

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)

12TH INTERNATIONAL WORKSHOP ON HEAVY QUARKONIUM
NOVEMBER 6-10, 2017, PEKING UNIVERSITY, BEIJING, CHINA

OUTLINE

- ▶ Mixing in BSM models
- ▶ Effective field theory for stop and antistop near threshold
- ▶ Effective field theory calculation of $gg \rightarrow \gamma\gamma$ 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.

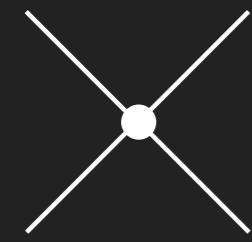
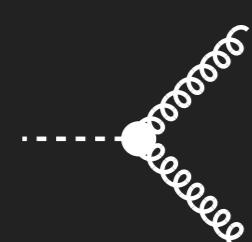
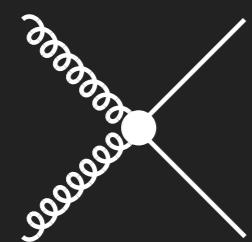
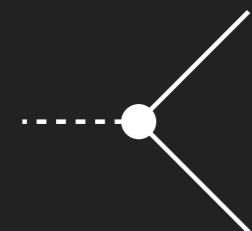
Djouadi and Pilaftsis, PLB765, 175 (2017) [arXiv:1605.01040]

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

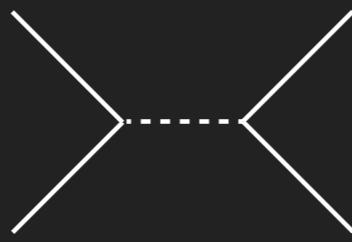
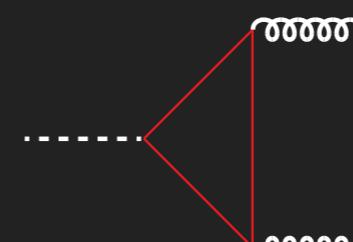
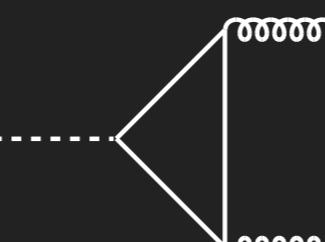
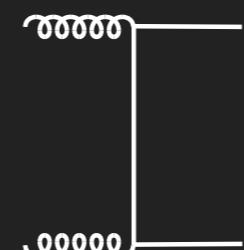
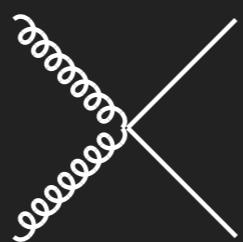
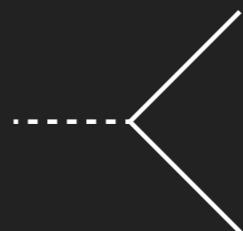
EFFECTIVE FIELD THEORY FOR STOPONIUM

- Operators at leading order in v

EFT operators



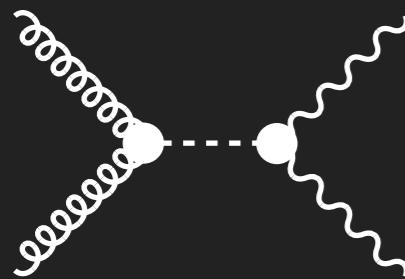
Full-theory diagrams



gluon or photon
 stop or antistop
 heavy Higgs
 SM fermions

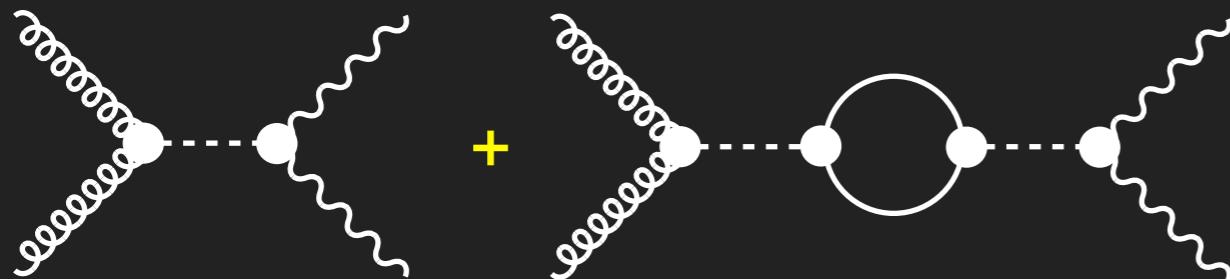
TWO-PHOTON PRODUCTION NEAR STOP-ANTISTOP THRESHOLD

- ▶ $gg \rightarrow H \rightarrow \gamma\gamma$: tree-level diagram



TWO-PHOTON PRODUCTION NEAR STOP-ANTISTOP THRESHOLD

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



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

$$\text{Diagram: } \text{circle} + \text{circle with vertical gluon} + \text{circle with horizontal gluons} + \dots = \text{shaded circle} = -iG/(4m_t^2)$$

STOP-ANTISTOP GREEN'S FUNCTION

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

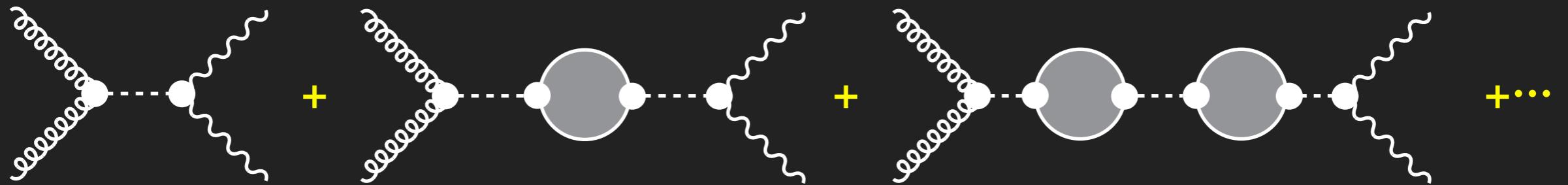
$$\text{Diagram: } \text{---} + \text{---} + \text{---} + \dots = \text{---} = -iG/(4m_t^2)$$

The diagram shows a series of Feynman-like diagrams representing the perturbative expansion of the Green's function. It consists of three terms separated by plus signs, followed by an ellipsis. Each term shows two vertices connected by a horizontal line, with a vertical wavy line (representing a gluon) connecting them. The third term in the sequence has a shaded gray circle around its two vertices. This visualizes the iterative nature of the perturbative expansion.

- ▶ Green's function G is sharply peaked near bound states of $t\bar{t}$ 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

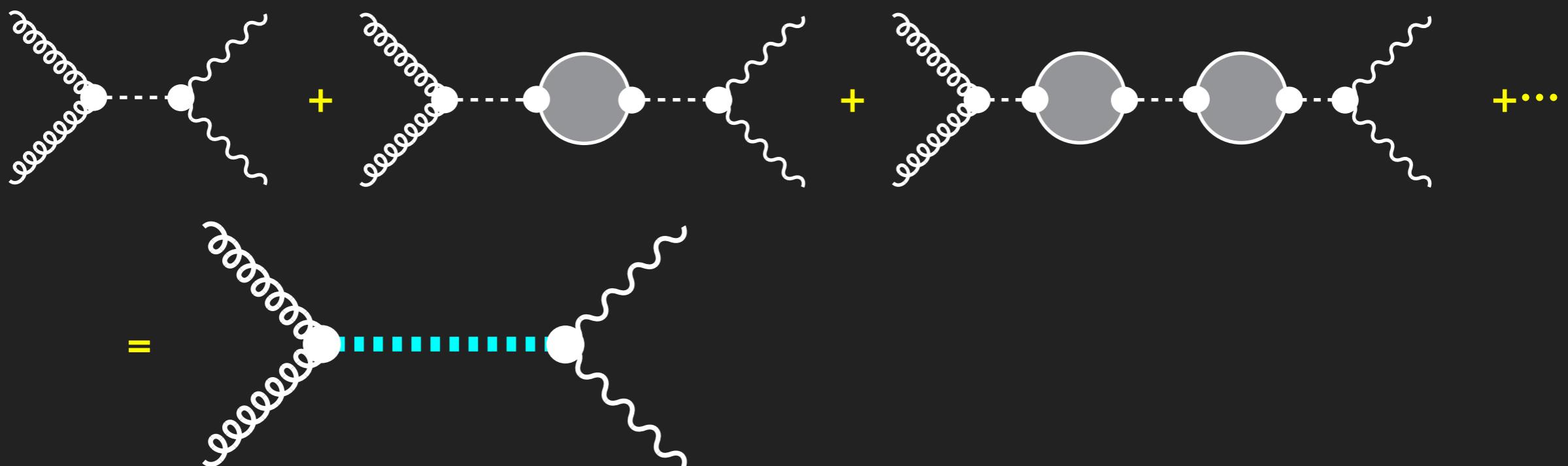
- ▶ $gg \rightarrow H \rightarrow \gamma\gamma$: tree-level diagram + corrections from $\tilde{t}\tilde{t}$



- ▶ 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 $\rightarrow H \rightarrow \gamma\gamma$: $\tilde{t}\tilde{t}$ Green's function resummed to all orders

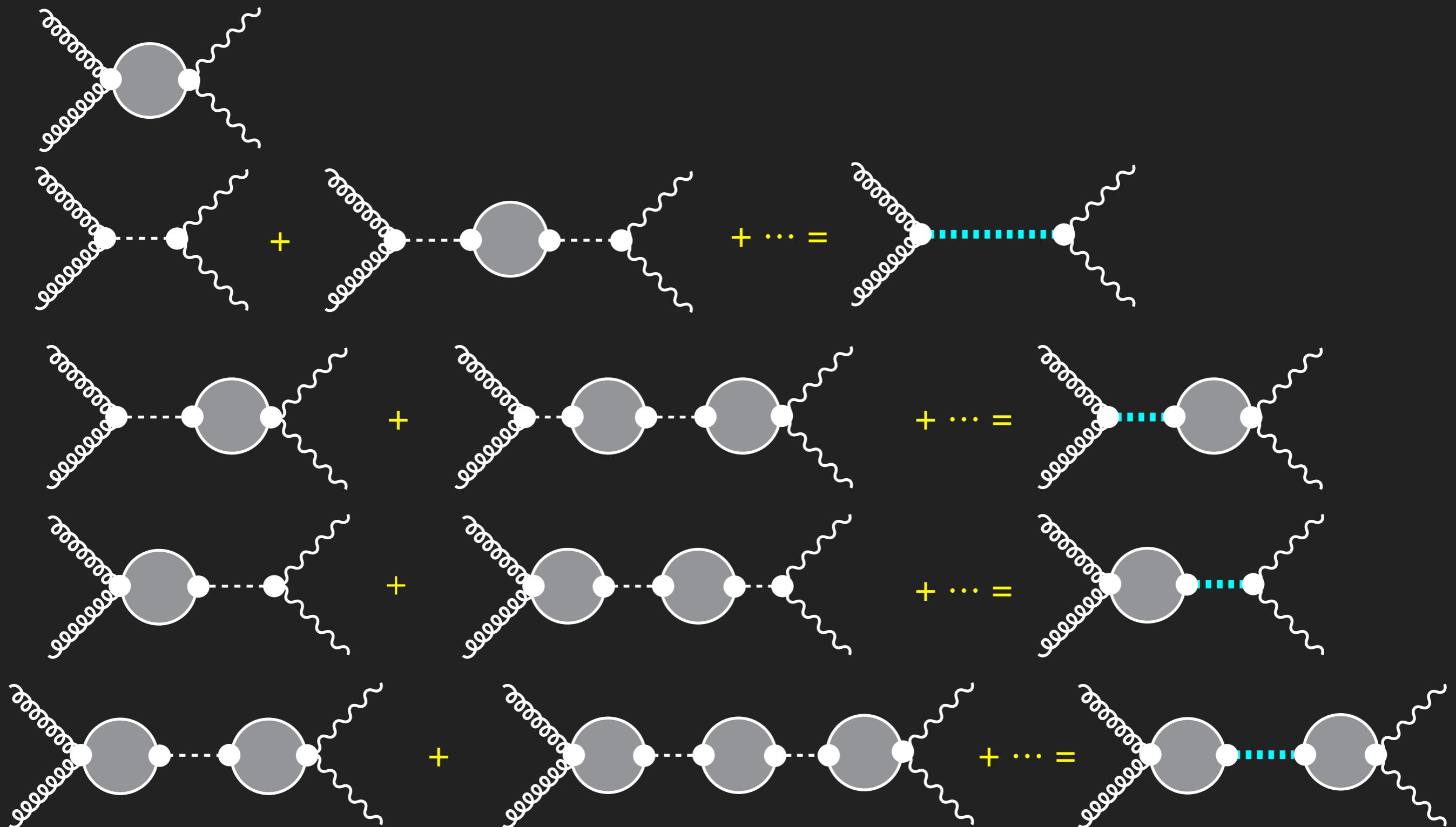


- Resummation dresses Higgs propagator

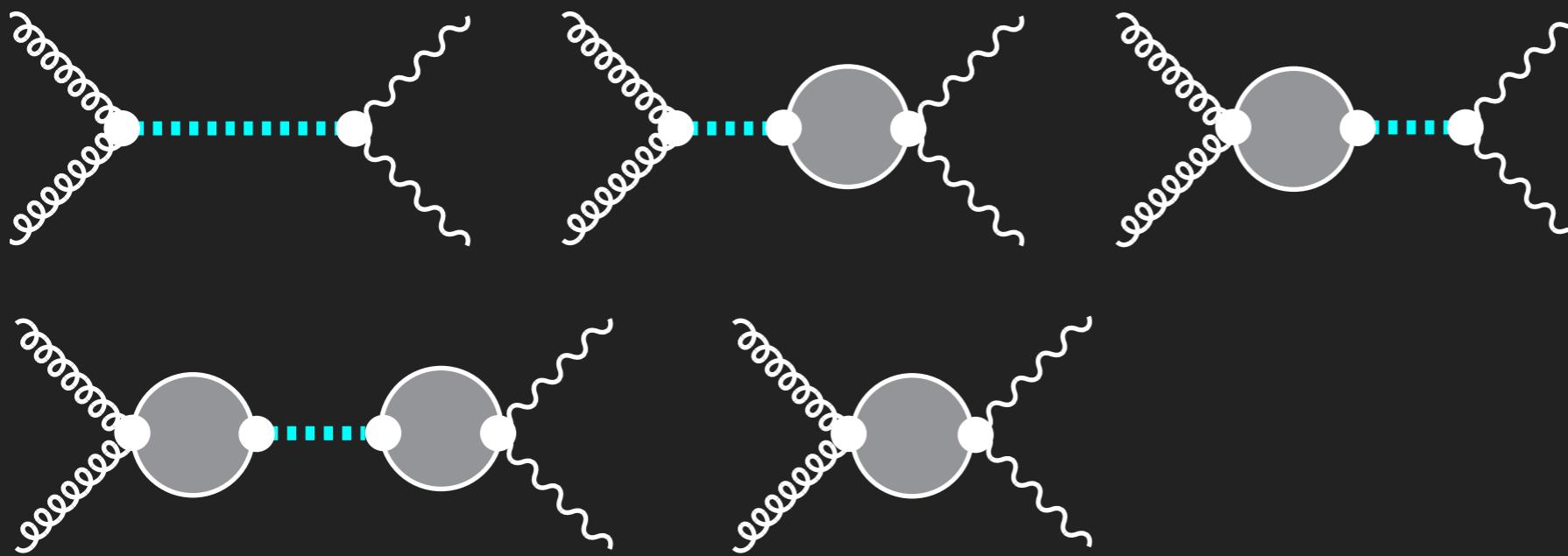
$$\text{dashed line} = (\text{dashed line}^{-1} - \text{shaded loop})^{-1}$$

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.

$$A_{\text{tot}}(gg \rightarrow \gamma\gamma) = \begin{pmatrix} \text{Diagram 1} & \text{Diagram 2} \\ \text{Diagram 3} & \text{Diagram 4} \end{pmatrix}$$

The equation shows the total amplitude for gluon-gluon to two-photon production as a 2x2 matrix. The elements are represented by Feynman diagrams:

- Top-left element: Two gluons (curly lines) enter from the left and couple to a Higgs boson (crossed lines). The Higgs boson then decays into two photons (wavy lines).
- Top-right element: Two gluons enter from the left and couple to a stoponium state (represented by a shaded circle). The stoponium state then decays into two photons.
- Bottom-left element: Two gluons enter from the left and couple to a Higgs boson. The Higgs boson then decays into two photons. A minus sign is placed before this diagram.
- Bottom-right element: Two gluons enter from the left and couple to a stoponium state. The stoponium state then decays into two photons. A minus sign is placed before this diagram.

- 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 $A_{\text{tot}}(gg \rightarrow \gamma\gamma)$ when the heavy Higgs mass is near the stoponium threshold.

$A_{\text{tot}}(gg \rightarrow \gamma\gamma) =$

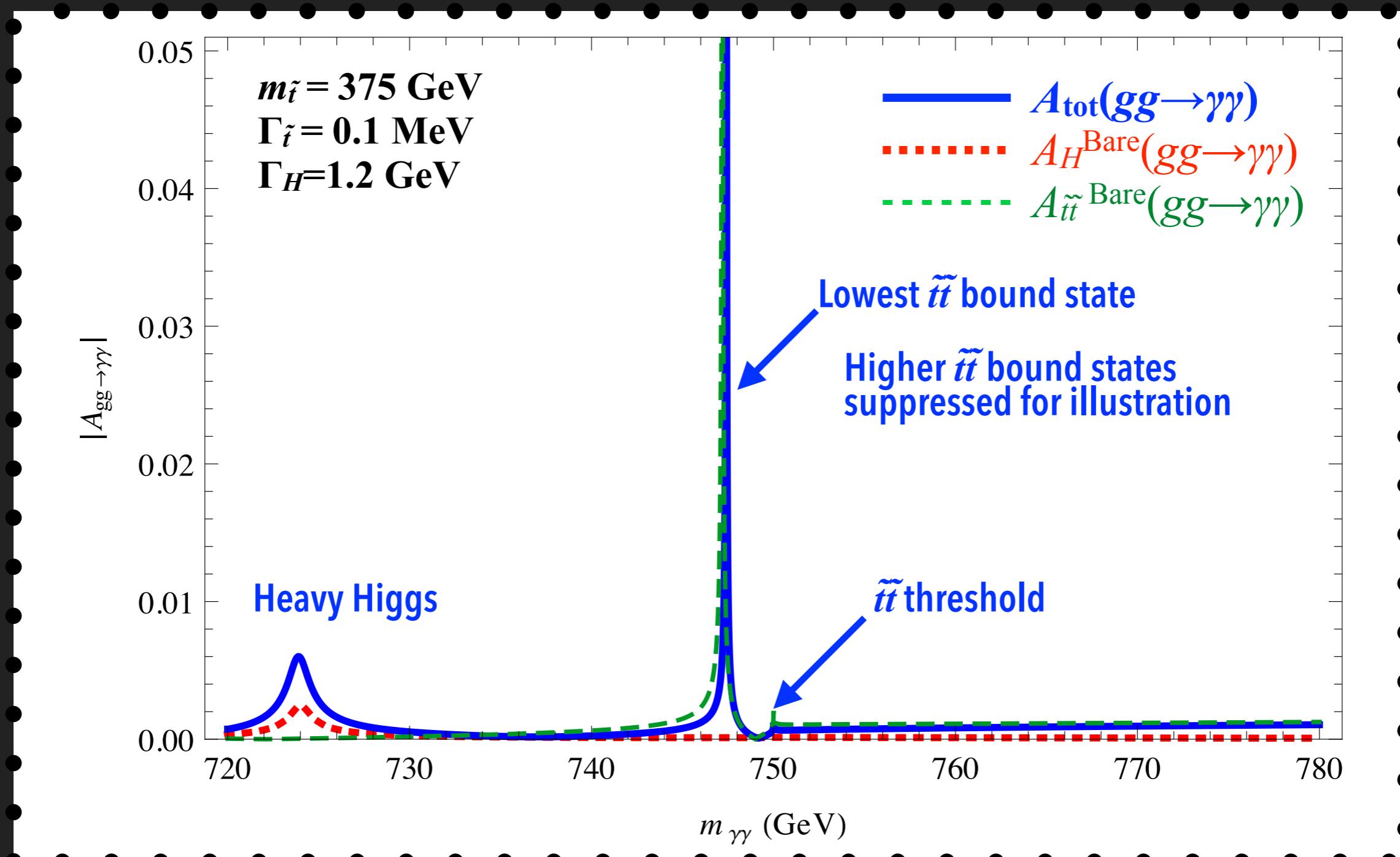
Naïve prediction for Higgs contribution

$A_H^{\text{Bare}}(gg \rightarrow \gamma\gamma) =$

Contribution from stoponium only

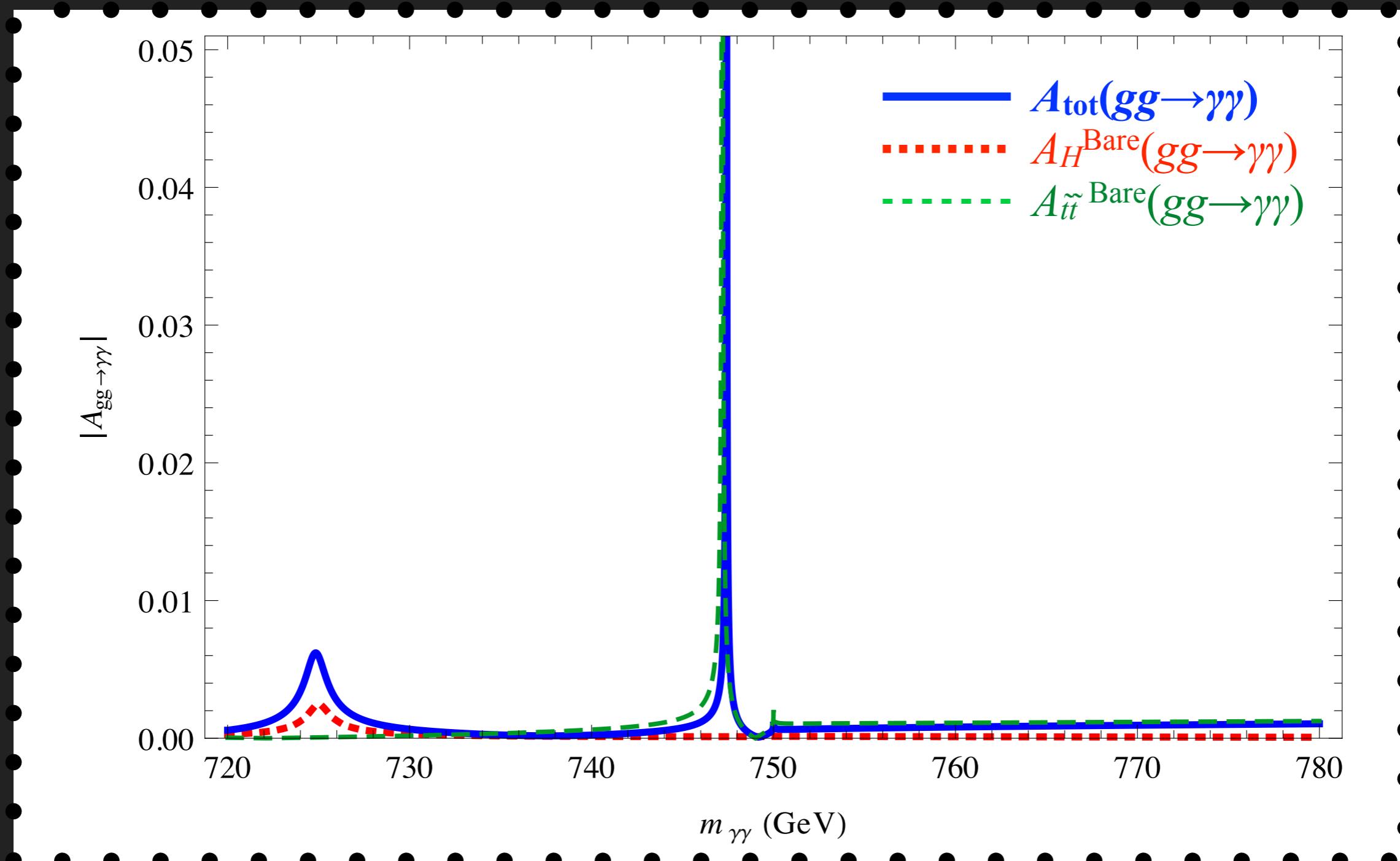
$A_{\tilde{t}\tilde{t}}^{\text{Bare}}(gg \rightarrow \gamma\gamma) =$

HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION

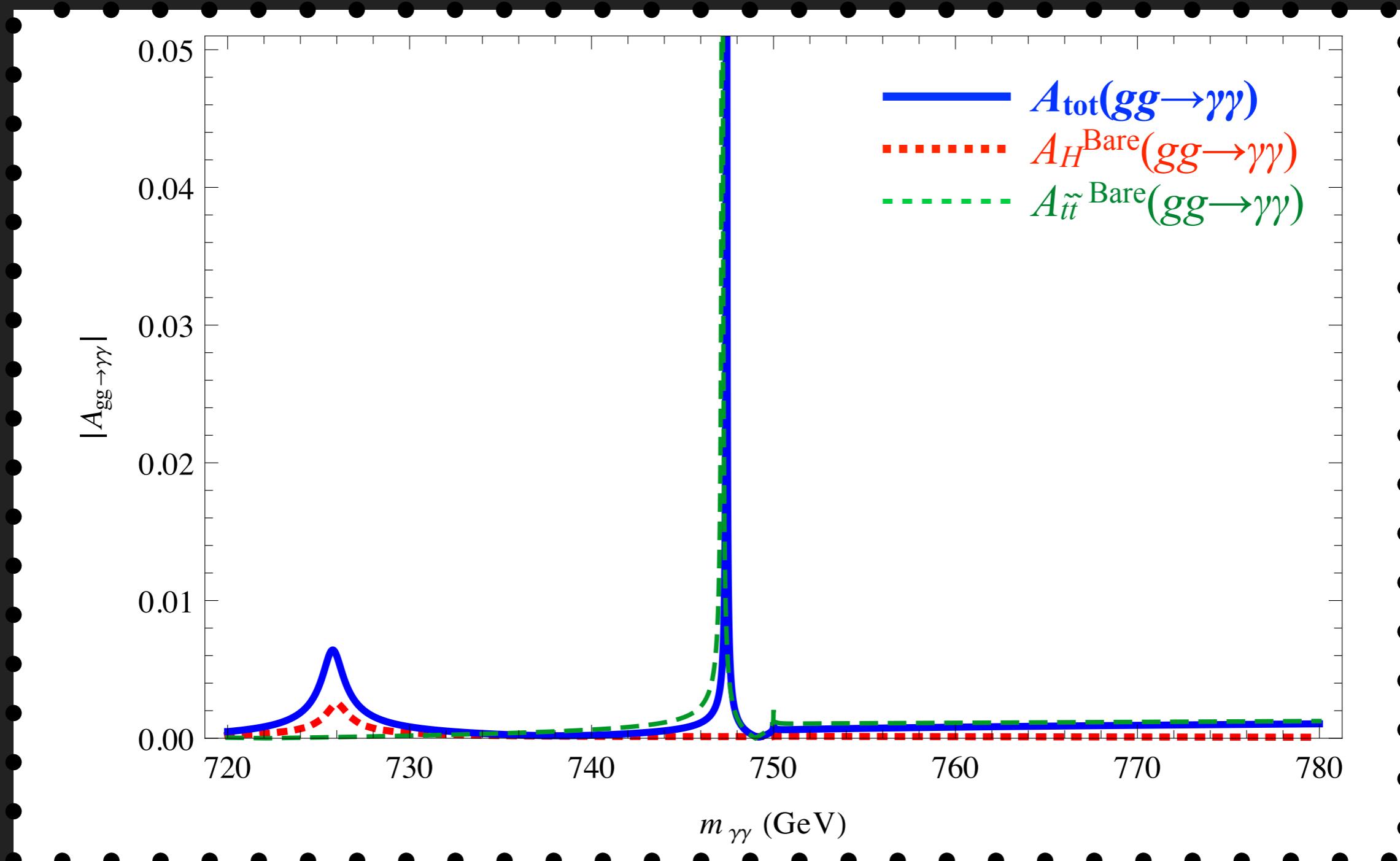


Now, we increase the heavy Higgs mass...

