THE UNIVERSITY OF IOWA

Calorimetry R&D for Future Lepton Colliders

Y.Onel

University of Iowa

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Calorimetry for Future Lepton Colliders

- Should be able to reflect the advancements in both concept and technology
- Should be able to comply with future new physics requirements (with best estimates)
- Should have strong evidence that it will work

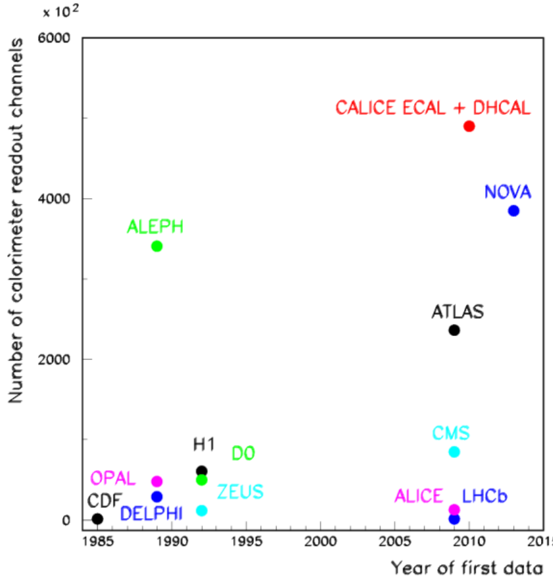
The Digital Calorimeter Project

RPC – based imaging calorimeter

DHCAL = First large scale calorimeter prototype with

Embedded front-end electronics
Digital (= 1 – bit) readout
Pad readout of RPCs (RPCs usually read out with strips)

DHCAL = World record channel count for calorimetry



Argonne National Laboratory
Boston University
Fermi National Accelerator Laboratory
IHEP Beijing
Illinois Institute of Technology
University of Iowa
McGill University
Northwestern University
University of Texas at Arlington

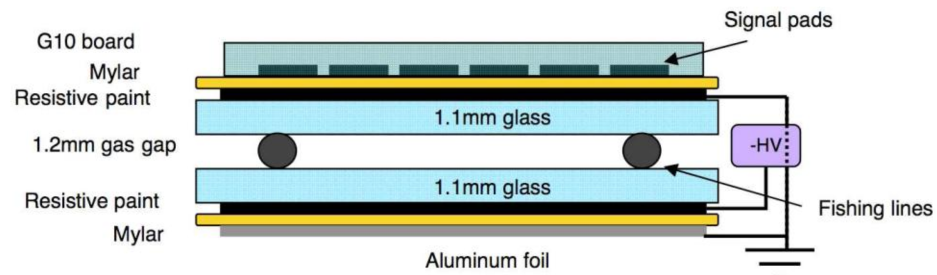
DCHAL Collaboration	Heads
Engineers/Technicians	22
Students/Postdocs	9
Physicists	10
Total	**41**

…and integral part of CALICE Calorimeter for ILC

1 m^3 – Digital Hadron Calorimeter Physics Prototype

Description

Readout of 1 x 1 cm^2 pads with one threshold (1-bit) → **Digital Calorimeter**
Layers inserted into the existing CALICE Analog (scintillator) HCAL and TCMT structures
38 layers in DHCAL and 14 in tail catcher (TCMT), each ~ 1 x 1 m^2
Each layer with 3 RPCs, each 32 x 96 cm^2
~480,000 readout channels



Purpose

Validate DHCAL concept
Gain experience running large RPC systems
Measure hadronic showers in great detail
Validate hadronic shower models (Geant4)

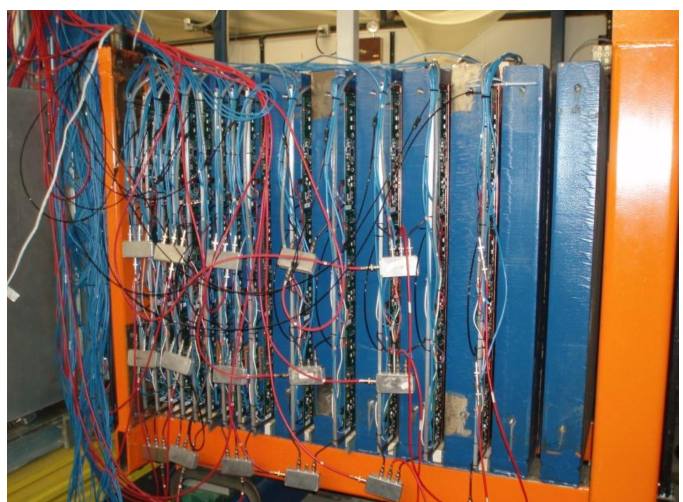
Status

Started construction in 2008
Completed in 2010
Several test beam campaigns at Fermilab

The DHCAL in the Test Beam

Run	Date	DHCAL layers	RPC_TCMT layers	SC_TCMT layers	Total RPC layers	Total layers	Readout channels
Run I	10/14/2010 – 11/3/2010	38	0	16	38	54	350,208+320
Run II	1/7/2011 – 1/10/2011	38	0	8	38	46	350,208+160
	1/11/2011 – 1/20/2011	38	4	8	42	50	387,072+160
	1/21/2011 – 2/4/2011	38	9	6	47	53	433,152+120
	2/5/2011 – 2/7/2011	38	13	0	51	51	470,016+0
Run III	4/6/2011 – 5/11/2011	38	14	0	52	52	479,232+0
Run IV	5/26/2011 – 6/28/2011	38	14	0	52	52	479,232+0
Run V	11/2/2011 – 12/6/2011	50	0	0	50	50	460800

~ 480K readout channels
~ 35M events



General DHCAL Analysis Strategy

Noise measurement

- Determine noise rate (correlated and not-correlated)
- Identify (and possibly mask) noisy channels
- Provide random trigger events for overlay with MC events (if necessary)

Measurements with muons

- Geometrically align layers in x and y
- Determine efficiency and multiplicity in ‘clean’ areas
- Simulate response with GEANT4 + RPCSIM (requires tuning 3-6 parameters)
- Determine efficiency and multiplicity over the whole 1 x 1 m^2
- Compare to simulation of tuned MC
- Perform additional measurements, such as scan over pads, etc…

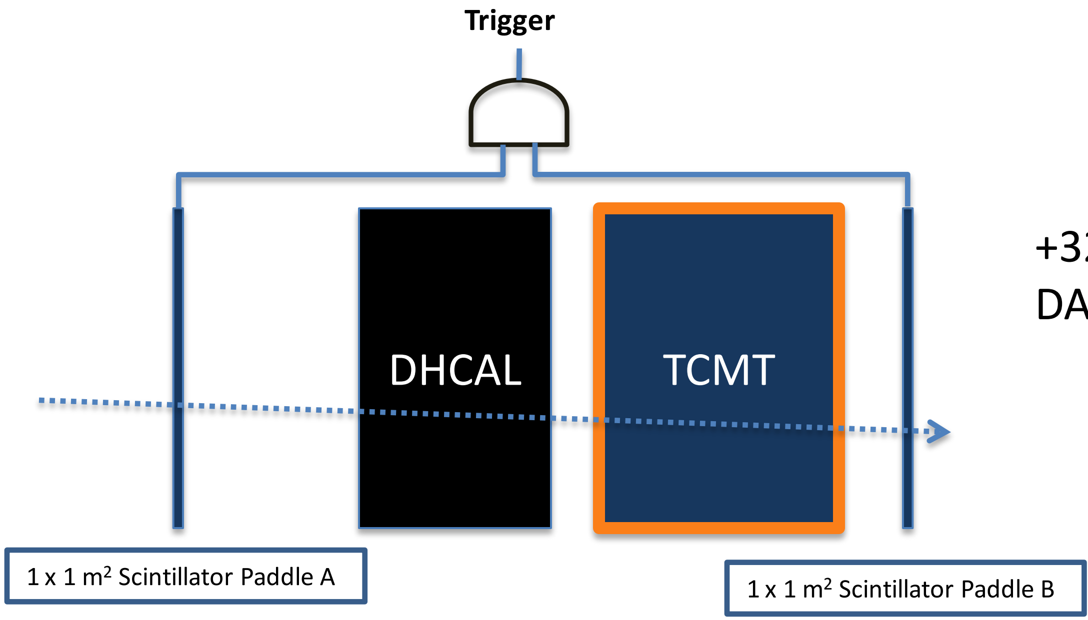
Measurement with positrons

- Determine response
- Compare to MC and tune 4^{th} (d_{cut}) parameter of RPCSIM
- Perform additional studies, e.g. software compensation…

Measurement with pions

- Determine response
- Compare to MC (no more tuning) with different hadronic shower models
- Perform additional studies, e.g. software compensation, leakage correction…

Beam and Trigger for Muon events



+32 GeV/c secondary beam + 3m Fe
DAQ rate typically 500 - 1000/spill

Run	# of muon events
October 2010	1.4 Million
January 2011	1.6 Million
April 2011	2.5 Million
June 2011	2.2 Million
November 2011	1 Million
TOTAL	**~ 9 Million**

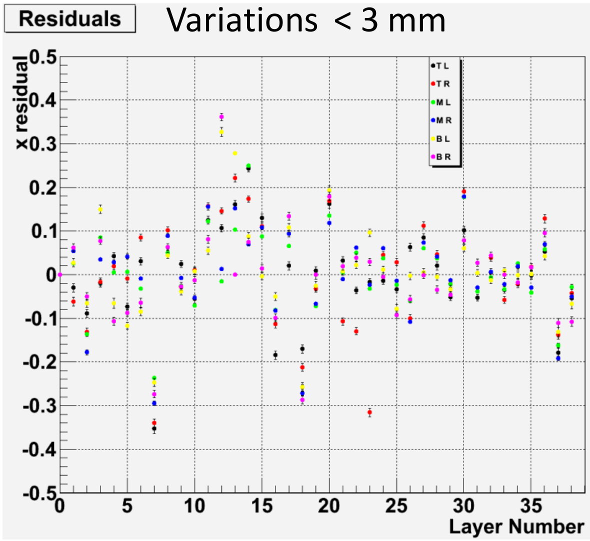
Alignment

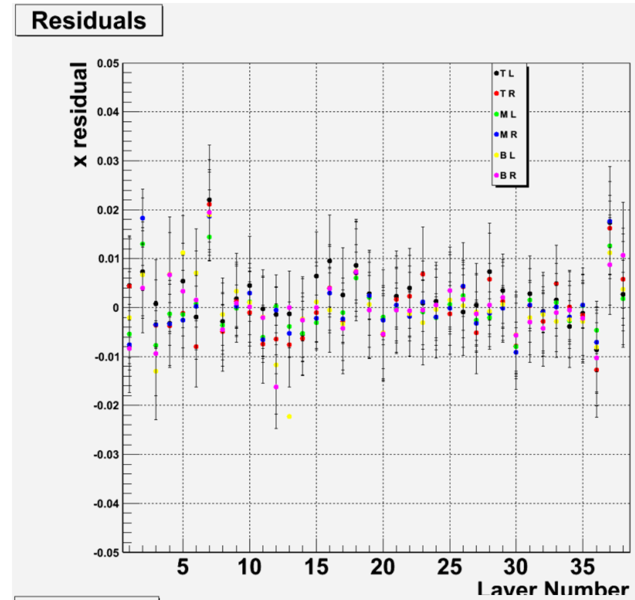
For each readout board i plot residual in x/y

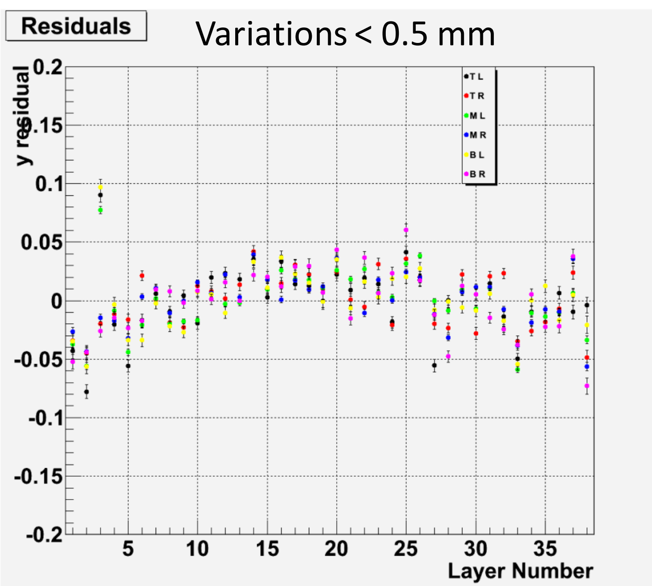
$R^i_x = x^i_{cluster} - x^i_{track}$

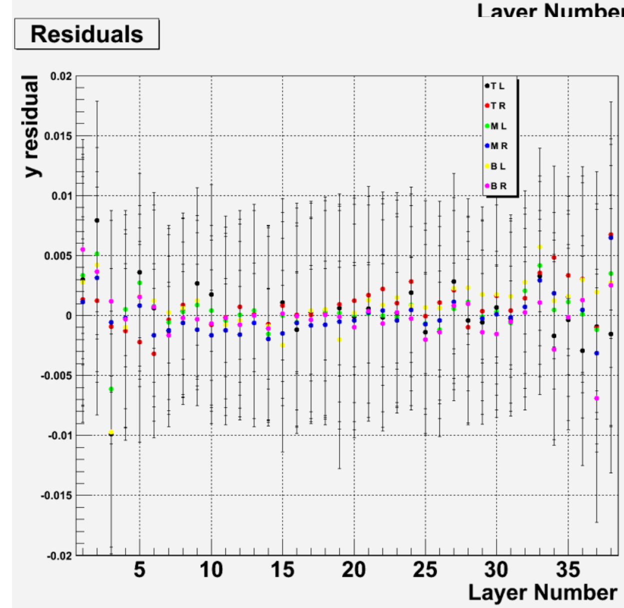
$R^i_y = y^i_{cluster} - y^i_{track}$

Dimensions in [cm]



