New Physics Searches in Hadronic Processes

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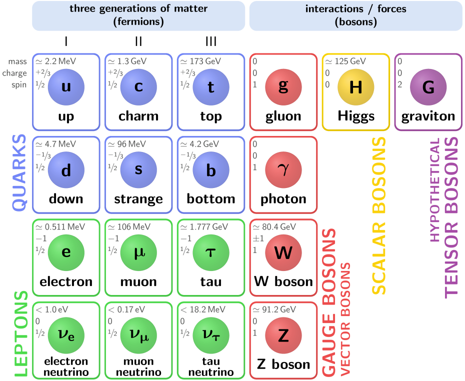
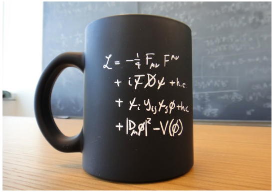
The Standard Model of Particle Physics

- Describes **Nature** in a economic and elegant way

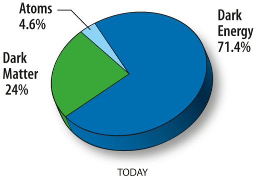




- **Validated** over a wide variety of energy scales
- Is the SM the **final** theory of Nature?

Beyond the Standard Model

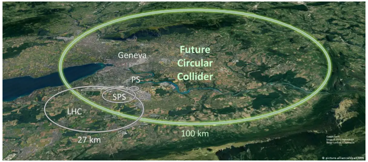
- The SM **fails** to explain:
  - **Dark matter**: what is the most prevalent kind of matter in our Universe?
  - **Dark Energy**: what drives the accelerated expansion of the Universe?

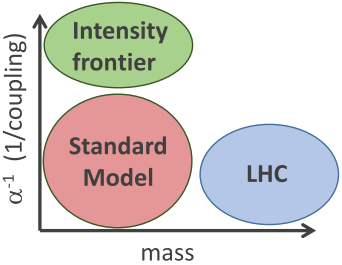


  - **Neutrino** masses and oscillations: why do neutrinos have mass? what makes neutrinos disappear and then re-appear in a different form?
  - **Baryon asymmetry** of the Universe: what mechanism created the tiny matter-antimatter imbalance in the early Universe?
  - Several **anomalies in data**: $(g-2)_\mu$,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

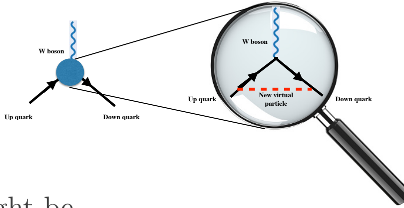
Finding New Physics: energy vs precision frontier

- **Energy frontier**: smash protons as hard as you can, and see what comes out (LHC, FCC 9,000M€)
  - create **new** (heavy) particles
    and/or study their **effects** on rare processes





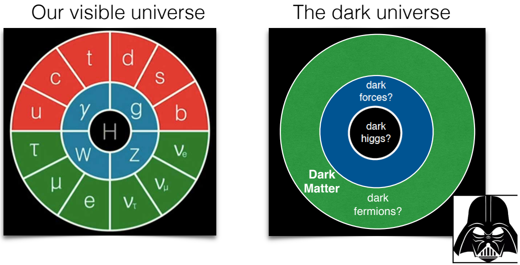
- **Intensity frontier**: new feebly interacting particles
  - search for tiny indirect effects,
    with no (or very precisely known) SM background



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

Dark sector physics

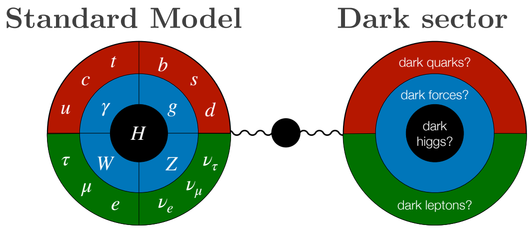
- **Why** a dark sector?
  - Many open problem in particle physics, *e.g.* dark matter, neutrino mass generation or anomalies in data, let us think about dark particles
- **What** is a dark sector particle?
  - Any particle that does not interact through the SM forces (not charged under the SM symmetries)



- How can we **access** (and test) the **dark sector**?

Dark sector portals to the Standard Model

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



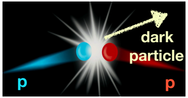
Portal	**Mediators**	**Portal interactions**
Vector	Dark photon	$\epsilon B^{\mu\nu} A'_{\mu\nu}$
Scalar	Dark scalar	$\kappa \vert H\vert^2 \vert S\vert^2$
Neutrino	Sterile Neutrino	$yHLN$
Axion	Axion	$\frac{a}{f_a}\tilde{G}_{\mu\nu}G^{\mu\nu}$

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

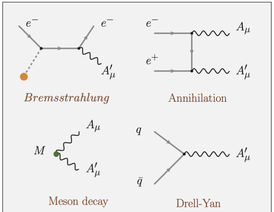
Unique access to dark sectors!

Other ongoing/future experiments

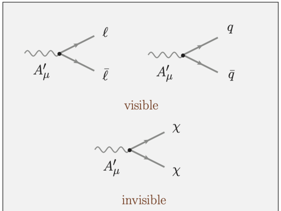
REDTOP NA62 GlueX SeaQuest E906

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

Production modes



Decay modes



High-intensity programs in meson factories

- η/η'-factories

Wasa-at-COSY $\sim 3 \times 10^7$

KLOE-2 (Frascati) $\sim 10^9$

BESIII $\sim 4 \times 10^7$

HADES $\sim 4.5 \times 10^8$

CB@ MAMI $\sim 3 \times 10^8$

CMS $\eta \sim 10^{12}$

Experiment	Technique	Total η mesons
GlueX@JLAB (running)	$\gamma_{12\ \mathrm{GeV}}\, p \to \eta\, X \to$ neutrals	5.5×10^7 /yr
JEF@JLAB (approved)	$\gamma_{12\ \mathrm{GeV}}\, p \to \eta\, X \to$ neutrals	1.5×10^8 /yr
HIAF (approved)		$\sim 10^{13}$/yr
REDTOP (proposing)	$p_{1.8\ GeV}\ Li \to \eta\ X$	3.4×10^{13} /yr

- π-factories (PIENU, PIONEER), K-factories (E949, E391, NA62, KOTO), B-factories (LHCb, Belle-(II))

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 $\mathcal{O}((m_u - m_d)^2)$
- **Search** strategies (visible final states):
  - Resonance searches (bump hunting)
  - Displaced vertices (long-lived decays)
  - Rare decays: new physics process mimics highly-suppressed SM channels
- Other possibilities: Invisible (or partially-invisible) decays
- 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 $(g\text{-}2)_\mu$
- 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)

Rich physics program at η,η′ factories

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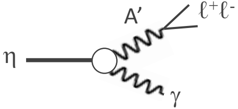
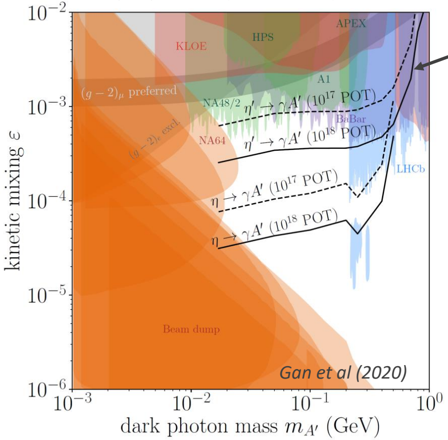
Gan, Kubis, Passemar, ST (2020)

