Probing light dark particles with η/η' decays

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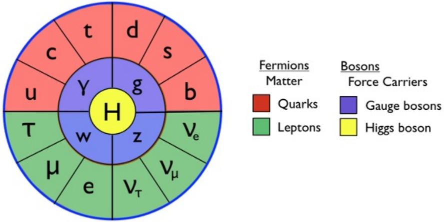
The Standard Model

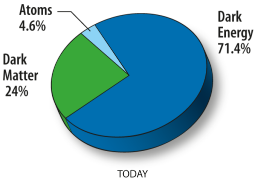
- Matter particles (quarks and leptons) in three families and mediator particles (bosons) of three interactions: electromagnetic, strong and weak
- Provides a consistent **description** of Nature's fundamental constituents and their interactions
- **Predictions** tested and confirmed by numerous experiments
- Experimental **completion** in 2012 (Higgs discovery)



Particles of the Standard Model

Beyond the Standard Model

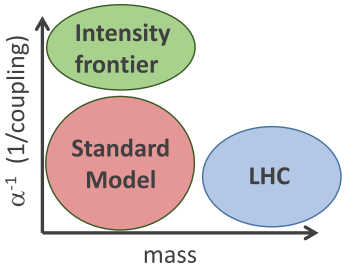
- However, the SM **fails** to explain several observed phenomena in particle physics, astrophysics and cosmology:
  - **Dark matter**: what is the most prevalent kind of matter in our Universe?
  - **Dark Energy**: what drives the accelerated expansion of the Universe?



  - **Neutrino** masses and oscillations: why do neutrinos have mass? what makes neutrinos disappear and then re-appear in a different form?
  - **Baryon asymmetry** of the Universe: what mechanism created the tiny matter-antimatter imbalance in the early Universe?
  - Several **anomalies in data**: $(g-2)_\mu$, B-physics anomalies, KOTO anomaly ($K_L \to \pi^0 \nu \bar{\nu}$), ^{8}Be excited decay, ...

Energy and Intensity Frontier Research

- **New Physics** would be needed to explain observed phenomena
- Why have **not** new particles yet been observed?
  - Hypothetical new particles are **heavy** and require even higher collision energy to be observed ⇒ **Energy Frontier** research (LHC@CERN, Tevatron@FermiLab)
  - Another possibility is that our inability to observe new particles lies not in their heavy mass, but rather in their extremely **feeble interactions** ⇒ **Intensity Frontier** research

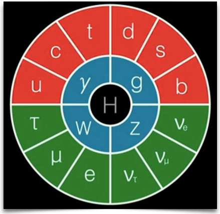


- We don't know in which **direction** BSM physics might be

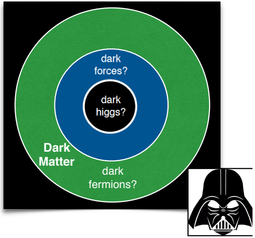
Dark sector physics

- **Why** a dark sector?
  - Many open problem in particle physics, *e.g.* dark matter, neutrino mass generation or anomalies in data, let us think about dark particles
- **What** is a dark sector particle?
  - Any particle that does not interact through the SM forces (not charged under the SM symmetries)

Our visible universe



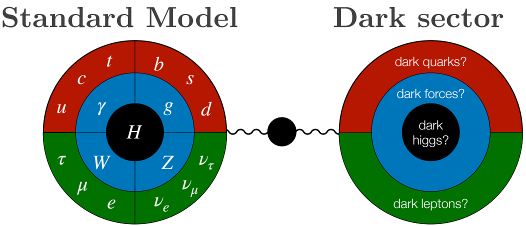
The dark universe



Dark sector portals to the Standard Model

We live in the SM world, how can we **access** (and test) the **dark sector**?

⇒ **Portal** interactions with the SM, only a few are allowed by the SM symmetries



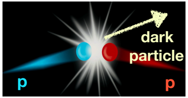
Portal	**Mediators**	**Portal interactions**
Vector	Dark photon	$\epsilon B^{\mu\nu} A'_{\mu\nu}$
Scalar	Dark scalar	$\kappa \lvert H \rvert^2 \lvert S \rvert^2$
Neutrino	Sterile Neutrino	$y H L N$
Axion	Axion	$\frac{a}{f_a} \tilde{G}_{\mu\nu} G^{\mu\nu}$

A broad program of searches of dark particles

- Vigorous effort of the community proposing **new** experiments & measurements

Energy frontier

LHC



Novel search strategies are needed!

Flavor-factories

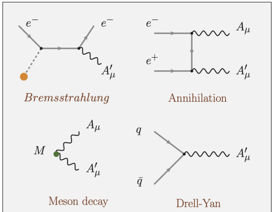
High-luminosity e^+e^- colliders

Unique access to dark sectors!

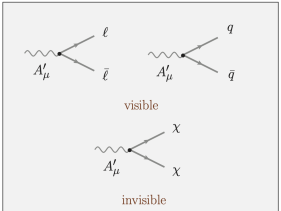
Other ongoing/future experiments

- Plenty of dark particles can be produced from **meson decays!!**

Production modes



Decay modes



η/η' laboratory for dark sectors

- The η is a pNGB, with $m_\eta \simeq 548$ MeV and $\Gamma_\eta = 1.31$ keV
- The η': not a pNGB due to $U(1)_A$ anomaly, $m_{\eta'} \simeq 958$ MeV, $\Gamma_{\eta'} = 196$ keV
- Eigenstates of the C, P, CP and G operators: $I^G J^{PC} = 0^+ 0^{-+}$
- Flavor **conserving** decays $\Rightarrow$ laboratory for symmetry tests
- All their EM and strong decays are **suppressed** at LO $\sim \mathcal{O}(\alpha_{\rm em}^2)$ or $\mathcal{O}((m_u - m_d)^2)$
- Window to **BSM** physics $\Rightarrow$ Dark sector physics:
  - **Search** strategy: decays to new light dark particles are 2/-or 3-body decays that mimic 3-,4-, or 5-body final states (often very rare)

$$e.g.: \quad \eta/\eta' \to \gamma A' \to \gamma \ell^+ \ell^- \,, \quad \eta/\eta' \to \pi\pi \text{axion} \to \pi\pi \ell^+ \ell^- \,, \quad (\ell = e, \mu)$$

- Perfect **laboratory** to stress-test the SM in search for BSM physics

Large η/η' samples at future facilities

- Previous experiments:

Experiment	Total η	Total η'
CB at AGS	10^7	-
CB MAMI-B	$2\text{x}10^7$	-
CB MAMI-C	$6\text{x}10^7$	10^6
WASA-COSY	~$3\text{x}10^7$ (p+d), ~$5\text{x}10^8$ (p+p)	-
KLOE-II	$3\text{x}10^8$	$5\text{x}10^5$
BESIII	~10^7	~$5\text{x}10^7$

- Future experiments:
  - Approved: Jefferson Lab Eta Factory Experiment (**JEF**) at JLab Hall D: 6.5×10^7 η and 4.9×10^7 η' per 100 days (see talk by W. Briscoe)
  - Proposed: **REDTOP** (2203.07651 [hep-exp]): 10^{13} η and 10^{11} η' per year (see talk by M. Zieliński); **STCF**: $10^9/10^{10}$ η/η' year (M. Achasov, et.al. Front. Phys. 19(1), 14701 (2024)); η factory at **HIAF** (Huizhou) with 10^{13} η per year (2407.00874 [hep-ph]),

Rich physics program at η,η′ factories

Standard Model highlights

- Theory input for light-by-light scattering for $(g-2)_\mu$
- Extraction of light quark masses
- QCD scalar dynamics

Fundamental symmetry tests

- P,CP violation
- C,CP violation

[Kobzarev & Okun (1964), Prentki & Veltman (1965), Lee (1965), Lee & Wolfenstein (1965), Bernstein et al (1965)]

Dark sectors (MeV—GeV)

- Vector bosons (dark photon, B boson, X boson)
- Scalars
- Pseudoscalars (ALPs)

(Plus other channels that have not been searched for to date)

Channel	Expt. branching ratio	Discussion
$\eta \to 2\gamma$	39.41(20)%	chiral anomaly, η–η' mixing
$\eta \to 3\pi^0$	32.68(23)%	$m_u - m_d$
$\eta \to \pi^0\gamma\gamma$	$2.56(22) \times 10^{-4}$	χPT at $O(p^6)$, leptophobic B boson, light Higgs scalars
$\eta \to \pi^0\pi^0\gamma\gamma$	$< 1.2 \times 10^{-3}$	χPT, axion-like particles (ALPs)
$\eta \to 4\gamma$	$< 2.8 \times 10^{-4}$	$< 10^{-11}$ [52]
$\eta \to \pi^+\pi^-\pi^0$	22.92(28)%	$m_u - m_d$, C/CP violation, light Higgs scalars
$\eta \to \pi^+\pi^-\gamma$	4.22(8)%	chiral anomaly, theory input for singly-virtual TFF and $(g-2)_\mu$, P/CP violation
$\eta \to \pi^+\pi^-\gamma\gamma$	$< 2.1 \times 10^{-3}$	χPT, ALPs
$\eta \to e^+e^-\gamma$	$6.9(4) \times 10^{-3}$	theory input for $(g-2)_\mu$, dark photon, protophobic X boson
$\eta \to \mu^+\mu^-\gamma$	$3.1(4) \times 10^{-4}$	theory input for $(g-2)_\mu$, dark photon
$\eta \to e^+e^-$	$< 7 \times 10^{-7}$	theory input for $(g-2)_\mu$, BSM weak decays
$\eta \to \mu^+\mu^-$	$5.8(8) \times 10^{-6}$	theory input for $(g-2)_\mu$, BSM weak decays, P/CP violation
$\eta \to \pi^0\pi^0\ell^+\ell^-$		C/CP violation, ALPs
$\eta \to \pi^+\pi^-e^+e^-$	$2.68(11) \times 10^{-4}$	theory input for doubly-virtual TFF and $(g-2)_\mu$, P/CP violation, ALPs
$\eta \to \pi^+\pi^-\mu^+\mu^-$	$< 3.6 \times 10^{-4}$	theory input for doubly-virtual TFF and $(g-2)_\mu$, P/CP violation, ALPs
$\eta \to e^+e^-e^+e^-$	$2.40(22) \times 10^{-5}$	theory input for $(g-2)_\mu$
$\eta \to e^+e^-\mu^+\mu^-$	$< 1.6 \times 10^{-4}$	theory input for $(g-2)_\mu$
$\eta \to \mu^+\mu^-\mu^+\mu^-$	$< 3.6 \times 10^{-4}$	theory input for $(g-2)_\mu$
$\eta \to \pi^+\pi^-\pi^0\gamma$	$< 5 \times 10^{-4}$	direct emission only
$\eta \to \pi^\pm e^\mp \nu_e$	$< 1.7 \times 10^{-4}$	second-class current
$\eta \to \pi^+\pi^-$	$< 4.4 \times 10^{-6}$ [53]	P/CP violation
$\eta \to 2\pi^0$	$< 3.5 \times 10^{-4}$	P/CP violation
$\eta \to 4\pi^0$	$< 6.9 \times 10^{-7}$	P/CP violation

