Updates on REDTOP

Rare Eta Decays with a TPC for Optical Photons

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Physics Beyond Colliders Working Group Meeting
CERN, 5-6 Nov. 2019
For the REDTOP Collaboration
Updates on REDTOP

• Short reminder of the REDTOP main points
  – (physics, beam, detector,…)

• New sensitivities using better simulation

• Two additional models for BC4 (Dark scalar)
  – Hadrophilic Scalar Mediator
  – Spontaneous Flavor Violation

• Status and plan
Why the $\eta$?
- Eigenstate of C,P,CP,G; Goldstone boson
  - Strong and EM decays forbidden in lowest order
  - Contributions from higher order are enhanced by a factor 100,000
  - Decays with leptons in the final state have very small SM background
  - Internal loops and lepton pairs can probe new physics

REDTOP Physics
- >20 interesting channels
- 3(5) are “golden” (will be described in details in the proposal)
- 4 benchmark channels are studied in details for the PBC (2 of them are golden)

REDTOP beam
- $8 \times 10^{12} \, \text{et}/\text{yr}$ for $10^{17} \, \text{POT/yr}$, 1.8 GeV protons
- $8 \times 10^{10} \, \text{et}/\text{yr}$ for $10^{17} \, \text{POT/yr}$, 3.5 GeV protons (phase II)

REDTOP detector
- Optical TPC: use Cherenkov effect for tracking charged particles
- ADRIANO2 (Dual readout calorimeter): for reconstructing EM showers and particle ID
- Fiber Tracker for vertexing

http://redtop.fnal.gov
REDTOP Detector + Magnet
Simulation and PCB benchmarks

- Simulation tools ready (slic, lcsim, ilcroot frameworks)
  - Full simulation, including background and efficiencies
  - Only missing full reconstruction in the OTPC
- 10-15 years timescale and $10^{17}$ pot/year

Since last workshop (Jan. 2019):
- Secondary vertex reconstruction (BSM particles have long lifetimes)
- Beam transverse profile: $\sigma_y \sim 0.5$ mm (gaussian), $\sigma_x \sim 1$ cm (uniform)
  - it was 1 cm uniform both $x$ and $y$;
  - now: small $\sigma$ for more constraints, large $\sigma$ to separate multiple events
- More constraints in $z$ using target thickness
- Background reduced by a factor 100-300, signal efficiency ~25-35%

Ongoing simulations for PBC benchmarks (Visible final states)
- Dark photons (BC 1) $\eta \rightarrow \gamma A' \rightarrow \ell\ell$
- Dark scalars mixing with the Higgs (BC 4) $\eta \rightarrow \pi^0 H \rightarrow \ell\ell$
- ALP coupled with fermions (BC 10) $\eta \rightarrow \pi\pi a \rightarrow \ell\ell$
- ALP coupled with gluons (BC 11) $p Li \rightarrow p Li a \rightarrow \ell\ell$
PBC benchmarks

Dark photons

Dark scalar mixing with Higgs

BC1

BC4
PBC benchmarks

ALP with fermion coupling

BC10

ALP with gluon coupling

BC11
Light Scalar Meson $\eta \rightarrow \pi S$

$S \rightarrow ee, \mu\mu, \pi\pi$

- **Minimal SM Higgs extension**
  - Viable DM candidates coupling to Higgs portal
  - S-H mixing via mixing angle
  - It couples mostly to top quarks and gluons
  - Favorite exp. techniques: B factories (LHCb)
  - *Disfavorite at REDTOP*

- **Hadrophilic Scalar Mediator**

- **Spontaneous Flavor Violation**
  - Much less constrained by cosmological and EDM bounds
  - It couples mostly to u,d quarks
  - *Favorite exp. Techniques: $\eta/\eta'$ factories*
  - Disfavorite at LHCb, Belle
  - Moderate discovery potential with K
Dark scalar coupling
Exclusively to the up quark $g_u$

KOTO signal:
$K_L \rightarrow \pi^0 \nu \nu$
What if $K_L \rightarrow \pi^0 S$?
“off-shell” sensitivity ($2\pi$ decay)
Status and Plan

- **Cost:** ~ 50 M$ (including 50 % contingence)
- **Beam:** requires further study (PS, $10^{17}$ p/yr)
- **Detector**
  - ADRIANO2 new prototype; funded by NIU, INFN
  - Fiber Tracker (LHCb like)
  - OTPC not started
- **Detector/Simulation plan:**
  - Triple readout: disentangle neutron component using time history
    - (contributions after 50 ns from are neutrons only)
  - Full reconstruction for OTPC
    - (improves vertexing and background rejection)
- **Collaboration:** several institutions joined during the last year; still growing
- **Proposal to SPSC after ESPP process**
Summary

