Rare Electromagnetic Decays $\eta'(\eta) \to \pi^0(\eta)\gamma\gamma$ as a Probe of New Physics

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Overview

1. Rare electromagnetic decays of mesons, $\eta^{(\prime)} \to (\eta)\,\pi^0\gamma\gamma$
2. Inconsistency with VMD + LσM framework, preliminary estimations.
3. Leptophobic Dark Photon explains the discrepancy
4. VMD+LσM, new $VP\gamma$ couplings (2020), **discrepancy remains.**
5. **New fit of the Dark Photon parameters reconciles theory and experiment.**
6. Conclusions

Rare electromagnetic decays of mesons, $\eta^{(\prime)} \to (\eta)\,\pi^0\gamma\gamma$

New Physics in rare decays

- [a] Data on the η and η' decays provides unique opportunities for the search of New Physics.
- $\eta' \to \pi^0\gamma\gamma$, $\eta \to \pi^0\gamma\gamma$, and $\eta' \to \eta\gamma\gamma$ are especially interesting since [b] *Dark Photon (or $\mathcal{B}$ boson) may manifest itself as a $\pi^0\gamma$ and $\eta\gamma$ resonance*.

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[a] L. Gan, B. Kubis, E. Passemar, and S. Tulin, arXiv:2007.00664.

[b] "New weakly-coupled forces hidden in low-energy QCD", Phys.Rev.D 89(2014) 11, 114008, Sean Tulin, [arXiv:1404.4370 [hep-ph]]

Dominant contribution: Vector Meson Dominance (VMD)

Tree-level VMD diagrams

- These decays involve ω, ρ and ϕ, with ω and ρ **dominating**.

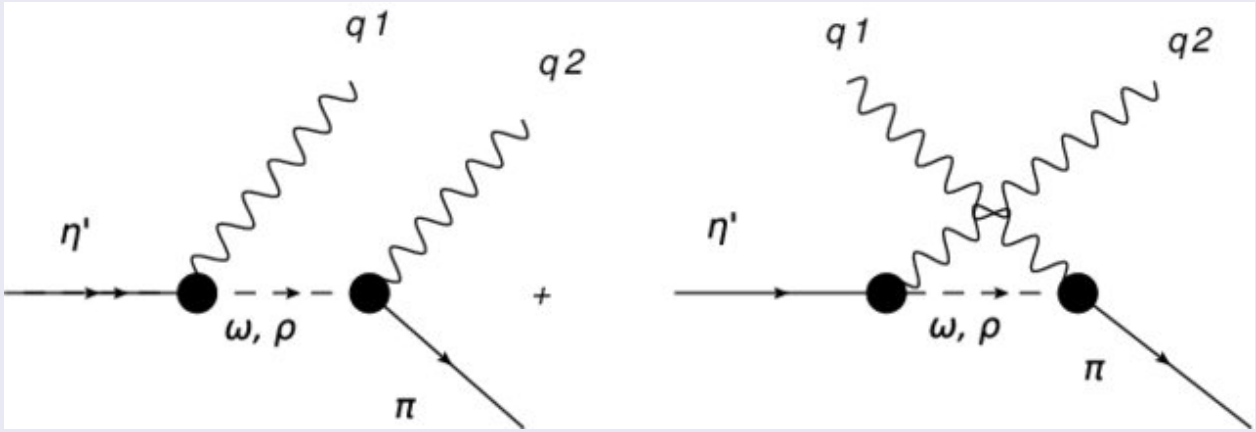

Figure: Dominant diagrams for the $\eta' \to \pi^0\gamma\gamma$ decay

Dominant contribution: Vector Meson Dominance (VMD)

Matrix element

$$\mathcal{A}^{VMD}_{\eta'(\eta)\to\pi^0(\eta)\gamma\gamma} =$$

$$\sum_{V=\omega,\rho,\phi} g_{V\eta'(\eta)\gamma} g_{V\eta(\pi^0)\gamma} \left(\frac{\left(P\cdot q_2 - m^2_{\eta'(\eta)}\right)\{a\} - \{b\}}{D_V(t)} + \{q_1 \leftrightarrow q_2, t \leftrightarrow u\} \right)$$

