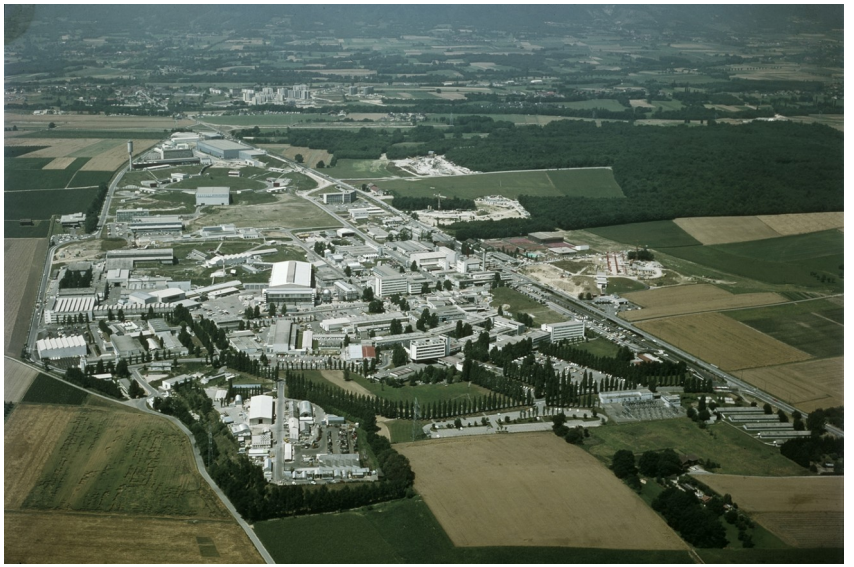
REDTOP

Rare Eta Decays with a TPC for Optical Photons



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Workshop on Physics Beyond Colliders

CERN, 16 jan. 2019

For the REDTOP Collaboration

Fermilab

INFN

REDTOP Key Points

- Yield of 8×10^{12} η mesons/year for 10^{17} POT (x-section >10 mbarns, 1.8 GeV proton beam)
  - Possibly ~8×10^{10} η' mesons/years in a second phase (3.5 GeV protons)
- 4π detector coverage (almost)
- 3 (5) “golden” channels (will be described in details in the proposal)
  - But at least ~20 interesting channels (simmetry violations, new particles and forces searches, precision measurements)
  - 4 benchmark channels are studied in details for the BPC (2 of them are golden)
- Innovative detector techniques
  - Dual readout calorimeter
  - Optical TPC
- Detector blind to protons and slow pions
- Significant improvement (10^6 in some cases) to the current limits.
- **`http://redtop.fnal.gov`**

Why the η ?

- Decays are flavor conserving
- Eigenstate of C, P, CP and G: $I^G J^{PC} = 0^+ 0^{-+}$
  - *can be used to test C and CP invariances*
- *Very narrow state (1.3 keV) – overconstraints events → low background*
- Strong decays forbidden in lowest order by C, P, CP, G, and Isospin invariance
- EM decays forbidden in lowest order by C and angular momentum conservation
  - *contributions from higher orders are enhanced by a factor of ~100,000*
  - *η decays with leptons in the final state have very small SM backgrounds*
  - *Internal loops and lepton pairs can probe new physics*
- **η is an excellent laboratory to search for physics Beyond Standard Model**

BSM Physics Program (η and η' factory)

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): $\eta \to \pi^o l^+ l^-$ **and** $\eta \to 3\gamma$*
- *Test of CP invariance via μ^+ longitudinal polarization: $\eta \to \mu^+ \mu^-$*
- *Test of CP invariance via γ^* polarization studies: $\eta \to \pi^+ \pi^- e^+ e^-$ and $\eta \to \pi^+ \pi^- \mu^+ \mu^-$*
- *Test of CP invariance in angular correlation studies: $\eta \to \mu^+ \mu^- e^+ e^-$*
- *Test of T invariance via μ transverse polarization: $\eta \to \pi^o \mu^+ \mu^-$ and $\eta \to \gamma \mu^+ \mu^-$*
- *CPT violation: μ polariz. in $\eta \to \pi^+ \mu^- \nu$ vs $\eta \to \pi \mu^+ \nu$ and γ polarization in $\eta \to \gamma\gamma$*

