ rather than above

First noted in

Shift in the LHC Higgs diphoton mass peak from interference with background

Stephen P. Martin

1208.1533

“Real part” of interference

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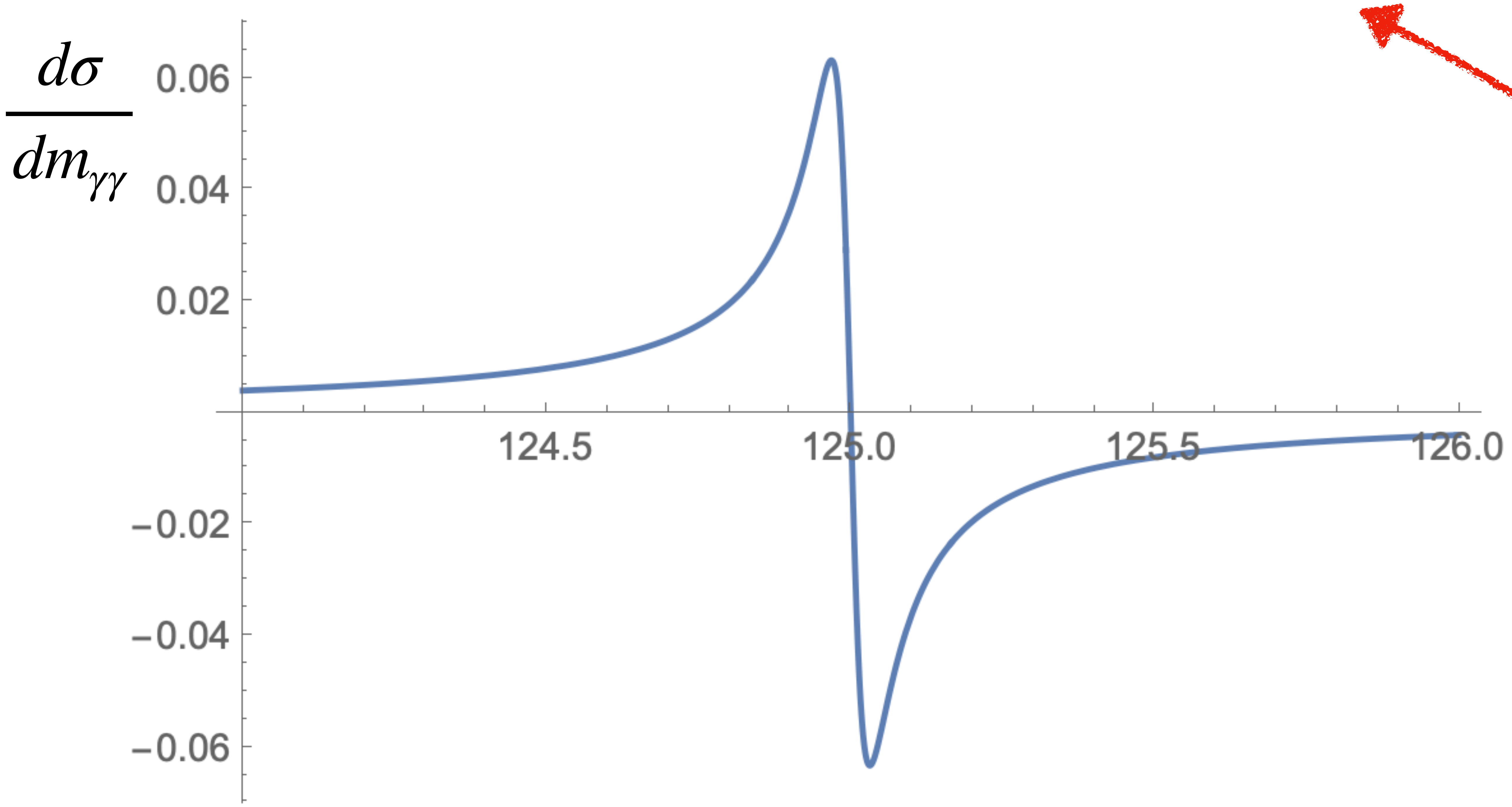
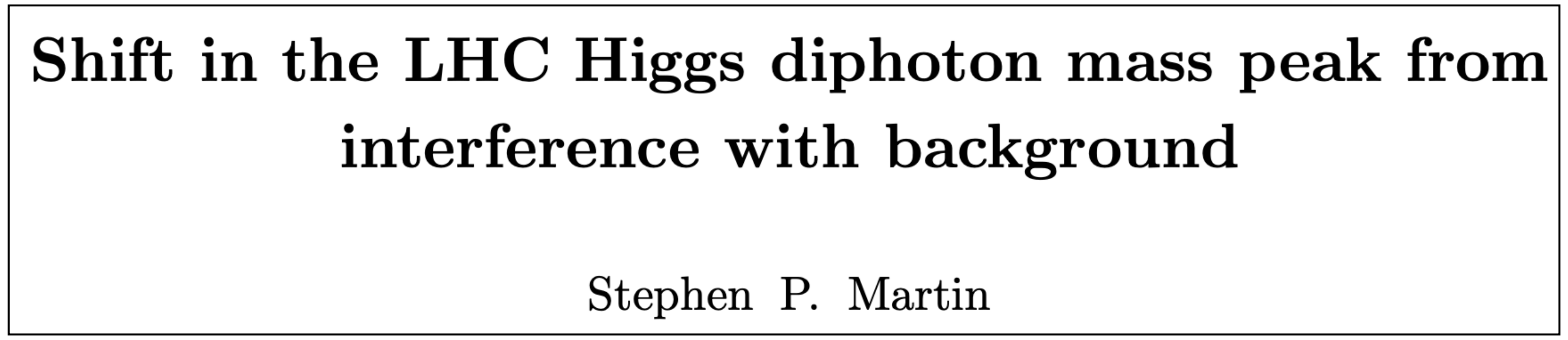
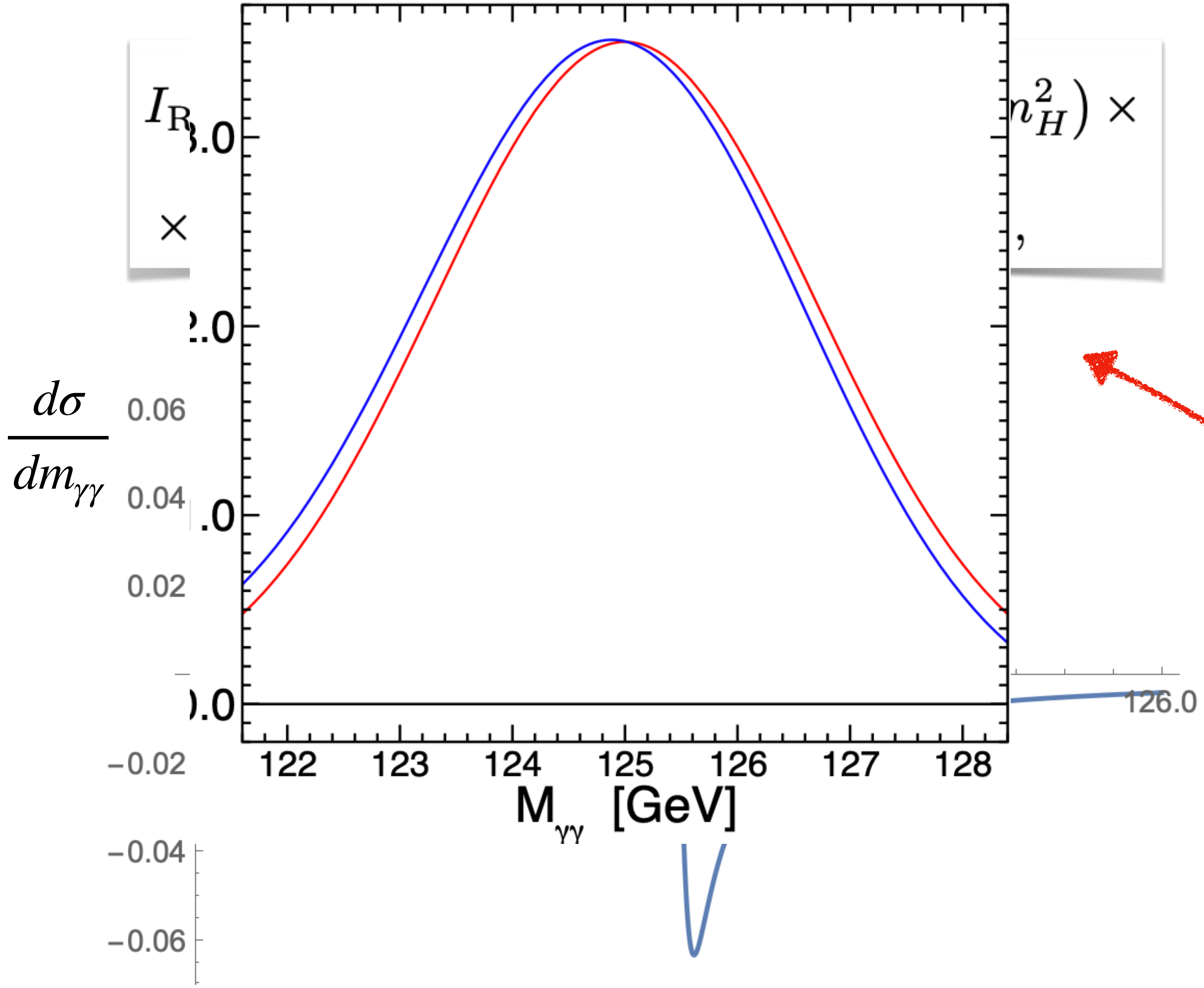


First noted in



1208.1533

“Real part” of interference



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First noted in

Shift in the LHC Higgs diphoton mass peak from interference with background

Stephen P. Martin

1208.1533

From the mass to the width

[Dixon, Li 1305.3854]

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

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

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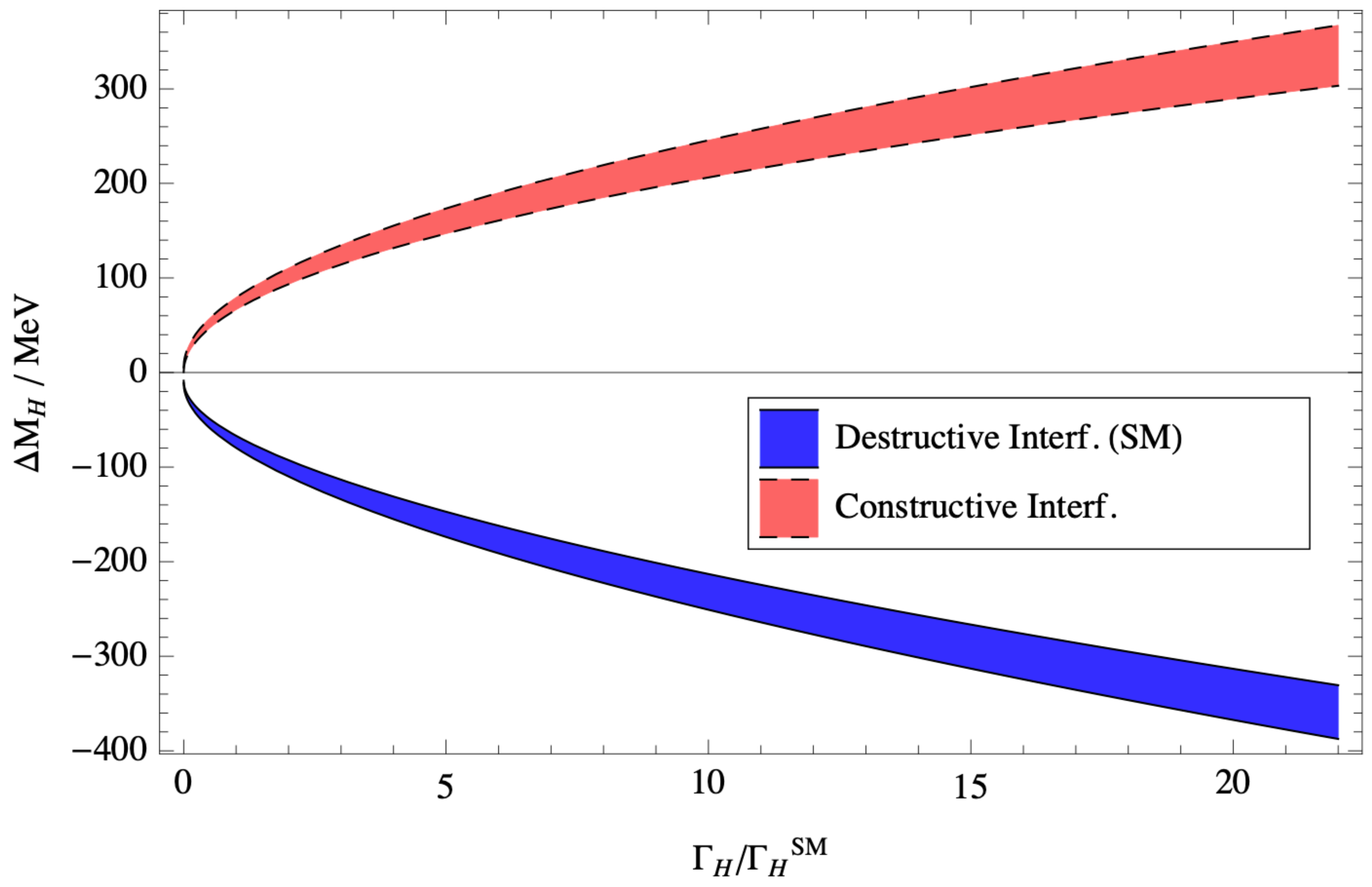


