THE REDTOP EXPERIMENT

***R**are **E**ta **D**ecays with a **T**PC for **O**ptical **P**hotons*

Erik Ramberg

For the REDTOP Collaboration

Eta meson is equal mixture of quark/antiquark – part of the Eightfold Way

η $\quad I^G(J^{PC}) = 0^+(0^{-+})$

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 $A_\phi = (-0.6 \pm 3.1) \times 10^{-2}$

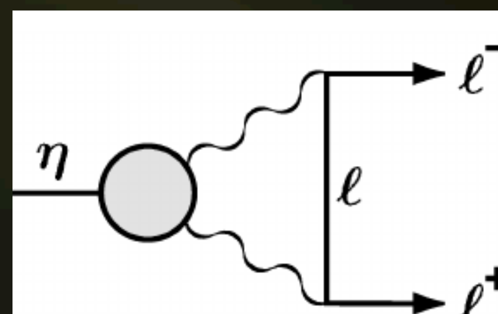
Dalitz plot parameter

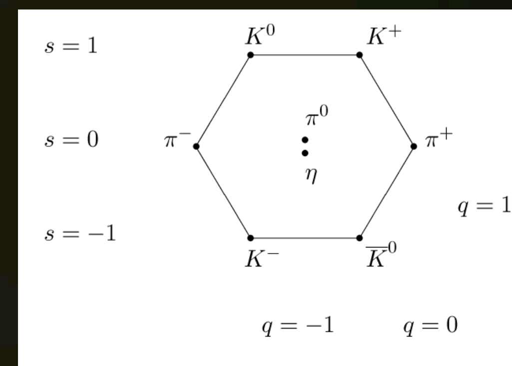
$\pi^0\pi^0\pi^0$ $\quad \alpha = -0.0318 \pm 0.0015$

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

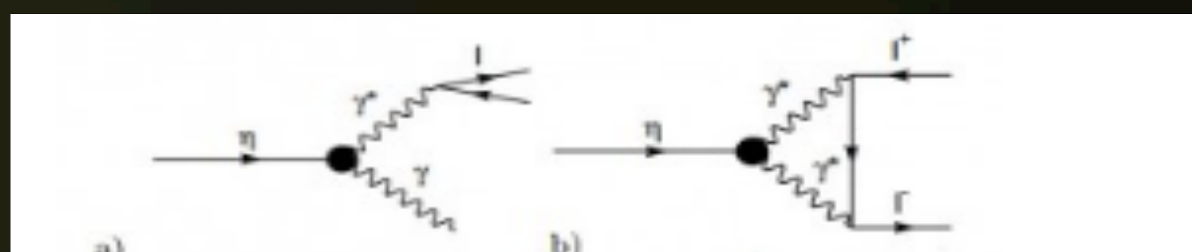
$$\eta' :\approx \frac{u\bar{u}+d\bar{d}+s\bar{s}}{\sqrt{3}}$$

Technically, these are the η_1 and η_8





Internal loops and lepton pairs can probe new physics at high mass scales



Why is the η meson special?

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)
All its possible strong decays are forbidden in lowest order by P and CP invariance, G-parity conservation and isospin and charge symmetry invariance.	It is a very narrow state (Γ_η=1.3 KeV vs Γ_ρ=149 MeV)
EM decays are forbidden in lowest order by C invariance and angular momentum conservation	Contributions from higher orders are enhanced by a factor of ~100,000 Excellent for testing invariances

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

Only modest limits on a wide variety of SM violating processes

"MAMI" = "Mainz Microtron"
"CB" = "Crystal Ball"
"WASA" = "Wide Angle Shower Apparatus "
"COSY" = Cooler Synchrotron in Julich

Table 1: Present and future η samples.

Experiment	Technique	Total η
CB at AGS	$\pi^- p \to \eta n$	10^7
CB at MAMI-B	$\gamma p \to \eta p$	2×10^7
CB at MAMI-C	$\gamma p \to \eta p$	6×10^7
KLOE	$e^+e^- \to \phi(1020) \to \eta\gamma$	5×10^7
WASA at COSY	$pp \to \eta pp,\, pd \to \eta\, ^3He$	$> 10^8,\, 3 \times 10^7$
GlueX at JLab (proposed)	$\gamma p \to \eta p \to neutrals$	$4.5 \times 10^7/yr$
REDTOP at FNAL (proposing)	$pp \to \eta pp,\, pn \to \eta pp$	2×10^{12}

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
$e^+e^-\gamma$	$(6.9 \pm 0.4) \times 10^{-3}$	S=1.3	274
$\mu^+\mu^-\gamma$	$(3.1 \pm 0.4) \times 10^{-4}$		253
e^+e^-	$< 2.3 \times 10^{-6}$	CL=90%	274
$\mu^+\mu^-$	$(5.8 \pm 0.8) \times 10^{-6}$		253
$2e^+2e^-$	$(2.40 \pm 0.22) \times 10^{-5}$		274
$\pi^+\pi^-e^+e^-(\gamma)$	$(2.68 \pm 0.11) \times 10^{-4}$		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

Some REDTOP Key Points

The experiment will yield 2×10^{12} η mesons/year. (Consequence of the relatively large proton production cross section (10-20) mbarn in the 2 GeV beam energy region)

Incorporates a detector blind to protons and slow charged pions, with excellent neutron rejection, using innovative technology (Optical Photon TPC and Homogenous Dual Readout Calorimetry)

The very small width (1.3 keV) overconstrains events, yielding low backgrounds.