Other discrete symmetry violations

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

BSM Physics Program (η and η' factory)

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 $A' \to l^+l^-$*
- *Protophobic fifth force searches : $\eta \to \gamma X_{17}$ with $X_{17} \to e^+e^-$*
- *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: $\eta \to \gamma(\mu^+\mu^-)|_{2M_\mu} \to \gamma e^+e^-$*

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})*

BSM Physics Program (η and η' factory)

Non-η/η' based BSM Physics

- *Dark photon and ALP searches in Drell-Yan processes: qqbar → A'/a → **l⁺l⁻***
- *ALP's searches in Primakoff processes: p Z → p Z a → **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: $\pi^o \to \gamma A' \to \gamma e^+e^-$*

Non-BSM Physics Program (η and η' factory)

High precision studies on low energy physics

- *Nuclear models*
- *Chiral perturbation theory*
- *Non-perturbative QCD*
- *Isospin breaking due to the u-d quark mass difference*
- *Octet-singlet mixing angle*
- *ππ interactions*
- *Electromagnetic transition form-factors (important input for g-2)*
- *Lots of other bread&butter physics*

Beam and η yield

- Incident proton energy ~1.8 GeV (3.5 for η')
- Continuous beam, 10^{17} POT/yr
  - At Fermilab: ~10^{18} p/yr
- Target system: 10x0.5 mm Li or 10x0.33 mm Be spaced 10 cm apart
  - Low Z (primary hadrons multiplicity ~$A^{1/3}$)
- p-inelastic production: 2x10^{8} evts/sec
- Large beam spot size (~1 cm) with small divergence (<1^{0})
- Eta production: 8x10^{12} η/year
  - At Fermilab: 8x10^{13} η/year

Detection Techniques

Charged Tracks Detection

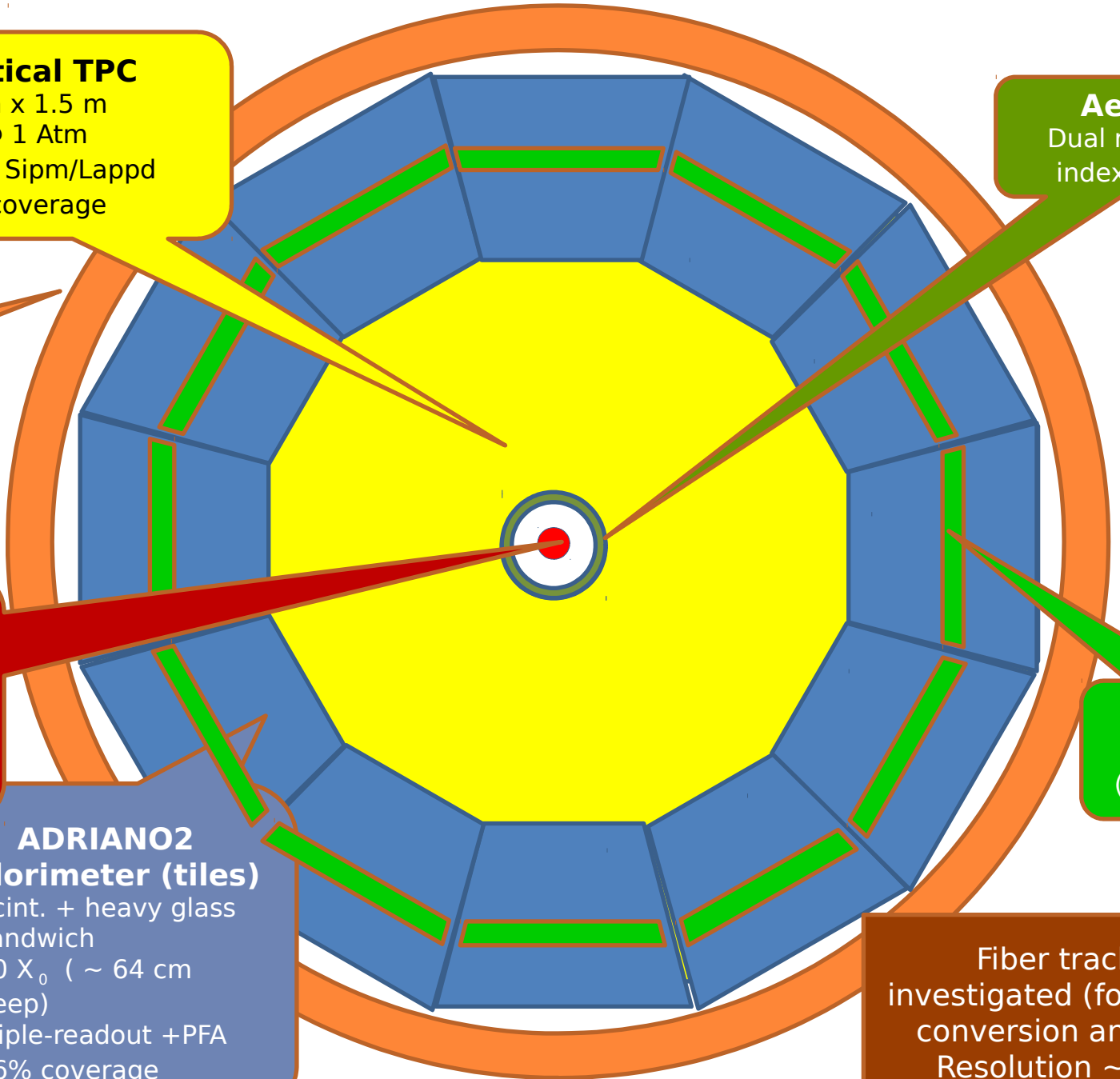
- Use Cherenkov effect in an Optical-TPC for tracking charged particles
- Baryons and most pions are below Cherenkov threshold
- Electrons and most muons are detected and reconstructed
- Fiber-tracker for vertexing and rejection of gamma conversion (being investigated)

