The REDTOP experiment: a η/η′ factory to explore dark matter and physics beyond the Standard Model

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Presented at HTC2024

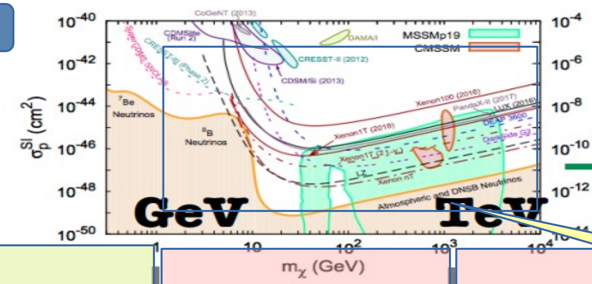
Rationale for an η/η' Factory

REDTOP

Cold dark matter scenarios

CDM bound ← BBN bound ←

keV MeV GeV TeV



~100 TeV, Violate unitarity →

Almost no space left for New Physics

Bound by cosmological observations	Mostly unconstrained	Disfavorite by LHC/Direct detection	Requires new facilities

"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 **η/η′ mesons** and the **Higgs boson (also the vacuum!)** ->very rare in nature
- The η meson is a **Goldstone boson** (the η′ meson is not!)
- The η/η′ 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 (~ 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 η/η′ factory is equivalent to a low energy Higgs factory and an excellent laboratory to probe New Physics below 1 GeV

REDTOP Key Points

REDTOP: η/η′ yielding ~10^{14}(10^{12}) mesons

- $\mathcal{O}(10^5)$ the existing world sample with a 3-yr run
- Existing worls 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

Test of CP invariance via Dalitz plot mirror asymmetry: $\eta \to \pi^o \pi^+ \pi^-$

Search for asymmetries in the dalitz plot with very high statistics

Test of CP invariance via μ polarization studies: $\eta \to \pi^o \mu^+ \mu^-$, $\eta \to \gamma \mu^+ \mu^-$, $\eta \to \mu^+ \mu^-$,

Measure the angular asymmetry between spin and momentum

Dark photon searches: $\eta \to \gamma A'$, with $A' \to \mu^+ \mu^-$, $A' \to e^+ e^-$

Need excellent vertexing and particle ID

QCD axion and ALP searches: $\eta \to \pi\pi a$, with $a \to \gamma\gamma$, $a \to \mu^+ \mu^-$, $a \to e^+ e^-$

Dual (or triple!) calorimeters and vertexing

Dark scalar searches: $\eta \to \pi^o H$, with $H \to \mu^+ \mu^-$, $H \to e^+ e^-$

Dual (or triple!) calorimeters and particle ID

Lepton Flavor Universality studies: $\eta \to \mu^+ \mu^- X$, $\eta \to e^+ e^- X$

Need excellent particle ID

Detecting BSM Physics with REDTOP (η/η' factory)

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

C, T, CP-violation

- *CP Violation via Dalitz plot mirror asymmetry:* $\eta \to \pi^o \pi^+ \pi^-$
- *CP Violation (Type I – P and T odd , C even):* $\eta \to 4\pi^o \to 8\gamma$
- *CP Violation (Type II - C and T odd , P even):* $\eta \to \pi^o \ell^+ \ell^-$ **and** $\eta \to 3\gamma$
- *Test of CP invariance via* μ *longitudinal polarization:* $\eta \to \mu^+ \mu^-$
- *CP inv. via* $\gamma*$ *polarization studies:* $\eta \to \pi^+ \pi^- e^+ e^-$ & $\eta \to \pi^+ \pi^- \mu^+ \mu^-$
- *CP invariance in angular correlation studies:* $\eta \to \mu^+ \mu^- e^+ e^-$
- *CP invariance in angular correlation studies:* $\eta \to \mu^+ \mu^- \pi^+ \pi^-$
- *CP invariance in* μ *polar. in studies:* $\eta \to \pi^o \mu^+ \mu^-$
- *T invar. via* μ *transverse polarization:* $\eta \to \pi^o \mu^+ \mu^-$ *and* $\eta \to \gamma \mu^+ \mu^-$
- *CPT violation:* μ *polr. in* $\eta \to \pi^+ \mu^- \nu$ *vs* $\eta \to \pi^- \mu^+ \nu$ *-* γ *polar. in* $\eta \to \gamma\gamma$

Other discrete symmetry violations

- *Lepton Flavor Violation:* $\eta \to \mu^+ e^- + c.c.$
- *Radiative Lepton Flavor Violation:* $\eta \to \gamma \mu^+ e^- + c.c.$
- *Double lepton Flavor Violation:* $\eta \to \mu^+ \mu^+ e^- e^- + c.c.$

Non-η/η' based BSM Physics

- *Neutral pion decay:* $\pi^o \to \gamma A' \to \gamma e^+ e^-$
- *ALP's searches in Primakoff processes:* $p\ Z \to p\ Z\ a \to l^+ l^-$
- *Charged pion and kaon decays:* $\pi+ \to \mu^+ \nu A' \to \mu^+ \nu e^+ e^-$ *and* $K+ \to \mu^+ \nu A' \to \mu^+ \nu e^+ e^-$
- *Dark photon and ALP searches in Drell-Yan processes: qqbar* $\to A'/a \to l^+ l^-$

New particles and forces searches

- *Scalar meson searches (charged channel):* $\eta \to \pi^o H$ *with* $H \to e^+ e^-$ *and* $H \to \mu^+ \mu^-$
- *Dark photon searches:* $\eta \to \gamma A'$ *with* $A' \to \ell^+ \ell^-$
- *Protophobic fifth force searches :* $\eta \to \gamma X_{17}$ *with* $X_{17} \to \pi^+ \pi^-$
- *QCD axion searches :* $\eta \to \pi\pi \boldsymbol{a}_{17}$ *with* $\boldsymbol{a}_{17} \to e^+ e^-$
- *New leptophobic baryonic force searches :* $\eta \to \gamma B$ *with* $B \to e^+ e^-$ *or* $B \to \gamma \pi^o$
- *Indirect searches for dark photons new gauge bosons and leptoquark:* $\eta \to \mu^+ \mu^-$ *and* $\eta \to e^+ e^-$
- *Search for true muonium:* $\eta \to \gamma (\mu^+ \mu^-)|_{2M_\mu} \to \gamma e^+ e^-$
- *Lepton Universality*
- $\eta \to \pi^o H$ *with* $H \to \nu N_2$ *,* $N_2 \to h' N_1$ *,* $h' \to e^+ e^-$

Other Precision Physics measurements

- *Proton radius anomaly:* $\eta \to \gamma \mu^+ \mu^-$ *vs* $\eta \to \gamma e^+ e^-$
- *All unseen leptonic decay mode of* η / η' *(SM predicts* 10^{-6} *-* 10^{-9}*)*

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)*

Detecting BSM Physics with REDTOP (η/η' factory)

REDTOP

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

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- *CPT violation:* μ *polar. [illegible]* $\to \pi\mu$ [illegible]

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- $\eta \to \pi H$ *with* $H \to \nu N_2$, $N_2 \to [illegible] N_1$, [illegible] $\to e^+e^-$

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

REDTOP detector

Central Tracker

~ 1m x 1.5 m

Thin LGAD

98% coverage

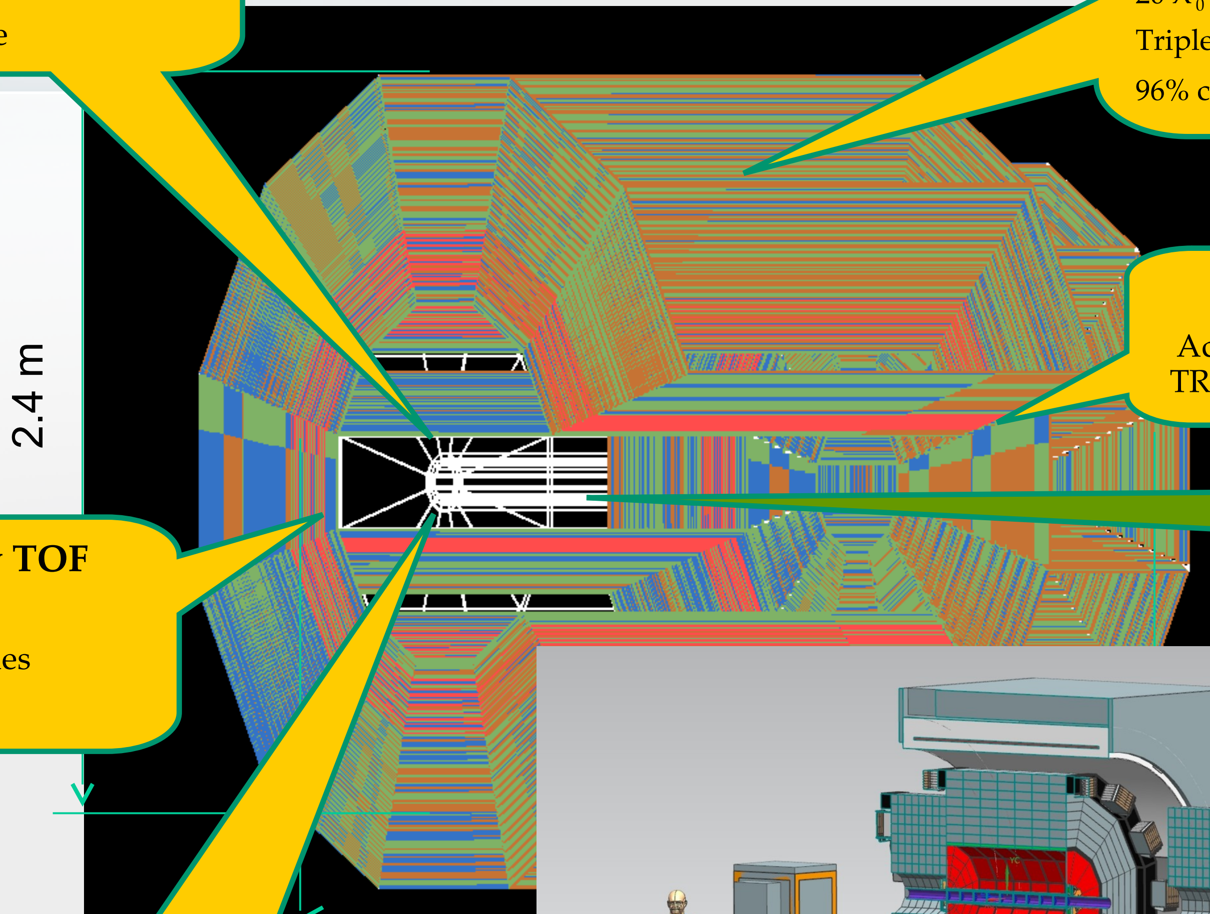
ADRIANO2(3) Calorimeter (tiles)

