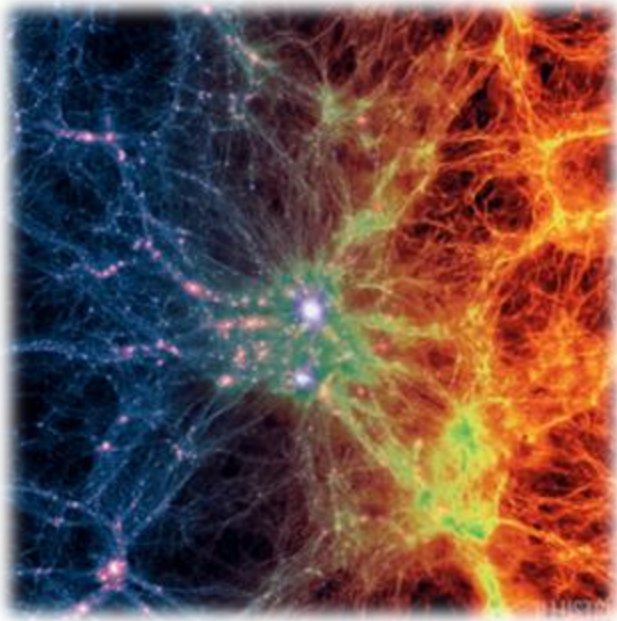




The **REDTOP** Experiment: a η/η' factory to explore Dark Matter and physics Beyond the Standard Model

Marcin Zieliński, Corrado Gatto
on behalf of REDTOP Collaboration



General motivation

Examples of experimentally observed anomalies:

4.2 σ effect

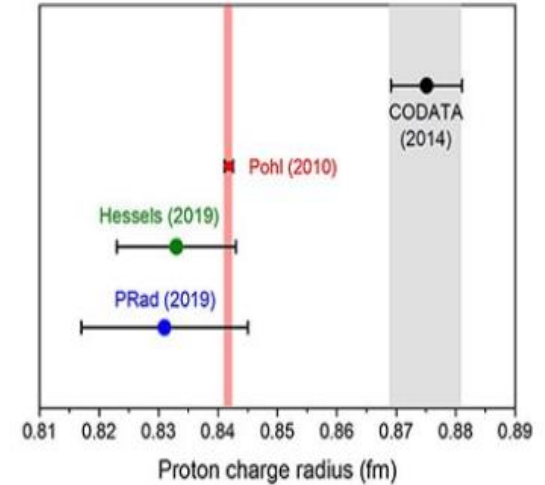
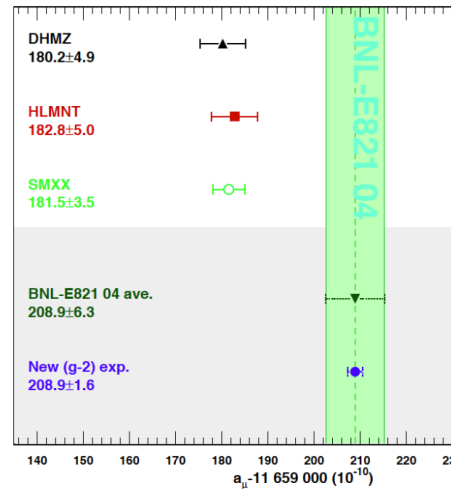
Muonic puzzle

$$(g-2)_\mu$$

Latest measurement at Fermilab

Proton radius

Energy levels in muonic hydrogen are different than standard hydrogen

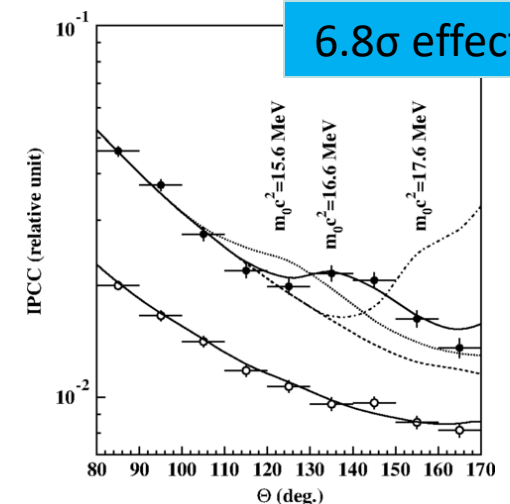
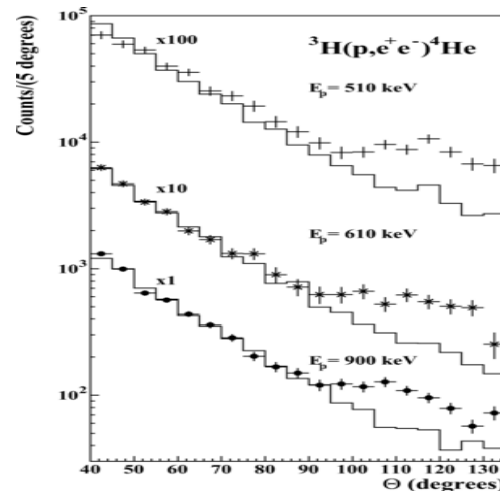


Maybe close to be solved

X_{17} in the e^+e^- spectra

$$X_{17}$$

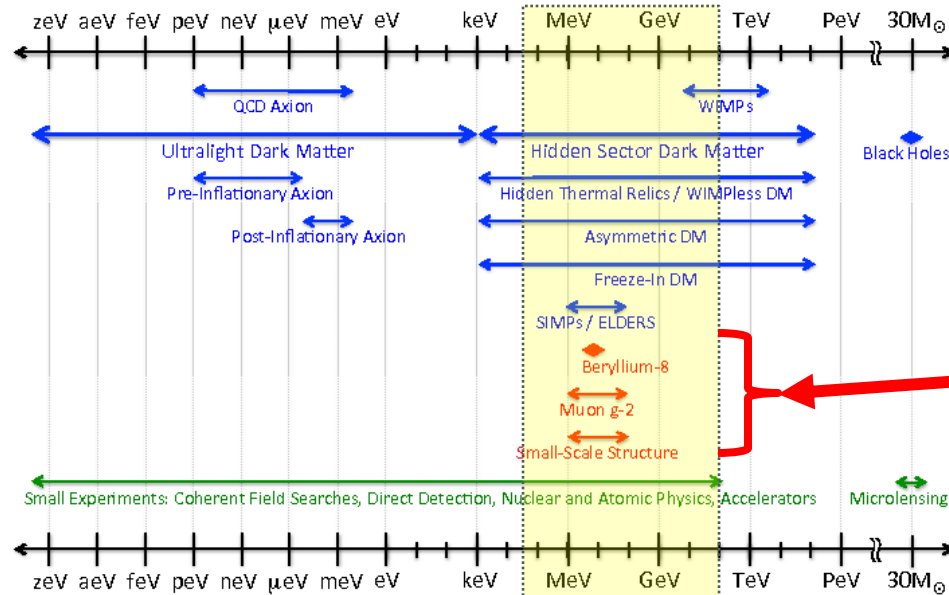
„Bumblike” structure in the emission spectra of opening angles for e^+e^- pairs in the isoscalar magnetic transitions of ^8Be and ^4He nuclei



6.8 σ effect?

General motivation

Dark Sector Candidates, Anomalies, and Search Techniques



- In SM: violation from weak interaction is not sufficient to create observed asymmetry

- Parameter space for BSM is running out at HEP

- several anomalies in experiments point to possible new physics, weakly coupled to familiar matter in the 1 MeV - 1 GeV scale

Ref: Marco Battaglieri, [arXiv:1707.04591](https://arxiv.org/abs/1707.04591) [hep-ph]

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)

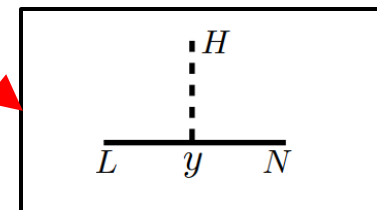
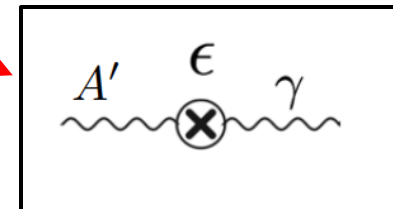
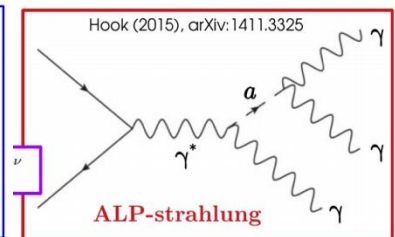
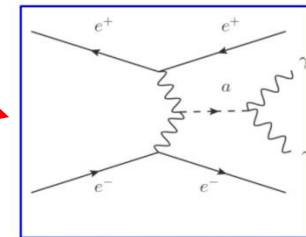
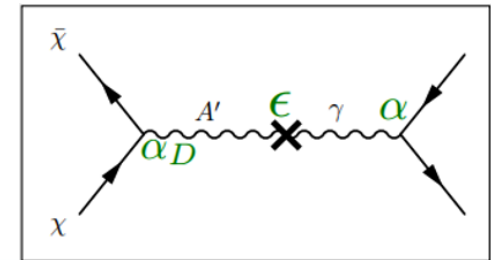
How can we try to address SM problems experimentally?

