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The REDTOP experiment: a low energy meson factory to explore Dark Matter and physics beyond the Standard Model

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The η and η' mesons are almost unique in the particle universe since they are Goldstone boson and the dynamics of their decay are strongly constrained. The integrated eta meson samples collected in earlier experiments have been about $\sim 10^9$ events, dominated by the WASA at Cosy experiment, limiting considerably the search for such rare decays. A new experiment, REDTOP, is being proposed, with the intent of collecting more than 10^{13} η/yr (10^{11} η'/year) for studying of rare decays of these mesons. Such statistics are sufficient for investigating several symmetry violations, and for searches of new particles beyond the Standard Model.

1. Introduction

The fact that the LHC program has not uncovered physics Beyond the Standard Model (BSM) at energies of order of few TeV has drastically changed the HEP landscape for the the next decade, and it constitues an almost unique opportunity for laboratories with High Intensity proton accelerators to uncover Dark Matter or New Physics. Possible reasons for that could be either because the most immediately accessible to the experimenter lies at low energies, or because New Physics is elusive, and it the couple to the Standard Model physics too faintly to be detected by experiments based on colliding beams, whose luminosity rarely exceed the 10^{34}-10^{35} cm^{-2}sec^{-1} range. In particular, in the MeV-GeV mass regime[1, 2, 3], strong astrophysical and cosmological constraints are weakened or eliminated, while constraints from high energy colliders are, in most cases, inapplicable. Such energy range is worth an immediate exploration with fixed target experiments, as their higher luminosity could be advantageous in searching for rare processes.

Among the possible systems to explore, the η and η' mesons are almost unique in the particle universe. They have the same quantum number of the Higgs boson and the vacuum (except for parity), and no Standard Model charges, a fact which is very rare in Nature. As a consequence, the dynamics of their Standard Model decays is highly constrained: the latter are flavor-conserving and forbidden at the tree-level. This suggests that an η/η' factory would be an excellent laboratory for studying rare processes and physics BSM at low energy. Furthermore, the existing η/η' world sample is not sufficient for testing violation of conservation laws or for searching for new particles with small coupling to the Standard Model. An η/η' factory with a yield of order 10^{14}(10^{12}) $\eta(\eta')$ mesons has the ability to address most of the recent theoretical models predicting New Physiscs in the MeV-GeV energy range. Such meson factory would have enough sensitivity to explore all four portals connecting the Dark Sector with the Standard Model as well as to probe conservation laws.

The REDTOP Collaboration is proposing an η/η' factory capable of a similar meson yield. No similar experiment exists or is currently planned by the international HEP Community.

The design of the REDTOP experiment is guided by the above observations. REDTOP is a high intensity, fixed target, η/η'-factoryrequiring a beam luminosity of at least 10^{34} cm^{-2}sec^{-1} at low energy. The mass range for potential discoveries is roughly [15 MeV-950 MeV], limited on the lower side by the resolution of the detector and on the upper side by the mass of the decaying mesons. In order to estimate the sensitivity of REDTOP to New Physics, a large effort aiming at studying the performance of the detector for various BSM processes associated to the decay of the η/η' mesons and for the Standard Model background. Nineteen processes driven by New Physics and seventeen theoretical models have been recently benchmarked[4] using a full Montecarlo simulation and digitization and reconstruction of the events in the detector. About 5×10^{10} background events have been generated and fully reconstructed to estimate the sensitivity of REDTOP. A summary of such studies is presented in this article.

