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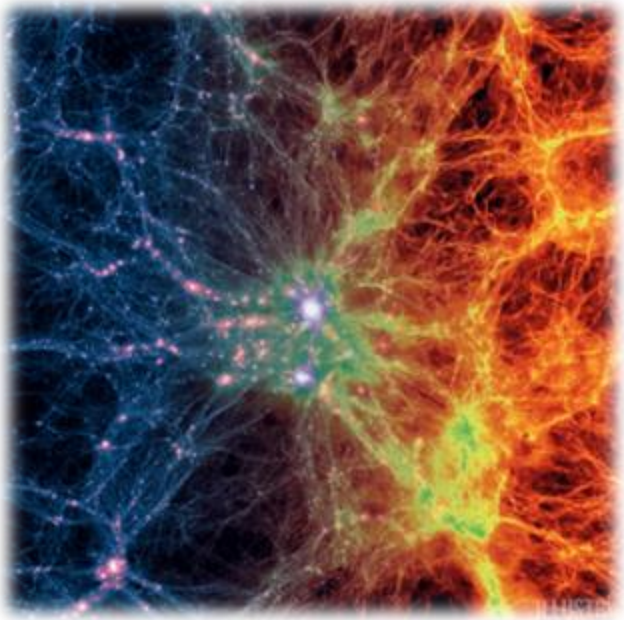

The REDTOP experiment: a η/η' factory to explore dark matter and physics beyond the Standard Model

Marcin Zieliński, Corrado Gatto
on behalf of REDTOP Collaboration

Workshop @ 1GeV Scale, Jagiellonian University, 20.09.2024

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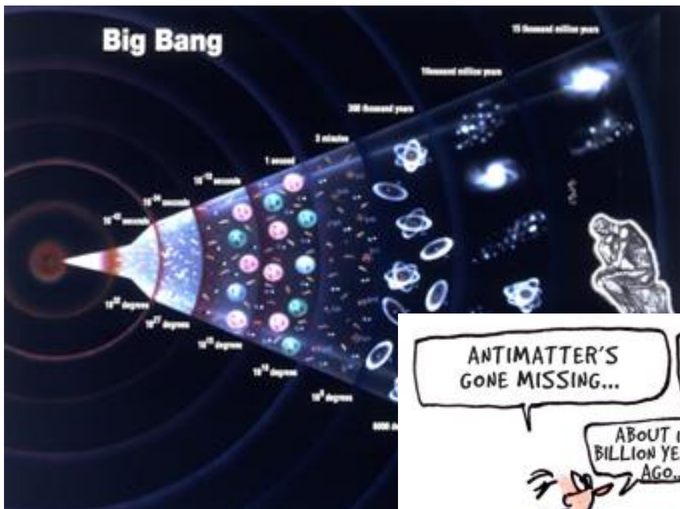
General motivation

The general and main motivation for research is to answer the question:

How did our 'Material Universe' survive the cooling after the Big Bang?



Big Bang:
an equal amount of matter and antimatter was produced during the hot phase

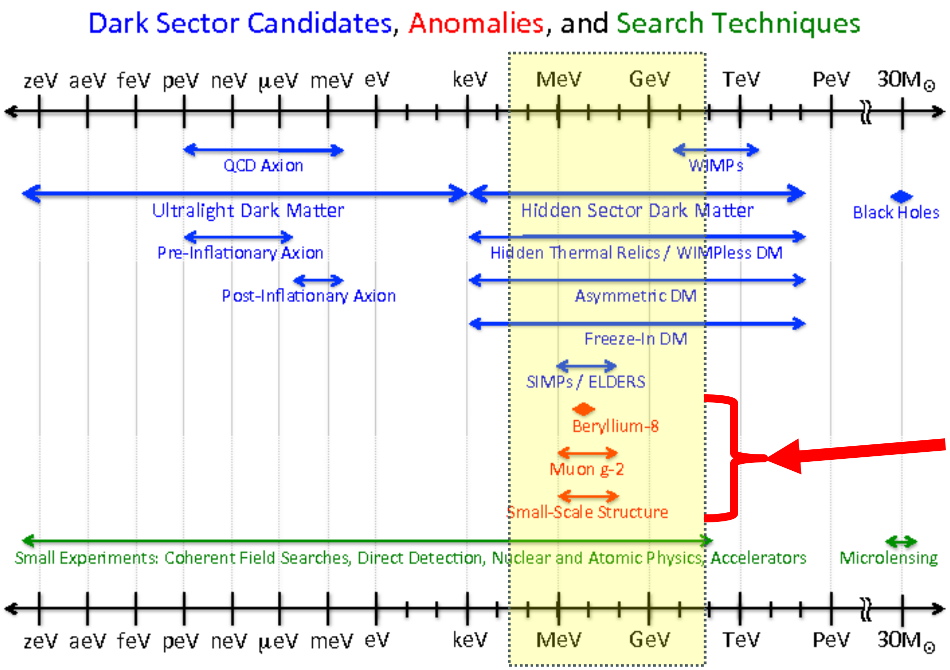
During cooling and expansion
matter and antimatter annihilated 😐

Baryon - Antibaryon
ASYMMETRY!

Most of the cosmic energy budget is of an unknown form

Where did the asymmetry come from, and how can it be experimentally investigated?
Searching for differences between particles and antiparticles by studying symmetries with light mesons at scale of ~ 1 GeV → **Physics Beyond SM**

General motivation



- In SM: violation from weak interaction is not sufficient to create observed asymmetry
- DM mass range from a keV to several GeV
- DM annihilates directly into SM particles over most of the sub-GeV mass range
- several anomalies in experiments point to possible new physics, weakly coupled to familiar matter in the 1 - 100 MeV scale

Ref: Marco Battaglieri, arXiv:1707.04591 [hep-ph]

Strong CP problem → Peccei-Quinn-Weinberg-Wilczek (PQWW)

Axions and Axion-Like-Particles (ALP's)

Newest theoretical models prefer gauge bosons in MeV-GeV mass range as "…many of the more severe astrophysical and cosmological constraints that apply to lighter states are weakened or eliminated, while those from high energy colliders are often inapplicable" *(B. Batell , M. Pospelov, A. Ritz – 2009)*

Current experimental studies:

- Direct searches
- Proton beam dump
- Electron beam dump
- Fixed target electron scattering
- Fixed target proton experiments
- Colliders

Cosmic rays (Direct searches)

Higher Luminosity Accelerators (Proton beam dump, Electron beam dump, Fixed target electron scattering, Fixed target proton experiments)

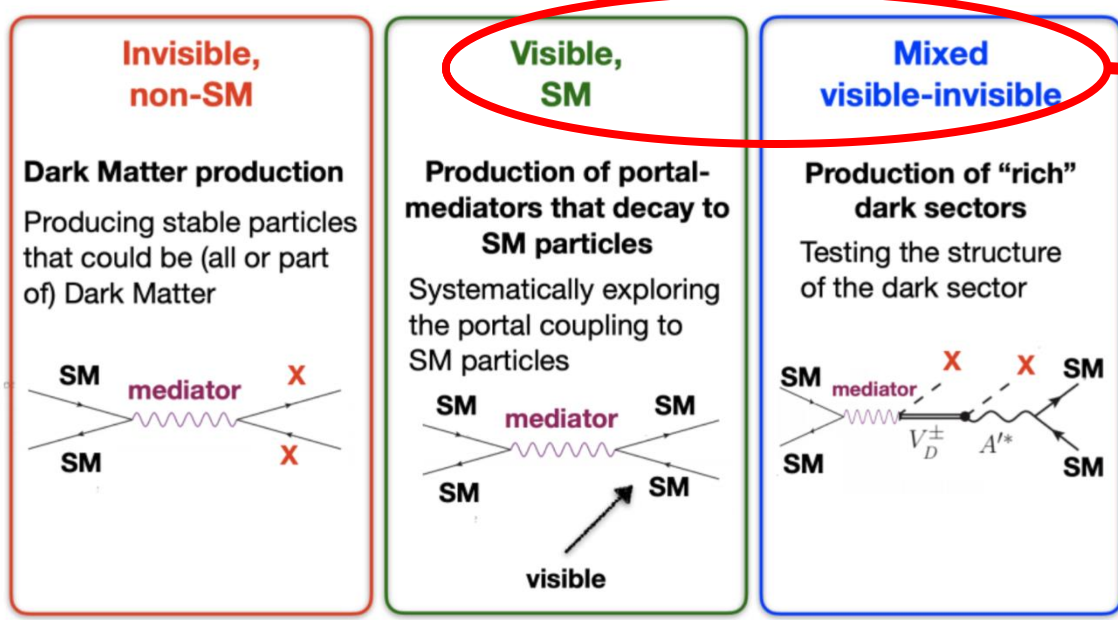
Lower Luminosity Accelerators (Colliders)

Connection between Standard and Dark Matter

New Physics connects to Standard Model particles through four portals:

Portal	Particles	Operator(s)
"Vector"	Dark photons	$-\frac{\epsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu}$
"Axion"	Pseudoscalars	$\frac{a}{f_a} F_{\mu\nu} \widetilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i\mu\nu} \widetilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$
"Higgs"	Dark scalars	$(\mu S + \lambda S^2) H^\dagger H$
"Neutrino"	Sterile neutrinos	$y_N L H N$

Ref: ***Sergi Gonzalez-Solis, Thursday talk.***



Stefania Gori, Mike Williams

Hight intensity Mesons factories

η/η'

Connection between Standard and Dark Matter

"Light dark matter must be neutral under SM charges, otherwise it would have been discovered at previous colliders"

[G. Krnjaic RF6 Meeting, 8/2020]

- The only known particles with all-zero quantum numbers: Q = I = J = S = B = L = 0 are the **η/η' mesons** and the **Higgs boson (also the vacuum!)** -> very rare
- The η meson is a Goldstone boson (the η' meson is not!)
- The **η/η'** decays are flavor-conserving reactions

Experimental advantages:

- Hadronic production cross section is quite large (~ 0.1 barn) → much easier to produce than heavier mesons
- All its possible strong decays are forbidden in lowest order by P and CP invariance, G-parity conservation and isospin and charge symmetry invariance.
- EM decays are forbidden in lowest order by C invariance and angular momentum conservation Branching Ratio of processes from New Physics are enhanced compared to SM.

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A η/η′ factory is equivalent to a low energy Higgs factory and an excellent laboratory to probe New Physics at scale of 1 GeV

REDTOP - **R**are **E**ta **D**ecays **TO P**robe New Physics

The general key points:

REDTOP: η(/η□) yielding ~10^{14}(10^{12}) mesons
O(10^5) the existing world sample with a 3-yr run

Hadro-produced mesons: requires proton beam
Pion beam also well suited

Designed to search for BSM physics in the MeV-GeV region
Main search fields: dark matter and CP-violation
Sensitive to 17 MeV resonances

Moderate cost:
$55M excl. contingency and labor

η/η'

REDTOP - Rare Eta Decays TO Probe New Physics

Main physics program and goals:

Test of CP invariance via Dalitz plot mirror asymmetry: $\eta \to \pi^0\pi^+\pi^-$
Search for asymmetries in the Dalitz plot with very high statistics

Test of CP invariance via μ polarization studies:
$\eta \to \pi^0\mu^+\mu^-$, $\eta \to \gamma\mu^+\mu^-$, $\eta \to \mu^+\mu^-$,
Measure the angular asymmetry between spin and momentum

Dark photon searches: $\eta \to \gamma A$□, **with** A□$\to \mu^+\mu^-$, A□$\to e^+e^-$
Need excellent vertexing and particle ID

QCD axion and ALP searches: $\eta \to \pi\pi a$, with $a \to \gamma\gamma$, $a \to \mu^+\mu^-$, $a \to e^+e^-$
Dual (or triple!) calorimeters and vertexing

Dark scalar searches: $\eta \to \pi^0 H$, **with** $H \to \mu^+\mu^-$, $H \to e^+e^-$
Dual (or triple!) calorimeters and particle ID

Lepton Flavor Universality studies: $\eta \to \mu^+\mu^- X$, $\eta \to e^+e^- X$
Need excellent particle ID

η/η'