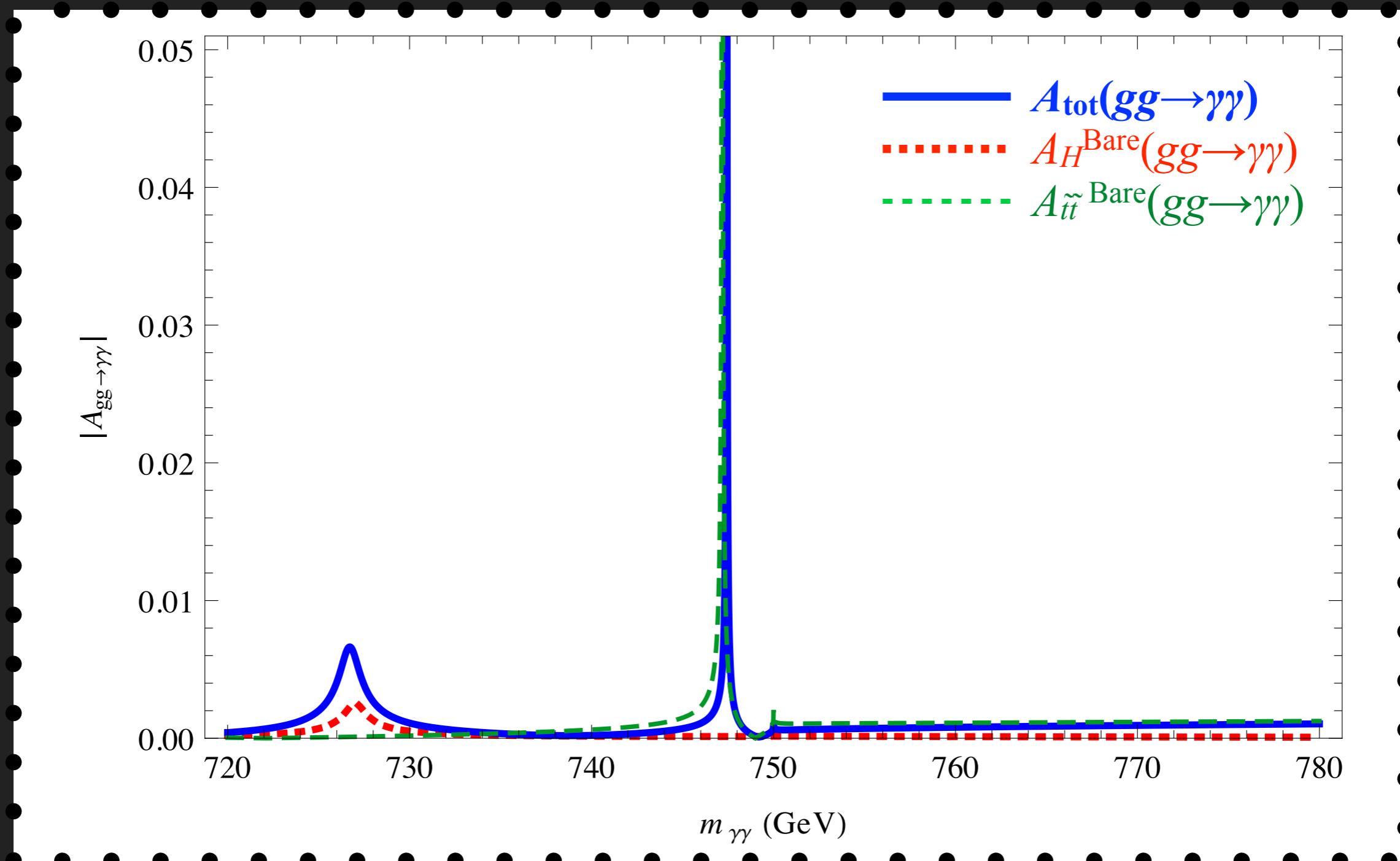
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



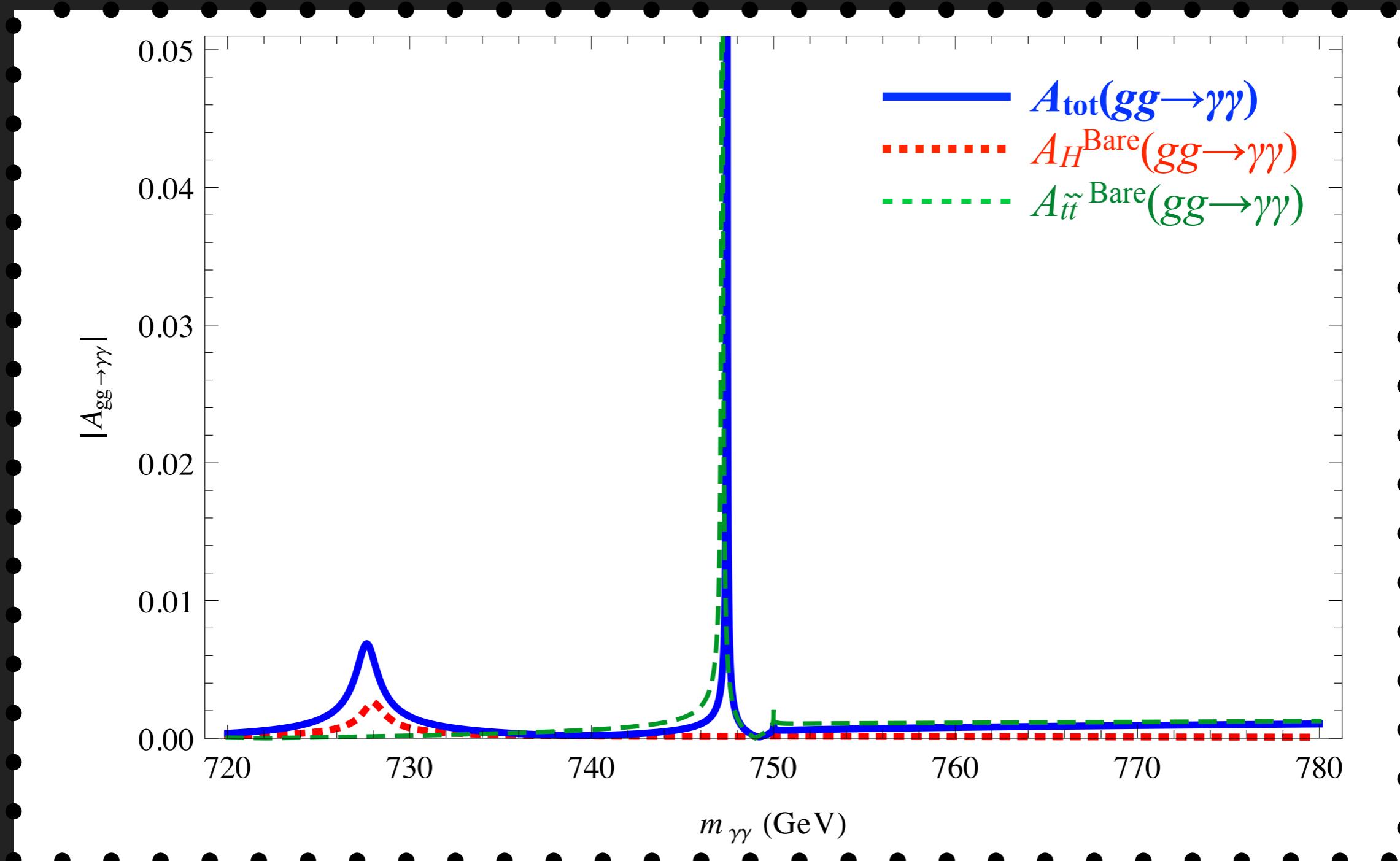
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



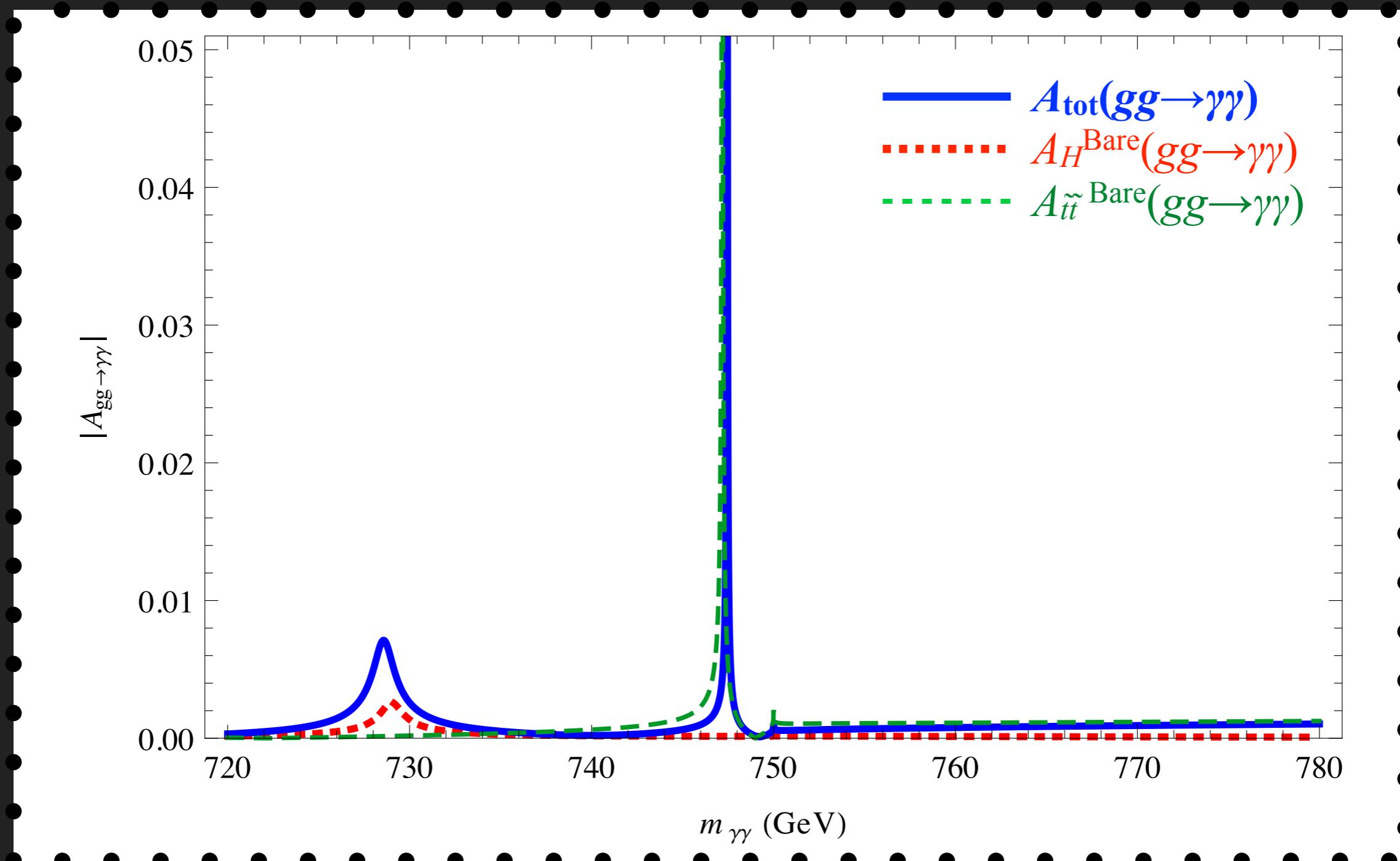
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



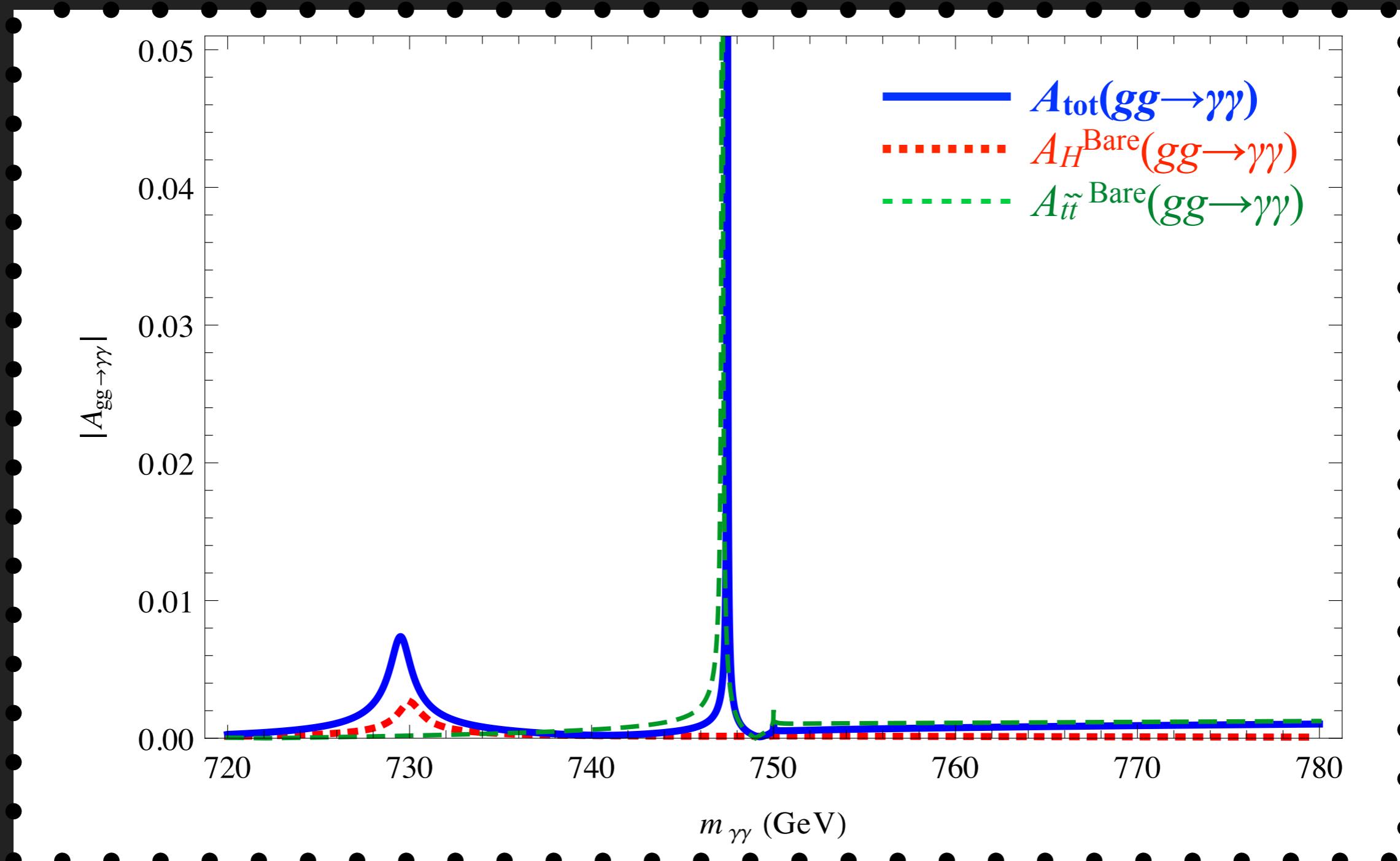
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



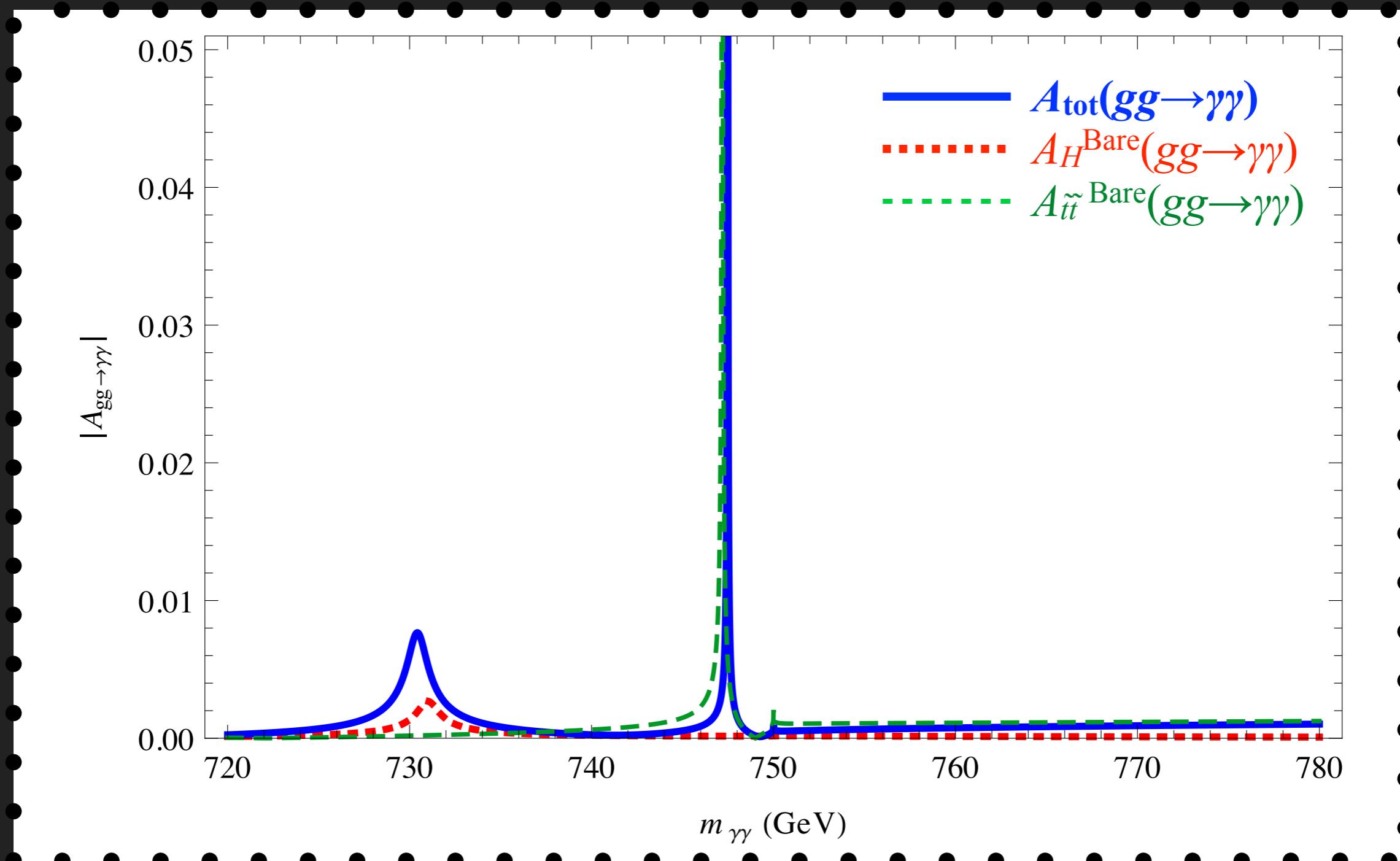
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



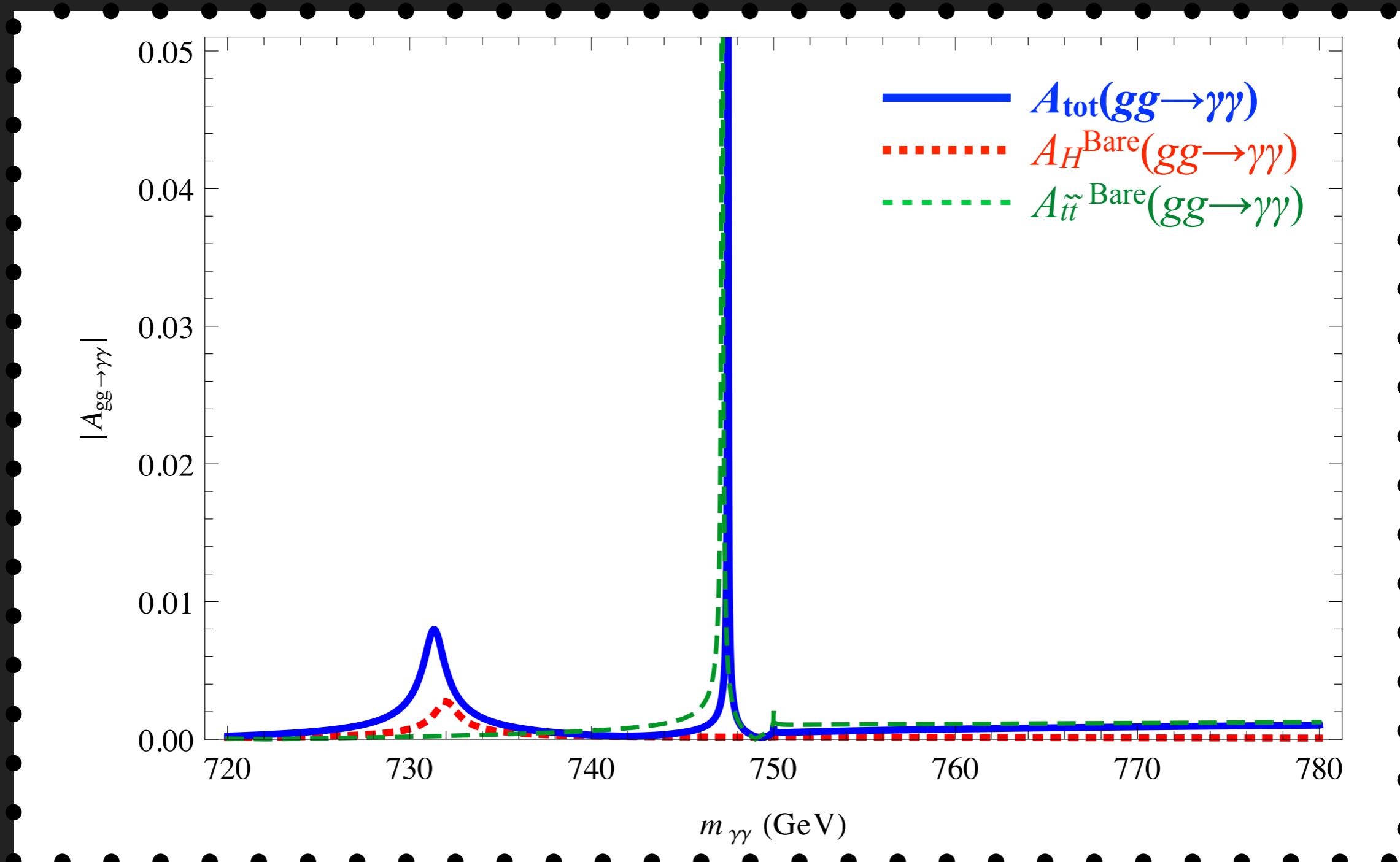
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



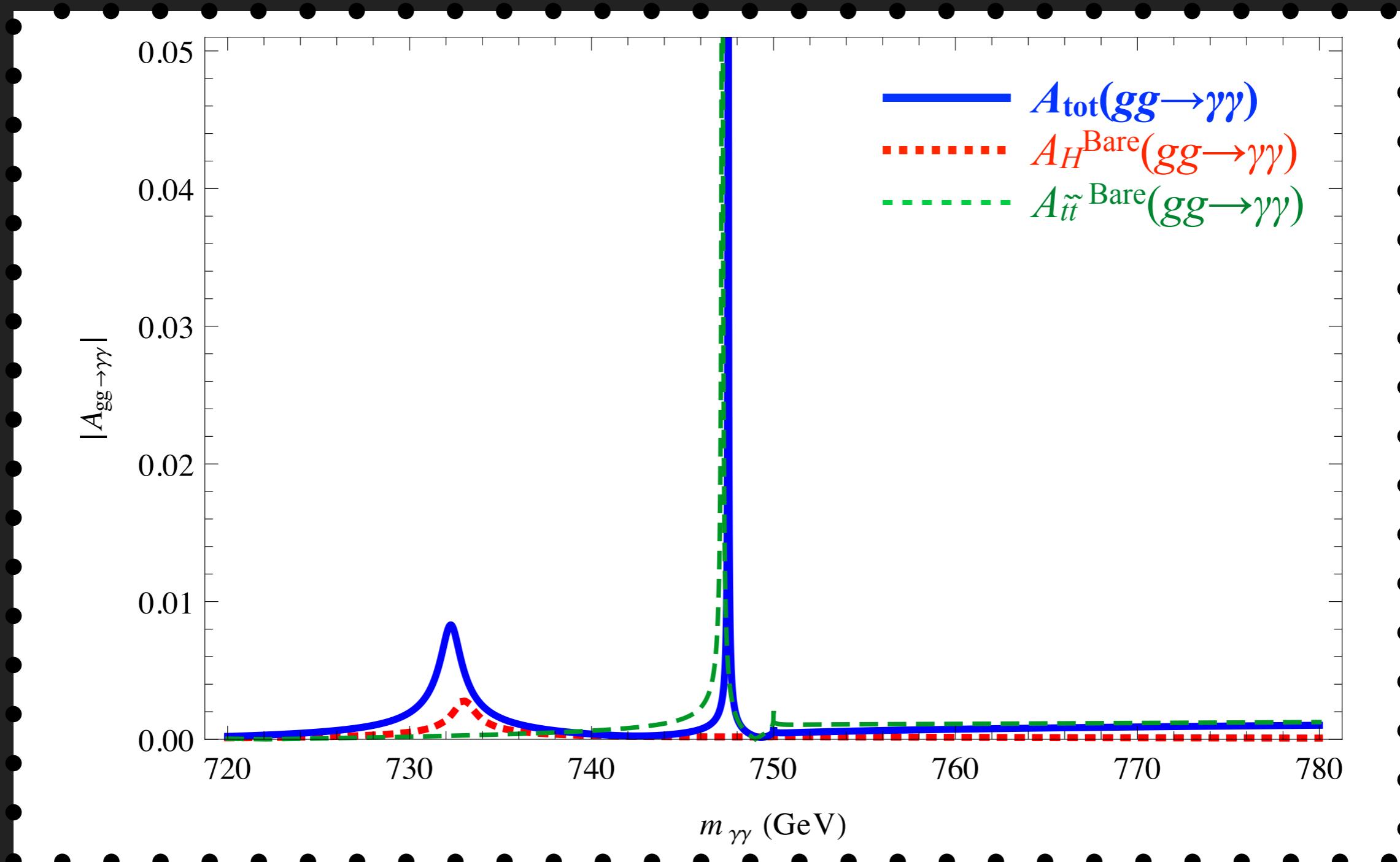
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



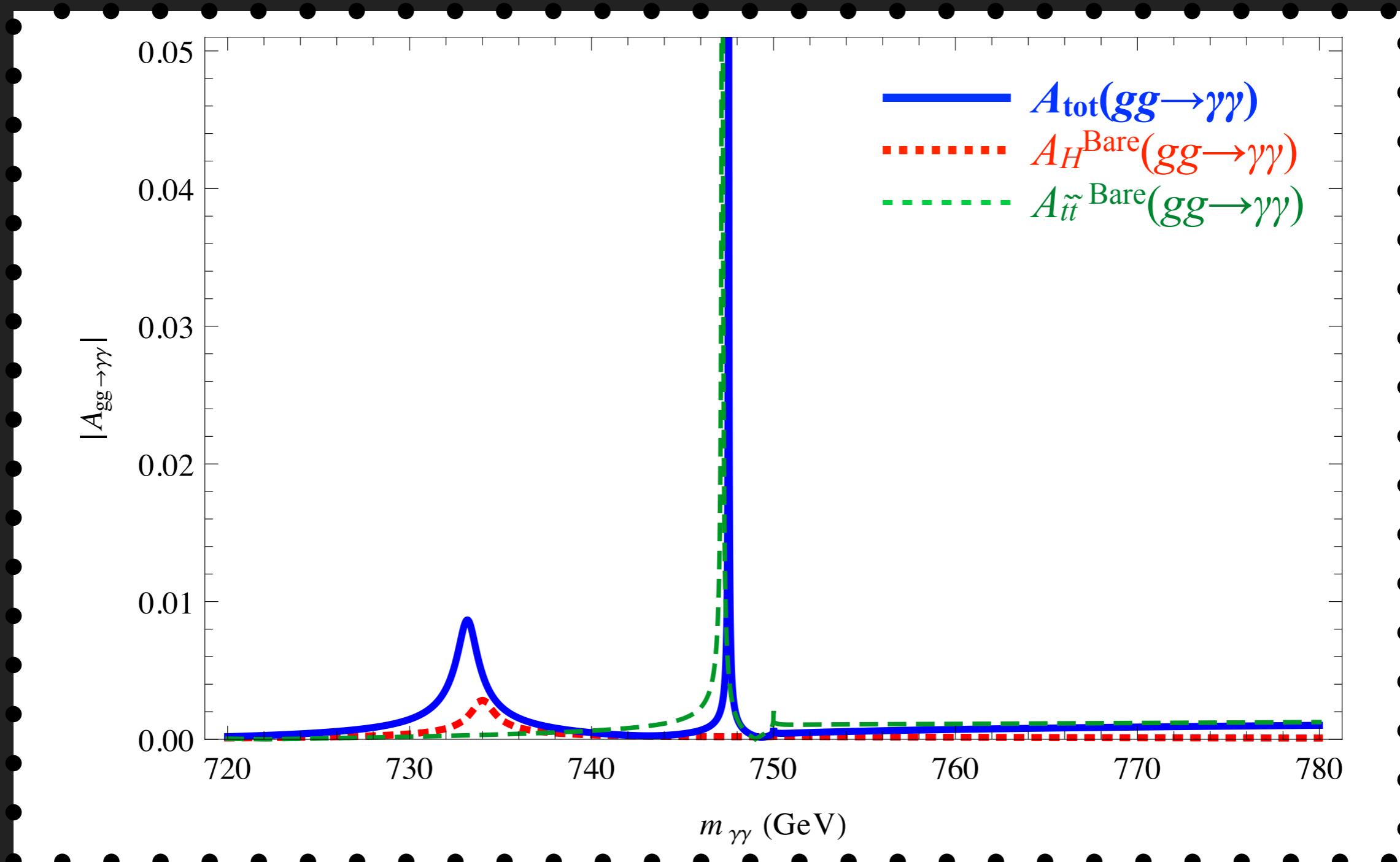
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



