η/η' decays into ALPs

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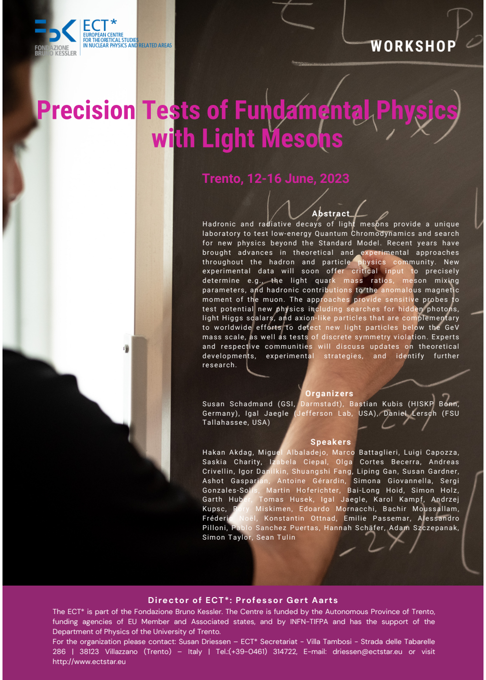
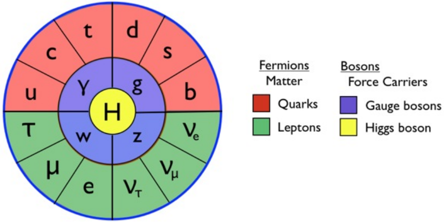


The Standard Model

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



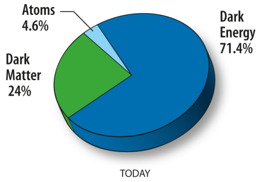
Particles of the Standard Model

Beyond the Standard Model

- However, the SM **fails** to explain several observed phenomena in particle physics, astrophysics and cosmology:

  — **Dark matter**: what is the most prevalent kind of matter in our Universe?

  — **Dark Energy**: what drives the accelerated expansion of the Universe?



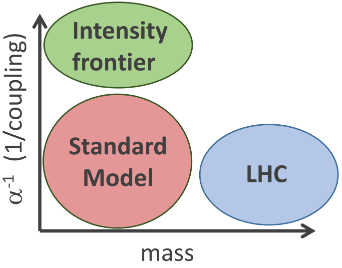
  — **Neutrino** masses and oscillations: why do neutrinos have mass? what makes neutrinos disappear and then re-appear in a different form?

  — **Baryon asymmetry** of the Universe: what mechanism created the tiny matter-antimatter imbalance in the early Universe?

  — Several **anomalies in data**: $(g-2)_\mu$, B-physics anomalies, KOTO anomaly ($K_L \to \pi^0 \nu\bar{\nu}$), ^{8}Be excited decay, ...

Energy and Intensity Frontier Research

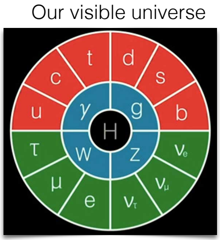
- **New Physics** would be needed to explain observed phenomena
- Why have **not** new particles yet been observed?
  - Hypothetical new particles are **heavy** and require even higher collision energy to be observed ⇒ **Energy Frontier** research (LHC@CERN, Tevatron@FermiLab)
  - Another possibility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

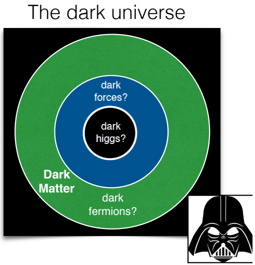


(figure from S. Tulin)

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)



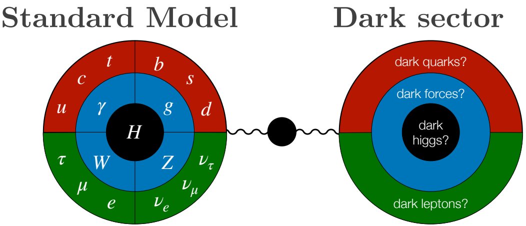


- We live in the SM world, how can we **access** (and test) the **dark sector**?

