REDTOP EXPERIMENT: STATUS UPDATE

Rare ***E***ta ***D***ecays with a
Tpc for ***O***ptical ***P***hotons

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For the REDTOP Collaboration

The Physics Landscape for REDTOP

- *SM is showing its age*
  - *SM matter: Dark matter:Dark energy=5%:25%:70%*
  - *Baryon Asymmetry of the Universe*
  - *Expansion of the universe is accelerating (hint to more forces)*
  - *. . . .*
- *New physics is elusive: probability of processes where new physics is coupled to SM physics is low*
- *LHC found no hint of new physics at high energy so far*
  - *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)*
- *Newest theoretical models prefer gauge bosons in MeV-GeV mass range as "…many of the more severe astrophysical and cosmological constraints that apply to lighter states are weakened or eliminated, while those from high energy colliders are often inapplicable" (B. Batell , M. Pospelov, A. Ritz – 2009)*

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

Why the η meson is special?

- It is a Goldstone boson → Symmetry constrains its QCD dynamics

- It is an eigenstate of the C, P, CP and G operators (very rare in nature): $I^G J^{PC} = 0^+ 0^{-+}$ → It can be used to test C and CP invariance.

- All its additive quantum numbers are zero

  $Q = I = j = S = B = L = 0$ → Its decays are not influenced by a change of flavor (as in K decays) and violations are "pure"

- All its possible strong decays are forbidden in lowest order by P and CP invariance, G-parity conservation and isospin and charge symmetry invariance.
- EM decays are forbidden in lowest order by C invariance and angular momentum conservation

→ It is a very narrow state (Γ_η=1.3 KeV vs Γ_ρ=149 MeV)

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

Excellent for testing invariances

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

New particles and forces searches

- *Scalar meson searches (charged channel): $\eta \to \pi^o H$ with $H \to e^+e^-$ and $H \to \mu^+\mu^-$*
- *Dark photon searches: $\eta \to \gamma A'$ with $A' \to \ell^+\ell^-$*
- *Protophobic fifth force searches : $\eta \to \gamma X_{17}$ with $X_{17} \to e^+e^-$*
- *New leptophobic baryonic force searches : $\eta \to \gamma B$ with $B \to e^+e^-$ or $B \to \gamma\pi^o$*
- *Indirect searches for dark photons new gauge bosons and leptoquark: $\eta \to \mu^+\mu^-$ and $\eta \to e^+e^-$*
- *Search for true muonium: $\eta \to \gamma(\mu^+\mu^-)|_{2M_\mu} \to \gamma e^+e^-$*

Other discrete symmetry violations

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

Other Precision Physics measurements

- *Proton radius anomaly: $\eta \to \gamma\mu^+\mu^-$ vs $\eta \to \gamma e^+e^-$*
- *All unseen leptonic decay mode of η / η' (SM predicts 10^{-6} -10^{-9})*

Non-η/η' based BSM Physics

- *Dark photon and ALP searches in Drell-Yan processes: $qqbar \to A'/a \to l^+l^-$*
- *ALP's searches in Primakoff processes: $p\,Z \to p\,Z\,a \to l^+l^-$ (F. Kahlhoefer)*
- *Charged pion and kaon decays: $\pi+ \to \mu^+\nu A' \to \mu^+\nu e^+e^-$ and $K+ \to \mu^+\nu A' \to \mu^+\nu e^+e^-$*
- *Neutral pion decay: $\pi^o \to \gamma A' \to \gamma e^+e^-$*

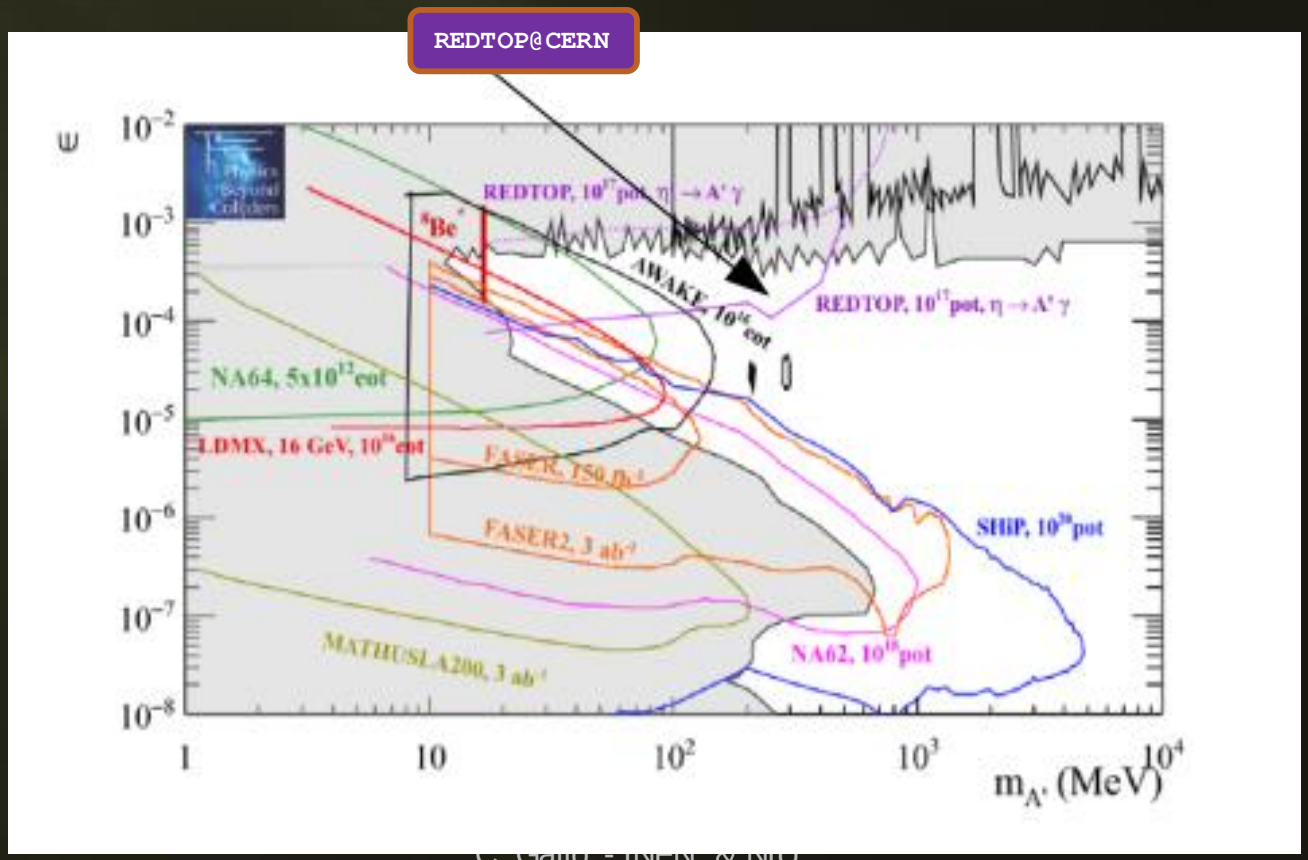
High precision studies on medium energy physics

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

Dark photon searches:

$\eta \rightarrow \gamma A'$ 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". Adding vertexing improve the sensitivity to physics BSM by 10x (K. Maamary summer project)*



Searches for light scalar mesons

$\eta \rightarrow \pi^o H$ with $H \rightarrow \mu^+ \mu^-$ 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*
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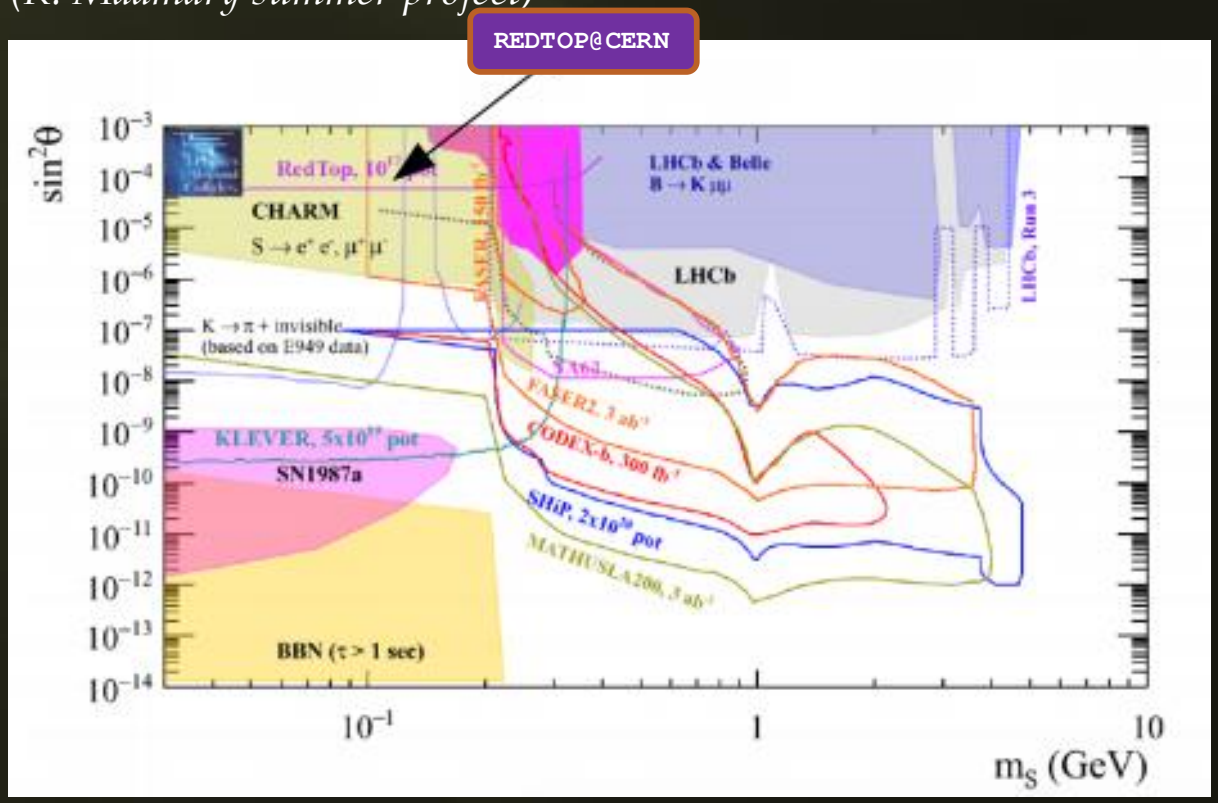
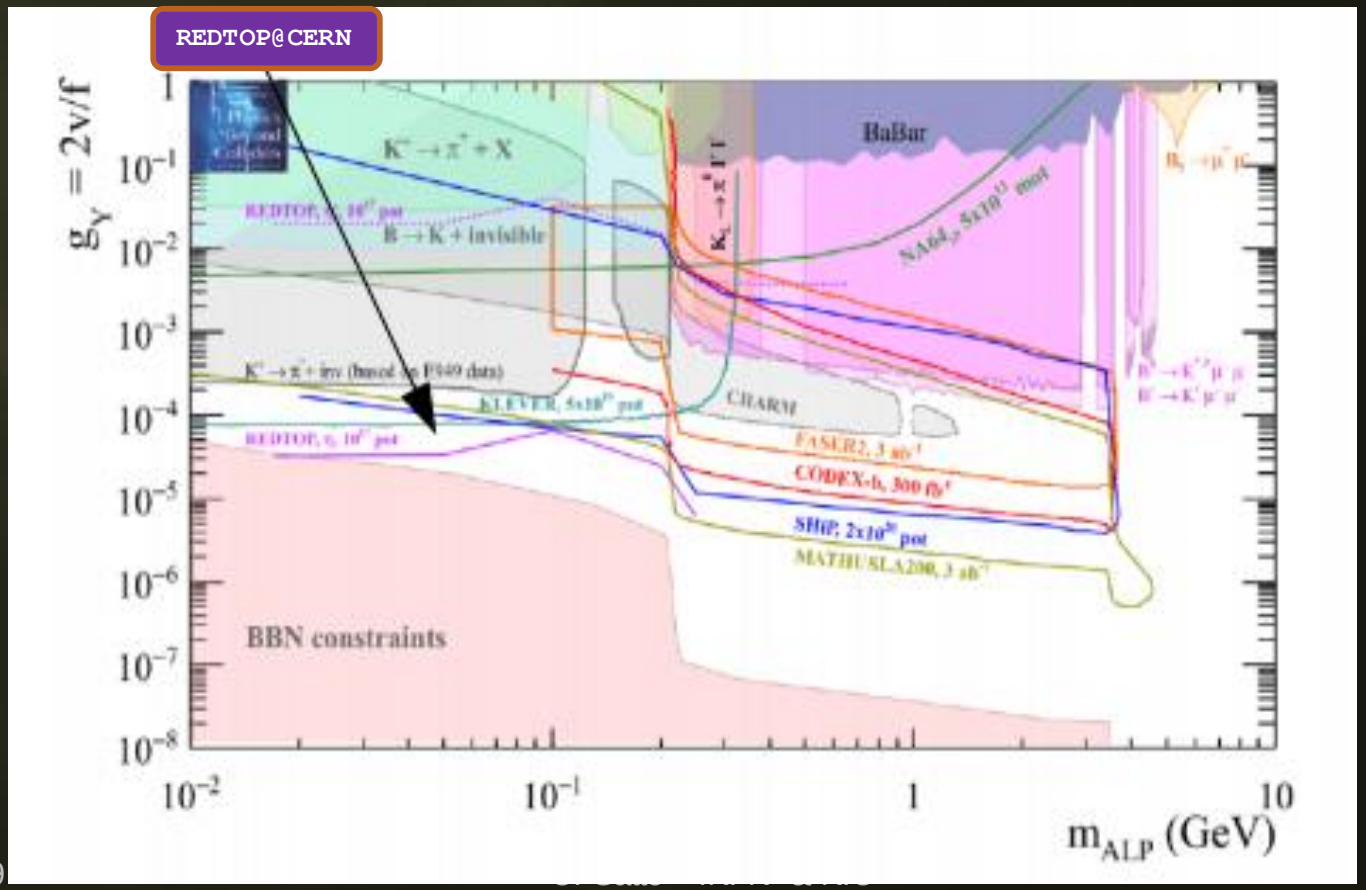


Searches for ALPs with fermion coupling

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

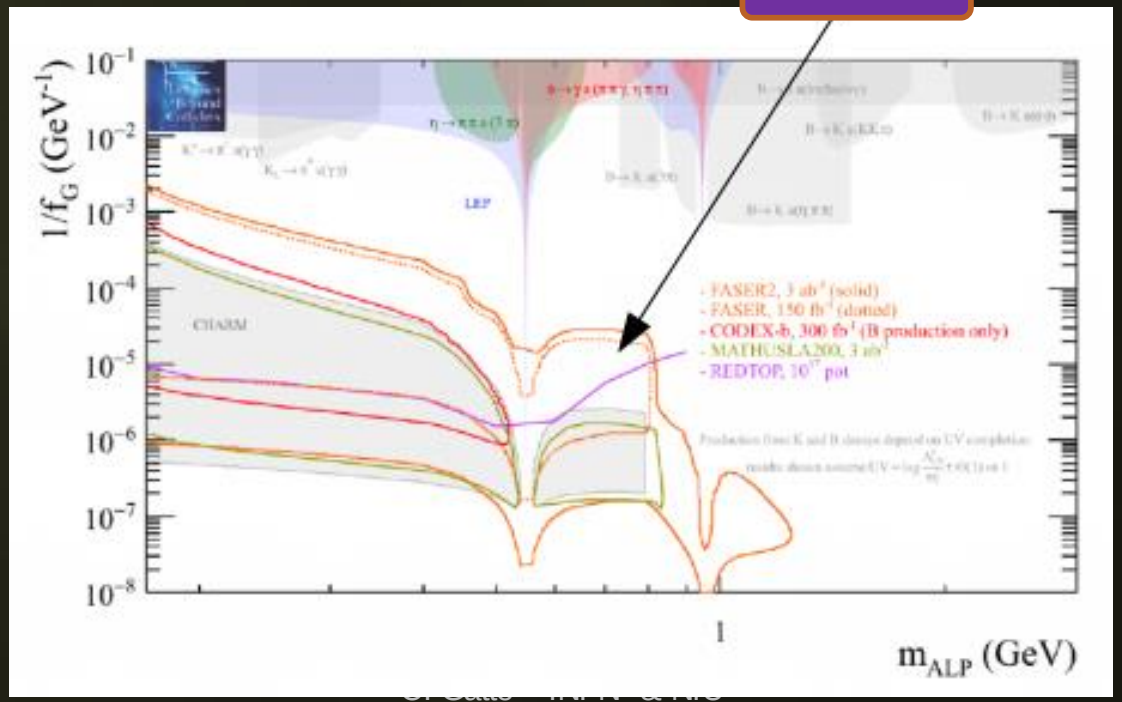
- *Studied within the "Physics Beyond Collider" program at CERN for 10^{17} POT*
- *FNAL and BNL can provide 10x more POT*
- *Only "bump hunt analysis". Will add vertexing to the analysis.*



Searches for ALPs with gluon coupling

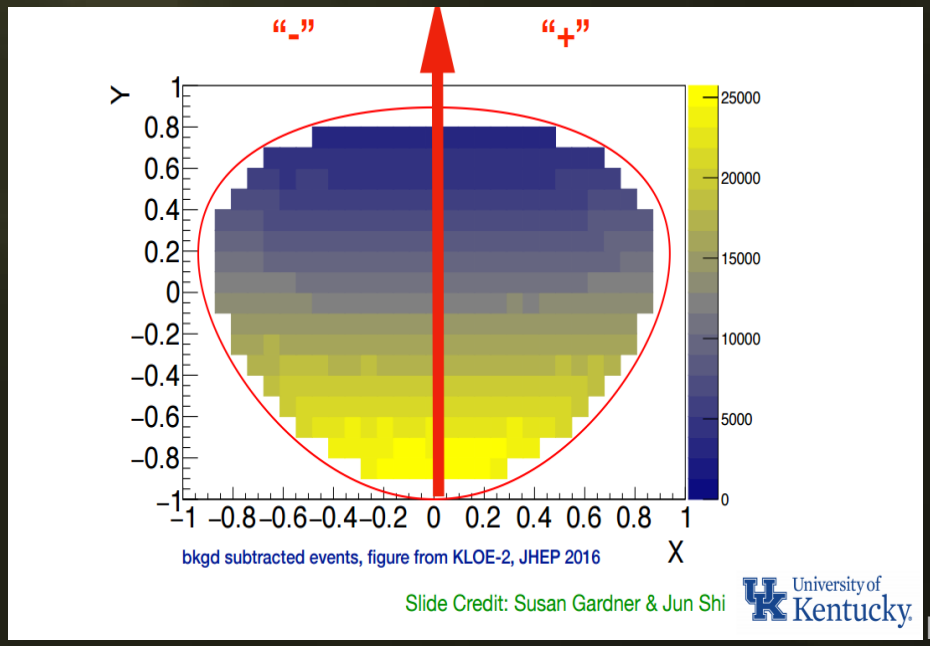
- *Beam emitted ALP's from the following processes:*
  - *Drell-Yan processes:* $qqbar \rightarrow A'/a \rightarrow l^+l^-$
  - *Proton bremsstrahlung processes:* $p\,N \rightarrow p\,N\,A'/a$ *with* $A'/a \rightarrow l^+l^-$ *(J. Blümlein and J. Brunner)*
  - *Primakoff processes:* $p\,Z \rightarrow p\,Z\,a \rightarrow l^+l^{- -}$ *(F. Kahlhoefer, et. Al.)*
- *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.*
- *Redtop@PIP-II will provide x100 sensitivity (ALPACA study)*

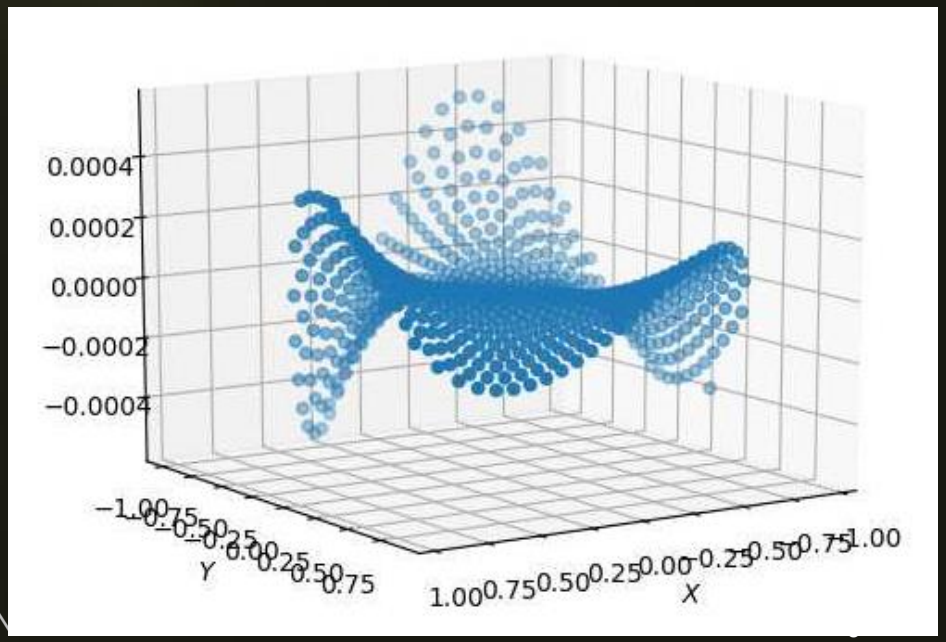
REDTOP@CERN



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

- *CP-violation from this process is not bounded by EDM as is the case for the $\eta \to 4\pi$ process.*
- *Complementary to EDM searches even in the case of T and P odd observables, since the flavor structure of the eta is different from the nucleus*
- *Current PDG limits consistent with no asymmetry*
- *REDTOP will collect $4x10^{11}$ such decay (factor 100 in stat. error)*
- *New model in GenieHad (collaboration with S. Gardner & J. Shi – UK) based on* https://arxiv.org/abs/1903.11617





Present & Future η Samples

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

REDTOP Requirements

- Medium energy proton beam 1.5 – 4 GeV
- 10^{17} POT/yr (10^{18} POT/yr better-FNAL and 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.
- -near 4π detector acceptance.