- $q_{1,2}$ - momenta of outgoing photons.
- $D_V(t) = m_V^2 - t - i m_V \Gamma_V$ - vector meson propagator.
- $\Gamma_{\omega,\phi} = const$, $\Gamma_\rho(t) = \Gamma_\rho \times \left(\frac{t-4m_\pi^2}{m_\rho^2-4m_\pi^2}\right)^{\frac{3}{2}} \theta\left(t-4m_\pi^2\right)$

Sub-leading contribution: Linear Sigma Model (LσM)

Additionally, LσM contributes:

- Two processes, $\eta \to \pi^0\gamma\gamma$ and $\eta' \to \pi^0\gamma\gamma$, involve the kaon loop and an exchange of the $a_0\,(980)$.
- $\eta' \to \eta\gamma\gamma$ involves both the kaon and pion loops as well as the exchange of $a_0\,(980)$, $\sigma\,(600)$ and $f_0\,(980)$.
- In the $\eta' \to \eta\gamma\gamma$ decay, LσM gives a sizable contribution.
- But still VMD gives a dominant contribution in all three cases.

Theoretical studies of $\eta \to \pi^0\gamma\gamma$ decay

$\eta \to \pi^0\gamma\gamma$ decay was studied in a number of frameworks:

- [a][b]VMD
- [c]Chiral Perturbation Theory (ChPT).
- [d][e]Chiral amplitudes.
- [f]Dispersive formalisms.

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[a] G. Oppo and S. Oneda, Phys. Rev. 160, 1397 (1967).

[b] A. Baracca and A. Bramon, Nuovo Cimento A 69, 613(1970).

[c] L. Ametller, J. Bijnens, A. Bramon, and F. Cornet, Phys. Lett. B 276, 185 (1992).

[d] E. Oset, J. R. Pelaez, and L. Roca, Phys. Rev. D 77, 073001 (2008).

[e] E. Oset, J. R. Pelaez, and L. Roca, Phys. Rev. D 67, 073013 (2003).

[f] I. Danilkin, O. Deineka, and M. Vanderhaeghen, Phys. Rev. D 96, 114018 (2017).

Preliminary results on $\eta^{(\prime)} \to (\eta)\,\pi^0\gamma\gamma$ decays

$\eta^{(\prime)} \to (\eta)\,\pi^0\gamma\gamma$

[a][b][c][d]Preliminary estimations were done in the frameworks of VMD, ChPT and LσM

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[a] R. Escribano, Proc. Sci., QNP2012 (2012) 079
[b] R. Jora, Nucl. Phys. B, Proc. Suppl. 207–208, 224 (2010)
[c] Y.B., arXiv:1804.02607
[d] Y.B., arXiv:1811.01402

Sharp disagreement experiment/preliminary results

Roughly 2 times discrepancy for $\eta' \to (\eta)\,\pi^0\gamma\gamma$ decays

- [a] $\eta' \to \pi^0\gamma\gamma$
- [b] $\eta' \to \eta\gamma\gamma$

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[a] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. D 96, 012005 (2017).

[b] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. D 100, 052015 (2019).

Dark Photon (DP)

- [a]Hypothetical particle, a force carrier similar to the photon in EM.
- Possibly connected to Dark Matter particles and can be coupled with the visible charged particles by a kinetic mixing with the usual photon.
- [bc]In the DP searches, it is assumed it has predominantly **leptonic** coupling.

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[a] B. Holdom, "Two U(1)'s and charge shifts", Physics Letters B.166 (2): 196-198.

[b] Omar Moreno and Matthew Solt, for the HPS Collaboration, "Search for a Dark Photon in Electro- Produced e+e Pairs with the Heavy Photon Search Experiment at JLab", PoS ICHEP2018 (2019) 076, [arXiv:1812.02169[hep-ex]].