Gan, Kubis, Passemar, ST (2020)

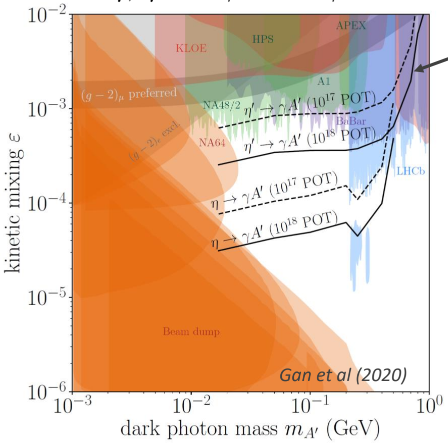
Dark particles in η/η' decays

BSM particle	Decay mode	Signal channel	Search strategy
Dark photon (A')	$\eta/\eta' \to \gamma^{(*)} A'$	$A' \to \ell^+\ell^-$	Bump-hunt in $d\Gamma/dm_{\ell\ell}$
		$A' \to \pi^+\pi^-$	Bump-hunt in $d\Gamma/dm_{\pi\pi}$
Leptophobic boson (B)	$\eta \to \gamma B$	$B \to \gamma\pi^0$	Enhancement in $m_{\pi^0\gamma}$
		$B \to \pi^+\pi^-$	Isospin suppressed
	$\eta' \to \gamma B$	$B \to \gamma\pi^0, \pi^+\pi^-, \pi^+\pi^-\pi^0, \gamma\eta$	Enhancement in $m_{\pi^0\gamma}$
ALPs (a)	$\eta \to \pi\pi a$	$a \to \gamma\gamma, \ell^+\ell^-$ $(\ell = e, \mu)$	Bump-hunt in $d\Gamma/dm_{\gamma\gamma}$
	$\eta' \to \pi\pi a$	$a \to \gamma\gamma, \ell^+\ell^-, \pi^+\pi^-\gamma, 3\pi$	Bump-hunt in $d\Gamma/dm_{\gamma\gamma}$
	$\eta^{(\prime)} \to \ell^+\ell^-$		$\eta^{(\prime)}$-a mixing
Scalar boson (S)	$\eta/\eta' \to \pi^0 S$	$S \to \gamma\gamma, \ell^+\ell^-, \pi\pi$	Bump-hunt in $d\Gamma/dm_{\gamma\gamma}$
	$\eta' \to \eta S$	$S \to \gamma\gamma, \ell^+\ell^-, \pi\pi$	Bump-hunt in $d\Gamma/dm_{\gamma\gamma}$

Dark photon searches

- **Broad** worldwide effort to search for dark photons (A')
- Most searches are for A' coupling to **leptons**, *i.e.* in $A' \to \ell^+\ell^-$ ($\ell = e, \mu$)

$$\eta, \eta' \to \gamma A' \to \gamma \ell^+ \ell^-$$



REDTOP sensitivities projected for FNAL/BNL (10^{18}) or CERN (10^{17}) POT

Gatto (2019)

Many other experiments targeting same dark photon parameter space

Worthwhile to also consider

$$\eta' \to \pi^+\pi^- A' \to \pi^+\pi^- \ell^+\ell^-$$

since $\mathcal{B}(\eta' \to \pi^+\pi^-\gamma) \approx 10 \times \mathcal{B}(\eta' \to \gamma\gamma)$

Searches of a leptophobic dark photon in rare $\eta^{(\prime)}$ decays

- What if a **new force** couples mainly to quarks?
- **Simplest model**: gauge boson (B) coupled to baryon number

$$\mathcal{L}_{\text{int}} = \frac{1}{3} g_B \bar{q}\gamma^\mu q B_\mu \, ,$$

  - g_B: flavor-universal coupling to all quarks, preserves QCD symmetries (C, P, T)
  - Also known as: B boson, leptophobic Z' or baryonic photon γ_B

	Dark-photon-like	Novel signatures (m_B [MeV])		
Decay $\rightarrow$ / Production $\downarrow$	$B \to e^+e^-$ $m_B \sim 1 - 140$ MeV	$B \to \pi^0\gamma$ $140 - 620$ MeV	$B \to \pi^+\pi^-\pi^0$ $620 - 1000$ MeV	$B \to \eta\gamma$
$\pi^0 \to B\gamma$	$\pi^0 \to e^+e^-\gamma$	–	–	–
$\eta \to B\gamma$	$\eta \to e^+e^-\gamma$	$\eta \to \pi^0\gamma\gamma$	–	–
$\eta' \to B\gamma$	$\eta' \to e^+e^-\gamma$	$\eta' \to \pi^0\gamma\gamma$	$\eta' \to \pi^+\pi^-\pi^0\gamma$	$\eta' \to \eta\gamma\gamma$
$\omega \to \eta B$	$\omega \to \eta e^+e^-$	$\omega \to \eta\pi^0\gamma$	–	–
$\phi \to \eta B$	$\phi \to \eta e^+e^-$	$\phi \to \eta\pi^0\gamma$	–	

- Searches in meson factories are gaining attention
  - $\eta \to \gamma B \to \gamma\gamma\pi^0$ (JEF), $\phi \to \eta B \to \eta\pi^0\gamma$ (KLOE-II), $\eta \to B\gamma \to \pi^+\pi^-\gamma$ (Belle-II)

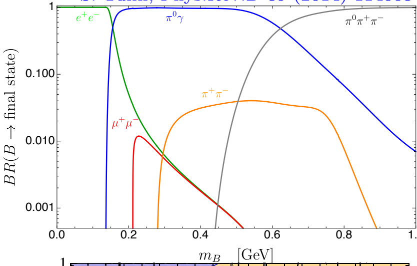
Previous limits on α_B and m_B

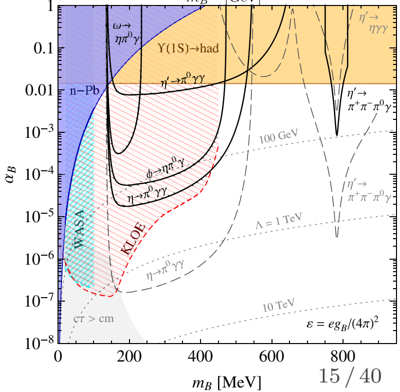
- **New** boson from a new $U(1)_B$ gauge symmetry

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

- New gauge coupling: $\alpha_B = g_B^2/4\pi$,
- B is a singlet under isospin: $\Rightarrow$ B is ω**-meson** like
- Assuming **Narrow-Width** Approximation: $\mathrm{BR}(\eta \to \pi^0\gamma\gamma) = \mathrm{BR}(\eta \to B\gamma) \times \mathrm{BR}(B \to \pi^0\gamma)$
- Assuming **zero** SM contribution
- $\mathrm{BR}(\eta \to \pi^0\gamma\gamma) < \mathrm{BR}_{\mathrm{exp}}$ at 2σ
  - $\mathrm{BR}(\eta \to \pi^0\gamma\gamma)_{\mathrm{exp}} = 2.21(53) \times 10^{-4}$
  - $\mathrm{BR}(\eta' \to \pi^0\gamma\gamma)_{\mathrm{exp}} < 8 \times 10^{-4}$ (90% $C.L.$)
  - $\mathrm{BR}(\eta' \to \eta\gamma\gamma)_{\mathrm{exp}}$ no data

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





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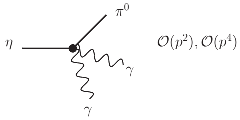
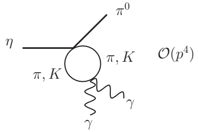
$\eta \to \pi^0\gamma\gamma$ decays: Theoretical motivation

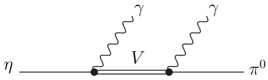
- **SM motivation**:



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)



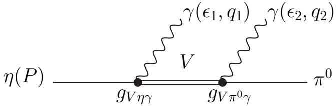
- — 1^{st} sizable contribution comes at $\mathcal{O}(p^6)$, but LEC's are not well known
- — To **test ChPT** and a wide range of chiral models, *e. g.* VMD and LσM



- **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:

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

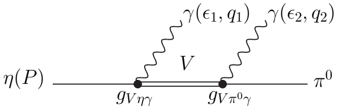
$$\{a\} = (\epsilon_1\cdot\epsilon_2)(q_1\cdot q_2) - (\epsilon_1\cdot q_2)(\epsilon_2\cdot q_1) \ ,$$

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

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

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

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



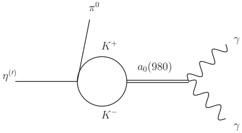
$$\mathcal{A}^{\rm VMD}_{\eta\to\pi^0\gamma\gamma} = \sum_{V=\rho^0,\omega,\phi} g_{V\eta\gamma}\, g_{V\pi^0\gamma} \left[\frac{(P\cdot q_2 - m_\eta^2)\{a\} - \{b\}}{D_V(t)} + \left\{ \begin{array}{c} q_2 \leftrightarrow q_1 \\ t \leftrightarrow u \end{array} \right\} \right] ,$$