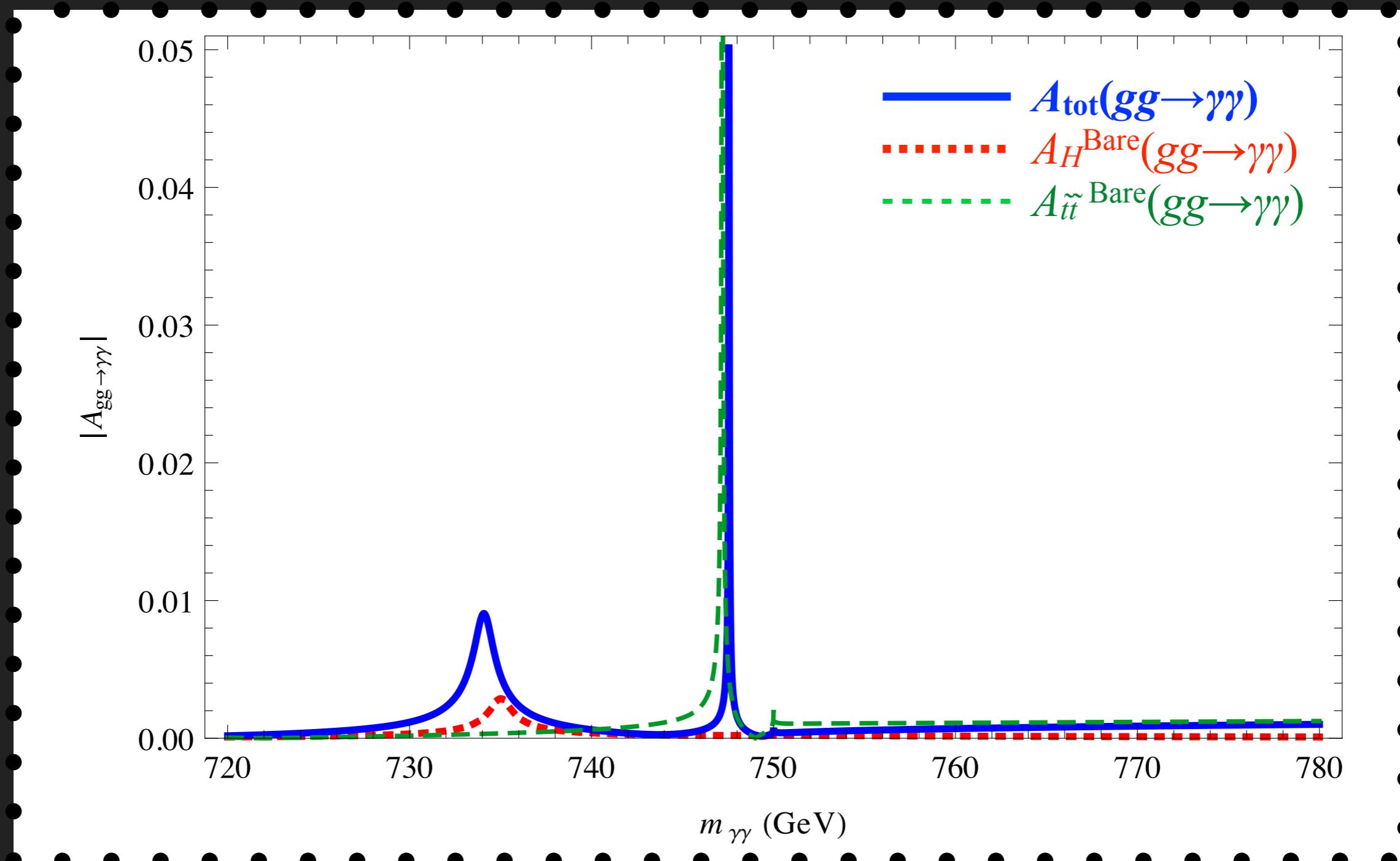
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



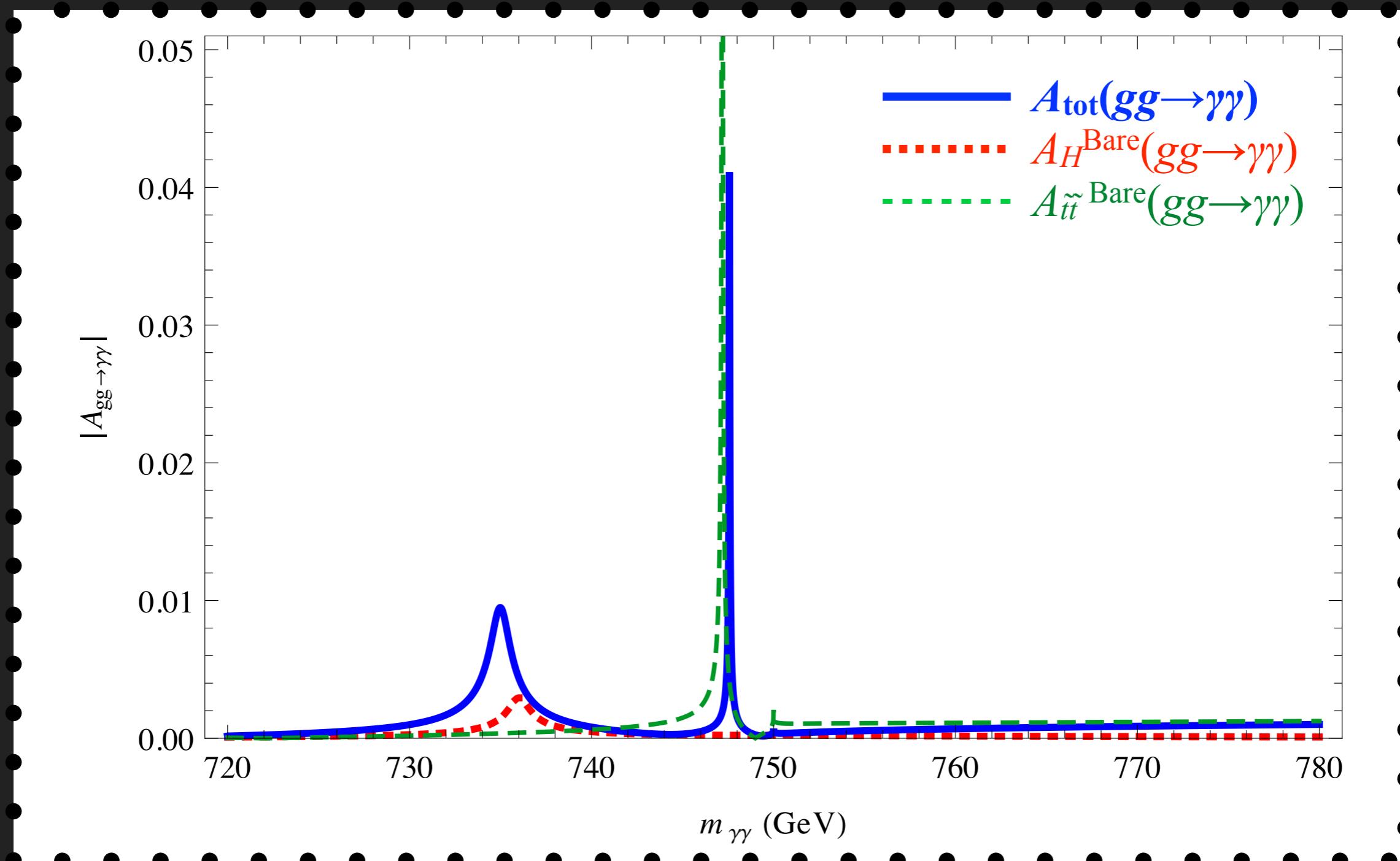
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



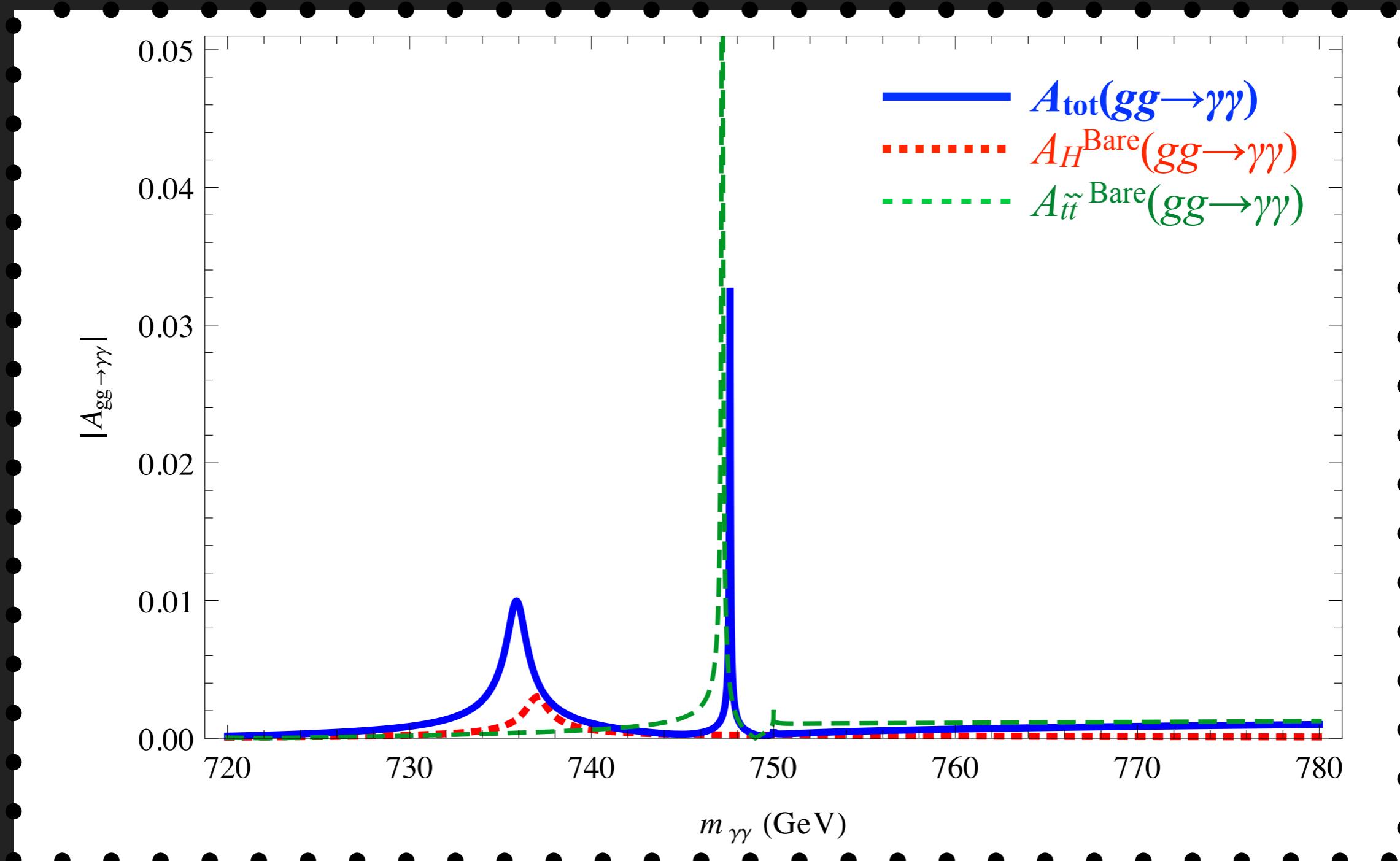
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



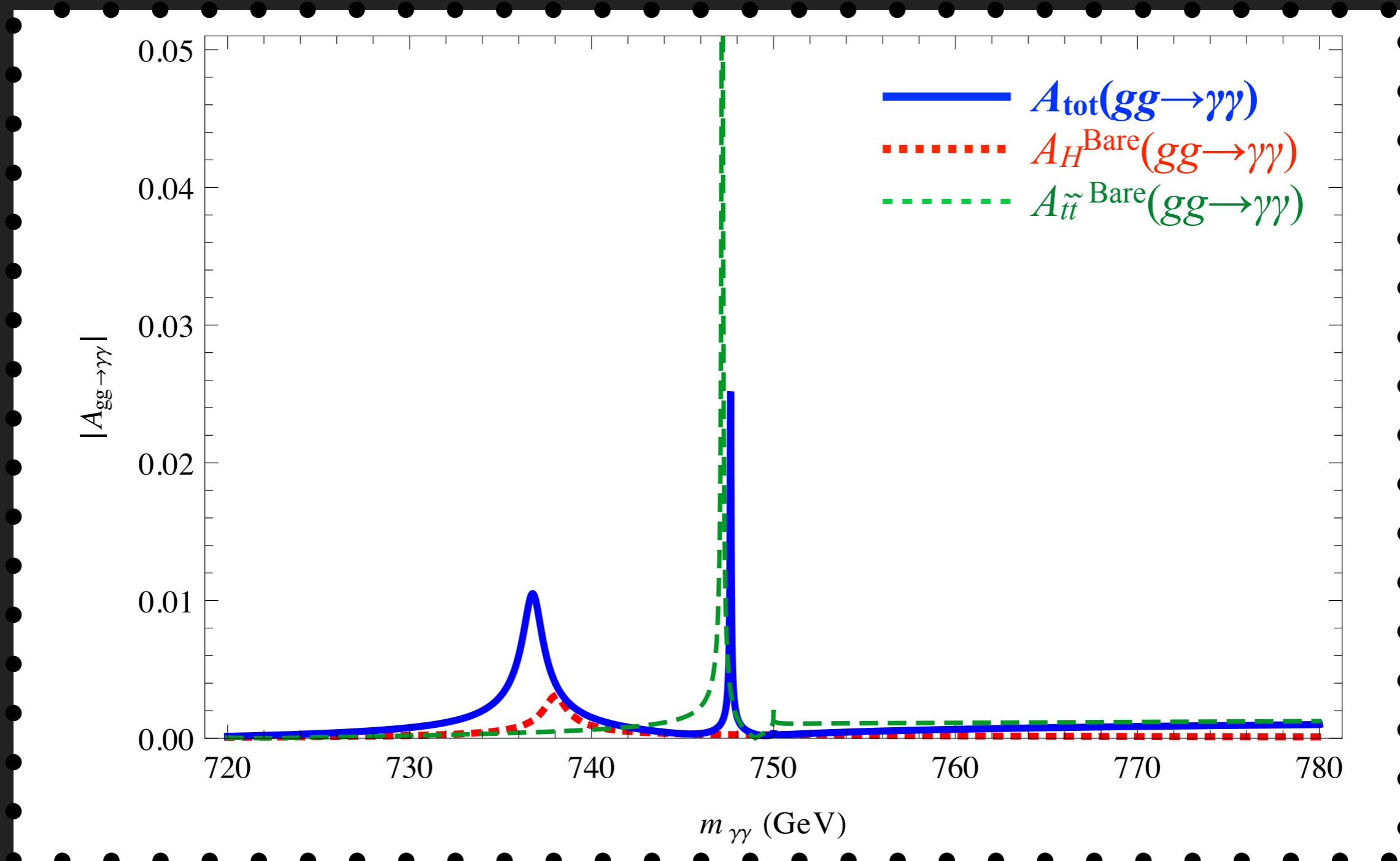
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



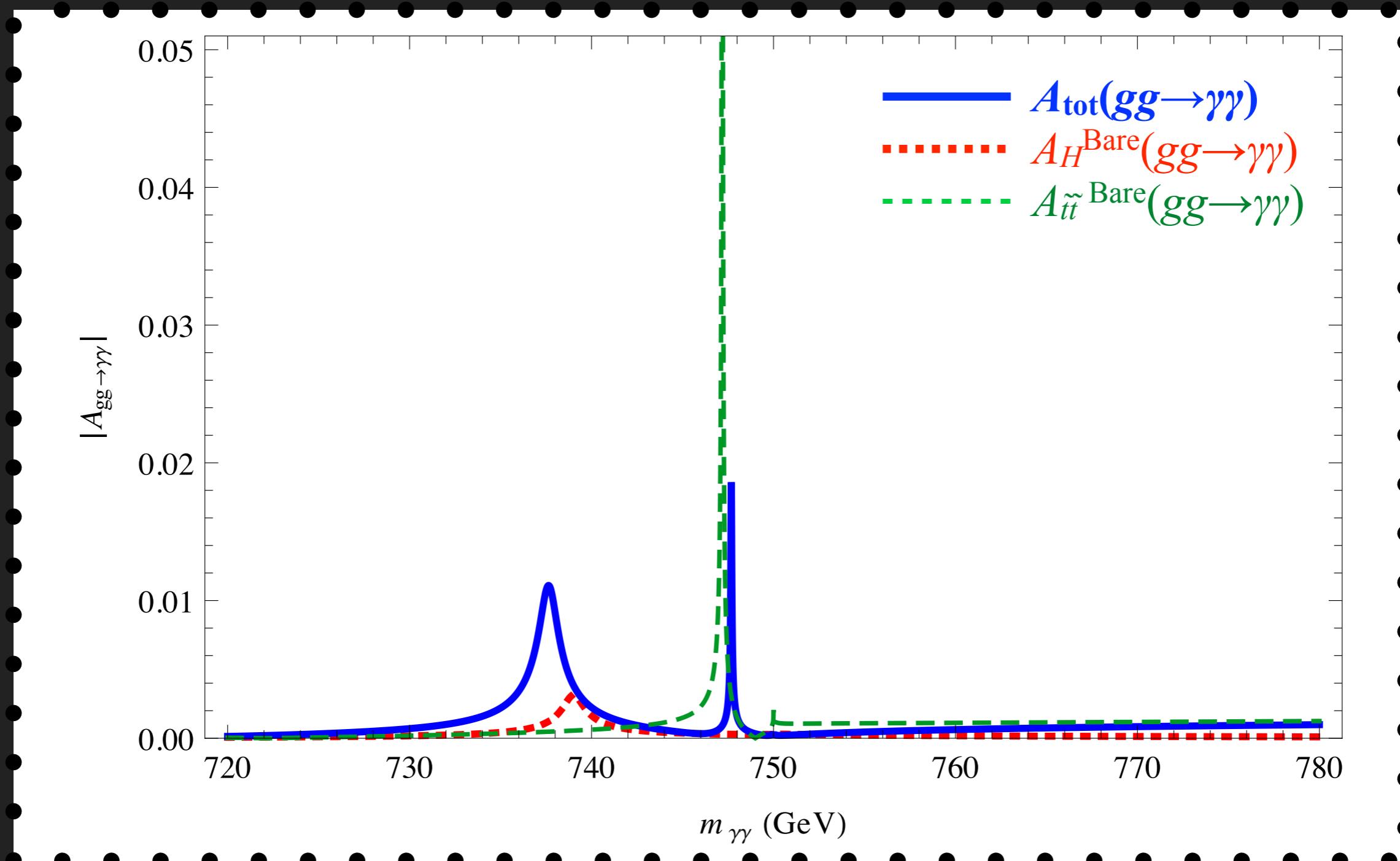
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



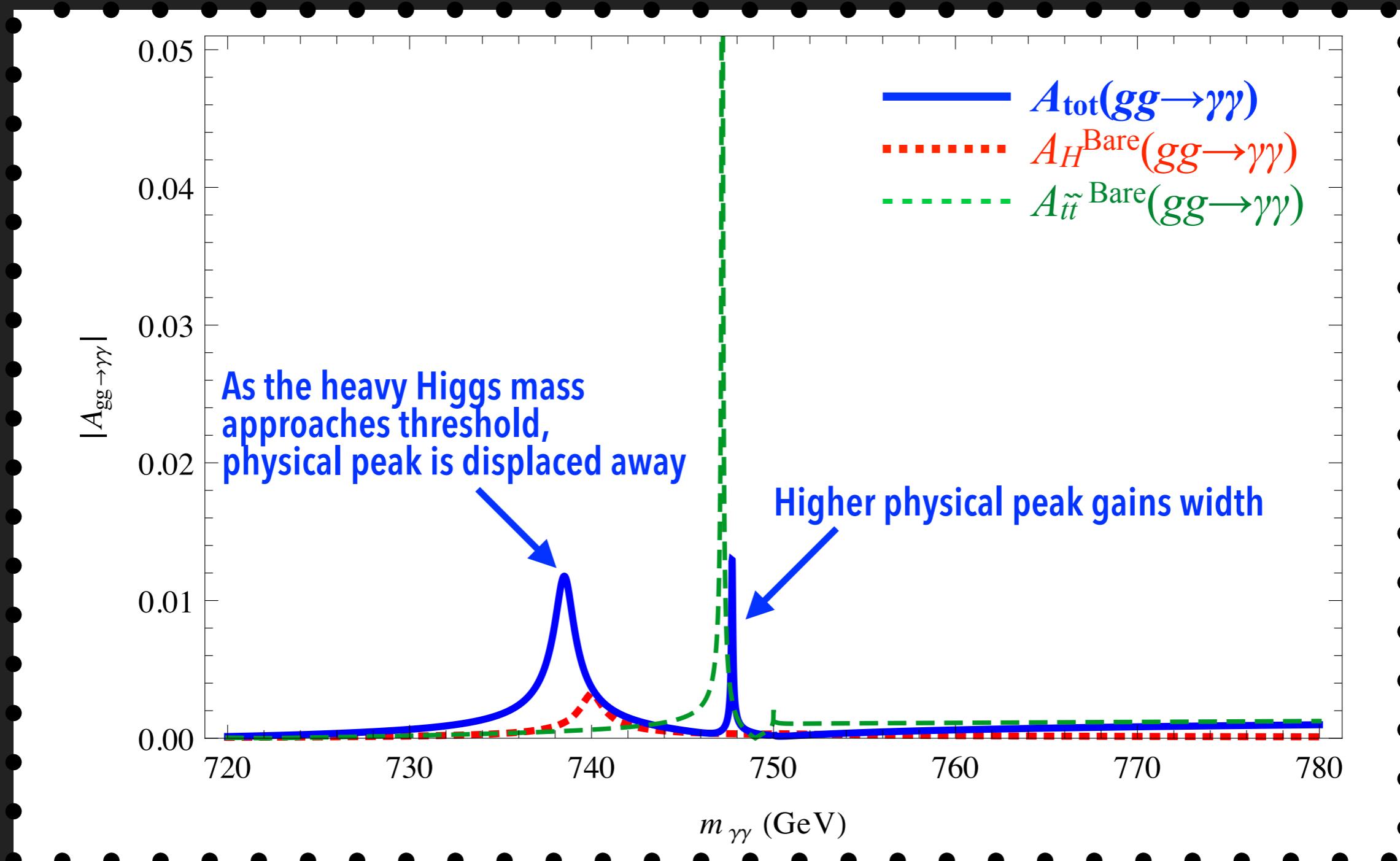
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



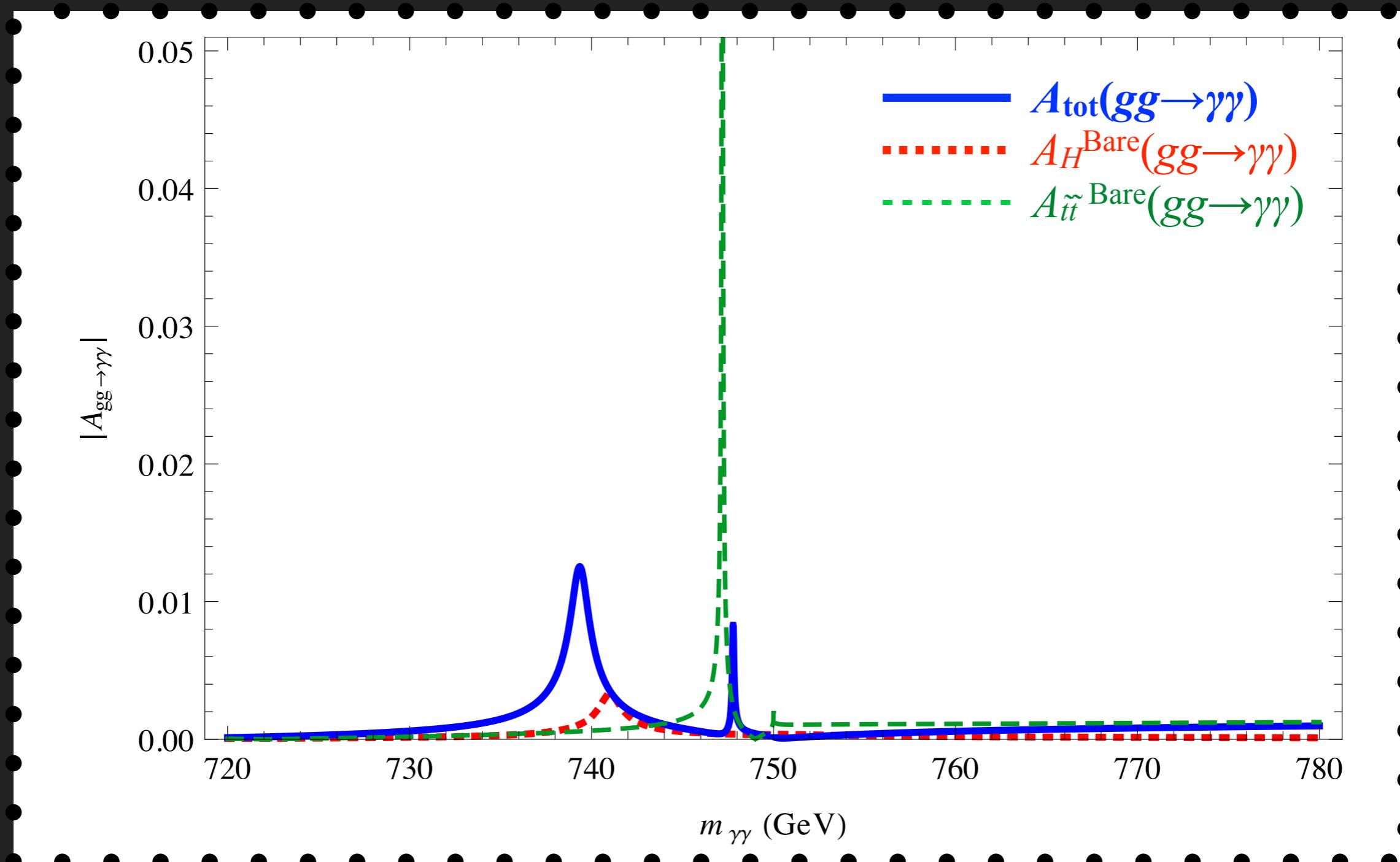
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



