The "REDTOP" Experiment as a Laboratory for Symmetry Violations in Rare η/η′ Decays

Corrado Gatto
INFN Napoli and Northern Illinois University

Erik Ramberg
Fermilab

For the REDTOP Collaboration

Quest for BSM Physics

- *LHC has found no hint of new physics at high energy (i.e. ~10^{11} eV)*
- *Dark Energy and Neutrino masses and strong CP violation operate, on the other hand, in a dramatically lower energy regime (i.e. ~10^{-3} eV) ???*
- *Does this point to a common, dynamical origin? Can EM fit into such a regime?*
- *An η/η' factory with 10^4 increase in world statistics could search for discrepancies in the Standard Model at the 0.1 GeV energy regime with couplings at the level of 10^{-8}*
- *The quark content of the η/η' is extremely simple and thus the SM background currents play a minimal role*

REDTOP = "Rare Eta Decays with a TPC for Optical Photons"

Why the η meson is special

- It is a Goldstone boson
- It is an eigenstate of the C, P, CP and G operators (very rare in nature): $I^G J^{PC} = 0^+ 0^{-+}$
- All its additive quantum numbers are zero

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

Symmetry constrains its QCD dynamic
It can be used to test C and CP invariance.

Its decays are not influenced by a change of flavor (as in K decays) and violations are "pure"

It is a very narrow state

G_h=1.3 KeV vs G_r=149 MeV)

Contributions from higher orders are enhanced by a factor of ~100,000

Excellent for testing invariances

Decays are free of SM backgrounds for new physics search

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

Main Physics Goals of REDTOP:

CP Violation via Dalitz plot mirror asymmetry: $h \rightarrow p^o\, p^+p^-$

Search for asymmetries in the Dalitz plot with very high statistics

Test of CP invariance via γ* polarization studies: $\eta \rightarrow \pi^+\pi^-e^+e^-$ *and* $\eta \rightarrow \pi^+\pi^-\mu^+\mu$

Measure the angular asymmetries between the l^+l^- *and* $\pi^+\pi^-$ *planes*

Dark photon searches: $\eta \rightarrow \gamma A'$ **with** $A' \rightarrow \ell^+\ell$

Need excellent vertexing and particle i.d.

Scalar meson searches (charged channel): $\eta \rightarrow \pi^o H$ *with* $H \rightarrow e^+e^-$ *and* $H \rightarrow \mu^+\mu$

Dual (or triple!) calorimeters and optcal TPC play important role

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

Assume a yield ~10^{13} η mesons/yr and ~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: $\eta \to \mu^+ \mu^-$
- 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 $\eta \to \gamma\gamma$

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 $X_{17} \to e^+e^-$
- 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 discrete symmetry violations

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

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})

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

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)

Searches for light scalar mesons

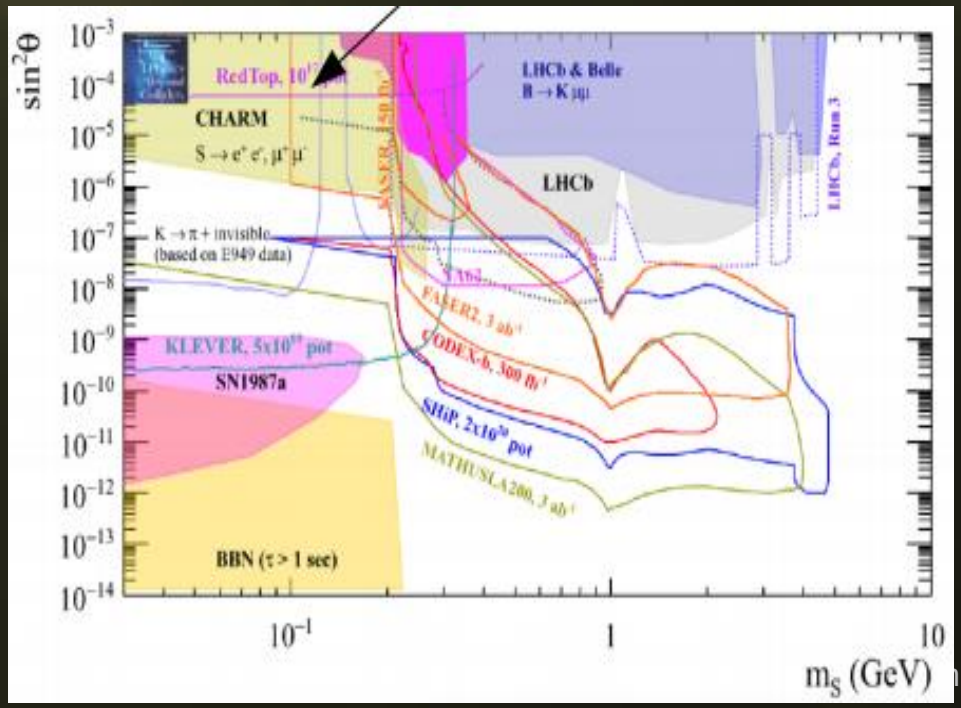
Minimal SM Higgs extension

- *Studied within the "Physics Beyond Collider" program at CERN for 10^{17} POT*
- *FNAL and BNL can provide 10x more POT*
- *Only "bump hunt analysis". Vertexing add 10x more sensitivity*

Hadrophilic Scalar Mediator

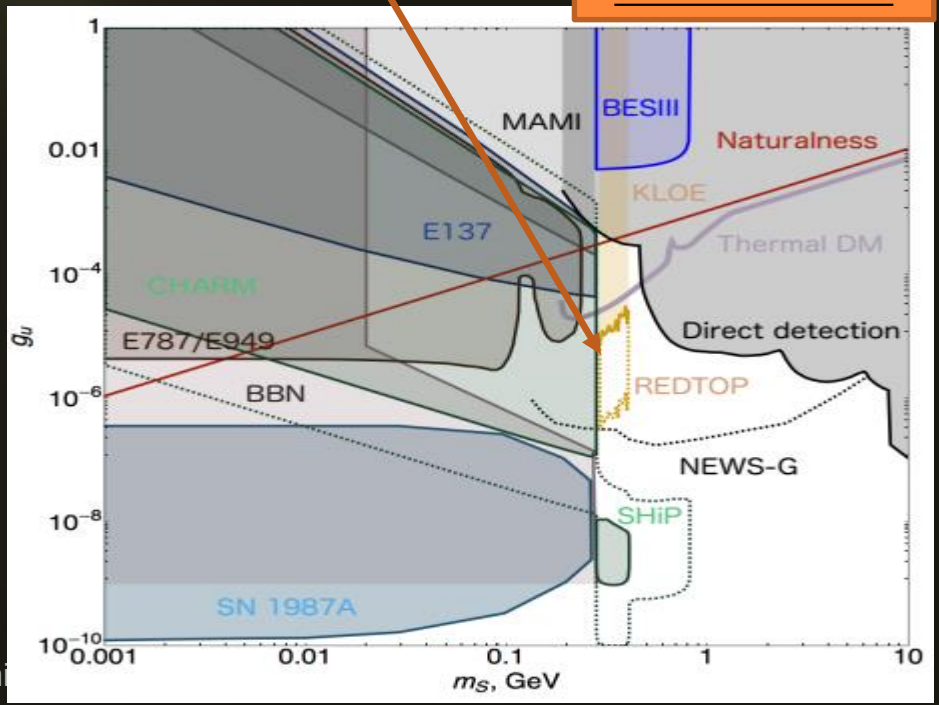
- *Studied in arXiv:1812.05103*
- *Only bump hunt - no vertexing*

