REDTOP

Rare Eta Decays with a TPC for Optical Photons

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for the REDTOP Collaboration

Why the η ?

The η decays are flavor-conserving reactions	⇒	Decays are free of SM backgrounds for new physics search
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.	⇒	Its decays are not influenced by a change of flavor (as in K decays) and violations are "pure"
All its possible strong decays are forbidden in lowest order by P and CP invariance, G-parity conservation and isospin and charge symmetry invariance.	⇒	It is a very narrow state (Γ_η=1.3 KeV vs Γ_ρ=149 MeV)
EM decays are forbidden in lowest order by C invariance and angular momentum conservation	⇒	Contributions from higher orders are enhanced by a factor of ~100,000

η is an excellent laboratory to search for physics Beyond Standard Model

Current Samples

	Technique	$\eta \to 3\pi^0$	$\eta \to e^- e^+ \gamma$	Total η
CB@AGS	$\pi^- p \to \eta n$	9×10^5		10^7
CB@MAMI-B	$\gamma p \to \eta p$	1.8×10^6	5000	2×10^7
CB@MAMI-C	$\gamma p \to \eta p$	6×10^6		6×10^7
KLOE	$e^+ e^- \to \phi(1020) \to \eta\gamma$	6.5×10^5	????	5×10^7
WASA@COSY	$pp \to \eta pp$ $pd \to \eta\ ^3He$			$>10^9$ 3×10^7
CB@MAMI (proposed)	$\gamma p \to \eta p$	3×10^7	1.5×10^5	3×10^8

A truly high-statistics experiment like the proposed one can make significant impact on measuring rare SM processes and hunting for physics beyond the Standard Model

Summary of Physics Program

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: $\eta \to \mu^+\mu^-$
- Test of T invariance via μ transverse polarization: $\eta \to \pi^o\mu^+\mu^-$ and $\eta \to \gamma\mu^+\mu^-$
- Test of CP invariance via γ^* polarization studies: $\eta \to \pi^+\pi^-e^+e^-$ and $\eta \to \pi^+\pi^-\mu^+\mu^-$
- 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: $\eta \to \mu e$
- Double lepton Flavor Violation: $\eta \to \mu\mu ee$

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 $A' \to \ell^+\ell$ and $A' \to 2\gamma$
- New leptophobic baryonic force searches : $\eta \to \gamma B$ with $B \to e^+e^-$ or $B \to \gamma\pi^o$
- Protophobic fifth force searches : $\eta \to \gamma X_{17}$ with $X_{17} \to e^+e^-$
- Leptoquark searches: $\eta \to \mu^+\mu^-$ and $\eta \to e^+e^-$
- Search for true muonium: $\eta \to \gamma(\mu^+\mu^-)|_{2M_\mu} \to \gamma e^+e^-$

Summary of Physics Program

Other Precision Physics measurements

- *Proton radius anomaly:* $\eta \to \gamma \mu^+\mu^-$ *vs* $\eta \to \gamma e^+e^-$

Non-η/η' based BSM Physics

- *Dark photon and ALP searches in Drell-Yan processes:* $qq\bar{q} \to A'/a \to l^+l^-$
- *ALPS searches in Primakoff processes:* $p\,Z \to p\,Z\,a \to l^+l^-$
- *Charged pion and kaon decays:* $\pi^+ \to \mu^+\nu\,A' \to \mu^+\nu\,e^+e^-$ *and* $K^+ \to \mu^+\nu\,A' \to \mu^+\nu\,e^+e^-$
- *Neutral pion decay:* $\pi^o \to \gamma A' \to \gamma e^+e^-$

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

- *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*

Searches for Light Scalar Mesons

- $\eta \rightarrow \pi^0 H$; $H \rightarrow e^+ e^-$ vs $\mu^+ \mu^-$
- Potentially viable DM candidate - *Pospelov et al, PRD 78 115012 (2008)*
- Existence of this light scalar can significantly enhance this BR compared to the SM value (~ 10^{-9})
- REDTOP expected sensitivity to be better than 10^{-10}
- Implications for R_p anomaly

