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

Rare **E**ta **D**ecays
To **O**bserve new **P**hysics

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

- "*….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 could be interpreted as a low energy Higgs factory

The REDTOP Experiment

REDTOP is a propose **η/η'** factory which aims at detecting small deviations from the Standard Model by collecting a large set of events from protons impinging on a fixed target

The experiment will produce ~10^{13} η mesons or ~10^{11} η' mesons per year corresponding to an increase of the existing world sample by four order of magnitude

All electromagnetic and strong decays of the neutral and long-lived and ′ 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.

REDTOP will collect the existing η and η' World sample in ~20 min of running

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

Assuming a yield $\sim 10^{13}$ η mesons/yr and $\sim 10^{11}$ 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 $\gamma*$ 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 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 $X_{17} \to e^+ e^-$
- 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)

Assuming a yield ~10^{13} η mesons/yr and ~10^{11} η′ mesons/yr

Only experiment, along with SHIP, sensitive to all four dark matter 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):* $\eta \rightarrow 4\pi^o \rightarrow 8\gamma$
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- *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 μ polar. in studies:* $\eta \rightarrow \pi^o \mu^+\mu^-$
- *T invar. via μ* [illegible]
- *CPT violation: μ polar. in* $\eta \rightarrow \pi^+\mu^-\nu$ *vs* $\eta \rightarrow \pi^-\mu^+\nu$ *and γ polar. in* $\eta \rightarrow \gamma\gamma$

Other discrete symmetry violations

- *Lepton Flavor Violation:* $\eta \rightarrow \mu^+ e^- + c.c.$
- *Radiative Lepton Flavor Violation:* $\eta \rightarrow \gamma\mu^+ e^- + c.c.$
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- *Charged pion and kaon decays:* $\pi+ \rightarrow \mu^+\nu A' \rightarrow \mu^+\nu e^+e^-$ *and* $K+ \rightarrow \mu^+\nu A' \rightarrow \mu^+\nu e^+e^-$
- *Neutral pion decay:* $\pi^o \rightarrow \gamma A' \rightarrow \gamma e^+e^-$

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* $X_{17} \rightarrow e^+e^-$
- *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 leptoquarks:* [illegible] $\eta \rightarrow e^+e^-$
- *Search for true muonium:* $\eta \rightarrow \gamma(\mu^+\mu^-)|_{2M_\mu} \rightarrow \gamma e^+e^-$
- *Lepton universality*
- $\eta \rightarrow \pi^o H$ *with* $H \rightarrow \nu N_2$, $N_2 \rightarrow n' N_1$, $n' \rightarrow e^+e^-$

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

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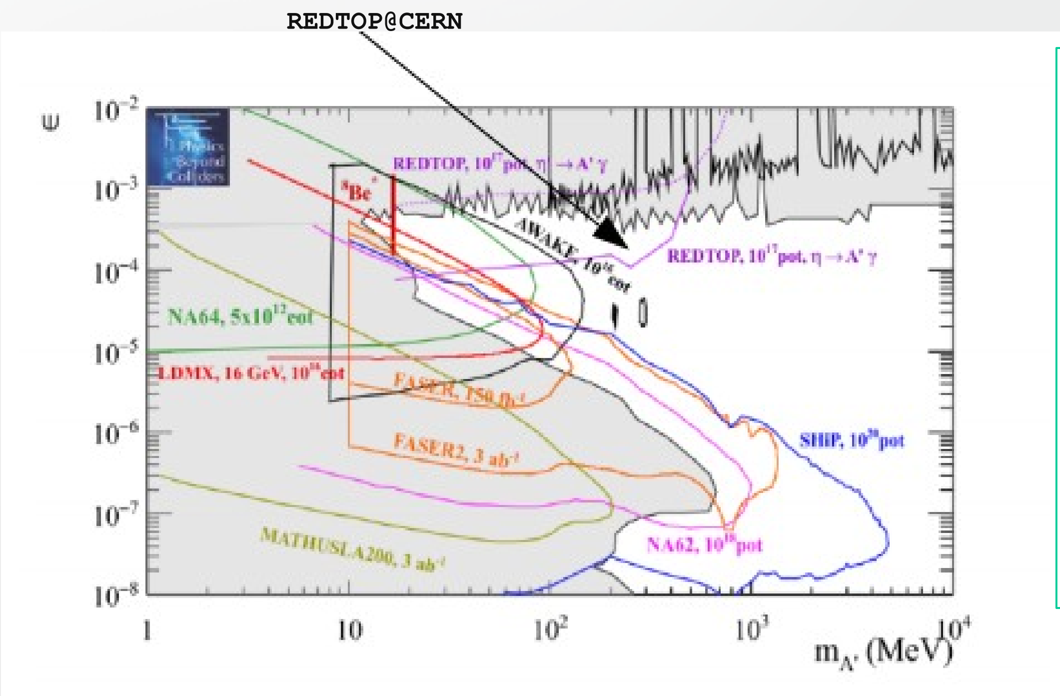
- *Isospin breaking due to the u-d quark mass difference*
- *Octet-singlet mixing angle*
- *Electromagnetic transition form-factors (important input for g-2)*

Vector Portal searches:

$$\eta \rightarrow \gamma A' \;\; with \;\; A' \rightarrow \mu^+ \mu^- \;\; and \;\; e^+ e^-$$

- Studied within the "Physics Beyond Collider" program at CERN for 10^{17} POT
- Other laboratories can provide 10x more POT
- Only "bump hunt analysis". Vertexing being added in studies for Snowmass-2022 to improve the sensitivity to physics BSM by 10x



Models studied for Snowmass

- Minimal dark photon model
  - kinetic mixing of γ and A'
- Protophobic Fifth Force
  - J. Feng et al
  - Explains the Atomki anomaly

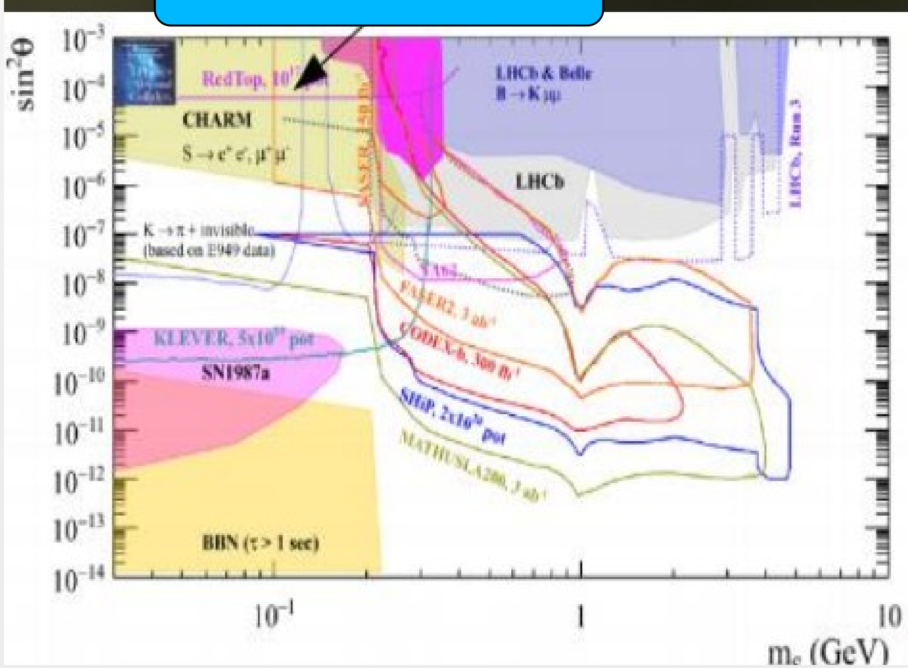
Scalar Portal searches:

