

REDTOP EXPERIMENT: STATUS UPDATE

*Rare Eta Decays with a
Tpc for Optical Photons*

Corrado Gatto

INFN Napoli and Northern Illinois University

For the REDTOP Collaboration

REDTOP Quest for BSM Physics

- *As LHC found no hint of new physics at high energy so far*
 - *New physics could be at much lower energy*
 - *Colliders have insufficient luminosity ($\mathcal{O}(10^{41}) \text{ cm}^{-2}$ vs $\mathcal{O}(10^{44}) \text{ cm}^{-2}$ for 1-mm fixed target)*
- *An η/η' factory with $10^4 \times$ world statistics would search for discrepancies in the Standard Model at the 1 GeV energy regime with couplings at the level of 10^{-8}*
 - *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)*

Main Physics Goals of REDTOP:

CP Violation via Dalitz plot mirror asymmetry: $\eta \rightarrow \pi^0 \pi^+ \pi^-$

Search for asymmetries in the Dalitz plot.

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 $A' \rightarrow e^+ e^-$

Scalar meson searches (charged channel): $\eta \rightarrow \pi^0 H$ with $H \rightarrow e^+ e^-$ and $H \rightarrow \mu^+ \mu^-$

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 ($\Gamma_\eta = 1.3 \text{ KeV}$ vs $\Gamma_\rho = 149 \text{ MeV}$)

Contributions from higher orders are enhanced by a factor of $\sim 100,000$

Excellent for testing invariances

- The η decays are flavor-conserving reactions



Decays are free of SM backgrounds for new physics search



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

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

Assume a yield $\sim 10^{13}$ η mesons/yr and $\sim 10^{11}$ η' mesons/yr

C, T, CP-violation

- CP Violation via Dalitz plot mirror asymmetry: $\eta \rightarrow \pi^0 \pi^+ \pi^-$
- CP Violation (Type I - P and T odd, C even): $\eta \rightarrow 4\pi^0 \rightarrow 8\gamma$
- CP Violation (Type II - C and T odd, P even): $\eta \rightarrow \pi^0 \ell^+ \ell^-$ and $\eta \rightarrow 3\gamma$
- Test of CP invariance via μ longitudinal polarization: $\eta \rightarrow \mu^+ \mu^-$
- Test of CP invariance via γ^* polarization studies: $\eta \rightarrow \pi^+ \pi^- e^+ e^-$ and $\eta \rightarrow \pi^+ \pi^- \mu^+ \mu^-$
- Test of CP invariance in angular correlation studies: $\eta \rightarrow \mu^+ \mu^- e^+ e^-$
- Test of T invariance via μ transverse polarization: $\eta \rightarrow \pi^0 \mu^+ \mu^-$ and $\eta \rightarrow \gamma \mu^+ \mu^-$
- CPT violation: μ polariz. in $\eta \rightarrow \pi^+ \mu^- \nu$ vs $\eta \rightarrow \pi^- \mu^+ \nu$ and γ polarization in $\eta \rightarrow \gamma \gamma$

New particles and forces searches

- Scalar meson searches (charged channel): $\eta \rightarrow \pi^0 H$ 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 $B \rightarrow \gamma \pi^0$
- 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 discrete symmetry violations

- Lepton Flavor Violation: $\eta \rightarrow \mu^+ e^- + \text{c.c.}$
- Double lepton Flavor Violation: $\eta \rightarrow \mu^+ \mu^+ e^- e^- + \text{c.c.}$

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})

Non- η/η' based BSM Physics

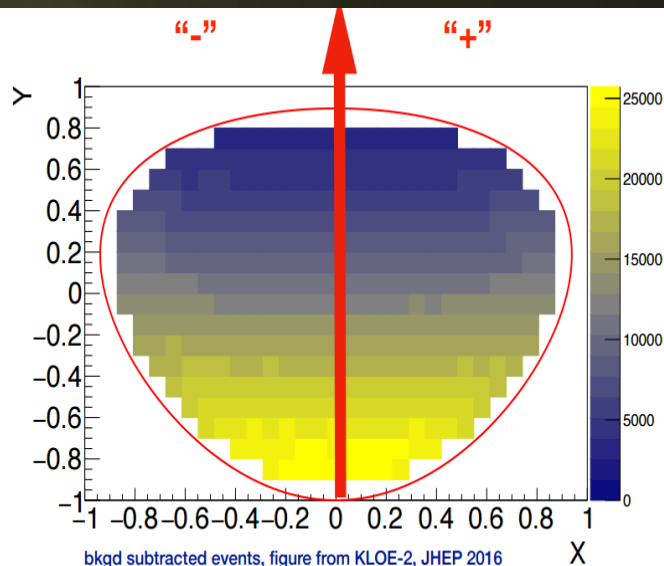
- Dark photon and ALP searches in Drell-Yan processes: $q\bar{q} \rightarrow A' / a \rightarrow l^+ l^-$
- ALP's searches in Primakoff processes: $p Z \rightarrow p Z a \rightarrow l^+ l^-$ (F. Kahlhoefer)
- Charged pion and kaon decays: $\pi^+ \rightarrow \mu^+ \nu A' \rightarrow \mu^+ \nu e^+ e^-$ and $K^+ \rightarrow \mu^+ \nu A' \rightarrow \mu^+ \nu e^+ e^-$
- Neutral pion decay: $\pi^0 \rightarrow \gamma A' \rightarrow \gamma e^+ e^-$

High precision studies on medium energy physics

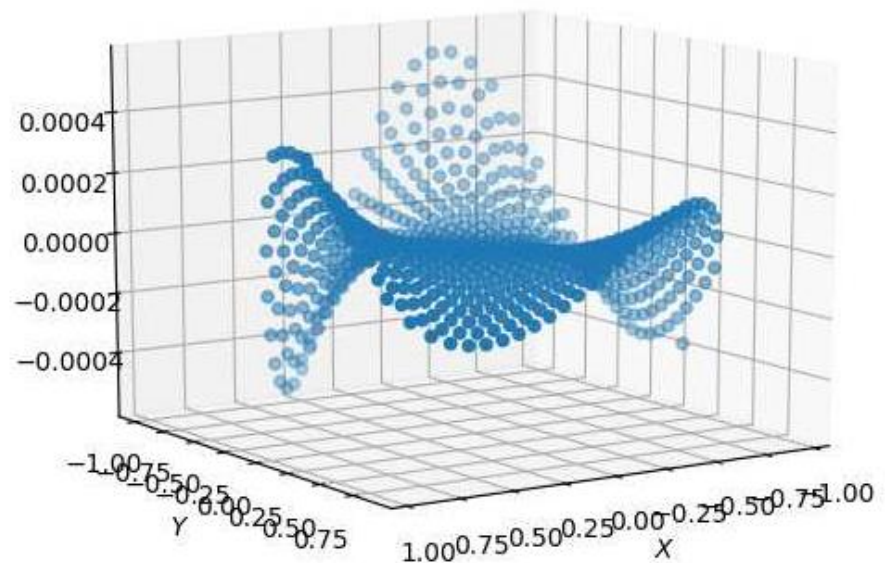
- Nuclear models
- Chiral perturbation theory
- Non-perturbative QCD
- Isospin breaking due to the u-d quark mass difference
- Octet-singlet mixing angle
- Electromagnetic transition form-factors (important input for g-2)

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

- CP-violation from this process is not bounded by EDM as is the case for the $\eta \rightarrow 4\pi$ 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 4×10^{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>



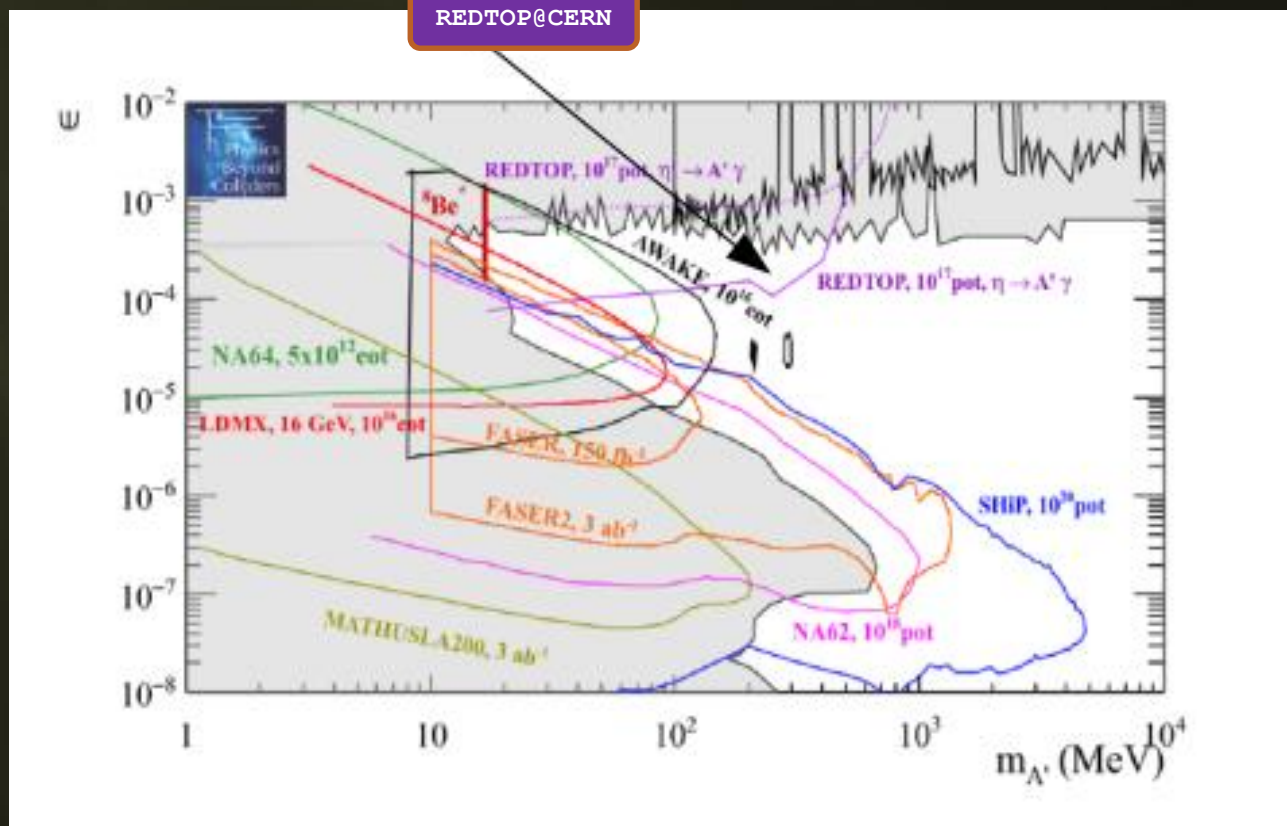
Slide Credit: Susan Gardner & Jun Shi



Dark photon searches:

$$\eta \rightarrow \gamma A' \text{ with } A' \rightarrow \mu^+ \mu^- \text{ and } e^+ e^-$$

- 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”. Studies in progress add vertexing+timing to improve the sensitivity to physics BSM.



Searches for ALPs with fermion or gluon coupling

- Beam emitted ALP's from the following processes:
 - Drell-Yan processes: $q\bar{q} \rightarrow A' / a \rightarrow l^+ l^-$
 - Proton bremsstrahlung processes: $p N \rightarrow p N A' / a$ with $A' / a \rightarrow l^+ l^-$ (J. Blümlein and J. Brunner)
 - Primakoff processes: $p Z \rightarrow p Z a \rightarrow l^+ l^-$ (F. Kahlhoefer, et. Al.)
- Only “bump hunt analysis” with 10^{17} POT (CERN). Will add vertexing+timing to the analysis.
- Redtop@PIP-II will provide $\times 100$ sensitivity (ALPACA study).

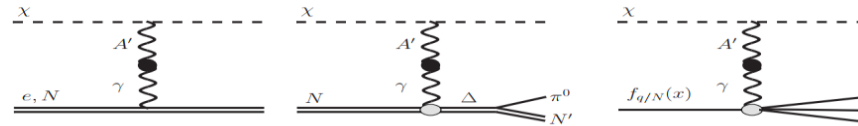
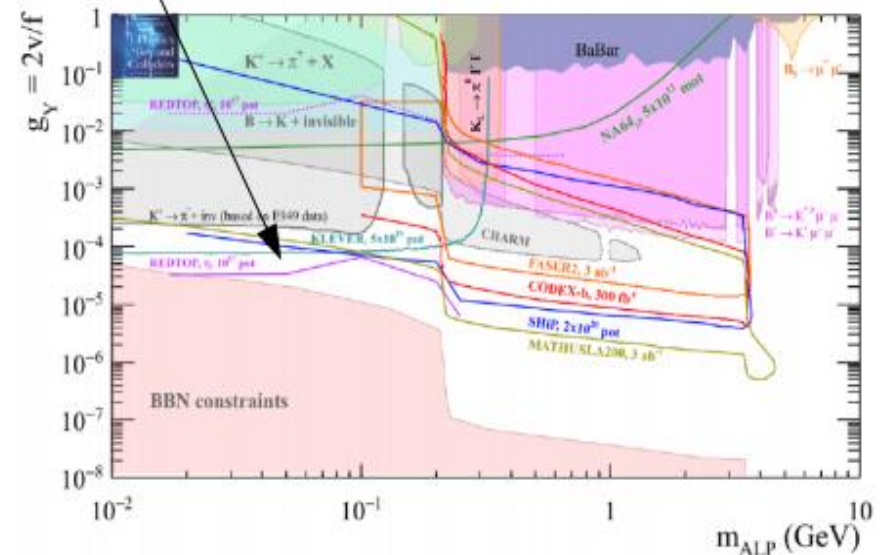
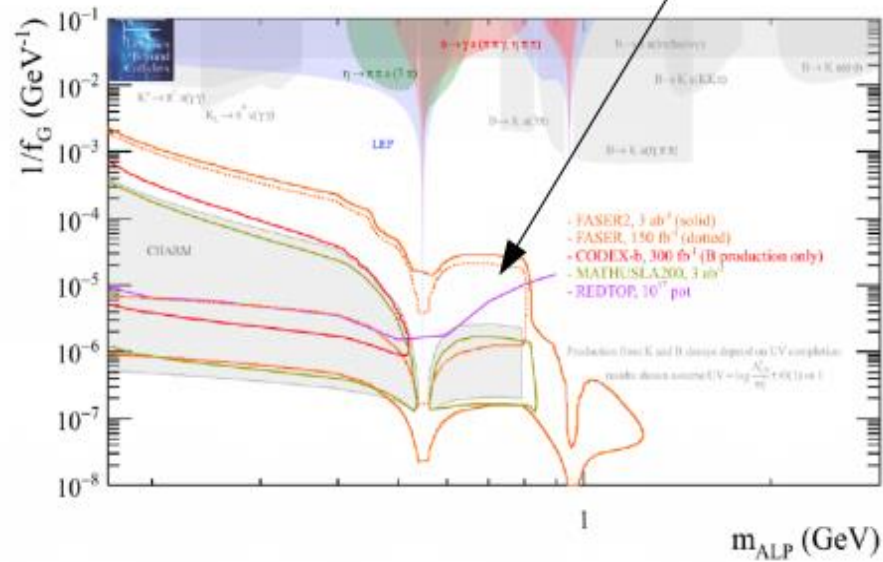


FIG. 4. Scattering channels analyzed: from left to right, elastic scattering on electrons or nucleons, quasielastic (incoherent) single pion production, and deep inelastic scattering.

Patrick deNiverville,¹ Chien-Yi Chen,^{1, 2} Maxim Pospelov,^{1, 2} and Adam Ritz¹

REDTOP@CERN


REDTOP@CERN




Experimental Techniques- η/η' production+detetection

- ❑ Incident proton energy ~ 1.8 GeV (3.5 GeV for η')
- ❑ CW beam, 10^{17} - 10^{18} POT/yr (depending on the host laboratory)
- ❑ η/η' hadro-production from inelastic scattering of protons on Li or Be targets
- ❑ Use multiple thin targets to minimize combinatorics background

charged tracks detection

- ❑ Use Cerenkov effect for tracking charged particles
- 
- ❑ Baryons and most pions are below \checkmark 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 ($\sim 70\mu\text{m}$ resolution)

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 $\sim 10^{13}$ η mesons/yr – reco eff > 10%*
 - *Produce $\sim 10^{11}$ 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.*

REDTOP detector

Optical TPC

- $\sim 1\text{ m} \times 1.5\text{ m}$
- CH_4 @ 1 Atm
- 5×10^5 Sipm/Lappd
- 98% coverage

ADRIANO2

Calorimeter (tiles)

- Scint. + heavy glass sandwich
- $20 X_0$ ($\sim 64\text{ cm}$ 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

Aerogel

Dual refractive index system

OTPC

Fiber tracker

for rejection of g-conversion and vertexing

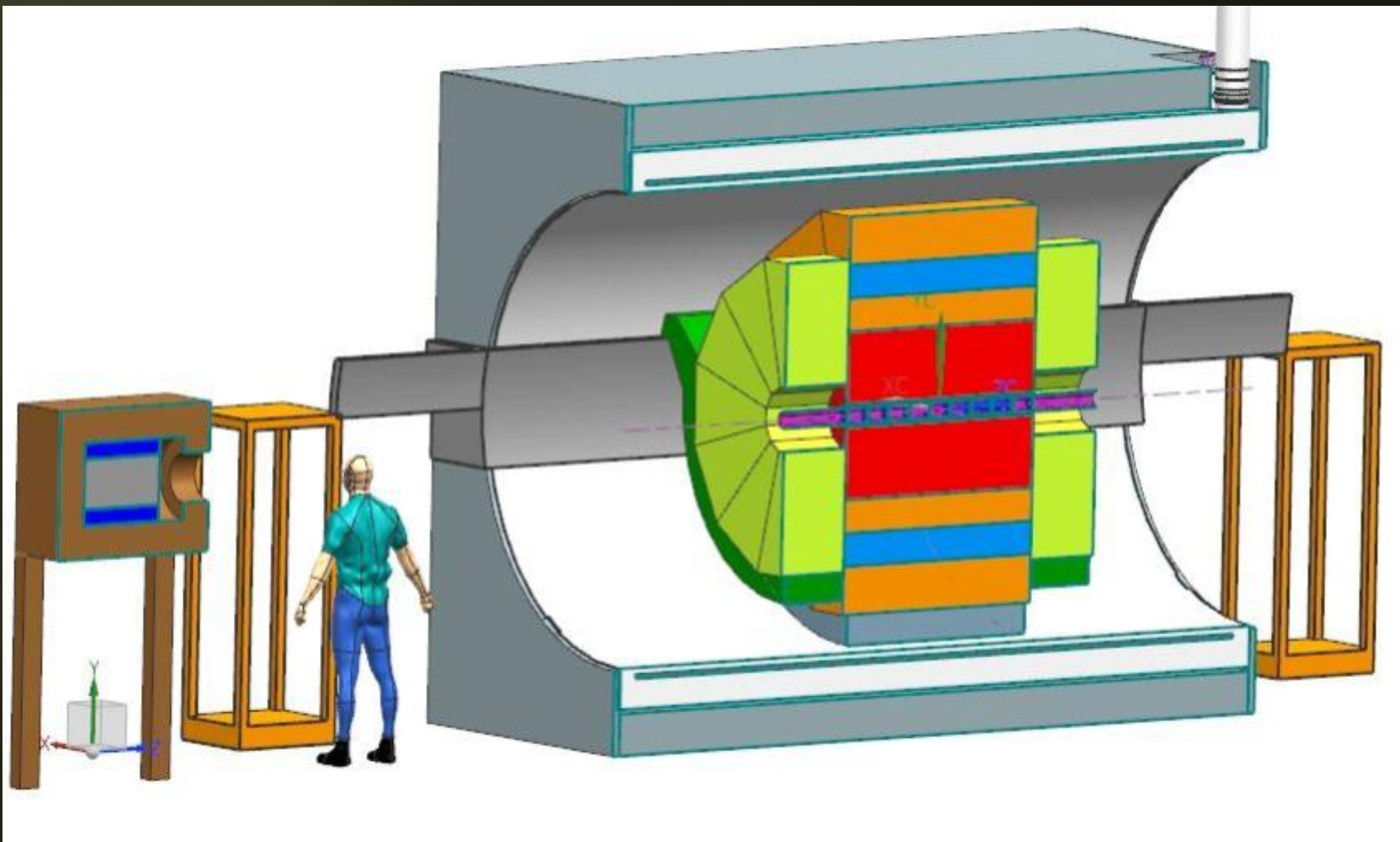
2.4 m

2.7 m

1.5 m

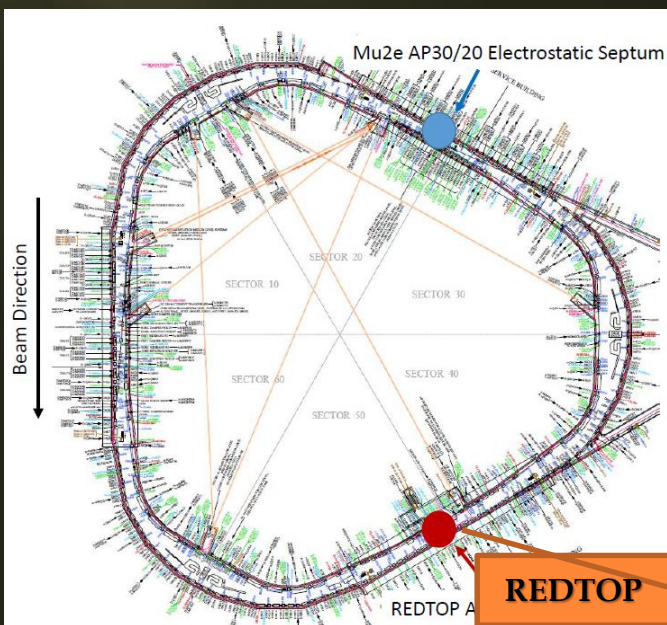
1 m

REDTOP Detector+ Magnet



Acceleration Scheme (M. Syphers)

