The REDTOP calorimeter: a path toward PFA+Dual readout techniques for future colliders

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Introduction

- Next generation calorimeters: BRN guidelines

PRD #1 High precision 5D calorimetry with a resolutions of ~15%/√E EM and ~35%/√E hadronic and shower $\Delta T < 30$ 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 $\Delta T < 5$ 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.

- PFA vs dual readout for High Energy and High Intensity experiments
- Not only calorimetry: μ/γ polarimetry with PFA+dual readout
- A path toward calorimetry for future colliders
- All MC studies presented are from SLIC (enhanced), lcsim and ILCroot (unless otherwise noted)

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 $\gamma *$ 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 $X_{17} \to e^+ e^-$
- QCD axion searches : $\eta \to \pi\pi \boldsymbol{a}_{17}$ with $\boldsymbol{a}_{17} \to e^+ e^-$
- 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: $qqbar \to A'/a \to \boldsymbol{l}^+ \boldsymbol{l}^-$
- ALP's searches in Primakoff processes: $p\, Z \to p\, Z\, a \to \boldsymbol{l}^+ \boldsymbol{l}^-$ (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: $\pi^0 \to \gamma A' \to \gamma e^+ e^-$

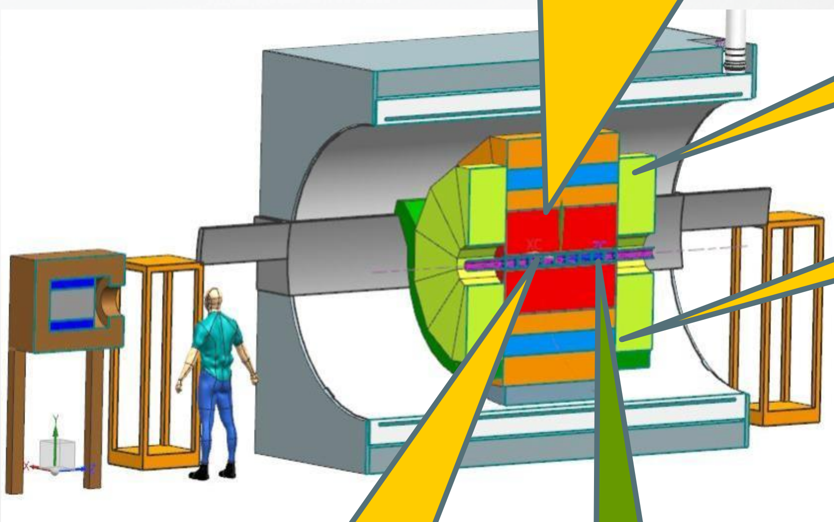
High precision studies on medium energy physics

- 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)

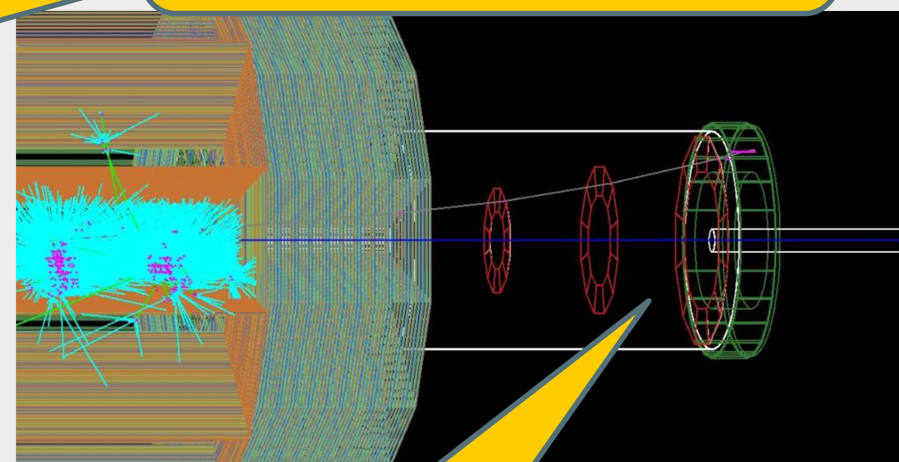
REDTOP Detector

Optical-TPC
For slow background rejection
or
LGAD Tracker surrounded by Quartz cells
For 4D track reconstruction and TOF measurements

6D- Calorimeter: ADRIANO2
(Dual-readout +PFA)
Sci and Cer light read by SiPM or SPAD
For excellent energy , position resolution and PID



μ-polarimeter (optional)
sandwich of fused silica and Si-pixel
for measurement of muon polarization



Vertex Fiber tracker
for rejection of γ-conversion and identifying displaced vertices from long lived particles

10x Be or Li targets

Forward Detector for Option 2
for tagging $^{3}He^{++}$ ions

The Experimental Environment

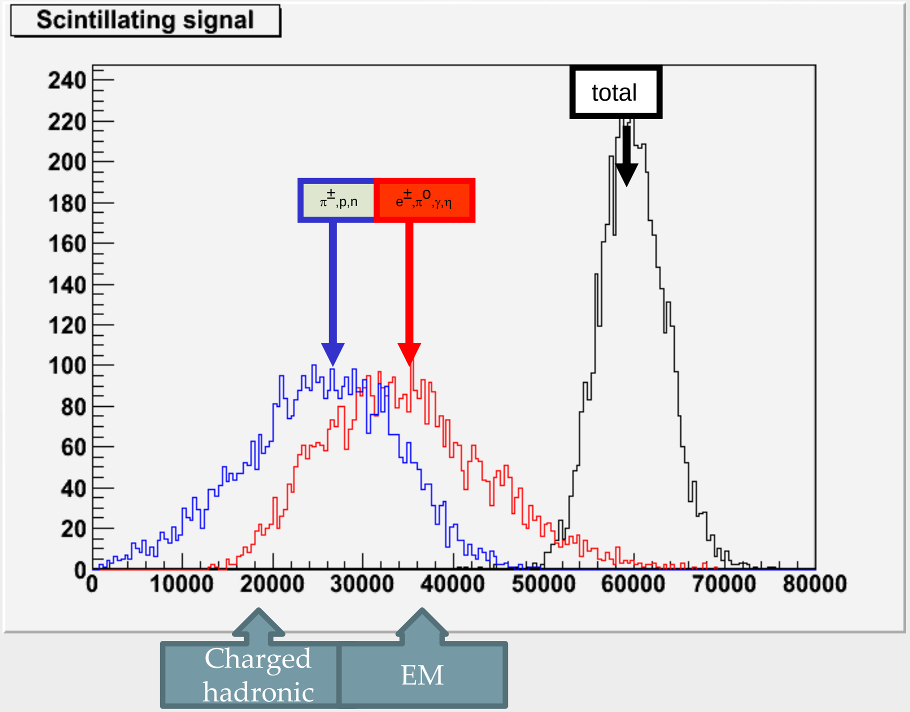
- 1 inelastic interaction/2 nsec
  - ~ 1 GHz including elastic events
  - > 30x LHCB
- η production: 1/400 nsec
- Average charged track multiplicity: 5-6 particles (mostly low energy **protons** and some **pions**)
- Average particles in the calorimeter: 6-8-> ~1/10 the rate at HL-LHC
- Search topology: 2 leptons + X (pre-scale η->3pi)

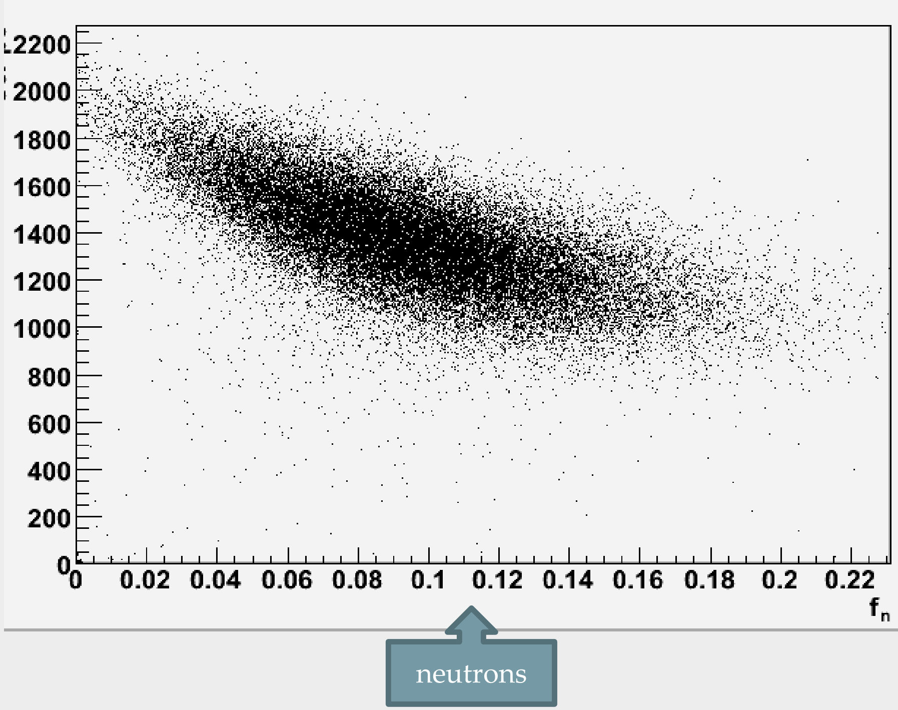
- Calorimeter must feed L0 trigger at ~ GHz rate
- Fast PID (<50 nsec) at L1 trigger
- Software L2 trigger
- **PID key elements but energy resolution also important**

Dual-readout is a possible solution, but it might not be enough

Energy Compensation in Calorimetry

- The vast majority of calorimeters have $e/h \neq 1 \rightarrow$ compensation is required
  - Software compensation → PFA
  - Hardware compensation → multiple-readout
- PFA tries to match info from tracking and calorimeters in a MSP approach
- The multiple-readout techniques is based on the separate measure of 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





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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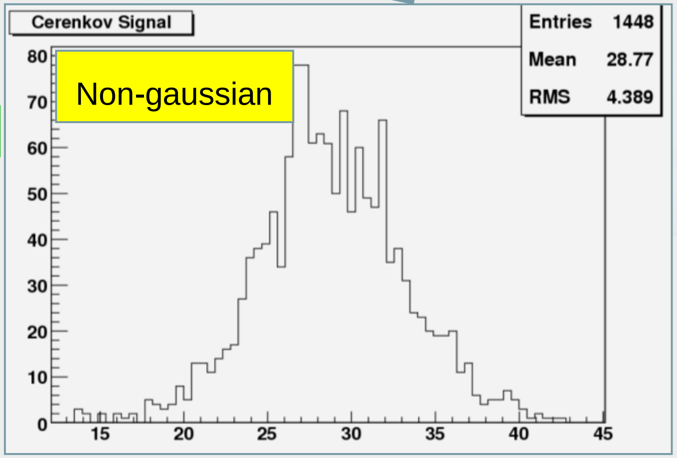
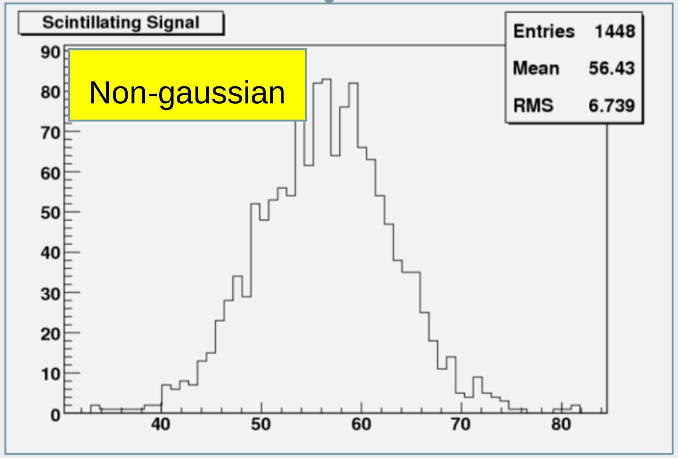
ILCroot simulations





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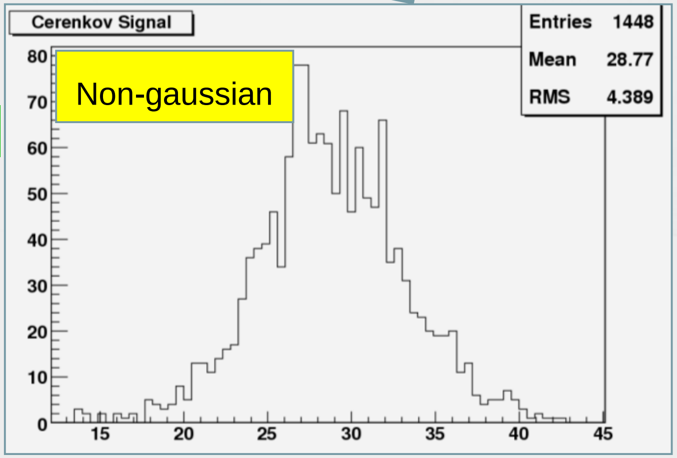

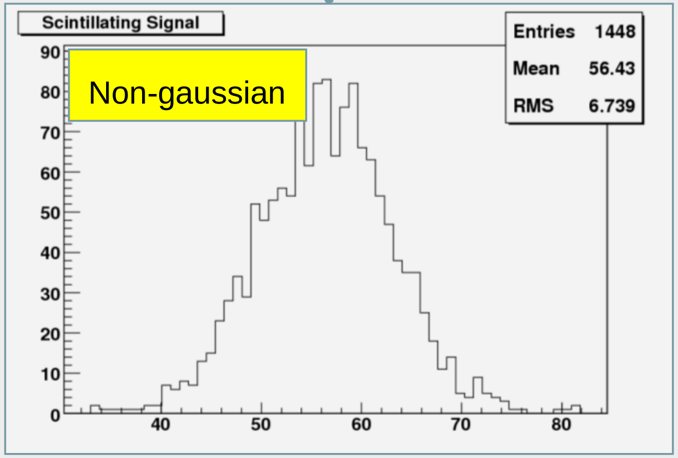

$$\eta_c = \left(\frac{e}{h}\right)_C \quad \eta_S = \left(\frac{e}{h}\right)_S$$

