Dark sectors in η,η' decays

Sean Tulin

Review article: Precision tests of fundamental physics with η and η' mesons
L. Gan, B. Kubis, E. Passemar, ST (arxiv:2007.00664)

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$\eta \to 2\gamma$	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)
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$\eta \to 4\pi^0$	$< 6.9 \times 10^{-7}$	P/CP violation

Many η final states relevant for SM and BSM physics

Both total and differential rates

Plus many more for η’

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- P,CP violation
- C,CP violation

[Kobzarev & Okun (1964), Prentki & Veltman (1965), Lee (1965), Lee & Wolfenstein (1965), Bernstein et al (1965)]

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Dark sectors (MeV—GeV)

- Vector bosons
- Scalars
- Pseudoscalars (ALPs)

(Plus other channels that have not been searched for to date)

Tagged η and η' data samples

Previous Experiments:

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

Upcoming experiments

Jefferson Eta Factory (JEF) at JLab Hall D (approved)

	η	η'
Tagged mesons	$6.5x10^7$	$4.9x10^7$

per 100 days

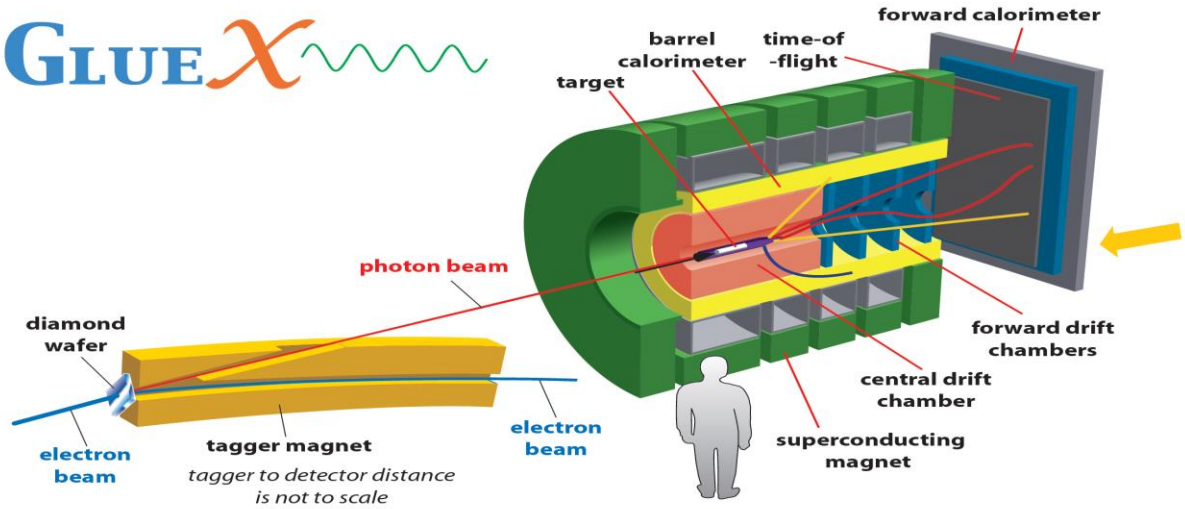
Rare Eta Decays with a TPC for Optical Photons (REDTOP) possibly at Fermilab (proposed)

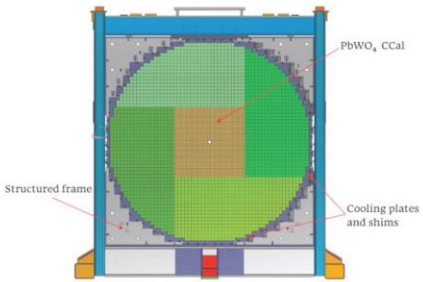
Phase I (untagged mode)	$2x10^{13}$	10^{11}
Phase II+ (tagged mode)	$1x10^{13}$	10^{11}

