Studying eta decays at REDTOP

Rare **E**ta **D**ecays
TO Probe New Physics

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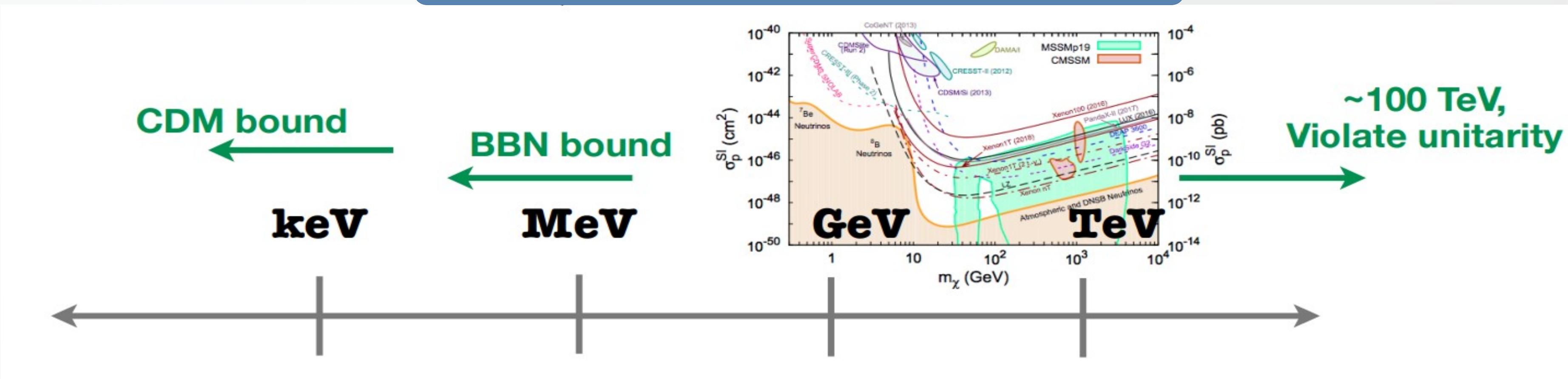
Where to Look for BSM Physics

Cold dark matter scenarios



Bound by cosmological observations

Mostly unconstrained

Disfavorite by LHC/Direct detection

Requires new facilities

The MeV-GeV is the region to explore in the next ~10 years

Increasing effort in Europe and Asia to deploy new experiments

Low-energy, high-intensity accelerators are better suited vs high-energy ones

Rationale for an η/η‘ Factory

"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 flavor-conserving reactions

Experimental advantages:

- Hadronic production cross section is quite large (~ 0.1 barn) → much easier to produce than heavier mesons
- All its possible strong decays are forbidden in lowest order by P and CP invariance, G-parity conservation and isospin and charge symmetry invariance.
- EM decays are forbidden in lowest order by C invariance and angular momentum conservation Branching Ratio 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

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

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- Test of CP invariance via μ longitudinal polarization: $\eta \rightarrow \mu^+ \mu^-$
- CP inv. via γ^* 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 p[illegible]
- T invar. via μ transverse polarization: $\eta \rightarrow \pi^o \mu^+ \mu^-$ and $\eta \rightarrow \gamma \mu^+ \mu^-$
- CPT violation: μ polar[illegible] $\rightarrow \pi \mu^+ \nu$ - γ polar. in $\eta \rightarrow$ [illegible]

Other discrete symmetry violations

- Lepton Flavor Violation: $\eta \rightarrow \mu^+ e^- + c.c.$
- Radiative Lepton Flavor Violation: $\eta \rightarrow \gamma \mu^+ e^- + c$[illegible]
- Double lepton Flavor Violation: $\eta \rightarrow \mu^+ \mu^+ e^- e^- + c.c.$

Non-η/η' based BSM Physics

- Neutral pion decay: $\pi^o \rightarrow \gamma A' \rightarrow \gamma e^+ e^-$
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- 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 $\eta \rightarrow e^+ e^-$
- [illegible] true [illegible] $)_{2M_\mu} \rightarrow \gamma e^+ e^-$
- Lepton Universality
- [illegible] H [illegible] $H \rightarrow$ [illegible] $N \rightarrow$ [illegible] $e^+ e^-$

Other Precision Physics measurements

- [illegible]: $\eta \rightarrow \gamma \mu^+ \mu^-$ 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

- 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)

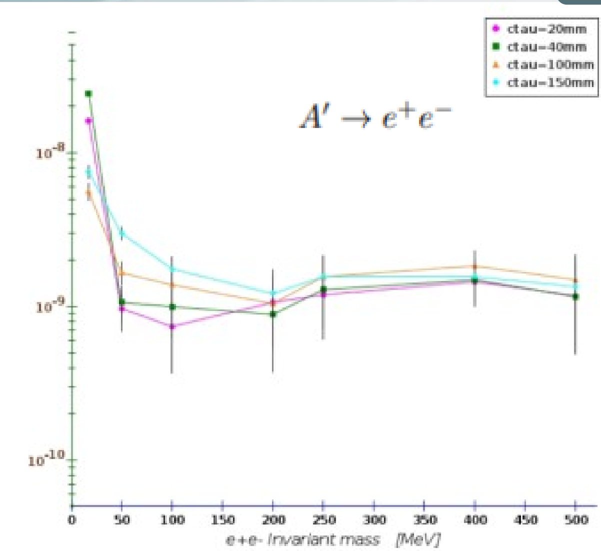
Only experiment, along with SHIP, sensitive to all four BSM portals

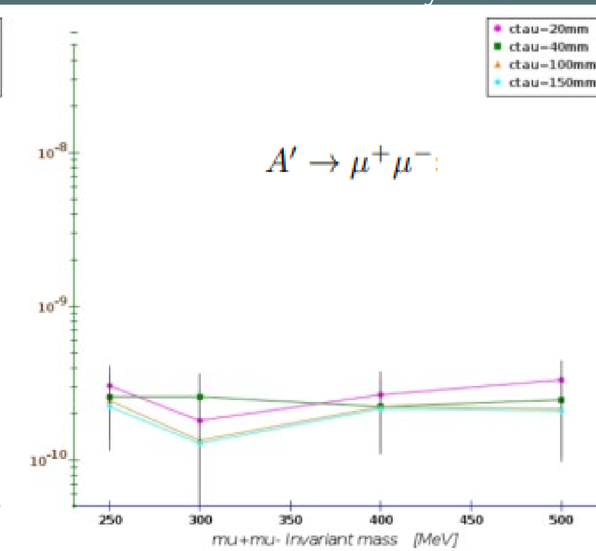
New particles & forces

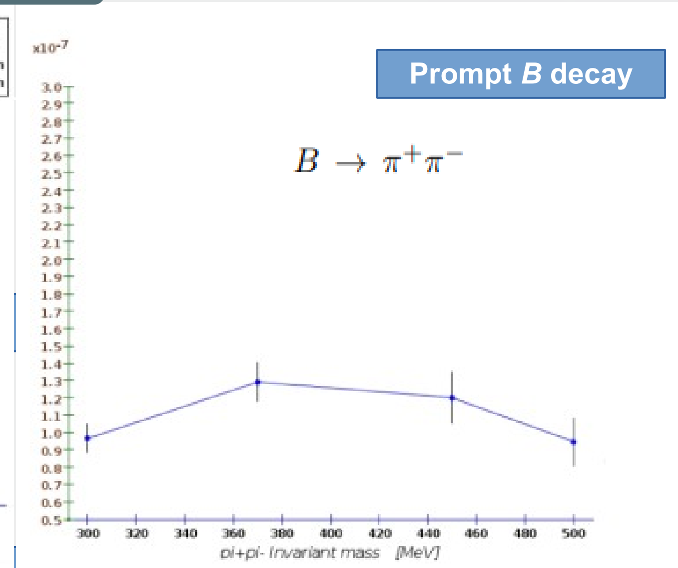
Vector Portal: $\eta \rightarrow \gamma A'$ with $A' \rightarrow l^+l^-$ or $\pi^+\pi^-$

REDTOP

Some BR sensitivity curves







Sensitivity curves for Minimal Dark Photon Model

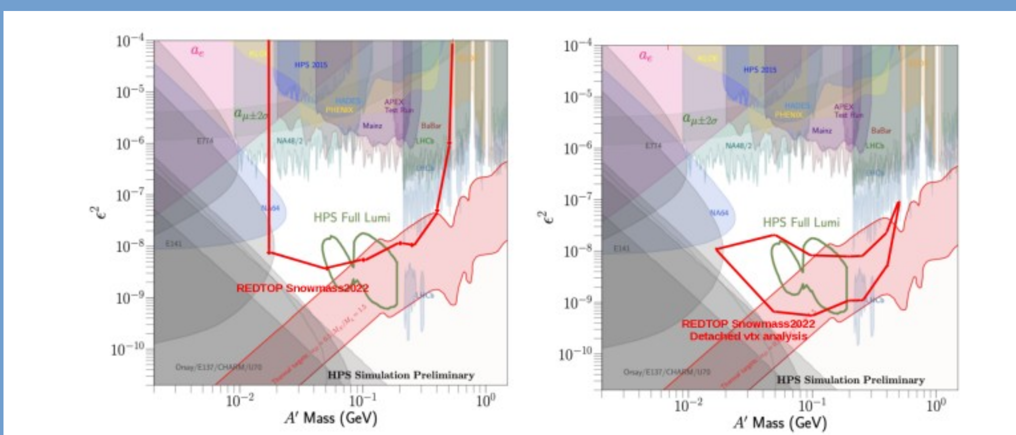


FIG. 36. Sensitivity to to ε^2 for the processes $\eta \rightarrow \gamma A'$ for integrated beam flux of 3.3×10^{18} POT. Left plot: *bump-hunt* analysis. Right plot: *detached-vertex* analysis).