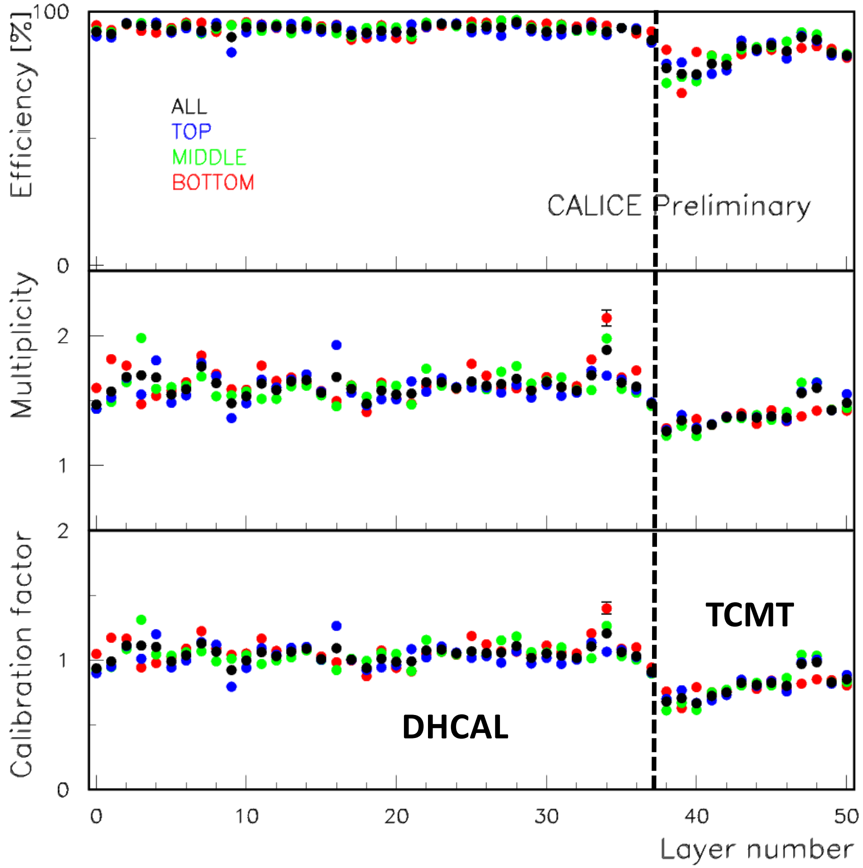


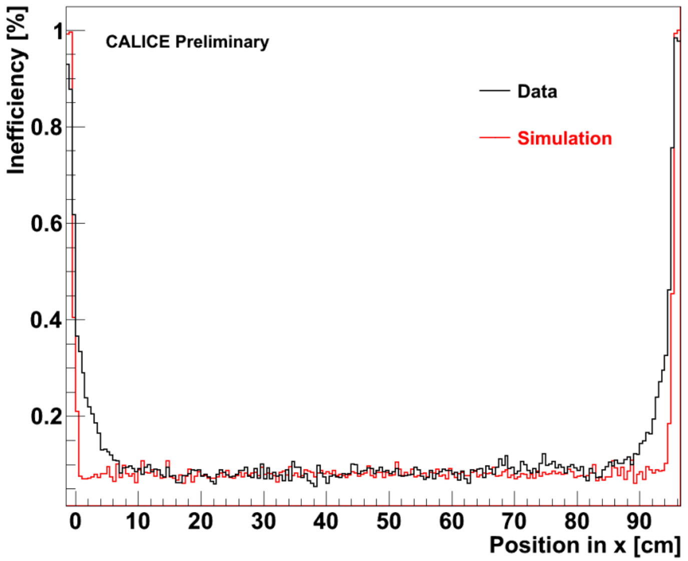


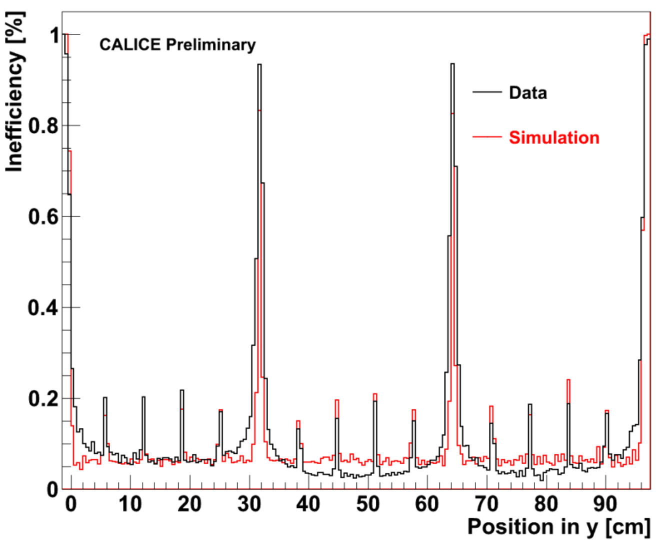


Efficiencies, multiplicities

Tail catcher is cooler
→ lower efficiency, multiplicity

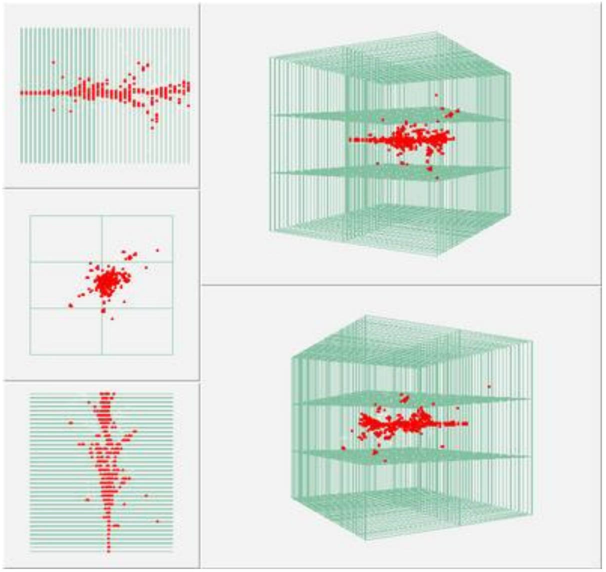






Calibration factors = mean of multiplicity distribution/(average over detector) = $\varepsilon \cdot \mu / \varepsilon_0 \cdot \mu_0$

Pion-Positron Preliminary Analysis



First look at data

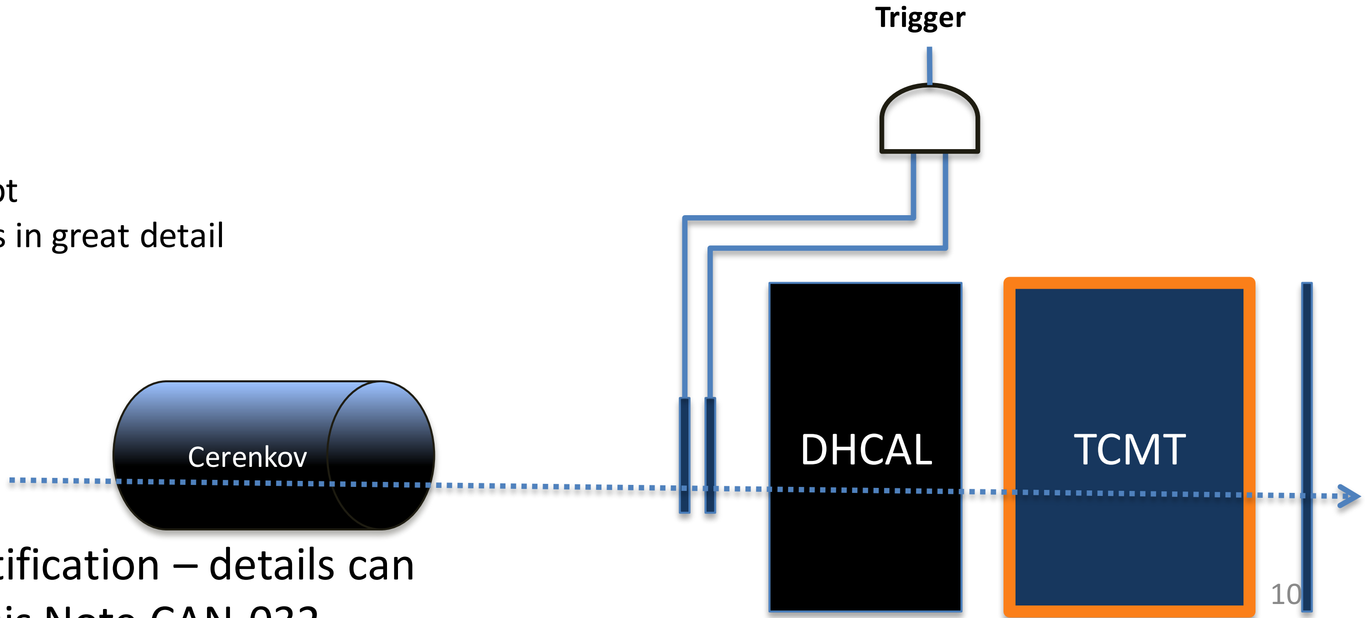
To provide possible feedback to data taking and setup
Speed is important!

Develop analysis tools

Final analysis will require large effort
This is the beginning…

Ultimate goals

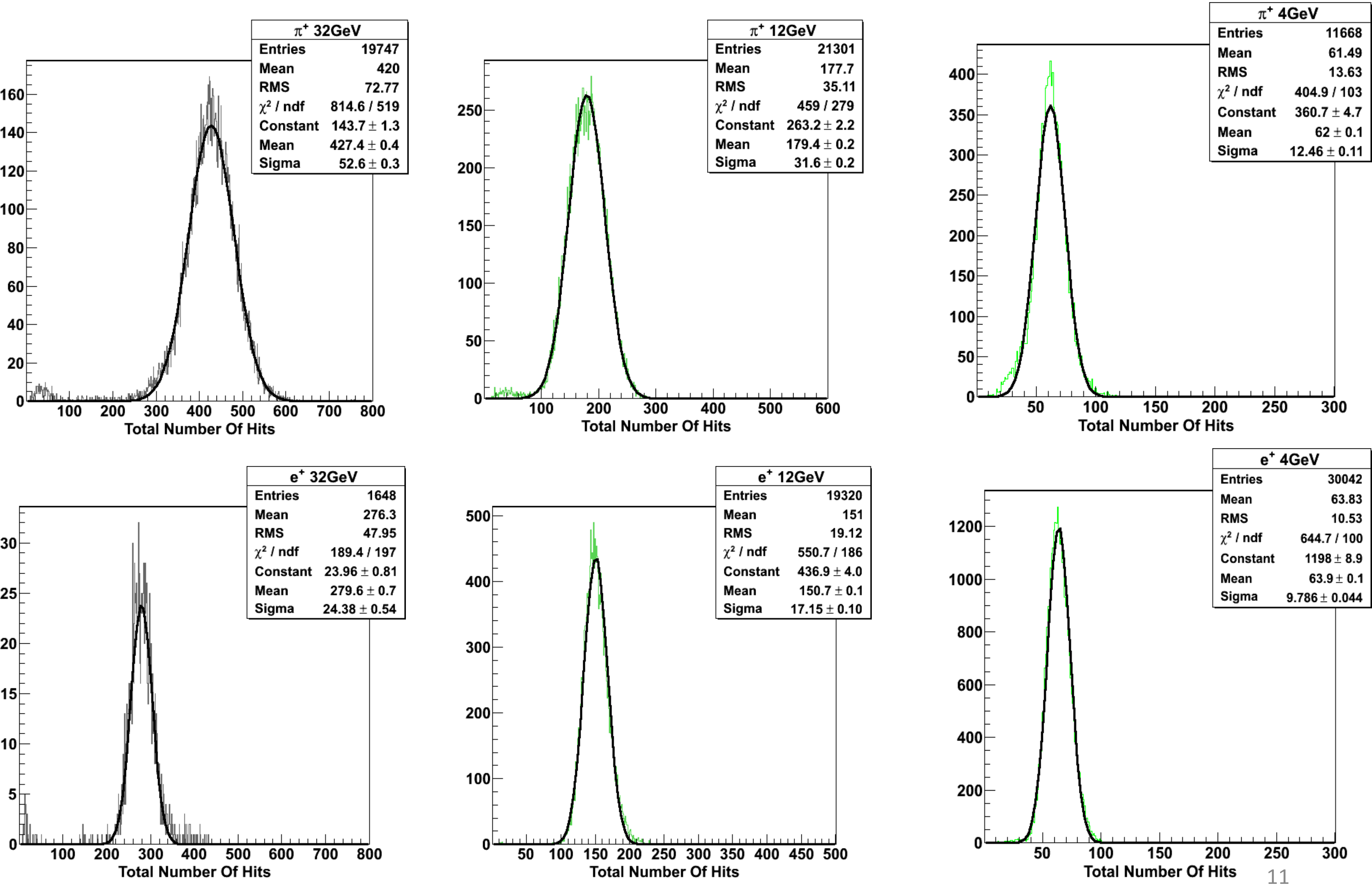
Validate the DHCAL concept
Measure hadronic showers in great detail



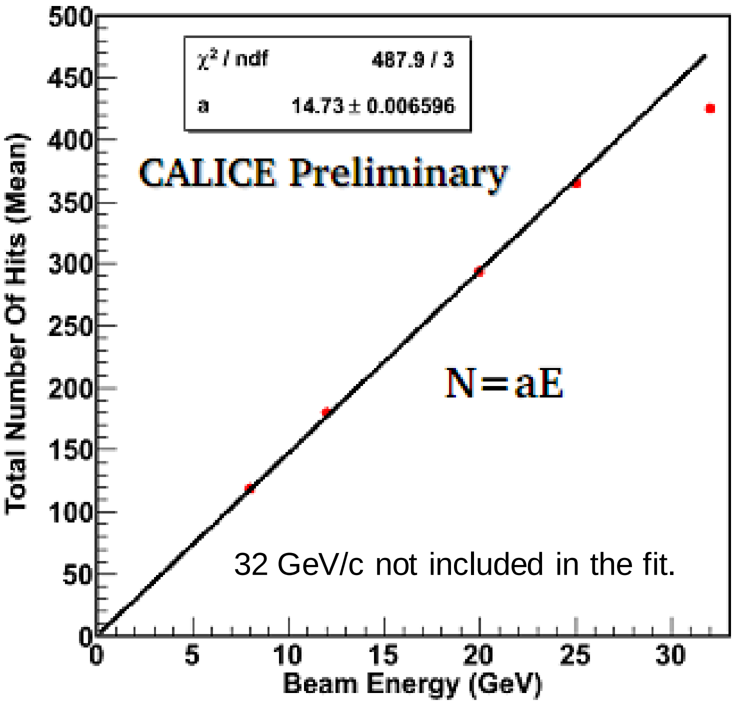
Topological particle identification – details can be found in Calice Analysis Note CAN-032

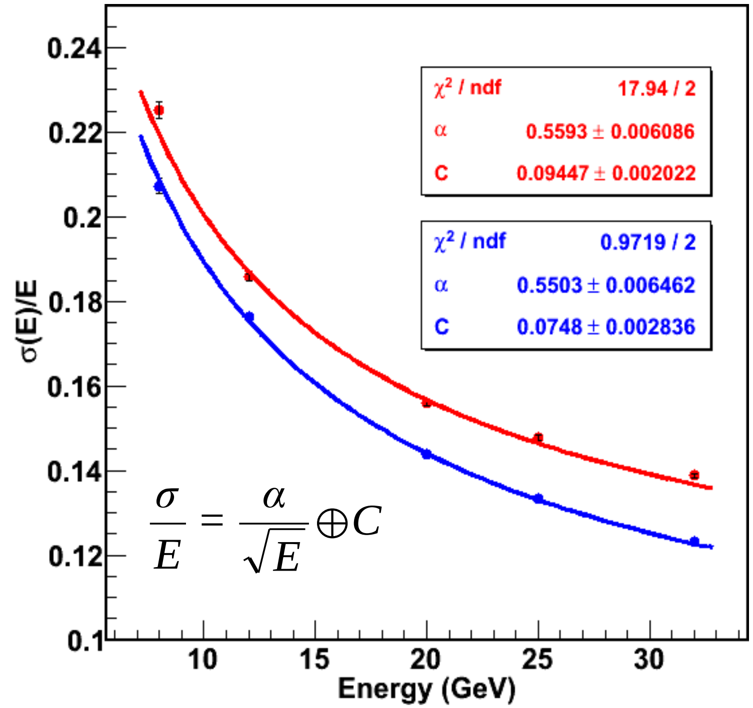
Results - October 2010 Data

CALICE Preliminary



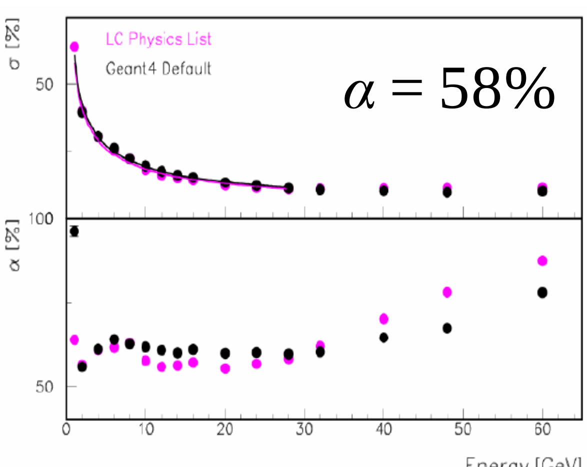
DHCAL Response to Hadrons **response not calibrated**





Standard pion selection

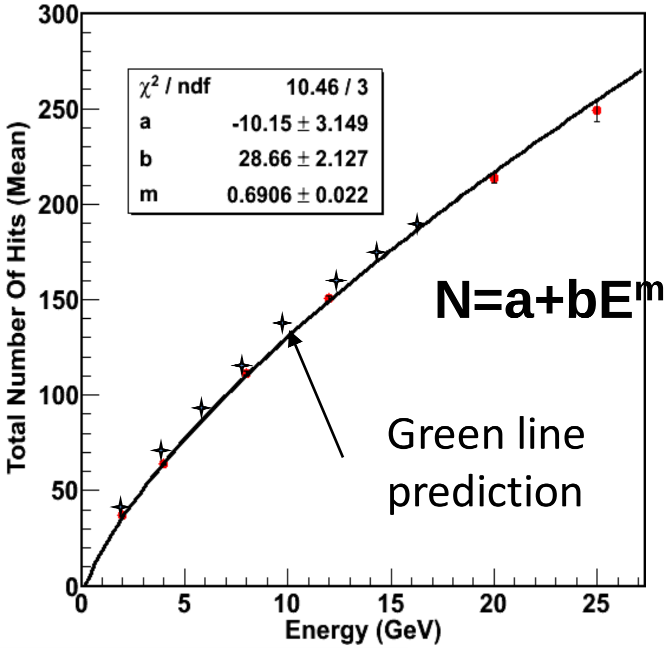
+ No hits in last two layers (longitudinal containment)

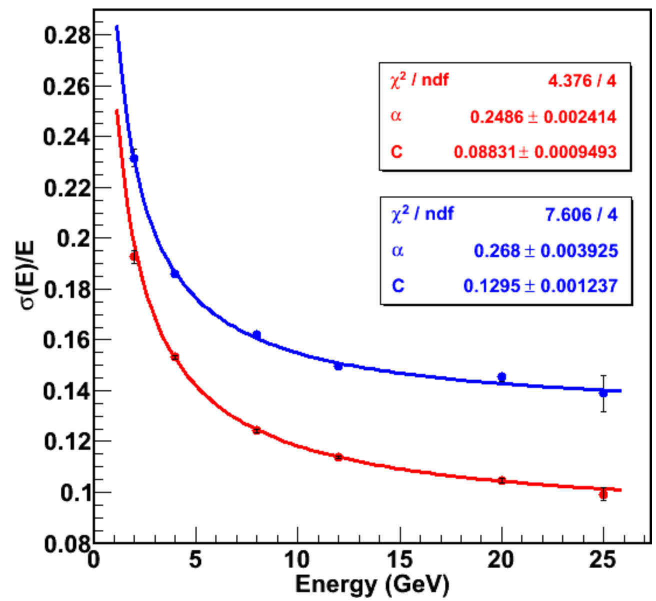


B. Bilki et.al. JINST4 P10008, 2009.

MC predictions for a large-size DHCAL based on the Vertical Slice Test.