REDTOP - Rare Eta Decays TO Probe New Physics

Assuming a yield $\sim 10^{14}$ η mesons/yr and $\sim 10^{12}$ η' mesons/yr

C, T, CP-violation

- *CP Violation via Dalitz plot mirror asymmetry: $\eta \to \pi^o \pi^+ \pi$*
- *CP Violation (Type I – P and T odd , C even): $\eta \to 4\pi^o \to 8\gamma$*
- *CP Violation (Type II - C and T odd , P even): $\eta \to \pi^o e^+ e$ **and** $\eta \to 3\gamma$*
- *Test of CP invariance via μ longitudinal polarization: $\eta \to \mu^+ \mu^-$*
- *CP inv. via γ^* polarization studies: $\eta \to \pi^+ \pi^- e^+ e^-$ & $\eta \to \pi^+ \pi^- \mu^+ \mu^-$*
- *CP invariance in angular correlation studies: $\eta \to \mu^+ \mu^- e^+ e^-$*
- *CP invariance in angular correlation studies: $\eta \to \mu^+ \mu^- \pi^+ \pi^-$*
- *CP invariance in μ polar. in studies: η □ $\pi^o \mu^+ \mu^-$*
- *T invar. via μ transverse polarization: $\eta \to \pi^o \mu^+ \mu^-$ and $\eta \to \gamma \mu^+ \mu^-$*
- *CPT violation: μ polr. in $\eta \to \pi^+ \mu \nu$ vs $\eta \to \pi^- \mu^+ \nu$ - γ polar. in $\eta \to \gamma\gamma$*

New particles and forces searches

- *Scalar meson searches (charged channel): $\eta \to \pi^o H$ with $H \to e^+ e^-$ and $H \to \mu^+ \mu$*
- *Dark photon searches: $\eta \to \gamma A'$ with $A' \to \ell^+ \ell$*
- *Protophobic fifth force searches : $\eta \to \gamma X_{17}$ with $X_{17} \to \pi^+ \pi^-$*
- *QCD axion searches : $\eta \to \pi\pi \boldsymbol{a}_{17}$ with $\boldsymbol{a}_{17} \to e^+ e^-$*
- *New leptophobic baryonic force searches : $\eta \to \gamma B$ with $B \to e^+ e^-$ or $B \to \gamma \pi^o$*
- *Indirect searches for dark photons new gauge bosons and leptoquark: $\eta \to \mu^+ \mu$ and $\eta \to e^+ e^-$*
- *Search for true muonium: $\eta \to \gamma (\mu^+ \mu^-)|_{2M_\mu} \to \gamma e^+ e^-$*
- *Lepton Universality*
- *$\eta \to \pi^o H$ with $H \to \nu N_2$, $N_2 \to h' N_1$, $h' \to e^+ e^-$*

Other discrete symmetry violations

- *Lepton Flavor Violation: $\eta \to \mu^+ e^- + c.c.$*
- *Radiative Lepton Flavor Violation: $\eta \to \gamma \mu^+ e^- + c.c.$*
- *Double lepton Flavor Violation: $\eta \to \mu^+ \mu^+ e^- e^- + c.c.$*

Other Precision Physics measurements

- *Proton radius anomaly: $\eta \to \gamma \mu^+ \mu^-$ vs $\eta \to \gamma e^+ e^-$*
- *All unseen leptonic decay mode of η / η' (SM predicts 10^{-6} -10^{-9})*

World η data samples:

	Technique	$\eta \to 3\pi^0$	$\eta \to e^+e^-\gamma$	Total η mesons
CB@AGS	$\pi^- p \to \eta n$	9×10^5		10^7
CB@MAMI C&B	$\gamma p \to \eta p$	1.8×10^6	5000	$2\times10^7 + 6\times10^7$
BES-III	$e^+e^- \to J/\psi \to \eta\gamma + \eta$ hadrons	6×10^6		$1.1\times10^7 + 2.5\times10^7$
KLOE-II	$e+e- \to \Phi \to \eta\gamma$	6.5×10^5		$\sim10^9$
WASA@COSY	$pp \to \eta pp$ $pd \to \eta\, ^3He$			$>10^9$ (untagged) 3×10^7 (tagged)
CB@MAMI 10 wk (proposed 2014)	$\gamma p \to \eta p$	3×10^7	1.5×10^5	3×10^8
Phenix	$d\,Au \to \eta X$			5×10^9
Hades	$pp \to \eta pp$ $p\,Au \to \eta X$			4.5×10^8
Near future samples				
GlueX@JLAB (running)	$\gamma_{12\,GeV} p \to \eta X \to$ neutrals			5.5×10^7/yr
JEF@JLAB (approved)	$\gamma_{12\,GeV} p \to \eta X \to$ neutrals			3.9×10^5/day
REDTOP (proposing)	$p_{1.8\,GeV} Li \to \eta X$			3.4×10^{13}/yr

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Present physics case for REDTOP

Physics case presented in „White Paper” available on arXiv:

arXiv > hep-ex > arXiv:2203.07651

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High Energy Physics – Experiment

[Submitted on 15 Mar 2022 (v1), last revised 7 Sep 2022 (this version, v3)]

The REDTOP experiment: Rare η/η' Decays To Probe New Physics

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REDTOP Collaboration

The η and η' mesons are nearly unique in the particle universe since they are almost Goldstone bosons and the dynamics of their decays are strongly constrained. The integrated η-meson samples collected in earlier experiments amount to $\sim 10^9$ events. A new experiment, REDTOP (Rare Eta Decays To Probe New Physics), is being proposed, with the intent of collecting a data sample of order 10^{14} η (10^{12} η') for studying very rare decays. Such statistics are sufficient for investigating several symmetry violations, and for searching for particles and fields beyond the Standard Model. In this work we present several studies evaluating REDTOP sensitivity to processes that couple the Standard Model to New Physics through all four of the so-called \emph{portals}: the Vector, the Scalar, the Axion and the Heavy Lepton portal. The sensitivity of the experiment is also adequate for probing several conservation laws, in particular CP, T and Lepton Universality, and for the determination of the η form factors, which is crucial for the interpretation of the recent measurement of muon $g-2$.

