Status of REDTOP and preliminary results from the 2025 Montecarlo campaign

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Presented at HTC2025

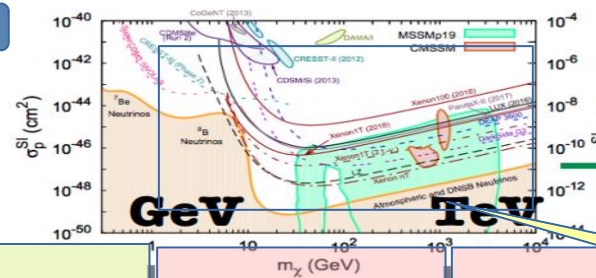
Rationale for an η/η' Factory

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:

<$100M excl. contingency and labor

Main Physics Goals of REDTOP

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

Search for asymmetries in the dalitz plot with very high statistics

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

Measure the angular asymmetry between spin and momentum

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

Need excellent vertexing and particle ID

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

Dual (or triple!) calorimeters and vertexing

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

Dual (or triple!) calorimeters and particle ID

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

Need excellent particle ID

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

REDTOP

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: η □ $\pi^o \mu^+\mu^-$*
- *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 $\eta \to \gamma\gamma$*

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 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: $\eta \to \mu^+\mu^+e^-e^- + c.c.$*

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})*

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 $\to A'/a \to l^+l^-$*

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 $\sim 10^{14}$ η mesons/yr and $\sim 10^{12}$ η' mesons/yr

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

C, T, CP-violation

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

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-η/η' based BSM Physics

- Neutral pion decay: $\pi^o \rightarrow \gamma A' \rightarrow \gamma e^+ e^-$
- 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: $qqbar \rightarrow A'/a \rightarrow l^+ l^-$

New particles and forces searches

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

Other Precision Physics measurements

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

High precision studies on medium energy physics

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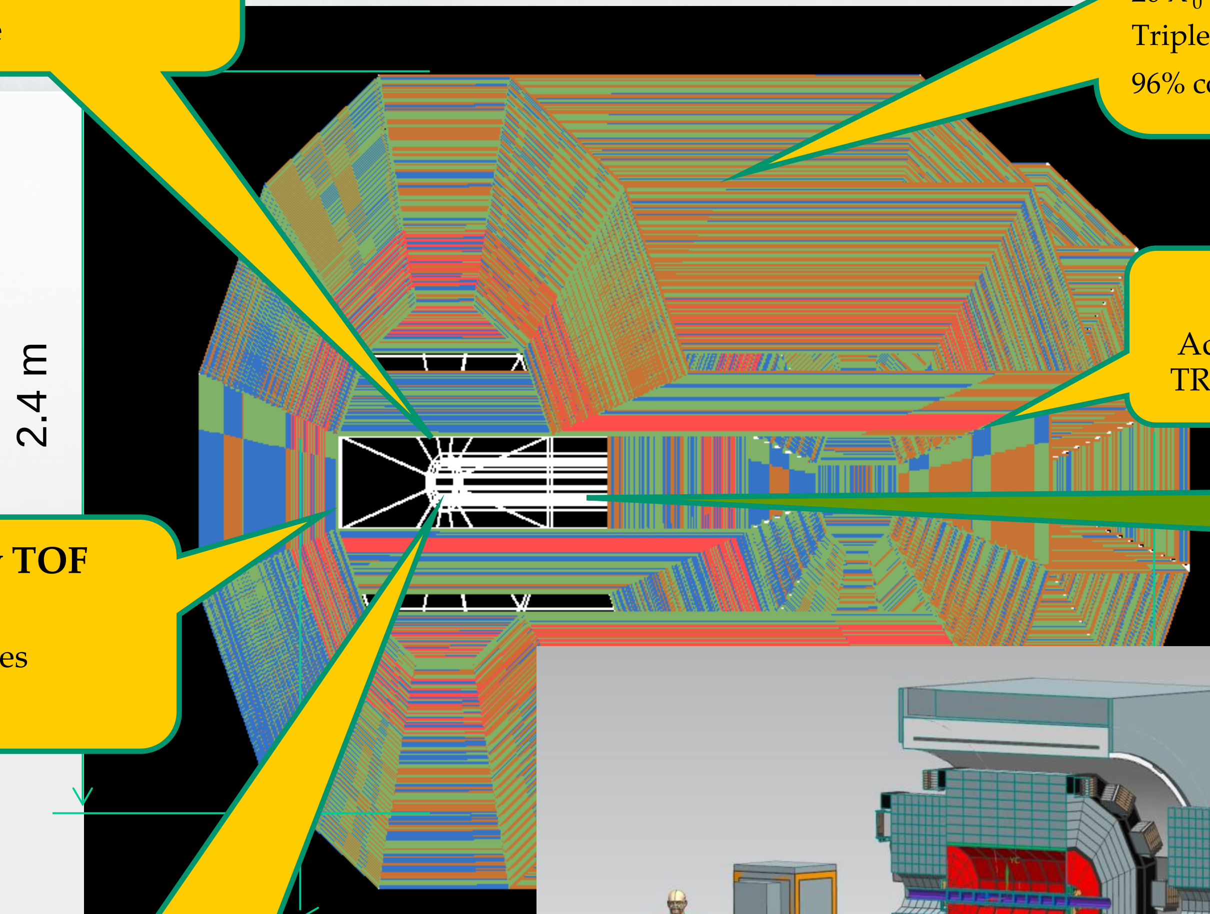
- Electromagnetic transition form-factors (important input for g-2)

REDTOP detector

Central Tracker
~ 1m x 1.5 m
Thin LGAD
98% coverage

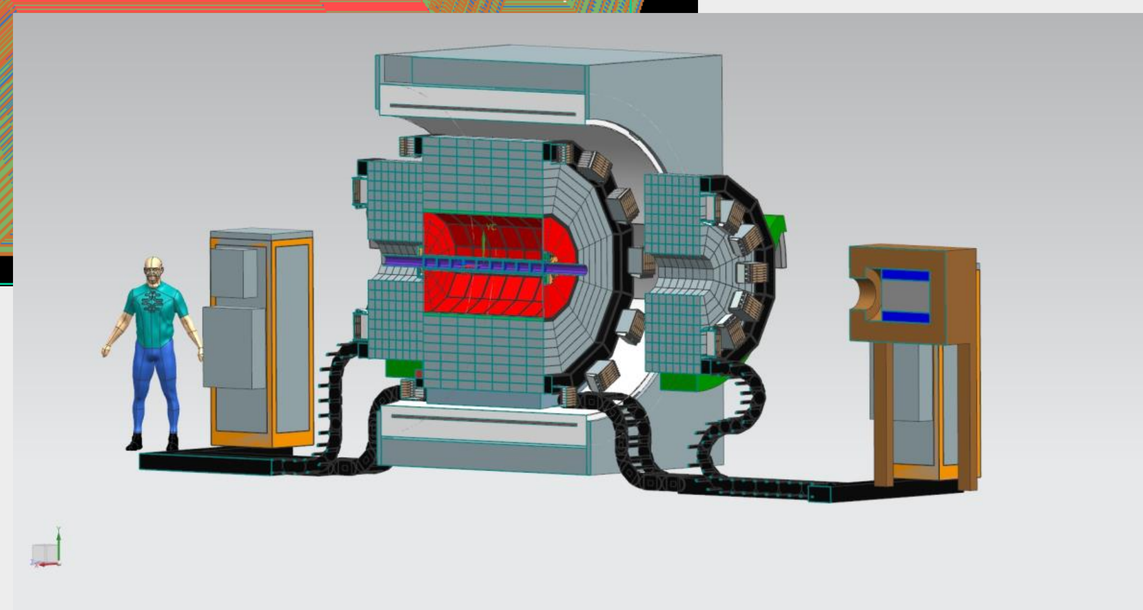
ADRIANO2(3) Calorimeter (tiles)
Scint. + heavy glass sandwich + RPC
20 X_0 (~ 64 cm deep)
Triple-readout +PFA
96% coverage



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
  - ADRIANO2 SiPM's ($2x10^6$ – $4x10^6$)
  - LGAD mechanics
- **No labor considered (usually 1/3 of the total)**

Cost optimization is in progress

Based on new sensitivity studies (2025 Montecarlo campaign)

	Baseline option	Optimized option	Full sensitivity option
Target+beam pipe	0.5	[illegible].5	0.[illegible]
Vtx detector	0.93	3.11	2[illegible].4
LGAD tracker	[illegible]	[illegible]	1[illegible].6
CTOF	0.6	1.3	3.[illegible]
ADRIANO2	47.7	23.9	4[illegible].7
Solenoid	0.2	0.2	0.[illegible]
Supporting structure	1	1	1
Trigger	1.3	1.3	5
DAQ	5	5	5
Total	**69.7**	**54.8**	**1[illegible]1.8**
Contingency 50%	34.9	27.4	5[illegible].9
Grand total	**104.6**	**82.2**	**1[illegible]52.7**