Scint. + heavy glass sandwich + RPC

20 X_0 (~ 64 cm deep)

Triple-readout +PFA

96% coverage



μ-polarizer

Active version (from TREK exp.) - optional

10x Be or Li targets

•0.33 mm thin

•Spaced 10 cm

Cerenkov TOF

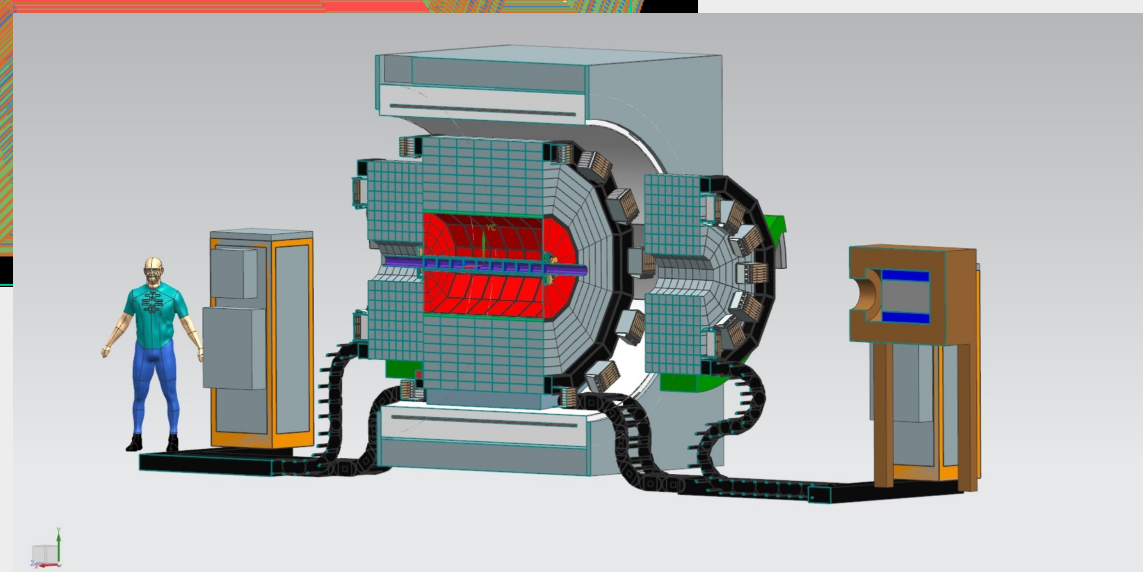
~ 1m x 1.5 m

Fused quartz tiles

98% coverage

Fiber tracker or HV-MAPS

for rejection of γ-conversion and vertexing



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)**

	Baseline option	Optimized option	Expensive option
Target+beam pipe	0.5	**0.5**	0.9
Vtx detector	0.93	**3.11**	25.4
LGAD tracker	18.5	**18.5**	19.6
CTOF	0.6	**1.3**	3.0
ADRIANO2	47.7	**23.9**	47.7
Solenoid	0.2	**0.2**	0.2
Supporting structure	1	**1**	1
Trigger	1.3	**1.3**	5
DAQ	5	**5**	5
Total	**69.7**	**54.8**	**101.8**
Contingency 50%	34.9	**27.4**	50.9
Grand total	**104.6**	**82.2**	**152.7**

Cost estimate ($2022)

- Three funding scenarios considered
- Largest cost uncertainties
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- No labor considered (usually, 1/3 of the total)

Cost optimization is in progress
Based on sensitivity studies for Snowmass 2022

	[illegible]	[illegible]	[illegible] option
Target+beam pipe	0.5	0.5	0.9
Vtx detector	[illegible]	[illegible]	[illegible]
LGAD tracker	[illegible]	[illegible]	[illegible]
CTOF	0.6	1.3	3.0
ADRIANO2	47.7	23.9	47.7
Solenoid	0.2	0.2	0.2
Supporting structure	1	1	1
Trigger	1.3	1.3	5
DAQ	5	5	5
Total	**69.7**	**54.8**	**101.8**
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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)

18x LHCb

Trigger stage	*Input event rate Hz*	*Event size bytes*	*Input data rate bytes/s*	*Event rejection*
Level 0	$7. \times 10^8$	1.4×10^3	9.8×10^{11}	~ 4.6
Level 1	1.5×10^8	1.5×10^3	2.3×10^{11}	~ 60
Level 2	2.5×10^6	1.5×10^3	3.8×10^9	~ 4.5
Storage	0.56×10^6	1.6×10^3	0.9×10^9	

Hardware

Software

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*
  - ***Geniehad*** *(C++, Fortran77, Fortran90) https://redtop.fnal.gov/the-geniehadevent-generation-framework/*
  - *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*

Simulation Architecture

REDTOP

Evt generation
GenieHad

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

- *Moderate need ofresource*
- *Requirements:*
  - *1CPU;*
  - *1250MB memory;*
  - *2GB disk*
- *Apptainer container + some dependencies from CVMFS*

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

- *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*

reconstruction
lcsim/java

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

- *Use as input 100 trigger jobs*
- *requirements:*
  - *1CPU;*
  - *1500MB memory;*
  - *5GB disk*
- *Apptainer container + some dependencies from CVMFS*

OSG Usage Statistics (01/23 - 07/07)

Core Hours per Project	total
REDTOP	32.9 Mil
LIGO	31.2 Mil
IceCube	24.1 Mil
dune	22.2 Mil
CLAS12	18.4 Mil
cms.org.cern	16.5 Mil
WSU_3DHydro	16.1 Mil
cms.org.ku	11.2 Mil
fermilab	9.92 Mil
KOTO	9.12 Mil
PixleyLab	7.60 Mil
ePIC	6.95 Mil
microboone	6.63 Mil
gluex	6.44 Mil
UConn_Le	6.01 Mil
CMU_Isayev	5.46 Mil
Rice_Mulligan	5.39 Mil
gm2	5.25 Mil
EvolSims	5.05 Mil
Syracuse_Nitz	4.61 Mil
mu2e	4.20 Mil
nova	4.18 Mil
BiomedInfo	3.82 Mil
cms.org.baylor	3.77 Mil
UCSD_Politis	3.76 Mil
icarus	3.62 Mil
SSGAforCSP	3.11 Mil
CSUN_Katz	3.01 Mil
xenon	3.00 Mil
NCSU_Hall	2.99 Mil
Vanderbilt_Paquet	2.54 Mil

CPU Hours per Project	total
REDTOP	28.4 Mil
CLAS12	14.1 Mil
WSU_3DHydro	13.7 Mil
LIGO	14.0 Mil
IceCube	13.3 Mil
dune	7.69 Mil
KOTO	6.73 Mil
PixleyLab	5.90 Mil
ePIC	5.80 Mil
UConn_Le	5.54 Mil
fermilab	5.72 Mil
gluex	5.01 Mil
cms.org.cern	4.97 Mil
Syracuse_Nitz	3.61 Mil
gm2	3.21 Mil
EvolSims	3.06 Mil
UCSD_Politis	2.77 Mil
CSUN_Katz	2.72 Mil
NCSU_Hall	2.45 Mil
microboone	2.52 Mil
Vanderbilt_Paquet	2.34 Mil
Rice_Mulligan	2.30 Mil
UCBerkeley_Altman	2.10 Mil
BiomedInfo	2.10 Mil
xenon	1.92 Mil
Rice_Li	1.77 Mil
mu2e	1.61 Mil
PSI_Kaib	1.46 Mil
SSGAforCSP	1.41 Mil
SBU_Jia	1.15 Mil
CMU_Isayev	1.16 Mil

Job Count per Project	total
BiomedInfo	23.0 Mil
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IceCube	16.5 Mil
PixleyLab	15.1 Mil
dune	10.3 Mil
WSU_3DHydro	9.19 Mil
EvolSims	7.93 Mil
CPSC_5520	7.76 Mil
REDTOP	5.86 Mil
fermilab	5.42 Mil
xenon	5.22 Mil
des	4.85 Mil
microboone	4.75 Mil
UCBerkeley_Altman	4.71 Mil
UAB_Thyme	4.52 Mil
icarus	3.87 Mil
KOTO	3.74 Mil
cms.org.cern	3.59 Mil
CLAS12	2.70 Mil
CSUN_Katz	2.56 Mil
ePIC	2.27 Mil
nova	1.96 Mil
Syracuse_Nitz	1.95 Mil
gluex	1.86 Mil
NOAA_Bell	1.84 Mil
UCSD_Politis	1.77 Mil
gm2	1.76 Mil
PSFmodeling	1.65 Mil
NCSU_Hall	1.46 Mil
DemoSims	1.23 Mil
Vanderbilt_Paquet	1.23 Mil

