HIGGS-STOPONIUM MIXING

HEE SOK CHUNG

TECHNICAL UNIVERSITY OF MUNICH

IN COLLABORATION WITH G.T.BODWIN (ANL) AND C.E.M.WAGNER (ANL & U. CHICAGO), BASED ON PHYS. REV. D95, 015013 (2017)

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OUTLINE

- Mixing in BSM models
- Effective field theory for stop and antistop near threshold
- Effective field theory calculation of $gg\to\gamma\gamma$ near threshold
- Mixing effects in two-photon rates at LHC
- Summary

MIXING IN BSM MODELS

- Many BSM models feature
  - ✓ Heavy versions of the SM Higgs,
  - ✓ Strongly interacting scalar particles (scalar tops).
- Heavy Higgs and stop-antistop bound state (stoponium) have same quantum numbers and can mix in amplitudes.
- Heavy Higgs and stop-antistop bound states both decay into two photons. Many BSM searches focus on diphoton final states.

MIXING IN BSM MODELS

- *A naïve estimate :*
  If the heavy Higgs and stoponium have similar masses, their mixing in the amplitude will lead to large enhancement of the two-photon cross section, ranging from factors of 2−8.

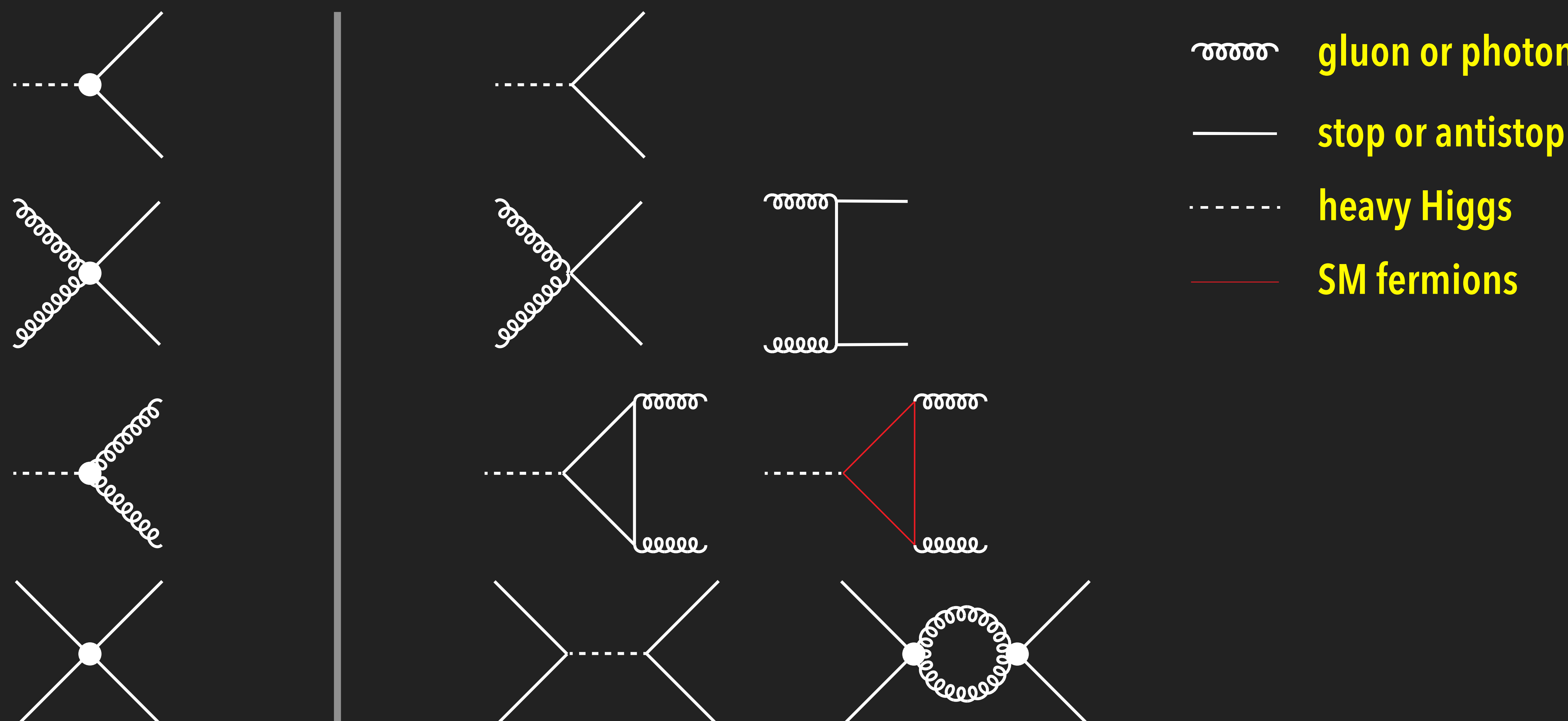
  Djouadi and Pilaftsis, PLB765, 175 (2017) [arXiv:1605.01040]

- We perform an analysis using nonrelativistic effective field theory methods to investigate how mixing effects actually impact two-photon cross sections at LHC.

EFFECTIVE FIELD THEORY FOR STOPONIUM

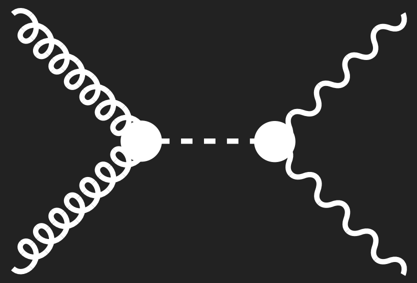
- Operators at leading order in v

EFT operators **Full-theory diagrams**



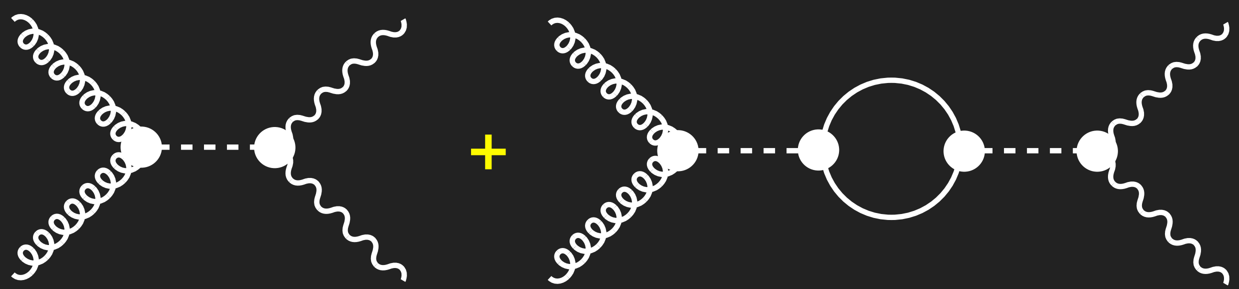
TWO-PHOTON PRODUCTION NEAR STOP-ANTISTOP THRESHOLD

- $gg \to H \to \gamma\gamma$: tree-level diagram

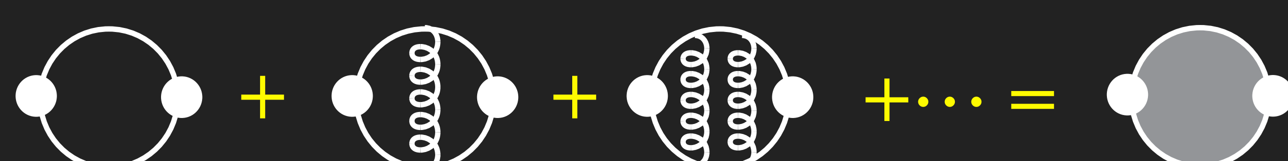


TWO-PHOTON PRODUCTION NEAR STOP-ANTISTOP THRESHOLD

- $gg \to H \to \gamma\gamma$: tree-level diagram + corrections from $\tilde{t}\tilde{t}$



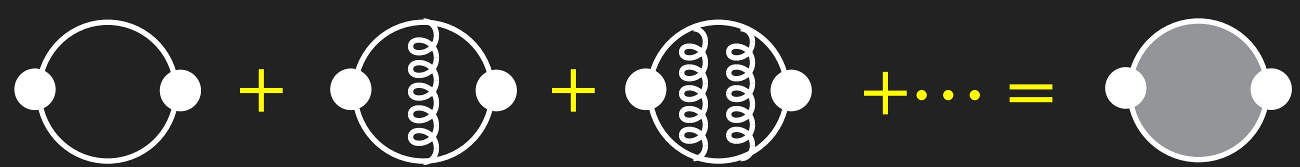
- $\tilde{t}\tilde{t}$ near threshold receives Coulomb-divergent corrections of the form $(\alpha_s/v)^n$. ***The resummation near threshold gives rise to a Green's function.***



$= -iG/(4m_{\tilde{t}}^2)$

STOP-ANTISTOP GREEN'S FUNCTION

- Green's function can be computed by solving a Schrödinger equation.



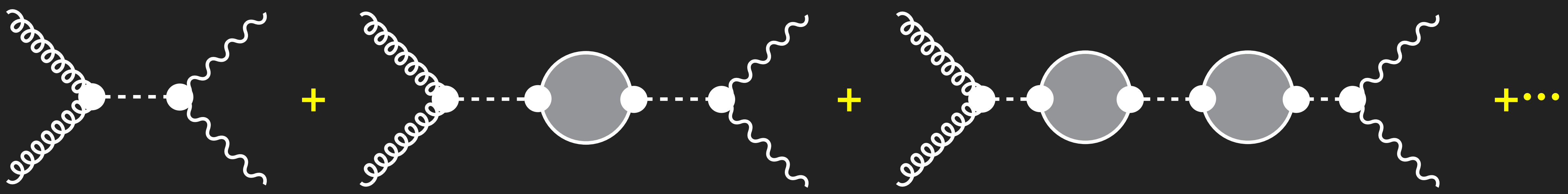
$$= -iG/(4m_{\tilde{t}}^2)$$

- Green's function G is sharply peaked near bound states of $\tilde{t}\tilde{t}$ and develops imaginary parts near peaks and above threshold.

- Coulomb Green's function is a good approximation for G when stop is heavy.

TWO-PHOTON PRODUCTION NEAR STOP-ANTISTOP THRESHOLD

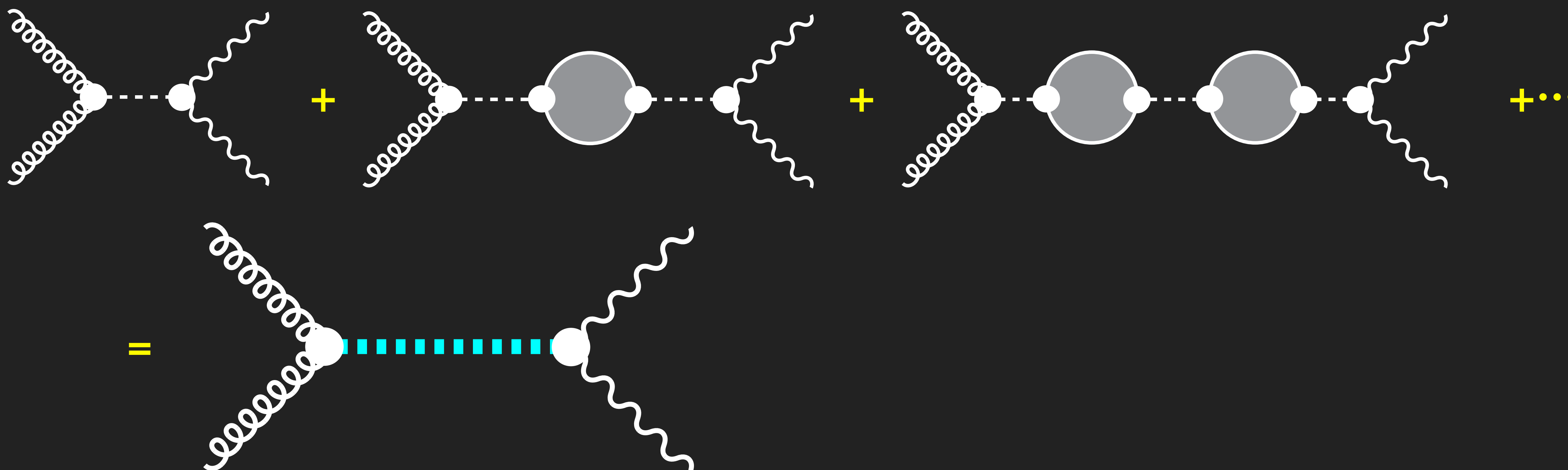
- $gg \to H \to \gamma\gamma$: tree-level diagram + corrections from $\tilde{t}\tilde{t}$



- Corrections from $\tilde{t}\tilde{t}$ are greatly enhanced near threshold, ***must be resummed to all orders***.

TWO-PHOTON PRODUCTION NEAR STOP-ANTISTOP THRESHOLD

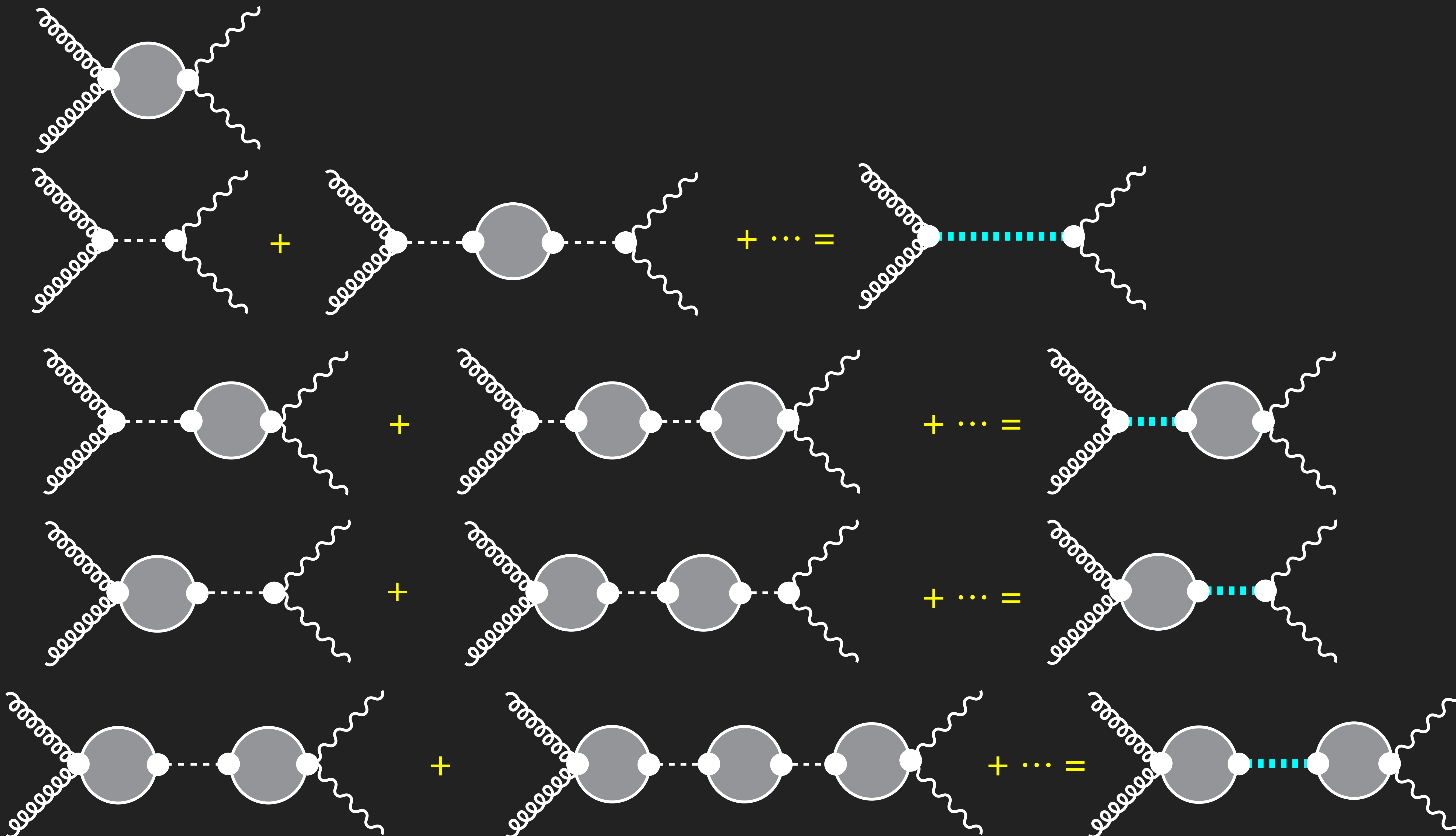
- $gg \to H \to \gamma\gamma$: $\tilde{t}\tilde{\bar{t}}$ *Green's function resummed to all orders*



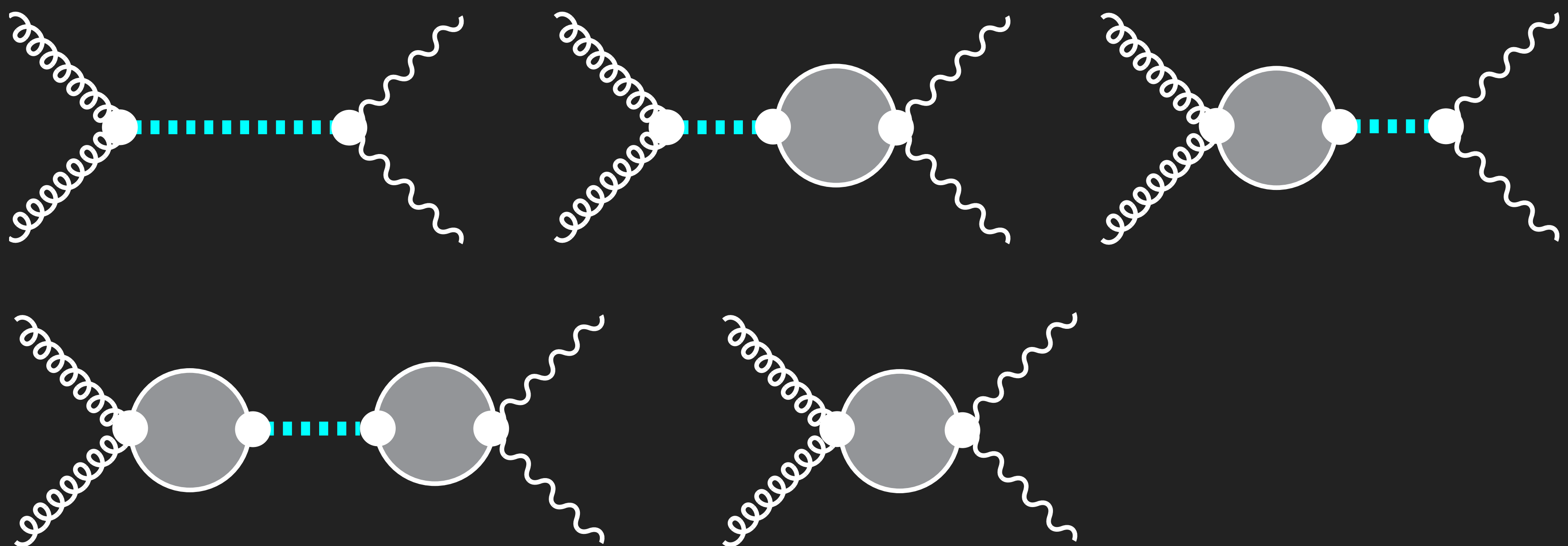
- ***Resummation dresses Higgs propagator***

Green's function modifies ***both the mass and the width of the heavy Higgs***

DIAGRAMS AT LEADING ORDER + RESUMMATION



HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



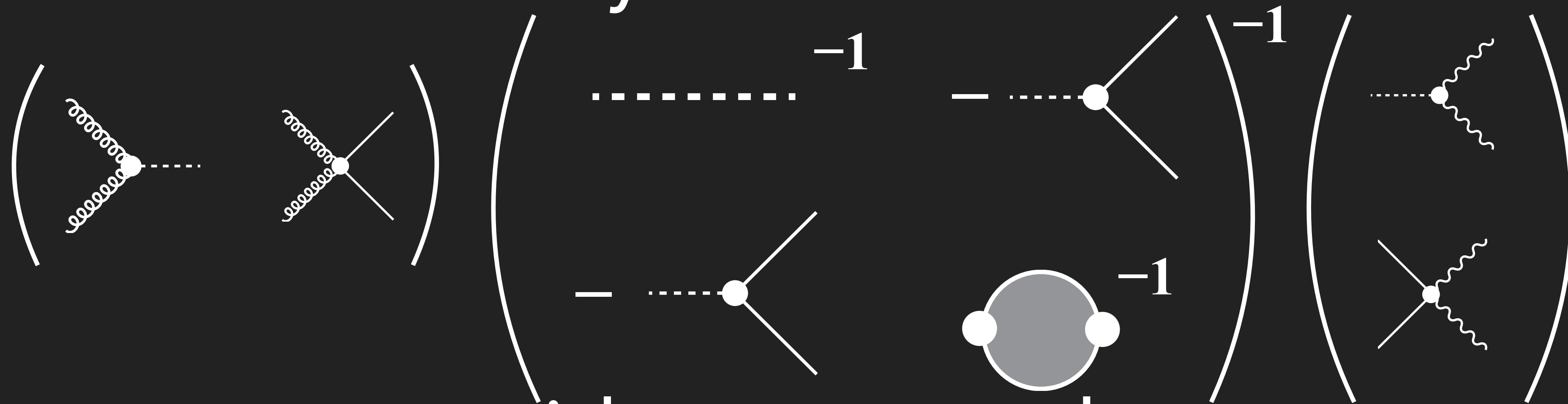
- If we ignore the modifications to the Higgs propagator, there is enhancement from the peaks of the $\tilde{t}\tilde{t}$ Green's function.

- Near threshold, the mixing displaces physical mass peaks away from threshold, and the enhancement becomes mostly ineffective.

HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION

- Total amplitude is conveniently written in matrix form.

$$A_{\rm tot}(gg\to\gamma\gamma) =$$



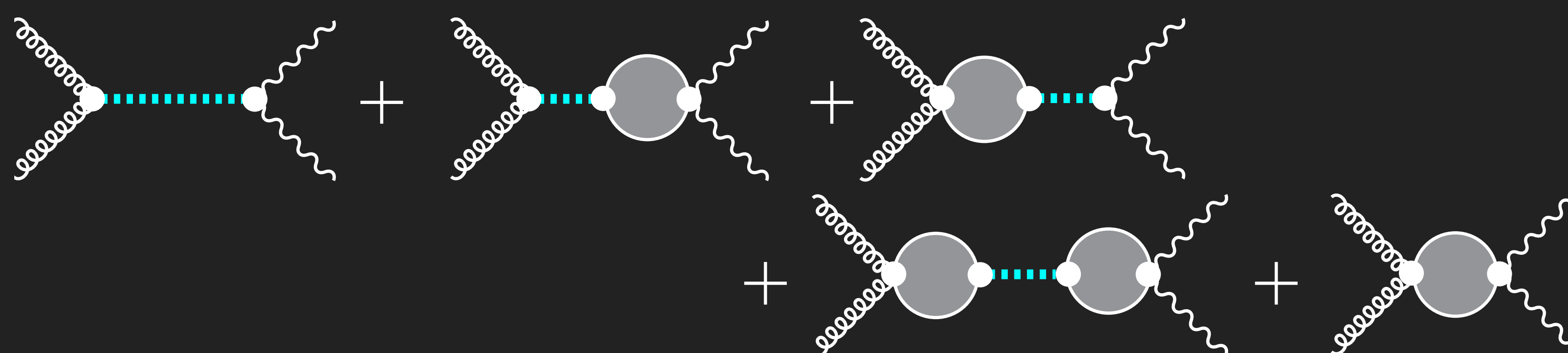
- Diagonal elements near-vanish at mass peaks.
  When both diagonal elements are small, off-diagonal elements dominate and the mixing is maximal.

- At maximal mixing, physical peaks are displaced proportionally to the $H\tilde{t}\tilde{t}$ coupling, and widths also change.

HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION

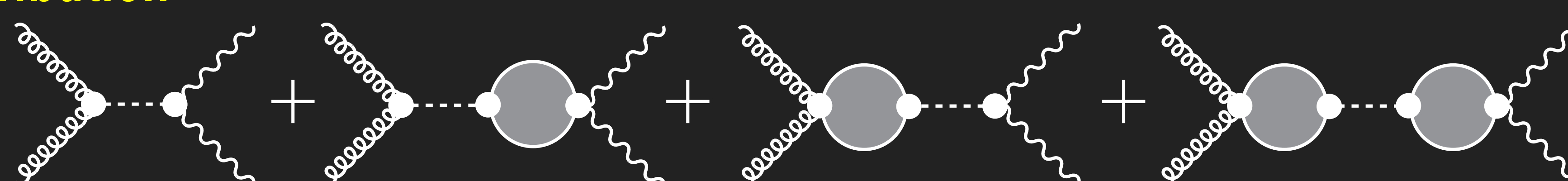
- We show the behavior of the amplitude $A_{\rm tot}(gg\to\gamma\gamma)$ when the heavy Higgs mass is near the stoponium threshold.

- $A_{\rm tot}(gg\to\gamma\gamma) =$



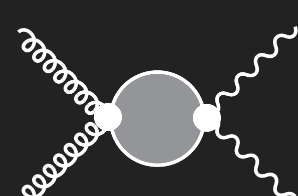
Naïve prediction for Higgs contribution

- $A_H^{\rm Bare}(gg\to\gamma\gamma) =$



Contribution from stoponium only

- $A_{\tilde{t}\tilde{t}}^{\rm Bare}(gg\to\gamma\gamma) =$



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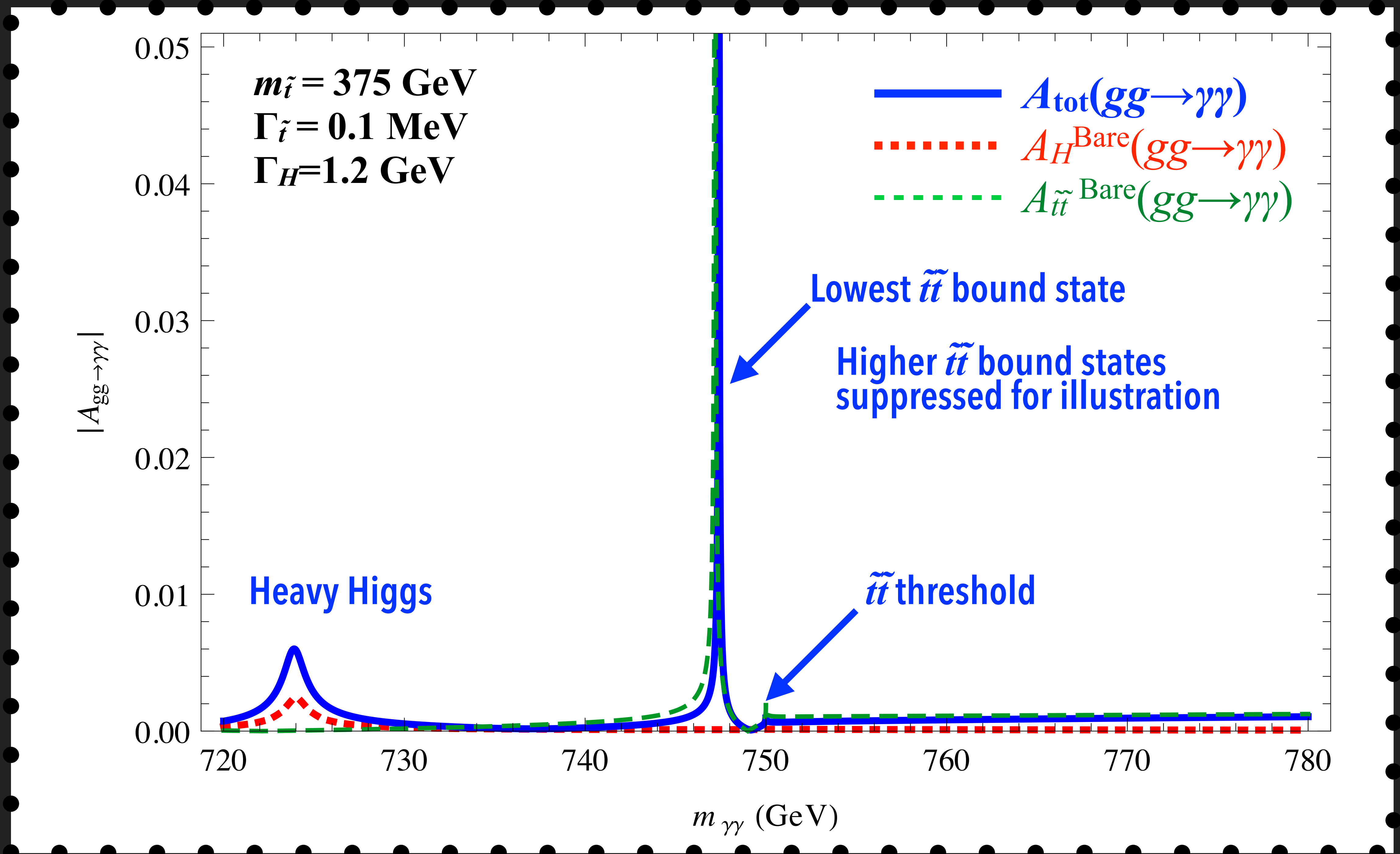