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15 Countries

62 Institutions

138 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}	$\sim$4.6
Level 1	1.5×10^8	1.5×10^3	2.3×10^{11}	$\sim$60
Level 2	2.5×10^6	1.5×10^3	3.8×10^9	$\sim$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 2025

Purpose of the campaign

- *In 2023 GSI Director (P. Giubellino) formally asked REDTOP Collaboration to submit a proposal to run at GSI (Germany)*
- *GSI could provide fewer protons (~1/10) than requred for REDTOP physics program*
- *Several modifications were made to the detector and target systems*
- *The campaign tests the sensitivity of REDTOP to fewer protons*
- *CERN could make available a similar integrated POT as GSI*

Simulation schema

Event generation

- ***Step 1: Event generation: 1.5 x 10^{11}** events (1:10,000 of the expected interactions)*
  - ***Geniehad*** (C++, *Fortran77, Fortran90) https://redtop.fnal.gov/the-geniehadevent-generation-framework/*
  - *I/O: root, hepevt, stdhep, lhe, lcio*

***Step 2: Geant4 simulation: 0.8 x 10^{11}** events*

- ***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

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;*
  - *950MB memory;*
  - *2GB disk*
- *Apptainer container with all software dependencies*

simulation
slic/G4

#events:	5k
runtime:	~1h÷3h
memory:	~0.6-0.7MB
input:	~17 MB
output:	~1.3 GB

TL0/TL1/Reco
lcsim/java

#events:	from previous stage
runtime:	15 minutes
memory:	0.8÷0.9 GB
input:	~1.3GB data
output:	~3MB

- *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 with all software dependencies*

OSG Usage Statistics (01/24 - 05/25)

Core Hours per Project	total
dune	108 Mil
CLAS12	105 Mil
LIGO	102 Mil
IceCube	78.1 Mil
REDTOP	71.9 Mil
WSU_3DHydro	67.7 Mil
PixleyLab	32.0 Mil
KOTO	31.8 Mil
ePIC	23.1 Mil
cms.org.cern	18.3 Mil
microboone	18.1 Mil
xenon	17.5 Mil
gluex	16.1 Mil
Caltech_2024_Reitze	15.3 Mil
gm2	15.3 Mil
fermilab	14.5 Mil
CMU_Isayev	14.3 Mil
icarus	13.5 Mil
UConn_Le	12.8 Mil
cms.org.ku	11.9 Mil
SSGAforCSP	11.7 Mil
Michigan_2023_Riles	10.4 Mil
nova	9.61 Mil
EvolSims	9.40 Mil
UCBerkeley_Altman	8.39 Mil
MSU_Berz	8.37 Mil
PSI_Kaib	7.77 Mil
BiomedInfo	7.75 Mil
Rice_Mulligan	6.99 Mil
LSU_Wilson	6.85 Mil
mu2e	5.99 Mil
PortlandState_Venkata	5.64 Mil
UAB_Thyme	5.59 Mil
DemoSims	5.49 Mil
UCSD_Politis	5.44 Mil

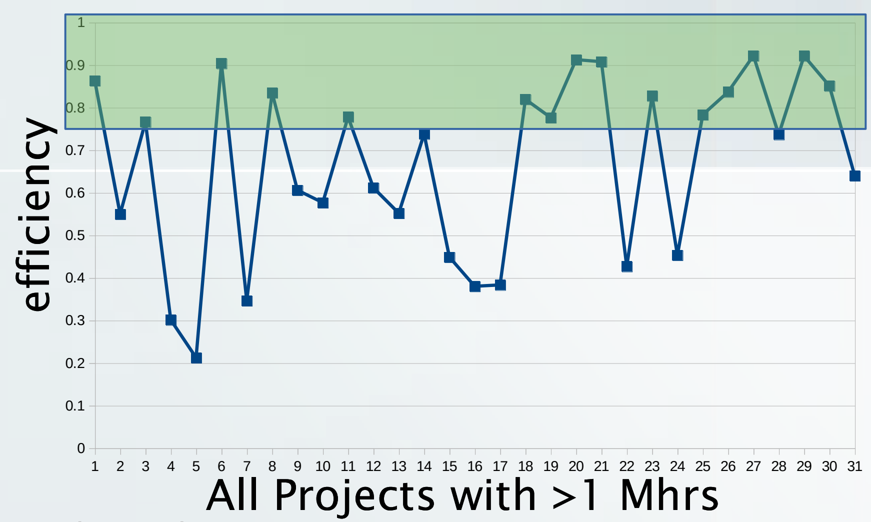
CPU Hours per Project	total
CLAS12	77.0 Mil
REDTOP	63.9 Mil
WSU_3DHydro	57.0 Mil
dune	54.7 Mil
LIGO	47.6 Mil
IceCube	46.3 Mil
KOTO	22.5 Mil
PixleyLab	21.4 Mil
ePIC	19.1 Mil
UConn_Le	11.7 Mil
gluex	10.5 Mil
Michigan_2023_Riles	9.25 Mil
microboone	8.87 Mil
fermilab	8.39 Mil
MSU_Berz	7.93 Mil
PSI_Kaib	7.19 Mil
xenon	7.28 Mil
CMU_Isayev	6.53 Mil
icarus	6.55 Mil
UCBerkeley_Altman	6.13 Mil
EvolSims	6.13 Mil
gm2	5.39 Mil
cms.org.cern	5.18 Mil
BiomedInfo	5.02 Mil
Caltech_2024_Reitze	4.97 Mil
SSGAforCSP	4.74 Mil
Vanderbilt_Paquet	4.36 Mil
UCSD_Politis	4.04 Mil
Syracuse_Nitz	3.66 Mil
Rice_Mulligan	3.48 Mil
NCSU_Hall	3.45 Mil
CSUN_Katz	3.15 Mil
FIU_Li	3.07 Mil
DemoSims	2.88 Mil
UCSD_Xu	2.87 Mil

Job Count per Project	total
LIGO	55.2 Mil
dune	53.1 Mil
IceCube	49.4 Mil
PixleyLab	46.1 Mil
BiomedInfo	44.9 Mil
WSU_3DHydro	43.9 Mil
FIU_Li	37.2 Mil
REDTOP	24.3 Mil
des	16.2 Mil
icarus	15.9 Mil
KOTO	15.6 Mil
microboone	14.6 Mil
OSG_OSGUS24	13.7 Mil
EvolSims	12.9 Mil
xenon	11.7 Mil
CLAS12	9.50 Mil
CPSC_5520	7.77 Mil
ePIC	7.47 Mil
fermilab	7.39 Mil
UCBerkeley_Altman	7.17 Mil
sbnd	6.95 Mil
UAB_Thyme	6.70 Mil
SeattleU_CPSC_5520_2	6.62 Mil
MIT_submit	6.29 Mil
nova	6.26 Mil
gluex	4.94 Mil
LSU_Wilson	4.57 Mil
CompBinFormMod	4.52 Mil
DemoSims	4.31 Mil
MSU_Berz	4.25 Mil
cms.org.cern	4.07 Mil
gm2	3.92 Mil
PSFmodeling	3.85 Mil
UCSD_Rappel	3.11 Mil
NCSU_Hall	3.08 Mil

Summary for 01/2024 - 05/2025 running:

- #jobs: 24.3M
- WallHours: 71.9M
- Core-h: 71.9M
- CPU-h: 63.9M
- Eff: 89% - 91%

Job efficiency - REDTOP



OSG Usage Statistics (01/24 - 05/25)

Core Hours per Project	total
dune	108 Mil
CLAS12	105 Mil
LIGO	102 Mil
IceCube	78.1 Mil
REDTOP	71.9 Mil
WSU_3DHydro	67.7 Mil
PixleyLab	32.0 Mil
KOTO	31.8 Mil
ePIC	23.1 Mil
cms.org.cern	18.3 Mil
microboone	18.1 Mil
xenon	17.5 Mil
gluex	16.1 Mil
Caltech_2024_Reitze	15.3 Mil
gm2	15.3 Mil
fermilab	14.5 Mil
CMU_Isayev	14.3 Mil
icarus	13.5 Mil
UConn_Le	12.8 Mil
cms.org.ku	11.9 Mil
SSGAforCSP	11.7 Mil
Michigan_2023_Riles	10.4 Mil
nova	9.61 Mil
EvolSims	9.40 Mil
UCBerkeley_Altman	8.39 Mil
MSU_Berz	8.37 Mil
PSI_Kaib	7.77 Mil
BiomedInfo	7.75 Mil
Rice_Mulligan	6.99 Mil
LSU_Wilson	6.85 Mil
mu2e	5.99 Mil
PortlandState_Venkatai	5.64 Mil
UAB_Thyme	5.59 Mil
DemoSims	5.49 Mil
UCSD_Politis	5.44 Mil

