

Sensitivity of the $\eta^{(\prime)} \rightarrow \pi^0 \gamma \gamma$ and $\eta' \rightarrow \eta \gamma \gamma$ decays to a sub-GeV leptophobic $U(1)_B$ boson

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LA-UR-23-26270

Based on:

Escribano, SGS, Jora, Royo, *Phys.Rev.D* 102, 034026 (2020)

Escribano, SGS, Royo, *Phys.Rev.D* 106, 114007 (2022)

Trento, June 15, 2023



Precision Tests of Fundamental Physics with Light Mesons

Trento, 12-16 June, 2023

Abstract

Hadronic and radiative decays of light mesons provide a unique laboratory to test low-energy Quantum Chromodynamics and search for new physics beyond the Standard Model. Recent years have brought advances in theoretical and experimental approaches throughout the hadron and particle physics community. New experimental data will soon offer critical input to precisely determine e.g. the light quark mass ratios, meson mixing parameters, and hadronic contributions to the anomalous magnetic moment of the muon. The approaches provide sensitive probes to test potential new physics including searches for hidden photons, light Higgs scalars, and axion-like particles that are complementary to worldwide efforts to detect new light particles below the GeV mass scale, as well as tests of discrete symmetry violation. Experts and respective communities will discuss updates on theoretical developments, experimental strategies, and identify further research.

Organizers

Susan Schadmand (GSF, Darmstadt), Bastian Kubis (HISKP Bonn, Germany), Igal Jeon (Jefferson Lab, USA), Daniel Lersner (FSU Tallahassee, USA)

Speakers

Hakan Akdag, Miguel Albaladejo, Marco Battaglieri, Luigi Capozza, Saskia Charity, Izabela Clepal, Olga Cortes Becerra, Andreas Crivellin, Igor Danilkin, Shuangshi Fang, Liping Gan, Susan Gardner, Ashot Gasparian, Antoine Gerardin, Simona Giovannella, Sergi González-Solís, Martin Hoferichter, Bai-Long Hoid, Simon Holz, Garth Husek, Tomas Husak, Igal Jeon, Karol Kampf, Andrzej Kupsc, Jari Miskinen, Edoardo Mornacchi, Bachir Moussallam, Frederik Naelt, Konstantin Ottmäd, Emilie Passemar, Alessandro Pilloni, Pablo Sanchez Puertas, Hannah Schäfer, Adam Szczepanek, Simon Taylor, Sean Tulin

Director of ECT*: Professor Gert Aarts

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- ▶ $\eta \rightarrow \pi^0 \gamma \gamma$ decays: testing χPT and VMD models
- ▶ $\eta \rightarrow \pi^0 \gamma \gamma$ decays: leptophobic B -boson contribution
- ▶ Summary

Why is it interesting to study η/η' physics?

- Quantum numbers $I^G J^{PC} = 0^+ 0^{-+}$:
 - Eigenstates of the C, P, CP and G operators
 - Flavor conserving decays \Rightarrow laboratory for symmetry tests
 - All their strong and EM decays are forbidden at lowest order
 - The η is a pseudo-Goldstone boson
 - The η' is largely influenced by the $U(1)$ anomaly
- Large amount of data have been collected:
 - A2@MAMI, BESIII, CLAS, CrystalBall, GlueX, KLOE(-II), WASA
- More to come:
 - JEF, REDTOP

Why is it interesting to study η/η' physics?

- Unique opportunity to:
 - Test chiral dynamics at low energy
 - Extract fundamental parameters of the Standard Model (light quark masses, η - η' mixing)
 - Study of fundamental symmetries: P & CP and P & CP violation
 - Looking for BSM physics \Rightarrow Dark sector
- Theoretical methods:
 - ChPT and its extensions (large- N_c)
 - Vector-meson dominance
 - Dispersion theory

Selected η/η' decays

- **High priority** $\eta^{(\prime)}$ decays for experiment and theory

(L. Gan, B. Kubis, E. Passemar and S. Tulin, 2007.00664)

Decay channel	Standard Model	Discrete symmetries	BSM particles
$\eta^{(\prime)} \rightarrow \pi^+ \pi^- \pi^0$	light quark masses	C/CP violation	scalar bosons
$\eta^{(\prime)} \rightarrow \gamma\gamma$	η - η' mixing, width	—	—
$\eta^{(\prime)} \rightarrow \ell^+ \ell^- \gamma$	$(g-2)_\mu$	—	Z' , dark photon
$\eta^{(\prime)} \rightarrow \pi^0 \gamma\gamma$ and $\eta' \rightarrow \eta\gamma\gamma$	higher-order χ PT, scalar dynamics	—	$U(1)_B$ boson, scalar boson
$\eta^{(\prime)} \rightarrow \mu^+ \mu^-$	$(g-2)_\mu$, precision tests	CP violation	—
$\eta^{(\prime)} \rightarrow \pi^0 \ell^+ \ell^-$	—	C violation	scalar bosons
$\eta^{(\prime)} \rightarrow \pi^+ \pi^- \ell^+ \ell^-$	$(g-2)_\mu$	—	ALP, dark photon
$\eta^{(\prime)} \rightarrow \pi^0 \pi^0 \ell^+ \ell^-$	—	C violation	ALP

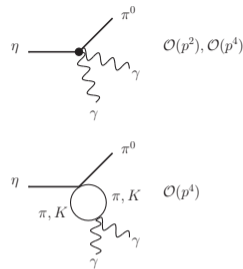
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$\eta \rightarrow \pi^0 \gamma \gamma$ decays: Theoretical motivation