Theoretical Models considered

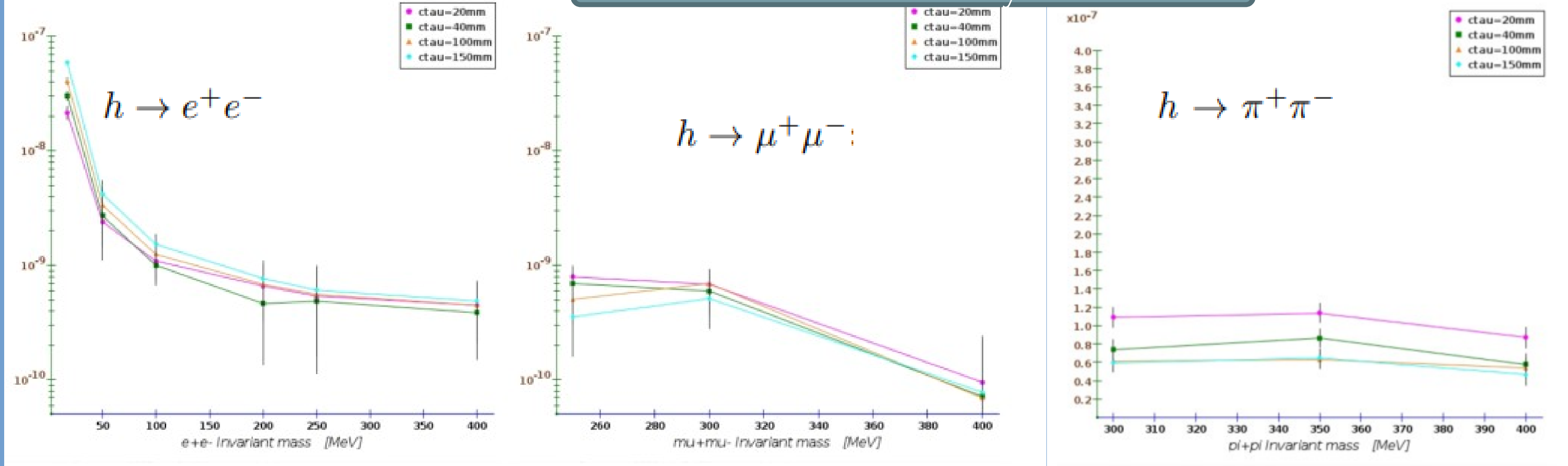
- *Minimal dark photon model*
  - *Most popular model*
- *Leptophobic B boson Model*
- *Protophobic Fifth Force*
  - *Explains the Atomki anomaly*

New particles & forces

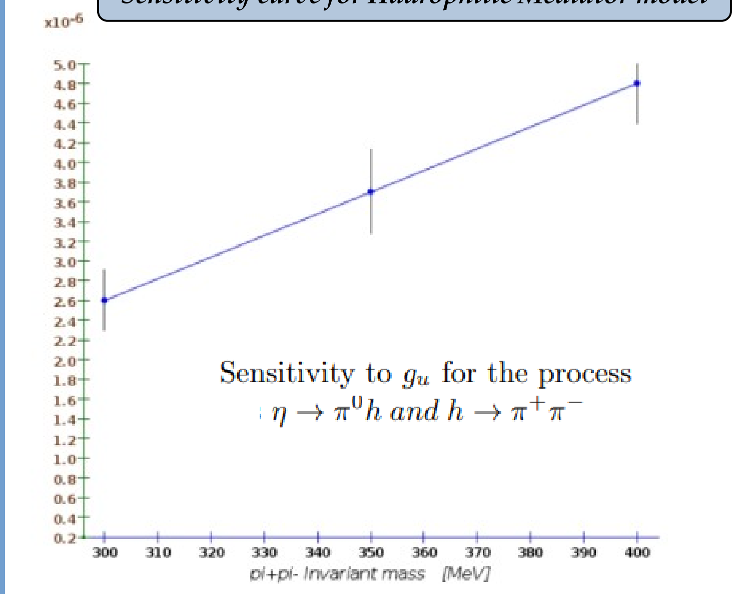
REDTOP

Scalar Portal searches: $\eta \to \pi^0 h$ with $h \to \mu^+\mu^-, \pi^+\pi^-, e^+e^-$

Some BR sensitivity curves



Sensitivity curve for Hadrophilic Mediator model



Sensitivity for Two-Higgs doublet model

Process	m_S	*Analysis*	$(\lambda_u - \lambda_d)^2$ sensitivity
$\eta \to \pi^0 S$; $S \to e^+e^-$	17 MeV	bump hunt	2.0×10^{-13}
$\eta \to \pi^0 S$; $S \to \mu^+\mu^-$	17 MeV	detached vertex	3.2×10^{-13}

TABLE XXV. Sensitivity to $(\lambda_u - \lambda_d)^2$ for the process $\eta \to \pi^0 S$ and $S \to e^+e^-$ and $S \to \mu^+\mu^-$.

Theoretical models considered

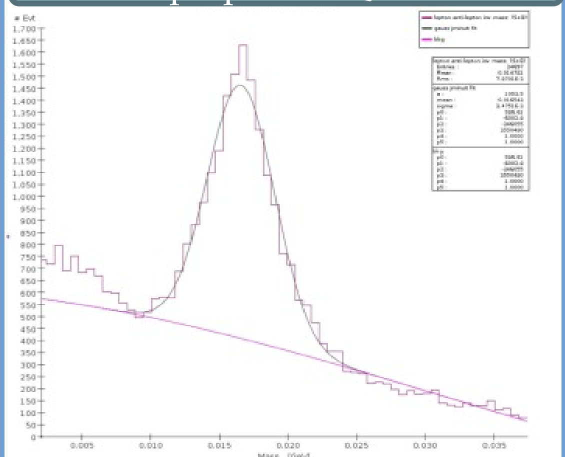
- ***Hadrophilic Scalar Mediator*** *(B. Batell, A. Freitas, A. Ismail, D. McKeen)*
- ***Spontaneous Flavor Violation*** *(D.Egana-Ugrinovic, S. Homiller, P. Meade)*
- ***Two-Higgs doublet model*** *(W. Abdallah, R. Gandhi, and S. Roy)*
- ***Minimal scalar model*** *(C.P. Burgess, M. Pospelov, T. ter Veldhuis)*

New particles & forces

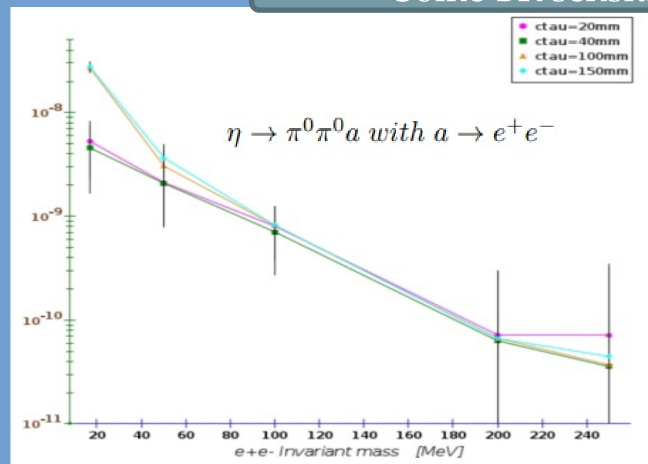
Pseudoscalar Portal: $\eta \rightarrow \pi^o \pi^o a$ & $\eta \rightarrow \pi^+ \pi^- a$ with $a \rightarrow \gamma\gamma$, $\mu^+ \mu^-$ and $e^+ e^-$

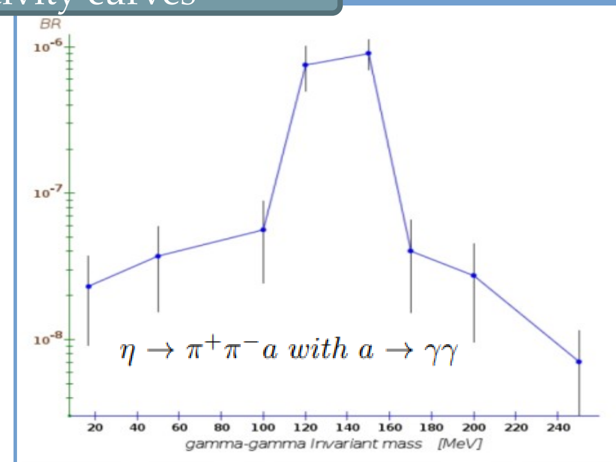
REDTOP

17 MeV piophobic QCD axion

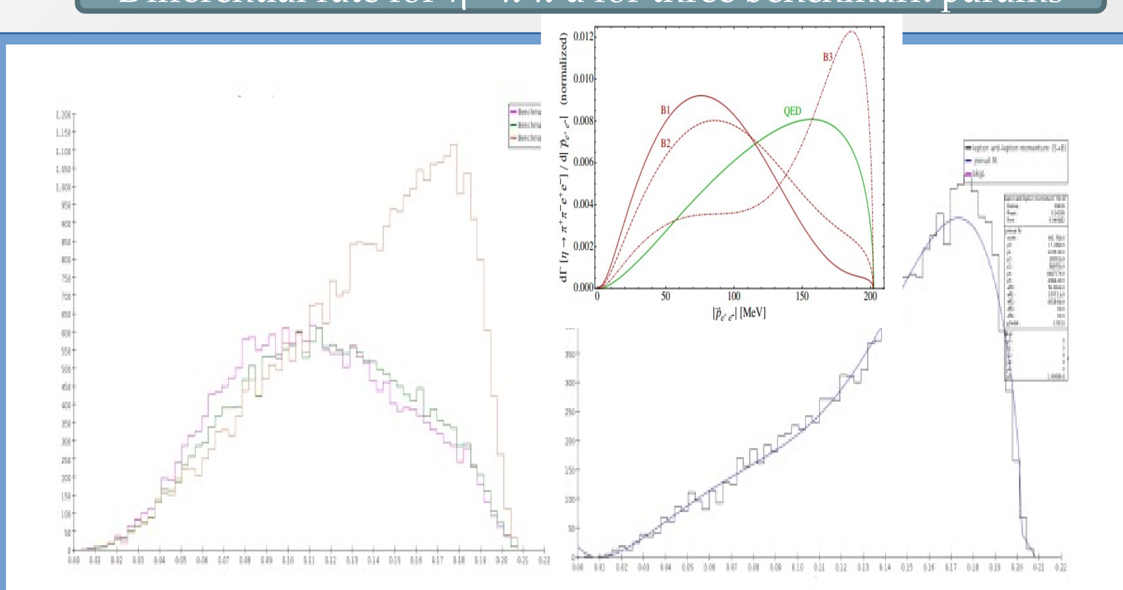


Some BR sensitivity curves





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 evts with SM expectation of 10*
- ***Heavy Axion Effective Theories***

New particles & forces

Heavy Neutral Lepton Portal: $\eta \to \pi^0 H$; $H \to \nu N_2$; $N_2 \to N_1 h_0$; $h_0 \to e^+e^-$

REDTOP

Model considered for Snowmass

- *Two-Higgs doublet model (W. Abdallah, R. Gandhi, and S. Roy) with the following benchmark parameters:*

m_{N_1}	m_{N_2}	m_{N_3}	$y^{h'}_{e(\mu)} \times 10^4$	$y^{H}_{e(\mu)} \times 10^4$
85 MeV	130 MeV	10 GeV	0.23(1.6)	2.29(15.9)
$m_{h'}$	m_H	$\sin\delta$	$y^{h'(H)}_{\nu_{12}} \times 10^3$	$\lambda^{h'(H)}_{N_{12}} \times 10^3$
17 MeV	250 MeV	0.1	1.25(12.4)	74.6(−7.5)

TABLE XXVIII. Benchmark parameters for REDTOP.