CPU Hours per Project	total
CLAS12	77.0 Mil
REDTOP	63.9 Mil
WSU_3DHydro	57.0 Mil
dune	54.7 Mil
LIGO	47.6 Mil
IceCube	46.3 Mil
KOTO	22.5 Mil
PixleyLab	21.4 Mil
ePIC	19.1 Mil
UConn_Le	11.7 Mil
gluex	[illegible]
Michigan_2023_Riles	9.25 Mil
microboone	8.87 Mil
fermilab	8.39 Mil
MSU_Berz	7.93 Mil
PSI_Kaib	7.19 Mil
xenon	7.28 Mil
CMU_Isayev	6.53 Mil
[illegible]	6.55 Mil
[illegible]	[illegible]
EvolSims	6.13 Mil
gm2	5.39 Mil
cms.org.cern	5.18 Mil
BiomedInfo	5.02 Mil
Caltech_2024_Reitze	4.97 Mil
SSGAforCSP	4.74 Mil
Vanderbilt_Paquet	4.36 Mil
UCSD_Politis	4.04 Mil
Syracuse_Nitz	3.66 Mil
Rice_Mulligan	3.48 Mil
NCSU_Hall	3.45 Mil
CSUN_Katz	3.15 Mil
FIU_Li	3.07 Mil
DemoSims	2.88 Mil
UCSD_Xu	2.87 Mil

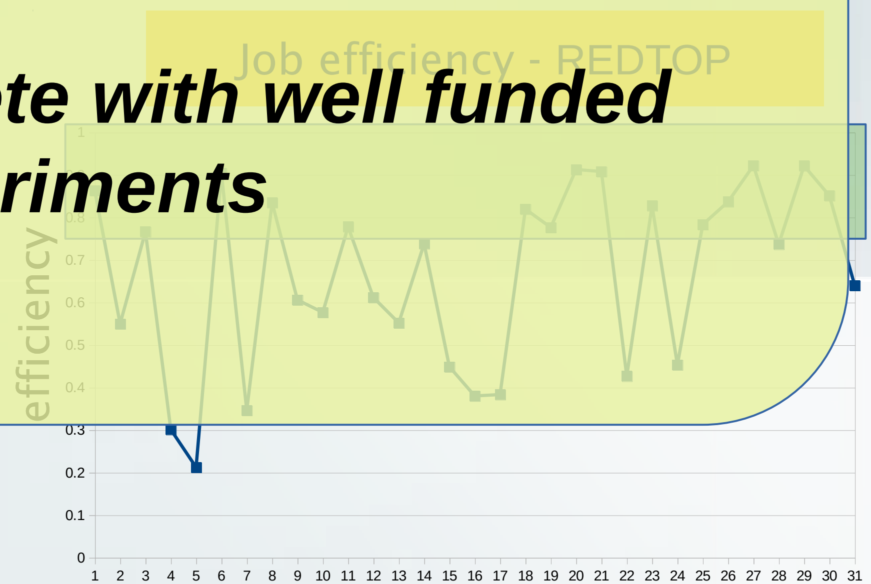
Job Count per Project	total
LIGO	55.2 Mil
dune	53.1 Mil
IceCube	49.4 Mil
PixleyLab	46.1 Mil
BiomedInfo	44.9 Mil
WSU_3DHydro	43.9 Mil
FIU_Li	37.2 Mil
REDTOP	24.3 Mil
[illegible]	16.2 Mil
[illegible]	15.9 Mil
KOTO	[illegible]
microboone	14.6 Mil
OSG_OS[illegible]	13.7 Mil
EvolSims	[illegible]
xenon	11.7 Mil
CLAS12	9.50 Mil
CPSC_5520	7.77 Mil
ePIC	7.47 Mil
fermilab	7.29 Mil
UCBerkeley_Altman	[illegible]
sbnd	6.95 Mil
UAB_Thyme	[illegible]
SeattleU_CPSC_5520_2	6.62 Mil
MIT_submit	6.29 Mil
nova	6.26 Mil
gluex	4.94 Mil
LSU_Wilson	4.57 Mil
CompBinFormMod	4.52 Mil
DemoSims	4.31 Mil
MSU_Berz	4.25 Mil
cms.org.cern	4.07 Mil
gm2	3.92 Mil
PSFmodeling	3.85 Mil
UCSD_Rappel	3.11 Mil
NCSU_Hall	3.08 Mil

Summary for 01/2024 - 05/2025 running:

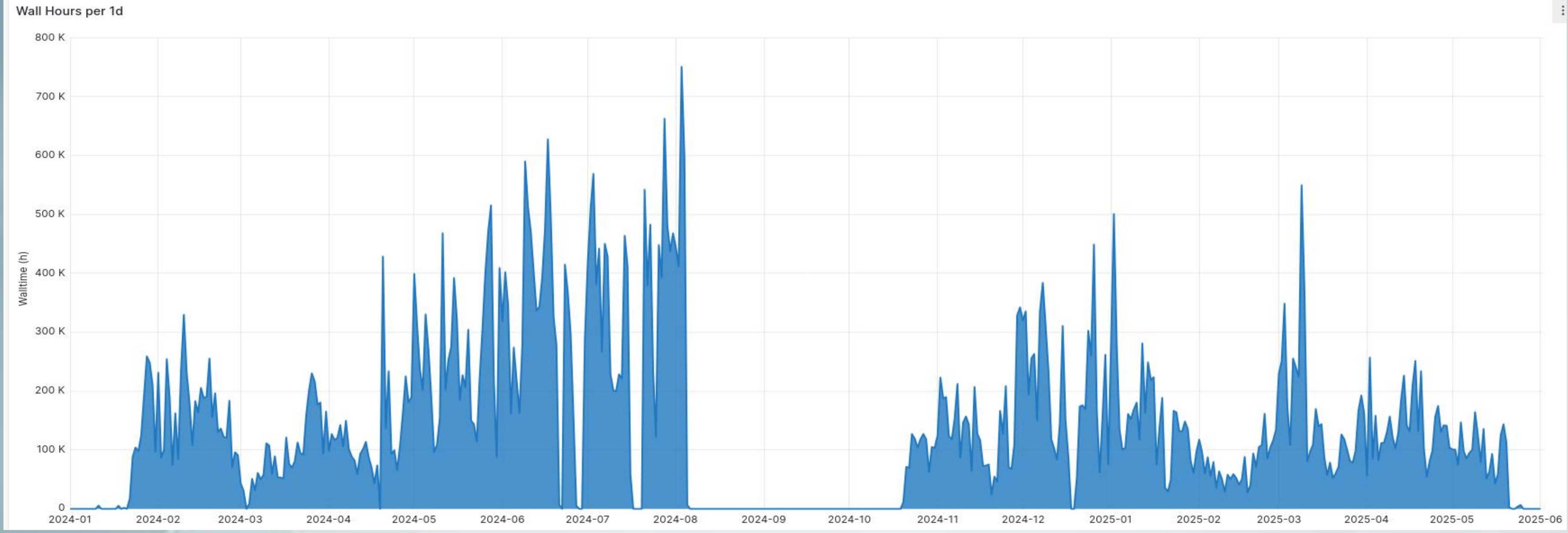
- #jobs: 24.3M
- WallHours: 71.9M
- Core-h: 71.9M
- CPU-h: 63.9M

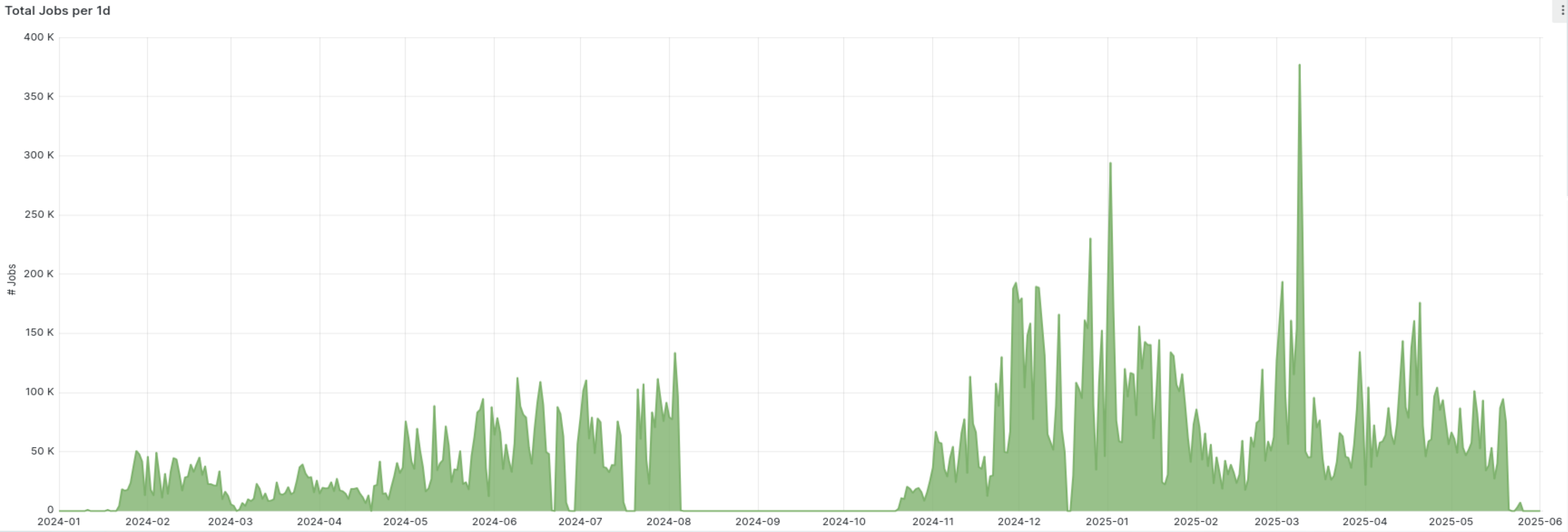
REDTOP is a propose project
With no funds

