Precision tests of fundamental physics with light pseudoscalar mesons

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- Introduction
- $\eta \to \pi^0\gamma\gamma$ decays: testing χPT and VMD models
- $\eta \to \pi^0\gamma\gamma$ 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 (talk by B. Briscoe), REDTOP (talk by C. Gatto)

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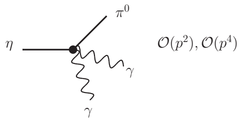
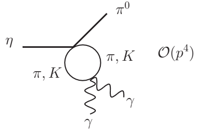
$\eta \to \pi^0\gamma\gamma$ decays: Theoretical motivation

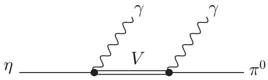




- **SM motivation**:

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)

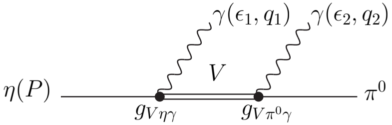
  - 1^{st} sizable contribution comes at $\mathcal{O}(p^6)$, but LEC's are not well known
  - To **test ChPT** and a wide range of chiral models, *e. g.* VMD and LσM



- **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 $V = \rho^0, \omega, \phi$



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

- Mandelstam variables and Lorentz structures given by:

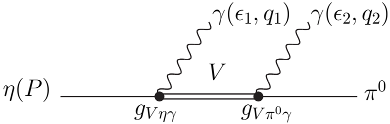
$$t, u = (P - q_{2,1})^2 = m_\eta^2 - 2P\cdot q_{2,1} \ ,$$

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

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

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

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



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

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

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

  - 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

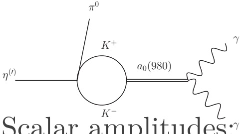
- $g_{VP\gamma}$ couplings fixed from the measured widths ($P = \pi^0, \eta, \eta'$)

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

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:

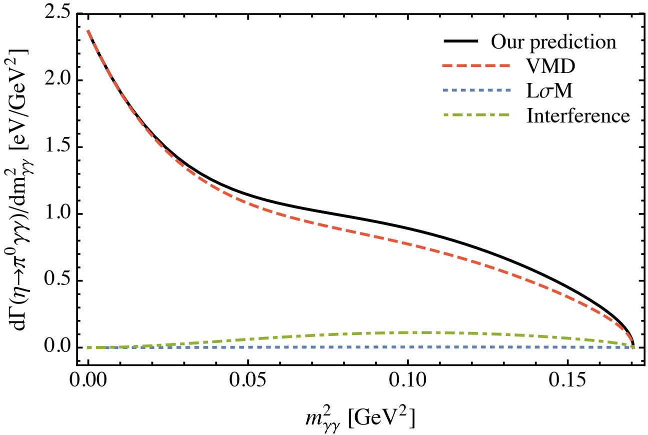
$$\mathcal{A}^{\mathrm{L}\sigma\mathrm{M}}_{K^+K^-\to\pi^0\eta^{(\prime)}} = \frac{1}{2f_\pi f_K}\Bigg\{(s-m^2_{\eta^{(\prime)}})\frac{m^2_K-m^2_{a_0}}{D_{a_0}(s)}\cos\varphi_P + \frac{1}{6}\Big[(5m^2_{\eta^{(\prime)}}+m^2_\pi-3s)\cos\varphi_P - \sqrt{2}(m^2_{\eta^{(\prime)}}+4m^2_K+m^2_\pi-3s)\sin\varphi_P\Big]\Bigg\}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

- Complete one-loop propagator for the scalar resonances:

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

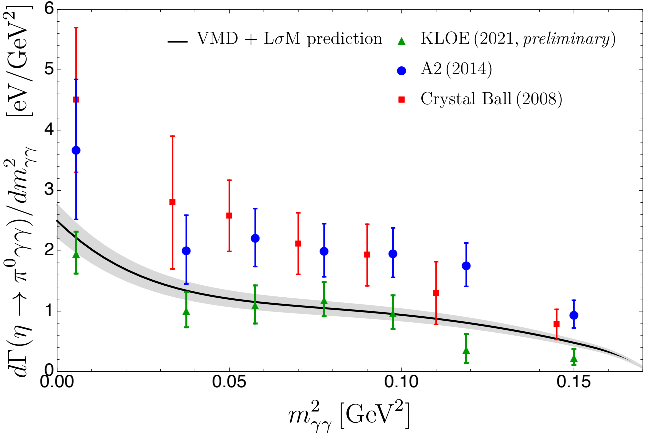
$\eta \to \pi^0\gamma\gamma$ predictions