per year

Slide: Liping Gan

Jefferson Eta Factory (JEF) experiment





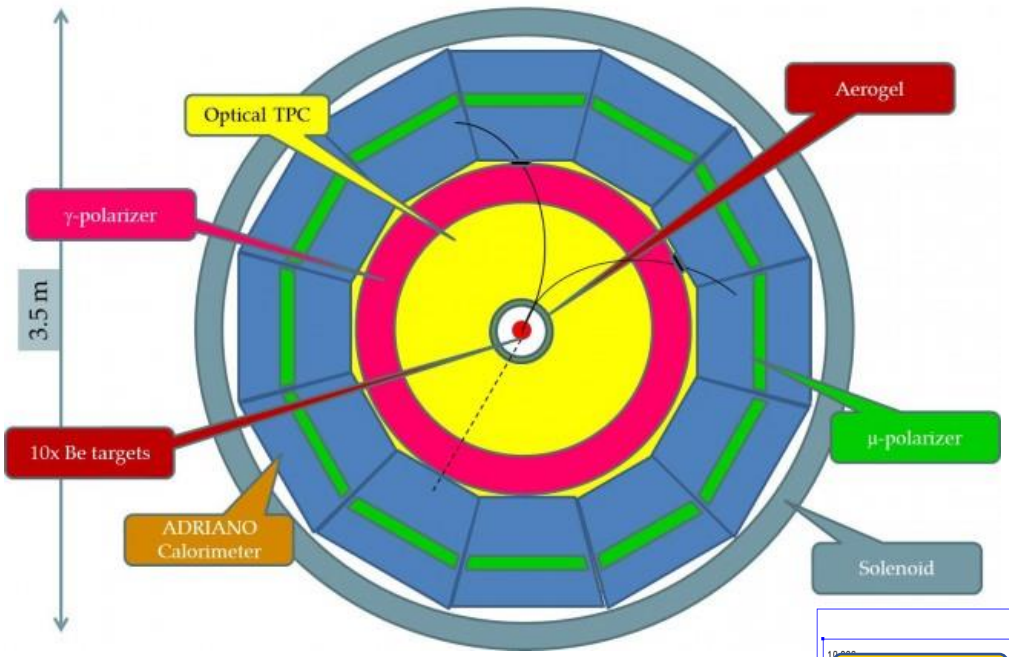
FCAL-II

Simultaneously measure η/η' decays: $\eta \to \pi^0\gamma\gamma$, $\eta \to 3\gamma$, and …

- η/η' produced on LH_2 target with 8.4-11.7 GeV tagged photon beam: $\gamma + p \to \eta/\eta' + p$
- Reduce non-coplanar backgrounds by detecting recoil protons with GlueX detector
- Upgraded Forward Calorimeter with High resolution, high granularity PWO insertion (FCAL-II) to detect multi-photons from the η decays

Main focus on neutral final states to γs and π^0s

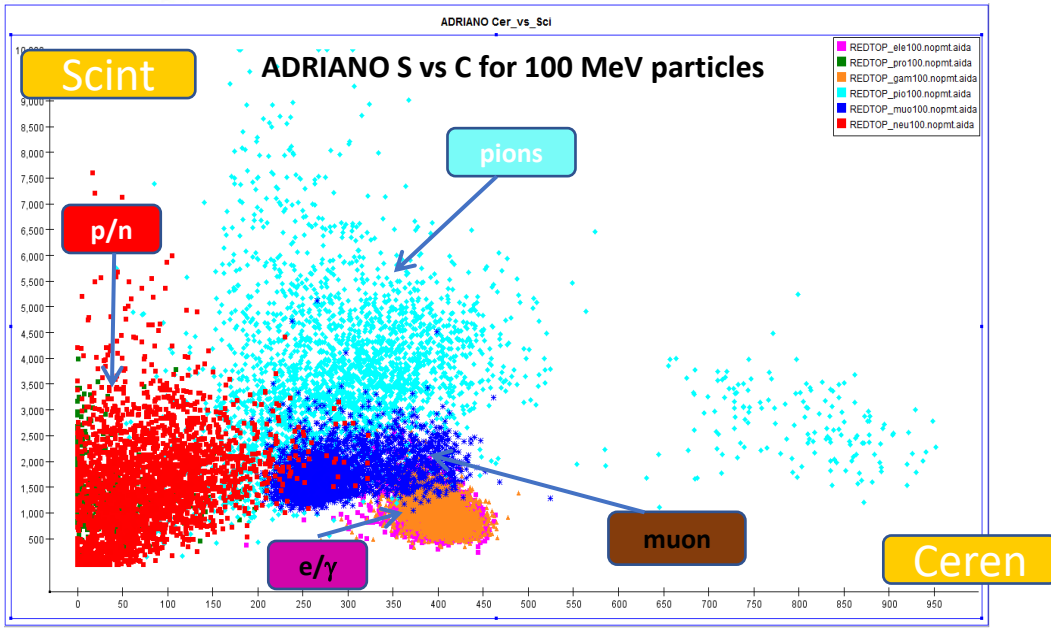
Rare Eta Decays with a TPC for Optical Photons (REDTOP)