Gamma Detection

- Use ADRIANO2 calorimeter for reconstructing EM showers
- Resolution <5%/sqrt(E)
- PID from dual-readout to disentangle showers from γ/μ/hadrons
- 96.5% coverage
- High granularity
- Good time resolution (<100 psec) for high rate DAQ

ADRIANO: **A** **D**ual-**R**eadout **I**ntegrally **A**ctive **N**on-segmented **O**ption

The REDTOP Detector



Optical TPC
- ~ 1m x 1.5 m
- CH_4 @ 1 Atm
- $5x10^5$ Sipm/Lappd
- 98% coverage

Aerogel
Dual refractive index system

Solenoid
0.6-0.8 T

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

μ-polarizer
Active version (from TREK exp.)

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

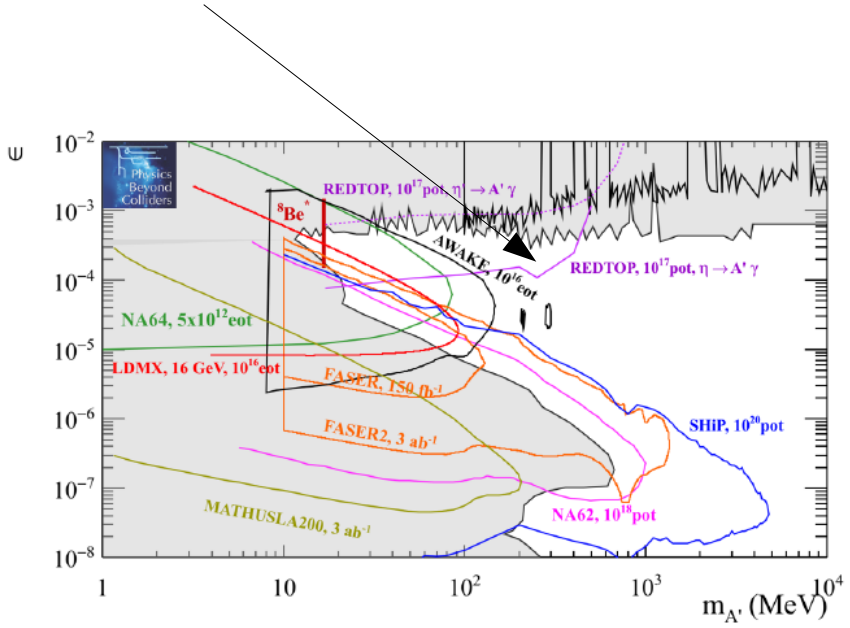
Fiber tracker being investigated (for rejection of γ-conversion and vertexing)
Resolution ~66μm/point

