η, η’ mesons as laboratories for new light physics

Sean Tulin (York U)
on behalf of the REDTOP collaboration

History: η, η'-mesons as "BSM" laboratories

Proposal of discrete symmetry violation	*Purcell & Ramsey (1950)*
Parity violation in beta decay	*Lee & Yang (1955); Wu et al (1957)*
CP violation (CPV) in $K_L \to \pi\pi$	*Christenson et al (1964)*

CPV weak decays via KM mechanism	*Kobayashi & Maskawa (1973)*
… establishment of Standard Model	

History: η, η'-mesons as "BSM" laboratories

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CP violation (CPV) in $K_L \to \pi\pi$ — *Christenson et al (1964)*

Interlude: spotlight on η,η'

New "semi-strong" force (H')

Prentki & Veltman; Lee; Lee & Wolfenstein; Bernstein et al (1965)

$H_{CPV} = H_{weak} \times H'$

S-violating CP-preserving

S-preserving CP-violating

Test CPV without changing strangeness

New unsuppressed decays

$$\eta, \eta' \to 3\gamma,\ 2\pi,\ \pi^0\ell^+\ell^-$$

New asymmetries

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

Breaking the Law

The news from the USA caused great excitement in the world of sub-nuclear physics; once again one of the accepted laws about the behaviour of elementary particles appeared to have been broken. In this article we will try to explain what the excitement is about.

CERN Courier Vol 6, Number 9, 1966

CPV weak decays via KM mechanism — *Kobayashi & Maskawa (1973)*

… establishment of Standard Model

Motivation for η, η’ factory

ELSEVIER

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Precision tests of fundamental physics with η and η' mesons

Liping Gan [a], Bastian Kubis [b], Emilie Passemar [c d e], Sean Tulin [f]

Motivation for η, η’ factory

Accidentally small widths:

$\Gamma_{\eta} = 1.31$ keV, $\Gamma_{\eta'} = 230$ keV

Channel	Expt. branching ratio	Discussion
$\eta \to 2\gamma$	39.41(20)%	chiral anomaly,
$\eta \to 3\pi^0$	32.68(23)%	$m_u - m_d$
$\eta \to \pi^+\pi^-\pi^0$	22.92(28)%	$m_u - m_d$,

Compare to vector mesons:

$\Gamma_{\rho} = 150$ MeV, $\Gamma_{\omega} = 8.49$ MeV, $\Gamma_{\varphi} = 4.26$ MeV

Access suppressed flavor-conserving SM processes to test QCD at low-energy

Search for BSM physics in η, η’ decays

Motivation for η, η' factory

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$\eta \to 3\pi^0$	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)
$\eta \to 4\gamma$	$< 2.8 \times 10^{-4}$	$< 10^{-11}$[55]
$\eta \to \pi^+\pi^-\pi^0$	22.92(28)%	$m_u - m_d$, C/CP violation, light Higgs scalars
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$\eta \to \mu^+\mu^-\gamma$	$3.1(4) \times 10^{-4}$	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
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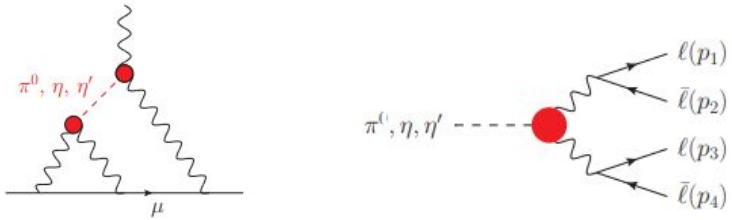
$\eta \to \pi^+\pi^-$	$< 4.4 \times 10^{-6}$ [56]	P/CP violation
$\eta \to 2\pi^0$	$< 3.5 \times 10^{-4}$	P/CP violation
$\eta \to 4\pi^0$	$< 6.9 \times 10^{-7}$	P/CP violation

Gan, Kubis, Passamar, ST (2020)

Motivation for η, η’ factory

Standard Model highlights

- Extraction of light quark masses (m_u - m_d)
- Tests of χPT and extensions
- Theory input for light-by-light scattering for $(g\text{-}2)_\mu$



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Dark sectors (MeV-GeV)

- Vector bosons (dark photon, X_{17}, hadrophilic, …)
- Light Higgs scalars
- Axions and ALPs

Fundamental symmetry tests

- C violation
- CP violation

Many effects strongly constrained by EDMs, but can test CPV for 2nd generation

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Gan, Kubis, Passamar, ST (2020)

