

EMMI Workshop: Science at the luminosity frontier: Jefferson Lab at 22 GeV

December 9-13, 2024 • LNF, Frascati, Italy

TOPICS

- Charmed and light hadron spectroscopy
- Structure of hadrons
- QCD in Nuclei
- Opportunities for BSM opportunities

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ABSTRACT

This workshop will focus on the continuing development of the scientific case for a 22 GeV upgrade to CEBAF made possible by recent novel advances in accelerator technology, CEBAF's envisioned capabilities, at the highest luminosities, will enable exciting opportunities that give scientists the full suite of tools necessary to comprehensively understand how QCD builds hadronic matter in the valence region. Through this workshop, JLab and its user community will continue to build the science case with descriptions and concrete projections for experiments that would become possible with an upgrade. While the JLab 12 GeV program is running, it is already time to plan the future developments for the facility.

Probing light dark particles with η/η' decays

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Frascati, December 12, 2024



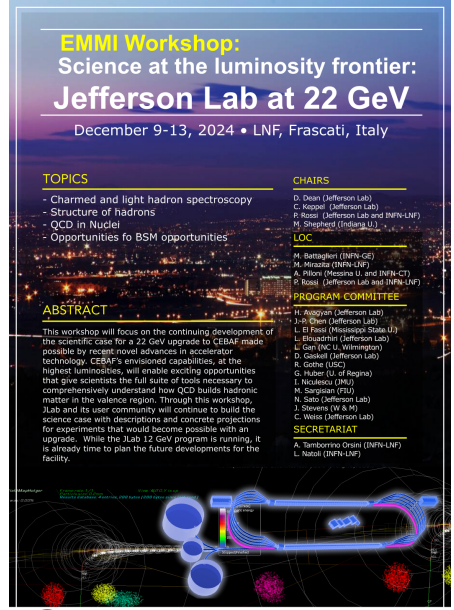
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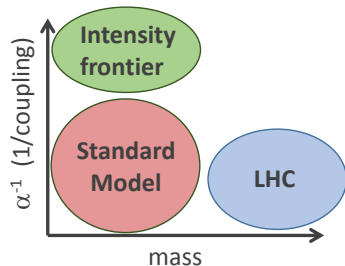
Program and abstract submission on:

<https://agenda.infn.it/event/39742/>



Energy and Intensity Frontier Research

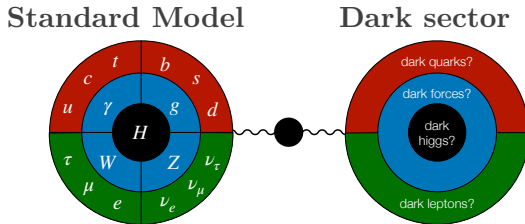
- **New Physics** would be needed to explain observed phenomena in particle physics, astrophysics and cosmology, *e.g.* dark matter, dark energy, neutrino masses, (anomalies in data: $(g-2)_\mu$, ^8Be excited decay, KOTO ($K_L \rightarrow \pi^0 \nu \bar{\nu}$))
- Why have **not** new particles yet been observed?
 - Hypothetical new particles are **heavy** and require even higher collision energy to be observed \Rightarrow **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** \Rightarrow **Intensity Frontier** research
- We don't know in which **direction** BSM physics might be



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

Vector

Scalar

Neutrino

Axion

Mediators

Dark photon

Dark scalar

Sterile Neutrino

Axion

Portal interactions

$$\epsilon B^{\mu\nu} A'_{\mu\nu}$$

$$\kappa |H|^2 |S|^2$$

$$y H L N$$

$$\frac{a}{f_a} \tilde{G}_{\mu\nu} G^{\mu\nu}$$

η/η' laboratory for dark sectors

- The η is a pNGB, $m_\eta \simeq 548$ 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 $\sim \mathcal{O}(\alpha_{\text{em}}^2)$ or $\mathcal{O}((m_u - m_d)^2)$
- Window to **BSM** physics through rare decays:

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

Large η/η' samples at future facilities

- Previous experiments:

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

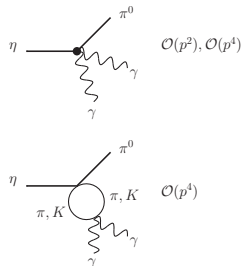
- Future experiments:

- 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
- Proposed: **REDTOP** (2203.07651 [hep-exp]): 10^{13} η and 10^{11} η' per year;
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]),

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

- SM motivation:

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



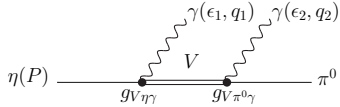
- 1st sizable contribution comes at $\mathcal{O}(p^6)$, but LEC's are not well known
- To test **ChPT** and a wide range of chiral models, *e. g.* VMD and $L\sigma M$



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

$\eta \rightarrow \pi^0 \gamma \gamma$: Vector meson exchange contributions

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



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

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

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

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

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

$$+ (\epsilon_2 \cdot q_1)(\epsilon_1 \cdot P)(P \cdot q_2)$$

$$- (\epsilon_1 \cdot \epsilon_2)(P \cdot q_1)(P \cdot q_2)$$

$$- (\epsilon_1 \cdot P)(\epsilon_2 \cdot P)(q_1 \cdot q_2)$$

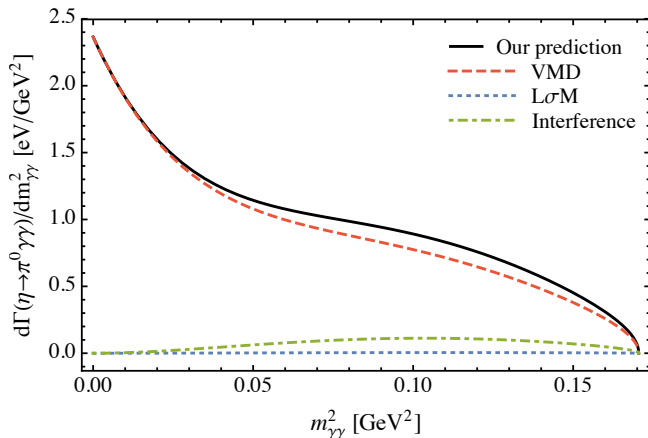
- The decays $\eta' \rightarrow \{\pi^0, \eta\} \gamma \gamma$ are formally identical: $g_{V\eta\gamma} g_{V\pi^0\gamma} \rightarrow g_{V\eta'\gamma} g_{V\{\pi^0, \eta\}\gamma}$