- Searching for new particles
- Studying violation of discrete symmetries

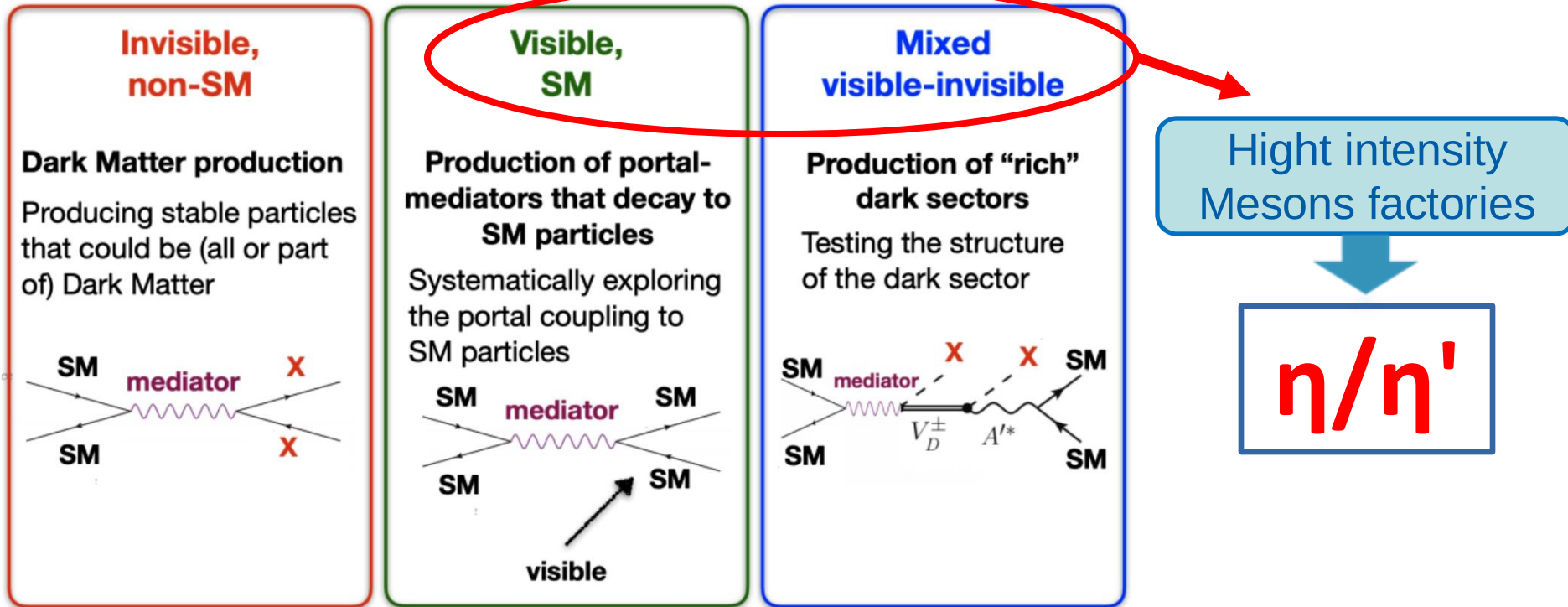
Connection between Standard and Dark Matter

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	$\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}, \frac{a}{f_a}G_{i\mu\nu}\tilde{G}_i^{\mu\nu}, \frac{\partial_\mu a}{f_a}\bar{\psi}\gamma^\mu\gamma^5\psi$
"Higgs"	Dark scalars	$(\mu S + \lambda S^2)H^\dagger H$
"Neutrino"	Sterile neutrinos	$y_N L H N$



Connection between Standard and Dark Matter



Stefania Gori, Mike Williams

η/η' Factory sensitive for all 4 portals
(Vector, Axion, Higgs, Neutrino)

Mesons advantages

“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 **pseudoscalar η/η' mesons** and the **Higgs boson** -> **very rare**
- The **η** meson is a Goldstone boson (the η' meson is not!)
- The **η/η'** decays are flavor-conserving reactions

Experimental advantages of η/η' :

- **Hadronic production cross section is quite large (~ 0.1 barn)**
 $\rightarrow$ 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.

Mesons advantages

“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 **pseudoscalar η/η' mesons** and the **Higgs boson** -> **very rare**
- The **η** meson is a Goldstone boson (the η' meson is not!)
- The **η/η'** decays are flavor-conserving reactions

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**

World η data samples:

Experiments studying η and η' with number of tagged η events :



$\sim 3 \times 10^7$

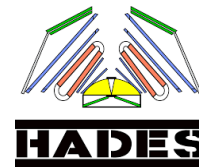


KLOE-2 (Frascati)

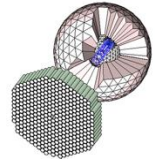
$\sim 10^9$



$\sim 4 \times 10^7$



$\sim 4.5 \times 10^8$



CB@ MAMI

$\sim 3 \times 10^8$

Experiment	Technique	Total η mesons
<i>GlueX@JLAB (running)</i>	$\gamma_{12 \text{ GeV}} \text{ p} \rightarrow \eta \text{ X} \rightarrow \text{neutrals}$	$5.5 \times 10^7 / \text{yr}$
<i>JEF@JLAB (approved)</i>	$\gamma_{12 \text{ GeV}} \text{ p} \rightarrow \eta \text{ X} \rightarrow \text{neutrals}$	$1.5 \times 10^8 / \text{yr}$
<i>HIAF (approved)</i>		$\sim 10^{13} / \text{yr}$
<i>REDTOP (proposing)</i>	$p_{1.8 \text{ GeV}} \text{ Li} \rightarrow \eta \text{ X}$	$3.4 \times 10^{13} / \text{yr}$



REDTOP - Rare Eta Decays TO Probe New Physics

The general key points:

REDTOP: $\eta(\eta')$ yielding $\sim 10^{13}(10^{12})$ mesons
O(10^5) the existing world sample with a 3-yr run

Hadro-produced mesons
requires proton or pion beam

Designed to search for BSM physics in the MeV-GeV region
Main search fields: dark matter and CP-violation
Sensitive to ALP's (Axion-Like-Particles)



η/η'



REDTOP - Rare Eta Decays TO Probe New Physics

Main physics program and goals:

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

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

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

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

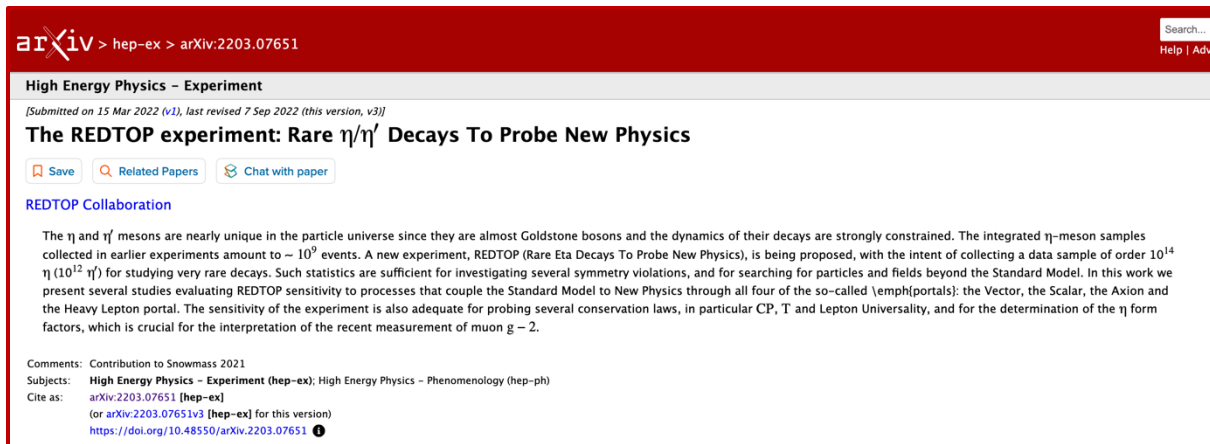
Dark scalar searches: $\eta \rightarrow \pi^0 H$, with $H \rightarrow \mu^+ \mu^-$, $H \rightarrow e^+ e^-$
Dual (or triple!) calorimeters and particle ID

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



Physics case for REDTOP is very strong

Physics case presented in „White Paper” available on **arXiv:2203.07651**



arXiv > hep-ex > arXiv:2203.07651

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

Save Related Papers Chat with paper

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 (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>

