

η/η' decays into ALPs

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Precision Tests of Fundamental Physics with Light Mesons

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Abstract

Hadronic and radiative decays of light mesons provide a unique laboratory to test low-energy Quantum Chromodynamics and search for new physics beyond the Standard Model. Recent years have brought advances in theoretical and experimental approaches throughout the hadron and particle physics community. New experimental data will soon offer critical input to precisely determine e.g. the light quark mass ratios, meson mixing parameters, and hadronic contributions to the anomalous magnetic moment of the muon. The approaches provide sensitive probes to test potential new physics including searches for hidden photons, light Higgs scalars, and axion-like particles that are complementary to worldwide efforts to detect new light particles below the GeV mass scale, as well as tests of discrete symmetry violation. Experts and respective communities will discuss updates on theoretical developments, experimental strategies, and identify further research.

Organizers

Susan Schadmand (GSF, Darmstadt), Bastian Kubis (HISKP Bonn, Germany), Igor Jaegle (Jefferson Lab, USA), Daniel Lersbø (FSU Tallahassee, USA)

Speakers

Hakan Akdag, Miguel Albaladejo, Marco Battaglieri, Luigi Capozza, Saskia Charity, Izabela Clepal, Olga Cortes Becerra, Andreas Crivellin, Igor Danilkin, Shuangshi Fang, Liping Gan, Susan Gardner, Ashot Gasparian, Antoine Gerardin, Simona Giovannella, Sergi González-Solís, Martin Hoferichter, Bai-Long Hoid, Simon Holz, Garth Husek, Tomas Husek, Igor Jaegle, Karol Kampf, Andrzej Kupsc, Jari Mäkinen, Edoardo Mornacchi, Bachir Moussallam, Frédéric Noël, Konstantin Otmad, Emilie Passemar, Alessandro Pilloni, Pablo Sanchez Puertas, Hannah Schäfer, Adam Szczepanek, Simon Taylor, Sean Tulin

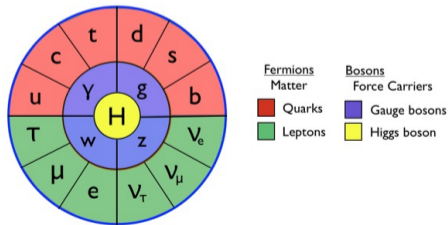
Director of ECT*: Professor Gert Aarts

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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)

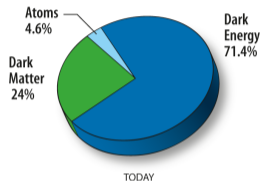


Particles of the Standard Model

Beyond the Standard Model

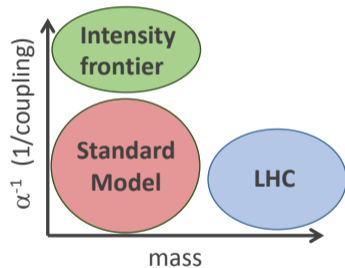
- However, the SM **fails** to explain several observed phenomena in particle physics, astrophysics and cosmology:

- **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 ($K_L \rightarrow \pi^0 \nu \bar{\nu}$), ^8Be excited decay, ...



Energy and Intensity Frontier Research

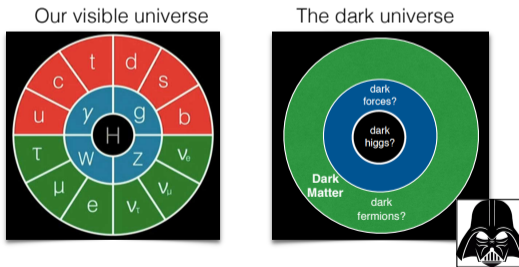
- **New Physics** would be needed to explain observed phenomena
- Why have **not** new particles yet been observed?
 - Hypothetical new particles are **heavy** and require even higher collision energy to be observed \Rightarrow **Energy Frontier** research (LHC@CERN, Tevatron@FermiLab)
 - Another possibility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



(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)

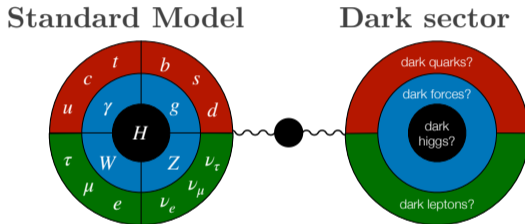


- We live in the SM world, how can we **access** (and test) the **dark sector**?