2. Rationale for an η/η'-factory

The η and η ' meson have been widely studied in the past, because of their peculiarities[5]. The η is a Goldstone boson, therefore its QCD dynamics is strongly constrained by that property. In nature there are

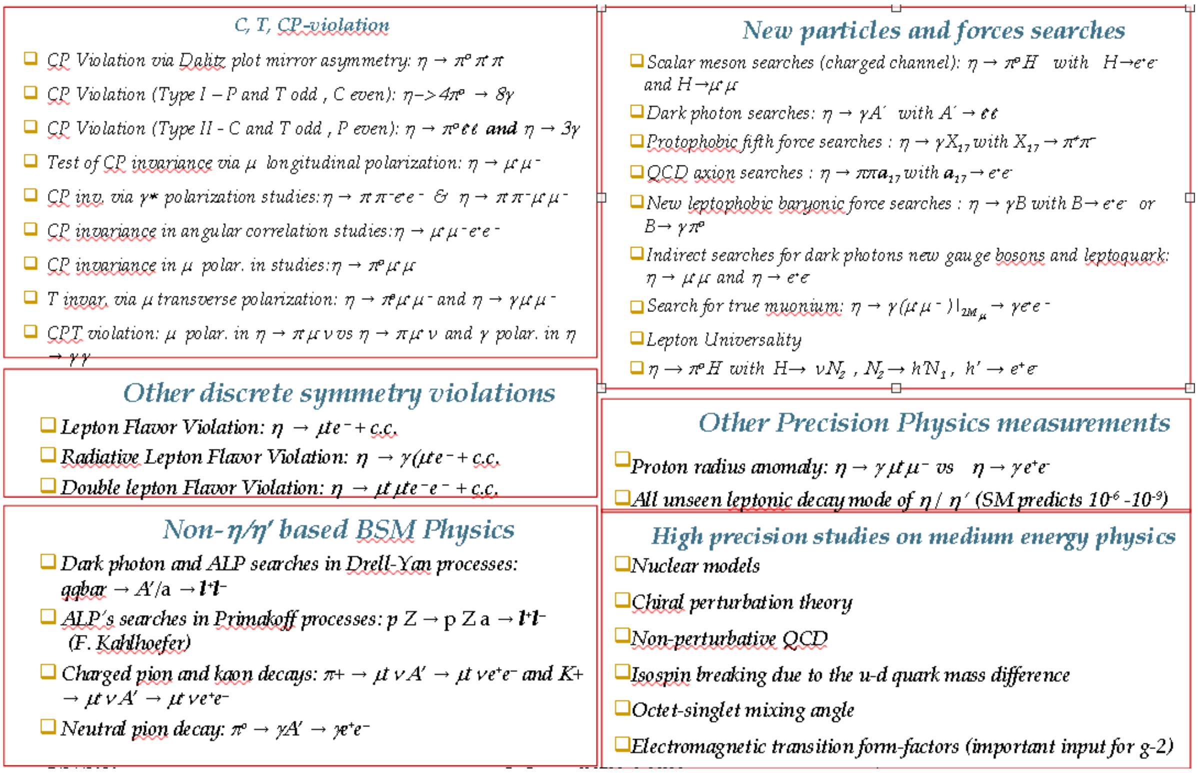

Figure 1: Physics landscape for an η/η' factory.

only few Goldstone bosons. Furthermore, the η is, at the same time, an eigenstate of the ***C***, ***P***, ***CP***, ***I*** and ***G*** operators with all zero eigenvalues (namely: $I^G J^{PC} = 0^+0^{-+}$). Since it carries no Standard Model charges, its decays do not involve charge-changing currents. Furthermore, the structure of the η and η ' mesons has never been fully understood. Although their largest components is known to be u, d and s quarks, the absence of any charge associated to Standard Model operators would allow a mixing with exotic states (i.e., glueballs, tetraquark, hybrids, etc.) or with BSM particles.

Another consequence of the properties listed above is that the η and η ' have small decay width: electromagnetic and strong decays are suppressed up to the order O(10^{-6}) which enhances the branching ratio of rare decays, especially into BSM particles or violation one (or more) of the Standard Model discrete symmetries.

A summary of the most relevant processes which can be studied at REDTOP is presented in Fig. **??** Besides the exploration of New Physics, the availability of a large sample of flavor-conserving decays would allow the probing of the isospin violating sector of low energy QCD to an unprecedented degree of precision. A full discussion of the physics reach of REDTOP can be found in Ref. [4].