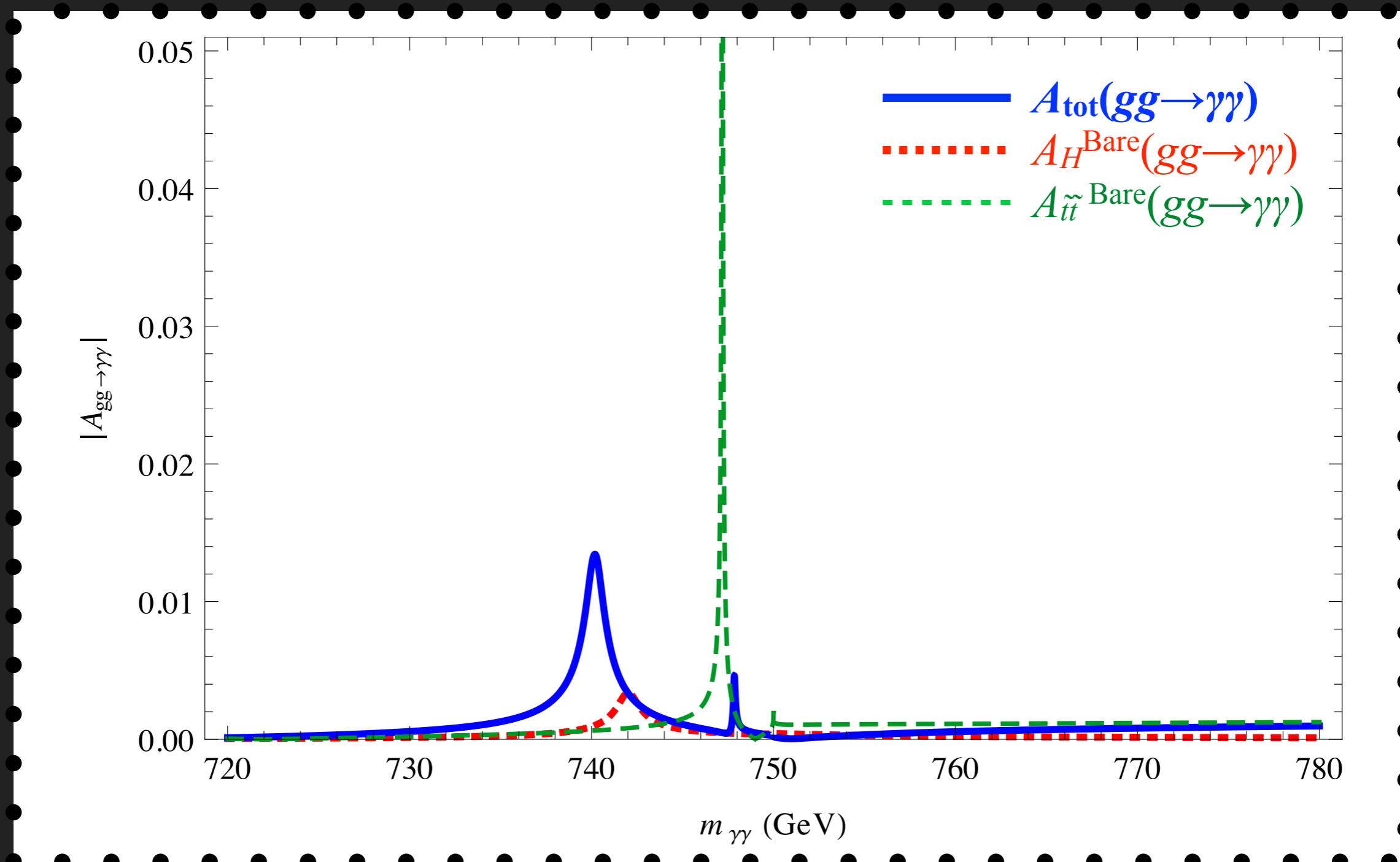
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



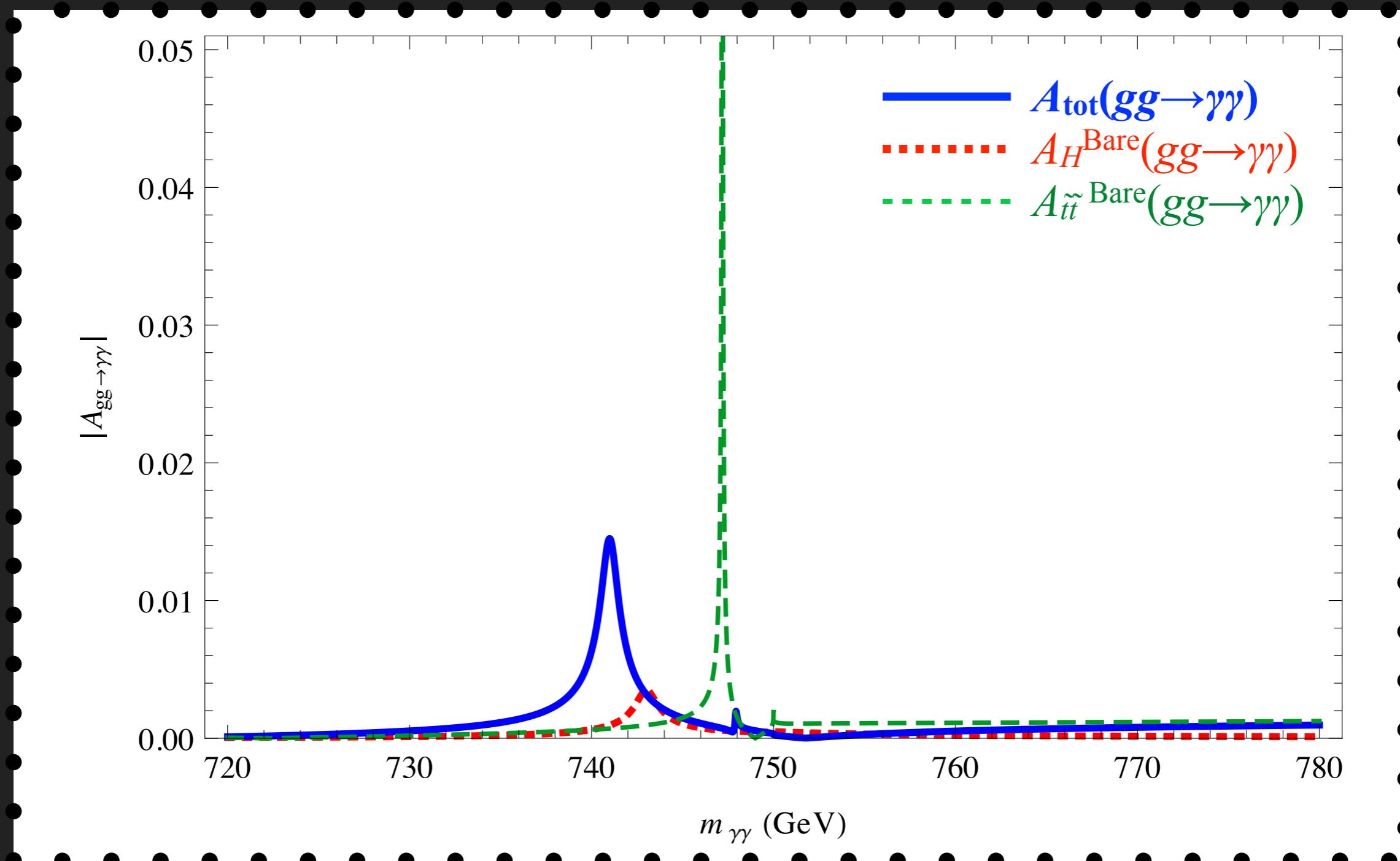
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



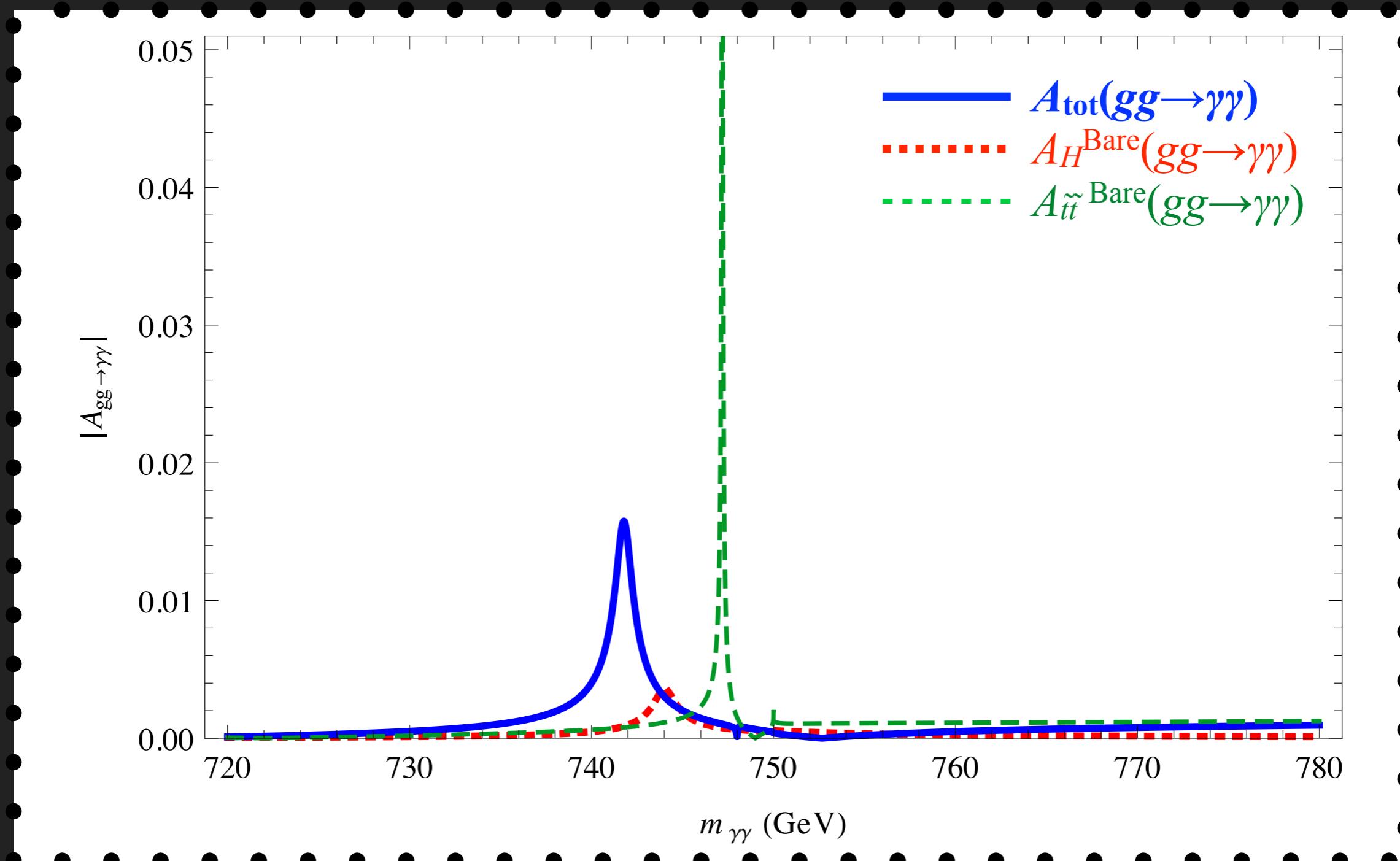
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



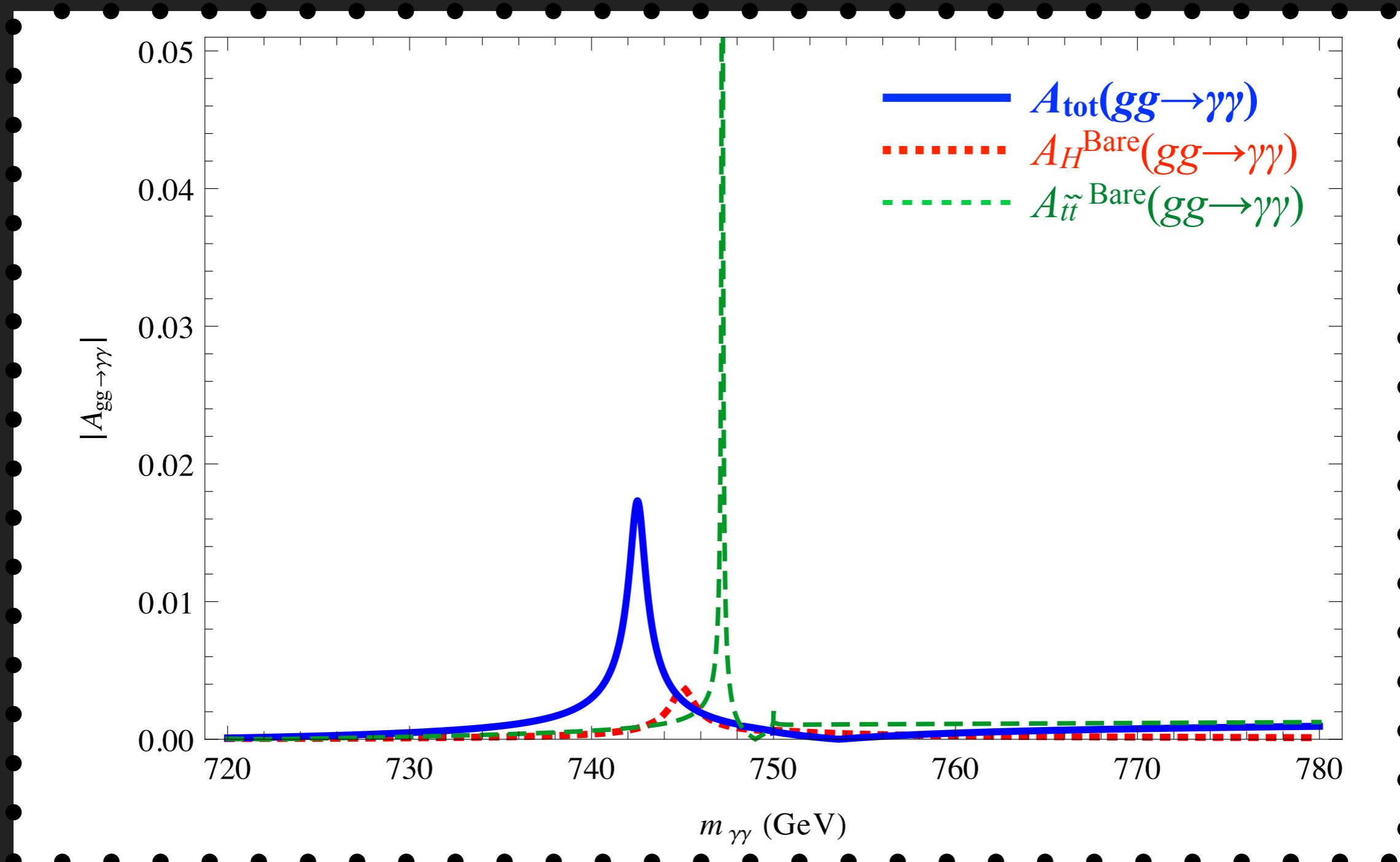
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



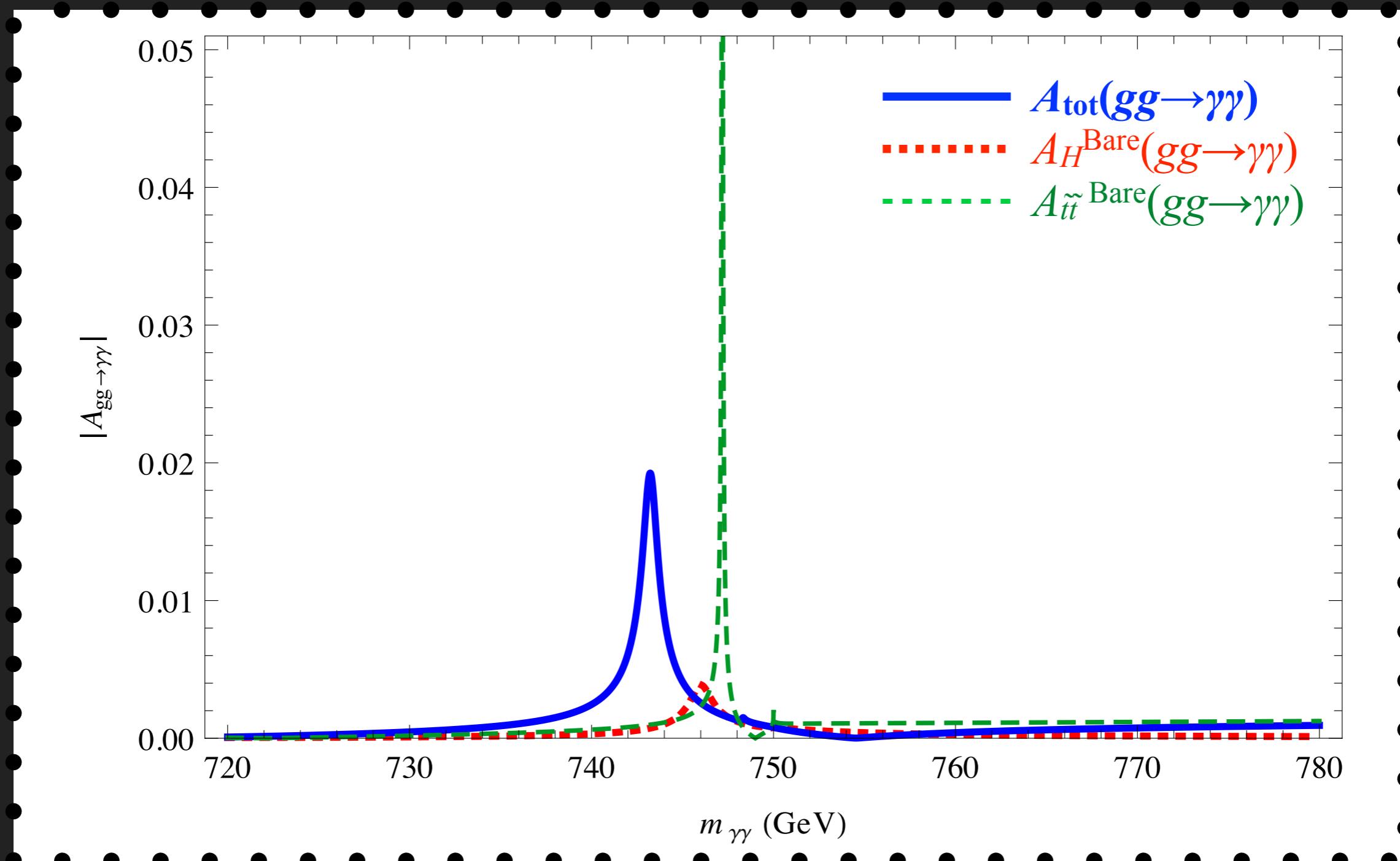
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



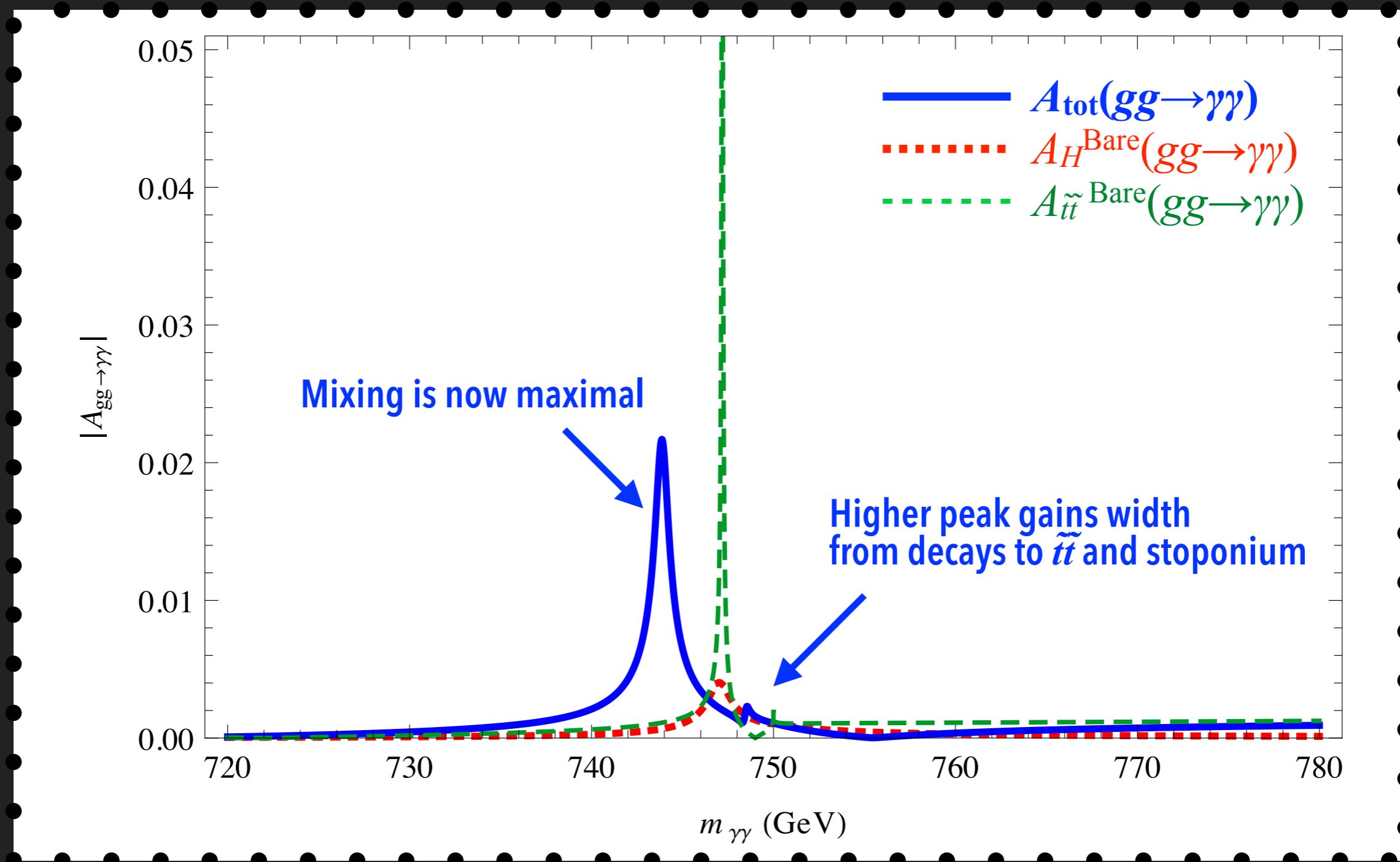
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



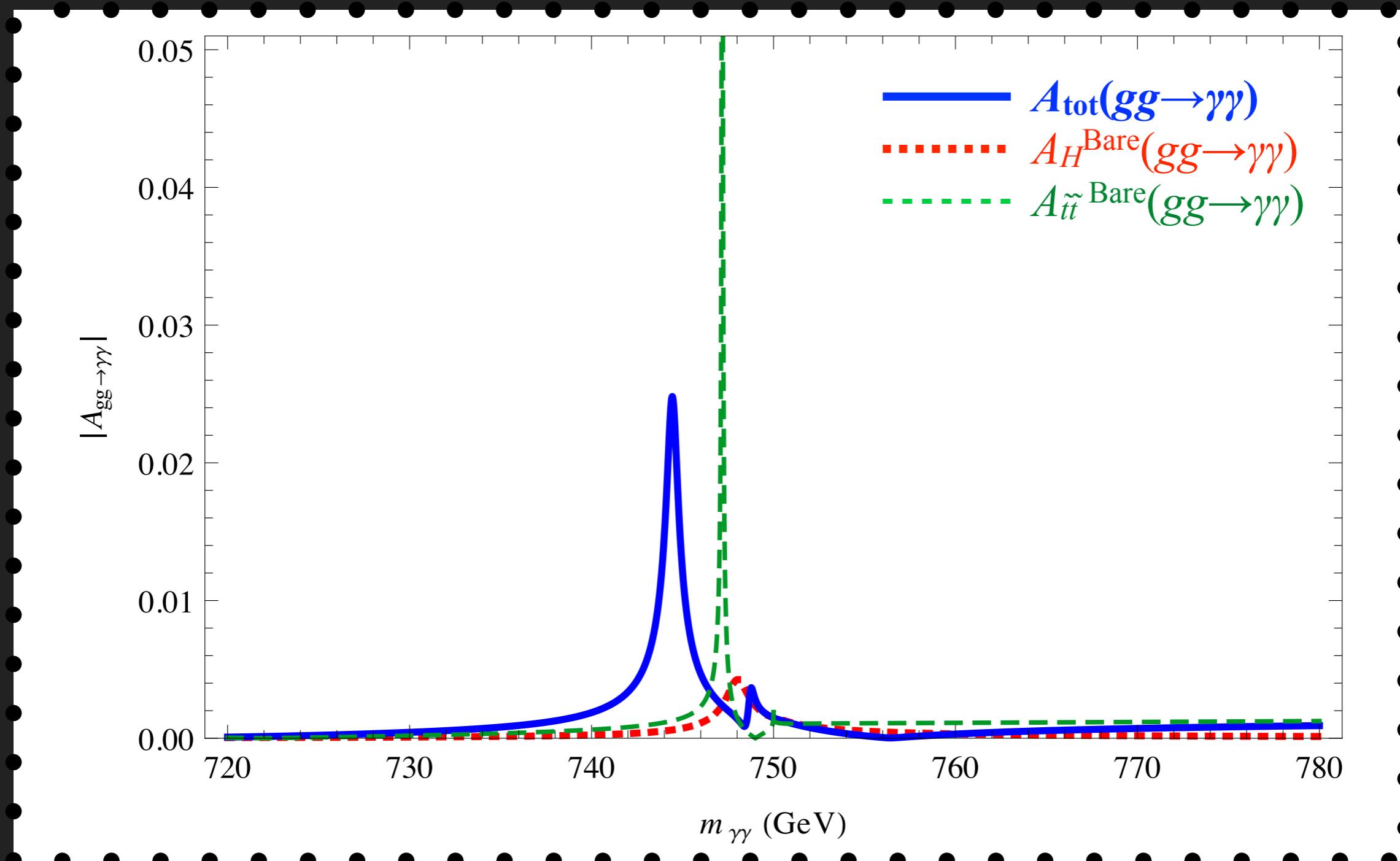
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



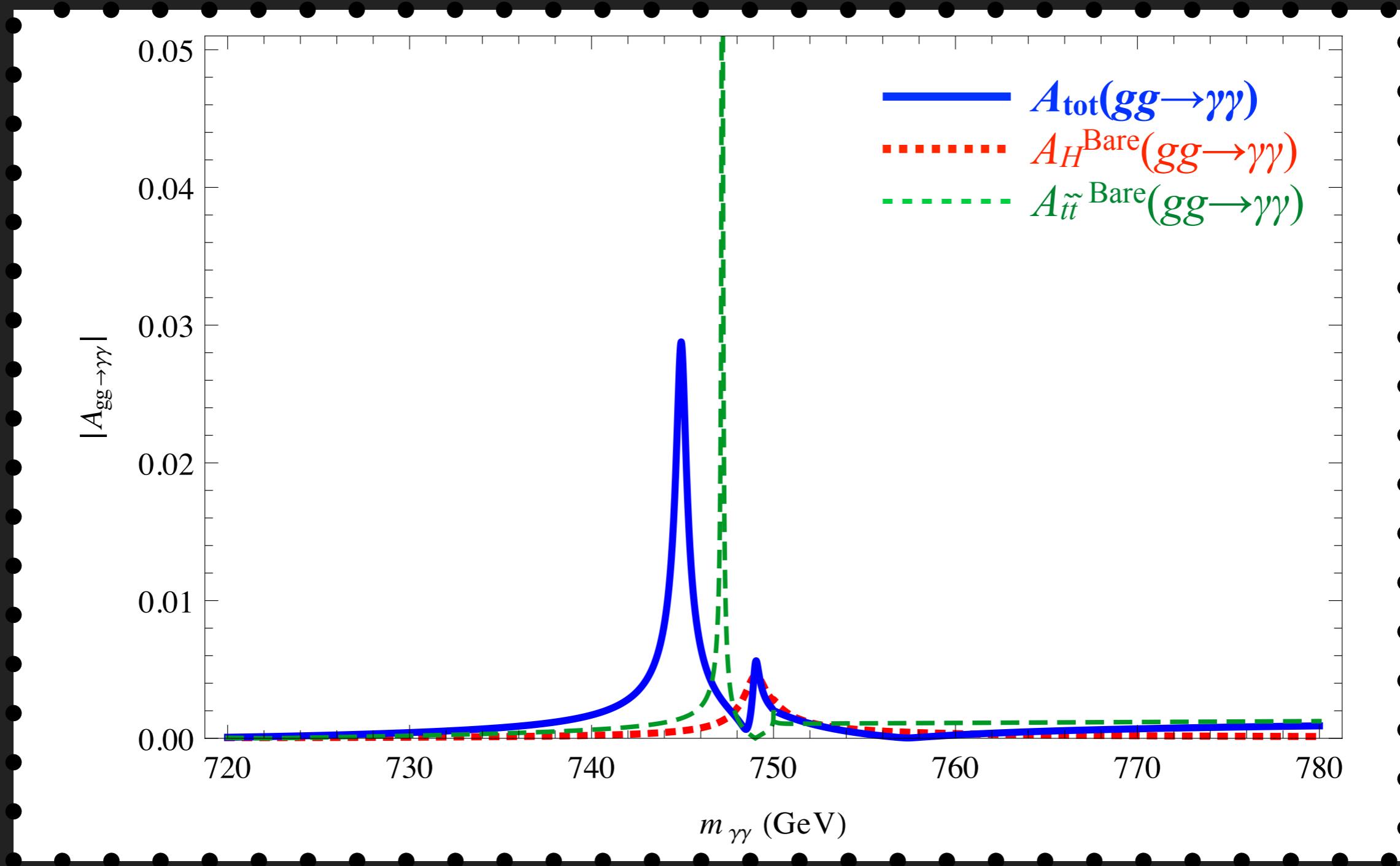
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