- SM motivation:

Reference	$\Gamma(\eta \rightarrow \pi^0 \gamma \gamma)$ [eV]
$\mathcal{O}(p^2), \mathcal{O}(p^4)$ tree-level χ PT	0
$\pi + K$ loops at $\mathcal{O}(p^4)$	1.87×10^{-3}
Experimental value (pdg)	0.34(3)



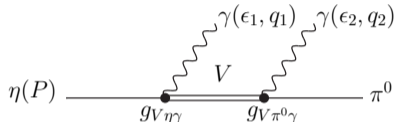
- 1st sizable contribution comes at $\mathcal{O}(p^6)$, but LEC's are not well known
- To test **ChPT** and a wide range of chiral models, *e. g.* VMD and $L\sigma M$



- BSM motivation: search for a B boson via $\eta \rightarrow B \gamma \rightarrow \pi^0 \gamma \gamma$

Vector meson exchange contributions

- Six diagrams corresponding to the exchange of $V = \rho^0, \omega, \phi$



$$\mathcal{A}_{\eta \rightarrow \pi^0 \gamma \gamma}^{\text{VMD}} = \sum_{V=\rho^0, \omega, \phi} g_{V\eta\gamma} g_{V\pi^0\gamma} \left[\frac{(P \cdot q_2 - m_\eta^2) \{a\} - \{b\}}{D_V(t)} + \left\{ \begin{array}{l} q_2 \leftrightarrow q_1 \\ t \leftrightarrow u \end{array} \right\} \right],$$

- Mandelstam variables and Lorentz structures given by:

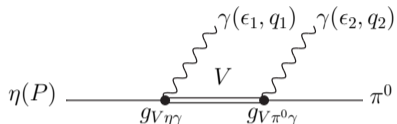
$$t, u = (P - q_{2,1})^2 = m_\eta^2 - 2P \cdot q_{2,1},$$

$$\{a\} = (\epsilon_1 \cdot \epsilon_2)(q_1 \cdot q_2) - (\epsilon_1 \cdot q_2)(\epsilon_2 \cdot q_1),$$

$$\begin{aligned} \{b\} &= (\epsilon_1 \cdot q_2)(\epsilon_2 \cdot P)(P \cdot q_1) + (\epsilon_2 \cdot q_1)(\epsilon_1 \cdot P)(P \cdot q_2) \\ &\quad - (\epsilon_1 \cdot \epsilon_2)(P \cdot q_1)(P \cdot q_2) - (\epsilon_1 \cdot P)(\epsilon_2 \cdot P)(q_1 \cdot q_2) \end{aligned}$$

$\eta \rightarrow \pi^0 \gamma \gamma$ decays: VMD calculation

- Six **diagrams** corresponding to the exchange of $V = \rho^0, \omega, \phi$



$$\mathcal{A}_{\eta \rightarrow \pi^0 \gamma \gamma}^{\text{VMD}} = \sum_{V=\rho^0, \omega, \phi} g_{V\eta\gamma} g_{V\pi^0\gamma} \left[\frac{(P \cdot q_2 - m_\eta^2)\{a\} - \{b\}}{D_V(t)} + \left\{ \begin{array}{l} q_2 \leftrightarrow q_1 \\ t \leftrightarrow u \end{array} \right\} \right],$$

- $g_{VP\gamma}$ **couplings**:

— Model-based:

$$\mathcal{L}_{VVP} = \frac{G}{\sqrt{2}} \epsilon^{\mu\nu\alpha\beta} \text{tr} [\partial_\mu V_\nu \partial_\alpha V_\beta P], \quad \mathcal{L}_{V\gamma} = -2egf_\pi^2 A^\mu \text{tr} [QV_\mu],$$

— Empirical: measured $\Gamma_{V(P) \rightarrow P(V)\gamma}^{\text{exp}}$ widths

- The decays $\eta' \rightarrow \{\pi^0, \eta\} \gamma \gamma$ are formally identical: $g_{V\eta\gamma} g_{V\pi^0\gamma} \rightarrow g_{V\eta'\gamma} g_{V\{\pi^0, \eta\}\gamma}$

Input for the $g_{VP\gamma}$ couplings

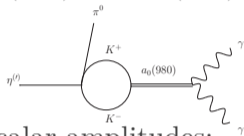
- $g_{VP\gamma}$ couplings fixed from the measured widths ($P = \pi^0, \eta, \eta'$)

$$\Gamma_{V \rightarrow P\gamma}^{\text{exp}} = \frac{1}{3} \frac{g_{VP\gamma}^2}{32\pi} \left(\frac{m_V^2 - m_P^2}{m_V} \right)^3, \quad \Gamma_{P \rightarrow V\gamma}^{\text{exp}} = \frac{g_{VP\gamma}^2}{32\pi} \left(\frac{m_P^2 - m_V^2}{m_P} \right)^3,$$