~2 (3) GeV proton beam for η (η')

Optical TPC detects muons, electrons, fast pions (Cerenkov), but blind to other hadrons

C. Gatto

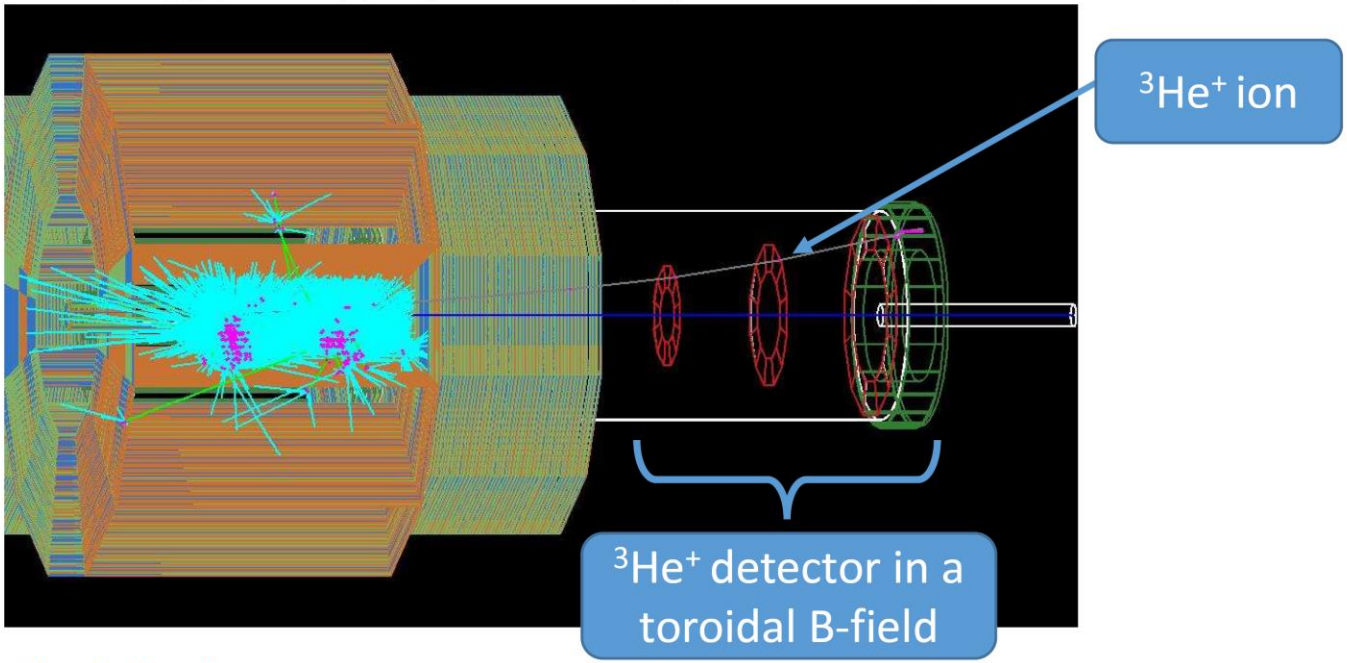


ADRIANO calorimeter detects EM showers (sandwich of scintillator and Cerenkov layers)

Slide: C. Gatto

REDTOP phase II+

Tagged η / η' factory (tREDTOP)



- Production based on the following process:

$$p + De \rightarrow \eta/\eta' + {}^3He^+$$

- The $^3He^+$ ion is produced/detected in a narrow forward cone (3° -5 °)
- Requires 1 MW proton beam at low energy (900 MeV/1700 MeV) and a $^3He^+$ forward detector

Kinematics fully determined and possible to study (partially) invisible decays with high statistics