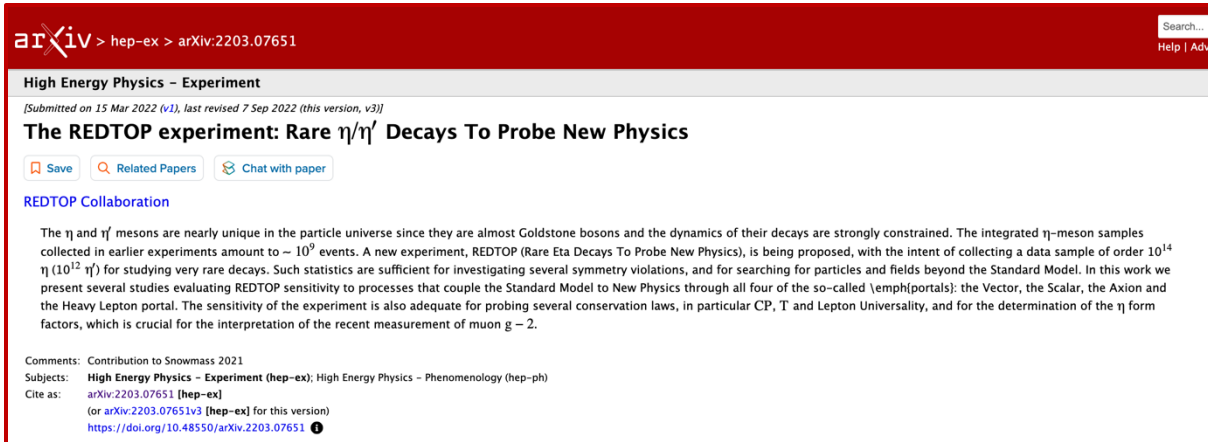
Sensitivity studies based on
 $\sim 10^{14}$ η mesons
 $(3.3 \times 10^{18}$ p OT and 3-year run)

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

Physics case for REDTOP is very strong

Physics case presented in „White Paper” available on **arXiv:2203.07651**



arXiv > hep-ex > arXiv:2203.07651

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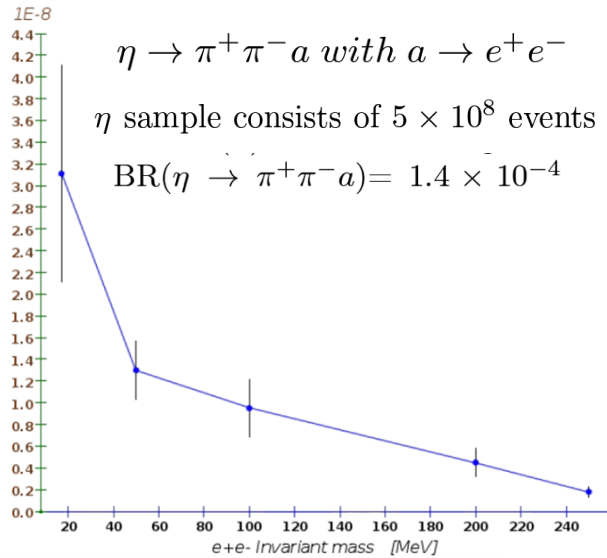
Cite as: arXiv:2203.07651 [hep-ex]
(or arXiv:2203.07651v3 [hep-ex] for this version)
<https://doi.org/10.48550/arXiv.2203.07651>

Sensitivity studies based on
 $\sim 10^{14}$ η mesons
 $(3.3 \times 10^{18}$ p OT and 3-year run)

Key detector parameters

- Large sensitivity to < 20 MeV mass resonances (compared to WASA and KLOE)
- Tracking capable to reconstruct detached vertices up to ~ 100 cm
- Sensitivity to $\text{BR} \sim \mathcal{O}(10^{-11})$ with protons and $\sim \mathcal{O}(10^{-12})$ with pion beam
- Detector optimization under way

Pseudoscalar Portal: $\eta \rightarrow \pi^+ \pi^- a$ ($a \rightarrow \gamma\gamma$ and $a \rightarrow e^+ e^-$)

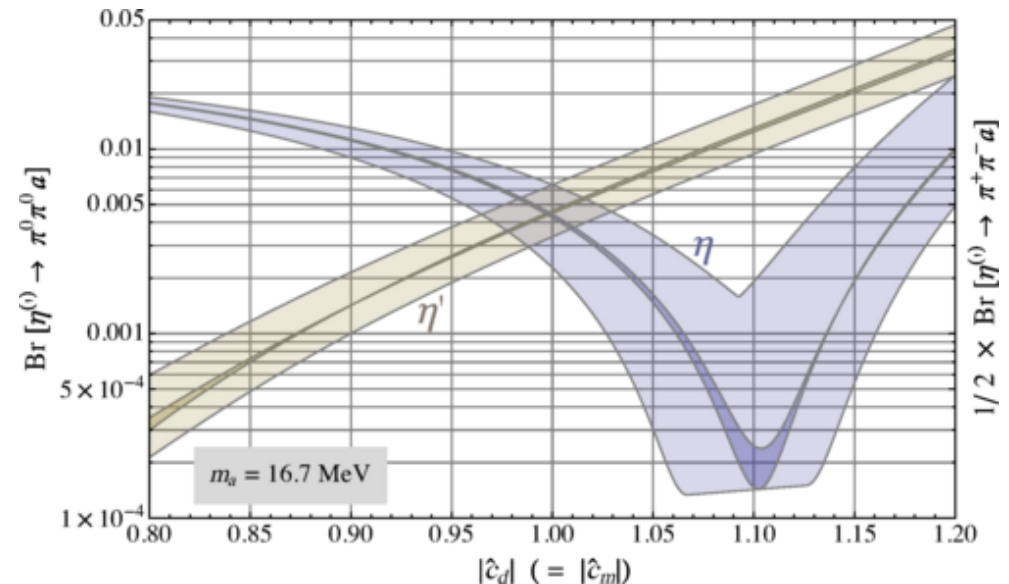


17 MeV piophobic QCD axion

Process	Benchmark set	Trigger L0	Trigger L1	Trigger L2	Reconstruction	Analysis	Total	BR sensitivity
$\eta \rightarrow \pi^+ \pi^- a ; a \rightarrow e^+ e^-$	B1	55.28%	21.81%	76.41%	75.12%	42.94%	2.97%	2.07×10^{-8}
$\eta \rightarrow \pi^+ \pi^- a ; a \rightarrow e^+ e^-$	B2	56.15%	22.32%	76.76%	75.12%	42.83%	3.10%	1.98×10^{-8}
$\eta \rightarrow \pi^+ \pi^- a ; a \rightarrow e^+ e^-$	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%	$2.31 \times 10^{-6}\%$	

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



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**

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

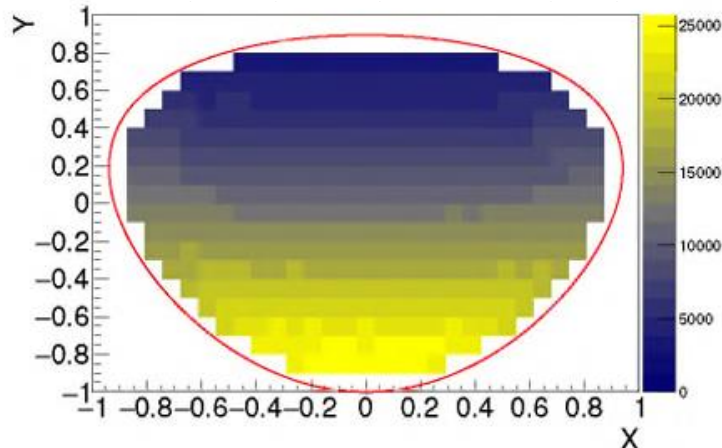
- CP-violation from this process is not bounded by EDM as is the case for the $\eta \rightarrow 4\pi$ process.
- Complementary to EDM searches even in the case of T and P odd observables, since the flavor structure of the η is different from the nucleus
- Current PDG limits consistent with no asymmetry

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

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

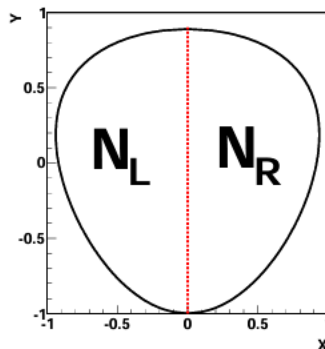
Precision measurement of the $\eta \rightarrow \pi^+ \pi^- \pi^0$ Dalitz plot distribution with the KLOE detector

