THE REDTOP EXPERIMENT

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

Corrado Gatto

INFN Napoli and NIU

For the REDTOP Collaboration

The Physics Landscape for REDTOP

- *SM is showing its age*
  - *SM matter: Dark matter:Dark energy=5%:25%:70%*
  - *Baryon Asymmetry of the Universe*
  - *Expansion of the universe is accelerating (hint to more forces)*
  - . . . .
- *New physics is elusive: probability of processes where new physics is coupled to SM physics is low*
- *LHC found no hint of new physics at high energy so far*
- *Newest theoretical models prefer gauge bosons in MeV-GeV mass range as "…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)*

- *High intensity-low energy experiments are growing in popularity (Fixed target and beam dump)*

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

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

REDTOP Key Points

The experiment will yield 2.5 x 10^{13} η mesons/year and 2 x 10^{11} η' mesons/year

That is a consequence of a relatively large η/η' hadro-production cross section (10-20 mbar in the 2 GeV beam energy region and 0.1 mbar at 3 GeV)

Requires a detector blind to protons and slow pions

Near-4π detector can be used with beams of different energy and/or particles

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):* $\eta \to \pi^o \ell^+ \ell$ **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):* $\eta \rightarrow \pi^o H$ *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* $X_{17} \rightarrow e^+e^-$
- *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 leptoquark:* $\eta \rightarrow \mu^+\mu^-$ *and* $\eta \rightarrow e^+e^-$
- *Search for true muonium:* $\eta \rightarrow \gamma(\mu^+\mu^-)|_{2M_\mu} \rightarrow \gamma e^+e^-$

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}*)*

BSM Physics Program (η and η' factory)

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:* $\pi^0 \to \gamma A' \to \gamma e^+e^-$

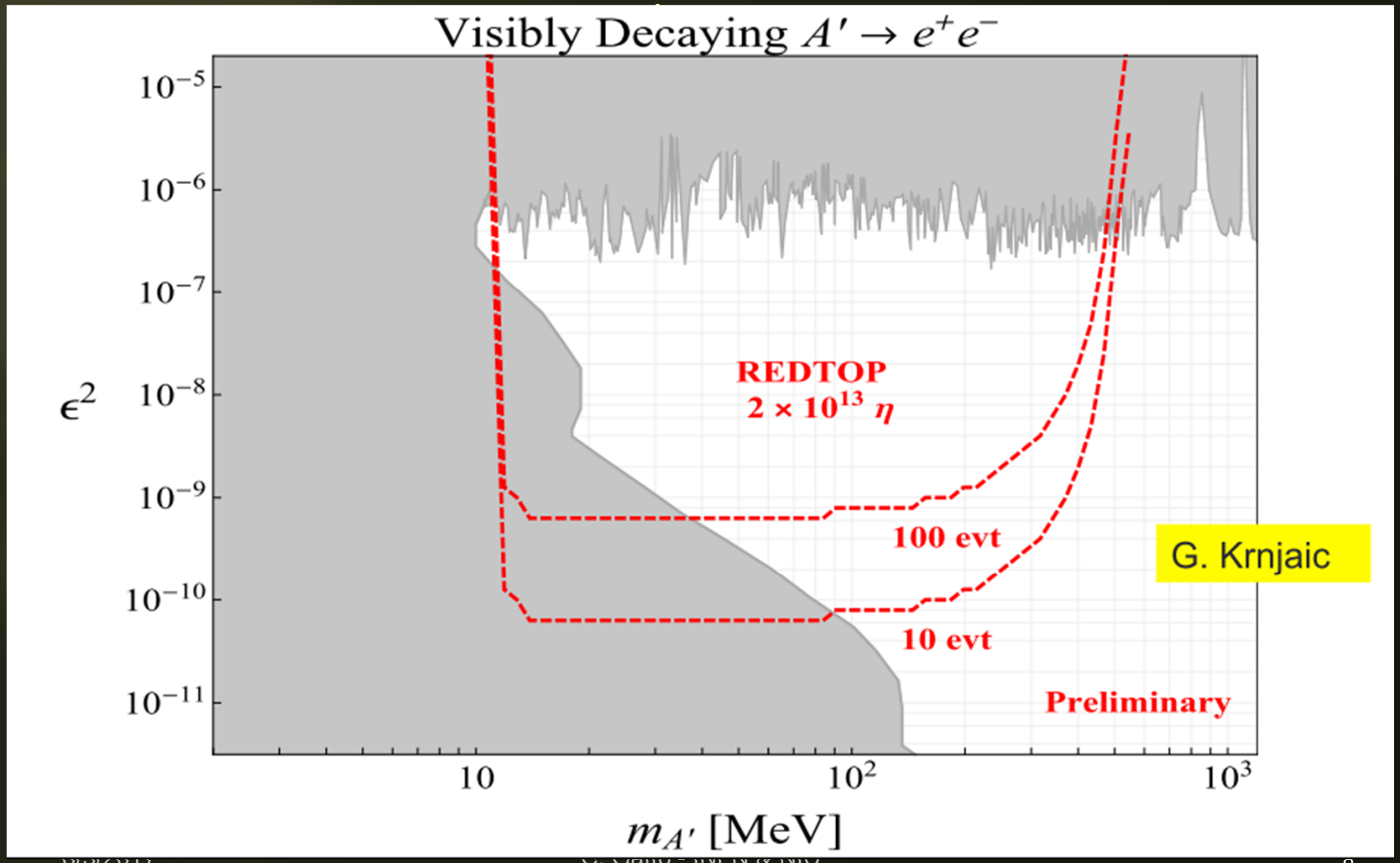
Non-BSM Physics Program (η and η' factory)

High precision studies on low energy physics

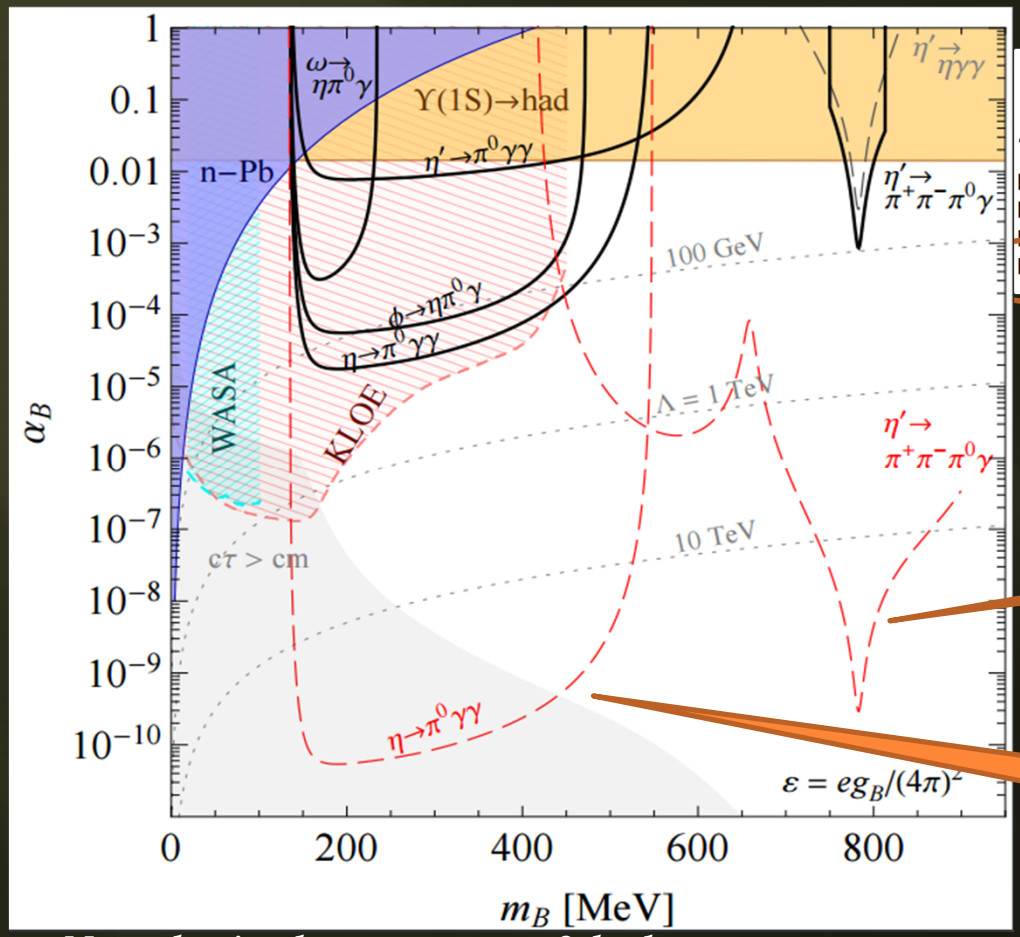
- *Nuclear models*
- *Chiral perturbation theory*
- *Non-perturbative QCD*
- *Isospin breaking due to the u-d quark mass difference*
- *Octet-singlet mixing angle*
- *$\pi\pi$ interactions*
- *Electromagnetic transition form-factors (important input for g-2)*
- *Lots of other bread&butter physics*

REDTOP - Golden Channel III

Dark photon searches:



REDTOP Constraints on a new baryonic force (courtesy of S. Tulin – U. York)



η DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Neutral modes		
Γ_1	neutral modes	(72.12±0.34) %	S=1.2
Γ_2	2γ	(39.41±0.20) %	S=1.1
Γ_3	$3\pi^0$	(32.68±0.23) %	S=1.1
Γ_4	$\pi^0 2\gamma$	(2.7 ±0.5) × 10^{-4}	S=1.1

REDTOP constraints at the level of BR($\eta' \to B\gamma \to \pi + \pi - \pi^0\gamma$) < 10^{-8}

REDTOP constraints at the level of BR($\eta \to B\gamma \to \pi^0\gamma\gamma$) < 3×10^{-9}

