REDTOP: Rare Eta Decays TO Explore New Physics

Back-up document

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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. 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 the 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. SUMMARY OF REDTOP KEY POINTS

Laboratories with high intensity proton accelerators have a unique opportunity to uncover dark matter or New Physics within a decade through production and study of extremely large η/η' samples.

An η/η' factory is an excellent laboratory for studying rare processes and Beyond Standard Model physics at low energy. There are strong theoretical reasons to search for New Physics in the MeV–GeV range. The η and η' mesons are unique particles since they carry the same quantum numbers as the Higgs (except for parity), and have no Standard Model charges. Their decays are flavor-conserving and most of them forbidden at leading order (in various symmetry-breaking parameters) within the Standard Model. New Physics must, also, be neutral under Standard Model charges: its production from the decay of the η and η' mesons would occur without Standard Model charged currents, opposite to the case of heavy flavor mesons. Rare decays are therefore enhanced compared to the remaining flavor-neutral mesons.

A sample of order $10^{14}(10^{12}\ )$ η/η' mesons can address most of the recent theoretical models. Such an experiment would have enough sensitivity to explore a very large portion of the unexplored parameter space for all the four portals connecting the Dark Sector with the Standard Model. Lepton Universality and the CP and T symmetries can also be probed with excellent sensitivity. Many other studies can be conducted with such a large data sample, including, for example, the determination of the η form factors, which is crucial to understanding the $(g-2)_\mu$ measurement. For example, it was recently pointed out [MartinCamalich:2020dfe, Bauer:2021mvw, Guadagnoli:2025xnt] that meson decays such as $K \to \pi\nu\bar{\nu}$ and $K \to \pi\pi\nu\bar{\nu}$ can impose significant constraints on 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. For instance, the $K^+ \to \pi^+\nu\bar{\nu}$ decay sets a limit on the coupling-rescaled f_a, denoted as $(F_V)_{23}$ [MartinCamalich:2020dfe] (see also [Bauer:2021mvw, MartinCamalich:2025srw]), reaching up to 1.1×10^{12} GeV [Guadagnoli:2025xnt].

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 similar studies. 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.

The REDTOP Collaboration is proposing an η/η' factory. No similar experiment exists or is currently planned by the international scientific community. The accelerator complex available presently at GSI and the experimental infrastructure fulfill all requirements to achieve the proposed research program. Furthermore, the capabilities will be boosted once the new accelerator facility FAIR is taken into operation.

A detailed detector simulation and reconstruction has been implemented to study several processes driven by New Physics, and many theoretical models have been benchmarked. About 5×10^{10} background events have been generated and fully reconstructed to estimate the sensitivity of REDTOP. This took over three years to complete and required about 4×10^7 core-hours of computing on the Open Science Grid.

The Physics case for REDTOP is fully presented in a White Paper presented submitted to the Snowmass 2022 process [WHITEPAPER2022].

II. THE REDTOP COLLABORATION

The REDTOP Collaboration has been developing since 2015 and currently includes 138 members from 62 institutions. A list of participating scientists can be found at the beginning of this addendum.

III. MONTECARLO SIMULATIONS

The two software frameworks used for the sensitivity studies [WHITEPAPER2022] are *GenieHad* and *slic-lcsim*.Both frameworks have been in development for over twelve years, are robust and mature, and include all aspects of digitization and reconstruction. These include charged track fitting in a magnetic field, using either a Kalman filter or a circle-fitting algorithm. The only missing component is a realistic pattern recognition algorithm, for which, information from Monte Carlo truth is used. At this stage, this does not significantly affect the reliability of our results.

The most critical aspect of the background estimation lies in the generation of primary interactions between the proton beam and nuclear matter. There are currently no experimental data available for the scattering of 1.8 to 3.5 GeV protons on lithium or beryllium. As a result, simulations rely heavily on nuclear models, which are known to have important uncertainties at the energy range relevant for REDTOP. To partially mitigate this limitation, we have implemented the *GenieHad* event generator framework [GenieHad], which follows a methodology similar to that used by the Intermediate Energy Physics Community. Currently, eleven nuclear scattering models have been implemented: Smash, DMPJET3, Incl++, Urqmd, PHSD, Gibuu, Jam, Achilles, Geant4 nuclear models, exclusive decays (via Gibuu LUT), and Intranuke allowing comparison of simulations with different models. Clusterization, de-excitation, and evaporation of nuclear remnants are also modeled using state-of-the-art simulations such as Abla++, Abla7, Gemini, and SMM.