Now, we increase the heavy Higgs mass…

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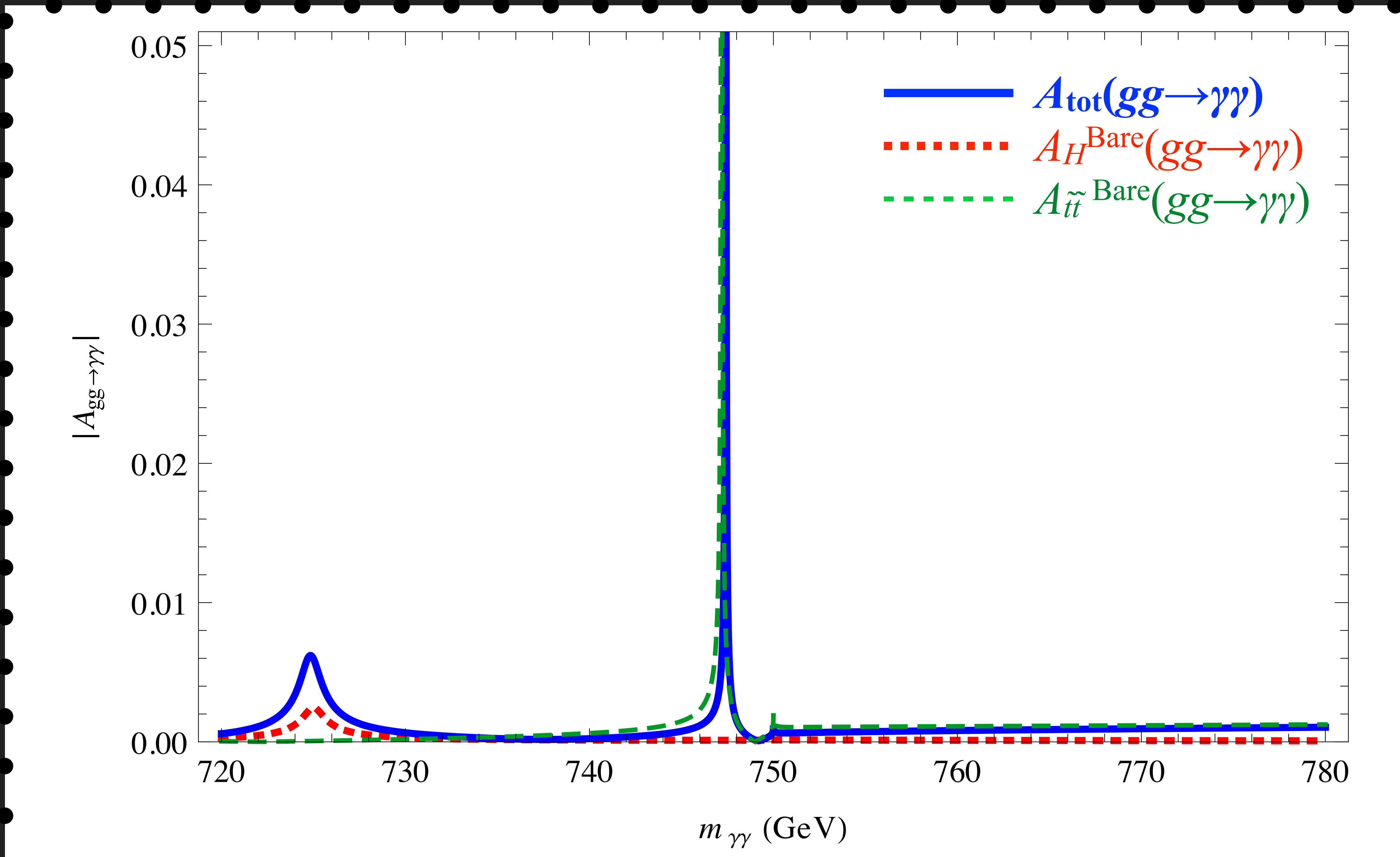

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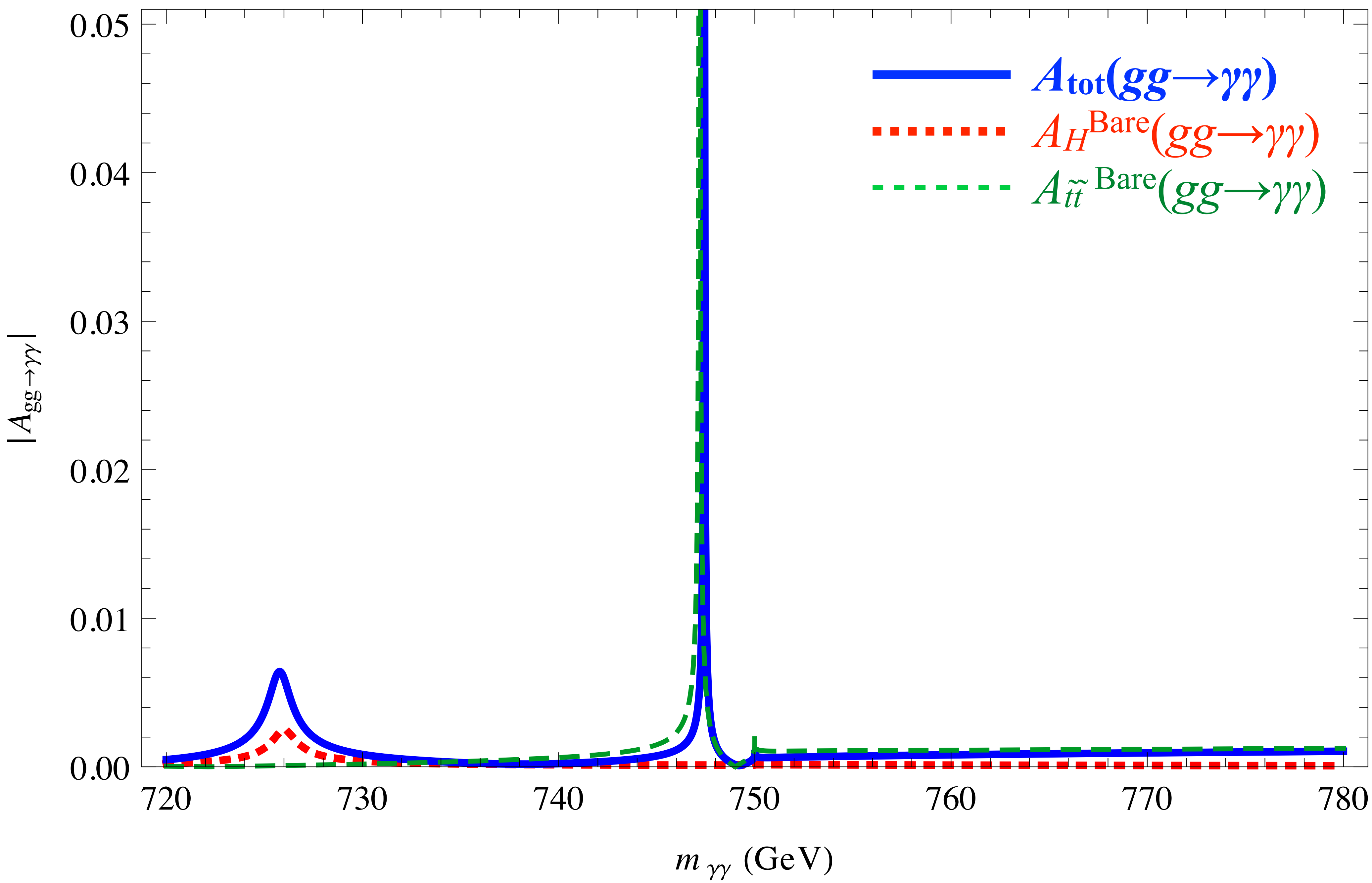

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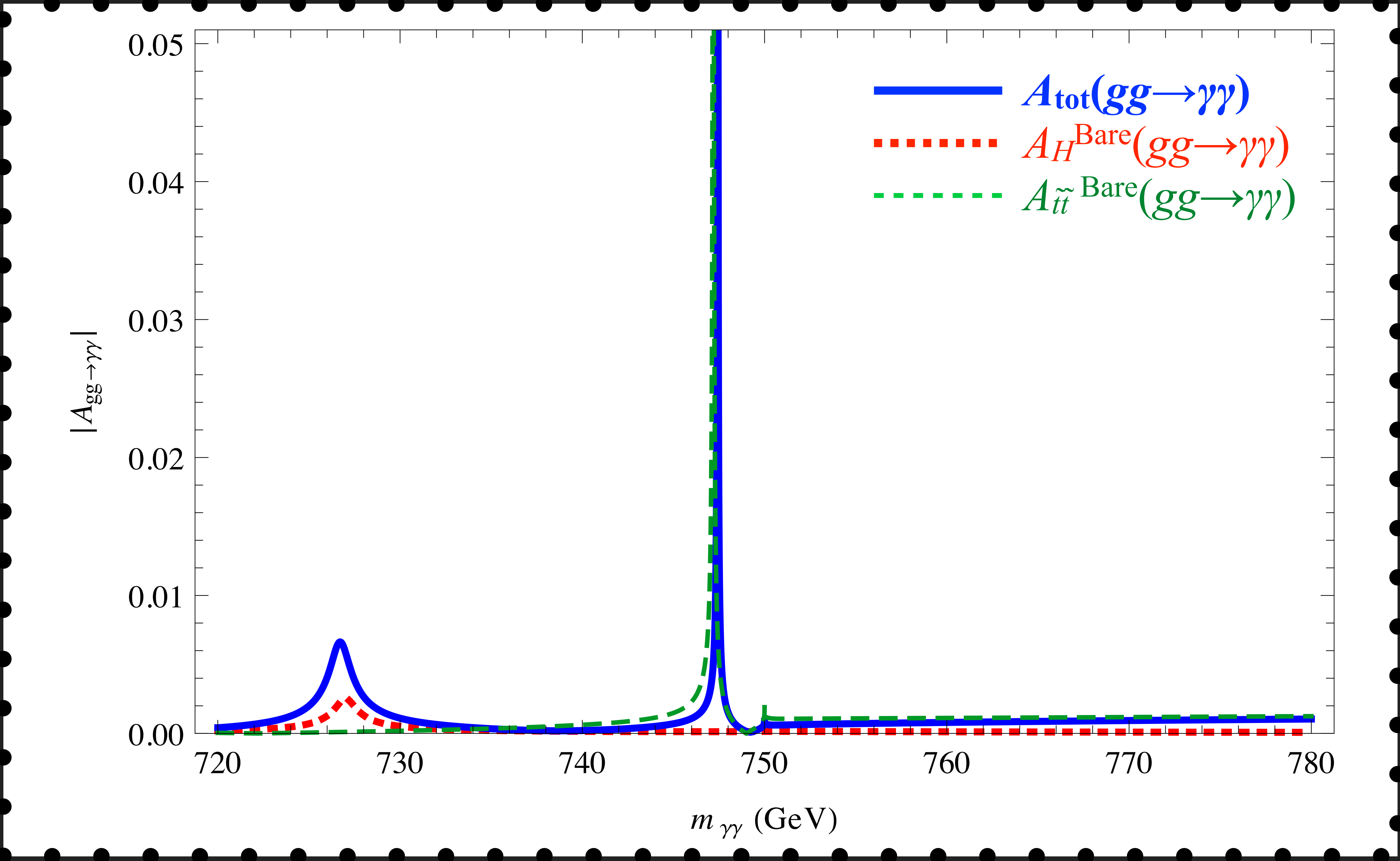

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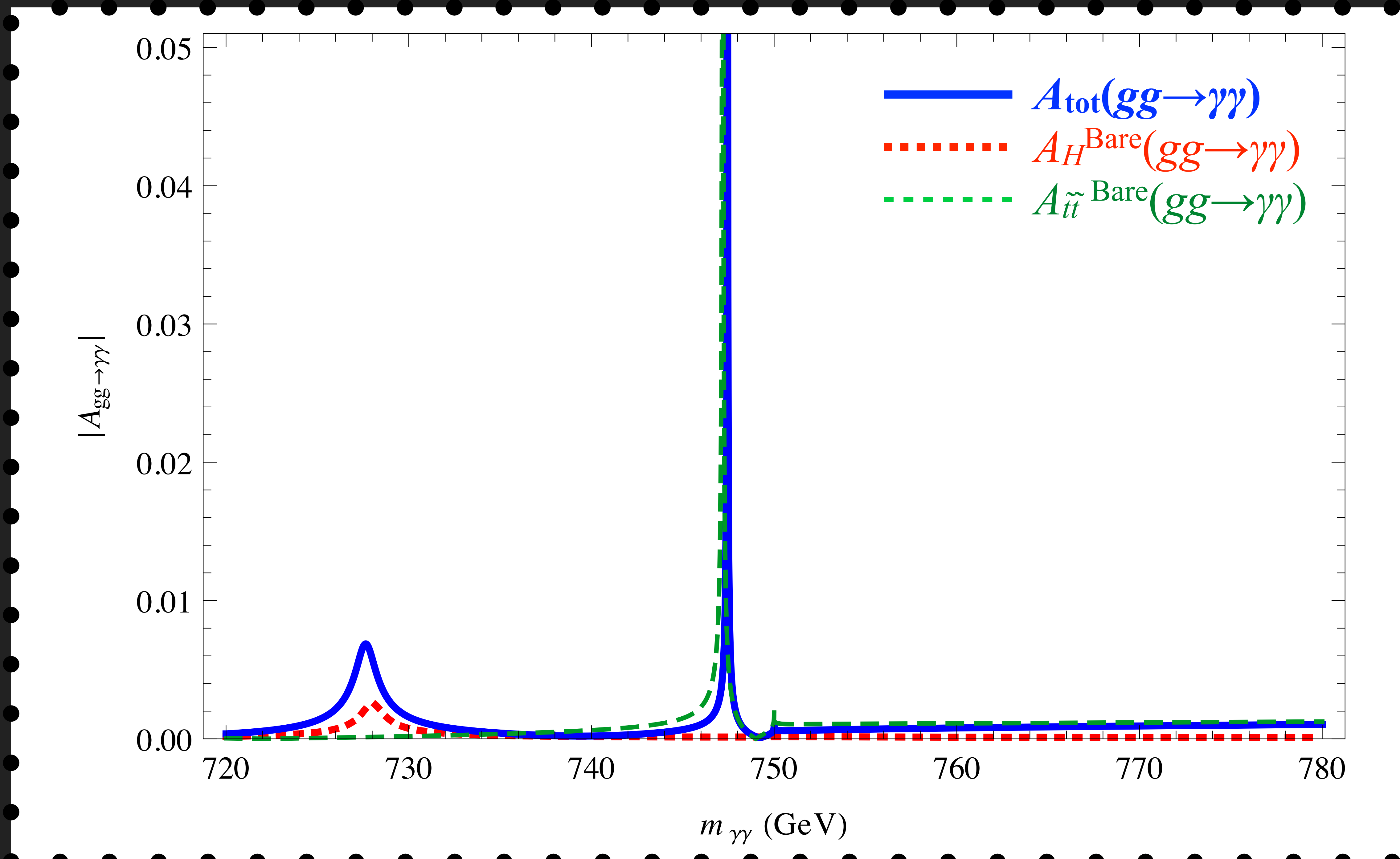

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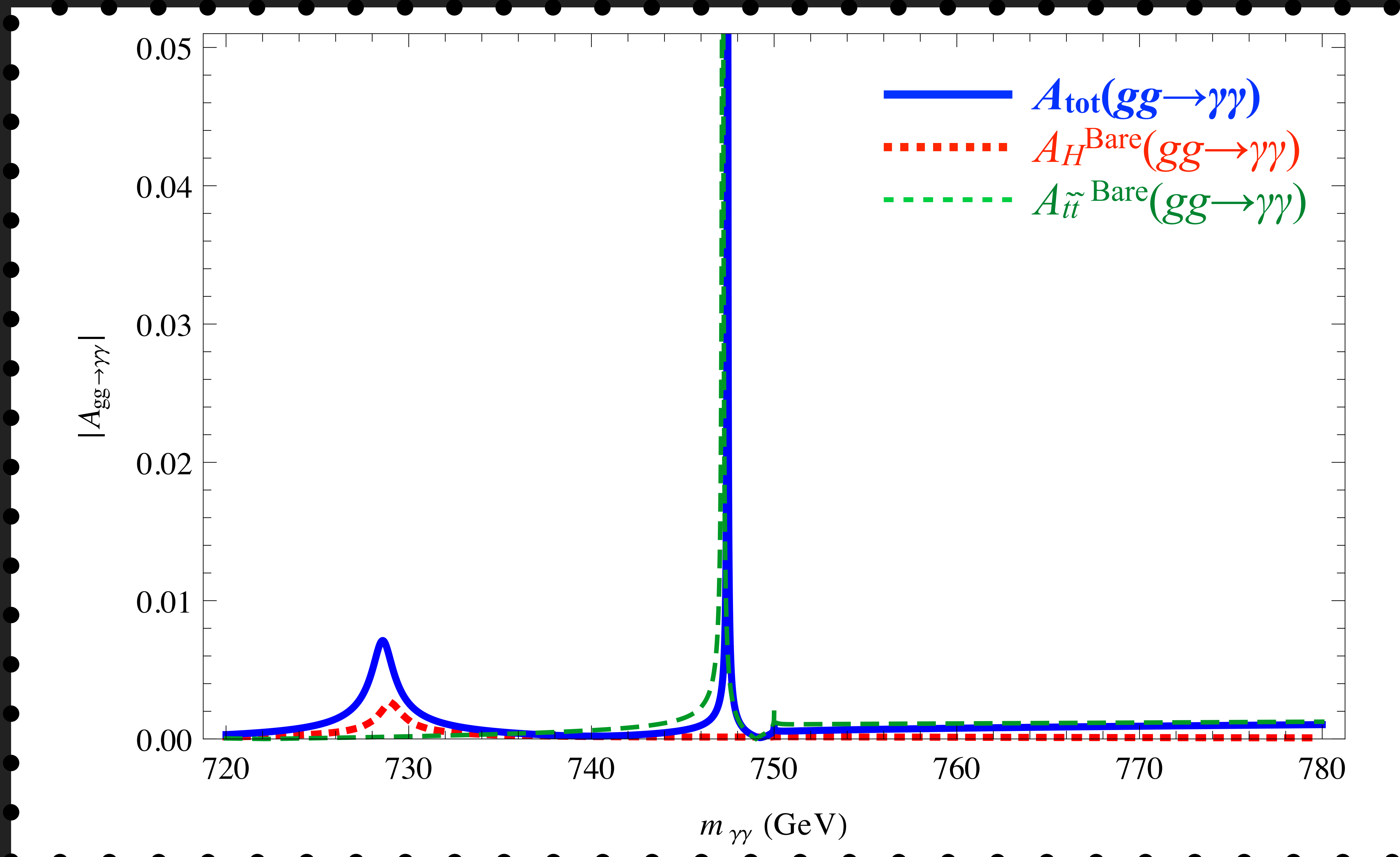

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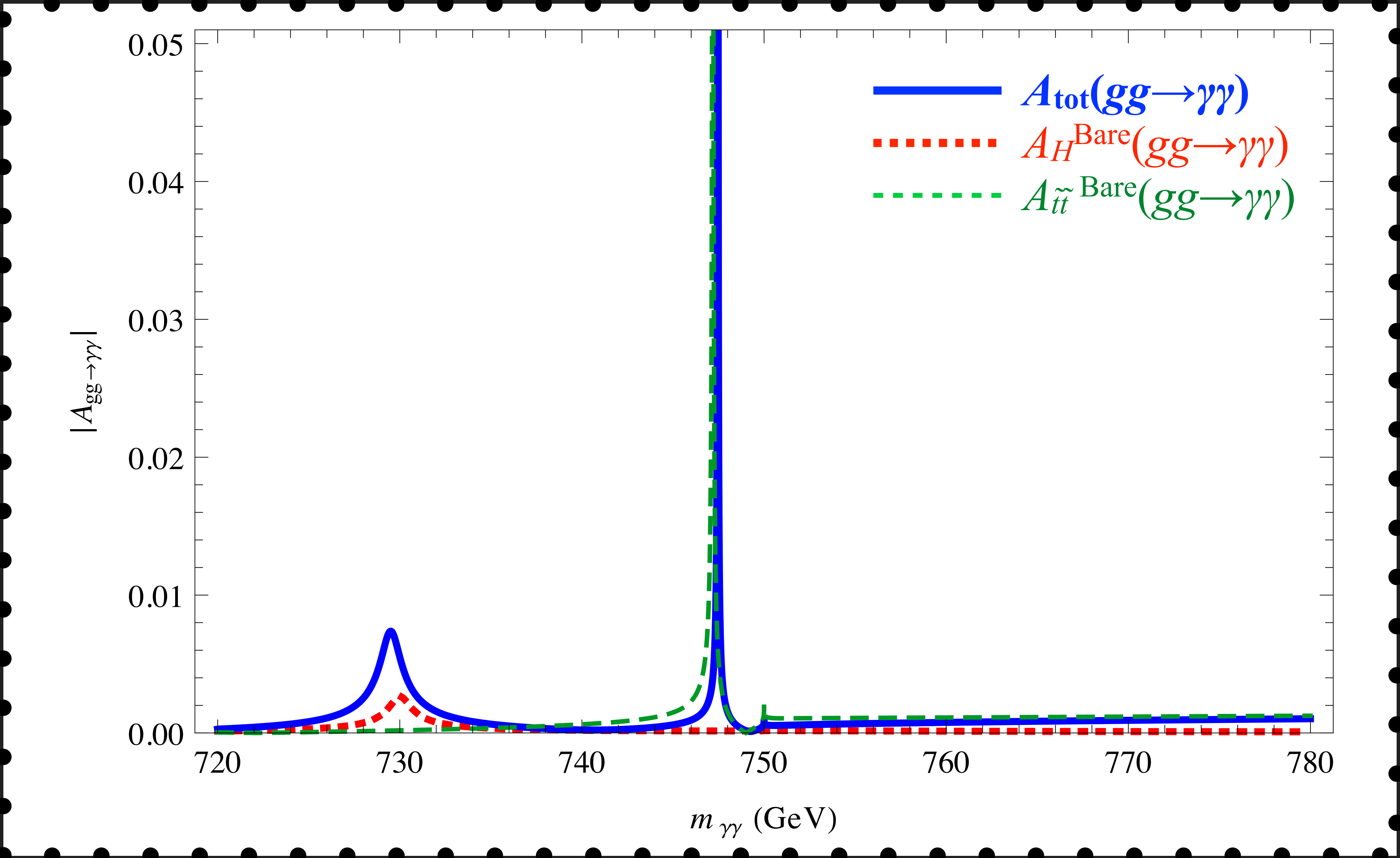

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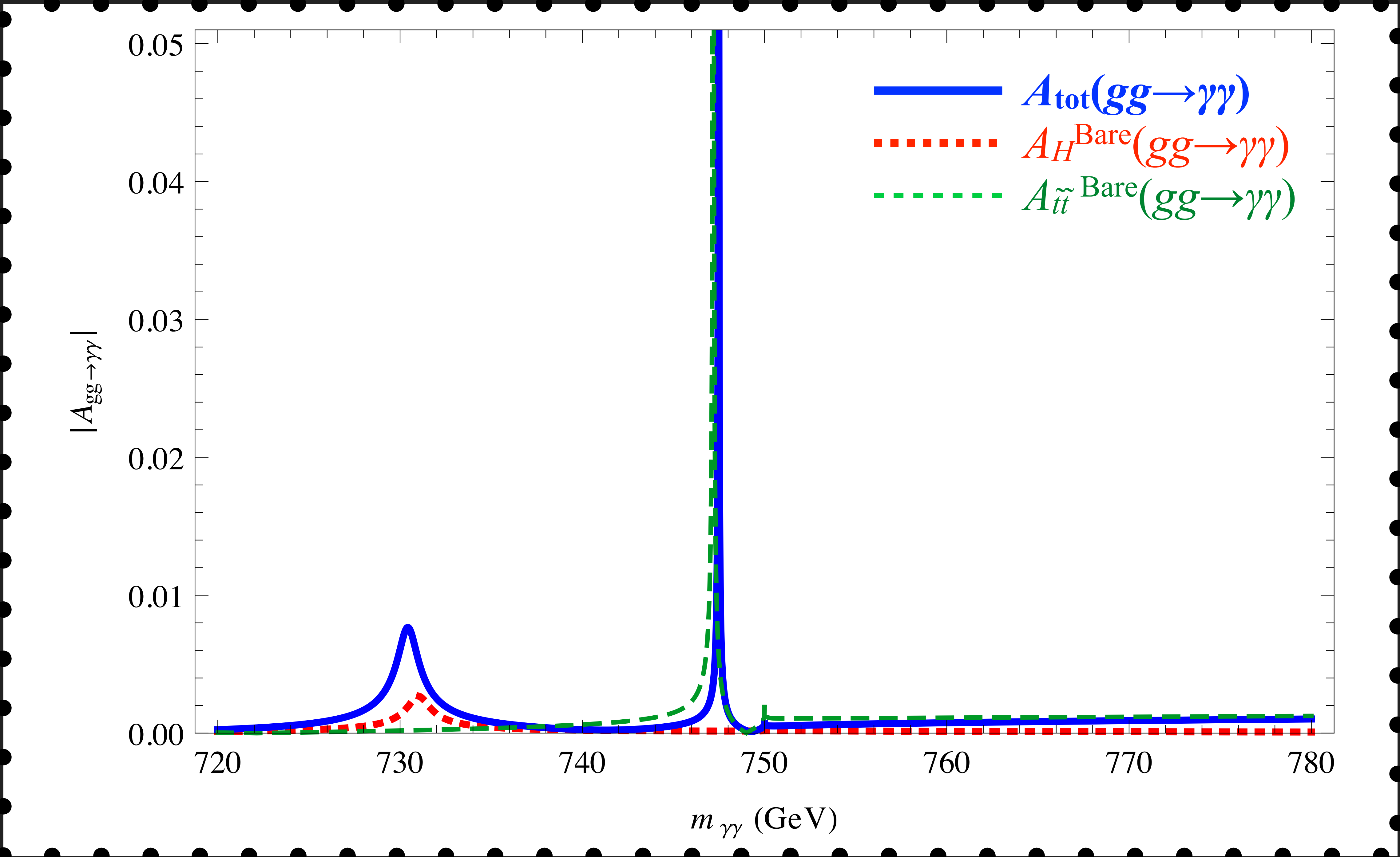

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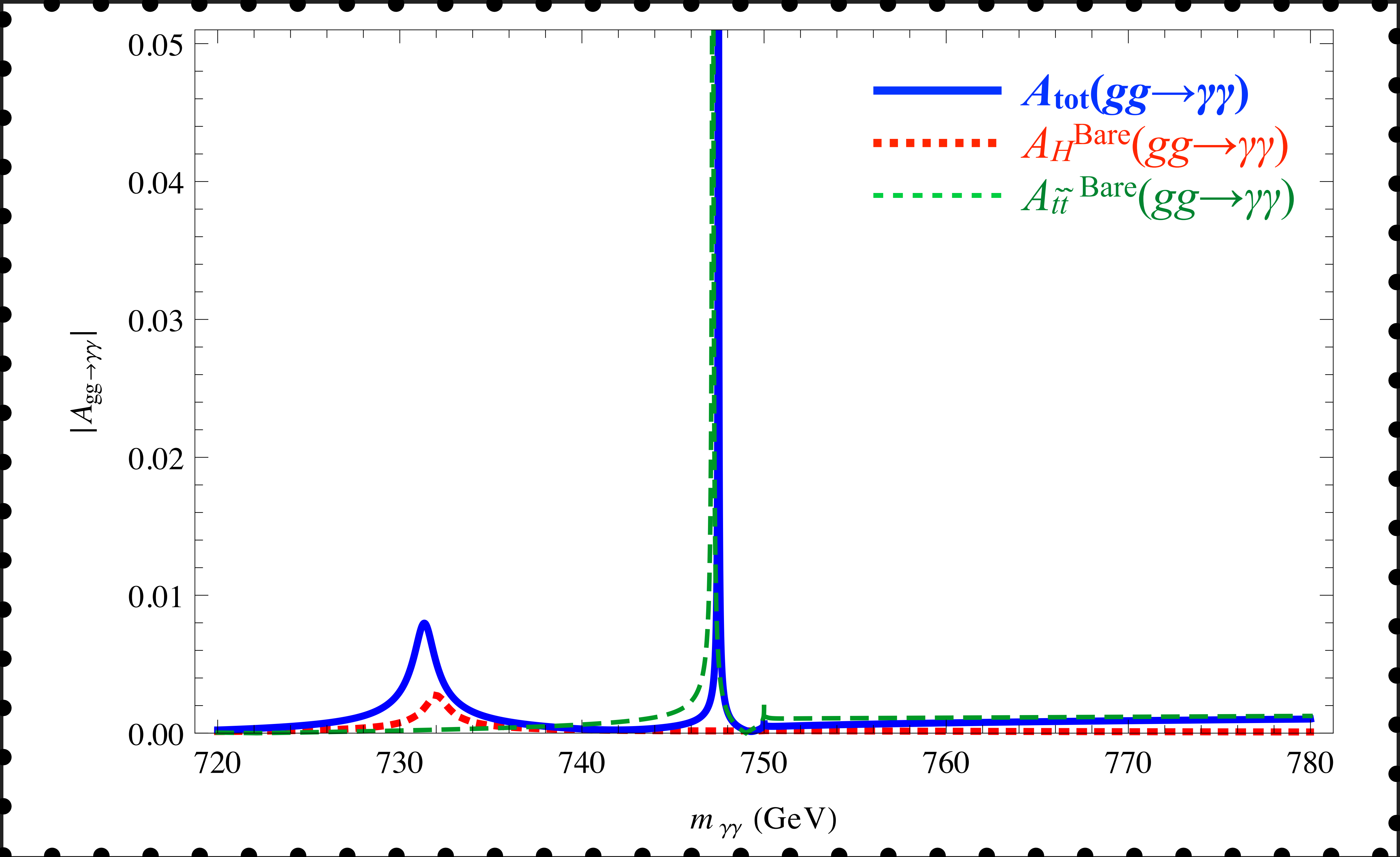