Needs to compete with well funded experiments



OSG Daily Usage Statistics

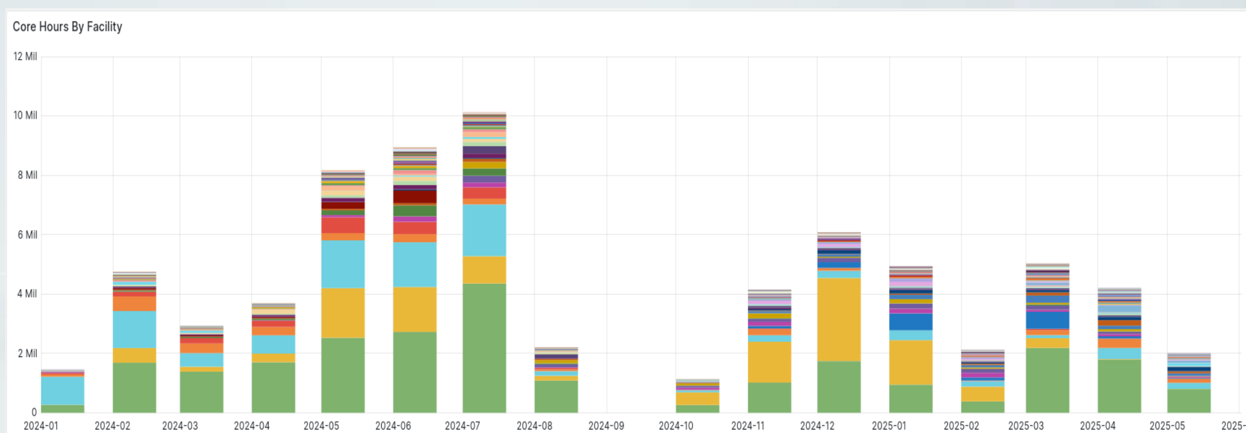




OSG Yearly Usage Statistics for REDTOP project

Core Hours By Facility	total
SU ITS	25 Mil
FermiGrid	12 Mil
MWT2 ATLAS UC	10 Mil
GLOW	3 Mil
AGLT2	2 Mil
Purdue Anvil	2 Mil
Nebraska-Omaha	1 Mil
UChicago	1 Mil
Michigan HORUS	1 Mil
IRISHEP-SSL-UCHICAGO	928 K
Montana State RCI	831 K
Clemson-Palmetto	816 K
BNL ATLAS Tier1	800 K
FANDM-ITS	767 K
UColorado_HEP	740 K
Pervasive Technology Institute	696 K
UConn-HPC	652 K
PSU LIGO	628 K
Beocat	595 K
University of Washington Resear	456 K

- Time range: 01/24 – 05/25
- Total Core Hours: 71.9 million
- Total jobs: 24.3 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 and HHaS) sensitive to all 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	$\eta \to 3\pi^0$	$\eta \to e^+e^-\gamma$	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	$e^+e^- \to J/\psi \to \eta\gamma$ + η 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)	$\gamma_{12\,\mathrm{GeV}}\mathrm{p} \to \eta\, X \to$ neutrals			5.5×10^7/yr
JEF@JLAB (construction)	$\gamma_{12\,\mathrm{GeV}}\mathrm{p} \to \eta\, X \to$ 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.)*

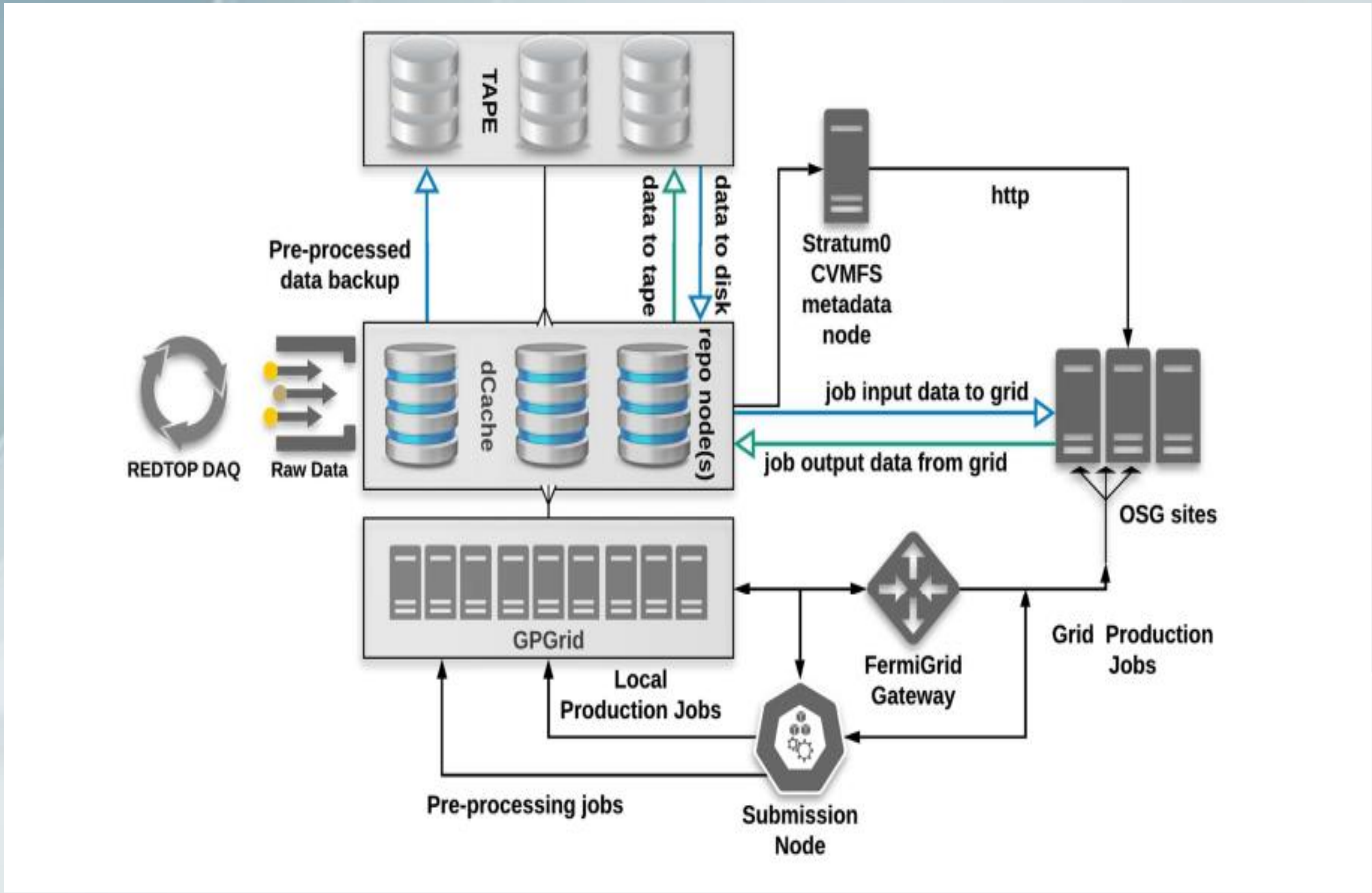
- *Storage:*
  - *DataStream from the L-2 farm will be staged at (FNAL) dCache storage and sent to tape (or wherever is cheaper when the experiment runs: FNAL at present)*
  - *Stratum-0 server hosts a CVMFS repository of the REDTOP software*

