Summary of U.S. ILC Hadron Calorimetry

DOE/NSF ILC Detector R&D Review

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Overview

- Physics motivation for ILC Calorimetry

- PFA approach – implications for detector design

- Calorimeter system design(s)

- Digital/semi-digital/analog hadron calorimetry for PFAs

- Calorimeter technologies – R&D summary, Prototypes, Future Plans.

- Summary

Physics examples driving calorimeter design

Higgs production e.g. e^+e^- -> Z h ← Missing mass peak or bbar jets

separate from WW, ZZ (in all jet modes)

Higgs couplings e.g.

- g_{tth} from e^+e^- -> tth -> WWbbbb -> qqqqbbbb !
- g_{hhh} from e^+e^- -> Zhh

Higgs branching ratios h -> bb, WW^*, cc, gg, $\tau\tau$

Strong WW scattering: separation of

e^+e^- -> $\nu\nu$WW -> $\nu\nu$qqqq e^+e^- -> $\nu\nu$ZZ -> $\nu\nu$qqqq

and e^+e^- -> $\nu\nu$tt

Physics driving calorimeter design

-All of these critical physics studies involving the calorimeter demand:

- Efficient jet separation and reconstruction
- Excellent jet energy resolution (Goal σ/E ~3-4%)
- Excellent jet-jet mass resolution

+ jet flavor tagging

and have excellent performance for electrons, photons (direct from IP and off-angle), and taus,

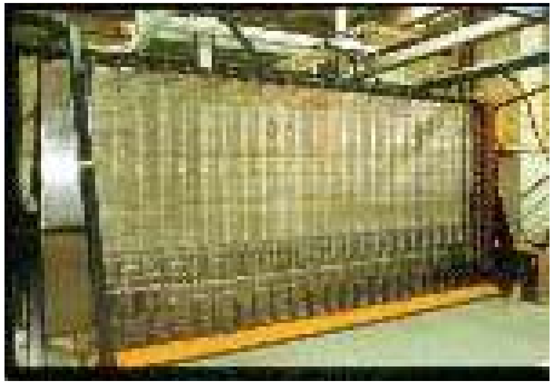
Plus… We need very good forward calorimetry for e.g. SUSY selectron studies (see LEP talk).

Why not use "traditional" calorimeters?

- Equalized EM and HAD responses ("compensation")
- Optimized sampling fractions

EXAMPLES:

ZEUS - Uranium/Scintillator



Single hadrons $35\%/\sqrt{E} \oplus 1\%$

Electrons $17\%/\sqrt{E} \oplus 1\%$

Jets $50\%/\sqrt{E}$

D0 – Uranium/Liquid Argon

Single hadrons $50\%/\sqrt{E} \oplus 4\%$

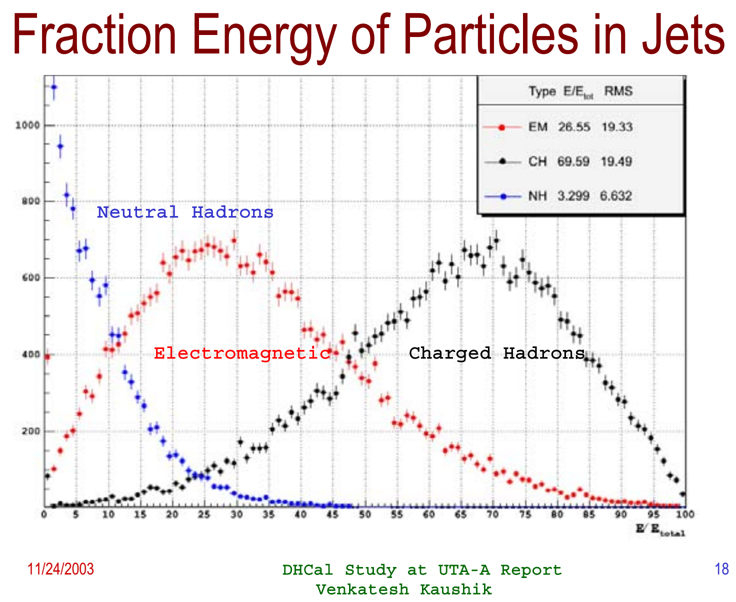
Jets $80\%/\sqrt{E}$

Clearly a significant improvement is needed for LC.

$\sigma/E \sim 3\text{-}4\%$ needed for jets

The PFA Approach – a major issue for ILC Calorimetry (to show it works!)

PFA approach holds prospect of required solution and has been used in other experiments effectively – promising developments for the ILC! (see previous talk)



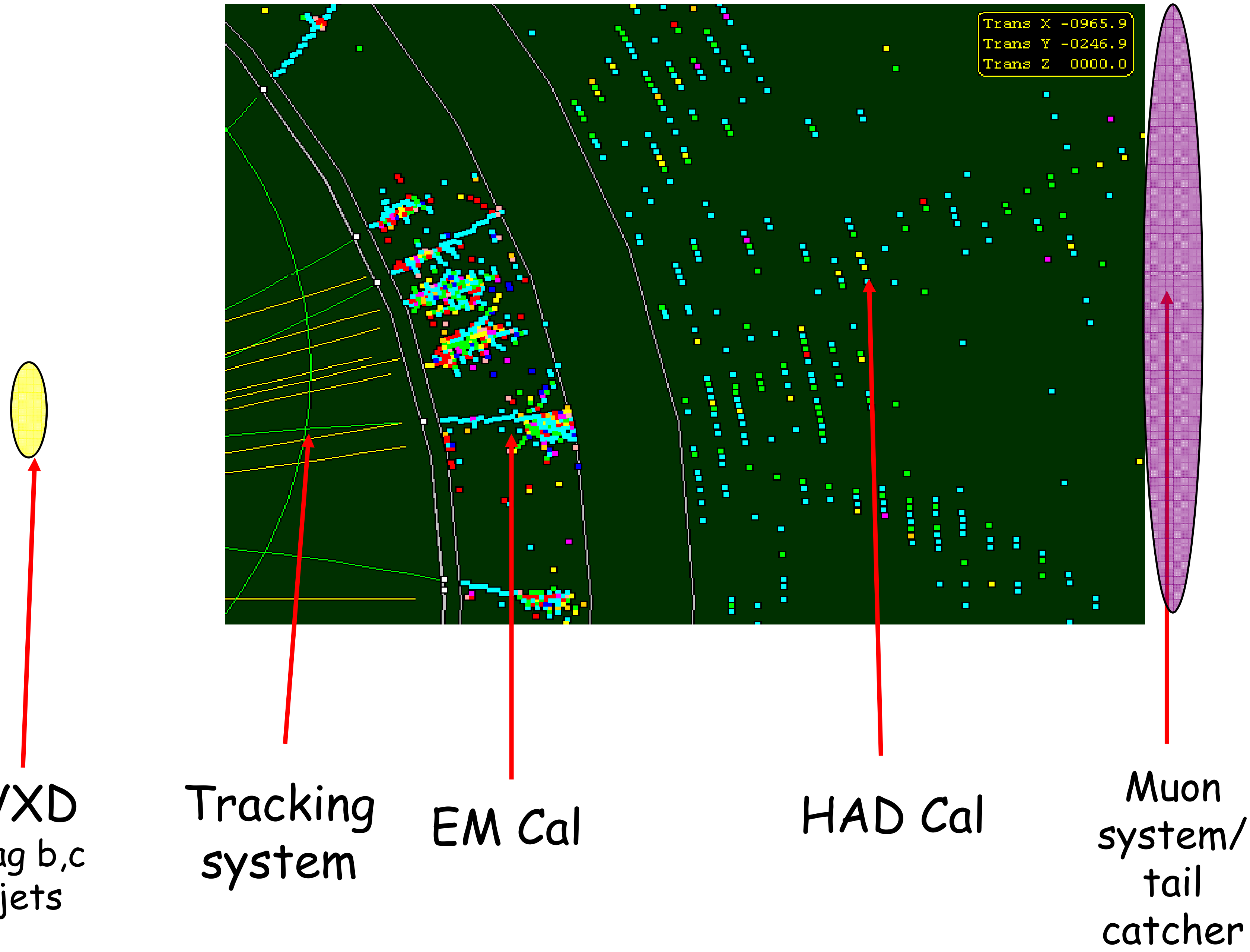
-> Use tracker to measure Pt of dominant, charged particle energy contributions in jets; photons measured in ECal.

-> Need efficient separation of different throughout calorimeter system

-> Energy measurement of only the relatively small neutral hadron contribution de-emphasizes intrinsic energy resolution, but highlights need for very efficient "pattern recognition" in calorimeter.

-> Measure (or veto) energy leakage from calorimeter through coil into muon system with "tail-catcher"??

PFA ➡ Integrated Detector Design



Integrated Detector Design

So now we must consider the detector as a *whole*.

e.g. the tracker not only provides excellent momentum resolution (certainly good enough for replacing cluster energies in the calorimeter with track momenta), but *also* must:

- efficiently find *all* the charged tracks:

  Any missed charged tracks will result in the corresponding energy clusters in the calorimeter being measured with lower energy resolution *and* a potentially larger confusion term.

Even though R&D is carried out independently for each subsystem, ultimately it must all deliver a viable, coherent detector design for the PFA.

Calorimeter System Design

▶ Identify and measure each jet energy component as well as possible

Following charged particles through calorimeter demands
high granularity…

Two options explored in detail:

(1) Analog ECal + Analog (or "semi-digital") HCal

- for HCal: cost of system for required granularity?

(2) Analog ECal + Digital HCal

- high granularity suggests a digital HCal solution
- resolution (for residual neutral energy) of a purely digital calorimeter??

Calorimeter System Design

In the U.S. much of the hadron calorimeter development for the ILC detectors has been within the context of the PFA approach (but note the following talk).

Technologies studied in the U.S. seek to implement this approach through the use of digital or analog/semi-digital techniques.

Most groups working in this area have their main interest in the SiD detector concept, and are also members of the CALICE Calorimeter R&D Collaboration. However, the ideas being developed are applicable to other detector design concepts.

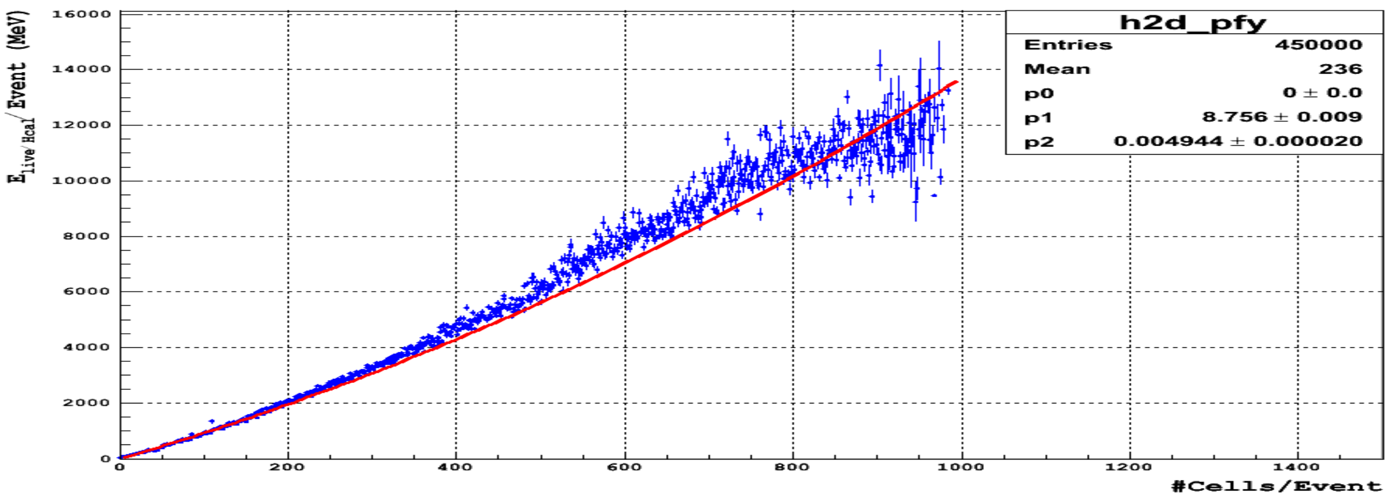
Digital hadron calorimetry

A new approach:

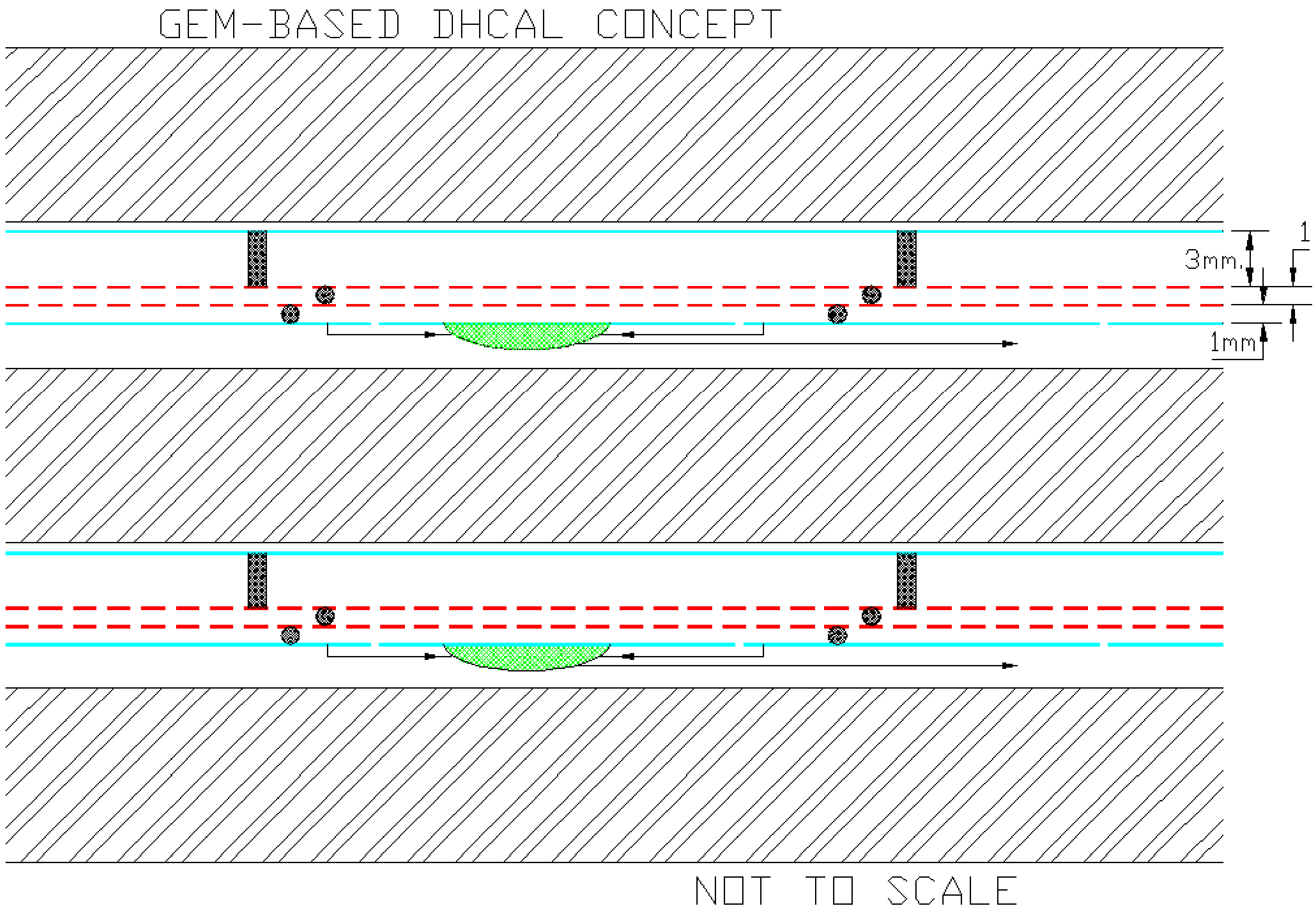
- use small cells (~1cm x 1cm -> ~3cm x 3cm), cell is either ON or OFF (digital) or use analog/semi-digital (multiple thresholds) approach.

- high granularity allows charged track following

- good correlation between energy and number of cells hit.

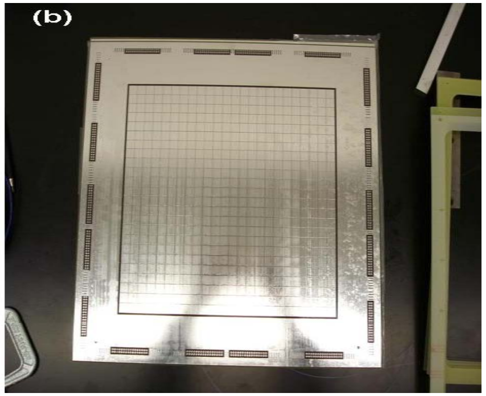


Digital Calorimeter Concept

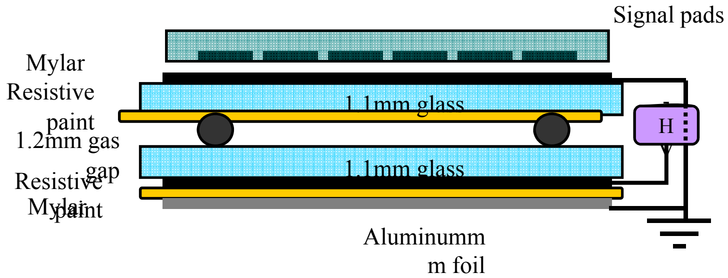


Hadron Calorimeter: technology choices

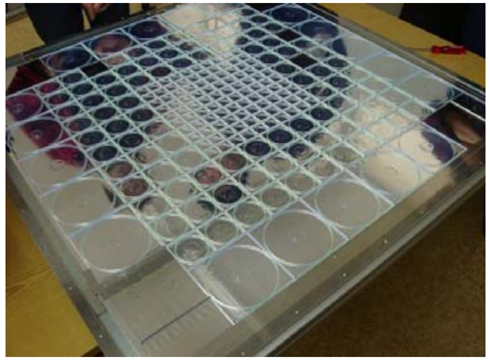
- HCAL: imaging requirements impose small cell size. Several possible ways to achieve this -> competing technologies:



UTA + UW, CALICE



ANL, BU, UI, UC, CALICE



NIU, CU, CALICE

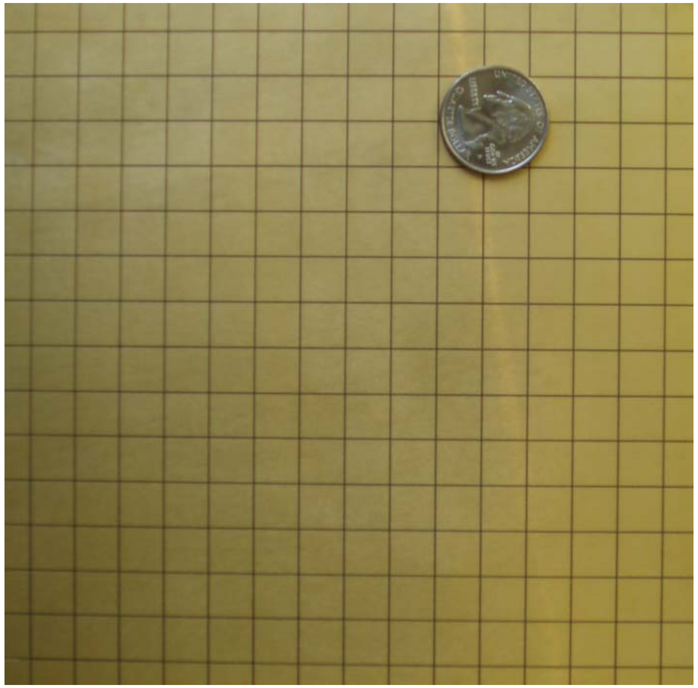
Digital

Analog/semi-digital

Technology selection requires prototype tests, simulated physics performance comparisons, evaluation of risks, estimation of costs -> framework for a selection plan.

