The REDTOP experiment: a low energy meson factory to explore dark matter and physics beyond the Standard model

Rare Eta Decays TO Probe New Physics

Corrado Gatto

INFN Napoli and Northern Illinois University

Rationale for an η/η' Factory

Recent LHC results suggest that the next search for New Physics should be in the MeV-GeV mass range with high-intensity beams.

"…many of the more severe astrophysical and cosmological constraints that apply to lighter states are weakened or eliminated, while those from high energy colliders are often inapplicable" (B. Batell , M. Pospelov, A. Ritz – 2009).

"…*Light dark matter must be **neutral** under SM charges, otherwise it would have been discovered at previous colliders*…" [G. Krnjaic RF6 Kickoff Meeting, August 12, 2020]

The only known particles with all-zero quantum numbers are the **η/η' mesons** and the **Higgs boson**

All electromagnetic and strong decays of the neutral and long-lived **η** and **η**' are suppressed at first order and weak decays have branching ratios of order 10^{-11}. Branching Ratio of processes from New Physics are enhanced compared to SM.

"….*The physics sectors which can be probed at REDTOP range from the violation of discrete symmetries to the search for new particles*…" [S. Tulin et al. https://arxiv.org/abs/2007.00664]

A η/η' factory is equivalent to a low energy Higgs factory

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

Assuming a yield ~10^{13} η mesons/yr and ~10^{11} 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* 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 *polar. in* $\eta \to \pi^+ \mu^- \nu$ *vs* $\eta \to \pi^- \mu^+ \nu$ *and* 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

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

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)*

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- *CP invariance in angular correlation studies:* $\eta \to \mu^+\mu^-e^+e^-$
- *CP invariance in μ polar. in studies:* $\eta \to \pi^o \mu^+\mu^-$, $\eta \to \pi^o \mu^+\mu^-$ [illegible]
- *T invar. via μ transverse polarization:* [illegible] *and* $\eta \to \gamma\mu^+\mu^-$
- *CPT violation: μ pol. in* [illegible] $\eta \to \pi\mu^+\nu$ *and γ polar. in* [illegible] $\to \gamma\gamma$

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

Sensitivity Studies on BSM Physics

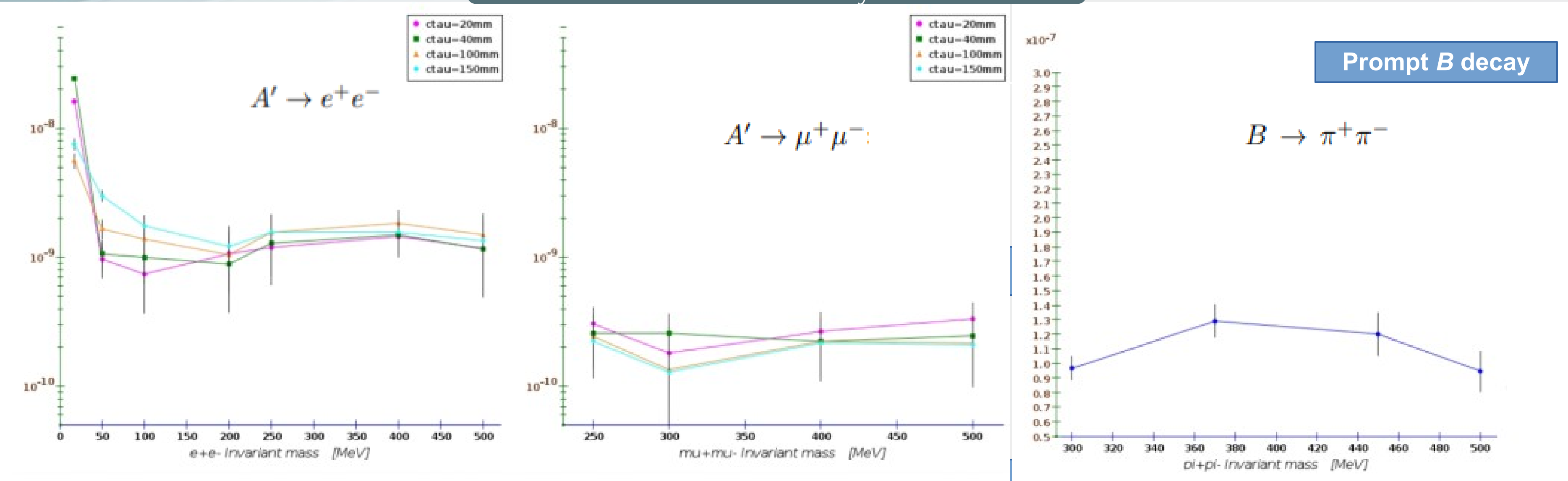
- REDTOP physics case presented in a 172-pp White Paper
- Sensitivity studies based on $\sim 10^{14}$ η mesons, include:
  - Four BSM portals
  - Three CP violating processes requiring no μ-polarization measurement
  - Three CP violating processes requiring μ-polarization measurement
  - Two lepton universality studies
  - Two LFV studies
- (Almost) full simulation using *GenieHad* + *slic* + *lcsim* (heavily modified for REDTOP) with 5×10^{10} generated background event ($>4 \times 10^{7}$ 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)

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

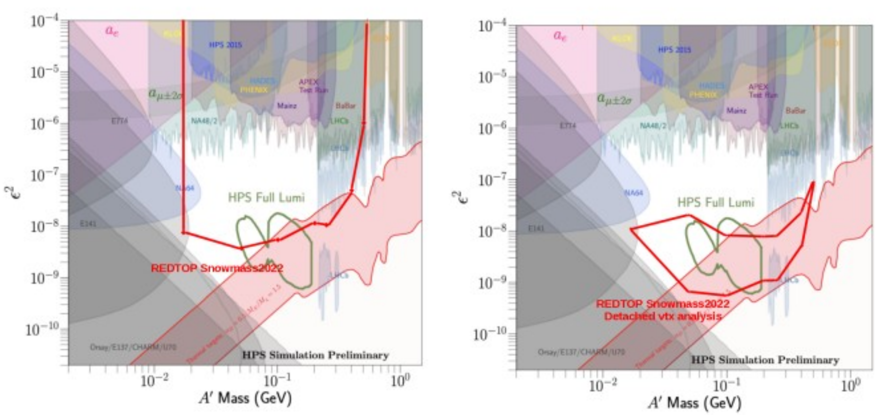


FIG. 36. Sensitivity to to ε^2 for the processes $\eta \rightarrow \gamma A'$ for integrated beam flux of 3.3×10^{18} POT. Left plot: *bump-hunt* analysis. Right plot: *detached-vertex* analysis).

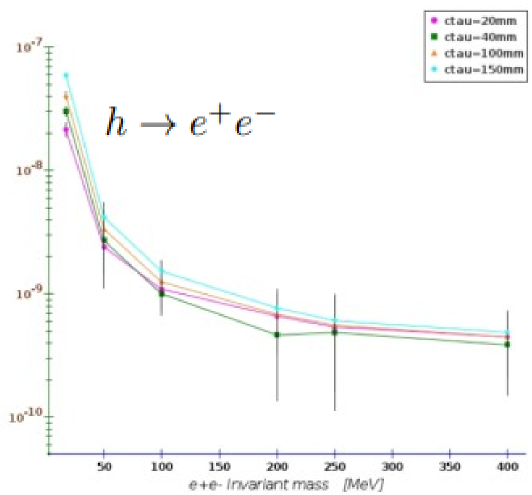
Theoretical Models considered

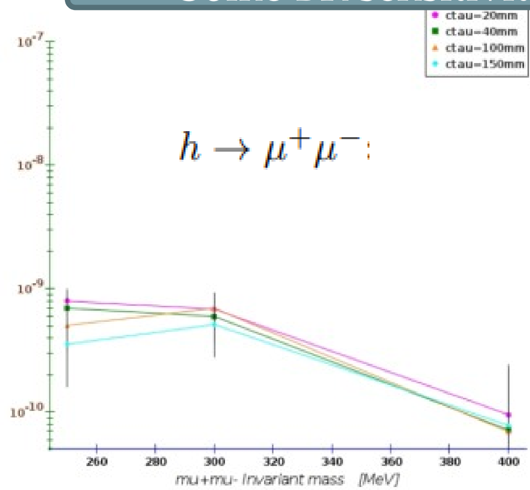
- *Minimal dark photon model*
  - *Most popular model*
- *Leptophobic B boson Model*
- *Protophobic Fifth Force*
  - *Explains the Atomki anomaly*