- The $\eta/\eta'$ meson is an excellent laboratory for studying rare processes
- Existing world samples not sufficient for studying decays violating conservations laws
- REDTOP goal is to produce $\sim 10^{13} \eta$ mesons/year in phase I and $\sim 10^{11} \eta'/year$ in phase II
- Very rich physics program, including “golden” processes:
  - CP violation via Dalitz plot mirror asymmetry
  - Dark photons
  - Scalar meson searches
  - Axion-like particles
- New generation, super-fast detector techniques
- An exciting phase of detector R&D ahead
- Full proposal in preparation
- http://redtop.fnal.gov
Thank you!
$$\eta : \approx \frac{{u\bar{u}+d\bar{d}-2s\bar{s}}}{{\sqrt{6}}}$$

$$\eta' : \approx \frac{{u\bar{u}+d\bar{d}+s\bar{s}}}{{\sqrt{3}}}$$

$$I^G(J^{PC}) = 0^+(0^-+)$$

Mass $m = 547.862 \pm 0.017$ MeV
Full width $\Gamma = 1.31 \pm 0.05$ keV

C-nonconserving decay parameters
- $\pi^+\pi^-\pi^0$ left-right asymmetry = $(0.09^{+0.11}_{-0.12}) \times 10^{-2}$
- $\pi^+\pi^-\pi^0$ sextant asymmetry = $(0.12^{+0.10}_{-0.11}) \times 10^{-2}$
- $\pi^+\pi^-\pi^0$ quadrant asymmetry = $(-0.09 \pm 0.09) \times 10^{-2}$
- $\pi^+\pi^-\gamma$ left-right asymmetry = $(0.9 \pm 0.4) \times 10^{-2}$
- $\pi^+\pi^-\gamma$ $\beta$ (D-wave) = $-0.02 \pm 0.07$ ($S = 1.3$)

CP-nonconserving decay parameters
- $\pi^+\pi^-e^+e^-$ decay-plane asymmetry $A_\phi = (-0.6 \pm 3.1) \times 10^{-2}$