Beyond Standard Model processes are enhanced compared to similar K and B decays because of symmetry state $0^{+}(0^{-+})$. No flavor changing neutral currents

Current limits can be improved in some cases by 6 orders of magnitude

REDTOP Collaboration (mid-2016)

- Arizona State University
- Budker Institute of Nuclear Physics Novosibirsk
- Fermi National Accelerator Laboratory
- Istituto Nazionale di Fisica Nucleare – Sezione di Napoli
- Istituto Nazionale di Fisica Nucleare - Sezione di Ferrara
- Universidad Autonoma de Zacatecas
- Northern Illinois University
- Perimeter Institute for Theoretical Physics – Waterloo
- Benementia Universidad Autonoma de Puebla
- University of Kentucky
- University of Minnesota
- Universita di Modena e Reggio Emilia
- Universita di Salerno

Two examples of REDTOP Physics

CP Violation :

Dalitz plot mirror asymmetry in

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

- *Any mirror-asymmetry in the Dalitz plot is an indication of* ***CP and C*** *violation.*
  - S. Gardner and J. Tandean, Phys.Rev.D69:034011,2004 for B meson Dalitz analysis
- *Such asymmetry does not arise from SM operators at tree level, nor can the operators that generate EDMs contribute to it (at tree level).*
- *Consequently, the violation of discrete symmetry resulting from studying this process is not bounded by EDM as is the case for the* $\eta \rightarrow 4\pi$ *process.*
- *Furthermore, this measurement is 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*
- *Expected background not calculated yet*
- *2-masses constrained decay*
- *Current PDG limits consistent with no asymmetry*

REDTOP Physics Program (cont.)

Searches for light pseudoscalar or scalar mesons :

$$\eta \rightarrow \pi^o X \quad ; X \rightarrow \mu^+ \mu^- \; vs \quad e^+ e^-$$

- *M. Pospelov, A. Ritz and M. Voloshin, Phys. Rev. D 78, 115012 (2008)*
  - *- Superweak particle as an ultralite dark matter candidate*
- *Occur in the SM via a two-photon exchange diagram. Branching ratio on the order of 10^{-9}.*
- *REDTOP's expected sensitivity is better than 10^{-10}*
- *A precision measurement of the BR, along with unitarity constraints and with the measurements from $\eta \rightarrow \pi^o \gamma \gamma$ will reveal if there is any "abnormality" in the two photon channel.*
- *Postulated scalar meson H could solve the 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%

Summary of Physics Program

Golden processes

- *CP Violation via Dalitz plot mirror asymmetry:* $\eta \rightarrow \pi^o \pi^+\pi^-$
- *New baryonic force searches (charged channel):* $\eta \rightarrow \gamma X$ *with* $X \rightarrow e^+e^-$
- *Scalar meson searches (charged channel):* $\eta \rightarrow \pi^o H$ *with* $H \rightarrow e^+e^-$ *and* $H \rightarrow \mu^+\mu^-$

Complementary processes

- *Lepton Flavor Violation:* $\eta \rightarrow \mu e$
- *Double lepton Flavor Violation:* $\eta \rightarrow \mu\mu ee$
- *CP Violation (Type II):* $\eta \rightarrow \pi^o \ell^+\ell^-$
- *Dark photon searches (charged channel):* $\eta \rightarrow \gamma A' \; \gamma + \ell^+\ell^-$
- *Test of T invariance:* $\eta \rightarrow \mu^+\mu^-$; $\eta \rightarrow \pi^o\mu^+\mu^-$ *and* $\eta \rightarrow \gamma\mu^+\mu^-$
- *CP Violation (Type I):* $\eta \text{->} 4\pi \rightarrow 8\gamma$ *or* $4\gamma \; \pi^+\pi^-$ *or* $\pi^+\pi^-\pi^+\pi^-$
- *Dark photon searches (neutral channel):* $\eta \rightarrow \gamma A' \rightarrow 3\gamma$
- *New baryonic force searches (neutral channel):* $\eta \rightarrow \gamma B$ *with* $B \rightarrow \gamma\gamma\pi^o$
- *Leptoquark searches:* $\eta \rightarrow \mu^+\mu^-$ *and* $\eta \rightarrow e^+e^-$
- *Search for true muonium:* $\eta \rightarrow \gamma(\mu^+\mu^-)|_{2M_\mu} \rightarrow \gamma e^+e^-$
- *CPT violation:* μ *polarization in* $\eta \rightarrow \pi^+\mu^-\nu$ *vs* $\eta \rightarrow \pi^-\mu^+\nu$ *and* γ *polarization in* $\eta \rightarrow \gamma\gamma$
- *High precision studies on physics beyond the Standard Model - Low energy* η *physics*

How will we produce enough η's?
How will we detect these rare decays?