$\eta \rightarrow \pi^o H$ *with* $H \rightarrow \mu^+ \mu^-$ *and* $e^+ e^-$

Models studied for Snowmass

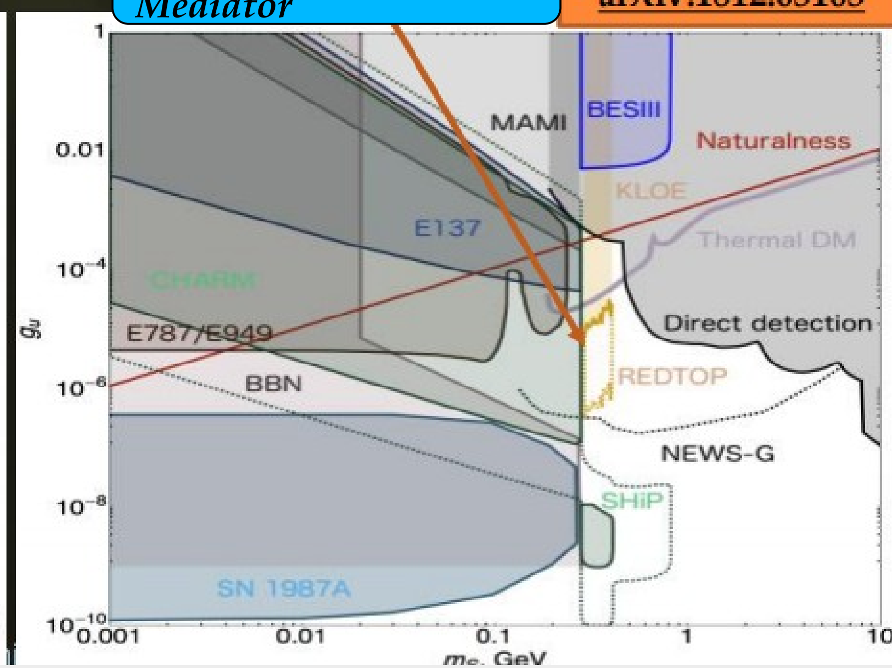
- ***Spontaneous Flavor Violation*** *(D.Egana-Ugrinovic, S. Homiller, P. Meade)*
- ***Hadrophilic Scalar Mediator*** *(B. Batell, A. Freitas, A. Ismail, D. McKeen)*
- ***Two-Higgs doublet model*** *(W. Abdallah, R. Gandhi, and S. Roy)*
- ***Minimal scalar model*** *(C.P. Burgess, M. Pospelov, T. ter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

Minimal Scalar Model



Hadrophilic Scalar Mediator

arXiv:1812.05103



Pseudoscalar Portal searches:

$\eta \rightarrow \pi^o \pi^o a$ & $\boldsymbol{\eta} \rightarrow \pi^+ \pi^- a$

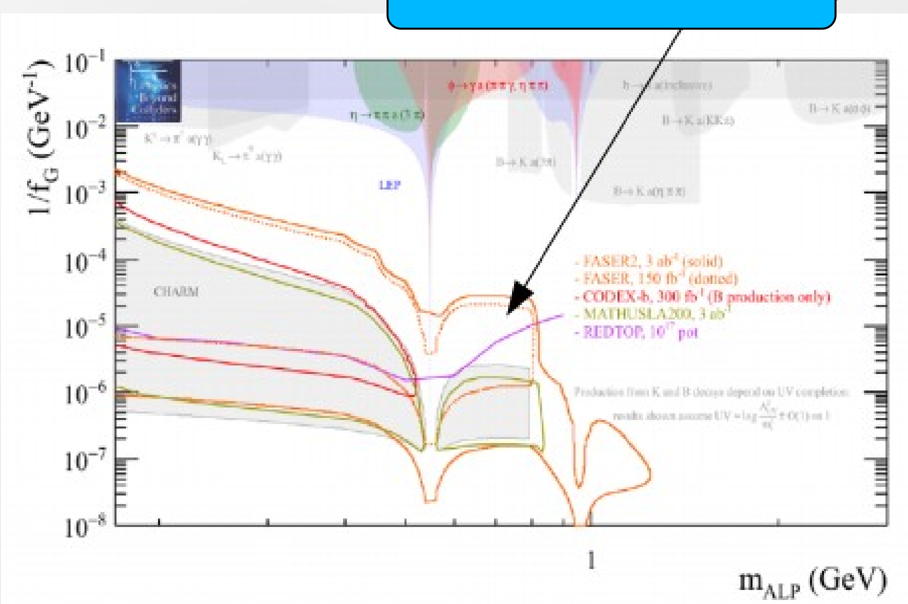
with $a \rightarrow \gamma\gamma$, $\mu^+ \mu^-$ *and* $e^+ e^-$

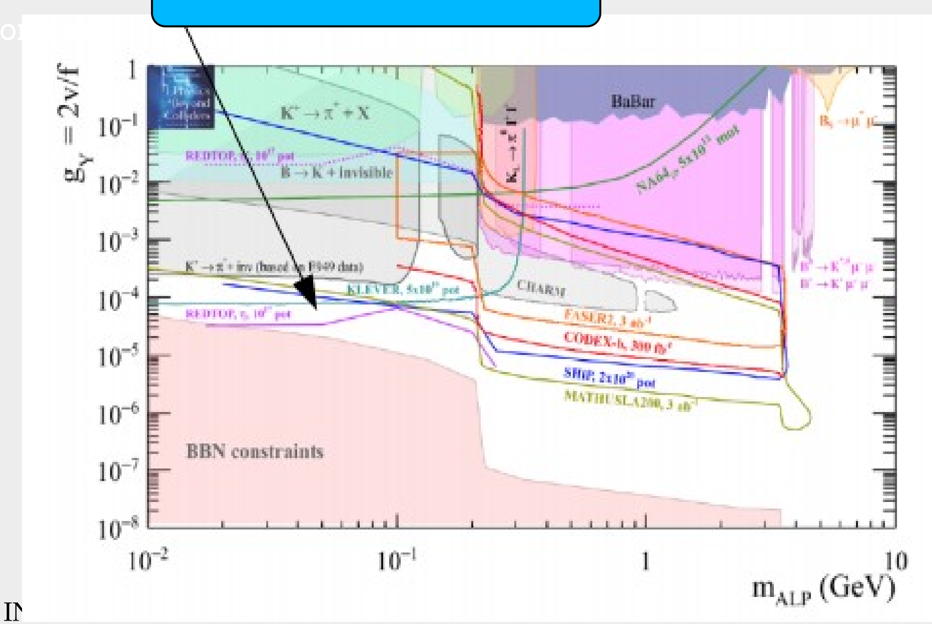
Models studied for Snowmass

- ***Piophobic axion model*** *(D. S. M. Alves)*
- ***Effective interactions with gluon coupling dominance*** *(L. Harland–Lang, J. Jaeckel M. Spannowsky)*
- ***Effective interactions with fermion coupling dominance***

Fermion Dominance

Gluon Dominance





Heavy Neutral Lepton Portal searches:

$\eta \rightarrow \pi^o H$ *with* $H \rightarrow \nu N_2$, $N_2 \rightarrow h' N_1$, $h' \rightarrow e^+ e^-$

Models studied for Snowmass

- ***Two-Higgs doublet model*** *(W. Abdallah, R. Gandhi, and S. Roy)*

m_{N_1}	m_{N_2}	m_{N_3}	$y_u^{h'(H)} \times 10^6$	$y_{e(\mu)}^{h'} \times 10^4$	$y_{e(\mu)}^{H} \times 10^4$
85 MeV	130 MeV	10 GeV	0.8(8)	0.23(1.6)	2.29(15.9)
$m_{h'}$	m_H	$\sin\delta$	$y_d^{h'(H)} \times 10^6$	$y_{\nu_{i2}}^{h'(H)} \times 10^3$	$\lambda_{N_{12}}^{h'(H)} \times 10^3$
17 MeV	750 MeV	0.1	0.8(8)	1.25(12.4)	74.6(−7.5)

TABLE I: Benchmark point (BP) used for event generation in LSND, MB and for calculating the muon $g-2$.

Parameter s to explain LSND, Miniboone and g-2 anomalies

From arxiv 2010.06159

$\mathrm{BR}(H \to \nu_i N_2) = 98.84\%$, $\mathrm{BR}(H \to N_1 N_2) = 0.12\%$, $\mathrm{BR}(H \to \mu^+\mu^-) = 1.0$

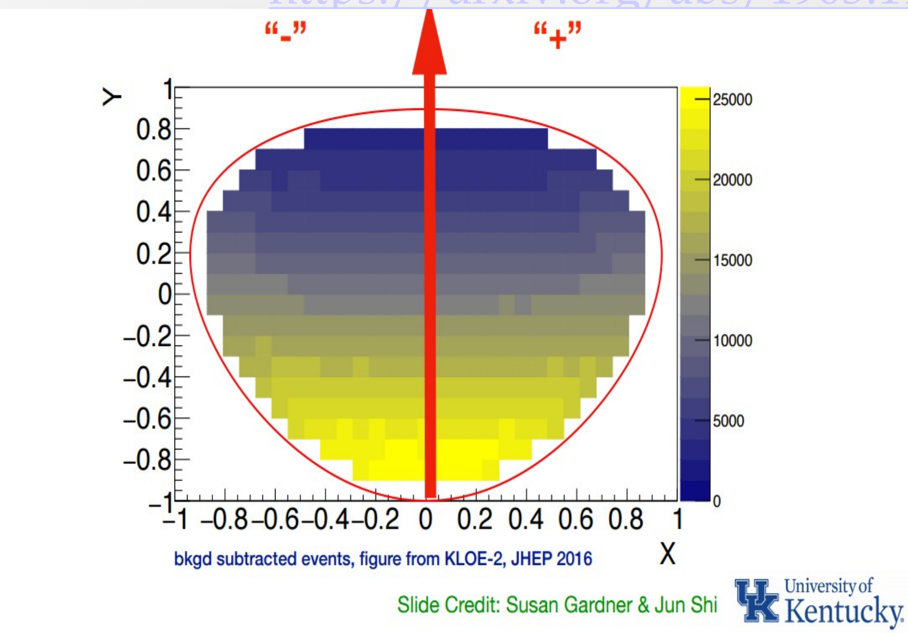
$\mathrm{BR}(H \to e^+e^-) = 0.024\%$, $\mathrm{BR}(H \to \gamma\gamma) = 4.16 \times 10^{-10}\%$,