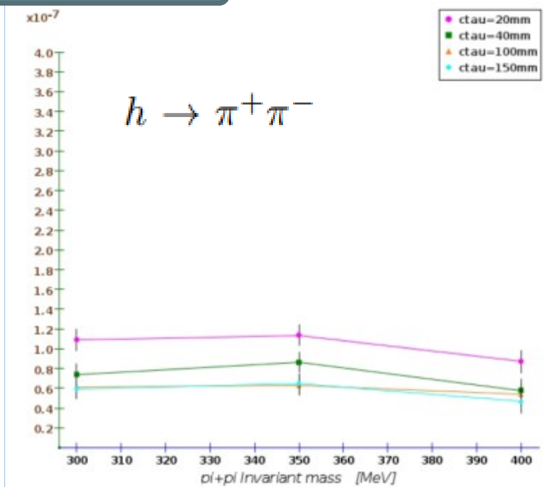
New particles & forces

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

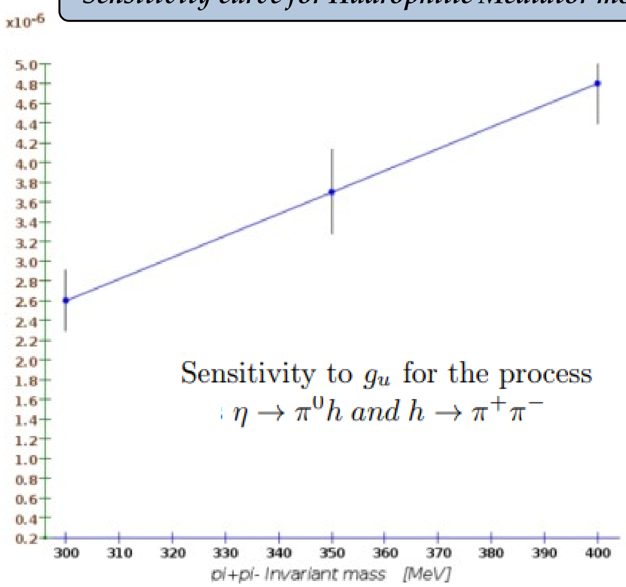
Some BR sensitivity curves







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 $S \to \mu^+\mu^-$.

Models considered

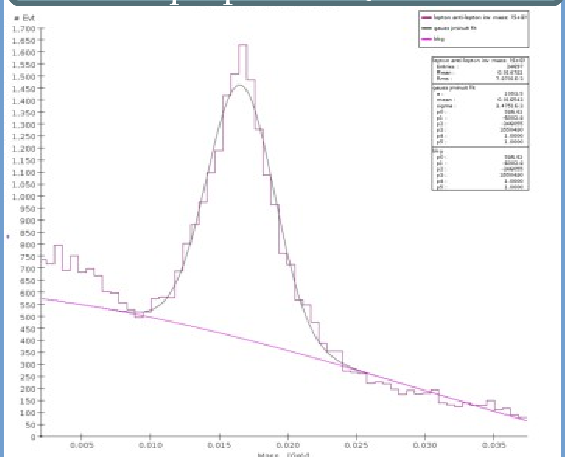
- ***Hadrophilic Scalar Mediator*** *(B. Batell, A. Freitas, A. Ismail, D. McKeen)*
- ***Spontaneous Flavor Violation*** *(D.Egana-Ugrinovic, S. Homiller, P. Meade)*
- ***Two-Higgs doublet model*** *(W. Abdallah, R. Gandhi, and S. Roy)*
- ***Minimal scalar model*** *(C.P. Burgess, M. Pospelov, T. ter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

New particles & forces

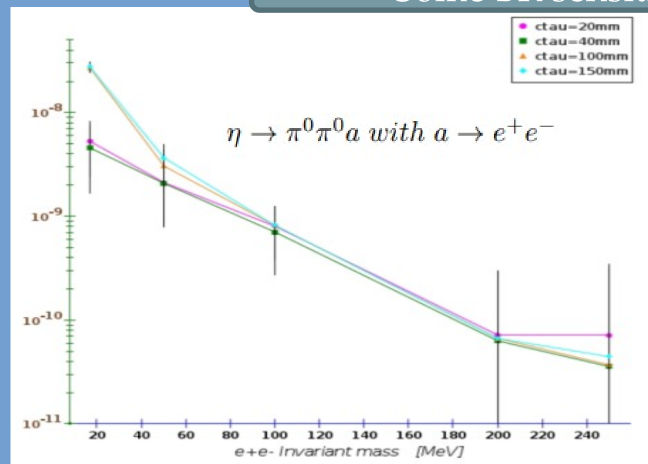
Pseudoscalar Portal: $\eta \to \pi^o \pi^o a$ & $\eta \to \pi^+ \pi^- a$ with $a \to \gamma\gamma$, $\mu^+ \mu^-$ and $e^+ e^-$

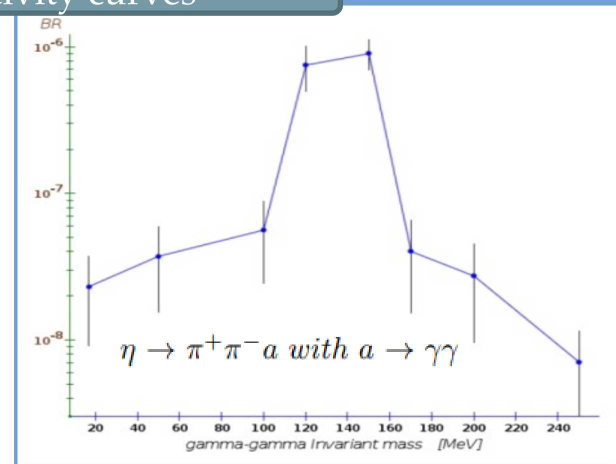
REDTOP

17 MeV piophobic QCD axion

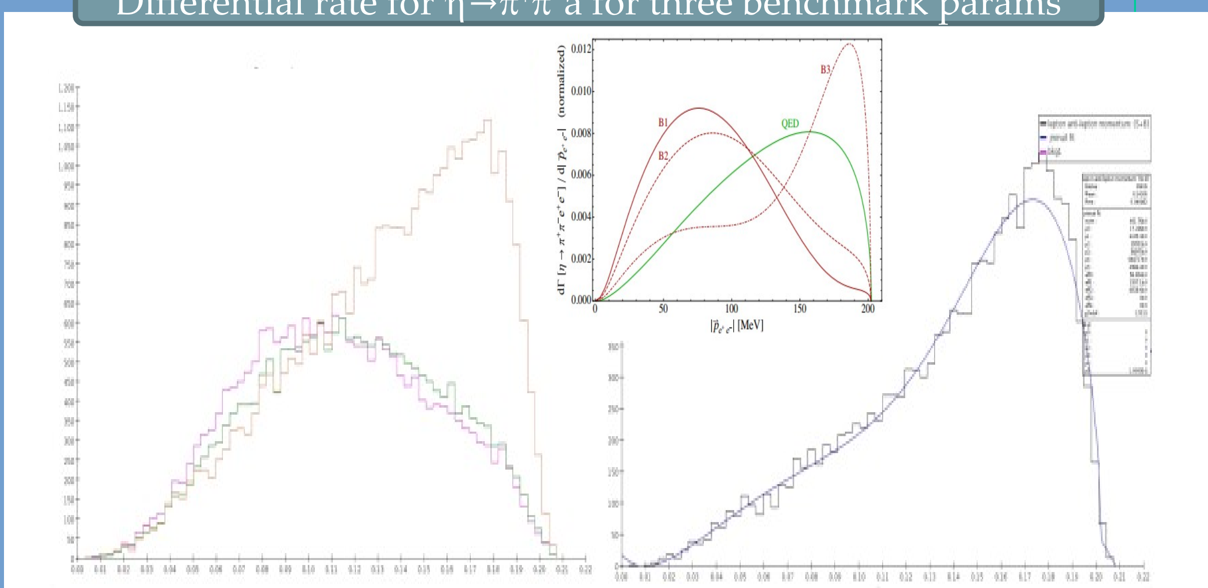


Some BR sensitivity curves





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



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

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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

