Probing low-energy QCD and BSM searches with light mesons

Sergi Gonzàlez-Solís (sergig@icc.ub.edu)

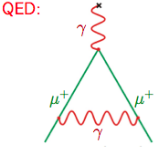
Barcelona, Feb 6, 2024

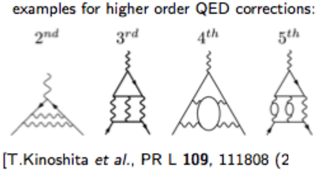
UNIVERSITAT DE BARCELONA

ICCUB | Institut de Ciències del Cosmos
UNIVERSITAT DE BARCELONA

The Standard Model

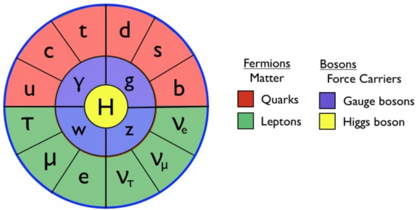
- Matter particles (quarks and leptons) in three families and mediator particles (bosons) of three interactions: electromagnetic, strong and weak
- Provides a consistent **description** of Nature's fundamental constituents and their interactions
- **Predictions** tested and confirmed by numerous experiments





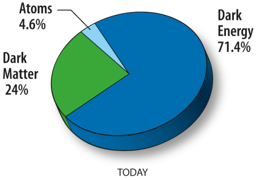
$$a_e(\text{exp}) = 1159652180.73(28) \cdot 10^{-12}$$
$$a_e^{\text{QED}}(\text{theory}) = 1159652181.78(77) \cdot 10^{-12}$$

- Experimental **completion** in 2012 (Higgs discovery)



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?

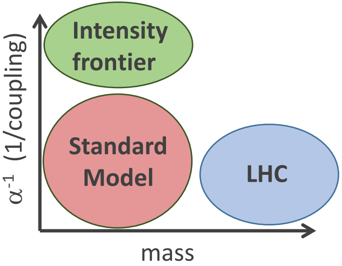
  — **Neutrino** masses and oscillations: why do neutrinos have mass? what makes neutrinos disappear and then re-appear in a different form?

  — **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

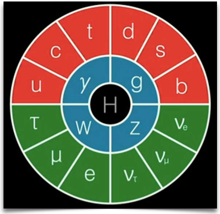


- We don't know in which **direction** BSM physics might be

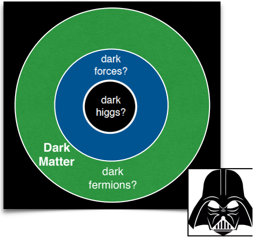
Dark sector physics

- **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

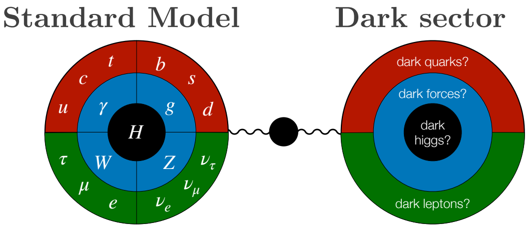


- We live in the SM world, how can we **access** (and test) the **dark sector**?

Dark sector portals to the Standard Model

We live in the Standard Model world, how can we access/test the **dark sector**?

$\Rightarrow$ **Portal** interactions with the SM, only a few are allowed by the SM symmetries



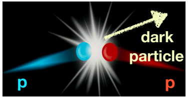
Portal	**Mediators**	**Portal interactions**
Vector	Dark photon	$\epsilon B^{\mu\nu} A'_{\mu\nu}$
Scalar	Dark scalar	$\kappa \lvert H \rvert^2 \lvert S \rvert^2$
Neutrino	Sterile Neutrino	$y H L N$
Axion	Axion	$\frac{a}{f_a} \tilde{G}_{\mu\nu} G^{\mu\nu}$

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

Belle II, BESIII, KLOE

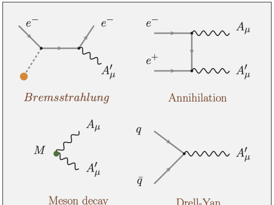
Unique access to dark sectors!

Other ongoing/future experiments

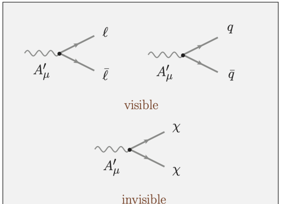
REDTOP, NA62, P326, GlueX, SeaQuest E906

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

Production modes

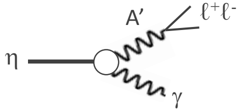


Decay modes



η/η' mesons

- The η and η' are **special**:
  - The η is a pNGB, with $m_\eta = 547.862$ MeV and $\Gamma_\eta = 1.31$ keV
  - The η': not a pNGB due to $U(1)_A$ anomaly, $m_\eta = 957.78(6)$ 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 $\sim \mathcal{O}(\alpha_{\mathrm{em}}^2)$ or $\mathcal{O}((m_u - m_d)^2)$
  - Window to **BSM** physics $\Rightarrow$ Dark sector physics:
    - **Decays** to new light dark particles are 2/-or 3-body decays that mimic 3-,4-, or 5-body final states (often very rare)



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

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)

Rich physics program at η,η′ factories

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Gan, Kubis, Passemar, ST (2020)

Large η/η' samples at future facilities

- Previous/current experiments:

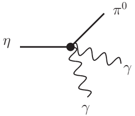
Experiment	Total η	Total η'
CB at AGS	10^7	-
CB MAMI-B	$2x10^7$	-
CB MAMI-C	$6x10^7$	10^6
WASA-COSY	~$3x10^7$ (p+d), ~$5x10^8$ (p+p)	-
KLOE-II	$3x10^8$	$5x10^5$
BESIII	~10^7	~$5x10^7$

- Future experiments:
  - JEF at JLab Hall D (approved): 6.5×10^7 η and 4.9×10^7 η' per 100 days
  - REDTOP (proposed, 2203.07651 [hep-exp]): 10^{13} η and 10^{11} η' per year
  - Super Tau-Charm Facility (China?), $e^+e^- \to J/\psi$, 3.4×10^{12} J/ψ/year

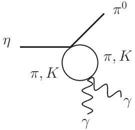
Decay mode	η/η' events (BESIII)	η/η' events (STCF)
$J/\psi \to \gamma\eta'$	5.2×10^7	1.8×10^{10}
$J/\psi \to \gamma\eta$	1.1×10^7	3.7×10^9
$J/\psi \to \phi\eta'$	2.5×10^6	2.5×10^9
$J/\psi \to \phi\eta$	4×10^6	1.6×10^9

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

- **SM motivation**:

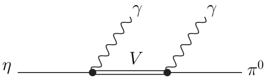


Reference	$\Gamma(\eta \to \pi^0\gamma\gamma)$ [eV]
$\mathcal{O}(p^2)$, $\mathcal{O}(p^4)$ tree-level χPT	0
$\pi + K$ loops at $\mathcal{O}(p^4)$	1.87×10^{-3}
Experimental value (pdg)	0.34(3)



— 1^{st} sizable contribution comes at $\mathcal{O}(p^6)$, but LEC's are not well known

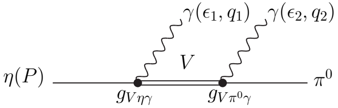
— To **test ChPT** and a wide range of chiral models, *e. g.* VMD and LσM



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

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

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



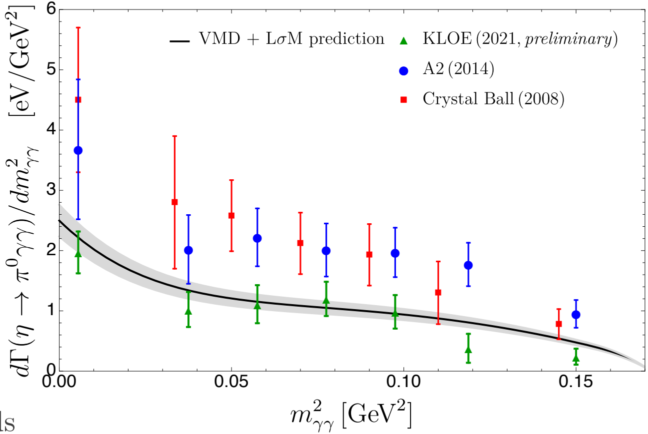
$$\mathcal{A}^{\text{VMD}}_{\eta\to\pi^0\gamma\gamma} = \sum_{V=\rho^0,\omega,\phi} g_{V\eta\gamma}g_{V\pi^0\gamma}\left[\frac{(P\cdot q_2 - m_\eta^2)\{a\} - \{b\}}{D_V(t)} + \left\{\begin{array}{c} q_2 \leftrightarrow q_1 \\ t \leftrightarrow u \end{array}\right\}\right],$$

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

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

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

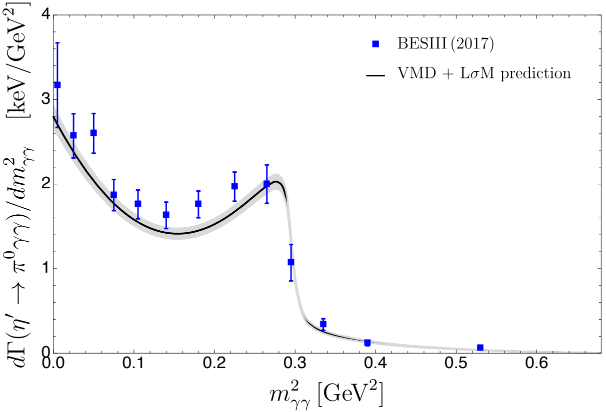
- Our theoretical prediction $BR = 1.35(8) \times 10^{-4}$
  (Escribano, SGS, Jora, Royo, Phys.Rev.D 102, 034026 (2020))
- $BR_{\text{exp}} = 2.55(22) \times 10^{-4}$ (pdg)
- Comparison with data
  - Shape of the A2 and Crystal Ball spectra is captured well (normalization offset)
  - Good agreement with (preliminary) KLOE data
    (B. Cao, PoS EPS-HEP2021 (2022) 409)



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

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

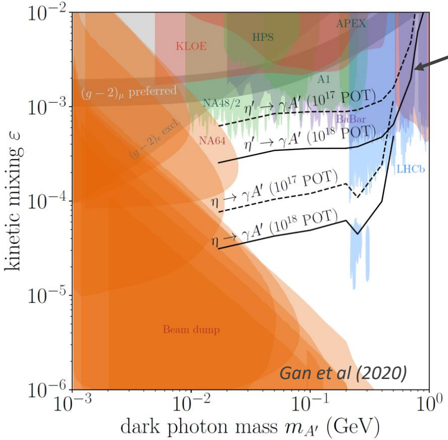
- Our theoretical prediction $BR = 2.91(21) \times 10^{-3}$ (Phys.Rev.D 102, 034026 (2020))
- First time $m_{\gamma\gamma}$ invariant mass distribution by BESIII; $BR = 3.20(7)(23) \times 10^{-3}$ (Ablikim *et. al.* Phys.Rev.D 96, 012005 (2017))



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

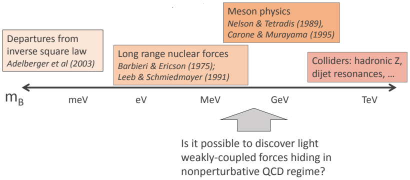
Searches of a leptophobic boson in rare $\eta^{(\prime)}$ decays

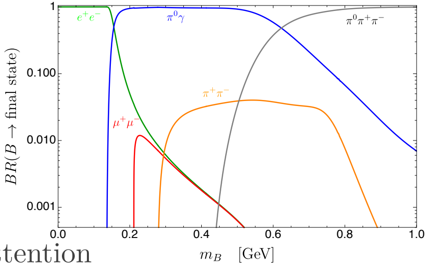
- What if a **new force** couples mainly to quarks?
- **Simplest model**: gauge boson (B) coupled to baryon number

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

  — g_B: flavor-universal coupling to all quarks, preserves QCD symmetries (C, P, T)

- Discovery signals depend on the mass m_B and decay channels S. Tulin, PRD 89 (2014) 114008





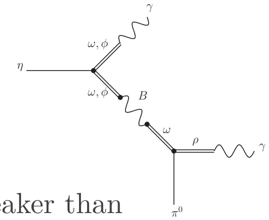
- Searches in meson factories are gaining attention

  — $\eta \to \gamma B \to \gamma\gamma\pi^0$ (JEF), $\phi \to \eta B \to \eta\pi^0\gamma$ (KLOE-II), $\eta \to B\gamma \to \pi^+\pi^-\gamma$ (Belle-II)

$\eta \to \pi^0\gamma\gamma$ decays: Limits on α_B and m_B

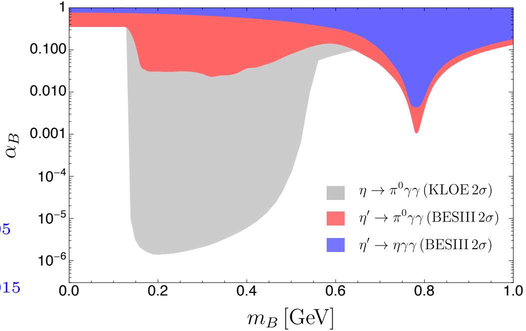
- Two diagrams corresponding to the exchange of a B **boson**