Dark photon searches

- **Broad** worldwide effort to search for dark photons (A')
- Most searches are for A' coupling to **leptons**, $\mathcal{L}_{\text{int}} = -e\varepsilon j^{\mu}_{\text{em}} A'_{\mu}$



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



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?
- **New** boson from a new $U(1)_B$ gauge symmetry (aka B boson, leptophobic Z')

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

  — 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

Dark-photon-like | m_B [MeV] | Novel signatures

Decay → Production ↓	$B \to e^+e^-$ $m_B \sim 1 - 140$ MeV	$B \to \pi^0\gamma$ $140 - 620$ MeV	$B \to \pi^+\pi^-\pi^0$ $620 - 1000$ MeV	$B \to \eta\gamma$
$\pi^0 \to B\gamma$	$\pi^0 \to e^+e^-\gamma$	–	–	–
$\eta \to B\gamma$	$\eta \to e^+e^-\gamma$	$\eta \to \pi^0\gamma\gamma$	–	–
$\eta' \to B\gamma$	$\eta' \to e^+e^-\gamma$	$\eta' \to \pi^0\gamma\gamma$	$\eta' \to \pi^+\pi^-\pi^0\gamma$	$\eta' \to \eta\gamma\gamma$
$\omega \to \eta B$	$\omega \to \eta e^+e^-$	$\omega \to \eta\pi^0\gamma$	–	–
$\phi \to \eta B$	$\phi \to \eta e^+e^-$	$\phi \to \eta\pi^0\gamma$	–	

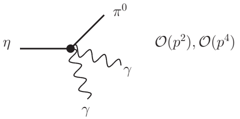
- Searches in meson factories are gaining attention

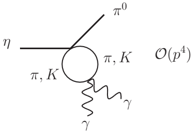
  — $\eta \to \gamma B \to \gamma\gamma\pi^0$ (JEF), $\phi \to \eta B \to \eta\pi^0\gamma$ (KLOE-II), $\eta \to B\gamma \to \pi^+\pi^-\gamma$ (Belle-II)

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

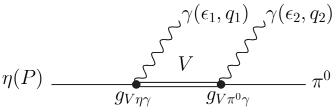
- **SM motivation**:

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)





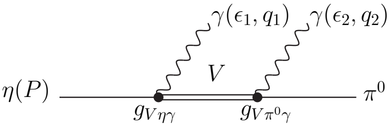
  - 1^{st} sizable contribution comes at $\mathcal{O}(p^6)$, but LEC's are not well known
  - To **test ChPT** and a wide range of chiral models, *e.g.* VMD and LσM



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

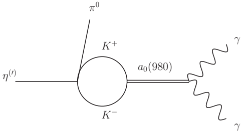


- $g_{VP\gamma}$ **couplings**: $\Gamma^{\text{exp}}_{V\to P\gamma} = \frac{1}{3}\frac{g^2_{VP\gamma}}{32\pi}\left(\frac{m_V^2 - m_P^2}{m_V}\right)^3$, $\Gamma^{\text{exp}}_{P\to V\gamma} = \frac{g^2_{VP\gamma}}{32\pi}\left(\frac{m_P^2 - m_V^2}{m_P}\right)^3$,

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)

LσM for the scalar resonance contributions

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



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

- Scalar amplitudes:

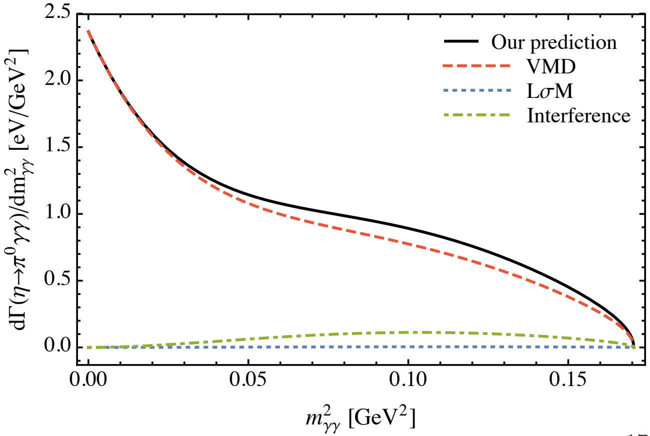
$$\mathcal{A}^{\mathrm{L}\sigma\mathrm{M}}_{K^+K^-\to\pi^0\eta^{(\prime)}} = \frac{1}{2f_\pi f_K}\Bigg\{(s-m^2_{\eta^{(\prime)}})\frac{m^2_K-m^2_{a_0}}{D_{a_0}(s)}\cos\varphi_P+\frac{1}{6}\Big[(5m^2_{\eta^{(\prime)}}+m^2_\pi-3s)\cos\varphi_P$$
$$-\sqrt{2}(m^2_{\eta^{(\prime)}}+4m^2_K+m^2_\pi-3s)\sin\varphi_P\Big]\Bigg\}\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

- Complete one-loop propagator for the scalar resonances:

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

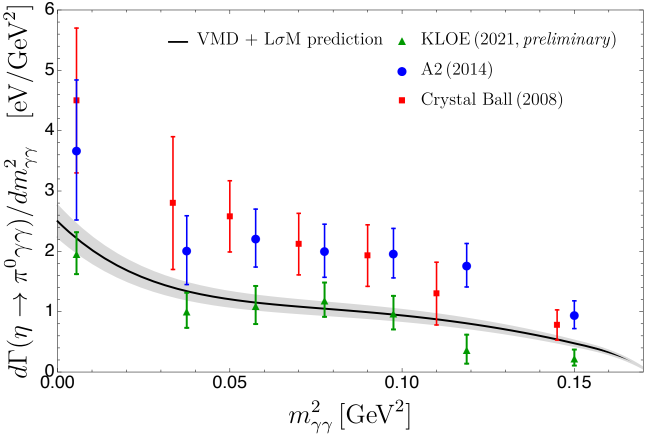
$\eta \to \pi^0\gamma\gamma$ predictions

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

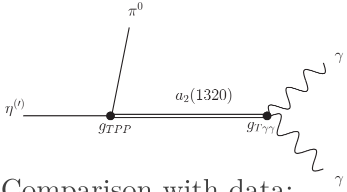
- Comparison of our prediction ($\mathrm{BR} = 1.35(8) \times 10^{-4}$) with experimental data (Escribano, SGS, Jora, Royo, Phys.Rev.D 102, 034026 (2020))
  - Shape of the A2 ($\mathrm{BR} = 2.54(27) \times 10^{-4}$) and Crystal Ball ($\mathrm{BR} = 2.21(24)(47) \times 10^{-4}$) spectra is captured well (normalization offset)
  - Good agreement with KLOE data ($\mathrm{BR} = 0.98(11)(14) \times 10^{-4}$)



