REDTOP
The η/η' factory

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The present documents summarizes the physics and detector studies for REDTOP proposal to the hosting laboratory. Four sets of such studies have been identified:

1. Basic physics studies;
2. Physics studies with event pileup;
3. Detector performance;
4. Trigger performance.

A rough estimate of the total effort required is 6.5 FTE. A break-up of the manpower needed for each task is also presented. The estimate of such effort is based upon the assumption that the proposal will be submitted in December 2017.

1 Basic physics studies. Total estimated effort: 1.5 FTE

These studies are intended to investigate the sensitivity of REDTOP for the three golden processes we have selected. Given the relatively short time to prepare the proposal and the novelty of the detector technologies, a full reconstruction of the event (pattern recognition + fit to extract the track/shower parameters) is probably not realistic. Instead, we can obtain the 4-momentum of the particle from the Montecarlo truth and smear the latter using either a gaussian or an educated guess. In any case, we will be analyzing the event after the latter has been processed by *Geant4* (rather than using the bare primary particles, as generated by *GenieHad*). The former contains, indeed, all the secondary particles being produced in the detector by the interaction of the primaries with the matter therein. On the contrary, *GenieHad* events only contains the particles produced from the primary interaction of the proton beam with the target nuclei.

1.1 CP violation from the Dalitz plot asymmetry in $\eta \to \pi^+\pi^-\pi^o$. Estimated effort: 0.5 FTE

The observable for this channel is (see also eq. (14) in S. Gardner and J. Tandean: "Observing Direct CP Violation in Untagged B-Meson Decays", https://arxiv.org/pdf/hep-ph/0308228v2.pdf)

$$A_{3\pi} = \frac{\Gamma_{3\pi}(s_{+0} \geq s_{-0}) - \Gamma_{3\pi}(s_{+0} \leq s_{-0})}{\Gamma_{3\pi}(s_{+0} \geq s_{-0}) + \Gamma_{3\pi}(s_{+0} \leq s_{-0})} \tag{1}$$

The asymmetry espressed in Eq. (1) needs to be studied as a function of:

1. Momentum and energy resolution of the three pions;
2. Uncertainty in the determination of the primary vertex of the event;
3. A fake pion passing the requirement that the products of the η decay have a common vertex.

The momentum and energy resolution can be approximated with a gaussian or an educated smearing of the true values (from Montecarlo truth). The uncertainty on the reconstruction of the primary vertex, similarly, can be approximated using a gaussian distribution. Different values of the smearing parameters should be used in order to investigate how sensitive observable (1) is to the the detector response. Fake pions originate, in the most cases, from one of the following sources:

1. A primary pion generated from the interaction of the proton beam with the target;
2. A pion that *Geant4* generated from the interaction of particles with the detector matter;
3. A mis-identified muon.

1.2 Search for a scalar meson H in $\eta \to H\pi^o \to e^+e^-\pi^o$ and $\eta \to H\pi^o \to \mu^+\mu^-\pi^o$. Estimated effort: 0.5 FTE

The observable in this channel corresponds to the invariant mass of the lepton pair (see also M. Pospelov et al.: "Bosonic super-WIMPs as keV-scale dark matter", https://arxiv.org/abs/0807.3279v4).

The latter needs be studied as a function of:

1. Momentum and energy resolution of the three final state particles;
2. Uncertainty in the determination of the primary vertex of the event;
3. A fake pion passing the requirement that the products of the η decay have a common vertex.
4. Fake lepton passing the requirement that the products of the η decay have a common vertex.

As for the case discussed in Sec. 1.1, the momentum and energy resolution can be approximated with a gaussian or an educated smearing of the true values (from Montecarlo truth). The uncertainty on the reconstruction of the primary vertex can, also, be approximated by a gaussian distribution. Different values of the smearing parameter should be used in order to study the uncertainty on the reconstructed invariant mass of the $lepton - antilepton$ pair as a function of the detector response.

