Invariant mass reconstruction of the $\eta$ meson in the decay channel $\pi^+\pi^-\pi^0$ with the REDTOP experiment

S. D. Escobar Martínez$^{1,2}$, B. Fabela Enríquez$^{2,3}$, M. I. Pedraza Morales$^2$ on behalf of the REDTOP collaboration

$^1$Universidad Nacional Autónoma de Honduras, Honduras, $^2$Benemérita Universidad Autónoma de Puebla, Mexico, $^3$Universidad Autónoma de Zacatecas, Mexico.

E-mail: sdem2393@gmail.com

Abstract. REDTOP is a novel experiment proposed at the Delivery Ring of Fermilab with the intent of producing more than $10^{13}$ $\eta$ mesons per year to detect possible rare $\eta$ decays which can be a clear evidence of the existence of Physics Beyond the Standard Model. Such statistics are sufficient for investigating several discrete symmetry violations, searching for new particles and interactions and to perform precision studies. One of the golden processes to study is the $\eta \rightarrow \pi^+\pi^-\pi^0$ decay [7], where $\pi^0$ decays promptly into two photons. In the context of the Standard Model, the dynamics of the charged pions is symmetric in this process. Thus, any mirror asymmetry in the Dalitz plot would be a direct indication of $C$ and $CP$ violation. We present a study on the performance of the REDTOP experiment detector by reconstructing the invariant mass of the final state $\pi^+\pi^-\gamma\gamma$ using Monte Carlo samples.

1. Introduction
The Rare Eta Decays with a Time Projection Chamber (TPC) for Optical Photons (REDTOP) experiment is a project in its proposal stage. It intends to produce about $10^{13}$ $\eta$ mesons in one year of running. The $\eta \rightarrow \pi^+\pi^-\pi^0$ decay channel is used to study the performance of the detector based on the smearing of the energy response of the calorimeter.

2. $\eta \rightarrow \pi^+\pi^-\pi^0$ process
The $\eta$ meson is a pseudo-Goldstone boson symmetrically constrained by its QCD dynamics; it is an eigenstate of the $C$, $P$, $CP$ and $G$ operators: $I^GJ^{PC} = 0^+0^{-+}$. Thus, the $\eta$ meson can be used to test $C$ and $CP$ invariance and all of its possible main decays are forbidden in lowest order by $P$ and $CP$ invariance, $G$-parity conservation as well as by isospin and charge symmetry invariance.

The $\eta$ decays are mostly constituted by three-body decays; the eta decay to three pions ($\eta \rightarrow \pi\pi\pi$) does not conserve isospin and the partial widths are similar to the second order electromagnetic processes. However, the contribution of these processes are suppressed and the decays are driven by an isospin violation in the QCD lagrangian proportional to $m_d - m_u$. Thus, it is ideal for testing Chiral Perturbation Theory (ChPT), $CP$ and $C$ invariance.
3. The REDTOP experiment

REDTOP is a high intensity fixed target experiment, which is planned to use a continuous proton beam of 1.8 GeV to produce $\eta$ mesons via the hadronic production from inelastic scattering of protons in beryllium (Be) targets. The target system consists of ten round foils of beryllium; each foil will be of $\frac{1}{3}$ mm thick. The target system will be held inside the beam pipe made of carbon-fiber or beryllium. The expected production of $\eta$ mesons in one year of running is about $2 \times 10^{13}$ $\eta$, considering an average intensity of the beam of $10^{11}$ protons/s.

The Optical Time Projection Chamber (OTPC) is designed to measure the momentum and position in space of a charged track by using a deflecting solenoidal field of 0.6 T. The OTPC is based on the Cerenkov effect instead of the conventional gas ionization; the pattern of Cerenkov light emitted by the particle will be detected by an array of photo-sensors surrounding the radiator (approximately 500,000 SiPM).

The two Cerenkov radiators present in the OTPC are:

- A double aerogel cylinder of about 3 cm of thickness at the inner wall supported by the beam pipe. The innermost aerogel has a refractive index of 1.2 and the outermost has a refractive index of 1.3.
- A low-pressure methane gas filling the rest of the volume of the OTPC. The pressure is adjusted in order for its refractive index to be very close to 1.0.

The OTPC will be only sensitive to muons, electrons/positrons and fast pions, that are generated in the decays of the $\eta$ meson. Hadrons and slower pions will be under the Cerenkov threshold and will not contribute to the recorded hits.

The ADRIANO calorimeter (A Dual-Readout Integrally Active Non-segmented Option) is a dual-readout calorimeter based on the two simultaneous measurements of the energy deposited by a hadronic or electromagnetic showers into two media with different properties. Typically, the first medium is a plastic scintillator; any charged particle will produce a scintillation signal
there. The second medium is a heavy glass with high refractive index and high density where only the charged electromagnetic component of the shower will emit light via the Cerenkov effect; the high density of the medium will be ideal to absorb all the particles impinging the detector.