[c] "Search for a Hypothetical 16.7 MeV Gauge Boson and Dark Photons in the NA64 Experiment at CERN", Phys.Rev.Lett. 120 (2018) 23, 231802, [arXiv:1803.07748v2 [hep-ex]].

Leptophobic Dark Photon (or $\mathcal{B}$ boson)

[a] $\mathcal{B}$ boson: **coupling to quarks dominating over the coupling to leptons**:

$$\mathcal{L}_{int} = \left(\frac{g_B}{3} + \epsilon Q_q e\right) \bar{q}\gamma^\mu q \cdot \mathcal{B}_\mu - \epsilon e \bar{l}\gamma^\mu l \cdot \mathcal{B}_\mu$$

- $\mathcal{B}$ boson mass was estimated in the range 140 MeV – 1 GeV.
- It should have the same quantum numbers as ω meson, $I^G\left(J^{PC}\right) = 0^-\left(1^{--}\right)$, to preserve the symmetries of low-energy QCD.
- **May manifest itself on the $\pi^0\gamma$ and $\eta\gamma$ spectrum**, VMD is modified:

$$\sum_{V=\omega,\rho,\phi} \quad \Rightarrow \underbrace{\sum_{V=\omega,\rho,\phi,\mathcal{B}}}_{\textit{Additional contribution of } \mathcal{B}}$$

[a] "New weakly-coupled forces hidden in low-energy QCD", Phys.Rev.D89(2014) 11, 114008, Sean Tulin, [arXiv:1404.4370 [hep-ph]]

$\pi^0\gamma$ spectrum of $\eta' \to \pi^0\gamma\gamma$:

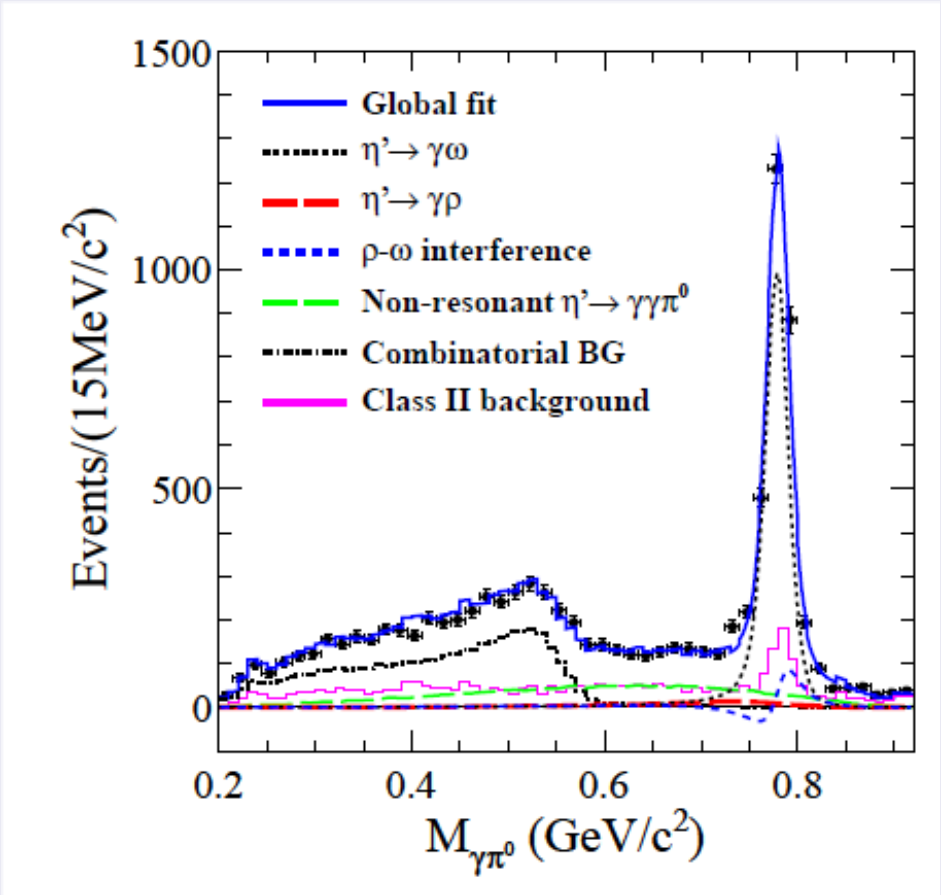

Figure: [a] **The peak of the new particle is not seen.**

[a] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. D 96, 012005 (2017).

Another opportunity: DP hidden behind the ω peak

If the following condition is fulfilled:

$$m_\omega - \Gamma_\omega \leq m_{\mathcal{B}} - \Gamma_{\mathcal{B}};\ \ m_{\mathcal{B}} + \Gamma_{\mathcal{B}} \leq m_\omega + \Gamma_\omega$$

$$\downarrow$$

$$\boxed{m_\omega - \Gamma_\omega + \Gamma_{\mathcal{B}} \leq m_{\mathcal{B}} \leq m_\omega + \Gamma_\omega - \Gamma_{\mathcal{B}}}$$

- The peak of the hypothetical $\mathcal{B}$ is not seen on the $\pi^0\gamma$ spectrum.
- But still, it can give a significant contribution to the overall decay rate.

$\eta' \to \pi^0\gamma\gamma$ preliminary model + $\mathcal{B}$ boson.

- [a]Taking $m_{\mathcal{B}} = m_\omega$, $\Gamma_{\mathcal{B}} = \Gamma_\omega$, fit the coupling constant $c_{\mathcal{B}}$.

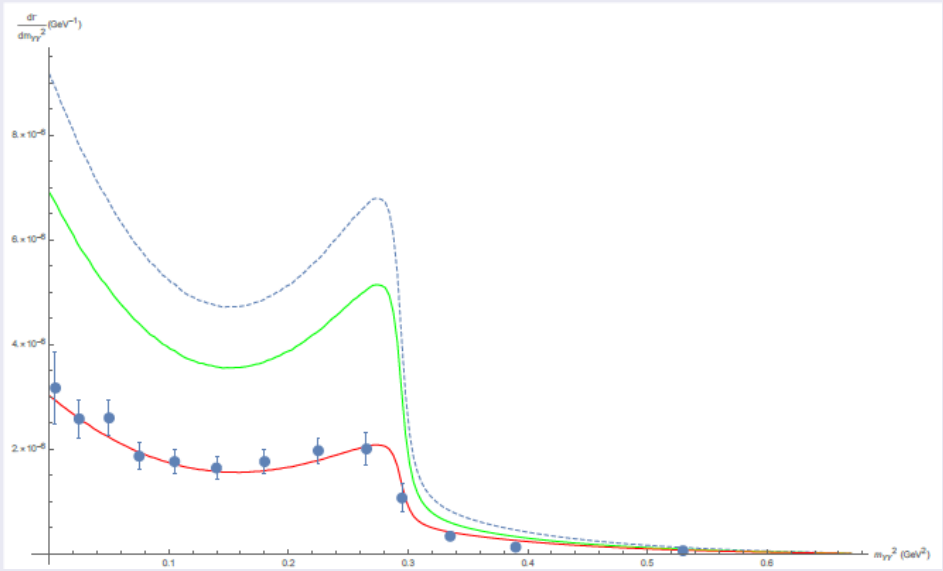

Figure: The upper blue dashed and the green lines correspond to the maximum and minimum values of the VMD coupling constants, and the lower red line includes the possible contribution of "$\mathcal{B}$ boson".