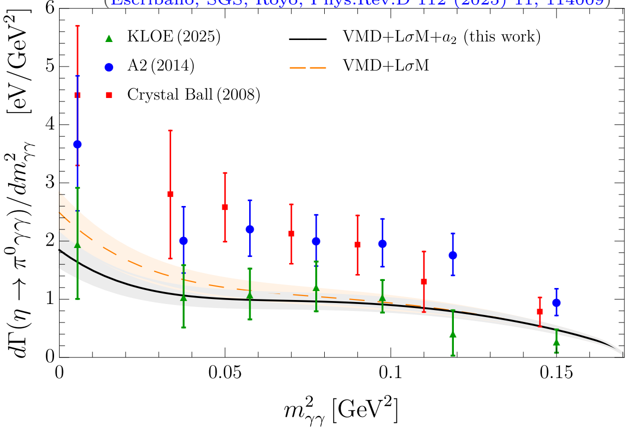
- The experimental situation needs to be **clarified** (A2, JEF, REDTOP)

$a_2(1320)$ 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, Phys.Rev.D 112 (2025) 11, 114009)

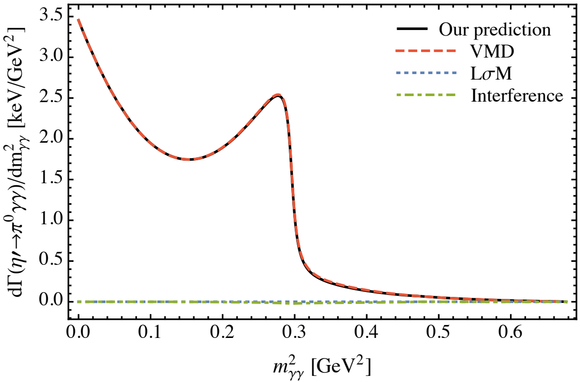


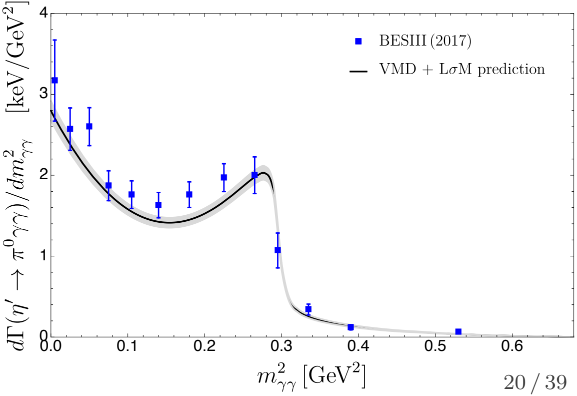
- Comparison with data:
  - **Destructive** vector-tensor interference: good agreement with KLOE-II data (2505.09285)

- 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

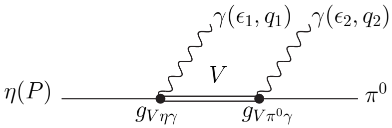
- $\mathrm{BR} = 2.91(21) \times 10^{-3}$ (Escribano, SGS, Jora, Royo, Phys.Rev.D 102, 034026 (2020))
  - VMD completely dominates: ω (78%), ρ (5%), ϕ (0%), interference (17%)
- First time $m_{\gamma\gamma}$ invariant mass distribution by BESIII;
  $\mathrm{BR} = 3.20(7)(23) \times 10^{-3}$ (Ablikim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

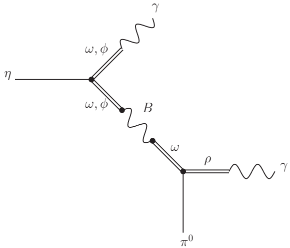




New limits on α_B, m_B

- SM+B-boson



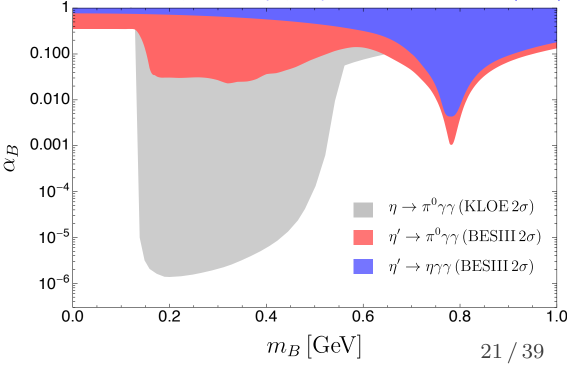


- $\mathrm{BR}_{\mathrm{VMD+Bboson}} < \mathrm{BR}_{\mathrm{exp}}$ at 2σ

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

$\mathrm{BR}(\eta \to \pi^0\gamma\gamma)^{\mathrm{KLOE}}_{\mathrm{exp}} = 0.98(11)(14) \times 10^{-4}$

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



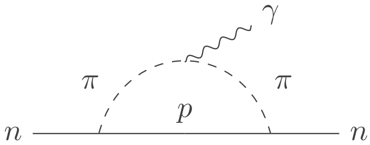
Strong CP problem

- QCD Lagrangian with a θ term:

$$\mathcal{L}_{\text{QCD}} = \mathcal{L}_{\text{quarks}} - \frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} + \theta \frac{g_s^2}{32\pi^2} \tilde{G}^a_{\mu\nu} G^{a,\mu\nu} \,,$$

- The θ term implies that QCD violates P and CP
- This CP-violation is measurable: the θ term causes an EDM for the neutron

$$|d_n| \sim \bar{\theta} \,, \text{ with } \bar{\theta} = \theta + \arg(\det M_q)$$



- Experimental upper limits on the neutron EDM:

  $|d_n| \lesssim 1.8 \times 10^{-26} e$ cm (C. Abel et. al., PRL 124, 081803 (2020))
- Constrains $\bar{\theta} \lesssim 10^{-10}$
- Why is θ so small? (one of the open issues of the SM)

The QCD axion

- The Peccei-Quinn solution of the strong CP-problem (Peccei, Quinn'77)
  - New $U(1)_A$ global symmetry (a.k.a $U(1)_{\rm PQ}$),
  - Broken spontaneously at the high energy scale f_a and anomalous
- Nambu-Goldstone boson: the axion a (Weinberg'78; Wilczek'78)

$$\mathcal{L} \supset -\left(\theta + \frac{a}{f_a}\right) \frac{g_s^2}{32\pi^2} \tilde{G}^a_{\mu\nu} G^{a,\mu\nu} \,.$$

- Its VEV cancels the θ-term: $\theta + \frac{\langle a \rangle}{f_a} = 0$, and solves the strong CP-problem:

$$a \to \langle a \rangle + a \,, \quad \mathcal{L} \supset -\frac{a}{f_a} \frac{g_s^2}{32\pi^2} \tilde{G}^a_{\mu\nu} G^{a,\mu\nu} \,.$$

- Axion mass: $m_a^2 = \frac{m_u m_d}{(m_u+m_d)^2} \frac{m_\pi^2 f_\pi^2}{f_a^2}$
- The scale f_a is identified with the electroweak symmetry breaking scale v:

$$f_a \sim v = (\sqrt{2} G_F)^{-1/2} \approx 246\,\mathrm{GeV}\,,$$

  - The PQWW axion ruled out experimentally

Invisible axion models

- *Invisible* models were developed to make the axion weakly coupled ($f_a \gg v$):
  - Dine-Fischler-Srednicki-Zhitnisky (DFSZ) (PLB 104, 199 (1981), SJNP 31, 260 (1980))