REDTOP@CERN



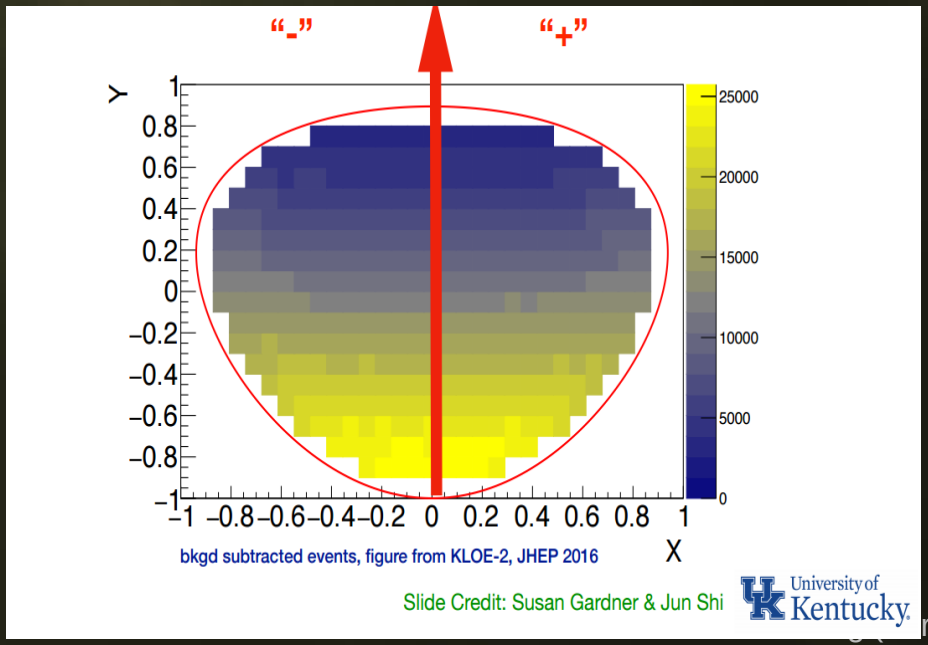
REDTOP@Fermilab

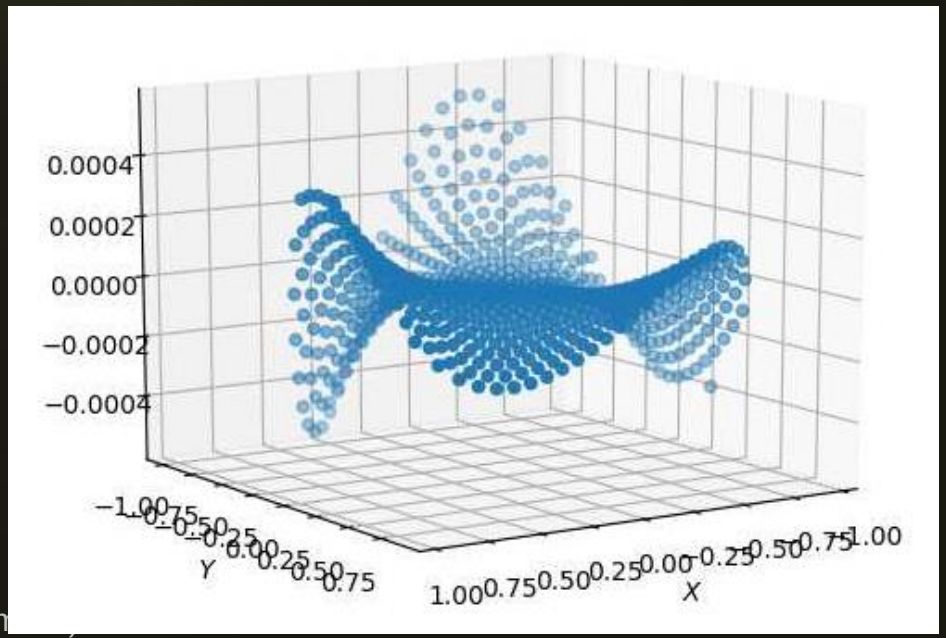
arXiv:1812.05103



CP Violation from Dalitz plot mirror asymmetry in $\eta \to \pi^+\pi^-\pi^0$

- *CP-violation from this process is not bounded by EDM as is the case for the $\eta \to 4\pi$ 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 $4x10^{11}$ decays (100x in stat. err.) in B-field insensitive detector*
- *New model in GenieHad (collaboration with S. Gardner & J. Shi – UK) based on* https://arxiv.org/abs/1903.11617

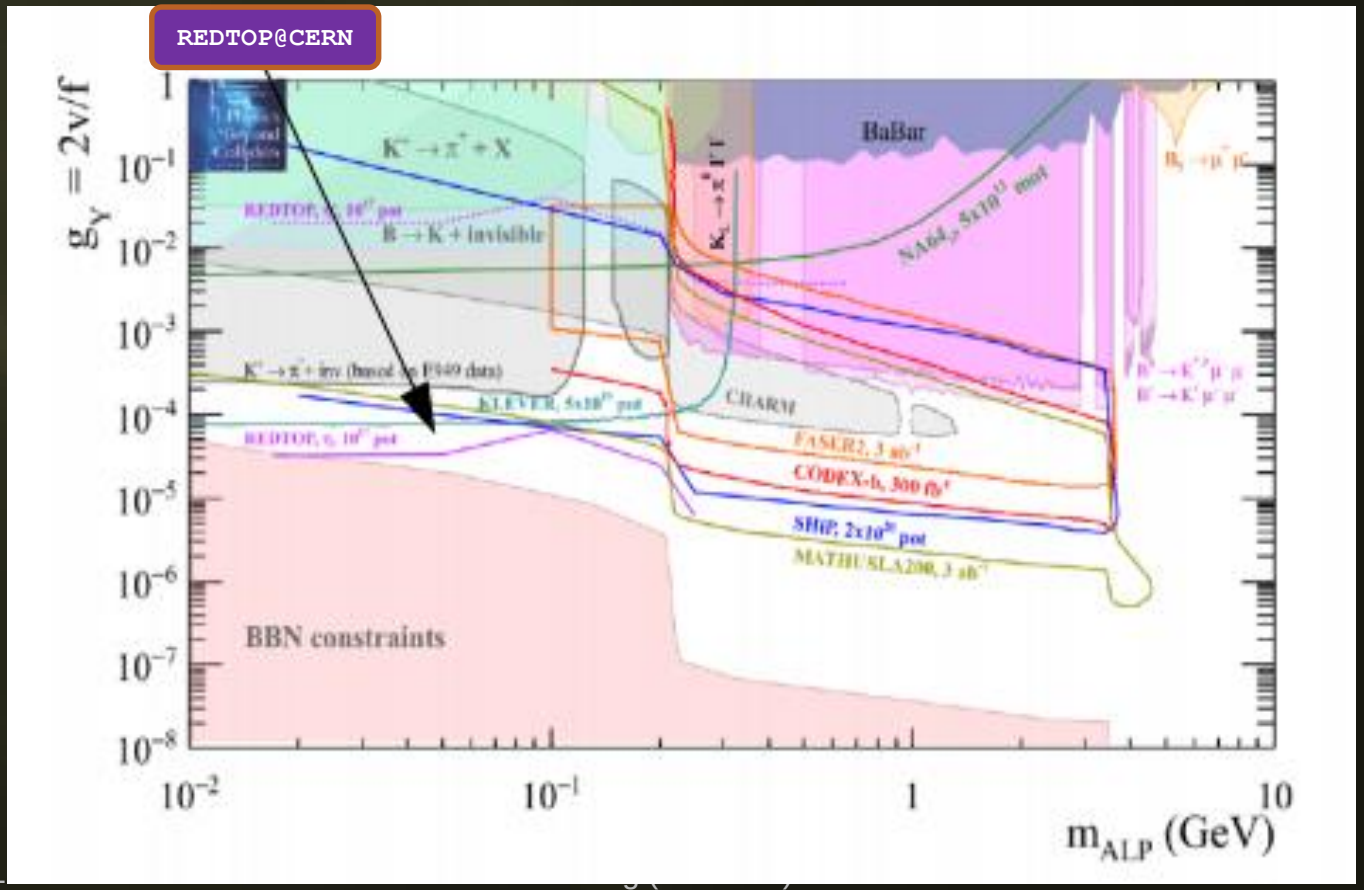




Searches for ALPs with fermion coupling

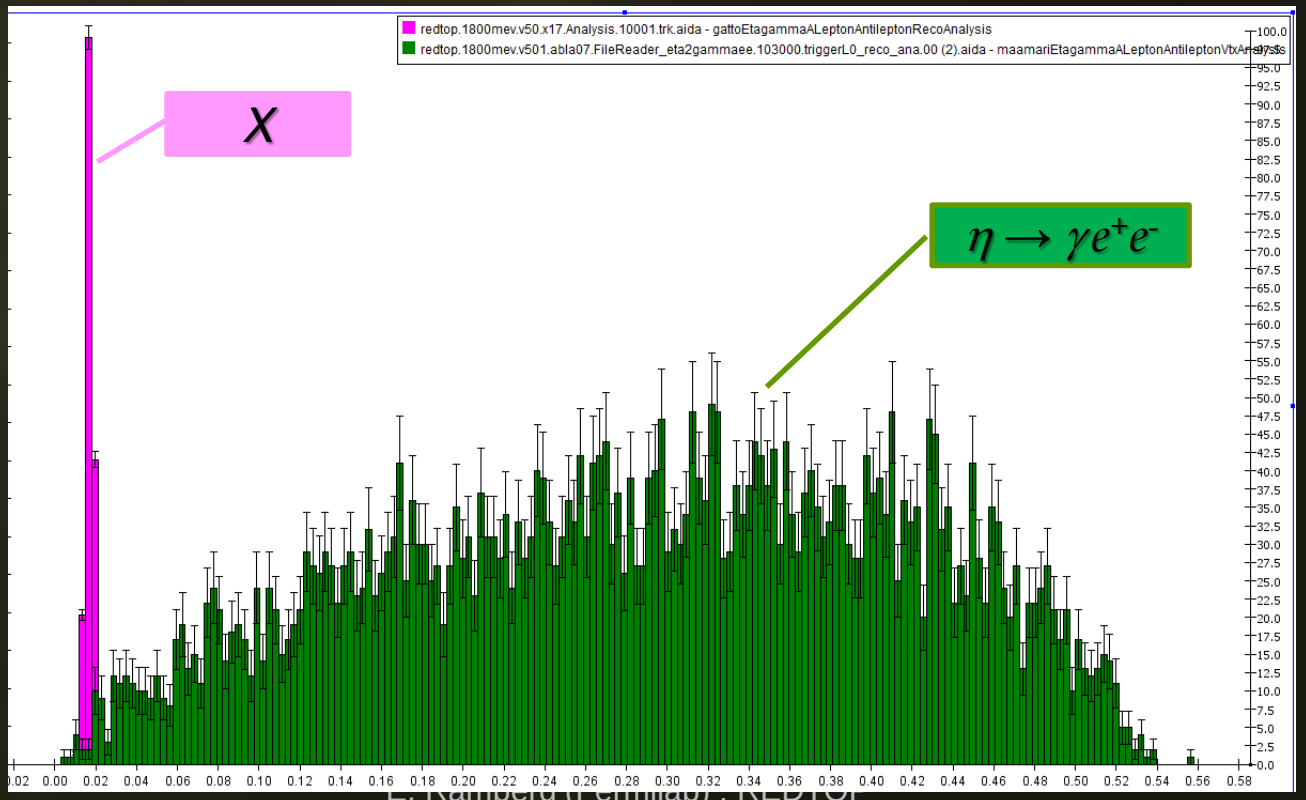
$\eta \to \pi^o \pi^o a$ and $\eta \to \pi^+ \pi^- a$ with $a \to \mu^+ \mu^-$ and $e^+ e^-$