3. Golden channels

Among the physics processes listed in Fig. **??**, some have a larger signal/background ratio and have more potential for a discovery or for a direct measurement. A few of these g*olden channels* are briefly discussed below.

3.1 Searches for Dark photons

A search for a dark photon can be carried out at an η/η'-factory by looking for final states with a photon and two leptons. Considering the process:

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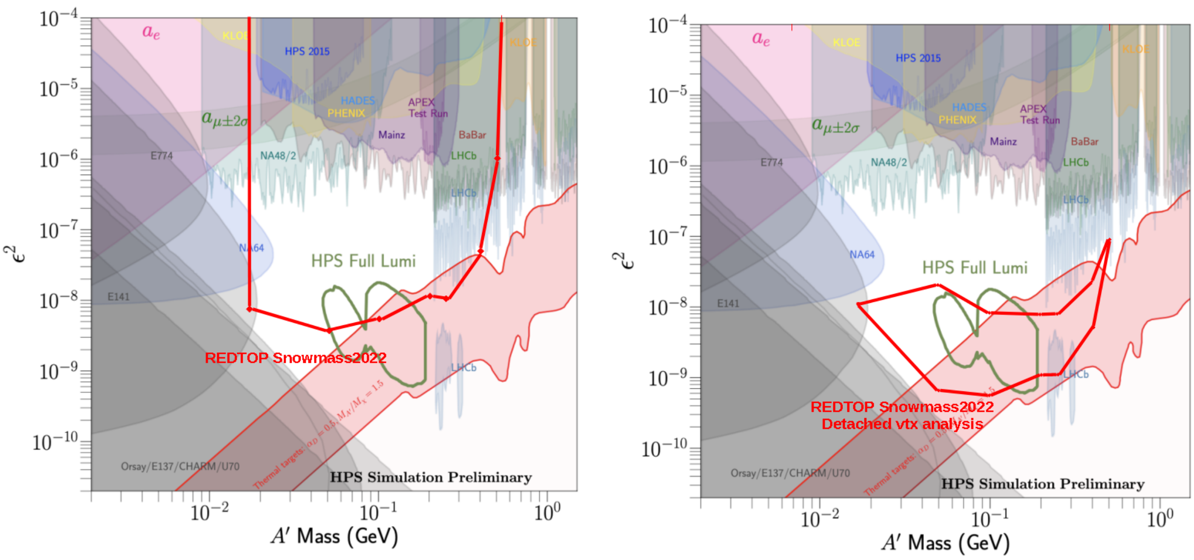

Figure 2: Sensitivity to to ε^2 for the processes $\eta \to \gamma A'$ for integrated beam flux of 3.3×10^{18} POT. Left plot: bump-hunt analysis. Right plot: detached vertex analysis.

$$\eta \to \gamma A' \to \gamma + l^+ l^- \tag{1}$$

in the hypothesis that the mass of this dark photon is smaller than the mass of the η/η' mesons, it will be relatively straightforward to observe it. A detailed simulation of the process and the expected background, including many instrumental effects, has been performed by the Collaboration within the "Snowmass2021" program[4]. An integrated beam flux of 3.3×10^{18} POT has been assumed in those studies. A simple "*bump-hunt*" analysis was performed, by looking at the invariant mass of di-leptons associated to a prompt photon. The sensitivity to the ϵ coupling constant for η decays is shown in the left plot of Fig. 2. The largest contributing background was found to be from mis-identified leptons from the 3-body decay $\eta \to \gamma + l^+l^-$. The sensitivity to this channel is greatly enhanced by the reconstruction of secondary vertexes (associated to long decaying dark photons), since no Standard Model background could generate such effect . A detailed sensitivity analysis for REDTOP indicates that the sensitivity to branching ratio for this process is in the 10^{-10} - 10^{-8} range, depending on the mass and width of the BSM vector boson.

