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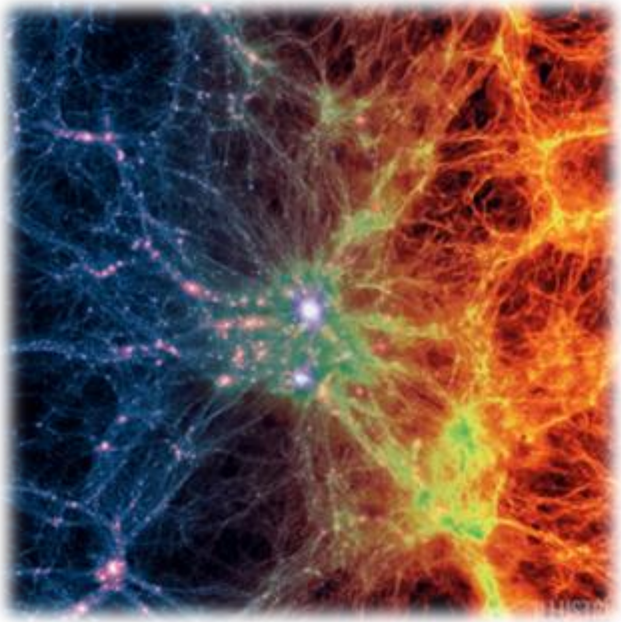

The REDTOP Experiment: a η/η' factory to explore Dark Matter and physics Beyond the Standard Model

Marcin Zieliński, Corrado Gatto
on behalf of REDTOP Collaboration

FNPP @ ESS Workshop, Lund University, 17.01.2025

General motivation

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

Why does the Universe exist?

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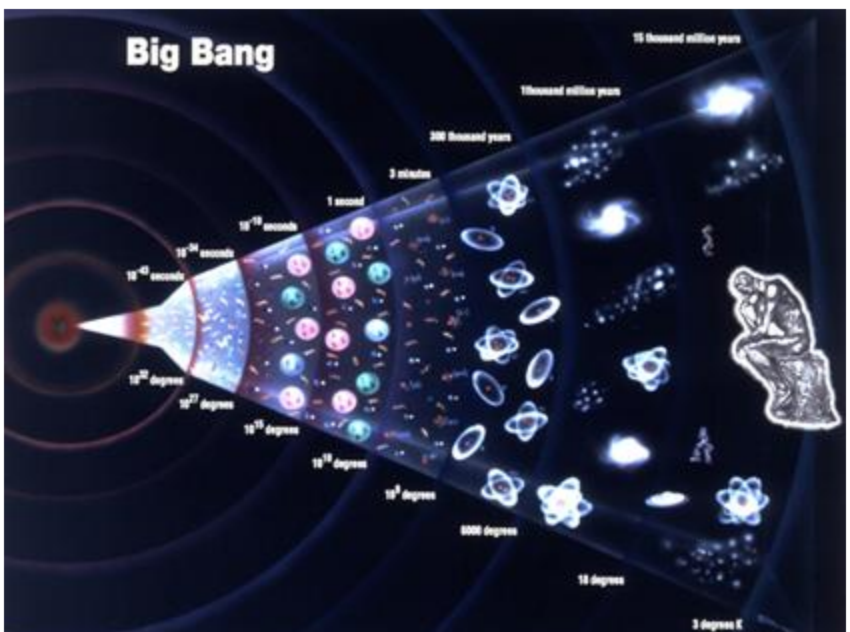

Big Bang:
an equal amount of matter and antimatter was produced during the hot phase

During cooling and expansion
matter and antimatter annihilated 😐

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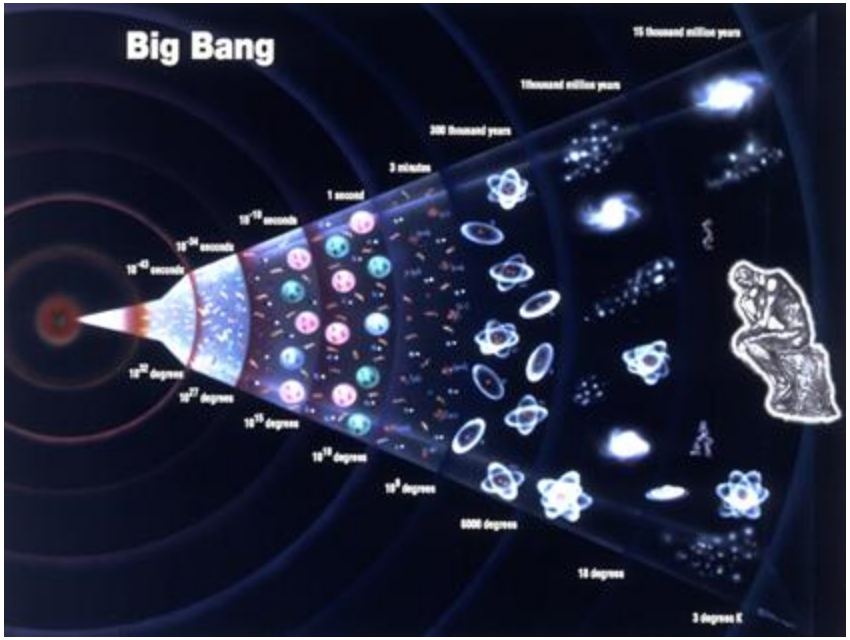


Big Bang:
an equal amount of matter and antimatter was produced during the hot phase

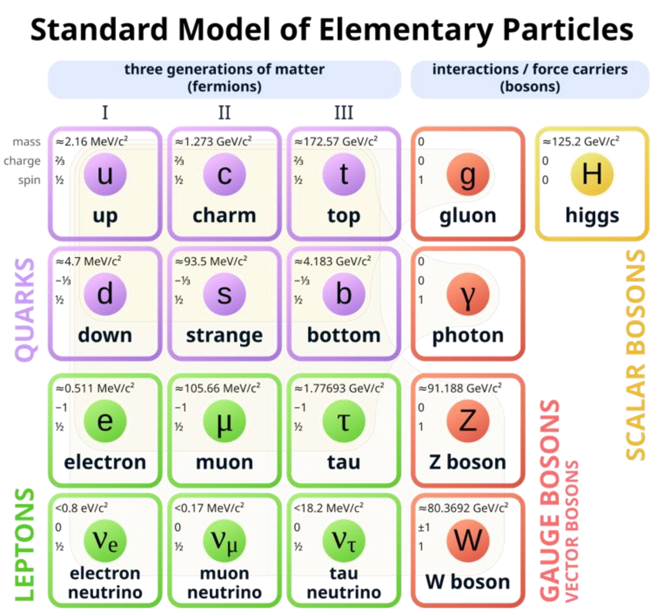
During cooling and expansion
matter and antimatter annihilated 😐

Most of the cosmic energy/matter budget is of an unknown form

General motivation

Status of Standard Model in HEP:

- **The Standard Model has served us well for 50 years!**
- **Recent measurements indicates SM can't be the final answer.**



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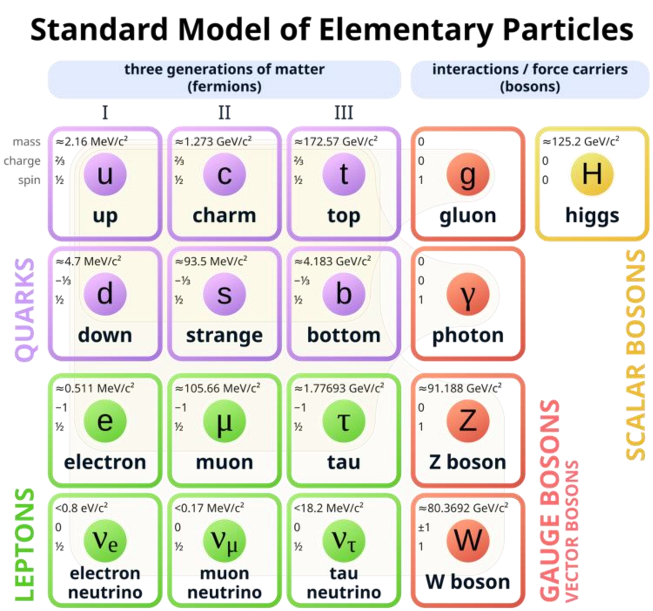
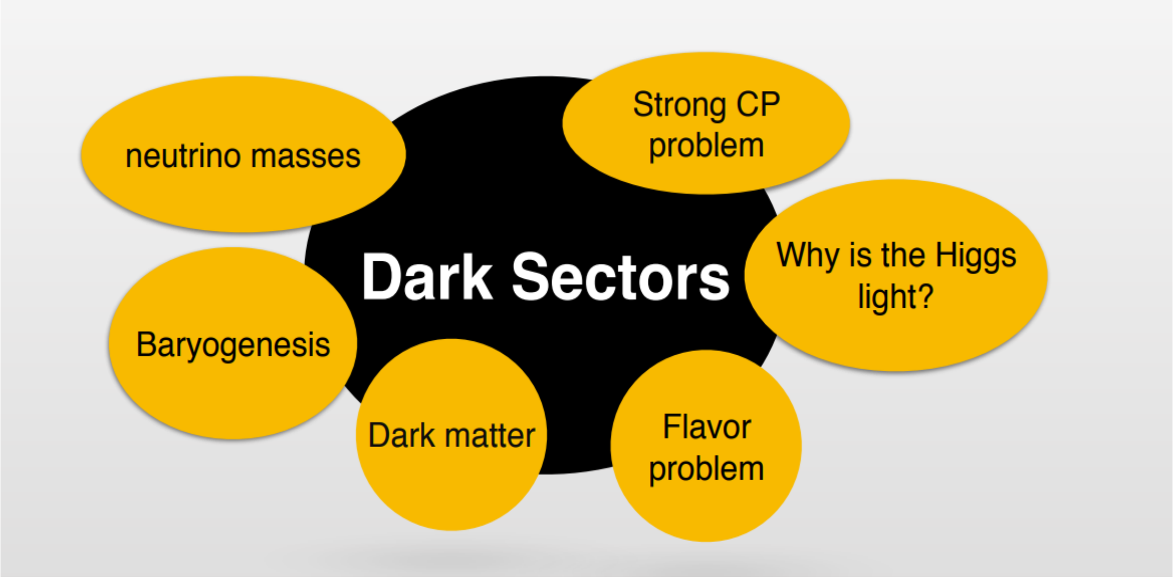
- **Recent measurements indicates SM can’t be the final answer.**
- **Six categories of problems have arisen in SM.**





General motivation

Examples of experimentally observed anomalies:

Muonic puzzle

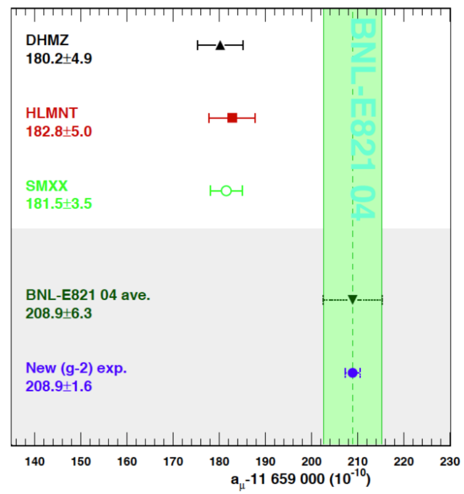
$(g-2)_\mu$

Latest measurement at Fermilab

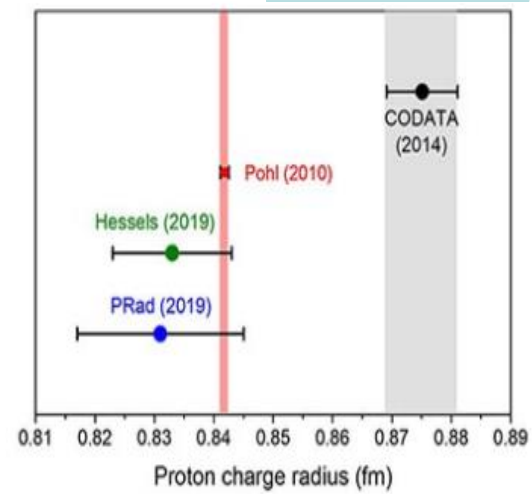
Proton radius

Energy levels in muonic hydrogen are different than standard hydrogen

4.2σ effect



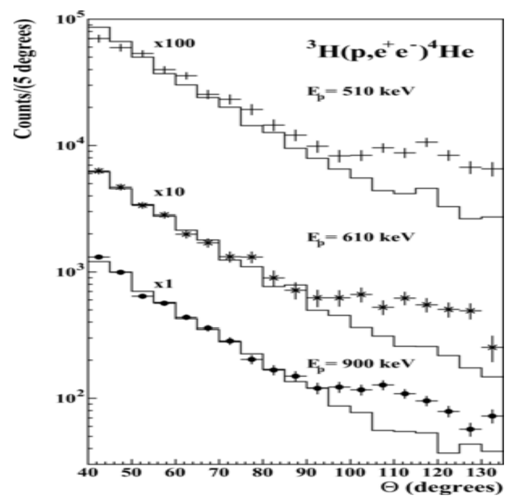
Maybe close to be solved



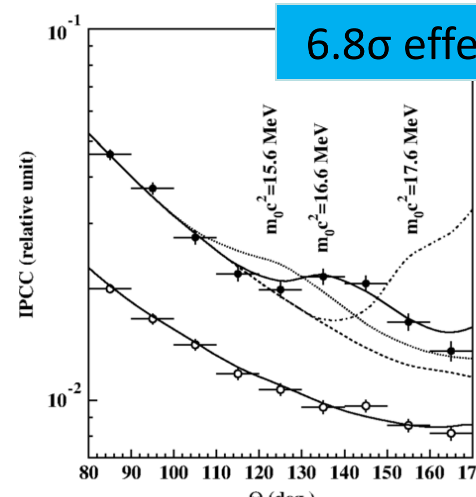
X_{17} in the e^+e^- spectra

X_{17}

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



6.8σ effect?



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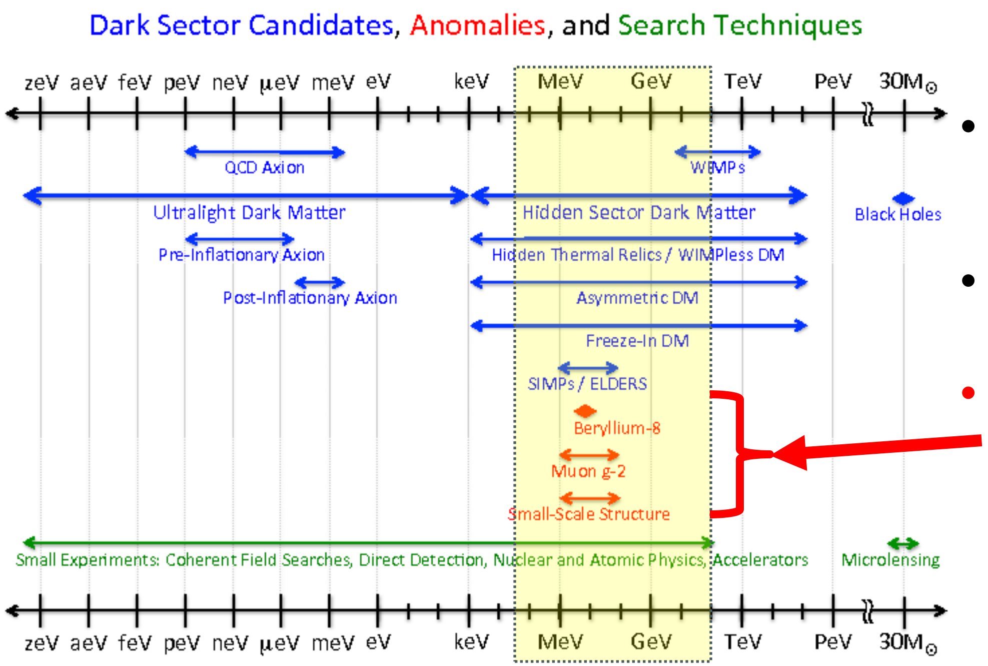

- In SM: violation from weak interaction is not sufficient to create observed asymmetry
- Parameter space for BSM is running out at HEP
- several anomalies in experiments point to possible new physics, weakly coupled to familiar matter in the 1MeV - 1 GeV scale

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

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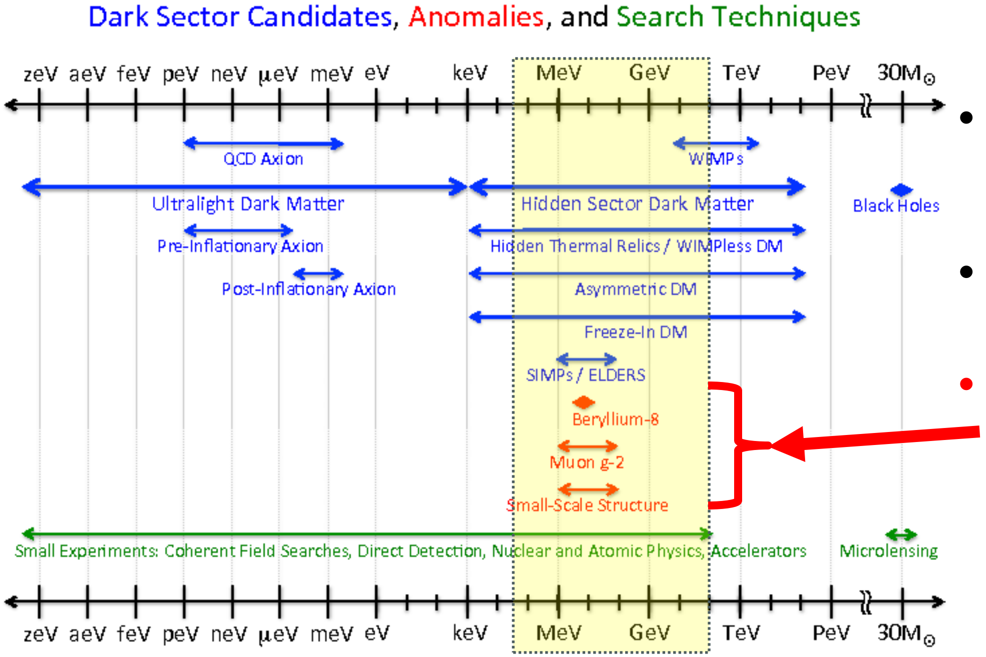

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Newest theoretical models prefer gauge bosons in MeV-GeV mass range as "…many of the more severe astrophysical and cosmological constraints that apply to lighter states are weakened or eliminated, while those from high energy colliders are often inapplicable"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

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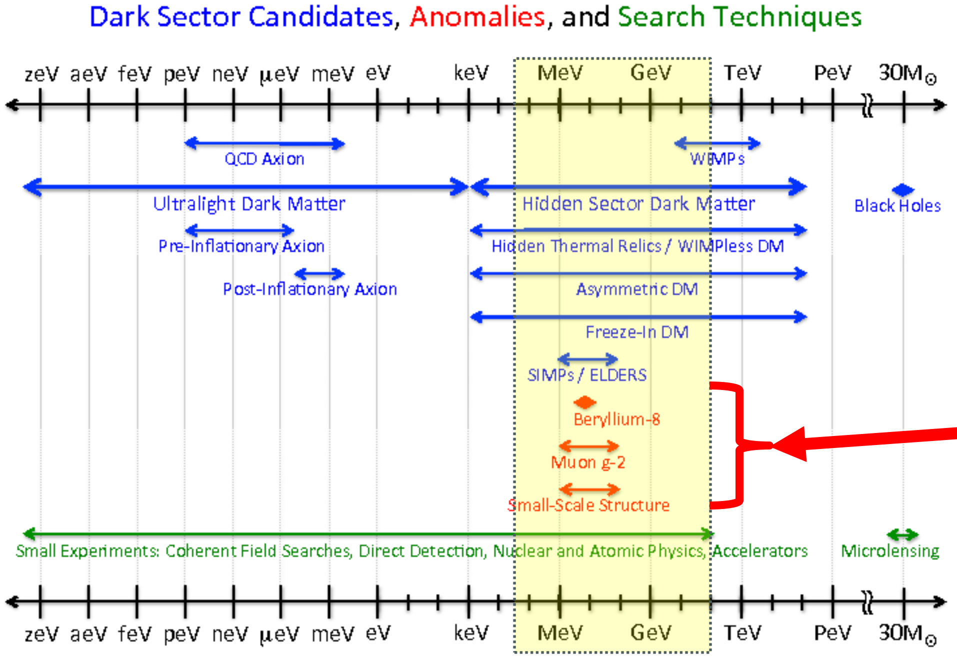

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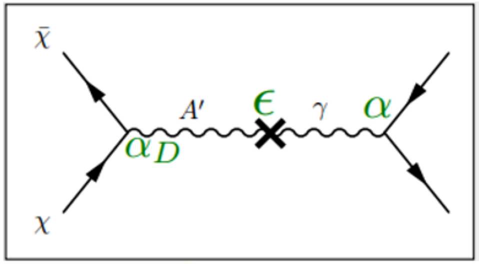
How can we try to address SM problems experimentally?