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

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

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

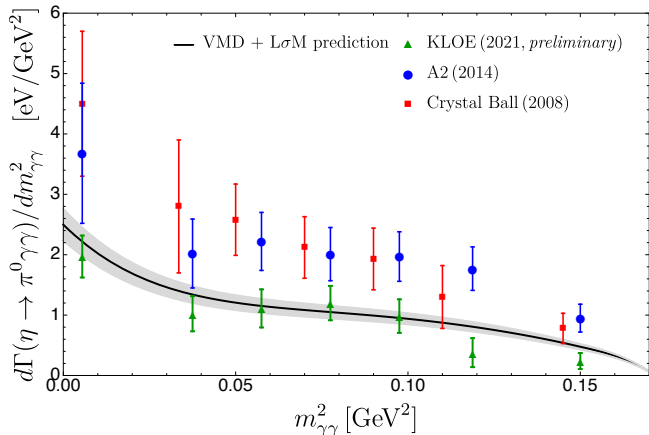
- VMD dominates:
- ρ : 27% of the signal
- ω : 21% of the signal
- ϕ : 0% of the signal
- interference between ρ - ω - ϕ : 52%
- interference between scalar and vector mesons: 7%



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

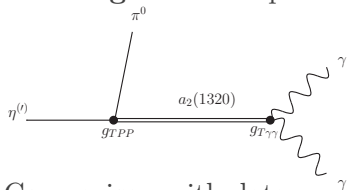
- Shape of the A2 (BR = $2.54(27) \times 10^{-4}$) and Crystal Ball (BR = $2.21(24)(47) \times 10^{-4}$) spectra is captured well (normalization offset)
- Good agreement with (preliminary) KLOE data (BR = $1.23(14) \times 10^{-4}$) [B. Cao, PoS EPS-HEP2021 (2022) 409]



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

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

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



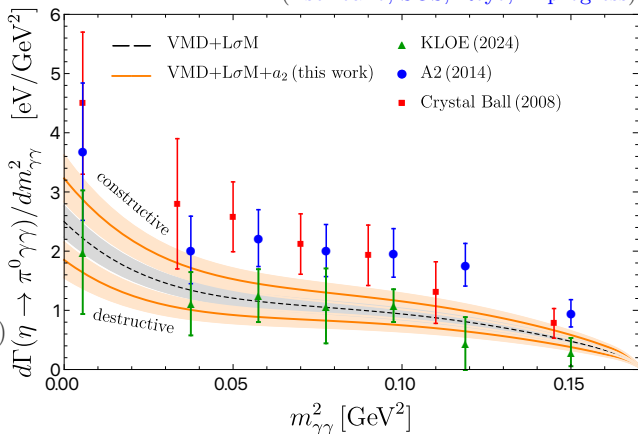
(Escribano, SGS, Royo, in progress)

- Comparison with data:

- **Destructive** vector-tensor interference: good agreement with (preliminary) KLOE-II data

(P. Gauzzi, PoS EPS-HEP2023 (2024) 246)

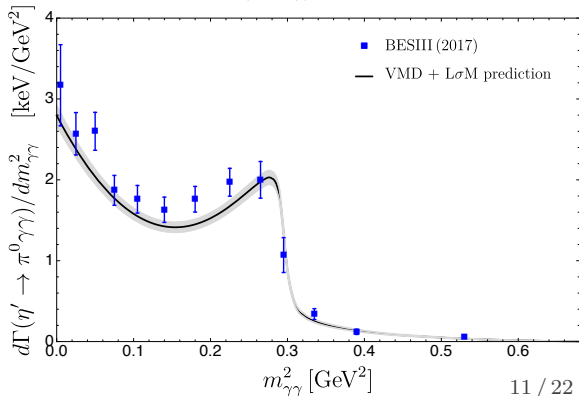
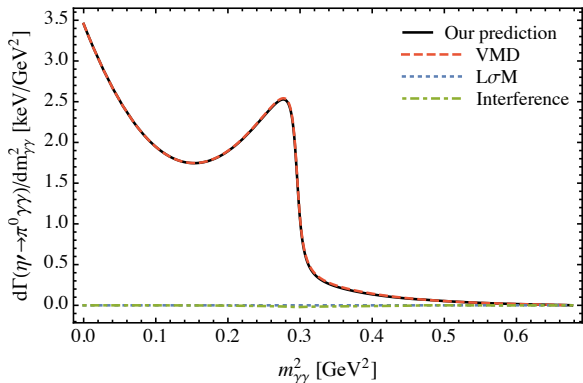
- **Constructive** vector-tensor interference: inconclusive



- VMD- a_2 interference $\sim 20\%$ of the signal (could be tested and distinguished from VMD with precise measurements at *e.g.* JEF)

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

- $\text{BR} = 2.91(21) \times 10^{-3}$ (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;
 $\text{BR} = 3.20(7)(23) \times 10^{-3}$ (Ablikim *et. al.* Phys.Rev.D 96, 012005 (2017))



Previous limits on α_B and m_B

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

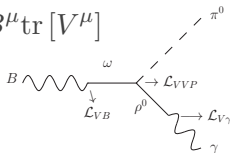
$$\mathcal{L}_{\text{int}} = \left(\frac{1}{3} g_B + \varepsilon Q_q e \right) \bar{q} \gamma^\mu q B_\mu - \varepsilon e \bar{l} \gamma^\mu l B_\mu,$$

- Conventional VMD picture:

$$\mathcal{L}_{V\gamma} \rightarrow \mathcal{L}_{VB} = -2 \frac{1}{3} g_B g f_\pi^2 B^\mu \text{tr} [V^\mu]$$

$$A^\mu \rightarrow B^\mu$$

$$e \rightarrow g_B$$



- Assuming **Narrow-Width Approximation**:

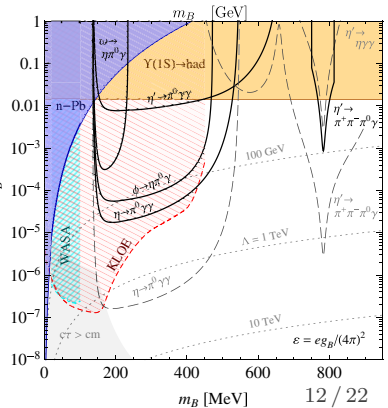
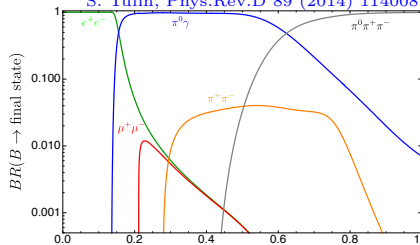
$$\text{BR}(\eta \rightarrow \pi^0 \gamma \gamma)_{\text{Bboson}} = \text{BR}(\eta \rightarrow B \gamma) \times \text{BR}(B \rightarrow \pi^0 \gamma)^{\alpha_B}$$

- Assuming **zero** SM contribution

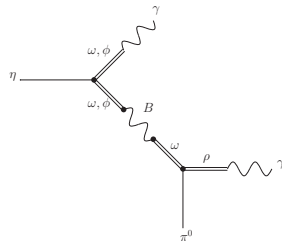
- $\text{BR}(\eta \rightarrow \pi^0 \gamma \gamma)_{\text{Bboson}} < \text{BR}_{\text{exp}}$ at 2σ