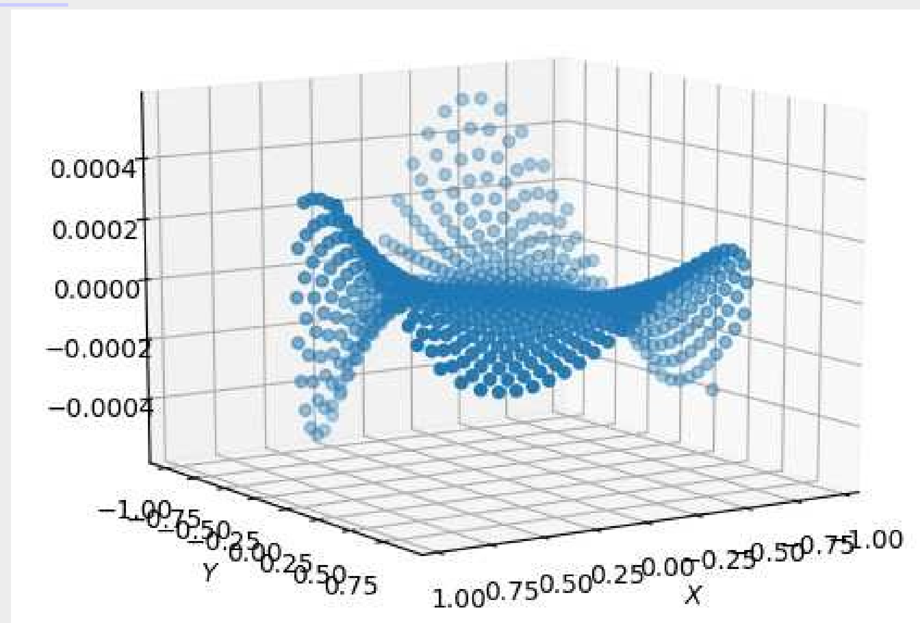
$\mathrm{BR}(h' \to e^+e^-) = 100\%$, $\mathrm{BR}(h' \to \gamma\gamma) = 6.42 \times 10^{-9}\%$,

$\mathrm{BR}(N_2 \to N_1 h') = 90.15\%$, $\mathrm{BR}(N_2 \to \nu_i h') = 9.84\%$.

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

- *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*
- *REDTOP will collect $4x10^{11}$ such decay (factor 100 in stat. error vs PDG)*
- *New model in GenieHad (collaboration with S. Gardner & J. Shi – UK) based on* https://arxiv.org/abs/1903.11617





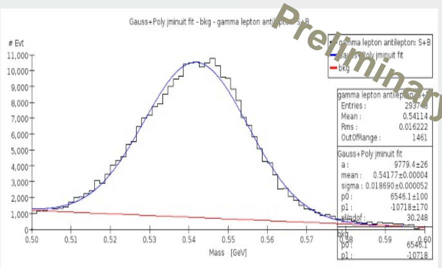
Lepton Universality Test

REDTOP

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

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

- *Preliminary studies based on* $3\text{x}10^{10}$ *POT* ($9\text{x}10^{7}$ η *mesons) or* 10^{-5} *of the 1-year run statistics*
- *Background rejection from* $\eta \rightarrow \gamma\gamma$ *using high-resolution (ADRIANO2) and vertex reconstruction*
- *Preliminary statistical uncertainty :*
  - < 0.3% *for* $\eta \rightarrow \gamma\, e^+ e^-$ (*cfr LHCb @ 4.2% with 1640 evts)*
  - < 0.9% *for* $\eta \rightarrow \gamma\, \mu^+ \mu^-$ (*cfr LHCb @ 1.8% with 3850 evts)*

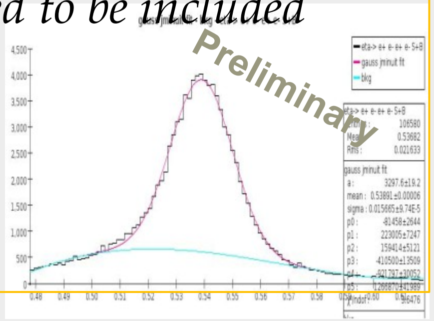


$\eta \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ *vs* $e^+ e^- \mu^+ \mu^-$ *vs* $e^+ e^- e^+ e^-$

- *Theoretical calculations at the* 10^{-3} *precision from Kampf, Novotný, Sanchez-Puertas (PR D 97, 056010 (2018)) – hard photon corrections need to be included*
- *Preliminary studies based on* $3\text{x}10^{10}$ *POT* ($9\text{x}10^{7}$ η *mesons)*

or 10^{-5} *of the 1-year run statistics*

- *Preliminary stat uncertainty: ~ 0.5%*



More BSM Physics Studies

- *CP-violation in $\eta \rightarrow$lepton antilepton processes (P. Sanchez-Puertas, P.Masjuan, 1810.13228, 1909.07491, 1512.09292).*
- *CP-violation in $\eta \rightarrow \pi^+ \pi^- e^+ e^-$ (Dao-Neng Gao, /hep-ph/0202002).*
- *LF-violation in $\eta \rightarrow \mu^+ \mu^-$ processes (A. Petrov , D. Hazard, 1607.00815).*
- *LF-violation in $\eta \rightarrow \gamma \mu^+ \mu^-$ processes (A. Petrov , D. Hazard, 1711.05314).*
- *CP-violation from muon polarization in $\eta \rightarrow \pi^o \mu^+ \mu^-$ $\eta \rightarrow 4\pi$ processes (IFAE group, in-progress).*
- *Beamshtrahlung of ALPs (Based on work by S., W. Altmannshofer , L. Harland-Lang J. Jaeckel, and Michael Spannowsky, Felix Kahlhoefer. Et al. Using interface between GenieHad and ALPCA event generator [arXiv:1902.04878 [hep-ph]])*

QCD axion studies

- *Based on D. Alves model (PR D 103, 055018 (2021))*

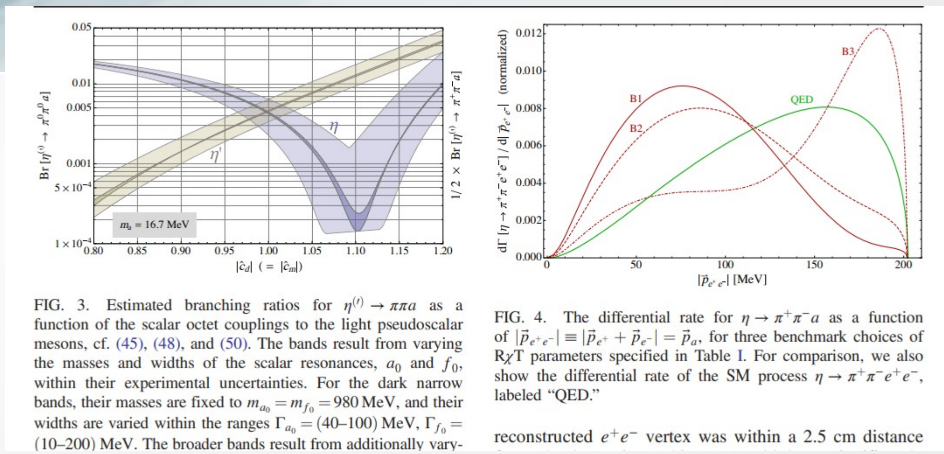
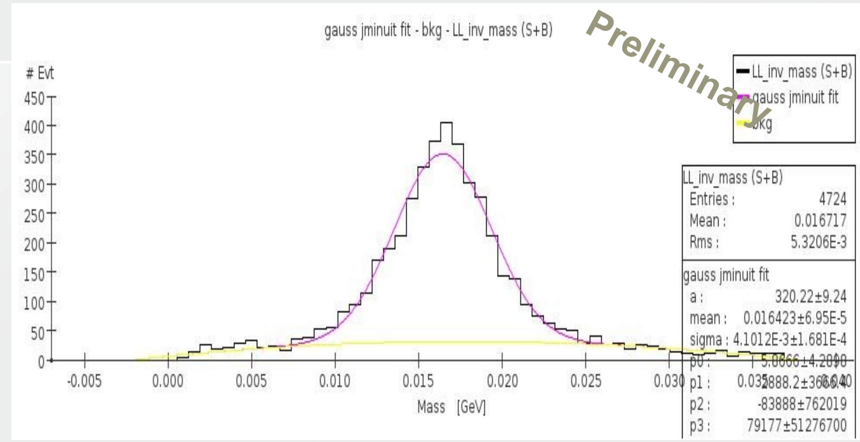