Simulation and PCB benchmarks

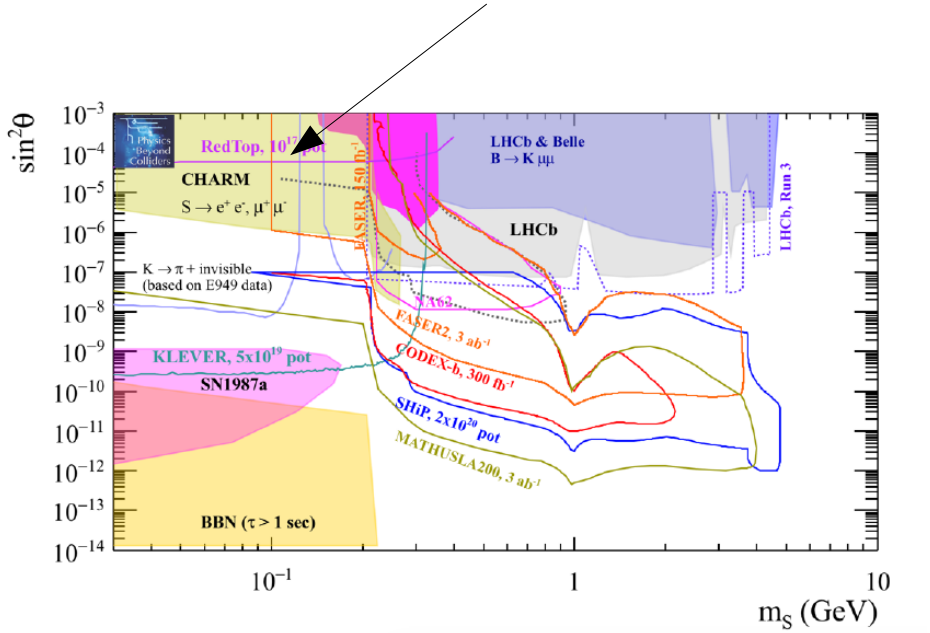
- Simulation tools ready (`slic`, `lcsim`, `ilcroot` frameworks)
  - Full simulation, including background and efficiencies
  - Only missing full reconstruction in the OTPC
- 10-15 years timescale and 10^{17} pot/year
- Ongoing simulations for PBC benchmarks (**Visible** final states)
  - Dark photons (BC 1) $\eta \rightarrow \gamma A' \rightarrow \ell^+\ell^-$
  - Dark scalars mixing with the Higgs (BC 4,5) $\eta \rightarrow \pi^0 H \rightarrow \ell^+\ell^-$
  - ALP coupled with fermions (BC 10)
  - ALP with Primakoff processes (BC 11) $pZ \rightarrow pZ\, a \rightarrow \ell^+\ell^-$

PCB benchmarks

(from PBC report, Cern 2018/007)