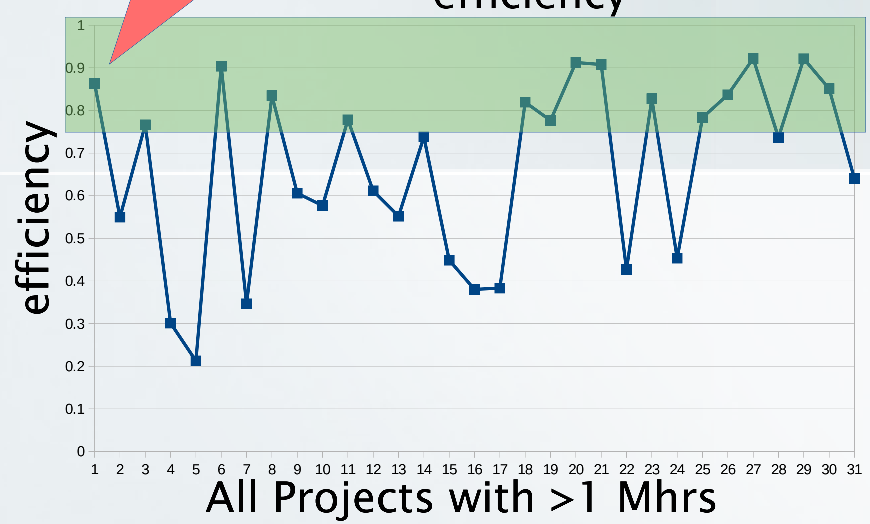
Summary for last 5.5 months of running:

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

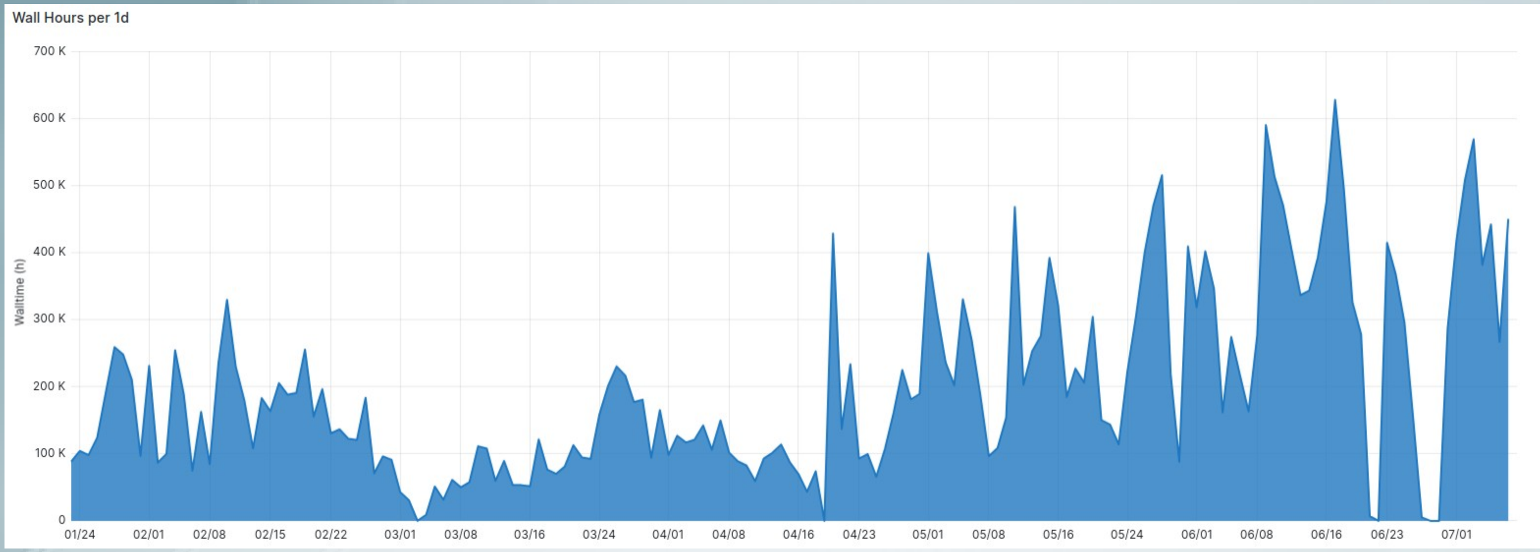
- ~10k total failed jobs
  mostly due to file transfers
  and worker node issues
- 98 failed jobs due to code issues

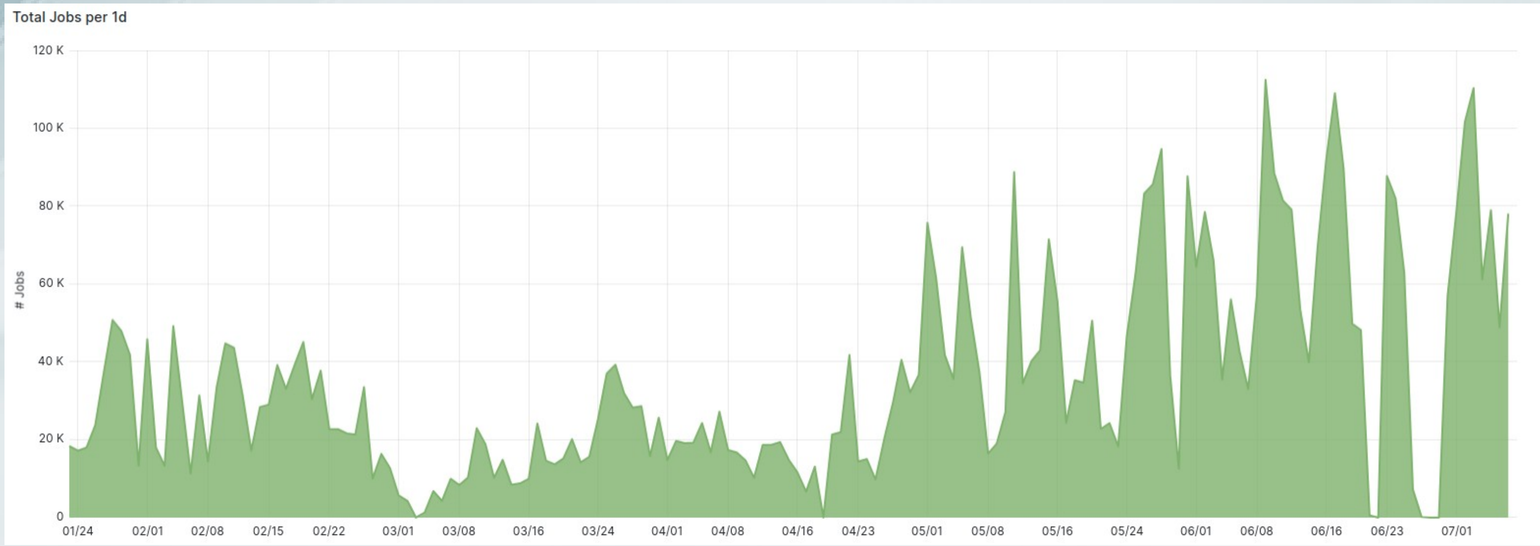
REDTOP

- Job efficiency



OSG Daily Usage Statistics





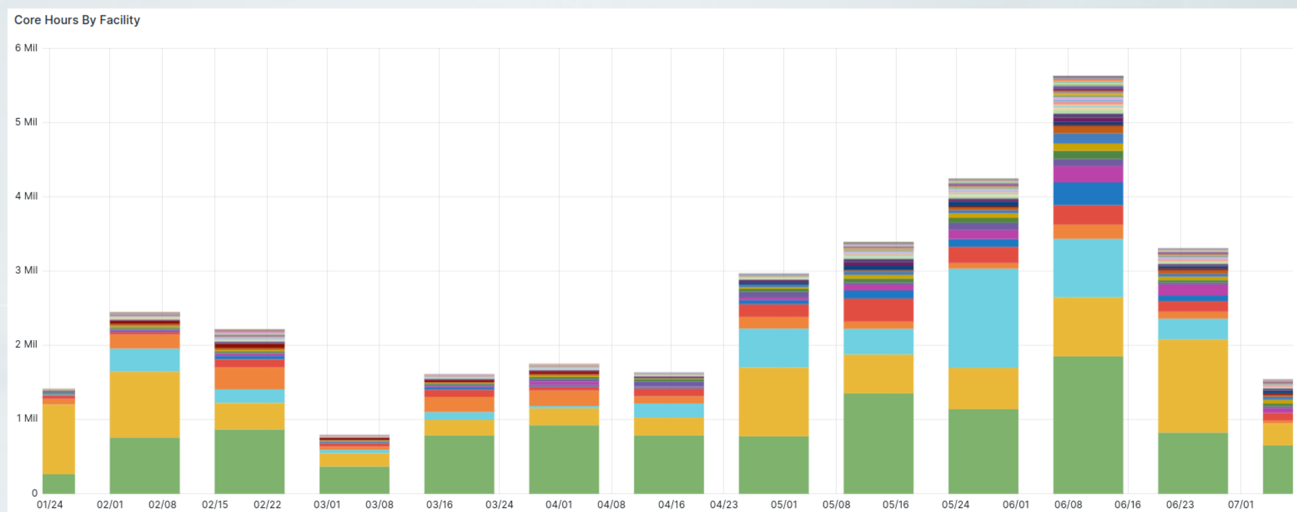
OSG Yearly Usage Statistics for REDTOP project

REDTOP

Core Hours by Facility

Facility	total
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

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



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 η /η' 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

More details: https://redtop.fnal.gov and https://arxiv.org/abs/2203.07651

Backup Slides

Present & Future η Samples

	Technique	$\eta \to 3\pi^o$	$\eta \to e^+e^-\gamma$	Total η mesons
CB@AGS	$\pi^- p \to \eta\, n$	9×10^5		10^7
CB@MAMI C&B	$\gamma p \to \eta\, p$	1.8×10^6	5000	$2\times10^7 + 6\times10^7$
BES-III	$e^+e^- \to J/\psi \to \eta\gamma\ + \eta$ hadrons	6×10^6		$1.1\times10^7 + 2.5\times10^7$
KLOE-II	$e+e- \to \Phi \to \eta\gamma$	6.5×10^5		$\sim10^9$
WASA@COSY	$pp \to \eta\, pp$ $pd \to \eta\, ^3He$			$>10^9$ (untagged) 3×10^7 (tagged)
CB@MAMI 10 wk (proposed 2014)	$\gamma p \to \eta\, p$	3×10^7	1.5×10^5	3×10^8
Phenix	$d\, Au \to \eta\, X$			5×10^9
Hades	$pp \to \eta\, pp$ $p\, Au \to \eta\, X$			4.5×10^8
Near future samples				
GlueX@JLAB (running)	$\gamma_{12\ GeV} p \to \eta\ X \to$ neutrals			5.5×10^7/yr
JEF@JLAB (construction)	$\gamma_{12\ GeV} p \to \eta\ X \to$ neutrals			3.9×10^5/day
REDTOP (proposing)	$p_{1.8\ GeV} Li \to \eta\ X$			3.4×10^{13}/yr