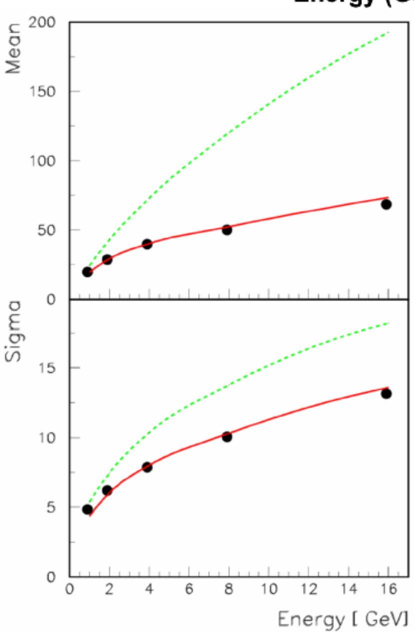
DHCAL Response to Positrons **response not calibrated**





$$\frac{\sigma}{E} = \frac{\alpha}{\sqrt{E}} \oplus C$$

Uncorrected for non-linearity
Corrected for non-linearity



Correction for non-linearity

Needed to establish resolution
Correction on an event-by-event basis

B. Bilki et.al. JINST4 P04006, 2009.

Data (points) and MC (red line) for the Vertical Slice Test and the MC predictions for a large-size DHCAL (green, dashed line).

Digital Calorimetry

Hadron showers were observed with unprecedented spatial resolution.

DHCAL-specific algorithms are being generated.

Calorimetric properties are within expectations with a first-look analysis.

The DHCAL concept is being validated.

Total Absorption Dual Readout Calorimetry

IOWA-FNAL-FAIRFIELD-MISSISSIPPI-TRIESTE

- **Focus on establishing a proof of concept for totally active hadron calorimetry.**

- **Evaluate the performance of:**
  - **Different crystal and glass samples**
  - **Different readout techniques to optimize the simultaneous collection of Čerenkov and scintillation light components for application of the Dual Readout technique to Total Absorption Calorimetry.**

- **Obtain a baseline for the detailed simulations of Čerenkov and scintillation light production in different crystals.**

Beam Test at FTBF

One 5 x 5 x 5 cm^3 BGO crystal. Provides information about scintillation and Čerenkov light yield as a function of time, wavelength, position and photodetector type.

- **All sides equipped with UV or visible filters**
- **Two sides viewed with PMTs (one through UV, one through visible filter)**
- **Remaining four sides equipped with 9 Hamamatsu SiPMs each, located at different positions**
- **1 mm Hamamatsu MPPCs with 25, 50 and 100 micron pixels**

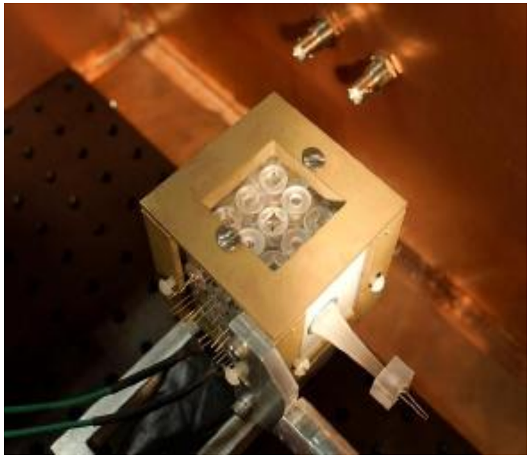
Beam Test at FTBF

Six BGO and six PbF_2 crystals.

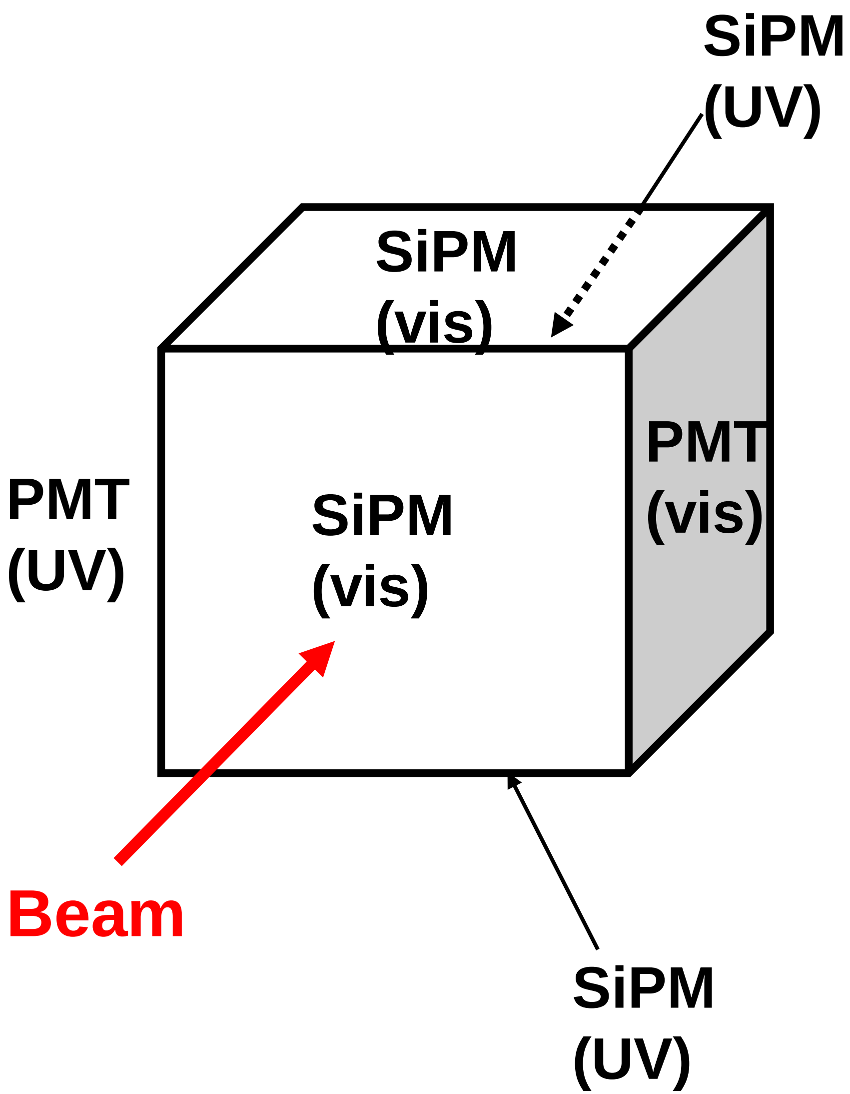
- **All 5 cm length.**
- **2 x 2 cm^2, 3 x 3 cm^2, 4 x 4 cm^2. 3 mm Hamamatsu MPPCs located at the center of the downstream face.**
- **Different wrapping (black paper/Tyvek) and different surface finishes to provide information about light collection for Čerenkov (PbF_2) and scintillation (BGO) as a function of crystal geometry and surface conditions.**

Beam Test at FTBF

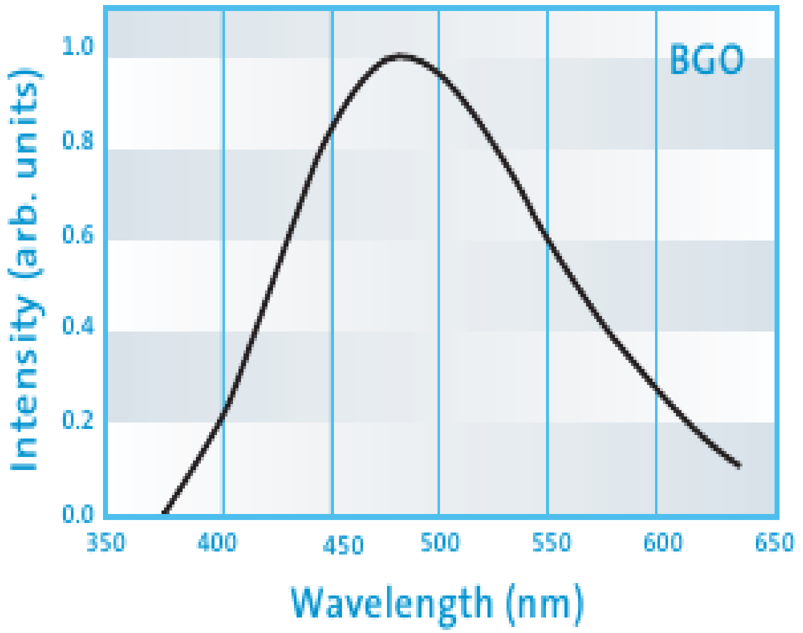
- 120 GeV/c primary proton beam
- Fermilab TB4 readout boards (provide 64 channels of waveform digitizers)



Single BGO Crystal



BGO Emission Spectrum

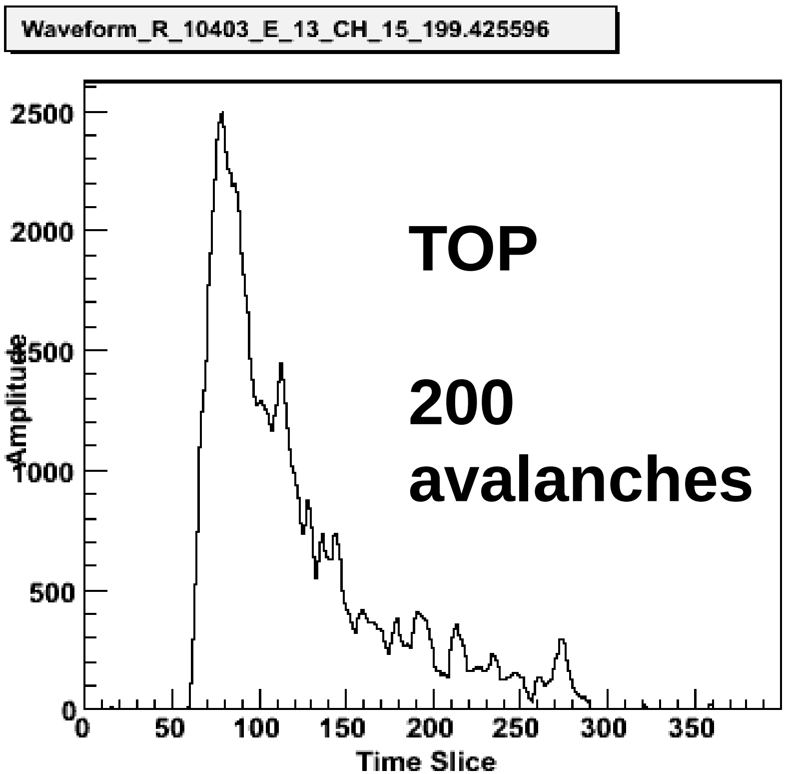


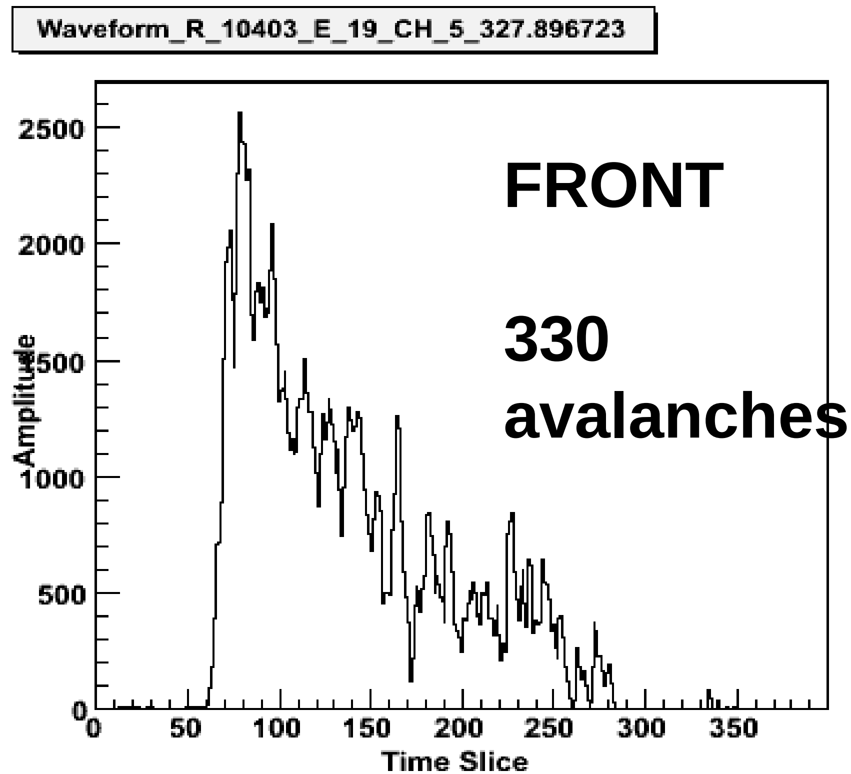
vis → Scintillation

UV → Čerenkov

Single BGO Crystal – Visible Filter Sides

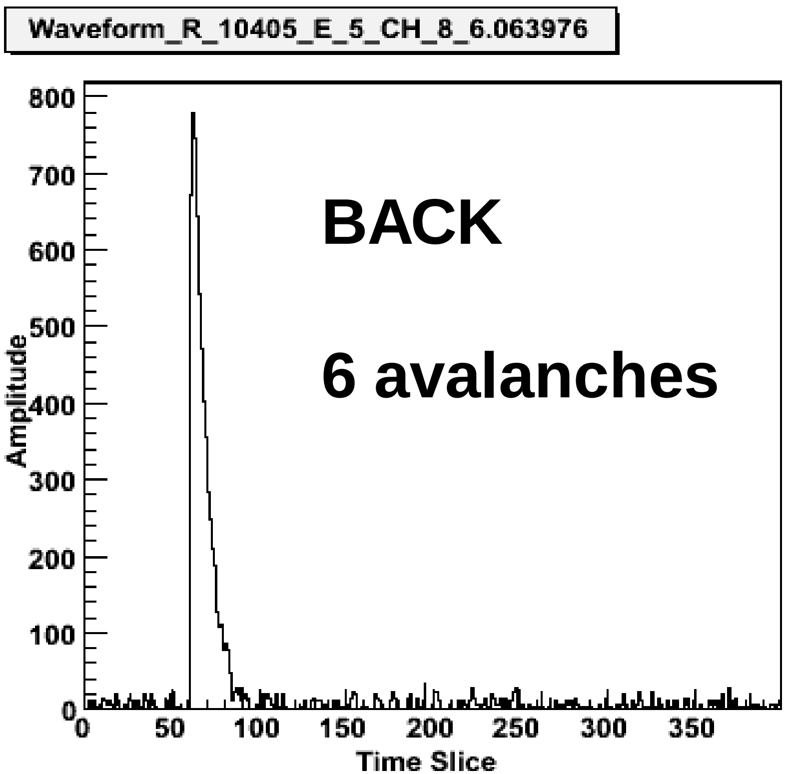
Single event waveforms

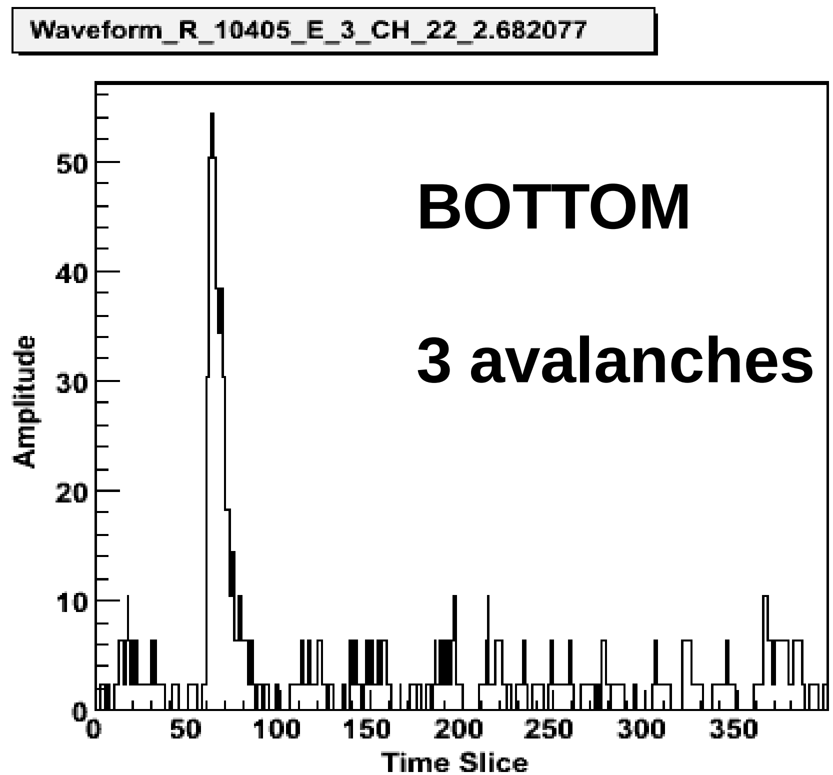




Single BGO Crystal – UV Filter Sides

Single event waveforms





Total Absorption Dual Readout Calorimetry

Preliminary analyses indicate that:

- **The Čerenkov and scintillation signals are observed with the SiPMs directly coupled to the crystals.**

- **Filters provide measurable separation of the two signals.**

A lot of data to:

- **Study the spatial and timing structure of the two kinds of light production,**

- **Study the effects of type, shape, surface finish and optical coupling of the crystals on these two mechanisms,**

- **Perform detailed simulations of light production and collection both for Čerenkov and scintillation components.**

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Calorimetry Based On Secondary Emission

Iowa-Fairfield-Mississippi

In a Secondary Emission detector module, Secondary Emission electrons (SEe) are generated from an SE cathode when charged hadron or electromagnetic particles or particularly shower particles penetrate the sampling module placed between absorber materials.