REDTOP sensitivity to model parameters

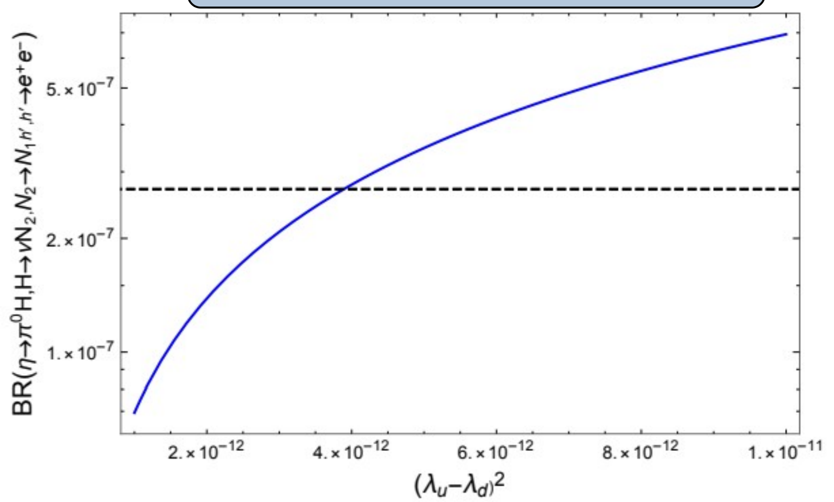
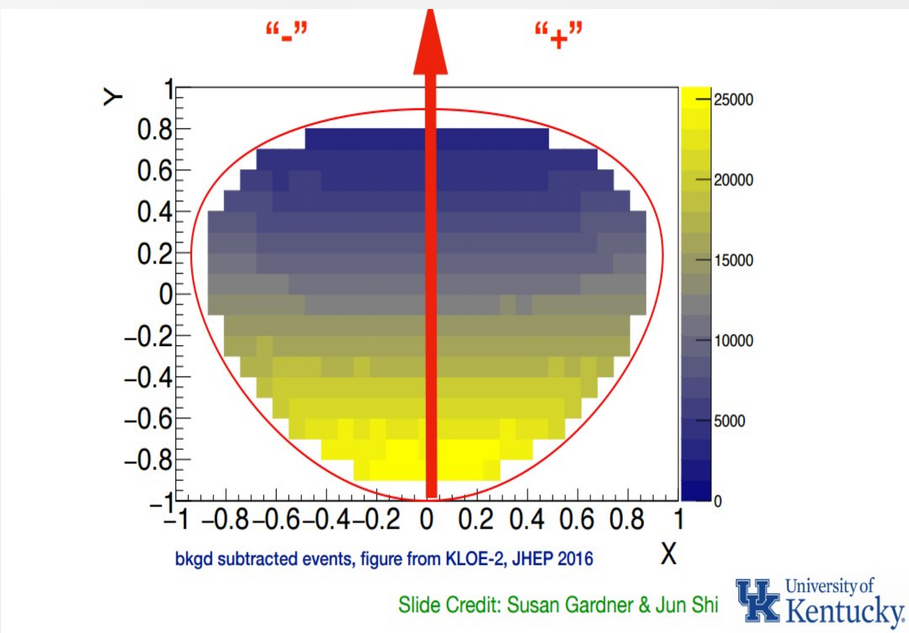


FIG. 61. Branching ratio for the process $\eta \to \pi^0 H$; $H \to \nu N_2$; $N_2 \to N_1 h'$; $h' \to e^+e^-$ predicted by the Two Higgs Doublet model [51] as a function of $(\lambda_u - \lambda_d)^2$. The dashed line corresponds to the experimental limit for REDTOP with an integrated luminosity of 3.3×10^{18} POT.

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*
- *New model in GenieHad (collaboration with S. Gardner & J. Shi) based on* https://arxiv.org/abs/1903.11617



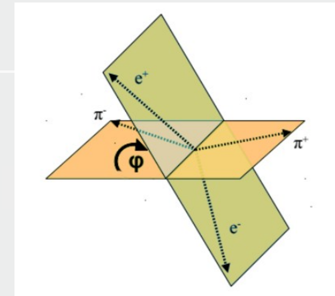
REDTOP sensitivity to model parameters

#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%

REDTOP

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

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

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

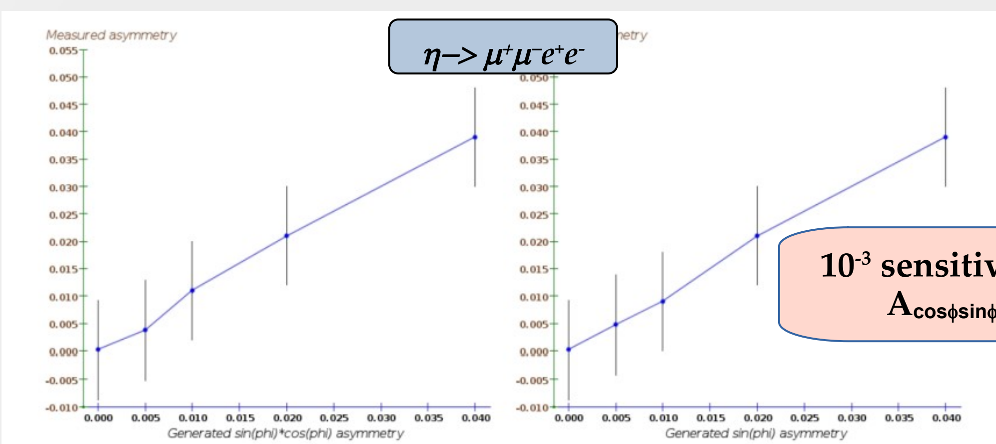
through Wilson coefficients

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

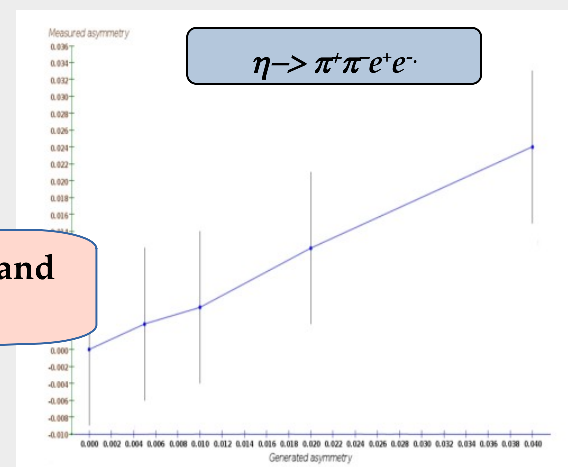
CP violation is related to asymmetries in $\eta \to \pi^+\pi^- e^+e^-$

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

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



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



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

CP-violation from μ–polarization

CP Violation in $\eta \to \mu^+\mu^-$

REDTOP

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*

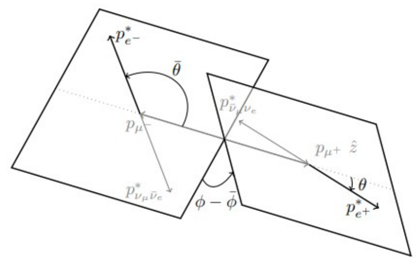


FIG. 11. Kinematics of the process. The decaying muons' momenta in the η rest frame are noted as $p_{\mu^\pm}$, while the $e^\pm$ momenta, $p^*_{e^\pm}$, is shown in the corresponding $\mu^\pm$ reference frame along with the momenta of the $\nu\bar{\nu}$ system. The $\hat{z}$ axis is chosen along p_{μ^+}.

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}%	-

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

Lepton Flavor Violation Studies

REDTOP

LF-violation in $\eta \rightarrow e^+ \mu^-$ + c.c. processes (A. Petrov , D. Hazard, 1607.00815).

LF-violation in $\eta \rightarrow \gamma e^+ \mu^-$ + c.c. processes (A. Petrov , D

1711.05314).

Still in progress

Process	*Trigger* L0	*Trigger* L1	*Trigger* L2	*Reco*	**Total**	Branching ratio sensitivity
$\eta \rightarrow e^+\mu^- + c.c.$	79.3	21.3%	89.7%	14.0%	2.1%	$1.4 \times 10^{-7} \pm 2 \times 10^{-9}$
Urqmd	21.7%	1.7%	22.2%	0.01%	8.2×10^{-6}%	

Also worth considering, doubly LF-violation processes: $\eta \rightarrow \boldsymbol{e^+ e^+} \mu^- \mu^-$ + c.c.

Lepton Universality Studies

REDTOP

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

REDTOP statistical error for ~10^{11} POT

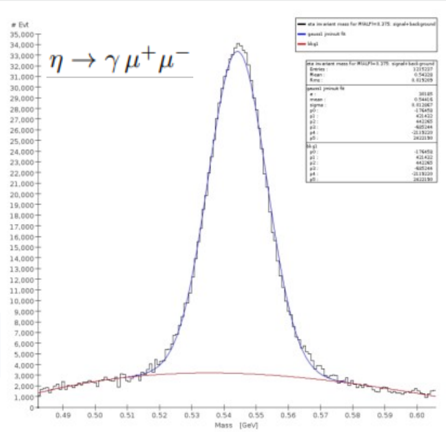
$\eta \rightarrow \gamma\mu^+\mu^-$ *vs* γe^+e^-

Process	POT	Signal events	Background events	$\frac{S}{\sqrt{B}}$	**Statistical err**
$\eta \rightarrow \gamma e^+e^-$	1.38×10^{11}	[illegible]$.13 \times 10^6$	2.52×10^4	1.3×10^4	**0.09%**
$\eta \rightarrow \gamma\mu^+\mu^-$	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 $\eta \rightarrow \gamma$ *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



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

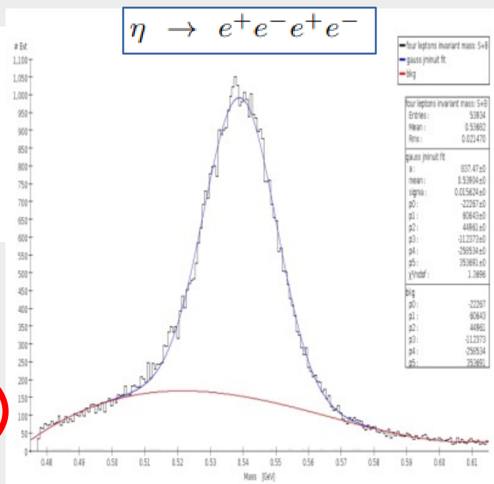
- *Theoretical calculations at the 10^{-3} precision from Kampf, Novotný, Sanchez-Puertas (PR D 97, 056010 (2018))*

