Achievements and Future Plan of the Calorimeter R&D for GLC

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Contents

One Column Summary

Single-particle energy resolution and Granularity are the key performances

- Energy resolution is understood and almost established.
- Granularity studies are in progress to go beyond 'Required'
  - Optimization by Simulation
  - Feasiblity studies at bench and with test modules

The most crucial component is photon detectors. (Tiles are no more problem.)

- Various promissing devices are being studied.

As soon as above established, we need to go to Engineering Prototype stage.

1.Overview of the Calorimeter R&D

Design Criteria on the total detector system

- Two-jet mass resolution be as good as to separate Z/W
- Hermeticity
- Operational in 3T-field

Qualitative Requirement to the Calorimeter

Good Jet Energy Resolution (often refered to be 30%/√E, but no validation with simulation)

which is decomposed to

- Fine granularity for topological reconstruction (reconstruct every particle)
- Good single-particle energy measurement (assign correct energy to reconstructed **neutrals**)

Energy-Flow algorithm; use tracker momentum for charged, and calorimeter energy for neutral

Standard analysis in e+e- experiments.

Refined by ALEPH utilizing their fine-granularity calorimeter, and named 'Energy Flow'.

Seems recently renamed as 'Particle Flow'.

1.Overview of the Calorimeter R&D - 2

As a result of quick-simulation studies, we defined quantitative 'base-line' requirements of

- single-particle energy resolution

  $\sigma_E/E = 15\%/\sqrt{E} + 1\%$ for EM particles

  $40\%/\sqrt{E} + 2\%$ for hadrons

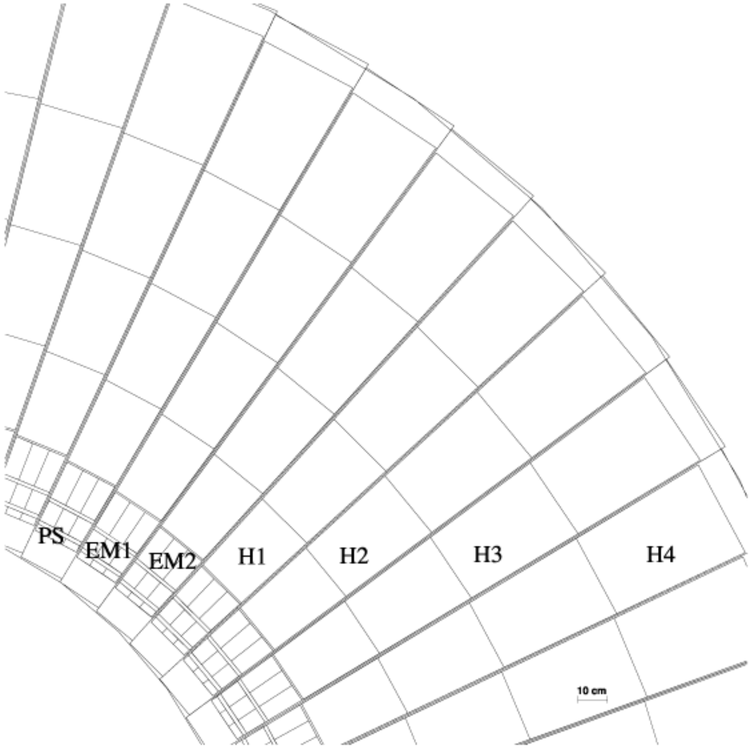
- granularity

  transverse; 24mrad x 24mrad (4cmx4cm) for EM

  72mrad x 72mrad for HCAL

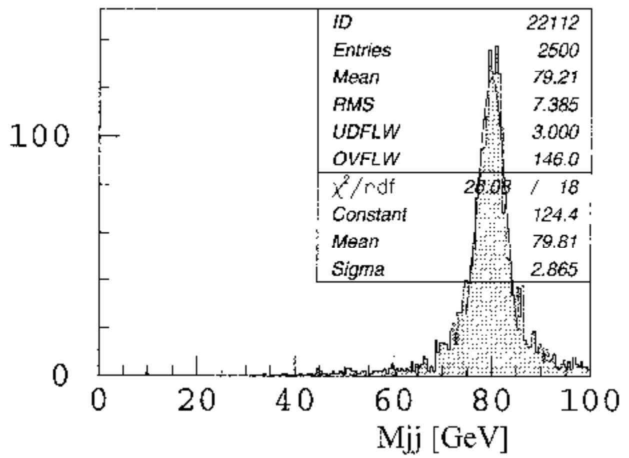
  longitudinal ; 3 sections with shower position detectors in between for EMC

  4 sections for HCAL



1.Overview of the Calorimeter R&D - 3

Reconstructed W-mass for e+e- -> WW at 400GeV with quick simulation,
assuming above energy resolution but 10cm EM cell size,
gives 2-jet mass resolution of **2.9 GeV; acceptabe.**



Decomposed sources of W-width

Natural width of W	~ 1.6 GeV (in terms of σ)
Neutrino escape	~ 0.8 GeV
CDC mom. resolution	~ 1.3 GeV
CAL energy resolution	~ 1.2 GeV
Track-cluster association	~ 1.9 GeV
Jet Clustering	~ 1.1 GeV

Since T-C association was the biggest factor, transverse cell size wass made smaller.

1.Overview of the Calorimeter R&D - 4

In order to achieve base-line requirements, we have chosen calorimeter design of

lead/plastic-scintillator sampling calorimeter with

- tile/fiber technique (for hermeticity and high potential for longitudinal granularity)
- hardware-compensation (for excellent hadron energy resolution and linearity)

This enables excellent timing resolution for bunch-identification to reduce event overlap.

The base-line requirements are established to be feasible (except for engineering aspects).

Now moving to 'beyond required' studies, **finer granularity**, to compete with w-w studies.

Key R&D Issues for studies beyond are

- Single-particle energy resolution
- Small tile size for **finer transverse granularity**
- Photon detectors for **further finer longitudinal granularity**

for Tile/Fiber module and for Strip-Array module.

2.Calorimeter - a) Single-particle energy resolution

Determined by material composition, provided that photon statistics effect is negligible.

Test Modules constructed, and series of beam tests has been carried out.

