REDTOP: Rare Eta Decays TO Explore New Physics

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Abstract: REDTOP will undertake an unprecedented experimental effort to search for Beyond Standard Model (BSM) physics by studying rare decays of the η and η' mesons. Strong theoretical motivations exist to explore New Physics in the MeV to GeV range. The η and η' mesons are unique particles as they carry no standard model charges, a property shared only by the Higgs boson and the vacuum. The mesons also possess the same quantum numbers as he Higgs (except for parity). Since New Physics is also expected to be neutral under Standard Model charges, an η/η' factory is an excellent laboratory for studying rare processes and BSM physics at low energy.

The REDTOP experiment is designed to explore violations of fundamental symmetries and search for new particles and fields in the MeV to GeV energy range. The experiment focuses of producing an η and η' sample that is five orders of magnitude larger than the existing world sample, using high-intensity proton or pion beams with energies of a few GeV. REDTOP aims to improve the sensitivity of key physics conservation laws by several orders of magnitude beyond previous experiments by exploring η and η' processes with branching ratios as low as $\sim 10^{-12}$.

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I. SCIENTIFIC CONTEXT AND OBJECTIVES

The Standard Model (SM) is not a complete description of nature. The exact nature of dark energy, dark matter, neutrino mass, and the baryon asymmetry of the universe (BAU) are among the major questions that must find answers Beyond the Standard Model (BSM). These and similar issues provide strong hints that BSM physics could contain new particles and/or forces that may violate some of the discrete symmetries of the universe. For example, baryon asymmetry can arise only through C, CP, and baryon number violations outside of thermal equilibrium.

To date, the LHC has found few, if any, hints of New Physics at high energy, indicating that new physics is more elusive than expected and may lie at low energies. On the other hand, New Physics is much easier to accommodate in the 1-GeV energy regime, where many of the stringent astrophysical and cosmological constraints are either significantly weakened or completely eliminated. Additionally, constraints from high-energy colliders often do not apply in this energy range. This scenario, commonly referred to as "Light Cold Dark Matter", has been gaining significant attention within the theoretical physics community.

A key feature of the latest models is that New Physics interactions with the Standard Model would occur with coupling constants on the order of 10^{-8} or lower. In this context, fixed-target and low-energy experiments with intense beams could play a crucial role in the discovery of New Physics. These experiments require integrated luminosities on the order of 10^{-45} cm^{-2}, a level that high-energy colliders are unlikely to achieve in the foreseeable future. By considering different production scenarios, the production rates for neutral GeV-scale states in fixed-target experiments can be enhanced by several orders of magnitude compared to searches at colliders. As a result, these experiments can produce a large number of events, enabling the exploration of extremely rare processes.

To explore this new regime, the proposed REDTOP experiment is primarily intended to look for new particles and for new violations of the fundamental symmetries. REDTOP aims to improve the sensitivity level of key physics conservation laws by several orders of magnitude beyond those of previous experiments. In doing so, it will open doorways for possible Physics Beyond the Standard Model including dark matter and energy, and/or new forces.

The REDTOP measurements will focus on rare decays of the η and η' mesons produced by a proton or pion beam of a few GeV energy. The additive quantum numbers for these particles are all zero, the same as for the vacuum and the Higgs boson, with the exception of their negative parity, a feature occurring very rarely in nature. Therefore, an η/η' factory would be different from any other meson factory realized in the past. Early measurements will be aimed at testing C, CP, and T conservation laws to many orders of magnitude below current levels and to discover new particles and Light Cold Dark Matter.

To meet the associated high rate and high background challenges, REDTOP will extend and develop new and innovative detector technology. The features will provide many new opportunities for future experiments in particle and nuclear physics, and possibly other fields as well. REDTOP will require the following improvements:

- Timing resolution of ≤ 100 psec, to cope with event production rates of several hundred MHz and for Time of Flight (TOF) purposes;
- A Particle-Identification (PID) efficiency in the 95%-99% range depending on particle species and, in particular, the capability to disentangle photons from neutrons;
- High radiation hardness.