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 (vs Nb as Hades-like experiments)*
- *Use multiple thin targets to minimize combinatorics background*

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 **ADRIANO** calorimeter for reconstructing EM showers*

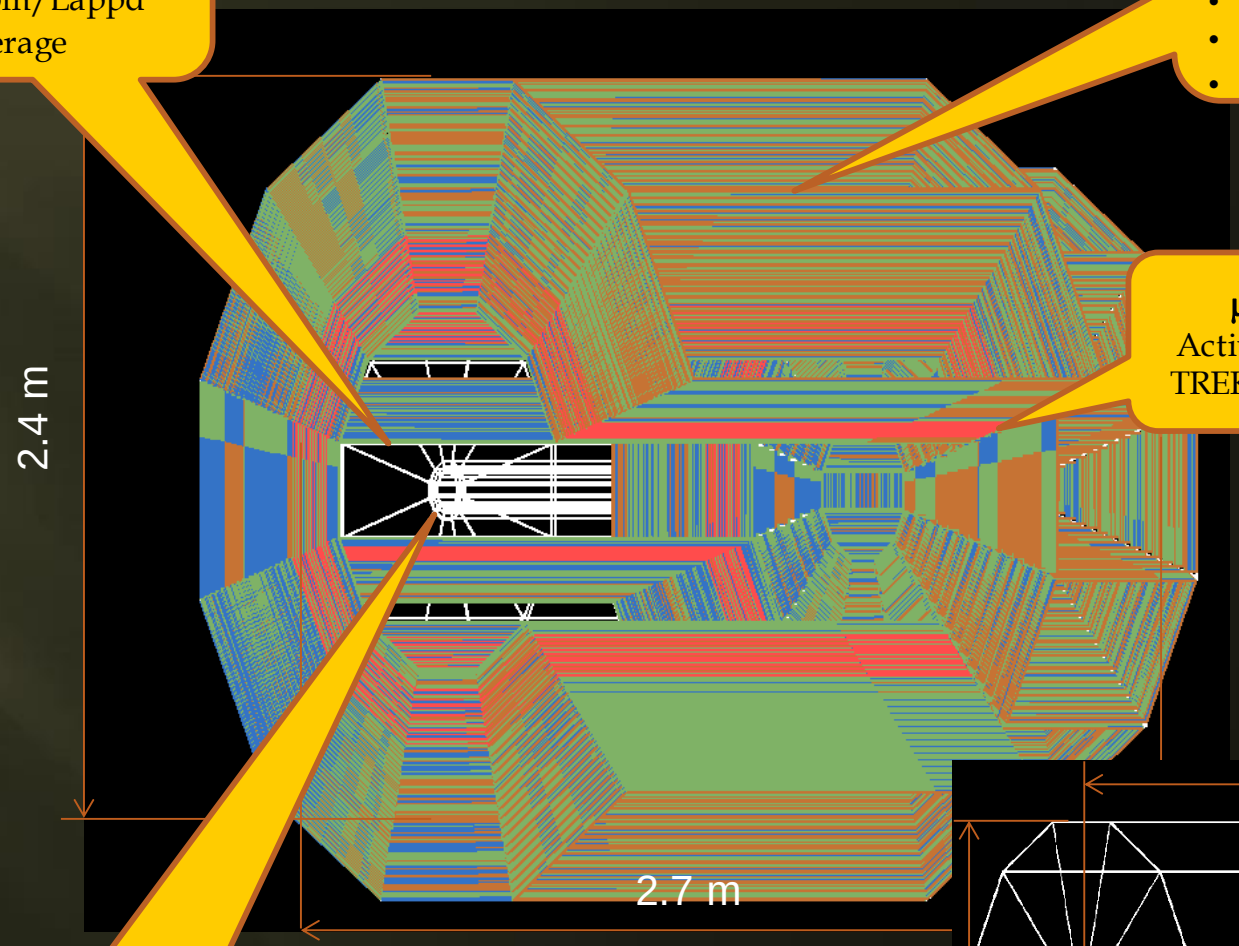
- $\sigma_E/E < 5\%/\sqrt{E}$
- *PID from dual-readout to disentangle showers from γ/μ/hadrons*
- *96.5% coverage*

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

REDTOP detector

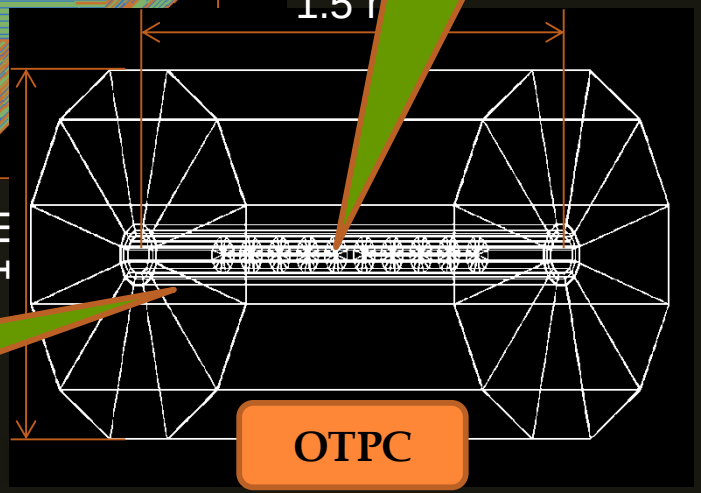
Optical TPC
- ~ 1m x 1.5 m
- CH_4 @ 1 Atm
- $5x10^5$ Sipm/Lappd
- 98% coverage

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



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

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



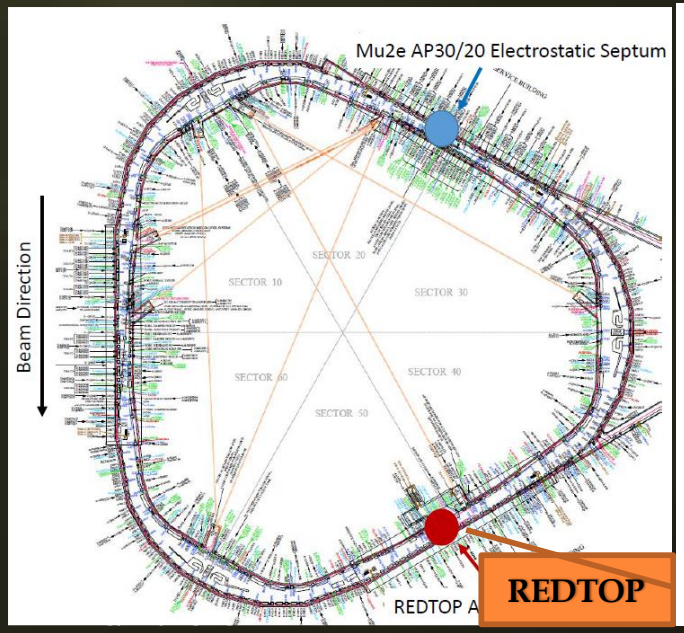
Fiber tracker
for rejection of g-conversion and vertexing

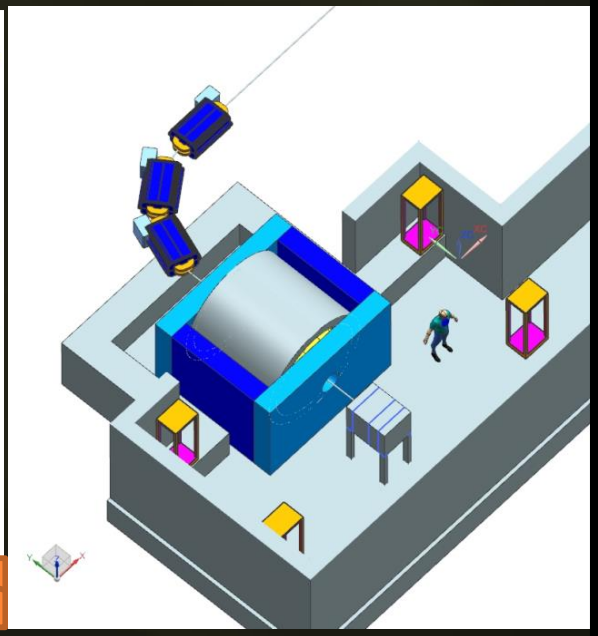
Aerogel
Dual refractive index system

OTPC

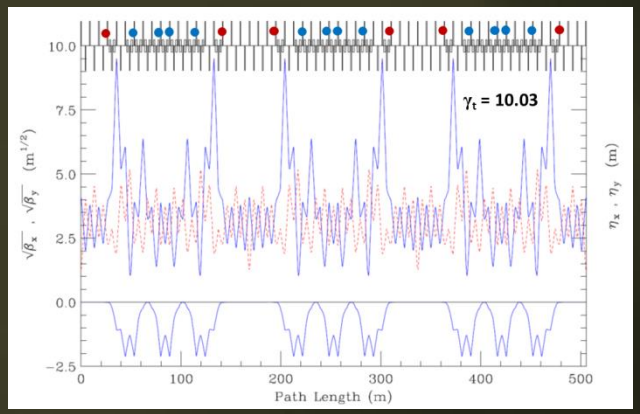
Acceleration Scheme (M. Syphers)

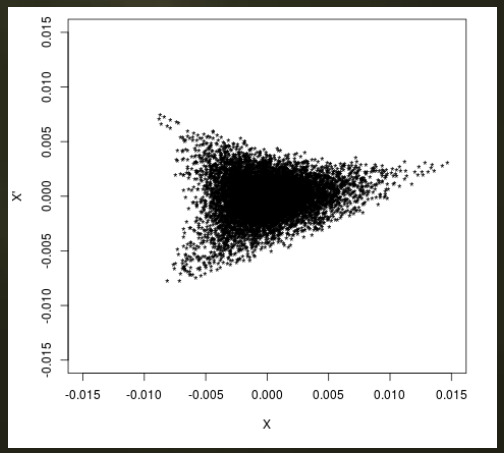
- *Single p pulse from booster (≤4x10^{12} p) injected in the DR (former debuncher in anti-p production at Tevatron) at fixed energy (8 GeV)*
- *Energy is removed by adding 1-2 RF cavities identical to the one already planned (~5 seconds)*
- *Slow extraction to REDTOP over ~40 seconds.*
- *The 270° of 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%*





Accelerator Physics Issues



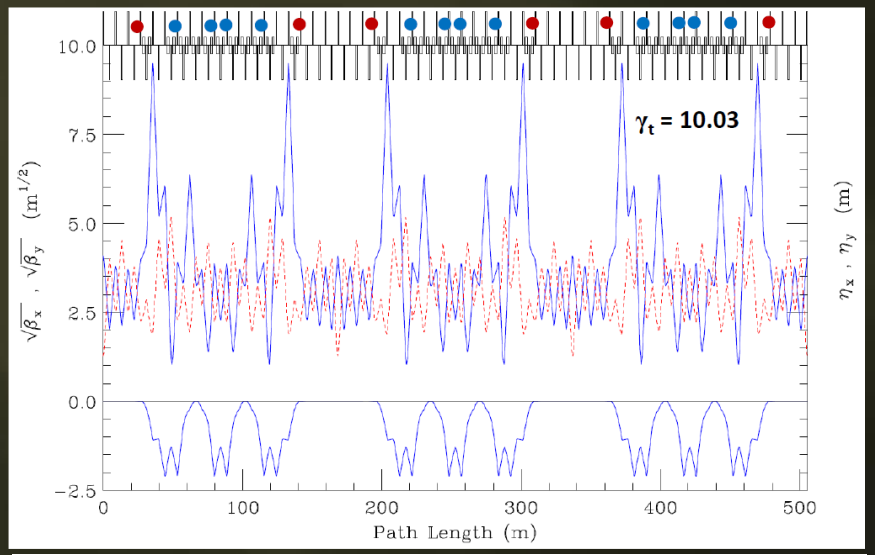


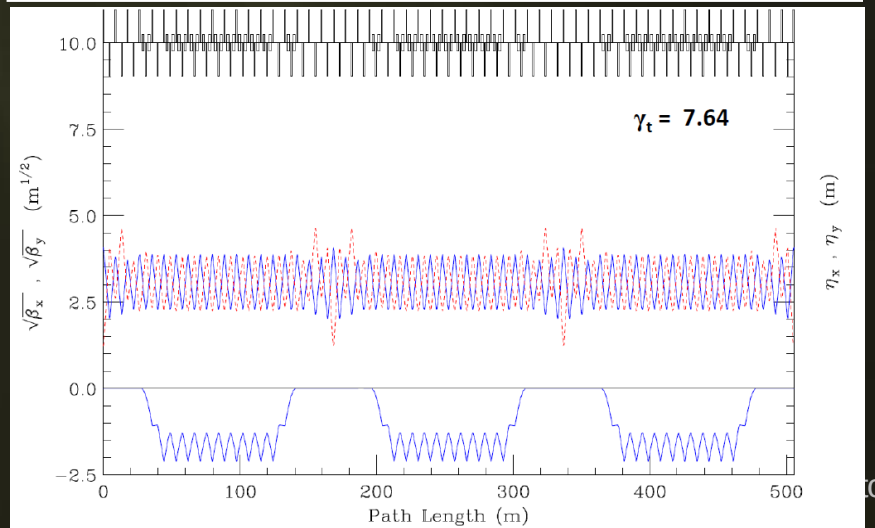
- ***Transition Energy***
  - γ_t is where $\Delta f/f = 1/\gamma 2 - \langle D/\rho \rangle = 0$; synchrotron motion stops momentarily, can often lead to beam loss
  - beam decelerates from $\gamma = 9.5$ to $\gamma = 3.1$
  - original Delivery Ring $\gamma_t = 7.6$
  - a re-powering of 18 quadrupole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

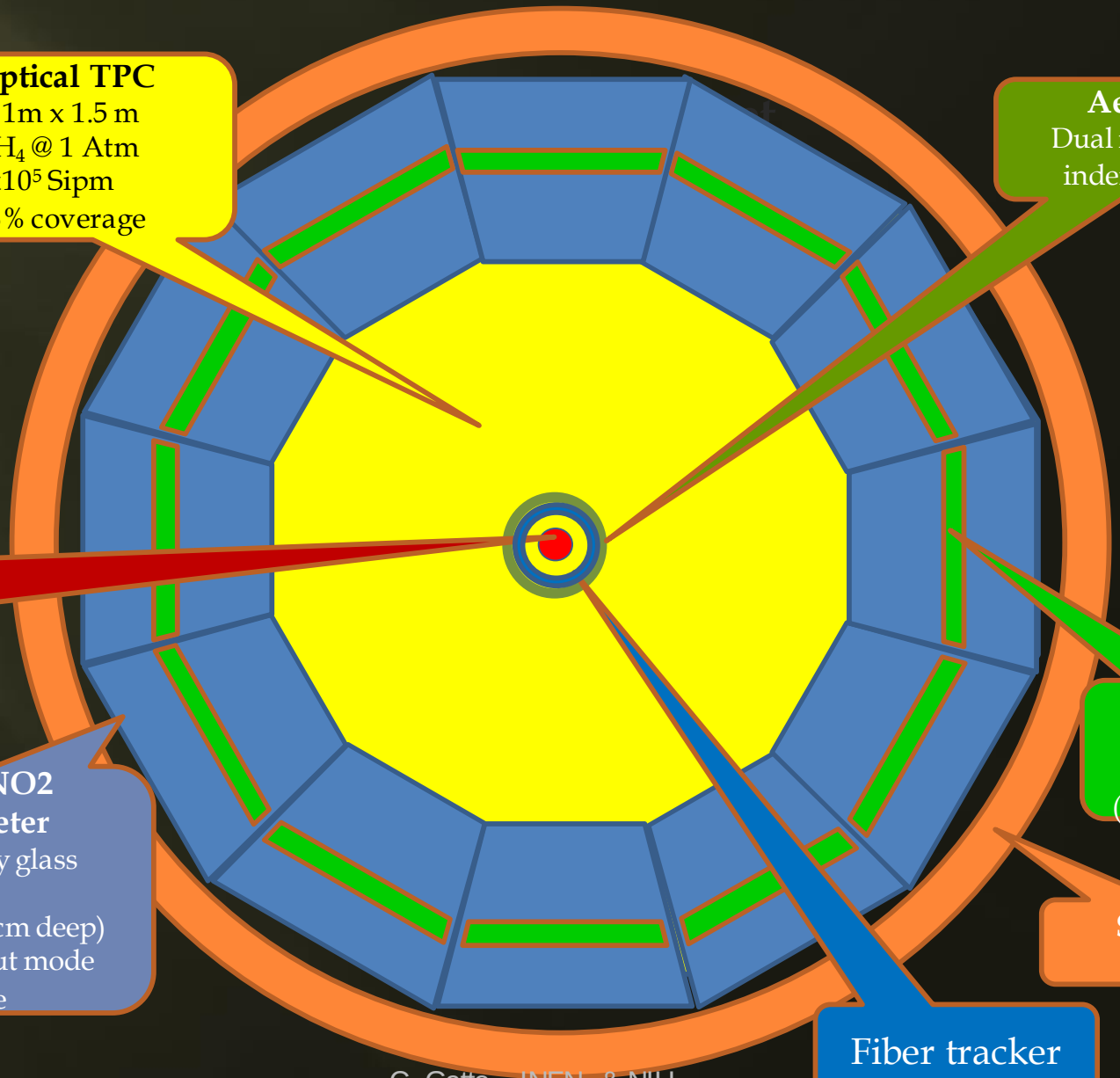
"J.Johnstone, M.Syphers, NA-PAC, Chicago (2016)"

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)*

The REDTOP Detector



Optical TPC
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- CH_4 @ 1 Atm
- $5x10^5$ Sipm
- 98% coverage

Aerogel
Dual refractive index system

10x Li/Be targets
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ADRIANO2 Calorimeter
- Scint. + heavy glass sandwich
- 20 X_0 (~ 64 cm deep)
- Triple-readout mode
- 96% coverage

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

Solenoid
0.6-0.8 T

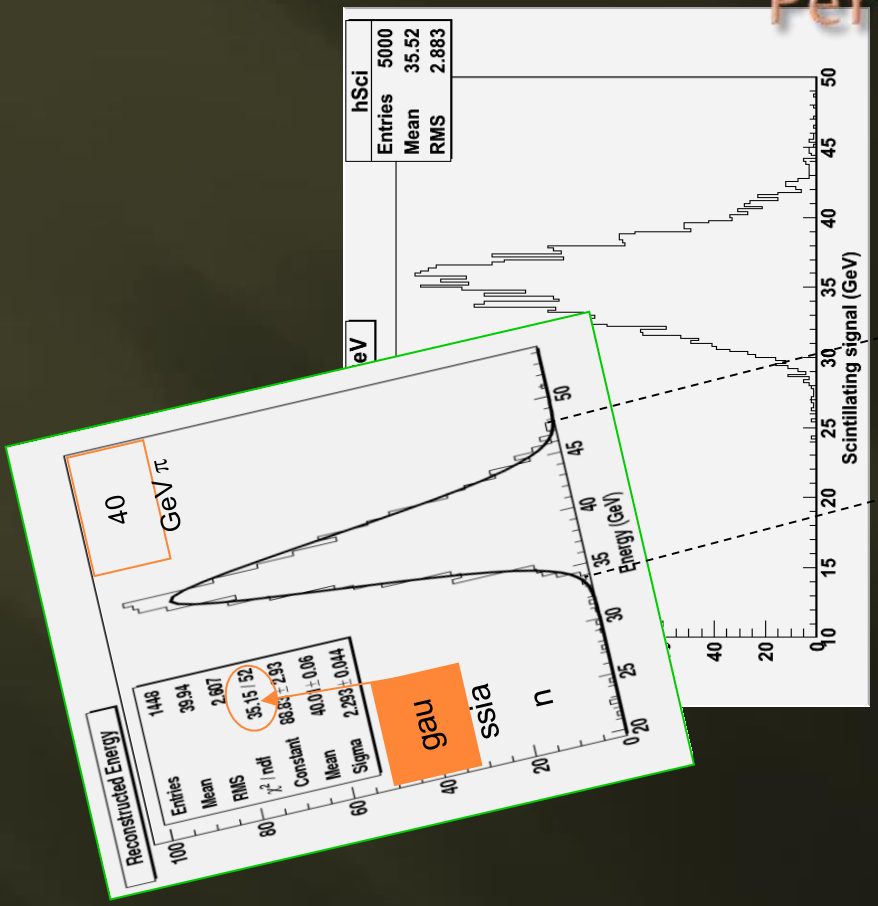
Fiber tracker

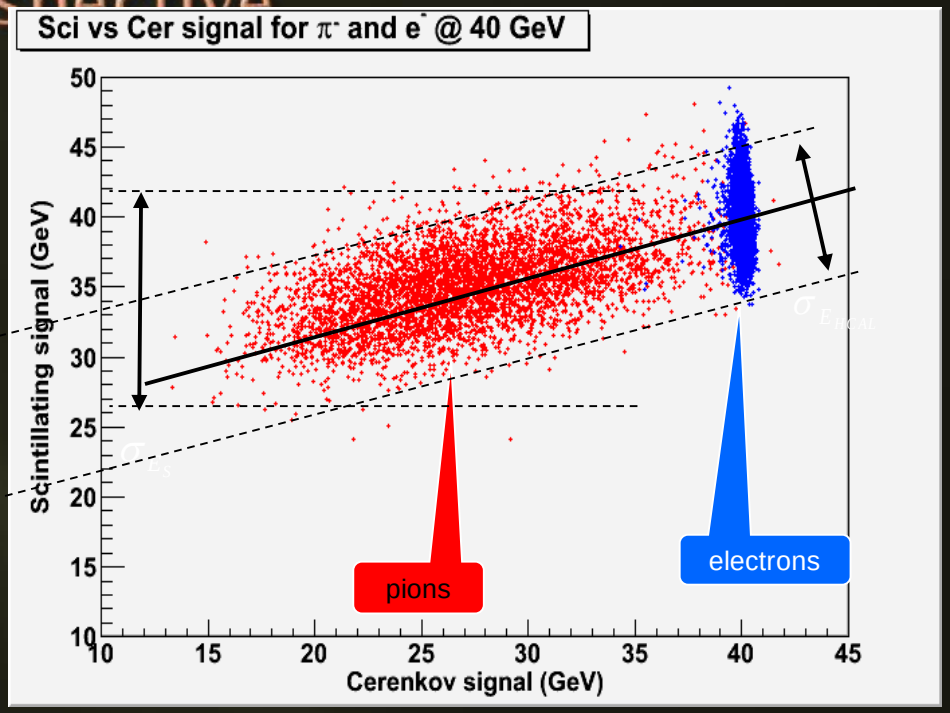
The ADRIANO2 Calorimeter

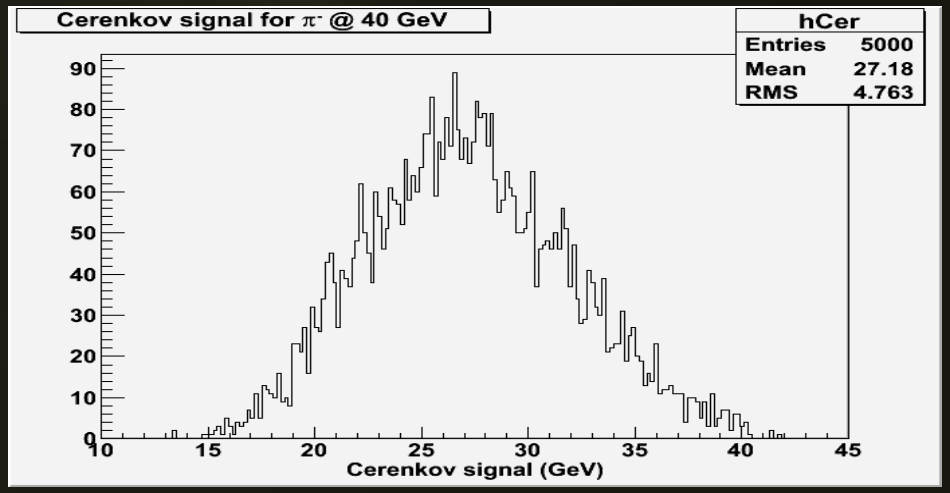
- *Sandwich of Pb-glass and scintillating plastic tiles with direct SiPM reading*
  - *Evolution of ADRIANO dual-readout calorimeter (A Dual-Readiut Integrally Active Non-segmented Option)*
- *Triple-readout obtained from waveform analysis*