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

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, $a_0(980), \kappa, \sigma, f_0(980)$, 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:

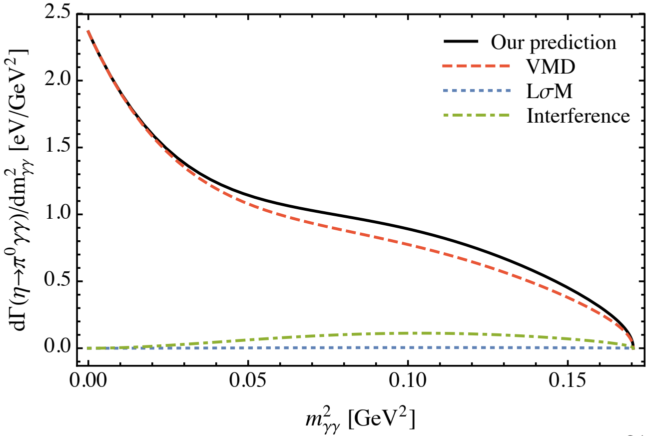
$$\mathcal{A}^{\mathrm{L}\sigma\mathrm{M}}_{K^+K^-\to\pi^0\eta^{(\prime)}} = \frac{1}{2f_\pi f_K}\Bigg\{(s-m^2_{\eta^{(\prime)}})\frac{m^2_K-m^2_{a_0}}{D_{a_0}(s)}\cos\varphi_P+\frac{1}{6}\Big[(5m^2_{\eta^{(\prime)}}+m^2_\pi-3s)\cos\varphi_P - \sqrt{2}(m^2_{\eta^{(\prime)}}+4m^2_K+m^2_\pi-3s)\sin\varphi_P\Big]\Bigg\}\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

- Complete one-loop propagator for the scalar resonances:

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

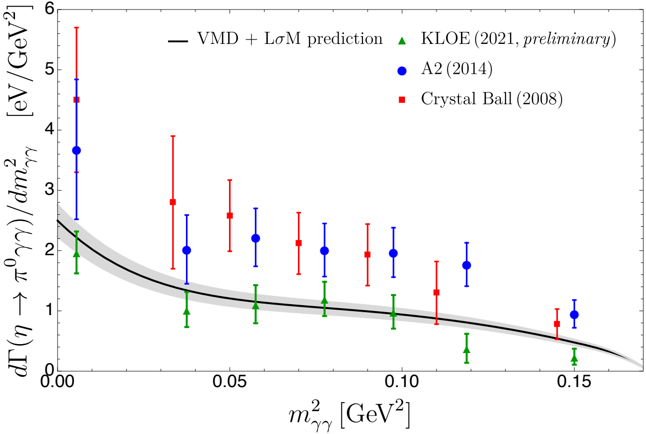
$\eta \to \pi^0\gamma\gamma$ predictions

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

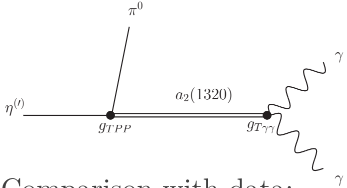
- Comparison of our prediction ($\text{BR} = 1.35(8) \times 10^{-4}$) with experimental data
  (Escribano, SGS, Jora, Royo, Phys.Rev.D 102, 034026 (2020))
  - Shape of the A2 ($\text{BR} = 2.54(27) \times 10^{-4}$) and Crystal Ball ($\text{BR} = 2.21(24)(47) \times 10^{-4}$) spectra is captured well (normalization offset)
  - Good agreement with (preliminary) KLOE data ($\text{BR} = 1.23(14) \times 10^{-4}$) [B. Cao, PoS EPS-HEP2021 (2022) 409]



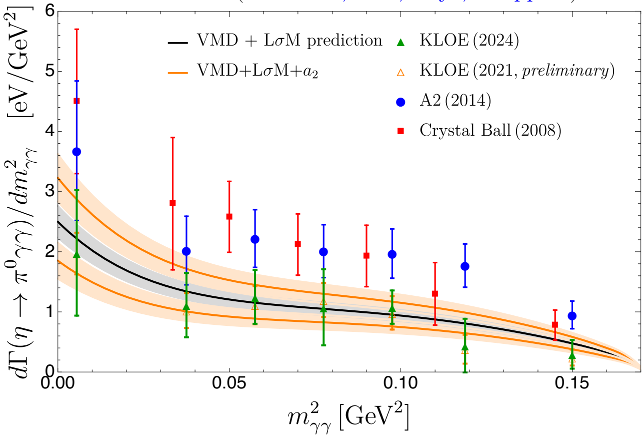
- The experimental situation needs to be **clarified** (A2, JEF, REDTOP)

$a_2(1320)$ tensor meson contribution to $\eta \to \pi^0\gamma\gamma$

- One **diagram** corresponding to the exchange of $a_2(1320)$ in the s-channel



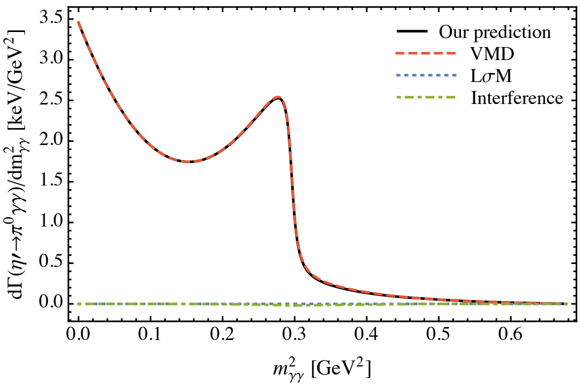
(Escribano, SGS, Royo, to appear)

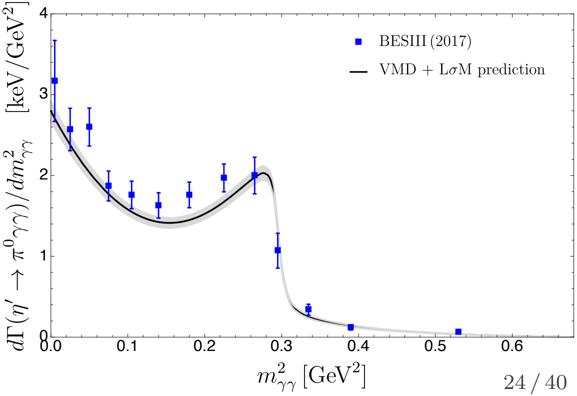


- Comparison with data:
  - **Destructive** vector-tensor interference: good agreement with (preliminary) KLOE-II data (P. Gauzzi, PoS EPS-HEP2023 (2024) 246)
  - **Constructive** vector-tensor interference: inconclusive
- VMD-a_2 interference $\sim 20\%$ of the signal (could be tested and distinguished from VMD with precise measurements at *e.g.* JEF)

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

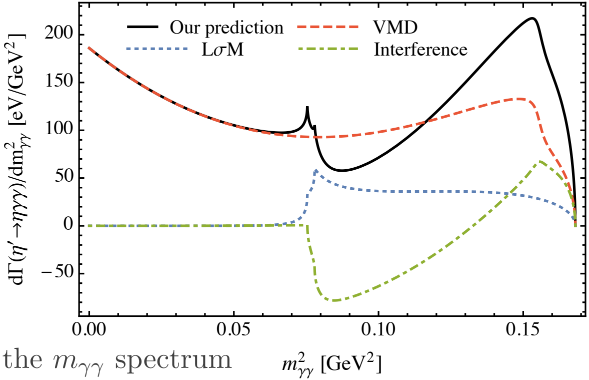
- $\mathrm{BR} = 2.91(21) \times 10^{-3}$ (Escribano, SGS, Jora, Royo, Phys.Rev.D 102, 034026 (2020))
  - VMD completely dominates: ω (78%), ρ (5%), ϕ (0%), interference (17%)
- First time $m_{\gamma\gamma}$ invariant mass distribution by BESIII;
  $\mathrm{BR} = 3.20(7)(23) \times 10^{-3}$ (Ablikim *et. al.* Phys.Rev.D 96, 012005 (2017))





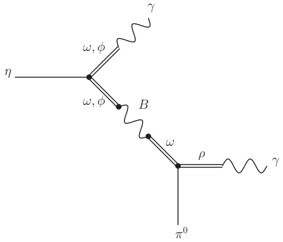
$\eta' \to \eta\gamma\gamma$ predictions

- 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

New limits on α_B, m_B (B-boson+SM)



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

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

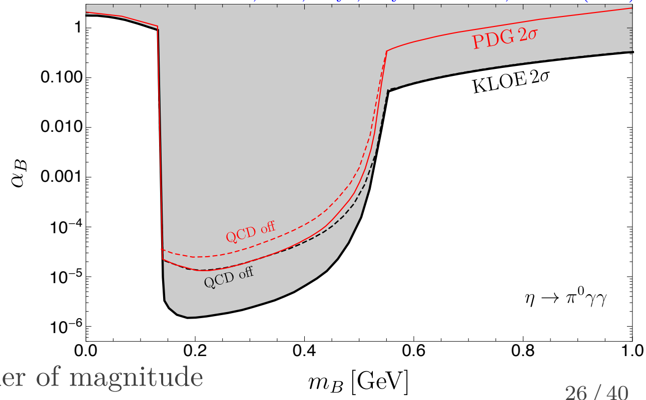
- **Not** assuming the **NWA**
- QCD contribution **on**
- $\mathrm{BR}_{\mathrm{VMD+Bboson}} < \mathrm{BR}_{\mathrm{exp}}$ at 2σ