Dalitz plot parameter
- $\pi^0\pi^0\pi^0$ $\alpha = -0.0318 \pm 0.0015$

PARAMETER $\Lambda IN \eta \rightarrow \mu^+\mu^-\gamma$ DECAY $= 0.719 \pm 0.014$ GeV/$c^2$
<table>
<thead>
<tr>
<th>Decay Modes</th>
<th>Fraction ($\Gamma_f/\Gamma$)</th>
<th>Scale factor</th>
<th>Confidence level</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Neutral modes</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$2\gamma$</td>
<td>(72.12±0.34) %</td>
<td>S=1.2</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>$3\pi^0$</td>
<td>(39.41±0.20) %</td>
<td>S=1.1</td>
<td>274</td>
<td></td>
</tr>
<tr>
<td>$\pi^02\gamma$</td>
<td>(32.68±0.23) %</td>
<td>S=1.1</td>
<td>179</td>
<td></td>
</tr>
<tr>
<td>$2\pi^0\gamma$</td>
<td>(2.56±0.22) x 10^{-4}</td>
<td>CL=90%</td>
<td>257</td>
<td></td>
</tr>
<tr>
<td>$4\gamma$</td>
<td>(2.8 x 10^{-4})</td>
<td>CL=90%</td>
<td>274</td>
<td></td>
</tr>
<tr>
<td>invisible</td>
<td>(1.0 x 10^{-4})</td>
<td>CL=90%</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td><strong>Charged modes</strong></td>
<td></td>
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<td></td>
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<tr>
<td>$\pi^+\pi^-\pi^0$</td>
<td>(28.10±0.34) %</td>
<td>S=1.2</td>
<td>-</td>
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<tr>
<td>$\pi^+\pi^-\pi^0$</td>
<td>(22.92±0.28) %</td>
<td>S=1.2</td>
<td>174</td>
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<tr>
<td>$e^+e^-\gamma$</td>
<td>(4.22±0.08) %</td>
<td>S=1.1</td>
<td>236</td>
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<tr>
<td>$\mu^+\mu^-\gamma$</td>
<td>(6.9 ±0.4) x 10^{-3}</td>
<td>S=1.3</td>
<td>274</td>
<td></td>
</tr>
<tr>
<td>$e^+e^-$</td>
<td>(3.1 ±0.4) x 10^{-4}</td>
<td></td>
<td>253</td>
<td></td>
</tr>
<tr>
<td>$\mu^+\mu^-$</td>
<td>(5.8 ±0.8) x 10^{-6}</td>
<td>CL=90%</td>
<td>274</td>
<td></td>
</tr>
<tr>
<td>$2e^+e^-$</td>
<td>(2.40±0.22) x 10^{-5}</td>
<td></td>
<td>274</td>
<td></td>
</tr>
<tr>
<td>$\pi^+\pi^-e^+e^-(\gamma)$</td>
<td>(2.68±0.11) x 10^{-4}</td>
<td></td>
<td>235</td>
<td></td>
</tr>
<tr>
<td>$e^+e^-\mu^+\mu^-$</td>
<td>(1.6 x 10^{-4})</td>
<td>CL=90%</td>
<td>253</td>
<td></td>
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<tr>
<td>$2\mu^+2\mu^-$</td>
<td>(3.6 x 10^{-4})</td>
<td>CL=90%</td>
<td>161</td>
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<tr>
<td>$\mu^+\mu^-\pi^+\pi^-$</td>
<td>(3.6 x 10^{-4})</td>
<td>CL=90%</td>
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<tr>
<td>$\pi^+\pi^-\nu_\mu + c.c.$</td>
<td>(1.7 x 10^{-4})</td>
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</tr>
<tr>
<td>$\pi^+\pi^-2\gamma$</td>
<td>(2.1 x 10^{-3})</td>
<td></td>
<td>236</td>
<td></td>
</tr>
<tr>
<td>$\pi^+\pi^-\pi^0\gamma$</td>
<td>(5 x 10^{-4})</td>
<td>CL=90%</td>
<td>174</td>
<td></td>
</tr>
<tr>
<td>$\pi^0\mu^+\mu^-$</td>
<td>(3 x 10^{-6})</td>
<td>CL=90%</td>
<td>210</td>
<td></td>
</tr>
</tbody>
</table>

**Charge conjugation (C), Parity (P),**
**Charge conjugation x Parity (CP), or**
**Lepton Family number (LF) violating modes**

<table>
<thead>
<tr>
<th>Decay Modes</th>
<th>C</th>
<th>P.CP</th>
<th>LF</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0\gamma$</td>
<td>&lt; 9 x 10^{-5}</td>
<td>CL=90%</td>
<td>257</td>
</tr>
<tr>
<td>$\pi^+\pi^-$</td>
<td>$P.CP$ &lt; 1.3 x 10^{-5}</td>
<td>CL=90%</td>
<td>236</td>
</tr>
<tr>
<td>$2\pi^0$</td>
<td>$P.CP$ &lt; 3.5 x 10^{-4}</td>
<td>CL=90%</td>
<td>238</td>
</tr>
<tr>
<td>$2\pi^0$</td>
<td>$P.CP$ &lt; 5 x 10^{-4}</td>
<td>CL=90%</td>
<td>238</td>
</tr>
<tr>
<td>$3\pi^0$</td>
<td>$P.CP$ &lt; 6 x 10^{-5}</td>
<td>CL=90%</td>
<td>170</td>
</tr>
<tr>
<td>$3\gamma$</td>
<td>$P.CP$ &lt; 1.6 x 10^{-5}</td>
<td>CL=90%</td>
<td>274</td>
</tr>
<tr>
<td>$4\pi^0$</td>
<td>$P.CP$ &lt; 6.9 x 10^{-7}</td>
<td>CL=90%</td>
<td>40</td>
</tr>
<tr>
<td>$\pi^0e^+e^-$</td>
<td>C</td>
<td>[n] &lt; 4 x 10^{-5}</td>
<td>CL=90%</td>
</tr>
<tr>
<td>$\pi^0\mu^+\mu^-$</td>
<td>C</td>
<td>[n] &lt; 5 x 10^{-5}</td>
<td>CL=90%</td>
</tr>
<tr>
<td>$\mu^+e^- + \mu^-e^+$</td>
<td>LF</td>
<td>&lt; 6 x 10^{-6}</td>
<td>CL=90%</td>
</tr>
</tbody>
</table>
BSM Physics Program (\(\eta\) and \(\eta'\) factory)