- *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

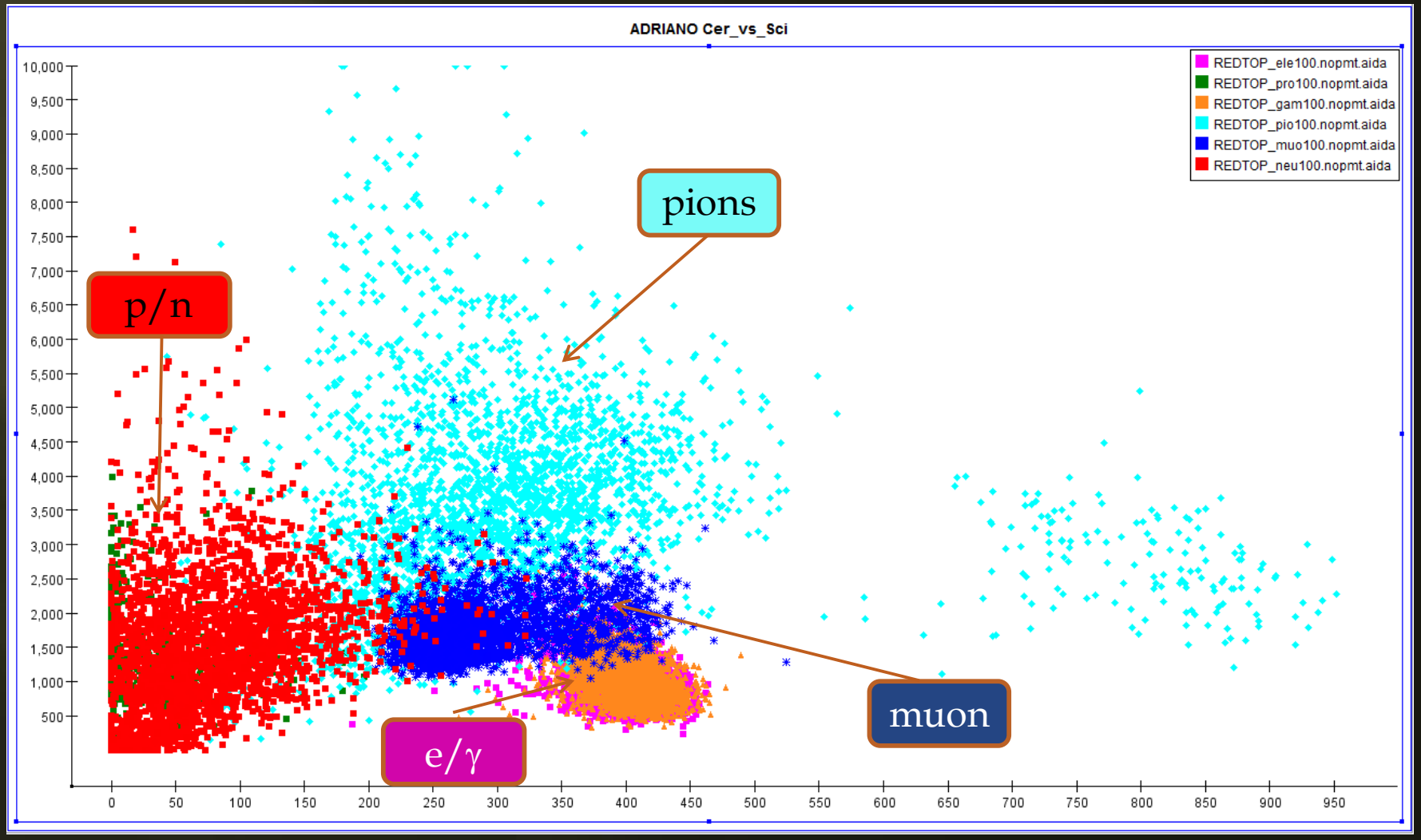






Triple-readout adds the measurement of the neutron component improving the energy resolution even further

ADRIANO PID @ 100MeV

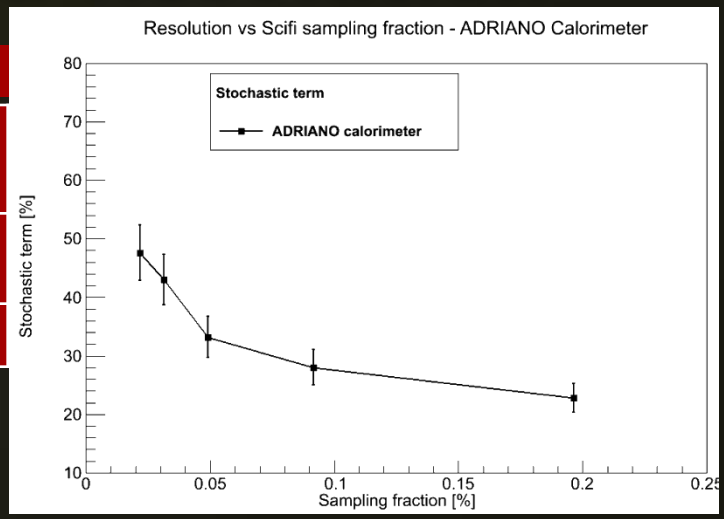


ADRIANO Light Yield and Resolution

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
$\langle pe_S/GeV \rangle$	1053	430	**254**	163	124	500	110	250	200
$\langle pe_C/GeV \rangle$	340	360	**360**	355	355	355	350	350	7.5

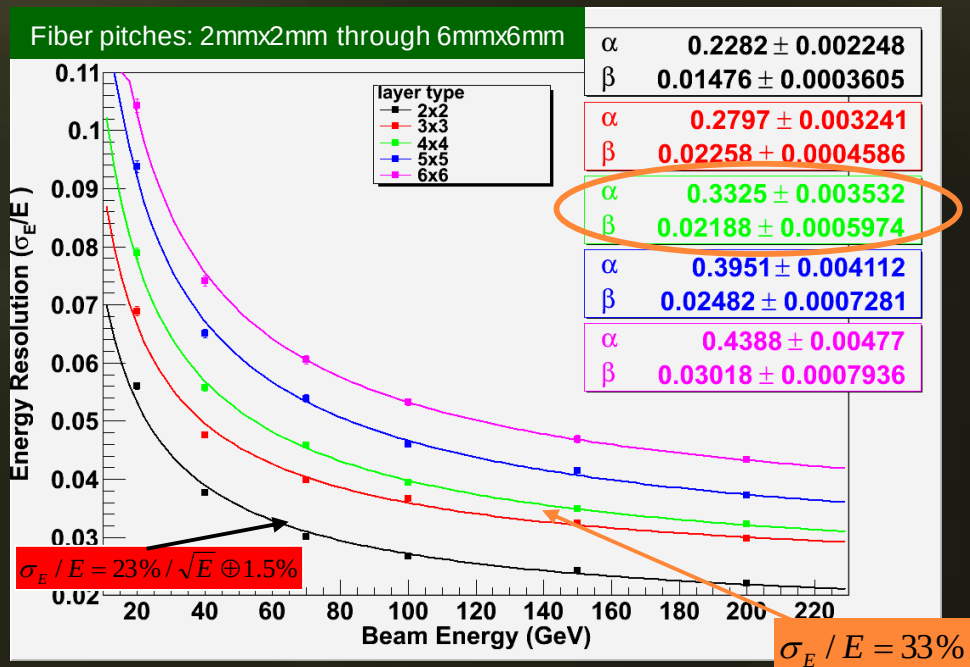
Baseline configuration

1-side readout

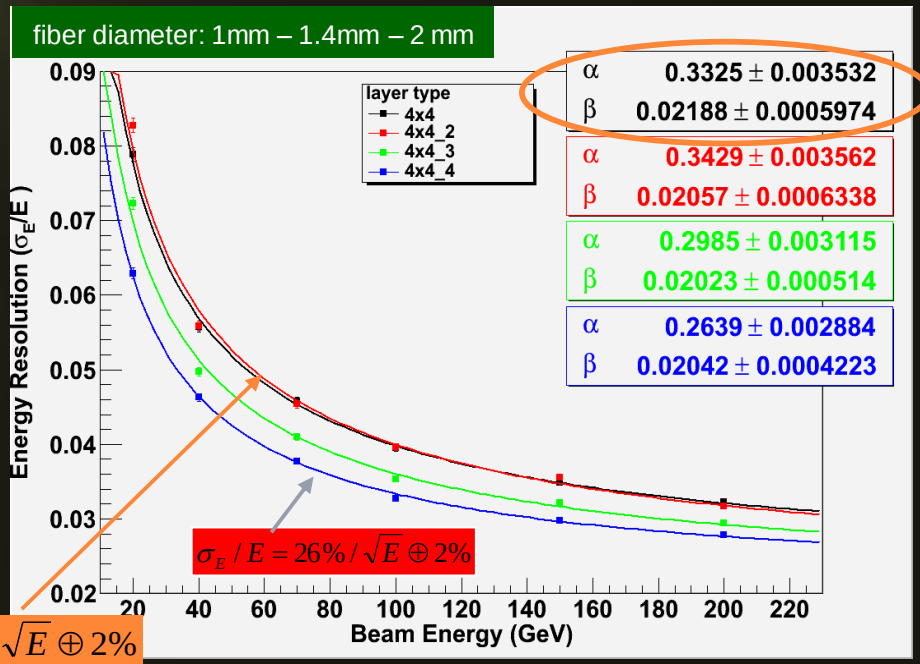


ILCroot simulations

Fiber pitches: 2mmx2mm through 6mmx6mm



fiber diameter: 1mm – 1.4mm – 2 mm

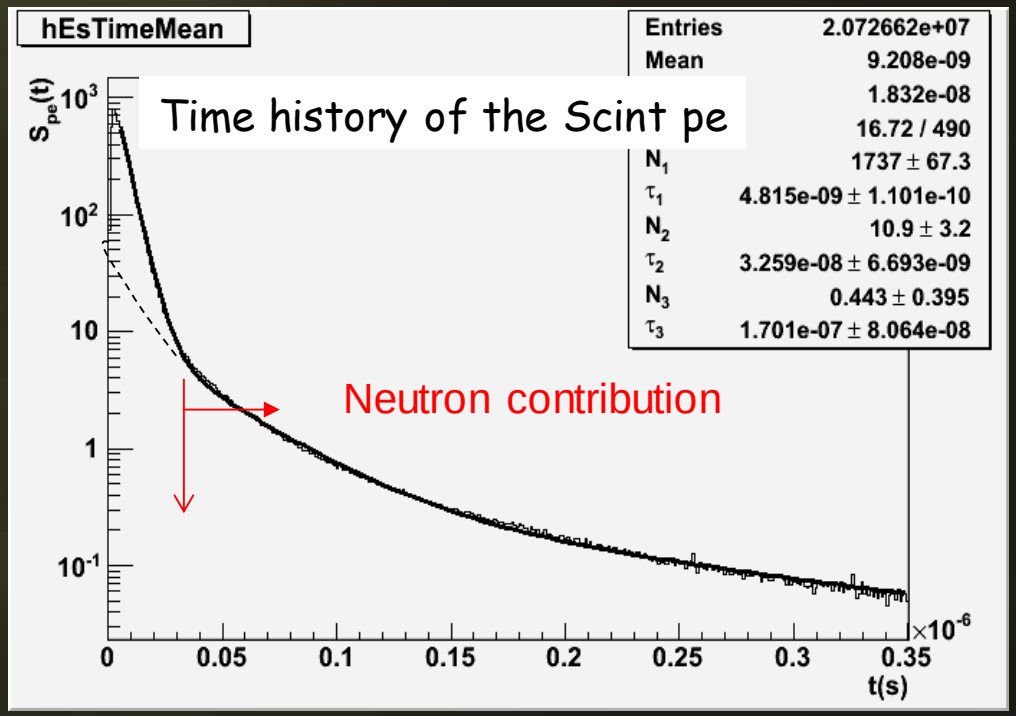


$\sigma_E / E = 33\% / \sqrt{E} \oplus 2\%$

All numbers include the effect of photodetector QE

From Dual to Triple Readout

Disentangling neutron component from waveform



40 Gev pions

ILCroot simulations

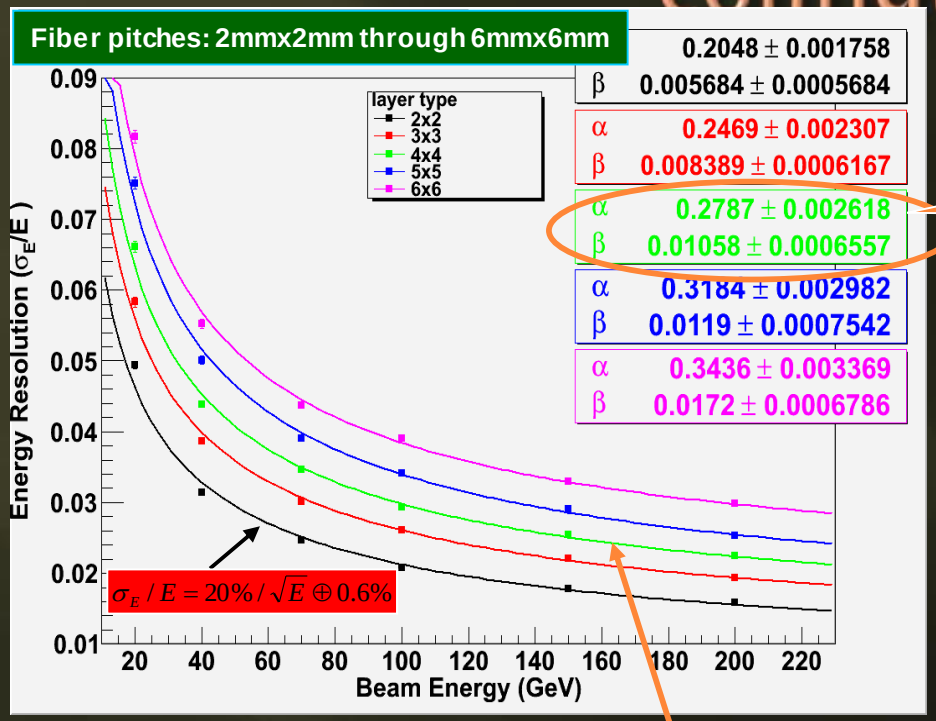
Time history of the scintillation signal in *ADRIANO* for π^-@40 GeV.

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

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

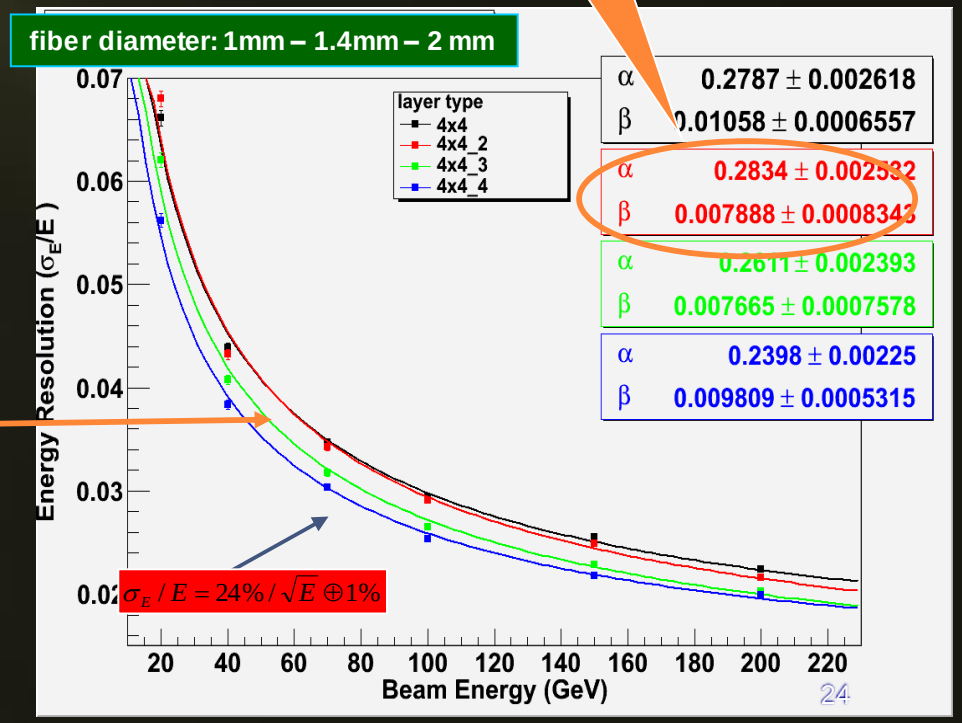
Triple Readout aka Dual Readout with time history readout

ADRIANO in Triple Readout configuration



Baseline configuration

Pion beams



ILCroot simulations

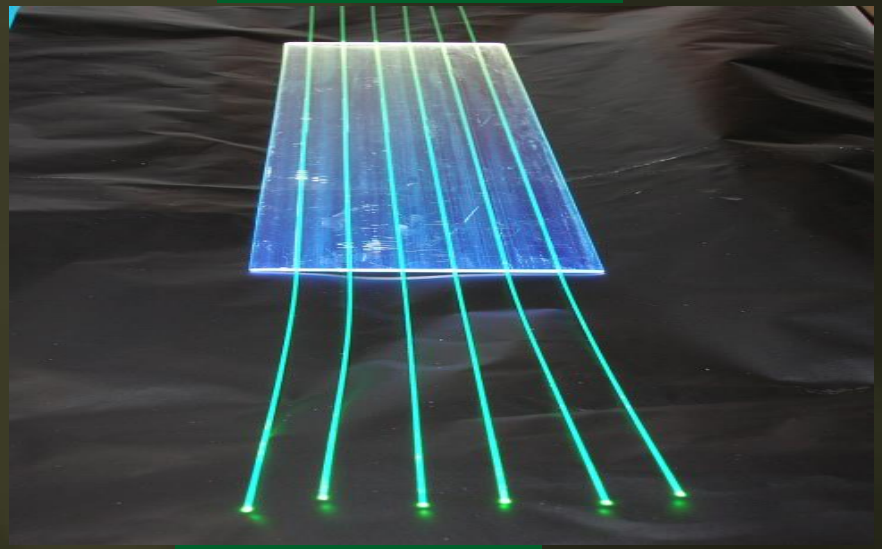
$$\sigma_E / E = 28\% / \sqrt{E} \oplus 1\%$$

ompare to ADRIANO in Double Readout configuration

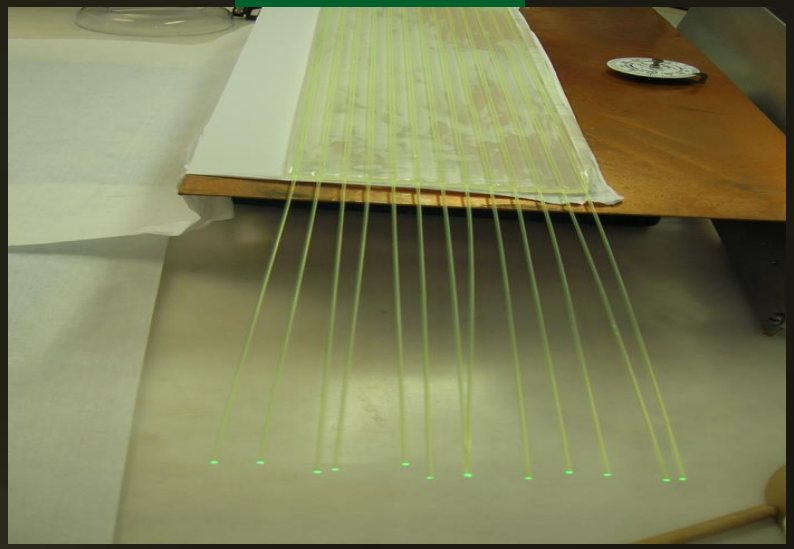
$$\sigma_E / E = 33\% / \sqrt{E} \oplus 2\%$$

