HIDDEN SECTOR SEARCHES WITH REDTOP

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

Corrado Gatto
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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 ($\mathcal{O}(10^{41})$ cm^{-2} vs $\mathcal{O}(10^{44})$ cm^{-2} for 1–mm fixed target)*
- *An η /η' factory with 10^4x 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: $\eta \to \pi^o \pi^+ \pi^-$

Search for asymmetries in the Dalitz plot.

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

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

Dark photon searches: $\eta \to \gamma A'$ with $A' \to \ell^+ \ell^-$

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

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 (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

- 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 ~10^{13} η mesons/yr and ~10^{11} η' mesons/yr

C, T, CP-violation

- *CP Violation via Dalitz plot mirror asymmetry: $\eta \rightarrow \pi^o \pi^+ \pi^-$*
- *CP Violation (Type I – P and T odd , C even): $\eta \rightarrow 4\pi^o \rightarrow 8\gamma$*
- *CP Violation (Type II - C and T odd , P even): $\eta \rightarrow \pi^o \ell^+ \ell^-$ 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: $\eta \rightarrow \pi^o \mu^+ \mu^-$ 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): $\eta \rightarrow \pi^o H$ 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 discrete symmetry violations

- *Lepton Flavor Violation: $\eta \rightarrow \mu^+ e^-$ + c.c.*
- *Double lepton Flavor Violation: $\eta \rightarrow \mu^+ \mu^+ e^- e^-$ + c.c.*
- *Lepton Number Violation: $\eta \rightarrow \pi^- \pi^- e/\mu^+ e/\mu^+$ + 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: qqbar $\rightarrow A'/a \rightarrow l^+ l^-$*
- *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: $\pi^o \rightarrow \gamma A' \rightarrow \gamma e^+ e^-$*

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)*

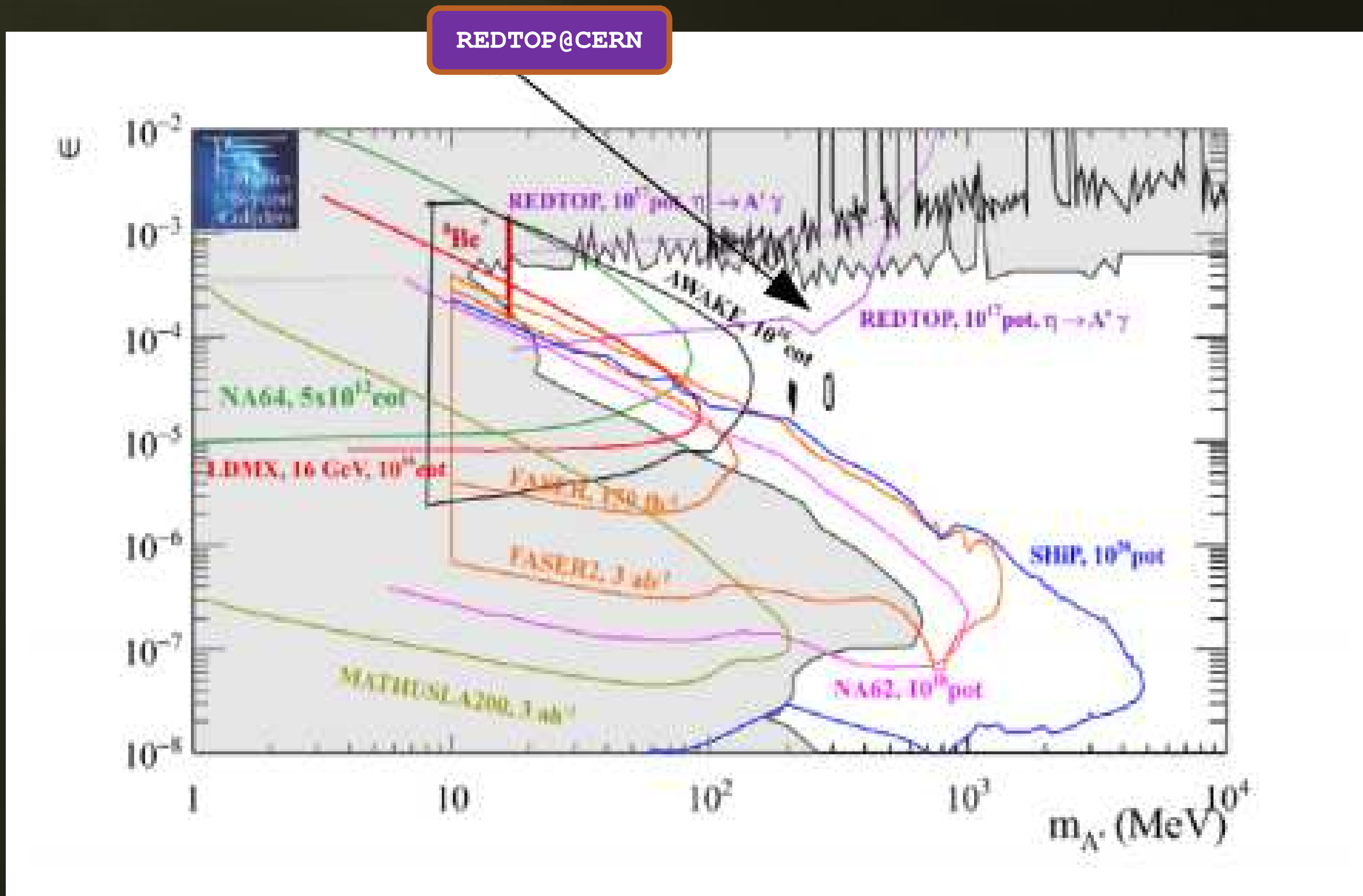
Physics Beyond Collider Program

- *Instituted by CERN's Director in 2016 to exploit physics BSM at smaller experiments*
- *Exploratory study aimed at exploiting the scientific potential of its accelerator complex projects complementary to the LHC*
- *Study provide input for the future of CERN's scientific diversity Programme and ESPP*
- *Three committees coordinating accelerator, experimental, and theoretical particle physics*
- *Four portals and twelve benchmark processes under consideration: Vector – Scalar– Heavy Neutrino – Axions and ALPs*
- *21 participating experiments: mostly beam-dump or aimed at invisible searches*
- *REDTOP unique in terms of experimental technique – sensitive to:*
  - *Vector portal with visible η/η' decays*
  - *Scalar porta with visible η/η' decays*
  - *ALPs portal with visible η/η' decays and beam ALPsstrahlung*

Dark photon searches:

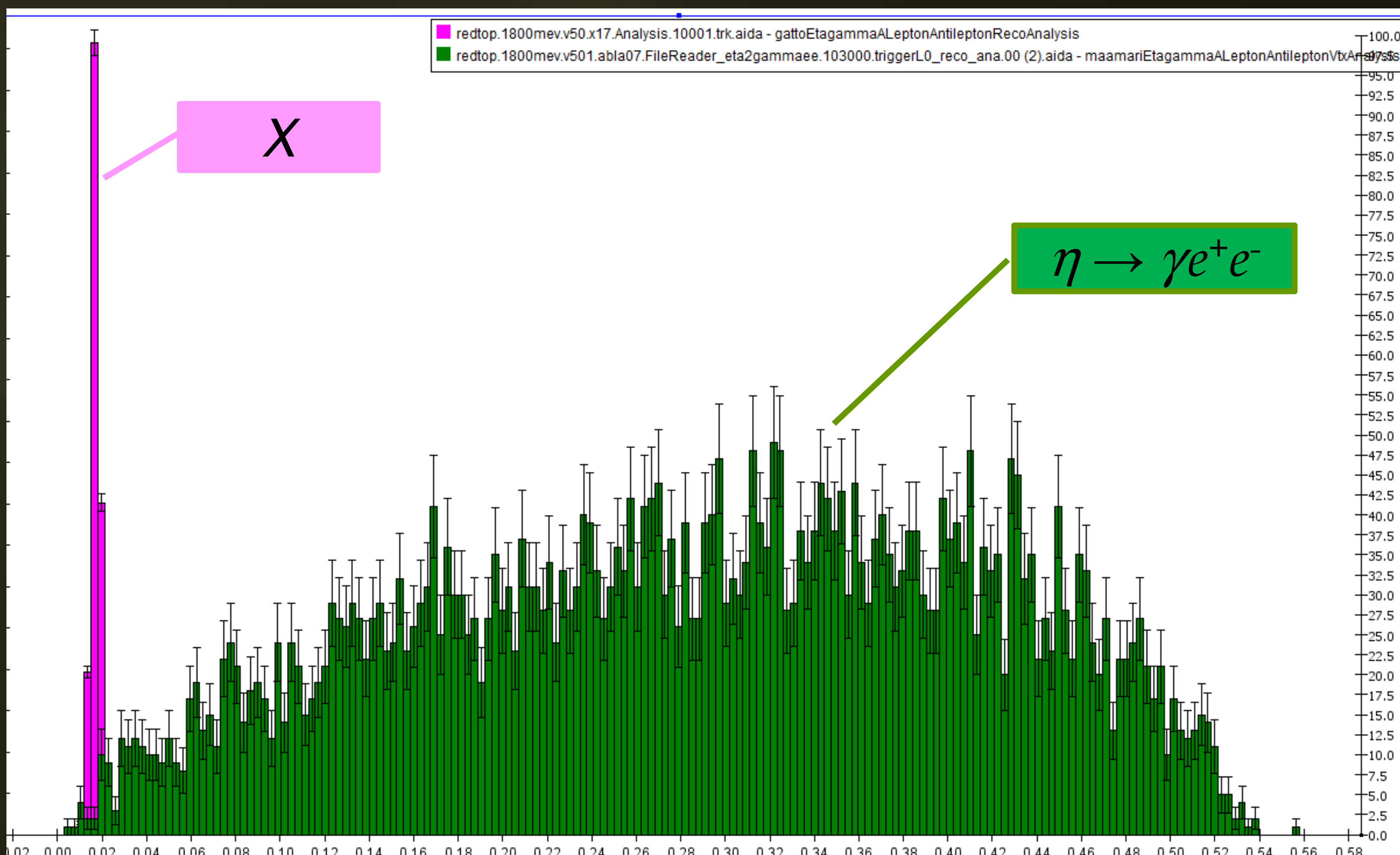
$\eta \to \gamma A'$ with $A' \to \mu^+ \mu^-$ and $e^+ e^-$

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



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*



Searches for light scalar mesons

$\eta \rightarrow \pi^0 S$ with $S \rightarrow \gamma\gamma, \pi^+\pi^-, \mu^+\mu^-$ and e^+e^-

Two categories of theoretical models

Minimal SM Higgs extension

- *Viable DM candidate (in certain circumstances) coupling to Higgs portal - D. O'Connell, M. J. Ramsey-Musolf and M. B. Wise, Phys. Rev. D75 (2007) 037701 and , G. Krnjaic, Phys. Rev.D94 (2016)*
- *$S - H$ mixing in the Higgs potential via a mixing angle*
- *It couples mostly to top quark and gluons*
- *Favorite experimental technique: B factories (LHCb)*
- *Disvavorite at REDTOP*

Hadrophilic Scalar Mediator

(or Spontaneous Flavor Violation)

- B. Batell, A. Freitas, A. Ismail, and D. McKeen - **arXiv:1812.05103**
- *D. Egana-Ugrinovic, S. Homiller, P. Meade* - **arXiv:1908.11376**
- *Much less constrained by cosmological and EDM bounds*
- *It couples mostly to up and down quarks*
- *Favorite experimental technique: η/η' factories*
- *Disvavorite at LHCb and Belle*
- *Moderate discovery potential with K beams*

Searches for light scalar mesons

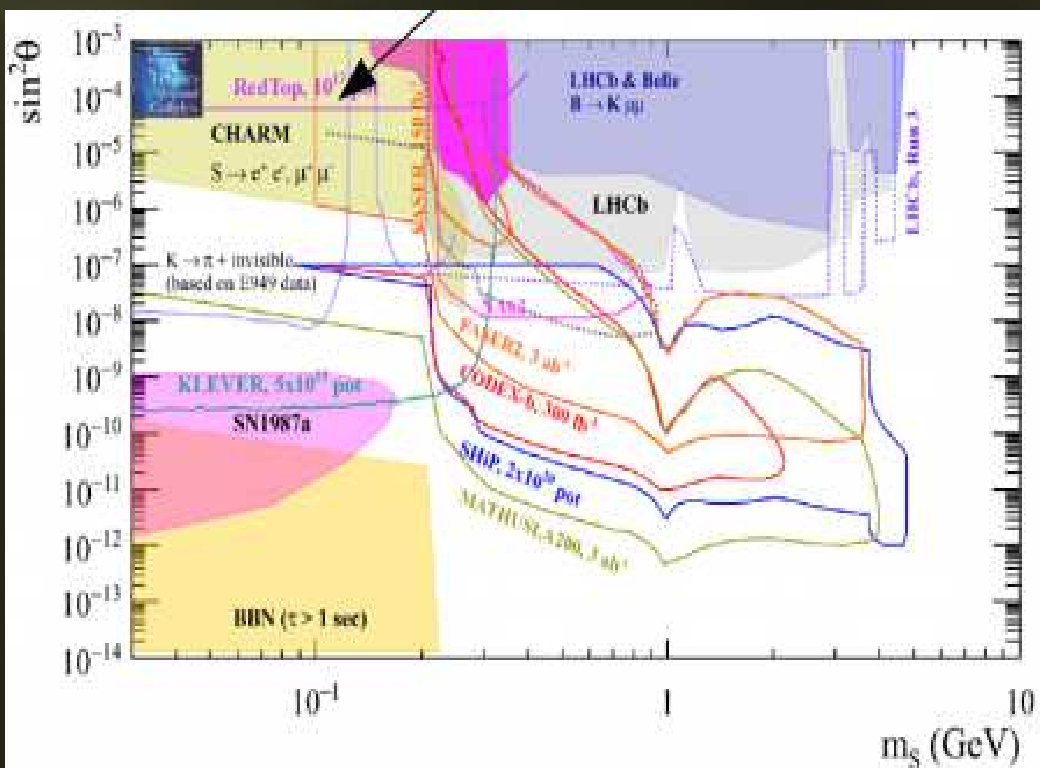
Minimal SM Higgs extension

- *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

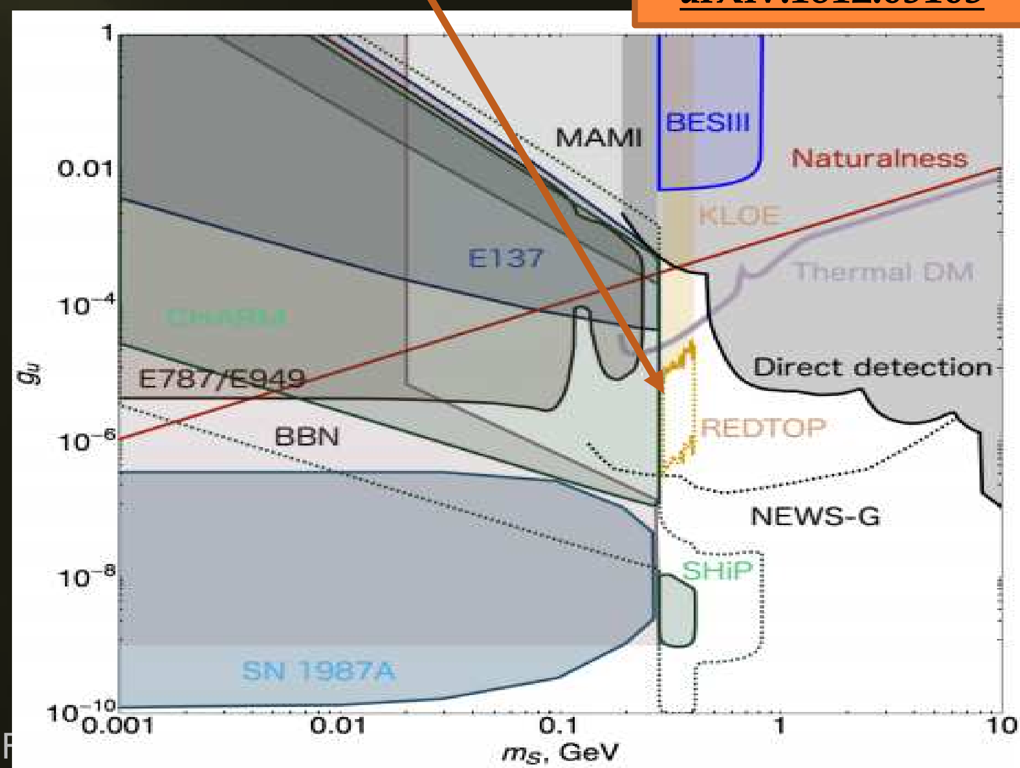
- *Studied in arXiv:1812.05103*
- *Only bump hunt - no vertexing*

REDTOP@CERN



REDTOP@Fermilab

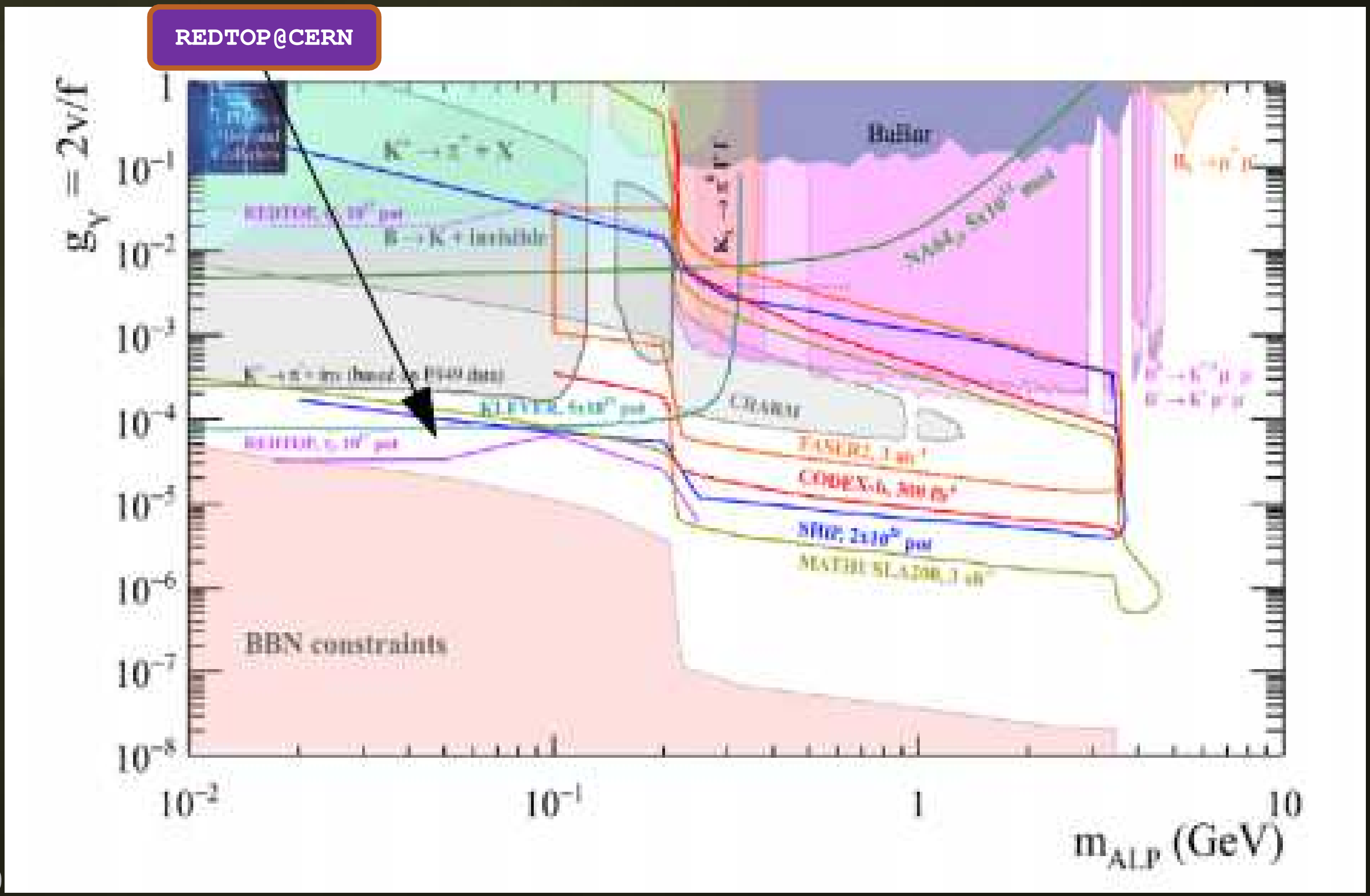
arXiv:1812.05103



Searches for ALPs with fermion coupling

$\eta \rightarrow \pi^o \pi^o a$ and $\eta \rightarrow \pi^+ \pi^- a$ with $a \rightarrow \mu^+ \mu^-$ 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.*



Searches for ALPs with gluon coupling

- *Beam emitted ALP's from the following processes:*
  - *Drell-Yan processes: qqbar* → *A'/a* → l^+l^-
  - *Proton bremsstrahlung processes: p N* → *p N A'/a with A'/a* → l^+l^- *(J. Blümlein and J. Brunner)*
  - *Primakoff processes: p Z* → *p Z a* → l^+l^{-} *(F. Kahlhoefer, et. Al.)*

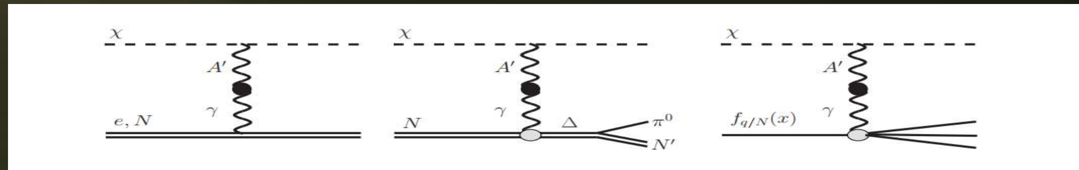
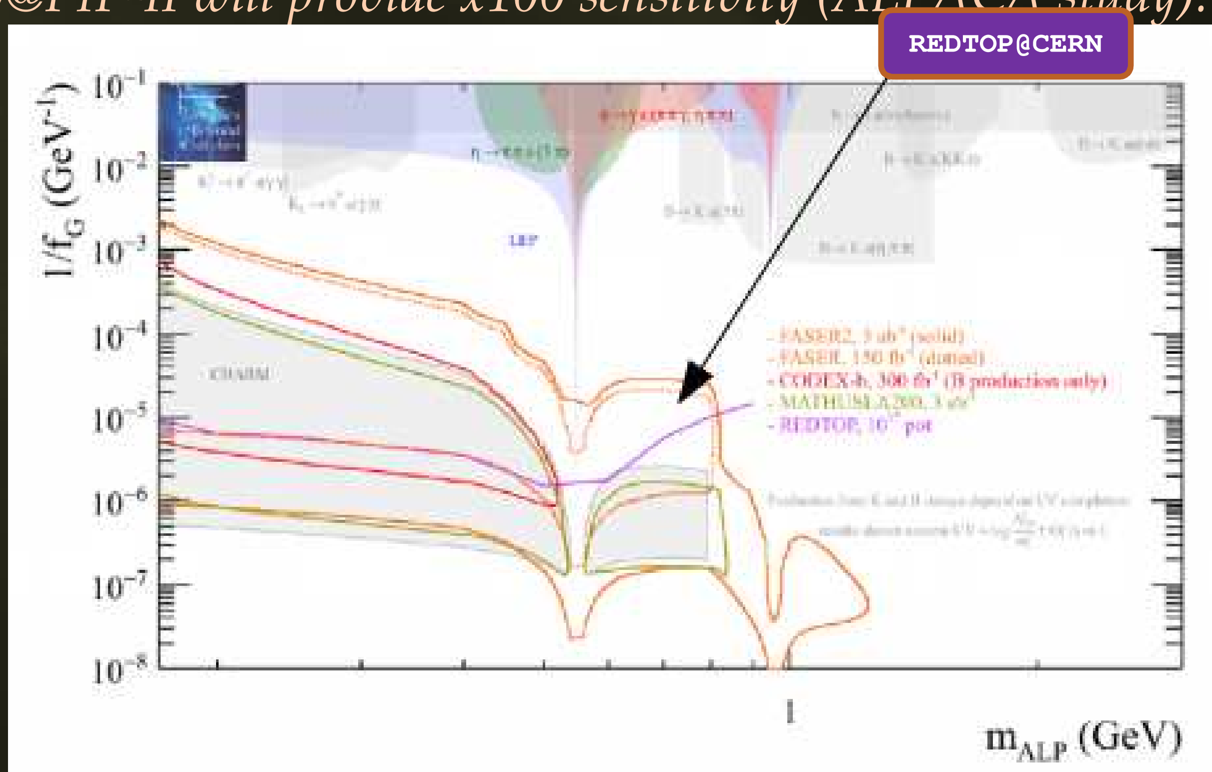


FIG. 4. Scattering channels analyzed: from left to right, elastic scattering on electrons or nucleons, quasielastic (incoherent) single pion production, and deep inelastic scattering.