Fake leptons originate, mainly, from one of the following main sources:

1. A primary lepton from the interaction of the proton beam with the target;

2. A lepton generated from the interaction of a particle in the event with the detector matter (for example, an electron back-splash from the calorimeter);

3. A mis-identified lepton in either the O-TPC or ADRIANO.

A fake π^o could feed in the reconstruction from one of following main sources:

1. A primary π^o from the interaction of the proton beam with the target;

2. A photon or π^o generated from the interaction of one of the particles in the event with matter ;

3. A wrong photon from combinatorics in ADRIANO;

4. A particle mis-identified as a photon in ADRIANO..

1.3 Search for a 17 Mev vector gauge boson X in $\eta \rightarrow X\gamma \rightarrow e^+e^-\gamma$ or for a dark photon A' in $\eta \rightarrow A'\gamma \rightarrow e^+e^-\gamma$. Estimated effort: 0.5 FTE

The observable in these channel is the invariant mass of the lepton pair (see also J. Feng et al.: "Evidence for a Protophobic Fifth Force from ^{8}Be Nuclear Transitions", https://arxiv.org/abs/1604.07411).

The latter should be studied as a function of:

1. Momentum and energy resolution of the three final state particles: $e^+e^-\gamma$

2. Uncertainty on the determination of the primary vertex of the event;

3. Fake gammas in the calorimeter.

4. Fake electron/positron surviving the requirement that the products of the η decay originate from a common vertex.

As for the case discussed in Sec. 1.1, the momentum and energy resolution can be approximated by a gaussian or by an educated smearing of the true values (from Montecarlo truth). The uncertainty on the primary vertex is, also, approximated using a gaussian distribution. Different values of the smearing parameters needs to be used in order to study the uncertainty on the reconstructed invariant mass of the e^+e^- pair as a function of the detector response.

Fake electron/positron mainly originate from one of the following sources:

1. A primary electron from the interaction of the proton beam with the target;

2. An electron produced in the interaction of one of the particles with matter (for example, an electron back-splash from the calorimeter or a delta-ray in the O-TPC);

3. A mis-identified electron and/or positron in either the O-TPC or ADRIANO.

A fake $\gamma's$ originate, in most cases, from one of the following sources:

1. A primary photon from the interaction of the proton beam with the target;

2. A photon generated from the interaction of one of the particles in the event with matter;

3. a bremmstralung photon;

4. A wrong or mis-identified photon from combinatorics in ADRIANO.

1.4 Montecarlo dataset

The Montecarlo data for the studies discussed above have been already generated with *GenieHad* and processed with *Geant4*. They are available for download at the following address:

ftp://t1015-svn.fnal.gov/U0/v4.1/slcio/

The filename of the files therein reflects the underlying physics process according to the following table:

Physics process	filename
$\eta \to \pi^+\pi^-\pi^o$	redtop.1800mev.v41.eta3pi.###.slcio
$\eta \to H\pi^o \to \mu^+\mu^-\pi^o$.	redtop.1800mev.v41.eta2pi0hmumu.###.slcio*
$\eta \to H\pi^o \to e^+e^-\pi^o$	redtop.1800mev.v41.eta2pi0hee.###.slcio*
$\eta \to X\gamma \to e^+e^-\gamma$	redtop.1800mev.v41.x17.###.slcio
$\eta \to A'\gamma \to e^+e^-\gamma$	redtop.1800mev.v41.hphch.###.slcio

* still in production

2 Physics studies with event pile-up. Total estimated effort: 1.0 FTE

These studies will investigate the effect of event pile-up (mostly, inelastic scattering of protons from the beam onto the target) on the physics at REDTOP. They will be carried over identically to those described in Sec. 1, the only difference being that the dataset is obtained by merging one signal event with multiple background events. Since, in the basic physics studies, the uncertainty on the observable is determined using the Montecarlo truth, only the effect of combinatorics (fake particles feeding in the signal) will contribute to the resolution. Consequently, the effort in performing the studies with event pileup would require only a fraction of the effort as compared to the basic physics study. A rough estimate of the former is about 0.2 FTE per each of the five channels considered.