Why Secondary Emission Ionization Calorimeters?

- Secondary Emission: Rad-Hard + Fast
  - *a) Metal-Oxide SE PMT Dynodes survive > 100 GigaRad*

  - *b) SE Beam Monitors survive 10^{20} mip particles/cm^2*

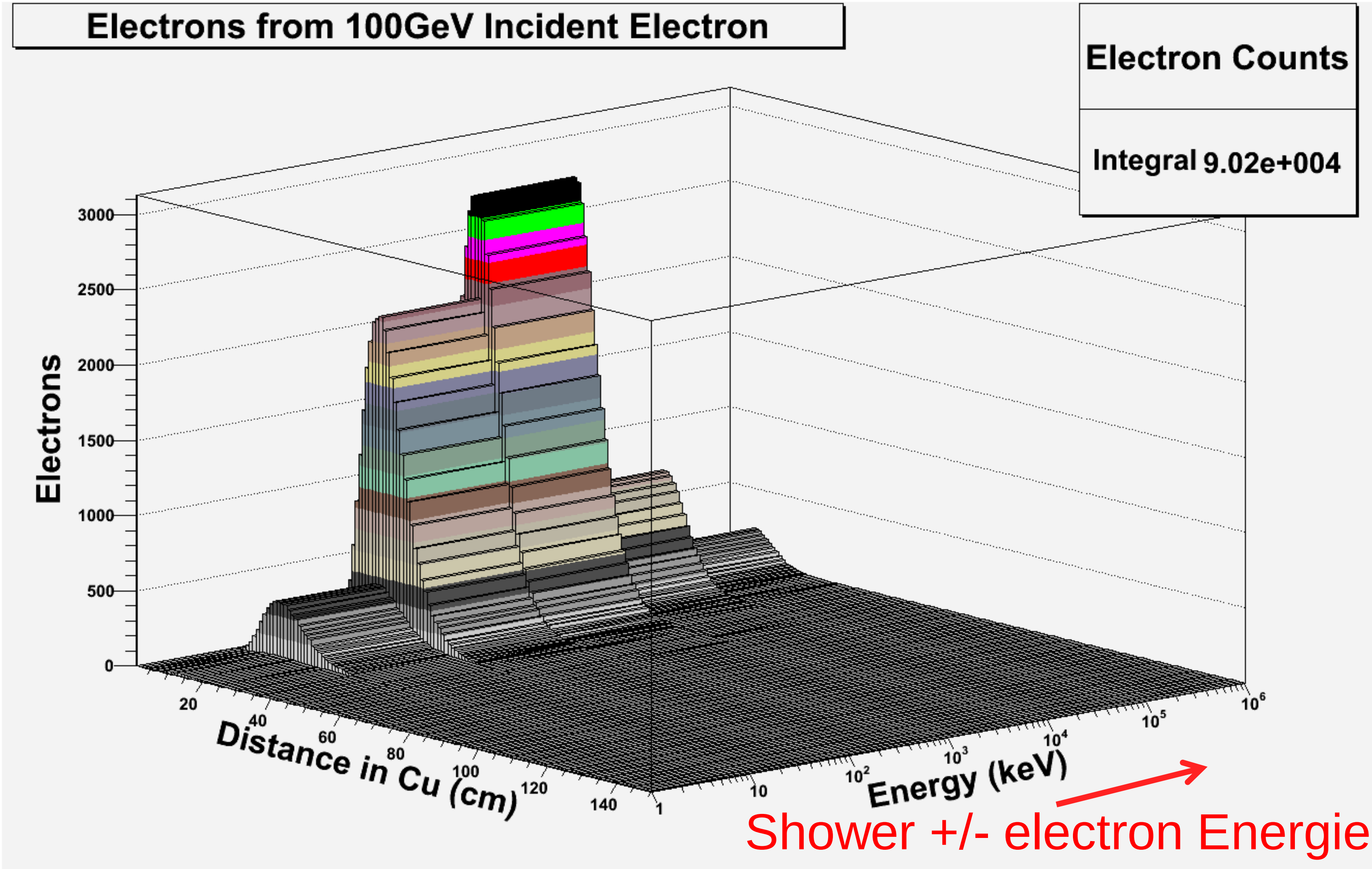
- ***SEe signal:*** *SE surfaces inside em/had Showers:*
  - SE yield δ: Scales with particle momentum ~dE/dx
  - e^-: 3 < δ <100, per 0.05 <e^-<100 KeV (material depnt)
  - δ~1.05 -1.1 or 0.05-0.1 SEe^- per MIP

Ex: ~6-24 MIP equiv per GeV sampling calorimeters - *a **lower limit** on hadron shower SE signals*

–> ~60-240 SEe^- per 100 GeV pion shower w/ MIPs alone

BUT SEe^- Must be Amplified! Exactly like p.e.!

GEANT4: Cu Block, 1cm "plates", 100 GeV e incident. Shower $e^{+/-}$ that cross the 1 cm "gaps" are binned in both energy and depth in Cu

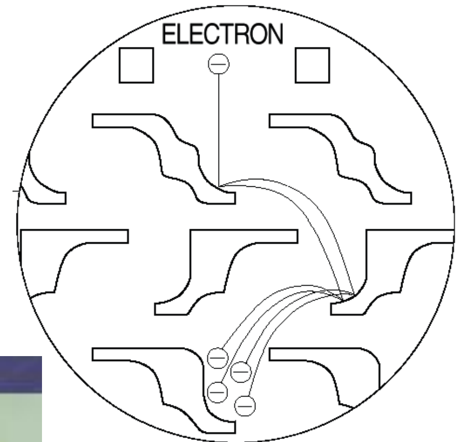


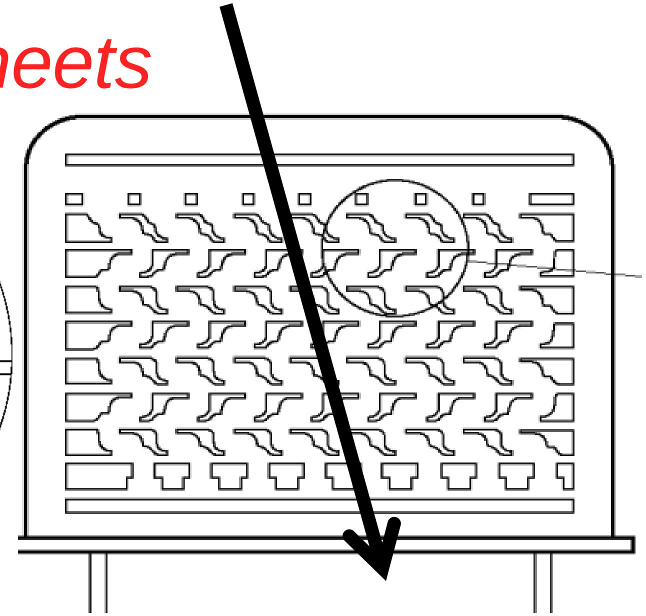
Secondary Emission Module Design

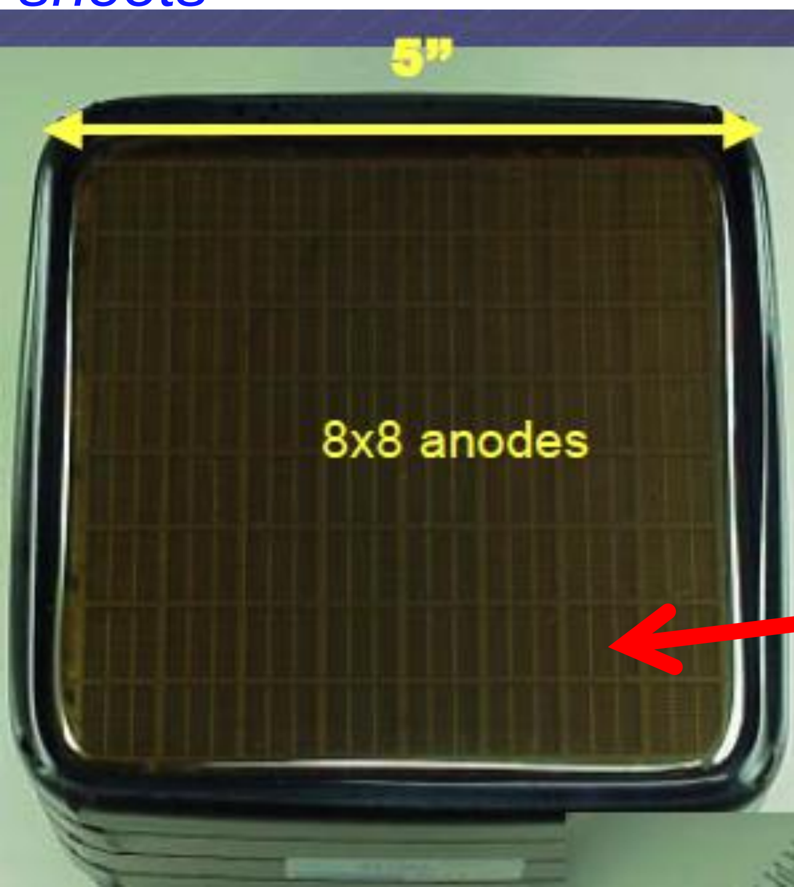
- The modules envisioned are compact, high gain, high speed, exceptionally radiation damage resistant, rugged, and cost effective, and can be fabricated in arbitrary tileable shapes.
- The SE sensor module anodes can be segmented transversely to sizes appropriate to reconstruct electromagnetic cores with high precision.
- The GEANT4 estimated in a 1(5) cm sampling Cu calorimeter response performance is between 35-50 (7-10) Secondary Emission electrons per GeV, with a gain per SEe $>10^5$ per SEe, and an e/pi<1.2. The calorimeter pulse width is estimated to be <15 ns.
- A recent test using a mesh dynode PMT has confirmed MC results.

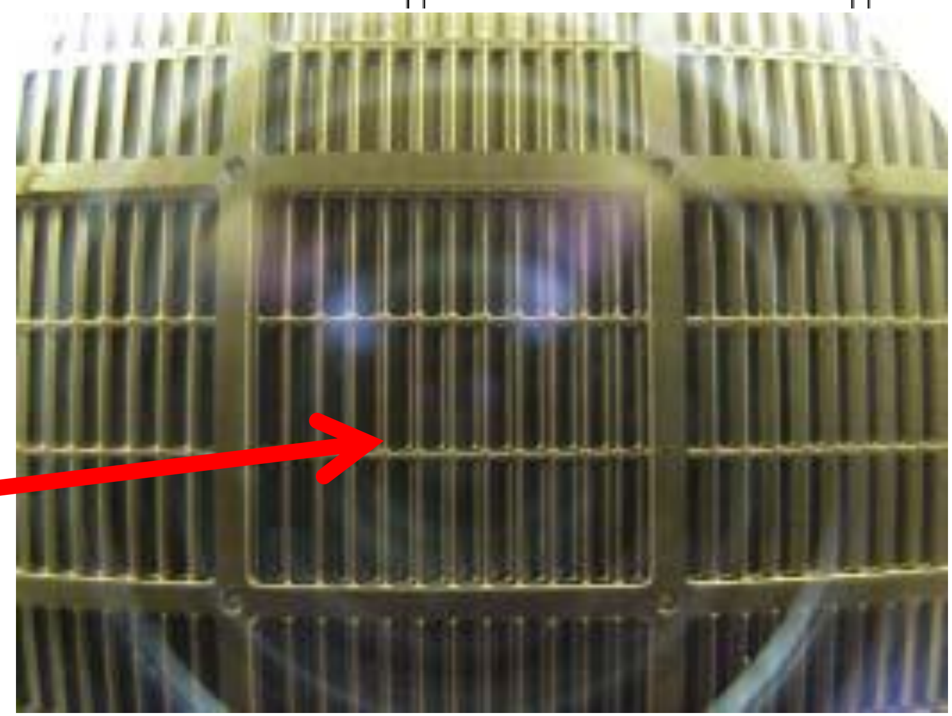
SEe Dynodes: *Etched Metal Sheets*

Hamamatsu Dynodes
15 cm now -> ~50 cm
Already diced from large sheets



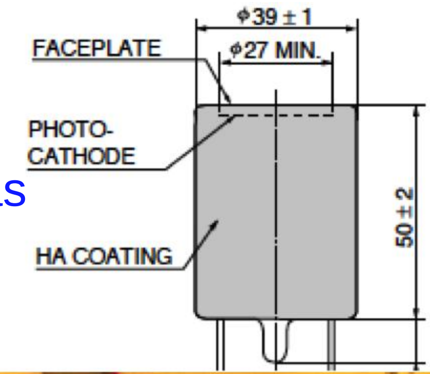






BEAM TEST of SEe Sensor

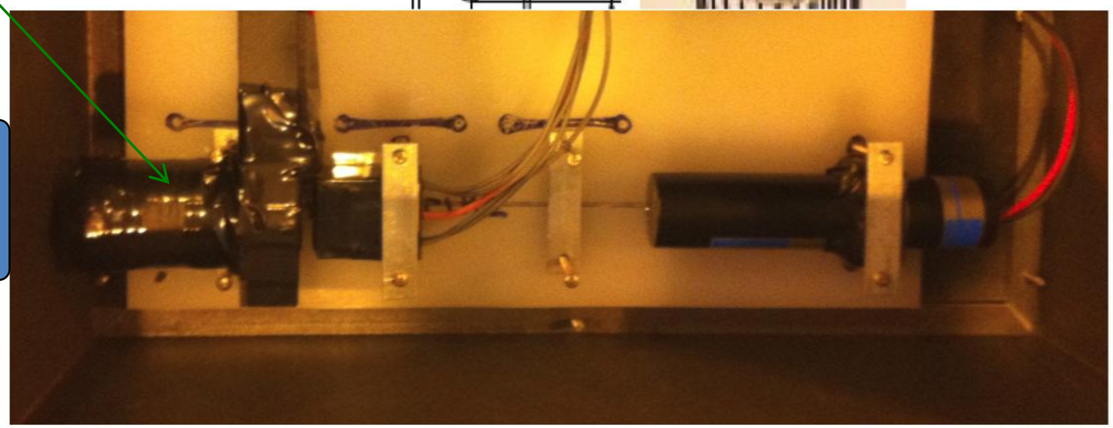
Mesh PMT and Base
Facing Downstream
Photocathode Reverse Bias