The KLOE-2 collaboration

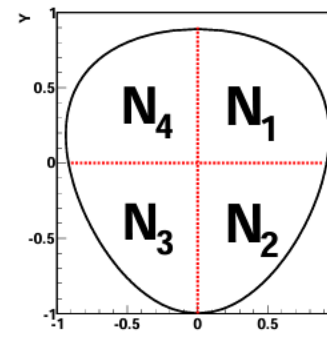


REDTOP sensitivity to model parameters

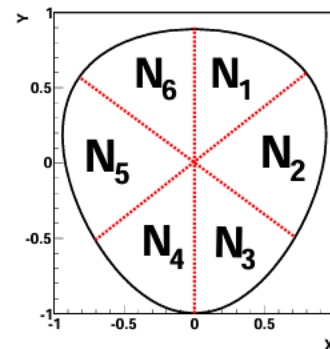
#Rec. Events	Re(α)	Im(α)	Re(β)	Im(β)	p-value
10^8 (no-bkg)	3.3×10^{-1}	3.7×10^{-1}	4.4×10^{-4}	5.6×10^{-4}	17%
Full stat. (no-bkg)	1.9×10^{-2}	2.1×10^{-2}	2.5×10^{-5}	3.2×10^{-5}	17%
Full stat. (100%-bkg)	2.3×10^{-2}	3.0×10^{-2}	3.5×10^{-5}	4.5×10^{-5}	16%



$$A_{LR} = \frac{N_R - N_L}{N_R + N_L},$$



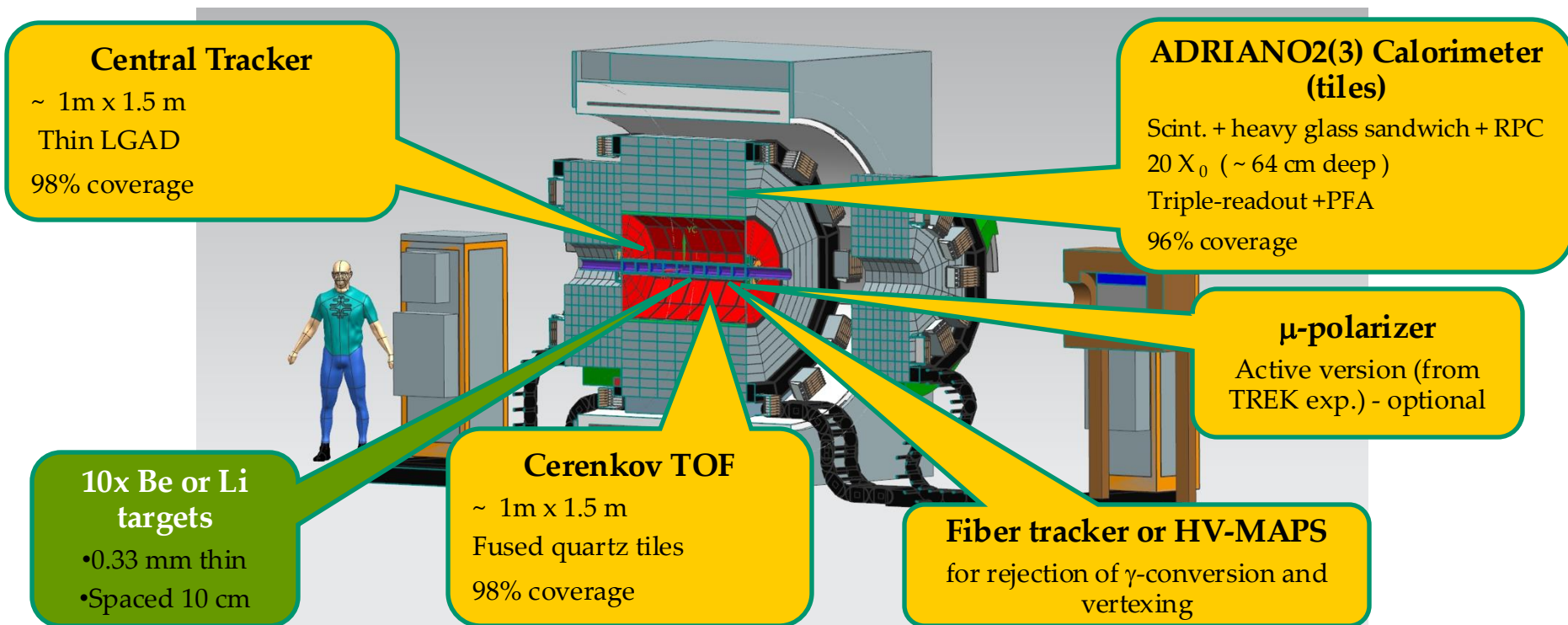
$$A_Q = \frac{N_1 + N_3 - N_2 - N_4}{N_1 + N_2 + N_3 + N_4},$$



$$A_S = \frac{N_1 + N_3 + N_5 - N_2 - N_4 - N_6}{N_1 + N_2 + N_3 + N_4 + N_5 + N_6},$$

Proposed REDTOP Detector design

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





Beam options for 10^{13} 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 - 2.5×10^{10} π OT/sec
- ❑ More expensive but lower background (**ESS**, ORNL - Oak Ridge Nat. Lab.)
- ❑ η : inelastic background = 1:50 $\rightarrow$ 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 forward tagging detector for He_3^{++}
- ❑ Fully tagged production from nuclear reaction: $p + \text{De} \rightarrow \eta + \text{He}_3^{++}$

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58 Institutions
128 Collaborators

Cost estimates...

□ Largest cost uncertainties

- ADRIANO2 SiPM's ($2 \times 10^6 - 4 \times 10^6$)
- LGAD mechanics

□ No labor considered (in the US, ~1/3 of the total)

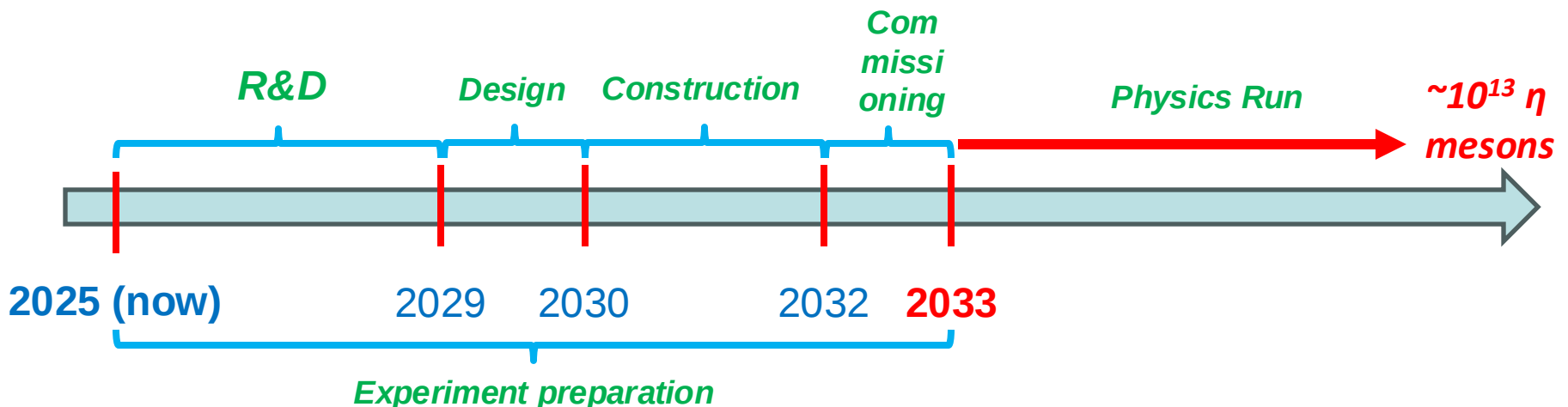
	2023 US\$
Target+beam pipe	0.1
Vtx detector	2.1
LGAD tracker	22.5
CTOF	0.75
ADRIANO2	22.5
Solenoid	0.3
Supporting structure	1.3
Trigger	2.4
DAQ	1.1
Computing	0.4
Total	54.8
Contingency 50%	26.7
Grand total	80.2



Timeline

- One approved at a laboratory, REDTOP needs:
 - 2-3 years for detector R&D
 - 1 year for design
 - 2 years for construction
- Running time – based on 3×10^{18} pOT or 3×10^{17} π OT
 - 1 year for engineering run
 - **3 year for physics run**
 - 1 year for contingency

In total:
~11 years



Necessary infrastructure at ESS:

- Only 1% of the proton or pion beam interacts with target and can be useful for REDTOP
- Remaining beam can be used for a downstream pion or muon precision experiments.
- ESS could take a staged approach

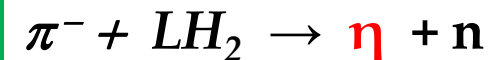


❑ Proton beam :

- extract ~30 W of protons at 1.8 – 2.0 GeV
- Transport beam line into the experimental hall

❑ Pion beam:

- Extract ~200 kW of protons > 1.3 GeV
- Transport beam line to the experimental hall
- Pion target and pion collector station



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 sensitive to all four DM portals.*
- *New detector techniques benefit the next generation of high intensity experiments.*
- *Beam requirements could be met by the **ESS infrastructure after 2030***

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

<https://arxiv.org/abs/2203.07651>



World η data samples:

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



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: $\eta \rightarrow \pi^0 \pi^+ \pi^-$
- CP Violation (Type I – P and T odd, C even): $\eta \rightarrow 4\pi^0 \rightarrow 8\gamma$
- CP Violation (Type II – C and T odd, P even): $\eta \rightarrow \pi^0 e^+ e^-$ and $\eta \rightarrow 3\gamma$
- Test of CP invariance via μ longitudinal polarization: $\eta \rightarrow \mu^+ \mu^-$
- CP inv. via γ^* polarization studies: $\eta \rightarrow \pi^+ \pi^- e^+ e^-$ & $\eta \rightarrow \pi^+ \pi^- \mu^+ \mu^-$
- CP invariance in angular correlation studies: $\eta \rightarrow \mu^+ \mu^- e^+ e^-$
- CP invariance in angular correlation studies: $\eta \rightarrow \mu^+ \mu^- \pi^+ \pi^-$
- CP invariance in μ polar. in studies: $\eta \rightarrow \pi^0 \mu^+ \mu^-$
- T invar. via μ transverse polarization: $\eta \rightarrow \pi^0 \mu^+ \mu^-$ and $\eta \rightarrow \gamma \mu^+ \mu^-$
- CPT violation: μ polr. in $\eta \rightarrow \pi^+ \mu^- \nu$ vs $\eta \rightarrow \pi^- \mu^+ \nu$ - γ polar. in $\eta \rightarrow \gamma \gamma$

New particles and forces searches

- Scalar meson searches (charged channel): $\eta \rightarrow \pi^0 H$ with $H \rightarrow e^+ e^-$ and $H \rightarrow \mu^+ \mu^-$
- Dark photon searches: $\eta \rightarrow \gamma A'$ with $A' \rightarrow e^+ e^-$
- Protophobic fifth force searches: $\eta \rightarrow \gamma X_{17}$ with $X_{17} \rightarrow \pi^+ \pi^-$
- QCD axion searches: $\eta \rightarrow \pi \pi a_{17}$ with $a_{17} \rightarrow e^+ e^-$
- New leptophobic baryonic force searches: $\eta \rightarrow \gamma B$ with $B \rightarrow e^+ e^-$ or $B \rightarrow \gamma \pi^0$
- Indirect searches for dark photons new gauge bosons and leptoquark: $\eta \rightarrow \mu^+ \mu^-$ and $\eta \rightarrow e^+ e^-$
- Search for true muonium: $\eta \rightarrow \gamma (\mu^+ \mu^-)_{2M_\mu} \rightarrow \gamma e^+ e^-$
- Lepton Universality
- $\eta \rightarrow \pi^0 H$ with $H \rightarrow \nu N_2$, $N_2 \rightarrow h' N_1$, $h' \rightarrow e^+ e^-$

Other discrete symmetry violations

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

Other Precision Physics measurements

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

Non- η/η' based BSM Physics

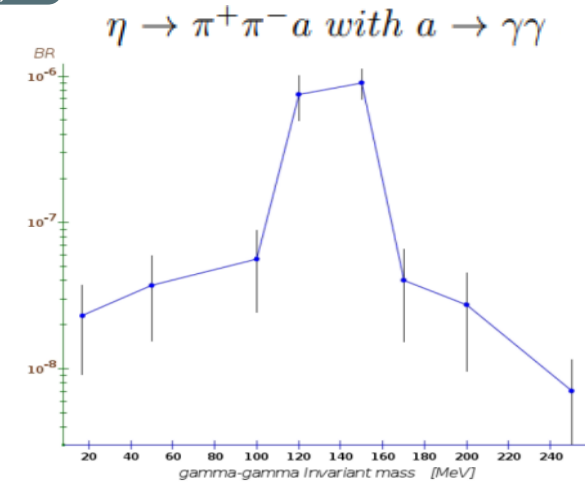
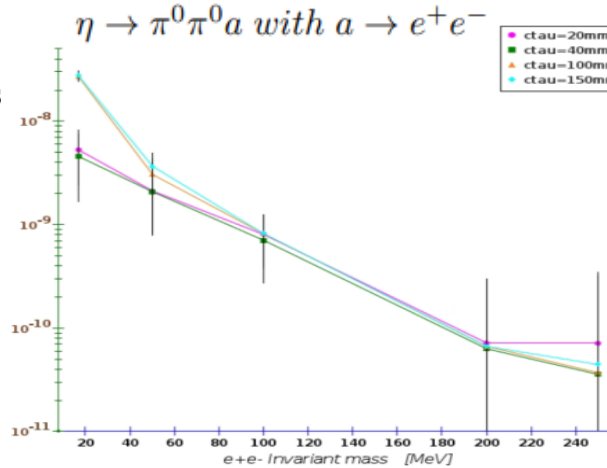
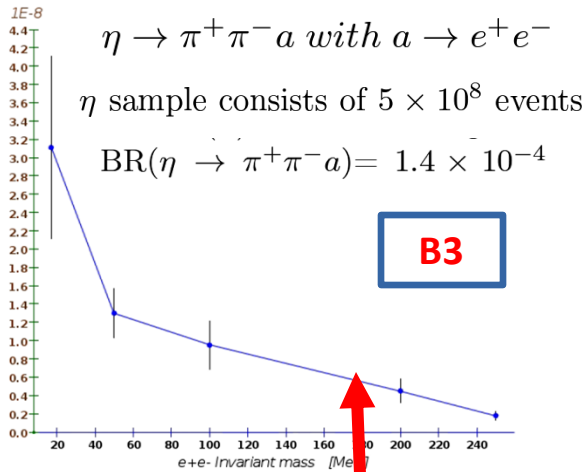
- Neutral pion decay: $\pi^0 \rightarrow \gamma A' \rightarrow \gamma e^+ e^-$
- ALP's searches in Primakoff processes: $p Z \rightarrow p Z a \rightarrow l^+ l^-$
- Dark photon and ALP searches in Drell-Yan processes:

High precision studies on medium energy physics

- Nuclear models
- Chiral perturbation theory
- Non-perturbative QCD
- Isospin breaking due to the u-d quark mass diff.
- Octet-singlet mixing angle
- Electromagnetic transition form-factors

Pseudoscalar Portal: $\eta \rightarrow \pi^0 \pi^0 a$, $\eta \rightarrow \pi^+ \pi^- a$ ($a \rightarrow \gamma\gamma$ and $a \rightarrow e^+ e^-$)

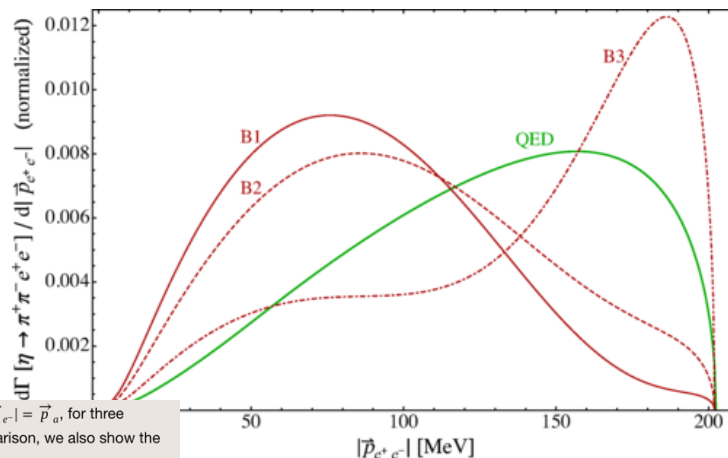
17 MeV piophobic QCD axion (ALP)



Differential rate for $\eta \rightarrow \pi^+ \pi^- a$ 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