Patrick deNiverville,[1] Chien-Yi Chen,[1,2] Maxim Pospelov,[1,2] and Adam Ritz[1]

- *Studied within the "Physics Beyond Collider" program at CERN for 10^{17} POT*
- *Redtop@PIP-II will provide x100 sensitivity (ALPACA study).*



Missing 4-P Searches: tREDTOP (@ PIP-II)

$$\sigma_T(pd \to {}^3\mathrm{He}\,\eta) = \left(\frac{p_\eta}{p_p}\right) \frac{22}{(1+1.6p_\eta)^2 + (3.8p_\eta)^2}\ \mu\mathrm{b}\,,$$

η production already a puzzle of his own

- *Fully constrained kinematics*
- *Unique experimental apparatus to explore visible and invisible decays of LDM*
- *Tagging expected to lower the background by >100x*
- *Requires 800 MeV p-beam, De target and 3He$^+$ detector*
- *No η' production (need about 1.4 GeV beam)*

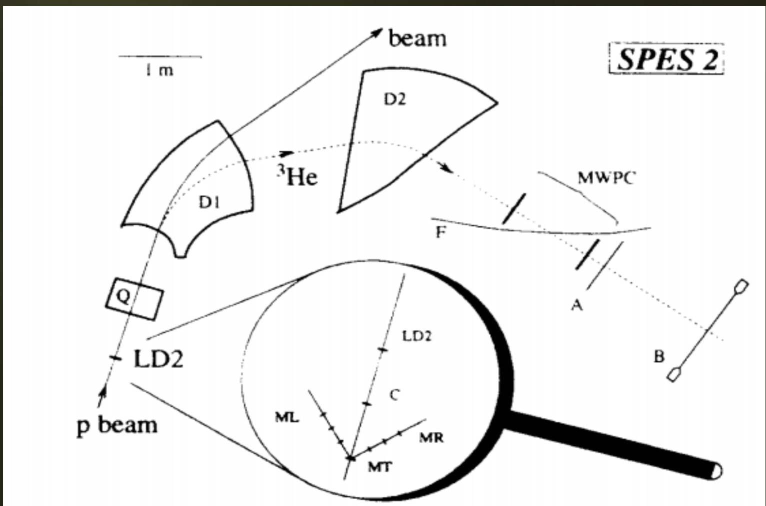
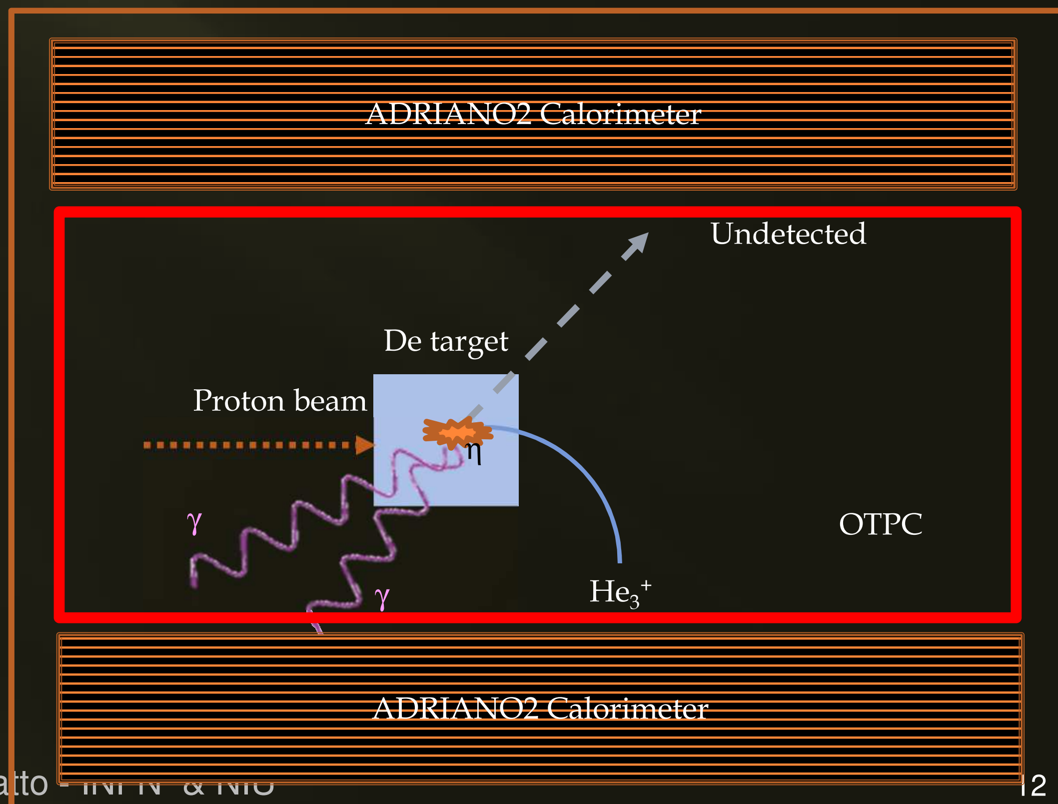


FIG. 1. Top view of the experimental set-up. LD2 is the liquid deuterium target, MT is a thin polypropylene monitor target, ML and MR are two telescopes of scintillators. C is a retractable ^{12}C target used for absolute normalization. Q is

B. Mayer et al., Phys. Rev. C53, 2068 (1996);



Experimental Techniques- η/η' production+detection

- *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*
- *η yield: 2.5 x 10^6 η/sec (2.5 x 10^4 η'/sec) or 2.5 x 10^{13} η/yr (2.5 x 10^{11} η'/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)*

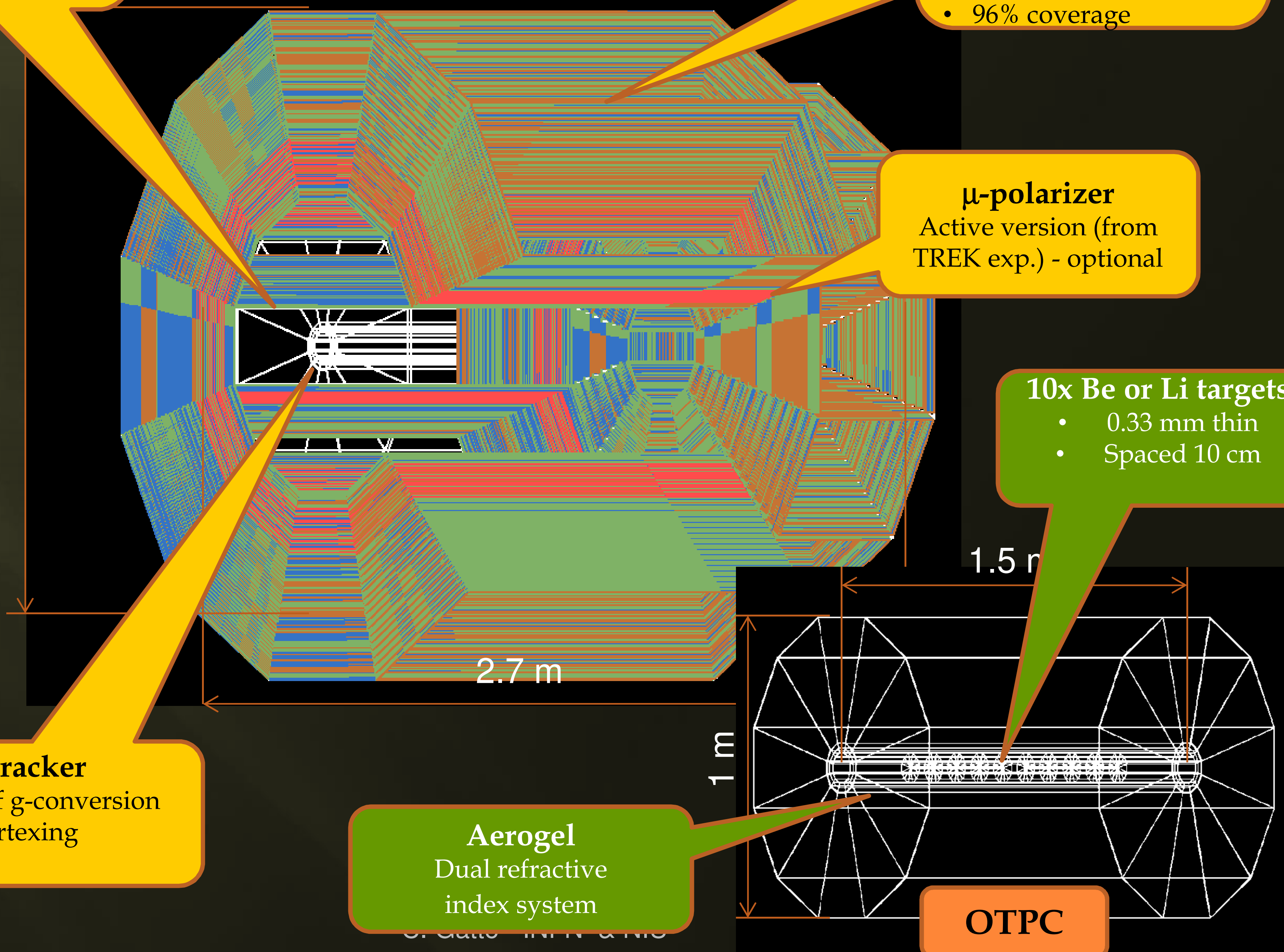
REDTOP Requirements

- *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.*

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



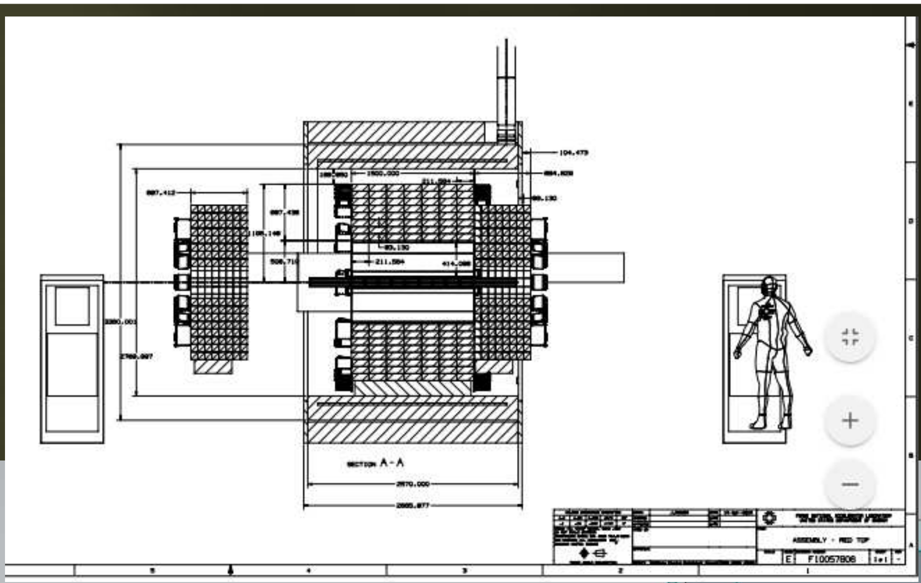
μ-polarizer
Active version (from TREK exp.) - optional

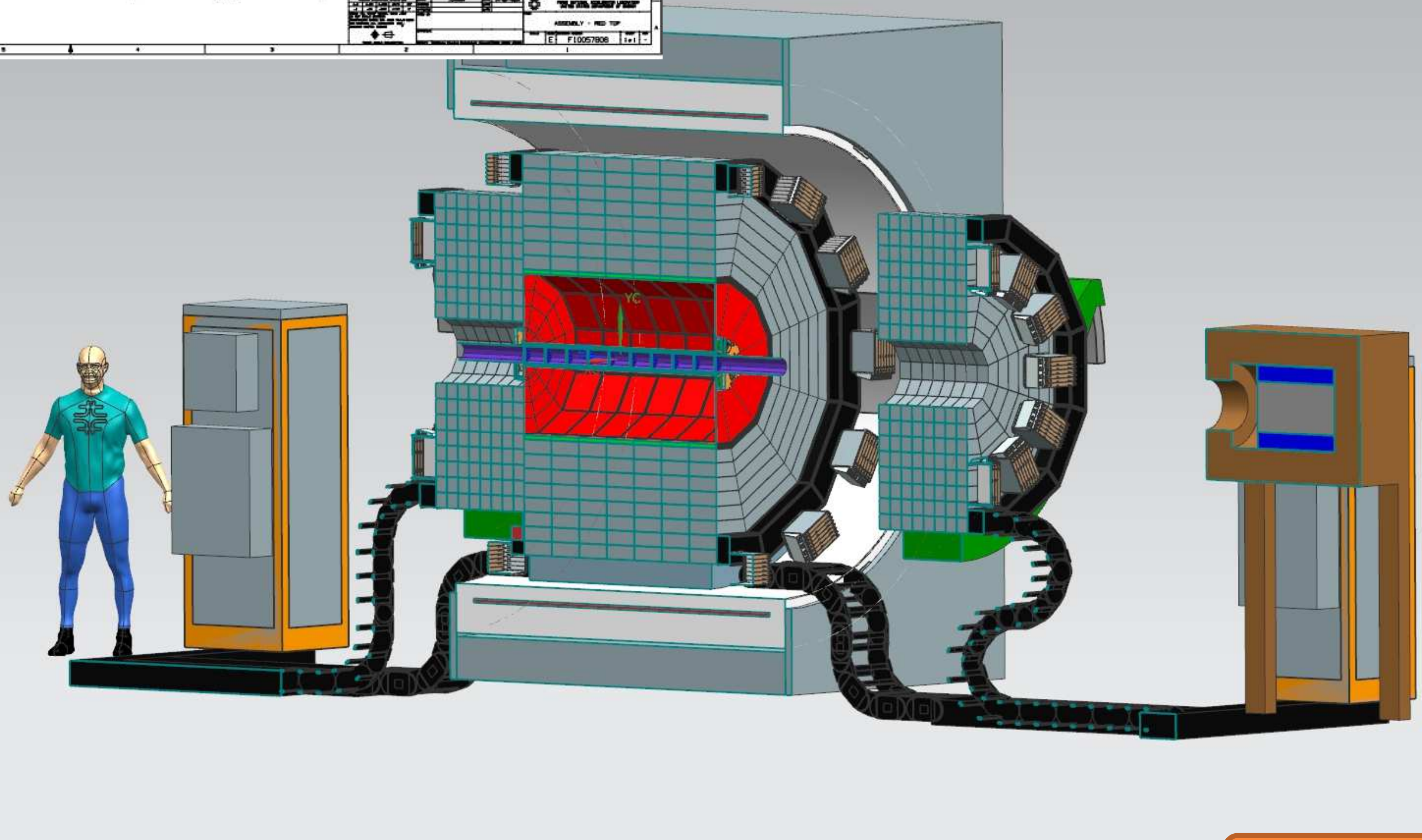
10x Be or Li targets
- 0.33 mm thin
- Spaced 10 cm

Fiber tracker
for rejection of g-conversion and vertexing

Aerogel
Dual refractive index system

REDTOP Detector + Finuda Magnet

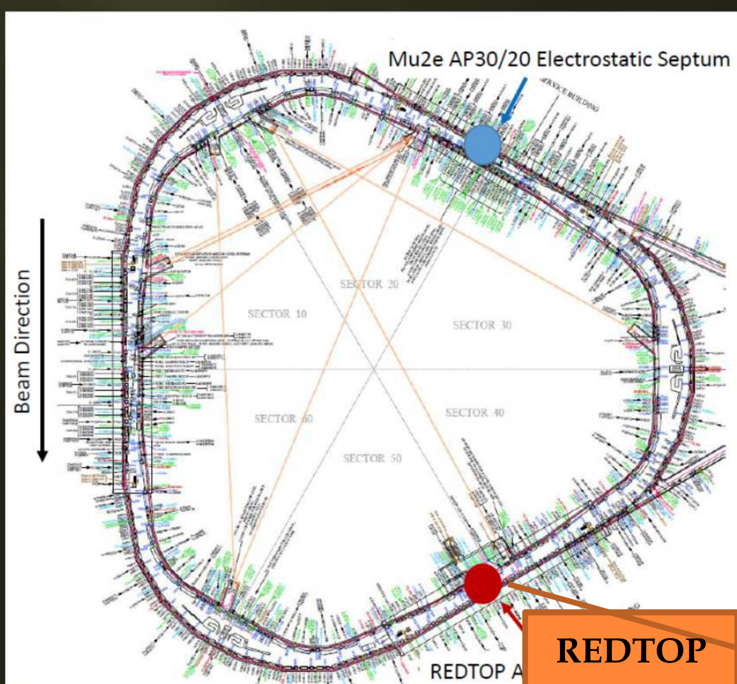


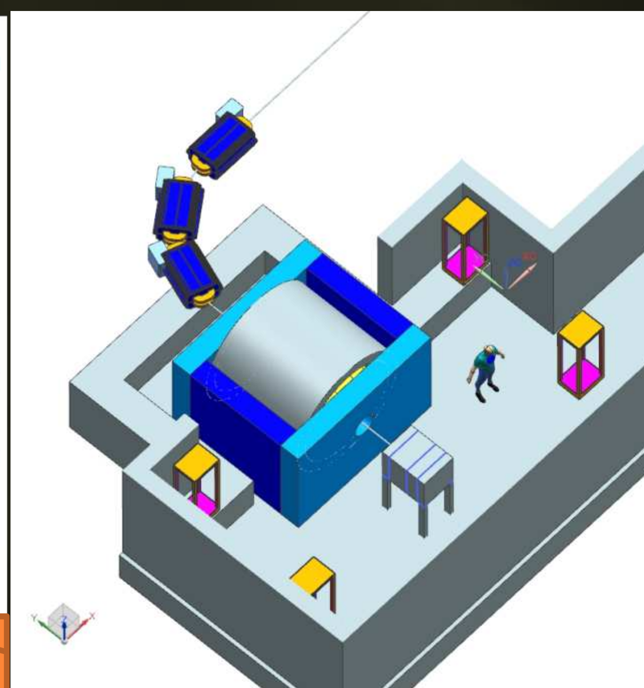


J. Kilmer – J. Rauch

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° 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%*





Timeline & Costing

- *Once approved and funded, REDTOP needs:*
  - *2 years detector R&D*
  - *1 year detector design*
  - *2 years 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 ¾ 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)*
  - *¾ 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