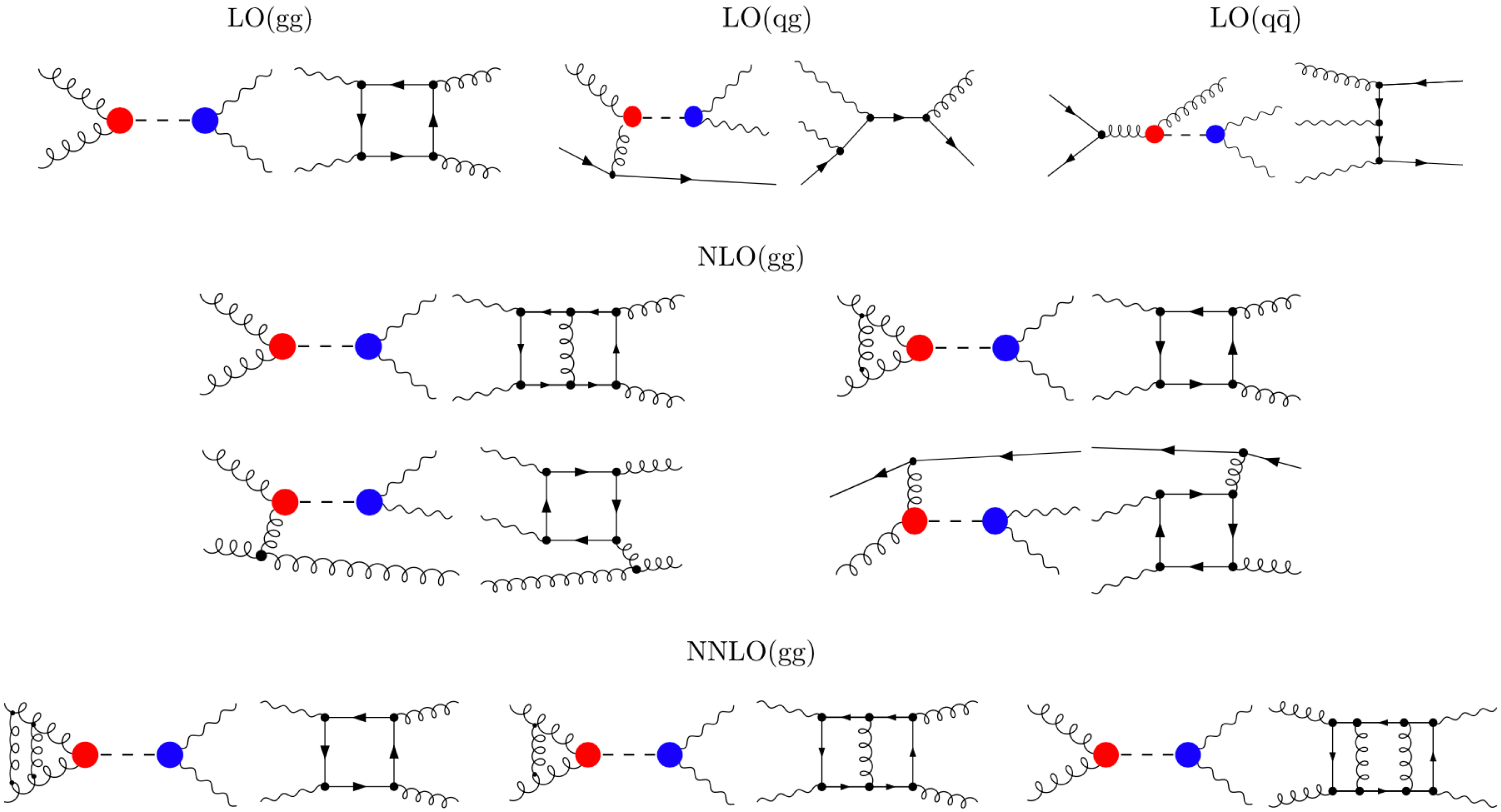
State of the art

- LO gg: Martin '12, $\Delta M_{\gamma\gamma} \sim -120\,\mathrm{MeV}$
- LO qg/qqb: De Florian et al '12, other channels impact $\sim +30\,\mathrm{MeV}$
- NLO QCD: Dixon,Li '13, $\Delta M_{\gamma\gamma} \sim -70\,\mathrm{MeV}$ + first bound on the width from diphoton lineshape
- NLO QCD: Campbell et al '17, bounds on width from integrated cross section

$\mathcal{O}(40\%)$ corrections from LO to NLO!
Calls for higher order analysis

Gabriele's talk yesterday - NLO EW corrections

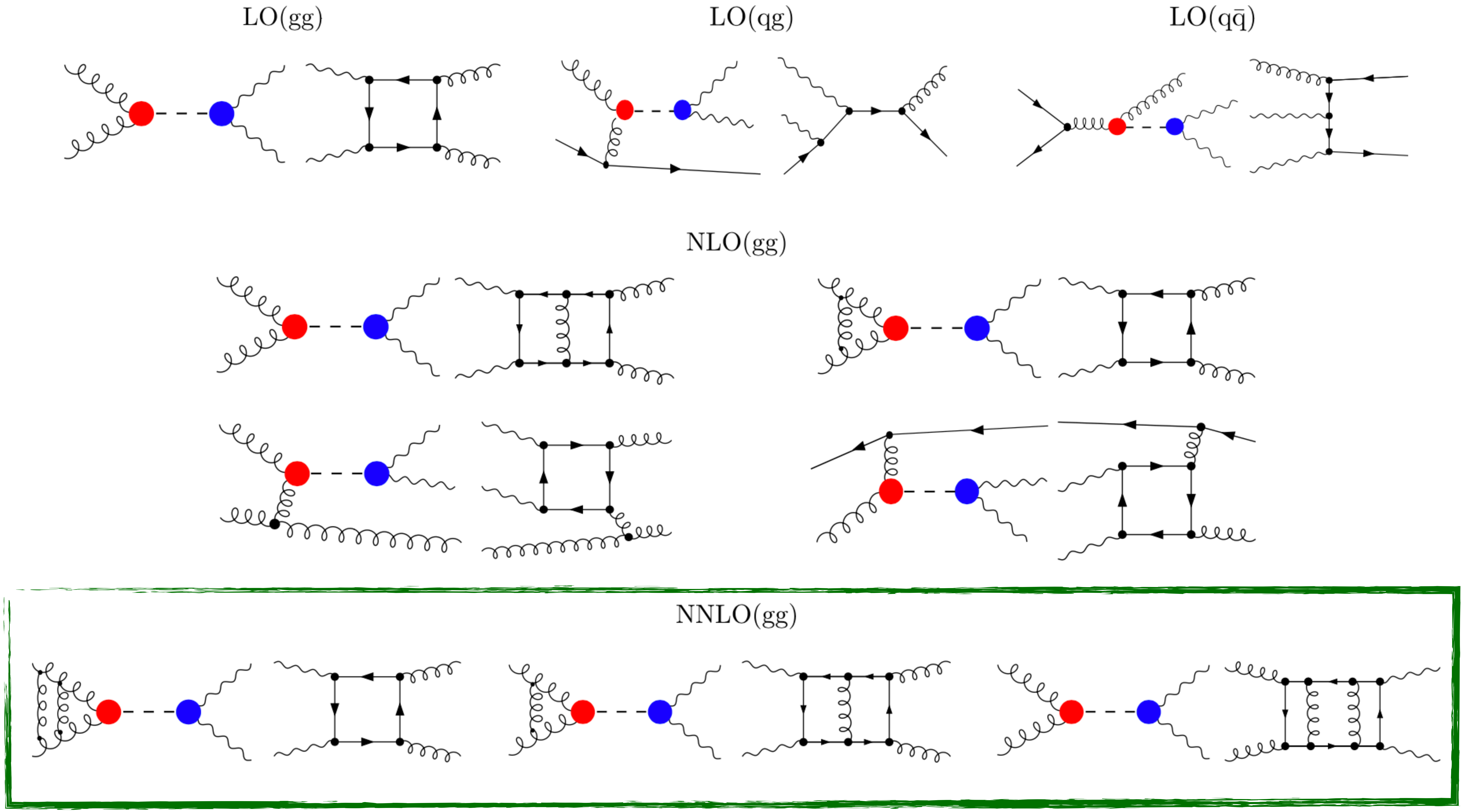
Interference beyond NLO QCD



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

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

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



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

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

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

Subtraction

Amplitudes

NNLO subtraction for color singlet production

Well established by now…

3-loop amplitudes for $gg \to \gamma\gamma$

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

2-loop 5-point background amplitudes

[Badger et al, ’21] [Agarwal et al, ’21]

All ingredients available… but potentially cumbersome on a technical level
First step: soft-virtual approximation

Setup

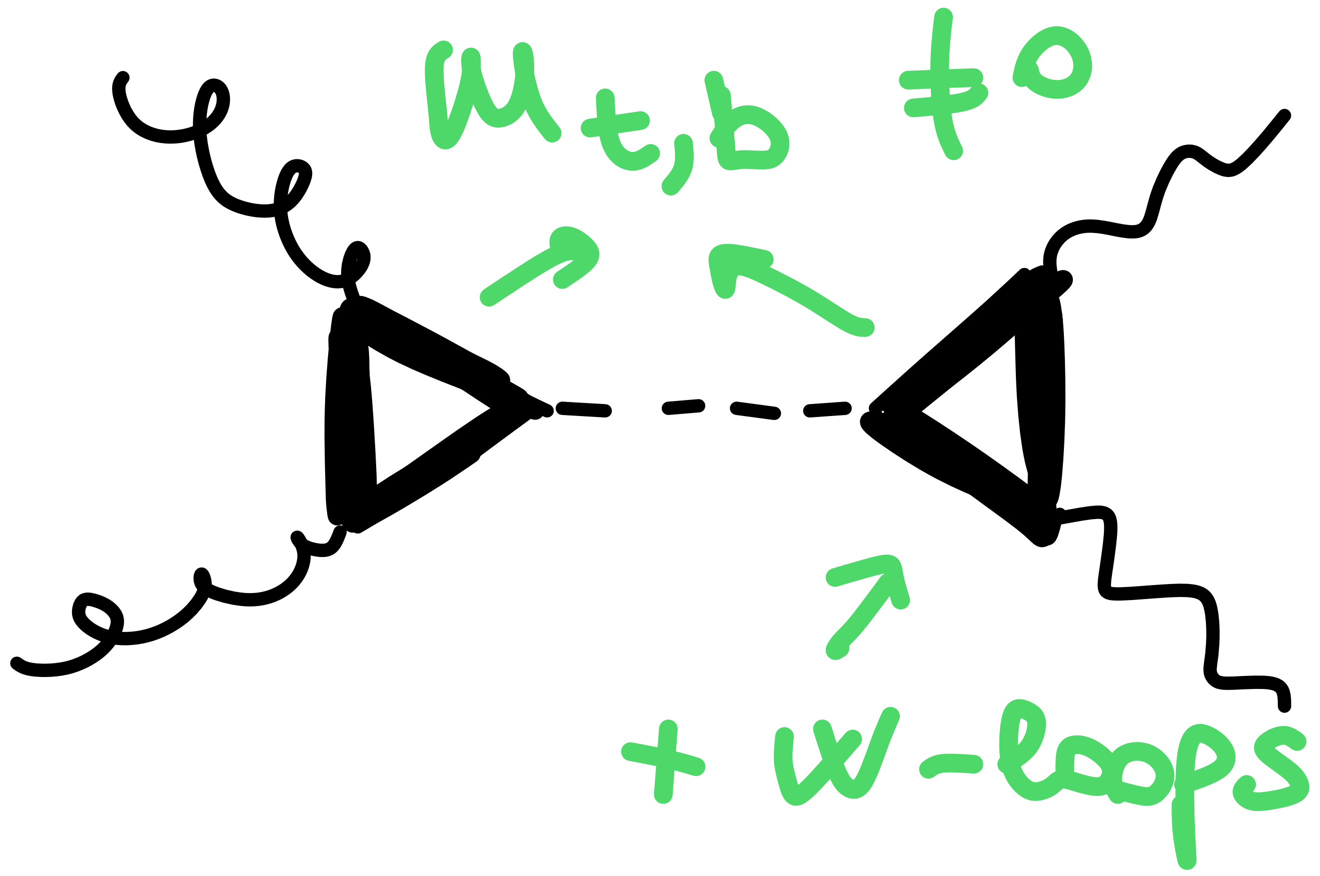
- $\sqrt{s} = 13.6\,\mathrm{TeV}$
- PDF set: NNPDF31_nnlo_as_0118
- Dynamic scale: $\mu_F = \mu_R \equiv \mu = \dfrac{m_{\gamma\gamma}}{2}$
- Fiducial cuts:
  - $p_{T\,\gamma_{1,2}} > 20\,\mathrm{GeV}$
  - $|\eta_\gamma| < 2.5$
  - $\boxed{p_{T\,\gamma_1} p_{T\,\gamma_2} > (35\,\mathrm{GeV})^2}$
  -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