- *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



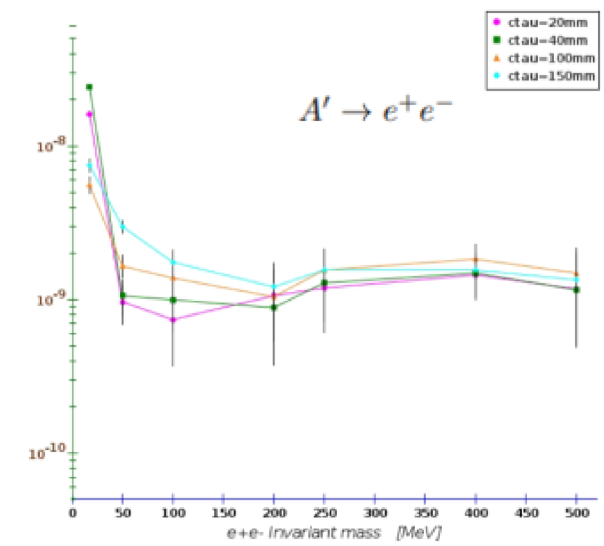
For more details: http://redtop.fnal.gov/wp-content/uploads/2020/05/redtop-compute_v3.pdf

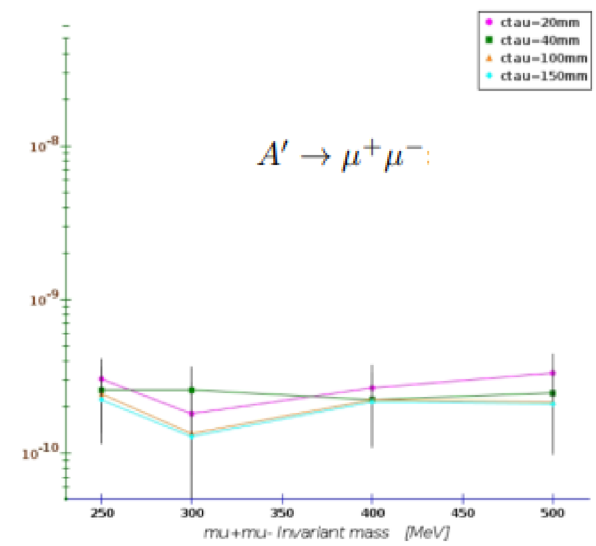
New particles & forces

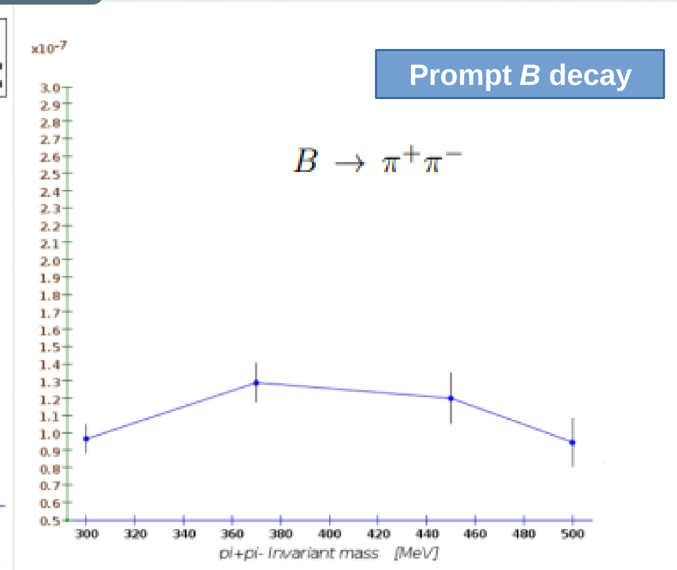
Vector Portal: $\eta \to \gamma A'$ with $A' \to l^+ l^-$ or $\pi^+\pi^-$

REDTOP

Some BR sensitivity curves







Sensitivity curves for Minimal Dark Photon Model

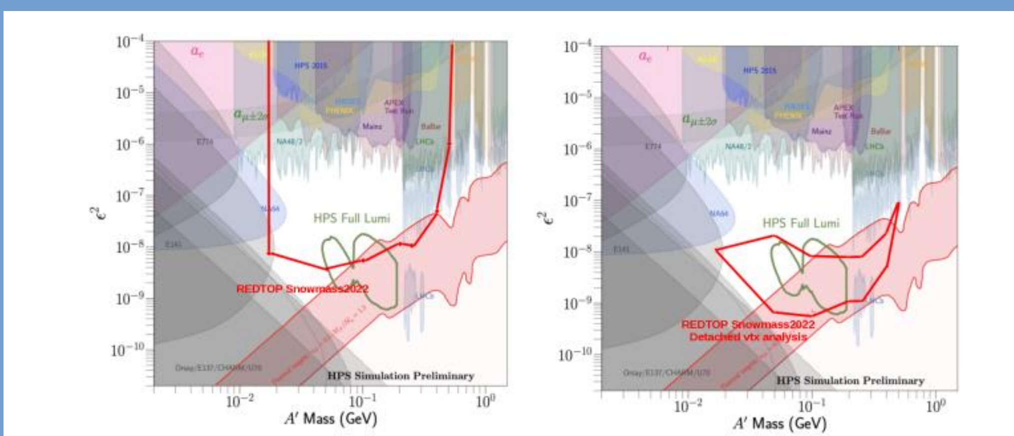


FIG. 36. Sensitivity to to ε^2 for the processes $\eta \to \gamma A'$ for integrated beam flux of 3.3×10^{18} POT. Left plot: *bump-hunt* analysis. Right plot: *detached-vertex* analysis).

Theoretical Models considered

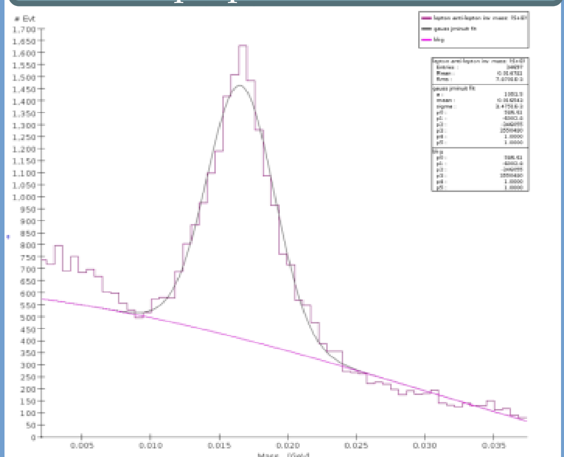
- *Minimal dark photon model*
  - *Most popular model*
- *Leptophobic B boson Model*
- *Protophobic Fifth Force*
  - *Explains the Atomki anomaly*

New particles & forces

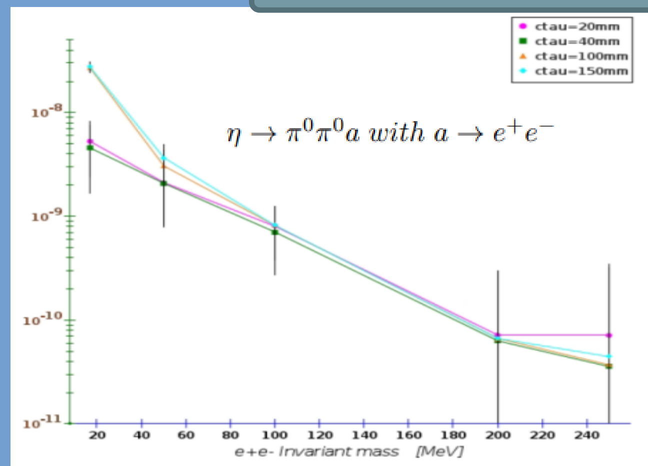
Pseudoscalar Portal: $\eta \to \pi^o \pi^o a$ & $\eta \to \pi^+ \pi^- a$ with $a \to \gamma\gamma$, $\mu^+ \mu^-$ and $e^+ e^-$