The physics case for REDTOP

Physics case presented in 176-pp White Paper. Sensitivity studies based on ~10^{14} η mesons (3.3×10^{18} POT and 3-yr run), >30×10^{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 μ-polarization measurement
- A fourth CP violating processes under study
- Three CP violating processes requiring μ-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 verteces up to ~100 cm
- Sensitivity to BR ~$\mathcal{O}(10^{-11})$ (~$\mathcal{O}(10^{-12})$ 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.)*

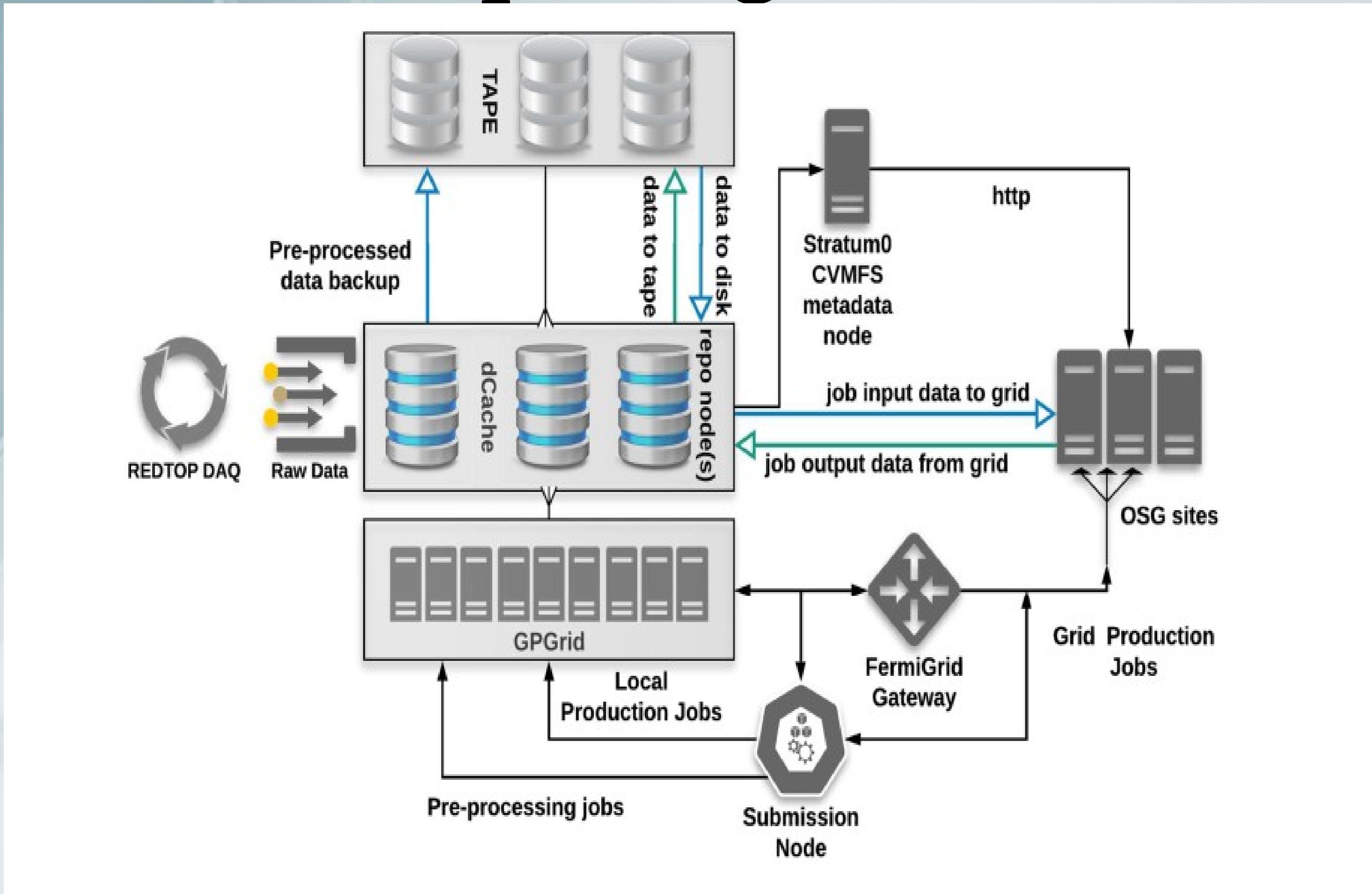
- *Storage:*
  - *DataStream from the L-2 farm will be staged at (FNAL) dCache storage and sent to tape (or wherever is cheaper when the experiment runs: FNAL at present)*
  - *Stratum-0 server hosts a CVMFS repository of the REDTOP software*

- *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.*

REDTOP Computing Model

- *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.*

REDTOP Baseline Computing Model

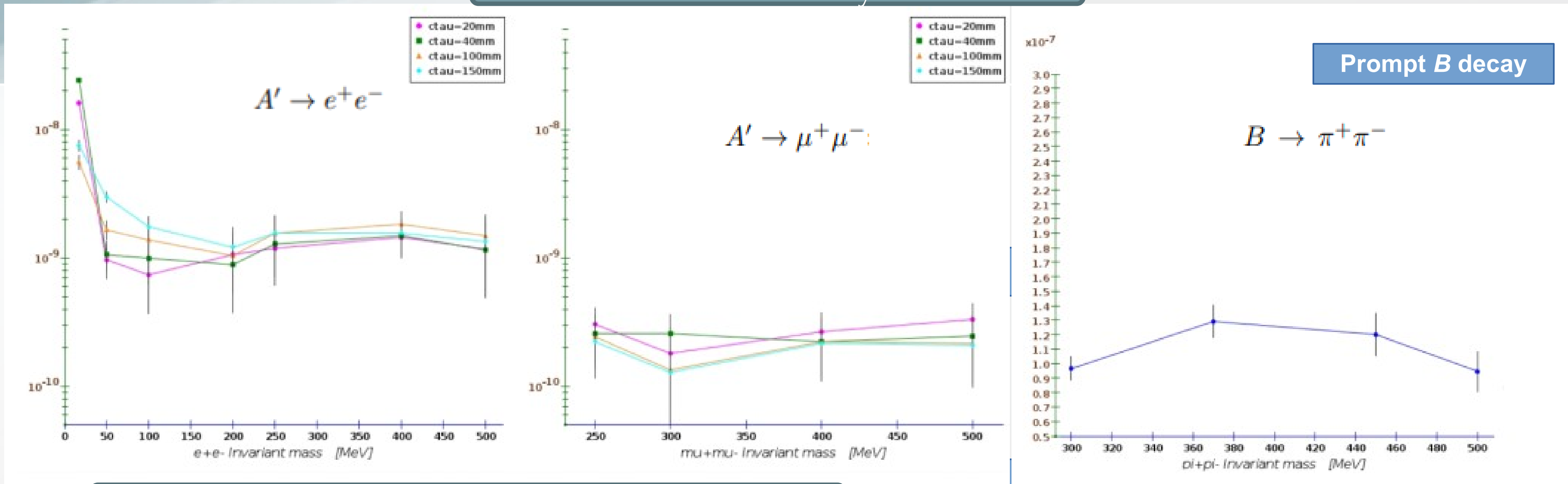


For more details: http://redtop.fnal.gov/wp-content/uploads/2020/05/redtop-compute_v3.pdf

Vector Portal: $\eta \rightarrow \gamma A'$ with $A' \rightarrow l^+l^-$ or $\pi^+\pi^-$

REDTOP

Some BR sensitivity curves



Sensitivity curves for Minimal Dark Photon Model

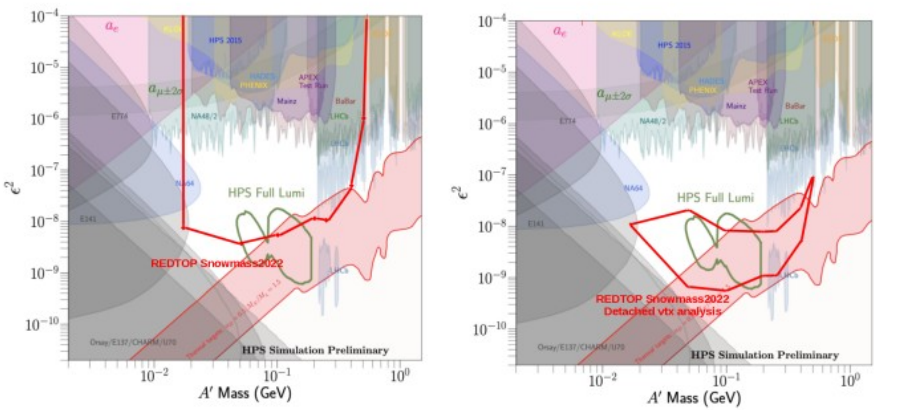


FIG. 36. Sensitivity to to ε^2 for the processes $\eta \rightarrow \gamma A'$ for integrated beam flux of 3.3×10^{18} POT. Left plot: *bump-hunt* analysis. Right plot: *detached-vertex* analysis).

