The REDTOP Experiment
Isabel Pedraza for the REDTOP Collaboration
Meritorious Autonomous University Of Puebla, Mexico

Subatomic decay patterns and the Eta Carinae nebula
Kysa Jhonson
REDTOP presented on November workshop for the first time in the PBC.

Since then developments on simulations, detector R&D and CERN accelerators compatibility have been done.

1.8 or 3.5 GeV proton beam under study at the CERN PS. Initial studies for 10^{18} POT. Nevertheless 10^{17} will also allows to provide large sensitivity for physics BSM.
It is a Goldstone boson

It is an eigenstate of the C, P, CP and G operators (very rare in nature): $I^G J^{PC} = 0^+ 0^+$

All its additive quantum numbers are zero (very clean state)

$Q = I = j = S = B = L = 0$

All its possible strong decays are forbidden in the lowest order by P and CP invariance, G-parity conservation and isospin and charge symmetry invariance.

EM decays are forbidden in lowest order by C invariance and angular momentum conservation.

Symmetry constrains its QCD dynamics

It can be used to test C and CP invariance.

Its decays are not influenced by a change of flavor (as in K decays) and violations are “pure”

It is a very narrow state ($\Gamma_\eta = 1.3$ KeV vs $\Gamma_\rho = 149$ MeV)

Contributions from higher orders are enhanced by a factor of ~100,000

Excellent for testing invariances

REDTOP a $\eta - \eta'$ meson factory

$\eta$ factories are excellent laboratories to search for physics Beyond Standard Model
Very rich BSM Physics Program (η and η’ factory)

C, T, CP-violation

- CP Violation via pattern of mirror symmetry breaking asymmetry in the Dalitz plot: \( \eta \rightarrow \pi^0 \pi^+\pi^- \) (New paper from S. Gardner soon on arXiv).
- CP Violation (Type I – P and T odd, C even): \( \eta \rightarrow 4\pi^0 \rightarrow 8\gamma \)
- CP Violation (Type II - C and T odd, P even): \( \eta \rightarrow \pi^0 \ell\ell \) and \( \eta \rightarrow 3\gamma \)
- Test of CP invariance via \( \mu \) longitudinal polarization: \( \eta \rightarrow \mu^+\mu^- \)
- Test of CP invariance via \( \gamma^* \) polarization studies: \( \eta \rightarrow \pi^\pm\pi^\pm e^+e^- \) and \( \eta \rightarrow \pi^\pm\pi^\pm\mu^\pm\mu^- \)
- Test of CP invariance in angular correlation studies: \( \eta \rightarrow \pi^0\mu^+\mu^- \) and \( \eta \rightarrow l^+l^-l^+l^- \)
- Test of T invariance via \( \mu \) transverse polarization: \( \eta \rightarrow \pi^0\mu^+\mu^- \) and \( \eta \rightarrow \gamma \mu^+\mu^- \)
- CPT violation: \( \mu \) polariz. in \( \eta \rightarrow \pi^\pm\mu^\pm \nu \) vs \( \eta \rightarrow \pi^0\mu^+\nu \) and \( \gamma \) polarization in \( \eta \rightarrow \gamma \gamma \)

Other discrete symmetry violations

- Lepton Flavor Violation: \( \eta \rightarrow \mu^+e^- + \text{c.c.} \)
- Double lepton Flavor Violation: \( \eta \rightarrow \mu^+\mu^+e^-e^- + \text{c.c.} \)
- Lepton Flavor universality \( \eta \rightarrow \pi^0 \ell\ell \). \( \eta \rightarrow \gamma \ell\ell \)
Very reach BSM Physics Program ($\eta$ and $\eta'$ factory)