From calibration

@ 1 Energy only

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

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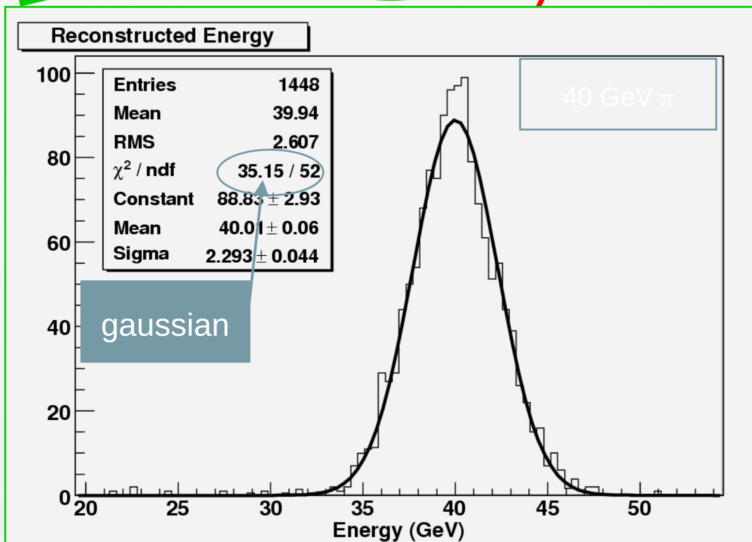
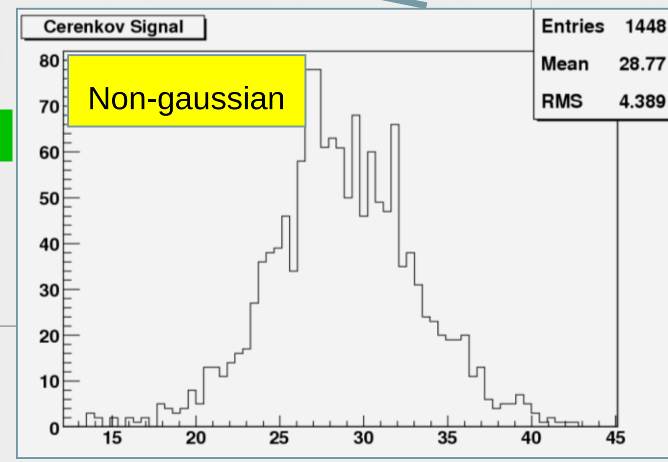
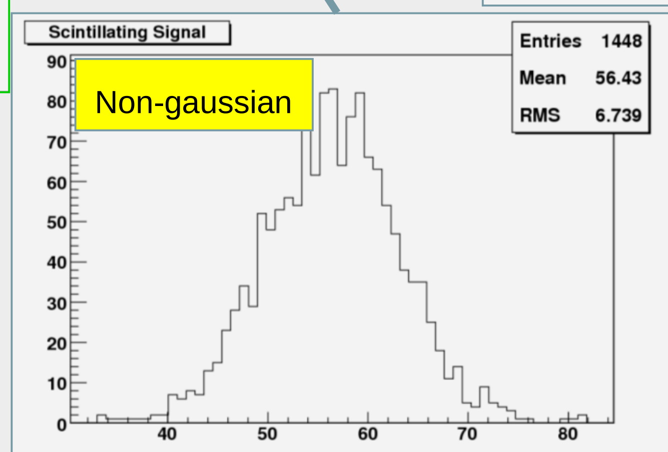


ILCroot simulations





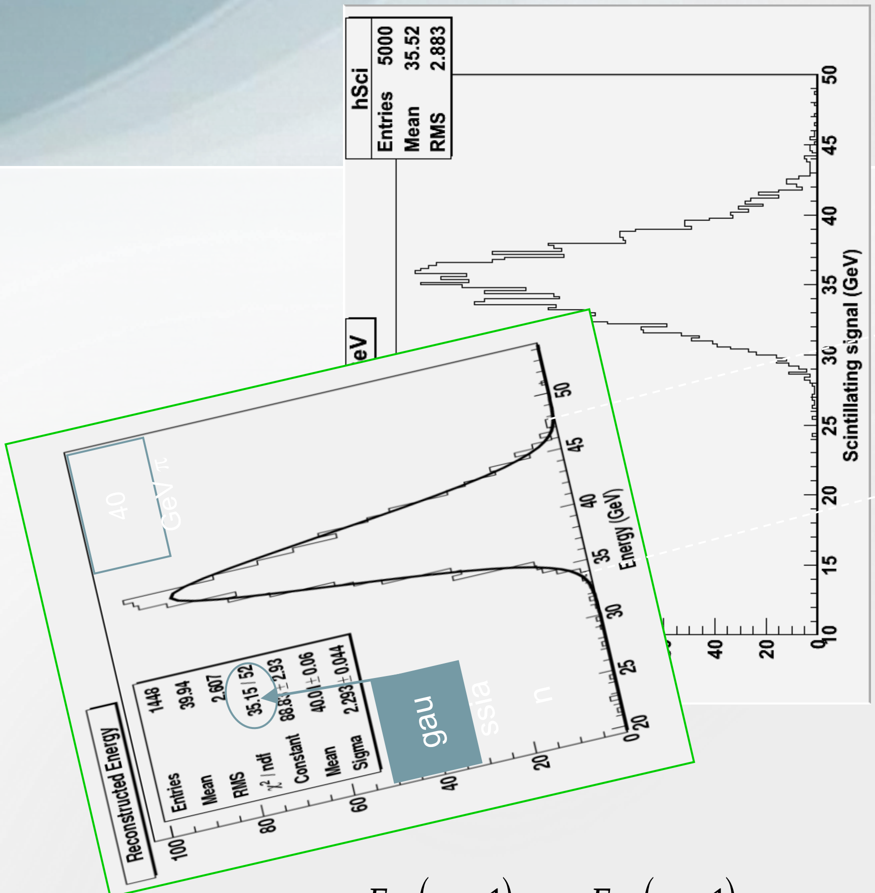
$$\eta_c = \left(\frac{e}{h}\right)_C \quad \eta_S = \left(\frac{e}{h}\right)_S$$

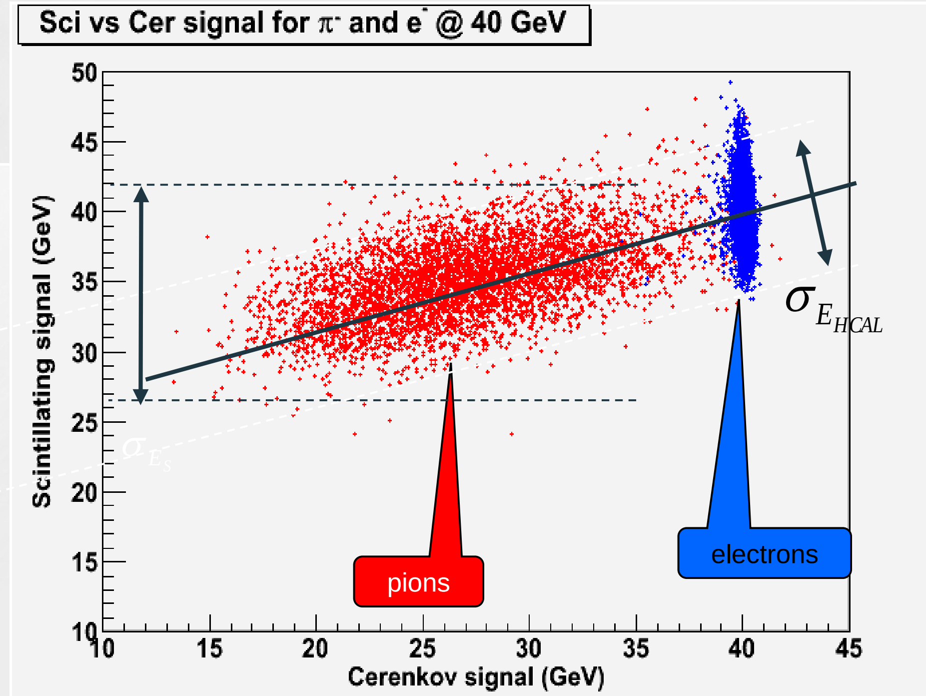
From calibration

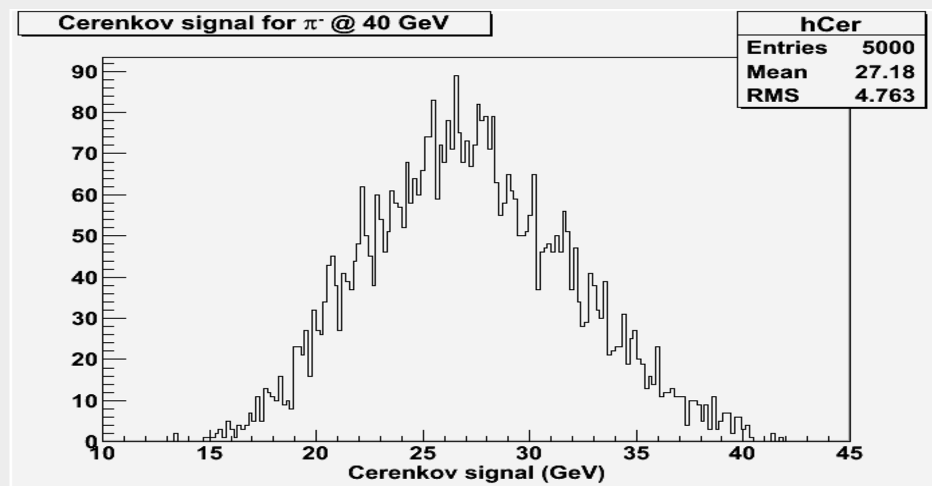
@ 1 Energy only

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





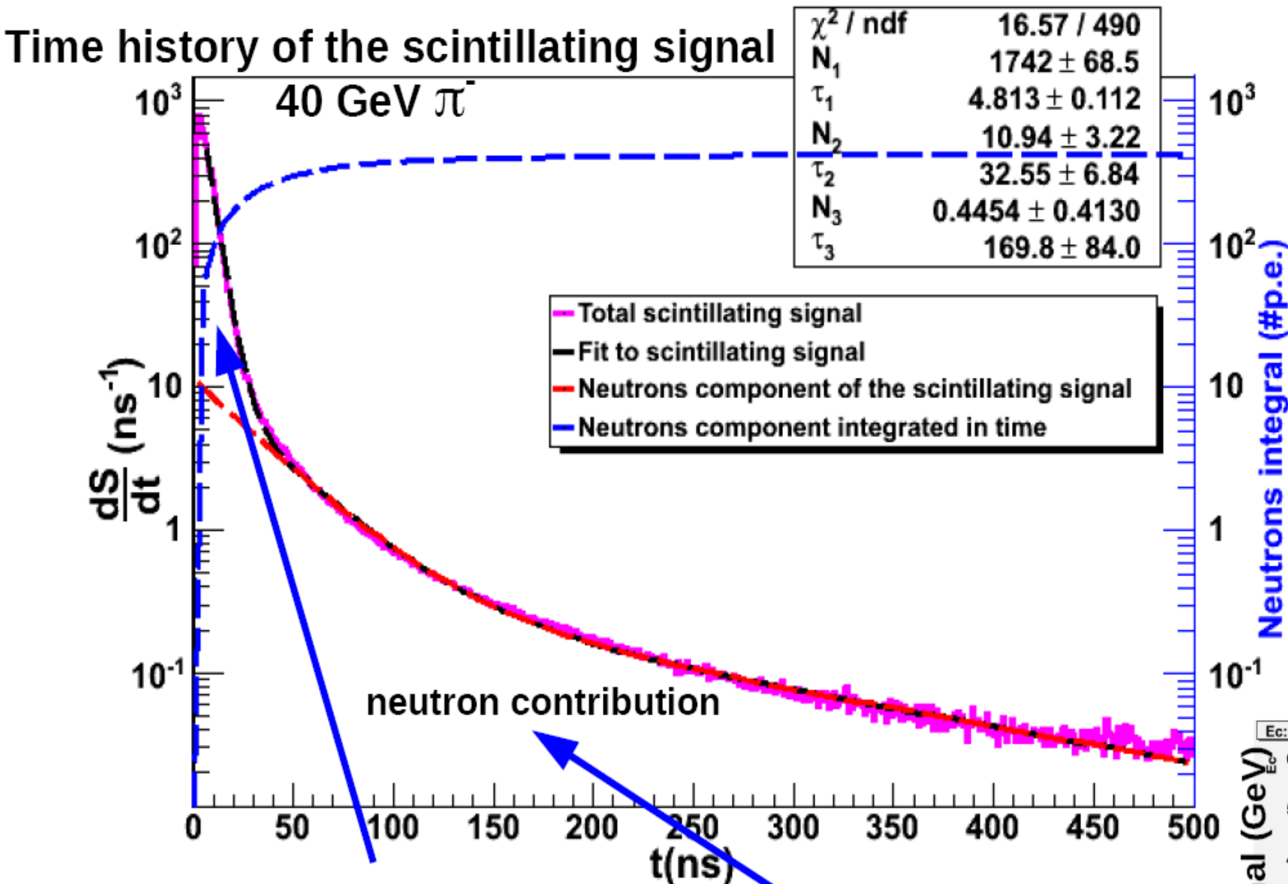


$$E_{HCAL} = \frac{\eta_S \cdot E_S \cdot (\eta_C - 1) - \eta_C \cdot E_C \cdot (\eta_S - 1)}{\eta_C - \eta_S}$$

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

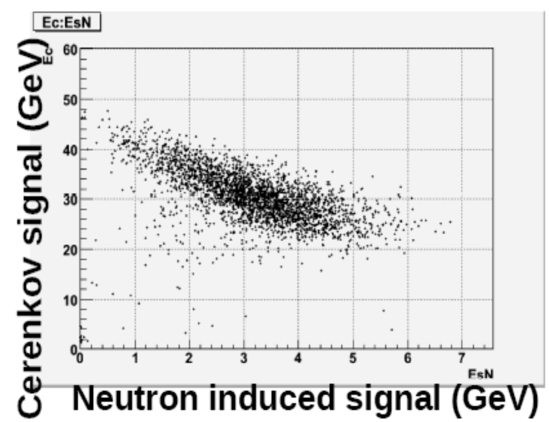
If $\eta_s \neq \eta_c$ then the system can be solved for E_{HCAL}

Triple-readout



- The distribution has been fitted with a triple exponential function.
- After 50 ns only neutrons contribute to the signal.