- *Single p pulse from booster ($\leq 4 \times 10^{12}$ 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° 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 $\sim 80\%$*



Expected η/η' Yield

- Assume: 1×10^{11} POT/sec – CW
 - Beam power @ 3 GeV: 10^{11} p/sec \times 1.9 GeV \times 1.6×10^{-10} J/GeV = 30 Watts (48 W for η')
- Target system : 10 x 0.33mm Be or 0.5 mm Li foils, spaced 10 cm apart
 - Be is thinner (better vertex resolution) but makes more primary hadrons (final state hadron multiplicity $\approx A^{1/3}$)
 - Prob($p + \text{target} \rightarrow X$) \sim 0.5% or 5×10^8 p-Be inelastic collisions per second



- p-inelastic production: 5×10^8 evt/sec (1 interaction/2 nsec in any of the 10 targets)
- Probability of 2 events in the same target in 2 nsec: 7%
- η production: 2.5×10^6 η /sec (2.5×10^4 η' /sec) or 2.5×10^{13} η /yr (2.5×10^{11} η' /yr)
- Preliminary di-lepton reconstruction efficiency (no-vertexing/timing): 30-50%
- Preliminary background rejection (no-vertexing/timing): $< 10^{-8}$ (from QCD) or $\approx 0.1\%$ from η (need to improve 100x with vertexin+timing)

Timeline & Costing

- ▣ *Once approved and funded, REDTOP needs:*
 - 2-3 years detector R&D
 - 1 year detector design
 - 2-3 yrs construction
- ▣ *Accelerator mods requires:*
 - BNL: <1yr (only requiring a new electronics for the extraction line (C4))
 - CERN: need further studies
 - FNAL: ~1yr (add a SC cavity to the DR and build an extraction line)
- ▣ *Total cost (for ESPP): ~50 M\$ (including 50% contingency)*
 - Solenoid and $\frac{3}{4}$ of Pb-Glass for ADRIANO in-kind contributions from INFN (Finuda and NA64 experiments)
 - Construction at participating institutions
 - Assembly at hosting laboratory

Cost (estimate for ESPP)

- ❑ *In kind contribution from INFN*
 - ❑ *Solenoid (from Finuda experiment at Frascati)*
 - ❑ *$\frac{3}{4}$ of Pb-glass (from NA62)*

Solenoid	0.2
Refurbishing, shipping	0.2
Supporting structure	1.0
Target+beam pipe	0.5
Fiber tracker	0.93
Fiber mats	0.01
Tooling	0.45
SiPM array	0.1
Front-end electronics	0.12
Back-end electronics	0.05
Mechanics and cooling	0.2
Optical-TPC	10.0
Vessel	0.5
Aerogel	1.0
Photo-sensors (LAPPD option)	6.0
Front-end electronics	1.8
Back-end electronics	0.7

ADRIANO2	16.0
Pb-glass	2.7
Cast scintillator	0.75
Tile fabrication	0.6
SiPM	6.0
Front-end electronics	4.0
Back-end electronics	1.5
Mechanics and cooling	0.5
Trigger	1.2
L0 + L1	1.0
L2 farm + networking	0.2
DAQ	5.0
Digitizer	
Networking	
Contingency	17.0
50% Contingency	17.0
Total REDTOP	51.3

- ❑ *For Fermilab*
 - ❑ *Add labor and accelerator (R.F.cavities and EM septum are available at Fermilab)*
 - ❑ *Adjust contingency from 50% to 25%*

Status of the collaboration

The REDTOP collaboration

8 Countries, 23 Institutions, 67 Collaborators

J. Comfort, P. Mauskopf, D. McFarland, L. Thomas
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J. Kilmer, G. Krnjaic, T. Kobilarcik, A. Kronfeld, K. Krempetz, M. May, A. Mazzacane, N. Mokhov, W. Pellico, A. Pla-Dalmau, V. Pronskikh,
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L. E. Marcucci⁴
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M. Guida³
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 DR and/or PIP-II)*

Future Prospects

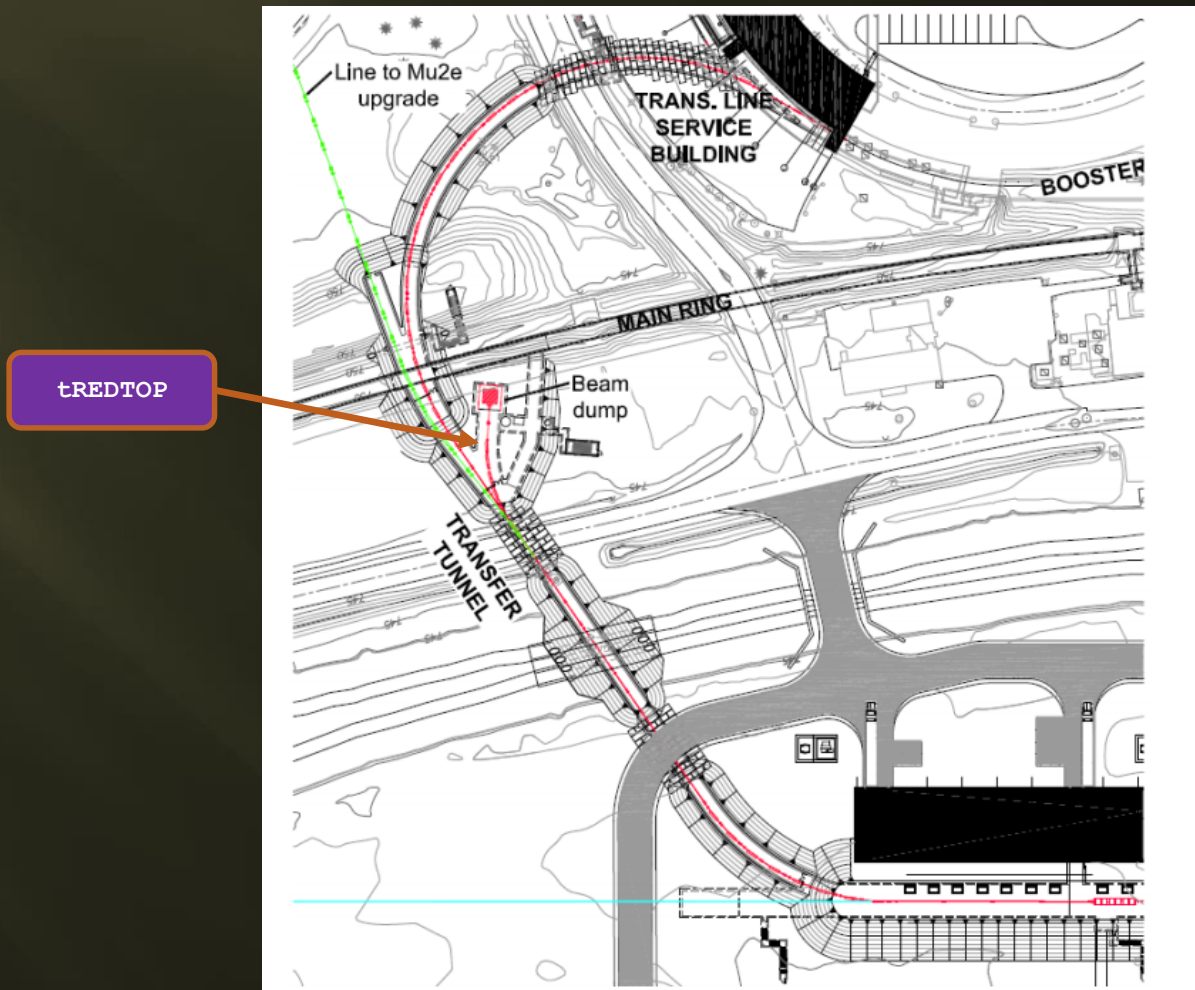
- ▣ *The Collaboration is currently engaged in the ESPP process and preparing for the P5-Snowmass process*
- ▣ *Endorsement by the community and/or laboratories is needed to fund detector R&D activities*
- ▣ *Current activities aim at the preparation of a full proposal in a timeframe consistent with 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>***

Summary

- ▣ *The η/η' meson is an excellent laboratory for studying rare processes and physics BSM*
- ▣ *Existing world sample not sufficient for breaching into decays violating conservation laws or searching for new particles*
- ▣ *REDTOP goal is to produce $\sim 10^{13}$ η mesons/yr in phase I and $\sim 10^{11}$ η' /year in phase II*
- ▣ *More running phases could use different beam species:*
 - *PIP-II for a tagged- η experiment*
- ▣ *Several labs could host the experiment (FNAL is the most optimal)*
- ▣ *New detector technique would set the stage for next generation High Intensity experiments*
- ▣ *Moderate cost (50-60 M\$)*

Tagged REDTOP at PIP-II

The ultimate eta factory



Backup slides

History of the Project

❑ *Dec. 2014*

- ❑ *Born at FTBF (A. M., C. G. , H. F.)*

❑ *Sept. 2017*

- ❑ *LOI submitted to Fermilab's PAC in Sept. 2017*
- ❑ *PAC did not at this time*
- ❑ *Fermilab's Director recommended a two-year waiting period (still ongoing).*

❑ *Jan. 2018*

- ❑ *REDTOP admitted into the "Physics Beyond Colliders" program to explore a possible implementation at CERN*
- ❑ *Near full simulations studies indicate very good sensitivity studies to physics BSM for 3 out of 4 "portals"*
- ❑ *Final report from PBC indicate that the experiment is feasible at CERN, but with lower (1/10x) beam luminosity and larger impact on existing physics program cfr. FNAL*

❑ *Dec. 2018*

- ❑ *EOI submitted to European Strategy for Particle Physics*

❑ *Apr. 2019*

- ❑ *Fermilab SAC's considered REDTOP among the projects of interest for Snowmass-P5*

Timeline & Costing

- ▣ *Once approved and funded, REDTOP needs:*
 - 2 years detector R&D (could be done before formal approval)
 - 1 year detector design
 - 2-3 years construction+commissioning
- ▣ *Accelerator mods required:*
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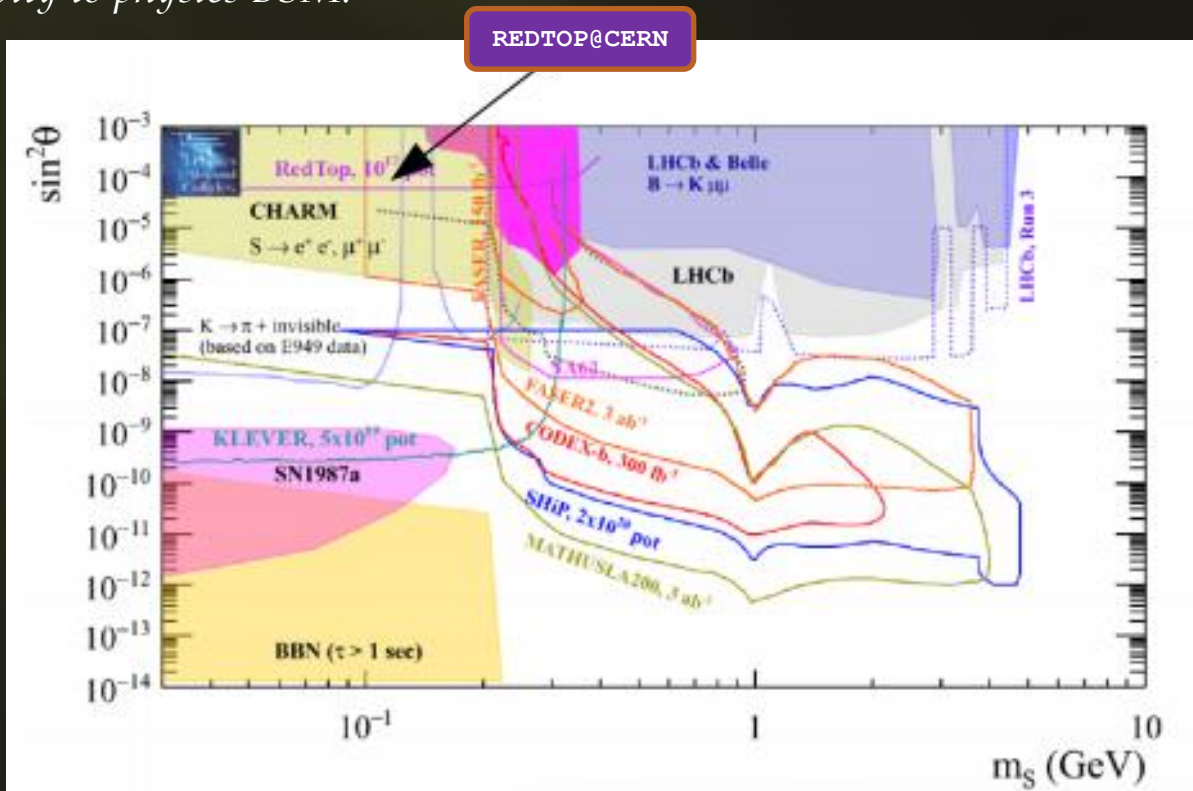
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 - *But, REDTOP experimental techniques is substantially different*
- ▣ ***More details: <https://redtop.fnal.gov>***

Searches for light scalar mesons

$$\eta \rightarrow \pi^0 H \quad \text{with } H \rightarrow \mu^+ \mu^- \text{ and } e^+ e^-$$

- Viable DM candidate (in certain circumstances) coupling to Higgs portal - M. Pospelov, A. Ritz and M. Voloshin, *Phys. Rev. D* 78, 115012 (2008)
- 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”. Studies in progress add vertexing+timing to improve the sensitivity to physics BSM.



Present & Future η Samples

	Technique	$\eta \rightarrow 3\pi^0$	$\eta \rightarrow e^+e^-\gamma$	Total η
CB@AGS	$\pi^- p \rightarrow \eta n$	9×10^5		10^7
CB@MAMI-B	$\gamma p \rightarrow \eta p$	1.8×10^6	5000	2×10^7
CB@MAMI-C	$\gamma p \rightarrow \eta p$	6×10^6		6×10^7
KLOE	$e^+e^- \rightarrow \Phi \rightarrow \eta\gamma$	6.5×10^5		5×10^7
WASA@COSY	$pp \rightarrow \eta pp$ $pd \rightarrow \eta {}^3\text{He}$			$>10^9$ (untagged) 3×10^7 (tagged)
CB@MAMI 10 <i>wk</i> (proposed 2014)	$\gamma p \rightarrow \eta p$	3×10^7	1.5×10^5	3×10^8
Phenix	$d \text{ Au} \rightarrow \eta X$			5×10^9
Hades	$pp \rightarrow \eta pp$ $p \text{ Au} \rightarrow \eta X$			4.5×10^8
<i>Near future samples</i>				
GlueX@JLAB (just started)	$\gamma_{12 \text{ GeV}} p \rightarrow \eta X$ $\rightarrow \text{neutrals}$			$5.5 \times 10^7/\text{yr}$
JEF@JLAB (recently approved)	$\gamma_{12 \text{ GeV}} p \rightarrow \eta X$ $\rightarrow \text{neutrals}$			$3.9 \times 10^5/\text{day}$
REDTOP@FNAL (proposing)	$p_{1.8 \text{ GeV}} \text{ Be} \rightarrow \eta X$			$2.5 \times 10^{13}/\text{yr}$

Cost (estimate for ESPP)

- ❑ *In kind contribution from INFN*
 - ❑ *Solenoid (from Finuda experiment at Frascati)*
 - ❑ *$\frac{3}{4}$ of Pb-glass (from NA62)*

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Networking	
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Accelerator Physics Issues

■ Transition Energy

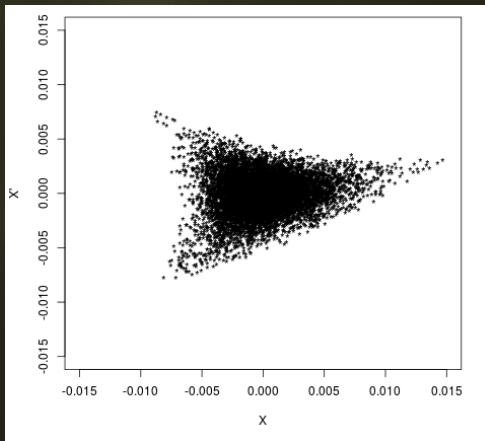
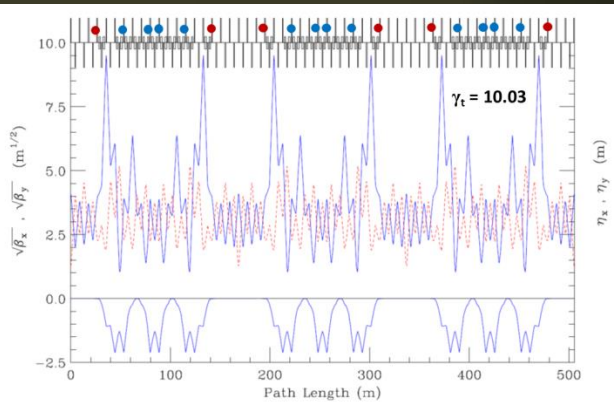
- γ_t is where $\Delta f/f = 1/\gamma^2 - \langle D/\rho \rangle = 0$; synchrotron motion stops momentarily, can often lead to beam loss
- beam decelerates from $\gamma = 9.5$ to $\gamma = 3.1$
- original Delivery Ring $\gamma_t = 7.6$
- a re-powering of 18 quadrupole magnets can create a $\gamma_t = 10$, thus avoiding passing through this condition
 - Johnstone and Syphers, *Proc. NA-PAC 2016*, Chicago (2016).