Dark sector portals to the Standard Model

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

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



Portal

Vector

Scalar

Neutrino

Axion

Mediators

Dark photon

Dark scalar

Sterile Neutrino

Axion

Portal interactions

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

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

$$y H L N$$

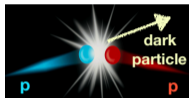
$$\frac{a}{f_a} \tilde{G}_{\mu\nu} G^{\mu\nu}$$

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



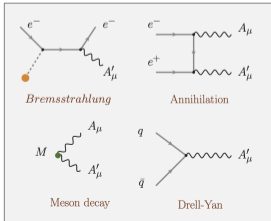
Unique access to dark sectors!

Other ongoing/future experiments

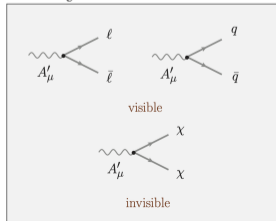


- Plenty of dark particles can be produced from **meson decays!!**

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.*:
 - $\eta/\eta' \rightarrow 3\pi$ break isospin, $\eta/\eta' \rightarrow 2\pi, 4\pi^0$ by P and CP, $\eta/\eta' \rightarrow \gamma\gamma$ 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')	$\eta/\eta' \rightarrow \gamma^{(*)} A'$	$A' \rightarrow \ell^+ \ell^-$	Bump-hunt in $d\Gamma/dm_{\ell\ell}$
		$A' \rightarrow \pi^+ \pi^-$	Bump-hunt in $d\Gamma/dm_{\pi\pi}$
Leptophobic boson (B)	$\eta \rightarrow \gamma B$	$B \rightarrow \gamma \pi^0$	Enhancement in $m_{\pi^0 \gamma}$
		$B \rightarrow \pi^+ \pi^-$	Isospin suppressed
	$\eta' \rightarrow \gamma B$	$B \rightarrow \gamma \pi^0, \pi^+ \pi^-, \pi^+ \pi^- \pi^0, \gamma \eta$	Enhancement in $m_{\pi^0 \gamma}$
ALPs (a)	$\eta \rightarrow \pi \pi a$	$a \rightarrow \gamma \gamma, \ell^+ \ell^-$ ($\ell = e, \mu$)	Bump-hunt in $d\Gamma/dm_{\gamma\gamma}$
	$\eta' \rightarrow \pi \pi a$	$a \rightarrow \gamma \gamma, \ell^+ \ell^-, \pi^+ \pi^- \gamma, 3\pi$	Bump-hunt in $d\Gamma/dm_{\gamma\gamma}$
	$\eta^{(\prime)} \rightarrow \ell^+ \ell^-$		$\eta^{(\prime)}-a$ mixing
Scalar boson (S)	$\eta/\eta' \rightarrow \pi^0 S$	$S \rightarrow \gamma \gamma, \ell^+ \ell^-, \pi \pi$	Bump-hunt in $d\Gamma/dm_{\gamma\gamma}$
	$\eta' \rightarrow \eta S$	$S \rightarrow \gamma \gamma, \ell^+ \ell^-, \pi \pi$	Bump-hunt in $d\Gamma/dm_{\gamma\gamma}$

Other meson decays

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

Lagrangian for ALPs coupled to QCD

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

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

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

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

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

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

Lagrangian for ALPs coupled to mesons

- Step 1: **map** \mathcal{L}_{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 \Rightarrow mixing angles

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

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

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

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

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

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

Mixing angles I

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

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

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

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

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

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

One can **fix** m_0^2 from the physical $m_{\bar{\eta}(\nu)}^2$ mass, which yields $m_0 = 0.807$ GeV and $\theta = -21.4^\circ$, or from the measured mixing angle $\theta = -13.3^\circ$, 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

