5-D Dual-readout Calorimetry for Future Experiments

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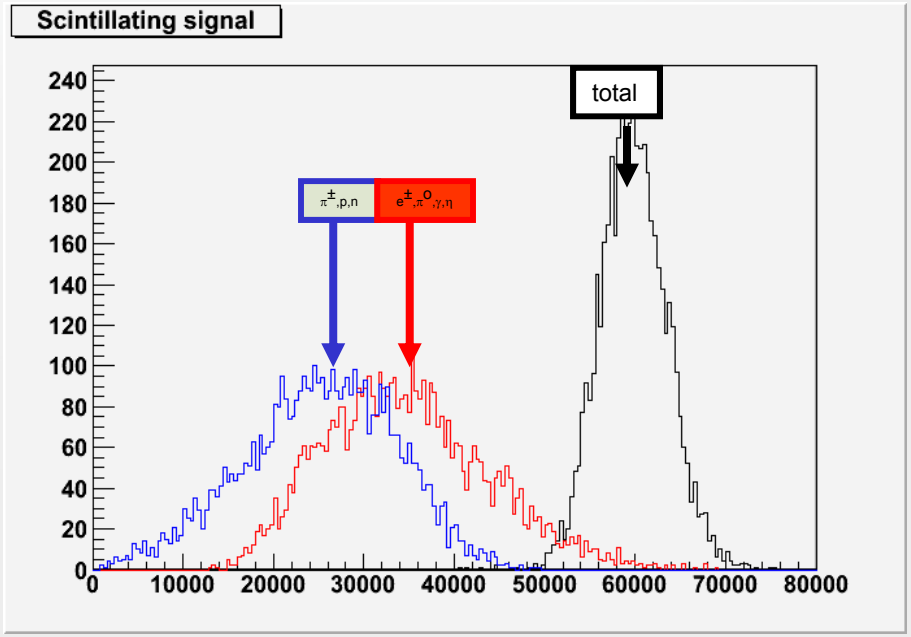
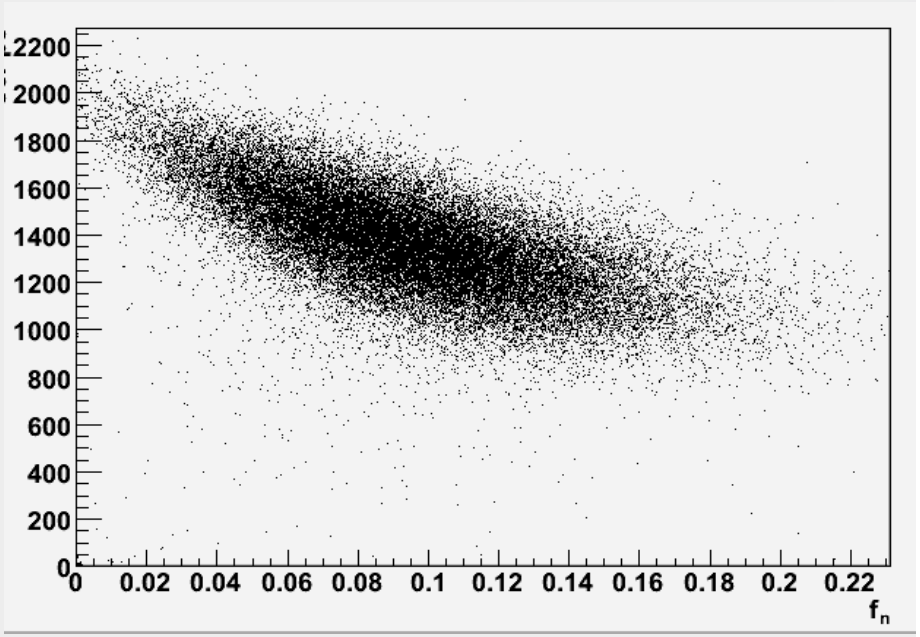
Rational for Multiple-readout Calorimetry

- The multiple-readout techniques intend to measure separately the individual components of an hadronic shower: electromagnetic, charged hadronic and neutrons
- Each of the component fluctuates and contributes to the fluctuations in energy measurement
- The measurement is done per each shower. Therefore, the compensation to the total energy occurs event-by-event





Charged hadronic

EM

neutrons

Dual Readout Calorimetry

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

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

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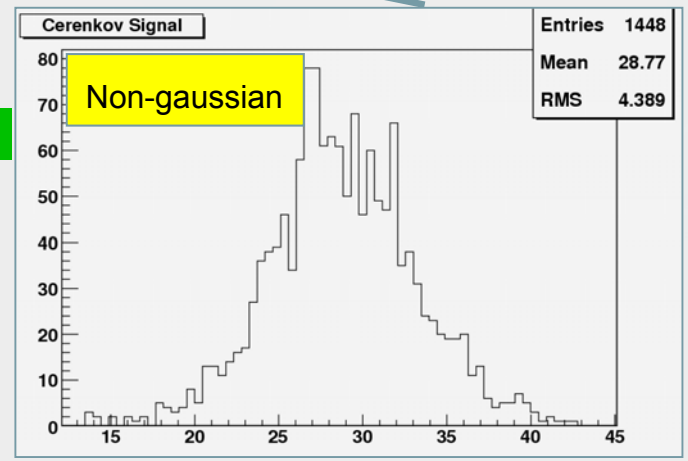
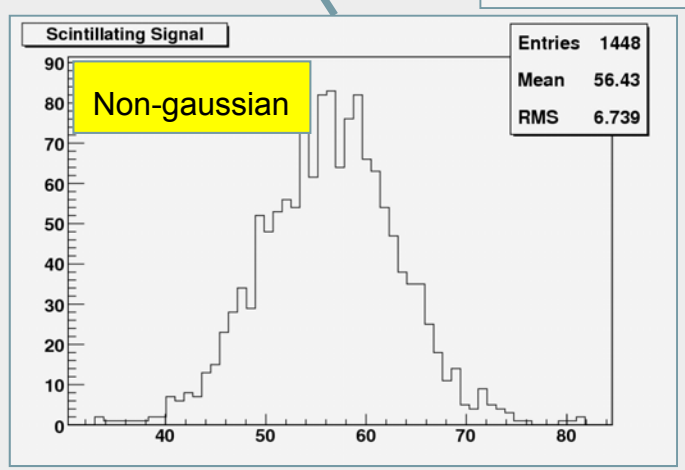
ILCroot simulations





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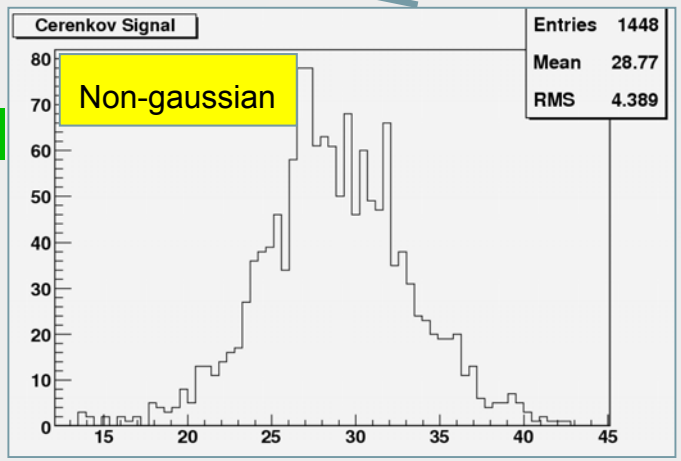
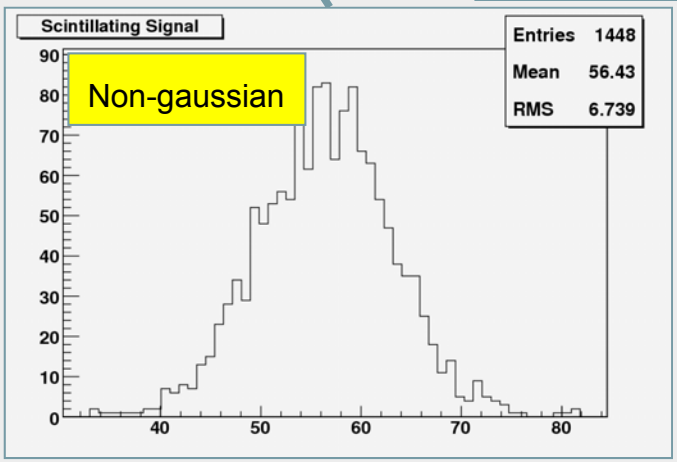




$$\eta_c = \left(\frac{e}{h}\right)_C \quad \eta_S = \left(\frac{e}{h}\right)_S$$

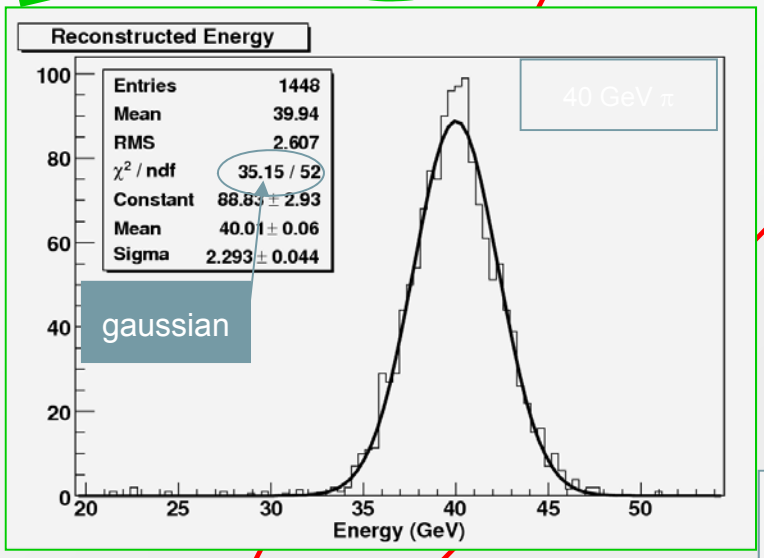
From calibration

@ 1 Energy only

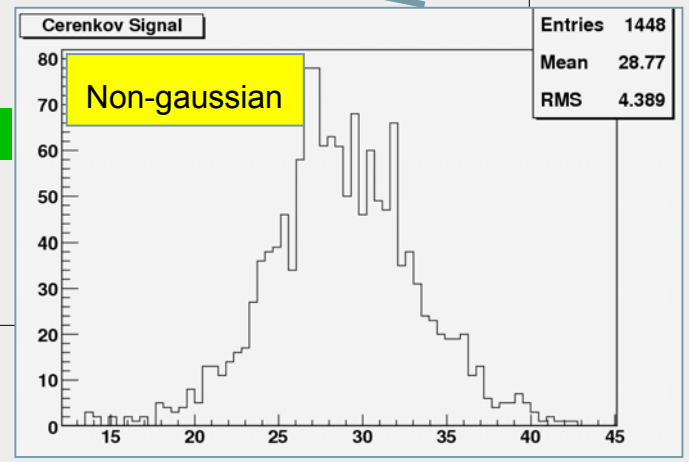
Dual Readout Calorimetry

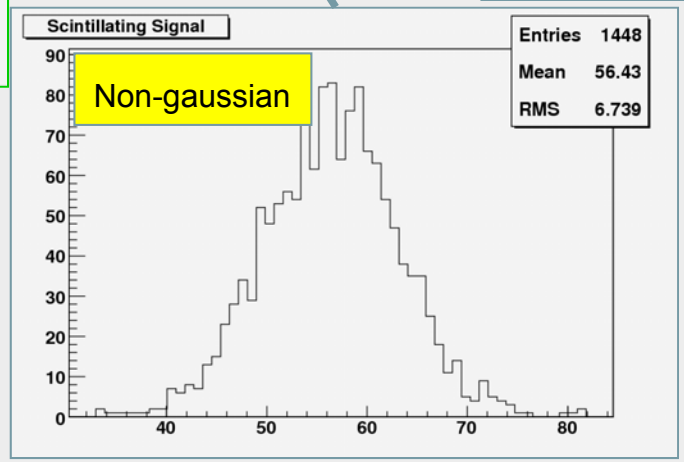
Total calorimeter energy: use two measured signals and two, energy-independent, calibration constants.

