The REDTOP experiment

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Fermilab

Rare Processes and Precision Frontier Townhall Meeting

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Rationale for an η/η' Factory

- Recent results from the LHC suggest that the next search for New Physics should be performed in the low-energy mass range (MeV-GeV) using high-intensity beams.

- Light dark matter must be neutral under SM charges, otherwise it would have been discovered at previous colliders
  [G. Krnjaic RF6 Kickoff Meeting, August 12, 2020]

- The only known particles with all-zero quantum numbers are the η/η' mesons and the Higgs boson

- An η/η' factory is an excellent laboratory for precision measurements and a unique window to search for Physics Beyond the Standard Model in the MeV-GeV mass range.

The REDTOP Experiment

- REDTOP is a proposed η/η' factory which aims at detecting small deviations from the Standard Model by collecting a large set of events from protons impinging on a fixed target

- The experiment will produce $\sim 10^{13}$ η mesons or ~ 10^{11} η'mesons per year corresponding to an increase of the existing world sample by four order of magnitude

- All electromagnetic and strong decays of the neutral and long-lived η and η' are suppressed at first order and weak decays have branching ratios of order 10^{-11}

- Branching Ratio of processes from New Physics are enhanced compared to other systems.

Physics Program

REDTOP

C, T, CP-violation

- CP Violation via Dalitz plot mirror asymmetry: $\eta \to \pi^0\pi^+\pi^-$
- CP Violation (Type I - P and T odd , C even): $\eta \to 4\pi^0 \to 8\gamma$
- CP Violation (Type II - C and T odd , P even): $\eta \to 4\pi^0 l^+ l^-$ and $\eta \to 3\gamma$
- Test of CP invariance via μ longitudinal polarization: $\eta \to \mu^+\mu^-$
- Test of CP invariance via γ^* polarization studies: $\eta \to \pi^+\pi^- e^+e^-$ and $\eta \to \pi^+\pi^-\mu^+\mu^-$
- Test of CP invariance in angular correlation studies: $\eta \to \mu^+\mu^- e^+e^-$
- Test of T invariance via μ transverse polarization: $\eta \to \pi^0\mu^+\mu^-$ and $\eta \to \gamma\mu^+\mu^-$
- CPT violation: μ polarization in $\eta \to \pi^+\mu^-\nu$ vs $\eta \to \pi^-\mu^+\nu$ and γ polarization in $\eta \to \gamma\gamma$

New particles and forces searches

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

Other discrete symmetry violations

- Lepton Flavor Violation: $\eta \to \mu^+e^- + c.c.$
- 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 $10^{-6} \div 10^{-9}$)

Non-η/η' based BSM Physics

- Dark photon and ALP searches in Drell-Yan processes: $q\bar{q} \to A'/a \to l^+l^-$
- $p + D \to {}^3\mathrm{He}^+ + X_{17}$ with $X_{17} \to e^+e^-$
- ALP's searches in Primakoff processes: $pZ \to pZa \to l^+l^-$ (F. Kahlhoefer)
- Charged pion and kaon decays: $\pi^+ \to \mu^+\nu A' \to \mu^+\nu e^+e^-$ and $K^+ \to \mu^+\nu A' \to \mu^+\nu\, e^+e^-$
- Neutral pion decay: $\pi^0 \to \gamma A' \to \gamma\, e^+e^-$

High precision studies on medium energy physics

- Nuclear models
- Chiral perturbation theory
- Non-perturbative QCD
- Isospin breaking due to the u-d quark mass difference
- Octet-singlet mixing angle
- Electromagnetic transition form-factors (important input for g-2)

- The physics sectors which can be probed at REDTOP range from the violation of discrete symmetries to the search for new particles
  [S. Tulin et al. https://arxiv.org/abs/2007.00664]

- Non-eta meson sectors can also be explored, such as ALPS and QCD-axions
  [D. S. M. Alves, arXiv:2009.05578]

- Finally, the Standard Model can be probed at low energy at an unprecedented precision level.