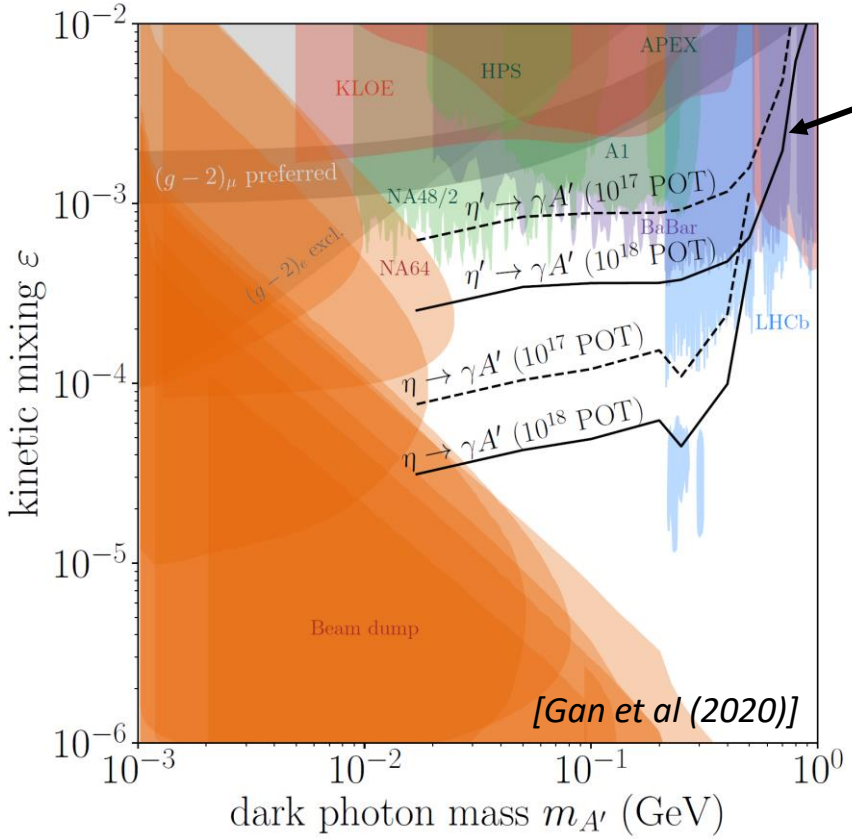
η, η' laboratory for dark sectors

- Focus on visible final states (bump hunt)
- Leading decays of η are already suppressed $\sim \mathcal{O}\left(\alpha_{\rm em}^2\right)$ or $\mathcal{O}\left((m_u - m_d)^2\right)$
- Larger mass reach for η' but worse sensitivity (total width larger by ~100)
- Decays to light hidden particles are 2- or 3-body decays that mimic 3-, 4-, or 5-body final states (often very rare)
- Other possibilities: invisible or partially-invisible decays, displaced vertices

Dark photon

[Fayet (2007), Reece & Wang (2009), …]

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



[Gan et al (2020)]

REDTOP sensitivities projected for FNAL/BNL (10^{18}) or CERN (10^{17}) POT

[Gatto (2019)]

Worthwhile to also consider

$$\eta' \to \pi^+\pi^- A' \to \pi^+\pi^-\ell^+\ell^-$$

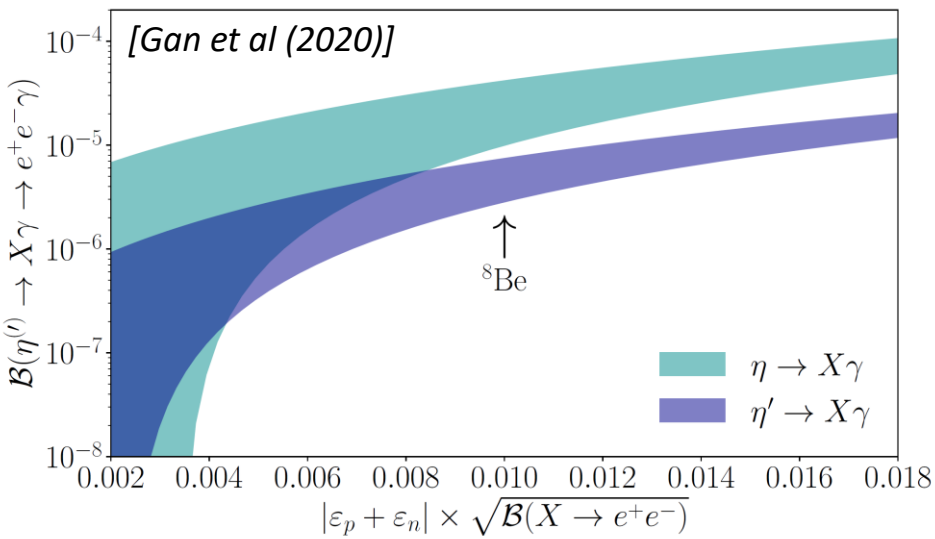
since $\mathcal{B}(\eta' \to \pi^+\pi^-\gamma) \approx 10 \times \mathcal{B}(\eta' \to \gamma\gamma)$

