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

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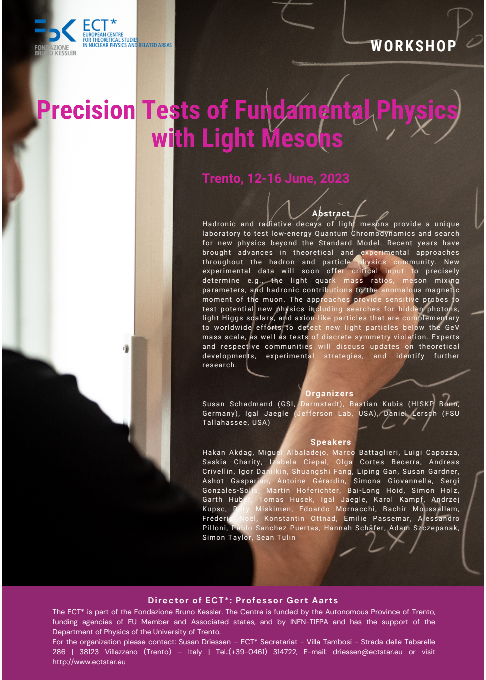
Based on:

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

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

Trento, June 15, 2023

Los Alamos
NATIONAL LABORATORY



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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
$\eta^{(\prime)} \to \pi^+\pi^-\pi^0$	light quark masses	C/CP violation	scalar bosons
$\eta^{(\prime)} \to \gamma\gamma$	η-η' mixing, width	—	—
$\eta^{(\prime)} \to \ell^+\ell^-\gamma$	$(g-2)_\mu$	—	Z', dark photon
$\eta^{(\prime)} \to \pi^0\gamma\gamma$ and $\eta' \to \eta\gamma\gamma$	higher-order χPT, scalar dynamics	—	$U(1)_B$ boson, scalar boson
$\eta^{(\prime)} \to \mu^+\mu^-$	$(g-2)_\mu$, precision tests	CP violation	—
$\eta^{(\prime)} \to \pi^0\ell^+\ell^-$	—	C violation	scalar bosons
$\eta^{(\prime)} \to \pi^+\pi^-\ell^+\ell^-$	$(g-2)_\mu$	—	ALP, dark photon
$\eta^{(\prime)} \to \pi^0\pi^0\ell^+\ell^-$	—	C violation	ALP

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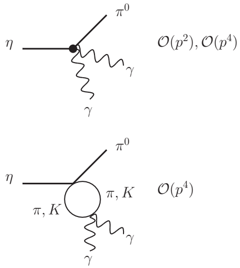
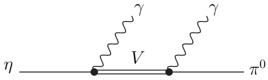
$\eta \to \pi^0\gamma\gamma$ decays: Theoretical motivation



- **SM motivation**:

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

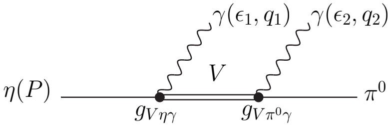
  - 1^{st} sizable contribution comes at $\mathcal{O}(p^6)$, but LEC's are not well known
  - To **test ChPT** and a wide range of chiral models, *e. g.* VMD and LσM



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

Vector meson exchange contributions

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



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

- Mandelstam variables and Lorentz structures given by:

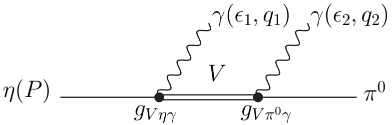
$$t, u = (P - q_{2,1})^2 = m_\eta^2 - 2P\cdot q_{2,1} \ ,$$

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

$$\{b\} = (\epsilon_1\cdot q_2)(\epsilon_2\cdot P)(P\cdot q_1) + (\epsilon_2\cdot q_1)(\epsilon_1\cdot P)(P\cdot q_2) - (\epsilon_1\cdot\epsilon_2)(P\cdot q_1)(P\cdot q_2) - (\epsilon_1\cdot P)(\epsilon_2\cdot P)(q_1\cdot q_2)$$

