Calorimetry

Summary Talk

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ILC Workshop

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Overview

- Physics processes driving calorimeter design
- Calorimeter design issues and examples
- Calorimeter technologies:
    - Electromagnetic
    - Hadronic
    - Other technologies (inc. Forward)
- Conclusions

	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	$\delta m_{\tilde{\chi}^0_1}$=50 MeV	T
	$ee \to \tilde{\tau}^+_1\tilde{\tau}^-_1$, $\tilde{\chi}^+_1\tilde{\chi}^-_1$ (Point 1)	0.5	E_π, $E_{2\pi}$, $E_{3\pi}$	$\delta(m_{\tilde{\tau}_1} - m_{\tilde{\chi}^0_1})$=200 MeV	T
	$ee \to \tilde{t}_1\bar{\tilde{t}}_1$ (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, $\delta m_{\tilde{\chi}^0_1}$=500 MeV,	F
	$ee \to \tilde{\chi}^0_2\tilde{\chi}^0_3$, $\chi^+_1\chi^-_1$ (Point 2)	0.5	M_{jj} in $jj\not{E}$, $M_{\ell\ell}$ in $jj\ell\ell\not{E}$	$\delta\sigma_{\chi_2\chi_3} = 4\%$, $\delta(m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1})$= 500 MeV	C
	$ee \to \chi^+_1\chi^-_1/\tilde{\chi}^0_i\tilde{\chi}^0_j$ (Point 5)	0.5/1.0	$ZZ\not{E}$, $WW\not{E}$	$\delta\sigma_{\tilde{\chi}\tilde{\chi}}$=10%, $\delta(m_{\tilde{\chi}^0_3} - m\tilde{\chi}^0_1)$ =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	$ee \to \tilde{\tau}^+_1\tilde{\tau}^-_1$ (Point 6)	0.5	Heavy stable particle	$\delta m_{\tilde{\tau}_1}$	T
SUSY	$\chi^0_1 \to \gamma + \not{E}$ (Point 7)	0.5	Non-pointing γ	$\delta c\tau$=10%	C
breaking	$\tilde{\chi}^\pm_1 \to \tilde{\chi}^0_1 + \pi^\pm_{soft}$ (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	σ_{ff}, 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	$ee \to ee_{fwd}$	0.3/1.0		δm_{top}=50 MeV	T
Meas.	$ee \to Z^0\gamma$	0.5/1.0			T

Physics examples driving calorimeter design

Higgs production e.g. $e^+e^- \to Z\,h$ ← Missing mass peak or bbar jets

separate from WW, ZZ (in all jet modes)

Higgs couplings e.g.

- g_{tth} from $e^+e^- \to tth \to WWbbbb \to qqqqbbbb$!
- g_{hhh} from $e^+e^- \to Zhh$

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

Strong WW scattering: separation of

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

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

Physics examples driving calorimeter design

-All of these critical physics studies demand:

- ✧ Efficient jet separation and reconstruction
- ✧ Excellent jet energy resolution
- ✧ Excellent jet-jet mass resolution

+ jet flavor tagging

Plus... We need very good forward calorimetry for e.g. SUSY selectron studies,

and... ability to find/reconstruct photons from secondary vertices e.g. from long-lived NLSP -> γG

Calorimeter system/overall detector design

TWO APPROACHES:

- 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).

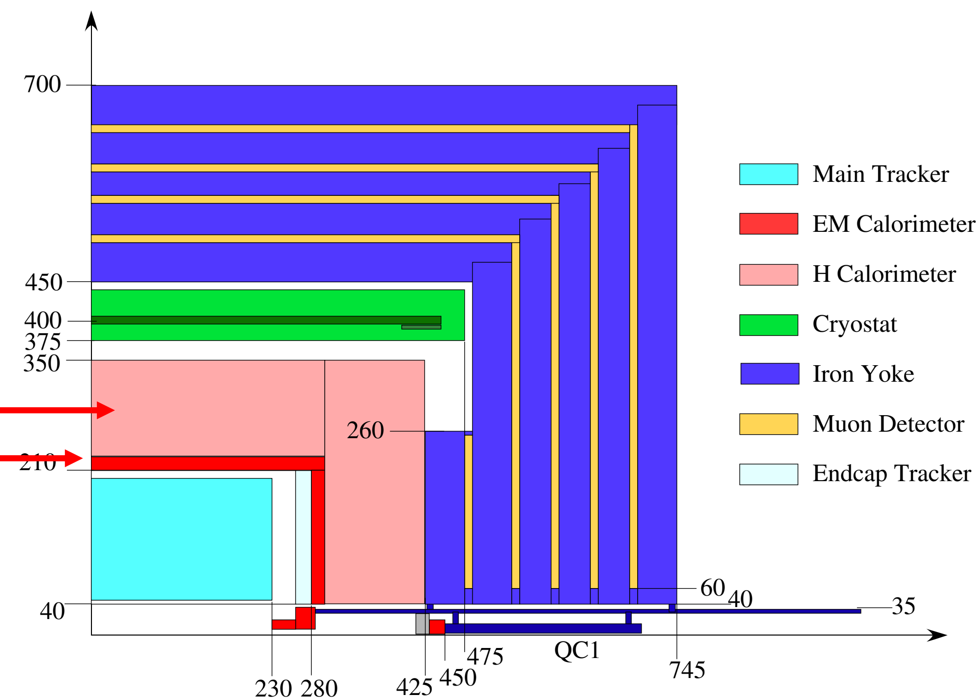
  EXAMPLES: Large Detector, GLD,…?

LDC

GLD

HCal

ECal



Calorimeter system/overall detector design

(2) Compact detector – reduced inner calorimeter radius.

Use Si/W for the ECal -> excellent resolution/separation of γ/charged. 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.

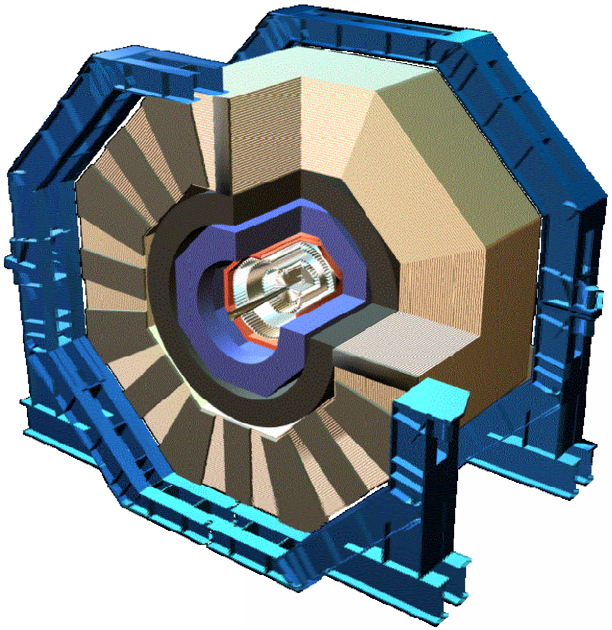
Also demands a calorimeter technology offering fine granularity -> restriction of technology choice ??

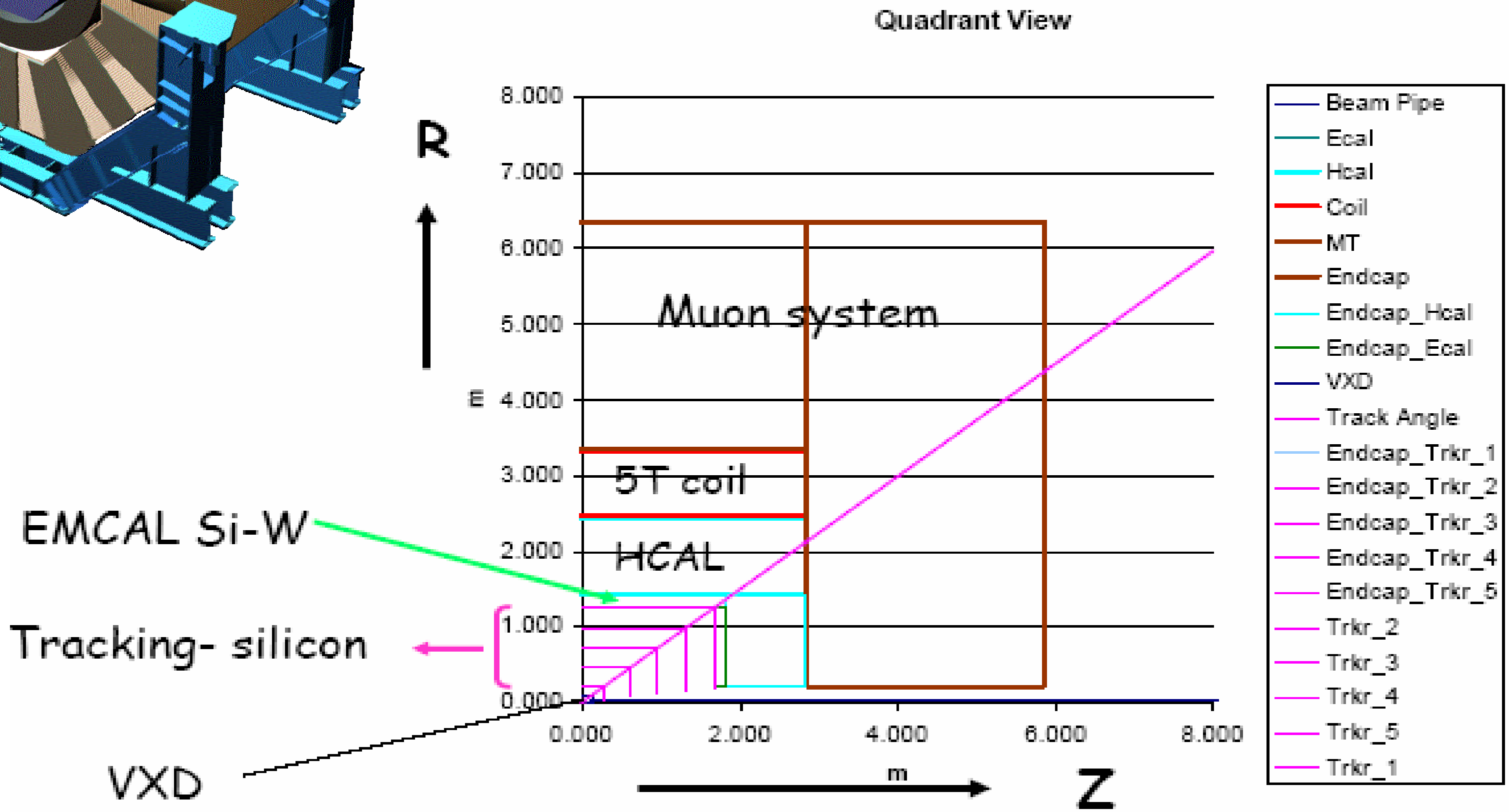
To restore BR^2, boost B -> 5T (stored energy, forces?)

EXAMPLE: SiD

SiD

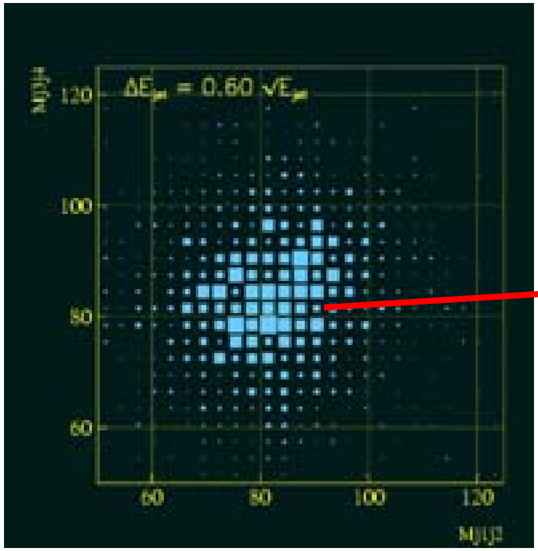
Compact detector

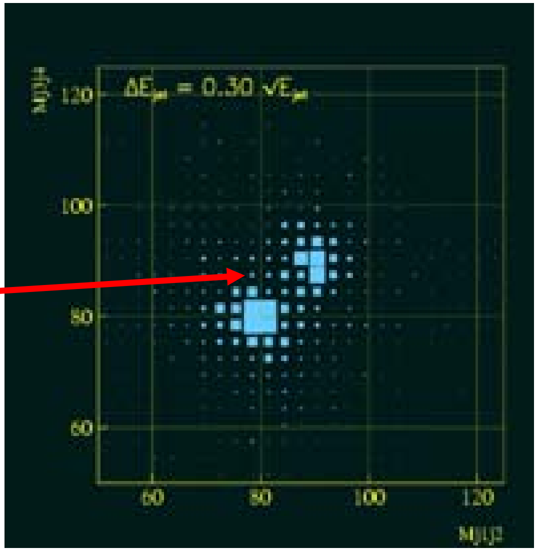




The critical issue – jet energy resolution, jet-jet mass resolution

-> Separation of W,Z,... on an event by event basis





This meeting: is this the right target? What is the physics impact of a lesser requirement?

