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

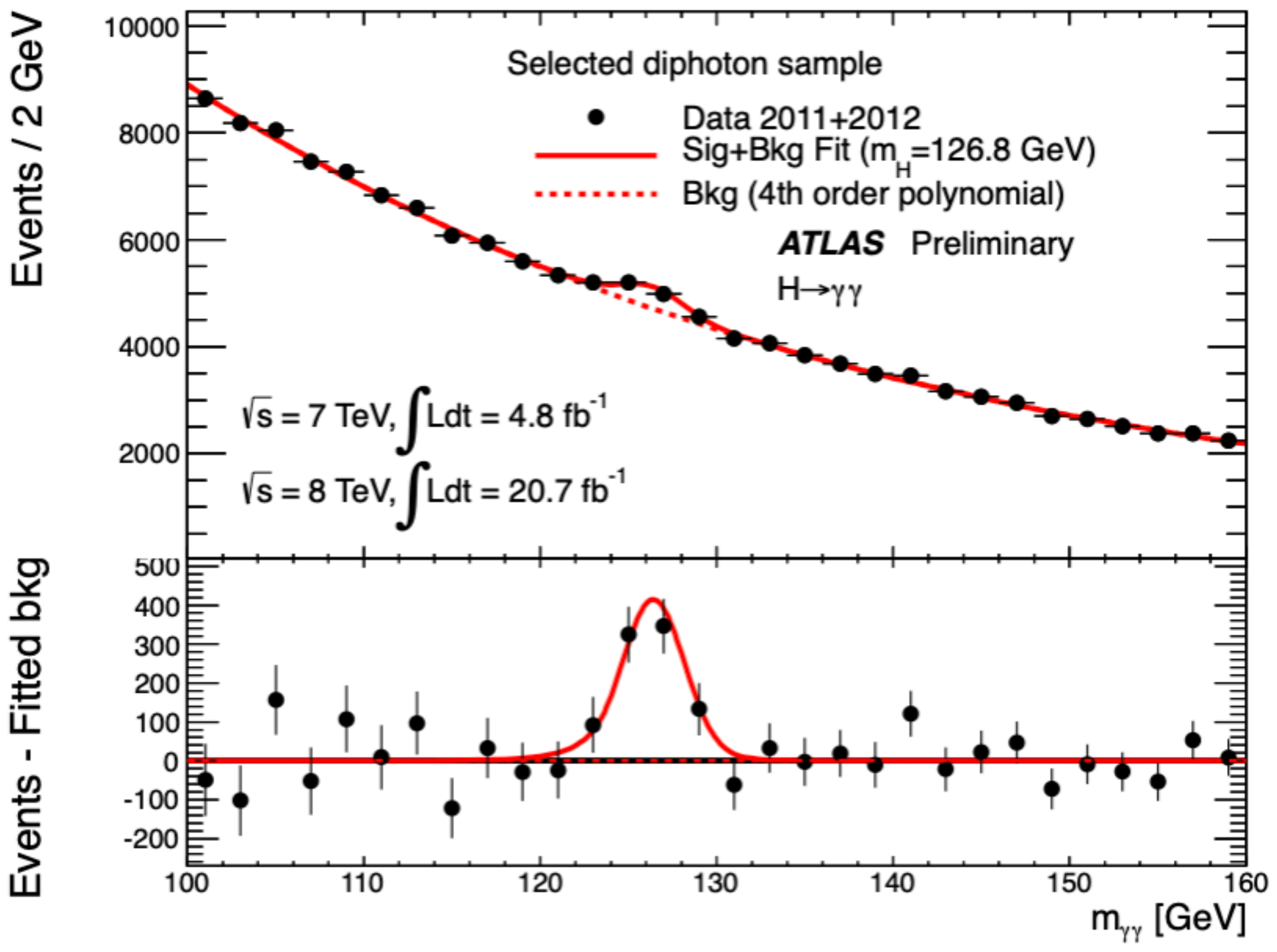
In collaboration with: P. Bargiela, F. Buccioni, F. Caola, A. von Manteuffel, L.Tancredi

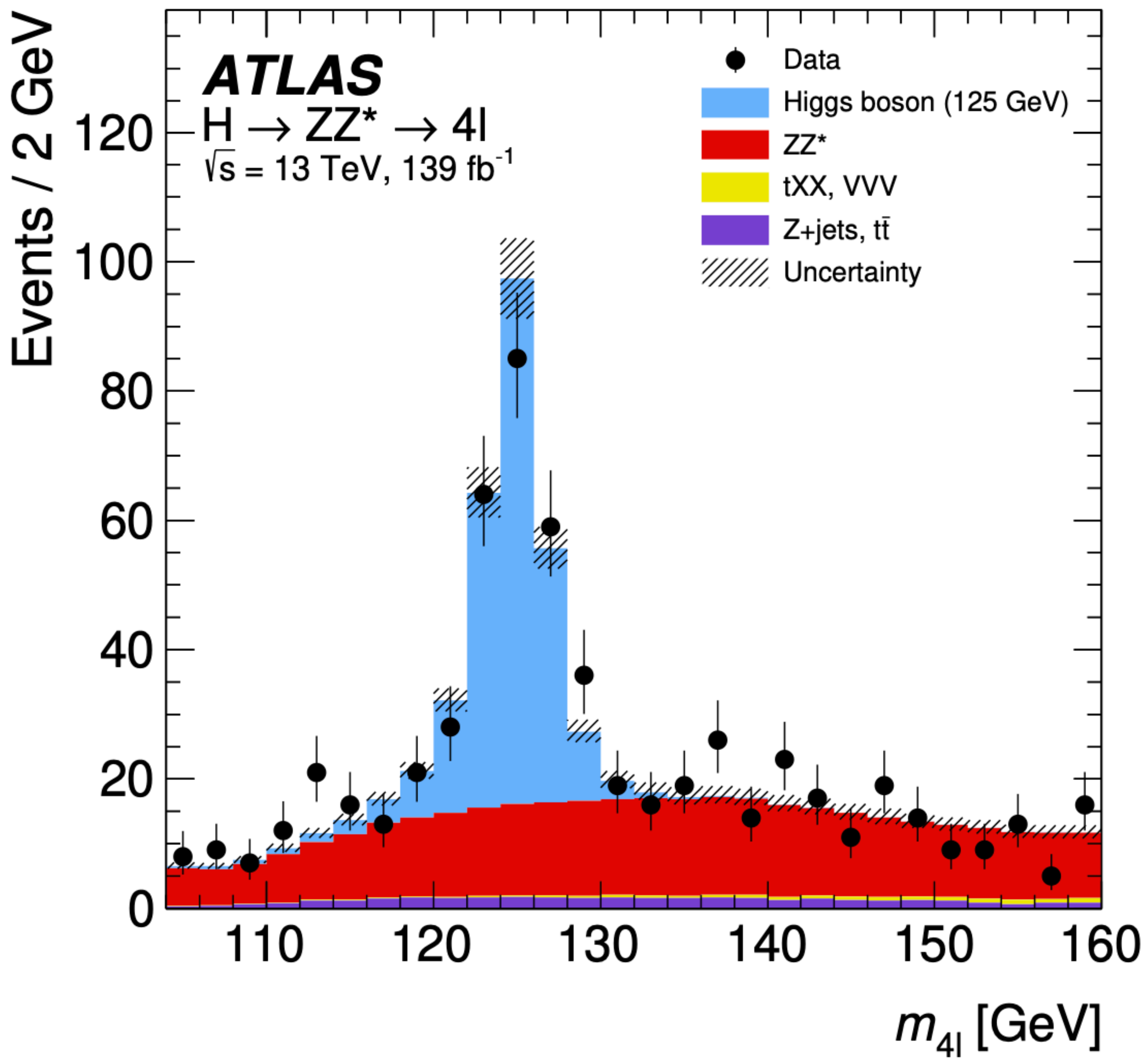
Based on arXiv:2212.06287

Outline

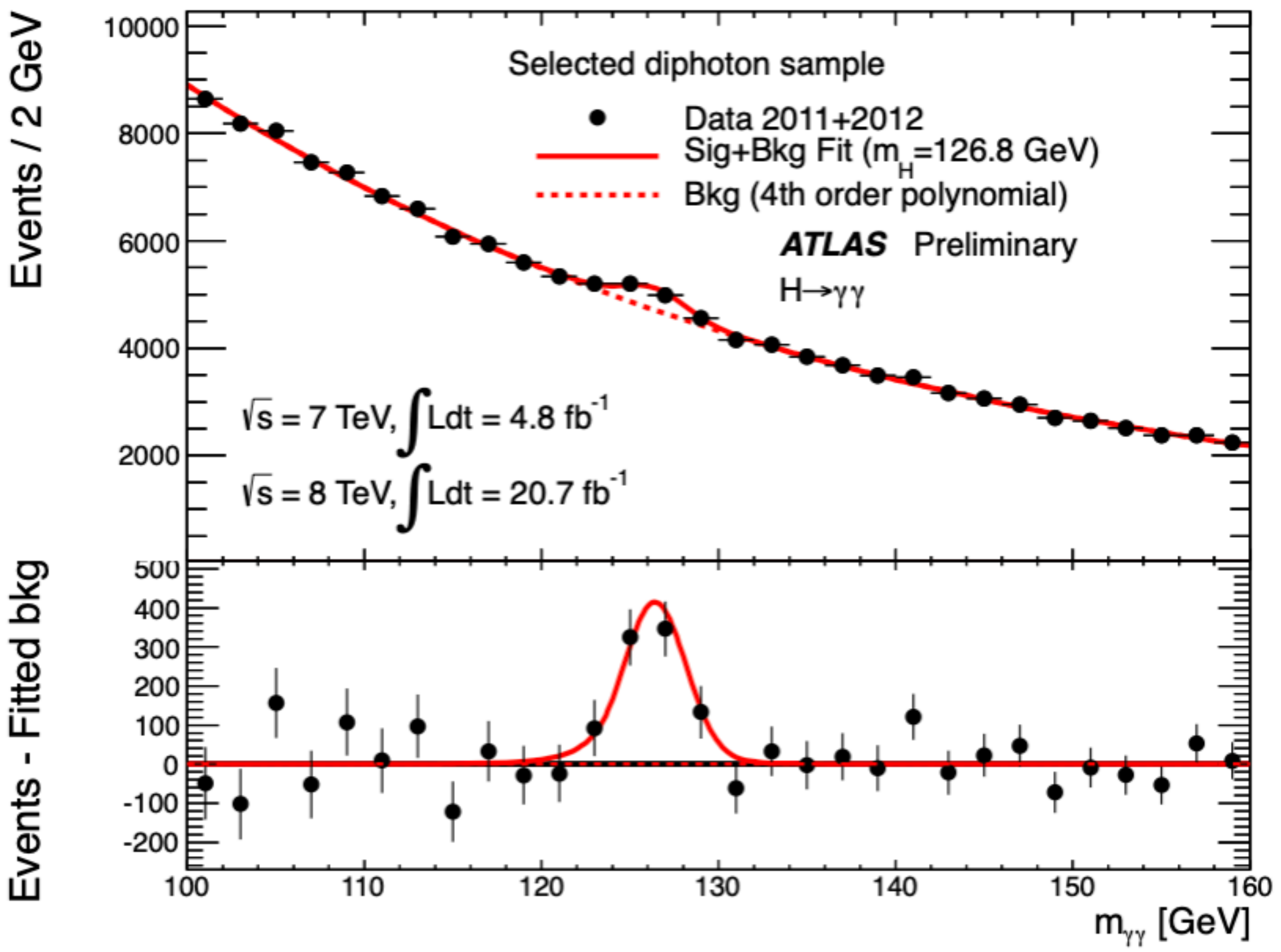
- Motivation: we should we care about signal-background interference effects in Higgs production?
- Review of the basic ideas behind “Higgs interferometry”: mass-shift in diphoton invariant mass distribution, link between interference effects and Higgs boson decay width
- New results! First calculation of signal-background interference contribution at NNLO soft-virtual and updated bounds on Higgs width determination

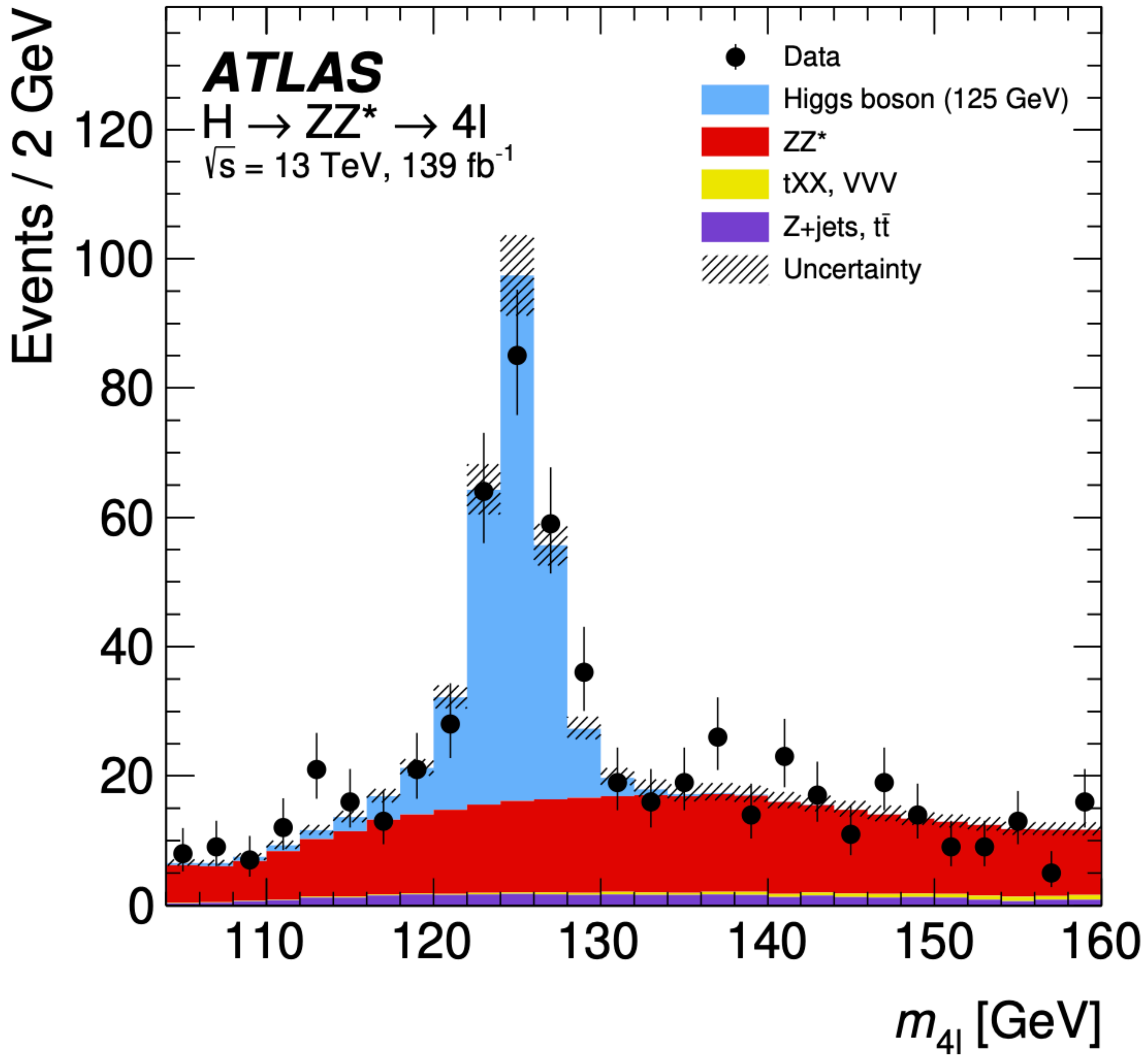
The Higgs boson decade





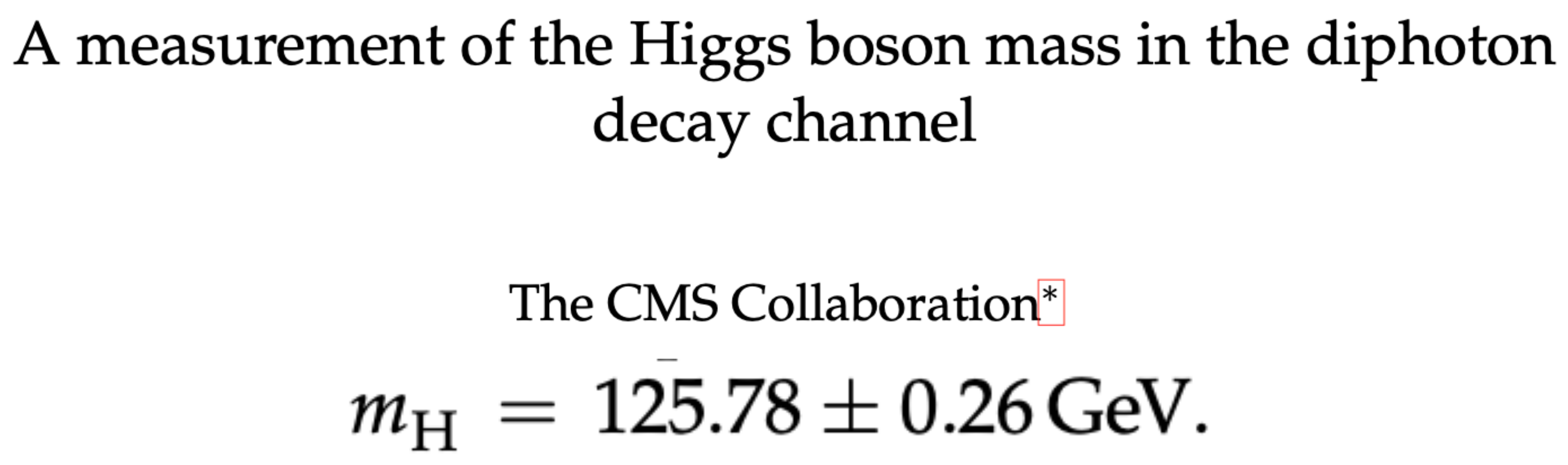
The Higgs boson decade





A decade of Higgs studies… and more to come!

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


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

The CMS Collaboration*

$$m_{\mathrm{H}} = 125.78 \pm 0.26\,\mathrm{GeV}.$$


nature physics

https://doi.org/10.103

OPEN

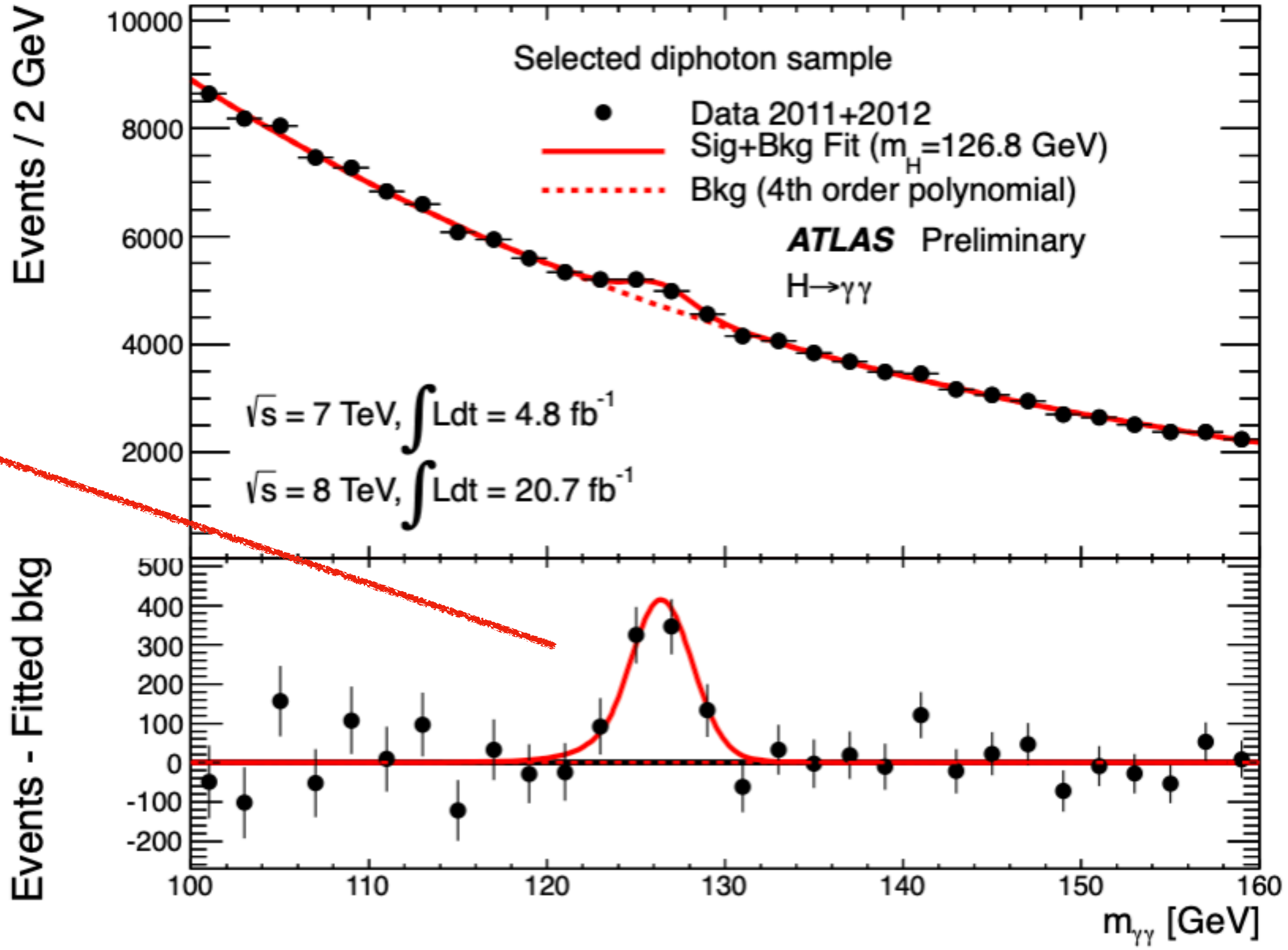
Measurement of the Higgs boson width and evidence of its off-shell contributions to ZZ production

The CMS Collaboration*✉

The Higgs decay width

- Higgs width Γ_H : predicted by the Standard Model to be ~ 4 MeV
- Direct sensitivity at the LHC is $\mathcal{O}$(GeV)

Impossible to measure directly
Need indirect measurements/ bounds



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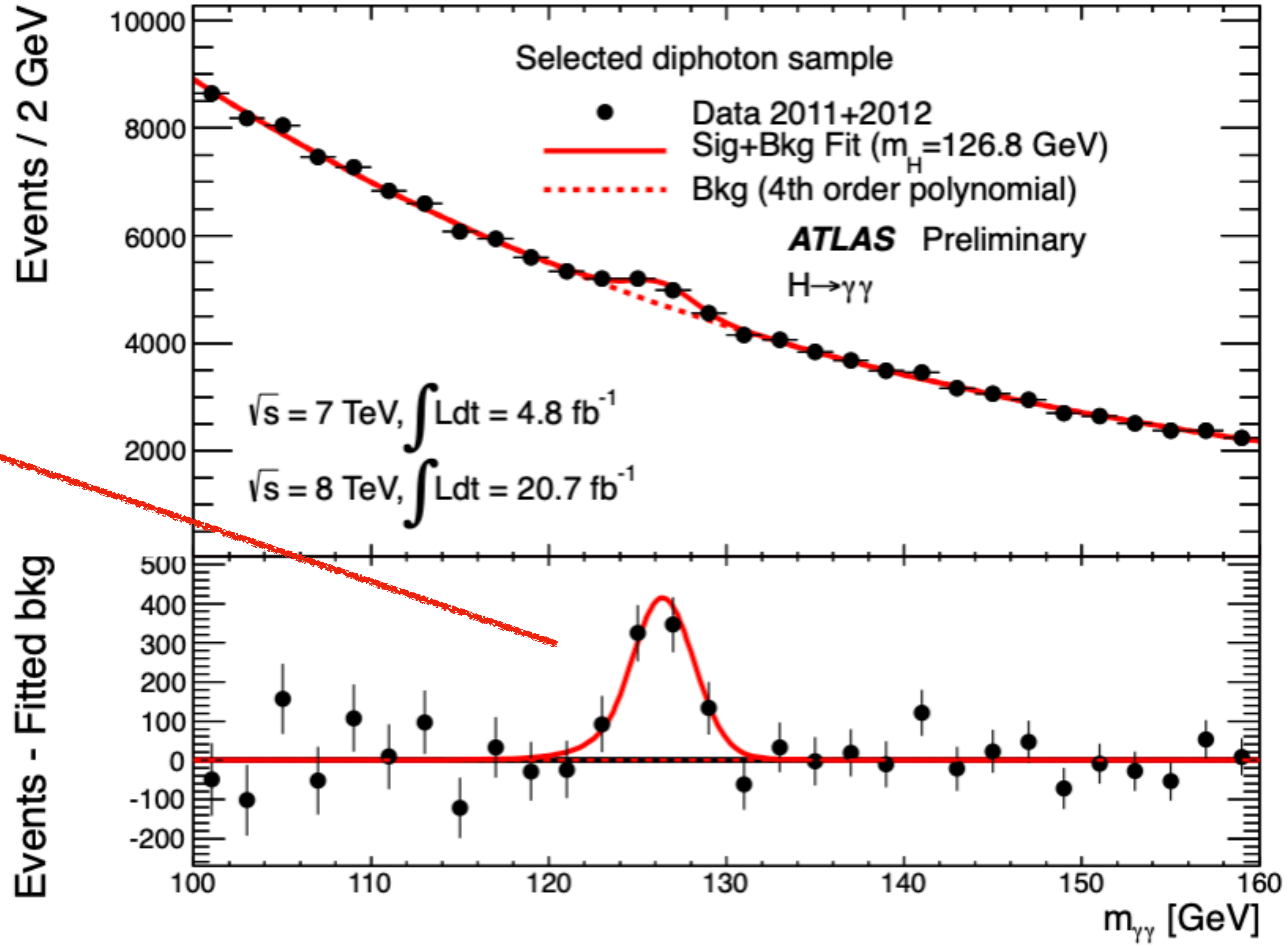
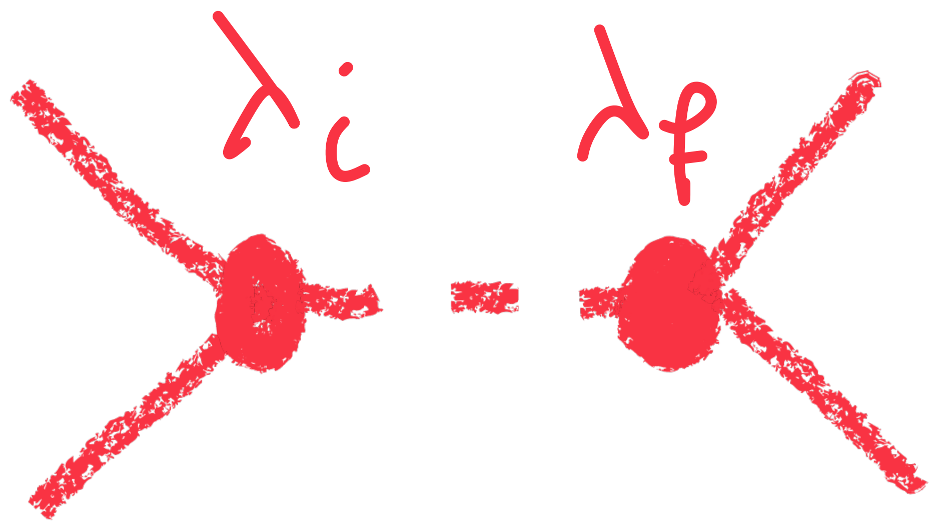


On-shell Higgs cross sections

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

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

Cross section unchanged upon such rescaling



On-shell Higgs cross sections

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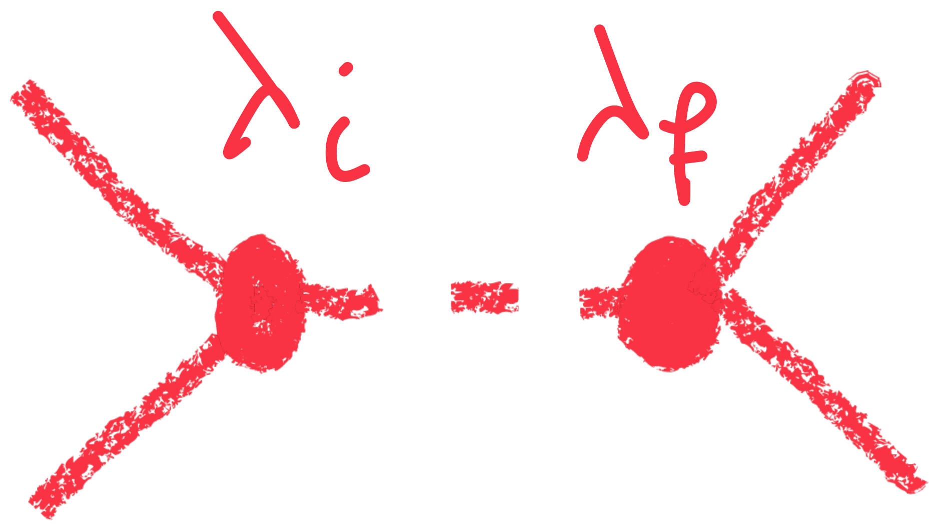
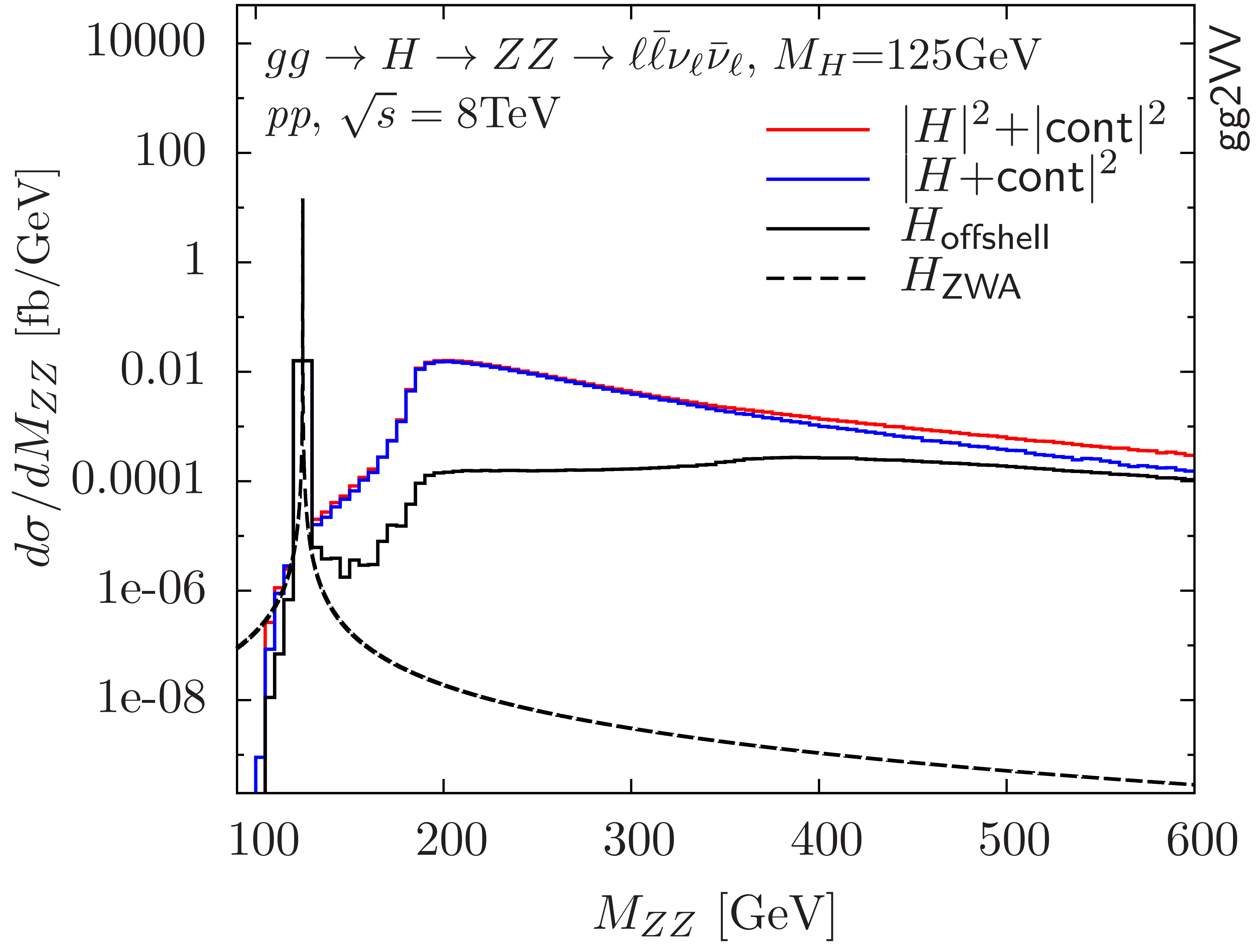


How can we lift this degeneracy?
Need to find an observable with different dependence on couplings and width

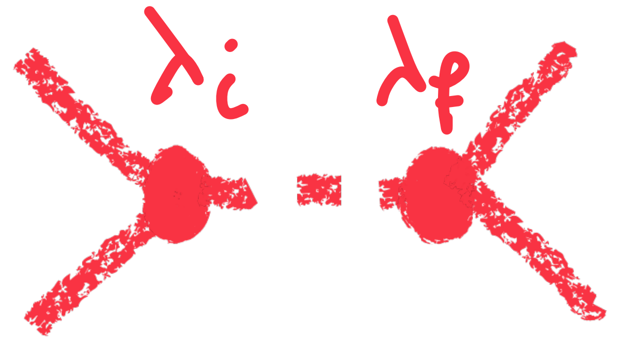
Some existing ideas: off-shell cross sections

N. Kauer, G.Passarino 1206.4803
F. Caola, K.Melnikov 1307.4935
J.M. Campbell, R.K.Ellis, C.Williams 1311.3589



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

CMS collaboration, Nat. Phys. (2022)



$$\sigma \propto \int \left| \lambda_i \quad \lambda_f \right|^2 \sim \int \frac{\lambda_i^2 \lambda_f^2}{(s-m_H^2)^2 + \Gamma_H^2 m_H^2}$$

$i \to H \to f$

$s >> m_H^2$

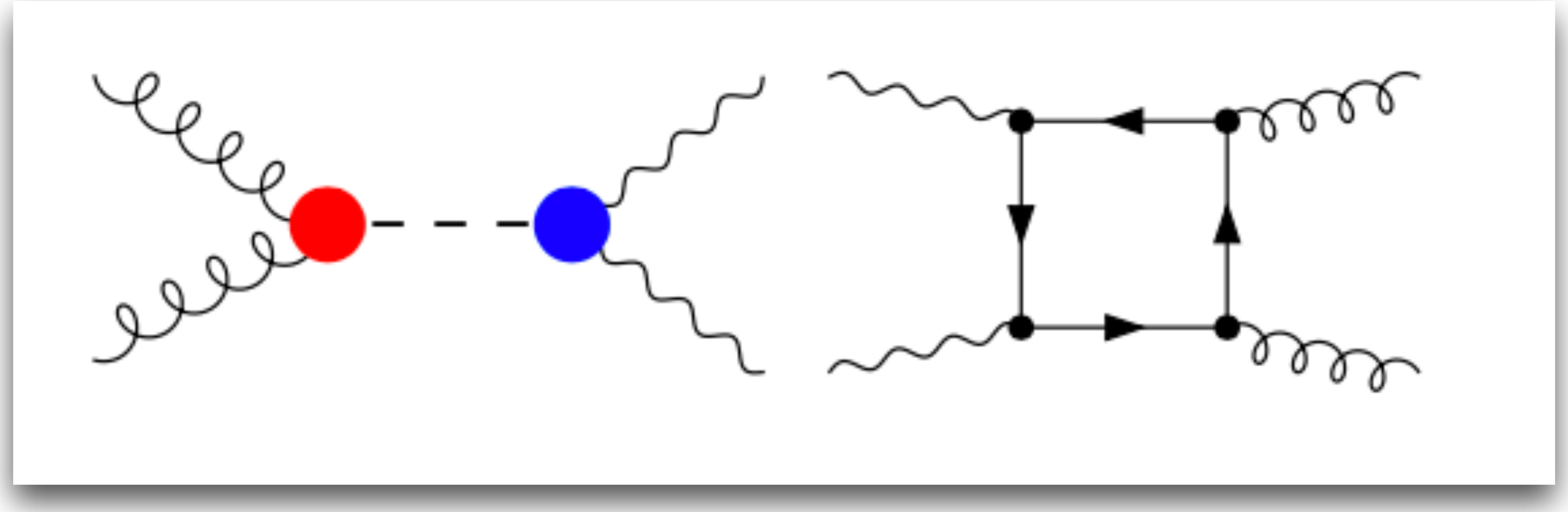
$$\int \frac{\lambda_i^2 \lambda_f^2}{(s-m_H^2)^2}$$

Independent of the decay width!
This breaks degeneracy upon rescaling

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

Some existing ideas: Higgs interferometry

- Look at signal-background interference effects in diphoton production at the LHC

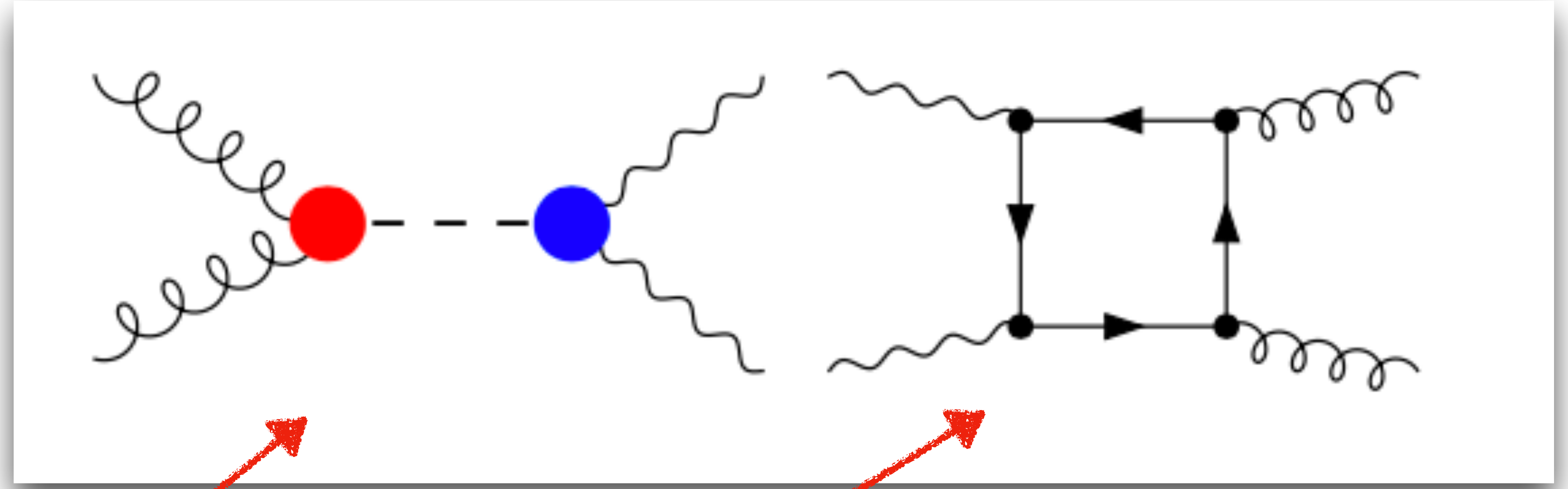


S.P. Martin 1208.1533
D. De Florian et al 1303.1397
L.J. Dixon, Y. Li 1305.3854

Focus of the talk

- Consider on-shell Higgs production
- Need diphoton final state, why? We'll see shortly
- Purely quantum interference effect!