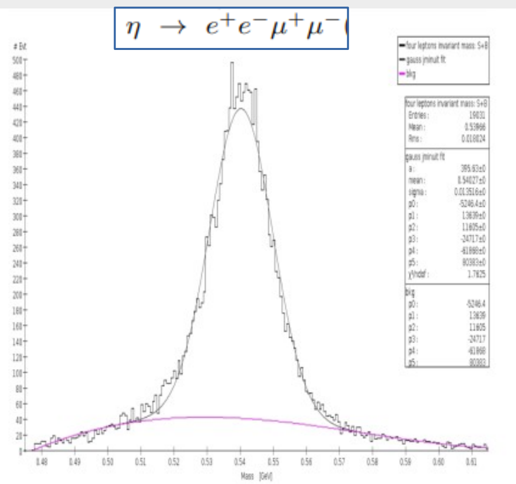
REDTOP reconstruction efficiency

Process	*Trigger* L0	*Trigger* L1	*Trigger* L2	*Reconstruction*	*Analysis*	**Total**
$\eta \rightarrow e^+e^-e^+e^-$	96.1%	80.7%	15.5%	63.3%	61.2%	4.5%
$\eta \rightarrow e^+e^-\mu^+\mu^-$	80.4%	57.0%	20.4%	16.6%	52.8%	0.8%
$\eta \rightarrow \mu^+\mu^-\mu^+\mu^-$	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**
$\eta \rightarrow e^+e^-e^+e^-$	4.4×10^{14}	53,934	**0.5%**
$\eta \rightarrow e^+e^-\mu^+\mu^-$	1.6×10^{15}	18,841	**0.8%**
$\eta \rightarrow \mu^+\mu^-\mu^+\mu^-$	2.2×10^{18}	10,548	**1.0%**





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 (approved)	$\gamma_{12\ GeV} p \to \eta\ X \to$ neutrals			3.9×10^5/day
REDTOP (proposing)	$p_{1.8\ GeV} Li \to \eta\ X$			3.4×10^{13}/yr

REDTOP Running Modes for 10^{14} η mesons

REDTOP

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 - 2.5×10^{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 nuclear reaction: p+De → η +He_3^{+}

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

REDTOP Running Modes 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*

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 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 - 2.5x10^{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 neclear reaction: p+De → η +He_3^{+}*

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

Detector Requirements and Technology

- *Sustain 0.7 GHz event rate with avg final state multiplicity of 8 particles*
- *Calorimetric $\sigma(E)/E \sim 3\text{-}5\%/\sqrt{E}$*
- *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

- *Use ADRIANO2 calorimeter (Calice+T1604)*
- *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*
- *Next generation technology*

Cerenkov Threshold TOF

Option 1: Quartz tiles

- *Established and low-cost technology*
- *~50psec timing with T1604 prototype*

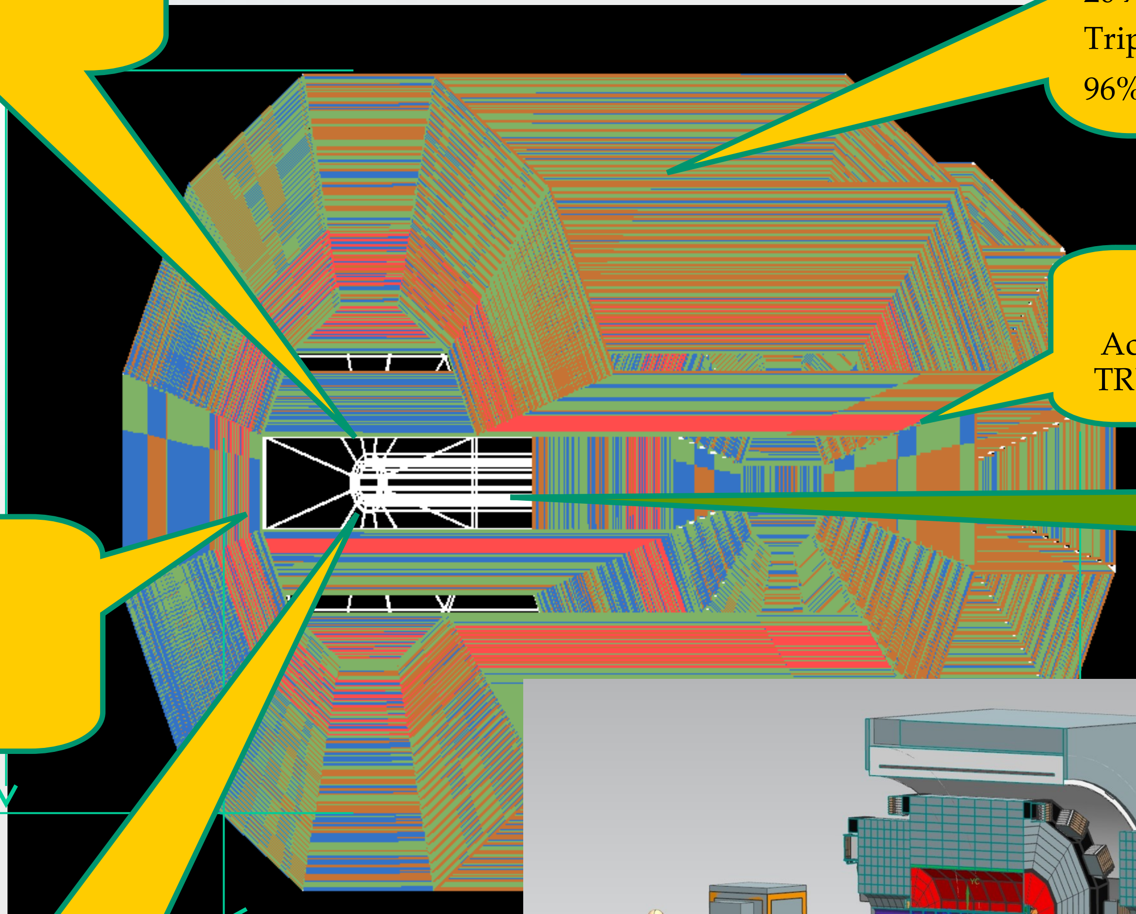
Option 2: EIC-style LGAD

- *~30-40 psec timing, but expensive*

REDTOP detector

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

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

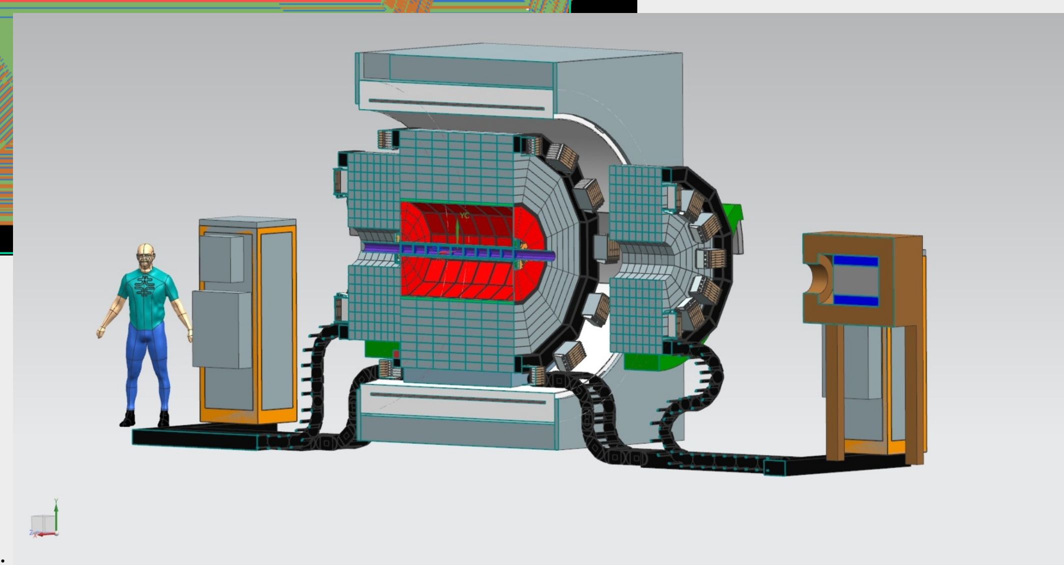


μ-polarizer
Active version (from TREK exp.) - optional

10x Be or Li targets
- 0.33 mm thin
- Spaced 10 cm

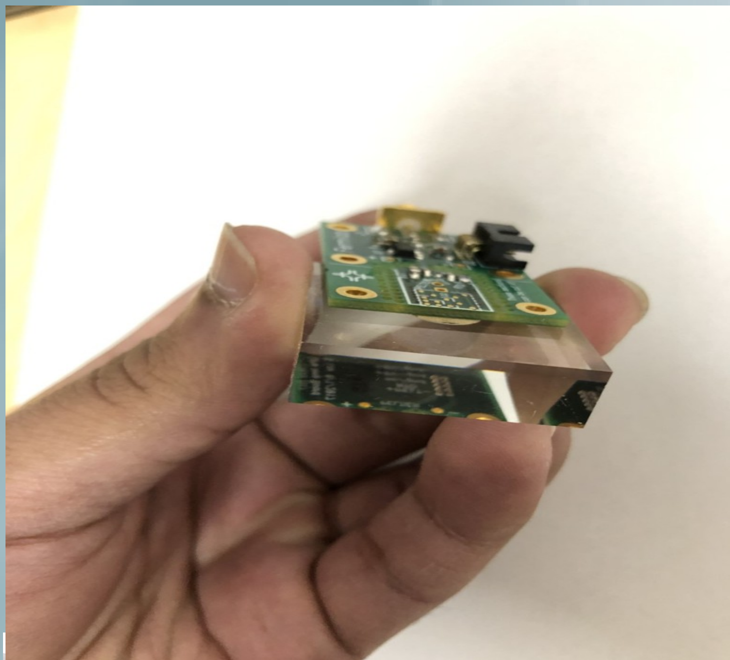
RICH
~ 1m x 1.5 m
Lead-glass tiles
98% coverage