60%/√E

30%/√E

Target region for jet energy resolution

H. Videau

Must be answered soon!

Results from "traditional" calorimeter systems

- 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.

The Particle Flow Approach

Particle Flow approach holds promise of required solution and has been used in other experiments effectively – *but still remains to be proved for the Linear Collider!*

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

-> Need efficient separation of different types of energy deposition 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".

The Energy Flow Approach

- A lot of work before/at this meeting!

- Subject of a separate talk after this by A. Raspereza.

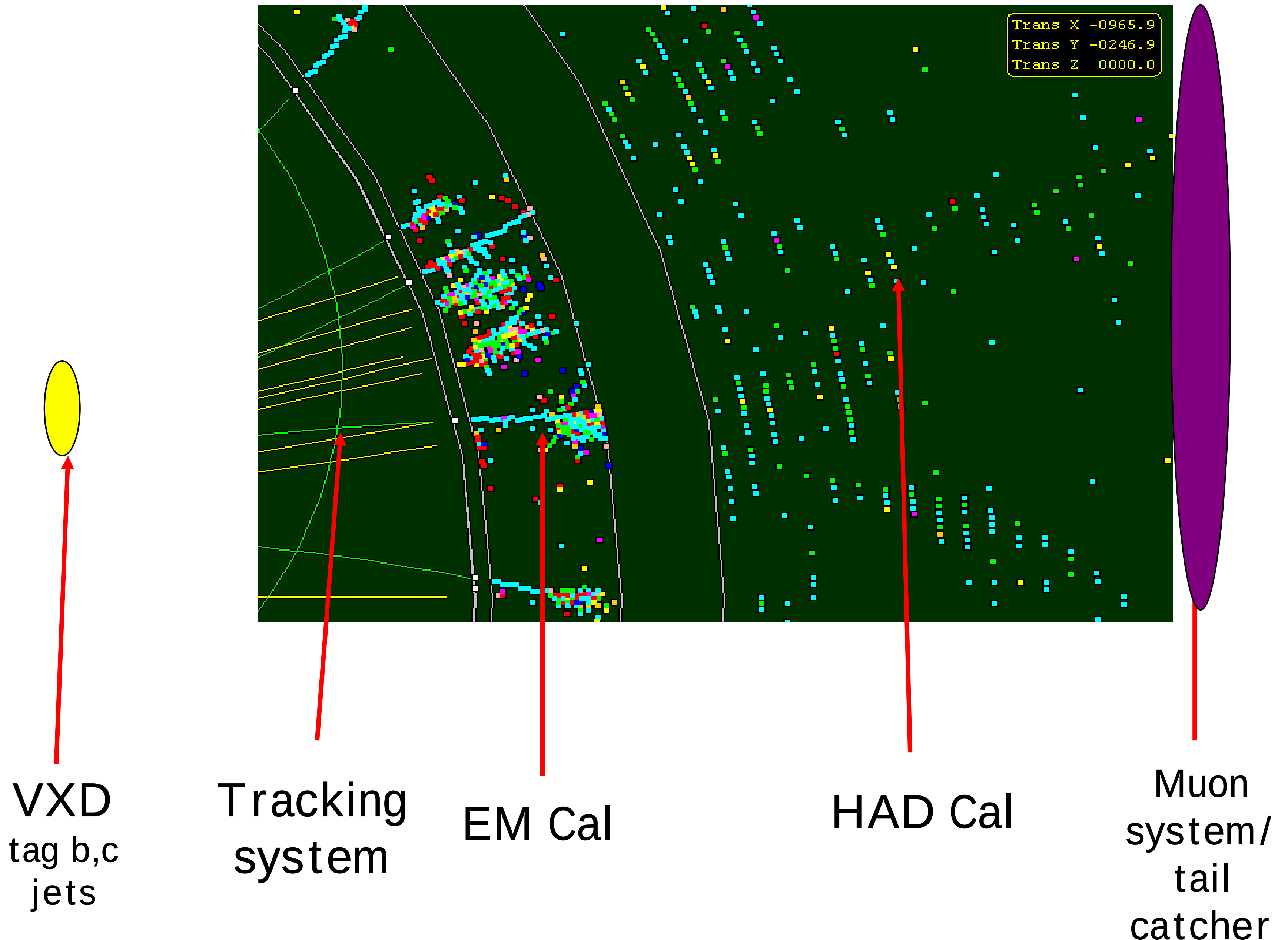
- Ongoing -> performance(s) of PFA(s) is critical input to detector design and performance requirements:

It drives – radial detector locations

- segmentation

- choice of absorber material/active layer thickness (R_M).

Integrated Detector Design



Integrated Detector Design

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

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.

- Muon finding/tracking through calorimeter....etc.

Calorimeter System Design

So how do we realize the requirements in terms of actual calorimeter systems?

Calorimeter System Design

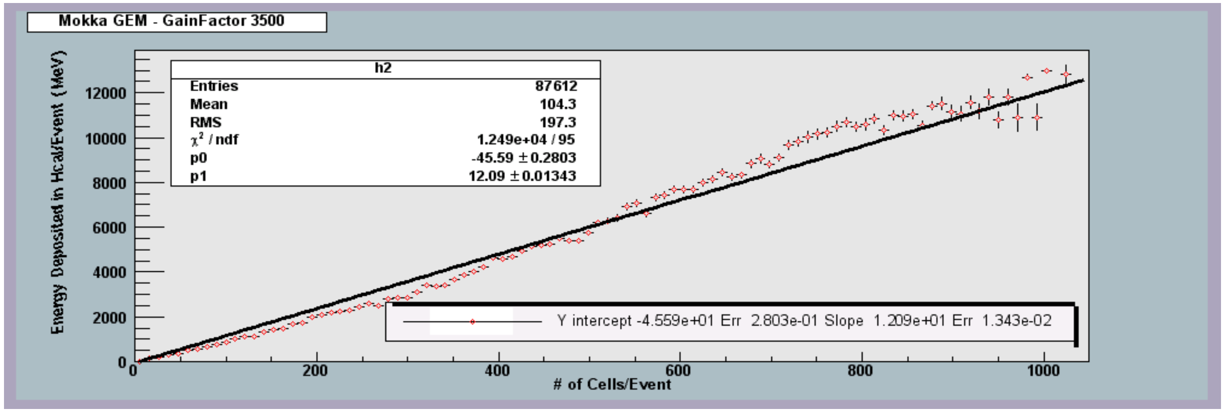
Two options explored in detail:

(1) Analog ECal + Analog 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 Technologies

Electromagnetic Calorimeter

Physics requirements emphasize segmentation/granularity (transverse AND longitudinal) over intrinsic energy resolution.

Localization of e.m. showers and e.m./hadron separation -> dense (small X_0) ECal with fine segmentation.

Moliere radius -> O(1 cm.)

$$f_E \simeq \frac{R_{cal}}{\sqrt{R_M^2 + (4d_{pad})^2}}$$

David Strom

Transverse segmentation≈ Moliere radius

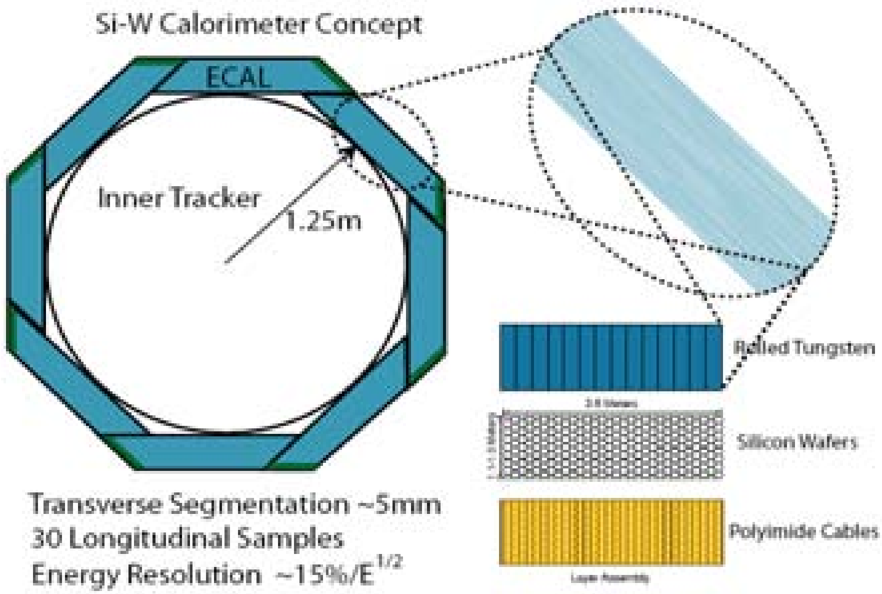
Charged/e.m. separation -> fine transverse segmentation (first layers of ECal).

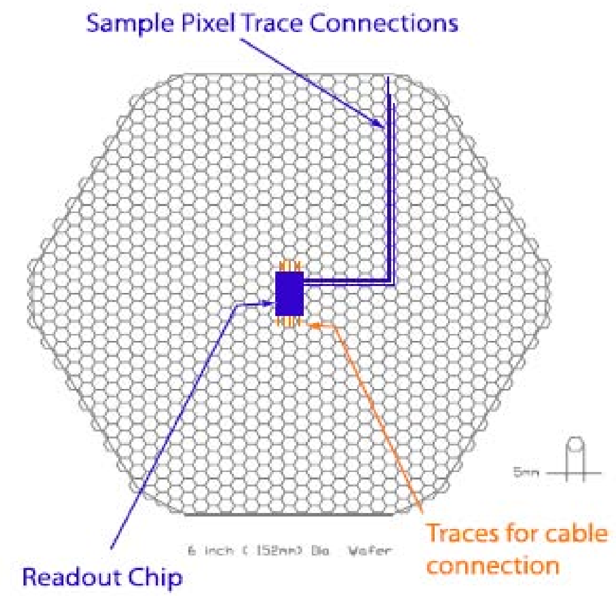
Tracking charged particles through ECal -> fine longitudinal segmentation and high MIP efficiency.

Excellent photon direction determination (e.g. GMSB)

Keep the cost (Si) under control!

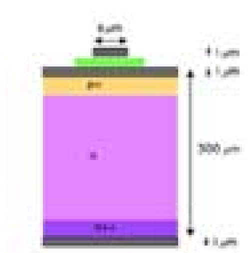
SLAC-Oregon-UC Davis-BNL Si-W ECal R&D

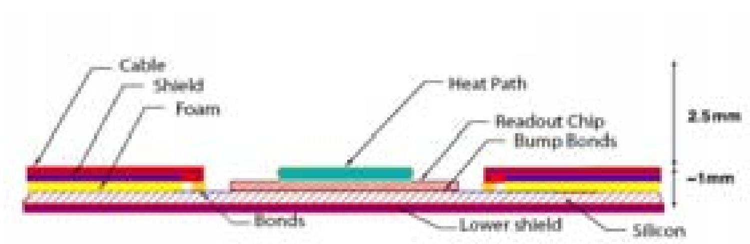




David Strom

Effective 4 x 4 mm^2





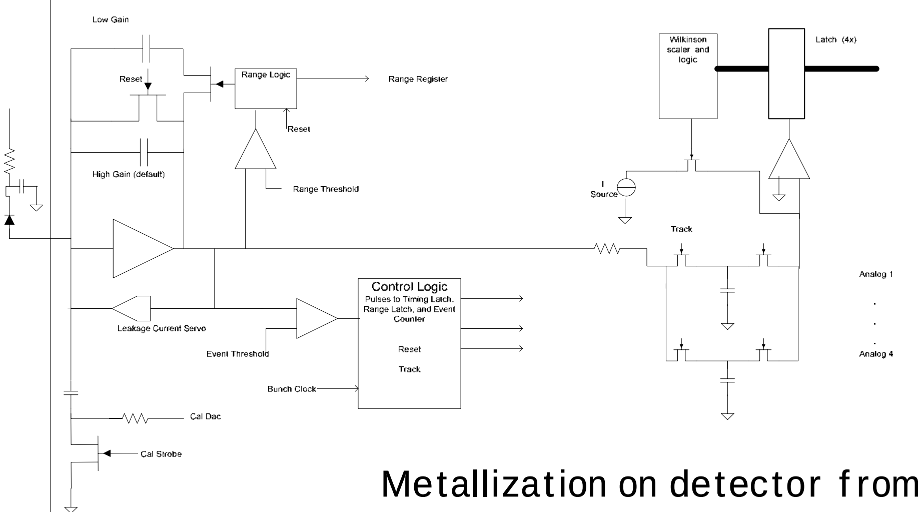
Critical parameter: minimum space between tungsten layers.