Comments: Contribution to Snowmass 2021
Subjects: **High Energy Physics – Experiment (hep-ex)**; High Energy Physics – Phenomenology (hep-ph)
Cite as: arXiv:2203.07651 **[hep-ex]**
(or arXiv:2203.07651v3 **[hep-ex]** for this version)
https://doi.org/10.48550/arXiv.2203.07651

Sensitivity studies based on ~10^{14} η mesons (3.3x10^{18} POT and 3-year run)

15 processes fully simulated and reconstructed – 20 theoretical models benchmarked:

- Four BSM portals
- Three CP violating processes requiring no μ-polarization measurement
- A fourth CP violating processes under study
- Three CP violating processes requiring μ-polarization measurement
- Two lepton flavor universality studies
- Two lepton flavor violation studies

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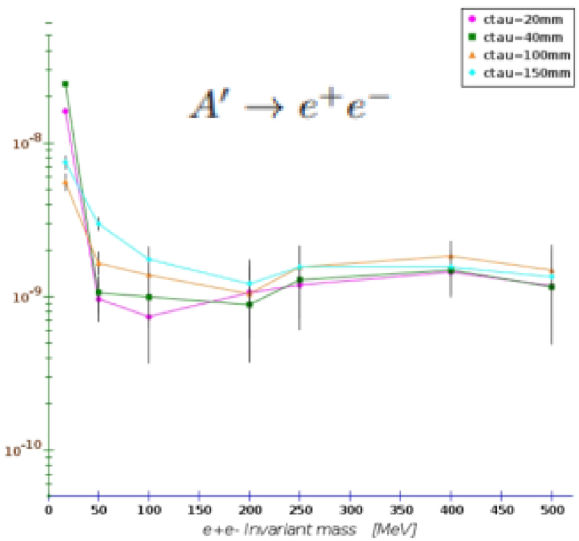
Sensitivity studies based on
~10^{14} η mesons
(3.3x10^{18} POT and 3-year run)

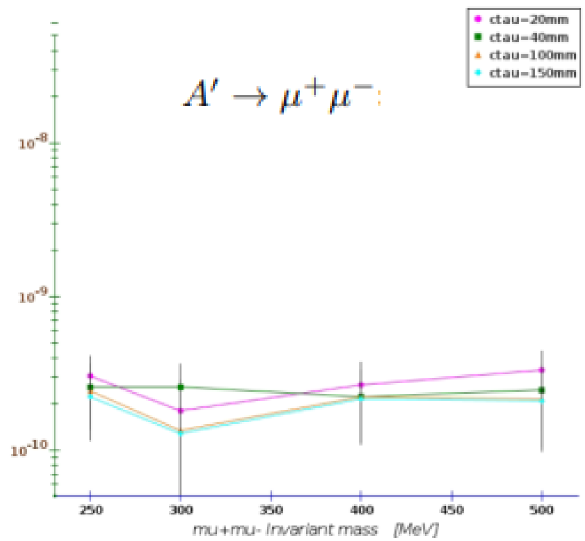
Key detector parameters

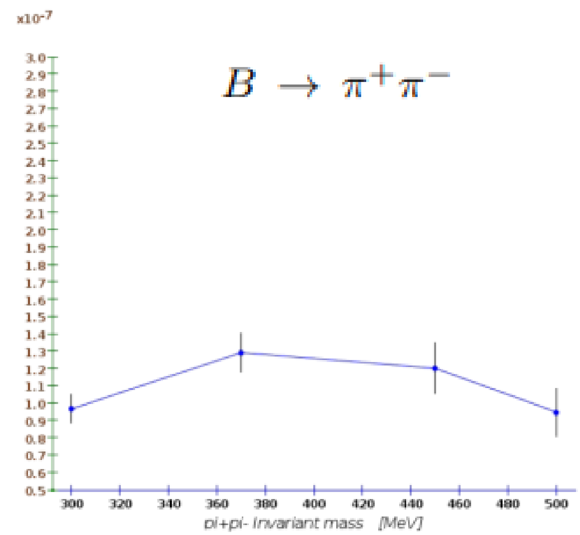
- Large sensitivity to <17 MeV mass resonances (compared to WASA and KLOE)
- Tracking capable to reconstruct detached vertices up to ~100 cm
- Sensitivity to BR $\sim\mathcal{O}(10^{-11})$ ($\sim\mathcal{O}(10^{-12})$ with pion beam)
- Detector optimization under way

Vector Portal: $\eta \rightarrow \gamma A'$ with $A' \rightarrow l^+ l^-$ or $\pi^+\pi^-$

Some BR sensitivity curves







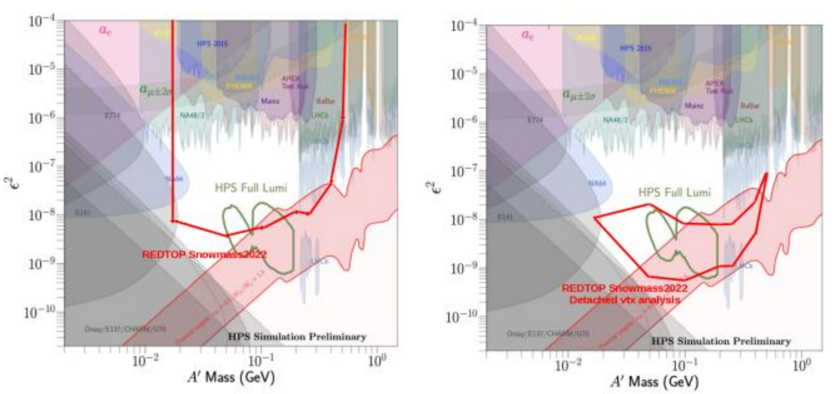


FIG. 36. Sensitivity to to ε^2 for the processes $\eta \rightarrow \gamma A'$ for integrated beam flux of 3.3×10^{18} POT. Left plot: *bump-hunt* analysis. Right plot: *detached-vertex* analysis).

