Probing low-energy QCD and BSM physics with light mesons

Sergi Gonzàlez-Solís (sergig@lanl.gov)

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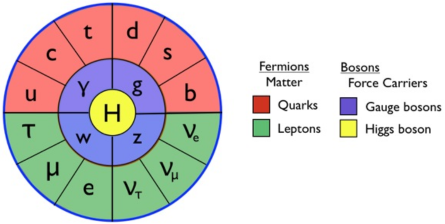
Los Alamos NATIONAL LABORATORY

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)



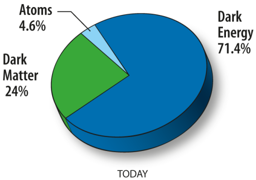
Particles of the Standard Model

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?



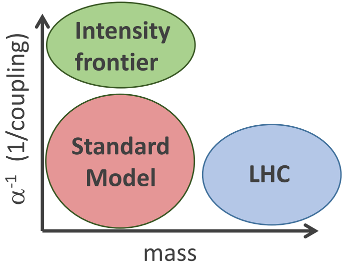
  — **Neutrino** masses and oscillations: why do neutrinos have mass? what makes neutrinos disappear and then re-appear in a different form?

  — **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

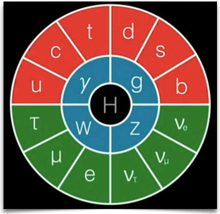
- **New Physics** would be needed to explain observed phenomena
- Why have **not** new particles yet been observed?
  - Hypothetical new particles are **heavy** and require even higher collision energy to be observed ⇒ **Energy Frontier** research (LHC@CERN, Tevatron@FermiLab)
  - Another possibility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



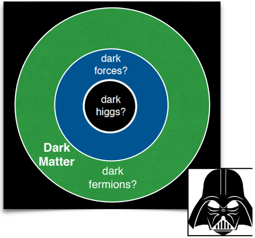
Dark sector physics

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

Our visible universe



The dark universe

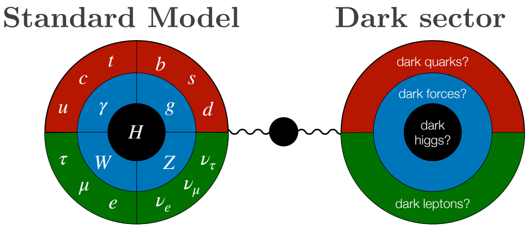


- We live in the SM world, how can we **access** (and test) the **dark sector**?

Dark sector portals to the Standard Model

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

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



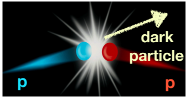
Portal	Mediators	Portal interactions
Vector	Dark photon	$\epsilon B^{\mu\nu} A'_{\mu\nu}$
Scalar	Dark scalar	$\kappa \|H\|^2 \|S\|^2$
Neutrino	Sterile Neutrino	$yHLN$
Axion	Axion	$\frac{a}{f_a} \tilde{F}_{\mu\nu} F^{\mu\nu}$

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

Unique access to dark sectors!

Other ongoing/future experiments

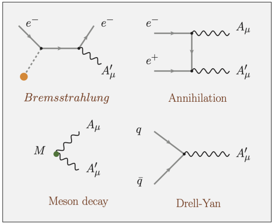
REDTOP

P326 NA62

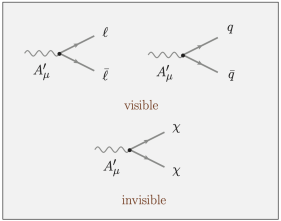
E906

- 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 [talks by S. Schadmand, L. Gan]:
  - 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 $m_{\pi^0\gamma}$

See also talks by [J. Pinzino, A. Notari]

Testing Axion-like particles with η/η' decays

- ALP Lagrangian coupled to QCD

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

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

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

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

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

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

$$\pi^0 \to \pi^0 + \theta_{a\pi} a^{\rm phys}\,, \quad \eta_8 \to \cos\theta\eta + \sin\theta\eta' + \theta_{\eta_8 a} a^{\rm phys}\,, \quad \eta_0 \to -\sin\theta\eta + \cos\theta\eta' + \theta_{\eta_0 a} a^{\rm phys}\,,$$