Beam Requirements for η-factory

- *η production: > 2×10^{12} η /yr*
- *Incident proton beam energy of ~1.8 GeV (broad maximum around this value)*
- *Intensity: >$1x10^{11}$ POT/sec – CW*
- *Beam power @ 1.9 GeV: 10^{11} p/sec × 1.9 GeV × 1.6 × 10^{-10} J/GeV = 30 W*
- *Target: 10 x 0.1mm Nb or 10 x 0.33mm Be foils, spaced 10 cm apart*
  - *Nb is thinner (better vertex resolution) but makes more primary hadrons (final state hadron multiplicity ≈ $A^{1/3}$)*
- *Time between inelastic p interaction in one target: ~100 nsec*
- *Keep down primary multiplicity of hadrons (from p scattering onto the target)*
- *Large beam spot size (~ 1 cm), small divergence (< 1^o at first target) but minimal halo*
- *Power dissipated from target: 150 mW total : 15 mW per target foil*

Detection Techniques–based on Cerenkov

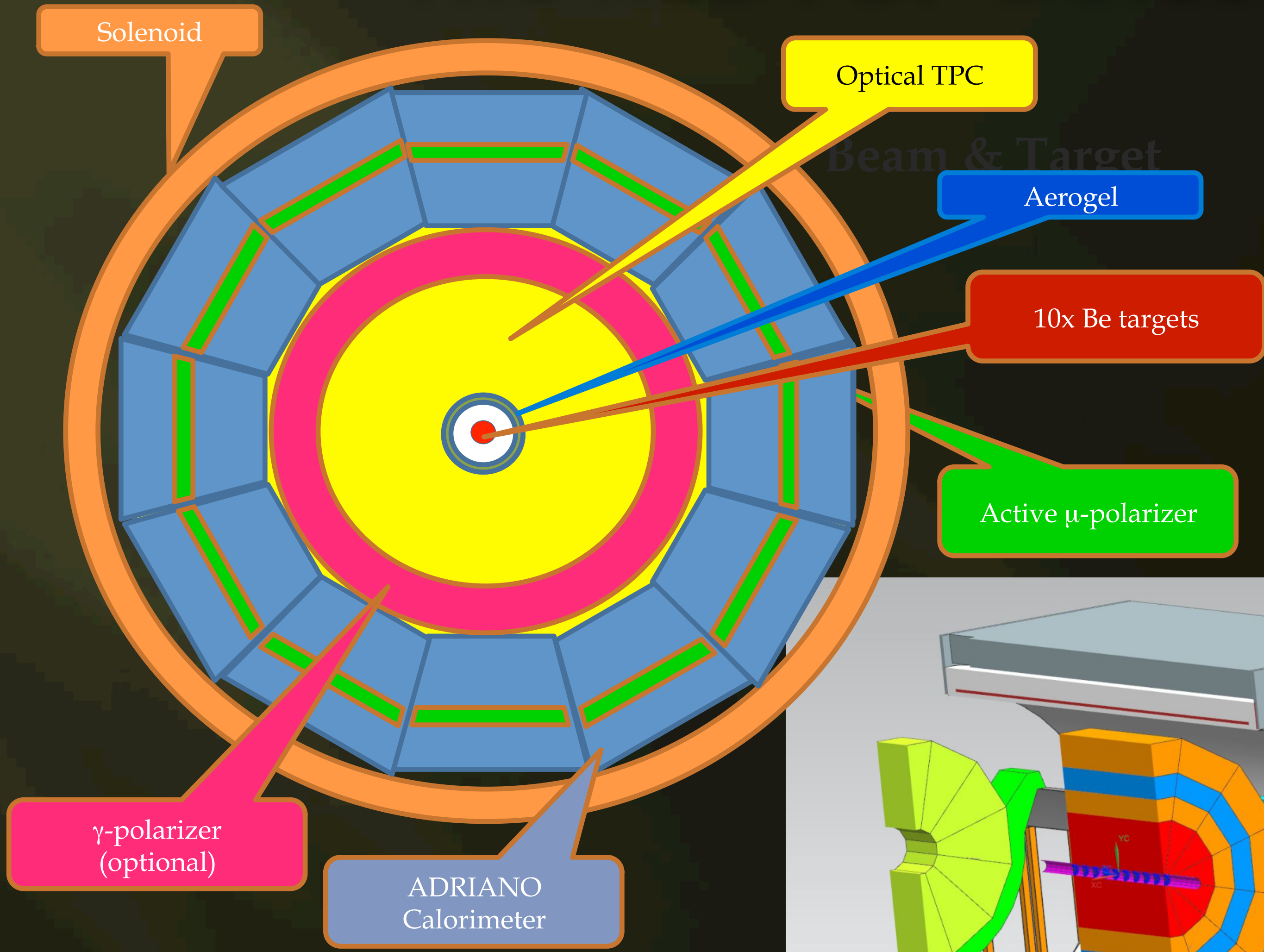
charged tracks detection

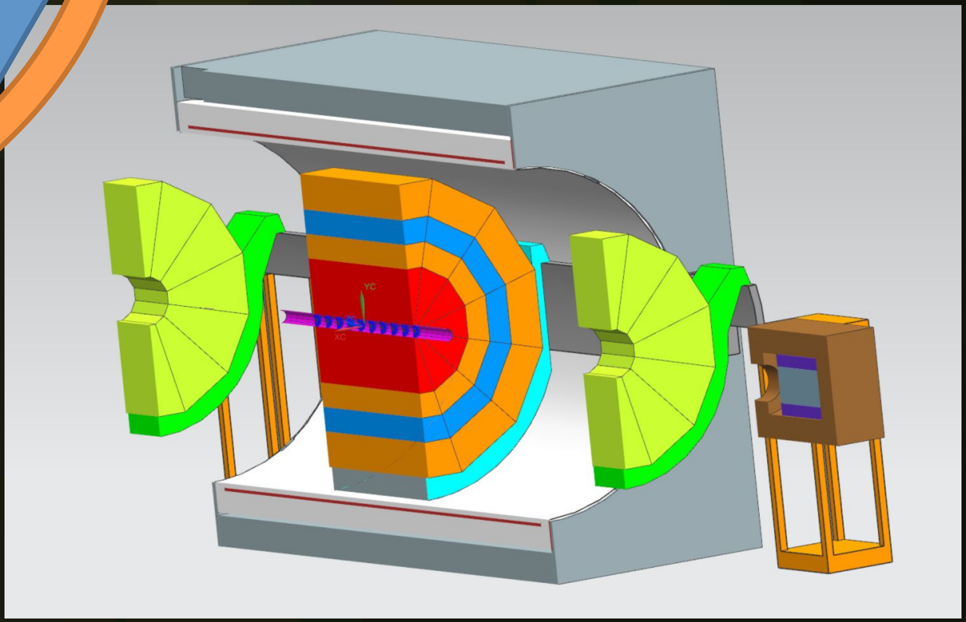
- *Use Cerenkov detectors for tracking charged particles*
- *Baryons and most pions are below Č threshold*
- *Electrons and most muons are detected and reconstructed in an optical-TPC*
- *Very fast timing (<50 psec) required*

γ detection

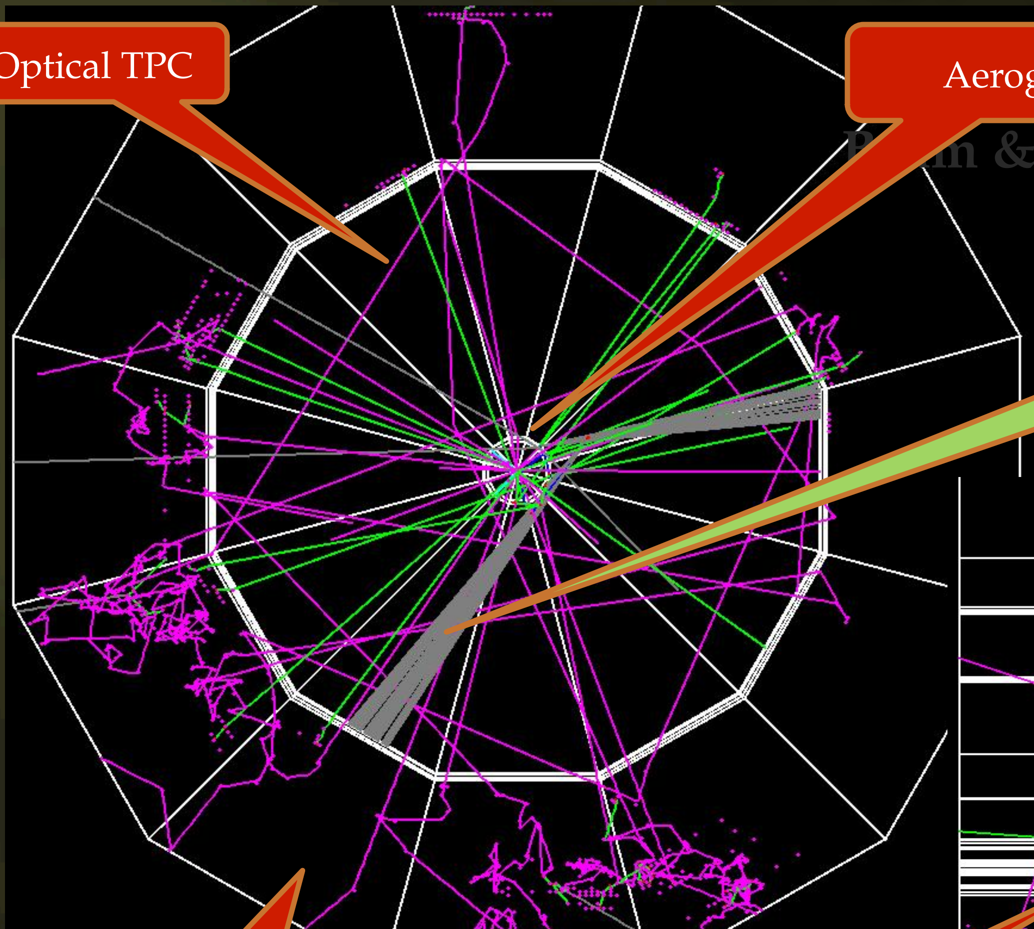
- *Use dual readout calorimeter (Ckov and Scint) for reconstructing showers and disentangling them from γ/μ/hadrons*
- *Fast timing enhances particle i.d. through TOF measurement*
- $\sigma_E/E < 5\%/\sqrt{E}$
- *PID from dual-readout techniques to disentangle showers from γ/μ/hadrons*
- *>95% coverage*