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



ILCroot simulations





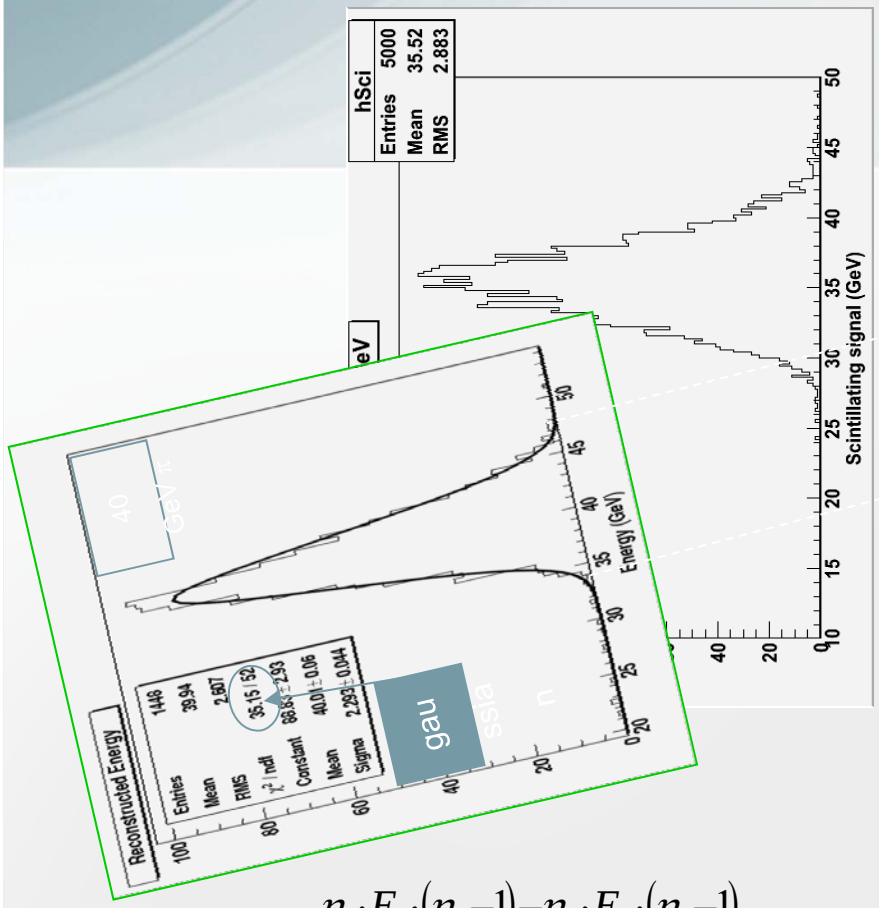
$$\eta_c = \left(\frac{e}{h}\right)_C \quad \eta_S = \left(\frac{e}{h}\right)_S$$

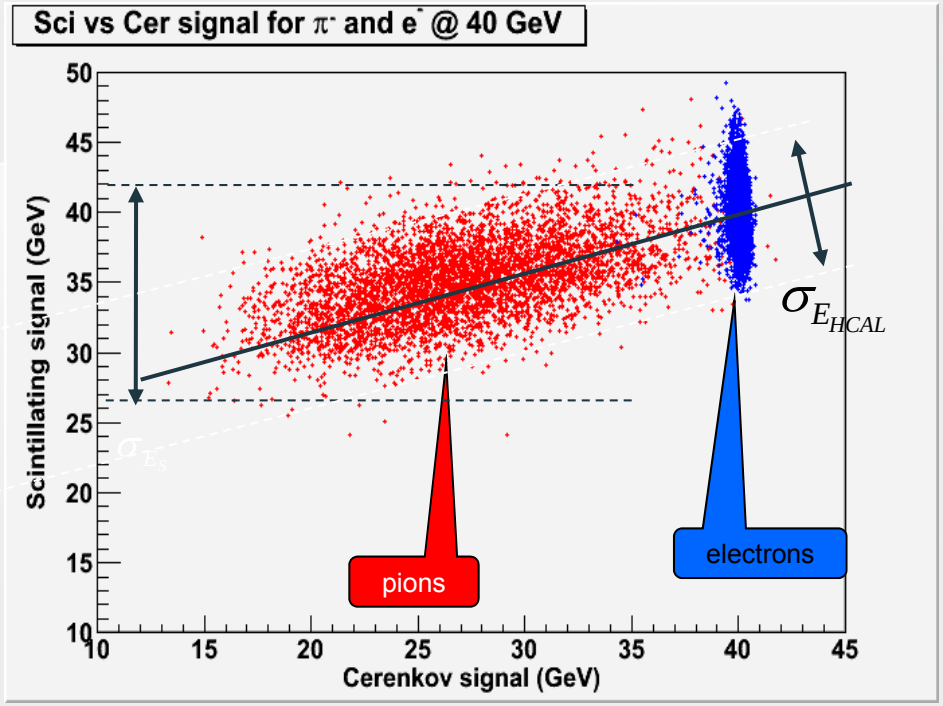
From calibration

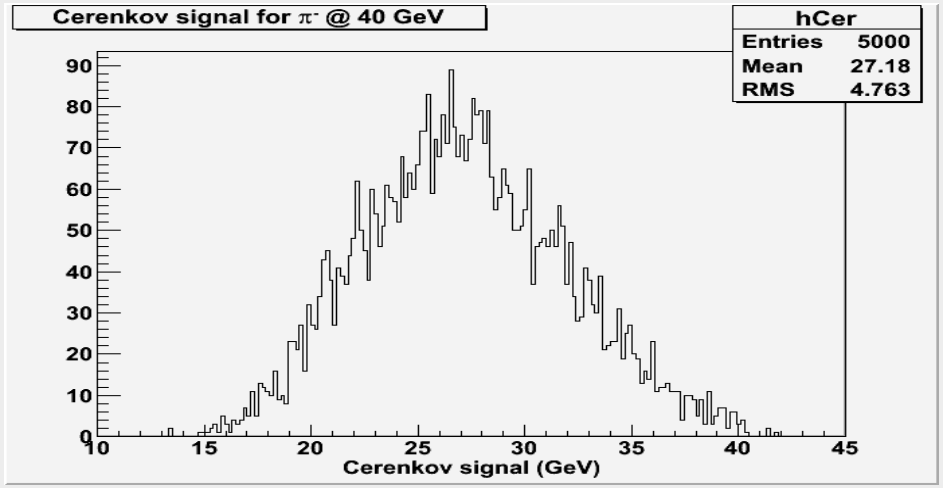
@ 1 Energy only

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







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

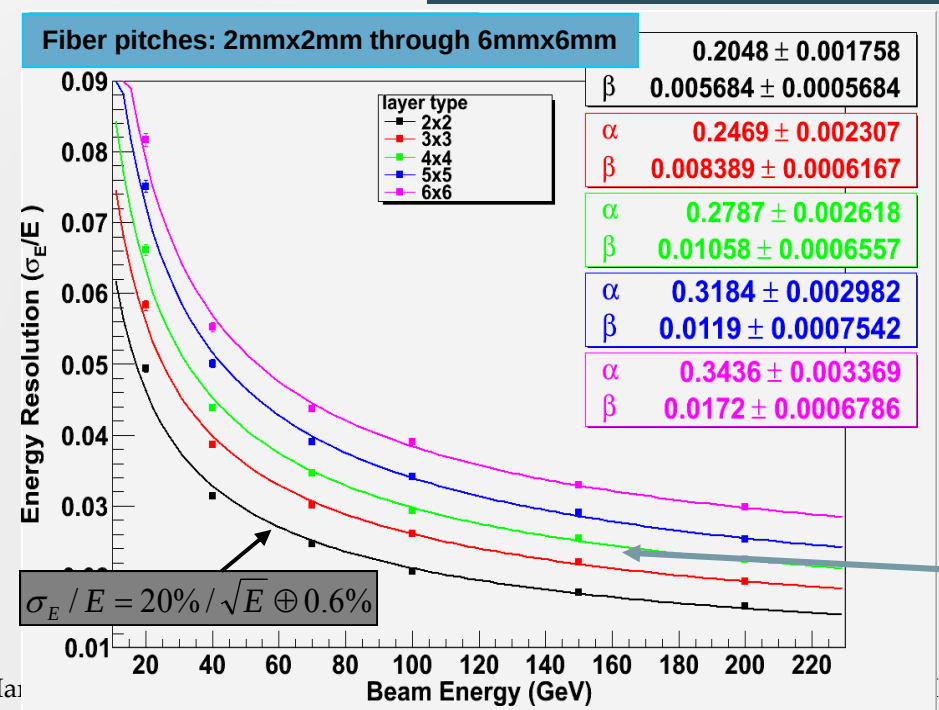
$$\left(\eta_S = \left(\frac{e}{h}\right)_s \quad ; \quad \eta_C = \left(\frac{e}{h}\right)_C \right)$$

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

Triple-readout

- The electromagnetic and charged hadronic components of the shower are evaluated via S and Č. The neutron component N is evaluated independently (Boron loaded fibers, waveform analysis, etc.)
- The compensation is total since the fluctuations of neutrons is accounted for
- S , Č and N are independent: they provide the total energy with the following formula