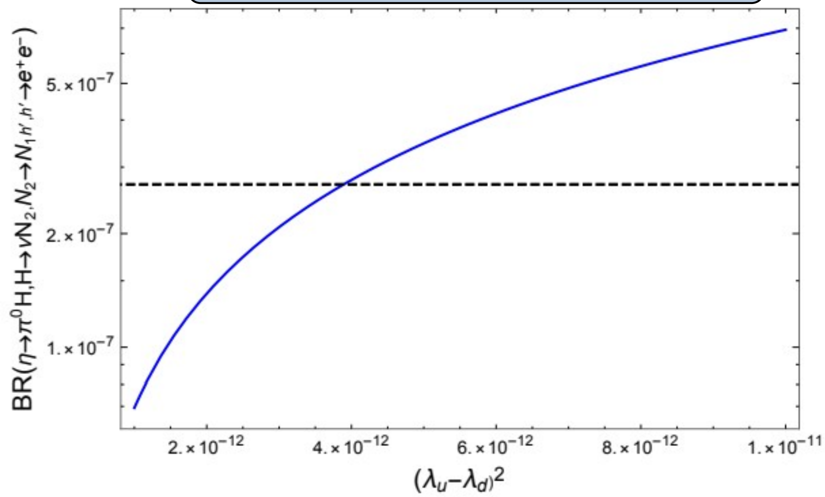
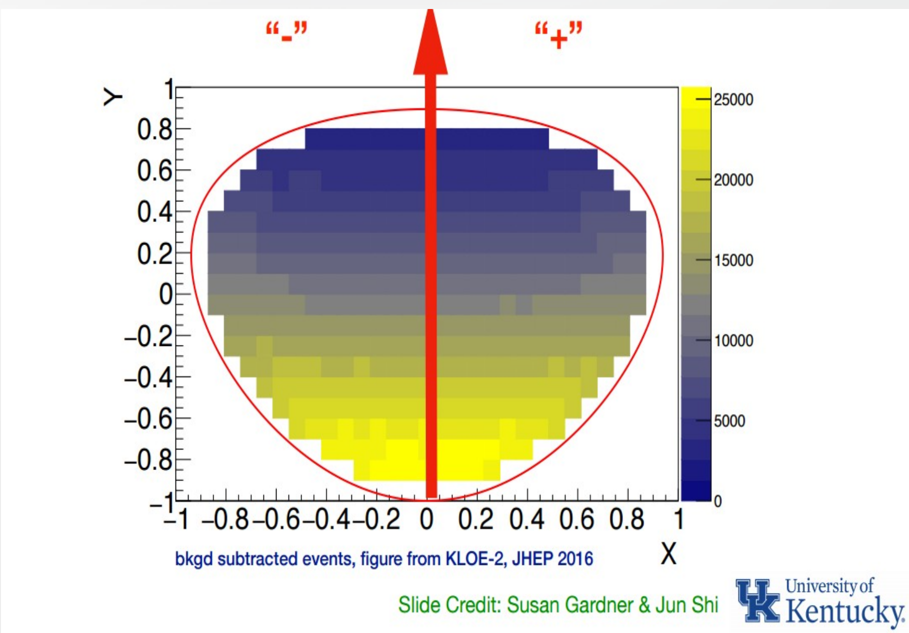


FIG. 61. Branching ratio for the process $\eta \to \pi^0 H$; $H \to \nu N_2$; $N_2 \to N_1 h'$; $h' \to e^+e^-$ predicted by the Two Higgs Doublet model [51] as a function of $(\lambda_u - \lambda_d)^2$. The dashed line corresponds to the experimental limit for REDTOP with an integrated luminosity of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

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

REDTOP

- *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

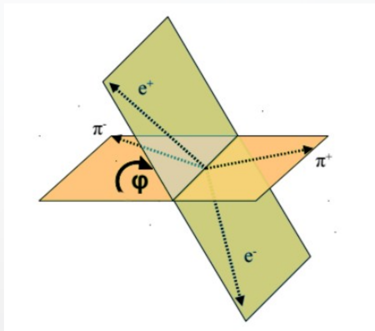


REDTOP sensitivity to model parameters

#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%

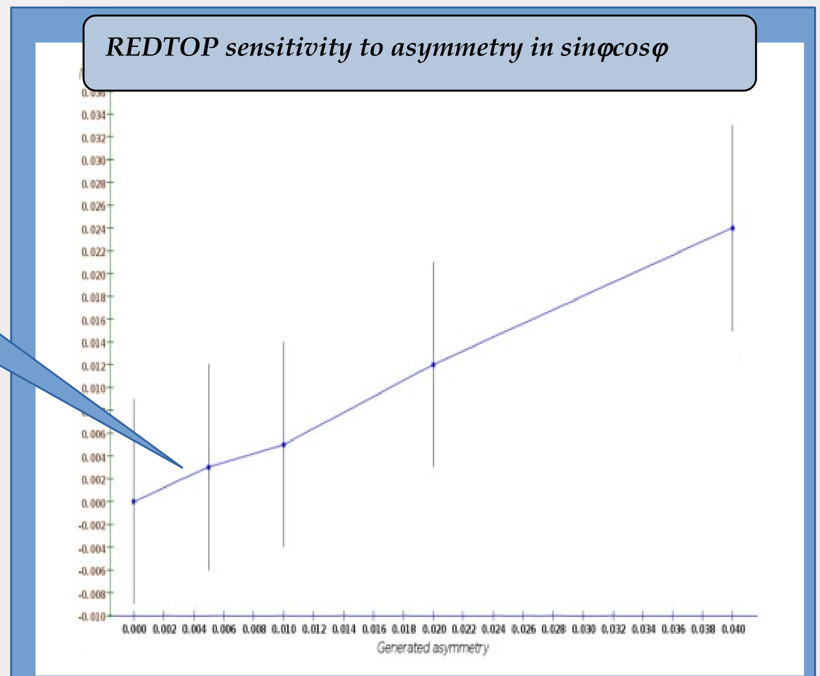
CP Violation from the asymmetry of the decay planes in $\eta \to \pi^+\pi^- e^+e^-$

- *From model: Dao-Neng Gao, /hep-ph/0202002*
- *Requires the measurement of angle between pions and leptons decay planes*



CP violation is proportional to:

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



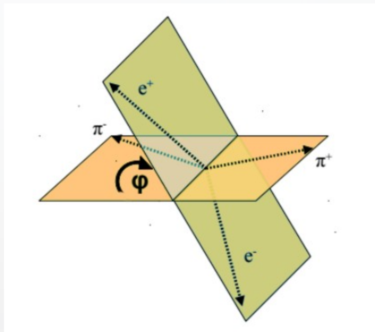
10^{-3} sensitivity to A_ϕ

Test of discrete symmetries

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

REDTOP

- *From model: P. Sanchez-Puertas, JHEP 01, 031 (2019), 1810.13228*
- *Requires the measurement of angle between pions and leptons decay planes*



CP violation is related to asymmetries

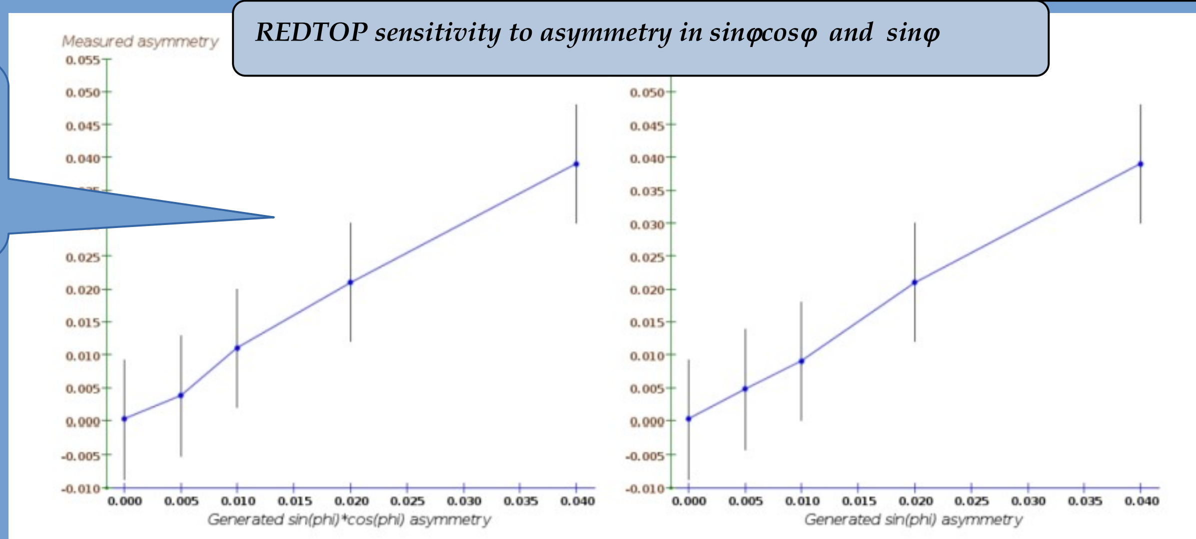
$$A_{sin\Phi cos\Phi} = \frac{N(\sin\phi\cos\phi > 0) - N(\sin\phi\cos\phi < 0)}{N(\sin\phi\cos\phi > 0) + N(\sin\phi\cos\phi < 0)}$$