Two theoretical models, predicting the existence of a dark vector particle decaying visibly, have been benchmarked: the Minimal Dark Photon Model[6], and the *Protophobic Fifth Force*[7]. The latter also explain the 17 MeV anomaly observed by the Atomki experiment, a mass value which is above the sensitivity of REDTOP. The sensitivity to the ϵ coupling constant for η decays, in this case, is shown in the right plot of Fig. 2.

3.2 Searches for Pseudoscalar Particles

The *Pseudoscalar portal* is a very rich sector of BSM physics and several theoretical models have been considered in REDTOP studies. Assuming a single ALP state which predominant couples to fermions or photons, all phenomenology (production and decay) can be determined as a function of $\{m_{ALP}, f_l^{-1}, f_q^{-1}\}$. The processes considered are:

$$\eta \to \pi^+\pi^- ALP \to \pi^+\pi^- + \gamma\gamma \tag{2}$$

$$\eta \to \pi^+\pi^- ALP \to \pi^+\pi^- + l^+l^- \tag{3}$$

$$\eta \to \pi^+\pi^- ALP \to \pi^o\pi^o + l^+l^- \tag{4}$$

An integrated beam flux of 3.3×10^{18} POT has been assumed. A simple "*bump-hunt*" analysis was performed, looking at the invariant mass of di-leptons or of two photons associated to two pions in the final state. If the ALP has a dominant coupling to gluons, instead, it would mostly be produced from beamsstrahlung processes associated to the proton beam interacting with the target matter. Several processes can be responsible for the emission of an ALP: a) Drell-Yan processes: $q\bar{q} \to ALP \to l^+l^-$, b) proton beamsstrahlung processes[8]: $p\,N \to p\,N\,ALP$ with $ALP \to l^+l^-$, c) Primakoff processes[9]: $p\,Z \to p\,Z\,ALP$.

The sensitivity to a ALP decaying into leptons is greatly enhanced by including in the analysis the reconstruction of secondary vertexes (observed in case of long decaying ALPs). A detailed sensitivity analysis for REDTOP indicates that the sensitivity to branching ratio for this process is in the 10^{-11} - 10^{-8} range, depending on the mass and width of the pseudoscalar boson.

Three models, related to the pseudoscalar portal, are currently under consideration by REDTOP: *the piophobic axion model*[10, 11], the *axion-like particles with quark dominance*, and the *axion-like particles with gluon dominance*. The two latter models belong to the *Heavy Axion Effective Field Theories* (EFT) class of models, where a heavy axion is introduced that solves the Strong *CP* Problem as well as the Quality problem of the Standard Model. A detailed analysis has been conducted for the case of the *piophobic axion model,* with the assumption that its mass is 17 MeV. The sensitivity to branching ratio for this process is ~2×10^{-8} , showing a very good potential for discovering a QCD axion with this mass. Sensitivity to { f_l^{-1}, f_q^{-1} } for the *Heavy Axion Effective Field* class of theories are in the 10^{-5} - 10^{-3} range, depending on the mass and width of the pseudoscalar boson.

3.3 New scalar particles

A scalar H could be observed in a η/η' final state in association with a π^0:

$$\eta \to \pi^0 H \to \pi^0 + l^+l^-. \tag{5}$$

Within the Standard Model, this process can only occur via a two-photon exchange diagram with a branching ratio of the order of 10^{-9}. If such a light particle exists, even with a mass larger than the η/η' meson, which couples the leptons to the quarks, the probability for this process could be increased by several orders of magnitude, changing dramatically the dynamics of the process. Two groups of theoretical models postulating a BSM light scalar are receiving great attention lately: the Minimal Extension of the Standard Model Scalar Sector[12, 13] and the models containing Higgs bosons with large couplings to light quarks[14, 15, 16]. From the experimental point of view, these models are complementary: the former predicting large coupling to the b-quark and to gluons but a small one to the light quarks, while the latter predicts a large coupling to light quarks. An observation at a η/η' factory of the process (5) would be an indication that the second set of models would be the most likely extension to the SM. Vice-versa, an observation of a scalar at a B-factory but not at REDTOP would favor the first group of models.