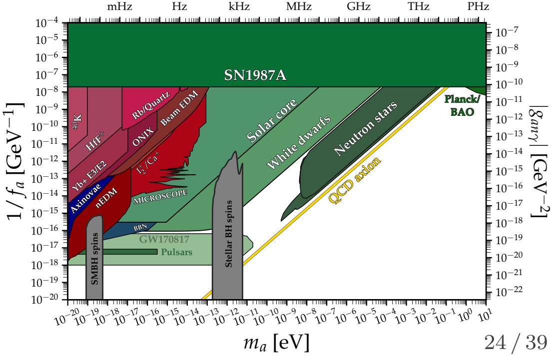
    SM quarks carry PQ charges
  - Kim-Shifman-Vainshtein-Zakharov (KSVZ) (PRL 43, 103 (1979), NPB 166, 493 (1980))

    SM quarks uncharged under the PQ symmetry
- Axion decay constant window from astrophysical and cosmological data:

$$10^8\,\mathrm{GeV} \lesssim f_a \lesssim 10^{18}\,\mathrm{GeV}\,,$$

(for compilations of various constraints,

see: https://cajohare.github.io/AxionLimits/)



Axion-Like Particles (ALPs)

- "Yukawa basis": ALP with gluon and quark couplings (*à la* DFSZ)

$$\mathcal{L}_{\text{ALP}} = \mathcal{L}_{\text{QCD}} + \frac{1}{2}\left(\partial_\mu a\right)\left(\partial^\mu a\right) - \frac{1}{2} M^2_{\not{\text{PQ}}} a^2 - Q_G \frac{\alpha_s}{8\pi}\frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu} + \sum_{q=u,d,s} m_q \bar{q}\left(e^{iQ_q \frac{a}{f_a}\gamma_5}\right) q\,,$$

  $M_{\not{\text{PQ}}}$: PQ-breaking contribution to the mass

  $Q_{q,G}$: PQ charges

- The heavy-flavor c, b, t quarks contributions have been integrated out
- Equivalent to the "usual" derivative basis (related via chiral rotations of the quarks)[1]

[1] if weak interactions are neglected

Lagrangian for ALPs coupled to mesons

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

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

with the ALP-dependent quark mass matrix:

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

and the representation of the pNGB chiral meson nonet:

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

Diagonalization of the mass matrix

- Step 2: **diagonalization** of the mass matrix ($\phi \equiv (\pi_3, \eta_8, \eta_0, a)$)

$$\mathcal{L}_{\text{ALP}}^{\chi\text{PT@LO}} \supset -\frac{1}{2}\phi^T \widetilde{M}^2 \phi\,, \quad \widetilde{M}^2 = \begin{pmatrix} m_{\pi_3}^2 & m_{\pi_3\eta_8}^2 & m_{\pi\eta_0}^2 & m_{\pi_3 a}^2 \\ & m_{\eta_8}^2 & m_{\eta_8\eta_0}^2 & m_{\eta_8 a}^2 \\ & & m_{\eta_0}^2 & m_{\eta_0 a}^2 \\ & & & m_a^2 \end{pmatrix},$$

$$\begin{pmatrix} \pi_3 \\ \eta_8 \\ \eta_0 \\ a \end{pmatrix} = \left(\begin{array}{ccc|c} & & & \theta_{a\pi} \\ & \mathbb{1}_{3\times 3} & & \theta_{a\eta_8} \\ & & & \theta_{a\eta_0} \\ \hline -\theta_{a\pi} & -\theta_{a\eta_8} & -\theta_{a\eta_0} & 1 \end{array}\right) \left(\begin{array}{ccc|c} & & & 0 \\ & \mathbb{R}_{3\times 3} & & 0 \\ & & & 0 \\ \hline 0 & 0 & 0 & 1 \end{array}\right) \begin{pmatrix} \pi^0 \\ \eta \\ \eta' \\ a_{\text{phys}} \end{pmatrix},$$

where $\mathbb{R}$ is an orthogonal matrix that diagonalizes of the π^0-η-η' subsystem

$$\mathbb{R} = \begin{pmatrix} 1 & -\theta_{\pi\eta} & -\theta_{\pi\eta'} \\ (\theta_{\pi\eta}\cos\theta_{\eta\eta'} + \theta_{\pi\eta'}\sin\theta_{\eta\eta'}) & \cos\theta_{\eta\eta'} & \sin\theta_{\eta\eta'} \\ (\theta_{\pi\eta'}\cos\theta_{\eta\eta'} - \theta_{\pi\eta}\sin\theta_{\eta\eta'}) & -\sin\theta_{\eta\eta'} & \cos\theta_{\eta\eta'} \end{pmatrix}.$$

Mixing angles and physical axion mass

- In the PQ-preserving limit, *i.e.* $M_{\not{\mathrm{PQ}}} = 0$:

$$\theta_{a\pi}^{(\mathrm{PQ})} = -\frac{f_\pi}{f_a}\frac{1}{(1+\epsilon)}\left(\frac{Q_u m_u - Q_d m_d}{m_u + m_d} + \frac{m_u - m_d}{m_u + m_d}\,\frac{Q_s + Q_G}{2} + \epsilon\,\frac{Q_u - Q_d}{2}\right) + \mathcal{O}\left(f_a^{-2}\right),$$

$$\theta_{a\eta_8}^{(\mathrm{PQ})} = \frac{f_\pi}{f_a}\frac{\sqrt{3}}{2}\frac{1}{(1+\epsilon)}\left(Q_s + \frac{Q_G}{3} - \epsilon\,\frac{(Q_u + Q_d + 2Q_G/3) + \frac{2B_0 m_s}{m_0^2}(Q_u + Q_d - 2Q_s)}{1 + \frac{6B_0 m_s}{m_0^2}}\right) + \mathcal{O}\left(f_a^{-2}\right),$$

$$\theta_{a\eta_0}^{(\mathrm{PQ})} = \frac{f_\pi}{f_a}\frac{1}{\sqrt{6}}\frac{1}{(1+\epsilon)}\left(Q_G + \epsilon\,\frac{Q_G - \frac{6B_0 m_s}{m_0^2}(Q_u + Q_d + Q_s)}{1 + \frac{6B_0 m_s}{m_0^2}}\right) + \mathcal{O}\left(f_a^{-2}\right),$$

where $\epsilon \equiv \frac{m_u m_d}{m_s(m_u+m_d)}\left(1 + 6\,\frac{B_0 m_s}{m_0^2}\right) \approx 0.04$.