Role of possible TCMT under study (analog/hybrid case?)

Digital Hadron Calorimetry using Resistive Plate Chambers (RPC)



Absorber

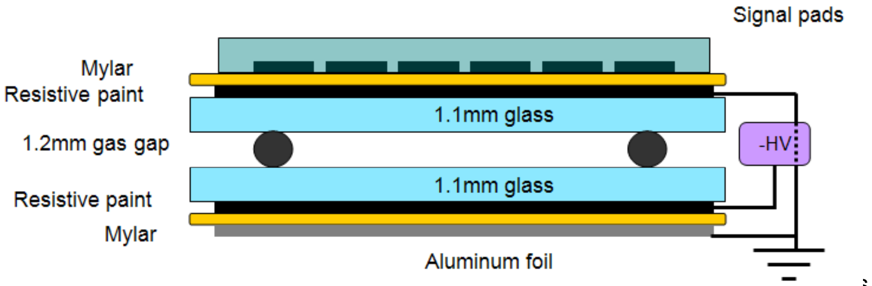
40 Steel plates of 20mm (~1 X_0)
Corresponds to ~4 λ_I

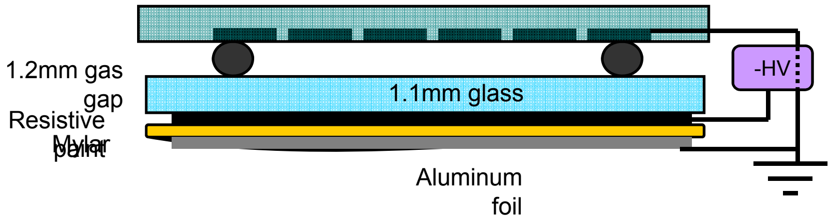
Active medium

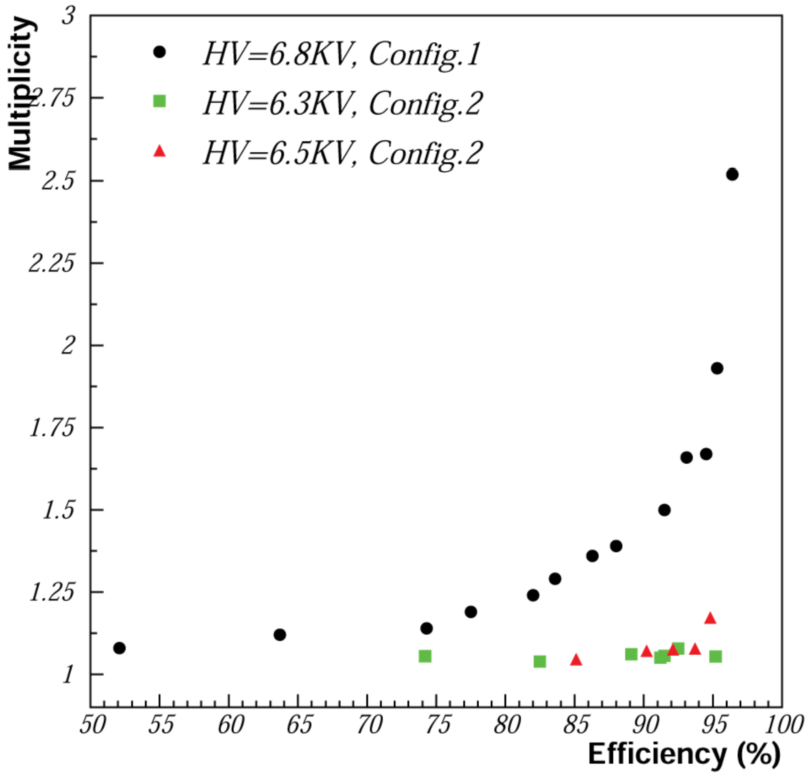
Resistive Plate Chambers with 1 single gap
Glass as resistive plates
Operated in avalanche mode

Readout

1 x 1 cm^2 pads → $5 \cdot 10^7$ channels for the entire HCAL
1-bit resolution per pad (digital readout) ← preserves single particle resolutions

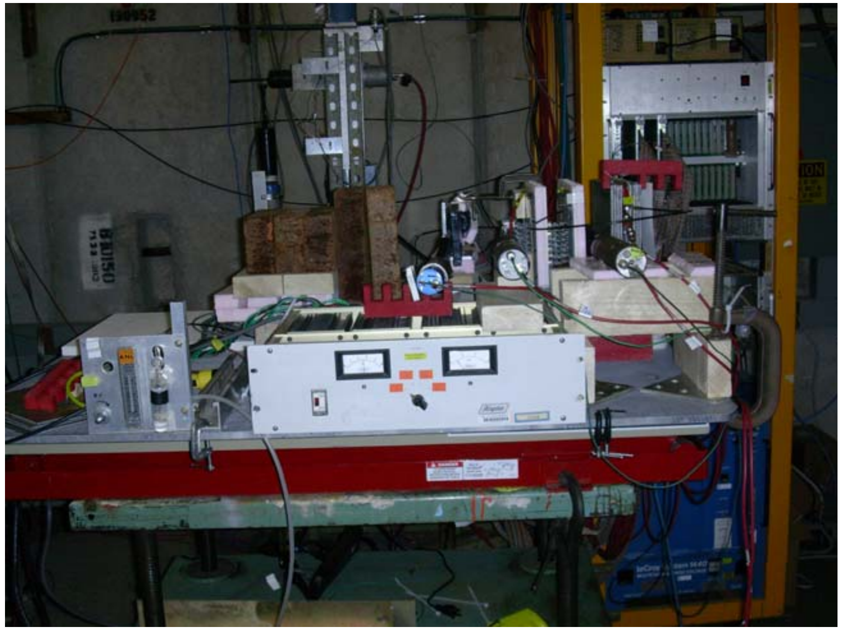


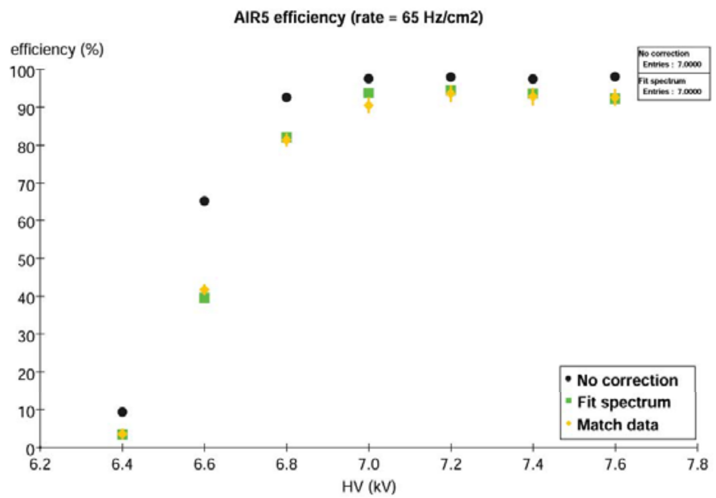




Long-term stability of 1-glass RPC?

Exposure to Fermilab Test beam

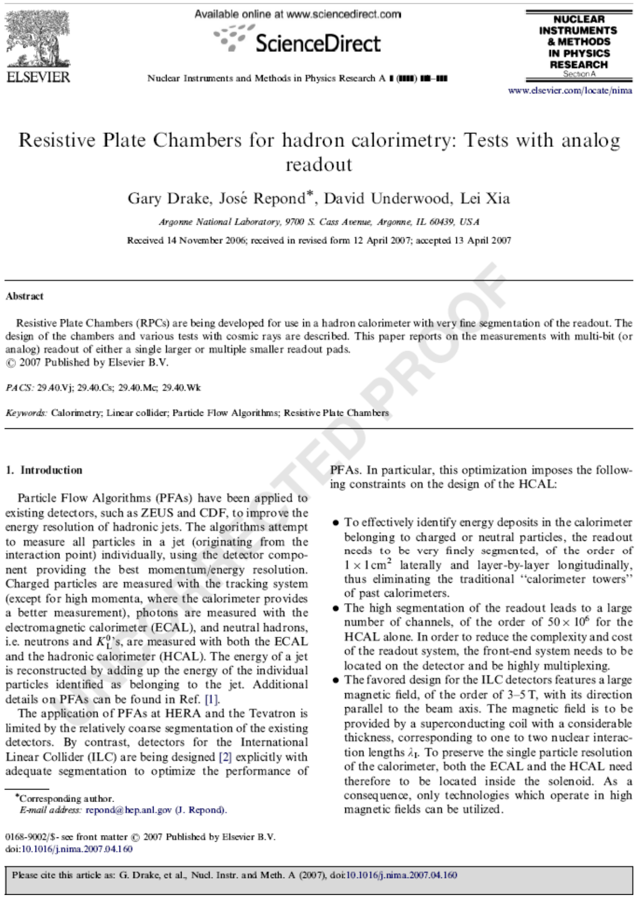




Summary of R&D with RPCs

R&D virtually complete

Measurement	RPC Russia	RPC US
Signal characterization	yes	yes
HV dependence	yes	yes
Single pad efficiencies	yes	yes
Geometrical efficiency	yes	yes
Tests with different gases	yes	yes
Mechanical properties	?	yes
Multi-pad efficiencies	yes	yes
Hit multiplicities	yes	yes
Noise rates	yes	yes
Rate capability	yes	yes
Tests in 5 T field	yes	no
Tests in particle beams	yes	yes
Long term tests	ongoing	ongoing
Design of larger chamber	ongoing	ongoing



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Resistive Plate Chambers for hadron calorimetry: Tests with analog readout

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Abstract

Resistive Plate Chambers (RPCs) are being developed for use in a hadron calorimeter with very fine segmentation of the readout. The design of the chambers and various tests with cosmic rays are described. This paper reports on the measurements with multi-bit (or analog) readout of either a single larger or multiple smaller readout pads.

PACS: 29.40.Vj; 29.40.Cs; 29.40.Mc; 29.40.Wk

Keywords: Calorimetry; Linear collider; Particle Flow Algorithms; Resistive Plate Chambers

1. Introduction

Particle Flow Algorithms (PFAs) have been applied to existing detectors, such as ZEUS and CDF, to improve the energy resolution of hadronic jets. The algorithms attempt to measure all particles in a jet (originating from the interaction point) individually, using the detector component providing the best momentum/energy resolution. Charged particles are measured with the tracking system (except for high momenta, where the calorimeter provides a better measurement), photons are measured with the electromagnetic calorimeter (ECAL), and neutral hadrons, i.e. neutrons and K_L^0's, are measured with both the ECAL and the hadronic calorimeter (HCAL). The energy of a jet is reconstructed by adding up the energy of the individual particles identified as belonging to the jet. Additional details on PFAs can be found in Ref. [1].

The application of PFAs at HERA and the Tevatron is limited by the relatively coarse segmentation of the existing detectors. By contrast, detectors for the International Linear Collider (ILC) are being designed [2] explicitly with adequate segmentation to optimize the performance of PFAs. In particular, this optimization imposes the following constraints on the design of the HCAL:

- To effectively identify energy deposits in the calorimeter belonging to charged or neutral particles, the readout needs to be very finely segmented, of the order of $1 \times 1\,cm^2$ laterally and layer-by-layer longitudinally, thus eliminating the traditional "calorimeter towers" of past calorimeters.
- The high segmentation of the readout leads to a large number of channels, of the order of 50×10^6 for the HCAL alone. In order to reduce the complexity and cost of the readout system, the front-end system needs to be located on the detector and be highly multiplexing.
- The favored design for the ILC detectors features a large magnetic field, of the order of 3–5 T, with its direction parallel to the beam axis. The magnetic field is to be provided by a superconducting coil with a considerable thickness, corresponding to one to two nuclear interaction lengths λ_I. To preserve the single particle resolution of the calorimeter, both the ECAL and the HCAL need therefore to be located inside the solenoid. As a consequence, only technologies which operate in high magnetic fields can be utilized.

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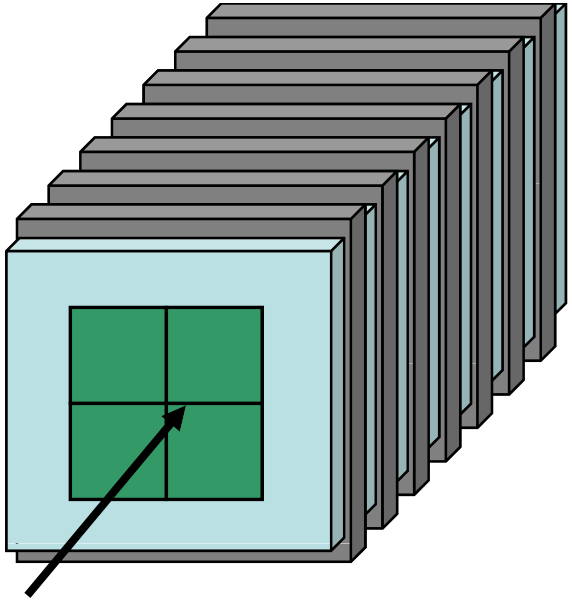
Vertical Slice Test

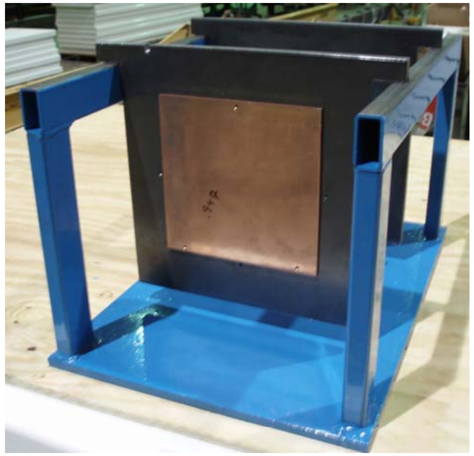


Uses the 40 front-end ASICs from the 2nd prototype run

Equip ~12 chambers with 4 chips each

256 channels/chamber
~3000 channels total

Chambers interleaved with 20 mm steel-copper absorber plates



Electronic readout system (almost) identical to the one of the prototype section

Tests in FNAL test beam

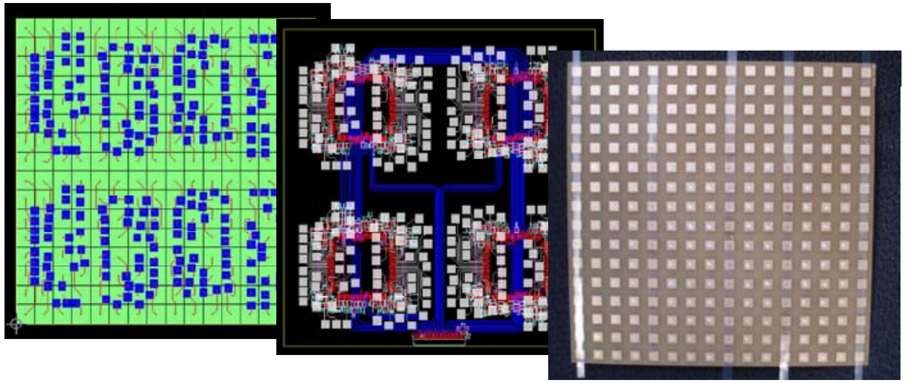
Design accommodates 20 x 20 cm^2 RPCs as well as 30 x 30 cm^2 GEMs

Planned for July 19 – August 6 2007
MoU being signed now

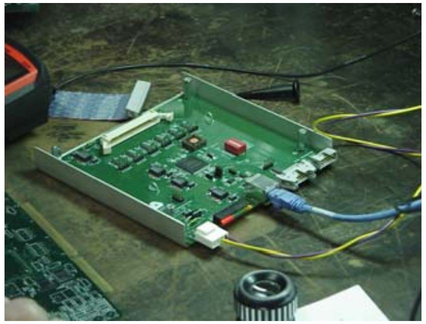
→ Measure efficiency, pad multiplicity, rate capability of individual chambers
→ Measure hadronic showers and compare to simulation

Validate RPC/GEM approach to finely segmented calorimetry
Validate concept of electronic readout