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

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

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

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

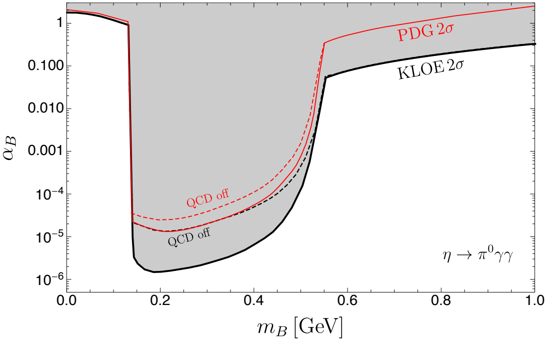


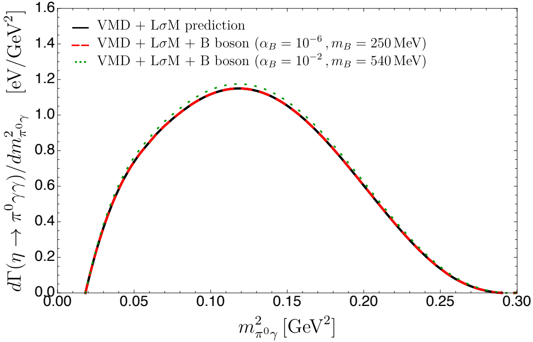
- Limits **strengthened** by one order of magnitude

$\pi^0\gamma$ mass distribution

- These constraints would make a B boson signature suppressed

$$\Gamma(\eta \to \pi^0\gamma\gamma) \propto \int \frac{\alpha_B^2\, dt}{|\mathcal{D}_B(t)|^2} \to \frac{\alpha_B^2\, \pi}{m_B\, \Gamma_B(m_B^2)} \,.$$

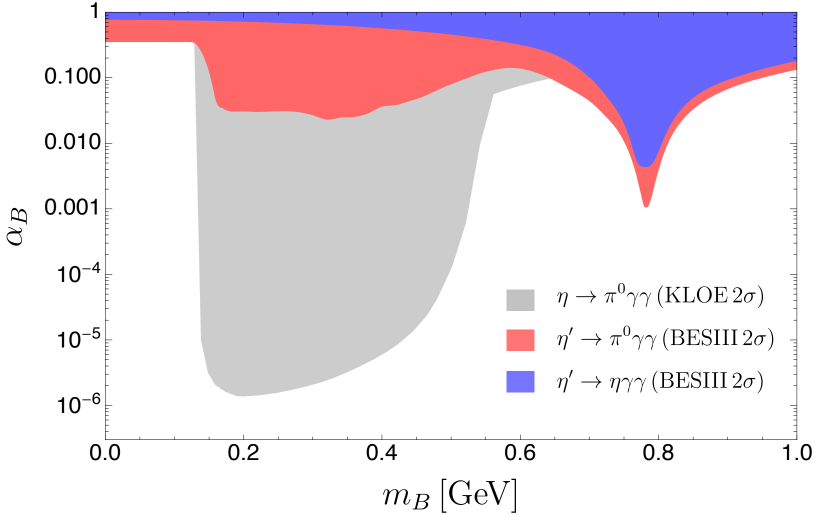




- Experimental $\pi^0\gamma$ distribution will be very welcome (JEF?)

New limits on α_B and m_B

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



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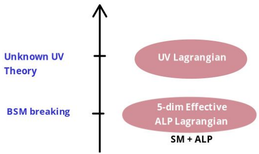
Axion-Like Particles (ALPs)



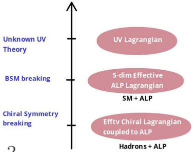
- Pseudo-Goldstone bosons from global symmetry breaking
- Example: QCD axion (Peccei-Quinn) $\rightarrow$ solution of the CP problem, potential dark matter candidate. QCD axion mass: $m_a^2 \propto \frac{1}{f_a^2}$.
- "Yukawa basis" (at GeV scale): ALP with gluon and mass couplings

$$\mathcal{L}_{\text{ALP}} = \mathcal{L}_{\text{QCD}} + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{1}{2}M_a^2 a^2 - Q_G \frac{\alpha_s}{8\pi}\frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu} + \sum_{q=u,d,s} m_q \bar{q}\left(e^{iQ_q \frac{a}{f_a}\gamma_5}\right) q \,,$$

M_a^2: PQ contribution to the mass, f_a: axion decay constant, $Q_{q,G}$: PQ charges

- Equivalent to the "usual" derivative basis (related via chiral rotations of the quarks) if weak interactions are neglected
- The heavy-flavor c, b, t quarks contributions are absorbed in $Q_G \rightarrow Q_G + Q_{t,b,c}$

Lagrangian for ALPs coupled to mesons



- Step 1: **map** $\mathcal{L}_{\rm ALP}$ into χPT at leading order

$$\mathcal{L}_{\rm ALP}^{\chi{\rm PT@LO}} = \frac{f_\pi^2}{4}{\rm Tr}\left[\partial_\mu U^\dagger \partial^\mu U\right] + \frac{f_\pi^2}{4}\left[2B_0(M_q(a)U + M_q(a)^\dagger U^\dagger)\right] - \frac{1}{2}m_0^2\left(\eta_0 - \frac{Q_G}{\sqrt{6}}\frac{f_\pi}{f_a}a\right)^2 + \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2}M_a^2 a^2$$

$$M_q(a) = {\rm diag}(m_u e^{iQ_u a/f_a}, m_d e^{iQ_d a/f_a}, m_s e^{iQ_s a/f_a}),$$

$$U = \exp\left(\frac{i\sqrt{2}\Phi}{f}\right), \quad \Phi = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi_3 + \frac{1}{\sqrt{6}}\eta_8 + \frac{1}{\sqrt{3}}\eta_0 & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi_3 + \frac{1}{\sqrt{6}}\eta_8 + \frac{1}{\sqrt{3}}\eta_0 & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta_8 + \frac{1}{\sqrt{3}}\eta_0 \end{pmatrix}.$$

- Step 2: **diagonalization** of the mass matrix $\Rightarrow$ mixing angles $\theta_{\pi_3 a}, \theta_{\eta_8 a}, \theta_{\eta_0 a}$

$$\widetilde{M}^2 = \begin{pmatrix} m_{\pi_3}^2 & m_{\pi_3\eta_8}^2 & m_{\pi\eta_0}^2 & m_{\pi_3 a}^2 \\ & m_{\eta_8}^2 & m_{\eta_8\eta_0}^2 & m_{\eta_8 a}^2 \\ & & m_{\eta_0}^2 & m_{\eta_0 a}^2 \\ & & & m_a^2 \end{pmatrix},$$

$$m_{\pi_3}^2 = B_0(m_u + m_d), \quad m_{\pi_3\eta_8}^2 = \frac{B_0}{\sqrt{3}}(m_u - m_d), \quad m_{\pi_3\eta_0}^2 = \sqrt{\frac{2}{3}}B_0(m_u - m_d),$$

$$m_{\eta_8}^2 = \frac{B_0}{3}(m_u + m_d + 4m_s), \quad m_{\eta_8\eta_0}^2 = \frac{\sqrt{2}}{3}B_0(m_u + m_d - 2m_s), \quad m_{\eta_0}^2 = m_0^2 + \frac{2}{3}B_0(m_u + m_d + m_s$$

$$m_{\pi_3 a}^2 = \frac{f_\pi}{f_a}B_0(m_u Q_u - m_d Q_d), \quad m_{\eta_8 a}^2 = \frac{f_\pi}{f_a}\frac{B_0}{\sqrt{3}}(m_u Q_u + m_d Q_d - 2m_s Q_s),$$

$$m_{\eta_0 a}^2 = \frac{f_\pi}{f_a}\sqrt{\frac{2}{3}}B_0(m_u Q_u + m_d Q_d + m_s Q_s) - \frac{f_\pi}{f_a}m_0^2\frac{Q_G}{\sqrt{6}},$$

$$m_a^2 = \frac{f_\pi^2}{f_a^2}B_0(m_u Q_u^2 + m_d Q_d^2 + m_s Q_s^2) + \frac{f_\pi^2}{f_a^2}m_0^2\frac{Q_G^2}{6} + M_a^2.$$

$\eta/\eta' \to \pi\pi a$ decay amplitudes at LO

- Step 3: re-express $\mathcal{L}_{\text{ALP}}^{\chi\text{PT@LO}}$ in terms of the **physical states**

$$\pi_3 \to \pi_3 + \theta_{\pi_3 a} a^{\text{phys}}\,, \quad \eta_8 \to \cos\theta\eta + \sin\theta\eta' + \theta_{\eta_8 a} a^{\text{phys}}\,, \quad \eta_0 \to -\sin\theta\eta + \cos\theta\eta' + \theta_{\eta_0 a} a^{\text{phys}}\,,$$

- Physical ALP mass: $m^2_{a_{\text{phys}}} = \dfrac{(Q_u+Q_d+Q_s+Q_G)^2 B_0 m_u m_d m_s}{\left(m_u m_d + m_u m_s + m_d m_s + \frac{6B_0 m_u m_d m_s}{m_0^2}\right)} \dfrac{f_\pi^2}{f_a^2} + M_a^2\,,$

$$\mathcal{A}(\eta \to 2\pi^0 a)|_{\text{LO}} = 2!\,\frac{m_\pi^2}{f_\pi^2}\left(\cos\theta - \sqrt{2}\sin\theta\right)\left[\frac{f_\pi}{2\sqrt{3}f_a}\frac{Q_u m_u + Q_d m_d}{m_u + m_d} - \frac{1}{2\sqrt{3}}\frac{m_d - m_u}{m_u + m_d}\theta_{\pi_3 a} + \frac{1}{6}\theta_{\eta_8 a} + \frac{\sqrt{2}}{6}\theta_{\eta_0 a}\right],$$