- Physical axion mass:

$$\left(m_{a_{\mathrm{phys}}}^{(\mathrm{PQ})}\right)^2 = (Q_u + Q_d + Q_s + Q_G)^2\,\frac{B_0 m_u m_d m_s}{\left(m_u m_d + m_u m_s + m_d m_s + \frac{6B_0 m_u m_d m_s}{m_0^2}\right)}\frac{f_\pi^2}{f_a^2},$$

ALP-meson mixing angles

- In the PQ-breaking limit, *i.e.* $M_{\not{\text{PQ}}} \neq 0$:

$$\theta_{a\pi} = \theta_{a\pi}^{(\text{PQ})} \left(1 + \frac{M_{\not{\text{PQ}}}^2}{m_\pi^2 - m_a^2} \right),$$

$$\theta_{a\eta_8} = \theta_{a\eta_8}^{(\text{PQ})} \left(1 + \cos^2\theta_{\eta\eta'} \frac{M_{\not{\text{PQ}}}^2}{m_\eta^2 - m_a^2} + \sin^2\theta_{\eta\eta'} \frac{M_{\not{\text{PQ}}}^2}{m_{\eta'}^2 - m_a^2} \right) + \theta_{a\eta_0}^{(\text{PQ})} \frac{\sin 2\theta_{\eta\eta'}}{2} \left(\frac{M_{\not{\text{PQ}}}^2}{m_{\eta'}^2 - m_a^2} - \frac{M_{\not{\text{PQ}}}^2}{m_\eta^2 - m_a^2} \right),$$

$$\theta_{a\eta_0} = \theta_{a\eta_0}^{(\text{PQ})} \left(1 + \sin^2\theta_{\eta\eta'} \frac{M_{\not{\text{PQ}}}^2}{m_\eta^2 - m_a^2} + \cos^2\theta_{\eta\eta'} \frac{M_{\not{\text{PQ}}}^2}{m_{\eta'}^2 - m_a^2} \right) + \theta_{a\eta_8}^{(\text{PQ})} \frac{\sin 2\theta_{\eta\eta'}}{2} \left(\frac{M_{\not{\text{PQ}}}^2}{m_{\eta'}^2 - m_a^2} - \frac{M_{\not{\text{PQ}}}^2}{m_\eta^2 - m_a^2} \right).$$

- Valid in the small mixing angle approximation, *i.e.* when $\theta_{a\pi}^{(\text{PQ})}, \theta_{a\eta_8}^{(\text{PQ})}, \theta_{a\eta_0}^{(\text{PQ})} \ll 1$
- Physical ALP mass:

$$m_a^2 \equiv m_{a_{\text{phys}}}^2 = \left(m_{a_{\text{phys}}}^{(\text{PQ})}\right)^2 + M_{\not{\text{PQ}}}^2 .$$

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

$$\pi_3 \to \pi^0 + \theta_{a\pi} a^{\text{phys}}, \; \eta_8 \to \cos\theta_{\eta\eta'}\eta + \sin\theta_{\eta\eta'}\eta' + \theta_{a\eta_8} a^{\text{phys}}, \; \eta_0 \to -\sin\theta_{\eta\eta'}\eta + \cos\theta_{\eta\eta'}\eta' + \theta_{a\eta_0} a^{\text{phys}},$$

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

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

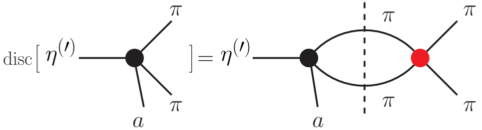
$$\mathcal{A}(\eta \to \pi^+\pi^- a) = \frac{m_\pi^2}{f_\pi^2}\left(\cos\theta - \sqrt{2}\sin\theta\right)\left[\frac{f_\pi}{\sqrt{3}f_a}\frac{Q_u m_u + Q_d m_d}{m_u + m_d} - \frac{1}{3\sqrt{3}}\frac{m_d - m_u}{m_u + m_d}\theta_{\pi_3 a} + \frac{1}{3}\theta_{\eta_8 a} + \frac{\sqrt{2}}{3}\theta_{\eta_0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

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

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

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

- Unitarity:



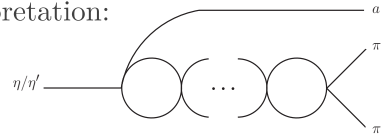
$$\text{disc}\mathcal{A}(s) = 2i\mathcal{A}(s)\sigma_\pi(s)T_0^{0*}(s) = 2i\mathcal{A}(s)\sin\delta_0^0(s)e^{-i\delta_0^0(s)}\,,$$

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

- Analytic solution:

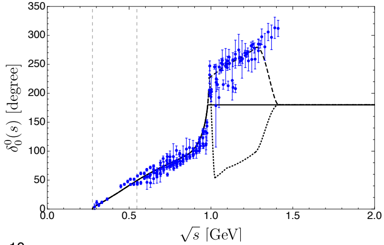
$$\mathcal{A}(s) = \mathcal{A}(\eta\to 2\pi a)|_{\text{LO}} \times \Omega_0^0(s)\,, \quad \Omega_0^0(s) = \exp\left\{\frac{s}{\pi}\int_{4M_\pi^2}^{\infty} ds' \frac{\delta_0^0(s')}{s'(s'-s-i\varepsilon)}\right\},$$

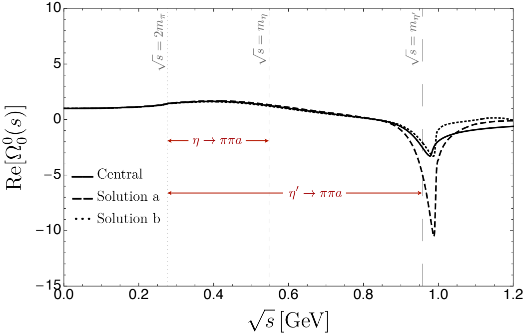
- Diagrammatic interpretation:

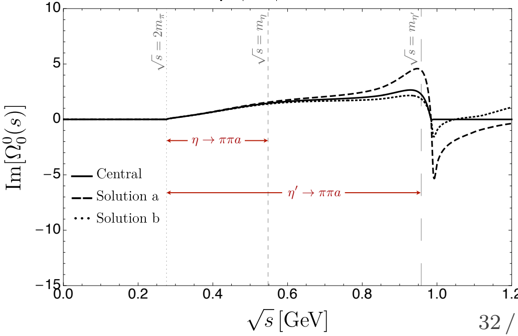


Solution of the Omnès function $\Omega_0^0(s)$

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

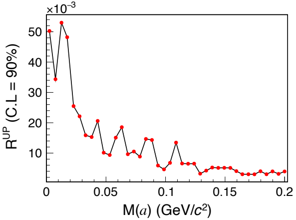




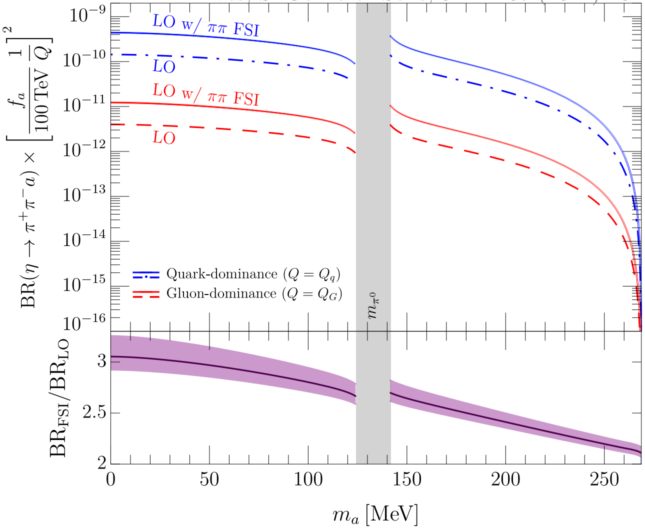


Branching ratio predictions for $\eta \to \pi^+\pi^- a$

- Two scenarios:
  Quark-dominance ($Q_G = 0$)
  Gluon-dominance ($Q_q = 0$)
- Experimental searches in
  $\eta \to \pi\pi a \to \pi\pi\{\gamma\gamma, \ell^+\ell^-\}$
  (CMS, JEF, KLOE, REDTOP
  HADES [talk by K. Prościński])
- First upper bounds
  from BESIII (2501.10130)