C, T, CP-violation
CP Violation (Type I – P and T odd , C even): $\eta \to 4\pi^0$
CP Violation (Type II - C and T odd , P even): $\eta \to \pi^+\pi^-\pi^0$ and $\eta \to \gamma\gamma\gamma$
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 m transverse polarization: $\eta \to \pi^o\mu^+\mu^-$ and $\eta \to \gamma\mu^+\mu^-$
CPT violation: μ polariz. in $\eta \to \pi^+\mu^-\nu$ vs $\eta \to \pi^-\mu^+\nu$ and γ polarization in $\eta \to \gamma\gamma$
Searches for new particles and forces
Scalar meson searches (charged channel): $\eta \to \pi^0 H$, with $H \to e^+e^-$, $\mu^+\mu^-$
Dark photon searches: $\eta \to \gamma A'$ with $A' \to l^+l^-$
New leptophobic baryonic force searches : $\eta \to \gamma B$, with $B \to e^+e^-$, $\pi^o\gamma$
Indirect searches for new gauge bosons and leptoquark: $\eta \to \mu^+\mu^-$ and $\eta \to e^+e^-$
Search for true muonium: $\eta \to \gamma\ (\mu^+\mu^-)_{2M_\mu} \to \eta \to \gamma\ e^+e^-$
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 modes of η/η' (SM predicts $10^{-6} - 10^{-9}$)
Non-η/η'' based BSM Physics
Dark photon and ALP searches in Drell-Yan processes: $q\bar{q} \to A'/a \to l^+l^-$
ALP's searches in Primakoff processes: $pZ \to pZa \to l^+l^-$ (F. Kahlhoefer)
Charged pion and kaon decays: $\pi^+ \to \mu^+\nu A' \to \mu^-\nu l^+l^-$ and $K^+ \to \mu^+\nu A' \to \mu^-\nu l^+l^-$
Neutral pion decay:$\pi^o \to \gamma A' \to \gamma e^+e^-$
High precision studies on non-perturbative QCD physics

Table I. Summary of REDTOP physics program

II. PHYSICS MEASUREMENTS

We have compiled a comprehensive list of potential measurements that can be performed with REDTOP, categorized into six groups, as outlined in Table I. While the experiment has a broad scope, we highlight a few processes that are particularly interesting.

A key advantage of the η meson is its flavor-neutral nature, so its Standard Model C- and CP-violating interactions are expected to be extremely small. Therefore the η decays provide a promising window for BSM physics, offering unique insights into conservation laws. The REDTOP experiment aims to improve sensitivity beyond present branching fraction limits of 10^{-9} reaching below of 10^{-11} for most η decay modes.

Among the numerous processes that can be studied at REDTOP, a few "Golden Channels" provide exceptional opportunities to explore BSM physics:

- $\eta \to \pi^+\pi^-\pi^0$ (CP Violation in Dalitz Plot).

  Observation of the Dalitz plot asymmetry would be direct evidence of C and/or CP violation.

- $\eta \to \mu^+\mu^-e^+e^-$ (CP Violation in Angular Asymmetry).

  This decay can probe CP by measuring angular asymmetries between the (e^+, e^-) and (μ^+, μ^-) decay planes. Current experimental results are limited by statistics, while REDTOP will provide a large improvement with better systematics.

- $\eta \to \gamma A'$, with $A' \to e^+e^-$ or $\mu^+\mu^-$ (Dark Photon and Light Gauge Boson Search).

  This decay provides opportunities to search for new physics such as a mediator of a fifth, milli-weak force.

- $\eta \to \pi^0 H$, with $H \to e^+e^-$ (Higgs-Like Scalar Search).