- *New physics decays as a two 2-body*
- *SM decay as 3-body*
- *Current limit: baryonic force is 2000 times weaker than electromagnetism*
- *Better limits from Dalitz plot analysis of $\eta \to \pi^0\gamma\gamma$. Not been done so far.*
- *REDTOP will collect 10^9 such event: sensitivity is under study*

Experimental Techniques

η/η' production

- *η/η' hadro-production from inelastic scattering of protons on Be targets*
- *Use multiple thin targets to minimize combinatorics background*

charged tracks detection

- *Use Cerenkov effect in an Optical-TPC for tracking charged particles*

⇩

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

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*
- *Use tiles for high granularity and PFA reconstruction*

Beam Rquirements

- *Assume: $1x10^{11}$ POT/sec – CW*
  - *Beam power for η factory: @ 1.9 GeV: 10^{11} p/sec $\times$ 1.9 GeV $\times$ 1.6 $\times$ 10^{-10} J/GeV = 30 Watts*
  - *Beam power for η' factory: @ 3 GeV: 10^{11} p/sec $\times$ 3GeV $\times$ 1.6 $\times$ 10^{-10} J/GeV = 48Watts*

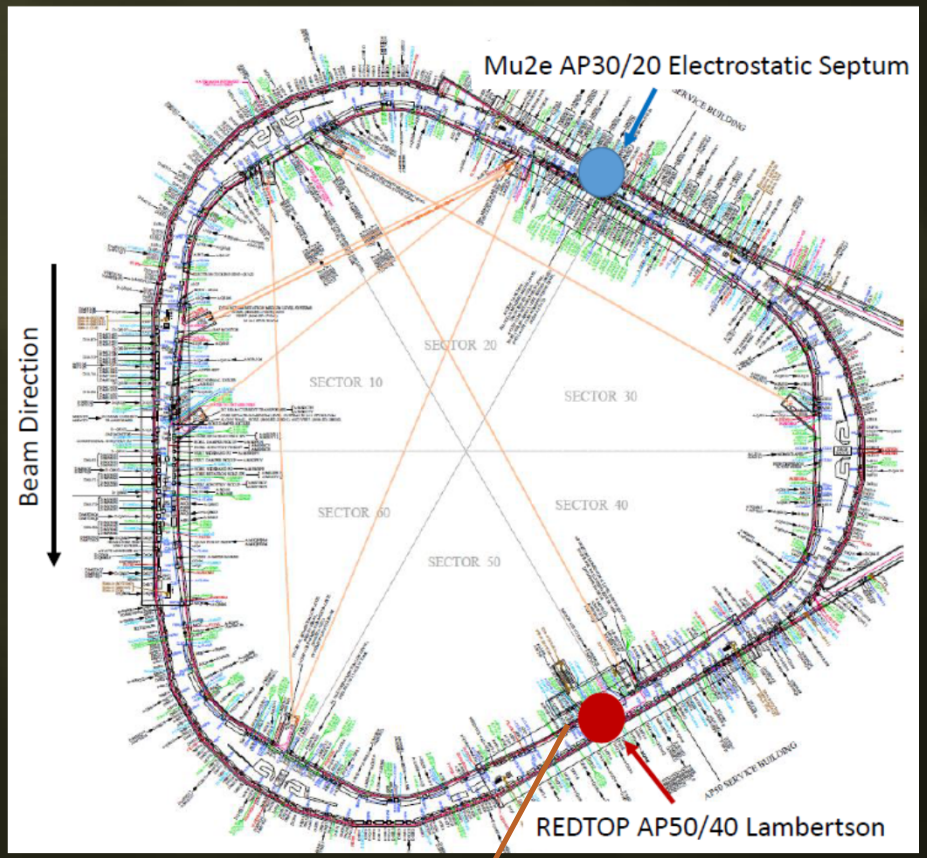
- *Target system : 10 x 0.33mm Be foils, spaced 10 cm apart*
  - *Prob(p + target $\rightarrow$ X) = 0.5%*

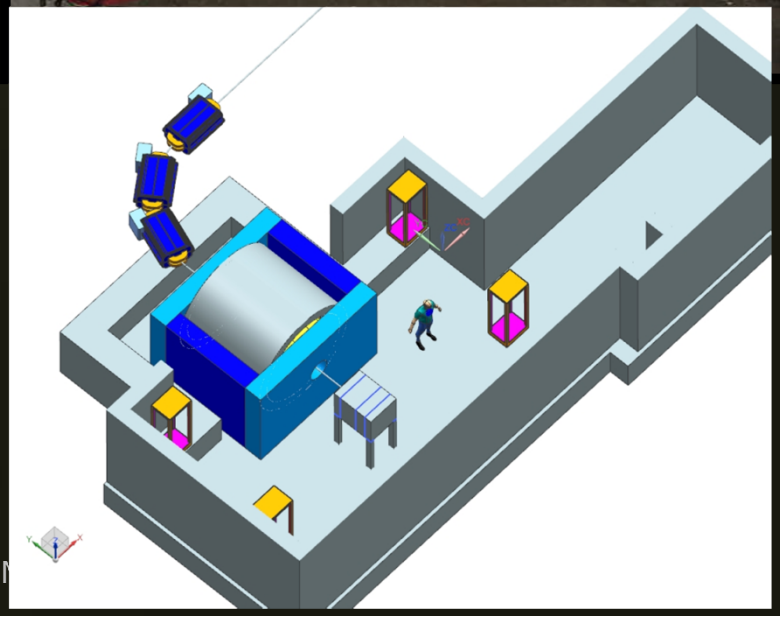
- *Power dissipated from target:*
  - *Heat produced for η factory: 150 mW total - 15 mW per target foil*
  - *Heat produced for η factory: 240mW total - 24 mW per target foil*

- *p-inelastic interaction: 5 x 10^8 evt/sec (1 interaction/2 nsec in the targets)*
- *η production: 2.5 x 10^6 η/sec or 2.5 x 10^{13} η/yr*
- *η' production: 1.5 x 10^4 η'/sec or 1.5 x 10^{11} η'/yr*

Accelerator complex for REDTOP Fermilab Option: AP50 hall

- Use delivery ring and extract beam at A
- Decelerate the 8 GeV beam to desired e





REDTOP

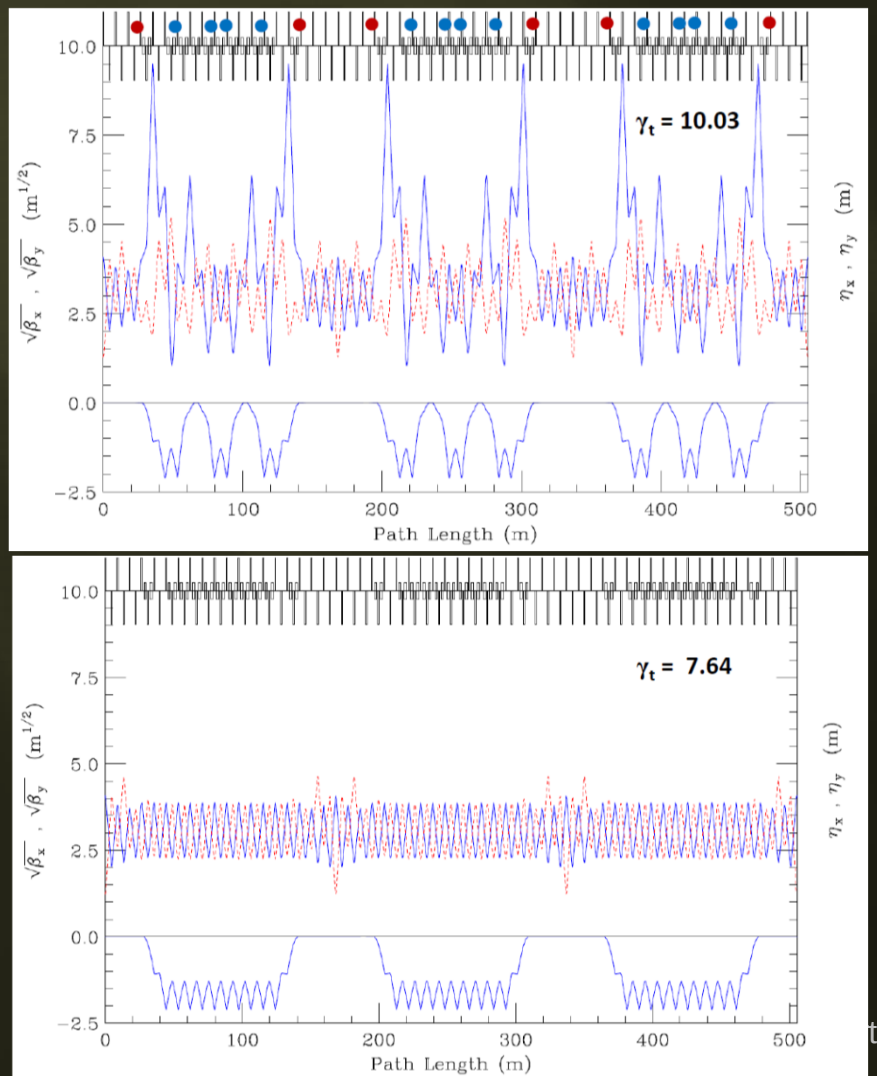
Acceleration Scheme (M. Syphers)

- *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 adding 1-2 RF cavities identical to the one already planned for mu2e (J. Dey)*
- *Spare RF cavities already existing (owned by mu2e and AD)*
- *Debunching occurs adiabatically inside the DR*
- *Slow extraction to REDTOP over ~40 seconds.*
- *The 270° of betatron phase advance between the Mu2e Electrostatic Septum and REDTOP Lambertson is ideal for AP50 extraction to the inside of the ring.* ***A DEDICATED SEPTUM IS NOT REQUIRED***
- *Total time to decelerate-debunch-extract: 51 sec: duty cycle ~80%*

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 γ_t = 7.64 and beam γ = 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)