ADRIANO for ORKA Construction

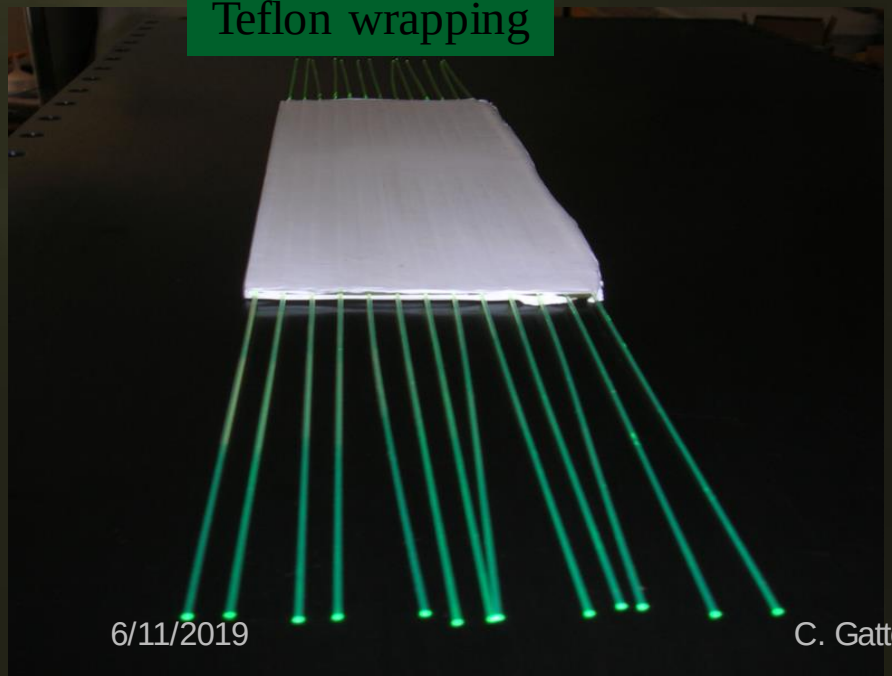
WLS + scintillator



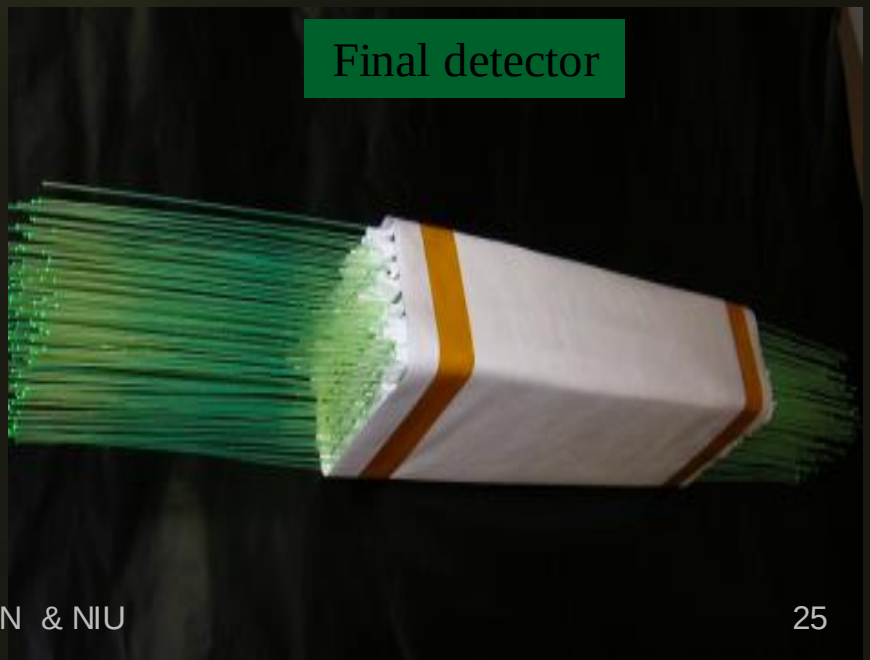
WLS + glass



Teflon wrapping

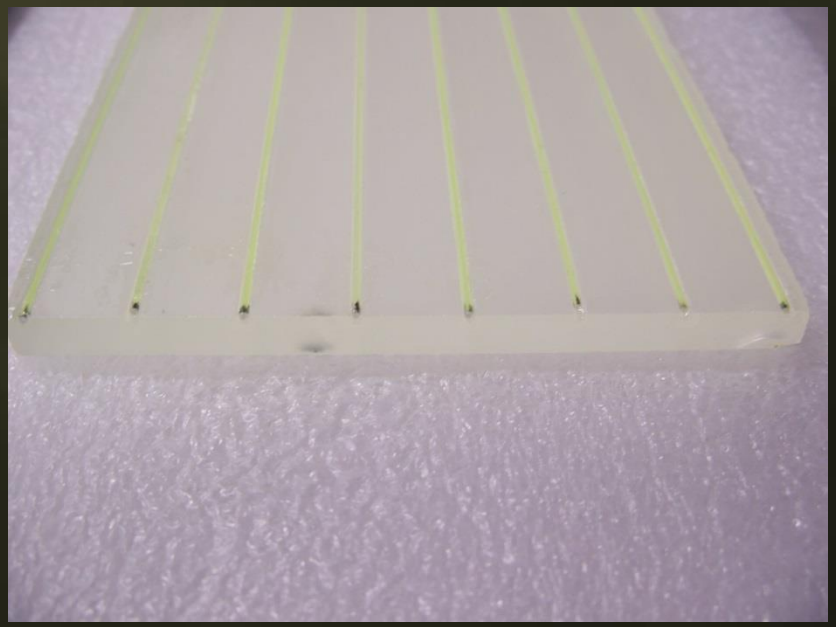


Final detector

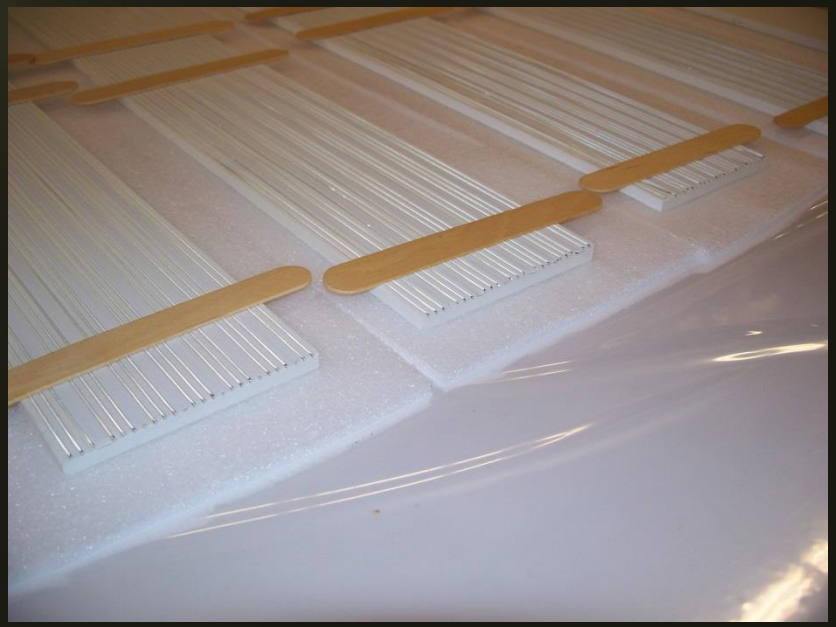


ADRIANO-2014

- 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

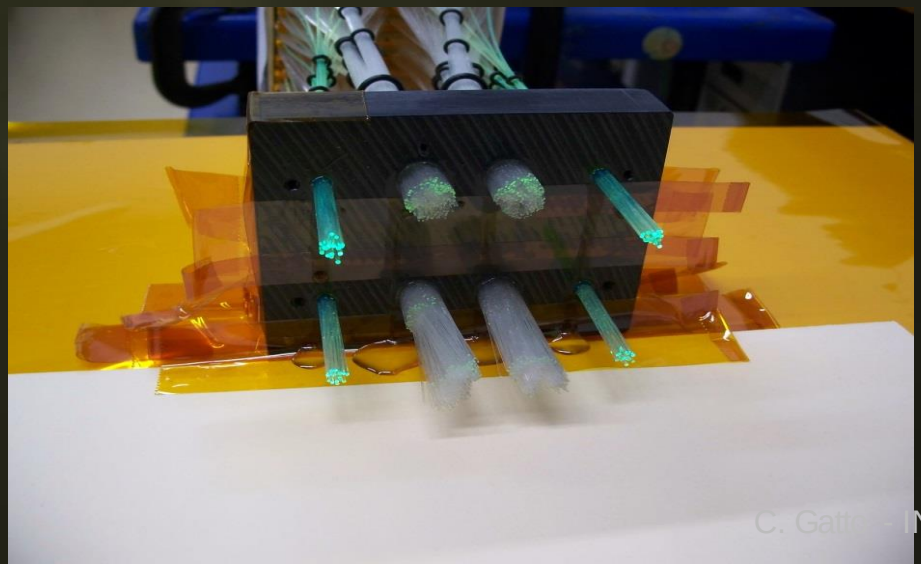


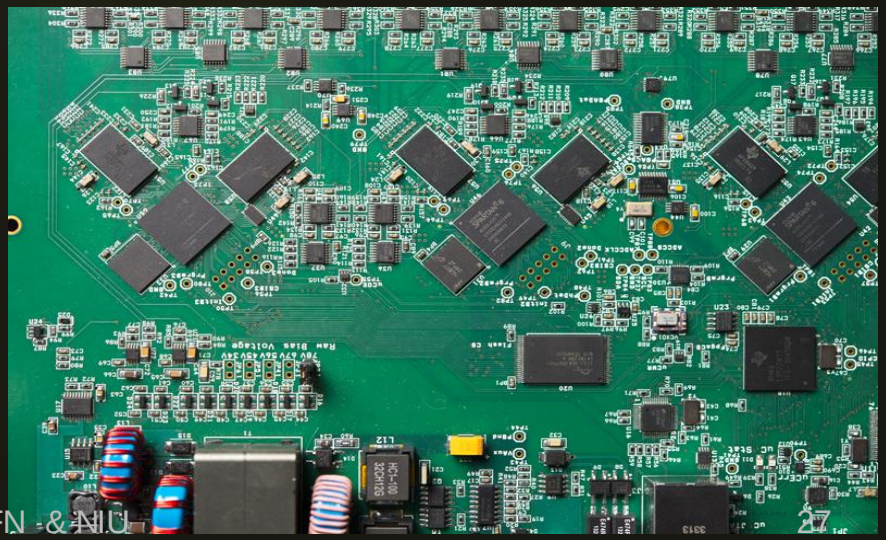
ADRIANO 2014A: 8 grooves



ADRIANO 2014B: 23 grooves

ADRIANO for High Energy



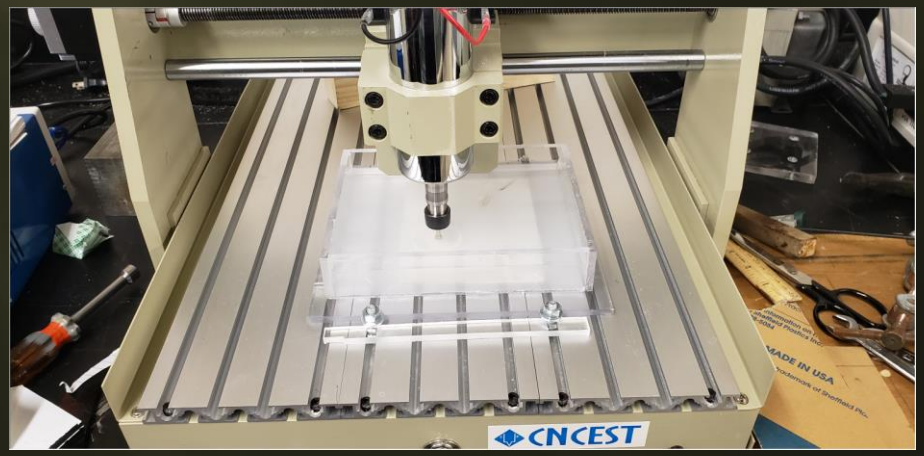


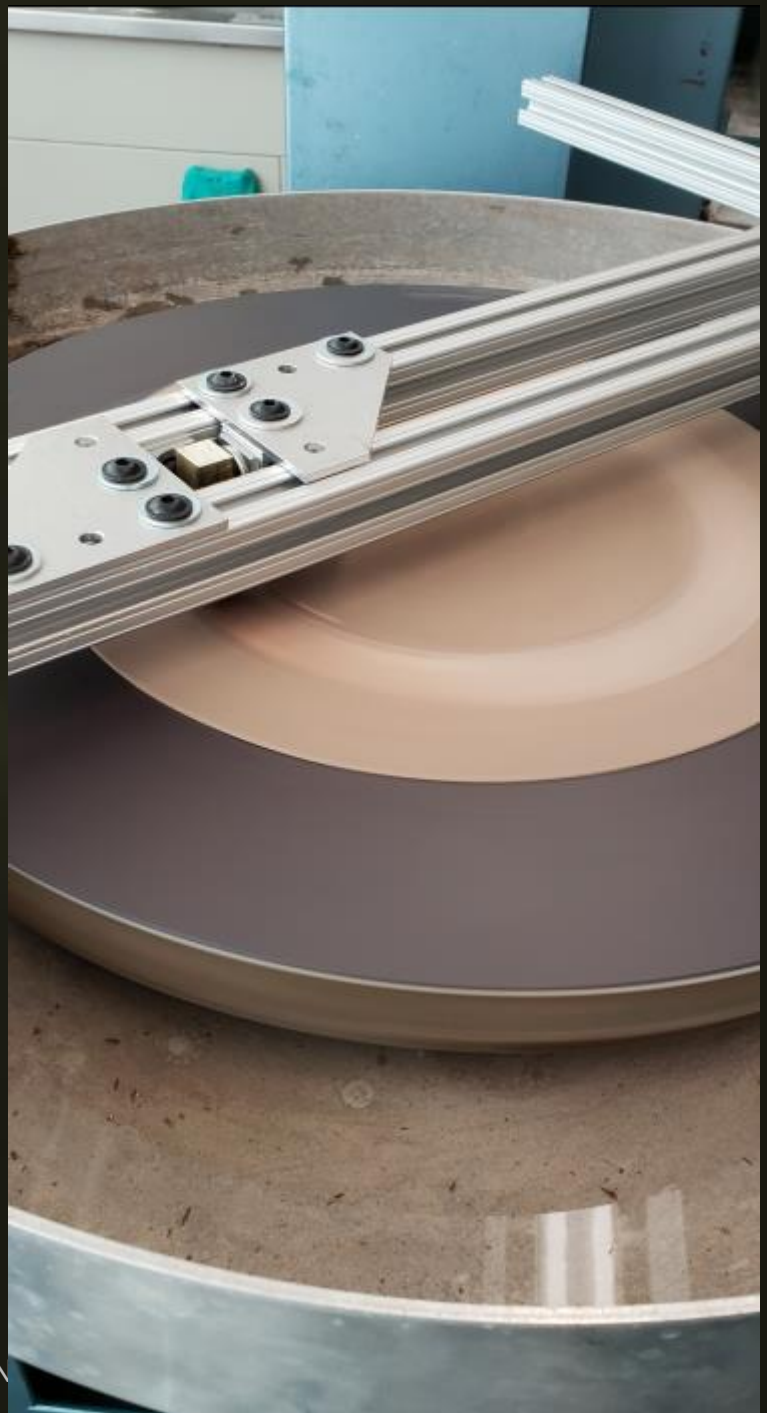
Nov. 2015 test Beam at Fermilab

ADRIANO2 R&D

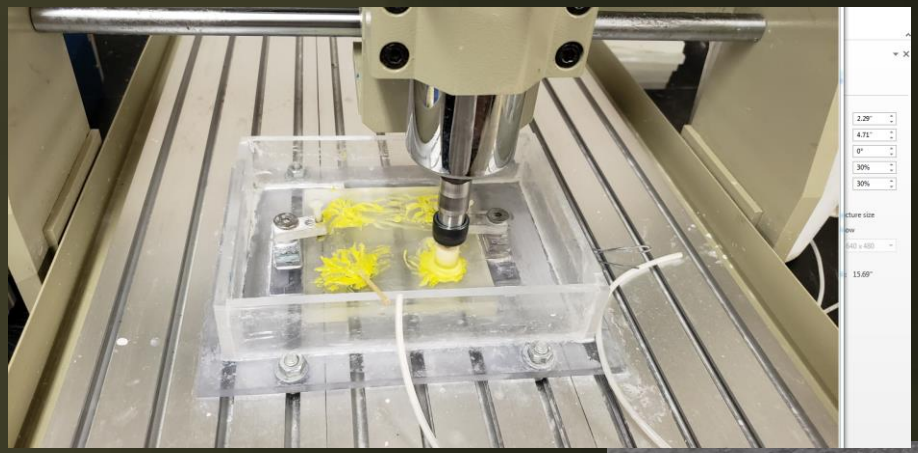
- Evolution of ADRIANO: log layout->tiles
- Sandwich of 3mm scintillating plastics and 10 mm Pb-glass (10cm x 10cm transverse size)
- WLS light capture -> SiPM directly coupled to glass and plastic
- Prompt Cerenkov signal used in L0 trigger
- Granularity can be made extremely fine
- 16 layers – prototype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