SLAC-Oregon-UC Davis-BNL Si-W ECal R&D

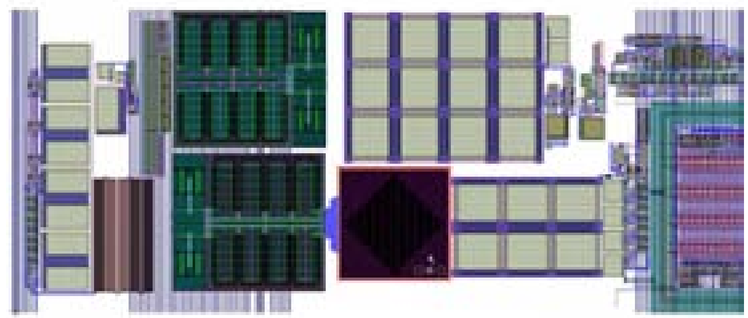
M.Breidenbach

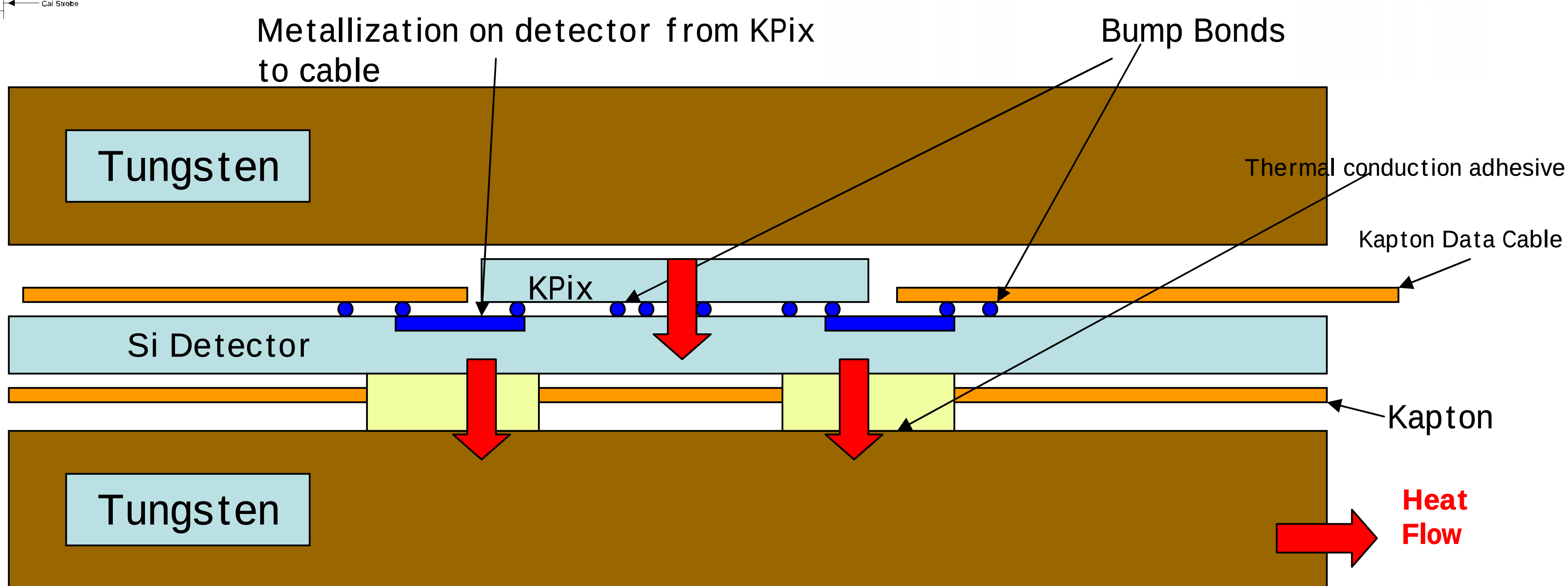
Si-W Pixel Analog Section

1 of 1024 pixels



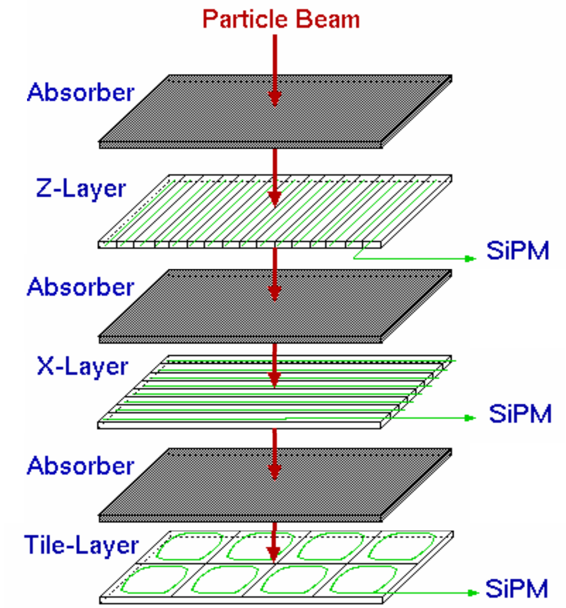
KPix Cell 1 of 1024

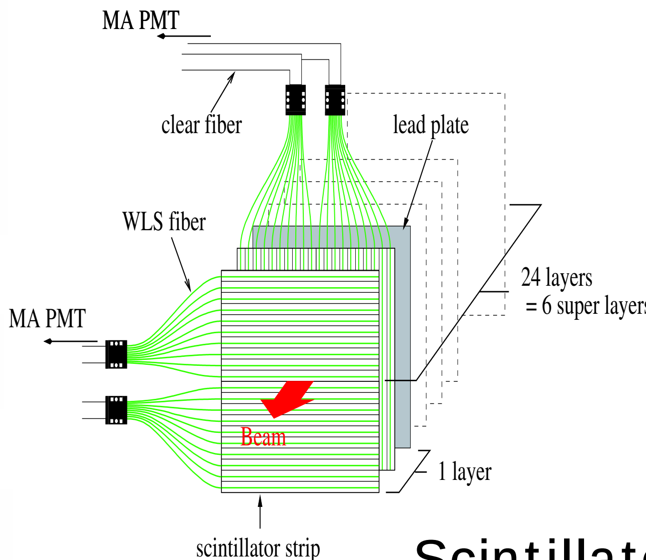




GLD ECal work in Asia (Japan-Korea-Russia)

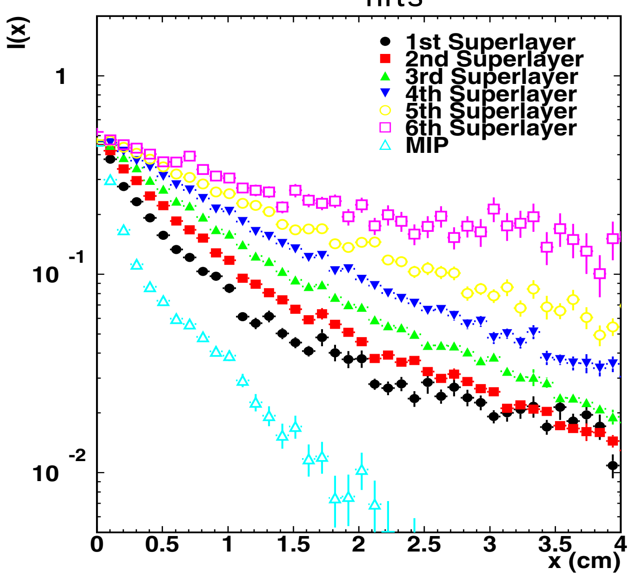
Effectively small granularity of 1cmx1cm

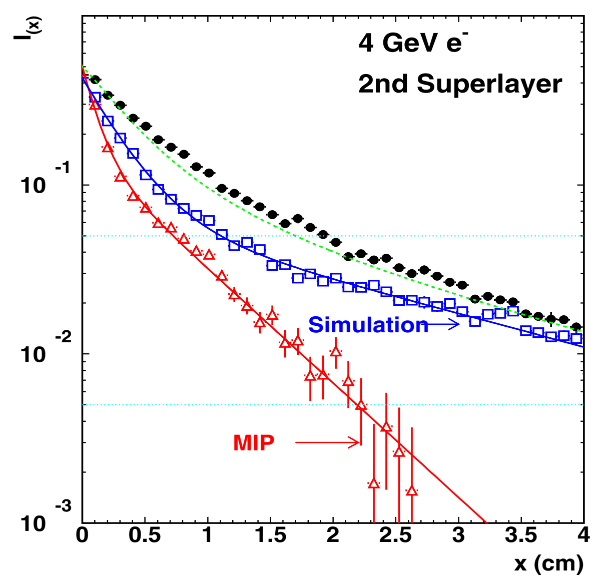




Scintillator 1cm X 20cm X 0.2cm

- 4cmx4cm tiles to resolve ghost hits



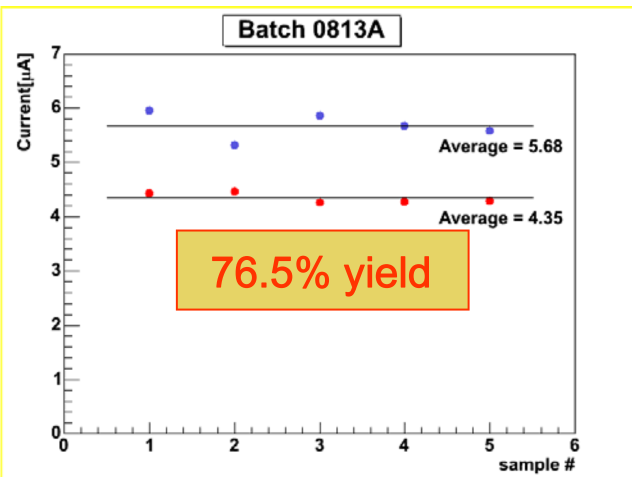


Lateral shower profiles – data/simulation

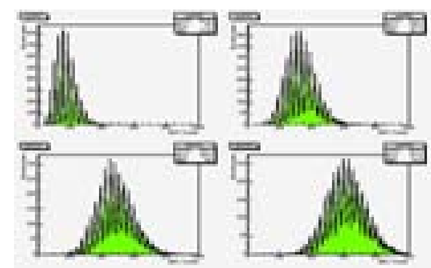
GLD ECal work in Asia (Japan-Korea-Russia)