- *Studied within the "Physics Beyond Collider" program at CERN for 10^{17} POT*
- *FNAL and BNL can provide 10x more POT*
- *Only "bump hunt analysis". Will add vertexing to the analysis.*



Special case: protophobic gauge boson X with M_X=17 MeV: $\eta \rightarrow \gamma X$ with $X \rightarrow e^+e^-$

- *Recently postulated to explain a 6.8σ anomaly in the invariant mass distributions of e^+e^- pairs produced in ^{8}Be nuclear transitions – J. Feng et al (2016) - arXiv:1608.03591*
- *Will also explain the 3.6σ discrepancy between the predicted and measured values of the muon's anomalous magnetic*
- *Below WASA (and all other η-producing experiments) sensitivity*
- *Boost from η helps to increase sensitivity to 17 MeV invariant masses*



REDTOP Requirements

- *Medium energy proton beam 1.5 – 4 GeV*
- *Proton economics:*
  - *Min: 10^{17} POT/yr - CERN*
  - *Optimal: 10^{18} POT/yr - FNAL or BNL*
  - *Produce ~10^{13} η mesons/yr – reco eff > 10%*
  - *Produce ~10^{11} η' mesons/yr– reco eff > 10%*
- *Efficient detection of the leptonic decays of the η*
- *Blind to protons and low energy charged pions.*
- *Neutron rejection (via dual-readout)*
- *near 4π detector acceptance.*

Status of the collaboration

The REDTOP collaboration

8 Countries, 23 Institutions, 67 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
Brown University, (USA)

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

Y. Alexahin, A. Pla-Dalmau, J. Dey, V. Di Benedetto, B. Dobrescu, E. Gianfelice-Wendt, E. Hahn, D. Jensen, C. Johnstone, J. Johnstone, J. Kilmer, G.Krnjaic, T. Kobilarcik, A. Kronfeld, K. Krempetz, M. May, A. Mazzacane, N. Mokhov, W. Pellico, A. Pla-Dalmau, V. Pronskikh, E. Ramberg, J. Rauch, L. Ristori, G. Sellberg, G. Tassotto

Fermi National Accelerator Laboratory, (USA)

P. Sanchez-Ouertas
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)

S. Pastore
Los Alamos National Laboratory, (USA)

M. Berlowski
National Centre for Nuclear Research – Warsaw, (Poland)

G. Blazey, M. Syphers, V. Zutshii, P. Chintalapati, T. Malla, M. Figora
Northern Illinois University, (USA)

M. Pospelov
Perimeter Institute for Theoretical Physiscs – Waterloo, (Canada)

Y. Kahn
Princeton University – Princeton, (USA)

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

B. Fabela-Enriquez
Vanderbilt University, (USA)

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)

J. Konisberg
University of Florida, (USA)

S. Gardner, J. Shi, X. Yan
University of Kentucky, (USA)

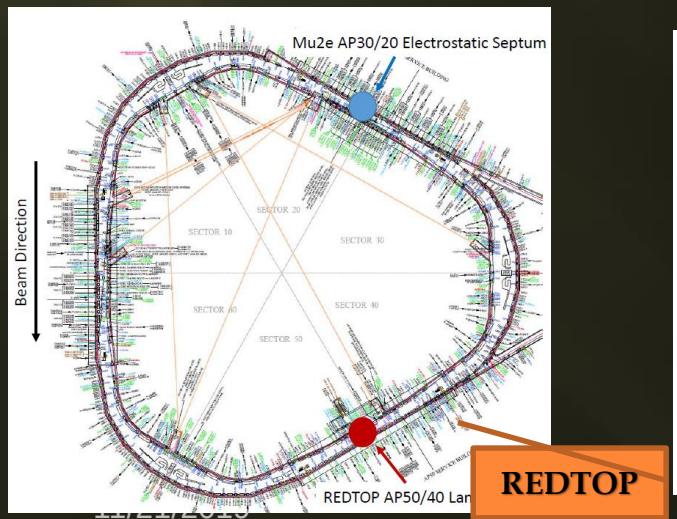
R. Rusack
University of Minnesota, (USA)

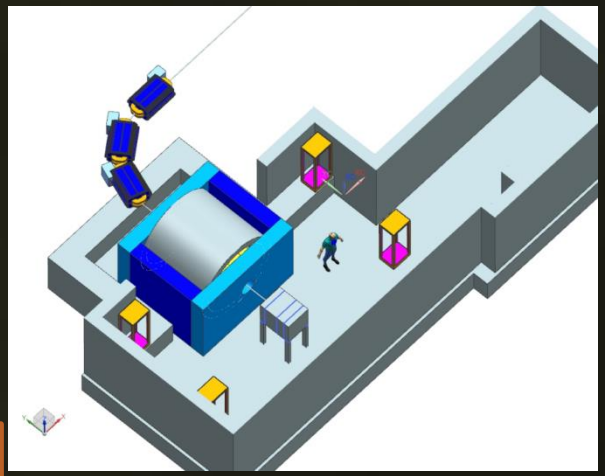
A. Kupsc
University of Uppsala, (Sweden)

- *Potential hosting laboratories: BNL, CERN, FNAL (either Delivery Ring and/or PIP-II)*

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 (~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%*





Experimental Techniques- η/η' production+detection

- Beam Characteristics:

- Incident proton energy ~1.8 GeV (3.5 GeV for h')
- CW beam, 10^{17}-10^{18} POT/yr (depending on the host laboratory)
- h/h' hadro-production from inelastic scattering of protons on Li or Be targets
- Use multiple thin targets to minimize combinatorics background
- h yield: 2.5 x 10^{6} h /sec (2.5 x 10^{4} h '/sec) or 2.5 x 10^{13} h /yr (2.5 x 10^{11} h ' /yr)

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

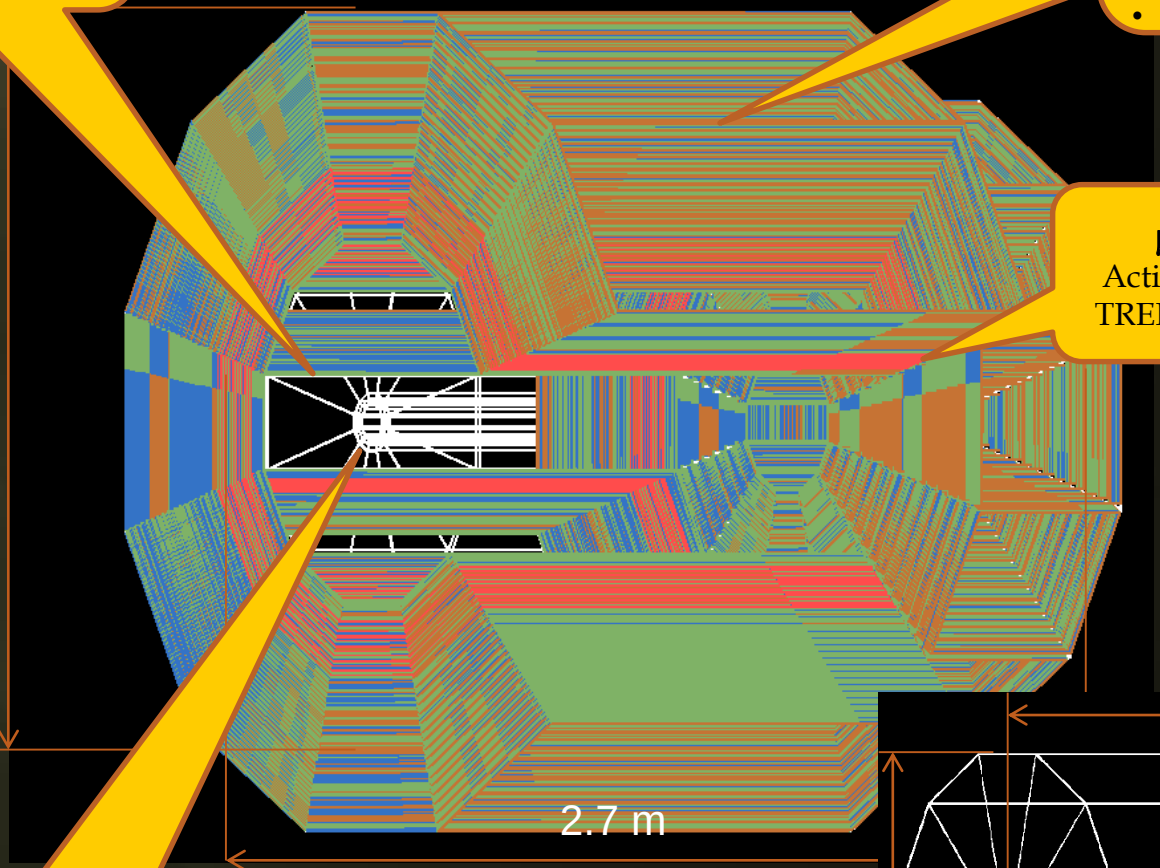
- *Use **ADRIANO2** calorimeter (Calice+T1015) for reconstructing EM showers*
- $\sigma_E/E < 5\%/\sqrt{E}$
- *PID from dual-readout to disentangle showers from γ/μ/hadrons*
- *96.5% coverage*

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

REDTOP detector (from simulation)