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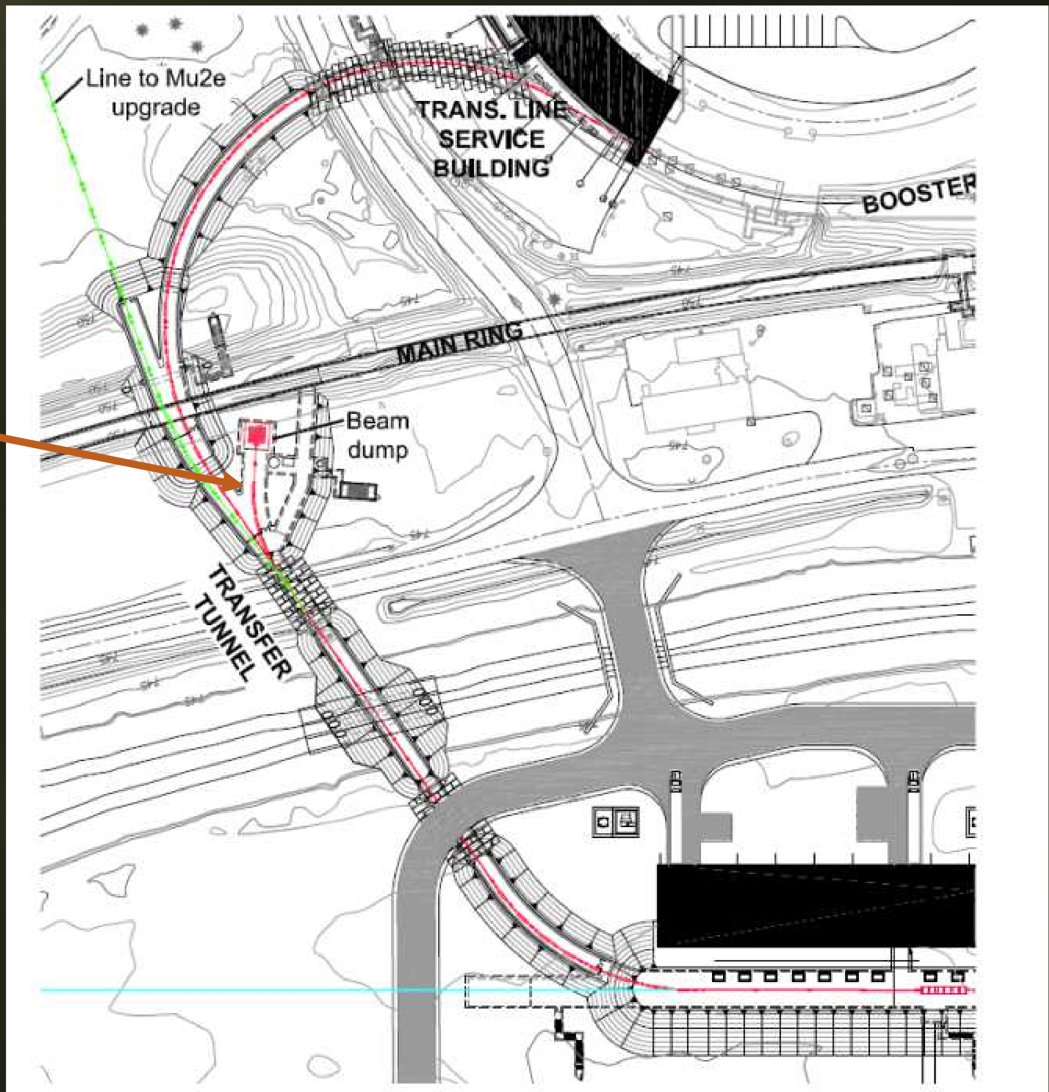
- *Potential hosting laboratories: BNL, CERN, FNAL (either Delivery Ring and/or PIP-II)*

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*
- *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 techniques would set the stage for next generation High Intensity experiments*
- *Moderate cost (50-60 M$)*
- ***More details: https://redtop.fnal.gov***

Tagged REDTOP at PIP-II
The ultimate eta factory

tREDTOP



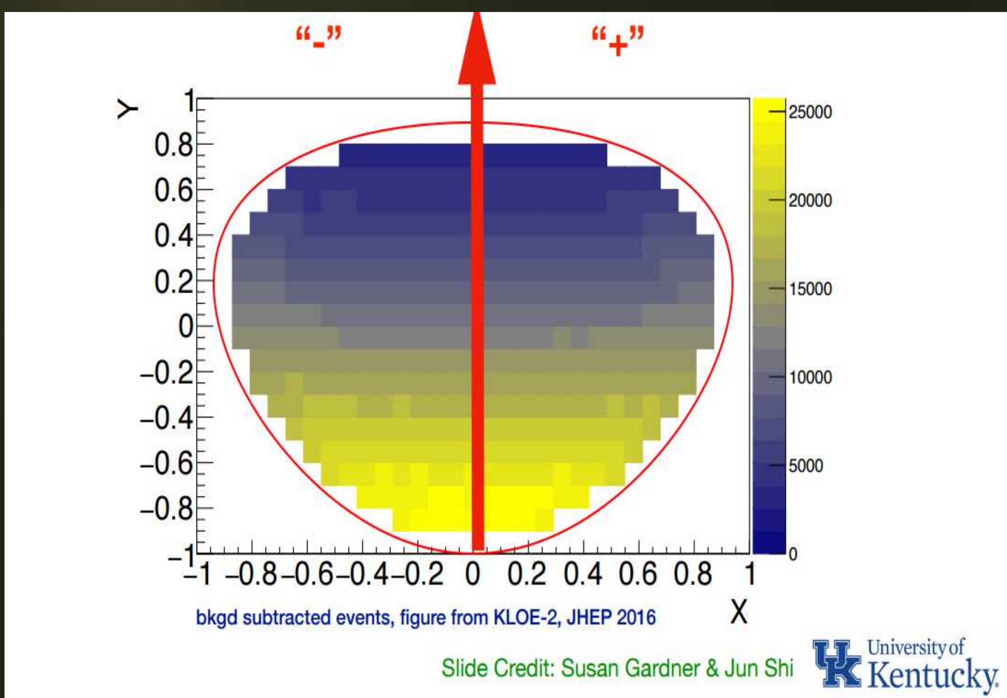
Backup slides

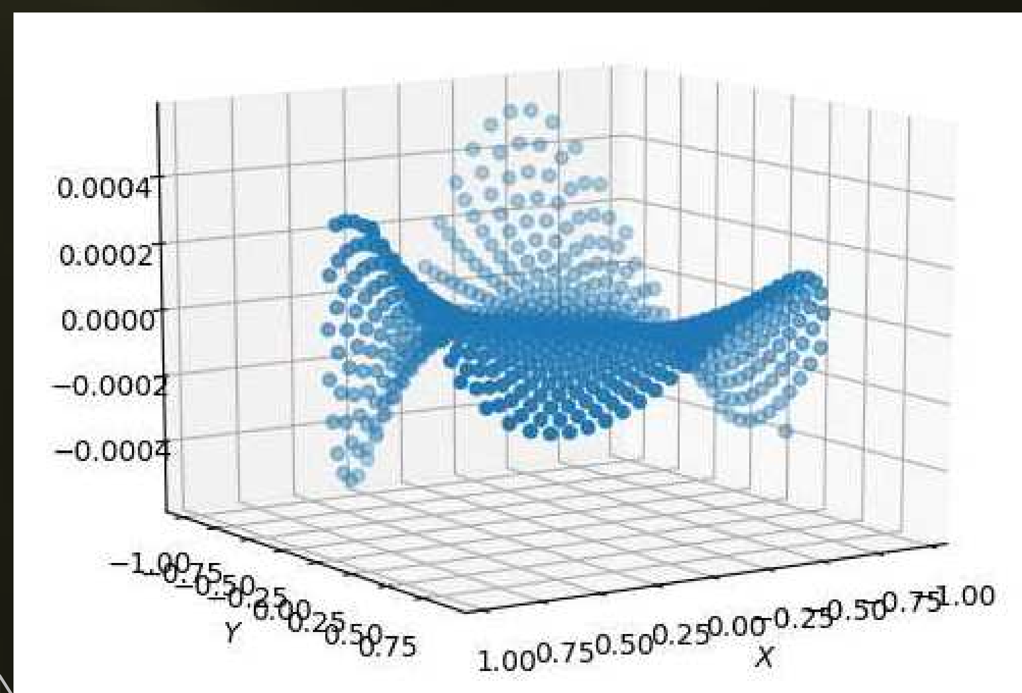
Future Prospects

- *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/ √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***

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

- *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 $4x10^{11}$ 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





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:*
  - *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 ¾ of Pb-Glass for ADRIANO in-kind contributions from INFN (Finuda and NA64 experiments)*
  - *Construction at participating institutions*
  - *Assembly at hosting laboratory*

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***

Present & Future 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	$pp \to \eta\, pp$ $pd \to \eta\, ^3He$			$>10^9$ (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)	$\gamma_{12\,GeV} p \to \eta\, X \to$ neutrals			5.5×10^7/yr
JEF@JLAB (recently approved)	$\gamma_{12\,GeV} p \to \eta\, X \to$ neutrals			3.9×10^5/day
REDTOP@FNAL (proposing)	$p_{1.8\,GeV} Be \to \eta\, X$			2.5×10^{13}/yr

Cost (estimate for ESPP)

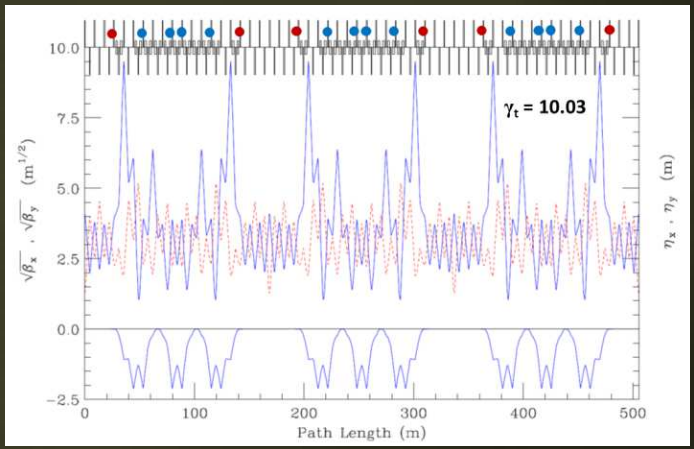
- ***In kind contribution from INFN***
  - *Solenoid (from Finuda experiment at Frascati)*
  - *¾ of Pb-glass (from NA62)*

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

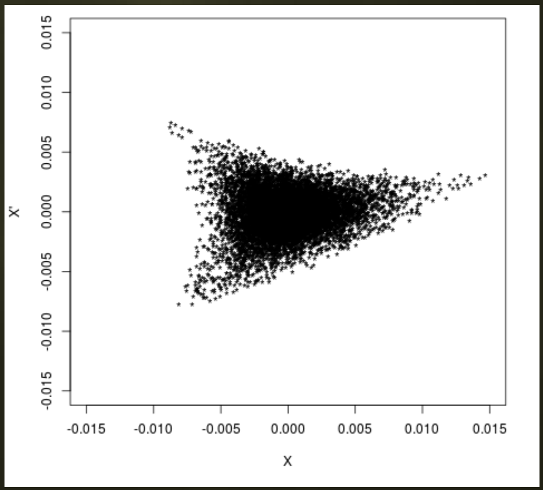
ADRIANO2	**16.0**
Pb-glass	2.7
Cast scintillator	0.75
Tile fabrication	0.6
SiPM	6.0
Front-end electronics	4.0
Back-end electronics	1.5
Mechanics and cooling	0.5
Trigger	**1.2**
L0 + L1	1.0
L2 farm + networking	0.2
DAQ	**5.0**
Digitizer	
Networking	
Contingency	**17.0**
50% Contingency	17.0
Total REDTOP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

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

Accelerator Physics Issues



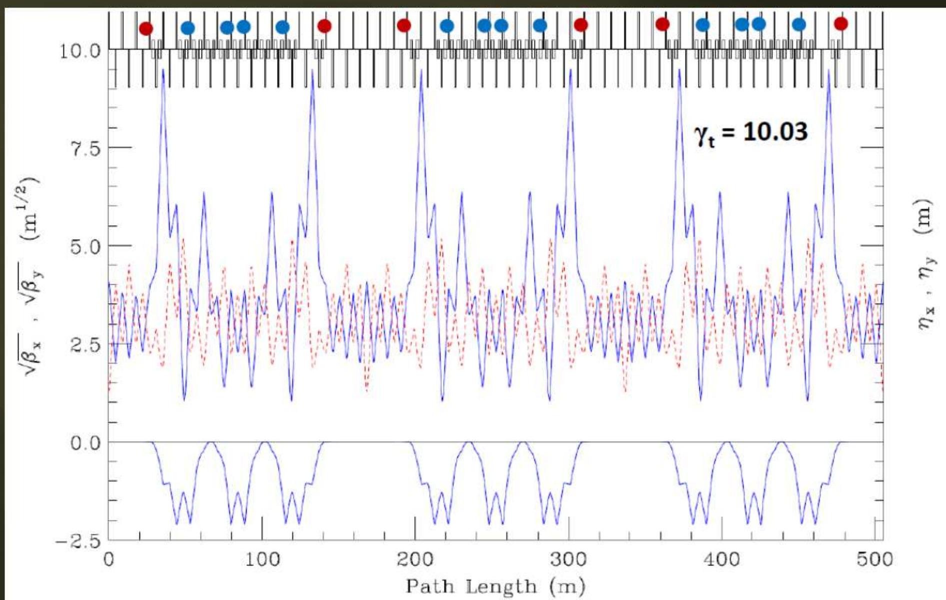
- *Transition Energy*
  - γ_t is where $\Delta f/f = 1/\gamma 2 - \langle D/\rho \rangle = 0$; synchrotron motion stops momentarily, can often lead to beam loss
  - beam decelerates from $\gamma = 9.5$ to $\gamma = 3.1$
  - original Delivery Ring $\gamma_t = 7.6$
  - a re-powering of 18 quadrupole magnets 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

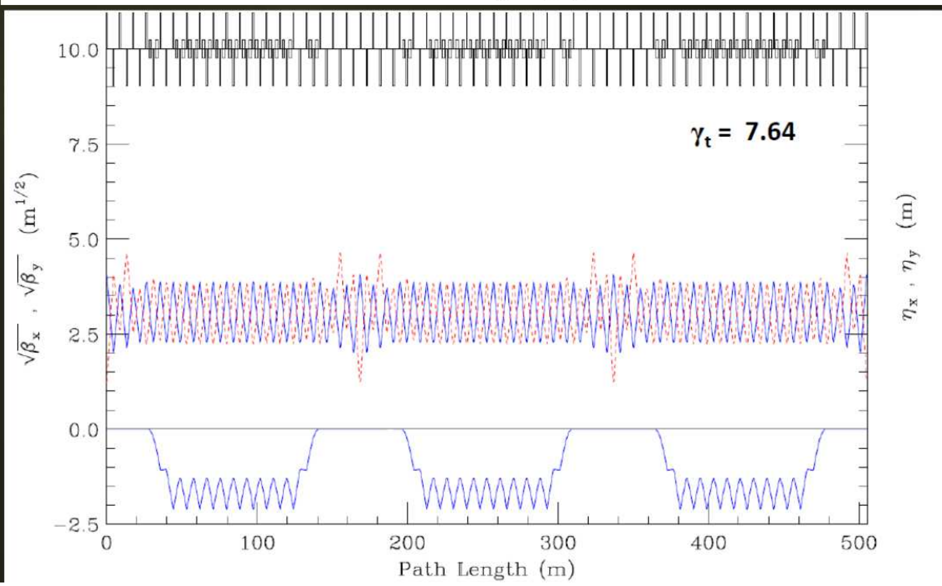


Ring Optics through Deceleration (J. Johnstone)

Transition is avoided by using select quad triplets to boost 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)

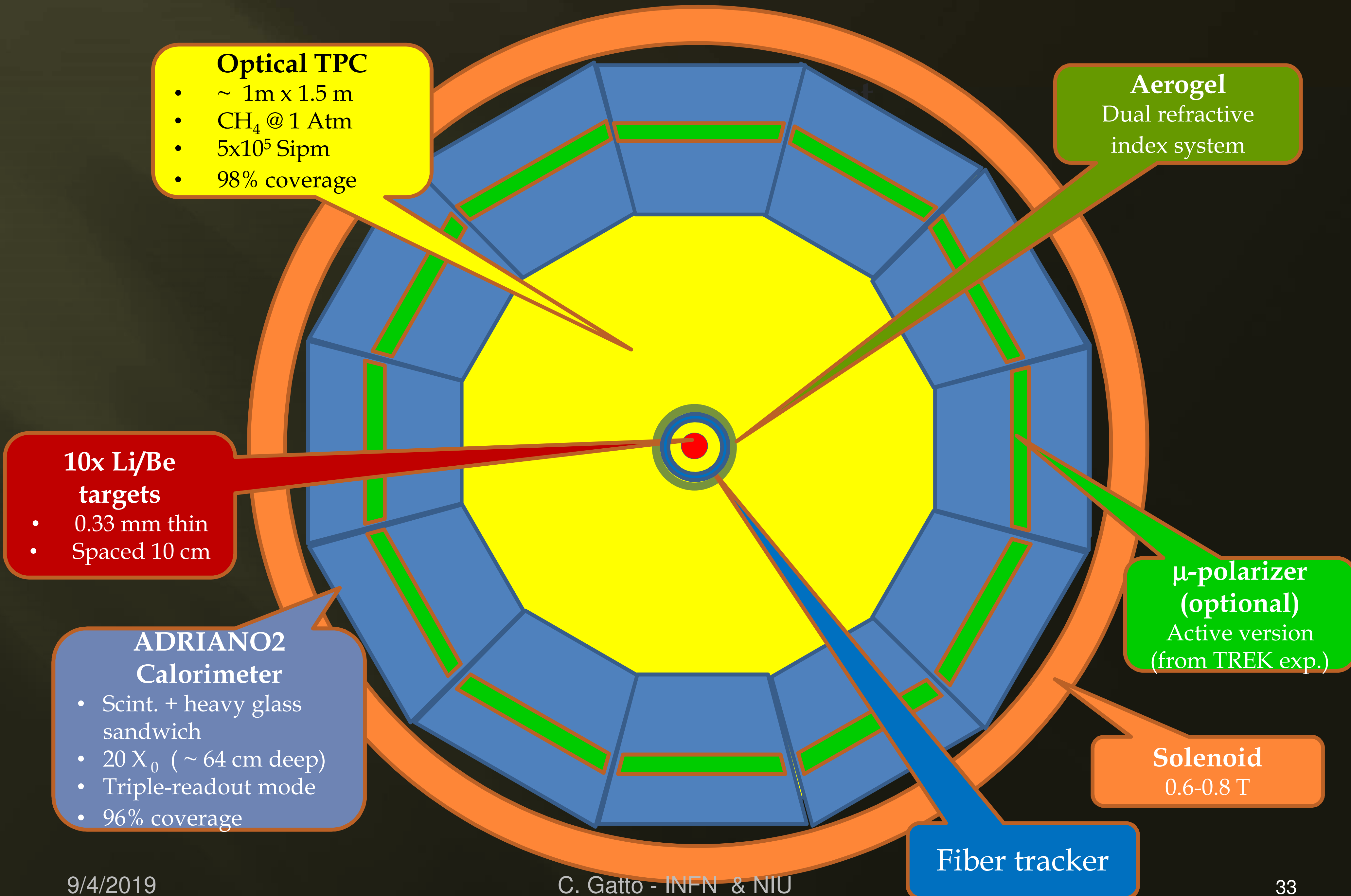
- Blue & red circles indicate sites of the γ_t quad triplets.