  The exceptionally high yields expected at REDTOP make decays involving axions, such as $\eta^{(\prime)} \to M_1 a$ or $\eta^{(\prime)} \to M_1 M_2$ a (with M_i denoting mesons), highly promising for studying the the couplings of the QCD axion [Peccei:1977hh, Peccei:1977ur, Weinberg:1977ma, Wilczek:1977pj] to quarks, as well as provide model-independent bounds on the Peccei-Quinn scale f_a. In particular, the requirement that the axion decays into detectable final states such as e^+e^- will allow REDTOP to probe both axion-quark interactions and, potentially, the decay-level coupling that parametrically governs the axion decay length. This underscores REDTOP capability to probe *unknown high scales* within *well-motivated* BSM scenarios in controlled collider setups. The potential of this approach warrants further investigation.

- Axion-Like Particle (ALP) Searches.

  REDTOP will provide outstanding opportunities to search for axion-like particles (ALPs) [Holdom] as signatures of BSM physics. Some ALPs can be produced from $\eta \to \pi^0\pi^0 a$ or $\eta' \to \pi^+\pi^- a$ decays, where a is an ALP that decays into e^+e^- [O'Connell]. For other portals, the ALP can decay to $\gamma\gamma$, 3π, or $\pi\pi\eta$ without an initial η or η' [Batell,Pospelov].

The REDTOP physics program will require a CW proton beam with an energy range of 1.8–3.5 GeV, and a minimum intensity of 10^{11} POT/sec (corresponding to an annual integrated flux of 10^{18} POT). Several laboratories have the capability to provide such a beam. Based on these parameters, we estimate an annual yield of about 3.3×10^{13} η and $\sim 5 \times 10^{12}$ η'. By achieving an unprecedented level of sensitivity in rare η/η' decays, REDTOP has the potential to redefine the landscape of BSM physics searches in the MeV-GeV energy range.

III. THE REDTOP DETECTOR

The REDTOP detector consists of several critical subsystems that must function together to achieve the sensitivity to New Physics targeted by the experiment. Three major subsystems: the all-silicon tracking system, the ADRIANO3 calorimeter, and the active Muon Polarimeter are novel technologies currently under active development. As a result, REDTOP will not only push the boundaries of fundamental physics but also represent a significant advancement in detector technology, laying