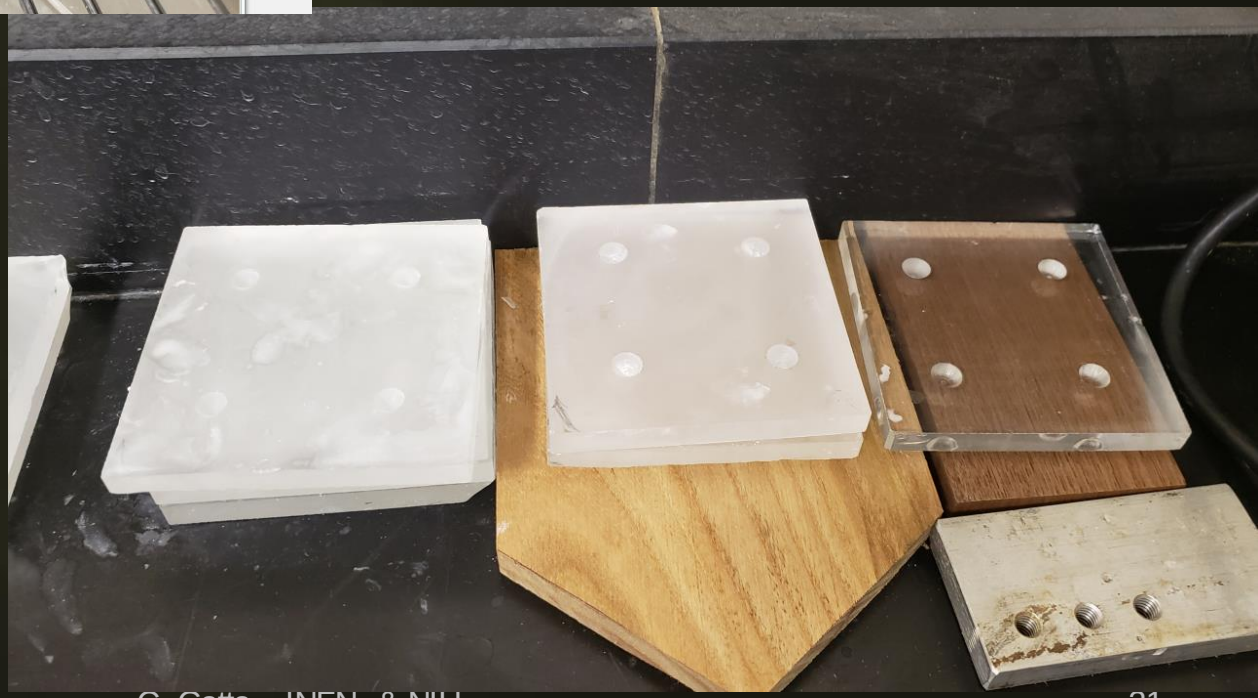
Glass preparation





Polishing



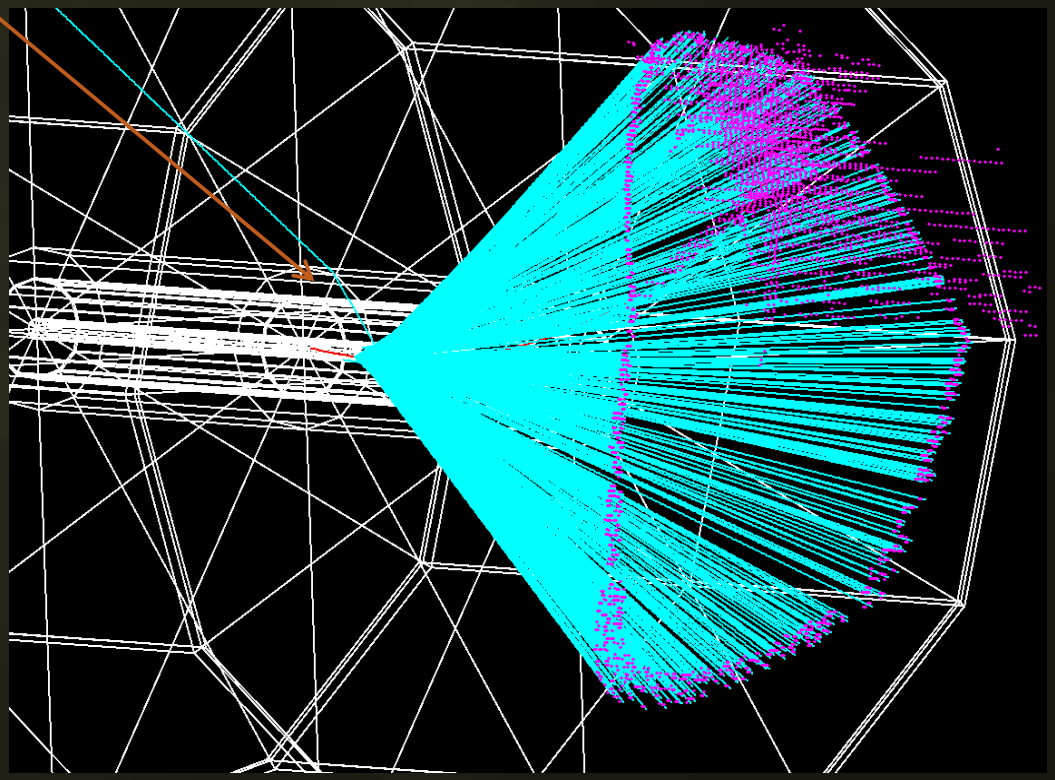


Coating and testing

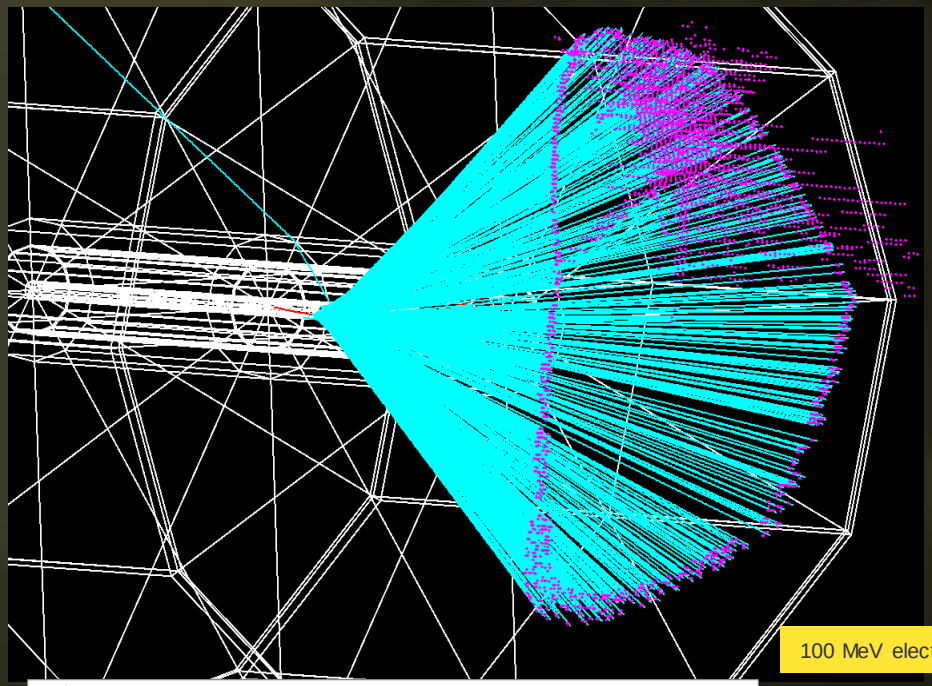
The Optical TPC Concept

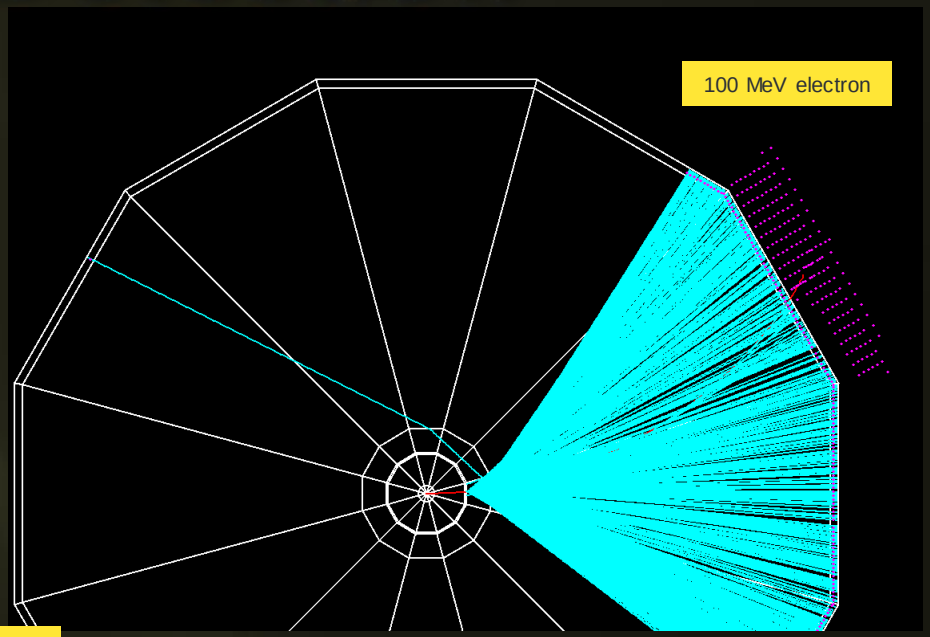
Rationale for an Optical- TPC

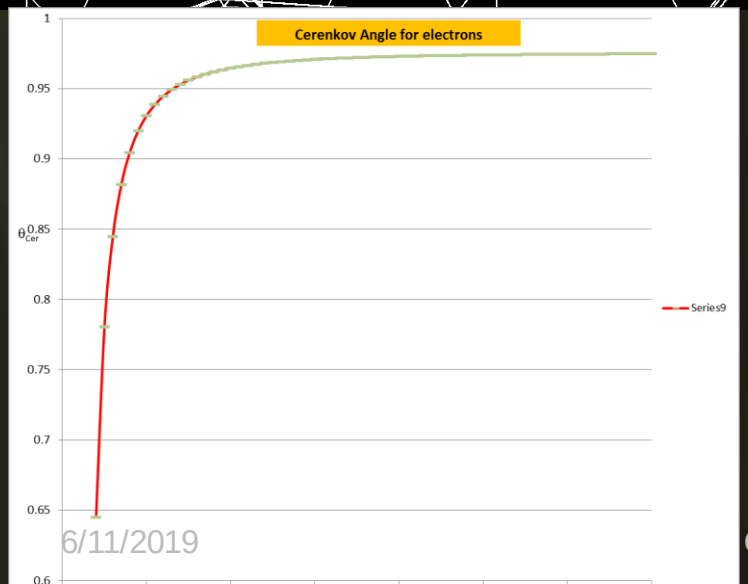
- *At 1 GHz inelastic interaction rate, a conventional, gas detector is suboptimal*
- *Hadronic particles (p, ion remnants, slow pions, etc.) will clutter the tracker*
- *Use the Cerenkov effect to detect the fast (leptons and fast pions) tracks*
- *Prompt signal is also fed to the L0 trigger for fast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



Electron Detection







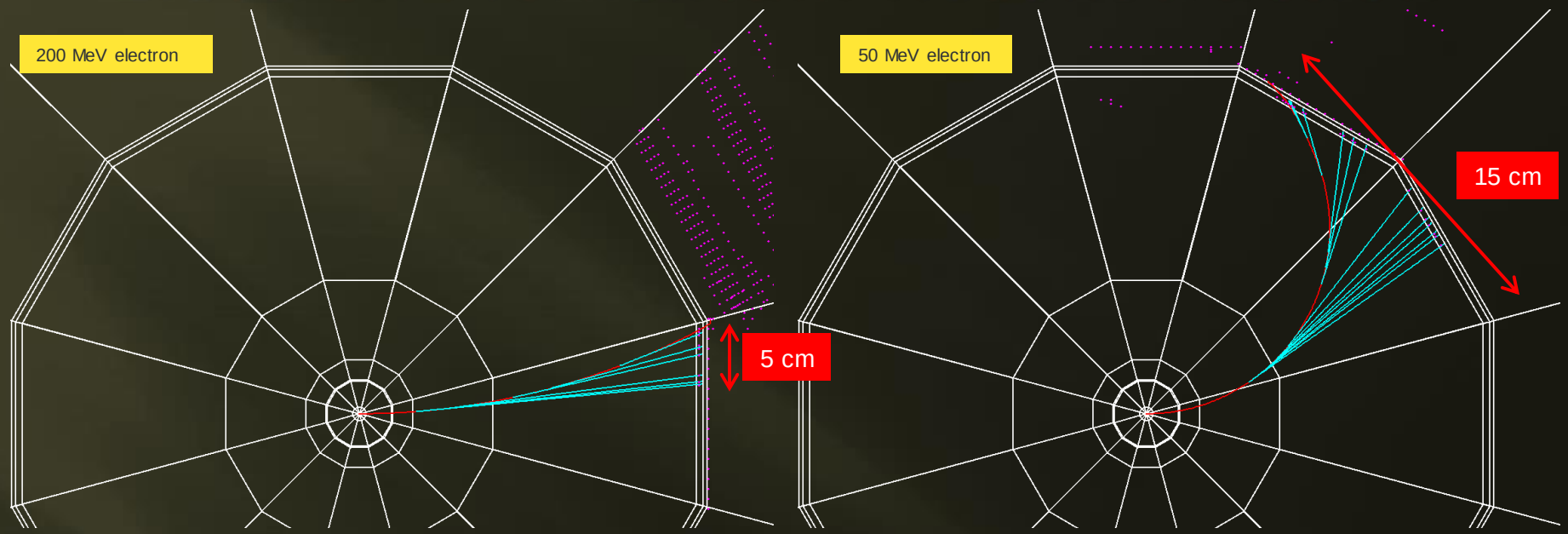
$n_D(N_2@2.7psi)=1.000145$

Č threshold for e- in N_2: P=40 mev

$n_D(aerogel1)=1.12$

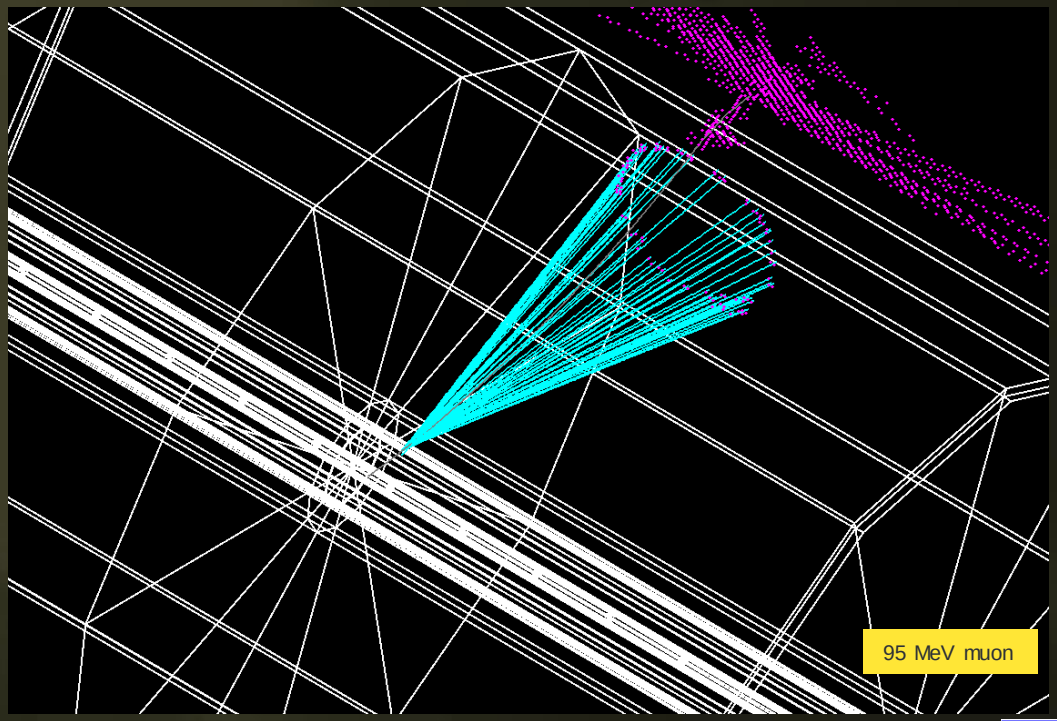
$n_D(aerogel2)=1.22$

Electron Momentum Reconstruction

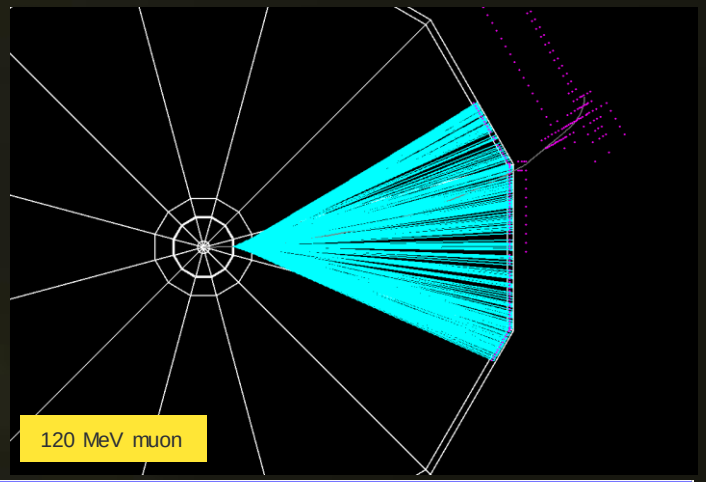


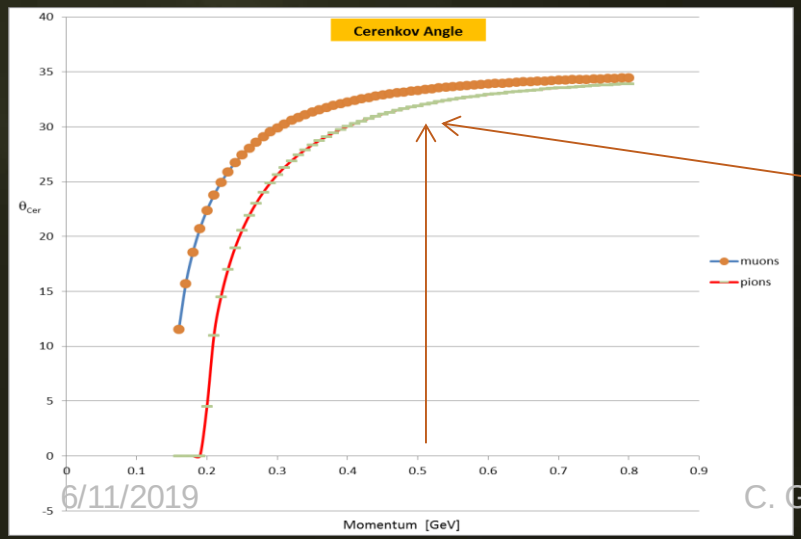
- Electrons are recognized by:
  1. a large (>30 cm dia) circle of photons generated in the aerogel
  2. A sweep of photons circles with dia < 1cm and several cm long (depends on P_t)
  3. An EM shower in ADRIANO (identified by Č vs S)

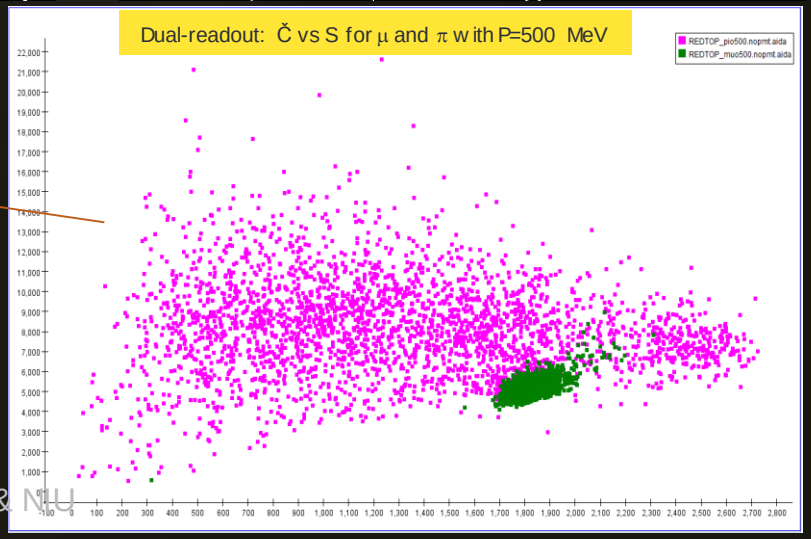
Muon/pion Detection



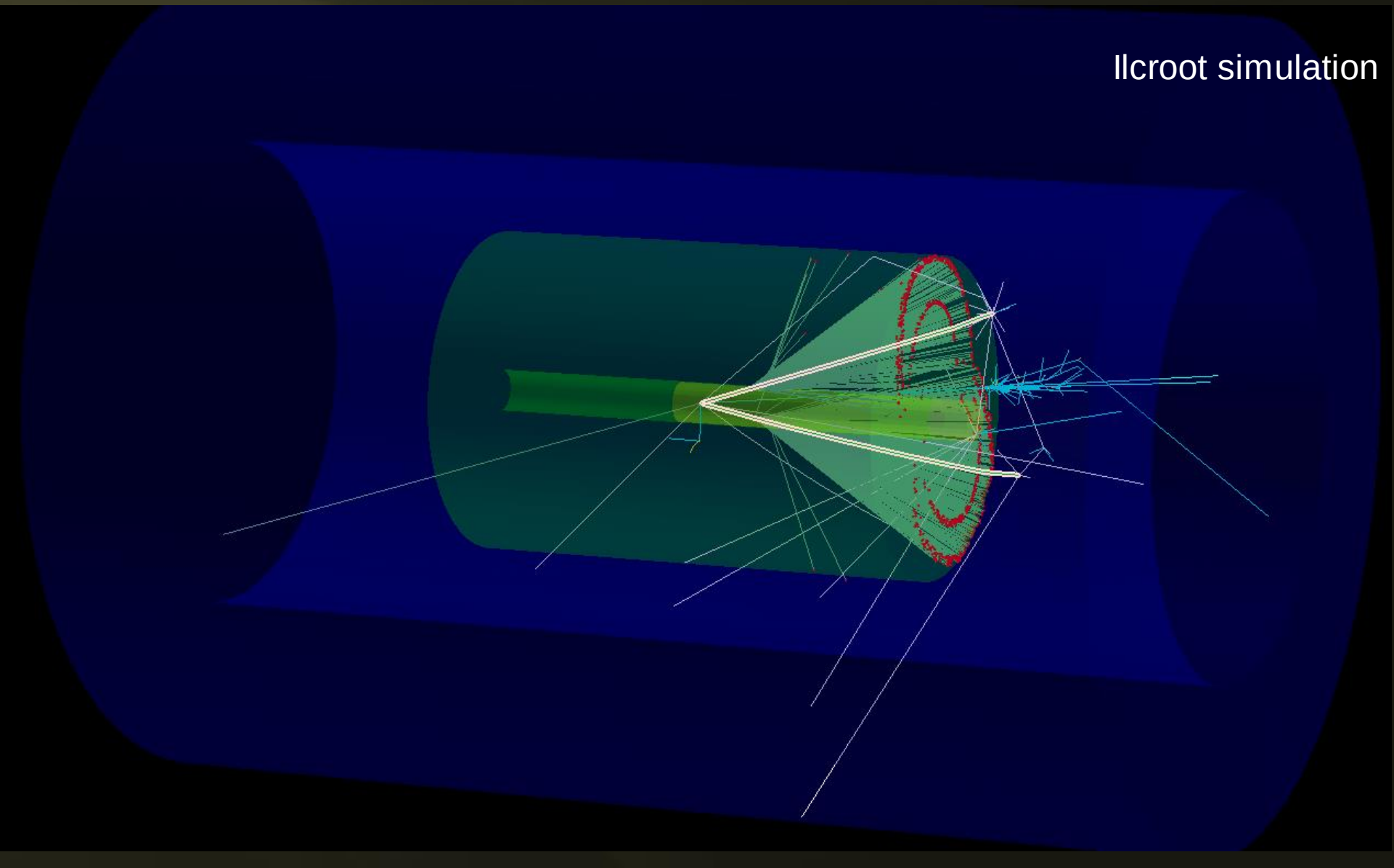
- n_D(aerogel)=1.22/1.12
- Č threshold for muons: P=160 mev
- Č threshold for pions: P=200 mev





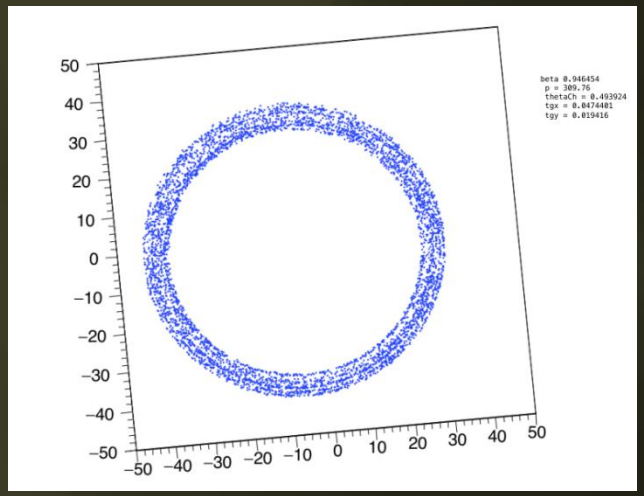


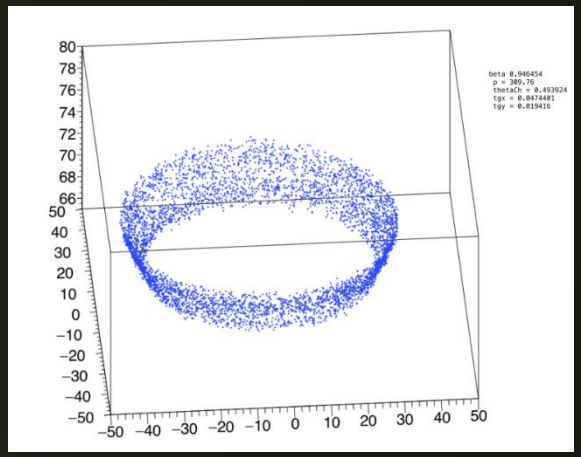
$\eta \rightarrow \pi^+ \pi^- \pi^0$



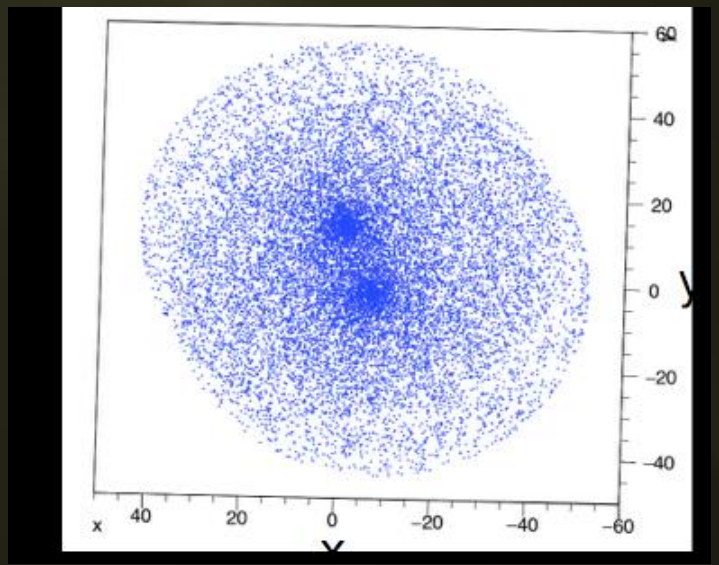
Improvement with timing (~10 nsec)