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

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



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

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

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

  - Empirical: measured $\Gamma^{\text{exp}}_{V(P)\to P(V)\gamma}$ widths

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

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

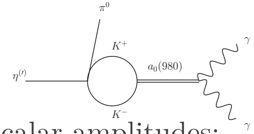
- $g_{VP\gamma}$ couplings fixed from the measured widths $(P = \pi^0, \eta, \eta')$

$$\Gamma^{\text{exp}}_{V\to P\gamma} = \frac{1}{3}\frac{g^2_{VP\gamma}}{32\pi}\left(\frac{m_V^2 - m_P^2}{m_V}\right)^3 , \quad \Gamma^{\text{exp}}_{P\to V\gamma} = \frac{g^2_{VP\gamma}}{32\pi}\left(\frac{m_P^2 - m_V^2}{m_P}\right)^3 ,$$

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

LσM for the scalar resonance contributions

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



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

- Scalar amplitudes:

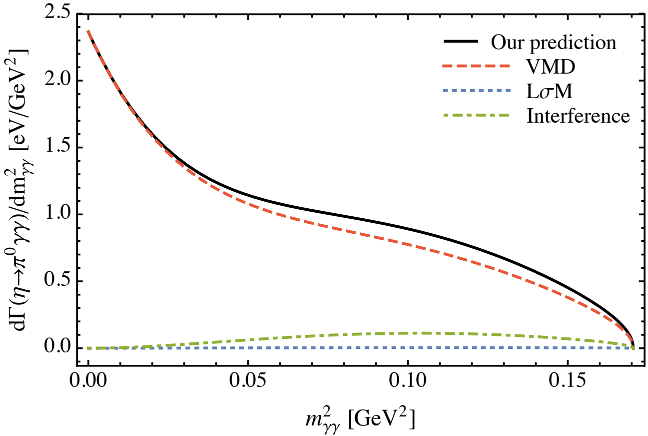
$$\mathcal{A}^{\mathrm{L}\sigma\mathrm{M}}_{K^+K^-\to\pi^0\eta^{(\prime)}} = \frac{1}{2f_\pi f_K}\left\{(s-m^2_{\eta^{(\prime)}})\frac{m_K^2-m_{a_0}^2}{D_{a_0}(s)}\cos\varphi_P+\frac{1}{6}\left[(5m^2_{\eta^{(\prime)}}+m_\pi^2-3s)\cos\varphi_P - \sqrt{2}(m^2_{\eta^{(\prime)}}+4m_K^2+m_\pi^2-3s)\sin\varphi_P\right]\right\}\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

- Complete one-loop propagator for the scalar resonances:

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

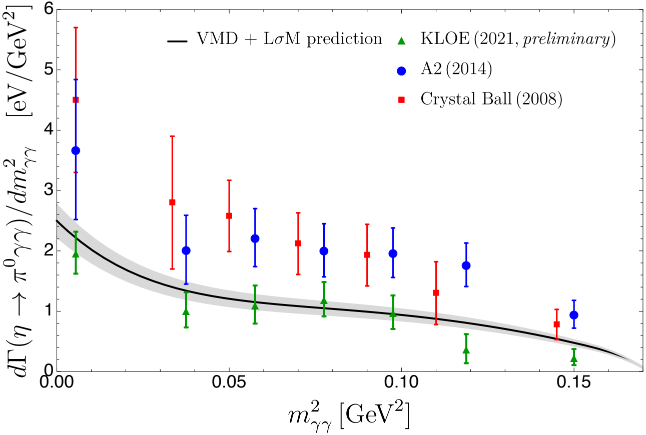
$\eta \to \pi^0\gamma\gamma$ predictions