η Factories and Outstanding Anomalies

Muonic puzzle (aka, proton radius and muon g – 2 Anomalies)

- Solved by postulating a new scalar boson ϕ decaying into e^+e^-:

$$\eta \rightarrow \phi\, \pi^o \rightarrow e^+e^-\, \gamma\gamma$$

$\eta \rightarrow \pi^o e^- e+$ is forbidden in the SM by charge conjugation symmetry at tree level but allowed by a virtual ϕ emission

[Y. Liu,1, I.C. Cloët, G. A. Miller, *Nucl.Phys.* B (2019) 114638]

- Also interesting:

$$BR(\eta \rightarrow e^+e^-) \text{ vs } BR(\eta \rightarrow \mu^+\mu^-)$$

branching ratios (BR) jn SM range from 10^{-9} to 10^{-6}

[Pere Masjuan,a Pablo Sanchez-Puertas, *Phys.Rev.D* 26 (1982) 3302]

X17 in the e^+e^- emission spectra of isoscalar magnetic transitions of ^{8}Be and ^{4}He nuclei

- Solved by postulating a 17 MeV QCD-axion or a protophobic gauge boson decaying into e^+e^-

$$\eta \rightarrow a\, \pi^+ \pi^- \rightarrow e^+e^-\, \pi^+ \pi^- \quad \textit{and} \quad \eta \rightarrow a\, \pi^0\pi^0 \rightarrow e^+e\, \gamma\gamma\gamma\gamma$$

[D. S. M. Alves, arXiv:2009.05578]

$$\eta \rightarrow X17\gamma \rightarrow e^+e^-\, \gamma$$

[J.L. Feng et Al. Phys. Rev. D **95**, 035017]

KOTO anomaly (100x excess of events in $K^o \rightarrow \pi^o \nu\nu$)

- Solved by postulating a new Hadrophilic scalar boson H decaying into e^+e^-

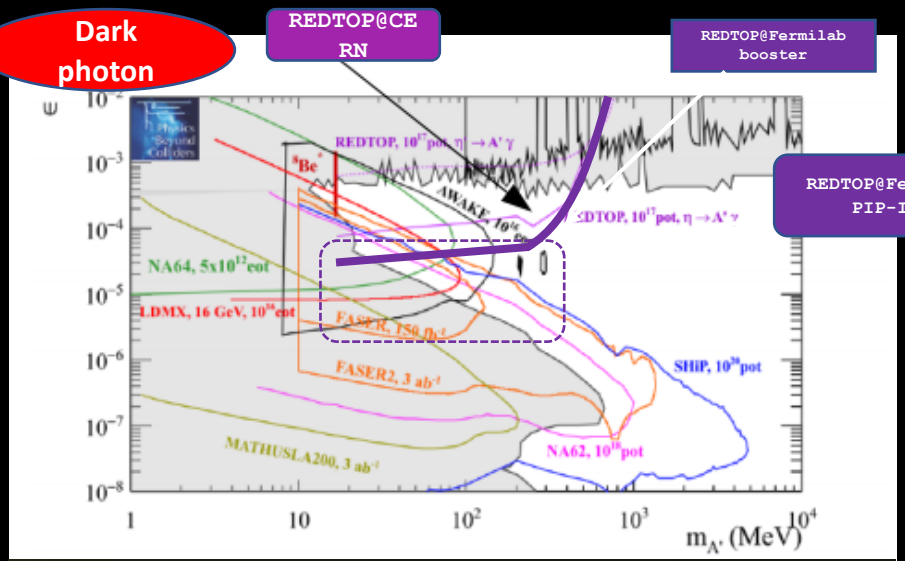
$$\eta \rightarrow H\, \pi^o \rightarrow e^+e^-\, \gamma\gamma$$

[D. Egana-Ugrinovic , S. Homiller , and Patrick Meade, Phys. Rev. Lett. 124, 191801 (2020)]