Decay	Branching ratio (pdg)	$ g_{VP\gamma} \text{ GeV}^{-1}$
$\rho^0 \rightarrow \pi^0\gamma$	$(4.7 \pm 0.6) \times 10^{-4}$	0.22(1)
$\rho^0 \rightarrow \eta\gamma$	$(3.00 \pm 0.21) \times 10^{-4}$	0.48(2)
$\eta' \rightarrow \rho^0\gamma$	$(28.9 \pm 0.5)\%$	0.40(1)
$\omega \rightarrow \pi^0\gamma$	$(8.40 \pm 0.22)\%$	0.70(1)
$\omega \rightarrow \eta\gamma$	$(4.5 \pm 0.4) \times 10^{-4}$	0.135(6)
$\eta' \rightarrow \omega\gamma$	$(2.62 \pm 0.13)\%$	0.127(4)
$\phi \rightarrow \pi^0\gamma$	$(1.30 \pm 0.05) \times 10^{-3}$	0.041(1)
$\phi \rightarrow \eta\gamma$	$(1.303 \pm 0.025)\%$	0.2093(20)
$\phi \rightarrow \eta'\gamma$	$(6.22 \pm 0.21) \times 10^{-5}$	0.216(4)

$L\sigma M$ for the scalar resonance contributions

- χ PT loops complemented by the exchange of scalar resonances, $a_0(980)$, κ , σ , $f_0(980)$, e.g.:



$$\mathcal{A}_{\eta^{(\prime)} \rightarrow \pi^0 \gamma \gamma}^{\text{L}\sigma\text{M}} = \frac{2\alpha}{\pi} \frac{1}{m_{K^+}^2} L(s_K) \{a\} \times \mathcal{A}_{K^+ K^- \rightarrow \pi^0 \eta^{(\prime)}}^{\text{L}\sigma\text{M}},$$

- Scalar amplitudes:

$$\mathcal{A}_{K^+ K^- \rightarrow \pi^0 \eta^{(\prime)}}^{\text{L}\sigma\text{M}} = \frac{1}{2f_\pi f_K} \left\{ (s - m_{\eta^{(\prime)}}^2) \frac{m_K^2 - m_{a_0}^2}{D_{a_0}(s)} \cos \varphi_P + \frac{1}{6} \left[(5m_{\eta^{(\prime)}}^2 + m_\pi^2 - 3s) \cos \varphi_P - \sqrt{2}(m_{\eta^{(\prime)}}^2 + 4m_K^2 + m_\pi^2 - 3s) \sin \varphi_P \right] \right\},$$

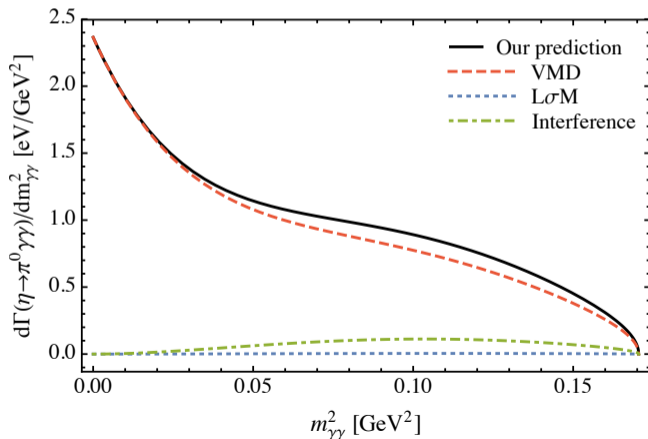
- Complete one-loop propagator for the scalar resonances:

$$D_R(s) = s - m_R^2 + \text{Re}\Pi(s) - \text{Re}\Pi(m_R^2) + i\text{Im}\Pi(s),$$

$\eta \rightarrow \pi^0 \gamma \gamma$ predictions

- Our theoretical prediction $BR = 1.35(8) \times 10^{-4}$
(Escribano, SGS, Jora, Royo, Phys.Rev.D 102, 034026 (2020))

- VMD dominates:
- ρ : 27% of the signal
- ω : 21% of the signal
- ϕ : 0% of the signal
- interference between ρ - ω - ϕ : 52%
- interference between scalar and vector mesons: 7%

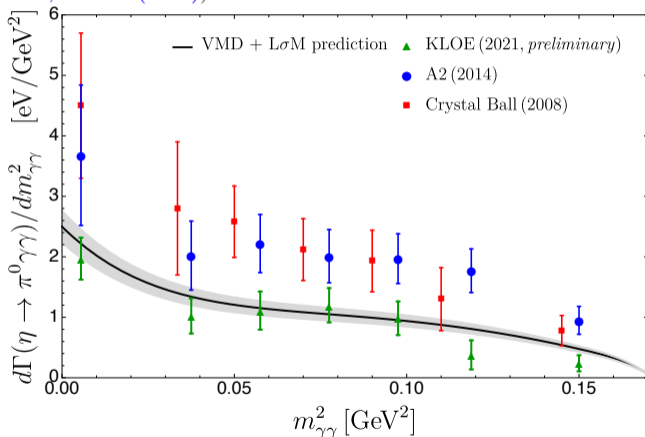


$\eta \rightarrow \pi^0 \gamma \gamma$ predictions

- Comparison with experimental data

(Escribano, SGS, Jora, Royo, Phys.Rev.D 102, 034026 (2020))

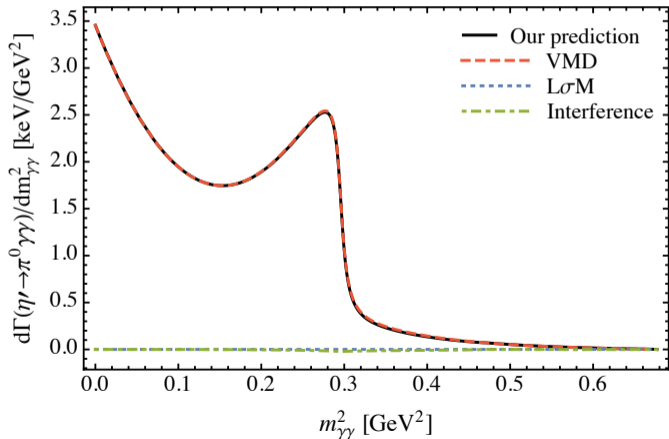
- Shape of the A2 and Crystal Ball spectra is captured well (normalization offset)
- Good agreement with (preliminary) KLOE data (talk by Giovanella)