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



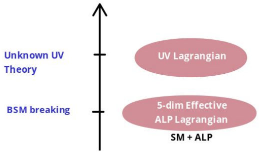
- η decays sensitive to forces hidden in QCD up to 10^5 times weaker than electromagnetism
- $BR_{\text{th}} < BR_{\text{exp}}$ at 2σ
  - $BR(\eta \to \pi^0\gamma\gamma)^{\text{pdg}}_{\text{exp}} = 2.56(22) \times 10^{-4}$
  - $BR(\eta \to \pi^0\gamma\gamma)^{\text{KLOE}}_{\text{exp}} = 1.23(14) \times 10^{-4}$
    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)



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: $m_a^2 \propto \frac{1}{f_a^2}$.
- Signatures: many complicated 4-and 5-body final states
  - $\eta/\eta' \rightarrow \pi\pi a \rightarrow \pi\pi\gamma\gamma, \pi\pi\ell^+\ell^-$ $(\ell = e, \mu)$
  - $\eta' \rightarrow \pi\pi a \rightarrow \pi\pi\pi^+\pi^-\gamma, 5\pi$
  - $\eta' \rightarrow \eta\pi^0 a \rightarrow \eta\pi^0\gamma\gamma, \eta\pi^0\ell^+\ell^-$
- Most of these have not been studied, can they be searched for?



- ALP-meson Lagrangian

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

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

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

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

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

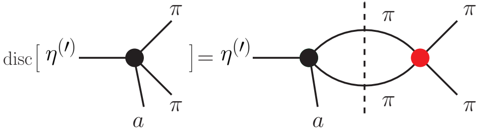
$$\mathcal{A}(\eta \to \pi^+\pi^- a)|_{\text{LO}} = \frac{m_\pi^2}{f_\pi^2}\left(\cos\theta - \sqrt{2}\sin\theta\right)\left[\frac{f_\pi}{\sqrt{3}f_a}\frac{Q_u m_u + Q_d m_d}{m_u + m_d} - \frac{1}{3\sqrt{3}}\frac{m_d - m_u}{m_u + m_d}\theta_{\pi_3 a} + \frac{1}{3}\theta_{\eta_8 a} + \frac{\sqrt{2}}{3}\theta_{\eta_0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

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

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

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

- Unitarity:



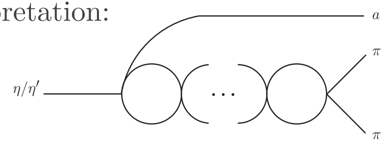
$$
\mathrm{disc}\mathcal{A}(s) = 2i\mathcal{A}(s)\sigma_\pi(s)T_0^{0*}(s) = 2i\mathcal{A}(s)\sin\delta_0^0(s)e^{-i\delta_0^0(s)}\,,
$$

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

- Analytic solution:

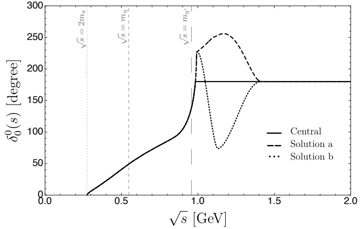
$$
\mathcal{A}(s) = \mathcal{A}(\eta\to 2\pi a)|_{\mathrm{LO}} \times \Omega_0^0(s)\,, \quad \Omega_0^0(s) = \exp\left\{\frac{s}{\pi}\int_{4M_\pi^2}^{\infty} ds'\,\frac{\delta_0^0(s')}{s'(s'-s-i\varepsilon)}\right\},
$$

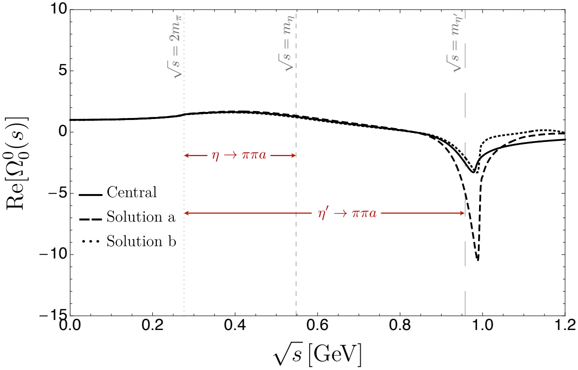
- Diagrammatic interpretation:

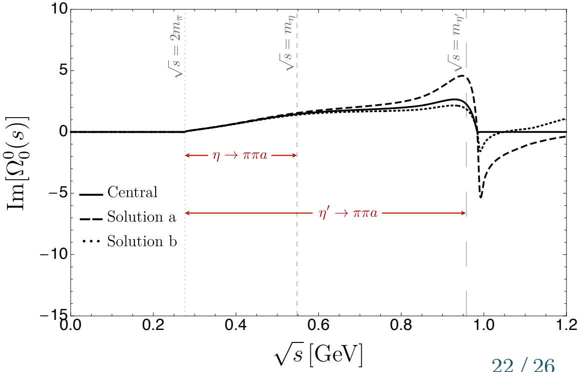


Solution of the Omnès function $\Omega_0^0(s)$

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



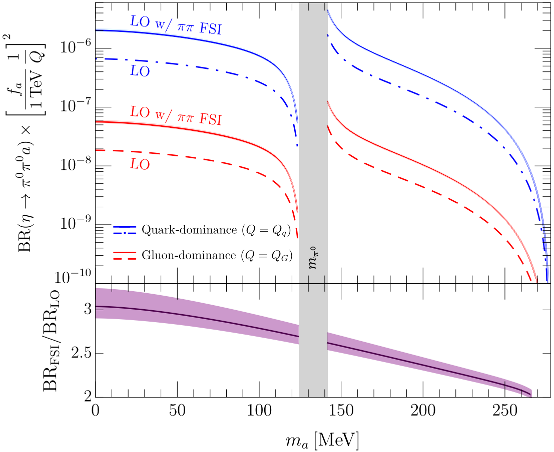


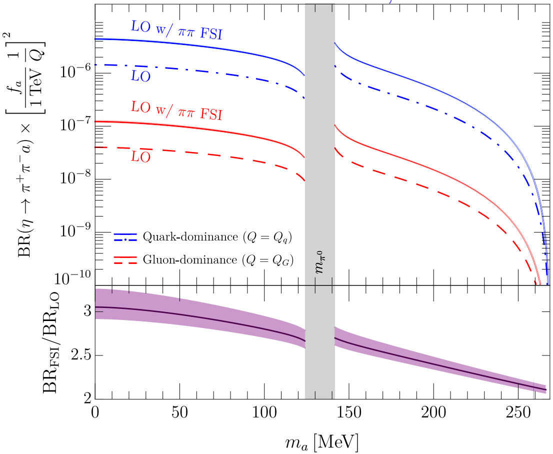


Branching ratio predictions for $\eta \to \pi\pi a$

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

D. Alves and S. Gonzàlez-Solís, 2402.02993 Today!



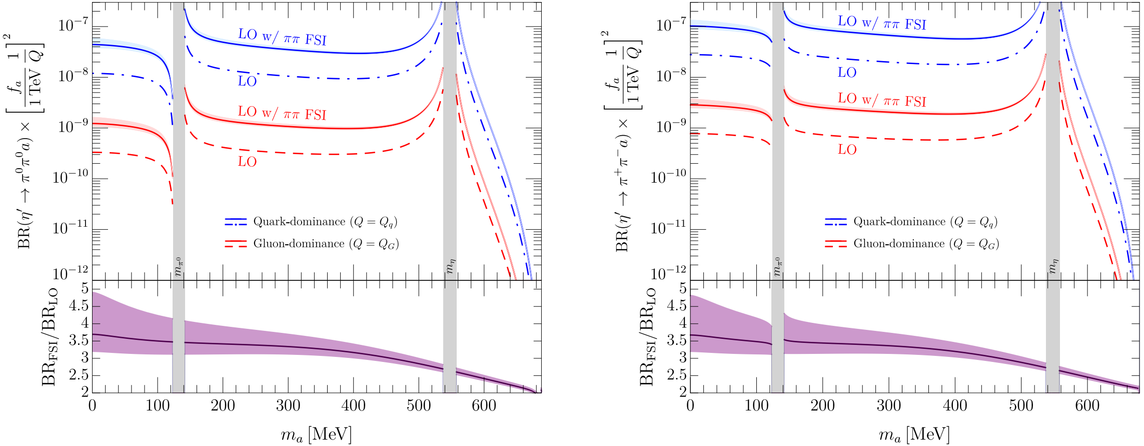


- We encourage searches in $\eta \to \pi\pi a \to \pi\pi\gamma\gamma$ and $\eta \to \pi\pi a \to \pi\pi\ell^+\ell^-$ (BESIII, KLOE, CMS, JEF, REDTOP)

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

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

D. Alves and S. Gonzàlez-Solís, 2402.02993 Today!

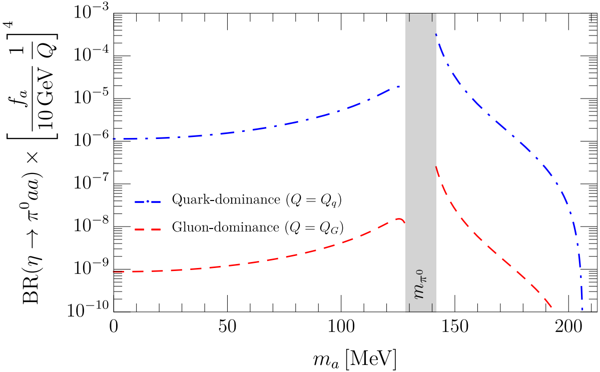


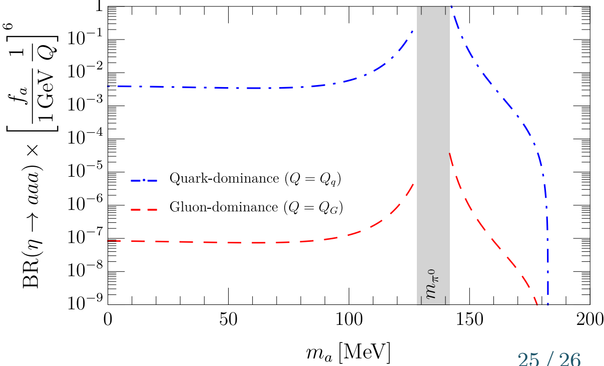
- We encourage searches in $\eta' \to \pi\pi a \to \pi\pi\gamma\gamma$ and $\eta' \to \pi\pi a \to \pi\pi\ell^+\ell^-$ (BESIII: 2402.01993 Today!, KLOE, CMS, JEF, REDTOP)

Multiple production of ALPs in η/η' decays

- $\eta/\eta' \to \pi^0 aa, aaa$ decays
- Extra power of $1/f_a$ suppression, BR $\sim \mathcal{O}(1/f_a^4), \mathcal{O}(1/f_a^6)$
- $f_a \sim \mathcal{O}(1-10)$ GeV to be sensitive probes of ALPs

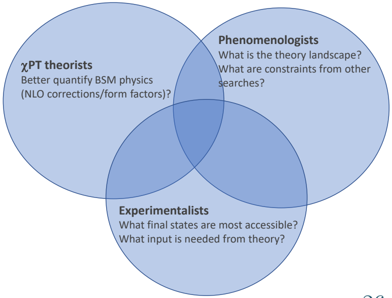
D. Alves and S. Gonzàlez-Solís, 2402.02993 Today!





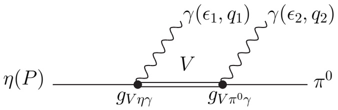
Conclusions

- 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**!



Vector meson exchange contributions

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



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

- Mandelstam variables and Lorentz structures given by:

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

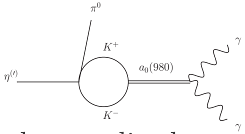
$$\{a\} = (\epsilon_1\cdot\epsilon_2)(q_1\cdot q_2) - (\epsilon_1\cdot q_2)(\epsilon_2\cdot q_1) \ ,$$

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

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

LσM for the scalar resonance contributions

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



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

- Scalar amplitudes:

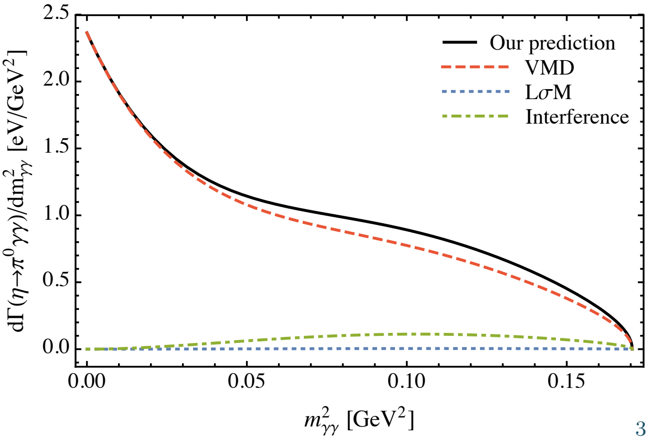
$$\mathcal{A}^{\mathrm{L}\sigma\mathrm{M}}_{K^+K^-\to\pi^0\eta^{(\prime)}} = \frac{1}{2f_\pi f_K}\left\{(s-m^2_{\eta^{(\prime)}})\frac{m^2_K-m^2_{a_0}}{D_{a_0}(s)}\cos\varphi_P+\frac{1}{6}\left[(5m^2_{\eta^{(\prime)}}+m^2_\pi-3s)\cos\varphi_P - \sqrt{2}(m^2_{\eta^{(\prime)}}+4m^2_K+m^2_\pi-3s)\sin\varphi_P\right]\right\}\,,$$