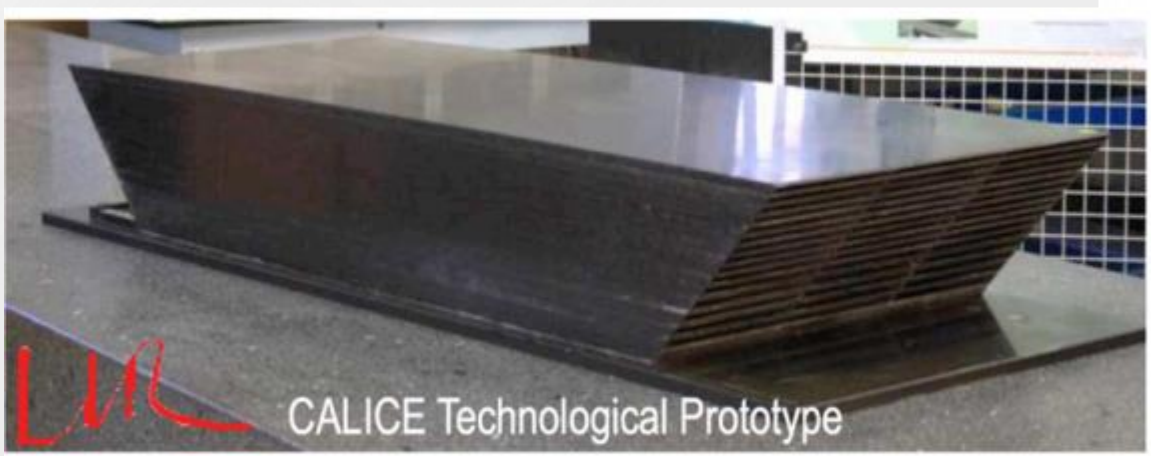
$$E_{shower} = \frac{S_{fast} - \chi C}{1-\chi} + \xi S_{slow}$$

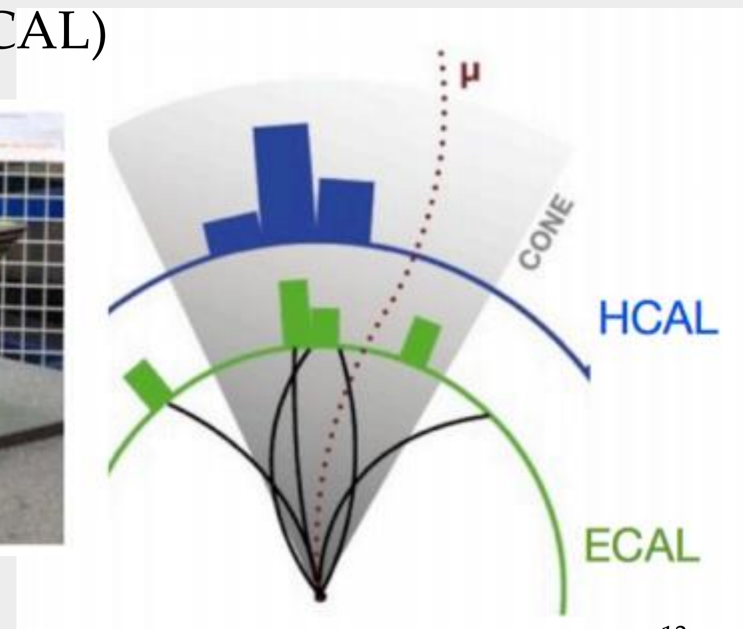


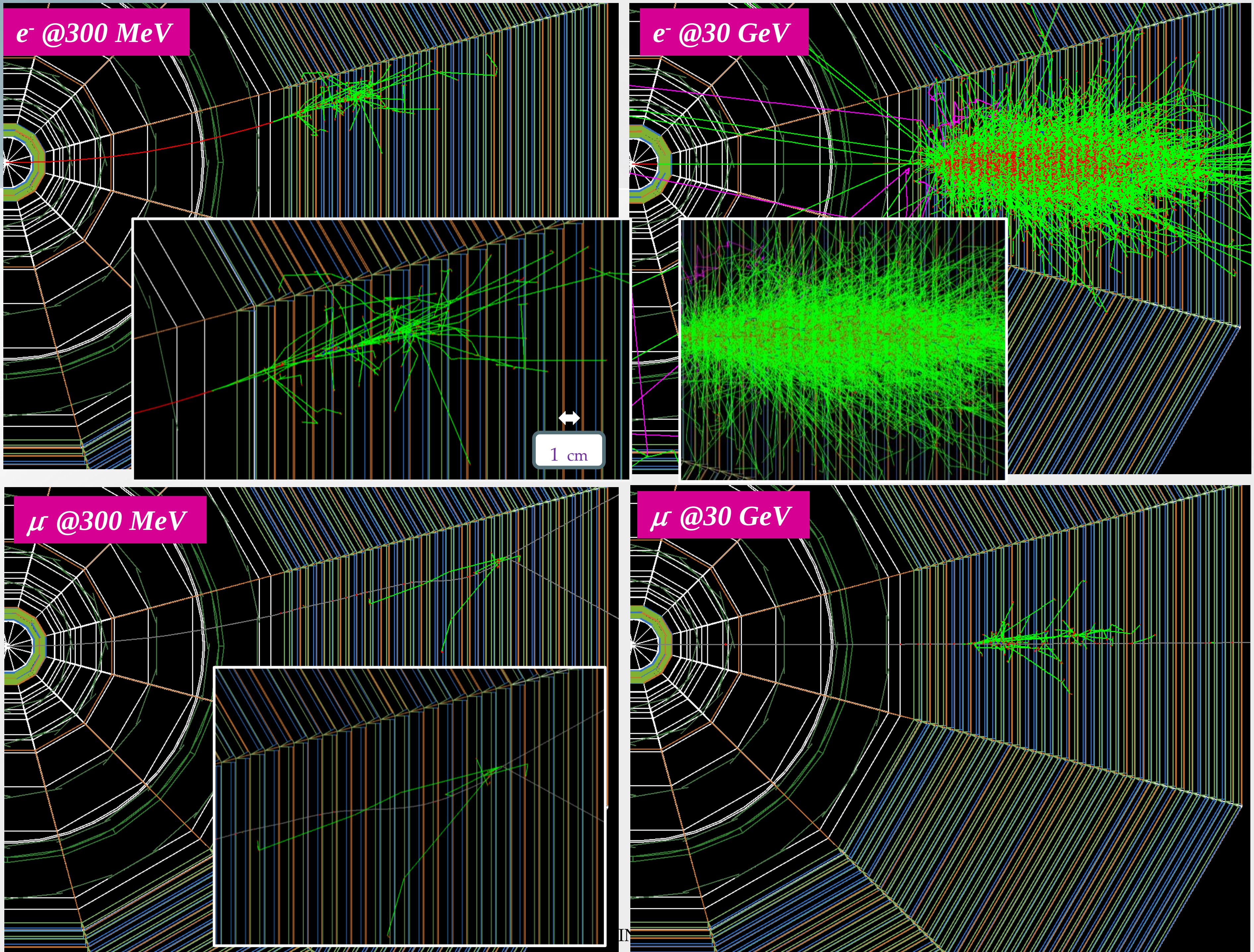
Tran, H.L., Krüger, K., Sefkow, F. *et al.* *Eur. Phys. J. C* **77**, 698 (2017)

Particle Flow Analysis

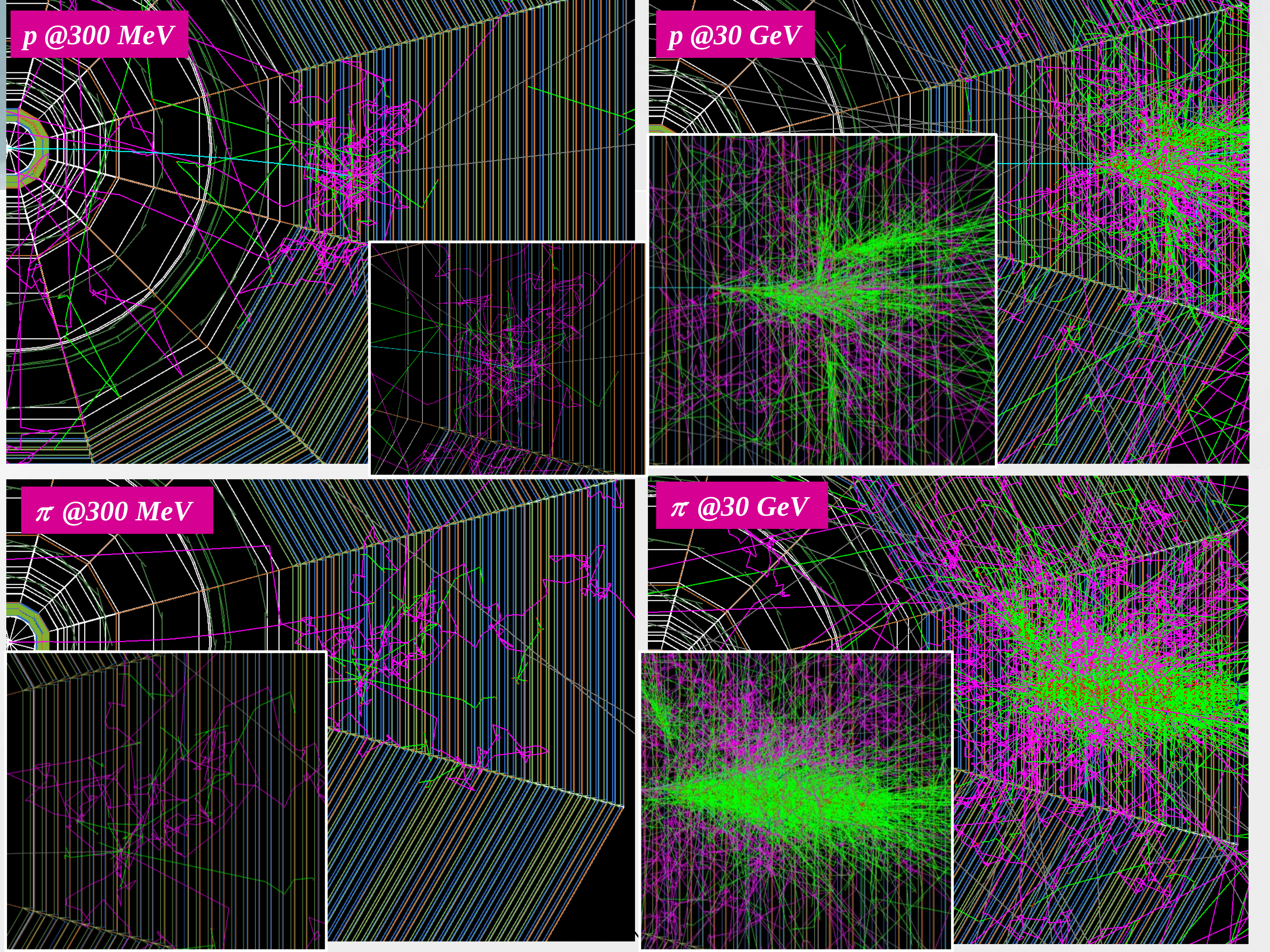
- ***e*/*h*** compensation is done in software
- reconstruct and identify individual particles in complex event topologies.
- Requires high spatial granularity, together with analogue energy information
- Combine information from all sub-detectors for jet reconstruction & use the hadron calorimeter predominantly for the neutral hadron component (ex. CALICE and CMS HGCAL)







e- @300 MeV
1 cm
e- @30 GeV
μ @300 MeV
μ @30 GeV

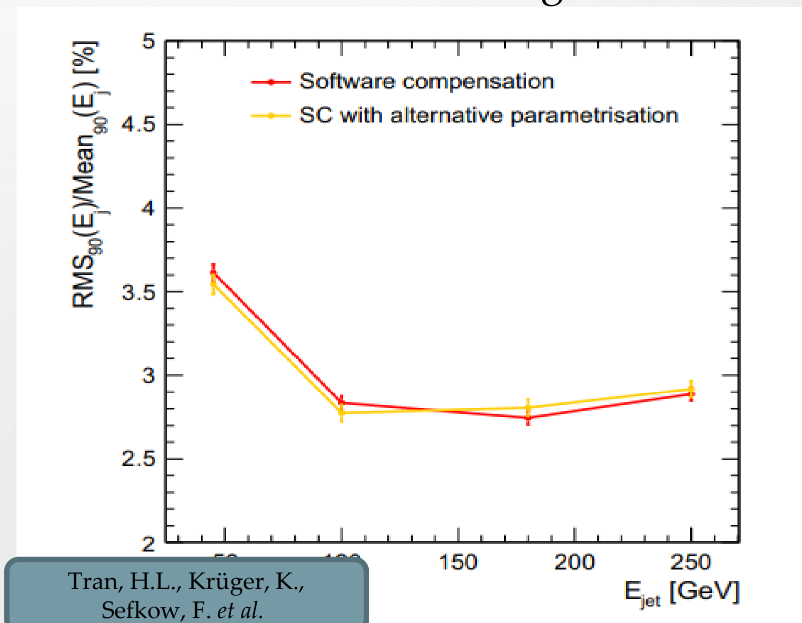


p @300 MeV
p @30 GeV
π @300 MeV
π @30 GeV

PFA vs Dual-readout

PFA

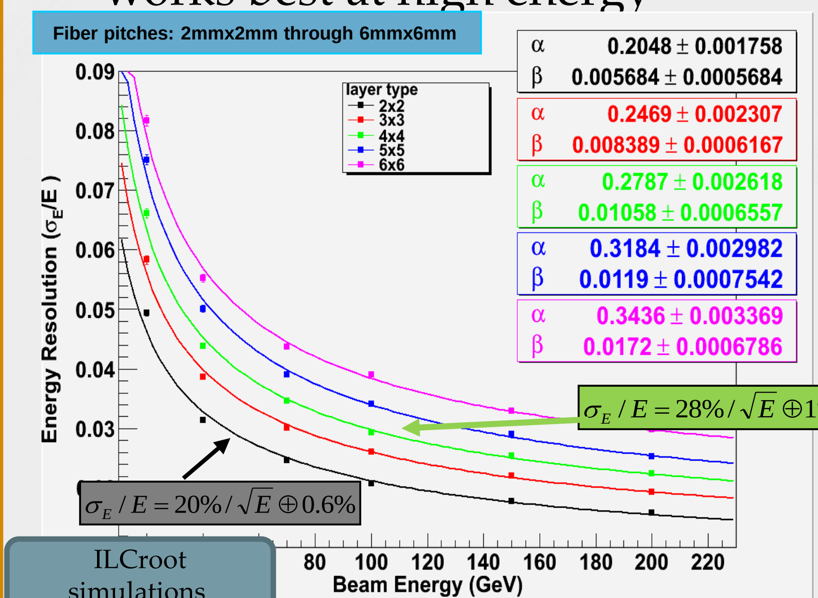
- Combines tracking with calorimetry
- PID from software algorithm
- Fantastic energy resolution with small constant term at low energies



Tran, H.L., Krüger, K., Sefkow, F. *et al.*

Dual-readout

- Exploit the stochastic side only of calorimetry
- PID in hardware (from S/Č)
- works best at high energy