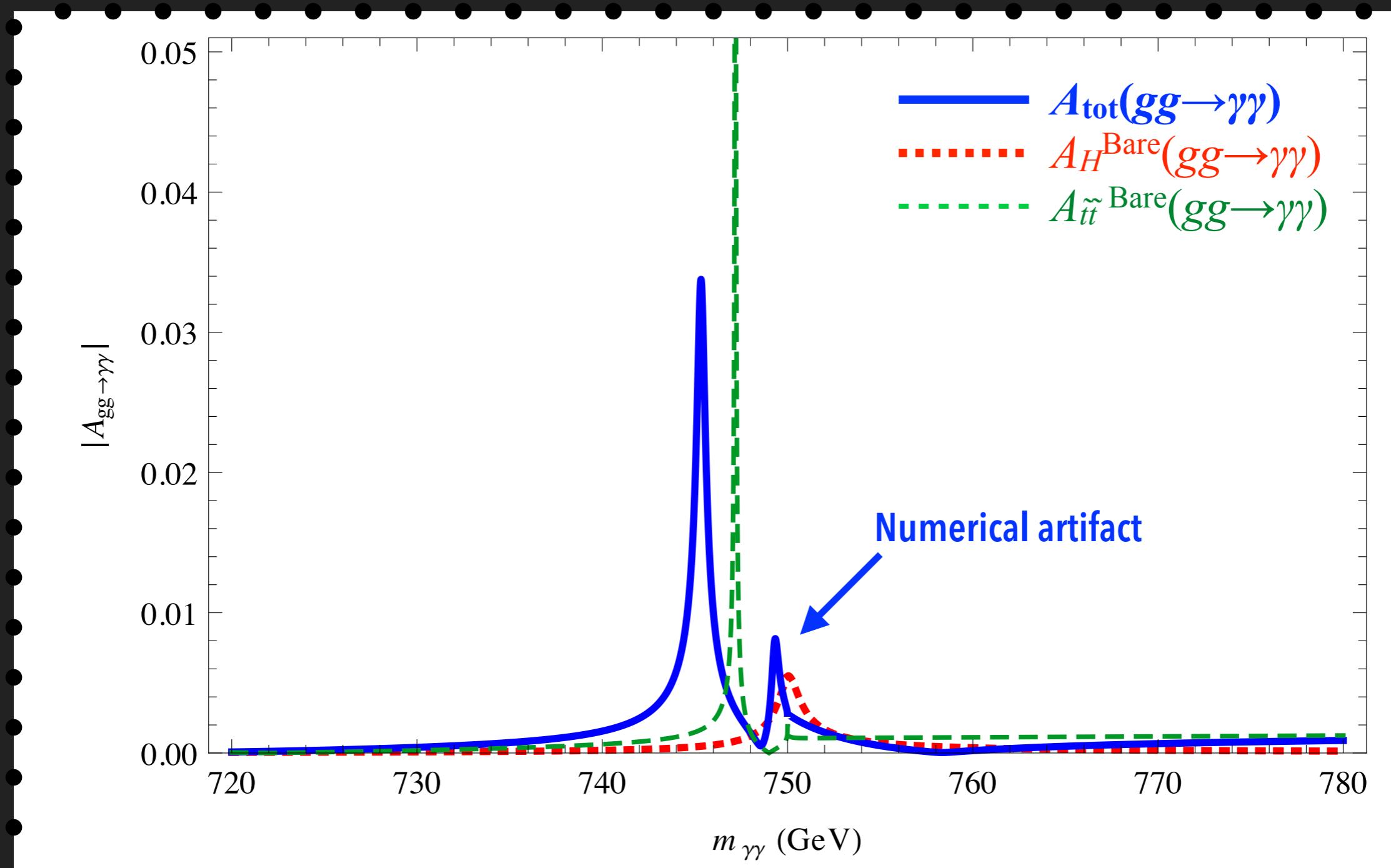
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION

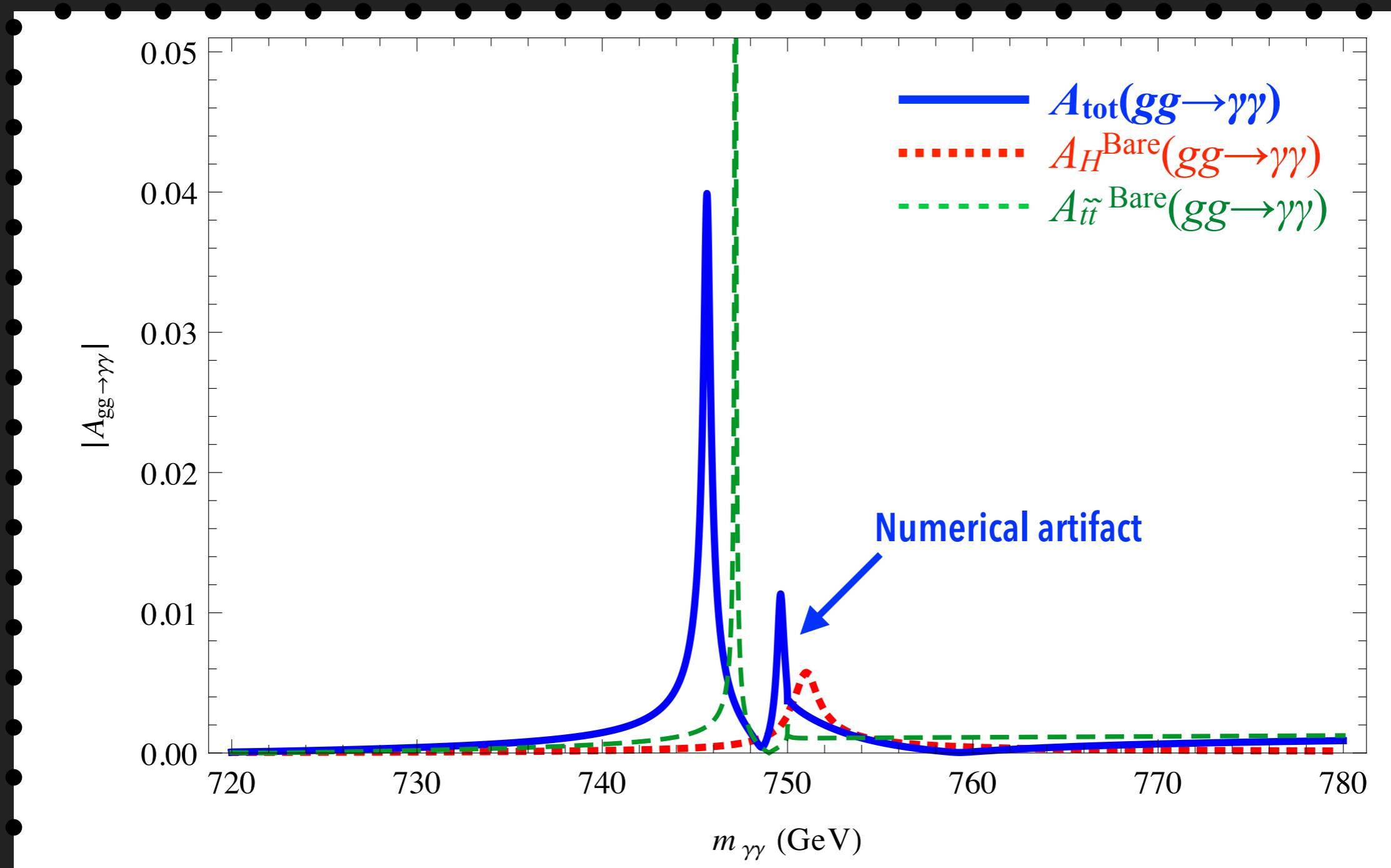


HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



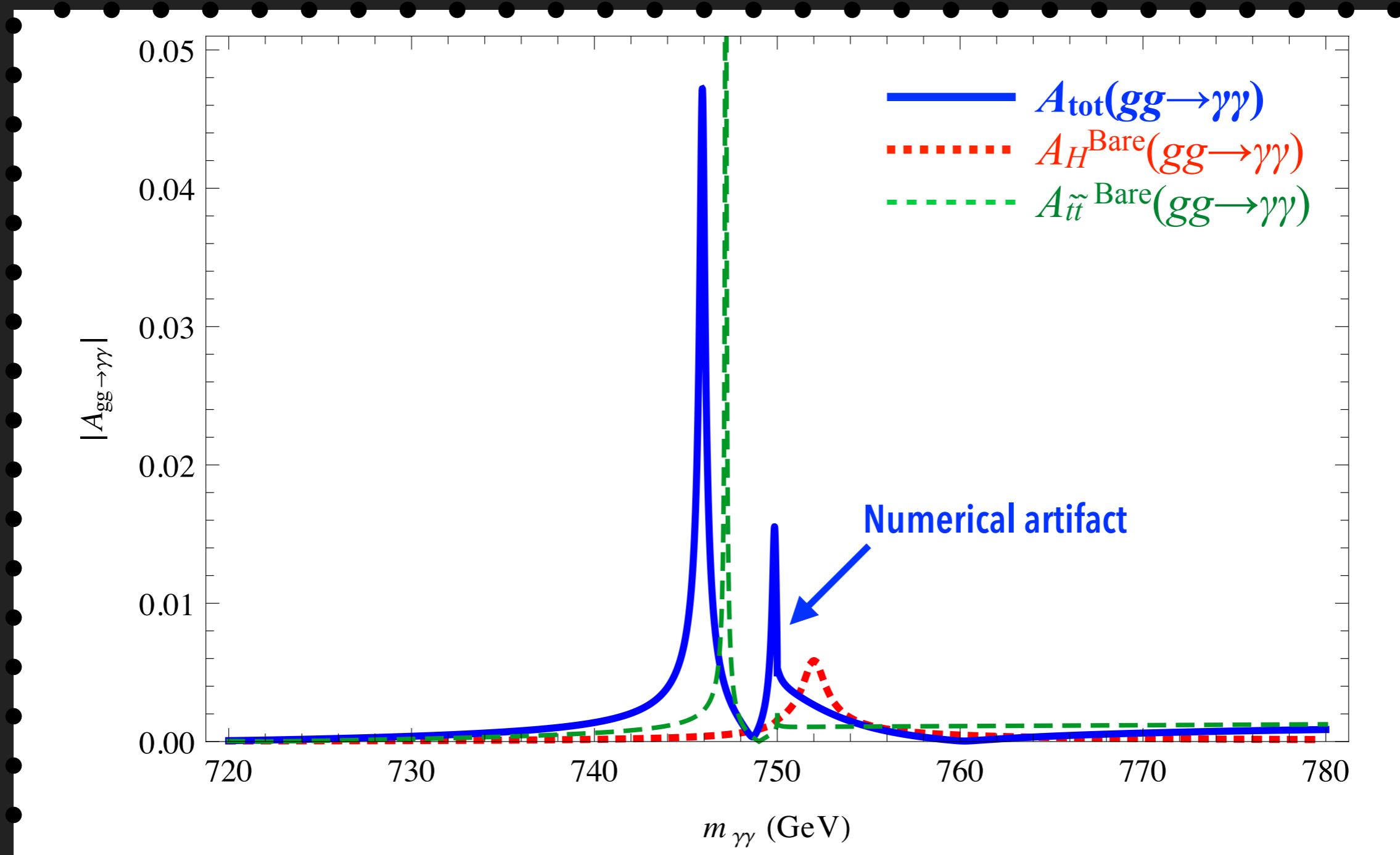
Numerical artifact at threshold from approximations used for Green's functions,
NOT a physical peak, negligible contribution to cross section

HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



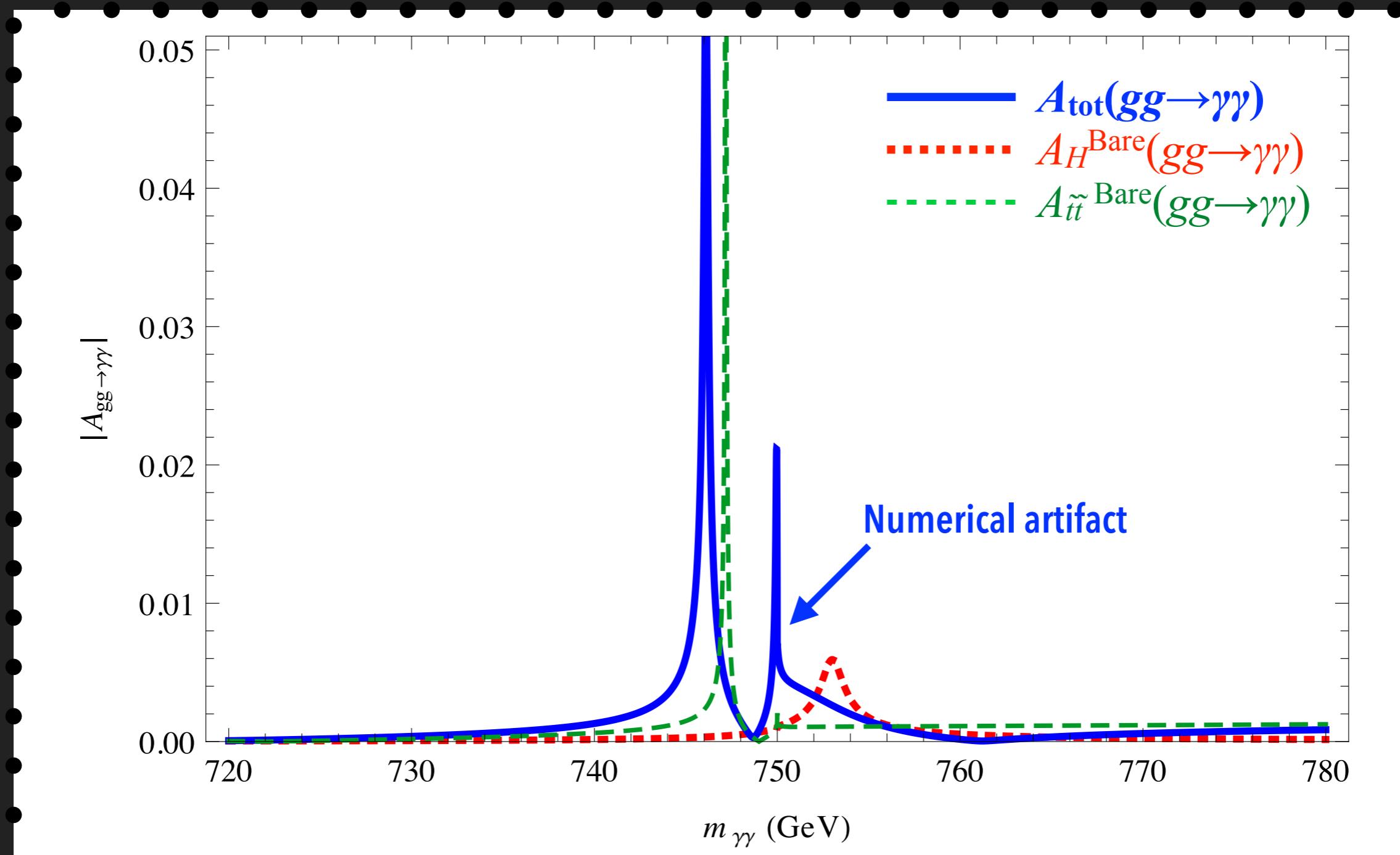
Numerical artifact at threshold from approximations used for Green's functions,
NOT a physical peak, negligible contribution to cross section

HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



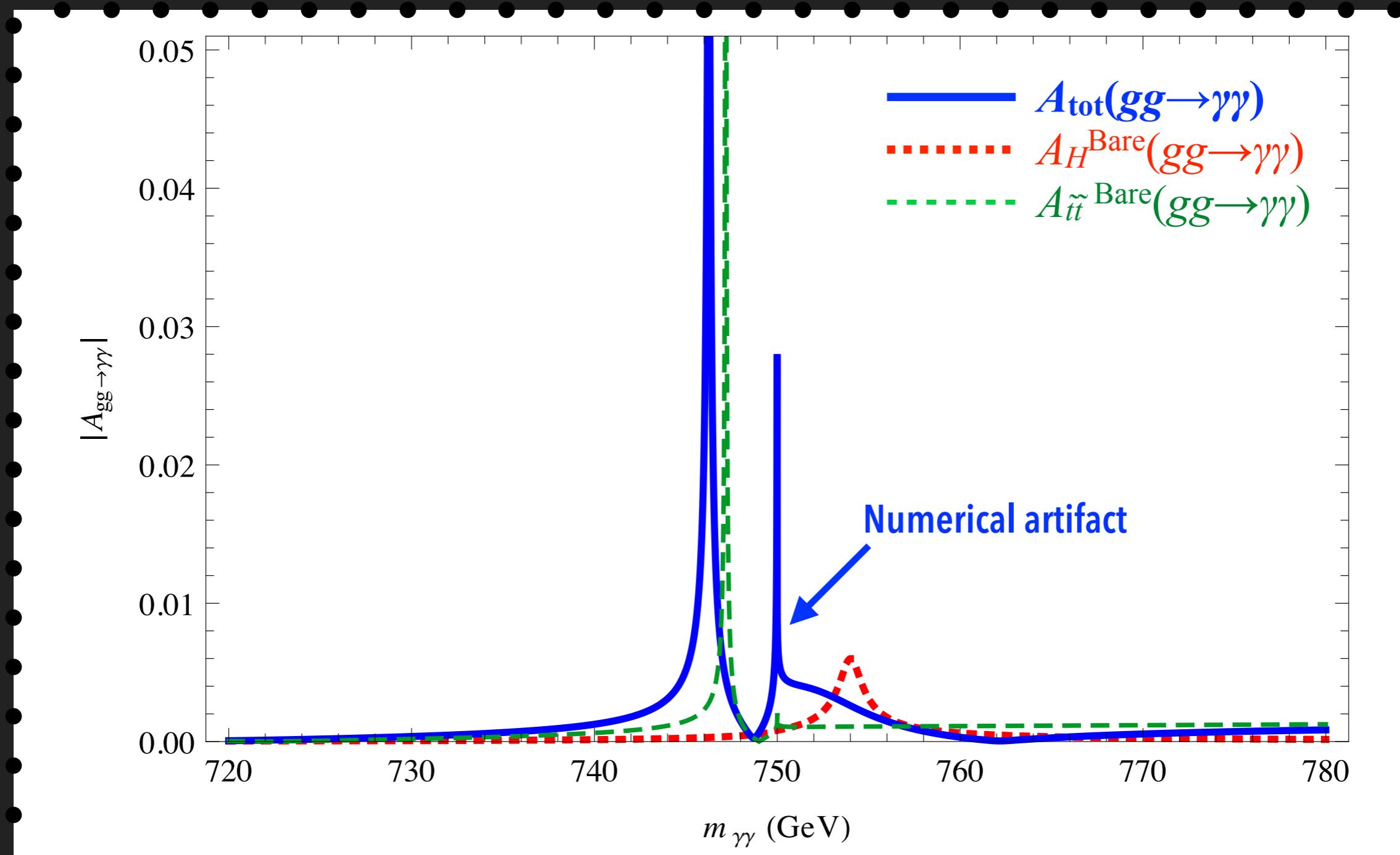
Numerical artifact at threshold from approximations used for Green's functions,
NOT a physical peak, negligible contribution to cross section

HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



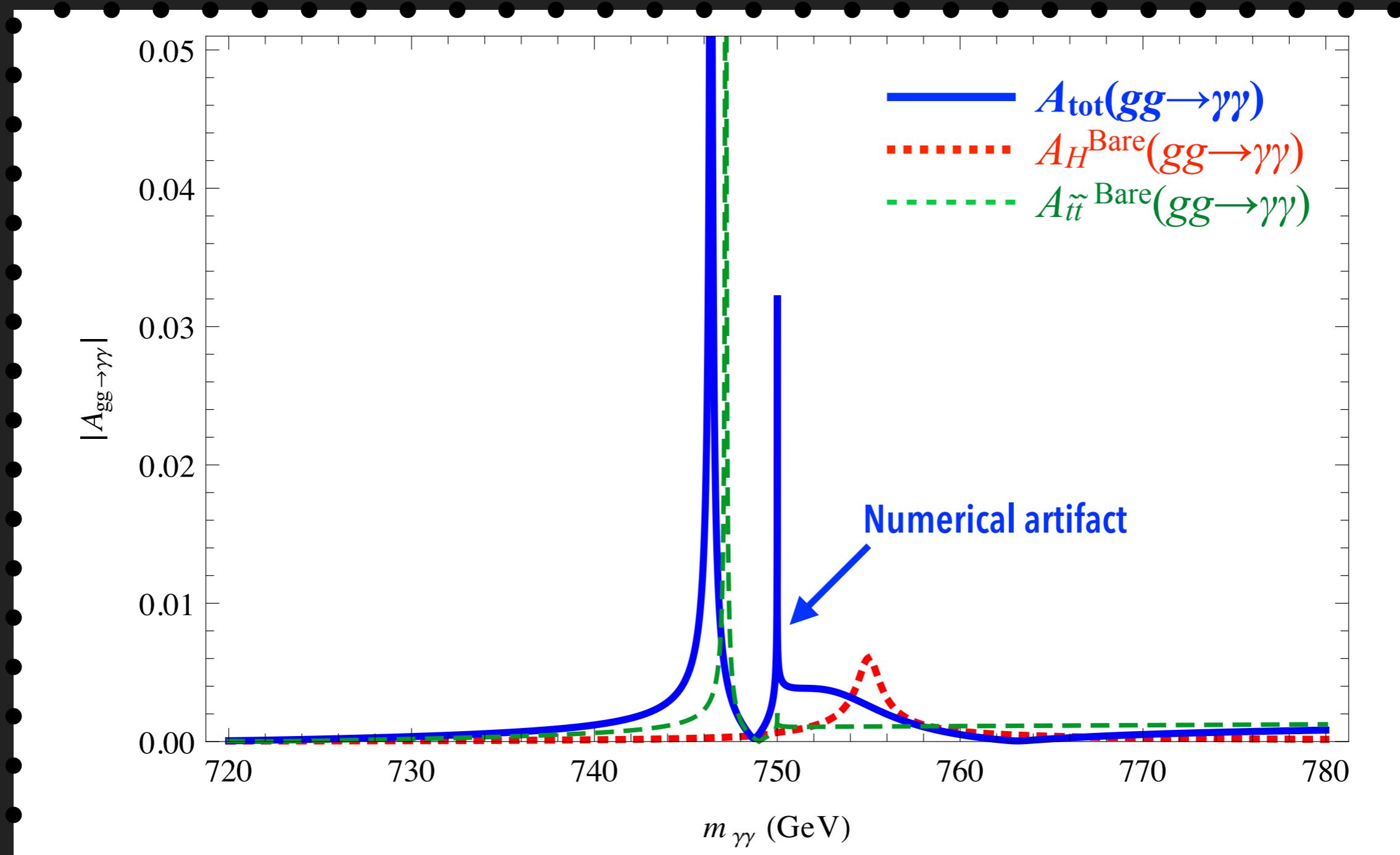
Numerical artifact at threshold from approximations used for Green's functions,
NOT a physical peak, negligible contribution to cross section

HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



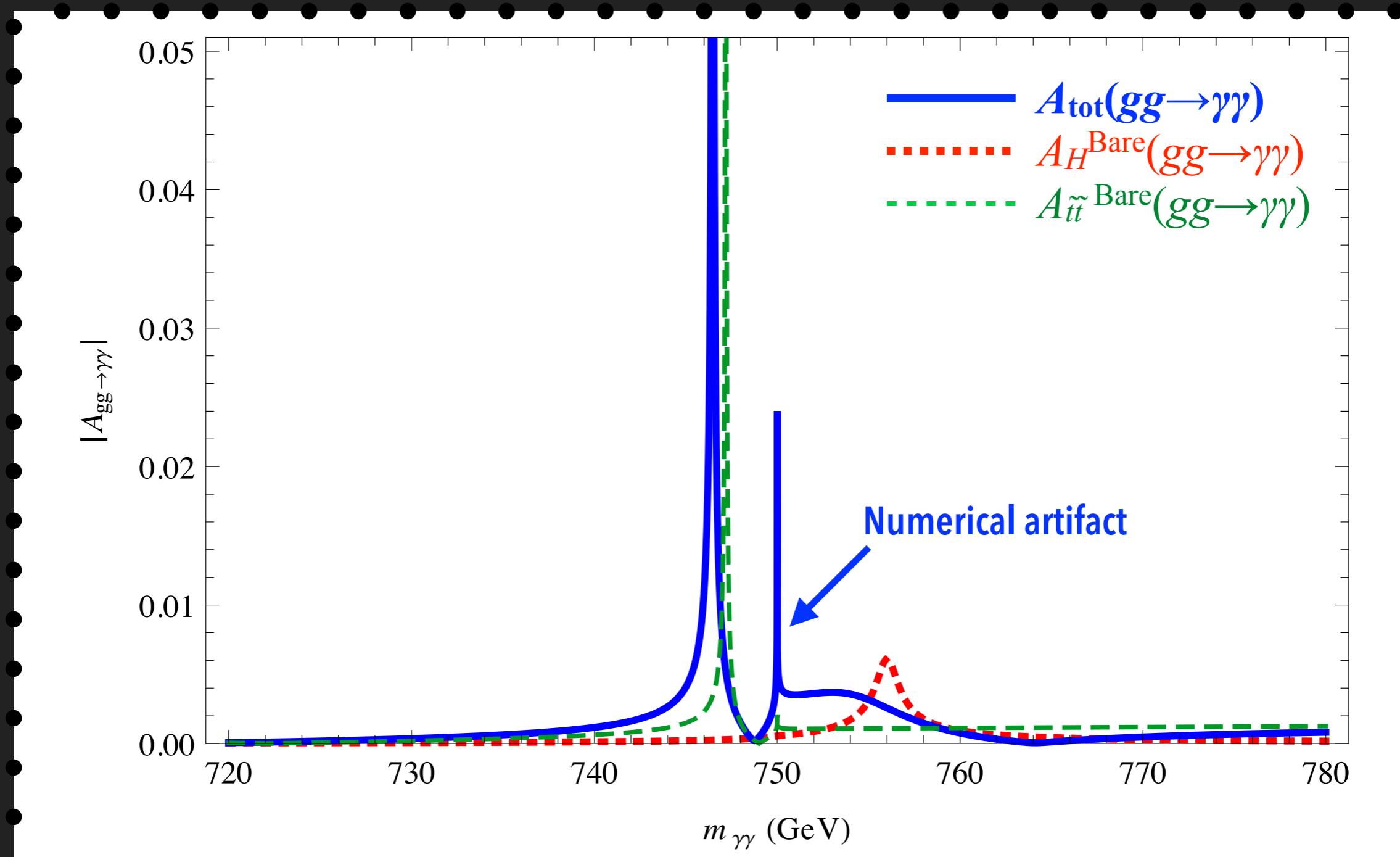
Numerical artifact at threshold from approximations used for Green's functions,
NOT a physical peak, negligible contribution to cross section

HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



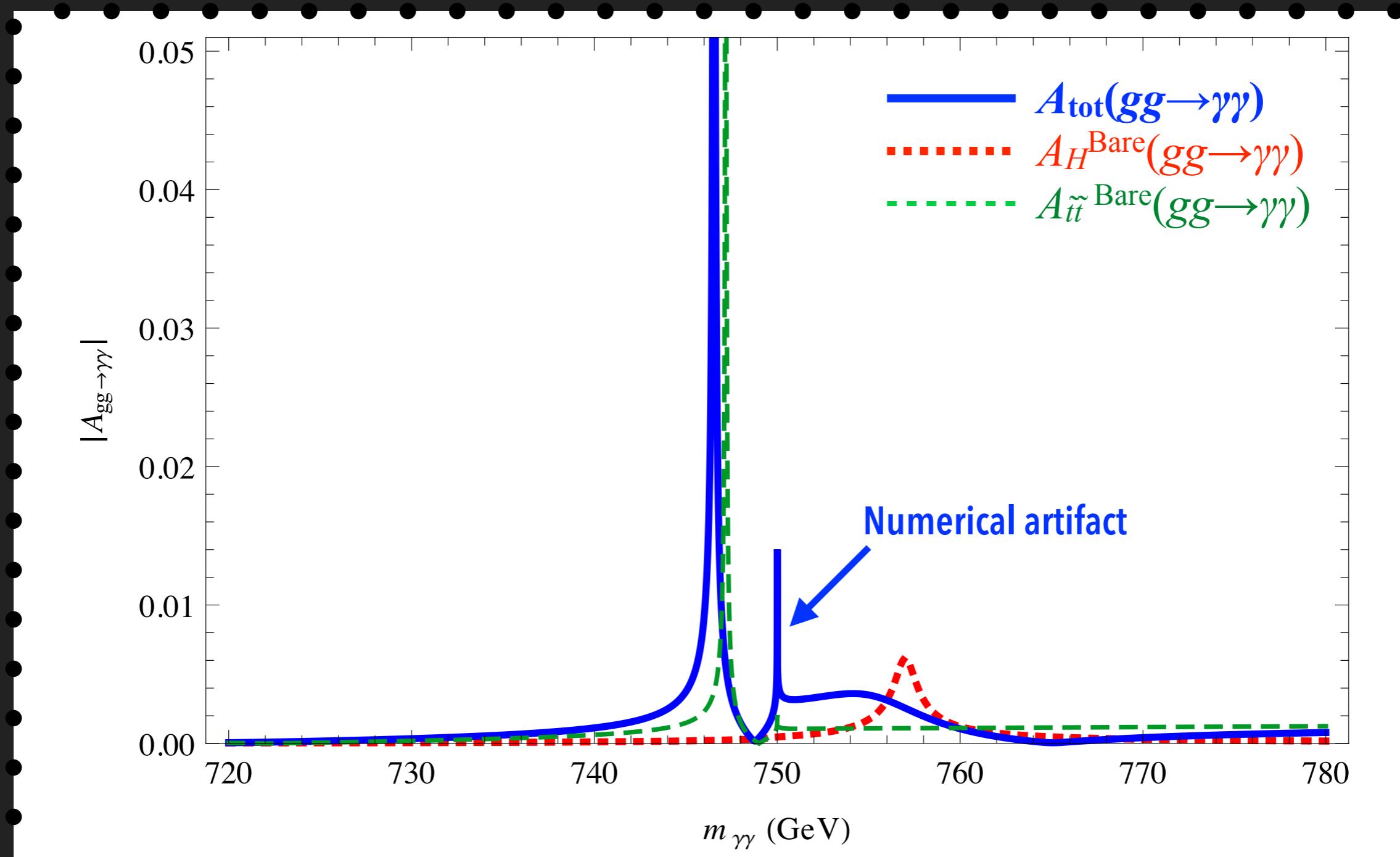
Numerical artifact at threshold from approximations used for Green's functions,
NOT a physical peak, negligible contribution to cross section

HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



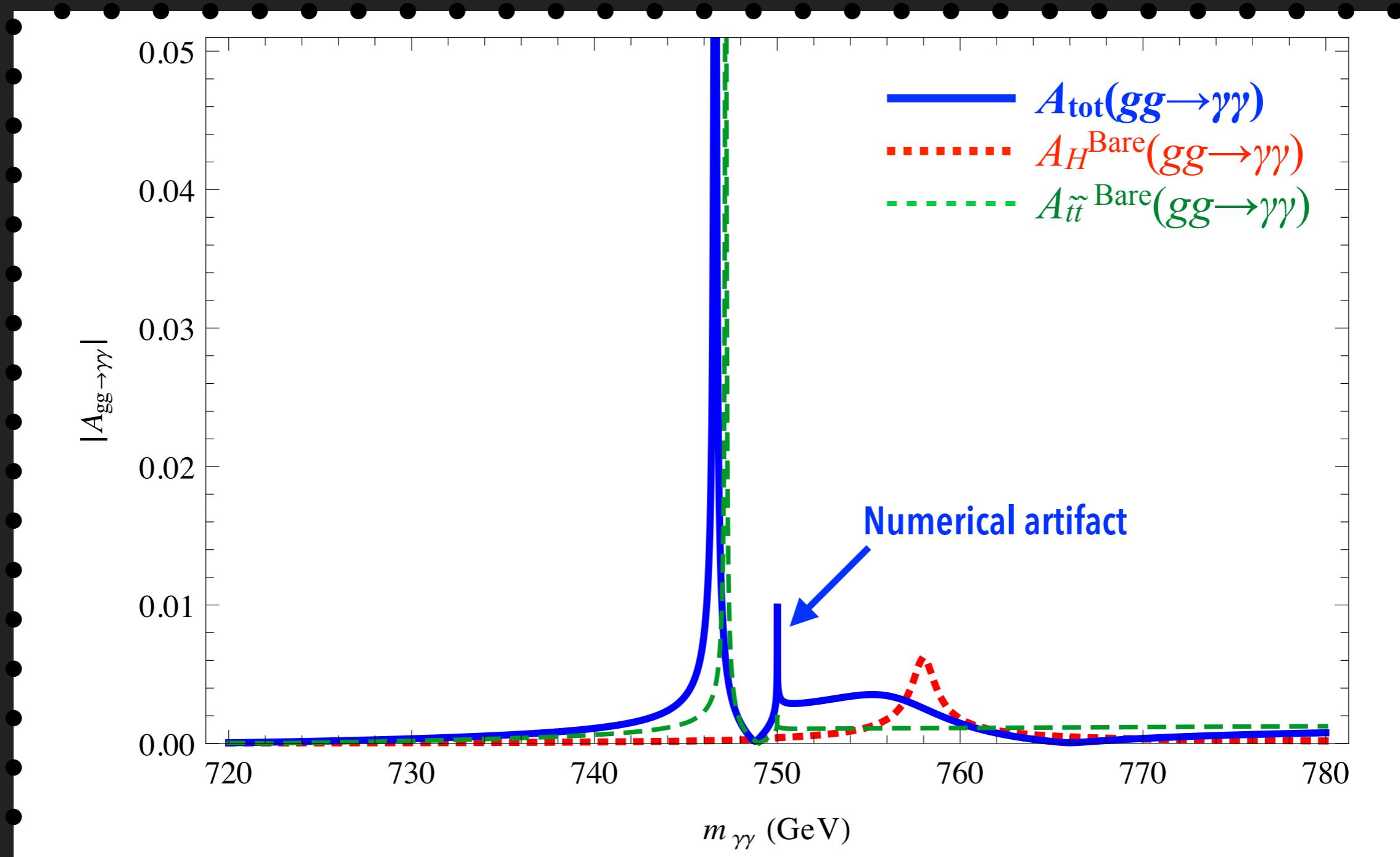
Numerical artifact at threshold from approximations used for Green's functions,
NOT a physical peak, negligible contribution to cross section

HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



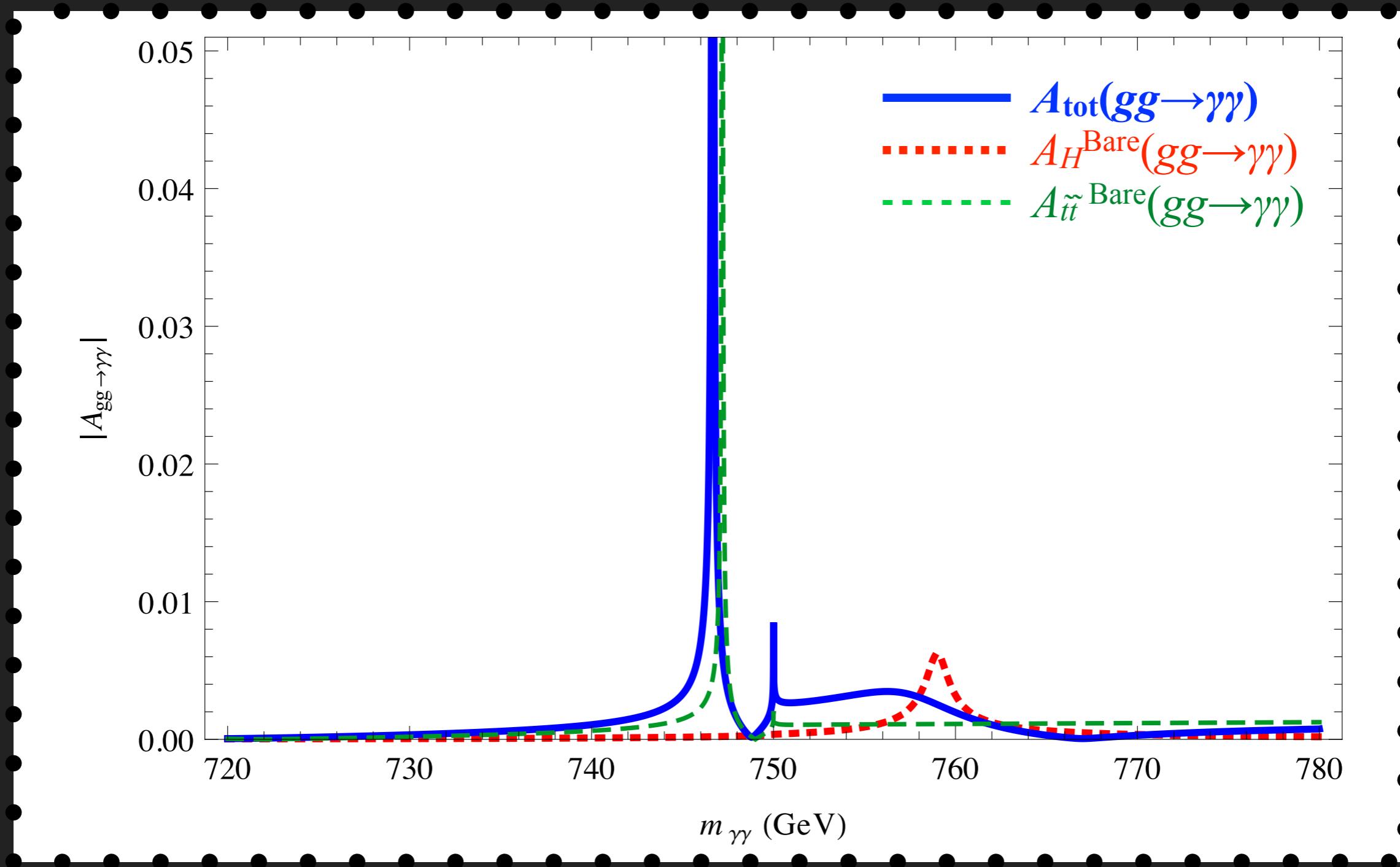
Numerical artifact at threshold from approximations used for Green's functions,
NOT a physical peak, negligible contribution to cross section

HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION

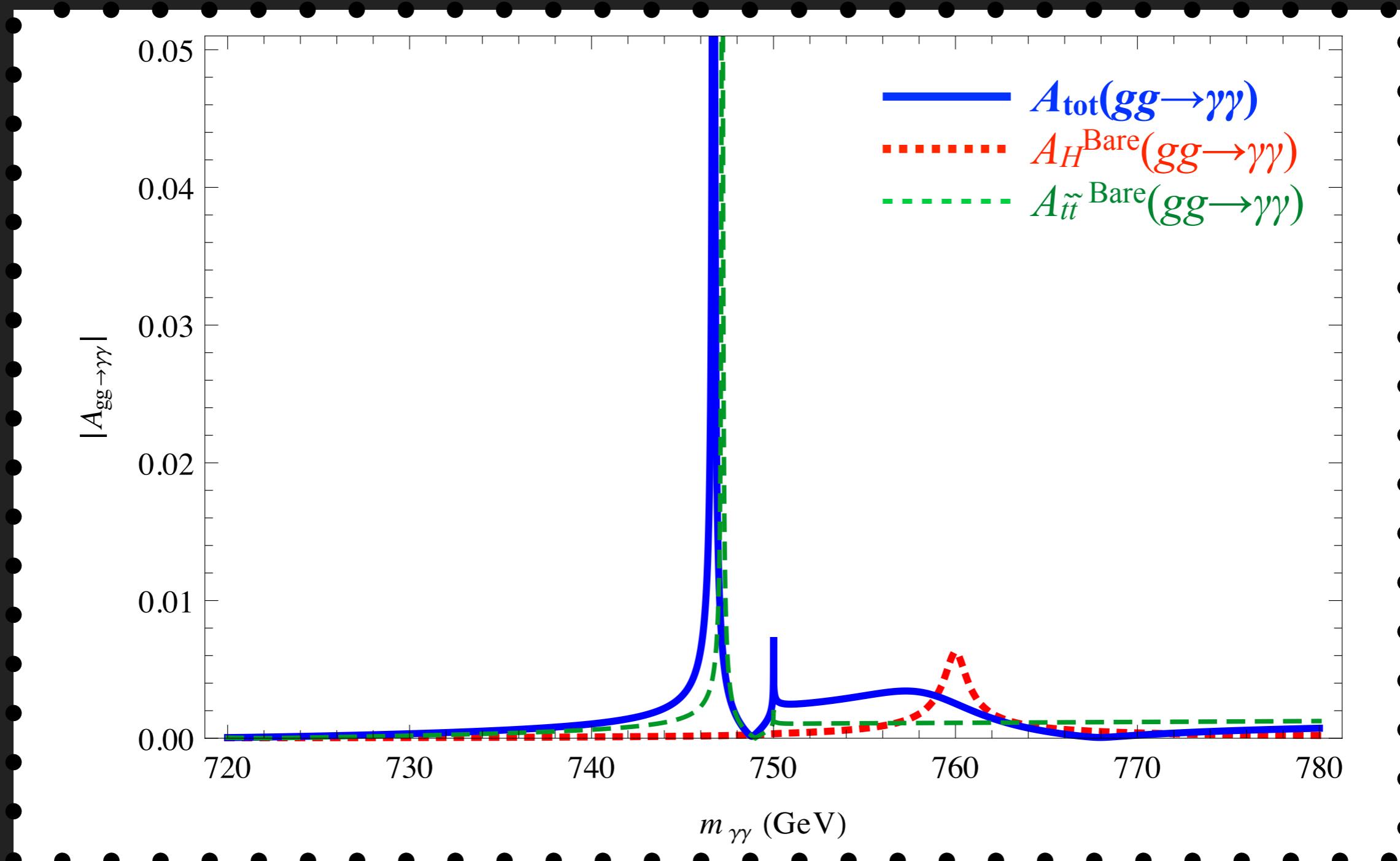


Numerical artifact at threshold from approximations used for Green's functions,
NOT a physical peak, negligible contribution to cross section

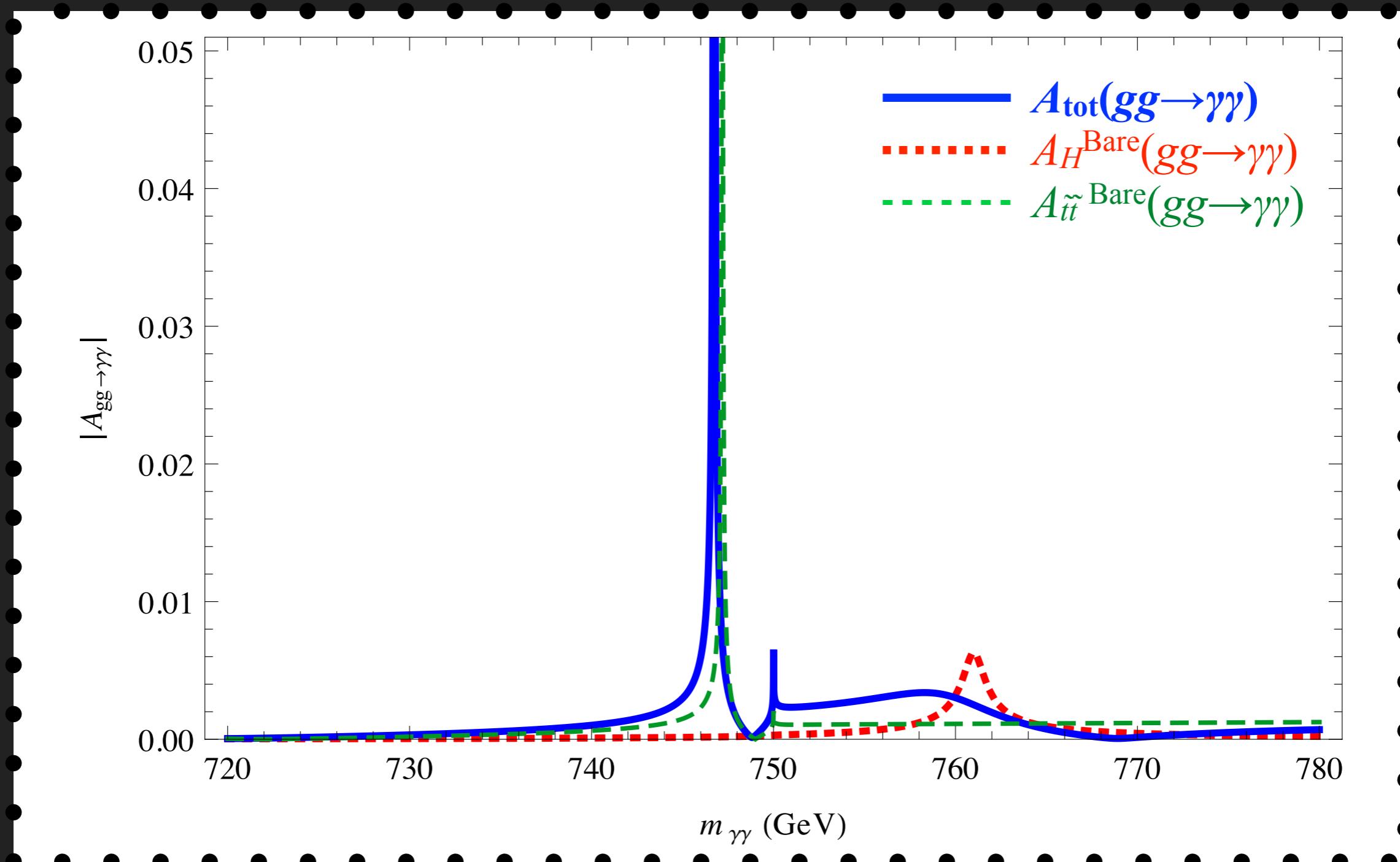
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



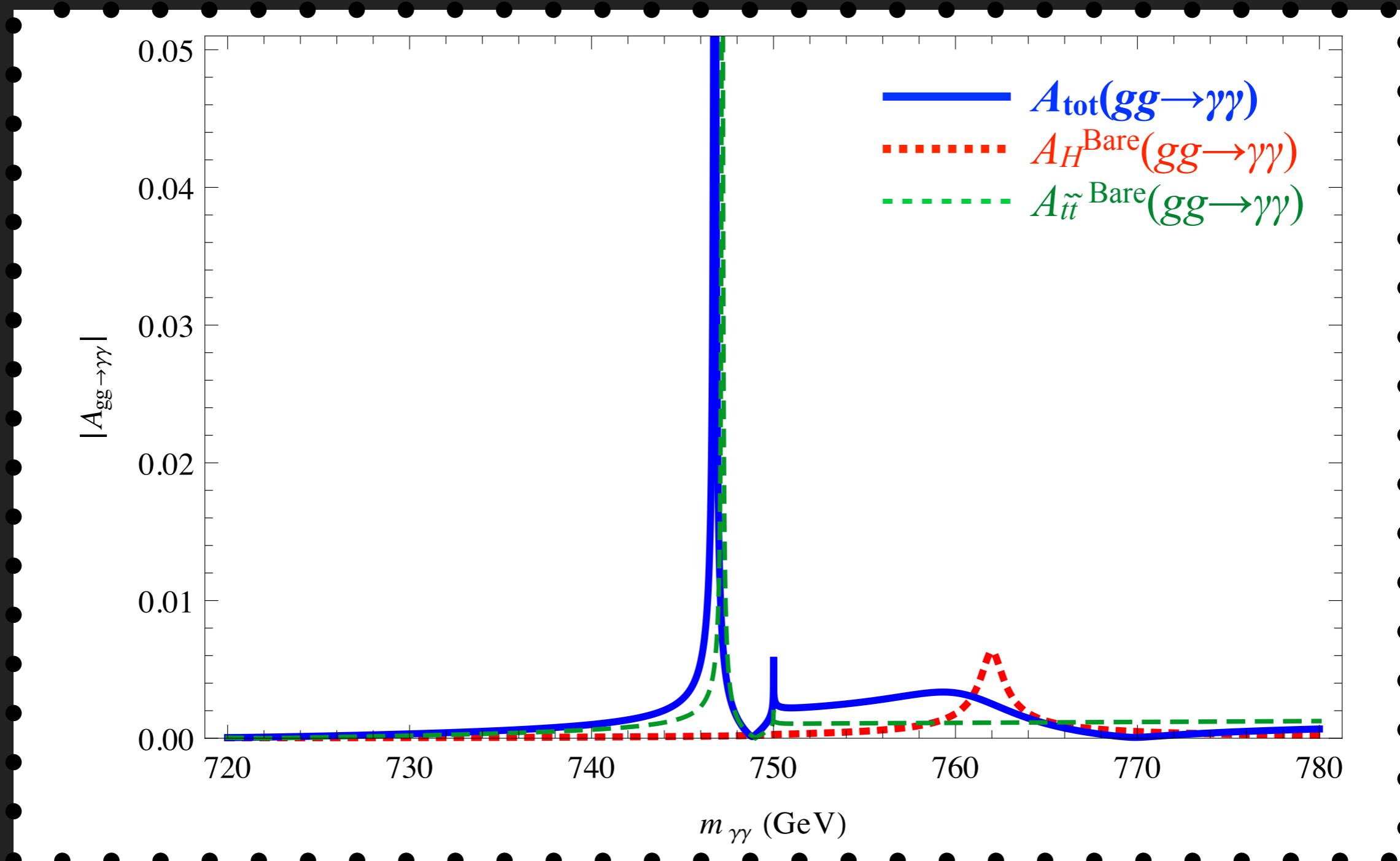
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



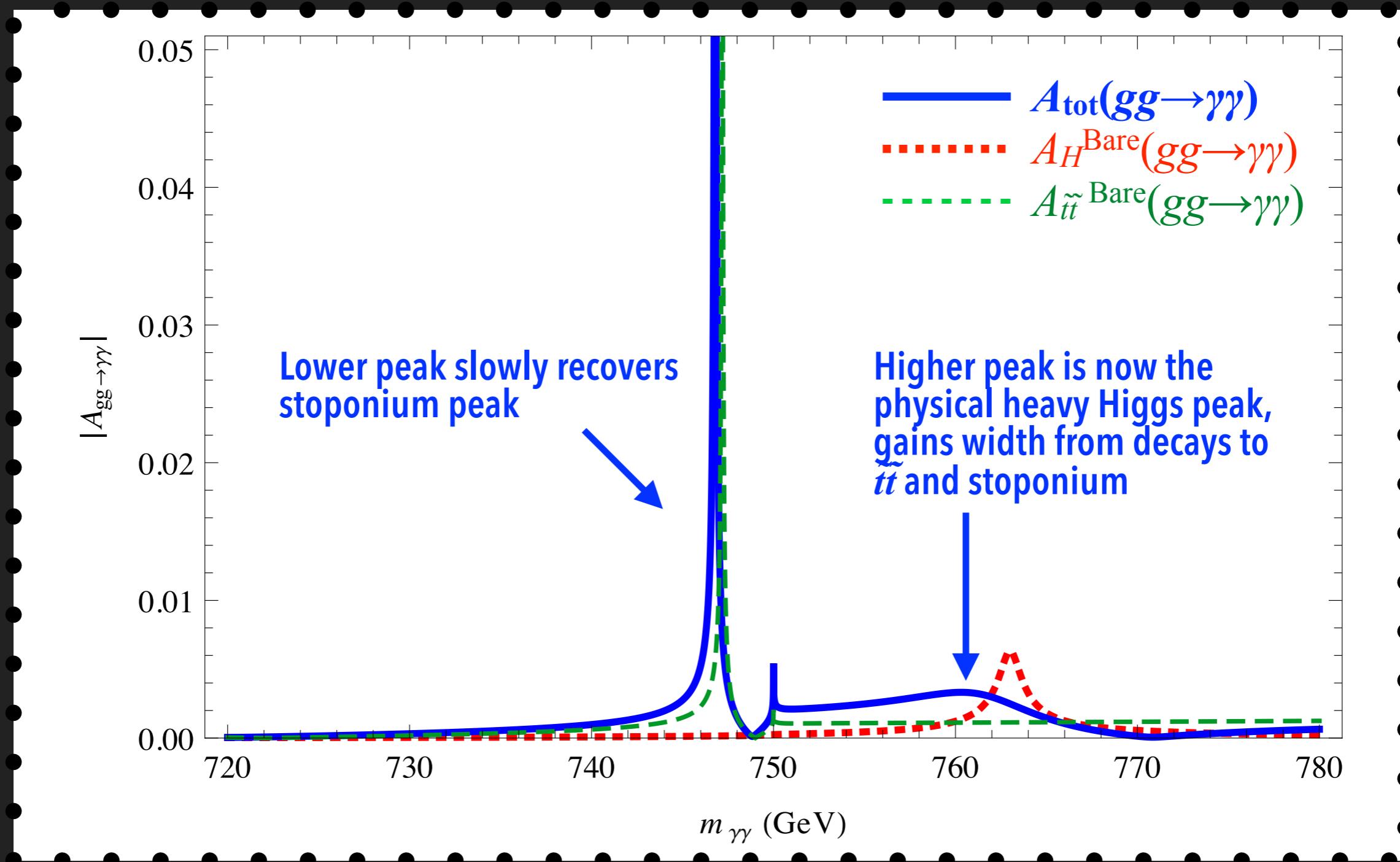
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



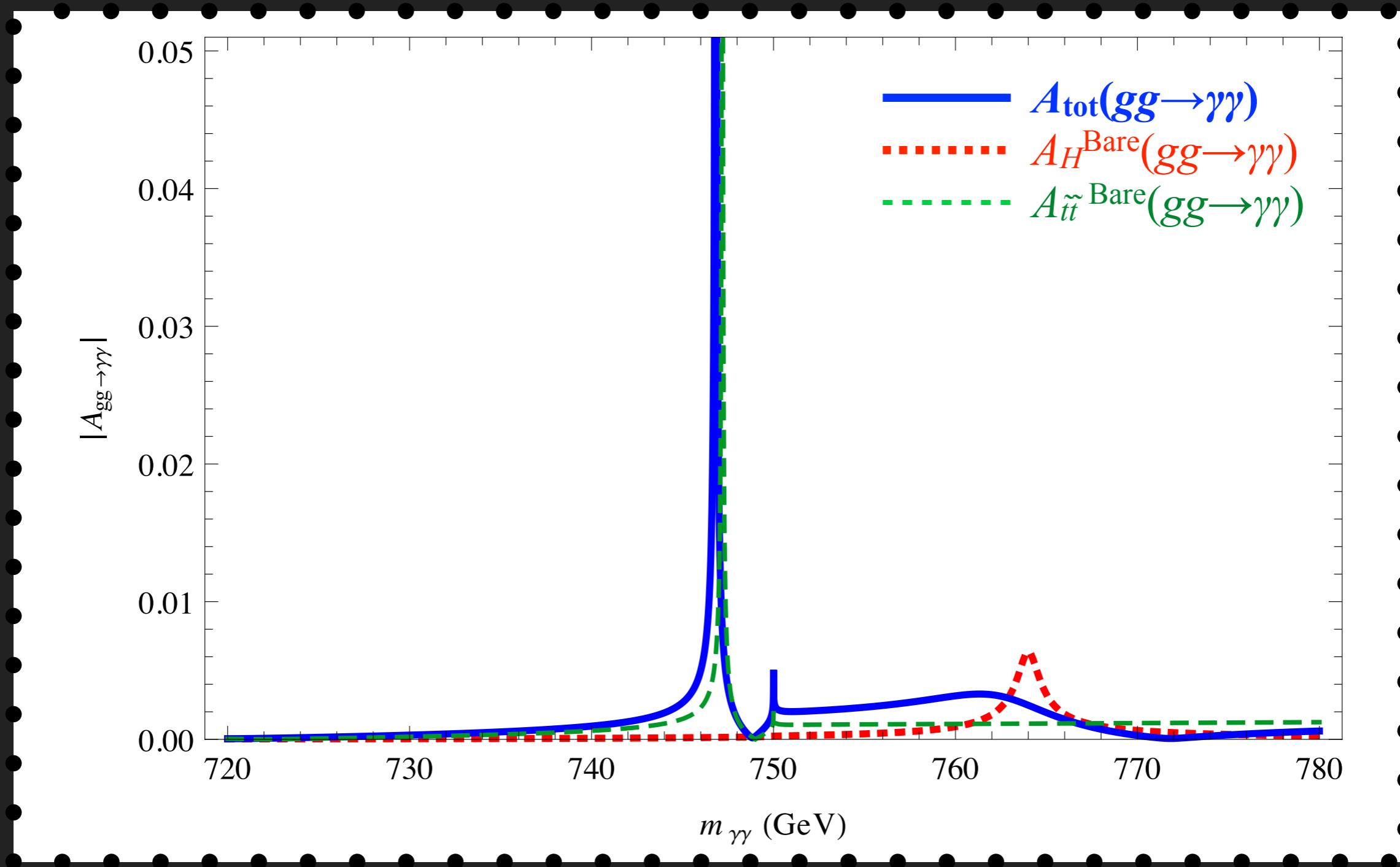
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