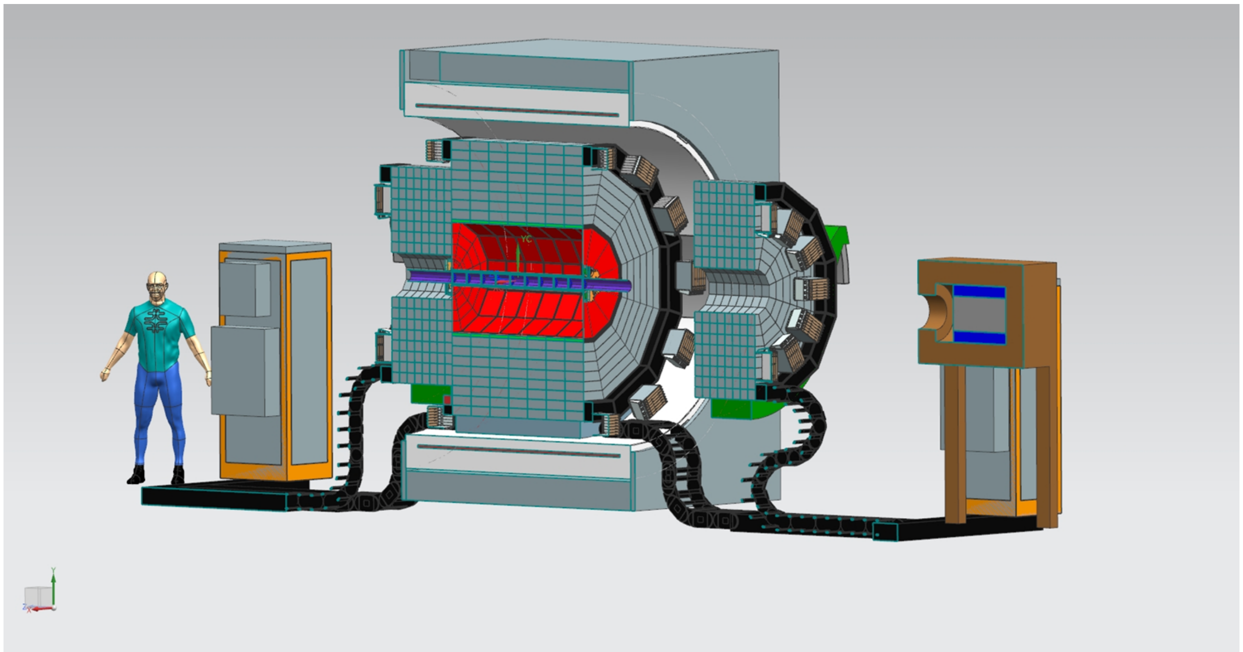

Figure 1. The REDTOP experimental apparatus.

the groundwork for even more challenging future experiments. A schematic of the detector is shown in Fig. 1, followed by a brief description of its main components.

Due to the quantum numbers of the η mesons, hadro-production is the only viable mechanism to achieve the required yield. The experimental technique proposed for REDTOP introduces three major challenges for the detector:

1. High Interaction Rate: The inelastic hadronic interaction rate between the beam and the target is almost 1 GHz, requiring fast-timing and a high-granularity detector.

2. High Baryon Production: The production rate of uninteresting baryons (primarily slow protons and neutrons) is also around 1 GHz, requiring a tracker that is mostly insensitive to them to minimize background.

3. New Physics Signatures: Since new physics signals are almost always accompanied by leptons and/or photons, a calorimeter with excellent particle identification is essential for effective detection and separation of final-state particles.

III.A. The Beam Pipe and Target System

The target system (represented by the blue disks along the beam axis in Fig. 1) consists of ten, round, low-Z foils made of lithium or beryllium, each approximately **240-300** μm thick and 1 cm in diameter. These foils are suspended in the center of a beryllium or carbon-fiber beam pipe using thin AlBeMet wires. The beam pipe serves two main purposes: a) maintaining a vacuum around the target system and b) providing structural support for a Si-pixel detector mounted on its external wall.

A proton with 1.8 GeV of kinetic energy has a $\approx$ **2%** probability of undergoing inelastic scattering in any of the foils while, the probability of η meson is about **0.4%**. With an integrated flux of 10^{17} protons on target (POT), the total number of η mesons produced is expected to be around 8×10^{12}. The physics goals of the experiment are designed to be achieved within a three-year run.

In contrast to the use of a gaseous target (*e.g.* [WASA14]), the distributed target system offers significant advantages in background suppression. The primary background source, inelastically scattered protons from the target material, can be more effectively distinguished from η-meson events due to the discrete nature of the targets.

The spacing between foils allows for precise identification of the primary vertex, minimizing ambiguities, while the tracking system provides accurate $r\varphi$ coordinates. Additionally, preliminary Monte Carlo simulations indicate that the decay products of the η meson are minimally affected when passing through the thin beryllium foils.

Only about 2% of the beam is absorbed by the target system, meaning that each beryllium foil will need to dissipate just 2 mW of power. This is easily managed through thermal radiation and conduction via the supporting metal wires. The material budget of the beam pipe is $\simeq$0.2% of X/X_o

III.B. The Vertex Detector

The vertex detector represented by the innermost volume in Fig. 1) has four main tasks: a) identifying events with a detached secondary vertex; b) contributing to the reconstruction of charged tracks originating from the target; c) rejecting photons converting in the target; and d) reconstructing tracks with very low transverse momentum. The most critical aspects of REDTOP vertex detector are related to the material budget and to its proximity to the interaction region. The former needs to be kept as low as possible to reduce multiple scattering, which, in the momentum range of interest for REDTOP, is the major source of resolution loss.

The main requirements for the vertex detector are a) spatial resolution near the IP better than 20 mm, b) material budget: <0.1% X_0/layer, and c) timing resolution of a few ns. Radiation hardness up to $\sim 5 \times 10^6/\mathrm{cm}^2/\mathrm{s}$ "*1-MeV ENF*" is also an important aspect of this subsystem.