- The experimental situation needs to be **clarified** (A2 talk by Mornacchi, JEF, REDTOP)

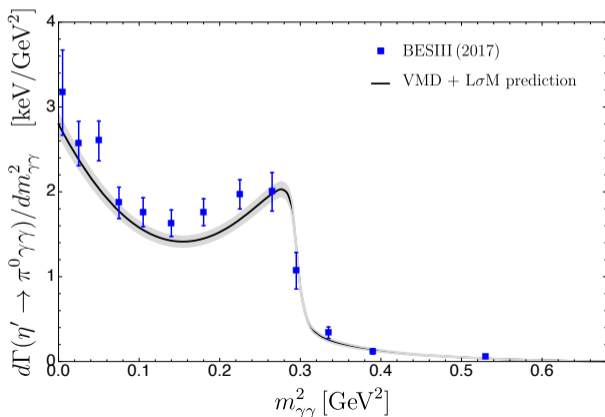
$\eta' \rightarrow \pi^0 \gamma \gamma$ predictions

- Our theoretical prediction $BR = 2.91(21) \times 10^{-3}$
(Escribano, SGS, Jora, Royo, Phys.Rev.D 102, 034026 (2020))
 - VMD completely dominates:
 - ω : 78% of the signal
 - ρ : 5% of the signal
 - ϕ : 0% of the signal
 - interference: 17%



$\eta' \rightarrow \pi^0 \gamma \gamma$ predictions

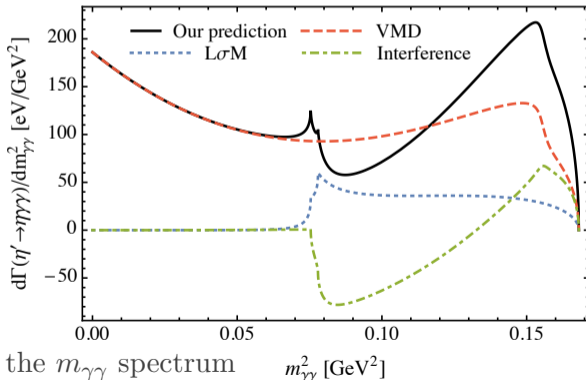
- Our theoretical prediction $BR = 2.91(21) \times 10^{-3}$ ([Phys.Rev.D 102, 034026 \(2020\)](#))
- First time $m_{\gamma\gamma}$ invariant mass distribution by BESIII;
 $BR = 3.20(7)(23) \times 10^{-3}$ ([Ablikim *et. al.* Phys.Rev.D 96, 012005 \(2017\)](#))



$\eta' \rightarrow \eta\gamma\gamma$ predictions

- 1st BR measurement by BESIII, $BR = 8.25(3.41)(0.72) \times 10^{-5}$ or $BR < 1.33 \times 10^{-4}$ at 90% C.L. (Ablikim *et. al.* Phys.Rev.D 100, 052015 (2019))
- Our theoretical predictions $BR = 1.17(8) \times 10^{-4}$
(R. Escribano, S. G-S, R. Jora, E. Royo, Phys.Rev.D 102, 034026 (2020))

- VMD predominates (91% of the signal)
- Substantial scalar meson effects (16%)
- Interference between scalar and vector mesons (7%)



- We look forward to the release of the $m_{\gamma\gamma}$ spectrum

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Leptophobic B boson model

- New boson arising from a new $U(1)_B$ gauge symmetry

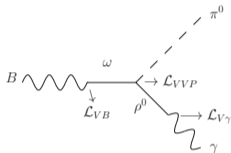
$$\mathcal{L}_{\text{int}} = \left(\frac{1}{3} g_B + \varepsilon Q_q e \right) \bar{q} \gamma^\mu q B_\mu - \varepsilon e \bar{\ell} \gamma^\mu \ell B_\mu,$$

- Couples (predominantly) to quarks
- g_B new gauge (universal?) coupling, $\alpha_B = g_B^2/4\pi$
- Preserves QCD symmetries (C, P, T)
- B is a singlet under isospin:
 $I^G(J^{PC}) = 0^-(1^{--}) \Rightarrow B$ is ω **meson** like
- $\varepsilon = eg_B/(4\pi)^2$: (subleading) γ -like coupling to fermions

- Searches depend on the mass m_B and decay channels
- Searches on meson decays are gaining attention
 - $\phi \rightarrow \eta B \rightarrow \eta \pi^0 \gamma$ (KLOE-II), $\eta \rightarrow \pi^0 \gamma \gamma$ (JEF), $\eta \rightarrow \pi^+ \pi^- \gamma$ (Belle-II)