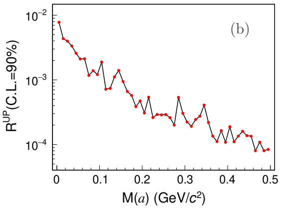


D. Alves, S. Gonzàlez-Solís, JHEP 07 (2024) 264

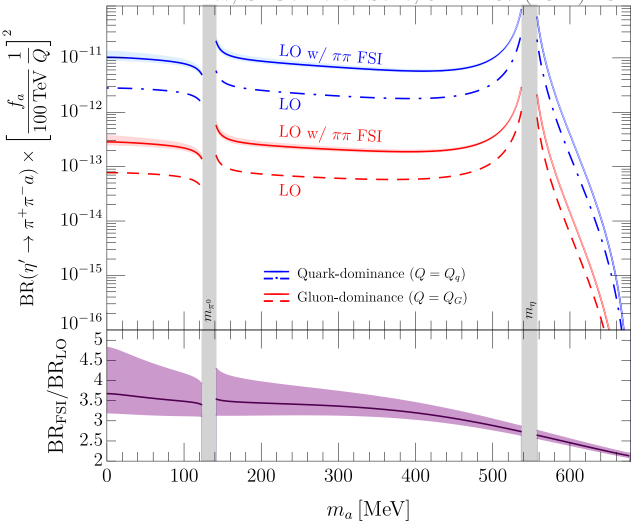


Branching ratio predictions for $\eta' \to \pi\pi a$

- Two scenarios:
  Quark-dominance ($Q_G = 0$)
  Gluon-dominance ($Q_q = 0$)
- Experimental searches in
  $\eta' \to \pi\pi a \to \pi\pi\{\gamma\gamma, \ell^+\ell^-\}$
  (CMS, JEF, KLOE, REDTOP HADES)
- First upper bounds from BESIII (JHEP 07 (2024) 135)



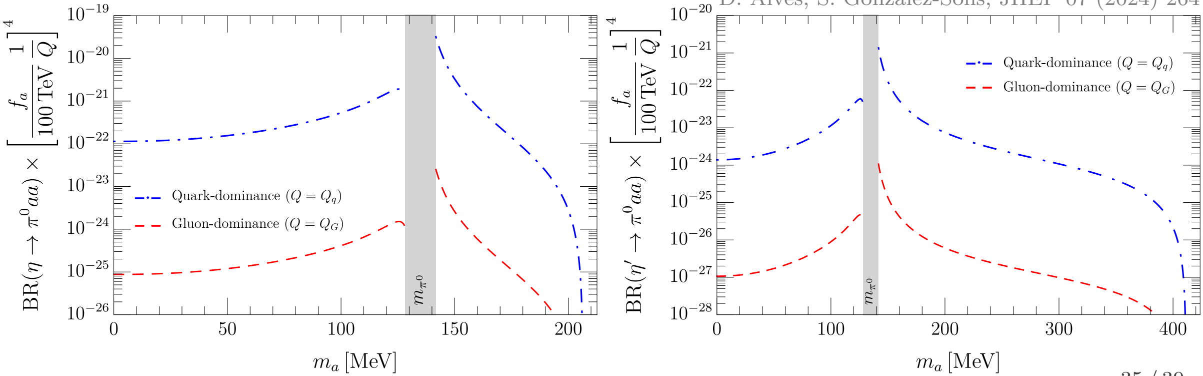
D. Alves, S. Gonzàlez-Solís, JHEP 07 (2024) 264



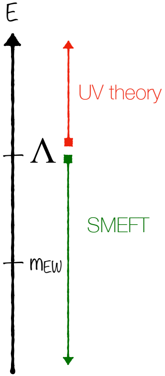
Double production of ALPs in η/η' decays

- $\eta/\eta' \to \pi^0 aa$ 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



SMEFT



- The SM is an EFT valid up to some scale Λ, beyond it must be extended
- If we are interested in physics at $E \ll \Lambda$ we can write the low-energy Lagrangian as a series in powers of $1/\Lambda$: SMEFT

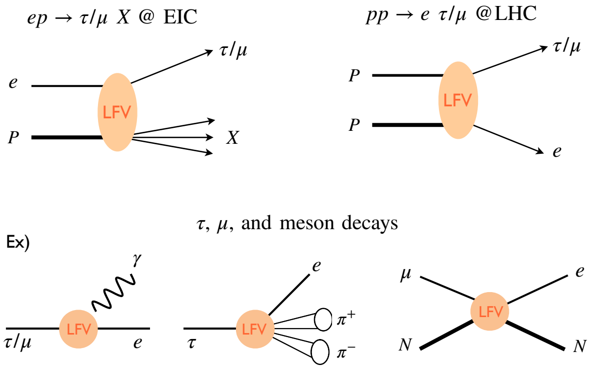
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}}^{(d=4)} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(d=6)}$$

- In general $\mathcal{L}_{\text{SMEFT}}^{(d=6)}$ violate all the accidental symmetries and properties of the SM: LFV, CP effects, suppression of FCNC, etc.
- Precision test of forbidden or suppressed processes in the SM are powerful probes of physics BSM

Global analysis of $\mu \to e$ with SMEFT

- Model-independent analysis of CLFV processes at low-and high-energy

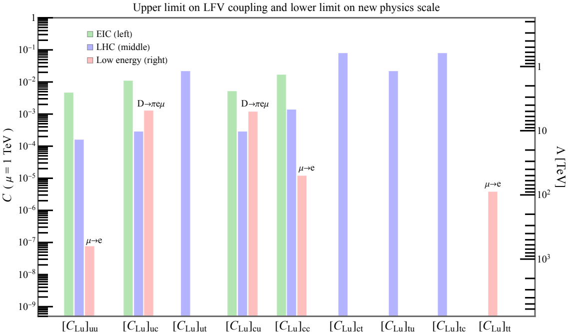
F. Delzanno, K. Fuyuto, S. Gonzàlez-Solís, E. Mereghetti JHEP 07 (2025) 283

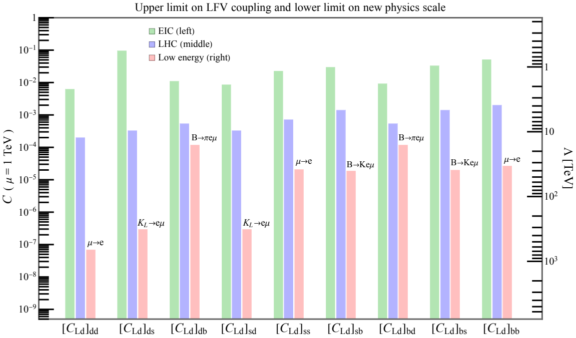


Global analysis of $\mu \to e$ with SMEFT

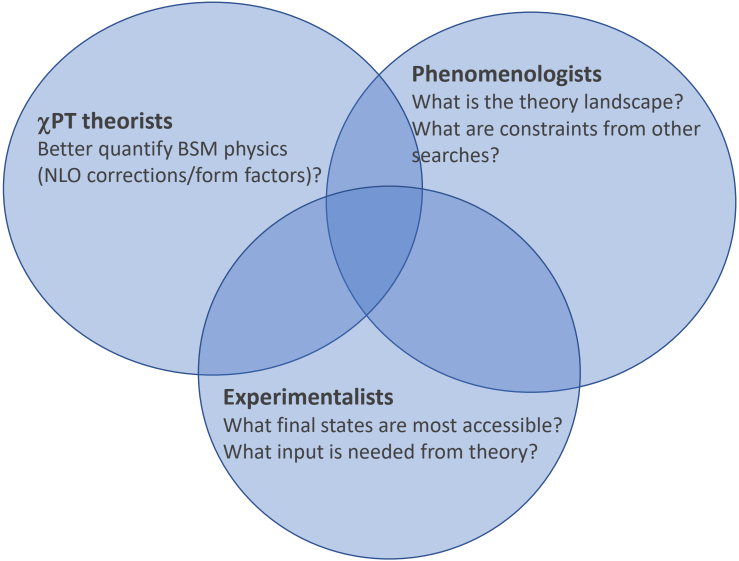
- Model-independent analysis of CLFV processes at low-and high-energy