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

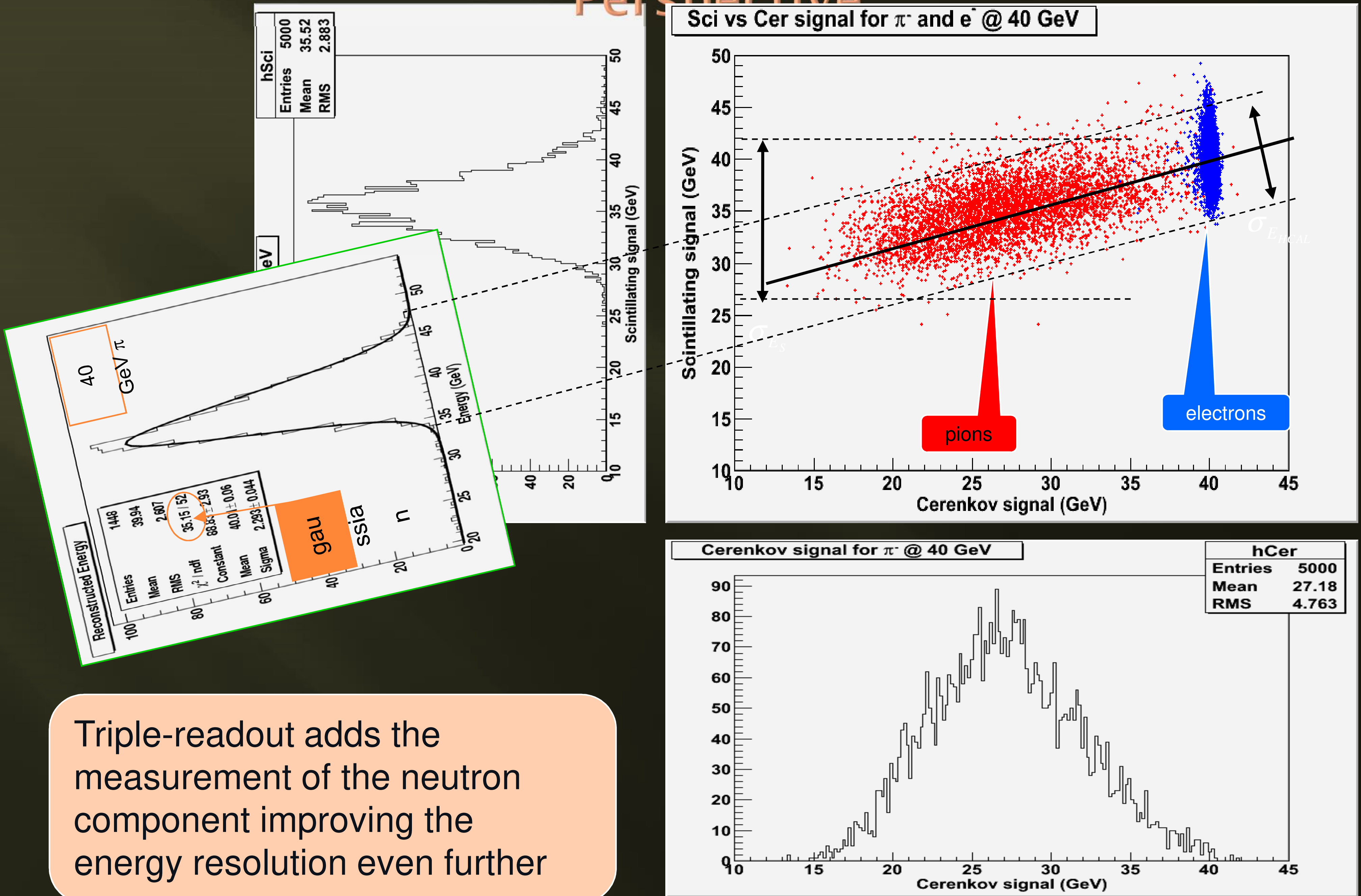


The ADRIANO2 Calorimeter

- *Sandwich of Pb-glass and scintillating plastic tiles with direct SiPM reading*
  - *Evolution of ADRIANO dual-readout calorimeter (A Dual-Readiut Integrally Active Non-segmented Option)*
- *Triple-readout obtained from waveform analysis*

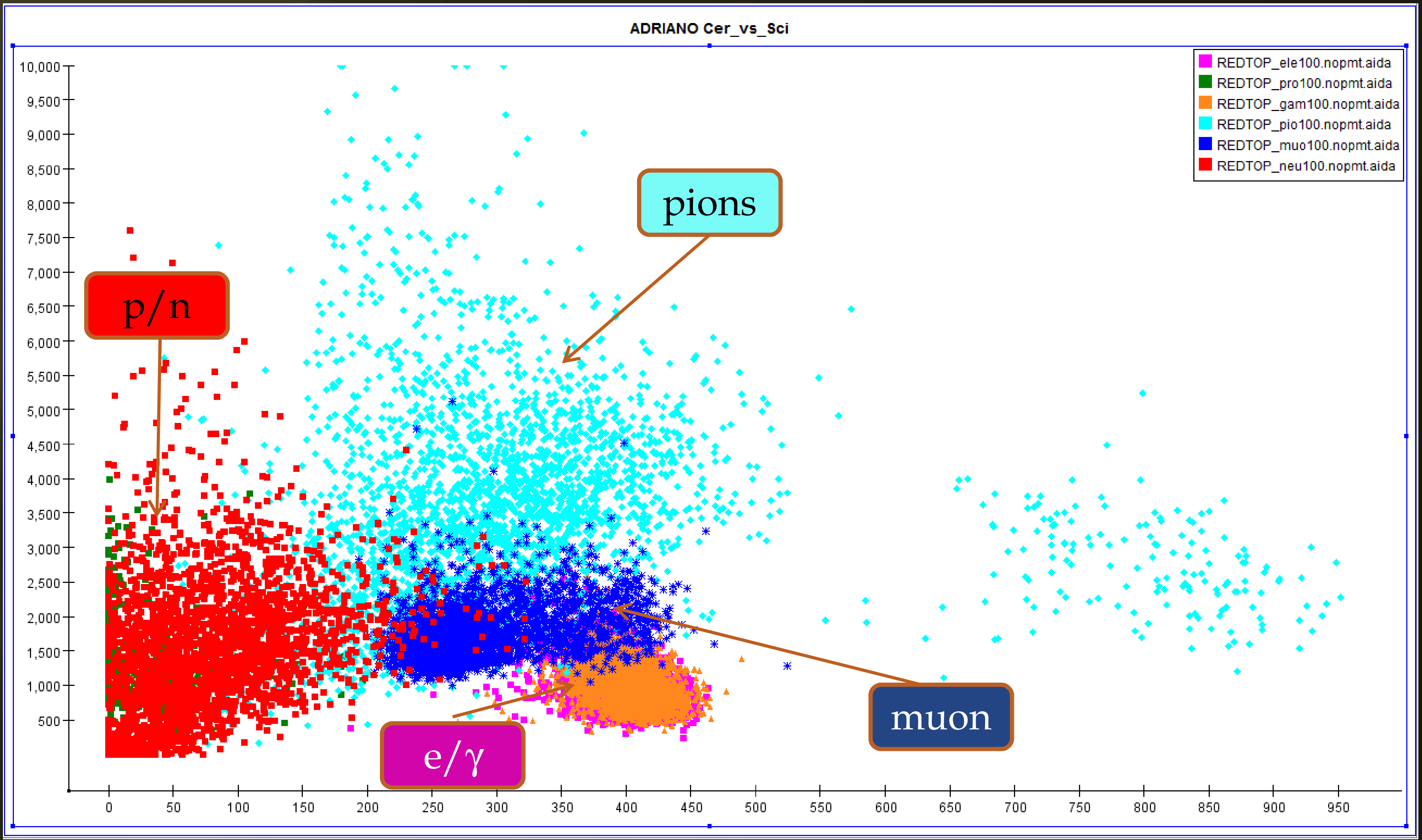
- *Rationale for multiple readout calorimetry at η -factory*
  - *Particle identification (see next)*
  - *Integrally active (no sampling)*
  - *Prompt Cerenkov light fed to L) trigger*
  - *Good granularity helps disentangling overlapping showers*

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



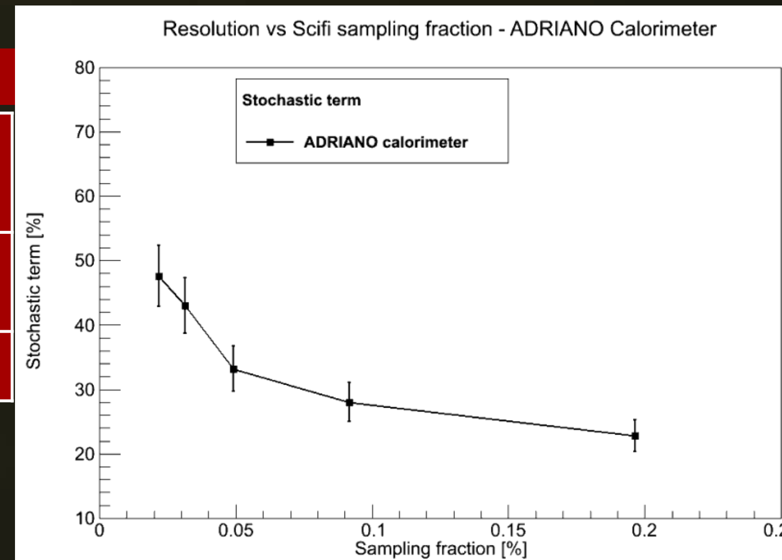
ADRIANO Light Yield and Resolution

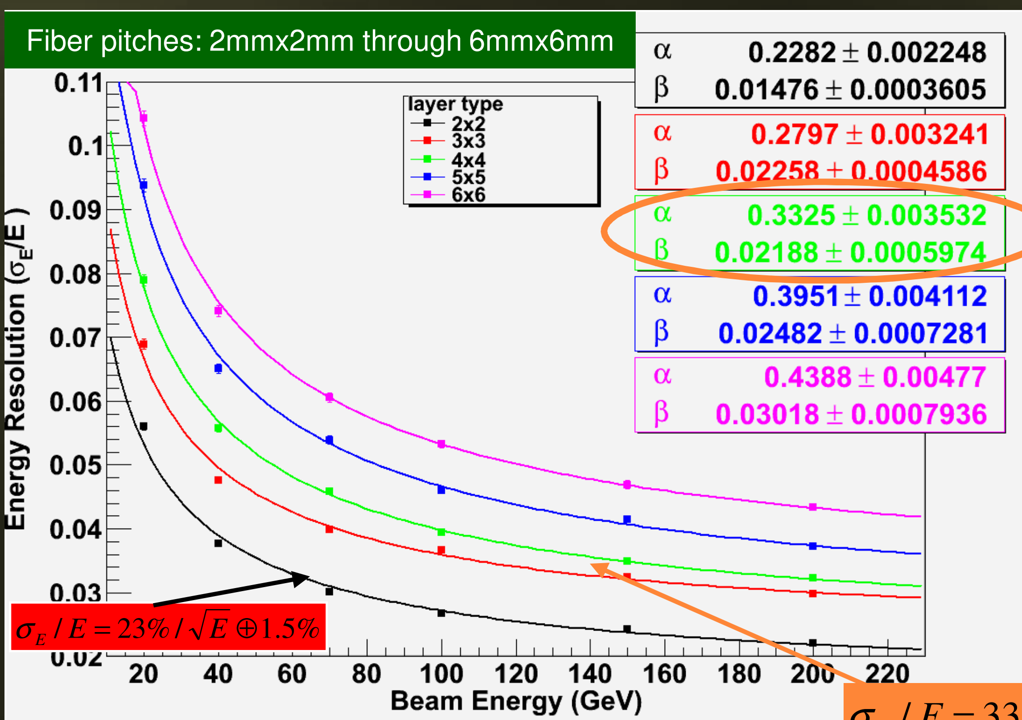
Integrally Active with Double side readout (*ADRIANO*)									Sampling
Pitch [mm²] Diameter	2x2 1mm	3x3 1mm	4x4 1mm	5x5 1mm	6x6 1mm	4x4 1.4mm	4x4 2mm	4x4 capillry	Sampling
$<pe_S/GeV>$	1053	430	254	163	124	500	110	250	200
$<pe_C/GeV>$	340	360	360	355	355	355	350	350	7.5

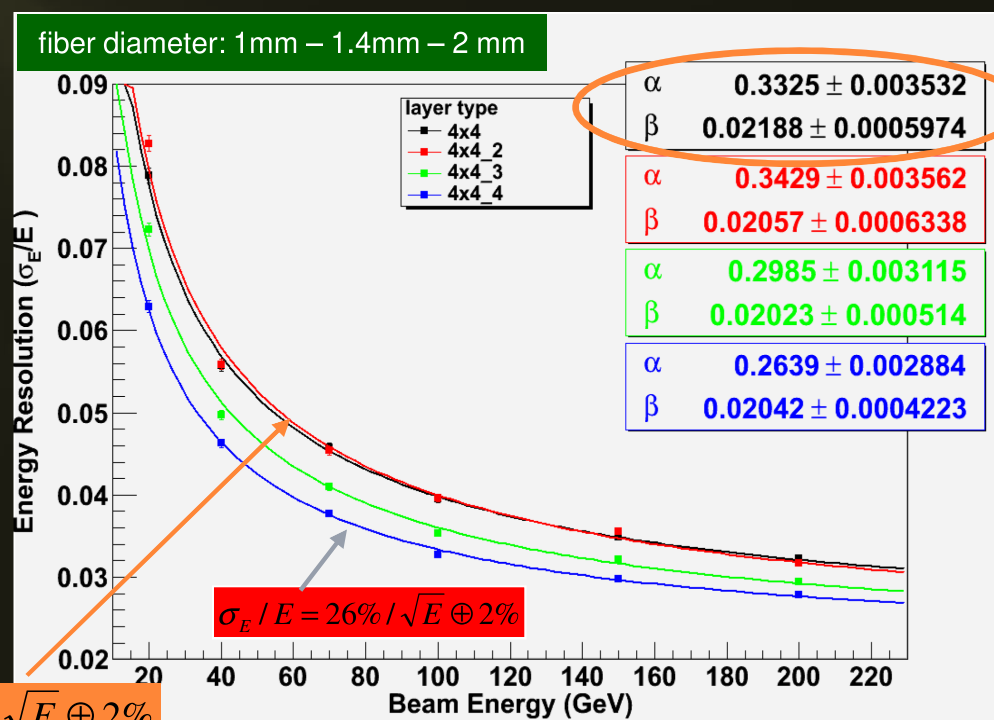
Baseline configuration (4x4, 1mm)

1-side readout (Sampling)

ILCroot simulations





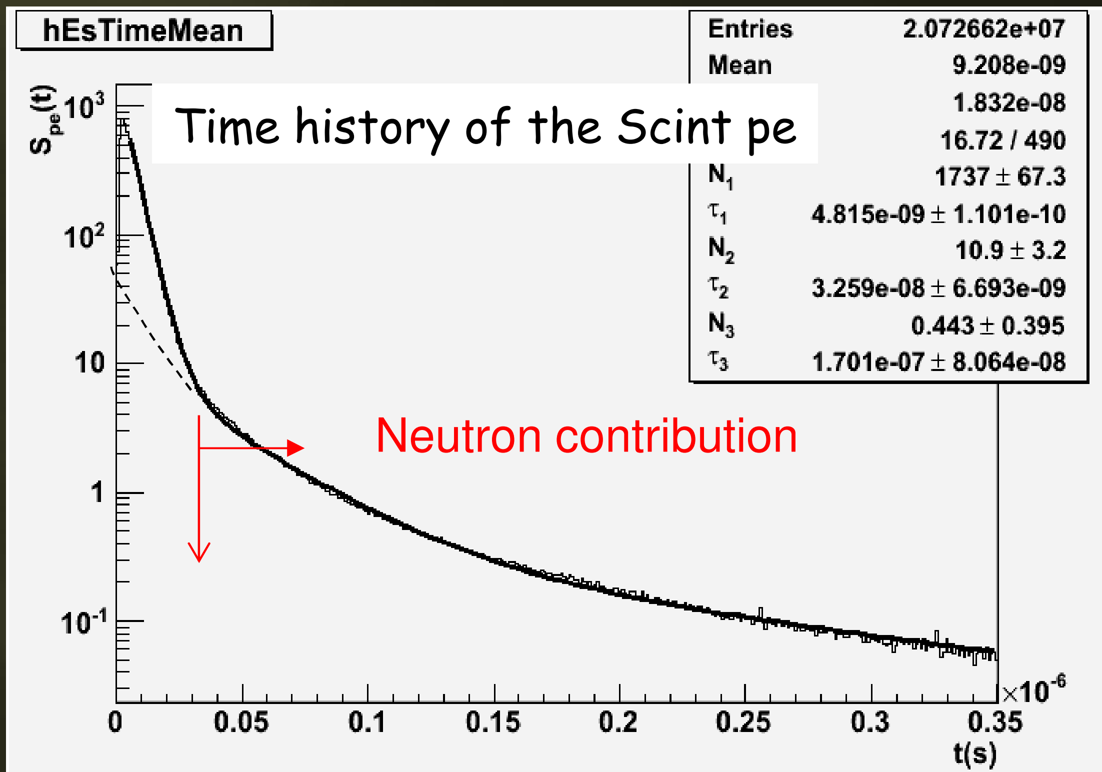


$\sigma_E / E = 33\% / \sqrt{E} \oplus 2\%$

All numbers include the effect of photodetector QE

From Dual to Triple Readout

Disentangling neutron component from waveform



ILCroot simulations

40 Gev pions

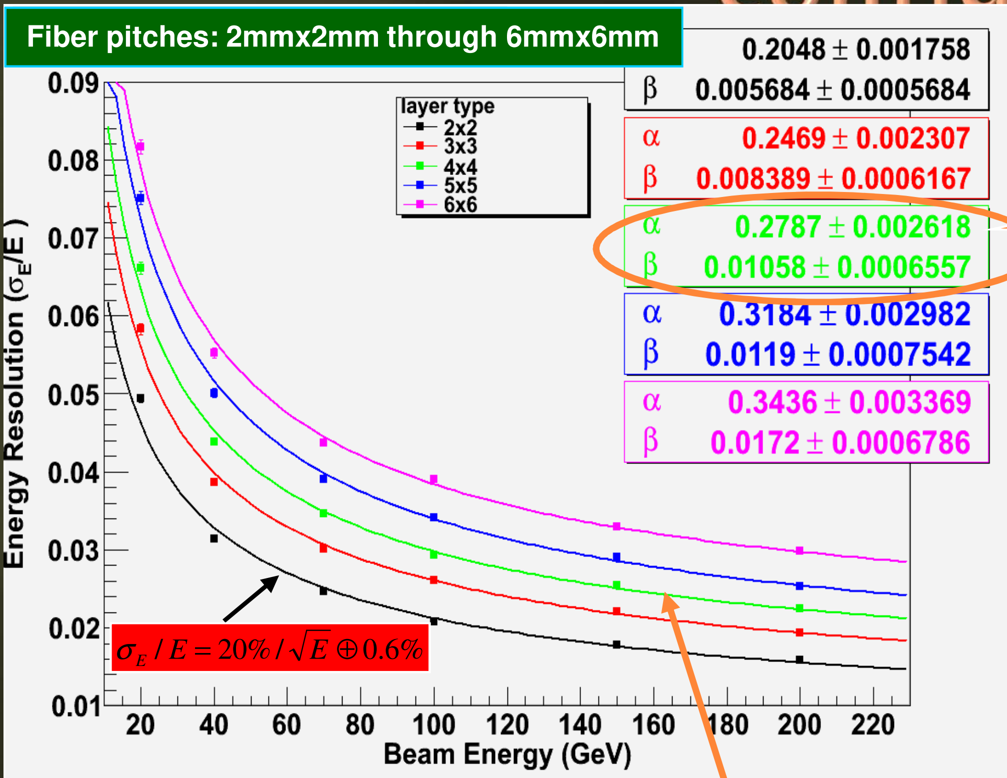
Time history of the scintillation signal in *ADRIANO* for π^-@40 GeV.

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

$$E_{HCAL} = \frac{\eta_S \cdot E_S \cdot (\eta_C - 1) - \eta_C \cdot E_C \cdot (\eta_S - 1)}{\eta_C - \eta_S} + \eta_n \cdot E_{neutrons}$$

Triple Readout aka Dual Readout with time history readout

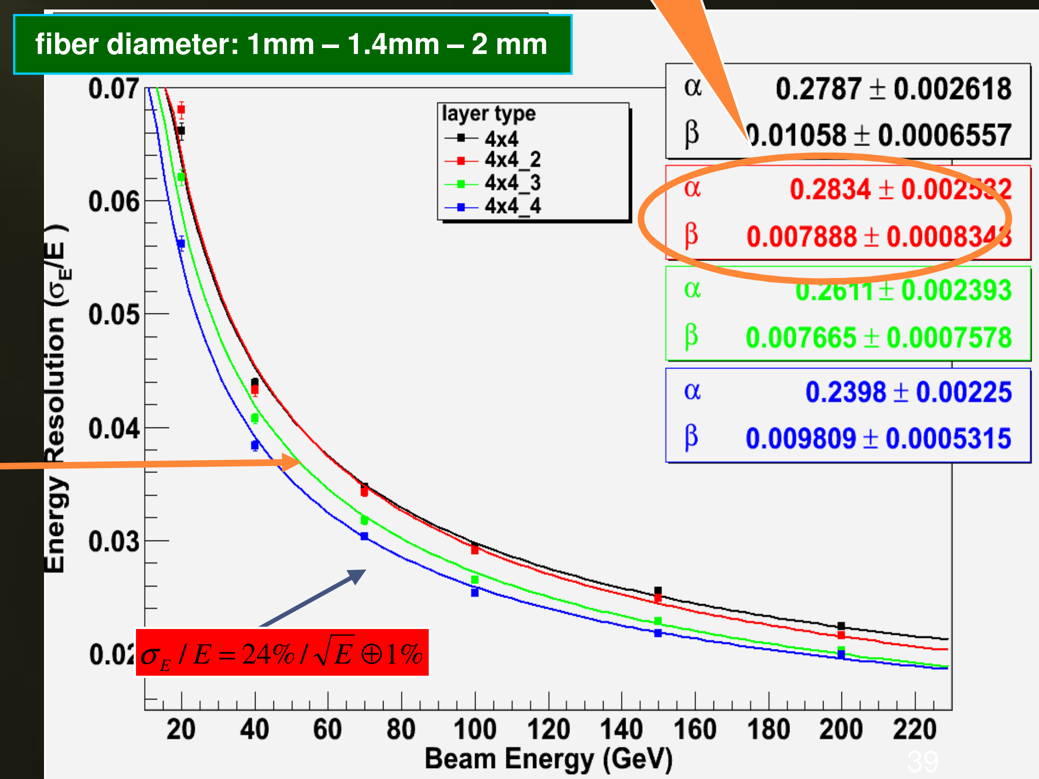
ADRIANO in Triple Readout configuration



Baseline configuration

Pion beams

ILCroot simulations



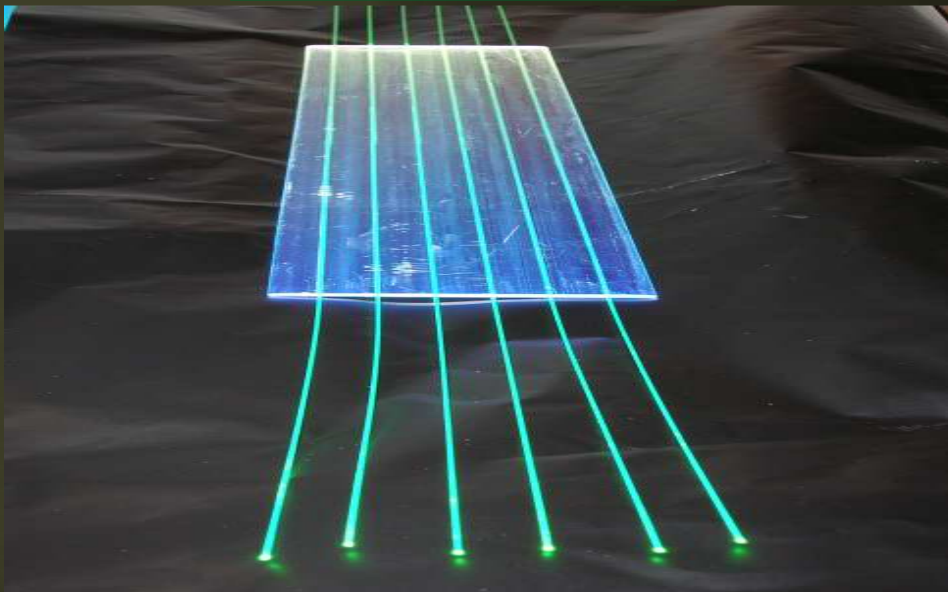
$$\sigma_E / E = 28\% / \sqrt{E} \oplus 1\%$$

ompare to ADRIANO in Double Readout configuration

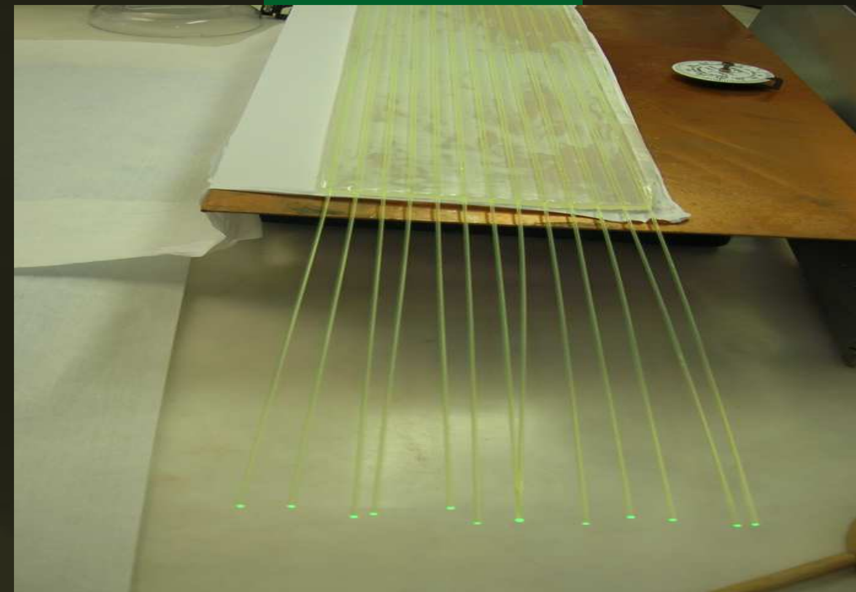
$$\sigma_E / E = 33\% / \sqrt{E} \oplus 2\%$$