**C, T, CP-violation**

- CP Violation via Dalitz plot mirror asymmetry: \(\eta \rightarrow \pi^0 \pi^+ \pi^-\)
- 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): \(\eta \rightarrow \pi^0 \pi^0 \pi^+ \pi^-\) 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: \(\eta \rightarrow \pi^+ \pi^- e^+ e^-\) and \(\eta \rightarrow \pi^+ \pi^- \mu^+ \mu^-\)
- Test of CP invariance in angular correlation studies: \(\eta \rightarrow \mu^+ \mu^- e^+ e^-\)
- 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 \(\eta \rightarrow \pi^+ \mu^- \nu\) vs \(\eta \rightarrow \pi^0 \mu^+ \nu\) and \(\gamma\) polarization in \(\eta \rightarrow \gamma \gamma\)

**Other discrete symmetry violations**

- Lepton Flavor Violation: \(\eta \rightarrow \mu^+ e^- + c.c.\)
- Double lepton Flavor Violation: \(\eta \rightarrow \mu^+ \mu^+ e^- e^- + c.c.\)
BSM Physics Program (η and η’ factory)

New particles and forces searches

- Scalar meson searches (charged channel): $\eta \rightarrow \pi^0 H$ with $H \rightarrow e^+e^-$ and $H \rightarrow \mu^+\mu^-$
- Dark photon searches: $\eta \rightarrow \gamma A'$ with $A' \rightarrow l^+l^-$
- 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 $10^{-6}$ - $10^{-9}$)
BSM Physics Program (η and η’ factory)

Non-η/η’ based BSM Physics
- Dark photon and ALP searches in Drell-Yan processes: \( qq\bar{q} \rightarrow A'/a \rightarrow l^+l^- \)
- ALP’s searches in Primakoff processes: \( pZ \rightarrow pZ a \rightarrow l^+l^- \) (F. Kahlhoefer)
- 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 (η and η’ 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)
- Lots of other bread&butter physics
### η Samples – Present and future

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Technique</th>
<th>Total η</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB @AGS</td>
<td>$\pi p \to \eta n$</td>
<td>$10^7$</td>
</tr>
<tr>
<td>CB @MAMI-B</td>
<td>$\gamma p \to \eta p$</td>
<td>$2 \times 10^7$</td>
</tr>
<tr>
<td>CB @MAMI-C</td>
<td>$\gamma p \to \eta p$</td>
<td>$6 \times 10^7$</td>
</tr>
<tr>
<td>KLOE @DAFNE</td>
<td>$e^+e^- \to \Phi \to \eta \gamma$</td>
<td>$5 \times 10^7$</td>
</tr>
<tr>
<td>WASA @COSY</td>
<td>$pp \to \eta pp \quad pD \to \eta ^3He$</td>
<td>$\geq 10^9$ (unt.) $3 \times 10^7$ (tagged)</td>
</tr>
<tr>
<td>CB @MAMI 10 wk (proposed 2014)</td>
<td>$\gamma p \to \eta p$</td>
<td>$3 \times 10^8$</td>
</tr>
<tr>
<td>Phenix @RHIC</td>
<td>$dAu \to \eta X$</td>
<td>$5 \times 10^9$</td>
</tr>
<tr>
<td>Hades @GSI</td>
<td>$pp \to \eta pp \quad pAu \to \eta X$</td>
<td>$4.5 \times 10^8$</td>
</tr>
<tr>
<td><strong>Near future samples:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GlueX @JLAB (just started)</td>
<td>$\gamma p \to \eta p \to \text{neutrals}$</td>
<td>$4.5 \times 10^7$/year</td>
</tr>
<tr>
<td>JEF @JLAB (recently approved)</td>
<td>$\gamma p \to \eta X \to \text{neutrals}$</td>
<td>$3.9 \times 10^5$/day</td>
</tr>
<tr>
<td>REDTOP @FNAL (proposing)</td>
<td>$p Be \to \eta X$</td>
<td>$2.5 \times 10^{13}$/year</td>
</tr>
</tbody>
</table>
REDTOP – Golden Channel I

**CP violation from Dalitz plot mirror asymmetry in \( \eta \rightarrow \pi^+ \pi^- \pi^0 \)**

- It is an Isospin-violating decay
- EM contributions are known to be strongly suppressed
- It can occur via Strong Interactions due to the mass difference \( m_u - m_d \)
- Any mirror-asymmetry in the Dalitz plot is an indication of CP and C violation
- Good for testing the Chiral Perturbation Theory
- Current PDG limits consistent with no asymmetry
- Largest data samples: WASA 2014 (1.2x10^7), KLOE2 2016 (4.7x10^6)
- REDTOP expected sample: 10^9 analyzed events.
- Test of CP invariance via \( \gamma \) polarization studies, as in \( \eta \rightarrow \pi^+ \pi^- \gamma; \gamma \rightarrow l^+l^- \) (golden channel)
REDTOP – Golden Channel II