$$\begin{aligned} \begin{pmatrix} \pi_3 \\ \bar{\eta} \\ \bar{\eta}' \\ a \end{pmatrix} &= \begin{pmatrix} \cos \epsilon_{\pi\eta} & -\sin \epsilon_{\pi\eta} & 0 & 0 \\ \sin \epsilon_{\pi\eta} & \cos \epsilon_{\pi\eta} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos \epsilon_{\pi\eta'} & 0 & -\sin \epsilon_{\pi\eta'} & 0 \\ 0 & 1 & 0 & 0 \\ \sin \epsilon_{\pi\eta'} & 0 & \cos \epsilon_{\pi\eta'} & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \pi^0 \\ \eta \\ \eta' \\ a \end{pmatrix}, \\ &\simeq \begin{pmatrix} 1 & -\epsilon_{\pi\eta} & -\epsilon_{\pi\eta'} & 0 \\ \epsilon_{\pi\eta} & 1 & 0 & 0 \\ \epsilon_{\pi\eta'} & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \pi^0 \\ \eta \\ \eta' \\ a \end{pmatrix} + \mathcal{O}(\epsilon_{\pi\eta}\epsilon_{\pi\eta'}). \end{aligned}$$

- The mixing angles **satisfy**:

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

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

Mixing angles II

- After this rotation, the mass matrix becomes:

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

where

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

- 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:

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

- 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

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

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

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

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

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

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

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

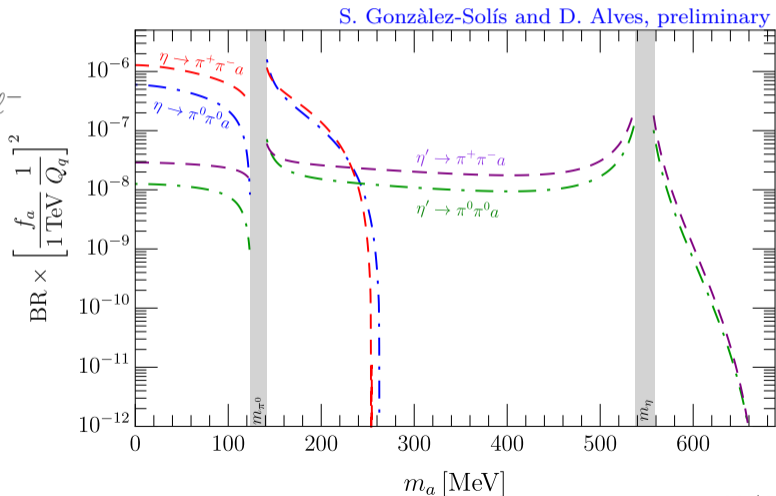
Branching ratio for $\eta/\eta' \rightarrow \pi\pi a$

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

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

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

(BESIII, KLOE,
CMS, REDTOP)



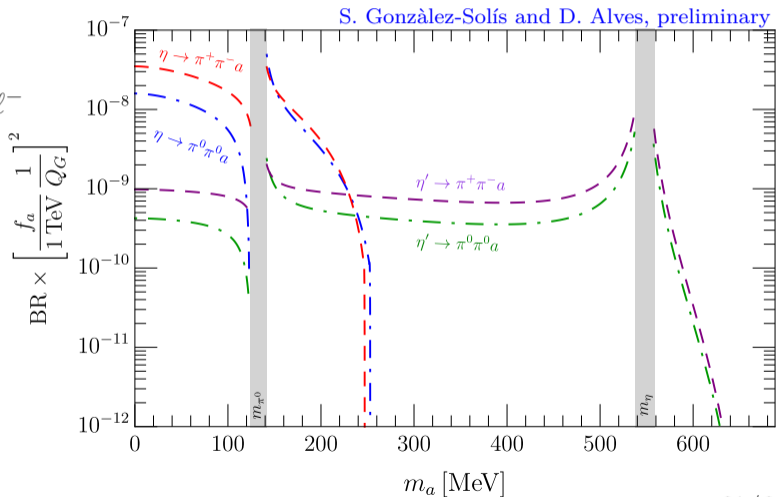
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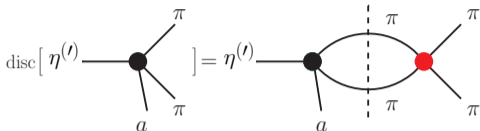
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Effects of pion-pion rescattering

- Unitarity:



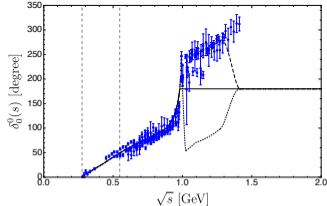
$$\text{disc} \mathcal{A}(s) = 2i \mathcal{A}(s) \sin \delta_0^0(s) e^{-i\delta_0^0(s)},$$