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

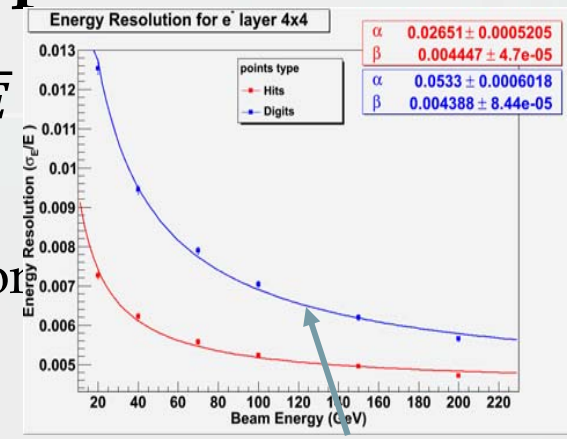


Simulated ADRIANO resolution in triple-readout mode

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

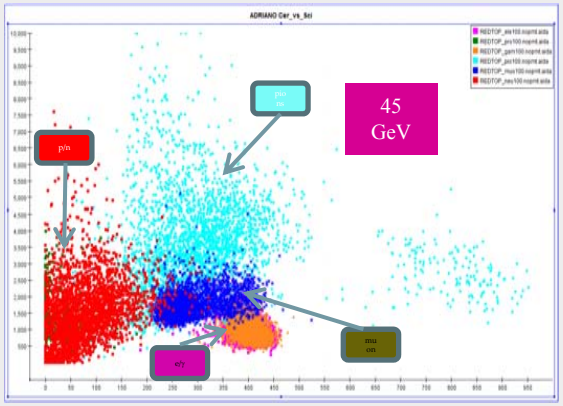
ADRIANO for High Intensity Experiments

- Typical electromagnetic energy resolution: $5\%/\sqrt{E}$ (includes effects from the electronics)
- Particle ID from S vs Č: neutron/gamma separation at 3σ level
- Fine granularity: it can be used as a range stack for muons and/or pions
- Sensitivity > 10 MeV (layout for ORKA and REDTOP experiments)