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

through Wilson coefficients

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

REDTOP sensitivity to asymmetry in sinφcosφ and sinφ



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

CP-violation from μ–polarization

REDTOP

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

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***

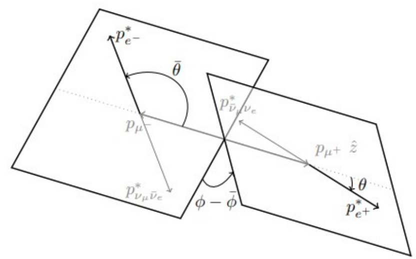


FIG. 11. Kinematics of the process. The decaying muons' momenta in the η rest frame are noted as $p_{\mu^\pm}$, while the $e^\pm$ momenta, $p^*_{e^\pm}$, is shown in the corresponding $\mu^\pm$ reference frame along with the momenta of the $\nu\bar{\nu}$ system. The $\hat{z}$ axis is chosen along p_{μ^+}.

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}%	-

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

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

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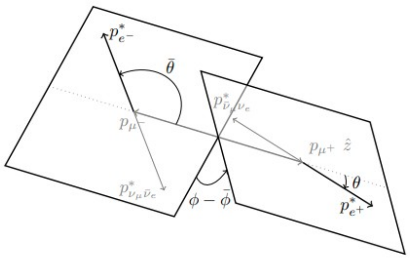
- *Requires the measurement of μ–polarization to form the following asymmetries*



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introduced two different muon's polarization asymmetries,

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

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

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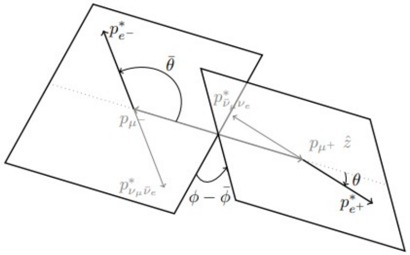
Process	*Trigger* L0	*Trigger* L1	*Trigger* L2	*Reconstruction + analysis*	**Total**	Branching ratio sensitivity
$\eta \to \gamma\mu^+\mu^-$	80.6%	64.6%	94.3%	92.9%	45.6%	$1.93\times10^{-9} \pm 0.9\times10^{-11}$
Urqmd	21.7%	1.7%	22.2%	4.7×10^{-3}%	4.7×10^{-6}%	-

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

REDTOP

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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introduced two different muon's polarization asymmetries,

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

$$A_\times^{\eta\to\pi^0\mu^+\mu^-} = 0.07(2)\,\mathrm{Im}\,c_{\ell equ}^{(1)2211} + 0.07(2)\,\mathrm{Im}\,c_{\ell edq}^{2211} + 7(3)\times10^{-3}\,\mathrm{Im}\,c_{\ell edq}^{2222}$$

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%	$9.4\times10^{-9}\pm1.3\times10^{-10}$
Urqmd	21.7%	1.7%	22.2%	1.6×10^{-2}%	1.3×10^{-5}%	-

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

Lepton Flavor Violation Studies

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 to consider, doubly LF-violation processes

Lepton Universality Test: 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

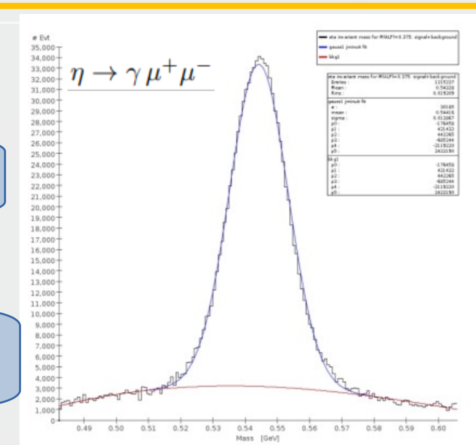
$\eta \to \gamma\mu^+\mu^-$ *vs* γe^+e^-

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



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

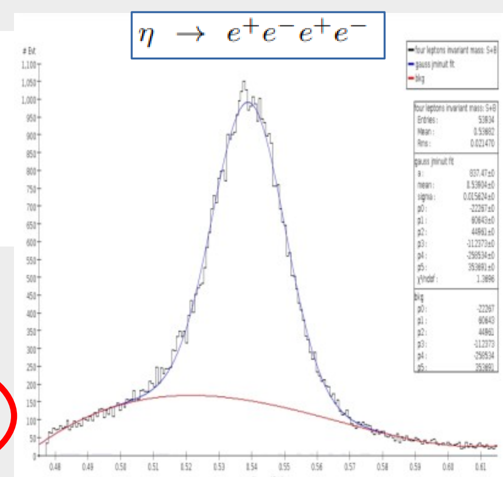
- *Theoretical calculations at the 10^-3 precision from Kampf, Novotný, Sanchez-Puertas (PR D 97, 056010 (2018))*

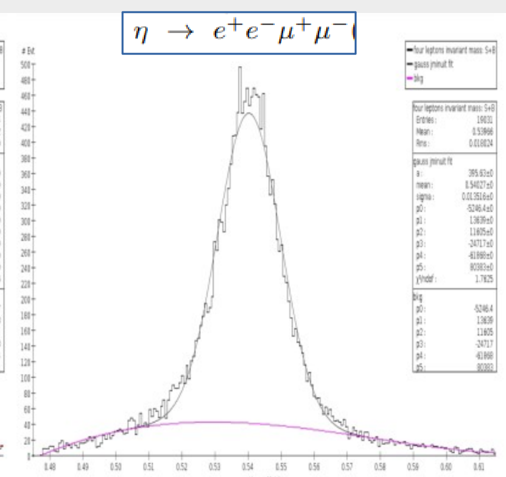
REDTOP reconstruction efficiency

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%**





Present & Future η Samples

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

REDTOP Running Modes for 10^{14} η mesons

REDTOP

Baseline option – medium-energy CW proton beam

vs LHCb@40 MHz

- *proton beam on thin Li/Be target :* ~2 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: ~ 0.5 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 - 2.5x10^9 πOT/sec
- *More expensive but lower background (ESS, FNAL(?), FAIR, HIAF, ORNL)*
- *η:inelastic background = 1:50*
- *Semi-tagged η production*

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

Fancy 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, HIAF, ORNL, PIP-II)*
- *Required fwd tagging detector for He_3*
- *Fully tagged production from reaction: $p+De \rightarrow \eta+He_3^{++}$*

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

Detector Requirements and Technology

- Calorimetric $\sigma(E)/E \sim 5\%/\sqrt{E}$
- 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
- Complemented with outer quartz tiles for TOF measurements

γ detection

- 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
- ~70mm vertex resolution