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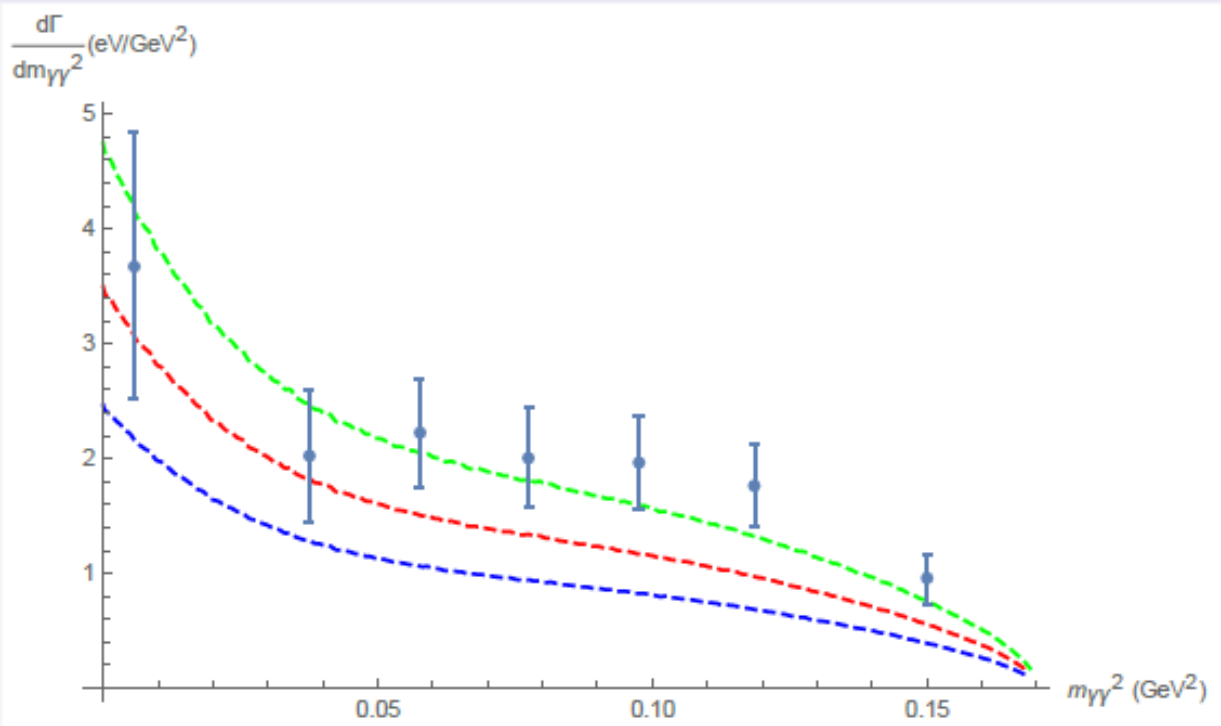
[a]Y.B., "Applying New Physics to the Problems of the $\eta' \to \pi^0\gamma\gamma$ Decay." *Letters in High Energy Physics (2020).*

Similarly, it can give a contribution to the $\eta \to \pi^0\gamma\gamma$ decay, preliminary model + $\mathcal{B}$ boson.

[a]Taking $m_{\mathcal{B}} = m_\omega$, $\Gamma_{\mathcal{B}} = \Gamma_\omega$, fit the coupling constant $c_{\mathcal{B}}$



[a]Y.B., "Applying New Physics to the Problems of the $\eta' \to \pi^0\gamma\gamma$ Decay." *Letters in High Energy Physics (2020).*

New fit of the $VP\gamma$ coupling constants (2020)

- [a]An new phenomenological model including the isospin-symmetry breaking effects was developed.
- A new fit of the $g_{V\eta'(\eta)\gamma}$ coupling constants was provided.
- These values of the VMD coupling constants can be used as an input for theoretical calculations, in a hope that it will fix these discrepancies.

[a]R. Escribano and E. Royo, Phys. Lett. B 807, 135534 (2020).

Discrepancy remains!!!