- Our theoretical prediction $BR = 1.35(8) \times 10^{-4}$ (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%



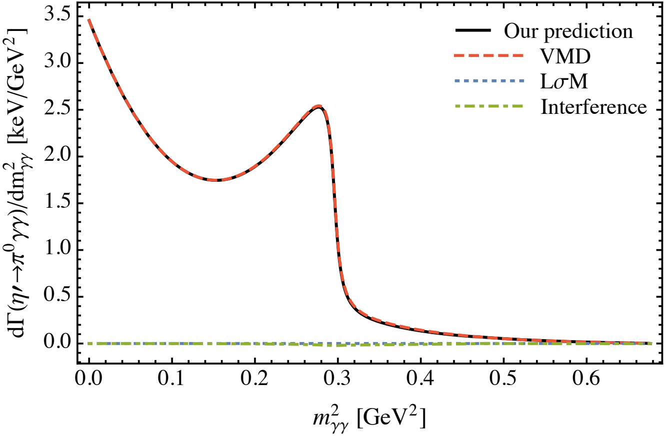
$\eta \to \pi^0\gamma\gamma$ predictions

- Comparison with experimental data (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 (del Rio CD'21)
  - KLOE: Last checks on systematics are ongoing (Berlowski DNP'22)



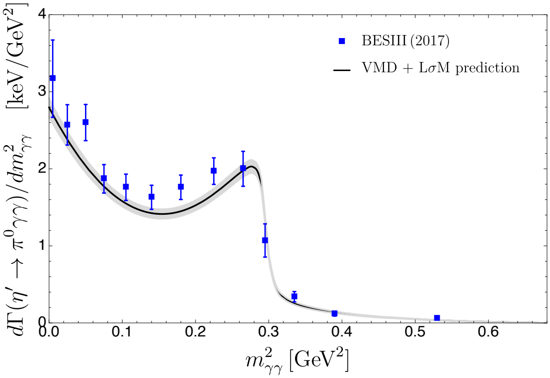
$\eta' \to \pi^0\gamma\gamma$ predictions

- Our theoretical prediction $BR = 2.91(21) \times 10^{-3}$ (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%



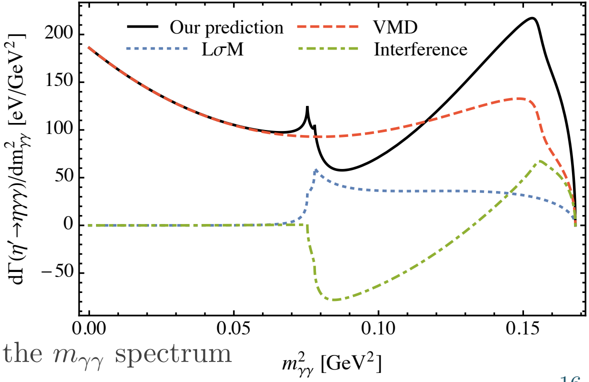
$\eta' \to \pi^0\gamma\gamma$ predictions

- 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

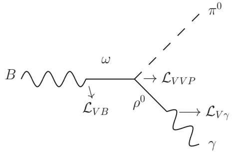
- **New** boson arising from a new $U(1)_B$ gauge symmetry

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

  - 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)