Theoretical Models considered

- Minimal dark photon model
  - Most popular model
- Leptophobic B boson Model
- Protophobic Fifth Force
  - Explains the ATOMKI result

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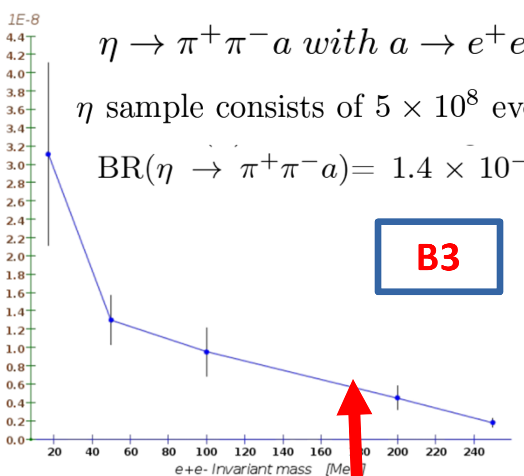
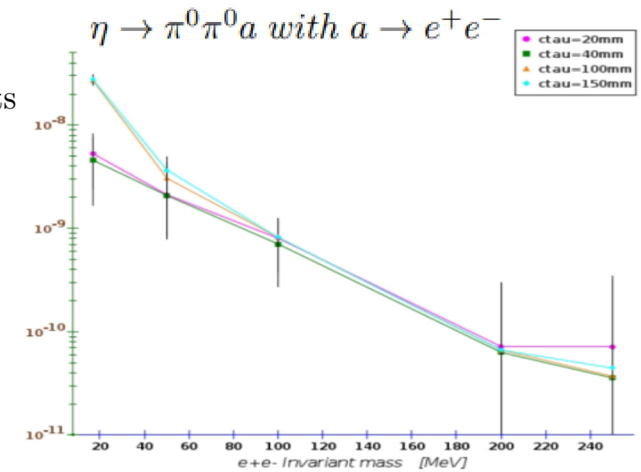
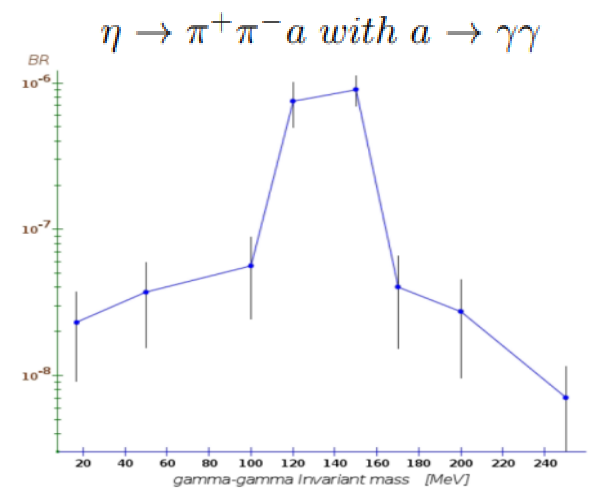
Pseudoscalar Portal: $\eta \to \pi^o \pi^o a,\ \eta \to \pi^+ \pi^- a\ \ (a \to \gamma\gamma\ \ \text{and}\ \ a \to e^+ e^-)$

17 MeV piophobic QCD axion





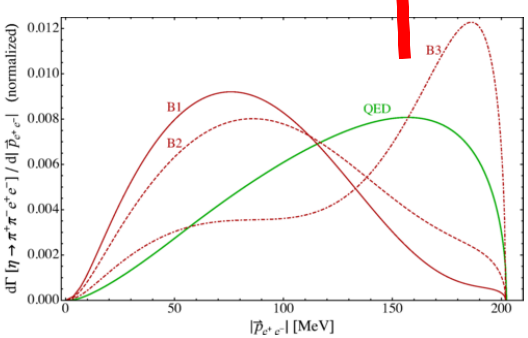


Differential rate for $\eta\square\pi^+\pi^- a$ for three benchmark params

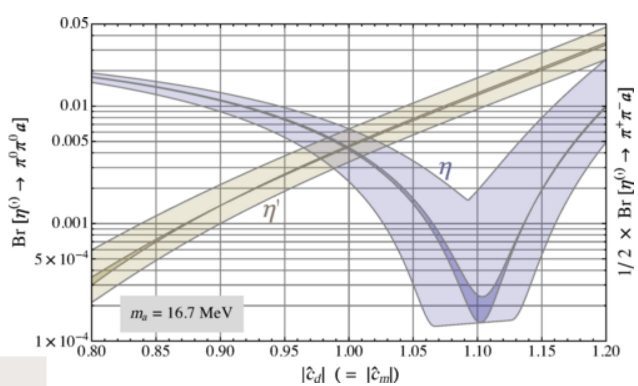
Signals of the QCD axion with mass of 17 MeV$/c^2$: Nuclear transitions and light meson decays

Daniele S. M. Alves

Phys. Rev. D **103**, 055018 – Published 23 March 2021



The differential rate for $\eta \to \pi^+\pi^- a$ as a function of $|\vec{p}_{e^+e^-}| \equiv |\vec{p}_{e^+} + \vec{p}_{e^-}| = \vec{p}_a$, for three benchmark choices of RχT parameters specified in Table I. For comparison, we also show the differential rate of the SM process $\eta \to \pi^+\pi^- e^+ e^-$, labeled "QED."



Theoretical models considered

- ***Piophobic QCD axion model***
  - *Below KLOE sensitivity*
  - *the CELSIUS/WASA Collaboration observed 24 evts with SM expectation of 10*
- ***Heavy Axion Effective Theories***

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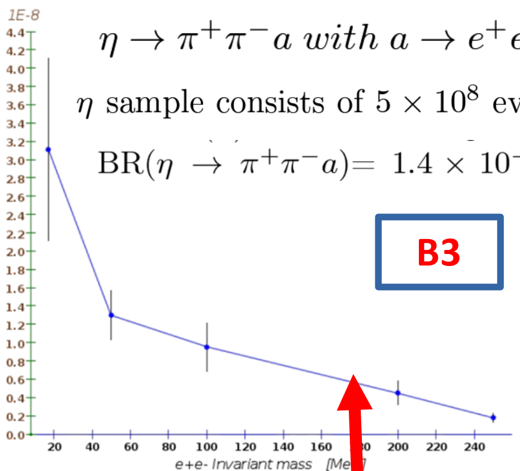

Process	Benchmark set	*Trigger* L0	*Trigger* L1	*Trigger* L2	*Reconstruction*	Analysis	**Total**	BR sensitivity
$\eta \to \pi^+\pi^- a$; $a \to e^+e^-$	B1	55.28%	21.81%	76.41%	75.12%	42.94%	2.97%	2.07×10^{-8}
$\eta \to \pi^+\pi^- a$; $a \to e^+e^-$	B2	56.15%	22.32%	76.76%	75.12%	42.83%	3.10%	1.98×10^{-8}
$\eta \to \pi^+\pi^- a$; $a \to e^+e^-$	B3	59.67%	23.06%	79.81%	76.14%	44.03%	3.68%	1.67×10^{-8}
Urqmd		21.7%	1.7%	22.2%	0.26%	1.04%	2.31×10^{-6}%	