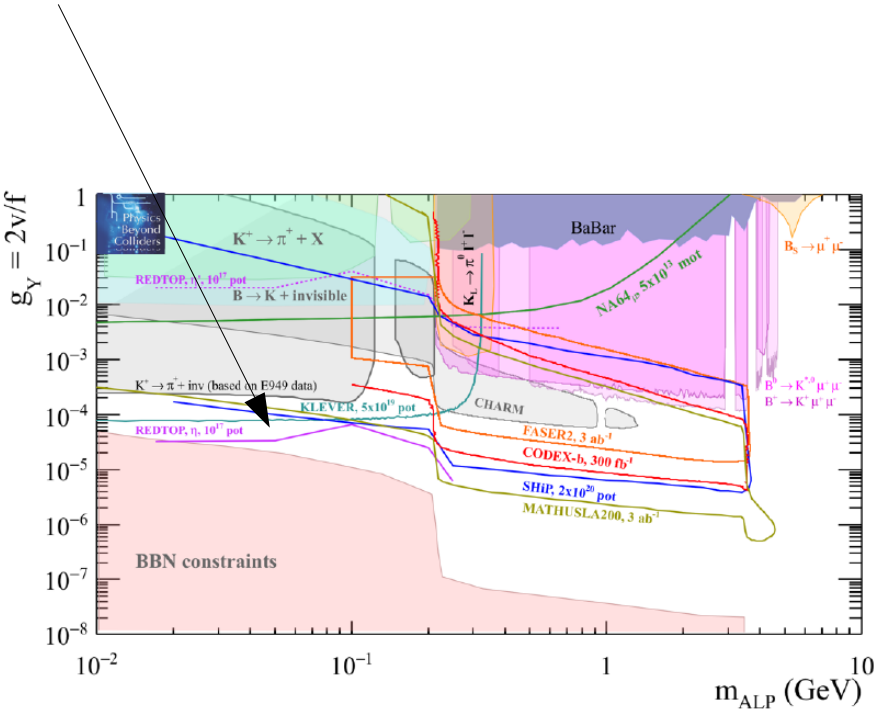
Dark photons



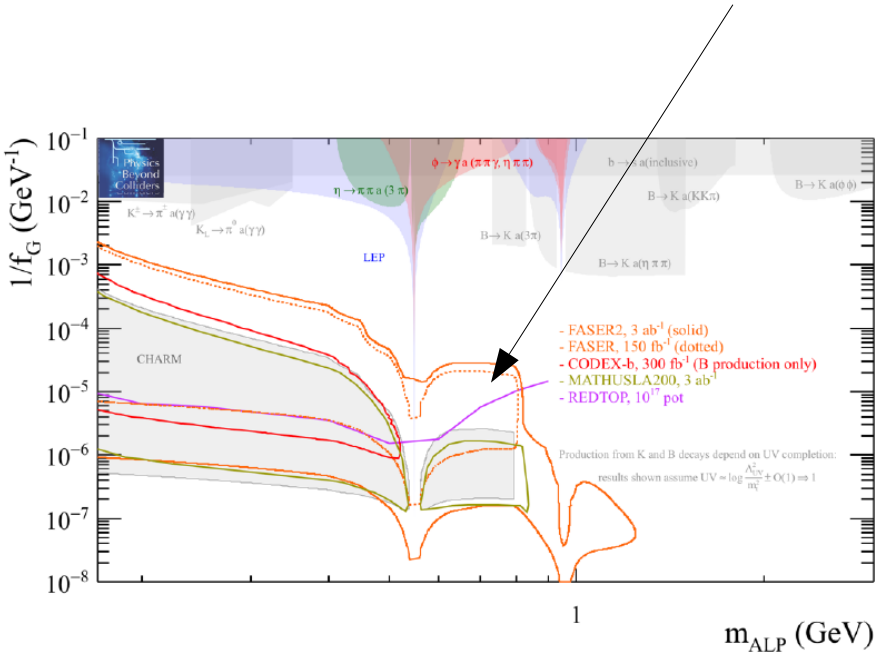
Dark scalar mixing with Higgs

PCB benchmarks

(from PBC report, Cern 2018/007)



ALP with fermion coupling



ALP with gluon coupling

Status and Plan

- Cost: ~ 50 M$
- Beam: under study (PS, 10^{17} p/yr)
- Detector
  - ADRIANO2 prototype funded by NIU, INFN
  - Fiber Tracker (LHCb like)
  - OTPC: not started
- Simulation:
  - In 2019, repeat the studies with secondary vertex reconstruction
  - (BSM particles have long lifetimes)
- Proposal to SPSC by ~ mid 2020 (after ESPP process)

Summary

- The η/η' meson is an excellent laboratory for studying rare processes
- Existing world samples not sufficient for studying decays violating conservations laws
- REDTOP goal is to produce ~10^{13} η mesons/year in phase I and ~ 10^{11} η'/year in phase II
- Very rich physics program, including "golden" processes:
  - CP violation via Dalitz plot mirror asymmetry
  - Dark photons
  - Scalar meson searches
  - Axion-like particles
- New generation, super-fast detector techniques
- An exciting phase of detector R&D ahead
- The collaboration is still forming
- Full proposal ~ mid 2020
- **`http://redtop.fnal.gov`**

Thank you!