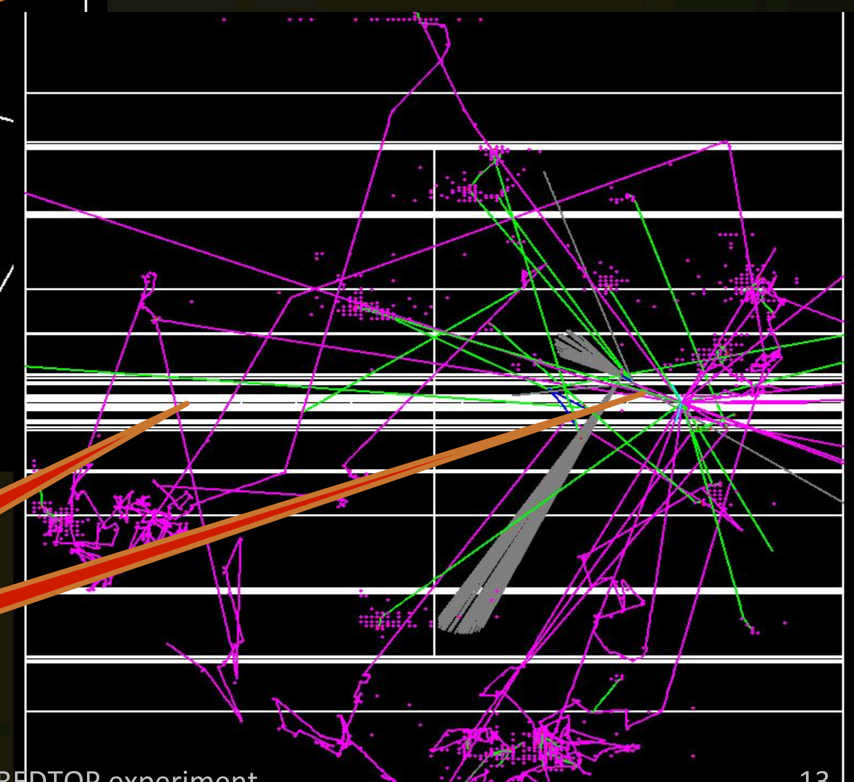
The REDTOP Detector





The REDTOP Detector



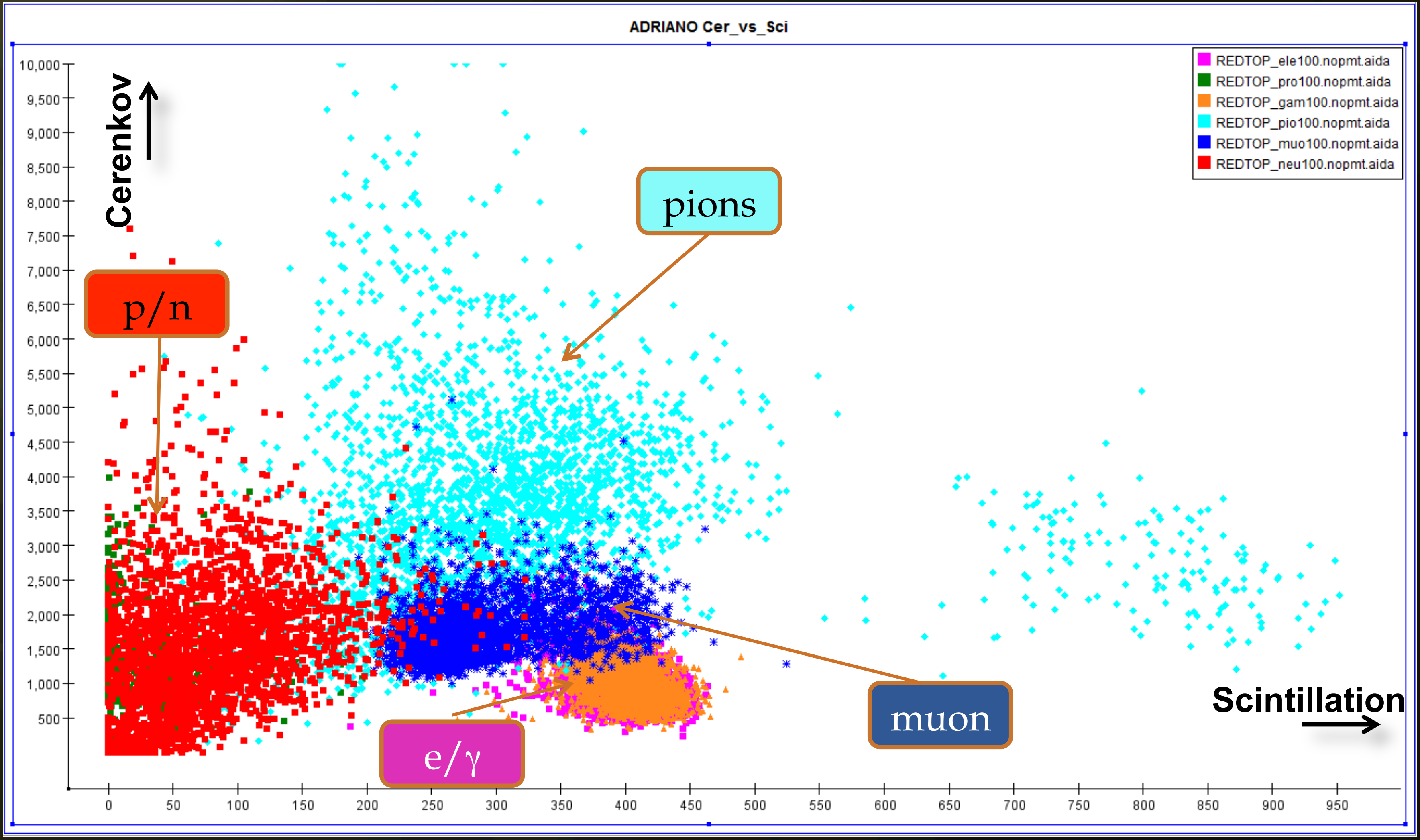


REDTOP Simulation Status

- Several samples of background with multiple detector configurations (target material, LAPPD thickness, etc.)
- Largest sample: 10^5 events with Urqmd and Incl++ with Be targets and 1mm LAPPD quartz window
- Simulated signal channels:
  1. $p\ Be \rightarrow \eta \rightarrow 4\pi^o$
  2. $p\ Be \rightarrow \eta \rightarrow e\ \mu$
  3. $p\ Be \rightarrow \eta \rightarrow A'\gamma \rightarrow e^+e^-\gamma$
  4. $p\ Be \rightarrow \eta \rightarrow A'\gamma \rightarrow \gamma\ \gamma\ \gamma$
  5. $p\ Be \rightarrow \eta \rightarrow e^+e^-\pi^o$
  6. $p\ Be \rightarrow \eta \rightarrow \mu^+\mu^-\pi^o$

- More channels will need to be studied (waiting for more collaborators):
  1. $p\ Be \rightarrow \eta \rightarrow 2\pi^o\pi^+\pi^-$
  2. $p\ Be \rightarrow \eta \rightarrow B\ \gamma \rightarrow \gamma\ \gamma\ \gamma$
  3. $p\ Be \rightarrow \eta \rightarrow B\ \gamma \rightarrow \gamma\ \gamma\ \pi^o$
  4. $p\ Be \rightarrow \eta \rightarrow B\ \gamma \rightarrow \gamma\ \gamma\ e^+e^-$
  5. $p\ Be \rightarrow \eta \rightarrow e^+e^-$
  6. $p\ Be \rightarrow \eta \rightarrow \mu^+\mu^-$
  7. $p\ Be \rightarrow \eta \rightarrow \mu^+\mu^-\ \gamma$
  8. $p\ Be \rightarrow \eta \rightarrow \mu^+\mu^-\ \gamma\ \pi^o$
  9. *Bread&butter physics*
  10. ?