The dataset for the studies in this category will be available approximately by the end of March 2017. The files will reside on the usual ftp server.

3 Detector performance. Total estimated effort: 2.0 FTE

The studies in this category are intended to determine the resolution and efficiency of each subdetector in REDTOP. They will be conducted using *Geant4*-generated, single particle events. Consequently, the effect of pattern recognition will not be taken into account at this stage of the simulations and studies aiming at determining the reconstruction efficiency will be deferred to a later time.

3.1 Optical-TPC. Estimated effort: 1 FTE

The pattern of Sipm's turned on by a charged particle above Cerenkov threshold is different for the different particle species. In all cases, though, two rings will be present, generated by the optical photons radiated from each of the two layers of aerogel at the inner wall of the O-TPC. The center of the ring and the skewness of the ellipse will provide information on the direction of the original particle. The radius of the ellipse will provide the particle's velocity, whenever the latter is below the plateau of the Cerenkov curve (as is the case for muons and pions). Electrons will also generate a complex pattern when they radiate in the gas of the chamber, as a consequence of the helical path they follow in the magnetic field. Most of the effort in evaluating the performance of the O-TPC will be spent in the determination of an algorithm capable of extracting the track parameters from an ellipse and from the pattern generated by the electrons. The main difficulties come from the fact that the Sipms's are located on a twelve-sided barrel and on the two endcaps. The three tasks being identified for this group of studies are summarized below:

- Determine an algorithm to extract the track direction and position in space, as well as the velocity for particles with velocity below the plateau;
- Determine an algorithm to extract the track velocity of electrons and positrons;
- Study the uncertainty of the track parameters by artificially smearing the position of the hits.

3.2 ADRIANO calorimeter. Estimated effort: 0.5 FTE

ADRIANO was studied extensively by T1015 Collaboration. Consequently, most of the software required for reconstruction and analysis of showers in such a detector is already available in *ilcroot* and *lcsim*. The main difference in REDTOP is in the fact that the Muon Polarimeter (MUPOL) is embedded in ADRIANO, taking away some of the energy of the shower. Consequently, most of the effort required for the studies on the performance of ADRIANO are related to extending the existing code to REDTOP layout. The three tasks required are summarized below:

- Add MUPOL the the existing ADRIANO reconstruction software;
- Determine the energy resolution for single particles;
- Determine particle identification efficiency and contamination for single particles.

3.3 Muon polarimeter. Estimated effort: 0.5 FTE

The Muon Polarimeter, as in the present version of the detector, consists in an array of scintillators aiming at reconstructing the direction of the electron from the decay of a muon. The transverse and longitudinal polarization of the muons are determined statistically from the left-right and forward-backward asymmetry of that decay inside a magnetic field. In principle, the algorithm for these studies is not overwelmingly difficult to implement. However, nothing exists at present either in *lcsim* nor in *ilcroot*. Consequently, most of the effort in this category of studies will be devoted to implementing the reconstruction of the Michel electron in MUPOL software. The two tasks related to the studies on MUPOL performance are summarized below:

- Implement an algorithm to reconstruct the direction of a Michel electron in MUPOL;
- Determine the polarization resolution for single muons consequent to a gaussian smearing of the electron direction.

3.4 Montecarlo dataset

The Montecarlo data for the above studies has been already generated with *Geant4*. That corresponds to single particles in the x-z plane, isotropically distributed with $10^o < \theta < 90^o$. The particles in each file are mono-energetic. They are available for download at the following address:

ftp://t1015-svn.fnal.gov/U1/v4.1/slcio/

The filename reflects the ID of the generated particle according to the following table. The energy in the filename is the kinetic energy of the particle (what you specify in *Geant4* macros). Due to the quirks in setting the polarization of a particle in *Geant4*, the polar direction of longitudinally polarized muons is fixed at 45^o.