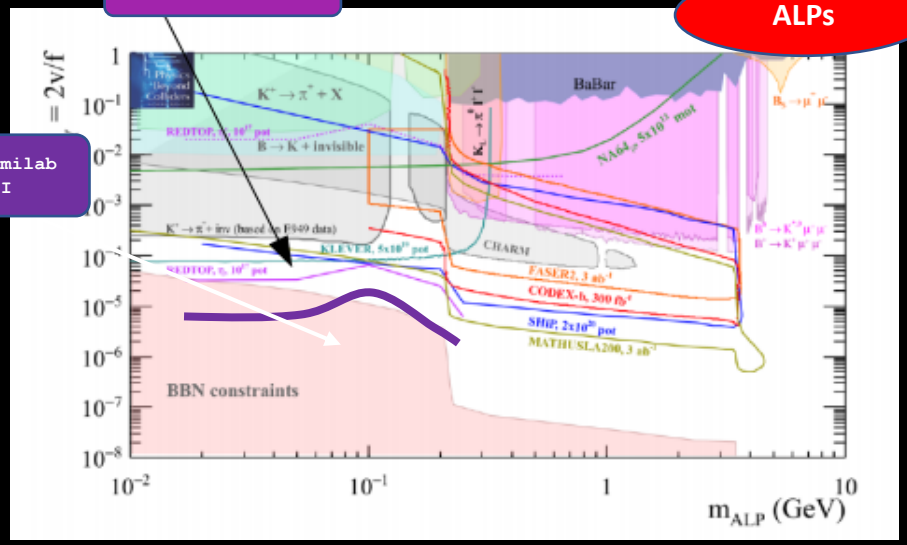
[B. Batell, A. Freitas, A. Ismail, D. McKeen, Phys. Rev. D **100**, 095020]