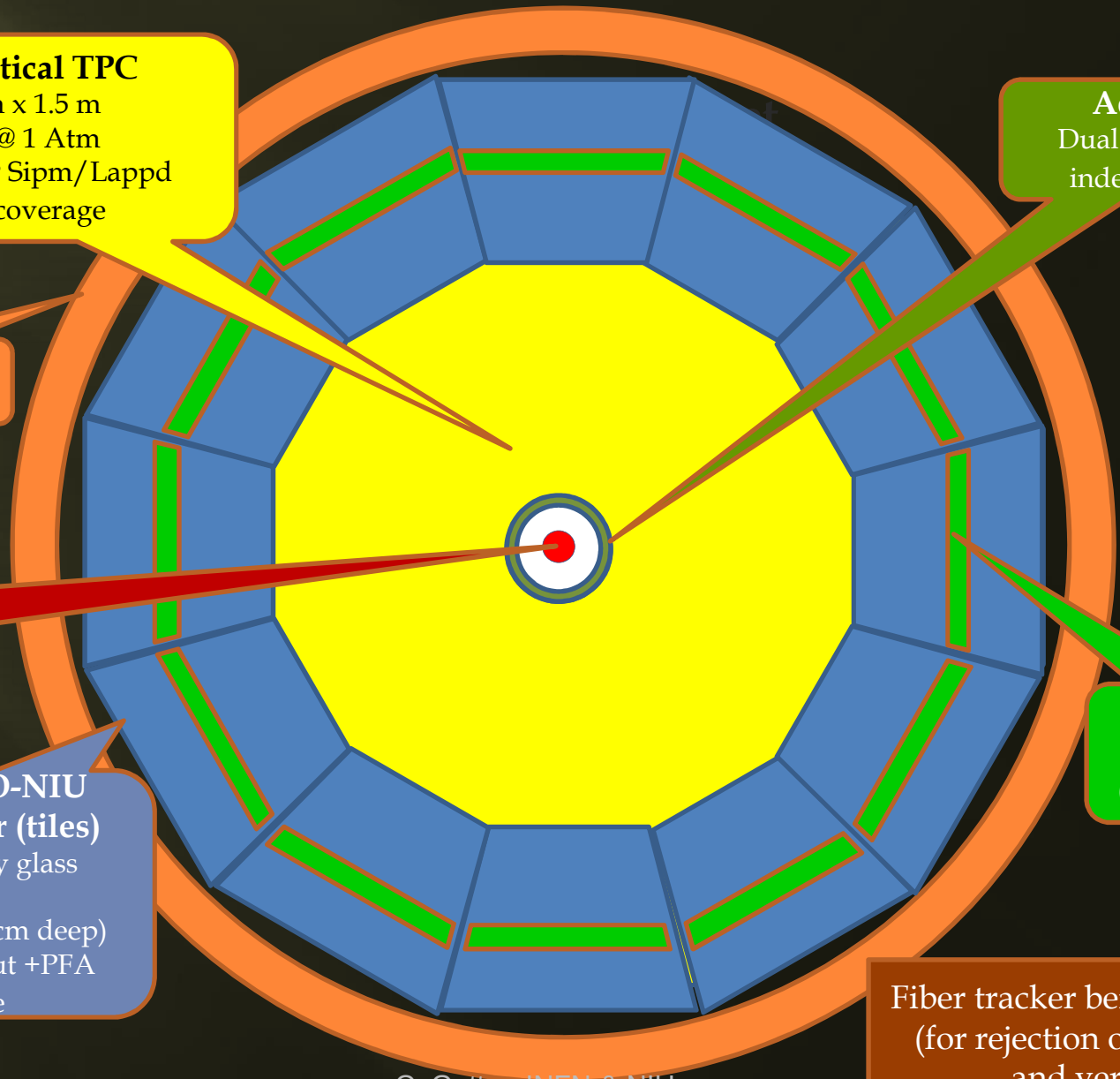
- Blue & red circles indicate sites of the γ_t quad triplets.

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)"

The REDTOP Detector (baseline)



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

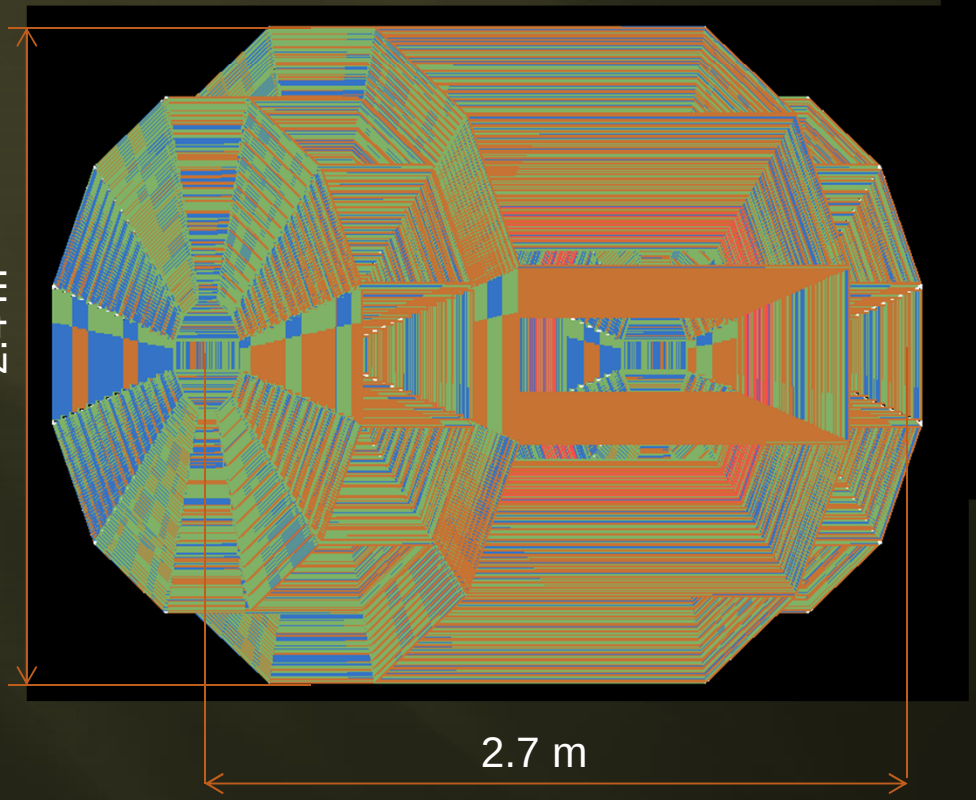
μ-polarizer
Active version (from TREK exp.)

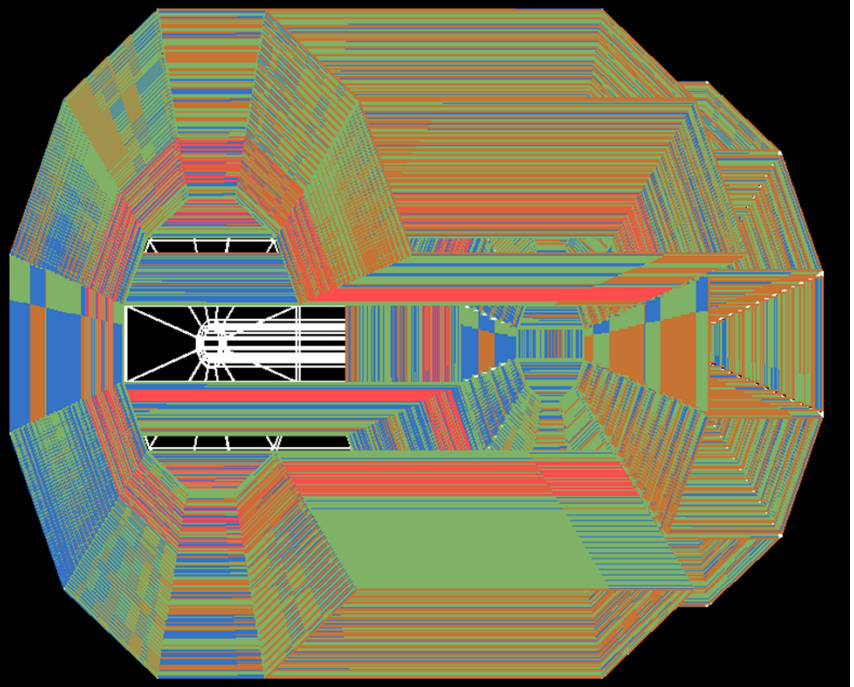
ADRIANO-NIU Calorimeter (tiles)
- Scint. + heavy glass sandwich
- 20 X_0 (~ 64 cm deep)
- Triple-readout +PFA
- 96% coverage

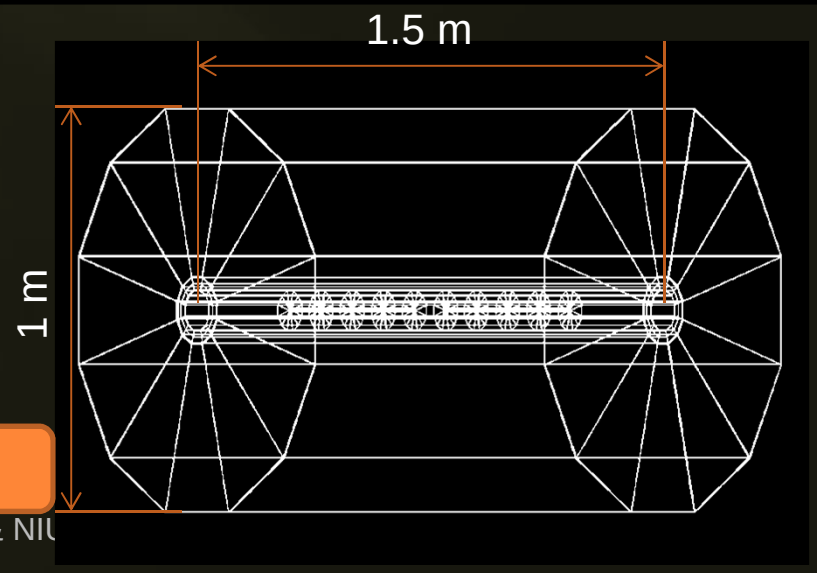
Fiber tracker being investigated (for rejection of γ-conversion and vertexing)