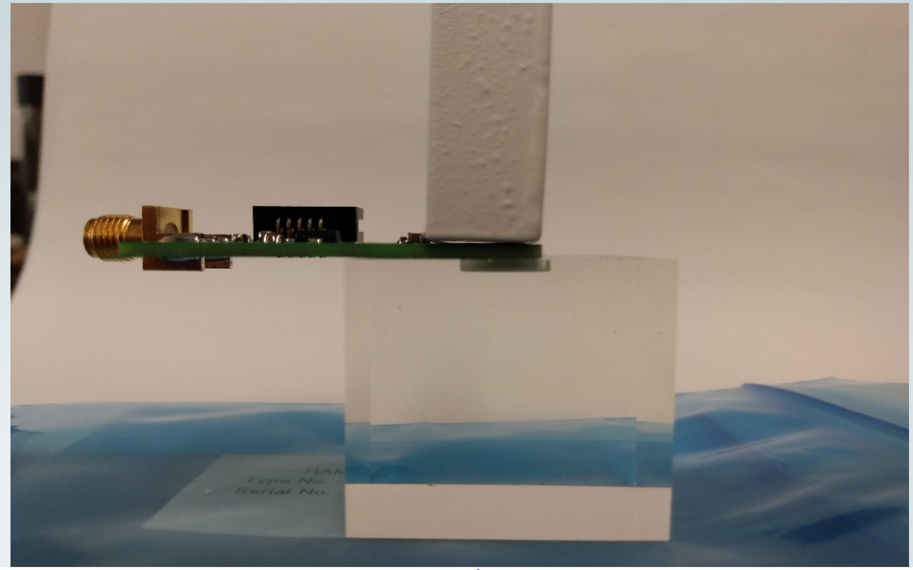
Fiber tracker or ITS3
for rejection of γ-conversion and vertexing

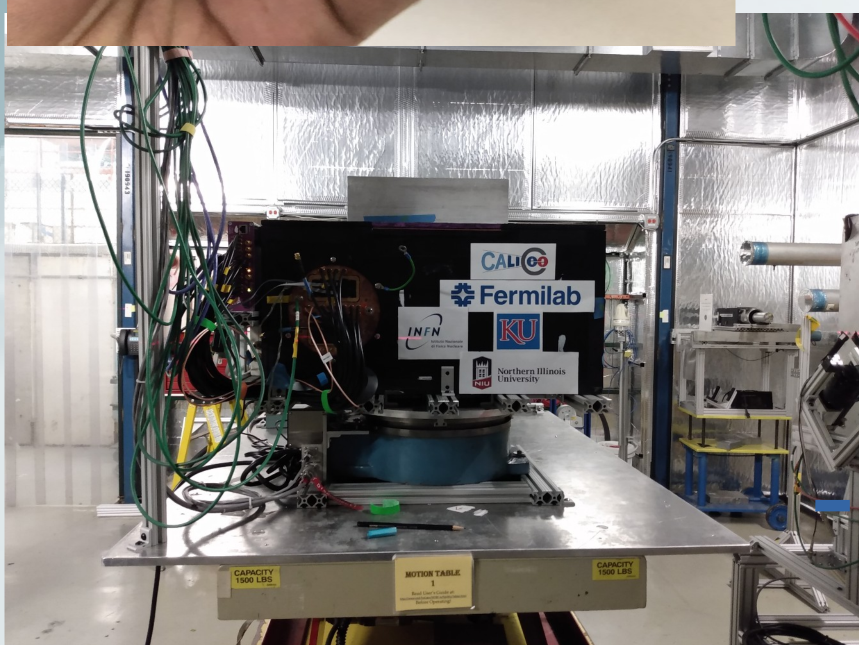


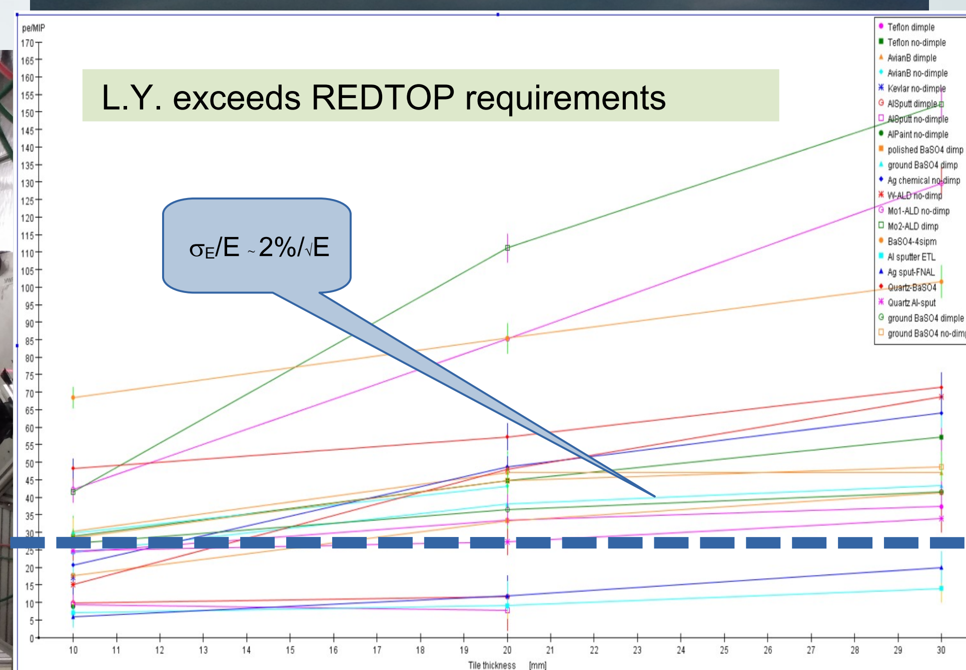
Slide from Calor2022

R&D on ADRIANO2 (from T1604)





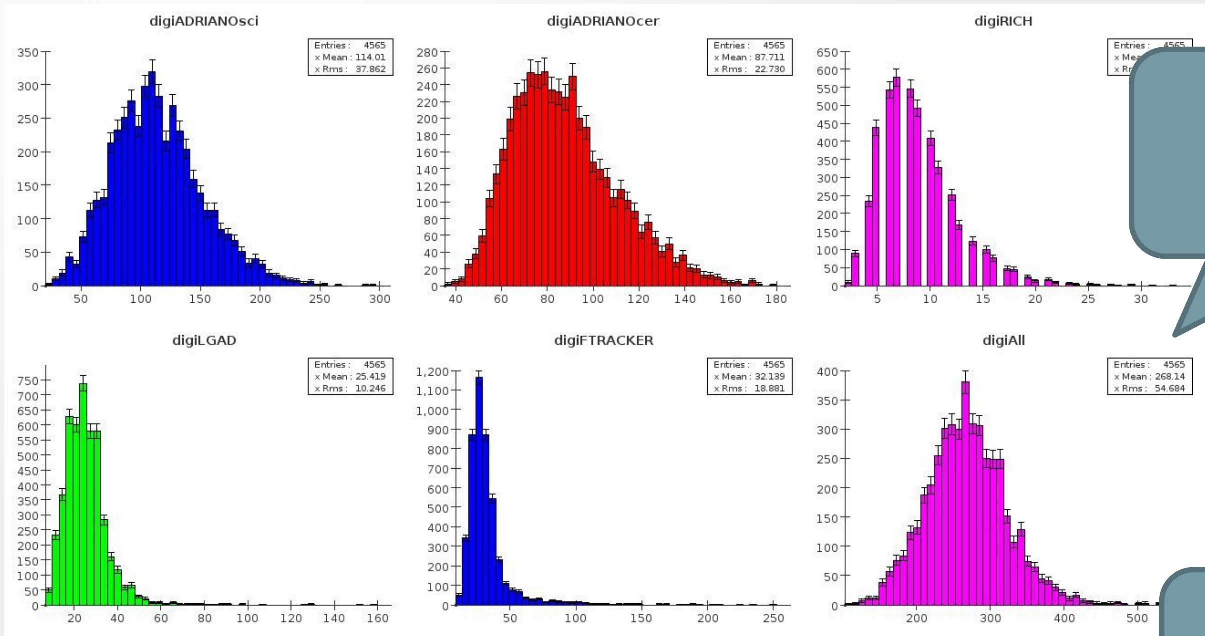




REDTOP Trigger Requirement

Untagged 10^{14} η/η' mesons

Hits from subdetectors



Total channel occupancy:
270 ± 50 /evt

~9 PB/year to tape
(1.6 kb event size)

18x LHCb

Trigger rejection factors

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 [illegible]
Level 1	1.5×10^{8}	1.5×10^{3}	2.3×10^{11}	[illegible]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

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56 Institutions
124 Collaborators

Future Prospects 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

- Four BSM portals
- Three CP violating processes requiring no μ-polarization measurement
- Three CP violating processes requiring μ-polarization measurement
- Two lepton flavor universality studies
- Two lepton flavor violation studies

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

- Sensitivity studies helped to consolidate the detector requirements
- VTX Fiber Tracker replaced by ITS3-class detector
- Muon polarimeter requires further studies

Next steps:

- New sensitivity studies based on a pion beam and rare η′ decays **(which is also a tagged η-factory!)**
- Prepare the CDR to support the proposal of the experiment to one (or more) of the interested laboratories
- Consolidate the detector R&D

Conclusions

- *HEP in the next 10 years will focus strongly 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 expressely to study rare processes and to discover physics BSM in the MeV-GeV mass region*
- *Only experiment (with SHIP) sensitive to four DM portals*
- *JEF and REDTOP delineate the world program of η/η' factories with sensitivity to complementary final states*
- *New detector techniques exploited for next generation high intensity experiments*
- *Beam requirements could be met by several labs in US, Europe, and Asia*

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

Backup slides

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

CP-violation from μ–polarization

CP Violation in $\eta \to \gamma\mu^+\mu^-$

- *From model: P. Sanchez-Puertas, JHEP 01, 031 (2019), 1810.13228.*
- ***Requires the measurement of μ–polarization to form the following asymmetries***

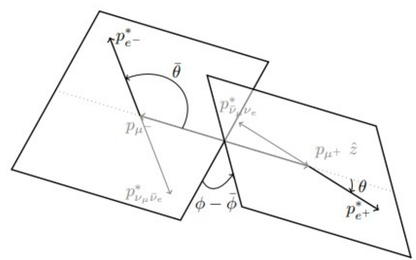


FIG. 11. Kinematics of the process. The decaying muons' momenta in the η rest frame are noted as $p_{\mu^\pm}$, while the $e^\pm$ momenta, $p^*_{e^\pm}$, is shown in the corresponding $\mu^\pm$ reference frame along with the momenta of the $\nu\bar{\nu}$ system. The $\hat{z}$ axis is chosen along p_{μ^+}.

introduced two different muon's polarization asymmetries,

$$A_L^{\eta\to\pi^0\mu^+\mu^-} = -0.19(6)\,\mathrm{Im}\,c^{(1)2211}_{\ell equ} - 0.19(6)\,\mathrm{Im}\,c^{2211}_{\ell edq} - 0.020(9)\,\mathrm{Im}\,c^{2222}_{\ell edq}\,,$$

$$A_\times^{\eta\to\pi^0\mu^+\mu^-} = 0.07(2)\,\mathrm{Im}\,c^{(1)2211}_{\ell equ} + 0.07(2)\,\mathrm{Im}\,c^{2211}_{\ell edq} + 7(3)\times 10^{-3}\,\mathrm{Im}\,c^{2222}_{\ell edq}$$