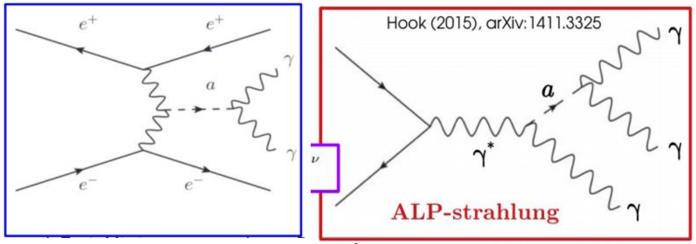
- Searching for new particles
- Studying violation of discrete symmetries

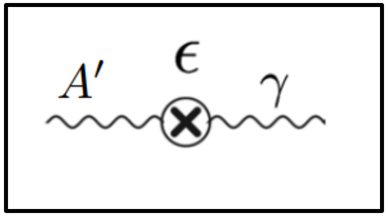
Connection between Standard and Dark Matter

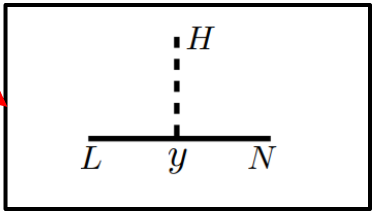
New Physics connects to Standard Model particles through four portals:

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









Connection between Standard and Dark Matter

Invisible, non-SM

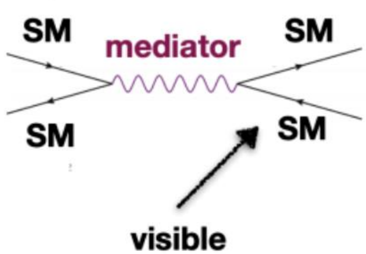
Dark Matter production

Producing stable particles that could be (all or part of) Dark Matter

Visible, SM

Production of portal-mediators that decay to SM particles

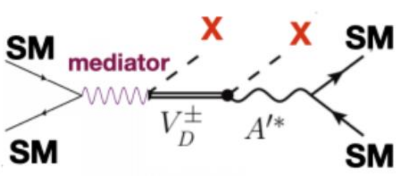
Systematically exploring the portal coupling to SM particles



Mixed visible-invisible

Production of "rich" dark sectors

Testing the structure of the dark sector



Stefania Gori, Mike Williams

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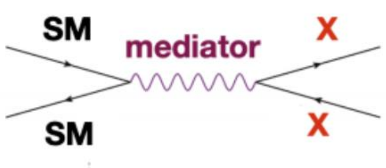

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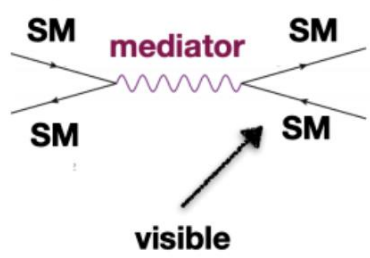

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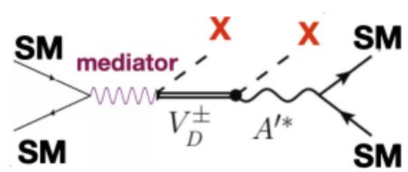

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Hight intensity Mesons factories

η/η'

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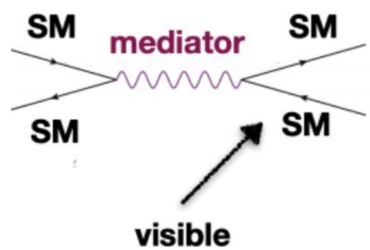

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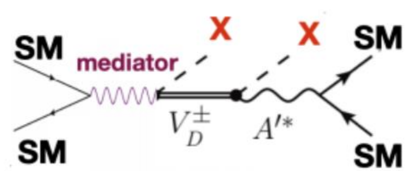

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Hight intensity Mesons factories

η/η'

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

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Experimental advantages of η/η' :

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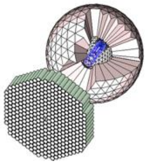
A η/η' factory is equivalent to a low energy Higgs factory and an excellent laboratory to probe New Physics at scale of 1 GeV

World η data samples:

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

Wasa-at-COSY	KLOE-2 (Frascati)	BESIII	HADES	CB@ MAMI
$\sim 3 \times 10^7$	$\sim 10^9$	$\sim 4 \times 10^7$	$\sim 4.5 \times 10^8$	$\sim 3 \times 10^8$



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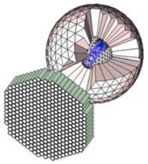

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Experiment	Technique	Total η mesons
GlueX@JLAB (running)	$\gamma_{12\ \mathrm{GeV}}\, p \to \eta\, X \to$ neutrals	5.5×10^{7} /yr
JEF@JLAB (approved)	$\gamma_{12\ \mathrm{GeV}}\, p \to \eta\, X \to$ neutrals	1.5×10^{8} /yr
HIAF (approved)		$\sim 10^{13}$/yr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

REDTOP - Rare Eta Decays TO Probe New Physics

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The general key points:

REDTOP: η(η') yielding ~$10^{13}(10^{12})$ 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

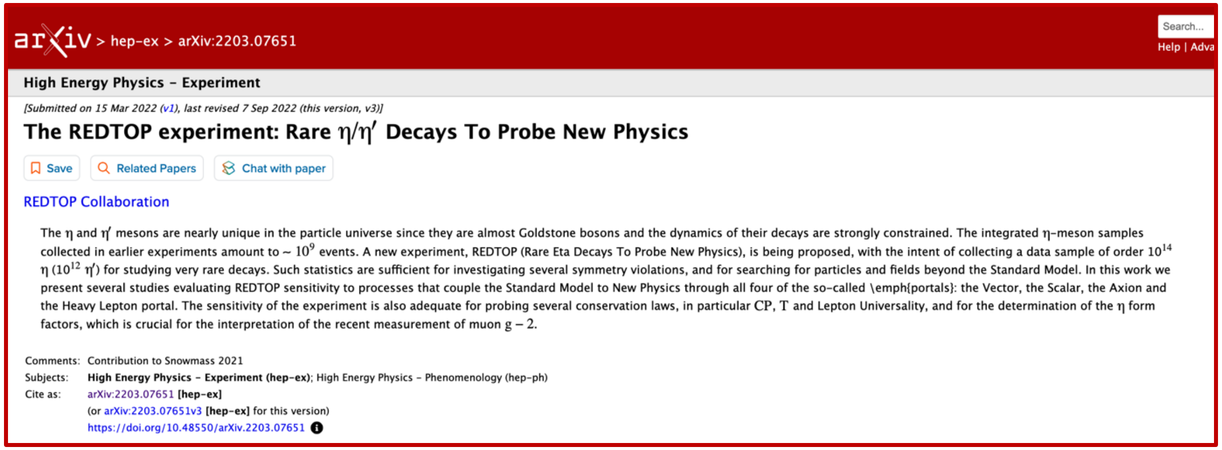
Lepton Flavor Universality studies: $\eta \rightarrow \mu^+\mu^- X$, $\eta \rightarrow e^+e^- X$
Need excellent particle ID

REDTOP

η/η'

Physics case for REDTOP is very strong

Physics case presented in „White Paper" available on 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} 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

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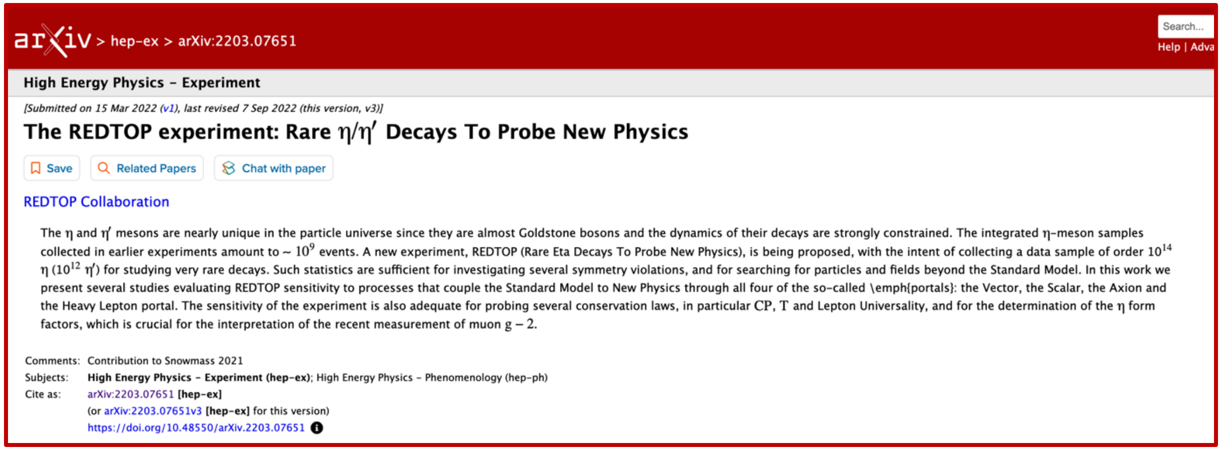
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Sensitivity studies based on ~10^{14} η mesons (3.3×10^{18} p OT and 3-year run)

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 BR ~$\mathcal{O}(10^{-11})$ with protons and ~$\mathcal{O}(10^{-12})$ with pion beam
- Detector optimization under way

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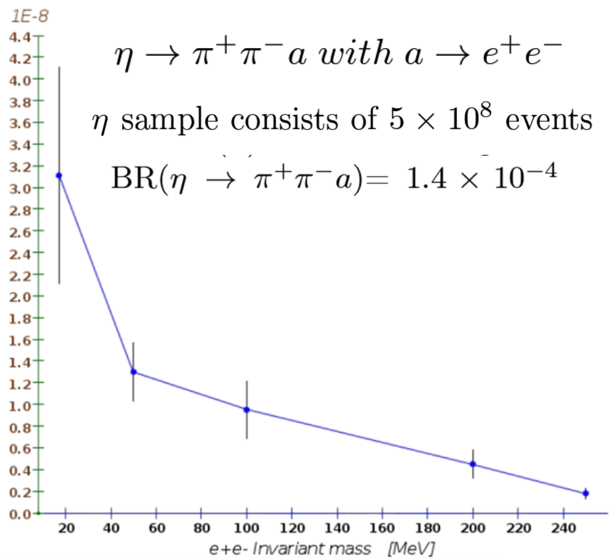
Pseudoscalar Portal: $\eta \rightarrow \pi^+ \pi^- a$ $(a \rightarrow \gamma\gamma$ and $a \rightarrow e^+ e^-)$

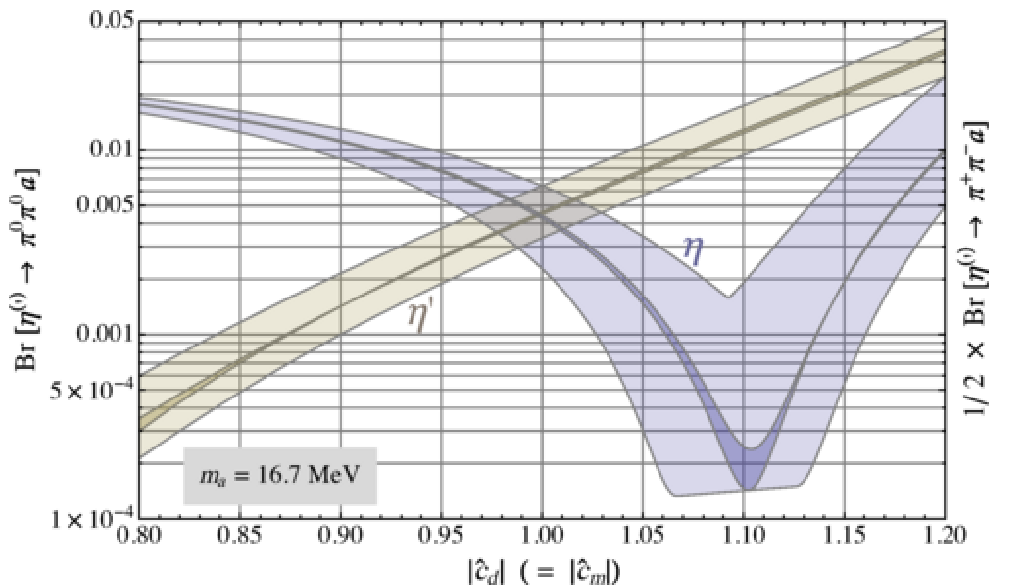


17 MeV piophobic QCD axion

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%	2.31×10^{-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 $\eta \to \pi^+\pi^-\pi^0$