Theoretical Models considered

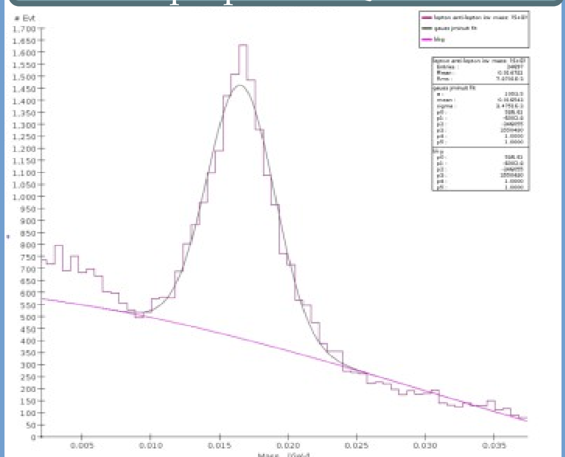
- *Minimal dark photon model*
  - *Most popular model*
- *Leptophobic B boson Model*
- *Protophobic Fifth Force*
  - *Explains the Atomki anomaly*

New particles & forces

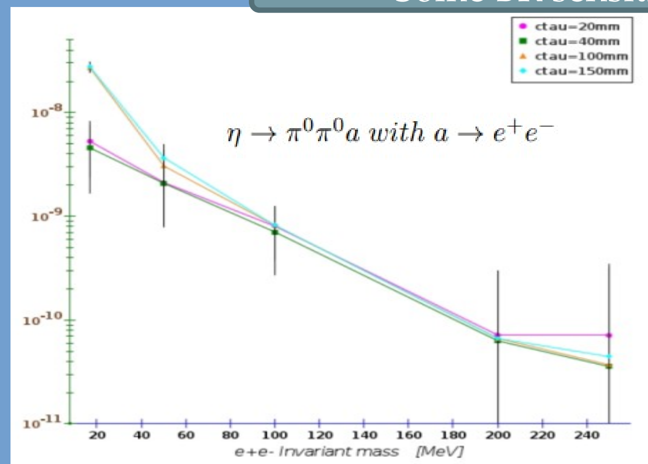
Pseudoscalar Portal: $\eta \to \pi^o \pi^o a$ & $\eta \to \pi^+ \pi^- a$ with $a \to \gamma\gamma$, $\mu^+ \mu^-$ and $e^+ e^-$

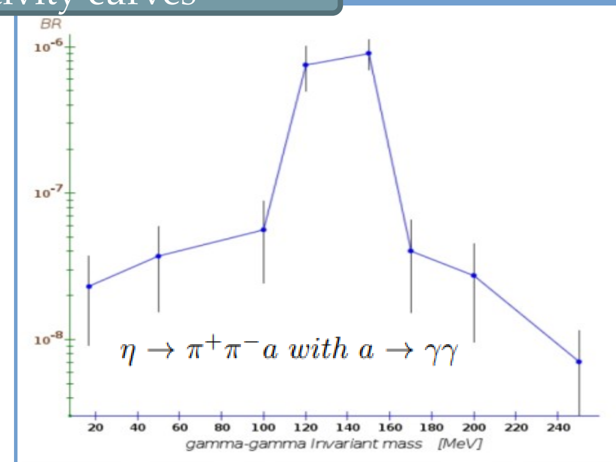
REDTOP

17 MeV piophobic QCD axion

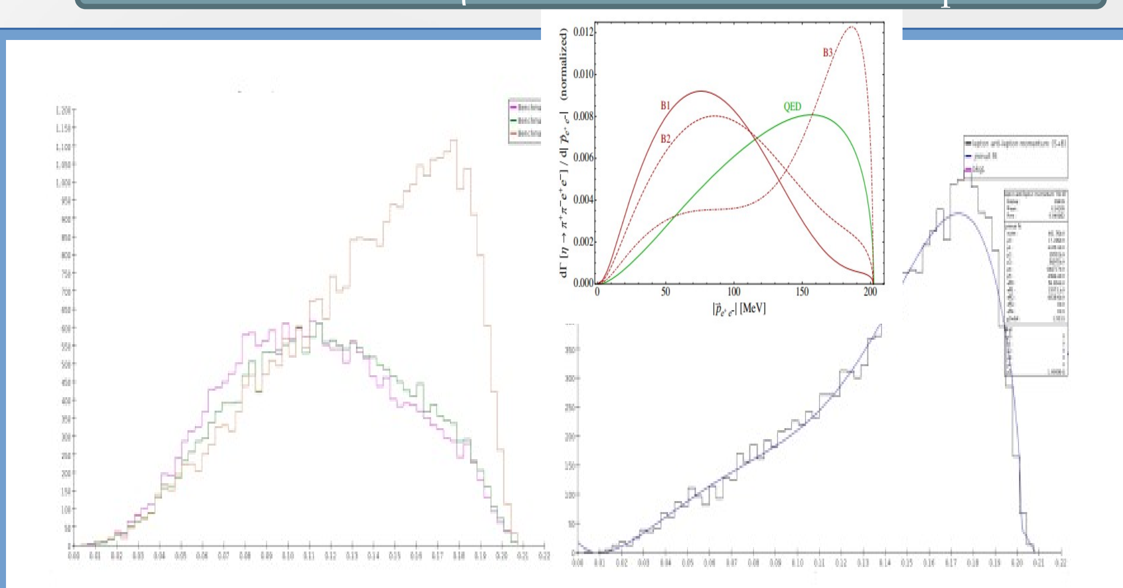


Some BR sensitivity curves





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

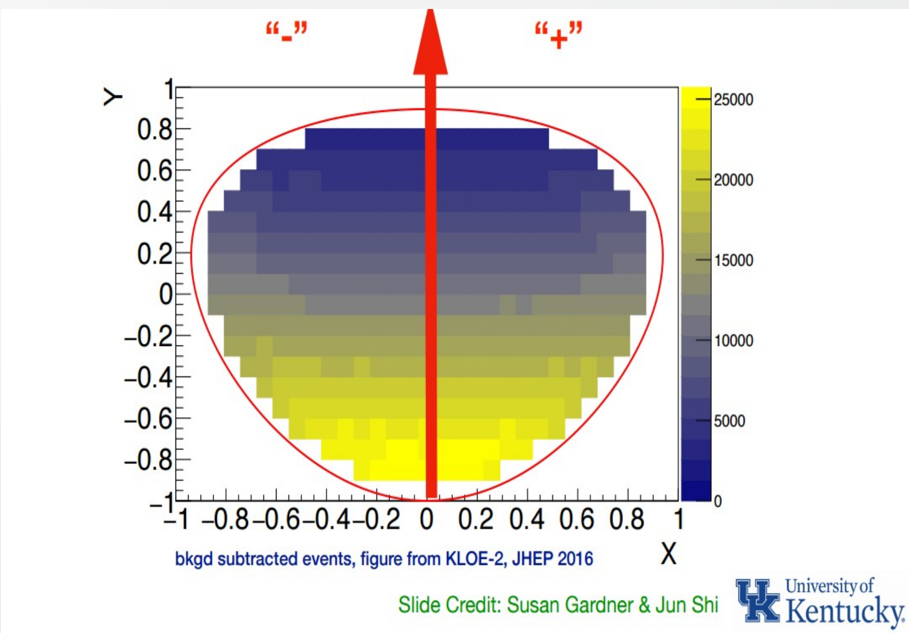


Theoretical models considered

- ***Piophobic QCD axion model*** *(D. S. M. Alves)*
  - *Below KLOE sensitivity*
  - *the CELSIUS/WASA Collaboration observed 24 evts with SM expectation of 10*
- ***Heavy Axion Effective Theories***

CP Violation from Dalitz plot mirror asymmetry in $\eta \to \pi^+\pi^-\pi^0$

- *CP-violation from this process is not bounded by EDM as is the case for the $\eta \to 4\pi$ 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*
- *New model in GenieHad (collaboration with S. Gardner & J. Shi) based on https://arxiv.org/abs/1903.11617*

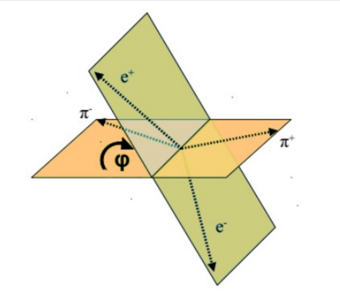


REDTOP sensitivity to model parameters

#Rec. Events	Re(α)	Im(α)	Re(β)	Im(β)	p-value
10^8 (no-bkg)	3.3×10^{-1}	3.7×10^{-1}	4.4×10^{-4}	5.6×10^{-4}	17%
Full stat. (no-bkg)	1.9×10^{-2}	2.1×10^{-2}	2.5×10^{-5}	3.2×10^{-5}	17%
Full stat. (100%-bkg)	2.3×10^{-2}	3.0×10^{-2}	3.5×10^{-5}	4.5×10^{-5}	16%

CP Violation from the asymmetry of the decay planes in $\eta \to \mu^+\mu^- e^+e^-$ and $\eta \to \pi^+\pi^- e^+e^-$

- *See: Dao-Neng Gao, /hep-ph/0202002 and P. Sanchez-Puertas, JHEP 01, 031 (2019)*
- *Requires the measurement of angle between pions and leptons decay planes*