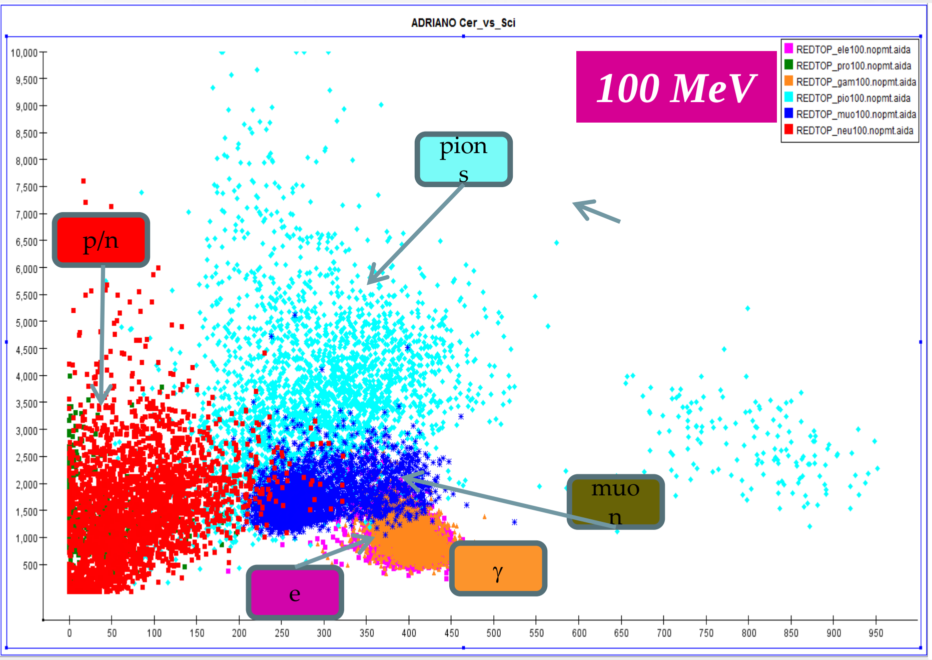
ILCroot simulations

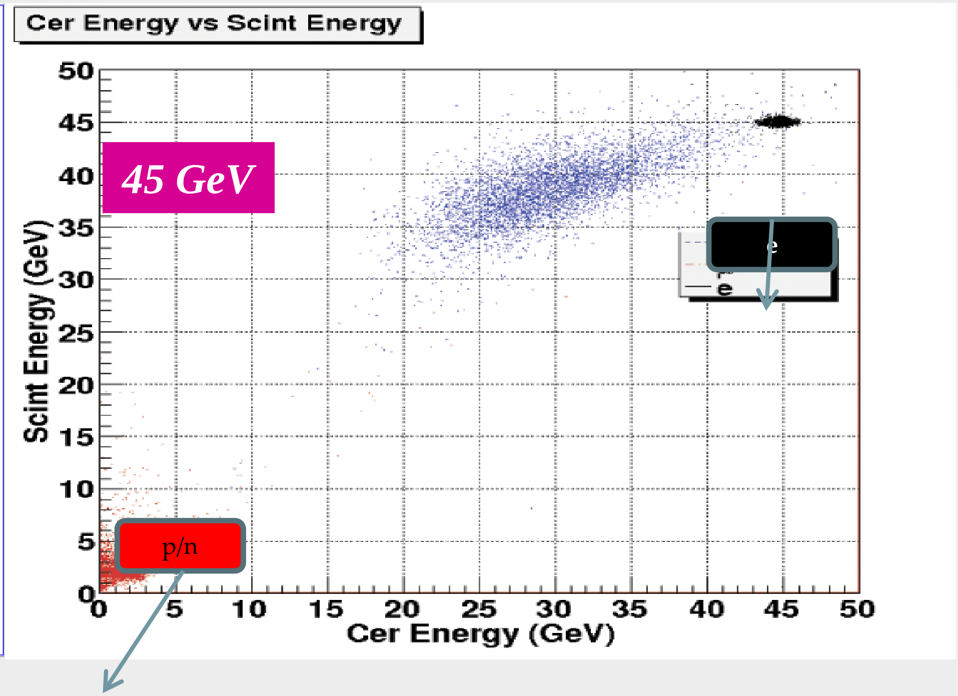
PFA + Dual-readout (with psec timing)= Ultimate calorimetry (6D)

ADRIANO PID @ 100MeV vs 45 GeV

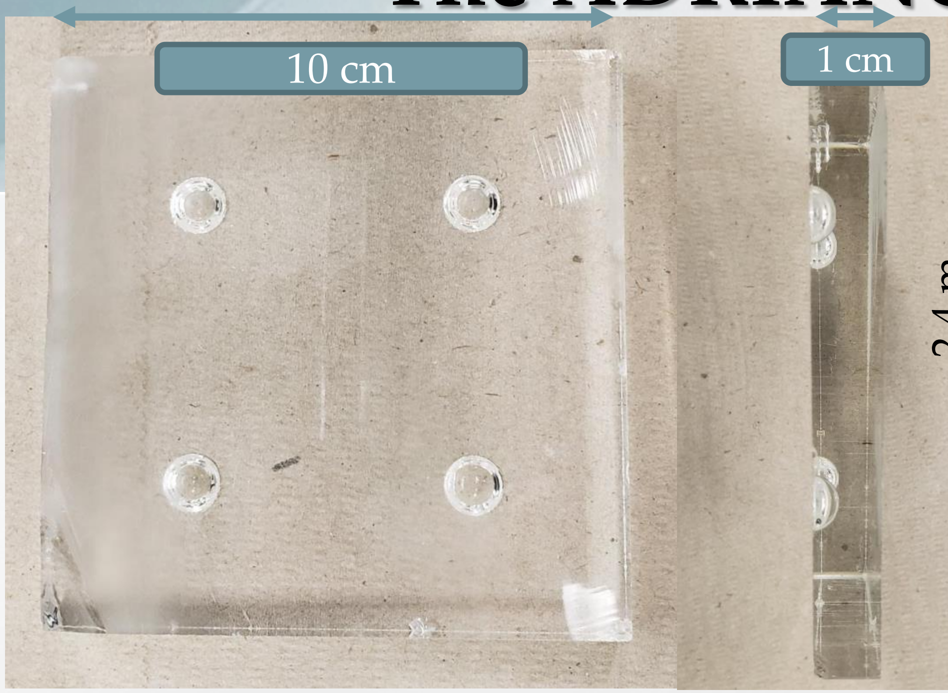
- High energy vs low energy implementations depend on ratio of plastic vs Pb-glass
- Integrally active layout makes it a EM and HAD calorimeter at the same time

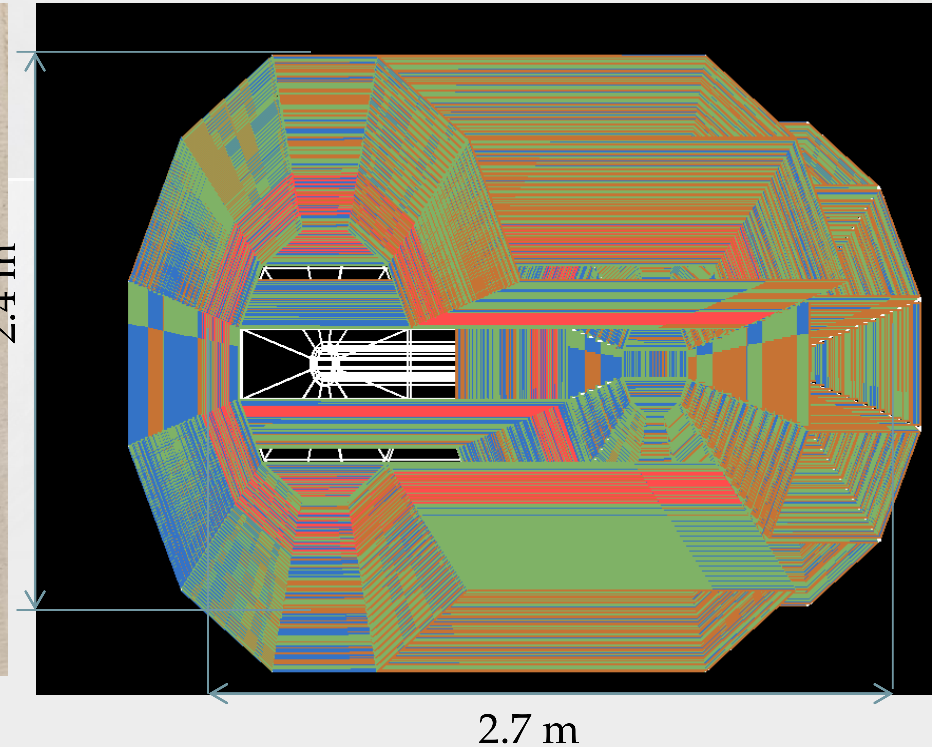
PID from C vs S





The ADRIANO2 Calorimeter



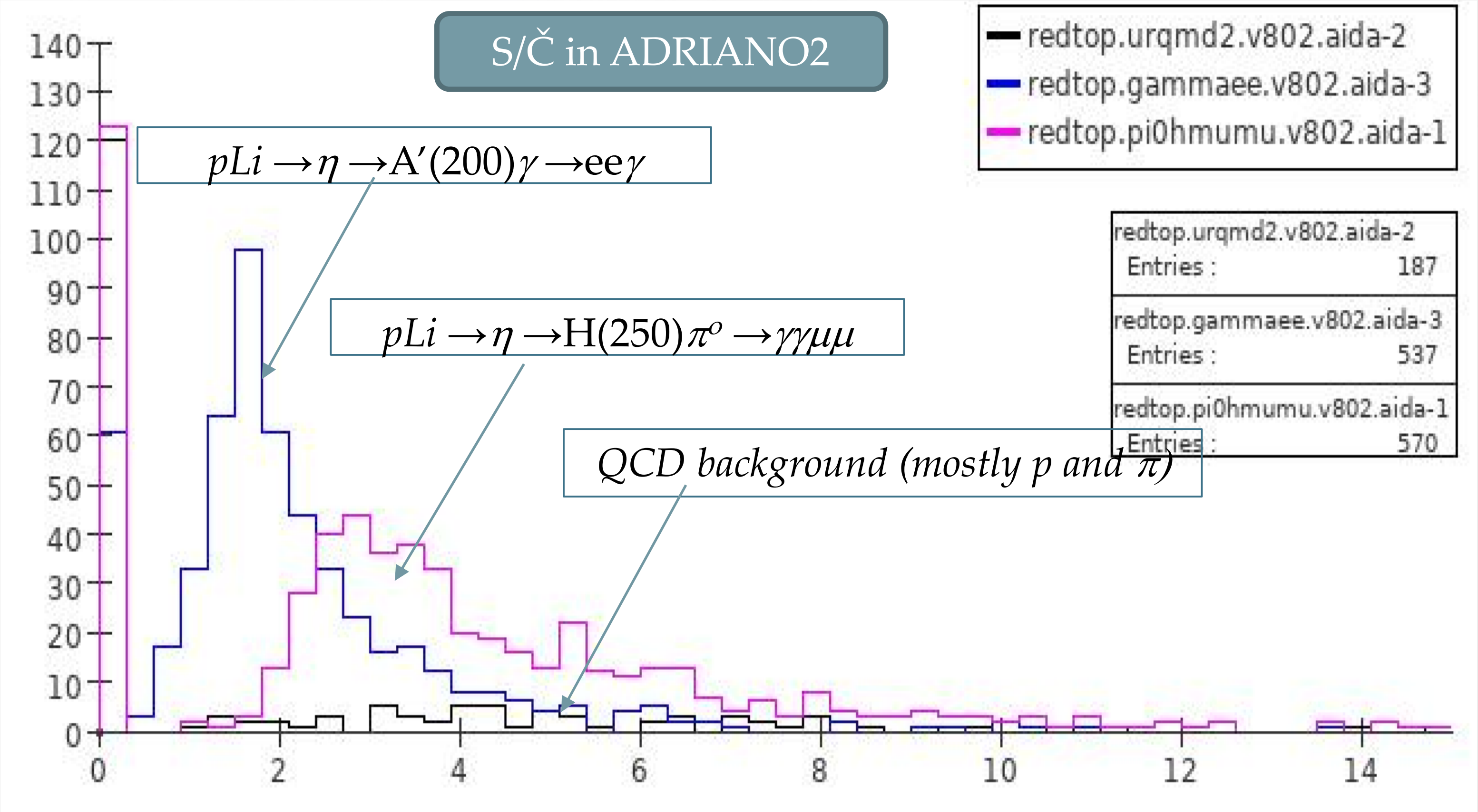


- Sandwich of small Pb-glass and scintillating tiles
- Direct SiPM/SPAD readout (with or without dimple)
- Pb-glass: 3x3x1 cm^3 – Plastic: 3x3x0.4 cm^3 – CALICE style
- 53+53 layers – 75 cm deep – 35 X_0 (~3 λ)
- ~750,000 tile pairs (~1.5x10^6 channels – vs 6x10^6 of CMS HGCAL)
- 27 Tons in 12 sectors
- 50 psec timing with prompt Cerenkov light from Pb-glass
- Triple readout when adding waveform digitizer to FEE

ADRIANO2 input to L0/L1 Trigger

- L0 input: total Č signal
- L1 input: TOF + S/Č
- L2: PFA (**not implemented yet**)

10,000x rejection factor



CP and T violation with muon polarimetry

- In the SM, the Higgs boson is a CP-even scalar
- Many extensions of the SM introduce additional Higgs possibly CP-odd
- boson mass eigenstates could be mixtures of even and odd CP states.
- In the SM, couplings of the Higgs boson to bosons and fermions are CP conserving,

- ***CP*** invariance does not allow the μ in $\eta \to \mu^+\mu^-$ to be longitudinally polarized.
- Any polarization requires a ***CP*** violating lepton-quark current.
- Since in the minimal SM the polarization of the μ is not observable, an immediate implication of observing a non-zero longitudinal polarization of the muons is the existence of an extra Higgs boson.
- If that is the case, then the μ polarization would be as high as 10^{-2}.

- *T* invariance requires a null transverse polarization of the μ in $\eta \to \pi^0\mu^+\mu^-$ *and* $\eta \to \gamma\mu^+\mu^-$
- Any observed polarization is a direct violation of T invariance.