REDTOP detector

ADRIANO calorimeter



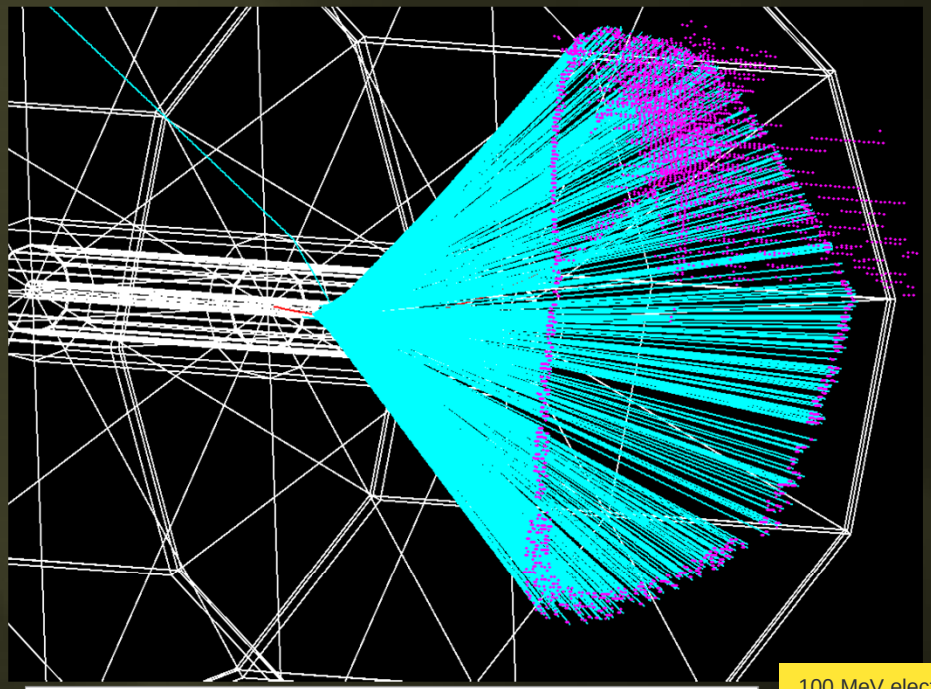


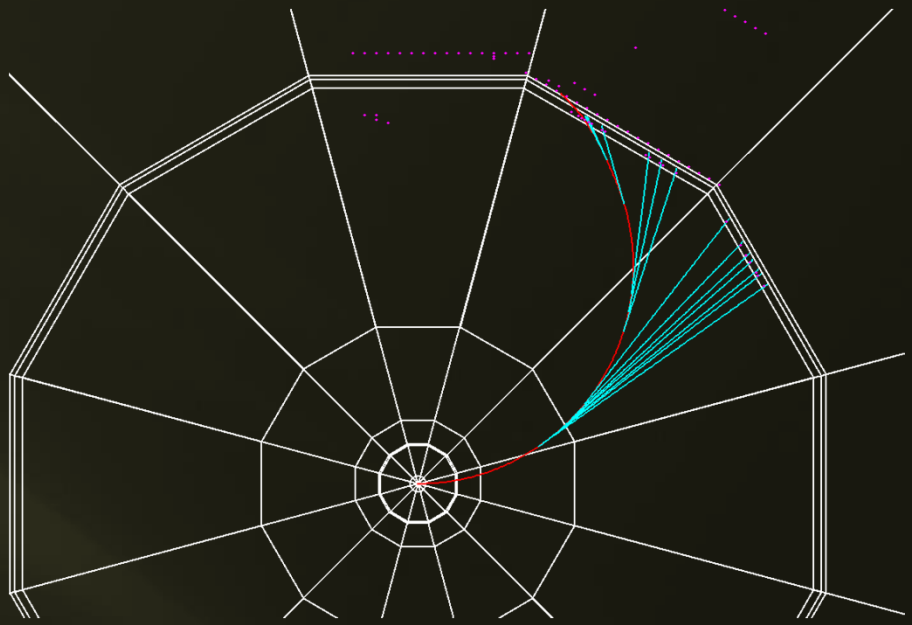


Ilcroot simulation

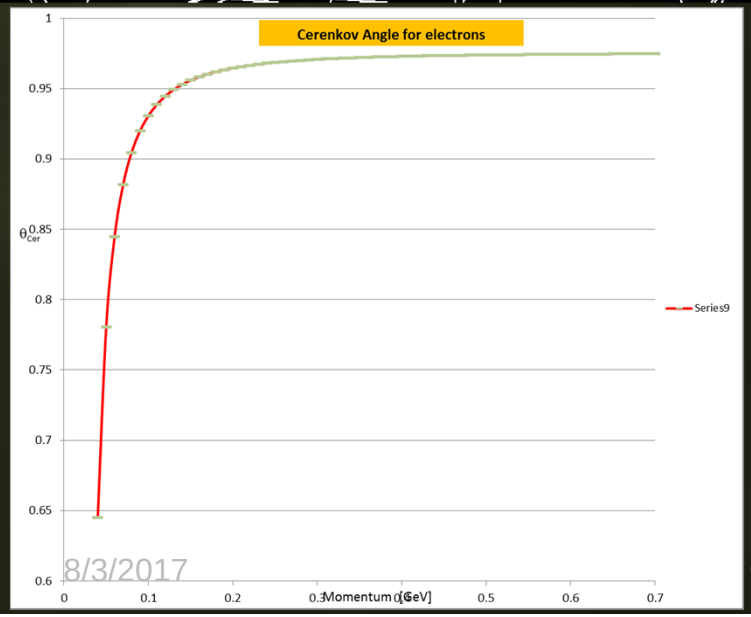
OTPC

Electron Detection





100 MeV electron



$n_D(N_2@2.7psi)=1.000145$

Č threshold for e- in N_2: P=40 mev

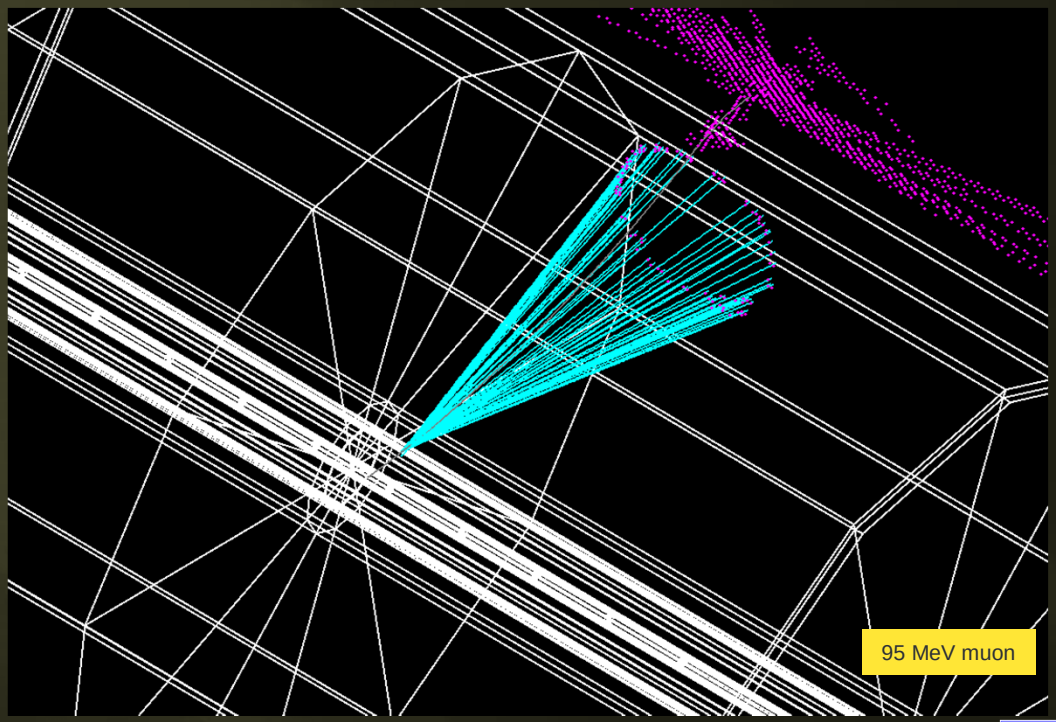
$n_D(aerogel1)=1.12$

$n_D(aerogel2)=1.22$

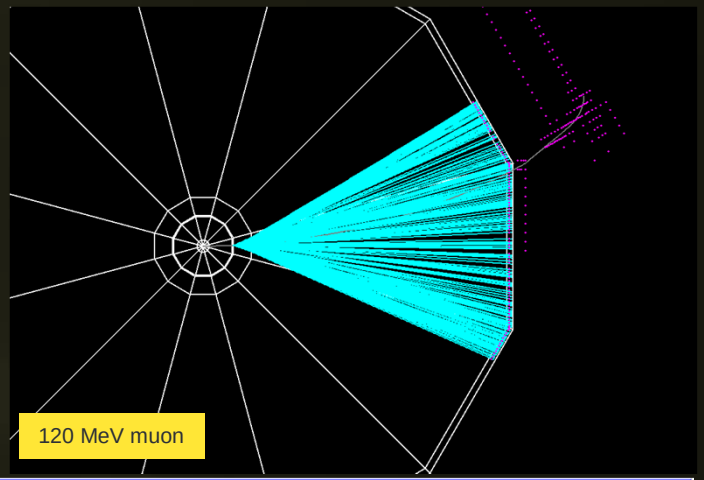
Slic/lcsim simulation

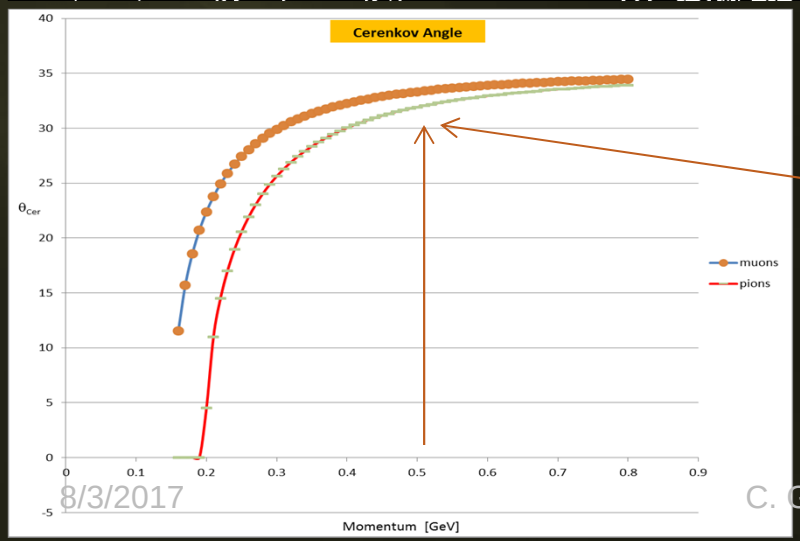
Slic/lcsim simulation

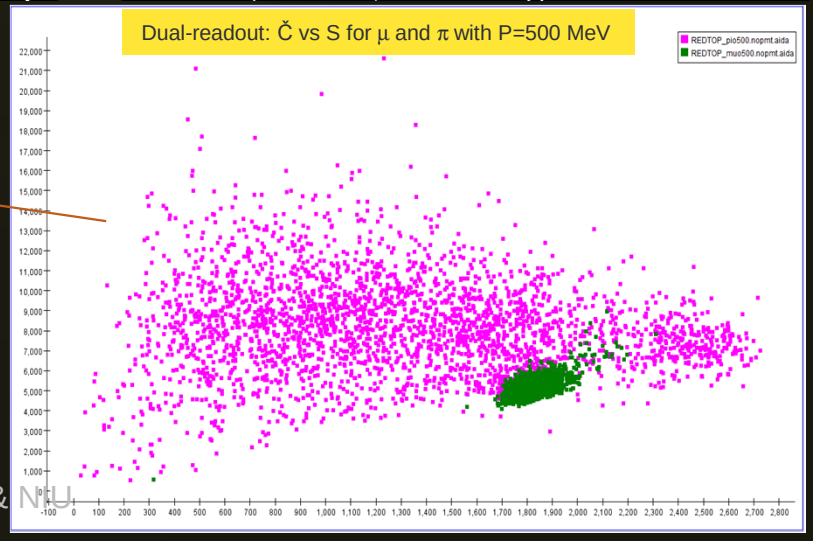
Muon/pion Detection



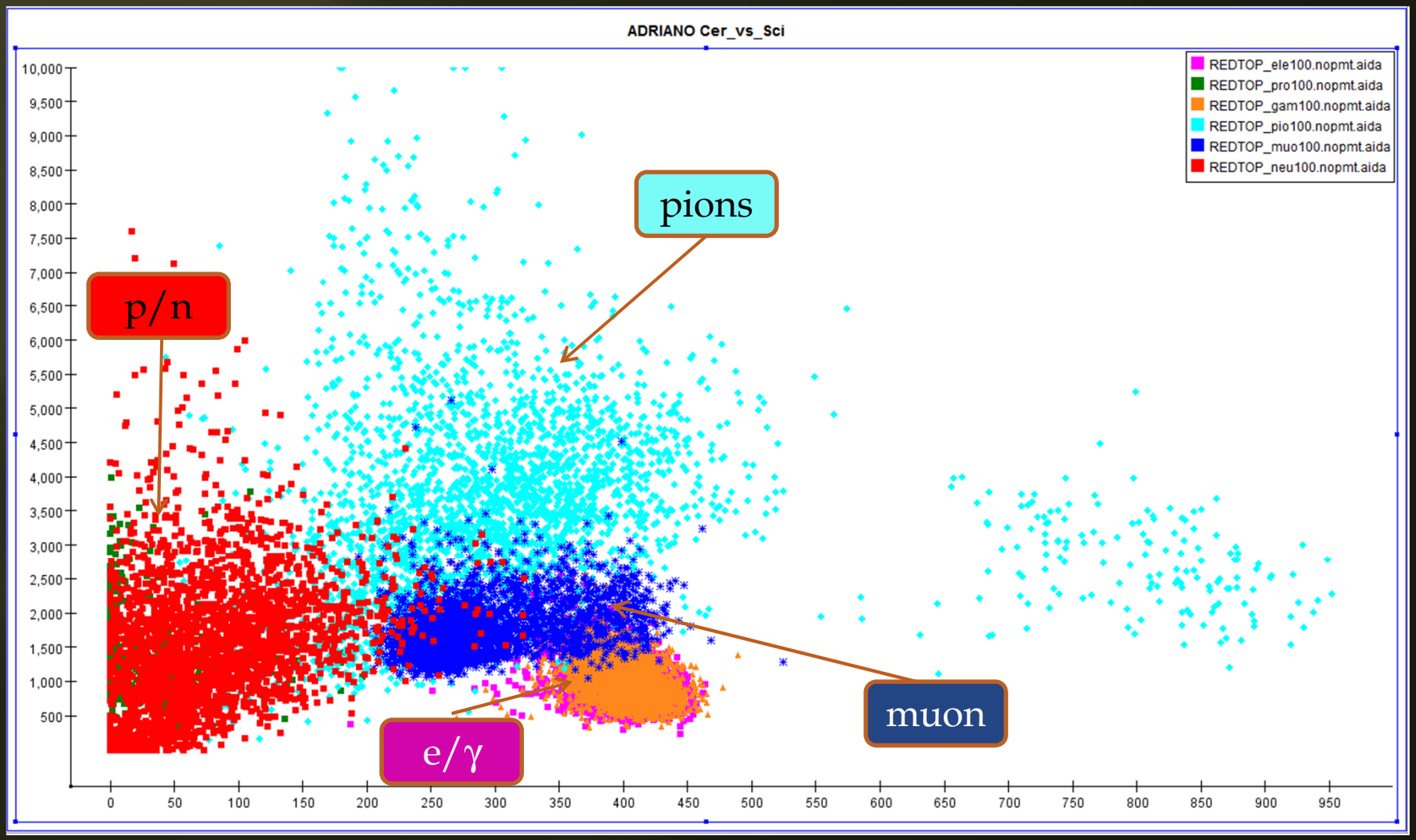
- n_D(aerogel)=1.22/1.12
- Č threshold for muons: P=160 mev
- Č threshold for pions: P=200 mev







ADRIANO PID @ 100MeV



Ilcroot simulation

REDTOP Running Phases

- Phase I: η-factory
  - Beam: protons
  - T_{beam}: 1.8-2.1 GeV
  - Detector: baseline
- Phase II: η ′-factory
  - Beam: protons
  - T_{beam}: 3.0-4.0 GeV (to be optimized)
  - Detector: baseline (change O-TPC gas pressure, probably the Aerogel section)
- Phase III: Muon Scattering Experiment (optional)
  - Beam: muons
  - T_{beam}: 0.2< <0.8 GeV (to be optimized)
  - Detector: baseline + front graphite target
- Phase IV: Rare Kaon Decays: $K^+ \rightarrow \pi^+ \nu \underline{\nu}$
  - Beam: kaons
  - T_{beam}: from 8 GeV protons
  - Detector: might need upgrade target and central tracker, add range stack

Summary

- *The η/η' meson is an excellent laboratory for studying rare processes*
- *Existing world sample not sufficient for breaching into decays violating conservation laws or searching for new particles*
- *REDTOP goal is to produce >2 x 10^{13} η mesons/yr in phase I and (~ 2x10^{11} η'/year) in phase II*
- *Two or more phases could extend the lifetime of the experiment considerably*