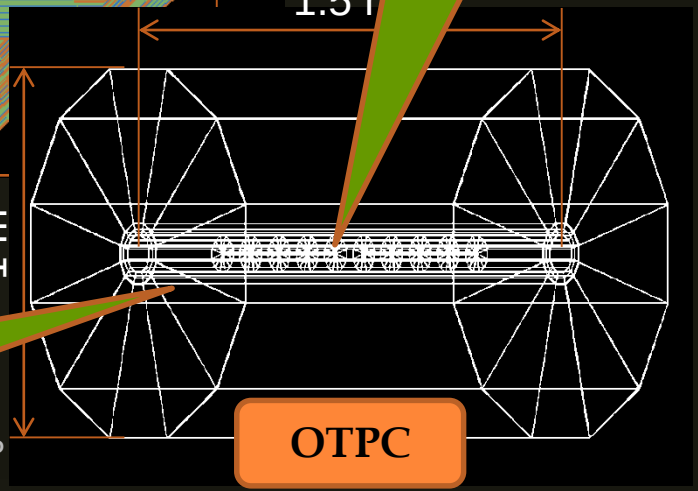
Optical TPC
- ~ 1m x 1.5 m
- CH_4 @ 1 Atm
- $5x10^5$ Sipm/Lappd
- 98% coverage

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

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



Fiber tracker
for rejection of g-conversion and vertexing

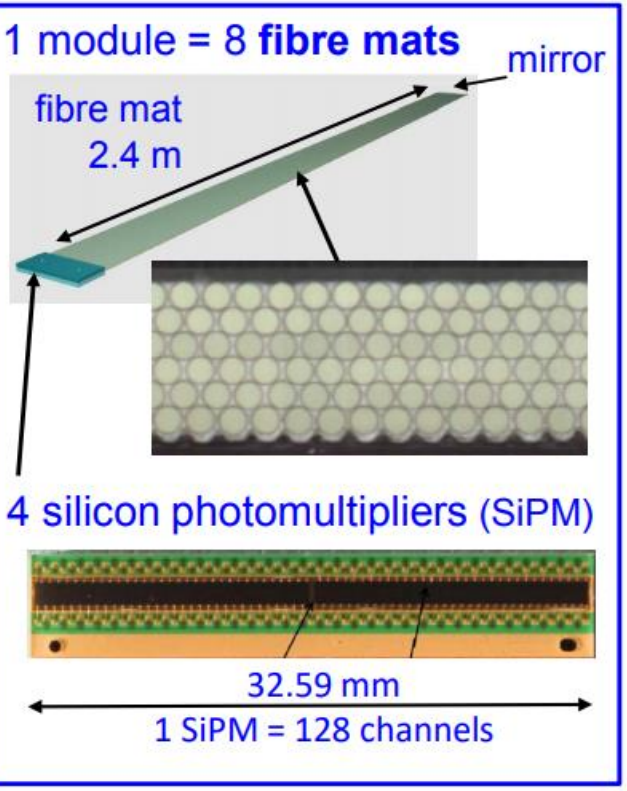
Aerogel
Dual refractive index system

OTPC

The Fiber Tracker – LHCb design

128 modules (0.5 x 5 m^2)
arranged in 3 stations × 4 layers
(XUVX)

1 module = 8 **fibre mats**



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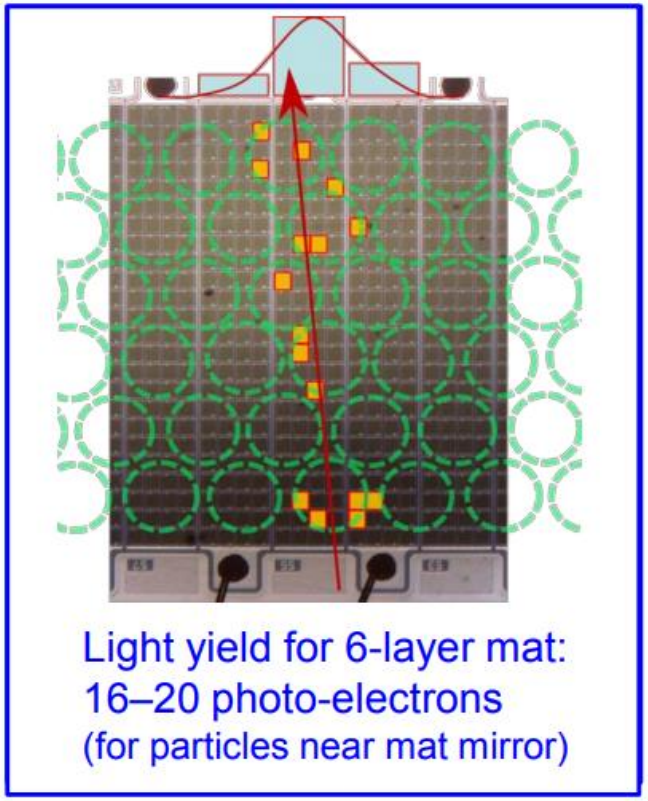
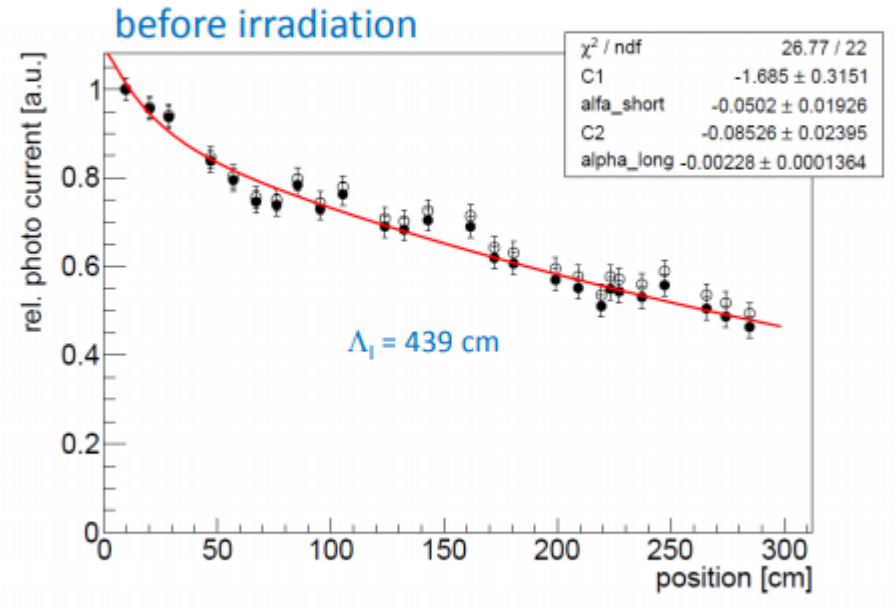
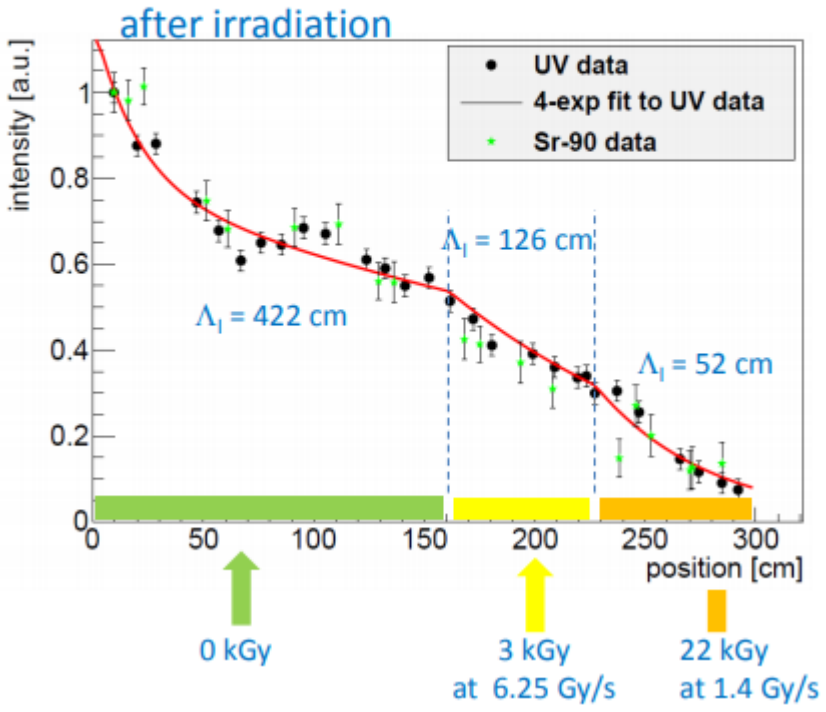


Light yield for 6-layer mat:
16–20 photo-electrons
(for particles near mat mirror)

Fiber Tracker Radiation Hardness

- 3 m long SCSF-78 fibres (Ø 0.25 mm), embedded in glue (EPOTEK H301-2)
- irradiated at CERN PS with 24 GeV protons (+ background of $5 \cdot 10^{12}$ n/cm2)