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

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



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

BR sensitivity curves

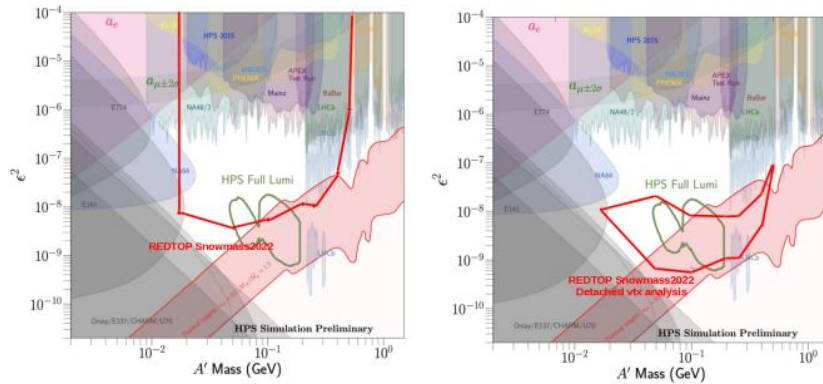
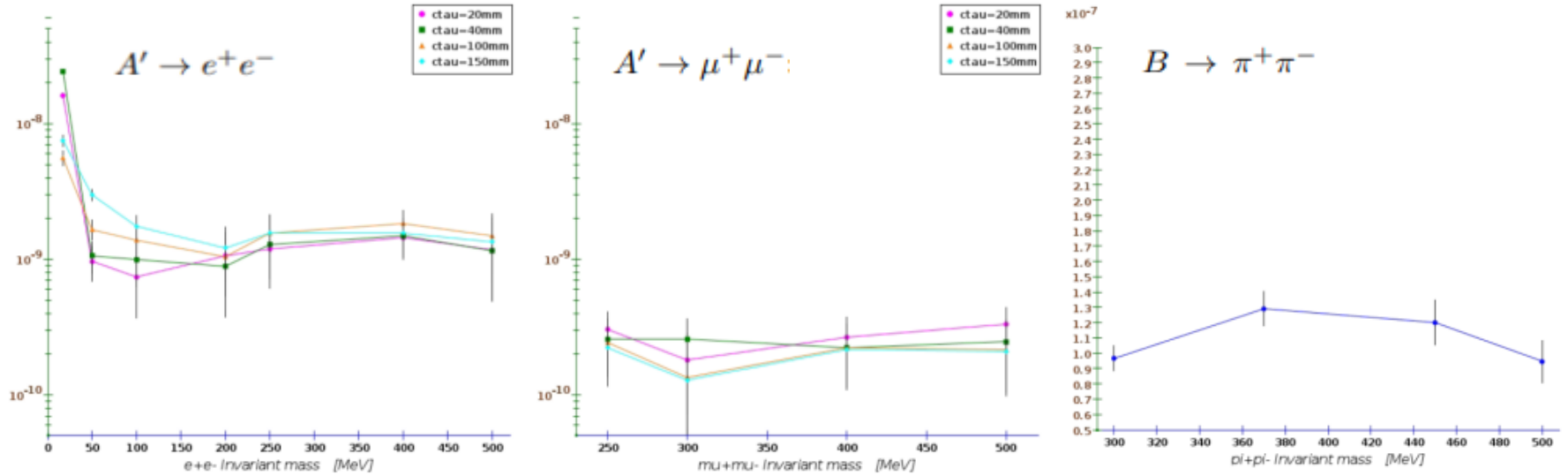


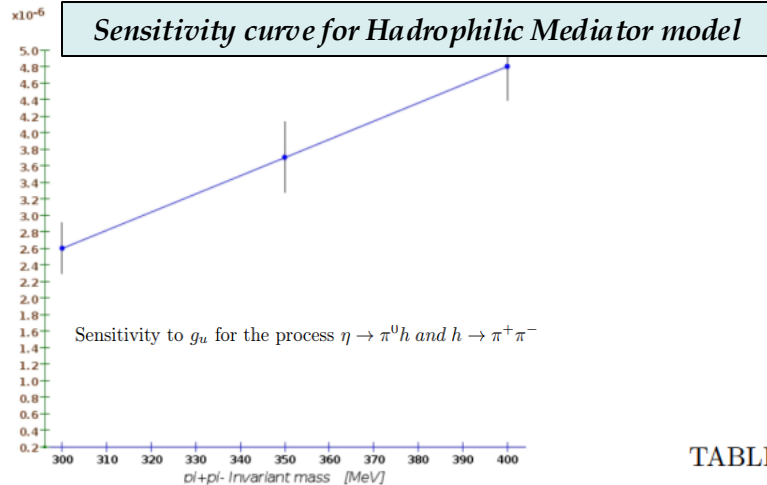
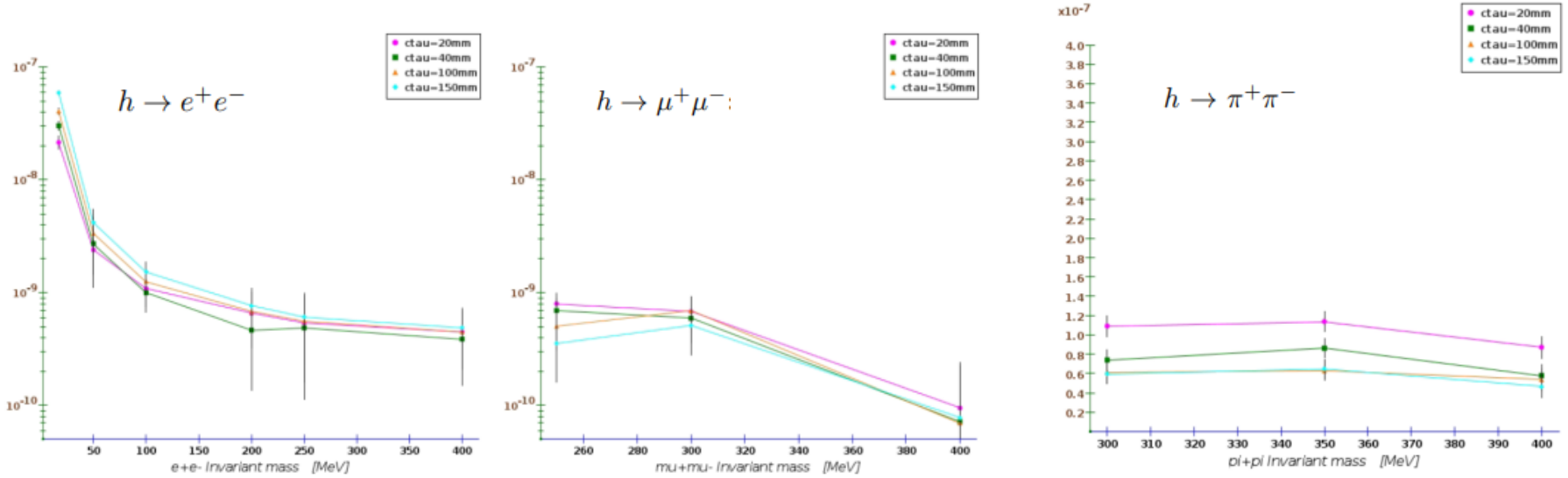
FIG. 36. Sensitivity to ϵ^2 for the processes $\eta \rightarrow \gamma A'$ for integrated beam flux of 3.3×10^{18} POT. Left plot: bump-hunt analysis. Right plot: detached-vertex analysis).

Theoretical Models considered

- ☐ Minimal dark photon model
 - Most popular model
- ☐ Leptophobic B boson Model
- ☐ Protophobic Fifth Force

Scalar Portal: $\eta \rightarrow \pi^0 h$ with $h \rightarrow \mu^+ \mu^-$ or $h \rightarrow \pi^+ \pi^-$ or $h \rightarrow e^+ e^-$

BR sensitivity curves



Theoretical Models considered

- Hadrophilic Scalar Mediator (B. Batell, A. Freitas, A. Ismail, D. McKeen)
- Spontaneous Flavor Violation (D. Egana-Ugrinovic, S. Homiller, P. Meade)

Process	m_S	Analysis	$(\lambda_u - \lambda_d)^2$ sensitivity
$\eta \rightarrow \pi^0 S$; $S \rightarrow e^+ e^-$	17 MeV	bump hunt	2.0×10^{-13}
$\eta \rightarrow \pi^0 S$; $S \rightarrow \mu^+ \mu^-$	17 MeV	detached vertex	3.2×10^{-13}

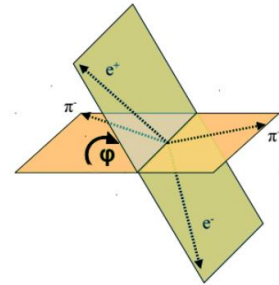
TABLE XXV. Sensitivity to $(\lambda_u - \lambda_d)^2$ for the process $\eta \rightarrow \pi^0 S$ and $S \rightarrow e^+ e^-$ and $S \rightarrow \mu^+ \mu^-$.



CP Violation from decay planes asymmetry in $\eta \rightarrow \pi^+ \pi^- e^+ e^-$ and in $\eta \rightarrow \mu^+ \mu^- e^+ e^-$

See: Dao-Neng Gao, /hep-ph/0202002 and P. Sanchez-Puertas, JHEP 01, 031 (2019)

Requires the measurement of angle between pions and leptons decay planes.