The above requirements are similar to those of the pixel tracker of the Mu3e experiment at PSI (muon stopping rate $\simeq 100MHz$ in phase-1 and $\simeq 2000MHz$ in phase-2 vs inelastic event rate $\simeq 500-700\ MHz$ for REDTOP; maximum track momentum $\simeq 53\ MeV/c$ vs $\simeq 1.1\ GeV/c$ for pions and $\simeq 2.2\ GeV/c$ for protons in REDTOP). Recent demonstrations show that the technology can reach a time resolution of $6-8\ ns$ with an appropriate time-walk correction [rudzki2021mu3e], which also fits well with REDTOP requirements. Therefore, we adopt the same HV-MAPS technology as Mu3e, based on the MuPix sensor [MU3ERP2012].

The vertex detector proposed for REDTOP will consist of three layers of HV-MAP sensors for the barrel and for the endcaps with a coverage >90% of full solid angle. The innermost layer is located at a distance of 2.4 cm from the beam axis, while the radius of the outermost layer is $\sim 4.2\ cm$, corresponding to a solid angle coverage of $\sim$ 91%. The material budget of the vertex detector is $\simeq$0.1% of X/X_o per layer.

III.C. The Central Tracker

A new generation, 4-D Si-tracking system based on the AC-LGAD technology [LGAD2020] is proposed for REDTOP, to complement the vertex detector in reconstructing charged tracks and the

$CTOF$ system in disentangling leptons from hadrons. At the same time, the material budget needs to be kept low to reduce multiple scattering for low momentum tracks. The main requirements for the central tracker are (cfr. reference [WHITEPAPER2022]): a) momentum resolution: $\sigma_{P_T}/P_T^2 \sim 2 \times 10^{-3}$ GeV^{-1}at P$_T$=1 GeV, b) material budget: ∼0.1% X_0/layer, and c) time resolutions: $< 30\ ps$/layer.

The pixel size of the REDTOP central tracker is dictated by the multiple scattering deviation that particles with momentum $\mathcal{O}(100\ MeV\ MeV/c)$ undergo between two layers. In the case of REDTOP, that size corresponds to $1 - 1.5\ mm$.

To meet the material budget of REDTOP, only passive cooling can be used. Carbon-fiber support structures similar to those planned for the HL-LHC upgrade of ATLAS pixel detector [ATLAS-HGTD-TDR] are strong, lightweight, and have good thermal conductivity. The system, particularly the readout electronics, must be designed to minimize the heat output.

The total thickness of an AC-LGAD layer (base + sensor) can be kept as low as $\simeq 100\mu m$). The material budget for the tracking region of the detector which includes the carbon fiber support structure is $\simeq 0.2\%$ per layer.

III.D. The Calorimeter

The REDTOP calorimeter system plays a critical role beyond measuring energy and time of arrival of incoming particles. It also contributes to particle identification (PID) and provides pre-processed information to all trigger levels, requiring it to operate on a very short timescale. The biggest challenge for the REDTOP calorimeter is to disentangle electromagnetic and hadronic showers, particularly those generated by neutral particles (photons and neutrons), as they are not detected by other systems. A multiple-readout calorimetric technique with high granularity fulfills all the above needs.

Extensive studies [WHITEPAPER2022] indicate that the REDTOP calorimeter system must meet the several requirements: a) energy resolution of $\sigma_E/E < 2\%/\sqrt{E}$, b) Particle Identification with separation efficiency between electromagnetic and hadronic particles higher than 99%, c) time resolution: $< 80\ ps$ in a single cell with energy deposit $>$ 7 photoelectrons, and d) Detector response: $<\ 100\ ns$;

Good energy resolution with high granularity are needed to identify π^0 mesons, which mostly decay into $\gamma\gamma$ and γe^+e^-. These mesons, produced either from the primary interaction or from η/η', contribute to one of the largest combinatorial backgrounds in the experiment.

For REDTOP, we propose a triple-readout version of ADRIANO2 [T1015-1, T1015-2, T1015-3, T1041], in which signals from three independent regions are recorded: scintillating plastics, lead-glass and Gd-doped RPC's. These regions provide independent measurements of the electromagnetic, hadronic, and neutron components of each shower.