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



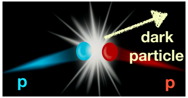
Portal	Mediators	Portal interactions
Vector	Dark photon	$\epsilon B^{\mu\nu} A'_{\mu\nu}$
Scalar	Dark scalar	$\kappa \lvert H \rvert^2 \lvert S \rvert^2$
Neutrino	Sterile Neutrino	$y H L N$
Axion	Axion	$\frac{a}{f_a} \tilde{G}_{\mu\nu} G^{\mu\nu}$

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

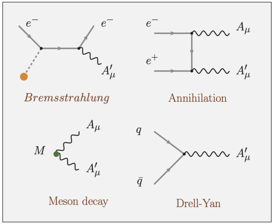
High-luminosity e^+e^- colliders

Unique access to dark sectors!

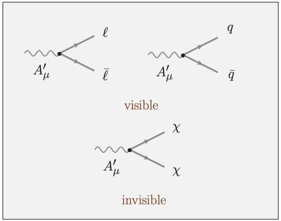
Other ongoing/future experiments

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

Production modes



Decay modes



Why is it interesting to study η/η' physics?

- Eigenstates of the C, P, CP and G operators
- Flavor **conserving** decays $\Rightarrow$ laboratory for symmetry tests
- All their strong and EM decays are **forbidden** at lowest order, *e.g.*:
  - $\eta/\eta' \to 3\pi$ break isospin, $\eta/\eta' \to 2\pi, 4\pi^0$ by P and CP, $\eta/\eta' \to \gamma\gamma$ is anomalous
- Large amount of **data** have been collected (A2, BESIII, GlueX, KLOE), **more** to come (JEF@JLab, CMS@CERN, REDTOP)
- Unique **opportunity** to:
  - Test chiral dynamics at low energy
  - Extract fundamental parameters of the Standard Model, *e.g.* light quark masses, η-η' mixing
  - Study of fundamental symmetries
  - Looking for BSM physics $\Rightarrow$ Dark sector

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 $m_{\pi^0\gamma}$

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

Lagrangian for ALPs coupled to mesons

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

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

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

$$U = \exp\left(\frac{i\sqrt{2}\Phi}{f}\right),$$

where

$$\Phi = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi_3 + \frac{1}{\sqrt{6}}\eta_8 + \frac{1}{\sqrt{3}}\eta_0 & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi_3 + \frac{1}{\sqrt{6}}\eta_8 + \frac{1}{\sqrt{3}}\eta_0 & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta_8 + \frac{1}{\sqrt{3}}\eta_0 \end{pmatrix}.$$

Lagrangian for ALPs coupled to mesons

- Step 2: **diagonalization** of the mass matrix ⇒ mixing angles

$$\widetilde{M}^2 = \begin{pmatrix} m^2_{\pi_3} & m^2_{\pi_3\eta_8} & m^2_{\pi\eta_0} & m^2_{\pi_3 a} \\ & m^2_{\eta_8} & m^2_{\eta_8\eta_0} & m^2_{\eta_8 a} \\ & & m^2_{\eta_0} & m^2_{\eta_0 a} \\ & & & m^2_a \end{pmatrix},$$

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

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

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

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

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

Mixing angles I

- We **first** diagonalize the $\eta_8 - \eta_0$ subsystem

$$\begin{pmatrix} \pi_3 \\ \eta_8 \\ \eta_0 \\ a \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta & \sin\theta & 0 \\ 0 & -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \pi_3 \\ \bar{\eta} \\ \bar{\eta}' \\ a \end{pmatrix} , \quad \sin(2\theta) = \frac{2m^2_{\eta_8\eta_0}}{m^2_{\bar{\eta}'} - m^2_{\bar{\eta}}} ,$$