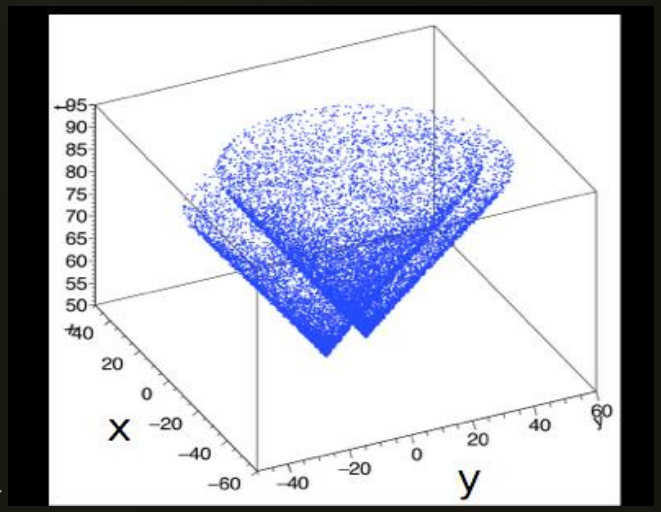
- *Uncertainty on the photon origin*





- *Two-track separation*

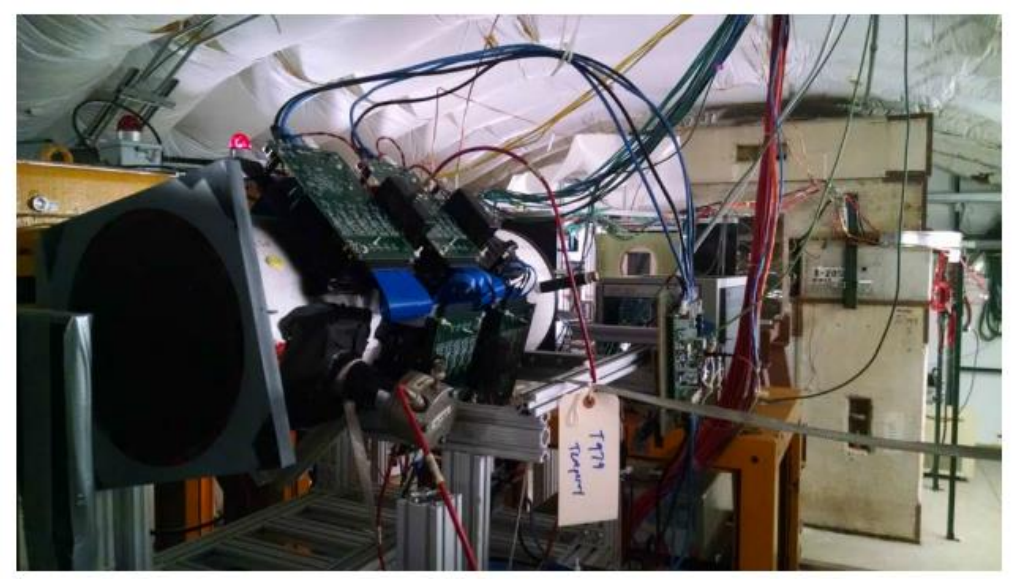


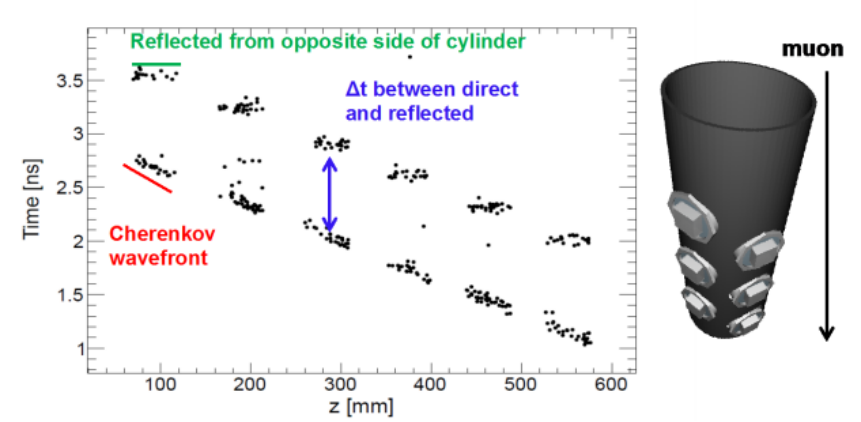


Detector R&D: OTPC

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*



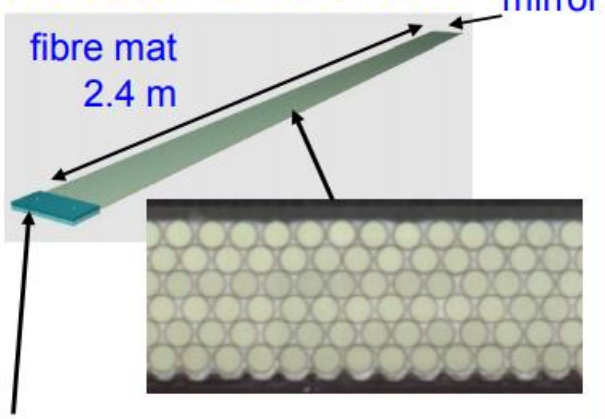


It requires a robust and dedicated R&D (LDRD)

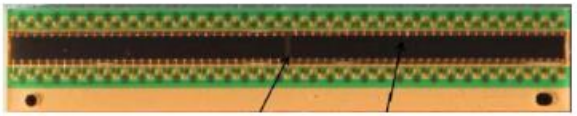
The Fiber Tracker – LHCb design

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

1 module = 8 **fibre mats**



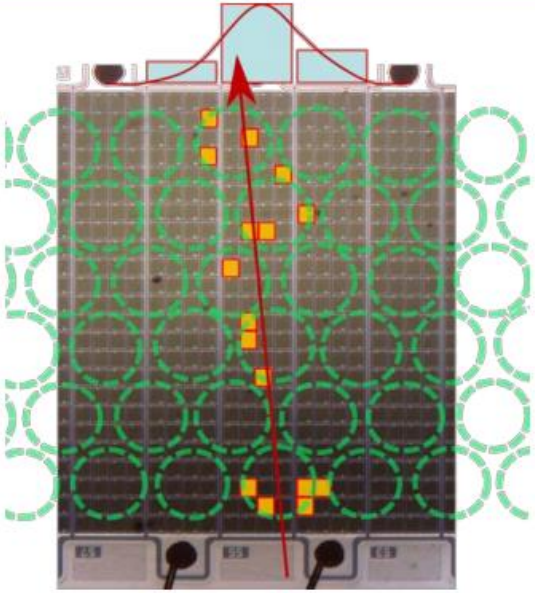
4 silicon photomultipliers (SiPM)



32.59 mm

1 SiPM = 128 channels

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



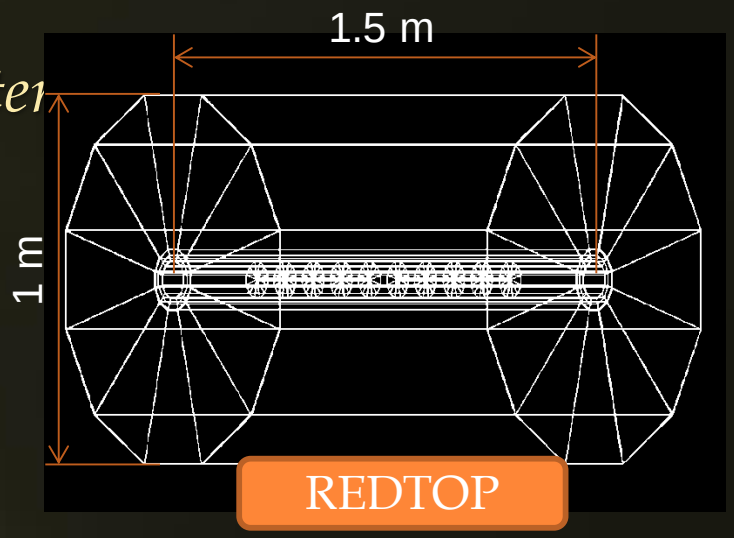
Light yield for 6-layer mat:
16–20 photo-electrons
(for particles near mat mirror)

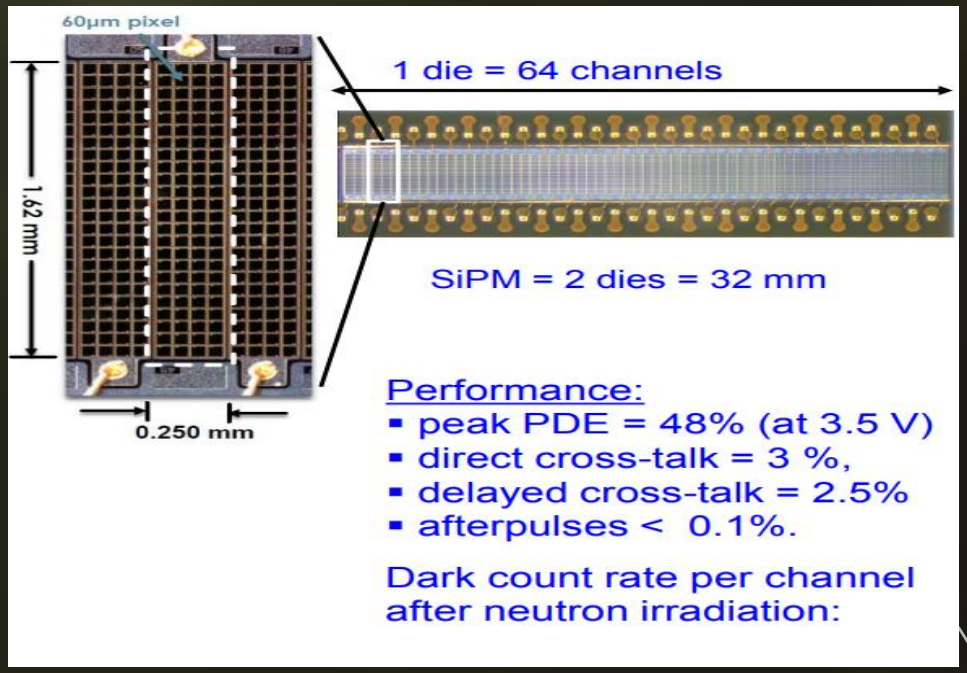
Ulrich Uwer

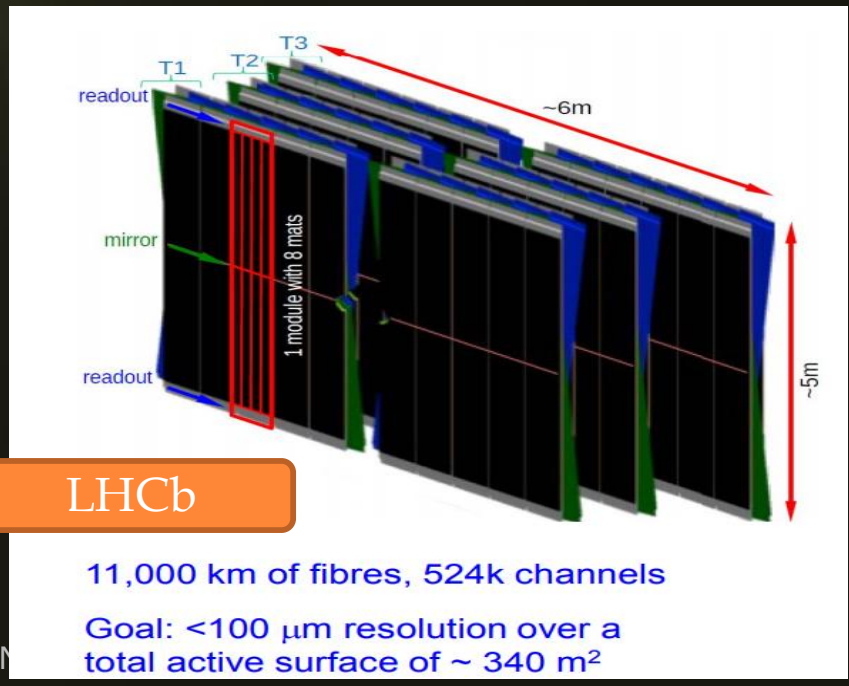
Layout for LHCb vs REDTOP

Input parameter

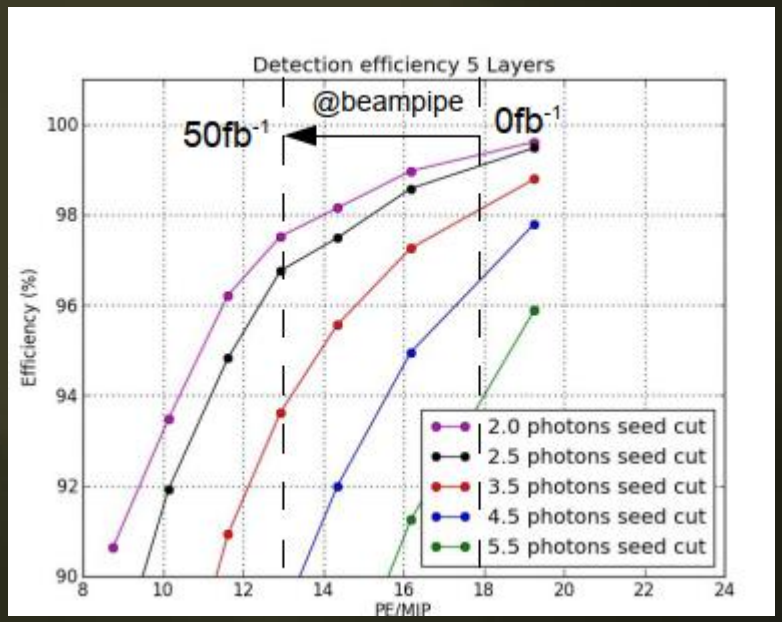
- ~ 360 m^2 vs 0.24m^2
- 1152 mats vs 36 mats
- 524,000 vs 18,000 channels

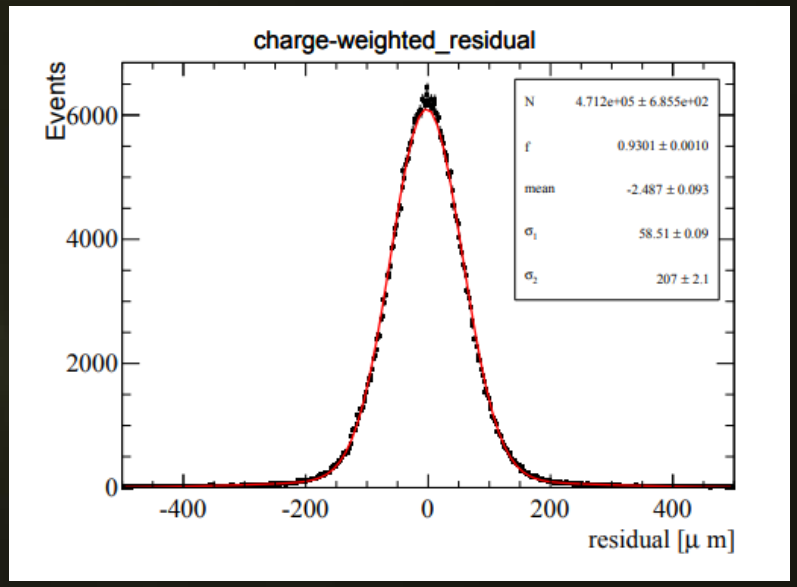






Reselts from LHCb Test Beam





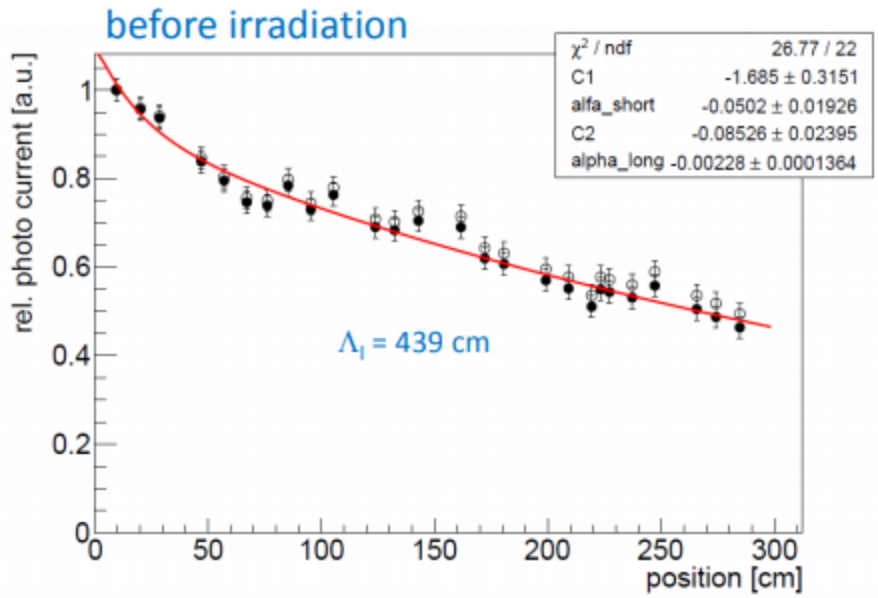
Seed	Neighbour	Sum	Hit Eff.
1.0	1.0	1.0	0.9993 ± 0.0001
1.5	1.5	1.5	0.9990 ± 0.0001
2.0	1.5	2.0	0.9972 ± 0.0002
2.5	1.5	2.5	0.9946 ± 0.0003
3.0	1.5	3.0	0.9990 ± 0.0004
3.5	1.5	3.5	0.9817 ± 0.0005
4.0	1.5	4.0	0.9693 ± 0.0006
4.5	1.5	4.5	0.9540 ± 0.0007
2.5	**1.5**	**4.0**	0.9866 ± 0.0004

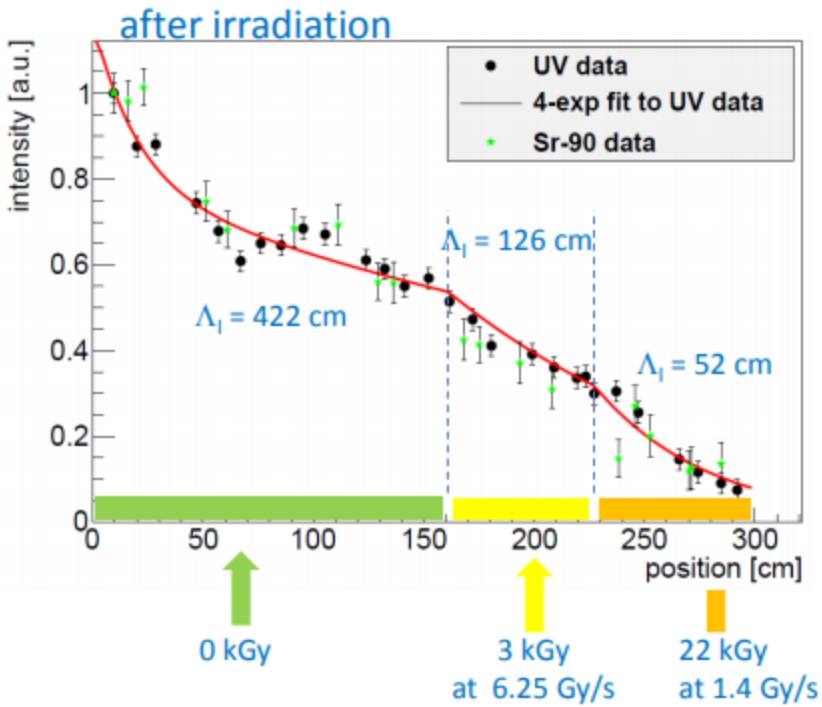
	at the mirror	centre	50 cm from SiPM
$\sigma_{eff,charge}$ [μm]	66.78 ± 0.23	65.93 ± 0.18	61.22 ± 0.21
$\sigma_{eff,Pacific}$ [μm]	73.27 ± 0.26	73.18 ± 0.20	73.64 ± 0.20

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

Trigger & DAQ

Input parameters

- ~5 × 10^8 p-Be inelastic collisions per second
- ~2.5× 10^6 (10^4)produced η (η') per second

Trigger requirements (L. Ristori)

Level	Algo	Detectors	Hardware	Rejection factor
L0	Σ OTPC & ADRIANO-Cer	OTPC, ADRIANO	Fast sum	100
L1	identification of a pair of leptons, γ-conversion rejection	OTPC, ADRIANO, Fiber Tracker	FPGA	100
L2	Reco	All	2000 CPU-cores	>100

Expected data rates

- About 100 Hz to be stored on tape
- ~1 MB/sec from L2
- ~5 PB/year to tape (assume 5 kb event size)

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%*

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 recommendation: "The PAC finds that the science goals of the experiment are very interesting….., the PAC does not recommend that the Laboratory invest resources into furthering the REDTOP proposal 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*

REDTOP Possible Running Phases

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

It could be made unnecessary by NA62+ and JPARC

Intermediate Phases

Pre-REDTOP with OTPC only

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

Status of the collaboration

The REDTOP collaboration

8 Countries, 23 Institutions, 67 Collaborators

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Benemérita Universidad Autónoma de Puebla, (Mexico)

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

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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)*

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*
  - *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*

Timeline

- *Once approved and funded, REDTOP needs about 2-3 years detector R&D + 1 year detector construction*
  - *Solenoid and ¾ of Pb-Glass for ADRIANO in-kind contributions from INFN (Finuda and NA64 experiments)*
- *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*

Future Prospects

- *The Collaboration is currently engaged in the ESPP and P5-Snowmass processes*
- *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 about 2-3 years (corresponding to the ESPP conclusion)*
  - *Fermilab best : either DR or PIP-II (tREDTOP)*
  - *Detector optimization and sensitivity studies*
  - *Detector R&D*
- *Competition from several other experiments (LHCB, et. Al.)*
  - *However, experimental techniques are quite different*
- ***More details: https://redtop.fnal.gov***

Summary

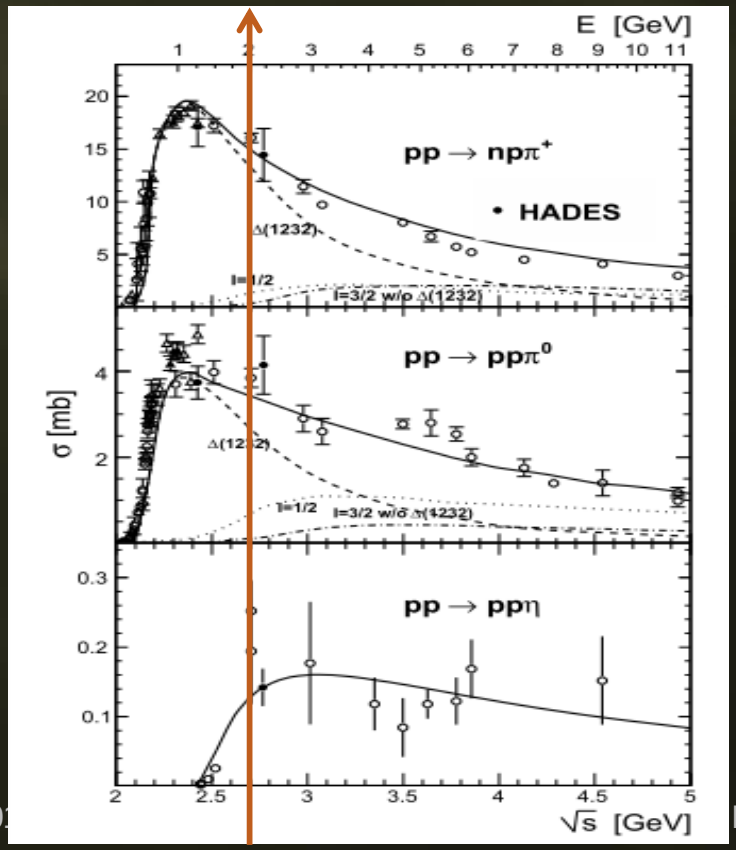
- *The η/η' meson is a fantastic laboratory for studying rare processes and physics BSM*
- *Existing world sample not sufficient for breaching into decays violating conservation laws or searching for new particles*
- *REDTOP goal is to produce ~10^{13} η mesons/yr in phase I and ~ 10^{11} η' /year in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