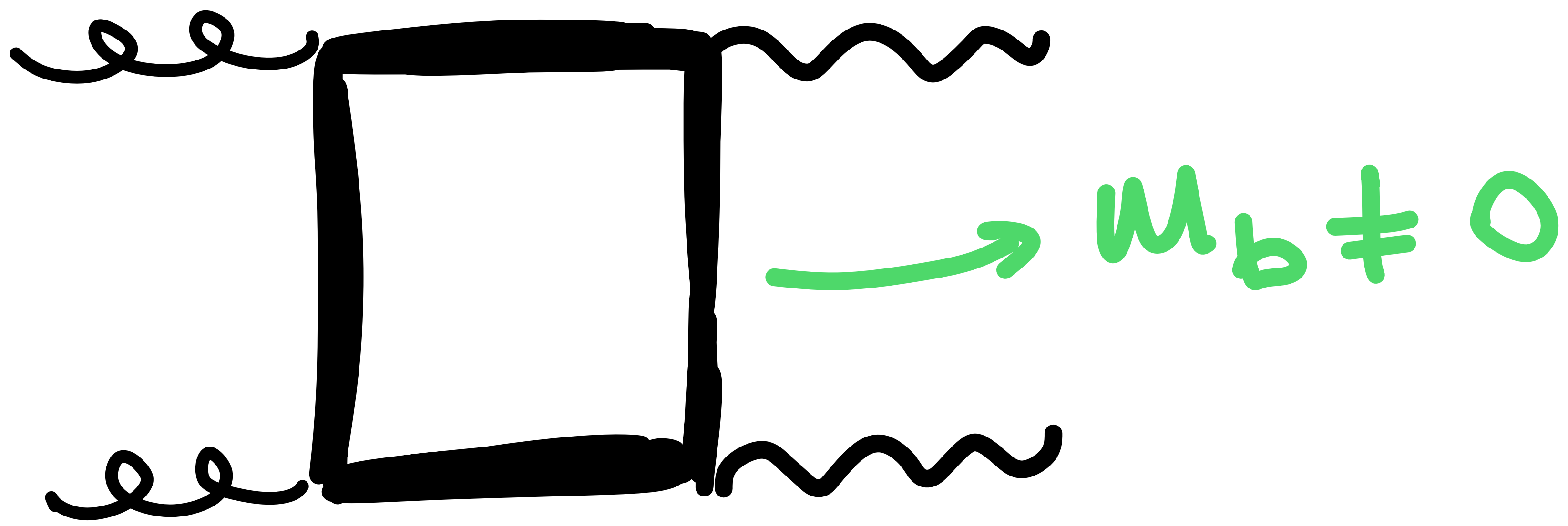
Signal-background interference receives large corrections
"Usual" cuts plagued by unphysical sensitivity to IR physics

[Salam, Slade 2106.08329]

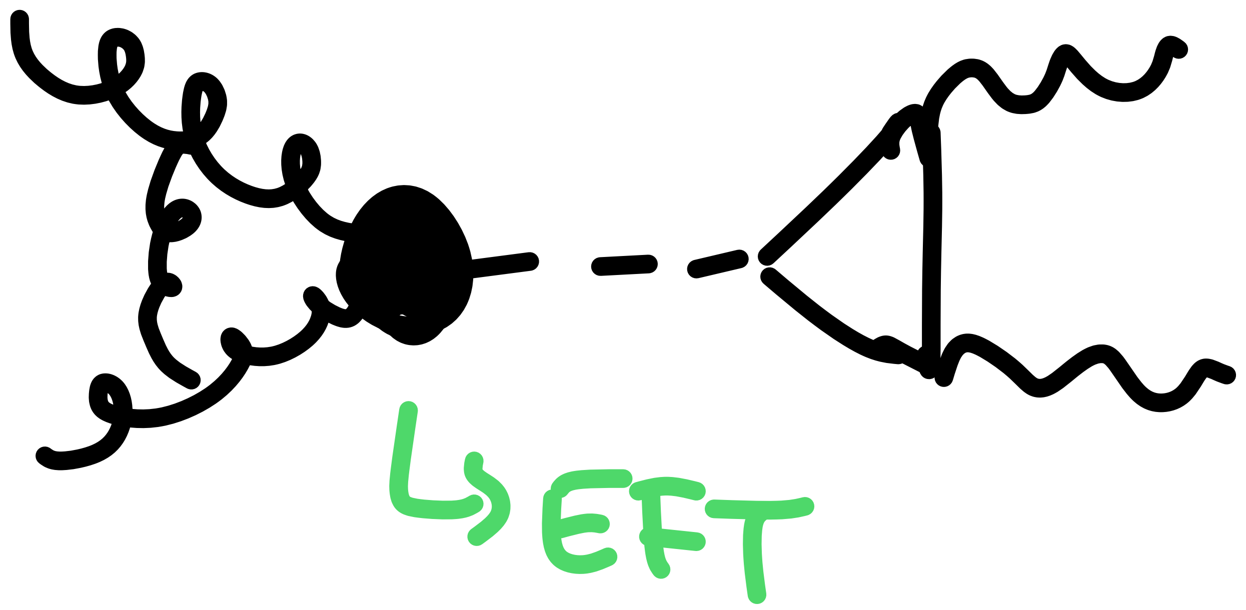
Setup

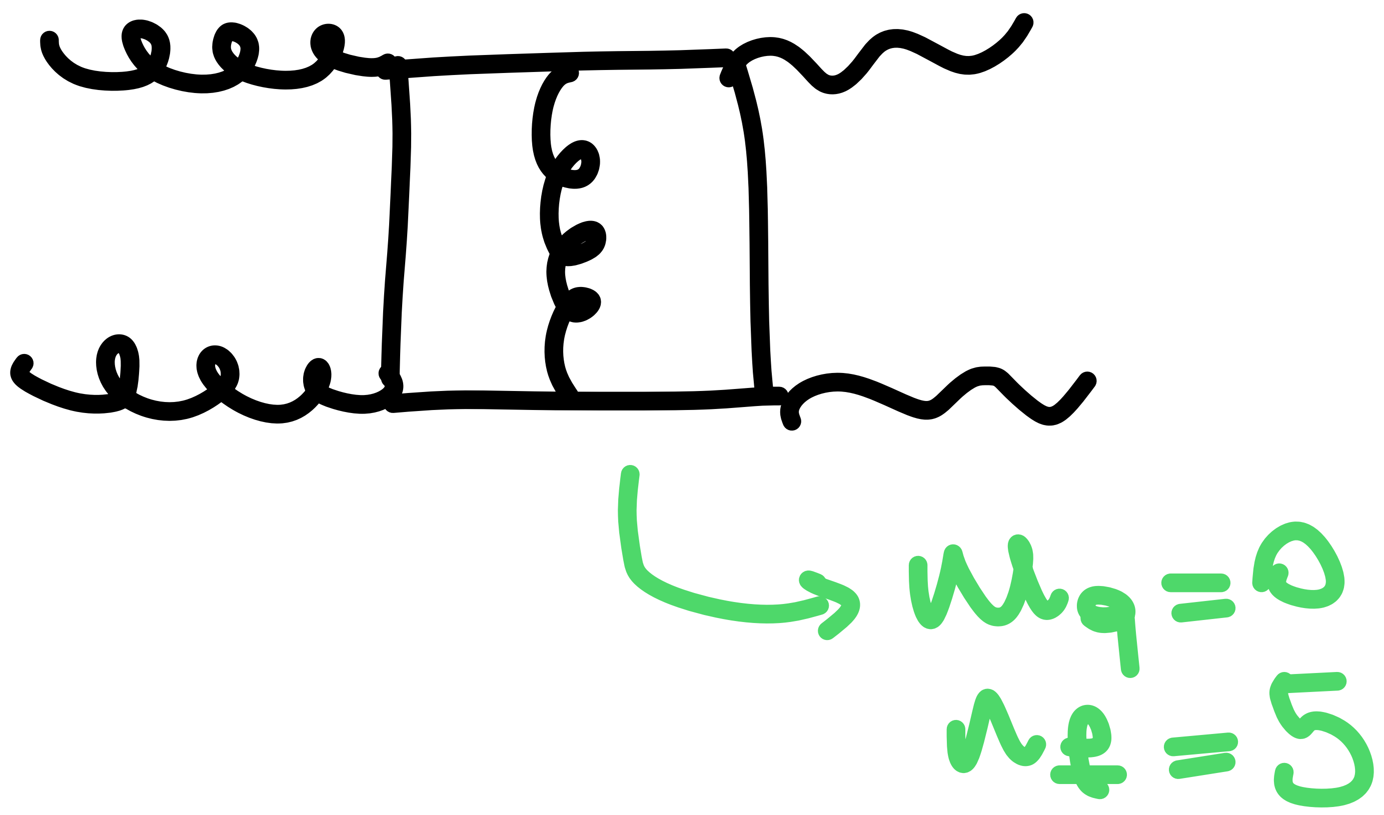
- @LO:



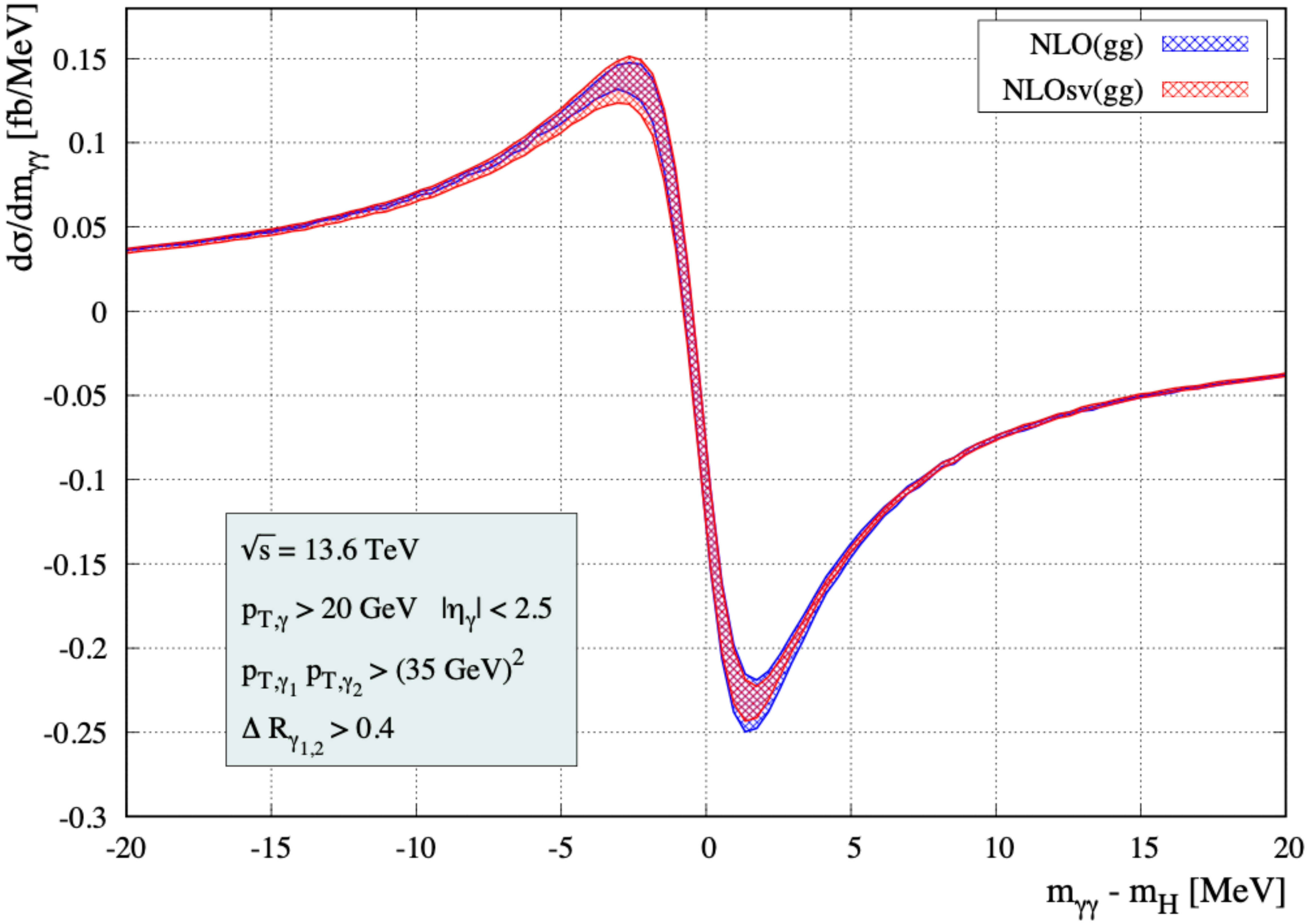


- @NLO and NNLOsv:

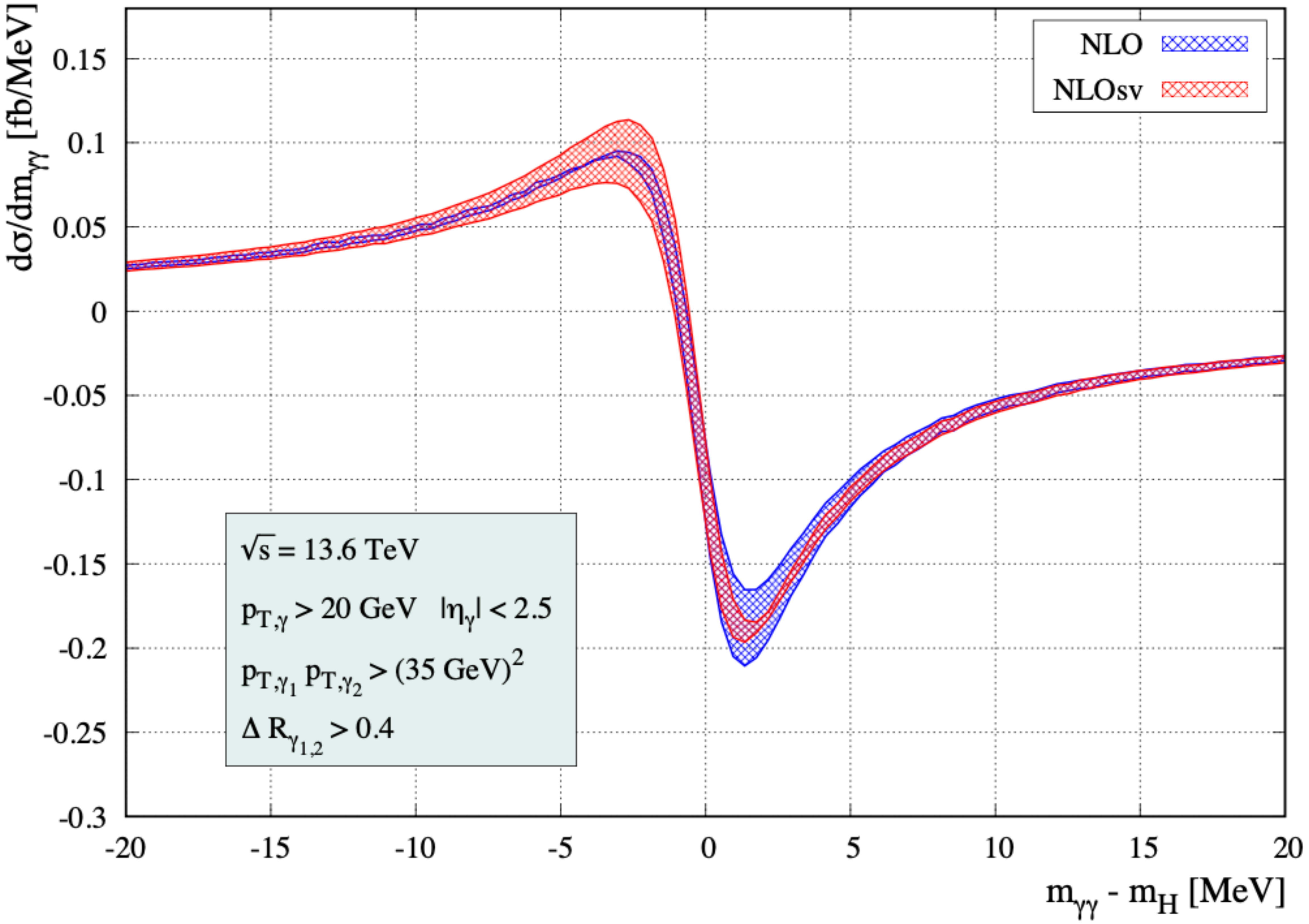




Validation of soft-virtual



gg only



all channels

Results

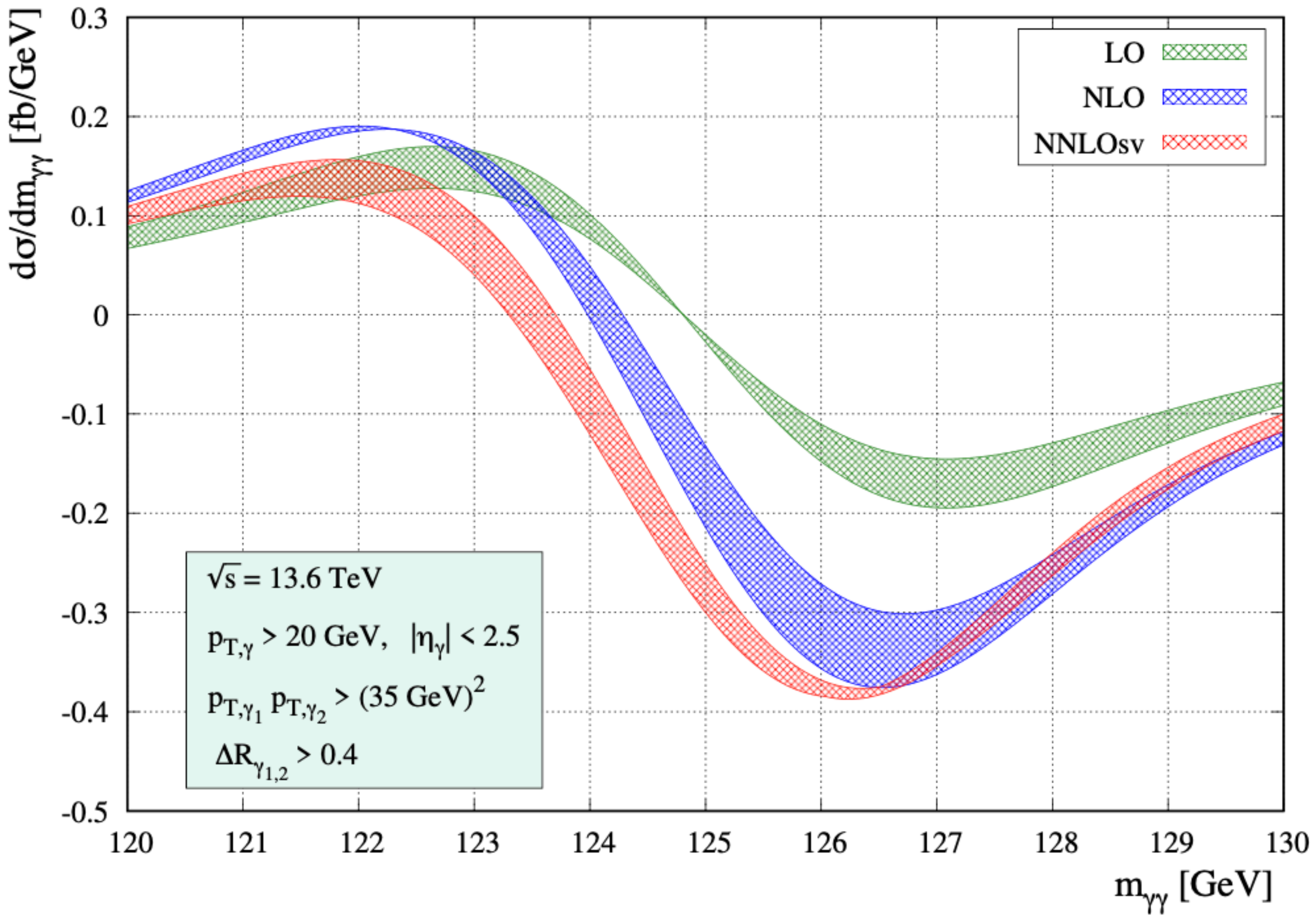
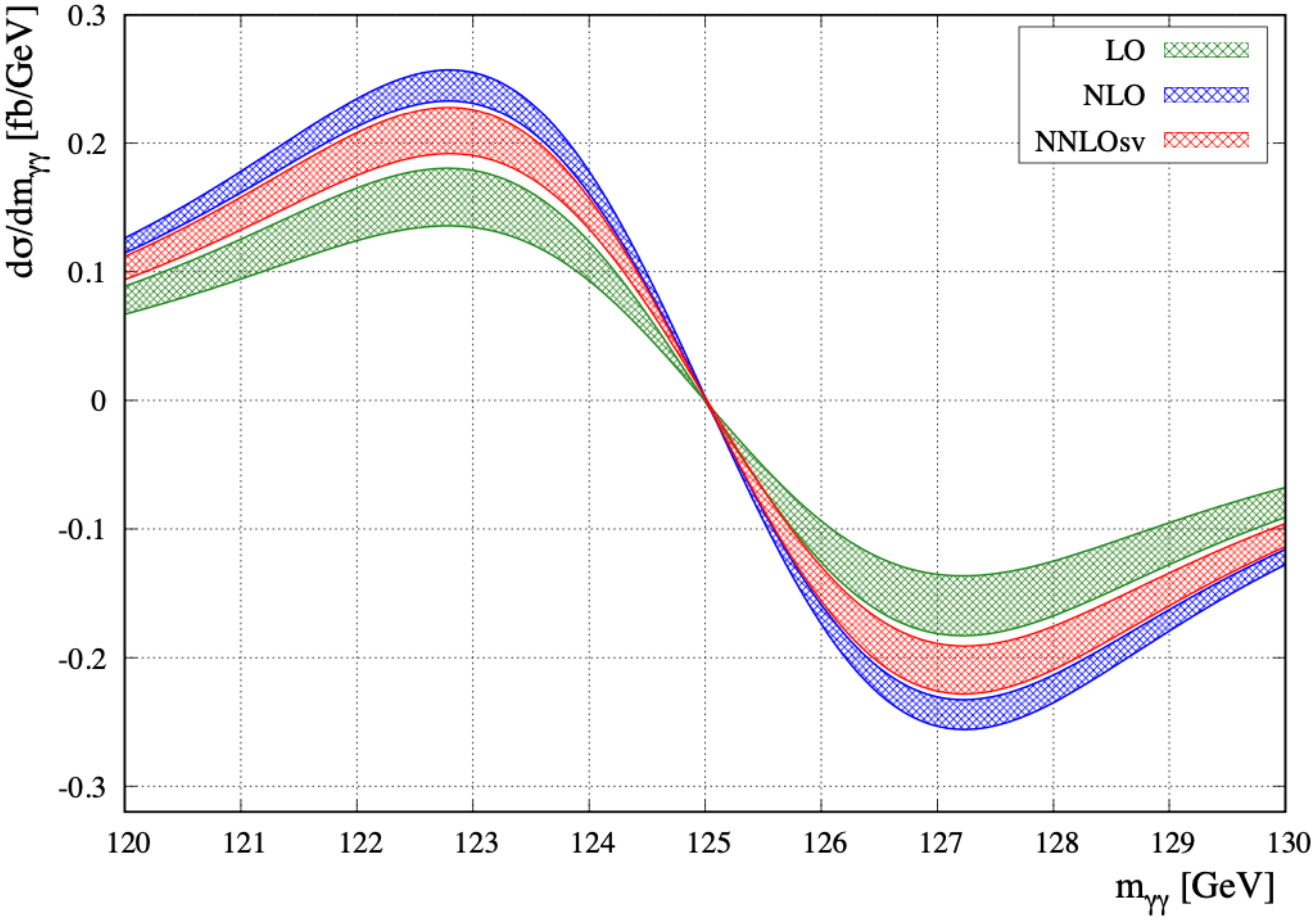
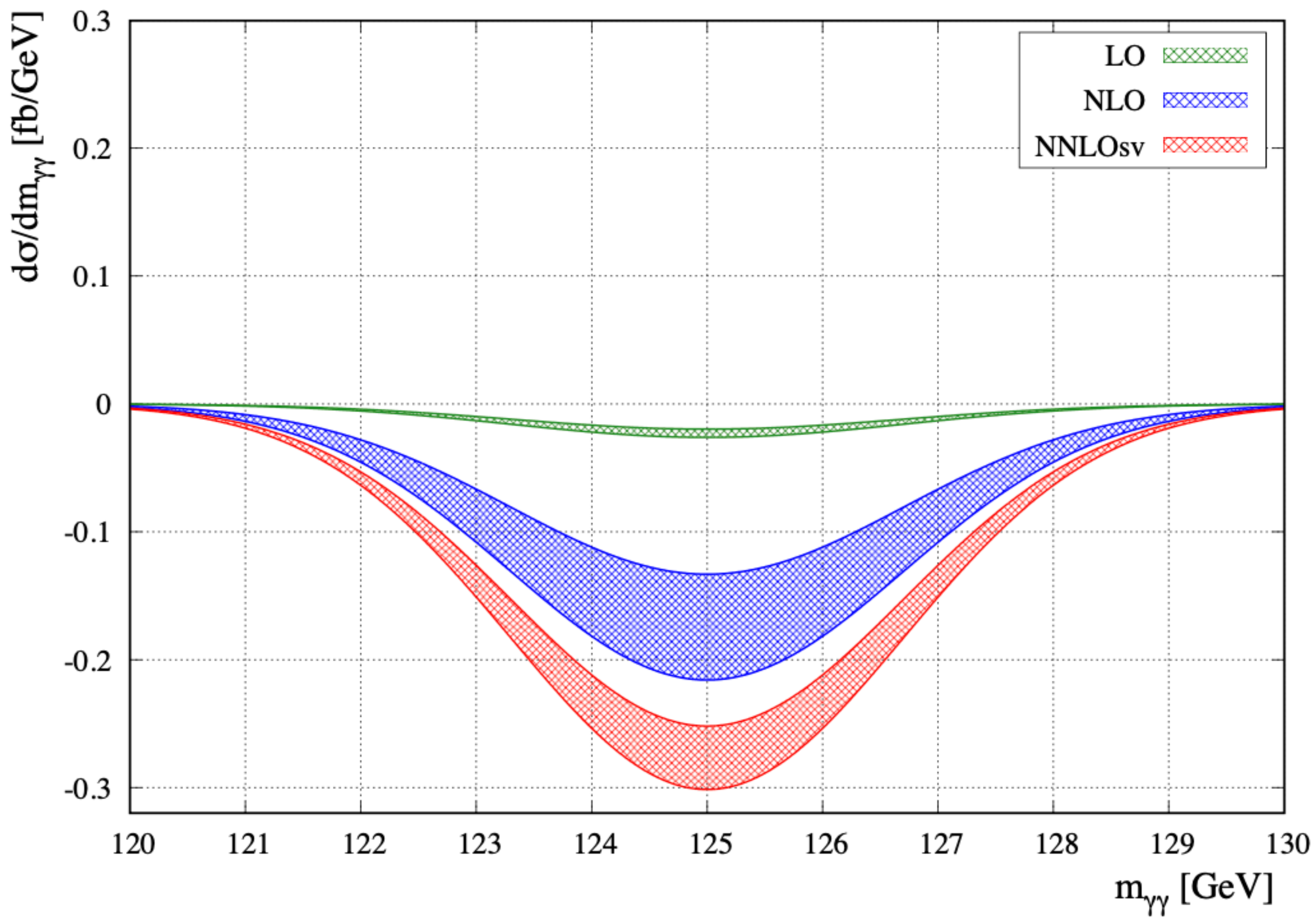