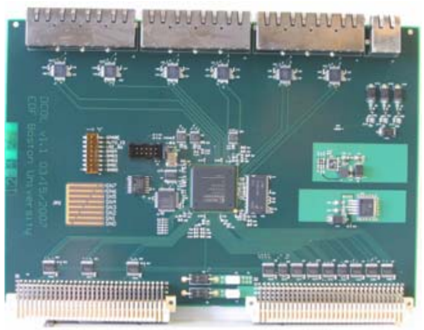
Pad- and Front-end Boards



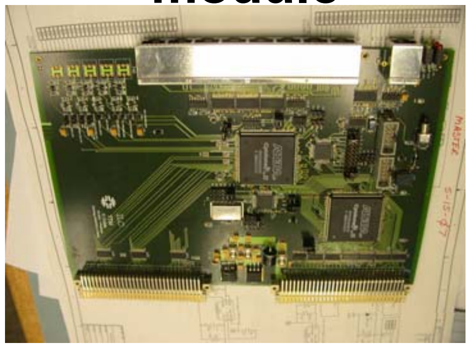
Data concentrator boards

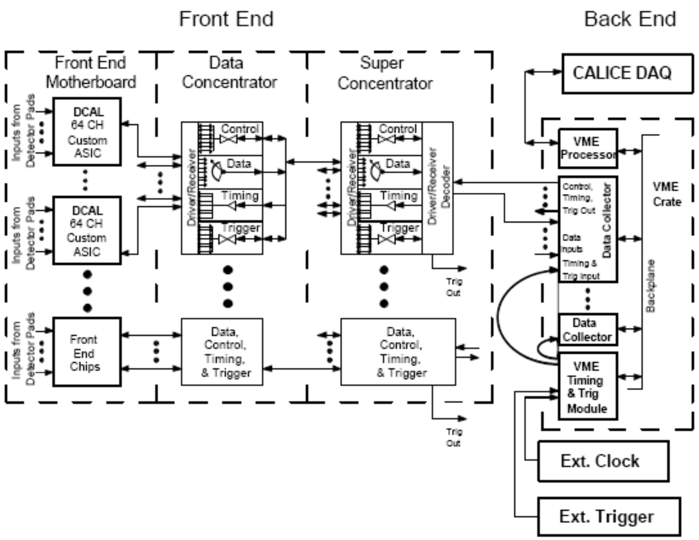


Data collector boards

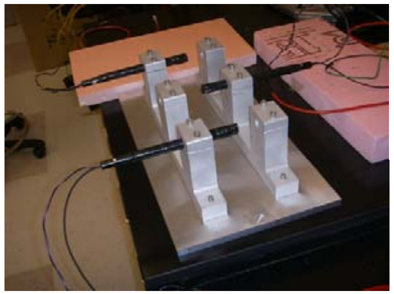


Timing and trigger module

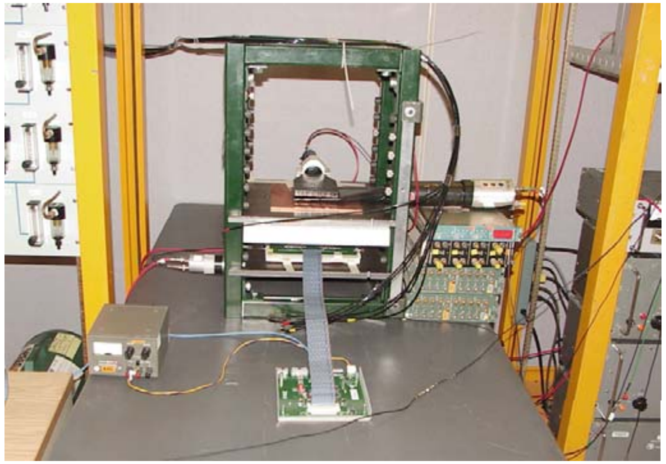




Beam telescope, HV, and gas

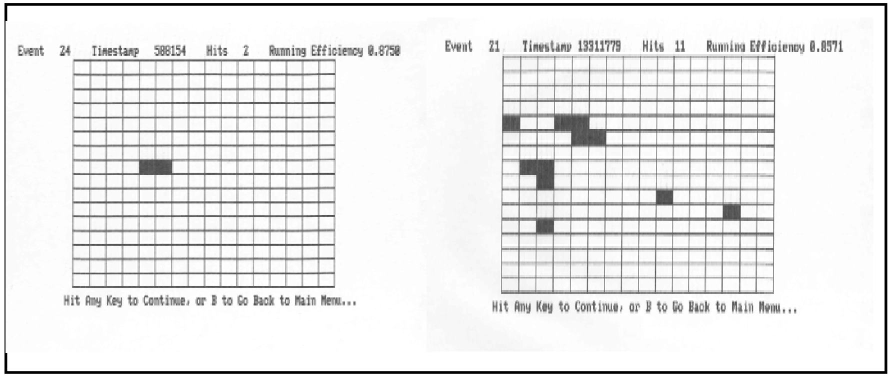


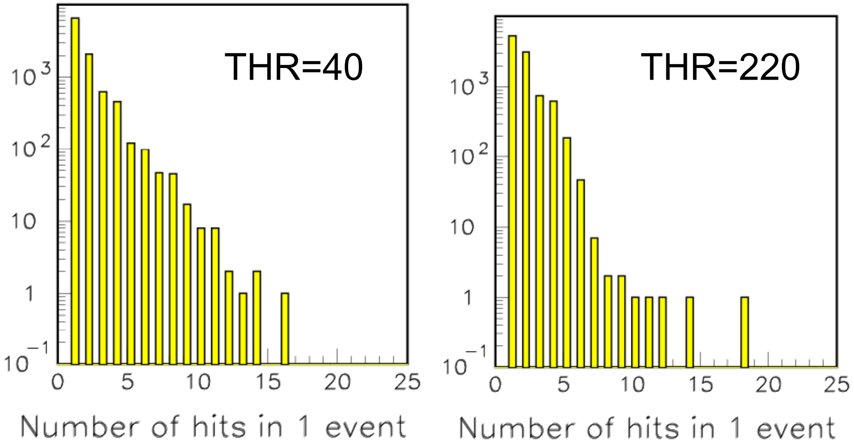
First Slice Test Results

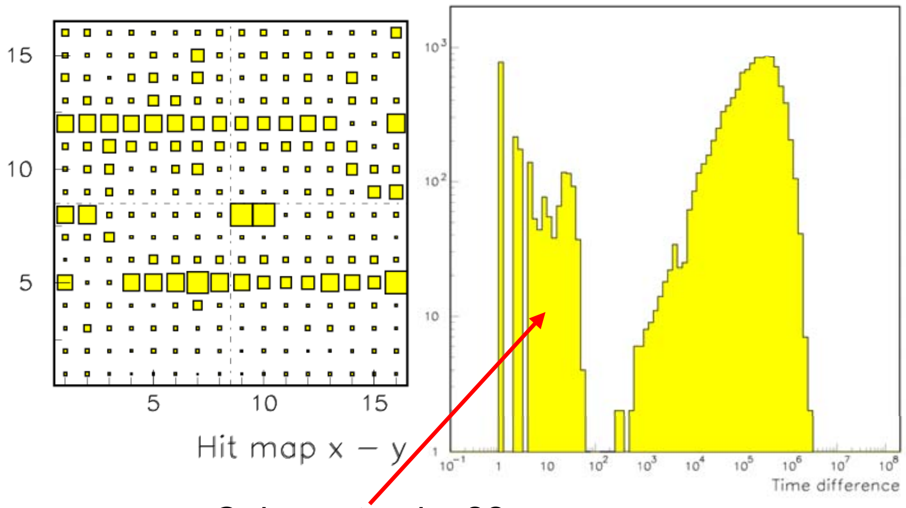


Working in self-triggered mode with 1-5 RPCs

First 30,000 cosmic ray events collected



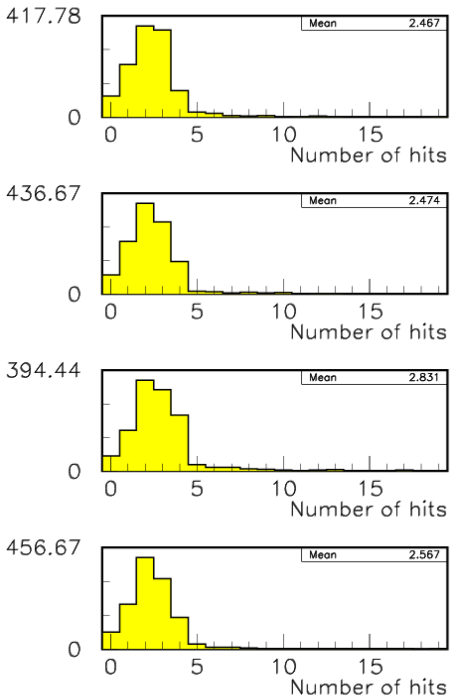




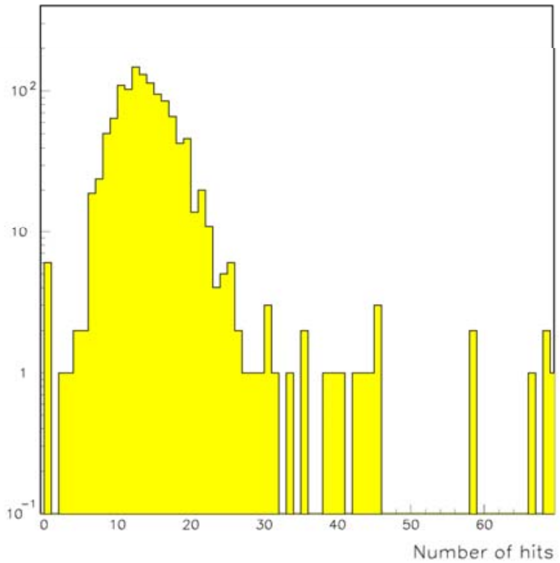
Up to 17 hits/event
Lower multiplicity with higher threshold

Coherent noise??
With times up to 5 μs??

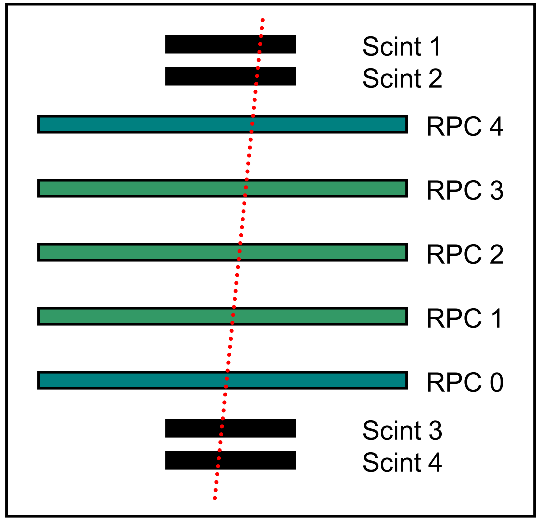
First Slice Test Results



Σ_{hits} **in 5 chambers**

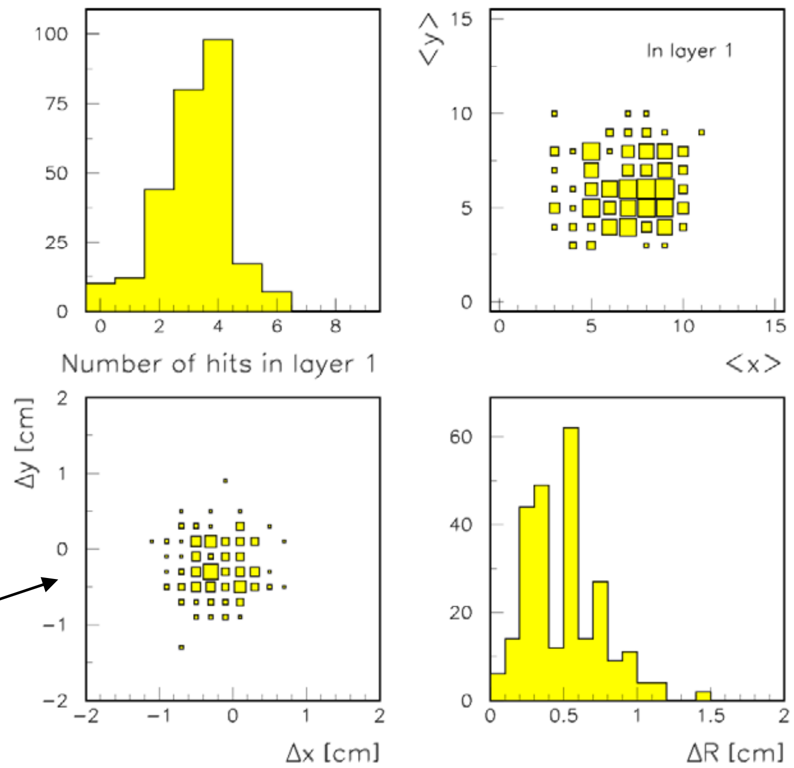


Multiplicity ~ 2.5
(threshold too low)



Outer chambers (RPC 0/4)
used for tracking

Predicted and measured
x – y positions agree



Prototype section 1m^3

40 layers of RPCs interleaved with Fe/Cu plates
Each layer ~ 1 m^2
With 1 x 1 cm^2 → 400,000 readout channels
Reuses stack and movable stage of CALICE AHCAL

Provided the VST is successful

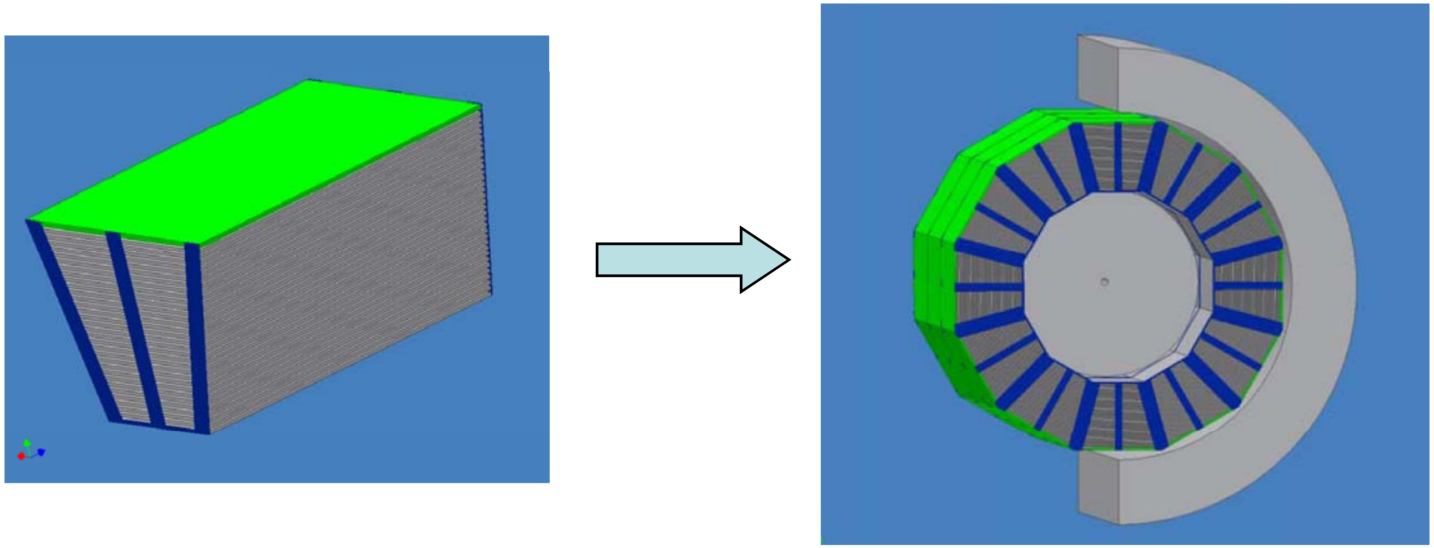
→ will need a small amount of R&D and prototyping for PS

- Larger chamber with new design
- Larger pad board (no active components)
- Gluing techniques (automatic)
- Data concentrator board with 12 inputs
- Super-concentrator boards (similar to concentrator)
- HV system for 120 chambers
- Gas system for 120 chambers (??)

Planned for 2008-9

RPC DHCAL – Future Plans

- Successful completion of vertical slice test	Jul/Aug	2007
- Completion of construction of the $1m^3$ stack	Oct	2008
- First physics results from $1m^3$ stack	Mar	2009
- Redesign of the RPC's and the readout system	Dec	2009
- Completion of the assembly of the scalable prototype	Dec	2010
- Completion of beam tests of the scalable prototype	Dec	2011



Digital Calorimetry using Gas Electron Multipliers

We have chosen a new approach:

Gas electron multiplier/1cm x 1cm pads:

C. GEMs

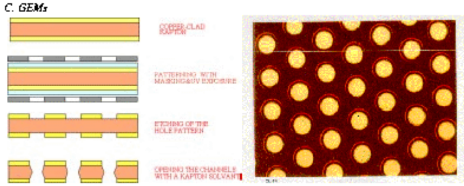


Fig. 14 (a) Chemical etching Process of a GEM (b) A GEM foil

A new concept of gas amplification was introduced in 1996 by Sauli: the Gas Electron multiplier (GEM) [27] manufactured by using standard printed circuit wet etching techniques' schematically shown in Fig. 14(a). Comprising a thin (~50 μm) Kapton foil, double sided clad with Copper, holes are perforated through (fig. 15b). The two surfaces are maintained at a potential gradient, thus providing the necessary field for electron amplification, as shown in Fig. 15(a), and an avalanche of electrons as in Fig. 15(b).

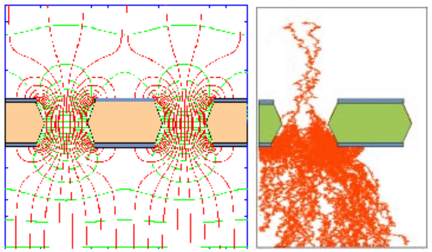


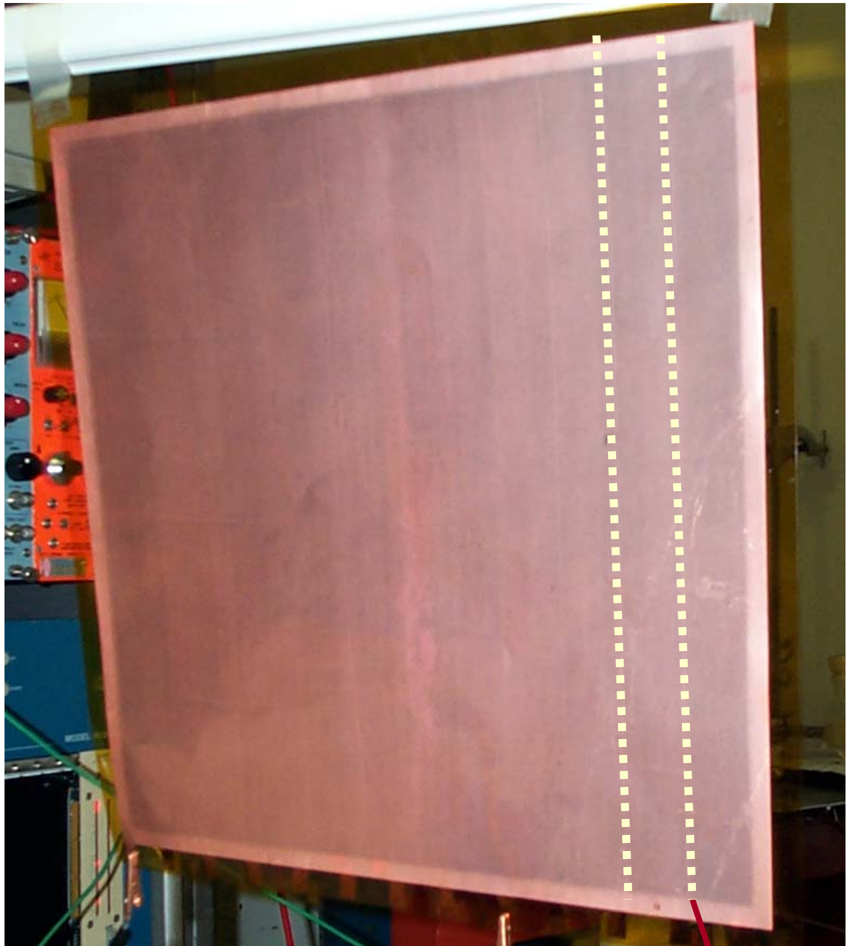
Fig. 15(a) Electric Field and (b) an avalanche across a GEM channel

Coupled with a drift electrode above and a readout electrode below, it acts as a highly performing micropattern detector. The essential and advantageous feature of this detector is that amplification and detection are decoupled, and the readout is at zero potential. Permitting charge transfer to a second amplification device, this opens up the possibility of using a GEM in tandem with an MSGC or a second GEM.