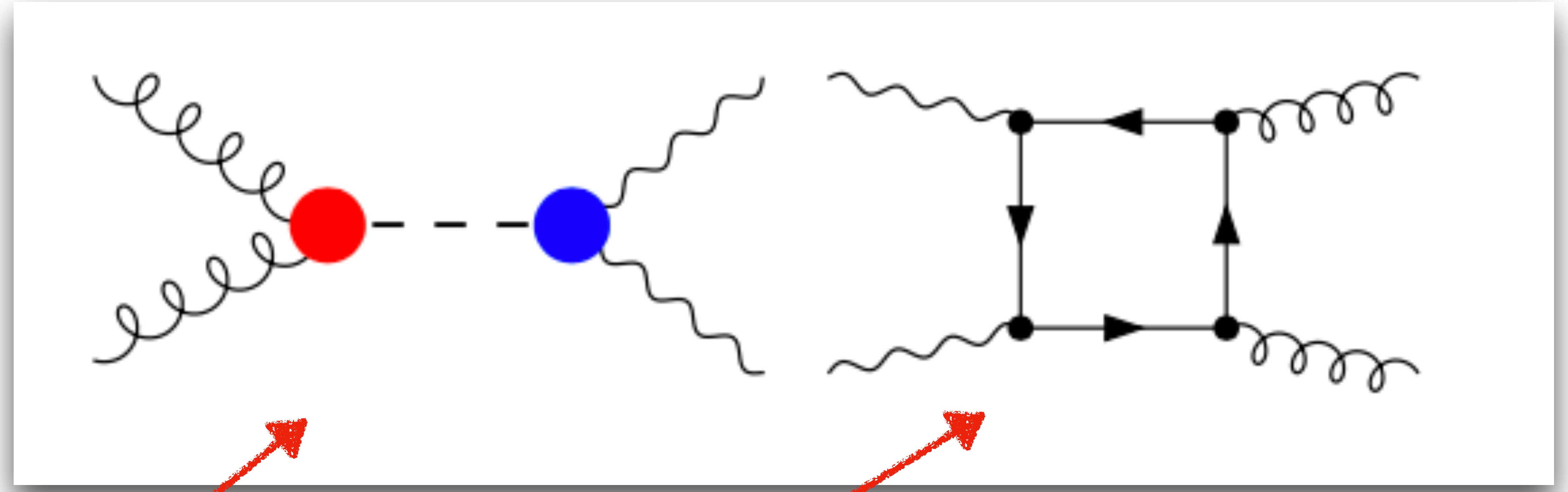
Higgs interferometry (I)



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

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

Higgs interferometry (I)



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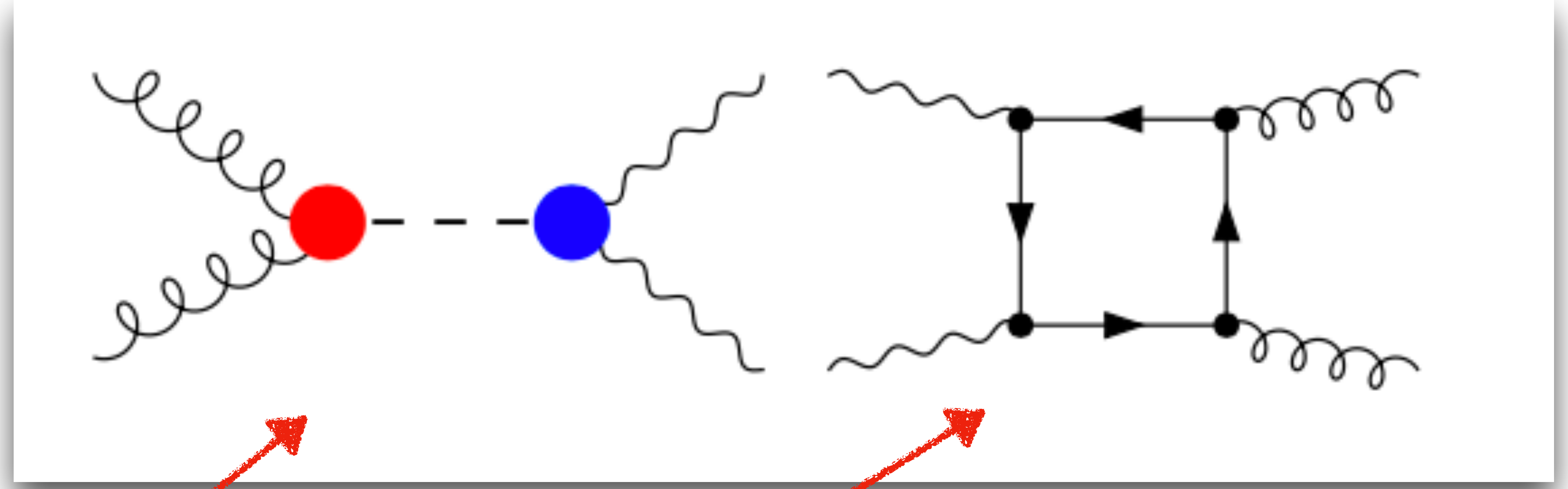
$$+ \boxed{2\,\mathrm{Re}\left(\frac{\mathcal{M}_{\rm sig}}{m_{\gamma\gamma}^2 - m_H^2 + i\Gamma_H m_H}\mathcal{M}_{\rm bkg}^{\dagger}\right)}$$

Higgs interferometry (I)



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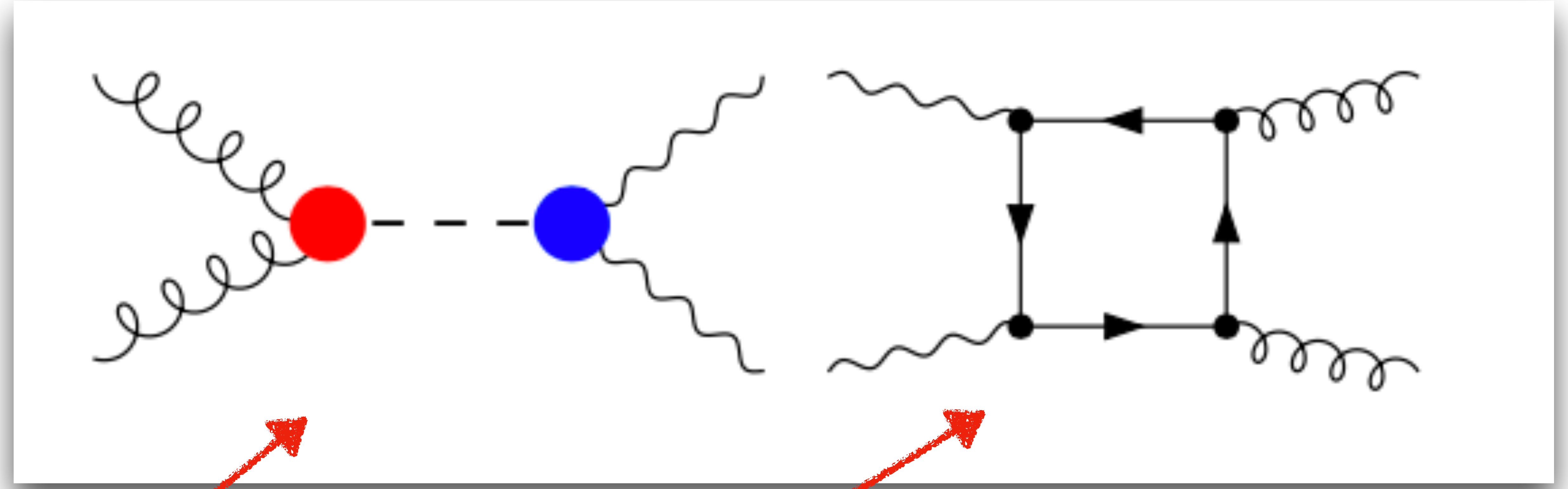

Signal-background interference

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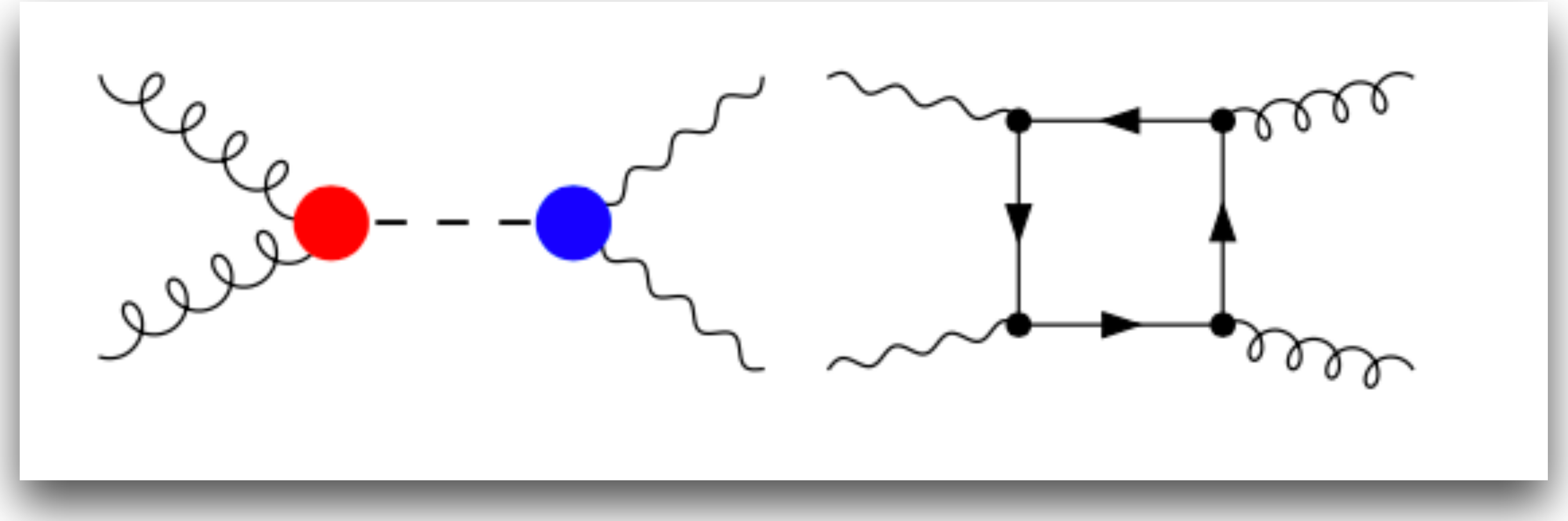
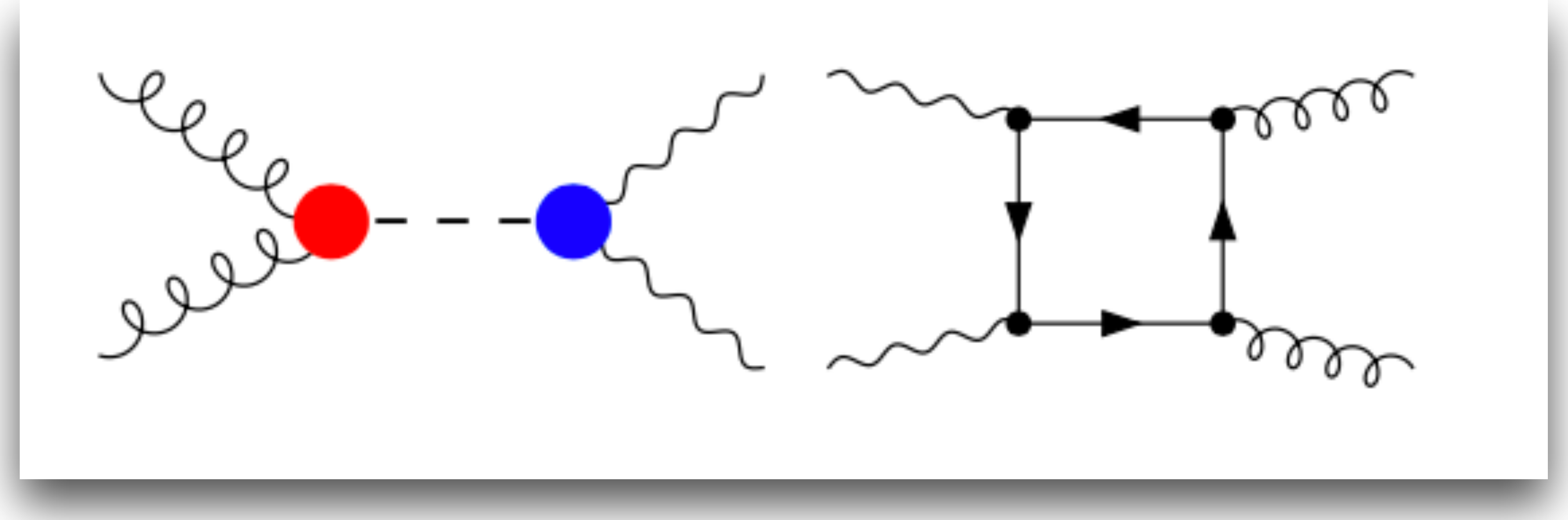
Higgs interferometry (II)



$$\frac{\mathrm{d}\sigma}{\mathrm{d}m_{\gamma\gamma}} \sim |S|^2 + |B|^2 + \boxed{I}$$

Higgs interferometry (II)



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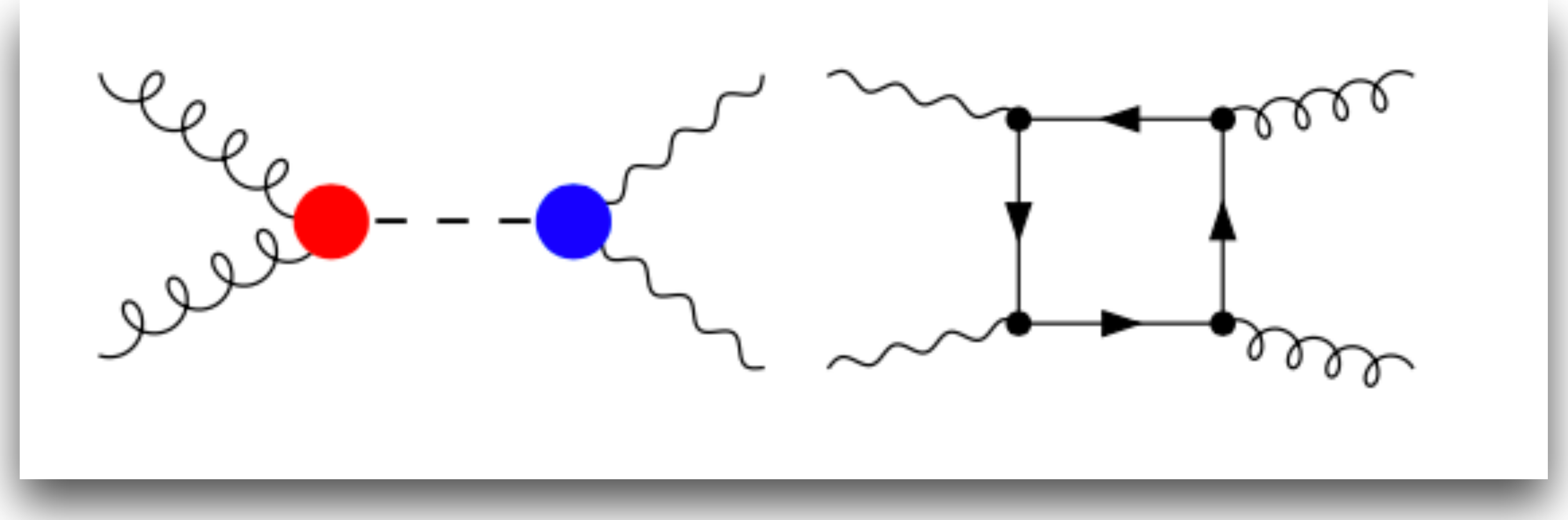

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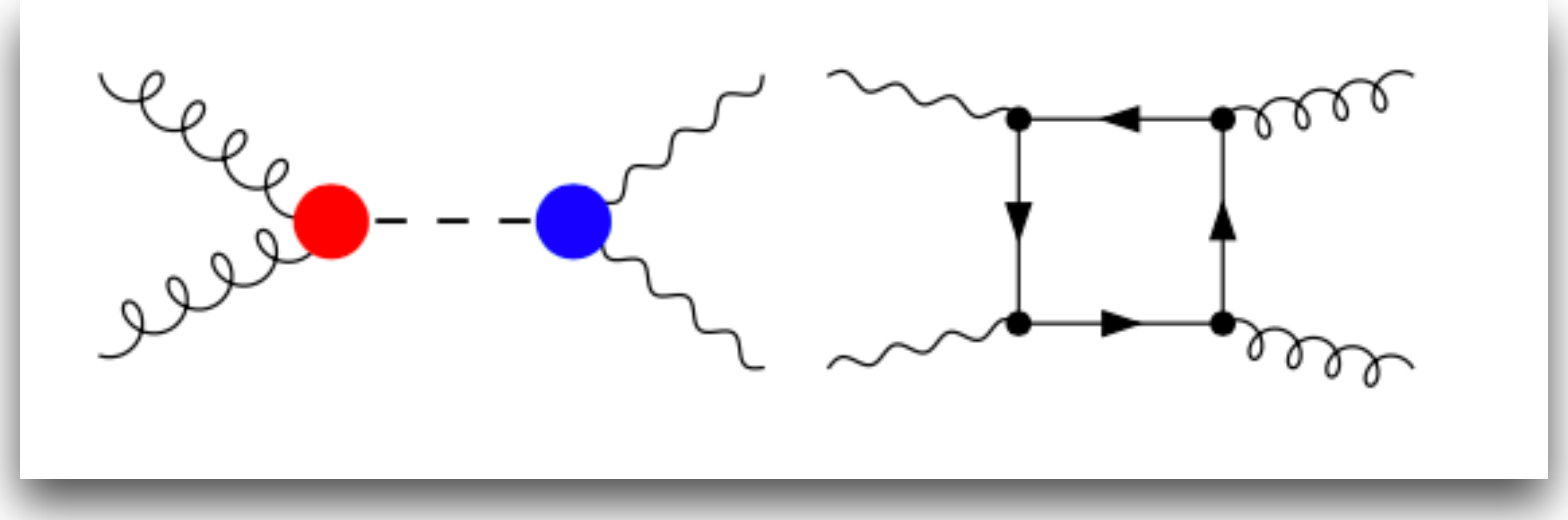

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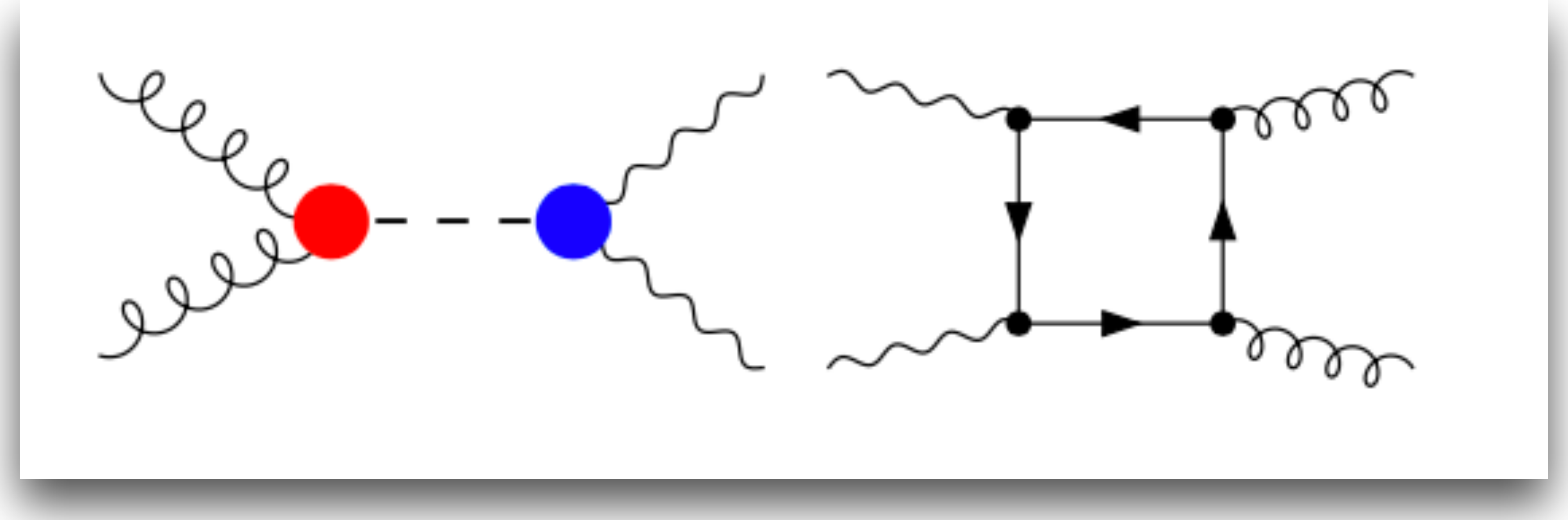

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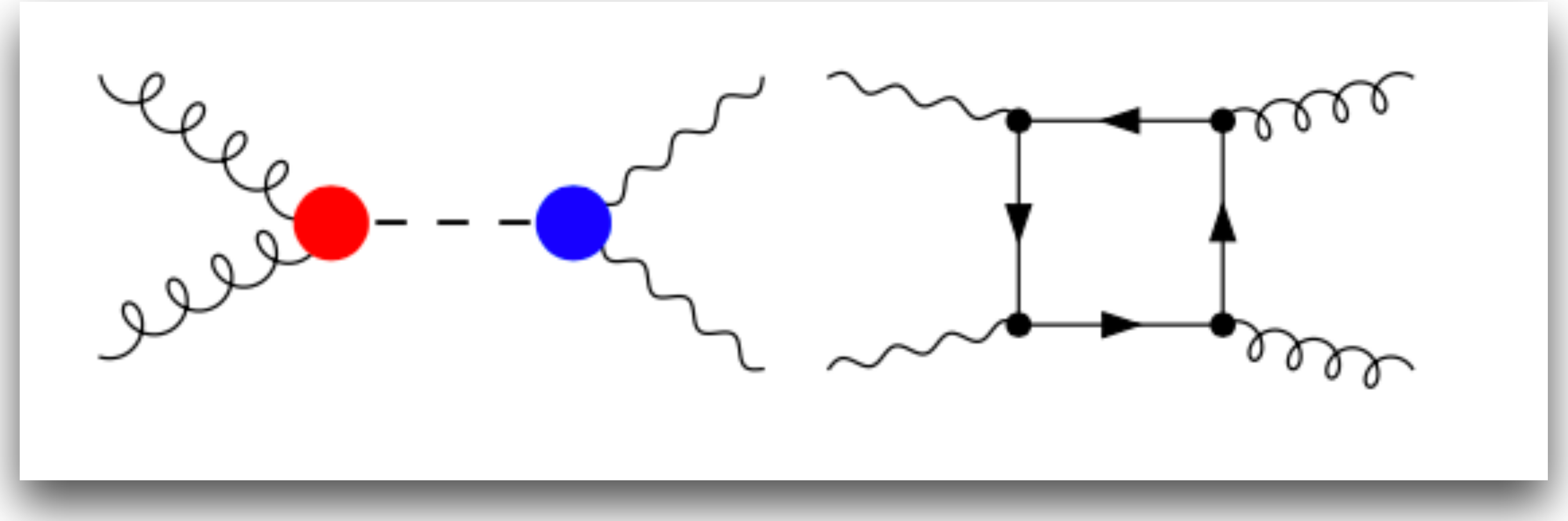

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$$\downarrow$$

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

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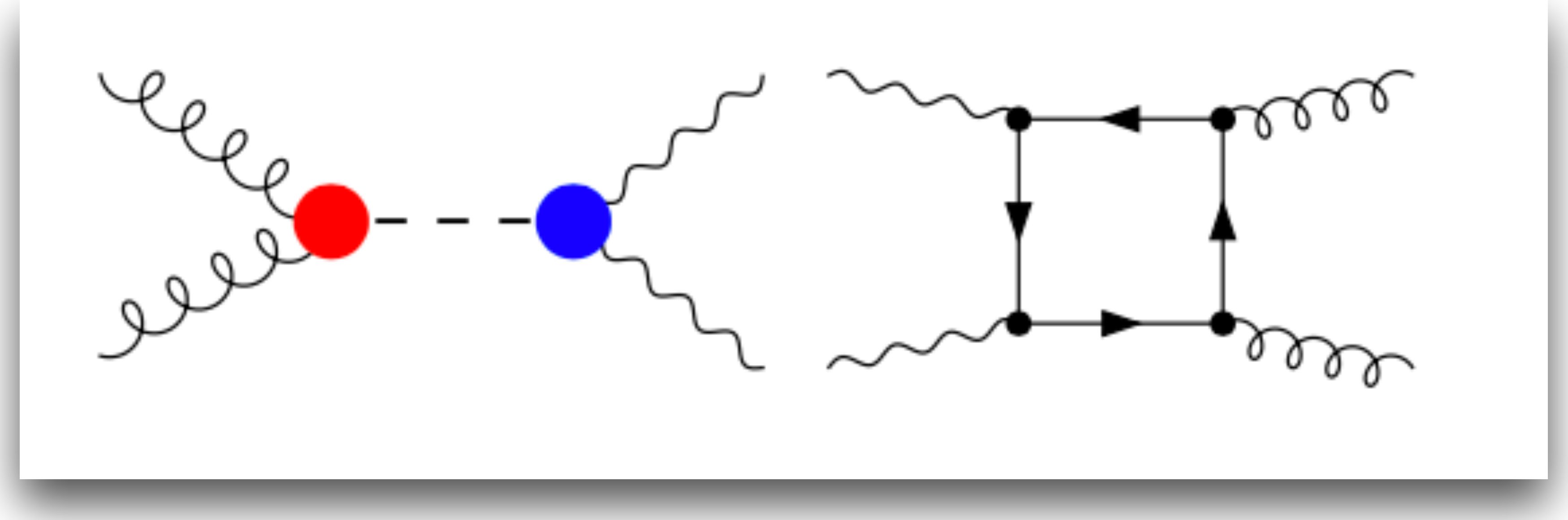

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$$I_{\mathrm{Re}} \propto \frac{2}{(m_{\gamma\gamma}^2 - m_H^2)^2 + \Gamma_H^2 m_H^2} (m_{\gamma\gamma}^2 - m_H^2) \times$$
$$\times \left[\mathrm{Re}\mathcal{M}_{\mathrm{bkg}}\mathrm{Re}\mathcal{M}_{\mathrm{sig}} + \mathrm{Im}\mathcal{M}_{\mathrm{bkg}}\mathrm{Im}\mathcal{M}_{\mathrm{sig}}\right],$$

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$$\Big\downarrow$$

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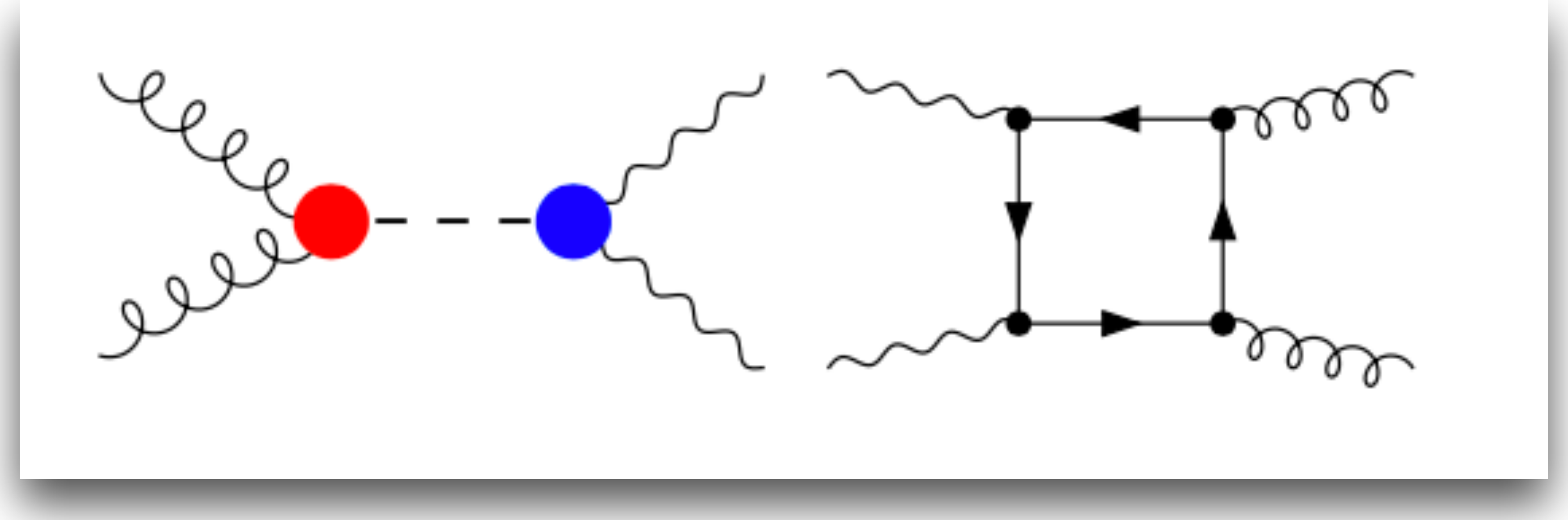

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$$\times \left[\mathrm{Re}\mathcal{M}_{\mathrm{bkg}}\mathrm{Re}\mathcal{M}_{\mathrm{sig}} + \mathrm{Im}\mathcal{M}_{\mathrm{bkg}}\mathrm{Im}\mathcal{M}_{\mathrm{sig}}\right],$$

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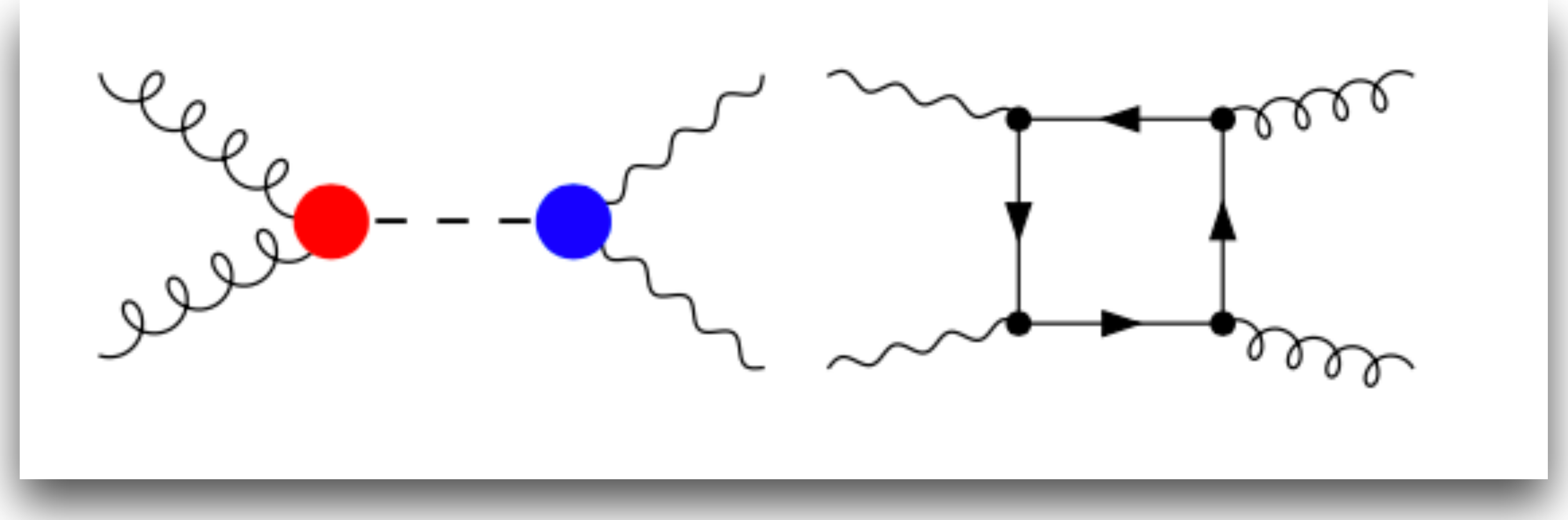
$$I_{\mathrm{Re}} + I_{\mathrm{Im}}$$

Higgs interferometry (II)



$$\frac{d\sigma}{dm_{\gamma\gamma}} \sim |S|^2 + |B|^2 + \boxed{I}$$

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

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“Real part”

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

$$\downarrow$$

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

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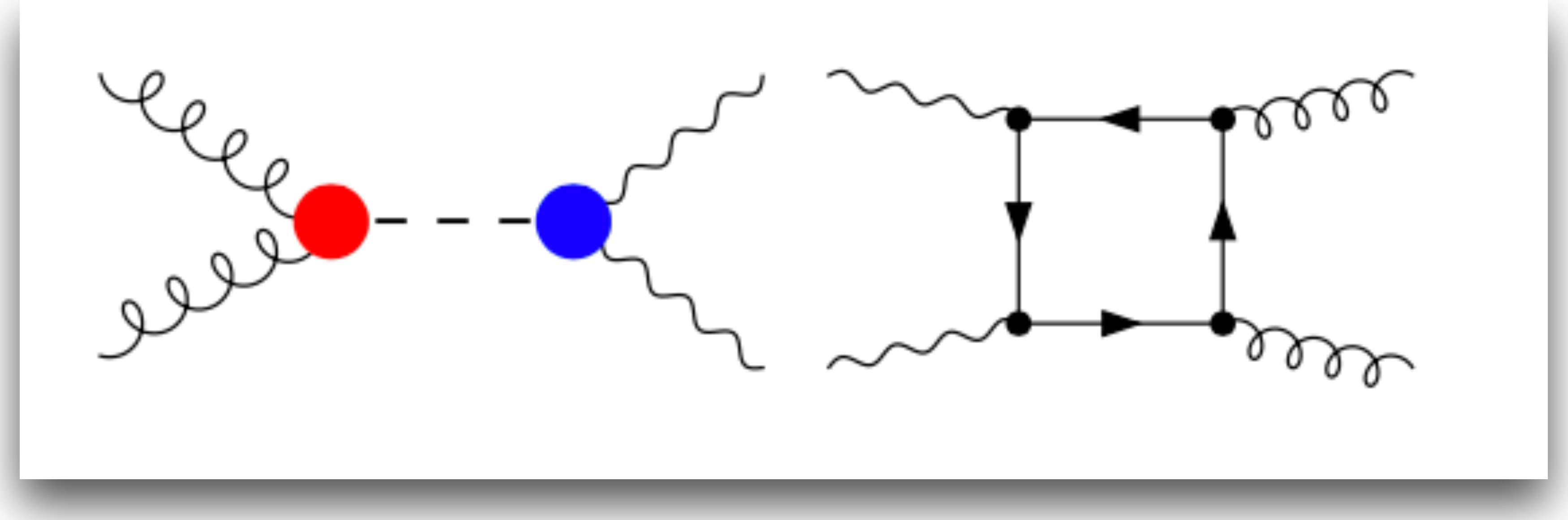

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$$I_{\mathrm{Re}} \propto \frac{2}{(m_{\gamma\gamma}^2 - m_H^2)^2 + \Gamma_H^2 m_H^2}(m_{\gamma\gamma}^2 - m_H^2) \times \\ \times \left[\mathrm{Re}\mathcal{M}_{\mathrm{bkg}}\mathrm{Re}\mathcal{M}_{\mathrm{sig}} + \mathrm{Im}\mathcal{M}_{\mathrm{bkg}}\mathrm{Im}\mathcal{M}_{\mathrm{sig}}\right],$$

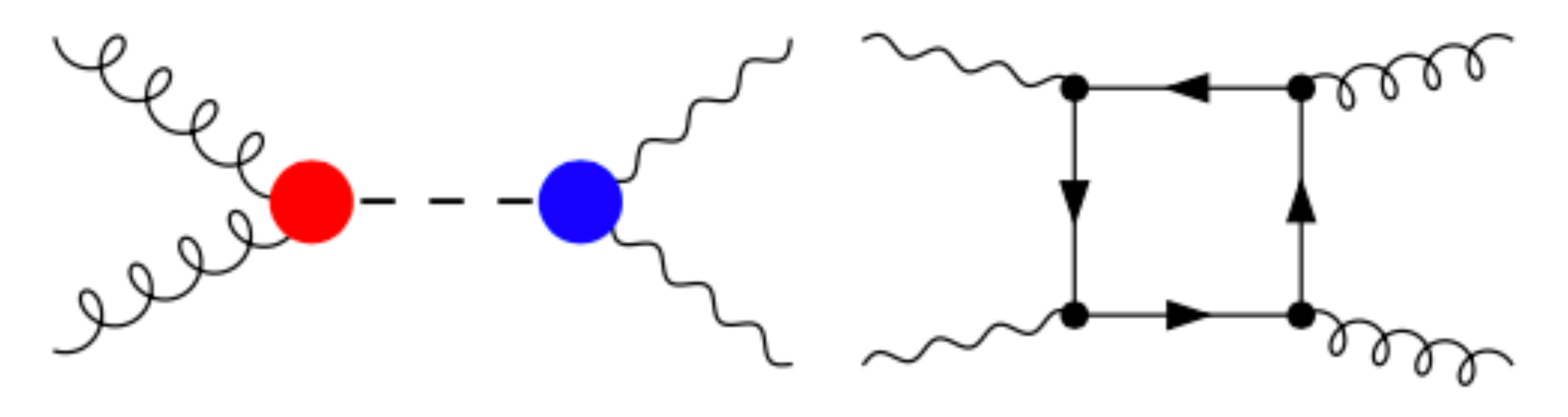
"Real part"

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

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

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

Higgs interferometry (II)



$$\frac{d\sigma}{dm_{\gamma\gamma}} \sim |S|^2 + |B|^2 + \boxed{I}$$

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

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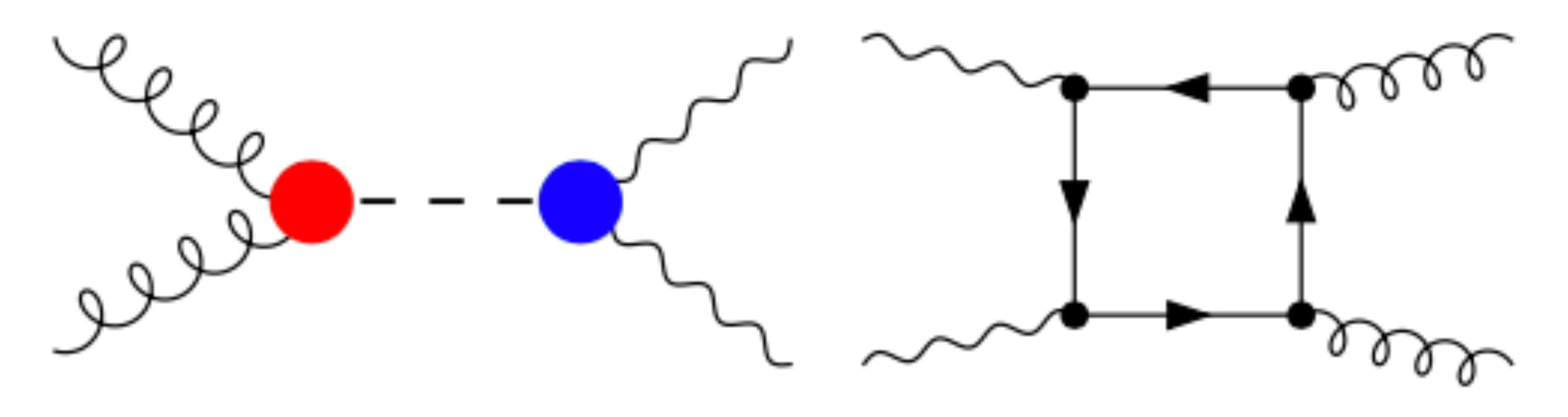
$$I_{\mathrm{Re}} + I_{\mathrm{Im}}$$

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

"Real part"

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

Higgs interferometry (II)



$$\frac{\mathrm{d}\sigma}{\mathrm{d}m_{\gamma\gamma}} \sim |S|^2 + |B|^2 + \boxed{I}$$

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

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

$$\downarrow$$

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

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

“Real part”

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

“Imaginary part”

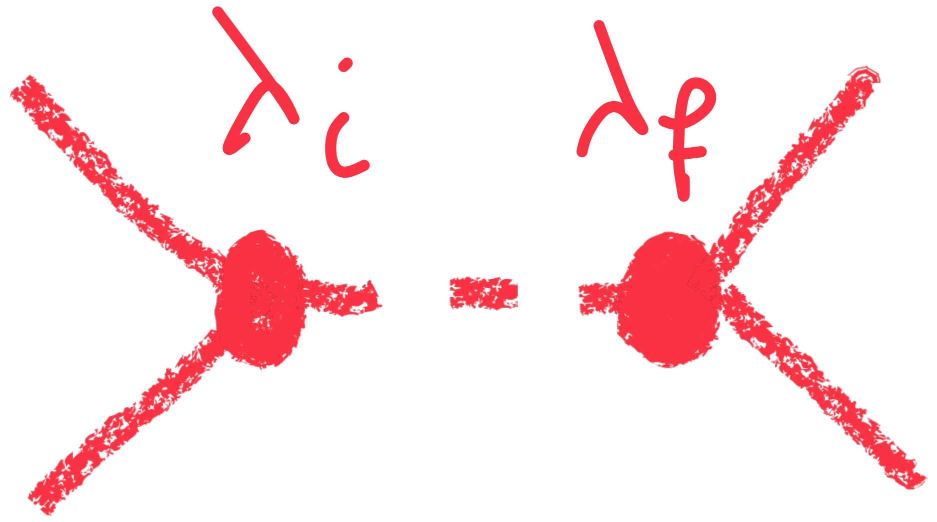
Higgs interferometry (III)

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

$\propto \lambda_i \lambda_f$

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

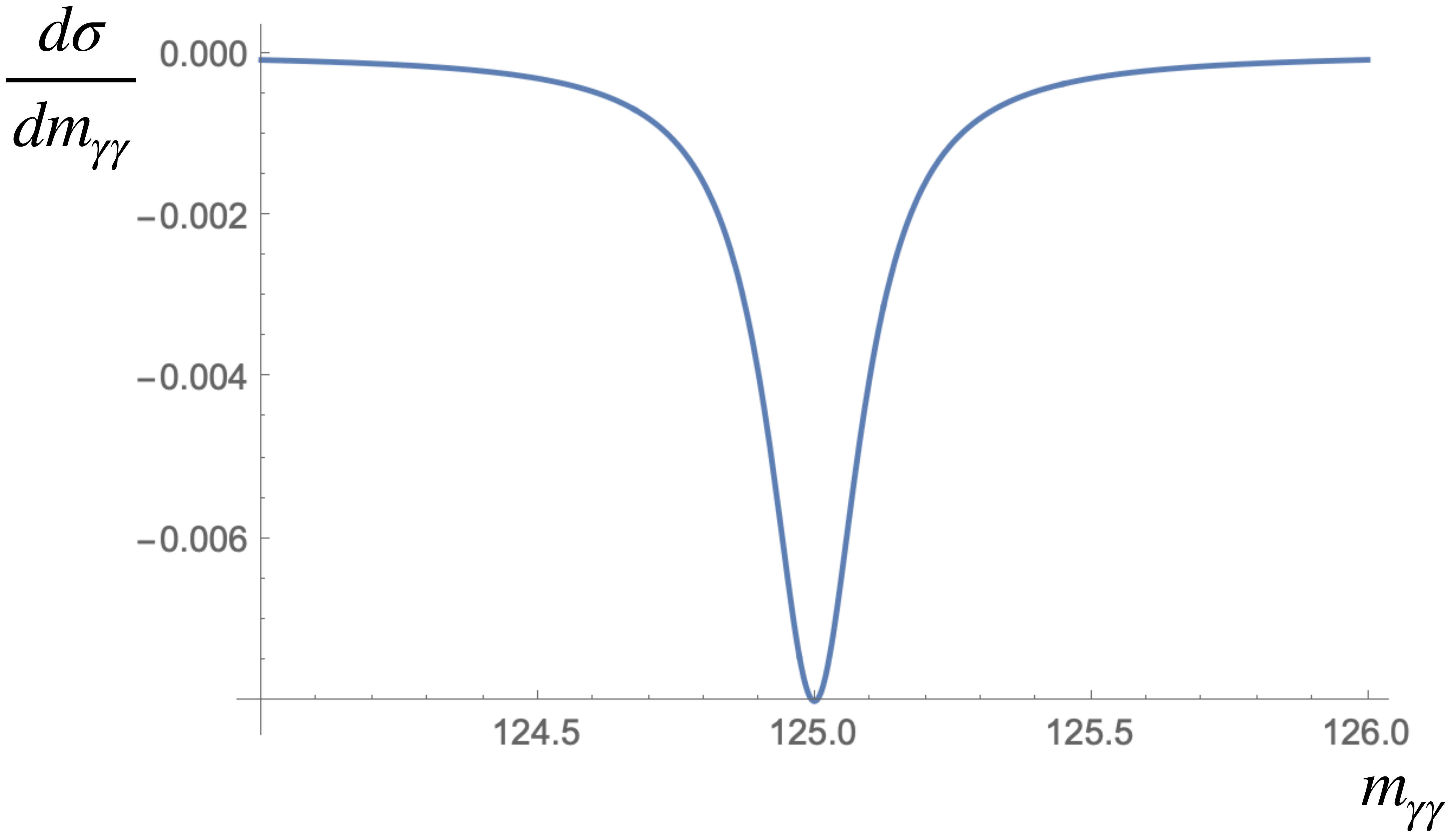
Both real and imaginary parts depend linearly on the couplings, any effect due to them can be in principle used to constrain Γ_H…



…but the two contributions have very different properties

Imaginary part: a closer look

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



- 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

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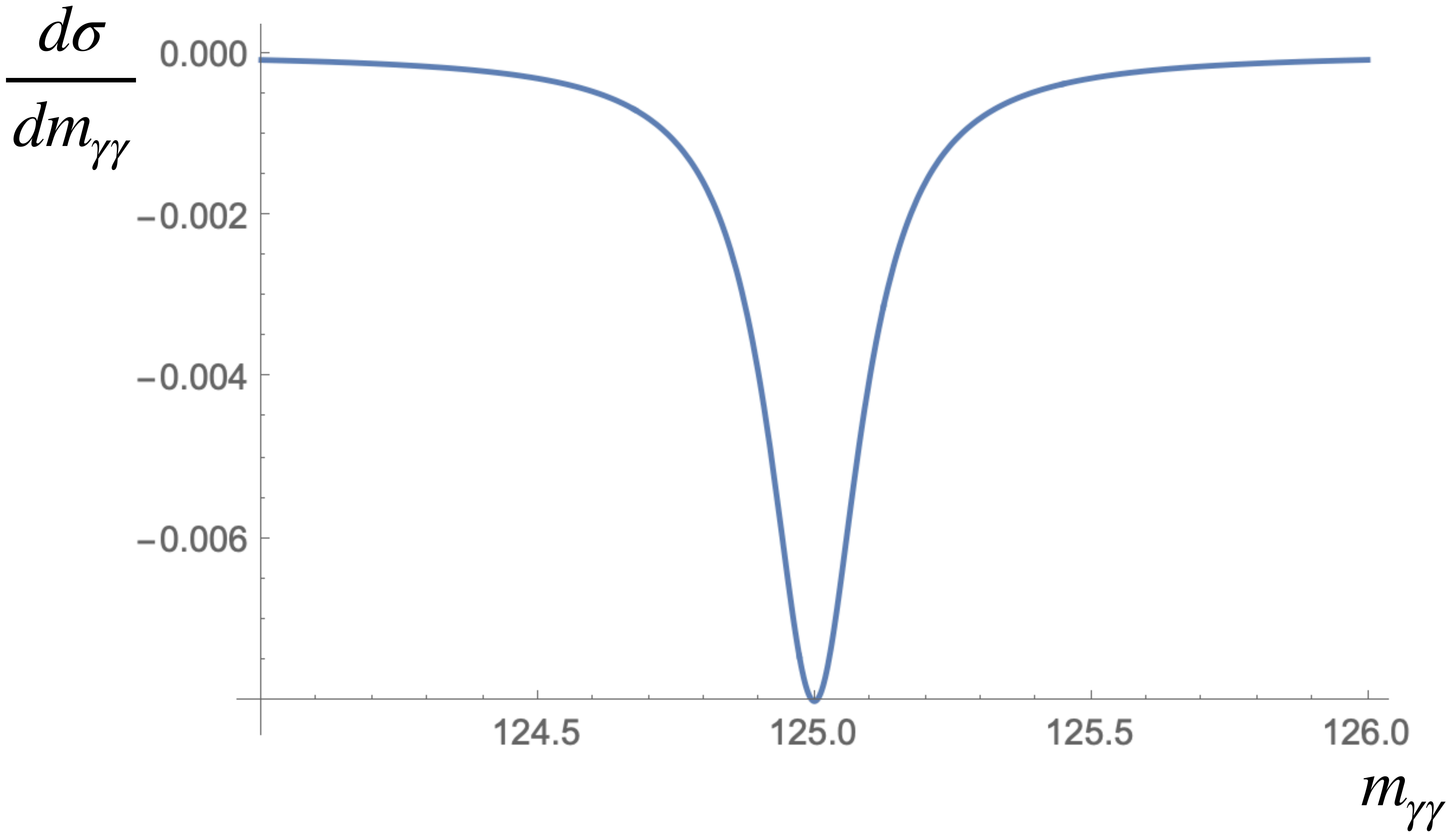