A detailed simulation of the process (5) and of the foreseen background, including many instrumental effects, has been performed. An integrated beam flux of 3.3×10^{18} POT was assumed. A simple "*bump-hunt*" analysis as well as a "*detached-vertex*" analysis were performed, looking at the invariant mass of di-leptons associated to a prompt photon and/or at a displaced vertex. The largest contributing background was found to be from the 3-body decay $\eta \to \gamma + l^+l^-$ where an extra γ fakes a π^0 in the final state. A detailed sensitivity analysis for REDTOP indicates that the sensitivity to branching ratio for this process is in the 10^{-11} - 10^{-8} range, depending on the mass and width of the scalar boson.

Four theoretical models, predicting the existence of a Dark Vector particle decaying visibly, were benchmarked: the Spontaneous Flavor Violation[15], the Hadrophilic Scalar Mediator[17] , the Two-Higgs doublet model[18], and Minimal scalar model[19].

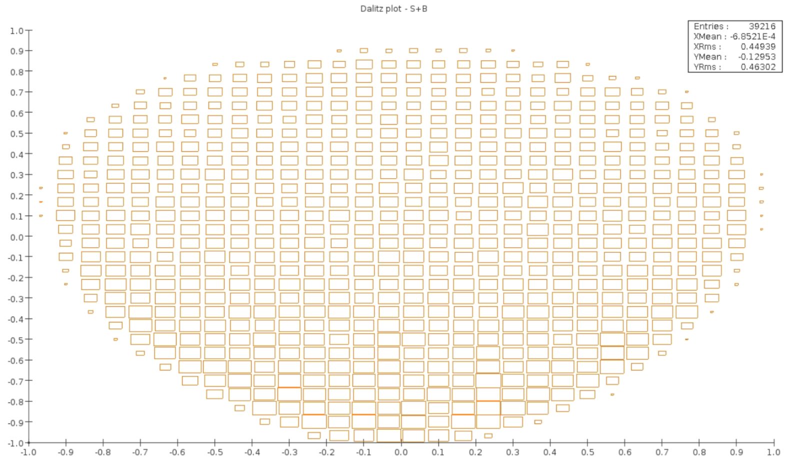

Figure 3: Dalitz plot of $\eta \rightarrow \pi+\pi-\pi0$ combined with the Urqmd background

3.4 CP Violation from Dalitz plot mirror asymmetry in $\eta/\eta' \rightarrow \pi^+\pi^-\pi^o$

Considering the η meson decay:

$$\eta \rightarrow \pi^+\pi^-\pi^o \tag{6}$$

if **CP** invariance is satisfied, the dynamics of the charged pions should be totally symmetric. This would imply that, the Dalitz plot of decay (6) should show no signs of asymmetries. If on the other hand the Dalitz plot shows any mirror-asymmetry, this would be an indication of **CP** and **C** violation. This asymmetry cannot be generated by SM operators at tree level, nor by higher level operators that generate also EDMs (at tree level). Therefore, CP-violation from this process is not bounded by EDM as is the case, for example, for the process: $\eta \rightarrow 4\pi$. Consequently, this channel is complementary to EDM searches even in the case of T and P odd observables, since the flavor structure of the η/η' is different from the nucleus. In this situation, CP violation could arise from the interference of the CP-conserving weak interaction with a new interaction that breaks C and CP generating a charge asymmetry in the momentum distribution of the$\pi^+\pi^-$ systems. Recent studies[20] indicate that the C- and CP-violating amplitude with total isospin I=2 is much more severely suppressed than that with total isospin I=0. Consequently, the I=0 η/η' systems is privileged, compared to any other mesonic systems, for CP-violation searches.

Eighteen Dalitz plots were generated, by generating and reconstructing events with different CP-violating parameters. The Dalitz plot of $\eta \rightarrow \pi^+\pi^-\pi^0$ for the set of parameters corresponding to Kloe-II is shown in Fig. **??**. The parameters obtained from the fits to the Standard Model configuration, where the CP-violating parameters are all zero, are summarized in Table 1. The same binning of the Dalitz plot as in KLOE experiment was used with 372 bins in the (X, Y) plane.