Differential rate for $\eta \to \pi^+\pi^- a$ for three benchmark params

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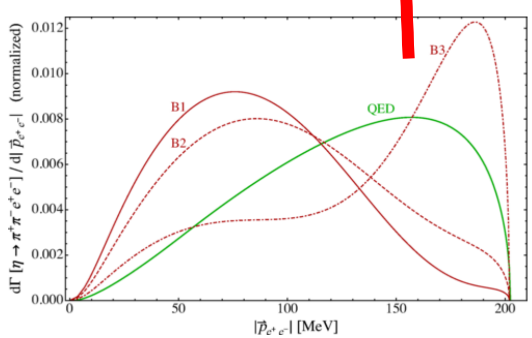

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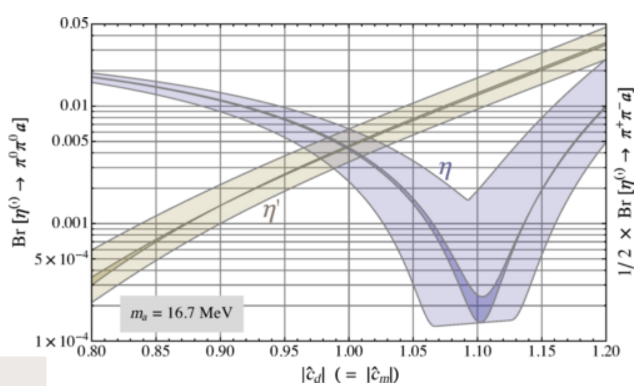

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- ***Heavy Axion Effective Theories***

CP Violation from Dalitz plot mirror asymmetry in $\eta \to \pi^+\pi^-\pi^0$

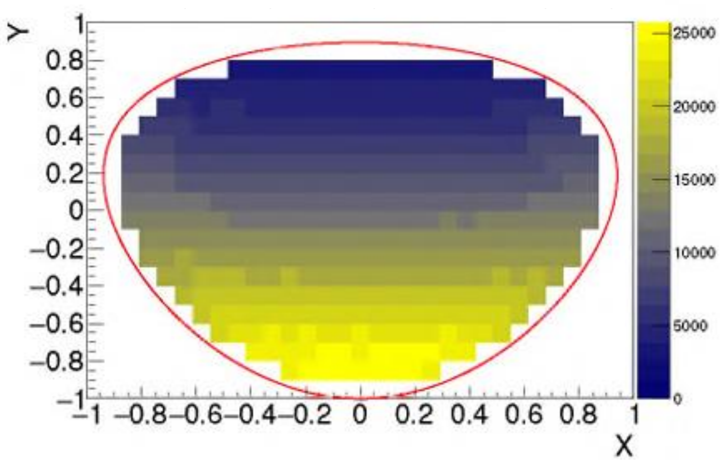
- *CP-violation from this process is not bounded by EDM as is the case for the $\eta \to 4\pi$ process.*
- *Complementary to EDM searches even in the case of T and P odd observables, since the flavor structure of the η is different from the nucleus*
- *Current PDG limits consistent with no asymmetry*

$$X = \sqrt{3}\left(\frac{T_+ - T_-}{Q}\right), \qquad Y = \frac{3T_0}{Q} - 1,$$

$$|M|^2 = A_0^2(1 + aY + bY^2 + cX + dX^2 + fY^3 + ...),$$

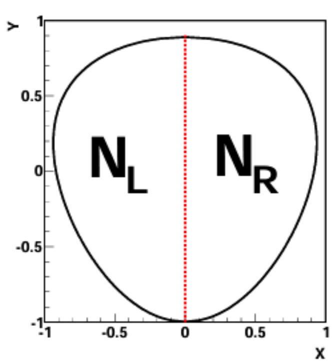
Precision measurement of the $\eta \to \pi^+\pi^-\pi^0$ Dalitz plot distribution with the KLOE detector

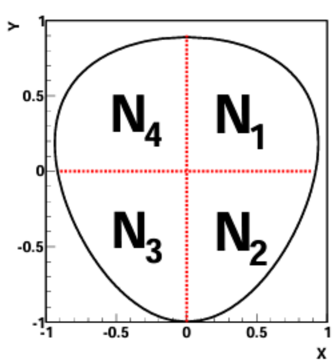
The KLOE-2 collaboration

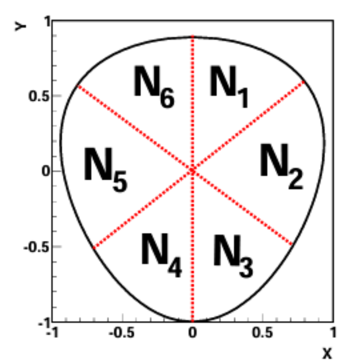


REDTOP sensitivity to model parameters

#Rec. Events	Re(α)	Im(α)	Re(β)	Im(β)	p-value
10^8 (no-bkg)	3.3×10^{-1}	3.7×10^{-1}	4.4×10^{-4}	5.6×10^{-4}	17%
Full stat. (no-bkg)	1.9×10^{-2}	2.1×10^{-2}	2.5×10^{-5}	3.2×10^{-5}	17%
Full stat. (100%-bkg)	2.3×10^{-2}	3.0×10^{-2}	3.5×10^{-5}	4.5×10^{-5}	16%