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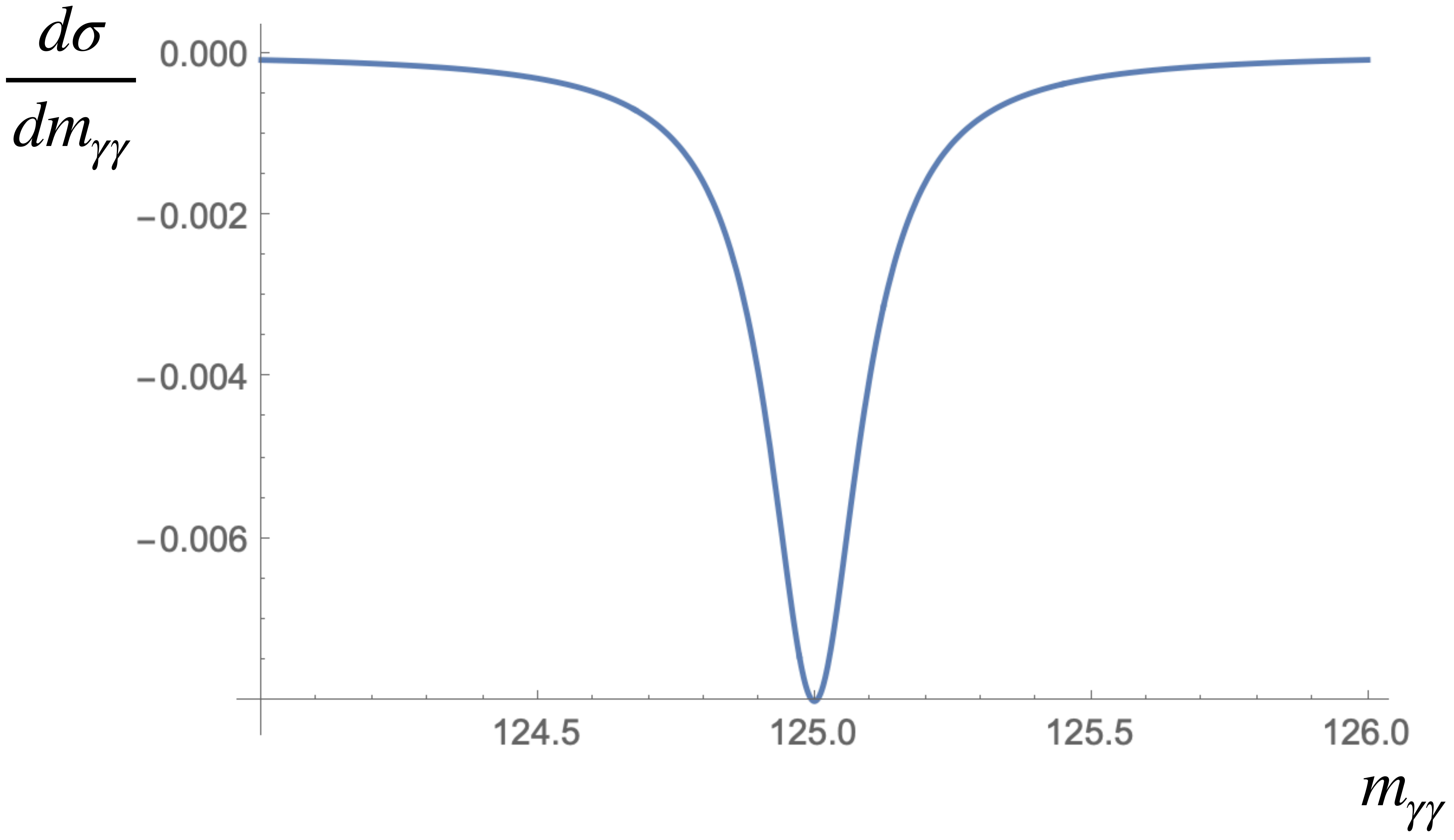

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Federica Devoto University of Genova, 28/02/2023

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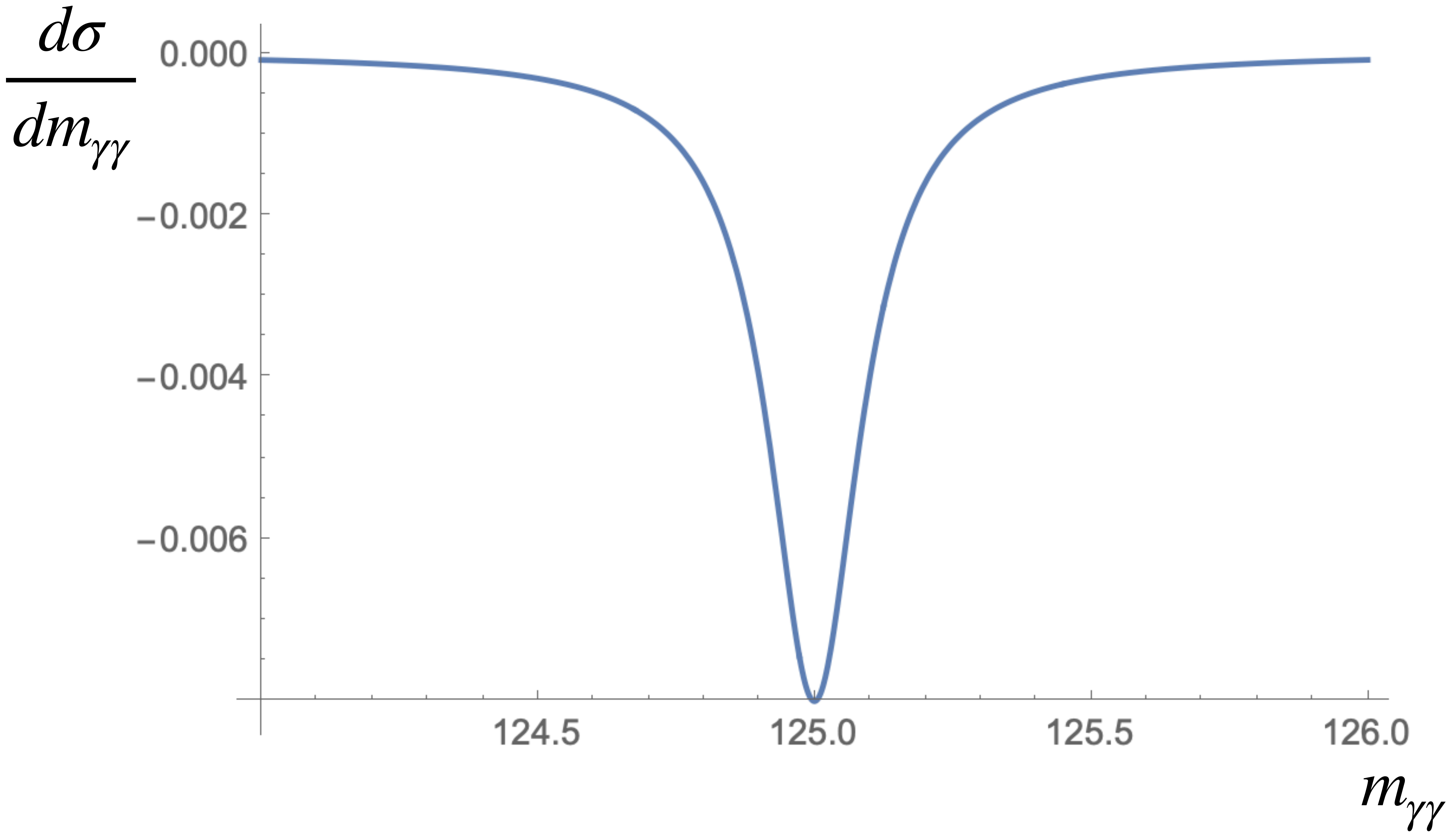

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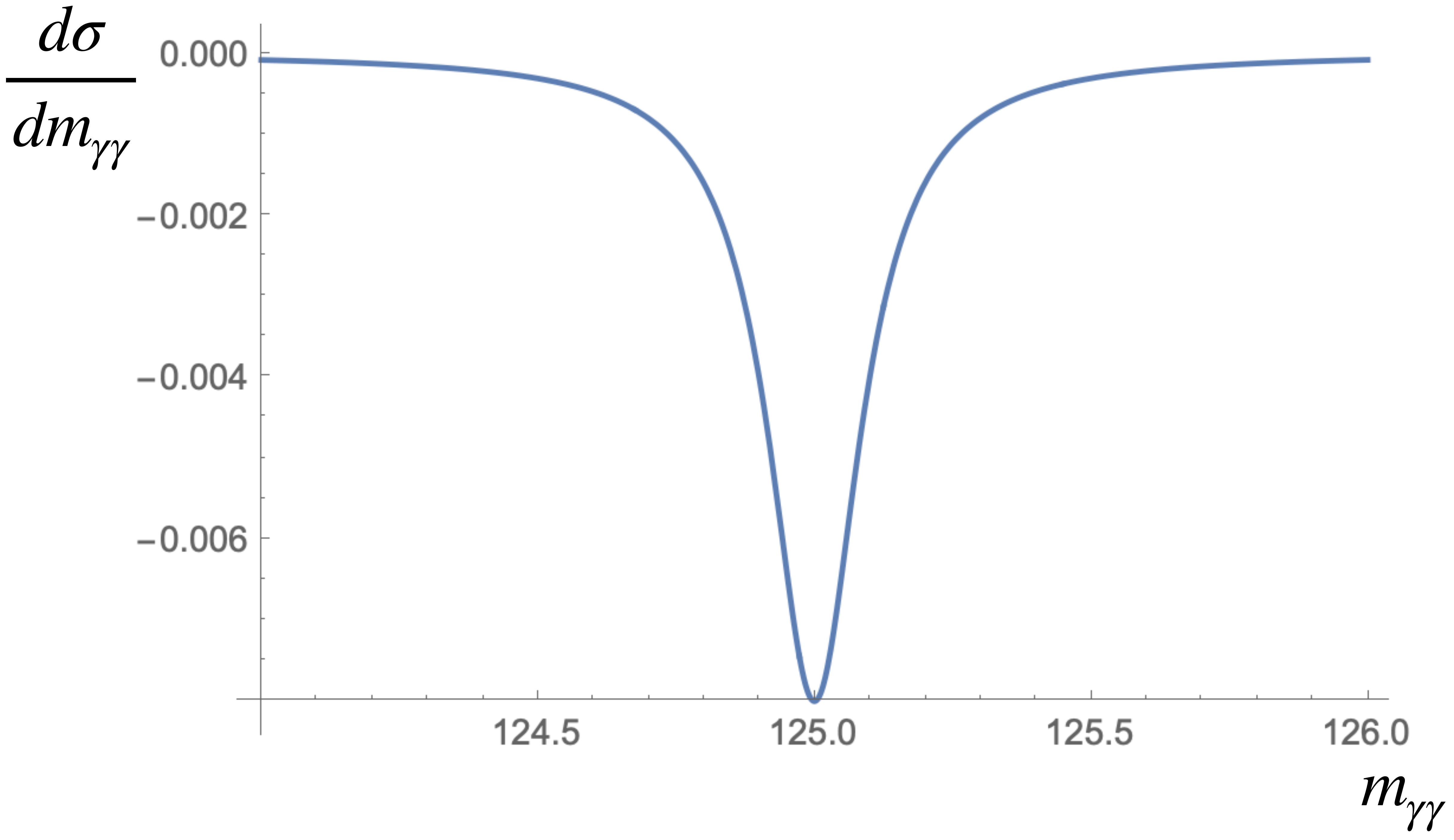

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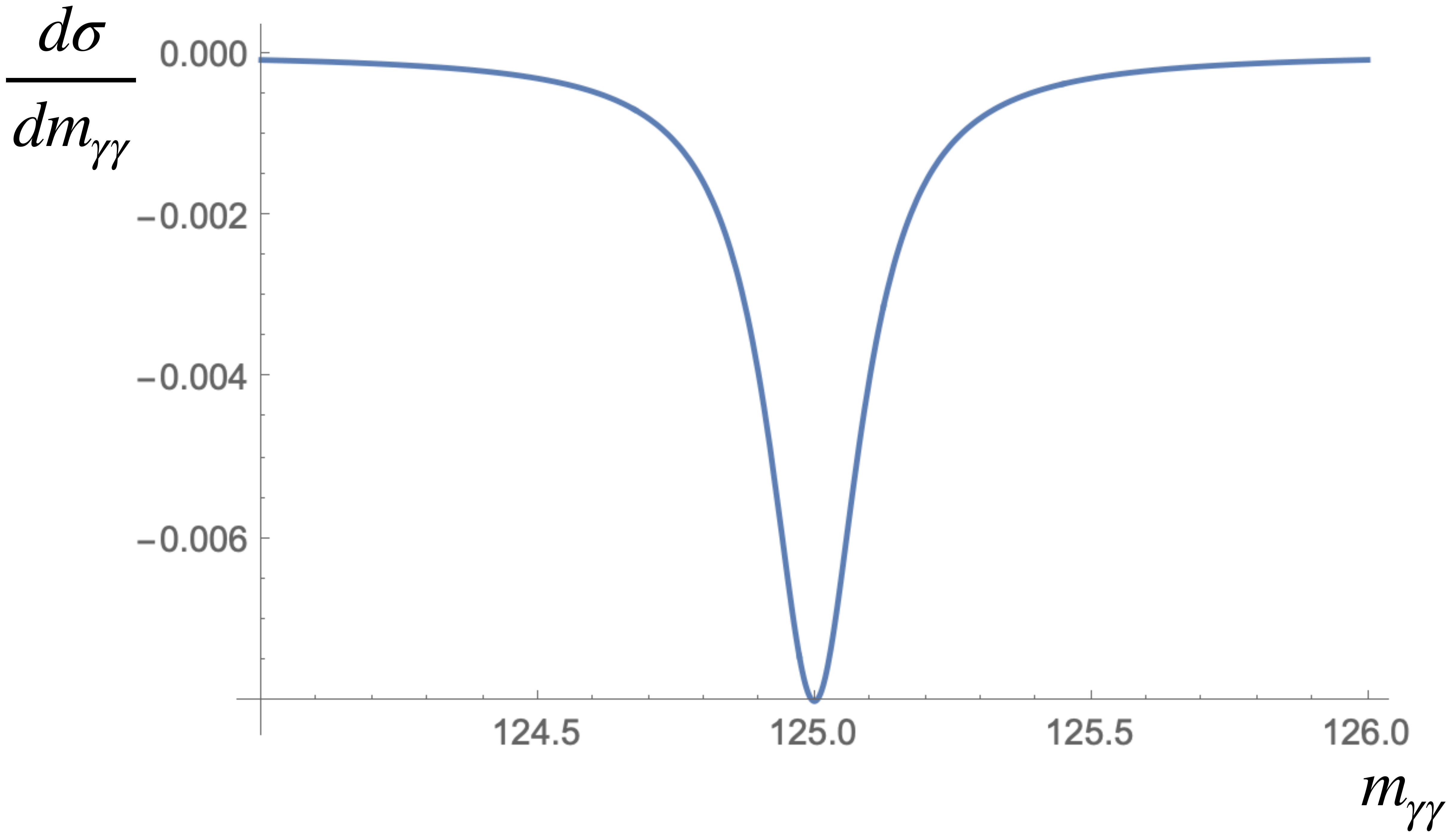

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Why?

Scalar nature of the Higgs boson

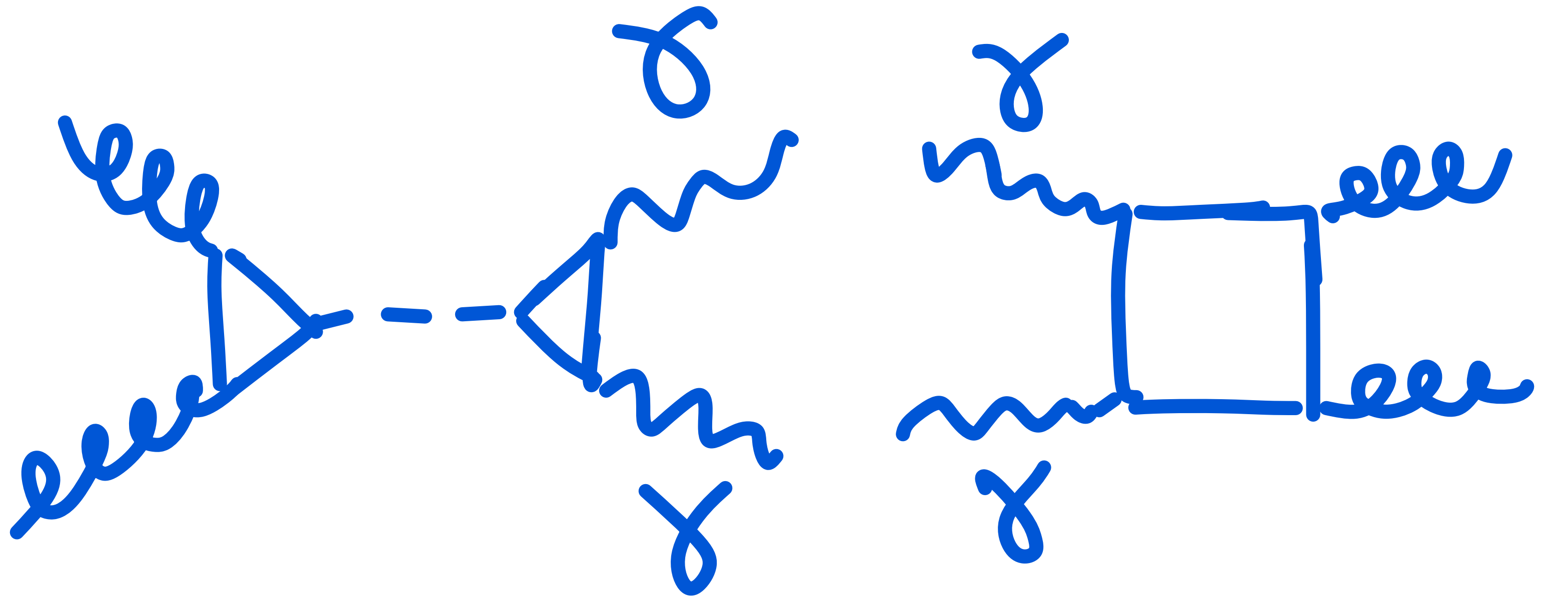
+

Missing cut in background amplitudes

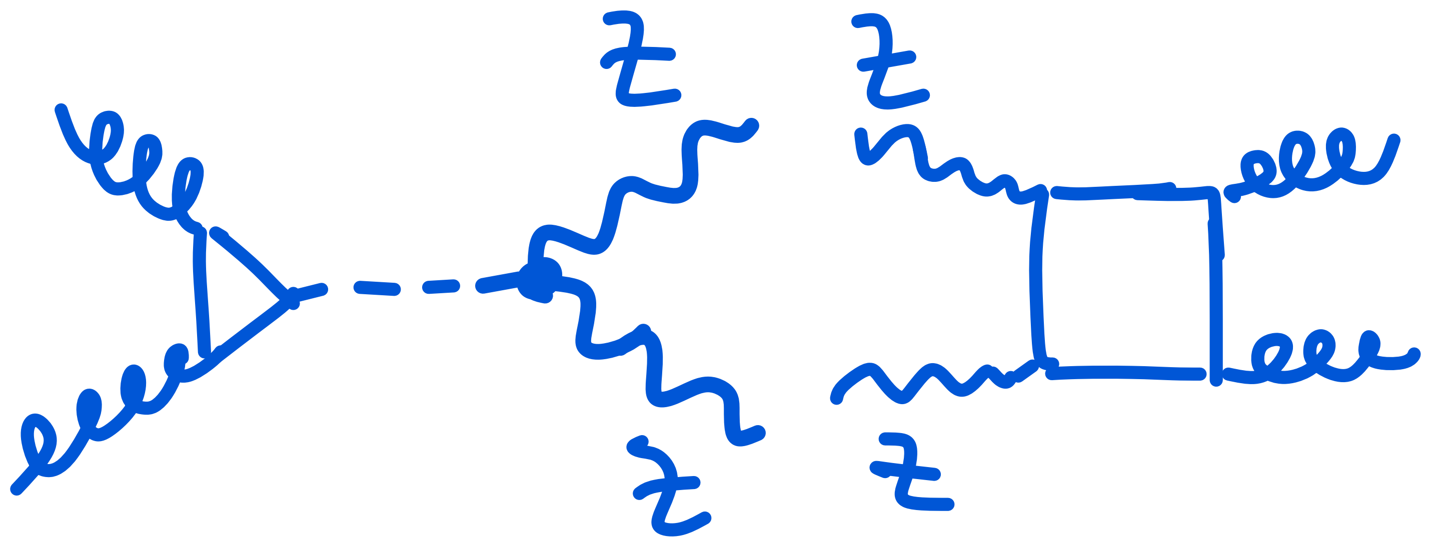
Interference effect: $\gamma\gamma$ vs ZZ

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

Diphoton channel: 3-loops



ZZ channel: 2-loops



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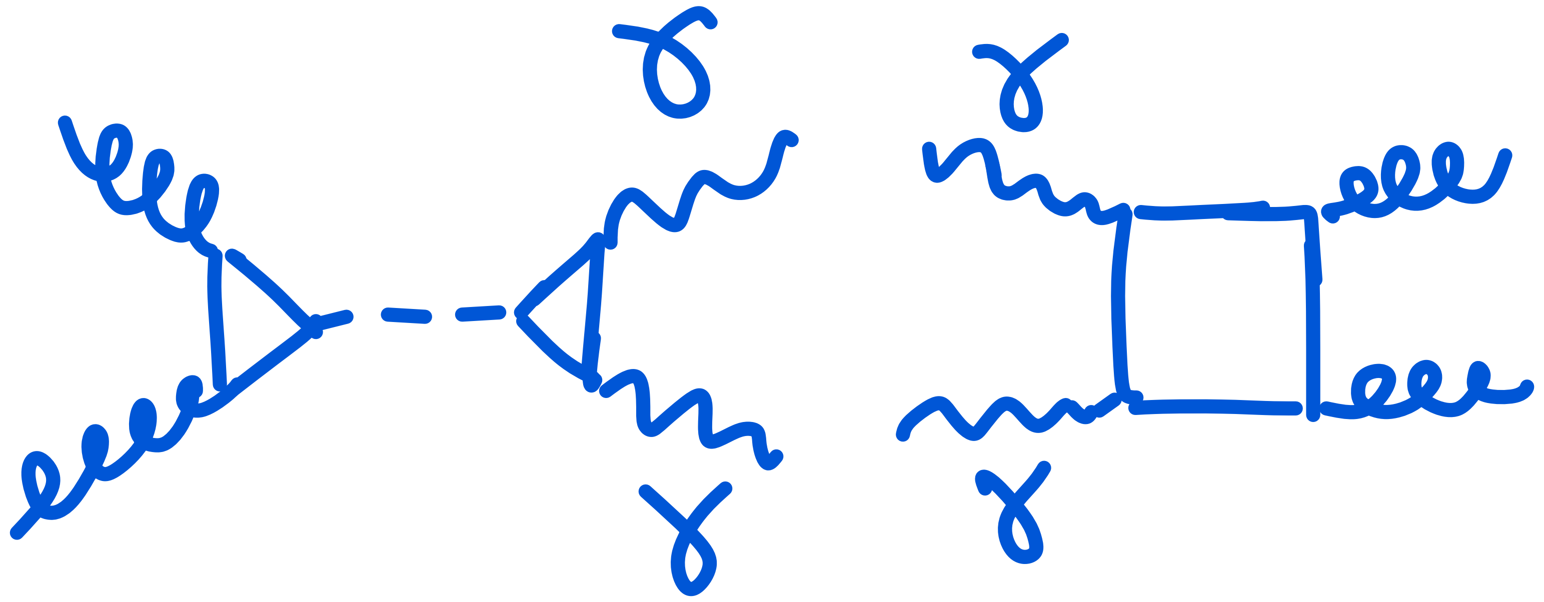

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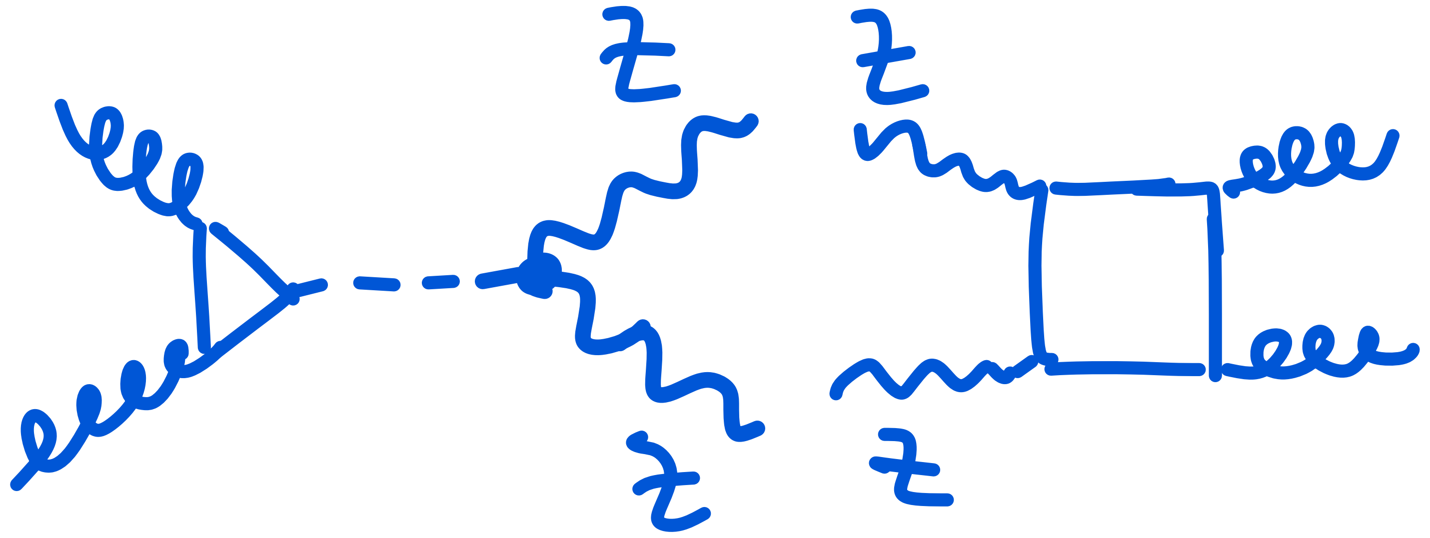

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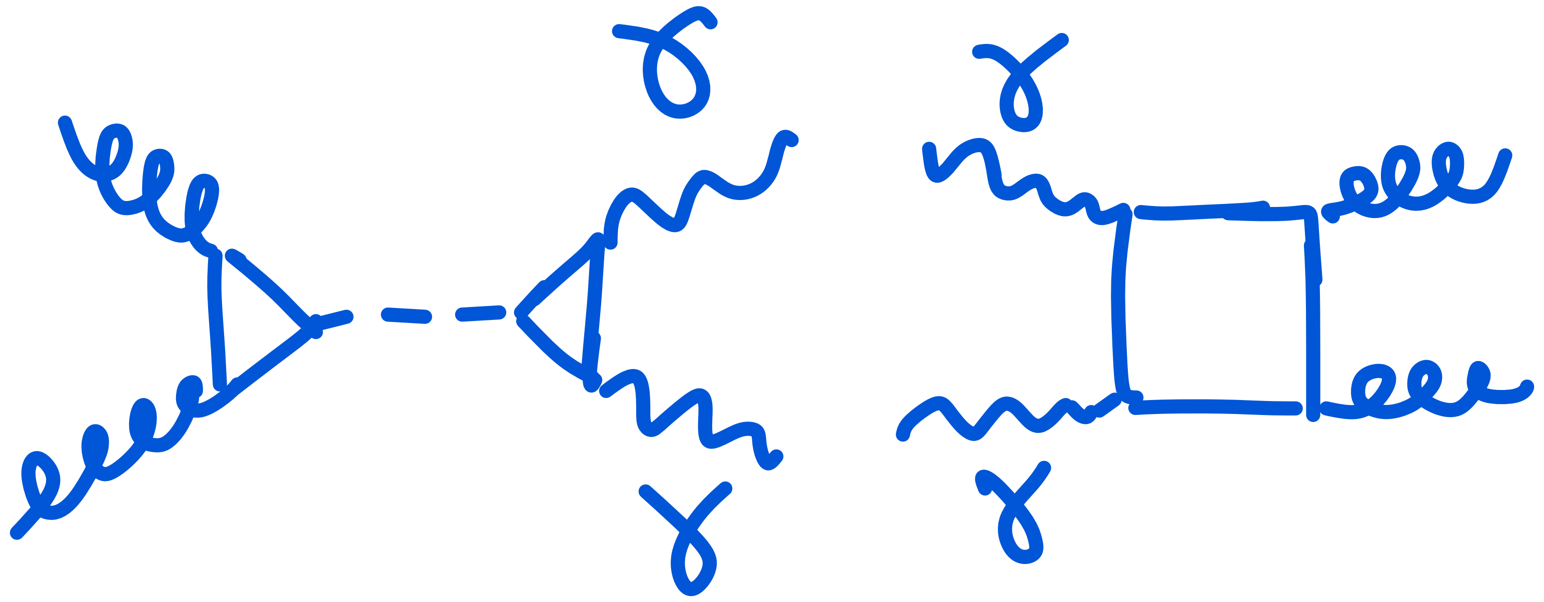

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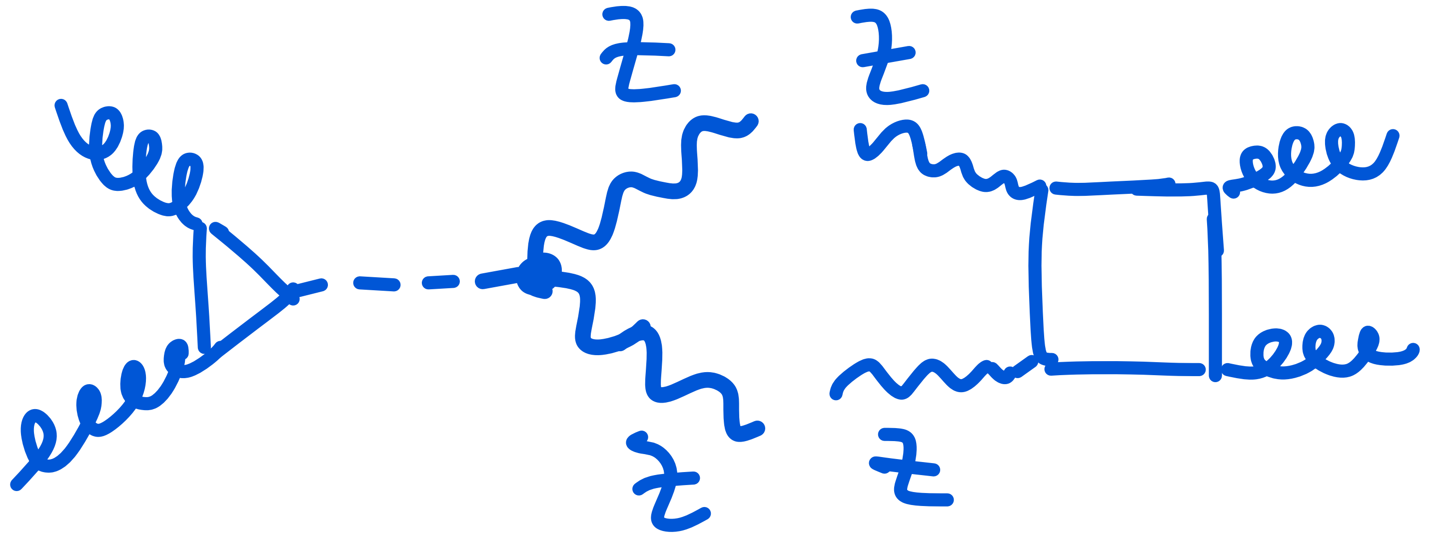

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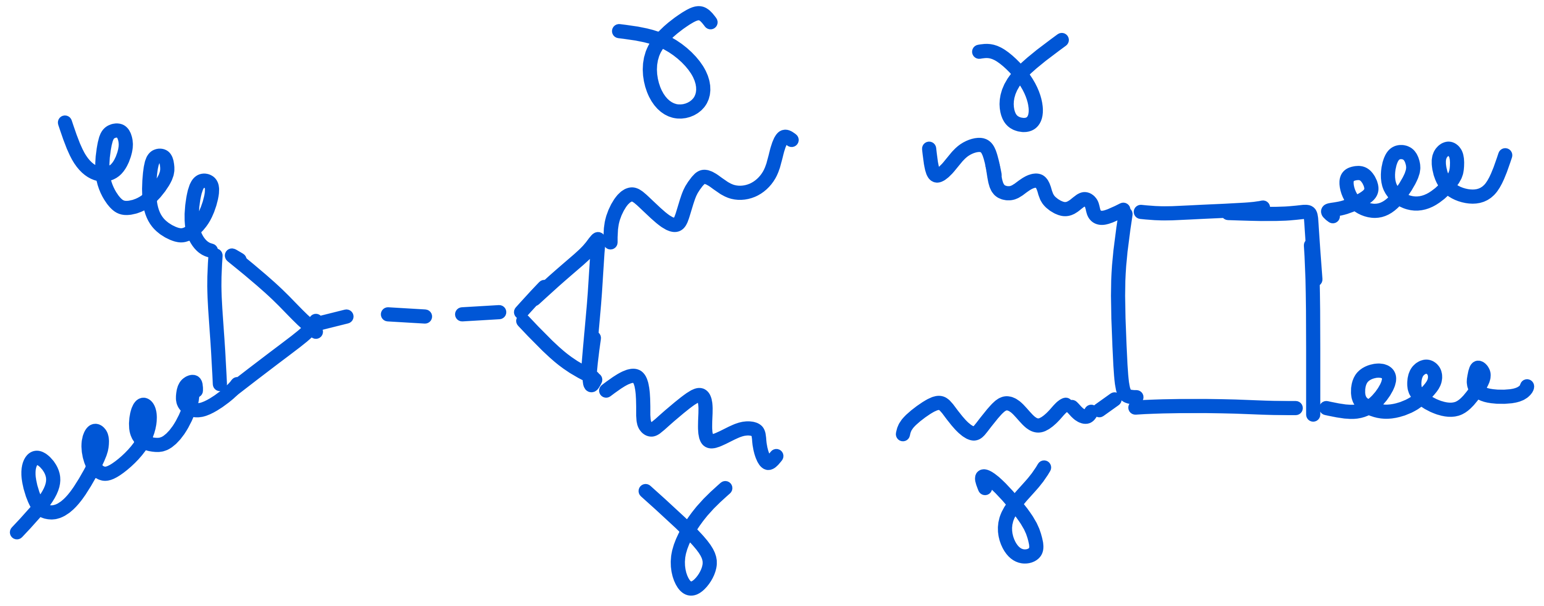

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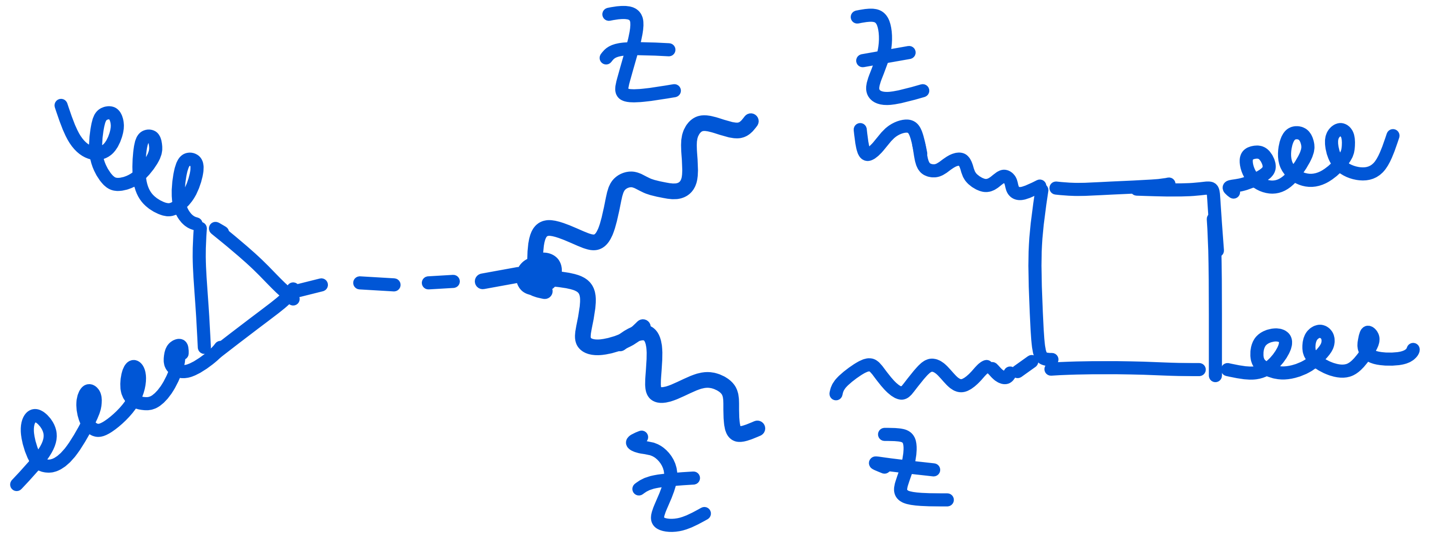

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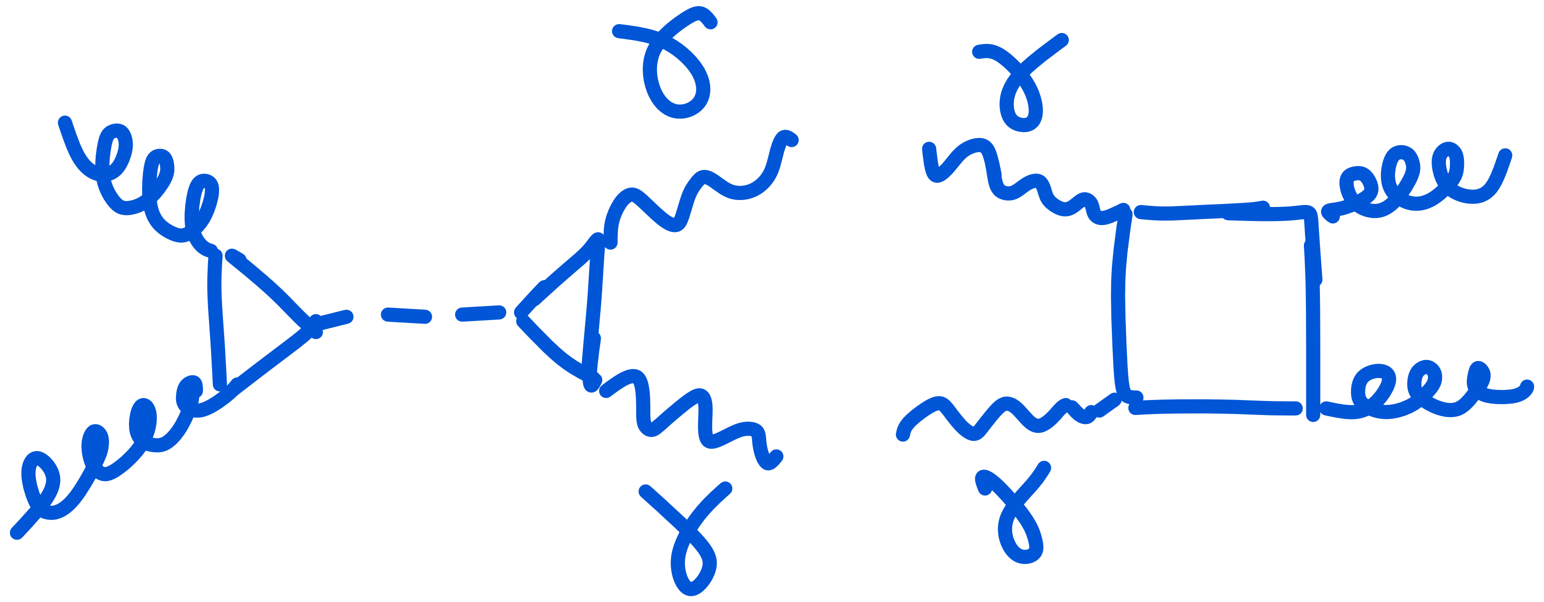

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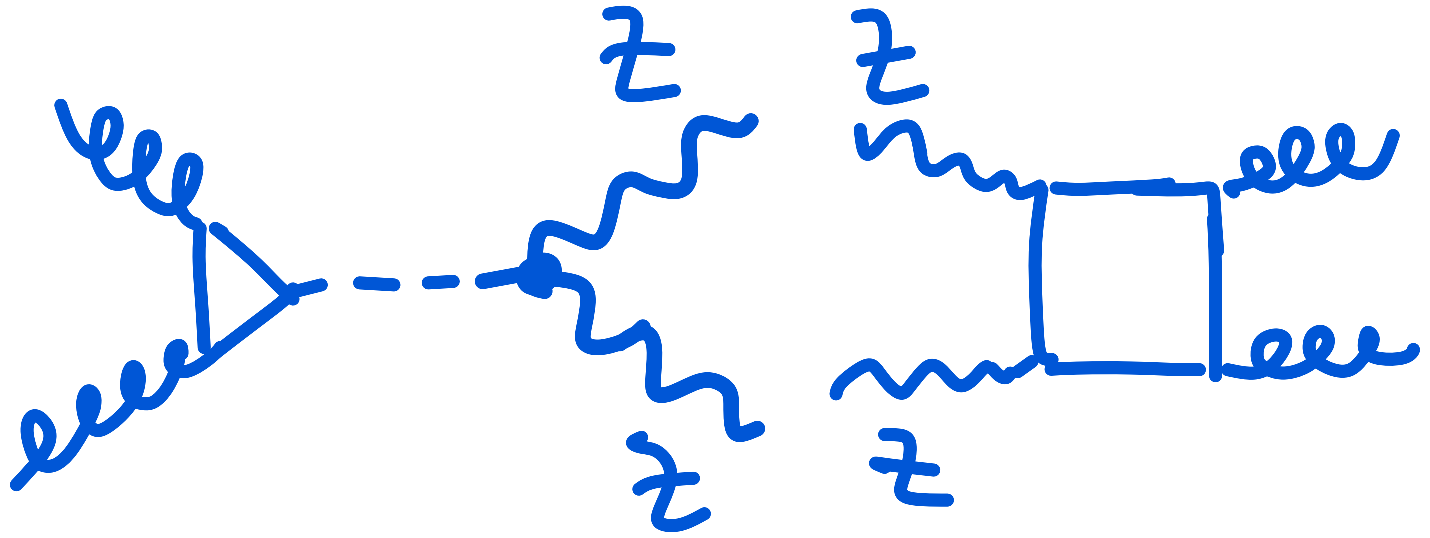