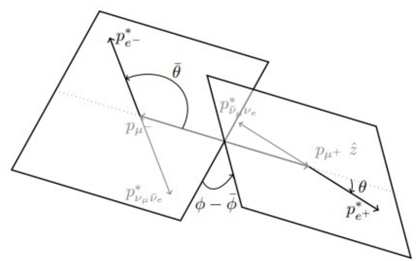
REDTOP sensitivity to Wilson CP violating Wilson coeffiecients

Process	*Trigger* L0	*Trigger* L1	*Trigger* L2	*Reconstruction + analysis*	**Total**	Branching ratio sensitivity
$\eta \to \gamma\mu^+\mu^-$	80.6%	64.6%	94.3%	92.9%	45.6%	$1.93 \times 10^{-9} \pm 0.9 \times 10^{-11}$
Urqmd	21.7%	1.7%	22.2%	4.7×10^{-3}%	4.7×10^{-6}%	-

$$\Delta(c^{1122}_{\ell equ}) = 2.6, \quad \Delta(c^{1122}_{\ell edq}) = 2.6, \quad \Delta(c^{2222}_{\ell edq}) = 1.7.$$

CP Violation in $\eta \to \pi^0 \mu^+ \mu^-$

- *From model: R. Escribano, et. al., JHEP 05 (2022) 147.*
- ***Requires the measurement of μ–polarization to form the following asymmetries***



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$$A_L^{\eta\to\pi^0\mu^+\mu^-} = -0.19(6)\,\mathrm{Im}\,c_{\ell equ}^{(1)2211} - 0.19(6)\,\mathrm{Im}\,c_{\ell edq}^{2211} - 0.020(9)\,\mathrm{Im}\,c_{\ell edq}^{2222}\,,$$

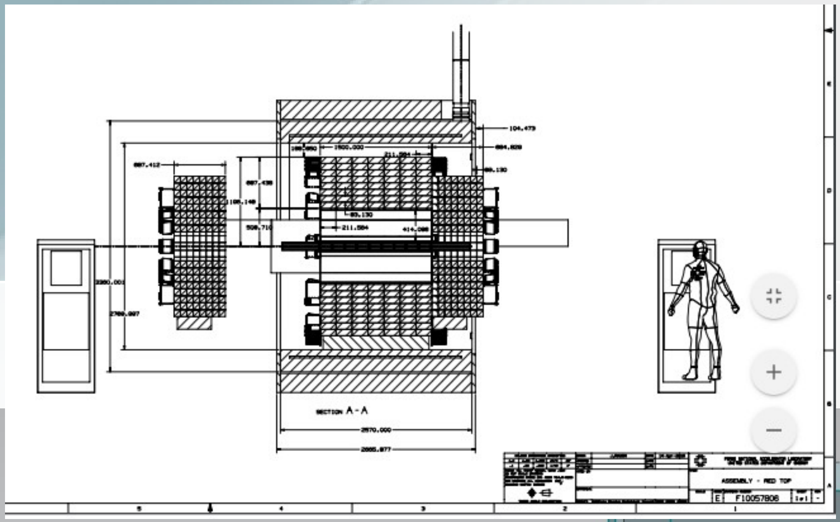
$$A_\times^{\eta\to\pi^0\mu^+\mu^-} = 0.07(2)\,\mathrm{Im}\,c_{\ell equ}^{(1)2211} + 0.07(2)\,\mathrm{Im}\,c_{\ell edq}^{2211} + 7(3)\times 10^{-3}\,\mathrm{Im}\,c_{\ell edq}^{2222}$$

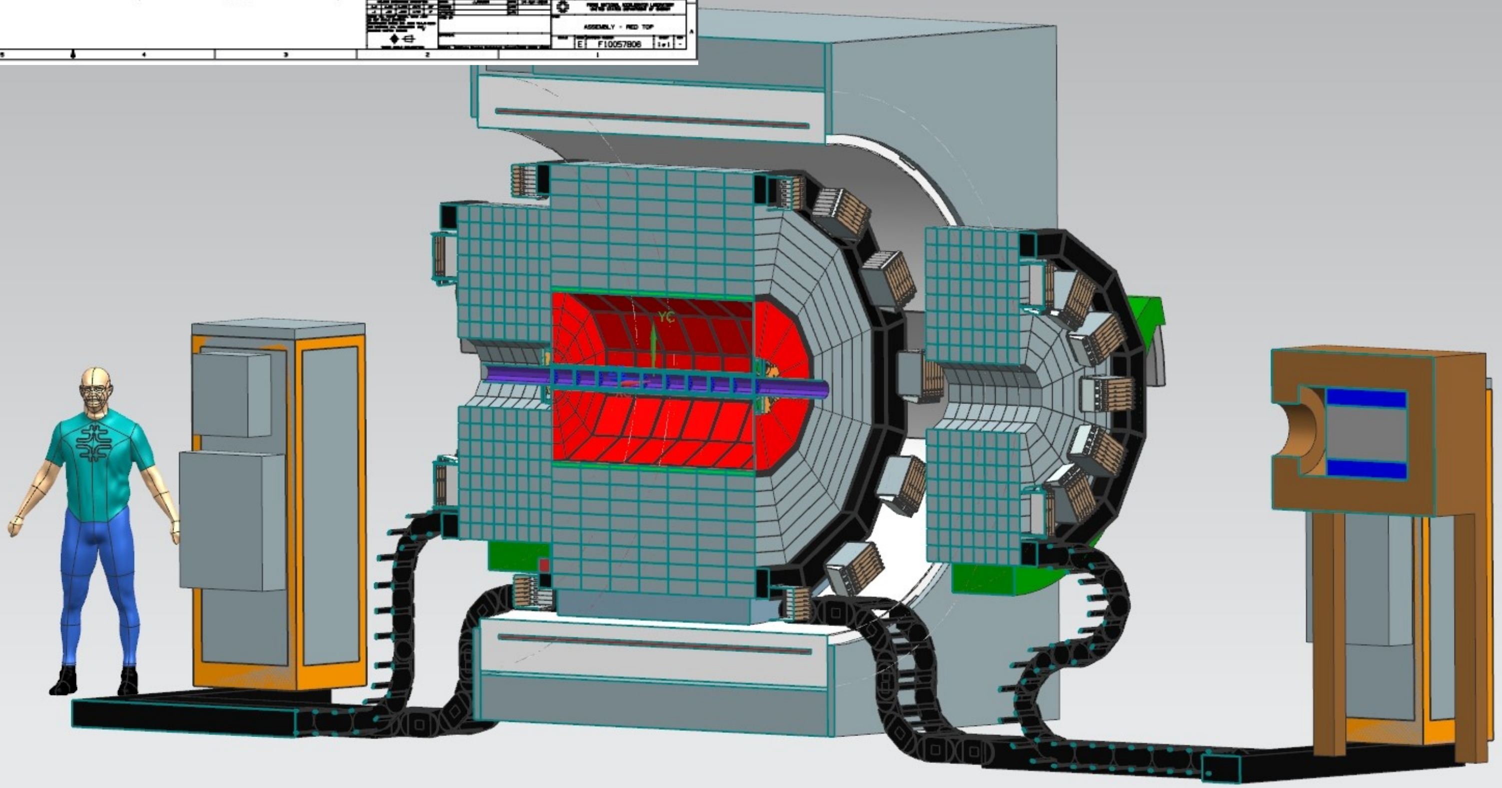
REDTOP sensitivity to Wilson CP violating Wilson coeffiecients

Process	*Trigger* L0	*Trigger* L1	*Trigger* L2	*Reconstruction + analysis*	**Total**	Branching ratio sensitivity
$\eta \to \pi^0\mu^+\mu^-$	64.1%	36.7%	91.4%	73.2%	15.7%	$9.4\times10^{-9} \pm 1.3\times10^{-10}$
Urqmd	21.7%	1.7%	22.2%	1.6×10^{-2}%	1.3×10^{-5}%	-

$$\Delta(c_{\ell equ}^{1122}) = 21, \quad \Delta(c_{\ell edq}^{1122}) = 21, \quad \Delta(c_{\ell edq}^{2222}) = 200.$$

REDTOP Detector + Finuda Magnet





J. Kilmer – J. Rauch

Acceleration Scheme for Run-I (M. Syphers)

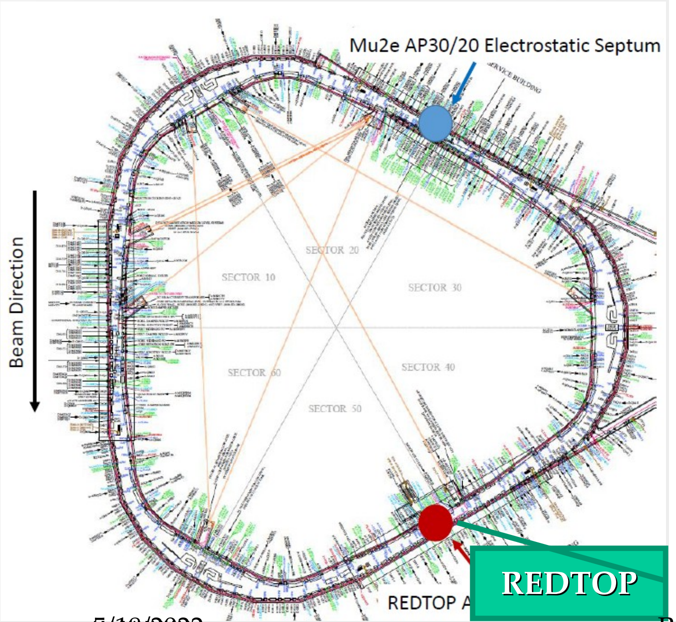
Single p pulse from booster (≤4x10^{12} p) injected in the DR (former debuncher in anti-p production at Tevatron) at fixed energy (8 GeV)