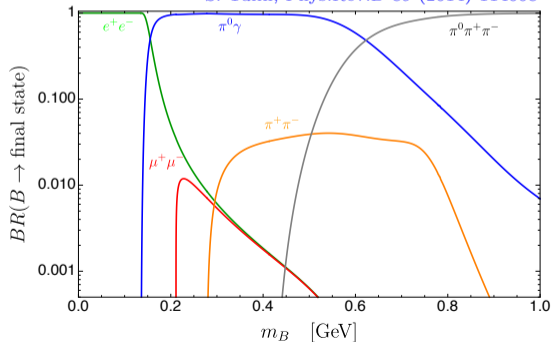
Calculation of hadronic processes

- Following the conventional **VMD picture**, $\mathcal{L}_{V\gamma} \rightarrow \mathcal{L}_{VB}$
 - $A^\mu \rightarrow B^\mu$, $e \rightarrow g_B$ and $Q = 1/3$, $\mathcal{L}_{VB} = -2\frac{1}{3}g_B g f_\pi^2 B^\mu \text{tr}[V^\mu]$,



$$\Gamma_{B \rightarrow \pi^0 \gamma} = \frac{\alpha_B \alpha_{em} m_B^3}{96 \pi^3 f_\pi^2} \left(1 - \frac{m_\pi^2}{m_B^2}\right)^3 |F_\omega(m_B^2)|^2,$$

S. Tulin, Phys.Rev.D 89 (2014) 114008



Previous limits on α_B and m_B

- Assuming the **Narrow-Width Approximation (NWA)**

$$BR(\eta \rightarrow \pi^0 \gamma \gamma) = BR(\eta \rightarrow B \gamma) \times BR(B \rightarrow \pi^0 \gamma),$$

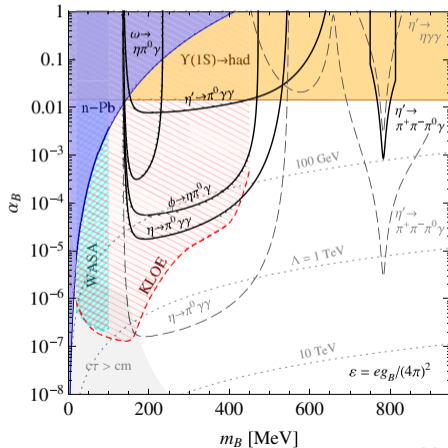
S. Tulin, Phys.Rev.D 89 (2014) 114008

- QCD contribution **off**
- $BR(\eta \rightarrow \pi^0 \gamma \gamma) < BR_{\text{exp}}$ at 2σ

— $BR(\eta \rightarrow \pi^0 \gamma \gamma)_{\text{exp}} = 2.21(53) \times 10^{-4}$

— $BR(\eta' \rightarrow \pi^0 \gamma \gamma)_{\text{exp}} < 8 \times 10^{-4}$ (90% C.L.)

— $BR(\eta' \rightarrow \eta \gamma \gamma)_{\text{exp}}$ no data



Present limits on α_B and m_B

- Assuming the **Narrow-Width Approximation (NWA)**

$$BR(\eta \rightarrow \pi^0 \gamma \gamma) = BR(\eta \rightarrow B \gamma) \times BR(B \rightarrow \pi^0 \gamma),$$

- QCD contribution **off**

- $BR(\eta \rightarrow \pi^0 \gamma \gamma) < BR_{\text{exp}}$ at 2σ

— $BR(\eta \rightarrow \pi^0 \gamma \gamma)_{\text{exp}}^{\text{PDG}} = 2.56(22) \times 10^{-4}$

— $BR(\eta \rightarrow \pi^0 \gamma \gamma)_{\text{exp}}^{\text{KLOE}} = 1.23(14) \times 10^{-4}$

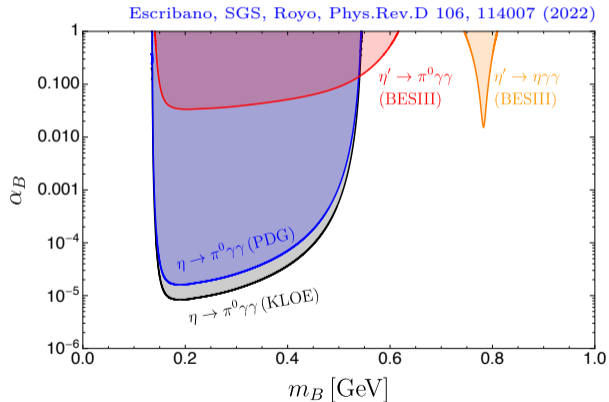
B. Cao [KLOE], PoS EPS-HEP2021 (2022) 409

— $BR(\eta' \rightarrow \pi^0 \gamma \gamma)_{\text{exp}} = 3.20(7)(23) \times 10^{-3}$

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

— $BR(\eta' \rightarrow \eta \gamma \gamma)_{\text{exp}} = 8.25(3.41)(72) \times 10^{-5}$

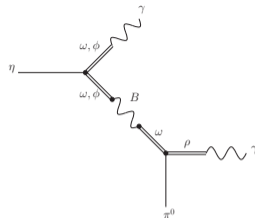
M. Ablikim *et.al* [BESIII], Phys.Rev. D 100 (2019) 052015



$\eta \rightarrow \pi^0 \gamma \gamma$ decays: B boson calculation

- Two diagrams corresponding to the exchange of a B boson

$$\mathcal{A}_{\eta \rightarrow \pi^0 \gamma \gamma}^{B \text{ boson}} = g_{B\eta\gamma}(t) g_{B\pi^0\gamma}(t) \left[\frac{(P \cdot q_2 - m_\eta^2)\{a\} - \{b\}}{m_B^2 - t - i\sqrt{t}\Gamma_B(t)} + \left\{ \begin{array}{l} q_2 \leftrightarrow q_1 \\ t \leftrightarrow u \end{array} \right\} \right],$$