#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%

Table 1: Sensitivities – statistical uncertainties for the two complex Dalitz plot CPV parameters α and β according to Ref. [20]. The generated distribution is the Standard Model configuration i.e., $\alpha, \beta = 0$. The fit reproduces the generated input, with the p-values given in the last column, within the statistical uncertainties given for the real and imaginary parts of the parameters as given in the columns 2–5.

All parameters are consistent with the generated values, within the fit error. The projected sensitivities for the event sample obtained with the full integrated luminosity of 3.3×10^{18} POT (corresponding to 3×10^{10} reconstructed $\eta \to \pi^+\pi^-\pi^0$ events) are given for case of no-background and 100\%-background contamination. They are much smaller than those obtained by the the KLOE experiment[20] and sufficient to detect non-zero values of the CP-violating parameters.

3.5 Test of CP invariance via μ-polarization studies:

Because of the peculiar properties of the η/η' mesons, the Standard Model forbids longitudinal or transverse polarization of the muons originating from their decays, as they would require CP-violation beyond that allowed by the Standard Model. Therefore, CP-violation can also be investigated with the following processes:

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

$$\eta \to \mu^+\mu^-. \tag{7}$$

$$\eta \to \gamma\mu^+\mu^- \tag{8}$$

$$\eta \to \pi^0\mu^+\mu^-. \tag{9}$$

These studies have been conducted by REDTOP collaboration in the assumption that the muon polarization can be measured with an efficiency of ~50%. Assuming an integrated beam flux of 3.3×10^{18} POT we find, for the most sensitive process, the following sensitivity to the Wilson coefficients:

$$\Delta(c^{1122}_{\ell equ}) = 0.1 \times 10^{-1}, \quad \Delta(c^{1122}_{\ell edq}) = 0.1, \quad \Delta(c^{2222}_{\ell edq}) = 6.6 \times 10^{-2}, \tag{10}$$

. The CP-violating coefficient, $c^{2222}_{\ell edq}$ can be measured with the same order of precision obtained from current nEDM bounds, although using a completely different experimental technique.

3.6 Test of CP invariance via γ* polarization studies:

CP-violation can also be investigated without the need to measure the polarization of the muon. The technique is based on the detection of an asymmetry associated to a virtual photon decaying into a lepton-antilepton pair. The processes considered in this case are:

$$\eta \to \pi^+\pi^-\gamma^* \text{ with } \gamma^* \to l^+ + l^-. \tag{11}$$

$$\eta \to \mu^+\mu^-\gamma^* \text{ with } \gamma^* \to l^+ + l^-. \tag{12}$$

The asymmetry is defined as:

$$A_\Phi = \frac{N(\sin\phi\cos\phi > 0) - N(\sin\phi\cos\phi < 0)}{N(\sin\phi\cos\phi > 0) + N(\sin\phi\cos\phi < 0)} \tag{13}$$

where ϕ is the angle between the decay planes of the lepton-antilepton pair and the two charged pions or muons. CP invariance requires A_Φ to vanish. The studies conducted in the assumption of an integrated beam flux of 3.3×10^{18} POT, indicate that A_Φ can be measured at REDTOP with a sensitivity of order 10^{-2} (statistical uncertainty only).

3.7 Tests of Lepton Flavor Universality (LFU).

Lepton flavor universality has become a hot topic recently following the observation by LHCb collaboration of a ~3σ discrepancy in a sample of few thousand semileptonic decays of B mesons[21]. Leptonic and semileptonic decays of the $\eta^{(\prime)}$ mesons have relatively clear signatures in an experimental apparatus, and they can be disentangled with good efficiency if lepton/hadron particle identification is properly implemented. In particular, two groups of processes: $\eta^{(\prime)} \to \ell_1\bar{\ell}_1\ell_2\bar{\ell}_2$, and $\eta^{(\prime)} \to \gamma\ell\bar{\ell}$ have been studied at REDTOP assuming an integrated beam flux of 3.3×10^{18} POT. The sample of fully reconstructed events belonging to the former set is estimated to be of order 10^9 while those belonging to the latter group is of order 10^{11} , bringing the test of LFU to unprecedented levels.