CP violation is related to asymmetries in $\eta \to \mu^+\mu^- e^+e^-$

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

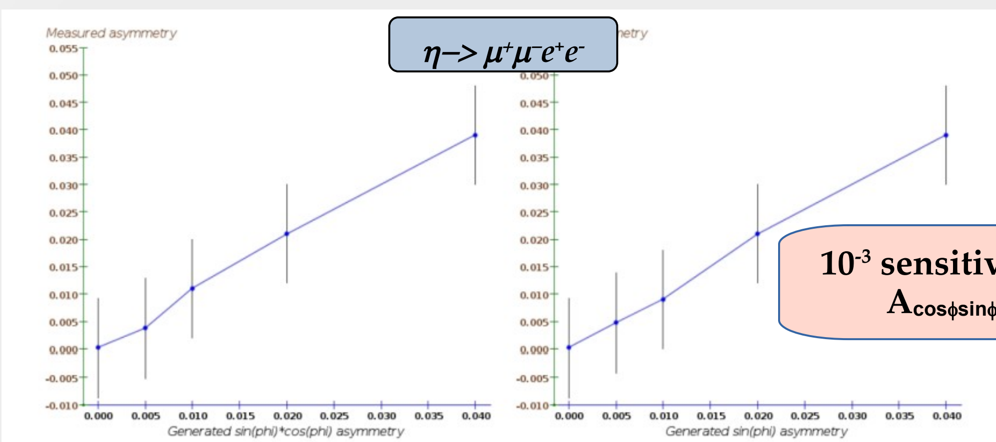
$$A_{sin\Phi} = \frac{N(\sin\phi > 0) - N(\sin\phi < 0)}{N(\sin\phi > 0) + N(\sin\phi < 0)}$$

through Wilson coefficients

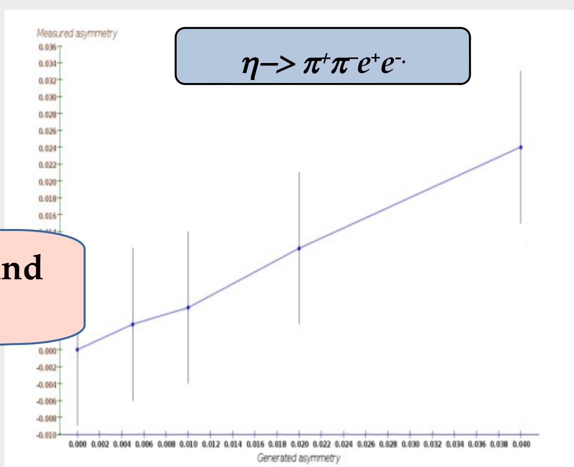
$$A_{\sin\phi\cos\phi} = \mathrm{Im}[1.9c^{2222}_{\ell edq} - 1.3(c^{(1)2211}_{\ell equ} + c^{1122}_{\ell edq})] \times 10^{-5} - 0.2\epsilon_1 + 0.0003\epsilon_2$$

CP violation is related to asymmetries in $\eta \to \pi^+\pi^- e^+e^-$

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



10^{-3} sensitivity to and $A_{\cos\phi\sin\phi}$ $A_{\sin\phi}$



REDTOP

CP Violation in $\eta \to (\gamma,\pi^0)\mu^+\mu^-$

From model: P. Masjuan and P. Sanchez-Puertas, JHEP 08, 108 (2016), 1512.09292 & JHEP 01, 031 (2019), 1810.13228.

- *Requires the measurement of μ–polarization to form the following asymmetries*

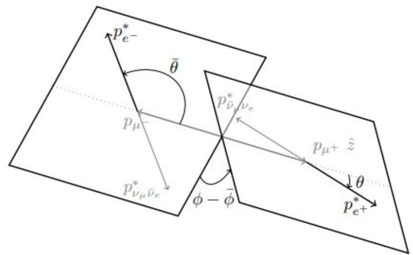


FIG. 11. Kinematics of the process. The decaying muons' momenta in the η rest frame are noted as $p_{\mu^\pm}$, while the $e^\pm$ momenta, $p^*_{e^\pm}$, is shown in the corresponding $\mu^\pm$ reference frame along with the momenta of the $\nu\bar\nu$ system. The $\hat z$ axis is chosen along p_{μ^+}.

introduced two different muon's polarization asymmetries,

$$A_L = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N} = \mathrm{Im}[4.1c^{2222}_{\ell edq} - 2.7(c^{(1)2211}_{\ell equ} + c^{2211}_{\ell edq})] \times 10^{-2}, \quad (47)$$

$$A_\times = \frac{N(\sin\Phi > 0) - N(\sin\Phi < 0)}{N} = \mathrm{Im}[2.5c^{2222}_{\ell edq} - 1.6(c^{(1)2211}_{\ell equ} + c^{2211}_{\ell edq})] \times 10^{-3}, \quad (48)$$

REDTOP sensitivity to Wilson CP violating Wilson coeffiecients

Process	*Trigger* L0	*Trigger* L1	*Trigger* L2	*Reconstruction + analysis*	**Total**	Branching ratio sensitivity
$\eta \to \mu^+\mu^-$	66.3%	16.3%	51.9%	69.6%	3.9%	$2.7 \times 10^{-8} \pm 3.0 \times 10^{-10}$
Urqmd	21.7%	1.7%	22.2%	8.6×10^{-3}%	7.0×10^{-6}%	-

$$\Delta(c^{1122}_{\ell equ}) = 0.1 \times 10^{-1}, \quad \Delta(c^{1122}_{\ell edq}) = 0.1, \quad \Delta(c^{2222}_{\ell edq}) = 6.6 \times 10^{-2},$$

LF-universality

Lepton Universality Studies

REDTOP

LHCb latest results using $B^+ \to \mu^+\mu^- K^+$ vs $e^+e^- K^+$: *3.1σ discrepancy vs SM*

REDTOP statistical error for ~10^{11} POT

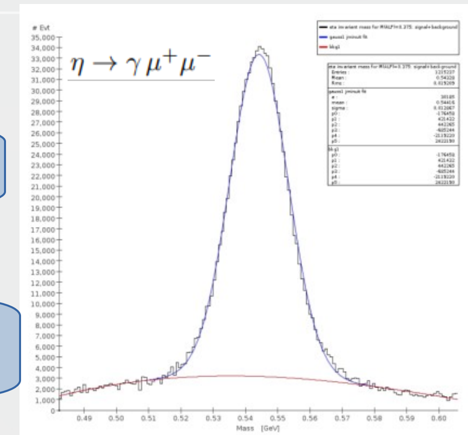
$\eta \to \gamma \mu^+ \mu^-$ *vs* $\gamma e^+ e^-$

Process	POT	Signal events	Background events	$\frac{S}{\sqrt{B}}$	**Statistical err**
$\eta \to \gamma e^+e^-$	1.38×10^{11}	2.13×10^6	2.52×10^4	1.3×10^4	**0.09%**
$\eta \to \gamma \mu^+\mu^-$	1.38×10^{11}	[illegible]$.84 \times 10^5$	6.5×10^3	3.5×10^3	**0.14%**

TABLE XLII. Statistical error from the fit of $\eta \to \gamma$ *lepton – antilepton* and Urqmd ge
background using a gaussian and a 5th-order polynomial, for 1.38×10^{18} POT

LHCb @ 4.2% with 1640 evts

LHCb @ 1.8% with 3850 evts



$\eta \to \mu^+\mu^- \mu^+\mu^-$, $e^+e^- \mu^+\mu^-$, $e^+e^- e^+e^-$

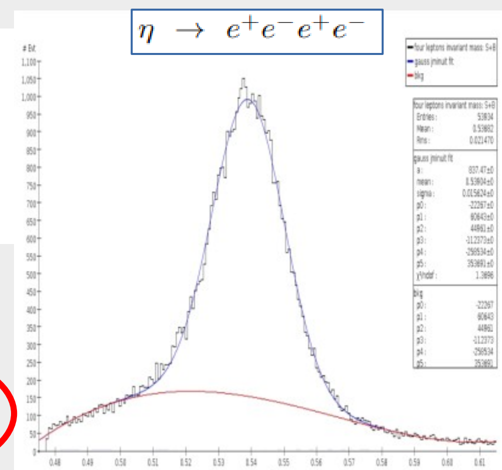
- *Theoretical calculations at the 10^{-3} precision from Kampf, Novotný, Sanchez-Puertas (PR D 97, 056010 (2018))*

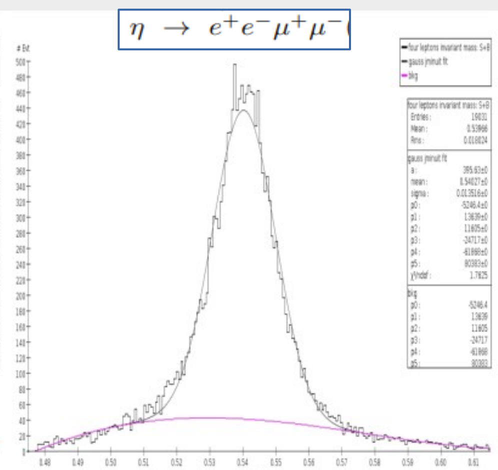
REDTOP reconstruction efficiency

Process	*Trigger* L0	*Trigger* L1	*Trigger* L2	*Reconstruction*	*Analysis*	**Total**
$\eta \to e^+e^-e^+e^-$	96.1%	80.7%	15.5%	63.3%	61.2%	4.5%
$\eta \to e^+e^-\mu^+\mu^-$	80.4%	57.0%	20.4%	16.6%	52.8%	0.8%
$\eta \to \mu^+\mu^-\mu^+\mu^-$	45.1%	31.9%	25.5%	61.3%	40.5%	0.9%
Urqmd	21.7%	1.7%	22.2%	$0.9 - 8.2 \times 10^{-4}$%	17.6%-30.7%	$0.7 - 6.7 \times 10^{-7}$%

REDTOP statistical error for various POT

Process	POT	Signal events	**Statistical error**
$\eta \to e^+e^-e^+e^-$	4.4×10^{14}	53,934	**0.5%**
$\eta \to e^+e^-\mu^+\mu^-$	1.6×10^{15}	18,841	**0.8%**
$\eta \to \mu^+\mu^-\mu^+\mu^-$	2.2×10^{18}	10,548	**1.0%**





Beam Options for 10^{14} η 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)
- η : inelastic background = 1:200
- Untagged η production

vs LHCb@40 MHz

Inelastic interaction rate: ~ 0.7 GHz
Average event multiplicity ≈ 4 charged + 4 neutral
η/η′ production rate: ~ 2.3 MHz

Preferred option – low-energy pion beam

- π^+ on Li/Be or π^- on LH: ~750 MeV - 2.5x10^{10} πOT/sec
- More expensive but lower background (ESS, FNAL(?), FAIR, HIAF, ORNL)
- η : inelastic background = 1:50 → sensitivity to BSM increased by > 2x
- Semi-tagged η production

Inelastic interaction rate: ~ 0.1GHz
η/η′ production rate: ~ 2.3 MHz

Ultimate option: Tagged 10^{13} η 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: $p+De \rightarrow \eta + He_3^{++}$

Inel. interaction rate: ~ 13 - 130 GHz
η/η′ production rate: ~ 0.1 - 1 MHz

Beam Options for 10^{14} η mesons

vs LHCb@40 MHz

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)
- η : inelastic background = 1:200
- Untag...