- The **mass matrix** after this transformation reads:

$$\begin{pmatrix} m^2_{\pi_3} & m^2_{\pi_3\bar{\eta}} & m^2_{\pi_3\bar{\eta}'} & m^2_{\pi_3 a} \\ & m^2_{\bar{\eta}} & 0 & m^2_{\bar{\eta}a} \\ & & m^2_{\bar{\eta}'} & m^2_{\bar{\eta}'a} \\ & & & m^2_a \end{pmatrix} , \quad m^2_{\bar{\eta},\bar{\eta}'} = \frac{1}{2}\left[m^2_{\eta_8} + m^2_{\eta_0} \mp \sqrt{(m^2_{\eta_8} - m^2_{\eta_0})^2 + 4m^4_{\eta_8\eta_0}} \right] ,$$

$$m^2_{\pi_3\bar{\eta}} = m^2_{\pi_3\eta_8}\cos\theta - m^2_{\pi_3\eta_0}\sin\theta , \quad m^2_{\pi_3\bar{\eta}'} = m^2_{\pi_3\eta_0}\cos\theta + m^2_{\pi_3\eta_8}\sin\theta ,$$

$$m^2_{\bar{\eta}a} = m^2_{\eta_8 a}\cos\theta - m^2_{\eta_0 a}\sin\theta , \quad m^2_{\bar{\eta}'a} = m^2_{\eta_8 a}\sin\theta + m^2_{\eta_0 a}\cos\theta .$$

One can **fix** m_0^2 from the physical $m^2_{\bar{\eta}^{(\prime)}}$ mass, which yields $m_0 = 0.807$ GeV and $\theta = -21.4°$, or from the measured mixing angle $\theta = -13.3°$, which yields $m_0 = 1.03$ GeV, and $m_{\bar{\eta}} = 534$ MeV and $m_{\bar{\eta}'} = 1.14$ GeV

Mixing angles II

- We **next** remove the $\pi_3 - \bar{\eta}$ and $\pi_3 - \bar{\eta}'$ mixing

$$
\begin{pmatrix} \pi_3 \\ \bar{\eta} \\ \bar{\eta}' \\ a \end{pmatrix} = \begin{pmatrix} \cos\epsilon_{\pi\eta} & -\sin\epsilon_{\pi\eta} & 0 & 0 \\ \sin\epsilon_{\pi\eta} & \cos\epsilon_{\pi\eta} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\epsilon_{\pi\eta'} & 0 & -\sin\epsilon_{\pi\eta'} & 0 \\ 0 & 1 & 0 & 0 \\ \sin\epsilon_{\pi\eta'} & 0 & \cos\epsilon_{\pi\eta'} & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \pi^0 \\ \eta \\ \eta' \\ a \end{pmatrix},
$$

$$
\simeq \begin{pmatrix} 1 & -\epsilon_{\pi\eta} & -\epsilon_{\pi\eta'} & 0 \\ \epsilon_{\pi\eta} & 1 & 0 & 0 \\ \epsilon_{\pi\eta'} & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \pi^0 \\ \eta \\ \eta' \\ a \end{pmatrix} + \mathcal{O}\left(\epsilon_{\pi\eta}\epsilon_{\pi\eta'}\right).
$$

- The mixing angles **satisfy**:

$$
\sin(2\epsilon_{\pi\eta}) = -\frac{2m^2_{\pi_3\bar{\eta}}}{m^2_\eta - m^2_{\pi^0}} \Rightarrow \epsilon_{\pi\eta} \approx \frac{\frac{m^2_\pi}{\sqrt{3}}\frac{m_d - m_u}{m_u + m_d}\left(\cos\theta - \sqrt{2}\sin\theta\right)}{m^2_\eta - m^2_{\pi^0}} = 0.018,
$$

$$
\sin(2\epsilon_{\pi\bar{\eta}'}) = -\frac{2m^2_{\pi_3\eta'}}{m^2_{\eta'} - m^2_{\pi^0}} \Rightarrow \epsilon_{\pi\eta'} \approx \frac{\frac{m^2_\pi}{\sqrt{3}}\frac{m_d - m_u}{m_u + m_d}\left(\sqrt{2}\cos\theta + \sin\theta\right)}{m^2_{\eta'} - m^2_{\pi^0}} = 0.0049.
$$