DongHee Kim

Evolution of scintillator strip extrusion



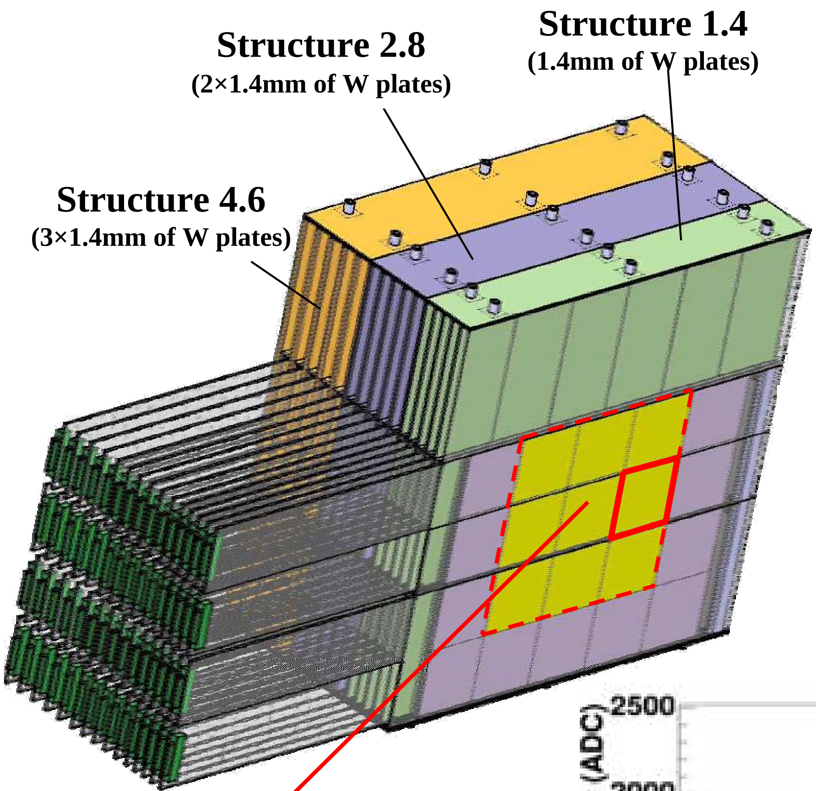
HAMAMATSU MPC

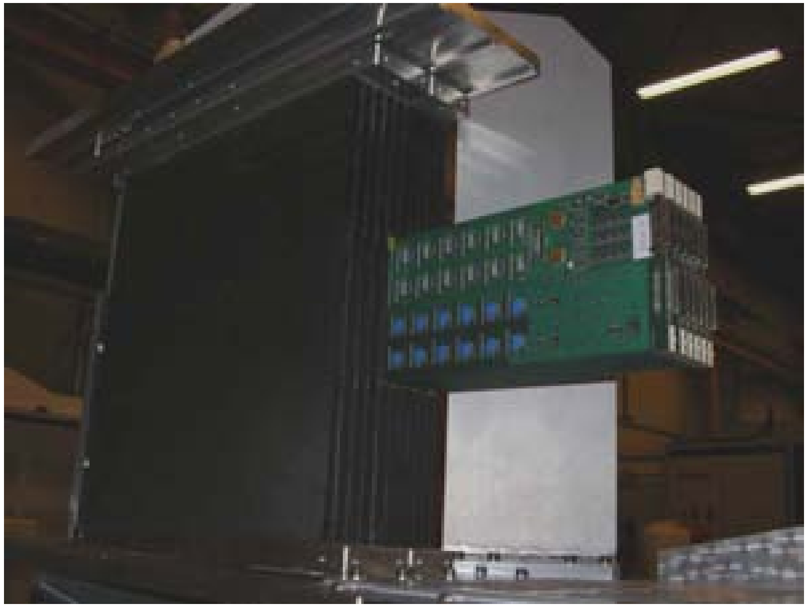


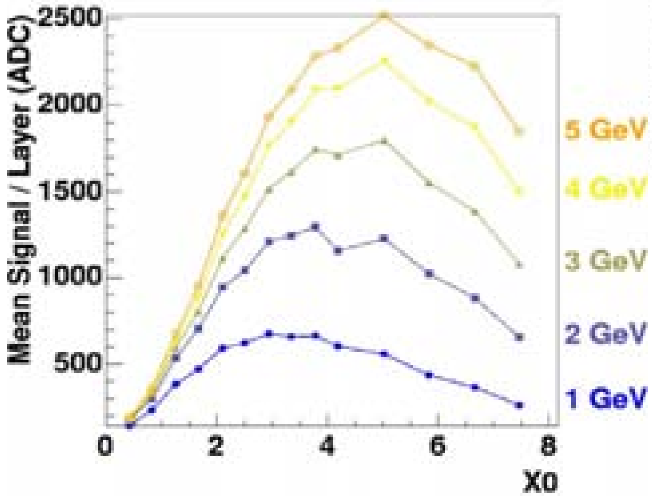
400 pixel

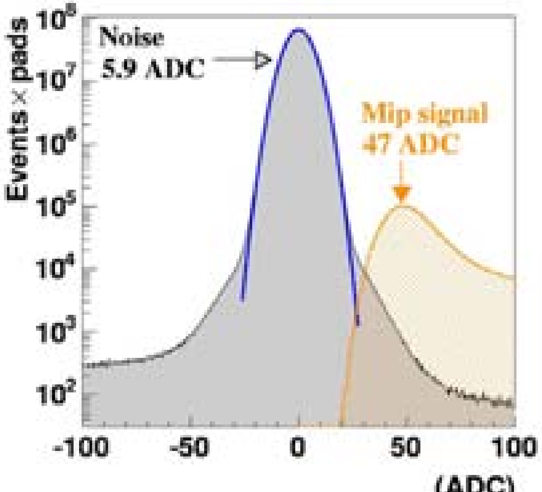
Observed up to 40~60 photon peaks

CALICE – Si/W Electromagnetic Calorimeter





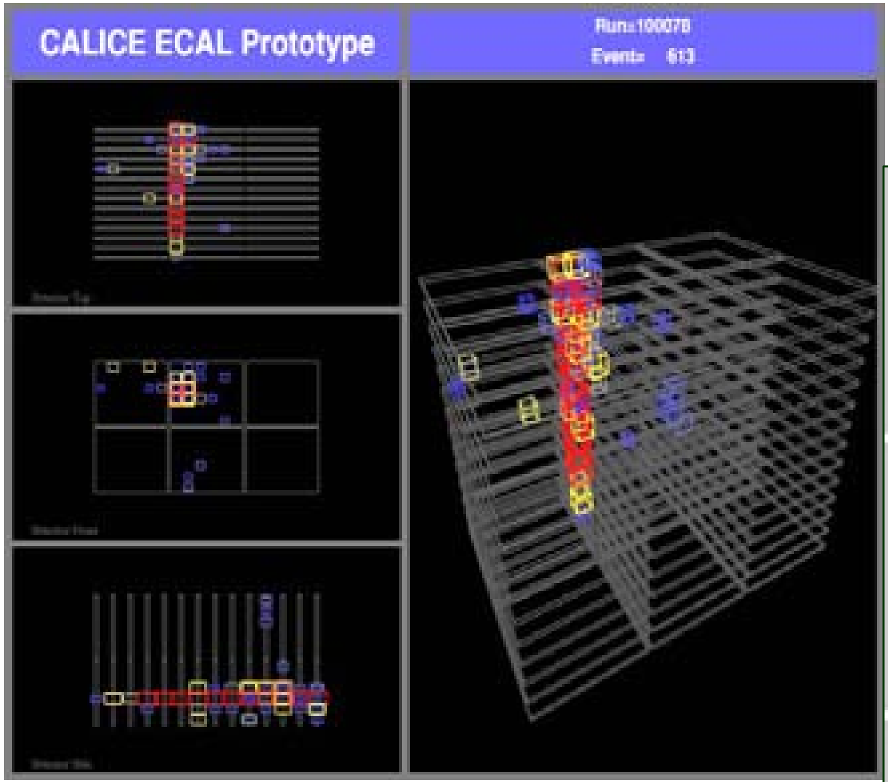




Jean-Claude BRIENT

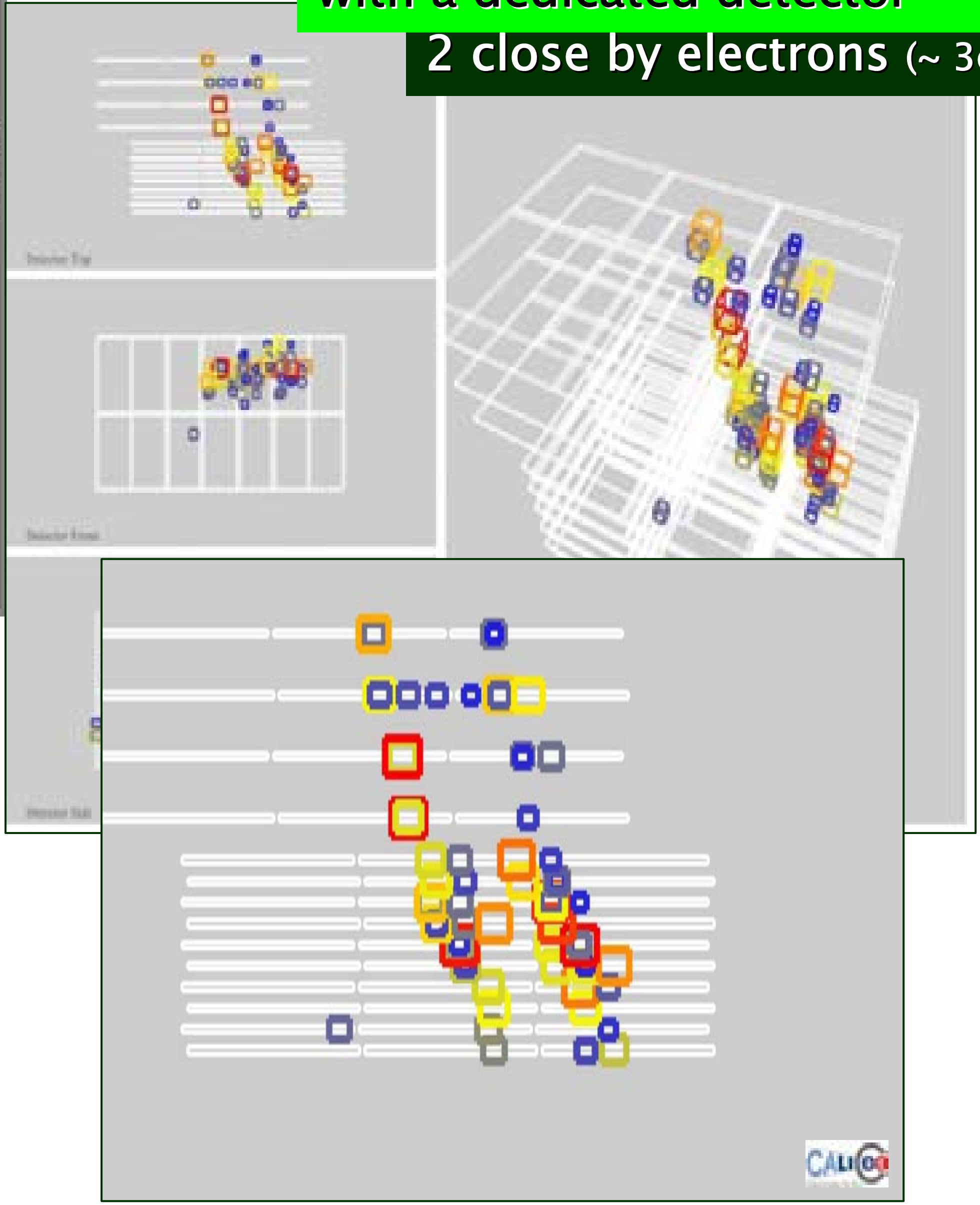
Goal: Test beam CERN/2006, Fermilab/2007

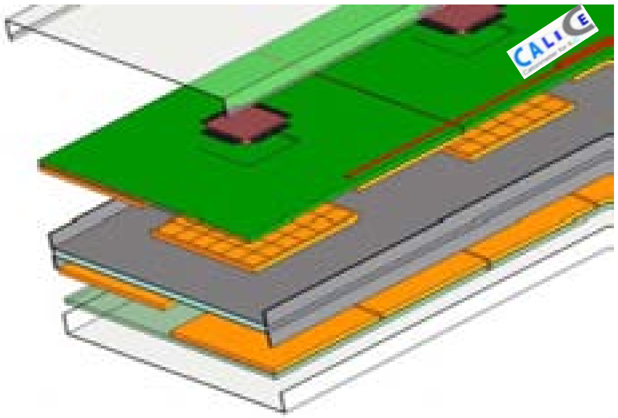
S/N ~ 8 !!