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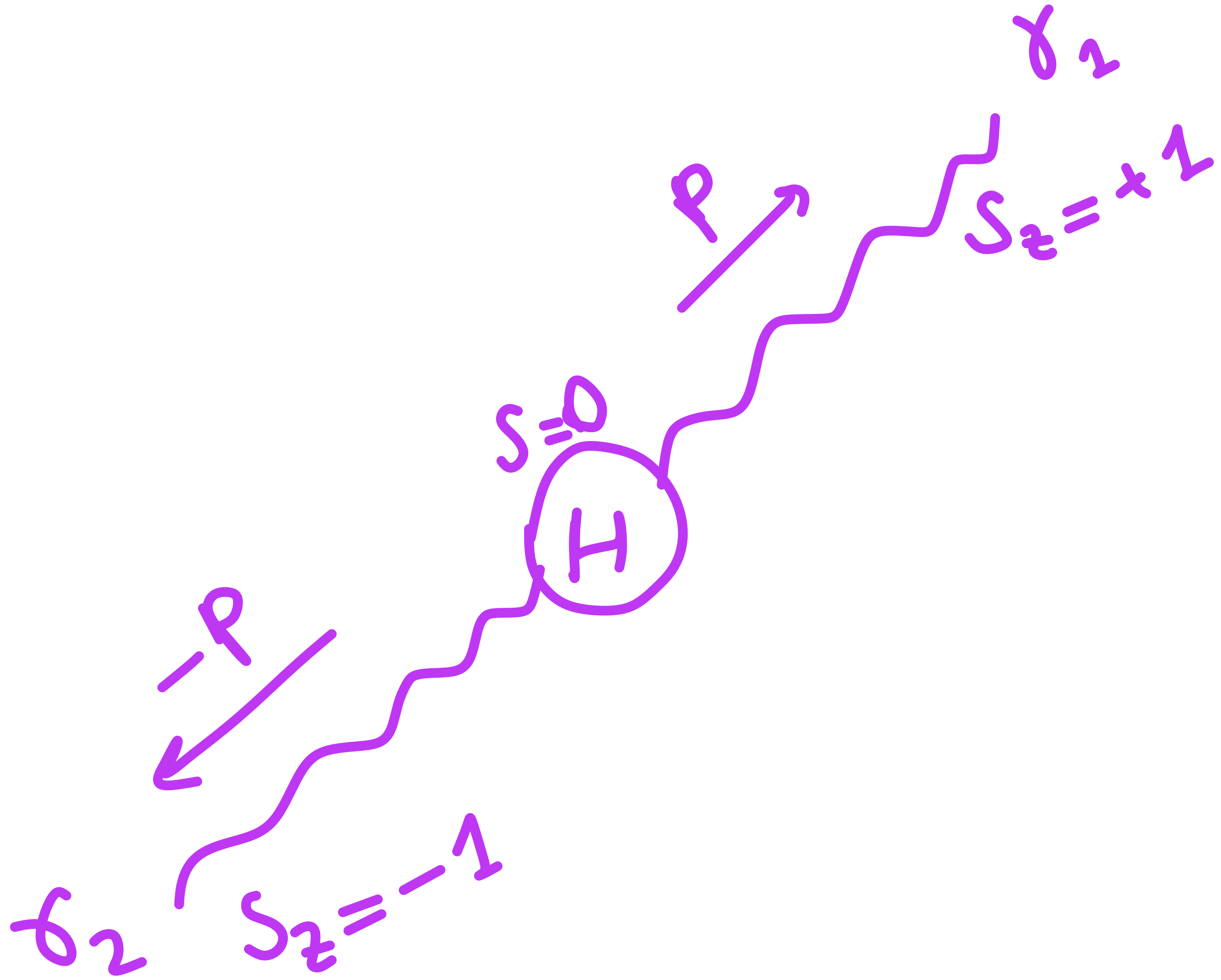
$$\frac{\sigma_{int,\gamma\gamma}}{\sigma_H} \sim \frac{2\,\Gamma_H}{m_H}\frac{(4\pi v)^2}{m_H^2} \sim 0.1$$

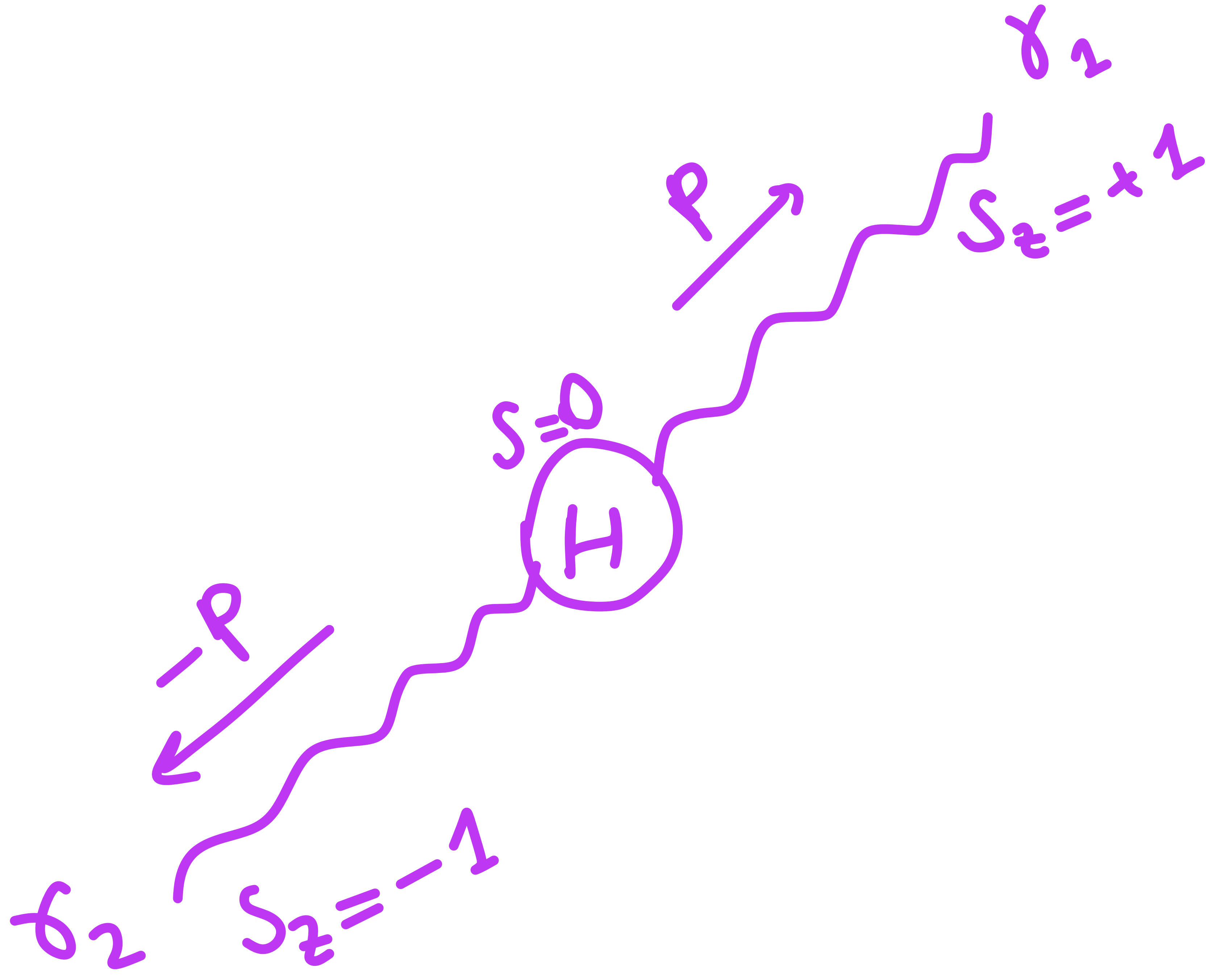
"Loop enhancement"

Spin and mass effects



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

Spin and mass effects



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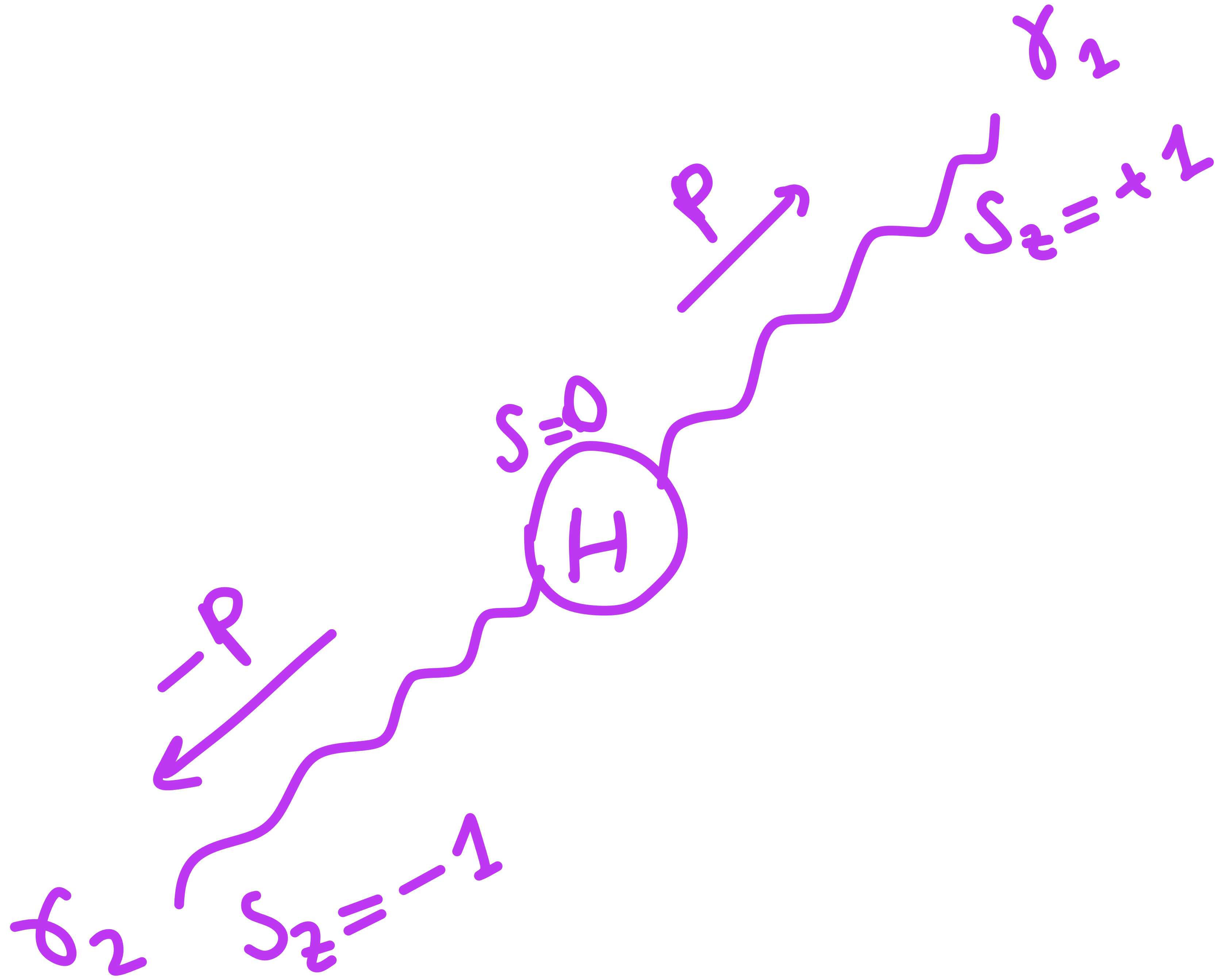
Simple conservation of angular momentum

Spin and mass effects



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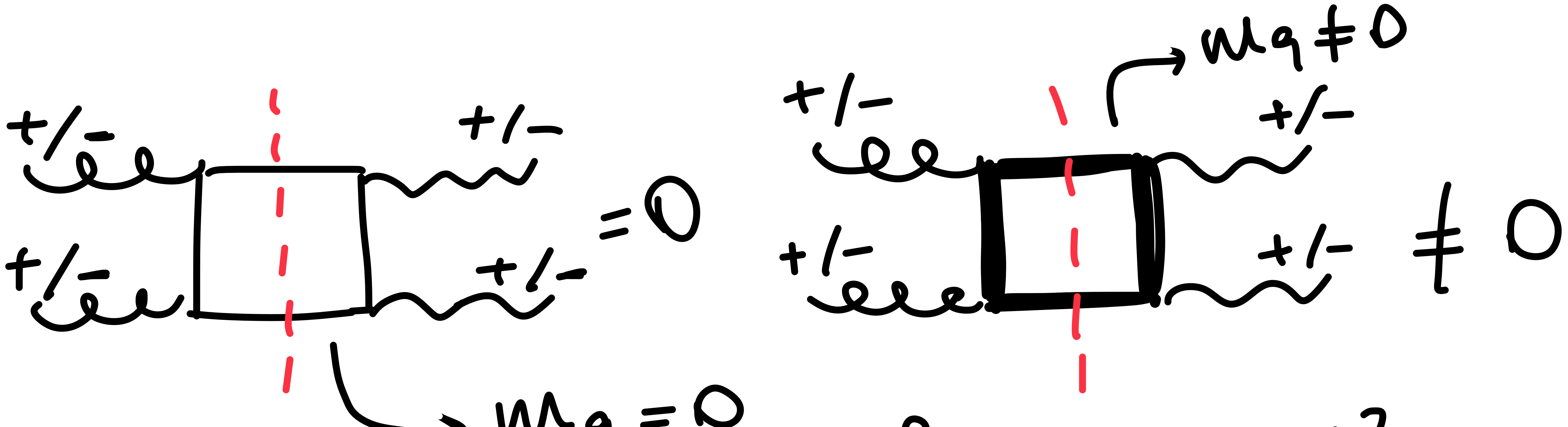
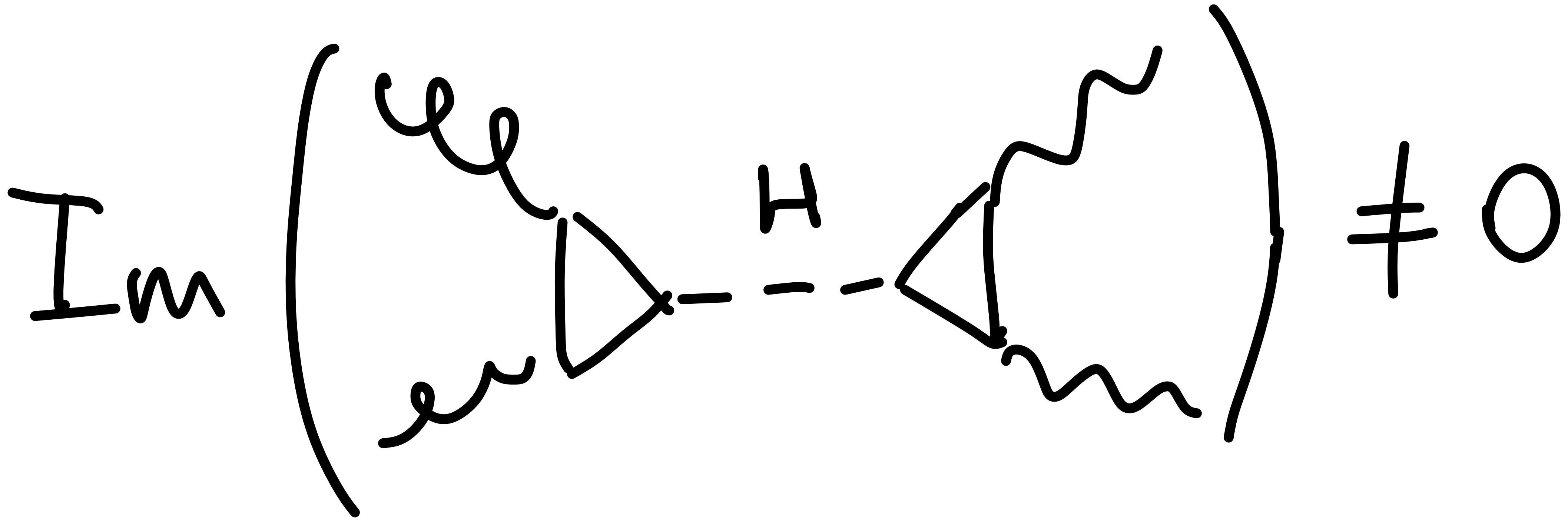


if $s > (2m_q)^2$



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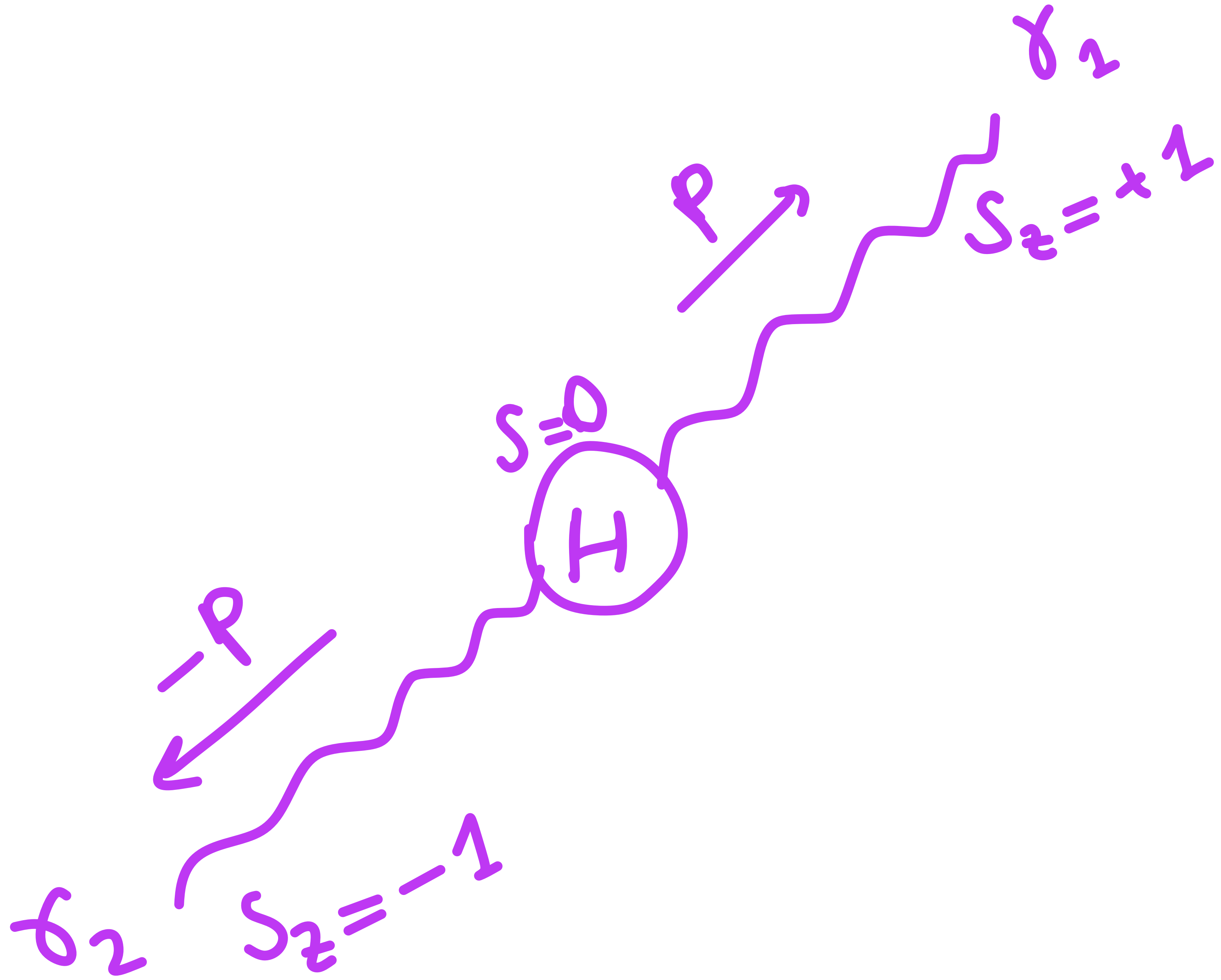

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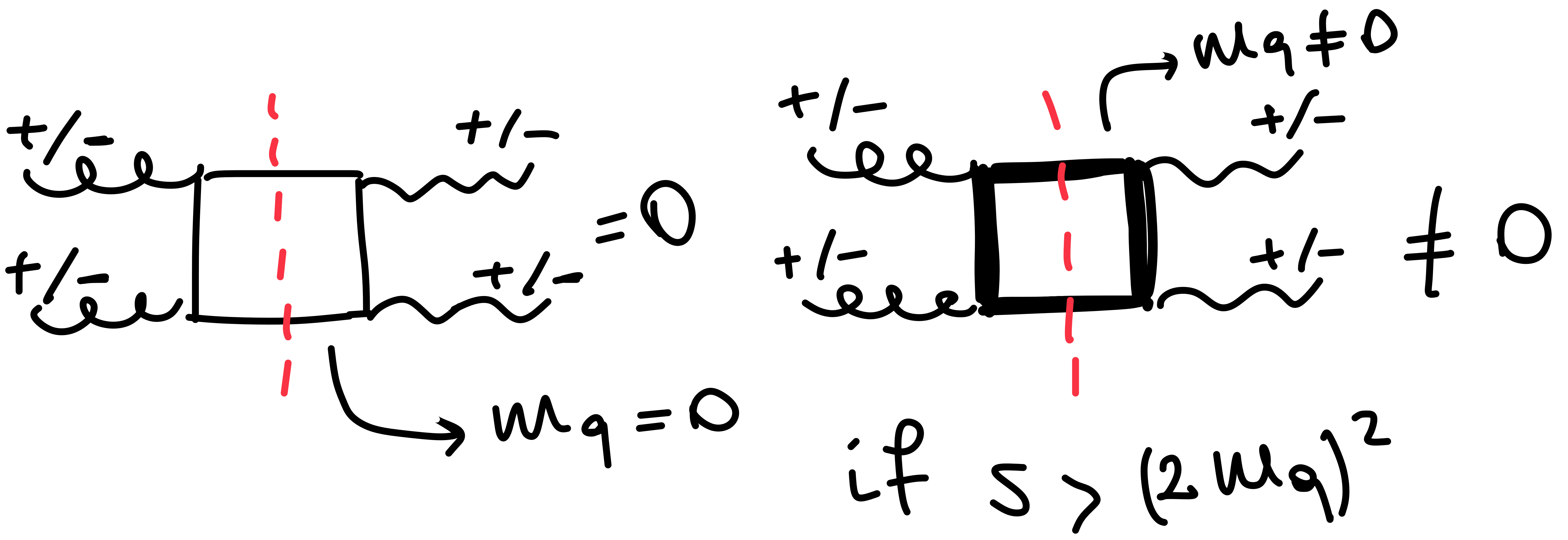
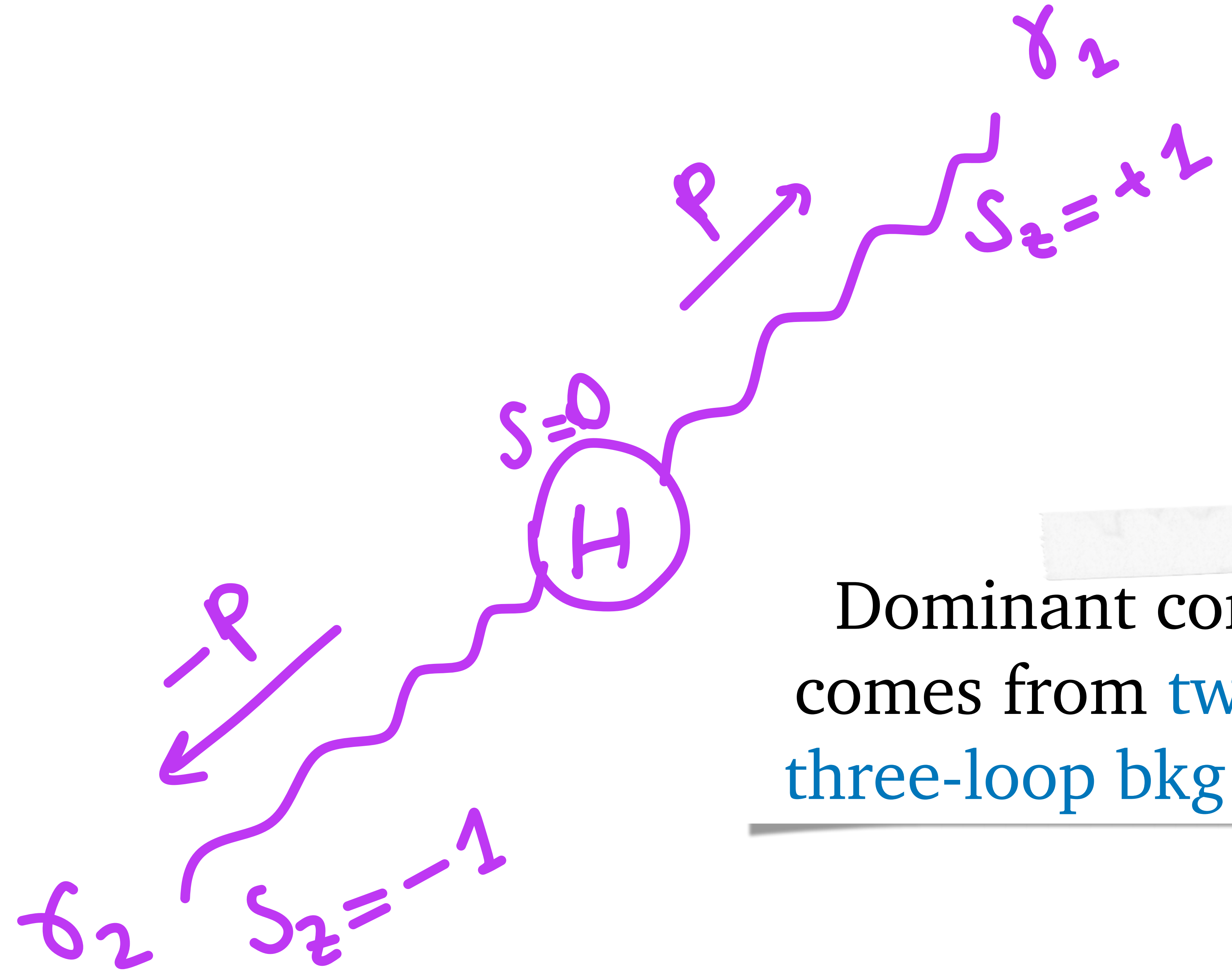


Small effect: ~permille effect at LO to be compared with NLO interference ~1%

Spin and mass effects



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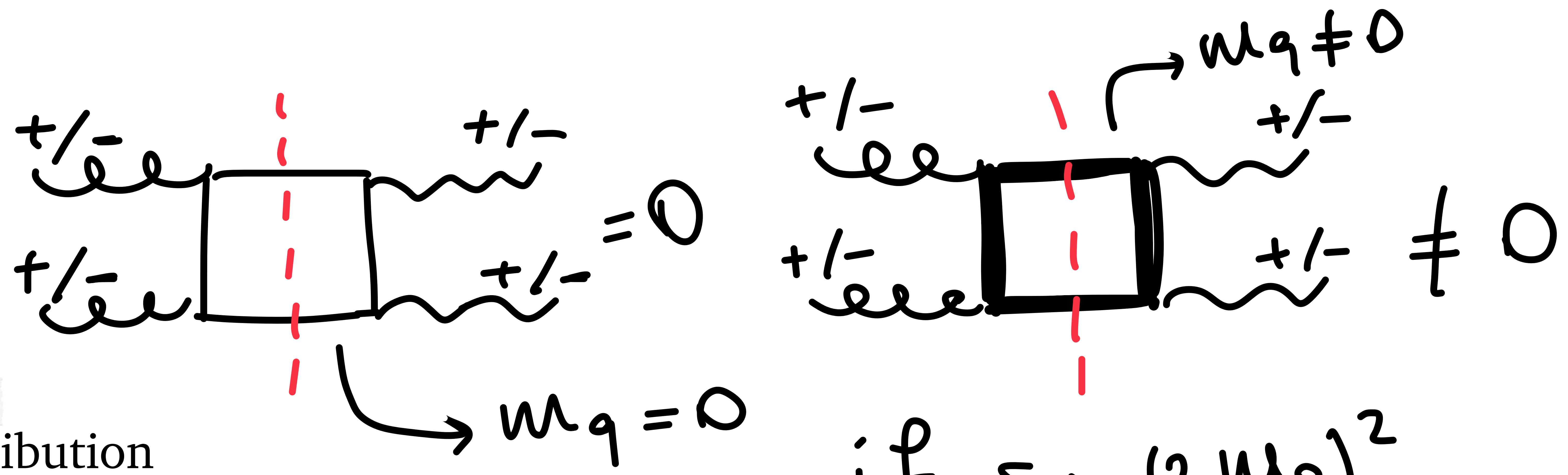

Dominant contribution comes from two-loop and three-loop bkg amplitudes

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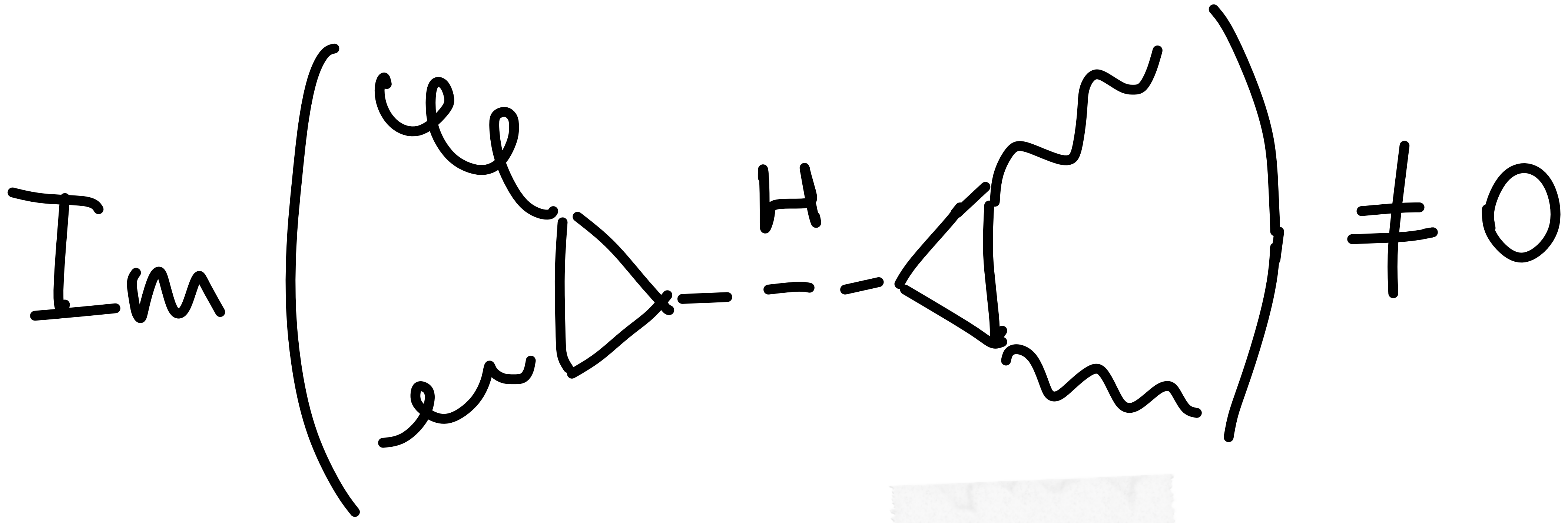

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Real part: a closer look

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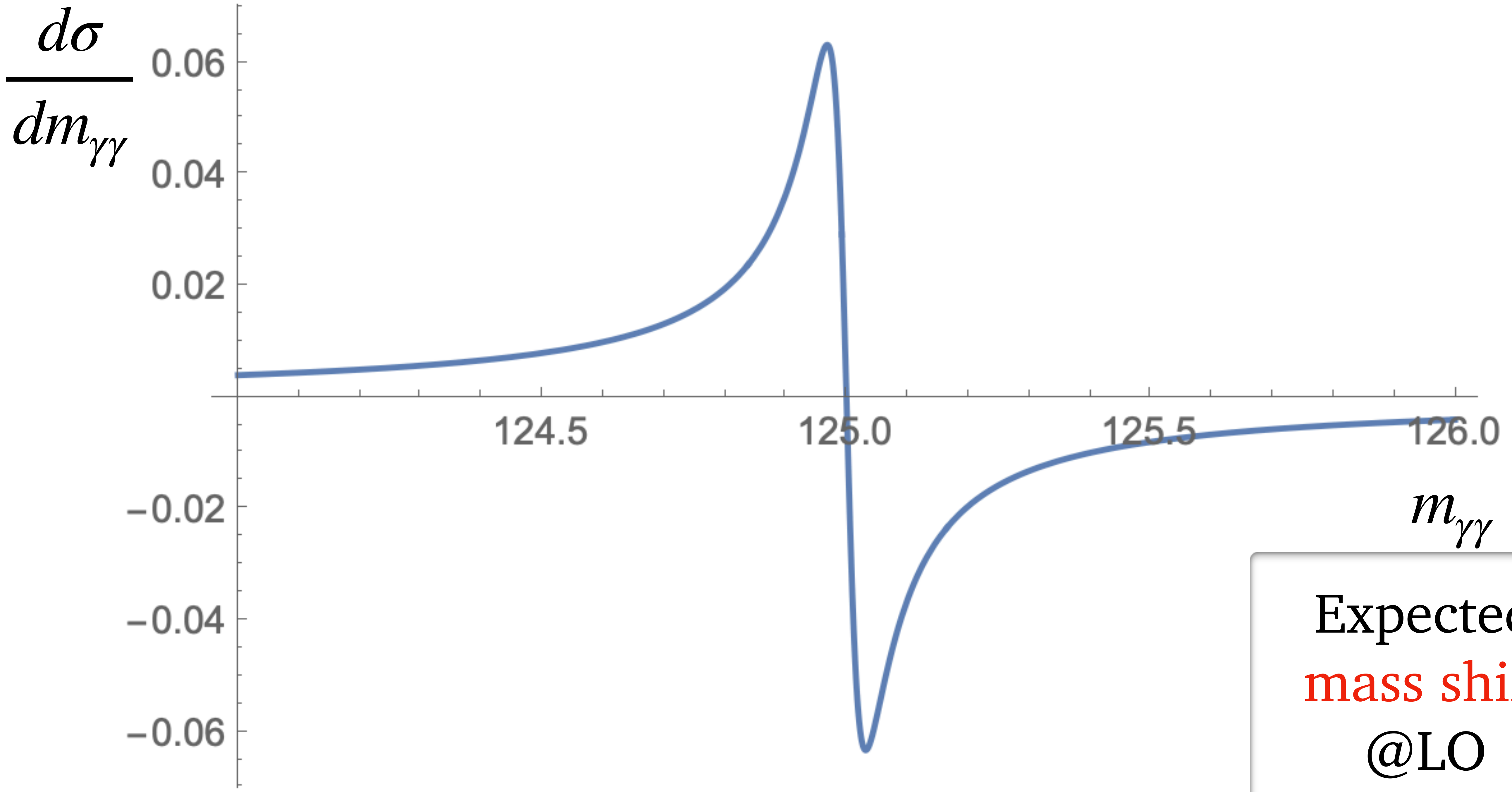
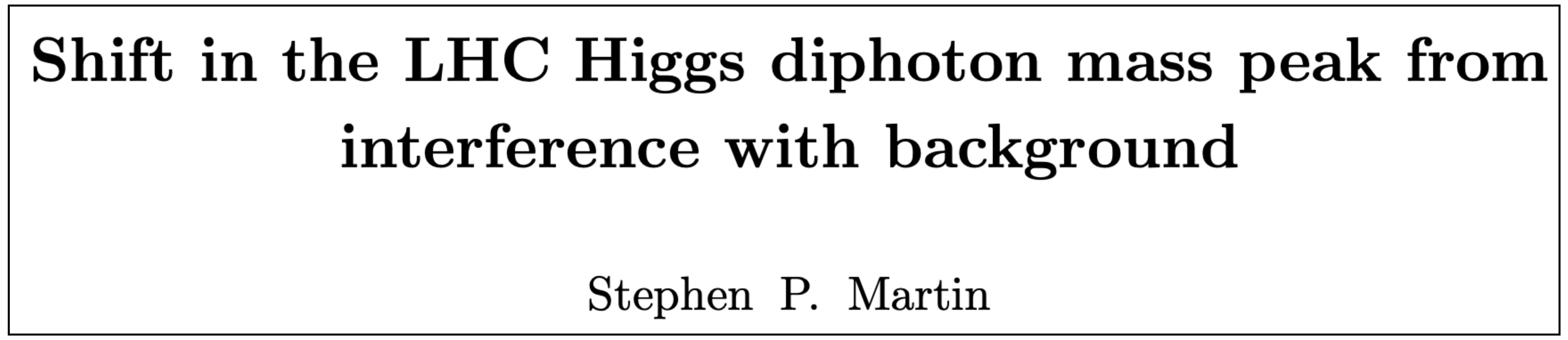


Expected
mass shift
@LO
$\mathcal{O}(100)$ MeV

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



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

Stephen P. Martin

1208.1533

Historically this was pointed out in the context of Higgs boson mass measurements

How can we exploit these effects to constrain the Higgs boson width?

Interference effects and Higgs width: real part

[Dixon, Li 1305.3854]

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

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

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

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Interference effect on cross section is small w.r.t integrated signal: I ~ 1 % of S

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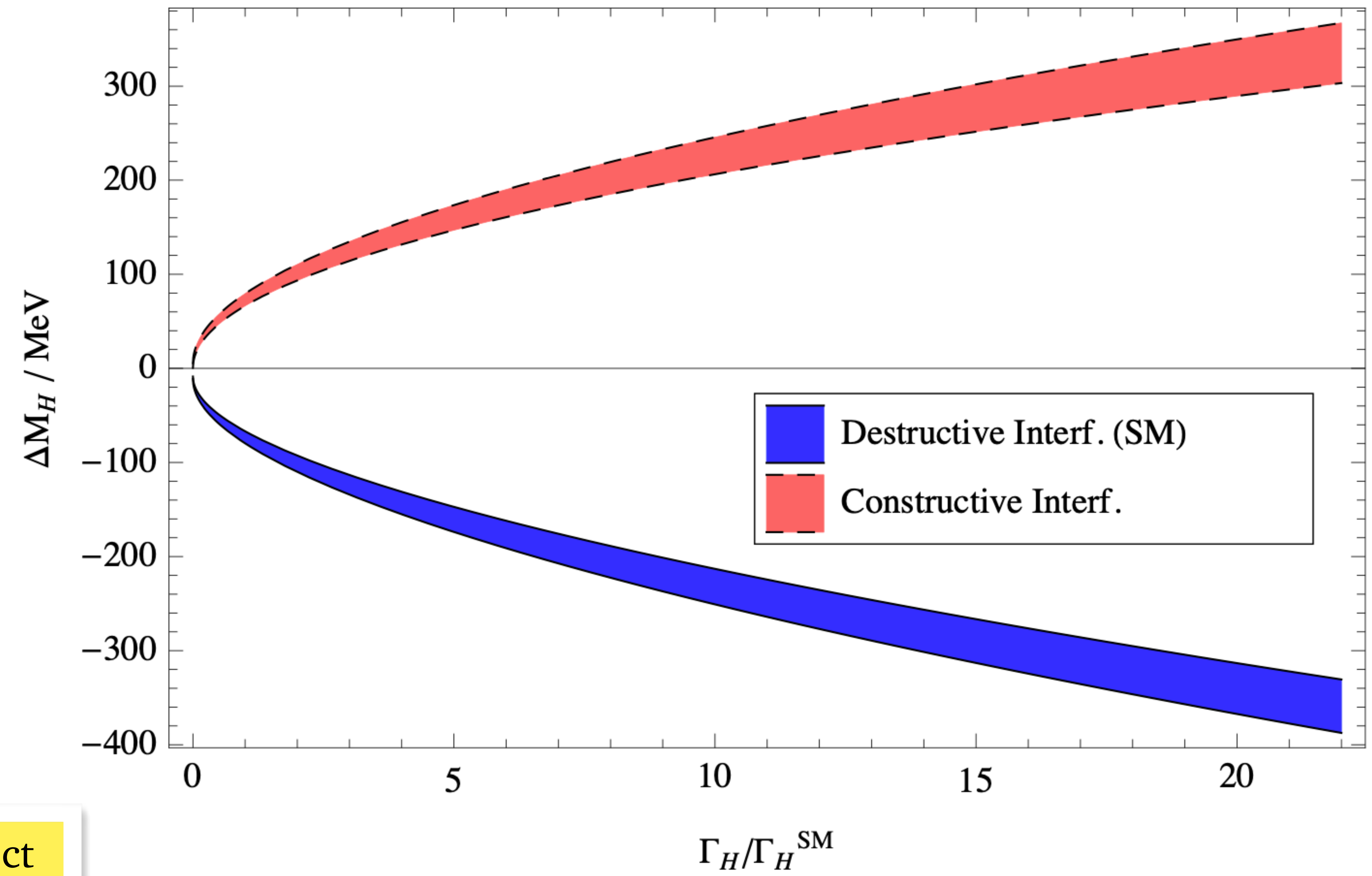

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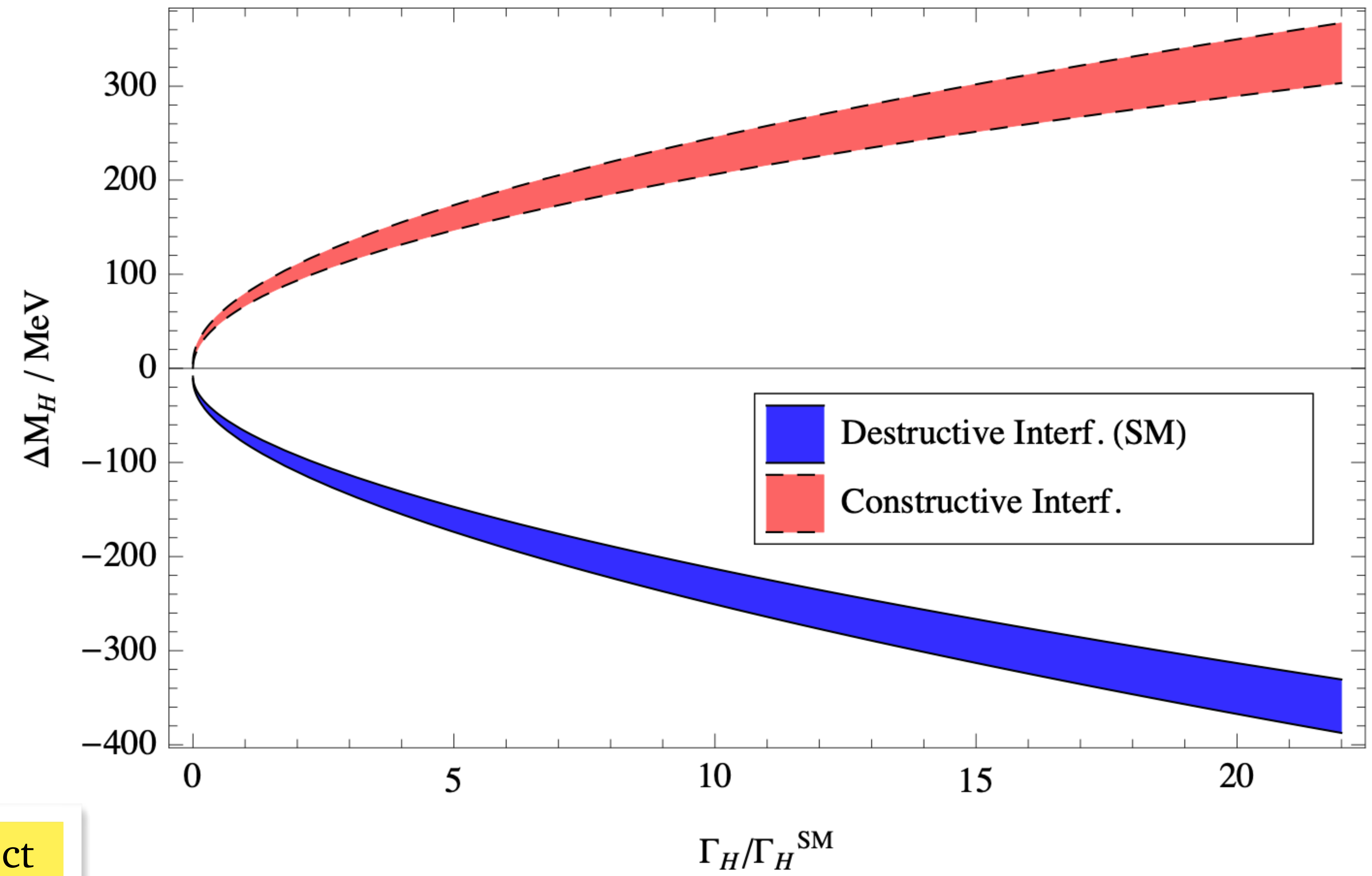
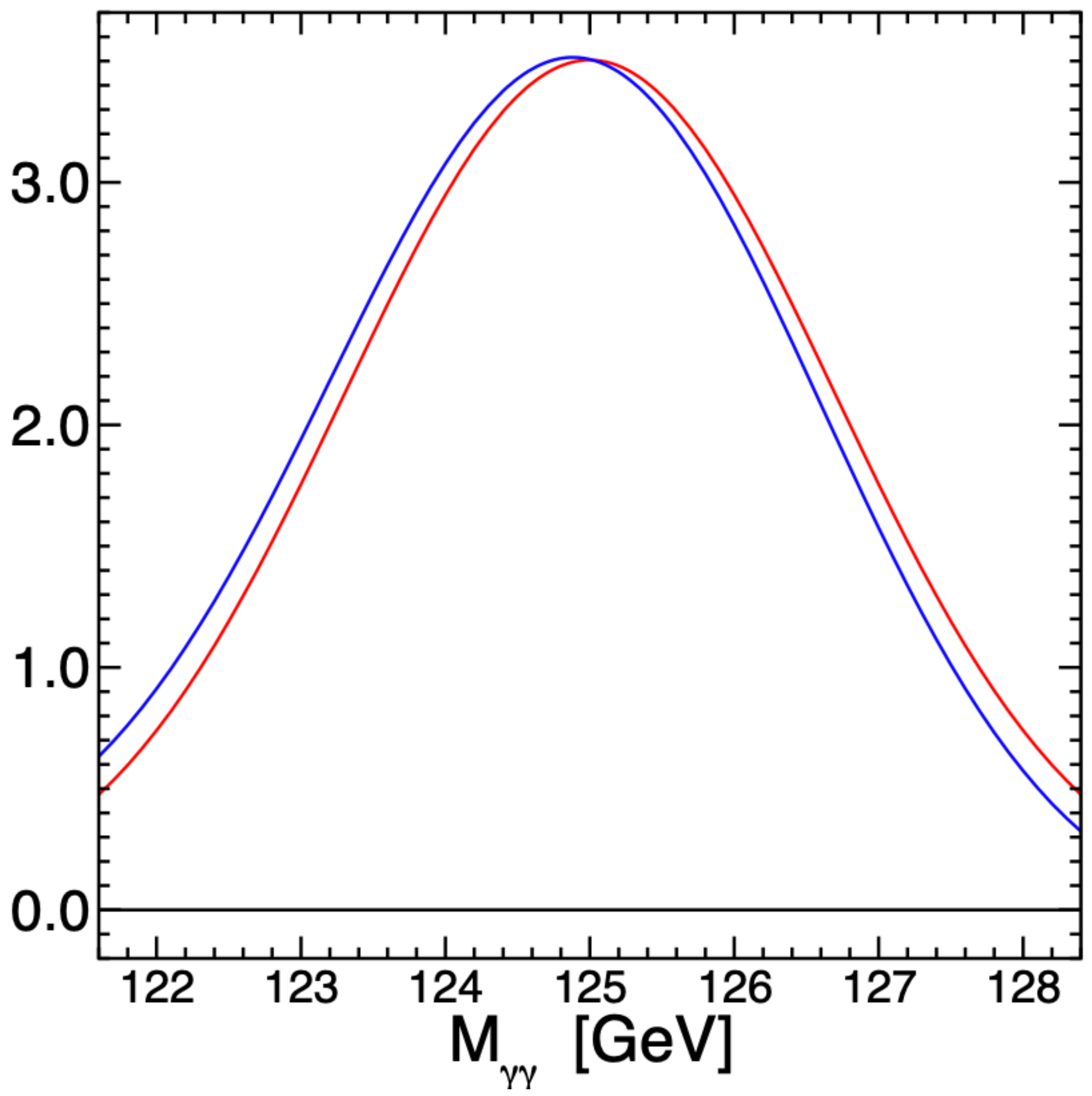


$$\xi_i\xi_f \propto \Delta M_{\gamma\gamma} \propto \sqrt{\Gamma_H}$$

Mass-shift estimate: theory

- How can we estimate it from a theory side?