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

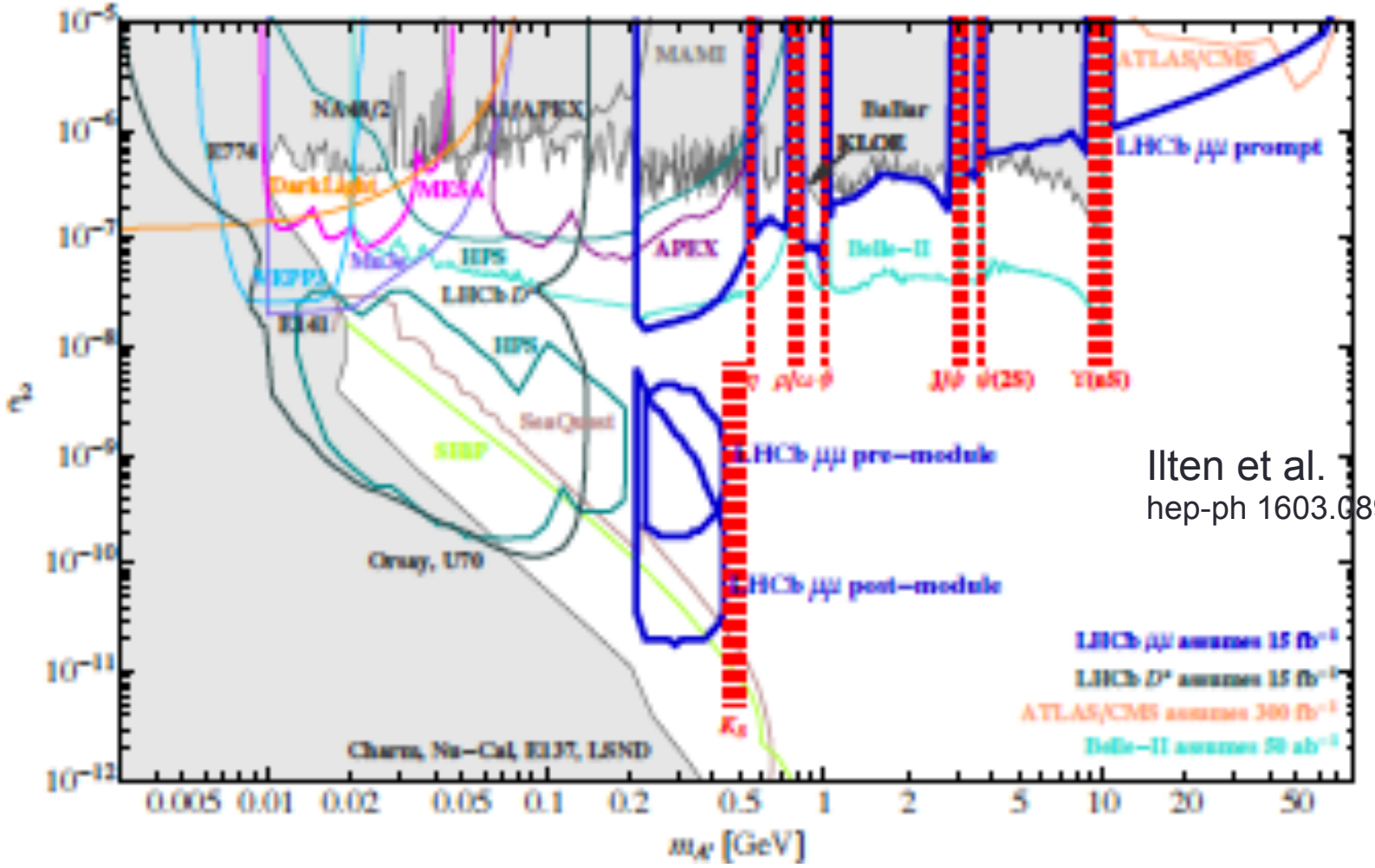
Γ_{24}	$\pi^0\gamma$	C		< 9	$\times 10^{-5}$	CL=90%
Γ_{25}	$\pi^+\pi^-$	P,CP		< 1.3	$\times 10^{-5}$	CL=90%
Γ_{26}	$2\pi^0$	P,CP		< 3.5	$\times 10^{-4}$	CL=90%
Γ_{27}	$2\pi^0\gamma$	C		< 5	$\times 10^{-4}$	CL=90%
Γ_{28}	$3\pi^0\gamma$	C		< 6	$\times 10^{-5}$	CL=90%
Γ_{29}	3γ	C		< 1.6	$\times 10^{-5}$	CL=90%
Γ_{30}	$4\pi^0$	P,CP		< 6.9	$\times 10^{-7}$	CL=90%
Γ_{31}	$\pi^0 e^+ e^-$	C	[a]	< 4	$\times 10^{-5}$	CL=90%
Γ_{32}	$\pi^0 \mu^+ \mu^-$	C	[a]	< 5	$\times 10^{-6}$	CL=90%
Γ_{33}	$\mu^+ e^- + \mu^- e^+$	LF		< 6	$\times 10^{-6}$	CL=90%

Dark Photon Searches

- $\eta \rightarrow \gamma A' \rightarrow 3\gamma$ or $\gamma + l^+ l^-$
- Motivations: possible cosmic ray excess, structure anomalies in dwarf galaxies and muon g-2 anomaly
- Popular model has A' mass in the MeV – GeV range coupling to SM charged particles with strength of ~ 10^{-3} – 10^{-4} of the photon
- REDTOP would complement the new experiments at JLAB and Frascati with γ and e^- beams
- Requires > 2 x 10^{11} η mesons