- *Five golden processes - Many other processes also within reach*
- *Currently the collaboration is forming and working at a proposal*
- *Fermilab is the preferred hosting lab. BNL has, also, expressed some interest*
- *Total cost: < 40 M$ (depending on re-use of existing infra-structure)*

The REDTOP collaboration

8 Countries, 20 Institutions, 60 Collaborators

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For more info see:
http://redtop.fnal.gov

Prospects

- *2016-1017: Collaboration forming and studies for the Proposal*
- *Dec. 2017-early 2018: proposal to Fermilab's PAC*
- *2018-2020: Detector R&D*
- *2021: Detector construction + engineering run*
- *>2022: Start physics run*
- *Successive phases depends from results of phase I, occupancy of the experimental hall and beam request from experiments*
- ***More details: http://redtop.fnal.gov***

All schedule contingent to upcoming P5 process (2022)
An exciting phase of detector R&D ahead

Time of facilities

Paolo Valente

Stepan Stepanyan

Backup slides

Possible Intermediate Phases

Pre-REDTOP with OTPC only

- $p\ ^{7}Li \rightarrow\ ^{8}Be^{*} \rightarrow e^{+}\ e^{-}\ X$
  - At 2.5 MeV IOTA proton source (Fermilab)
  - Confirm 17 MeV bump found in Prague experiment
- $p\ D \rightarrow\ ^{3}He\ e^{+}\ e^{-}$ (M. Viviani ,L. E. Marcucci and A. Kievsky)
  - At 40 MeV Fermilab p linac (Fermilab) or ATLAS facility (ANL)
- $p\ \ ^{9}Be \rightarrow\ ^{8}Be^{*} + X \rightarrow e^{+}\ e^{-}\ X$
  - At MCenter 2 GeV p beam (Fermilab)
- μ^{+} Nucleus scattering in fixed target mode
  - 1.5-3 GeV muon campus – Fermilab
- μ^{+} Nucleus in beam dump mode
- e^{-} Nucleus in fixed target mode
  - 250-500 MeV, 50 mA IOTA facility – Fermilab
- e^{-} Nucleus in beam dump mode
- OTPC test with 2 GeV protons dumped by g-2 - Fermilab

