The REDTOP experiment: a $\eta/\eta'$ factory to explore dark matter and physics beyond the Standard Model

Corrado Gatto
INFN Napoli and Northern Illinois University

Vito Di Benedetto
Fermilab

Presented at HTC2024
Rationale for an $\eta/\eta'$ Factory

Cold dark matter scenarios

CDM bound

BBN bound

keV

MeV

GeV

TeV

Bound by cosmological observations

Mostly unconstrained

Disfavorite by LHC/Direct detection

Requires new facilities

Almost no space left for New Physics

Cold dark matter scenarios

~100 TeV, Violate unitarity

“Light dark matter must be neutral under SM charges, otherwise it would have been discovered at previous colliders” [G. Krnjaic RF6 Meeting, 8/2020]

- The only known particles with all-zero quantum numbers: $Q = I = J = S = B = L = 0$ are the $\eta/\eta'$ mesons and the Higgs boson (also the vacuum!) -> very rare in nature
- The $\eta$ meson is a Goldstone boson (the $\eta'$ meson is not!)
- The $\eta/\eta'$ decays are the only mesons with flavor-conserving reactions
- 20%-40% of is NOT made of quarks

Experimental advantages:

- Hadronic production cross section is quite large ($\sim 0.1$ barn) → easy to produce
- Strong & EM decays are forbidden in lowest order by discrete symmetry invariance. BR of processes from New Physics are enhanced compared to SM.

A $\eta/\eta'$ factory is equivalent to a low energy Higgs factory and an excellent laboratory to probe New Physics below 1 GeV.
**REDTOP Key Points**

**REDTOP: $\eta/\eta'$ yielding $\sim 10^{14}(10^{12})$ mesons**

- $\mathcal{O}(10^5)$ the existing world sample with a 3-yr run
- Existing works sample replicated in ~20 min of REDTOP run

**Hadro-produced mesons: requires a 30W (55W) CW proton beam**

- Pion beam also well suited

**Designed to search for BSM physics in the MeV-GeV region**

- Main search fields: dark matter and CP-violation
- Sensitive to 17MeV resonances

**Moderate cost:**

- $55M$ excl. contingency and labor
## Main Physics Goals of REDTOP

<table>
<thead>
<tr>
<th>Goal</th>
<th>Details</th>
</tr>
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<tbody>
<tr>
<td>Test of CP invariance via Dalitz plot mirror asymmetry:</td>
<td>( \eta \to \pi^0\pi^+\pi^- )</td>
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<tr>
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<td>Search for asymmetries in the Dalitz plot with very high statistics</td>
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<td>Test of CP invariance via ( \mu ) polarization studies:</td>
<td>( \eta \to \pi^0\mu^+\mu^- ), ( \eta \to \gamma\mu^+\mu^- ), ( \eta \to \mu^+\mu^- )</td>
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<tr>
<td></td>
<td>Measure the angular asymmetry between spin and momentum</td>
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<td>Dark photon searches:</td>
<td>( \eta \to \gamma A' ) with ( A' \to \mu^+\mu^- ), ( A' \to e^+e^- )</td>
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<td>Need excellent vertexing and particle ID</td>
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<td>QCD axion and ALP searches:</td>
<td>( \eta \to \pi a ) with ( a \to \gamma\gamma ), ( a \to \mu^+\mu^- ), ( a \to e^+e^- )</td>
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<td>Dual (or triple!) calorimeters and vertexing</td>
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7/10/2024
### Detecting BSM Physics with REDTOP (η/η’ factory)

**Assuming a yield ~10^{14} η mesons/yr and ~10^{12} η’ mesons/yr**

<table>
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<tr>
<th>C, T, CP-violation</th>
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<tr>
<td>CP Violation via Dalitz plot mirror asymmetry: ( \eta \rightarrow \pi^0 \pi^0 \pi^0 )</td>
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<tr>
<td>CP Violation (Type I – P and T odd, C even): ( \eta \rightarrow 4\pi^0 \rightarrow 8\gamma )</td>
</tr>
<tr>
<td>CP Violation (Type II - C and T odd, P even): ( \eta \rightarrow 3\pi^0 ) and ( \eta \rightarrow 3\pi^0 \rightarrow 9\gamma )</td>
</tr>
<tr>
<td>Test of CP invariance via ( \mu ) longitudinal polarization: ( \eta \rightarrow \mu^+\mu^- )</td>
</tr>
<tr>
<td>CP inv. via γ* polarization studies: ( \eta \rightarrow \pi^+\pi^-e^+e^- ) and ( \eta \rightarrow \pi^+\pi^-\mu^+\mu^- )</td>
</tr>
<tr>
<td>CP invariance in angular correlation studies: ( \eta \rightarrow \mu^+\mu^-e^+e^- )</td>
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<tr>
<td>CP invariance in angular correlation studies: ( \eta \rightarrow \mu^+\mu^-\pi^+\pi^- )</td>
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<tr>
<td>CP invariance in ( \mu ) polar. in studies: ( \eta \rightarrow \pi^+\pi^-\mu^+\mu^- )</td>
</tr>
<tr>
<td>T invar. via ( \mu ) transverse polarization: ( \eta \rightarrow \pi^+\pi^-\mu^+\mu^- ) and ( \eta \rightarrow \gamma \mu^+\mu^- )</td>
</tr>
<tr>
<td>CPT violation: ( \mu ) pol. in ( \eta \rightarrow \pi^+\pi^-\nu\bar{\nu} ) and ( \gamma \mu^+\mu^- ) polar. in ( \eta \rightarrow \gamma \gamma )</td>
</tr>
</tbody>
</table>

### Other discrete symmetry violations

- Lepton Flavor Violation: \( \eta \rightarrow \mu^+e^- + c.c. \)
- Radiative Lepton Flavor Violation: \( \eta \rightarrow \gamma \mu^+e^- + c.c. \)
- Double lepton Flavor Violation: \( \eta \rightarrow \mu^+\mu^-e^-e^- + c.c. \)

### Non-\( \eta/\eta' \) based BSM Physics

- Neutral pion decay: \( \pi^0 \rightarrow \gamma A' \rightarrow \gamma e^+e^- \)
- ALP’s searches in Primakoff processes: \( p \, Z \rightarrow p \, Z \, a \rightarrow l^+l^- \)
- Charged pion and kaon decays: \( \pi^+ \rightarrow \mu^+\nu A' \rightarrow \mu^+\nu e^+e^- \) and \( K^+ \rightarrow \mu^+\nu A' \rightarrow \mu^+\nu e^+e^- \)
- Dark photon and ALP searches in Drell-Yan processes: \( q\bar{q} \rightarrow A'/a \rightarrow l^+l^- \)