ADRIANO for ORKA Construction

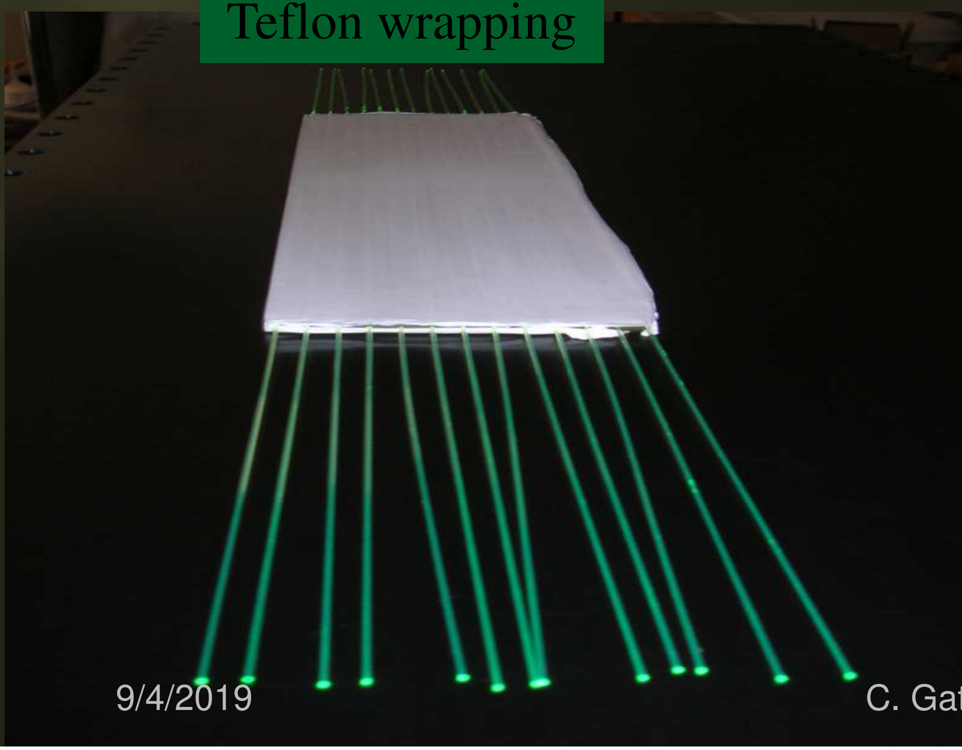
WLS + scintillator



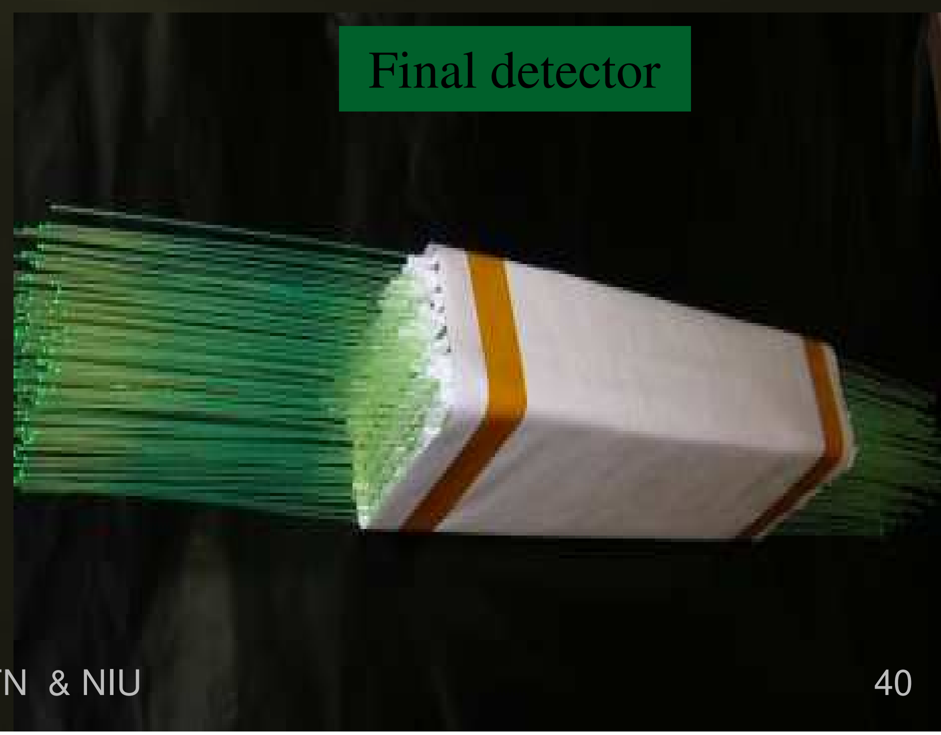
WLS + glass



Teflon wrapping

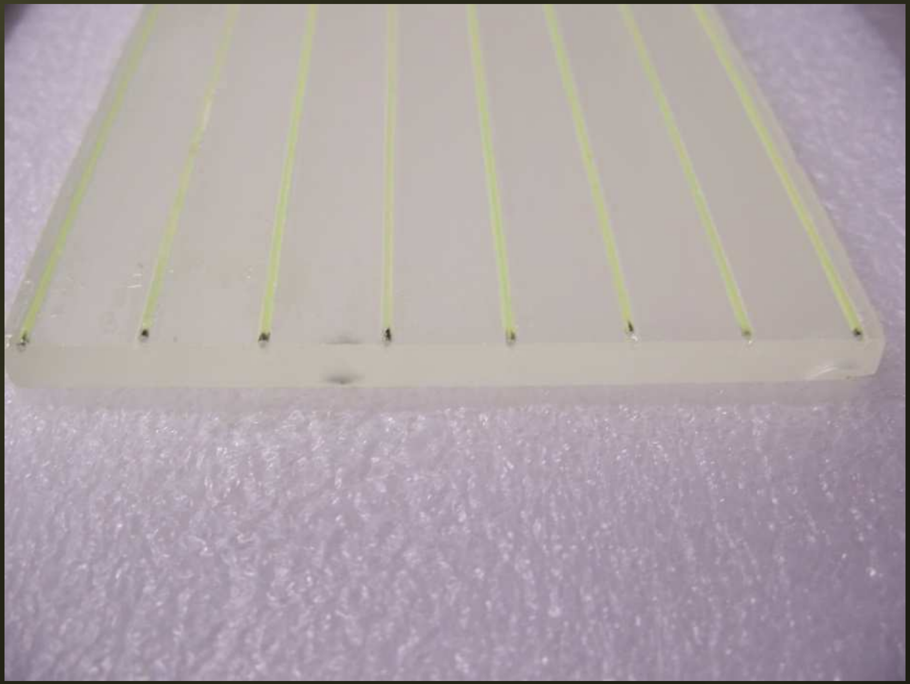


Final detector

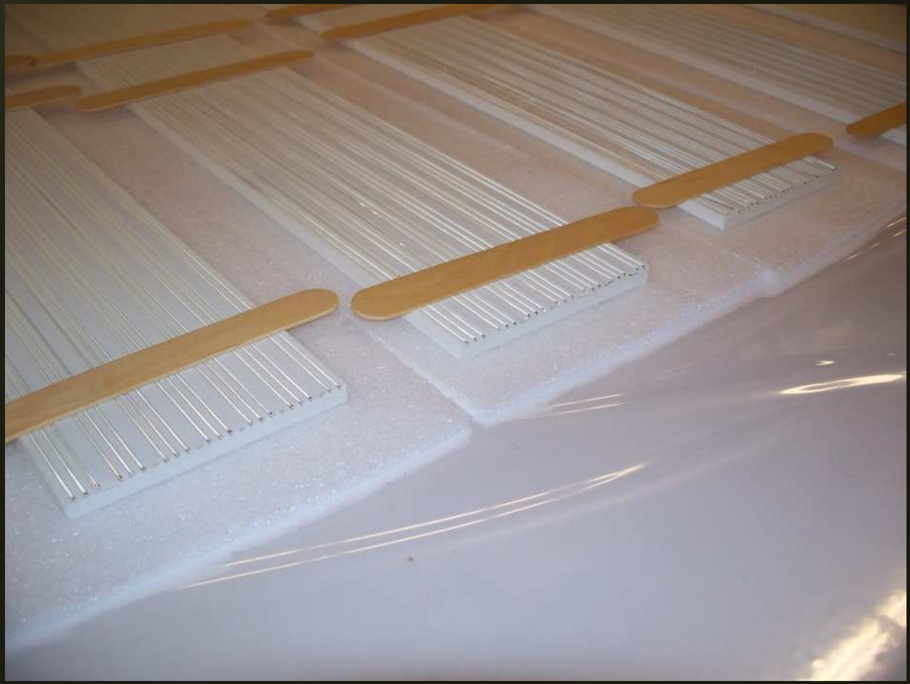


ADRIANO-2014

- Two versions built: scifi and scintillating plates
- 10 x 8 x105 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