FIG. 3. Estimated branching ratios for $\eta^{(\prime)} \to \pi\pi a$ as a function of the scalar octet couplings to the light pseudoscalar mesons, cf. (45), (48), and (50). The bands result from varying the masses and widths of the scalar resonances, a_0 and f_0, within their experimental uncertainties. For the dark narrow bands, their masses are fixed to $m_{a_0} = m_{f_0} = 980$ MeV, and their widths are varied within the ranges $\Gamma_{a_0} = (40\text{–}100)$ MeV, $\Gamma_{f_0} = (10\text{–}200)$ MeV. The broader bands result from additionally vary-

FIG. 4. The differential rate for $\eta \to \pi^+\pi^- a$ as a function of $|\vec{p}_{e^+e^-}| \equiv |\vec{p}_{e^+} + \vec{p}_{e^-}| = \vec{p}_a$, for three benchmark choices of RχT parameters specified in Table I. For comparison, we also show the differential rate of the SM process $\eta \to \pi^+\pi^- e^+ e^-$, labeled "QED."

reconstructed e^+e^- vertex was within a 2.5 cm distance



- *Assume the axion is the 17 MeV anomaly observed in Atomki experiment*
- *Below KLOE sensitivity*
- *the CELSIUS/WASA Collaboration observed 24 evts with SM expectation of 10*

- *Preliminary studies based on 3x10^{10} POT (9x10^{7} η mesons) or 10^{-5} of the 1-year run statistics*
- *Main background $\eta \to \pi^0 \pi^+ \pi^-$ $\eta \to \gamma \pi^+ \pi^-$ with ensuing gamma-conversion. Rejected with high resolution ADRIANO2 and vertexing*
- *Large statistics to disentangle the six parameters of the model*

Present & Future η Samples

	Technique	$\eta \rightarrow 3\pi^0$	$\eta \rightarrow e^+e^-\gamma$	Total η mesons
CB@AGS	$\pi^- p \rightarrow \eta\, n$	9×10^5		10^7
CB@MAMI-B	$\gamma p \rightarrow \eta\, p$	1.8×10^6	5000	2×10^7
CB@MAMI-C	$\gamma p \rightarrow \eta\, p$	6×10^6		6×10^7
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 (recently approved)	$\gamma_{12\ GeV} p \rightarrow \eta\, X \rightarrow$ neutrals			3.9×10^5/day
REDTOP (proposing)	$p_{1.8\ GeV} Li \rightarrow \eta\, X$			2.5×10^{13}/yr

REDTOP Beam Requirements

Phase – I: Untagged 10^{13} η/η' mesons

Delivery ring

- *CW beam:* **~2 GeV (η)– ~4(η') GeV - 30-60W**
- *Low intensity :* **10^{11} POT/sec** or **10^{18} POT/yr on solid target**
- *Multiple (10) thin* **Li or Be** *targets to disentangle event pileup*

Inelastic interaction rate: ~ 0.5 GHz
Average event multiplicity ≈
4 charged + 4 neutral
η/η' production rate: ~ 2.3 MHz

vs LHCb@40 MHz

Phase – II: Tagged 10^{12} – 10^{13} η/η' mesons

PIP-II

CW beam: **~0.9 GeV (η) *and* ~1.7(η') GeV -100-1000 KW**

- *High intensity beam :* **10^{21}-10^{22} POT/yr on De gaseous target**

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)***
- $\sigma_{tracker}(t) \sim 80psec$, $\sigma_{calorimeter}(t) \sim 80psec$, $\sigma_{Rich}(t) \sim 80psec$
- ***Low-mass vertex detector***
- ***Near 4π detector acceptance (as the η/η' decay is almost at rest).***

charged tracks detection

Option 1: Optical-TPC

- *Barions and most pions are below threshold*
- *Electrons and most muons are detected and reconstructed*

Option 2: 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

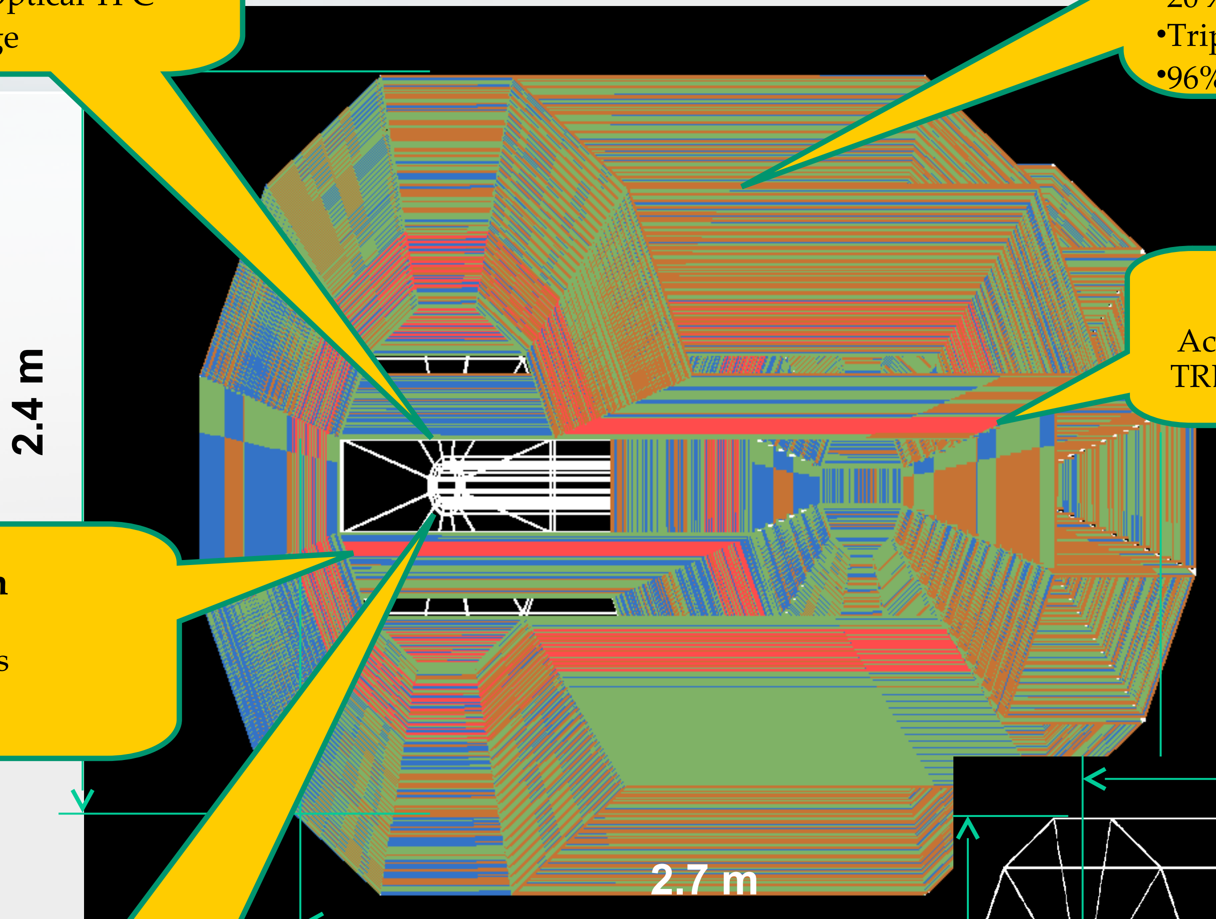
- *Light sensors: SiPM or SPADs*
- *96.5% coverage*

Fiber tracker (LHCb style) for rejection of background from γ-conversion and reconstruction of secondary vertices (~70μm resolution)

REDTOP detector

Central Tracker
- ~ 1m x 1.5 m
- Option #1: Thin LGAD
- Option #2: Optical TPC
- 98% coverage

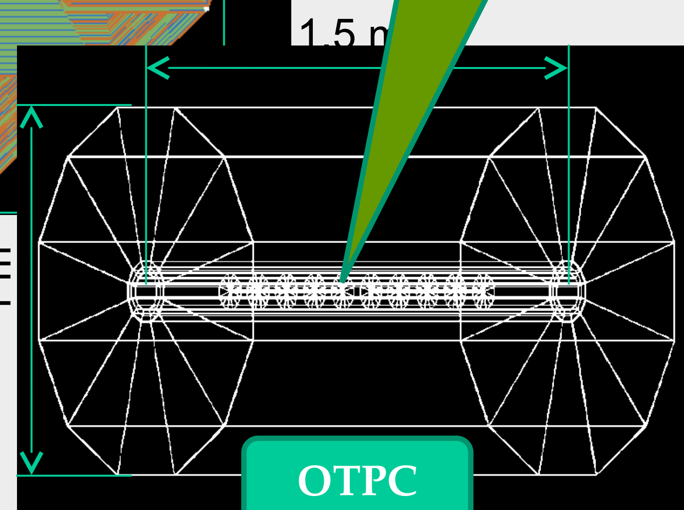
ADRIANO2 Calorimeter (tiles)
- Scint. + heavy glass sandwich
- 20 X_0 (~ 64 cm deep)
- Triple-readout +PFA
- 96% coverage