Physics process	filename
single π^-	redtop.##mev.v41.singlepionm.###.slcio
single π^o	redtop.##mev.v41.singlepion0.###.slcio
single unpolarized μ^-	redtop.##mev.v41.singlemuon.###.slcio
single trannsversly polarized μ^-	redtop.##mev.v41.singlemuon_tpol.###.slcio
single longitudinally polarized μ^-	redtop.##mev.v41.singlemuon_lpol.###.slcio
single e^-	redtop.##mev.v41.singleelectron.###.slcio
single γ	redtop.##mev.v41.singlegamma.###.slcio
single p	redtop.##mev.v41.singleproton.###.slcio
single n	redtop.##mev.v41.singleneutron.###.slcio

* still in production

4 Trigger performance. Total estimated effort: 2.0 FTE

The general consensus is that the trigger is the most important component of the REDTOP apparatus, as a consequence of the overwhelming background expected. The studies in this category are intended to determine the background rejection efficiency and the efficiency for retaining the processes of interest. Many insights related to possible trigger strategies for REDTOP come from an in-depth discussion with Luciano Ristori. Those are reflected in the following list of tasks for the proposal. The studies should be performed only on the three golden channels, as discussed in Sec. 1.

4.1 Basic trigger performance. Estimated effort: 0.5 FTE

These studies are based on simple algorithms for rejecting the background, like counting the fired Sipm's in the O-TPC, or the Cerenkov and scintillation cells with signal above a certain threshold in ADRIANO/MUPOL. The discrimination power of basic topological patterns (density of hits/energy in the detector, abundance of hits in certain regions, clusters of hit/energy, etc.) should also be investigated.

4.2 Extended trigger performance. Estimated effort: 1.5 FTE

This task corresponds to the investigation of more complex algorithms for rejecting the background, like searching for specific patterns in the detector (for example, rings in the O-TPC). Considering the high speed (40-50 MHz) and the low latency required for the trigger (of the order of 1 μsec), we need to rely on state-of-the art technologies based on ASICS/FPGA. Expertise in this field is typically available in high intensity experiments (for example, LHC-HL) However, the kind of primitives already available in such implementations are limited and large effort should be expected to perform these studies.

4.3 Trigger performance with event pile-up. Estimated effort: 0.5 FTE

This task would replicate the work described in Sec. (4.1) and (4.2), but the studies will be based on Montecarlo data containing the superposition of either multiple background events or of one signal event with multiple background events.

4.4 Montecarlo dataset

The Montecarlo dataset for trigger studies is the same as for the studies described in Sec. (1) through (3) above. Specialized datasets can be produced and made available upon request.

5 Optional studies

The list of studies discussed in this document should be considered as a minimal set: they reflect the manpower currently available within the collaboration. However, more studies could be performed in case that the collaboration grows larger within the next few months and more help will be made available. Below is a non-exhaustive list of further studies we could possibly include in our proposal.

1. Detector performance with event pile-up. All detector performance studies discussed in Sec. 3 are considered without pileup from background events. Studies with pile-up would add more insight to our understanding of detector performance.

2. Beam background. All events generated with *GenieHad* simulate a proton beam with a fixed energy and a fixed position. Therefore, no provision has been mad to consider more realistic effects like a beam halo, a divergence of particles inside the beam or spourious particles therein (like those eventually produce from the beam strucking the residual gas in the pipe). Given the high intensity of the beam, such studies are worth to be done at one point in the future.

6 Reconstruction and analysis software

At present, two software frameworks are available for the studies above: $ilcroot$ and $lcsim$.

Ilcsim *Ilcroot* is C++ and root based framework. It is very powerful for handling large amount of data, but not flexible as *lcsim*. At present, it runs only on linux computers, either locally or on the OSG. It reads the *GenieHad* generated events in stdhep format. *Geant4* is included in the simulation steps;

lcsim *lcsim* is java based. It is very flexible but not as fast and low-resource as *ilcroot*. It runs on all machines, including laptops, as long as a Java environment has been installed. It reads events in slcio format already being processed by *Geant4*.

A detailed description of $lcsim$, along with instructions for installing and run it, is available on REDTOP web site, at the following link: http://redtop.fnal.gov/lcsim-reconstruction-framework/

Similar instructions for *ilcroot* are in preparation and will be available shortly.