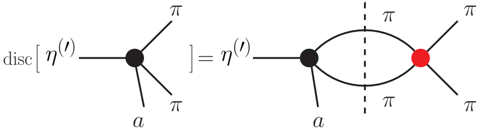
$$\mathcal{A}(\eta \to \pi^+\pi^- a)|_{\text{LO}} = \frac{m_\pi^2}{f_\pi^2}\left(\cos\theta - \sqrt{2}\sin\theta\right)\left[\frac{f_\pi}{\sqrt{3}f_a}\frac{Q_u m_u + Q_d m_d}{m_u + m_d} - \frac{1}{3\sqrt{3}}\frac{m_d - m_u}{m_u + m_d}\theta_{\pi_3 a} + \frac{1}{3}\theta_{\eta_8 a} + \frac{\sqrt{2}}{3}\theta_{\eta_0 a}\right],$$

$$\mathcal{A}(\eta' \to 2\pi^0 a)|_{\text{LO}} = 2!\,\frac{m_\pi^2}{f_\pi^2}\left(\sqrt{2}\cos\theta + \sin\theta\right)\left[\frac{f_\pi}{2\sqrt{3}f_a}\frac{Q_u m_u + Q_d m_d}{m_u + m_d} - \frac{1}{2\sqrt{3}}\frac{m_d - m_u}{m_u + m_d}\theta_{\pi_3 a} + \frac{1}{6}\theta_{\eta_8 a} + \frac{\sqrt{2}}{6}\theta_{\eta_0 a}\right],$$

$$\mathcal{A}(\eta' \to \pi^+\pi^- a)|_{\text{LO}} = \frac{m_\pi^2}{f_\pi^2}\left(\sqrt{2}\cos\theta + \sin\theta\right)\left[\frac{f_\pi}{\sqrt{3}f_a}\frac{Q_u m_u + Q_d m_d}{m_u + m_d} - \frac{1}{3\sqrt{3}}\frac{m_d - m_u}{m_u + m_d}\langle\pi^0 a\rangle + \frac{1}{3}\theta_{\eta_8 a} + \frac{\sqrt{2}}{3}\theta_{\eta_0 a}\right],$$

Effects of pion-pion final-state interactions (FSI)

- Unitarity:



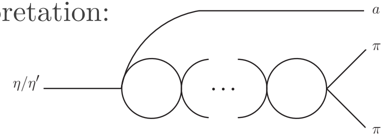
$$\mathrm{disc}\mathcal{A}(s) = 2i\mathcal{A}(s)\sigma_\pi(s)T_0^{0*}(s) = 2i\mathcal{A}(s)\sin\delta_0^0(s)e^{-i\delta_0^0(s)} \,,$$

$$\mathcal{A}(s) = \frac{1}{2i\pi}\int_{4M_\pi^2}^{\infty} ds' \frac{\mathrm{disc}\mathcal{A}(s')}{s'-s-i\varepsilon} \,,$$

- Analytic solution:

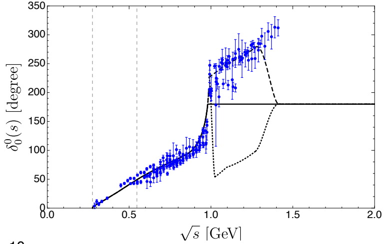
$$\mathcal{A}(s) = \mathcal{A}(\eta\to 2\pi a)|_{\mathrm{LO}} \times \Omega_0^0(s) \,, \quad \Omega_0^0(s) = \exp\left\{\frac{s}{\pi}\int_{4M_\pi^2}^{\infty} ds' \frac{\delta_0^0(s')}{s'(s'-s-i\varepsilon)}\right\} \,,$$

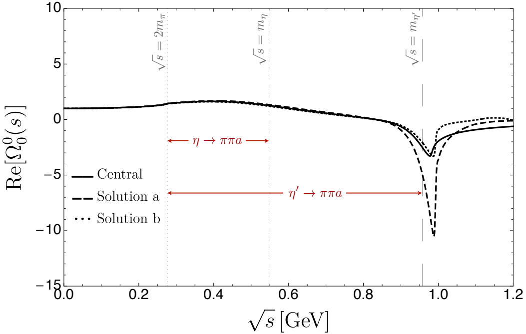
- Diagrammatic interpretation:

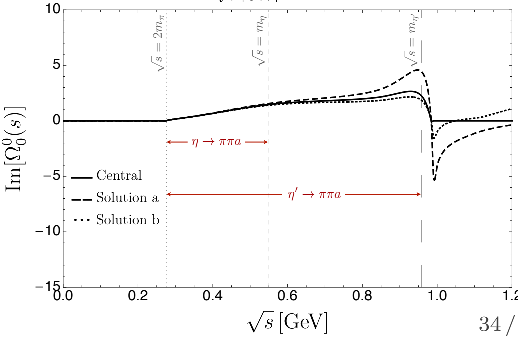


Solution of the Omnès function $\Omega_0^0(s)$

$$\Omega_0^0(s) = \exp\left\{ \frac{s}{\pi} \int_{4M_\pi^2}^{\infty} ds' \, \frac{\delta_0^0(s')}{s'(s'-s-i\varepsilon)} \right\},$$



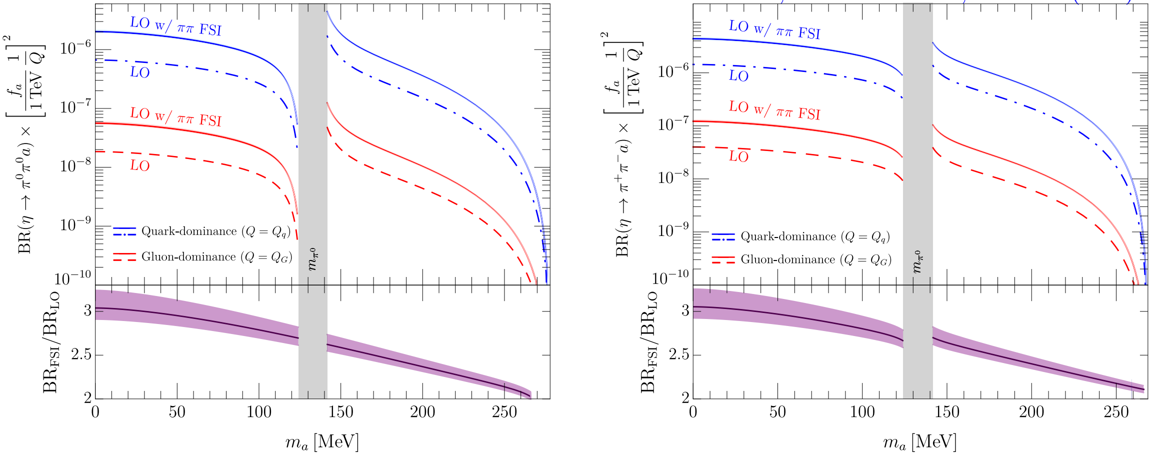




Branching ratio predictions for $\eta \to \pi\pi a$

- Two scenarios: **Quark-dominance** $Q_G = 0$ or **Gluon-dominance** $Q_q = 0$

D. Alves, S. Gonzàlez-Solís, JHEP 07 (2024) 264

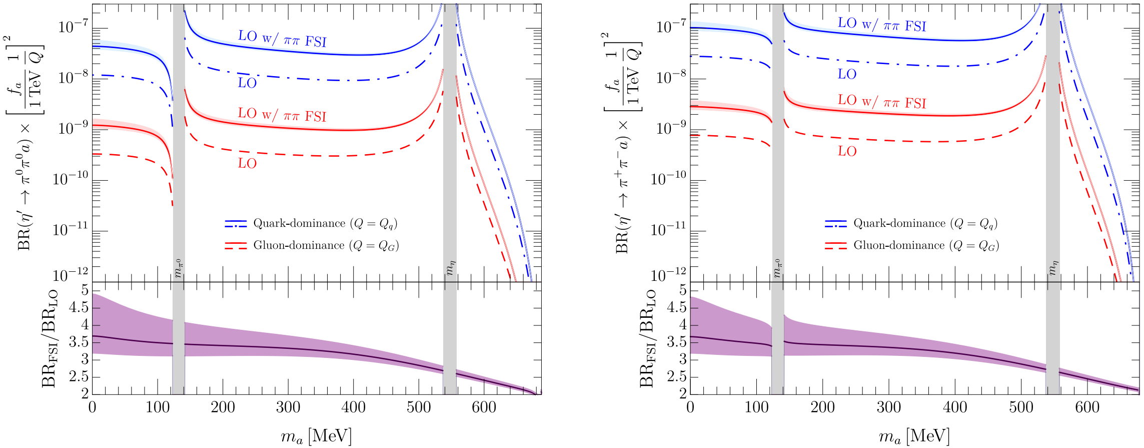


- Searches in $\eta \to \pi\pi a \to \pi\pi\gamma\gamma$ and $\eta \to \pi\pi a \to \pi\pi\ell^+\ell^-$ (BESIII, HADES [see talk by K. Prościński], KLOE, CMS, JEF, REDTOP)

Branching ratio predictions for $\eta' \to \pi\pi a$

- Two scenarios: **Quark-dominance** $Q_G = 0$ or **Gluon-dominance** $Q_q = 0$

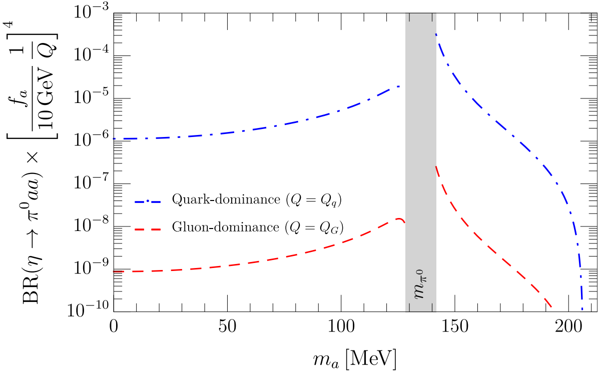
D. Alves, S. Gonzàlez-Solís, JHEP 07 (2024) 264



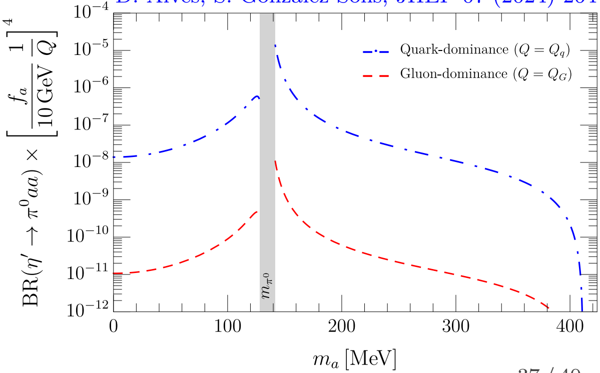
- Searches in $\eta' \to \pi\pi a \to \pi\pi\gamma\gamma$ and $\eta' \to \pi\pi a \to \pi\pi\ell^+\ell^-$ (BESIII [see talk by A. Kupść], KLOE, CMS, JEF, REDTOP)