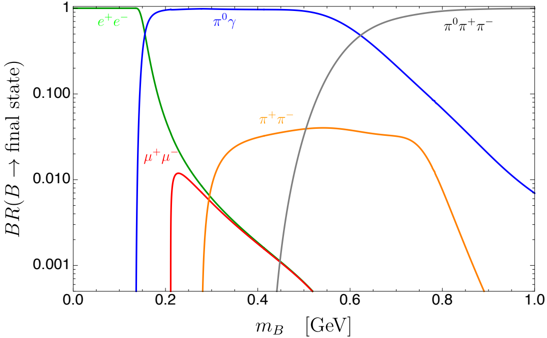
Calculation of hadronic processes

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



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

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



Previous limits on α_B and m_B

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

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

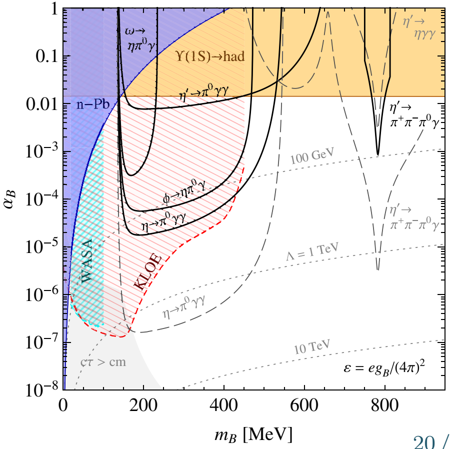
- QCD contribution **off**
- $BR(\eta \to \pi^0\gamma\gamma) < BR_{\rm exp}$ at 2σ

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

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

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

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



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**
- $BR(\eta \to \pi^0\gamma\gamma) < BR_{\text{exp}}$ 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

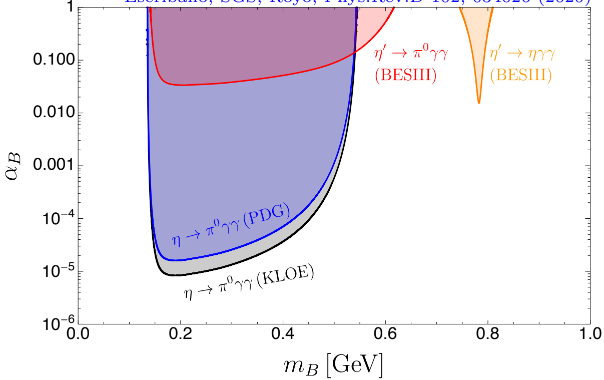
— $BR(\eta' \to \pi^0\gamma\gamma)_{\text{exp}} = 3.20(7)(23) \times 10^{-3}$

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

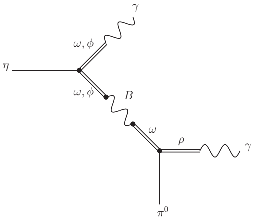
— $BR(\eta' \to \eta\gamma\gamma)_{\text{exp}} = 8.25(3.41)(72) \times 10^{-5}$

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

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



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



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

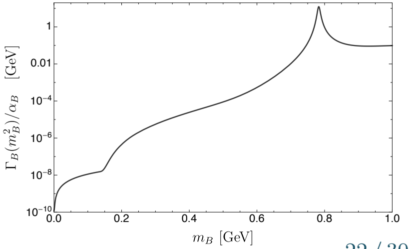
$$\mathcal{A}^{B\,\text{boson}}_{\eta\to\pi^0\gamma\gamma} = g_{B\eta\gamma}(t) g_{B\pi^0\gamma}(t) \left[\frac{(P\cdot q_2 - m_\eta^2)\{a\} - \{b\}}{m_B^2 - t - i\sqrt{t}\,\Gamma_B(t)} + \left\{ \begin{array}{c} q_2 \leftrightarrow q_1 \\ t \leftrightarrow u \end{array} \right\} \right],$$

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

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

- 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

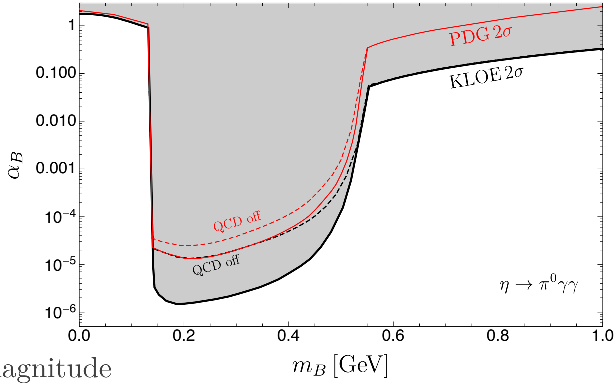
- **Not** assuming the **NWA**
- QCD contribution **on**
- $BR(\eta \to \pi^0\gamma\gamma) < BR_{\rm exp}$ at 2σ