'Excersizes'

1993	T305 at KEK	SPACAL-type and ZEUS-type HCAL
1995	T365 at KEK	ZEUS-type EMcal , Si-pad shower-position detector (SHmax)

HCAL Study Series

1996	**T405 at KEK**	**Hanging-File HCAL for generic study**
1997	**T411 at KEK**	**Hanging-File HCAL for generic study**
1998	**T411 at KEK**	**Tile/Fiber HCAL**
1999	**T912 at FNAL**	**Tile/Fiber HCAL , Sci-strip SHmax**

EMC Study Series for 'beyond required'

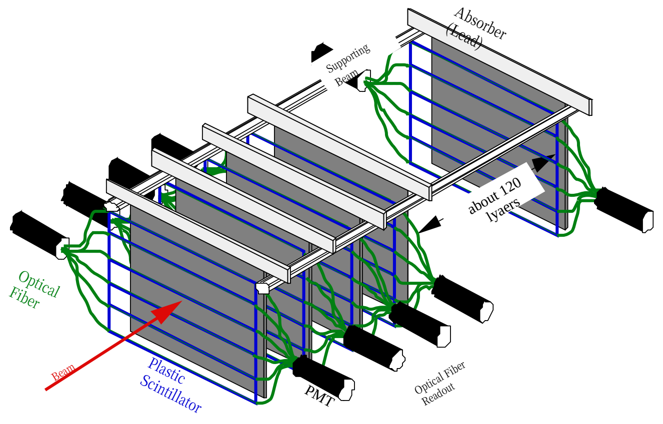
2002	**T517 at KEK**	**Tile/Fiber EMcal, Strip-Array EMcal, Sci-strip SHmax**
2003	**Test at DESY**	**Sci-strip SHmax**
2004	**T545 at KEK**	**Tile/Fiber EMcal, Strip-Array EMcal, Sci-strip SHmax**

2.Calorimeter - a) Single-particle energy resolution

i) HCAL Study Series

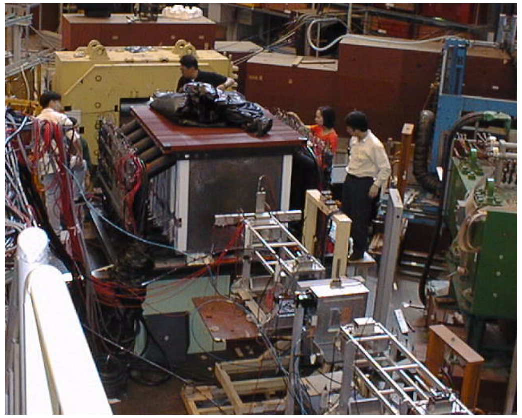
Hanging-file HCAL test module for generic studies

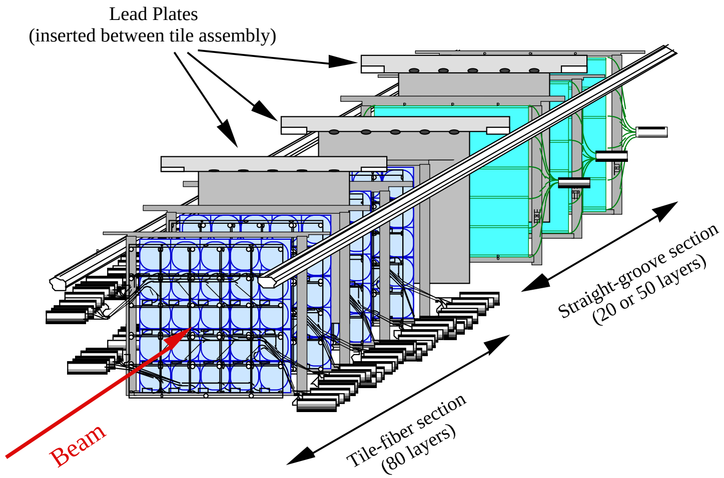
- 1m x 1m x 1m, ~12tons
- Measure various configurations
- Fine longitudinal sampling and longitudinal shower profile studies



Tile/Fiber HCAL test module for performance examination

- Measure realistic performance
- Uniformity and tile-boundary response

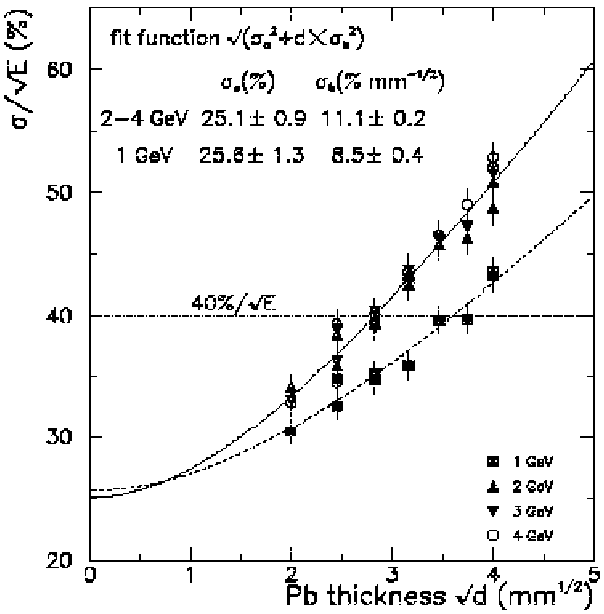




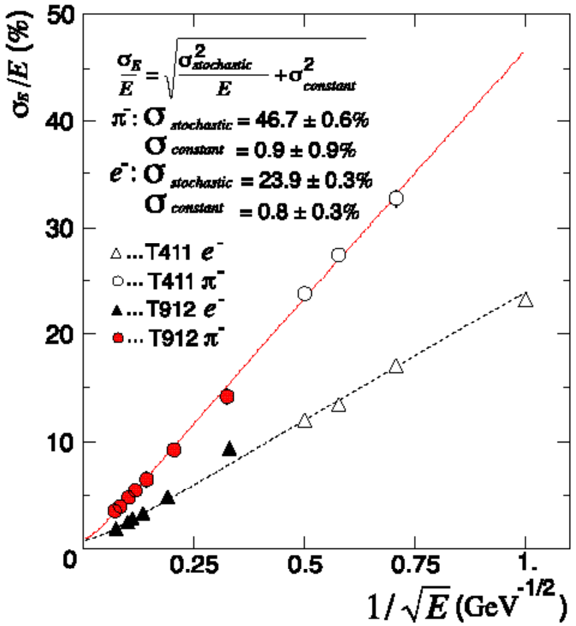
2.Calorimeter - a) Single-particle energy resolution - i) HCAL Study Series

- 8mm-Pb/2mm-scintillator achieved 39.7%/√E + 0.0% for pions.
- 8mm-Pb/2mm-scintillator/2mm-acryl barely showed 46.7%/√E + 0.9% for pions.