CP violation is related to asymmetries in $\eta \rightarrow \mu^+ \mu^- e^+ e^-$

$$A_{\sin\Phi\cos\Phi} = \frac{N(\sin\phi\cos\phi > 0) - N(\sin\phi\cos\phi < 0)}{N(\sin\phi\cos\phi > 0) + N(\sin\phi\cos\phi < 0)}$$

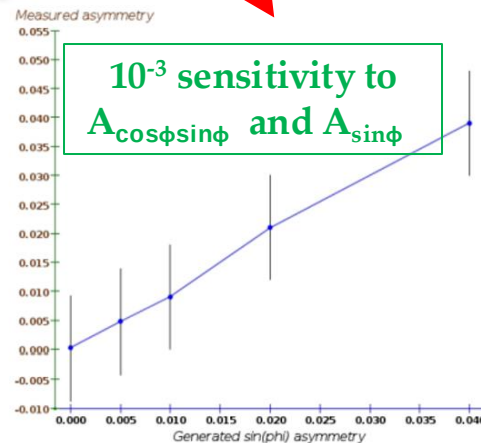
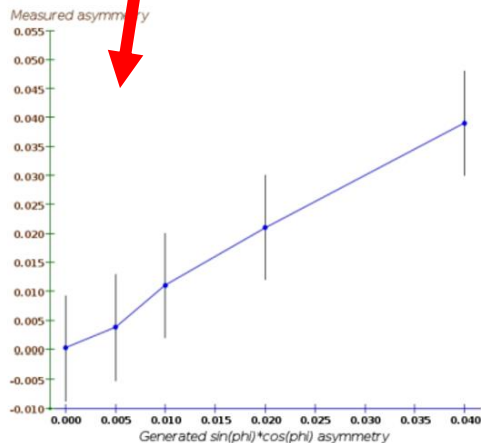
$$A_{\sin\Phi} = \frac{N(\sin\phi > 0) - N(\sin\phi < 0)}{N(\sin\phi > 0) + N(\sin\phi < 0)}$$

through Wilson coefficients

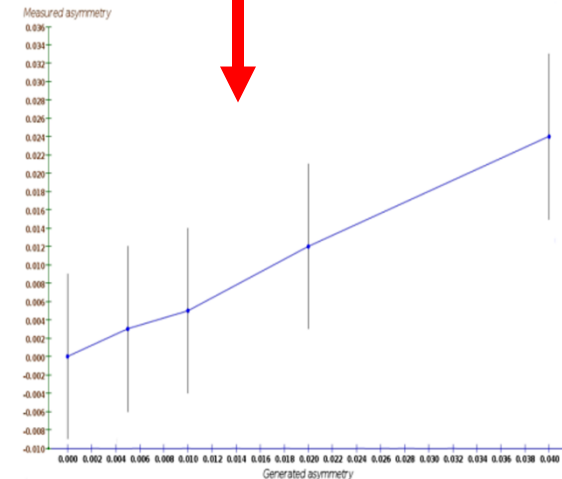
$$A_{\sin\phi\cos\phi} = \text{Im}[1.9c_{\ell e d q}^{2222} - 1.3(c_{\ell e q u}^{(1)2211} + c_{\ell e d q}^{1122})] \times 10^{-5} - 0.2\epsilon_1 + 0.0003\epsilon_2$$

CP violation is related to asymmetries in $\eta \rightarrow \pi^+ \pi^- e^+ e^-$

$$A_\phi = \frac{N(\sin\phi\cos\phi > 0) - N(\sin\phi\cos\phi < 0)}{N(\sin\phi\cos\phi > 0) + N(\sin\phi\cos\phi < 0)}$$



10^{-3} sensitivity to
 $A_{\cos\phi\sin\phi}$ and $A_{\sin\phi}$





Heavy Neutral Lepton Portal: $\eta \rightarrow \pi^0 H$; $H \rightarrow \nu N_2$; $N_2 \rightarrow N_1 h_0$; $h_0 \rightarrow e^+ e^-$

Theoretical Model considered

• **Two-Higgs doublet model (W. Abdallah, R. Gandhi, and S. Roy) with the following benchmark parameters:**

m_{N_1}	m_{N_2}	m_{N_3}	$y_{e(\mu)}^{h'} \times 10^4$	$y_{e(\mu)}^H \times 10^4$
85 MeV	130 MeV	10 GeV	0.23(1.6)	2.29(15.9)
$m_{h'}$	m_H	$\sin \delta$	$y_{\mu 2}^{h'(H)} \times 10^3$	$\lambda_{N_{12}}^{h'(H)} \times 10^3$
17 MeV	250 MeV	0.1	1.25(12.4)	74.6(-7.5)

TABLE XXVIII. Benchmark parameters for REDTOP.

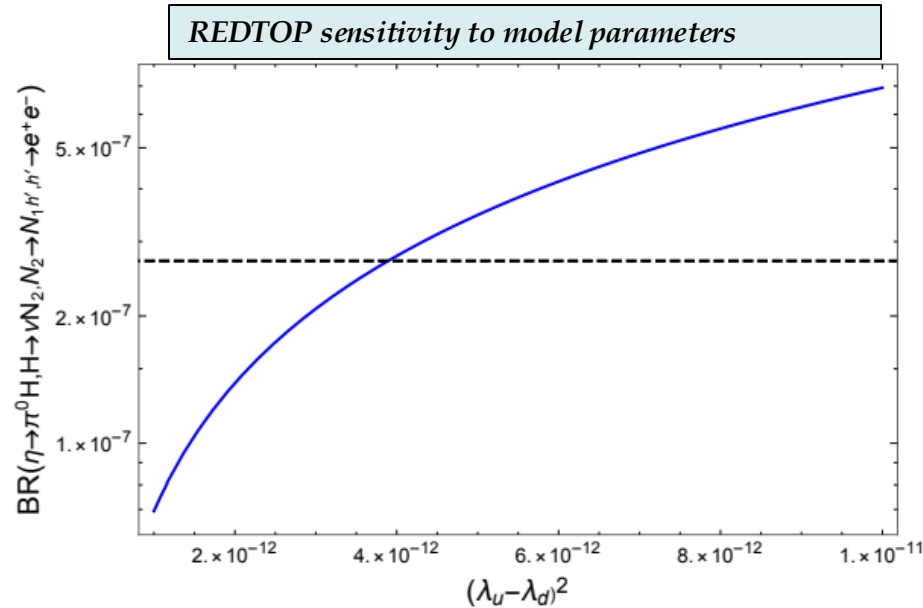


FIG. 61. Branching ratio for the process $\eta \rightarrow \pi^0 H$; $H \rightarrow \nu N_2$; $N_2 \rightarrow N_1 h'$; $h' \rightarrow e^+ e^-$ predicted by the Two Higgs Doublet model [51] as a function of $(\lambda_u - \lambda_d)^2$. The dashed line corresponds to the experimental limit for REDTOP with an integrated luminosity of 3.3×10^{18} POT.



REDTOP @ ESS

Low-cost, readily available (BNL, ESS, FIAN, GSI, HIAF)

Poprzedni slajd and is the only accelerator capable of supporting all three η production modes

Preferred option – low-energy pion beam

Only ~1% of the proton or pion beam interacts with REDTOP

More expensive but lower background (FAIR, HIAF, ORNL)

η : inelastic background = 1:50 $\rightarrow$ sensitivity to BSM increased by >

Semi-tagged η production

Remaining beam can be used for a downstream pion and/or muon precision experiment

Inelastic interaction GHz

event multiplicity charged + 4 n

production rate

Inelastic interaction 0.1 GeV

production rate

- Strong focus of ESS on sustainability in construction and operation
 - no waste to landfill, biofuel powered construction vehicles
 - all electrical power from renewable sources
 - waste heat recovery into local district heating system
- Academia, society and industry
 - development of science and innovation campus
 - opportunities for participation, empowering marginalized groups in society
- Pion beam for REDTOP
 - Unexplored medical applications (FoM radiotherapeutic treatments)
 - Pion dosimetry (human exposure in space)



REDTOP



Proposed **REDTOP** Detector design

- Sustain up to 0.7 GHz event rate with avg final state multiplicity of ~ 8 particles
- Calorimetric $\sigma(E)/E \sim 2-3\%/\sqrt{E}$
- High PID efficiency: 98/99% (e, γ), 95% (μ), 95% (π), 99.5% (p, n)
- $\sigma_{\text{tracker}}(t) \sim 30\text{psec}$, $\sigma_{\text{calorimeter}}(t) \sim 80\text{psec}$, $\sigma_{\text{TOF}}(t) \sim 50\text{psec}$
- 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
- ❑ $\sim 70\mu\text{m}$ vertex resolution in x-y. Stereo layers

Option 2: HV-MAPS (Mu3e style)

- ❑ Low material budget (0.11%/layer)
- ❑ $\sim 40\mu\text{m}$ vertex resolution in 3D

Cerenkov Threshold TOF

Option 1: Quartz tiles

- ❑ Established and low-cost technology
- ❑ $\sim 50\text{psec}$ timing with T1604 prototype