- Complete one-loop propagator for the scalar resonances:

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

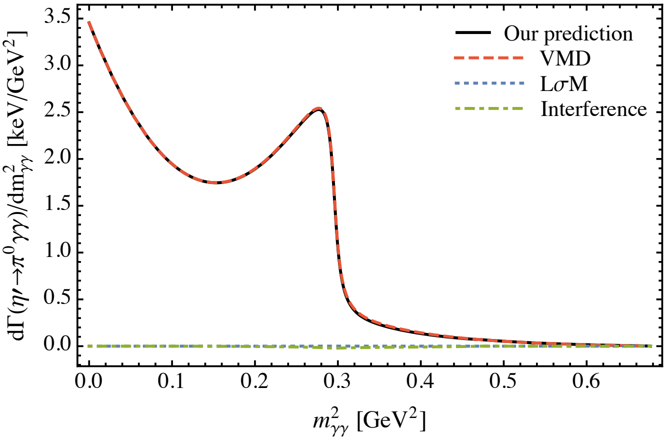
$\eta \to \pi^0\gamma\gamma$ predictions

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



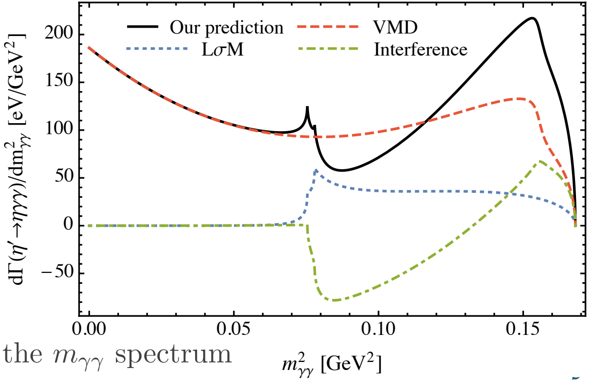
$\eta' \to \pi^0\gamma\gamma$ predictions

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



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

Selected η/η' decays

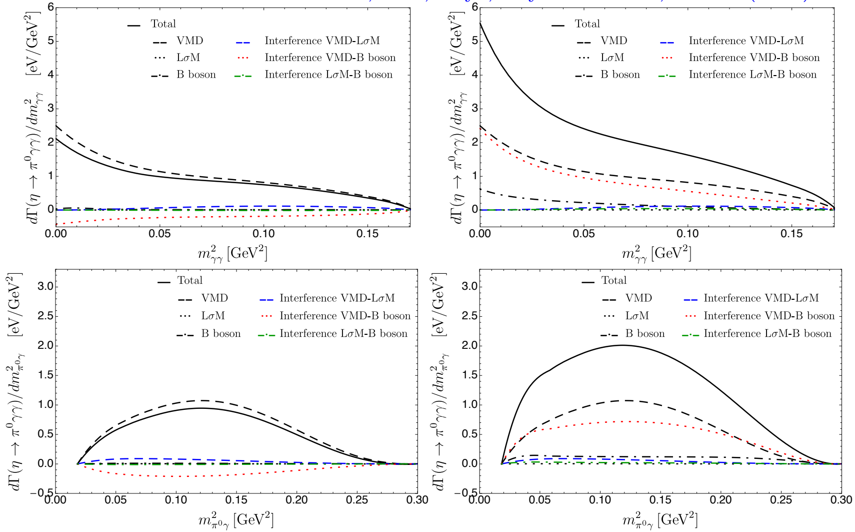
BSM particle	Decay mode	Signal channel	Search strategy
Dark photon (A')	$\eta/\eta' \to \gamma^{(*)} A'$	$A' \to \ell^+\ell^-$	Bump-hunt in $d\Gamma/dm_{\ell\ell}$
		$A' \to \pi^+\pi^-$	Bump-hunt in $d\Gamma/dm_{\pi\pi}$
Leptophobic boson (B)	$\eta \to \gamma B$	$B \to \gamma\pi^0$	Enhancement in $m_{\pi^0\gamma}$
		$B \to \pi^+\pi^-$	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 $d\Gamma/dm_{\gamma\gamma}$