Option 2: Alice ITS3

- Next generation technology

Cerenkov Threshold TOF

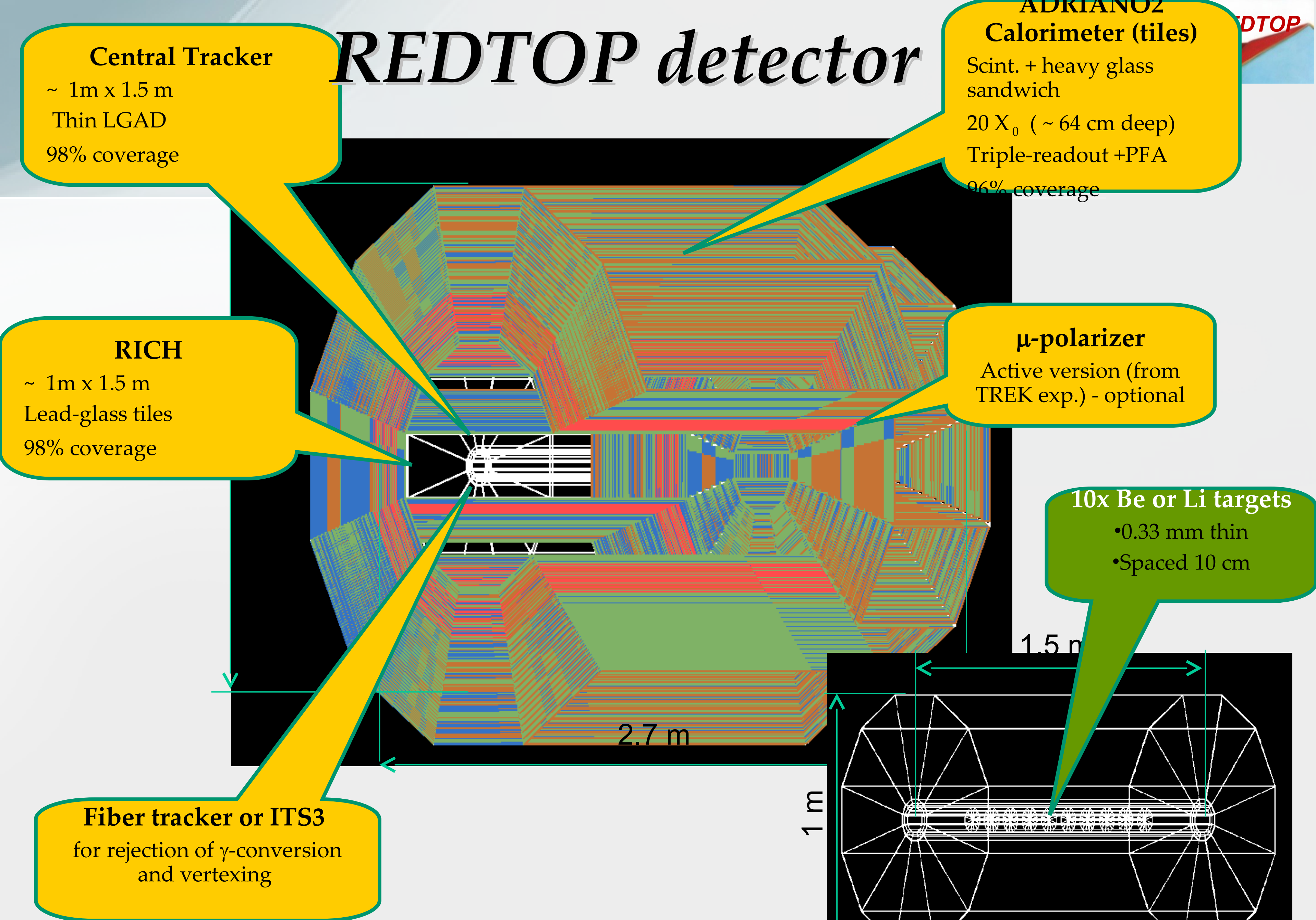
Option 1: Quartz tiles

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

Option 2: EIC

- ~30psec timing, but expensive

REDTOP detector



REDTOP Collaboration

REDTOP

J. Elam, A. Mane
Argonne National Laboratory, (USA)

J. Comfort, P. Mauskopf, D. McFarland, L. Thomas
Arizona State University, (USA)

I. Pedraza, D. Leon, S. Escobar, D. Herrera, D Silverio
Benemérita Universidad Autónoma de Puebla, (Mexico)

W. Abdallah
Faculty of Science, Cairo University, Giza, (Egypt)

D. Winn
Fairfield University, (USA)

A. Alqahtani
Georgetown University, (USA)

W. Abdallah
Cairo University, Cairo (Egypt)

A. Kotwal
Duke University, (USA)

M. Spannowski
Durham University, (UK)

A. Liu
Euclid Techlabs, (USA)

J. Dey, V. Di Benedetto, B. Dobrescu, D. Fagan, E. Gianfelice-Wendt, E. Hahn, D. Jensen, C. Johnstone, J. Johnstone, J. Kilmer, G.Krnjaic, T. Kobilarcik, A. Kronfeld, K. Krempetz, S. Los, M. May, A. Mazzacane, N. Mokhov, W. Pellico, A. Pla-Dalmau, V. Pronskikh, E. Ramberg, J. Rauch, L. Ristori, E. Schmidt, G. Sellberg, G. Tassotto, Y.D. Tsai

Fermi National Accelerator Laboratory, (USA)

J. Shi
Guangdong Provincial Key Laboratory of Nuclear Science, Institute of Quantum Matter, South China Normal University, I, Guangzhou 510006, (China)

R. Gandhi
Harish-Chandra Research Institute, HBNI, Jhunsi (India)

S. Homiller
Harvard University, Cambridge, MA (USA)

E. Passamar
Indiana University (USA)

P. Sanchez-Puertas
IFAE – Barcelona (Spain)

X. Chen, Q. Hu
Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou (China)

C. Gatto[1†]
Istituto Nazionale di Fisica Nucleare – Sezione di Napoli, (Italy)

W. Baldini
Istituto Nazionale di Fisica Nucleare – Sezione di Ferrara, (Italy)

R. Carosi, A. Kievsky, M. Viviani
Istituto Nazionale di Fisica Nucleare – Sezione di Pisa, (Italy)

W. Krzemień, M. Silarski, M. Zielinski
Jagiellonian University, Krakow, (Poland)

D. Guadagnoli
Laboratoire d'Annecy-le-Vieux de Physique Théorique, (France)

D. S. M. Alves, S. Gonzalez-Solis de la Fuente, S. Pastore
Los Alamos National Laboratory, (USA)

M. Berlowski
National Centre for Nuclear Research – Warsaw, (Poland)

G. Blazey, A. Dychkant, K. Francis, M. Syphers, V. Zutshii, P. Chintalapati, T. Malla, M. Figora, T. Fletcher
Northern Illinois University, (USA)

A. Ismail
Oklahoma State University, (USA)

D. Egaña-Ugrinovic
Perimeter Institute for Theoretical Physisos – Waterloo, (Canada)

S. Roy
Physical Research Laboratory, Ahmedabad – Ahmedabad, (India)

Y. Kahn
Princeton University – Princeton, (USA)

D. McKeen
TRIUMF (Canada)

Z. Ye
Tsinghua University, (China)

P. Meade
Stony Brook University – New York, (USA)

A. Gutiérrez-Rodriguez, M. A. Hernandez-Ruiz
Universidad Autónoma de Zacatecas, (Mexico)

R. Escribano, P. Masjuan, E. Royo
Universitat Autònoma de Barcelona, Departament de Fisica and Institut de Fisica d'Altes Energies, (Spain)

J. Jaeckel
Universität Heidelberg, (Germany)

B. Kubis
Universität Bonn, Helmholtz-Institut für Strahlen- und Kernphysik (Theorie) and Bethe Center for Theoretical Physics, (Germany)