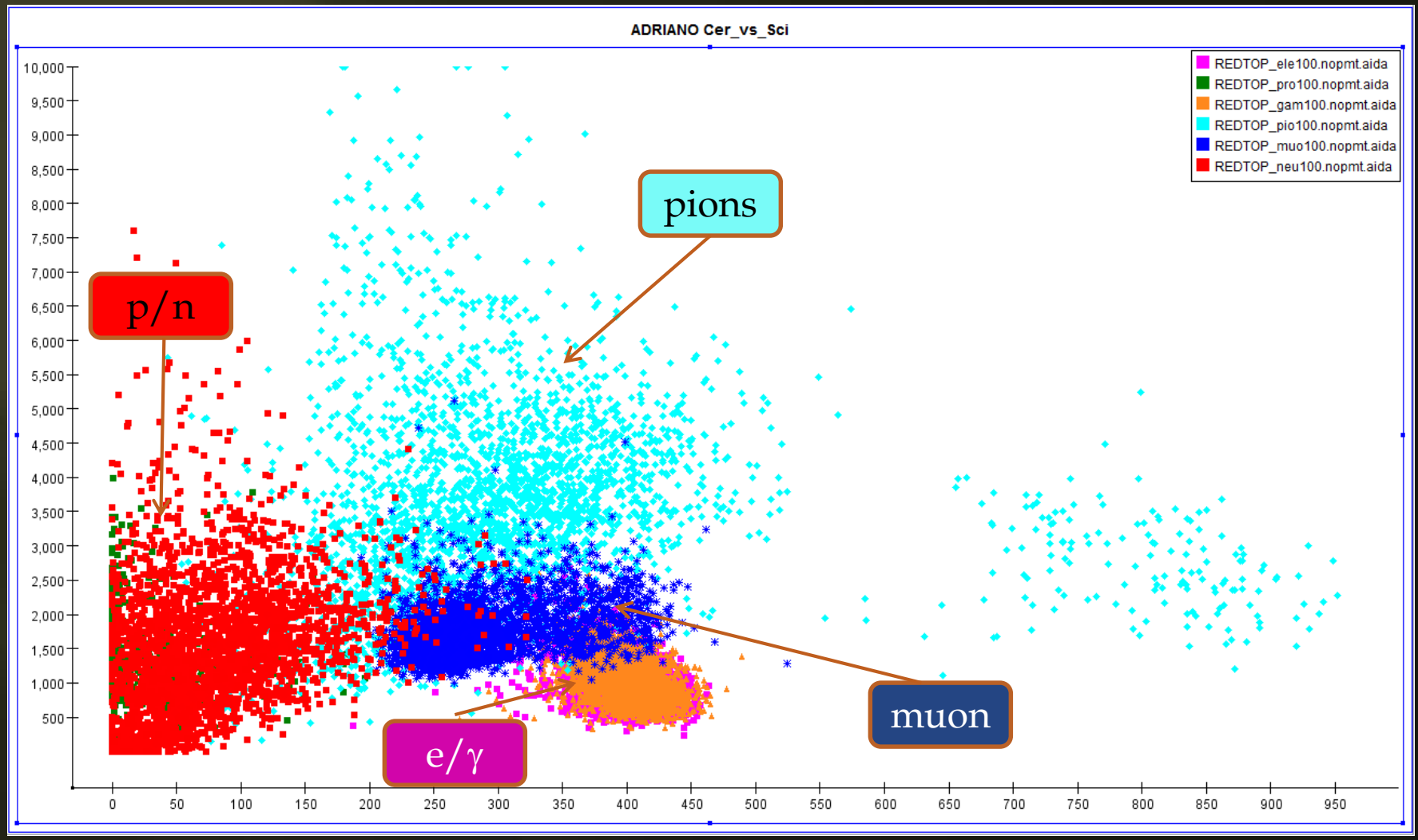


Christian Joram

Expected irradiation at REDTOP

- Worst case (forward detector): ~10^{13} n/cm^2
- Average: ~10^{12} n/cm^2

ADRIANO PID @ 100MeV

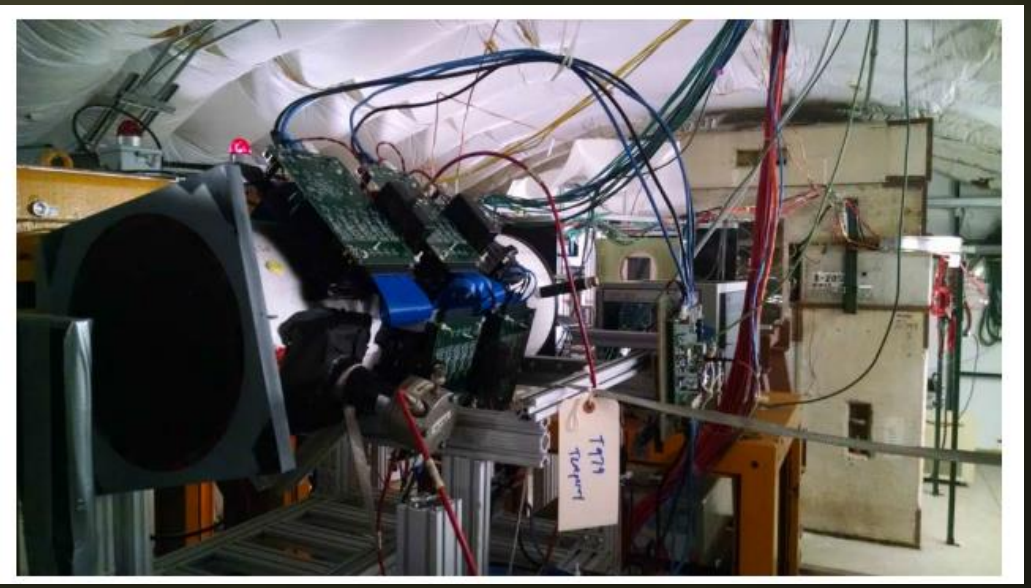


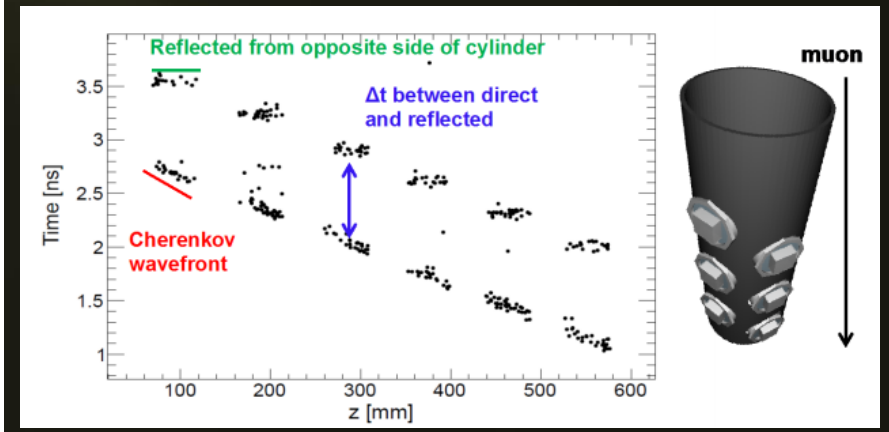
Nov. 2015 test Beam at Fermilab

Detector R&D: OTPC

Fnal –T1059 (H. Frisch, E. Oberla)

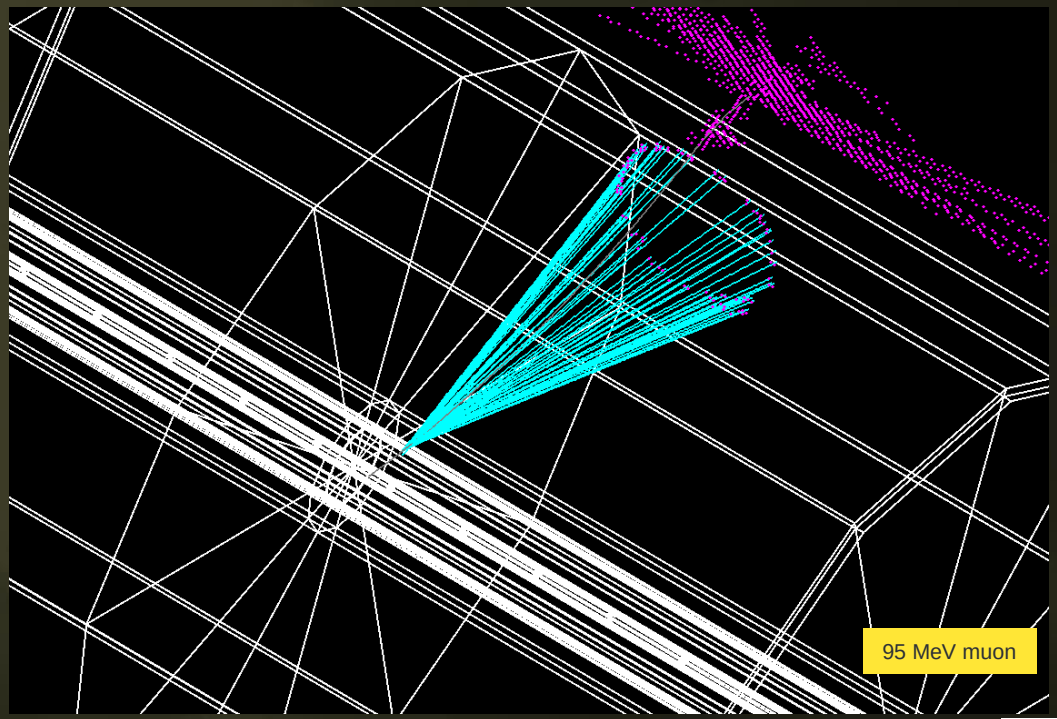
- *Successful proof of principle in 2015 at FTBF*
- *Instrumented with an MCP photo-detector, three boards each with thirty channels of 10 GSPS waveform digitizing readout*
- *http://ppd.fnal.gov/ftbf/TSW/PDF/T1059_tsw.pdf*