19 Stage Mesh

3 cm Pb

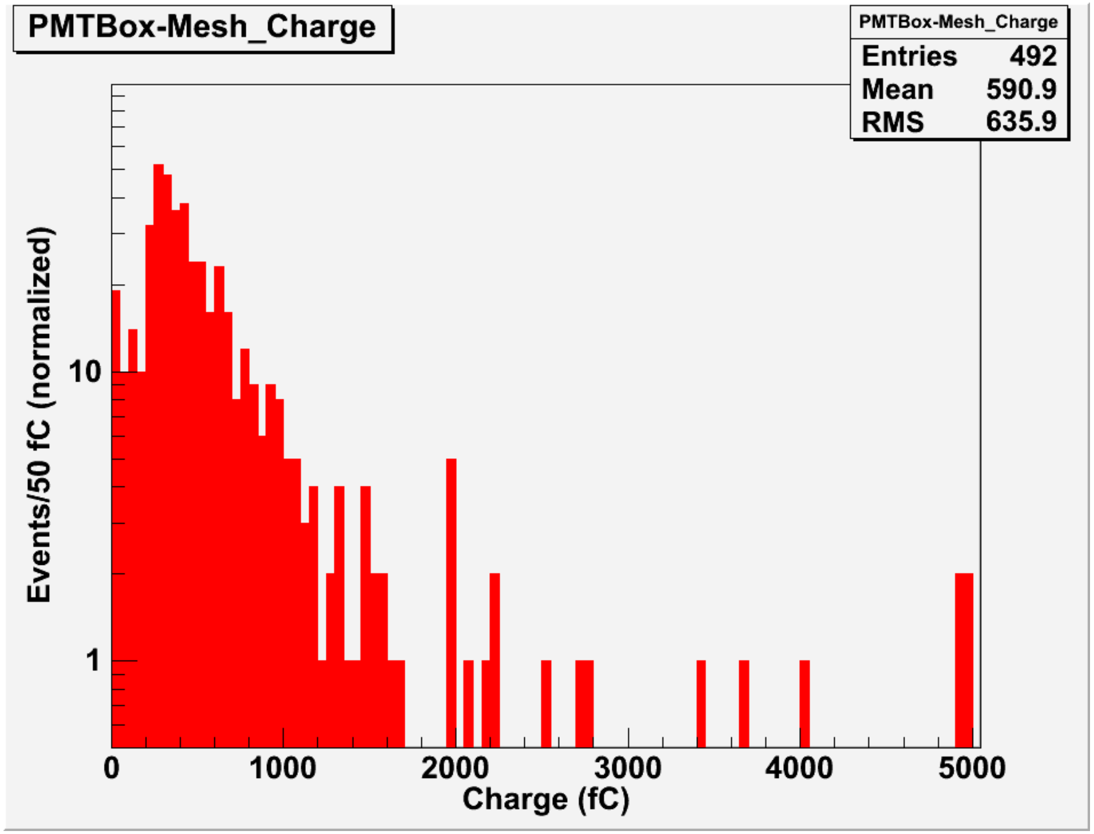
100 GeV e-



The Hamamatsu 19 stage mesh PMT used in the test beam at CERN – on left in the phototube test box in the beam line. Muons and 100 GeV electrons hitting 3 cm of Pb radiator were sent in on the left. The photocathode was completely disabled by using a +HV base, operating the anode at ~ +2KV, D1 at ground, and the photocathode at small positive voltages or connected to ground through 400kOhms.

We Expect ~500 Shower electrons to Cross Mesh
-> ~25-40 SEe ***assuming all Shower e = mips***

BEAM TEST: 100 GeV electrons
3 cm Pb ~ 5 Lrad Radiator ~ Shower Max
Preceding the mesh PMT w/ photocathode turned off



PRELIMINARY!

Fluctuations High!
- PMT Dia ~ Shower Dia
- Beam not centered
  Use Wire Ch to center

NOTE μ Mip:
Detection Effy ~10%
Response ~1-2 "SEe"

Peak corresponds to 41 SE electrons (mesh stack gain ~10^5)

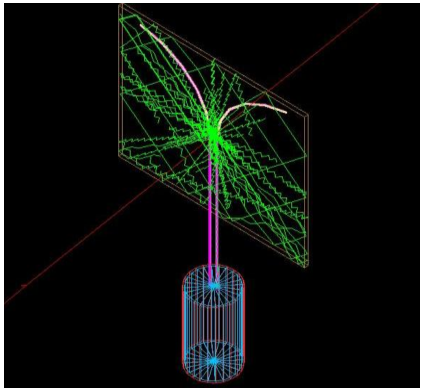
Implies ~100 SE.e./GeV, 1 Lrad sampling, possible!
(exactly like 100 p.e./GeV in scintillator calorimeter)

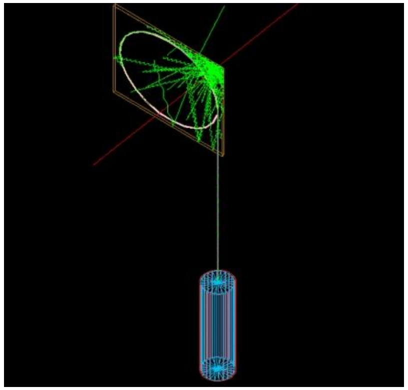
Scintillator/Crystal/Fiber Calorimetry

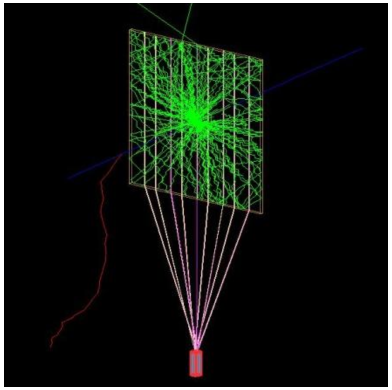
- R&D triggered by the SLHC upgrade
- Unexpectedly high improvements in design and readout
- New areas of applications

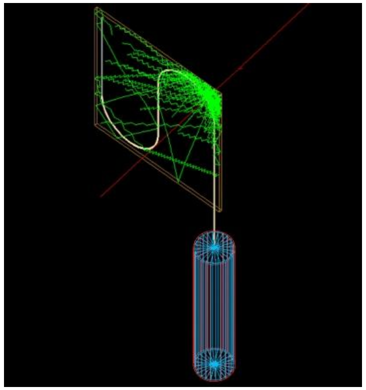
Cherenkov Light Collection in Quartz

- Good : Quartz is radiation hard.
- Bad : We have to collect Cerenkov photons. Very little light !! At fixed angle.
- Strategy: Go deep in UV to collect Cerenkov photons.
- We did R&D studies on
  - WLS fiber geometry
    - Cerenkov light collection, uniformity, and efficiency
  - Wrapping material reflectivity tests, Aluminum, Tyvek, HEM, Mylar.





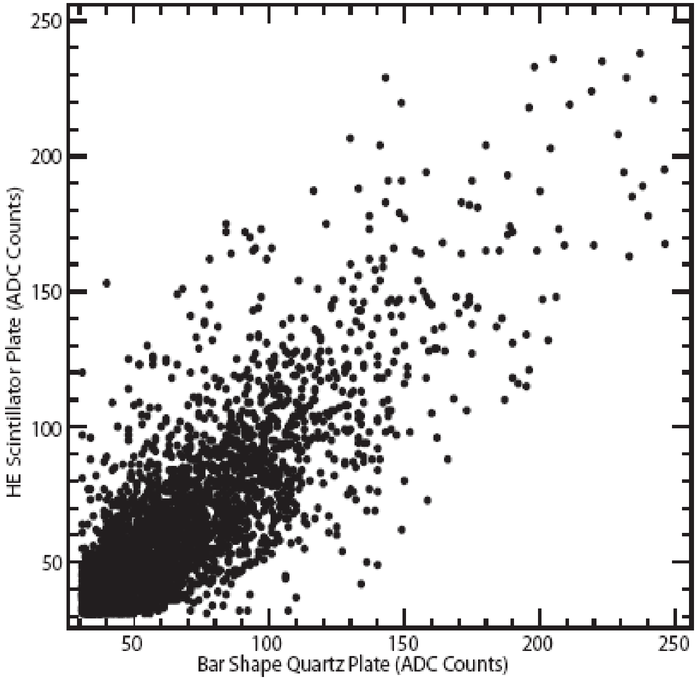




WLS Fibers in Quartz

We showed that Cherenkov light collection inside the quartz is feasible with UV absorbing WLS fibers.

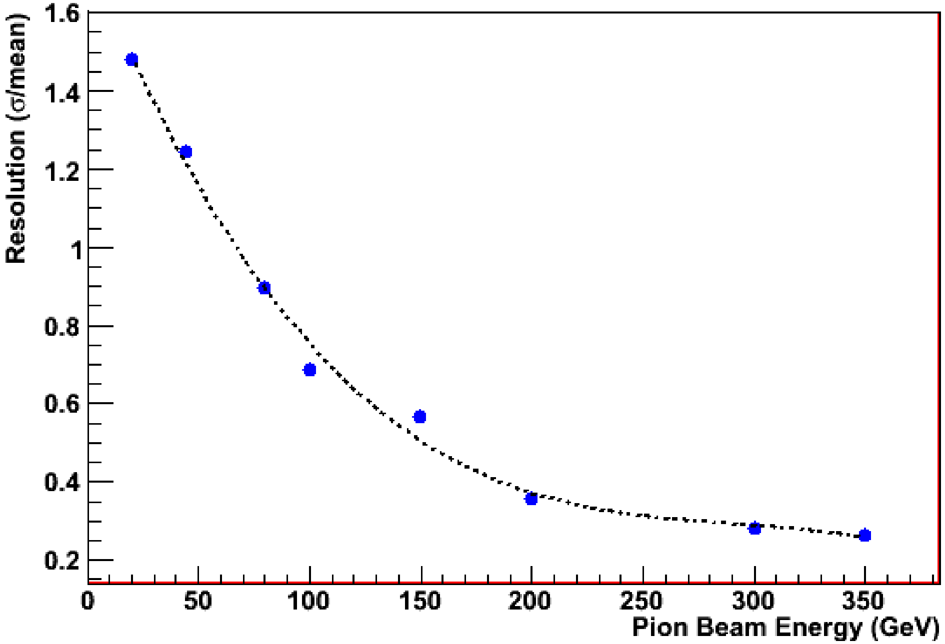
F. Duru *et al.* "CMS Hadronic EndCap Calorimeter Upgrade Studies for SLHC - Cerenkov Light Collection from Quartz Plates" , **IEEE Transactions on Nuclear Science, Vol 55, Issue 2, 734-740, 2008.**



QPCAL with WLS Fibers

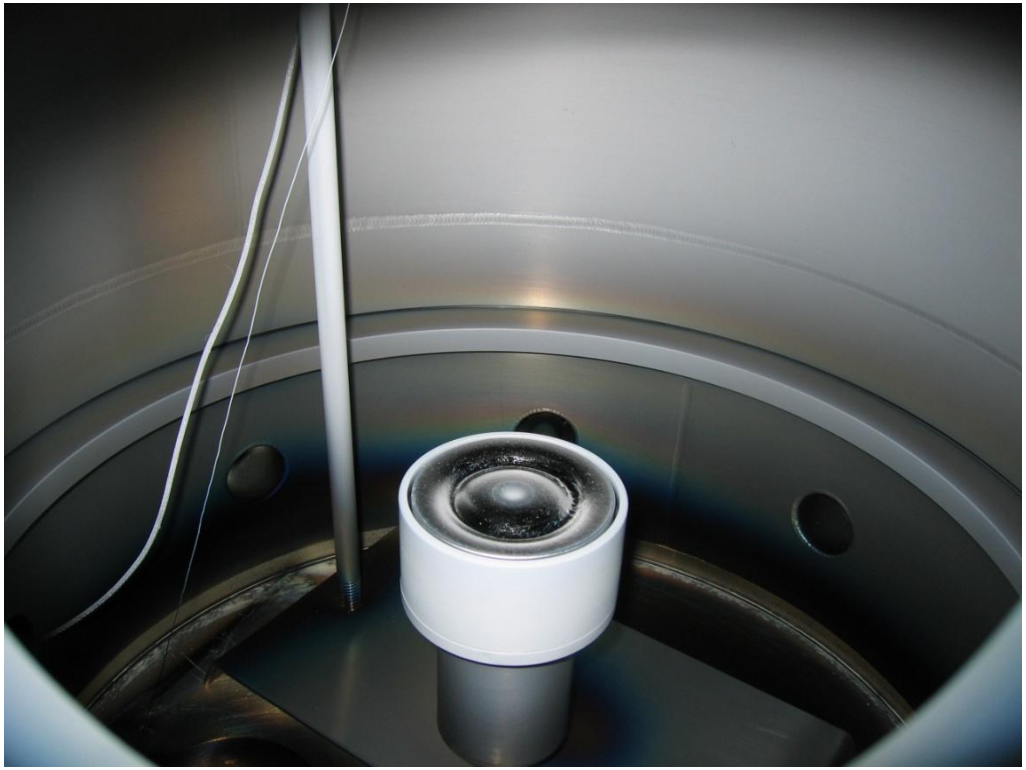
We built and tested "WLS Fiber Embedded Quartz Plate Calorimeter Prototype"

U. Akgun *et al.,* "Quartz Plate Calorimeter as SLHC Upgrade to CMS Hadronic Endcap Calorimeters", **XIII International Conference on Calorimetry in High Energy Physics, CALOR 2008, Pavio, Italy, May 2008, J.Phys.Conf.Ser.160:012015, 2009**



Covering Quartz Plates with pTp and ZnO

We evaporated PTP and RF sputtered ZnO over quartz plates

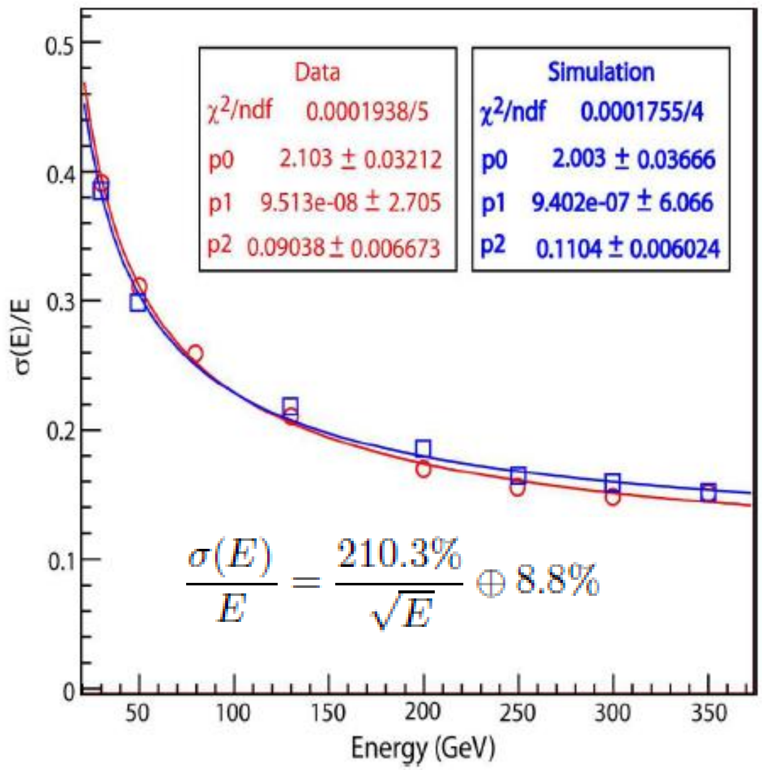


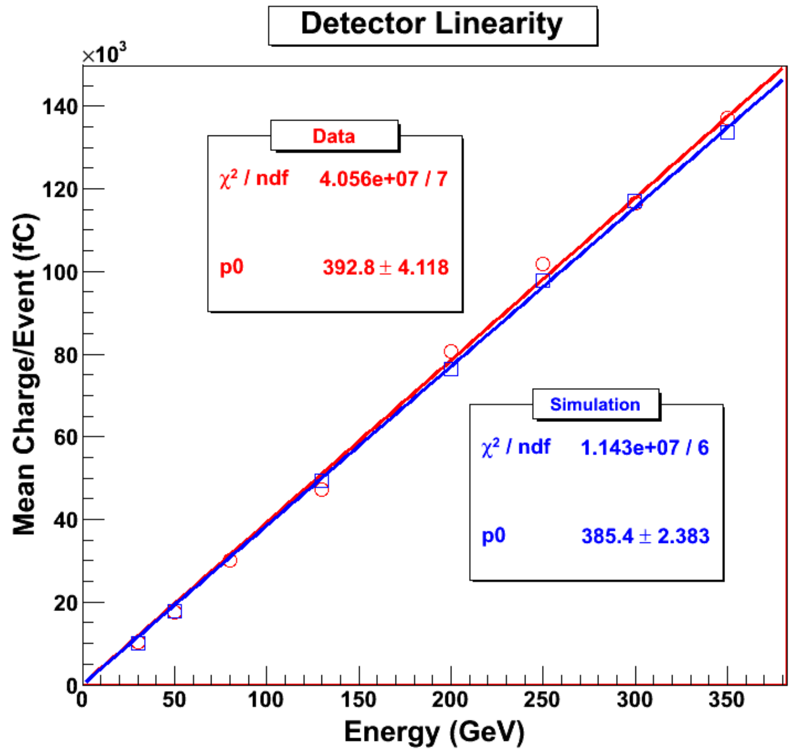
QPCAL with pTp

We built and tested "PTP Deposited Quartz Plate Calorimeter"