Double production of ALPs in η/η' decays

- $\eta/\eta' \to \pi^0 aa$ decays
- One extra power of $1/f_a$ suppression, BR $\sim \mathcal{O}(1/f_a^4)$
- $f_a \sim \mathcal{O}(1-10)$ GeV to be sensitive probes of ALPs



D. Alves, S. Gonzàlez-Solís, JHEP 07 (2024) 264



Other meson decays

BSM particle	Decay mode	Signal channel	Search strategy
ALPs (a)	$K^\pm \to \pi^\pm a$	$a \to \gamma\gamma, \ell^+\ell^-$ ($\ell = e, \mu$)	Bump-hunt in $d\Gamma/dm_{\gamma\gamma,\ell\ell}$
	$K^\pm \to \pi^\pm \pi^0 a$	$a \to \gamma\gamma, \ell^+\ell^-$ ($\ell = e, \mu$)	Bump-hunt in $d\Gamma/dm_{\gamma\gamma,\ell,\ell}$
	$K_L \to \pi^0 a$	$a \to \gamma\gamma, \ell^+\ell^-$ ($\ell = e, \mu$)	Bump-hunt in $d\Gamma/dm_{\gamma\gamma,\ell\ell}$
	$K_L \to \pi^0\pi^0 a$	$a \to \gamma\gamma, \ell^+\ell^-$ ($\ell = e, \mu$)	Bump-hunt in $d\Gamma/dm_{\gamma\gamma,\ell\ell}$
	$K_L \to \pi^+\pi^- a$	$a \to \gamma\gamma, \ell^+\ell^-$ ($\ell = e, \mu$)	Bump-hunt in $d\Gamma/dm_{\gamma\gamma,\ell\ell}$
	$B^\pm \to \pi^\pm a$	$a \to \ell^+\ell^-, 3\pi, \eta\pi\pi, KK\pi$	Higher ALP masses
	$B^\pm \to K^\pm a$	$a \to \ell^+\ell^-, 3\pi, \eta\pi\pi, KK\pi$	Higher ALP masses
	$B \to K^* a$	$a \to \ell^+\ell^-, 3\pi, \eta\pi\pi, KK\pi$	Higher ALP masses
	$\omega/\phi/J/\psi \to \pi^0\pi^0 a$	$a \to \gamma\gamma, \ell^+\ell^-$ ($\ell = e, \mu$)	Bump-hunt in $d\Gamma/dm_{\gamma\gamma,\ell\ell}$
	$\omega/\phi/J/\psi \to \pi^0\pi^0 a$	$a \to \pi^+\pi^-\gamma, 3\pi$	
Dark photon (A')	$\pi^0 \to \gamma A'$	$A' \to e^+e^-$	e^+e^- resonance
	$\pi^0 \to \gamma^* A'$	$\gamma^* \to e^+e^-, A' \to e^+e^-$	e^+e^- resonance
	$\omega/\phi/J/\psi \to \pi^0 A'$	$A' \to \ell^+\ell^-$ ($\ell = e, \mu$)	$\ell^+\ell^-$ resonance
	$\omega/\phi/J/\psi \to \pi^0 A'$	$A' \to \pi^+\pi^-$	$\pi^+\pi^-$ resonance
Leptophobic boson (B)	$\omega/\phi \to \eta B$	$B \to \gamma\pi^0$	Enhancement in $m_{\pi^0\gamma}$

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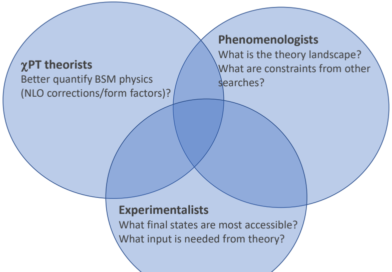
Conclusions

- Exploring **dark sectors** is an important and growing element of BSM physics
- A wealth of exciting ongoing/future **experiments** to search for dark sector particle signatures exist/planned
- η/η' mesons are an interesting place to look for dark particles because probe coupling to light quarks and gluons
- BSM searches in parallel with SM η/η' decay studies
- Progress on this front requires **collaboration**!



Rich physics program at η,η′ factories

Standard Model highlights

- Theory input for light-by-light scattering for $(g\text{-}2)_\mu$
- Extraction of light quark masses
- QCD scalar dynamics

Fundamental symmetry tests

- P,CP violation
- C,CP violation

[Kobzarev & Okun (1964), Prentki & Veltman (1965), Lee (1965), Lee & Wolfenstein (1965), Bernstein et al (1965)]

Dark sectors (MeV—GeV)

- Vector bosons (dark photon, B boson, X boson)
- Scalars
- Pseudoscalars (ALPs)

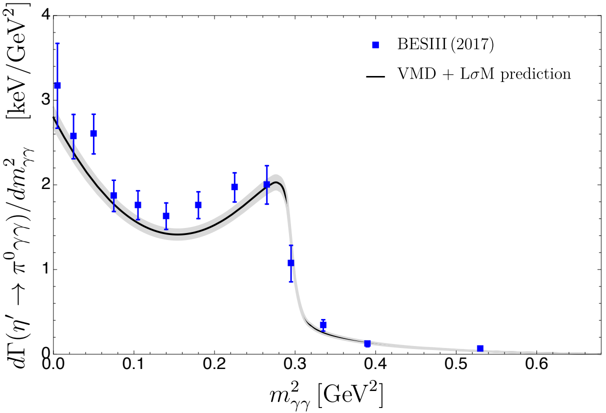
(Plus other channels that have not been searched for to date)

Channel	Expt. branching ratio	Discussion
$\eta \to 2\gamma$	39.41(20)%	chiral anomaly, η–η' mixing
$\eta \to 3\pi^0$	32.68(23)%	$m_u - m_d$
$\eta \to \pi^0\gamma\gamma$	$2.56(22) \times 10^{-4}$	χPT at $O(p^6)$, leptophobic B boson, light Higgs scalars
$\eta \to \pi^0\pi^0\gamma\gamma$	$< 1.2 \times 10^{-3}$	χPT, axion-like particles (ALPs)
$\eta \to 4\gamma$	$< 2.8 \times 10^{-4}$	$< 10^{-11}$ [52]
$\eta \to \pi^+\pi^-\pi^0$	22.92(28)%	$m_u - m_d$, C/CP violation, light Higgs scalars
$\eta \to \pi^+\pi^-\gamma$	4.22(8)%	chiral anomaly, theory input for singly-virtual TFF and $(g-2)_\mu$, P/CP violation
$\eta \to \pi^+\pi^-\gamma\gamma$	$< 2.1 \times 10^{-3}$	χPT, ALPs
$\eta \to e^+e^-\gamma$	$6.9(4) \times 10^{-3}$	theory input for $(g-2)_\mu$, dark photon, protophobic X boson
$\eta \to \mu^+\mu^-\gamma$	$3.1(4) \times 10^{-4}$	theory input for $(g-2)_\mu$, dark photon
$\eta \to e^+e^-$	$< 7 \times 10^{-7}$	theory input for $(g-2)_\mu$, BSM weak decays
$\eta \to \mu^+\mu^-$	$5.8(8) \times 10^{-6}$	theory input for $(g-2)_\mu$, BSM weak decays, P/CP violation
$\eta \to \pi^0\pi^0\ell^+\ell^-$		C/CP violation, ALPs
$\eta \to \pi^+\pi^-e^+e^-$	$2.68(11) \times 10^{-4}$	theory input for doubly-virtual TFF and $(g-2)_\mu$, P/CP violation, ALPs
$\eta \to \pi^+\pi^-\mu^+\mu^-$	$< 3.6 \times 10^{-4}$	theory input for doubly-virtual TFF and $(g-2)_\mu$, P/CP violation, ALPs
$\eta \to e^+e^-e^+e^-$	$2.40(22) \times 10^{-5}$	theory input for $(g-2)_\mu$
$\eta \to e^+e^-\mu^+\mu^-$	$< 1.6 \times 10^{-4}$	theory input for $(g-2)_\mu$
$\eta \to \mu^+\mu^-\mu^+\mu^-$	$< 3.6 \times 10^{-4}$	theory input for $(g-2)_\mu$
$\eta \to \pi^+\pi^-\pi^0\gamma$	$< 5 \times 10^{-4}$	direct emission only
$\eta \to \pi^\pm e^\mp \nu_e$	$< 1.7 \times 10^{-4}$	second-class current
$\eta \to \pi^+\pi^-$	$< 4.4 \times 10^{-6}$ [53]	P/CP violation
$\eta \to 2\pi^0$	$< 3.5 \times 10^{-4}$	P/CP violation
$\eta \to 4\pi^0$	$< 6.9 \times 10^{-7}$	P/CP violation

Gan, Kubis, Passemar, ST (2020)

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

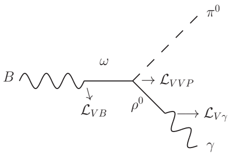


Leptophobic B boson model

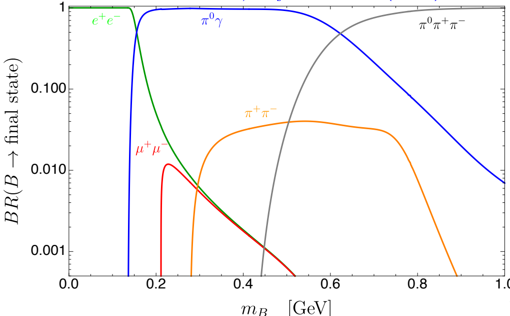
- **New** boson arising from a new $U(1)_B$ gauge symmetry

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

  — Couples (predominantly) to quarks, new gauge coupling $\alpha_B = g_B^2/4\pi$
  — 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