Mixing angles II

- **After** this rotation, the mass matrix becomes:

$$\begin{pmatrix} m^2_{\pi^0} & 0 & 0 & m^2_{\pi^0 a} \\ & m^2_{\eta} & 0 & m^2_{\eta a} \\ & & m^2_{\eta'} & m^2_{\eta' a} \\ & & & m^2_{a} \end{pmatrix} + \mathcal{O}((m_u - m_d)^2)\,,$$

where

$$\begin{aligned} m^2_{\pi^0 a} &= m^2_{\pi_3 a} + (m^2_{\eta_8 a}\epsilon_{\pi\eta} + m^2_{\eta_0 a}\epsilon_{\pi\eta'})\cos\theta + (m^2_{\eta_8 a}\epsilon_{\pi\eta'} - m^2_{\eta_0 a}\epsilon_{\pi\eta})\sin\theta\,, \\ m^2_{\eta a} &= -m^2_{\pi_3 a}\epsilon_{\pi\eta} + m^2_{\eta_8 a}\cos\theta - m^2_{\eta_0 a}\sin\theta\,, \\ m^2_{\eta' a} &= -m^2_{\pi_3 a}\epsilon_{\pi\eta'} + m^2_{\eta_8 a}\sin\theta + m^2_{\eta_0 a}\cos\theta\,, \end{aligned}$$

- The diagonal entries represent the **physical masses** of the mesons (the mixing with the ALP will change this by only $\mathcal{O}(f_\pi/f_a)$)

Mixing angles III

- Finally, we diagonalize the ALP-π^0, η, η' **mixing**
- **Solving** for the mixing angles to remove non-diagonal elements we find:

$$\sin(2\theta_{a\pi}) = \frac{2m^2_{\pi^0 a}}{m_a^2 - m_\pi^2}\,, \quad \sin(2\theta_{a\eta}) = \frac{2m^2_{\eta a}}{m_a^2 - m_\eta^2}\,, \quad \sin(2\theta_{a\eta'}) = \frac{2m^2_{\eta' a}}{m_a^2 - m_{\eta'}^2}\,.$$

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

$$\pi^3 = \pi^0 - \epsilon_{\pi\eta}\eta - \epsilon_{\pi\eta'}\eta' + \langle\pi^0 a\rangle a^{\text{phy}}\,,$$

$$\eta_8 = (\epsilon_{\pi\eta}\cos\theta + \epsilon_{\pi\eta'}\sin\theta)\,\pi^0 + \cos\theta\eta + \sin\theta\eta' + \langle\eta_8 a\rangle a^{\text{phy}}\,,$$

$$\eta_0 = (\epsilon_{\pi\eta'}\cos\theta - \epsilon_{\pi\eta}\sin\theta)\,\pi^0 - \sin\theta\eta + \cos\theta\eta' + \langle\eta_0 a\rangle a^{\text{phy}}\,,$$

$$a = a^{\text{phy}} + \mathcal{O}\left(\frac{f_\pi}{f_a}\right)\,,$$

$$\langle\pi^0 a\rangle = \sin\theta_{a\pi^0}\,, \quad \langle\eta_8 a\rangle = \cos\theta\sin\theta_{a\eta} + \sin\theta\sin\theta_{a\eta'}\,, \quad \langle\eta_0 a\rangle = \cos\theta\sin\theta_{a\eta'} - \sin\theta\sin\theta_{a\eta}$$

Mixing angles IV

- ALP **mass**

$$m_a^2 = \frac{(Q_u + Q_d + Q_s + Q_G)^2}{1+\epsilon} \frac{m_u m_d}{(m_u + m_d)^2} \frac{m_\pi^2 f_\pi^2}{f_a^2} + M_a^2 \,,$$

$$\epsilon = \frac{m_u m_d}{m_s (m_u + m_d)} \left(1 + 6 \frac{B_0 m_s}{m_0^2}\right) \,,$$

- **Assuming** $\theta_{a\pi^0}, \theta_{a\eta}$ and $\theta_{a\eta'}$ to be small (they are proportional to $f_\pi / f_a \ll 1$):

$$\langle \pi^0 a \rangle = \theta_{a\pi^0} \,, \quad \langle \eta_8 a \rangle = \theta_{a\eta} \cos\theta + \theta_{a\eta'} \sin\theta \,, \quad \langle \eta_0 a \rangle = \theta_{a\eta'} \cos\theta - \theta_{a\eta} \sin\theta \,,$$