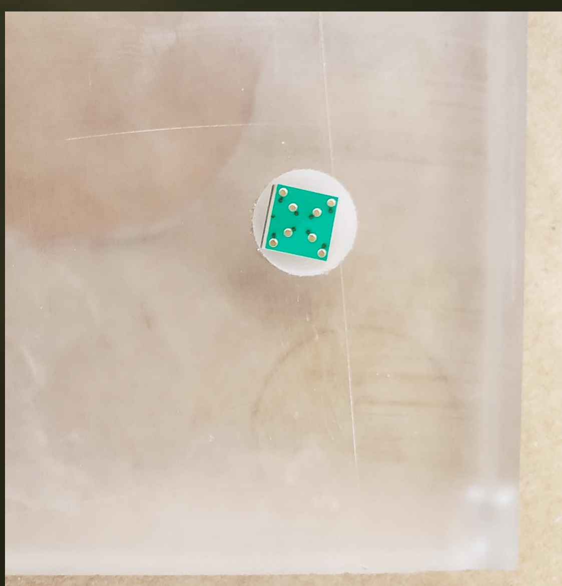
ADRIANO 2014B: 23 grooves

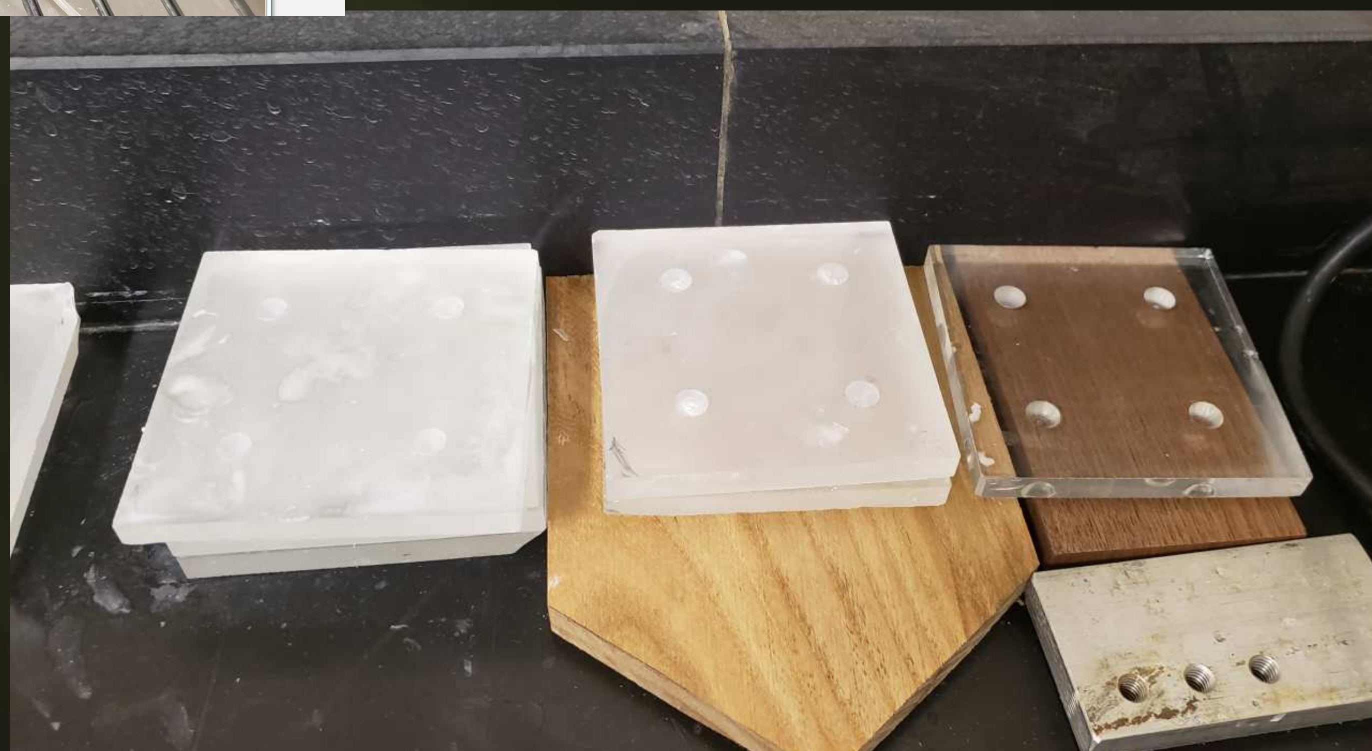
Nov. 2015 test Beam at Fermilab

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



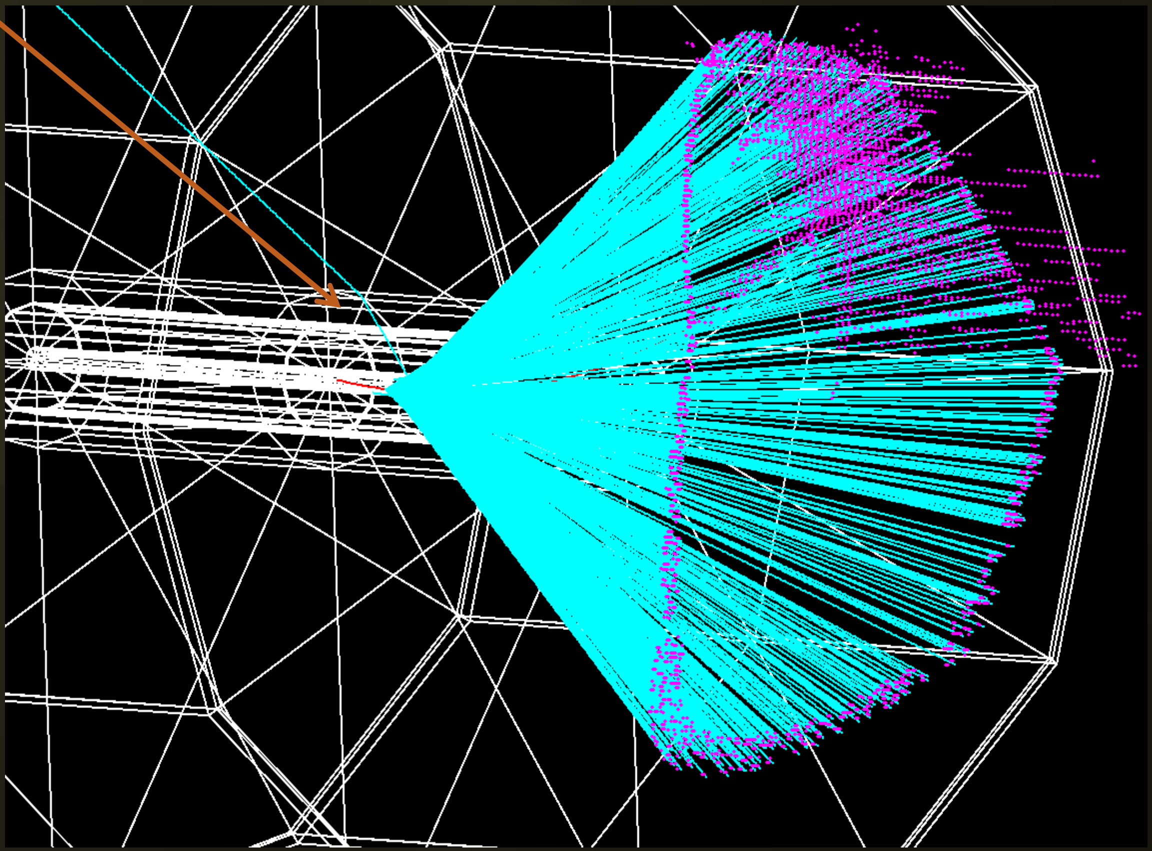


Coating and testing

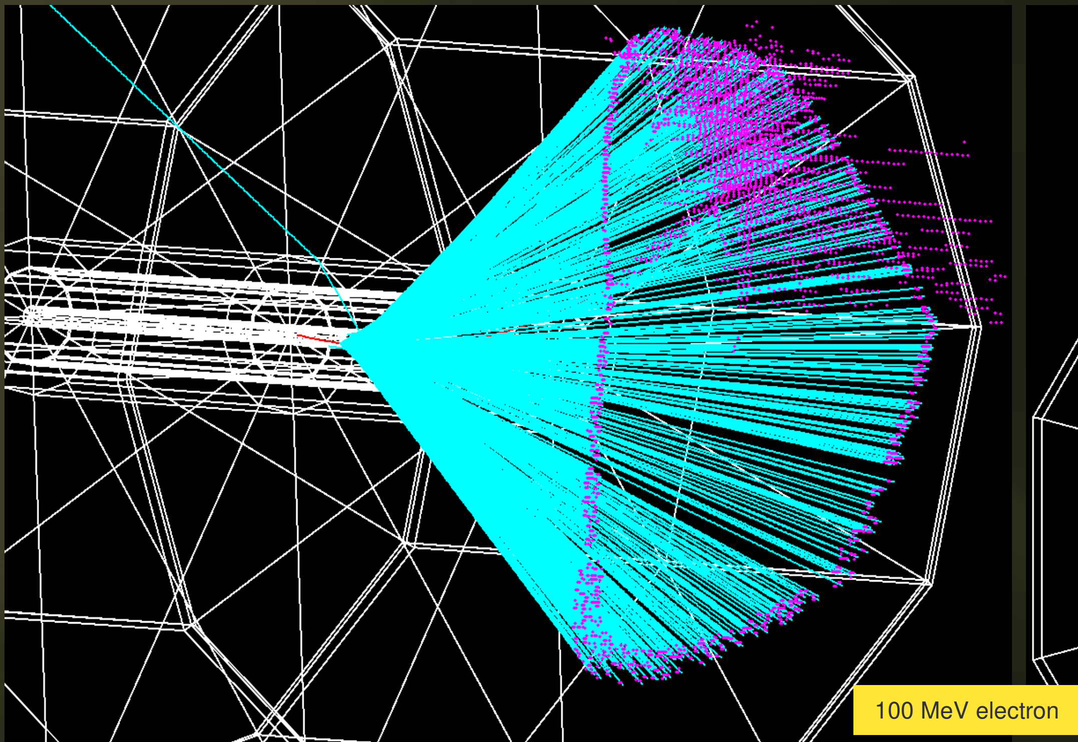
The Optical TPC Concept

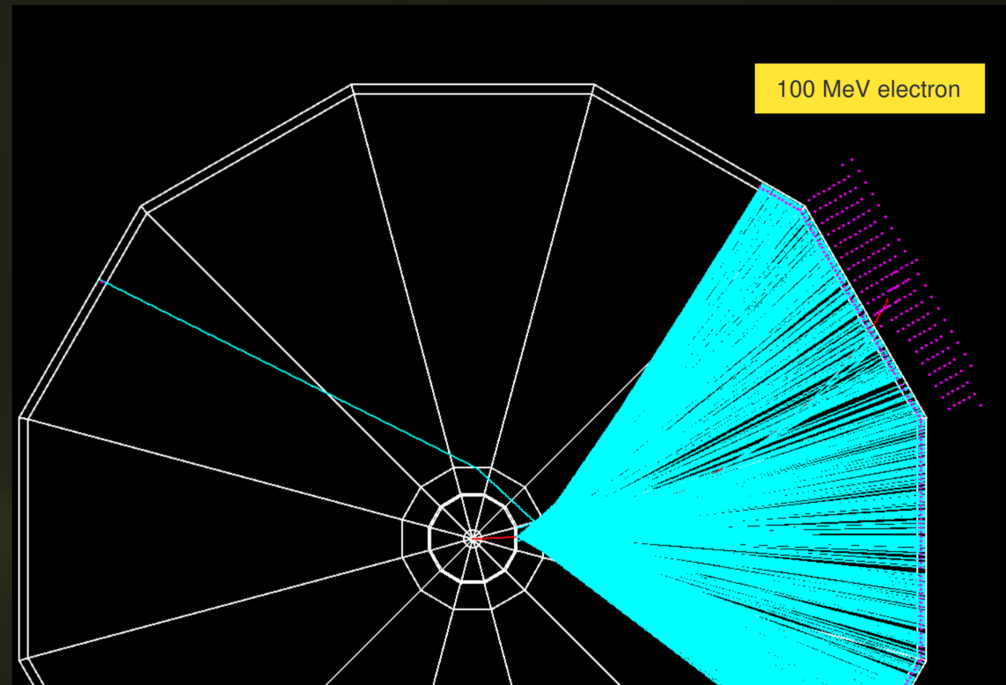
Rationale for an Optical- TPC

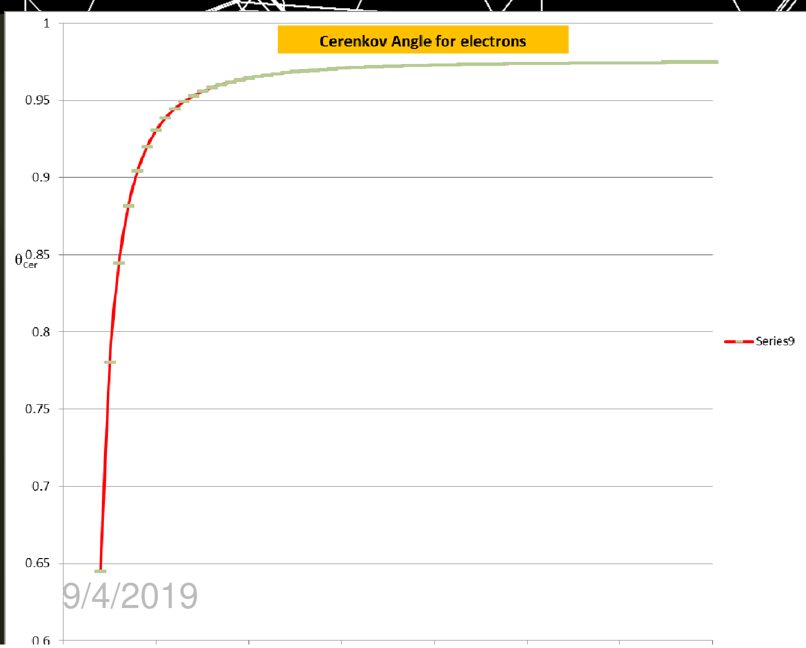
- *At 1 GHz inelastic interaction rate, a conventional, gas detector is suboptimal*
- *Hadronic particles (p, ion remnants, slow pions, etc.) will clutter the tracker*
- *Use the Cerenkov effect to detect the fast (leptons and fast pions) tracks*
- *Prompt signal is also fed to the L0 trigger for fast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



Electron Detection







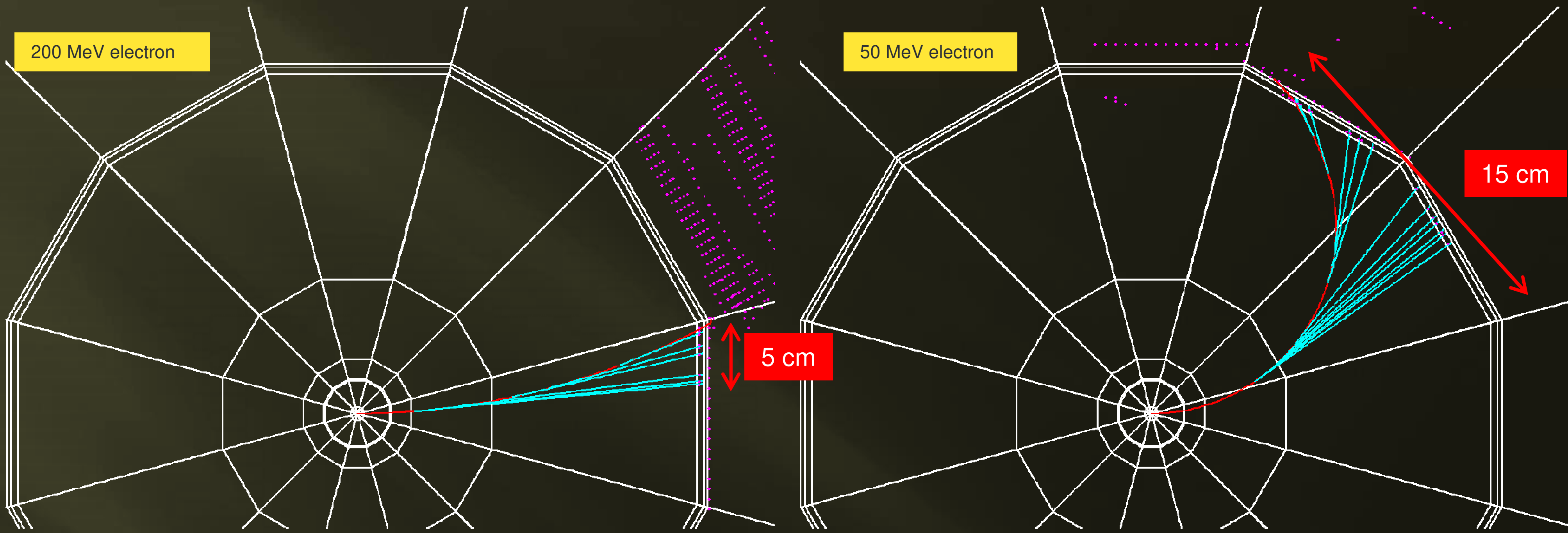
$n_D(N_2@2.7psi)=1.000145$

Č threshold for e- in N_2: P=40 mev

$n_D(aerogel1)=1.12$

$n_D(aerogel2)=1.22$

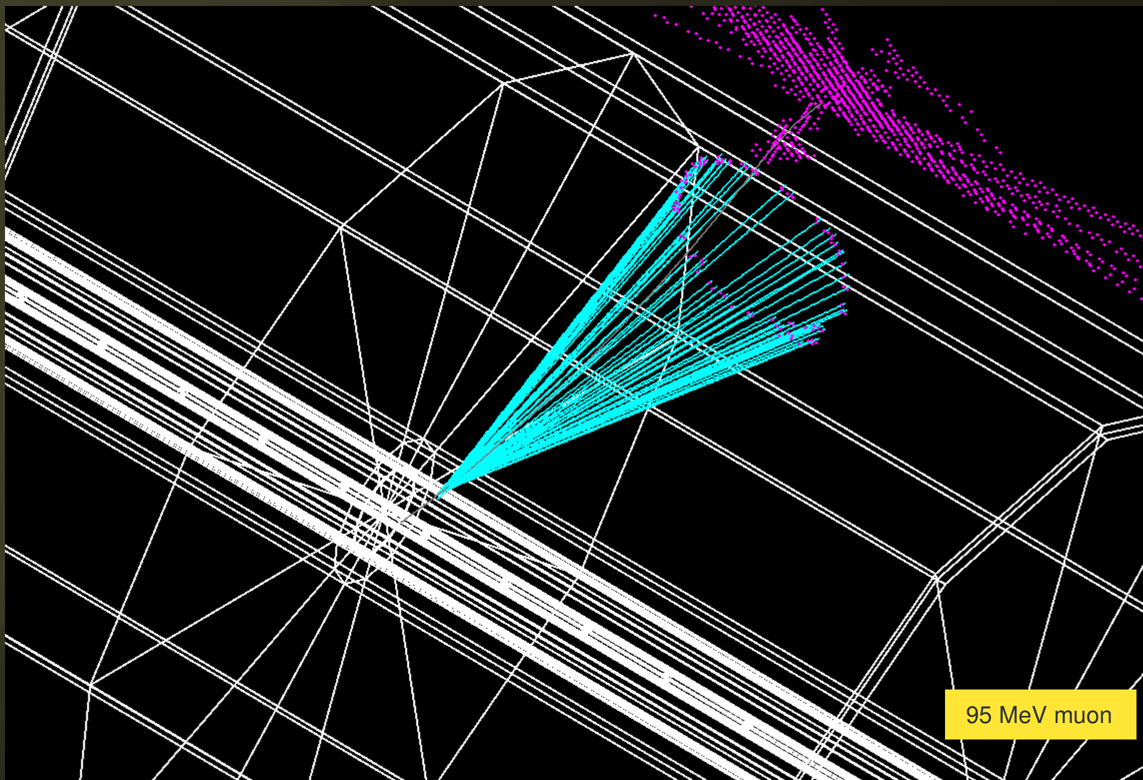
Electron Momentum Reconstruction

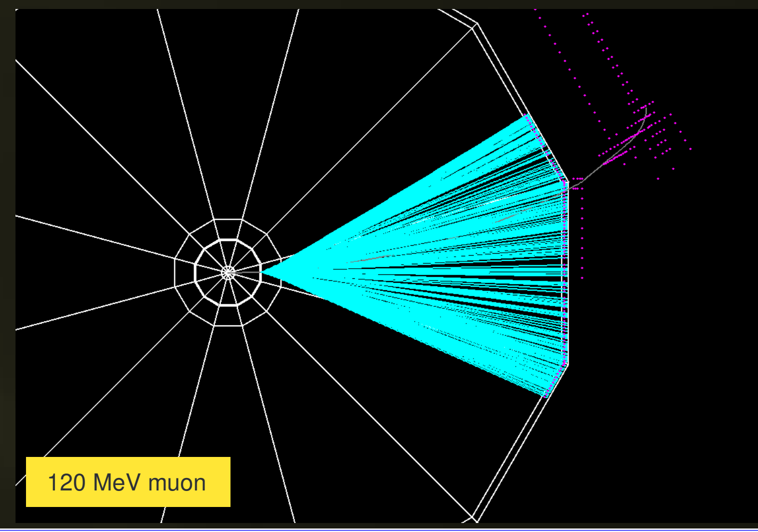


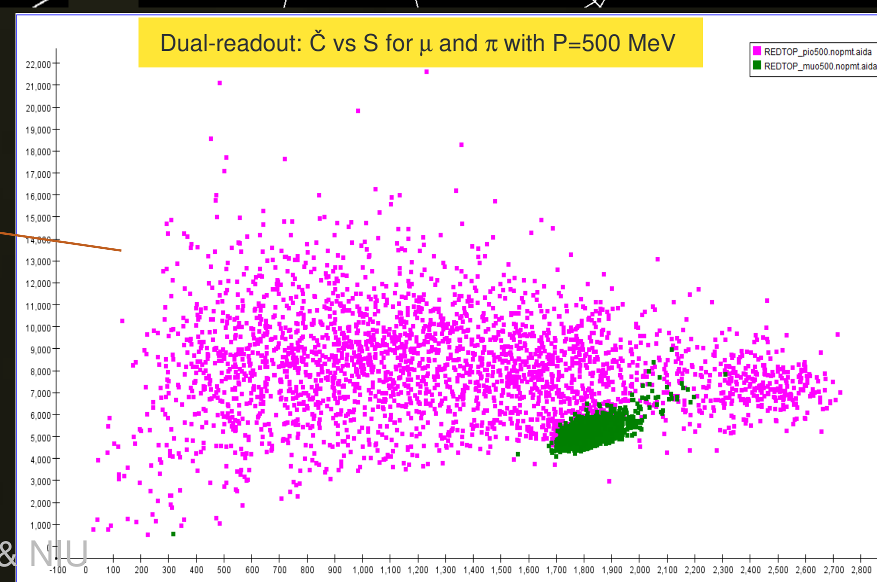
- Electrons are recognized by:
  1. a large (>30 cm dia) circle of photons generated in the aerogel
  2. A sweep of photons circles with dia < 1cm and several cm long (depends on P_t)
  3. An EM shower in ADRIANO (identified by Č vs S)

Muon/pion Detection

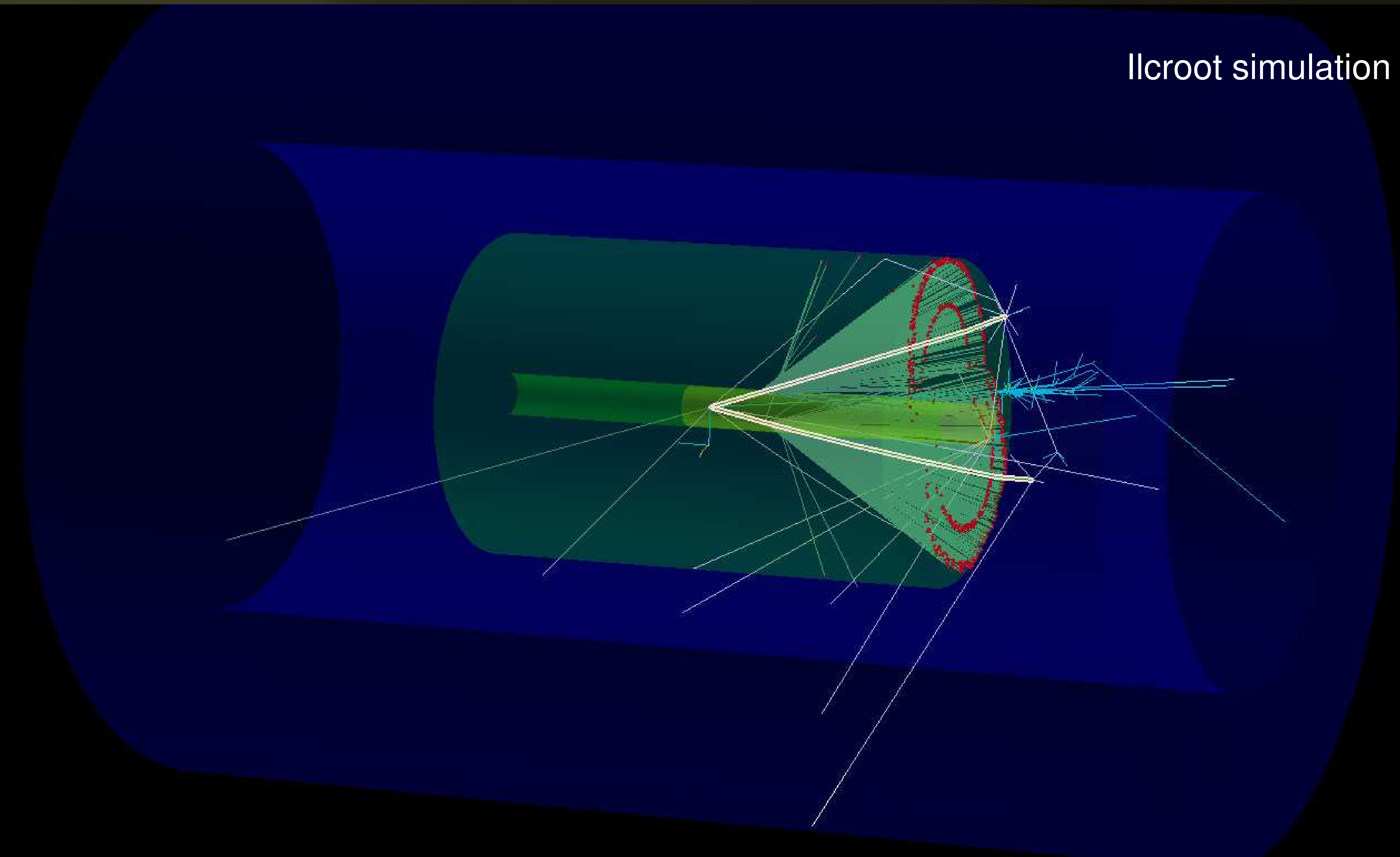
- n_D(aerogel)=1.22/1.12
- Č threshold for muons: P=160 mev
- Č threshold for pions: P=200 mev







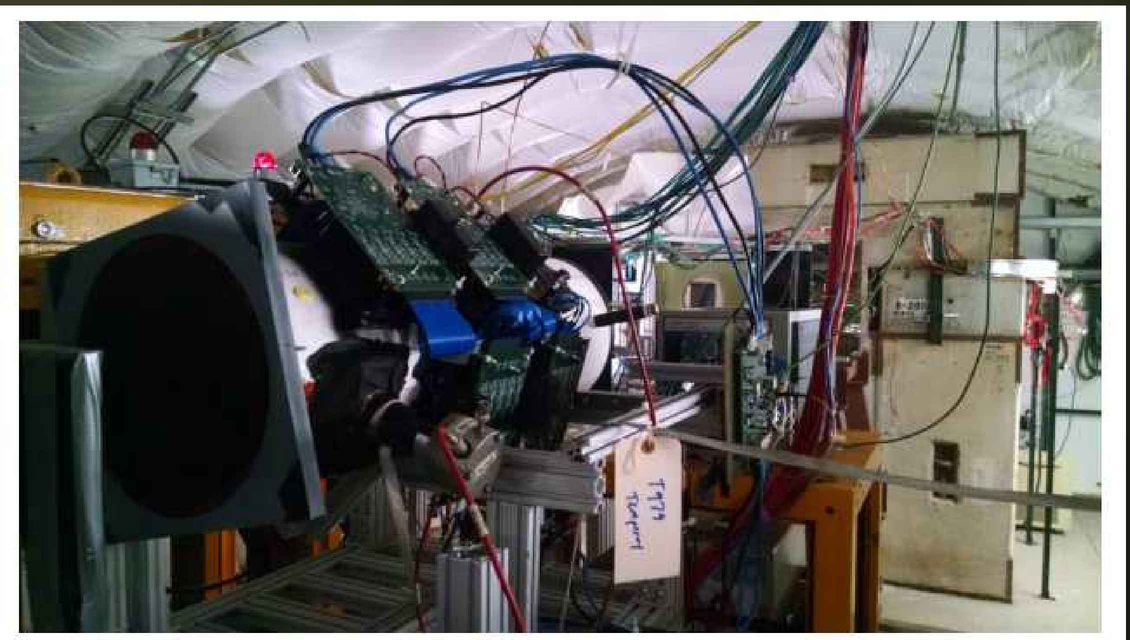
$\eta -> \pi^{+}\pi^{-}\pi^{o}$

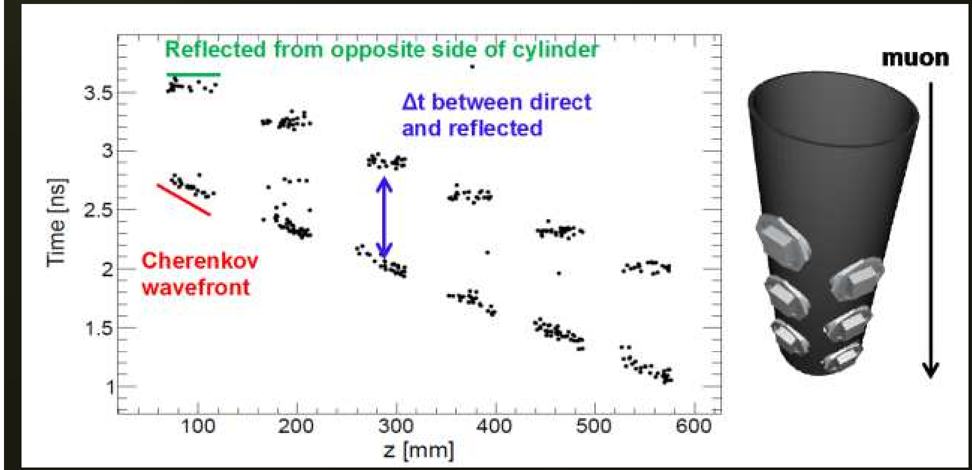


Detector R&D: OTPC

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*



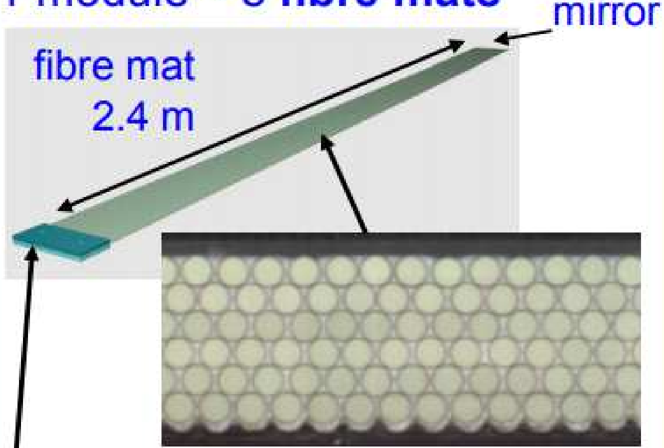


It requires a robust and dedicated R&D (LDRD)

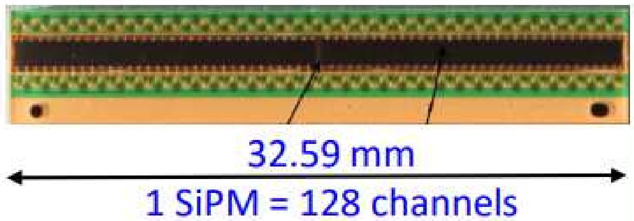
The Fiber Tracker – LHCb design

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

1 module = 8 **fibre mats**



4 silicon photomultipliers (SiPM)