- *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*

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

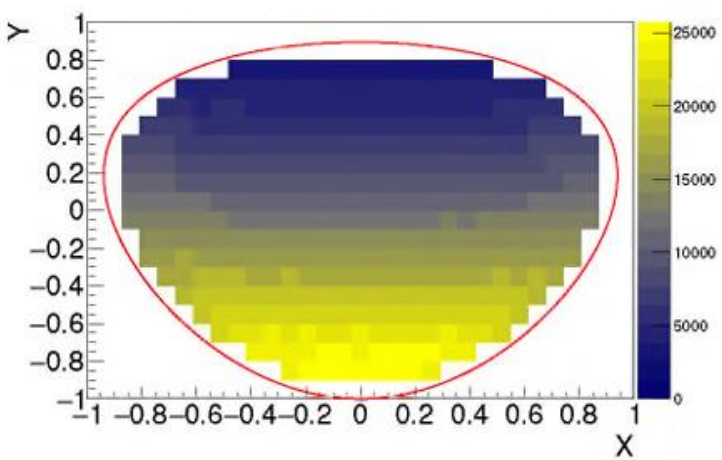
$$|M|^2 = A_0^2(1 + aY + bY^2 + cX + dX^2 + fY^3 + ...),$$

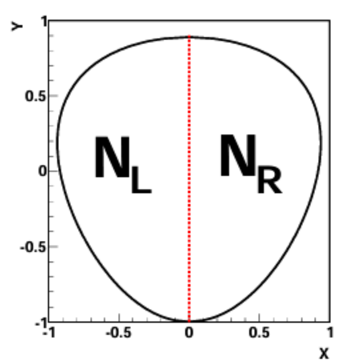
REDTOP sensitivity to model parameters

#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%

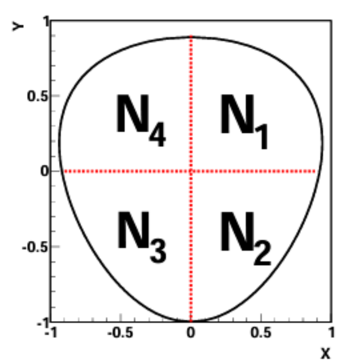
Precision measurement of the $\eta \to \pi^+\pi^-\pi^0$ Dalitz plot distribution with the KLOE detector

The KLOE-2 collaboration

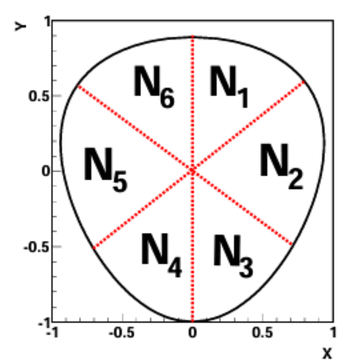




$$A_{LR} = \frac{N_R - N_L}{N_R + N_L},$$



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



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

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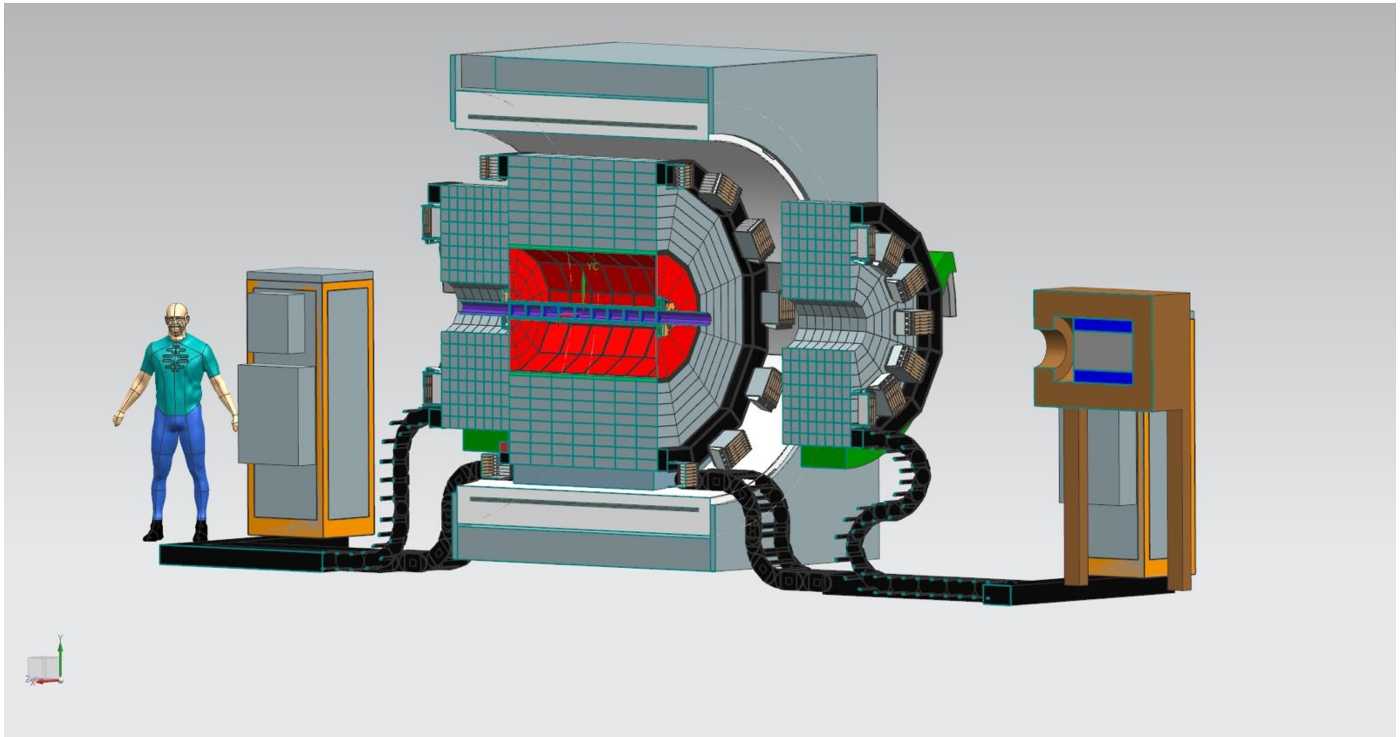
REDTOP

Proposed REDTOP Detector design

- ***Sustain up to 0.7 GHz event rate with avg final state multiplicity of ~8 particles***
- ***Calorimetric*** $\sigma(E)/E \sim 2\text{-}3\%/\sqrt{E}$
- ***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).***



Proposed REDTOP Detector design

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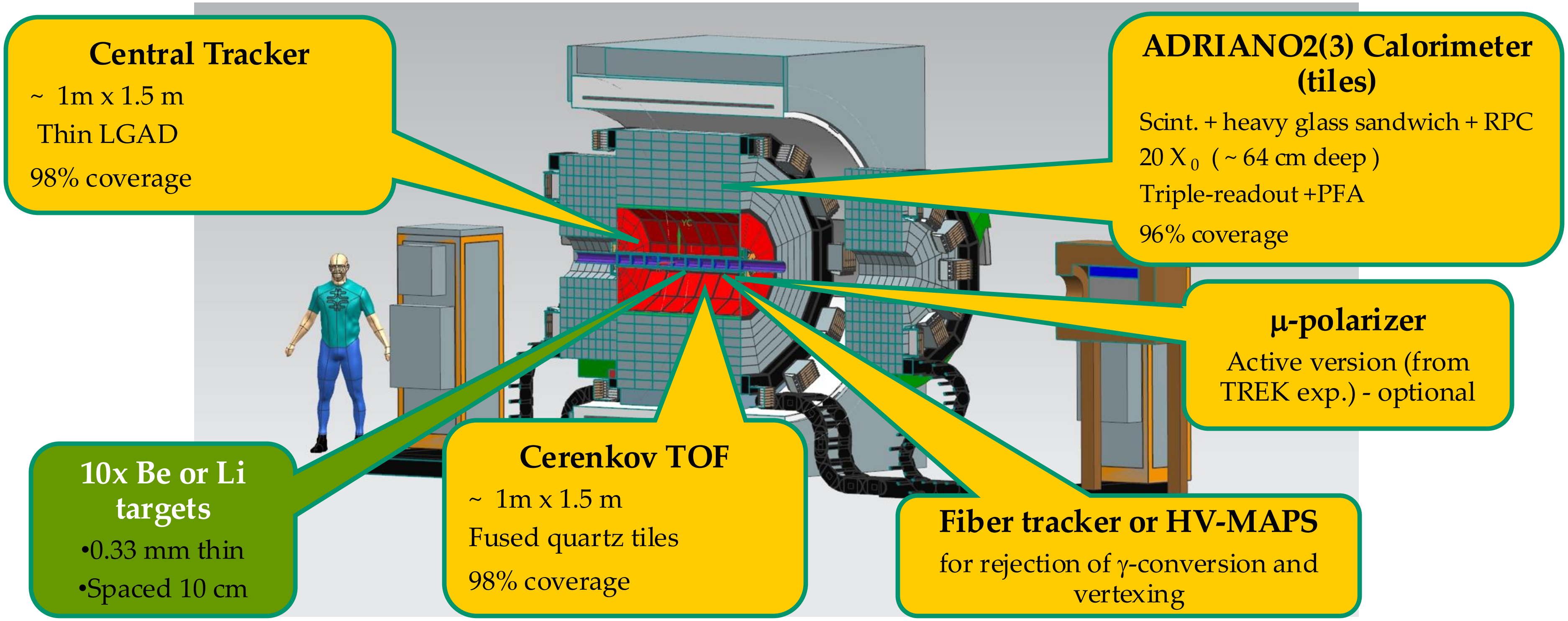

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REDTOP

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} πOT/sec*
- *More expensive but lower background (ESS, 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 forward tagging detector for He_3^{++}*
- *Fully tagged production from nuclear reaction: $p+De \rightarrow \eta + He_3^{++}$*