U. Akgun *et al.* "CMS Hadronic Calorimeter Upgrade Studies - P-Terphenyl Deposited Quartz Plate Calorimeter Prototype ", **APS 2009, Denver, CO, USA, May 2009**

B. Bilki *et al.* "CMS Hadron Endcap Calorimeter Upgrade Studies For Super-LHC", **CALOR 2010, Beijing, China, May 2010**



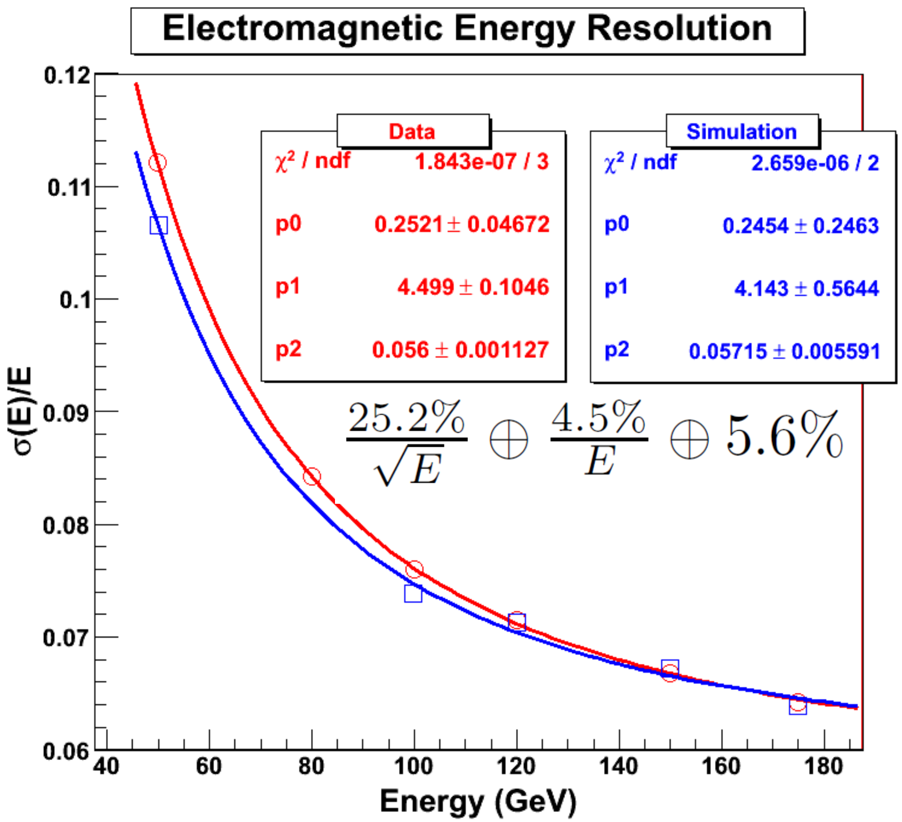


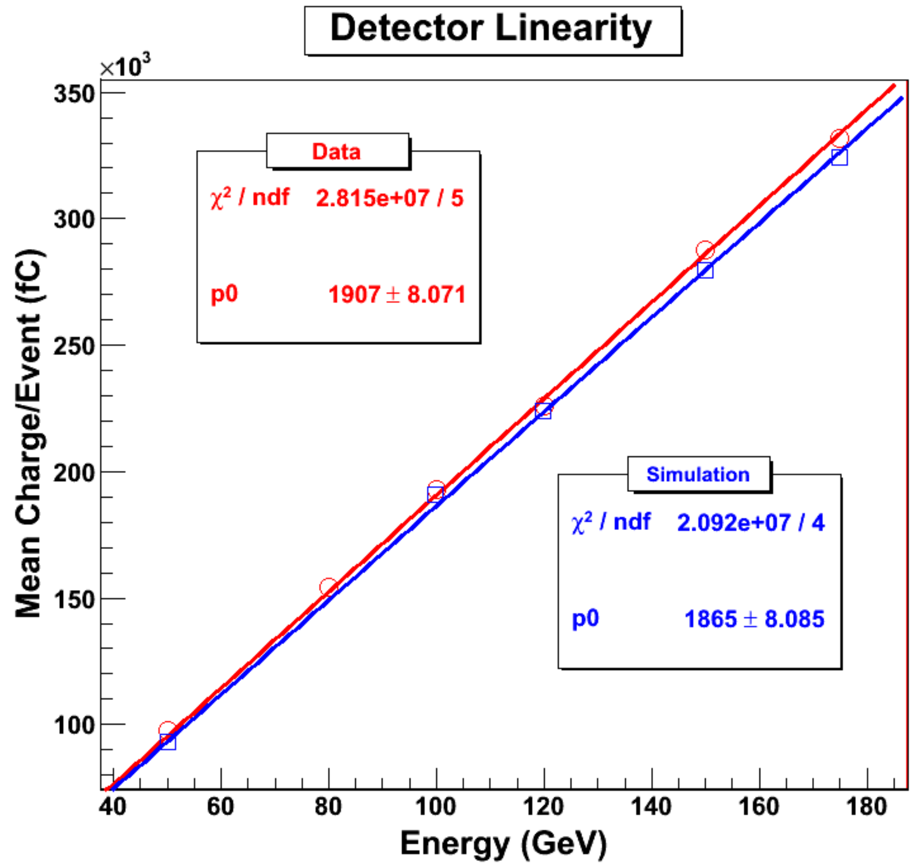
QPCAL with pTp – EM Mode

We can use combination as radiation hard CMS Endcap Calorimeter (EE + HE).

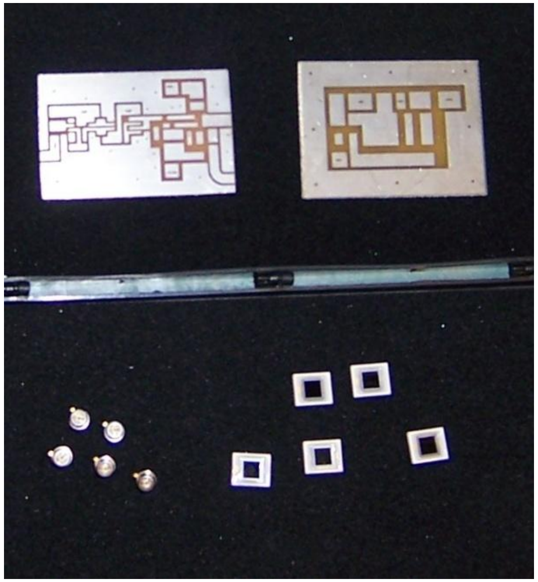
U. Akgun *et al.* "CMS Hadronic Endcap Calorimeter Upgrade Studies for SLHC P-Terphenyl Deposited Quartz Plate Calorimeter Prototype''

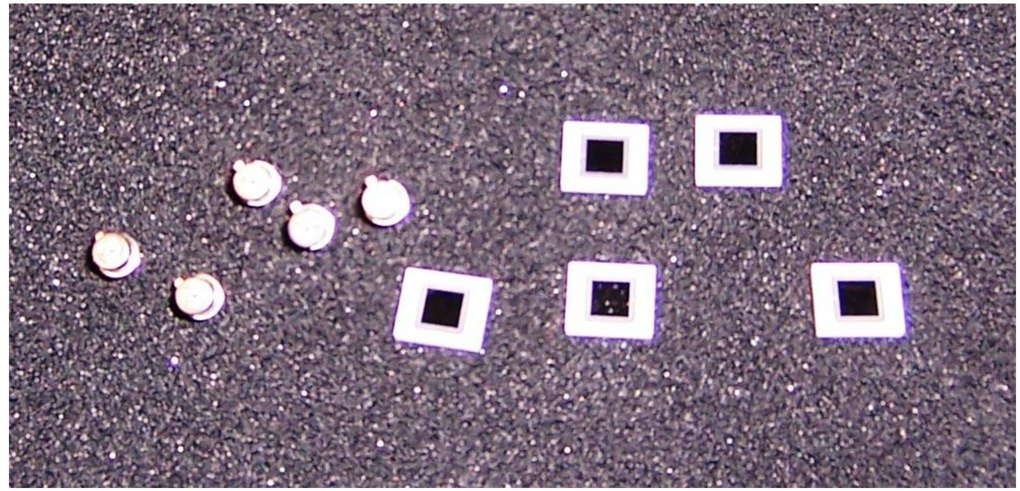
IEEE Transactions on Nuclear Science, Volume 57, Issue 2, 754-759, 2010

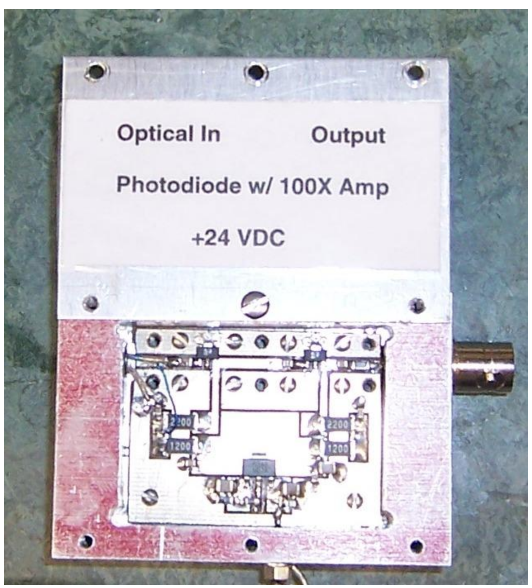




New Readout Options







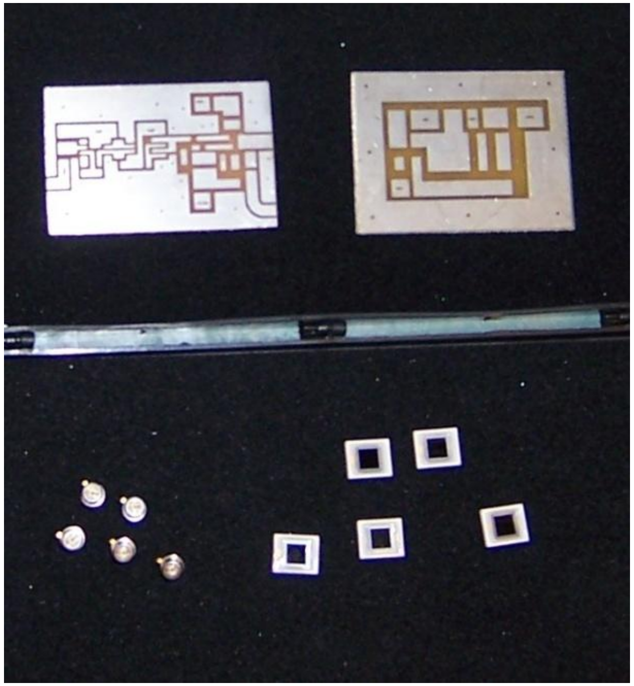
We tested;
*) Hamamatsu S8141 APDs (CMS ECAL APDs).
The circuits have been build at Iowa. These APDs are known to be radiation hard; *NIM A504, 44-47 (2003)*

*) Hamamatsu APDs: S5343, and S8664-10K
*) PIN diodes; Hamamatsu S5973 and S5973-02
*) Si PMTs

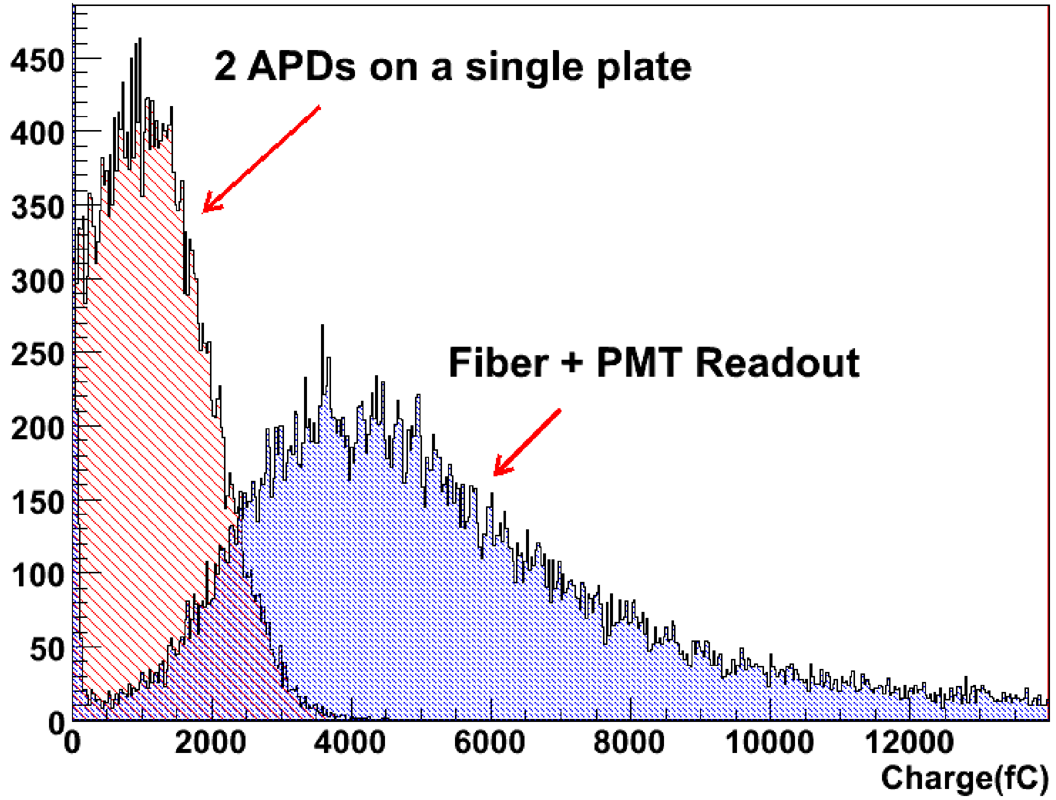
Alternative Readout

We constructed and tested alternative readout options from pTp deposited quartz plates: APD, SiPM, PIN diode.

They are not very effective and most importantly, the APD and SiPMs are not radiation hard enough for us.