The Muon and Photon Polarimeters are made from an array of plastic scintillators that will count the number of electron and positrons emitted when a muon is stopped inside the calorimeter or when a photon is converted into a $e^+e^-$ pair. The difference in the counting performed inside the solenoidal magnetic field will provide an estimate of the polarization of the particle.

4. Invariant mass reconstruction of the $\eta$ meson

The Monte Carlo samples with the process $\eta \rightarrow \pi^+\pi^-\pi^0 \rightarrow \pi^+\pi^-\gamma\gamma$ are generated using GenieHad and the decay is processed in the REDTOP experimental configuration using Geant4. The corresponding process is:

$$p + Be \rightarrow \eta X \quad \text{where} \quad \eta \rightarrow \pi^+\pi^-\pi^0$$

(1)

The proton beam energy is of 1.8 GeV and the Ultra Relativistic Quantum Molecular Dynamics (UrQMD) scattering model is used. In this study 4390 events were analyzed. Using the Monte Carlo information of the particles passed through the detector, the $\pi^0$ is reconstructed by summing up the Lorentz vectors of pairs of photons in each event; likewise the $\eta$ is reconstructed adding the 4-momentum vectors of the $\pi^+$, $\pi^-$ and $\pi^0$ in the event. It is important to mention that in a particular event, the presence of $\pi^+$, $\pi^-$ and $\pi^0$ which are not produced by the decay of an $\eta$ meson is possible, and for that reason, we can have more than one combination which does not correspond to a true $\eta$.

Figure 2. Hadronic resolution of the ADRIANO calorimeter in dual readout mode.

To test the performance of the REDTOP detector in this task, a smearing in the energy response of the ADRIANO calorimeter is done, using values based on simulations for the hadronic resolution, that is given by:

$$\sigma_E = \frac{\alpha}{\sqrt{E}} \oplus \beta.$$  

(2)

Here, the values of the $\alpha$ and $\beta$ parameters are varied and the goal is to show the differences on the invariant mass distributions. After obtaining the invariant mass distribution for the $\eta$ meson, a Gaussian fit is performed and the values of the $\eta$ mass and the resolution given by the $\sigma$ of the distribution are calculated using the Java Analysis Studio 3 (JAS3) framework.
5. Results

- Values used for the $\alpha$ and $\beta$ parameters and the obtained $\eta$ invariant mass (and corresponding sigmas) and obtained distributions.

$$\begin{array}{cccccc}
\alpha (\text{GeV}^{1/2}) & \beta & m(\eta) (\text{GeV}) & \sigma m(\eta) (\text{GeV}) & \frac{\sigma m(\eta)}{m(\eta)} (\%) \\
0.050 & 0.030 & 0.556 \pm 0.003 & 0.028 \pm 0.005 & 5.0 \pm 0.9 \\
0.100 & 0.000 & 0.560 \pm 0.005 & 0.044 \pm 0.008 & 7.8 \pm 1.4 \\
0.150 & 0.000 & 0.574 \pm 0.006 & 0.057 \pm 0.006 & 9.9 \pm 1.0 \\
0.191 & 0.040 & 0.579 \pm 0.009 & 0.081 \pm 0.012 & 14.0 \pm 1.9 \\
0.264 & 0.020 & 0.580 \pm 0.013 & 0.117 \pm 0.014 & 20.2 \pm 2.0 \\
0.298 & 0.020 & 0.590 \pm 0.014 & 0.126 \pm 0.014 & 21.4 \pm 1.8 \\
0.333 & 0.022 & 0.572 \pm 0.028 & 0.179 \pm 0.031 & 31.3 \pm 3.9 \\
0.343 & 0.021 & 0.564 \pm 0.033 & 0.194 \pm 0.038 & 34.4 \pm 4.7 
\end{array}$$

Table 1. Values of the invariant mass of the meson and its resolution for each value of the energy resolution for the calorimeter considered.

6. Conclusions and future work

The invariant mass of the meson was reconstructed, smearing on the energy resolution of the ADRIANO calorimeter, the obtained value $m(\eta) = 547.86 \pm 0.02$ MeV agrees with the previous reports[6]. The best energy resolution is achieved when $\alpha < 0.15$. The plan is to increase the statistics, and smear the size of the calorimeter cells and the parameters of the particle trajectories in the OTPC to refine and confirm the results presented here.
Acknowledgments
We thank to the REDTOP collaboration and specially to Joseph Comfort at Arizona State University and Corrado Gatto at INFN sezione di Napoli and Northern Illinois University for their advice and support in the simulation work as well as in the preparation of this poster; to the local organizing committee of the XXXI Annual Meeting of the Division of Particles and Fields of the Mexican Physical Society for providing us the full scholarship to attend the event and present this work.

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