? Is 47% acceptable or not ? be examined by simulation.



Hanging-file hadron energy resolution (at KEK)

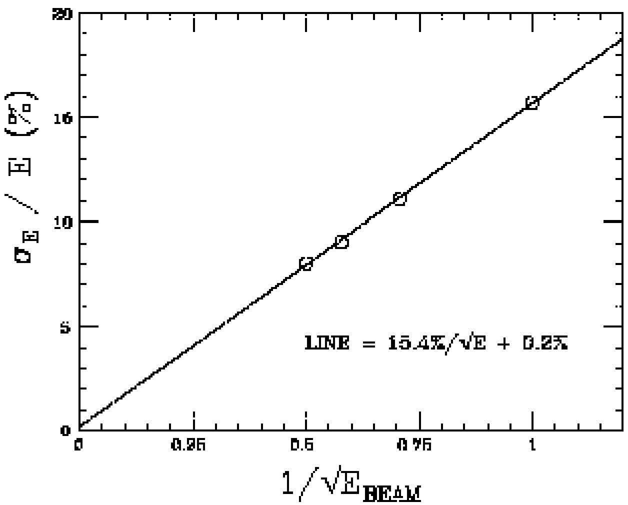


Tile/Fiber hadron energy resolution (at FNAL/KEK)

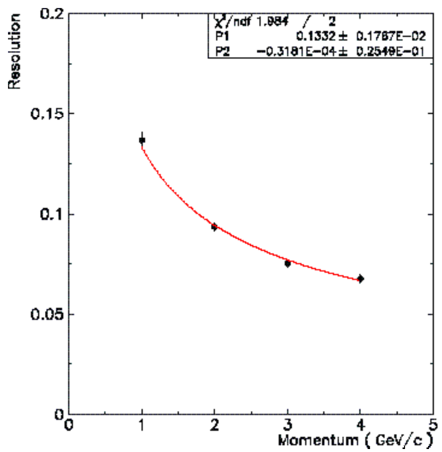
2.Calorimeter - a) Single-particle energy resolution

ii) EMC Study Series

- 4mm-Pb/1mm-scintillator achieved 15.4%/√E + 0.2% for electrons (ZEUS-type)
- 4mm-Pb/4mm-scintillator achieved 13.3%/√E + 0.0% for electrons (Strip Array)
- **4mm-Pb/1mm-scintillator/1mm-acryl (tile/fiber) will be tested in March 2004.**



T365 results



T517 results

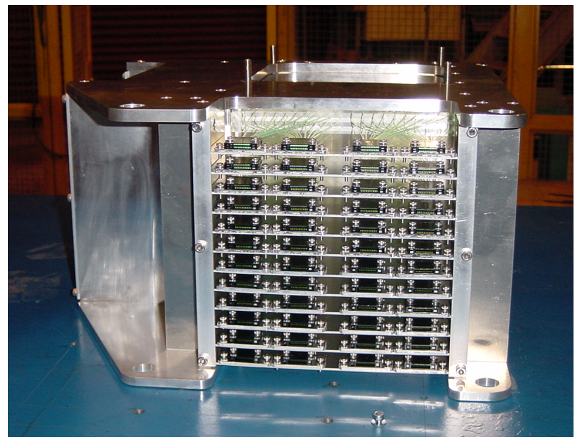


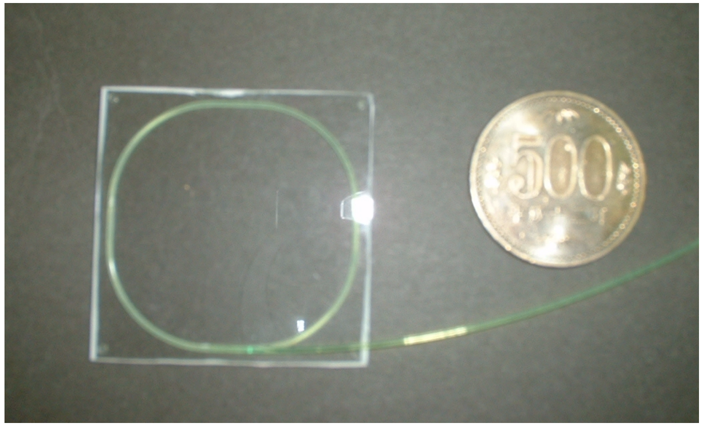
Photo = T517 EMcals ; above=Strip Array
below=Tile/Fiber

Obtained results are almost as expected.

2.Calorimeter - b) Feasibility of finer granularity

i) Transverse cell size

Target size = 4cm x 4cm x 1mm-thick (left photo)



Challenge-1 = WLS-fiber bending radius

Manufacture's recommendation ;

r=50mm for 0.5mm-ϕ fibers

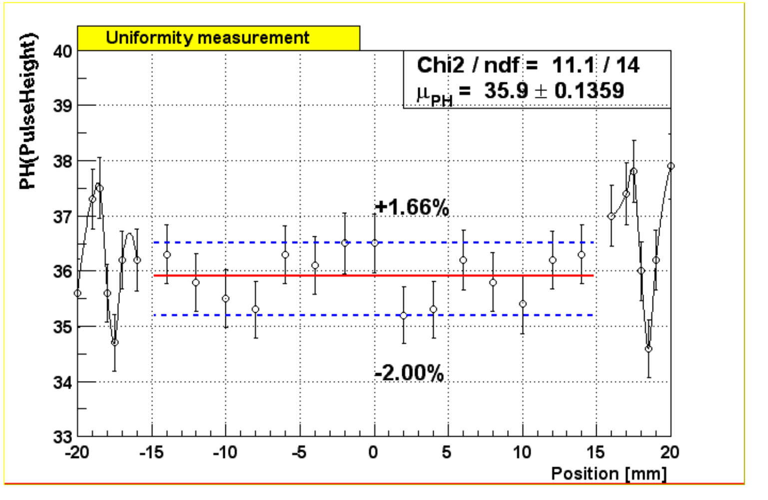
Our design ; r=15mm for 0.7mm-ϕ fibers

Pre-heating enables r=15mm for 1mm-ϕ fibers as Phenix or LHCb showed, but causes significant light loss (6%-loss / 90° bent ; by Phenix)