The calorimeter is indicated in gray in Fig. 1. The high granularity explored with ADRIANO3 provides improved pattern recognition and showers separation, along with a timing precision of about 50 ps or better, achievable from the prompt Čerenkov signal. Such fast timing will greatly enhance the trigger capability of the detector and the disentangling of overlapping events. Particle Flow Analysis (PFA) algorithms could be easily implemented, thanks to the high granularity of ADRIANO3, further enhancing the detector's performance by improving energy reconstruction and background rejection.

III.E. The Threshold Čerenkov Time of Flight ($CTOF$)

A thin Čerenkov radiator with relatively low refractive index is positioned between the central tracker and the calorimeter. The detector has two primary purposes: a) detection of particles above the Čerenkov threshold and b) measurement of the TOF of such particles. The information from the $CTOF$ will be integrated into the Level-0 trigger to help suppress background contamination from abundant but slow baryonic particles.

The baseline layout of the $CTOF$ consists of two layers of small quartz tiles. The momentum threshold for protons, in that case, is ≈870 MeV, while that for muons is only 100 MeV. Therefore, most of the background from protons reconstructed in the tracking systems is rejected by the $CTOF$. A detector with similar layout, using scintillating plastics instead of quartz, is currently being designed for the MU3E experiment at PSI [MU3ERP2012].

III.F. The Solenoid

The REDTOP detector will be housed within a large superconducting solenoid (represented by the white cylinder in Fig. 1) that will generate a 0.6-T solenoidal magnetic field. The magnetic field will serve two key functions: a) enabling the tracking systems to measure the transverse momentum of charged particles and b) facilitating analysis of the polarization of muons. For this purpose, the Finuda magnet [Bert99], previously used at the Frascati Φ-factory (DAPHNE), is being considered as a suitable option.

IV. EVENT TRIGGER SYSTEM

The goal of producing 5.2×10^{13} η mesons per year, (5.2×10^{6} η/s, assuming 10^{7} seconds of useful running time), requires about 7×10^{8} p-target inelastic collisions per second. This rate can be achieved with a proton or pion beam intensity of 10^{11} p/s (π/s) and a Li or Be target of 2×10^{-2} collision lengths (equivalent to $\approx$ 7.7 or 2.3 mm total thickness). The total event rate reaching the detector is estimated to be $\sim 7 \times 10^{8}$ Hz. The majority of particles entering the REDTOP detector will be hadrons produced by inelastic scattering of the beam on nuclear matter. The average multiplicity per p-Li (p-Be) interaction is found to be 3.5 (3.8) for the charged and 1.8 (1.9) for the neutral hadrons.

This event rate exceeds that observed in LHCb [Lhcb-2021] by more than an order of magnitude, highlighting the need for very fast detector technologies and/or topological trigger strategies to manage such rates effectively. To successfully reduce rates to acceptable levels, we propose a three-level trigger system.

Level-0 trigger The Level-0 (L0) trigger performs an initial event selection based on simple global features of the events produced in p/π-target inelastic collisions. All interesting events contain at least two leptons or two pions in their final state, often accompanied by at least one energetic photon detected in the calorimeter. The purpose of the Level-0 trigger will be to reject non-interesting events with a processing time of just a few tens of nanoseconds. The leptons and pions originating from the decay of the η meson are more energetic than those generated by the proton-nucleus interaction, and easy to identify with TOF methods. The expected event rate reduction factor and the average event size after L0 selection are presented in Table II.

Level-1 trigger The Level-1 (L1) trigger rejection is based on local information obtained directly from the sub-detectors. This requires the implementation of at least low-level pattern recognition and clusterization of hits. Given the low occupancy in the tracking system, the L1 trigger can be efficiently implemented using Vertically Integrated Pattern Recognition Associative Memory (VIPRAM) [Deputch2011]. The L1 trigger is designed to suppress primarily background from baryons produced in p/π-target inelastic collisions and from photon conversions into e^+e^- pair in the innermost detector region. The acceptance of the Level-1 trigger for p-Li inelastic collisions is summarized in Table II.