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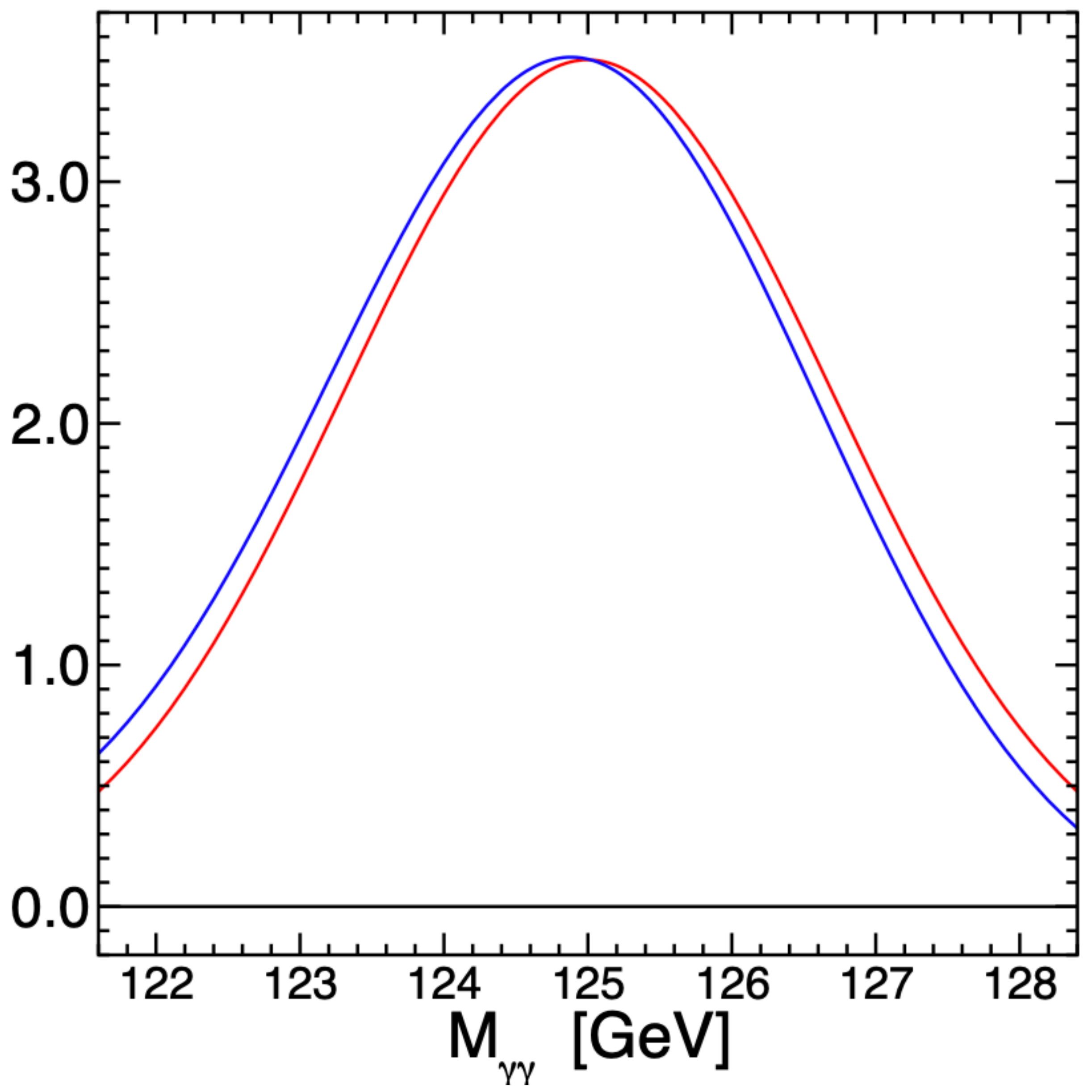

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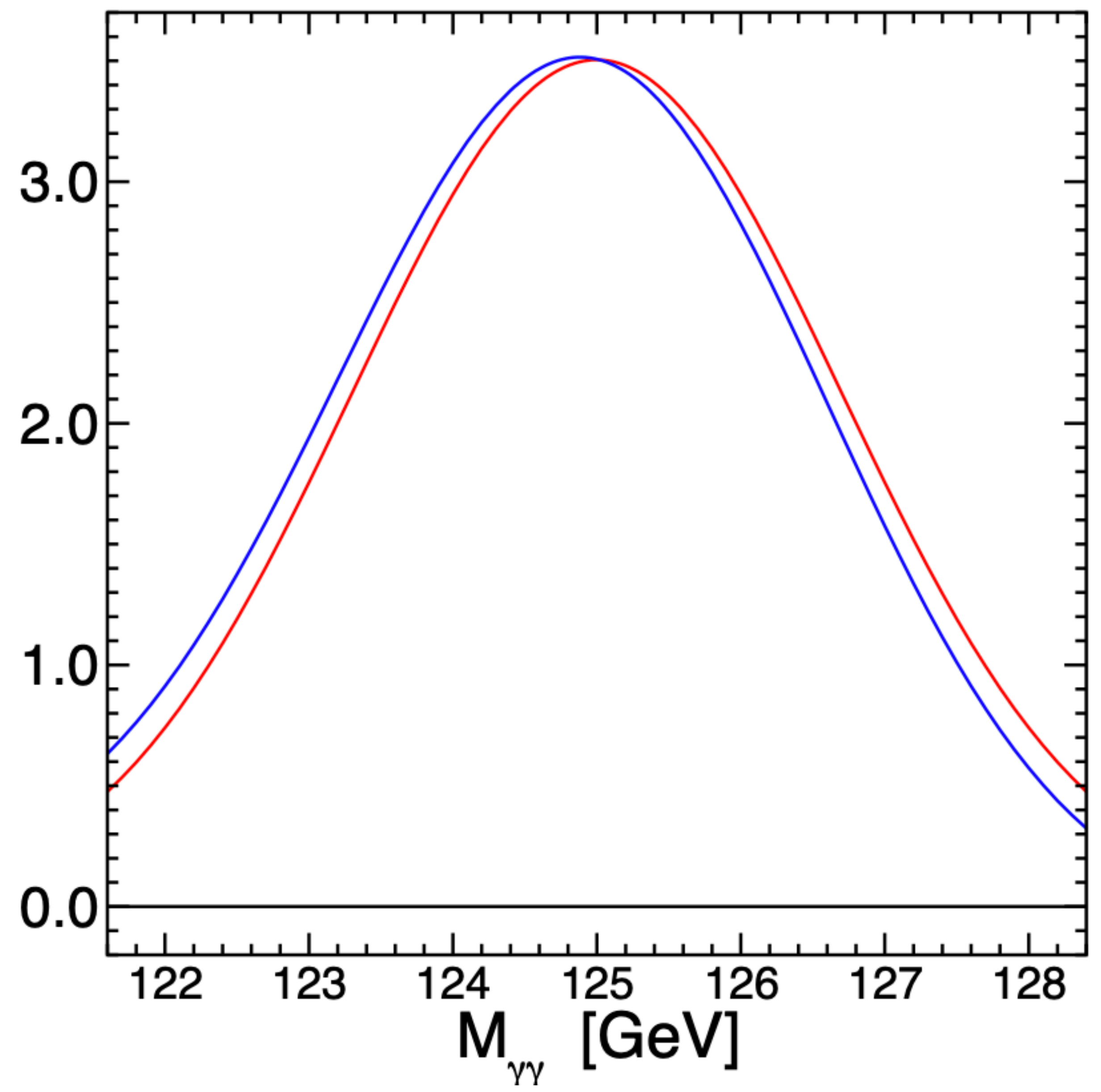
First moment method



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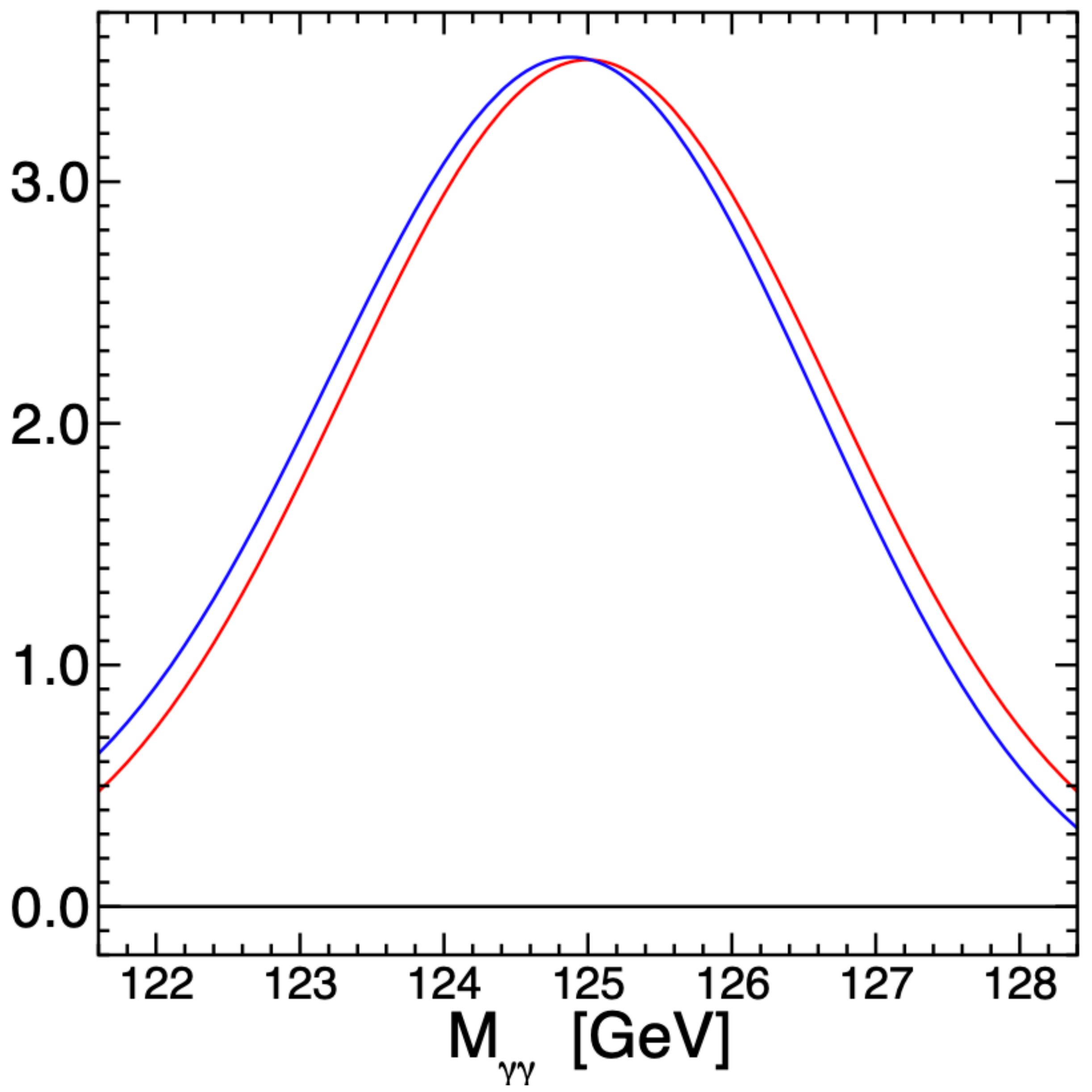

First moment method [Martin '12]

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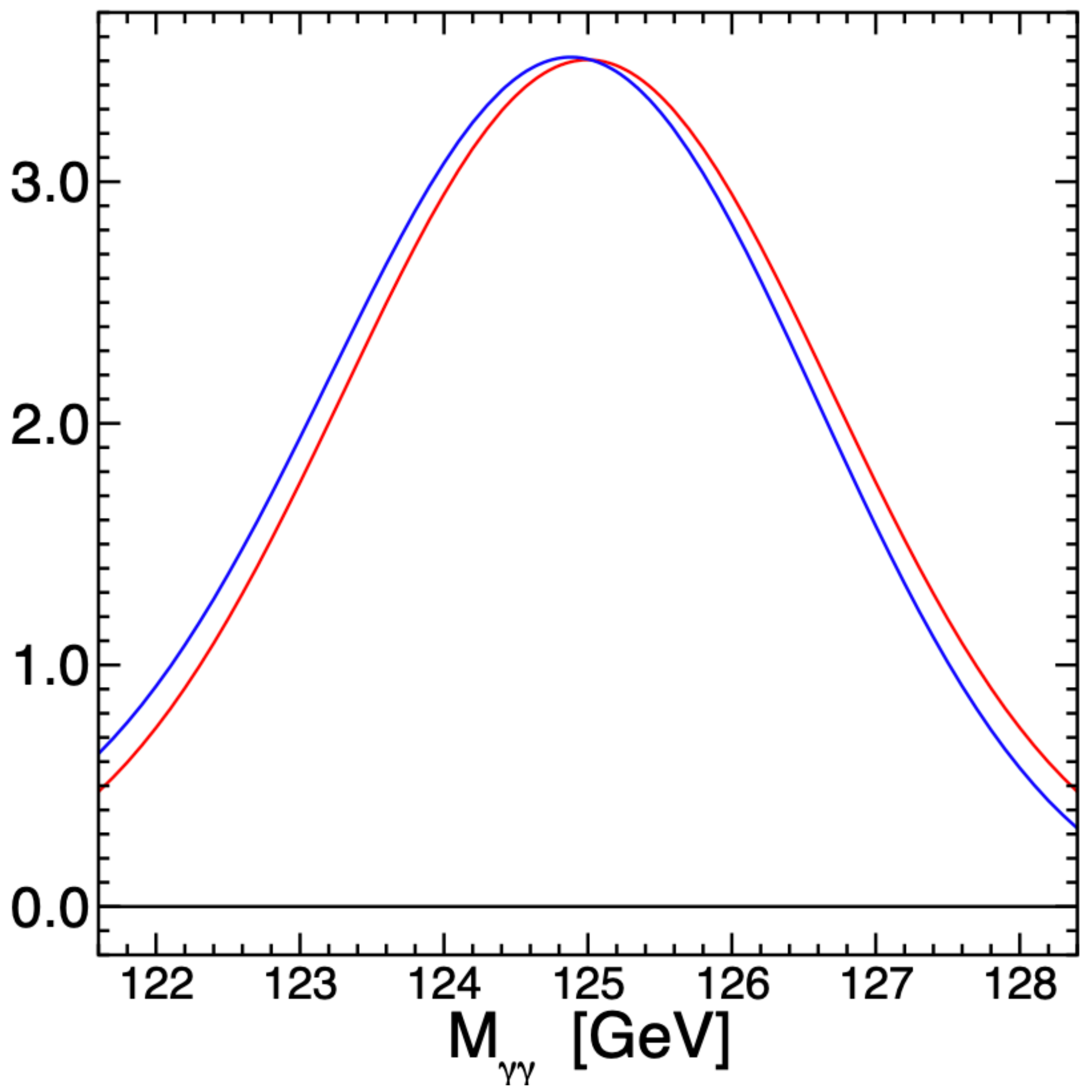

First moment method

[Martin ’12]

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

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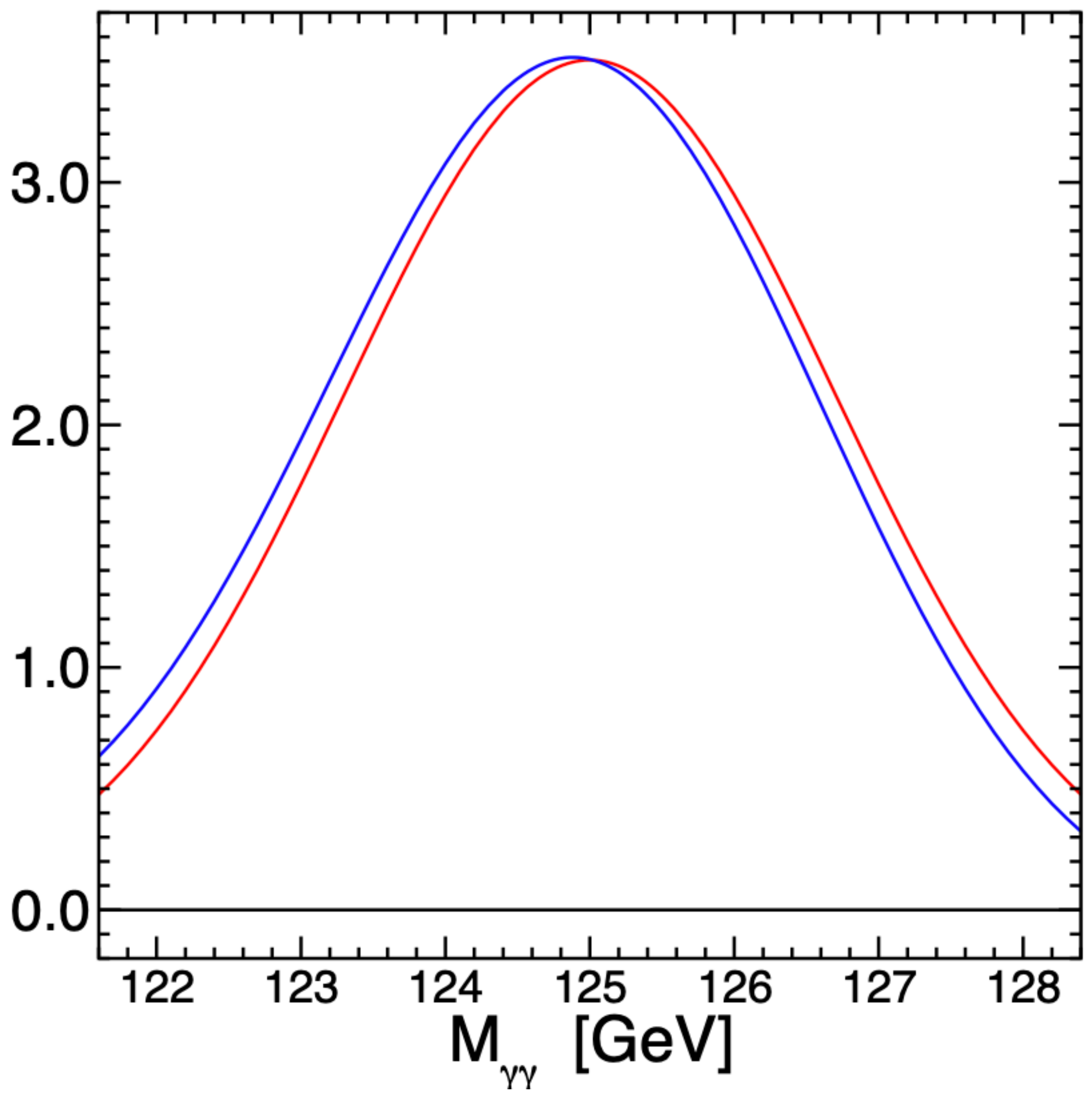

First moment method

[Martin '12]

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

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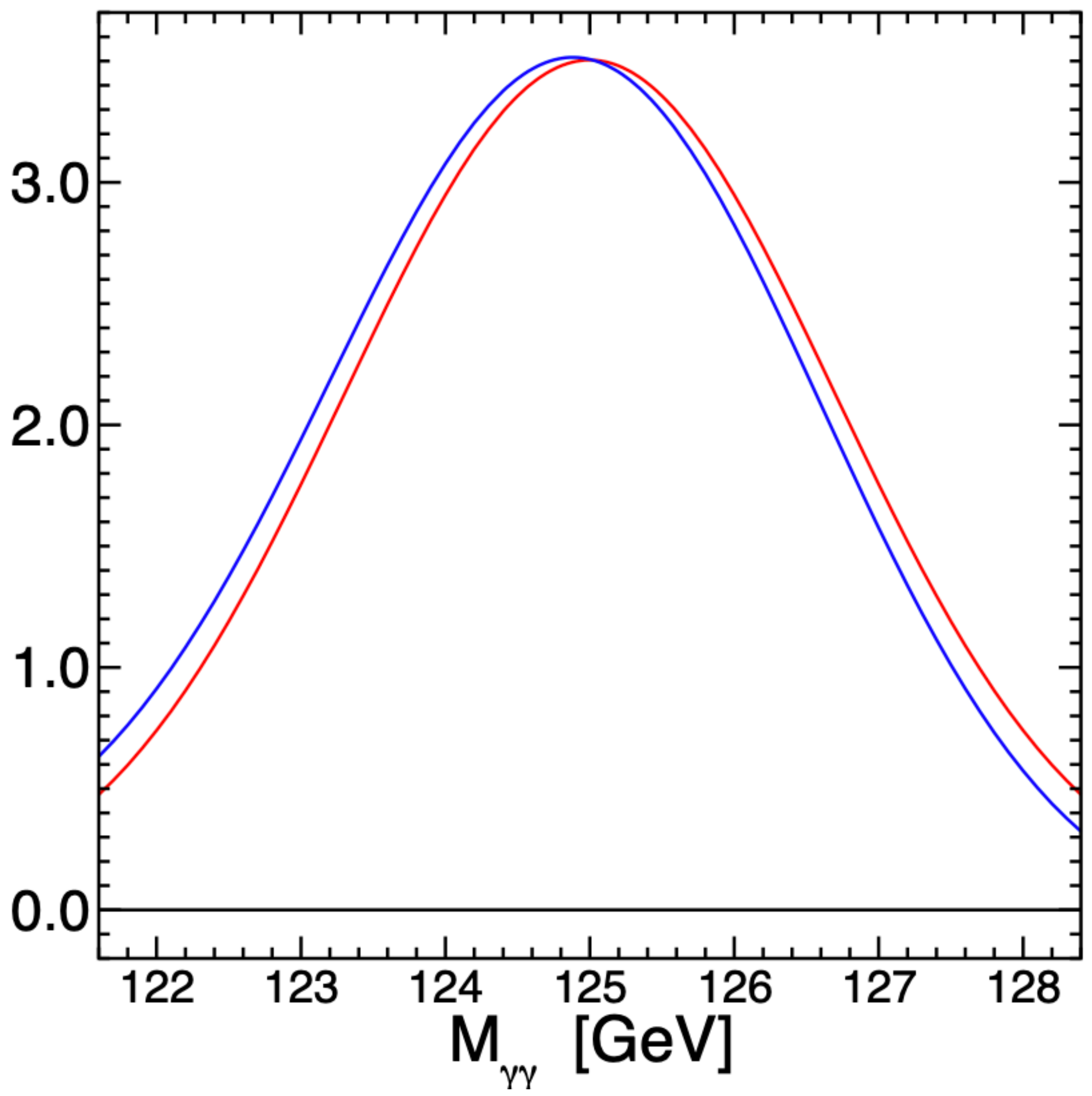

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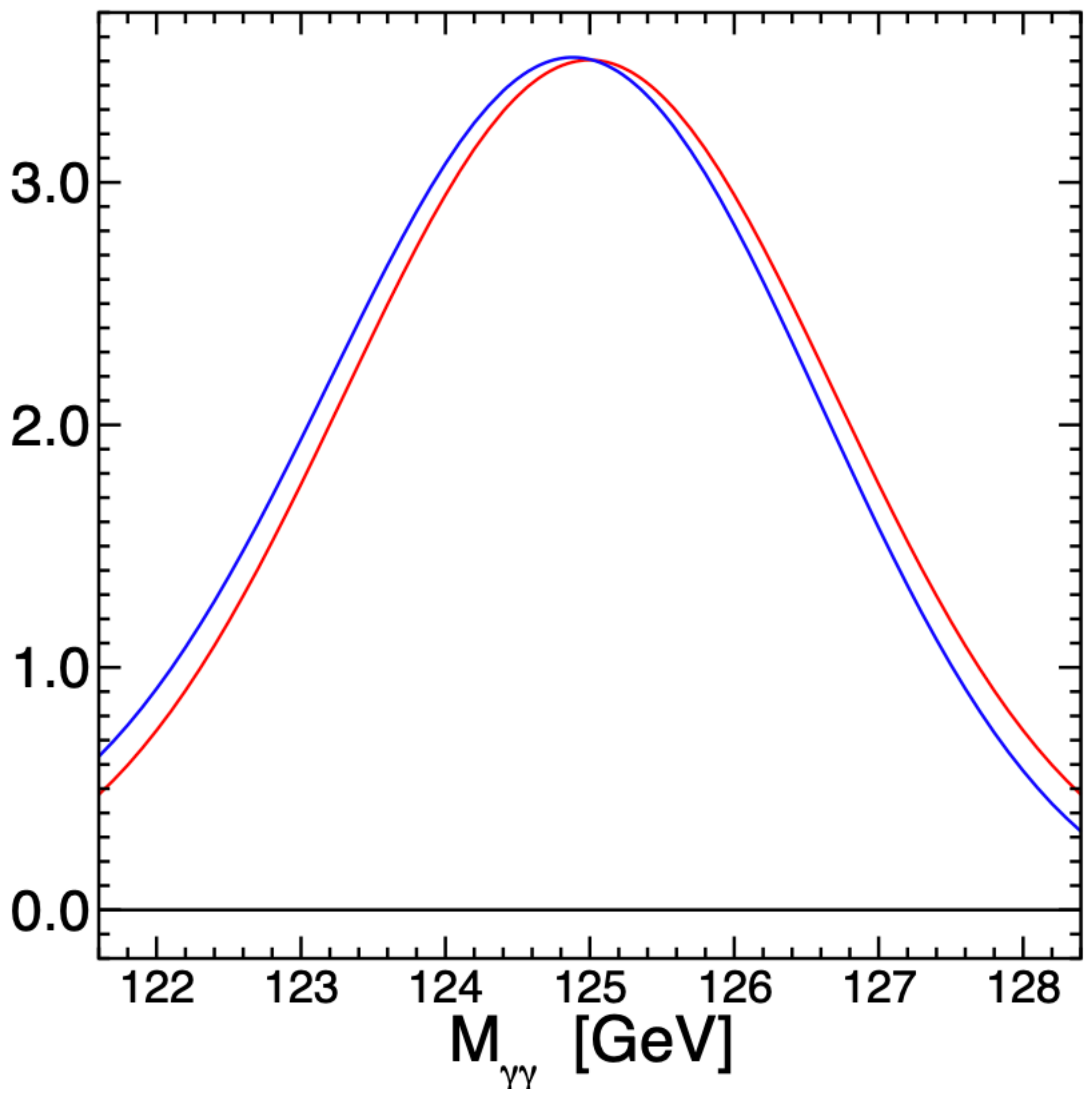

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Likelihood analysis,
e.g. gaussian fit

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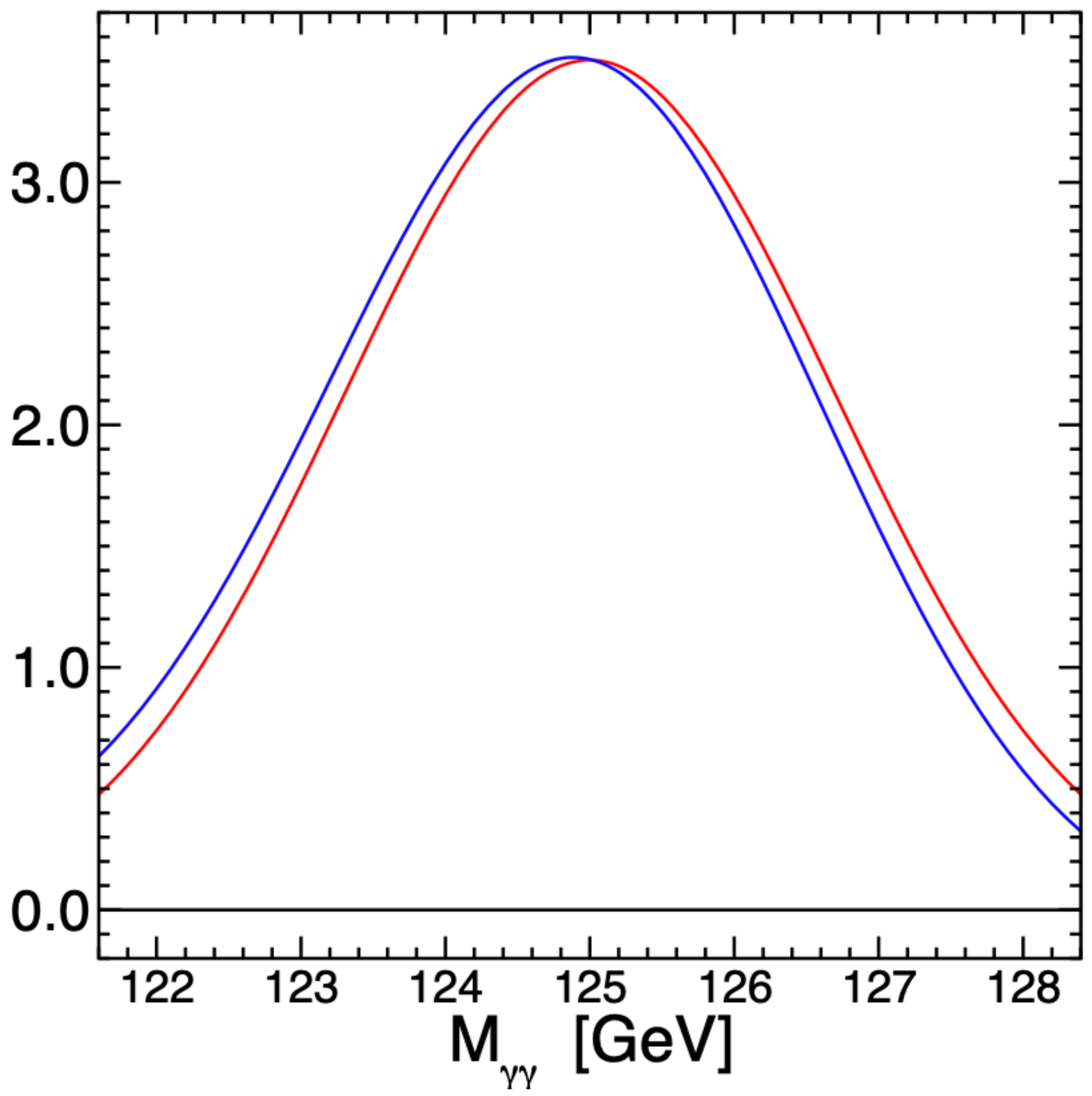

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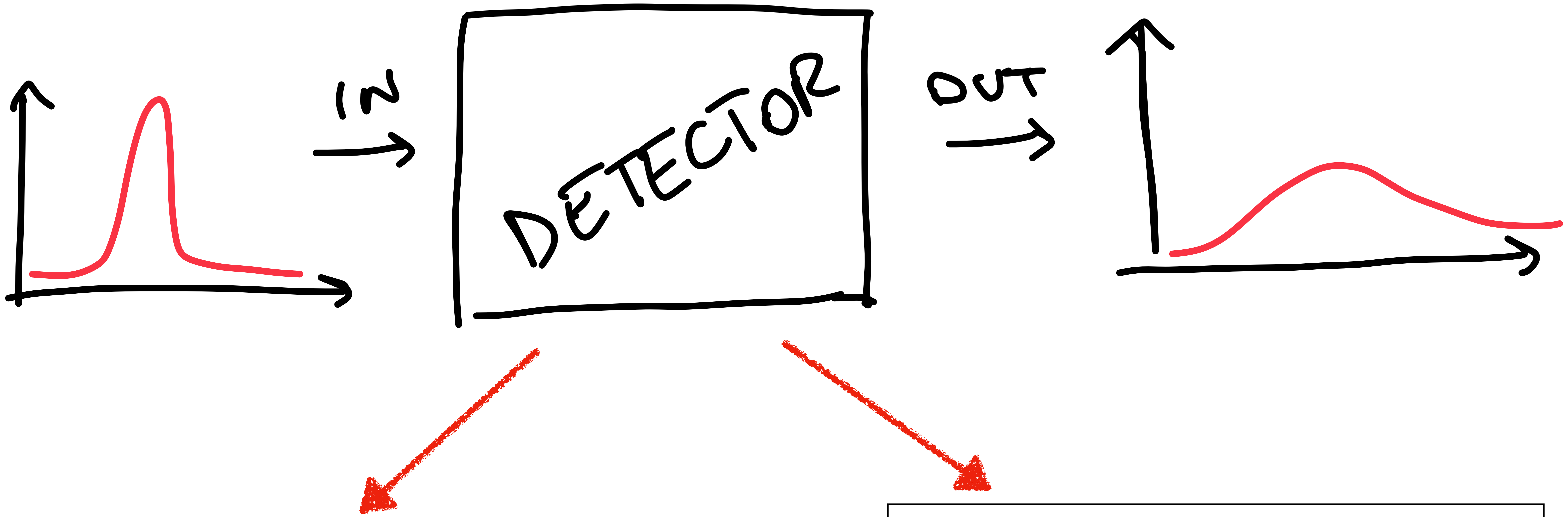
[Dixon, Li '13]

Mass shift estimates

- Need to take into account the smearing effects of the detector



Gaussian distribution

$\Delta M_{\gamma\gamma} \sim 70\,\mathrm{MeV}$

[Dixon, Li ’13]

Realistic detector simulation

$\Delta M_{\gamma\gamma} \sim 35\,\mathrm{MeV}$

[ATL-PHYS-PUB-2016-009]

Mass-shift estimate: experiments

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

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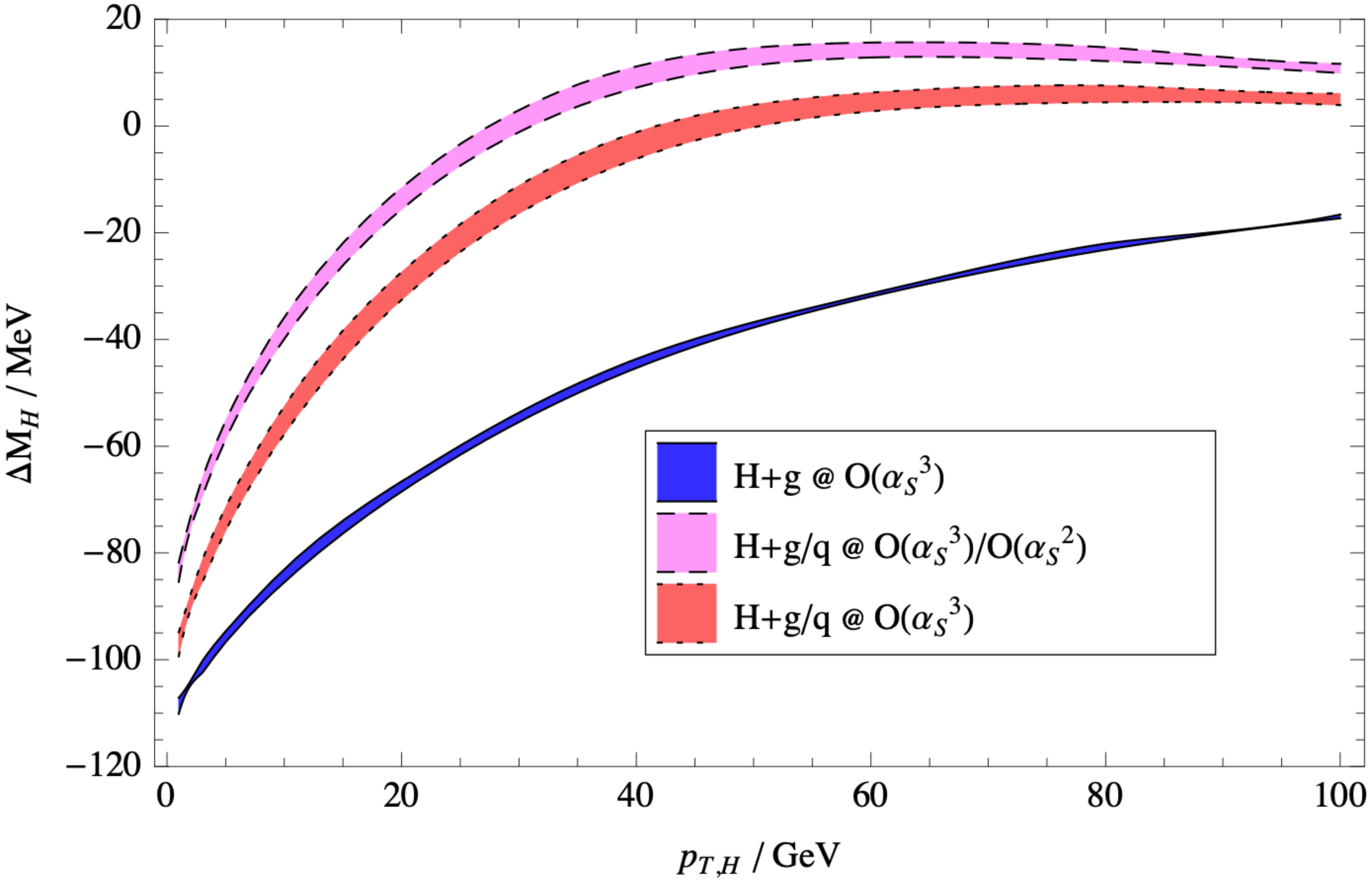

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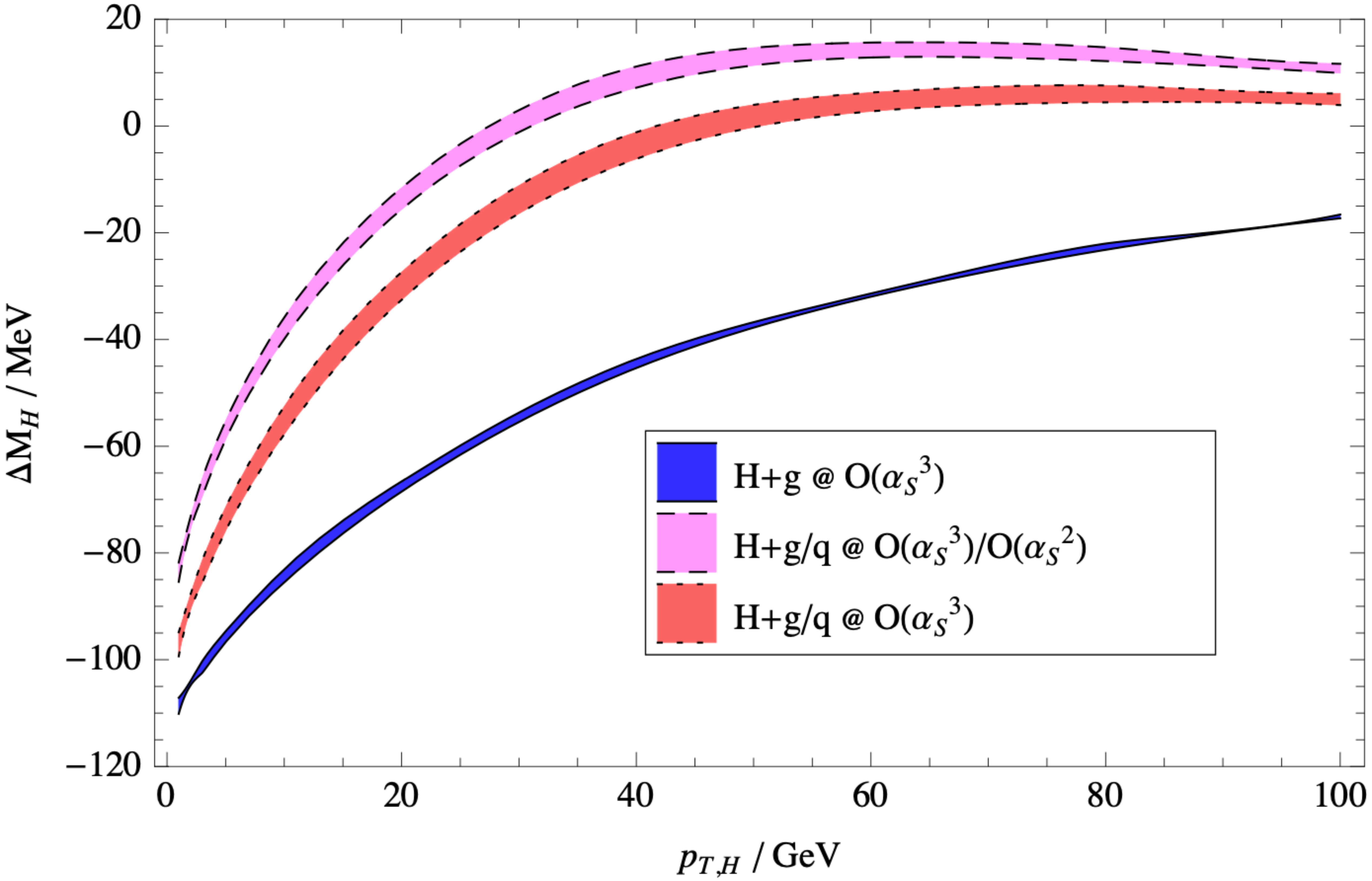