Sensitivity Studies at CERN PBC

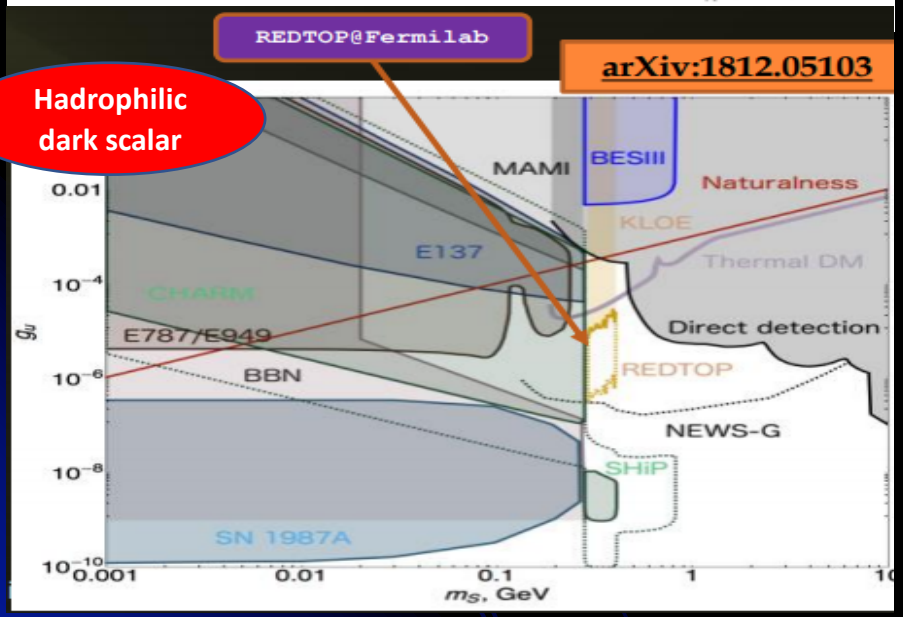
Dark photon



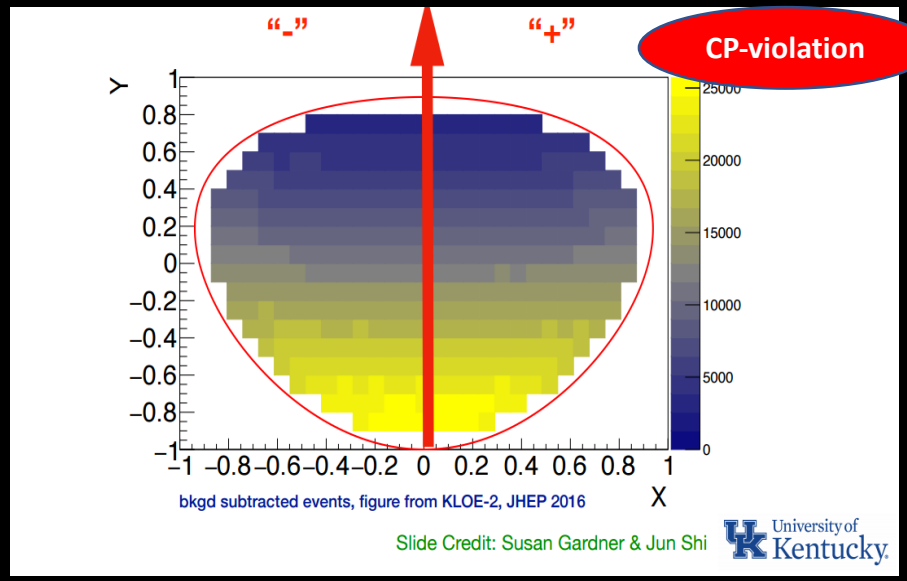
ALPs



Hadrophilic dark scalar



CP-violation



Physics beyond colliders at CERN: beyond the Standard Model working group report:arXiv:1901.09966v2

η/η' Production Option-1: High Energy - Low Intensity Beam

- The production mechanism is based on the formation and the decay of intra-nuclear baryonic resonances

- η and η ' mesons are produced from a proton beam scattered on a target made of multiple thin Lithium (or Beryllium) foils

- Monte Carlo studies indicate optimal beam energies 1.8-2.1 GeV (η) and *3.0-4.0 GeV (η')*

- Large production cross-section (several mbarn) relaxes the beam power requirement. A 30-50W beam is sufficient to generate the desired statistics.

- η/η' mesons are produced with small boost and almost 4π detector is necessary

- Hadronic inelastic background is reduced by using a Continuous Wave beam.

- Advantages:
  - Low intensity beam
- Disadvantages :
  - η/η' are not tagged

η/η' Production Option-2: Low Energy - High Intensity Beam

- η and η ' are produced on a gaseous Deuterium target via the nuclear process

$$p + D \rightarrow \eta + {}^{3}He^{++}$$

- A threshold of 880 MeV beam energy is required (1.7 GeV for η')

- A larger beam intensity (~ 1MW) will compensate for a smaller production cross section ~O($\mu barn$)

- Advantages:
  - The combinatorics background from non-η events is greatly reduced ($\sim 10^8$ from preliminary studies) by tagging the ${}^{3}He^{++}$ ion
  - The kinematics if fully closed and missing 4-P technique is applicable when searching for long lived particles escaping the detector same as B factories but with 40k x statistics

- Disadvantages:
  - A higher beam power is needed
  - An additional forward detector is required to tag the ${}^{3}He^{++}$

Experimental Techniques

- The interaction rate is large (1Ghz for option 1 and ~100Ghz for option 2) but event multiplicity is very low ($\leq$ 8 particles/event)
- Crucial requirements are:
  - *Excellent PID for lepton/hadron separation*
  - *Fast timing with ~30ps resolution (for TOF purposes)*

- Use multiple thin targets to minimize combinatorics background

Charged tracks detection

Option 1: Optical-TPC

Barions and most pions are below threshold

Electrons and most muons are detected and reconstructed

Option 2: LGAD Tracker

4D track reconstruction for multihadron rejection

Complemented with quartz cells for TOF measurements

γ detection

5D-Calorimeter ADRIANO2

(PFA+Dual-readout)

Sci and Cer light read by SiPM or SPAD

For excellent energy and position resolution and PID to disentangle showers from γ/μ/hadrons