**Dark photon searches:**

\[ \eta \rightarrow \gamma A' ; \quad A' \rightarrow \gamma l^+l^- \]

- **Motivations:**
  - Possible cosmic ray excesses from dark matter annihilation
  - Structures anomalies in dwarf galaxies (*Pospelov and Ritz, 2008; Arkani-Hamed et al., 2008*)
  - The muon g-2 anomaly.

- Most accredited model has A' mass is the MeV-GeV range, coupling to to SM charged particles with a strength \( \sim 10^{-3}-10^{-4} \) of that of the photon

- REDTOP could complement the new experiments at JLAB and Frascati with \( \gamma \) and e-beams.

- REDTOP can also make a clear statement on similar searches (\( \gamma e^+e^- \)) of the proposed 17 MeV super-weak gauge boson (*S.Gardner at al., 2016, arXiv:1608.03591*) – [Golden channel lia].

  - \( \eta \rightarrow \gamma X_{17}; \quad X_{17} \rightarrow e^+e^- \)
  - Below WASA sensitivity.
REDTOP – Golden Channel III

Search for light scalar mesons

$$\eta \rightarrow \pi^0 H ; \quad H \rightarrow l^+l^-$$

- Existence of this light scalar particle can significantly enhance this BR compared to the SM value ($\sim 10^{-9}$)
- REDTOP expected sensitivity is better than $10^{-10}$
  - Current limits are $\sim 10^{-5} – 10^{-6}$
- Implications for the $R_p$ anomaly. [Golden channel IIIa]
  - $\eta \rightarrow \gamma l^+l^-$
  - Conventional methods (levels of muonic atoms and elastic scattering experiments) find a discrepancy of about $7\sigma$. 
REDTOP – Search for Axion Like Particles

• ALP’s with fermion couplings
  - $\eta \rightarrow \pi \pi \ a \ ; \ a \rightarrow l^+l^-$

• ALP’s with gluon couplings
  - Not associated with $\eta/\eta'$ decays
  - Drell-Yan processes: $qq\overline{q} \rightarrow a \rightarrow l^+l^-$
  - Proton bremsstrahlung: $pN \rightarrow pN \ a \ ; \ a \rightarrow l^+l^-$
  - Primakoff processes: $pZ \rightarrow pZ \ a \ ; \ a \rightarrow l^+l^-$
## Effects of new simulation
*(secondary vertexes, beam profile, z-target, optimized cuts)*

<table>
<thead>
<tr>
<th>Benchmark channel</th>
<th>Signal efficiency (%)</th>
<th>Background efficiency (%)</th>
<th>Largest background</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark photon (BC1)</td>
<td>34</td>
<td>0.3</td>
<td>$\eta \rightarrow \gamma e^+e^-$</td>
</tr>
<tr>
<td>Dark scalar (BC4)</td>
<td>30</td>
<td>0.2</td>
<td>$\eta \rightarrow \gamma e^+e^-$</td>
</tr>
<tr>
<td>ALP “fermion dominance” (BC10)</td>
<td>35</td>
<td>0.2</td>
<td>$\eta \rightarrow \pi^+\pi^-e^+e^-$</td>
</tr>
<tr>
<td>ALP “gluon dominance” (BC11)</td>
<td>24</td>
<td>0.9</td>
<td></td>
</tr>
</tbody>
</table>
PBC benchmarks

(PBC, Cern 5-6 Nov. 2019)

Dark photons

Dark scalar mixing with Higgs
PBC benchmarks
(PBC, Cern 5-6 Nov. 2019)

ALP with fermion coupling

ALP with gluon coupling
KOTO results

4 events, \( BR(K_L \to \pi \nu \nu) \sim 2 \times 10^{-9} \), \( BR(K_L \to \pi \nu \nu)_{SM} = (3.4 \pm 0.6) \times 10^{-11} \)

\( K_L \to \pi^0 \ S \ ?? \)
KOTO/NA62 results

From arXiv 1909.11111: Kitahara, Okui, Perez, Sorez, Tobioka

*New physics implications of recent search for $K_L \to \pi\nu\bar{\nu}$ at KOTO*
REDTOP Running Phases
*(original plan)*