IV. INTERESTED COMMUNITIES

The primary goal of the REDTOP experiment is to search for physics beyond the Standard Model (BSM) in the MeV-GeV energy range using next-generation tracking and calorimetric techniques. Particular emphasis is placed on the exploration of Light Cold Dark Matter and the violation of fundamental symmetries.

Additionally, the large sample of η/η' mesons collected enables non-BSM studies with unprecedented precision. As a result, the REDTOP experiment is of interest not only to the High Energy Physics (HEP) community but also to research groups focused on developing nuclear and HEP detectors for high-intensity beam experiments.

The triple-readout technique employed in REDTOP can also be leveraged for high-precision, compensating hadronic calorimetry, with potential applications in future high-energy colliders. Furthermore, the technique of directly coupling a light sensor to Pb-glass and plastic tiles can be extended to medical imaging and hadron therapy, where costly crystal-based radiation monitoring could be replaced by an ADRIANO2 module.

V. COSTING

The following sections provide some details on the cost estimation method for the various components of the experiment. Table III of the main document summarizes the cost estimate. The total expected cost including contingency is about $80M.

V.A. Solenoid

The Collaboration intends to re-use the Finuda magnet[Bert99], currently stored at the *Laboratori Nazionali di Frascati* of INFN. A cost of about \$0.3M has been estimated for refurbishing the Dewar vessel, dismantling and shipping the cryostat and the return yoke. Cryogenics (cooler+power supply) is expected to be available at the hosting laboratory.

V.B. Supporting structure

The entire detector will be enclosed in a 1 cm thick, cylindrical steel supporting vessel, held inside the solenoid by two longitudinal rails. The cost of the vessel and the fixtures, including engineering, has been estimated at about \$1.3M.

V.C. Target systems and beam pipe

Beryllium foils with a sub-mm thickness are commercially available at modest cost ($\sim$ \$1k) [BEFOIL]. Laser-cutting the foil to the correct shape and size is also handled by commercial firms already serving GSI. Installing the foils inside the beam pipe can be handled by GSI Target Laboratory. The total estimated cost for engineering, components and manufacturing has been conservatively assessed to be no more than \$0.1M

V.D. Vertex detector

The cost of the REDTOP vertex detector is derived from the Mu3e pixel tracker by scaling the sensitive surfaces of the two experiments, since sensors, readout electronics and the mechanical structures are the same. Assuming that an existing sensors can be used, the estimate costs of that component is about \$120 per cm^2 active area [MU3ERP2012]. This value includes several readout-flexes, HV, LV and data-cables, connectors, and HV and LV supplies and interfaces PCBs. We note that this value is smaller compared to ATLAS ITK pixel, mainly due to savings of the interconnects. Scaling this price to REDTOP's vertex detector area results in a cost of about \$250k, which we double to take into account eventual R&D. We conservatively assume that dedicated sensors need to be developed for REDTOP. This is because the Mupix11 sensors used by Mu3e have a continuous readout and no trigger buffers. If a triggered readout is required, a new sensor needs to be produced. Each engineering run costs about \$200k, which we are conservatively including in the current cost estimate (two runs). In Mu3e a new and innovative gaseous helium cooling system is used which can deliver 50g/s at -20^{o}C. Preliminary engineering considerations indicate that a flux of 10g/s would be sufficient for REDTOP, considering the smaller area which needs to be cooled down. Based on the Mu3e experience, the cooling system for REDTOP will cost about \$400k, including the chiller, heat exchangers, turbo pumps and pipes. In total, we estimate a cost of about \$2.1M for the design and construction of the vertex detector.

V.E. Central tracker

The LGAD tracker is based on the technology under development for the Endcap Timing Layer (ETL) of the CMS experimenty [LGAD2020]. The sensor, readout chip, and powering cost is based on a recent (2022) report on that project to the CMS institutional board, scaled by the ratio of the surface areas (9.4/7.9). Carbon fiber (thermal pyrolitic graphite) is proposed for the mechanical structure due to its thermal transport properties, stiffness, and low contribution to the material budget. The cost estimate for it is based on the costs for the CMS pixel endcap upgrade for the HL-LHC and scaled to the area of this detector. The layout and dimensions in the case of REDTOP is such that an active cooling can be replaced by passive cooling. In total, we estimate a cost of about \$22.5M for the design and construction of the central tracker.