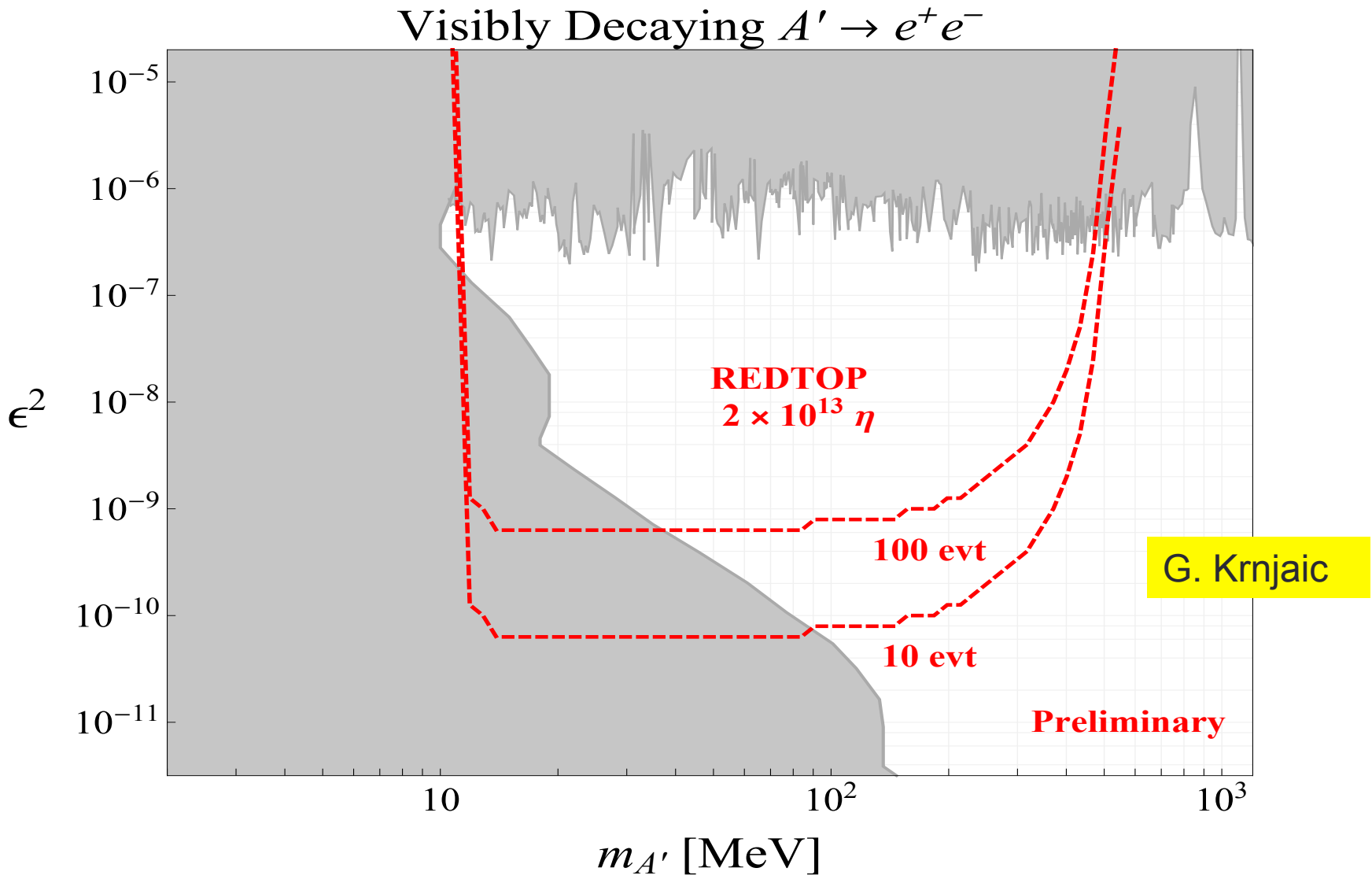
REDTOP can also make a clear statement on similar search ($\gamma e^+ e^-$) of the proposed 17 MeV super-weak gauge boson

Dark Photon Searches



Ilten et al.
hep-ph 1603.08926

Dark Photon Searches



REDTOP in a Nutshell

- Yield of 2 x 10^{13} η mesons per year (total inelatic x-section is 10 – 20 mbar in the 2 GeV beam energy region)
- Can also serve as a η' factory
- 4π (almost) detector which can be used with beams of different energies and particle species
- Proposes a detector blind to baryons and slow-moving pions along with excellent neutron ID by using O-TPC and homogeneous dual readout calorimetry
- Significant improvements (upto 6 orders of magnitude in some cases) to the current limits feasible

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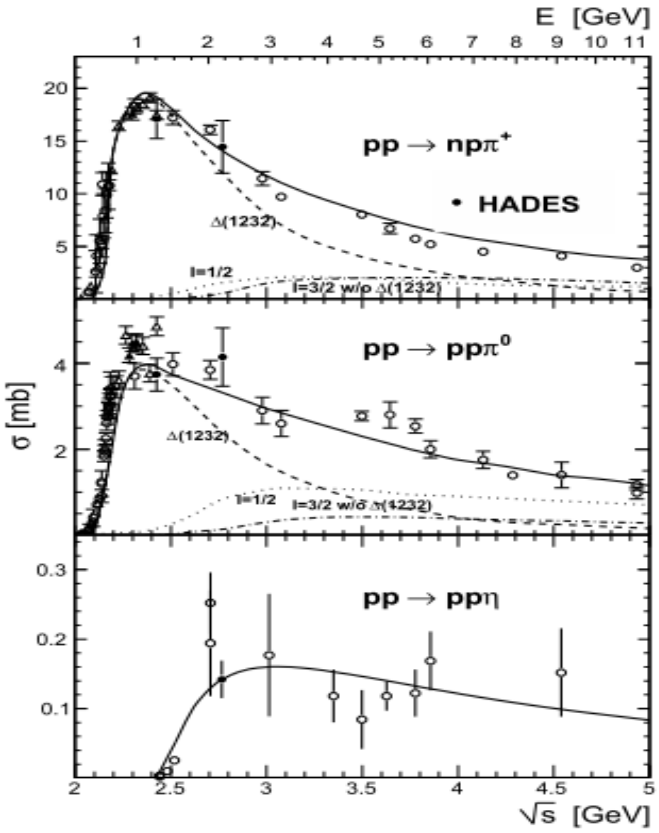
http://redtop.fnal.gov