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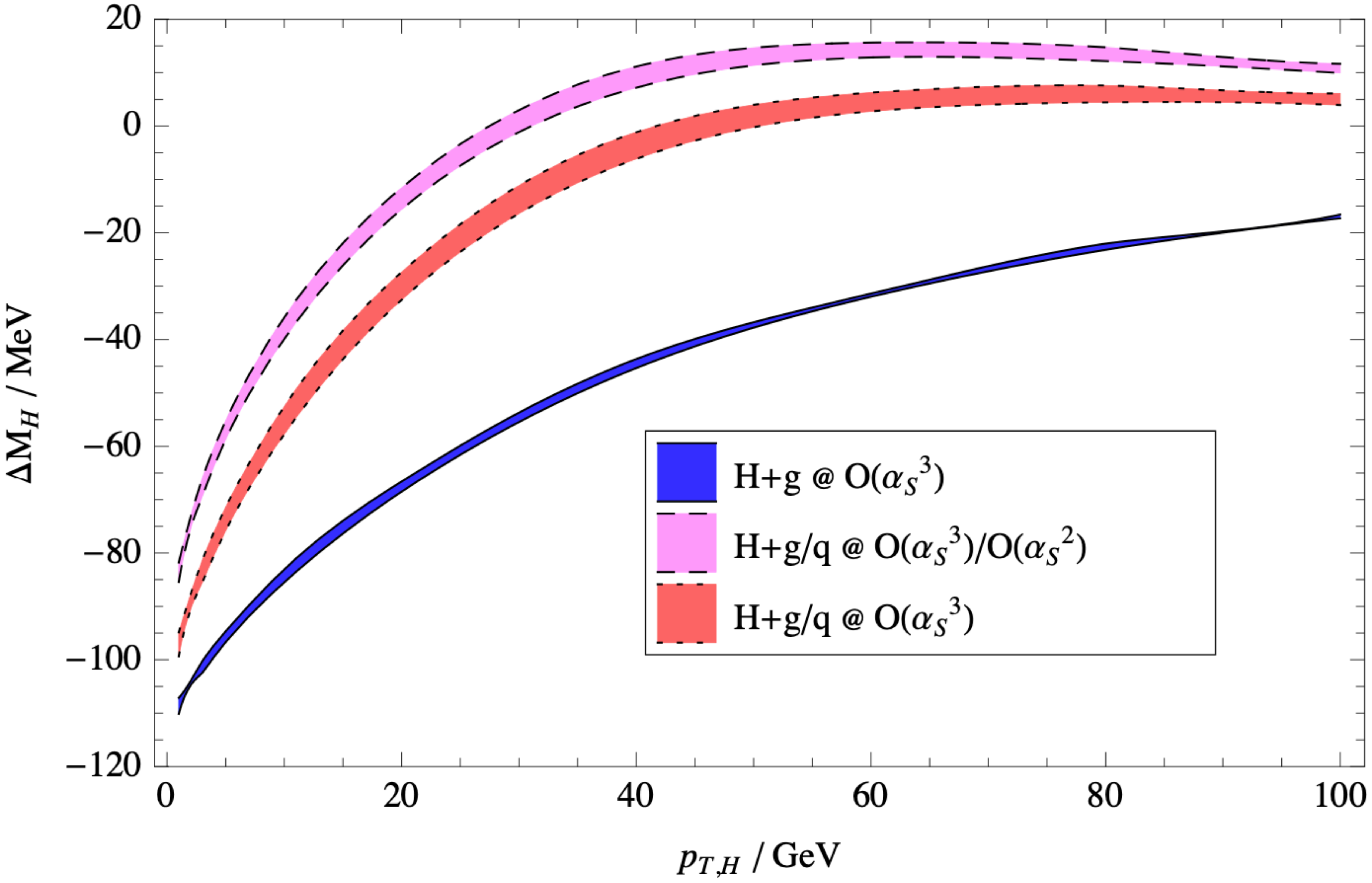

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$p_{T,H}$
dependent
measurements

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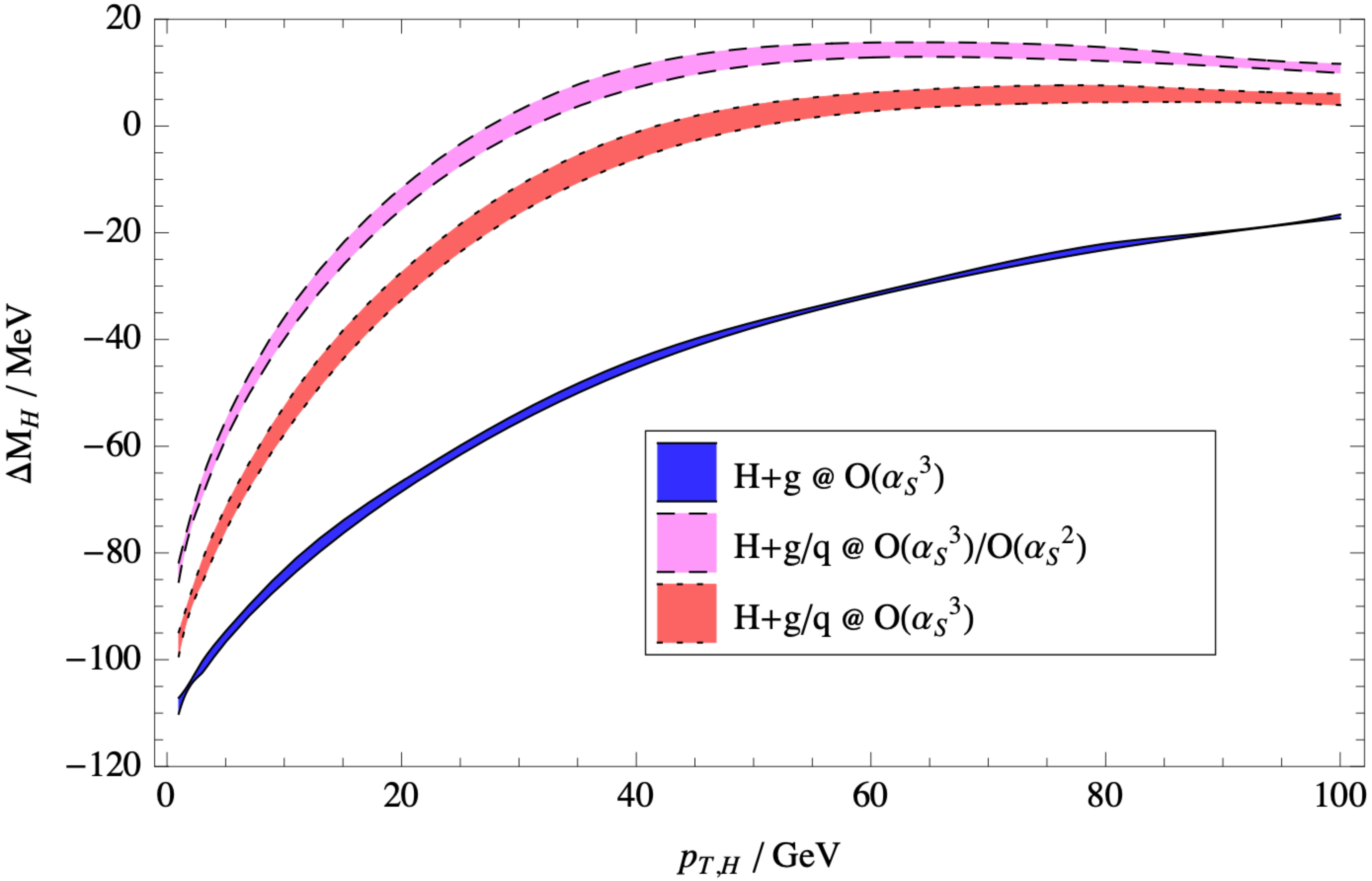

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- Recall that interference in diphoton channel is enhanced wrt ZZ channel

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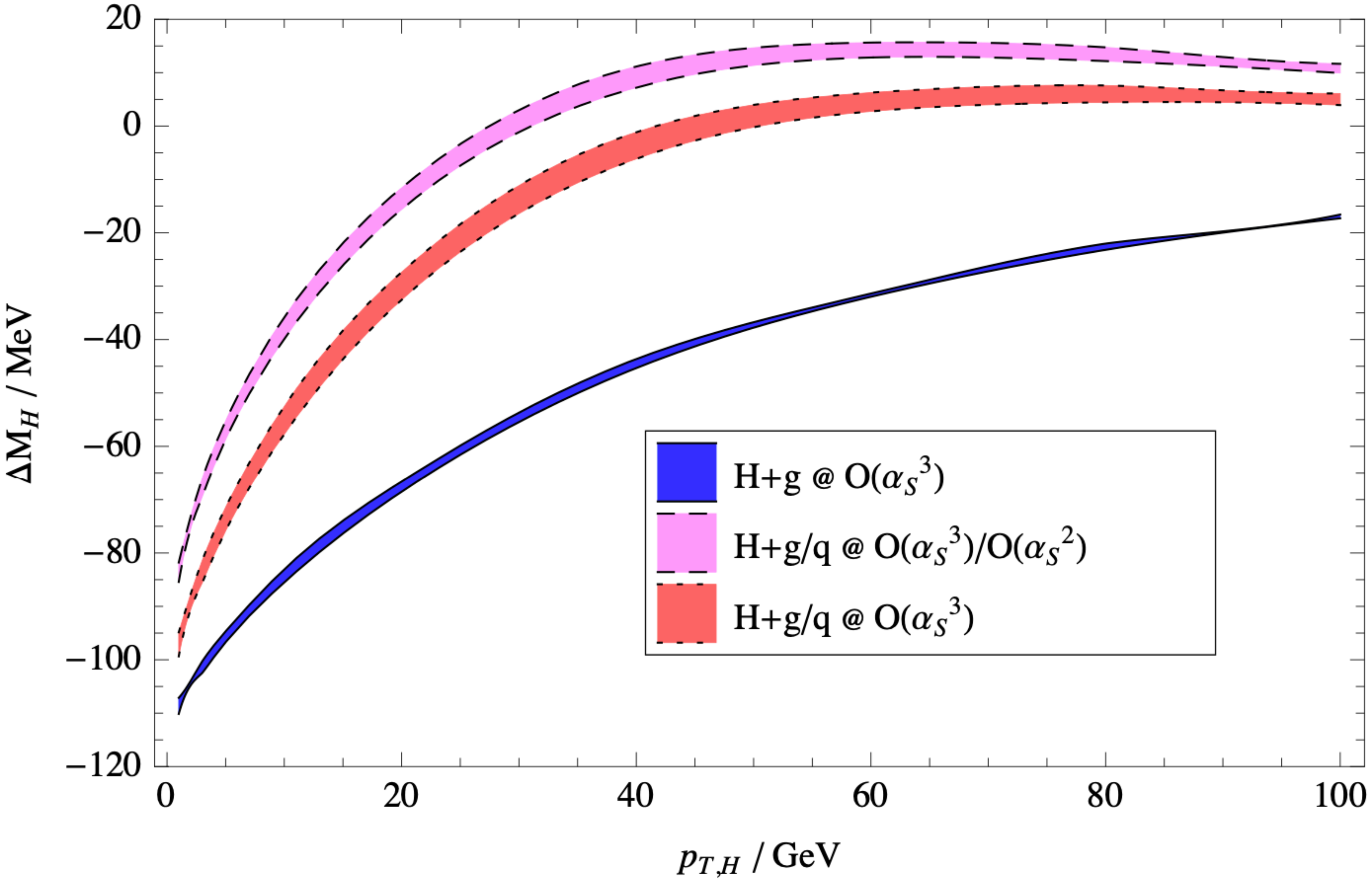

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$p_{T,H}$
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measurements

- 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

$$I_{\mathrm{Im}} \propto \frac{2}{(m_{\gamma\gamma}^2 - m_H^2)^2 + \Gamma_H^2 m_H^2} \Gamma_H m_H \times$$
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$$\sigma_{int} \propto \frac{\pi}{\cancel{\Gamma_H m_H}} \cdot \lambda_i \lambda_f \cancel{\Gamma_H m_H}$$

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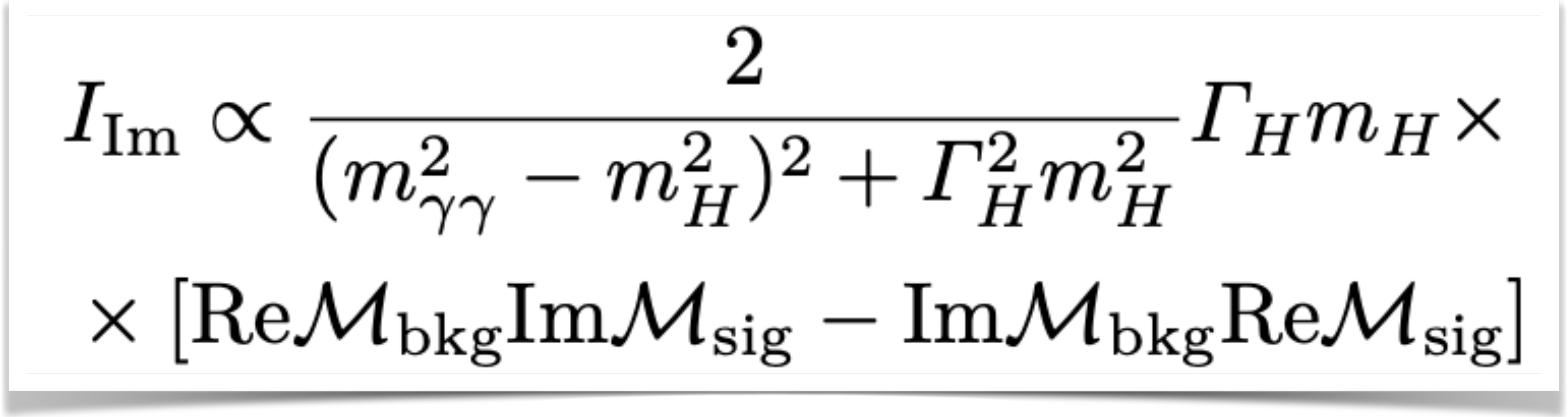

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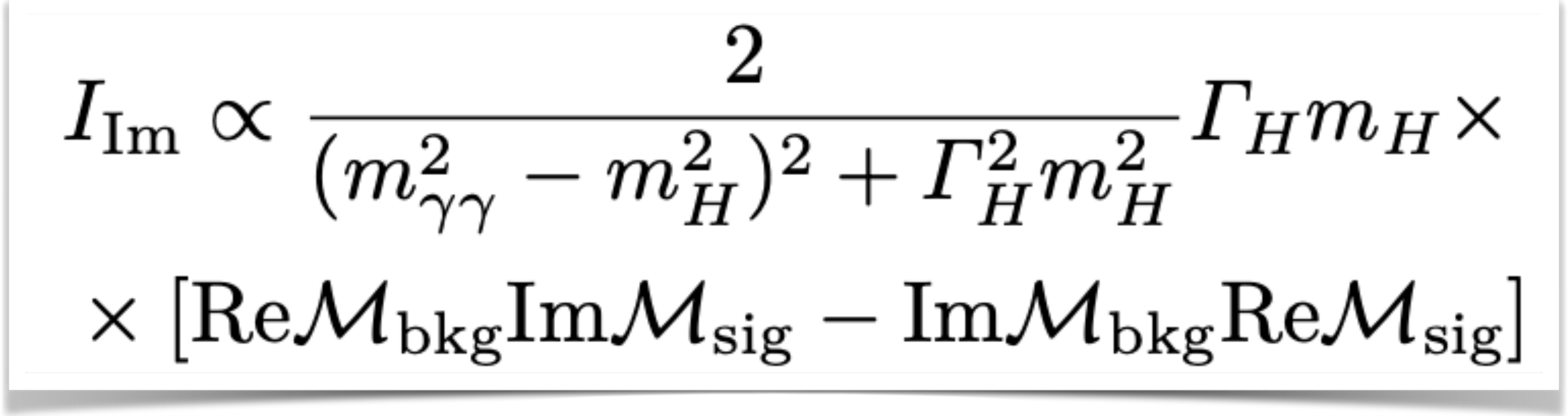

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@LO: ~(-5) permille
@NLO: ~(-1.3)%
@NNLO: ? (Will see shortly)

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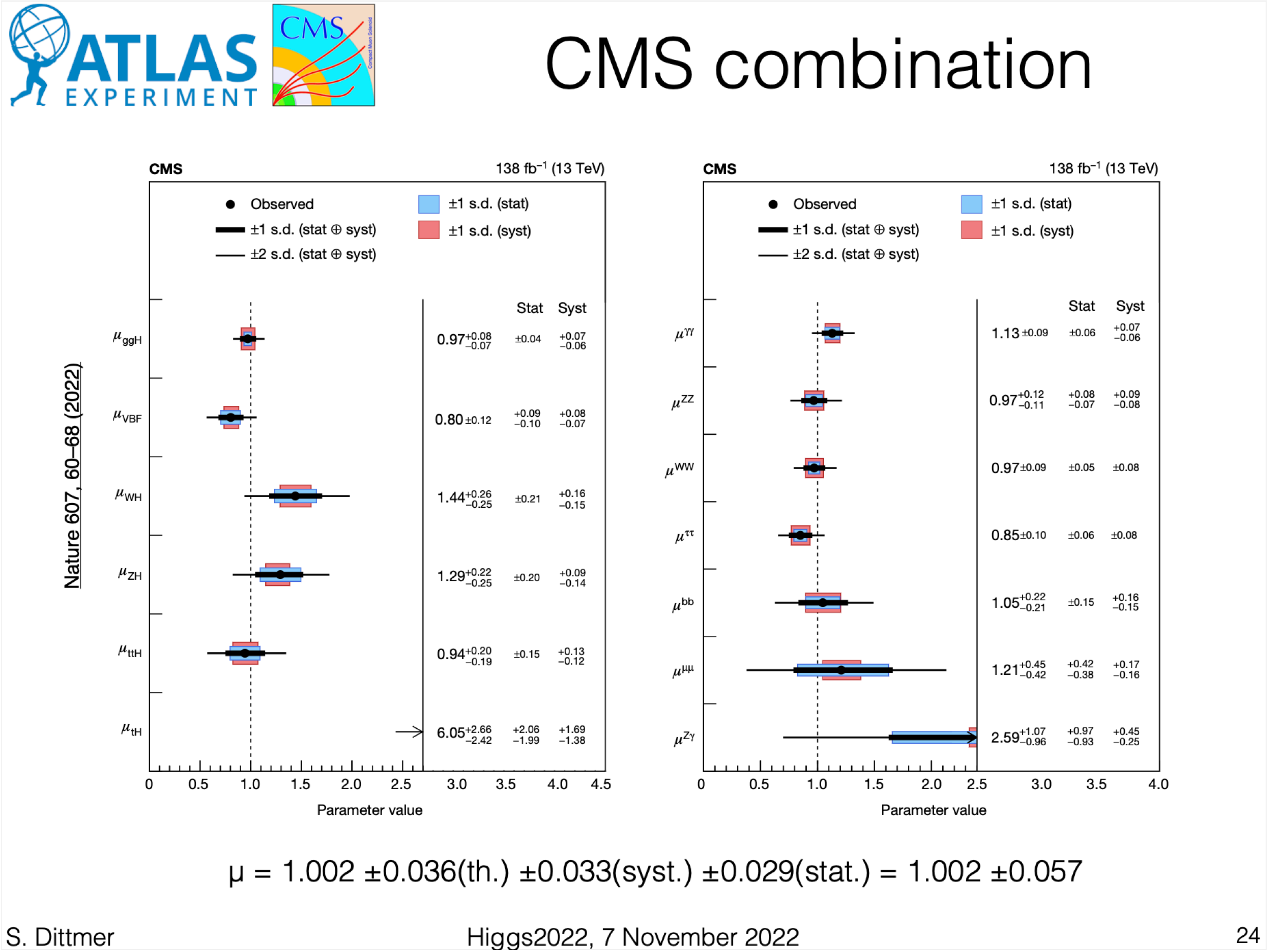


CMS combination

$$\mu = 1.002 \pm 0.036(\text{th.}) \pm 0.033(\text{syst.}) \pm 0.029(\text{stat.}) = 1.002 \pm 0.057$$

Slide from
Susan Dittmer
@ Higgs2022

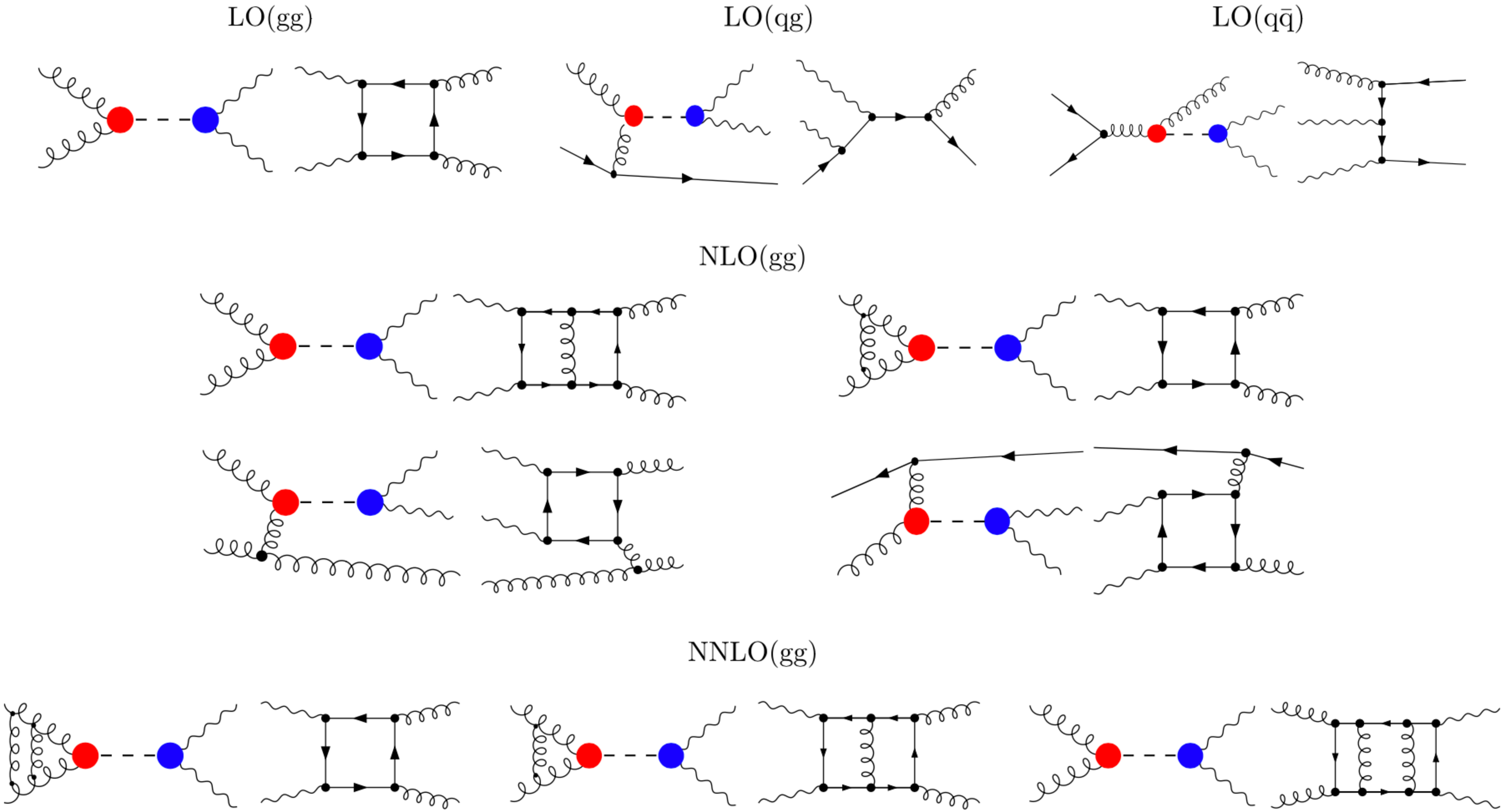
Uncertainty
on XS
(diphoton)
~9%

Brief history of diphoton interference effects

- Martin ’12: Leading order analysis including gg initial state only, mass shift calculated via first moment method ~150 MeV
- De Florian et al ’12: $qg \rightarrow \gamma\gamma q$ and $q\bar{q} \rightarrow \gamma\gamma g$ also included in the leading order analysis. Effect of ~30 MeV with opposite sign wrt gg channel coming almost entirely from qg initial state
- Dixon, Li ’13: Interference effects analysis in $\gamma\gamma$ channel performed up to next-to-leading order resulting in shift~70 MeV (LO estimate ~120 MeV) and first proposal to use this study to bound Higgs width
- Campbell et al ’17: analysis at NLO mostly focussed on width bounds from integrated on-shell cross sections

Large corrections
Higher order analysis
required

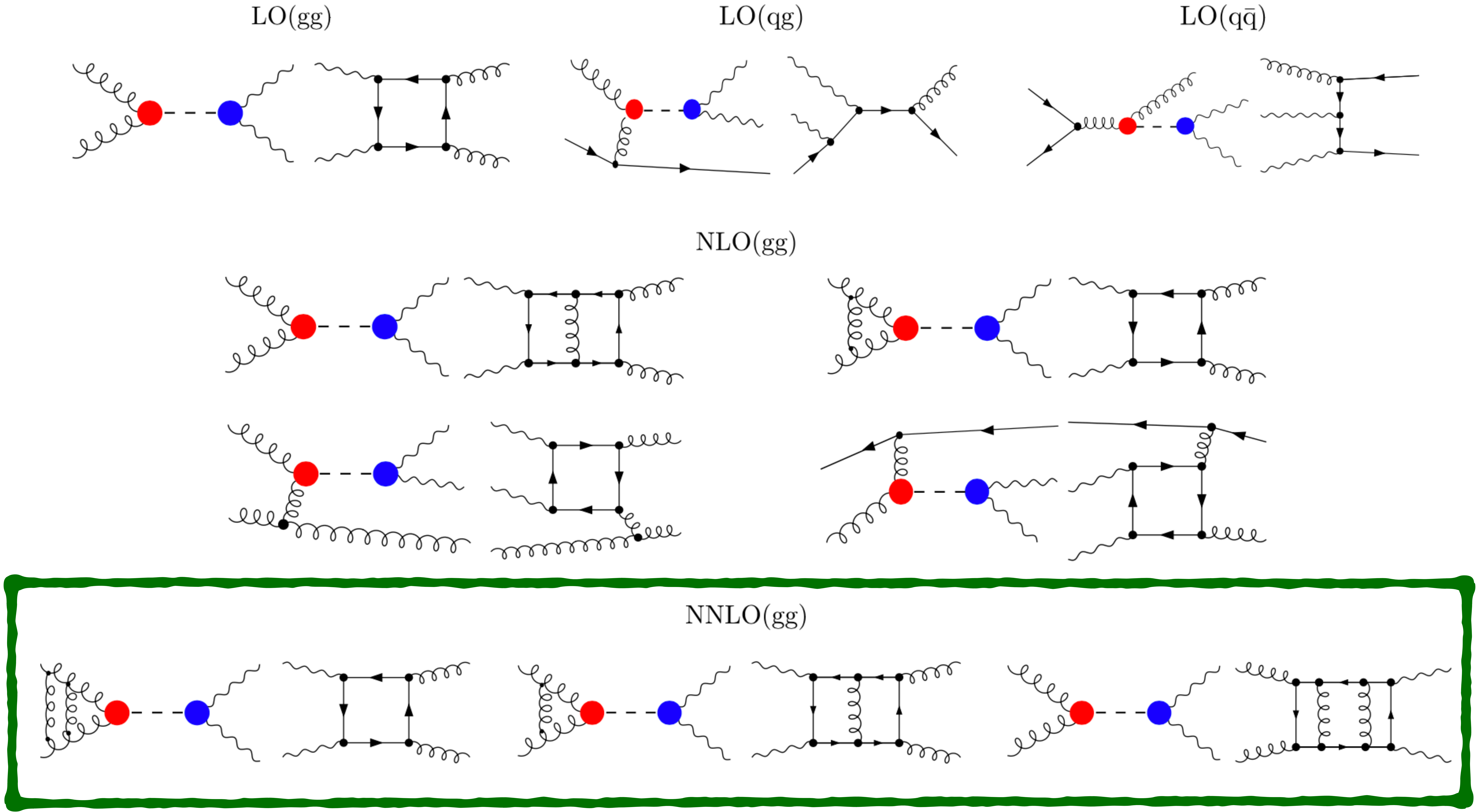
Interference effects beyond NLO



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

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

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



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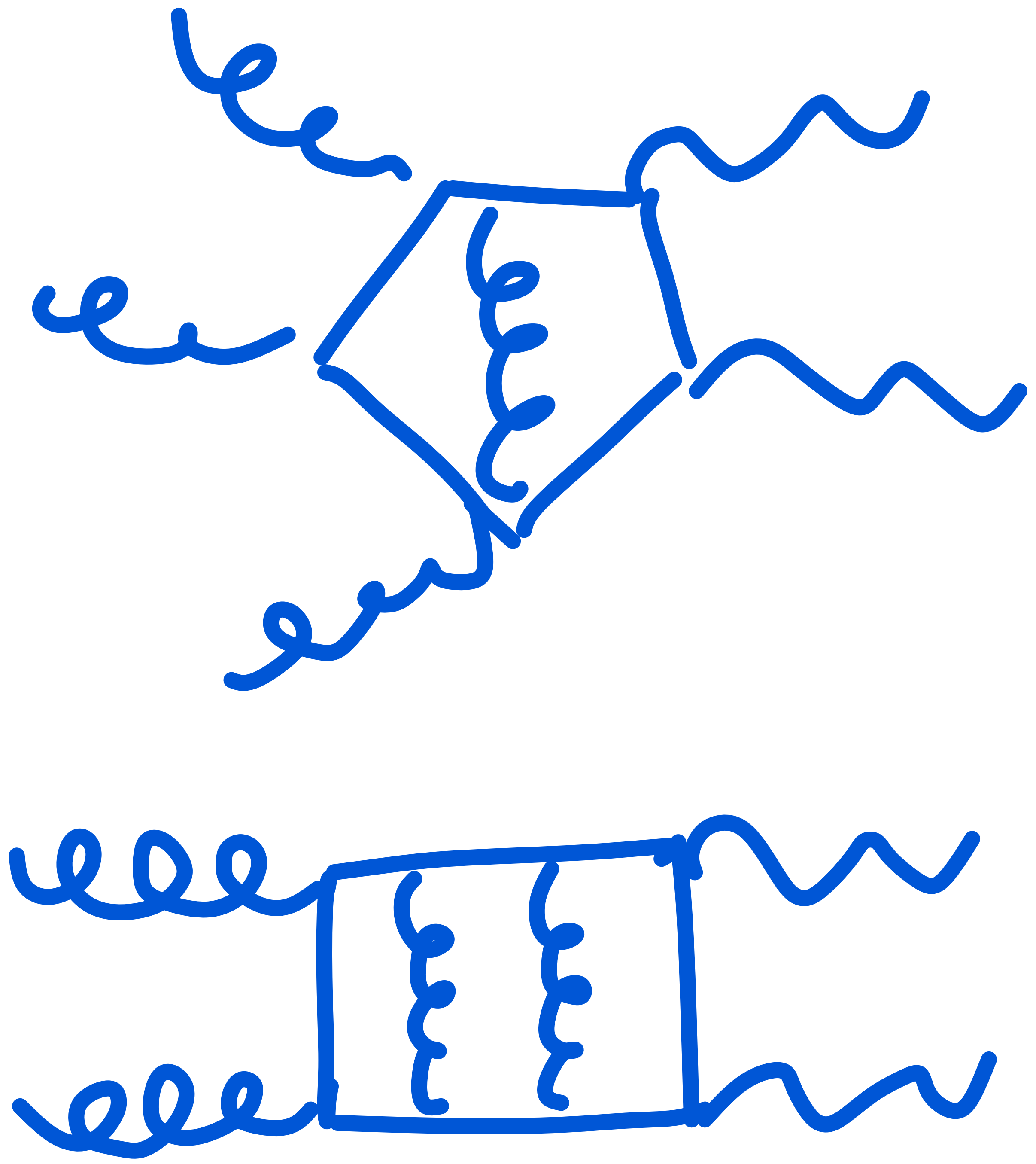
Interference@NNLO: ingredients



- 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.)

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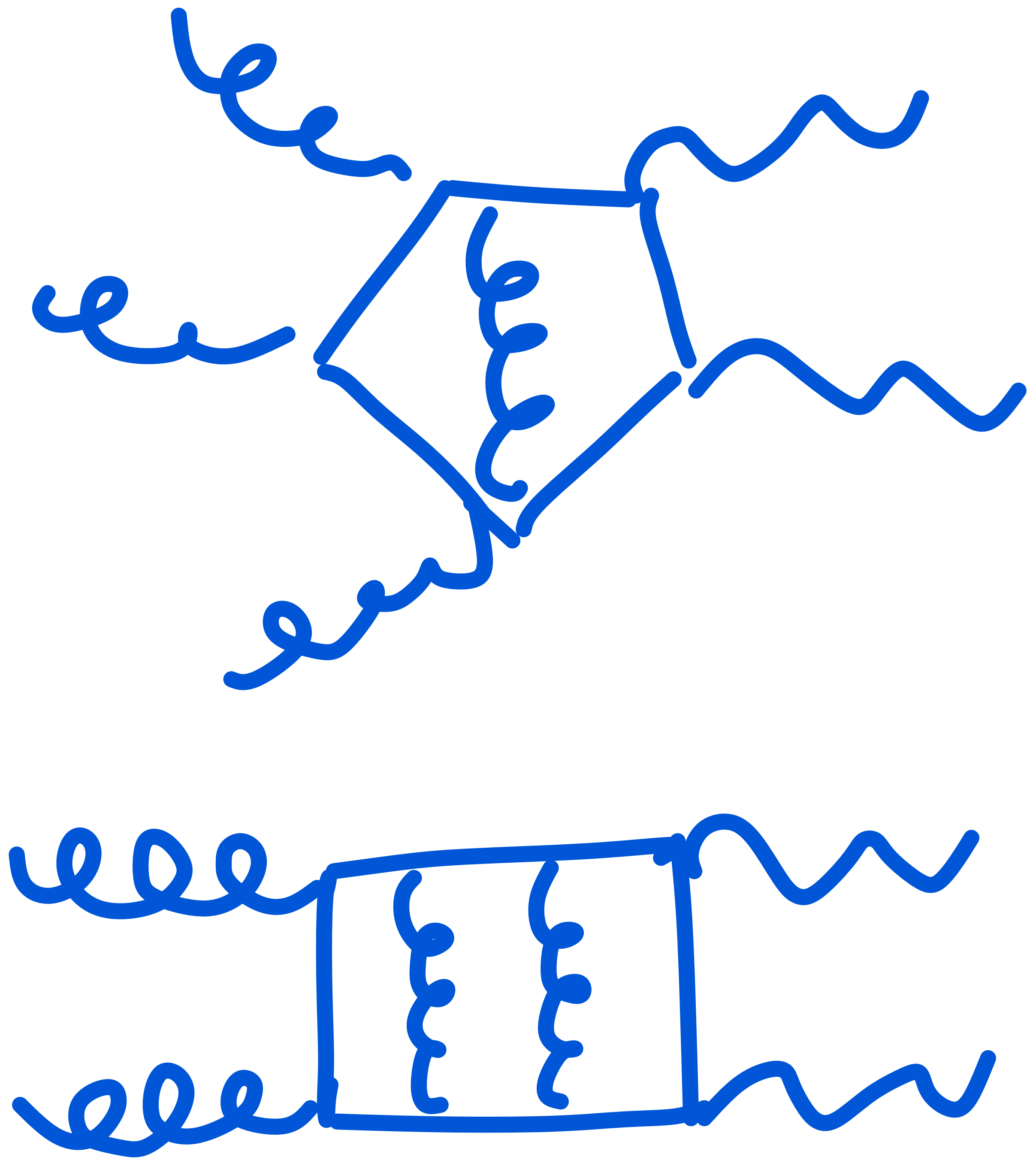

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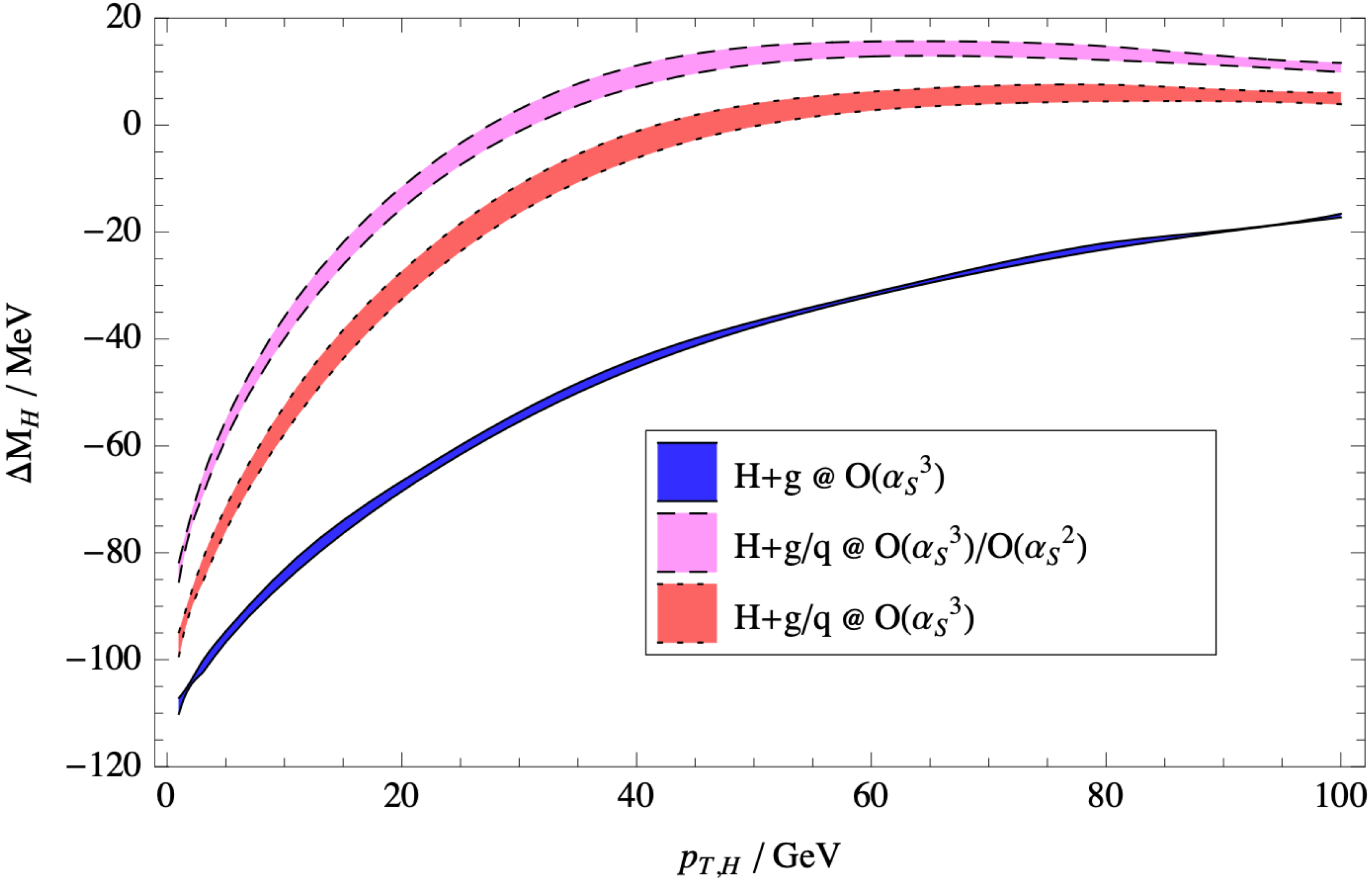
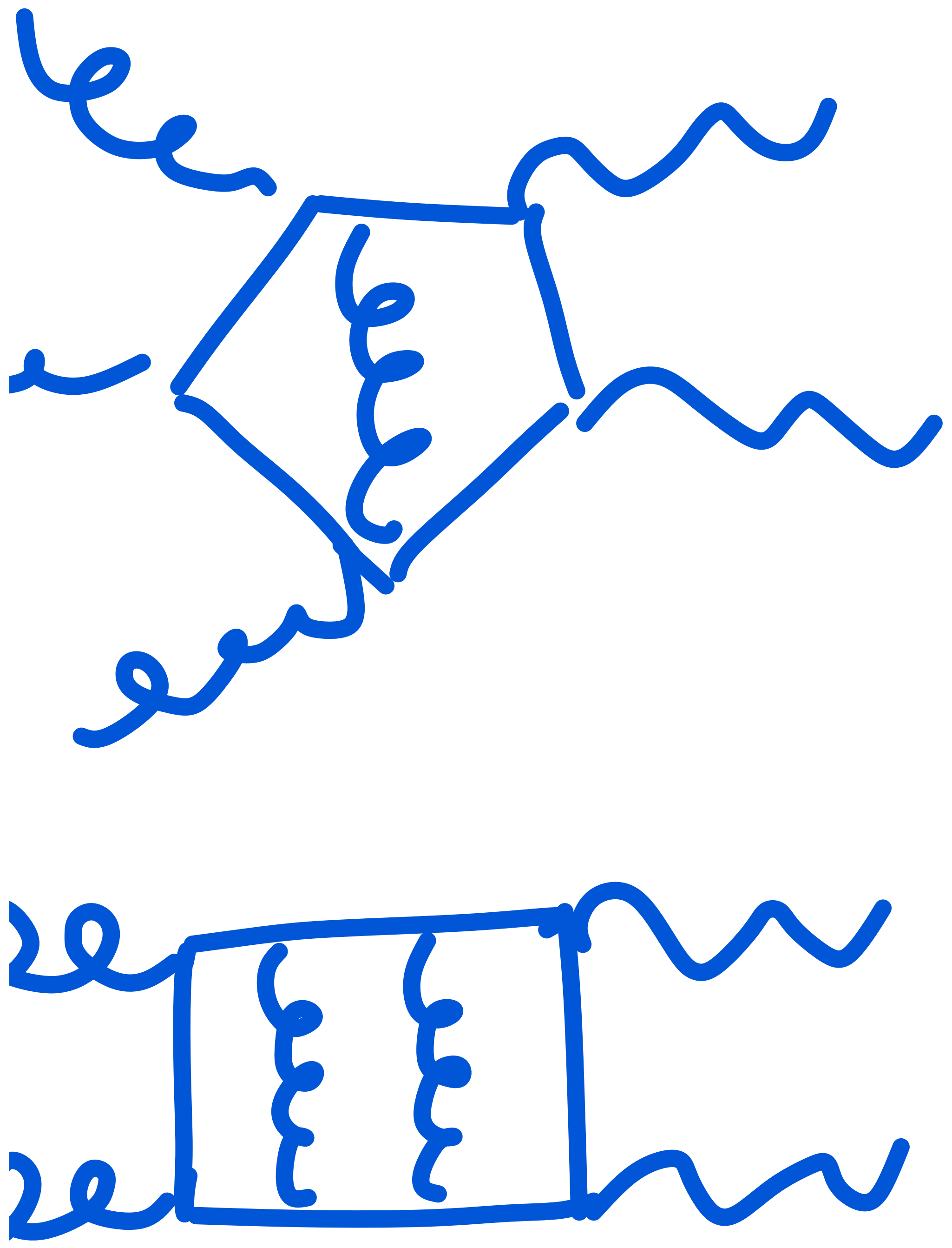
Interference is enhanced at low $p_{T,H}$,
bulk of the contribution coming from the virtuals