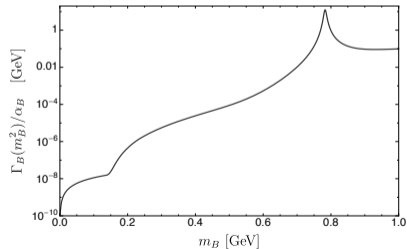


- $g_{BP\gamma}$ couplings:

$$g_{B\pi^0\gamma}(t) = \frac{\sqrt{2}eg_B}{4\pi^2 f_\pi} F_\omega(t), \quad g_{B\eta\gamma}(t) = \frac{eg_B}{12\pi^2 f_\pi \sqrt{3}} \left[(c_\theta - \sqrt{2}s_\theta)F_\omega(t) + (2c_\theta + \sqrt{2}s_\theta)F_\phi(t) \right],$$

- Energy-dependent width

$$\begin{aligned} \Gamma_B(q^2) &= \frac{\gamma_{B \rightarrow \ell^+ \ell^-}(q^2)}{\gamma_{B \rightarrow \ell^+ \ell^-}(m_B^2)} \Gamma_{B \rightarrow \ell^+ \ell^-} \theta(q^2 - 4m_\ell^2) \\ &+ \frac{\gamma_{B \rightarrow \pi^0 \gamma}(q^2)}{\gamma_{B \rightarrow \pi^0 \gamma}(m_B^2)} \Gamma_{B \rightarrow \pi^0 \gamma} \theta(q^2 - m_{\pi^0}^2) \\ &+ \frac{\gamma_{B \rightarrow \pi \pi}(q^2)}{\gamma_{B \rightarrow \pi \pi}(m_B^2)} \Gamma_{B \rightarrow \pi \pi} \theta(q^2 - 4m_\pi^2) \\ &+ \frac{\gamma_{B \rightarrow 3\pi}(q^2)}{\gamma_{B \rightarrow 3\pi}(m_B^2)} \Gamma_{B \rightarrow 3\pi} \theta(q^2 - 9m_\pi^2) \end{aligned}$$



New limits on α_B and m_B

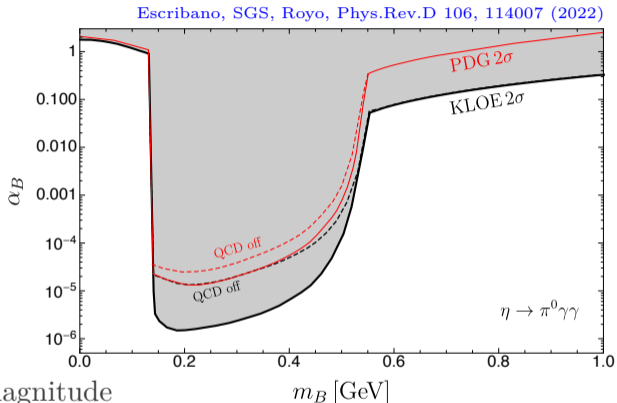
- **Not** assuming the NWA
- QCD contribution **on**
- $BR_{\text{VMD+Bboson}} < BR_{\text{exp}}$ at 2σ

— $BR(\eta \rightarrow \pi^0 \gamma \gamma)_{\text{exp}}^{\text{pdg}} = 2.56(22) \times 10^{-4}$

— $BR(\eta \rightarrow \pi^0 \gamma \gamma)_{\text{exp}}^{\text{KLOE}} = 1.23(14) \times 10^{-4}$

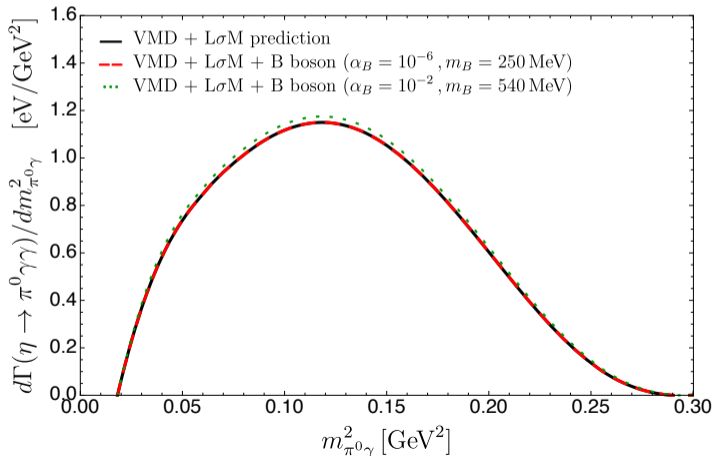
B. Cao [KLOE], PoS EPS-HEP2021 (2022) 409

- Limits **strengthened** by one order of magnitude



$\pi^0\gamma$ mass distribution

- These constraints would make a B boson signature suppressed
- $\pi^0\gamma$ distribution will be very welcome (JEF?)