Beam

- Incident proton energy of ~ 1.8 – 1.9 GeV
- Intensity > $1x10^{11}$ POT/sec
- Corresponds to beam power of ~ 30 W
- Impinges on a sparse target
  - 10 x 0.1 mm Nb or 10 x 0.33 mm Be spaced 10 cm apart
  - better vertex resol. w/ Nb but more primary hadrons
- Large beam spot (~1 cm) with small divergence (< 1°)
- Inelastic interaction every 100 nsec per target



Detection Techniques

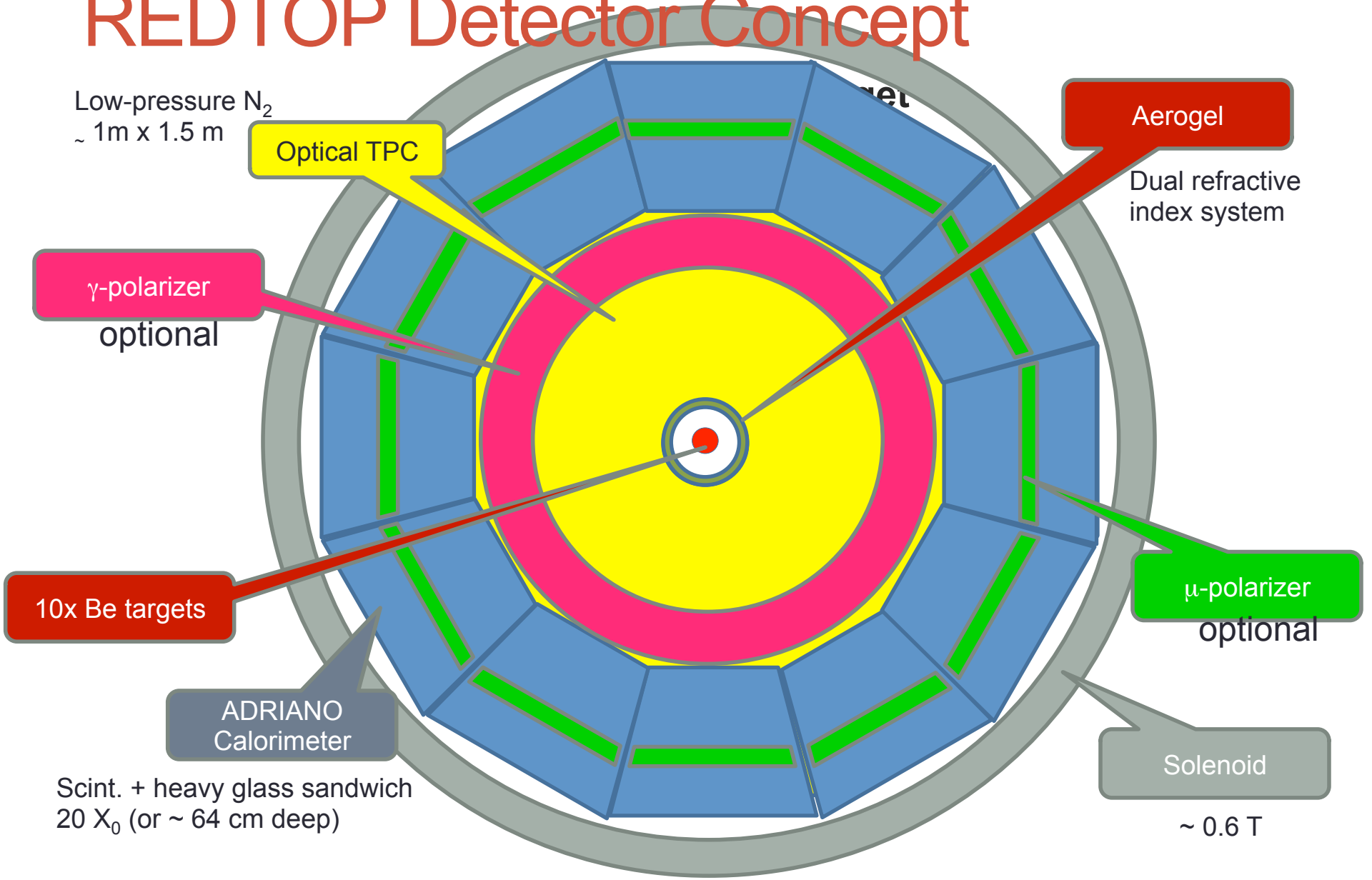
charged tracks detection

- *Use Cerenkov effect for tracking charged particles*
- *Baryons and most pions are below Č threshold*
- *Electrons and most muons are detected and reconstructed in an optical-TPC*