- 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%



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

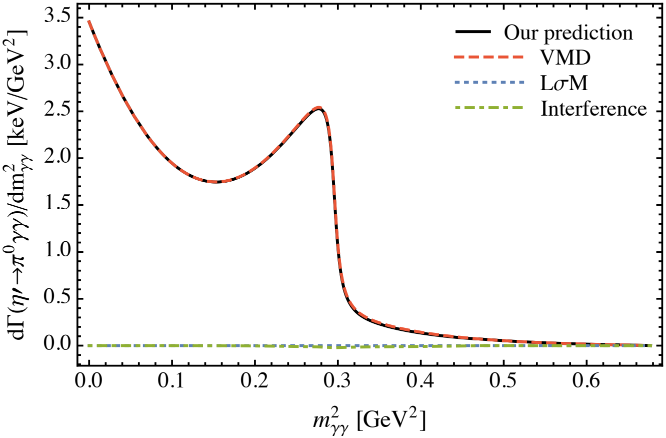
- Comparison with experimental data
  (Escribano, SGS, Jora, Royo, Phys.Rev.D 102, 034026 (2020))
  - Shape of the A2 and Crystal Ball spectra is captured well (normalization offset)
  - Good agreement with (preliminary) KLOE data (talk by Giovanella)



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

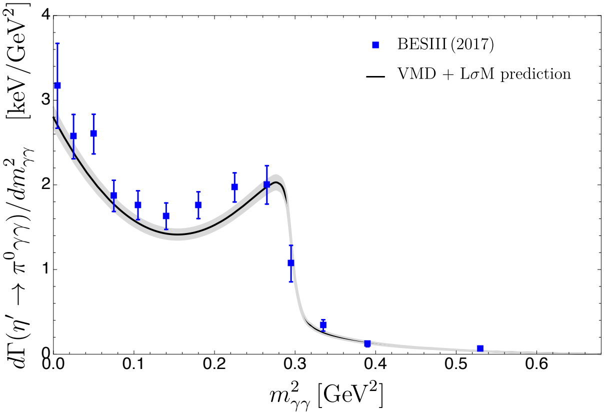
$\eta' \to \pi^0\gamma\gamma$ predictions

- 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%



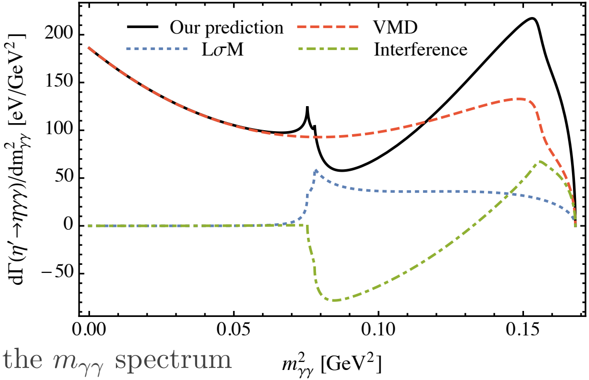
$\eta' \to \pi^0\gamma\gamma$ predictions

- 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))



$\eta' \to \eta\gamma\gamma$ predictions

- 1^{st} 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

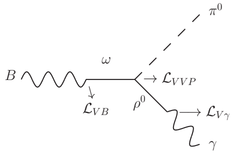
- **New** boson arising from a new $U(1)_B$ gauge symmetry

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

  - 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
  - $\varepsilon = e g_B/(4\pi)^2$: (subleading) γ-like coupling to fermions
- Searches depend on the mass m_B and decay channels
- Searches on meson decays are gaining attention
  - $\phi \to \eta B \to \eta\pi^0\gamma$ (KLOE-II), $\eta \to \pi^0\gamma\gamma$ (JEF), $\eta \to \pi^+\pi^-\gamma$ (Belle-II)