- [a] "While a **satisfactory description of the shape of the $\eta' \to \pi^0\gamma\gamma$ and $\eta' \to \eta\gamma\gamma$ decay spectra is obtained**, thus supporting the validity of the approach, the corresponding branching ratios cannot be reproduced simultaneously."
- **The $\eta \to \pi^0\gamma\gamma$ decay has two times discrepancy theory/experiment.**

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[a] Escribano R, Gonz'alez-Sol´ıs S and Jora R et al. A theoretical analysis of the doubly radiative decays $\eta'(\eta) \to \pi^0(\eta)\gamma\gamma$ *Phys Rev D* 2020; **102**: 034026.

The fit of $\eta \to \pi^0\gamma\gamma$ with the new VMD coupling constants

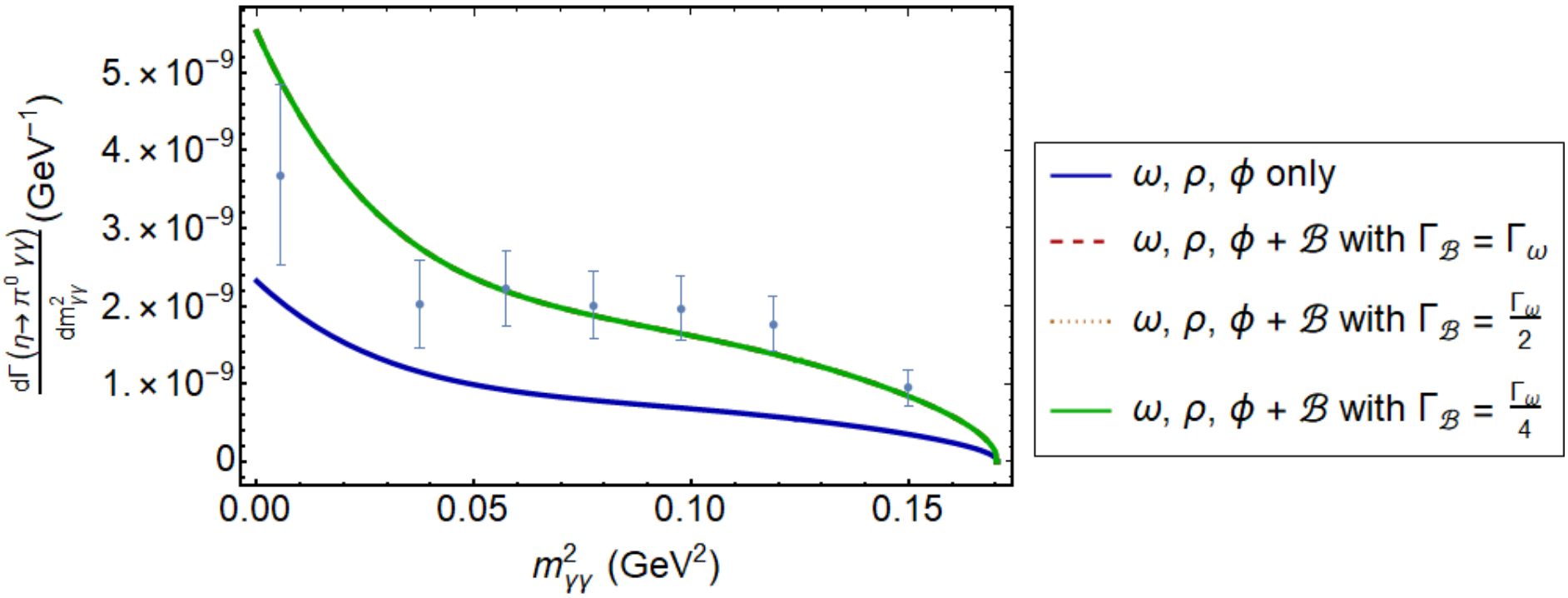


Figure: The value of was fixed, $m_{\mathcal{B}} = m_\omega$, and the coupling constant was fitted. We observe a weak dependence on the $\Gamma_{\mathcal{B}}$ (three lines overlap).