Motivation for η, η’ factory

Dark sectors (MeV-GeV)

- Vector bosons
  (dark photon, X_{17}, hadrophilic bosons, …)

$$\eta, \eta' \to \gamma V \to \ell^+\ell^-,\ \pi^+\pi^-,\ \pi^0\gamma,\ \pi^+\pi^-\pi^0,\ \text{invis.}$$

- Light Higgs scalars

$$\eta, \eta' \to \pi^0 S \to \ell^+\ell^-,\ \pi^+\pi^-,\ \pi^0\pi^0,\ \gamma\gamma,\ \text{invis.}$$

- Axions and ALPs

$$\eta, \eta' \to \pi\pi a \to \ell^+\ell^-,\ 3\pi,\ \gamma\gamma,\ \text{invis.}$$

Search strategies:

- BSM mimics rare decays: e.g.

$\eta \to \pi^0\gamma\gamma$ Suppressed in χPT

$\eta \to \pi^0\ell^+\ell^-$ CPV as single-γ

$\eta \to \pi^0\pi^0\ell^+\ell^-$ CPV as single-γ

- Bump hunting
- Displaced vertices
- (Semi-)invisible decays

η, η’ samples: past, present, and future

Previous:

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

On-going:

Jefferson Eta Factory (JEF)	$6x10^7$ per 100 days	$5x10^7$ per 100 days

Proposed:

REDTOP (3-year run)	**$5x10^{13}$ per year**	**~$5x10^{11}$ per year**
HHAS at HIAF	$7x10^{12}$ per year	…
NA64h (invisible decays)	10^8	10^8

REDTOP (Rare Eta Decays To Observe new Physics)

Hidden-sectors search and probe of discrete symmetries at the REDTOP experiment

C. Gatto[a,1,2], B. Kubis[b,3], A. Mazzacane[c,22], M. Zieliński[d,4], W. Abdallah[5], A. Alqahtani[6], D. S. M. Alves[7], W. Baldini[8], S. Barbi[9], B. Batell[10], A. Belias[11], J. M. Berryman[12], M. Berlowski[13], J. Bijnens[14], B. Bilki[15,16], G. Blazey[17], R. Carosi[18], X. Chen[19], S. Charlebois[20], P. Chintalapati[17], J. Comfort[21], J. Dey[22], V. Di Benedetto[22], B. Dobrescu[22], A. Dychkant[17], D. Egana-Ugrinovic[23], J. Elam[24], S. Escobar[25], R. Escribano[26], D. Fagan[22], B. Fabela-Enriquez[27], M. Figora[2], K. Francis[2], A. Freitas[10], J. Freeman[22], J. Friese[28], R. Gandhi[29], R. Gardner[30], S. Gardner[31], D. N. Gao[32], F. Gautier[33], E. Gianfelice-Wendt[34], S. Gonzalez-Solis[35], D. Guadagnoli[36], M. Guida[37,1], A. Gutierrez-Rodriguez[38], E. Hahn[22], L. Harland-Lang[39], D. Herrera[25], M. A. Hernandez-Ruiz[38], S. Homiller[10], Q. Hu[19], A. Ismail[40], T. Isidori[33], J. Jaeckel[41], M. Jadhav[24], C. Johnstone[22], J. Johnstone[22], Y. Kahn[42], A. Kievsky[18], J. Konisberg[43], T. Kobilarcik[22], W. Krzemień[13], A. Kronfeld[22], A. Kupść[44,13], D. Leon[25], Y. Litvinov[11,45], S. Los[22], M. Lucente[46], K. Maamari[47], L. E. Marcucci[48], T. Malla[2], P. Masjuan[26], P. Mauskopf[21], D. McFarland[21], D. McKeen[49], P. Meade[50], J. Metcalfe[24], D. Milstead[51], N. Minafra[33], N. Mokhov[22], C. Mugoni[9], M. Murray[33], A. Mane[24], A. Novikov[33], Y. Onel[16], M. Olvegård[44], S. Pastore[7], J. Pastika[22], P. Paschos[30], S. Pascoli[46], E. Passemar[52,53], I. Pedraza[25], W. Pellico[22], A. Petrov[54], A. Pla-Dalmau[22], M. Pospelov[55], V. Pronskikh[56], J. F. Pratte[20], J. Rauch[22], E. Ramberg[22], M. Rai[10], L. Ristori[22], C. Rogan[33], S. Roy[57], E. Royo[58], C. Royon[33], P. Rubinov[22], F. Sala[46], P. Sanchez-Puertas[59], V. Santoro[14], E. Schmidt[22], Z. Sheemanto[2], J. Shi[60], D. Silverio[25], C. Siligardi[9], M. Silarski[4], M. Spannowsky[61], M. Syphers[2], L. Thomas[21], D. Torretta[22], Y. D. Tsai[62], S. Tulin[63], M. Viviani[18], D. Winn[64], M. Wolke[44], X. Yan[31], Z. Ye[65], V. Zutshi[17]

arXiv:2606.12158 [hep-ex]