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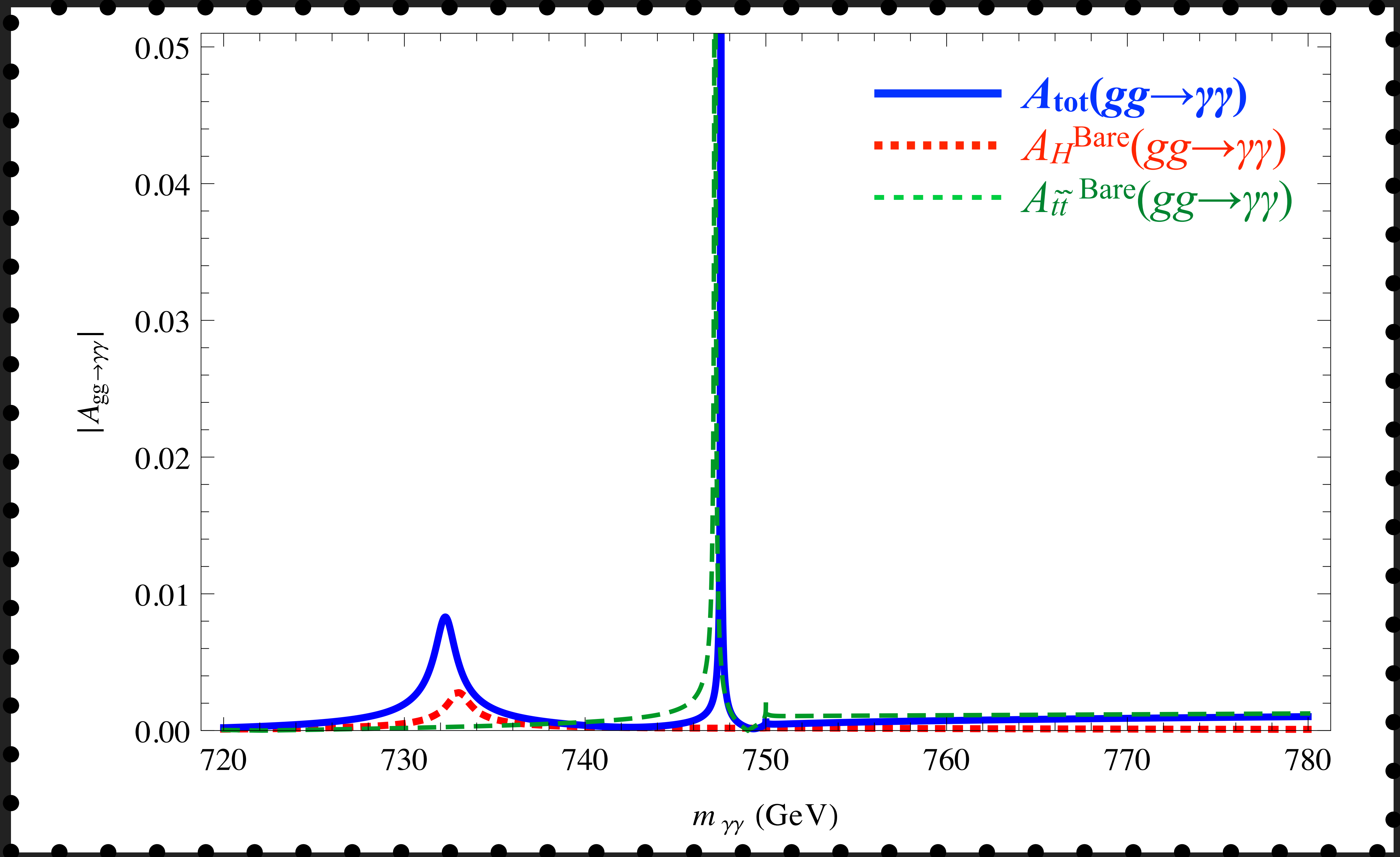

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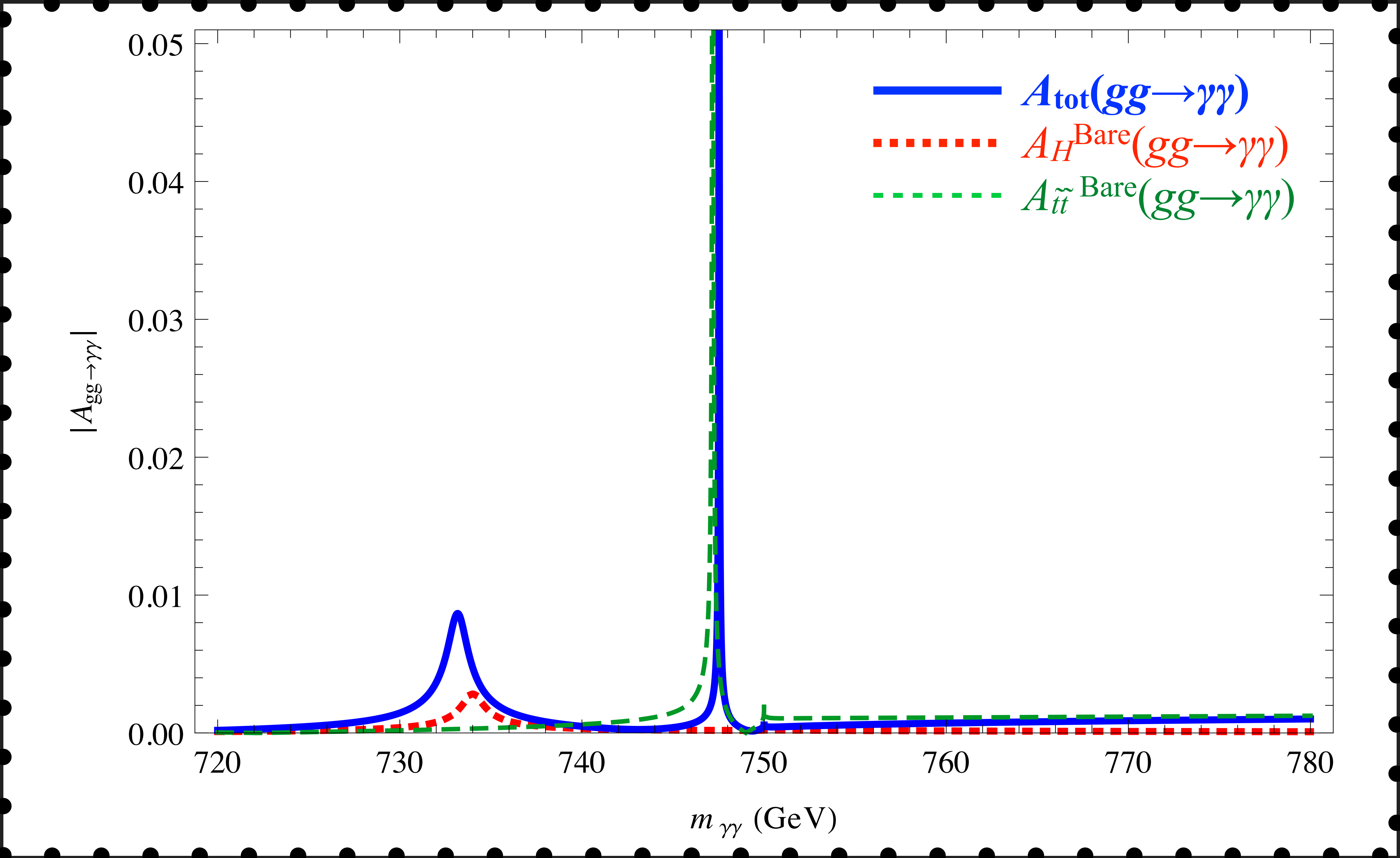

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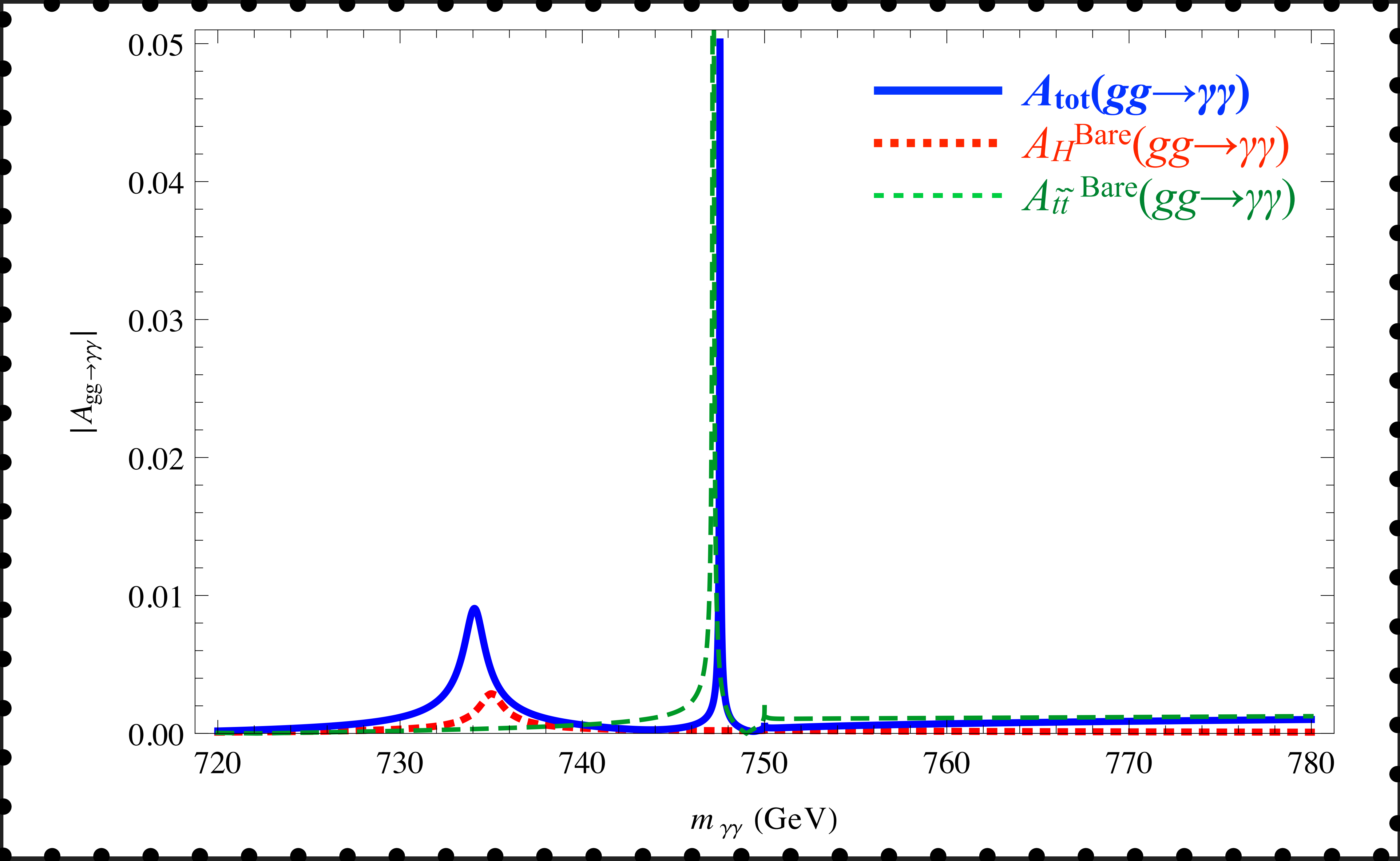

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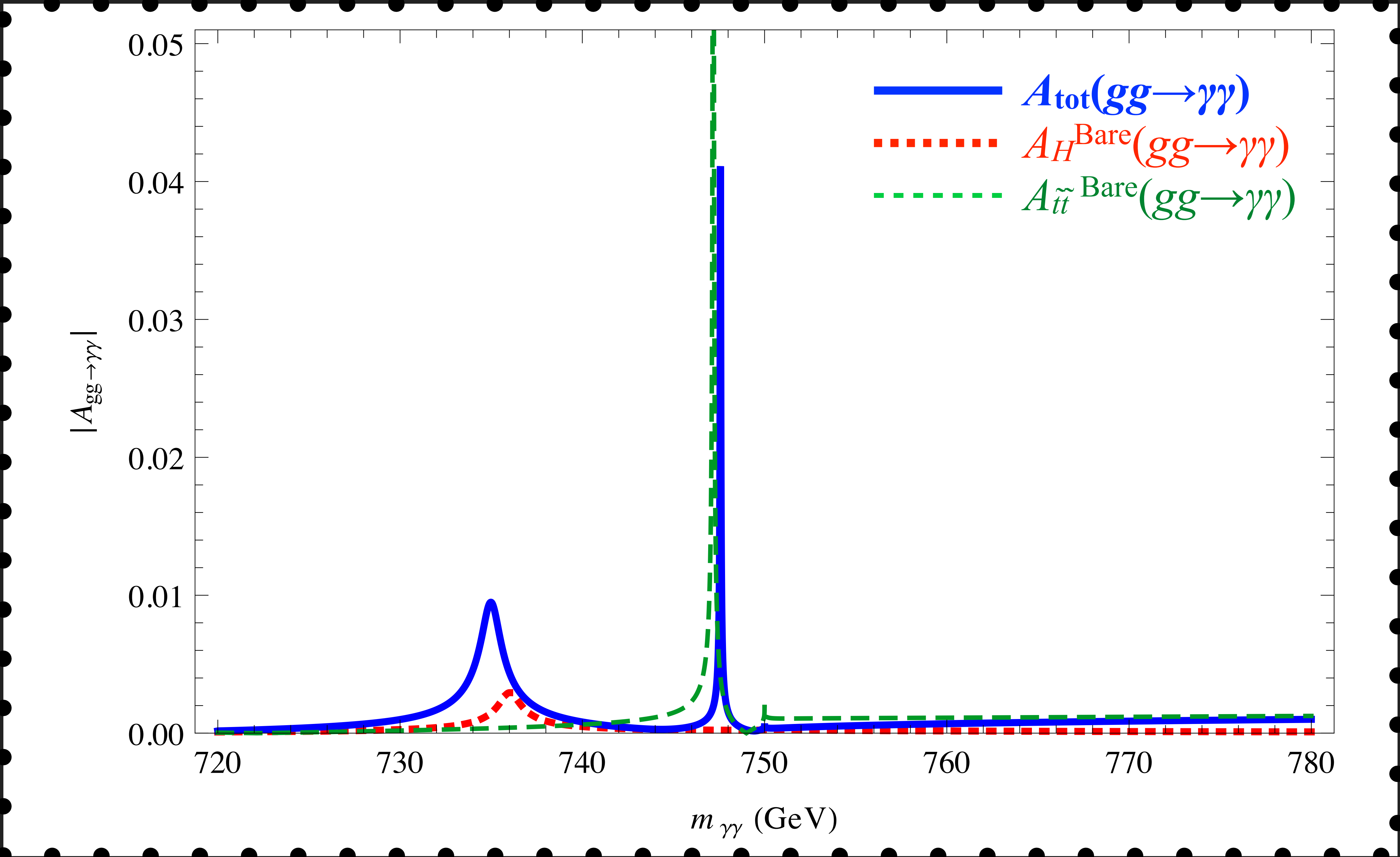

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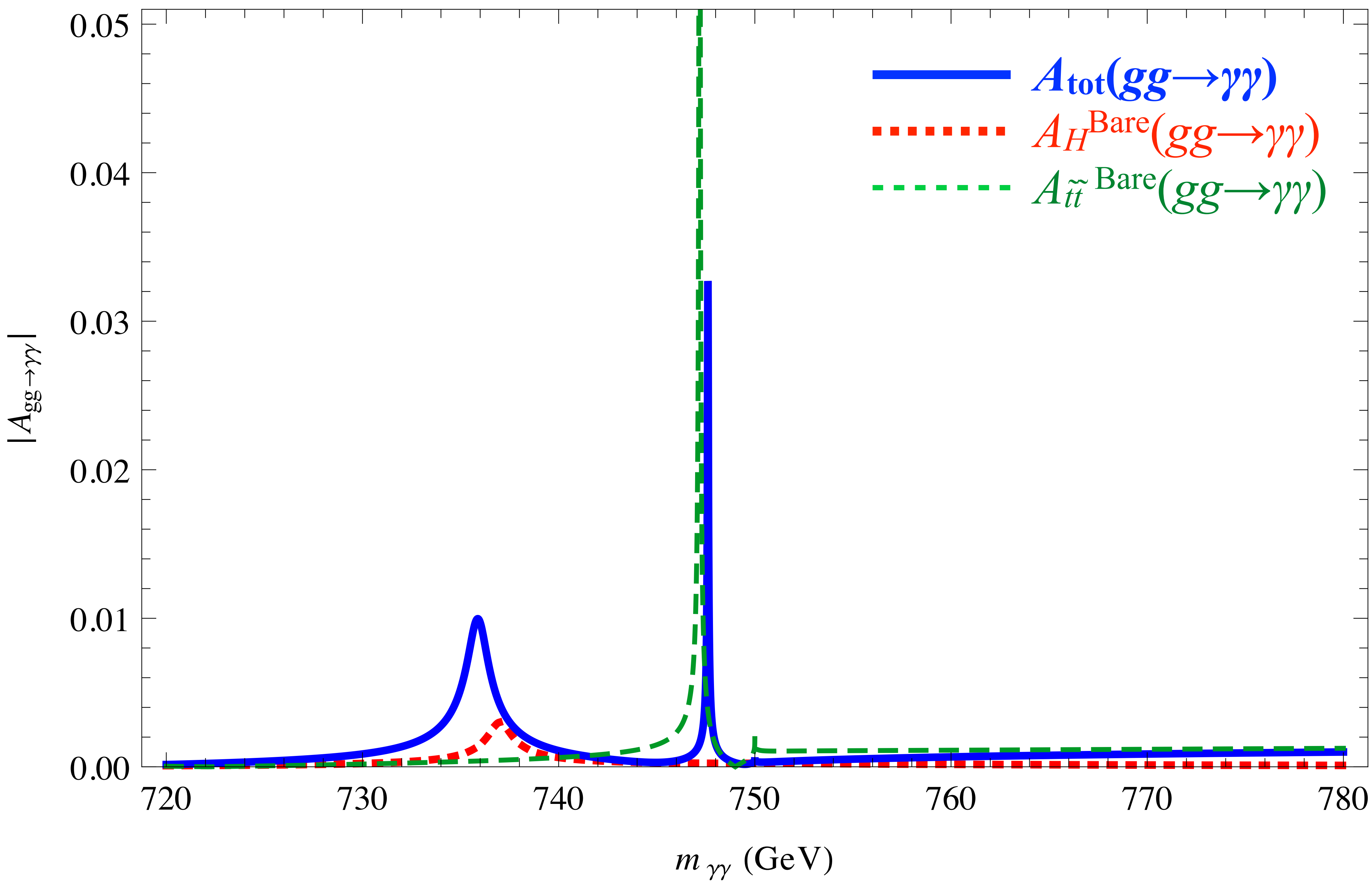

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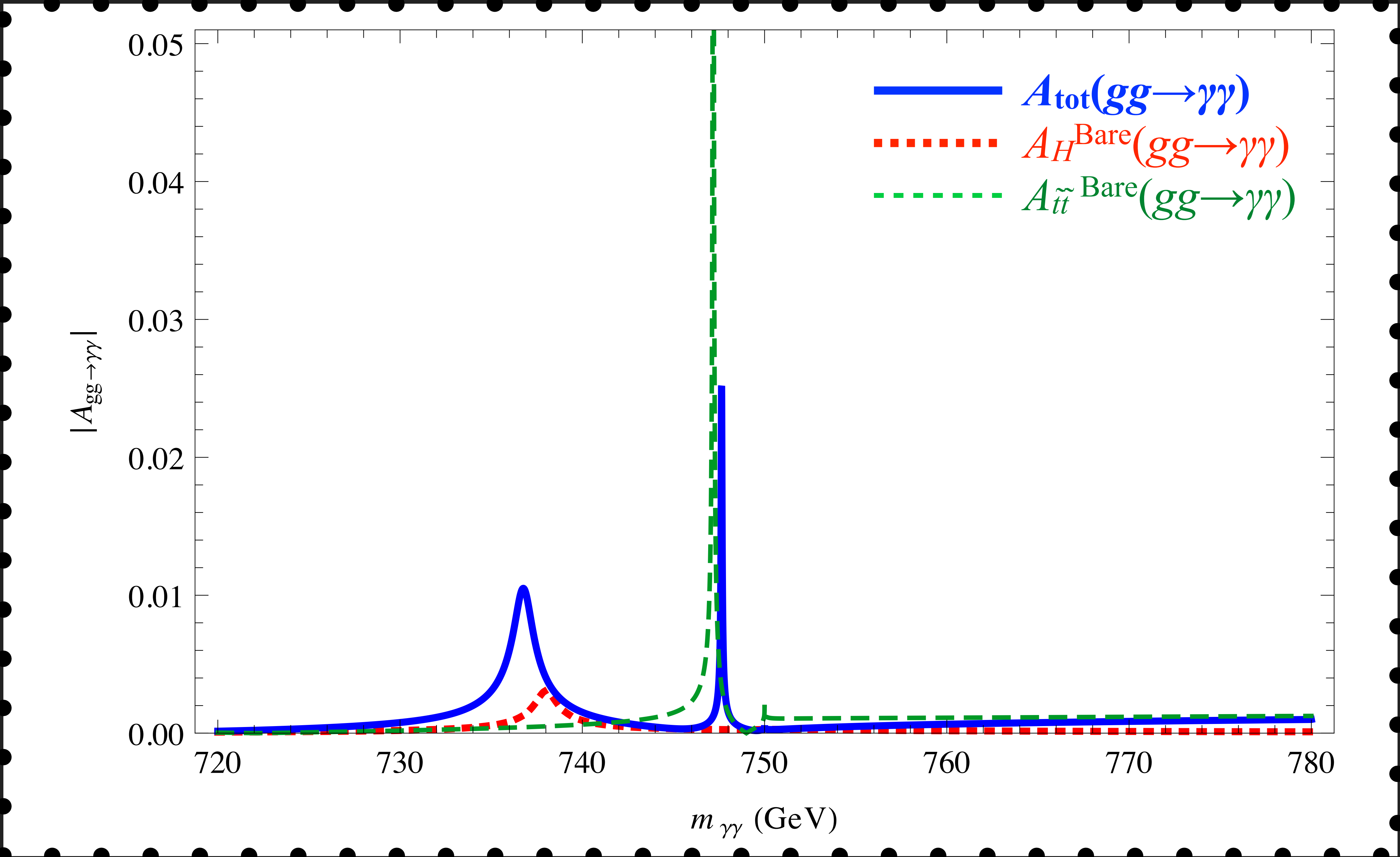

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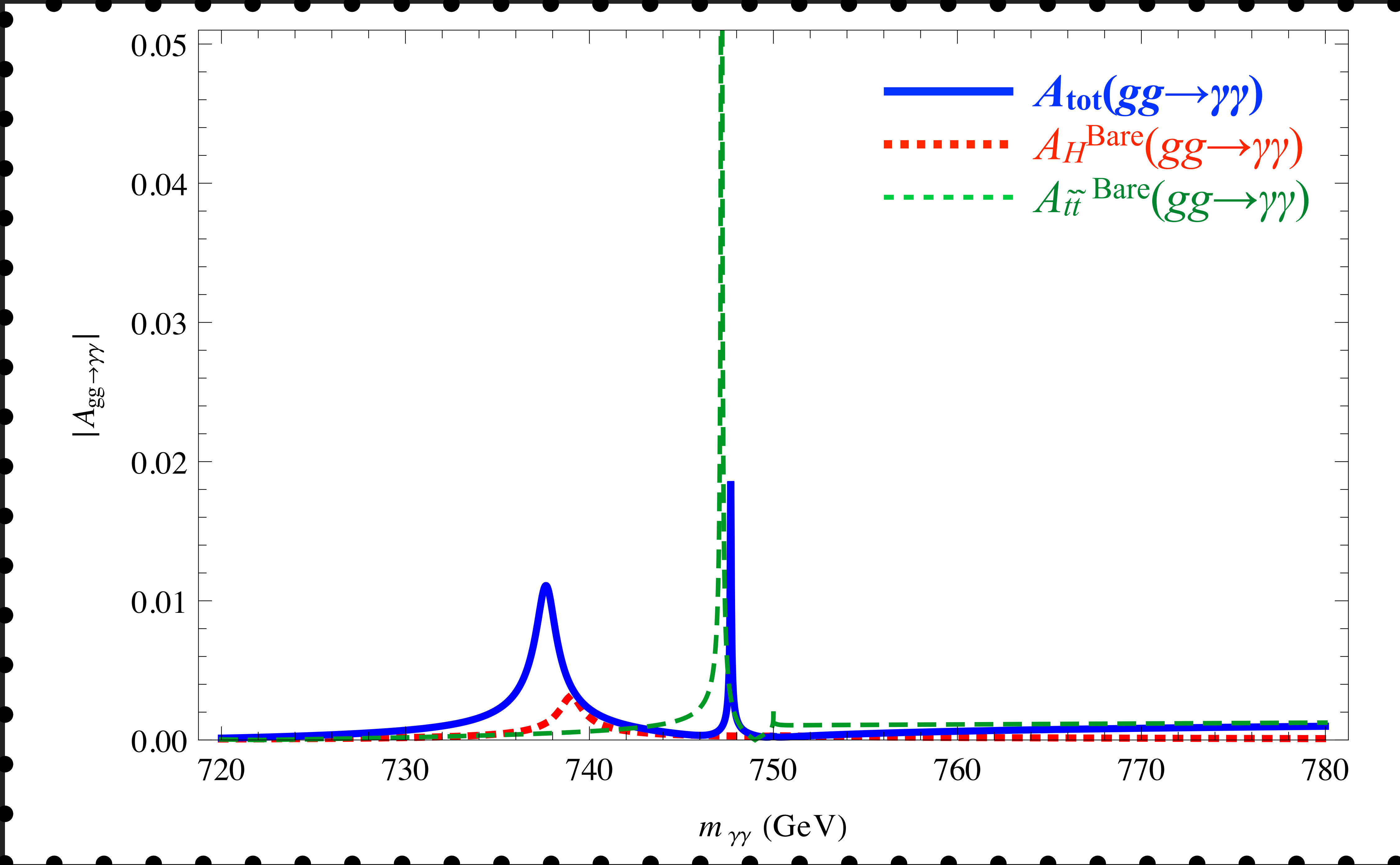

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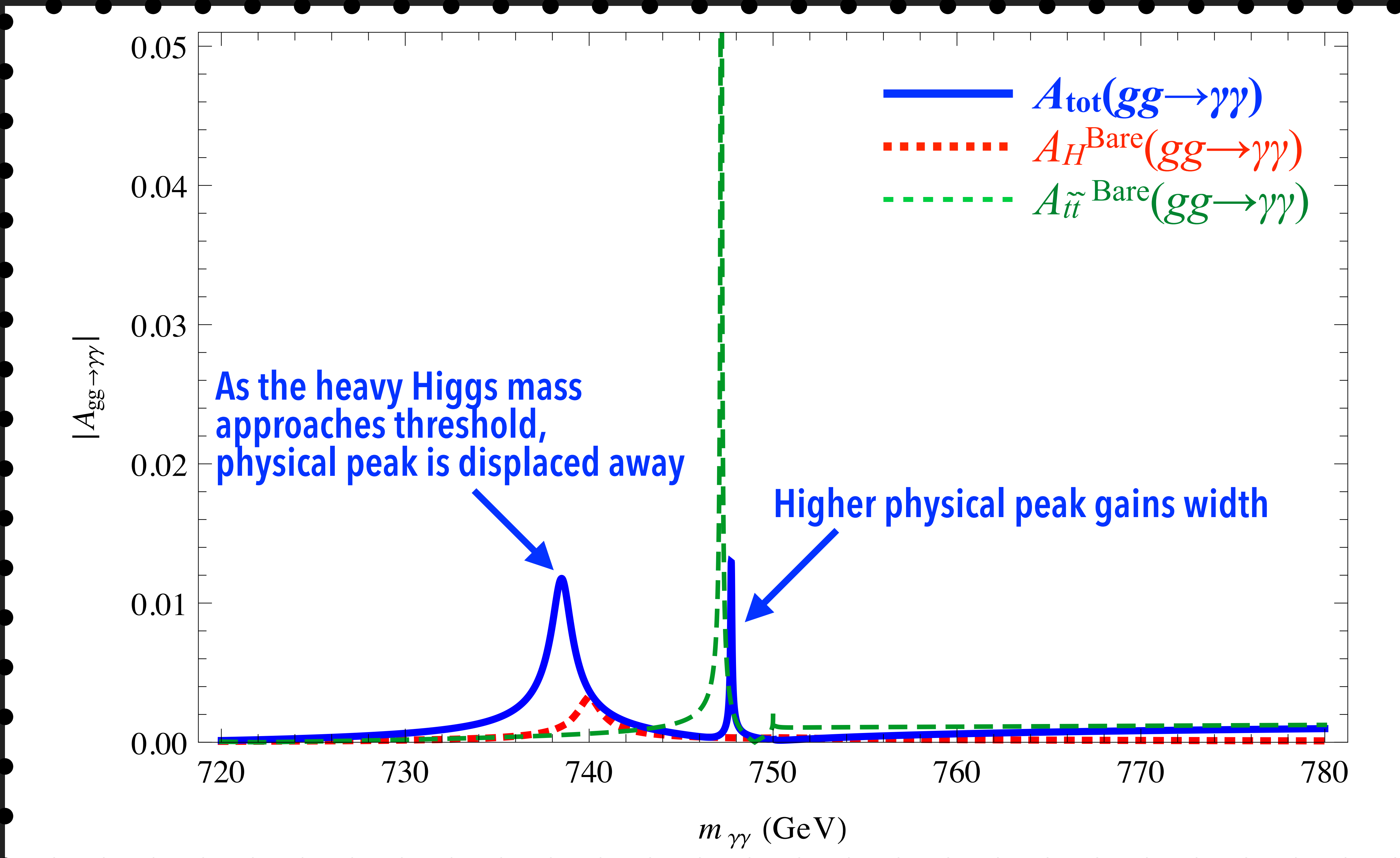