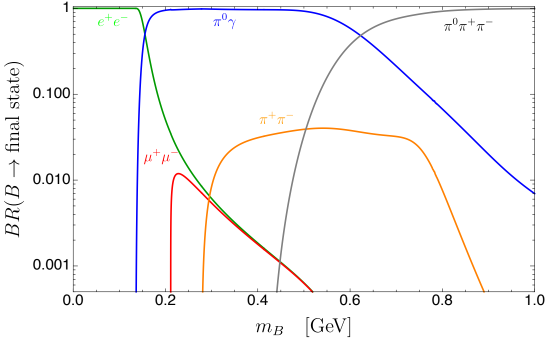
Calculation of hadronic processes

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



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

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



Previous limits on α_B and m_B

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

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

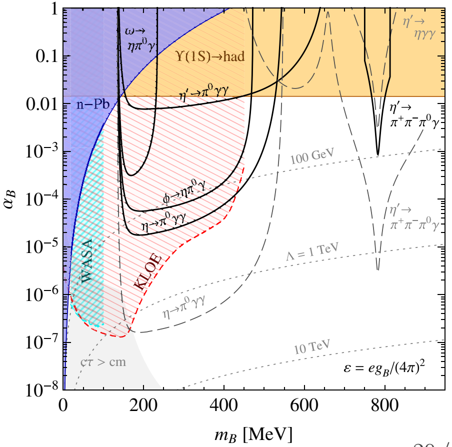
S. Tulin, Phys.Rev.D 89 (2014) 114008

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

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

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

— $BR(\eta' \to \eta\gamma\gamma)_{\rm exp}$ no data



Present limits on α_B and m_B

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

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

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

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

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

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

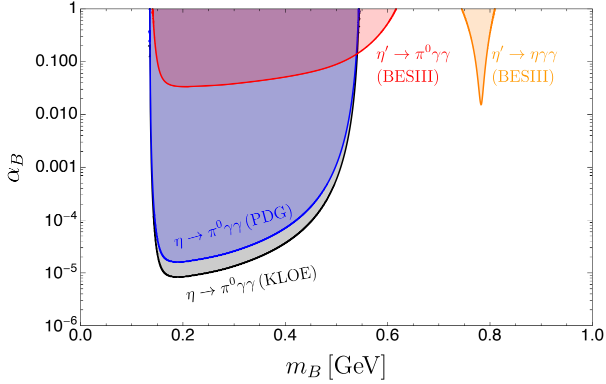
— $BR(\eta' \to \pi^0\gamma\gamma)_{\rm exp} = 3.20(7)(23) \times 10^{-3}$

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

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

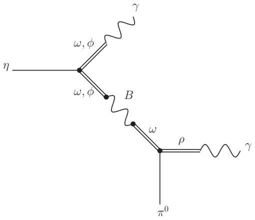
M. Ablikim *et.al* [BESIII], Phys.Rev. D 100 (2019) 052015

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



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

- Two diagrams corresponding to the exchange of a B **boson**



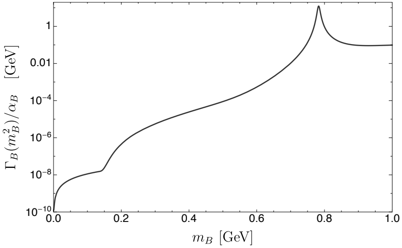
$$\mathcal{A}^{B\,\text{boson}}_{\eta\to\pi^0\gamma\gamma} = g_{B\eta\gamma}(t)g_{B\pi^0\gamma}(t)\left[\frac{(P\cdot q_2 - m_\eta^2)\{a\} - \{b\}}{m_B^2 - t - i\sqrt{t}\,\Gamma_B(t)} + \left\{\begin{array}{c} q_2 \leftrightarrow q_1 \\ t \leftrightarrow u \end{array}\right\}\right],$$

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

$$g_{B\pi^0\gamma}(t) = \frac{\sqrt{2}eg_B}{4\pi^2 f_\pi}F_\omega(t)\,,\quad g_{B\eta\gamma}(t) = \frac{eg_B}{12\pi^2 f_\pi}\frac{1}{\sqrt{3}}\left[(c_\theta - \sqrt{2}s_\theta)F_\omega(t) + (2c_\theta + \sqrt{2}s_\theta)F_\phi(t)\right],$$