### 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 \( A' \rightarrow e^+e^- \)
- Protophobic fifth force searches: \( \eta \rightarrow \gamma X_{17} \) with \( X_{17} \rightarrow \pi^0 \)
- QCD axion searches: \( \eta \rightarrow \pi a_{17} \) with \( a_{17} \rightarrow e^+e^- \)
- New leptophobic baryonic force searches: \( \eta \rightarrow \gamma B \) with \( B \rightarrow e^+e^- \) or \( B \rightarrow \pi^0 \)
- Indirect searches for dark photons new gauge bosons and leptoquark: \( \eta \rightarrow \mu^+\mu^- \) and \( \eta \rightarrow e^+e^- \)
- Search for true muonium: \( \eta \rightarrow \gamma (\mu^+\mu^-)_{12M} \rightarrow e^+e^- \)
- Lepton Universality
- \( \eta \rightarrow \pi^0 H \) with \( H \rightarrow \nu N', \eta \rightarrow h'N' \rightarrow \eta' \rightarrow e^+e^- \)

### Other Precision Physics measurements

- Proton radius anomaly: \( \eta \rightarrow \mu^+\mu^- \) vs \( \eta \rightarrow e^+e^- \)
- All unseen leptonic decay mode of \( \eta / \eta' \) (SM predicts 10^{-5} - 10^{-6})

### High precision studies on medium energy physics

- Nuclear models
- Chiral perturbation theory
- Non-perturbative QCD
- Isospin breaking due to the u-d quark mass difference
- Octet-singlet mixing angle
- Electromagnetic transition form-factors (important input for g-2)

C. Gatto – V. Di Benedetto
Detecting BSM Physics with REDTOP \((\eta/\eta' \text{ factory})\)

**Assuming a yield \(\sim 10^{14} \eta\) mesons/yr and \(\sim 10^{12} \eta'\) mesons/yr**

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| Search for true muonium: \(\eta \rightarrow (\gamma e^- \mu^-)^{1/2}_{\mu}\) \(\rightarrow \gamma e^+ e^-\) |

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| Proton radius anomaly: \(\eta \rightarrow \gamma \mu^+ \mu^-\) vs \(\eta \rightarrow \gamma e^+ e^-\) |
| All unseen leptonic decay mode of \(\eta / \eta'\) (SM predicts \(10^{-6} - 10^{-8}\)) |

**High precision studies on medium energy physics**

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**Only experiment, along with SHIP, sensitive to all four BSM portals**

C. Gatto – V. Di Benedetto
**Central Tracker**
- \(1 \times 1.5 \text{ m}\)
- Thin LGAD
- 98% coverage

**Cerenkov TOF**
- \(1 \times 1.5 \text{ m}\)
- Fused quartz tiles
- 98% coverage

**Fiber tracker or HV-MAPS**
- for rejection of \(\gamma\)-conversion and vertexing

**ADRIANO2(3) Calorimeter**
- (tiles)
- Scint. + heavy glass sandwich + RPC
- \(20 X_0 \ (\sim 64 \text{ cm deep})\)
- Triple-readout + PFA
- 96% coverage

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

**10x Be or Li targets**
- 0.33 mm thin
- Spaced 10 cm
## Cost estimate ($2022)

- Three funding scenarios considered
- Largest cost uncertainties
  - ADRIANO2 SiPM’s (2x10^6 – 4x10^6)
  - LGAD mechanics
- **No labor considered (usually, 1/3 of the total)**

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<th>Expensive option</th>
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<td>Target+beam pipe</td>
<td>0.5</td>
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<td>0.9</td>
</tr>
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<td>Vtx detector</td>
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<td>Trigger</td>
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</tr>
<tr>
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Cost estimate ($2022)

Three funding scenarios considered

Largest cost uncertainties

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Cost optimization is in progress

Based on sensitivity studies for Snowmass 2022

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REDTOP Collaboration

15 Countries
58 Institutions
128 Collaborators
Storage & CPU

Expected data rates from the experiment

- About 0.5 MHz to be stored on tape
- ~0.56 MB/sec from L2
- ~9 PB/year to tape (assume 1.6 kb event size)

<table>
<thead>
<tr>
<th>Trigger stage</th>
<th>Input event rate (Hz)</th>
<th>Event size (bytes)</th>
<th>Input data rate (bytes/s)</th>
<th>Event rejection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 0</td>
<td>$7 \times 10^8$</td>
<td>$1.4 \times 10^3$</td>
<td>$9.8 \times 10^{11}$</td>
<td>~4.6</td>
</tr>
<tr>
<td>Level 1</td>
<td>$1.3 \times 10^9$</td>
<td>$1.5 \times 10^3$</td>
<td>$2.3 \times 10^{11}$</td>
<td>~60</td>
</tr>
<tr>
<td>Level 2</td>
<td>$2.5 \times 10^6$</td>
<td>$1.5 \times 10^3$</td>
<td>$3.8 \times 10^9$</td>
<td>~4.5</td>
</tr>
<tr>
<td>Storage</td>
<td>$0.56 \times 10^9$</td>
<td>$1.6 \times 10^3$</td>
<td>$0.9 \times 10^9$</td>
<td></td>
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</table>

Data from DAQ and Montecarlo

- Montecarlo (~5x10^{11} events)
- Total: ~1.5 PB/year

CPU for Reconstruction Analysis and Montecarlo

- 120 million core-hours for Monte Carlo jobs
- 90 million core-hours for data reconstruction jobs
- Total: ~ 70 million core-hours /year

(estimates by projecting current OSG usage)
Montecarlo Campaign 2024

Detector performance and New Physics reach for proposal at GSI

- Generate & Process ~10^{11} events
- Corresponds to 1:10,000 of the expected interactions (20% of experiment Montecarlo production)