New limits on α_B and m_B

- Not assuming the NWA
- QCD contribution on
- $BR < BR_{\text{exp}}$ at 2σ

— $BR(\eta' \rightarrow \pi^0 \gamma \gamma)_{\text{exp}} = 3.20(7)(23) \times 10^{-3}$

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

— $BR(\eta' \rightarrow \eta \gamma \gamma)_{\text{exp}} = 8.25(3.41)(72) \times 10^{-5}$

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

- Sharp dip when $m_B \sim m_\omega$
- Bounds 4 orders of magnitude weaker than $\eta \rightarrow \pi^0 \gamma \gamma$

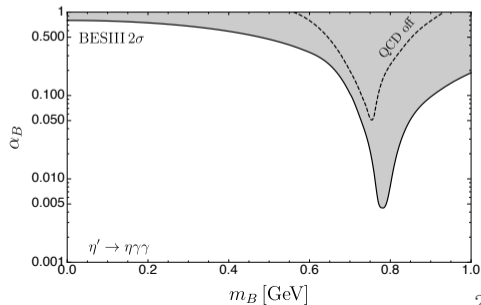
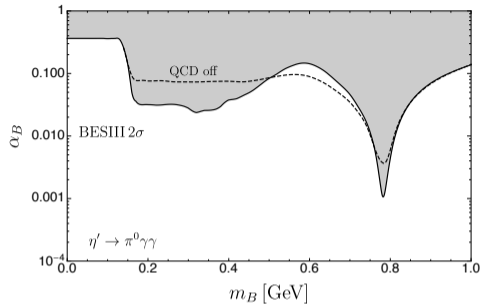


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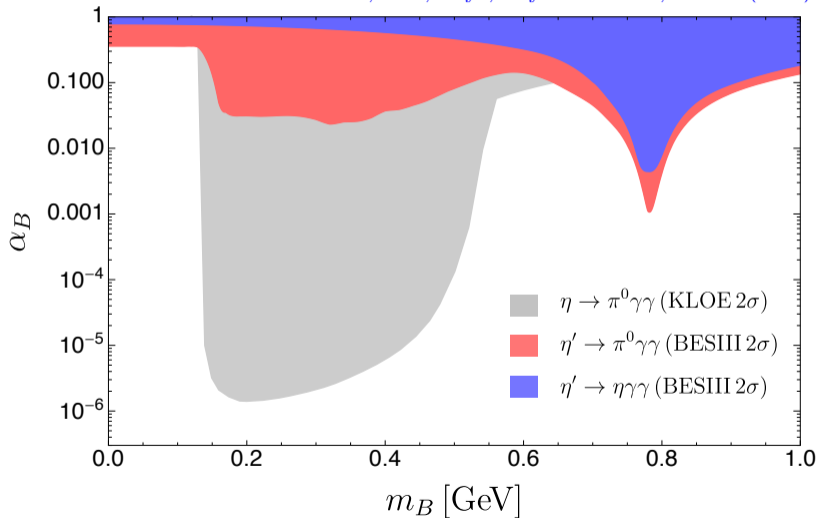
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Summary

- Within the VMD and $L\sigma M$ frameworks **we have described**
 - $\eta \rightarrow \pi^0 \gamma \gamma$: the situation is **not conclusive**
 $BR = 1.35(8) \times 10^{-4} \left\{ \begin{array}{l} \sim 1/2 \text{ of } BR = 2.54(27) \times 10^{-4} \quad (\text{A2, 2014}) \\ \sim 1.6\sigma \text{ from } BR = 2.21(24)(47) \times 10^{-4} \quad (\text{CB, 2008}) \\ \text{agrees with } BR = 1.23(14) \times 10^{-4} \quad (\text{KLOE prel., 2022}) \end{array} \right.$
 - $\eta' \rightarrow \pi^0 \gamma \gamma$: **in fair agreement** with BESIII data
 - $\eta' \rightarrow \eta \gamma \gamma$: **in line** with BESIII data
- **Sensitivity** to B boson has been analyzed
- **Constraints** on α_B, m_B have been strengthened by one order of magnitude from $\eta \rightarrow \pi^0 \gamma \gamma$
- The contribution of **new experiments** (A2, JEF, REDTOP), will be very welcome!

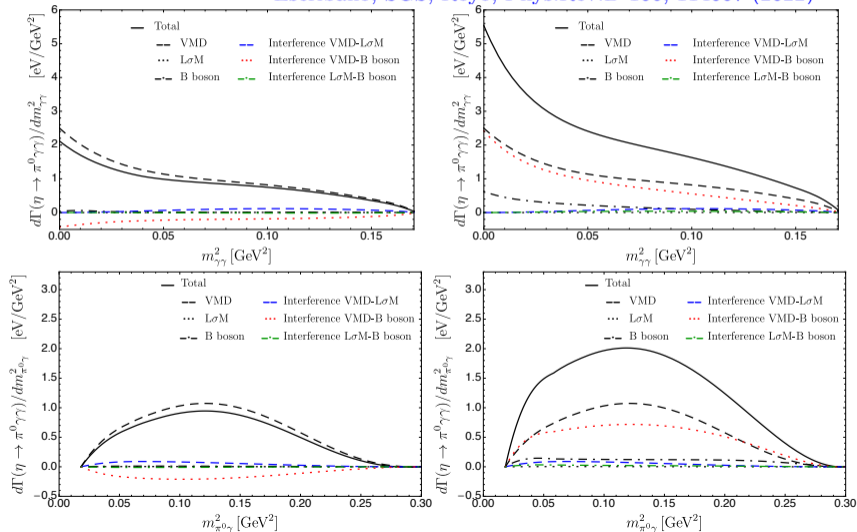
Summary

Escribano, SGS, Royo, Phys.Rev.D 106, 114007 (2022)