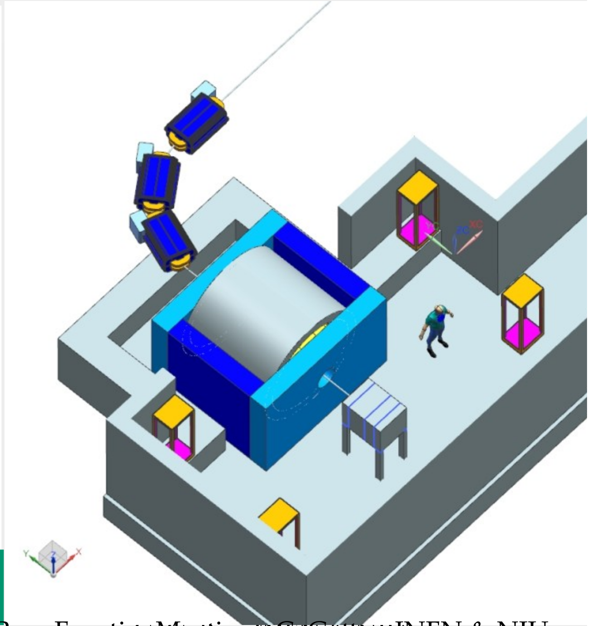
Energy is removed by inserting 1 or 2 RF cavities identical to the one already planned (~5 seconds)

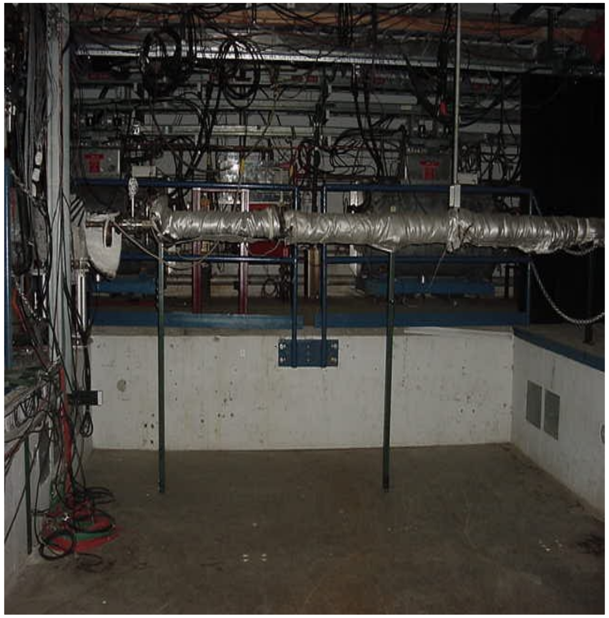
Slow extraction to REDTOP over ~40 seconds.

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.

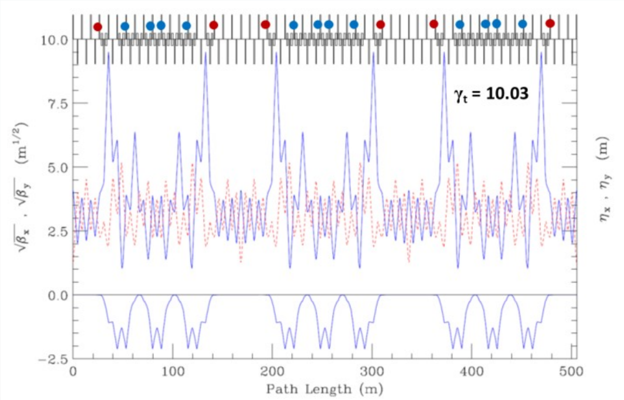
Total time to decelerate-debunch-extract: 51 sec: duty cycle ~80%

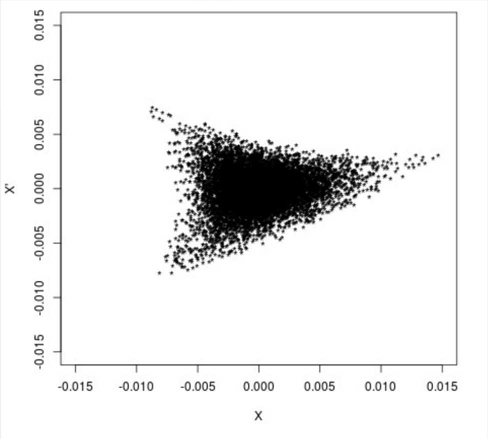






Accelerator Physics Issues



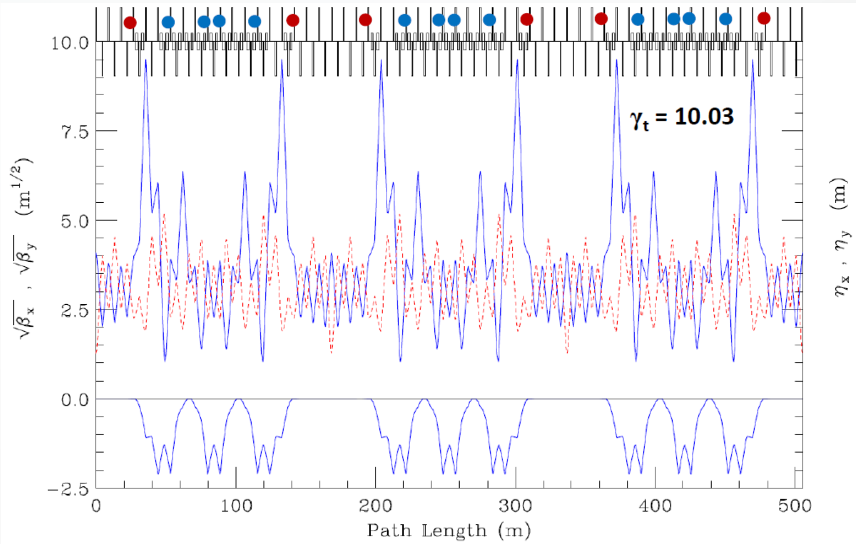


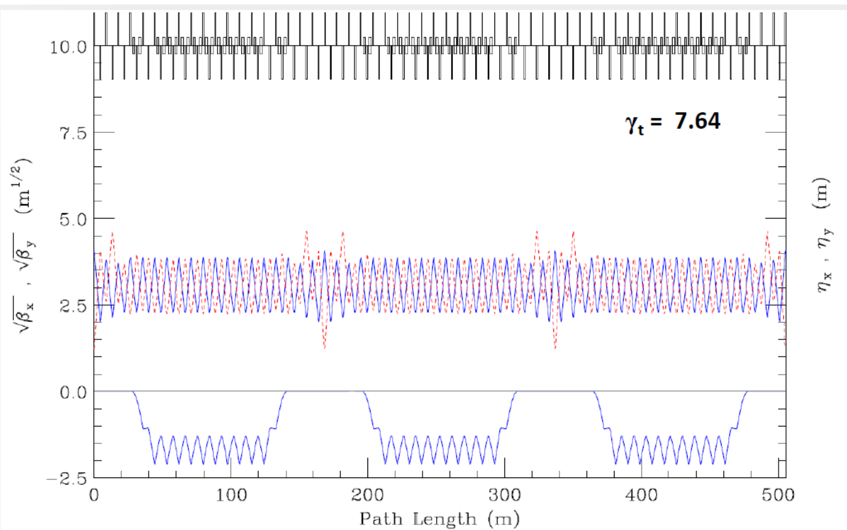
- *Transition Energy*
  - γ_t is where $\Delta f/f = 1/\gamma 2 - <D/\rho> = 0$; synchrotron motion stops momentarily, can often lead to beam loss
  - beam decelerates from γ = 9.5 to γ = 3.1
  - original Delivery Ring γ_t = 7.6
  - a re-powering of 18 quadrupole magnets can create a γ_t = 10, thus avoiding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

Ring Optics through Deceleration (J. Johnstone)

Transition is avoided by using select quad triplets to boost γt above beam γ by 0.5 units throughout deceleration until γ_t = 7.64 and beam γ = 7.14 (5.76 GeV kinetic).

Below 5.76 GeV the DR lattice reverts to the nominal design configuration





8 GeV injection energy (top) and <5.8 GeV (bottom)

- Blue & red circles indicate sites of the γ_t quad triplets.

p (GeV/c)	8.89	8.33	7.76	7.20	6.63
KE (GeV)	8.00	7.45	6.88	6.32	5.76
γ_{BEAM}	9.53	8.93	8.33	7.74	7.14
$\gamma_{transition}$	10.03	9.43	8.83	7.74	7.64
β_{max} (m)	94.9	72.5	49.5	30.1	15.1
q (m^{-1})	.0697	.0573	.0416	.0236	0.0
3σ (mm)	15.0	13.6	11.6	9.4	6.9

Variation of , β_{max}, and the 15π 99% beam envelope through deceleration

"J.Johnstone, M.Syphers, NA-PAC, Chicago (2016)"

to - INFN & NIU
33

REDTOP detector

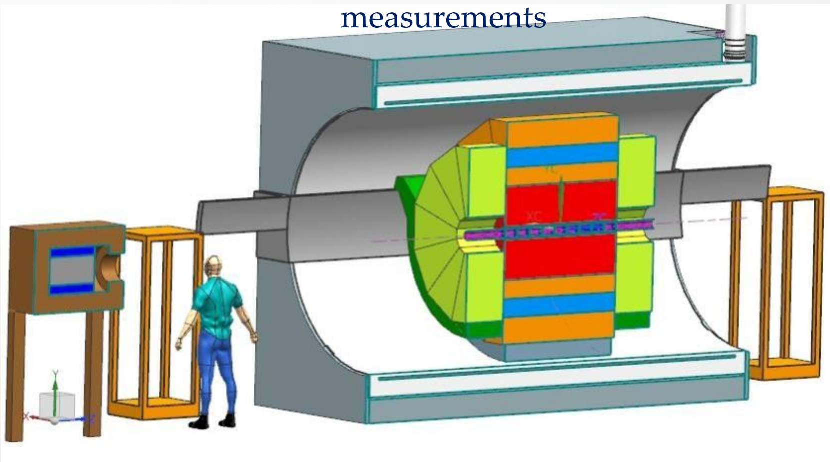
Optical-TPC

For slow background rejection

or

LGAD Tracker surrounded by Quartz cells

For 4D track reconstruction and TOF measurements



Vertex Fiber tracker

for rejection of -conversion and identifying displaced vertices from long lived particles

5D- Calorimeter: ADRIANO2 (Dual-readout +PFA)