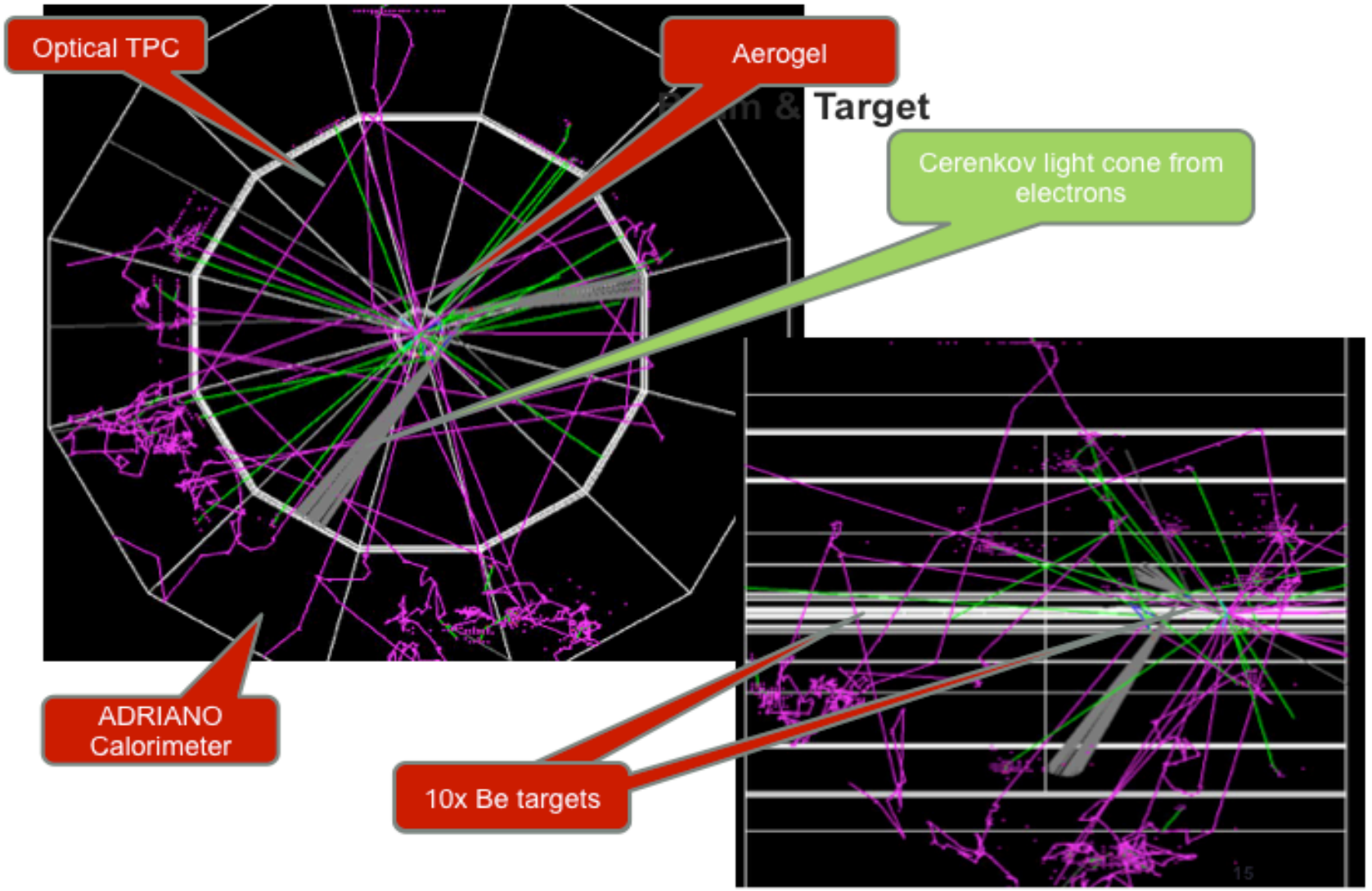
γ detection

- *Use ADRIANO calorimeter for reconstructing EM showers*
- *$\sigma_E/E < 5\%/\sqrt{E}$*
- *PID from dual-readout to disentangle showers from γ/μ/ hadrons*
- *96.5% coverage*