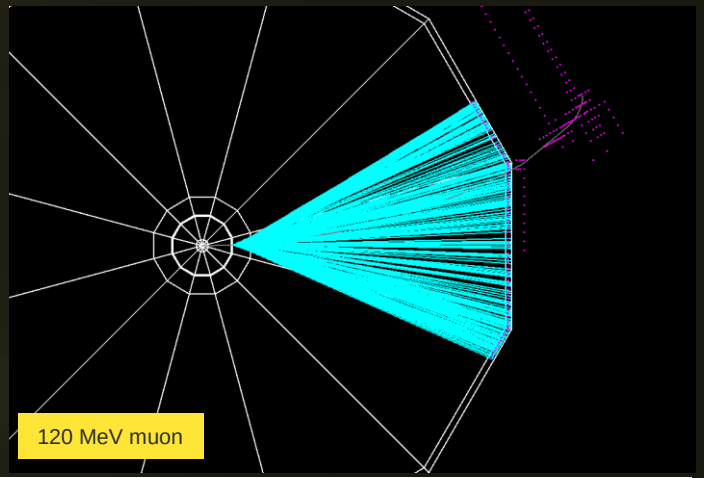


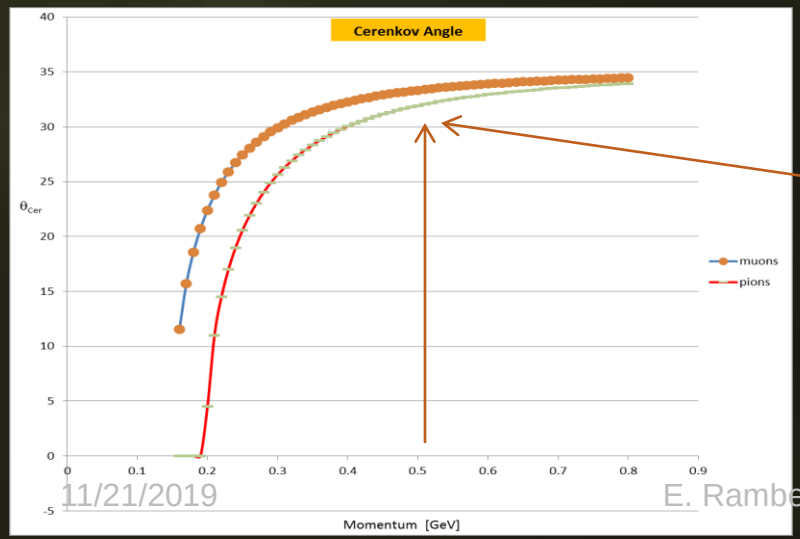
It requires a robust and dedicated R&D (LDRD)

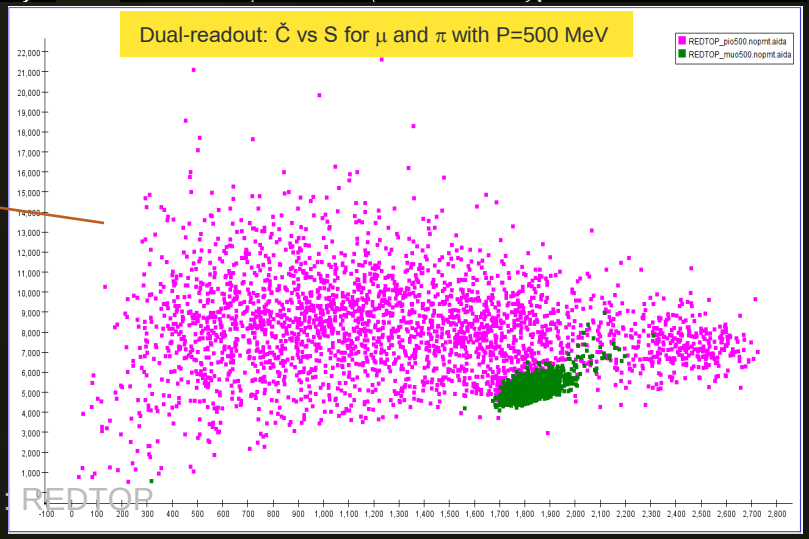
Muon/pion Detection



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







Summary

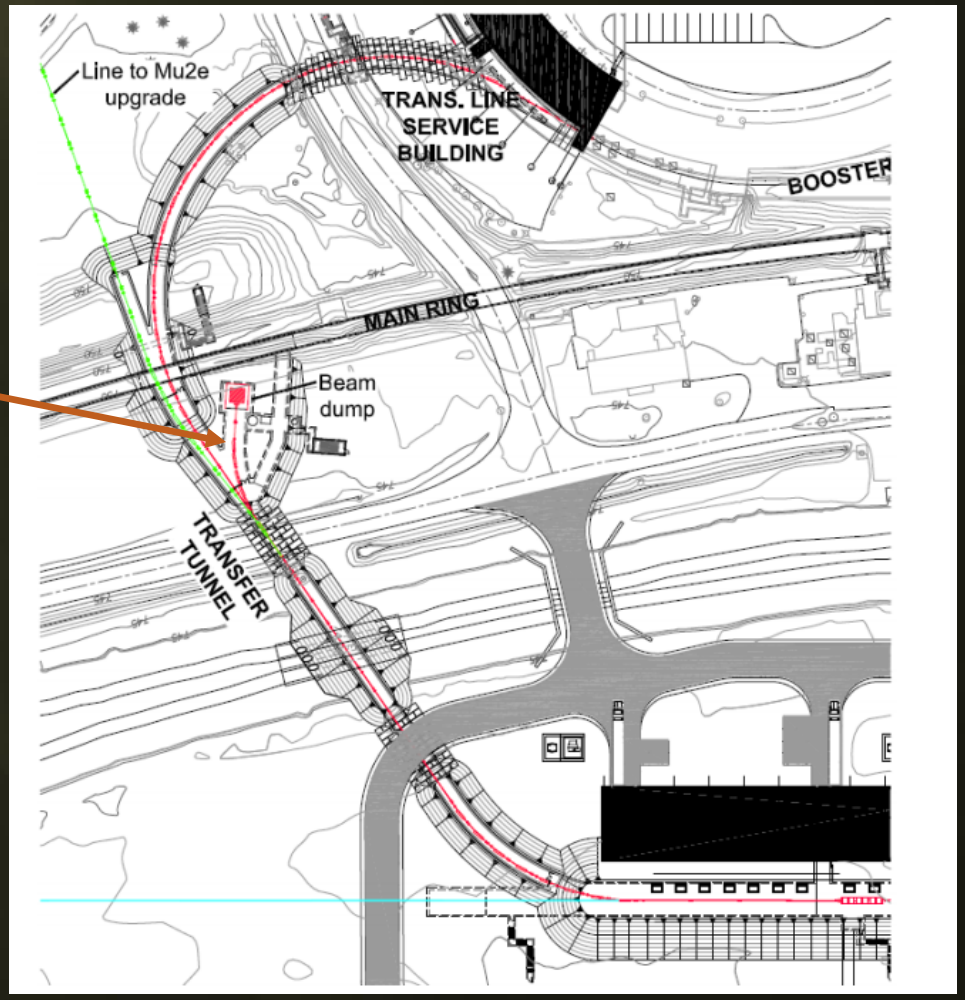
- *The η/η' meson is a excellent laboratory for studying rare processes and physics BSM (especially, LDM)*
- *Existing world sample not sufficient for breaching into decays violating conservation laws or searching for new particles*
- *REDTOP goal is to produce ~10^{13} η mesons/yr in phase I and ~ 10^{11} η' /year in phase II*
- *New detector techniques would set the stage for next generation High Intensity experiments*

- ***More details: https://redtop.fnal.gov***

Present & Future η Studies

	Technique	$\eta \to 3\pi^o$	$\eta \to e^+e^-\gamma$	*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	$pp \to \eta pp$ $pd \to \eta\, ^3He$			$>10^9$ *(untagged)* 3×10^7 *(tagged)*
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 samples				
GlueX@JLAB (just started)	$\gamma_{12\,\mathrm{GeV}} p \to \eta X$ $\to$ **neutrals**			5.5×10^7*/yr*
JEF@JLAB (recently approved)	$\gamma_{12\,\mathrm{GeV}} p \to \eta X$ $\to$ **neutrals**			3.9×10^5*/day*
REDTOP@FNAL (proposing)	$p_{1.8\,GeV} Be \to \eta X$			2.5×10^{13}*/yr*