Inelastic interaction rate: ~ 0.7 GHz

Average event multiplicity ≈ 4 charged + 4 neutral

η/η' production rate: ~ 2.3 MHz

Only ~1% of the proton or pion beam interacts with REDTOP

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

Preferred option – low-energy pion beam

- π^+ on Li/Be or π^- on LH: ~750 MeV - 2.5×10^{10} πOT/sec
- More expensive but lower background (ESS, FNAL(?), FAIR, HIAF, ORNL)
- η : inelastic background = 1:50 → sensitivity to BSM increased by > 2x
- Semi-tagged η production

Inel. interaction rate: ~ 0.1GHz

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Ultimate option: Tagged 10^{13} η mesons

- high intensity proton beam on De target: ~0.9 GeV ; 0.1-1 MW
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- Fully tagged production from neclear reaction: $p+De \rightarrow \eta + He_3^{++}$

Inel. interaction rate: ~ 13 - 130 GHz

η/η' production rate: ~ 0.1 - 1 MHz

Detector Requirements and Technology

- *Sustain up to 0.7 GHz event rate with avg final state multiplicity of ~8 particles*
- *Calorimetric $\sigma(E)/E \sim 2\text{-}3\%/\sqrt{E}$*
- *High PID efficiency: 98/99% (e,γ), 95% (μ), 95% (π), 99.5%(p,n)*
- $\sigma_{tracker}(t) \sim 30$psec, $\sigma_{calorimeter}(t) \sim 80$psec, $\sigma_{TOF}(t) \sim 50$psec
- *Low-mass vertex detector*
- *Near-4π detector acceptance (as the η/η' 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*
- *~70μm vertex resolution in x-y. Stereo layers*

Option 2: HV-MAPS (Mu3e style)

- *Low material budget (0.11%/layer)*
- *~40μm 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

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 η meson is special?

REDTOP

- 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 (Γ_η=1.3 KeV vs Γ_ρ=149 MeV)
- EM decays are forbidden in lowest order by C invariance and angular momentum conservation
  - Contributions from higher orders are enhanced by a factor of ~100,000
  - Excellent for testing invariances
- The η decays are flavor-conserving reactions
  - Decays are free of SM backgrounds for new physics search

η is an excellent laboratory to search for physics Beyond Standard Model

η/η' yield and background evaluation

Inelastic p-Li scattering probability (percentage):

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

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)

Nuclear collision model	*p+Li* η *yield*
Urqmd [208]	0.49%
Incl++ v6.2 [209]	1.48%
Gibuu v2019 [210]	0.74%
PHSD v 4.0 [211]	0.67%
Jam v1.9 [212]	0.26%
Average	$(0.73 \pm 0.46)\%$

	Total yield for E_{kin}=1.8 GeV
N_η	1.1×10^{14}
$N_{\eta'}$	0
N_{ni}	2.5×10^{16}

	Total yield for E_{kin}=3.6 GeV
N_η	5.9×10^{14}
$N_{\eta'}$	7.9×10^{11}
N_{ni}	3.2×10^{16}

η/η' production rate: ~ 2.3 MHz

Simulation Framework For Physics&Detector Studies

Event generator: GenieHad

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

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

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):

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

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)

Nuclear collision model	*p+Li η yield*
Urqmd [208]	0.49%
Incl++ v6.2 [209]	1.48%
Gibuu v2019 [210]	0.74%
PHSD v 4.0 [211]	0.67%
Jam v1.9 [212]	0.26%
Average	(0.73 ± 0.46)%

	Total yield for E_{kin}=1.8 GeV
N_η	1.1×10^{14}
$N_{\eta'}$	0
N_{ni}	2.5×10^{16}

	Total yield for E_{kin}=3.6 GeV
N_η	5.9×10^{14}
$N_{\eta'}$	7.9×10^{11}
N_{ni}	3.2×10^{16}

η/η' production rate: ~ 2.3 MHz

Beam scheme for FNAL option (M. Syphers)

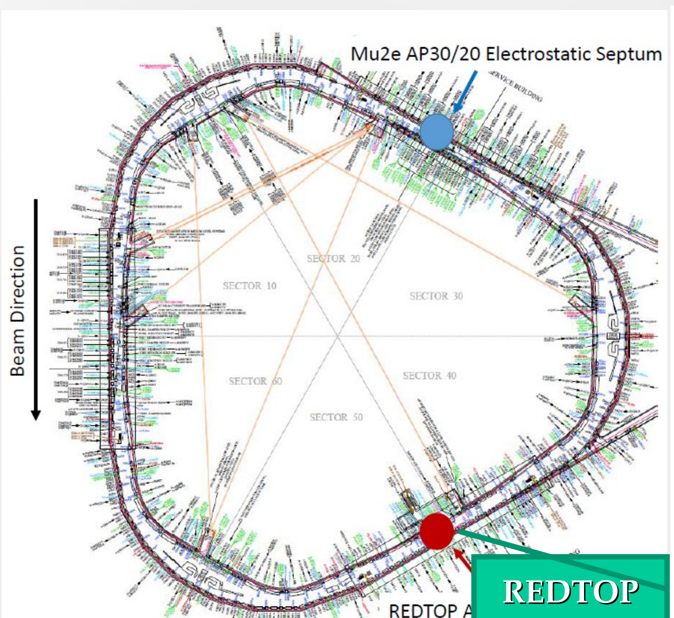
Single p pulse from booster ($\leq 4x10^{12}$ p) injected in the DR (former debuncher in anti-p production at Tevatron) at fixed energy (8 GeV)

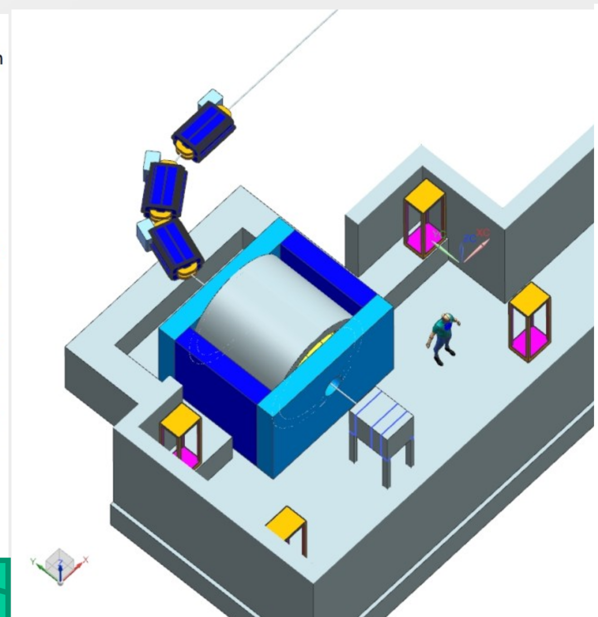
Energy is removed by inserting 1 or 2 RF cavities identical to the one already planned (~5 seconds)

Slow extraction to REDTOP over ~40 seconds.

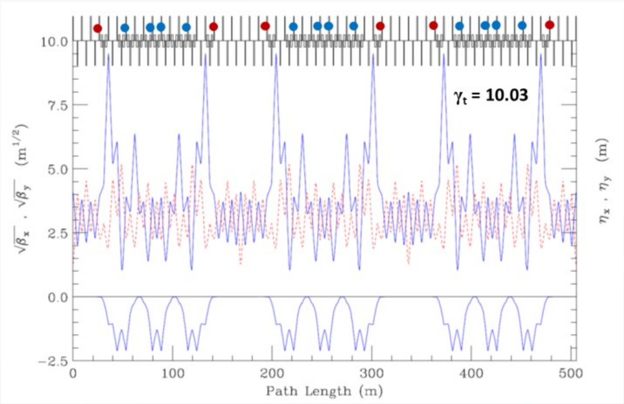
The 270º of betatron phase advance between the Mu2e Electrostatic Septum and REDTOP Lambertson is ideal for AP50 extraction to the inside of the ring.

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

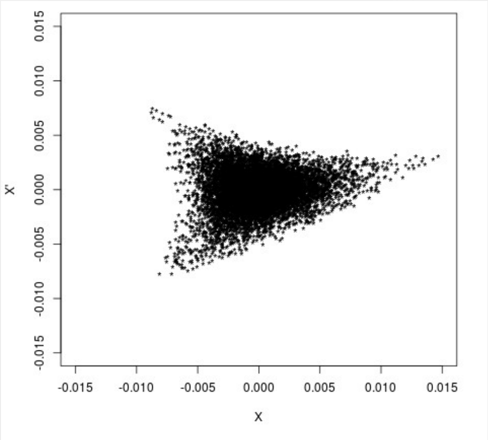




Accelerator Physics Issues



- ***Transition Energy***
  - γ_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
    - Johnstone and Syphers, *Proc. NA-PAC 2016*, Chicago (2016).
- ***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



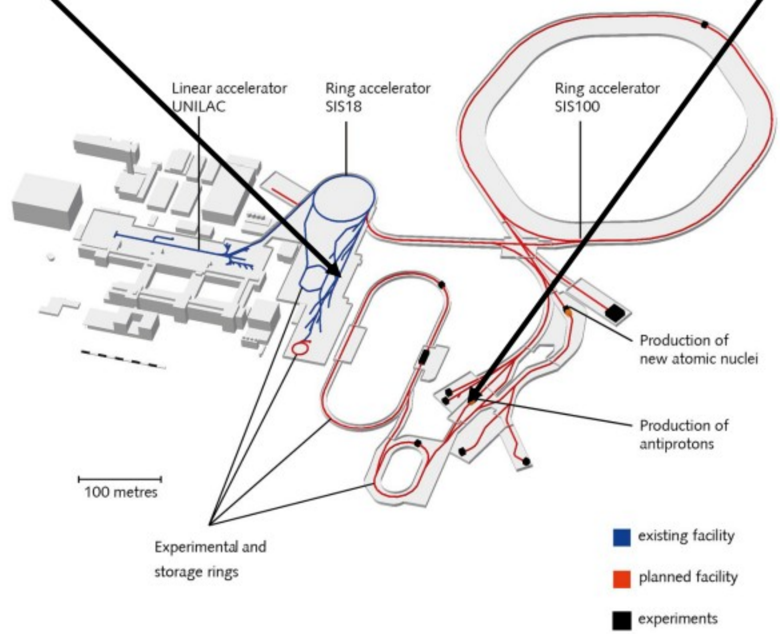
Beam Options at GSI/FAIR (near future)