C. Siligardi, S. Barbi, C. Mugoni
Università di Modena e Reggio Emilia, (Italy)

L. E. Marcucci*
Universita' di Pisa, (Italy)

M. Guida[3]
Università di Salerno, (Italy)

S. Charlebois, J. F. Pratte
Université de Sherbrooke, (Canada)

L. Harland-Lang
University of Oxford, (UK)

J. M. Berryman
University of California Berkeley, (USA)

S. Gori
University of California Santa Cruz, (USA)

R. Gardner, P. Paschos
University of Chicago, (USA)

J. Konisberg
University of Florida, (USA)

C. Mills[5]
University of Illinois Chicago, (USA)

M. Murray, C. Rogan, C. Royon, Nicola Minafra, A. Novikov, F. Gautier, T. Isidori
University of Kansas, (USA)

S. Gardner, X. Yan
University of Kentucky, (USA)

Y. Onel
University of Iowa, (USA)

B. Batell, A. Freitas, M. Rai
University of Pittsburgh, (USA)

M. Pospelov
University of Minnesota, (USA)

D. Gao
University of Science and Technology of China, (China)

K. Maamari
University of Southern California, (USA)

A. Kupsc
University of Uppsala, (Sweden)

B. Fabela-Enriquez
Vanderbilt University, (USA)

A. Petrov
Wayne State University, (USA)

S. Tulin
York University, (Canada)

13 Countries,
56 Institutions,
124 Collaborators

Conclusions

- *All meson factories: LHCb, B-factories, Dafne, J/psi factories - have produced a broad spectrum of nice physics*
- *The η /η' meson is a excellent laboratory for studying rare processes and physics BSM at a lower mass scale*
- *REDTOP only experiment (with SHIP) sensitive to four DM portals*
- *Excellent complementarities with JEF at JLAB*
- *Existing world sample not sufficient for breaching into decays violating conservation laws or searching for new particles*
- *REDTOP goal is to produce ~10^{14} untagged η mesons and ~ 10^{12} η' in Phase-I and ~10^{13} tagged mesons in Phase-II*
- *Modest beam requirements could be met by several laboratories in US, Europe, and Asia*

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

Backup slides

5/28/2022 C. Gatto - INFN & NIU

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.
- EM decays are forbidden in lowest order by C invariance and angular momentum conservation
  - 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
  - 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 Factories and Outstanding Anomalies

REDTOP

Muonic puzzle (aka, proton radius and muon g – 2 Anomalies)

- Solved by postulating a new scalar boson ϕ decaying into e^+e^-:

$$\eta \rightarrow \phi\, \pi^0 \rightarrow e^+e^-\, \gamma\gamma$$

$\eta \rightarrow \pi^0 e^- e^+$ is forbidden in the SM by charge conjugation symmetry at tree level but allowed by a virtual ϕ emission

[Y. Liu,1, I.C. Cloët, G. A. Miller, *Nucl.Phys.* B (2019) 114638]

- Also interesting:

$$BR(\eta \rightarrow e^+e^-) \text{ vs } BR(\eta \rightarrow \mu^+\mu^-)$$

branching ratios (BR) jn SM range from 10^{-9} to 10^{-6}

[Pere Masjuan,a Pablo Sanchez-Puertas, *Phys.Rev.D* 26 (1982) 3302]

X17 in the e^+e^- emission spectra of isoscalar magnetic transitions of ^{8}Be and ^{4}He nuclei

- Solved by postulating a 17 MeV QCD-axion or a protophobic gauge boson decaying into e^+e^-

$$\eta \rightarrow a\, \pi^+\pi^- \rightarrow e^+e^-\, \pi^+\pi^- \quad and \quad \eta \rightarrow a\, \pi^0\pi^0 \rightarrow e^+e^-\, \gamma\gamma\gamma\gamma$$

[D. S. M. Alves, arXiv:2009.05578]

$$\eta \rightarrow X17\gamma \rightarrow e^+e^-\, \gamma$$

[J.L. Feng et Al. Phys. Rev. D **95**, 035017]

KOTO anomaly (100x excess of events in $K^0 \rightarrow \pi^0 \nu\nu$)

- Solved by postulating a new Hadrophilic scalar boson H decaying into e^+e^-

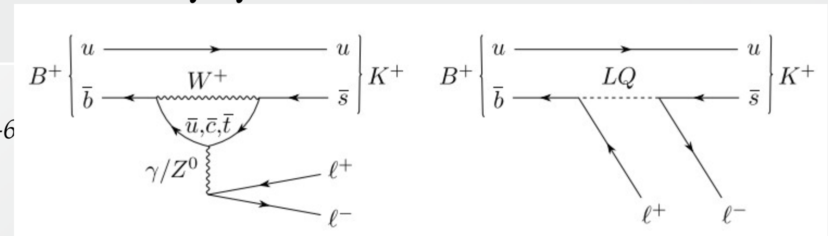
$$\eta \rightarrow H\, \pi^0 \rightarrow e^+e^-\, \gamma\gamma$$

[D. Egana-Ugrinovic , S. Homiller , and Patrick Meade, Phys. Rev. Lett. 124, 191801 (2020)]

[B. Batell, A. Freitas, A. Ismail, D. McKeen, Phys. Rev. D **100**, 095020]

Lepton Universality Test

LHCb latest results: with $B^+ \to \mu^+\mu^- K^+$ vs $e^+e^- K^+$



- ❑ *Based on 3850 vs 1640 evts (BR_{SM} = 10^{-6}*
- ❑ *3.1σ discrepancy vs SM*

η/η′ factories are especially important to confirm the anomaly

- ❑ *If new particle has a mass close to $2xM_{\mu}$, the m-e non-universality could be due to a phase space effect rather than a non-universal coupling*
- ❑ *Low energy experiments are more sensitive to that mass scale*
- ❑ *Several processes under study:*
- ❑ $\eta \to \gamma\, \mu^+ \mu^-$ *vs* $\gamma\, e^+ e^-$
- ❑ $\eta \to \mu^+ \mu^- \mu^+ \mu^-$ *vs* $e^+ e^- \mu^+ \mu^-$ *vs* $e^+ e^- e^+ e^-$
- ❑ $\eta \to \pi^o \mu^+ \mu^-$ *vs* $\pi^o e^+ e^-$
- ❑ *The most rare of the processes involving leptons could have as much as several 10^4 SM events ($BR_{SM} \sim 10^{-8}$)*

Acceleration Scheme for Run-I (M. Syphers)

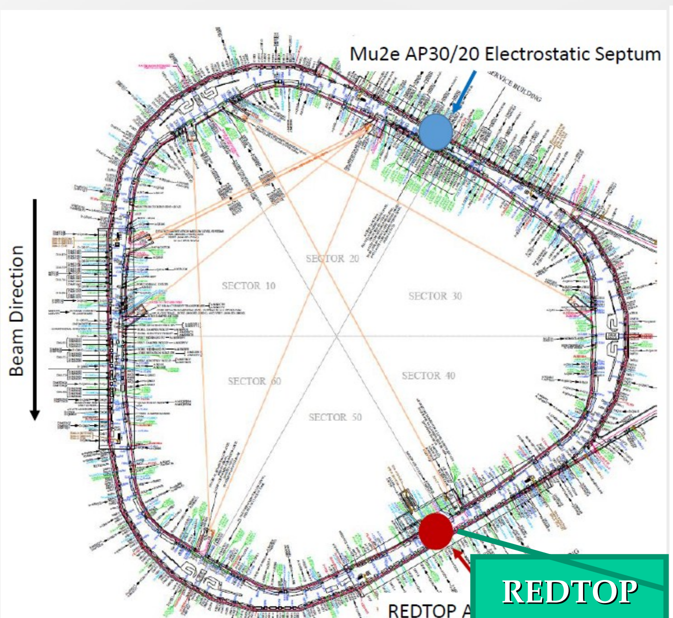
Single p pulse from booster (≤4x10^{12} p) injected in the DR (former debuncher in anti-p production at Tevatron) at fixed energy (8 GeV)

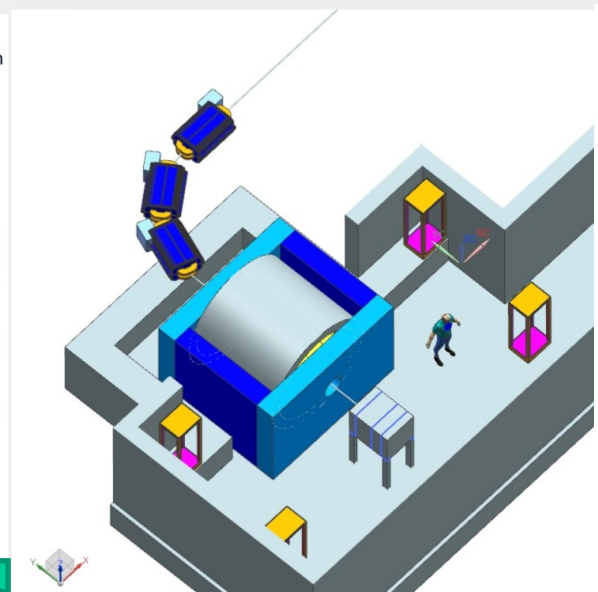
Energy is removed by inserting 1 or 2 RF cavities identical to the one already planned (~5 seconds)