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

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

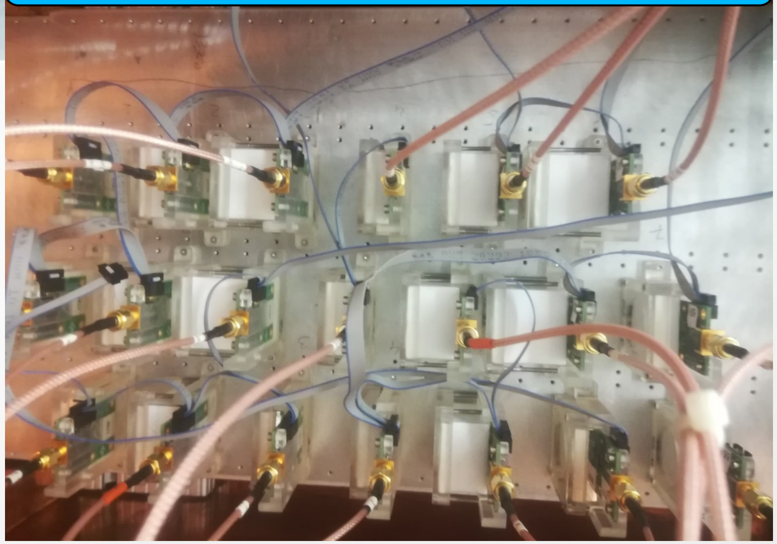
10x Be or Li targets
- 0.33 mm thin
- Spaced 10 cm



Fiber tracker
for rejection of γ-conversion and vertexing

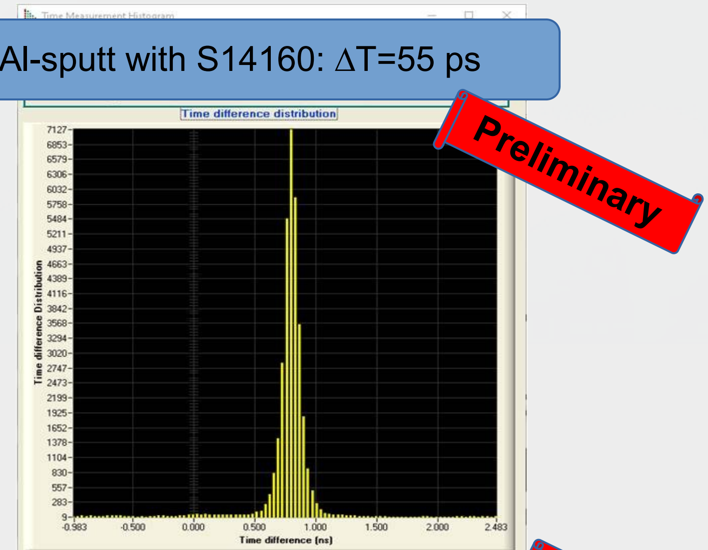
Detector Development

ADRIANO2 high granularity dual-readout



T1604 Collaboration (ANL, Fermilab, INFN, KU, NIU)
Member of CALICE collab.
30 prototypes under test at FTBF

Al-sputt with S14160: ΔT=55 ps

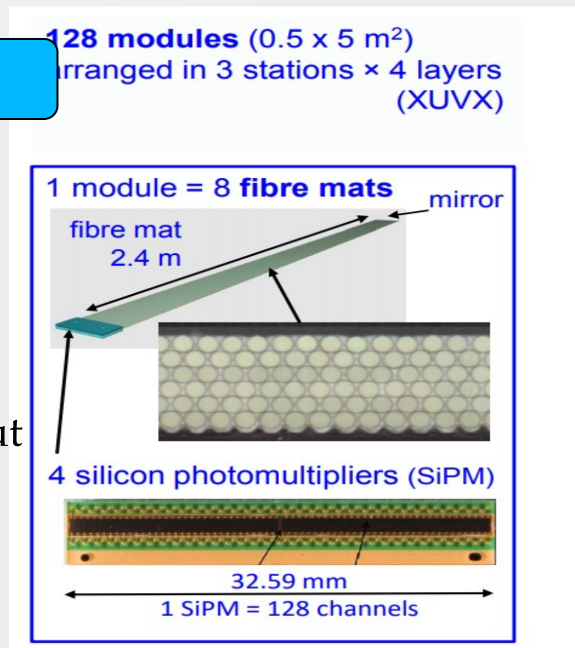


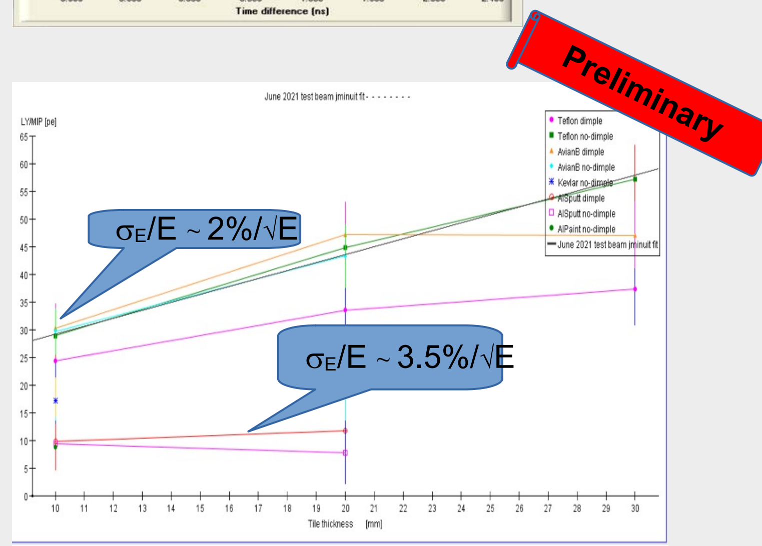
The Fiber Tracker

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 Collaboration

13 Countries, 43 Institutions, 98 Collaborators

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)

A. Alqahtani
Georgetown University, (USA)

F. Ignatov
Budker Institute of Nuclear Physics – Novosibirsk, (Russia)

W. Abdallah
Cairo University, Cairo (Egypt)

A. Kotwal
Duke University, (USA)

M. Spannowsky
Durham University, (UK)

J. Dey, V. Di Benedetto, B. Dobrescu, D. Fagan, E. Gianfelice-Wendt, E. Hahn, D. Jensen, C. Johnstone, J. John
G.Krnjaic, T. Kobilarcik, A. Kronfeld, K. Krempetz, S. Los, M. May, A. Mazzacane, N. Mokhov, W. Pellico, A. Pla-Da
E. Ramberg, J. Rauch, L. Ristori, E. Schmidt, G. Sellberg, G. Tassotto, Y.D. Tsai
Fermi National Accelerator Laboratory, (USA)

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

P. Sanchez-Puertas
IFAE – Barcelona (Spain)

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. S. M. Alves, 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
Northern Illinois University, (USA)

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

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

Y. Kahn
Princeton University – Princeton, (USA)

Princeton University – Princeton, (USA)

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

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

B. Fabela-Enriquez
Vanderbilt University, (USA)

J. Jaeckel
Universität Heidelberg, (Germany)

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

L. E. Marcucci[4]
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)

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, J. Shi, X. Yan
University of Kentucky, (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)

A. Petrov
Wayne State University, (USA)

S. Tulin
York University, (Canada)

Summary

- *All meson factories: LHCb, B-factories, Dafne, J/psi factories - all 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*
- *Only experiment (with SHIP) sensitive to all four DM portals. Nice complementarity with JEF*
- *Existing world sample not sufficient for breaching into decays violating conservation laws or searching for new particles*
- *REDTOP goal is to produce >10^{13} untagged η mesons/yr and ~10^{11} η' /year in Phase-I and ~10^{13} tagged mesons in Phase-II*
- *Relatively low beam requirements could be met by several laboratories in US, Europe and Asia*
- *More details: https://redtop.fnal.gov*

Backup slides

Why the η meson is special?