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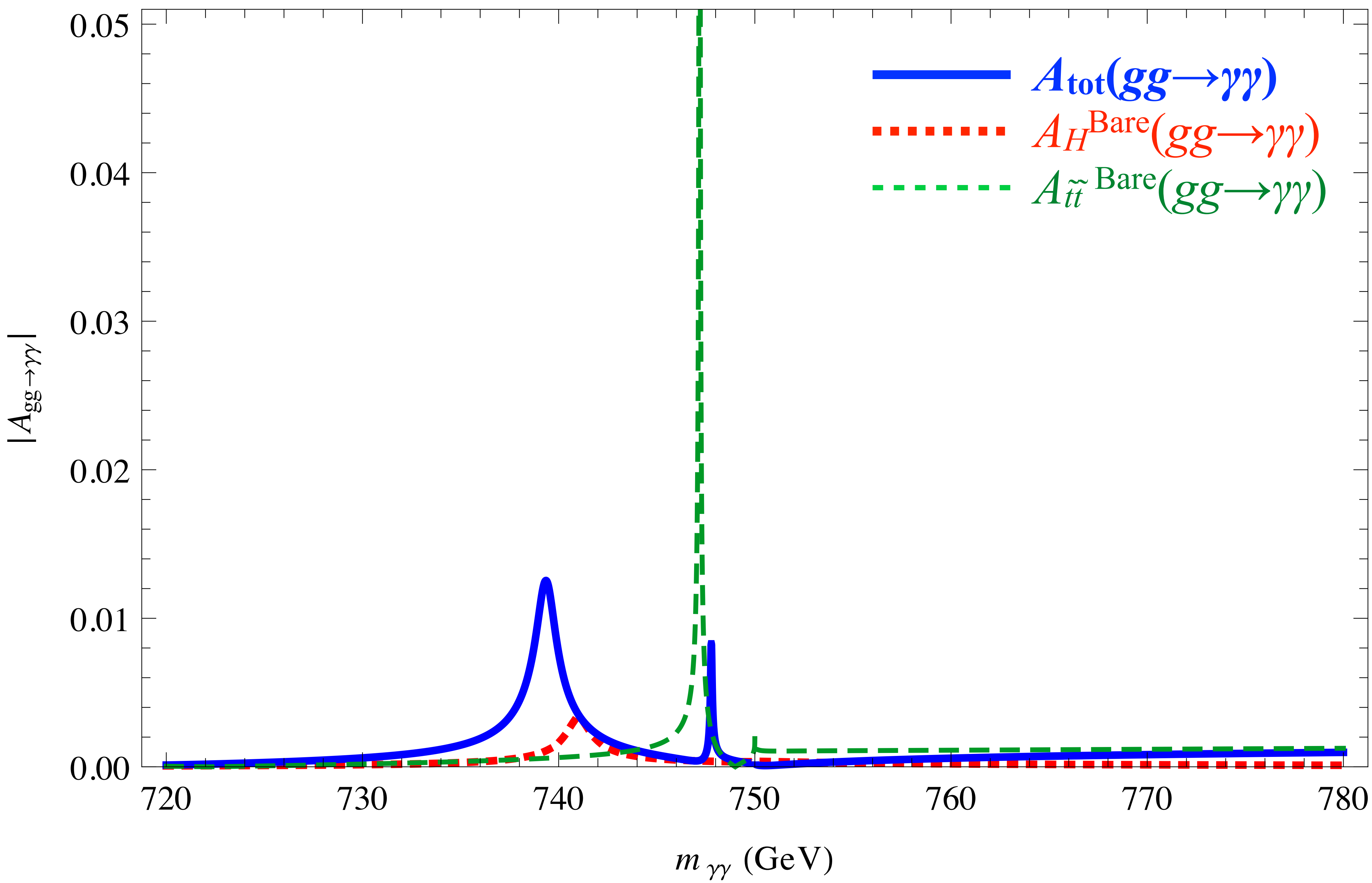

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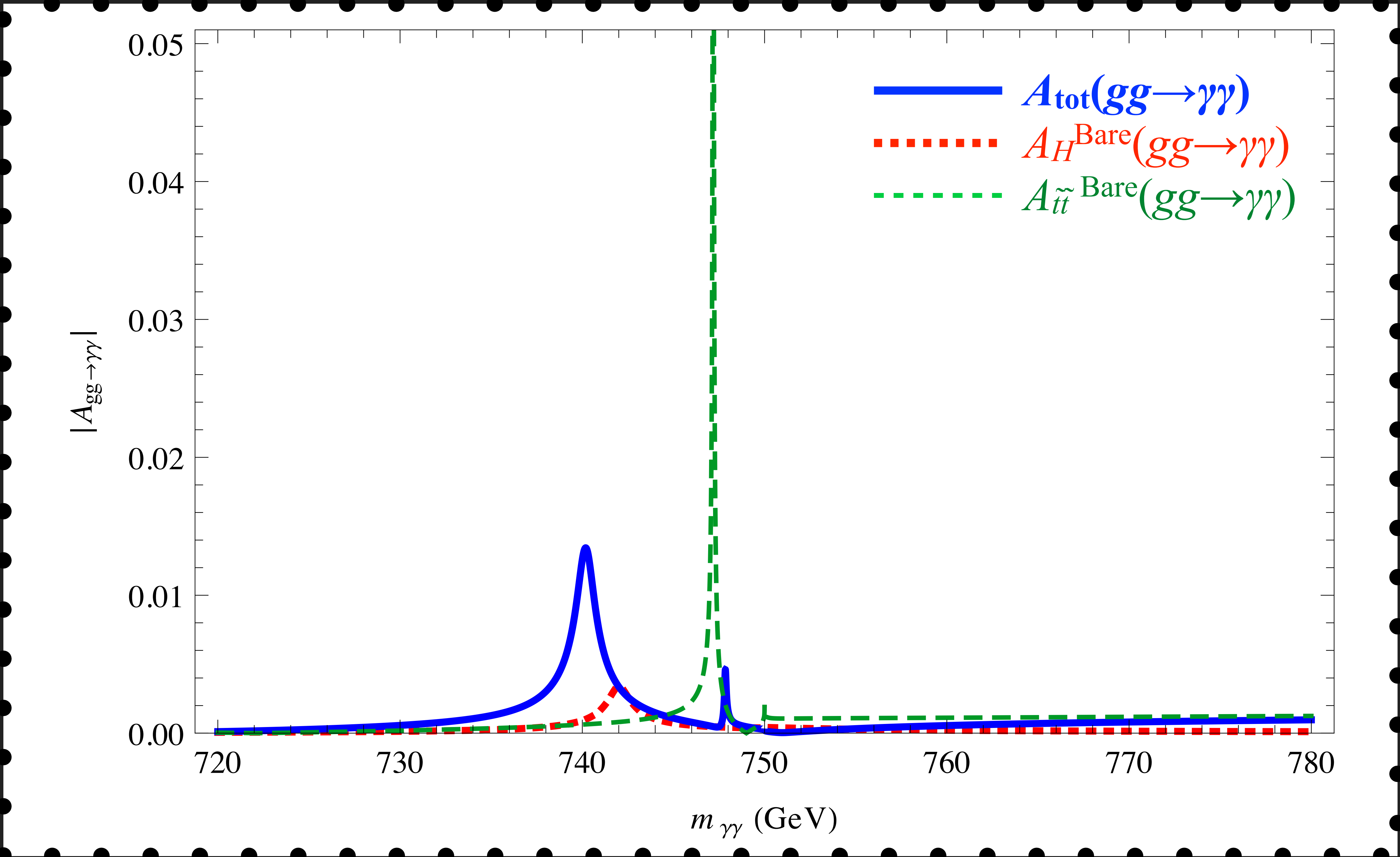

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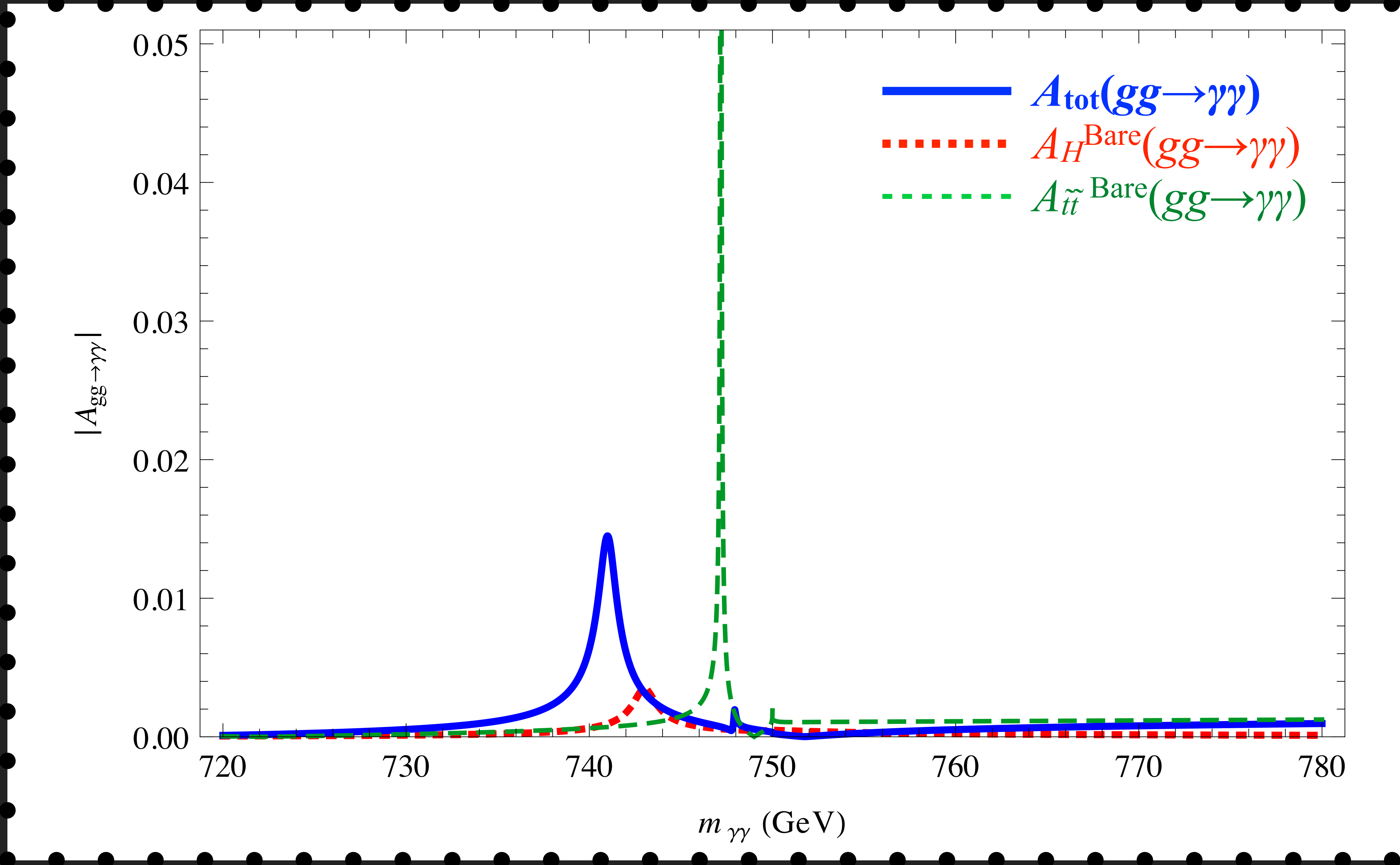

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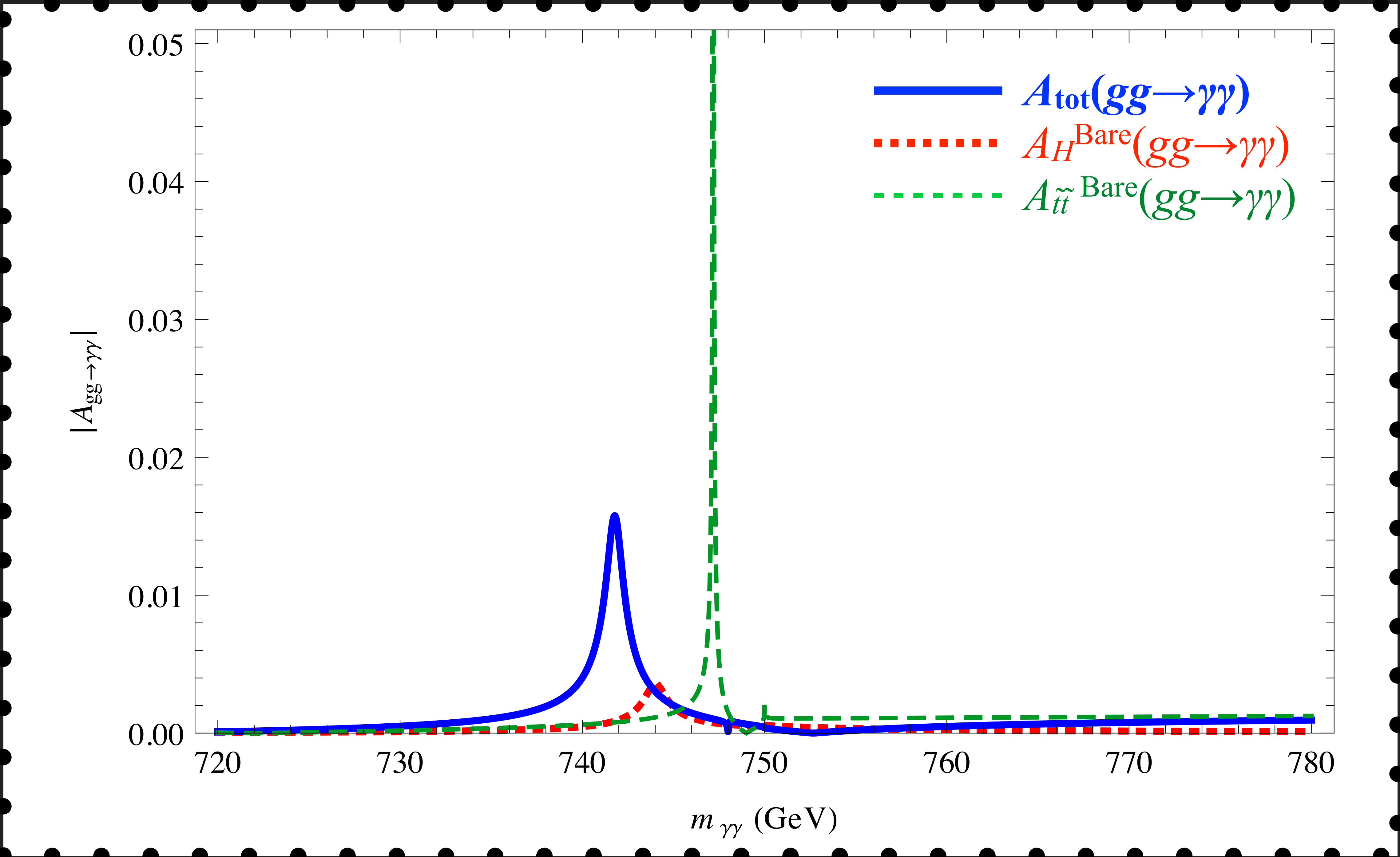

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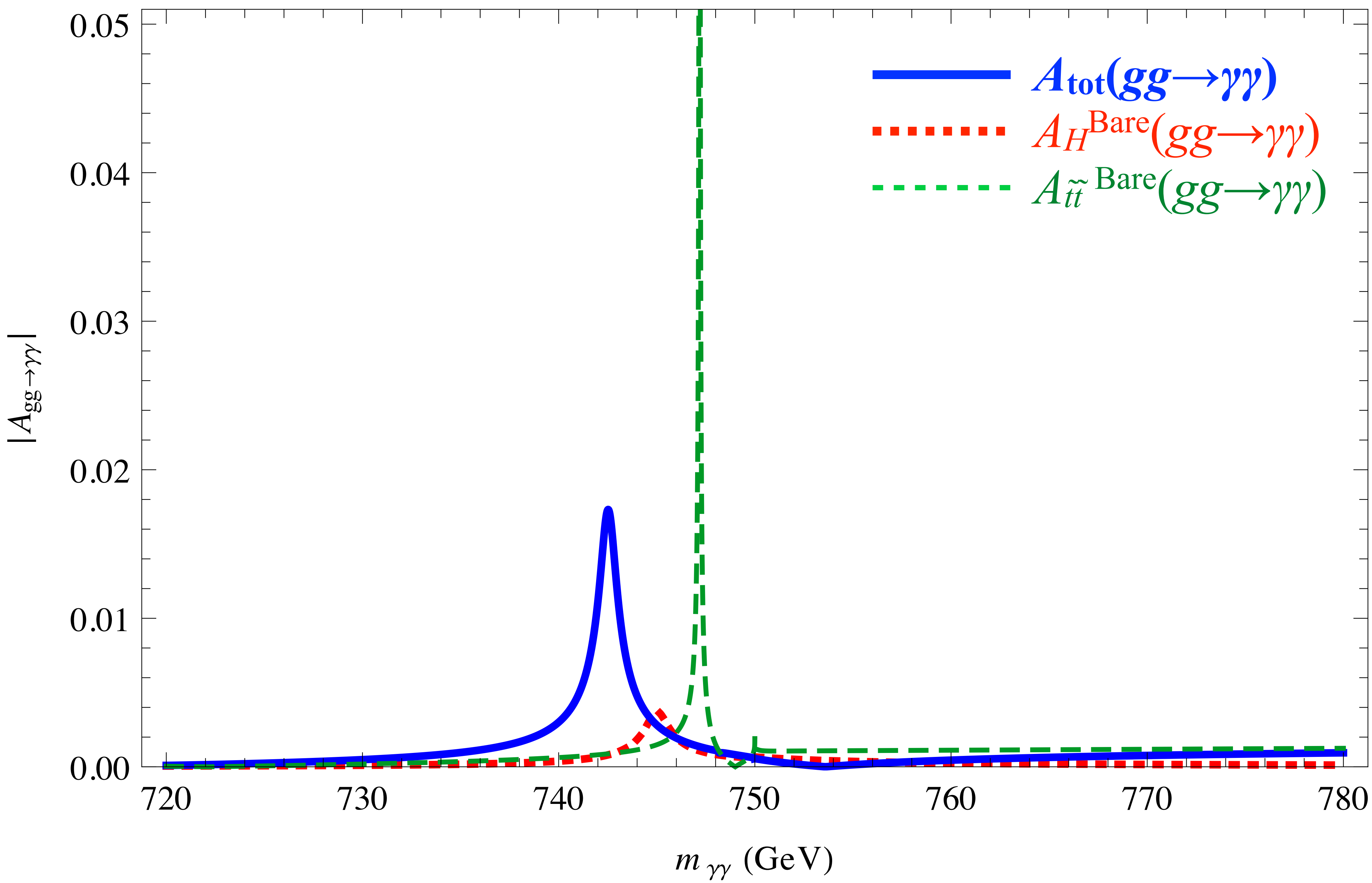

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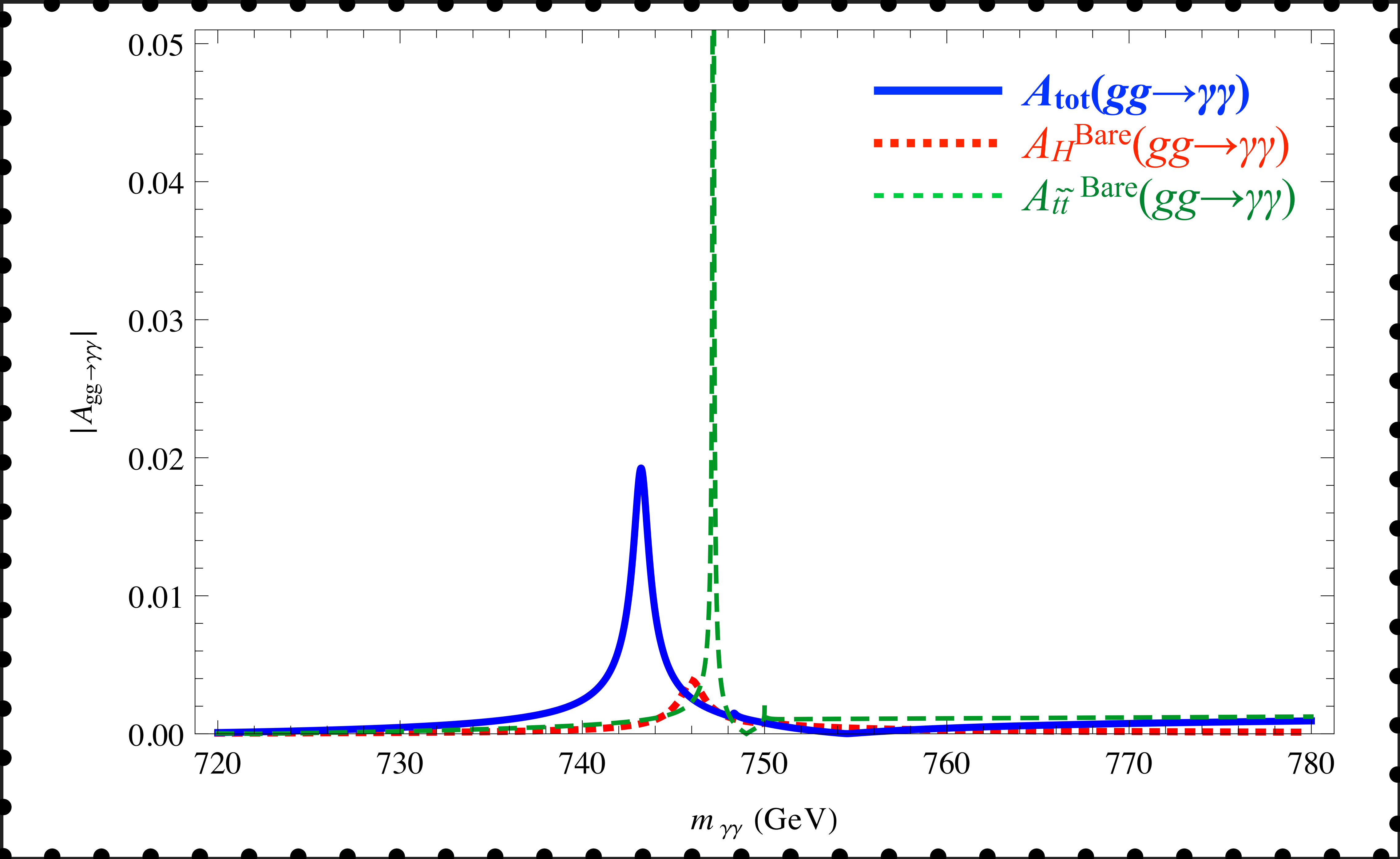

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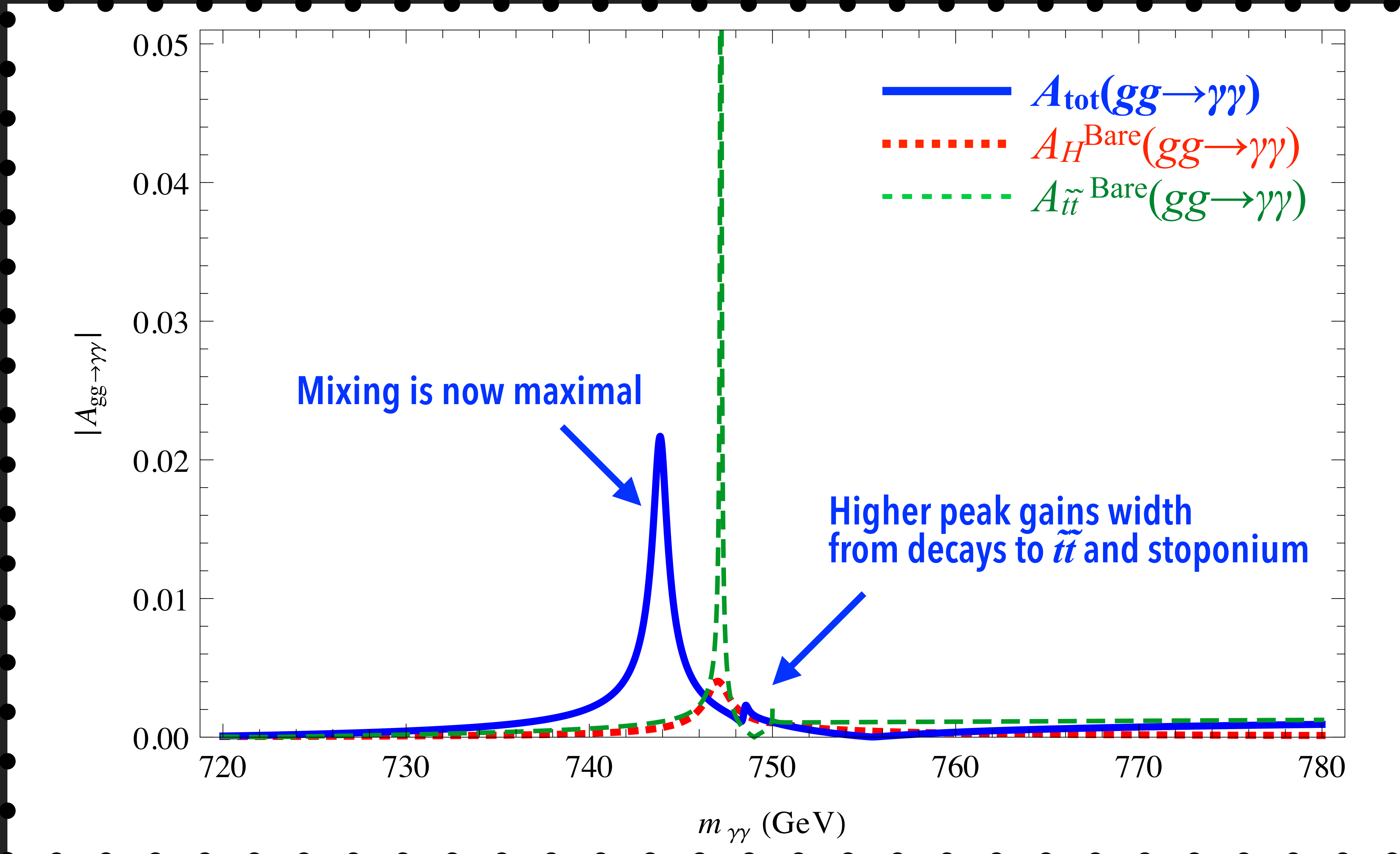

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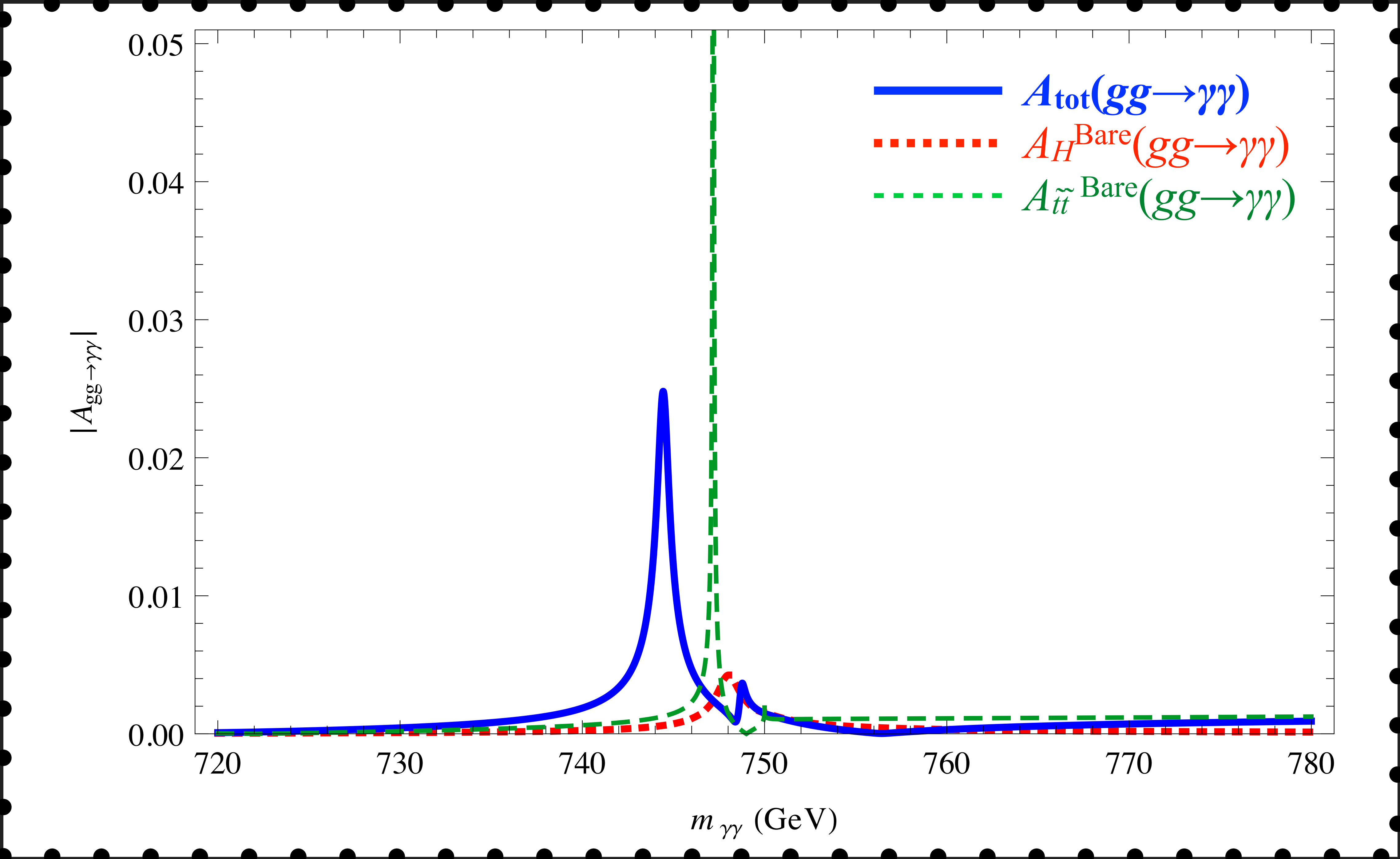

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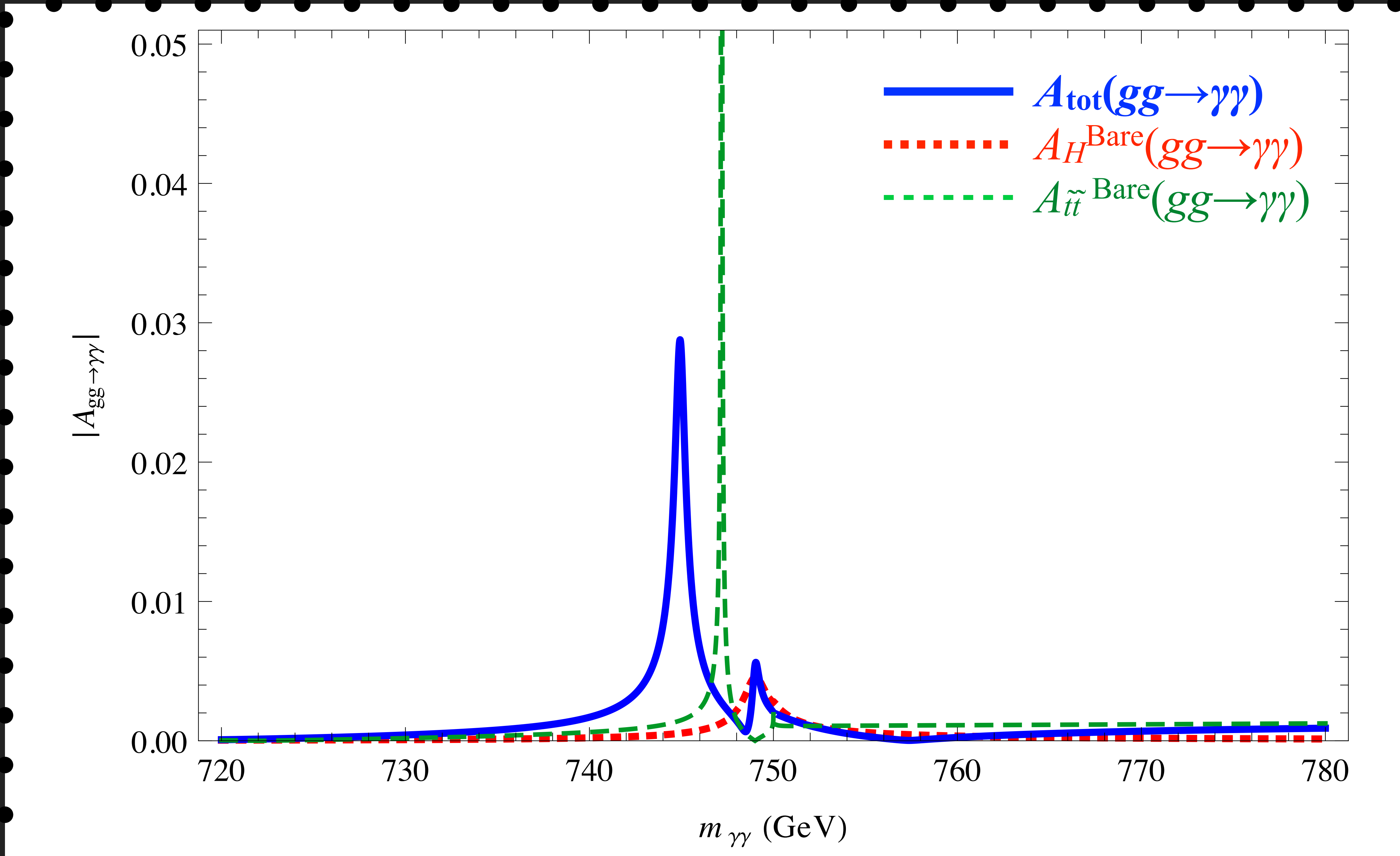