- easy to implement small cells
- fast
- robust
- high rate
- low HV operation
- simple gas (Ar/CO_2)
- stable operation

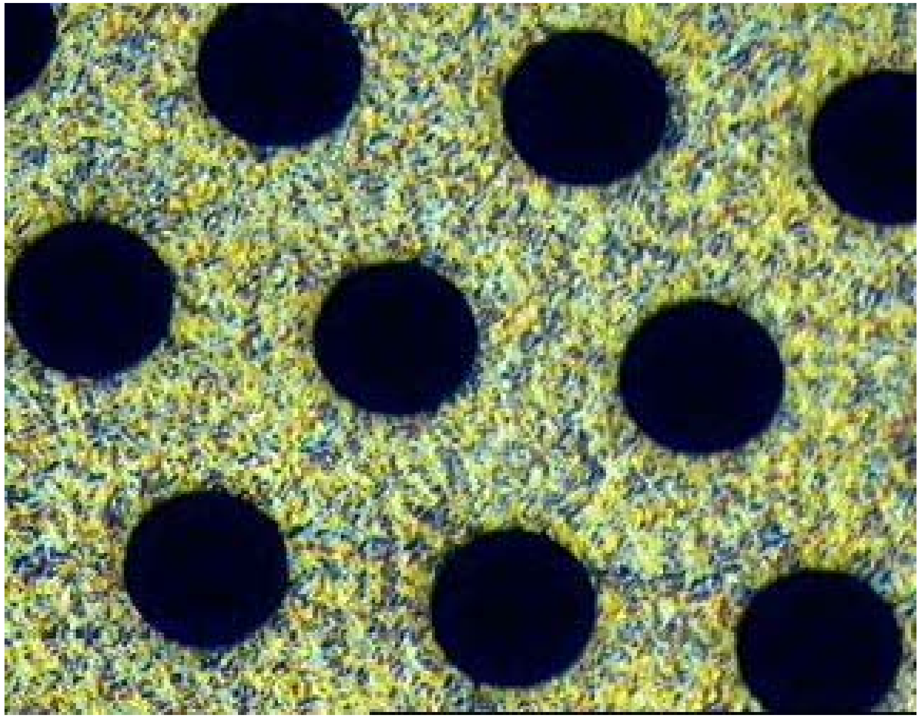
3M 30cm x 30cm GEM foils

12 HV sectors on one side of each foil.



HV Sector Boundary

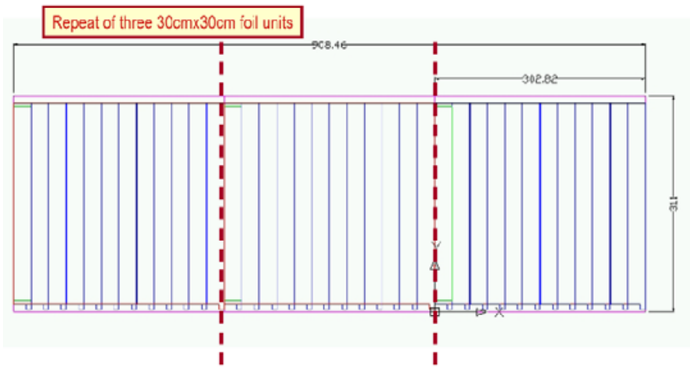
Magnified section of a 3M GEM foil.



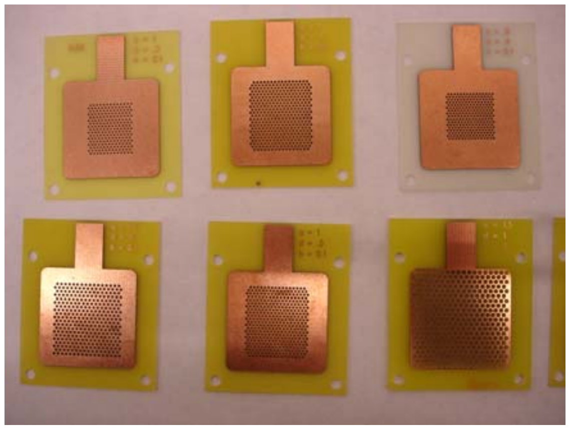
GEM Foil Design and Development

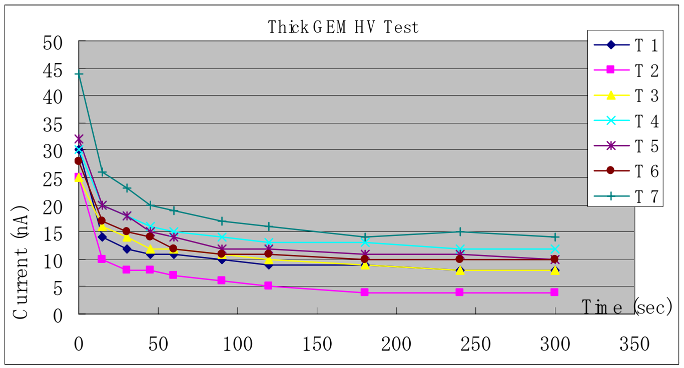
- We are working with 3M to develop larger foils for the 1m^3 prototype stack (the 30x30cm^2 foil development did not require 3M process modification).

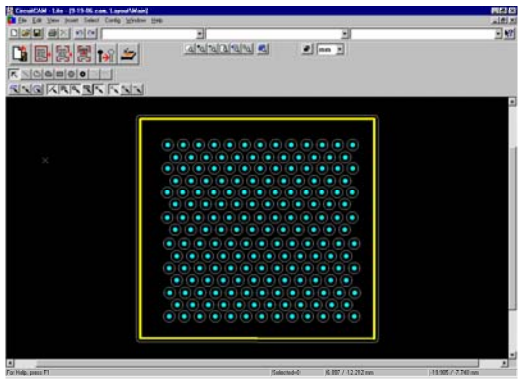
Proposed Initial 3M 30cmx100cm Foil Design



- In-house development at UTA of "Thick-GEMs"







Development of 30cm x 30cm GEM chamber(s)

- Foils HV tested.

- Jigs made to mount foils, stack chamber.

- Initial multilayer anode board made to work with Fermilab QPA02-based preamp cards.

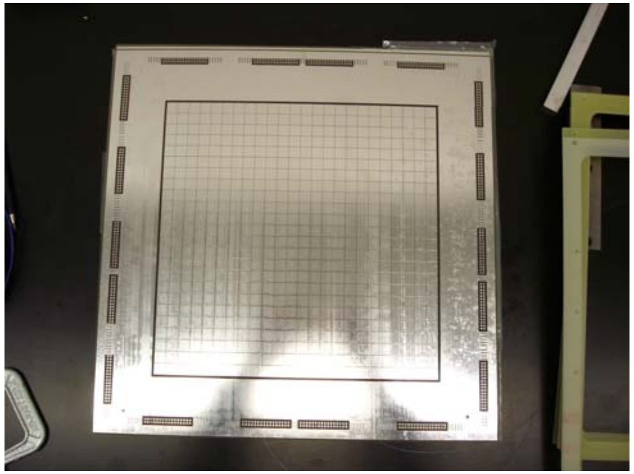
- Verify aspects of chamber operation:

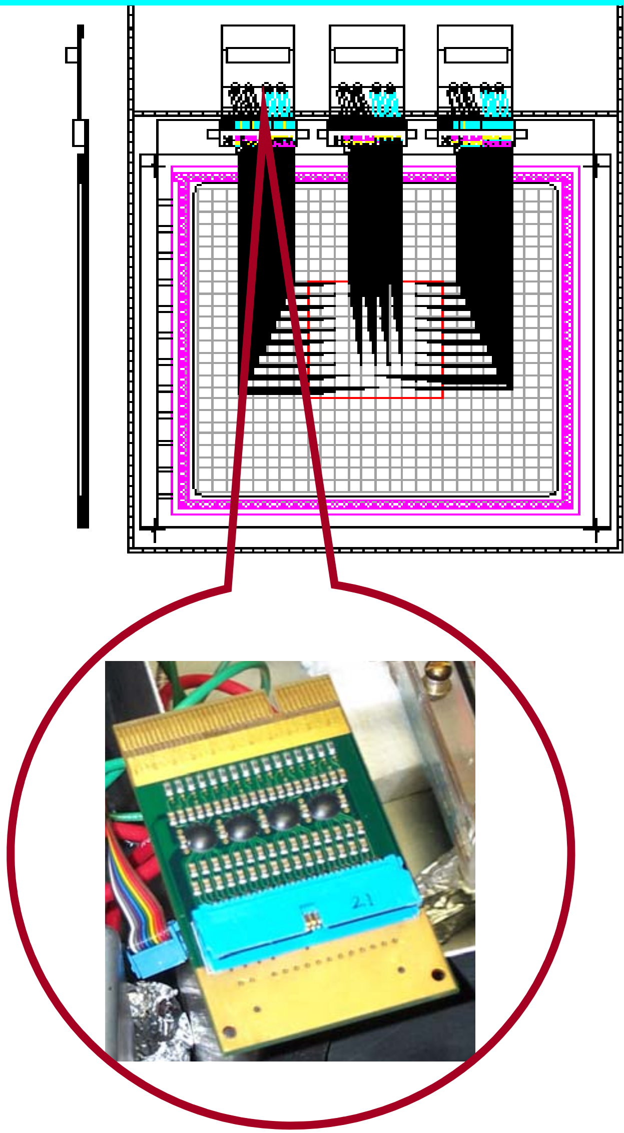
    - stability

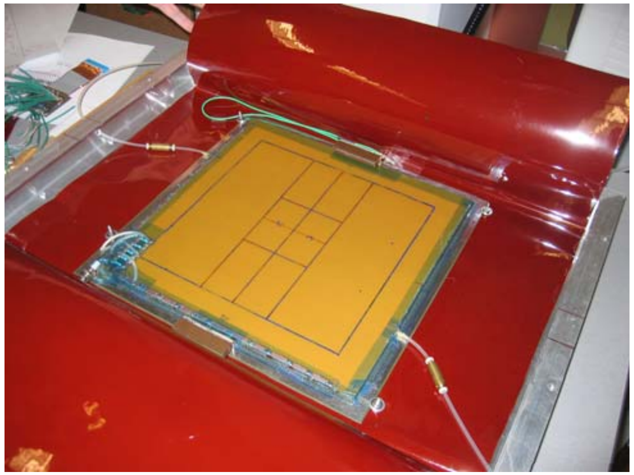
    - characteristics (cf. 10cm x 10cm chamber using CERN foils, Ar/CO_2 80:20, efficiency 95%, average hit multiplicity, 1.27)

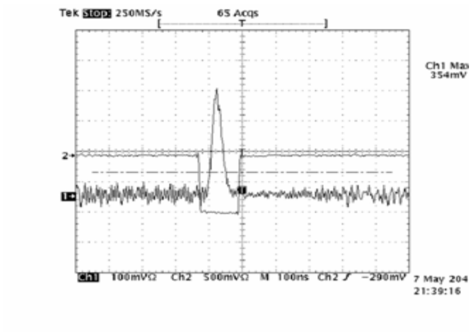
- Used for Korea/KAERI beam tests in May - Estimate ~2 x 10^{12} e-/pad in 2000 sec. (~ 1.6 x 10^{-2} mC/mm2) and GEM chamber continued normal operation.

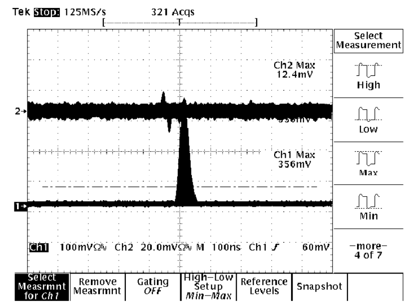
Development of 30cm x 30cm GEM chamber(s)