■ Resonant Extraction

- Mu2e will use 1/3-integer resonant extraction
- REDTOP can use same system, with use of the spare Mu2e magnetic septum
- initial calculations indicate sufficient phase space, even with the larger beam at the lower energies

■ Vacuum

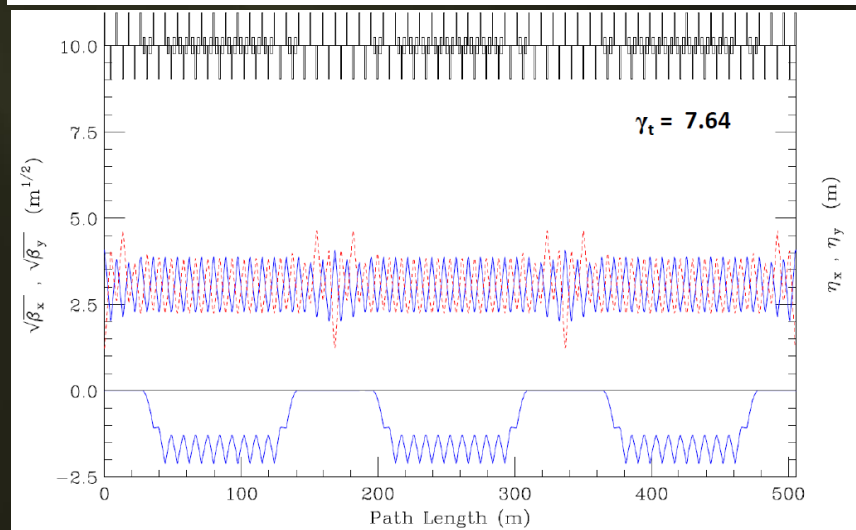
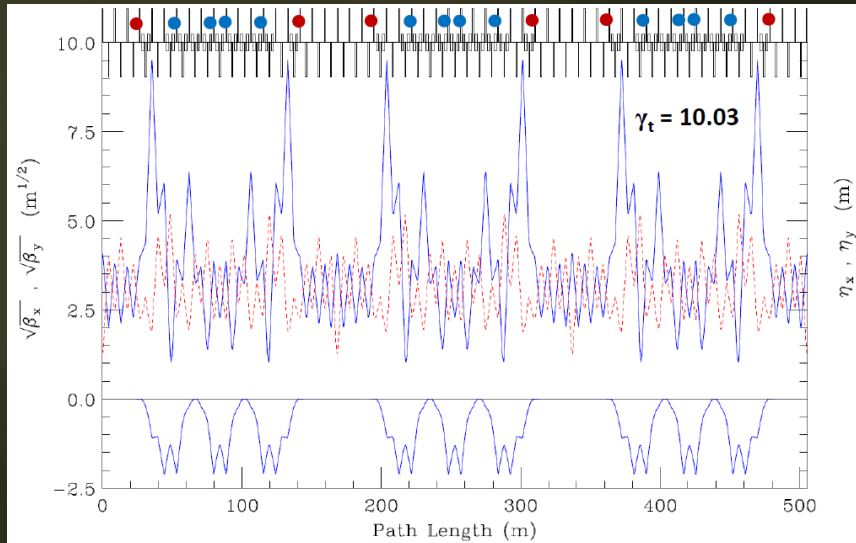
- REDTOP spill time is much longer than for Mu2e
- though beam-gas scattering emittance growth rate 3 times higher at lower energy, still tolerable level



Ring Optics through Deceleration (J. Johnstone)

Transition is avoided by using select quad triplets to boost γ_t above beam γ by 0.5 units throughout deceleration until $\gamma_t = 7.64$ and beam $\gamma = 7.14$ (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
$\gamma_{\text{transition}}$	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

Optical TPC

- $\sim 1\text{m} \times 1.5\text{m}$
- CH_4 @ 1 Atm
- 5×10^5 Sipm
- 98% coverage

Aerogel
Dual refractive
index system

10x Li/Be targets

- 0.33 mm thin
- Spaced 10 cm

ADRIANO2 Calorimeter

- Scint. + heavy glass sandwich
- $20 X_0$ ($\sim 64\text{ cm}$ deep)
- Triple-readout mode
- 96% coverage

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

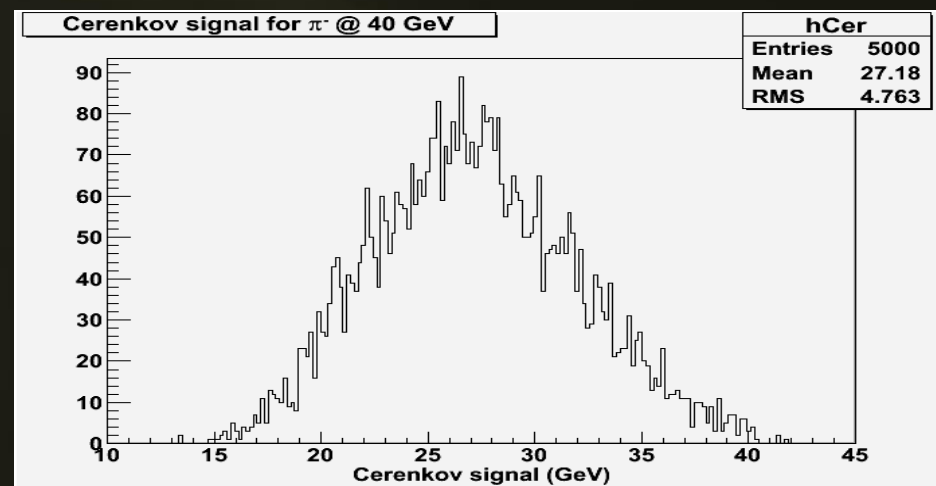
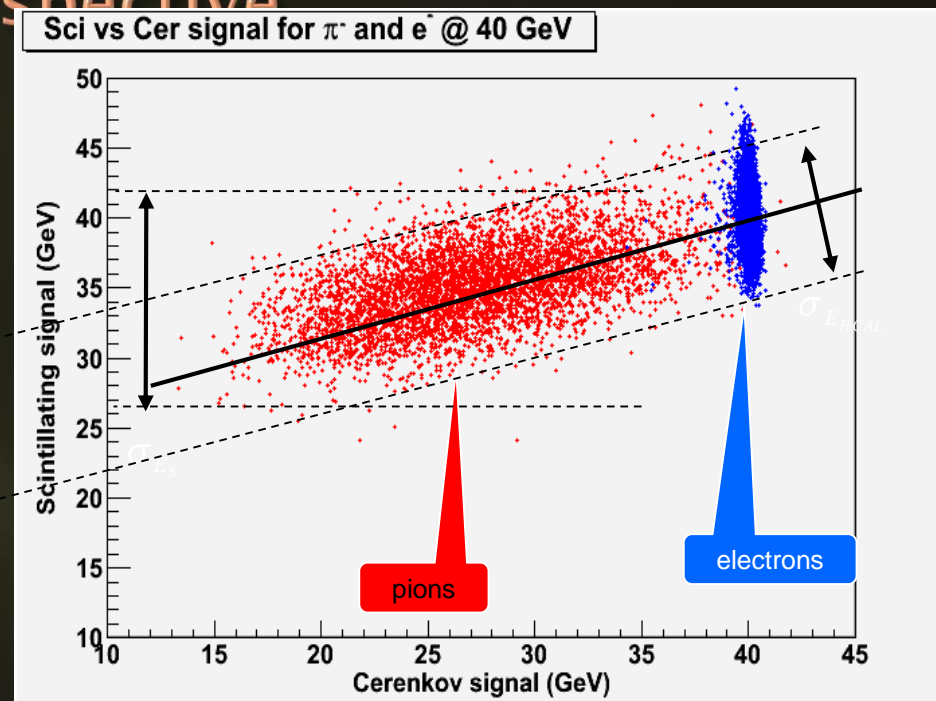
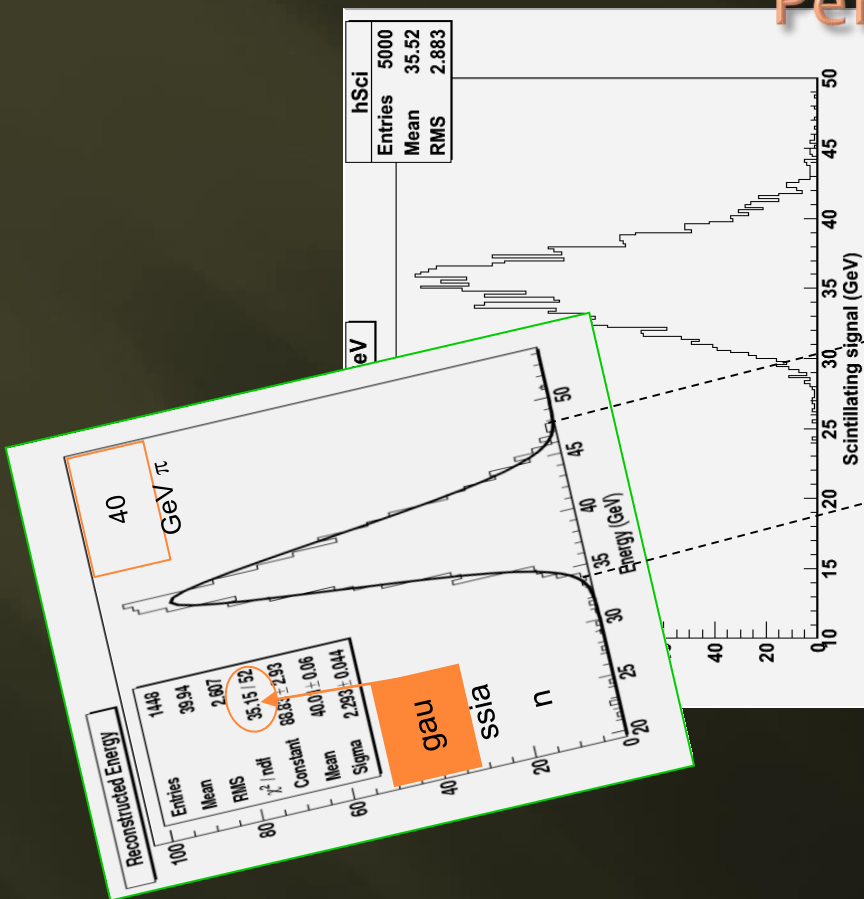
Solenoid
0.6-0.8 T

Fiber tracker

The ADRIANO2 Calorimeter

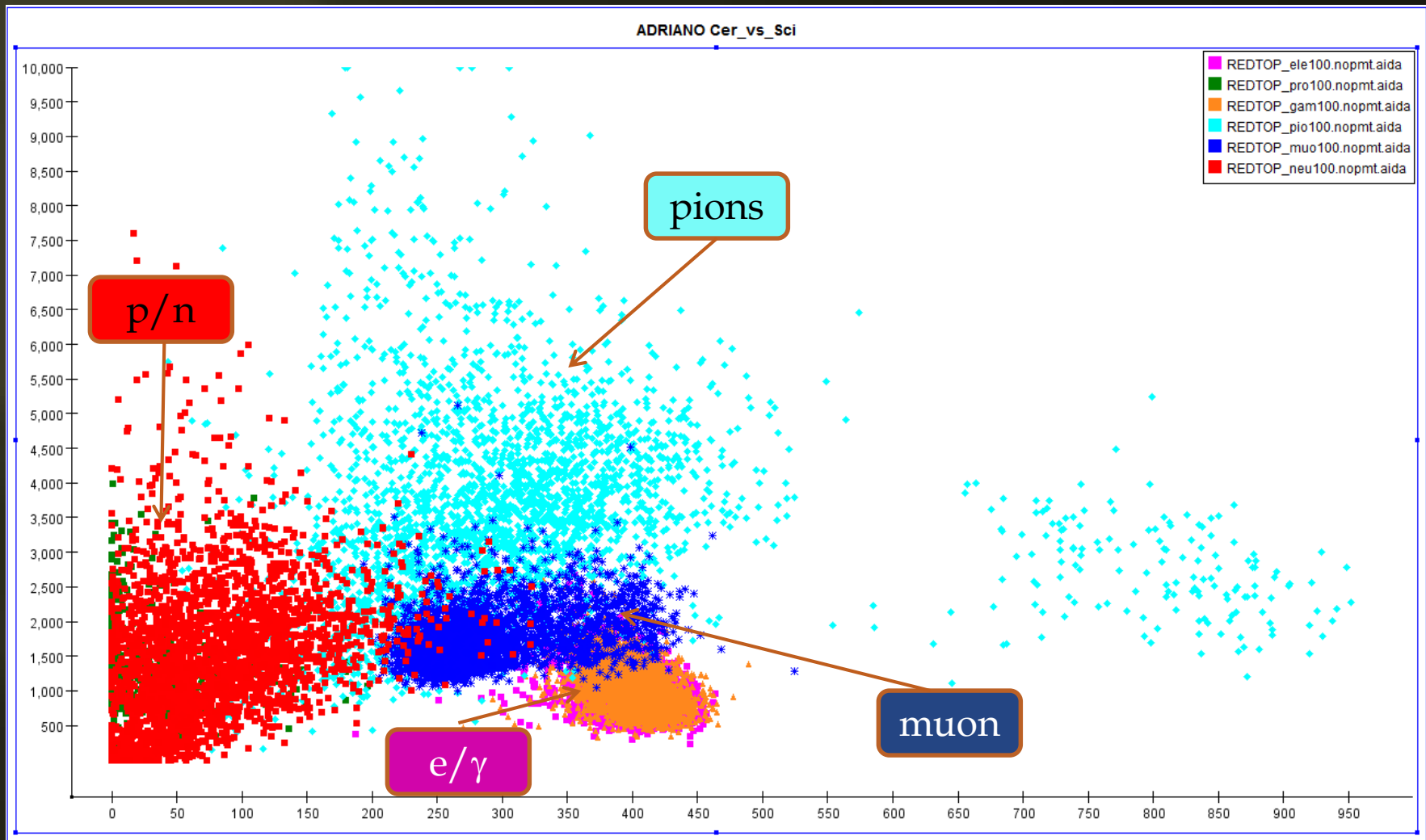
- ❑ *Sandwich of Pb-glass and scintillating plastic tiles with direct SiPM reading*
 - ❑ *Evolution of ADRIANO dual-readout calorimeter (A Dual-Readout Integrally Active Non-segmented Option)*
- ❑ *Triple-readout obtained from waveform analysis*
- ❑ *Rationale for multiple readout calorimetry at η -factory*
 - ❑ *Particle identification (see next)*
 - ❑ *Integrally active (no sampling)*
 - ❑ *Prompt Cerenkov light fed to L) trigger*
 - ❑ *Good granularity helps disentangling overlapping showers*

Dual Readout Calorimetry from a Different Perspective



Triple-readout adds the measurement of the neutron component improving the energy resolution even further

ADRIANO PID @ 100MeV



ADRIANO Light Yield and Resolution

Integrally Active with Double side readout (ADRIANO)

Sampling

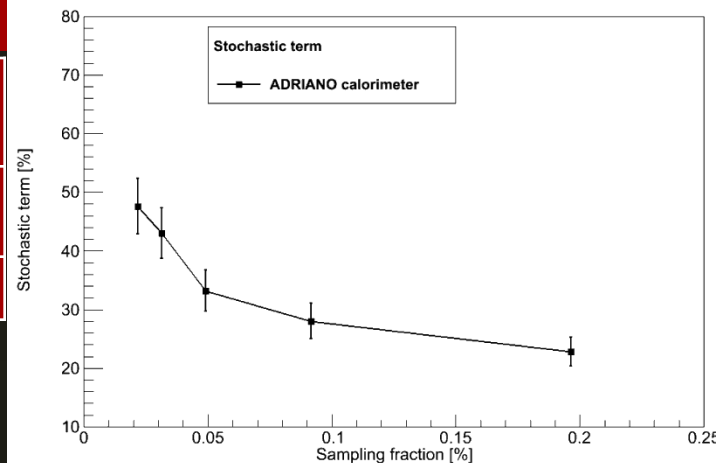
Pitch [mm ²] Diameter	2x2 1mm	3x3 1mm	4x4 1mm	5x5 1mm	6x6 1mm	4x4 1.4mm	4x4 2mm	4x4 capillary	Sampling
$\langle pe_s/GeV \rangle$	1053	430	254	163	124	500	110	250	200
$\langle pe_c/GeV \rangle$	340	360	360	355	355	355	350	350	7.5

Baseline
configuration

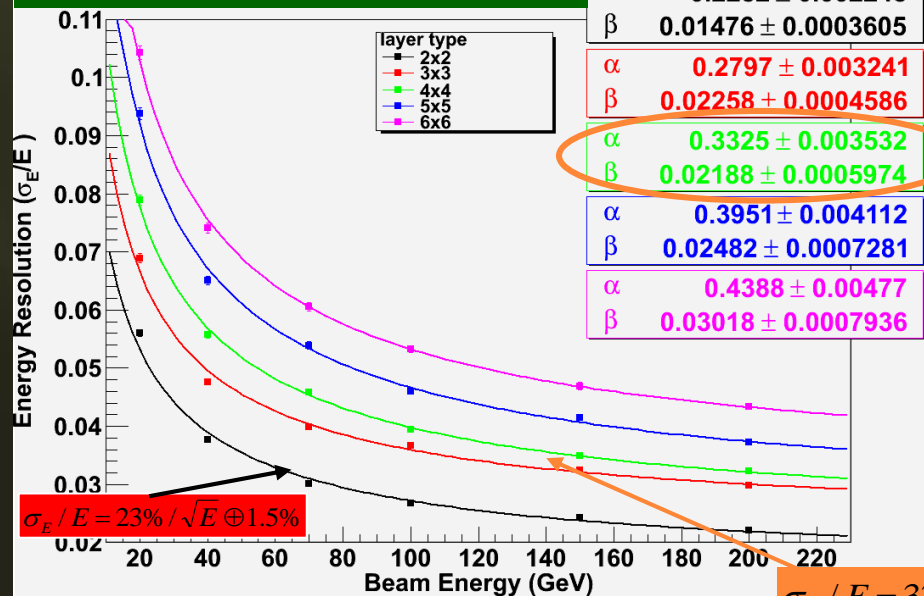
ILCroot simulations

1-side
readout

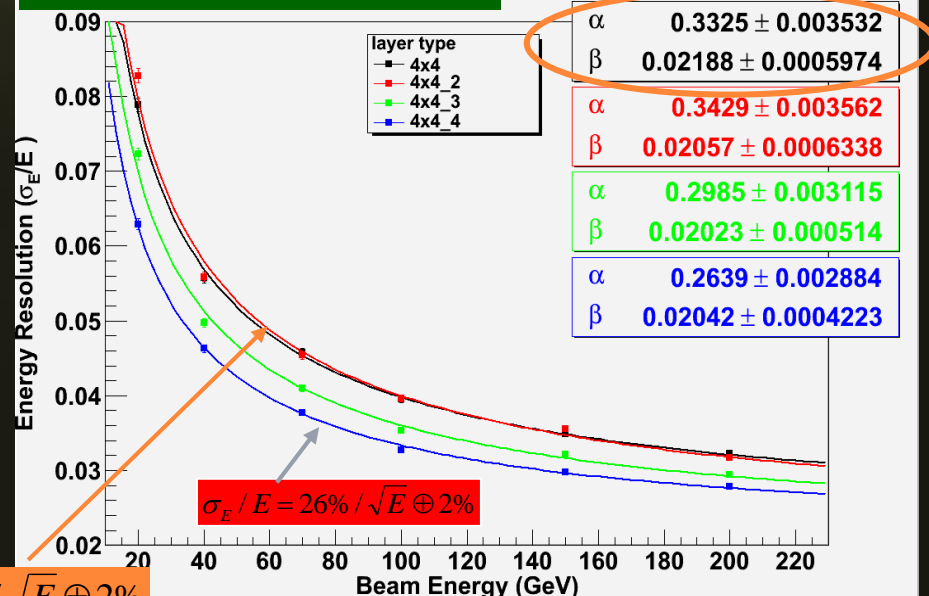
Resolution vs Scifi sampling fraction - ADRIANO Calorimeter