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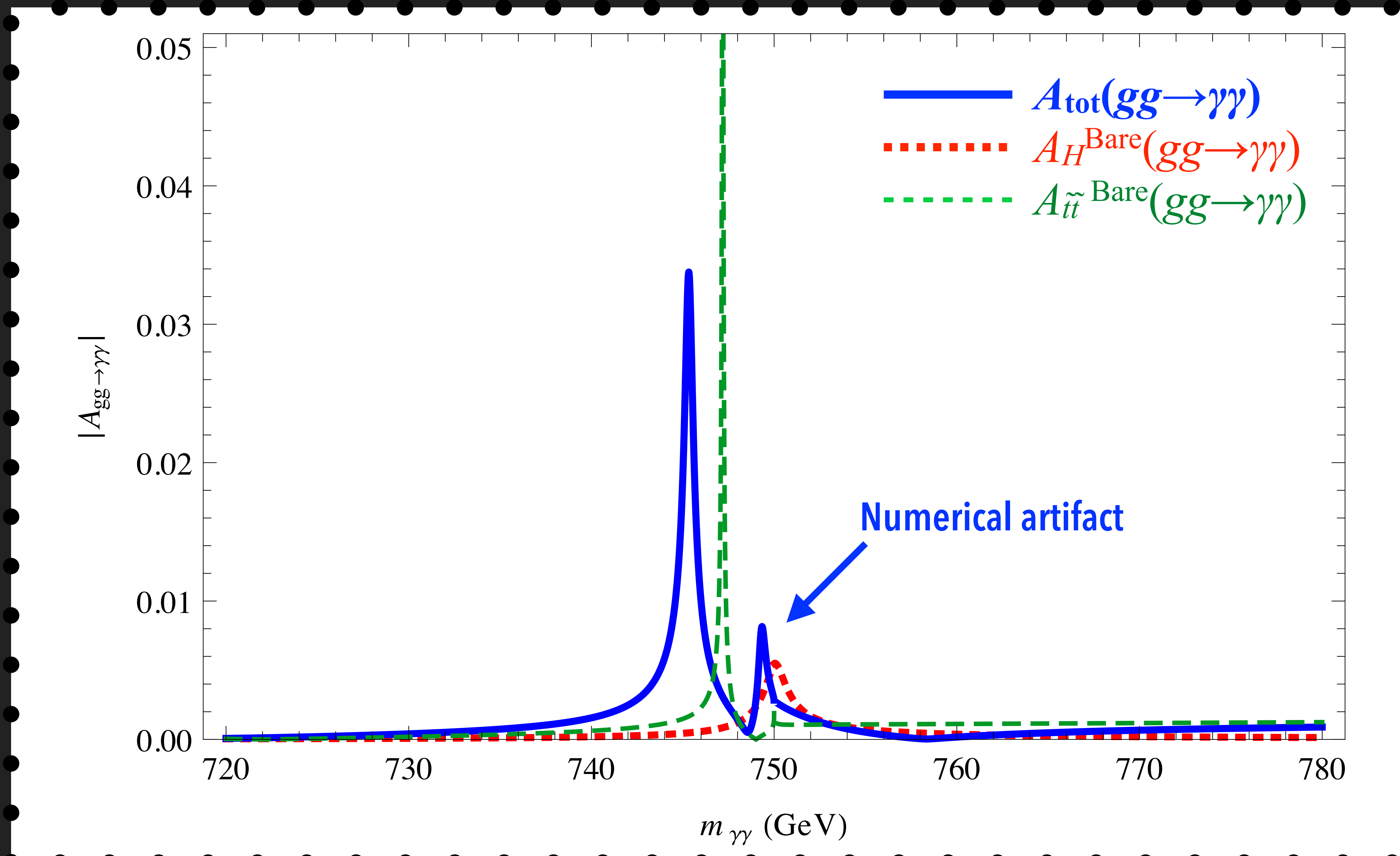

Numerical artifact at threshold from approximations used for Green's functions, NOT a physical peak, negligible contribution to cross section

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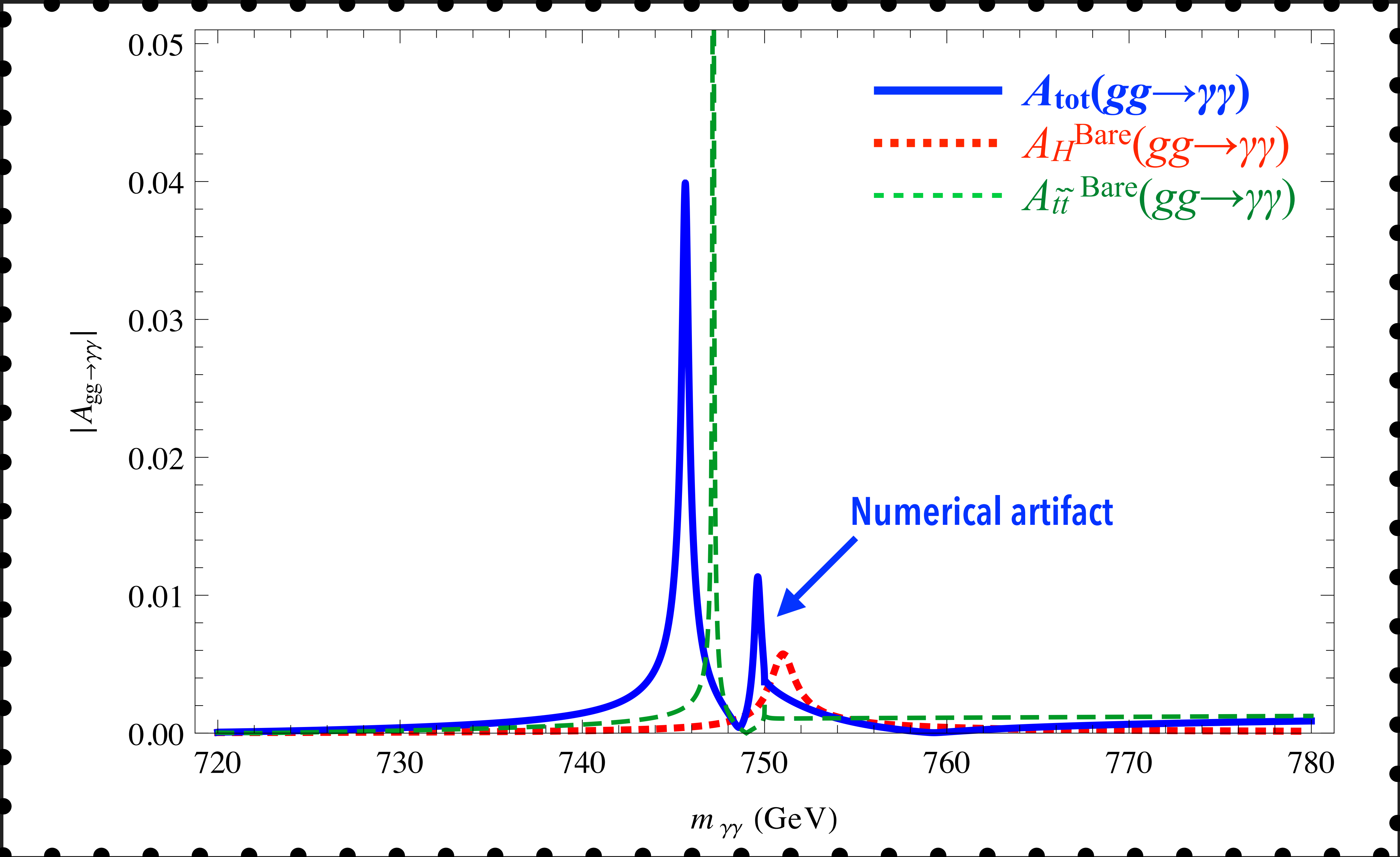

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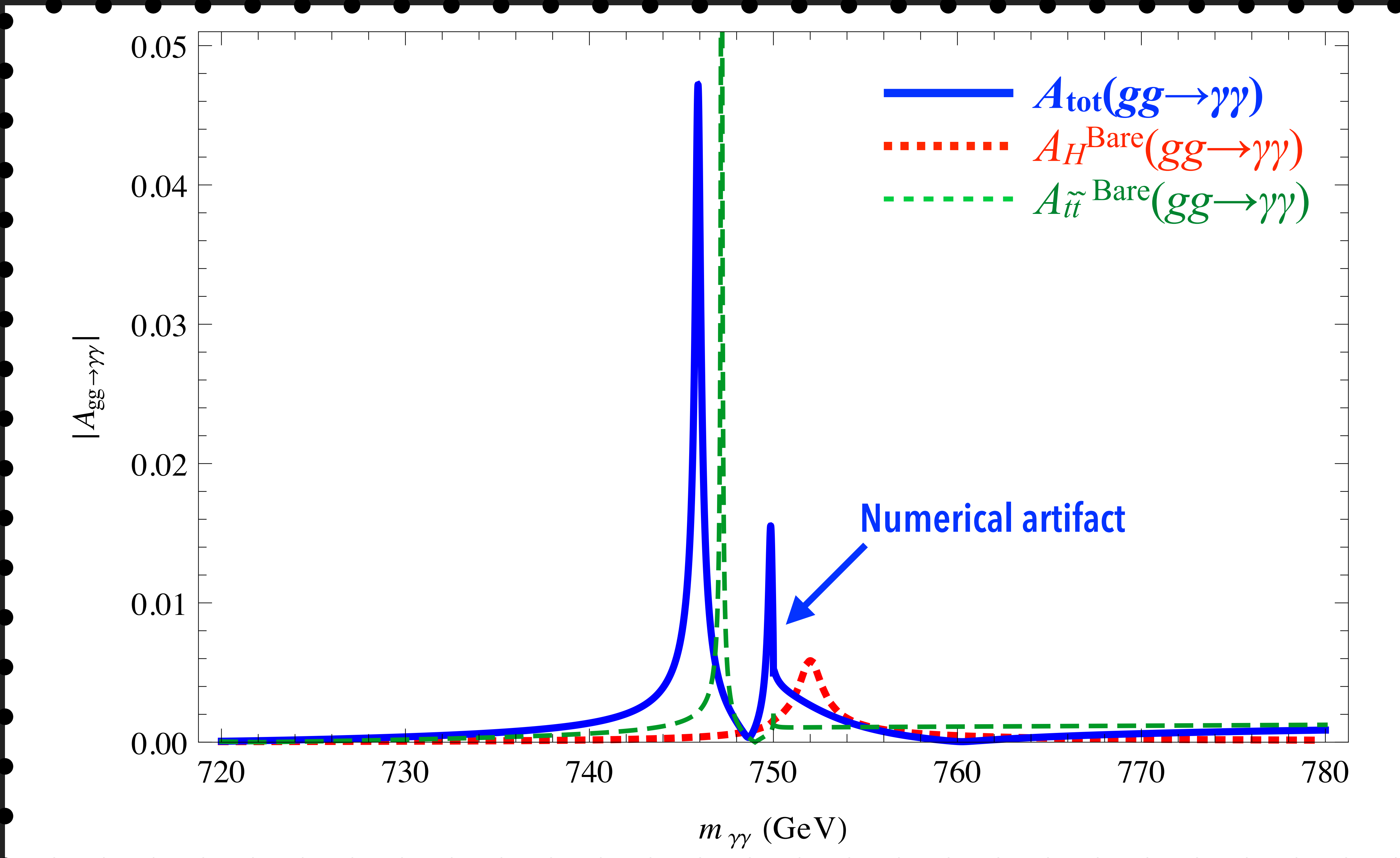

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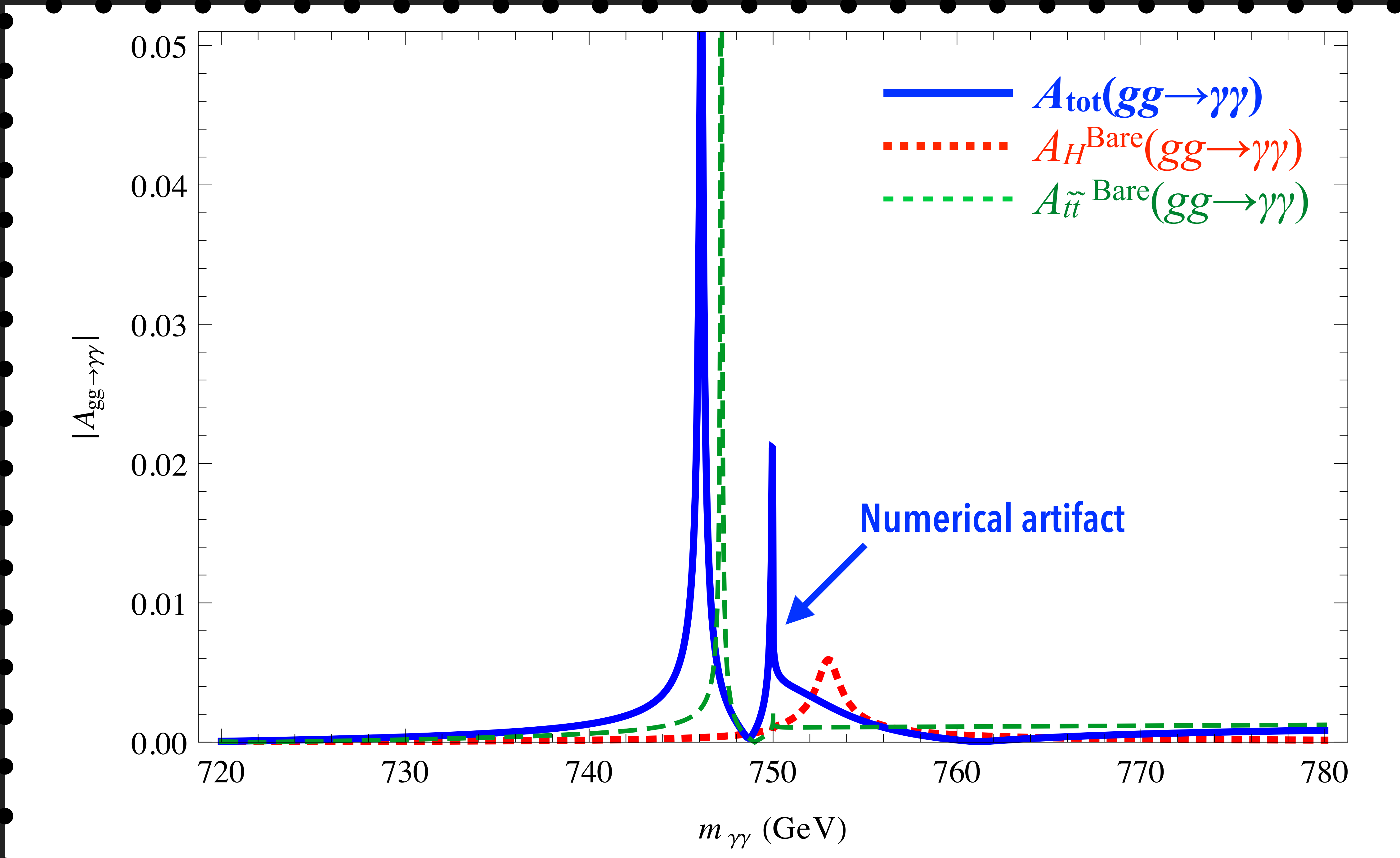

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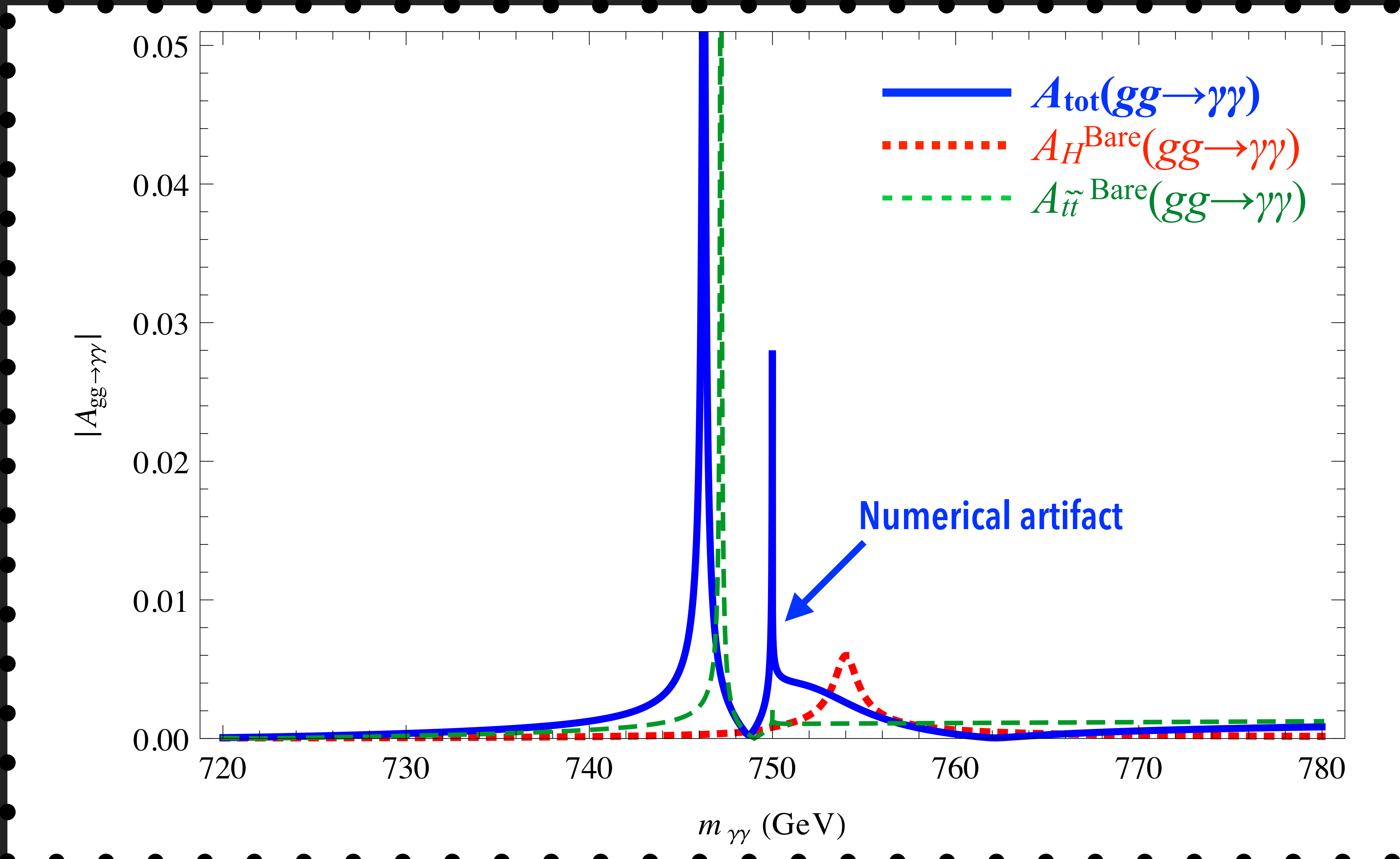

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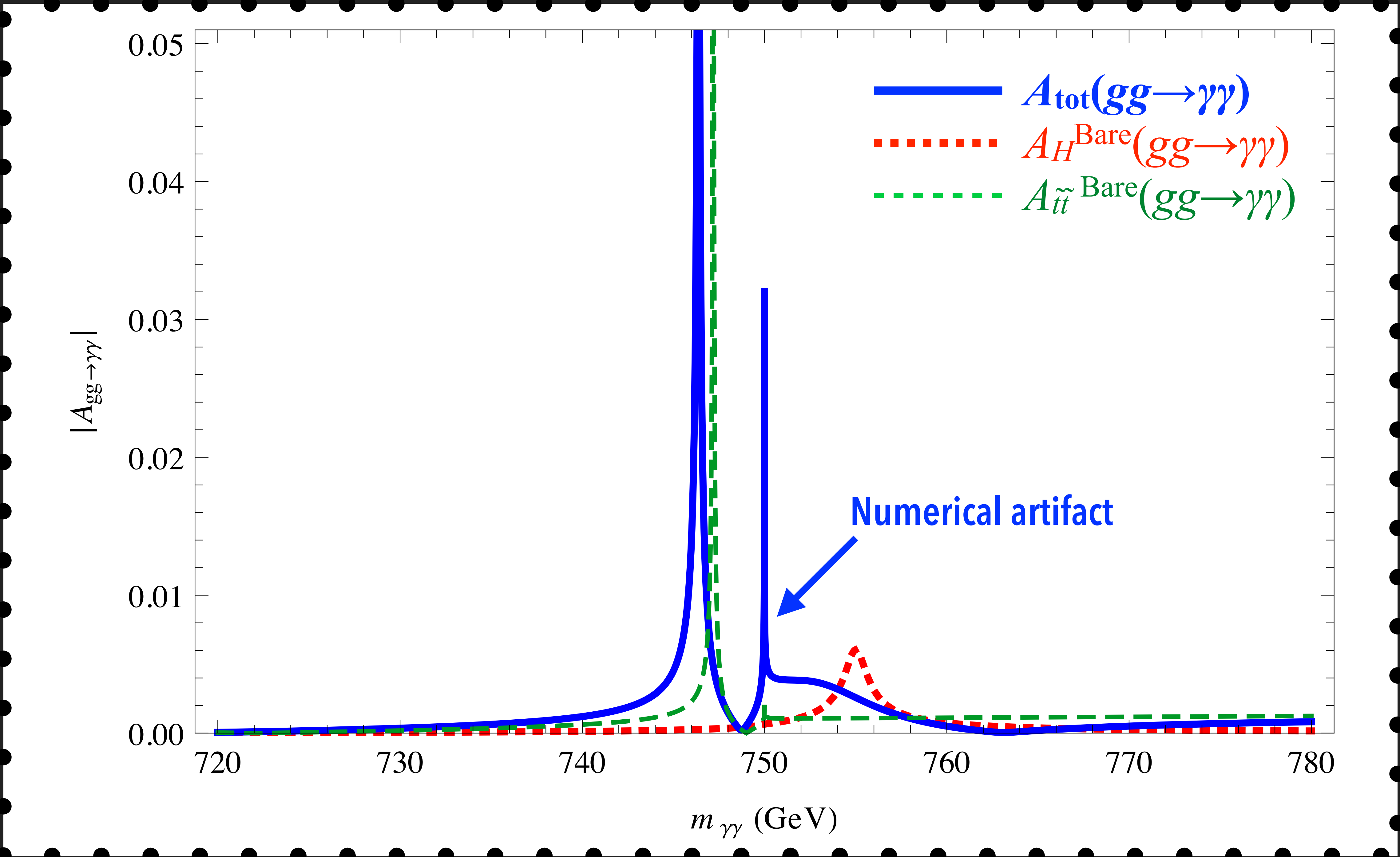

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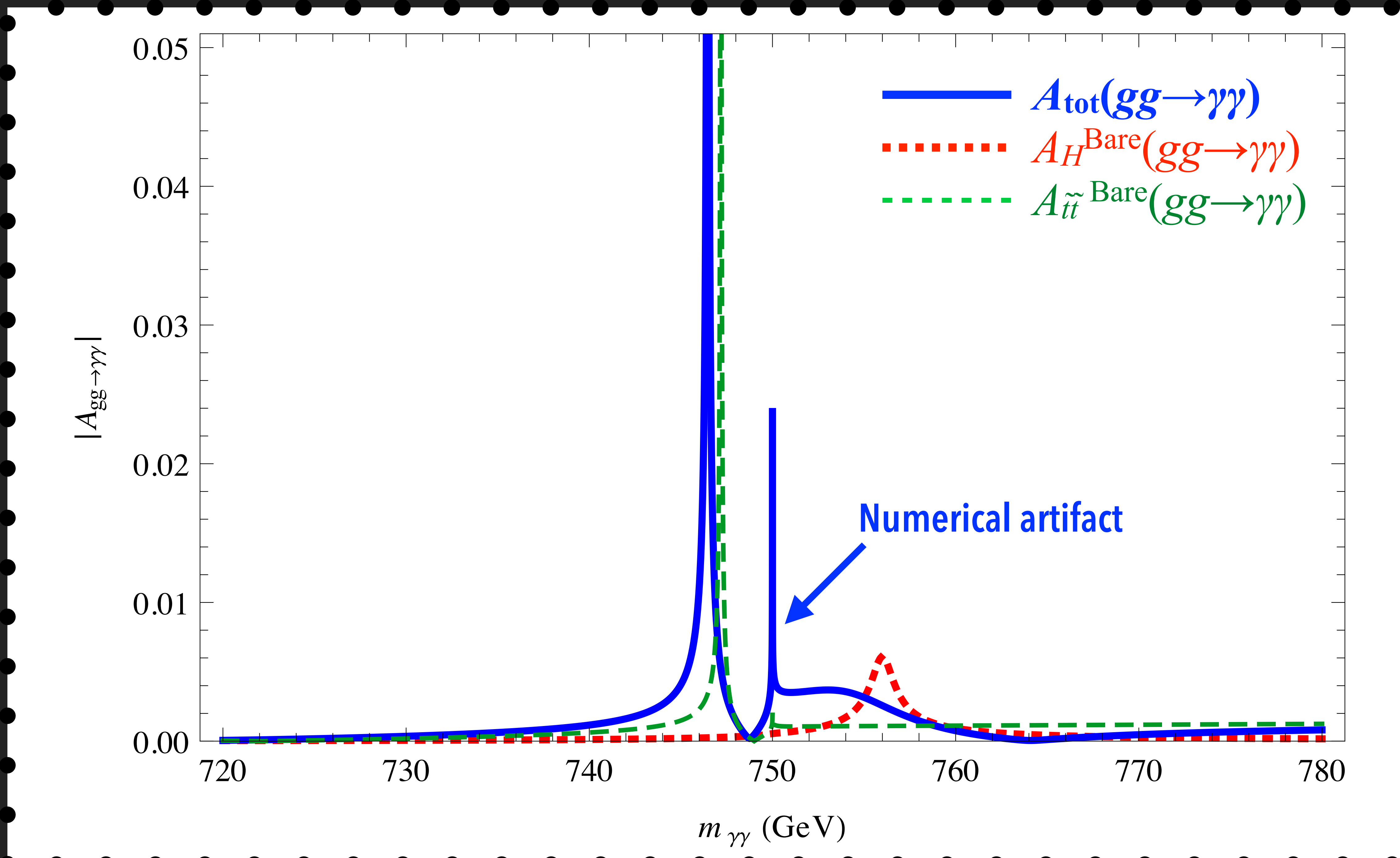

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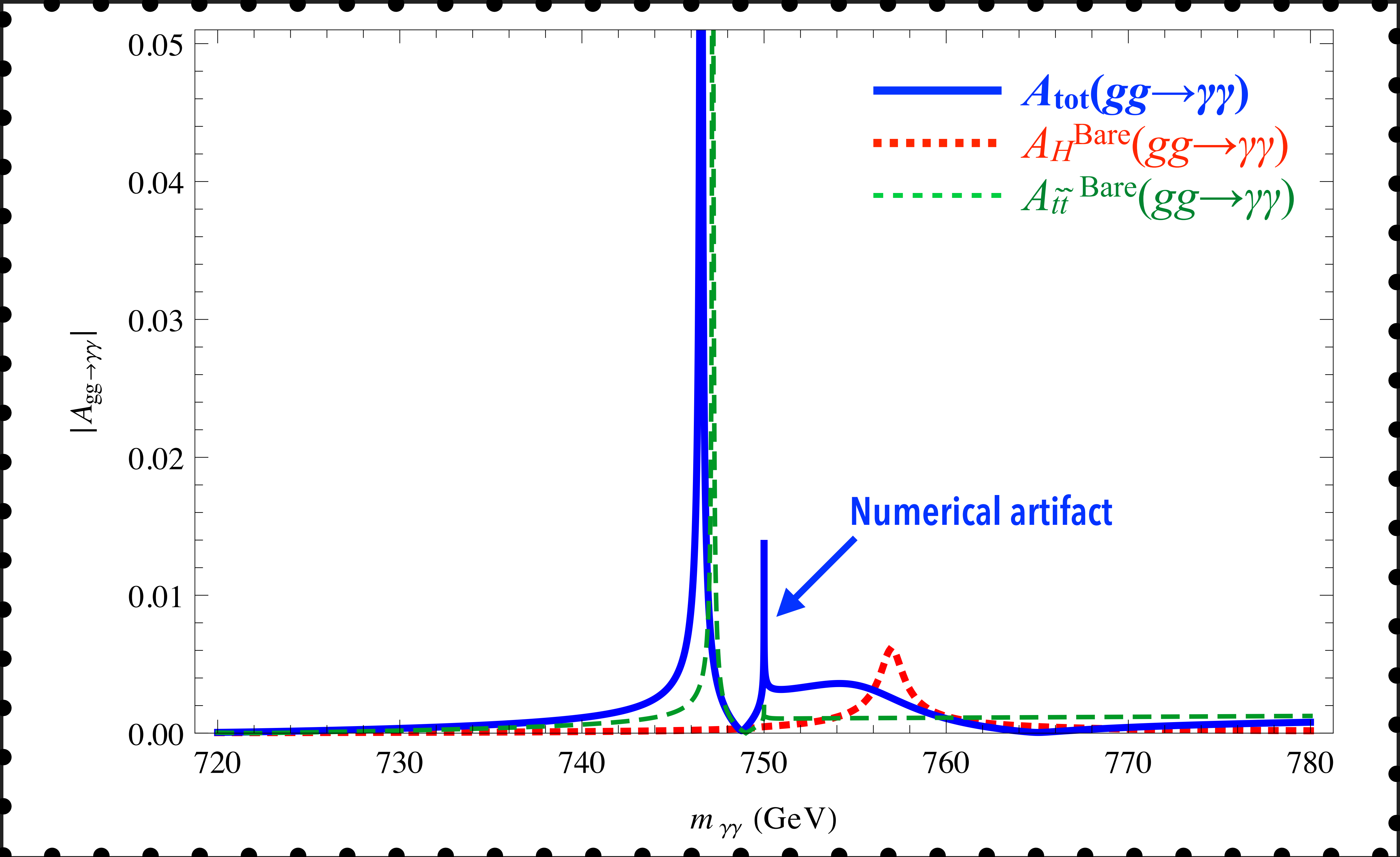