Fig. 4 Signal-background interference contribution to the diphoton invariant mass distribution after Gaussian smearing. Bands represent the envelope given by the scale variation.

- NNLO correction not captured by the NLO scale variation bands…
- …but starting to converge
- Recall this is the sum of real and imaginary part of the interference
- Real part dictates the shape, imaginary part responsible for shift to the left

Real part of interference





Imaginary part of interference

Destructive interference @ NNLOsv ~ -1.7 % of signal NNLO cross section

Table 1 Mass-shift at different proton-proton collider energies with Gaussian fit method

$\Delta m_{\gamma\gamma}$ (MeV)	7 TeV	8 TeV	13.6 TeV
LO	$-77.2^{+0.8\%}_{-1.0\%}$	$-79.5^{+0.6\%}_{-0.8\%}$	$-83.1^{+0\%}_{-0.3\%}$
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Soft-virtual “improved” approximation for Higgs XS Based on [R.D. Ball, Bonvini et al 1303.3590]

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Table 2 Mass-shift at different proton-proton collider energies with first moment 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	$-68.1^{+15\%}_{-17\%}$	$-68.4^{+13\%}_{-15\%}$	$-67.7^{+11\%}_{-12\%}$
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LO			
NLO			
NNL			
NNL			

Table 3 Comparison of K-factors, measured w.r.t. the LO value, for the mass-shift at $\sqrt{s} = 13.6$ TeV calculated via a gaussian fit method and via a first-moment method

$\Delta m_{\gamma\gamma}/\Delta m_{\gamma\gamma}^{\mathrm{LO}}$	First moment	Gaussian Fit
K_{NLO}	0.665	0.664
K_{NNLOsv}	0.554	0.554
$K_{\mathrm{NNLOsv}'}$	0.475	0.474

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

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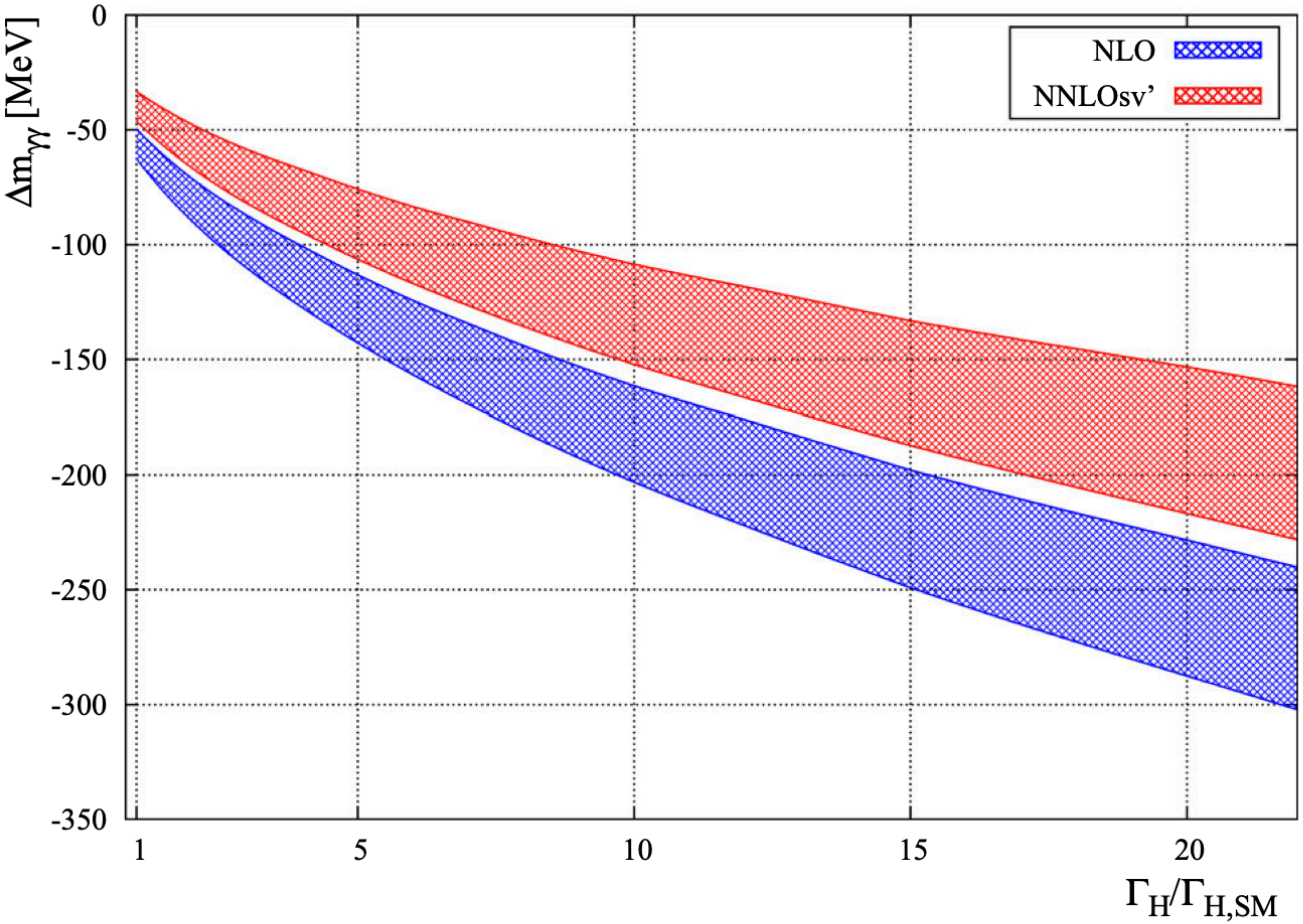
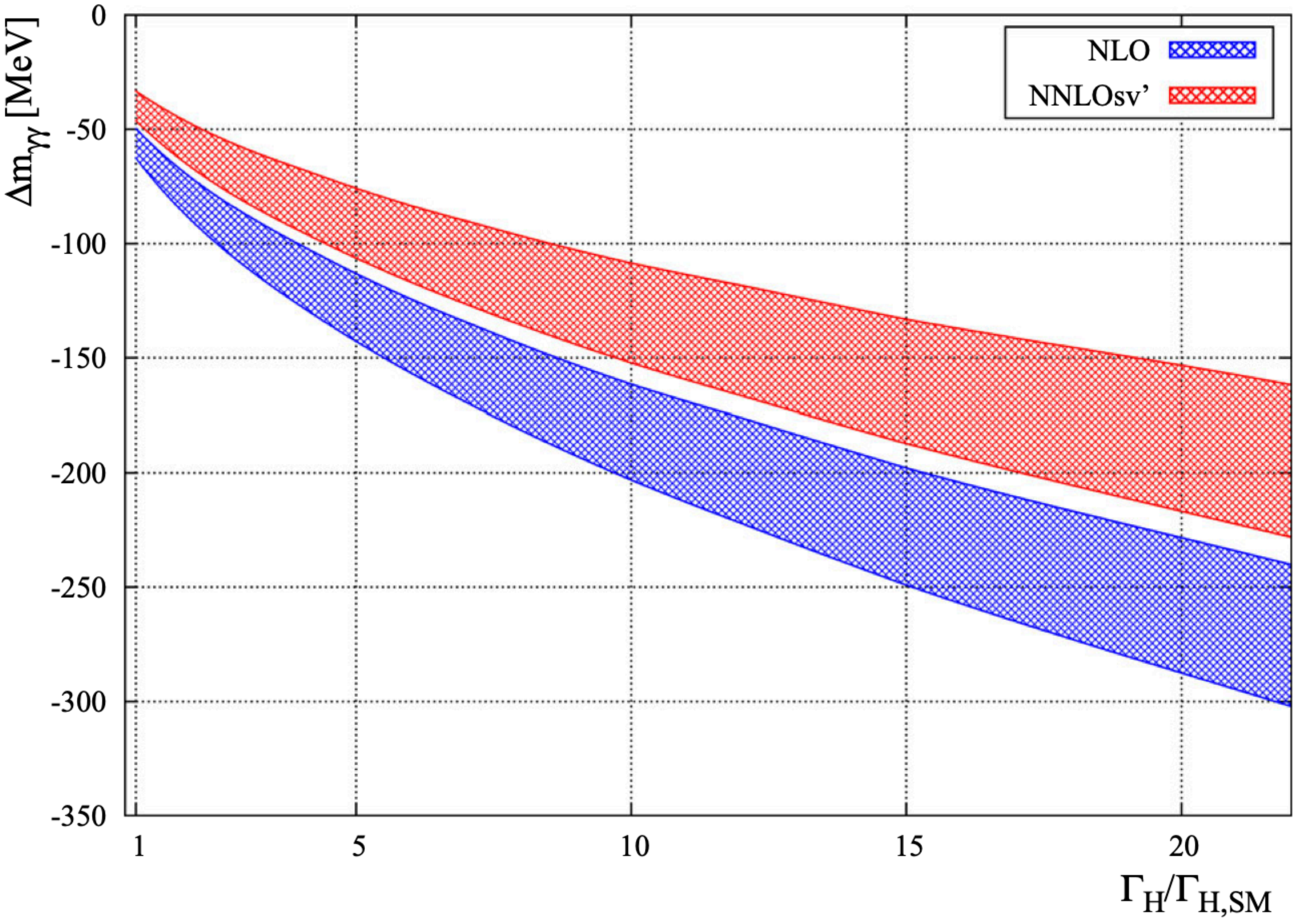


- NNLO curve lies above the NLO one resulting in looser bounds on Γ_H
- If error on the mass shift reaches 150 MeV: Γ_H<(10-20) $\Gamma_{H,SM}$
- To be compared with XS based method: 9% uncertainty ->Γ_H <(28-30)$\Gamma_{H,SM}$



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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

The ATLAS and CMS Collaborations

Exciting projections!!!