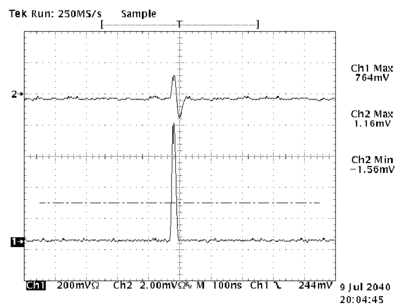




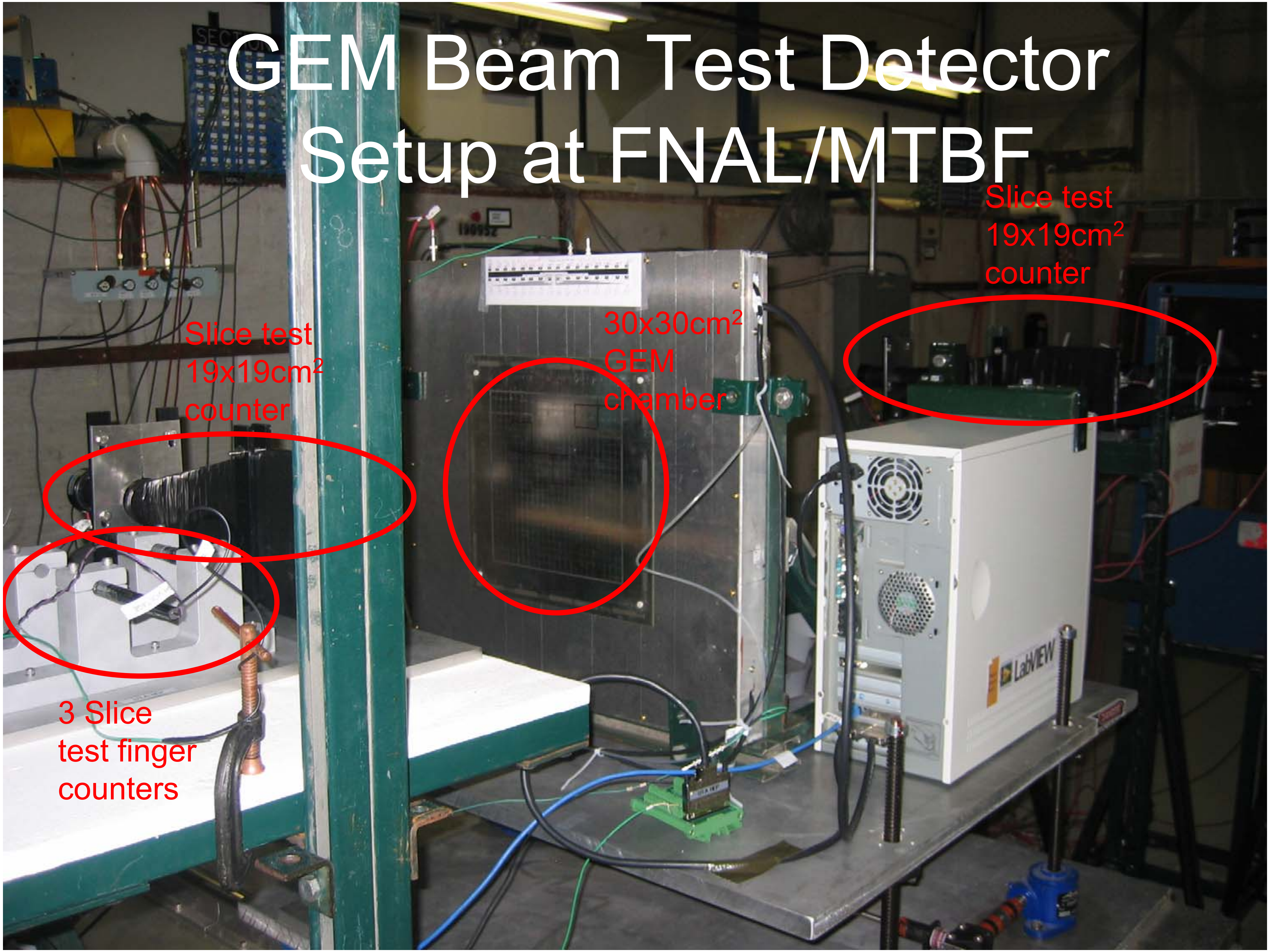




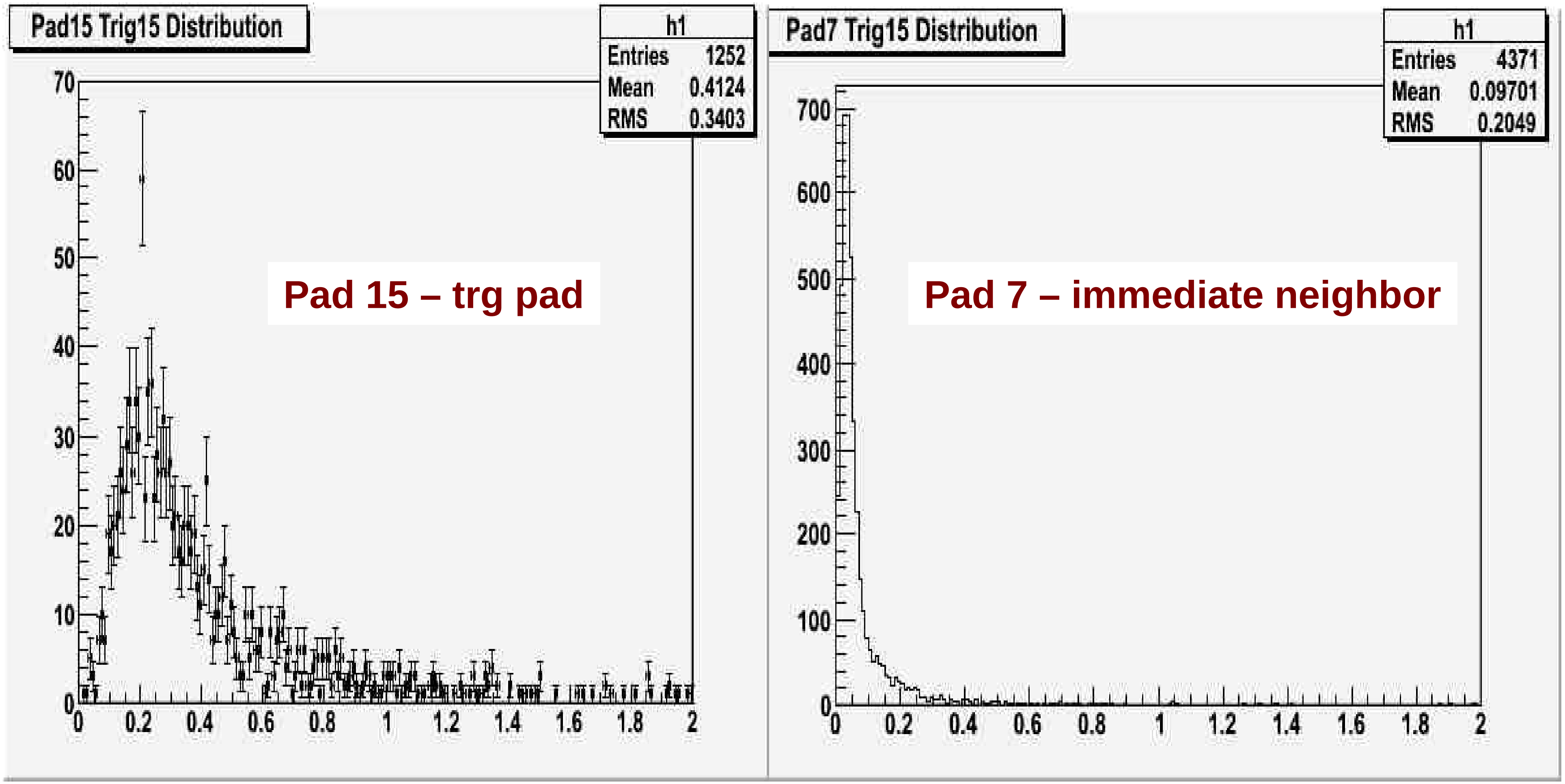




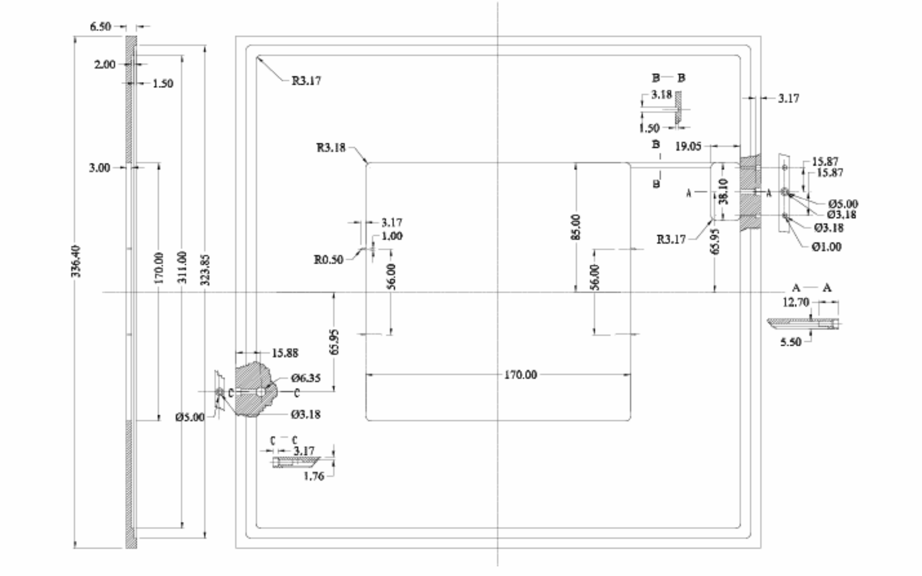
GEM Beam Test Detector Setup at FNAL/MTBF



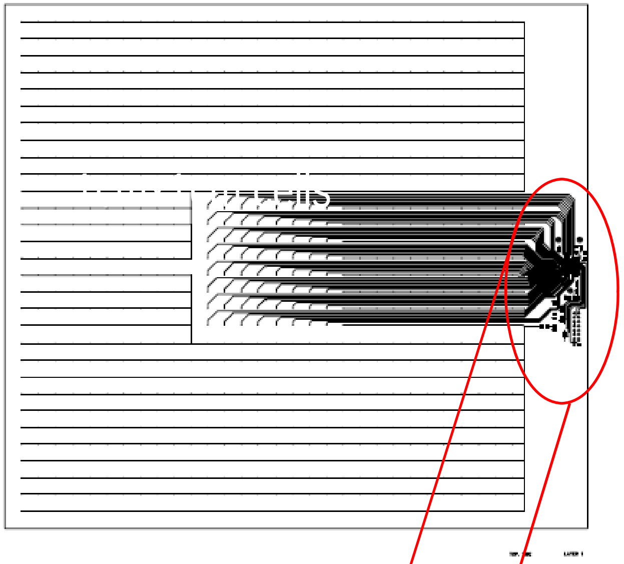
120GeV Proton – Triggered pad & Neighbor, X-Talk measurement



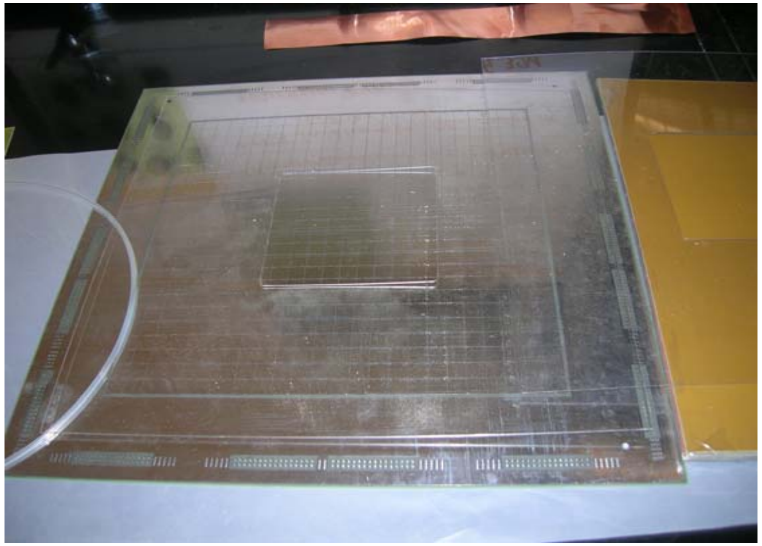
Readout for GEM: (1) DCal + KPiX Chips

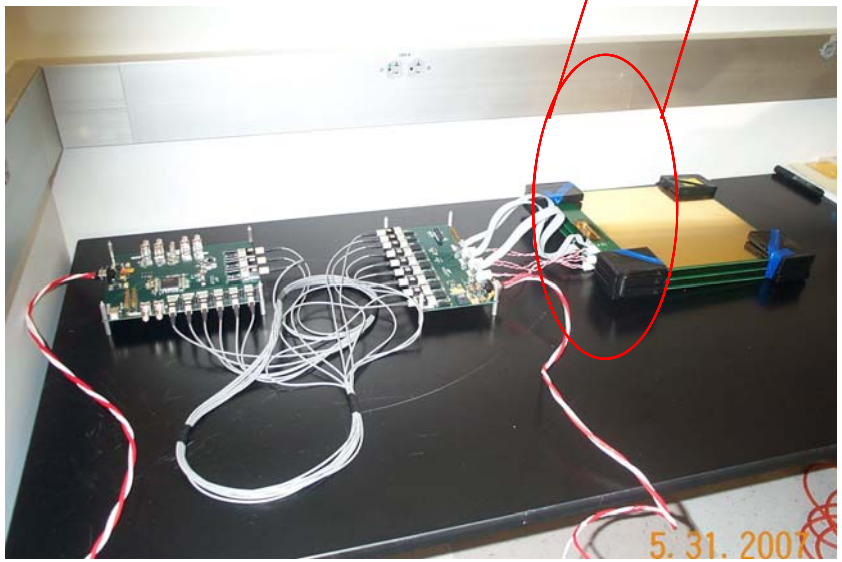


DCal



KPiX





M. Breidenbach/R. Herbst SLAC

GEM DHCAL – Future Plans

- Tests of KPiX Readout with GEM chamber June 2007
- Successful use of 2-3 GEM/KPiX chambers in slice test July 2007
- Construction of 1m x 30cm chambers for 1m^3 stack Dec 2007
- Completion of 1m^3 GEM stack with DCAL/KPiX readout Dec 2008
- Beam tests of GEM 1m^3 and comparison with simulations Late 2009
- Completion of construction of the scalable prototype Dec 2010
- Completion of beam tests of scalable prototype Dec 2011

Analog/Semi-Digital Calorimetry using Scintillator/SiPM

- Scintillator – a well-used/proven technology…but *small* cells?

- Impractical to use in "old" approach with photomultiplier tubes, with/without fibers (space, routing etc.)

- New technology – Silicon Photomultipliers (SiPM)!

- Now have the possibility of high granularity scintillator calorimeters at a reasonable cost.

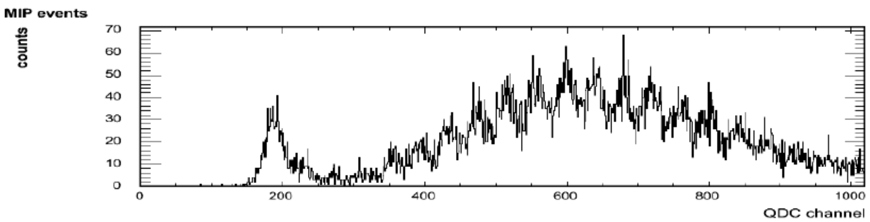
- Intense development using Scintillator/Fiber/SiPM

- Prototypes built/tested (MINICal, full-depth stack,…) and on to Technical (scalable) Prototype for ILC detector.

[1] G. Bondarenko, B. Dolgoshein, V. Golovin, A. Ilyin, R. Klanner, E. Popova, Nucl. Phys. B (Proc. Suppl.) 61B (1998) 347 and reference therein;

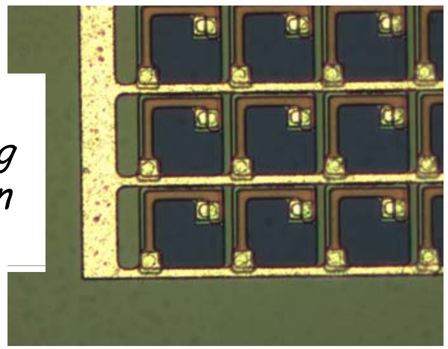
SiPM

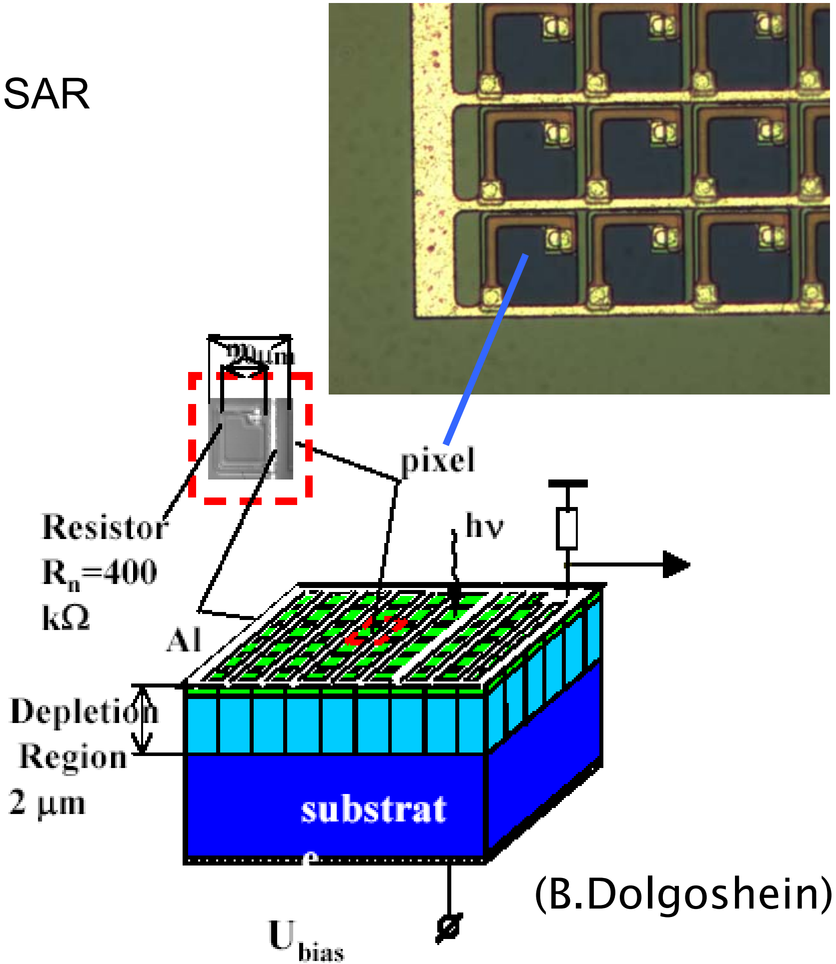
- From Moscow Engineering Physics Institute (MEPhI, Russia)
  - Multipixel Geiger Mode Photodiodes
    - Developed and produced by MPEPHI/PUSAR
    - Gain 10^6, bias ~ 50 V, size 1 mm^2
    - Insensitive to magnetic fields



Auto-calibrating but non-linear

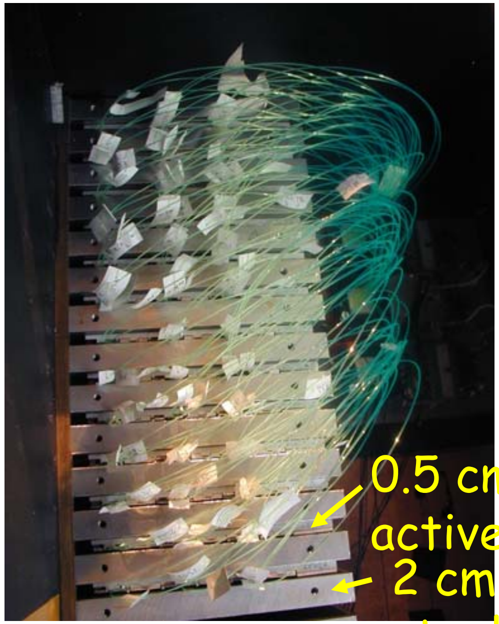
1156 pixels with individual quenching resistor on common substrate





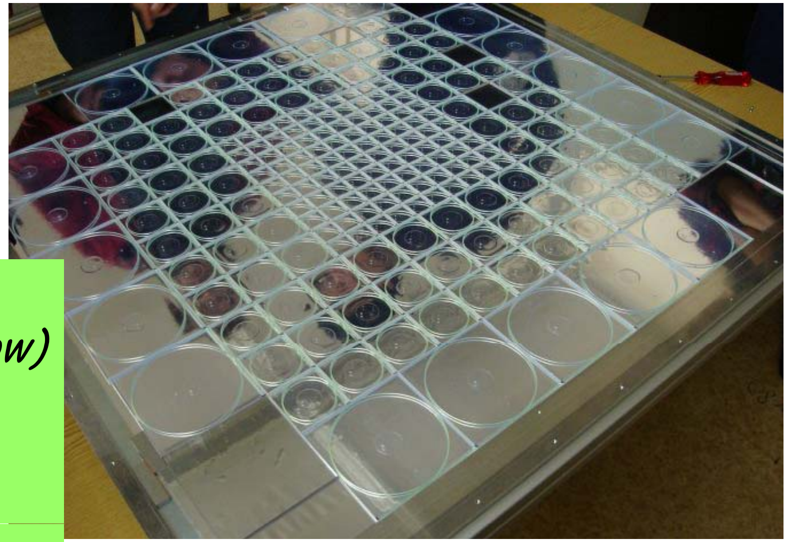
(B.Dolgoshein)

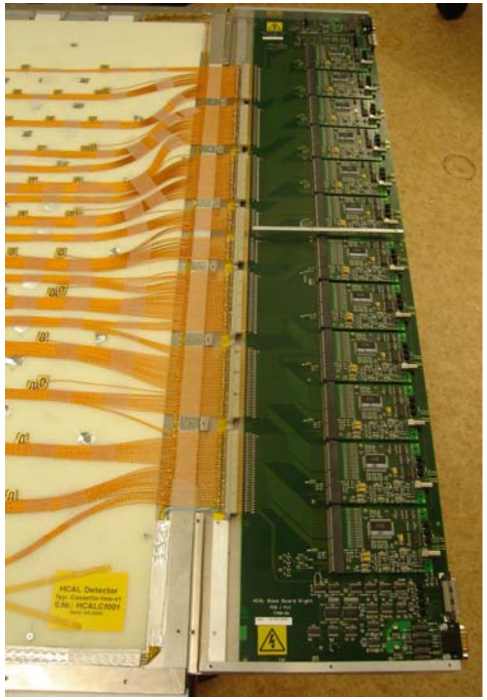
Scintillator/SiPM R&D



Minical

- 1 cubic meter
- 38 layers, 2cm steel plates
- 8000 tiles with SiPMs
- Electronics based on CALICE ECAL design, common back-end and DAQ



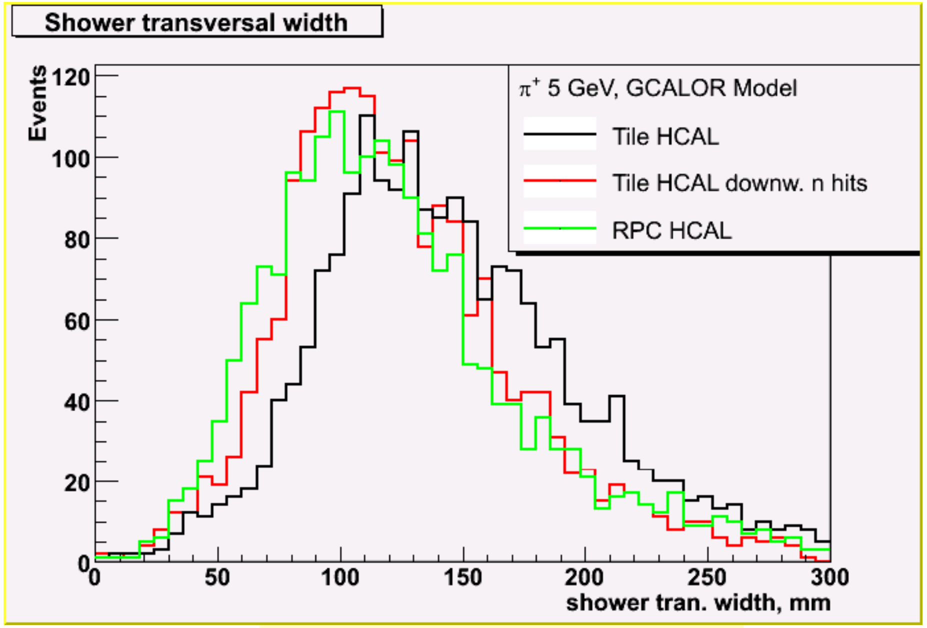


DESY, Hamburg U,
ITEP, MEPHI, LPI (Moscow)
Northern Illinois
LAL, Orsay
Prague
UK groups

1."Studies of silicon photodetectors for scintillator-based hadron calorimetry at the International Linear Collider'', D. Beznosko et al, NIM A {567} 62, (2006); 2. "Investigation of a solid-state photodetector", D. Beznosko et al, NIM A {533} 727 (2005); 3. "Small scintillating cells as the active elements in a digital hadron calorimeter for the e+e- Linear Collider Detector", Dyshkant et al, J. Phys. G30:N1 (2004).