Protophobic X(17) vector boson to explain Atomki ^{8}Be and ^{4}He anomalies

[Feng et al (2016,2017)]

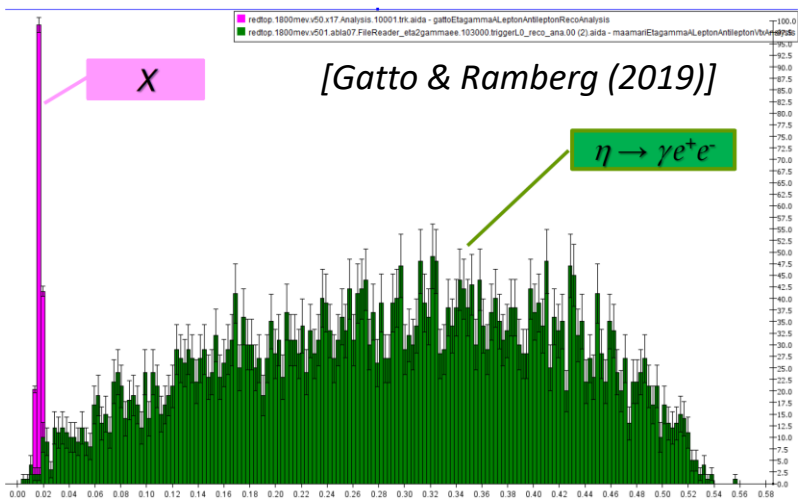
$$\eta, \eta' \to X\gamma \to e^+e^-\gamma$$

Theory prediction



Currently A2@MAMI limited to invariant mass m_{ee} > 30 MeV, but 17 MeV within reach of REDTOP

REDTOP Monte Carlo



Leptophobic B boson from gauged $U(1)_B$

[Lee & Yang (1955), Pais (1973), Nelson & Tetradis (1989), …]