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

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



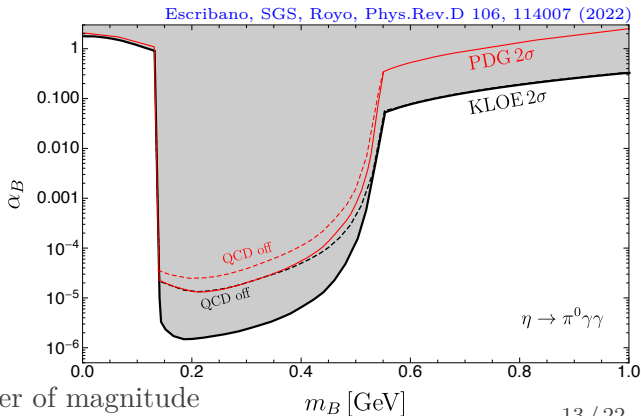
New limits on α_B, m_B (B -boson+SM)



- Two diagrams corresponding to the exchange of a B boson

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

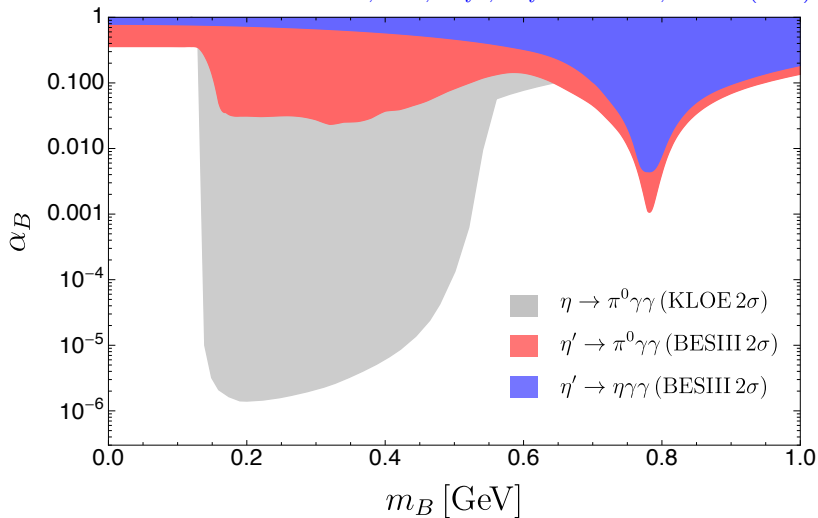
- Not assuming the NWA
- SM contribution on
- $\text{BR}_{\text{VMD+Bboson}} < \text{BR}_{\text{exp}}$ at 2σ
- $\text{BR}(\eta \rightarrow \pi^0 \gamma \gamma)_{\text{exp}}^{\text{pdg}} = 2.56(22) \times 10^{-4}$
- $\text{BR}(\eta \rightarrow \pi^0 \gamma \gamma)_{\text{exp}}^{\text{KLOE}} = 1.23(14) \times 10^{-4}$
- B. Cao [KLOE], PoS EPS-HEP2021 (2022) 409



- Limits strengthened by one order of magnitude

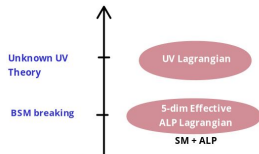
New limits on α_B and m_B

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



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



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

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 $Q_G \rightarrow Q_G + Q_{t,b,c}$

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

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

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

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

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

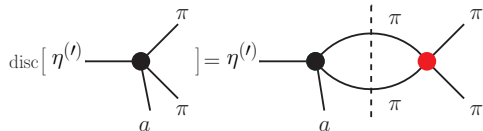
$$\mathcal{A}(\eta \rightarrow \pi^+ \pi^- a)|_{\text{LO}} = \frac{m_\pi^2}{f_\pi^2} (\cos\theta - \sqrt{2}\sin\theta) \left[\frac{f_\pi}{\sqrt{3}f_a} \frac{Q_u m_u + Q_d m_d}{m_u + m_d} - \frac{1}{3\sqrt{3}} \frac{m_d - m_u}{m_u + m_d} \theta_{\pi_3 a} + \frac{1}{3} \theta_{\eta_8 a} + \frac{\sqrt{2}}{3}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

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

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

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

- Unitarity:



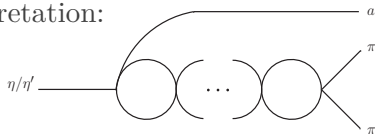
$$\text{disc}\mathcal{A}(s) = 2i\mathcal{A}(s)\sigma_{\pi}(s)T_0^{0*}(s) = 2i\mathcal{A}(s)\sin\delta_0^0(s)e^{-i\delta_0^0(s)},$$

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

- Analytic solution:

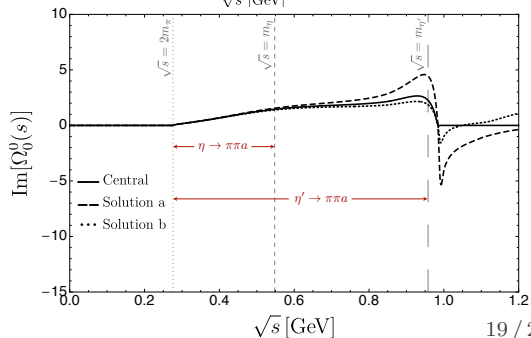
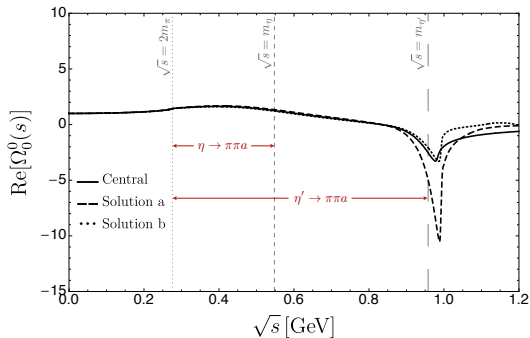
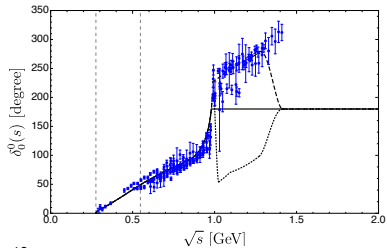
$$\mathcal{A}(s) = \mathcal{A}(\eta \rightarrow 2\pi a)|_{\text{LO}} \times \Omega_0^0(s), \quad \Omega_0^0(s) = \exp \left\{ \frac{s}{\pi} \int_{4M_{\pi}^2}^{\infty} ds' \frac{\delta_0^0(s')}{s'(s' - s - i\varepsilon)} \right\},$$

- Diagrammatic interpretation:



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

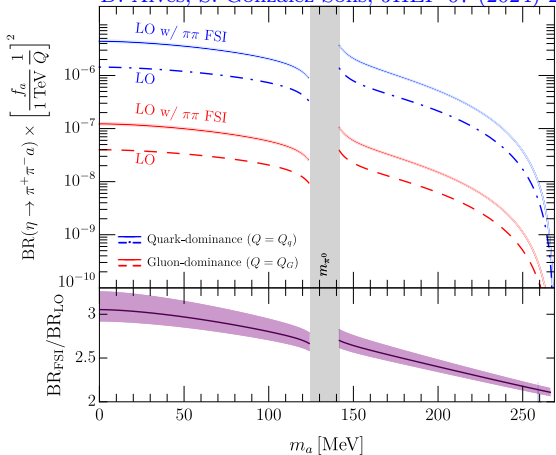
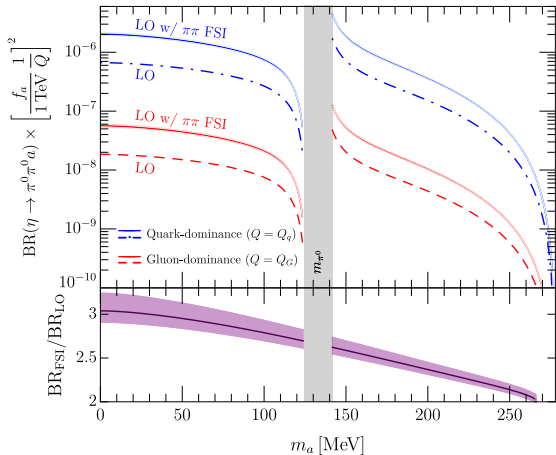
$$\Omega_0^0(s) = \exp \left\{ \frac{s}{\pi} \int_{4M_\pi^2}^{\infty} ds' \frac{\delta_0^0(s')}{s'(s' - s - i\epsilon)} \right\},$$



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

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

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

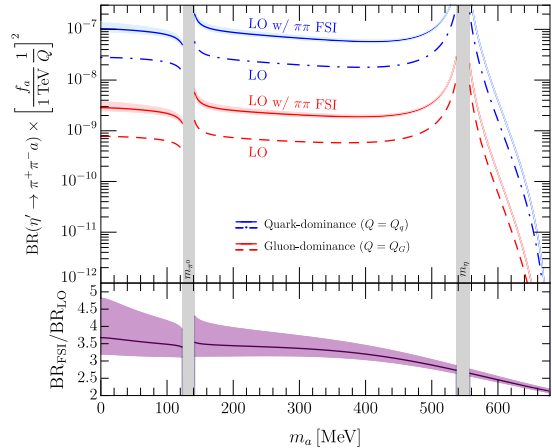
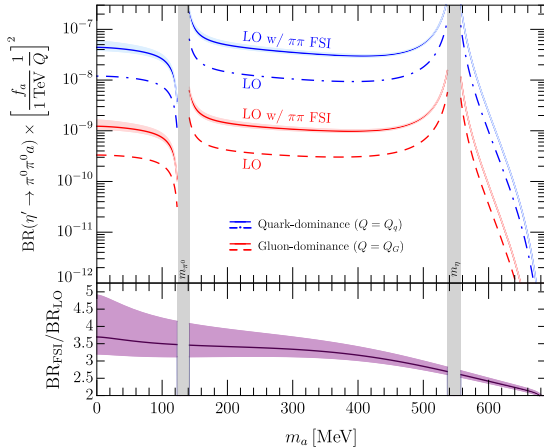


- Searches in $\eta \rightarrow \pi\pi a \rightarrow \pi\pi\gamma\gamma$ and $\eta \rightarrow \pi\pi a \rightarrow \pi\pi\ell^+\ell^-$ (BESIII, HADES, KLOE, CMS, JEF, REDTOP)

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

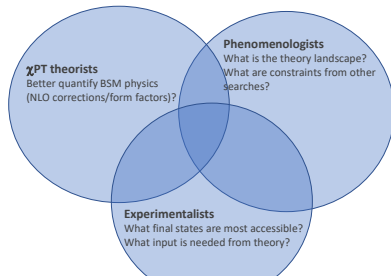
D. Alves, S. González-Solís, JHEP 07 (2024) 264



- Searches in $\eta' \rightarrow \pi\pi a \rightarrow \pi\pi\gamma\gamma$ and $\eta' \rightarrow \pi\pi a \rightarrow \pi\pi\ell^+\ell^-$ (BESIII [2402.01993], KLOE, CMS, JEF, REDTOP)

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

Gan, Kubis, Passemar, ST (2020)

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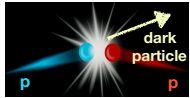
Gan, Kubis, Passemar, ST (2020)

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



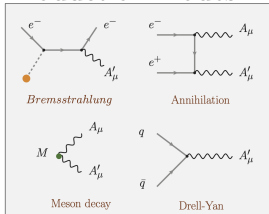
Unique access to dark sectors!

Other ongoing/future experiments

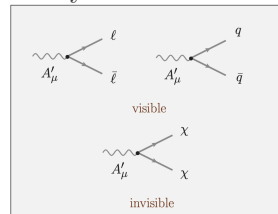


- Plenty of dark particles can be produced from **meson decays!!**

Production modes

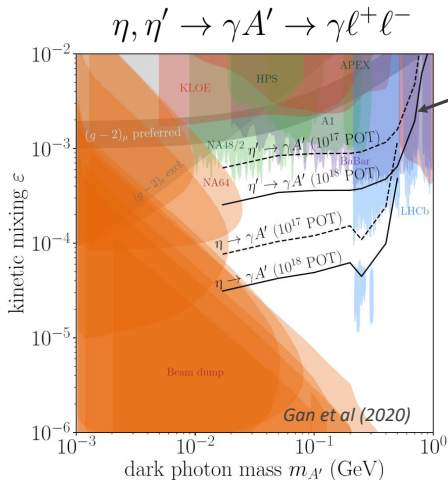


Decay modes



Dark photon searches

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



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

Gatto (2019)

Many other experiments targeting
same dark photon parameter space

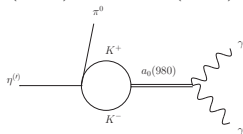
Worthwhile to also consider

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

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

$L\sigma M$ for the scalar resonance contributions

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



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

- Scalar amplitudes:

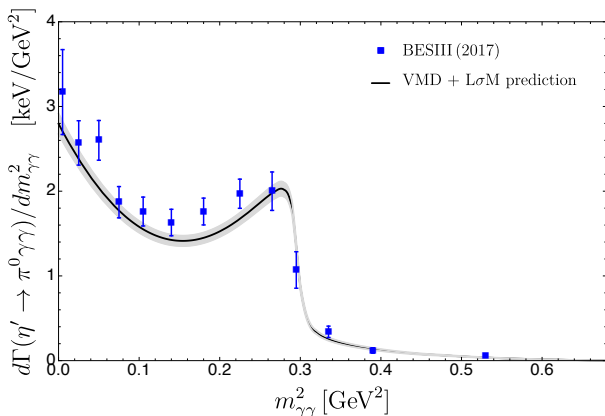
$$\mathcal{A}_{K^+ K^- \rightarrow \pi^0 \eta^{(\prime)}}^{\text{L}\sigma\text{M}} = \frac{1}{2f_\pi f_K} \left\{ (s - m_{\eta^{(\prime)}}^2) \frac{m_K^2 - m_{a_0}^2}{D_{a_0}(s)} \cos \varphi_P + \frac{1}{6} \left[(5m_{\eta^{(\prime)}}^2 + m_\pi^2 - 3s) \cos \varphi_P - \sqrt{2}(m_{\eta^{(\prime)}}^2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