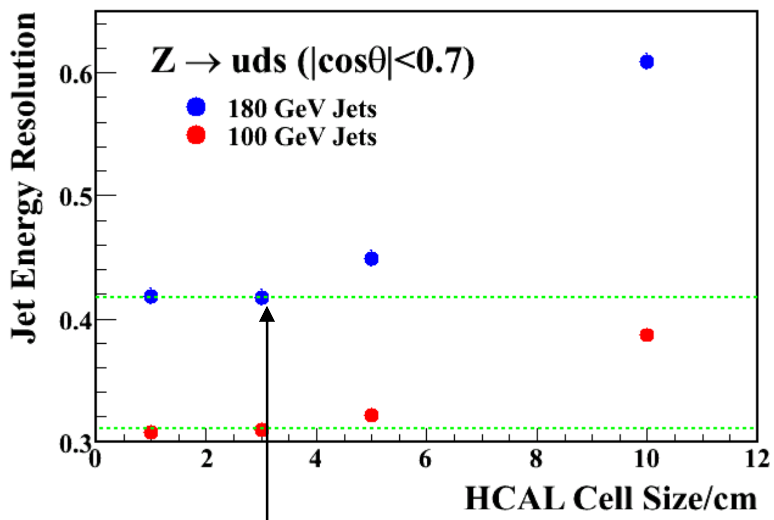
Scintillator tiles/SiPM - Issues

Shower spread Scint. vs. Gas



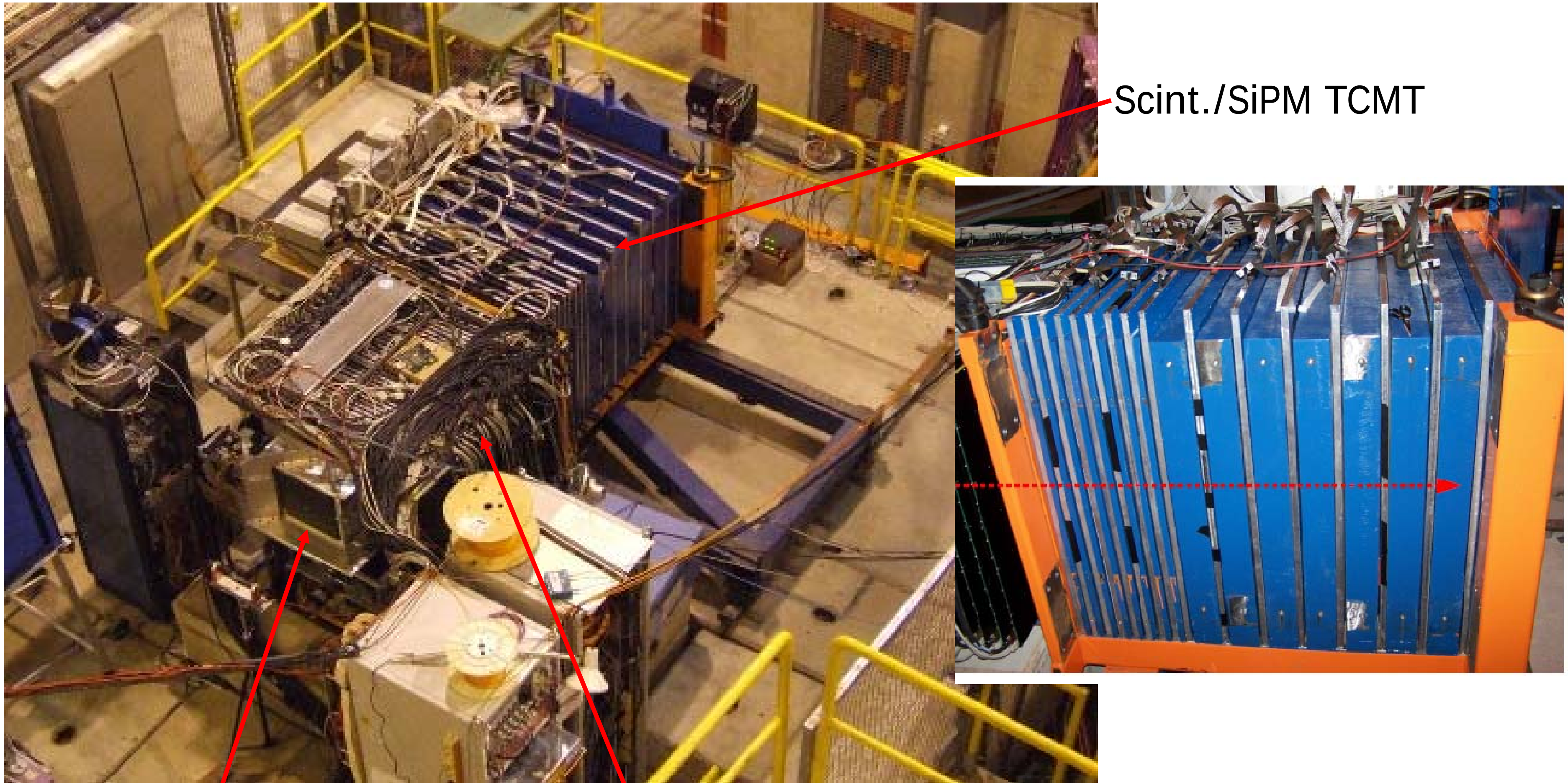
Use the weights which optimize hadron energy resolution

Tile Size?



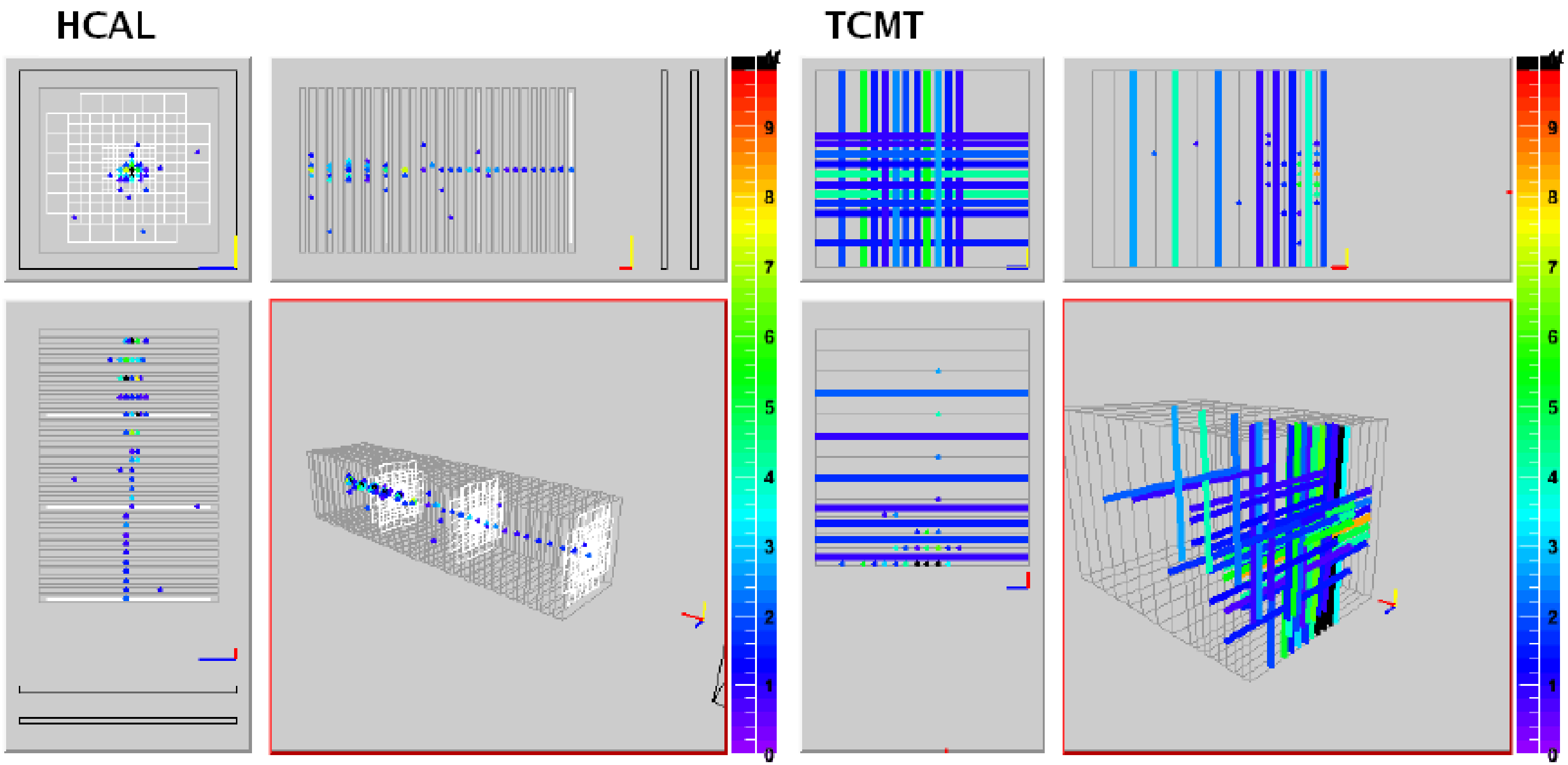
3 x 3 cm^2

CALICE Test Beam Setup



Example pion event display

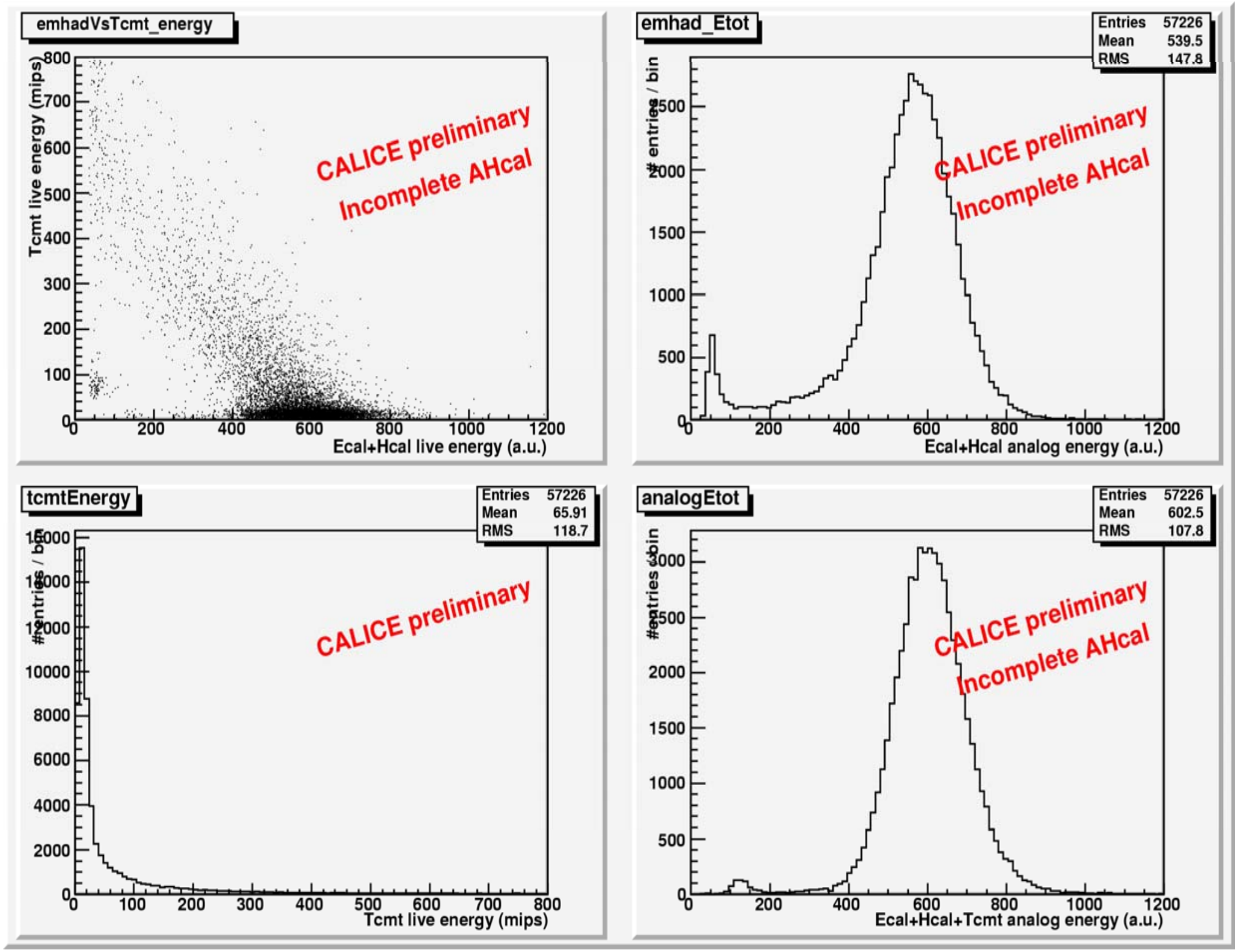
40GeV/c pion
with CALICE online analysis software



Late shower in HCAL

TCMT clearly needed to contain shower

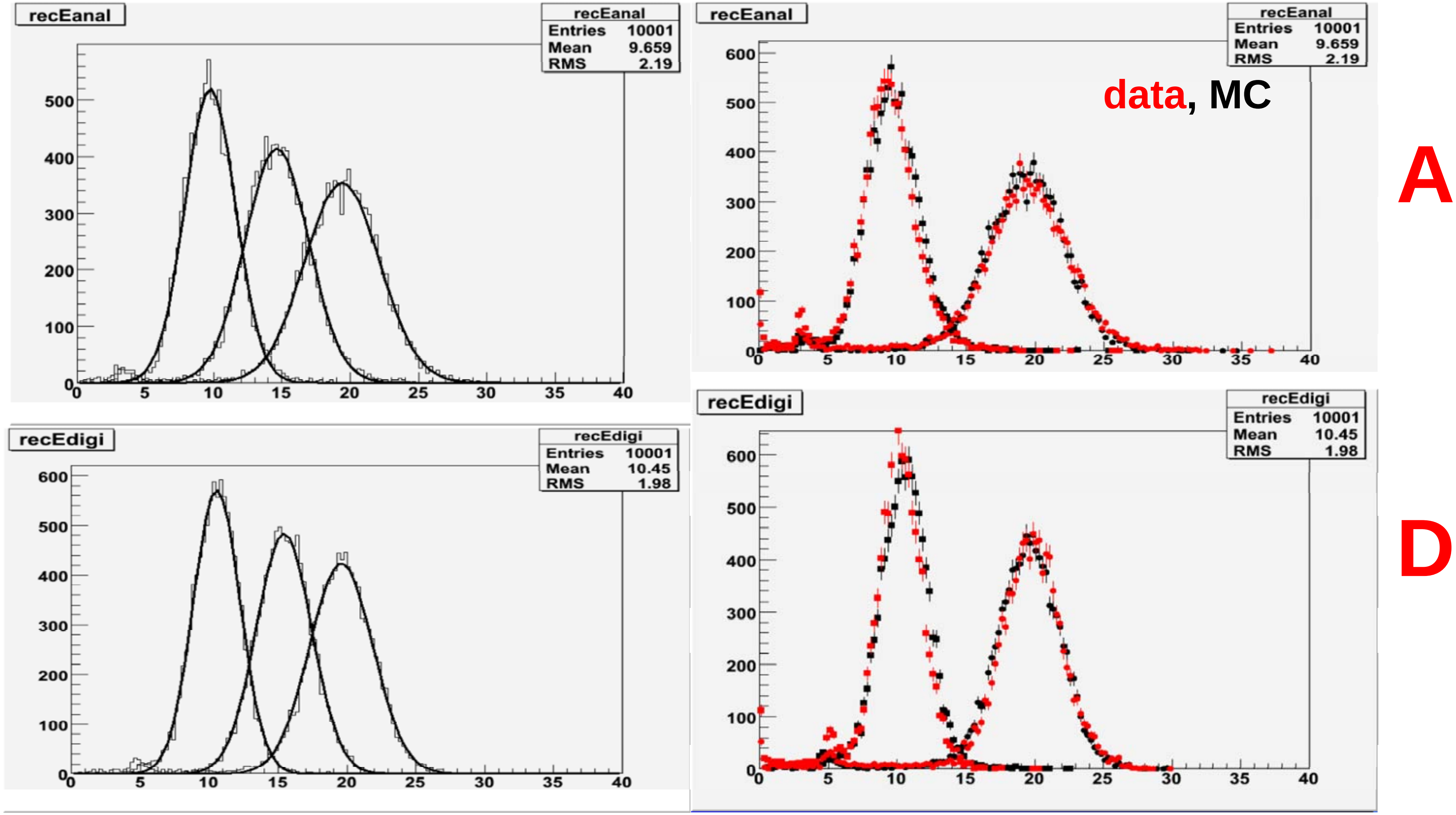
Adding TCMT to ECal & HCal : analog approach



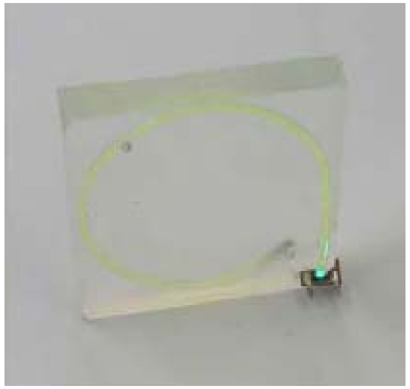
20 GeV
pions

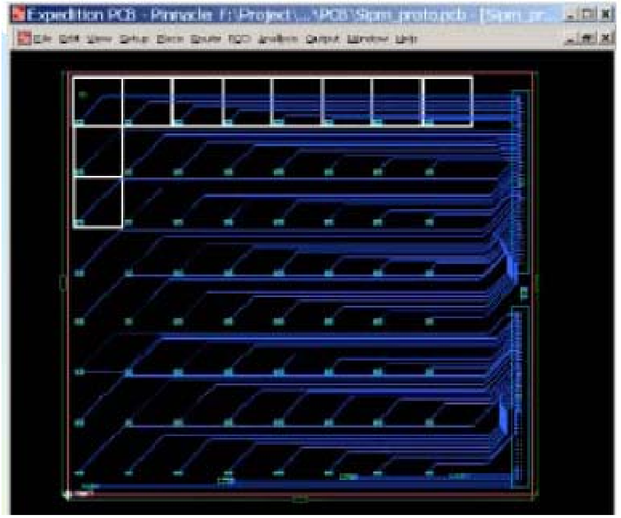
Reconstruction at different energies and comparison with MC

10, 15, 20 GeV pions



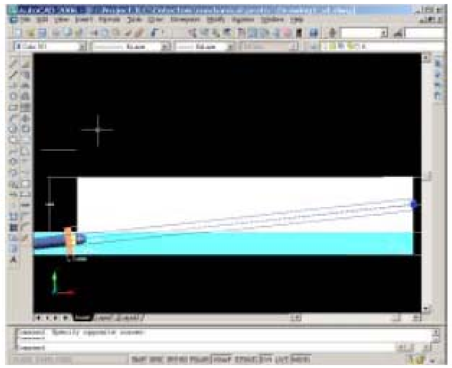
The next step: integrated active layer/direct coupling





Board being tested

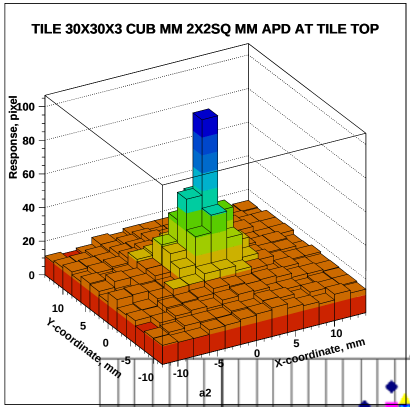
Direct coupling status: Summer 07
Integrated readout layer: End 07
Testing and modifications: 2008



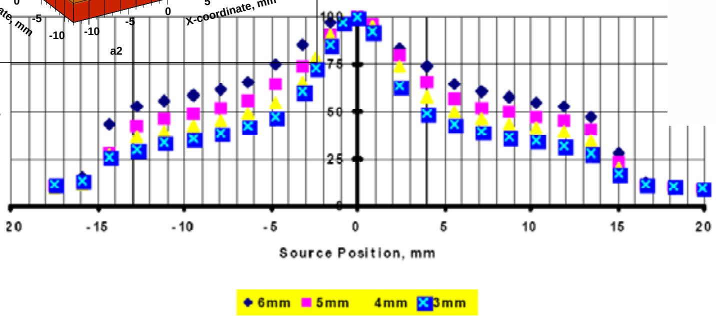
While this design can work with a fiber-in-cell elements a further simplification in assembly and large-scale production may be possible if direct coupling can be shown to work !