- Intermediate phases (during detector R&D, OTPC only)
  - $^7$Li → $^8$Be → e+e−X
  - $^2$H → $^3$He e+e− (M.Viviani et al.)
    - More possible beams (p/μ/e)
- Phase I: $\eta$ factory
- Phase II: $\eta'$ factory
- Phase III: Dark photons radiating from muons
- Phase IV: Muon Scattering Experiment (optional)
- Phase V: Tagged REDTOP (at PIP-II)
- Phase VI: Rare Kaon Decays: $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ (depending on NA62, JPARC)
Why the $\eta$?

- Decays are flavor conserving
- Eigenstate of C, P, CP and G: $I^GJ^{PC}=0^+0^-$
  - can be used to test C and CP invariances
- Very narrow state (1.3 keV) – overconstraints events → low background
- Strong decays forbidden in lowest order by C, P, CP, G, and Isospin invariance
- EM decays forbidden in lowest order by C and angular momentum conservation
  - contributions from higher orders are enhanced by a factor of $\sim 100,000$
  - $\eta$ decays with leptons in the final state have very small SM backgrounds
  - Internal loops and lepton pairs can probe new physics
- $\eta$ is an excellent laboratory to search for physics Beyond Standard Model
REDTOP Key Points

- Yield of \(8 \times 10^{12}\) \(\eta\) mesons/year for \(10^{17}\) POT
  - Possibly \(\sim 8 \times 10^{10}\) \(\eta\)’ mesons/years in a second phase

- 3 (5) “golden” channels (will be described in details in the proposal)
  - But at least \(\sim 20\) interesting channels (symmetry violations, new particles and forces searches, precision measurements)
  - 4 benchmark channels are studied in details for the PBC (2 of them are golden)

- Innovative detector techniques
  - Dual readout calorimeter
  - Optical TPC
  - Detector blind to protons and slow pions
  - \(4\pi\) detector coverage (almost)

- Significant improvement (10^6 in some cases) to the current limits.

- \texttt{http://redtop.fnal.gov}
Beam and $\eta$ yield

- Incident proton energy $\sim 1.8$ GeV (3.5 for $\eta'$)
- Continuous beam, $10^{17}$ POT/yr
  - At Fermilab: $\sim 10^{18}$ p/yr
- Target system: 10x0.5 mm Li or 10x0.33 mm Be spaced 10 cm apart
  - Low Z (primary hadrons multiplicity $\sim A^{1/3}$)
- Large beam spot size ($\sim 1$ cm) with small divergence ($<1^0$)
- $p$-inelastic production (event rate): $2 \times 10^8$ evts/sec
- Eta production: $8 \times 10^{12}$ $\eta$/year
  - At Fermilab: $8 \times 10^{13}$ $\eta$/year
- Possible second phase ($\eta'$): $8 \times 10^{10}$ $\eta$/year
  - At Fermilab: $8 \times 10^{11}$ $\eta$/year
Detection Techniques

**Charged Tracks Detection**
- Use Cherenkov effect in an Optical-TPC for tracking charged particles
- Baryons and most pions are below Cherenkov threshold
- Electrons and most muons are detected and reconstructed
- Fiber-tracker for vertexing and rejection of gamma conversion (being investigated)

**Gamma Detection**
- Use ADRIANO2 calorimeter for reconstructing EM showers
- Resolution <5%/sqrt(E)
- PID from dual-readout to disentangle showers from $\gamma/\mu$/hadrons
- 96.5% coverage
- High granularity
- Good time resolution (<100 psec) for high rate DAQ

ADRIANO: A Dual-Readout Integrally Active Non-segmented Option
The REDTOP Detector

**Optical TPC**
- ~ 1m x 1.5 m
- CH₄ @ 1 Atm
- 5x10⁵ Sipm/Lappd
- 98% coverage

**Solenoid**
0.6-0.8 T

**10x Be targets**
- 0.33 mm thin
- Spaced 10 cm

**ADRIANO2 Calorimeter (tiles)**
- Scint. + heavy glass sandwich
- 20 X₀ ( ~ 64 cm deep)
- Triple-readout +PFA
- 96% coverage

**μ-polarizer**
Active version (from TREK exp.)

**Aerogel**
Dual refractive index system

Fiber tracker being investigated (for rejection of γ-conversion and vertexing)
Resolution ~66μm/point
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