- Complete one-loop propagator for the scalar resonances:

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

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

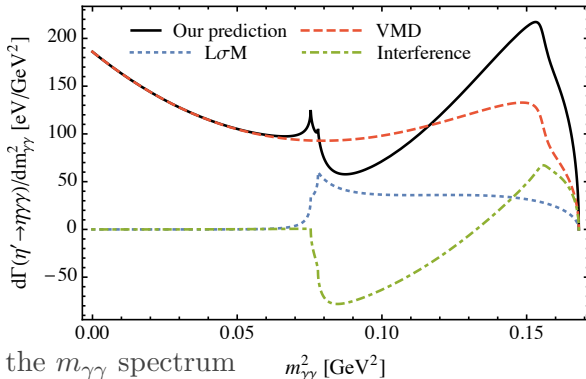
- Our theoretical prediction $BR = 2.91(21) \times 10^{-3}$ ([Phys.Rev.D 102, 034026 \(2020\)](#))
- First time $m_{\gamma\gamma}$ invariant mass distribution by BESIII;
 $BR = 3.20(7)(23) \times 10^{-3}$ ([Ablikim *et. al.* Phys.Rev.D 96, 012005 \(2017\)](#))



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

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

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



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

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	m_B [MeV]		Novel signatures
Decay \rightarrow	$B \rightarrow e^+e^-$	$B \rightarrow \pi^0\gamma$	$B \rightarrow \pi^+\pi^-\pi^0$	$B \rightarrow \eta\gamma$
Production \downarrow	$m_B \sim 1 - 140$ MeV	140 - 620 MeV	620 - 1000 MeV	
$\pi^0 \rightarrow B\gamma$	$\pi^0 \rightarrow e^+e^-\gamma$	-	-	-
$\eta \rightarrow B\gamma$	$\eta \rightarrow e^+e^-\gamma$	$\eta \rightarrow \pi^0\gamma\gamma$	-	-
$\eta' \rightarrow B\gamma$	$\eta' \rightarrow e^+e^-\gamma$	$\eta' \rightarrow \pi^0\gamma\gamma$	$\eta' \rightarrow \pi^+\pi^-\pi^0\gamma$	$\eta' \rightarrow \eta\gamma\gamma$
$\omega \rightarrow \eta B$	$\omega \rightarrow \eta e^+e^-$	$\omega \rightarrow \eta\pi^0\gamma$	-	-
$\phi \rightarrow \eta B$	$\phi \rightarrow \eta e^+e^-$	$\phi \rightarrow \eta\pi^0\gamma$	-	-

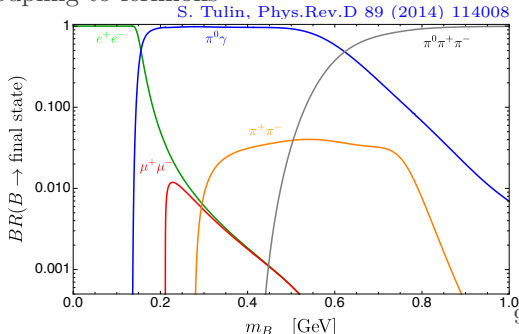
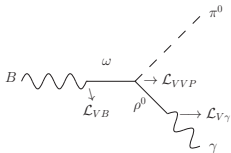
- Searches in meson factories are gaining attention
 - $\eta \rightarrow \gamma B \rightarrow \gamma\gamma\pi^0$ (JEF), $\phi \rightarrow \eta B \rightarrow \eta\pi^0\gamma$ (KLOE-II), $\eta \rightarrow B\gamma \rightarrow \pi^+\pi^-\gamma$ (Belle-II)

Leptophobic B boson model

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

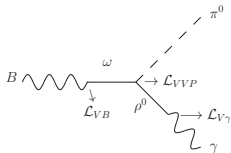
$$\mathcal{L}_{\text{int}} = \left(\frac{1}{3} g_B + \varepsilon Q_q e \right) \bar{q} \gamma^\mu q B_\mu - \varepsilon e \bar{l} \gamma^\mu l B_\mu,$$

- 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



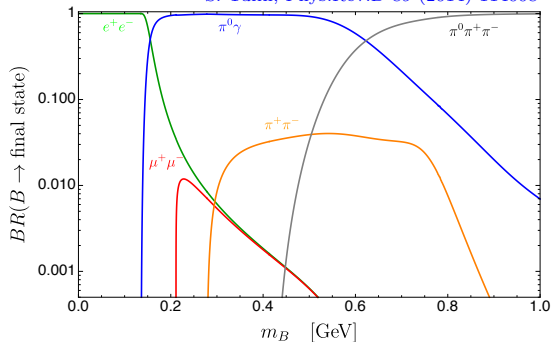
Calculation of hadronic processes

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



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

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



Present limits on α_B and m_B

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

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

- QCD contribution **off**

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

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

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

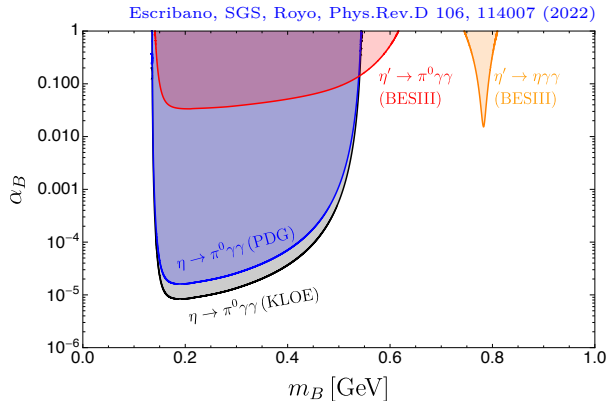
B. Cao [KLOE], PoS EPS-HEP2021 (2022) 409

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

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

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

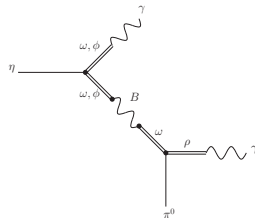
M. Ablikim *et.al* [BESIII], Phys.Rev. D 100 (2019) 052015