Level-2 trigger The Level-2 (L2) trigger is designed to positively identify the underlying physics process, relying heavily on the topology of the final state. Since the L2 algorithm requires a fully reconstructed event, it will be implemented entirely in software. The processor farm will receive data at a rate of 2.5 MHz, corresponding to approximately ∼3.8 GB/s, from the Level-1 trigger. These events must be reconstructed, filtered, and formatted for permanent storage. Assuming the event reconstruction can be completed in less than 100 ms of CPU time per event, a farm of 2000 CPUs should be sufficient to handle the processing load efficiently, this solution is scalable as needed.

Digitization and Compression: Summary of Trigger Performance The REDTOP trigger system is designed to reduce the event rate from the initial inelastic collision rate of $\sim 7 \times 10^8$ Hz down to approximately 3 MHz of events for permanent storage. The required $\sim 2.3 \times 10^3$ event rate reduction is achieved through the three-stage trigger system, as briefly described above. Table II summarizes the data rates and event rates at each trigger stage. Future detector improvements are expected to further reduce background levels. A topological trigger strategy, rather than the global approach used in the current studies, is planned for future implementations to enhance background suppression and signal efficiency.

Table II. Data and event rates for different stages.

Trigger stage	*Input event rate Hz*	*Event size bytes*	*Input data rate bytes/s*	*Event rejection*
Level 0	$7. \times 10^8$	1.4×10^3	9.8×10^{11}	∼4.6
Level 1	1.5×10^8	1.5×10^3	2.3×10^{11}	∼60
Level 2	2.5×10^6	1.5×10^3	3.8×10^9	∼4.5
Storage	0.56×10^6	1.6×10^3	0.9×10^9	

V. STATUS OF THE PROJECT AND CHALLENGES

The REDTOP Collaboration was formed in 2015 and currently includes 138 members from 62 institutions (see Addendum). Several groups are actively involved in physics and detector simulations as well as detector R&D. While several laboratories worldwide have beams capable of producing the required $> 10^{13}$ η/yr, the ESS is the preferred option for hosting REDTOP. The ESS can provide either a proton or pion beam with the adequate energy and intensity. The use of a pion beam would reduce the background by more one order of magnitude, thereby enhancing sensitivity to New Physics.

Beam delivery and experimental hall A feasibility study is underway to analyze the beam delivery system and experimental hall for REDTOP at the ESS. The envisioned scenario includes: a) a 2.86 ms proton pulse at 14 Hz from the ESS linac, b) a nominal ESS beam current of 50 mA, of which REDTOP would require only 0.015 μA, corresponding to an average beam power of 0.03 kW, c) extraction of the pulse from the ESS linac near its endpoint and transport to the REDTOP target via a transfer line.

There are two possible modes of operation. The first option is to utilize a 1.8 GeV proton beam directly to produce the η/η' particles from the decay of intra-nuclear resonances. Already in year 2026, such a proton beam would be available. The second option is to use a 1.8-2.0 GeV proton beam to produce a ≈830 MeV pion beam in a primary target. These pions would be focused by either a van der Meer horn or a direct-current focusing device [Koetke, Simion] and be used to produce η/η' in a secondary target. A 1.8 GeV proton beam can be available at ESS in 2030.

Physics and detector simulations The two software frameworks used for the sensitivity studies [WHITEPAPER2022] are *GenieHad* and *slic-lcsim*. They allow allow an almost full simulation of the experiment and have been used in two Montecarlo campaigns. Details are provided in the addendum.

Detector R&D Almost all REDTOP sub-detectors utilize state-of-the-art technologies that are already under development for new experiments or upgrades of existing ones. The only exceptions are the electromagnetic and hadronic calorimeters, as multiple-readout calorimetry has not yet been implemented in an experiment. Intense R&D is currently ongoing in both the U.S. and Europe on the ADRIANO2 and ADRIANO3 calorimeters. As a result, R&D efforts for the tracking detectors and CTOF are relatively minor, focusing primarily on optimization for REDTOP.