Challenge-2 = Uniformity

Excellent except for the WLS fiber neighbourhood

Effect of anomaly on WLS fiber needs investigation



2. Calorimeter - b) Feasibility of finer granularity - i) Transverse cell size -continued

Challenge-3 = Photon yield

Expected = 7 p.e. (extrapolation from the large thin tile)

Measured = 2.2 p.e. (stochastic term of 15.0%/$\sqrt{E}$ becomes 16.1%/$\sqrt{E}$)

- Needs improvements (better mirroring, die matching, Q.E. of photo-detector, etc.)

Challenge-4 = explosion of readout channels, and hence cost

- Photo-detectors ; see next section (longitudinal granularity)
- Tile ; MegaTile molding
- Fibers ; WLS-fiber co-molding / eliminating clear fibers / even eliminating WLS fibers

Strip-Array option may solve many of above challenges.

2. Calorimeter - b) Feasibility of much finer granularity - continued

ii) Longitudinal segmentation

In principle, tile/fiber configuration enables every-layer read-out (1M tiles/strips for EM).

Challenge = explosion of readout channles

Possible solutions

- Multi-channel **HPD** ; ~100ch/device, ~ $30/channel (real values).
  Yet a bit expensive, further need WLS/clear fibers
- **EBCCD** ; ~400ch/device, ~ $10/channel (reasonable guess)
  Good price, but still need WLS/clear fibers
- **SiPM** ; 1ch/device, ~ a few $/channel (ambicious guess ; ~ 10$/piece now)
  Cheap, no need for clear fibers = neat design (still need WLS fibers)

\- Multi-pixel **APD** ; 2$/channel
  Cheap, but still need WLS/clear fibers. Gain not enough to read a tile.

Described in detail later in dedicated section.

2. Calorimeter - b) Feasibility of finer granularity - continued

iii) Test-beam validation

Granularity is mostly an issue to be studied by Simulation. Thus beam-test results relevant to granularity is limited.

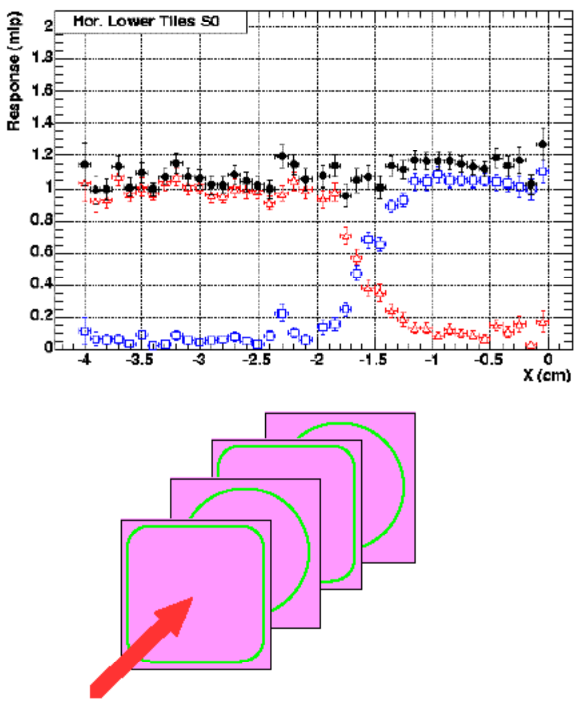
Uniformity

to smear out anomaly, two WLS-fiber layouts were tested; alternating and aligned.

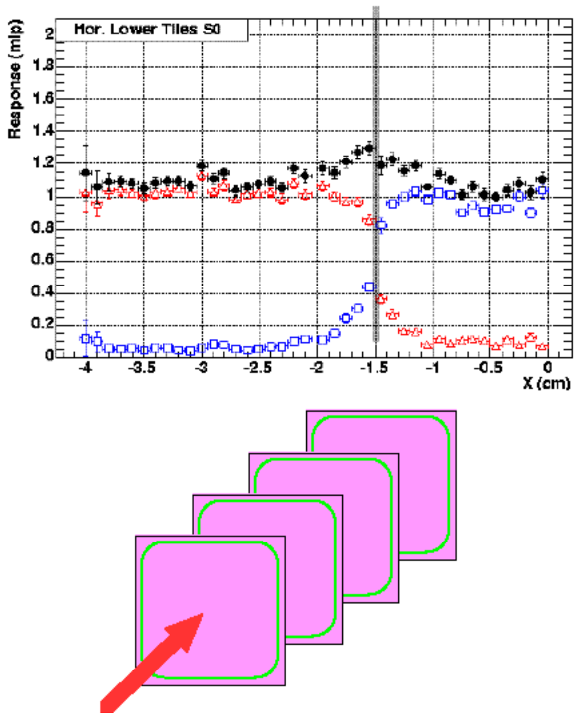
Still see boundary effects.

Further tuning of tile design needed.

Alternating WLS



Aligned WLS



2. Calorimeter - b) Feasibility of much finer granularity - continued

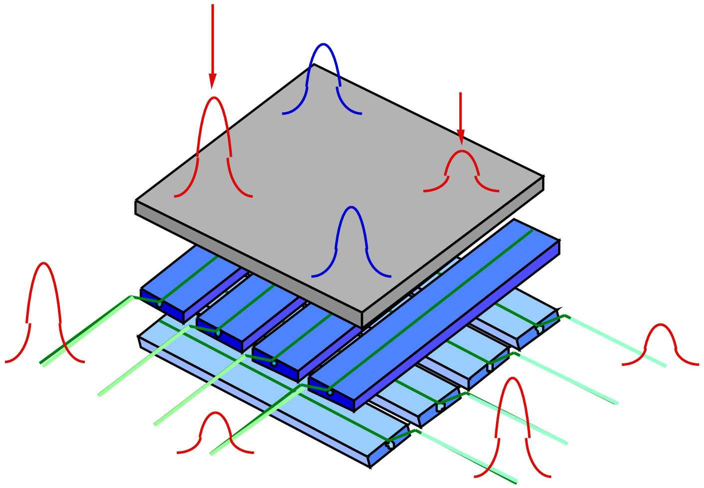
iv) Strip-Array EMC ; another option for higher granularity

The highest-granularity EMcal ever planned = W/Si (DELPHI HPC was the highest.)