V.F. ADRIANO2(3)

The granularity of ADRIANO2(3) calorimeter is very similar to that of the HGCAL of CMS and readout electronics are the same. The costing of the latter is, therefore, used as a template for REDTOP. The mechanical structure of the calorimeter is scaled by the total volume of the two subdetectors (8.6 m^3 vs 14 m^3). The water cooling adopted by REDTOP is substantially cheaper than the dual-phase system designed for CMS's HGCAL. Its cost is estimated separately. The cost of the scintillating tiles, the readout, power and slow control systems are obtained by scaling CMS HGCAL by the total number of readout channels (1.15x10^6 vs 6.24x10^6)[CERN-LHCC-2017-023, BARNEY2018]. The SiPM's for REDTOP are provided by a different vendor (Broadcom rather than Hamamatsu) and are costed based on an actual quote from the vendor.

The cost per m^2 for the thin-RPC system is obtained from the large-scale CALICE Digital Hadron Calorimeter (DHCAL) prototype [DHCAL]. The estimate (corrected for the inflation) includes also the readout and the slow control systems. In total, we estimate a cost of about $22.5M for the design and construction of the calorimetr systems.

V.G. Čerenkov TOF (*CTOF*)

The cost of the *CTOF* has been scaled from the BTL system of the CMS upgrade. The tile material adopted by REDTOP is less expensive than CMS' BGO, and has been costed separately. The cost of the mechanics is scaled based on the surface of the detector ($\sim$ 2.9 m^2 vs $\sim$ 38 m^2), while the readout electronics, power and, services are scaled by the number of readout channels ($\sim$ 13,600 vs $\sim$ 331,776). In total, we estimate a cost of about $0.75M for the design and construction of the vertex detector.

V.H. Hardware Trigger

The L0 and L1 of the trigger systems are implemented completely in hardware and receive input from the calorimeter and tracker back-end electronics board. The cost estimate for REDTOP trigger system is still in progress. We conservatively assume a cost of $2.4M for this subsystem.

V.I. DAQ and L2 trigger

The DAQ and the L2 trigger systems consist almost entirely of computing equipment, purchased when needed. The same strategy is used by CMS's Phase-II upgrade. A cost of $0.3M is quoted for the DAQ system. Therefore, the cost estimate for REDTOP DAQ system is obtained by scaling the data throughput of the two experiments (0.9 GB/s vs 61 GB/sec). The value obtained is inflated by 30% to compensate for non directly scalable components.

The cost of the L2 trigger is consistent with an independent estimate for the 2000 CPU receiving data from the L1 trigger. Since network requirements are not stringent, a 10G machine is sufficient. A conservative estimate for 20, dual socket 32 core EPIC AMD with "*hyperthreading*", equipped with 128 processors, each with 2 GB of memory and an SSD, stands at about $ 0.4M. These have 28% more computing power than needed, which can be used as backup or for the reconstruction /analysis of the data. An additional $ 0.4M would cover the cost of networking/infrastructures, for a total of $ 0.8M for the L2 trigger.

In summary a total cost of $ 1.1M has been estimated for the DAQ and L2 trigger systems.

V.J. Offline computing

Reconstruction of the raw data and Montecarlo simulation require $\sim 60,000$ CPU's. Approximately 80% of them will be accessed in oppurtunistic mode (i.e., at no cost) from the OSPool. The remaining will reside at the collaborating institutions. We conservatively assume that about 3/4 of them (namely, $\sim 9,000$) already exists as part of the computing centers of the collaborating institutions. Only $\sim 3,000$ would need to be purchased. The estimated cost is of order of $400,000.

V.K. Contingency

A contingency factor of 100% is included in the present cost estimate because of the early design stage of the subsystems.

Table III of the main document summarizes the cost estimated the subsystems discussed above. The total expected cost, including contingency, is about $ 107M.