The target system does not present any particular challenges, given its small dimensions and the low power dissipation required [TARGET].

VI. TIMELINE

As noted in Sec. V, most of the detector technologies adopted for REDTOP are already under development and require only modest R&D efforts. However, substantial effort is still needed for the technical design of the experiment. In both cases, project funding must be secured before moving forward. Therefore, the official start date of the REDTOP initiative will be determined once all necessary Detector R&D and engineering design funds are established for the participating institutions.

Assuming a project start date of January 1, 2026, a preliminary timeline for the R&D, construction, and operational phases is presented in Fig. 2.

Key Milestones:

- Detector R&D (except for the trigger system) will be completed within two years.
- Engineering and technical design will take approximately three years.
- Detector prototyping, construction, and assembly will span four years.
- Commissioning will require one year, during which short beam periods at increasing intensity will be requested from the hosting laboratory.
- Physics runs will follow, with their duration depending on beam availability.

Long-Term Outlook In total, the REDTOP project will require a little over a decade for full realization and exploitation. However, with subsequent upgrades, REDTOP has the potential to deliver a decades-long physics program, providing continuous scientific opportunities well into the future.

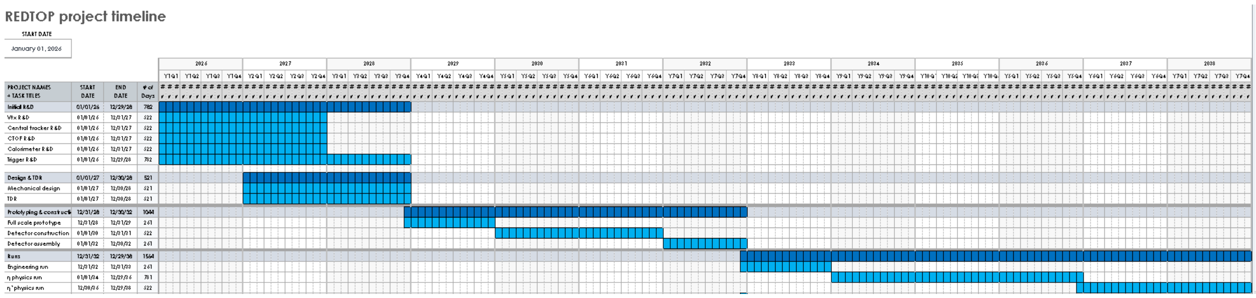

Figure 2. REDTOP R&D, construction and operation timeline

Table III. REDTOP cost estimate.

Component	M$ [Y2023]
Target+beam pipe	0.1
Vertex detector	2.1
LGAD tracker	22.5
Calorimeter	22.5
CTOF	0.75
Solenoid	0.3
Supporting structure	1.3
Hardware trigger	2.4
DAQ+L2 trigger	1.1
Computing	0.4
Contingency 100%	53.5
Total REDTOP	**107**

VII. COSTING

Design and construction costs The optimization of the detector design is progressing steadily, benefiting from the availability of a nearly full simulation and reconstruction framework. As a result, only an approximate cost estimate is available at this stage of the project.

The cost of electronic components and sensors (SiPMs, ASICs, LGADs, etc.) is based on 2023 vendor quotes. Several REDTOP subsystems are based on the same technology and design as existing detectors or their upgrades, for which detailed cost estimates are available. In such cases, REDTOP costs are estimated by appropriately scaling those figures, including adjustments for inflation.

Contingency is included in the estimate; however, labor costs are not. A detailed breakdown of individual component costs is provided in Appendix I. A summary of the total cost of REDTOP is summarized in Table III. Details can be found in the addendum.

Operating costs We assume that the costs for operating the detector and the accelerator and of delivering the beam to the experiment are entirely covered by the hosting laboratory. Other operating costs for the experiment consist mainly in the permanent storage of the offline data at hosting laboratory, which will be covered by the experiment. The estimate for the 9 PB/year required by REDTOP is ∼0.2 MEu/year.

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