Collaboration:
138 collaborators
62 institutions
15 countries

Spokesperson: Corrado Gatto

REDTOP (Rare Eta Decays To Observe new Physics)

Baseline mode: proton beam (1.8-4.0 GeV) on Li/Be target (untagged η,η')

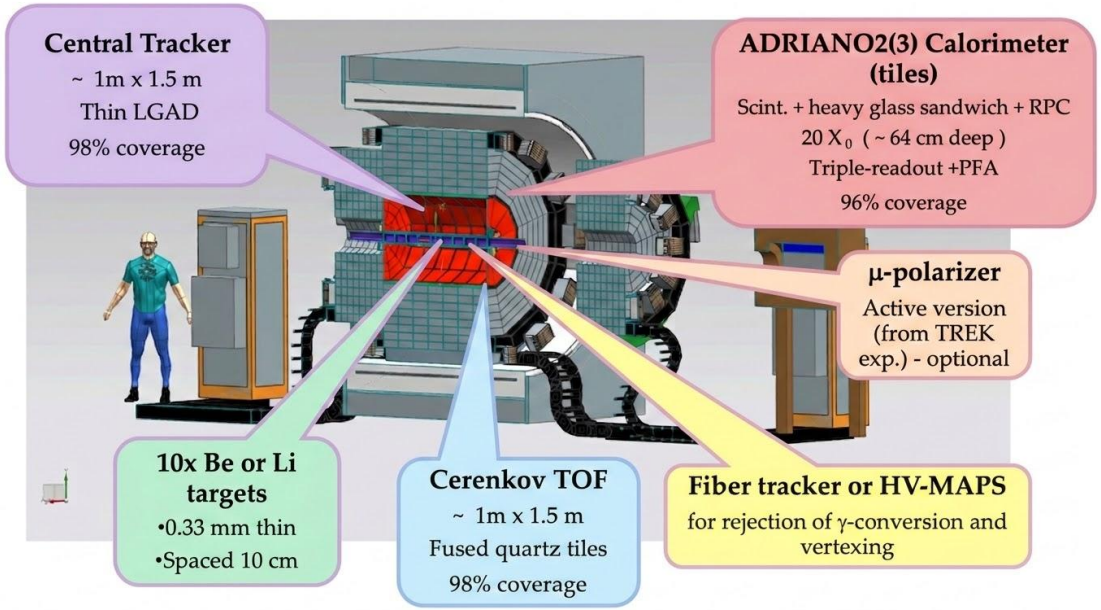
***N*(1535) DECAY MODES**	Fraction (Γ_i/Γ)
$N\pi$	32–52 %
$N\eta$	30–55 %
$N\pi\pi$	4–31 %

PDG

Total cross section ~ 200 mbarn
η production/total inelastic ~ 0.5%

Goal: $5x10^{13}$ η/yr and $5x10^{11}$ η'/yr (~10^4-10^5 times more than current datasets)
Requirements: 10^{18} POT/yr
Possible facilities: Fermilab, CERN, J-PARC, ORNL, BNL, ESS, GSI, and HIAF

REDTOP (Rare Eta Decays To Observe new Physics)



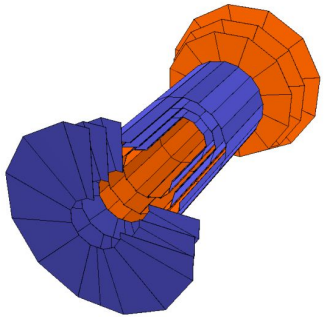
Gatto et al (2026)

REDTOP (Rare Eta Decays To Observe new Physics)