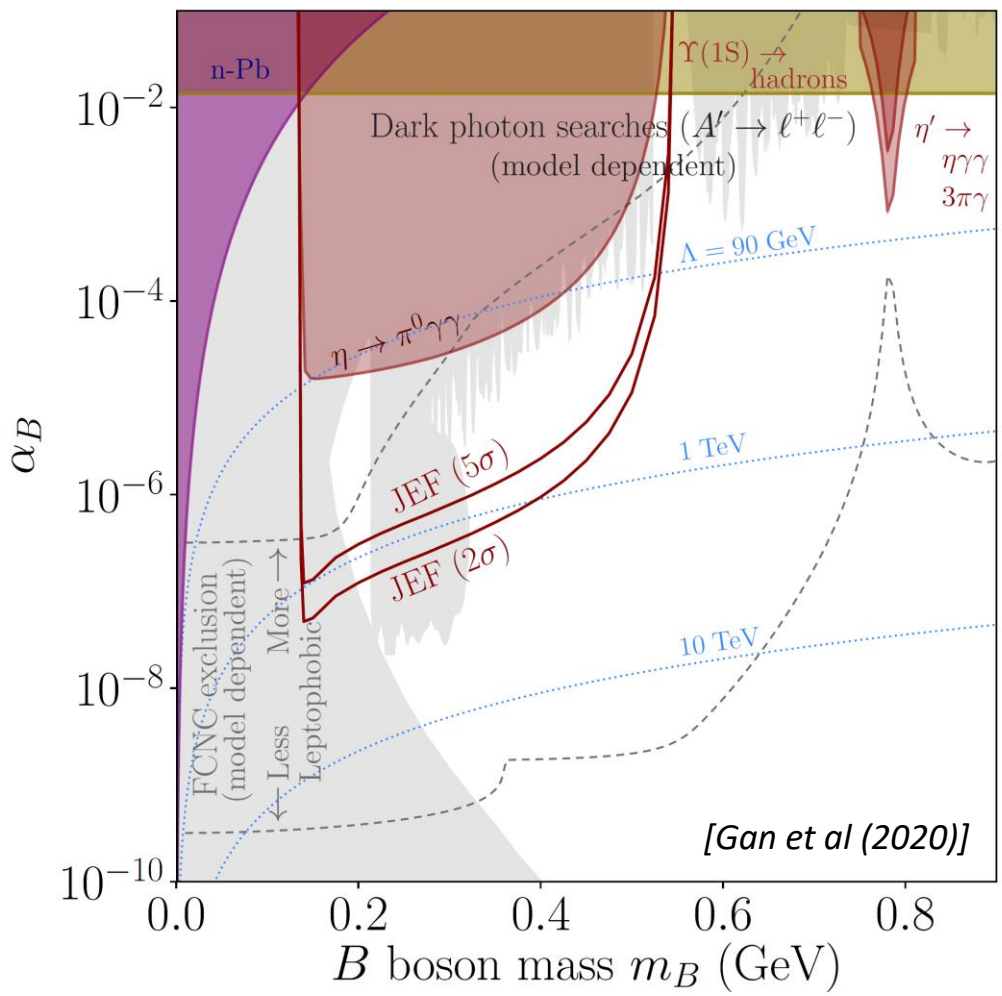
Model:

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

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

Mimics rare decay (0.025%) plus search for $\pi^0\gamma$ resonance

$$\eta' \to B\gamma \to \pi^0\gamma\gamma\,,\ \eta\gamma\gamma$$
$$\pi^+\pi^-\pi^0\gamma$$



Light scalar boson (S)

$$\eta, \eta' \to \pi^0 S \to \pi^0 \ell^+ \ell^- , \quad \eta' \to \eta S \to \eta \ell^+ \ell^-$$

Final states in SM arise via two-γ loop, very suppressed (single-γ process is C-violating)

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

$\gamma\gamma$ resonance in rare decay

$$\eta, \eta' \to \pi^0 S \to 3\pi, \quad \eta' \to \eta S \to \eta\pi\pi$$

Bump-hunting in Dalitz distributions

Light scalar boson (S)

- Originally considered as possible signature for (light) SM Higgs boson

[Ellis et al (1976), Vainshtein et al (1980), Leutwyler & Shifman (1990)]

- Higgs-mixed scalar (Higgs portal model)

$$\mathcal{B}(\eta \to \pi^0 S) \approx 1.8 \times 10^{-6} \sin^2\theta_S \times \lambda^{1/2}\left(1, \frac{M_{\pi^0}^2}{M_\eta^2}, \frac{m_S^2}{M_\eta^2}\right)$$

$$\mathcal{B}(\eta' \to \pi^0 S) \approx 5.4 \times 10^{-8} \sin^2\theta_S \times \lambda^{1/2}\left(1, \frac{M_{\pi^0}^2}{M_{\eta'}^2}, \frac{m_S^2}{M_{\eta'}^2}\right)$$

$$\mathcal{B}(\eta' \to \eta S) \approx 4.7 \times 10^{-5} \sin^2\theta_S \times \lambda^{1/2}\left(1, \frac{M_\eta^2}{M_{\eta'}^2}, \frac{m_S^2}{M_{\eta'}^2}\right)$$

[Gan et al (2020)]