Backup slides

Beam Requirements for η-factory (1)

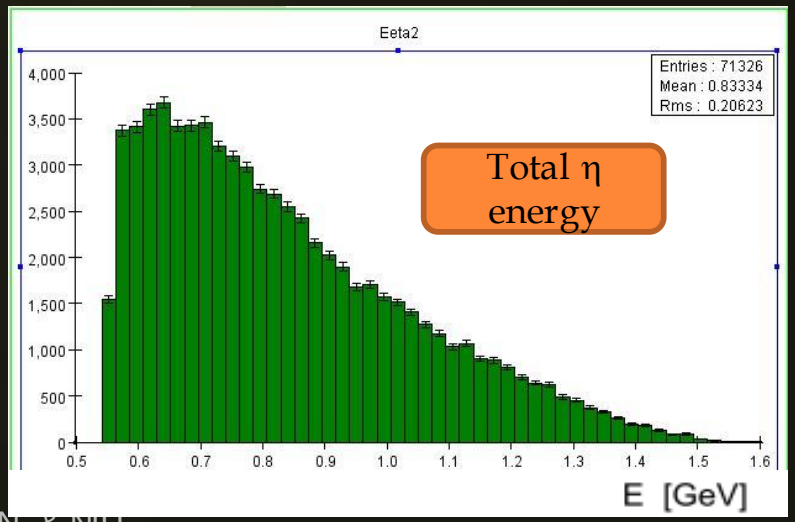
Beam energy

- *Constraints:*
  - *Beam energy large enough to get $\Gamma(\eta)/\Gamma(pX) \sim 1\%$*
  - *Beam energy low enough to make slow baryons (minimize background)*
  - *η meson energy low enough to make slow pions*
- *T_{beam} = 1.8 – 2.1 GeV (still under optimization but 1.9 GeV seems preferred)*



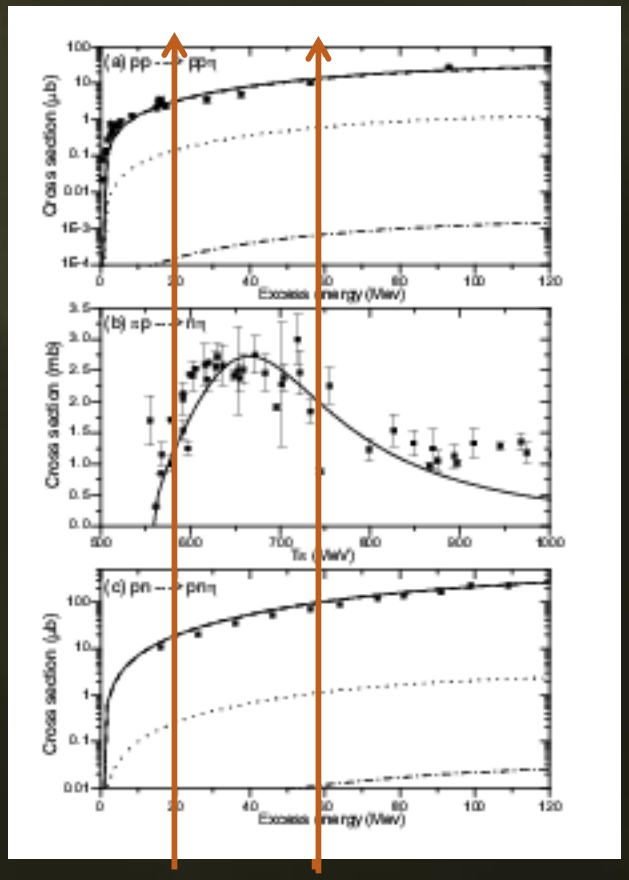
G. Agakishiev et al.
PHYSICAL REVIEW. C, NUCLEAR PHYSICS 2012, 48, 74-1

Total cross sections @ 2 GeV
pp → ppη
140 μbarn
Total inelastic cross sections @ 2 GeV
About 200x



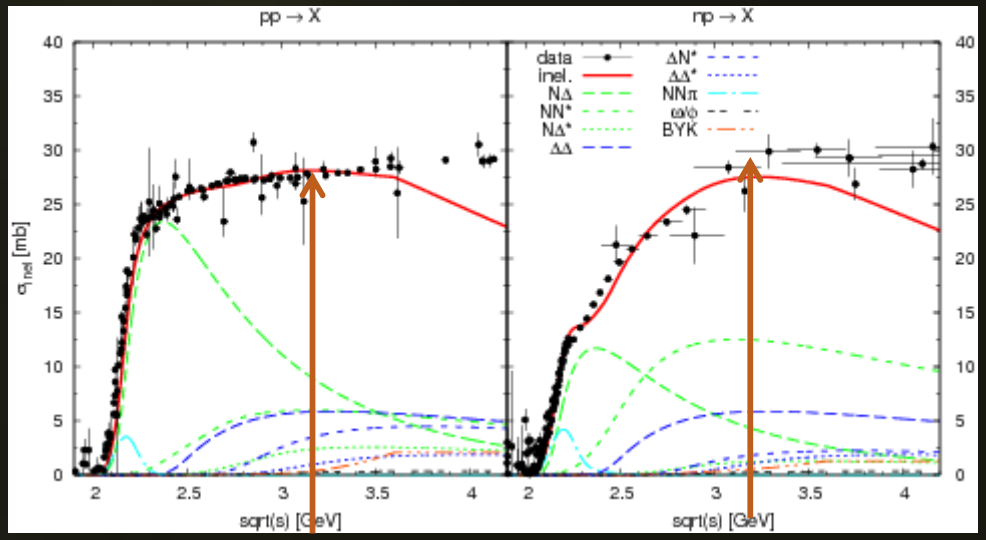
Beam Considerations for η' -factory

- *Constraints:*
  - *Same as for η-factory*
- E_{beam} = *3.0 – 4.0 GeV (yet to be optimized)*
- $R_{\eta'} = \sigma(pp \rightarrow pn\eta')/\sigma(pp \rightarrow pp\eta')$ slightly lower than R_η



Xu Cao and Xi-Guo Lee
Phys. Rev. C 78, 035207 –2008

Total cross sections @ 3.8 GeV
$pp \rightarrow pp\eta'$
1 μbarn
Total inelastic cross sections @ 2 GeV
About 25,000x



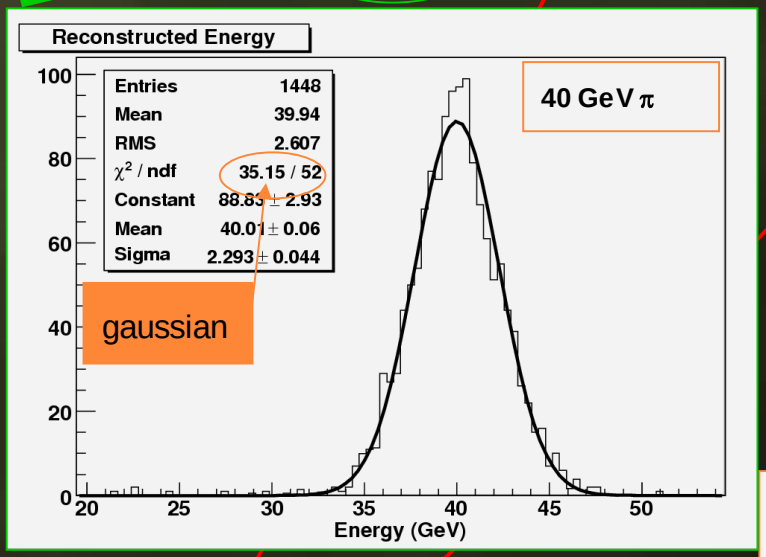
Transitionless Deceleration in the Delivery Ring (J. Johnstone)

- Large beam losses will occur if beam is decelerated from injection @ 8 GeV (γ = 9.53) to 2 GeV (γ = 3.13) through the DR natural transition energy γ_t = 7.64.
- 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
- Optical perturbations are localized within each triplet
- Straight sections are unaffected thereby keeping the nominal M3 injection beamline tune valid.

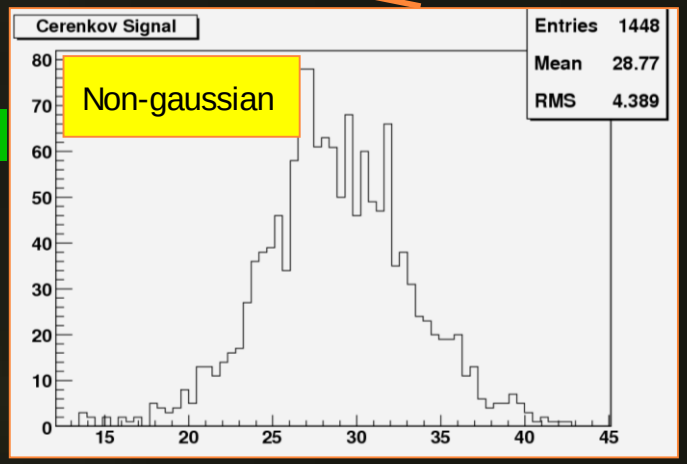
Dual Readout Calorimetry

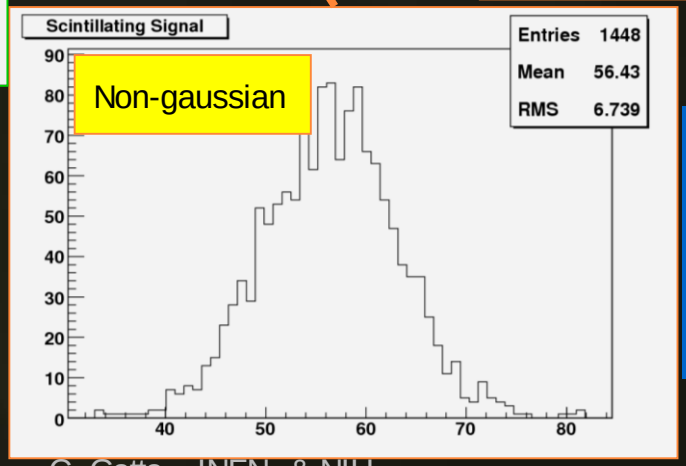
Total calorimeter energy: use two measured signals and two, energy-independent, calibration constants.

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



ILCroot simulations





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

From calibration

@ 1 Energy only

Dual readout calorimeter is two distinct calorimeters sharing the same absorber. Measured energy is gaussian because of compensation event by event.

Dual Readout Calorimetry from a Different Perspective

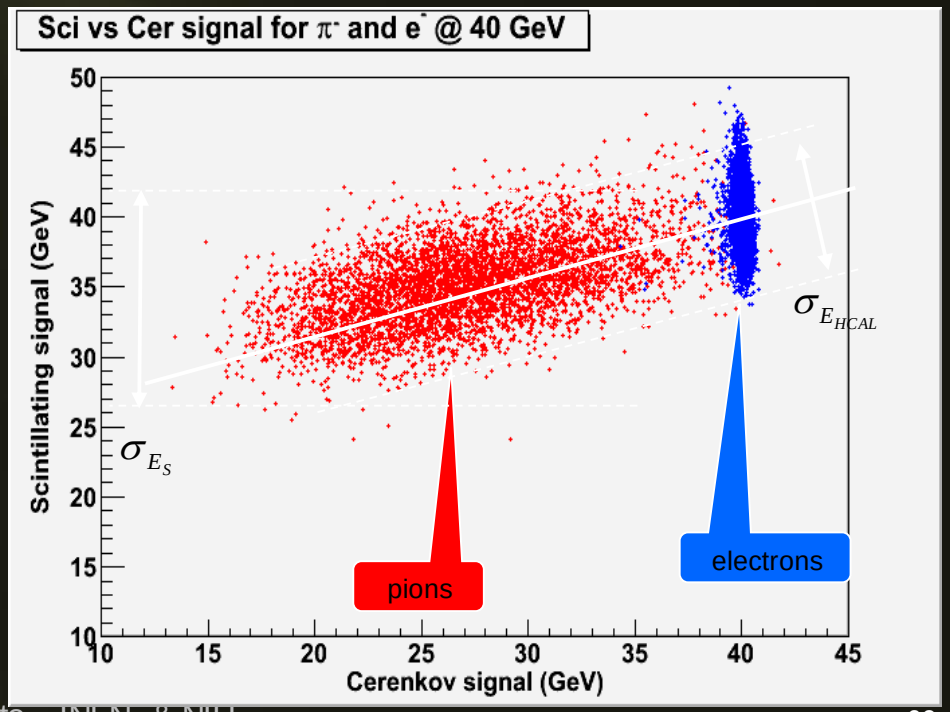
$$E_{HCAL} = \frac{\eta_S \cdot E_S \cdot (\eta_C - 1) - \eta_C \cdot E_C \cdot (\eta_S - 1)}{\eta_C - \eta_S}$$

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

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

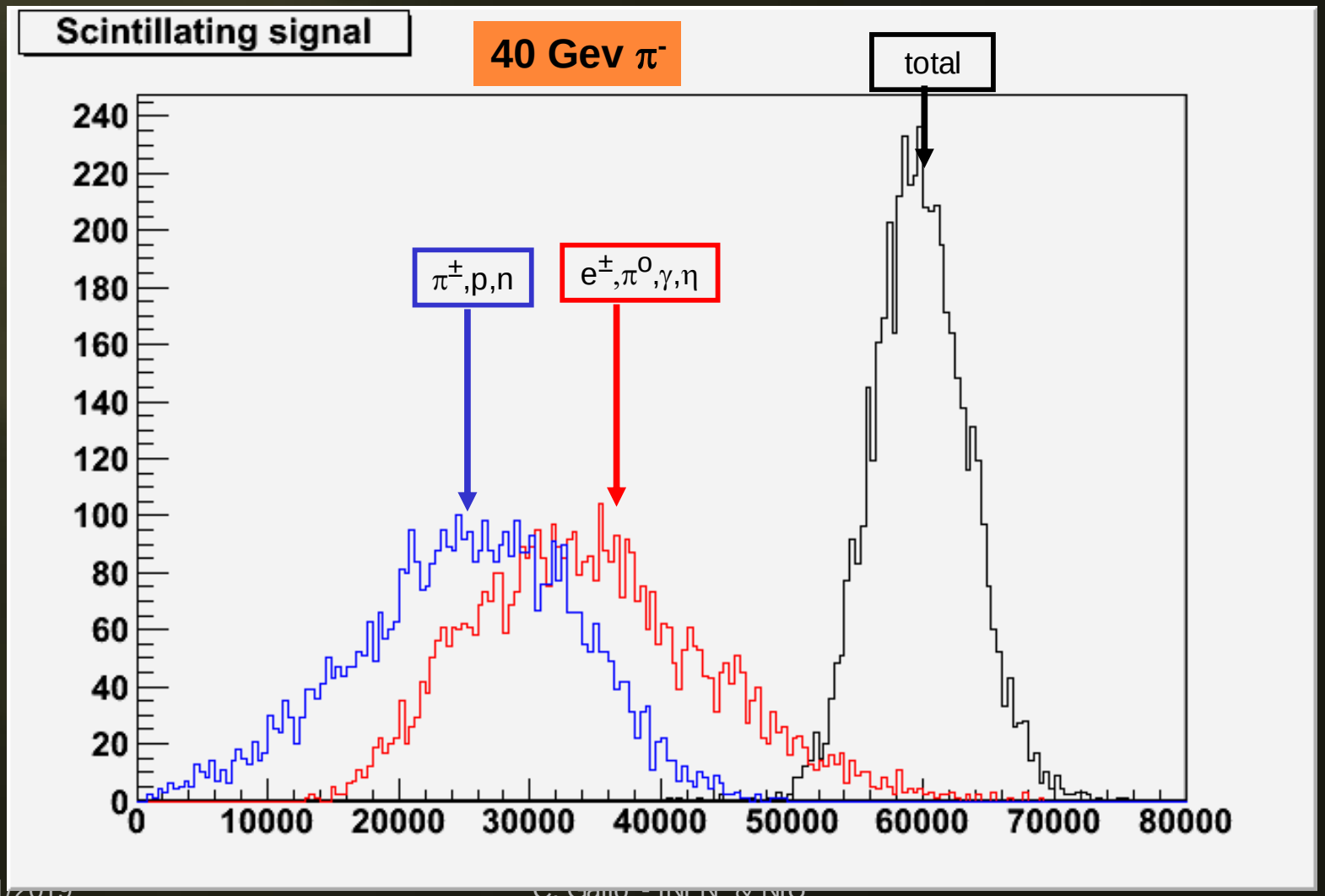
If $\eta_s \neq \eta_c$ then the system can be solved for E_{HCAL}

ILCroot simulations



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

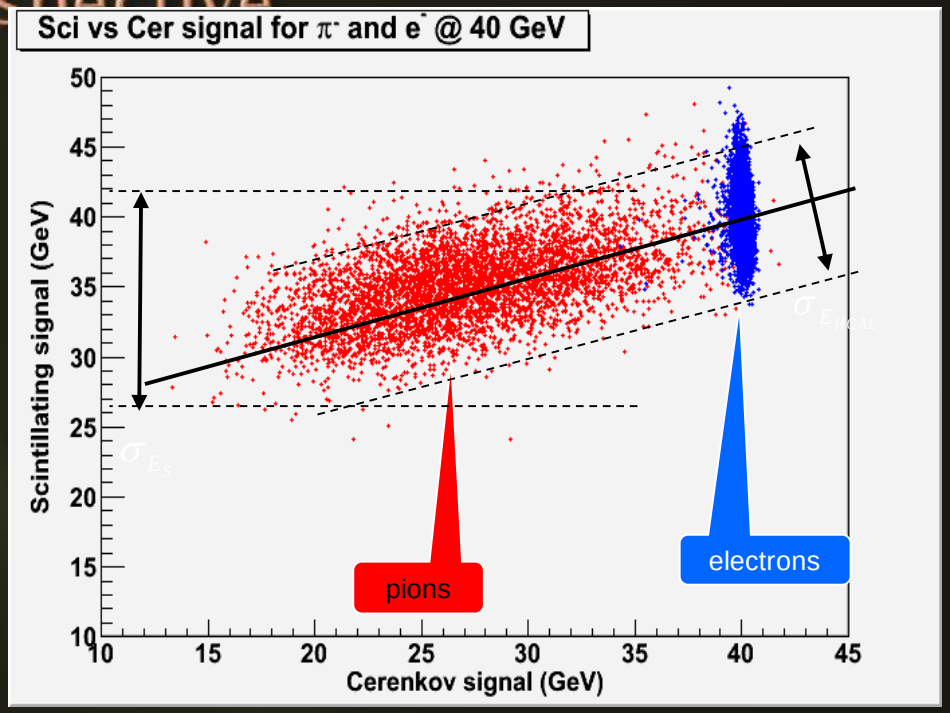
The major source of fluctuations: *fem*



Dual Readout Calorimetry from a Different Perspective

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

ILCroot simulations



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

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

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

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

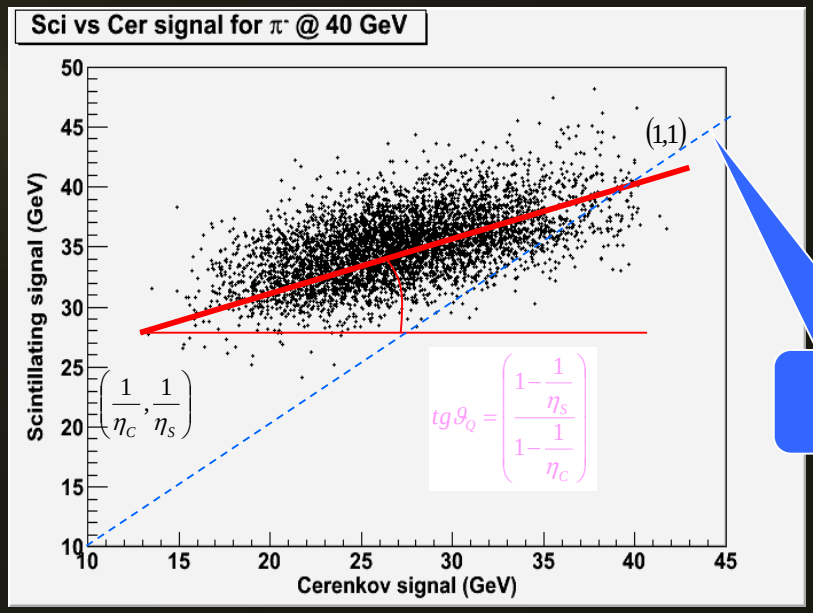
Figures of Merit for Dual-Readout Calorimeter