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

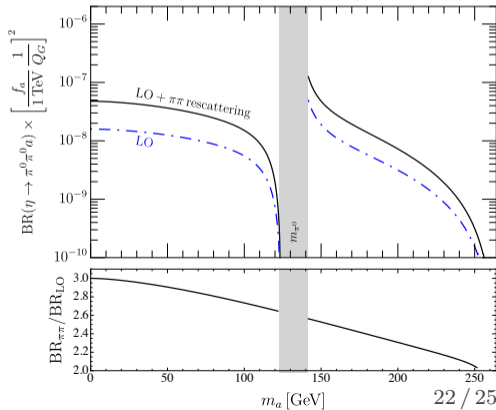
- Analytic solution:

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

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

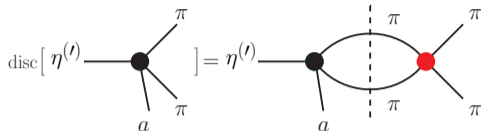


S. González-Solís and D. Spier, to appear



Effects of pion-pion rescattering

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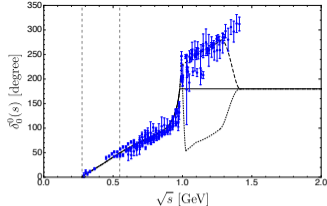
$$\text{disc}\mathcal{A}(s) = 2i\mathcal{A}(s)\sin\delta_0^0(s)e^{-i\delta_0^0(s)},$$

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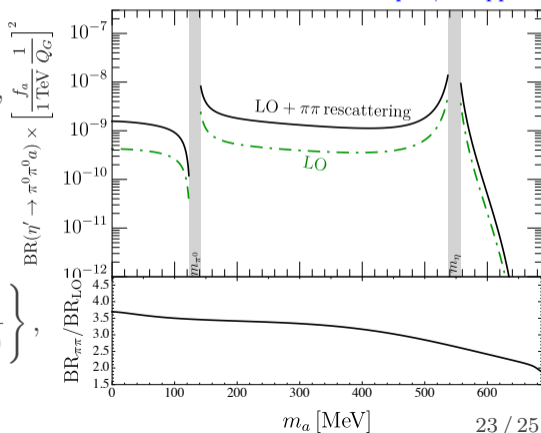
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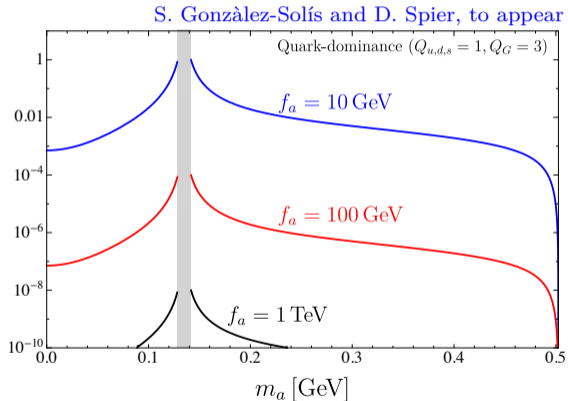
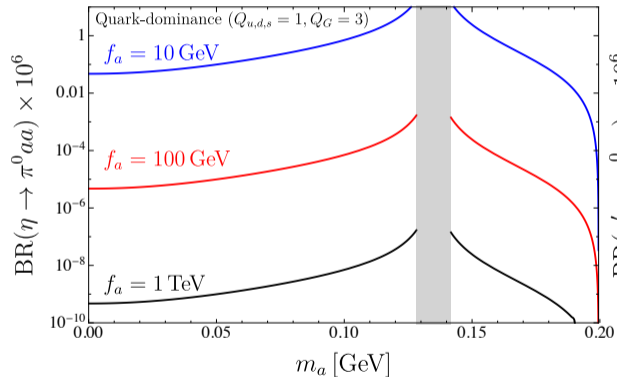


S. González-Solís and D. Spier, to appear



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

- One extra power of $1/f_a$ suppression



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 $\eta/\eta' \rightarrow \pi\pi a$ decays
 - We encourage searches in $\eta/\eta' \rightarrow \pi\pi a \rightarrow \pi\pi\gamma\gamma, \pi\pi\ell^+\ell^-$ (BESIII, KLOE, CMS, REDTOP)