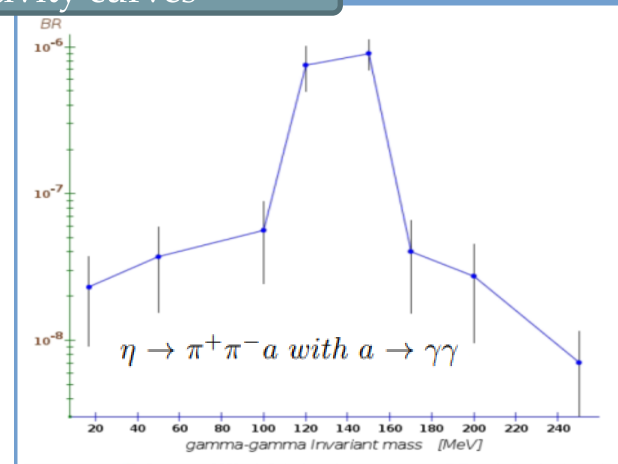
REDTOP

17 MeV piophobic QCD axion

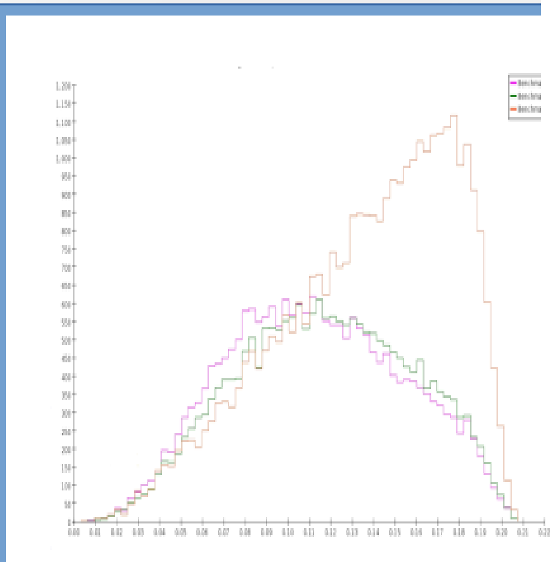


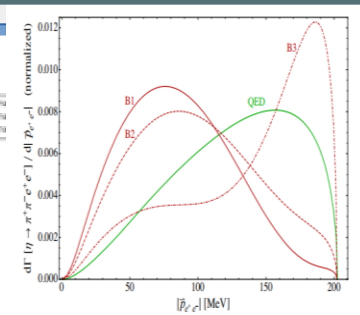
Some BR sensitivity curves

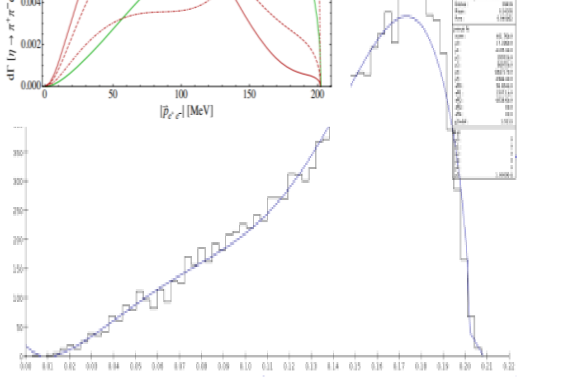




Differential rate for $\eta \to \pi^+\pi^- a$ for three benchmark params







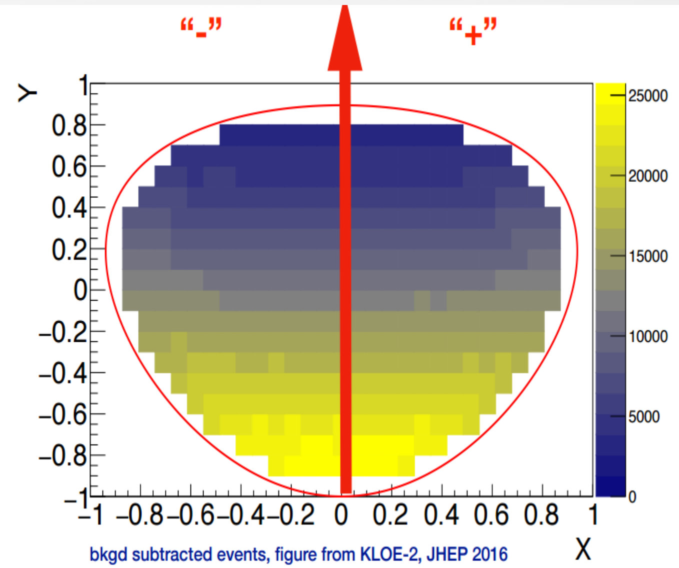
Theoretical models considered

- ***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***

Test of discrete symmetries

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

- *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



bkgd subtracted events, figure from KLOE-2, JHEP 2016

Slide Credit: Susan Gardner & Jun Shi

University of Kentucky

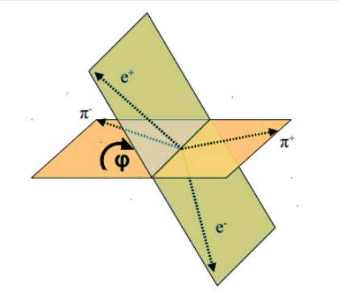
REDTOP sensitivity to model parameters

#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%

REDTOP

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

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

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

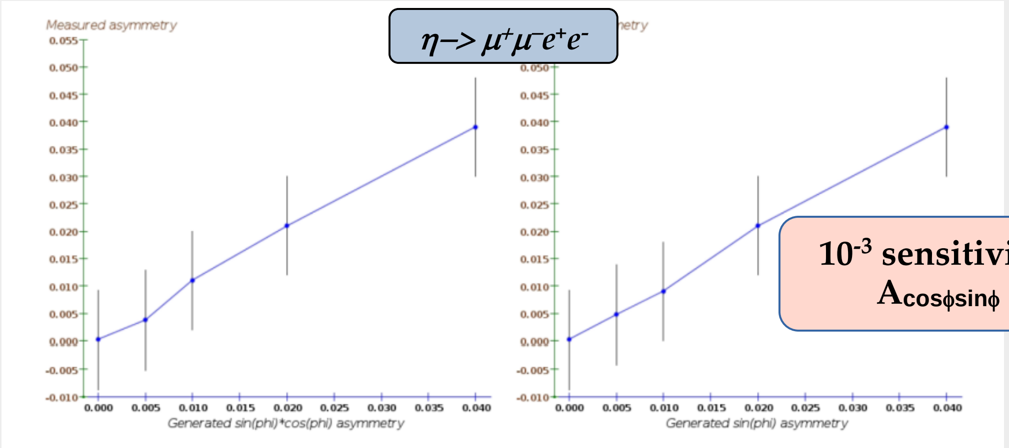
$$A_{sin\Phi} = \frac{N(\sin\phi > 0) - N(\sin\phi < 0)}{N(\sin\phi > 0) + N(\sin\phi < 0)}$$

through Wilson coefficients

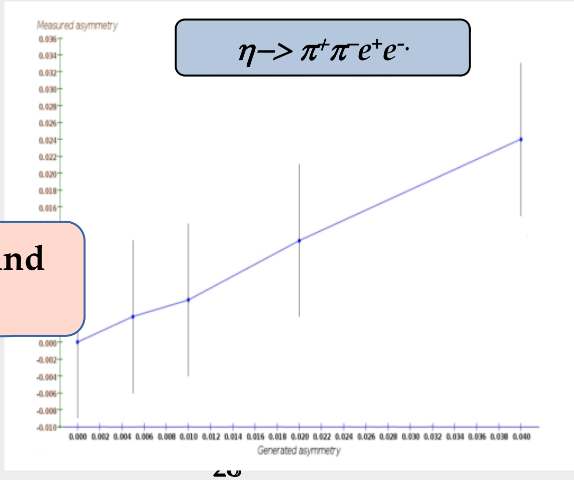
$$A_{\sin\phi\cos\phi} = \mathrm{Im}[1.9c^{2222}_{\ell edq} - 1.3(c^{(1)2211}_{\ell equ} + c^{1122}_{\ell edq})] \times 10^{-5} - 0.2\epsilon_1 + 0.0003\epsilon_2$$

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

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



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



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

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

CP-violation from μ–polarization

REDTOP

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

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***

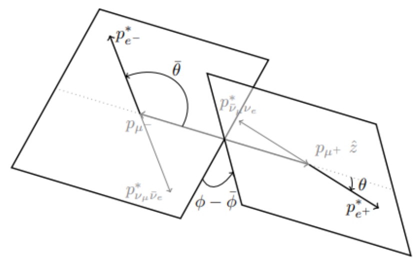


FIG. 11. Kinematics of the process. The decaying muons' momenta in the η rest frame are noted as $p_{\mu^\pm}$, while the $e^\pm$ momenta, $p^*_{e^\pm}$, is shown in the corresponding $\mu^\pm$ reference frame along with the momenta of the $\nu\bar{\nu}$ system. The $\hat{z}$ axis is chosen along p_{μ^+}.

introduced two different muon's polarization asymmetries,

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

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

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

REDTOP

Lepton Universality Studies

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

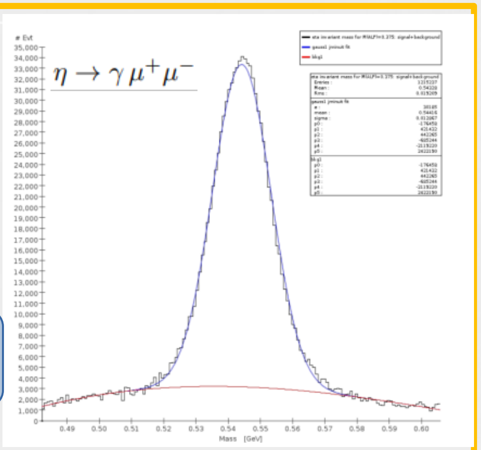
$\eta \to \gamma\, \mu^+ \mu^-$ *vs* $\gamma\, e^+ e^-$

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}	8.84×10^5	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