- 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

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

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

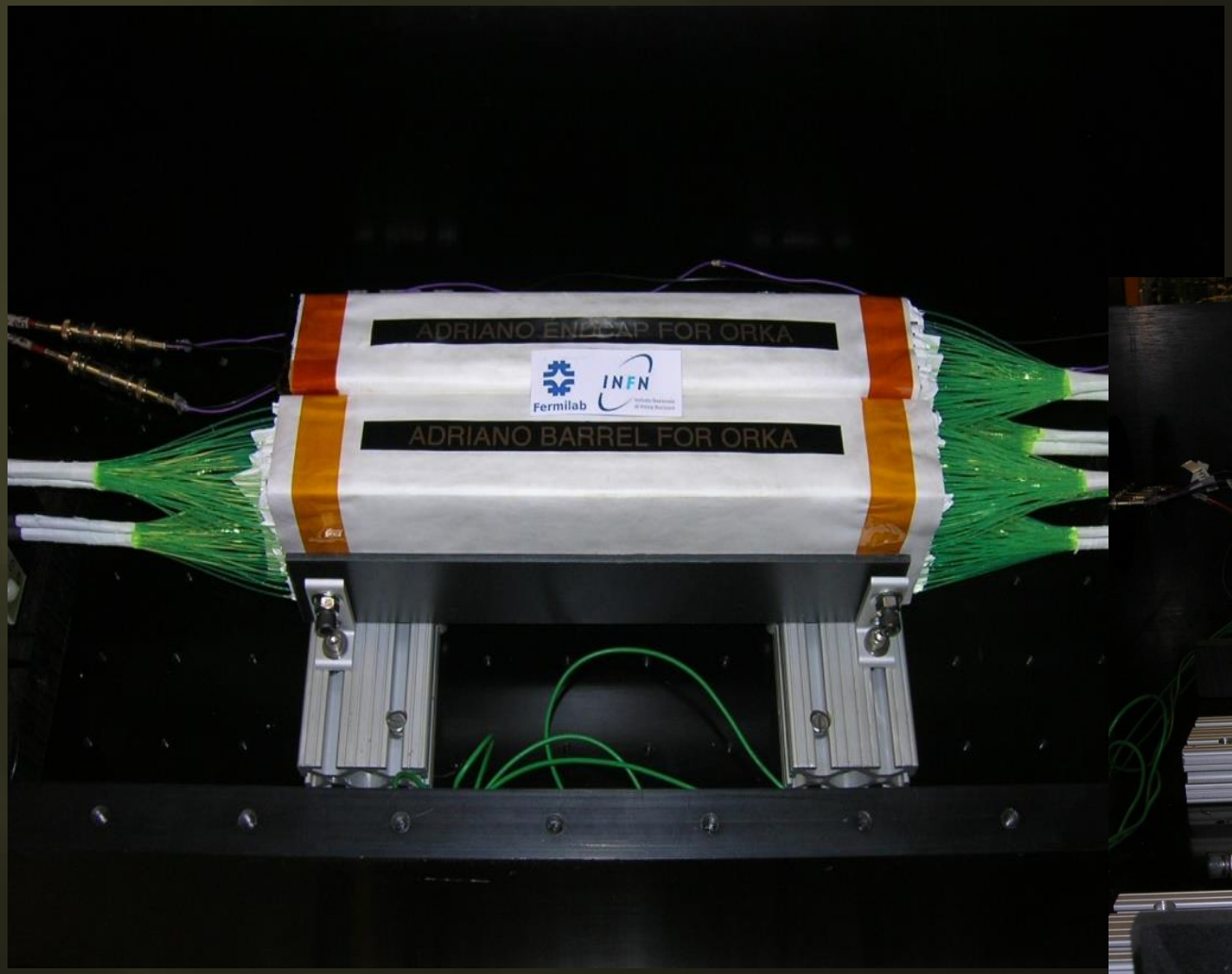
ILCroot simulations

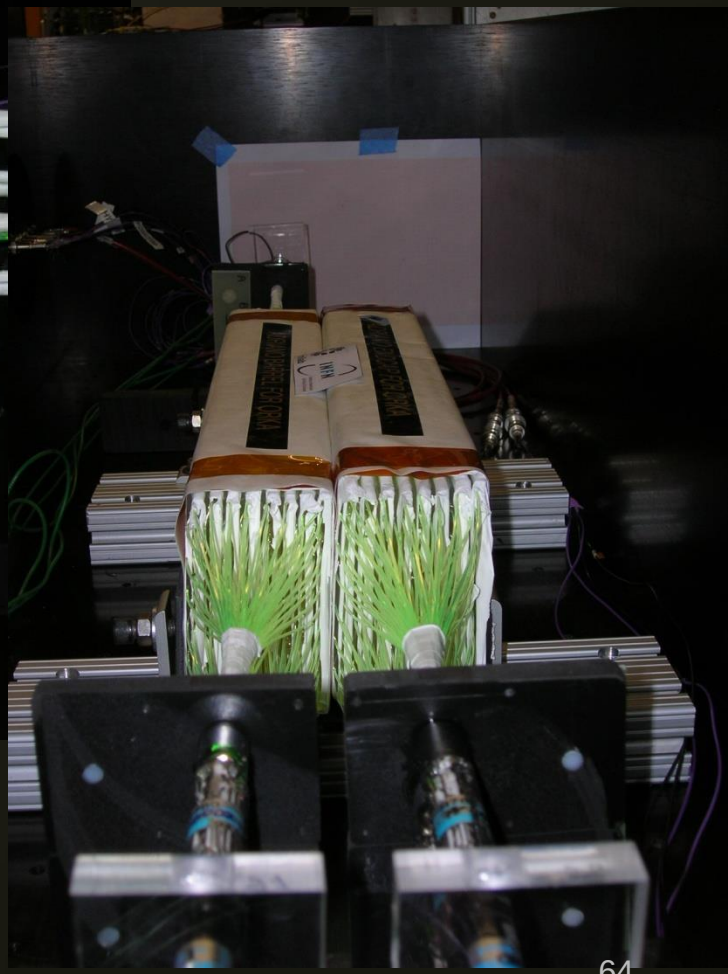


$\eta_S = \eta_C$

- 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

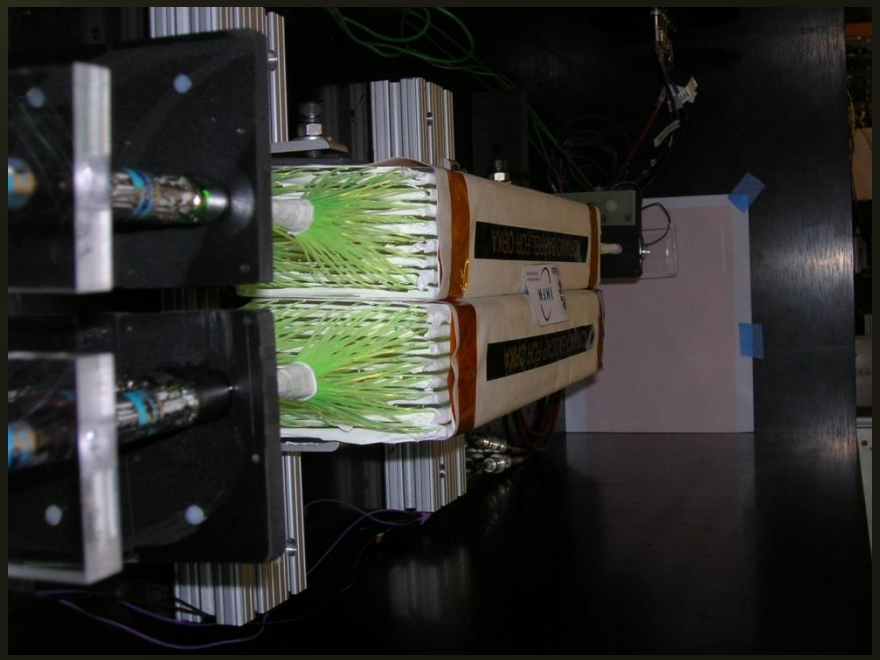
- Detection of Hadronic and EM showers with large S and Č light production
- Optimized for maximum shower containment (i.e. max detector density)

- 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



15 Prototypes Performance Summary

Prototype	Year	Glass	gr/cm³	Čerenkov L. Y./GeV	Notes
5 slices, machine grooved, unpolished, white	2011	Schott SF57HHT	5.6	82	SiPM readout
5 slices, machine grooved, unpolished, white, v2	2011	Schott SF57HHT	5.6	84	SiPM readout
5 slices, precision molded, unpolished, coated	2011	Schott SF57HHT	5.6	55	15 cm long
2 slices, ungrooved, unpolished, white wrap	2011	Ohara BBH1	6.6	65	
5 slices, scifi silver coated, grooved, clear, unpolished	2011	Schott SF57HHT	5.6	64	15 cm long
5 slices, scifi white coated, grooved, clear, unpolished	2011	Schott SF57HHT	5.6	120	
2 slices, plain, white wrap	2011	Ohara	7.5	-	DAQ problem
10 slices, white, ungrooved, polished	2012	Ohara PBH56	5.4	30	DAQ problems
10 slices, white, ungrooved, polished	2012	Schott SF57HHT	5.6	76	
5 slices, wifi Al sputter, grooved, clear, polished	2012	Schott SF57HHT	5.6	30	2 wls/groove
5 slices, white wrap, ungrooved, polished	2012	Schott SF57HHT	5.6	158	Small wls groove
ORKA barrel	2013	Schott SF57	5.6	2500/side	molded
ORKA endcaps	2013	Schott SF57	5.6	4000	molded
10 slices – 6.2 mm thick, scifi version	2014	Schott SF57	5.6	338	molded
10 slices – 6.2 mm thick, sci-plate version	2014	Schott SF57	5.6	354	molded

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

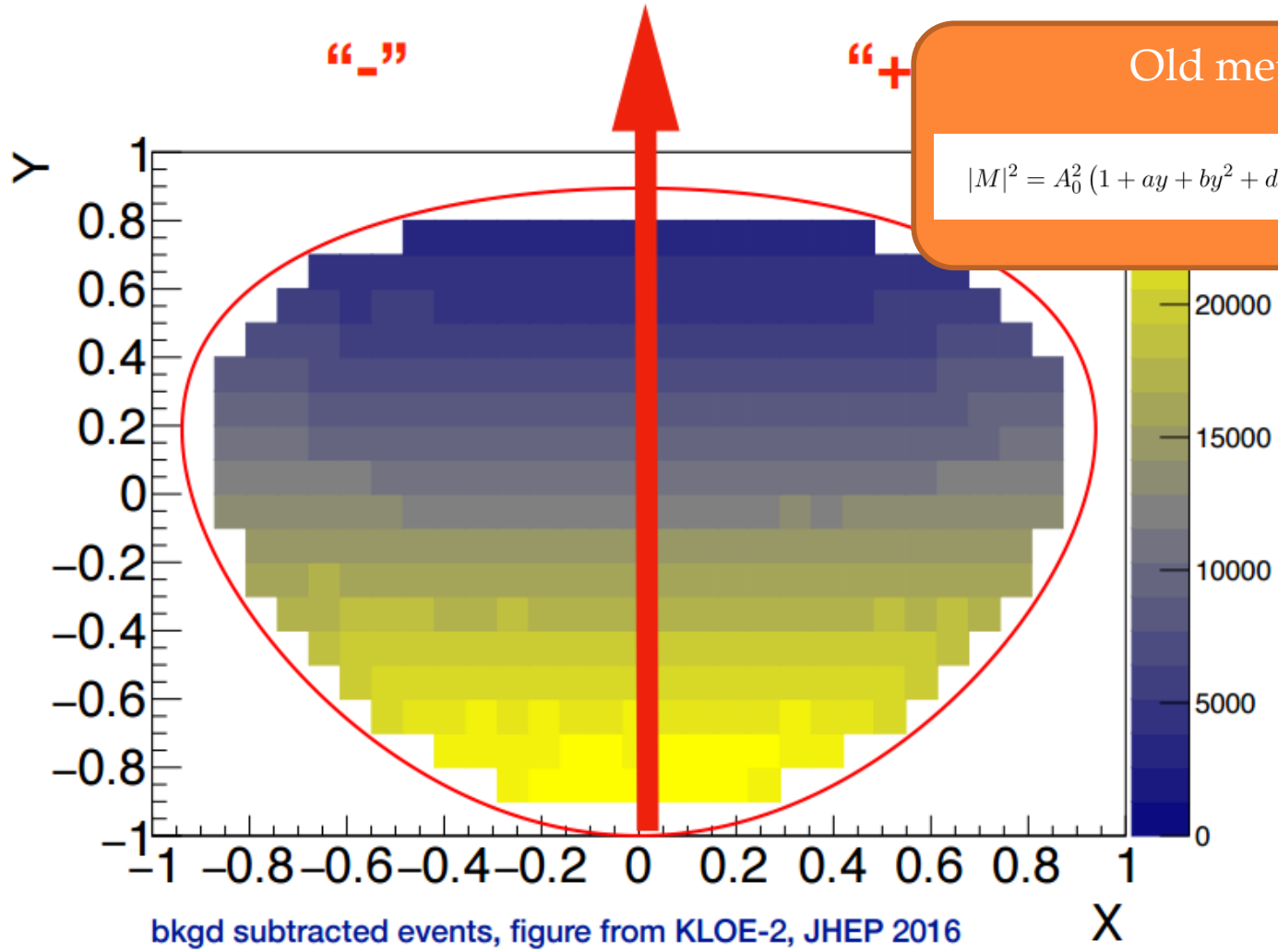
[Note Gardner & Tandean, 2004; Gardner & Shi, 2017, to appear]

Slide Credit: Susan Gardner & Jun Shi

University of Kentucky

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

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



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

Old method

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

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)

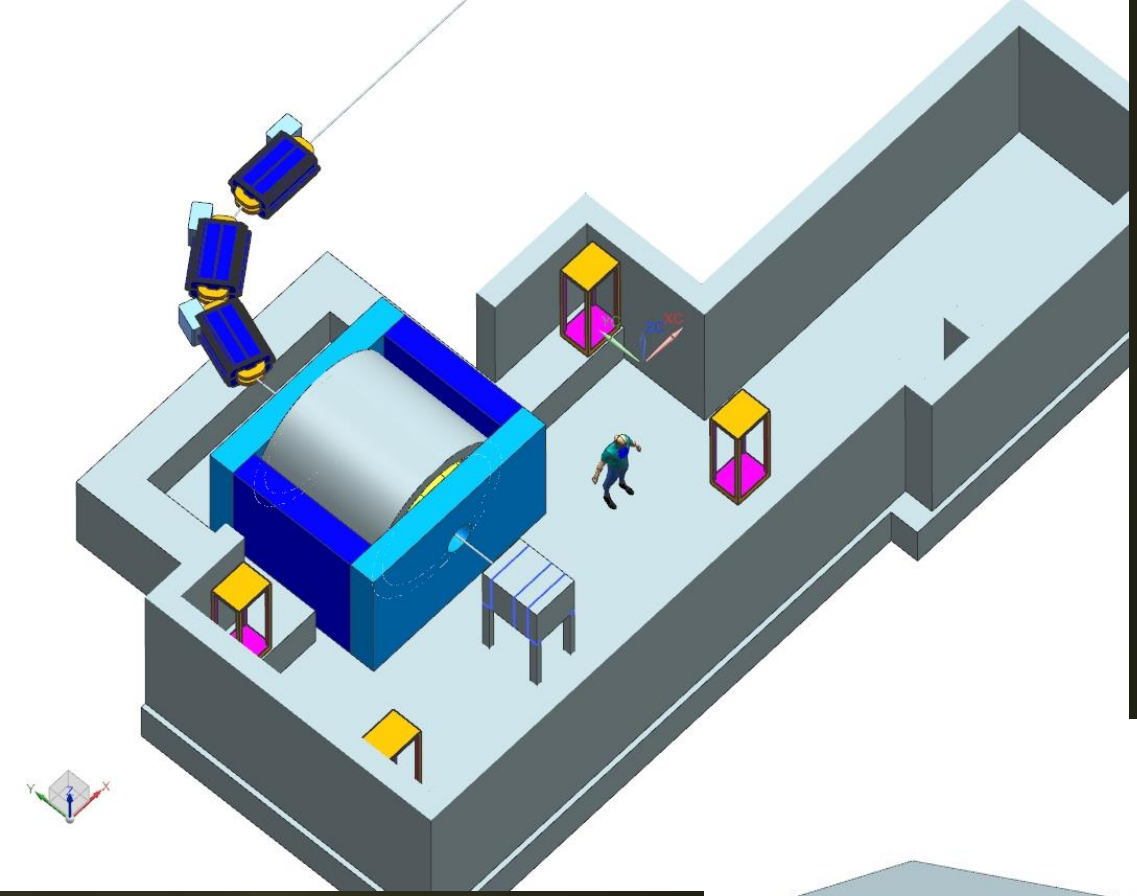
- Can fit the Dalitz plot to get Re(a), Im(a), Re(b), Im(b) and/or study charge asymmetries

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

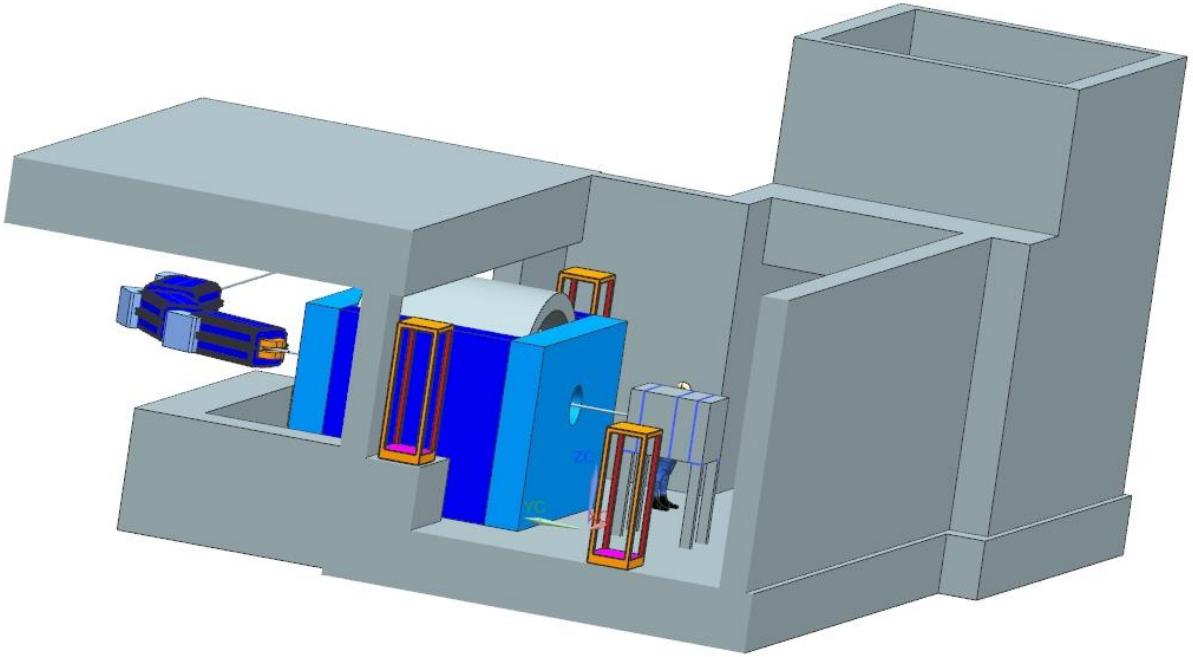
[Gardner & Shi, 2017, to appear]

Slide Credit: Susan Gardner & Jun Shi

University of Kentucky



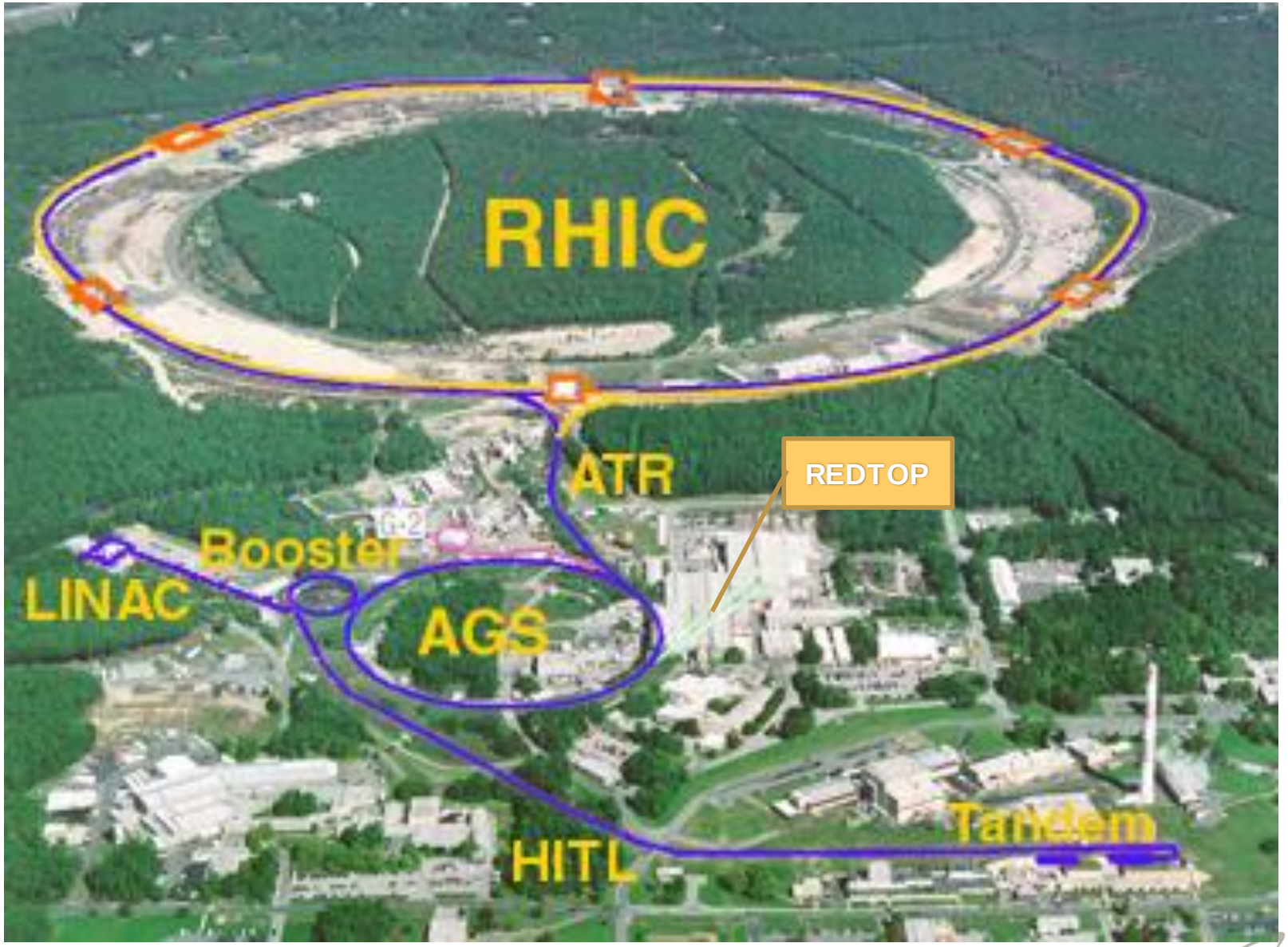
REDTOP detector in AP50



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)