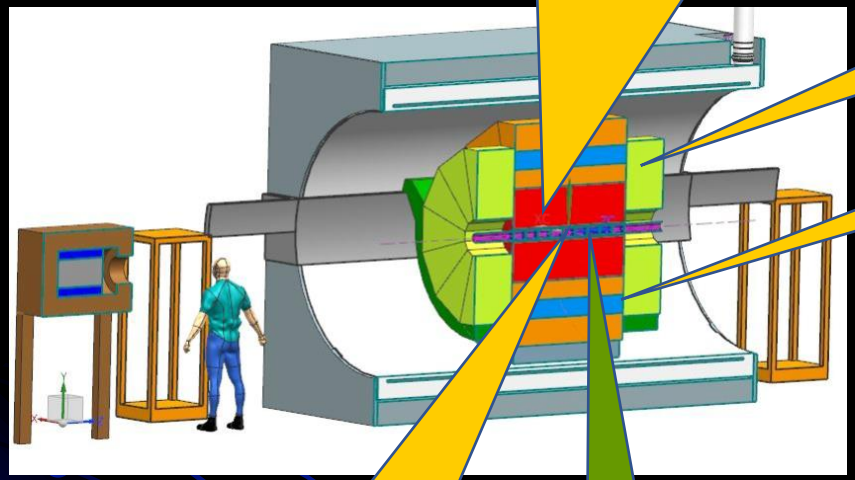
Fiber tracker (LHCB style)

for rejection of background from γ-conversion and reconstruction of secondary vertices (~70μm resolution)

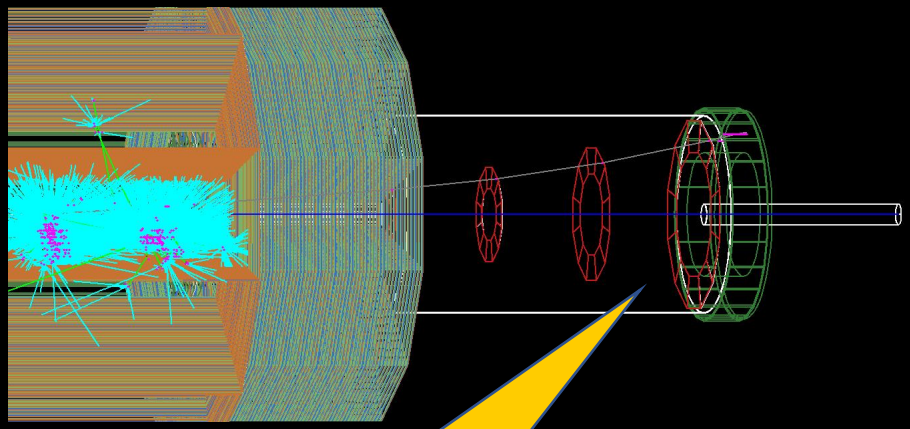
The REDTOP Detector

Optical-TPC
For slow background rejection
or
LGAD Tracker surrounded by Quartz cells
For 4D track reconstruction and TOF measurements

5D- Calorimeter: ADRIANO2
(Dual-readout +PFA)
Sci and Cer light read by SiPM or SPAD
For excellent energy , position resolution and PID



μ-polarimeter (optional)
sandwich of fused silica and Si-pixel
for measurement of muon polarization



Vertex Fiber tracker
for rejection of γ-conversion and identifying displaced vertices from long lived particles

10x Be or Li targets

Forward Detector for Option 2
for tagging $^{3}He^{++}$ ions

Collaboration

11 Countries, 35 Institutions, 92 Collaborators

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Summary

- The η/η' mesons provide an excellent laboratory to search for New Physics and precision tests of the Standard Model

- The REDTOP experiment is a η/η' factory designed to produce 10^{13} η and 10^{11} η' mesons

- The experiment is optimized to search for leptonic decays.
  It is fully complementary to JEF's searches

- Novel detector techniques need to be developed to cope with the high interaction rate

- Future High Energy and High Intensity experiments will benefit from the ensuing R&D.

- New studies are ongoing to improve the sensitivity for different running modes

- Multiple DOE laboratories have the capability of hosting REDTOP.