F. Delzanno, K. Fuyuto, S. Gonzàlez-Solís, E. Mereghetti JHEP 07 (2025) 283



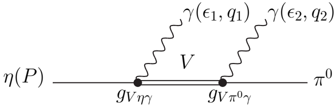


Conclusions



Vector meson exchange contributions

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



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

- Mandelstam variables and Lorentz structures given by:

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

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

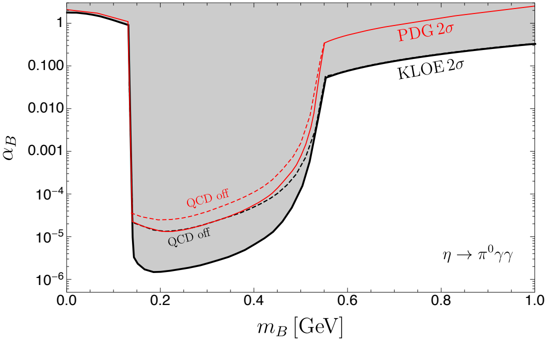
$$\begin{aligned}\{b\} = &(\epsilon_1\cdot q_2)(\epsilon_2\cdot P)(P\cdot q_1) + (\epsilon_2\cdot q_1)(\epsilon_1\cdot P)(P\cdot q_2) \\ &-(\epsilon_1\cdot\epsilon_2)(P\cdot q_1)(P\cdot q_2) - (\epsilon_1\cdot P)(\epsilon_2\cdot P)(q_1\cdot q_2)\end{aligned}$$

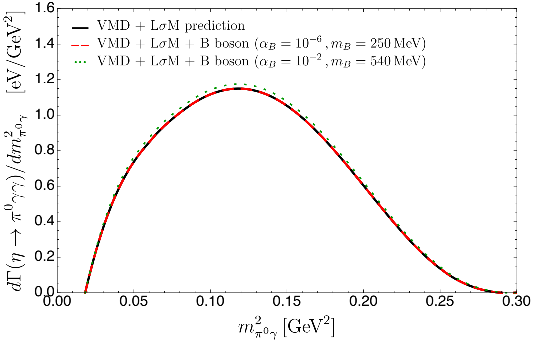
- The decays $\eta' \to \{\pi^0, \eta\}\gamma\gamma$ are formally identical: $g_{V\eta\gamma}g_{V\pi^0\gamma} \to g_{V\eta'\gamma}g_{V\{\pi^0,\eta\}\gamma}$

$\pi^0\gamma$ mass distribution

- These constraints would make a B boson signature suppressed

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

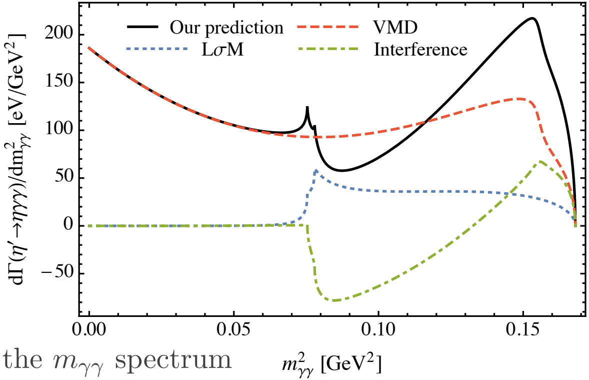




- Experimental $\pi^0\gamma$ distribution will be very welcome (JEF?)

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

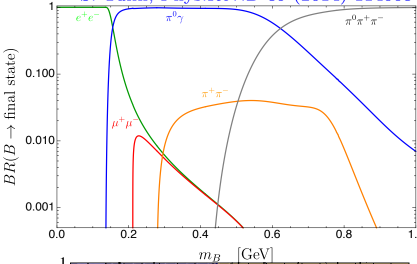
Previous limits on α_B and m_B

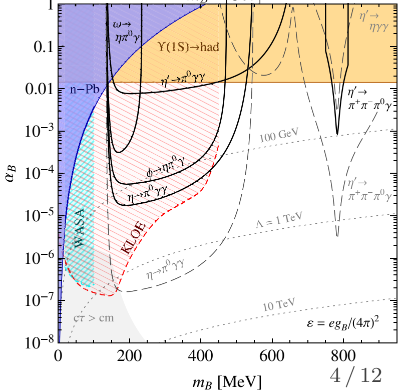
- **New** boson from a new $U(1)_B$ gauge symmetry

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

- 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:
  $\text{BR}(\eta \to \pi^0\gamma\gamma) = \text{BR}(\eta \to B\gamma) \times \text{BR}(B \to \pi^0\gamma)$
- Assuming **zero** SM contribution
- $\text{BR}(\eta \to \pi^0\gamma\gamma) < \text{BR}_{\text{exp}}$ at 2σ
  - $\text{BR}(\eta \to \pi^0\gamma\gamma)_{\text{exp}} = 2.21(53) \times 10^{-4}$
  - $\text{BR}(\eta' \to \pi^0\gamma\gamma)_{\text{exp}} < 8 \times 10^{-4}$ (90% $C.L.$)
  - $\text{BR}(\eta' \to \eta\gamma\gamma)_{\text{exp}}$ no data

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





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 $d\Gamma/dm_{\gamma\gamma}$

Lagrangian for ALPs coupled to QCD

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

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

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

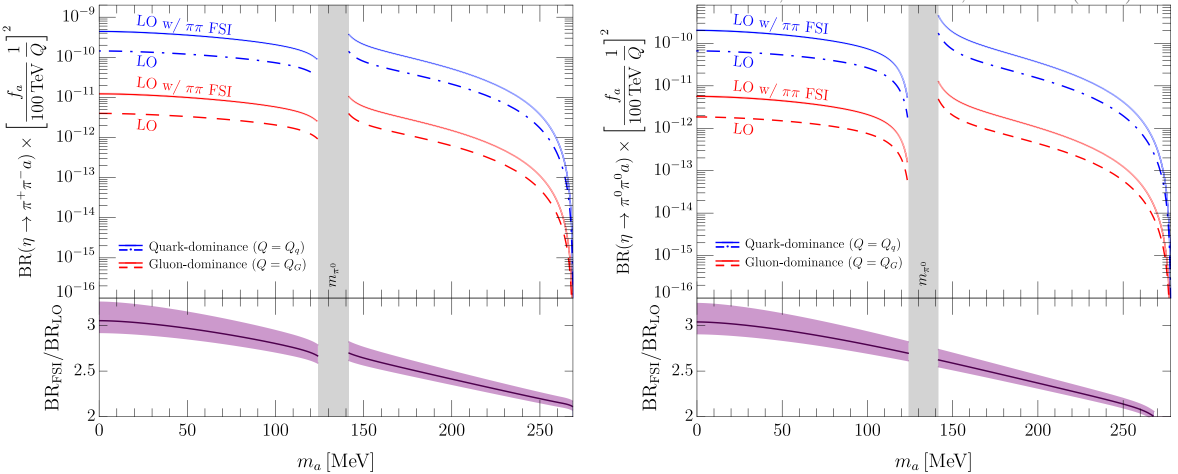
- "Yukawa basis" (this work, at GeV scale): ALP with gluon and mass couplings