Scalar mixing angle $\theta_S < 10^{-3}$ in accessible mass range

Not competitive with other probes from FCNCs

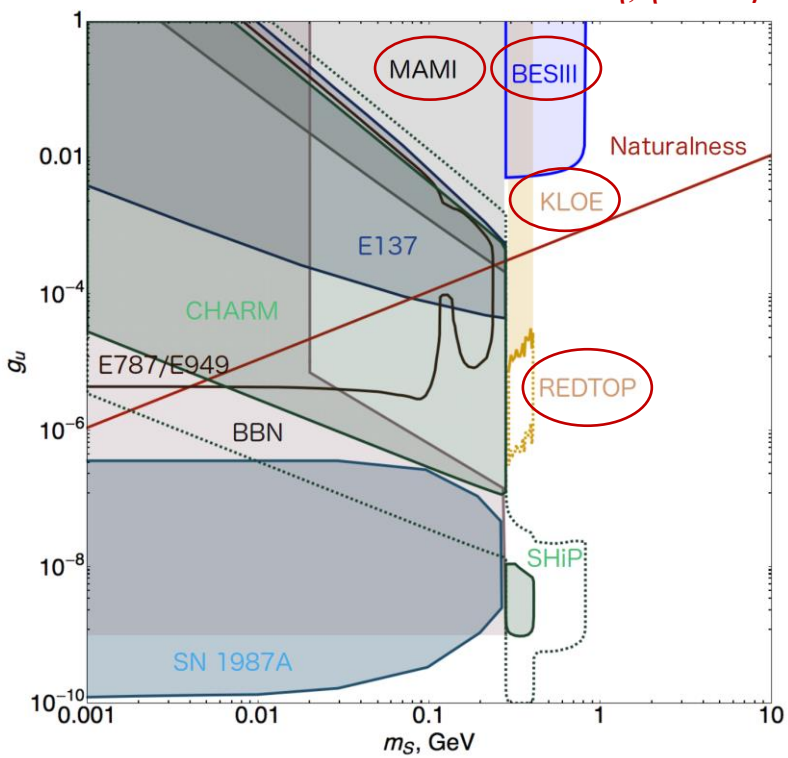
[Beacham et al (2019)]

- General scalar model:
  η,η' sensitive to light-quark couplings, FCNCs sensitive to top coupling

Hadrophilic scalar boson

[Batell et al (2017,2018)]

Constraints from η,η' decays



Light scalar coupling to *u*-quarks only

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

$$\eta, \eta' \to \pi^0 S \to 3\pi$$

More general couplings to *u,d*-quarks and e, μ, γ *[e.g., Liu, Cloet, Miller (2018)]*

Motivates searches for

$$\eta \to \pi^0 S \to \pi^0 \gamma\gamma,\ \pi^0 e^+ e^-,\ \pi^0 \mu^+ \mu^-$$

$$\eta, \eta' \to \pi^0 S \to 3\pi, \quad \eta' \to \eta S \to \eta\pi\pi$$

Axion-like particles (ALPs) and η,η' decays

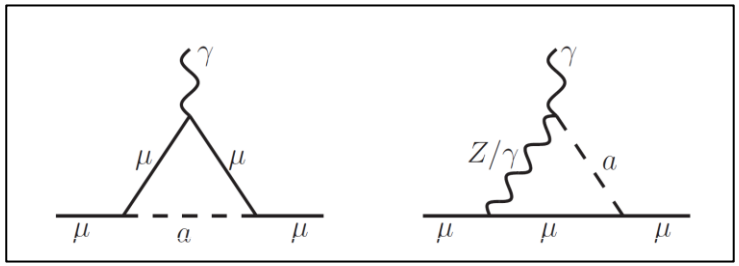
[Aloni et al (2019), Landini and Meggiolaro (2019)]

Model:

$$\mathcal{L}_{\rm ALP} = \mathcal{L}_{\rm QCD} + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{1}{2}m_0^2 a^2 - \frac{\alpha_s}{8\pi f_a} a\, G^a_{\mu\nu}\tilde{G}^{a\mu\nu} - \underbrace{\frac{\alpha_{\rm em} c_\gamma}{8\pi f_a} a\, F_{\mu\nu}\tilde{F}^{\mu\nu}} - \frac{\partial^\mu a}{2f_a}\bar{q}c_q\gamma_\mu\gamma_5 q - \underbrace{\frac{\partial^\mu a}{2f_a}\bar{\ell}c_\ell\gamma_\mu\gamma_5\ell}$$

Contribution to $(g\text{-}2)_\mu$

[Marciano et al (2016), Bauer et al (2017)]