- It is a Goldstone boson
  - Symmetry constrains its QCD dynamics
- It is an eigenstate of the C, P, CP and G operators (very rare in nature): $I^G J^{PC} = 0^+ 0^{-+}$
  - It can be used to test C and CP invariance.
- All its additive quantum numbers are zero

  $$Q = I = j = S = B = L = 0$$

  - Its decays are not influenced by a change of flavor (as in K decays) and violations are "pure"
- All its possible strong decays are forbidden in lowest order by P and CP invariance, G-parity conservation and isospin and charge symmetry invariance.
- 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^-:

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

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

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

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^-

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

[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 $K^o \rightarrow \pi^o \nu\nu$)

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

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

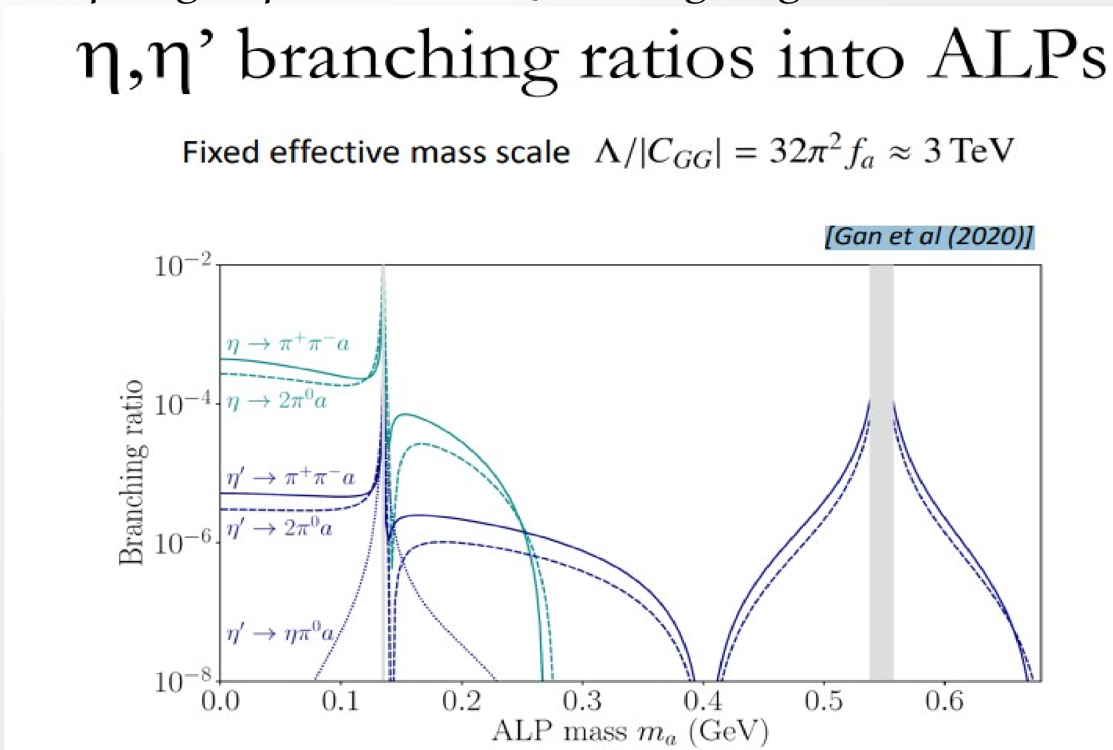
[D. Egana-Ugrinovic , S. Homiller , and Patrick Meade, Phys. Rev. Lett. 124, 191801 (2020)]

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

More ALPs studies

- *It an be searched at REDTOP in* $\eta \rightarrow \pi^{+} \pi^{-} a$ *with* $a \rightarrow \gamma\gamma$ *or* 3π

❑ *ALP–η coupling depends on a-η mixing angle*



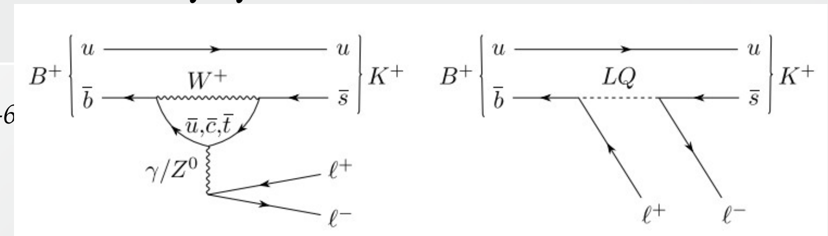
Dark sectors in η,η′ decays [S. Tulin, Snowmass 2021 RF6 Kickoff meeting]

❑ *Vertex detector and high energy resolution dual-readout calorimeter help to reject the background (*$\eta \rightarrow \pi^{0} \pi^{+} \pi^{-}$ *and* $\eta \rightarrow \gamma \pi^{+} \pi^{-}$*)*

❑ *Expect* 10^{5}*-*10^{9} *events at REDTOP, (*m_a *dependent)*

Lepton Universality Test

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



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

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

- *If new particle has a mass close to 2x*M_{μ}*, 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:*
- $\eta \rightarrow \gamma\, \mu^+ \mu^-$ *vs* $\gamma\, e^+ e^-$
- $\eta \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ *vs* $e^+ e^- \mu^+ \mu^-$ *vs* $e^+ e^- e^+ e^-$
- $\eta \rightarrow \pi^o\, \mu^+ \mu^-$ *vs* $\pi^o\, e^+ e^-$
- *The most rare of the processes involving leptons could have as much as several* 10^4 *SM events* $(BR_{SM} \sim 10^{-8})$

Searches for ALPs with fermion or gluon coupling

- Beam emitted ALP's from the following processes:
  - Drell-Yan processes: $q\bar{q} \to A'/a \to l^+l^-$
  - Proton bremsstrahlung processes: $p\,N \to p\,N\,A'/a$ with $A'/a \to l^+l^-$ (J. Blümlein and J. Brunner)
  - Primakoff processes: $p\,Z \to p\,Z\,a \to l^+l^-$ (F. Kahlhoefer, et. Al.)
- Only "bump hunt analysis" with 10^{17} POT (CERN). Will add vertexing+timing to the analysis.
- Redtop@PIP-II will provide x100 sensitivity (ALPACA study).

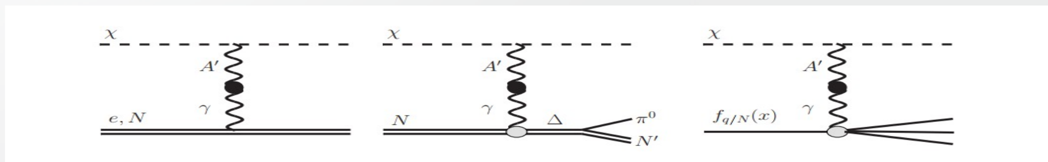
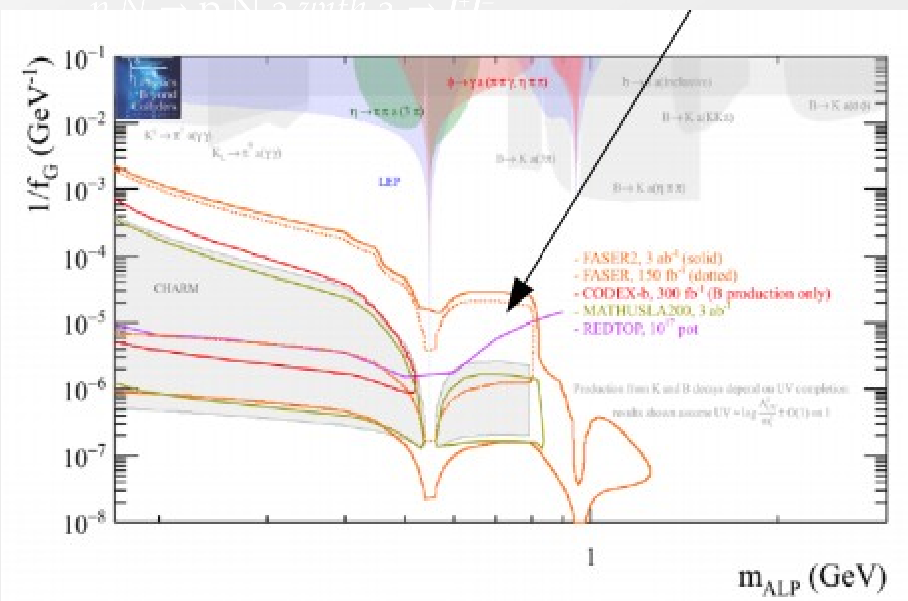


FIG. 4. Scattering channels analyzed: from left to right, elastic scattering on electrons or nucleons, quasielastic (incoherent) single pion production, and deep inelastic scattering.