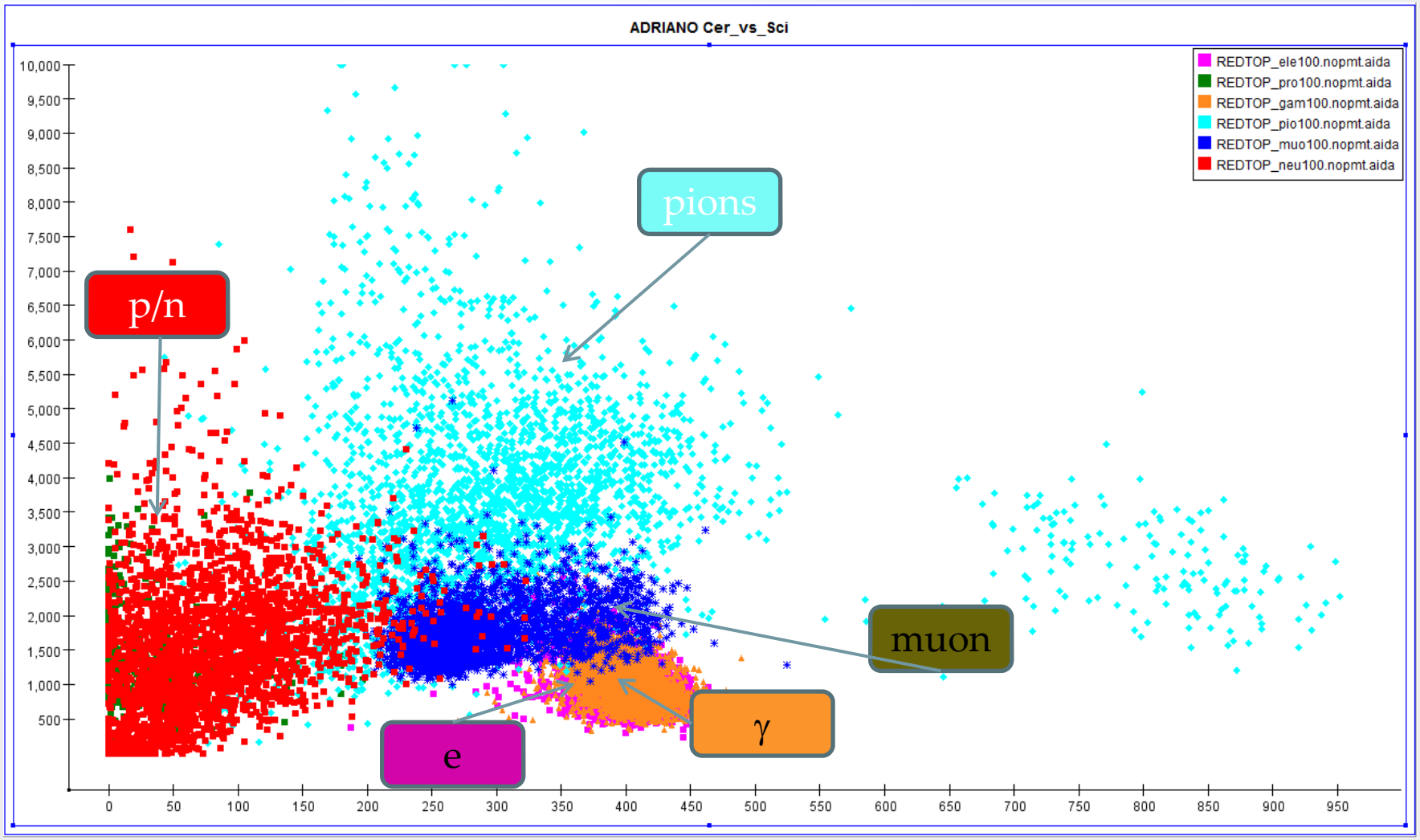


$\sigma_E / E = 5\% / \sqrt{E} \oplus 0.4\%$

PID from C vs S

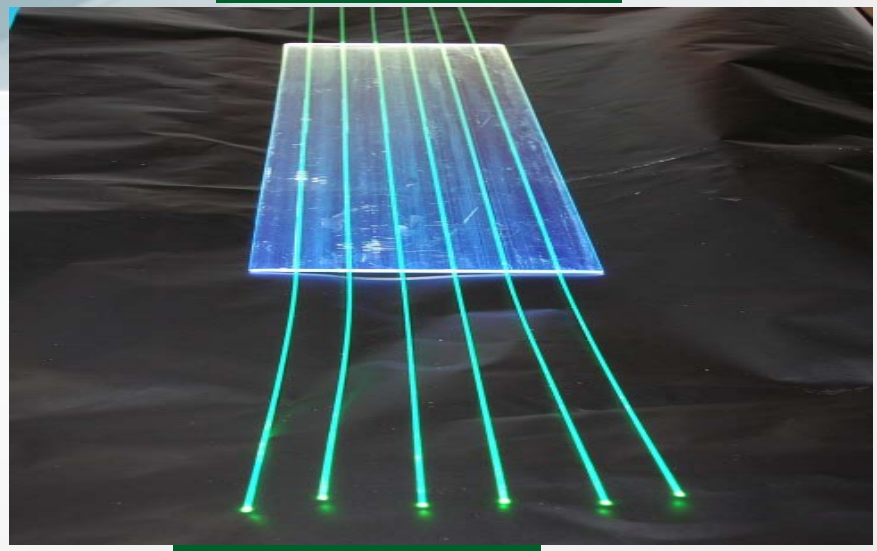


ADRIANO PID @ 100MeV

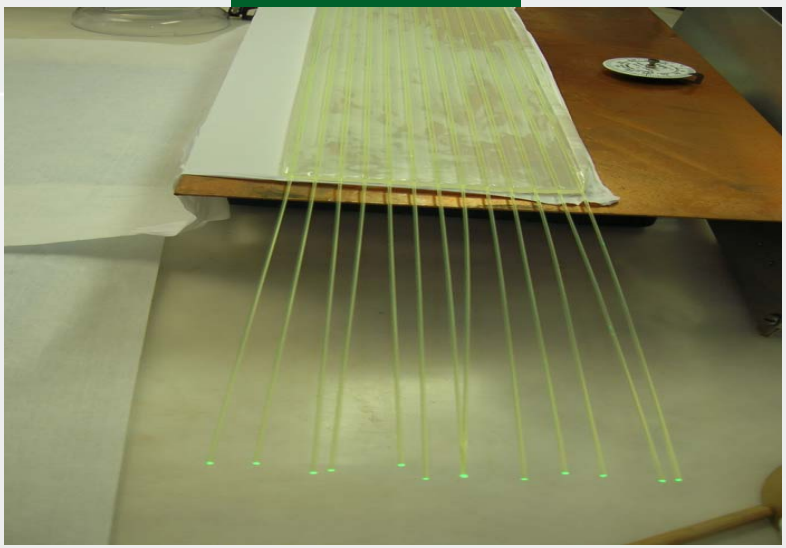


ADRIANO for ORKA Construction

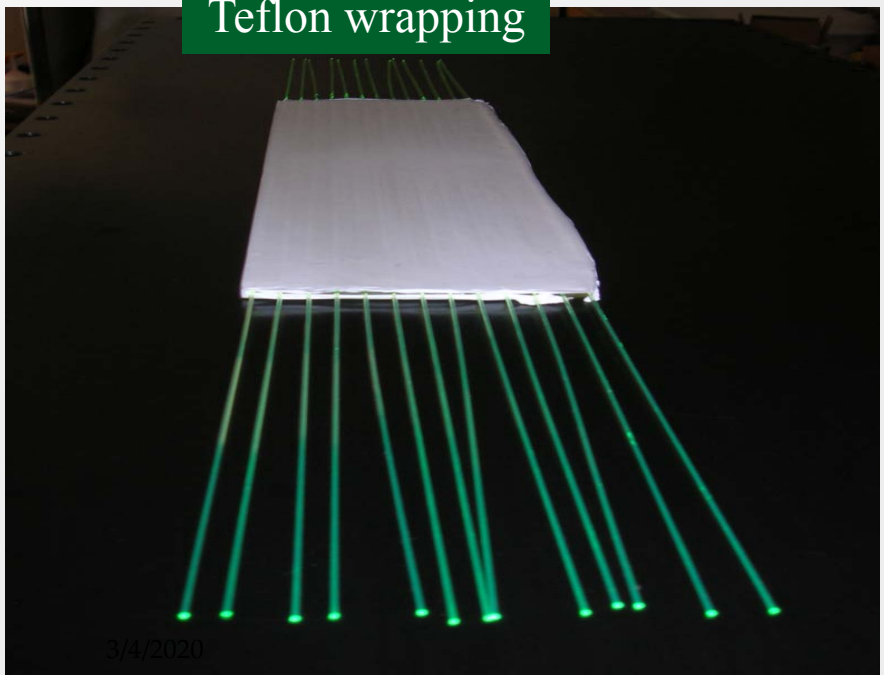
WLS + scintillator



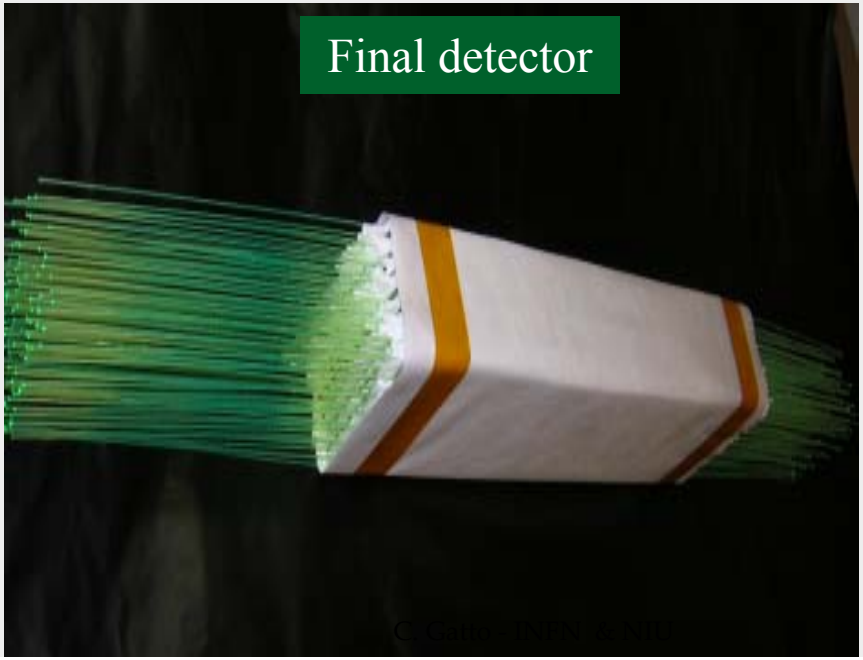
WLS + glass



Teflon wrapping

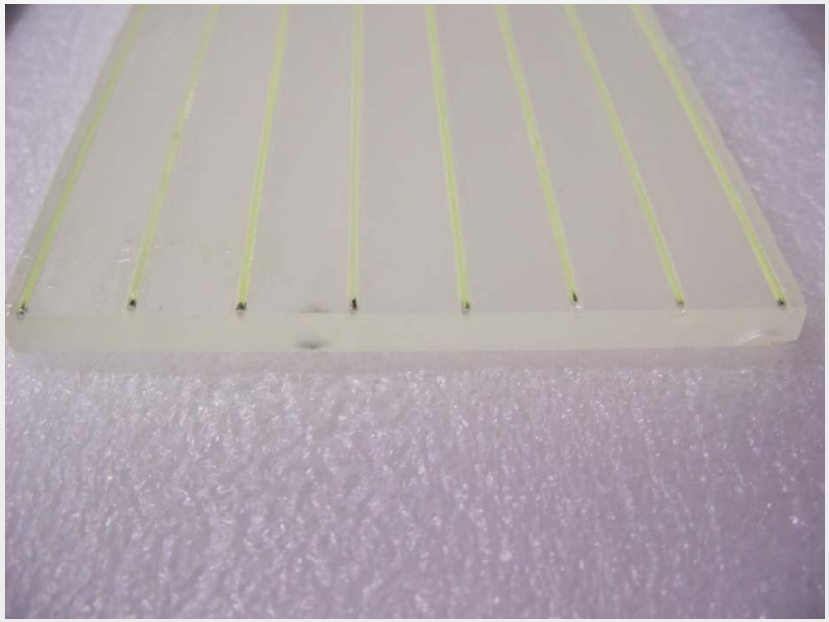


Final detector

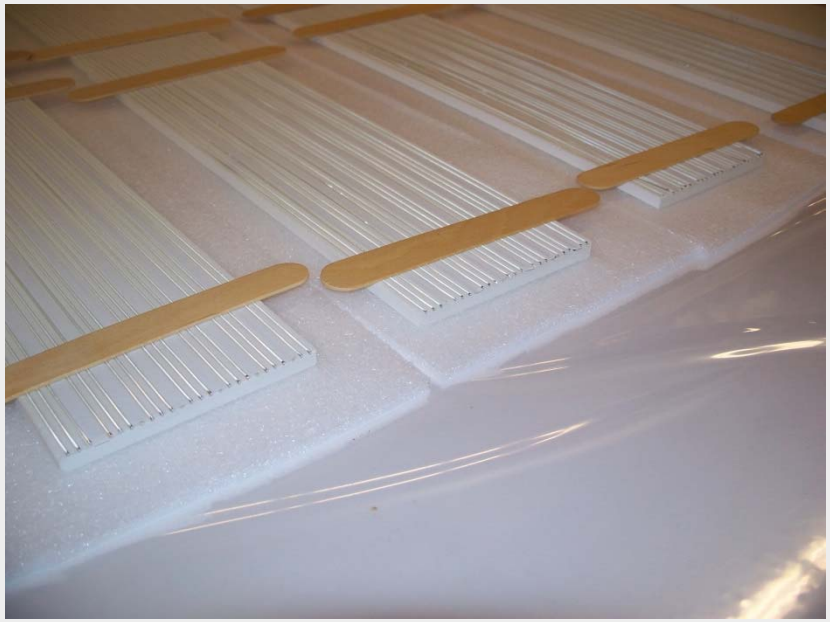


ADRIANO-2014

- 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

High Energy vs High Intensity Layouts

High Energy

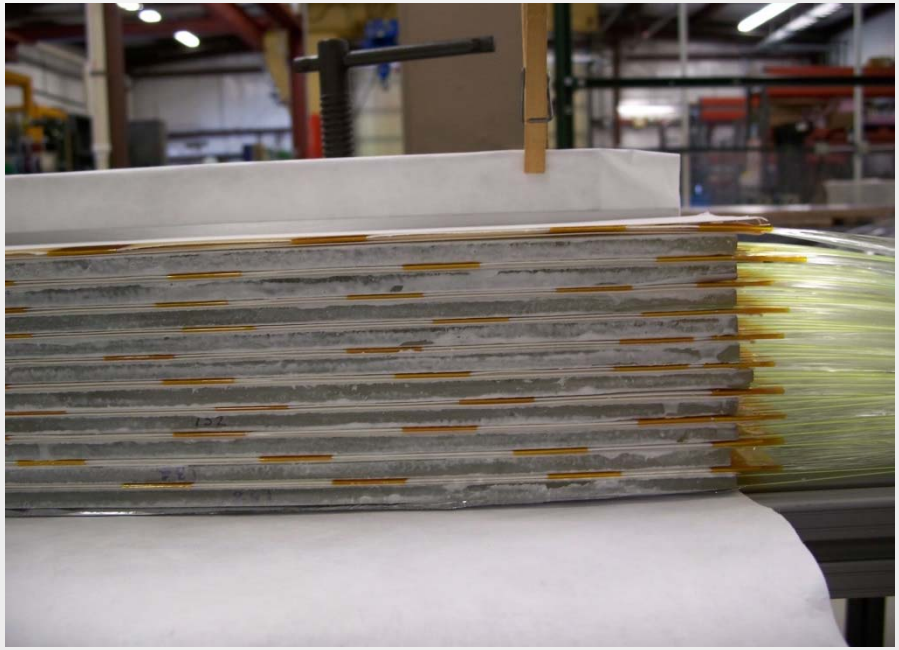
- Detection of Hadronic and EM showers with large S and Č light production
- Optimized for maximum shower containment (i.e. max detector density)

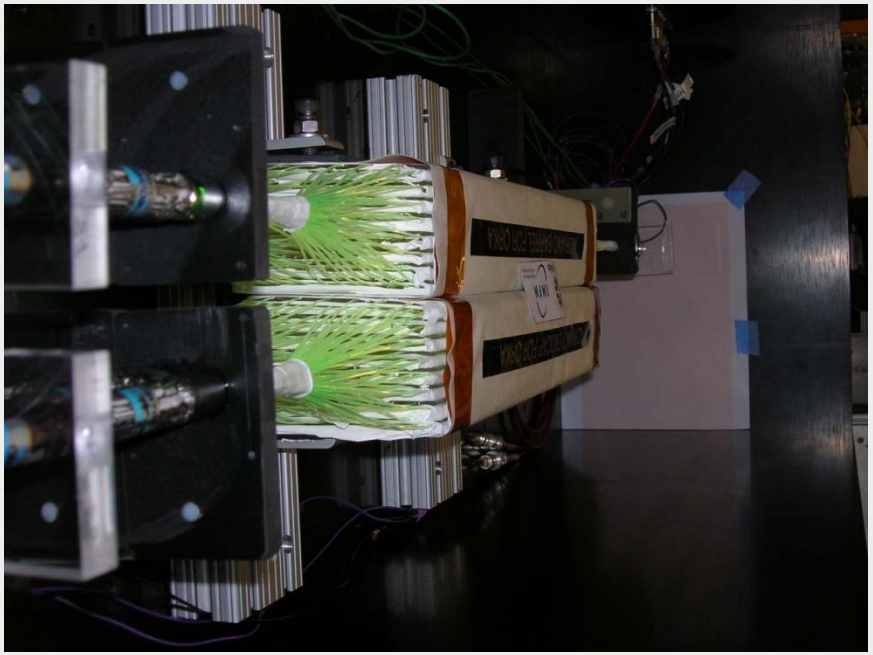
- Thicker glass
- Thin scintillating fibers or ribbons
- Fewer WLS fibers

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





16 Prototypes Performance Summary

Prototype	Year	Glass	gr/cm^3	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
10 slices - 6.2 mm thick, sci-ribbon version	2015	Schott SF57	5.6	354	molded

Detector Response

	ADRIANO 2014A	ADRIANO 2014B
Scintillation L.Y.	523 pe/GeV	256 pe/GeV
Čerenkov L.Y.	**354 pe/GeV**	**338 pe/GeV**
% scint. energy	6.0% @ 4 GeV	1.14% @ 4 GeV
% Cher. energy	94% @ 4 GeV	98.86% @ 4 GeV
% visible energy	89.7% @ 4 GeV	89.7% @ 4 GeV
Scint. pe/deposited energy [MeV]	0.215 GeV@ 4gev Or 18 pe/MeV	0.041 GeV@ 4gev or 44 pe/ MeV
Cher. pe/deposited energy [MeV]	3.37 GeV@ 4gev Or 0.36 pe/MeV	3.52 GeV@ 4gev Or 0.4 pe/MeV

Light yield goals for 30%/√E resolution achieved!