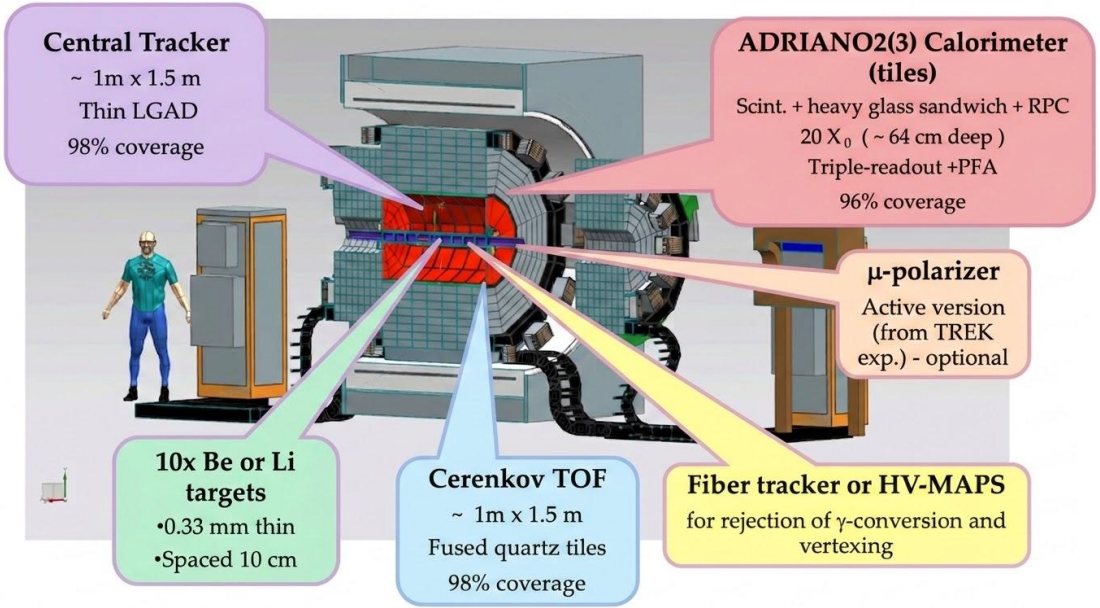
Vertex detector:

Similar to MuPix detector in Mu3e

High-Voltage Monolithic Active Pixel Sensors



Goal: ~20 μm spatial resolution

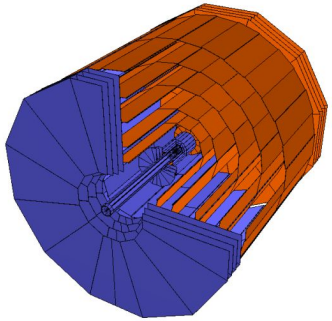


Gatto et al (2026)

REDTOP (Rare Eta Decays To Observe new Physics)

Central tracker:

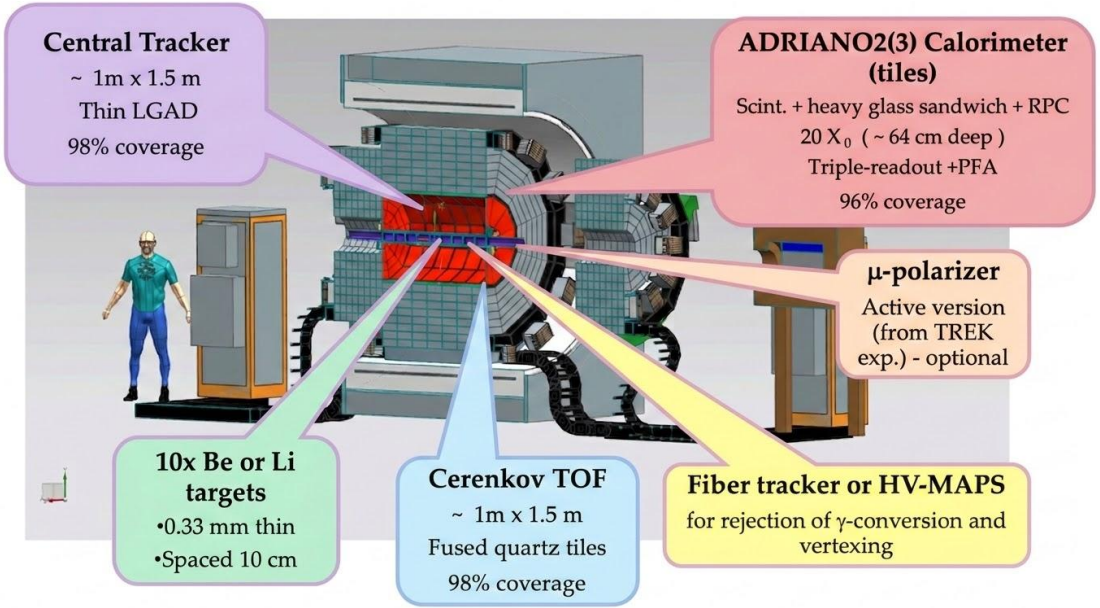
Low-Gain Avalanche Diodes
Used in ATLAS/CMS detectors
+ solenoid (0.6 T) repurposed from FINUDA