The fit of $\eta' \to \pi^0\gamma\gamma$ with the new VMD coupling constants

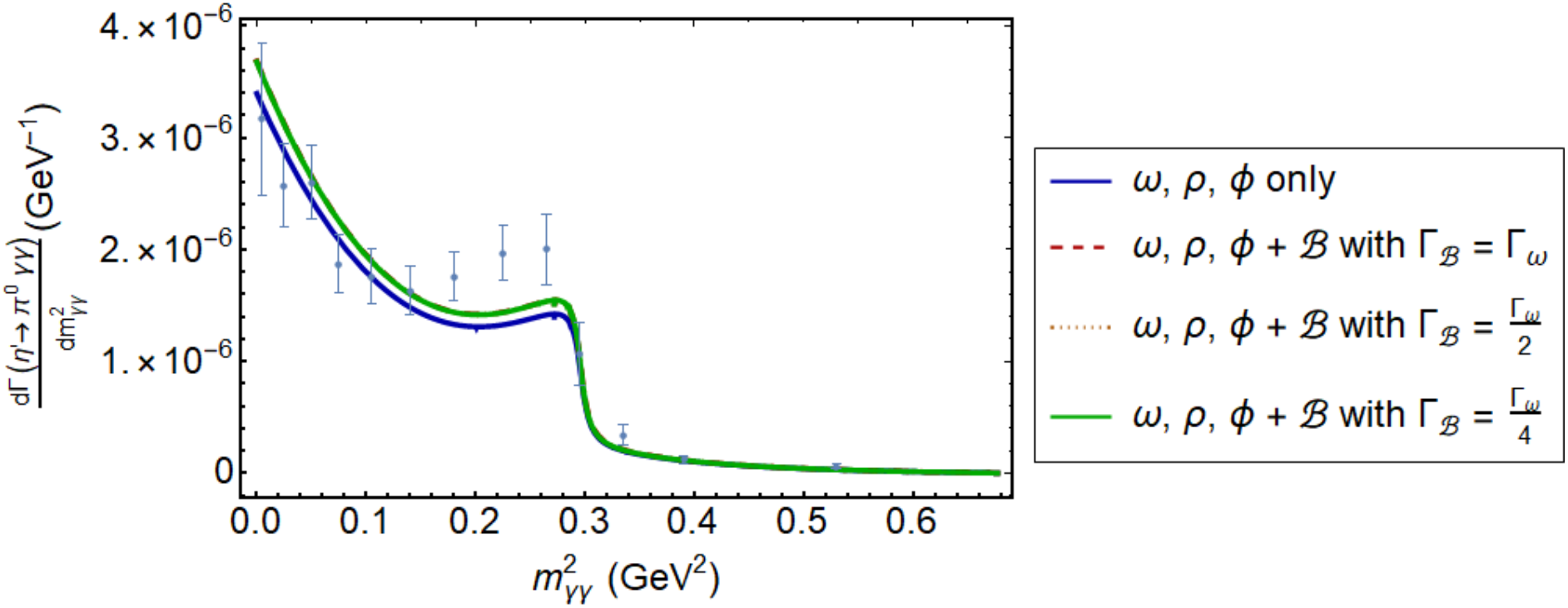
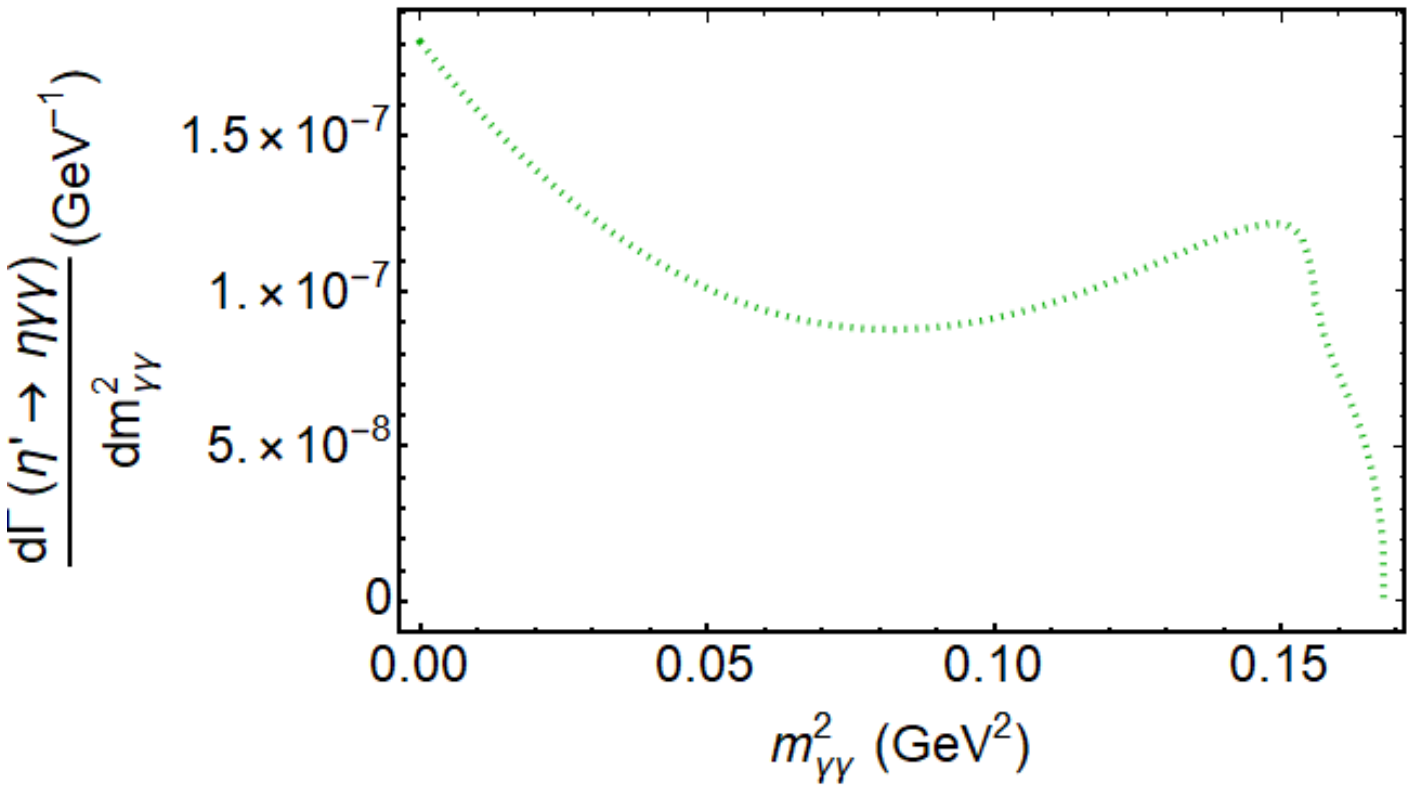


Figure: The value of was fixed, $m_{\mathcal{B}} = m_\omega$, and the coupling constant was fitted. We observe a weak dependence on the $\Gamma_{\mathcal{B}}$ (three lines overlap).

The spectrum for $\eta' \to \eta\gamma\gamma$ with the new VMD coupling constants (no experimental points yet).



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Conclusions

- The experimental data on the $\eta'(\eta) \to \pi^0(\eta)\gamma\gamma$ decays cannot be consistently reproduced within the VMD + LσM framework.
- This may indicate that a more refined theoretical framework is needed.
- New Physics scenario with the $\mathcal{B}$ boson giving a contribution to $\eta'(\eta) \to \pi^0(\eta)\gamma\gamma$ decays, and reconciling theory/experiment is also a viable scenario.
- If the discrepancy theory/experiment persists, these decays can serve as a sensitive probe of the parameter space of the $\mathcal{B}$ boson.