Simulation schema

Event generation

- Step 1: Event generation
  - I/O: root, hepevt, stdhep, lhe, lcio

- Step 2: Geant4 simulation
  - **Slic** (C++)
  - I/O: stdhep, lcio

Reconstruction/Analysis

- Step 3: Trigger
  - **Lcsim** (java)
  - I/O: lcio

- Step 4: Reconstruction
  - **Lcsim** (java)
  - I/O: lcio

3/4/2021 C. Gatto - INFN & NIU
Simulation Architecture

Evt generation
GenieHad

- #events: 20k
- runtime: ~2h+8h (with a tail up to 18h)
- memory: ~1250 MB
- input: none
- output: ~17MB

Simulation
slic/G4

- #events: 10k
- runtime: ~3h
- memory: 0.8+1.3 GB
- input: 17MB data
- output: ~3GB

TL0/TL1
lcsim/java

- #events: from previous stage
- runtime: 10minutes
- memory: 1.4+1.5 GB
- input: ~3GB data
- output: ~15MB

Reconstruction
lcsim/java

- #events: 100 files from previous stage
- runtime: 1h
- memory: 1.4+1.5 GB
- input: ~1.5GB data
- output: ~1.5GB

- These stages are combined in the same job
- requirements:
  - 1CPU;
  - 1500MB memory;
  - 5GB disk
- Intermediate data are removed (transient) saving several PB of I/O
- Apptainer container + some dependencies from CVMFS

- Use as input 100 trigger jobs
- requirements:
  - 1CPU;
  - 1500MB memory;
  - 5GB disk
- Apptainer container + some dependencies from CVMFS
Summary for last 5.5 months of running:

- **115B events**
- **5.86M jobs**
- **32.9M Core-h**
- **28.4M CPU-h**
- **Eff: ~0.86**

  - ~10k total failed jobs mostly due to file transfers and worker node issues
  - 98 failed jobs due to code issues

**REDTOP**

- Job efficiency

---

**Core Hours per Project**

- REDTOP: 22.9 Mh
- LIGO: 21.2 Mh
- IceCube: 24.1 Mh
- dune: 22.2 Mh
- CLAS12: 18.4 Mh
- cms.org.cern: 16.9 Mh
- WISU_3DHydro: 16.1 Mh
- cms.org.ku: 11.2 Mh
- fermilab: 9.92 Mh
- KOTO: 9.12 Mh
- PixleyLab: 7.60 Mh
- ePIC: 6.95 Mh
- microboone: 6.62 Mh
- gluex: 6.44 Mh
- UConn_Le: 8.01 Mh
- CMI_Uscayev: 5.46 Mh
- Rice_Mulligan: 5.39 Mh
- gm2: 5.25 Mh
- EvoSims: 5.05 Mh
- Syracuse_Nitz: 4.61 Mh
- mu2e: 4.20 Mh
- nova: 4.18 Mh
- Biomedinfo: 3.82 Mh
- cms.org.baylor: 3.77 Mh
- UCSF_Politis: 3.76 Mh
- icarus: 2.82 Mh
- SSGAforCSP: 3.11 Mh
- CSUN_Katz: 3.01 Mh
- xenon: 3.00 Mh
- NCSU_Hall: 2.99 Mh
- Vanderbilt_Paquet: 2.54 Mh

**CPU Hours per Project**

- REDTOP: 28.4 Mh
- LIGO: 14.1 Mh
- IceCube: 13.7 Mh
- dune: 14.0 Mh
- CLAS12: 13.3 Mh
- dune: 7.69 Mh
- KOTO: 6.73 Mh
- PixleyLab: 5.60 Mh
- ePIC: 5.80 Mh
- UConn_Le: 5.54 Mh
- fermilab: 5.72 Mh
- gluex: 5.01 Mh
- cms.org.cern: 4.97 Mh
- Syracuse_Nitz: 3.61 Mh
- gm2: 3.21 Mh
- EvoSims: 3.05 Mh
- UCSF_Politis: 2.77 Mh
- CSUN_Katz: 2.72 Mh
- NCSU_Hall: 2.45 Mh
- microboone: 2.52 Mh
- Vanderbilt_Paquet: 2.34 Mh
- Rice_Mulligan: 2.30 Mh
- UC_Berkeley_Altman: 2.10 Mh
- Biomedinfo: 2.10 Mh
- xenon: 1.92 Mh
- Rice_Li: 1.77 Mh
- mu2e: 1.61 Mh
- PSI_Kaib: 1.46 Mh
- SSGAforCSP: 1.41 Mh
- SNU_Lla: 1.15 Mh
- CMU_Uscayev: 1.16 Mh

**Job Count per Project**

- Biomedinfo: 23.0 Mh
- LIGO: 17.1 Mh
- IceCube: 16.5 Mh
- dune: 15.1 Mh
- KOTO: 10.3 Mh
- WISU_3DHydro: 9.19 Mh
- EvoSims: 7.93 Mh
- CSUN_Katz: 7.76 Mh
- REDTOP: 5.86 Mh
- fermilab: 5.42 Mh
- xenon: 5.22 Mh
- des: 4.85 Mh
- microboone: 4.75 Mh
- UC_Berkeley_Altman: 4.71 Mh
- UAR_Thyme: 4.52 Mh
- icarus: 3.87 Mh
- KOTO: 3.74 Mh
- cms.org.cern: 3.59 Mh
- CLAS12: 2.70 Mh
- CSUN_Katz: 2.56 Mh
- ePIC: 2.27 Mh
- nova: 1.96 Mh
- Syracuse_Nitz: 1.95 Mh
- gluex: 1.86 Mh
- NOAA_Bell: 1.84 Mh
- UCSF_Politis: 1.77 Mh
- gm2: 1.76 Mh
- PSFModeling: 1.65 Mh
- NCSU_Hall: 1.46 Mh
- DamoSims: 1.23 Mh
- Vanderbilt_Paquet: 1.23 Mh
OSG Daily Usage Statistics

Wall Hours per 1d

Total Jobs per 1d
OSG Yearly Usage Statistics for REDTOP project

- Time range: 01/23 – 07/07
- Total Core Hours: 32.9 million
- Total jobs: 5.86 million

Core Hours by Facility:

- SU ITS: 11 Mil
- MWT2 ATLAS UC: 7 Mil
- FermiGrid: 4 Mil
- GLOW: 2 Mil
- AGLT2: 2 Mil
- BNL ATLAS Tier1: 800 K
- Michigan HORUS: 779 K
- PSU LIGO: 502 K
- UColorado_HEP: 493 K
- UConn-HPC: 397 K
- Nebraska-Omaha: 380 K
- Nebraska-CMS: 315 K
- Beocat: 279 K
- University of Washington Research: 265 K
- Rhodes-HPC: 245 K
- San Diego Supercomputer Center: 208 K
- Clemson-Palmetto: 197 K
- NWICG_NDCMS: 107 K
- Lafayette College: 101 K
- SIUE - CC: 97 K
Conclusions