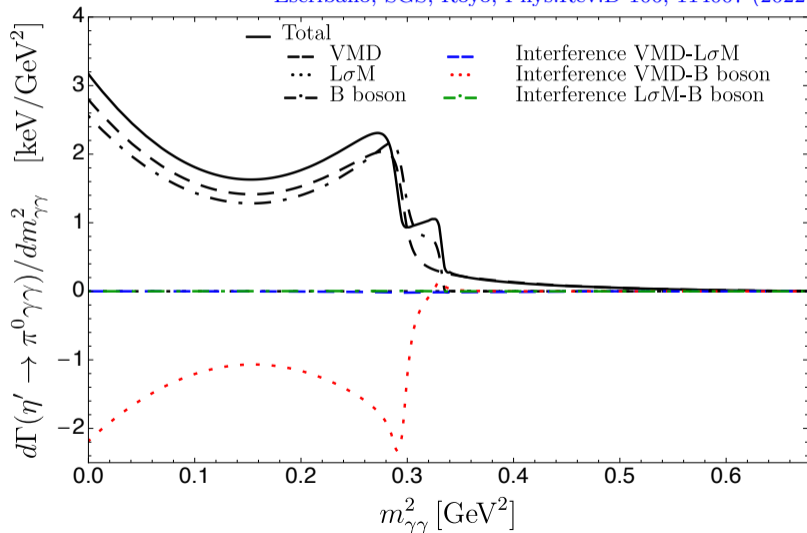
Individual contributions

Escribano, SGS, Royo, Phys.Rev.D 106, 114007 (2022)

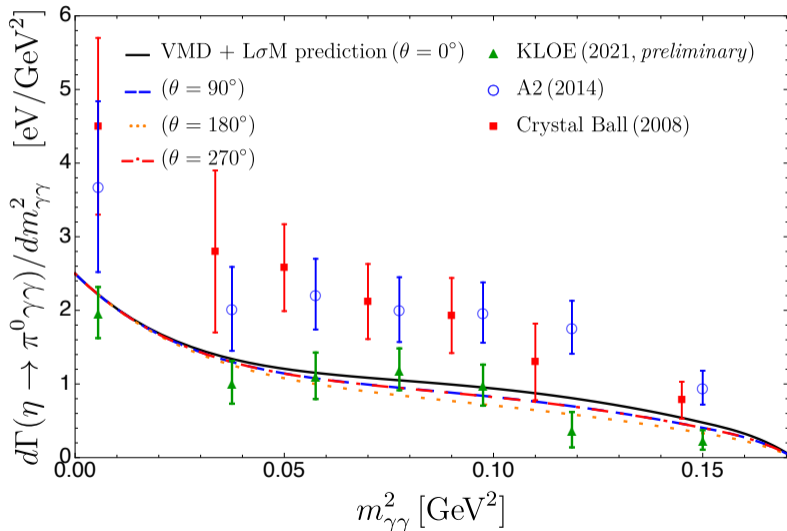


Individual contributions

Escribano, SGS, Royo, Phys.Rev.D 106, 114007 (2022)

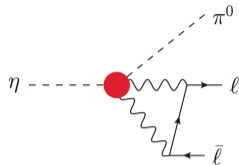


Interference phase between VMD and $L\sigma M$



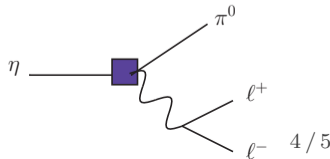
$\eta^{(\prime)} \rightarrow \{\pi^0, \eta\} \ell^+ \ell^-$ decays ($\ell = e, \mu$)

- In the SM:
 - $\eta \rightarrow \pi^0 \gamma^* \rightarrow \pi^0 \ell^+ \ell^-$ forbidden by C and CP
 - $\eta \rightarrow \pi^0 \ell^+ \ell^-$ proceed via C -conserving two-photon intermediate state



Decay channel	BR_{th} (Escribano&Royo 2007.12467)	BR_{exp} (pdg)
$\eta \rightarrow \pi^0 e^+ e^-$	$2.1(1)(2) \times 10^{-9}$	$< 7.5 \times 10^{-6}$ (CL=90%)
$\eta \rightarrow \pi^0 \mu^+ \mu^-$	$1.2(1)(1) \times 10^{-9}$	$< 5 \times 10^{-6}$ (CL=90%)
$\eta' \rightarrow \pi^0 e^+ e^-$	$4.6(3)(7) \times 10^{-9}$	$< 1.4 \times 10^{-3}$ (CL=90%)
$\eta' \rightarrow \pi^0 \mu^+ \mu^-$	$1.8(1)(2) \times 10^{-9}$	$< 6.0 \times 10^{-5}$ (CL=90%)
$\eta' \rightarrow \eta e^+ e^-$	$3.9(3)(4) \times 10^{-10}$	$< 2.4 \times 10^{-3}$ (CL=90%)
$\eta' \rightarrow \eta \mu^+ \mu^-$	$1.6(1)(2) \times 10^{-10}$	$< 1.5 \times 10^{-5}$ (CL=90%)

- Background for BSM searches, *e.g.* C -violating virtual photon exchange or new scalar mediators
- REDTOP can improve the experimental state



Fits to the $\eta \rightarrow \pi^0 \gamma \gamma$ decays

- Crystal Ball: $\alpha_B = 0.40_{-0.08}^{+0.07}$, $m_B = 583_{-20}^{+32}$ MeV, $\chi_{\text{dof}}^2 = 0.4/5 = 0.1$
- KLOE: $\alpha_B = 0.049_{-27}^{+40}$, $m_B = 135_{-135}^{+1}$ MeV, $\chi_{\text{dof}}^2 = 4.5/5 = 0.9$
- signatures outside $m_{\pi^0} \lesssim m_B \lesssim m_\eta$ may be visible