Goal: ~1% p_T resolution, low material budget, fast timing

Cerenkov TOF:

Goal: Level-0 trigger to reject slow moving hadrons from inelastic background



Gatto et al (2026)

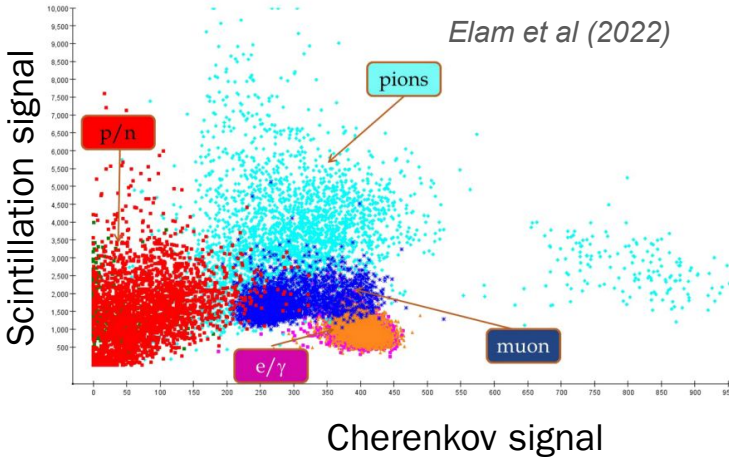
REDTOP (Rare Eta Decays To Observe new Physics)

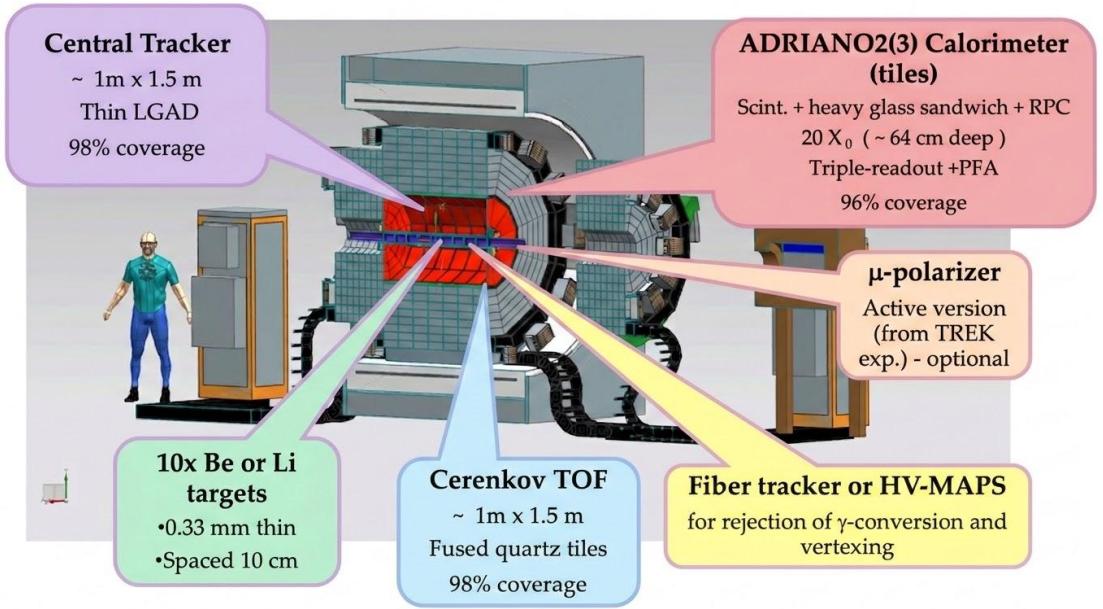
Calorimeter:

Prototyped at Fermilab
Goal: EM energy resolution + particle ID

Inner layer (EM): ADRIANO2.
Layers of scintillator + heavy glass (Cherenkov)

Outer layer (hadronic): ADRIANO3
ADRIANO2 + extra layers for neutron ID





Gatto et al (2026)

REDTOP (Rare Eta Decays To Observe new Physics)

Goals:

Handle ~GHz inelastic background event rate (10x larger than any other fixed target expt)

Trigger stage	Input event rate (Hz)	Event size (bytes)	Input data rate (bytes/s)	Event (rejection)
Level 0	$7. \times 10^8$	1.4×10^3	9.8×10^{11}	~ 4.6
Level 1	1.5×10^8	1.5×10^3	2.3×10^{11}	~ 60
Level 2	2.5×10^6	1.5×10^3	3.8×10^9	~ 4.5
Storage	0.56×10^6	1.6×10^3	0.9×10^9	

Gatto et al (2026)

Low material budget: 0.1% X_0 per vertex/tracker layer

Fast time resolution: tracker ~30 psec, calorimeter ~80 psec, TOF ~50 psec

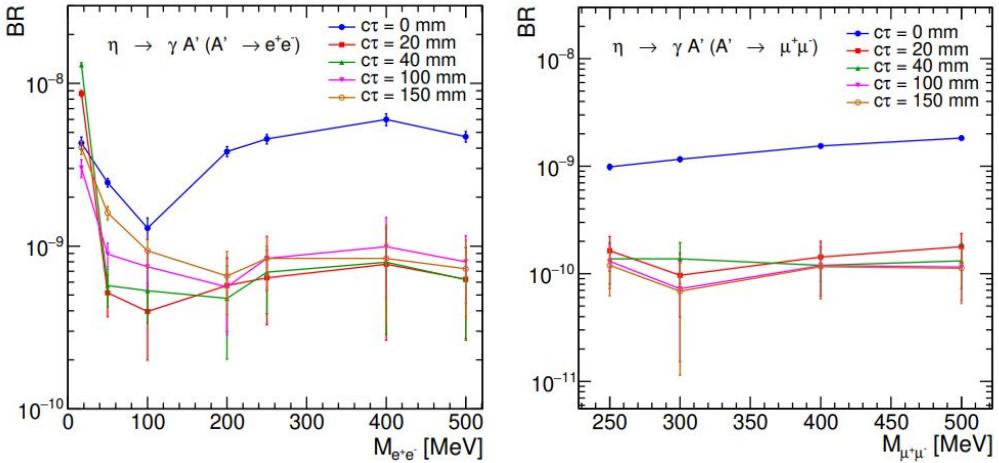
High particle ID: 98-99% e,γ, 95% μ, 95% π, 99% p,n

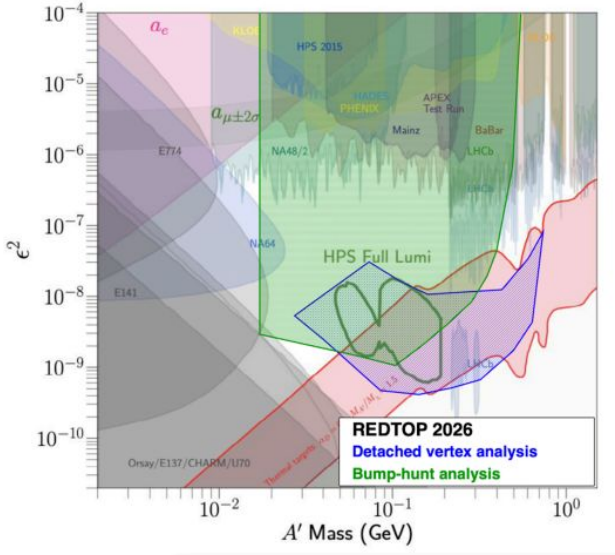
Detector coverage: near-4π

Projected sensitivities: dark photon model

$$\mathcal{B}(\eta \to A'\gamma) = 2\varepsilon^2 \mathcal{B}(\eta \to \gamma\gamma) \left|\bar{F}_{\eta\gamma^*\gamma^*}(m^2_{A'}, 0)\right|^2 \left(1 - m^2_{A'}/M^2_{\eta}\right)^3$$