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15 Countries

58 Institutions

128 Collaborators

Cost estimates…

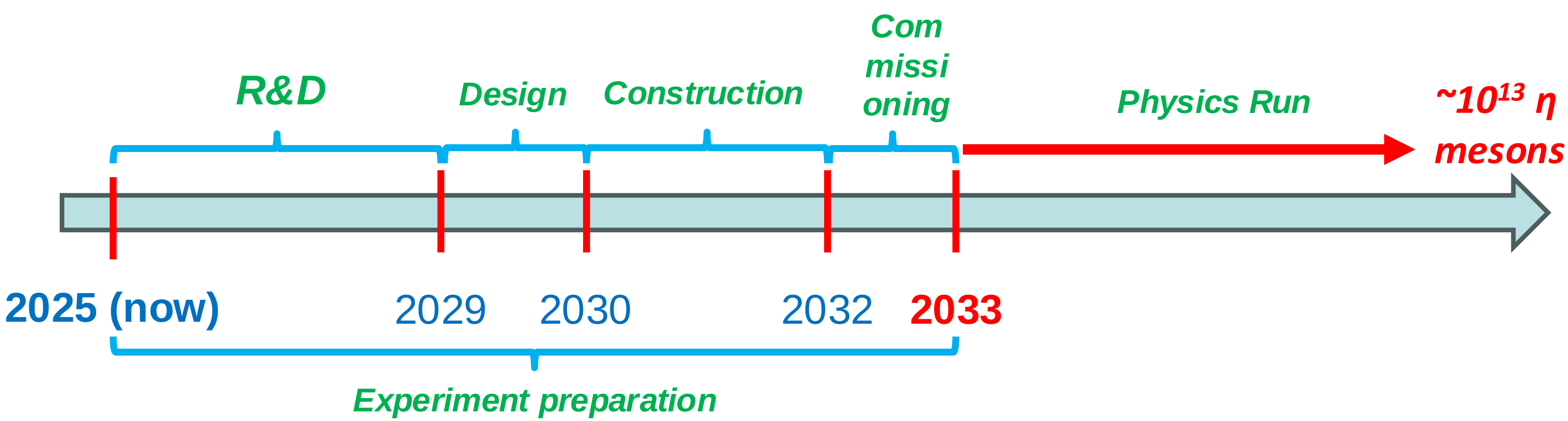
- Largest cost uncertainties
  - **ADRIANO2 SiPM's (2 x 10^6 – 4 x 10^6)**
  - **LGAD mechanics**
- **No labor considered (in the US, ~1/3 of the total)**

	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 3x10^{18} pOT or 3x10^{17} πOT**
  - **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

$$\pi^- + LH_2 \rightarrow \eta + \mathbf{n}$$

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

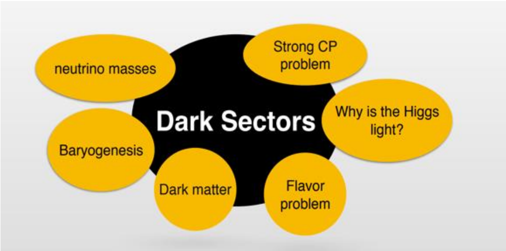
https://arxiv.org/abs/2203.07651

Thank you for your attention!

Backup

General motivation

Status of Standard Model in HEP:



Baryogenesis → ***CP Violation in SM not sufficient to explain BAU***
Baryon Number Violation still not observed

Dark Matter → ***Neither Dark Matter or Dark Energy exists in the SM***
None have been observed with direct measurements

Neutrino masses → ***Super-Kamiokande and SNO demonstrated that neutrino mass != 0 as they oscillate***
Neutrino mass = 0 in the Standard Model

Strong CP problem → ***Experiment are searching for the QCD axion.***
Nothing has been found yet.

Why is the Higgs light? → ***No explanation has been found within the SM for the hierarchy and the naturalness problems***

Flavor problem → **Plank's limit: the Standard Model is only a "low energy" approximation to a more fundamental theory**

General motivation

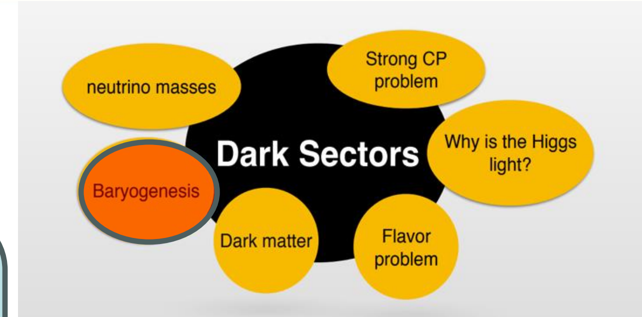
Baryon asymmetry of the universe (BAU):

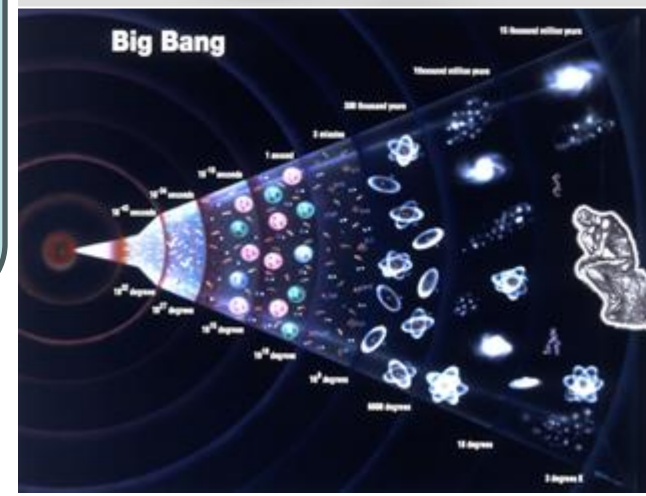
Necessary ingredients are:

- **Baryon number violation**
- **Therman no-equilibrium**
- **C and CP violation**

Sakarov - conditions

All of these ingredients were present in the Early Universe





CP Violation in SM not sufficient to explain BAU

Baryon Number Violation still not observed

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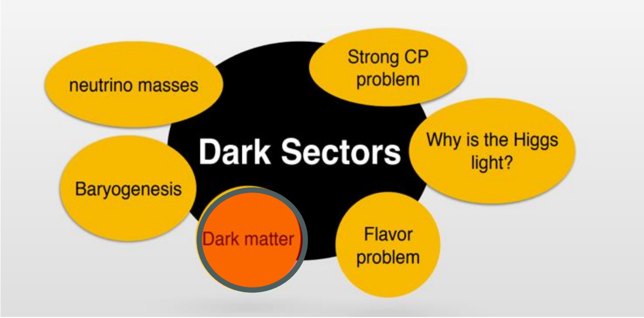
General motivation

Dark Matter:

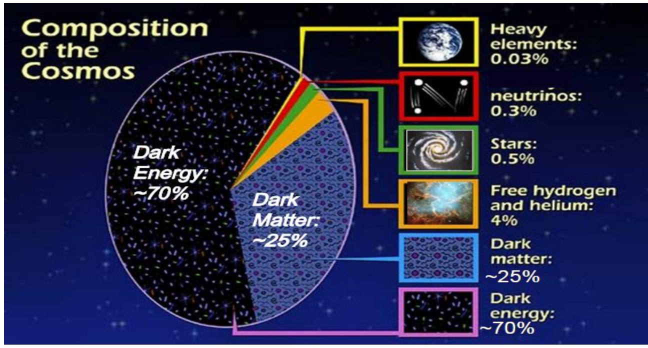


Hubble Constant (describing the expansion of the Universe)

- Latest measurements diverge from Standard Cosmology Model.

Expansion of the universe is accelerating

- Indicates large amounts of "dark energy" (~ 70% of total energy).
- Cosmologists have included a repulsive dark energy in their model of cosmic evolution.



Galactic rotation curves and cluster

- Indicates large amounts of "dark matter" (~ 5x standard matter).
- Presence of dark matter inferred via gravitational effects only.
- No dark matter with the required properties still observed.

Neither Dark Matter or Dark Energy exists in the Standard Model

None have been observed with direct measurements

General motivation

Current status of HEP:

- SM ingredients are insufficient to explain the nature. Most likely we need:
  - new forces (with adequate CP violation).
  - new particles.
- Mass of possible New Physics spans 40 order of magnitude.
- We don't have a clue of what's beyond the Standard Model.
- Parameter space for New Physics at High Energy is running out (from LHC results).
- Scientists are hard pressed to design new experiments for understanding what's going on.
- We are in a rare (and exciting time) when discoveries will set the stage for the next 30-50 years.

How we can try to contribute and 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 (BSM)

Current experimental studies:

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

Cosmic rays

Higher Luminosity Accelerators

Lower Luminosity Accelerators

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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REDTOP

REDTOP - Rare Eta Decays TO Probe New Physics

Assuming a yield ~10^{14} η mesons/yr and ~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):* $\eta \to \pi^o \ell^+\ell^-$ **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}*)*

Non-η/η′ based BSM Physics

- *Neutral pion decay:* $\pi^o \to \gamma A' \to \gamma e^+e^-$
- *ALP's searches in Primakoff processes:* $p\,Z \to p\,Z\,a \to l^+l^-$
- *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*

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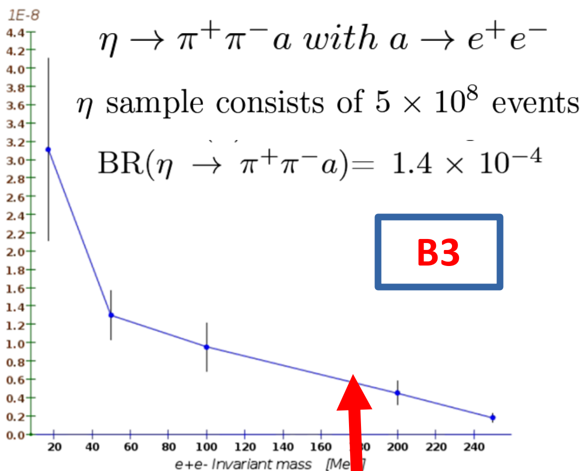
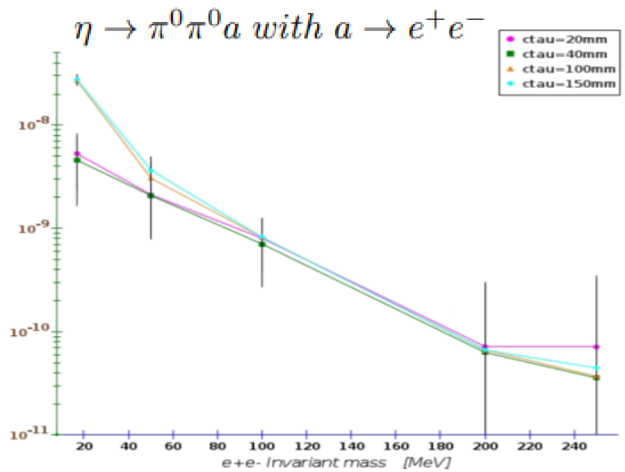
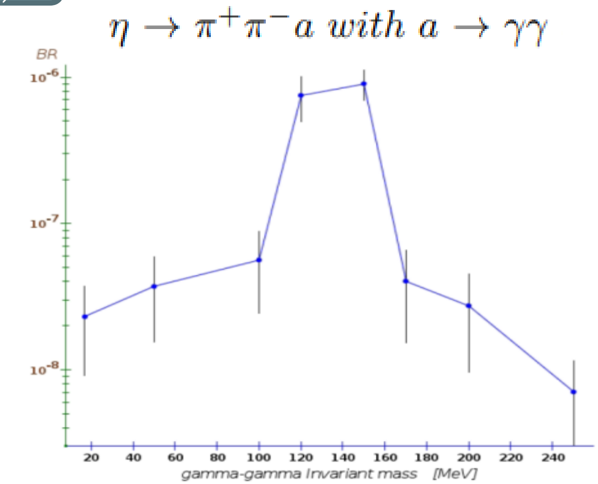
Pseudoscalar Portal: $\eta \rightarrow \pi^o \pi^o a$, $\eta \rightarrow \pi^+ \pi^- a$ ($a \rightarrow \gamma\gamma$ and $a \rightarrow e^+ e^-$)