• Medium-sized experiments complement large facilities in a much shorter time scale and focus on the MeV-GeV region

• All meson factories: LHCb, B-factories, Dafne, J/psi - have produced a broad spectrum of nice physics. An $\eta/\eta'$ factory will do the same

• REDTOP has been designed specifically to study rare processes and to discover physics BSM in the MeV-GeV mass region

• Only experiment (with SHIP) sensitive to all four DM portals

• Very large physics reach for NP as well

• New detector techniques benefit the next generation of high intensity experiments

• Beam requirements could be met by several labs in US, Europe, and Asia

Thanks to OSG Collaboration Support and Pascal Paschos for their effort on pushing REDTOP forward

Backup Slides
## Present & Future $\eta$ Samples

<table>
<thead>
<tr>
<th>Technique</th>
<th>$\eta \rightarrow 3\pi^0$</th>
<th>$\eta \rightarrow e^+e^-\gamma$</th>
<th>Total $\eta$ mesons</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB@AGS $\pi^- p \rightarrow \eta n$</td>
<td>9×10⁵</td>
<td></td>
<td>10⁷</td>
</tr>
<tr>
<td>CB@MAMI C&amp;B $\gamma p \rightarrow \eta p$</td>
<td>1.8×10⁶</td>
<td>5000</td>
<td>2×10⁷ + 6×10⁷</td>
</tr>
<tr>
<td>BES-III $e^+e^- \rightarrow J/\psi \rightarrow \eta \gamma + \eta$ hadrons</td>
<td>6×10⁶</td>
<td></td>
<td>1.1×10⁷ + 2.5×10⁷</td>
</tr>
<tr>
<td>KLOE-II $e^+e^- \rightarrow \Phi \rightarrow \eta \gamma$</td>
<td>6.5×10⁵</td>
<td></td>
<td>~10⁹</td>
</tr>
<tr>
<td>WASA@COSY $pp \rightarrow \eta pp$ $pd \rightarrow \eta ^3$He</td>
<td></td>
<td></td>
<td>&gt;10⁹ (untagged) 3×10⁷ (tagged)</td>
</tr>
<tr>
<td>CB@MAMI 10 wk (proposed 2014) $\gamma p \rightarrow \eta p$</td>
<td>3×10⁷</td>
<td>1.5×10⁵</td>
<td>3×10⁸</td>
</tr>
<tr>
<td>Phenix $d Au \rightarrow \eta X$</td>
<td></td>
<td></td>
<td>5×10⁹</td>
</tr>
<tr>
<td>Hades $pp \rightarrow \eta pp$ $p Au \rightarrow \eta X$</td>
<td></td>
<td></td>
<td>4.5×10⁸</td>
</tr>
</tbody>
</table>

### Near future samples

<table>
<thead>
<tr>
<th>Technique</th>
<th>$\gamma_{12\text{ GeV}} p \rightarrow \eta X \rightarrow$ neutrals</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GlueX@JLAB (running)</strong></td>
<td>$\gamma_{12\text{ GeV}} p \rightarrow \eta X \rightarrow$ neutrals</td>
<td>5.5×10⁷/yr</td>
</tr>
<tr>
<td><strong>JEF@JLAB (construction)</strong></td>
<td>$\gamma_{12\text{ GeV}} p \rightarrow \eta X \rightarrow$ neutrals</td>
<td>3.9×10⁵/day</td>
</tr>
<tr>
<td><strong>REDTOPO (proposing)</strong></td>
<td>$p_{1.8\text{ GeV}} Li \rightarrow \eta X$</td>
<td>3.4×10¹³/yr</td>
</tr>
</tbody>
</table>
The physics case for REDTOP

Physics case presented in 176-pp White Paper. Sensitivity studies based on \(10^{14}\) \(\eta\) mesons (3.3x10^{18} POT and 3-yr run), >30x10^6 CPU-Hr on OSG+NICADD

15 processes fully simulated and reconstructed – 20 theoretical models benchmarked

- Four BSM portals
- Three CP violating processes requiring no \(\mu\)-polarization measurement
- A fourth CP violating processes under study
- Three CP violating processes requiring \(\mu\)-polarization measurement
- Two lepton flavor universality studies
- Two lepton flavor violation studies

**Key detector parameters**

- Large sensitivity to <17 Mev mass resonances (compared to WASA and KLOE)
- Tracking capable to reconstruct detached vertices up to ~100 cm
- Sensitivity to BR \(\sim\mathcal{O}(10^{-11})\) (\(\sim\mathcal{O}(10^{-12})\) with pion beam)
- Detector optimization under way
REDTOP Computing Model

**Model architecture:**

- Single-core computational workflow has proven to be well suited for the distributed High Throughput Computing (DHTC) environment of the OSG.
- Model already adopted by other small Collaborations (IceCube, XENON, et. al.)

**Storage:**

- DataStream from the L-2 farm will be staged at (FNAL) dCache storage and sent to tape (or wherever is cheaper when the experiment runs: FNAL at present)
- Stratum-0 server hosts a CVMFS repository of the REDTOP software

**CPU:**

- Any (dedicated or opportunistic) OSG working node
- Member institutions can join the OSG federation and accept jobs from OSG’s GlideinWMS job factory via a HostedCE deployment.
Typical jobs are submitted from an OSG Connect submit host. Data are delivered to the remote worker nodes via stashcp and software over CVMFS.

Data designated for long term storage will be archived to tape at a collaboration facility.

Collaboration institutions might set up their own submit hosts but the bulk of the access to the OSG would be from the Connect infrastructure - at least in the beginning.