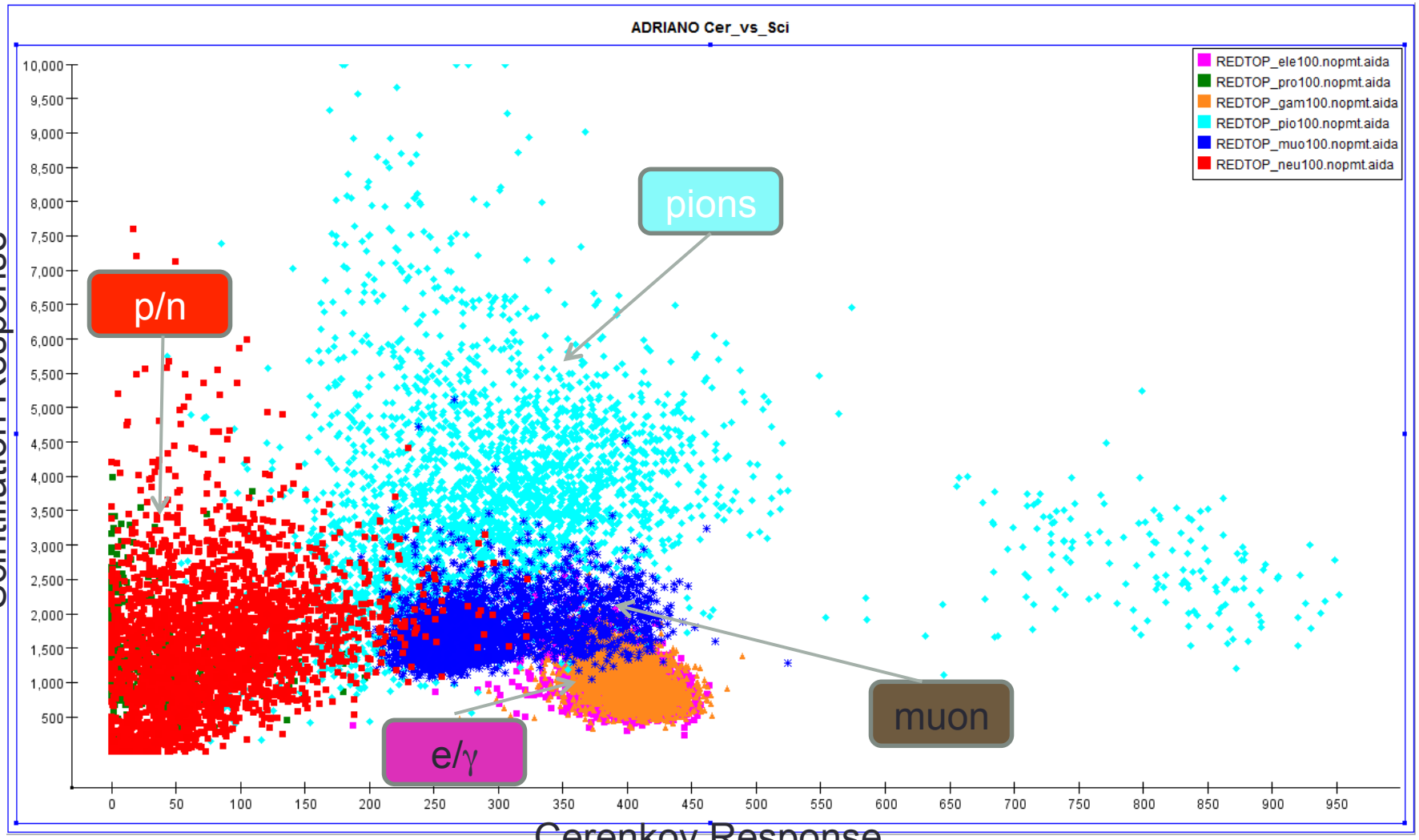
REDTOP Detector Concept



REDTOP Detector

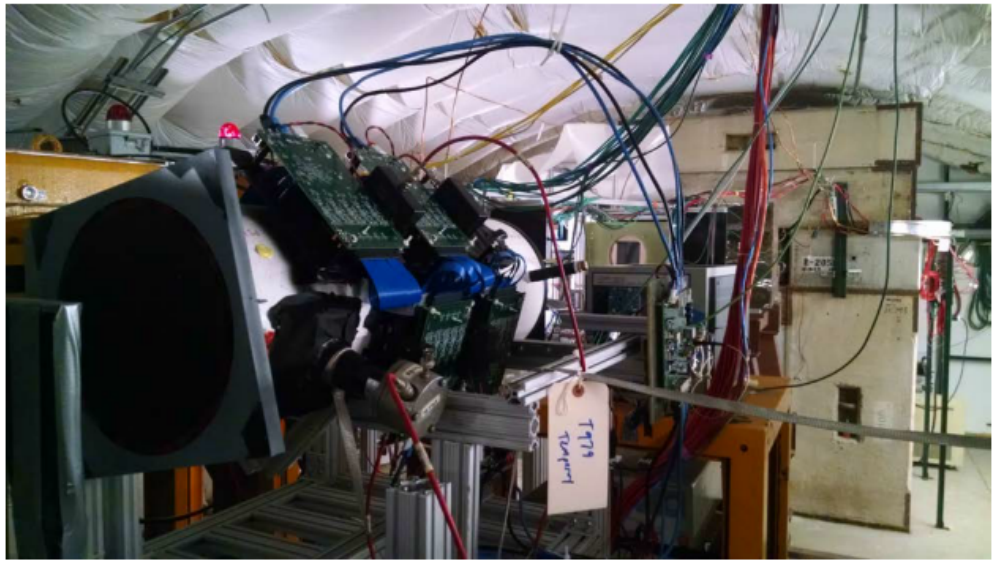


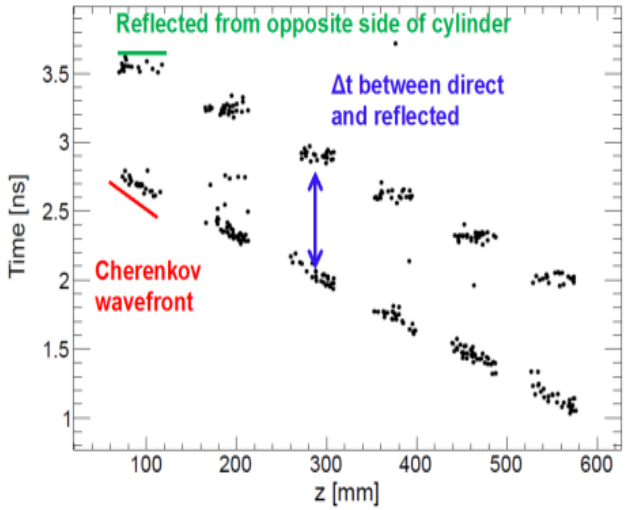
Dual-readout Calorimetry (ADRIANO)