- ***The Higgs can also decay into*** $\to \tau^+\tau^-$

Origin	$P_{\tau 1}$	$P_{\tau 1}$	Probability
Neutral Higgs boson	+1	-1	0.5
	-1	+1	0.5
Neutral vector boson Z/γ^*	+1	+1	$p_\tau z$
	-1	-1	$1 - p_\tau z$

CPT violation with γ and μ polarimetry

- *CPT* invariance can be probed with the following two processes:
- $\eta \rightarrow \pi^+\mu^-\nu$ *vs* $\eta \rightarrow \pi^-\mu^+\nu$
- If CPT holds, then we expect that the transverse polarization of the μ^- and that of the μ+ be reversed. Namely, $PT(\mu^+) = -PT(\mu^-)$. As an aside note, the $\eta \rightarrow \pi\mu\nu$ has not been observed yet.

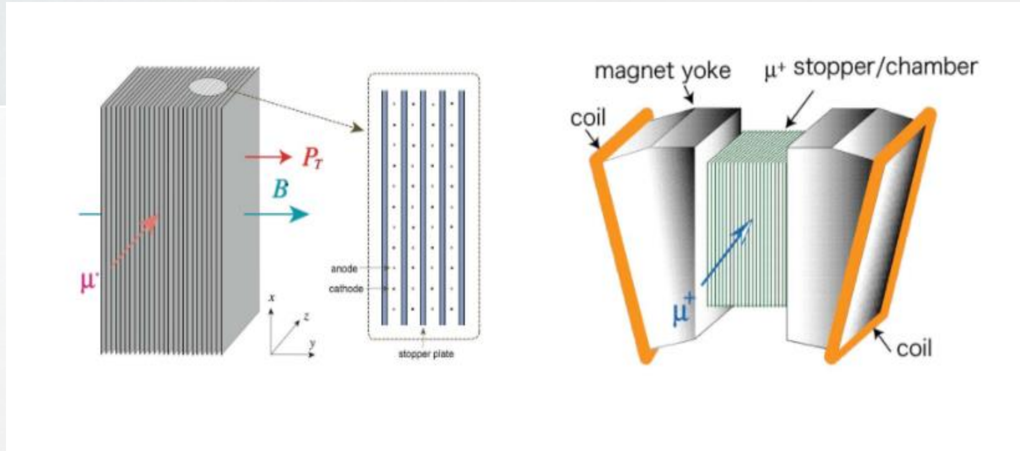
- CPT invariance and hermiticity of the lagrangian implies that in the following processes:
- $\eta \rightarrow \gamma\gamma$ *and* $\pi^o \rightarrow \gamma\gamma$
- the photons have null circular polarization.

Calorimeter vs Polarimeter

- A polarimeter measure the angle of a particle decaying inside a uni-directional B-field
- Asymmetry wrt the B-directions indicate a non-zero polarization
- Requirements of a polarimeter:
  - Large density to induce the decay
  - Absorber must not change the initial polarization
  - PID to identify the decaying particle
  - Sufficient granularity to measure the angle

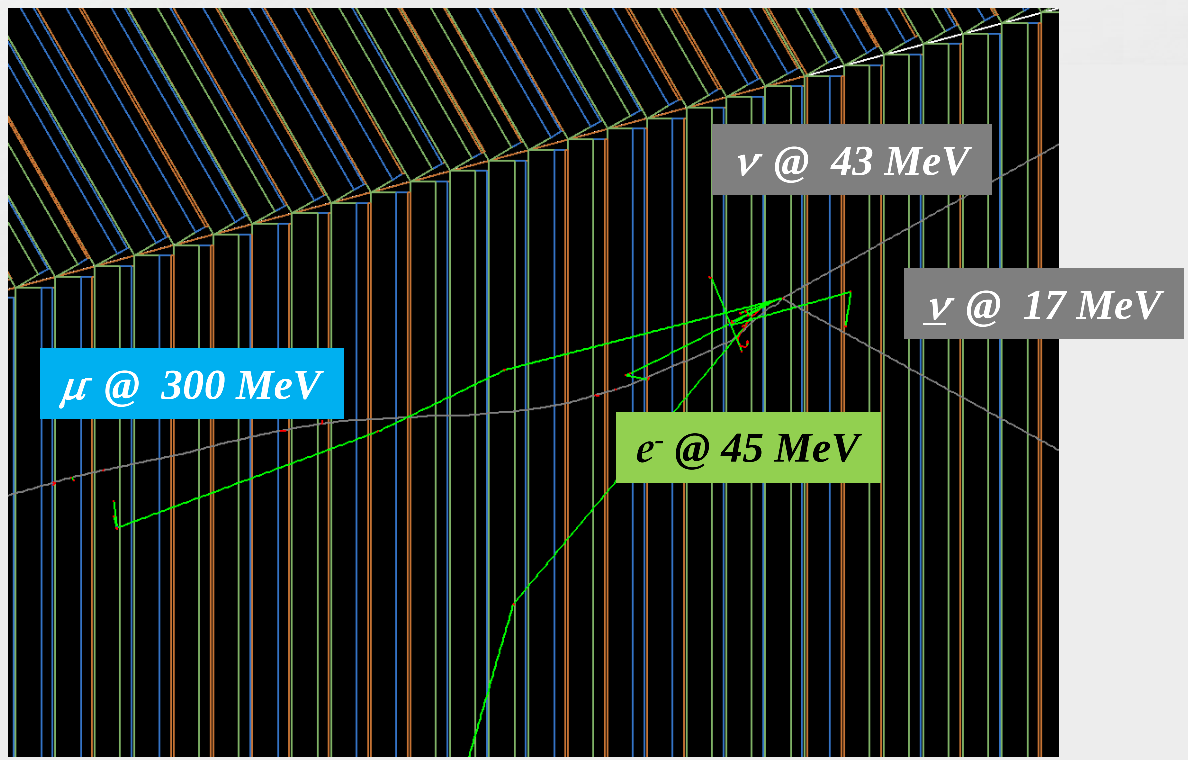
TREK vs ADRIANO2

TREK active polarimeter



ADRIANO2 calorimeter

Dual-readout for μ identification



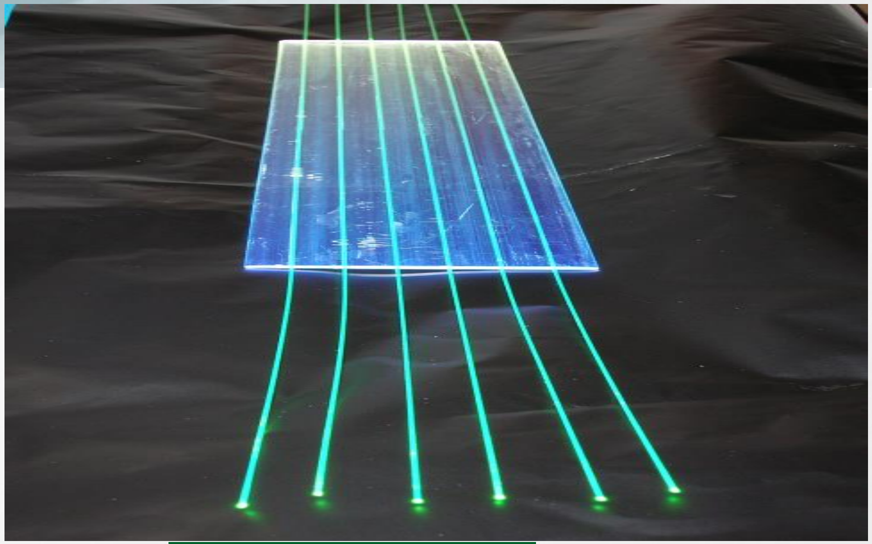
Some History of ADRIANO R&D

A **D**ual-**R**eadout **I**ntegrally **A**ctive **N**on-segmented **O**ption

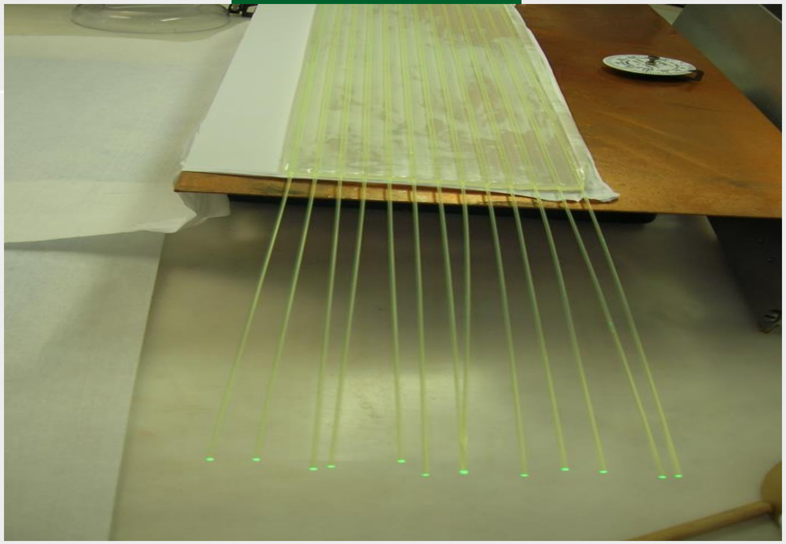
ADRIANO for Low Energy (ORKA)

2013

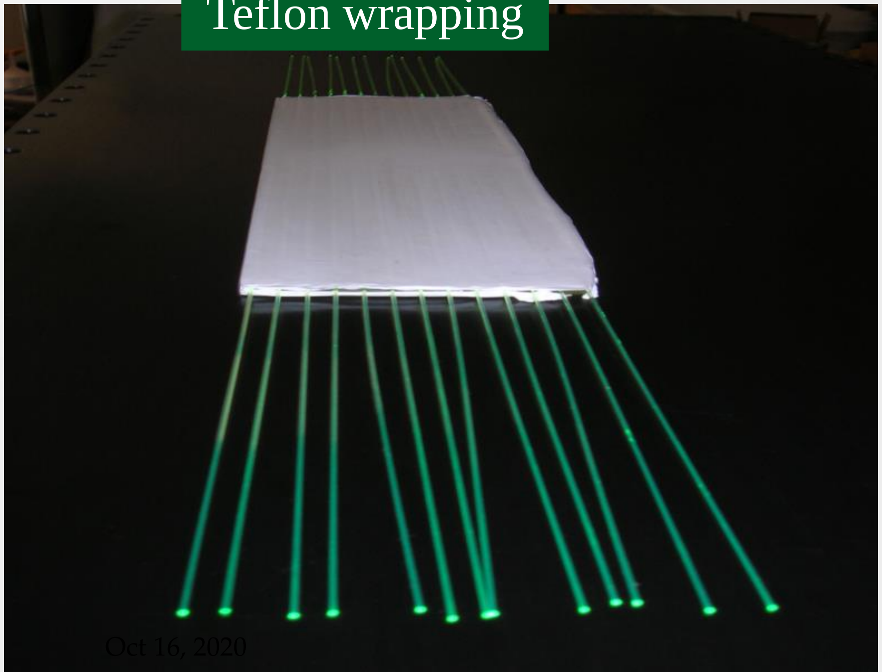
WLS + scintillator



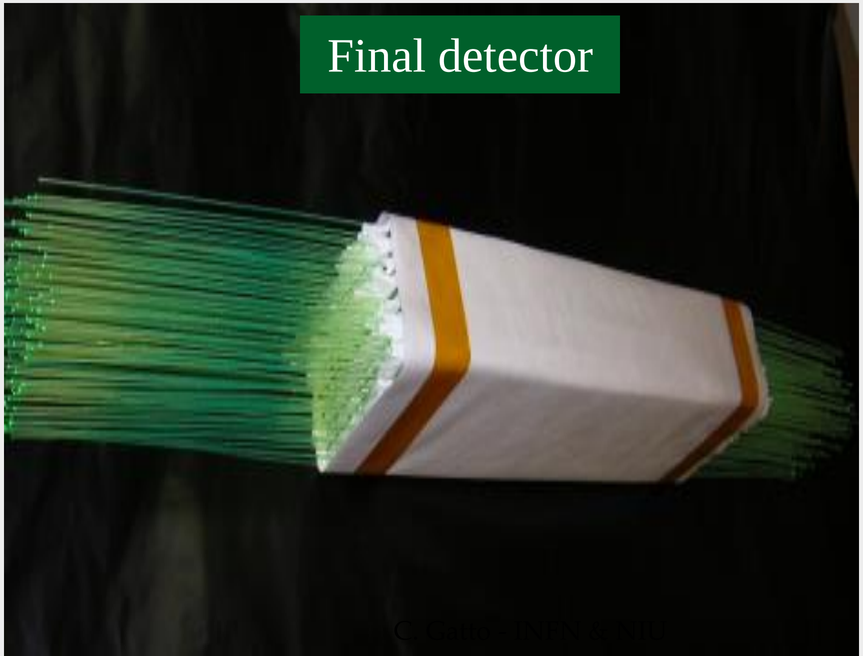
WLS + glass



Teflon wrapping

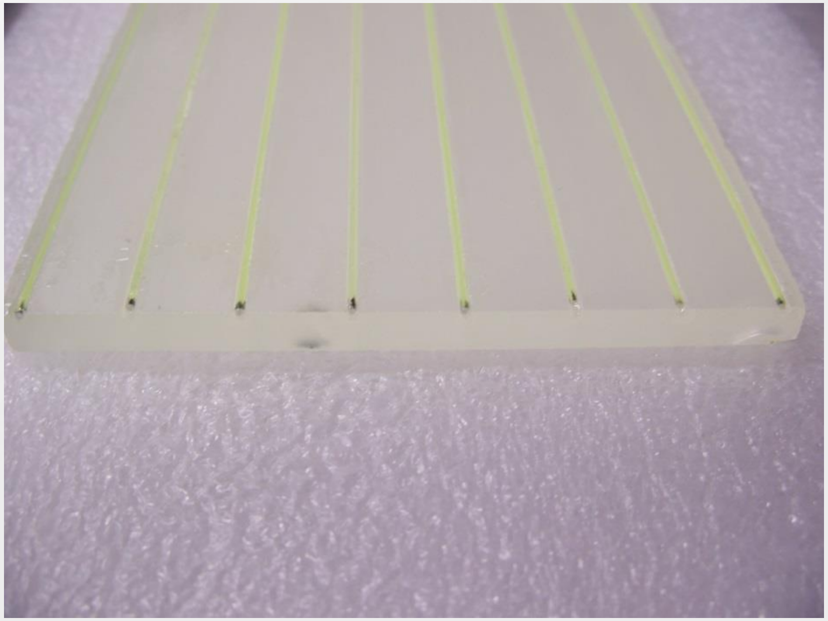


Final detector

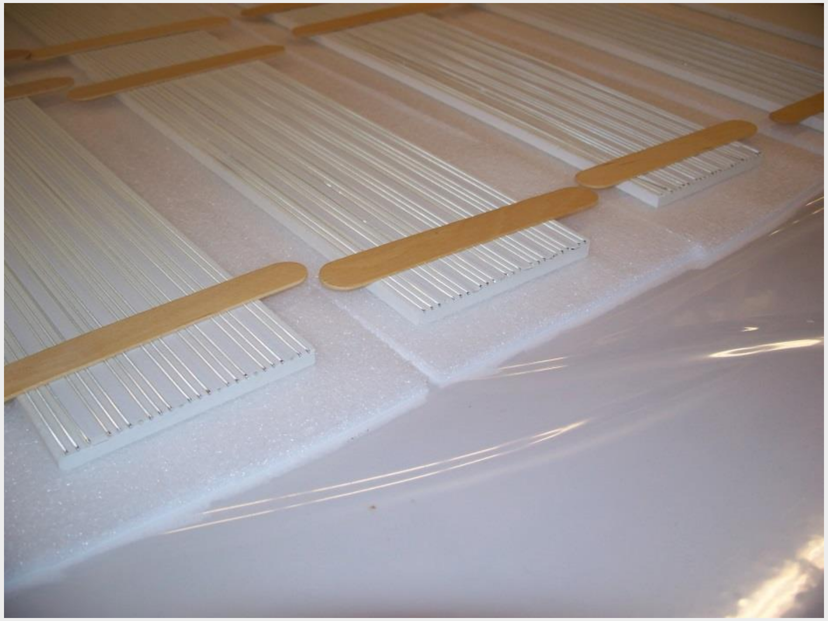


ADRIANO for High Energy

- Two versions built: scifi and scintillating plates (2014)
- 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