V.L. Cost reduction

Along with the optimization of the detector layout, the Collaboration is exploring alternative solutions to reduce the overall costs of the experiment. The largest contributions to the cost of REDTOP (cfr. Table III of the main document) correspond to the sensors for the Optical TPC and ADRIANO2, the front-end electronics and the back-end electronics of ADRIANO2. While the number of SiPM's reading each 10cm x 10cm tile cannot be reduced (or made smaller) without a proportional reduction in light-yield, we are considering techniques for ganging multiple tiles. This technique will reduce the number of read-out channels and the load on the L0 trigger. Passive and active ganging is rapidly becoming a cost-cutting resource in the latest large area detectors. The radial granularity of ADRIANO2 could easily support ganging multiple tiles of the same kind (i.e., glass or plastics), without loosing particle identification power. Studies have been planned to explore the effects of SiPM ganging on event pile-up, shower separation and muon-polarization measurements. A cheaper alternative (SiPM) is being considered for the sensors of the Optical-TPC. Studies are ongoing to verify if the, intrinsically noisier, SiPM's could be a valid replacement for the LAPPD.

VI. DETAILS OF DETECTOR R&D

This section provides a detailed discussion of the current status of R&D for each sub-component of the experiment, along with an estimate of the remaining effort required.

VI.A. Target

The beryllium target system requires thin foils, which are commercially available from multiple vendors at relatively low cost. Cutting is performed by specialized companies that have already been identified. Therefore, minimal R&D is required for this target option. More complex target options, such as lithium foils or gaseous/liquid deuterium, demand substantial R&D. However, this can be conducted in parallel with the detector development.

VI.B. Vertex detector

As previously discussed, the vertex detector will use the same technology developed for the Mu3e Phase-1 pixel tracker, whose requirements and surface area are similar to those of REDTOP [ARNDT2021165679]. Some R&D will be required to adapt the 6 ns timing resolution of the latest MuPix sensor to an environment with an average interaction rate of approximately $\simeq 500 - 700MHz$ and a different detector layout. Given the low average charged particle multiplicity ($\simeq 3.8$) and the small size of the MuPix pixel, we anticipate that any event pileup due to inadequate readout speed can be resolved during event reconstruction. The required R&D effort is modest, and we are confident that it can be completed within two years.

VI.C. Central tracker

The central tracker will benefit from R&D efforts conducted for the timing layers of the CMS and ATLAS HL-LHC upgrades. The required timing performance of 30 ps/layer has already been demonstrated. However, meeting the material budget requires either eliminating active cooling or displacing it from the detectors, which must be verified.

Key areas of study include:

- Optimizing the power consumption of both sensors and Read-Out Chips (ROC).
- Optimizing the thermal design and the materials for the support structure, leveraging the extensive work done on the carbon-fiber CMS pixel upgrade.
- Evaluating whether the ETROC can be used "as is" for REDTOP or if modifications are needed to reduce power consumption and accommodate the expected event rates.

VI.D. Cerenkov Time of Flight ($CTOF$)

The core technology for the CTOF is currently being developed by the T1604 Collaboration and Tsinghua University. The estimated R&D effort is modest and should be completed within two years.

Key progress so far:

- The desired timing resolution has been achieved using a Waveform TDC (Sampic).
- All key components have been identified.

Remaining R&D efforts focus on:

- Development and design of the mechanical structure.
- Adapting ETROC-based readout electronics designed for the CMS Endcap Timing Layer, whose timing requirements are more stringent than those of REDTOP.

Recent results from a test beam indicate that the quartz tiles considered for the CTOF achieve the required performance in terms of light yield and timing resolution. Detectors with a layout similar to the $CTOF$ have been built for various experiments in the past (for example, the tile detector of Mu3e). Given the relatively small size and weight of the device, we do not expect major challenges regarding the mechanics.

Some effort is, however, expected to design the connections between the flexprint, the SiPM's, and the ASICs on the readout board. The ETROC is currently designed to operate at 325 MHz, which is very close to the event rate foreseen at REDTOP. Simple tests would be needed to confirm if the speed of the chip can be extended further or if the ASIC requires minor modifications.