Tagged REDTOP at PIP-II
The ultimate eta factory

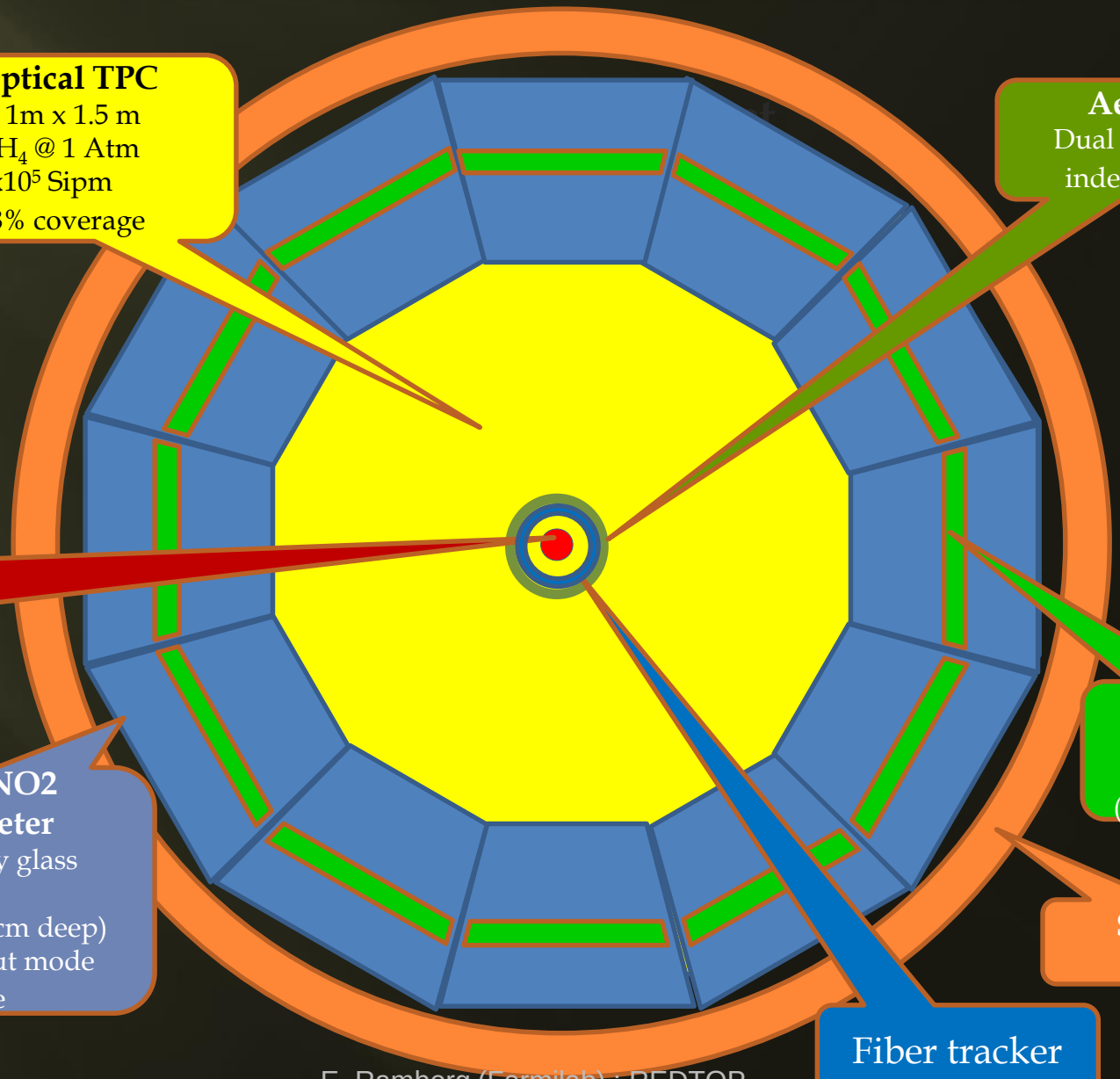


Future Prospects

- *The Collaboration is currently engaged in the ESPP process and preparing for the P5-Snowmass process*
- *Endorsement by the community and/or laboratories is needed to fund detector R&D activities*
- *Current activities aim at the preparation of a full proposal in a timeframe consistent with the ESPP and Snowmass-P5*
  - *Detector optimization and sensitivity studies are well established and ongoing. Goal is maximize $S/\sqrt{B}$*
  - *Detector R&D is minimal (ADRIANO2 only, at present)*
- *Competition from several other experiments (LHCB, et. Al.)*
  - *But, REDTOP experimental techniques is substantially different*
- ***More details: https://redtop.fnal.gov***

Backup Slides

The REDTOP Detector



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

Aerogel
Dual refractive index system

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

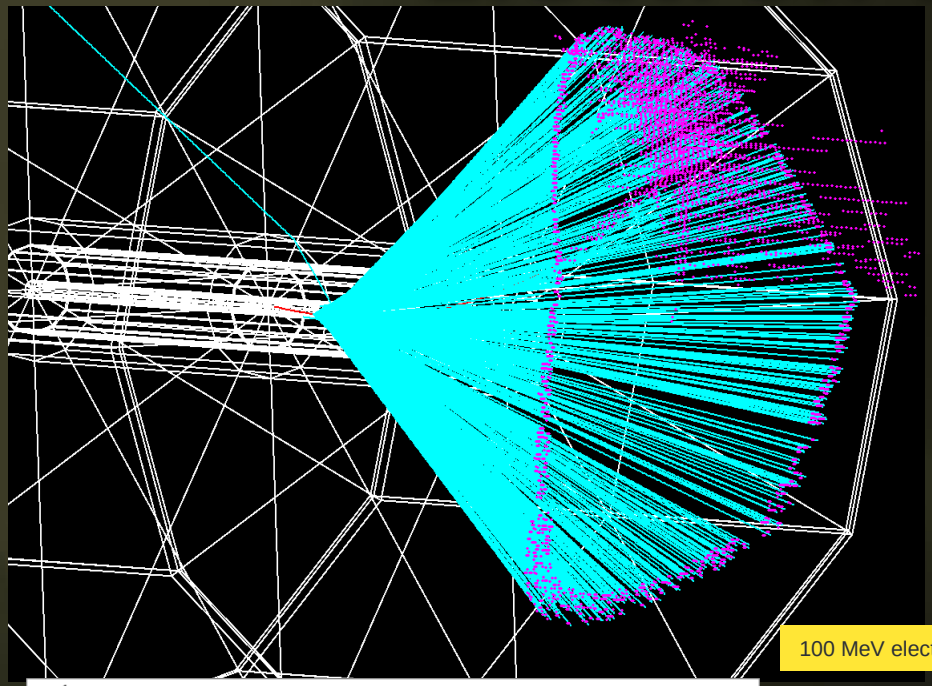
μ-polarizer (optional)
Active version (from TREK exp.)

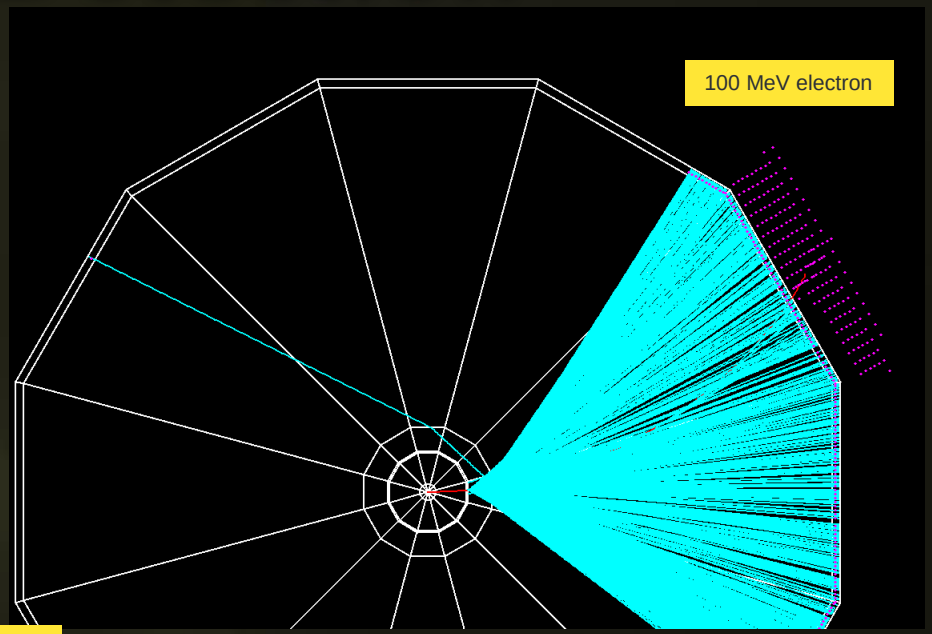
ADRIANO2 Calorimeter
- Scint. + heavy glass sandwich
- 20 X_0 (~ 64 cm deep)
- Triple-readout mode
- 96% coverage