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%





REDTOP detector

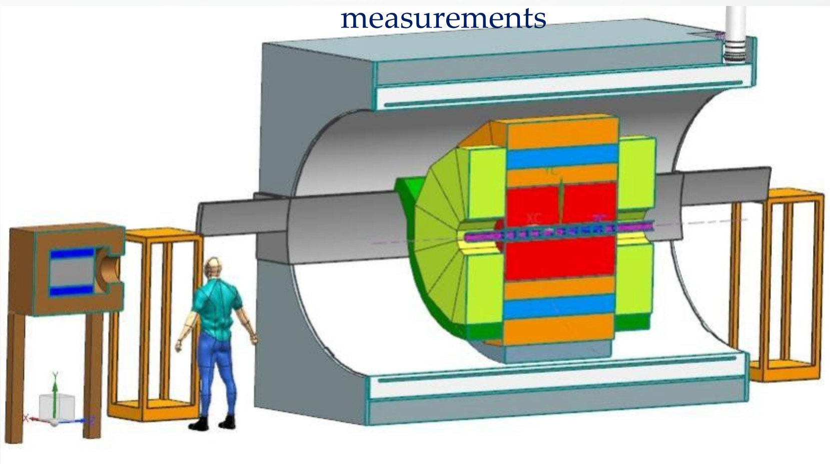
Optical-TPC

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

10x Be or Li targets

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

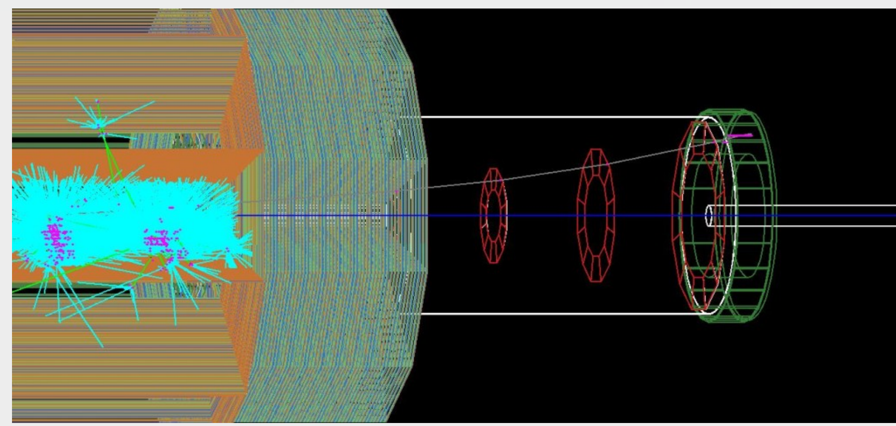
Sci and Cer light read by SiPM or SPAD

For excellent energy , position resolution and PID

-polarimeter (optional)

sandwich of fused silica and Si-pixel

for measurement of muon polarization

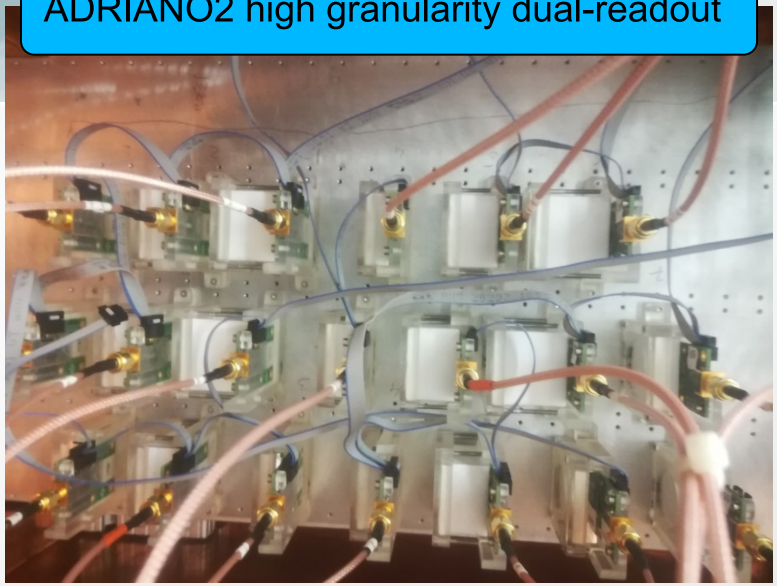


Forward Detector for Option 2

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

Detector Development

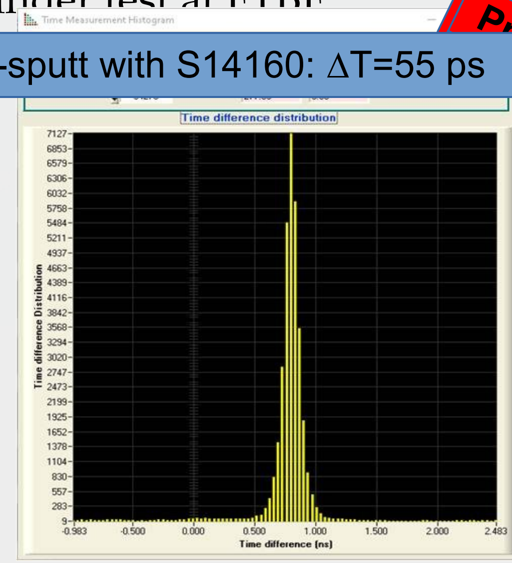
ADRIANO2 high granularity dual-readout



T1604 Collaboration (ANL, Fermilab, INFN, KU, NIU)

Member of CALICE collab.