17 MeV piophobic QCD axion (ALP)



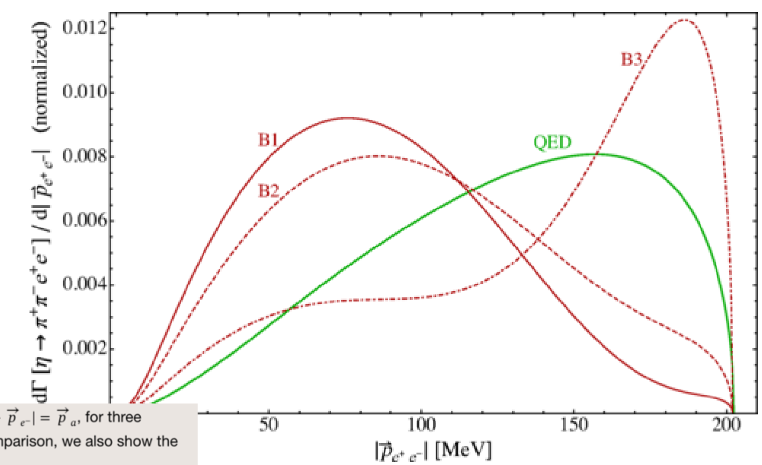




Differential rate for η□π⁺π⁻a for three benchmark params

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



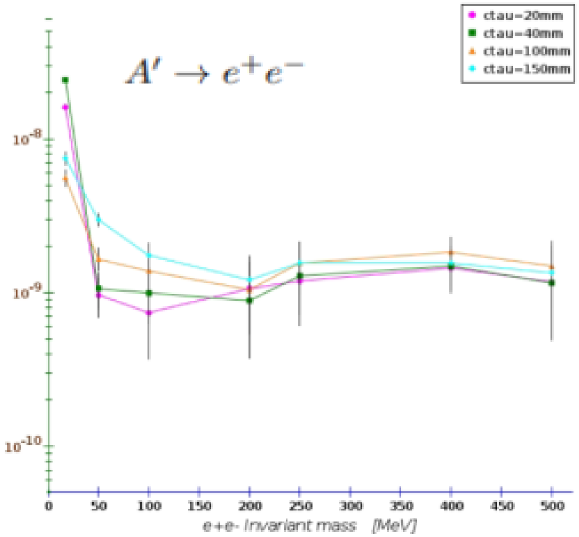
The differential rate for $\eta \rightarrow \pi^+\pi^- a$ as a function of $|\vec{p}_{e^+e^-}| \equiv |\vec{p}_{e^+} + \vec{p}_{e^-}| = \vec{p}_a$, for three benchmark choices of RχT parameters specified in Table I. For comparison, we also show the differential rate of the SM process $\eta \rightarrow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

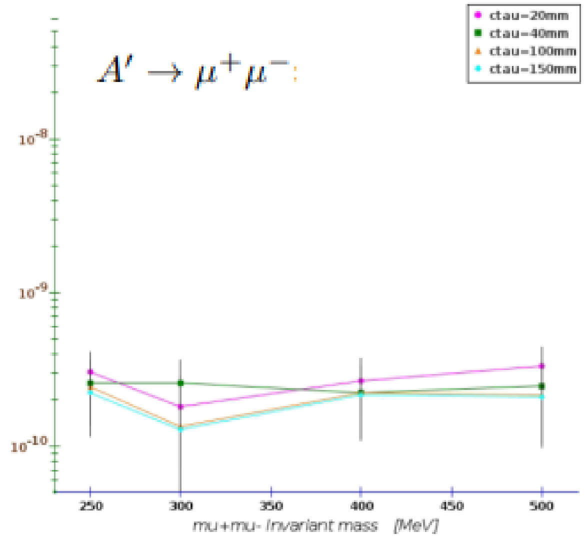
Theoretical models considered

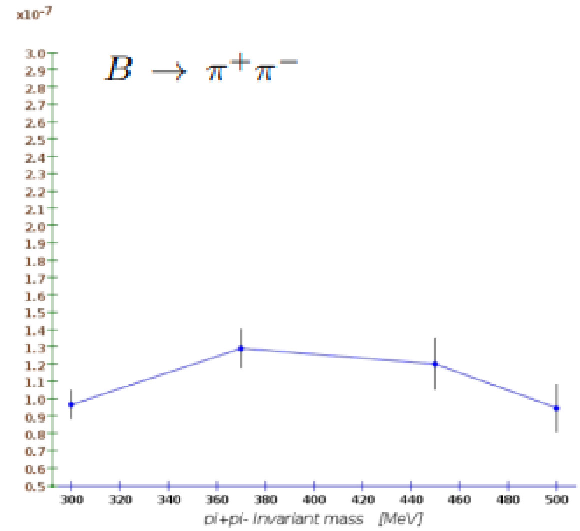
- ***Piophobic QCD axion model***
  - *Below KLOE sensitivity*
  - *the CELSIUS/WASA Collaboration observed 24 evts with SM expectation of 10*
- ***Heavy Axion Effective Theories***

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

BR sensitivity curves







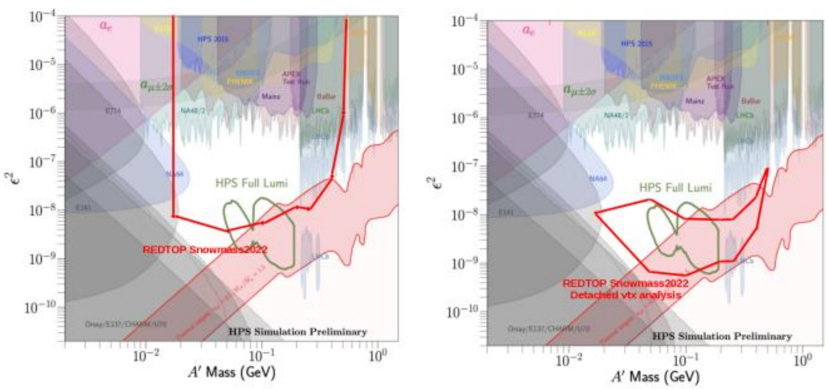


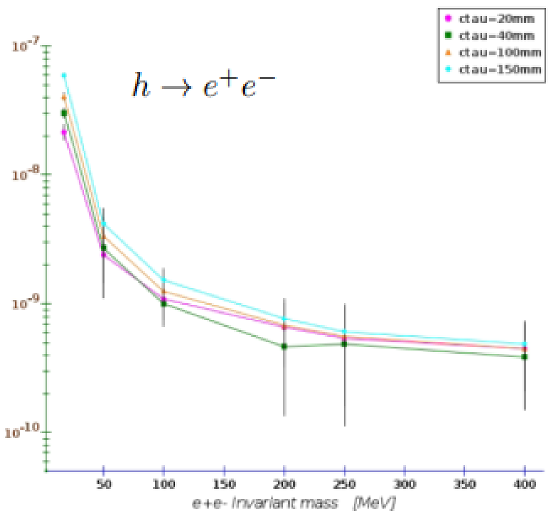
FIG. 36. Sensitivity to to ε^2 for the processes $\eta \to \gamma A'$ for integrated beam flux of 3.3×10^{18} POT. Left plot: *bump-hunt* analysis. Right plot: *detached-vertex* analysis).

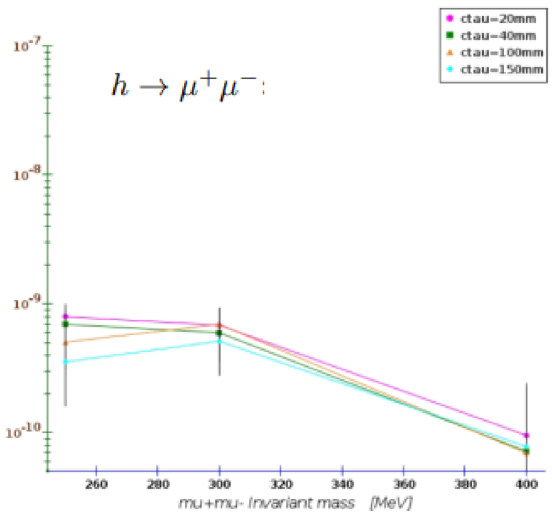
Theoretical Models considered

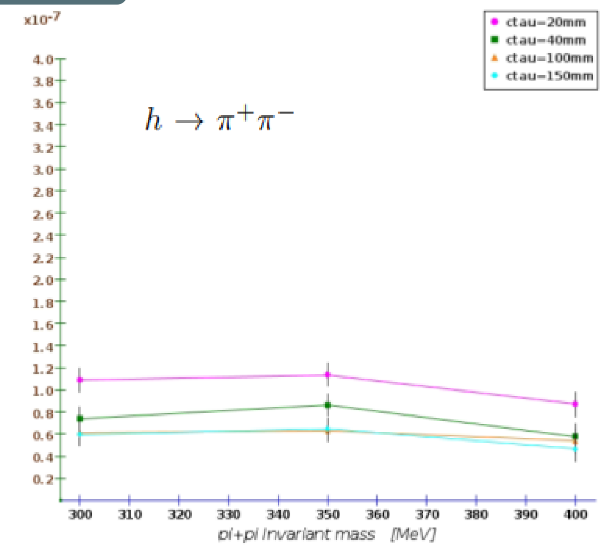
- Minimal dark photon model
  - Most popular model
- Leptophobic B boson Model
- Protophobic Fifth Force

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

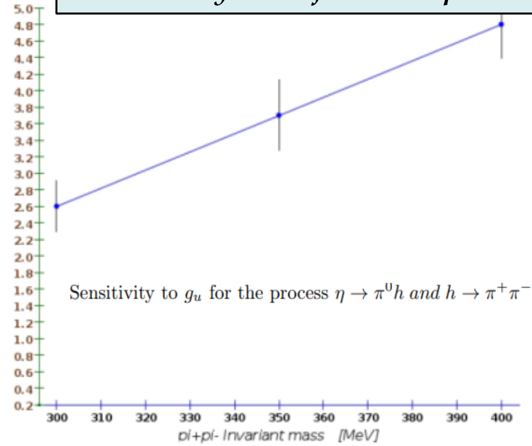
BR sensitivity curves







Sensitivity curve for Hadrophilic Mediator model



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
$\eta \to \pi^0 S$; $S \to e^+e^-$	17 MeV	bump hunt	2.0×10^{-13}
$\eta \to \pi^0 S$; $S \to \mu^+\mu^-$	17 MeV	detached vertex	3.2×10^{-13}