Detector R&D (O-TPC)

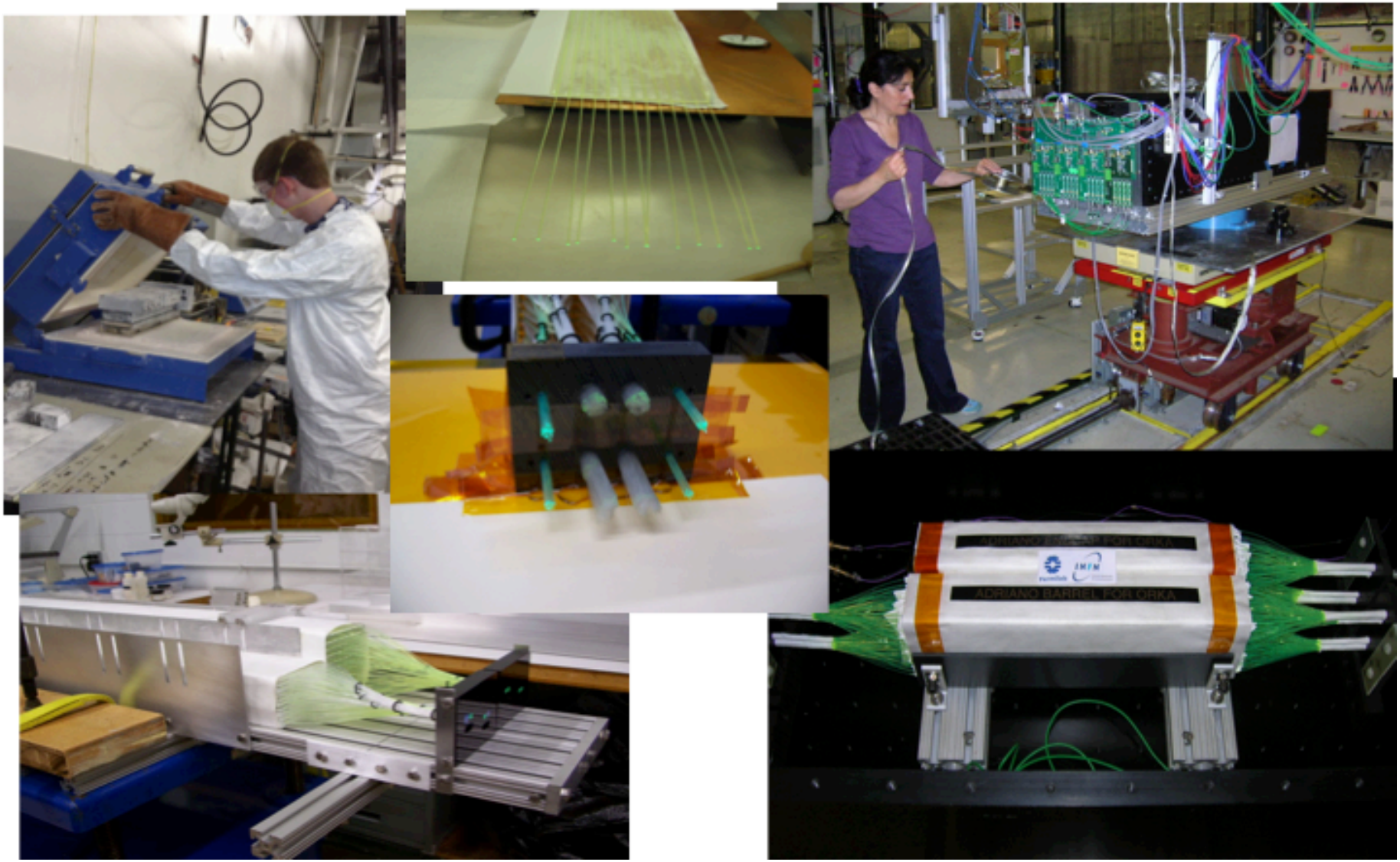
Successful proof-of-principle at FTBF in 2015 (Frisch et al.)
Prototype used Micro-channel plate photon detector readout with waveform digitizers
Possible photo-detector alternatives under considerations: SiPM
Substantial R&D still needed