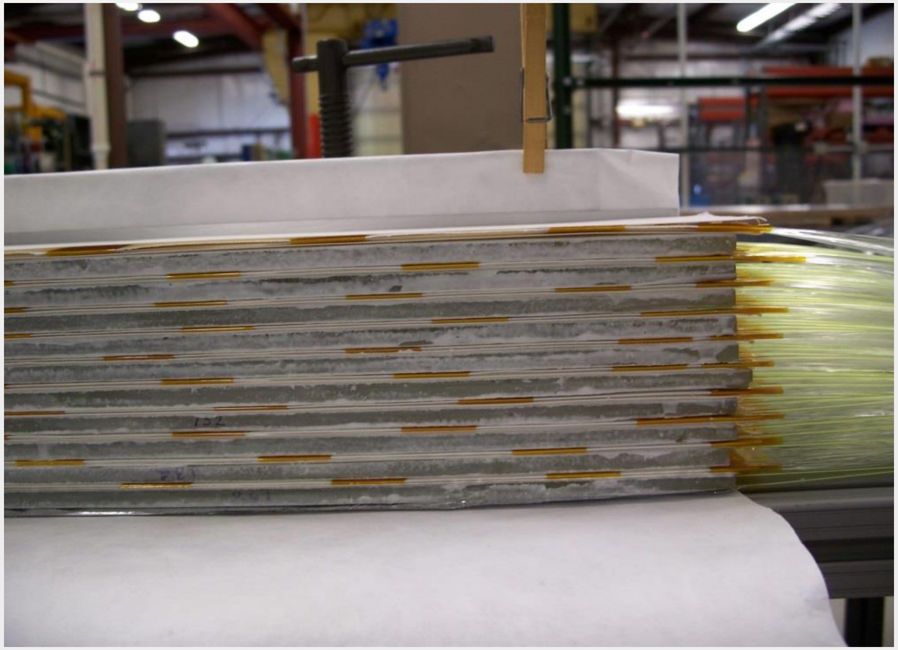
ADRIANO 2014B: 23 grooves

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)

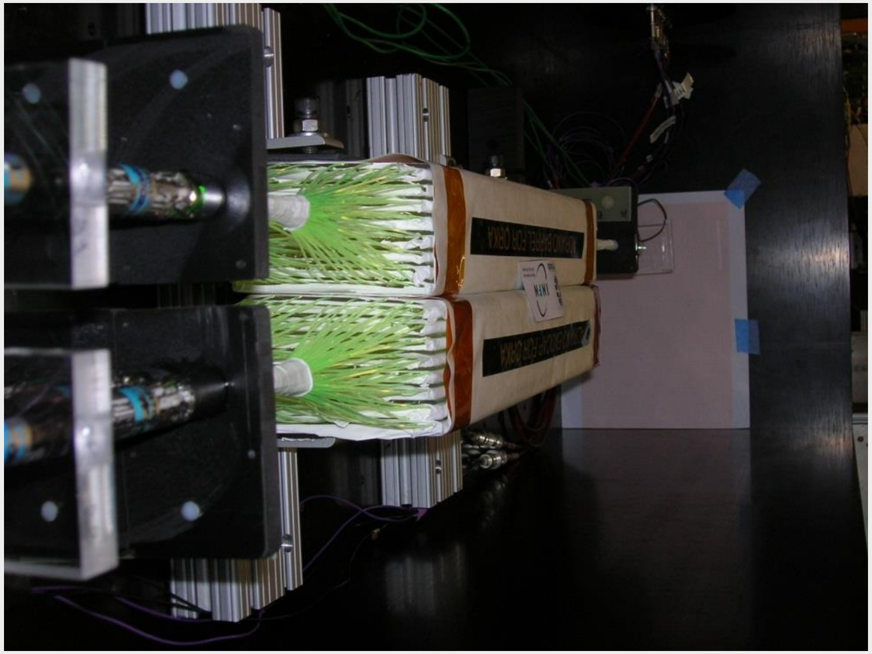
- Thicker glass
- Thin scintillating fibers or ribbons
- Fewer WLS fibers



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

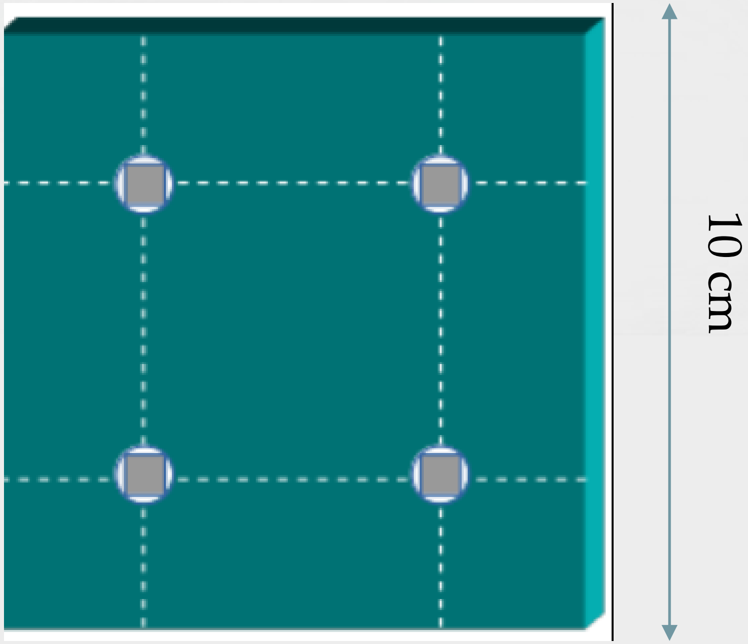
	ADRIANO 2014A	ADRIANO 2014B
Scintillation L.Y.	523 pe/GeV	256 pe/GeV
Čerenkov L.Y.	**354 pe/GeV**	**338 pe/GeV**
% scint. energy	6.0% @ 4 GeV	1.14% @ 4 GeV
% Cher. energy	94% @ 4 GeV	98.86% @ 4 GeV
% visible energy	89.7% @ 4 GeV	89.7% @ 4 GeV
Scint. pe/deposited energy [MeV]	0.215 GeV@ 4gev Or 18 pe/MeV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

From ADRIANO to ADRIANO2

Last ADRIANO test beams: 2015-2016

ADRIANO2 radiator (diagram)



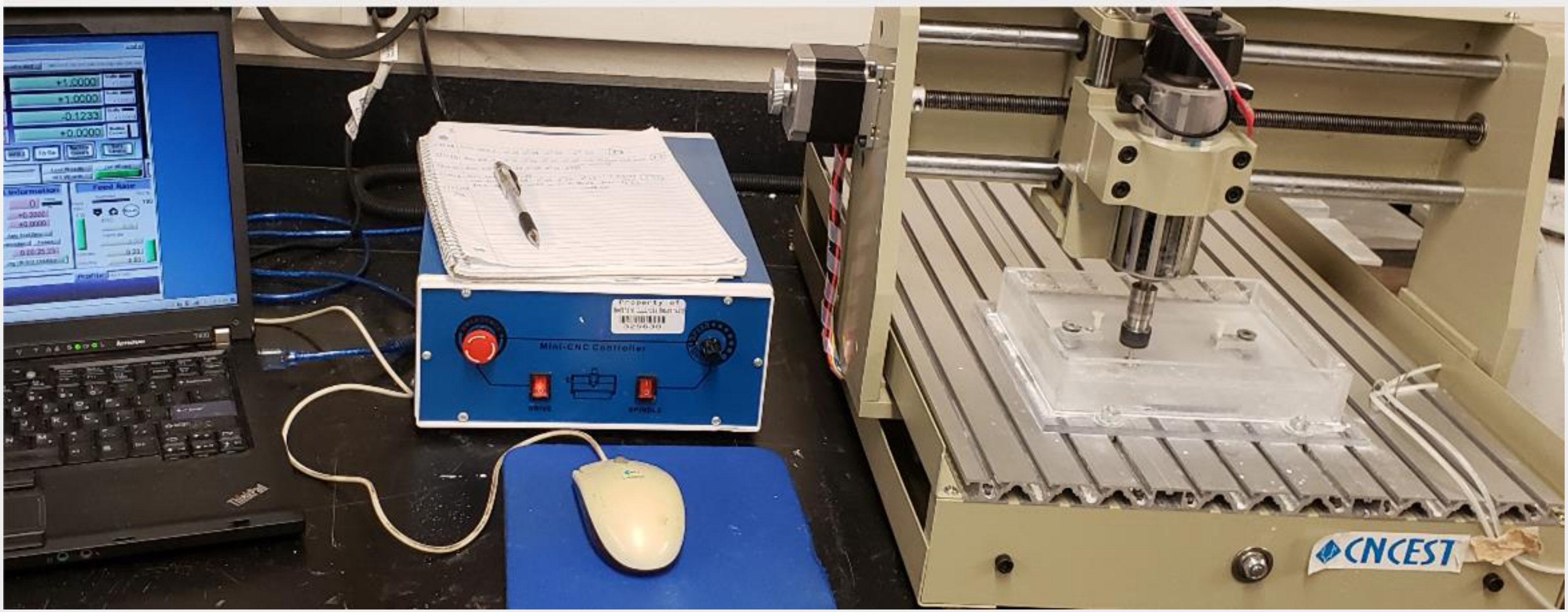
- Log style replaced by tiles CALICE style (but larger)
- light capture with wls fiber replaced by on-tile Sipm's
- FEE on tile

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

Casting resin

GAC-200

Glazing

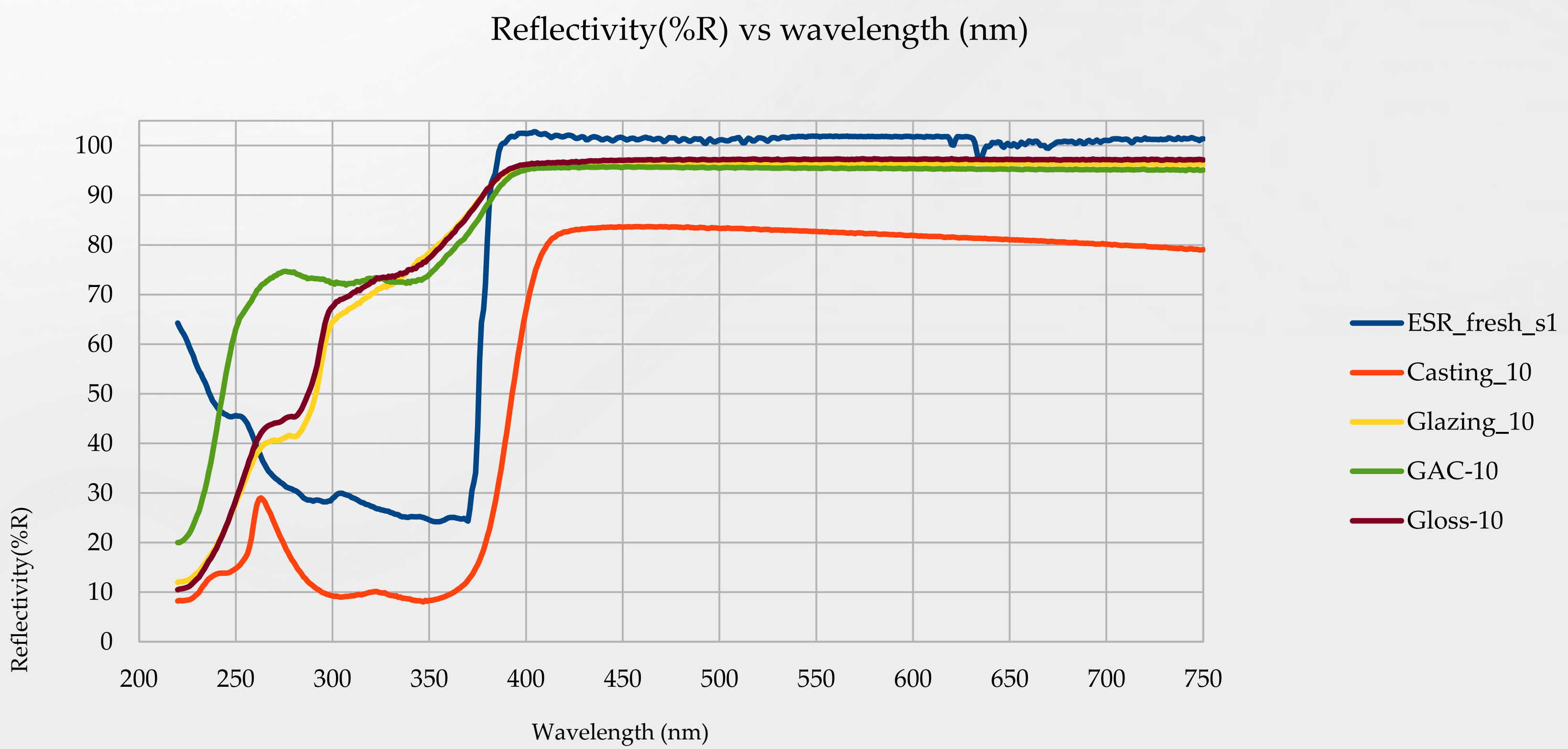
The final Tile

- Test Beam Radiators

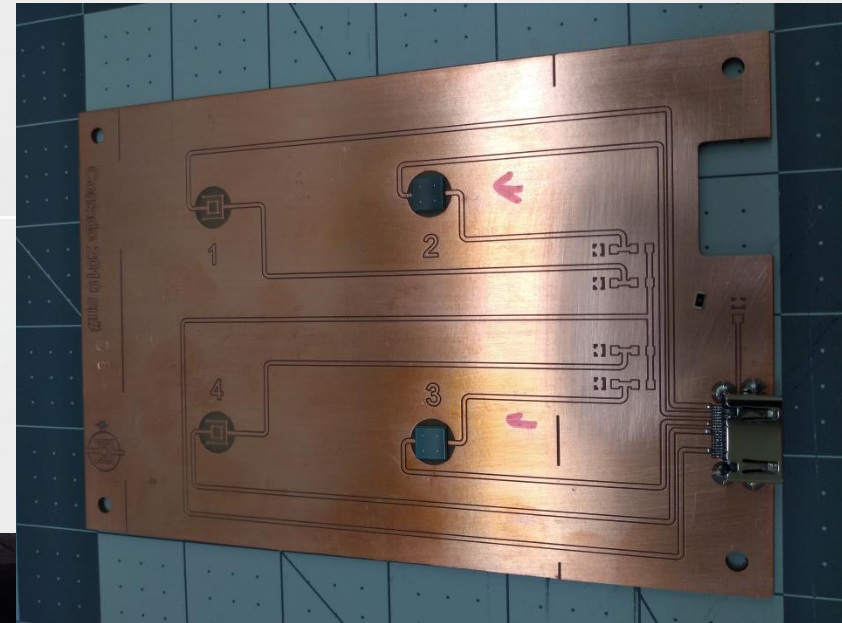
➢ We had chance to test 3 Cerenkov radiators: Barium sulfate coated and ESR2000 wrapped (with optical goo) & ESR wrapped with no optical glue