- Energy-dependent **width**

$$\begin{aligned}\Gamma_B(q^2) &= \frac{\gamma_{B\to\ell^+\ell^-}(q^2)}{\gamma_{B\to\ell^+\ell^-}(m_B^2)}\Gamma_{B\to\ell^+\ell^-}\theta(q^2 - 4m_\ell^2) \\ &+ \frac{\gamma_{B\to\pi^0\gamma}(q^2)}{\gamma_{B\to\pi^0\gamma}(m_B^2)}\Gamma_{B\to\pi^0\gamma}\theta(q^2 - m_{\pi^0}^2) \\ &+ \frac{\gamma_{B\to\pi\pi}(q^2)}{\gamma_{B\to\pi\pi}(m_B^2)}\Gamma_{B\to\pi\pi}\theta(q^2 - 4m_\pi^2) \\ &+ \frac{\gamma_{B\to3\pi}(q^2)}{\gamma_{B\to3\pi}(m_B^2)}\Gamma_{B\to3\pi}\theta(q^2 - 9m_\pi^2)\end{aligned}$$



New limits on α_B and m_B

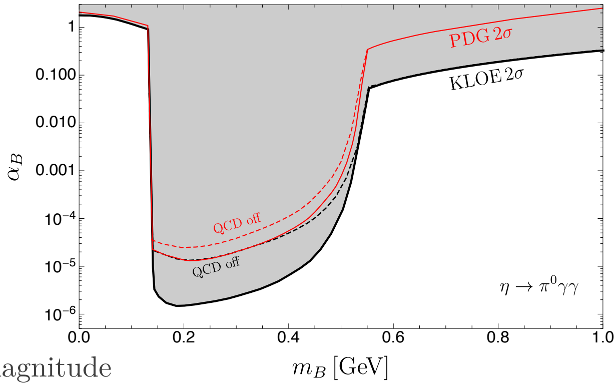
- **Not** assuming the **NWA**
- QCD contribution **on**
- $BR_{\text{VMD+Bboson}} < BR_{\text{exp}}$ at 2σ

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

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

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

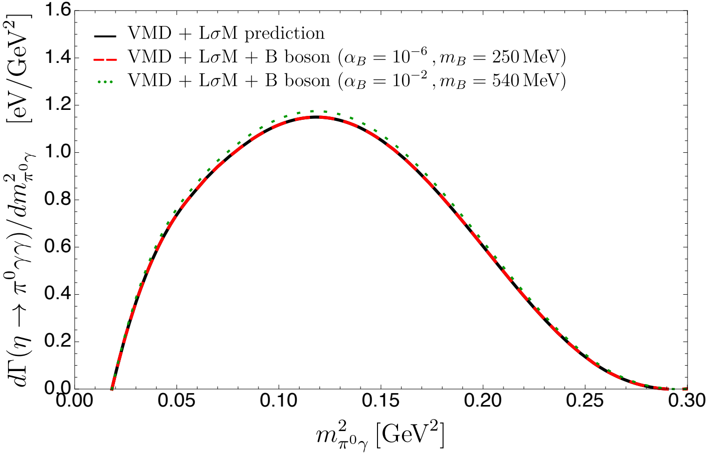
Escribano, SGS, Royo, Phys.Rev.D 106, 114007 (2022)



- 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?)



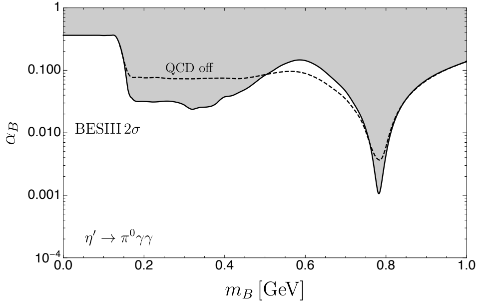
New limits on α_B and m_B

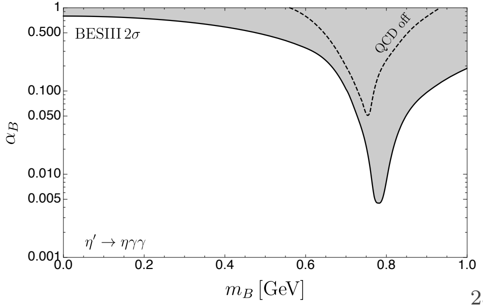
- **Not** assuming the **NWA**
- QCD contribution **on**
- $BR < BR_{\text{exp}}$ at 2σ