128 modules (0.5 x 5 m^2)
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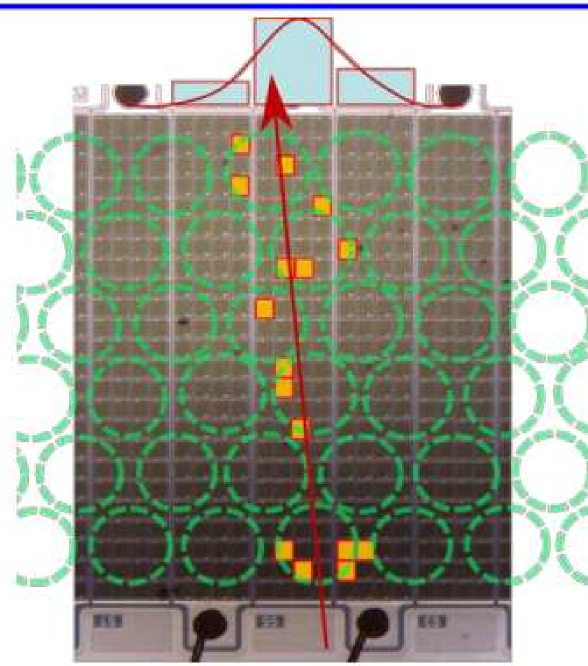


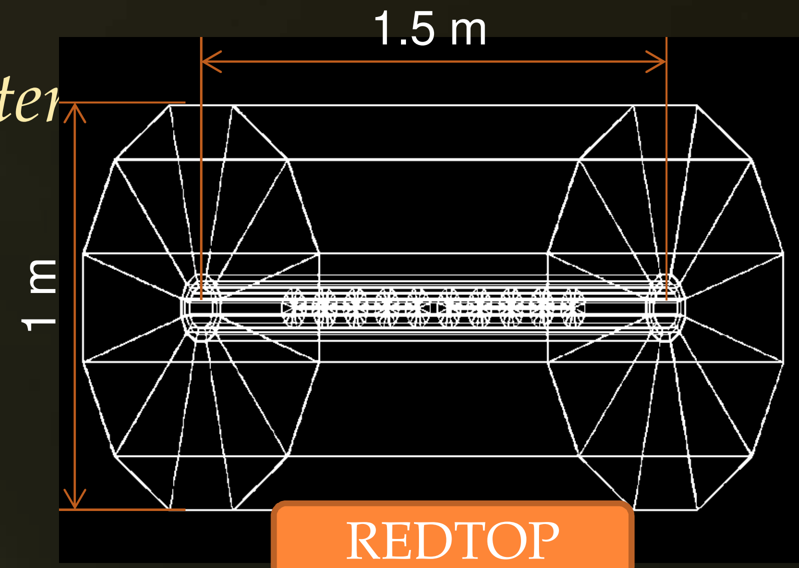
Light yield for 6-layer mat:
16–20 photo-electrons
(for particles near mat mirror)

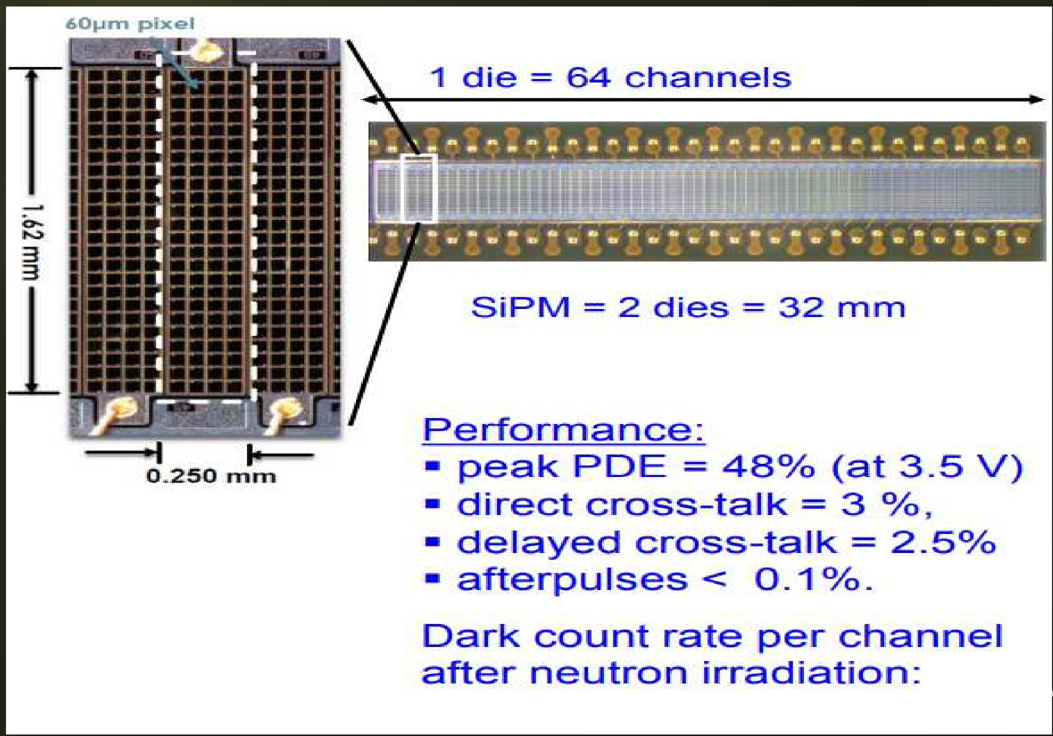
Ulrich Uwer

Layout for LHCb vs REDTOP

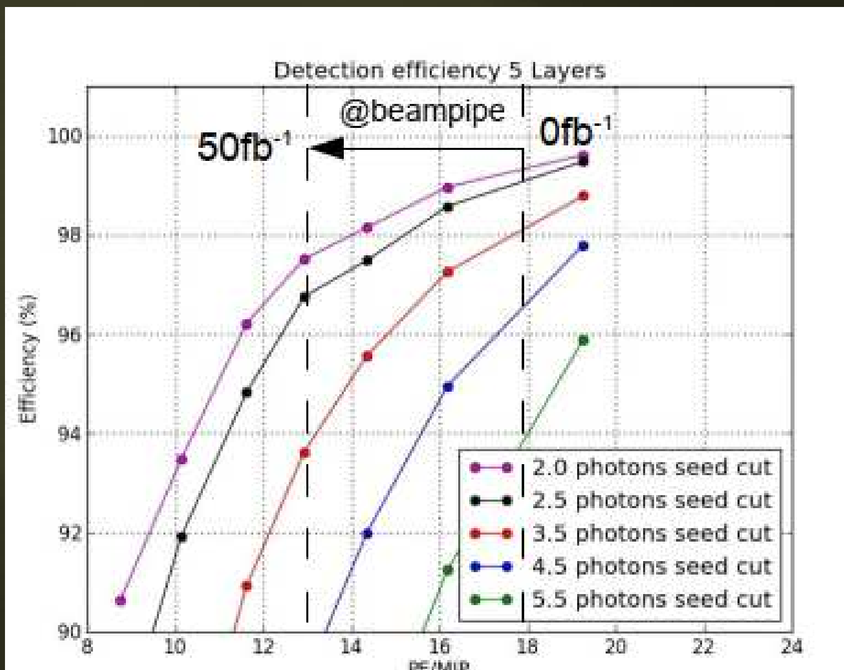
Input parameter

- ~ 360 m^2 vs 0.24m^2
- 1152 mats vs 36 mats
- 524,000 vs 18,000 channels

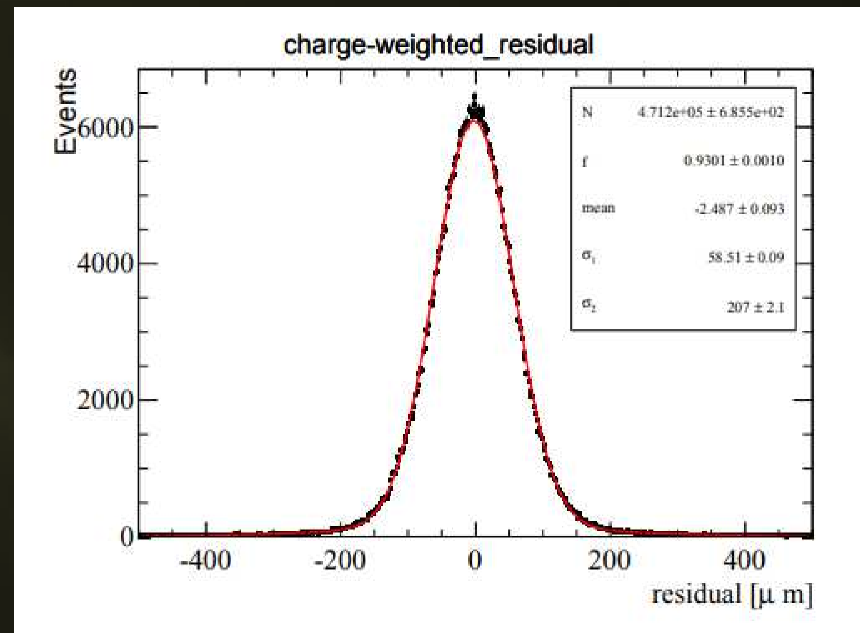




Results from LHCb Test Beam



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

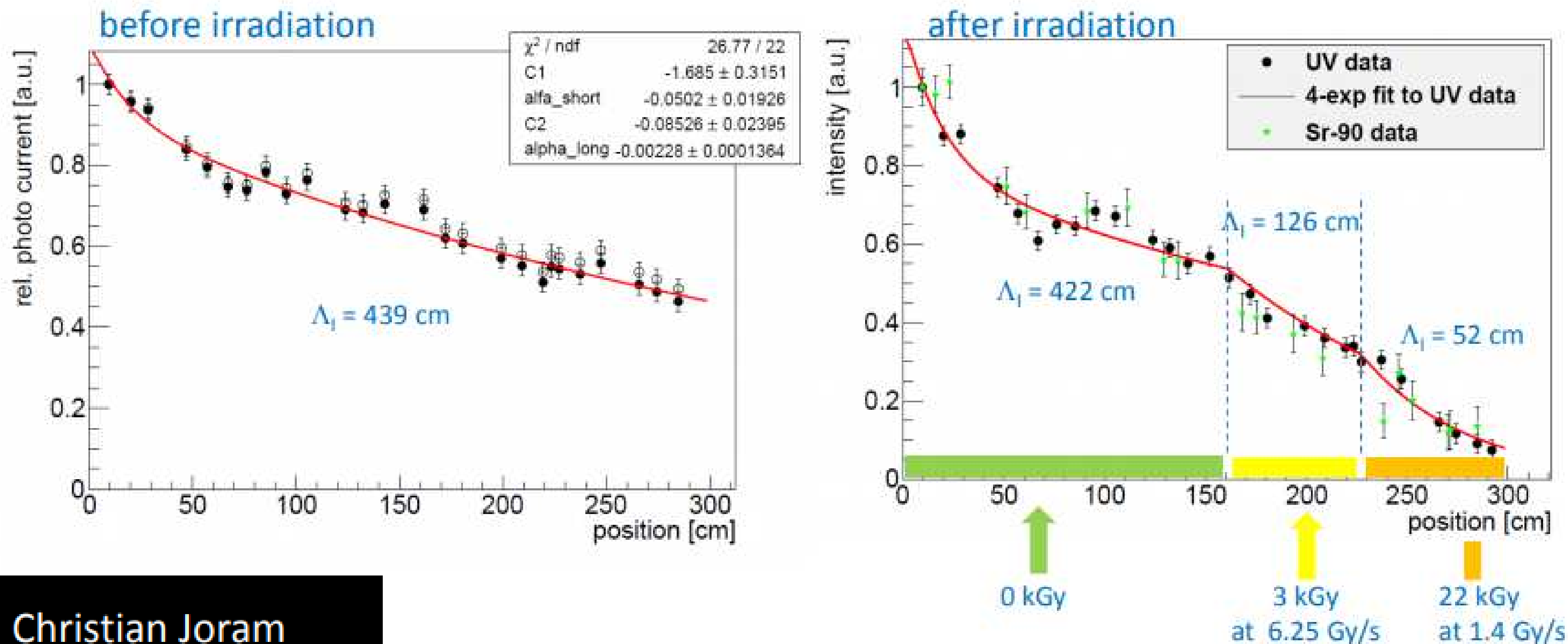


	at the mirror	centre	50 cm from SiPM
$\sigma_{eff,charge}$ [μm]	66.78 ± 0.23	65.93 ± 0.18	61.22 ± 0.21
$\sigma_{eff,Pacific}$ [μm]	73.27 ± 0.26	73.18 ± 0.20	73.64 ± 0.20

Christian Joram

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

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: ^{3}H
- 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*

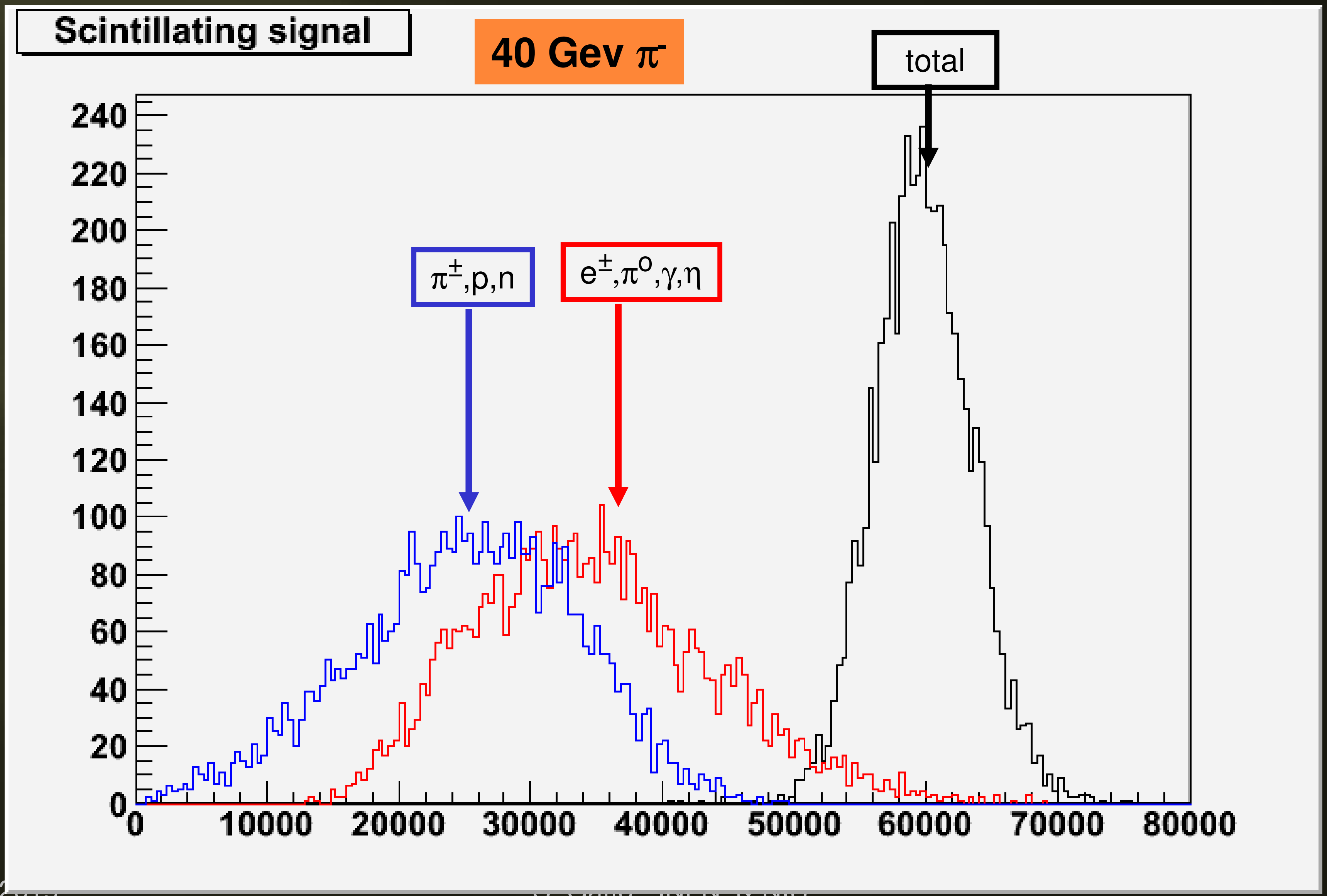
Ongoing activities – detector R&D

- *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*

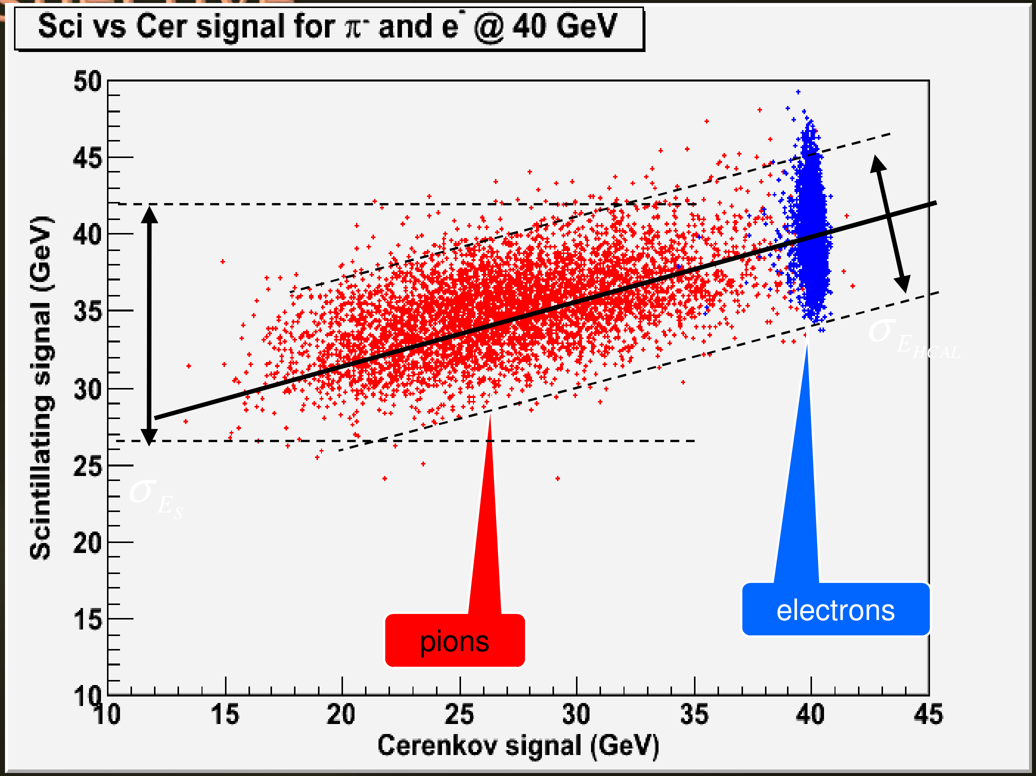
Transitionless Deceleration in the Delivery Ring (J. Johnstone)

- 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 γt 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

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

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

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

If $\eta_s \neq \eta_c$ then the system can be solved for E_{HCAL}

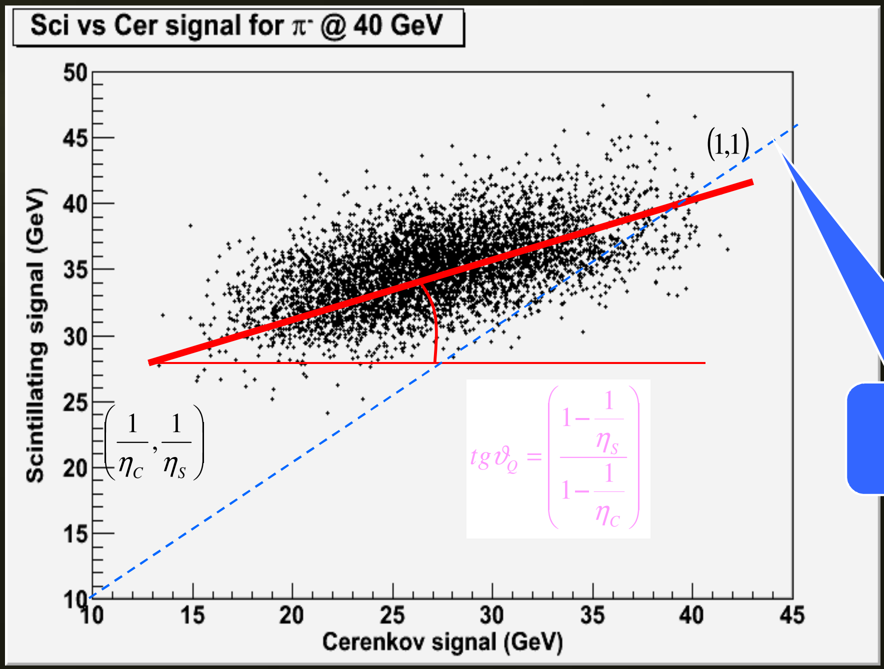
Figures of Merit for Dual-Readout Calorimeter

- 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, $tg(\theta_{S/Q})$ much diferent from 1

$$\sigma^2_{E_{corr}} = \left(\frac{1}{1-\chi}\right)^2 \sigma^2_S + \left(\frac{\chi}{1-\chi}\right)^2 \sigma^2_Q$$