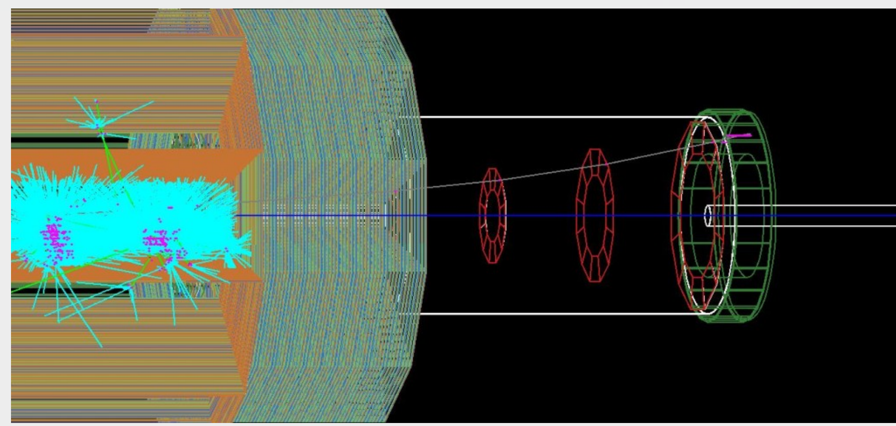
Sci and Cer light read by SiPM or SPAD

For excellent energy , position resolution and PID

-polarimeter (optional)

sandwich of fused silica and Si-pixel

for measurement of muon polarization



10x Be or Li targets

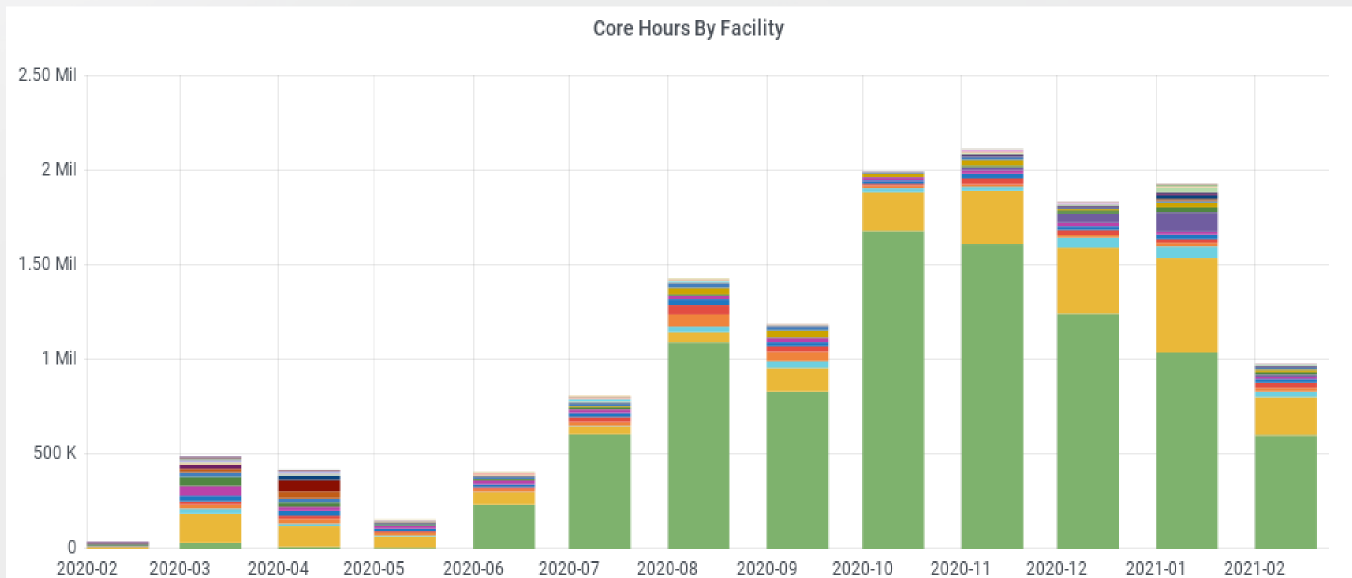
Forward Detector for Option 2

for tagging $^3He^{++}$ ions

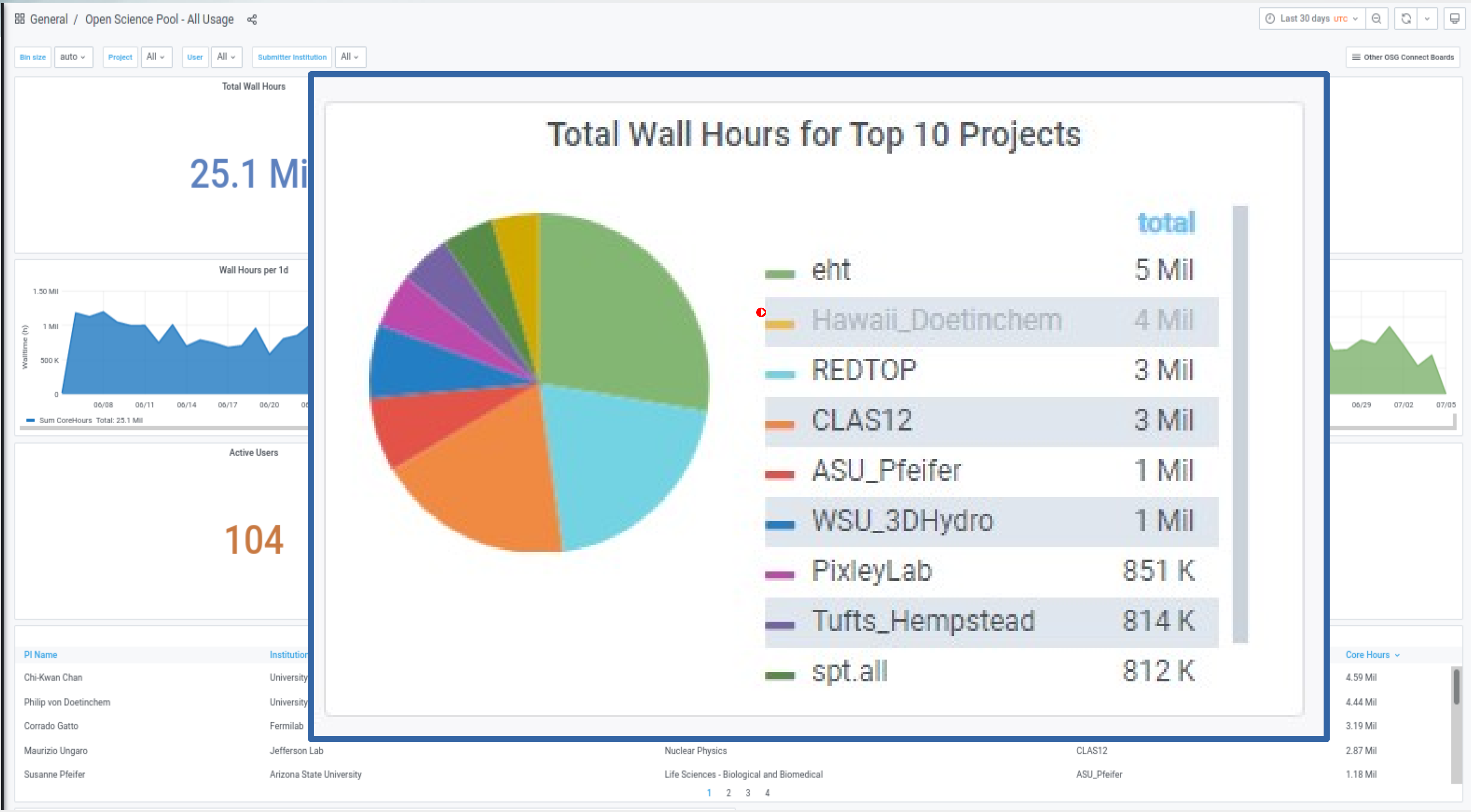
REDTOP OSG Yearly Usage Statistics

	total
SU ITS	9 Mil
MWT2 ATLAS UC	2 Mil
GLOW	303 K
TCNJ - ELSA	293 K
FSU_HNPGRID	267 K
BNL ATLAS Tier1	264 K
UConn-OSG	250 K
UConn-HPC	178 K
UColorado_HEP	174 K
OU ATLAS	173 K
ASU Research Computing	163 K
Nebraska-Omaha	75 K
ICC-SLATE-HTC	69 K
New Mexico State Discovery	61 K
NWICG_NDCMS	42 K
Clemson-Palmetto	41 K
AMNH	40 K
UPRM_HEP	34 K
FermiGrid	34 K
cinvestav	31 K

- Time range: Feb 2020 – Feb 2021
- Total Core Hours: 13.8 million
- Total jobs: 7.15 million



REDTOP OSG Monthly Usage Statistics



Overall Computing Usage

- *Computing resources for REDTOP are from three sources:*
  - *OSG: CPU and stash storage*
  - *NICADD/NIU: CPU and permanent storage*
  - *Fermilab (private farm hosted by AD) : CPU and permanent storage*

Summary of computing

Source	Storage	#core available	Jobs/yr	Wall hr/yr	Fraction
OSG	100 TB (with peaks of 140 TB)	opportunistic	$7x10^6$	$14x10^6$	72%
NICADD	15 TB	500-690	$4x10^6$	$5x10^6$	26%
Fermilab-AD	200 TB	350	300K	600K	2%

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.*

Storage & CPU

Expected data rates from the experiment

- About 500 kHz to be stored on tape
- ~0.9 GB/sec from L2
- ~6 PB/year to tape (assume 1.6 kb event size)

Data from DAQ and Montecarlo

- Data from experiment: ~6 PB/year to tape
- Processed data (reco, calib. Analysis, etc) : ~1.0 PB/year (tape and disk)
- Montecarlo (~10^{11} events): ~0.5 PB/run (tape and disk)
- ***Total: 7.5 PB/year***

CPU for Reconstruction Analysis and Montecarlo

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

(estimate by projecting current OSG usage)

REDTOP Simulation Framework

Event generator: GenieHad

- Proprietary (not yet public) package interfacing standalone generators

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

Dual-readout Calorimetry R&D

The ADRIANO2 high-granularity dual-readout

- Layout: sandwich of small (~cm^3) lead-glass and scintillating plastic tiles
- Tiles are optically separated (wrapped or coated) and individually readout with sipm(s)
- Optional dimple to accommodate the SiPM

Motivations

- Advantages:
  - Prompt Cerenkov signal for timing resolution and L0-trigger
  - Small Pb-glass tile unaffected by aging
  - Good energy resolution
  - High-granularity
- Disadvantaged
  - Cost
  - Large number of readout channels

Goals

- $\sigma_E/E<3\%\sqrt{E}$
- σ_t<80 psec

Exploring Sensitivity to BSM Physics

- REDTOP physics case presented in a 176-pp White Paper
- Sensitivity studies based on ~10^{14} η mesons, include:
  - Four BSM portals
  - Three CP violating processes requiring no μ-polarization measurement
  - Three CP violating processes requiring μ-polarization measurement
  - Two lepton flavor universality studies
  - Two lepton flavor violation studies
- (Almost) full simulation using *GenieHad* + *slic* + *lcsim* (heavily modified for REDTOP) with $5\text{x}10^{10}$ generated background event (>4×10^{7} CPU core-hrs on the OSG and NICADD)
- Assumptions for the the case study:
  - 1.8 GeV proton beam on 7.7 mm Li target with 3.3×10^{18} POT (~ 3-yr run @ 30 W)
  - Three level trigger
  - Baseline detector configuration (see later in this talk)