Backup slides

$$\eta : \approx \frac{u\bar{u}+d\bar{d}-2s\bar{s}}{\sqrt{6}}$$

$$\eta' : \approx \frac{u\bar{u}+d\bar{d}+s\bar{s}}{\sqrt{3}}$$

η

$I^G(J^{PC}) = 0^+(0^{-+})$

Mass $m = 547.862 \pm 0.017$ MeV
Full width $\Gamma = 1.31 \pm 0.05$ keV

C-nonconserving decay parameters

$\pi^+\pi^-\pi^0$	left-right asymmetry	$= (0.09^{+0.11}_{-0.12}) \times 10^{-2}$
$\pi^+\pi^-\pi^0$	sextant asymmetry	$= (0.12^{+0.10}_{-0.11}) \times 10^{-2}$
$\pi^+\pi^-\pi^0$	quadrant asymmetry	$= (-0.09 \pm 0.09) \times 10^{-2}$
$\pi^+\pi^-\gamma$	left-right asymmetry	$= (0.9 \pm 0.4) \times 10^{-2}$
$\pi^+\pi^-\gamma$	β (D-wave)	$= -0.02 \pm 0.07$ (S = 1.3)

CP-nonconserving decay parameters

$\pi^+\pi^-e^+e^-$ decay-plane asymmetry $A_\phi = (-0.6 \pm 3.1) \times 10^{-2}$

Dalitz plot parameter

$\pi^0\pi^0\pi^0$ $\alpha = -0.0318 \pm 0.0015$

PARAMETER Λ IN $\eta \to \mu^+\mu^-\gamma$ DECAY $= 0.719 \pm 0.014$ GeV/c^2

η DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Neutral modes			
neutral modes	(72.12±0.34) %	S=1.2	–
2γ	(39.41±0.20) %	S=1.1	274
$3\pi^0$	(32.68±0.23) %	S=1.1	179
$\pi^0 2\gamma$	(2.56±0.22) $\times 10^{-4}$		257
$2\pi^0 2\gamma$	< 1.2 $\times 10^{-3}$	CL=90%	238
4γ	< 2.8 $\times 10^{-4}$	CL=90%	274
invisible	< 1.0 $\times 10^{-4}$	CL=90%	–
Charged modes			
charged modes	(28.10±0.34) %	S=1.2	–
$\pi^+\pi^-\pi^0$	(22.92±0.28) %	S=1.2	174
$\pi^+\pi^-\gamma$	(4.22±0.08) %	S=1.1	236
$e^+e^-\gamma$	(6.9 ±0.4) $\times 10^{-3}$	S=1.3	274
$\mu^+\mu^-\gamma$	(3.1 ±0.4) $\times 10^{-4}$		253
e^+e^-	< 2.3 $\times 10^{-6}$	CL=90%	274
$\mu^+\mu^-$	(5.8 ±0.8) $\times 10^{-6}$		253
$2e^+2e^-$	(2.40±0.22) $\times 10^{-5}$		274
$\pi^+\pi^-e^+e^-(\gamma)$	(2.68±0.11) $\times 10^{-4}$		235
$e^+e^-\mu^+\mu^-$	< 1.6 $\times 10^{-4}$	CL=90%	253
$2\mu^+2\mu^-$	< 3.6 $\times 10^{-4}$	CL=90%	161
$\mu^+\mu^-\pi^+\pi^-$	< 3.6 $\times 10^{-4}$	CL=90%	113
$\pi^+e^-\overline{\nu}_e$ + c.c.	< 1.7 $\times 10^{-4}$	CL=90%	256
$\pi^+\pi^-2\gamma$	< 2.1 $\times 10^{-3}$		236
$\pi^+\pi^-\pi^0\gamma$	< 5 $\times 10^{-4}$	CL=90%	174
$\pi^0\mu^+\mu^-\gamma$	< 3 $\times 10^{-6}$	CL=90%	210

Charge conjugation (C), Parity (P), Charge conjugation × Parity (CP), or Lepton Family number (LF) violating modes