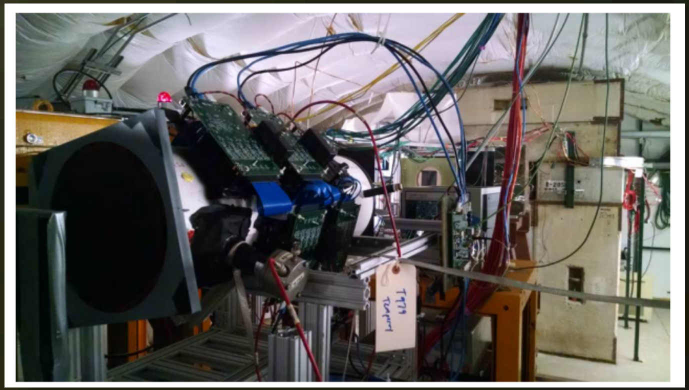
ADRIANO Calorimeter Particle ID @ 100MeV

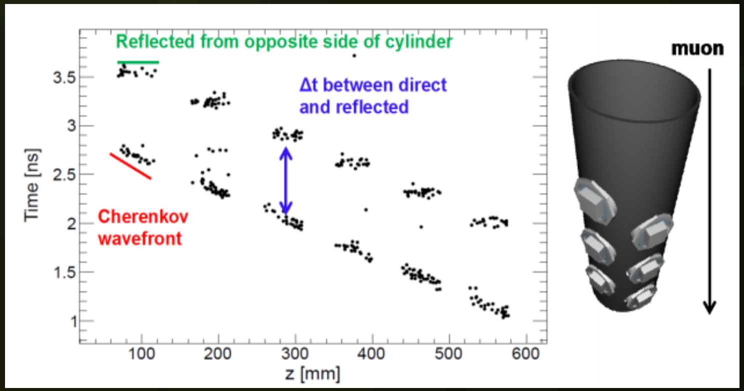


Detector R&D: OTPC

FNAL –T1059 (H. Frisch, E. Oberla)

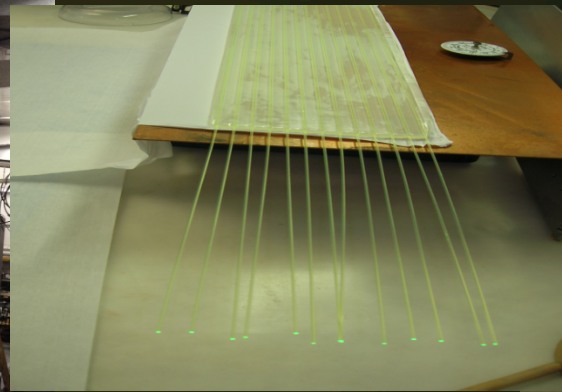
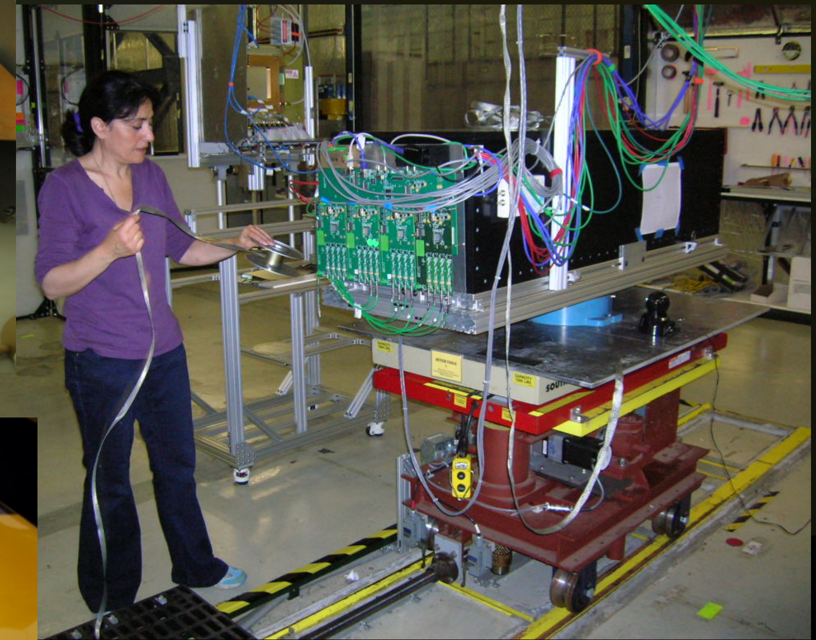
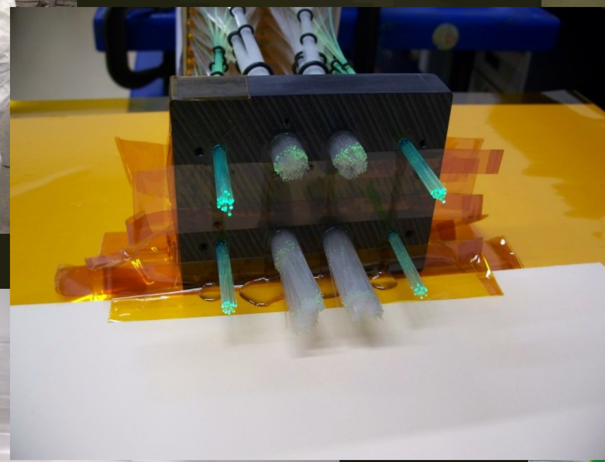
- *Cerenkov light cone photons measured with pixelated Microchannel Plate phototubes. Fast timing in the MCPMT's resolves trajectory. Mirrors used to collect photons in areas with no coverage.*
- *Successful proof of principle in 2015 at Fermilab Test Beam*
- *Instrumented with an MCP photo-detector, three boards each with thirty channels of 10 GSPS waveform digitizing readout*
- *http://ppd.fnal.gov/ftbf/TSW/PDF/T1059_tsw.pdf*