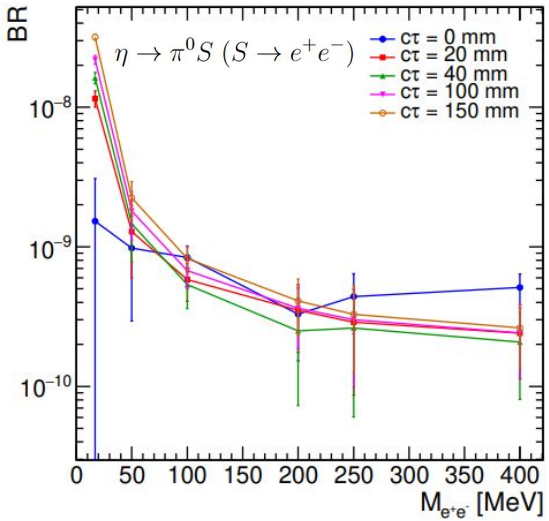
Branching ratio sensitivities

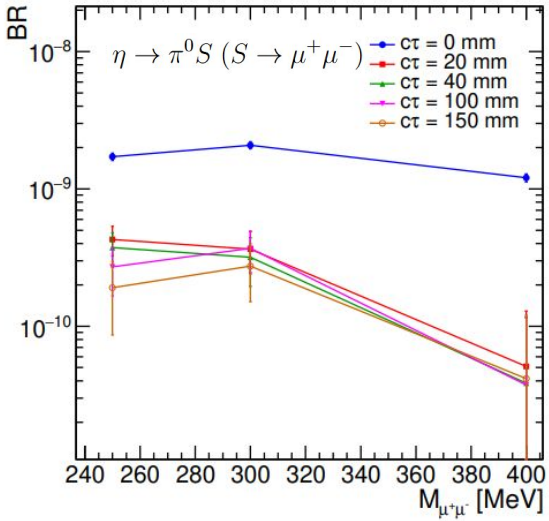




Gatto et al (2026)

Projected sensitivities: dark scalar model





Gatto et al (2026)

Higgs-mixed scalar

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

Leutwyler & Shifman (1990)

u-quark coupled scalar

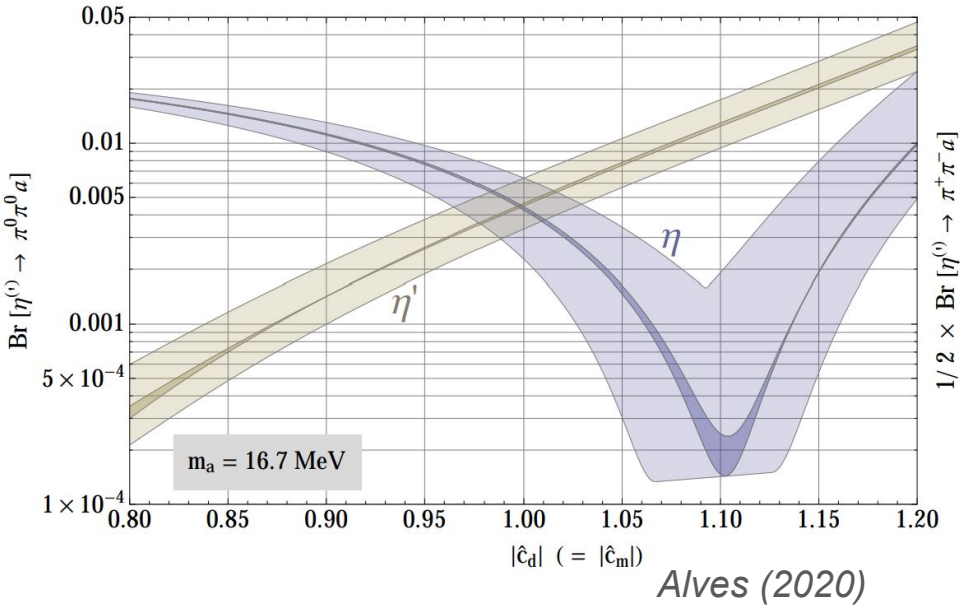
$$\mathcal{B}(\eta \to \pi^0 S) \approx 5.2 \times 10^{-2} \left(\frac{\lambda_u}{7 \times 10^{-4}}\right)^2 \times \lambda^{1/2}\left(1, \frac{M_{\pi^0}^2}{M_\eta^2}, \frac{m_S^2}{M_\eta^2}\right)$$

Batell, Freitas, Ismail, McKeen (2018)