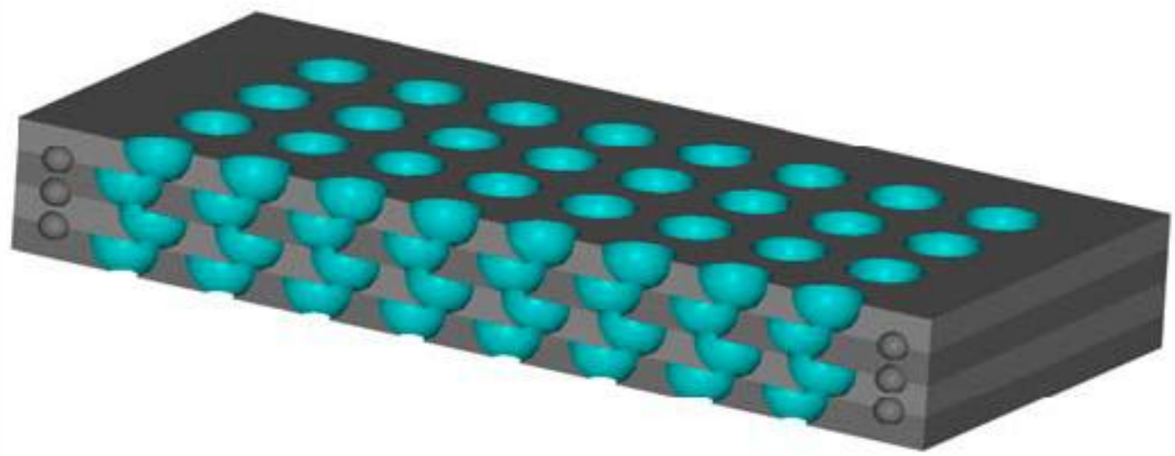


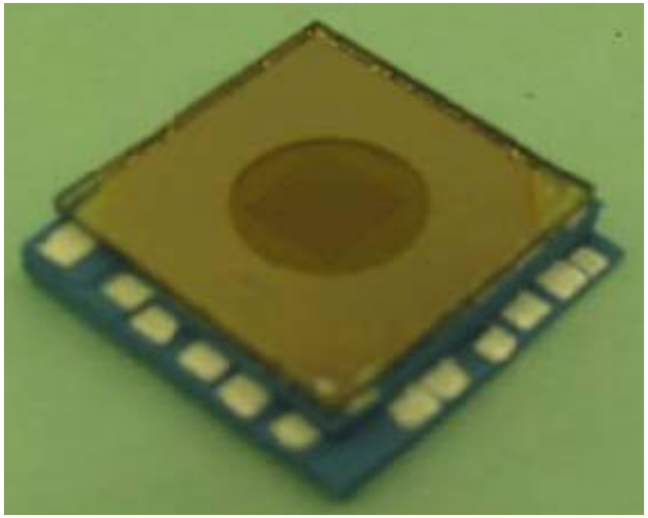
New Readout Options



We have tested ECAL APDs as a readout option. 2 APD connected to plain quartz Plate yields almost 4 times less light than fiber+PMT combination.

Microchannel PMT





➢ Fast response time, high gain, small size, robust construction, power efficiency, wide bandwidth, **radiation hardness**, and low cost.

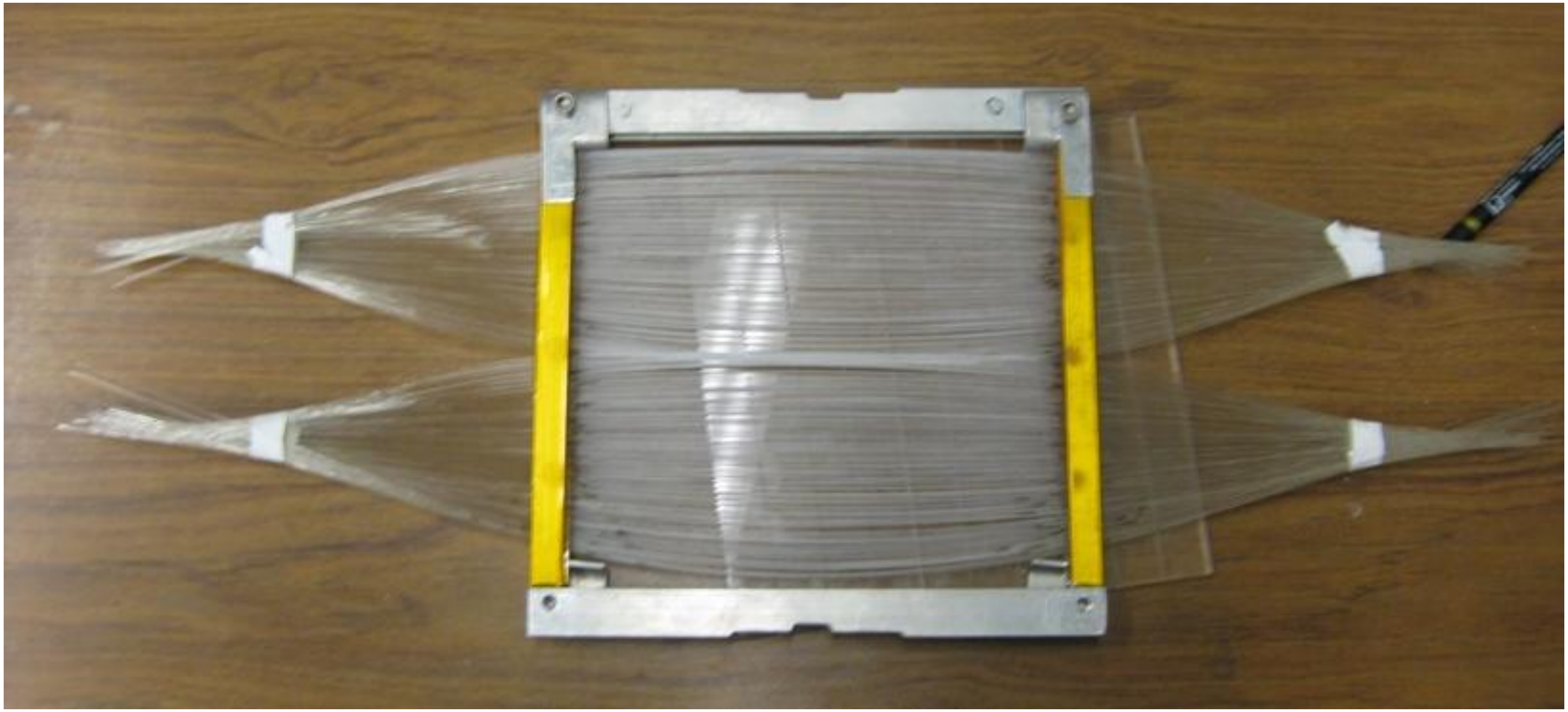
➢ 8 stage device is assembled from micro-machined dynodes which exhibits a gain of up to 2-4 per stage on single stage.

➢ The total thickness is less than 5 mm. 8x4 pixel micro-dynode array is shown

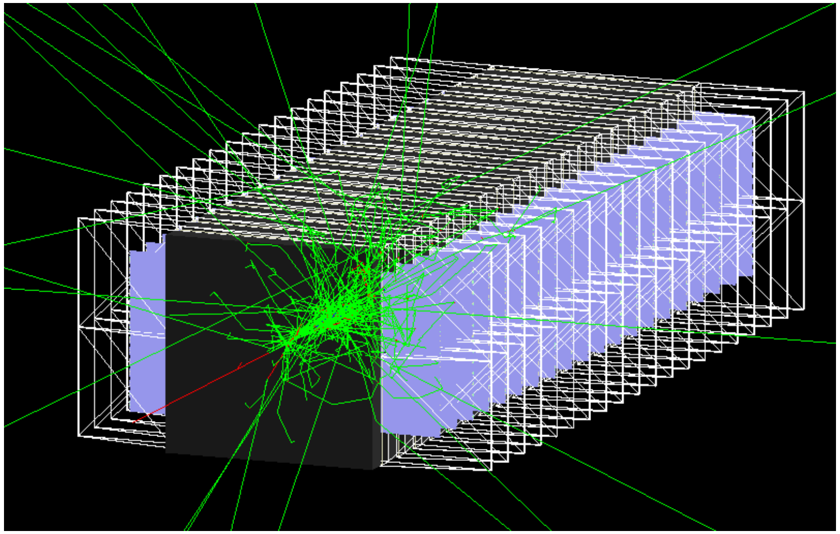
Radiation Hard WLS Fiber

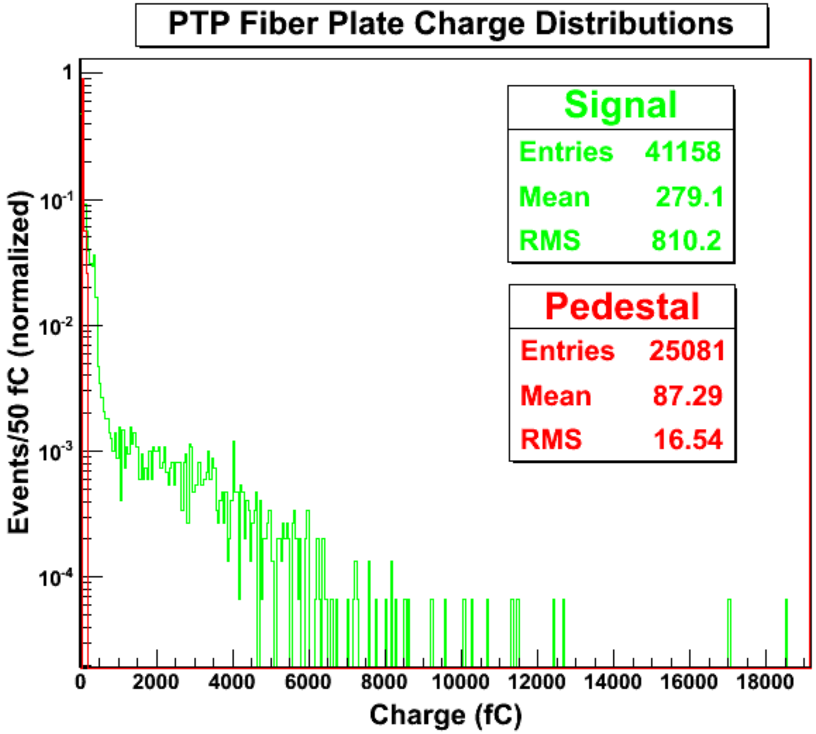
We Develop Radiation Hard Wavelength Shifing Fibers: Quartz fibers with PTP/ZnO covered core.

We built a radiation hard WLS fiber prototype. Deposited pTp on the stripped region, on both face. Then the whole ribbon will be sandwiched between quartz plates.



Radiation Hard WLS Fiber





We prepared a "homemade" rad-hard WLS fiber. We stripped the plastic cladding from QP fibers for "middle 20 cm" portion of 60 cm fibers.
This unit was tested with 80 GeV electron shower. The red line show the pedestal.
With a very simple prototype we collected substantial signal.

We try to optimize the model using Geant4 simulations.

Compton Polarimetry for Future Lepton Colliders

* Upstream polarimeter to measure the undisturbed beam before collisions.

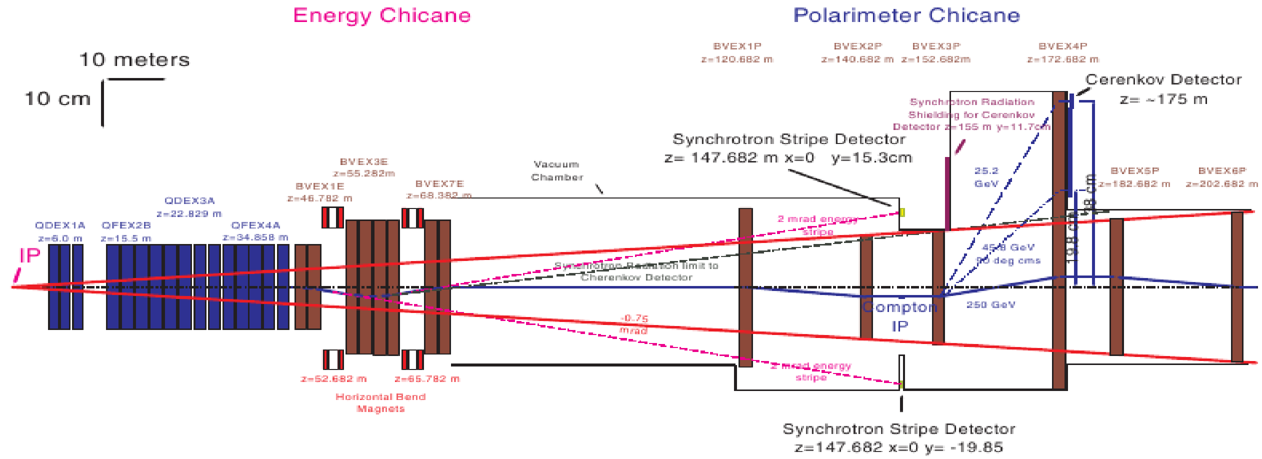
* SM asymmetries

* Compton polarimetry

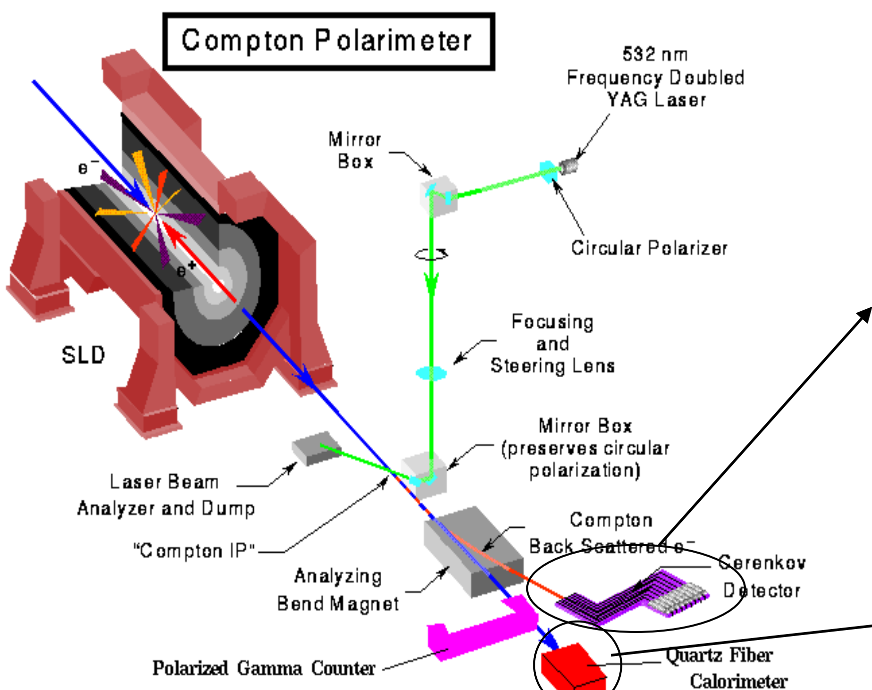
  - Necessary to obtain a sub-1% (~0.25%) polarization accuracy.

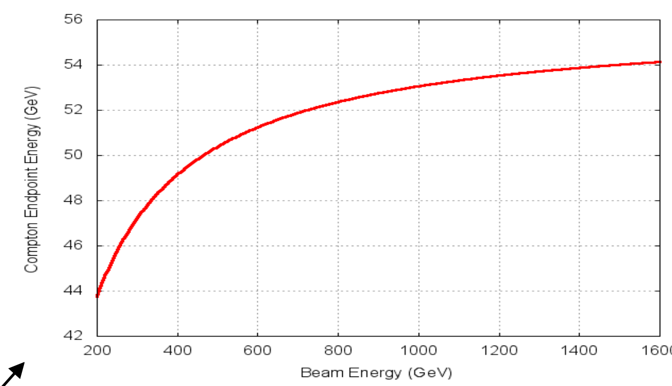
  - Accurately measure depolarization effects.