New particles and forces searches

- Scalar meson searches (charged channel): $\eta \rightarrow \pi^0 S$ with $S \rightarrow e^+e^-$ and $S \rightarrow \mu^+\mu^-$
- Dark photon searches: $\eta \rightarrow \gamma A'$ with $A' \rightarrow \ell^+\ell^-$ (considered the PBC benchmark)
- Protophobic fifth force searches: $\eta \rightarrow \gamma X_{17}$ with $X_{17} \rightarrow e^+e^-$
- New leptophobic baryonic force searches: $\eta \rightarrow \gamma B$ with $B \rightarrow e^+e^-$ or $B \rightarrow \gamma \pi^0$
- Indirect searches for dark photons, new gauge bosons, and leptoquark:
  - $\eta \rightarrow \mu^+\mu^-$ and $\eta \rightarrow e^+e^-$
- Search for true muonium: $\eta \rightarrow \gamma (\mu^+\mu^-)_{2M\mu} \rightarrow \gamma e^+e^-$

Other Precision Physics measurements

- Proton radius anomaly: $\eta \rightarrow \gamma \mu^+\mu^-$ vs $\eta \rightarrow \gamma e^+e^-$
- All unseen leptonic decay mode of $\eta / \eta'$ (SM predicts $10^{-6} - 10^{-9}$)
Non-$\eta/\eta'$ based BSM Physics

- Dark photon and ALP searches in Drell-Yan processes: $qq\bar{q} \rightarrow A'/a \rightarrow l^+l^-$
- Dark photon and ALP searches in proton bremsstrahlung processes: $p N \rightarrow p N A'/a$ with $A'/a \rightarrow l^+l^-$ (J. Blümlein and J. Brunner)
- ALP’s searches in Primakoff processes: $p Z \rightarrow p Z a \rightarrow l^+l^-$

![Figure 2: Primakoff production of ALPs in proton-nucleus collisions.](image)

- Charged pion and kaon decays: $\pi^+ \rightarrow \mu^+ \nu A' \rightarrow \mu^+ \nu e^+e^-$ and $K^+ \rightarrow \mu^+ \nu A' \rightarrow \mu^+ \nu e^+e^-$
- Neutral pion decay: $\pi^0 \rightarrow \gamma A' \rightarrow \gamma e^+e^-$
Non-BSM Physics Program ($\eta$ and $\eta'$ factory)

High precision studies on low energy physics

- Nuclear models
- Chiral perturbation theory
- Non-perturbative QCD
- Isospin breaking due to the u-d quark mass difference
- Octet-singlet mixing angle
- $\pi\pi$ interactions
- Electromagnetic transition form-factors (important input for g-2)
Optical TPC
- ~ 1m x 1.5 m
- CH₄ @ 1 Atm
- 5x10⁵ Sipm/Lappd
- 98% coverage

\( \mu \)-polarizer
Active version (from TREK exp.)

ADRIAN02 Calorimeter (tiles)
- Scint. + heavy glass sandwich
- 20 \( X_0 \) (~64 cm deep)
- Triple-readout +PFA
- 96% coverage

10x Be targets
0.33 mm thin
Spaced 10 cm

A fiber tracker has being considered for rejection of \( \gamma \)-conversion and vertexing

Aerogel
Dual refractive index system

REDTOP detector

OTPC
Recent developments on simulations

Almost full simulation

**Event generation:** GenieHad (fortran+ and C++)
- Urqmd + Abla7 for proton-target interaction (signal and background)

**Background**
- $2 \cdot 10^7$ Standard Model events (corresponding to about $10^9$ POT)
- $7 \cdot 10^5 \ p^+ \ ^7Li\rightarrow \eta \ X \ \ with \ \ \eta \rightarrow \gamma e^+e^-$ (corresponding to about $10^{12}$ POT)

**Detector prototyping:** Slic (C++) , lcsim (java)

**Almost Full simulations for the $\eta$-factory:** ilcroot
- All 3 subdetectors are digitized
- Pattern recognition from MC truth
- Reconstruction: mix of full reco and gaussian smearing

**Efficiency extrapolated for the $\eta'$-factory**
- PID is important. Assume the following particle identification efficiency (not impossible to achieve with dual-readout + OTPC):