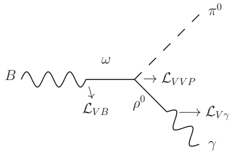


S. Tulin, Phys.Rev.D 89 (2014) 114008



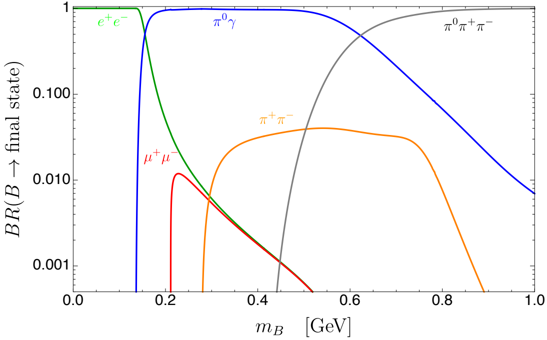
Calculation of hadronic processes

- 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

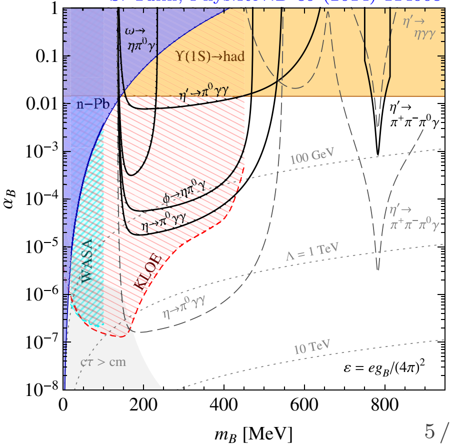


Previous limits on α_B and m_B

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

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

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

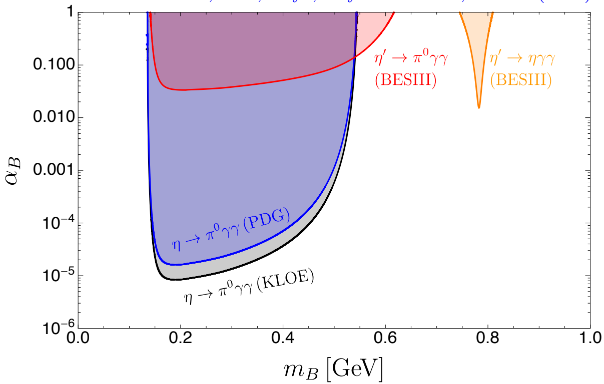
— $BR(\eta' \to \pi^0\gamma\gamma)_{\text{exp}} = 3.20(7)(23) \times 10^{-3}$

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

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

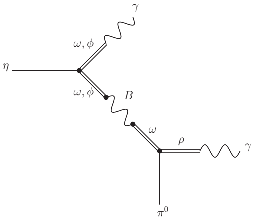
M. Ablikim *et.al* [BESIII], Phys.Rev. D 100 (2019) 052015

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



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

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



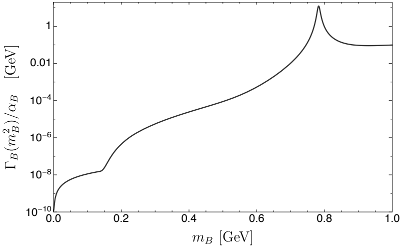
$$\mathcal{A}^{B\,\text{boson}}_{\eta\to\pi^0\gamma\gamma} = g_{B\eta\gamma}(t)g_{B\pi^0\gamma}(t)\left[\frac{(P\cdot q_2 - m_\eta^2)\{a\} - \{b\}}{m_B^2 - t - i\sqrt{t}\,\Gamma_B(t)} + \left\{\begin{array}{c} q_2 \leftrightarrow q_1 \\ t \leftrightarrow u \end{array}\right\}\right],$$

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

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

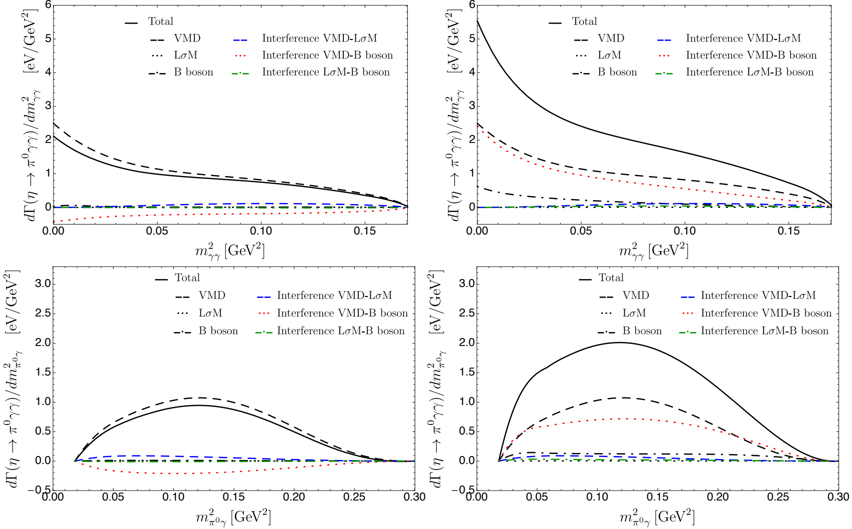
- Energy-dependent **width**

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



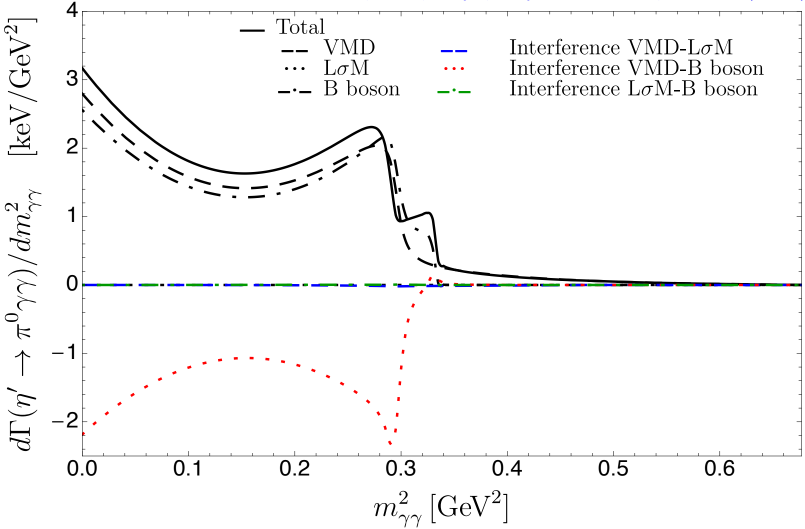
Individual contributions

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

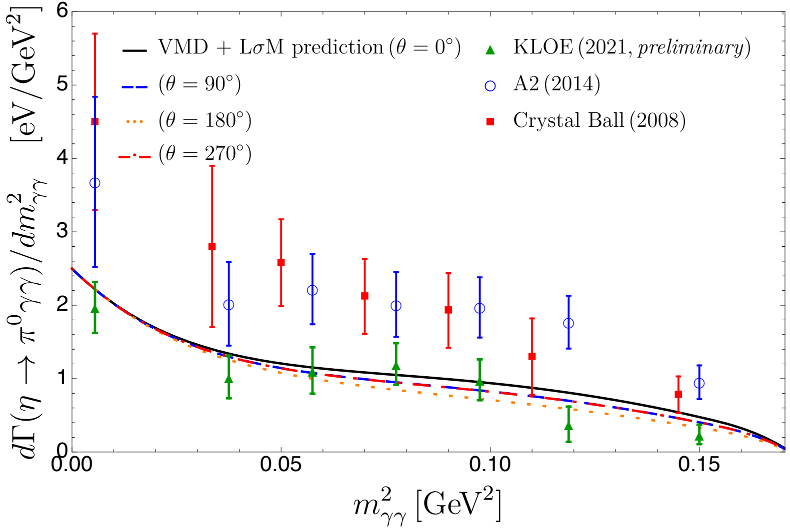


Individual contributions

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

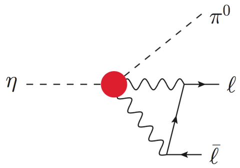


Interference phase between VMD and LσM



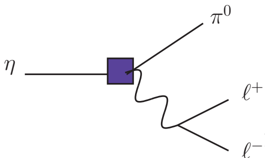
$\eta^{(\prime)} \to \{\pi^0, \eta\}\ell^+\ell^-$ decays $(\ell = e, \mu)$

- 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



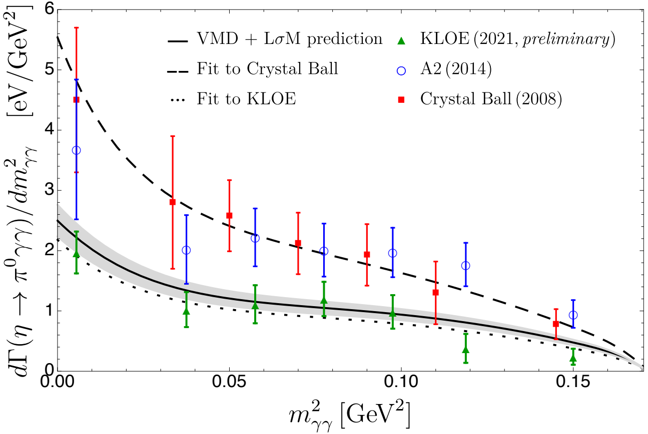
Decay channel	BR_{th} (Escribano&Royo 2007.12467)	BR_{exp} (pdg)
$\eta \to \pi^0 e^+e^-$	$2.1(1)(2) \times 10^{-9}$	$< 7.5 \times 10^{-6}$ (CL=90%)
$\eta \to \pi^0 \mu^+\mu^-$	$1.2(1)(1) \times 10^{-9}$	$< 5 \times 10^{-6}$ (CL=90%)
$\eta' \to \pi^0 e^+e^-$	$4.6(3)(7) \times 10^{-9}$	$< 1.4 \times 10^{-3}$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



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 $, \chi^2_{\text{dof}} = 0.4/5 = 0.1$
- KLOE: $\alpha_B = 0.049^{+40}_{-27}\,, m_B = 135^{+1}_{-135}$ MeV $, \chi^2_{\text{dof}} = 4.5/5 = 0.9$
- signatures outside $m_{\pi^0} \lesssim m_B \lesssim m_\eta$ may be visible