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

FAIR GmbH | GSI GmbH

Beam intensity: 1.8 GeV protons with 1e11/s

Daniel Severin

Beam Options at GSI (far future)

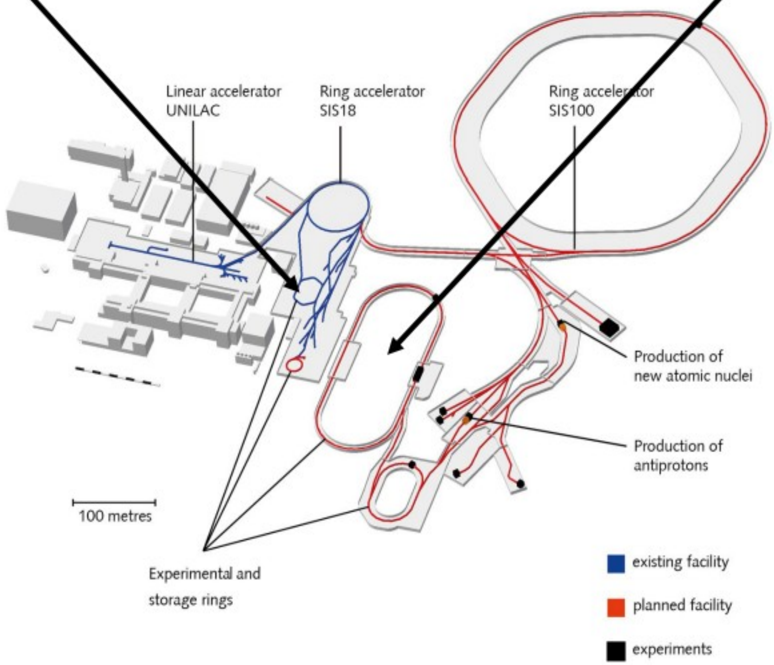
Opportunities as in-ring target exp.

OPTION C
ESR (SIS18)

OPTION D
HESR (SIS100)

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

- Lower intensity
- Parallel operation of UNILAC and SIS18 exp. possible
- Standard ESR exp. area needs to be dismounted
- Major disruption for the already approved program



- HESR or CR
- Intensity fully flexible
- Full beam usage

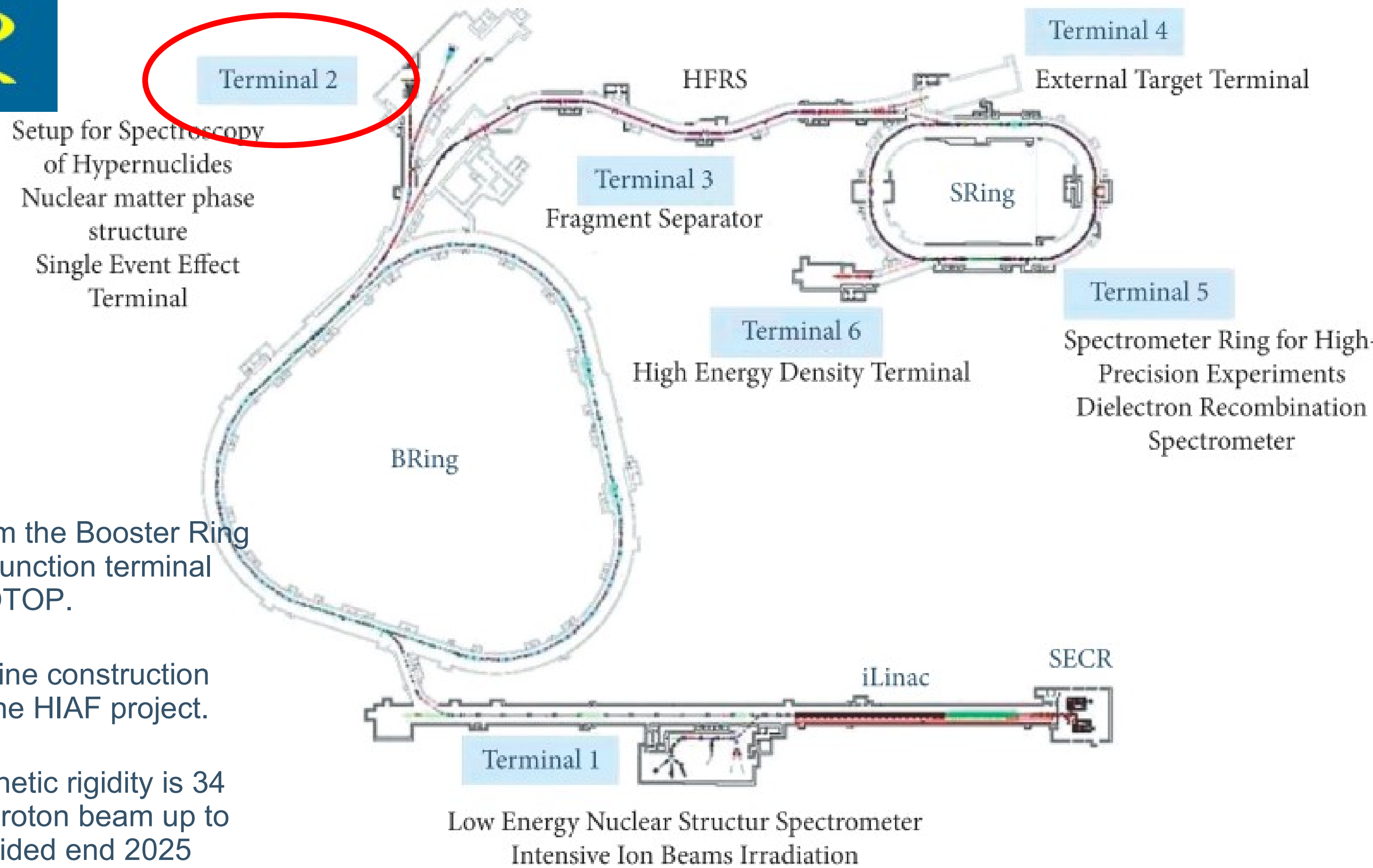
- Parallel operation possible due to p-LINAC
- Standard installation needs to be discussed
- Actual timeline beyond 2030

FAIR GmbH | GSI GmbH

Daniel Severin

Beam intensity: 1.8 GeV protons with 1e11/s

Beam Options at HIAF (near future)



- Beam extracted from the Booster Ring (BRing) to the Multi-function terminal ans 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

*Beam intensity: 0.5 ~1.0x10^{13} ppp (1~5*1x10^{13} pps) in Terminal 2 . $10^{(18\text{-}19)}$ POT /yr*

Energy from 2.0 to 9 GeV around 2028 – 2030

Plans are to combine REDTOP with an experiment on hypernuclei

Detector Requirements: BSM physics driven

LFU: Tagged lepton production from flavor-conserving decays

- excellent e/π/μ separation

QCD axion

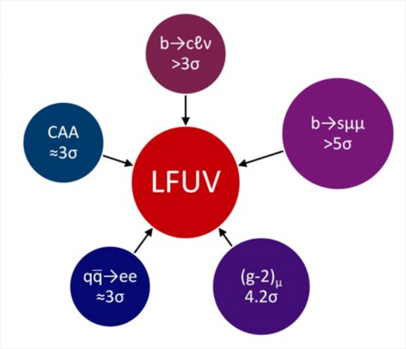
- *Calorimetric sensitivity to M(γγ)~30MeV*

17 MeV e^+e^- state (Atomki experiment)

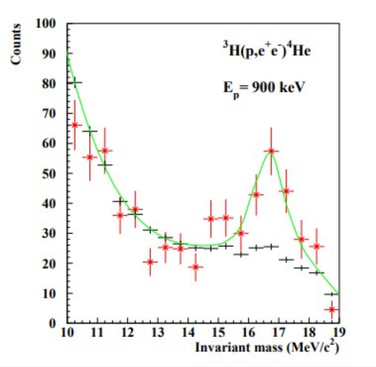
- *Tracker sensitivity to M(e^+e^-)~ 20 MeV*
- *Electron ID at very low energy*

CP violation with muons

- *Muon polarimeter or high-granularity calorimeter*



Mounting Evidence for the Violation of Lepton Flavor Universality https://arxiv.org/pdf/2111.12739.pdf (A. Crivellin, M. Hoferichter)



Subdetector Technologies

	Baseline (White paper)	Options
Target	Li foils: 10x 0.78mm	LH_2 11 cm
VTX	LHCb fiber tracker. REDTOP: 0.24m^2 vs LHCb: 360m^2	CMOS (ITS3) or hybrid (fiber+1 layer CMOS)
Central tracker	LGAD 100μm/layer eq., no active cooling (30 psec/layer). REDTOP: 14m^2 vs CMS: 16m^2	LGAD 120μm/layer eq., no active cooling (42 psec/layer)
TOF	1 layer 30x30x10 mm^3 JGS1 + Petiroc (50 psec/layer). Area: 3.7 m^2	2 layers, 30x30x10 or 20x20x10 mm^3 JGS1 + Liroc+Tsinghua TDC/PicoTDC (<30 psec/layer). Area: 9.4 m^2
Calorimeter	ADRIANO2: 53 layers 30x30x14 mm^3 SF57/cast scint (80 psec/cell) 800,000 tile pairs	ADRIANO2: 30 layers 30x30x14 mm^3 ZF2/ scint + 23 layers JGS1/Cu/scint (80 psec/cell) 400,000 tile pairs
μ-polarimeter	Not implemented	TBD