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

- 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 $Q_G \to Q_G + Q_{t,b,c}$

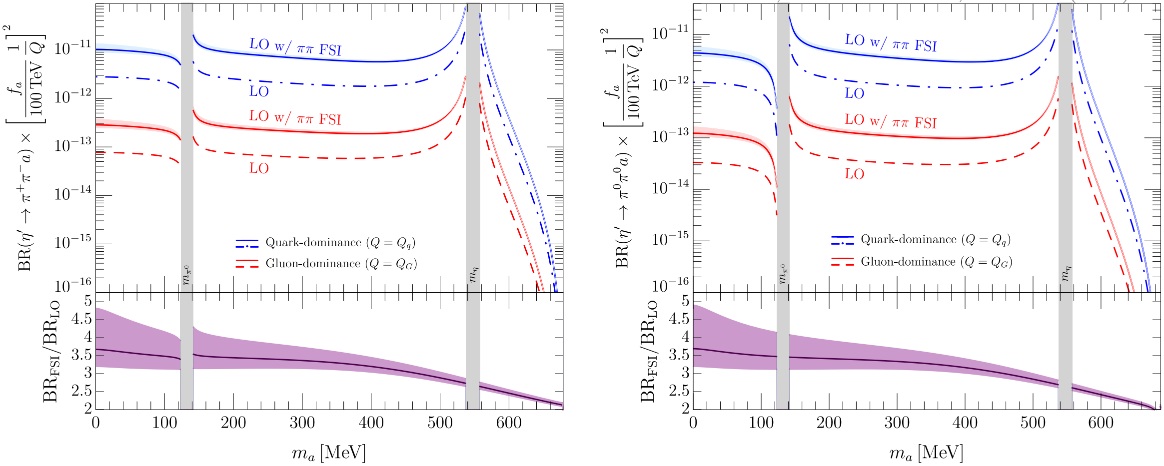
Branching ratio predictions for $\eta \to \pi\pi a$ $(\pi\pi = \pi^+\pi^-, \pi^0\pi^0)$

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

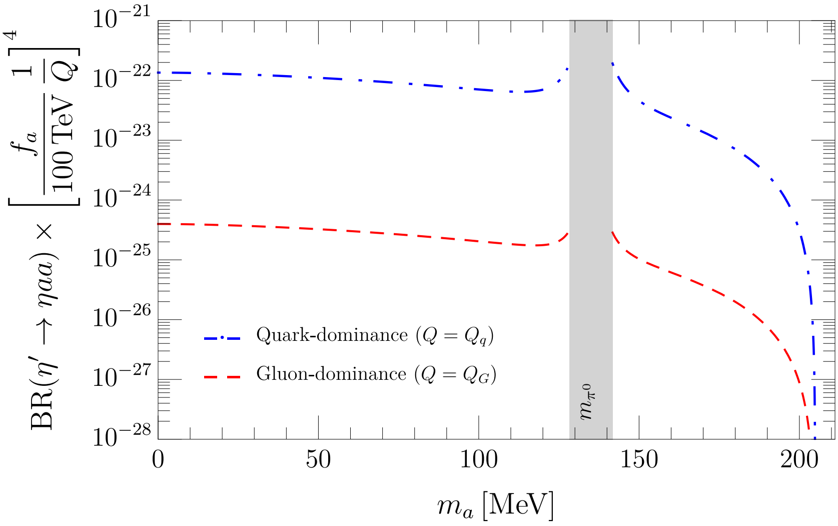


Branching ratio predictions for $\eta' \to \pi\pi a$

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



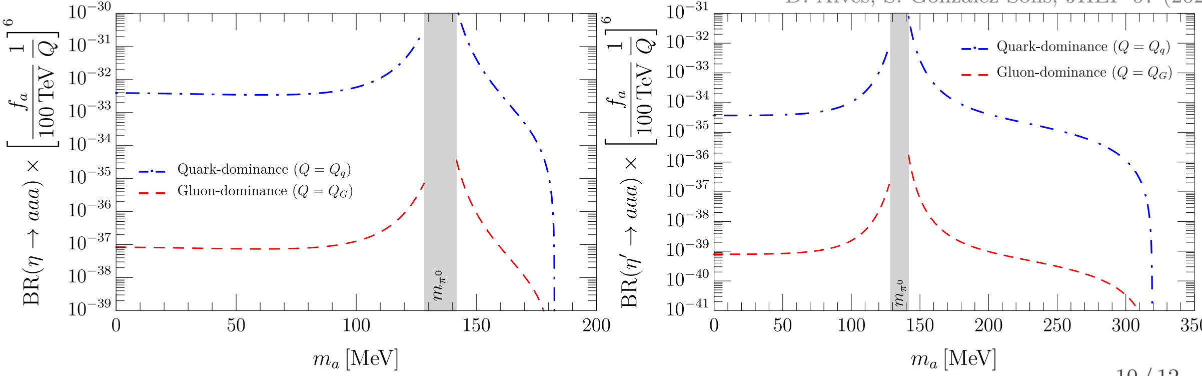
Double production of ALPs in η/η' decays



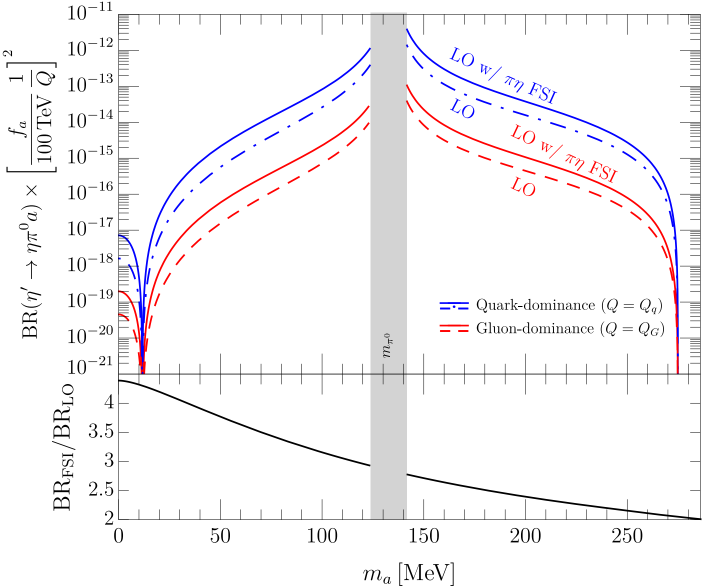
Triple production of ALPs in η/η' decays

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

D. Alves, S. Gonzàlez-Solís, JHEP 07 (202



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



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 $m_{\pi^0\gamma}$