New Directions in Calorimetry

Summary

We have identified three major detector research areas where the US can contribute to future high energy physics program needs.

PRD #1 High precision 5D calorimetry with a resolutions of ~15%/√E EM and ~35%/√E hadronic and shower ΔT < 30 ps for linear and circular e^+e^- machines.
Timescale ready in 10 years.

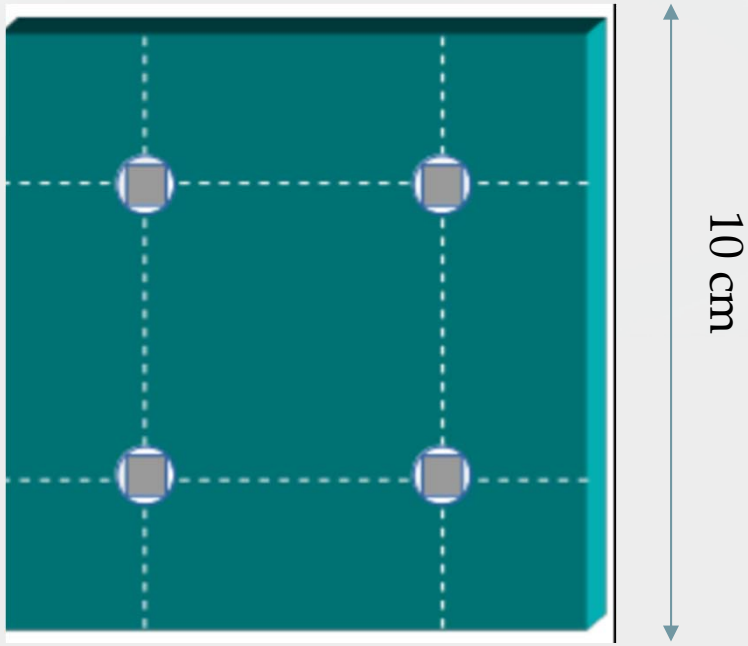
PRD #2 High precision 5D calorimetry for *hh* machines with an EM resolution of < 10%/√E and <30%/√E hadronic ΔT < 5 ps in an irradiation environment of > 10^{17} n/cm^2.
Timescale ready in 20 years.

PRD #3 Ultrafast calorimetry media with order 1 ps precision for low-energy electrons and photons.

From ADRIANO to ADRIANO2

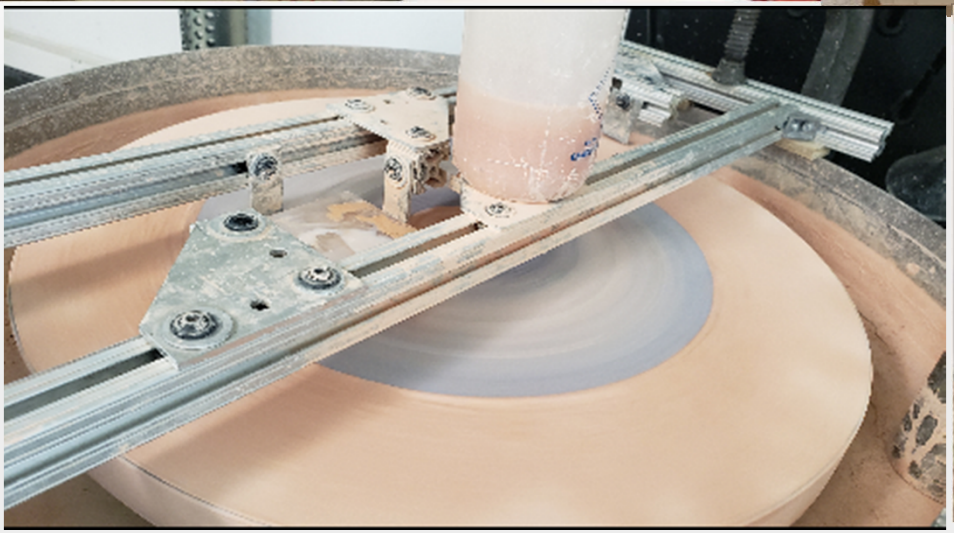
ADRIANO-2015

ADRIANO2 radiator (diagram)



- Log style replaced by tiles
- light capture with wls fiber replaced by on-tile Sipm's
- FEE on tile (ex. Weeroc)

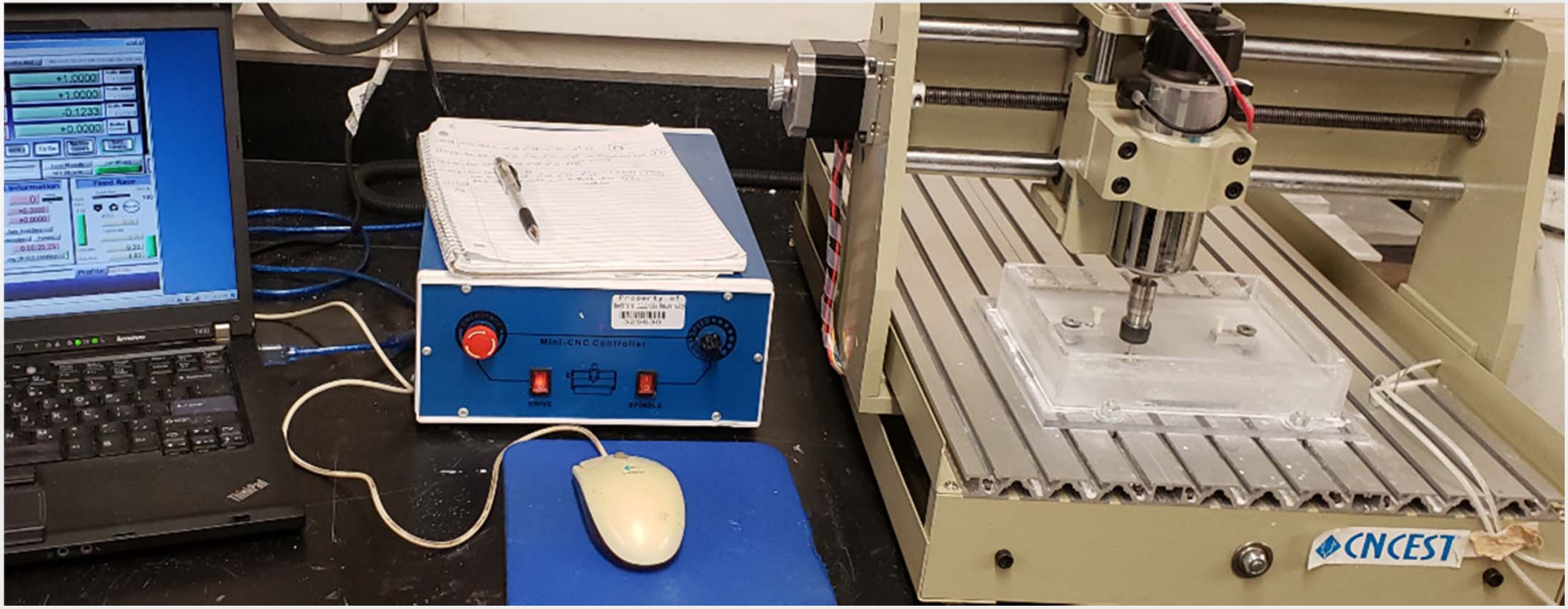
Slicing & Polising



All constructions at NIU (Geology + Chemistry Dept.)

Making Dimples

- Making Dimples
  - Software installation and calibration
  - No software to write g-code for this machine