- ALP mass

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

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

- $\eta/\eta' \to \pi\pi a$ decay amplitude:

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

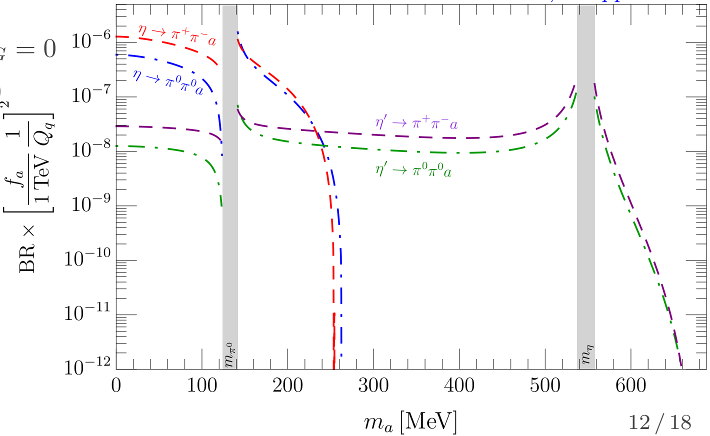
- Two scenarios:
  - **Quark-dominance**: $Q_{GG} = 0$
  - Gluon-dominance: $Q_q = 0$
- We can search for:

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

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

(BESIII, KLOE, CMS, REDTOP)

S. Gonzàlez-Solís and D. Alves, to appear soon



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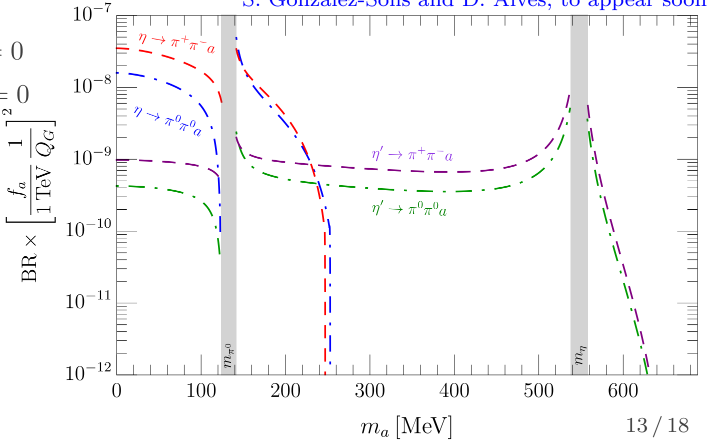
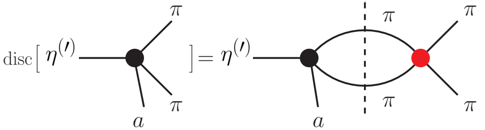


Effects of pion-pion rescattering

- Unitarity:



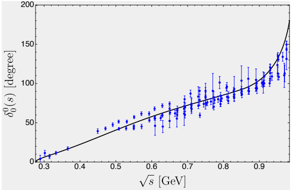
$$\mathrm{disc}\mathcal{A}(s) = 2i\mathcal{A}(s)\sin\delta_0^0(s)e^{-i\delta_0^0(s)}\,,$$

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

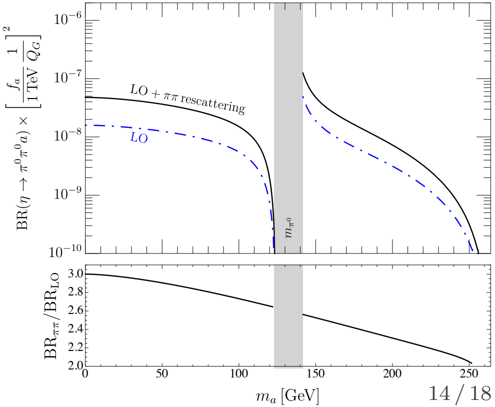
- Analytic solution:

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

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



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



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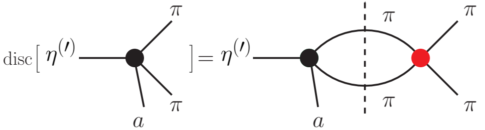