(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

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Conclusions

- We reviewed the Higgs interferometry framework which allows to access the Higgs boson width
- On-shell interference effects provide important complementary information to the present bounds on Γ_H, mostly coming from off-shell studies
- Although the mass shift extraction is highly dependent on the methodology, K-factors are universal and can be used to assess the order of magnitude of the missing higher order corrections
- New projections on error on mass-shift at HL-LHC: Γ_H<(2-5)$\Gamma_{H,SM}$ to be compared with direct sensitivity of LHC ~ Γ_H<250 $\Gamma_{H,SM}$!

Thank you!

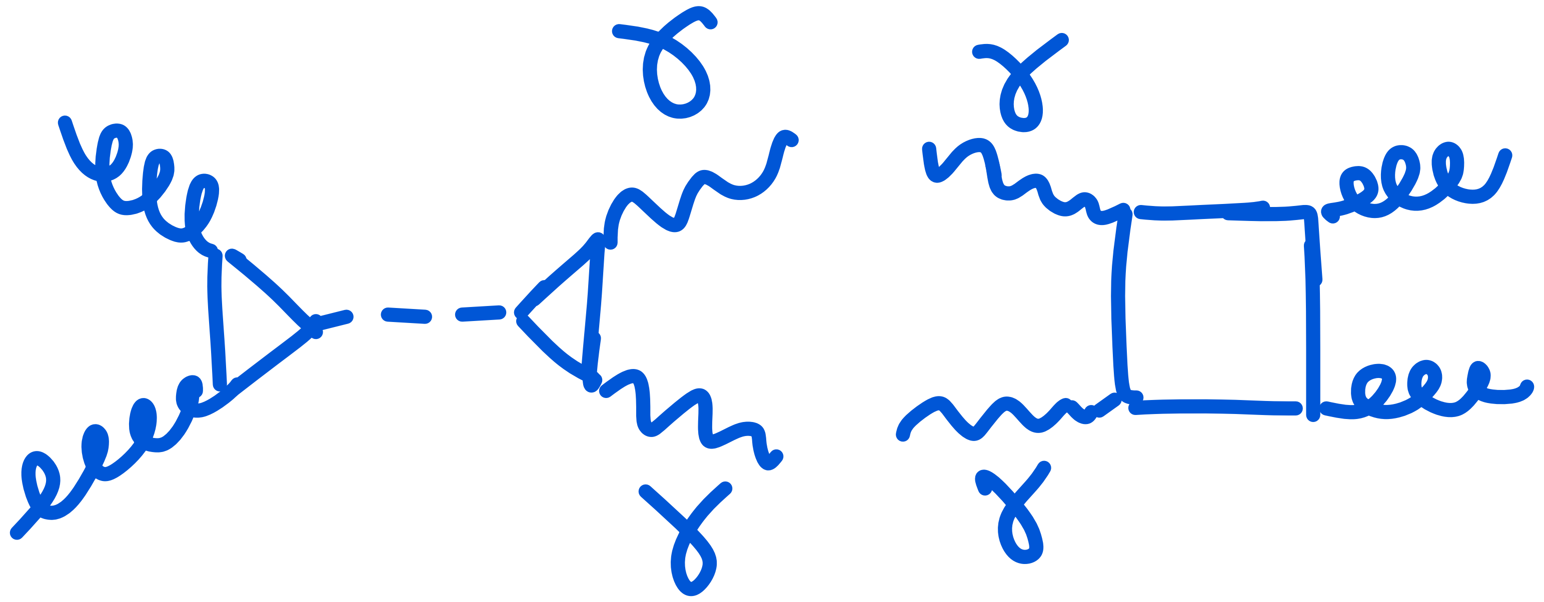
Back up

Interference effect: $\gamma\gamma$ vs ZZ

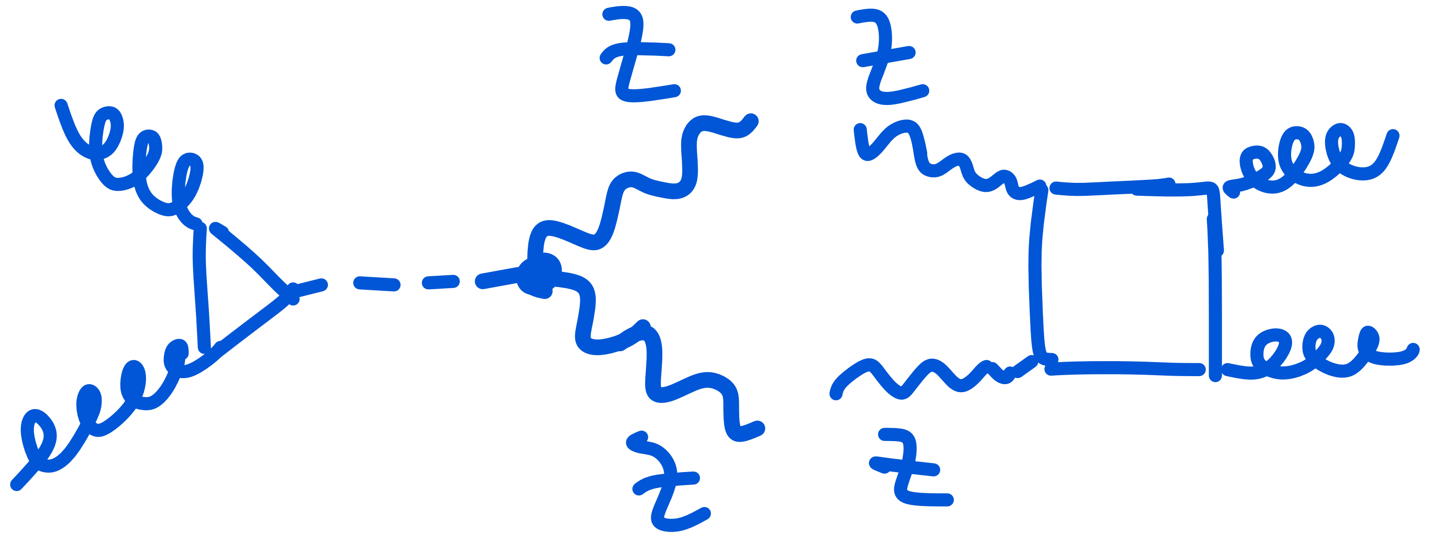
Size of the interference is governed by background to signal ratio

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

Diphoton channel: 3-loops



ZZ channel: 2-loops



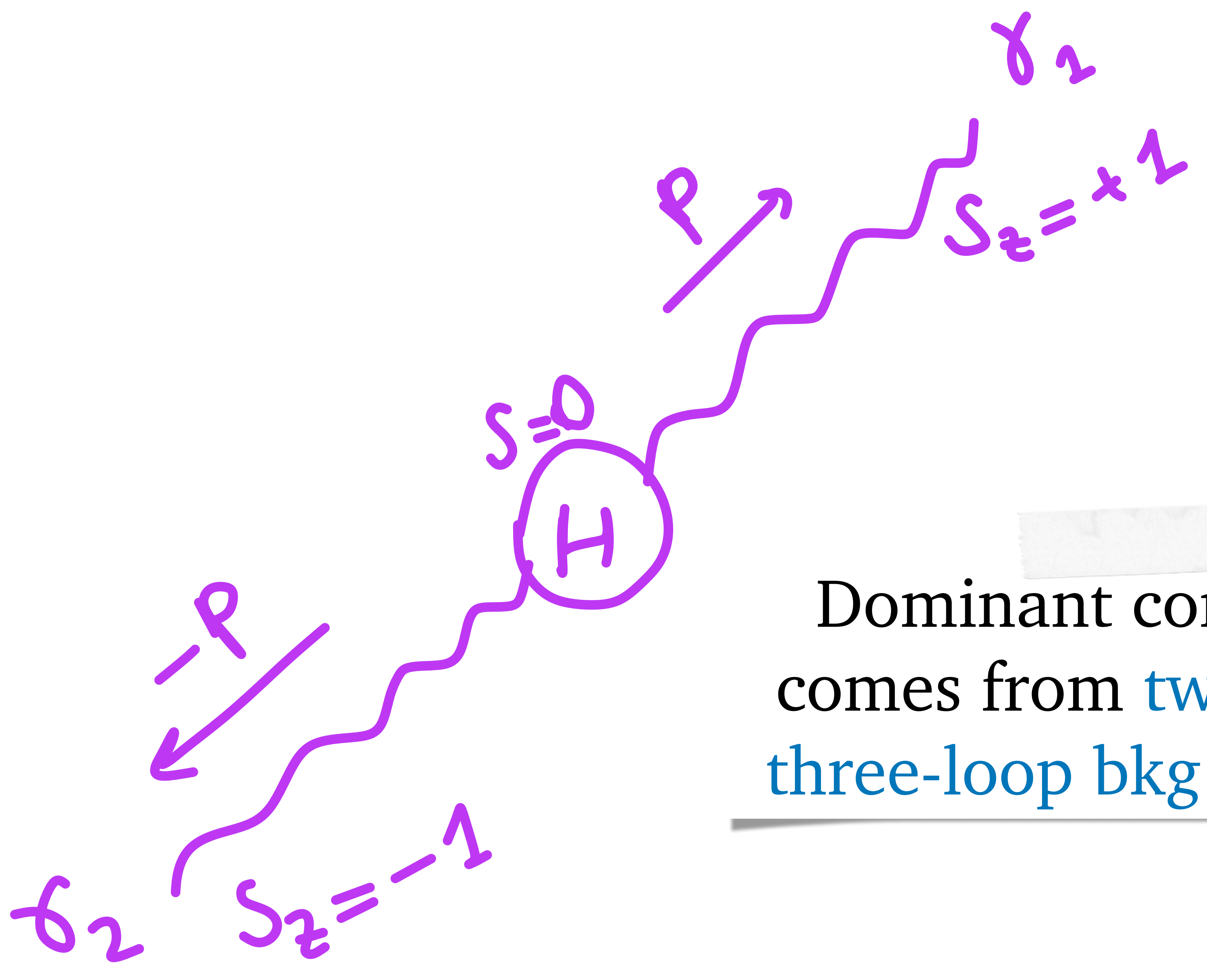
$$S_{\gamma\gamma} \sim \frac{\alpha_s\, \alpha\, m_H^2}{(4\pi v)^2}$$