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

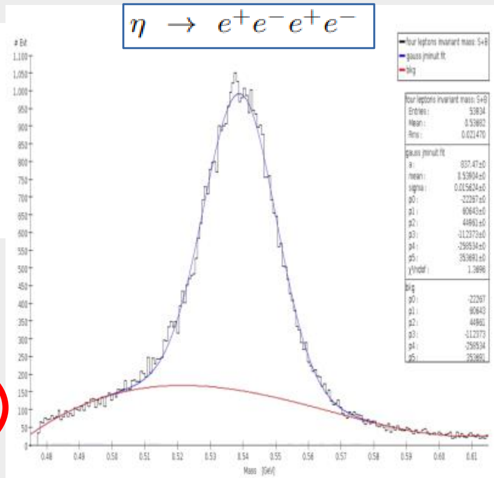
- Theoretical calculations at the 10^{-3} precision from Kampf, Novotný, Sanchez-Puertas (PR D 97, 056010 (2018))

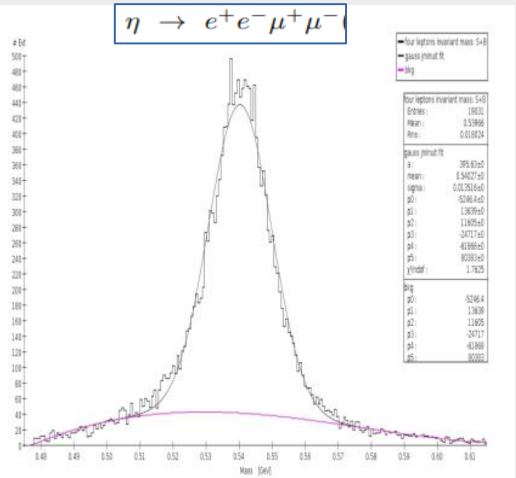
REDTOP reconstruction efficiency

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

vs LHCb@40 MHz

- *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*

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

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

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

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 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 σ(E)/E ~ 2-3%/ √ E***
- ***High PID efficiency: 98/99% (e,γ), 95% (μ), 95% (π), 99.5%(p,n)***
- $\sigma_{tracker}(t)$ ~ 30psec, $\sigma_{calorimeter}(t)$ ~ 80psec, $\sigma_{TOF}(t)$ ~ 50psec
- ***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

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) Contributions from higher orders are enhanced by a factor of ~100,000
• EM decays are forbidden in lowest order by C invariance and angular momentum conservation	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 3.3×10^{18} POT (3.3 years running at 1×10^{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

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

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$N_{\eta'}$	7.9×10^{11}
N_{ni}	3.2×10^{16}

η/η' production rate: ~ 2.3 MHz

Beam scheme for FNAL option (M. Syphers)

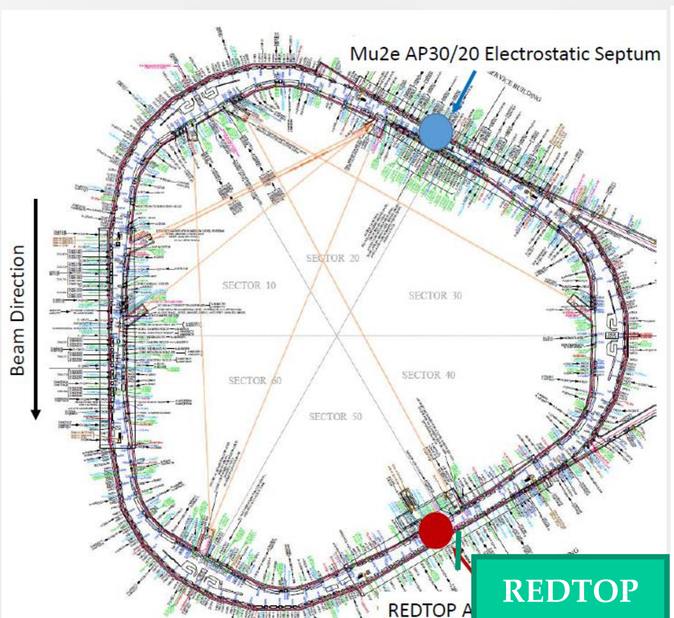
Single p pulse from booster (≤4x10^{12} p) injected in the DR (former debuncher in anti-p production at Tevatron) at fixed energy (8 GeV)

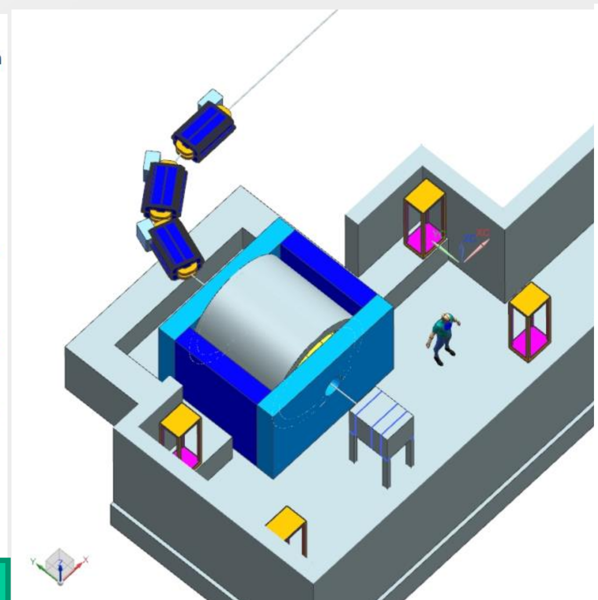
Energy is removed by inserting 1 or 2 RF cavities identical to the one already planned (~5 seconds)

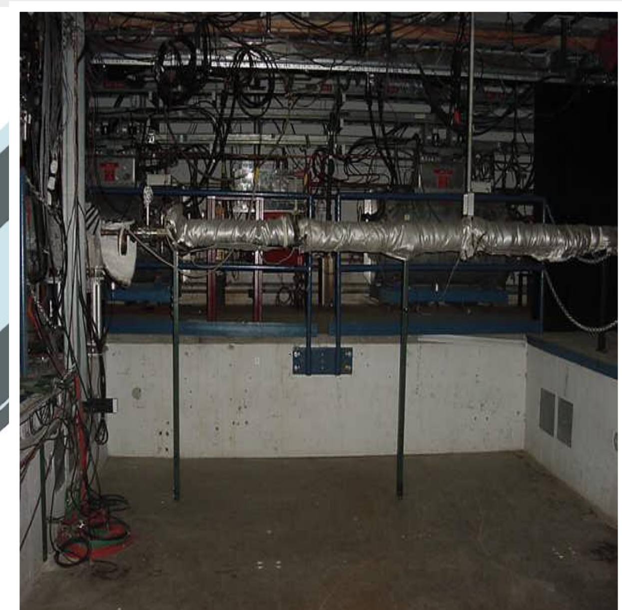
Slow extraction to REDTOP over ~40 seconds.

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

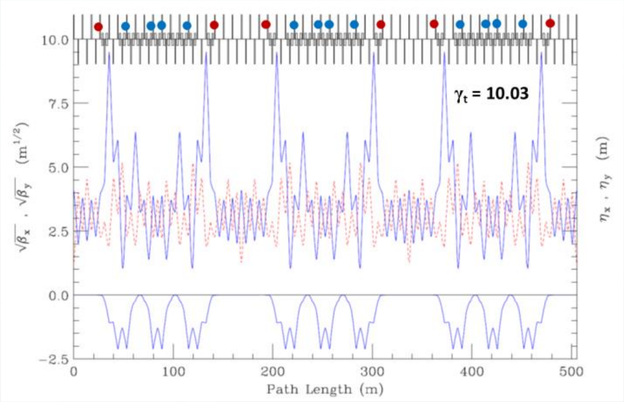
Total time to decelerate-debunch-extract: 51 sec: duty cycle ~80%

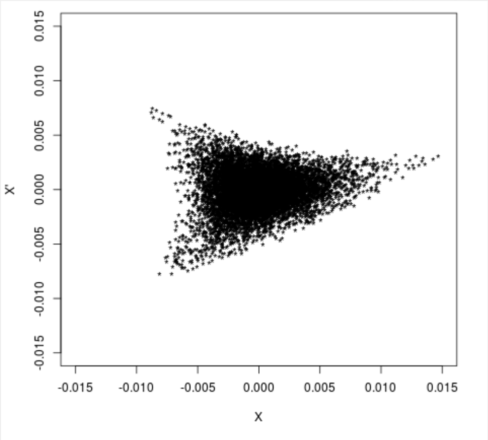






Accelerator Physics Issues





- ***Transition Energy***
  - γ_t is where $\Delta f/f = 1/\gamma 2$ - <D/ρ> = 0; synchrotron motion stops momentarily, can often lead to beam loss
  - beam decelerates from γ = 9.5 to γ = 3.1
  - original Delivery Ring γ_t = 7.6
  - a re-powering of 18 quadrupole magnets can create a γ_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