Option 2: EIC-style LGAD

- ❑ $\sim 30-40\text{psec}$ timing, but expensive



Proposed REDTOP 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

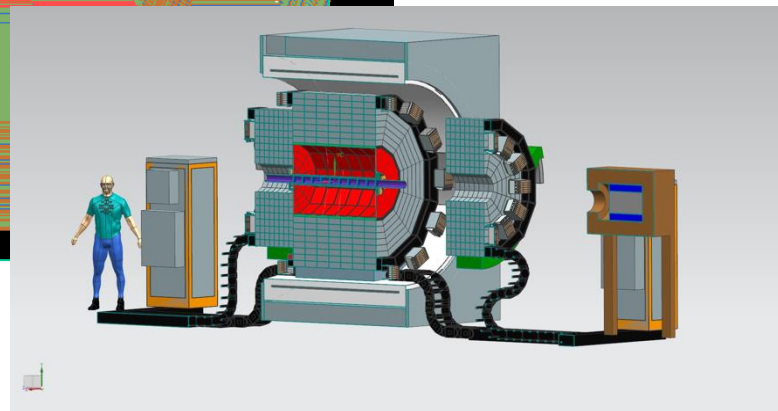
~ 1m x 1.5 m
Fused quartz tiles
98% coverage

Fiber tracker or HV-MAPS

for rejection of γ -conversion and
vertexing

2.4 m

2.7 m



REDTOP – target system

Target for π beams: : LH_2 (pellets or fluid)

- For π beams only
- More expensive, but less background
- Tagged η/η' production: $\pi^- p \rightarrow \eta/\eta' n$

Target for p and π^+ beams: 10x 0.78 mm Li foil

- For p and π^+ beams
- Inexpensive, but more background
- Untagged/semi-tagged η/η' production



REDTOP – vertex detector

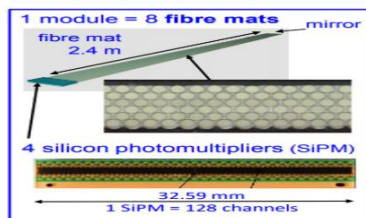
Requirements

- $<0.5\% X_0$
- $\leq 70\mu\text{m}$ vertex resolution in x-y.
- No active cooling
- Rad-hard $\sim 5 \times 10^5$ 1 MeV-neq n/cm²/sec
- Timing: ~ 10 nsec

Option 1: LHCb-style Fiber Tracker

- Established and simple technology – no R&D required
- Active surface is about 0.24 m² vs 360 m² for LHCb
- Readout channels is about 18,000 vs 590k for LHCb
- Cheap, but no z-measurement nor TOF
- Scale costing directly from LHCb upgrade's TDR

128 modules (0.5 x 5 m²)
arranged in 3 stations x 4 layers
(XUVX)



Option 2: MuPix (Mu3e vtx technology)

	Requirements	MuPix7	MuPix8	MuPix10
pixel size [μm^2]	80×80	103×80	81×80	80×80
sensor size [mm^2]	20×23	3.8×4.1	10.7×19.5	20.66×23.18
active area [mm^2]	20×20	3.2×3.2	10.3×16.0	20.48×20.00
active area [mm^2]	400	10.6	166	410
sensor thinned to thickness [μm]	50	50, 63, 75	63, 100	50, 100
LVDS links	3 + 1	1	3 + 1	3 + 1
maximum bandwidth [§] [Gbit/s]	3×1.6	1×1.6	3×1.6	3×1.6
timestamp clock [MHz]	≥ 50	62.5	125	625
RMS of spatial resolution [μm]	≤ 30	≤ 30	≤ 30	≤ 30
power consumption [mW/cm^2]	≤ 350	$\approx 300^\dagger$	250 – 300	≈ 200
time resolution per pixel [ns]	≤ 20	≈ 14	≈ 13 (6*)	not meas. [‡]
efficiency at 20 Hz/pix noise [%]	≥ 99	99.9	99.9	99.9
noise rate at 99% efficiency [Hz/pix]	≤ 20	< 10	< 1	< 1



REDTOP – LGAD tracker

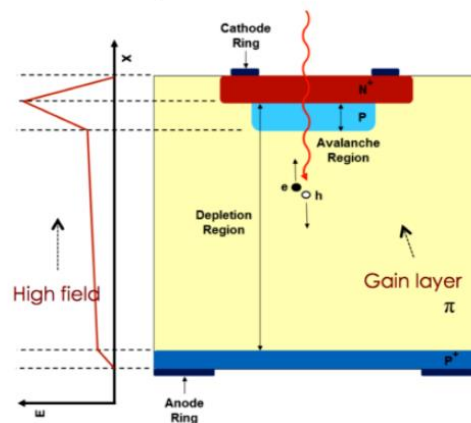
Requirements

- $<1\% X_0$
- 30 nsec timing resolution.
- No active cooling
- Rad-hard $\sim 1 \times 10^5$ 1 MeV-neq $n/cm^2/sec$

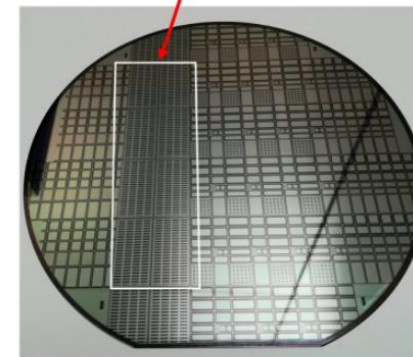
Option 1: CMS's ETL

- REDTOP vs CMS' ETL: 87.5% area
- use pixel upgrade for the mechanics
- 5-layer barrel
- 4-layer endcaps
- SID layout

- Demonstrated time resolution ~ 30 ps up to $1 \times 10^{15} n_{eq}/cm^2$, and about 40 psec up to $2 \times 10^{15} n_{eq}/cm^2$



CMS-designed 96-channel sensors



FBK wafer with CMS- and ATLAS- sensors

REDTOP – Calorimeter

Requirements

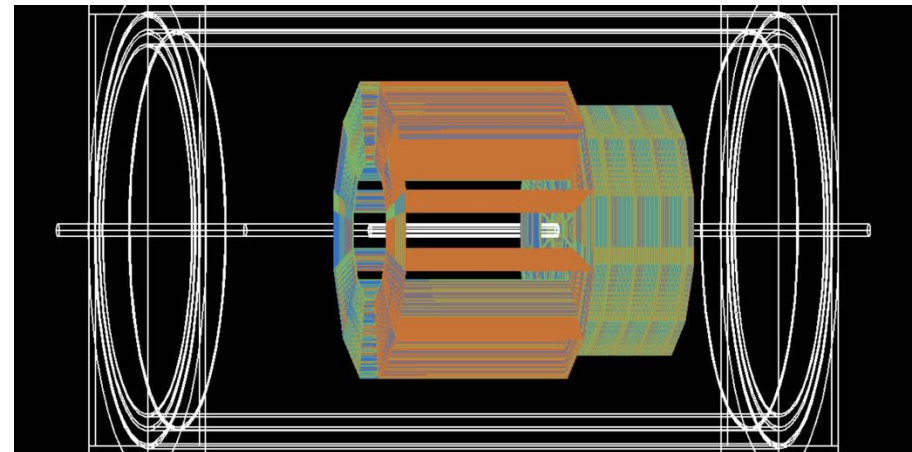
- $\sigma_E/E \sim 2\text{-}3\%/ \sqrt{E}$
- ~ 80 psec/cell timing resolution for MIPs.
- No active cooling
- Rad-hard $\sim 5 \times 10^4$ 1 MeV-neq n/cm²/sec

EM: dual-readout ADRIANO2

- Inner section: Pb-glass and scint. Tiles interleaved
- 10 layers – $6.6 X_0 / 0.55 \lambda_I$
- 120,00 tile-pairs
- Same plastic tiles as CMS' HGCAL
- FEE from Weeroc+Omega (costing being discussed) or TOFPET2

HAD: triple-readout ADRIANO3

- Outer section: Pb-glass + scint. + thin RPC + Fe
- 25 layers – $22 X_0 / 2.7 \lambda_I$
- Longer λ_I for better hadron shower containment
- 390,00 tile-pairs
- Heatsink: pyrolitic foil



REDTOP – Threshold Cerenkov and TOF

Requirements

- 99% efficiency
- Rad-hard $< 1 \times 10^5$ 1 MeV-neq n/cm²/sec
- Timing resolution: < 50 psec

Option 1: Small tiles of JGS1 & on-tile SiPM

- Different options: #layers and tile size
- Similar technologies: CMS' BTL (lyso) and Mu3e tile detector (scint. plastics)
- Wellmestablishe TOFHIR2 Asic (LIP)

Option 2: LGAD

- REDTOP vs CMS's ETL: 51% area
- Extra cost justified by position measurement, but loose energy measurement