Fiber pitches: 2mmx2mm through 6mmx6mm

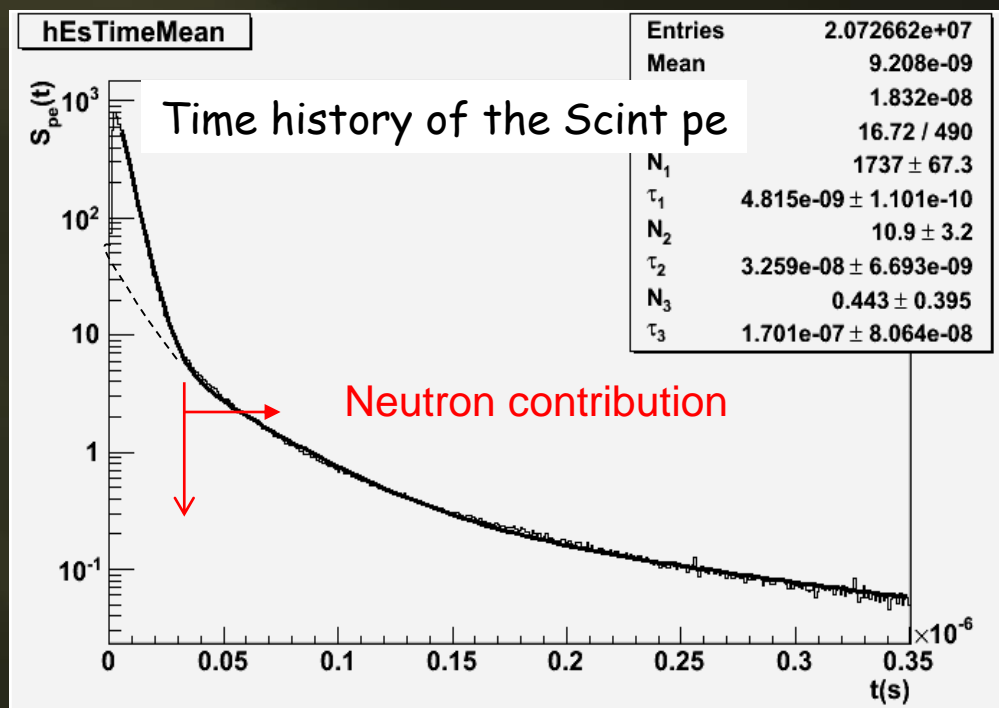


fiber diameter: 1mm – 1.4mm – 2 mm



From Dual to Triple Readout

Disentangling neutron component from waveform



ILCroot simulations

Time history of the scintillation signal in *ADRIANO* for π^- @40 GeV.

The contribution after 35 ns is from neutrons only. The distribution has been fitted with a triple exponential function .

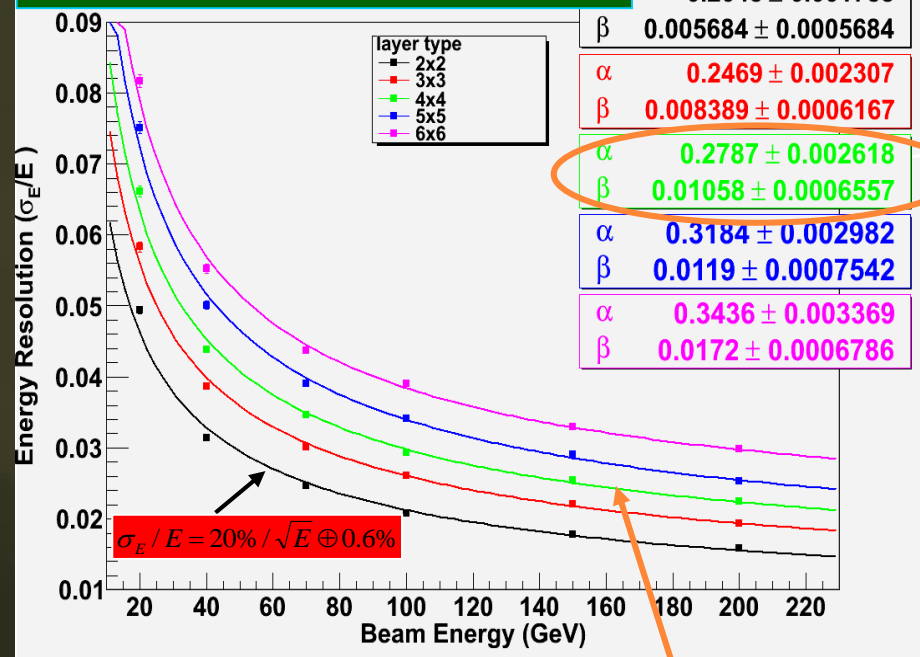
40 GeV pions

$$E_{HCAL} = \frac{\eta_s \cdot E_s \cdot (\eta_c - 1) - \eta_c \cdot E_c \cdot (\eta_s - 1)}{\eta_c - \eta_s} + \eta_n \cdot E_{neutrons}$$

Triple Readout aka Dual Readout with time history readout

ADRIANO in Triple Readout configuration

Fiber pitches: 2mmx2mm through 6mmx6mm



ILCroot simulations

$$\sigma_E / E = 28\% / \sqrt{E} \oplus 1\%$$

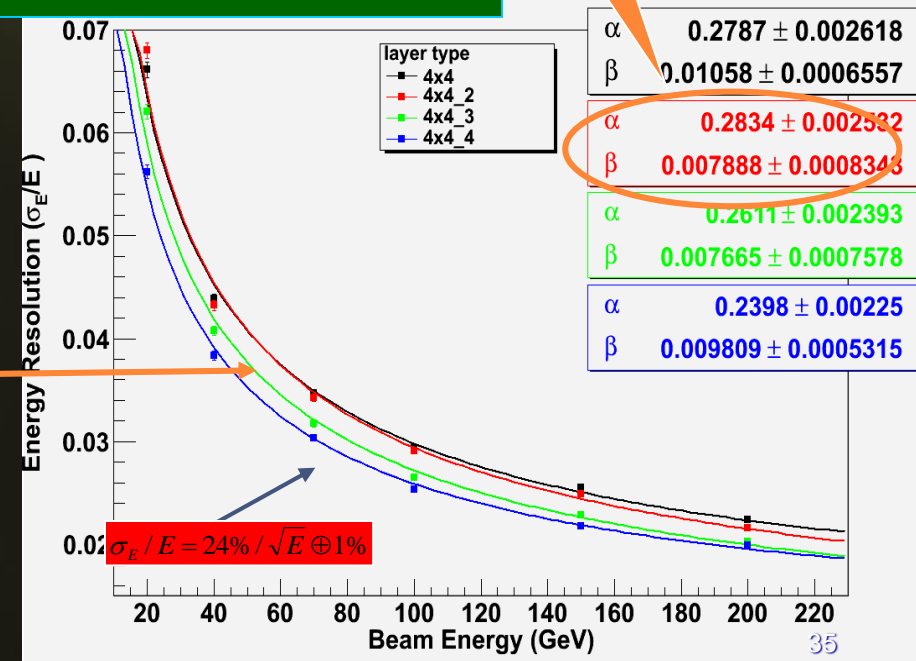
compare to ADRIANO in Double Readout configuration

$$\sigma_E / E = 33\% / \sqrt{E} \oplus 2\%$$

Baseline configuration

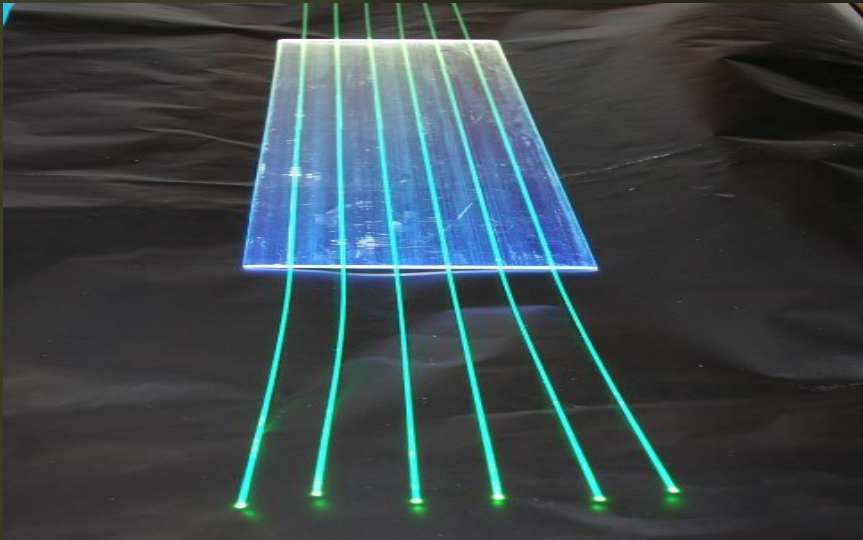
Pion beams

fiber diameter: 1mm – 1.4mm – 2 mm

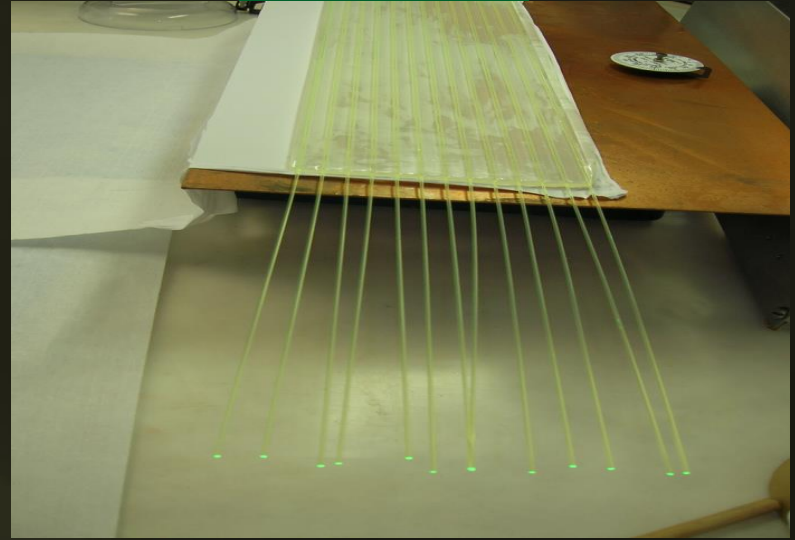


ADRIANO for ORKA Construction

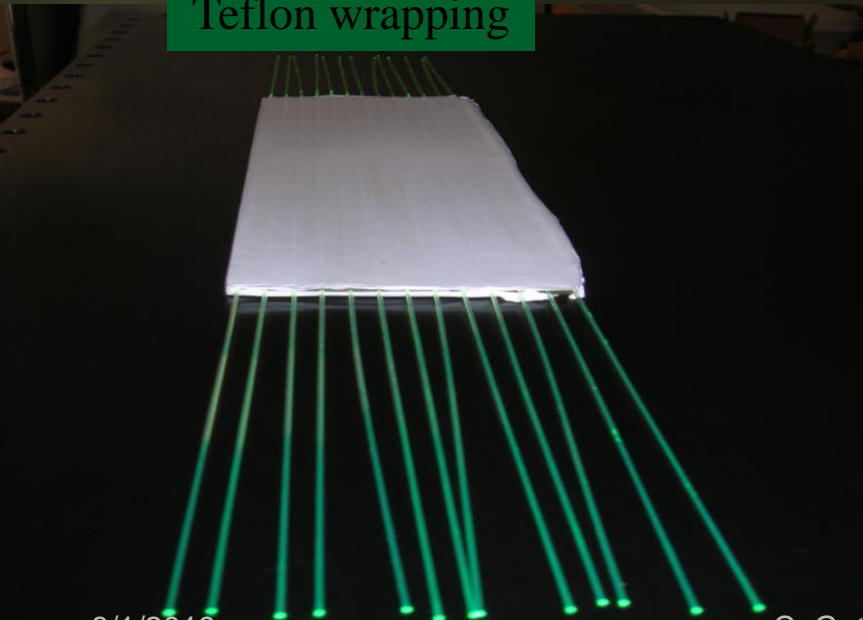
WLS + scintillator



WLS + glass



Teflon wrapping

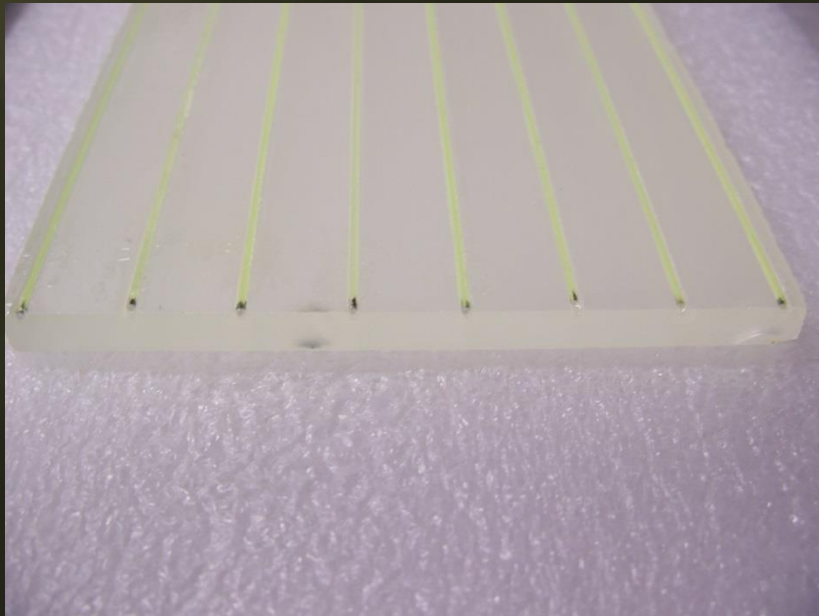


Final detector

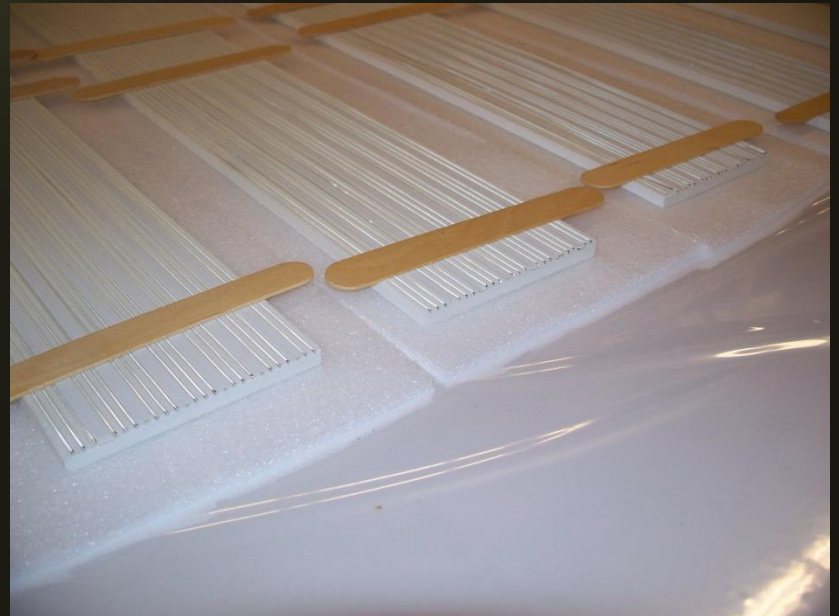


ADRIANO-2014

- Two versions built: scifi and scintillating plates
- 10 x 8 x 105 cm³ long prototypes, about 50 Kg each
- 4 cells total, front and back readout
- Hopefully , we will be able to test the dual-readout concept with integrally active detectors



ADRIANO 2014A: 8 grooves



ADRIANO 2014B: 23 grooves

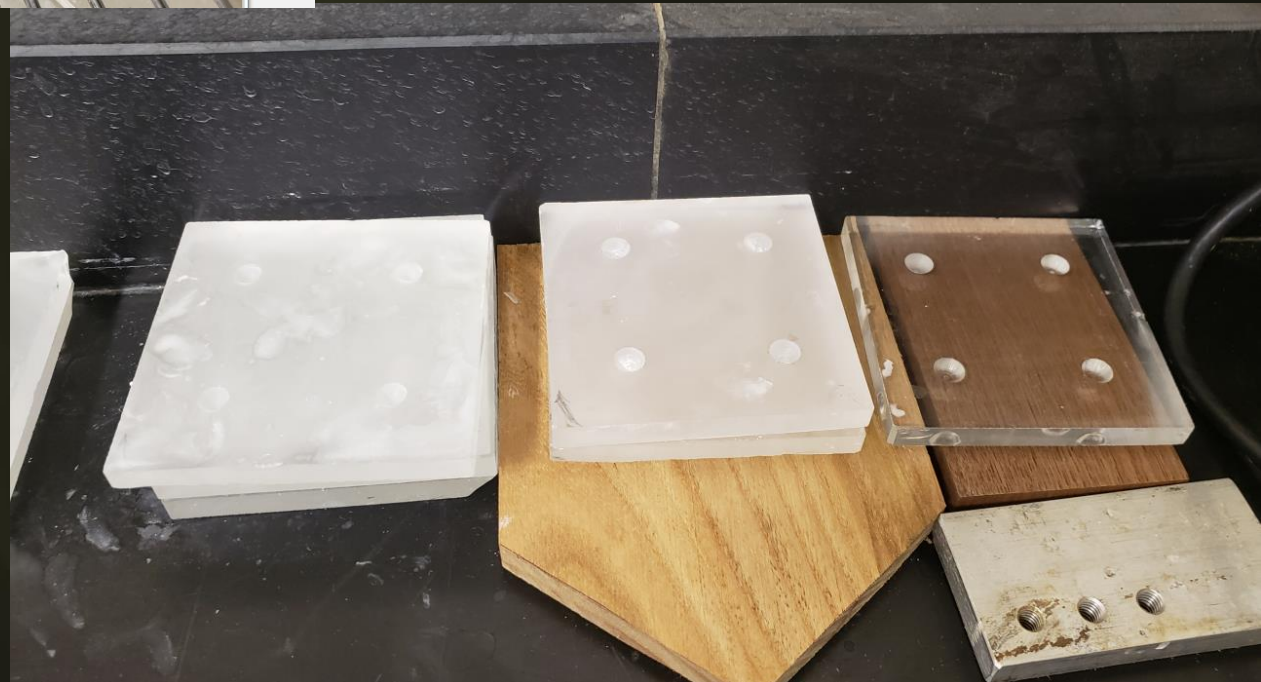
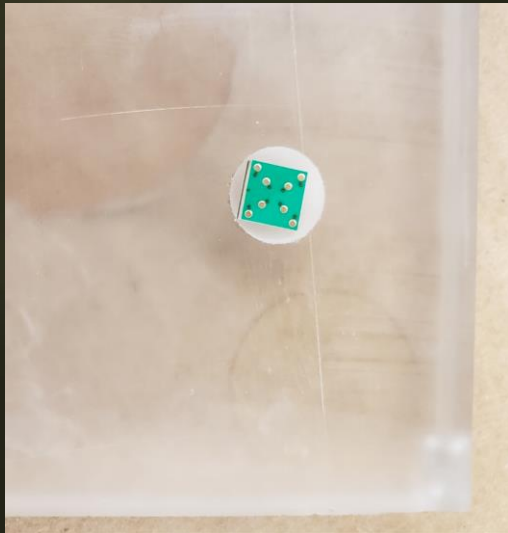
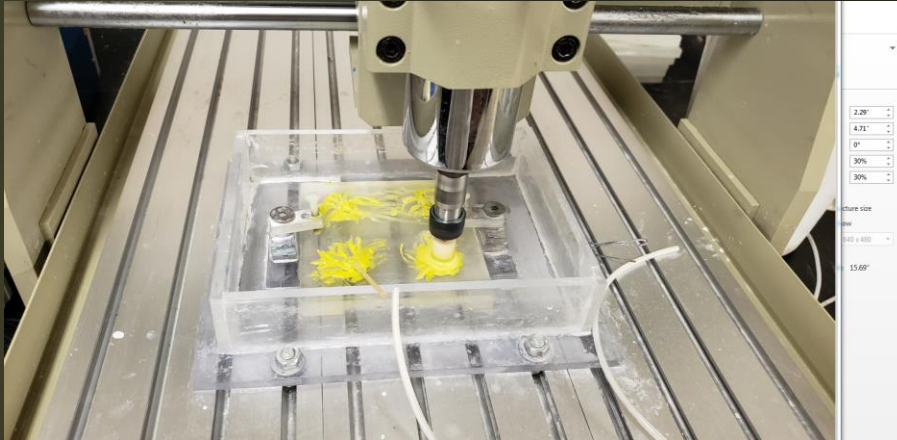
Nov. 2015 test Beam at Fermilab