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

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

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

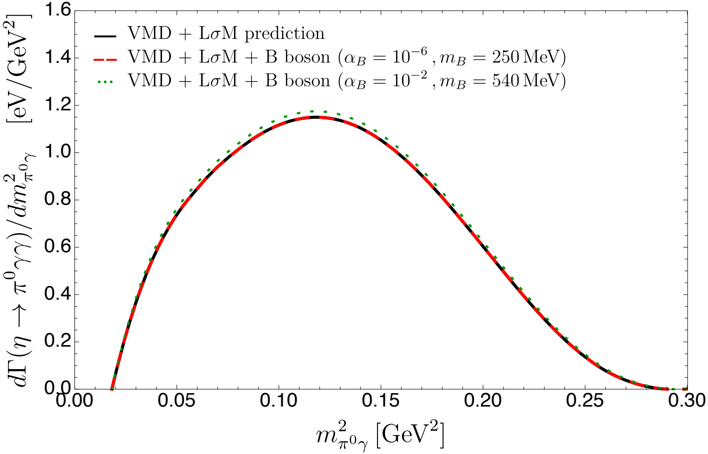
Escribano, SGS, Royo, Phys.Rev.D 102, 034026 (2020)



- 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**
- $BR < BR_{\mathrm{exp}}$ at 2σ

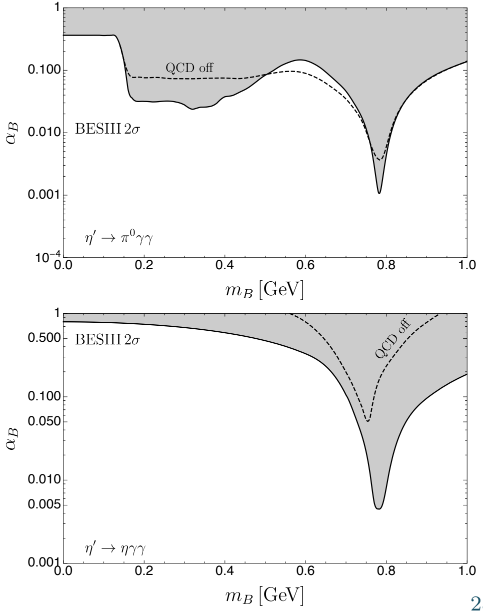
— $BR(\eta' \to \pi^0\gamma\gamma)_{\mathrm{exp}} = 3.20(7)(23) \times 10^{-3}$

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

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

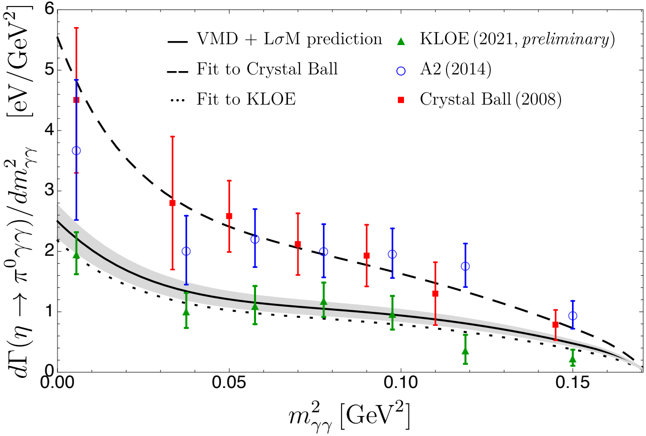
M. Ablikim *et.al* [BESIII], Phys.Rev. D 100 (2019) 052015

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



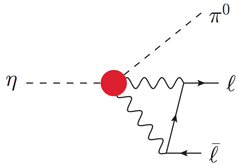
Fits to the $\eta \to \pi^0\gamma\gamma$ decays

- 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



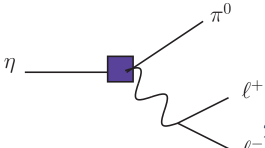
$\eta^{(\prime)} \to \{\pi^0, \eta\}\ell^+\ell^-$ **decays** $(\ell = e, \mu)$

- 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_{th} (Escribano&Royo 2007.12467)	BR_{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