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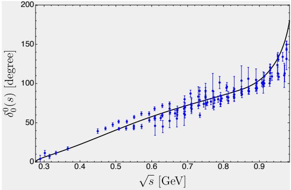
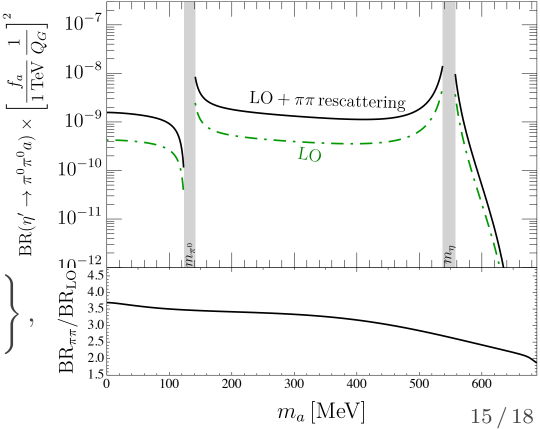


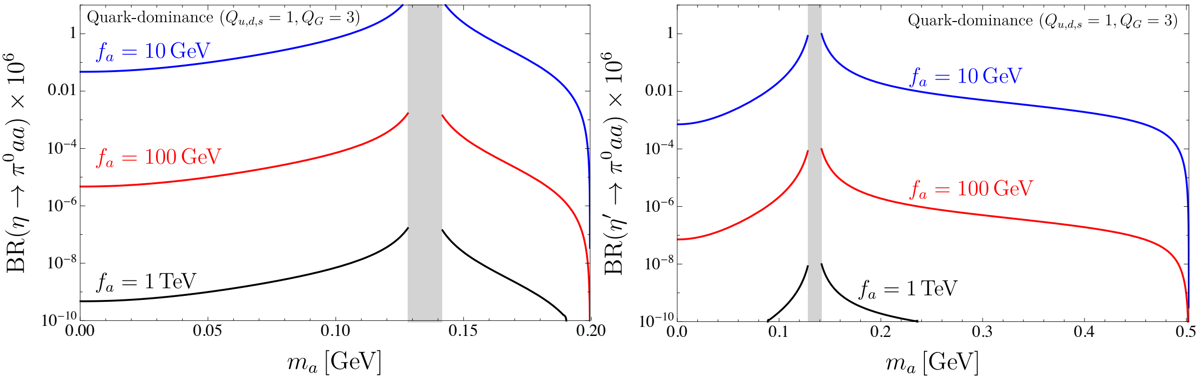
S. Gonzàlez-Solís and D. Spier, to appear



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

- One extra power of $1/f_a$ suppression

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

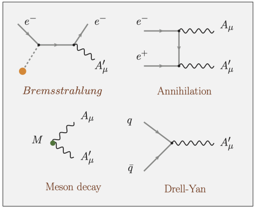


Summary

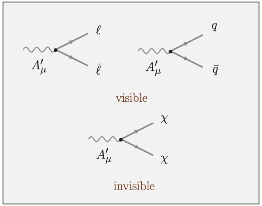
- Exploring **dark sectors** is an important and growing element of BSM physics
- A wealth of exciting ongoing **experiments** exist
- **Meson decays** offer a unique opportunity to look for New Physics
- We have tested ALPs with $\eta/\eta' \to \pi\pi a$ decays
  - We encourage searches in $\eta/\eta' \to \pi\pi a \to \pi\pi\gamma\gamma, \pi\pi\ell^+\ell^-$ (BESIII, KLOE,CMS, REDTOP)

Production modes and detection signatures

Production modes

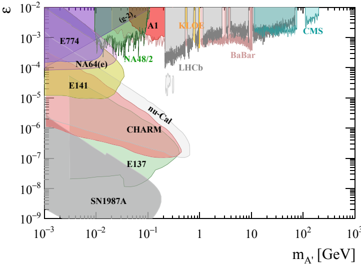


Decay modes

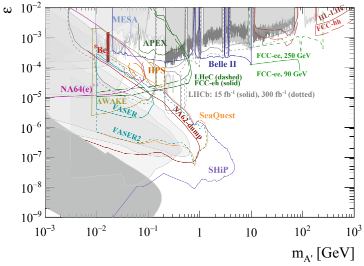


- Broad worldwide effort to search for dark photons (most in $A' \to e^+e^-$ decays)

Current exp. sensitivity



Future prospects



arXiv: 2005.01515