Patrick deNiverville,[1] Chien-Yi Chen,[1,2] Maxim Pospelov,[1,2] and Adam Ritz[1]

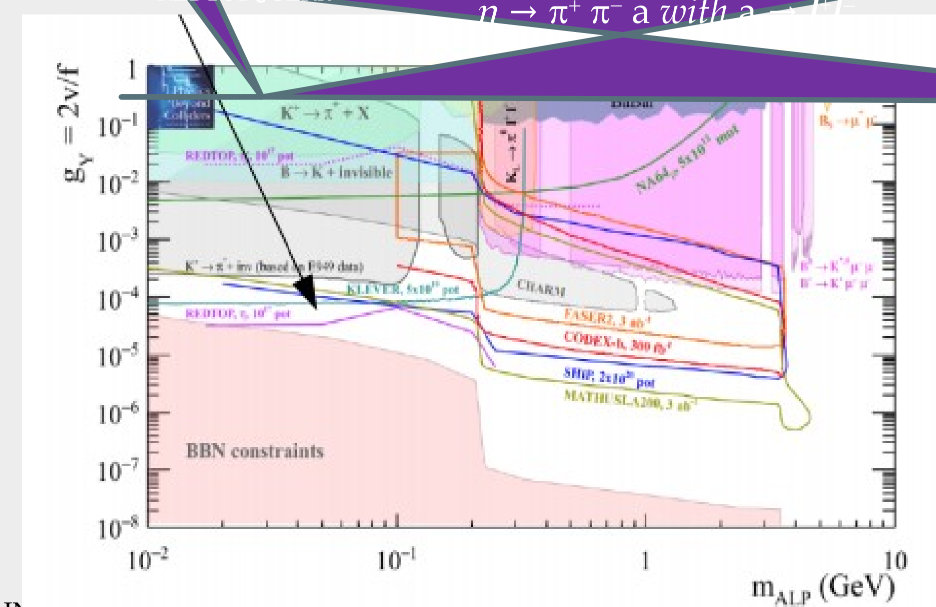
REDTOP@CERN

$p\,N \to p\,N\,a$ with $a \to l^+l^-$



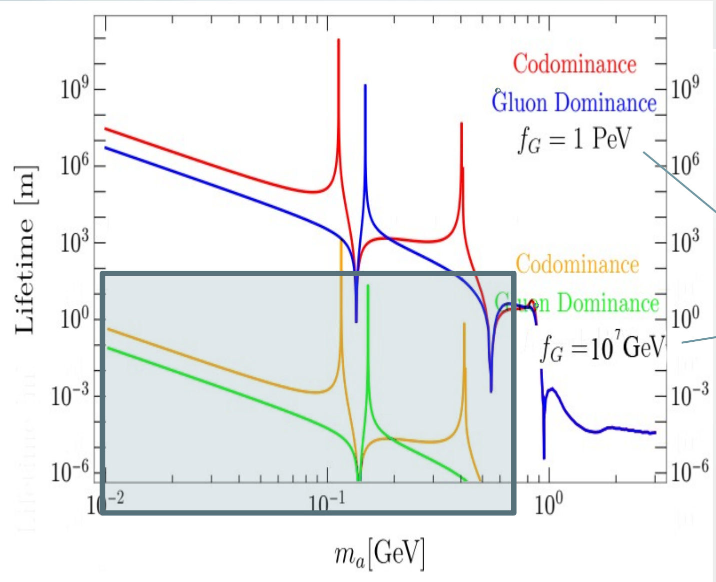
REDTOP@CERN

$\eta \to \pi^+\pi^-\,a$ with $a \to l^+l^-$



More ALPs studies

- *Based on [Gan et al (2020) , Kelly et al (2020)]*



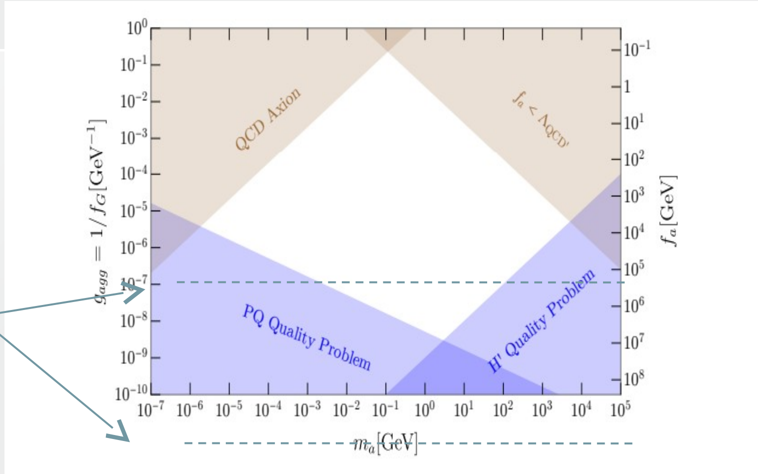
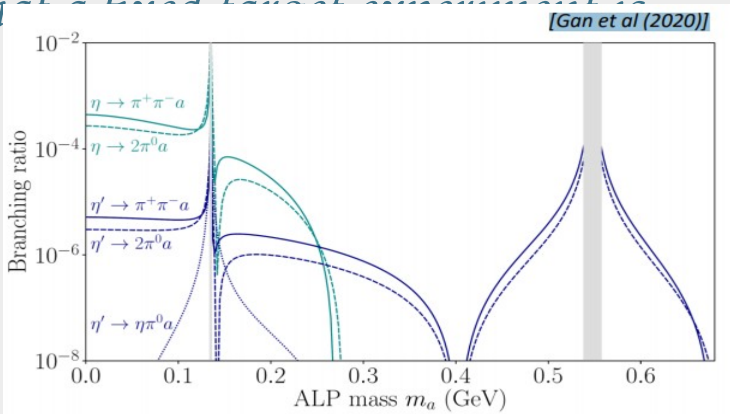


FIG. 2. Theoretical constraints on the axion parameter space for the class of models considered in this work that solve both the Strong CP and the Quality Problems, adapted from Ref. [15]. The white region is the theoretically allowed/motivated region. See the text for explanations of different labels. The parameters f_G and f_a are related by $f_G = 4\pi^2 f_a$.

- *Original work (tailored for beam dump experiments) assume $f_G = 10^{12}$ GeV*
- *More realistic assumption for f_G indicate that a fixed target experiment is way more suited than a beam dump*
- *Expect 10^5-10^9 events at REDTOP*



More Studies for Snowmass2021

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

- *Based on the work by Pere Masjuan and Pablo Sanchez-Puertas* [JHEP 1608, 108 (2016)]
- *Ultra rare process: very sensitive to physics BSM , in particular new couplings (necessarily SU(2) breaking), or lepton flavor violating (LFV) models*
- *One operator inducing CP-violation not baound by EDM measurements [arXiv:1909.07491]*

CP violation in $\eta \rightarrow \pi^+ \pi^- e^+ e^-$

- *Based on the work by D. N. Gao [*arXiv:hep-ph/0202002].
- *Study of the angular correlation of the* $e^+ e^-$ *and* $\pi^+ \pi^-$ *planes due to the interference between the magnetic and electric decay amplitudes.*

More alps studies from rare π^o and η decays

- *Based on the work by Stefania Gori, Wolfgang Altmannshofer , Lucian Harland-Lang Joerg Jaeckel, and Michael Spannowsky, Felix Kahlhoefer. Et al.*
- *Uses interface between GenieHad and ALPCA event generator [*arXiv:1902.04878 **[hep-ph]***]*

Muon polarization studies

- *Independent window on CPviolation*
- *Require implementation of polarimetry in the ADRIANO2 calorimeter*

REDTOP detector

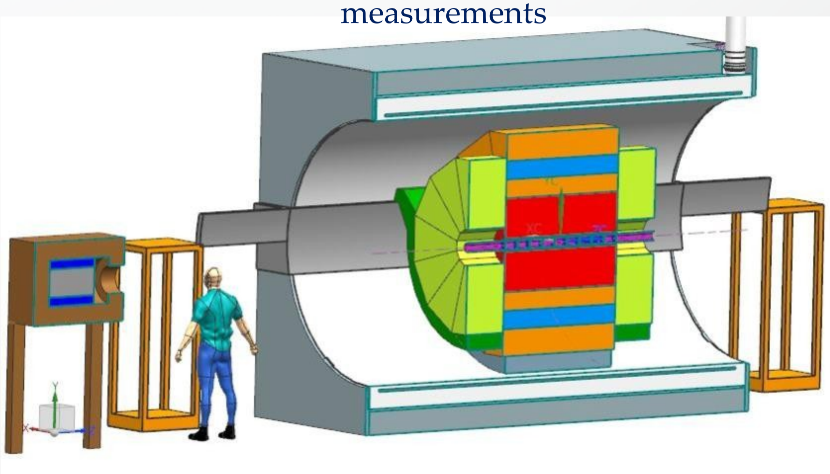
Optical-TPC

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)

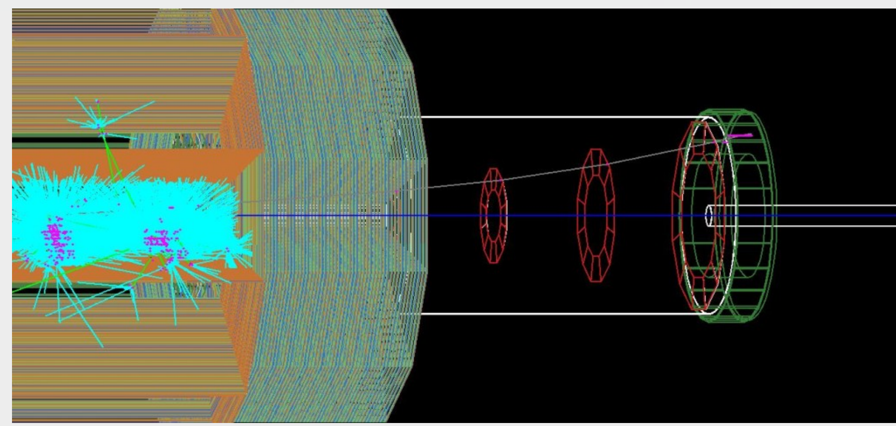
Sci and Cer light read by SiPM or SPAD

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

Acceleration Scheme for Run-I (M. Syphers)