$\pi^0\gamma$	C	<	9	$\times 10^{-5}$	CL=90%	257
$\pi^+\pi^-$	P,CP	<	1.3	$\times 10^{-5}$	CL=90%	236
$2\pi^0$	P,CP	<	3.5	$\times 10^{-4}$	CL=90%	238
$2\pi^0\gamma$	C	<	5	$\times 10^{-4}$	CL=90%	238
$3\pi^0\gamma$	C	<	6	$\times 10^{-5}$	CL=90%	179
3γ	C	<	1.6	$\times 10^{-5}$	CL=90%	274
$4\pi^0$	P,CP	<	6.9	$\times 10^{-7}$	CL=90%	40
$\pi^0e^+e^-$	C	[f] <	4	$\times 10^{-5}$	CL=90%	257
$\pi^0\mu^+\mu^-$	C	[f] <	5	$\times 10^{-6}$	CL=90%	210
$\mu^+e^- + \mu^-e^+$	LF	<	6	$\times 10^{-6}$	CL=90%	264

η Samples – Present and future

	Technique	Total η
CB @AGS	$\pi p \rightarrow \eta n$	10^7
CB @MAMI-B	$\gamma p \rightarrow \eta p$	2×10^7
CB @MAMI-C	$\gamma p \rightarrow \eta p$	6×10^7
KLOE @DAFNE	$e^+e^- \rightarrow \Phi \rightarrow \eta\gamma$	5×10^7
WASA @COSY	$pp \rightarrow \eta pp$ $pD \rightarrow \eta\ ^3He$	$>10^9$ (unt.) 3×10^7 (tagged)
CB @MAMI 10 wk *(proposed 2014)*	$\gamma p \rightarrow \eta p$	3×10^8
Phenix @RHIC	$d\,Au \rightarrow \eta X$	5×10^9
Hades @GSI	$pp \rightarrow \eta pp$ $p\,Au \rightarrow \eta X$	4.5×10^8
Near future samples:		
GlueX @JLAB *(just started)*	$\gamma p \rightarrow \eta p \rightarrow$ neutrals	4.5×10^7/year
JEF @JLAB *(recently approved)*	$\gamma p \rightarrow \eta X \rightarrow$ neutrals	3.9×10^5/day
REDTOP @FNAL *(proposing)*	**$p\,Be \rightarrow \eta X$**	**2.5×10^{13}/year**

REDTOP – Golden Channel I

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

- *J.Bijnens and K.Ghorbani, jhep11200730(2007), arXiv:0709.0230[hep-ph]; S.Gardner and J.Tandean, Phys. Rev. D69:034011, 2004, arXiv:hep-ph/0308228*
- It is an Isopin-violating decay
- EM contributions are known to be strongly suppressed
- It can occur via Strong Interactions due to the mass difference m_u-m_d
- Any mirror-asymmetry in the Dalitz plot is an indication of **CP and C** violation
- Good for testing the Chiral Perturbation Theory
- Current PDG limits consistent with no asymmetry
- Largest data samples: WASA 2014 (1.2×10^7), KLOE2 2016 (4.7×10^6)
- REDTOP expected sample: 10^9 analyzed events.

REDTOP – Golden Channel II

Dark photon searches:

$\eta \rightarrow \gamma A' \rightarrow \gamma + l^+ l^-$

- Motivations:
  - Possible cosmic ray excesses from dark matter annihilation
  - Structures anomalies in dwarf galaxies (*Pospelov and Ritz, 2008; Arkani-Hamed et al., 2008*)
  - The muon g-2 anomaly.
- Most accredited model has A' mass is the MeV-GeV range, coupling to to SM charged particles with a strength ~10^{-3}-10^{-4} of that of the photon
- REDTOP could complement the new experiments at JLAB and Frascati with γ and e^- beams.
- REDTOP can also make a clear statement on similar searches ($\gamma e^+ e^-$) of the proposed 17 MeV super-weak gauge boson (*S.Gardner at al., 2016, arXiv:1608.03591*) – [Golden channel IIa].
  - Below WASA sensitivity.