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

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

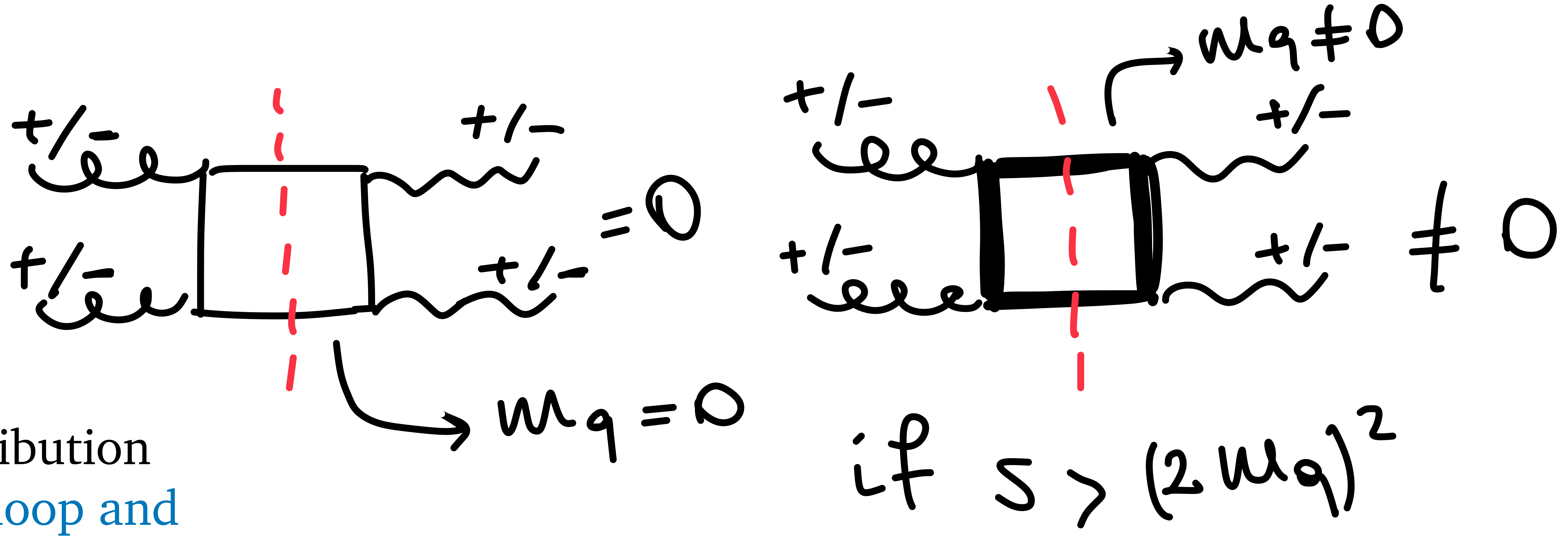
"Loop enhancement"

Spin and mass effects



$$h(\gamma_1) = h(\gamma_2) = +/-$$

Conservation of spin

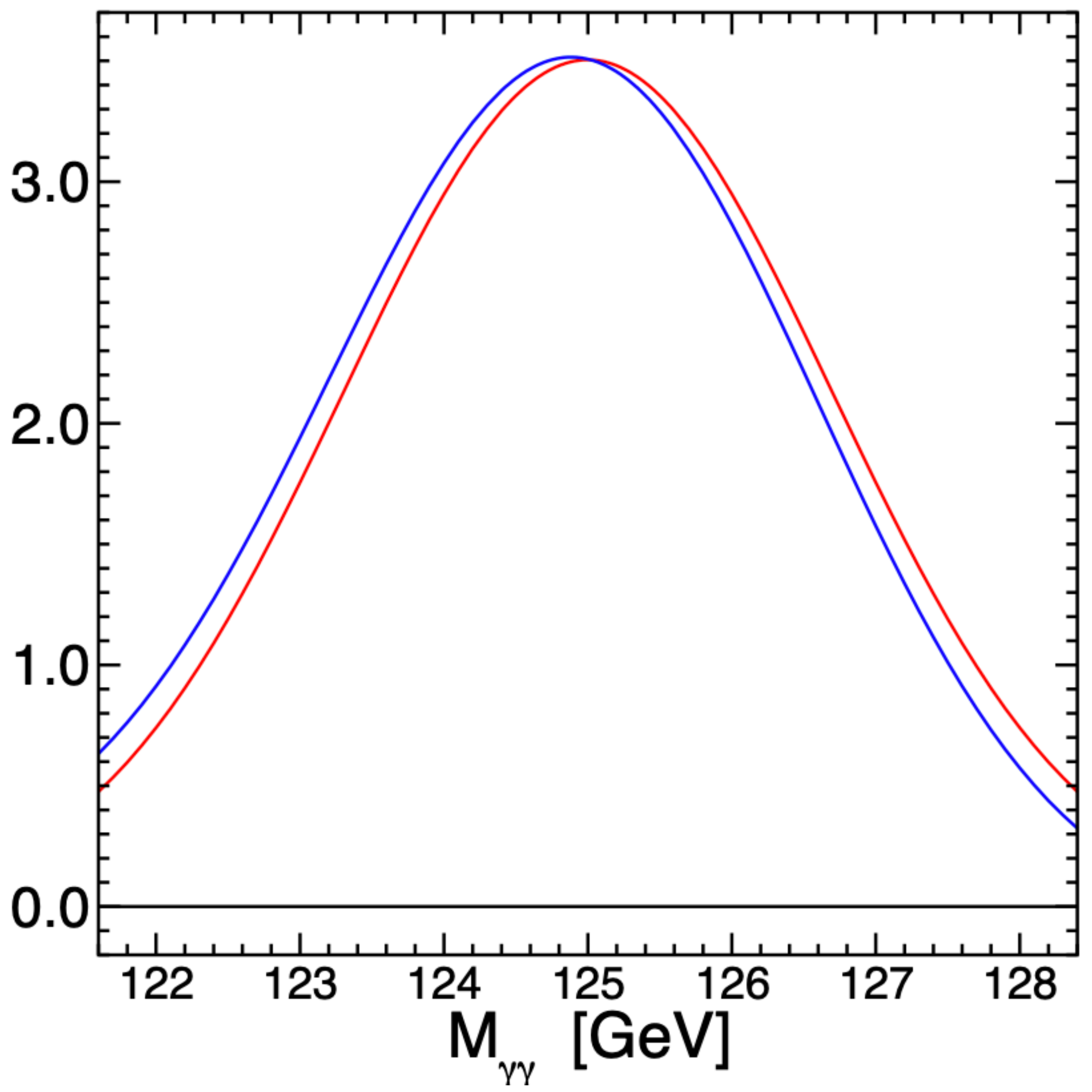


Dominant contribution comes from two-loop and three-loop bkg amplitudes

Small effect: ~permille effect at LO to be compared with NLO interference ~1%

Mass-shift estimate: theory

- How can we estimate it from a theory side?



$\boxed{\text{First moment method}}$ [Martin '12]

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

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

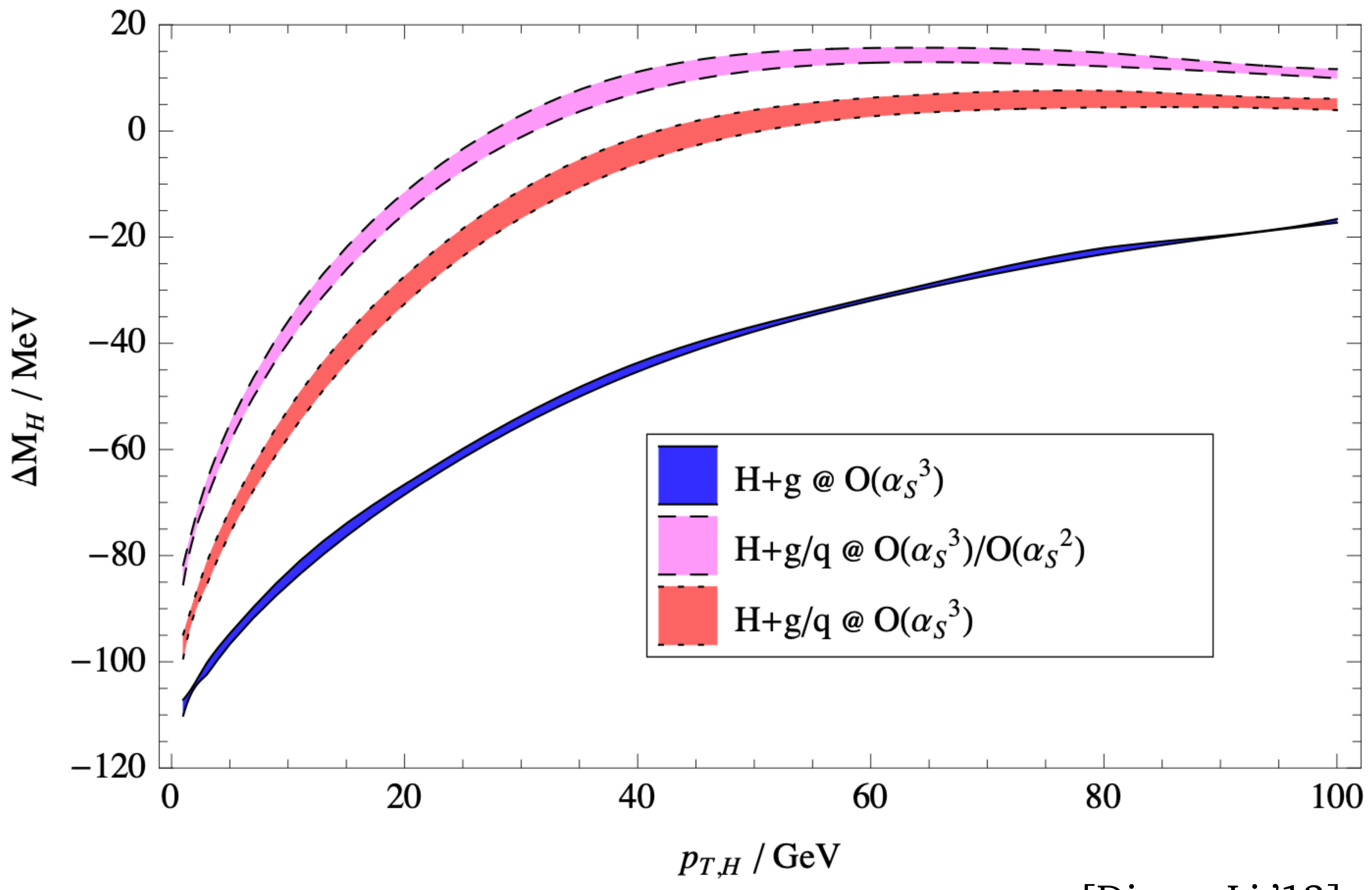
$$\Delta M_{\gamma\gamma} = \langle M_{\gamma\gamma}\rangle_{sig+int} - \langle M_{\gamma\gamma}\rangle_{sig}$$

$\boxed{\text{Likelihood analysis, e.g. gaussian fit}}$

[Dixon, Li '13]

Mass-shift estimate: experiments

- More realistic ways to extract the mass shift in experiments?



[Dixon, Li '13]

$p_{T,H}$ dependent measurements

- Recall that interference in diphoton channel is enhanced wrt ZZ channel

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

Interference effects and Higgs width: imaginary part

[J. Campbell et al 1704.08259]

- Let's go back to the imaginary part of the interference
- Integrated cross section also depends linearly on the couplings! Can be exploited to put bounds on the Higgs width

$$I_{\rm Im} \propto \frac{2}{(m_{\gamma\gamma}^2 - m_H^2)^2 + \Gamma_H^2 m_H^2} \Gamma_H m_H \times$$
$$\times \left[\mathrm{Re}\mathcal{M}_{\rm bkg}\mathrm{Im}\mathcal{M}_{\rm sig} - \mathrm{Im}\mathcal{M}_{\rm bkg}\mathrm{Re}\mathcal{M}_{\rm sig}\right]$$

$\downarrow$ NWA

$$\sigma_{int} \propto \frac{\pi}{\Gamma_{\cancel{H}} \cancel{m_H}} \cdot \lambda_i \lambda_f \Gamma_{\cancel{H}} \cancel{m_H}$$

$$\frac{\lambda_i^2 \lambda_f^2}{\Gamma_H} = \frac{\lambda_{i,SM}^2 \lambda_{f,SM}^2}{\Gamma_{H,SM}}$$