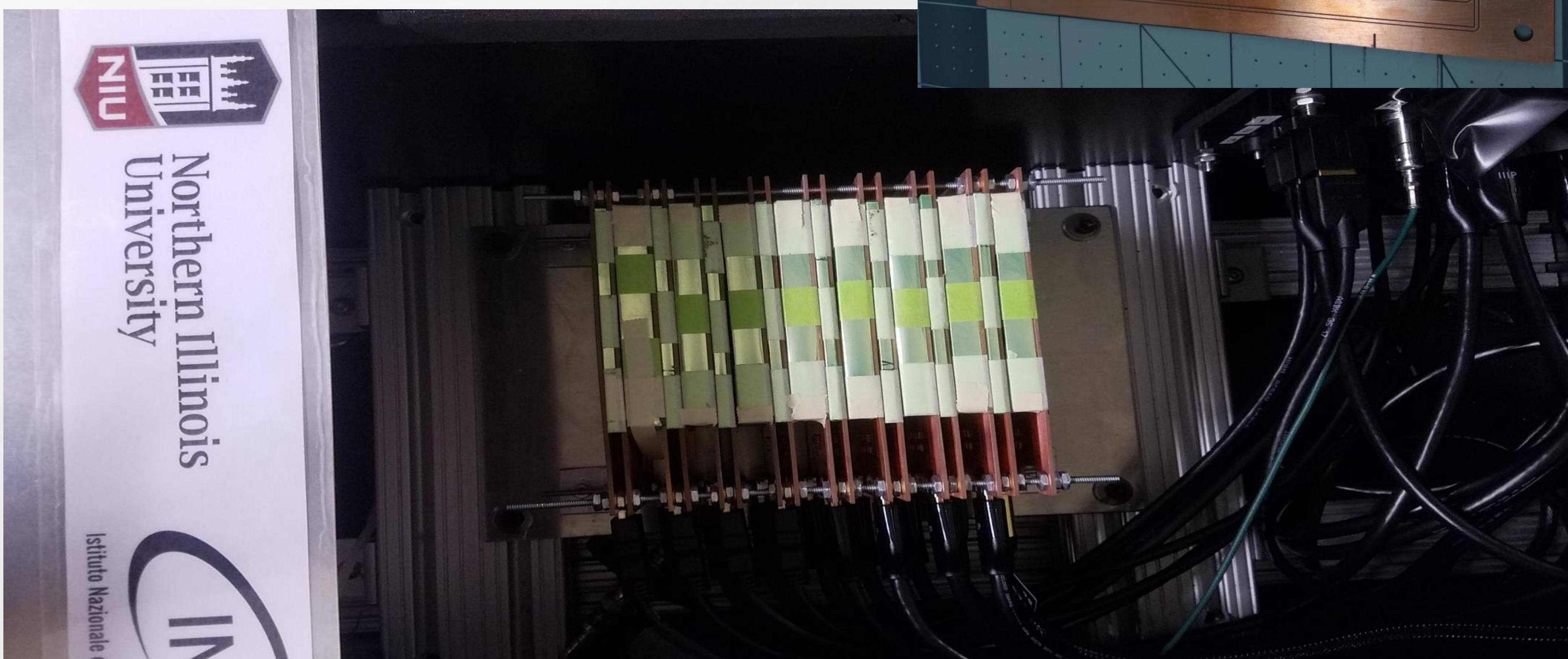
Reflectivity Measurements

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

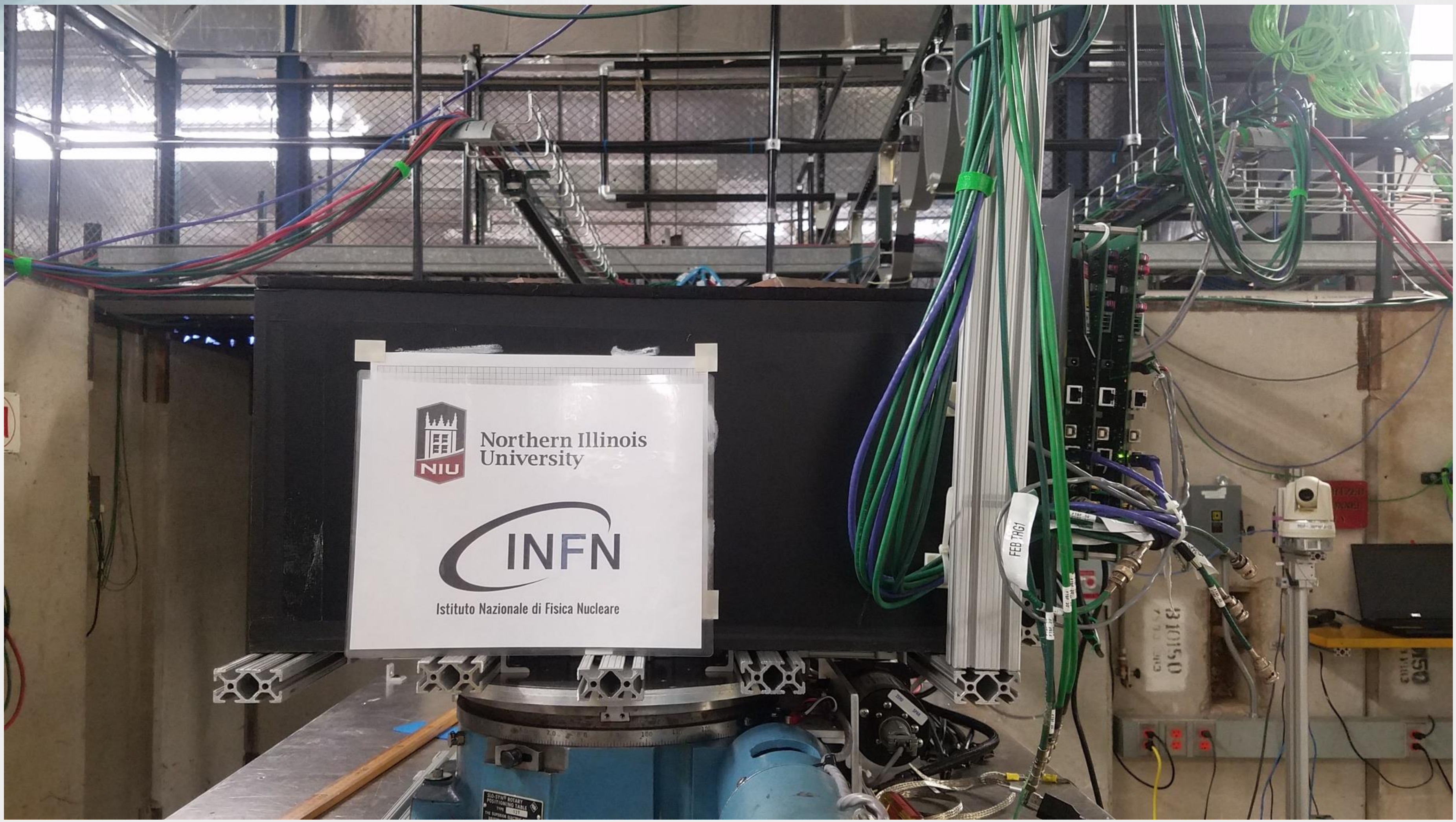


Final Detector Assembly 2019

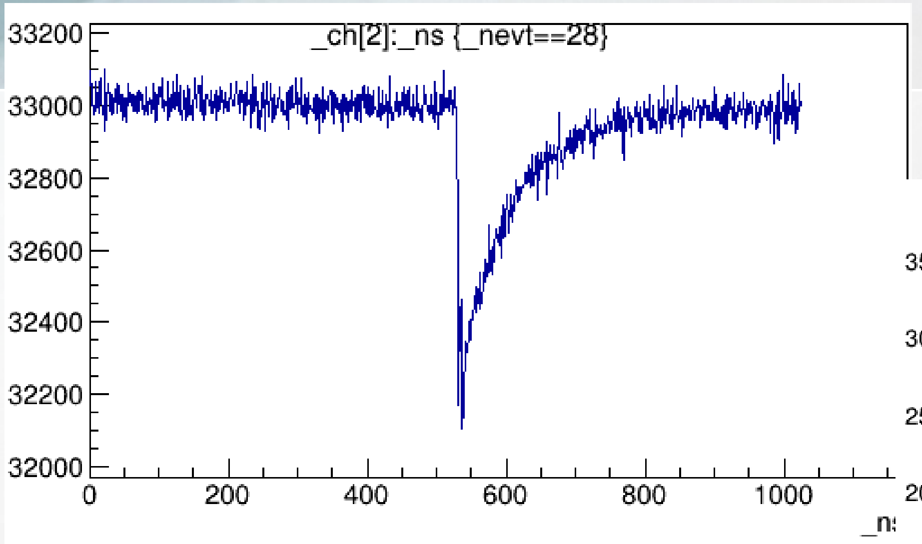


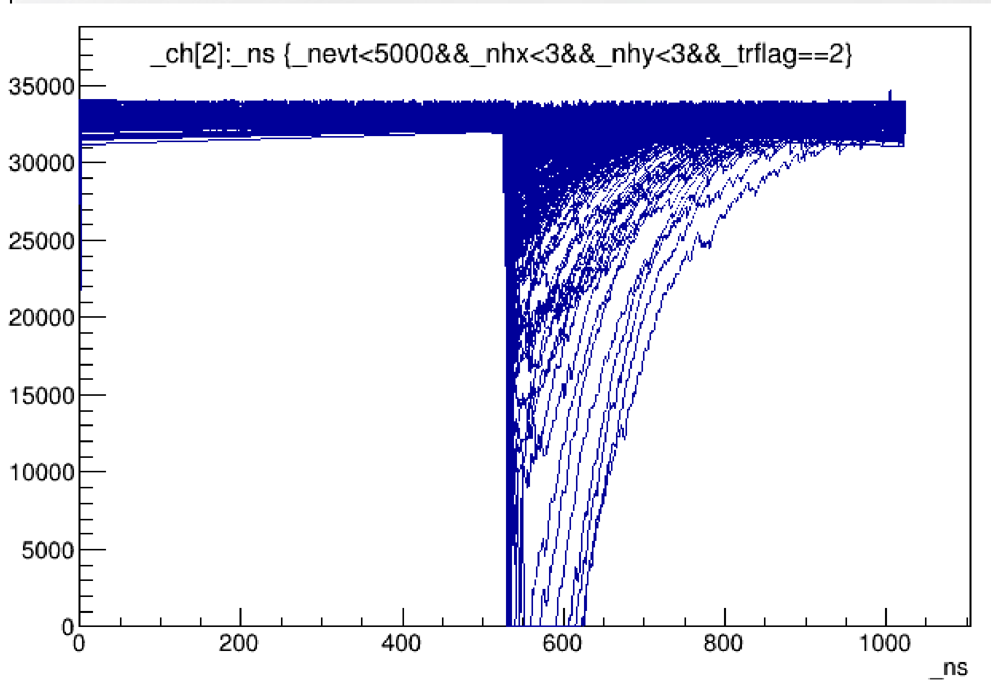


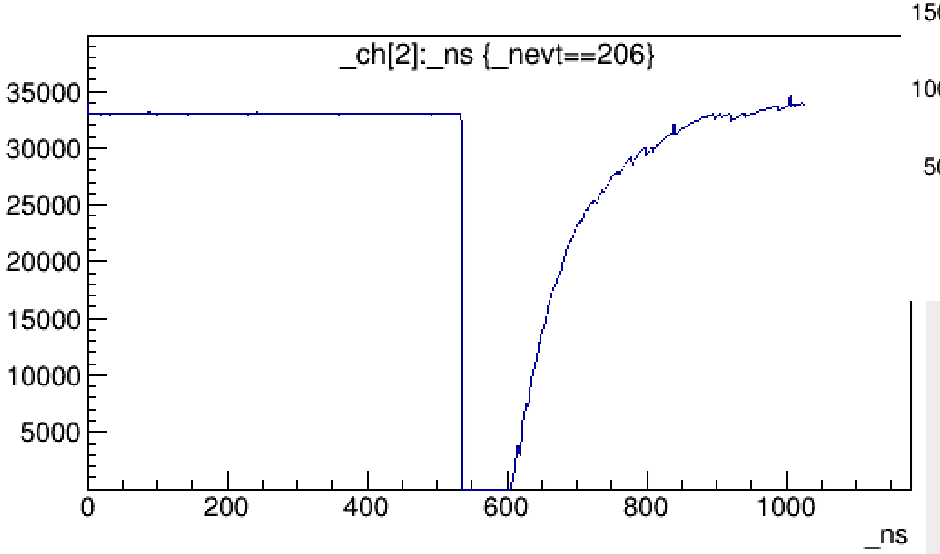
January 2020 Test Beam at Fermilab



Few Waveforms



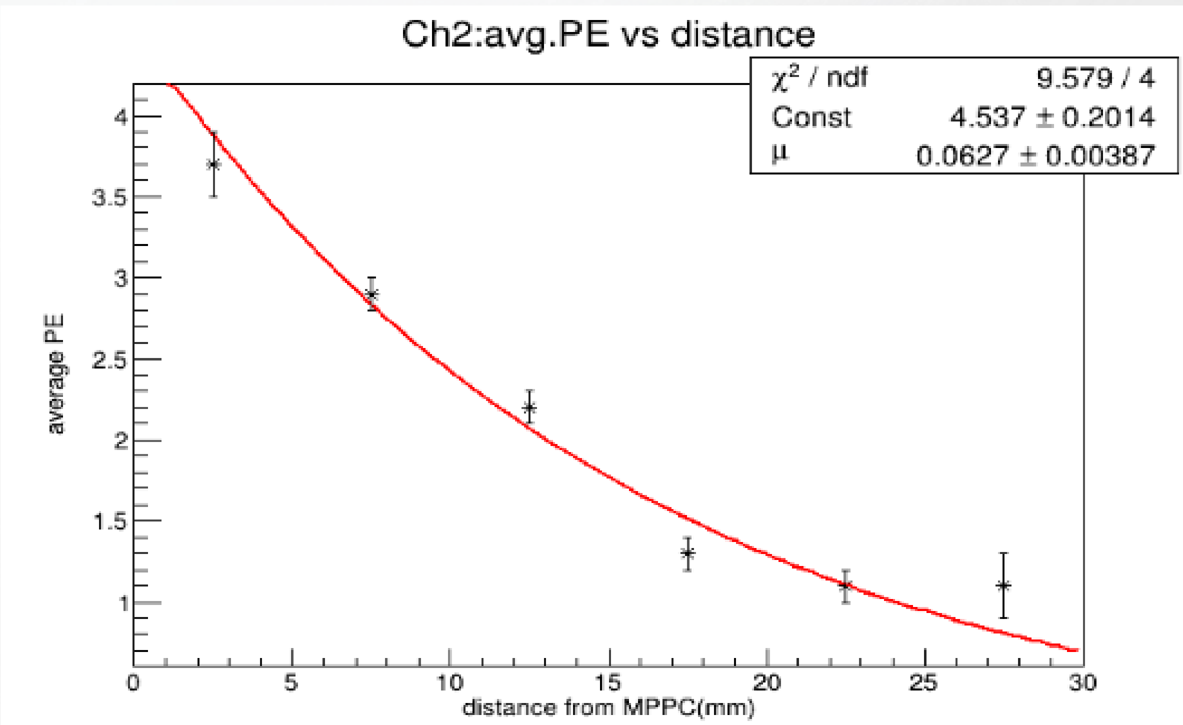


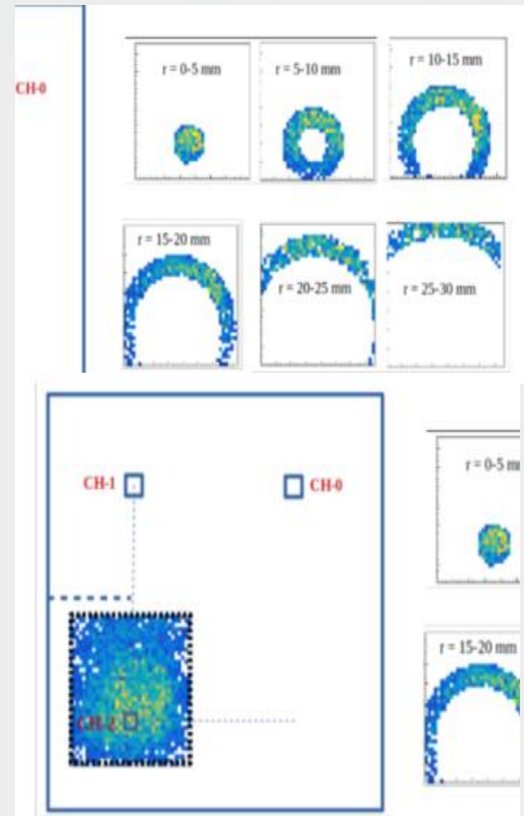


Preliminary Analysis

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





A Path Forward

- PFA + Dual-Readout = 6D (5D+PID) calorimetry
- CALICE opened the door to dual-readout techniques with high-granular calorimetry
- A DOE grant was obtained recently by NIU and KU for a preliminary generic R&D on ADRIANO2
- Fermilab joined with KA-25 funds and support with one EE (S. Loz)
- Two test beam planned at MTEST: fast timing is the goal
- Need assistance to implement PFA with ADRIANO2
- Can ILC and EIC benefit from that?

Conclusions

- ADRIANO2 is, ultimately, a CALICE-style calorimeter with an active absorber (Pb-glass)
- Plastic tiles can be replaces by other, non-Cerenkov techniques (ex. Si-pixels).
- Čerenkov ligth yield adequate for 25-30%/√E hadronic calorimetry. It can be improved further with PFA (especially at low energy).
- EM resolution is expected about 5%/√E
- PFA expected much better than dual-readout at low energy