The Polished Tile

Unpolished & polished dimples

Coating with different materials

GAC-200

Glazing

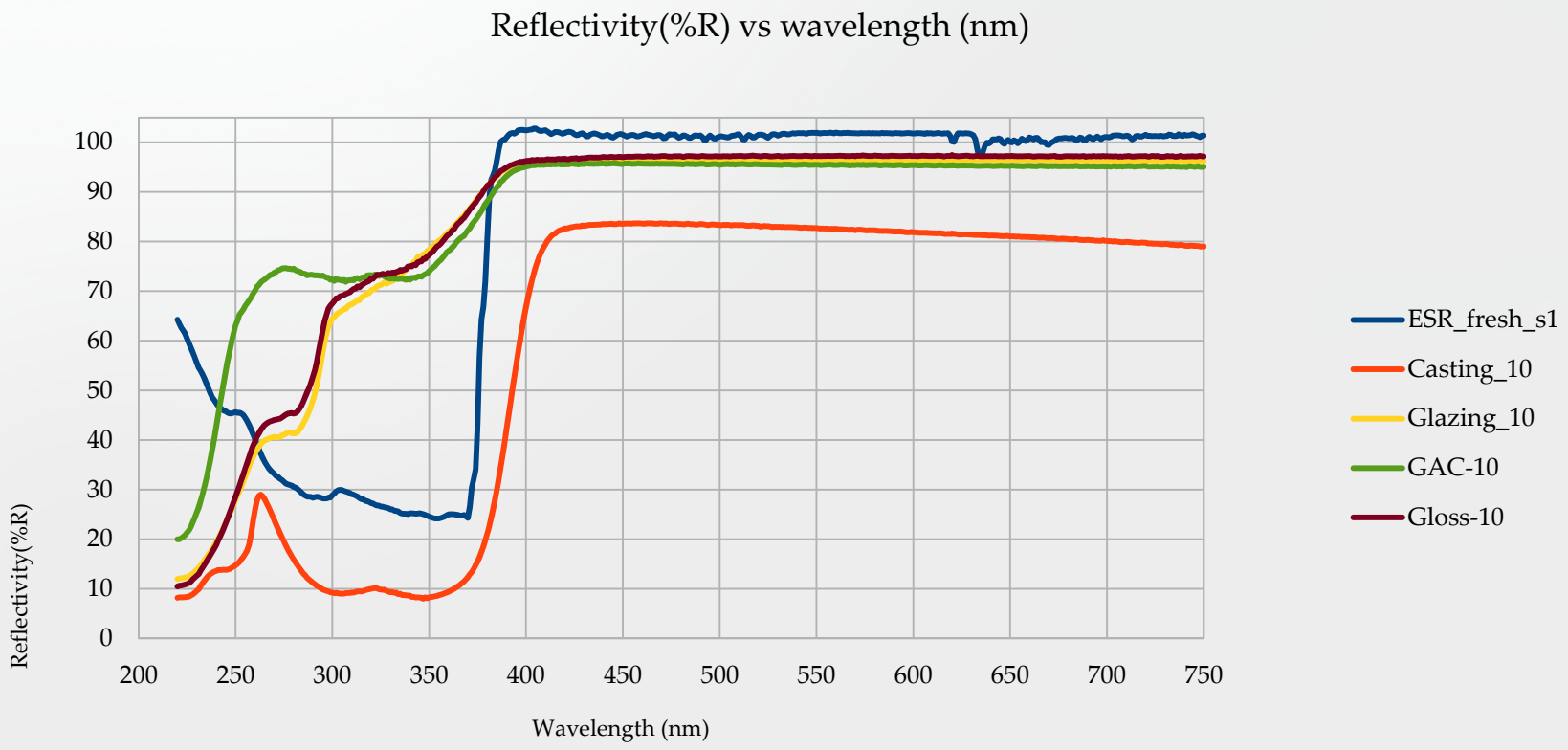
The final Tile

- Test Beam Radiators

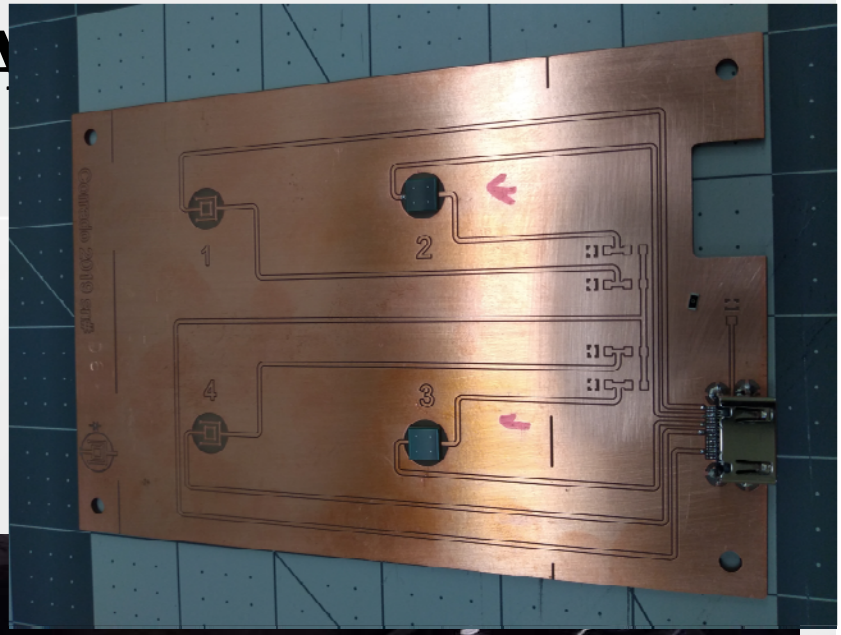
➢ We had chance to test 3 Cerenkov radiators: Barium sulfate coated and ESR wrapped (with optical goo) & ESR wrapped with no optical goo