4. The Experimental Technique and Requirements

The η/η' are abundantly produced in hadronic interaction of protons above the production threshold corresponding to $E_{kin} \approx$ 1.4 GeV . Several intra-nuclear baryonic resonances are created in such regime, which decay into an η or η' meson. The design of REDTOP experiment is based on such production mechanism

Beam and target requirements

Detailed studies, based on *GenieHad*[22] event-generator framework, indicate that a proton beam with $E_{kin} \approx 1.8 - 1.9$ GeV impinging on a thin, low-Z, high-A/Z material like a Beryllium or Lithium target is sufficient to generate approximately $3.3 \times 10^{13} \eta/yr$. The low-Z of the target lowers the multiplicity of the fragmentation products, generated by QCD processes, and suppresses the unwanted background. The relatively largeA/Z of Li and Be is advantageous because of an increase by a factor ~7x of the η production cross section for neutrons vs protons. The thin targets requirement constrains, on one side, the z-coordinate of the η production vertex, and, on the other side, it minimizes the multiple scattering affecting the η decay products when they escape from the target. REDTOP will use 10 foils, spaced by 10 cm , as they provide, at the same time, the total material budget for the required luminosity, while reducing the pile-up of events due to multiple beam interactions within the same trigger. A similar analysis for the η' case indicates that the optimal range for E_{kin} is about 3.5-4 GeV.

The inelastic interaction rate and the η/η' production have been estimated using several nuclear scattering models available in *GenieHad [22]* (more specifically, *Urqmd, Gibuu, PHSD* and *Jam*). They produced comparable results and predict an inelastic interaction probability of the order of 0.7% with a probability for an event to contain a η meson of the order of 0.25% - 0.5%. The probability to generate an η' meson is two orders of magnitude smaller. A CW proton beam delivering $\sim 1 \times 10^{11}$POT/sec would generate a rate of inelastic interaction of about 0.7 GHz and a η-meson yield of $\sim 2.3 \times 10^6 \eta/sec$, corresponding to $2.3 \times 10^{13} \eta/yr$. The beam power corresponding to the above parameters is approx. 30 W, of which 1% (or 300 mW) is absorbed in the target systems. These figures roughly double for the beam required at a η'-factory.

Detector requirements

The η mesons in REDTOP are generated almost at rest in the lab frame, since the most probable value of its kinetic energy is less than 50 MeV. *GenieHad* simulations indicate that the $\eta-$spectrum is mostly independent from the beam energies in the [1.46-2.1] GeV range. An efficient detector needs to cover the entire solid angle with excellent particle identification of the final states particles , in order to separate rare processes from the QCD background. This argument is corroborated by the fact that most of the interesting processes listed in Fig. **??** have two leptons at at least one photon in the final state. On the other side, the QCD background, which has a production rate two order of magnitudes larger, it is consituted almost invariably by protons, neutrons, slow pions and nuclear remnants. These are relatively slow particles and easy to identify. Regarding the background from neutral particles, without a proper PID system neutrons impinging onto the calorimeter would easily be mis-identified as photons and the identification of e^+e^- pairs from photons converting in the material upstream the central tracker will help to mitigate the background originating from π^o particles. The detector is inserted in a solenoidal magnetic field which bends the charged particles for proper P_t and electric charge measurement.