- European Studies ; 10mm x 10mm Si-pad x 40samplings ~30M channels
- American Studies ; 5mm hexagon Si-pad x 40?samplings ~50M pixels (channels?)

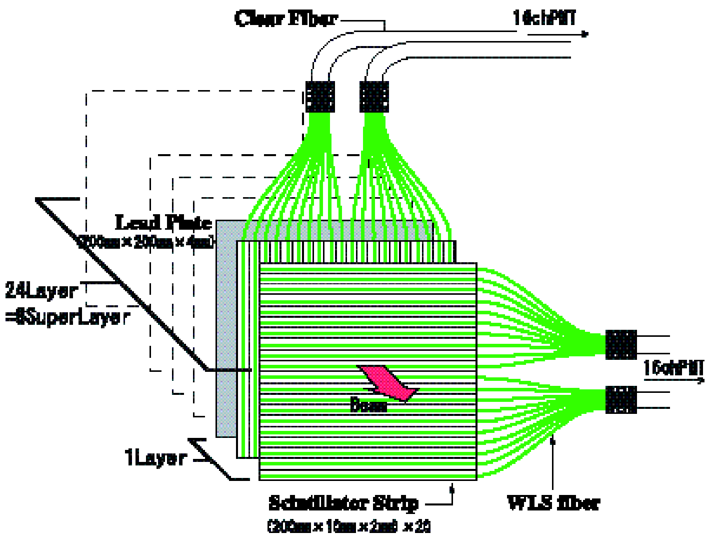
Excellent ! , if you forget about the cost (even if you hope to achieve a few $/channels)

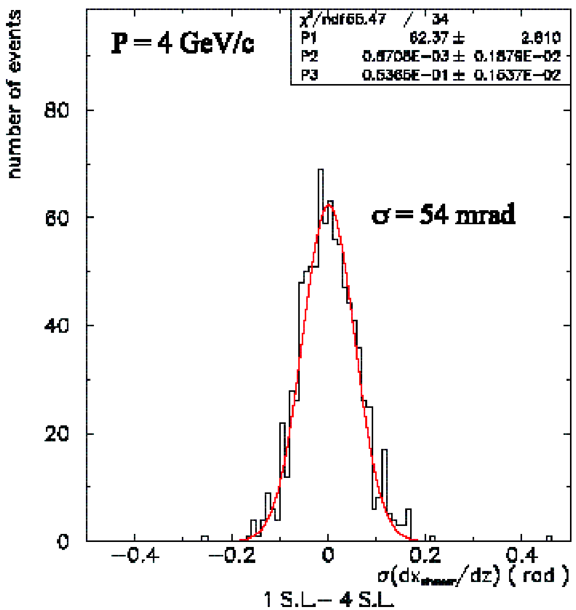
Scintillator-strip array EMC would provide similar granularity with reasonable cost, but crucially depend on EBCCD (super-multi-channel photon detectors), or SiPM.

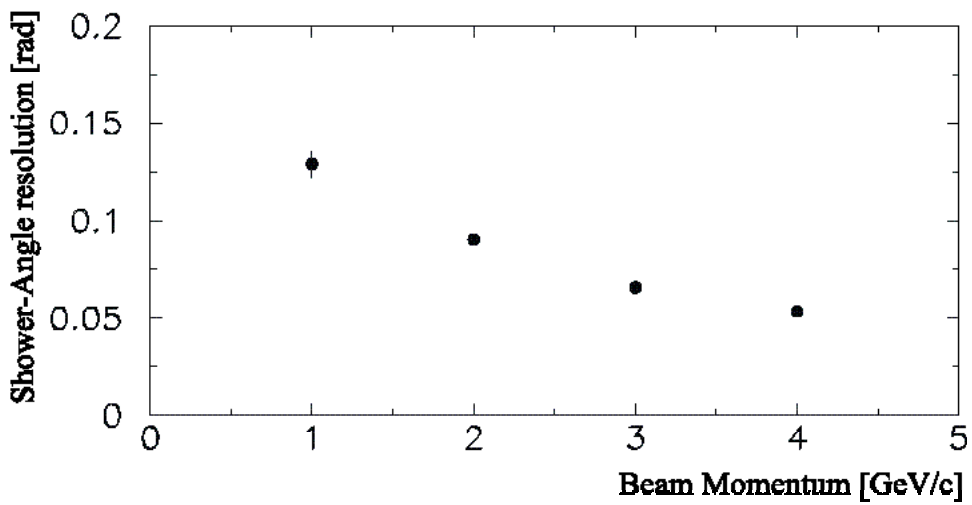


Strip-Array EMC test module (tentatively with PMT) constructed, and beam test carried out.

- Energy Resolution (already shown above)
- Position resolution, shower-axis resolution (below)
- Two-cluster separation (still in analysis)







2.Calorimeter - c) Shower-position Detectors

Purposes :

- Measure shower position precisely,
- Recognize closely-located clusters,
- Measure shower-axis by installing plural planes,
- Provide timing information if CAL uses EBCCD.

The 1st-phase studies were on Si-pad (1cm x 1cm) at shower maximum.

We switched SHmax design when we adopted tile/fiber configuration.