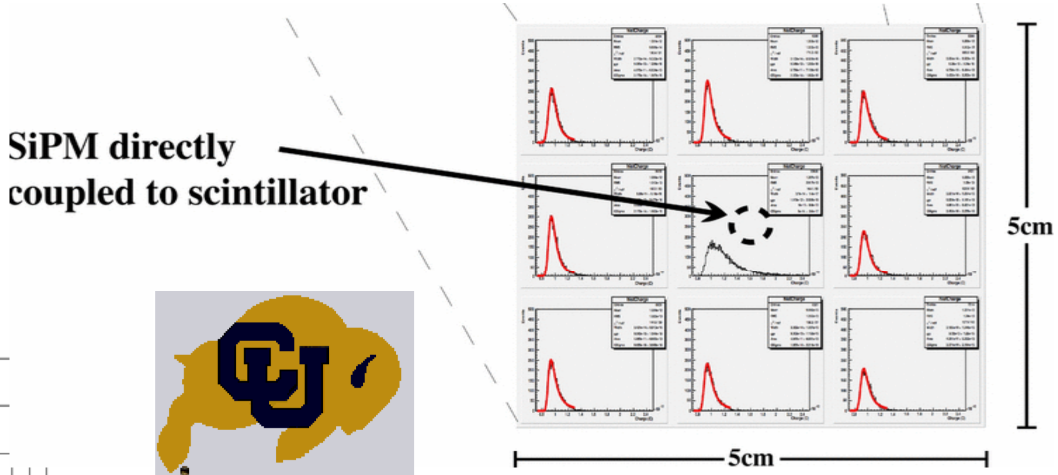
Direct SiPM/Tile Coupling - Uniformity

ITEP

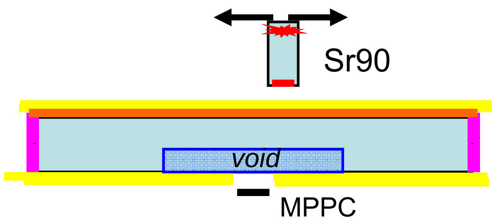


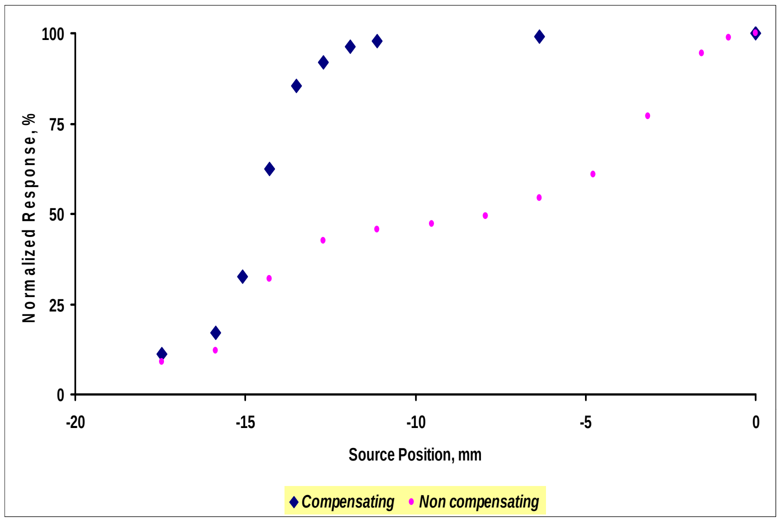
NIU



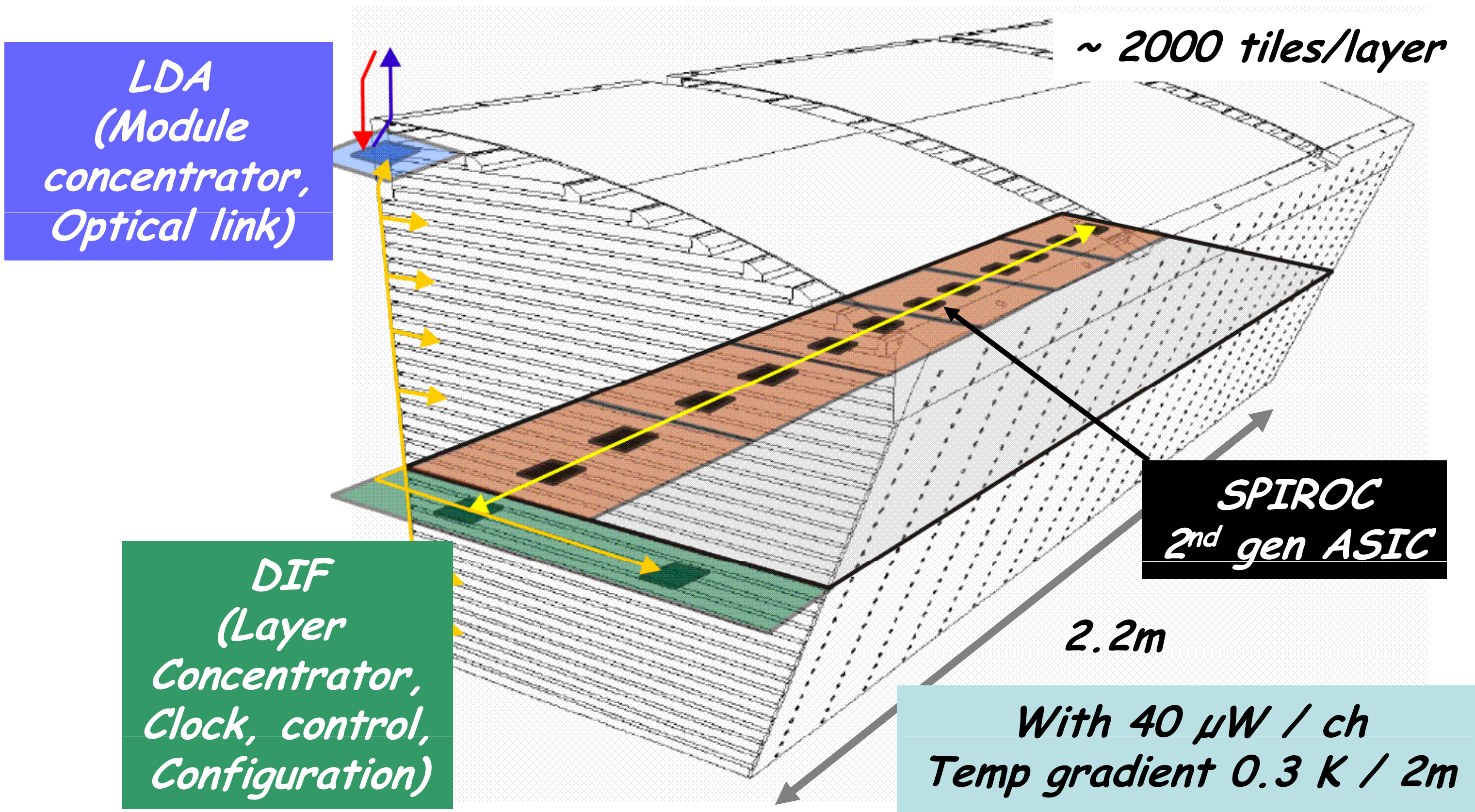


Improvements in Scintillating Cell Uniformity
Using Compensating Cell and Direct Coupling





Scint/SiPM - Technical (scalable) prototype architecture



Layer units (assembly) subdivided into smaller PCBs
HBUs:Typically 12*12 tiles, 4 ASICs

Scintillator-SiPM – Future Plans

- Tests of 40-layer AHCAL stack	2006-2008	
- Development of integrated Scint/SiPM/trace layer	Early	2007
- Cosmic Ray tests of integrated layer	Summer	2007
- Beam tests of multiple fully integrated layers	Oct	2008
- Start construction of scalable prototype	Jan	2009
- Beam Tests of scalable prototype	Dec	2010

Plan of NIU/UC/Fermilab

$1m^3$ test beam stacks - motivations

The $1m^3$ test beam stacks are a critical step in the development of PFA based calorimetry. There are several areas of testing and development depending on these stacks:

1) Technology tests

The technologies proposed as implementations of PFA-based calorimetry are new and untested. It is critical that these technologies be evaluated in systems with adequately large numbers of channels, and that are operated over extended periods.. The natural size scale is a stack that will contain a hadronic shower (see 2)). Test beam runs are expected to last for integrated periods of at least several months.

The main challenge (and cost driver) for the new HCals is the readout electronics for a very large number of channels ($O(10^7 - 10^8)$). While the readout technologies proposed represent various steps towards "final" systems, it is critical to demonstrate that a subset with a large number channels can be built and successfully operated.

continued…

$1m^3$ test beam stacks - motivations

The technologies proposed use either one or more thresholds (digital or semi-digital), or record data for offline treatment (analog). Each of these approaches has its own calibration, and stability requirements. Operation of the stacks over extended periods of time will provide essential input on these issues.

2) PFA related
It is essential that we demonstrate that we can successfully associate charged tracks and energy clusters (both directly track-connected, and disconnected neutral shower components) in single particle hadron showers. Some work in this direction has already started.

We also need to check the simulated descriptions of hadron showers against high statistics data samples. This will allow us to identify the best description of hadron showers, and indicate its reliability for use in physics analyses. Feedback will be provided to GEANT4 developers, but may not result in timely updates for ILC calorimeter studies. Facilities are in place to provide hadron beams over a wide range of energies.

continued…

$1m^3$ test beam stacks - motivations

3) Assembly techniques

The process of constructing the active layers, and readout electronics for the stacks will provide important input for the optimization of the design and development of the technical prototypes that will represent a scalable section of an actual ILC calorimeter system.

The successful construction, operation of, and data reconstruction from these $1m^3$ prototype stacks will provide the required validation of this new approach to calorimetry, and will allow the proposal of viable calorimetry and building of scalable prototypes for the future ILC detectors.

U.S. Hadron Calorimeter R&D - Institutions

- Argonne National Lab: RPC-DHCAL, DCAL digital readout for RPC's, HCal module design, PFA framework and simulations.
- Northern Illinois University: Scintillator HCal, TCMT, SiPM testing, PFA framework and simulations.
- University of Colorado: SiPM testing, ECal alternative design, simulations
- University of Texas at Arlington: GEM-DHCAL design, prototyping and testing, simulations.
- University of Washington: GEM-DHCAL prototype testing
- Boston University: Trigger/timing for Slice Test
- University of Iowa: PFA framework and simulations
- University of Chicago: Electronics
- MIT: GEM development, gas studies
- Fermilab: Electronics, mechanical engineering.

Summary of U.S. Hadron ILC Calorimetry

All three technologies:

- completed/completing needed initial R&D

- constructing/constructed large scale prototypes for beam tests

- working on development and design for technical prototypes -> actual ILC detector module design.

- following the overall ILC plan (machine and detectors)

- However, progress in the U.S. has been slower, and is significantly behind, e.g. Europe. Timely development of new calorimetry for the ILC needs increased support.

Additional material

ILC Calorimetry R&D - motivation

	Process and Final states	Energy (TeV)	Observables	Target Accuracy	Detector Challenge
Higgs	$ee \to Z^0h^0 \to \ell^+\ell^- X$	0.35	M_{recoil}, σ_{Zh}, BR_{bb}	$\delta\sigma_{Zh} = 2.5\%$, $\delta BR_{bb} = 1\%$	T
	$ee \to Z^0h^0, h^0 \to b\bar{b}/c\bar{c}/\tau\tau$	0.35	Jet flavour, jet $(E, \vec{p})$	δM_h=40 MeV, $\delta(\sigma_{Zh} \times BR)$=1%/7%/5%	V
	$ee \to Z^0h^0, h^0 \to WW^*$	0.35	M_Z, M_W, σ_{qqWW^*}	$\delta(\sigma_{Zh} \times BR_{WW^*})$=5%	C
	$ee \to Z^0h^0/h^0\nu\bar{\nu}, h^0 \to \gamma\gamma$	1.0	$M_{\gamma\gamma}$	$\delta(\sigma_{Zh} \times BR_{\gamma\gamma})$=5%	C
	$ee \to Z^0h^0, h^0\nu\bar{\nu}, h \to \mu^+\mu^-$	1.0	$M_{\mu\mu}$	5σ Evidence for $m_h = 120$ GeV	T
	$ee \to Z^0h^0, h^0 \to$ invisible	0.35	σ_{qqE}	5σ Evidence for $BR_{invisible}$=2.5%	C
	$ee \to h^0\nu\bar{\nu}$	0.5	$\sigma_{bb\nu\nu}$, M_{bb}	$\delta(\sigma_{\nu\nu h} \times BR_{bb}) = 1\%$	C
	$ee \to t\bar{t}h^0$	1.0	σ_{tth}	δg_{tth}=5%	C
	$ee \to Z^0h^0h^0$, $h^0h^0\nu\bar{\nu}$	0.5/1.0	σ_{Zhh}, $\sigma_{\nu\nu hh}$, M_{hh}	δg_{hhh}=20/10%	C
SSB	$ee \to W^+W^-$	0.5		$\Delta\kappa_\gamma, \lambda_\gamma = 2 \cdot 10^{-4}$	V
	$ee \to W^+W^-\nu\bar{\nu}/Z^0Z^0\nu\bar{\nu}$	1.0	σ	$\Lambda_{*4}, \Lambda_{*5} = 3$ TeV	C
SUSY	$ee \to \tilde{e}_R^+\tilde{e}_R^-$ (Point 1)	0.5	E_e	$\delta m_{\tilde{\chi}_1^0}$=50 MeV	T
	$ee \to \tilde{\tau}_1^+\tilde{\tau}_1^-$, $\tilde{\chi}_1^+\tilde{\chi}_1^-$ (Point 1)	0.5	E_π, $E_{2\pi}$, $E_{3\pi}$	$\delta(m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0})$=200 MeV	T
	$ee \to \tilde{t}_1\tilde{t}_1$ (Point 1)	1.0		$\delta m_{\tilde{t}_1}$=2 GeV	
-CDM	$ee \to \tilde{\tau}_1^+\tilde{\tau}_1^-$, $\tilde{\chi}_1^+\tilde{\chi}_1^-$ (Point 3)	0.5		$\delta m_{\tilde{\tau}_1}$=1 GeV, $\delta m_{\tilde{\chi}_1^0}$=500 MeV,	F
	$ee \to \tilde{\chi}_2^0\tilde{\chi}_3^0$, $\chi_1^+\chi_1^-$ (Point 2)	0.5	M_{jj} in $jj\not{E}$, $M_{\ell\ell}$ in $jj\ell\ell\not{E}$	$\delta\sigma_{\chi_2\chi_3} = 4\%$, $\delta(m_{\chi_2^0} - m_{\chi_1^0})$= 500 MeV	C
	$ee \to \chi_1^+\chi_1^-/\tilde{\chi}_i^0\tilde{\chi}_j^0$ (Point 5)	0.5/1.0	$ZZ\not{E}$, $WW\not{E}$	$\delta\sigma_{\tilde{\chi}\tilde{\chi}}$=10%, $\delta(m_{\tilde{\chi}_2^0} - m\tilde{\chi}_1^0)$ =2 GeV	C
	$ee \to H^0A^0 \to b\bar{b}b\bar{b}$ (Point 4)	1.0	Mass constrained M_{bb}	δm_A=1 GeV	C
-alternative SUSY breaking	$ee \to \tilde{\tau}_1^+\tilde{\tau}_1^-$ (Point 6)	0.5	Heavy stable particle	$\delta m_{\tilde{\tau}_1}$	T
	$\chi_1^0 \to \gamma + \not{E}$ (Point 7)	0.5	Non-pointing γ	$\delta c\tau$=10%	C
	$\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 + \pi^\pm_{soft}$ (Point 8)	0.5	Soft $\pi^\pm$ above $\gamma\gamma$ bkgd	5σ Evidence for $\Delta\tilde{m}$=0.2-2 GeV	F
Precision SM	$ee \to t\bar{t} \to 6$ *jets*	1.0		5σ Sensitivity for $(g-2)_t/2 \leq 10^{-3}$	V
	$ee \to f\bar{f}$ $(f = e, \mu, \tau; b, c)$	1.0	$\sigma_{f\bar{f}}$, A_{FB}, A_{LR}	5σ Sensitivity to $M(Z_{LR}) = 7$ TeV	V
New Physics	$ee \to \gamma G$ (ADD)	1.0	$\sigma(\gamma + \not{E})$	5σ Sensitivity	C
	$ee \to KK \to f\bar{f}$ (RS)	1.0			T
Energy/Lumi Meas.	$ee \to ee_{fwd}$	0.3/1.0		δm_{top}=50 MeV	T
	$ee \to Z^0\gamma$	0.5/1.0			T

Benchmarking the ILC Detectors
M. Battaglia

What Jet Energy Resolution do we Need?