Interf

- Subtra
- 5-point
- Three-l





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(e.g. evaluation

Interfe
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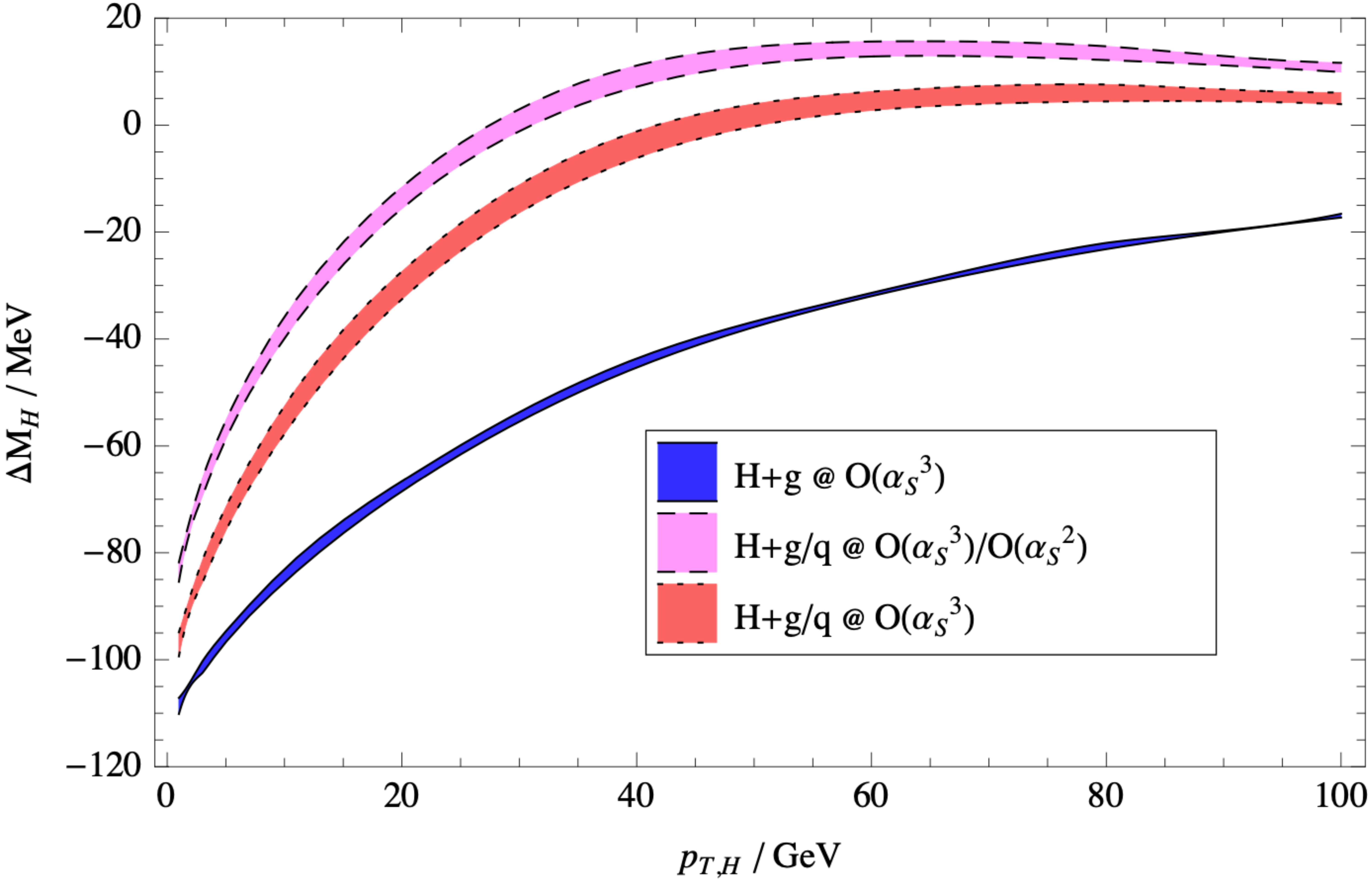

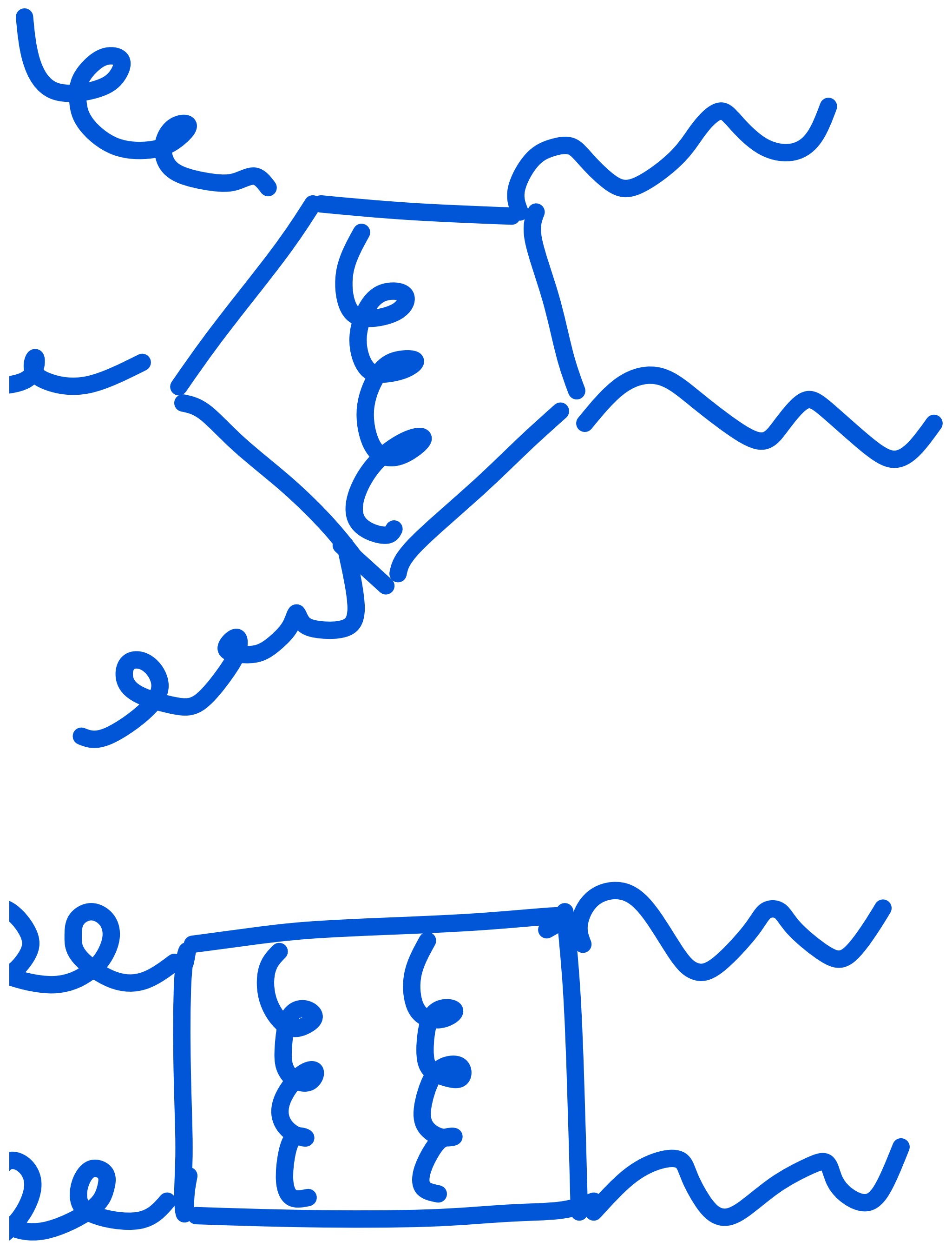

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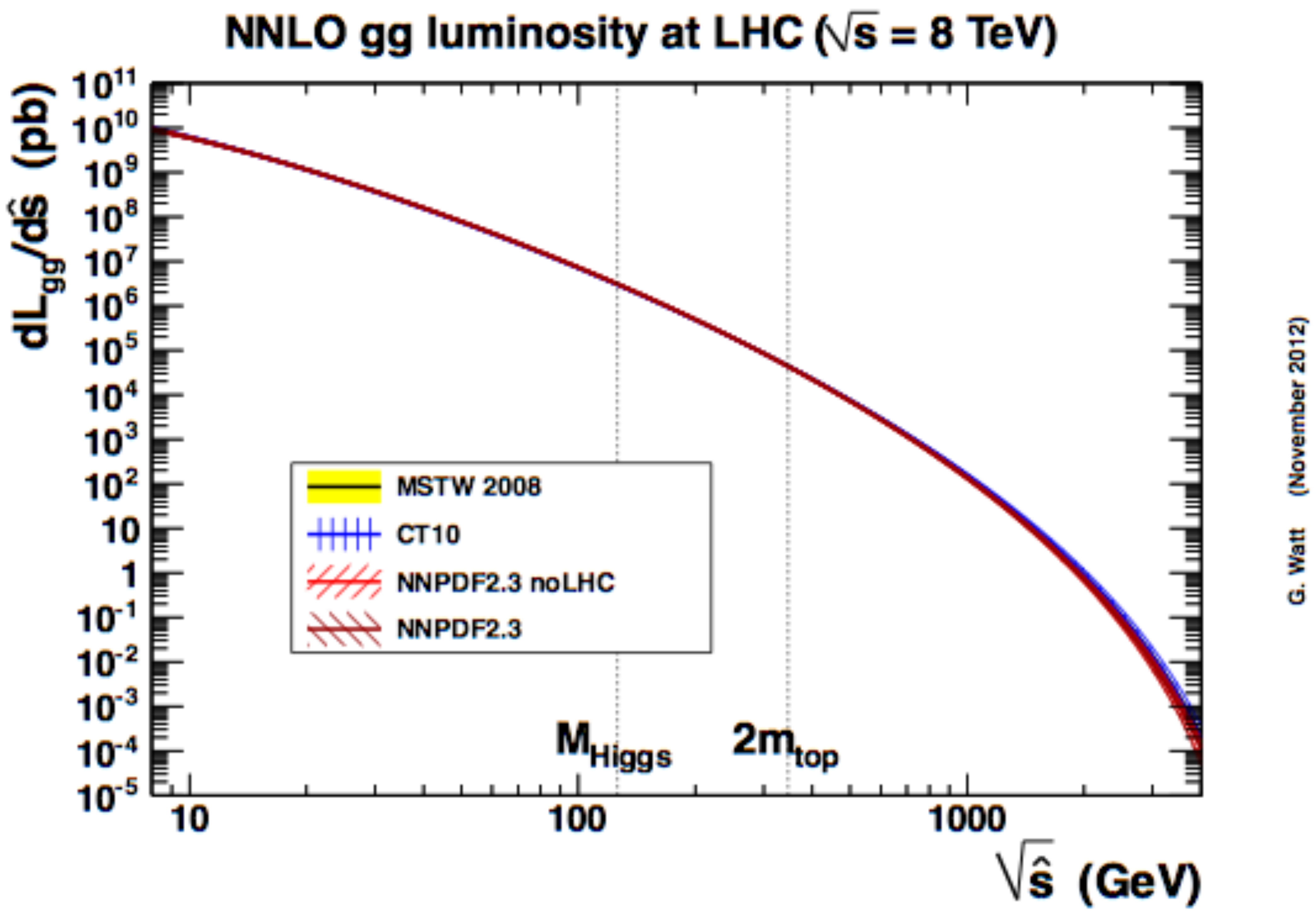
Soft-virtual approximation

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

$$\hat{\sigma} = \sigma_0 + \sigma_0 \frac{\alpha_s}{2\pi}\left(\underbrace{8C_A \left[\frac{\ln(1-z)}{1-z}\right]_+}_{\text{Universal structure}} + \underbrace{c_1\delta(1-z)}_{\text{Process-dependent, from virtual contributions}} + \text{reg} \right) + \text{h.o.}$$

Universal structure

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

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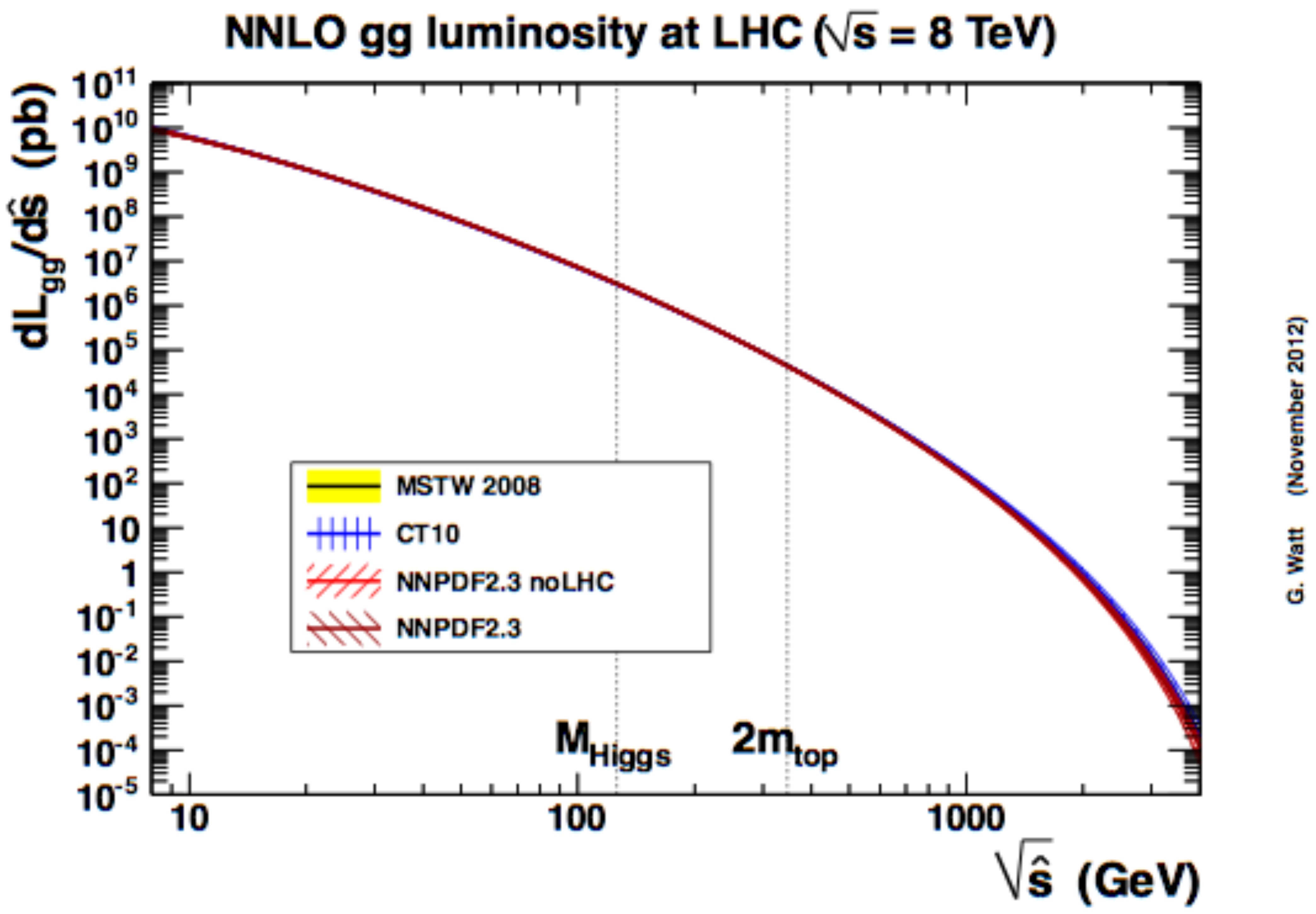

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In some cases subleading terms may be enhanced: resummation arguments allow to “tweak” the approx

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

NNLO soft-virtual interference: setup (I)

- $\sqrt{s} = 13.6\,\mathrm{TeV}$
- PDF set: NNPDF31_nnlo_as_0118
- Dynamic scale: $\mu_F = \mu_R \equiv \mu = \dfrac{m_{\gamma\gamma}}{2}$
- Fiducial cuts:
  - $p_{T\,\gamma_{1,2}} > 20\,\mathrm{GeV}$
  - $|\eta_\gamma| < 2.5$
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[Salam, Slade 2106.08329]

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- 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 2106.08329]

NNLO soft-virtual interference: setup (I)

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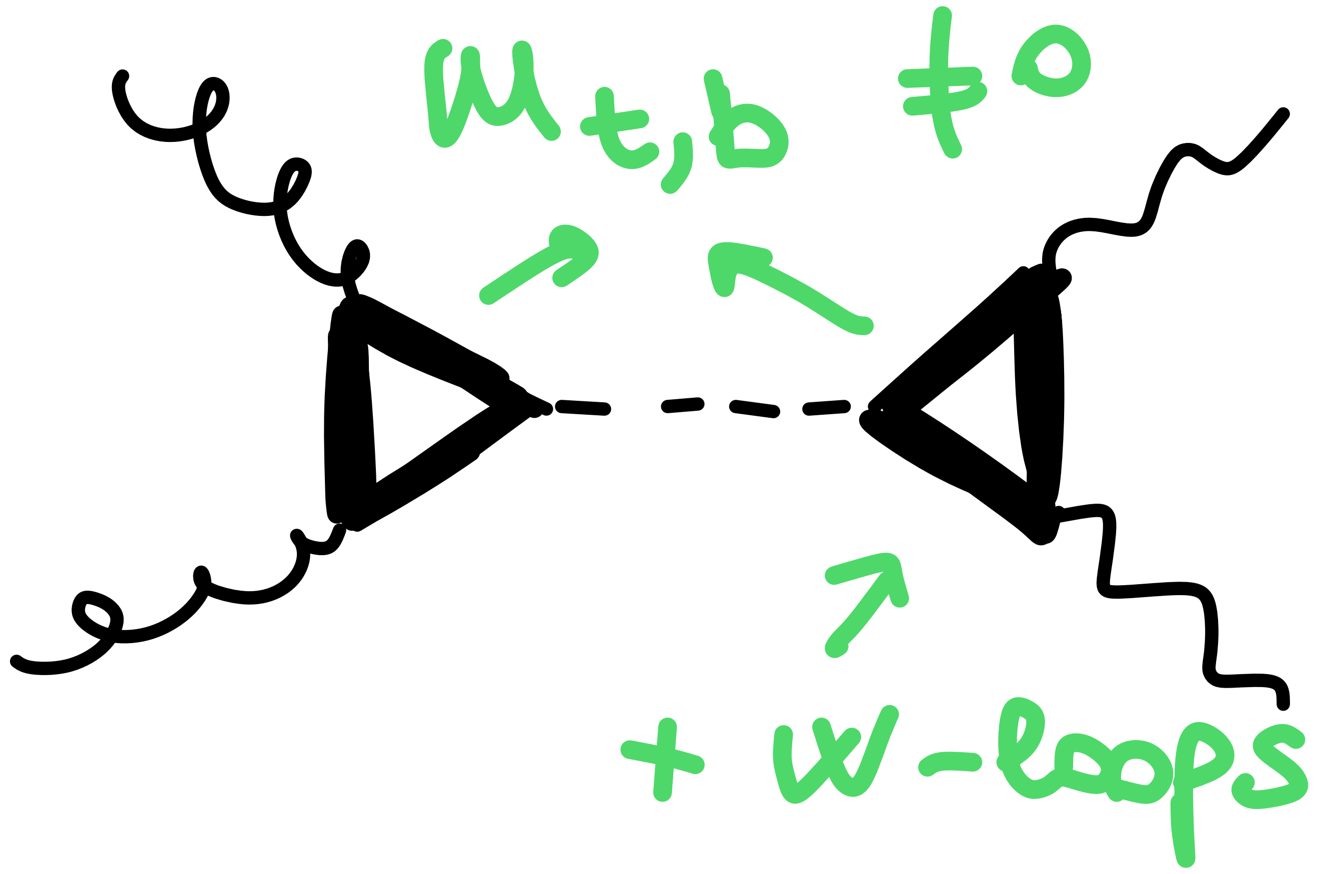
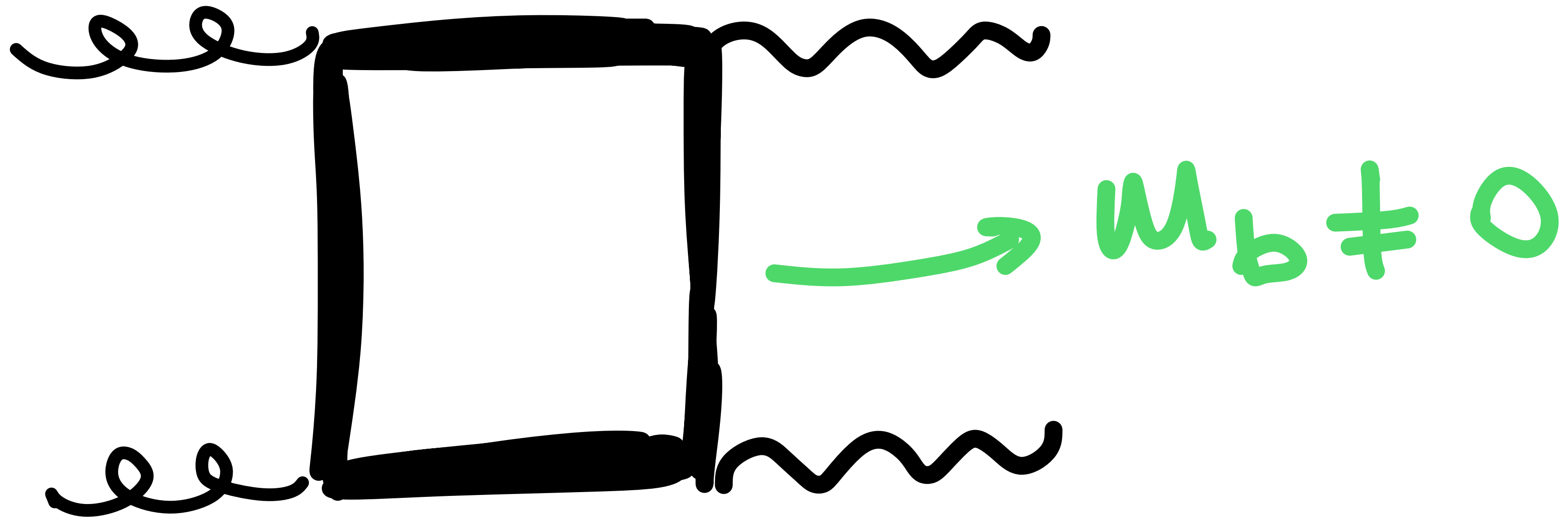
[Salam, Slade 2106.08329]

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

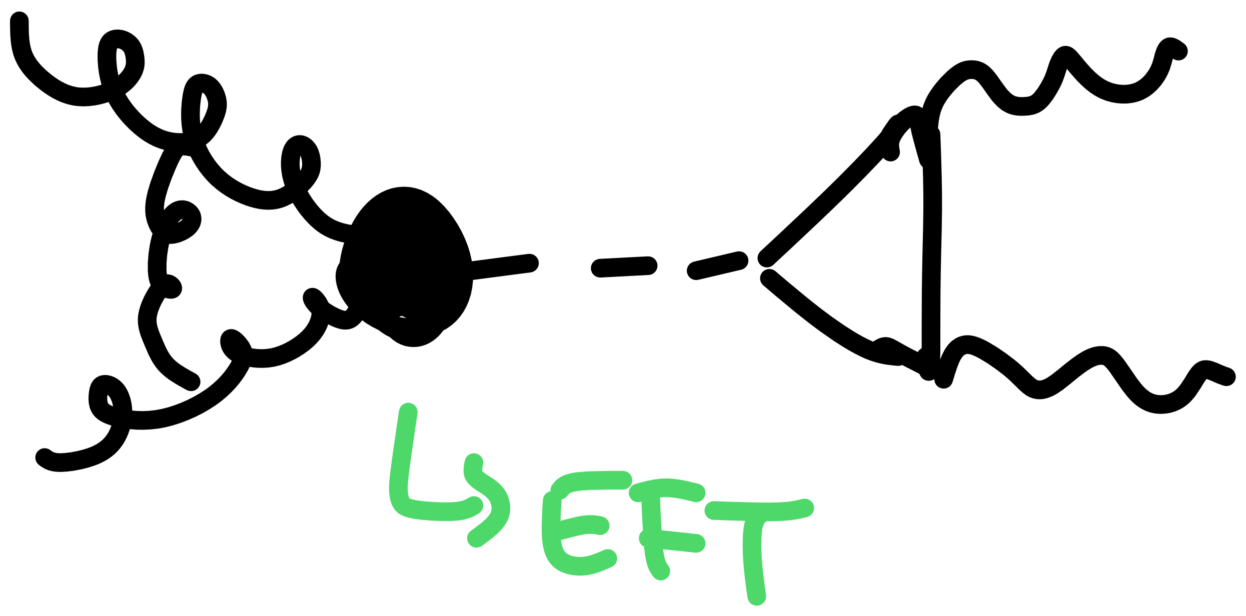
NNLO soft-virtual interference: setup (II)

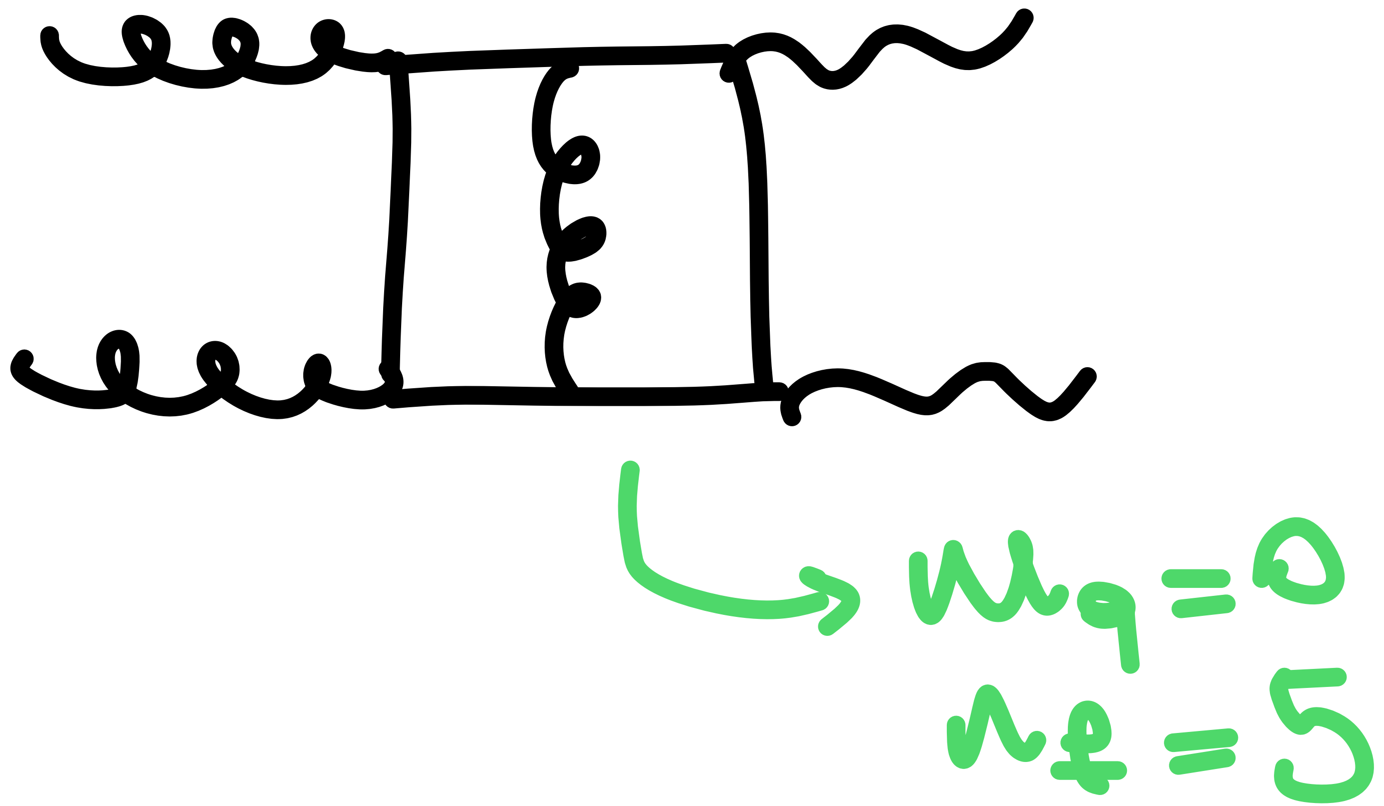
- @LO:





- @NLO and NNLOsv:





Results: integrated cross section

LO

With bottom mass both in signal and background amplitudes

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

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

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

dNNLOsv massless

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

Results: integrated cross section

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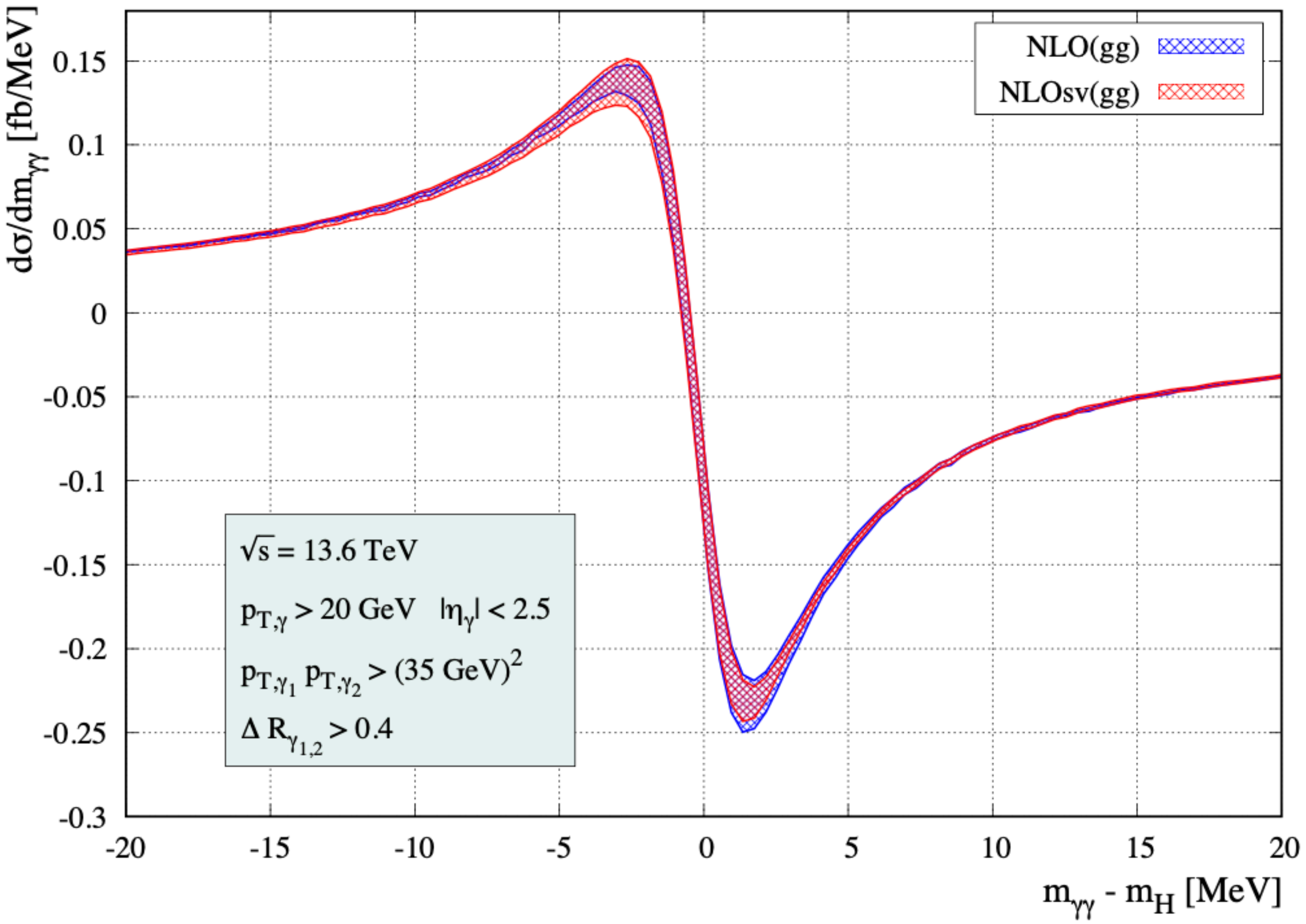
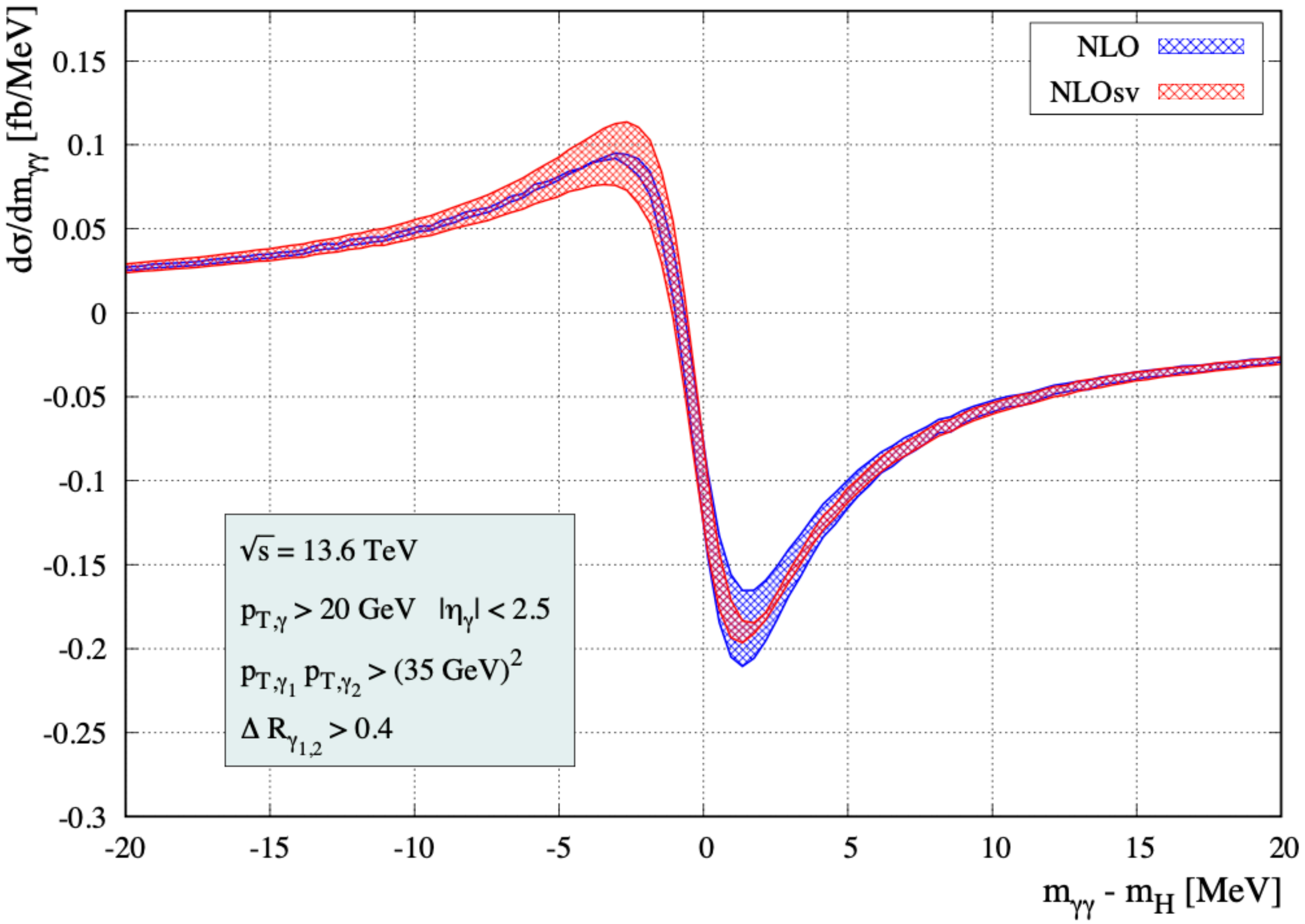
$$\sigma_{int} = -0.48\ \text{fb}$$

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

Validation of SV



gg only



all channels

Results: Interference @NNLOsv

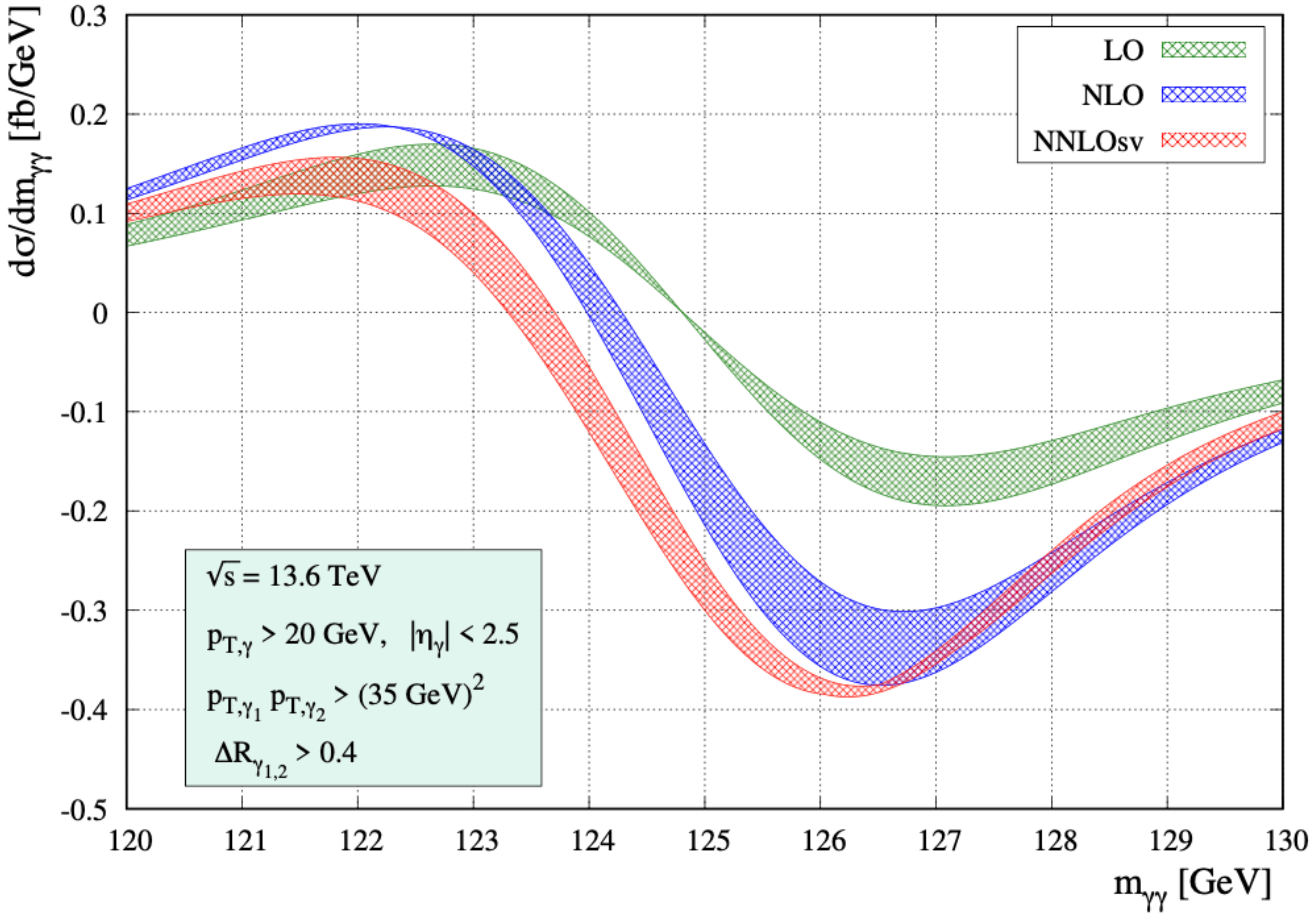
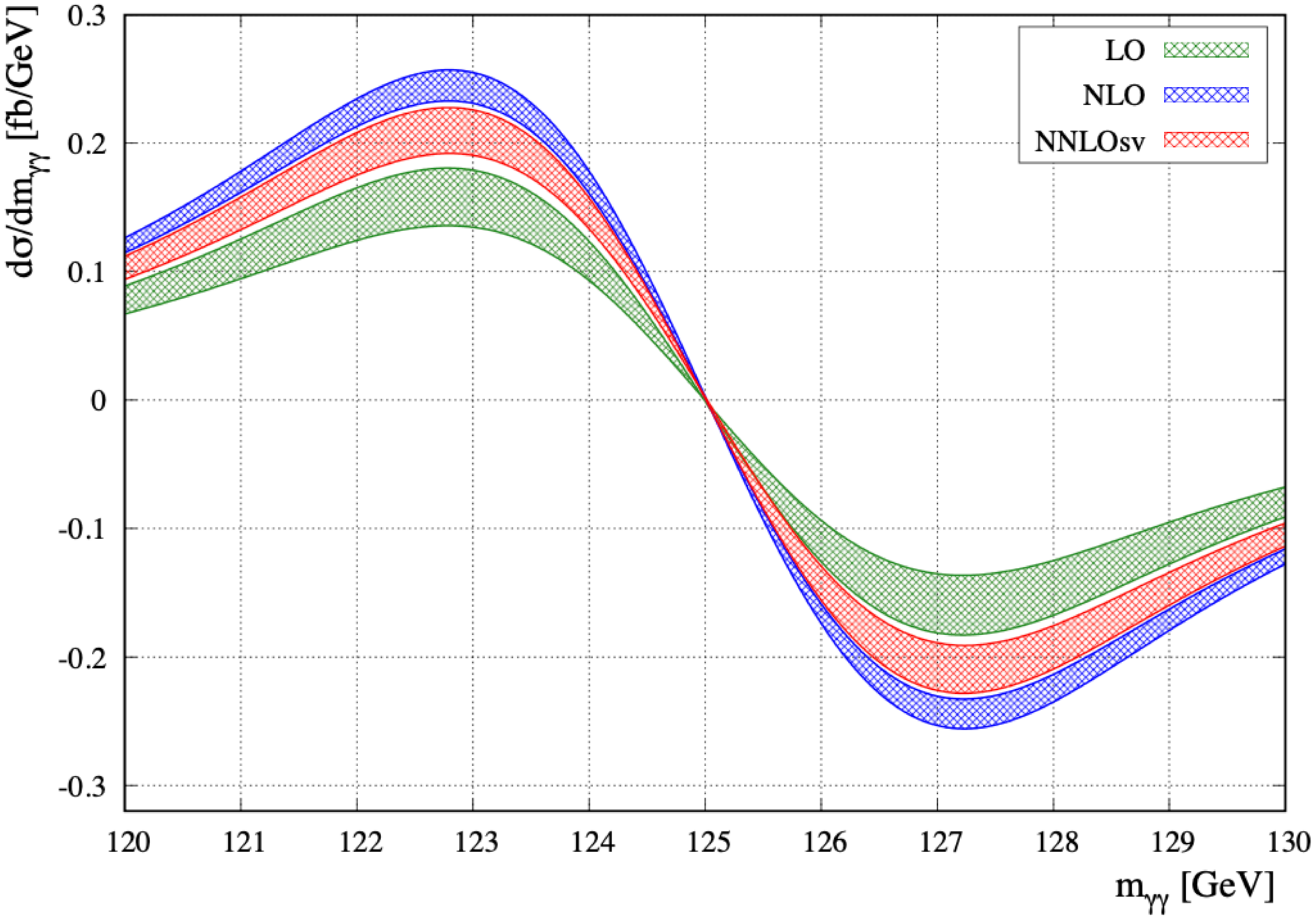


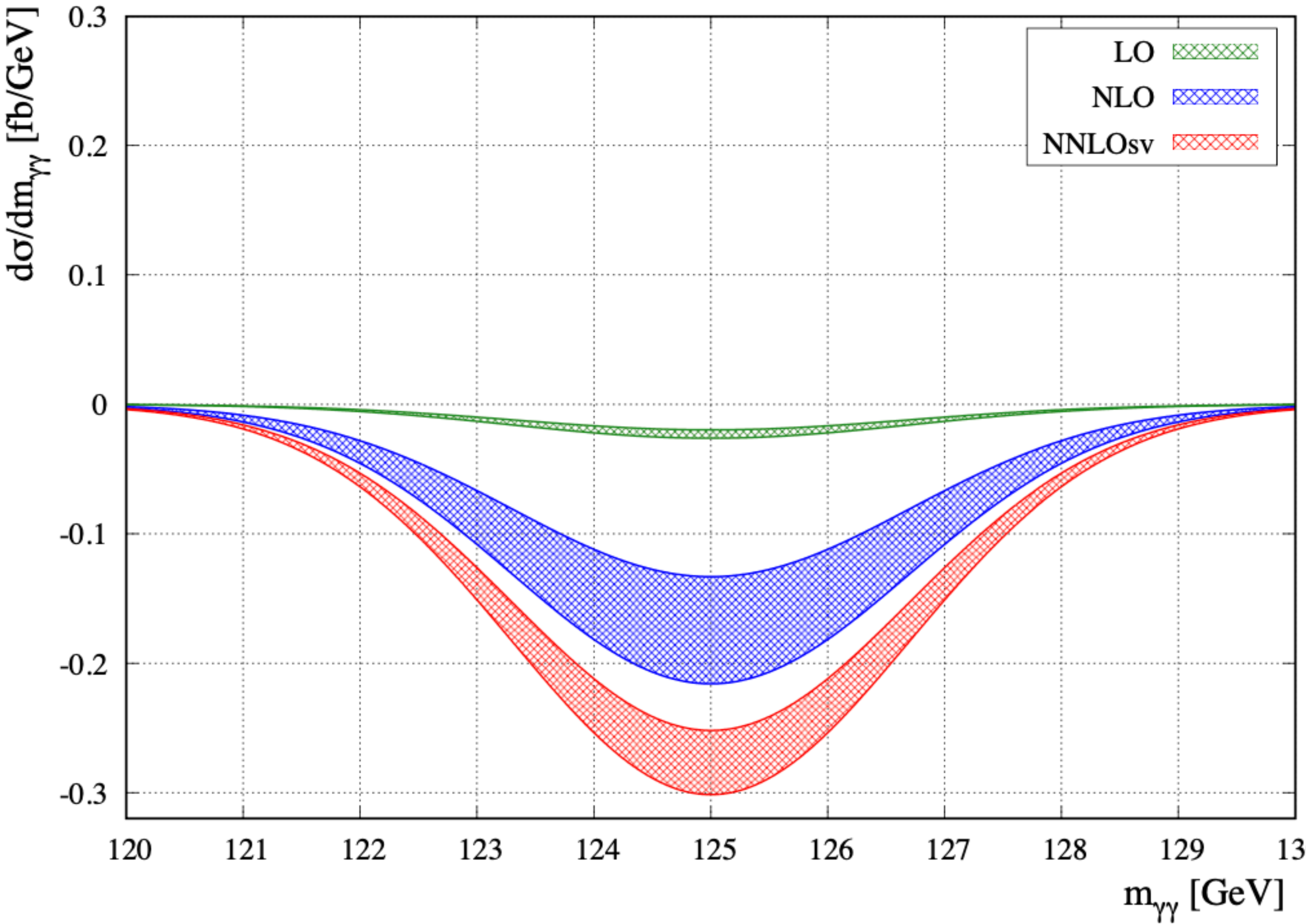
Fig. 4 Signal-background interference contribution to the diphoton invariant mass distribution after Gaussian smearing. Bands represent the envelope given by the scale variation.