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

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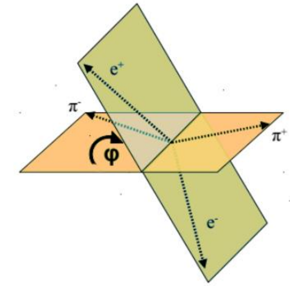
CP Violation from dacay planes asymmetry in $\eta \to \pi^+\pi^- e^+ e^-$ and in $\eta \to \mu^+\mu^- e^+ e^-$

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 $\eta \to \mu^+\mu^- e^+ e^-$

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

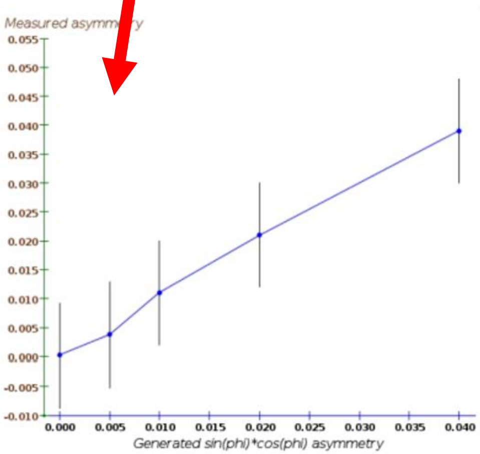
$$A_{sin\Phi} = \frac{N(\sin\phi > 0) - N(\sin\phi < 0)}{N(\sin\phi > 0) + N(\sin\phi < 0)}$$

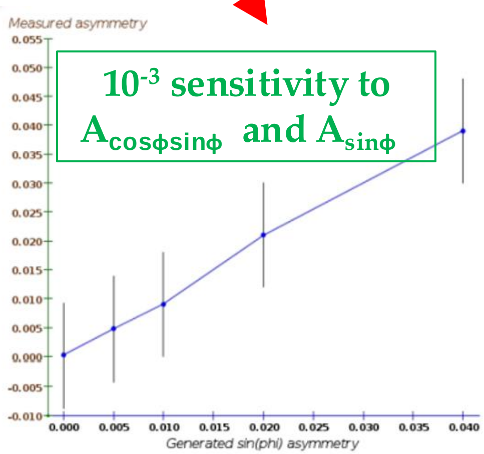
through Wilson coefficients

$$A_{\sin\phi\cos\phi} = \mathrm{Im}[1.9 c^{2222}_{\ell edq} - 1.3(c^{(1)2211}_{\ell equ} + c^{1122}_{\ell edq})] \times 10^{-5} - 0.2\epsilon_1 + 0.0003\epsilon_2$$

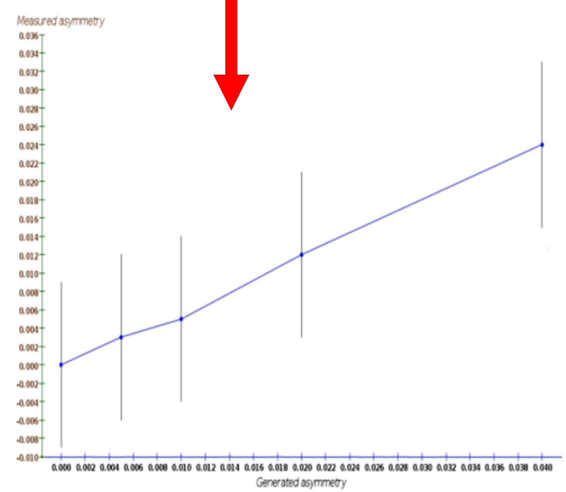
CP violation is related to asymmetries in $\eta \to \pi^+\pi^- e^+ e^-$

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





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



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

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}	$y^{h'}_{e(\mu)} \times 10^4$	$y^{H}_{e(\mu)} \times 10^4$
85 MeV	130 MeV	10 GeV	0.23(1.6)	2.29(15.9)
$m_{h'}$	m_H	$\sin\delta$	$y^{h'(H)}_{\nu_{12}} \times 10^3$	$\lambda^{h'(H)}_{N_{12}} \times 10^3$
17 MeV	250 MeV	0.1	1.25(12.4)	74.6(−7.5)

TABLE XXVIII. Benchmark parameters for REDTOP.

REDTOP sensitivity to model parameters

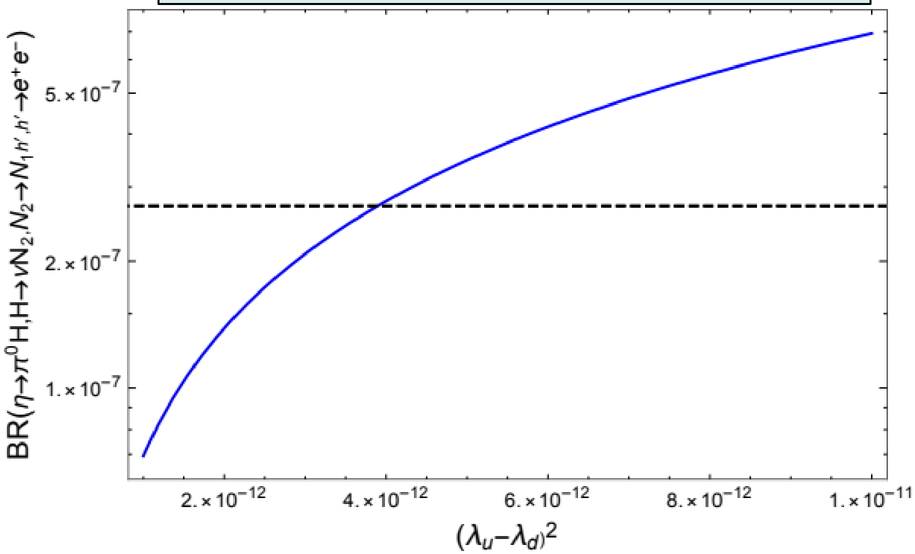


FIG. 61. Branching ratio for the process $\eta \to \pi^0 H$; $H \to \nu N_2$; $N_2 \to N_1 h'$; $h' \to e^+e^-$ predicted by the Two Higgs Doublet model [51] as a function of $(\lambda_u - \lambda_d)^2$. The dashed line corresponds to the experimental limit for REDTOP with an integrated luminosity of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

REDTOP @ ESS

- Many physics processes to study in High Energy and Nuclear Physics
  - Several PhD thesis on different topics
- Running time comparable to the duration of a PhD thesis
  - PhD student exposed to multiple phases of the experiment
- All new detector technologies: super-thin CMOS, LGAD tracker, triple-readout calorimetry, ASIC for triggerless DAQ, picosecond timing, etc.
  - Excellent know-how for new careers and training of young persons
- Pion beam
  - Only facility in the world

REDTOP @ ESS

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

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

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

- 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)

Proposed REDTOP Detector design

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

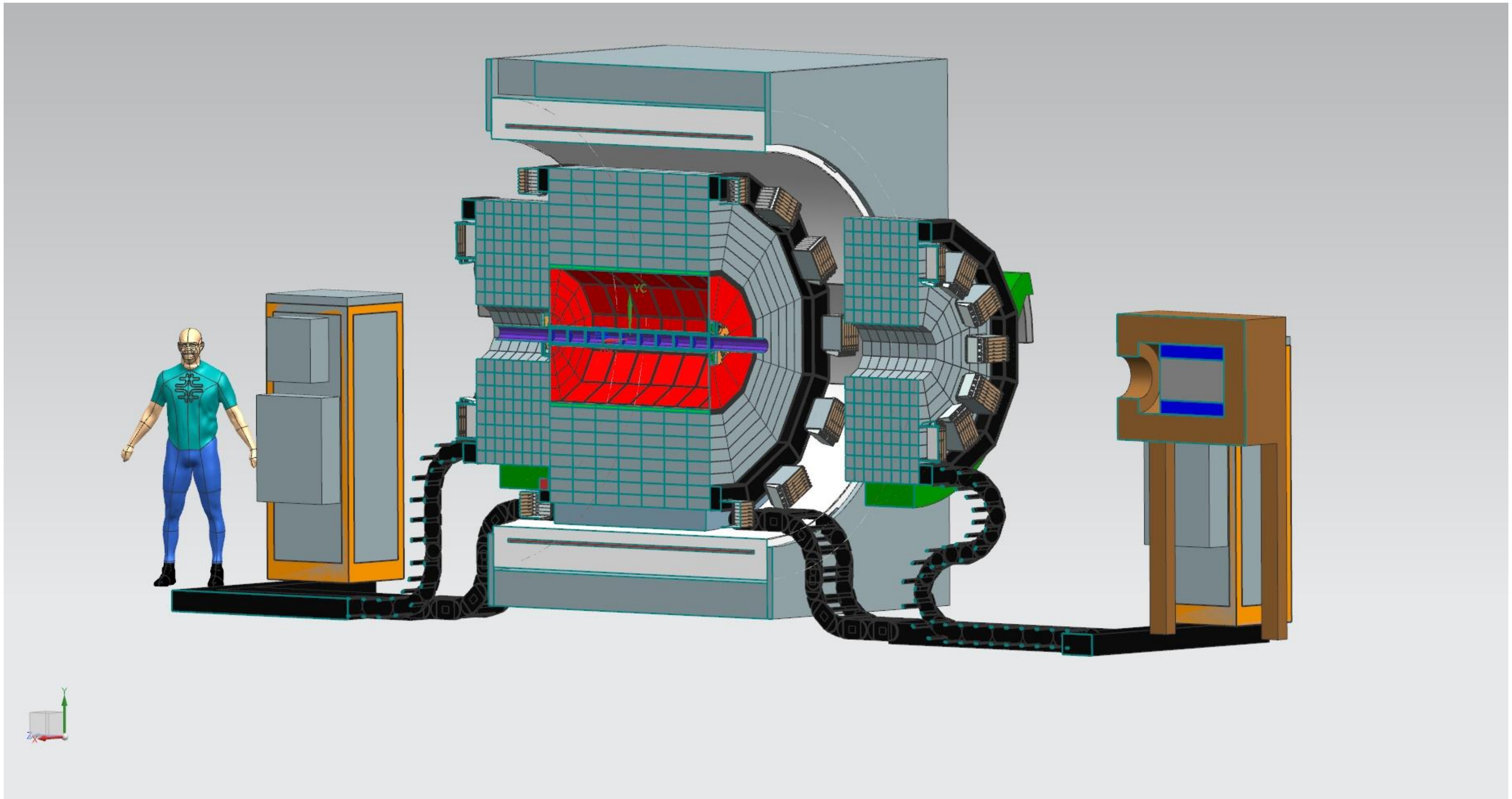
Option 1: Quartz tiles

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

Option 2: EIC-style LGAD

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

Proposed REDTOP Detector design



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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