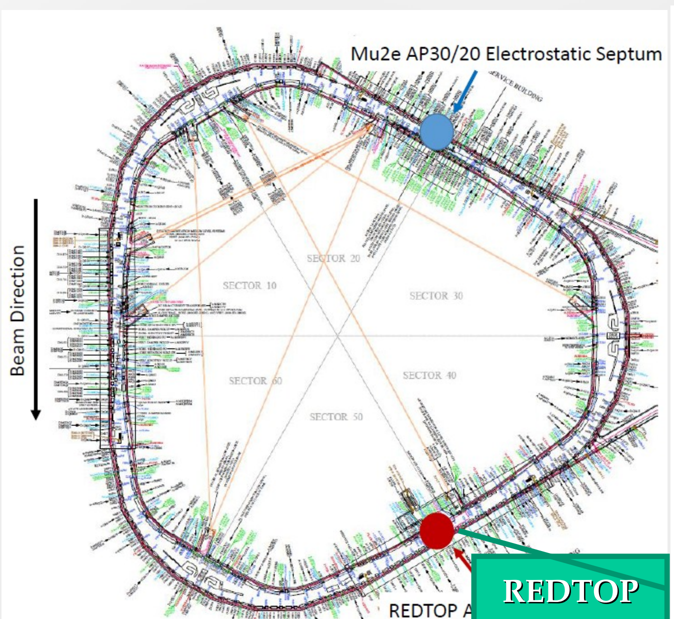
Single p pulse from booster ($\leq 4x10^{12}$ p) injected in the DR (former debuncher in anti-p production at Tevatron) at fixed energy (8 GeV)

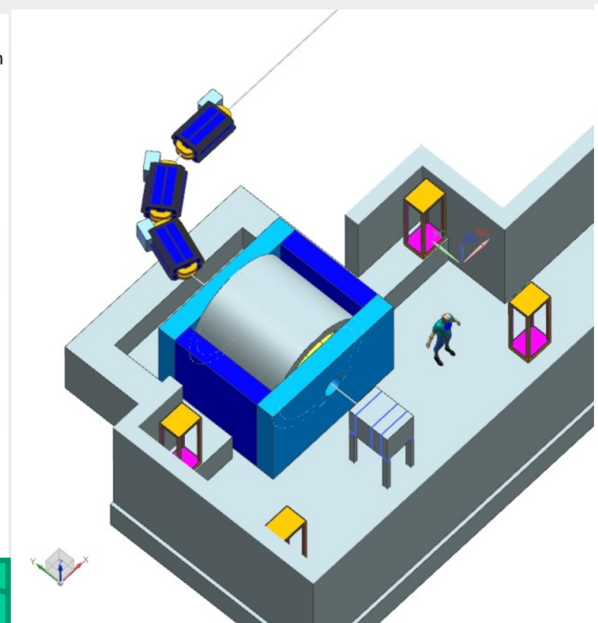
Energy is removed by adding 1-2 RF cavities identical to the one already planned (~5 seconds)

Slow extraction to REDTOP over ~40 seconds.

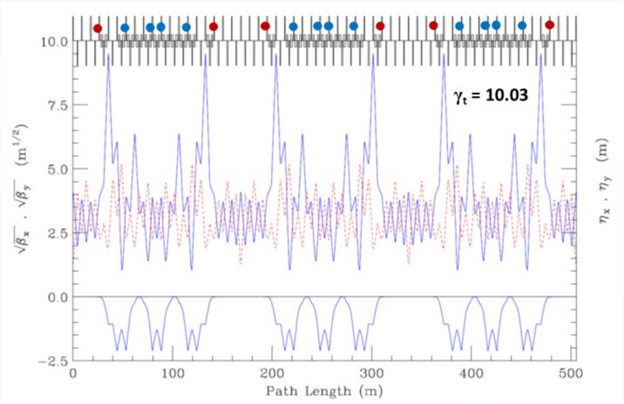
The 270^o of betatron phase advance between the Mu2e Electrostatic Septum and REDTOP Lambertson is ideal for AP50 extraction to the inside of the ring.

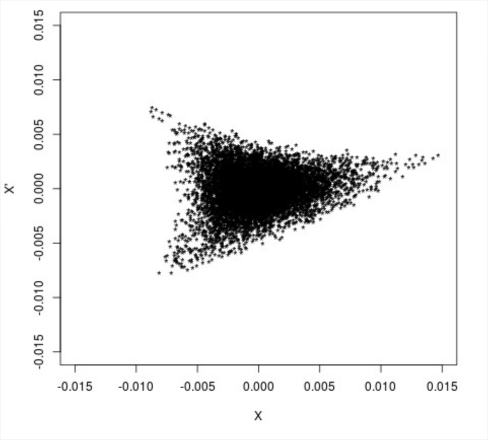
Total time to decelerate-debunch-extract: 51 sec: duty cycle ~80%





Accelerator Physics Issues



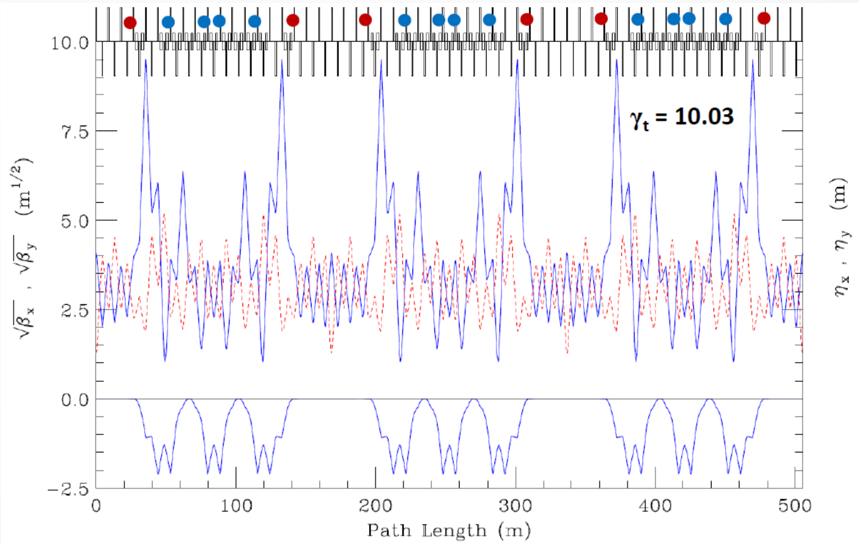


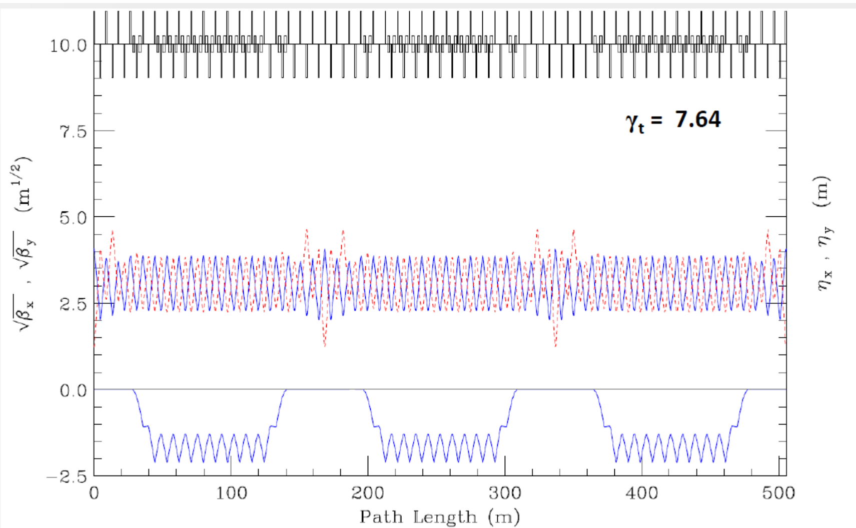
- ***Transition Energy***
  - γ_t is where $\Delta f/f = 1/\gamma 2$ - <D/ρ> = 0; synchrotron motion stops momentarily, can often lead to beam loss
  - beam decelerates from γ = 9.5 to γ = 3.1
  - original Delivery Ring γ_t = 7.6
  - a re-powering of 18 quadrupole magnets can create a γ_t = 10, thus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

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 $\gamma_t = 7.64$ and beam $\gamma = 7.14$ (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 γ_t, β_{max}, and the 15π 99% beam envelope through deceleration

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