A. Starostin - UCLA

Present η 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	$e^+e^- \to \Phi \to \eta\gamma$	6.5×10^5		5×10^7
WASA@COSY	$pp \to \eta pp$ $pd \to \eta\, {}^3He$			$>10^9$ 3×10^7
CB@MAMI 10 wk (proposed 2014)	$\gamma p \to \eta p$	3×10^7	1.5×10^5	3×10^8
Phenix	$d\,Au \to \eta X$			5×10^9
Hades	$pp \to \eta pp$ $p\,Au \to \eta X$			4.5×10^8

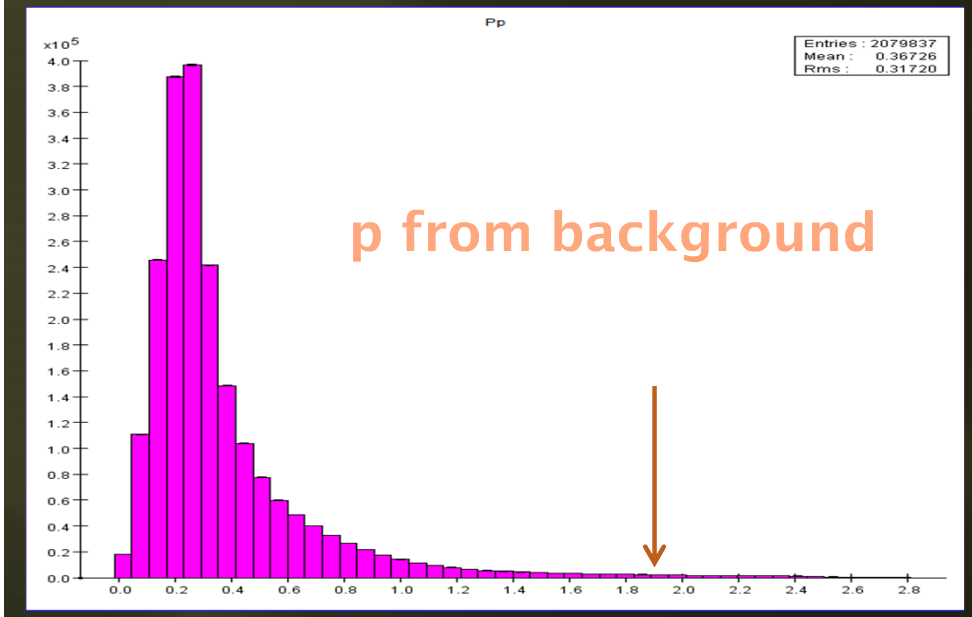
Near future η Samples

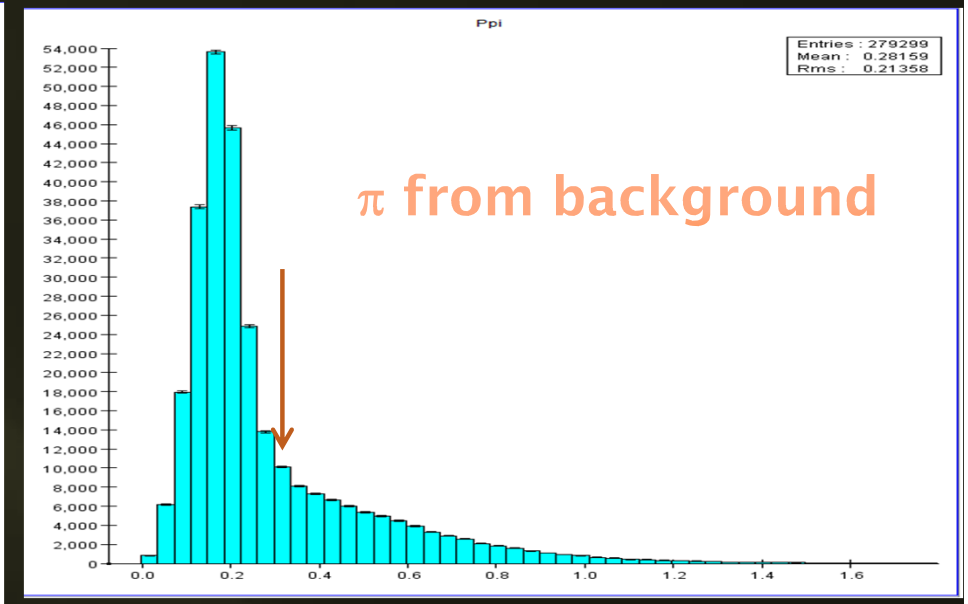
GlueX@JLAB (just started) $\gamma_{12\,\mathrm{GeV}} p \to \eta p \to$ neutrals 4.5×10^7/yr

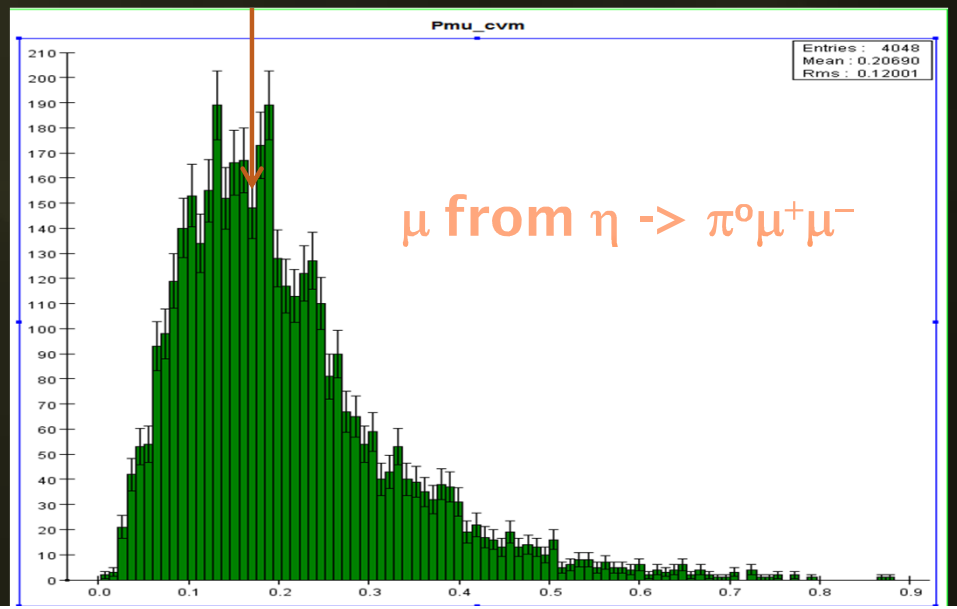
JEF@JLAB (proposing – not approved) $\gamma_{12\,\mathrm{GeV}} p \to \eta X \to$ neutrals 3.9×10^5/day