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 $m_{\pi^0\gamma}$

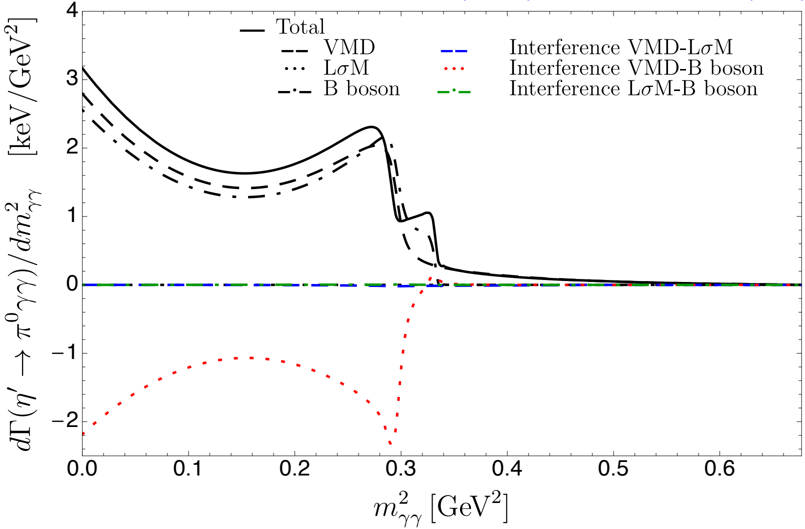
Individual contributions

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

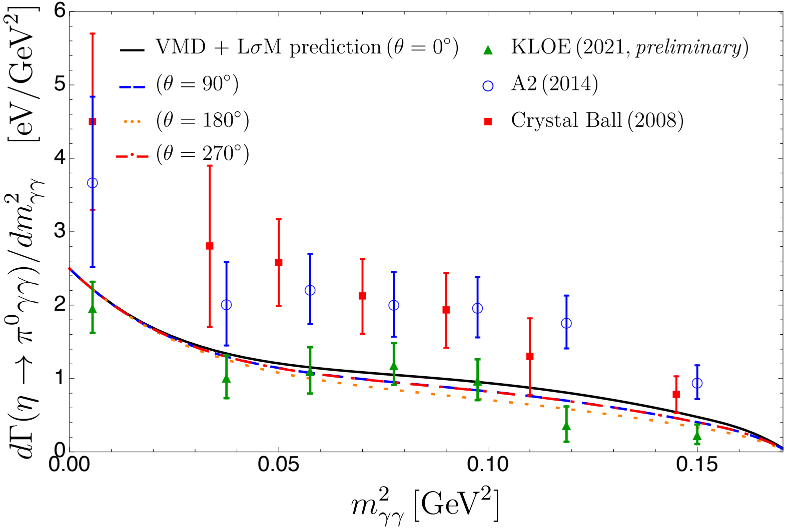


Individual contributions

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

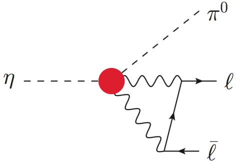


Interference phase between VMD and LσM



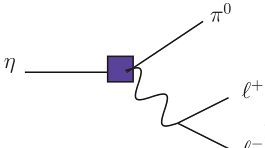
$\eta^{(\prime)} \to \{\pi^0, \eta\}\ell^+\ell^-$ decays $(\ell = e, \mu)$

- 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



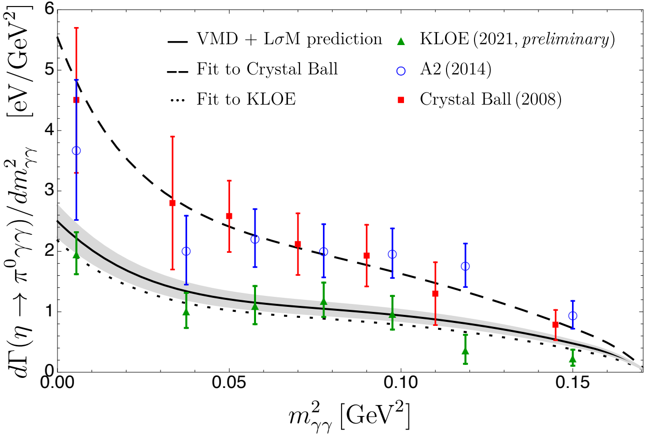
Decay channel	BR_{th} (Escribano&Royo 2007.12467)	BR_{exp} (pdg)
$\eta \to \pi^0 e^+e^-$	$2.1(1)(2) \times 10^{-9}$	$< 7.5 \times 10^{-6}$ (CL=90%)
$\eta \to \pi^0 \mu^+\mu^-$	$1.2(1)(1) \times 10^{-9}$	$< 5 \times 10^{-6}$ (CL=90%)
$\eta' \to \pi^0 e^+e^-$	$4.6(3)(7) \times 10^{-9}$	$< 1.4 \times 10^{-3}$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

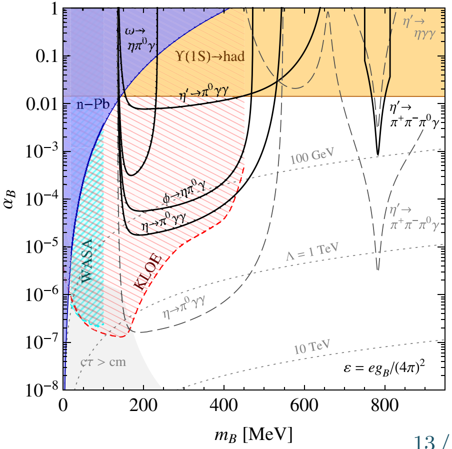


Previous limits on α_B and m_B

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

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

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

— $BR(\eta' \to \eta\gamma\gamma)_{\text{exp}}$ 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

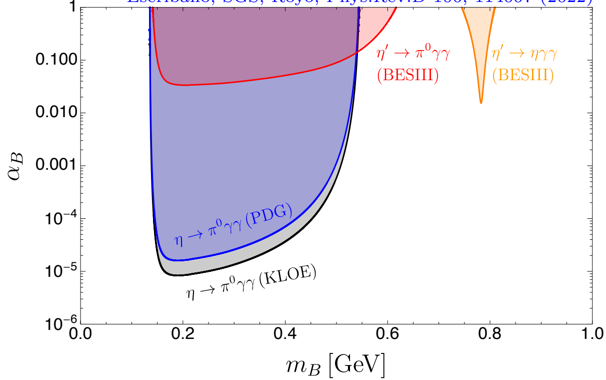
— $BR(\eta' \to \pi^0\gamma\gamma)_{\text{exp}} = 3.20(7)(23) \times 10^{-3}$

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)



New limits on α_B and m_B

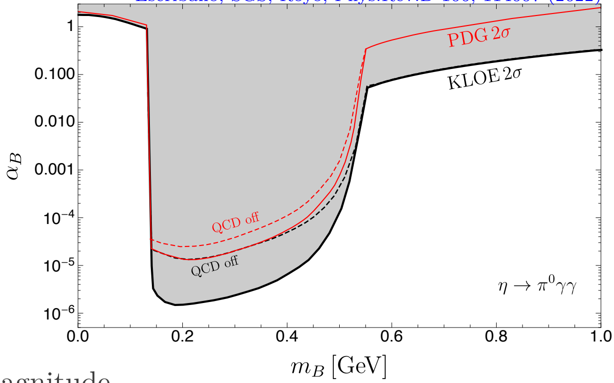
- **Not** assuming the **NWA**
- QCD contribution **on**
- $BR_{\text{VMD+Bboson}} < BR_{\text{exp}}$ at 2σ

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

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

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

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



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

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)