First real test versus
the « Particle Flow » method
with a dedicated detector

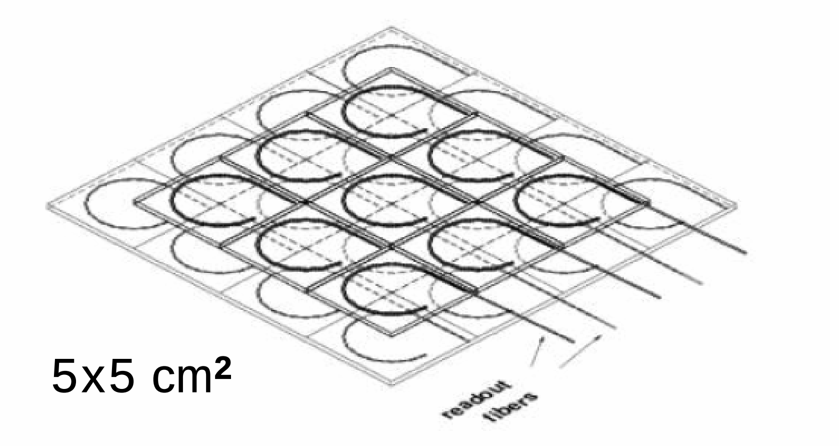
2 close by electrons (~ 3cm



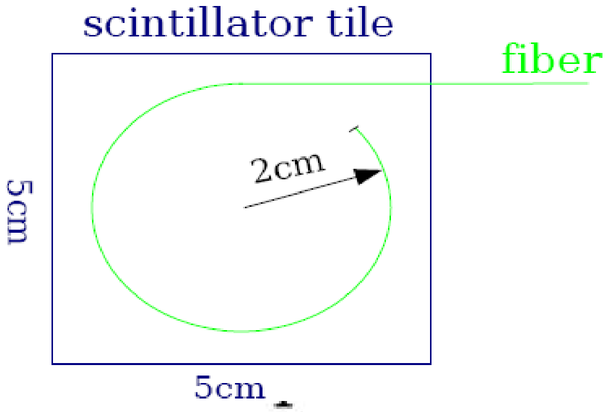


R&D for the final design

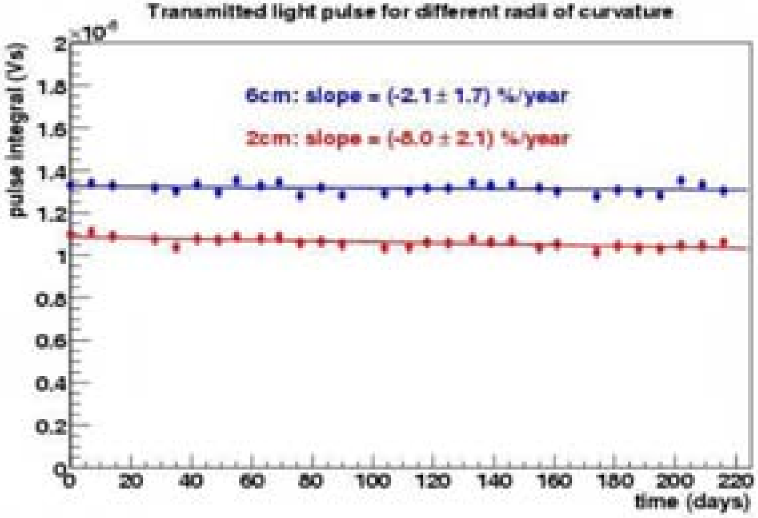
Scintillator / W – U. Colorado

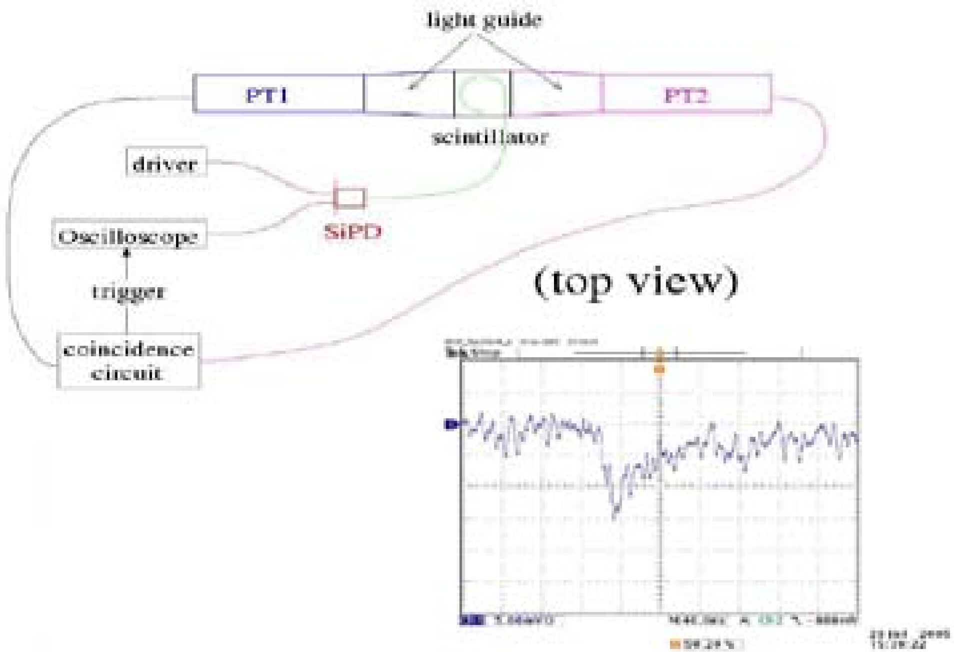


Martin Nagel



Degradation of optical fiber transmission over time for different radii of curvature





Calorimeter Technologies

Hadron Calorimeter

Physics requirements emphasize segmentation/granularity (transverse AND longitudinal) over intrinsic energy resolution.

- Depth $\geq 4\lambda$ (not including ECal ~ 1λ) Enough? Tail-catcher?

- Assuming PFlow:

  - sufficient segmentation to allow efficient charged particle tracking.

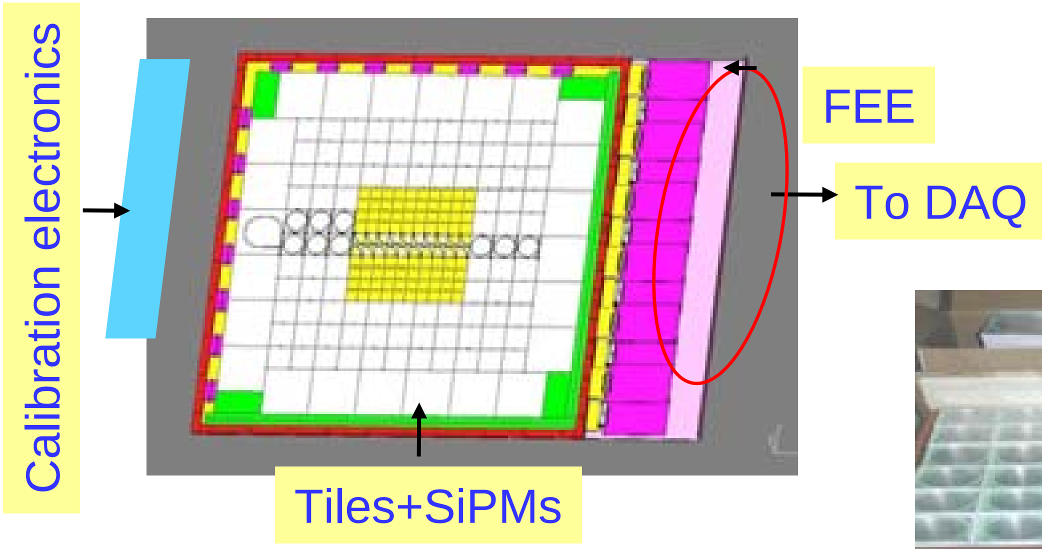
  - for "digital" approach – sufficiently fine segmentation to give linear energy vs. hits relation

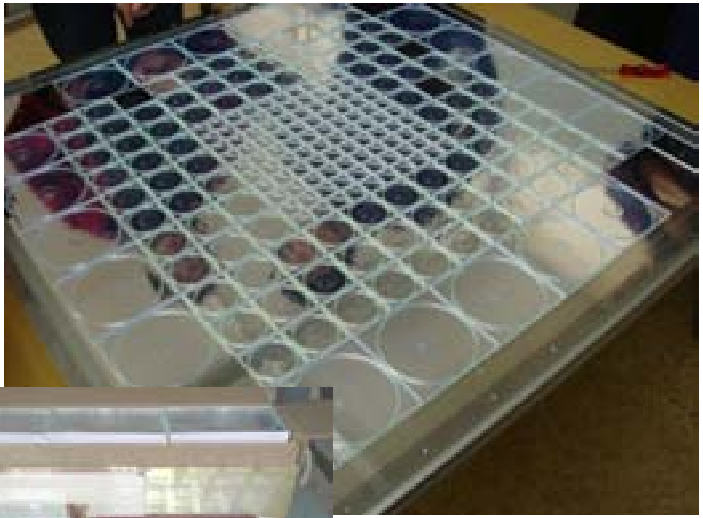
  - efficient MIP detection

  - intrinsic, single (neutral) hadron energy resolution must not degrade jet energy resolution.

Hadron Calorimeter – CALICE/analog

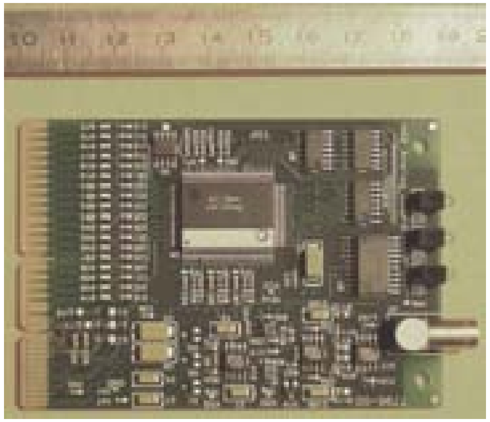
Vishnu V. Zutshi





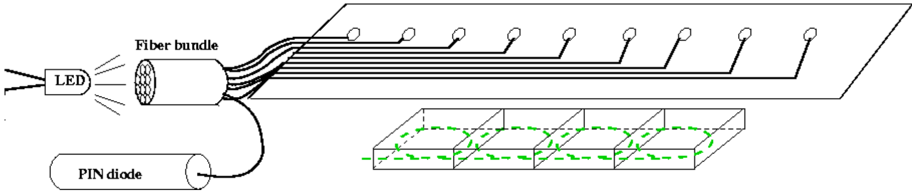
Tile size	3x3	6x6	12 x 12
need	3500	4000	1000
molded	3500	4000	1000
milled	3500	3000	800