<table>
<thead>
<tr>
<th>species</th>
<th>Particle identification efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>e+, e-</td>
<td>98%</td>
</tr>
<tr>
<td>muon</td>
<td>95%</td>
</tr>
<tr>
<td>pion</td>
<td>95%</td>
</tr>
<tr>
<td>proton</td>
<td>99%</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>99%</td>
</tr>
<tr>
<td>n</td>
<td>99%</td>
</tr>
</tbody>
</table>
REDTOP ongoing simulations for PBC’s Benchmarks

REDTOP is looking into DM using **visible** final states

- Two portals have/are being explored:
  - Dark photon: $\eta \rightarrow \gamma$ lepton – antilepton (BC1). *Prompt analysis results presented by Gaia.*
  - Dark scalar: $\eta \rightarrow \pi^0$ lepton – antilepton (It has small coupling to $\eta$). REDTOP can help to differentiate between Higgs models (M. Pospelov et al.) BC4 and BC5 and electrophobic models (J. Miller et al.) – NOT AMONG PBC BENCHMARKS

The ALP’s portal will be explored with *Primakoff processes*: $p \ Z \rightarrow p \ Z \ a \rightarrow \ell \ell$ (BC11)
BSM Physics Program ($\eta$ and $\eta'$ factory): reconstruction efficiency for dileptons in searches for DM vectors or scalars
DM Branching Ratios Sensitivity for $\eta$-factory (1.8 GeV) for final states with dileptons in searches for DM vectors or scalars

- Assume $10^{18}$ POT
- Interactions $2.29E+16$
- Eta production. $8.24E+13$
- $S/\sqrt{B}>3$
- Prompt analysis only (non detached vertex analysis yet)
- Expect x10 improved sensitivity with vertex analysis

Assume $10^{18}$ POT

Interactions $2.29E+16$

Eta production. $8.24E+13$

$S/\sqrt{B}>3$

Prompt analysis only (non detached vertex analysis yet)

Expect x10 improved sensitivity with vertex analysis
DM Branching Ratios Sensitivity for $\eta'$-factory (3.5 GeV) for final states with dileptons in searches for DM vectors or scalars

- Assume $10^{18}$ POT
- Interactions $2.29E+16$
- Eta-prime production $1.4E+12$
- $S/\sqrt{B}>3$
- Prompt analysis only (non detached vertex analysis yet)
- Expect x10 improved sensitivity with vertex analysis

$q \rightarrow \gamma \eta'$
$q \rightarrow \pi \pi$

$2M_{\mu\mu}$ threshold

$A' \rightarrow \pi\pi$ enhancement (Batell, Pospelov, Ritz 2009)
Sensitivity to $A'$ (\(\eta\)-factory, $e^+e^-$ only)

Visibly Decaying $A' \rightarrow e^+e^-$

\[
\varepsilon^2 \quad 10^{-7} \quad 10^{-6} \quad 10^{-5} \\
10^{-8} \quad 10^{-9} \\
10^{-9} \quad 10^{-10} \quad 10^{-11} \quad 10^{-12}
\]

\(m_{A'}\) [MeV]

\(10^{16}\) \(10^{17}\) \(10^{18} \text{ POT}\)

Courtesy G. Krnjić
Sensitivity to $A'$ ($\eta$ and $\eta'$, e/\(\mu\))

A'\text{-}\gamma$ lepton antilepton

$A'$ mass vs. $\eta$ (or $\eta'$) sensitivity for different POT levels.
The REDTOP collaboration

8 Countries, 23 Institutions, 63 Collaborators

J. Cervantes, P. Maksimov, D. McFarlane, L. Thomas
Arizona State University (USA)

I. Pedraza, D. Leon, S. Escobar, D. Herrera, D. Silveiro
Benemérita Universidad Autónoma de Puebla, (Mexico)

A. Aljofri
Brown University, (USA)

F. Ignatov
Budker Institute of Nuclear Physics – Novosibirsk, (Russia)

Fermil National Accelerator Laboratory, (USA)