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

- Two diagrams corresponding to the exchange of a B boson

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

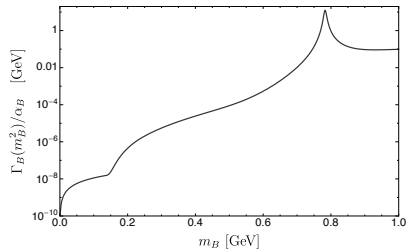


- $g_{BP\gamma}$ couplings:

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

- Energy-dependent width

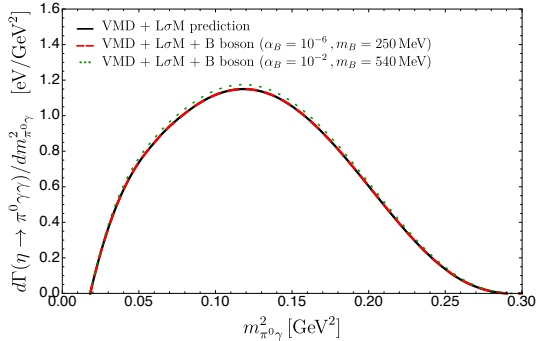
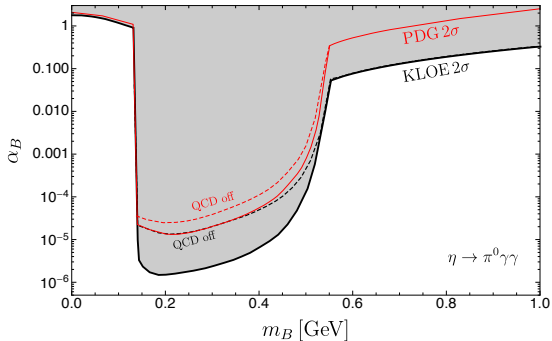
$$\begin{aligned} \Gamma_B(q^2) &= \frac{\gamma_{B \rightarrow \ell^+ \ell^-}(q^2)}{\gamma_{B \rightarrow \ell^+ \ell^-}(m_B^2)} \Gamma_{B \rightarrow \ell^+ \ell^-} \theta(q^2 - 4m_\ell^2) \\ &+ \frac{\gamma_{B \rightarrow \pi^0 \gamma}(q^2)}{\gamma_{B \rightarrow \pi^0 \gamma}(m_B^2)} \Gamma_{B \rightarrow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



$\pi^0\gamma$ mass distribution

- These constraints would make a B boson signature suppressed

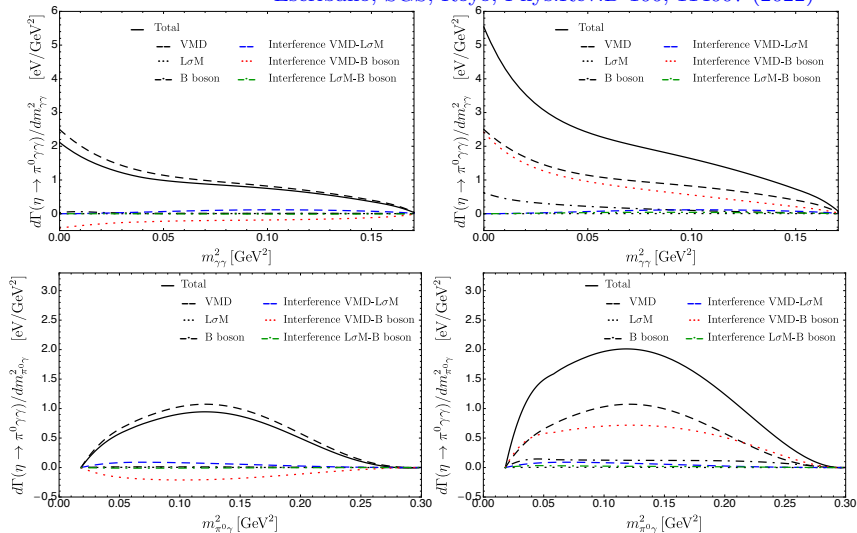
$$\Gamma(\eta \rightarrow \pi^0\gamma\gamma) \propto \int \frac{\alpha_B^2 dt}{|\mathcal{D}_B(t)|^2} \rightarrow \frac{\alpha_B^2 \pi}{m_B \Gamma_B(m_B^2)} .$$



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

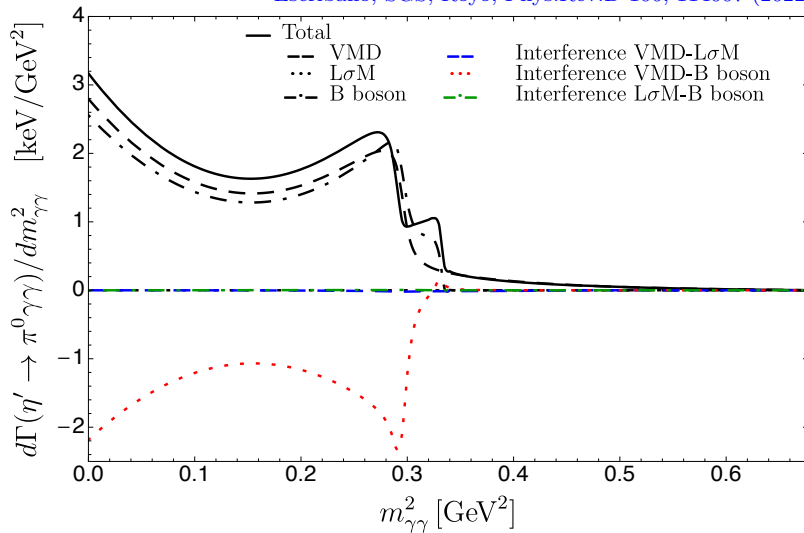
Individual contributions

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

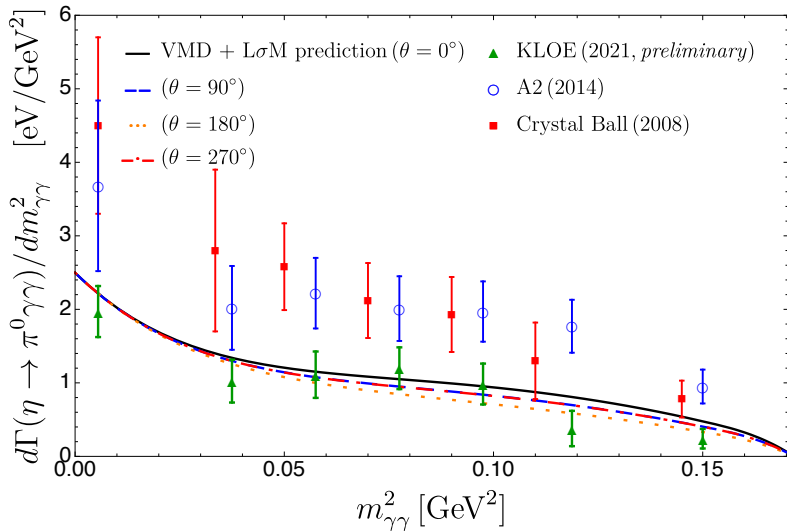


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Escribano, SGS, Royo, Phys.Rev.D 106, 114007 (2022)