Amplifier Board



Data Acquisition

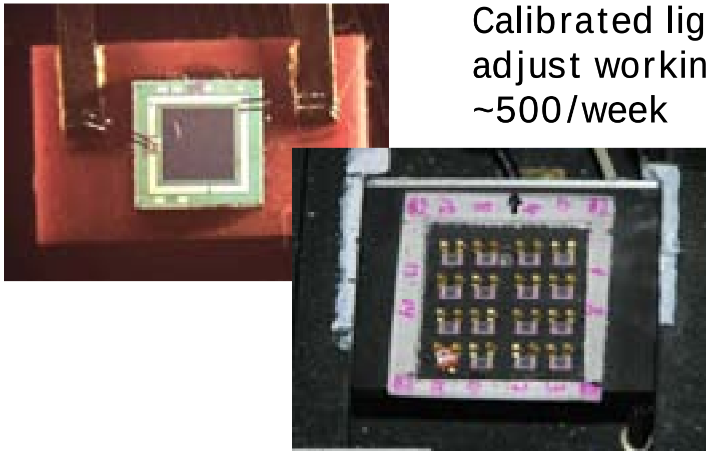
Monitoring



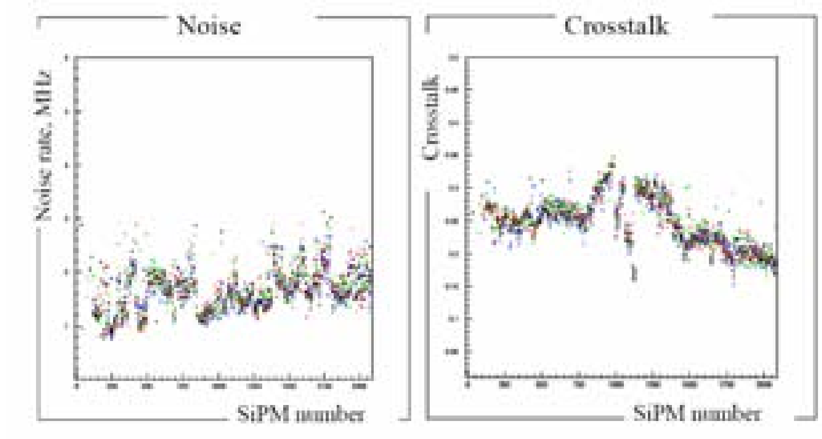
Hadron Calorimeter – CALICE/analog

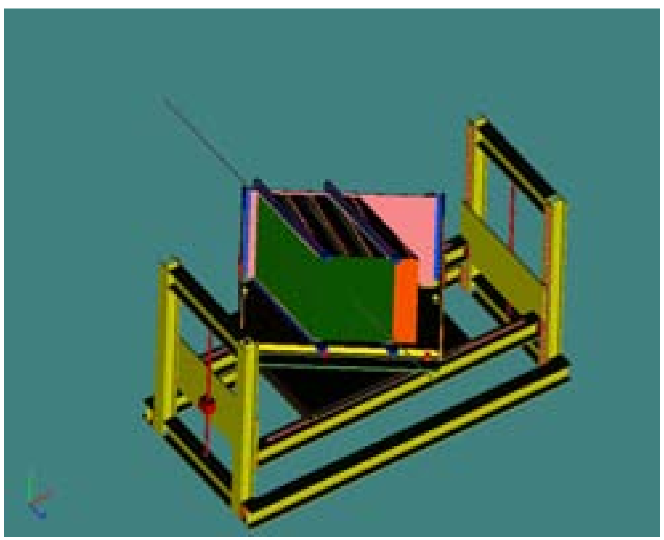
SiPM production/selection

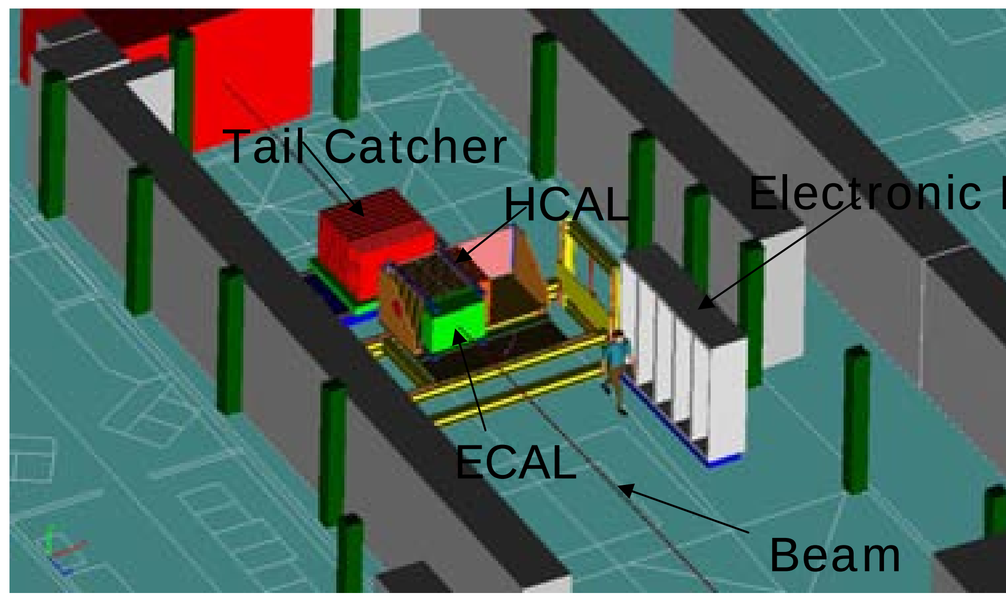
Felix Sefkow



Calibrated light source, adjust working point, ~500/week



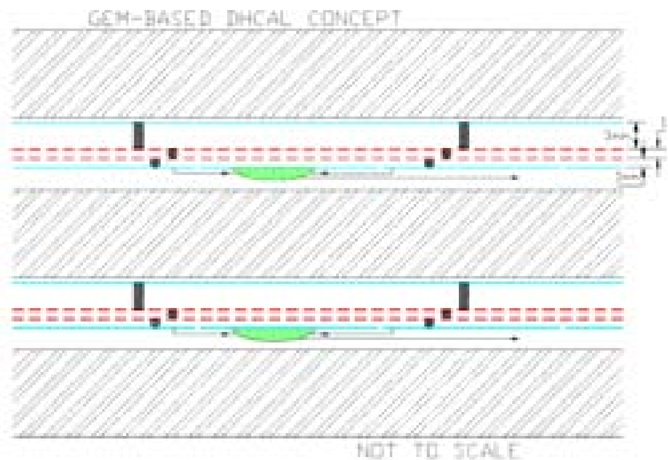


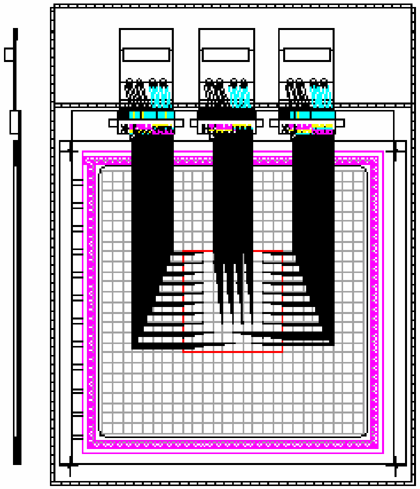


Preparing for test beam in summer-fall of 2006/CERN, 2007/Fermilab

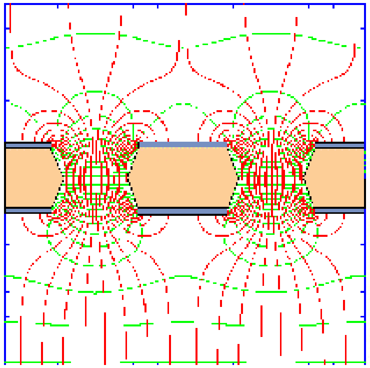
Hadron Calorimeter – CALICE/digital

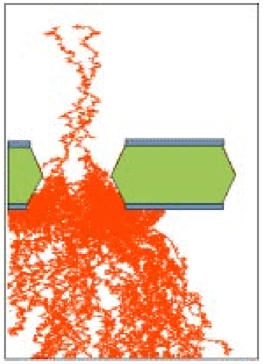
(1) Gas Electron Multiplier (GEM) – based DHCAL

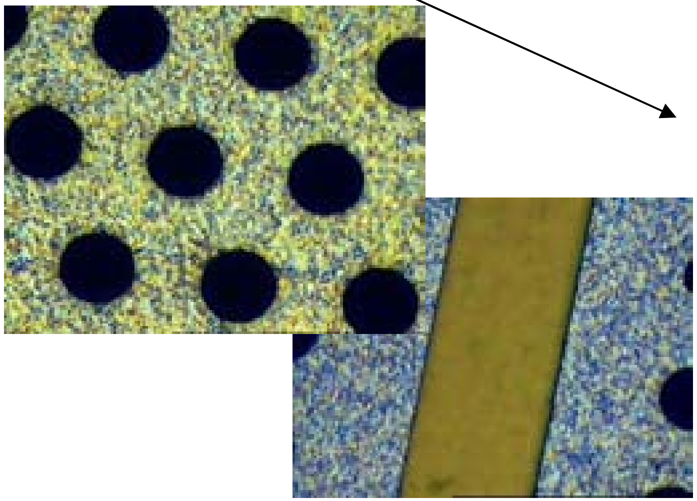




500 channel/5-layer test
30x30cm^2 foils

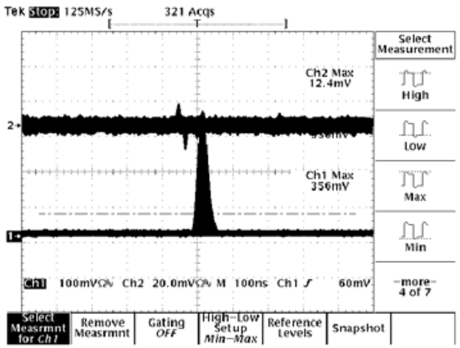


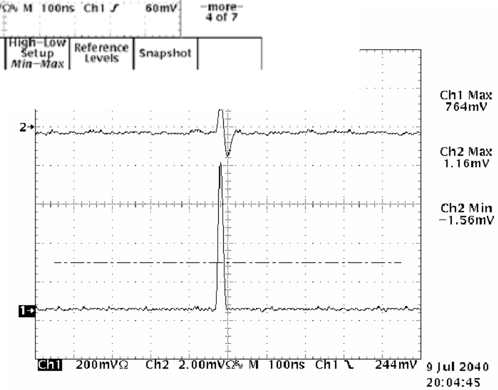




Details of new 30cm x 30cm foils from 3M

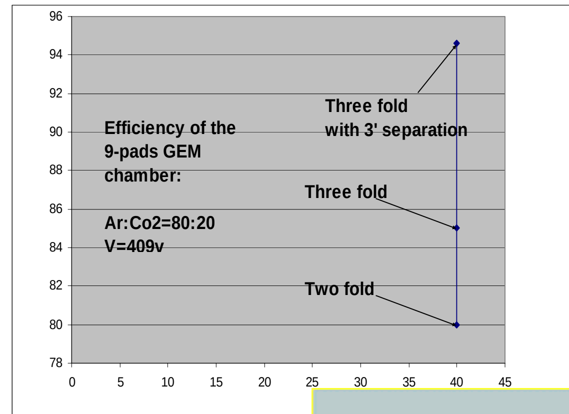
Hadron Calorimeter – CALICE/digital



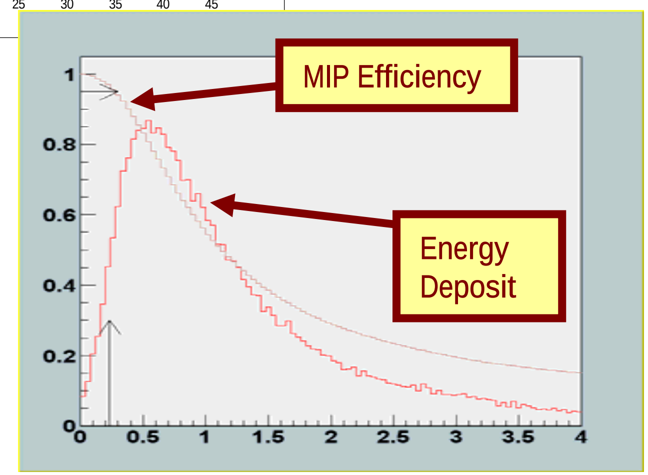


Cross talk studies

Average multiplicity = 1.27



MIP Efficiency study

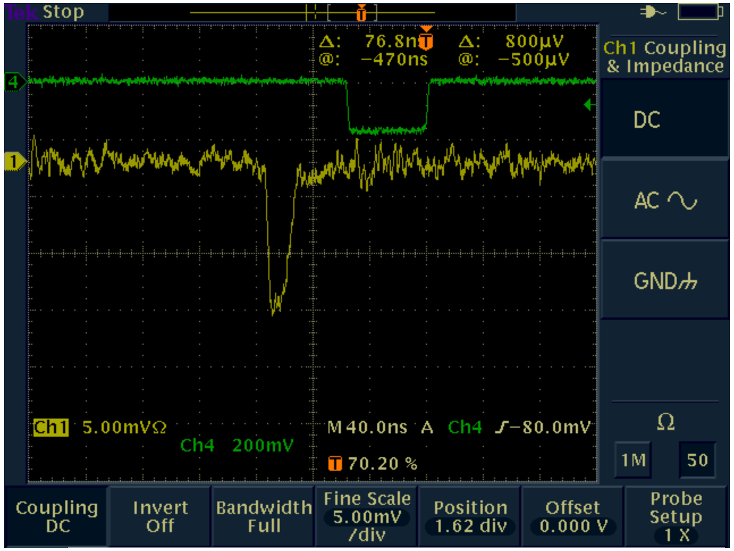


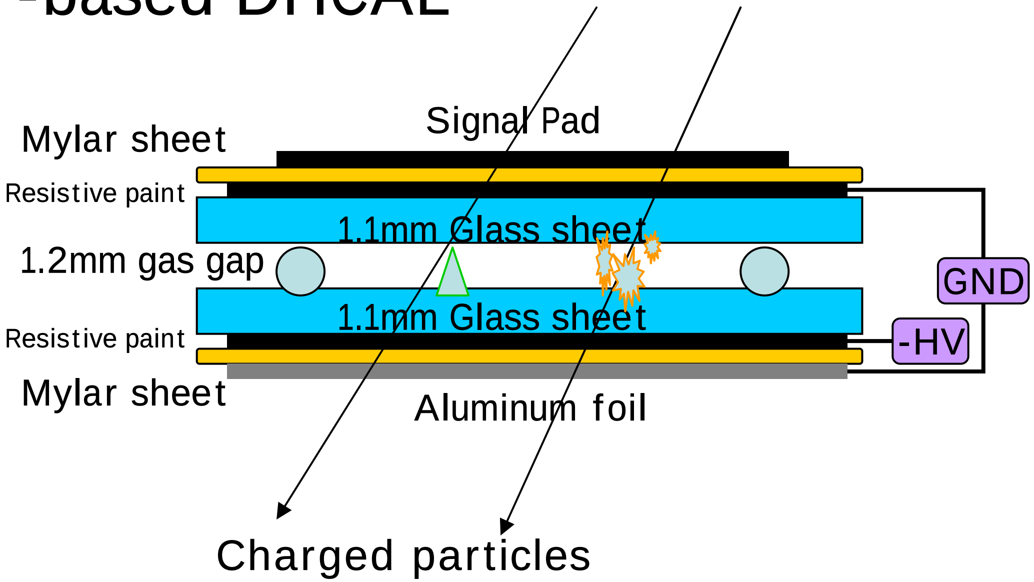
Assembly techniques for large scale GEM layers