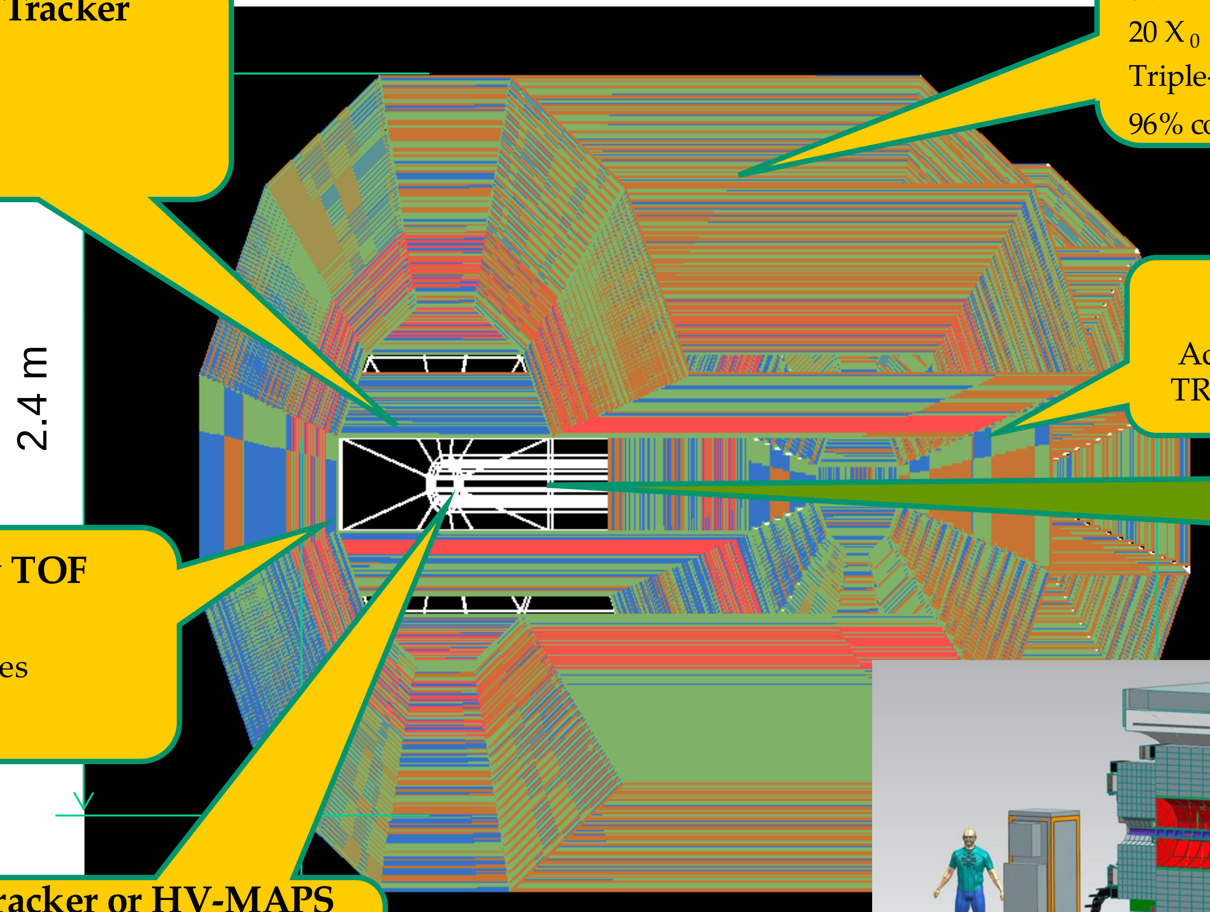






$$A_{LR} = \frac{N_R - N_L}{N_R + N_L}, \qquad A_Q = \frac{N_1 + N_3 - N_2 - N_4}{N_1 + N_2 + N_3 + N_4}, \qquad A_S = \frac{N_1 + N_3 + N_5 - N_2 - N_4 - N_6}{N_1 + N_2 + N_3 + N_4 + N_5 + N_6},$$

Proposed Detector design



Central Tracker

~ 1m x 1.5 m

Thin LGAD

98% coverage

ADRIANO2(3) Calorimeter (tiles)