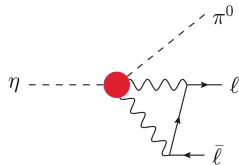


Interference phase between VMD and $L\sigma M$



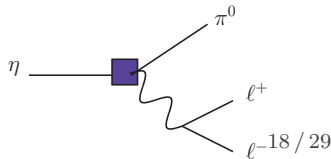
$\eta^{(\prime)} \rightarrow \{\pi^0, \eta\} \ell^+ \ell^-$ decays ($\ell = e, \mu$)

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



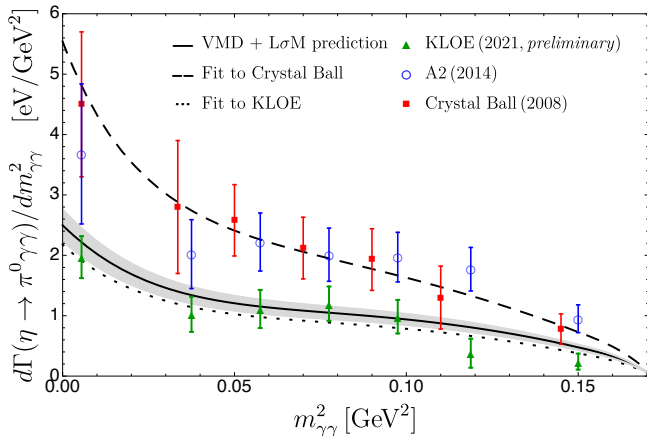
Decay channel	BR_{th} (Escribano&Royo 2007.12467)	BR_{exp} (pdg)
$\eta \rightarrow \pi^0 e^+ e^-$	$2.1(1)(2) \times 10^{-9}$	$< 7.5 \times 10^{-6}$ (CL=90%)
$\eta \rightarrow \pi^0 \mu^+ \mu^-$	$1.2(1)(1) \times 10^{-9}$	$< 5 \times 10^{-6}$ (CL=90%)
$\eta' \rightarrow \pi^0 e^+ e^-$	$4.6(3)(7) \times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

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



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

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



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 $L\sigma M$ frameworks **we have described**
 - $\eta \rightarrow \pi^0 \gamma \gamma$: the situation is **not conclusive**
 $BR = 1.35(8) \times 10^{-4} \left\{ \begin{array}{l} \sim 1/2 \text{ of } BR = 2.54(27) \times 10^{-4} \quad (\text{A2, 2014}) \\ \sim 1.6\sigma \text{ from } BR = 2.21(24)(47) \times 10^{-4} \quad (\text{CB, 2008}) \\ \text{agrees with } BR = 1.23(14) \times 10^{-4} \quad (\text{KLOE prel., 2022}) \end{array} \right.$
 - $\eta' \rightarrow \pi^0(\eta) \gamma \gamma$: **in line** with BESIII data
- **Constraints** on α_B, m_B have been strengthened by one order of magnitude from $\eta \rightarrow \pi^0 \gamma \gamma$
- We have tested ALPs with $\eta/\eta' \rightarrow \pi \pi a$ decays
 - We encourage searches in $\eta/\eta' \rightarrow \pi \pi a \rightarrow \pi \pi \gamma \gamma, \pi \pi \ell^+ \ell^-$ (BESIII, KLOE, CMS, REDTOP)

New limits on α_B and m_B

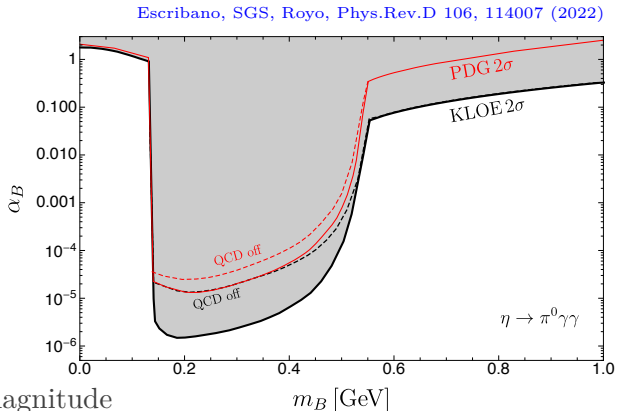
- **Not** assuming the NWA
- QCD contribution **on**
- $BR_{\text{VMD+Bboson}} < BR_{\text{exp}}$ at 2σ

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

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

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

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



New limits on α_B and m_B

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

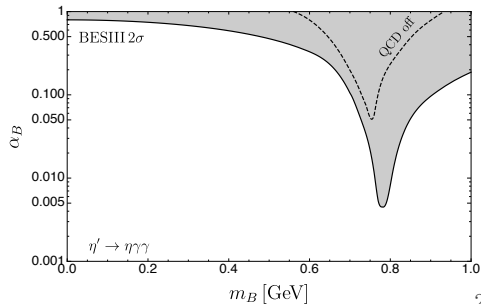
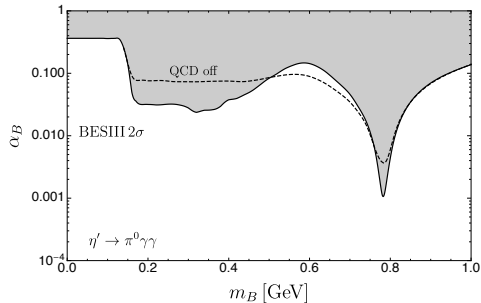
— $BR(\eta' \rightarrow \pi^0 \gamma \gamma)_{\text{exp}} = 3.20(7)(23) \times 10^{-3}$

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

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

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

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



Lagrangian for ALPs coupled to QCD

- “Derivative basis”: ALPs with gluon and derivative couplings

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

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

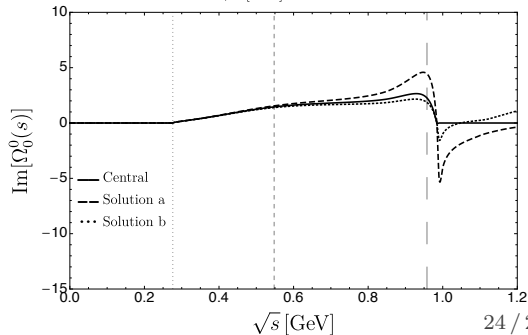
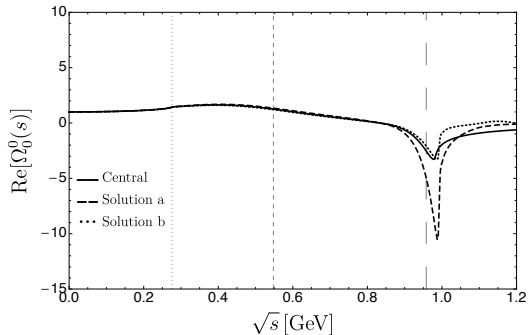
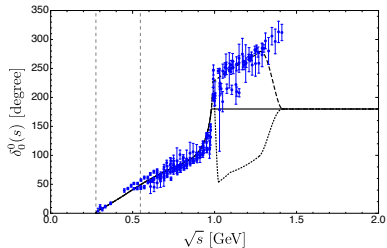
- “Yukawa basis” (this work, at GeV scale): ALP with gluon and mass couplings