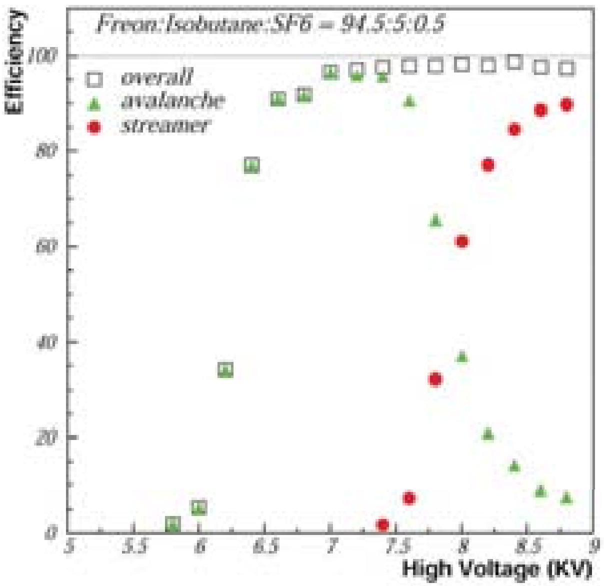
Goal: Test beam at Fermilab 2007

Hadron Calorimeter – CALICE/digital

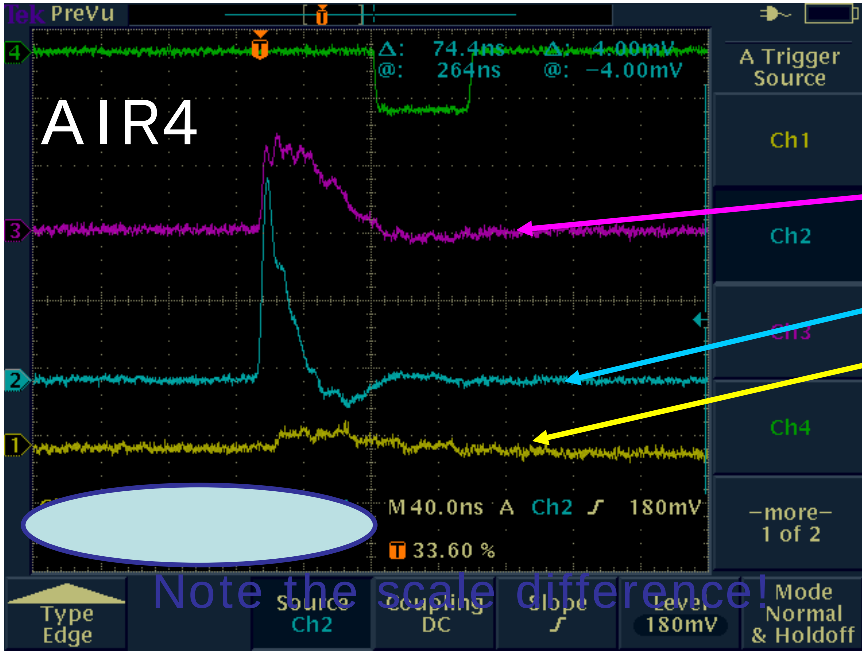
(2) Resistive Plate Chamber-based DHCAL



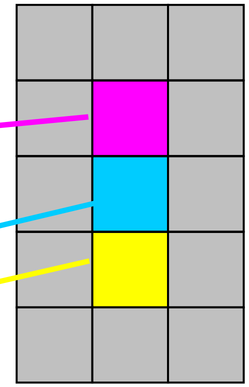


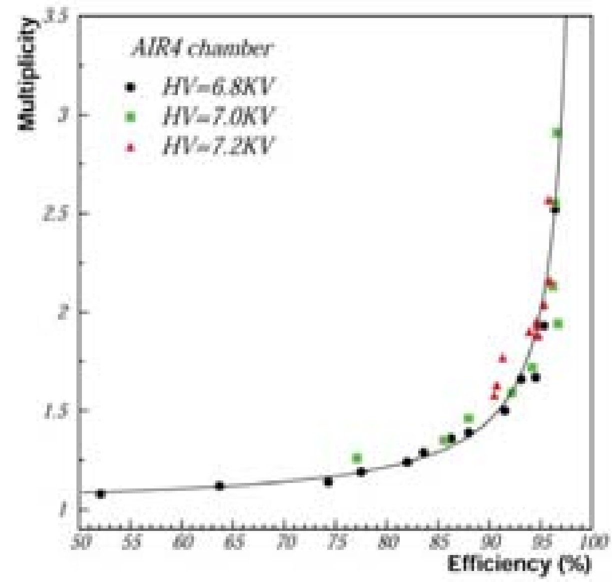


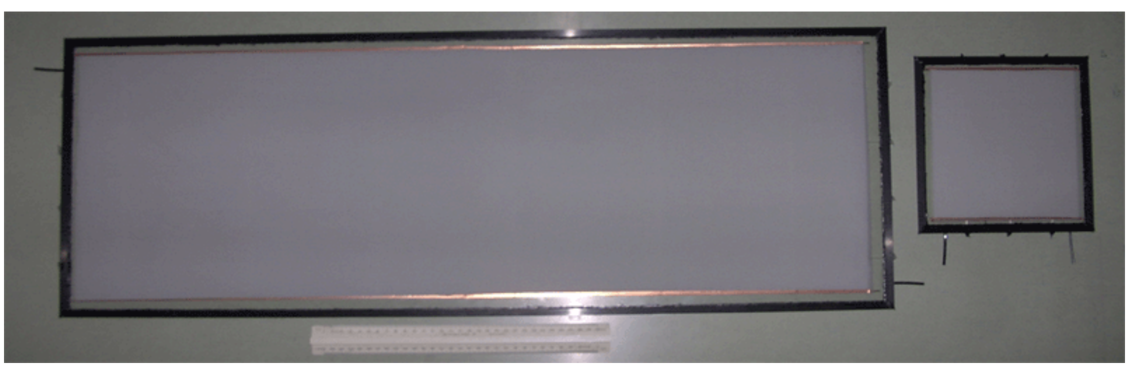
Hadron Calorimeter – CALICE/digital



Note the scale difference!







"RPC's totally understood - ready to build RPCs for the 1m3 test beam section"

Goal: Test beam at Fermilab 2007

Hadron Calorimeter – CALICE/digital

Common to RPC and GEM (400,000 channels/module)

Conceptual Design of the Readout System for the Linear Collider Digital HCAL Prototype Detector

John Dawson, Gary Drake, José Repond, Lei Xia
Argonne National Laboratory

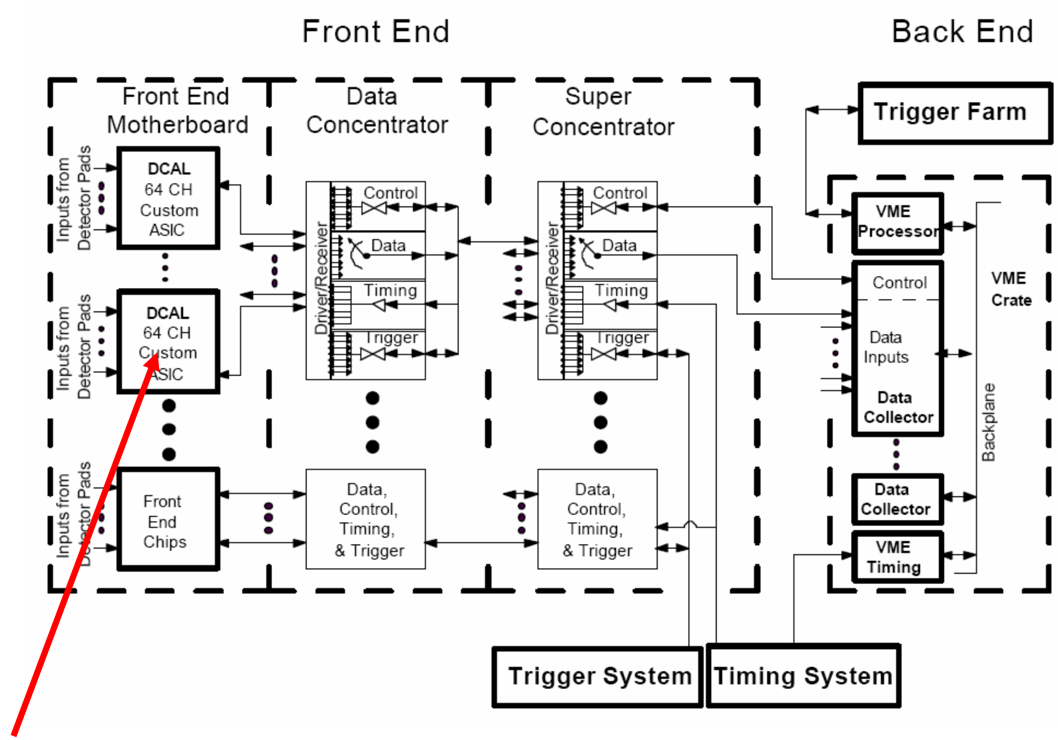
John Butler, Menakshi Narain
Boston University

Jim Hoff, Abder Mekonani, Raymond Yarema
Fermi National Accelerator Laboratory

Edwin Nobeck, Yasar Onel
University of Iowa

Andy White, Jaehoon Yu
University of Texas - Arlington

Version 1.10
July 25, 2005



FE ASIC needed to multiplex early on

Functionality specified by ANL; design work started June '04/FNAL

Prototype run submitted on March 18^{th} 2005

40 unpackaged chips in hand

Tests started: digital part tested: OK, analog tests next.

Digital HCal and SiW ECal in US

The evaluation in beam tests and comparison with GEANT4 simulations to underpin the PFA studies is the critical issue for LC calorimetry/detector design.

However, NSF/MRI was not funded and this needs urgent attention!

Module construction (~400,000 channels/module for HCal), testing, data analysis, and simulation comparison will take several years – a large fixed target experiment.

We must get started on this soon!

Other technologies/calorimetry

The DREAM solution

Richard WIGMANS

- *LESSON 6:* If you want to improve hadronic calorimeter performance

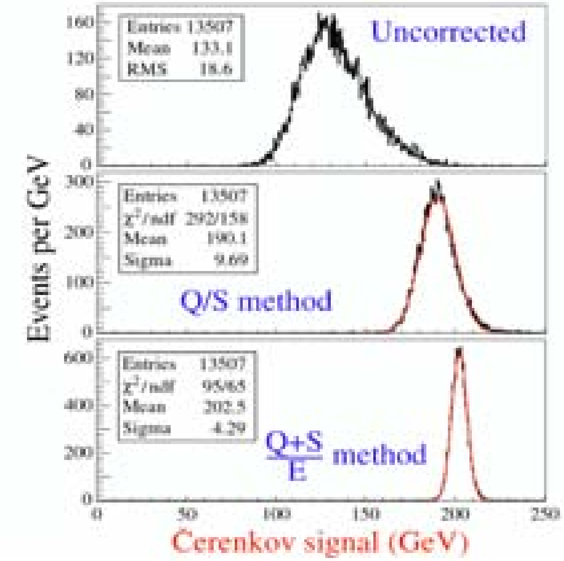
  → *reduce/eliminate the (effects of) fluctuations that dominate the performance*

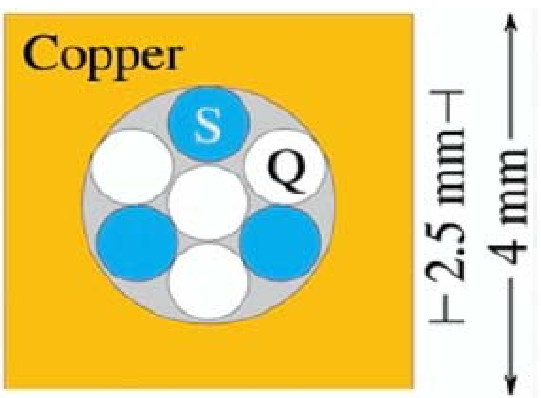
  1) Fluctuations in the em shower fraction, f_{em}

  2) Fluctuations in visible energy (nuclear binding energy losses)

➡ Use dual-readout system:

- Regular readout (scintillator, LAr,...) measures *visible* energy
- Quartz fibers measure em shower component E_{em}
- Combining both results makes it possible to determine f_{em} and the energy E of the showering hadron



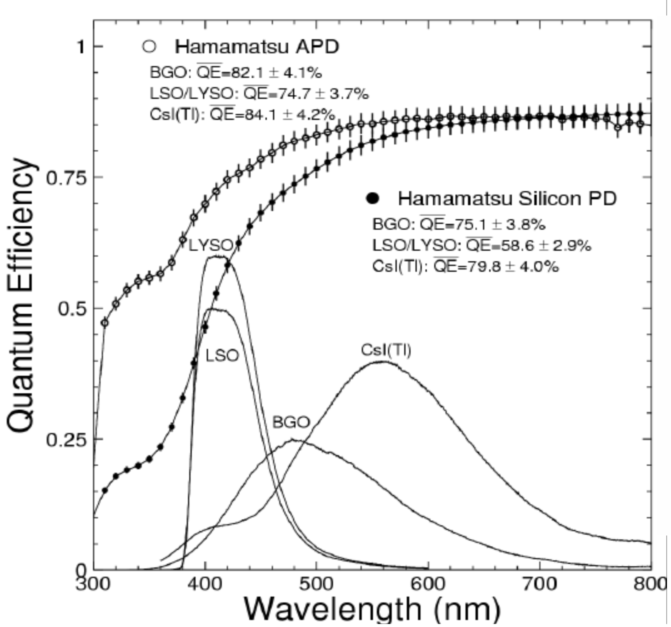


Challenge – how to configure for a LC calorimeter??

Crystal Calorimeter

Ren-Yuan Zhu

Empasize energy resolution, position/angular resolution



- A better energy resolution, σ(E)/E, at low energies than L3 BGO and CMS PWO because of its high light output and low readout noise:

$$2.0\%/\sqrt{E} \oplus 0.5\% \oplus .002/E$$

- Less demanding to the environment because of small temperature coefficient.
- Radiation damage is less an issue as compared to the CMS PWO ECAL.
- No degradation if ILC energy increases.