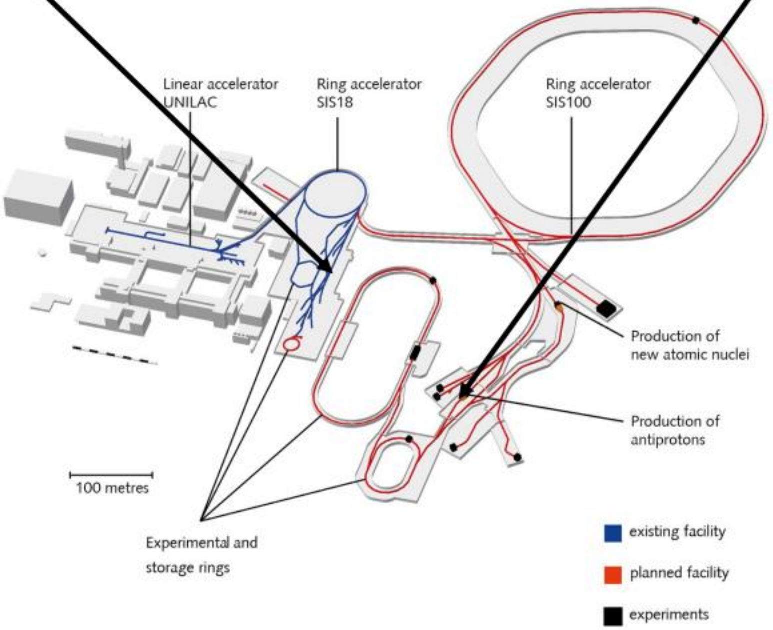
Beam Options at GSI/FAIR (near future)

Opportunities as fixt target exp.

FAIR GSI

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

Daniel Severin

Beam Options at GSI (far future)

Opportunities as in-ring target exp.

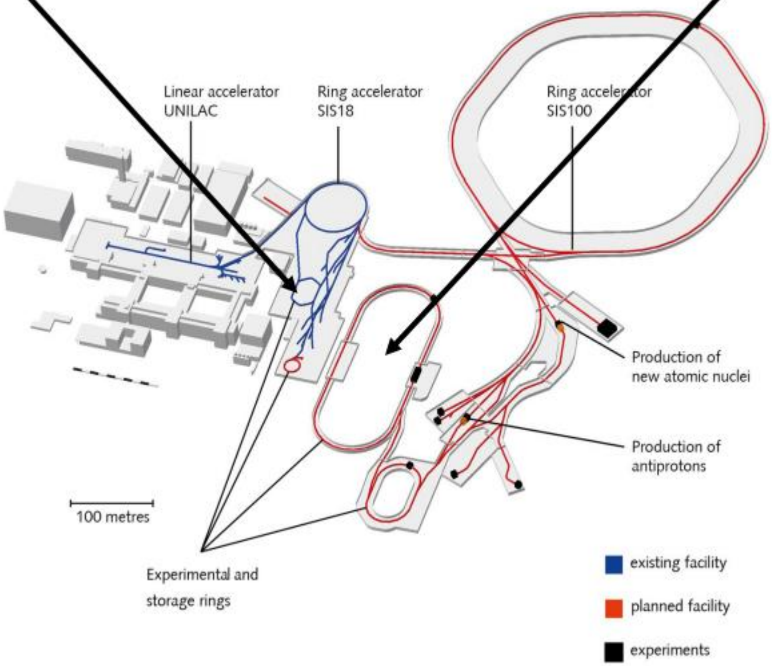
FAIR GSI

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



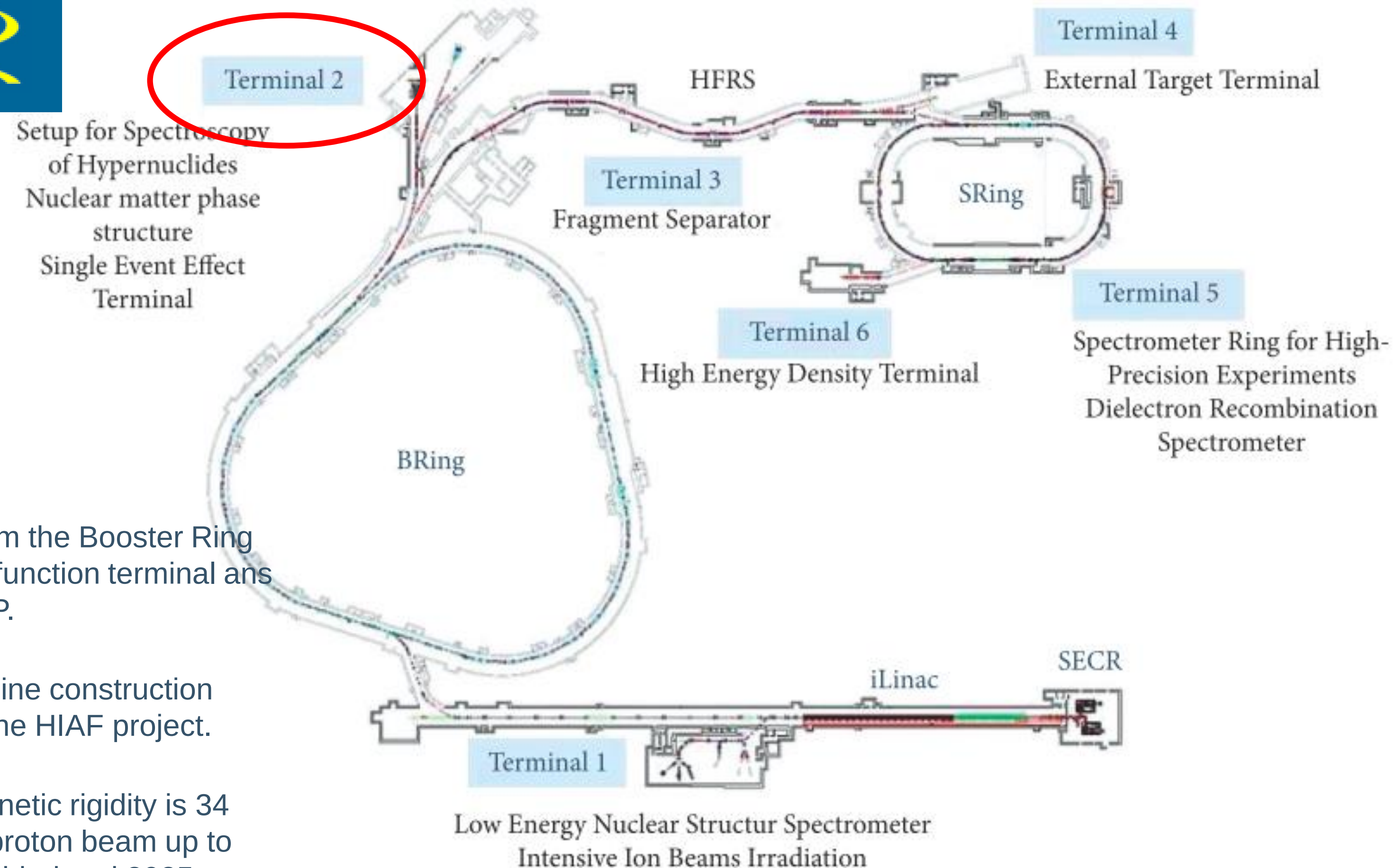
- HESR or CR
- Intensity fully flexible
- Full beam usage

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

Beam intensity: 1.8 GeV protons with 1e11/s

Daniel Severin

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 . $10^{(18-19)}$ 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

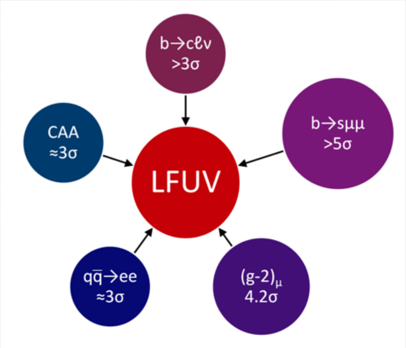
- *Calorimetric sensitivity to $M(\gamma\gamma)$~30MeV*

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

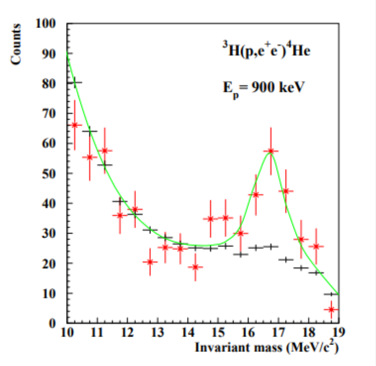
- *Tracker sensitivity to $M(e^+e^-)$~ 20 MeV*
- *Electron ID at very low energy*

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