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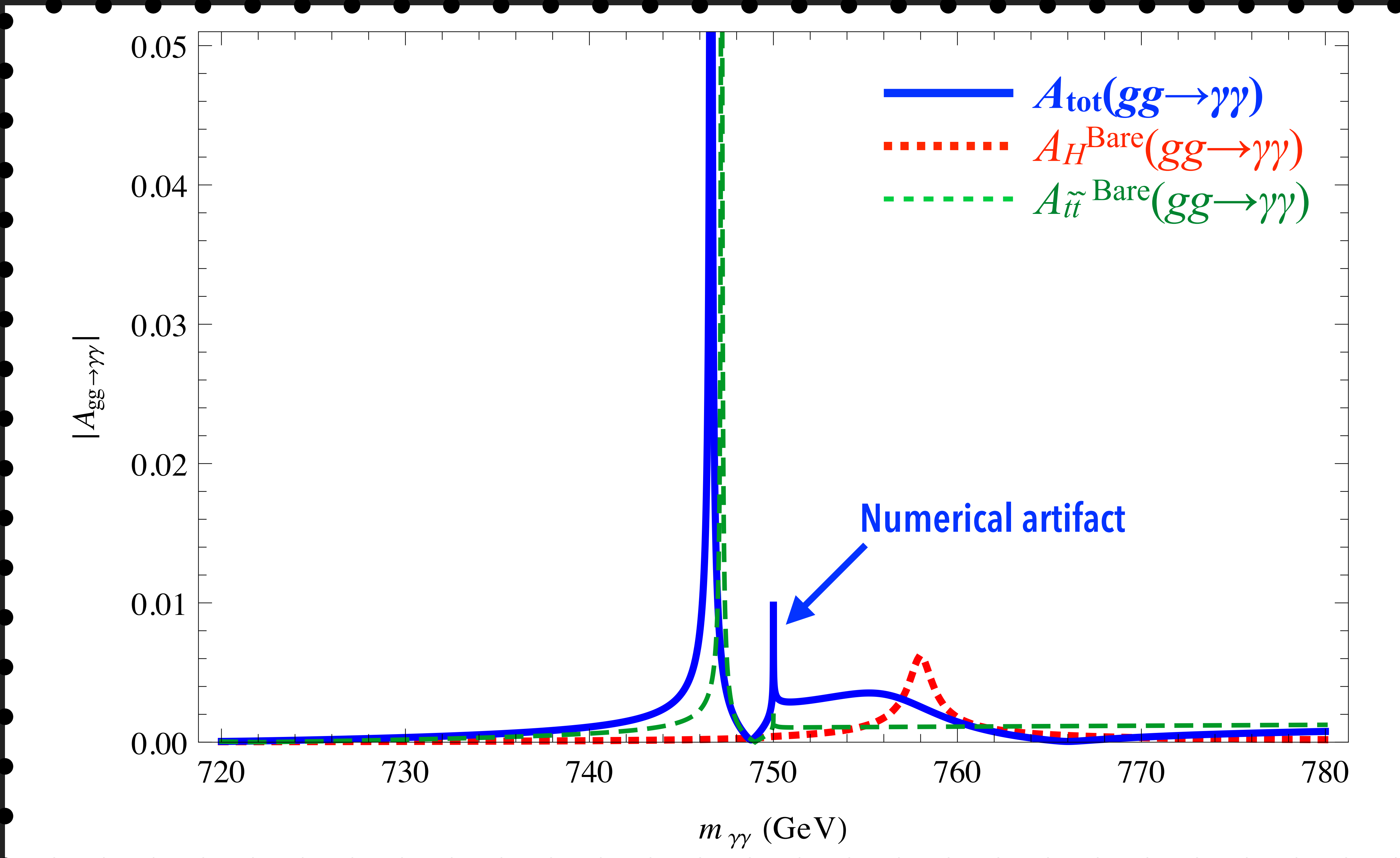

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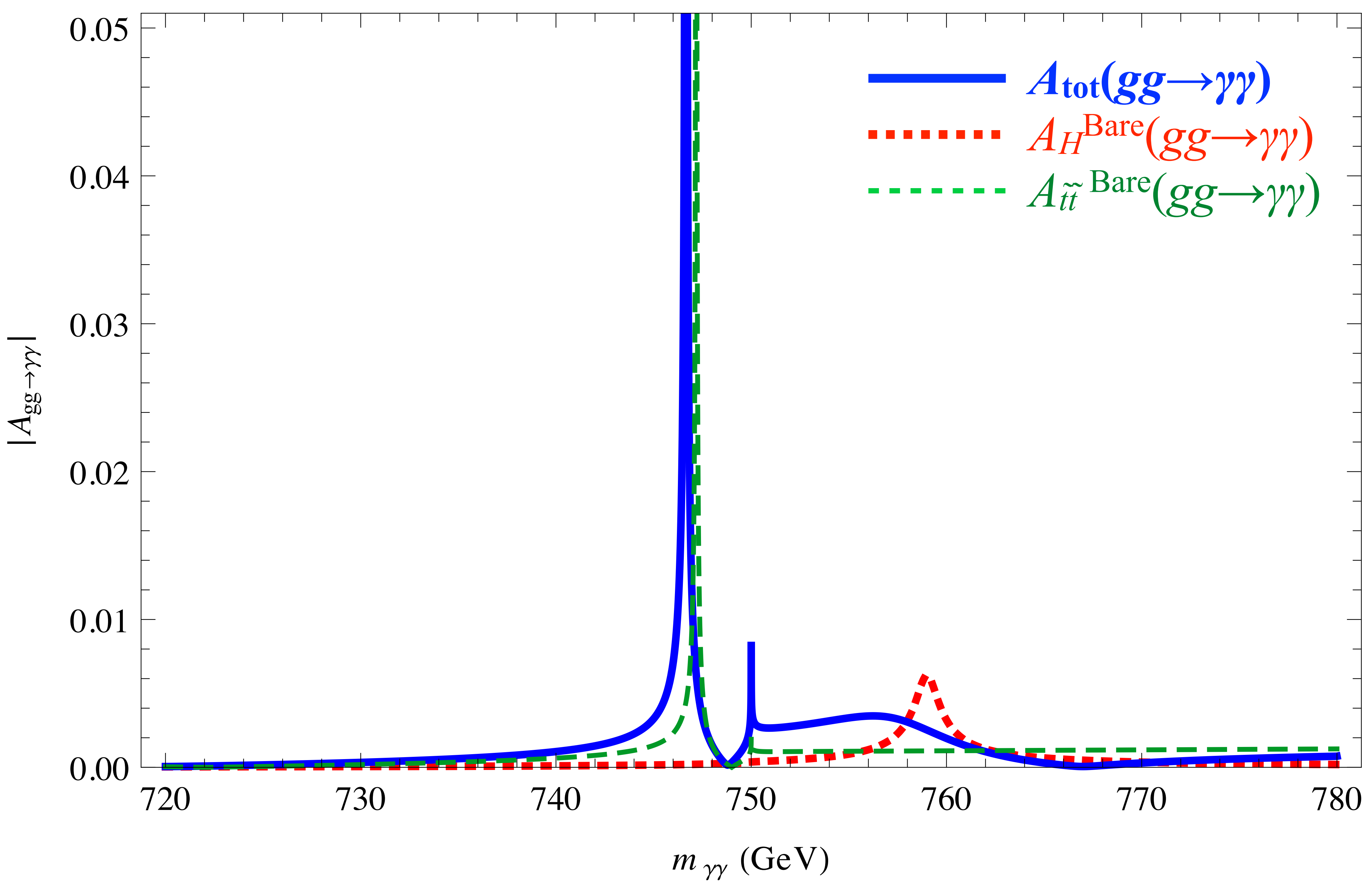

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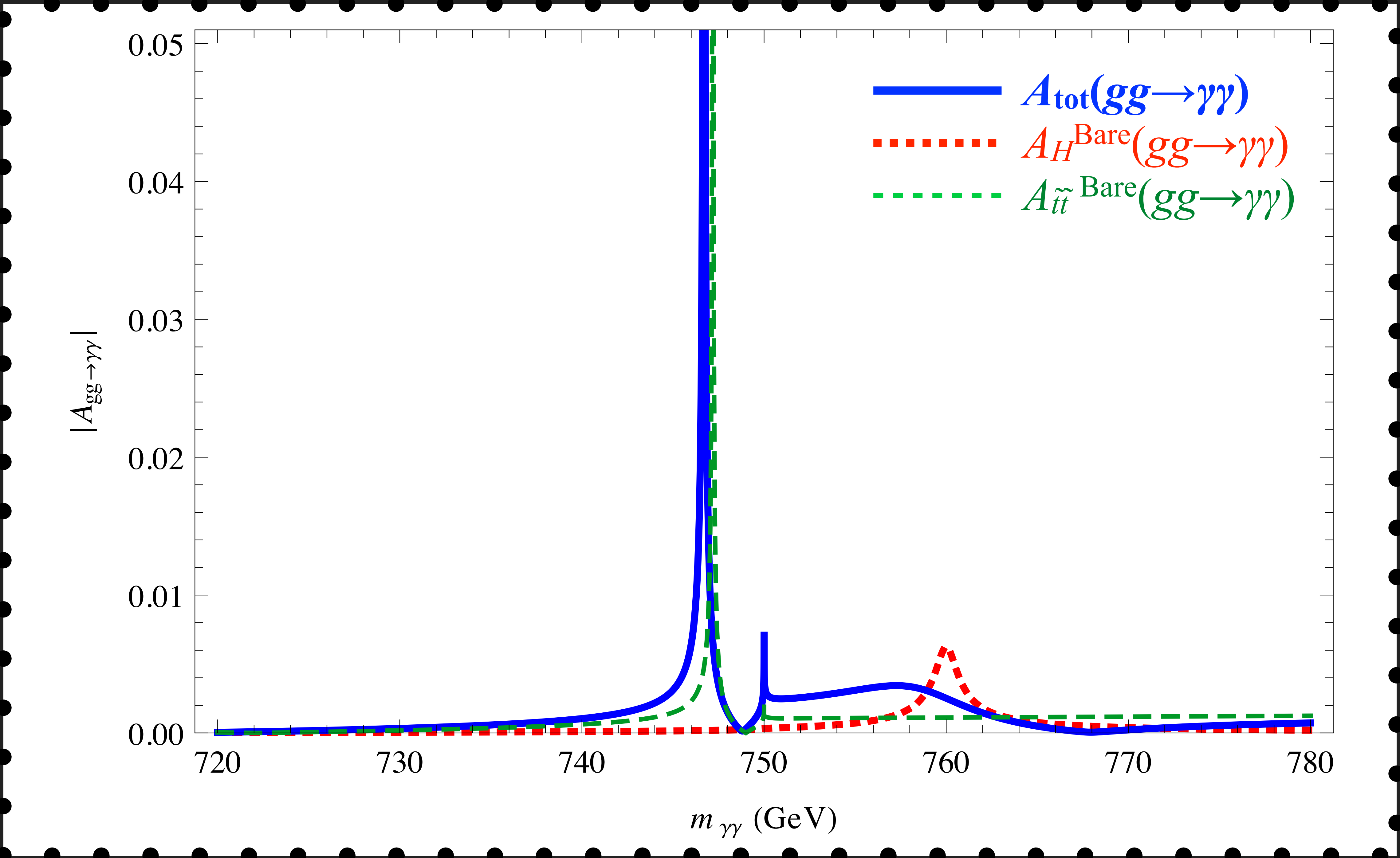

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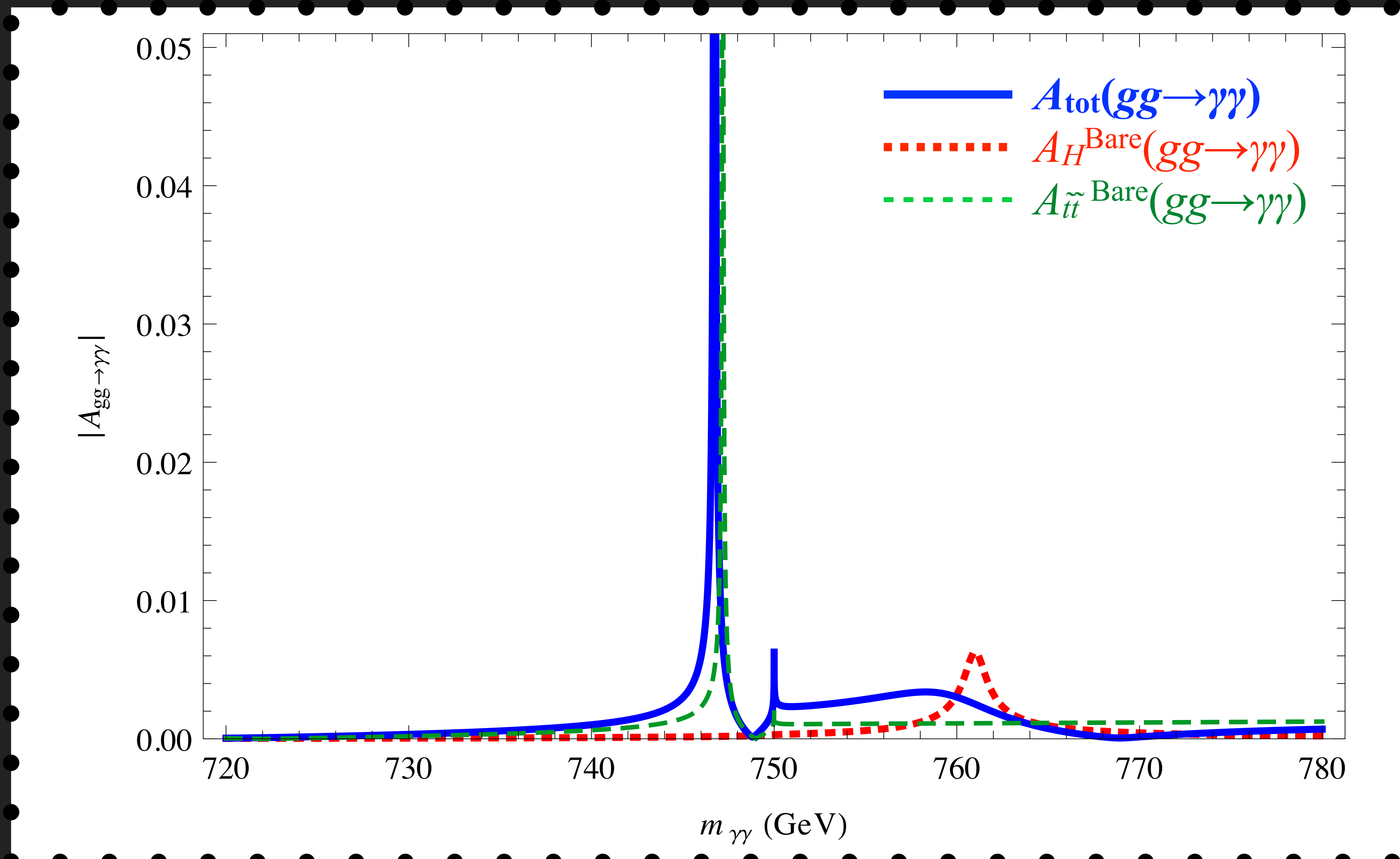

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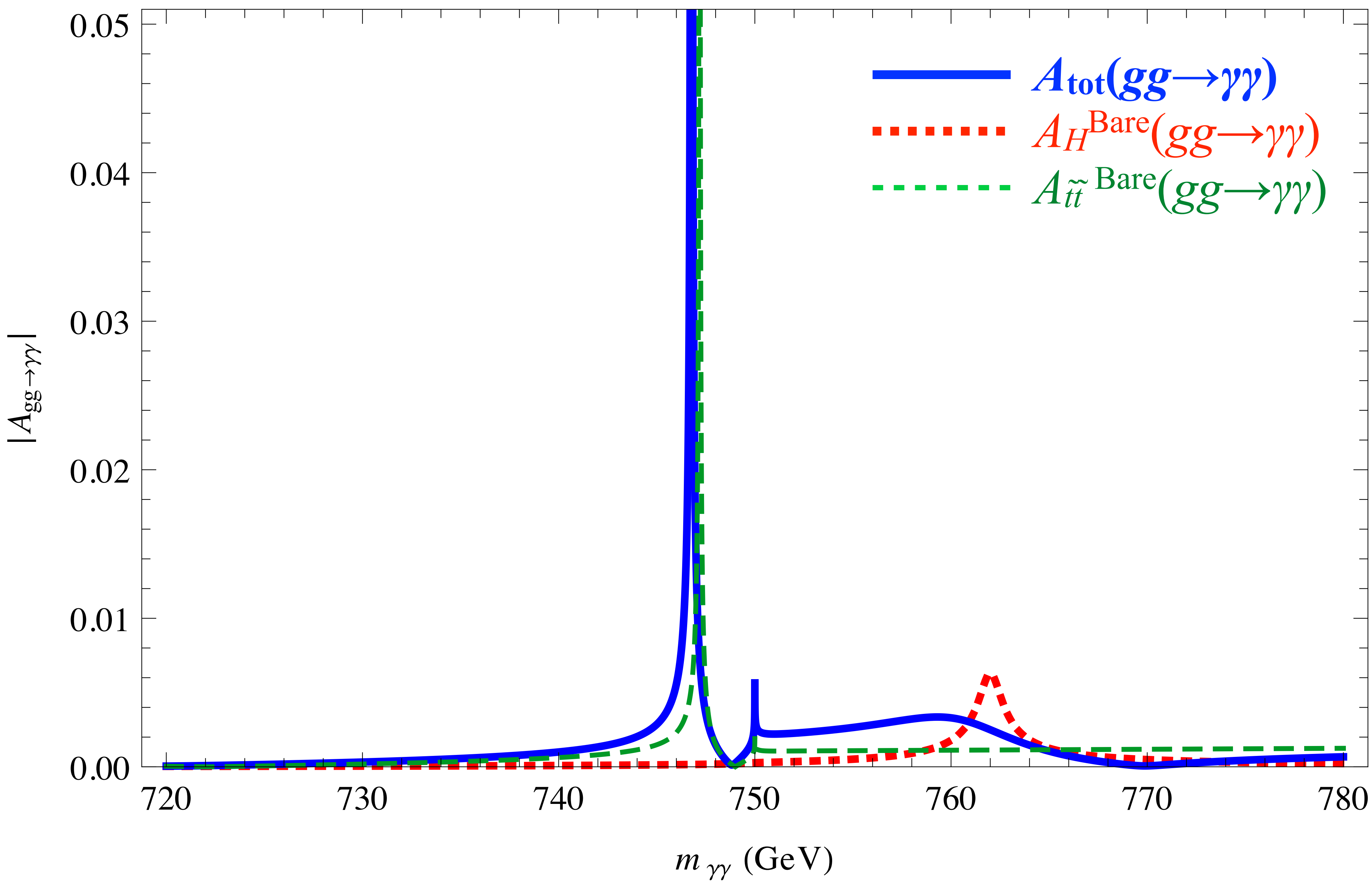

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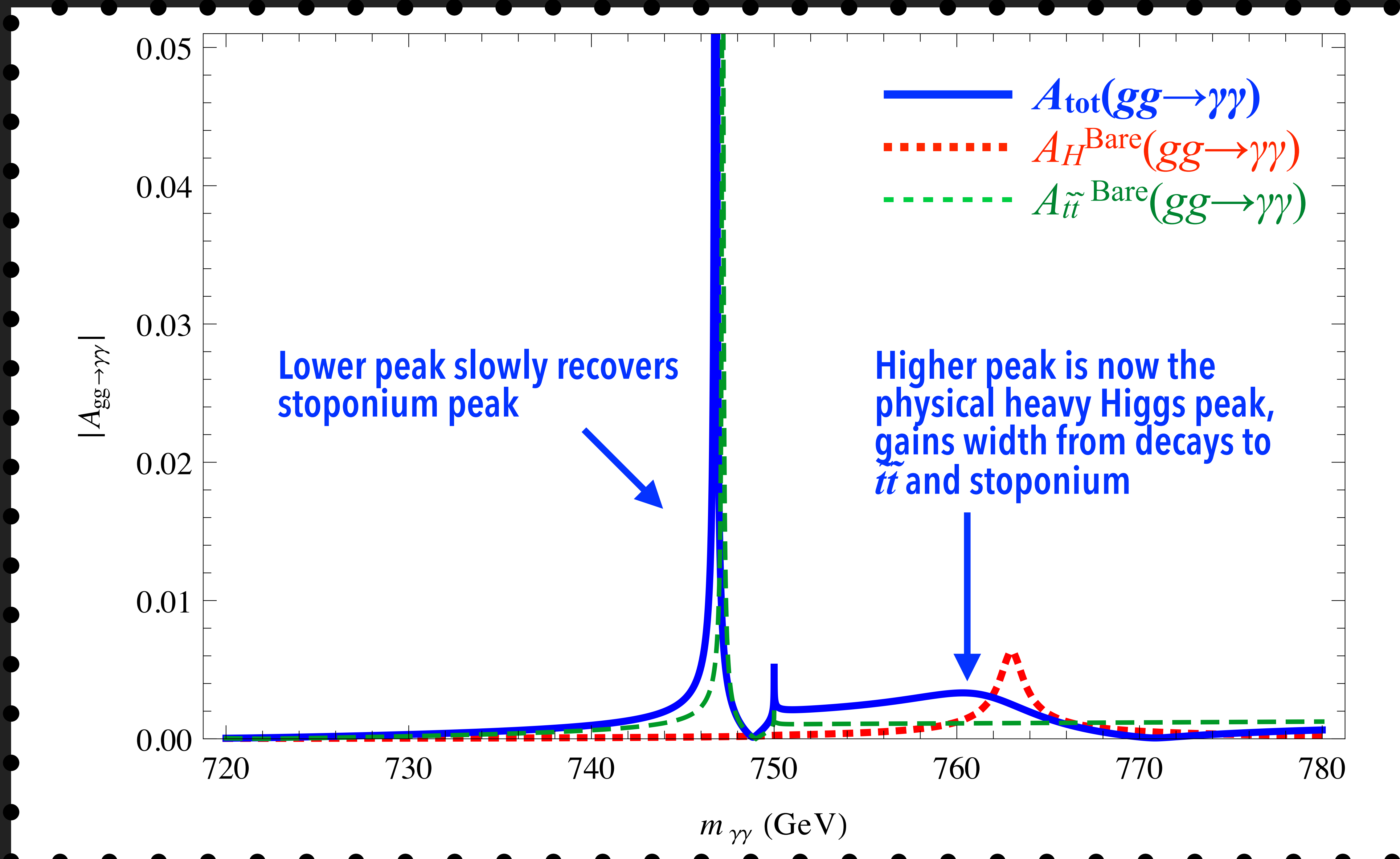

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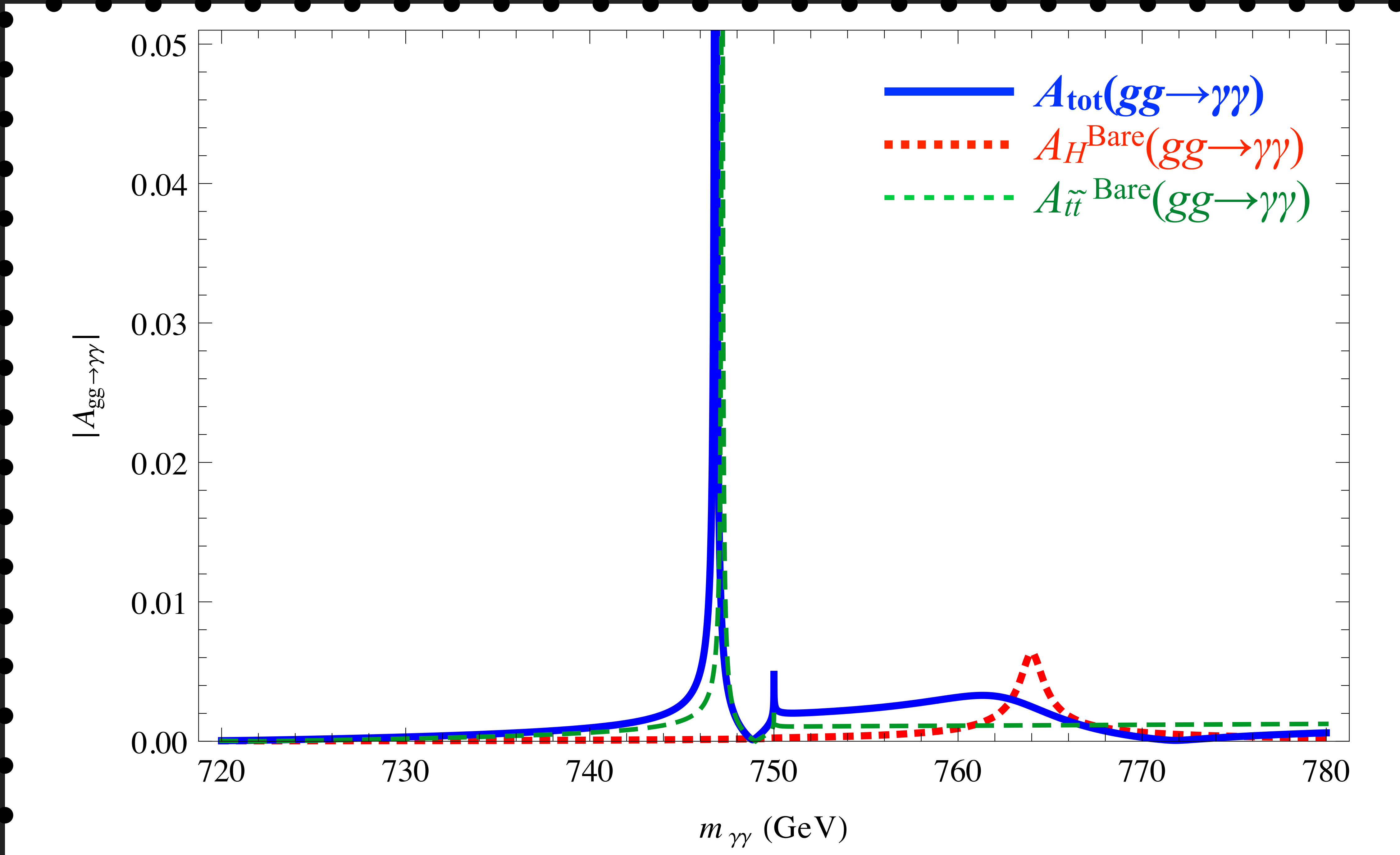

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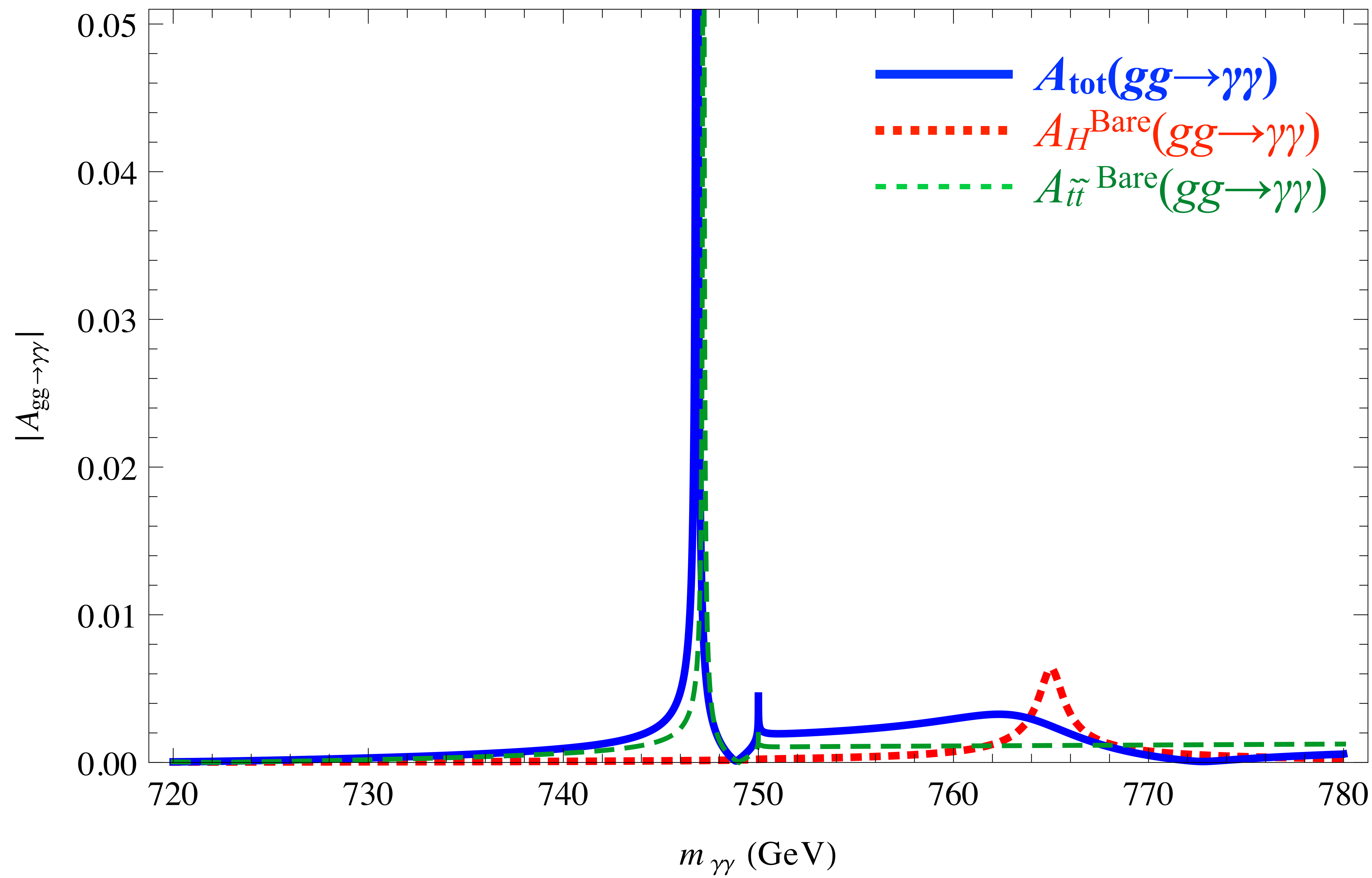