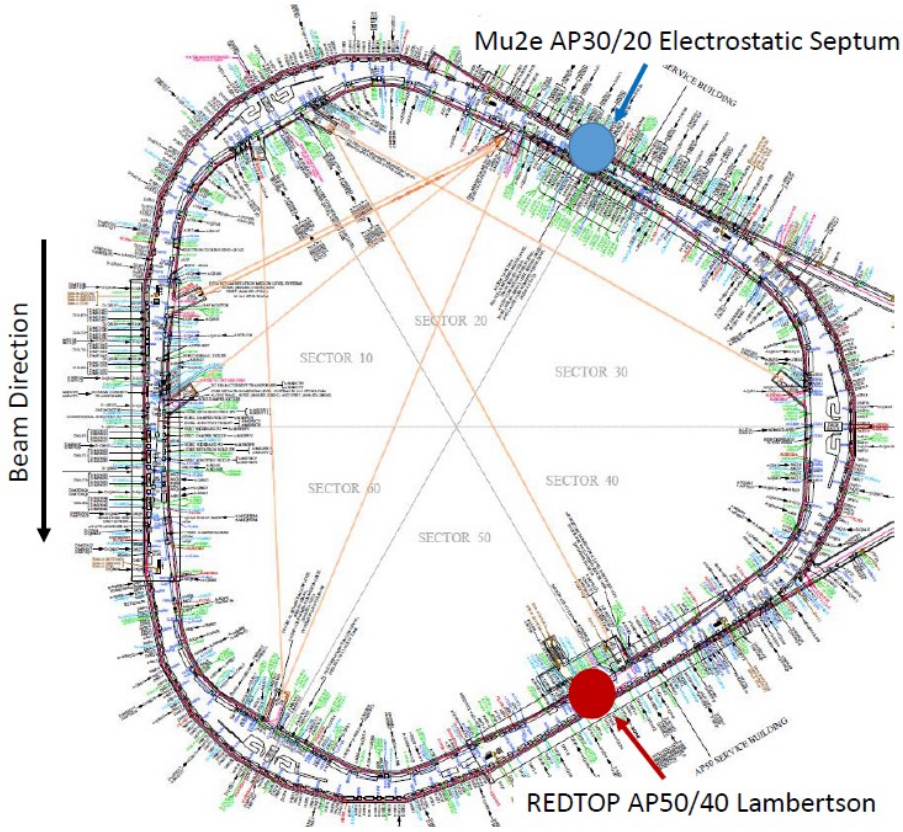


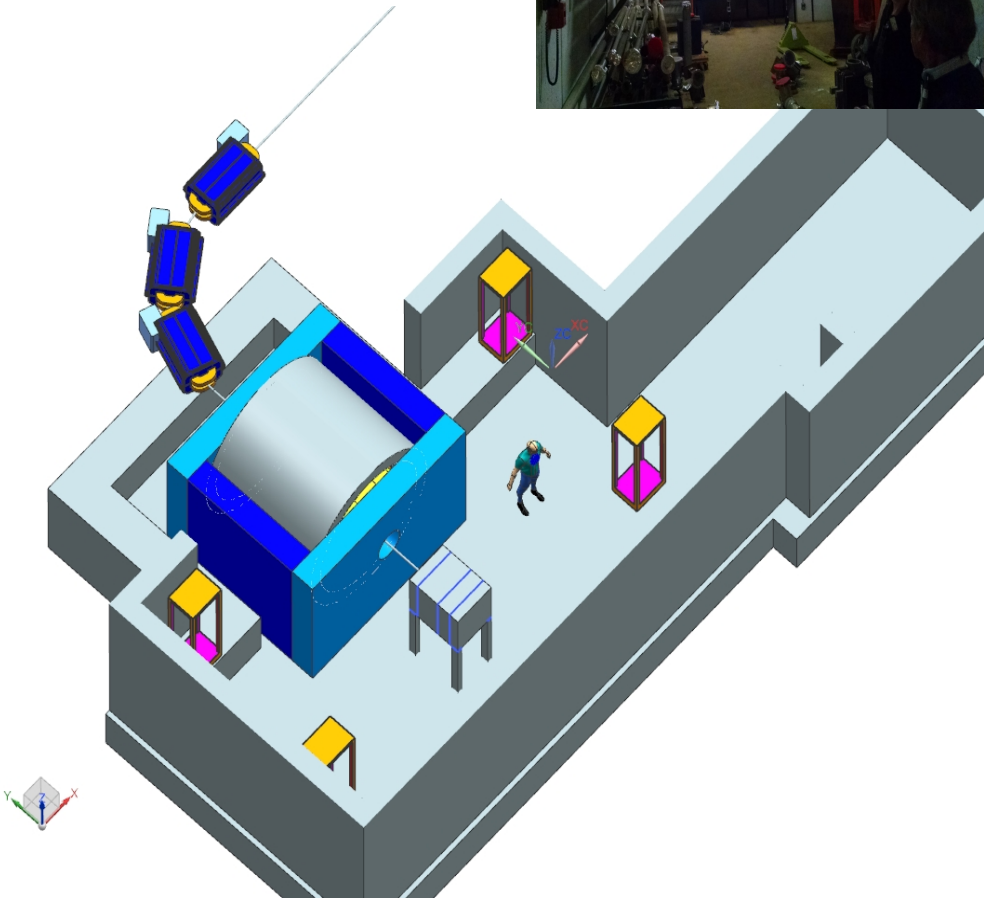
Measure position and momentum of charged track in a deflecting field albeit using Cerenkov radiation rather than ionization

Detector R&D (Calorimetry)



Experimental Hall @ Fermilab





Deacceleration of 8 GeV proton Booster beam followed by slow extraction

Strawman Schedule

- 2017 → Collaboration building and simulation studies
- Dec. 2017 – Jan. 2018 → proposal to Fermilab PAC
- 2018 – 2020 → Detector R&D
- 2021 → Detector construction and commissioning
- 2022 → Start of physics run

Summary

- The η (and η') meson promises to be a excellent laboratory for studying rare processes with potentially large sensitivity to physics beyond the Standard Model
- Given existing sample sizes, REDTOP which aims to produce $2x10^{13}$ η/year (~ $2x10^{11}$ η'/year) can make a significant impact
- Currently in the collaboration building phase, studying detector concepts and considering potential host laboratories
- An exciting phase of detector R&D ahead