ADRIANO2 R&D

- ▣ Evolution of ADRIANO: log layout->tiles
- ▣ Sandwich of 3mm scintillating plastics and 10 mm Pb-glass (10cm x 10cm transverse size)
- ▣ WLS light capture -> SiPM directly coupled to glass and plastic
- ▣ Prompt Cerenkov signal used in L0 trigger
- ▣ Granularity can be made extremely fine
- ▣ 16 layers – prototype (64 ch) under construction at NIU
- ▣ Will be tested in Fall 2019 at FTBF
- ▣ At present, Fermilab-INFN-NIU-UMN Collaboration

Polishing

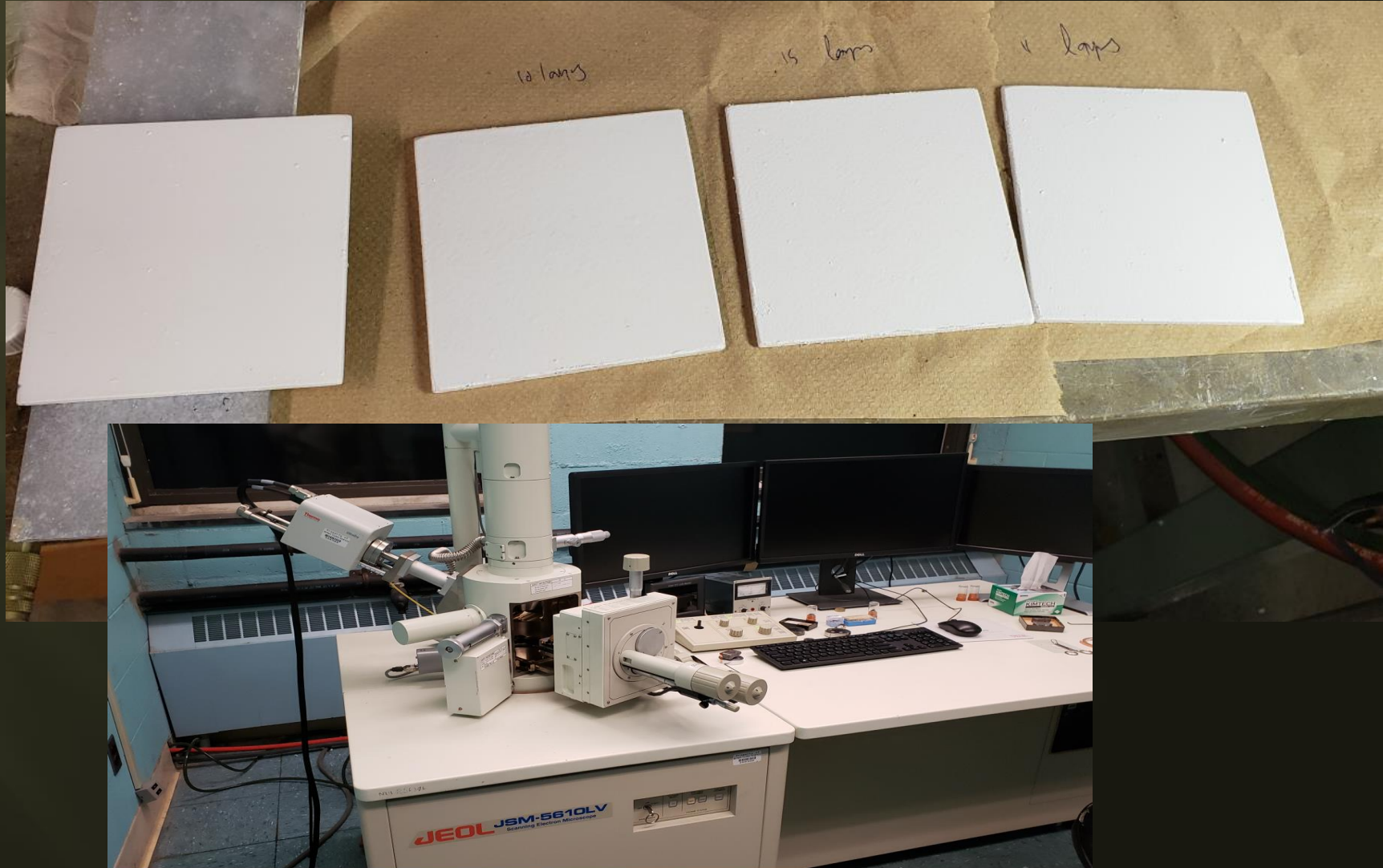


8/1/2019

C. Gatto - INFN & NIU

40

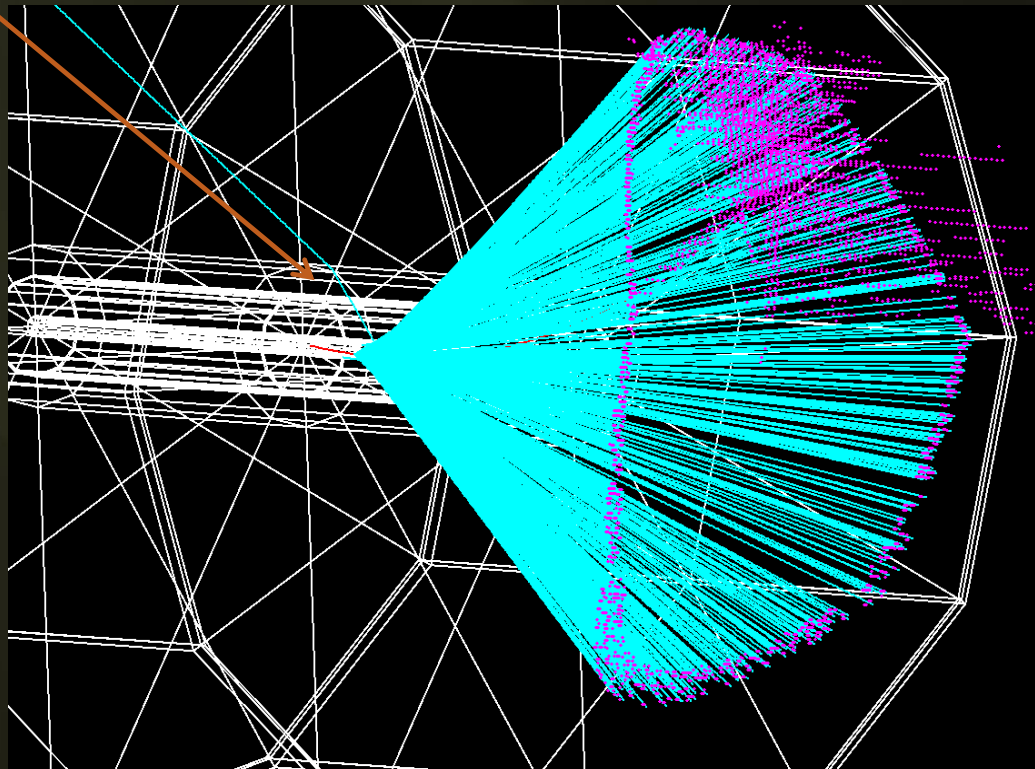
Coating and testing



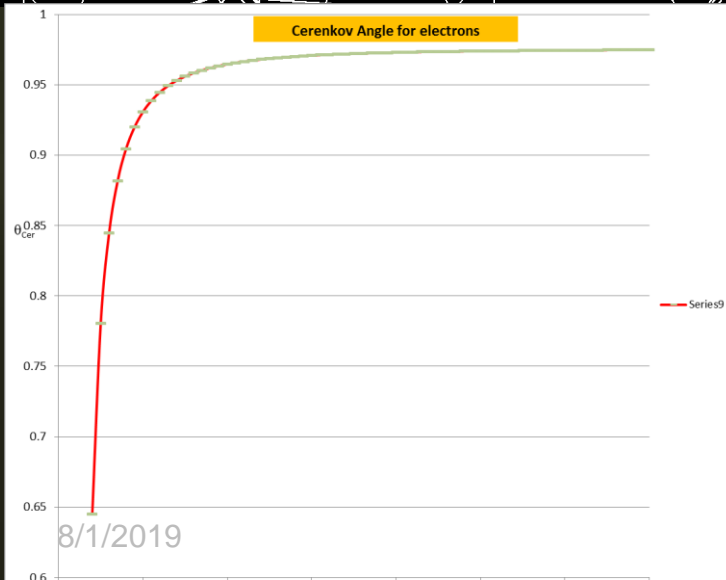
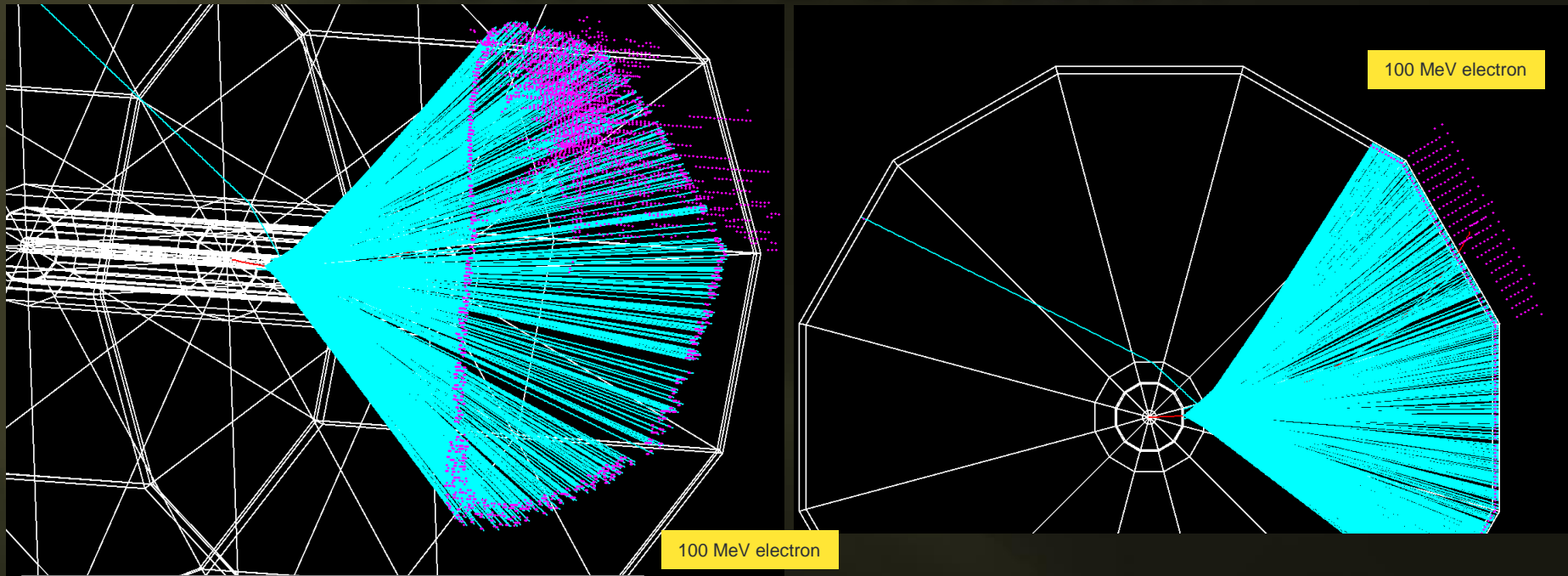
The Optical TPC Concept

Rationale for an Optical- TPC

- ❑ *At 1 GHz inelastic interaction rate, a conventional, gas detector is suboptimal*
- ❑ *Hadronic particles (p , ion remnants, slow pions, etc.) will clutter the tracker*
- ❑ *Use the Cerenkov effect to detect the fast (leptons and fast pions) tracks*
- ❑ *Prompt signal is also fed to the L0 trigger for fast selection of event with leptons*