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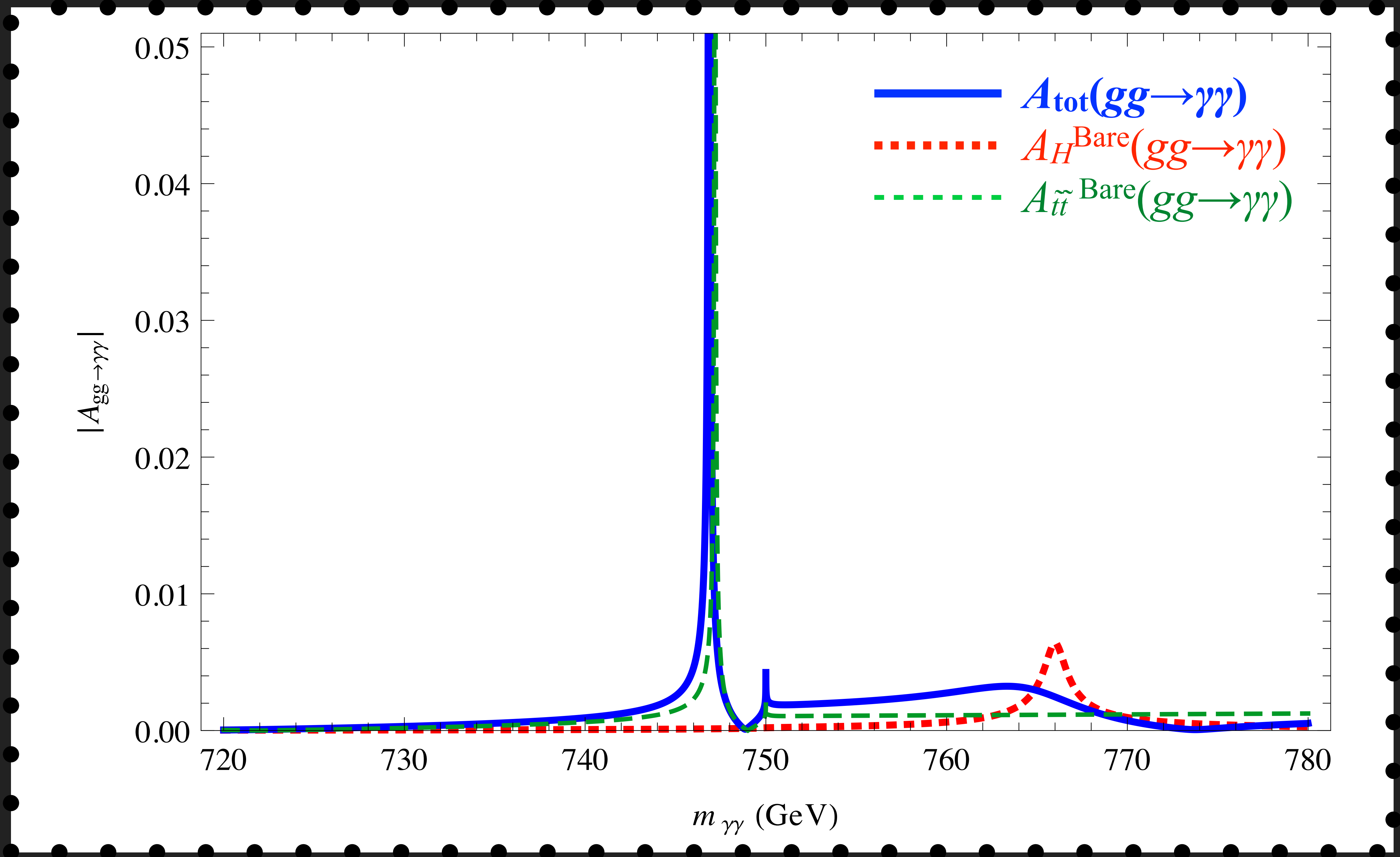

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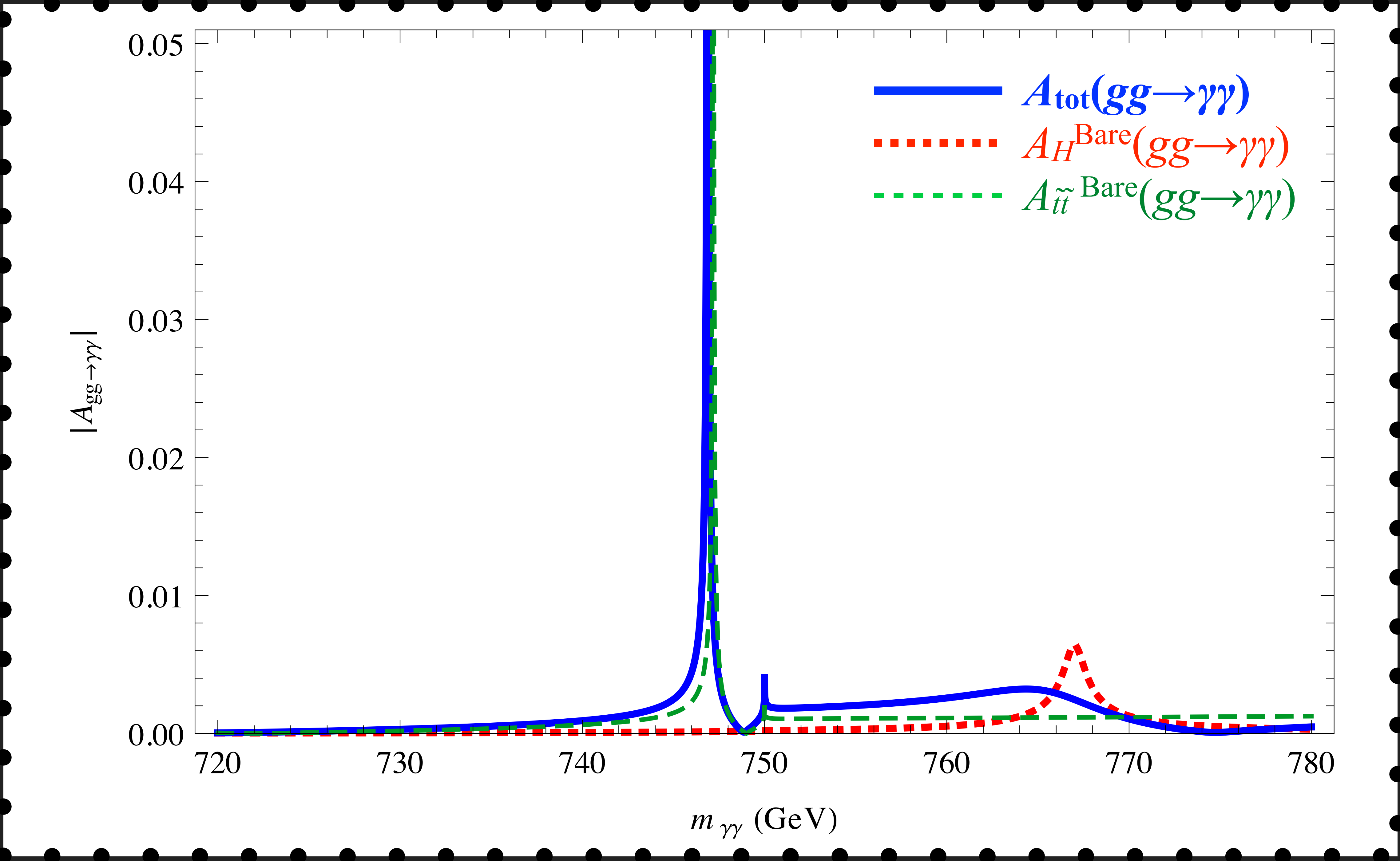

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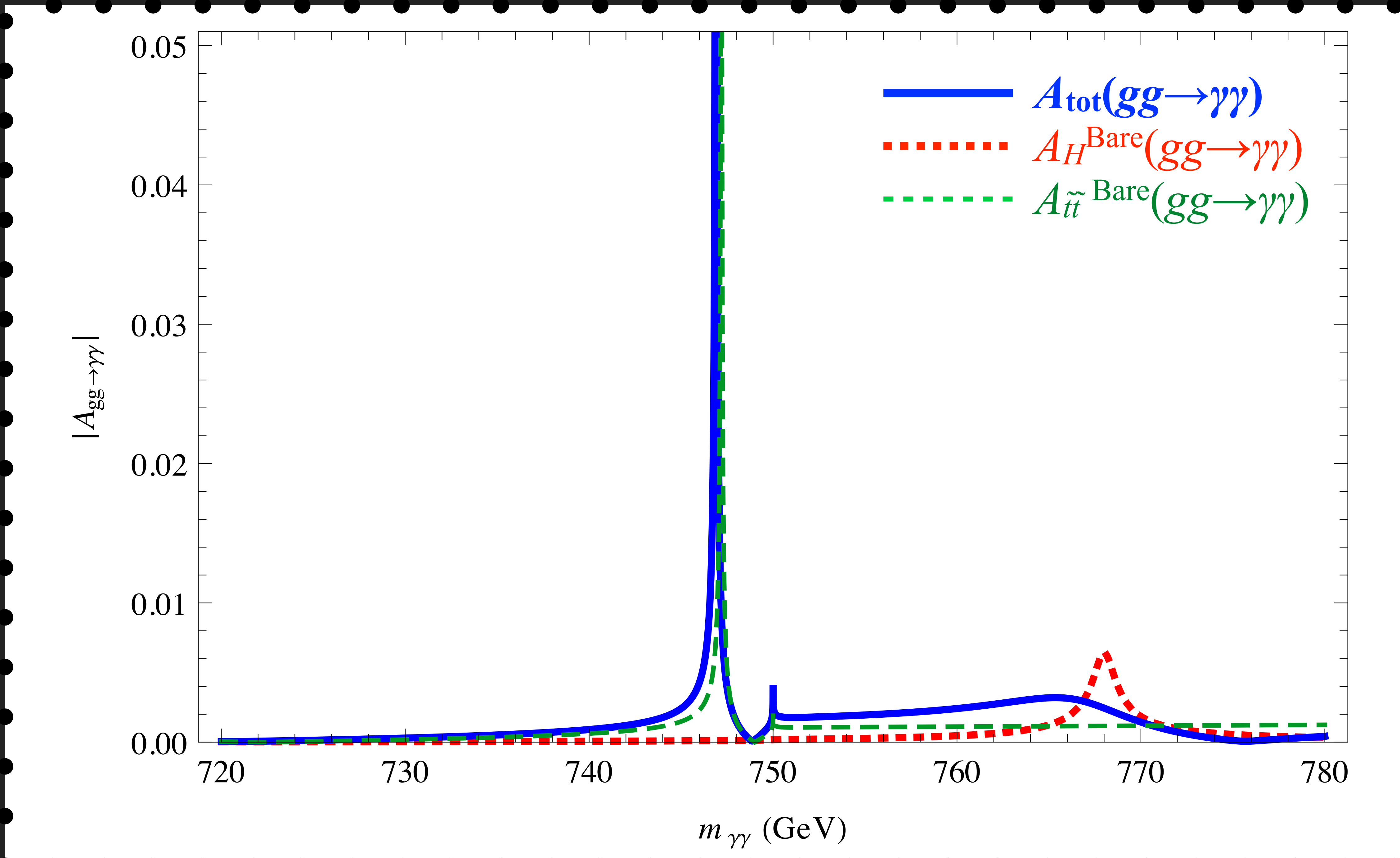

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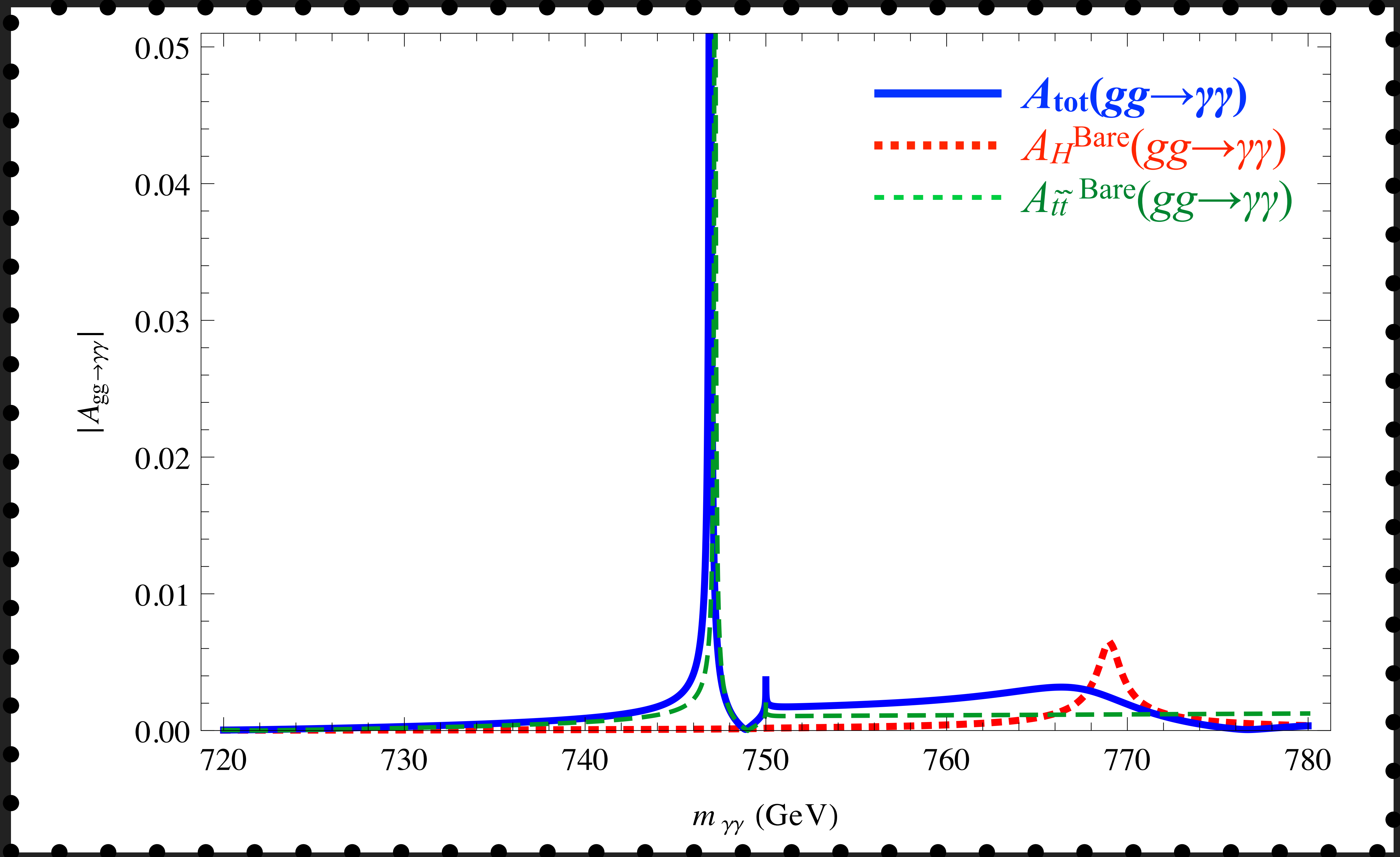

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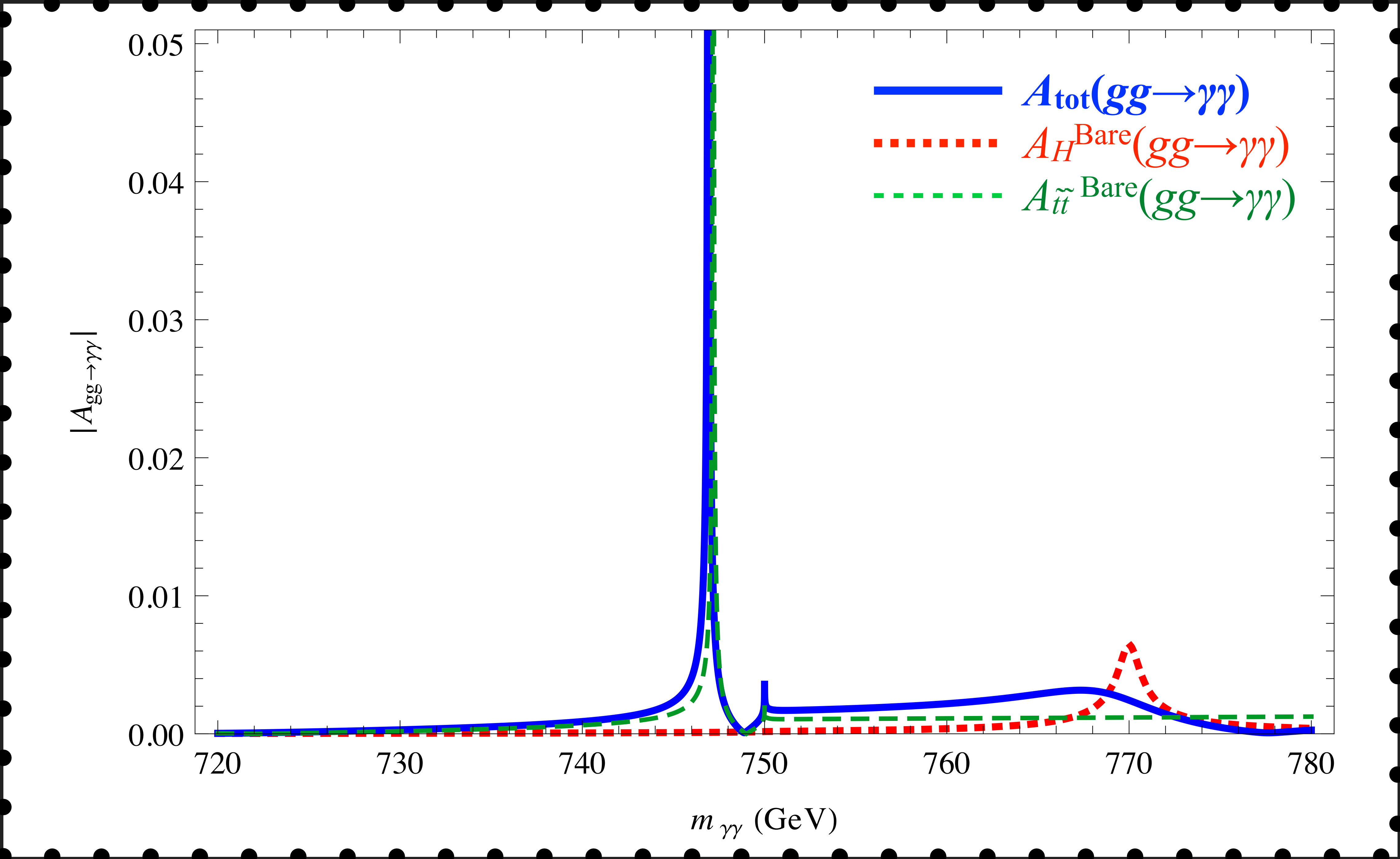

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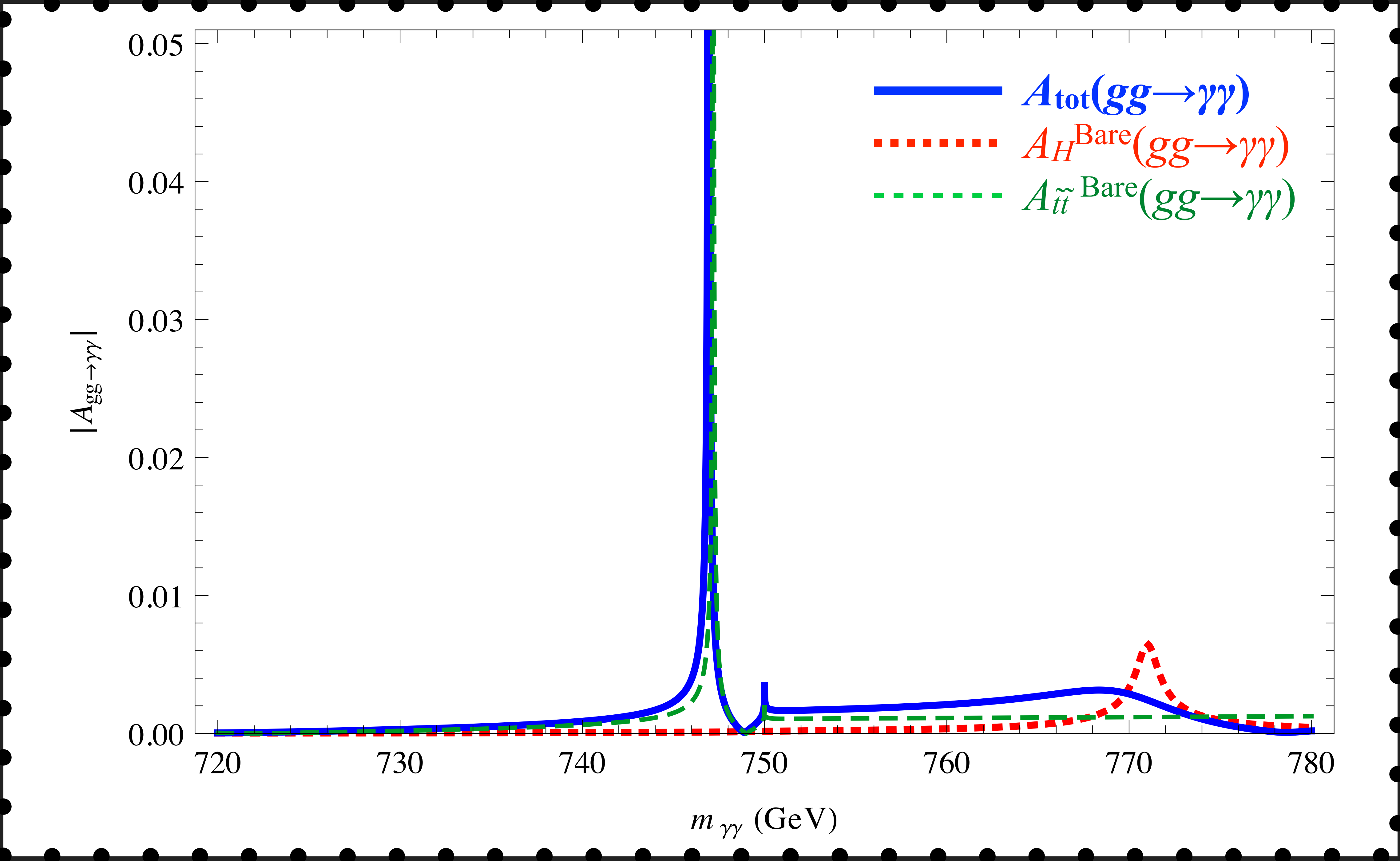

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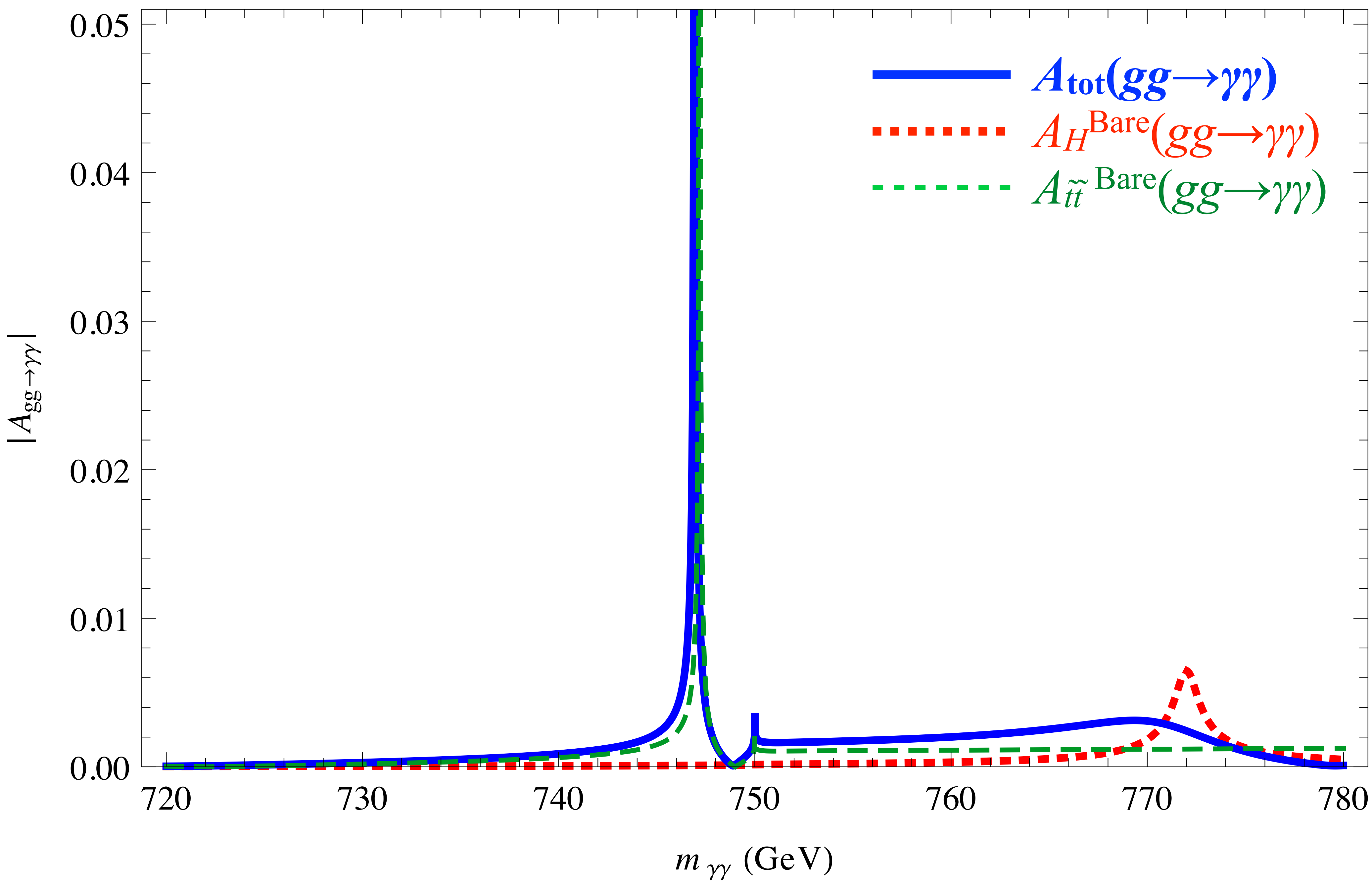

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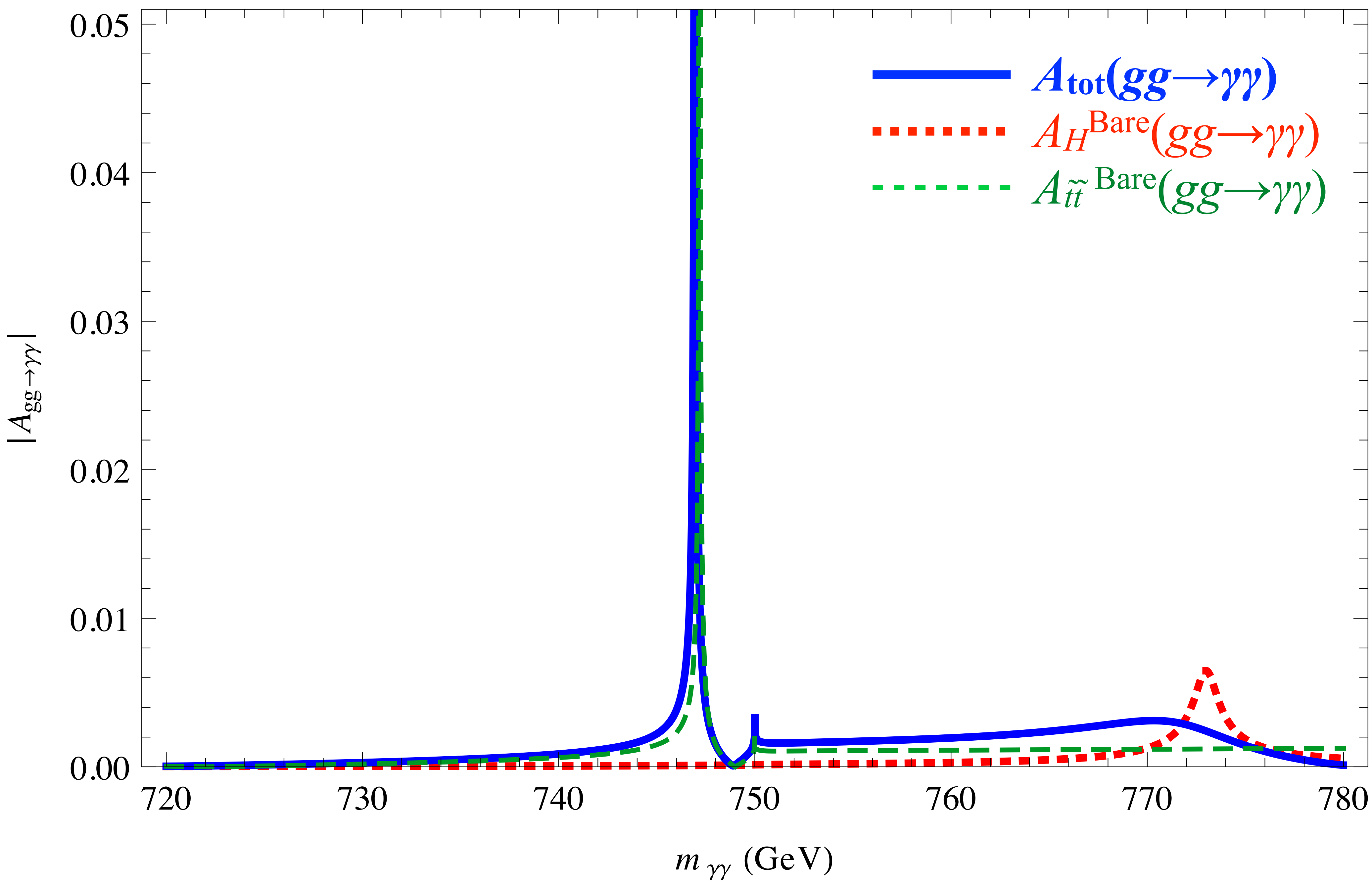