REDTOP@FNAL (proposing) $p_{1.9\,\mathrm{GeV}} Be \to \eta X$ 2.5×10^{13}/yr

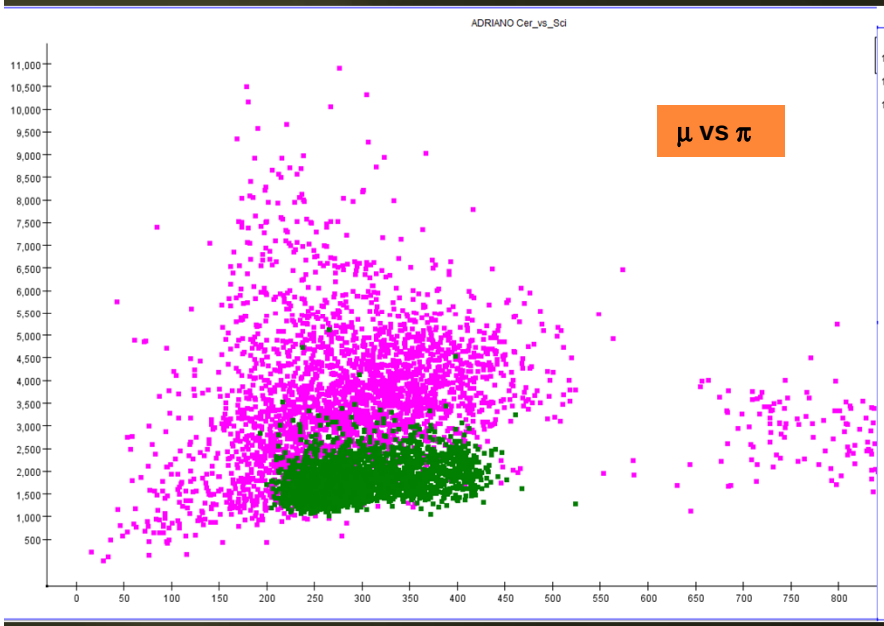
OTPC Thresholds

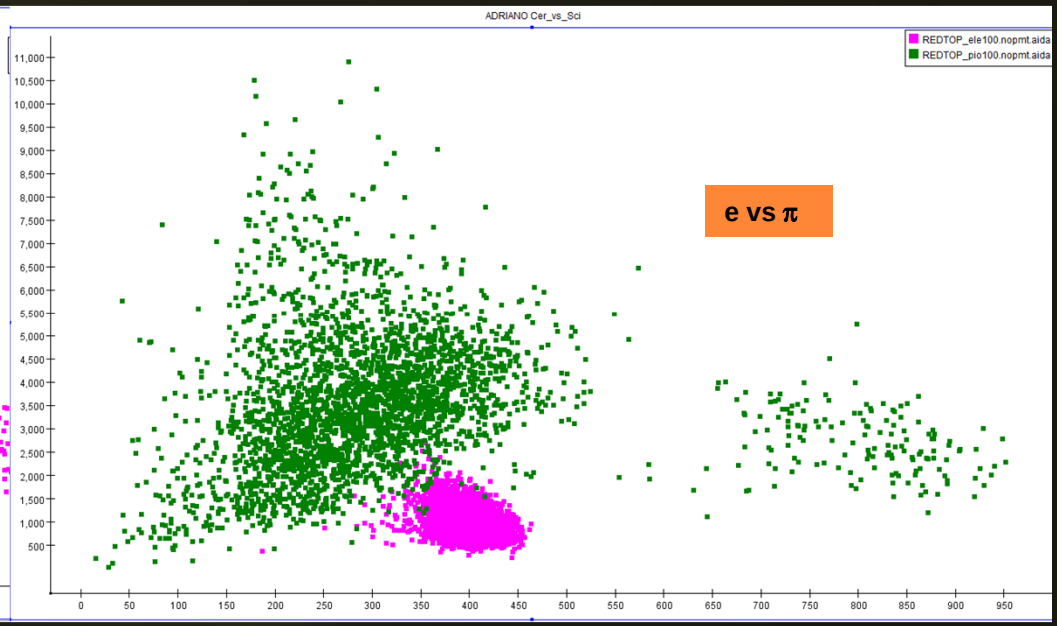


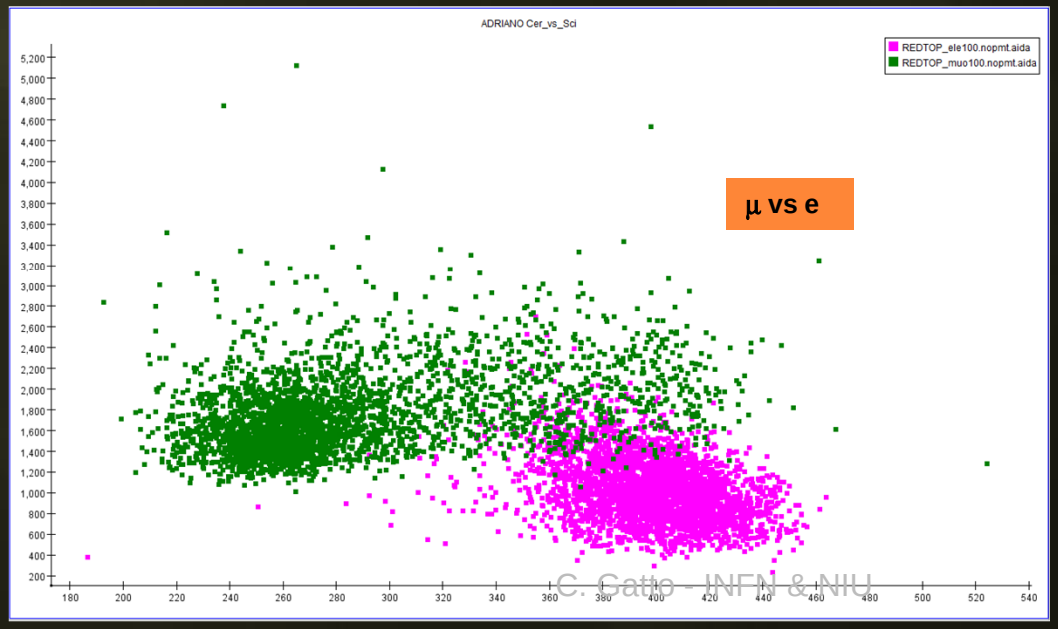




ADRIANO Particle ID @ 100MeV





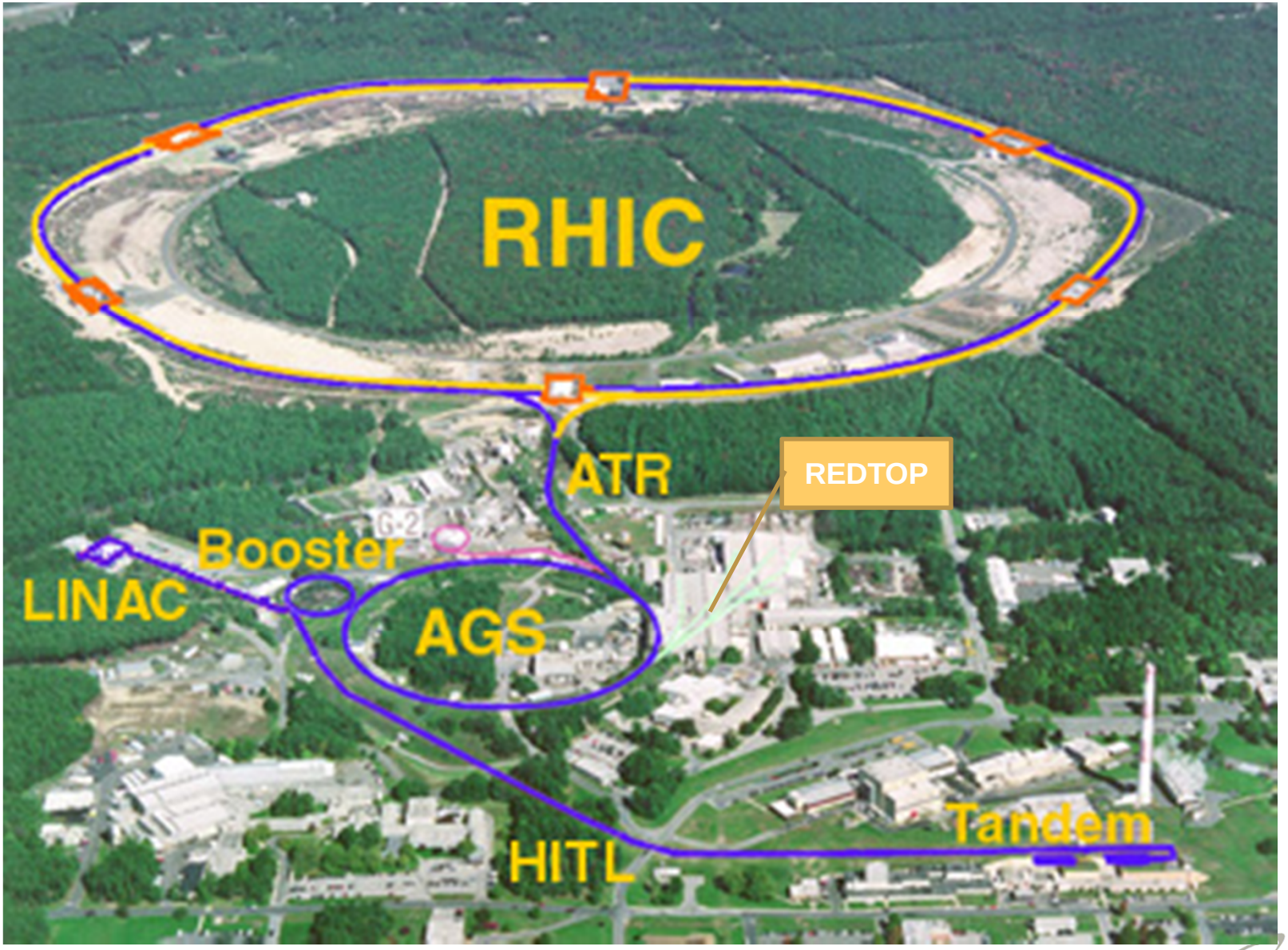


15 Prototypes Performance Summary

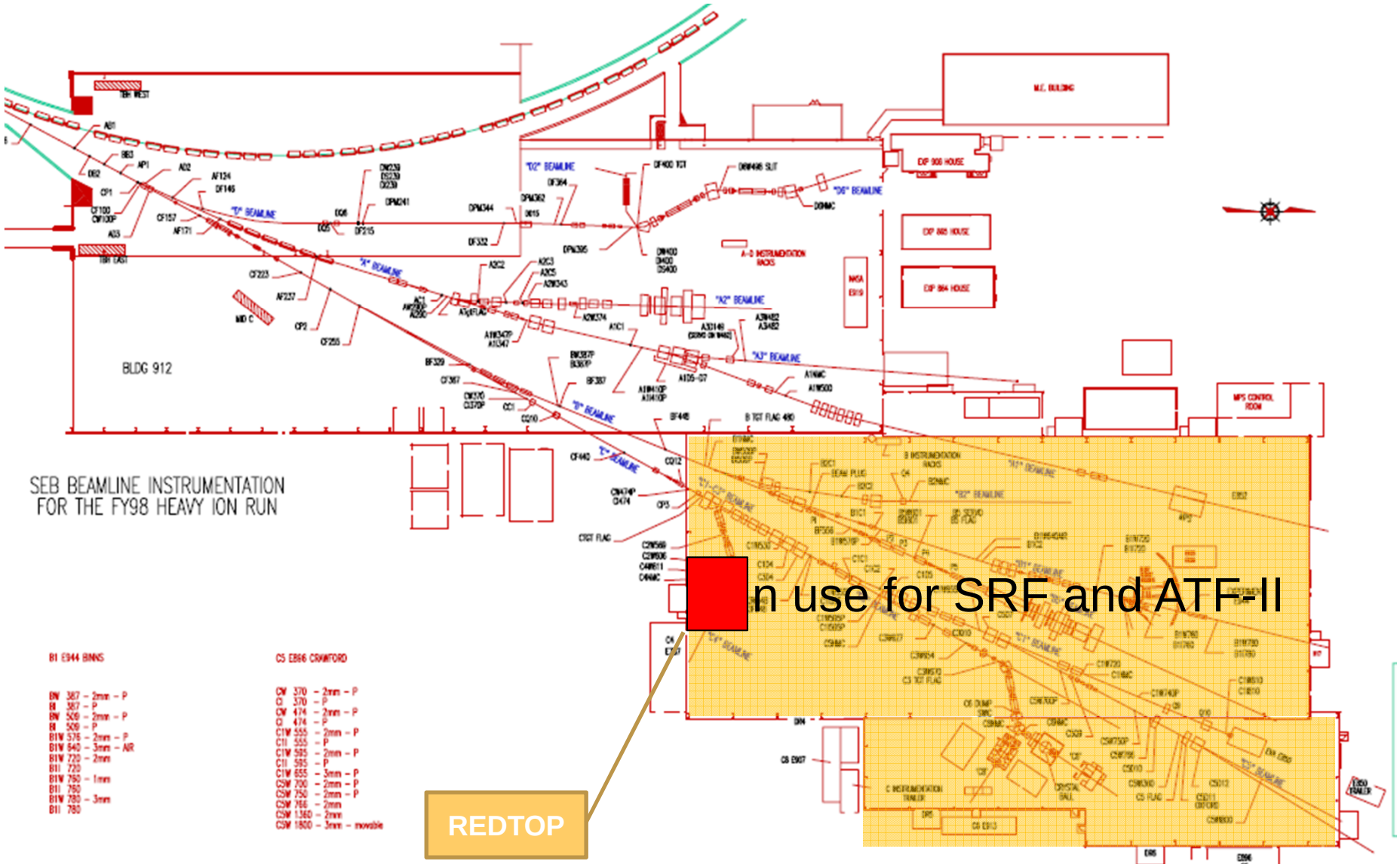
Prototype	Year	Glass	gr/cm³	Cerenkov L. Y./GeV	Notes
5 slices, machine grooved, unpolished, white	2011	Schott SF57HHT	5.6	82	SiPM readout
5 slices, machine grooved, unpolished, white, v2	2011	Schott SF57HHT	5.6	84	SiPM readout
5 slices, precision molded, unpolished, coated	2011	Schott SF57HHT	5.6	55	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