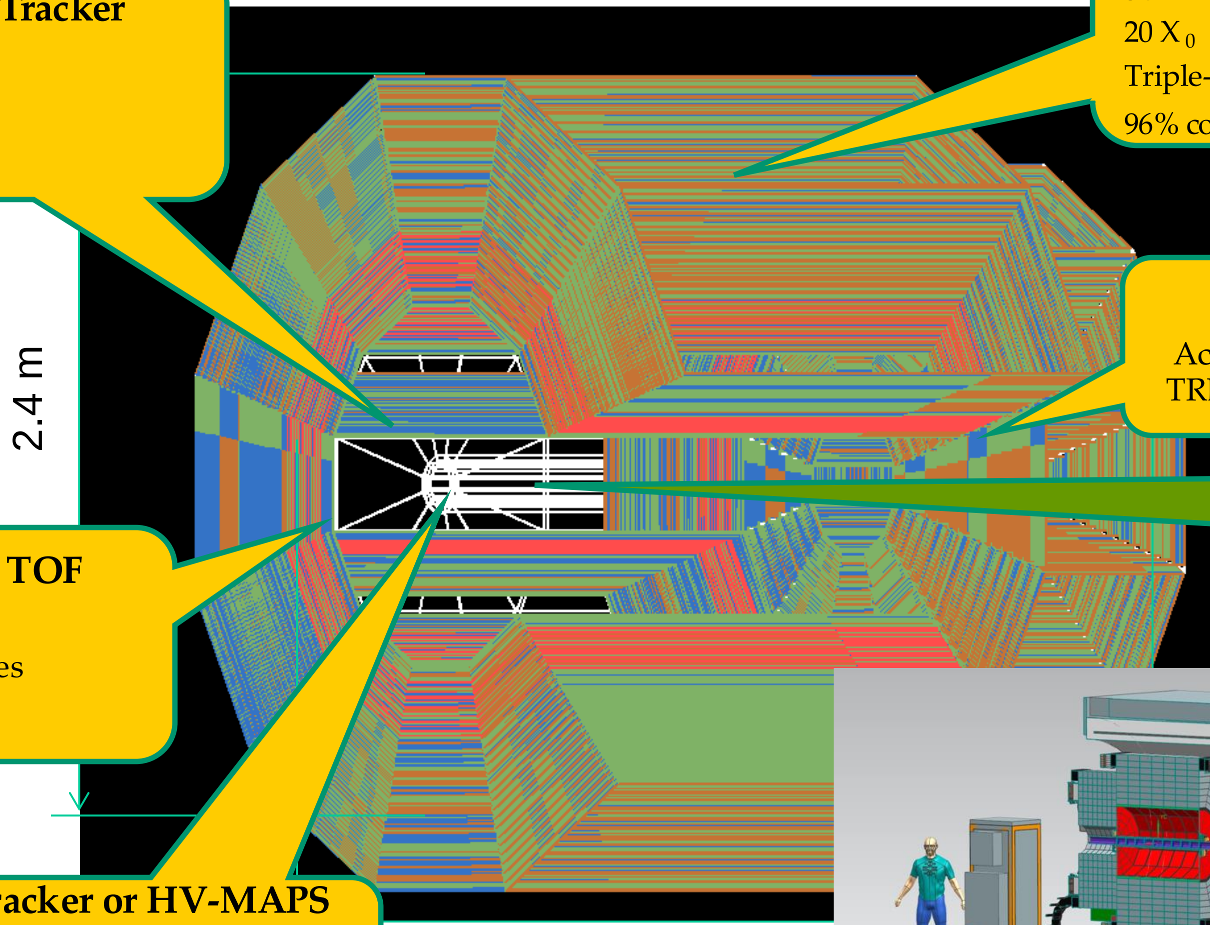
~ 1m x 1.5 m

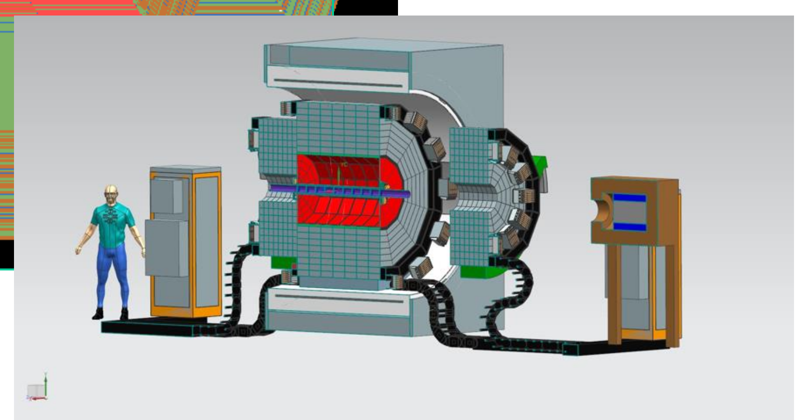
Fused quartz tiles

98% coverage

Fiber tracker or HV-MAPS

for rejection of γ-conversion and vertexing





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

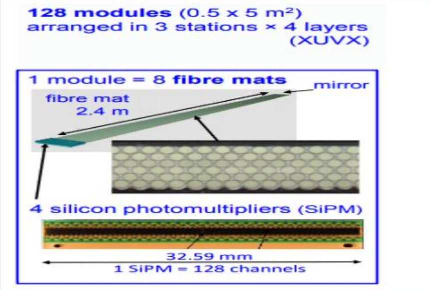
REDTOP – vertex detector

Requirements

- *<0.5% X0*
- *<=70µm vertex resolution in x-y.*
- *No active cooling*
- *Rad-hard ~5x10^5 1 MeV-neq n/cm2/sec*
- *Timing: ~10 nsec*

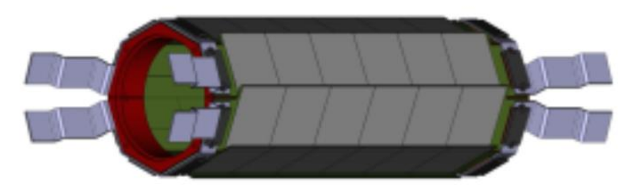
Option 1: LHCb-stile Fiber Tracker

- Established and simple technology – no R&D required
- Active surface is about 0.24 m^2 vs 360 m^2 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



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

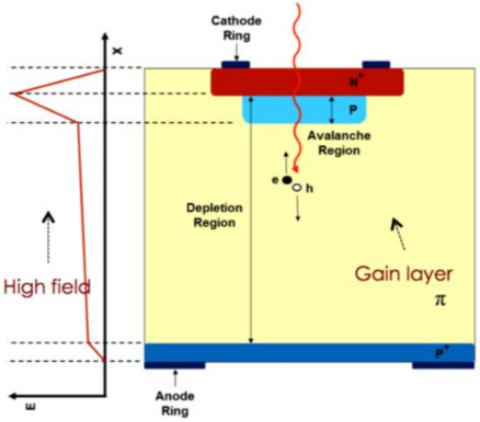
Requirements

- *<1% X0*
- *30 nsec timing resolution.*
- *No active cooling*
- *Rad-hard ~$1x10^5$ 1 MeV-neq n/cm2/sec*

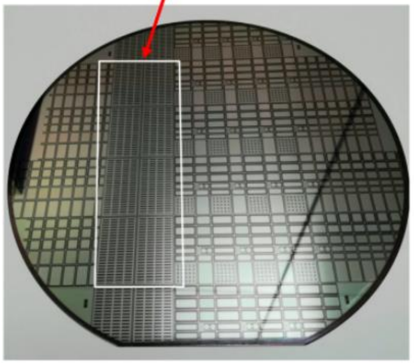
Option 1: CMS's ETL

- 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 $1x10^{15}$ n_{eq}/cm^2, and about 40 psec up to $2x10^{15}$ n_{eq}/cm^2



CMS-designed 96-channel sensors



FBK wafer with CMS- and ATLAS- sensors

REDTOP – Calorimeter

Requirements

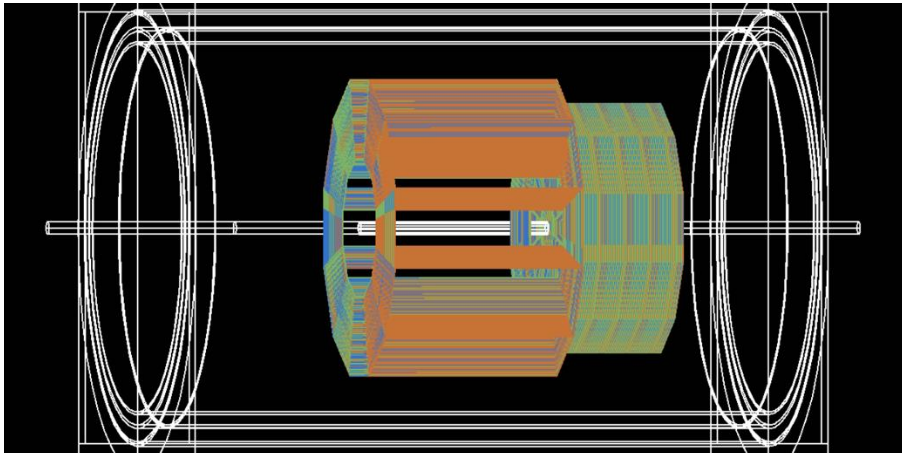
- *σ_E/E ~ 2-3%/√E*
- *~80 psec/cell timing resolution for MIPs.*
- *No active cooling*
- *Rad-hard ~5x10^4 1 MeV-neq n/cm2/sec*

EM: dual-readout ADRIANO2

- Inner section: Pb-glass and scint. Tiles interleaved
- 10 layers – 6.6 X0 / 0.55 λ_I
- 120,00 tile-pairs
- Same plastic tiles as CMS' HGCAL
- FEE from Weeroc+Omega (costing being discussed) or TOFPET2

HAD: triple-readout ADRIANO3

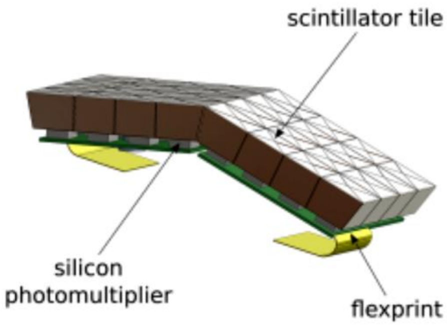
- Outer section: Pb-glass + scint. + thin RPC + Fe
- 25 layers – 22 X0 / 2.7 λ_I
- Longer λ_I for better hadron shower containement
- 390,00 tile-pairs
- Heatsink: pyrolitic foil



REDTOP – Threshold Cerenkov and TOF

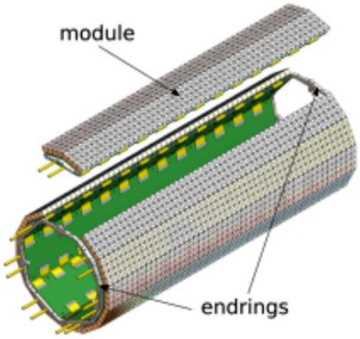
Requirements

- *99% efficiency*
- *Rad-hard <1x10^5 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)
- Wellmestablished TOFHIR2 Asic (LIP)



Option 2: LGAD

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

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