REDTOP – Golden Channel III

Search for light scalar mesons

$\eta \rightarrow \pi^0 H$; $H \rightarrow \mu^+\mu^-$ vs e^+e^-

- Potentially viable DM candidate, *Pospelov et al., Phys. Rev. D78, 115012, 2008.*
- Existence of this light scalar particle can significantly enhance this BR compared to the SM value (~10^{-9})
- REDTOP expected sensitivity is better than 10^{-10}
  - Current limits are ~10^{-5} – 10^{-6}
- Implications for the R_p anomaly. [Golden channel IIIa]
  - Conventional methods (levels of muonic atoms and elastic scattering experiments) find a discrepancy of about 7σ.

The REDTOP Detector

- **10x Be targets**
  - 0.33 mm thin
  - Spaced 10 cm
- **Optical TPC**
  - Measures momentum and trajectory of charged tracks
  - Cherenkov light is used
  - Tested at FNAL by T1059 (Frisch et al.) - successful proof of principle in 2015
  - First radiator: Aerogel, dual refractive index system
  - Low pressure N_2
  - ~1 mm x 1.5 m
  - ~10^5 SiPM
  - 98% coverage
- **Photon polarimeter** (optional)

The REDTOP Detector

- **ADRIANO Calorimeter**
  - PID and energy measurement (res. ~5%/sqrt(E))
  - Tested at FNAL by T1015
  - Use of Cherenkov light and Scintillation light (dual readout mode)
  - Scintillator + heavy glass sandwich
  - 20 X_0 (~64 cm deep)
  - 96% coverage
  - High granularity
  - Good time resolution (~100 psec) for high rate DAQ
- **Muon polarimeter**
  - From TREK exp.
  - Detect e^+e^- when a muon is stopped in the calorimeter to measure polarization
  - Array of plastic scintillators
- **Solenoid**
  - ~0.6-0.8 T

The REDTOP Detector

- Fiber tracker
  - Vertexing
  - Rejection of gamma conversion
- Trigger
  - Reduces the rate of events recorded to ~2x10^6 Hz
  - 3 level system
  - L0 (OTPC+ADRIANO-Ch): rejection factor 100
  - L1 (OTPC+ADRIANO for PID and γ-conversion rejection): rejection factor 100
  - L2 (reconstruction with CPUs): rejection factor ~200
- **Performances studies in progress**

Physics/Detector Issues

- Background
  - Rejection of multi-pion events
  - Mass resolution for di-leptons for bump hunting
  - η-tagging
- ADRIANO → ADRIANO2
  - Add tiles directly coupled to SiPM
- Sensors for O-TPC
  - Need to sustain >10^{11} n/cm^2
  - LAPPD as a possible choice
- Fiber tracker (LHCb style)
  - Radiation damage
- Trigger
  - Need to recognize Cherenkov rings at L1
  - L0/L1 from topological analysis of showers (PFA)
- Accelerator physics issues
- **R&D needed**

Trigger & DAQ

- Requirement:
  - $8 \times 10^{12}\ \eta$/yr → event rate ~2×10^{8} Hz
- Trigger task:
  - Reduce this rate to ~100 Hz for events recorded

Level	Algorithm	Detectors	Hardware	Rejection factor
L0	Σ OTPC && ADRIANO-Cher.	OTPC, ADRIANO	Fast sum	100
L1	Lepton pairs ID , γ conv. rejection	OTPC, ADRIANO, Fiber Tracker	FPGA	100
L2	Reconstruction	All	2000 CPU cores	~200

REDTOP Running Phases

(original plan)

- Intermediate phases (during detector R&D, OTPC only)
  - p ^{7}Li → ^{8}Be → $e^{+}e^{-}$ X
  - p ^{2}H → ^{3}He $e^{+}e^{-}$ (M.Viviani et al.)
  - Confirm 17 MeV bump in Hungary exp. (*J.Feng at al., arXiv:1604.07411; A.Krasznahorkay at al., Phys. Rev. Lett. 116, 042501, 2016*)
  - More possible beams (p/μ/e)
- Phase I: η factory
- Phase II: η' factory
- Phase III: Dark photons radiating from muons
- Phase IV: Muon Scattering Experiment (optional)
- Phase V: Tagged REDTOP (at PIP-II)
- Phase VI: Rare Kaon Decays: $K^{+} \rightarrow \pi^{+} \nu\nu$