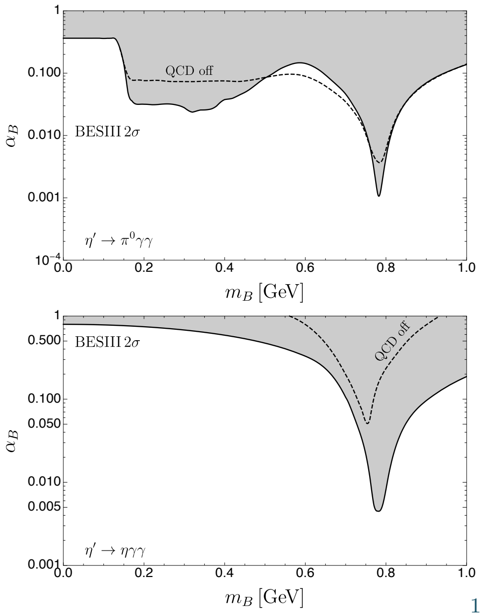
New limits on α_B and m_B

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

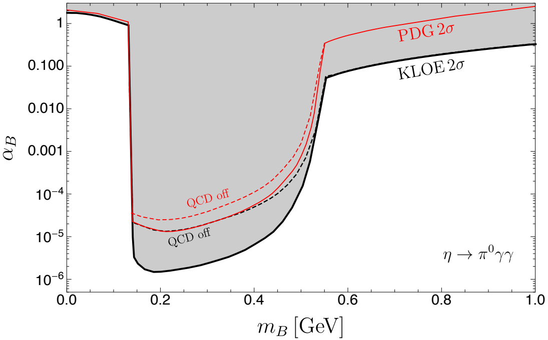
- Sharp dip when $m_B \sim m_\omega$
- Bounds 4 orders of magnitude weaker than $\eta \to \pi^0\gamma\gamma$

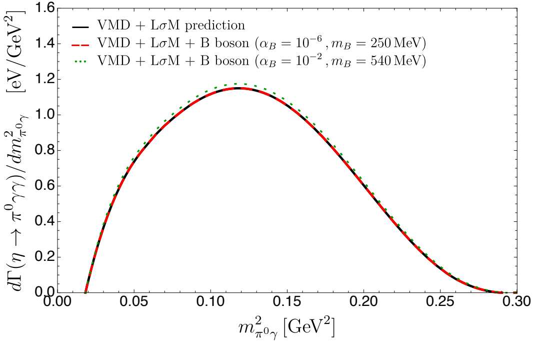


$\pi^0\gamma$ mass distribution

- 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?)

Leptophobic B boson model

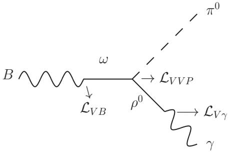
- **New** boson arising from a new $U(1)_B$ gauge symmetry

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

  — Couples (predominantly) to quarks
  — g_B new gauge (universal?) coupling, $\alpha_B = g_B^2/4\pi$
  — Preserves QCD symmetries (C, P, T)
  — B is a singlet under isospin:
  $I^G(J^{PC}) = 0^-(1^{--}) \Rightarrow B$ is ω **meson** like
  — $\varepsilon = eg_B/(4\pi)^2$: (subleading) γ-like coupling to fermions
- Searches depend on the mass m_B and decay channels
- Searches on meson decays are gaining attention
  — $\phi \to \eta B \to \eta\pi^0\gamma$ (KLOE-II), $\eta \to \pi^0\gamma\gamma$ (JEF), $\eta \to \pi^+\pi^-\gamma$ (Belle-II)

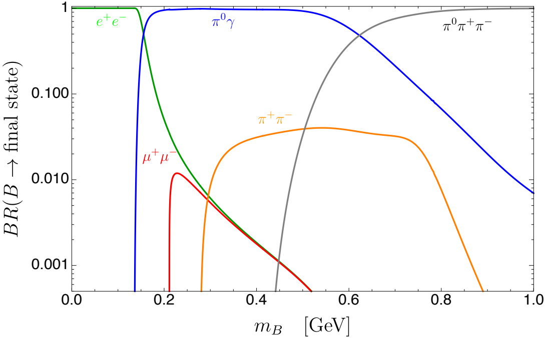
Calculation of hadronic processes

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



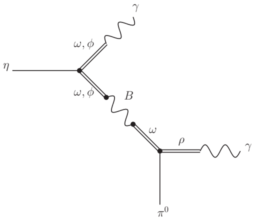
$$\Gamma_{B\to\pi^0\gamma} = \frac{\alpha_B \alpha_{em} m_B^3}{96\pi^3 f_\pi^2}\left(1 - \frac{m_\pi^2}{m_B^2}\right)^3 |F_\omega(m_B^2)|^2 ,$$

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



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

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



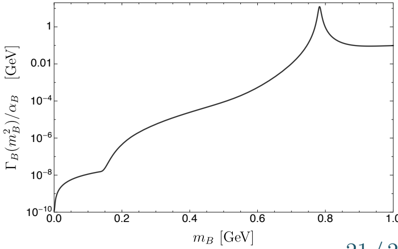
$$\mathcal{A}^{B\,\text{boson}}_{\eta\to\pi^0\gamma\gamma} = g_{B\eta\gamma}(t)g_{B\pi^0\gamma}(t)\left[\frac{(P\cdot q_2 - m_\eta^2)\{a\} - \{b\}}{m_B^2 - t - i\sqrt{t}\,\Gamma_B(t)} + \left\{\begin{array}{c} q_2 \leftrightarrow q_1 \\ t \leftrightarrow u \end{array}\right\}\right],$$

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

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

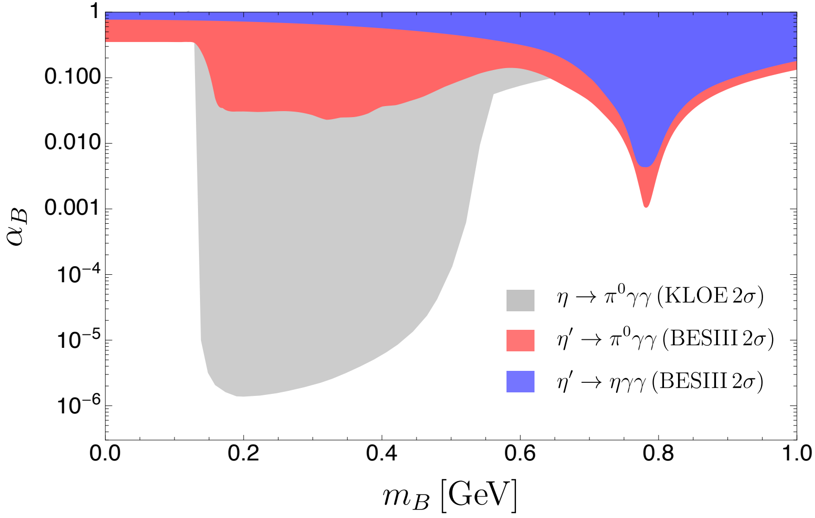
- Energy-dependent **width**

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



Limits on α_B and m_B

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



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

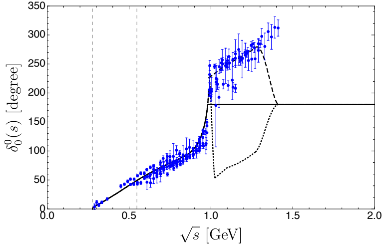
- "Yukawa basis" (this work, at GeV scale): ALP with gluon and mass couplings