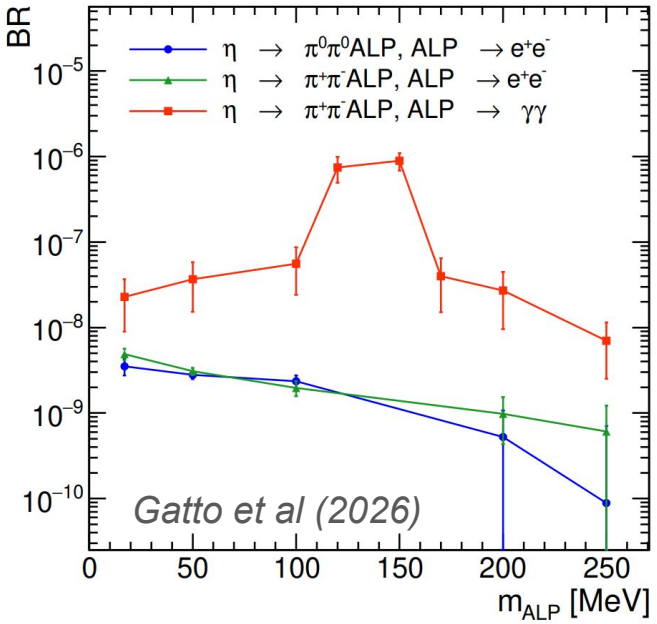
η,η’ decays less sensitive to Higgs-mixed scalar than K→πS, B→KS

More sensitive to S coupled to light quarks (complementary)

Projected sensitivities: ALP model



Alves (2020)



Predictions of piophobic axion for X_{17} anomaly

Conclusions: REDTOP wishlist

Ambitious proposal for testing many theories of light dark worlds (+ SM physics & symmetry tests)

~5 year R&D + construction
~5 year data taking
~100M USD

C-, T-, CP-violation tests
CP violation via Dalitz plot mirror asymmetry: $\eta \to \pi^+\pi^-\pi^0$
CP violation (Type I – P and T odd, C even): $\eta \to 4\pi^0$
CP violation (Type II - C and T odd, P even): $\eta \to \pi^+\pi^-\pi^0$ and $\eta \to \gamma\gamma\gamma$
Test of CP invariance via μ longitudinal polarization: $\eta \to \mu^+\mu^-$
Test of CP invariance via γ^* polarization studies: $\eta \to \pi^+\pi^-e^+e^-$ and $\eta \to \pi^+\pi^-\mu^+\mu^-$
Test of CP invariance in angular correlation studies: $\eta \to \mu^+\mu^-e^+e^-$
Test of T invariance via μ transverse polarization: $\eta \to \pi^0\mu^+\mu^-$ and $\eta \to \gamma\mu^+\mu^-$
CPT violation: μ polariz. in $\eta \to \pi^+\mu^-\nu$ vs $\eta \to \pi^-\mu^+\nu$ and γ polarization in $\eta \to \gamma\gamma$
Searches for new particles and forces
Scalar meson searches (charged channel): $\eta \to \pi^0 H$, with $H \to e^+e^-$, $\mu^+\mu^-$
Dark photon searches: $\eta \to \gamma A'$ with $A' \to l^+l^-$
Protophobic fifth force searches : $\eta \to \gamma a$ with $a \to e^+e^-$
New leptophobic baryonic force searches : $\eta \to \gamma B$, with $B \to e^+e^-$, $\pi^0\gamma$
Indirect searches for new gauge bosons and leptoquark: $\eta \to \mu^+\mu^-$ and $\eta \to e^+e^-$
Search for true muonium: $\eta \to \gamma\,(\mu^+\mu^-)_{2M_\mu} \to \eta \to \gamma\, e^+e^-$
All invisible or semi-visible η decays
Other discrete symmetry violations
Lepton flavor violation: $\eta \to \mu^+e^- + \text{c.c.}$
Double lepton flavor violation: $\eta \to \mu^+\mu^+e^-e^- + \text{c.c.}$
Other precision physics measurements
Proton radius anomaly: $\eta \to \gamma\mu^+\mu^-$ vs. $\eta \to \gamma e^+e^-$
All unseen leptonic decay modes of η/η' (SM predicts $10^{-6} - 10^{-9}$)
Non-η/η' based BSM physics
Dark photon and ALP searches in Drell–Yan processes: $q\bar{q} \to A'/a \to l^+l^-$
ALP searches in Primakoff processes: $pZ \to pZa \to l^+l^-$
Charged pion and kaon decays: $\pi^+ \to \mu^+\nu A' \to \mu^-\nu l^+l^-$ and $K^+ \to \mu^+\nu A' \to \mu^-\nu l^+l^-$
Neutral pion decay: $\pi^0 \to \gamma A' \to \gamma e^+e^-$
High-precision studies on nonperturbative QCD physics
Chiral perturbation theory
Nonperturbative QCD
Isospin breaking due to the u-d quark mass difference
Octet–singlet mixing angle
Electromagnetic transition form factors (important input for $g-2$)