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Summary

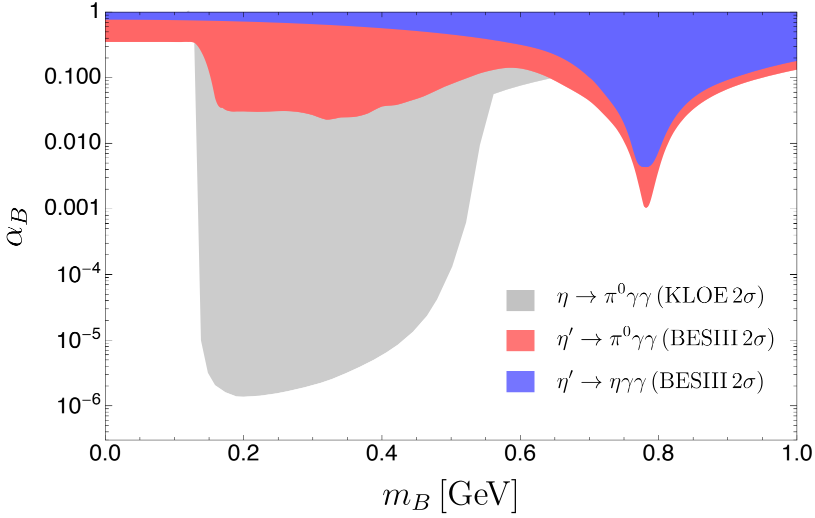
- Within the VMD and LσM frameworks **we have described**
  - $\eta \to \pi^0\gamma\gamma$: the situation is **not conclusive**

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

  - $\eta' \to \pi^0\gamma\gamma$: **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** (JEF, REDTOP), will be very welcome!

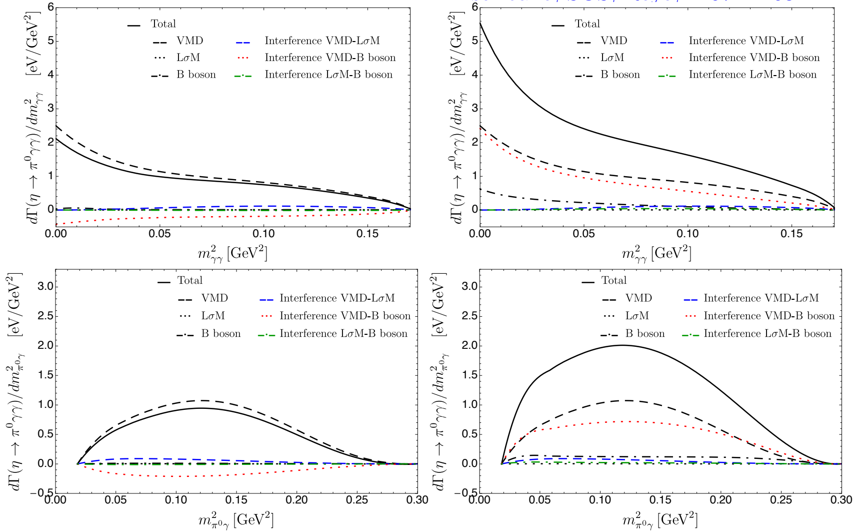
Summary

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



Individual contributions

Escribano, SGS, Royo, 2207.14263



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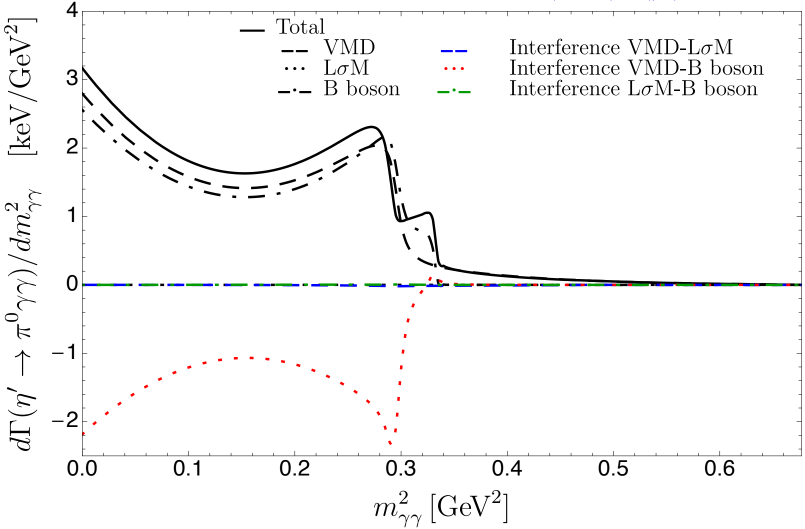

Interference phase between VMD and LσM