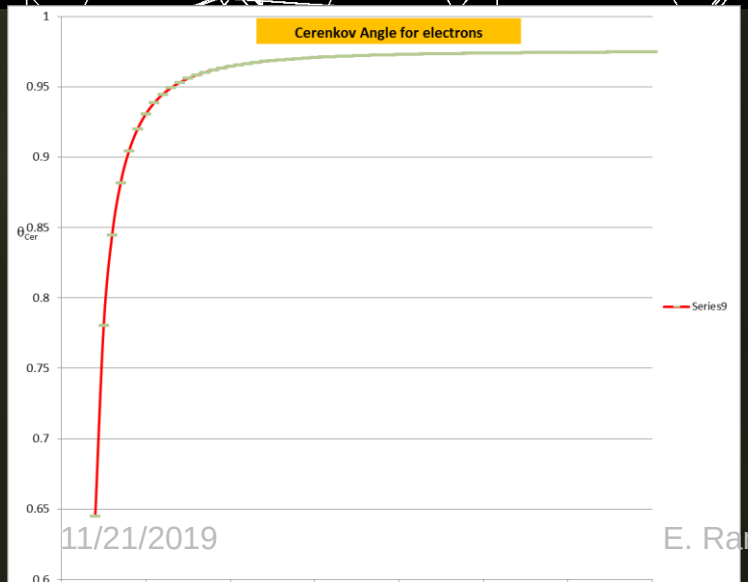
Solenoid
0.6-0.8 T

Fiber tracker

Electron Detection







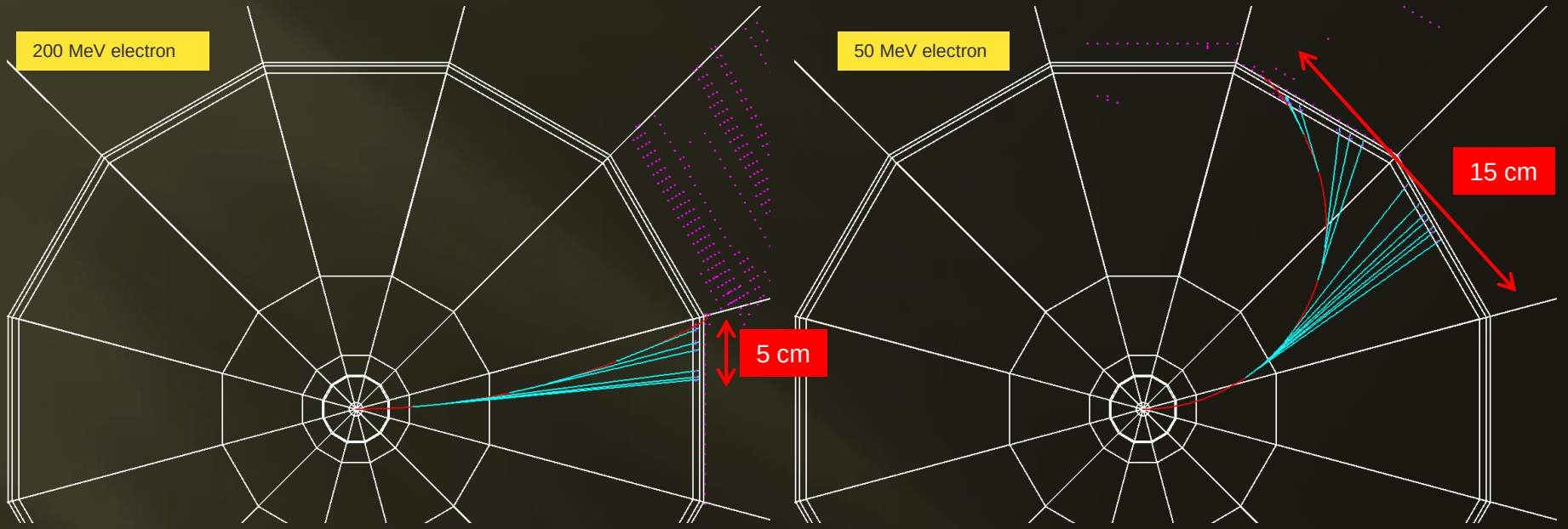
$n_D(N_2@2.7psi)=1.000145$

Č threshold for e- in N_2: P=40 mev

$n_D(aerogel1)=1.12$

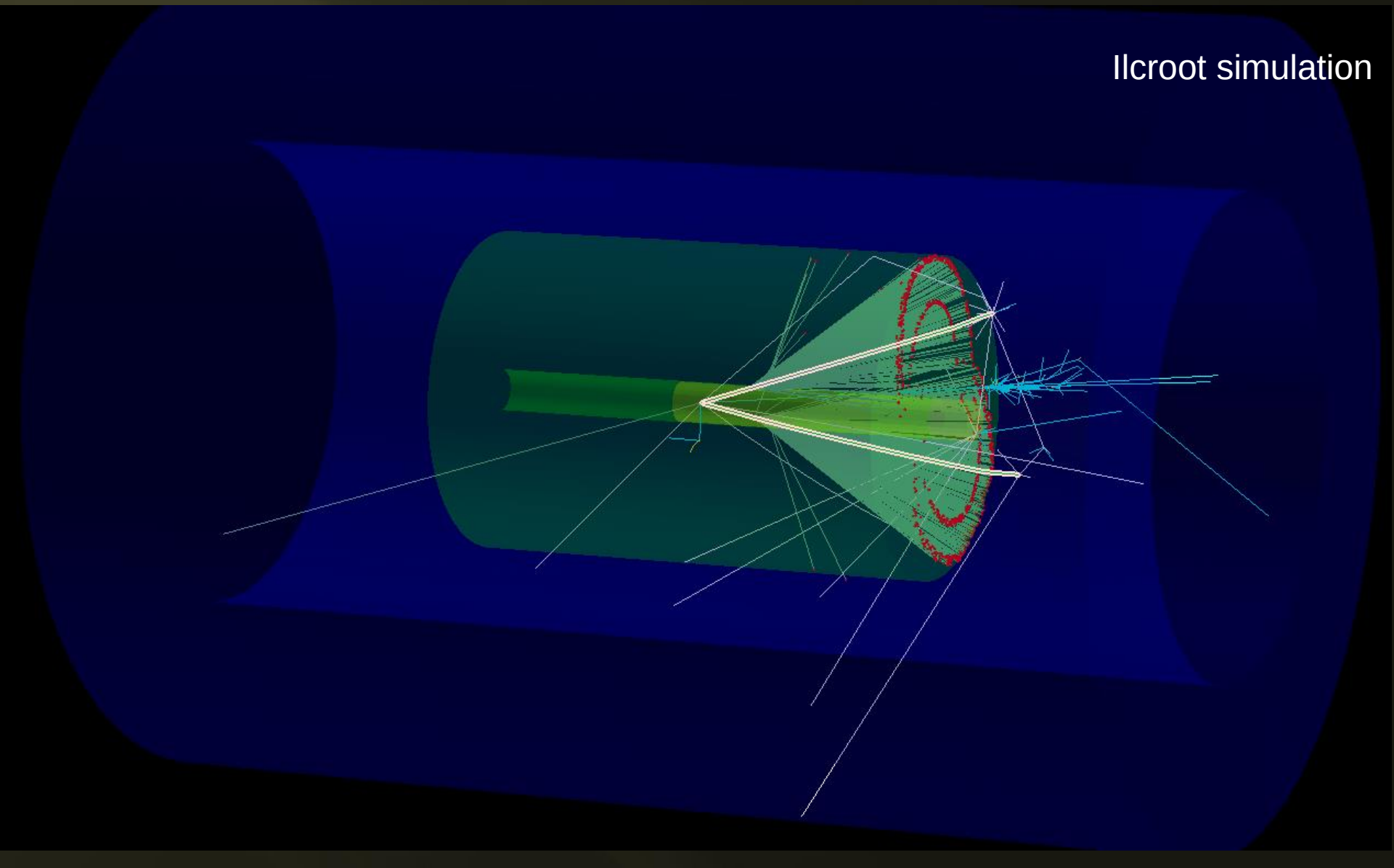
$n_D(aerogel2)=1.22$

Electron Momentum Reconstruction



- Electrons are recognized by:
  1. a large (>30 cm dia) circle of photons generated in the aerogel
  2. A sweep of photons circles with dia < 1cm and several cm long (depends on P_t)
  3. An EM shower in ADRIANO (identified by Č vs S)

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



REDTOP Possible Running Phases

- Phase I: η-factory. Goal is ~10^{13} η /yr
  - T_{beam}: 1.8-2.1 GeV
  - Power: 30 W
  - Target: 10 x 0.33 mm Be
- Phase II: η ′-factory. Goal is ~10^{11} η′ /yr
  - T_{beam}: 3.5-4.5 GeV (to be optimized)
  - Power: 60 W
  - Target: 10 x 0.33 mm Be
- Phase III: Dark photons radiating form muons. Goal is > 1.0 ×10^{13} μ/yr
  - (G. Krnjaic and Y. Kahn)
  - T_{beam}: 1< <3 GeV (to be optimized)
  - Target: H_2 gas
- Phase IV: Muon Scattering Experiment. Goal is > 2.0 ×10^{12} μ/yr
  - T_{beam}: 0.2< <0.8 GeV (to be optimized)
  - Muon yield: >1.6 ×10^{-8} μ/p
  - Target: 1 x 100 mm graphite
- Phase V: tagged REDTOP. Goal is > 2.0 ×10^{13} η/yr
  - T_{beam}: 1.2 GeV at PIP-II
  - Muon muon yield: >1.6 ×10^{-8} μ/p
  - Target: ^3H
- Phase VI: Rare Kaon Decays: $K^+ \rightarrow \pi^+ \nu \underline{\nu}$ Goal is > 1×10^{14} KOT/yr
  - T_{beam}: K^+ from 8 GeV protons
  - K^+/π yield: 1 /13 (neglecting very soft pions – factor 1.8 better than p@92 GeV)
  - Target: primary (PT: for K production) + secondary (active: scintillating plastics)

It could be made unnecessary by NA62+ and JPARC

Ongoing activities - simulations

- *Event generation*
  - *GenieHad (Genie add-on) event generator interfaces to: Urqmd, Gibuu, Phsd, Abla, Gemini, SMM, G4EM processes, Incl++, IAEA tables, LELAPS*
  - *New interfaces to JAM (JPARC) and ALPS (for PIP-II simulations) in preparation*
- *Simulation, digitization, reconstruction and analysis*
  - *Based on ILC frameworks (slic, lcsim and ilcroot)*
  - *Full simulation in place (except for OTPC-reco and vertexing)*
- *Detector optimization and sensitivity studies are ongoing*
  - *Improvement on BSM physics from detached vertices*

Ongoing activities – detector R&D

- *ADRIANO – dual readout calorimeter*
  - *ADRIANO2 prototype under construction at NIU (INFN-NIU-UMN collaboration). FNAL probably joining (J. Freeman)*
  - *Inherits from 10+ years R&D by T1015*
- *O-TPC*
  - *UC (H. Frish) only existing prorotype*
  - *Requires a more structured collaboration*
- *Fiber tracker*
  - *No R&D needed: technology is exact copy of LHCB's new tracker*
  - *In talk with Aachen-RWTH for joining*
  - *Otherwise, technology&tools transfer to REDTOP*