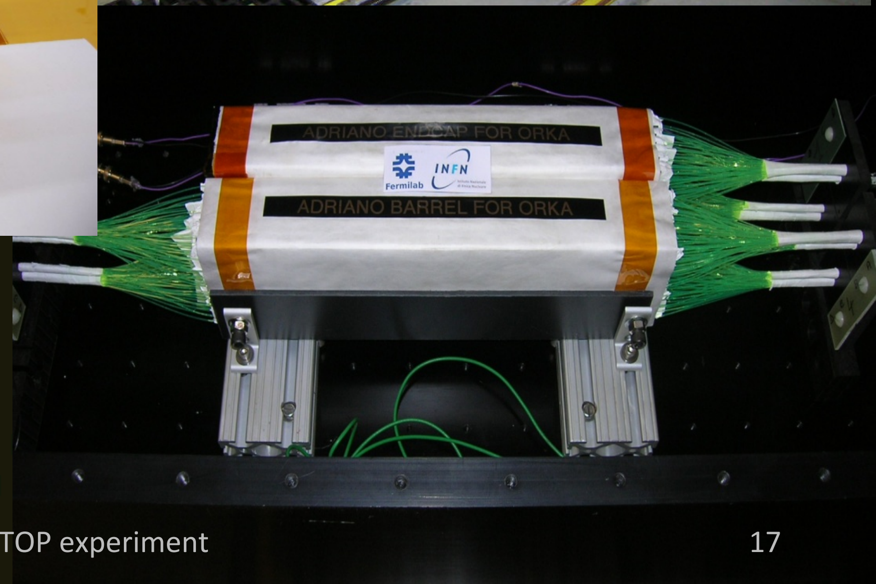




Optical Time Projection Chamber – More R&D Required

ADRIANO Calorimeter R&D
"Status of Dual-readout R&D for a linear collider in T1015 Collaboration": arXiv:1603.00909



15 ADRIANO Prototypes Performance Summary

Prototype	Year	Glass	gr/cm^3	Cerenkov L. Y./GeV	Notes
5 slices, machine grooved, unpolished, white	2011	Schott SF57HHT	5.6	82	SiPM readout
5 slices, machine grooved, unpolished, white, v2	2011	Schott SF57HHT	5.6	84	SiPM readout
5 slices, precision molded, unpolished, coated	2011	Schott SF57HHT	5.6	55	15 cm long
2 slices, ungrooved, unpolished, white wrap	2011	Ohara BBH1	6.6	65	
5 slices, scifi silver coated, grooved, clear, unpolished	2011	Schott SF57HHT	5.6	64	15 cm long
5 slices, scifi white coated, grooved, clear, unpolished	2011	Schott SF57HHT	5.6	120	
2 slices, plain, white wrap	2011	Ohara	7.5	-	DAQ problem
10 slices, white, ungrooved, polished	2012	Ohara PBH56	5.4	30	DAQ problems
10 slices, white, ungrooved, polished	2012	Schott SF57HHT	5.6	76	
5 slices, wifi Al sputter, grooved, clear, polished	2012	Schott SF57HHT	5.6	30	2 wls/groove
5 slices, white wrap, ungrooved, polished	2012	Schott SF57HHT	5.6	158	Small wls groove
ORKA barrel	2013	Schott SF57	5.6	2500/side	molded
ORKA endcaps	2013	Schott SF57	5.6	4000	molded
10 slices – 6.2 mm thick, scifi version	2014	Schott SF57	5.6	338	molded
10 slices – 6.2 mm thick, sci-plate version	2014	Schott SF57	5.6	354	molded
10 slices – 6.2 mm thick, sci-ribbon version	2015	Schott SF57	5.6	300	molded

Summary

- *The η meson is a fantastic laboratory for studying rare processes – has quantum numbers of the vacuum – enhanced sensitivity with respect to Standard Model decays*
- *Existing world sample not sufficient for studying decays violating C, P, CP, CPT conservation laws*
- *REDTOP goal is to produce 2 x 10^{12} η mesons/yr in phase I*
- *Three golden processes will be studied:*
  - ***CP Violation via Dalitz plot mirror asymmetry: $\eta \rightarrow \pi^o \pi^+ \pi^-$***
  - ***New baryonic force searches (charged channel): $\eta \rightarrow \gamma X$ with $X \rightarrow e^+e^-$***
  - ***Scalar meson searches (charged channel): $\eta \rightarrow \pi^o H$ with $H \rightarrow e^+e^-$ and $H \rightarrow \mu^+\mu^-$***
- *Many other processes can be studied – dark photons, proton radius anomaly, etc.*
- *Currently testing detector concepts and considering potential host laboratories*

Thank you !