- But, integrally active dual-readout still king for EM calorimetry
- Focus for future is on a 6D (5D + PID), tiled version of ADRIANO based on Calice + T1015 techniques
- Received grant from DOE for preliminary R&D

Backup Slides

REDTOP detector

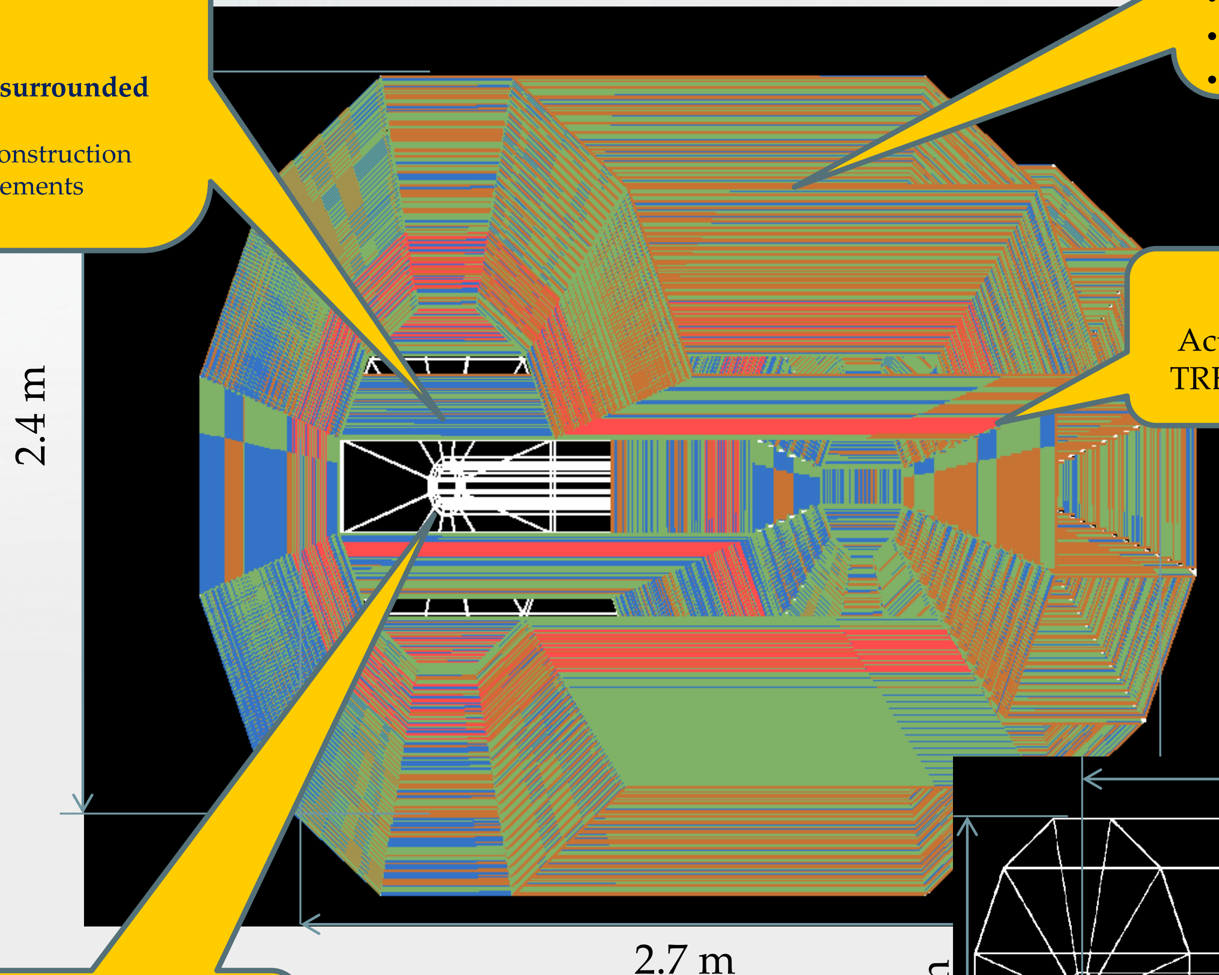
Optical TPC
- ~ 1m x 1.5 m
- CH_4 @ 1 Atm
- 5x10^5 Sipm/Lappd
- 98% coverage
- OR

or

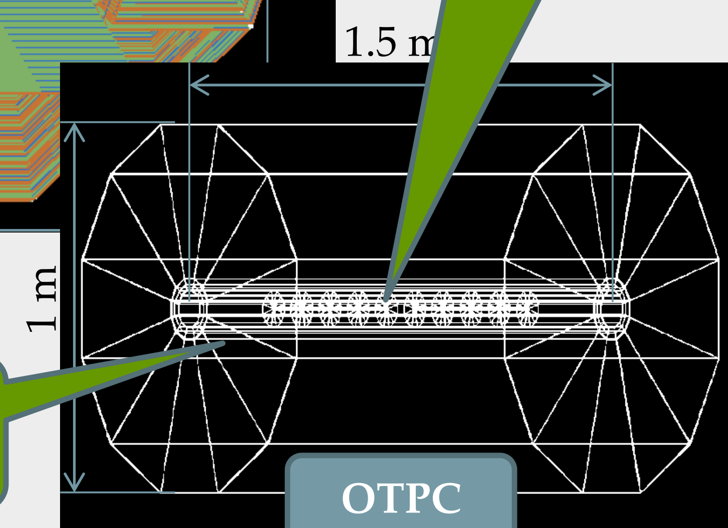
LGAD Tracker surrounded by Quartz cells
For 4D track reconstruction and TOF measurements

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

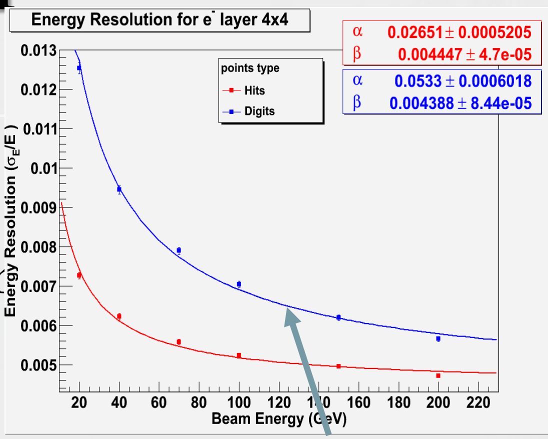


Fiber tracker
for rejection of g-conversion and vertexing

Aerogel
Dual refractive index system

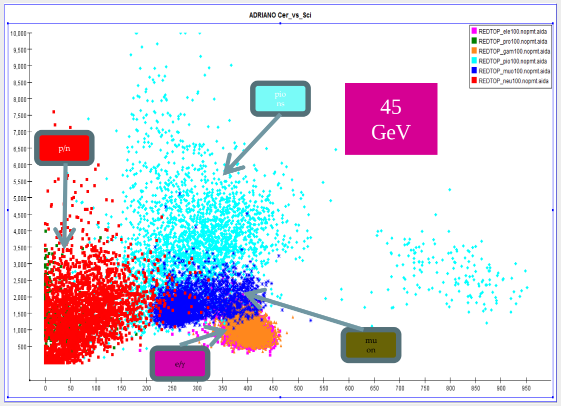
ADRIANO for High Intensity Experiments

- 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)



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

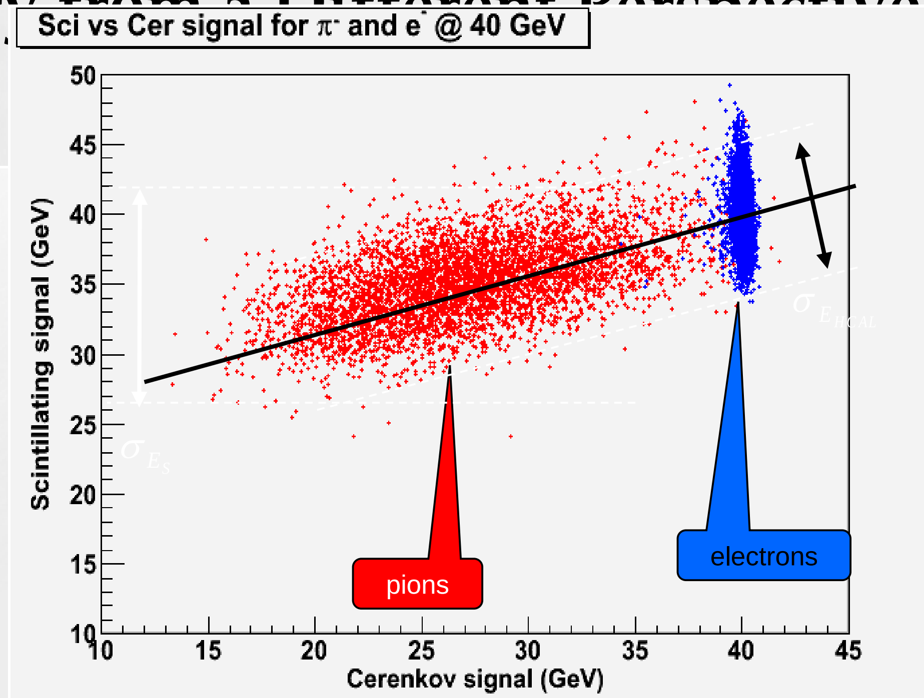
PID from C vs S



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}

η Factory vs Higgs Factory

- The η and Higgs have the exact quantum numbers (except for parity). They are both Goldstone bosons
- They are all 0: almost unique in the SM particle zoo
- Key mesons in the search for New Physics
- Light dark matter must be neutral under SM charges, otherwise it would have been discovered at previous colliders [G. Krnjaic]