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Signatures: many complicated 4- and 5-body final states

$$\eta \to \pi\pi a \to \pi\pi\gamma\gamma\,,\ \pi\pi e^+e^-\,,\ \pi\pi\mu^+\mu^-$$ (and same for η')

$$\eta' \to \pi\pi a \to \pi\pi\,\pi^+\pi^-\gamma\,,\ 5\pi$$

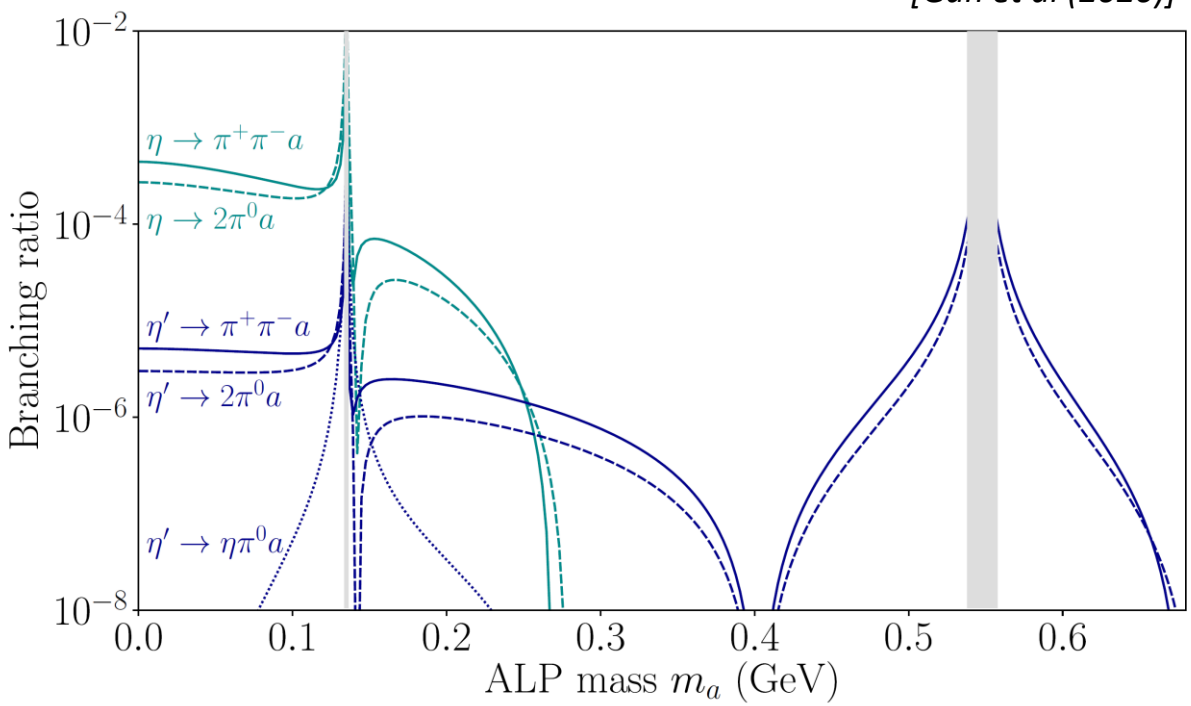
$$\eta' \to \eta\pi^0 a \to \eta\pi^0\gamma\gamma\,,\ \eta\pi^0 e^+e^-\,,\ \eta\pi^0\mu^+\mu^-$$

Most of these had no motivation to be studied. Can they be searched for?

η,η' branching ratios into ALPs

Fixed effective mass scale $\Lambda/|C_{GG}| = 32\pi^2 f_a \approx 3\,\mathrm{TeV}$

[Gan et al (2020)]



Calculated BR at leading order in χPT, but possible large corrections at NLO

Invisible and partially-invisible decays

- $\eta, \eta' \rightarrow$ invisible *[Gninenko & Krasnikov (2016)]*
- $\eta, \eta' \rightarrow \gamma A' \rightarrow \gamma$ + invisible
- $\eta, \eta' \rightarrow \gamma A' \rightarrow \gamma e^+ e^-$ + invisible *[Mohlabeng (2019), Tsai et al (2019)]*

Conclusions: η,η' physics – synergy of SM and BSM

Vector boson models: Models, parameter space, sensitivities well-studied

Scalar bosons, ALP models: Specific models studied but general framework needs further study.

Invisible (and partially) channels: What are the models and signatures?