The detector proposed for REDTOP covers 98.5% of the solid angle, with a dodecagon-based structure. A schematic drawing of the latter is shown in Fig. **??**. The charged tracks section consists of a 3-layer

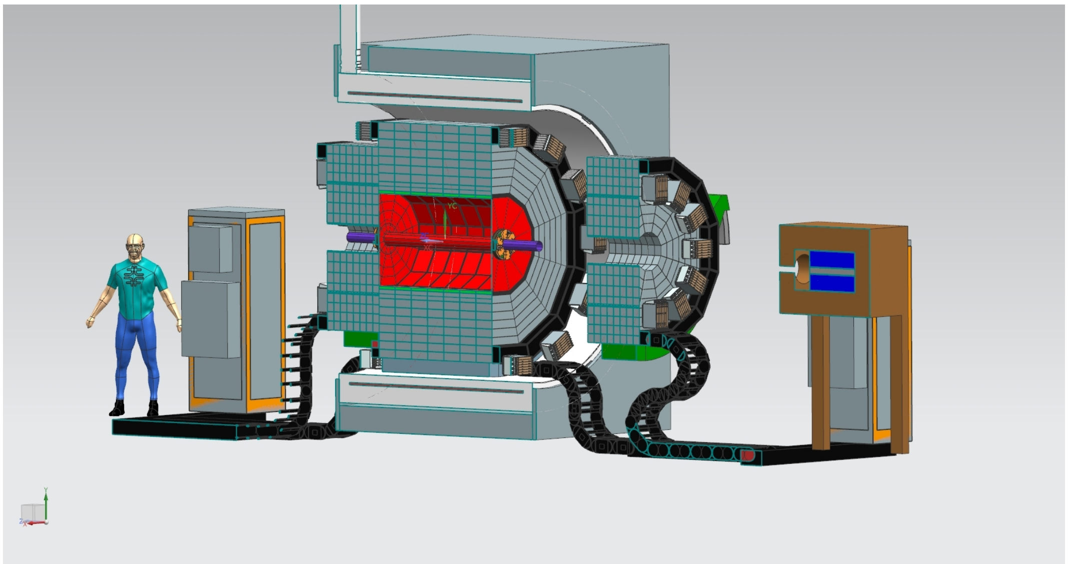

Figure 4: Cross section of REDTOP detector

vertex detector (either a fiber tracker or a CMOS detector), surrounding the beam pipe, and an LGAD central tracker, with five layers for the barrel and four layers for the endcaps, (the red subdetector in Fig. ??). They measures the transverse momentum of charged particles and reconstruct the detached vertex of potential BSM particles with long lifetime. The excellent timing resolution of the LGAD sensors contributes also to the measurement of the Time of Flight (TOF) of the reconstructed particles. A thin Cerenkov TOF detector (the green subdetector in Fig. ??) surrounds the central tracker and provides further information on the speed of the particles for PID purposes. Finally, a dual-readout calorimeter (the gray subdetector in Fig. ??), based on the ADRIANO2 technique, represents the outermost component of REDTOP. The high-granularity of ADRIANO2[23] allows the implementation of Particle Flow Analysis (PFA)[24] as long as dual-readout compensation techniques[25]. It is being designed to measure the energy of impinging particles with a resolution better than $\sigma_E/E = 3\%/\sqrt{E}$ and to participate to the PID by comparing the scintillation and the Cerenkov components. \On optimization of the detector granularity is currently ongoing.

5. Conclusions

The η and η' mesons are almost unique in the particle universe and constitute an excellent laboratory for studying rare processes and physics BSM in a flavor-conserving processes. Because of their relatively low mass, compared to flavored mesons, their decays can be exploited to explore New Physics in the MeV-GeV range, currently considered the most promising regime to probe Light Dark Matter. The existing world sample is not sufficient for breaching into decays violating conservation laws or for searching for new particles with small coupling to the Standard Model. A new η/η'-factory is being proposed: REDTOP, aiming at producing ~10^{14} η mesons in a three-year running period, and ~ 10^{12} η'. Such an η/η' factory would be able to study a very large portion of the unexplored parameter space for all the four portals connecting the Dark Sector with the Standard Model and probe the conservation of discrete symmetries: CP, T, and Lepton Universality. Novel detector techniques are being developed and/or optimized: the next generation of High Intensity experiments would also benefit by REDTOP's R&D. The moderate cost of REDTOP (below 100 M$), along with the many physics measurements accessible, make this experiment very attractive.

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