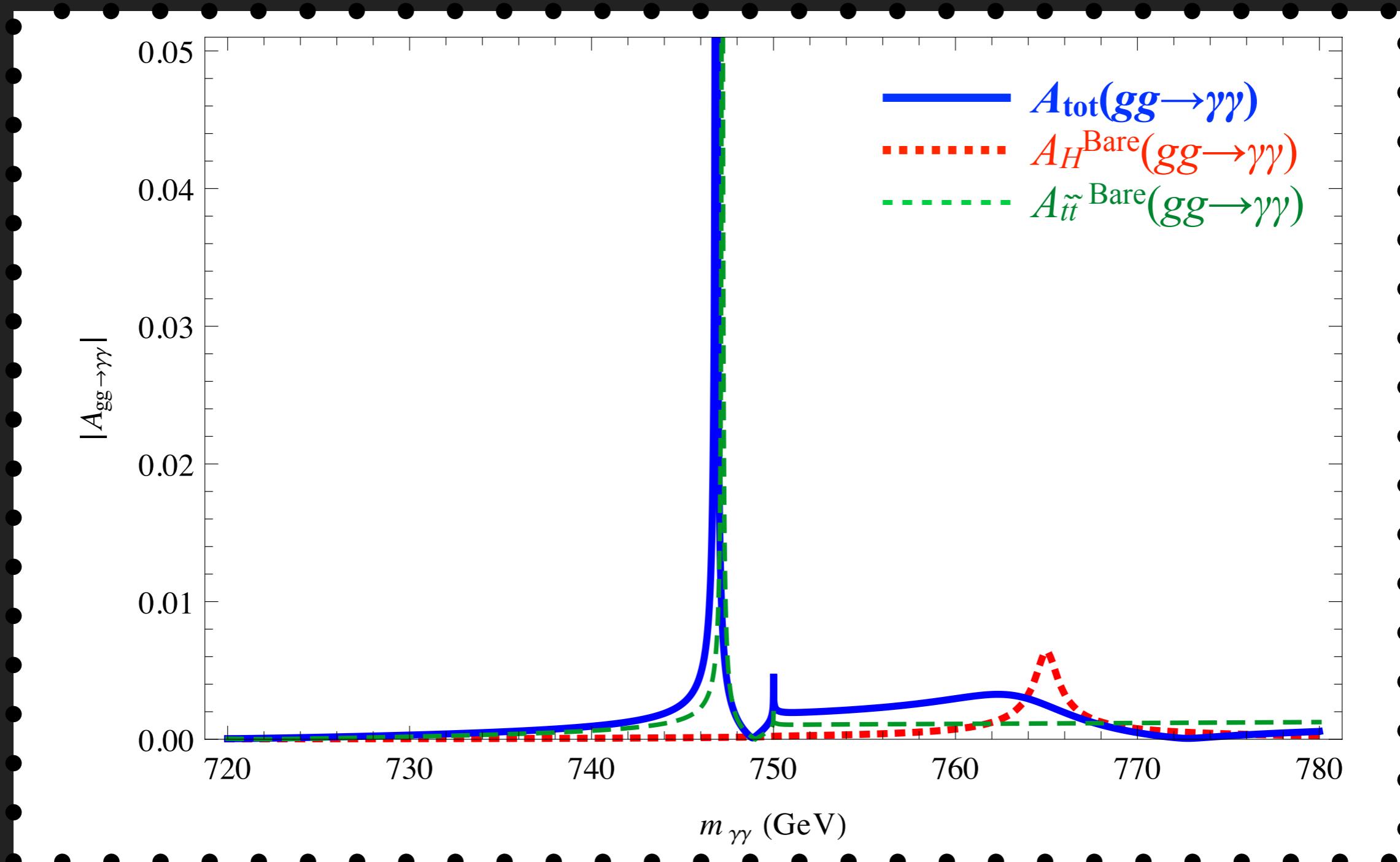
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



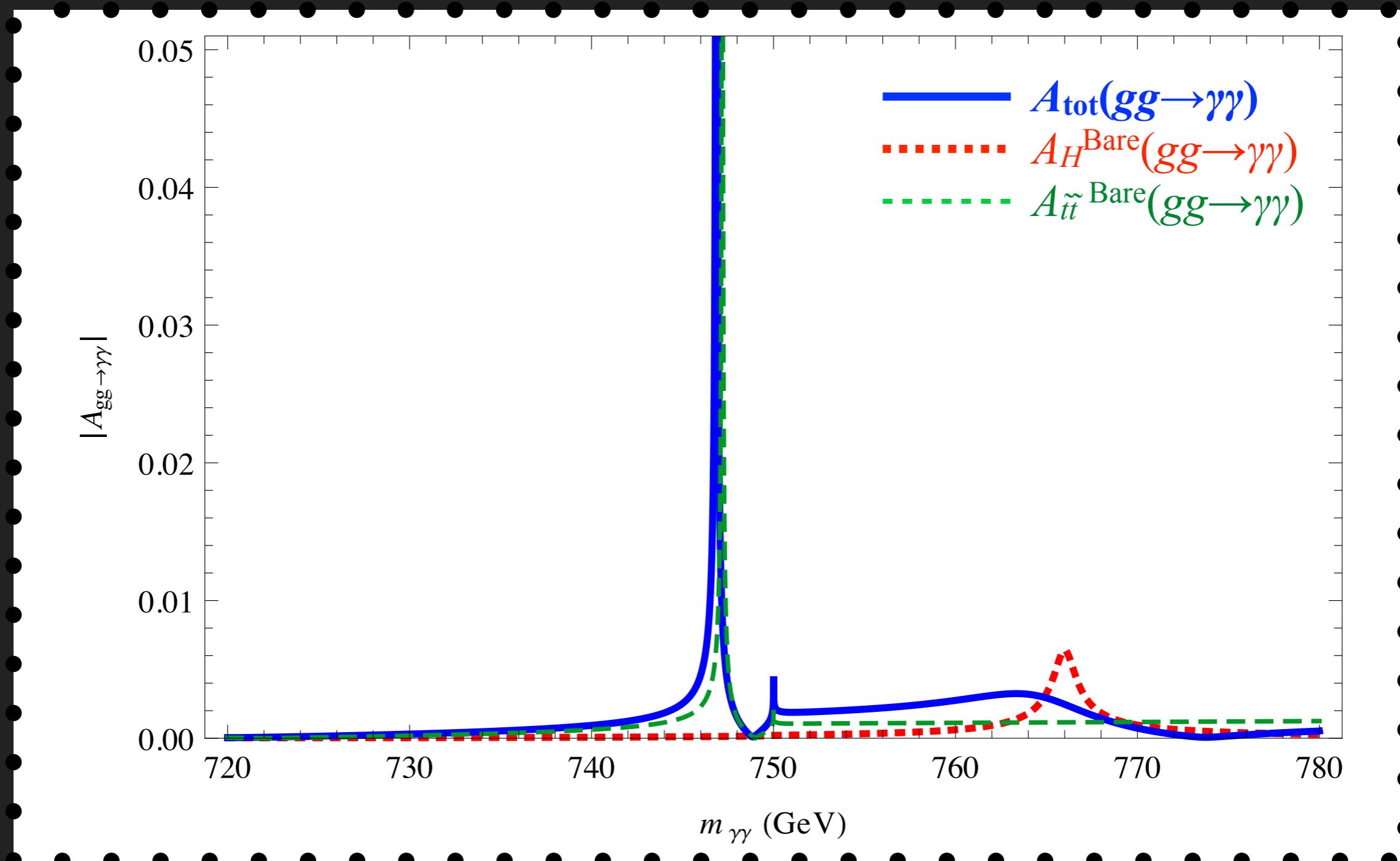
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



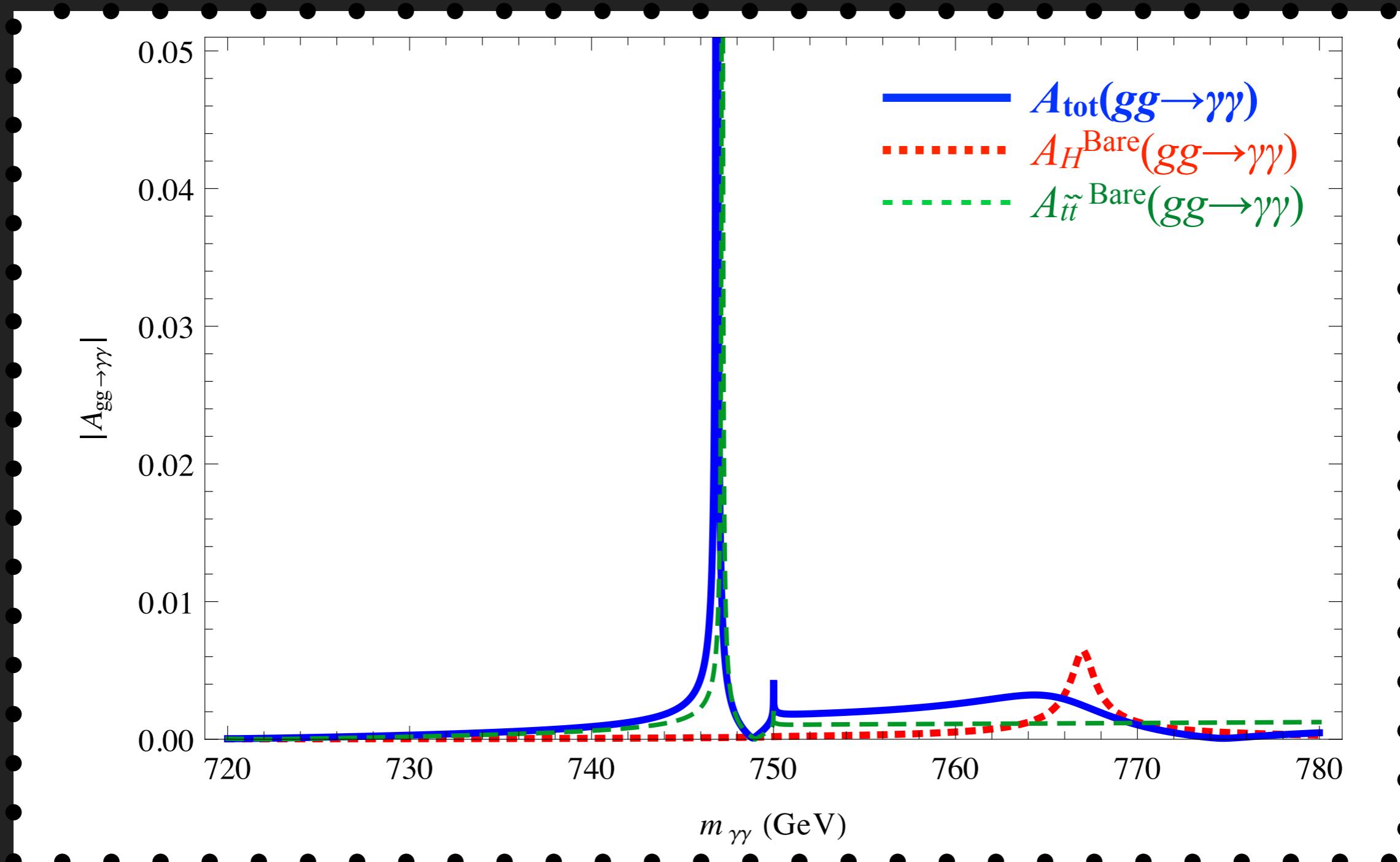
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



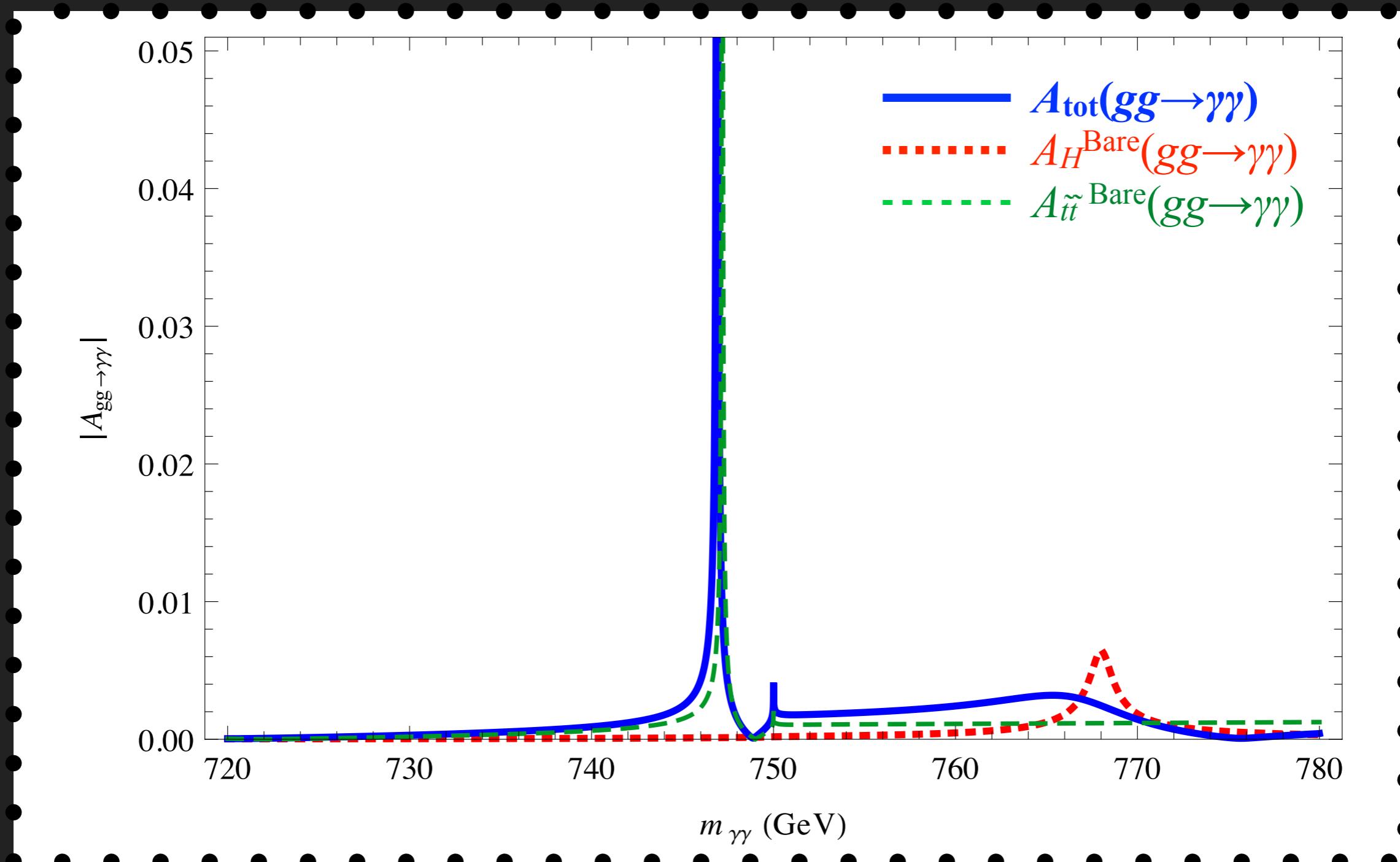
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



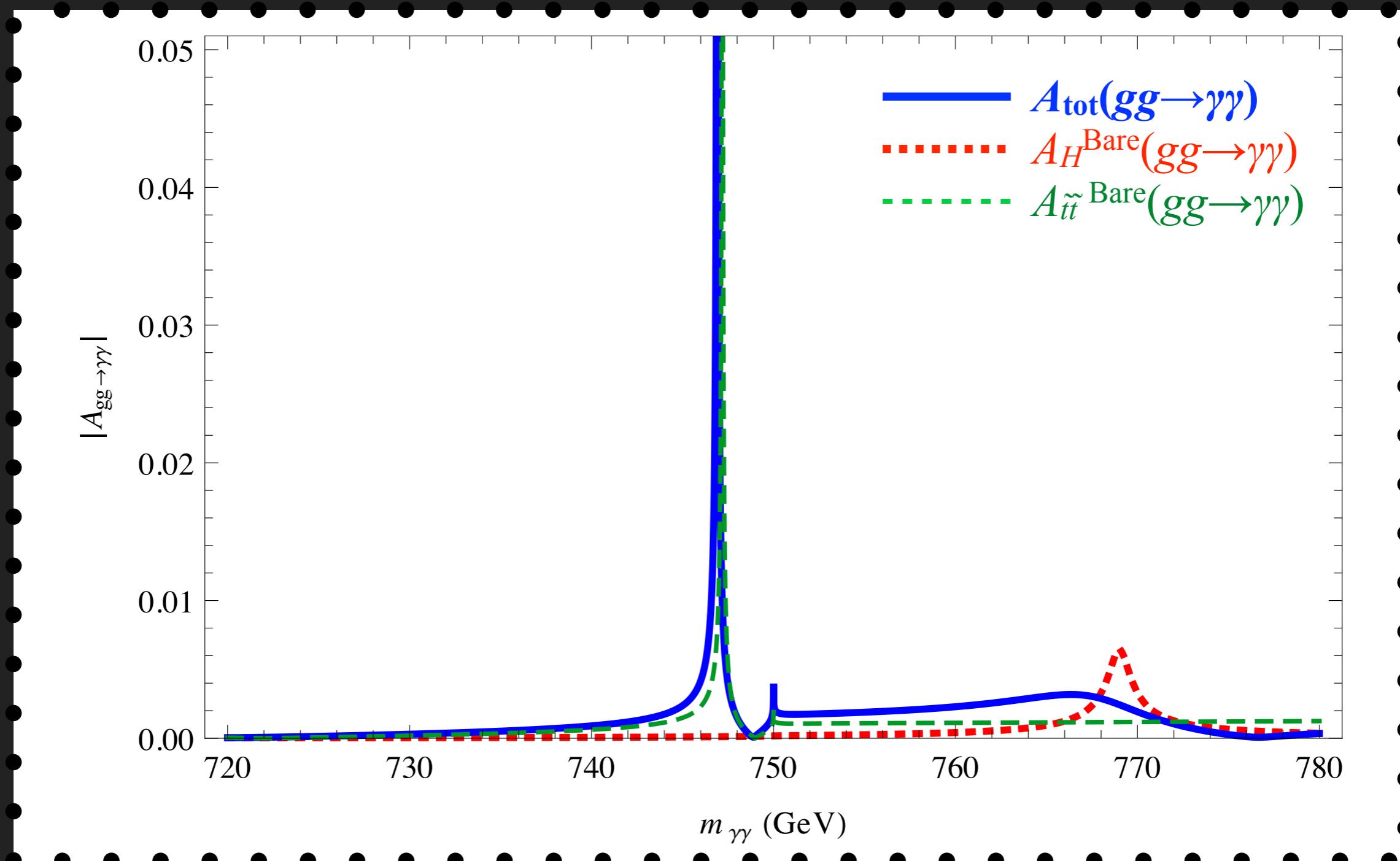
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



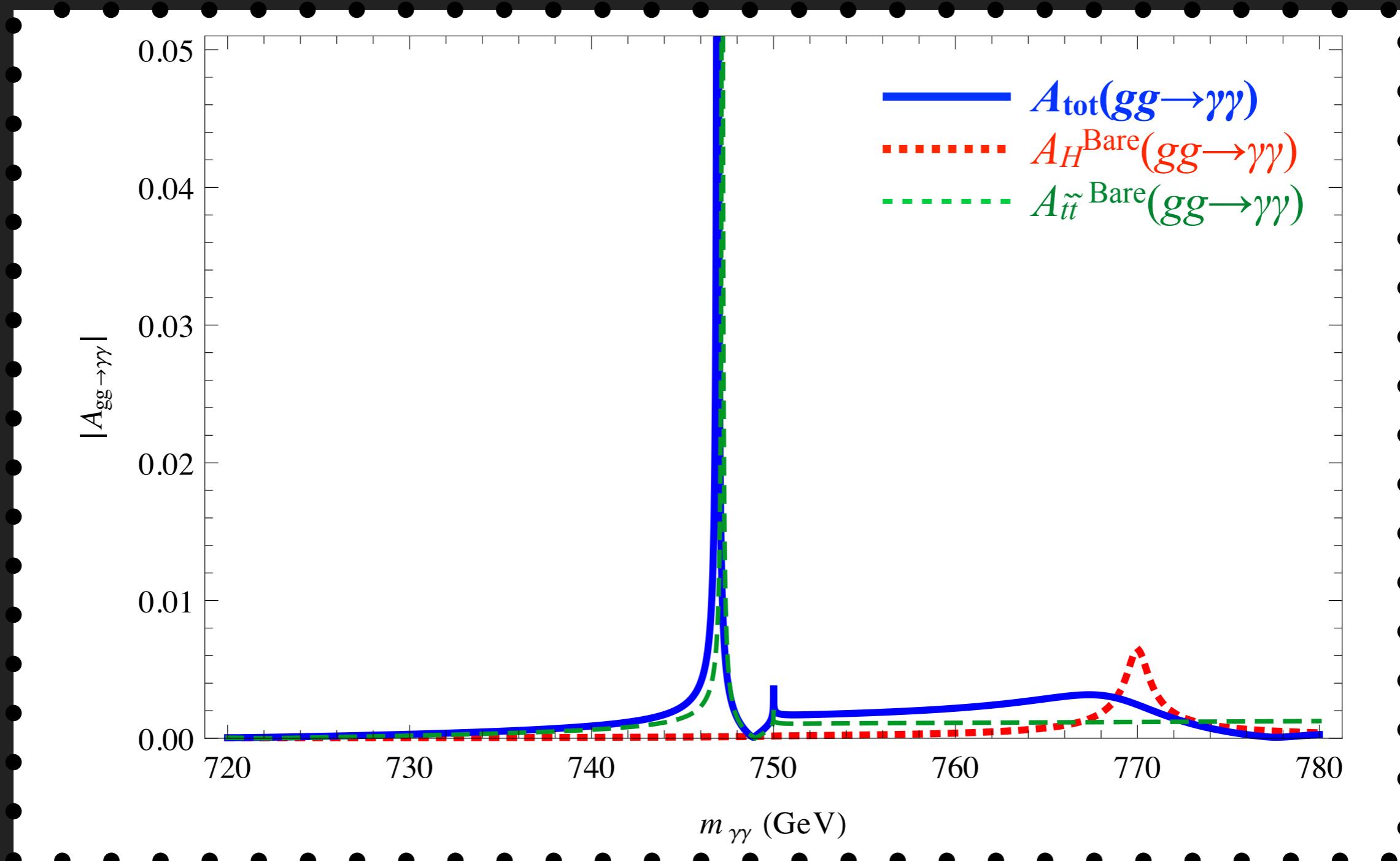
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



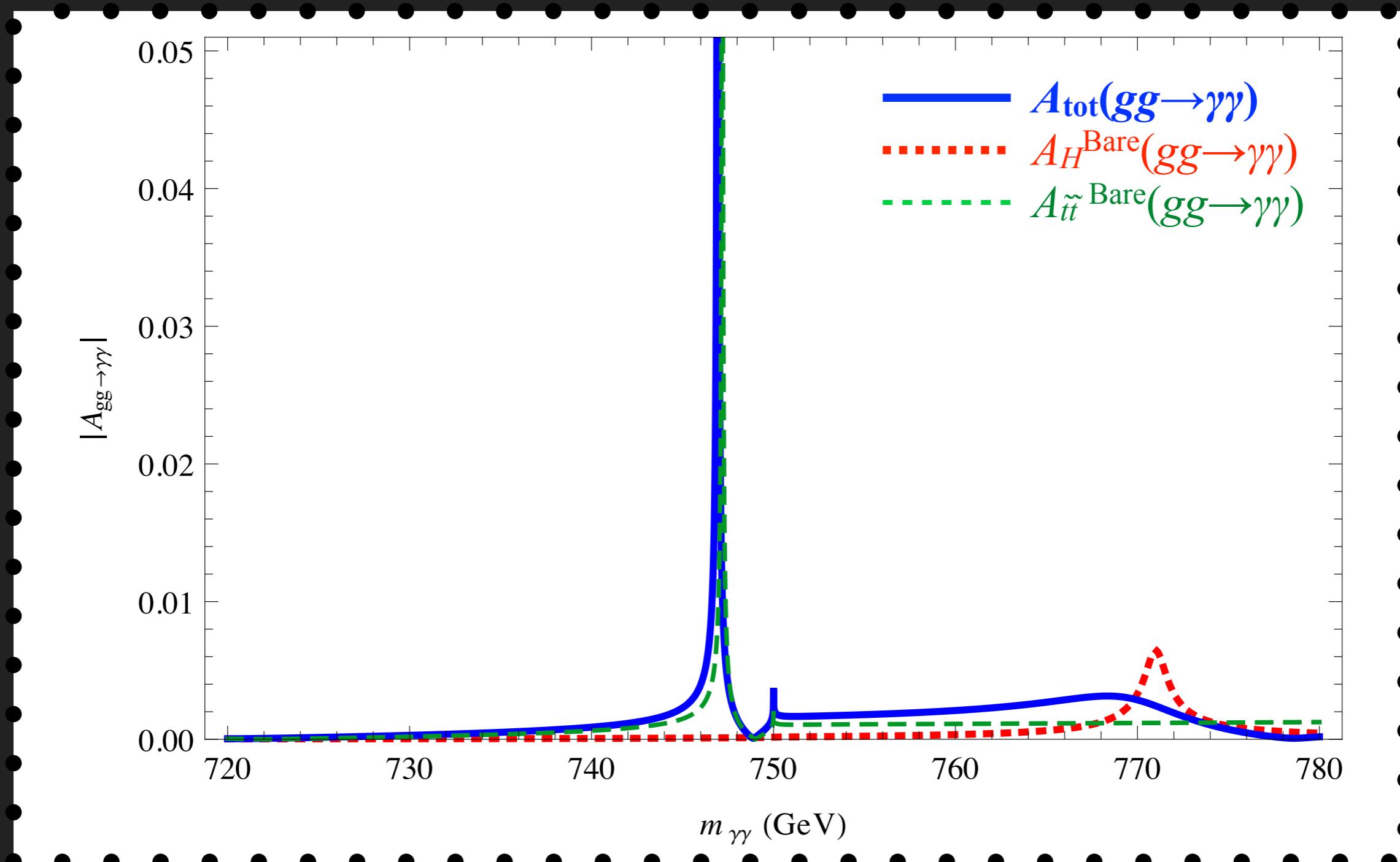
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



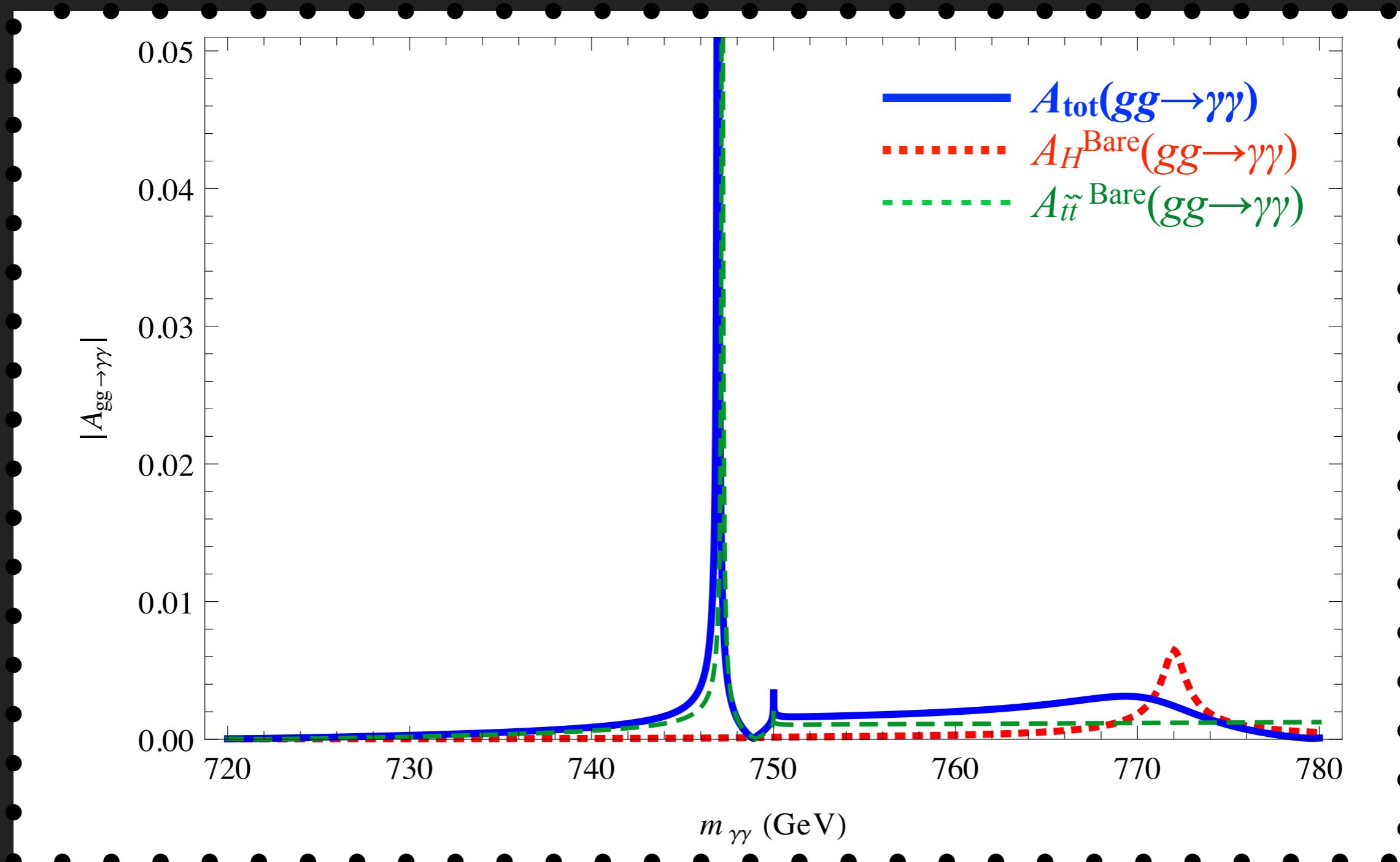
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