ADRIANO 2015 (for lepton colliders) is currently in the beam at FTBF

BNL hadron complex



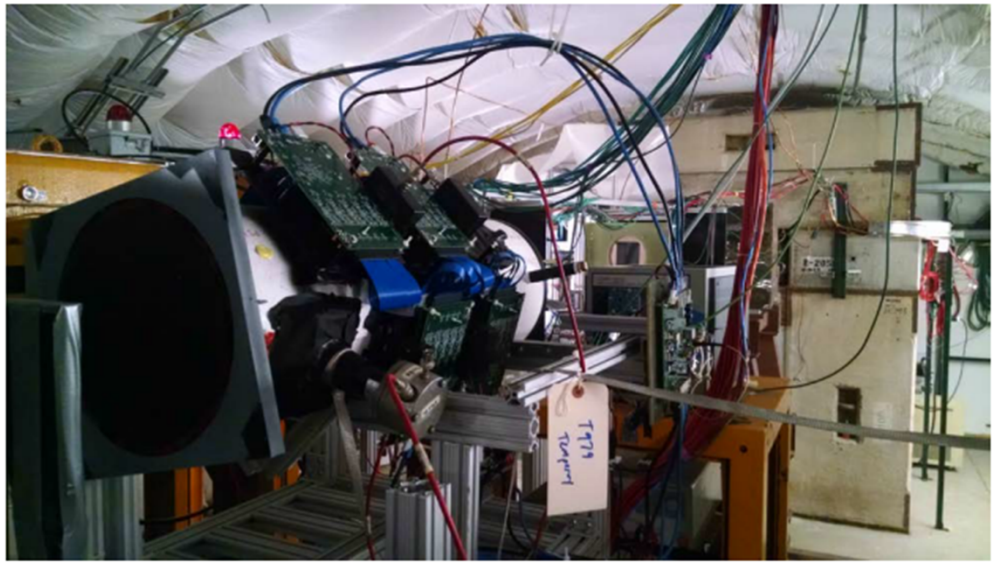
Building 912 AGS Experimental Area (1998)

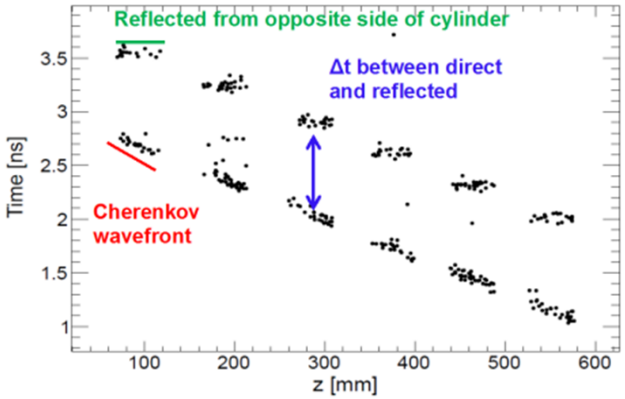


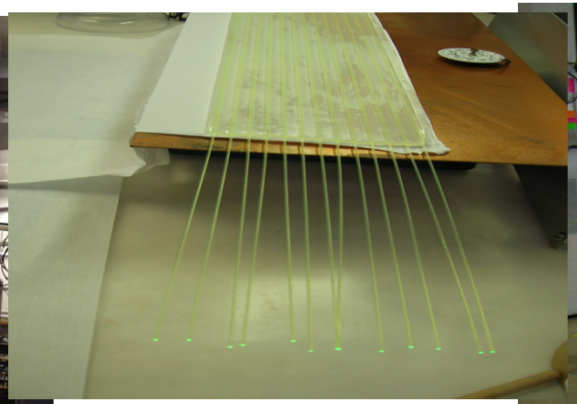
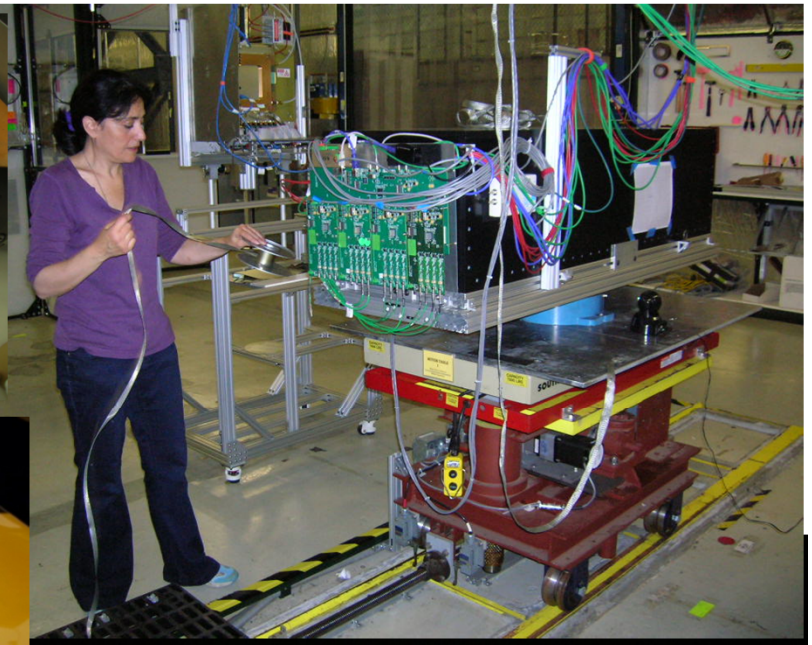
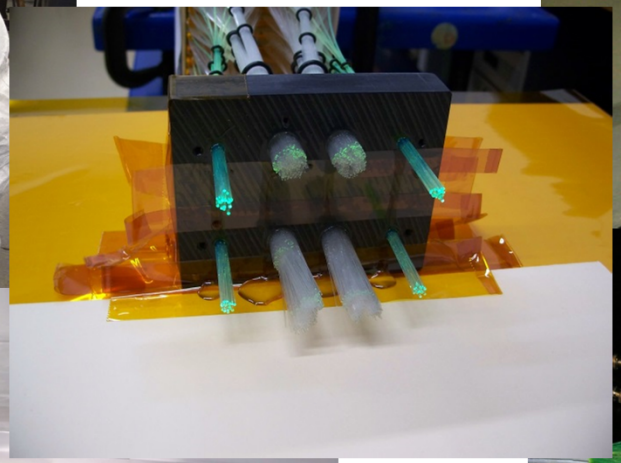
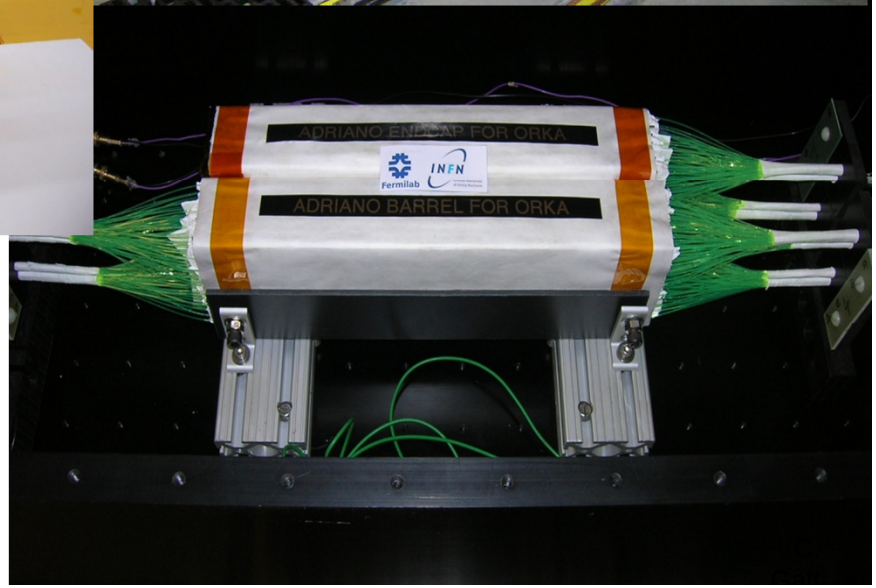
Detector R&D: OTPC

Fnal –T1059 (H. Frisch, E. Oberla)

- *Successful proof of principle in 2015 at FTBF*
- *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*





It requires a robust and dedicated R&D

Detector R&D: ADRIANO in T1015
Moving R&D from FNAL to NIU