Need clean identification of W's, Z's, H's, tops,…

This requires dijet mass resolution ≤ few GeV.

$$M_{12}^2 \approx 2E_1E_2\left(1-\cos\theta_{12}\right)$$

$$\frac{dM_{12}}{M_{12}} \approx \frac{1}{2}\left[\frac{dE_1}{E_1} \oplus \frac{dE_2}{E_2} \oplus \ \ldots\right]$$

Requiring $\sigma \sim \Gamma_Z$, sets dM/M = 2.5/92 = 2.7 %.

This requires

$dE_{jet}/E_{jet} = \sqrt{2}$ (2.7%) = 3.8 %, independent of E_{jet}.

This is roughly comparable to the goal often cited,

dE_{jet}/E_{jet} = 30%/$\sqrt{E}$(GeV), for $E_{jet} \leq$ 100 GeV.

Bill Morse, Rich Partridge, John Jaros

Calorimeter system/overall detector design

Initially two general approaches:

(1) Large inner calorimeter radius -> achieve good separation of e, γ, charged hadrons, jets,…

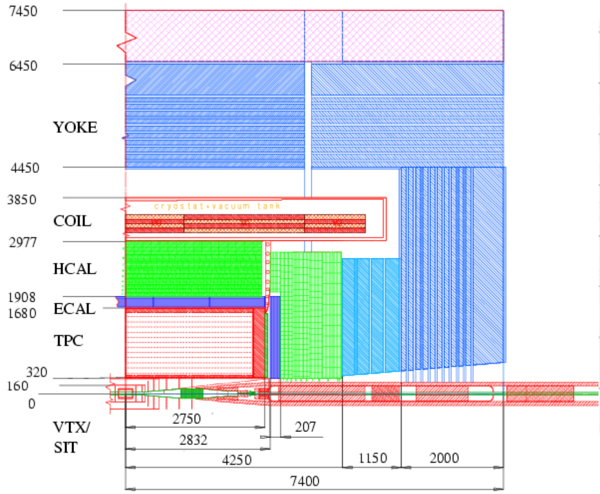
Matches well with having a large tracking volume with many measurements, good momentum resolution (BR^2) with moderate magnetic field, B ~2-3T

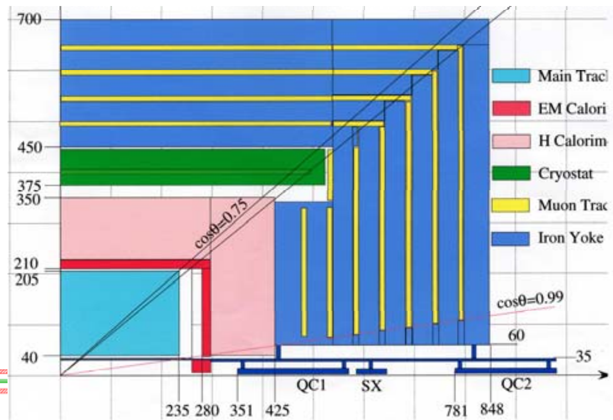
But… calorimeter and muon systems become large and potentially very expensive…

However…may allow a "traditional" approach to calorimeter technology(s).

EXAMPLES: **LDC, GLD**

Now merged !





Calorimeter system/overall detector design

(2) Compact detector – reduced inner calorimeter radius.

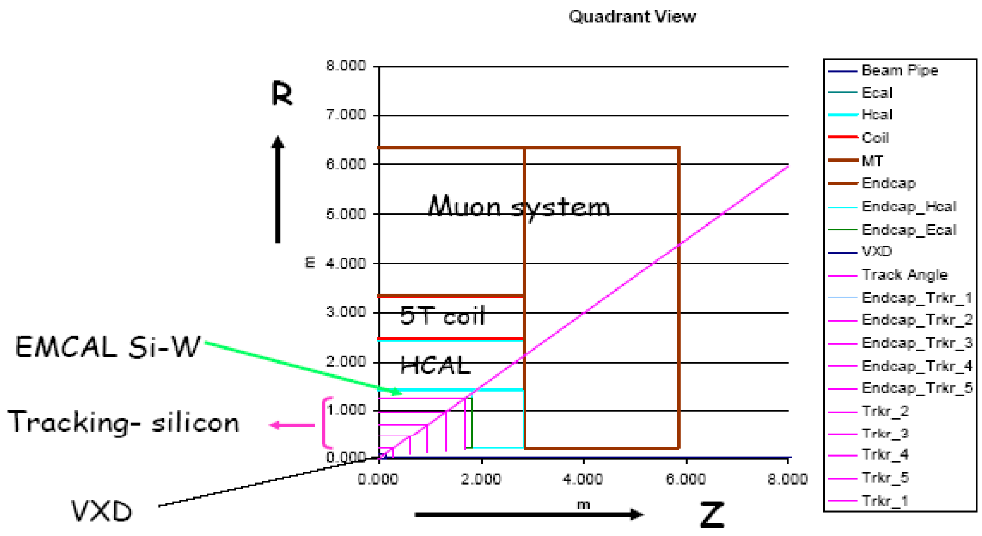
Use Si/W for the ECal -> excellent resolution/separation. Constrain the cost by limiting the size of the calorimeter (and muon) system.

This then requires a compact tracking system -> Silicon only with very precise (~10μm) point measurement.

Also demands a calorimeter technology offering fine granularity -> restriction of technology choice ??

To restore BR^2, boost B -> 5T (stored energy, forces?)

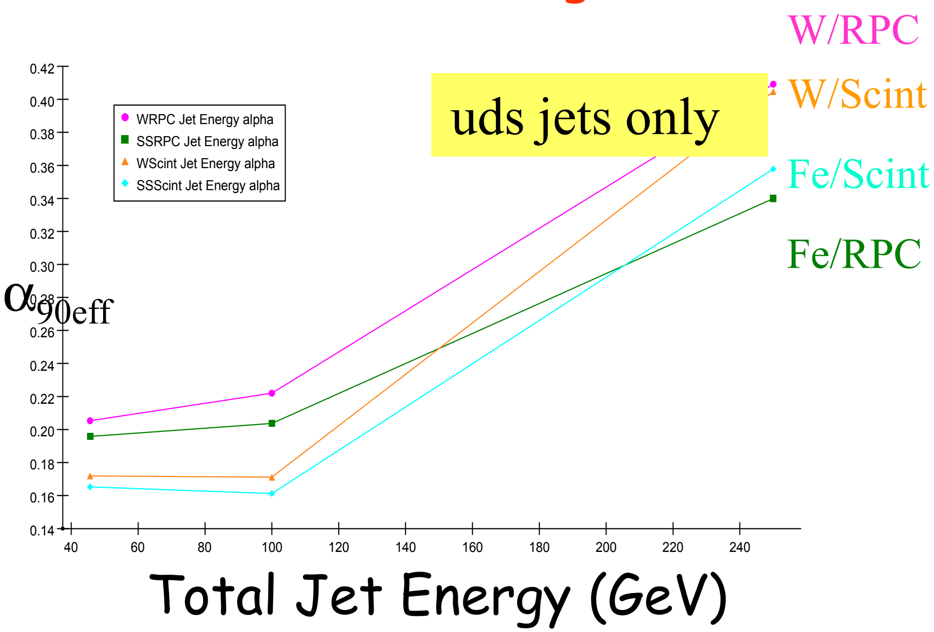
EXAMPLE: **SiD**



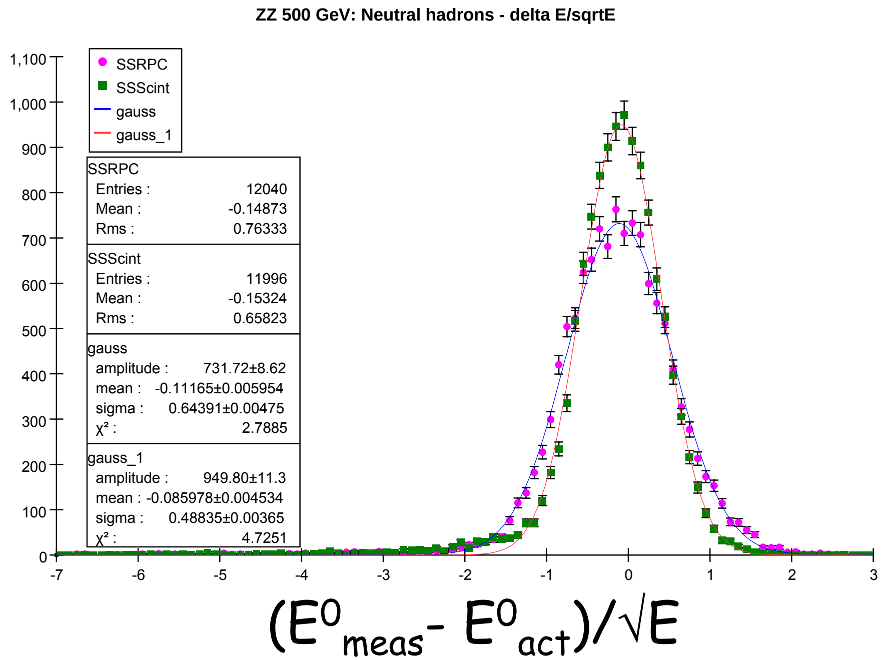
NOT A SMALL DETECTOR

Ron Cassell/SLAC

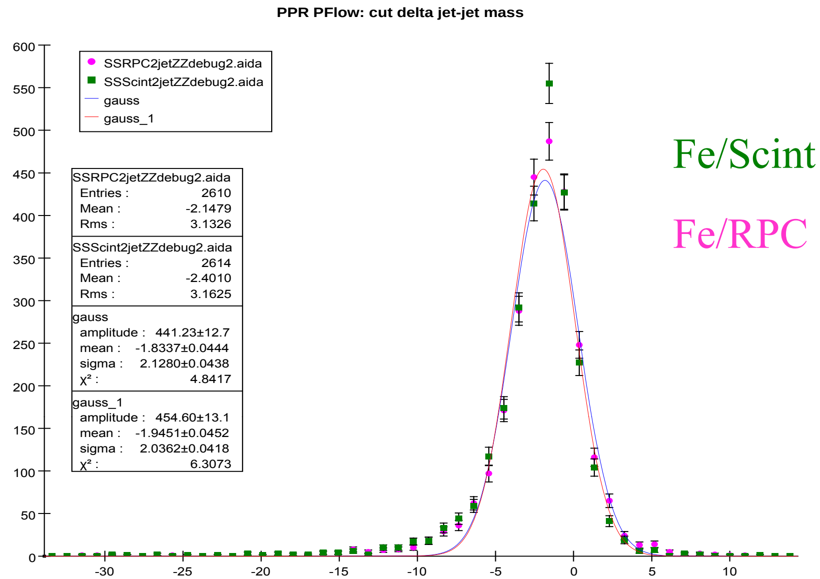
Jet Energy Resolution vs Jet Energy
Perfect Pattern Recognition



Energy Resolution for Neutrals in Jets



Effect on Dijet Mass Resolution…Small
(still assuming perfect pattern reconstruction)



Responsibilities and collaborators

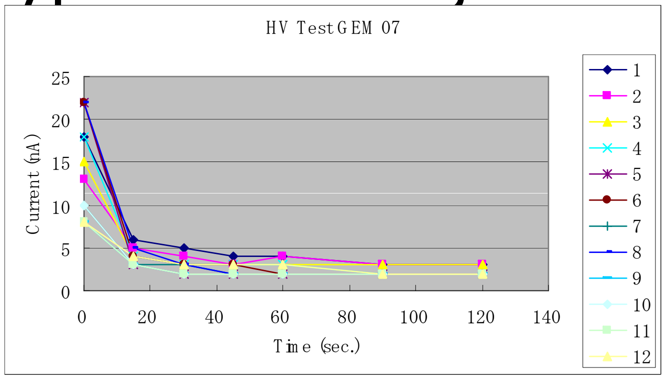
Vertical slice test

Item	Fabricated	Assembled	Glued/ painted	Tested	Commissioned	Needed
DCAL	40	-	-	1+	-	40+25 +40
Pad boards	15	-	1,2,3,4,5	1,2,3,4,5	1,2,3,4	12
FE-boards	15	1,2,3,4,5				
DCON	15	1,2,3,4,5 ,6,7,8,9	-	1,2,3,4,5 ,6,7	1,2,3	12
DCOL	3	3	-	3	2	1
TTM	6	5	-	2		1
RPCs	10	1,2,3,4,5 ,6,7	1,2,3,4,5 ,6,7	1,2,3,4	1,2,3,4	10
GEMs	2		-			2

Task	Responsible institutes
RPC construction	Argonne, (IHEP Protvino)
GEM construction	UTA
Mechanical structure (slice test)	Argonne
Mechanical structure (prototype section)	(DESY)
Overall electronic design	Argonne
ASIC design and testing	FNAL, Argonne
Front-end and Pad board design & testing	Argonne
Data concentrator design & testing	Argonne
Data collector design & testing	Boston, Argonne
Timing and trigger module design and testing	FNAL
DAQ Software	Argonne, CALICE
Data analysis software	Argonne, CALICE, FNAL
HV and gas system	Iowa
Beam telescope	UTA

GEM Foils from 3M

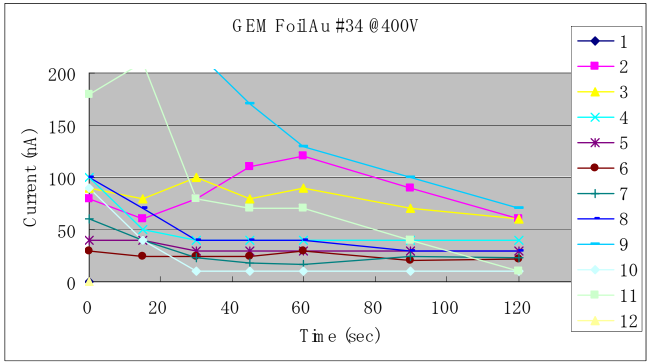
- 30cm x 30cm foils made with three types of coating:



a) bare copper

b) "organic polymer" coating

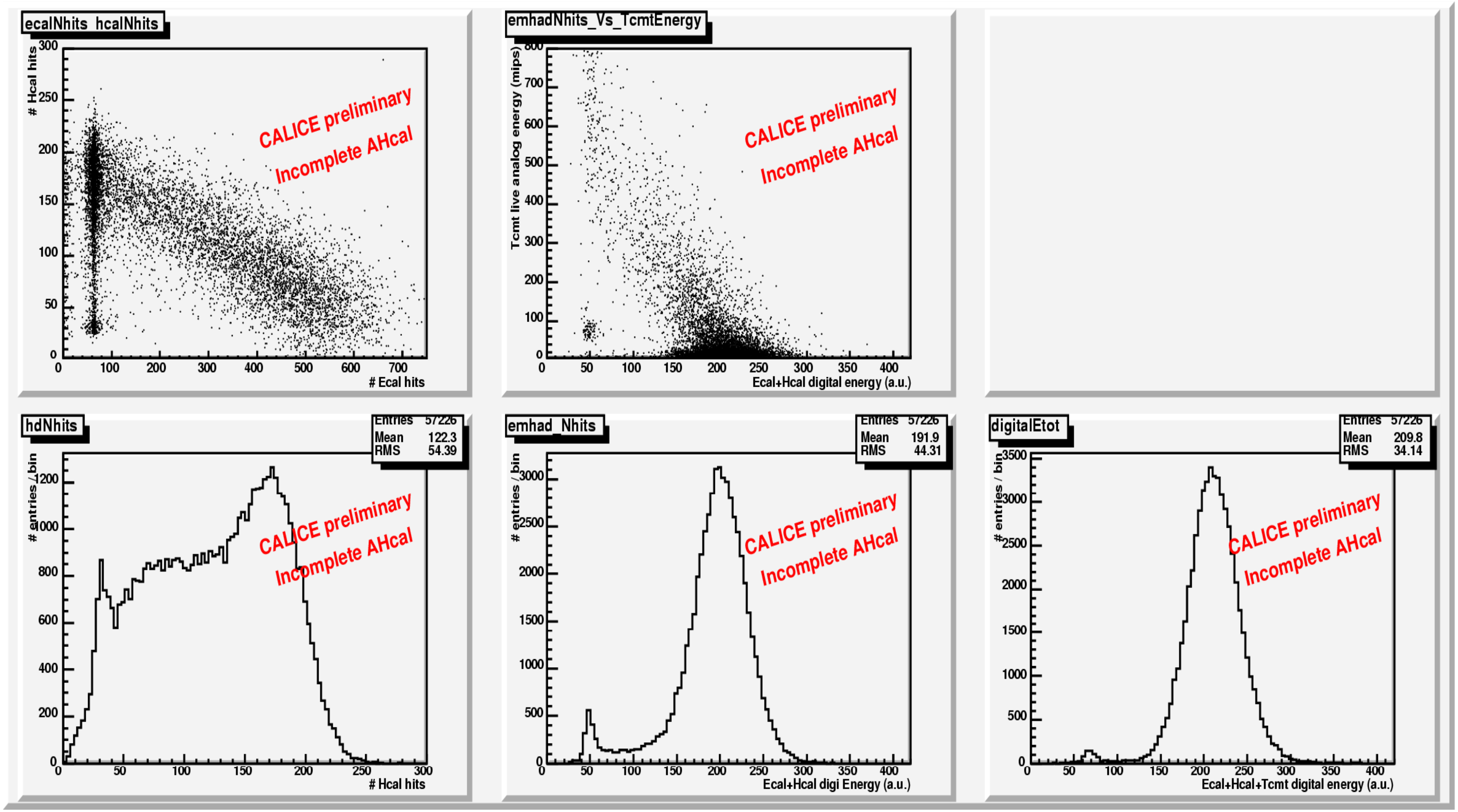
c) gold plating



- HV tests made on all three types -> conclusion is that we prefer to use the uncoated foils.

- We are using the uncoated foils in our current 30cm x 30cm chambers.

Semi-digital approach (D) 20 GeV pions



Technically Driven Timeline