— $BR(\eta' \to \pi^0\gamma\gamma)_{\text{exp}} = 3.20(7)(23) \times 10^{-3}$
M. Ablikim *et.al* [BESIII], Phys.Rev. D 96 (2017) 012005

— $BR(\eta' \to \eta\gamma\gamma)_{\text{exp}} = 8.25(3.41)(72) \times 10^{-5}$
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 $\eta \to \pi^0\gamma\gamma$





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Summary

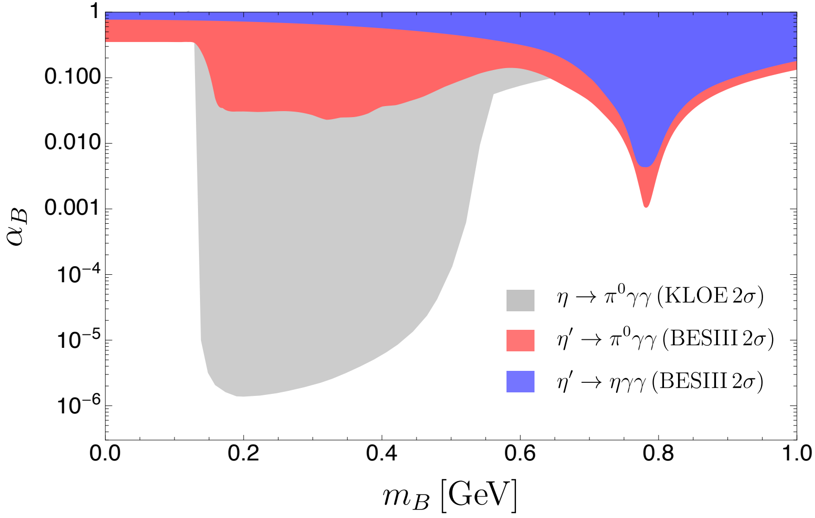
- Within the VMD and LσM frameworks **we have described**
  - $\eta \to \pi^0\gamma\gamma$: the situation is **not conclusive**

$$BR = 1.35(8) \times 10^{-4} \begin{cases} \sim 1/2 \text{ of } BR = 2.54(27) \times 10^{-4} & \text{(A2, 2014)} \\ \sim 1.6\sigma \text{ from } BR = 2.21(24)(47) \times 10^{-4} & \text{(CB, 2008)} \\ \text{agrees with } BR = 1.23(14) \times 10^{-4} & \text{(KLOE prel., 2022)} \end{cases}$$

  - $\eta' \to \pi^0\gamma\gamma$: **in fair agreement** with BESIII data
  - $\eta' \to \eta\gamma\gamma$: **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 $\eta \to \pi^0\gamma\gamma$
- The contribution of **new experiments** (A2, JEF, REDTOP), will be very welcome!