We are investigating the adoption of Rucio for the data management to allocated storage provided by participating institutions.
Vector Portal: $\eta \to \gamma A'$ with $A' \to l^+ l^-$ or $\pi \pi$

Some BR sensitivity curves

Theoretical Models considered
- Minimal dark photon model
  - Most popular model
- Leptophobic $B$ boson Model
- Protophobic Fifth Force
  - Explains the Atomki anomaly

FIG. 36. Sensitivity to to $\varepsilon^2$ for the processes $\eta \to \gamma A'$ for integrated beam flux of $3.3 \times 10^{18}$ POT. Left plot: bump-bump analysis. Right plot: detached-vertex analysis.
Pseudoscalar Portal: $\eta \rightarrow \pi^0 \pi^0 a$ & $\eta \rightarrow \pi^+ \pi^- a$

with $a \rightarrow \gamma \gamma$, $\mu^+ \mu^-$ and $e^+ e^-$

New particles & forces

17 MeV piophobic QCD axion

Some BR sensitivity curves

Differential rate for $\eta \rightarrow \pi^+ \pi^- a$ for three benchmark params

Theoretical models considered

- Piophobic QCD axion model (D. S. M. Alves)
  - Below KLOE sensitivity
  - the CELSIUS/WASA Collaboration observed 24 events with SM expectation of 10

- Heavy Axion Effective Theories
CP Violation from Dalitz plot mirror asymmetry in \( \eta \rightarrow \pi^+ \pi^- \pi^0 \)

- CP-violation from this process is not bounded by EDM as is the case for the \( \eta \rightarrow 4\pi \) process.

- Complementary to EDM searches even in the case of T and P odd observables, since the flavor structure of the eta is different from the nucleus.

- Current PDG limits consistent with no asymmetry.


Slide Credit: Susan Gardner & Jun Shi

REDTOP sensitivity to model parameters

<table>
<thead>
<tr>
<th>#Rec. Events</th>
<th>Re((\alpha))</th>
<th>Im((\alpha))</th>
<th>Re((\beta))</th>
<th>Im((\beta))</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(10^8) (no-bkg)</td>
<td>(3.3 \times 10^{-1})</td>
<td>(3.7 \times 10^{-1})</td>
<td>(4.4 \times 10^{-4})</td>
<td>(5.6 \times 10^{-4})</td>
<td>17%</td>
</tr>
<tr>
<td>Full stat. (no-bkg)</td>
<td>(1.9 \times 10^{-2})</td>
<td>(2.1 \times 10^{-2})</td>
<td>(2.5 \times 10^{-5})</td>
<td>(3.2 \times 10^{-5})</td>
<td>17%</td>
</tr>
<tr>
<td>Full stat. (100%-bkg)</td>
<td>(2.3 \times 10^{-2})</td>
<td>(3.0 \times 10^{-2})</td>
<td>(3.5 \times 10^{-5})</td>
<td>(4.5 \times 10^{-5})</td>
<td>16%</td>
</tr>
</tbody>
</table>
CP Violation from the asymmetry of the decay planes in $\eta \rightarrow \mu^+\mu^-e^+e^-$ and $\eta \rightarrow \pi^+\pi^-e^+e^-$

- Requires the measurement of angle between pions and leptons decay planes

**CP violation is related to asymmetries in**

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

$A_{\sin\phi\cos\phi} = \frac{N(\sin\phi\cos\phi > 0) - N(\sin\phi\cos\phi < 0)}{N(\sin\phi\cos\phi > 0) + N(\sin\phi\cos\phi < 0)}$

$A_{\sin\phi} = \frac{N(\sin\phi > 0) - N(\sin\phi < 0)}{N(\sin\phi > 0) + N(\sin\phi < 0)}$

**through Wilson coefficients**

$A_{\sin\phi\cos\phi} = \text{Im}[1.92^{222}_2 - 1.3(\eta_{\text{adj}}^{1121} + \eta_{\text{adj}}^{1122})] \times 10^{-5} - 0.2e_1 + 0.0003e_2$

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

$A_{\phi} = \frac{N(\sin\phi\cos\phi > 0) - N(\sin\phi\cos\phi < 0)}{N(\sin\phi\cos\phi > 0) + N(\sin\phi\cos\phi < 0)}$

**10^{-3} sensitivity to**

$A_{\cos\phi} \sin\phi$, $A_{\sin\phi}$
CP Violation in $\eta \rightarrow (\gamma, \pi^0)\mu^+\mu^-$


- Requires the measurement of $\mu$-polarization to form the following asymmetries

\[
\begin{align*}
A_L &= \frac{N(\cos \theta > 0) - N(\cos \theta < 0)}{N} = \text{Im}[4.1c_{\text{equ}}^{p_{222}} - 2.7(c_{\text{equ}}^{1122} + c_{\text{equ}}^{2211})] \times 10^{-2}, \\
A_x &= \frac{N(\sin \Phi > 0) - N(\sin \Phi < 0)}{N} = \text{Im}[2.5c_{\text{equ}}^{p_{222}} - 1.6(c_{\text{equ}}^{1122} + c_{\text{equ}}^{2211})] \times 10^{-3},
\end{align*}
\]

---

**REDTOP sensitivity to Wilson CP violating Wilson coefficients**

<table>
<thead>
<tr>
<th>Process</th>
<th>Trigger</th>
<th>Trigger</th>
<th>Trigger</th>
<th>Reconstruction + analysis</th>
<th>Total Branching ratio sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta \rightarrow \mu^+\mu^-$</td>
<td>L0</td>
<td>L1</td>
<td>L2</td>
<td></td>
<td>3.9%</td>
</tr>
<tr>
<td>Urqmd</td>
<td>21.7%</td>
<td>1.7%</td>
<td>22.2%</td>
<td>8.6 $\times 10^{-3}$%</td>
<td>7.0 $\times 10^{-6}$%</td>
</tr>
</tbody>
</table>

$\Delta(c_{\text{equ}}^{1122}) = 0.1 \times 10^{-1}$, $\Delta(c_{\text{equ}}^{1221}) = 0.1$, $\Delta(c_{\text{equ}}^{2222}) = 6.6 \times 10^{-2}$,
Lepton Universality Studies

LHCb latest results using $B^+ \rightarrow \mu^+\mu^-K^+$ vs $e^+e^-K^+$: $3.1\sigma$ discrepancy vs SM

### TABLE XLII. Statistical error from the fit of $\eta \rightarrow \gamma$ lepton – antilepton and Urqund background using a gaussian and a 5th-order polynomial, for $1.38 \times 10^{18}$ POT