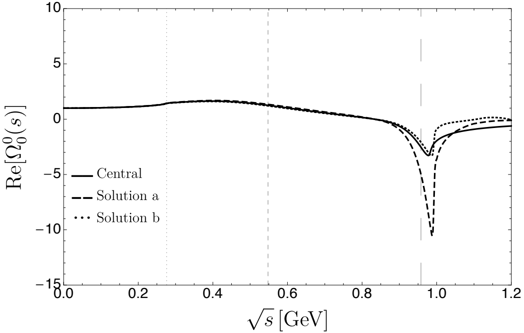
$$\mathcal{L}_{\text{ALP}} = \mathcal{L}_{\text{QCD}} + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{1}{2} M_a^2 a^2 - Q_G \frac{\alpha_s}{8\pi} \frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu} + \sum_{q=u,d,s} m_q \bar{q} \left(e^{i Q_q \frac{a}{f_a} \gamma_5} \right) q\,,$$

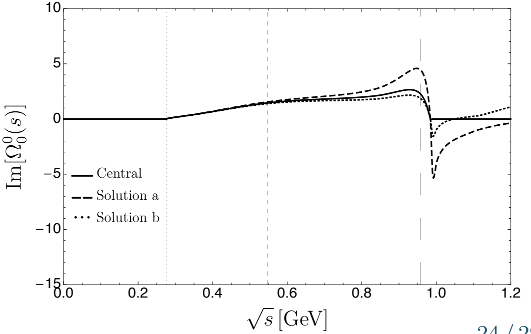
- Equivalent bases (related via chiral rotations of the quarks) if weak interactions are neglected
- The heavy-flavor c, b, t quarks contributions are absorbed in $Q_G \to Q_G + Q_{t,b,c}$

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

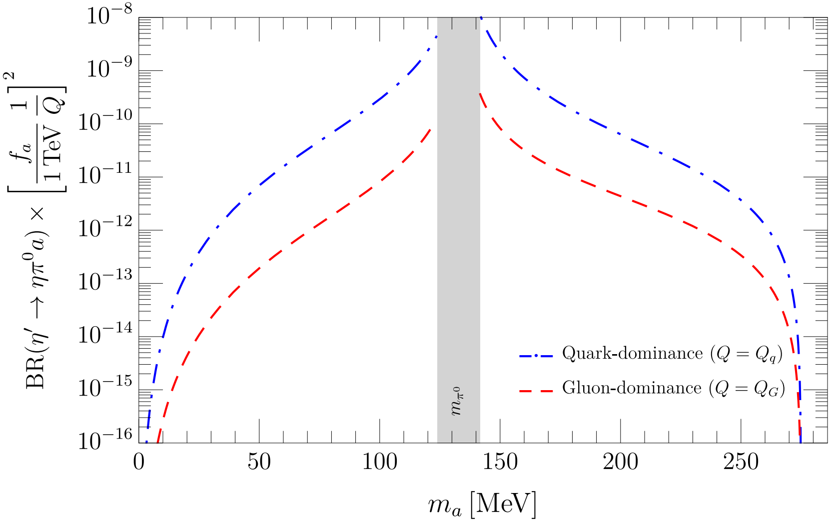
$$\Omega_0^0(s) = \exp\left\{ \frac{s}{\pi} \int_{4M_\pi^2}^{\infty} ds' \frac{\delta_0^0(s')}{s'(s'-s-i\varepsilon)} \right\},$$



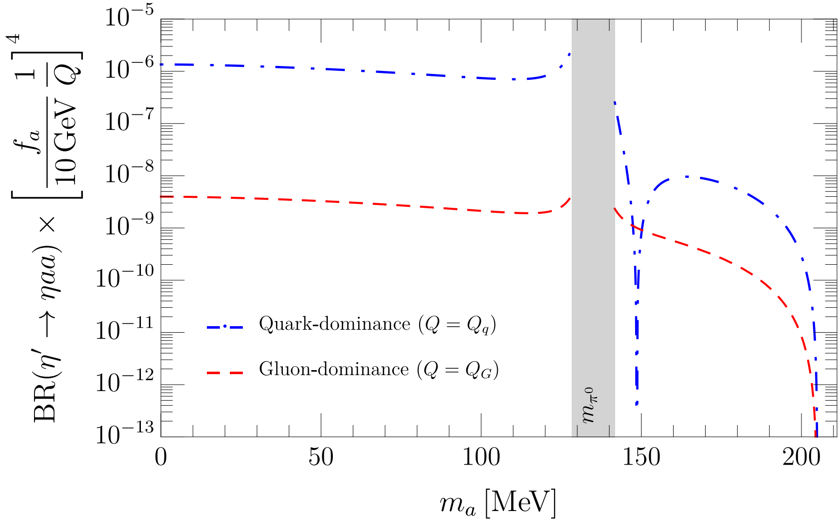




$\eta' \to \eta\pi^0 a$

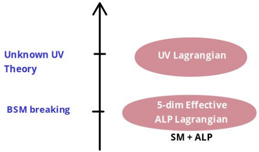


Multi production of ALPs



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: $m_a^2 \propto \frac{1}{f_a^2}$.



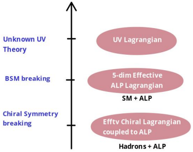
- "Yukawa basis" (at GeV scale): ALP with gluon and mass couplings

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

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

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

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

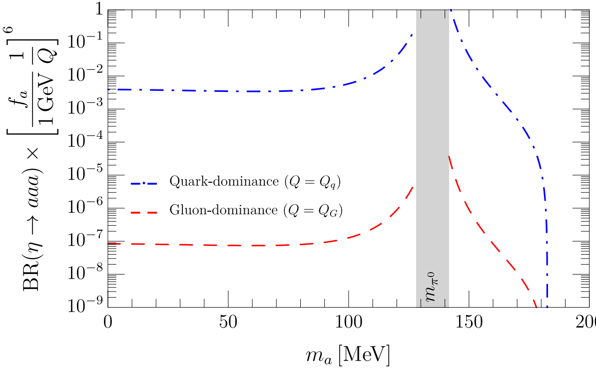
$$U = \exp\left(\frac{i\sqrt{2}\Phi}{f}\right), \quad \Phi = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi_3 + \frac{1}{\sqrt{6}}\eta_8 + \frac{1}{\sqrt{3}}\eta_0 & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi_3 + \frac{1}{\sqrt{6}}\eta_8 + \frac{1}{\sqrt{3}}\eta_0 & K^0 \\ K^- & K^0 & -\frac{2}{\sqrt{6}}\eta_8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

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

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

Triple production of ALPs in η/η' decays

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



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