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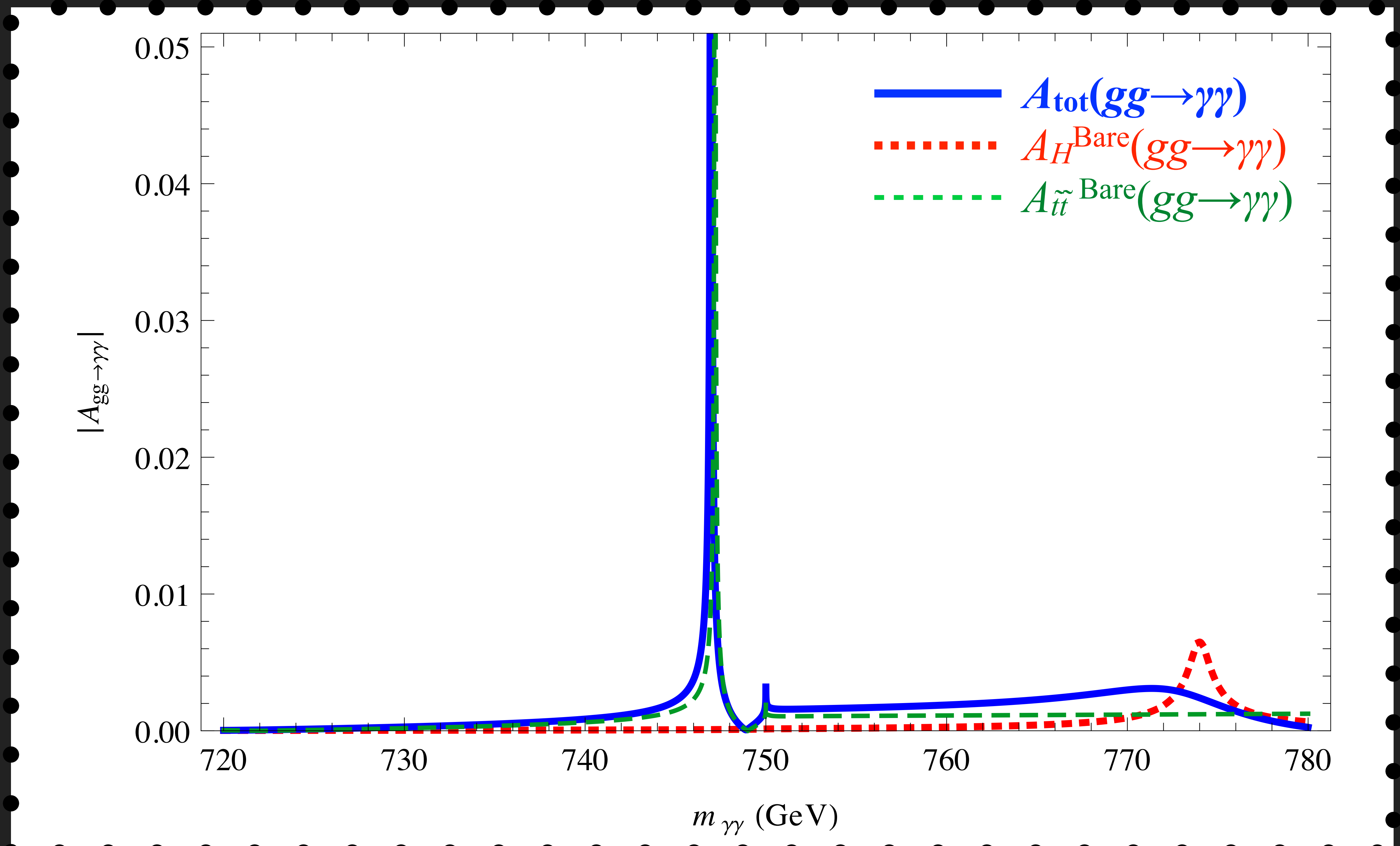

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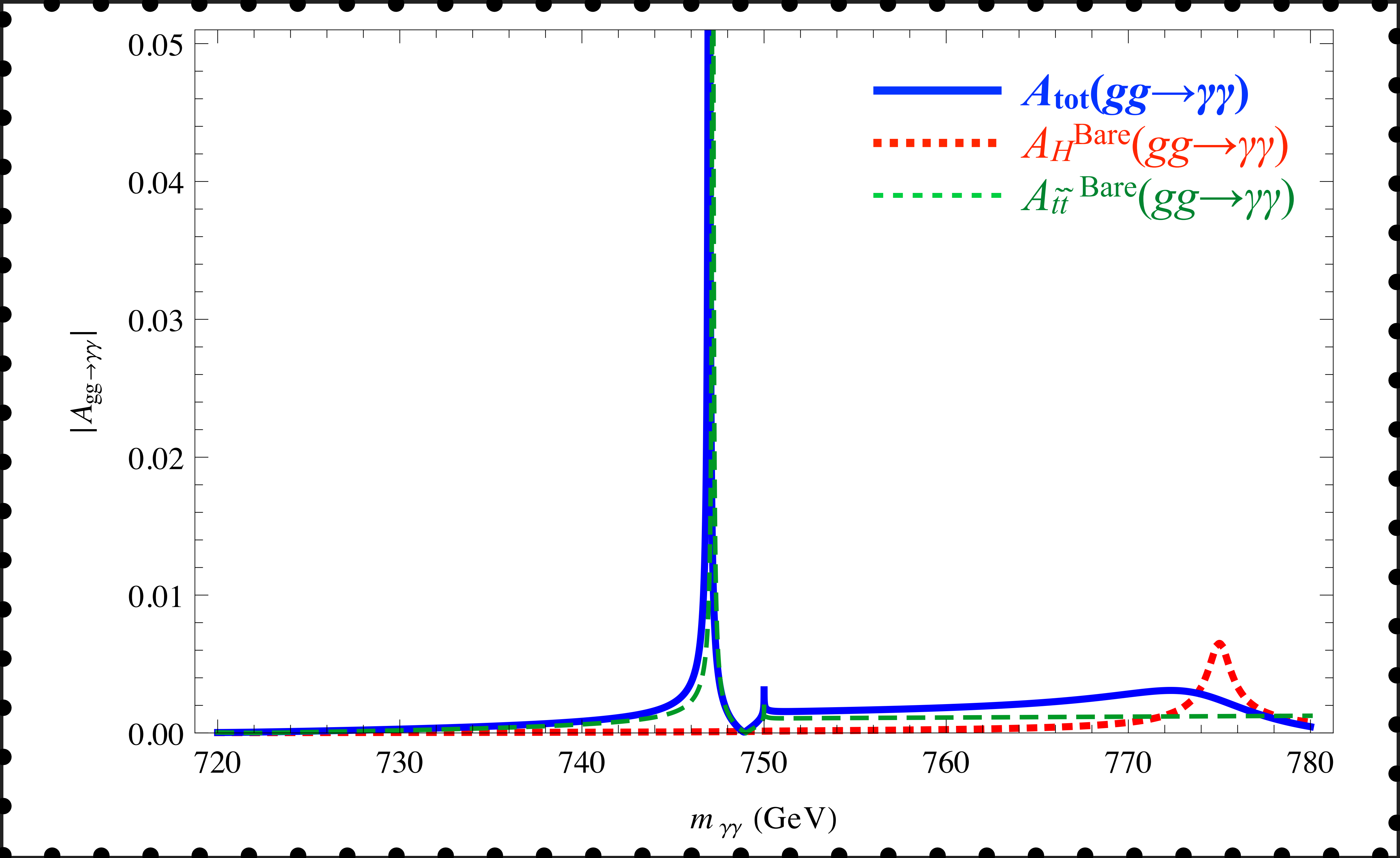

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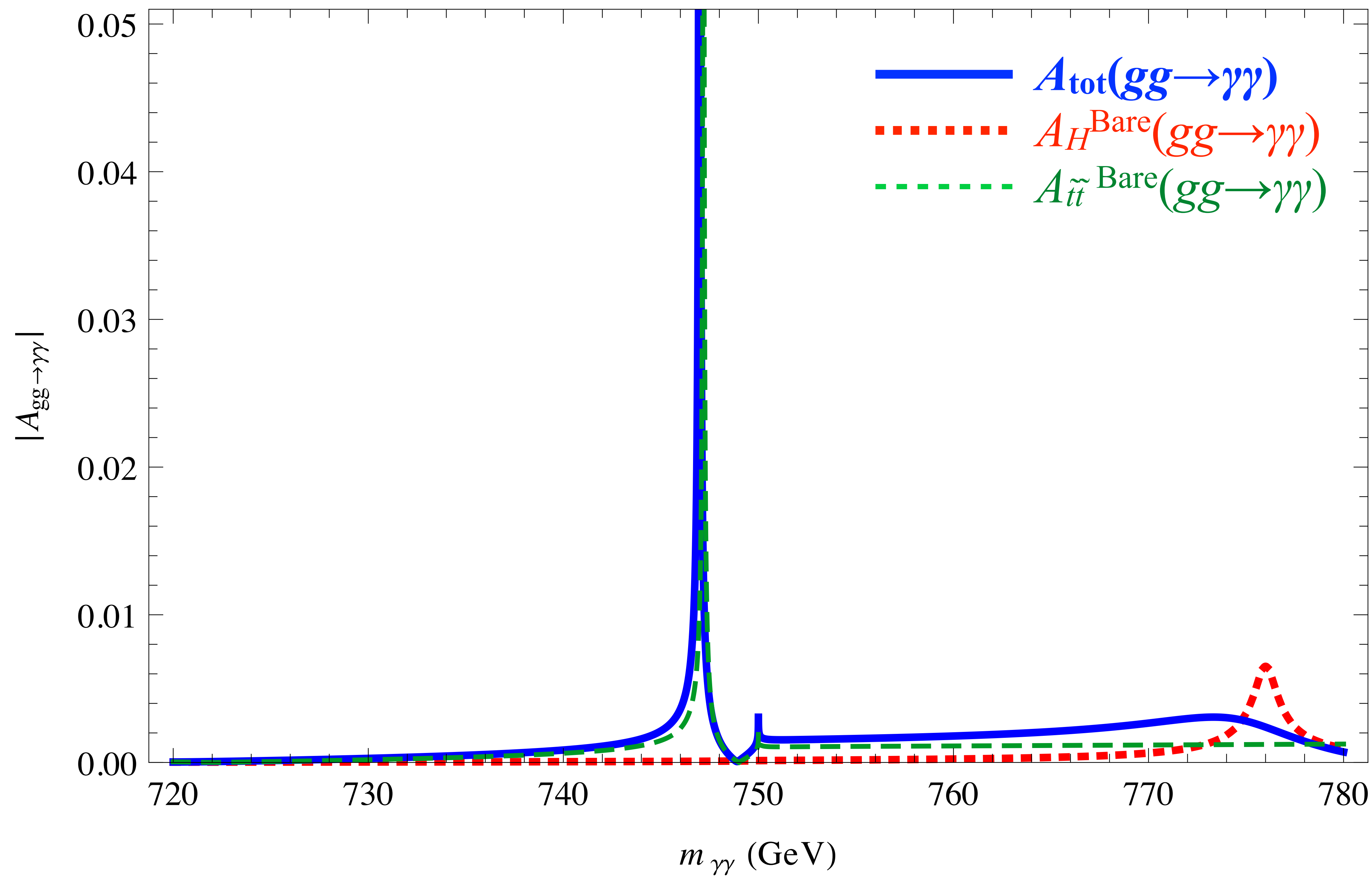

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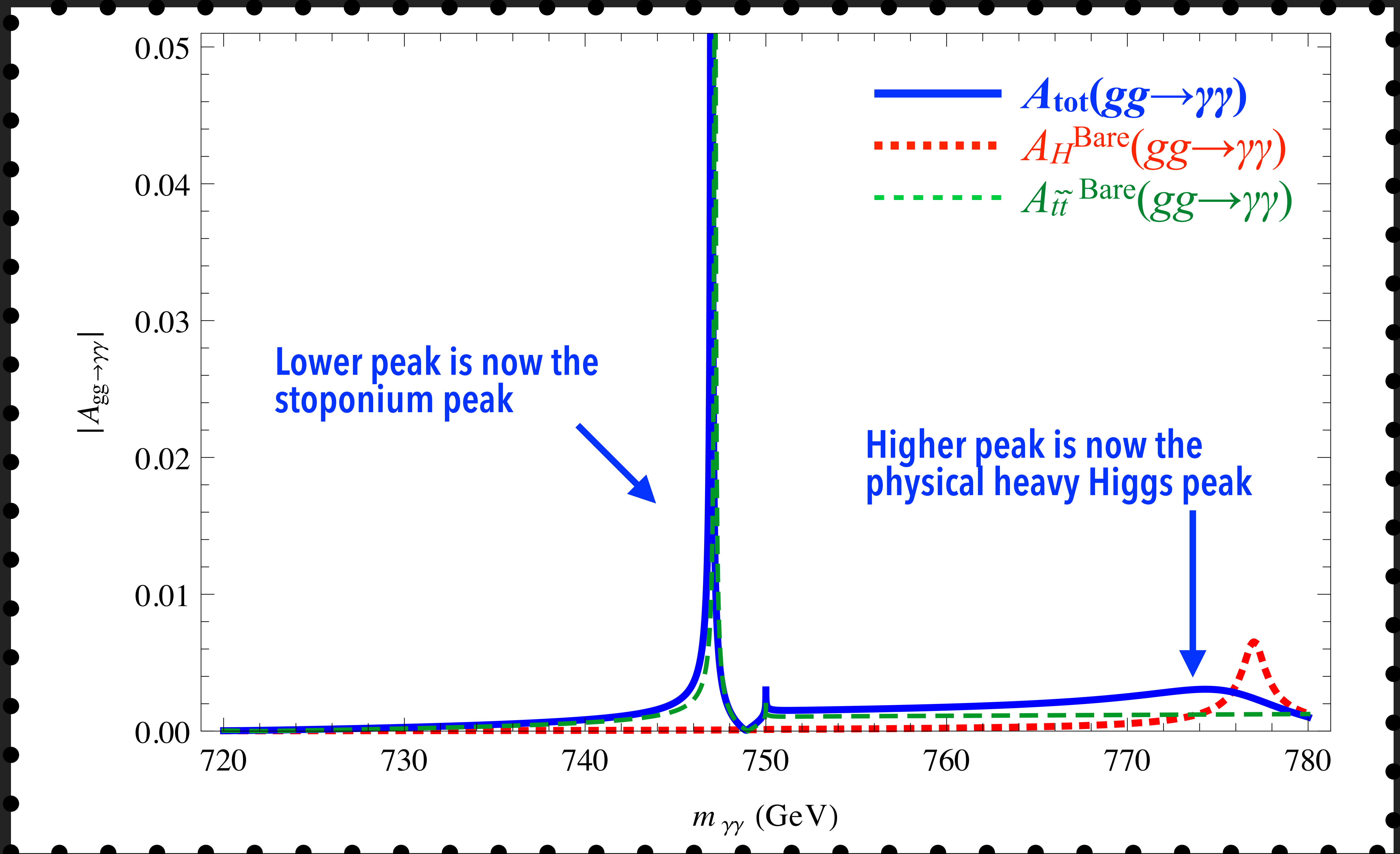
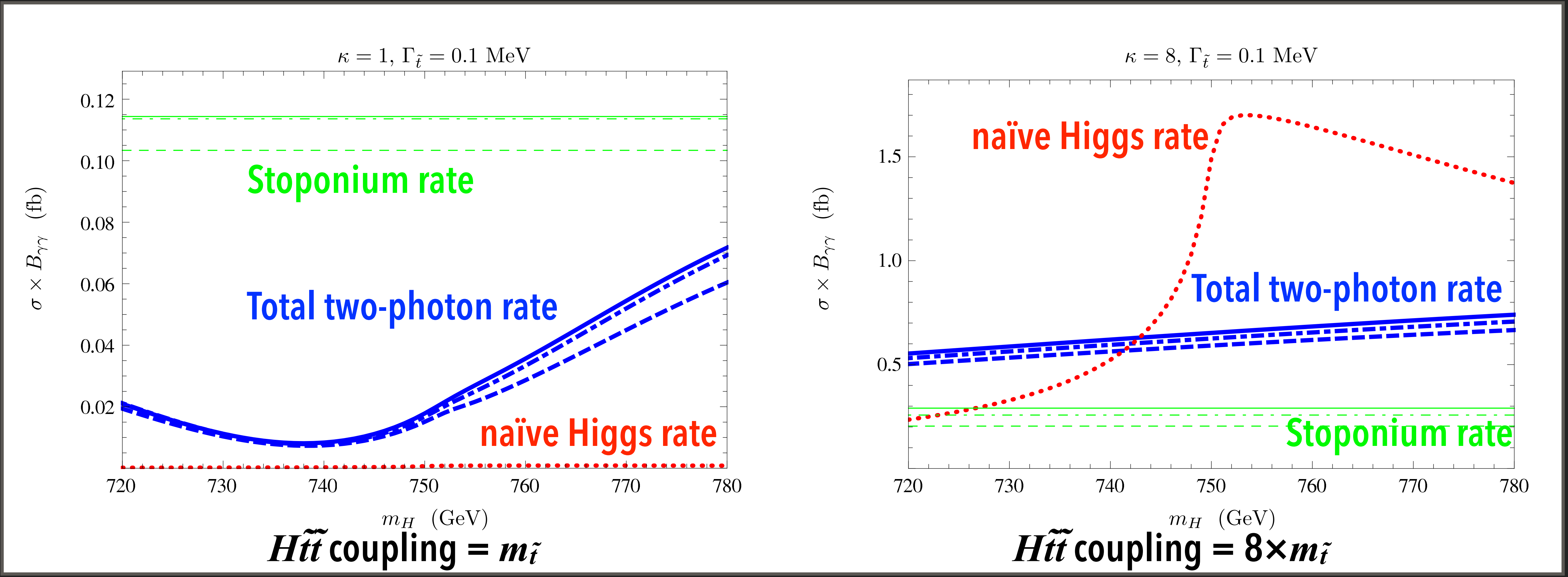


HIGGS–STOPONIUM MIXING IN TWO–PHOTON PRODUCTION

- Cross sections for small stop decay rate ($\Gamma_{\tilde{t}} = 1$ MeV) @ 13 TeV LHC

Stop mass $m_{\tilde{t}}$ = 375 GeV. Heavy Higgs mass varied from 720 to 780 GeV. Heavy Higgs width = 1.2 GeV



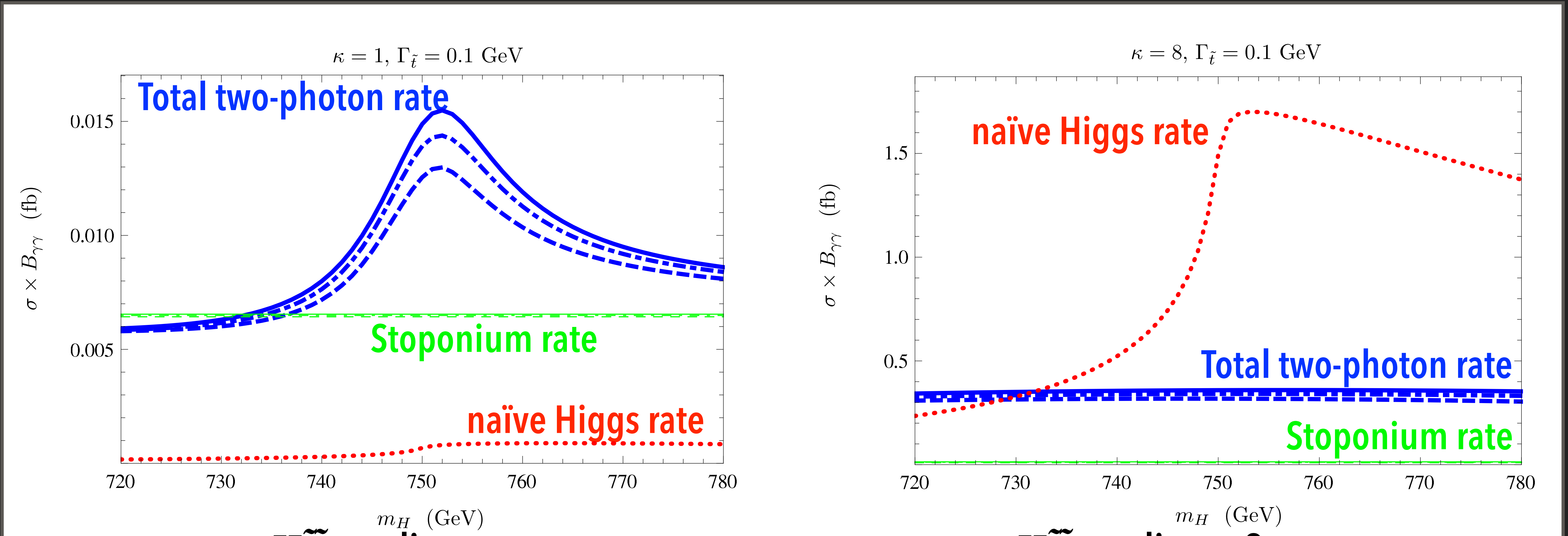
Considered different approximations for the Coulomb Green's function G with

- - - - - 1 bound state
— - — 3 bound states
—— All bound states

HIGGS–STOPONIUM MIXING IN TWO-PHOTON PRODUCTION

- Cross sections for large stop decay rate ($\Gamma_{\tilde{t}} = 1$ GeV) **@ 13 TeV LHC**

Stop mass $m_{\tilde{t}}$ = 375 GeV. Heavy Higgs mass varied from 720 to 780 GeV. Heavy Higgs width = 1.2 GeV
Peak-like structure arises from interference in mixing



$H\tilde{t}\tilde{t}$ coupling = $m_{\tilde{t}}$ **$H\tilde{t}\tilde{t}$ coupling = 8×$m_{\tilde{t}}$**

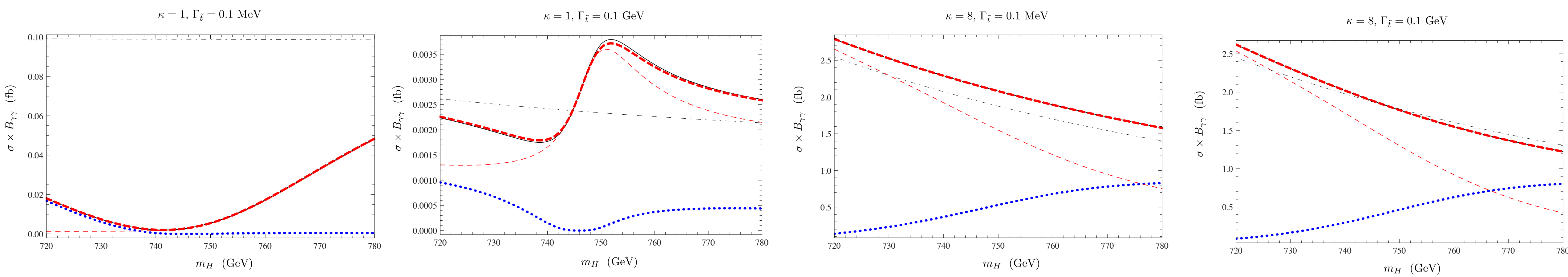
Considered different approximations for the Coulomb Green's function *G* with

- - - - - 1 bound state
— - — 3 bound states
——— All bound states

HIGGS–STOPONIUM MIXING IN TWO-PHOTON PRODUCTION

- The mixing effects we find are not accidental cancellations. We obtain qualitatively same results using two Breit-Wigner resonances, and we understand them very well in terms of mixing, interference and changes in widths.

Mixing effect with two Breit-Wigner resonances



Contribution from higher peak
Contribution from lower peak
Total cross section computed in narrow width approximation
Total cross section
Total cross section without mixing

SUMMARY

- We investigated mixing effects of stoponium and heavy Higgs in the two-photon cross section at the LHC.
- We used effective field theory techniques to resum large perturbative corrections that give rise to bound states.
- Mixing between heavy Higgs and stoponium displaces physical peaks away from threshold, and enhancement from bound states becomes inoperative.
- Good example where effective field theory methods developed for SM physics can prove useful for BSM phenomenology

BACKUP

EFFECTIVE FIELD THEORY FOR STOPONIUM

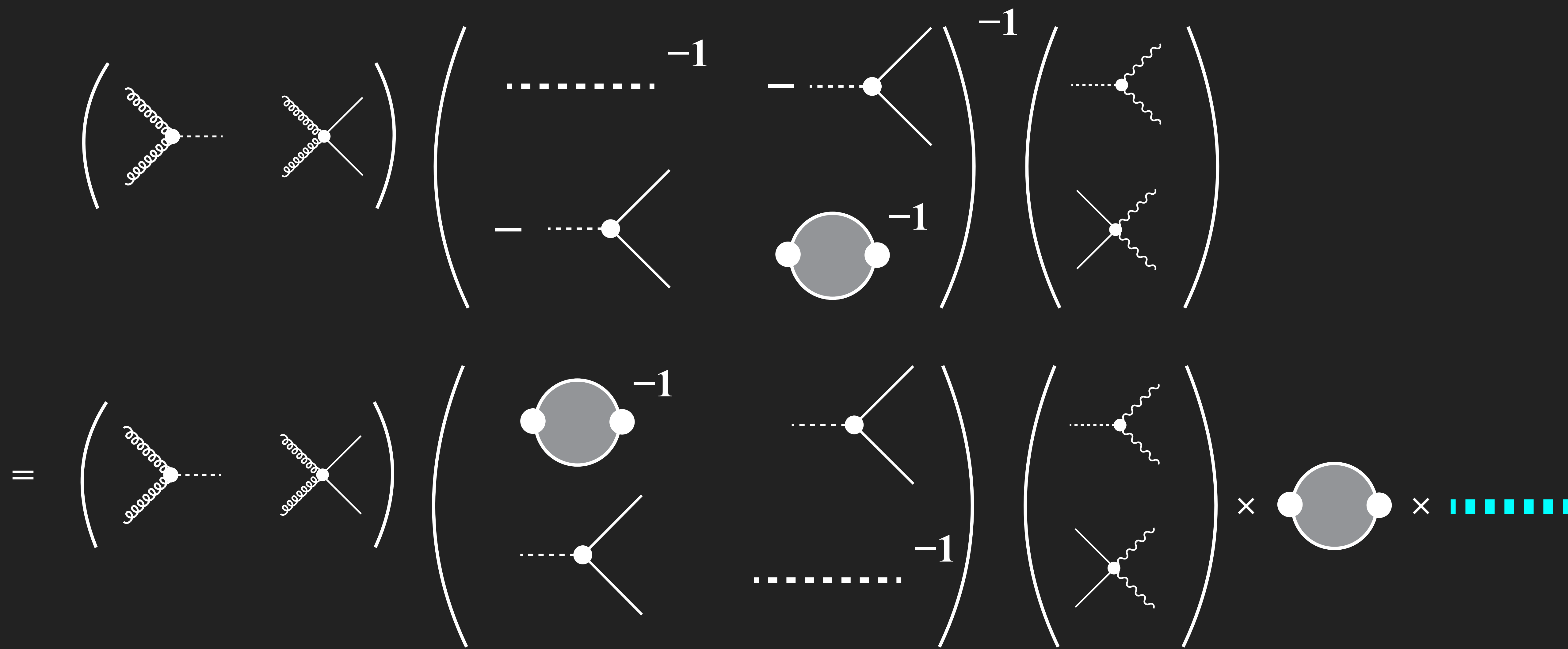
- Lagrangian for stops at leading order in v

$$\begin{aligned}\mathcal{L}_{\tilde{t}\tilde{t}} = {} & \psi^\dagger \left(2im_{\tilde{t}} D_0 + \boldsymbol{D}^2 \right) \psi + \chi^\dagger \left(2im_{\tilde{t}} D_0 + \boldsymbol{D}^2 \right) \chi - iC_{H\tilde{t}\tilde{t}} H (\psi^\dagger \chi + \chi^\dagger \psi) \\ & + (i/2) C_{gg\tilde{t}\tilde{t}} \frac{1}{N_c^2 - 1} (\psi^\dagger \chi + \chi^\dagger \psi) G^a_{\mu\nu} G^{a\mu\nu} + (i/2) C_{\gamma\gamma\tilde{t}\tilde{t}} (\psi^\dagger \chi + \chi^\dagger \psi) F_{\mu\nu} F^{\mu\nu} \\ & + (i/2) C_{ggH} \frac{1}{N_c^2 - 1} H G^a_{\mu\nu} G^{a\mu\nu} + (i/2) C_{\gamma\gamma H} H F_{\mu\nu} F^{\mu\nu} \\ & - iC_{\tilde{t}\tilde{t}H\tilde{t}\tilde{t}} \frac{1}{N_c} \psi^\dagger \chi \chi^\dagger \psi + i \mathrm{Im}\, T_{\tilde{t}\tilde{t} \to gg \to \tilde{t}\tilde{t}} \frac{1}{N_c} \psi^\dagger \chi \chi^\dagger \psi,\end{aligned}$$

- ψ, χ : stop and antistop fields H : heavy Higgs
  D : covariant derivative
  G, F : gluon and photon field-strength tensors

HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION

- Total amplitude is conveniently written in matrix form



HIGGS–STOPONIUM MIXING IN TWO-PHOTON PRODUCTION

- Large stop decay rate ($\Gamma_{\tilde{t}}= 1$ GeV), $H\tilde{t}\tilde{t}$ coupling = $m_{\tilde{t}}$

Stop mass $m_{\tilde{t}}$ = 375 GeV. Heavy Higgs mass varied from 720 to 780 GeV.

- Peak-like structure arises from interference in mixing, and *not from enhancement from stoponium peak*