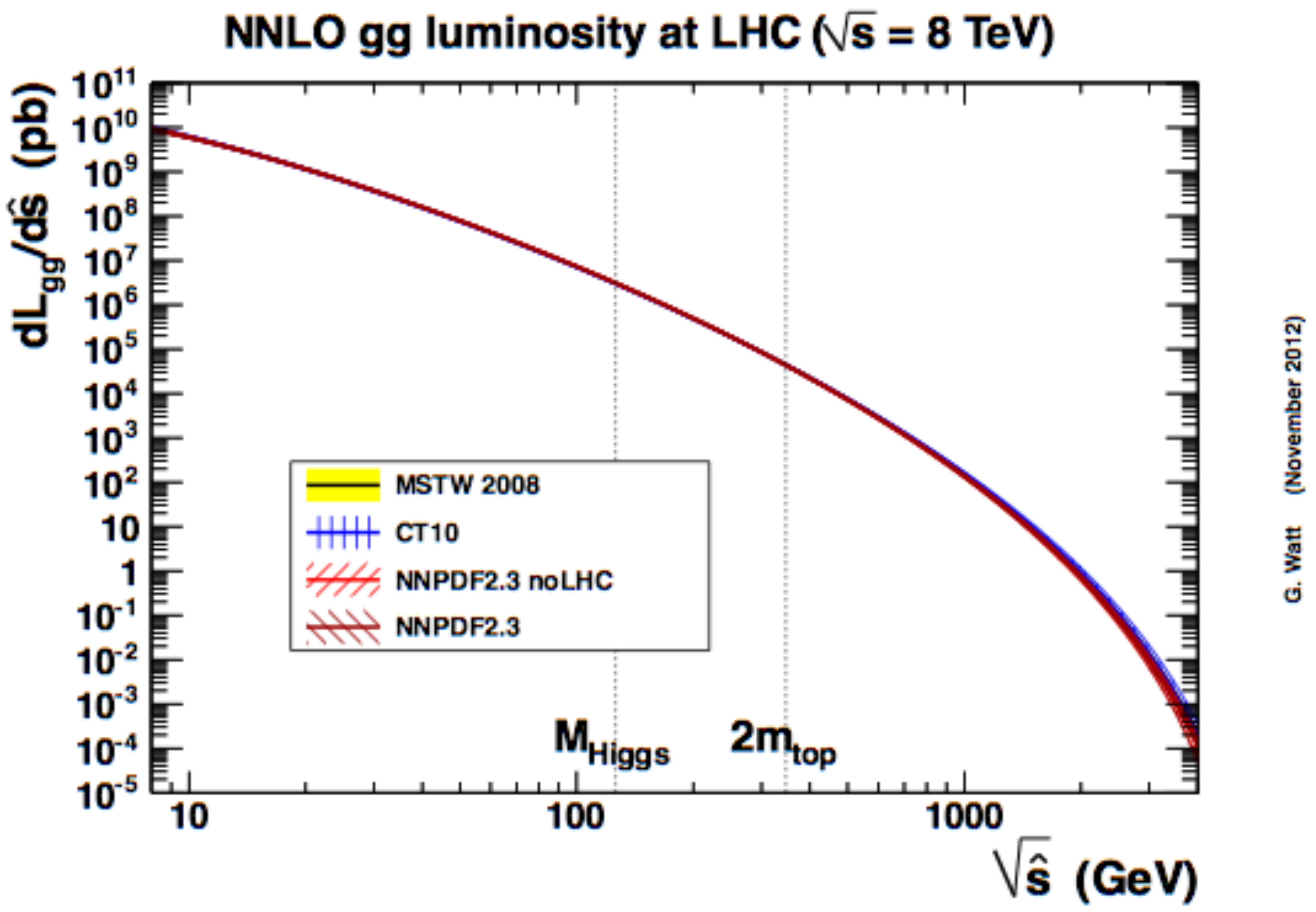
@LO: ~(-5) permille
@NLO: ~(-1.3)%
@NNLO: ? (Will see shortly)

$$\sigma_{sig+int} = \sigma_{sig,SM}\left(1 + \frac{\sigma_{int,SM}}{\sigma_{sig,SM}}\sqrt{\frac{\Gamma_H}{\Gamma_{H,SM}}}\right) \simeq \sigma_{sig,SM}\left(1 + \boxed{\frac{\sigma_{int}}{\sigma_{sig,SM}}}\sqrt{\frac{\Gamma_H}{\Gamma_{H,SM}}}\right)$$

Prediction of the calculation

Soft-virtual approximation in a nutshell

- Evaluation of soft contributions only, neglect hard emissions
- Consider the production of large invariant mass Q at the LHC



- Gluon PDFs enhanced at small x: center-of-mass energy tends to be close to invariant mass of the system ➡ only soft extra radiation allowed

$$\hat{\sigma} = \sigma_0 + \sigma_0 \frac{\alpha_s}{2\pi}\left(8C_A\left[\frac{\ln(1-z)}{1-z}\right]_+ + c_1\delta(1-z) + \text{reg}\right) + \text{h.o.}$$

Universal structure

Process-dependent, from virtual contributions

In some cases subleading terms may be enhanced: resummation arguments allow to “tweak” the approx

[R.D. Ball, Bonvini et al (2013)]

Results: integrated cross section

LO

With bottom mass both in signal and background amplitudes

$$\boxed{\sigma_{int} = -0.11 \text{ fb}}$$

With bottom mass in background amplitude only

$$\sigma_{int} = -0.02 \text{ fb}$$

With bottom mass in signal amplitude only

$$\sigma_{int} = -0.09 \text{ fb}$$

dNLO massless

$$\boxed{\sigma_{int} = -0.62 \text{ fb}}$$

6 times smaller than dNLO + further suppression from couplings, we neglect quark masses beyond NLO

dNNLOsv massless

$$\sigma_{int} = -0.48 \text{ fb}$$

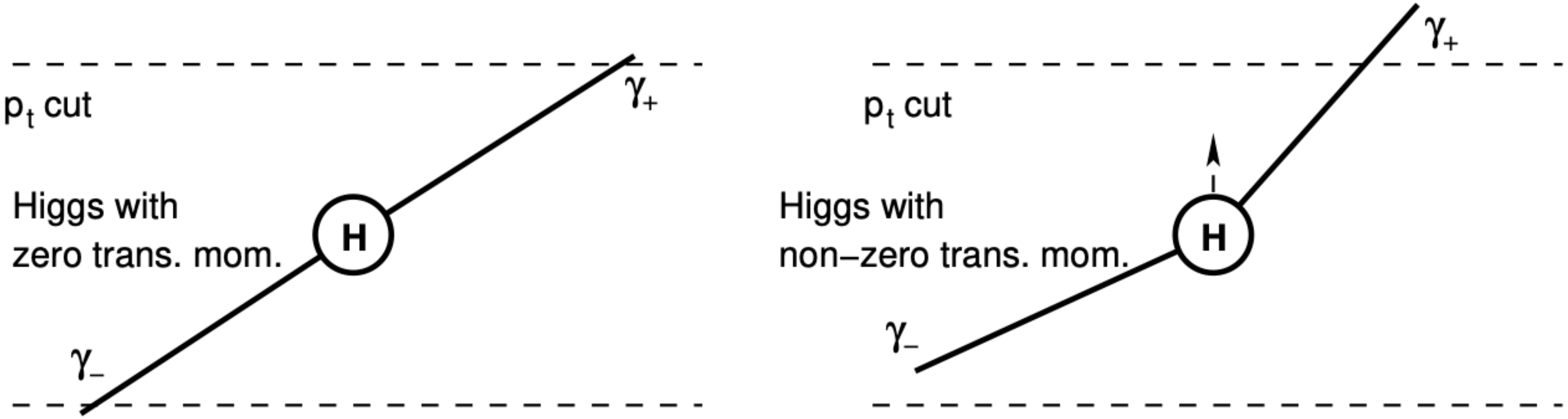
$$\boxed{\sigma_{int}^{NNLOsv} = -1.21 \text{ fb}}$$

Why product cuts?

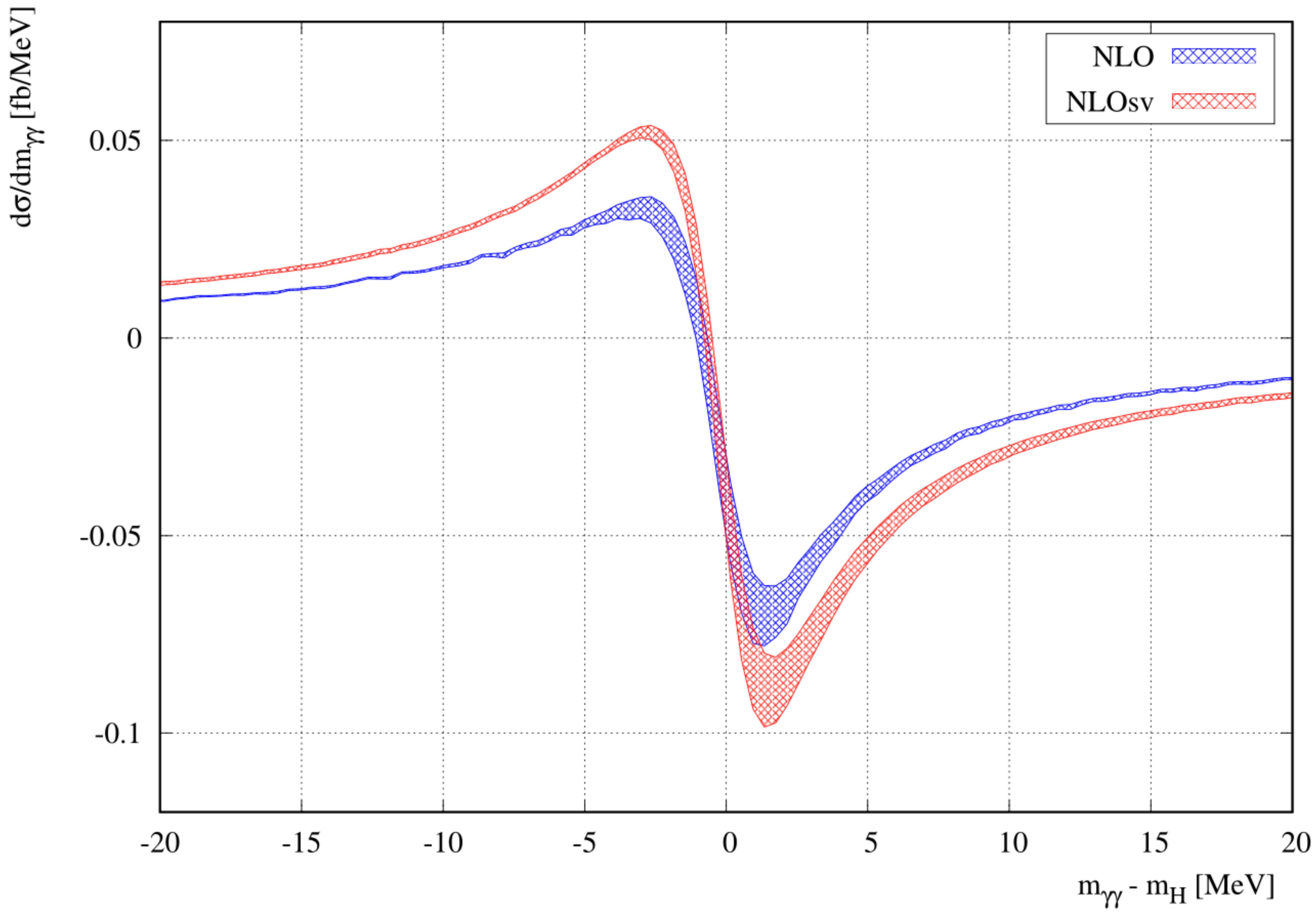
[Salam, Slade 2106.08329]

$$f(p_{t,\mathrm{H}}) = f_0 + f_1 \cdot \frac{p_{t,\mathrm{H}}}{m_{\mathrm{H}}} + \mathcal{O}\left(\frac{p_{t,\mathrm{H}}^2}{m_{\mathrm{H}}^2}\right)$$

- Symmetric and antisymmetric cuts yield an acceptance for $H \to \gamma\gamma$ decays with linear dependence on $p_{t,H}$
- Product cuts alleviate factorial divergence in perturbative series



SV approximation and asymmetric cuts



Comparison of the exact NLO calculation and the soft-virtual approximation for the interference process adopting asymmetric cuts on the photons, cfr. Ref.[21] (Dixon, Li [1305.3854])

Higgs width @ e+e- colliders

Physics Case for the 250 GeV Stage of the International Linear Collider

Keisuke Fujii (KEK, Tsukuba), Christophe Grojean (DESY and Humboldt U., Berlin), Michael E. Peskin (SLAC), Tim Barklow (SLAC), Yuanning Gao (Tsinghua U., Beijing) et al.

e-Print: 1710.07621 [hep-ex]

- $e^+e^- \to Zh$ @ 250 GeV. By looking at Z resonance one can measure the total XS with no reference to Higgs decay modes!

- "k-parametrization": assume Higgs couplings to be modified wrt SM with multiplicative factor k

$$\frac{\Gamma(h \to ZZ^*)}{SM} = \kappa_Z^2 \,, \qquad \frac{\sigma(e^+e^- \to Zh)}{SM} = \kappa_Z^2$$

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

The ratio is independent of k and yields total Higgs width!

In general limited by statistics!

Model dependence

Physics Case for the 250 GeV Stage of the International Linear Collider

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- Issue with k-formalism: it neglects couplings of the type $\zeta\, h\, Z_{\mu\nu}\, Z^{\mu\nu}$ which would have dependence on the momentum-configurations of the vector bosons

- If we consider such couplings the ratio $\sigma(e^+e^- \to Zh)/BR(h \to ZZ^*)$ does not determine the width unambiguously

- EFT formalism applied to e+e- allows to put strong constraints on couplings of Higgs boson both to Z_μ and $Z_{\mu\nu}$ and reduces the problem to measurement of $e^+e^- \to Zh$ and $h \to WW^*$, much less affected by statistics @ 250GeV e+e- machine