Scint. + heavy glass sandwich + RPC

20 X_0 (~ 64 cm deep)

Triple-readout +PFA

96% coverage

μ-polarizer

Active version (from TREK exp.) - optional

10x Be or Li targets

•0.33 mm thin

•Spaced 10 cm

Cerenkov TOF

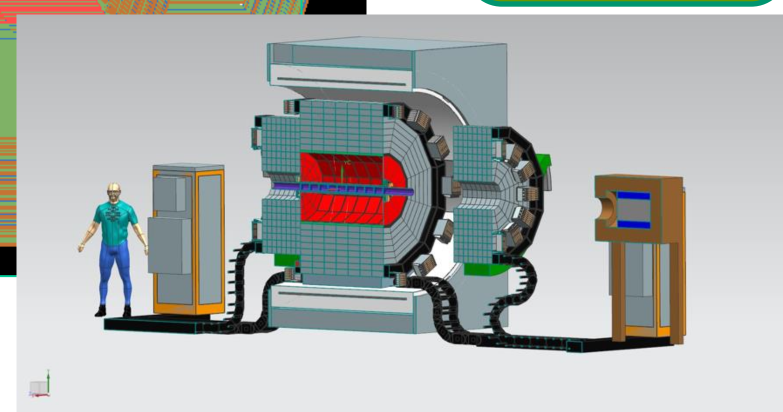
~ 1m x 1.5 m

Fused quartz tiles

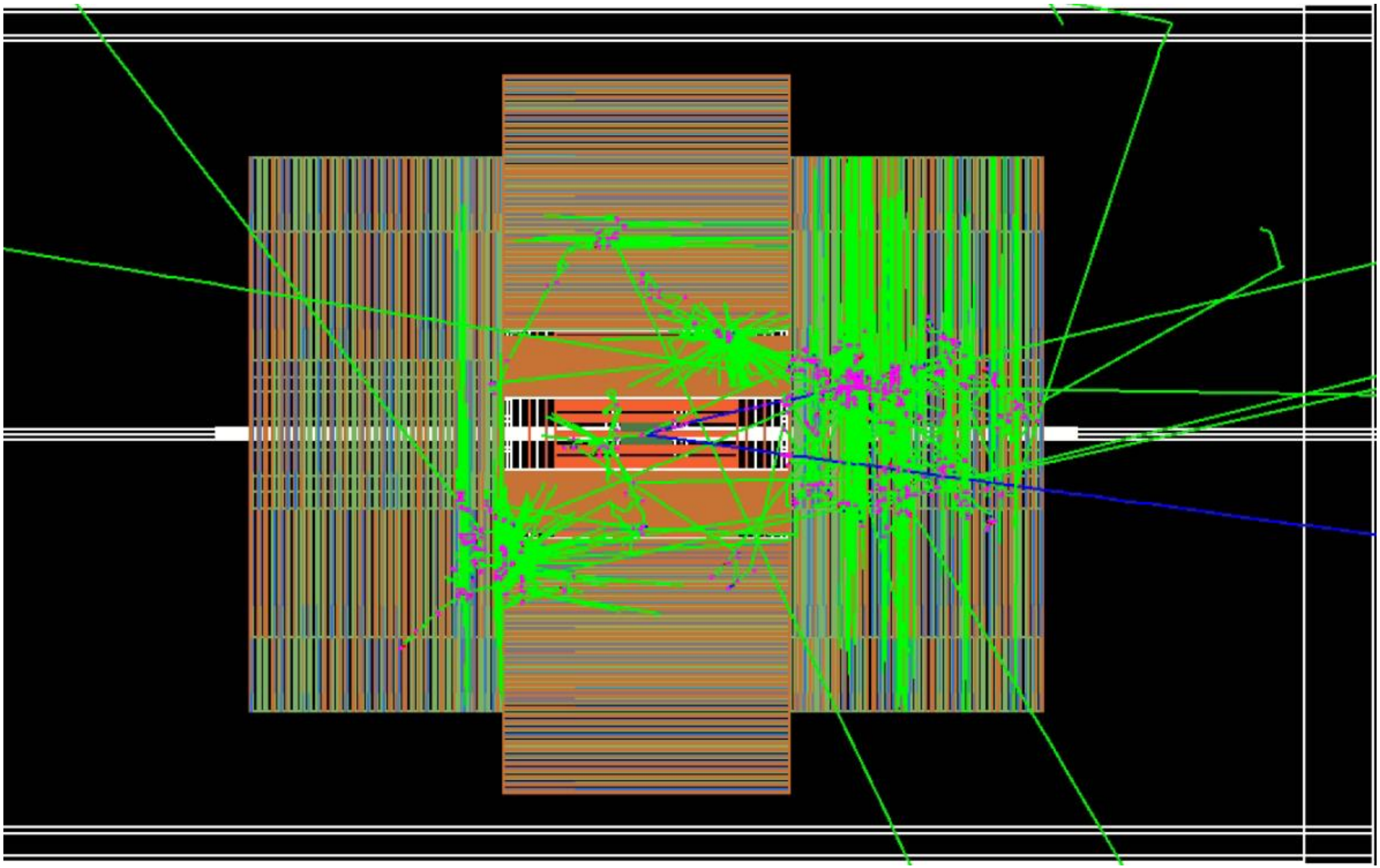
98% coverage

Fiber tracker or HV-MAPS

for rejection of γ-conversion and vertexing



Example of $\eta \rightarrow \gamma A'$ $with$ $A' \rightarrow e^+ e^-$ event in REDTOP



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Proposed Detector design

- *Sustain up to 0.7 GHz event rate with avg final state multiplicity of ~8 particles*
- *Calorimetric $\sigma(E)/E \sim 2\text{-}3\%/\sqrt{E}$*
- *High PID efficiency: 98/99% (e,γ), 95% (μ), 95% (π), 99.5%(p,n)*
- $\sigma_{tracker}(t) \sim 30psec$, $\sigma_{calorimeter}(t) \sim 80psec$, $\sigma_{TOF}(t) \sim 50psec$
- *Low-mass vertex detector*
- *Near-4π detector acceptance (as the η/η' decay is almost at rest).*

charged tracks detection

LGAD Tracker

- *4D track reconstruction for multihadron rejection*
- *Material budget < 0.1% r.l./layer*

EM + had calorimeter

- *ADRIANO2 calorimeter (Calice+T1604)*
- *ADRIANO3 rear section with Fe absorbers*
- *PFA + Dual-readout+HG*
- *Light sensors: SiPM or SPADs*
- *96.5% coverage*

Vertex reconstruction

Option 1: Fiber tracker (LHCb style)

- *Established and low-cost technology*
- *~70μm vertex resolution in x-y. Stereo layers*

Option 2: HV-MAPS (Mu3e style)

- *Low material budget (0.11%/layer)*
- *~40μm vertex resolution in 3D*

Cerenkov Threshold TOF

Option 1: Quartz tiles

- *Established and low-cost technology*
- *~50psec timing with T1604 prototype*

Option 2: EIC-style LGAD

- *~30-40 psec timing, but expensive*

Beam options for 10^{14} η mesons

Baseline option – medium-energy

- *proton beam on thin Li/Be target : ~1.8 GeV - 30 W (10^{11} POT/sec)*
- *Low-cost, readily available (BNL, ESS, FNAL, GSI, HIAF)*
- *η : inelastic background = 1:200*
- *Untagged η production*

Preferred option – low-energy pion beam

- *π^+ on Li/Be or π^- on LH: ~750 MeV - 2.5x10^{10} πOT/sec*
- *More expensive but lower background (ESS, FNAL, FAIR, HIAF, ORNL -Oak Ridge Nat. Lab.)*
- *η : inelastic background = 1:50 → sensitivity to BSM increased by > 2x*
- *Semi-tagged η production*

Ultimate option: Tagged 10^{13} η mesons

- *high intensity proton beam on De target: ~0.9 GeV; 0.1-1 MW*
- *Less readily available: (ESS, FAIR, CSNS, ORNL, PIP-II)*
- *Required fwd tagging detector for He_3^{++}*
- *Fully tagged production from nuclear reaction: $p+De \rightarrow \eta + He_3^{++}$*

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REDTOP

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Conclusions

- *HEP in the next 10 years will focus strongly on the MeV-GeV region*
- *All meson factories: LHCb, B-factories, Dafne, J/psi - have produced a broad spectrum of nice physics. An η/η' factory will do the same*
- *REDTOP has been designed expressly to study rare processes and to discover physics BSM in the MeV-GeV mass region*
- *Only experiment (with SHIP) sensitive to all four DM portals*
- *Very large physics reach for NP as well*
- *New detector techniques benefit the next generation of high intensity experiments*
- *Beam requirements could be met by several labs in US, Europe, and Asia*
  - *Before 2030: HIAF and GSI*
  - *After 2030: Fermilab and ESS*

More details: https://redtop.fnal.gov

https://arxiv.org/abs/2203.07651

Thank you for your attention!