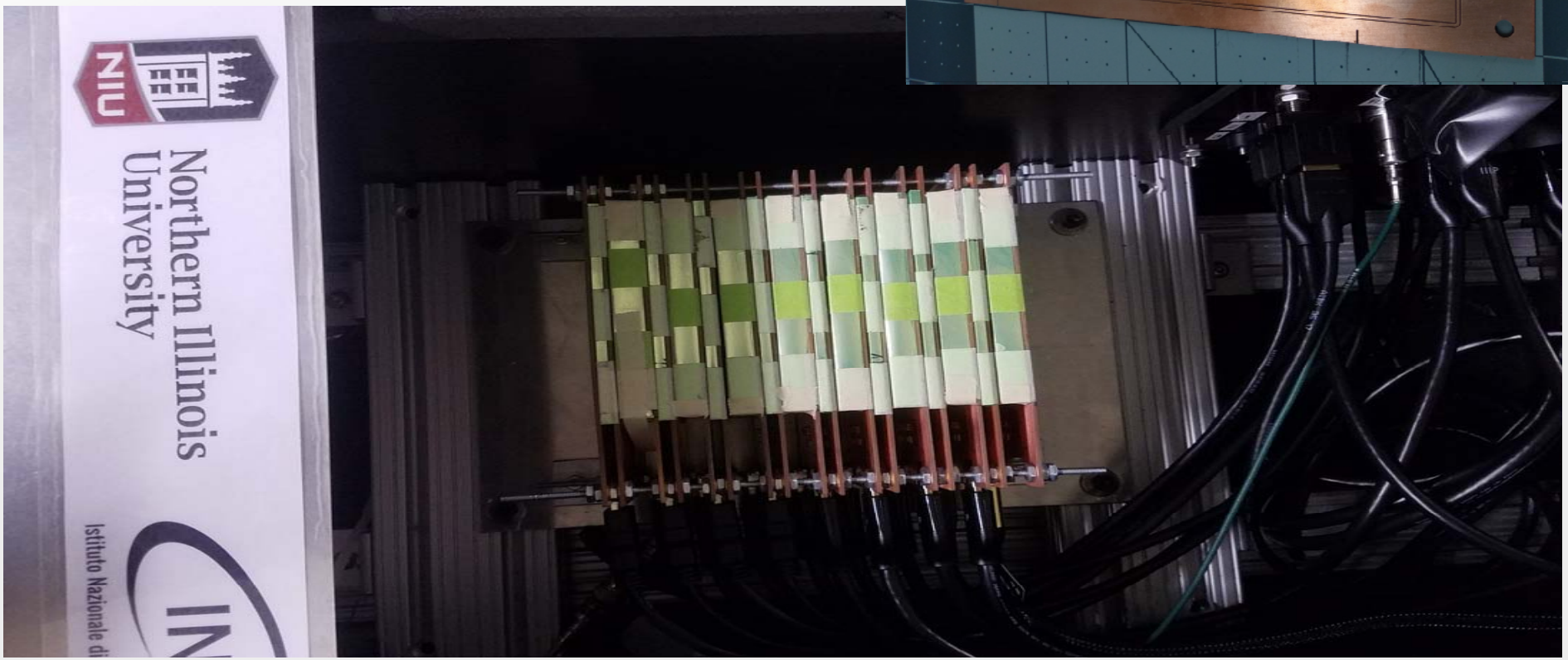
Reflectivity Measurements

- Reflectivity :ESR-2000 &Barium sulfate paint(in oil & water-based binders)
-

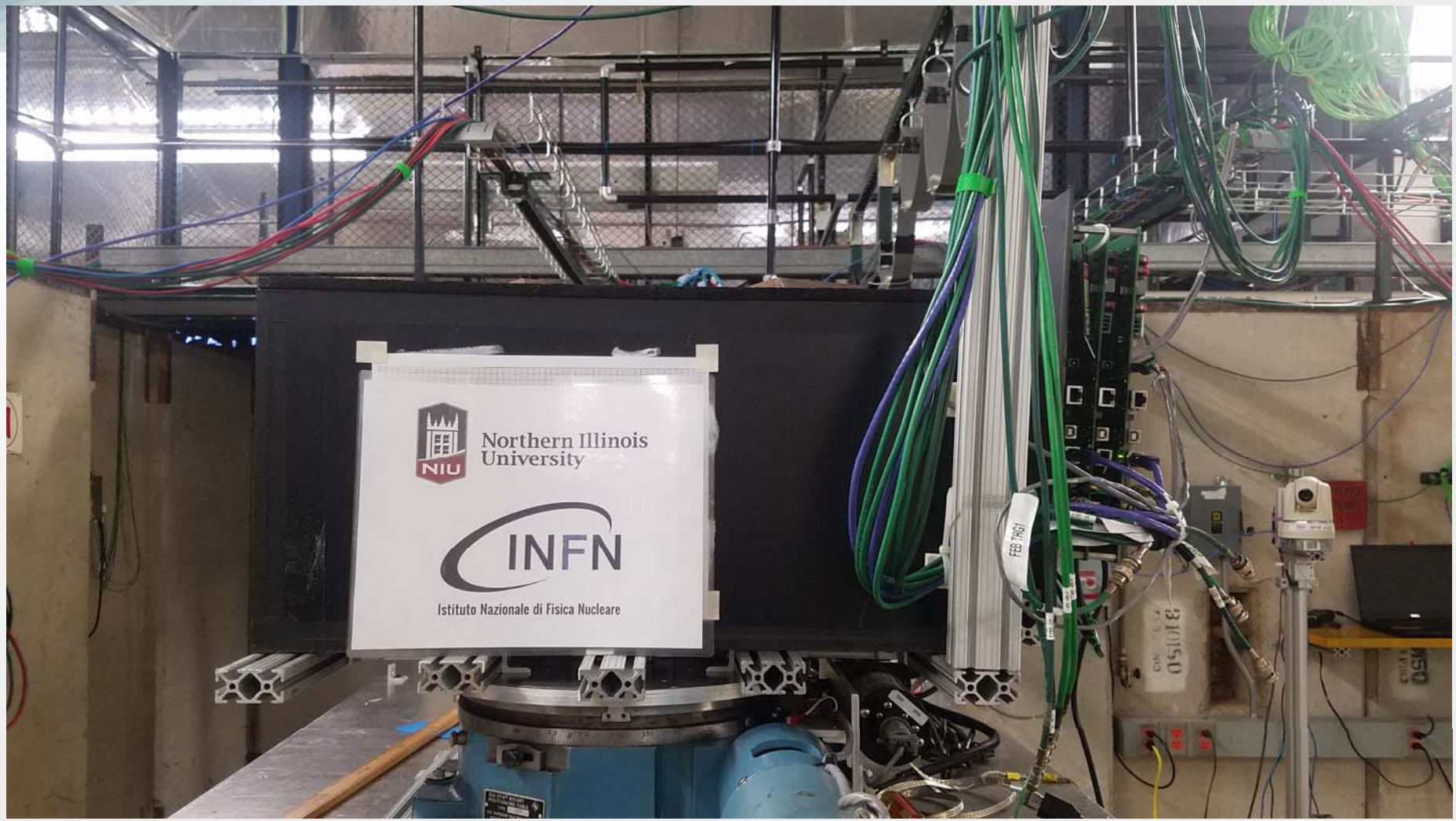


Final Detector A

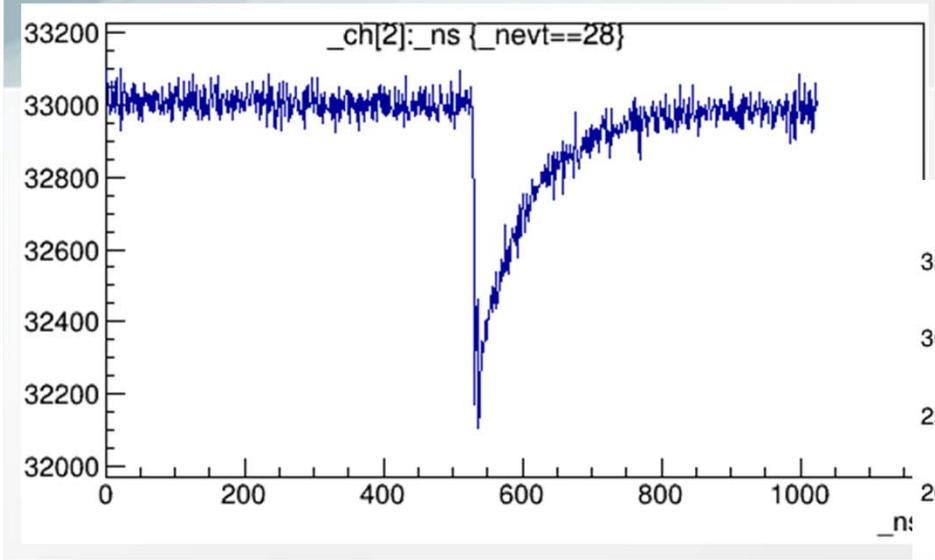


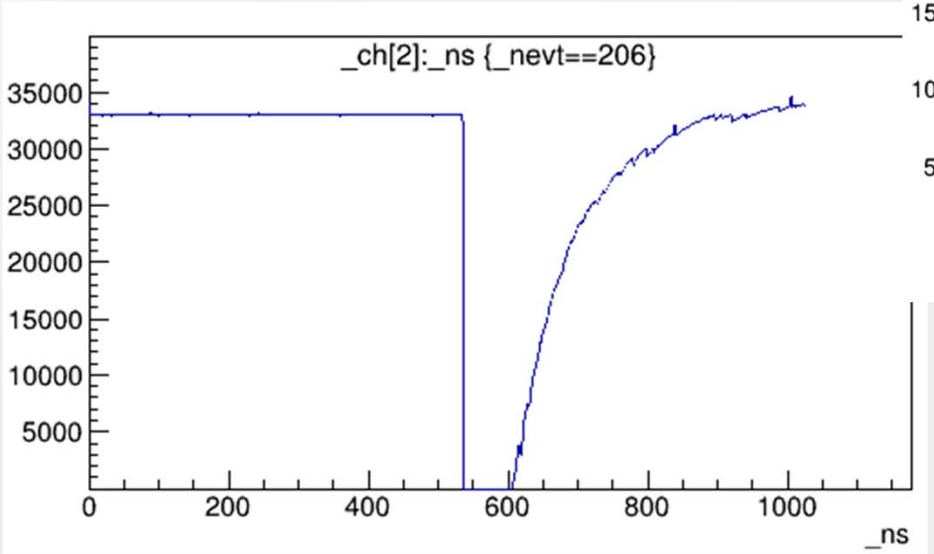


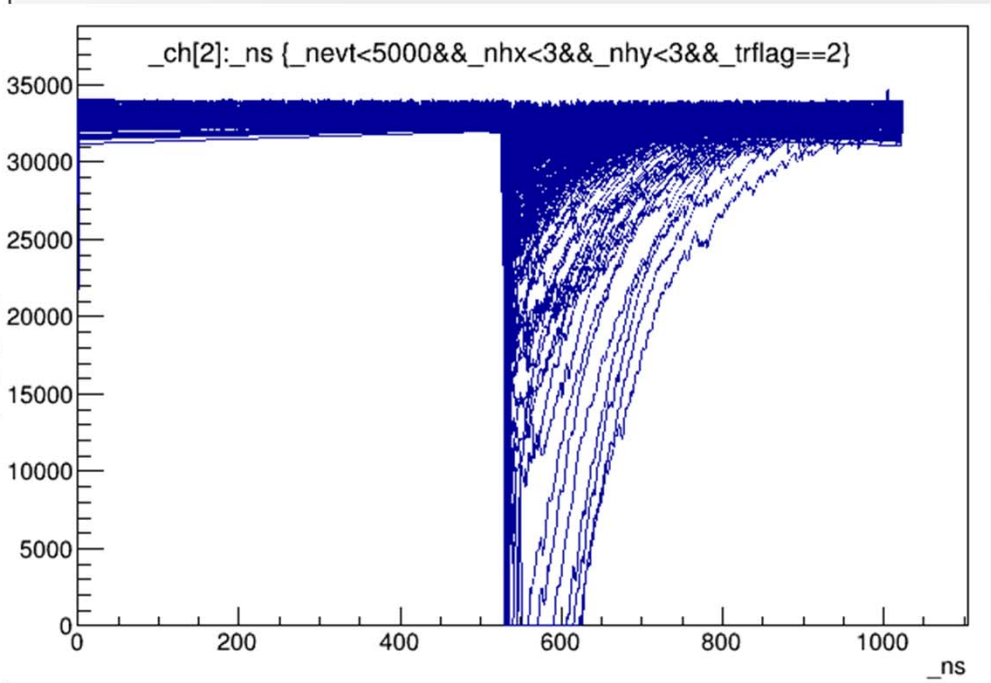
January 2020 Test Beam at Fermilab



Few Waveforms



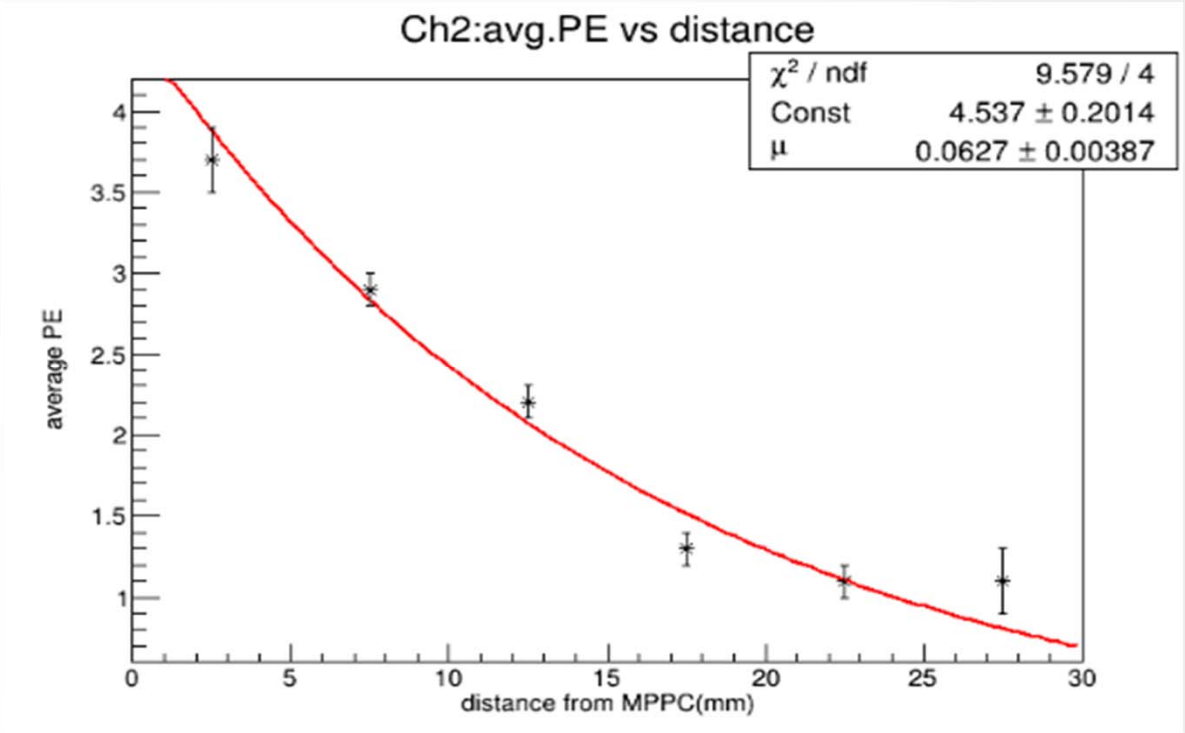


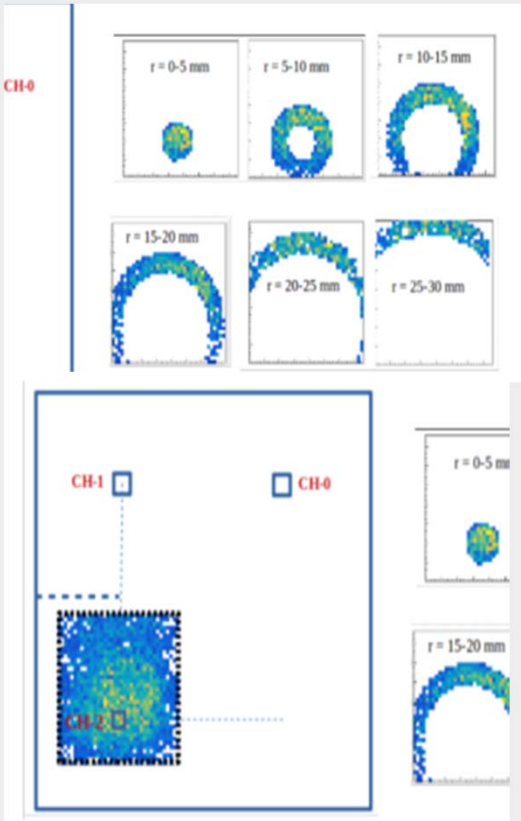


Preliminary Analysis

Data Analysis: <pe> vs distance(mm) of slices

$f(x) = 4.5e^{-0.06x}$, which gives 1/e of initial value at x = 1/0.06 =16.67mm

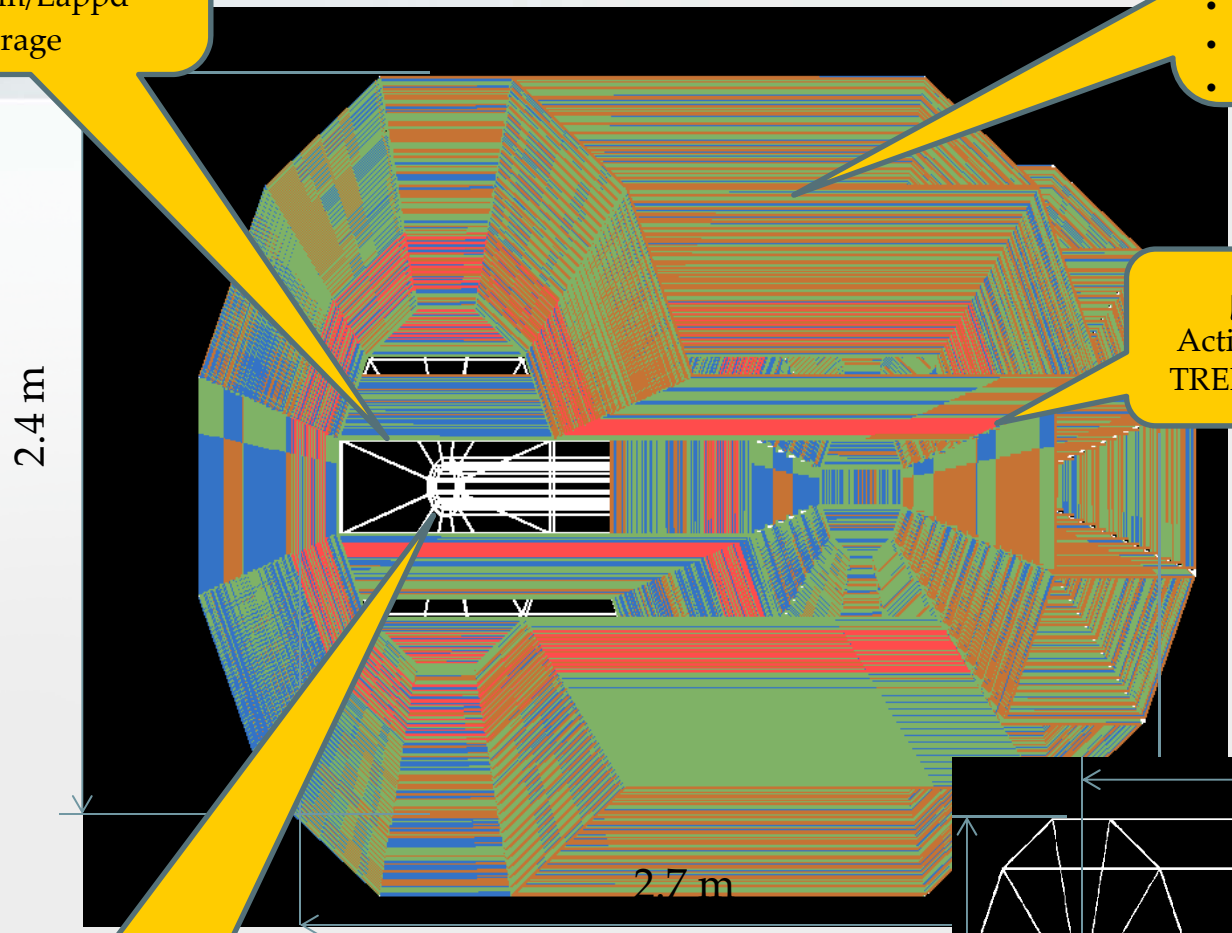




REDTOP detector

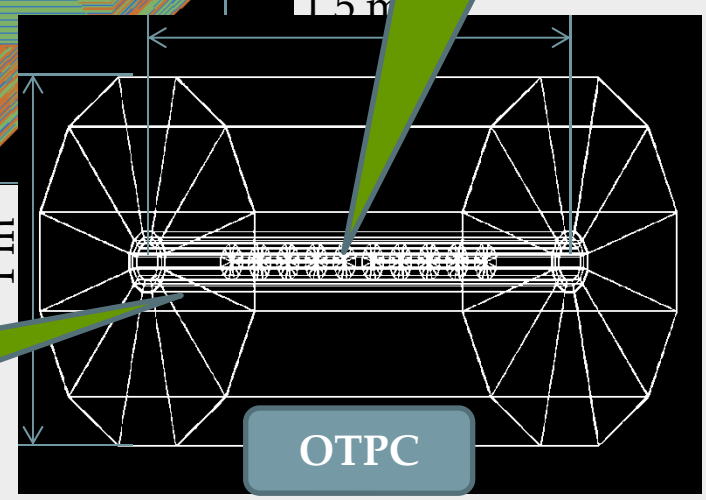
Optical TPC
- ~ 1m x 1.5 m
- CH_4 @ 1 Atm
- $5x10^5$ Sipm/Lappd
- 98% coverage

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



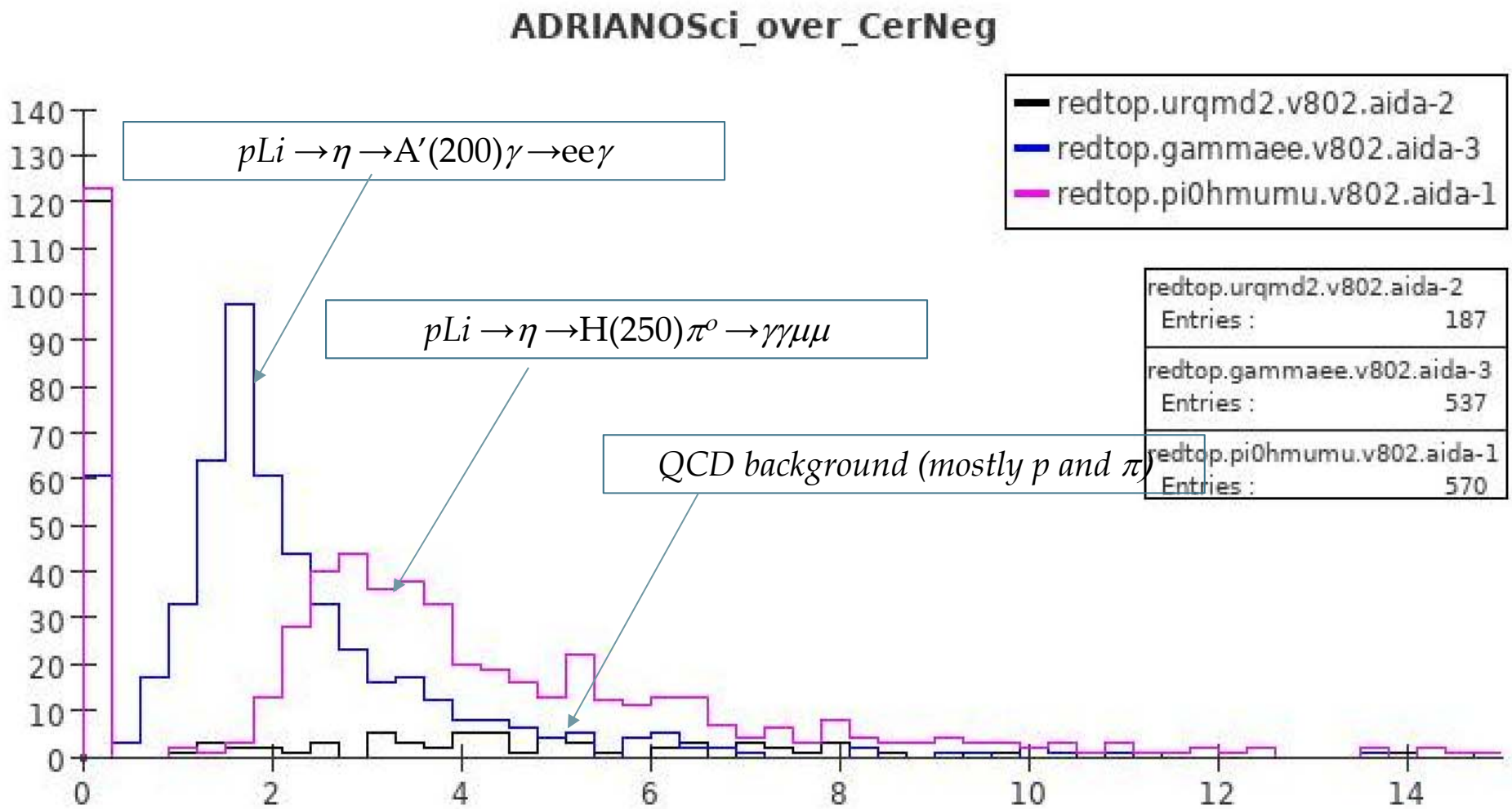