Electron Detection



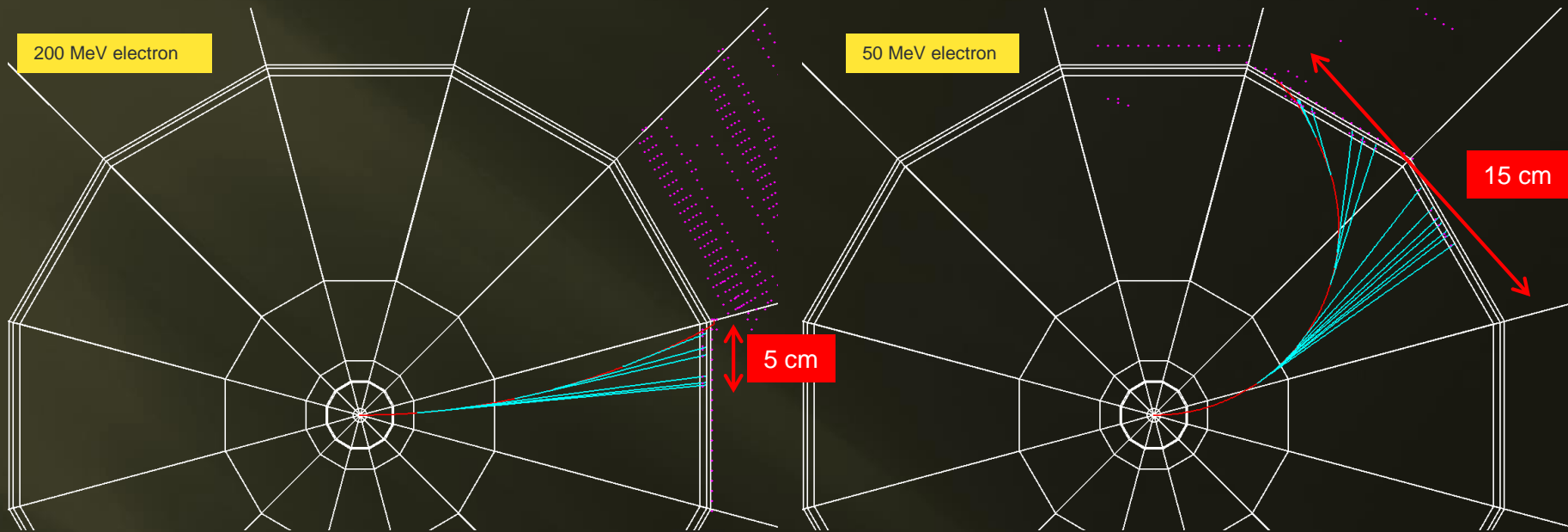
$$n_D(N_2@2.7\text{psi})=1.000145$$

\check{C} threshold for e^- in N_2 : $P=40$ mev

$$n_D(\text{aerogel1})=1.12$$

$$n_D(\text{aerogel2})=1.22$$

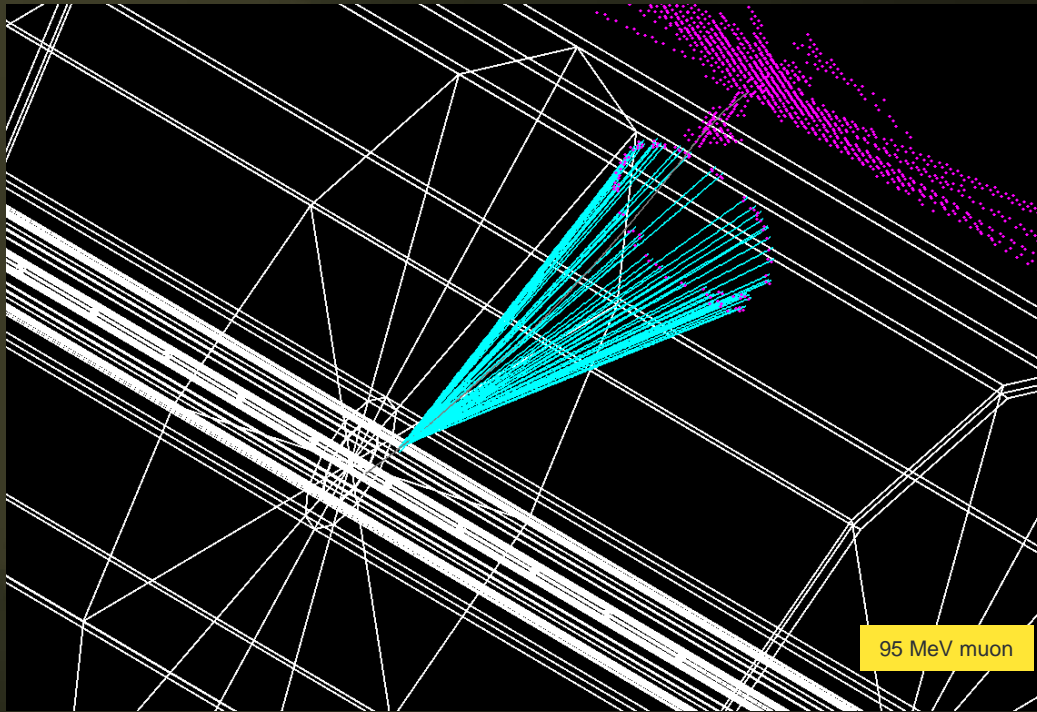
Electron Momentum Reconstruction



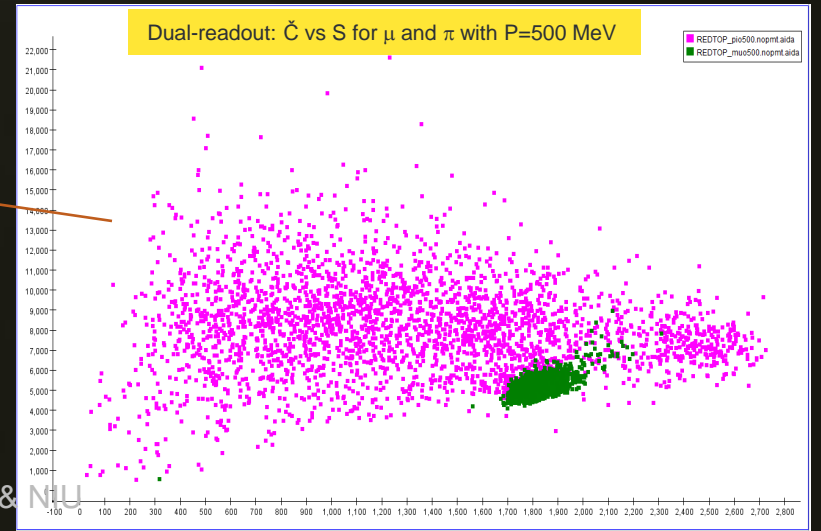
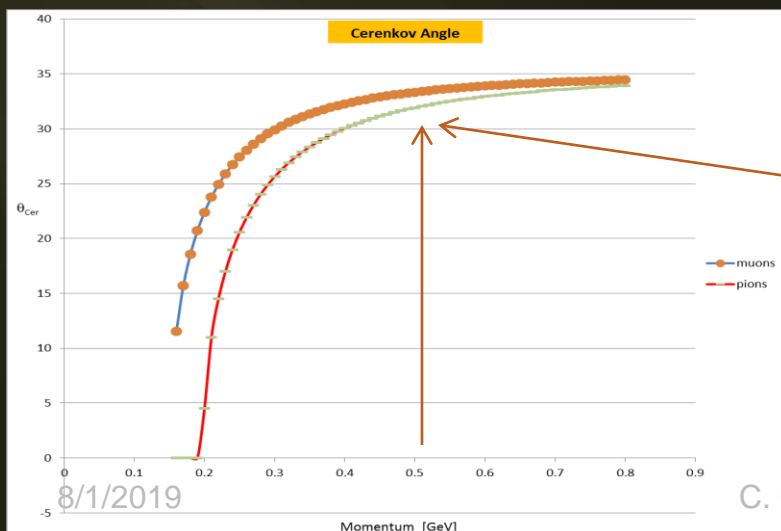
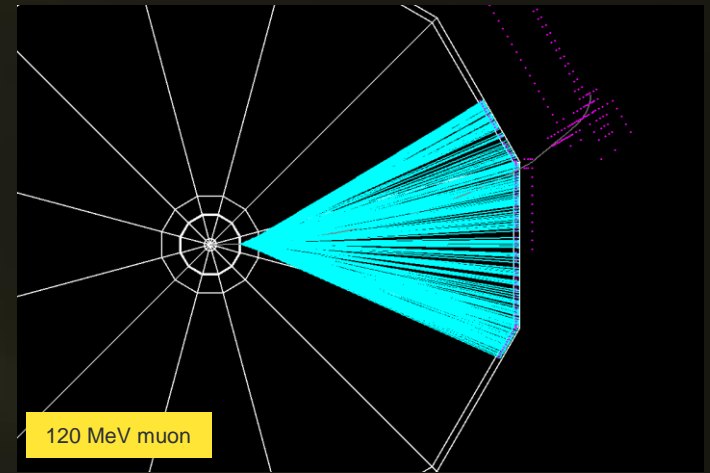
▣ Electrons are recognized by:

1. a large (>30 cm dia) circle of photons generated in the aerogel
2. A sweep of photons circles with dia < 1 cm and several cm long (depends on P_t)
3. An EM shower in ADRIANO (identified by \check{C} vs S)

Muon/pion Detection

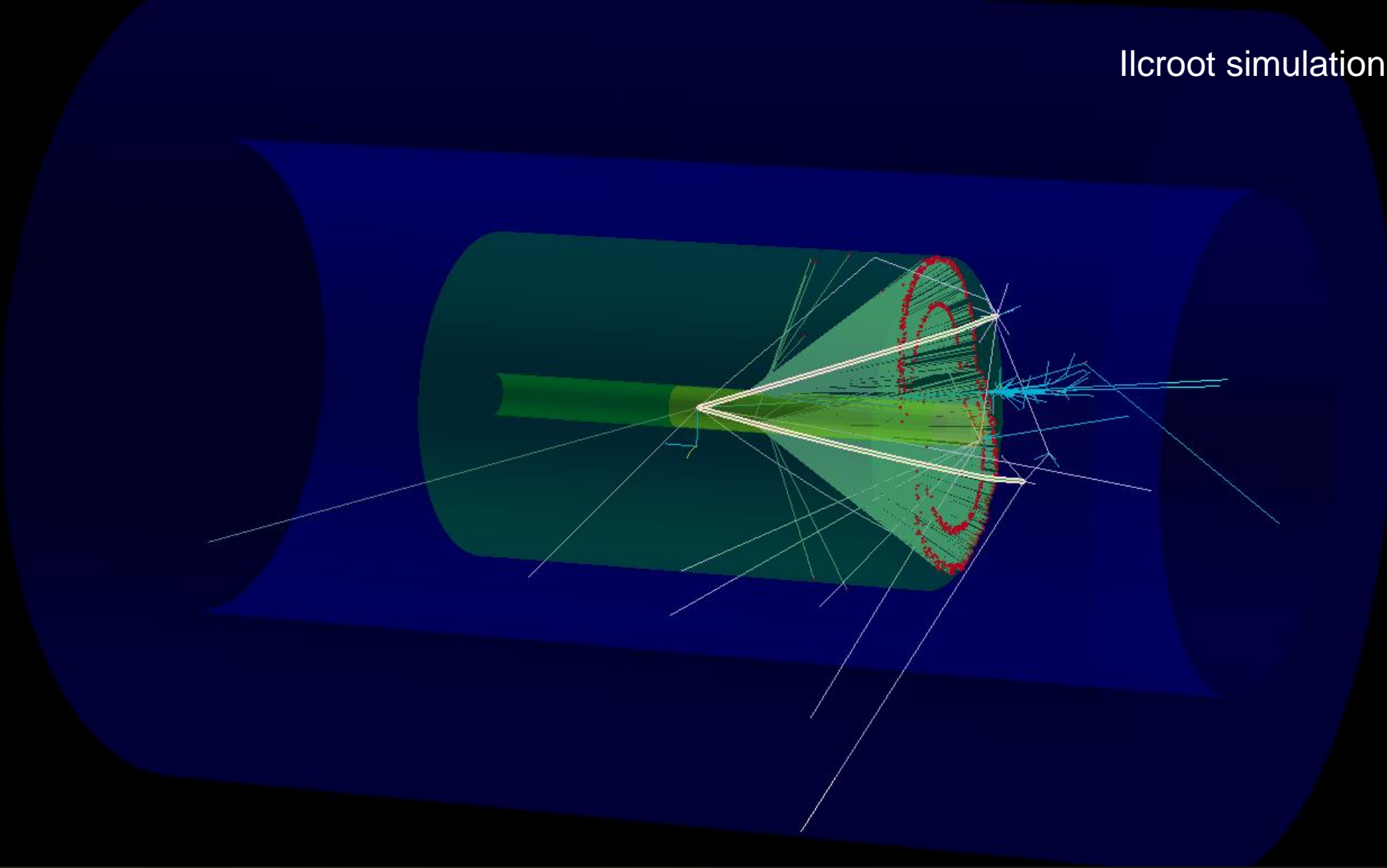


- ▣ $n_D(\text{aerogel})=1.22/1.12$
- ▣ \check{C} threshold for muons: $P=160 \text{ mev}$
- ▣ \check{C} threshold for pions: $P=200 \text{ mev}$



$$\eta \rightarrow \pi^+ \pi^- \pi^0$$

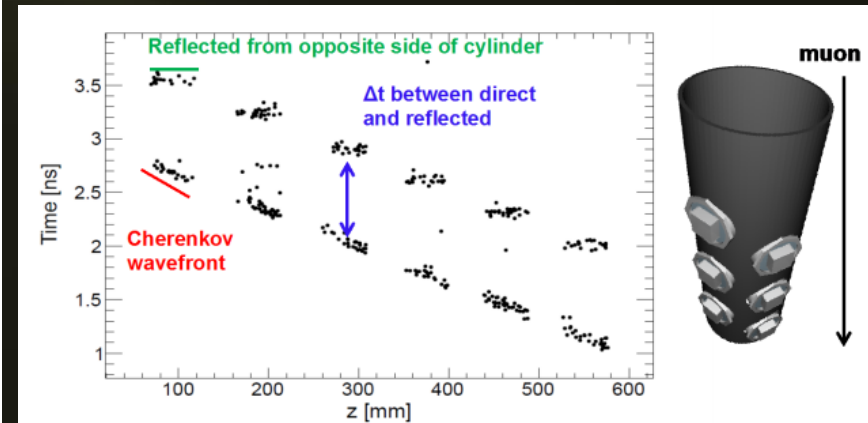
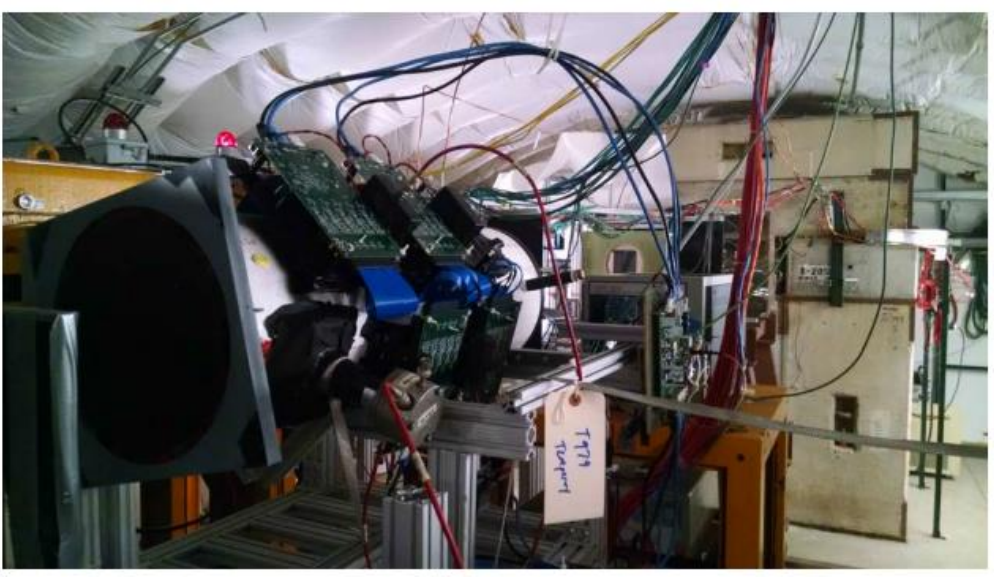
Ilcroot simulation



Detector R&D: OTPC

Fnal -T1059 (H. Frisch, E. Oberla)

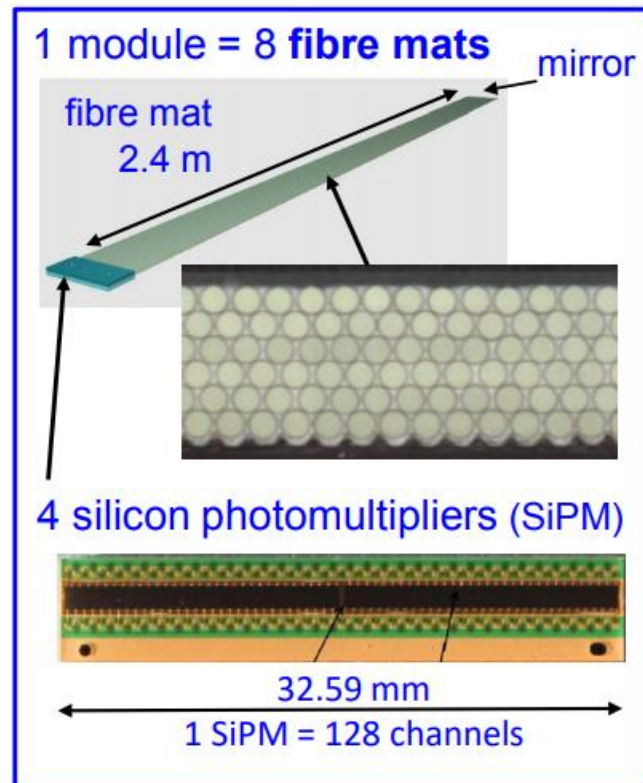
- ❑ *Successful proof of principle in 2015 at FTBF*
- ❑ *Instrumented with an MCP photo-detector, three boards each with thirty channels of 10 GSPS waveform digitizing readout*
- ❑ *http://ppd.fnal.gov/ftbf/TSW/PDF/T1059_tsw.pdf*



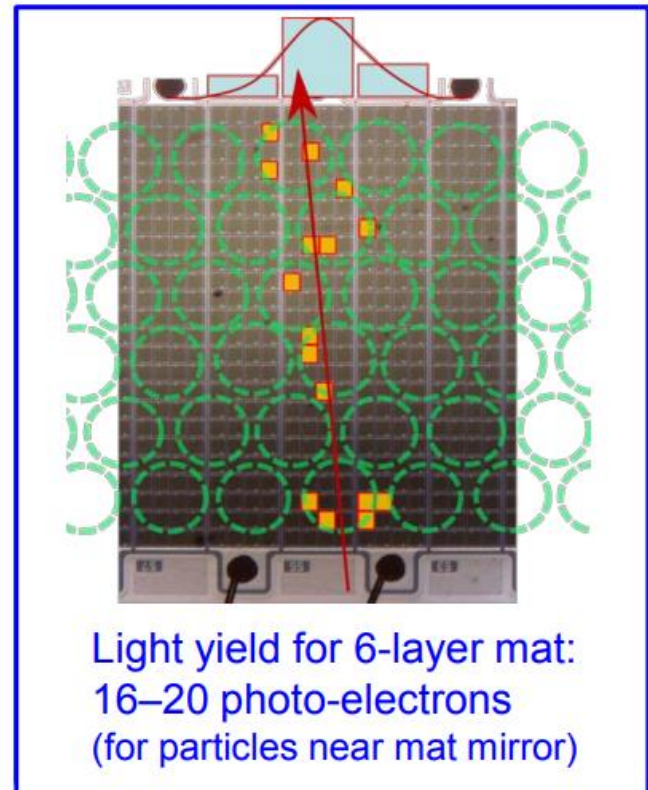
It requires a robust and dedicated R&D (LDRD)

The Fiber Tracker – LHCb design

128 modules ($0.5 \times 5 \text{ m}^2$)
arranged in 3 stations \times 4 layers
(XUVX)



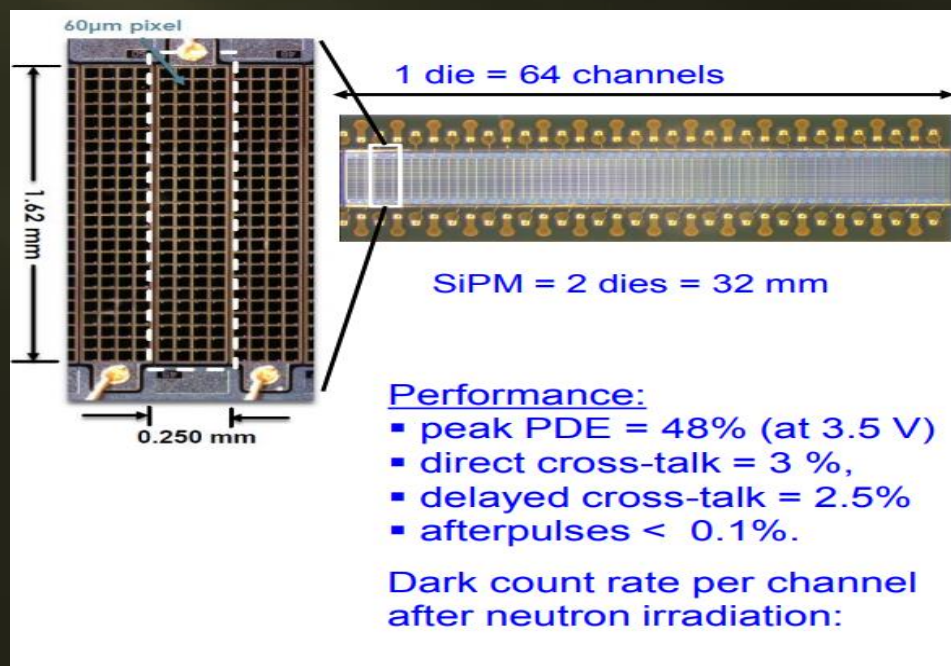
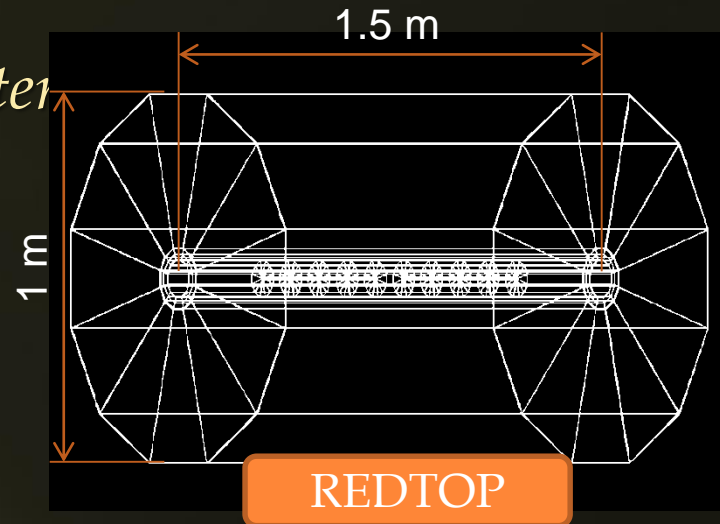
128 modules ($0.5 \times 5 \text{ m}^2$)
arranged in 3 stations \times 4 layers
(XUVX)