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

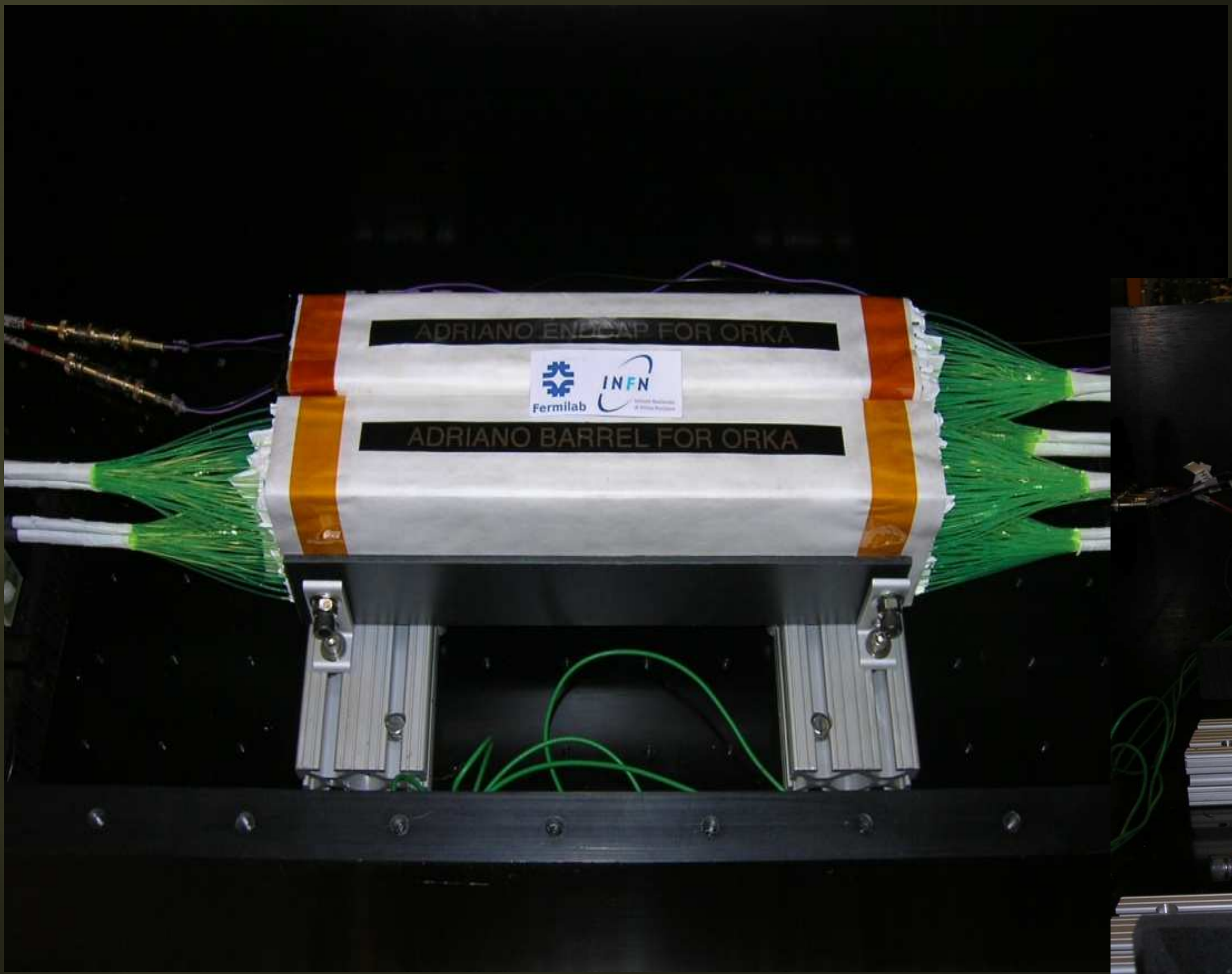
ILCroot simulations



$\eta_S = \eta_C$

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

ADRIANO for ORKA Final Prototypes



High Energy vs High Intensity Layouts

High Energy

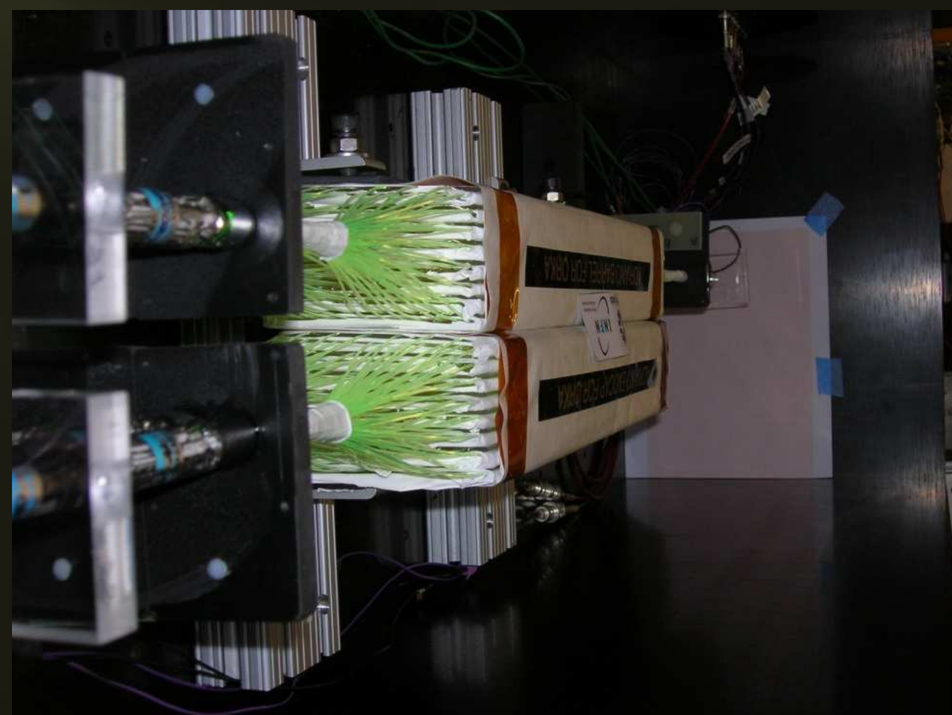
- Detection of Hadronic and EM showers with large S and Č light production
- Optimized for maximum shower containment (i.e. max detector density)

- 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



Expected η/η' Yield

- *Assume: $1x10^{11}$ POT/sec – CW*
  - *Beam power @ 3 GeV: 10^{11} p/sec × 1.9 GeV × 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 ≈ $A^{1/3}$)*
  - *Prob(p + target → X) ~ 0.5% or 5× 10^8 p-Be inelastic collisions per second*

⬇

- *p-inelastic production: 5 x 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 x 10^6 η/sec (2.5 x 10^4 η'/sec) or 2.5 x 10^{13} η/yr (2.5 x 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 ≈ 0.1% from η (need to improve 100x with vertexin+timing)*

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

Unlike $\eta \to \pi\pi$ 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, possibly through EM interactions [TD Lee & L Wolfenstein,1965; Lee, 1965; Nauenberg, 1965] [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. PRL1972 and, e.g., KLOE-2, JHEP 2016]

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

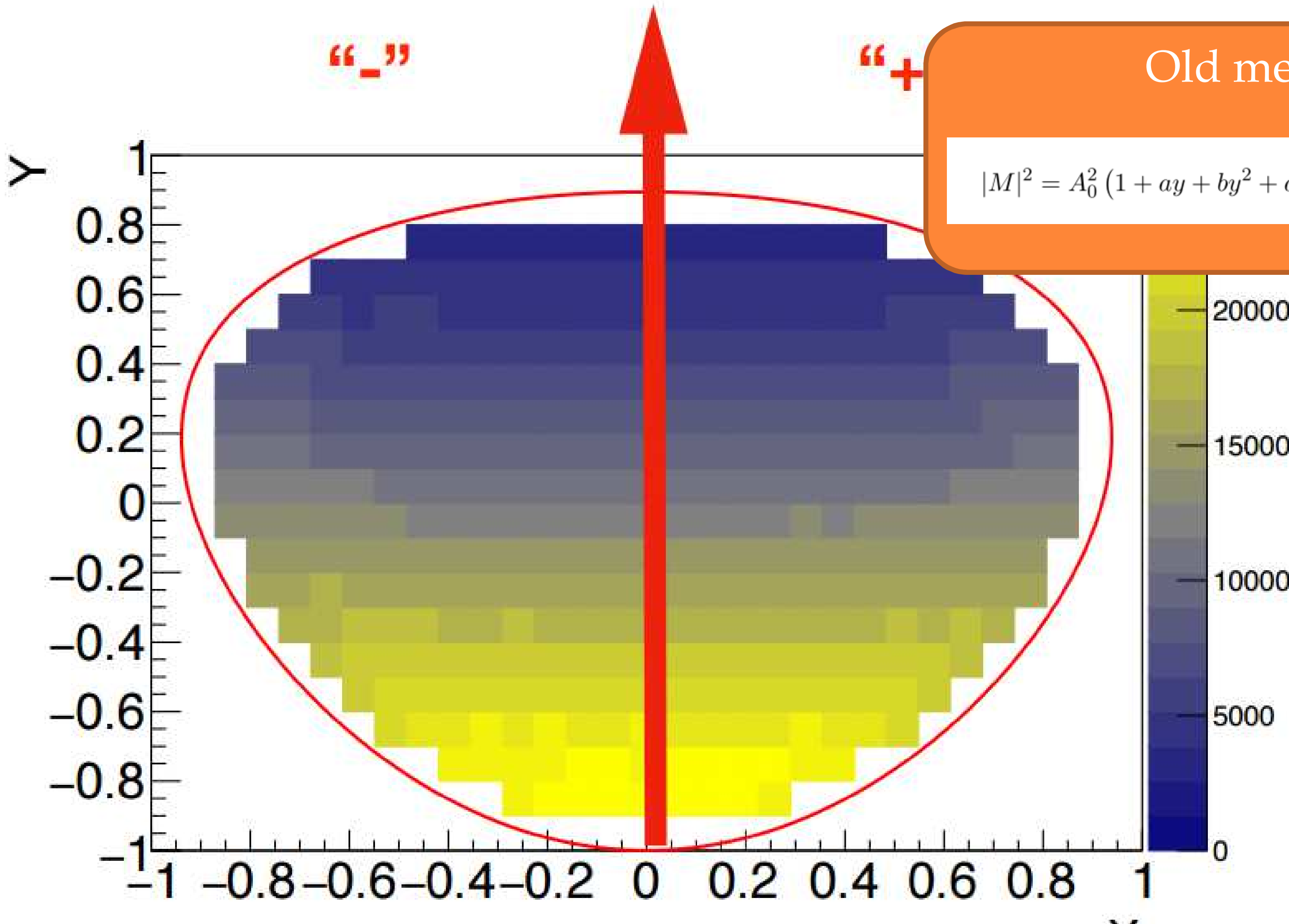
[Note Gardner & Tandean, 2004; Gardner & Shi, 2017, to appear]

Slide Credit: Susan Gardner & Jun Shi

University of Kentucky

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



Old method

$$|M|^2 = A_0^2 \left(1 + ay + by^2 + dx^2 + fy^3 + gx^2 y + \cdots \right) .$$

bkgd subtracted events, figure from KLOE-2, JHEP 2016

Slide Credit: Susan Gardner & Jun Shi

University of Kentucky

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

C and CP violation poorly constrained in flavor diagonal processes

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

- 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; Bijnens & 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 Re(a), Im(a), Re(b), Im(b) and/or study charge asymmetries

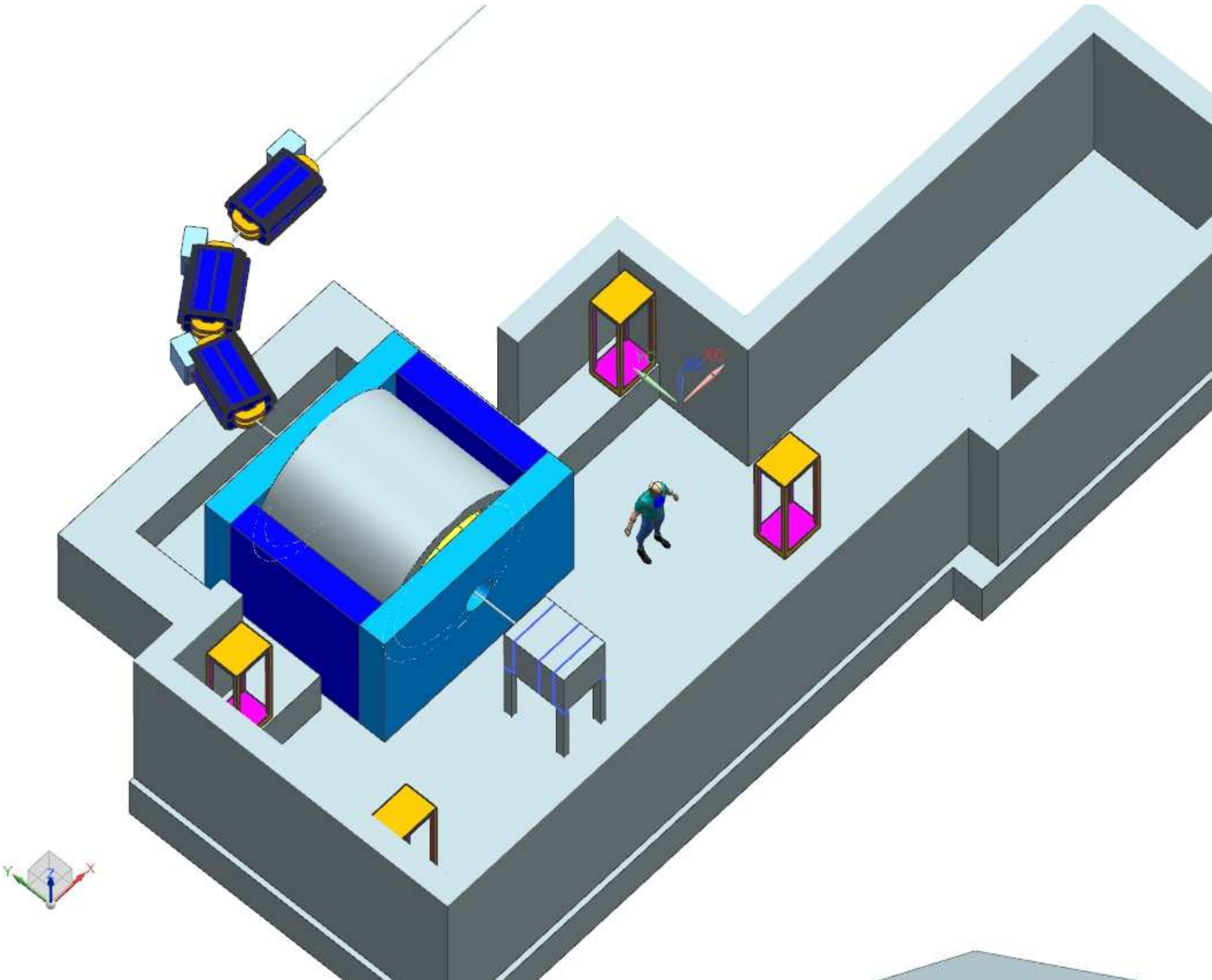
Preliminary analysis shows the largest CPV contributions could come from the interference with $M_0(s)$

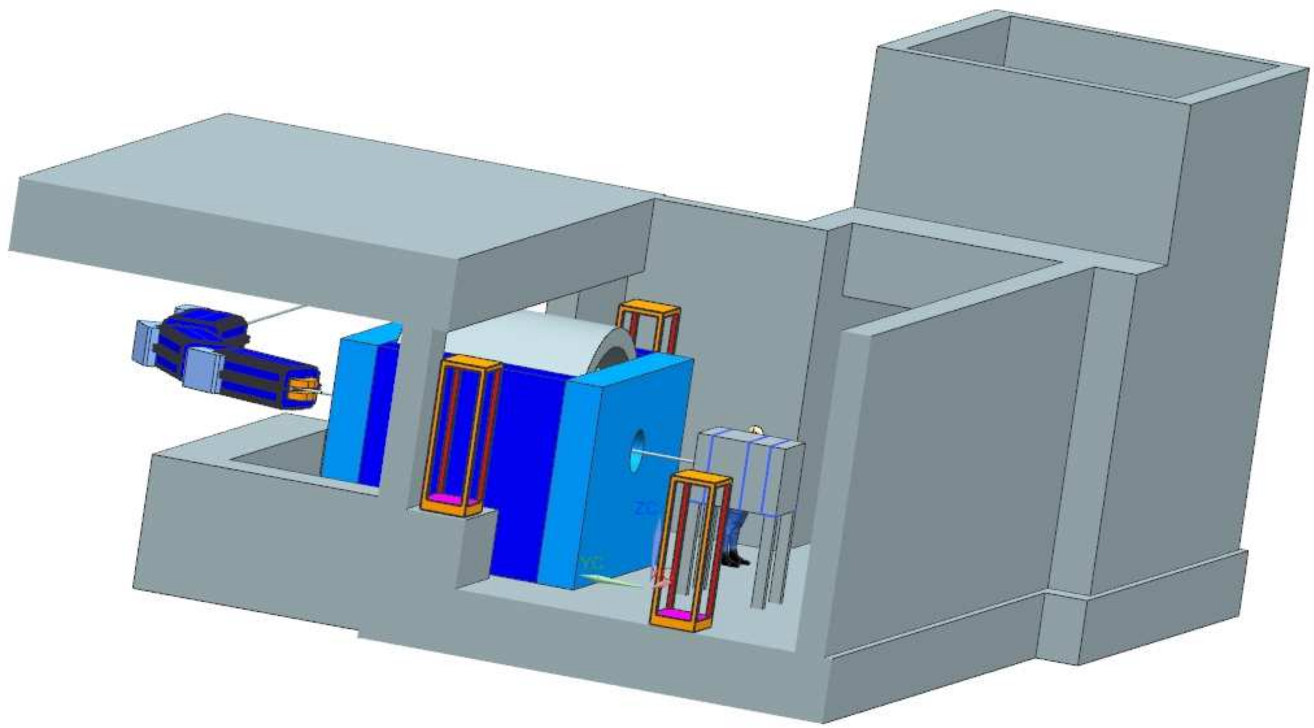
[Gardner & Shi, 2017, to appear]

Slide Credit: Susan Gardner & Jun Shi

University of Kentucky

REDTOP detector in AP50

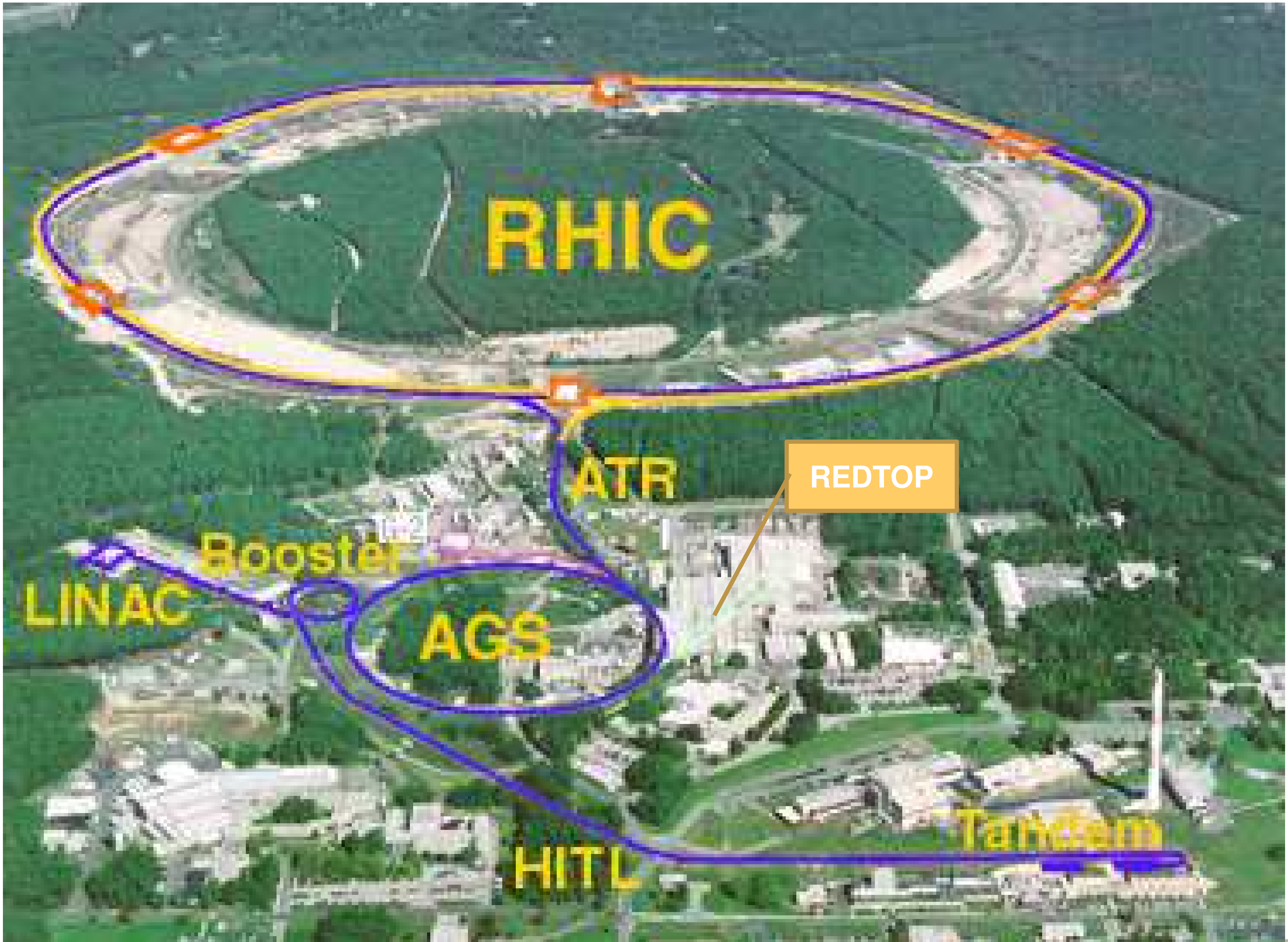




J. Kilmer
J. Rauch
E. Barzi (Solenoid and yoke)

(Many thanks to K. Krempetz, as well)

BNL hadron complex



Building 912 AGS Experimental Area (1998)