<table>
<thead>
<tr>
<th>Process</th>
<th>POT</th>
<th>Signal events</th>
<th>Background events</th>
<th>$\frac{S}{\sqrt{B}}$</th>
<th>Statistical error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta \rightarrow \gamma e^+e^-$</td>
<td>$1.38 \times 10^{11}$</td>
<td>$1.13 \times 10^6$</td>
<td>$2.52 \times 10^4$</td>
<td>$1.3 \times 10^4$</td>
<td>0.09%</td>
</tr>
<tr>
<td>$\eta \rightarrow \gamma \mu^+\mu^-$</td>
<td>$1.38 \times 10^{11}$</td>
<td>$8.4 \times 10^6$</td>
<td>$6.5 \times 10^3$</td>
<td>$3.5 \times 10^3$</td>
<td>0.14%</td>
</tr>
</tbody>
</table>

Theoretical calculations at the $10^{-3}$ precision from Kampf, Novotný, Sanchez-Puertas (PR D 97, 056010 (2018))

- REDTOP statistical error for $\sim 10^{11}$ POT
- $\eta \rightarrow \gamma \mu^+\mu^-$ vs $\gamma e^+e^-$

- REDTOP reconstruction efficiency

- REDTOP statistical error for various POT

- LHCb @ 4.2% with 1640 evts
- LHCb @ 1.8% with 3850 evts

$\eta \rightarrow \mu^+\mu^-\mu^+\mu^- , e^+e^-\mu^+\mu^- , e^+e^- e^+e^-$
Beam Options for $10^{14}$ $\eta$ mesons

Baseline option – medium-energy CW proton beam
- proton beam on thin Li/Be target: ~1.8 GeV - 30 W ($10^{11}$ POT/sec)
- Low-cost, readily available (BNL, ESS, FNAL, GSI, HIAF)
- $\eta$: inelastic background = 1:200
- Untagged $\eta$ production

Preferred option – low-energy pion beam
- $\pi^+$ on Li/Be or $\pi$ on LH: ~750 MeV - 2.5x10$^{10}$ $\pi$OT/sec
- More expensive but lower background (ESS, FNAL(?), FAIR, HIAF, ORNL)
- $\eta$: inelastic background = 1:50 → sensitivity to BSM increased by > 2x
- Semi-tagged $\eta$ production

Ultimate option: Tagged $10^{13}$ $\eta$ mesons
- high intensity proton beam on De target: ~0.9 GeV ; 0.1-1 MW
- Less readily available: (ESS, FAIR, CSNS, ORNL, PIP-II)
- Required fwd tagging detector for He$_3$$^{++}$
- Fully tagged production from nuclear reaction: $p+$De $\rightarrow$ $\eta$ +He$_3$$^{++}$
Beam Options for $10^{14}$ $\eta$ mesons

Baseline option – medium-energy CW proton beam

- Proton beam on thin Li/Be target: $\sim$ 1.8 GeV - 30 W ($10^{11}$ POT/sec)
- Low-cost, readily available (BNL, ESS, FNAL, GSI, HIAF)
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- $\pi^+$ on Li/Be or $\pi^-$ on LH: $\sim$750 MeV - 2.5x$10^{10}$ $\pi$OT/sec
- More expensive but lower background (ESS, FNAL, FAIR, HIAF, ORNL)
- $\eta$: inelastic background = 1:50 $\rightarrow$ sensitivity to BSM increased by $>2$x
- Semi-tagged $\eta$ production

Only $\sim$1% of the proton or pion beam interacts with REDTOP

Remaining beam can be used for a downstream pion and/or muon precision experiment

Ultimate option: Tagged $10^{13}$ $\eta$ mesons

- High intensity proton beam on De target: $\sim$0.9 GeV ; 0.1-1 MW
- Less readily available: (ESS, FAIR, CSNS, ORNL, PIP-II)
- Required fwd tagging detector for $\text{He}_3^{++}$
- Fully tagged production from nuclear reaction: $p+\text{De} \rightarrow \eta +\text{He}_3^{++}$

vs LHCb@40 MHz

Inelastic interaction rate: $\sim$ 0.7 GHz
Average event multiplicity $\approx$ 4 charged + 4 neutral
$\eta/\eta'$ production rate: $\sim$ 2.3 MHz

Remaining beam can be used for a downstream pion and/or muon precision experiment
Detector Requirements and Technology

- Sustain up to 0.7 GHz event rate with avg final state multiplicity of ~8 particles
- Calorimetric $\sigma(E)/E \sim 2-3%/\sqrt{E}$
- High PID efficiency: 98/99% (e,$\gamma$), 95% ($\mu$), 95% ($\pi$), 99.5%(p,n)
- $\sigma_{\text{tracker}}(t) \sim 30\,\text{psec}$, $\sigma_{\text{calorimeter}}(t) \sim 80\,\text{psec}$, $\sigma_{\text{TOF}}(t) \sim 50\,\text{psec}$
- Low-mass vertex detector
- Near-$4\pi$ detector acceptance (as the $\eta/\eta'$ decay is almost at rest).

**charged tracks detection**

- LGAD Tracker
  - 4D track reconstruction for multihadron rejection
  - Material budget < 0.1% r.l./layer

**EM + had calorimeter**

- ADRIANO2 calorimeter (Calice+T1604)
- ADRIANO3 rear section with Fe absorbers
- PFA + Dual-readout+HG
- Light sensors: SiPM or SPADs
- 96.5% coverage

**Vertex reconstruction**

- Option 1: Fiber tracker (LHCb style)
  - Established and low-cost technology
  - ~70$\mu$m vertex resolution in x-y. Stereo layers

- Option 2: HV-MAPS (Mu3e style)
  - Low material budget (0.11%/layer)
  - ~40$\mu$m vertex resolution in 3D

**Cerenkov Threshold TOF**

- Option 1: Quartz tiles
  - Established and low-cost technology
  - ~50psec timing with T1604 prototype

- Option 2: EIC-style LGAD
  - ~30-40 psec timing, but expensive
Future Prospects for REDTOP

Baseline detector layout defined (with options for vtx and μpol detectors)

- Sensitivity studies helped to consolidate the detector requirements and to drive cost optimization
- VTX Fiber Tracker replaced by HV-MAPS detector
- Muon polarimeter requires further studies

Next steps:

- **Initial funding from US agencies (mid-RI proposal – $2-10M)**
- Prepare a CDR to support the proposal of the experiment to one (or more) of the interested laboratories
- Consolidate the detector R&D (ongoing)
Why the $\eta$ meson is special?