Will be integrated to EMC for Stripp Array EMC

Present studies are on scintillator-strip array (1cm-width) at shower maximum with

- WLS+clear fiber readout (baseline design)

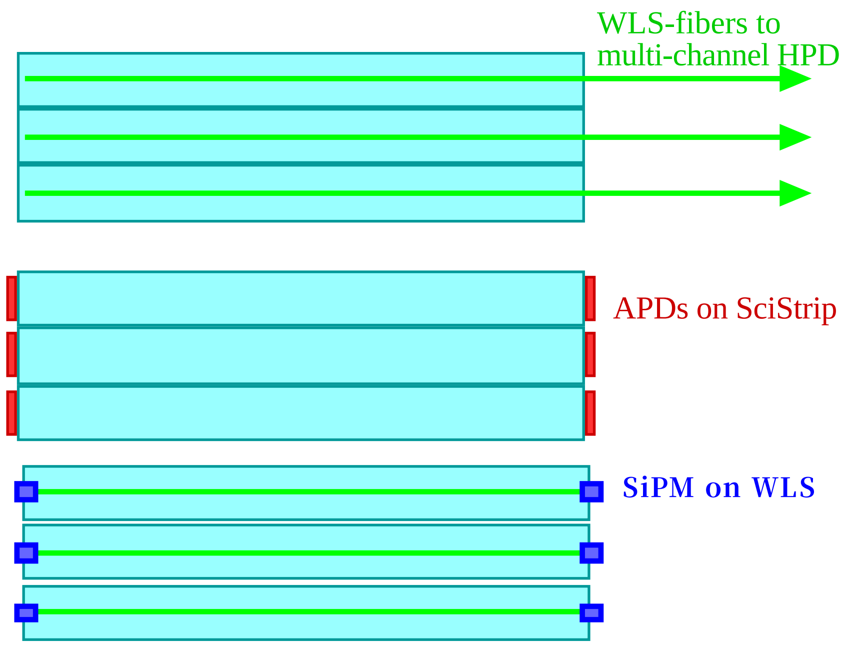
  Performance tested with beams.

- Direct-attached APD readout is a good option.

  Beam tests in progress.

- WLS-fiber +SiPM would be another good option.

  Not yet tested.



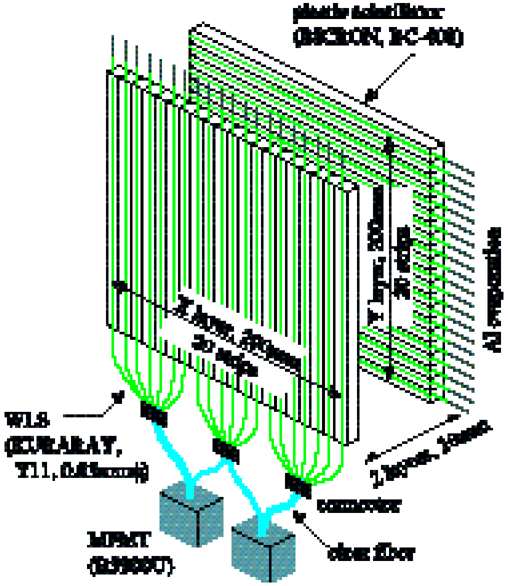
2.Calorimeter - c) Shower-position Detectors - continued

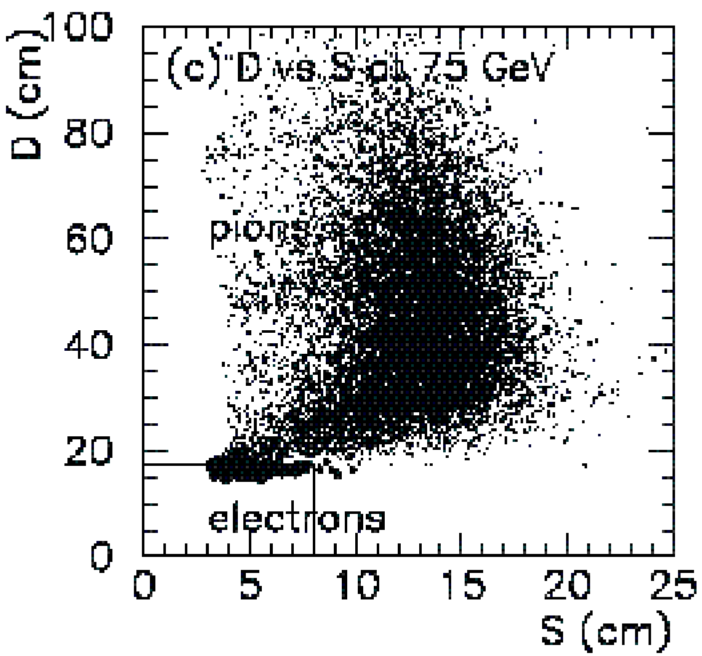
Strip size, and thus expected performances, are almost the same for three options.

The differences are

- Readiness of photon detectors
- Design simplicity, and hence Efforts on assembling
- Costs

i) WLS+clear fiber readout ; beam test results (used MA-PMT tentatively)





ε_π =1/1000 at ε_e=95%

using longitudinal and lateral shower spread.

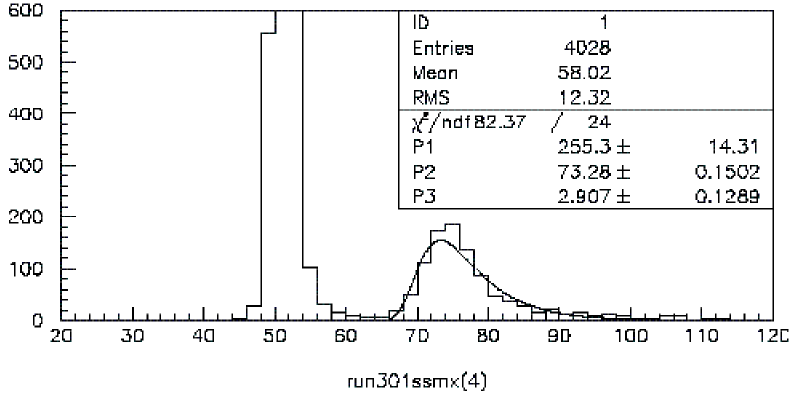
Will integrate with multi-channel HPD and do beam test in March 2004.