VI.E. Electromagnetic (ADRIANO2) and Hadronic (ADRIANO3) Calorimeters

Extensive R&D on dual-readout calorimetry has been conducted over the past twelve years by the T1015 and T1604 Collaborations at Fermilab. Hybrid RPCs for ADRIANO3 have undergone significant R&D by Beykent University and University of Iowa under the CALICE research program [CALICE]. Progress on the development is summarized below:

- Multiple ADRIANO2 prototypes have been constructed and tested in beam experiments.

- The scintillation component utilizes tiles similar to those in the CMS HGCAL, requiring no further R&D.
- The largest ADRIANO2 prototype to date (63 tiles, seven layers) has been built. A 12-layer version (192 cell pairs) is under construction and scheduled for beam testing in mid-2024.
- Thin RPCs fully functional and demonstrate excellent efficiency.

Remaining R&D efforts:

- Doping of thin RPC glass with gadolinium.
- Determining the optimal number of SiPMs per tile (single vs. quad-ganged).
- Validating the performance of the full readout chain once a front-end board becomes available from the manufacturer (OMEGA).

Recent results from the test beam indicate that several ADRIANO2/3 tiles configurations achieve or exceed the required performance in terms of light yield (30 pe/MIP) and timing resolution (80 ps). We anticipate that the above activities can be completed within two years. Additionally, recent advancements in hybrid RPCs by Beykent University [HybridRPCs] offer potential improvements in operational conditions and sensitivity to lower-energy particles. Further R&D is required to assess feasibility for REDTOP, which we estimate will take approximately two years.

VI.F. Trigger

The current trigger architecture proposed for REDTOP was designed by CMS experts and validated through extensive tests at Fermilab. Due to the critical role of this component, a conservative estimate for completing REDTOP trigger system R&D is three years.

Level-0 The trigger logic must be fine-tuned to accommodate the specifications of the HGCROC3 chip, which is integral to the calorimeter readout. This will involve:

- Multiple tests.
- Construction of a demonstrator to verify compliance with REDTOP requirements.

Level-1 A CMS Phase II Level-1 tracking trigger demonstrator has successfully shown that:

- Ten FPGA-based processors in a single ATCA crate, operated in time-multiplexing mode, can process event rates of 40 MHz from a unit corresponding to 1/48 of the CMS tracker.
- Each unit handled 500 hits across 400 fibers while reconstructing all tracks with P_t >3 GeV/c at high efficiency and within a few microseconds of latency.

The expected event rates and computational complexity for REDTOPâs Level-1 trigger are comparable to these CMS tests.

Level-2 The Level-3 trigger will be implemented entirely in software. Its final design can be completed at a later stage in the technical development of the experiment. Several algorithms are currently being tested as part of ongoing sensitivity studies.

VI.G. Conclusion

Most sub-systems of REDTOP leverage existing technologies and prior R&D, allowing for modest additional development efforts. The estimated completion times for key RD components are:

- Vertex detector: < 2 years.
- Central tracker: Dependent on validation of cooling and power requirements.
- CTOF: < 2 years.
- Calorimeters: 1 year for SiPM optimization and readout validation; 1 year for hybrid RPC assessment.
- Trigger system: 3 years.

These timelines suggest that the necessary R&D can be completed within a reasonable time-frame, positioning REDTOP for a successful transition to full-scale implementation.

VII. COMPUTING REQUIREMENTS

The REDTOP computing model is discussed in detail in Ref. [COMPUTING2022]. Based on the computing resources currently utilized on the Open Science Grid (OSG) for sensitivity studies, we estimate that raw data reconstruction and Monte Carlo simulations will require approximately 40 million CPU-hours per month. We anticipate that about 80% of this computing power will come from opportunistic use of the OSGPool (at no additional cost), while the remaining 20% will be provided by dedicated CPUs at REDTOP-affiliated institutions, federated with the national OSPool.Approximately three-quarters (12,000 CPUs) of these dedicated resources already exist at participating institutions' computing centers. The remaining 3,000 CPUs will be acquired if necessary when the experiment becomes operational, as part of the project costs.

The expected annual data volume of $\simeq 9PB/year$ can be accommodated within the existing disk and tape storage infrastructure at the hosting laboratory.Additionally, when not in use, the 2,000 CPUs dedicated to the Level-2 trigger, along with 560 spare CPUs from EPIC, can be leveraged to partially support computing tasks. Once processed, the data will be transferred to the central computing center of the hosting laboratory for storage and analysis.

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