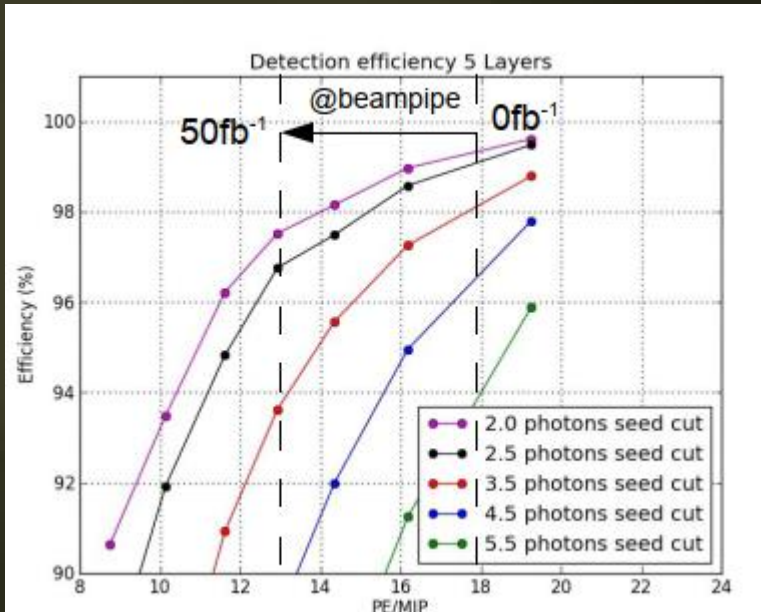
Layout for LHCb vs REDTOP

Input parameters

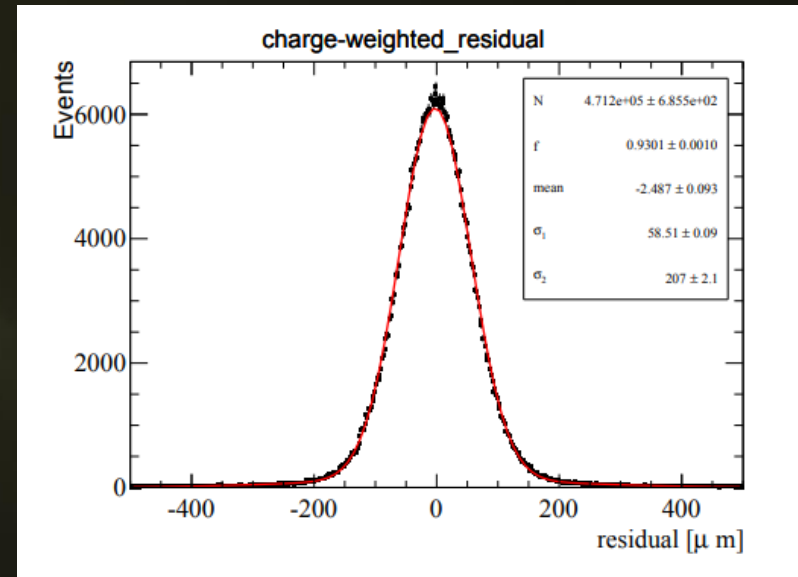
- $\sim 360 \text{ m}^2$ vs 0.24 m^2
- 1152 mats vs 36 mats
- 524,000 vs 18,000 channels



Results from LHCb Test Beam



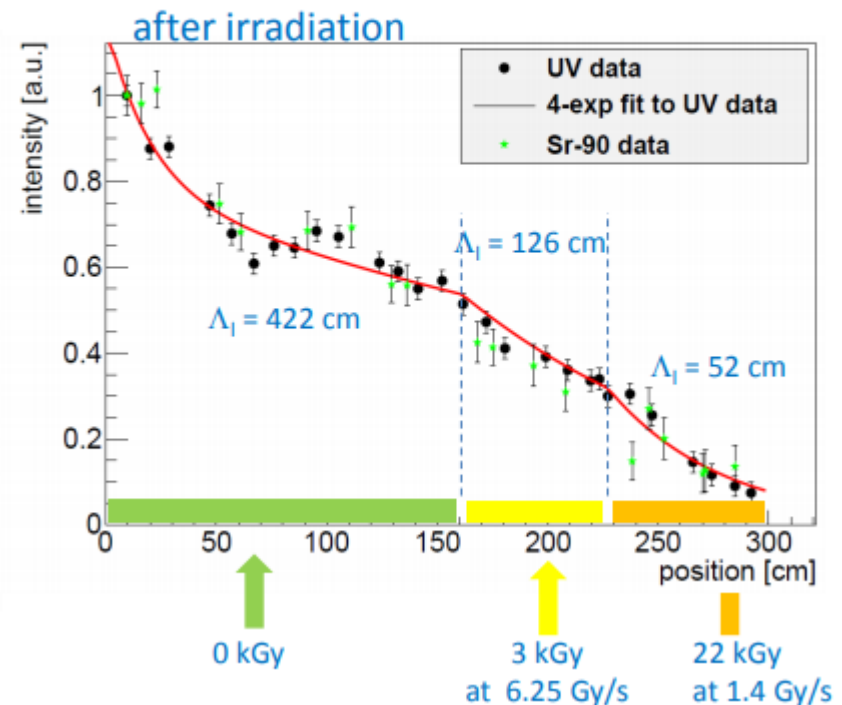
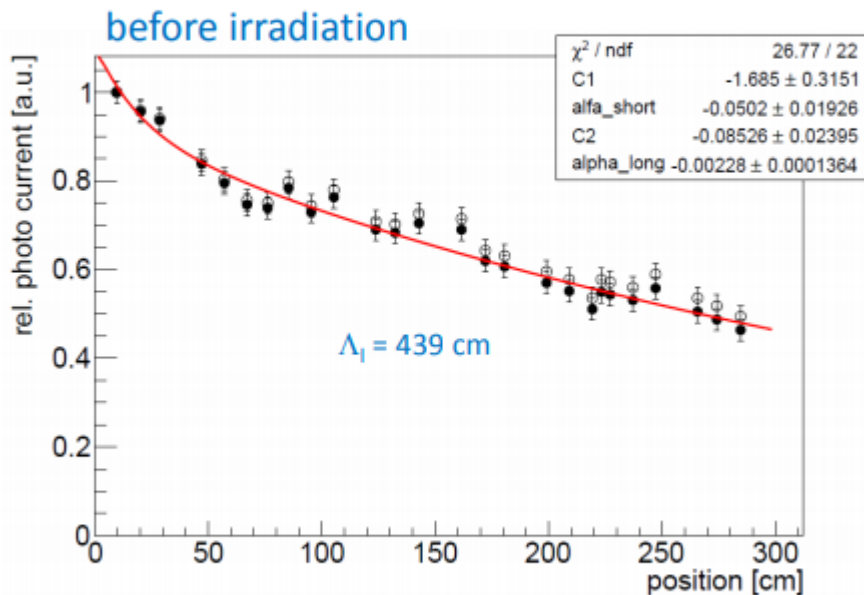
Seed	Neighbour	Sum	Hit Eff.
1.0	1.0	1.0	0.9993 ± 0.0001
1.5	1.5	1.5	0.9990 ± 0.0001
2.0	1.5	2.0	0.9972 ± 0.0002
2.5	1.5	2.5	0.9946 ± 0.0003
3.0	1.5	3.0	0.9990 ± 0.0004
3.5	1.5	3.5	0.9817 ± 0.0005
4.0	1.5	4.0	0.9693 ± 0.0006
4.5	1.5	4.5	0.9540 ± 0.0007
2.5	1.5	4.0	0.9866 ± 0.0004



	at the mirror	centre	50 cm from SiPM
$\sigma_{eff,charge} [\mu\text{m}]$	66.78 ± 0.23	65.93 ± 0.18	61.22 ± 0.21
$\sigma_{eff,Pacific} [\mu\text{m}]$	73.27 ± 0.26	73.18 ± 0.20	73.64 ± 0.20

Fiber Tracker Radiation Hardness

- 3 m long SCSF-78 fibres (\varnothing 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): $\sim 10^{13}$ n/cm²
- ❑ Average: $\sim 10^{12}$ n/cm²

REDTOP Possible Running Phases

- ▣ Phase I: η -factory. Goal is $\sim 10^{13}$ 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 $\sim 10^{11}$ 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 from muons. Goal is $> 1.0 \times 10^{13}$ μ /yr
 - (G. Krnjaic and Y. Kahn)
 - T_{beam} : $1 < E < 3$ GeV (to be optimized)
 - Target: H_2 gas
- ▣ Phase IV: Muon Scattering Experiment. Goal is $> 2.0 \times 10^{12}$ μ /yr
 - T_{beam} : $0.2 < E < 0.8$ GeV (to be optimized)
 - ▣ Muon yield: $> 1.6 \times 10^{-8}$ μ /p
 - ▣ Target: 1 x 100 mm graphite
- ▣ Phase V: tagged REDTOP. Goal is $> 2.0 \times 10^{13}$ η /yr
 - T_{beam} : 1.2 GeV at PIP-II
 - ▣ Muon muon yield: $> 1.6 \times 10^{-8}$ μ /p
 - ▣ Target: ^3H
- ▣ Phase VI: Rare Kaon Decays: $\text{K}^+ \rightarrow \pi^+ \nu \bar{\nu}$ Goal is $> 1 \times 10^{14}$ 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*

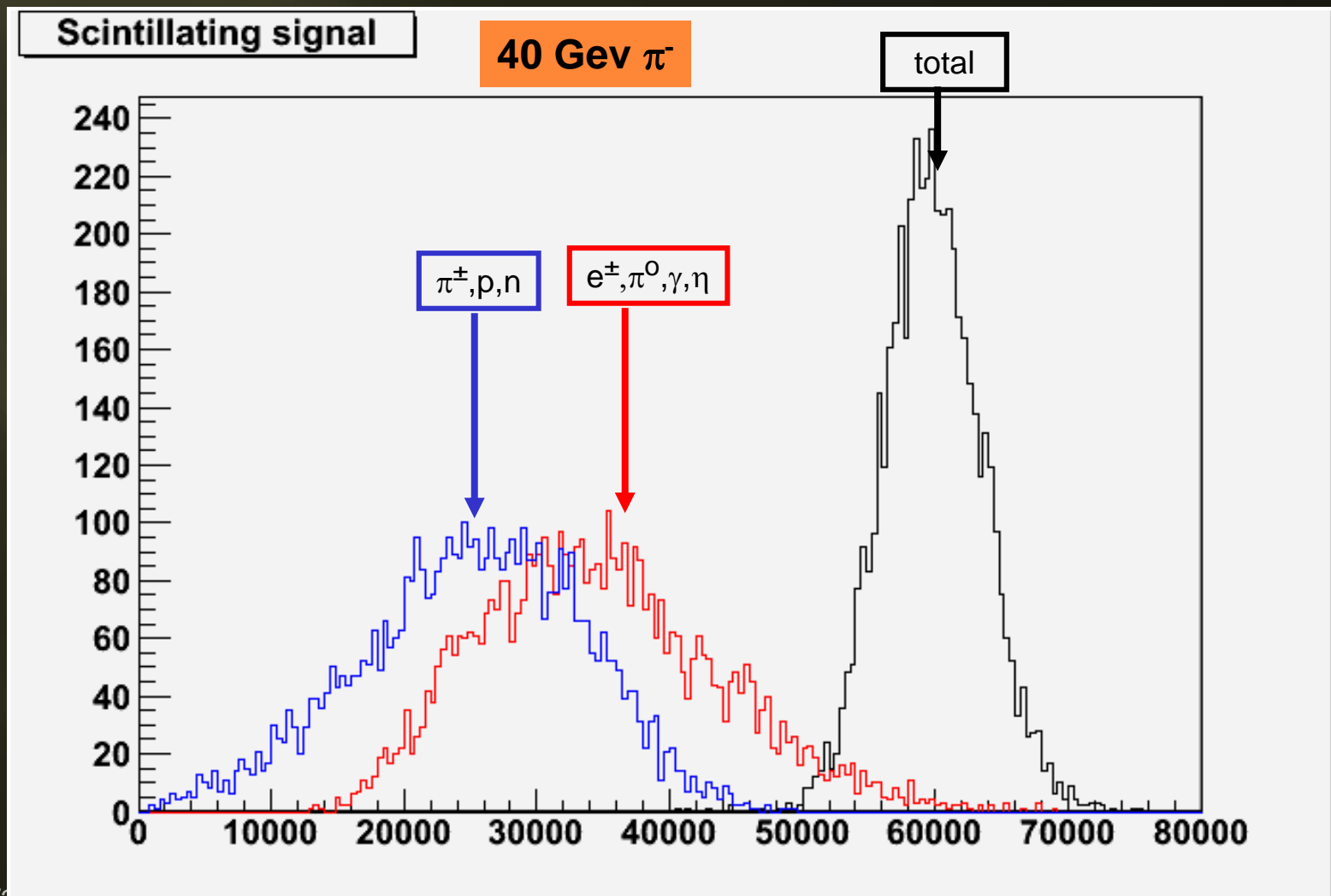
Ongoing activities – detector R&D

- ▣ *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 prototype*
 - *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*

Transitionless Deceleration in the Delivery Ring (J. Johnstone)

- ▣ Large beam losses will occur if beam is decelerated from injection @ 8 GeV ($\gamma = 9.53$) to 2 GeV ($\gamma = 3.13$) through the DR natural transition energy $\gamma_t = 7.64$.
- ▣ Transition is avoided by using select quad triplets to boost γ_t above beam γ by 0.5 units throughout deceleration until $\gamma_t = 7.64$ and beam $\gamma = 7.14$ (5.76 GeV kinetic).
- ▣ Below 5.76 GeV the DR lattice reverts to the nominal design configuration
- ▣ Optical perturbations are localized within each triplet
- ▣ Straight sections are unaffected thereby keeping the nominal M3 injection beamline tune valid.

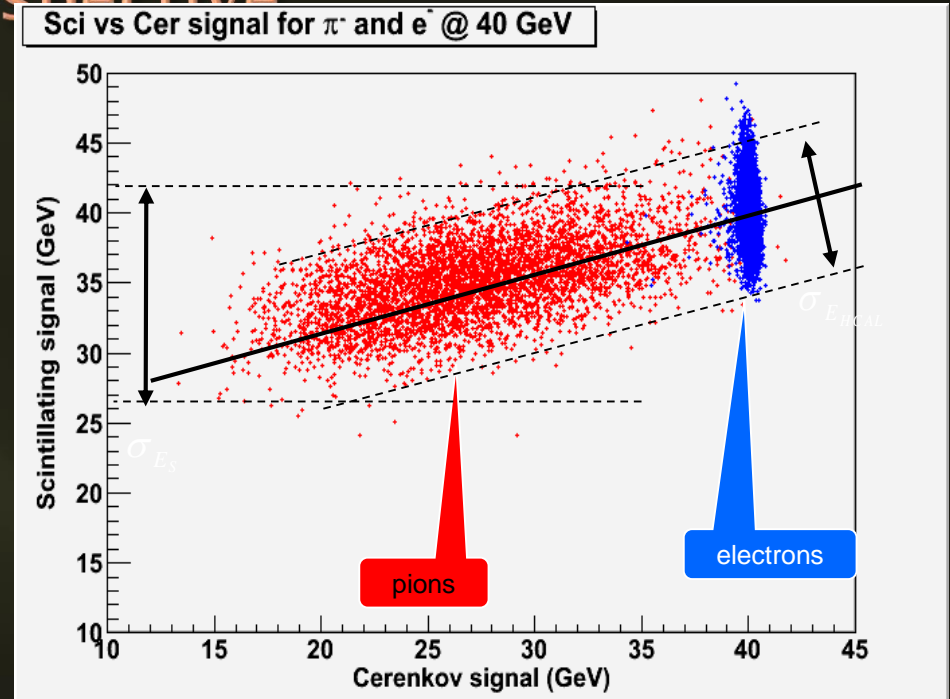
The major source of fluctuations: *fem*



Dual Readout Calorimetry from a Different Perspective

Dual Readout is nothing but a rotation in $E_S - E_C$ plane

ILCroot simulations



$$E_{H\text{CAL}} = \frac{\eta_S \cdot E_S \cdot (\eta_C - 1) - \eta_C \cdot E_C \cdot (\eta_S - 1)}{\eta_C - \eta_S}$$

$$\left(\eta_S = \left(\frac{e}{h} \right)_S ; \quad \eta_C = \left(\frac{e}{h} \right)_C \right)$$



$$\begin{cases} E_S = \left[fem + \frac{(1 - fem)}{\eta_S} \right] \cdot E_{H\text{CAL}} \\ E_C = \left[fem + \frac{(1 - fem)}{\eta_C} \right] \cdot E_{H\text{CAL}} \end{cases}$$

If $\eta_S \neq \eta_C$ then the system can be solved for $E_{H\text{CAL}}$

Figures of Merit for Dual-Readout Calorimeter

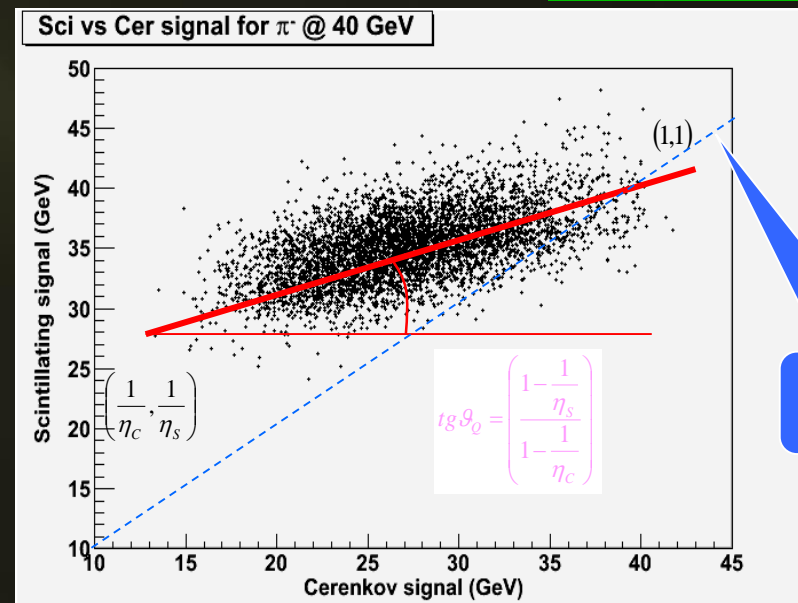
- **Large pe/GeV:** must be much greater than 45 pe/GeV (corresponding to 15% (teoretical limit) contrubution to stochastic term
- System is solvable only when $\eta_S \neq \eta_C$. The larger the compensation asymmetry the better. Aka, $\tan(\theta_{S/Q})$ much diferent from 1

ILCroot simulations



$$\sigma_{E_{corr}}^2 = \left(\frac{1}{1-\chi} \right)^2 \sigma_S^2 + \left(\frac{\chi}{1-\chi} \right)^2 \sigma_Q^2$$