2.Calorimeter - c) Shower-position Detectors - continued

ii) Direct-attached APD

- Simple in structure, easy assembling.
- only a few tens of photo-electrons expected for MIPs (commercial APD gain is only ~50)

Performance tested with beam in Nov.2002



Muon ADC spectra with S8664-55

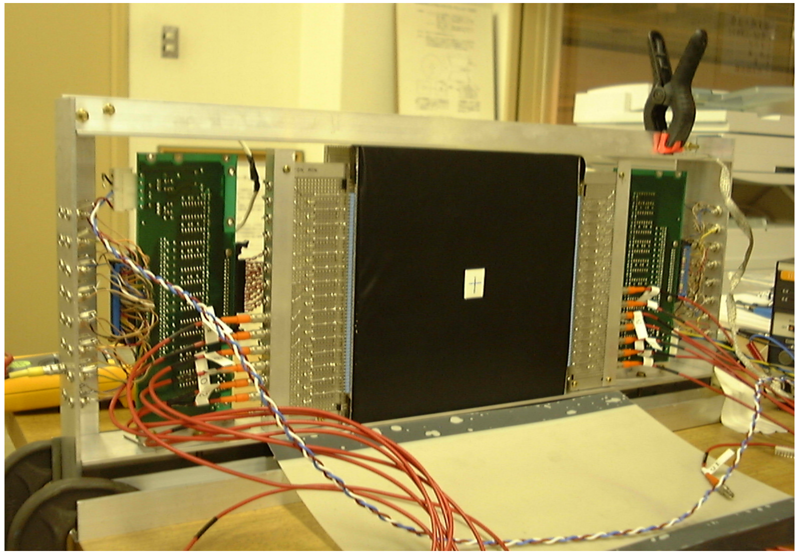


Photo of new SHmax (fully equipped) to be tested at DESY.

Position resolution ~ 4.4 mm (lateral distribution)

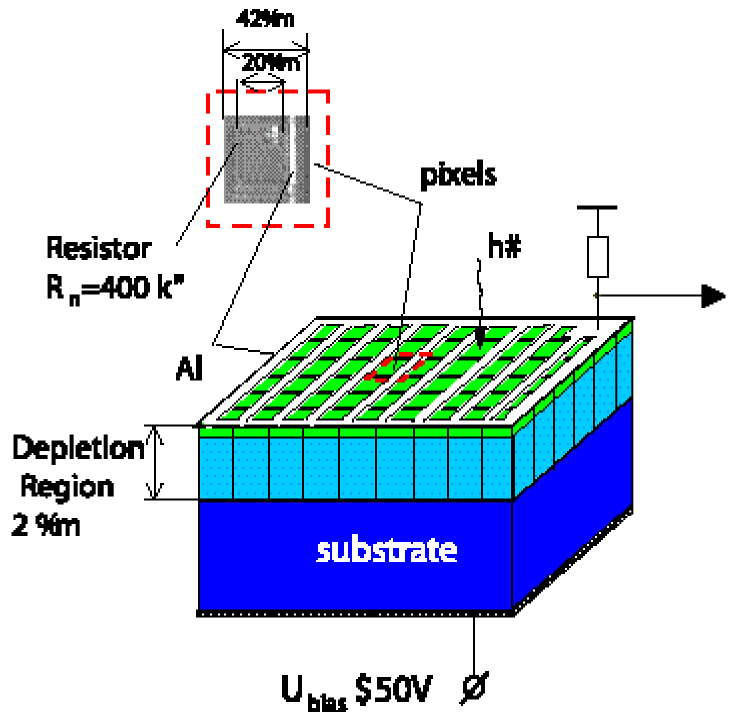
~ 2.8 cm ('charge' division)

High-gain APD will be tried in March 2004 at KEK.

2.Calorimeter - c) Shower-position Detectors - continued

iii) WLS-fiber + SiPM

- Simple in structure, easy assembling, especially when WLS-fiber is co-extruded or co-molded with mega-strips.
- only a few photo-electrons expected.
- Might be applicable to Strip-array EMC.



Stand-alone test of SiPM at bench is being done.

Both

more experience in SiPM operation and

quality-controlled SiPM

are needed.

3. Photon Detector R&Ds

Requirements on Photon Detectors

- Operational in 3 Tesla magnetic field
- High gain / high sensitivity (single-photon detection)
- Fast time reslution (to separate bunch crossing)
- Multi-channel readout
- Low cost/channel

Remember the challenge in finer granularity = explosion of readout channles

Possible Solutions

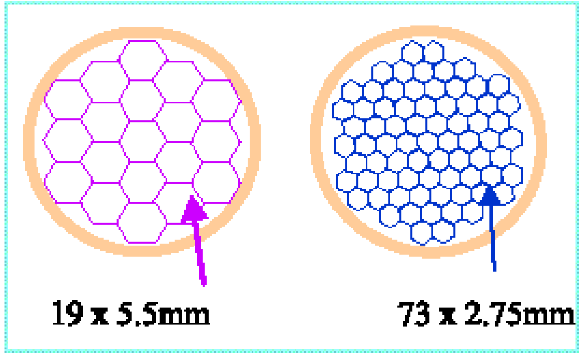
- multi-channel HPD ; Primary candidate
- EBCCD ; Excellent candidate for strip-array
- SiPM ; Excellent Possibility, but needs further studies.
- Multi-pixel APD ; Higher gain needed.

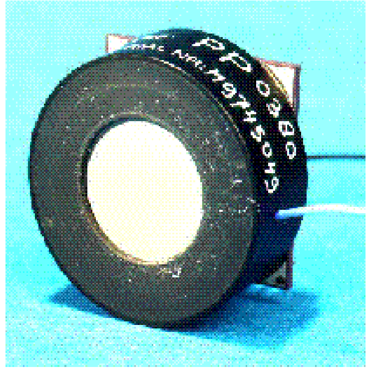
3. Photon Detector R&Ds - continued

a) Multi-channel HPD

DEP-HPD used for CMS-HCAL

- 19ch or 73ch/device
- $3000/device ; a bit expensive yet
- Gain=2500 @ 12kV ; a bit too low