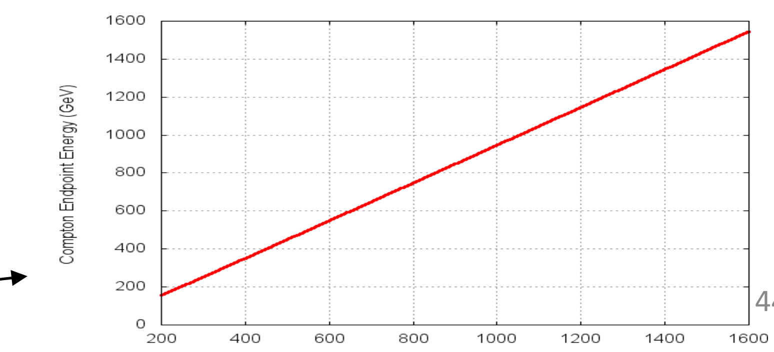
Compton Polarimetry Baseline



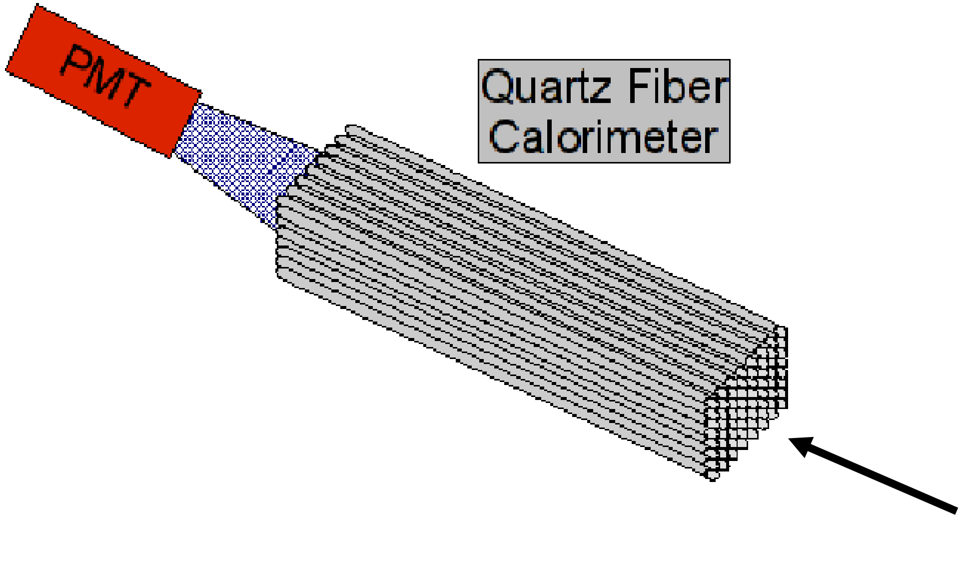
ILC RDR

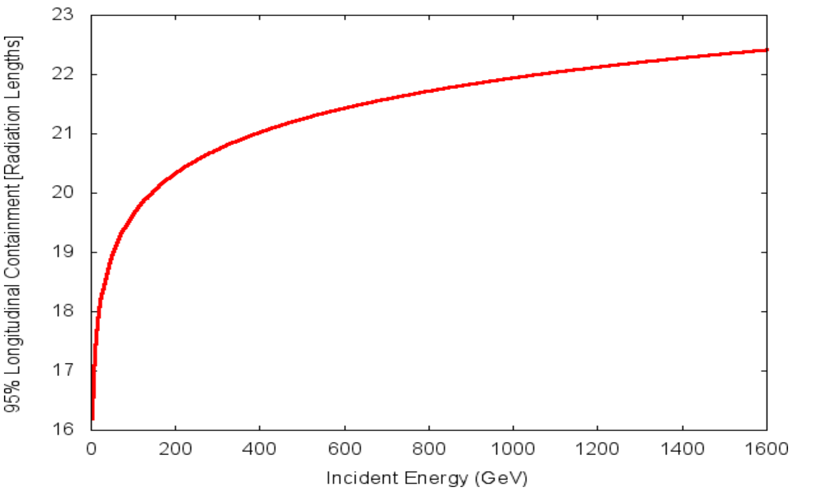






Quartz Fiber Calorimeter



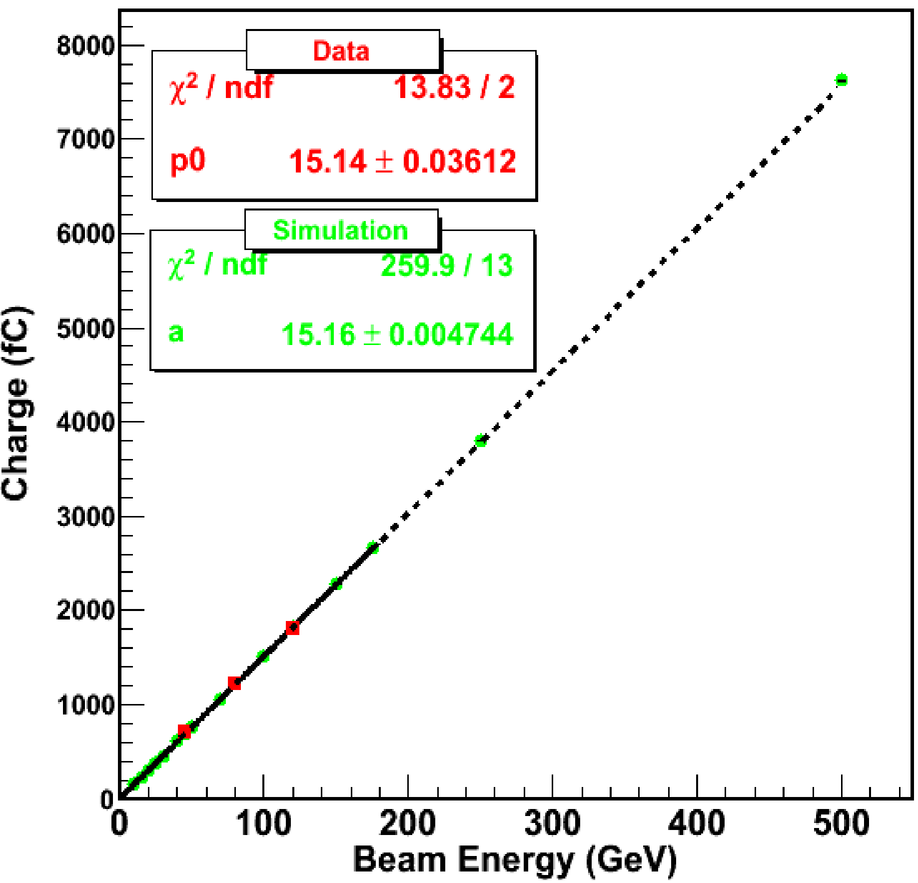


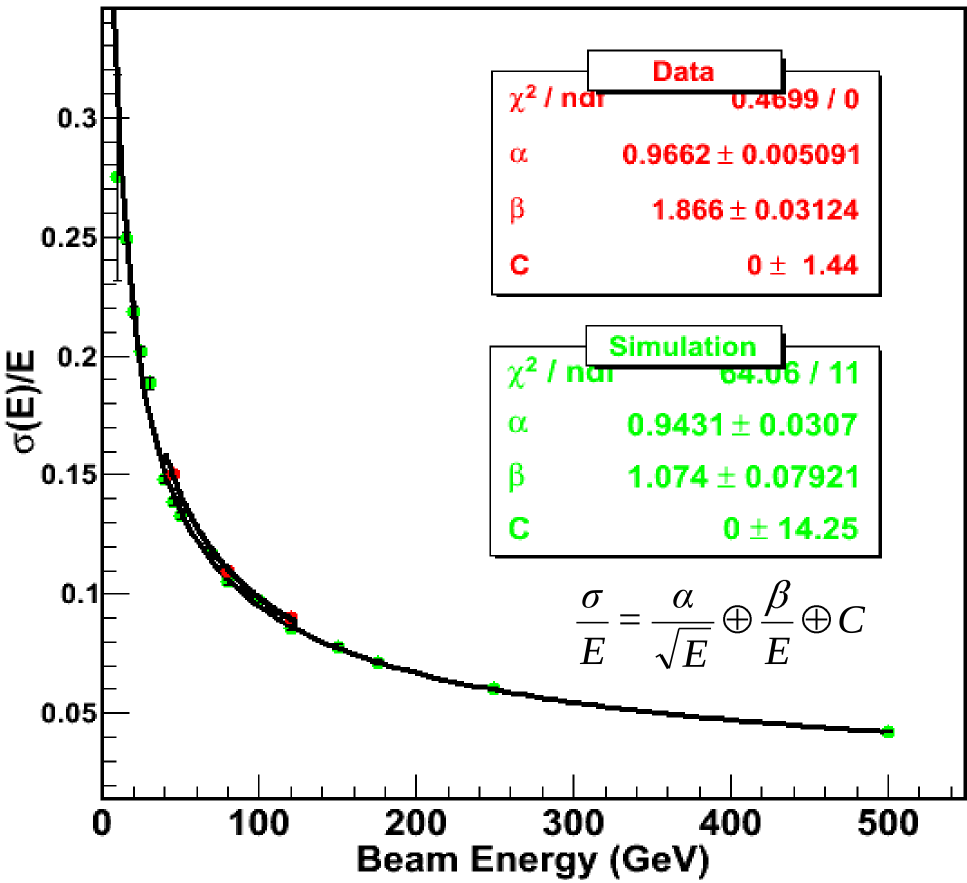
- Iron rods of 6 mm diameter, 45 cm length (~25X_0).
- Quartz fibers in between the rods (0.3 mm core diameter).
- 20 cm x 20 cm lateral size.
- Single readout of the bundled fibers.

Tested with 45, 80 and 120 GeV/c electron beams.

Needs to measure scattered photons – EM calorimetry

Quartz Fiber Calorimeter

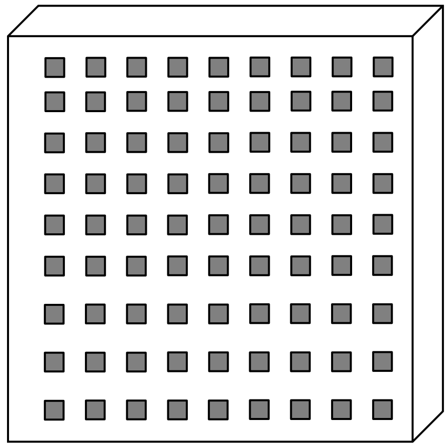




Čerenkov Detector
A Novel Approach!

SiPMs directly coupled to the downstream surface of the crystal!

Needs to have very good position resolution



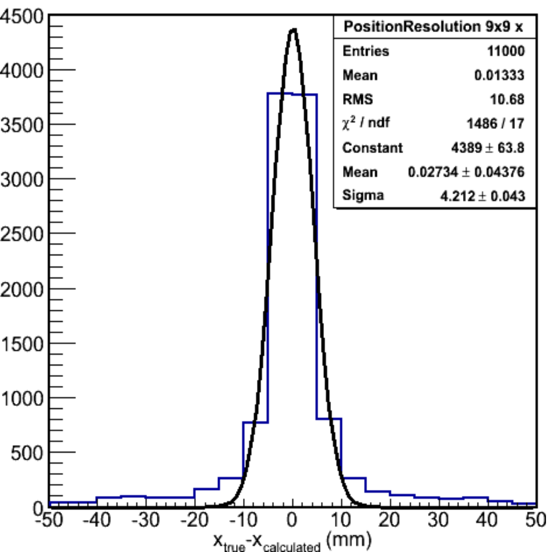
20 cm x 20 cm x 1 cm PbF_2

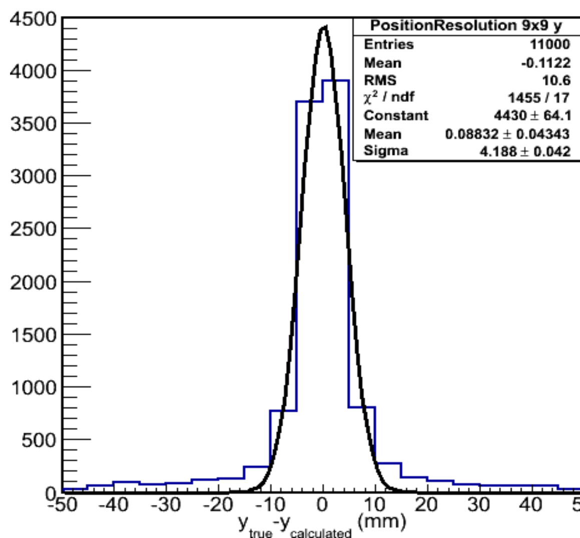
n=1.78 → Čerenkov angle ~ 57°

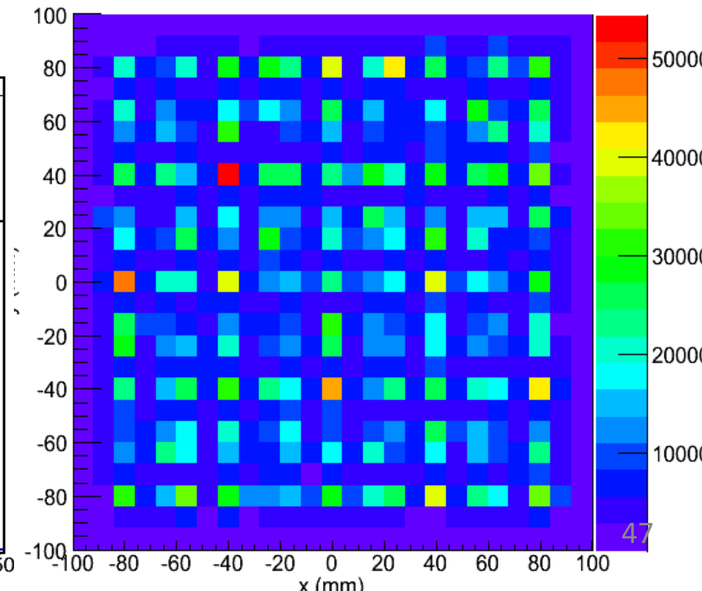
2 cm SiPM seperation

SiPM response ↔ number of photons

50 GeV e- beam ~ Compton edge @ 500 GeV







Summary

- Many new approaches with solid understanding and proof of concept.
- R&D in most of these projects will soon be completed and ready for real detector implementations.
- Many novel detector concepts are being validated and new areas of implementation are searched for.

Back-up

Noise Measurement

7 event categories in noise (self triggered) runs (in/out of spill):

1. Low multiplicity random noise
2. High multiplicity random noise
3. Cosmic rays & beam muons
4. Ground connector related noise
5. Board noise
6. Ground connector & board noise
7. Beam events

- Number of ‘dead’ asics is very small
- RPC’s are in good shape after several beam tests
  - Average noise level is stable
  - Absolute noise level fluctuates with temperature
- Noise contribution to triggered beam data is extremely small (~0.1 hit/event for entire DHCAL+TCMT – 480K channels)
  - This noise level corresponds to ~6MeV/event
  - RPCs contribute negligible noise hits to beam data
  - Correlated noise level needs more study
- Noise ‘hot spots’ are due to unclean surface
  - Not a problem if temperature is low

Track segment analysis

Method

Use clusters (= *source clusters*) in 2 layers to study layer in between (=*target cluster*)
e.g. use L_{i-1} and L_{i+1} to look at L_i

Source clusters

Required to have at most 3 hits
Lateral distance between source clusters at most 3 cm
No additional hits within 7 cm of source clusters

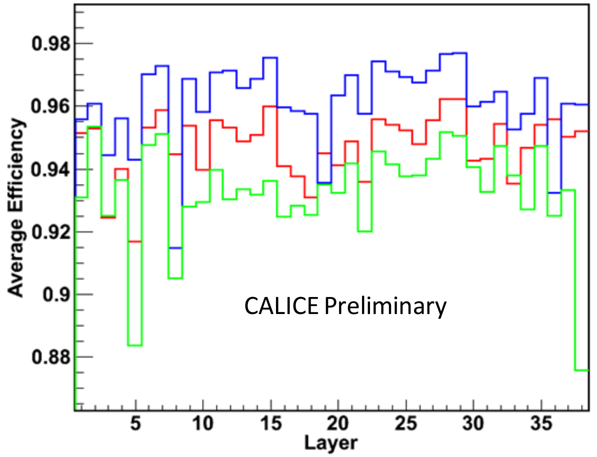
Target cluster

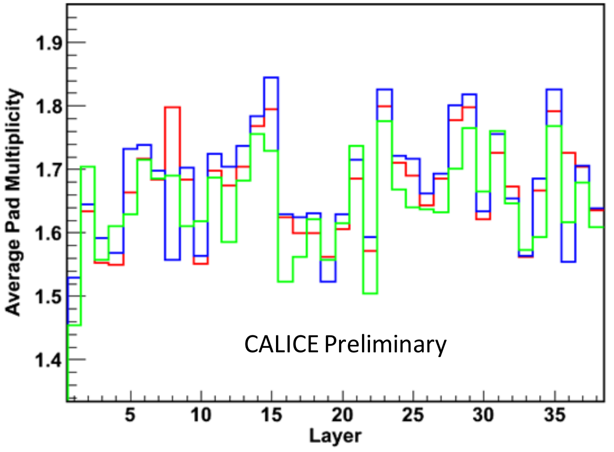
Searched for within radius of 2 cm from line between source clusters

Comparison of

Muon runs analyzed with tracks
Muon runs analyzed with track segments
Pion run analyzed with track segments

Clear correlation between different methods
…but systematic differences





Secondary Emission Calorimeter Sensor:

1.Top Metal Oxide/C SE Cathode, thin film SE inner Surface
Square/Hex/Rectangle/etc –can be thick!
2. Edge Wall: ceramic, or metal w/ceramic HV insulators; HV feedthrus; vacuum metal tip-off: ~1cm high
3. Dynode Stack – mesh, slats ~5-10 mm thick;
4. Bottom Metal Anode – thick ~Cathode; Vacuum pump tip; Seal – e-beam seam, braze, etc
5. Evacuate/Bake (Refractory T!), and Pinch-off tip.

***NO ACTIVATION! ASSEMBLE IN AIR*!**

No Photocathode processing (few hours).

Vacuum 100 times higher than PMT ok.

NOTE: Alternative gain – MCP et al.

Technologies to make SE Calorimeters: Cheap Mesh!

CuBe Mesh 37% transparent 75 µm apertures- <$18/m^2

15 mesh/Lrad x 25 Lrad x 3m^2 x 2 arms x $18/m^2 ~ $40k