- **QCD axion case**: By taking $M_a = 0$ and $m_a \ll m_\pi$ and keeping the leading expansions of m_π^2 / m_K^2 and m_π^2 / m_0^2

$$\langle \pi^0 a \rangle = \frac{f_\pi}{2 f_a (m_u + m_d)} \left(m_d (2Q_d + Q_s + Q_G) - m_u (2Q_u + Q_s + Q_G)\right) \,,$$

$$\langle \eta_8 a \rangle = \frac{f_\pi}{2\sqrt{3} f_a} (3Q_s + Q_G) \,, \quad \langle \eta_0 a \rangle = \frac{f_\pi}{\sqrt{6} f_a} Q_G \,.$$

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

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

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

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

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

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

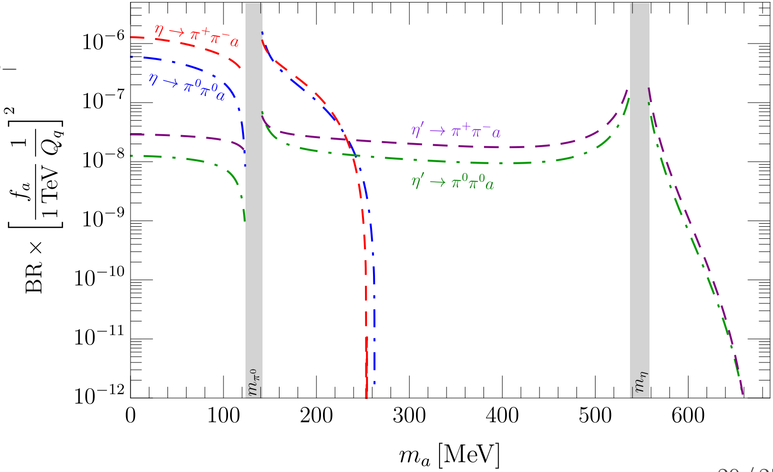
- Two scenarios: **Quark-dominance** $Q_G = 0$ or Gluon-dominance $Q_q = 0$
- We can search for:

  $\eta/\eta' \to \pi\pi a \to \pi\pi\gamma\gamma$

  $\eta/\eta' \to \pi\pi a \to \pi\pi\ell^+\ell^-$

  (BESIII, KLOE, CMS, REDTOP)

S. Gonzàlez-Solís and D. Alves, preliminary



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

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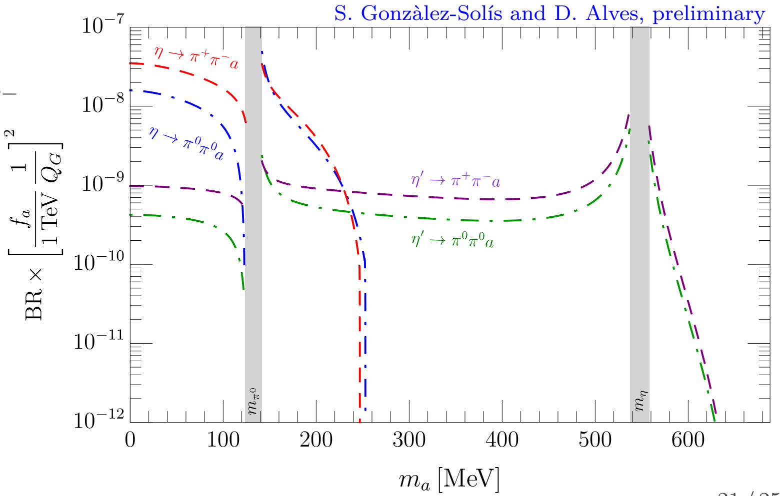
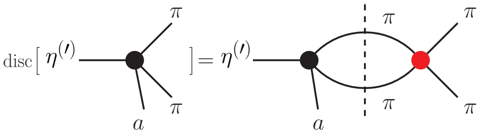
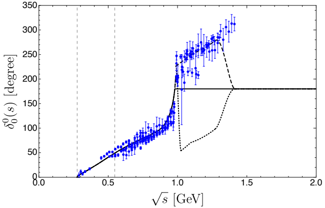


Effects of pion-pion rescattering

- Unitarity:





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

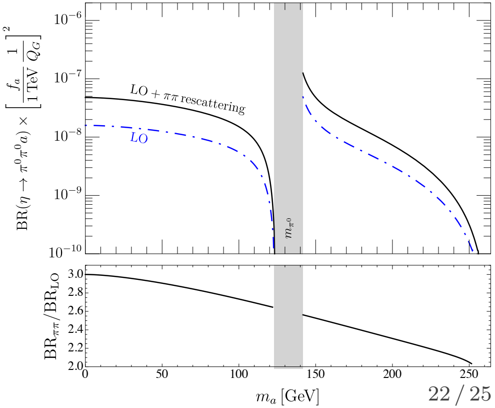
$$\mathcal{A}(s) = \frac{1}{2i\pi}\int_{4M_\pi^2}^{\infty} ds' \frac{\mathrm{disc}\mathcal{A}(s')}{s'-s-i\varepsilon},$$

- Analytic solution:

$$\mathcal{A}(s) = \mathcal{A}(\eta\to 2\pi^0 a)|_{\mathrm{LO}}\times\Omega_0^0(s),$$

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

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



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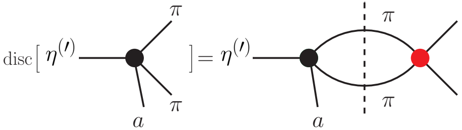

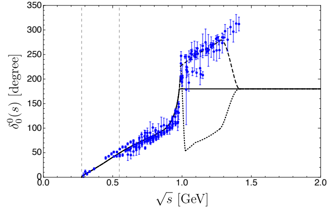

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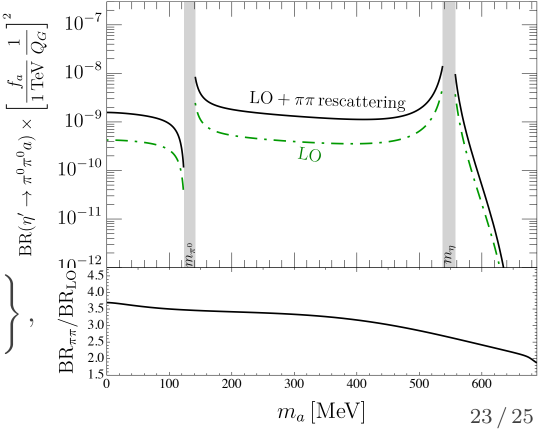
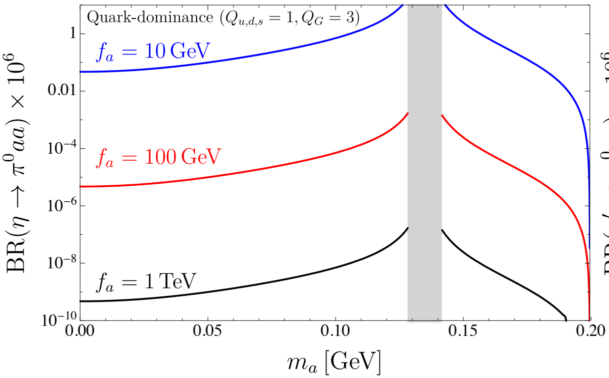
S. Gonzàlez-Solís and D. Spier, to appear

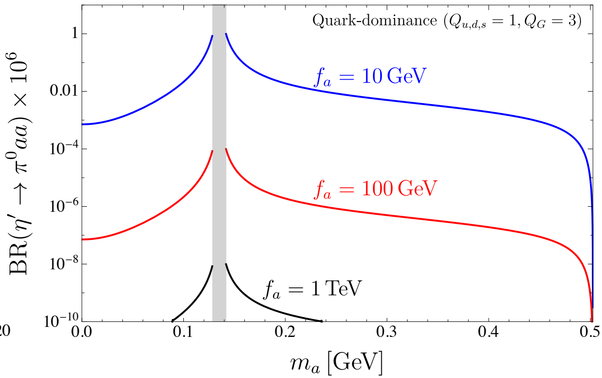


$\eta/\eta' \to \pi^0 aa$ decays

- One extra power of $1/f_a$ suppression

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





Summary

- 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
- 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)