30 prototypes under test at FTBF

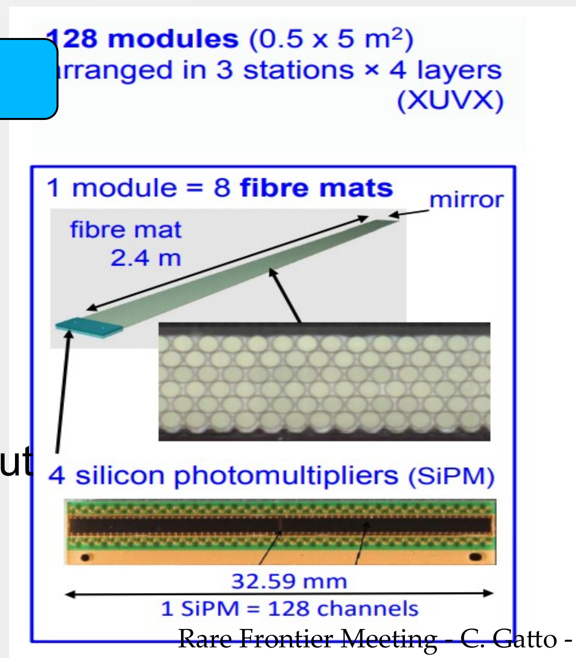


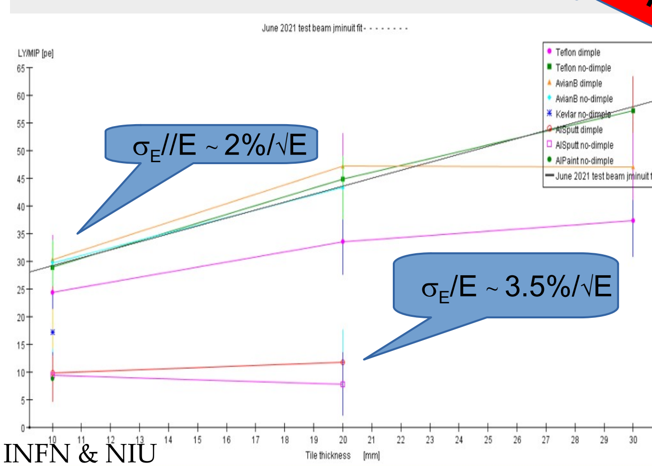
The Fiber Tracker

LHCb design

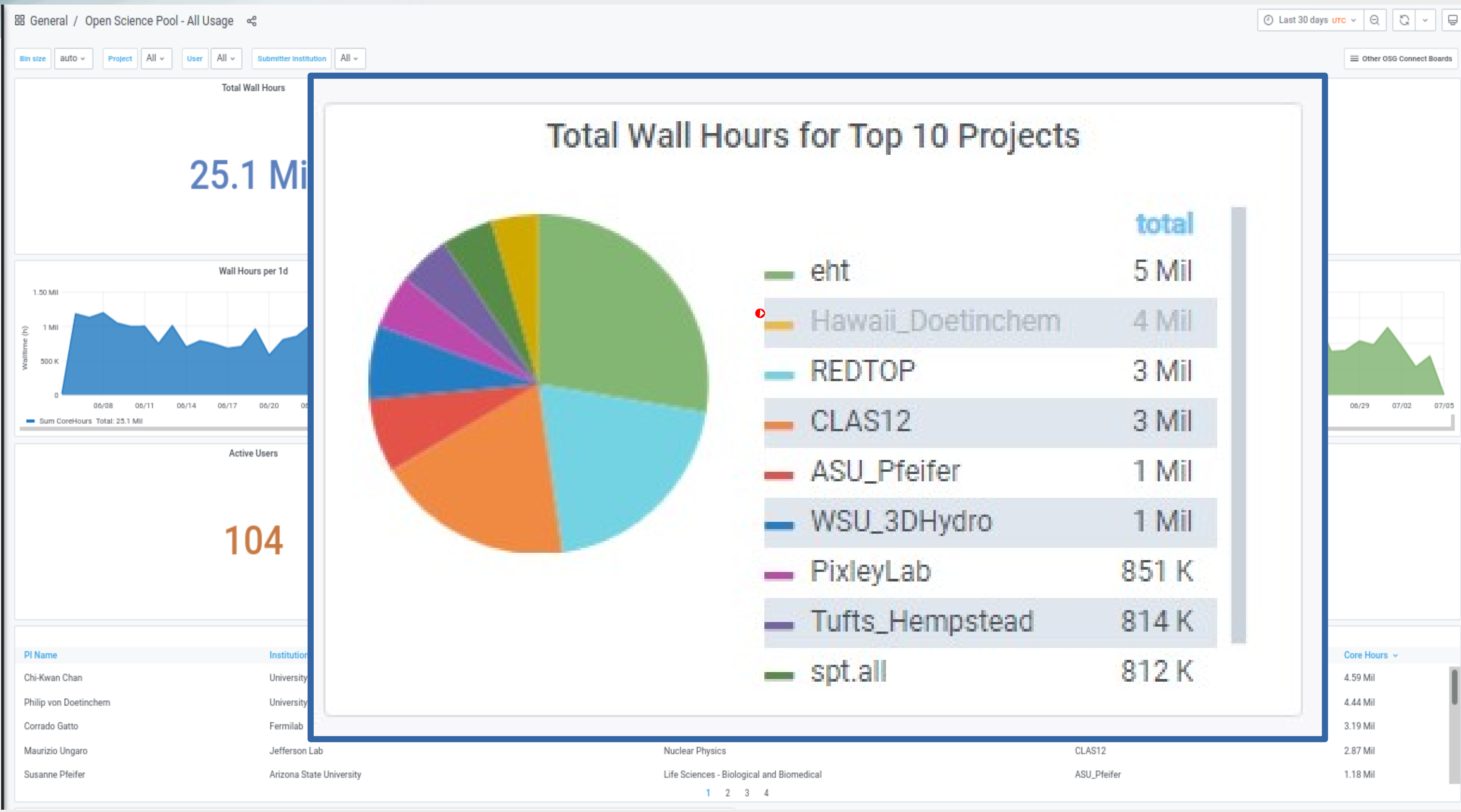
Active surface is about 0.24 m² vs 360 m² for LHCb.

Readout channels is about 18,000 (vs 590k for LHCB's tracker)





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.*

REDTOP Computing Requirements

- *Storage*

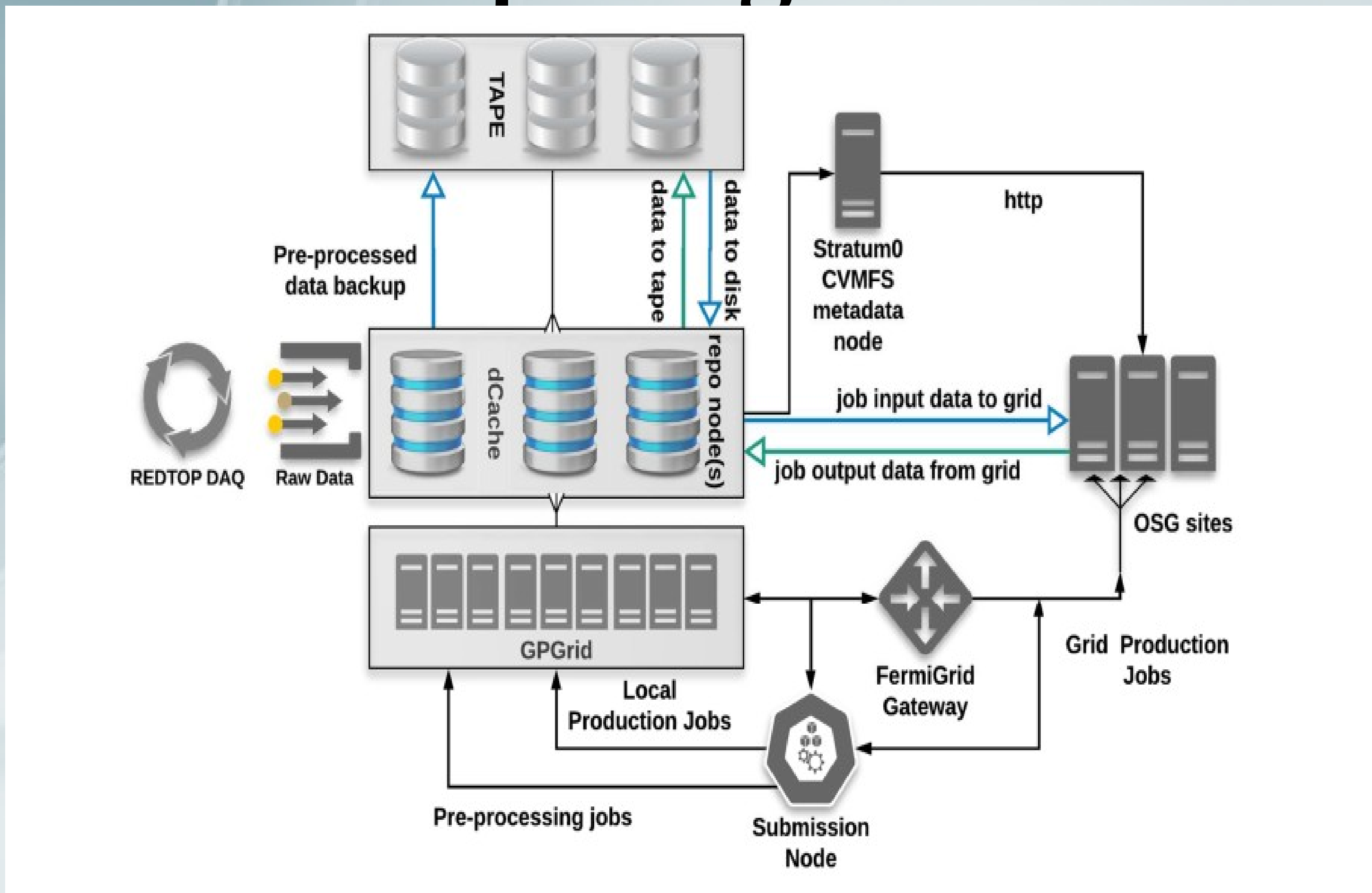
Trigger stage	*Input event rate Hz*	*Event size bytes*	*Input data rate bytes/s*	*Event rejection*
Level 0	$7. \times 10^8$	1.4×10^3	9.8×10^{11}	$\sim$4.6
Level 1	1.5×10^8	1.5×10^3	2.3×10^{11}	$\sim$60
Level 2	2.5×10^6	1.5×10^3	3.8×10^9	$\sim$4.5
Storage	0.56×10^6	1.6×10^3	0.9×10^9	

TABLE XVIII. Data and event rates for different stages

- *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 Baseline Computing Model



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