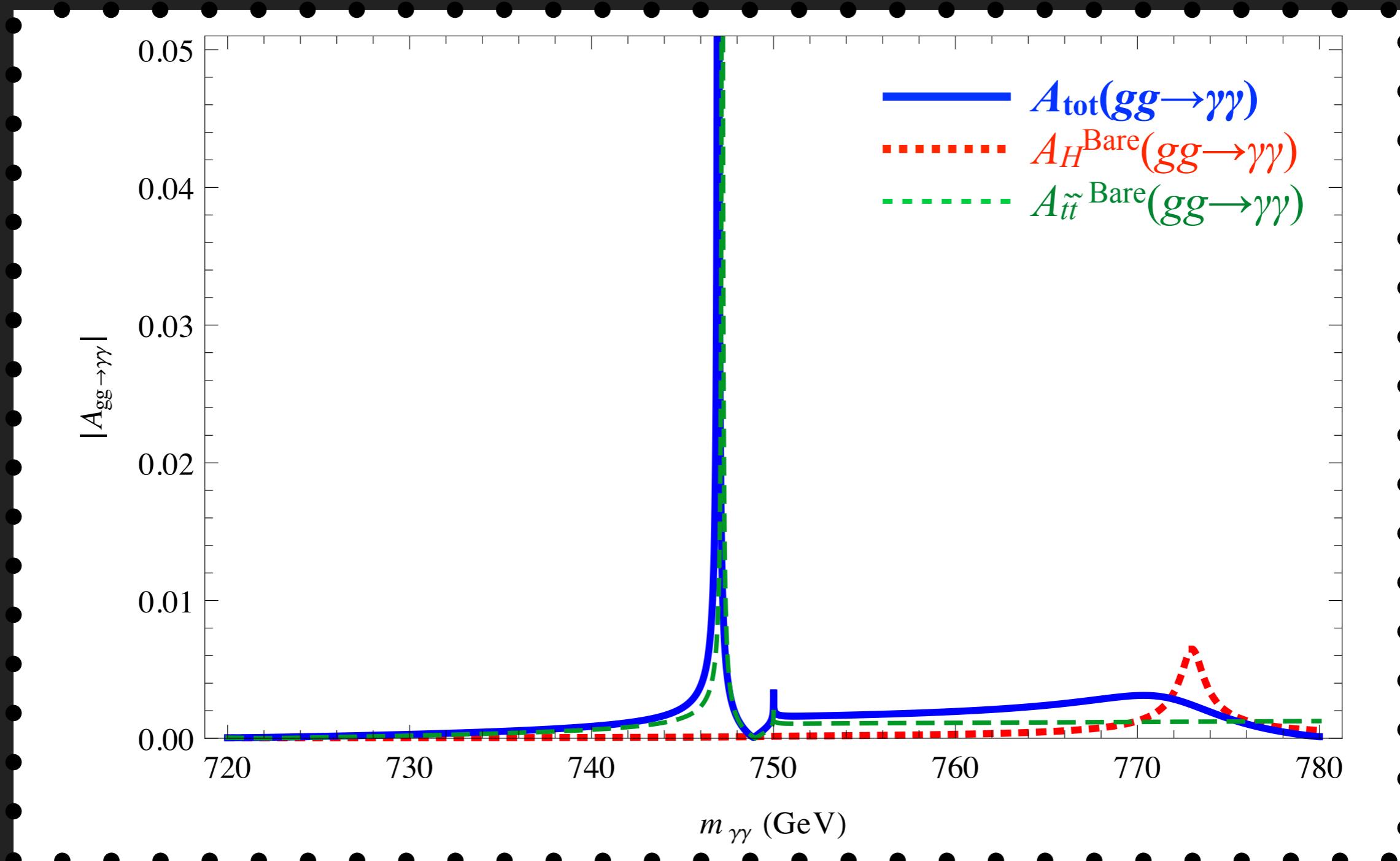
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



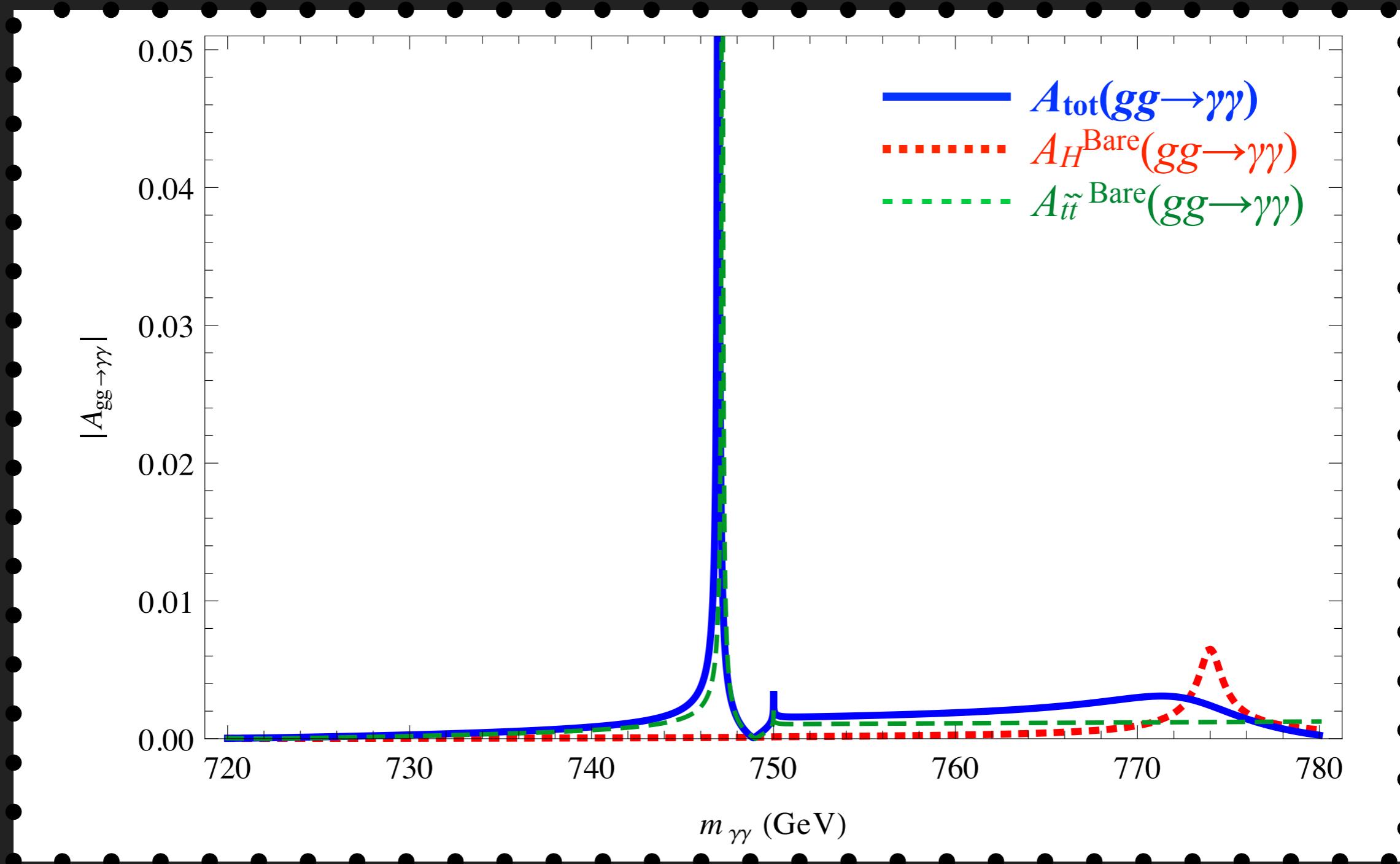
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



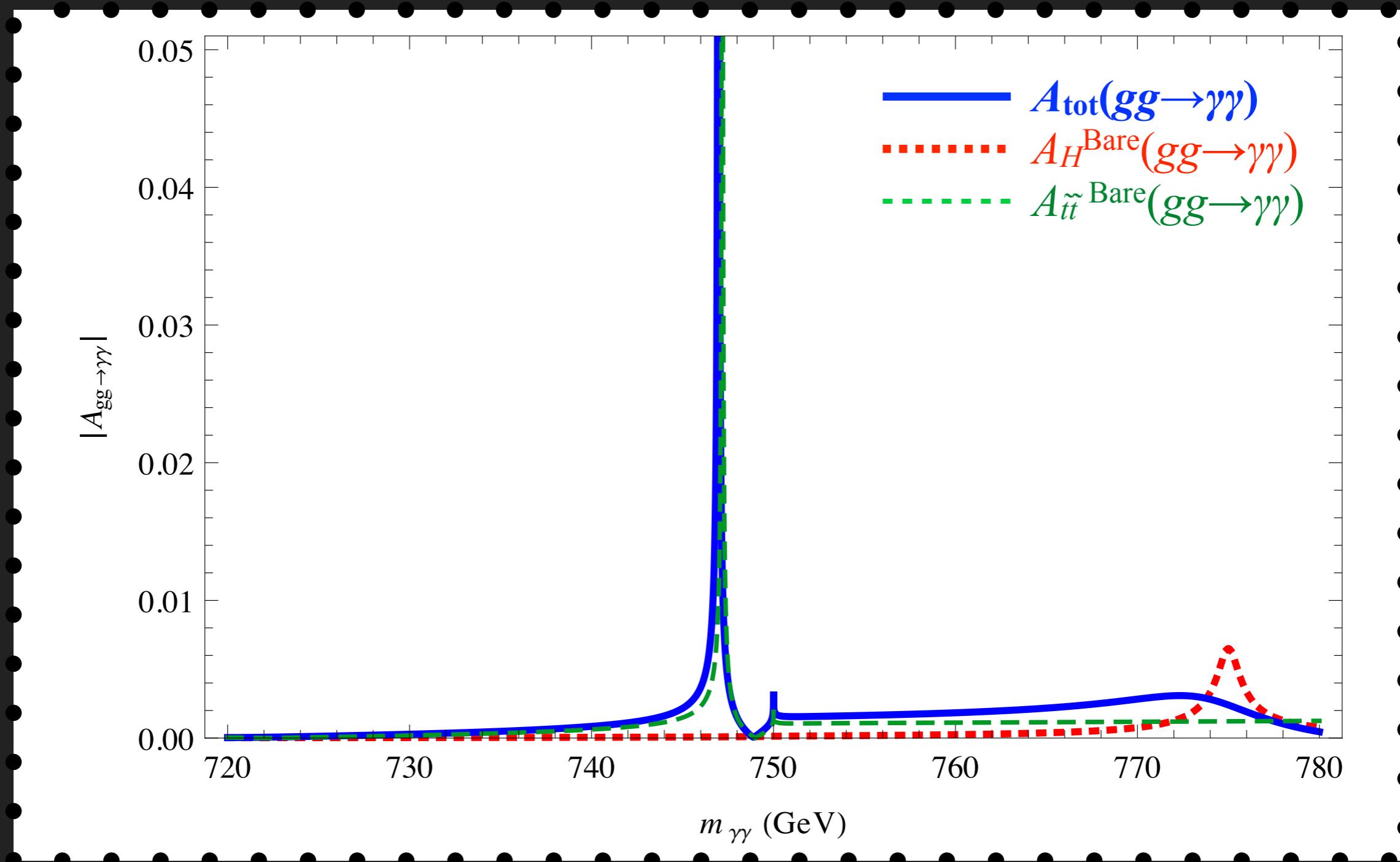
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



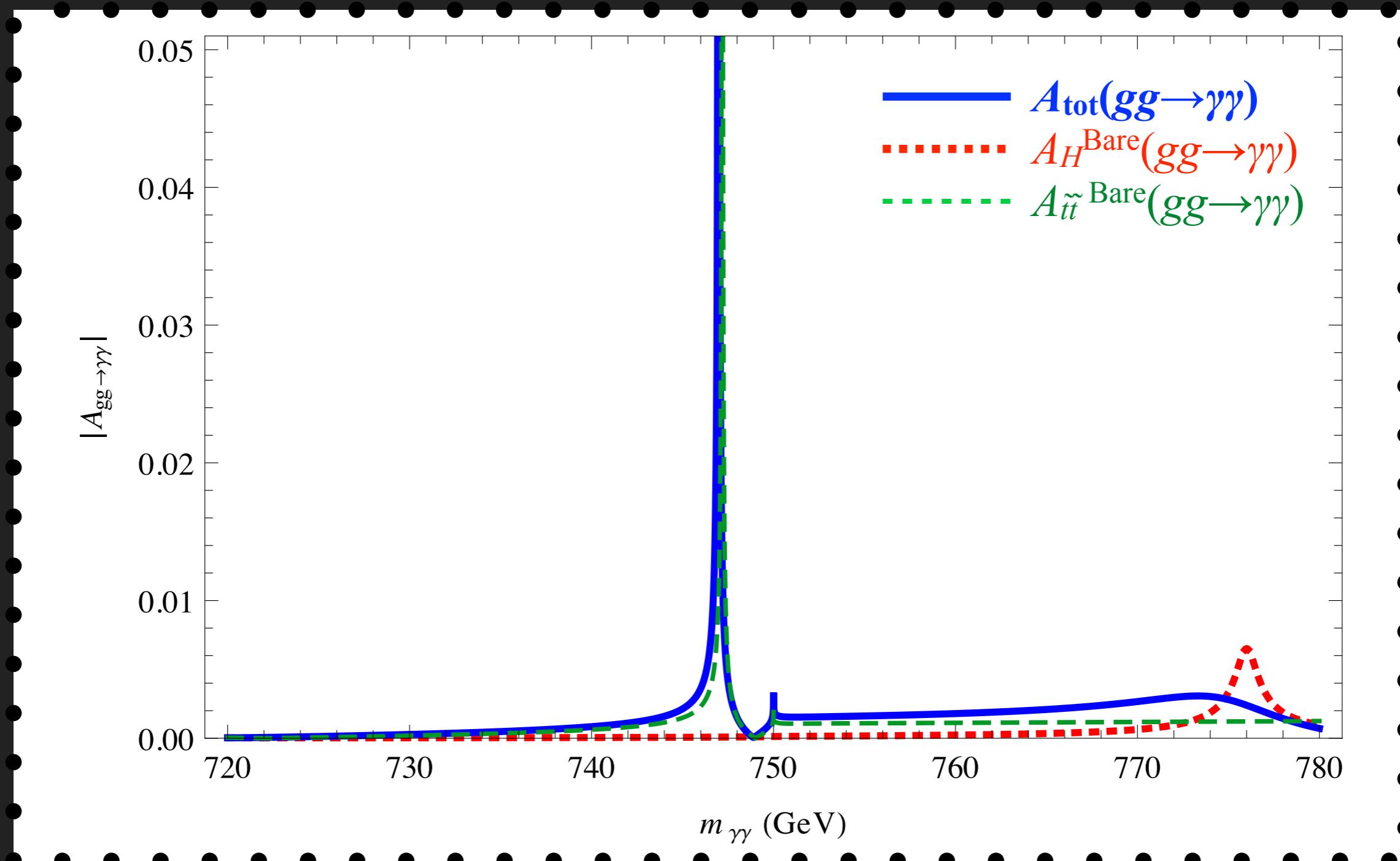
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



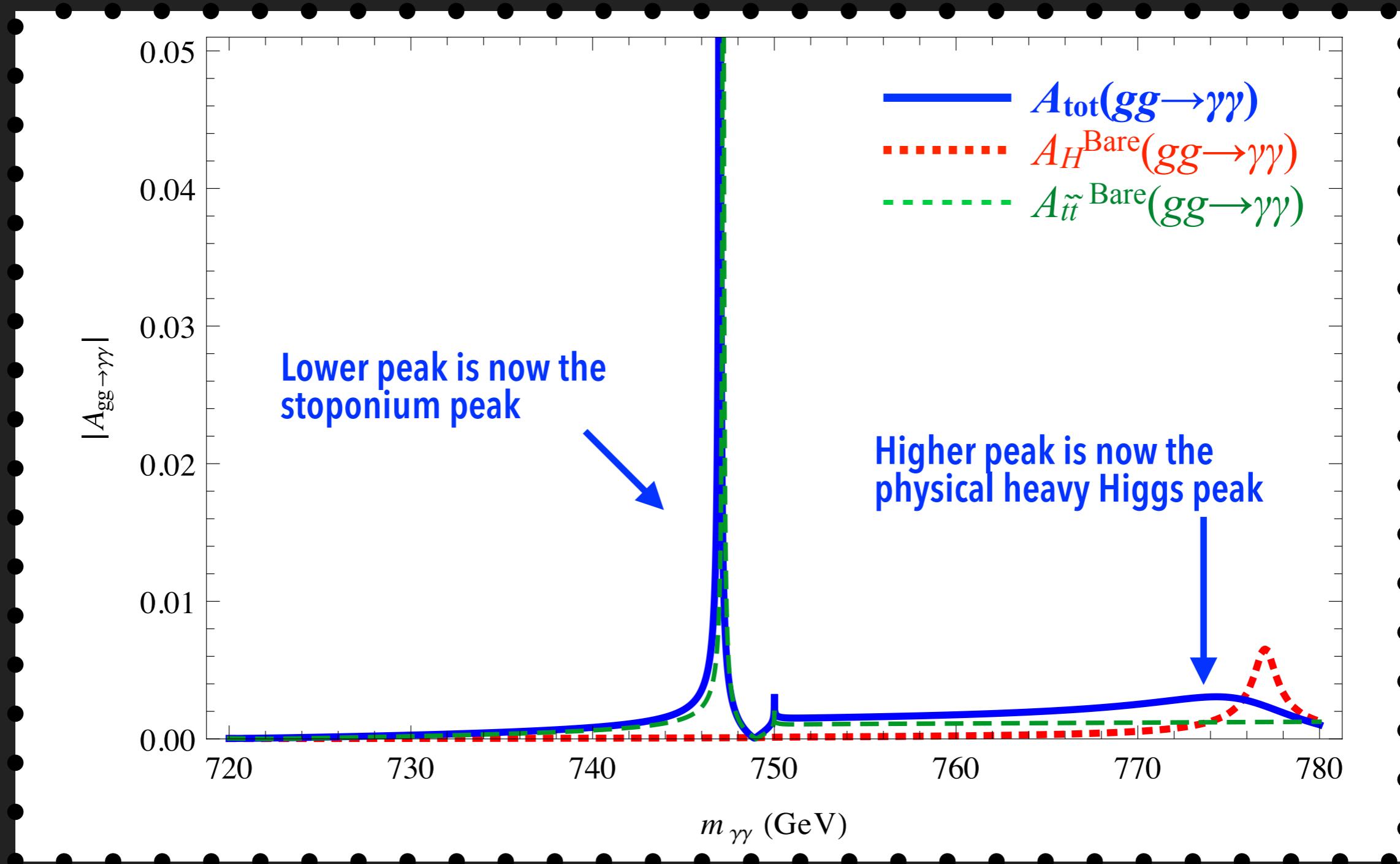
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



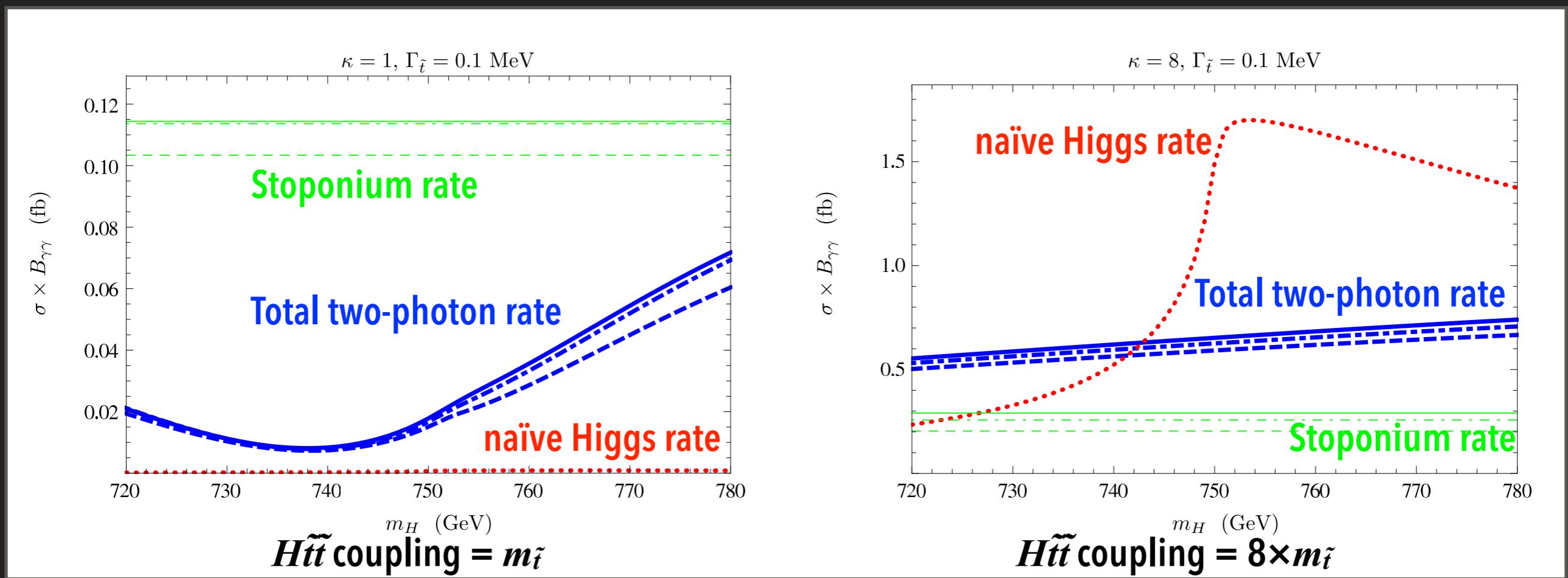
HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION



HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION

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

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



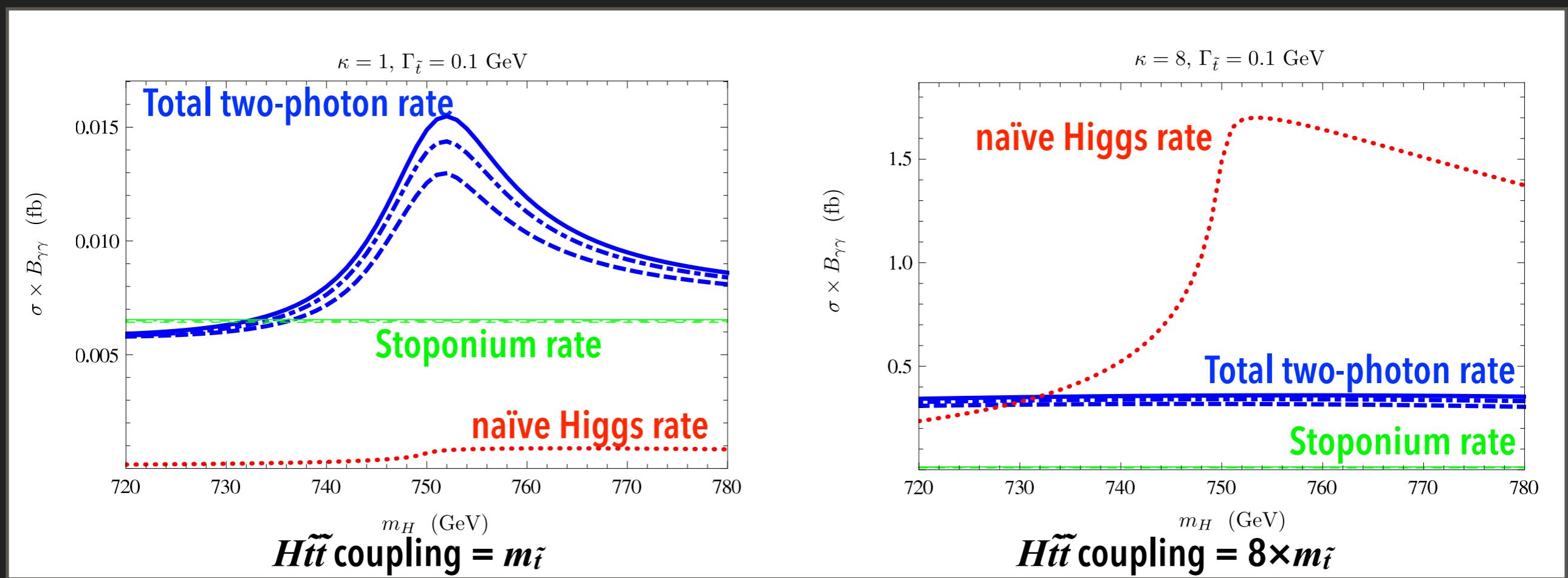
Considered different approximations for the Coulomb Green's function G with

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

HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION

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

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



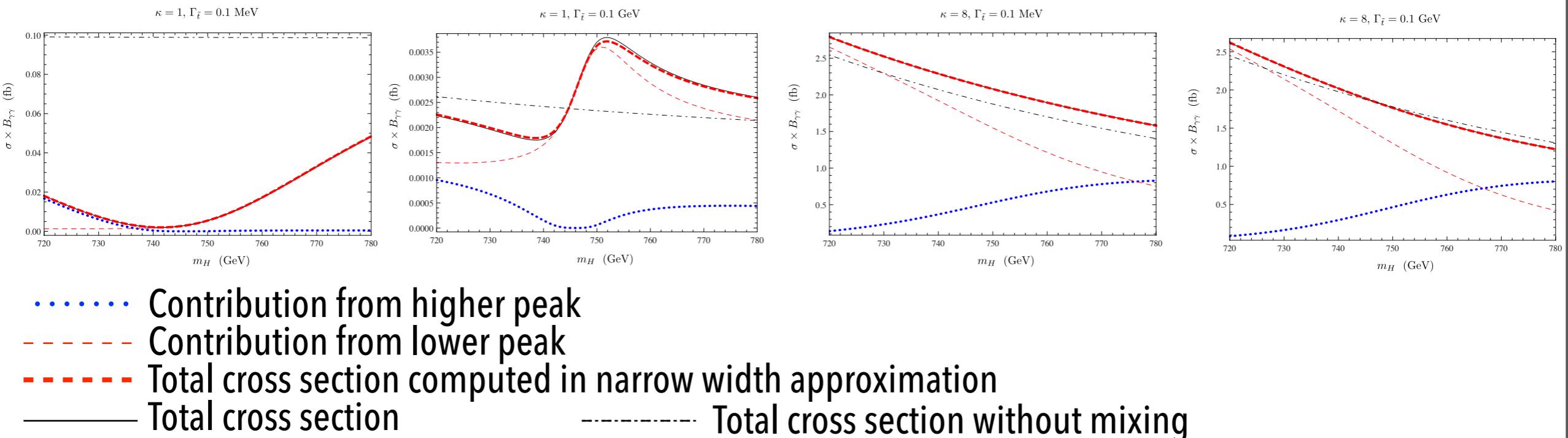
Considered different approximations for the Coulomb Green's function G with

- 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



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

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

- ▶ 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

$$\langle \text{Higgs-Stoponium Mixing} \rangle = \left(\begin{array}{c} \text{Higgs loop} \\ \text{Stoponium loop} \end{array} \right) \left(\begin{array}{c} \text{Higgs loop} \\ \text{Stoponium loop} \end{array} \right)^{-1} \left(\begin{array}{c} \text{Higgs loop} \\ \text{Stoponium loop} \end{array} \right)^{-1} \times \left(\begin{array}{c} \text{Higgs loop} \\ \text{Stoponium loop} \end{array} \right)^{-1} \times \dots$$

The diagram illustrates the total amplitude for Higgs-Stoponium mixing in two-photon production. It is represented as a product of four components:

- Top row:
 - Left: A Higgs boson loop diagram.
 - Right: A Stoponium loop diagram.
- Middle row:
 - Left: A Higgs boson loop diagram.
 - Right: A Stoponium loop diagram.
- Bottom row:
 - Left: A Higgs boson loop diagram.
 - Right: A Stoponium loop diagram.

Each component is enclosed in parentheses and has a superscript -1 , indicating it is the inverse of the corresponding loop diagram. The entire expression is multiplied by a series of dots, suggesting a continuation of the sequence.

HIGGS-STOPONIUM MIXING IN TWO-PHOTON PRODUCTION

- ▶ Large stop decay rate ($\Gamma_{\tilde{t}} = 1 \text{ GeV}$), $H\tilde{t}\tilde{t}$ coupling = $m_{\tilde{t}}$
Stop mass $m_{\tilde{t}} = 375 \text{ GeV}$. Heavy Higgs mass varied from 720 to 780 GeV.
- ▶ Peak-like structure arises from interference in mixing,
and *not from enhancement from stoponium peak*