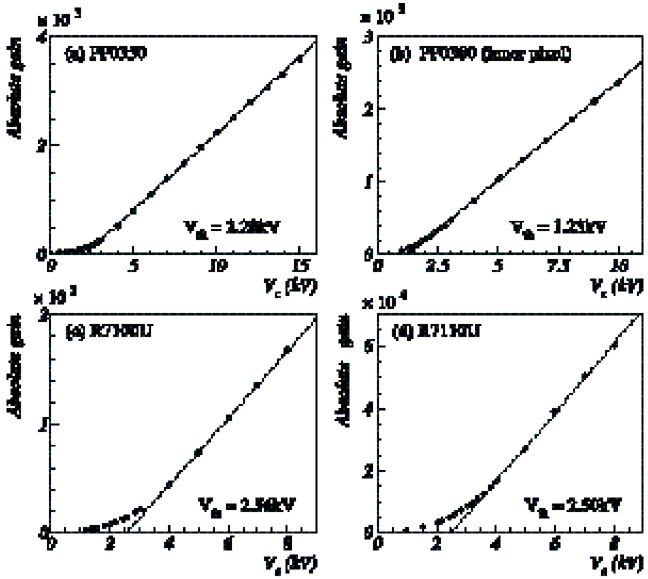


We have tested

- Advanced Photonix HAPD ; Gain=1.5×10^5 @13kV/bias=2.25kV. Production stopped.
- Hamamatsu HAPD ; Gain=6×10^4 @8kV/bias=2.5kV
- DEP 1, 7, and 61ch HPDs ; Gain=4000 @15kV in B.

  61ch-HPD will be integrated with SHmax and

  will be tested with beam in March 2004.



Almost established device, but

Needs WLS and clear fibers, therefore

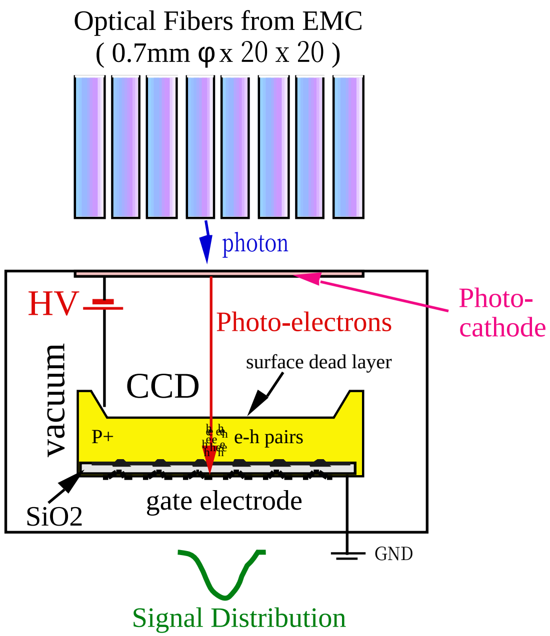
complex design and elaborative assembling, and thus costy.

3. Photon Detector R&Ds - continued

b) EBCCD

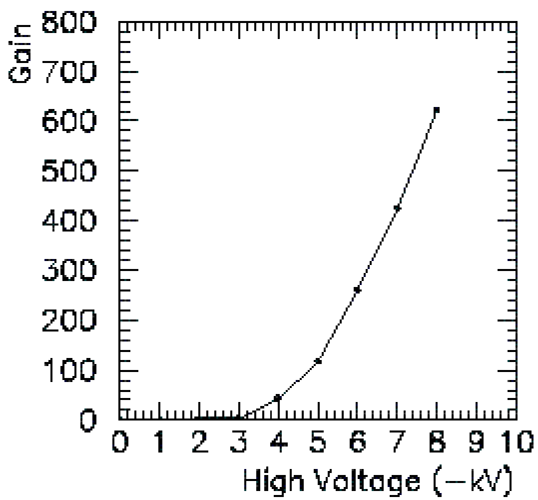
- Suitable for fiber readout ; ~400 fibers/device possible.
- $10/channel would be possible (reasonable guess)
- High sensitivity (single-photon demonstrated)
- No timing information available.

  Needs additional sub-detector for timing measurement.



Tests at bench in progress,

- Aiming at integration with SHmax for beam test in 2004.
- Gain yet too low.



Good price, but still need WLS and clear fibers.

Therefore complex design and elaborative assembling.

3. Photon Detector R&Ds - continued

c) SiPM

Micro-APD cell operated in Gaiger mode.

- 1ch/device, but cheap ; ~ a few $/channel (ambicious guess. ~ 10$/piece now?)
- very compact and very small sensitive area (~1mm sq.) ; optimum for fiber readout.
- very high gain (no need for amp.) but significant noise rate
- Can be directly attached to WLS-fiber end at tiles;

  Optimum for co-molded Mega-Tiles or co-extruded Mega-Strips.

- Cheap.
- No need for clear fibers, therefore enables neat design.
- Still need WLS fibers, but co-extrusion/co-molding eliminates effort of WLS assembling.

Very attractive option. Extensive studies be initiated.

4. Simulation

GEANT3-based full simulator has been used for studies.

- Tile/Fiber geometry in use.
- Strip Array geometry under coding.

Implementation of calorimter geometry into GEANT4-based full simulator is basically done, and will be refined soon.

Key issues to be studied

- hadron shower clustering.
- **track-cluster association, and eliminating charged clusters.**
- identification and elimination of low-energy background (albedo) photons.

5. Plan and Schedule

To Do Lists for 'beyond required' Studies:

Works to be completed before Engineering Study

- Granularity optimization with full-simulation studeis
- Establish feasibility of small tiles (4 challenges)
- Establish operation of photon detectors.

After solving above issues, following decision must be done.

- EMC type ; Tile/Fiber or Strip Array
- Photon Detectors ; HPD or EBCCD or SiPM or APD or ...
- Fiber design ; use clear fiber or
  attach photon detectors directly on WLS-fiber or Strip

At the Engineering Study stage, following should be established;

- Mass production of Mega-Tile (Mega-Strip)
- Absorber heavy metal (lead arroy: or could be tungsten?)
- Electronics/DAQ

A Possible Work Schedule and Japanese/Asian/World-wide Milestones

2003 - 2004	Finish granurality optimization		
	Establish technical feasibility for the concluded granularity		
		Technical Recommendation on Acc.Tech. by WPC	2004
2005	Serious Review and Decision on design options.		
		Decision expected on the host country	2005
2006 - 2007	Engineering studies		
	Enginnering proto-type construction and beam tests		
		Project is hoped to be approved by JPN government	2007
2008	Serious Review-2		
	Write a technical proposal for LC detector.		
		Project is hoped to be approved by US government	2009