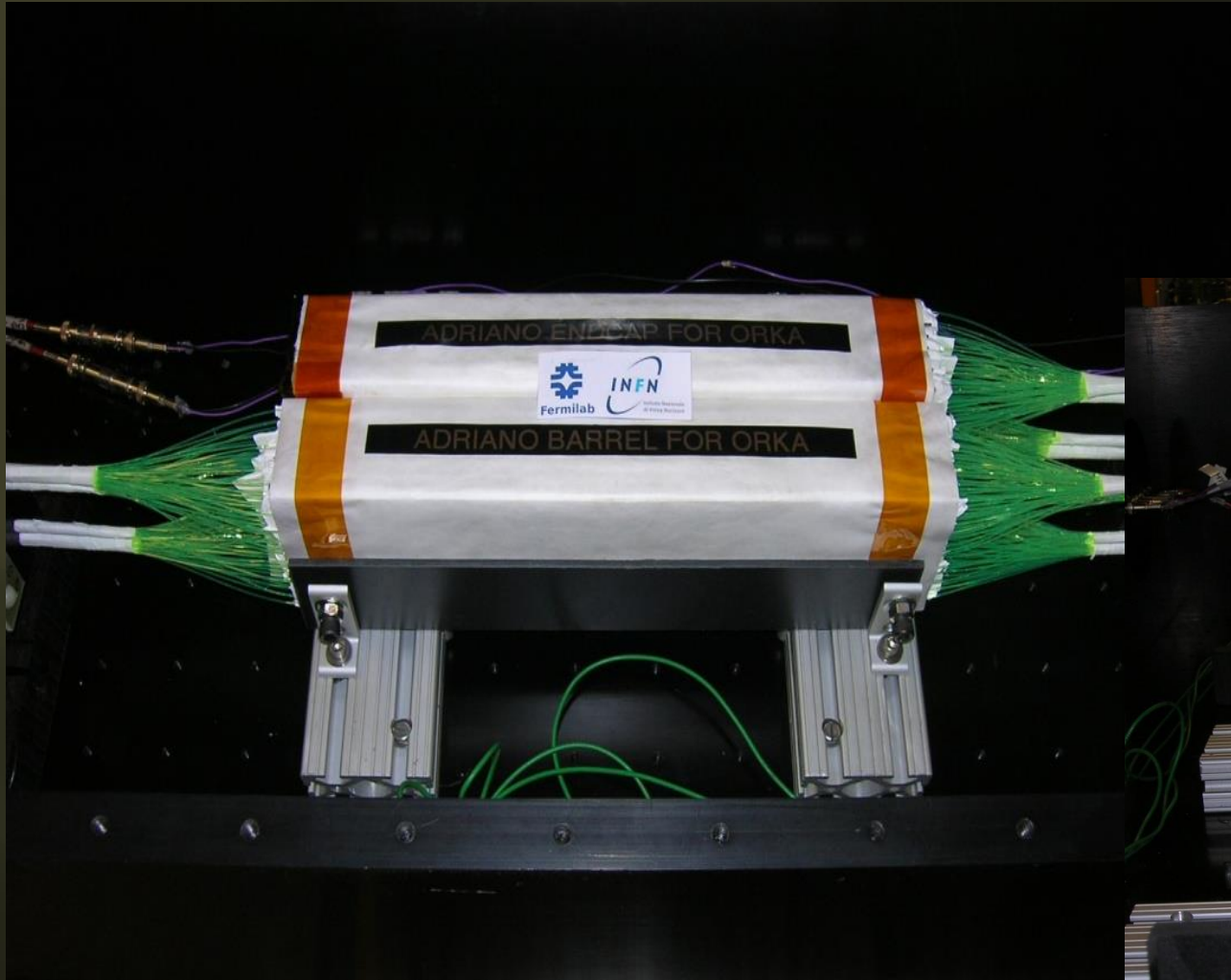
$$\chi \equiv \tan(\theta_{S/Q}) = \frac{1-1/\eta_C}{1-1/\eta_S}$$



$\eta_S = \eta_C$

- **Small Γ** = photodetector area/calorimeter area. $\Gamma_{DREAM} = 24\%$. $\Gamma_{4th} = 21\%$. Goal is $\Gamma < 10\%$.
- Small mixing of S and C components

ADRIANO for ORKA Final Prototypes



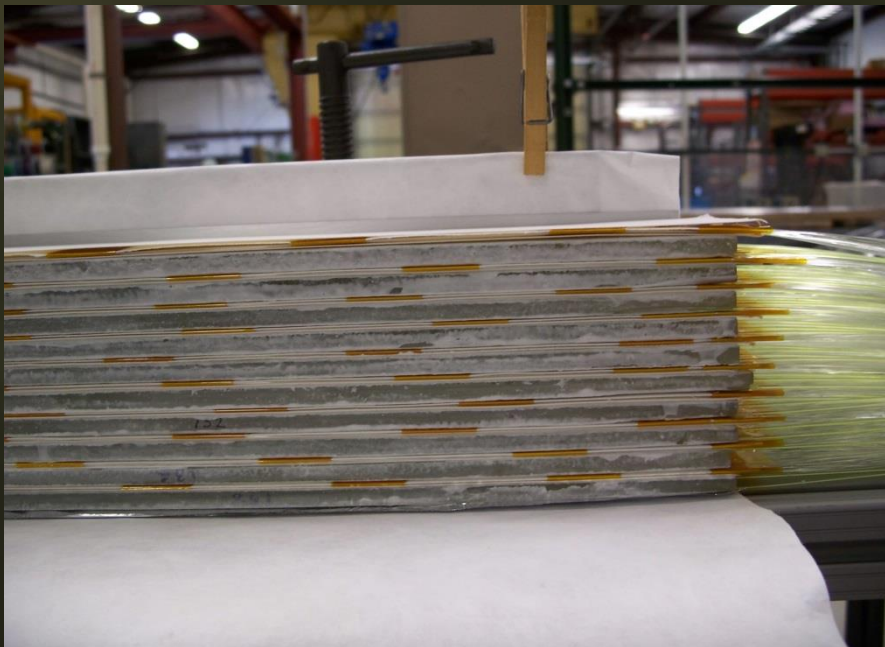
High Energy vs High Intensity Layouts

High Energy

- ▣ Detection of Hadronic and EM showers with large S and Č light production
- ▣ Optimized for maximum shower containment (i.e. max detector density)



- Thicker glass
- Thin scintillating fibers or ribbons
- Fewer WLS fibers

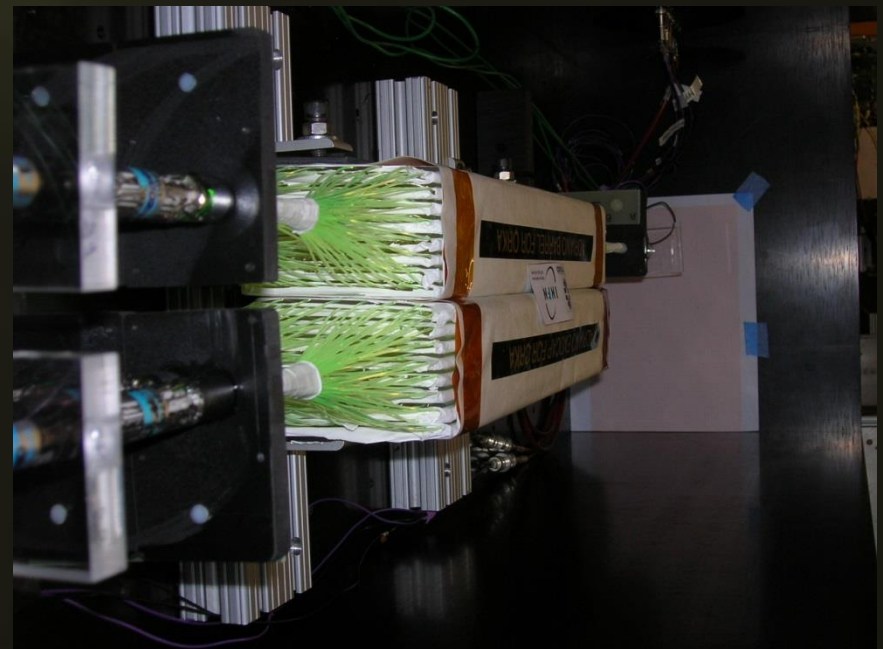


High Intensity

- ▣ Detection of EM showers only with small S and Č light production
- ▣ Optimized for high sensitivity in the 10 MeV range (i.e. max detector granularity)



- Thinner glass
- Thicker scintillator plates
- More WLS fibers



On CP violation (CPV) in $\eta \rightarrow \pi^+ \pi^- \pi^0$ decay

Unlike $\eta \rightarrow \pi \pi$ decay, CPV can appear via amplitude interference

➡ CPV effect would be linear in a CPV parameter

Multiple observables appear through the Dalitz plot

- Recall early discussions of C violation, [TD Lee & L Wolfenstein, 1965; Lee, 1965; Nauenberg, 1965] possibly through EM interactions [Bernstein, Feinberg, & Lee, 1965; Barshay, 1965]
- C violation can be discovered through a “charge asymmetry” in the Dalitz plot (difference in the π^+ / π^- energy spectra)

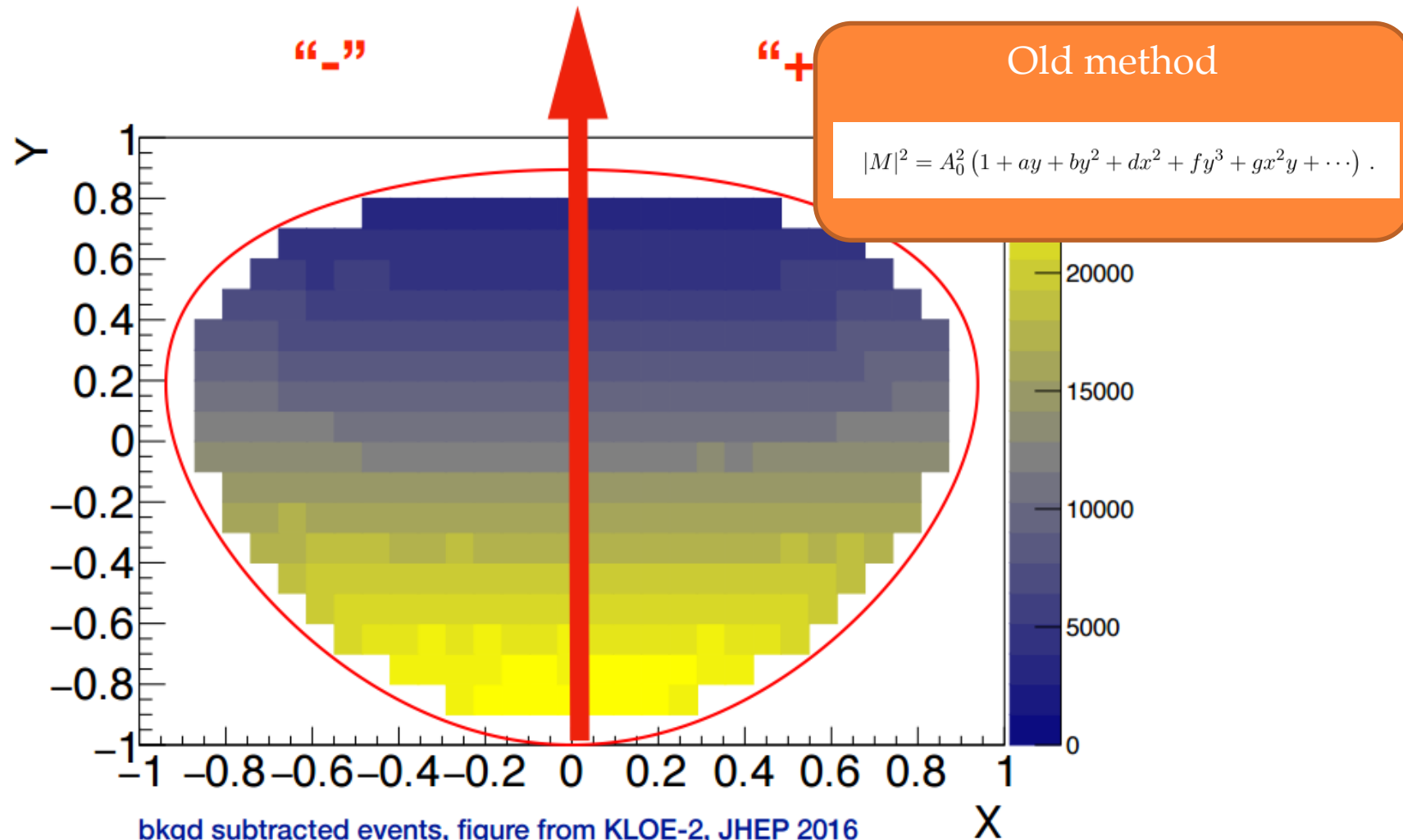
Note left-right (+/-) asymmetry — and asymmetries to probe if I is non-zero as well [Note also Layter et al. PRL 1972 and, e.g., KLOE-2, JHEP 2016]

* New! Note structure of possible CPV interferences in decay rate

[Note Gardner & Tandean, 2004; Gardner & Shi, 2017, to appear]

On CP violation (CPV) in $\eta \rightarrow \pi^+ \pi^- \pi^0$ decay

Terms in $|A|^2$ that are odd in X generate a charge (+/-) asymmetry
Can also fit Dalitz distribution for these X odd terms



Slide Credit: Susan Gardner & Jun Shi

Theoretical Analysis: $\eta \rightarrow \pi^+ \pi^- \pi^0$

C and CP violation poorly constrained in flavor diagonal processes

New way to construct CPV amplitudes in $\eta \rightarrow \pi^+ \pi^- \pi^0$

- Use NLO ChPT result & project it to the isospin basis of two pions ($I=0,1,2$)

[Gasser & Leutwyler, 1985; note also Anisovich & Leutwyler, 1996; Bijmans & Ghorbani, 2007]

- Add CP violating terms controlled by “a” and “b”

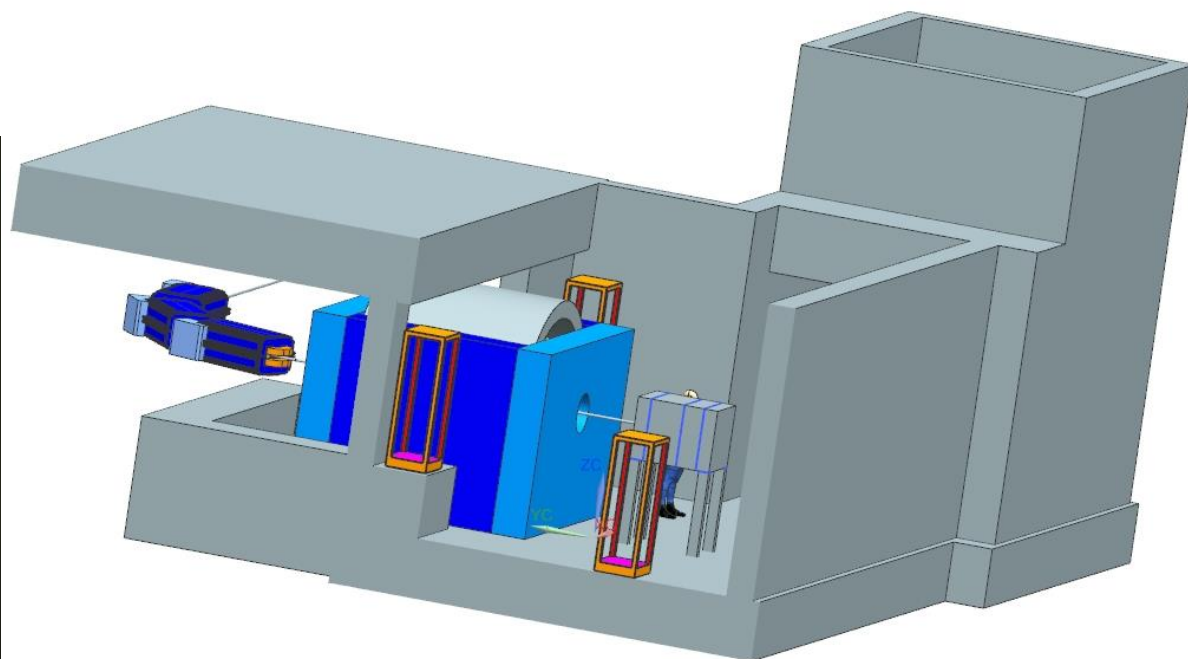
$$A(s, t, u) = M_0(s) + (s - u)M_1(t) + (s - t)M_1(u) + M_2(t) + M_2(u) - \frac{2}{3}M_2(s) \\ + a[(s - u)M_1(t) - (s - t)M_1(u)] + b[M_2(t) - M_2(u)]$$

- Expand 8 CPV interferences in $|A(s,t,u)|^2$ in terms of $(X, Y)=(0,0)$
- Can fit the Dalitz plot to get $\text{Re}(a)$, $\text{Im}(a)$, $\text{Re}(b)$, $\text{Im}(b)$ and/or study charge asymmetries

Preliminary analysis shows the largest CPV contributions could come from the interference with $M_0(s)$

[Gardner & Shi, 2017, to appear]

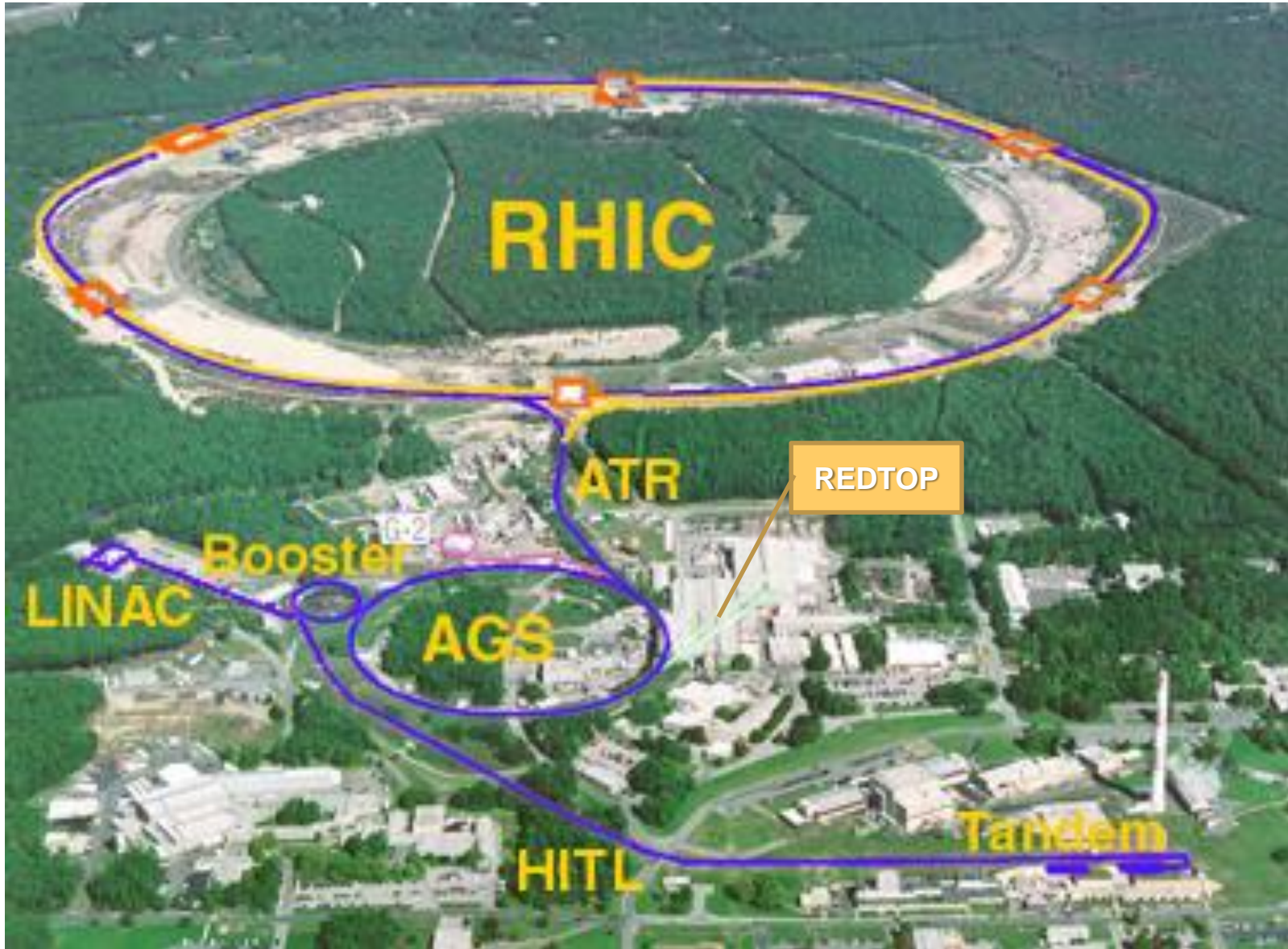
REDTOP detector in AP50



J. Kilmer
J. Rauch
E. Barzi (Solenoid and yoke)

(Many thanks to K. Krempetz, as well)

BNL hadron complex



661/2019