- It is a Goldstone boson
- Symmetry constrains its QCD dynamics

- It is an eigenstate of the C, P, CP and G operators (very rare in nature): $I^G J^{PC} = 0^+ 0^+$
- It can be used to test C and CP invariance.

- All its additive quantum numbers are zero
  
  \[ Q = I = j = S = B = L = 0 \]
- Its decays are not influenced by a change of flavor (as in K decays) and violations are “pure”

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

- EM decays are forbidden in lowest order by C invariance and angular momentum conservation
- Decays are free of SM backgrounds for new physics search

- The $\eta$ decays are flavor-conserving reactions
- $\eta$ is an excellent laboratory to search for physics Beyond Standard Model
Inelastic p-Li scattering probability (percentage):

<table>
<thead>
<tr>
<th>Model</th>
<th>p-Li cross section $[cm^{-2}]$</th>
<th>p-Li interaction prob.</th>
<th>p-Target interaction prob.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wellisch &amp; Axen</td>
<td>$2.01 \times 10^{-25}$</td>
<td>0.710</td>
<td>0.719</td>
</tr>
<tr>
<td>Tripathi Light</td>
<td>$1.96 \times 10^{-25}$</td>
<td>0.693</td>
<td>0.702</td>
</tr>
<tr>
<td>Incl++</td>
<td>$1.60 \times 10^{-25}$</td>
<td>0.567</td>
<td>0.574</td>
</tr>
<tr>
<td>Sihver et. al</td>
<td>$1.51 \times 10^{-25}$</td>
<td>0.535</td>
<td>0.543</td>
</tr>
<tr>
<td>Barashenkov</td>
<td>$1.73 \times 10^{-25}$</td>
<td>0.612</td>
<td>0.620</td>
</tr>
<tr>
<td>Shen et. al</td>
<td>$2.0 \times 10^{-25}$</td>
<td>0.707</td>
<td>0.715</td>
</tr>
<tr>
<td>Kox et. al</td>
<td>$2.98 \times 10^{-25}$</td>
<td>1.06</td>
<td>1.07</td>
</tr>
<tr>
<td>Average</td>
<td>$1.98 \pm 0.48 \times 10^{-25}$</td>
<td>0.70 $\pm$ 0.17</td>
<td>0.71 $\pm$ 0.17</td>
</tr>
</tbody>
</table>

Inelastic interaction rate: $\sim 0.7$ GHz

Evaluation of $\eta/\eta'$ yield for $3.3 \times 10^{18}$ POT (3.3 years running at $1 \times 10^{18}$ POT/yr)

<table>
<thead>
<tr>
<th>Nuclear collision model</th>
<th>$p+Li$ $\eta$ yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urqmd [208]</td>
<td>0.49%</td>
</tr>
<tr>
<td>Incl++ v6.2 [209]</td>
<td>1.48%</td>
</tr>
<tr>
<td>Gibuu v2019 [210]</td>
<td>0.74%</td>
</tr>
<tr>
<td>PHSD v 4.0 [211]</td>
<td>0.67%</td>
</tr>
<tr>
<td>Jam v1.9 [212]</td>
<td>0.26%</td>
</tr>
<tr>
<td>Average</td>
<td>(0.73 $\pm$ 0.46)%</td>
</tr>
</tbody>
</table>

$\eta/\eta'$ production rate: $\sim 2.3$ MHz
Simulation Framework For Physics & Detector Studies

**Event generator: GenieHad**

- Proprietary (not yet public) package interfacing standalone generators to genie

<table>
<thead>
<tr>
<th>Package</th>
<th>Model</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urqmd [210]</td>
<td>QMD</td>
<td>Microscopic many body approach</td>
</tr>
<tr>
<td>Incl ++ v6.2 [211]</td>
<td>INCL</td>
<td>Intranuclear cascade</td>
</tr>
<tr>
<td>Gibbs v2019 [212]</td>
<td>BUU</td>
<td>time evolution of Kadanoff-Baym-equations</td>
</tr>
<tr>
<td>PHSD v 4.0 [213]</td>
<td>HSD</td>
<td>covariant transport with NJL-type Lagrangian</td>
</tr>
<tr>
<td>Jam v1.9 [214]</td>
<td>Cascade/RQMD.RMF/BUU</td>
<td>Multi-model - hybrid approach</td>
</tr>
<tr>
<td>Dpmjet-III [240]</td>
<td>Dual Parton/ perturbative QCD</td>
<td>Multi-model approach</td>
</tr>
<tr>
<td>Pythia 7, 8 [239]</td>
<td>LUND</td>
<td>string hadronization model</td>
</tr>
<tr>
<td>IAEA tables [241]</td>
<td>LUT of measured cross sections</td>
<td>Look-up tables based on ENDF (by IAEA)</td>
</tr>
<tr>
<td>Intranuke [242]</td>
<td>Parametric</td>
<td></td>
</tr>
<tr>
<td>ALPACA [243]</td>
<td>Alpaca</td>
<td>Bremsstrahlung of Axion-Like-Particles (ALPs)</td>
</tr>
</tbody>
</table>

**Simulation: slic**

- Geant4 interface from SLAC
- Proprietary adds-on for REDTOP specific detectors

**Digitization, reconstruction, analysis: lcsim**

- Java package from ILC and HPS (jlab)
- Geometry adds-on for REDTOP specific detectors, beam components, and magnetic fields
- Histograms and fitting in Jas3, Jas4app
**η/η’ yield and background evaluation**

**Inelastic p-Li scattering probability (percentage):**

<table>
<thead>
<tr>
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<td>0.535</td>
<td>0.543</td>
</tr>
<tr>
<td>Barashenkov</td>
<td>(1.73 \times 10^{-25})</td>
<td>0.612</td>
<td>0.620</td>
</tr>
<tr>
<td>Shen et. al</td>
<td>(2.0 \times 10^{-25})</td>
<td>0.707</td>
<td>0.715</td>
</tr>
<tr>
<td>Kox et. al</td>
<td>(2.98 \times 10^{-25})</td>
<td>1.06</td>
<td>1.07</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>(1.98 \pm 0.48 \times 10^{-25})</td>
<td>0.70 \pm 0.17</td>
<td>0.71 \pm 0.17</td>
</tr>
</tbody>
</table>