$\sigma = 1.7\,\text{GeV}$

- 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

Results: Mass shift@NNLO soft-virtual

Results: Mass shift@NNLO soft-virtual

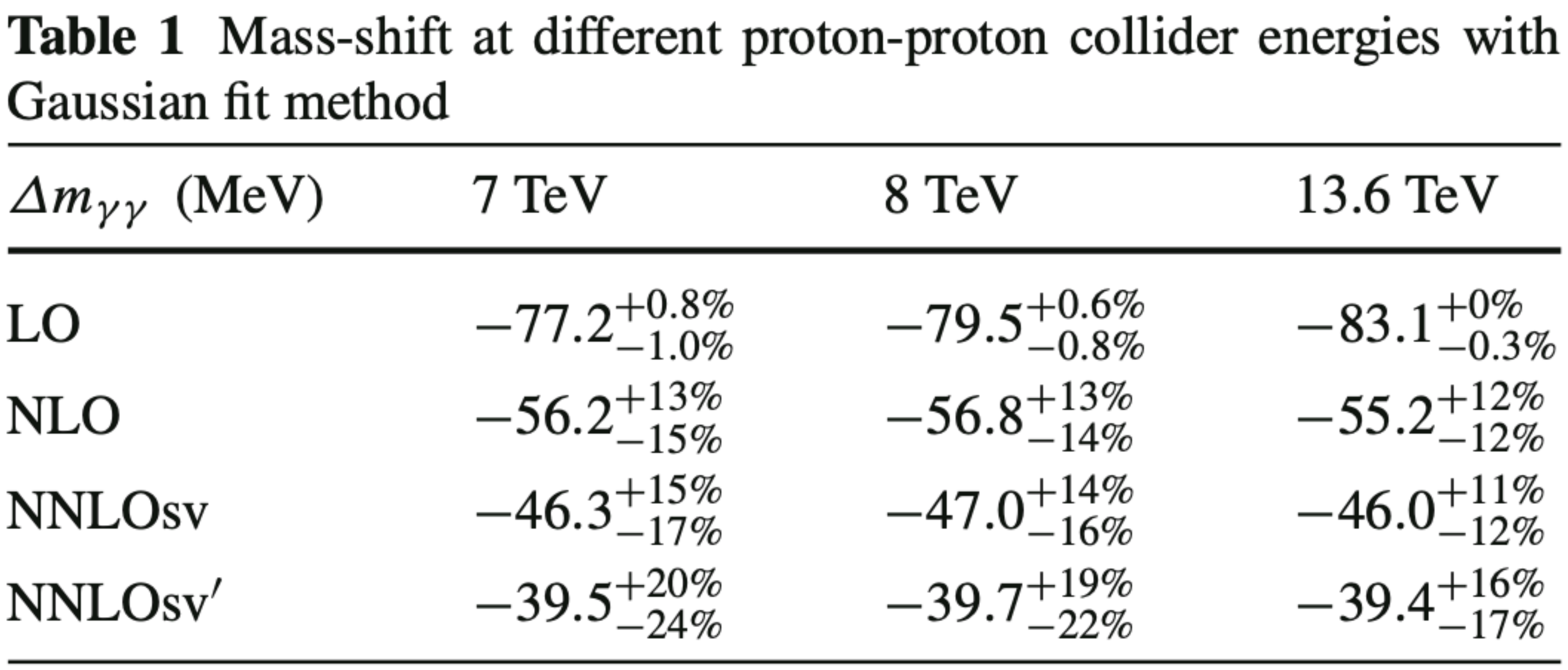


Table 1 Mass-shift at different proton-proton collider energies with Gaussian fit method

$\Delta m_{\gamma\gamma}$ (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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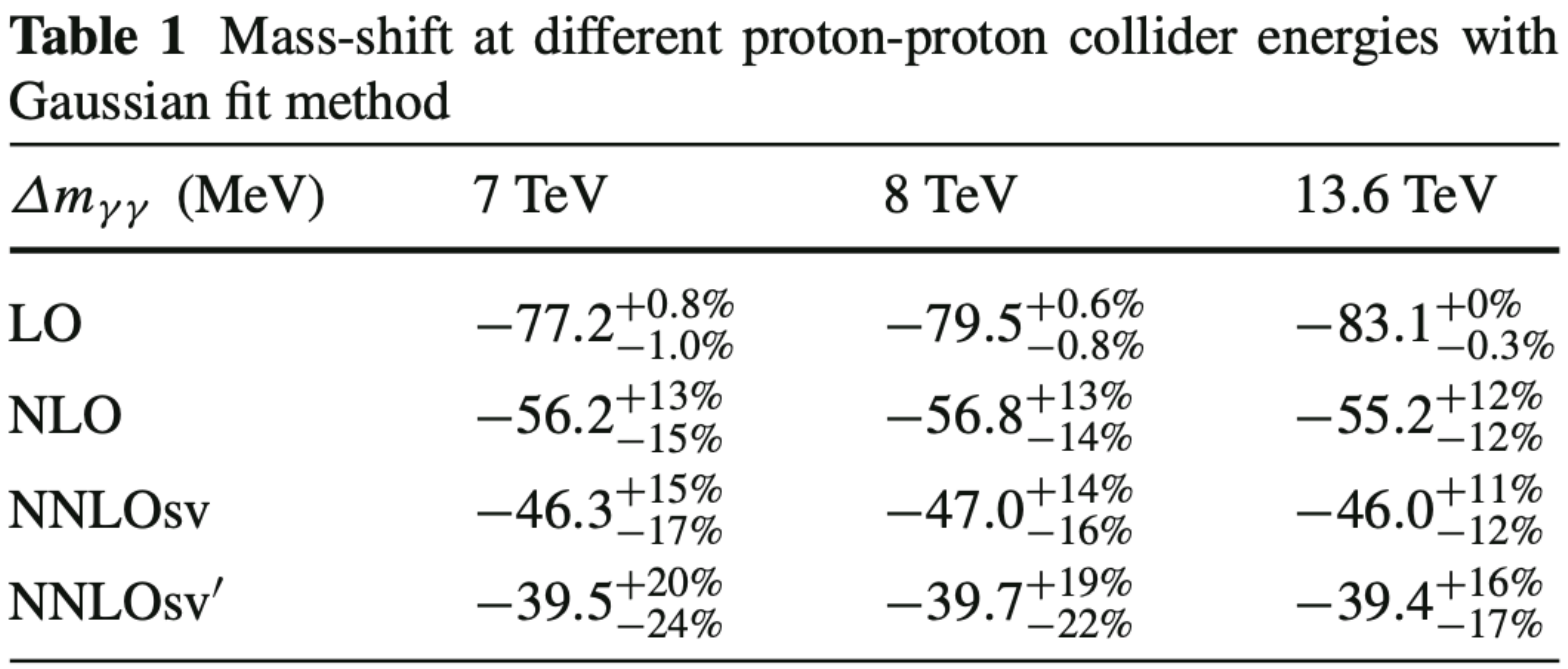
NNLOsv′	$-39.5^{+20\%}_{-24\%}$	$-39.7^{+19\%}_{-22\%}$	$-39.4^{+16\%}_{-17\%}$

Results: Mass shift@NNLO soft-virtual



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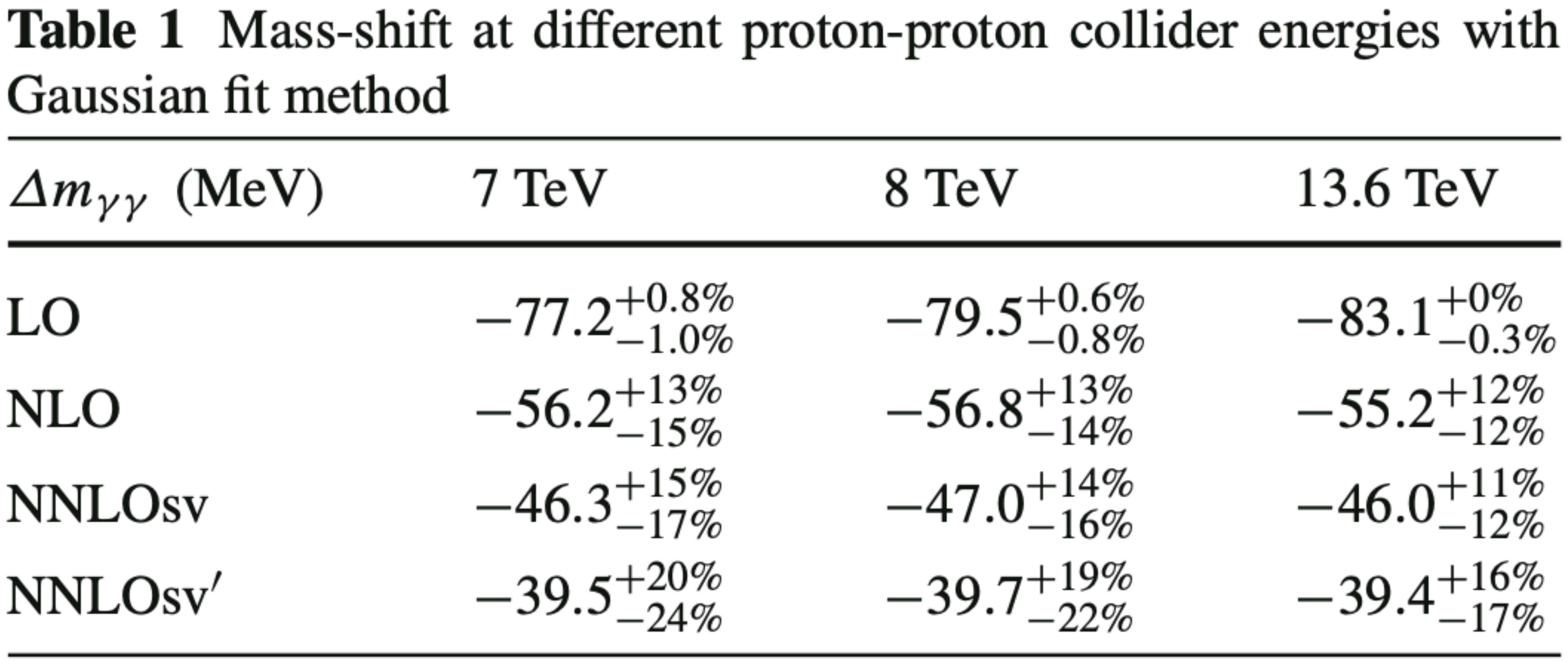

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$\sim 34\,\%$

Results: Mass shift@NNLO soft-virtual

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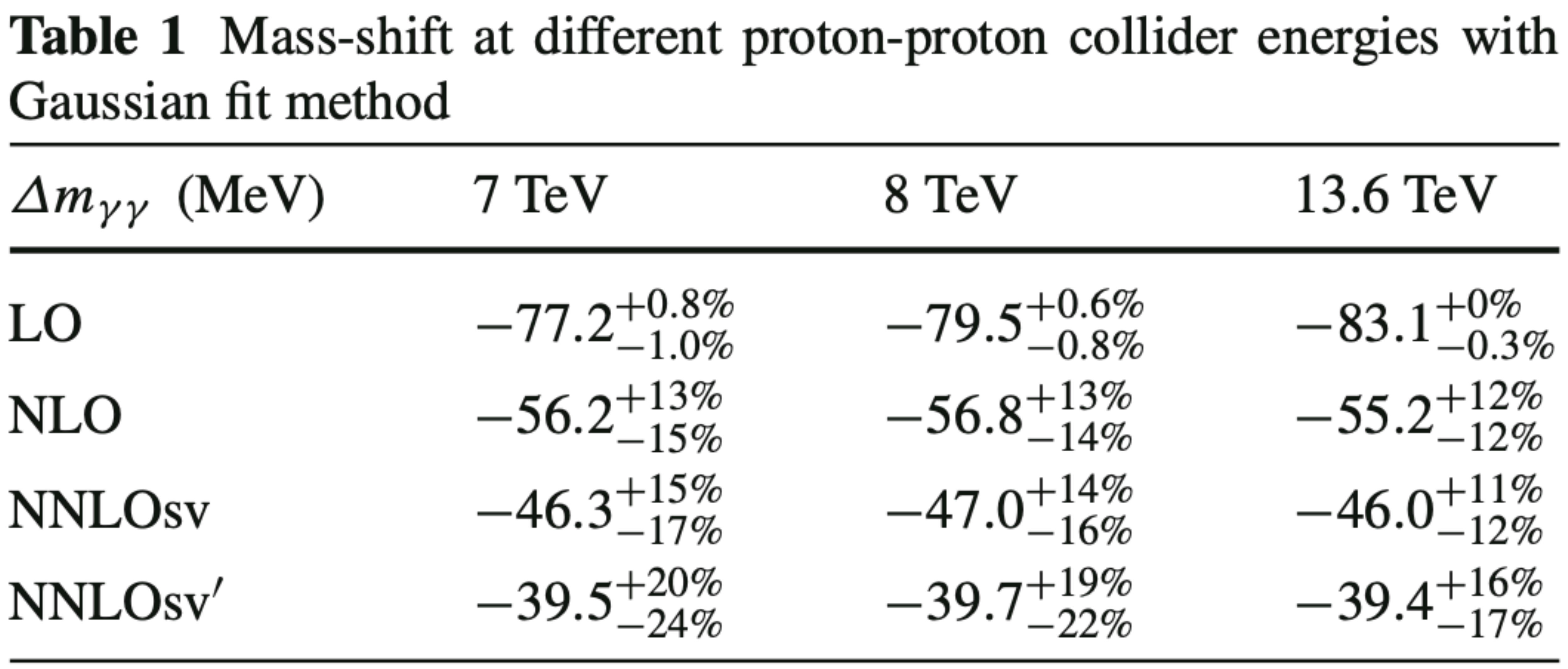

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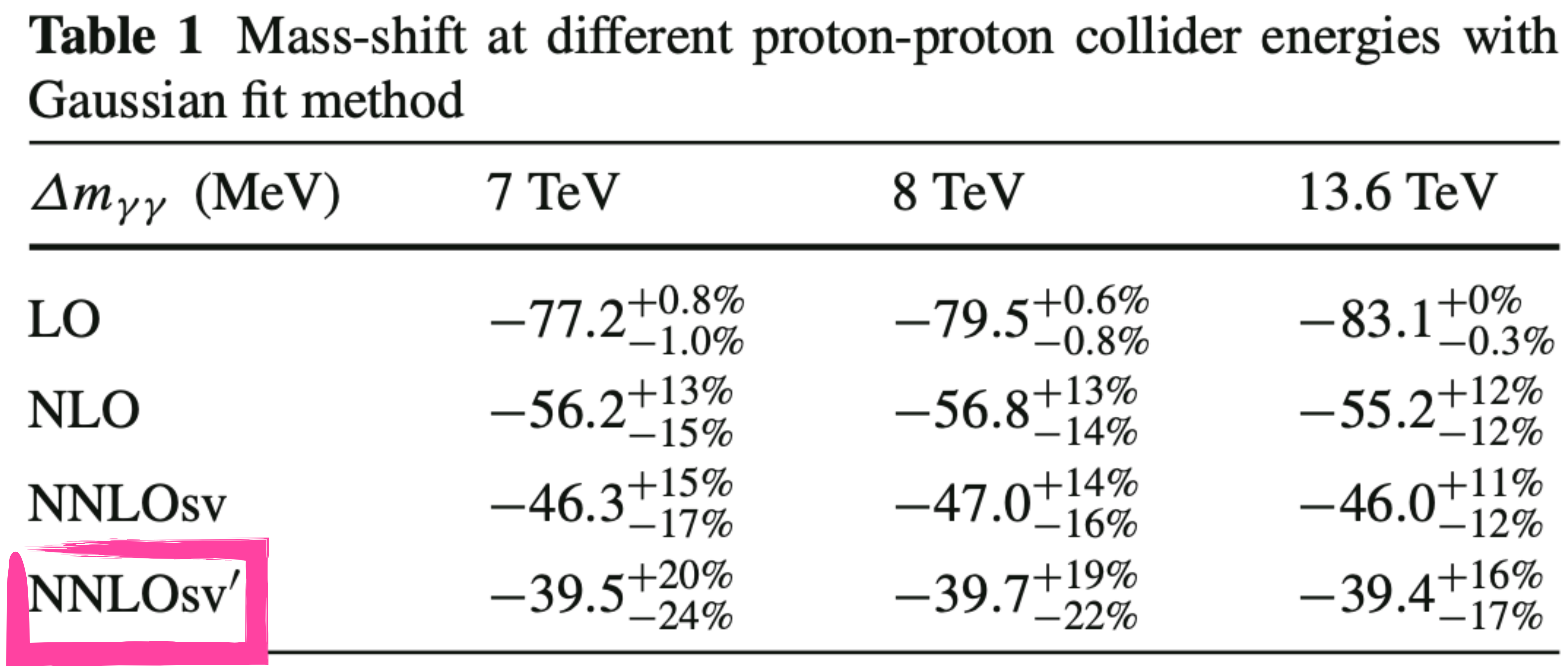
$\sim 34\ \%$

$\sim 28\ \%$

Results: Mass shift@NNLO soft-virtual



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NNLOsv$'$	$-39.5^{+20\%}_{-24\%}$	$-39.7^{+19\%}_{-22\%}$	$-39.4^{+16\%}_{-17\%}$

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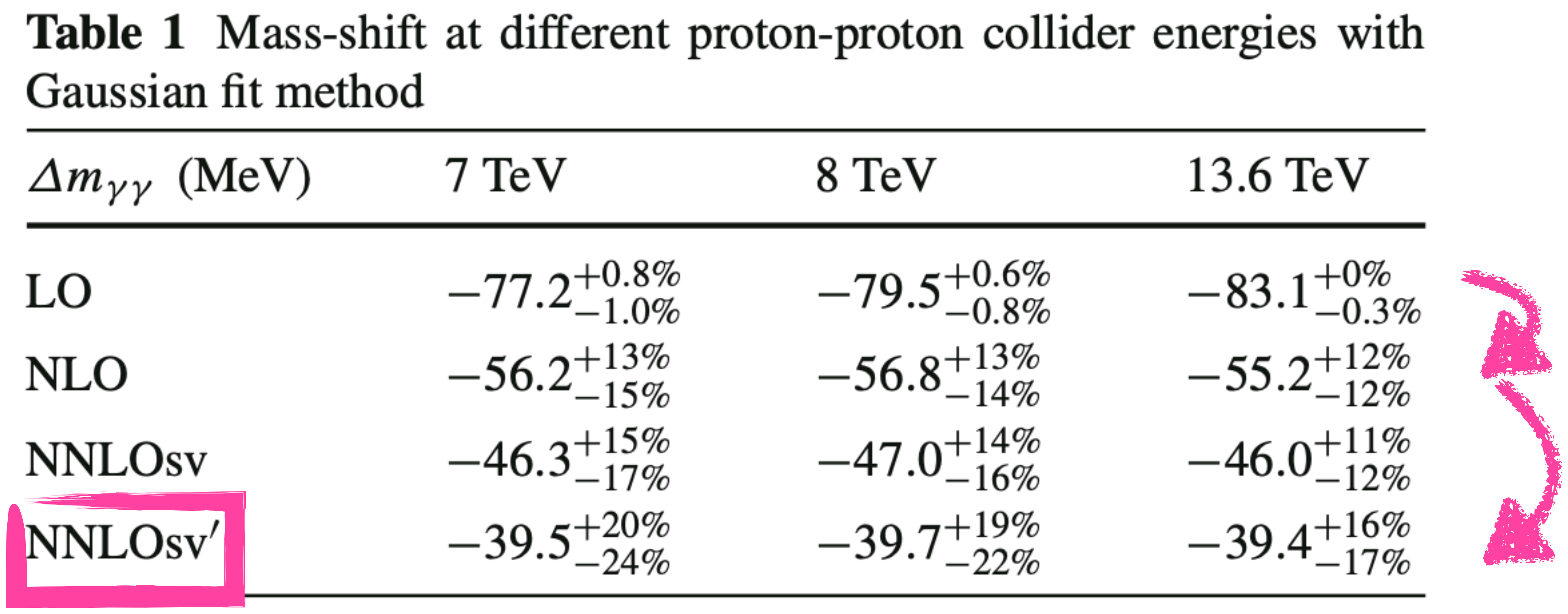
Results: Mass shift@NNLO soft-virtual



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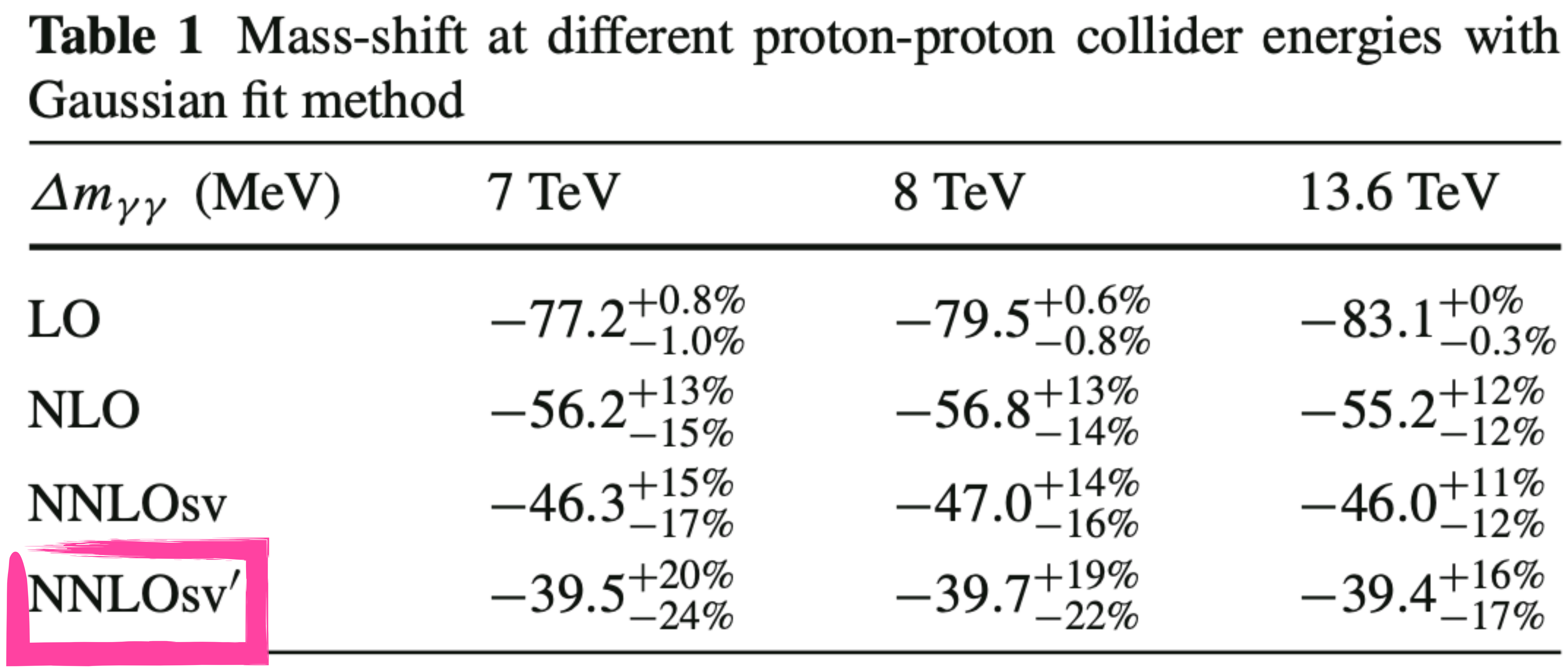
Results: Mass shift@NNLO soft-virtual



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NNLOsv′	$-39.5^{+20\%}_{-24\%}$	$-39.7^{+19\%}_{-22\%}$	$-39.4^{+16\%}_{-17\%}$

$\sim 34\ \%$

$\sim 28\ \%$

Soft-virtual “improved” approximation for Higgs XS Based on [R.D. Ball, Bonvini et al 1303.3590]

Results: Mass shift@NNLO soft-virtual

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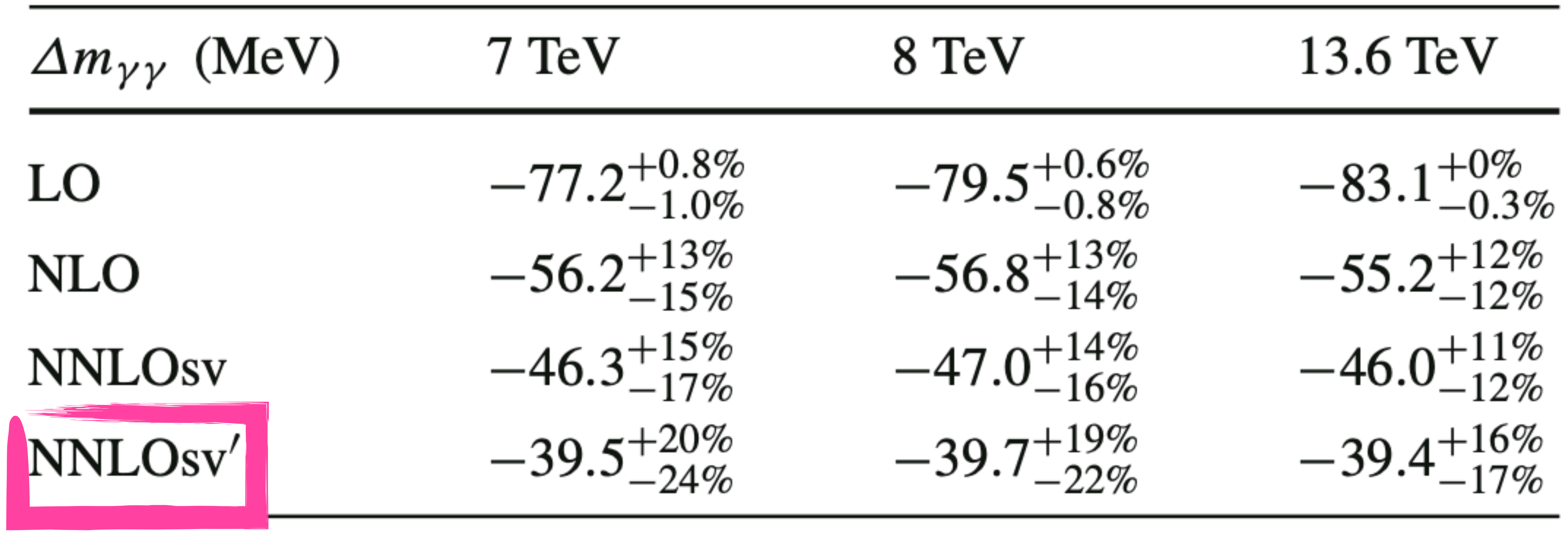

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~ 34 %

~ 28 %

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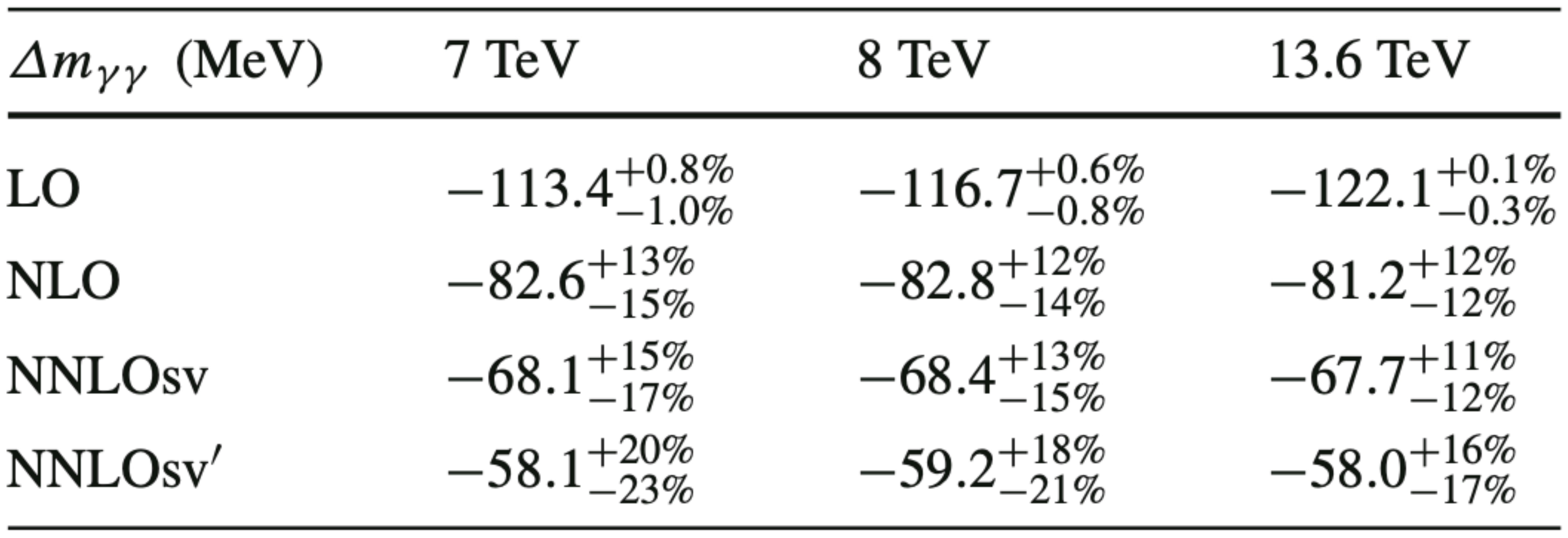
Table 2 Mass-shift at different proton-proton collider energies with first moment method



$\Delta m_{\gamma\gamma}$ (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	$-68.1^{+15\%}_{-17\%}$	$-68.4^{+13\%}_{-15\%}$	$-67.7^{+11\%}_{-12\%}$
NNLOsv′	$-58.1^{+20\%}_{-23\%}$	$-59.2^{+18\%}_{-21\%}$	$-58.0^{+16\%}_{-17\%}$

Results: Mass shift@NNLO soft-virtual

- Mass shifts calculated with different methods should be regarded as different observables

- Not surprising that numbers are so different in the two methods

- K-factors, however, are insensitive to the method used!

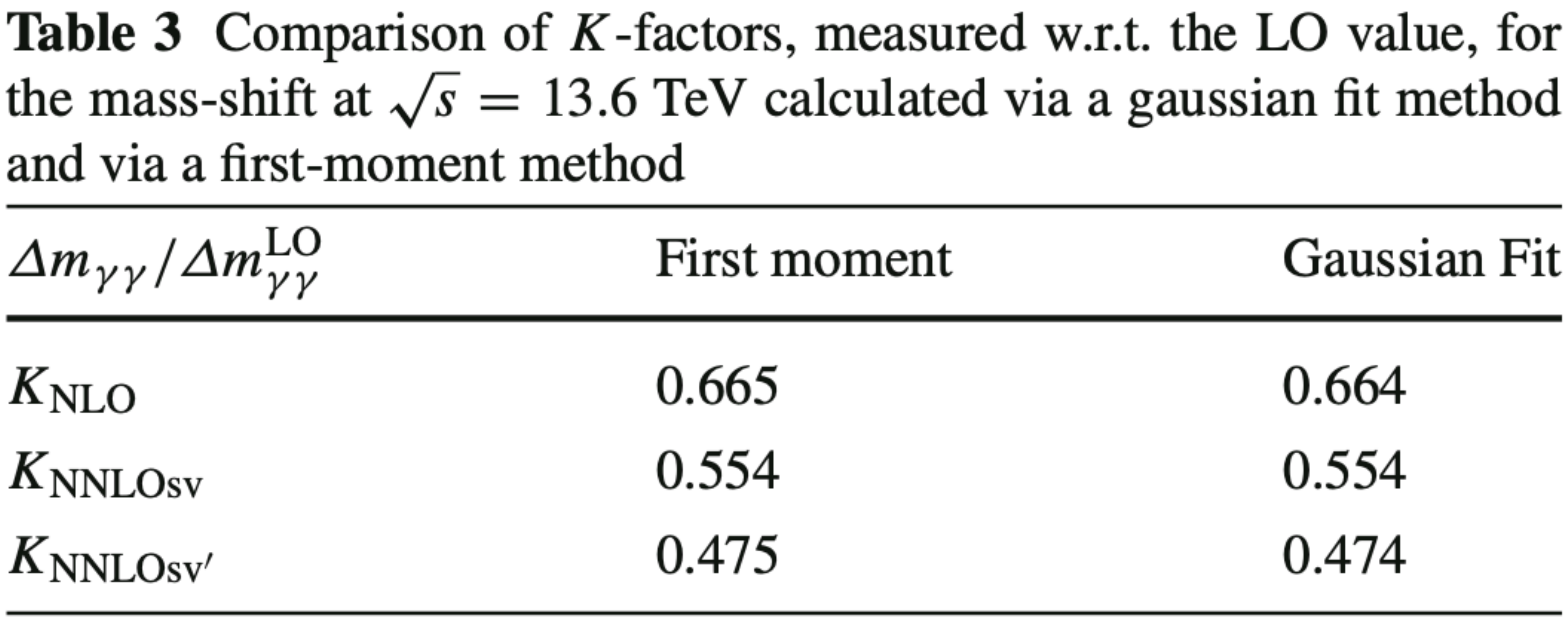


Table 3 Comparison of K-factors, measured w.r.t. the LO value, for the mass-shift at $\sqrt{s} = 13.6$ TeV calculated via a gaussian fit method and via a first-moment method

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

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

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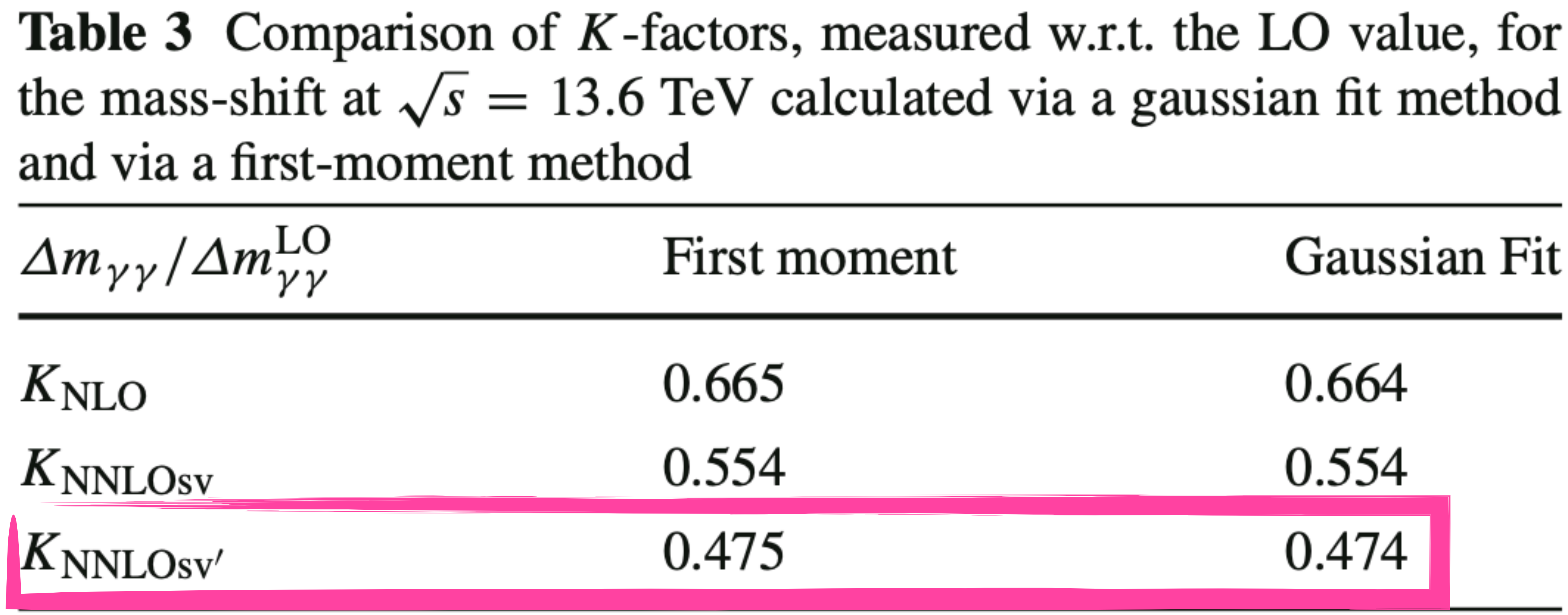

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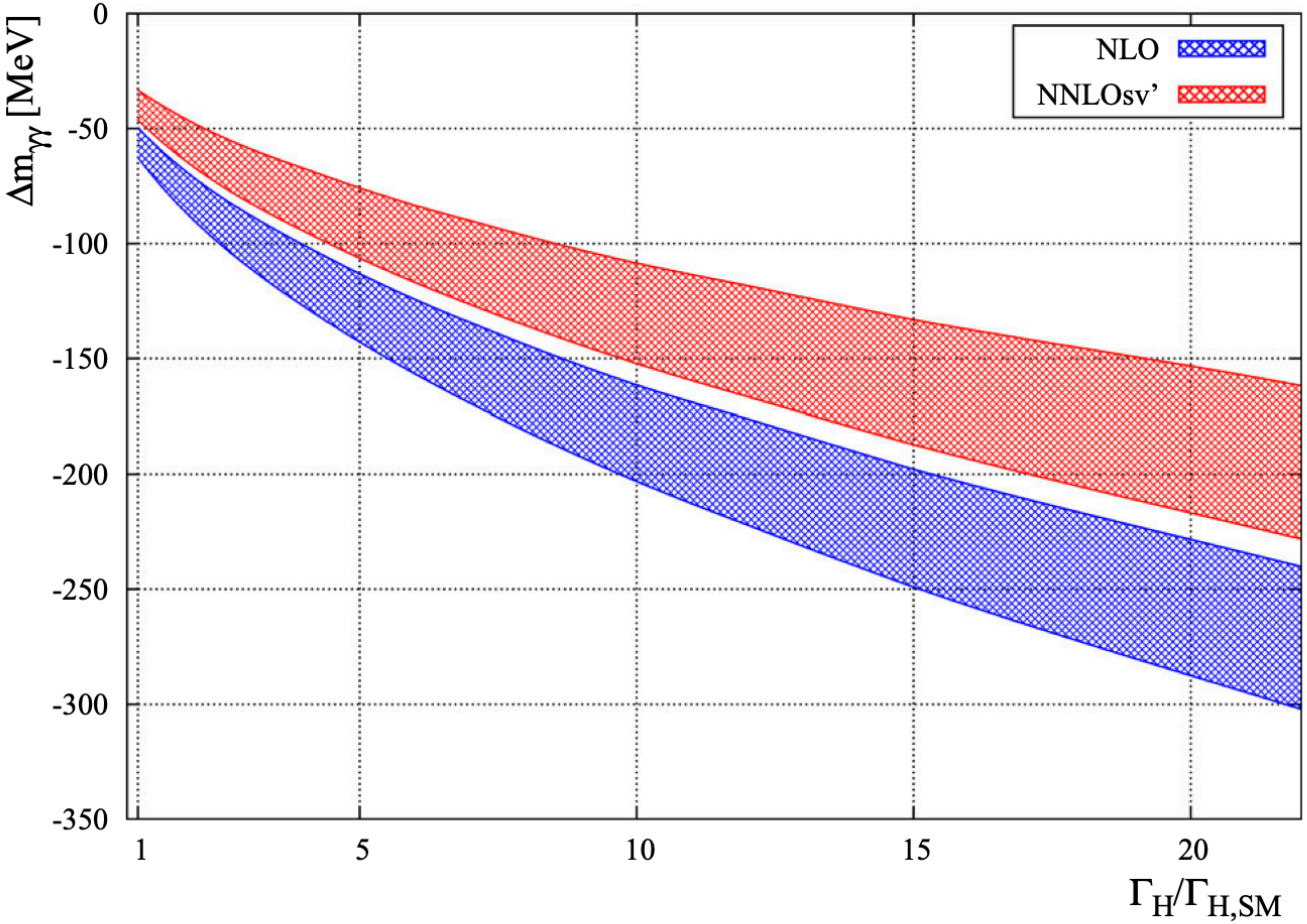
Results: bounds on Higgs boson width



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

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

- Assuming 150 MeV error on mass-shift: $\Gamma_H < (10\text{-}20)\Gamma_{H,SM}$ to be compared with direct sensitivity of LHC ~ $\Gamma_H < 250\ \Gamma_{H,SM}$!

Thank you for your attention!