Conclusions

- Exploring **dark sectors** is an important and growing element of BSM physics
- A wealth of exciting ongoing **experiments** exist
- **Meson decays** offer a unique opportunity to look for New Physics
- Within the VMD and LσM frameworks **we have described**
  - $\eta \to \pi^0\gamma\gamma$: the situation is **not conclusive**

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

  - $\eta' \to \pi^0(\eta)\gamma\gamma$: **in line** with BESIII data
- **Constraints** on α_B, m_B have been strengthened by one order of magnitude from $\eta \to \pi^0\gamma\gamma$
- We have tested ALPs with $\eta/\eta' \to \pi\pi a$ decays
  - We encourage searches in $\eta/\eta' \to \pi\pi a \to \pi\pi\gamma\gamma, \pi\pi\ell^+\ell^-$ (BESIII, KLOE,CMS, REDTOP)

New limits on α_B and m_B

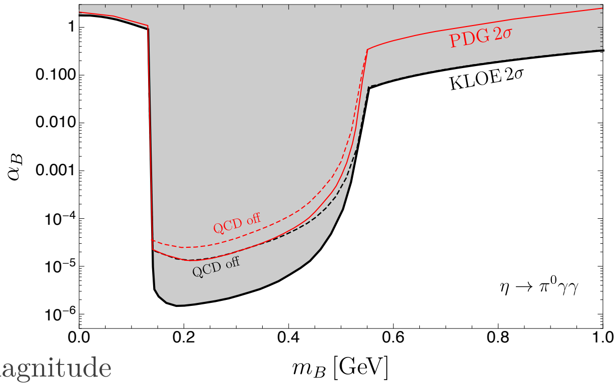
- **Not** assuming the **NWA**
- QCD contribution **on**
- $BR_{\text{VMD+Bboson}} < BR_{\text{exp}}$ at 2σ

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

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

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

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



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

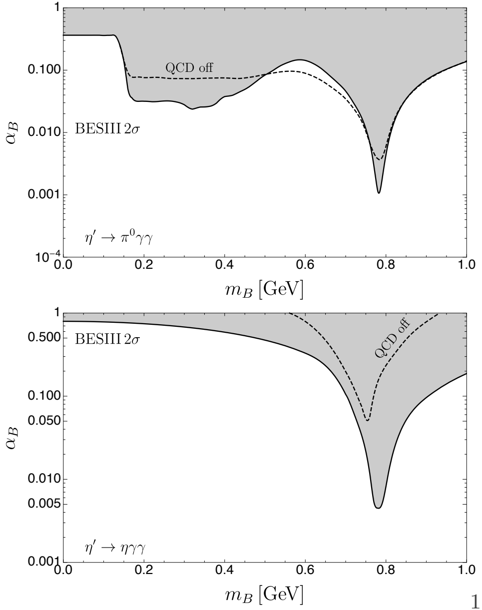
New limits on α_B and m_B

- **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 $\eta \to \pi^0\gamma\gamma$



Lagrangian for ALPs coupled to QCD

- "Derivative basis": ALPs with gluon and derivative couplings

$$\begin{aligned}\mathcal{L}_{\text{ALP}} &= \mathcal{L}_{\text{QCD}} + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{1}{2}M_a^2 a^2 \\ &\quad - \left(Q_G + \sum_{q=u,d,s} Q_q\right)\frac{\alpha_s}{8\pi}\frac{a}{f_a}G_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{\partial_\mu a}{f_a}\sum_{q=u,d,s}\frac{Q_q}{2}\bar{q}\gamma^\mu\gamma^5 q\,,\end{aligned}$$

M_a^2: PQ contribution to the mass, f_a: axion decay constant, $Q_{q,G}$: PQ charges

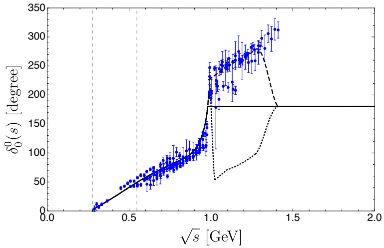
- "Yukawa basis" (this work, at GeV scale): ALP with gluon and mass couplings

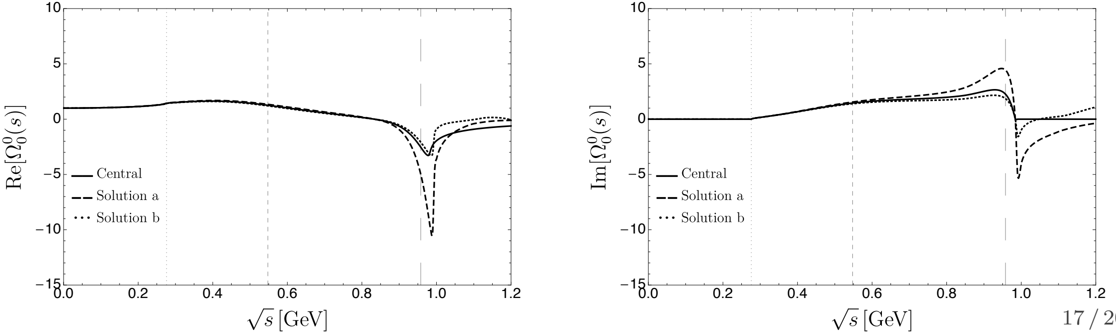
$$\mathcal{L}_{\text{ALP}} = \mathcal{L}_{\text{QCD}} + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{1}{2}M_a^2 a^2 - Q_G\frac{\alpha_s}{8\pi}\frac{a}{f_a}G_{\mu\nu}\tilde{G}^{\mu\nu} + \sum_{q=u,d,s} m_q\bar{q}\left(e^{iQ_q\frac{a}{f_a}\gamma_5}\right)q\,,$$

- Equivalent bases (related via chiral rotations of the quarks) if weak interactions are neglected
- The heavy-flavor c, b, t quarks contributions are absorbed in $Q_G \to Q_G + Q_{t,b,c}$

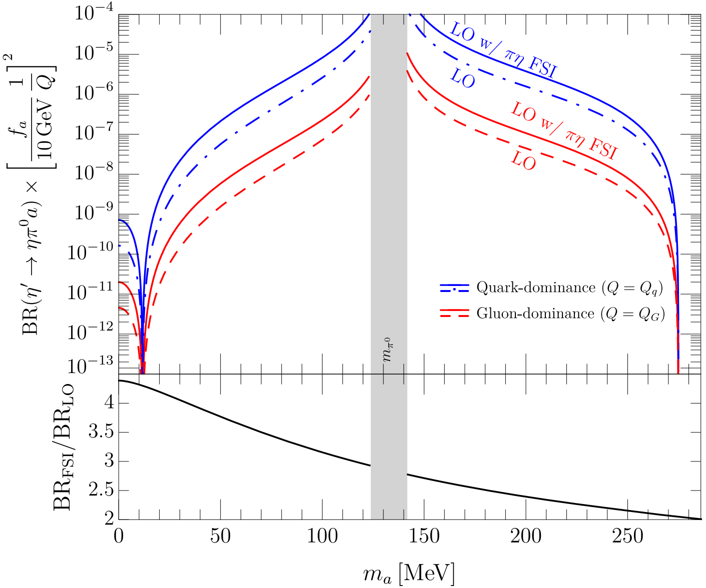
Solution of the Omnès function $\Omega_0^0(s)$

$$\Omega_0^0(s) = \exp\left\{ \frac{s}{\pi} \int_{4M_\pi^2}^{\infty} ds' \, \frac{\delta_0^0(s')}{s'(s'-s-i\varepsilon)} \right\},$$

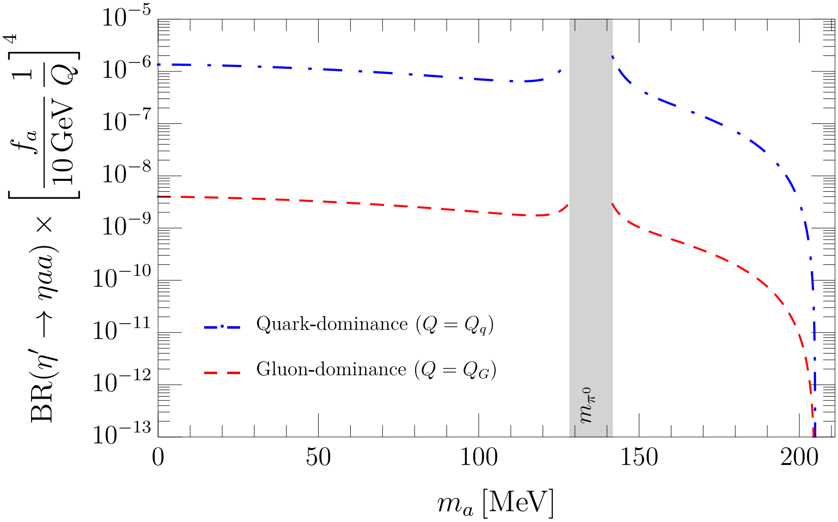




$\eta' \to \eta\pi^0 a$

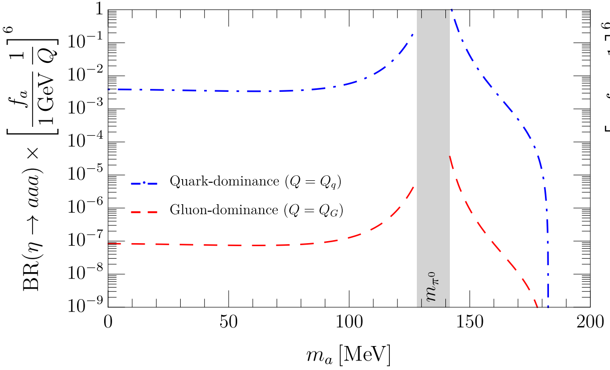


Multi production of ALPs



Triple production of ALPs in η/η' decays

- $\eta/\eta' \to aaa$ decays
- BR $\sim \mathcal{O}(1/f_a^6)$
- $f_a \sim \mathcal{O}(1)$ GeV to be sensitive probes of ALPs



D. Alves and S. Gonzàlez-Solís, to appear