Fiber tracker
for rejection of g-conversion and vertexing

Aerogel
Dual refractive index system

OTPC

Fast Dual Readout ADRIANO2

- 1 GHz interaction rate -> Cerenkov process a winner
- 1/200 η mesons produced -> large background



Conclusions

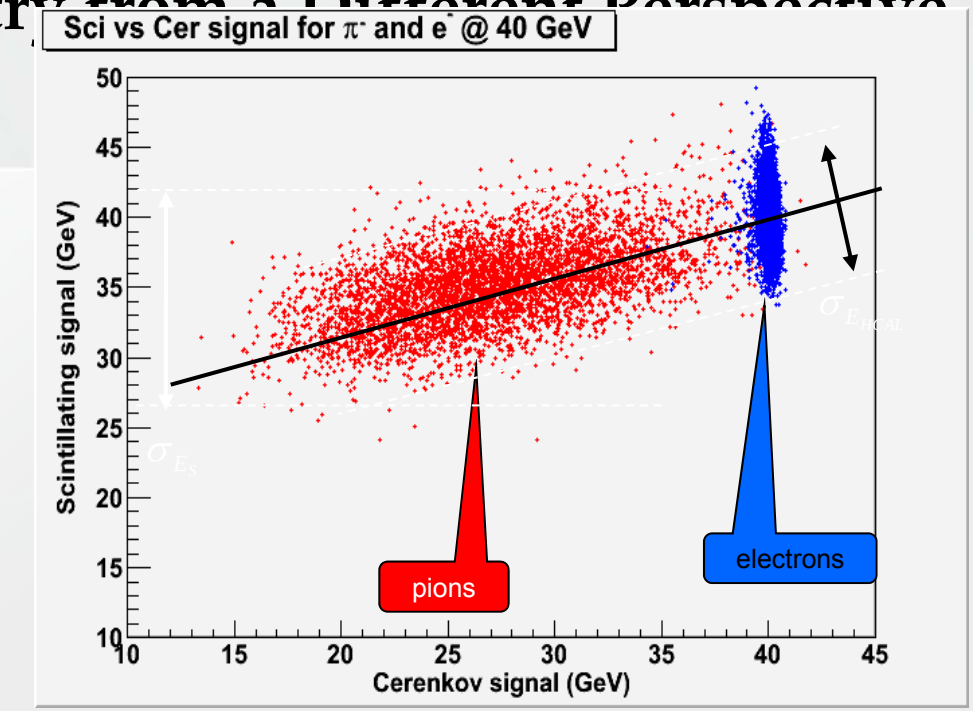
- T1015 started operation in 2010 and still rolling
- 16+1 detectors succesfully built and tested.
- ***We have mastered the technique of collecting light from glass with WLS fibers.***
- Čerenkov ligth yield more than adequate for 25-30%/sqrt(E) calorimetry. We have shown that it can be used for EM calorimetry as well
- Focus for future is on a 5D, tiled version of ADRIANO based on Calice techniques
- A proposal has been submitted to DOE for R&D targeting the EIC and REDTOP
- Would be nice to have Calice opening the doors to dual-readout

Backup Slides

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}