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

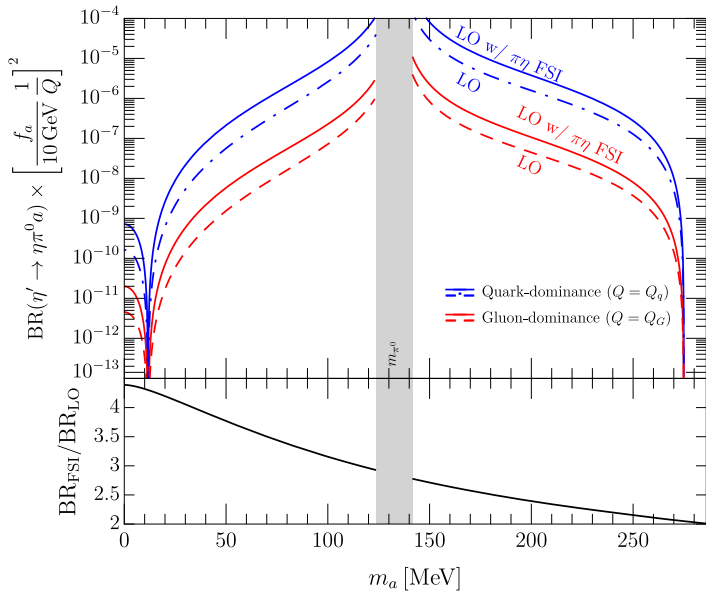
- Equivalent bases (related via chiral rotations of the quarks) if weak interactions are neglected
- The heavy-flavor c, b, t quarks contributions are absorbed in $Q_G \rightarrow Q_G + Q_{t,b,c}$

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

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

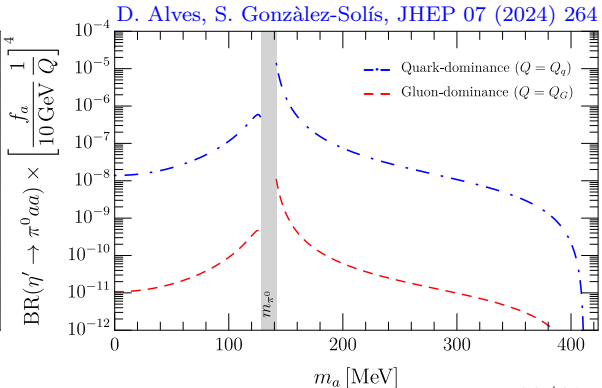
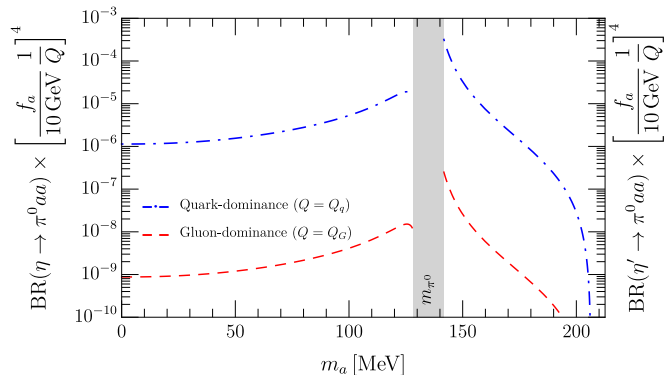


$$\eta' \rightarrow \eta\pi^0 a$$

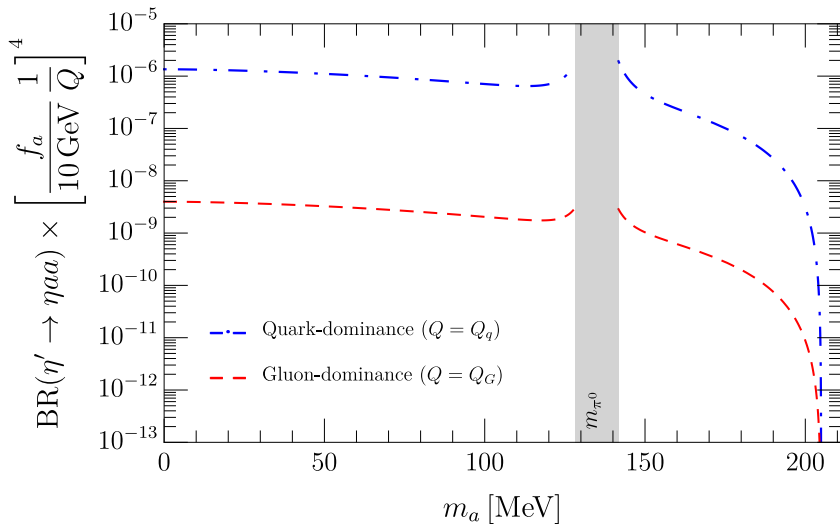


Double production of ALPs in η/η' decays

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

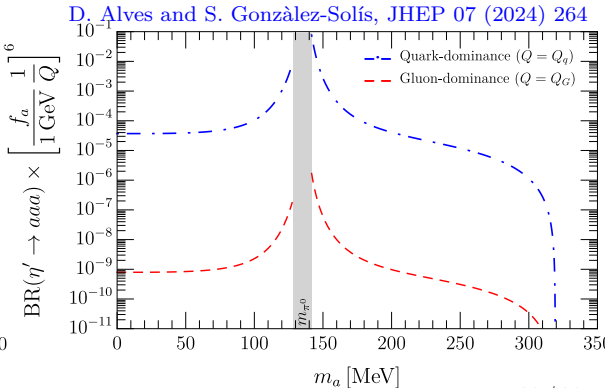
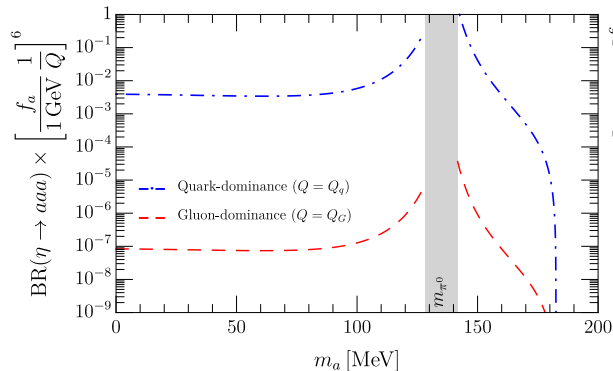


Multi production of ALPs



Triple production of ALPs in η/η' decays

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



Other meson decays

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