P. Sanchez-Duetz
Institute of Particles and Nuclear Physics – Charles University, Prague (Czech Republic)

C. Gatto
Istituto Nazionale di Fisica Nucleare – Sezione di Napoli, (Italy)

W. Baldini
Istituto Nazionale di Fisica Nucleare – Sezione di Ferrara, (Italy)

R. Caroli, A. Kowalski, M. Melani
Istituto Nazionale di Fisica Nucleare – Sezione di Pisa, (Italy)

W. Krasnialis, M. Silanski, M. Zielinski
Jagiellonian University, Krakow, (Poland)

G. Pentre
Los Alamos National Laboratory, (USA)

M. Burovski
National Centre for Nuclear Research – Warszawa, (Poland)

O. Blazy, M. Spyhans, V. Zdziaki, P. Chintaipati
Northern Illinois University, (USA)

M. Pepelev
Perimeter Institute for Theoretical Physics – Waterloo, (Canada)

Y. Kain
Princeton University – Princeton, (USA)

Universidad Autónoma de Zezitomacos, (Mexico)

C. Sibari, S. Barb, C. Magnen
Università di Modena e Reggio Emilia, (Italy)

L. E. Marcocchi
Università di Pisa, (Italy)

M. Ouda
Università di Salerno, (Italy)

J. Knecht
University of Florida, (USA)

S. Gardner, J. Shi, X. Yan
University of Kentucky, (USA)

R. Rucinski
University of Minnesota, (USA)

A. Khodis
University of Uppsala, (Sweden)

More details at: http://redtop.fnal.gov
On Detector R&D

**ADRIANO Calorimeter**
Almost 8 yrs R&D by T1015 Collaboration
Proved technology but need a cheaper construction technique
Ongoing R&D at NIU (NIU+INFN Collaboration)

**Fiber tracker**
Use LHCb technology without modifications
Simulations indicates that the technique has an acceptable performance at REDTOP energies.

**Optical-TPC**
Not yet started, an possible weak point for REDTOP. Nevertheless, taking into account POT we may consider a different technology.
Summary

The $\eta/\eta'$ meson is an excellent laboratory for studying rare processes.

Existing world sample not sufficient for breaching into decays violating conservation laws or searching for new particles.

Broad physics program expands beyond the benchmark proposed by the PBC.

Complementary to most other projects participating to the PBC program in the MeV-GeV mass scale.

REDTOPI goal is to produce $10^{13}$ $\eta$ mesons with a 1.8 GeV beam and (~ $10^{11}$ $\eta'$) with a 3.5 GeV beam – Assume $10^{17}$ POT for CERN implementation.

Currently the collaboration is forming and working at a full proposal.

Endorsement by a laboratory will help to get funds for the detector R&D.

Rough cost estimation is around 50 M$ (depending on re-use of existing infrastructure).

Working on a time line to be presented to the PBC.
Back up
Charged Tracks Detection

100 MeV electron

95 MeV muon

Cerenkov light in the OTPC
PID with ADRIANO @ 100MeV
Major Backgrounds

- $\eta \rightarrow \gamma e^+e^-$

$pLi \rightarrow \gamma X$
Typical Signals from Dark Bosons

$\eta \rightarrow \gamma A' (17 \text{ MeV})$

$\eta \rightarrow \pi^0 H (100 \text{ MeV})$

$\gamma\gamma + \text{Di-lepton invariant mass}$

$\eta \rightarrow \pi^0 H (100 \text{ MeV})$

Di-lepton invariant mass

$\gamma\gamma + \text{Di-lepton invariant mass}$

$\gamma$ invariant mass
Experimental Techniques

η/η’ production
- η and η’ hadro-produced from 1.8 and 3.5 GeV CW proton beams
- Use 10 x 0.33mm Be foils targets, spaced 10 cm apart to minimize combinatorics background

charged tracks detection
- Use Cerenkov effect in an Optical-TPC for tracking charged particles
- Baryons and most pions are below Č threshold
- Electrons and most muons are detected and reconstructed
- Use LHCb-style Fiber tracker vertexing and rejection of γ-conversion

γ detection
- Use ADRIANO calorimeter for reconstructing EM showers
- σ_E/E < 5%/E
- PID from dual-readout to disentangle showers from γ/μ/hadrons
- 96.5% coverage
- Use tiles for high granularity and PFA reconstruction
- 200 psec resolution for high rate DAQ