Inelastic interaction rate: \(~ 0.7\) GHz

**Evaluation of η/η’ yield for 3.3x10\(^{18}\) POT (3.3 years running at 1x10\(^{18}\) POT/yr)**

<table>
<thead>
<tr>
<th>Nuclear collision model</th>
<th>p+Li η yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urqmd [208]</td>
<td>0.49%</td>
</tr>
<tr>
<td>Incl++ v6.2 [209]</td>
<td>1.48%</td>
</tr>
<tr>
<td>Gibuu v2019 [210]</td>
<td>0.74%</td>
</tr>
<tr>
<td>PHSD v 4.0 [211]</td>
<td>0.67%</td>
</tr>
<tr>
<td>Jam v1.9 [212]</td>
<td>0.26%</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>(0.73 ± 0.46)%</td>
</tr>
</tbody>
</table>

η/η’ production rate: \(~ 2.3\) MHz
Beam scheme for FNAL option (M. Syphers)

Single $p$ pulse from booster ($\leq 4 \times 10^{12}$ $p$) injected in the DR (former debuncher in anti-$p$ production at Tevatron) at fixed energy (8 GeV)

Energy is removed by inserting 1 or 2 RF cavities identical to the one already planned (~5 seconds)

Slow extraction to REDTOP over ~40 seconds.

The $270^\circ$ of betatron phase advance between the Mu2e Electrostatic Septum and REDTOP Lambertson is ideal for AP50 extraction to the inside of the ring.

Total time to decelerate-debunch-extract: 51 sec: duty cycle ~80%
Accelerator Physics Issues

- **Transition Energy**
  - $\gamma_t$ is where $\Delta f/f = 1/\gamma 2 - \langle D/\rho \rangle = 0$; synchrotron motion stops momentarily, can often lead to beam loss
  - beam decelerates from $\gamma = 9.5$ to $\gamma = 3.1$
  - original Delivery Ring $\gamma_t = 7.6$
  - a re-powering of 18 quadrupole magnets can create a $\gamma_t = 10$, thus avoiding passing through this condition

- **Resonant Extraction**
  - Mu2e will use 1/3-integer resonant extraction
  - REDTOP can use same system, with use of the spare Mu2e magnetic septum
  - initial calculations indicate sufficient phase space, even with the larger beam at the lower energies

- **Vacuum**
  - REDTOP spill time is much longer than for Mu2e
  - though beam-gas scattering emittance growth rate 3 times higher at lower energy, still tolerable level
Beam Options at GSI/FAIR (near future)

Opportunities as fixt target exp.

OPTION A
Fixt target (SIS18)

- HEST towards pion target
- 1e11 p/spill (time structure flexible) at SIS18
- Residual beam might be used for Hades pion program
- Additional shielding and cave need to be evaluated
- High intensity needs exclusive proton operation

OPTION B
Fixt target (SIS100)

- p-bar target area
- 2e12 p/spill (time structure flexible) at SIS100
- Parallel operation possible due to p-LINAC
- Shielding and cave need to be evaluated
- Actual timeline beyond 2028

Beam intensity: 1.8 GeV protons with 1e11/s

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**Beam Options at GSI (far future)**

**Opportunities as in-ring target exp.**

- **OPTION C**
  - ESR
  - 1e6 p/injection (1-2 MHz revolution rate)
  - Full beam usage

- **OPTION D**
  - HESR or CR
  - Intensity fully flexible
  - Full beam usage

  - Parallel operation possible due to p-LINAC
  - Standard installation needs to be discussed
  - Actual timeline beyond 2030

---

**Beam intensity:** 1.8 GeV protons with 1e11/s

Daniel Severin

_C. Gatto – V. Di Benedetto_
Beam Options at HIAF (near future)

- Beam intensity: $0.5 \sim 1.0 \times 10^{13} \text{ ppp} (1 \sim 5 \times 10^{13} \text{ pps})$ in Terminal 2. $10^{18-19} \text{ POT/yr}$

- Energy from 2.0 to 9 GeV around 2028 – 2030

- Plans are to combine REDTOP with an experiment on hypernuclei

- Beam extracted from the Booster Ring (BRing) to the Multi-function terminal and be used for REDTOP.

- The transfer beam line construction already included in the HIAF project.

- The maximum magnetic rigidity is 34 Tm which means a proton beam up to 9.3 GeV can be provided end 2025
Detector Requirements: BSM physics driven

LFU: Tagged lepton production from flavor-conserving decays
• excellent e/π/μ separation

QCD axion
• *Calorimetric sensitivity to M(γγ)~30MeV*

17 MeV e⁺e⁻ state (Atomki experiment)
• *Tracker sensitivity to M(e⁺e⁻)~ 20 MeV*
• *Electron ID at very low energy*

CP violation with muons
• *Muon polarimeter or high-granularity calorimeter*
## Subdetector Technologies

<table>
<thead>
<tr>
<th>Target</th>
<th>Baseline (White paper)</th>
<th>Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li foils</td>
<td>10x 0.78mm</td>
<td>LH$_2$ 11 cm</td>
</tr>
<tr>
<td>VTX</td>
<td>LHCb fiber tracker. REDTOP: 0.24m$^2$ vs LHCb: 360m$^2$</td>
<td>CMOS (ITS3) or hybrid (fiber+1 layer CMOS)</td>
</tr>
<tr>
<td>Central tracker</td>
<td>LGAD 100μm/layer eq., no active cooling (30 psec/layer). REDTOP: 14m$^2$ vs CMS: 16m$^2$</td>
<td>LGAD 120μm/layer eq., no active cooling (42 psec/layer)</td>
</tr>
<tr>
<td>TOF</td>
<td>1 layer 30x30x10 mm$^3$ JGS1 + Petiroc (50 psec/layer). Area: 3.7 m$^2$</td>
<td>2 layers, 30x30x10 or 20x20x10 mm$^3$ JGS1 + Liroc+Tsinghua TDC/PicoTDC (&lt;30 psec/layer). Area: 9.4 m$^2$</td>
</tr>
<tr>
<td>Calorimeter</td>
<td>ADRIANO2: 53 layers 30x30x14 mm$^3$ SF57/cast scint (80 psec/cell) 800,000 tile pairs</td>
<td>ADRIANO2: 30 layers 30x30x14 mm$^3$ ZF2/ scint + 23 layers JGS1/Cu/scint (80 psec/cell) 400,000 tile pairs</td>
</tr>
<tr>
<td>μ-polarimeter</td>
<td>Not implemented</td>
<td>TBD</td>
</tr>
</tbody>
</table>