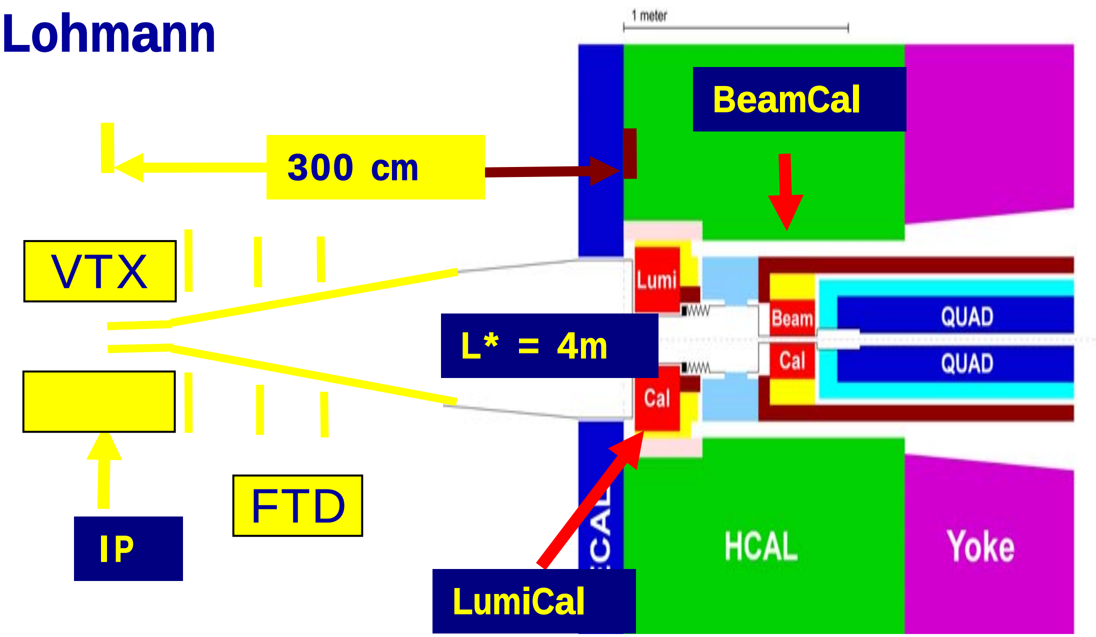
- An LSO/LYSO crystal calorimeter will provide excellent energy resolution even the beam energy increases, and will produce rich physics with precision electrons and photons at the ILC.

LC Detector design? HCal?

Other technologies/calorimetry

Very forward calorimetry/Luminosity Cal.

Wolfgang Lohmann

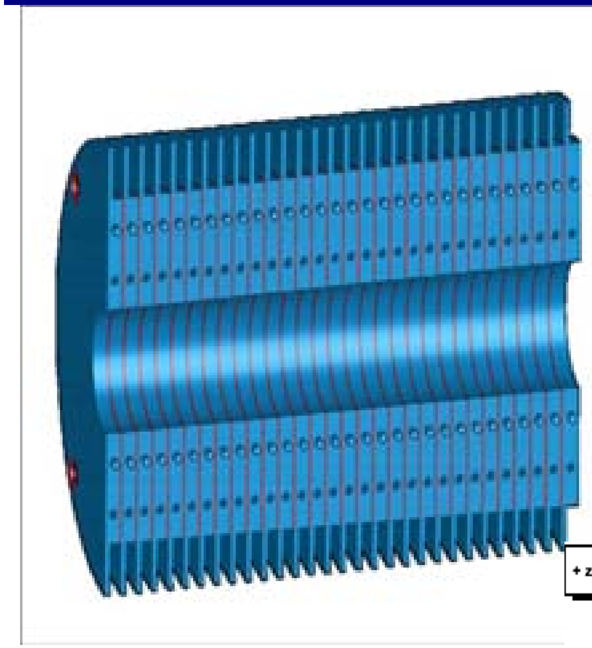


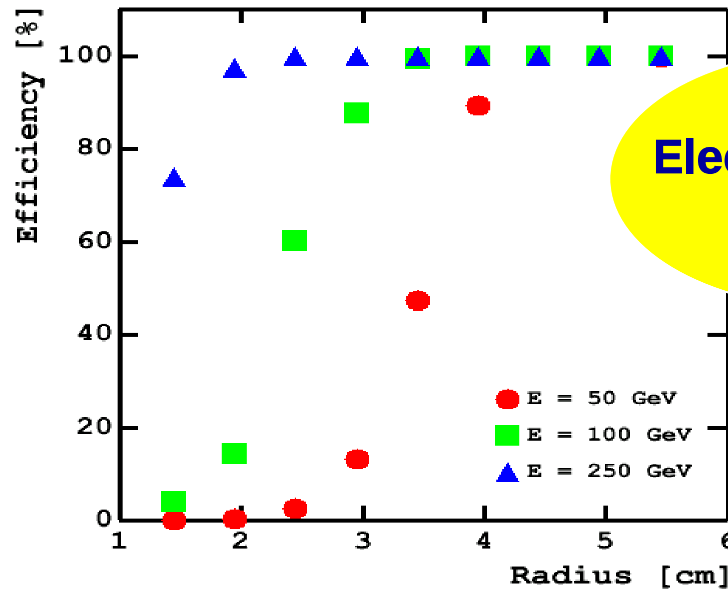
- **Measurement of the Luminosity with precision O(<10^{-3}) using Bhabha scattering**
- **Detection of electrons and photons at small polar angles- important for searches**
- **Fast Beam Diagnostics**
- **Shielding of the inner Detectors**

Other technologies/calorimetry

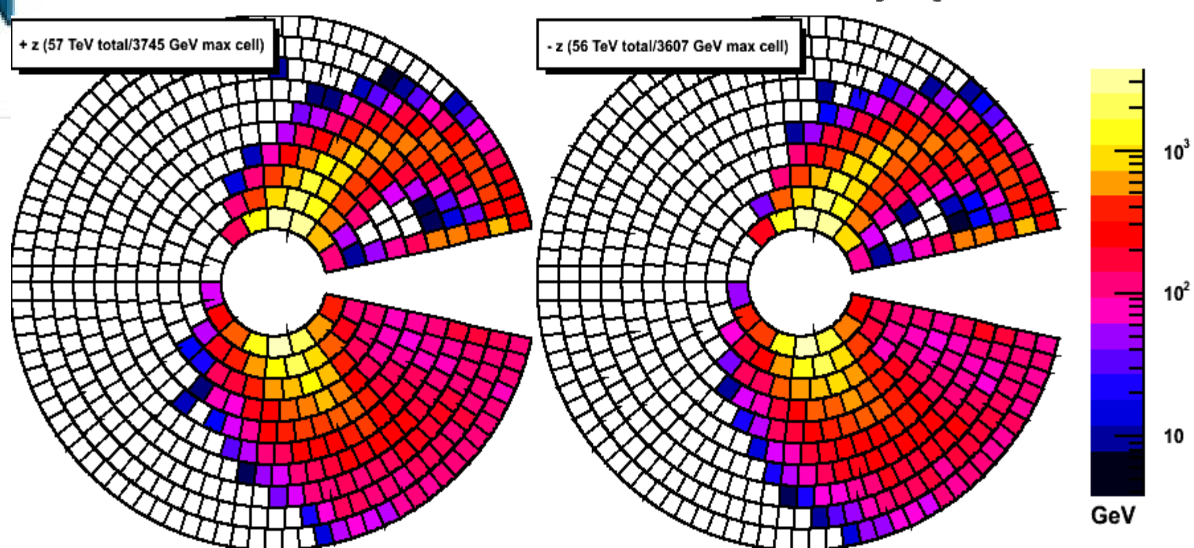
Technologies for the BeamCal:

W-Diamond sandwich





**Message:
Electrons can be detected!**



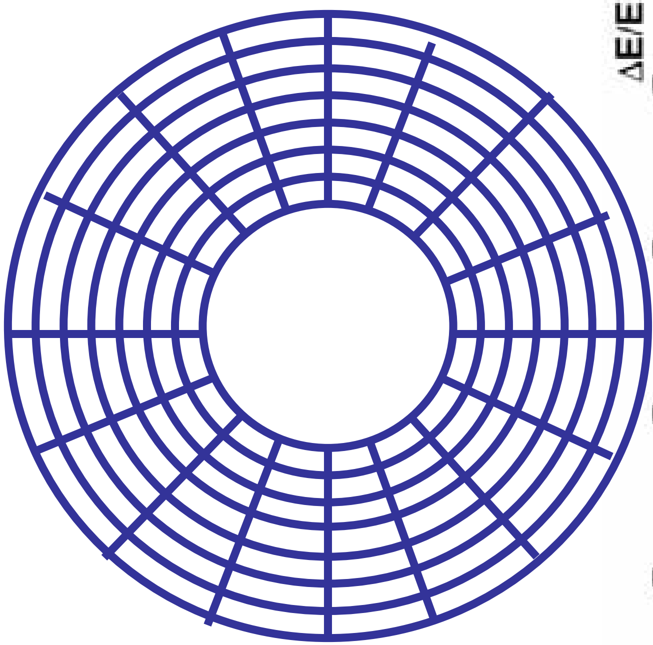
Wolfgang Lohmann

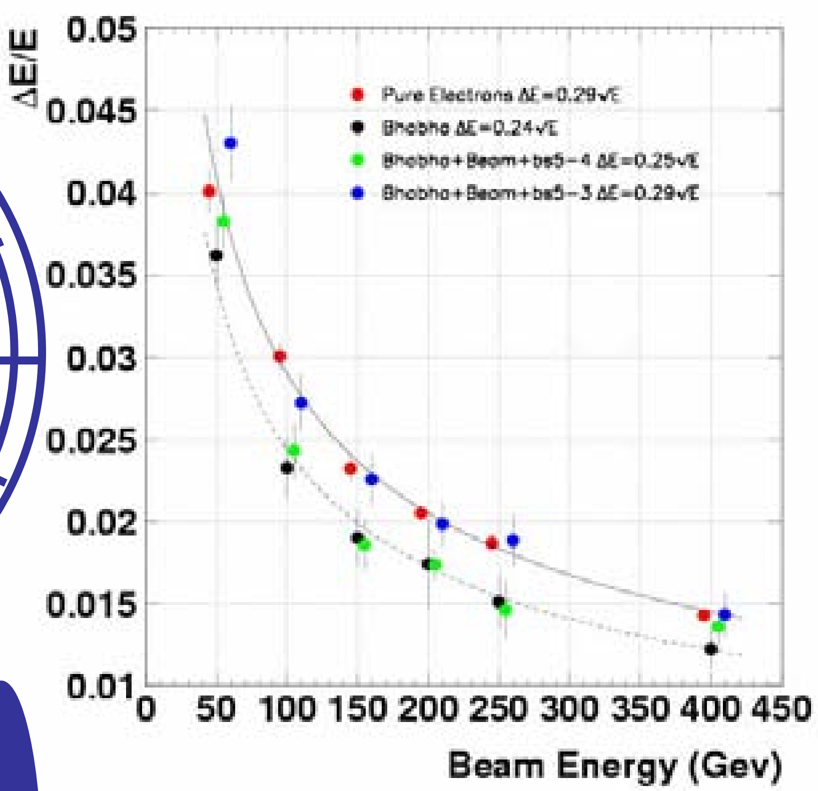
Other technologies

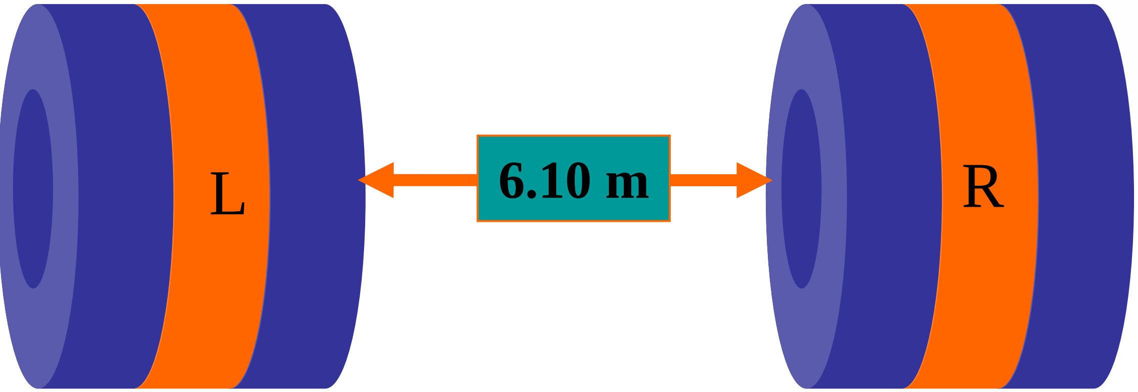
15 cylinders(θ)* 24 sectors(ϕ)* 30 rings(z)= 10800 cells

Luminosity detector

Beam monitor







Halina Abramowicz

Conclusions

- Steady progress (since LCWS05):

  - Calorimeter systems designs
  - Prototype construction/testing
  - Development of PFA's (later talk)

BUT ! A long way to go for a clear understanding of

Physics needs -> PFA performance -> Detector design

- Approaching a critical phase of large HCal module, and further ECal, construction/testing - essential to ensure adequate support is available!

- Designing LC calorimeters with the required performance for the physics is a fascinating challenge – let's keep up the momentum!