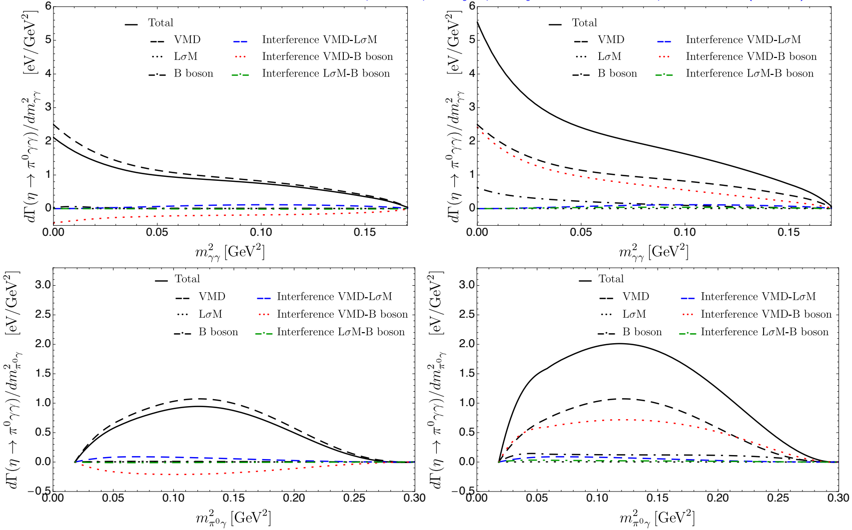
Summary

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



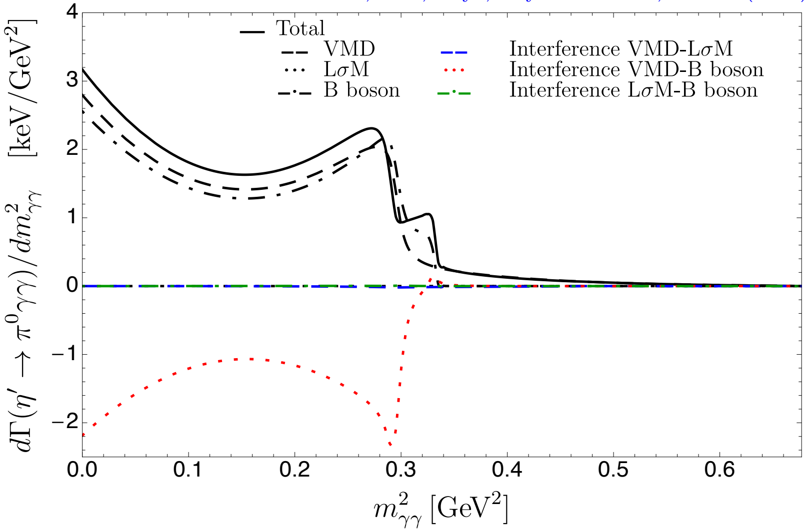
Individual contributions

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

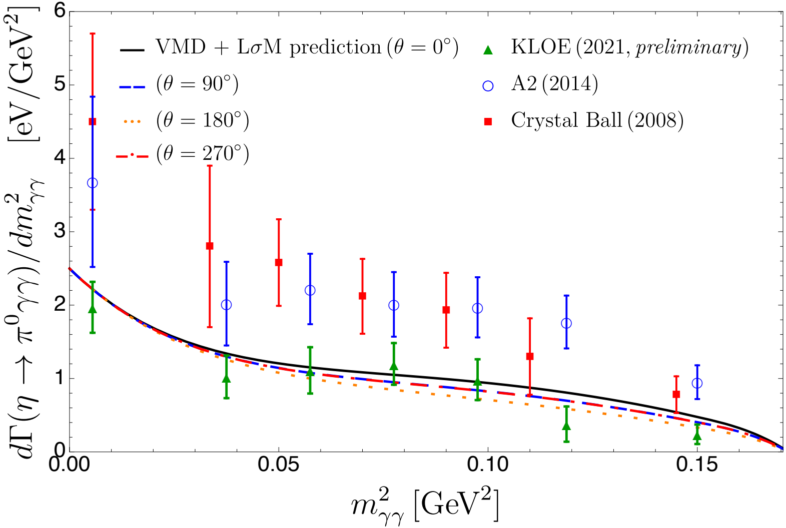


Individual contributions

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

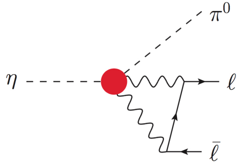


Interference phase between VMD and LσM



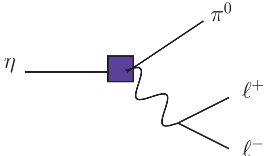
$\eta^{(\prime)} \to \{\pi^0, \eta\}\ell^+\ell^-$ decays $(\ell = e, \mu)$

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



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

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