JLC Calorimeter

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For the JLC-CAL Group

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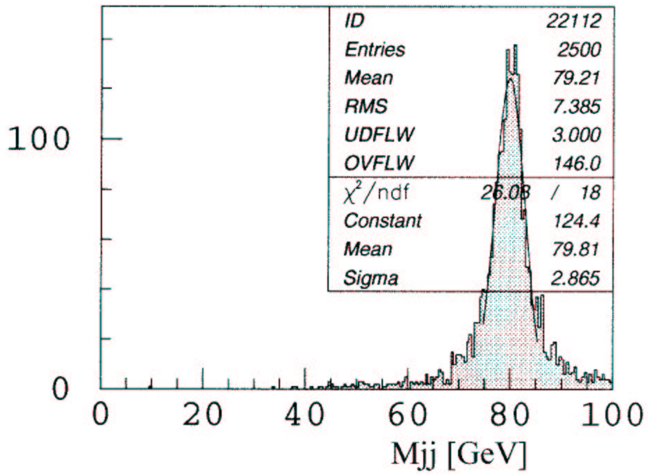
Outline

Required Performance

- **At LC energies, high mass particles (W, Z, t, H?...) are produced in most events**
- **Most likely they decay into hadronic jets**
- **Accurate jets energy measurement is needed to reconstruct the high mass particles**
- **Excellent Jet-mass resolution is required**
  → Di-jet mass resolution better than Γ_Z, Γ_W (JLC)



$\sigma_{M_{jj}}$ = 2.9 GeV including natural width of W

Reconstructed W mass for $e^+e^- \to W^+W^-$ at $\sqrt{s}$ = 400 GeV

(Result of quick simulation)

Required Performance

There are many design parameters to be optimized

2 basic parameters for calorimeter design:

- **Energy Resolution and Linearity**
  - Compensation (e/h = 1) with hardware or software
- **Granularity (Segmentation)**
  - Clustering Algorithm
  - Track-Cluster Association Algorithm
  - Energy Flow Analysis

Both hardware and simulation studies are needed.

Energy Flow Concept

Energy Flow Technique :

- Charged particles in jets more precisely measured in tracker
- Typical multi-jet events:
  $\sim$ 60 %: charged particles
  $\sim$ 30 %: photons
  $\sim$ 10 %: neutral hadrons
- Use tracker for charged particles
- EMCAL for Photon
- HCAL for neutral hadrons

Design optimization for energy flow :

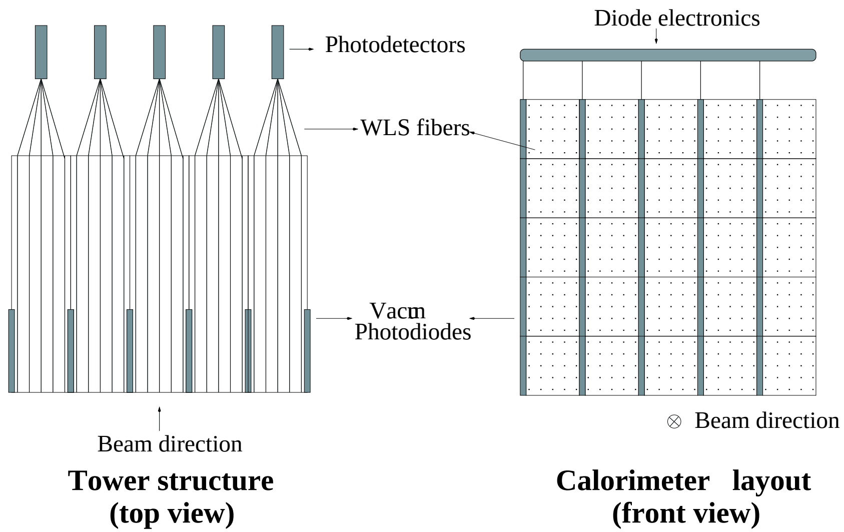
- Dense, highly granular EMCAL and HCAL
- High resolution and efficient tracker
- CAL inside coil

Design Ideas and Plans

Granularity	Very high	Reasonable
Experiment	TESLA, NLC(SD)	JLC, NLC (LD)
EMCAL	Si/W	Scint. Tiles/Fiber Scint. Strip Array
HCAL	“Digital” Calorimeter Scint. Tiles/Fiber	Scint. Tiles/Fiber

Other options:

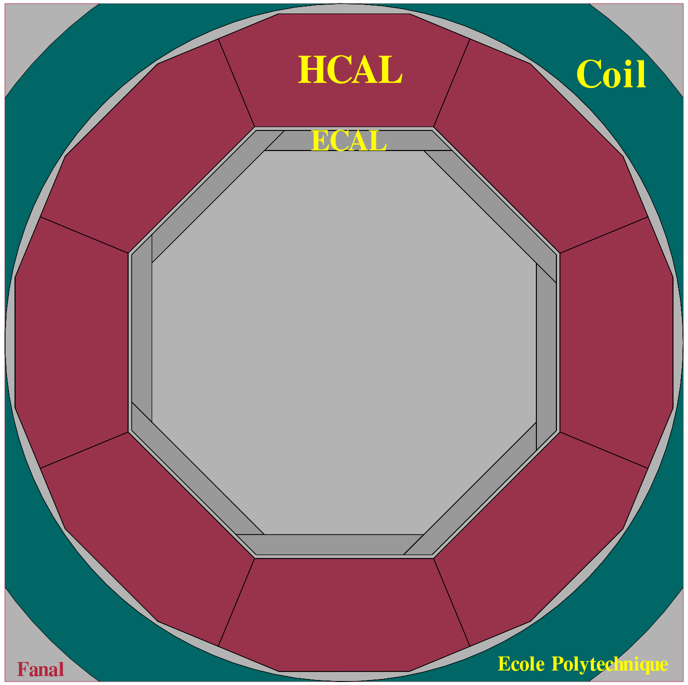
EMCAL : Crystal, Shashlik

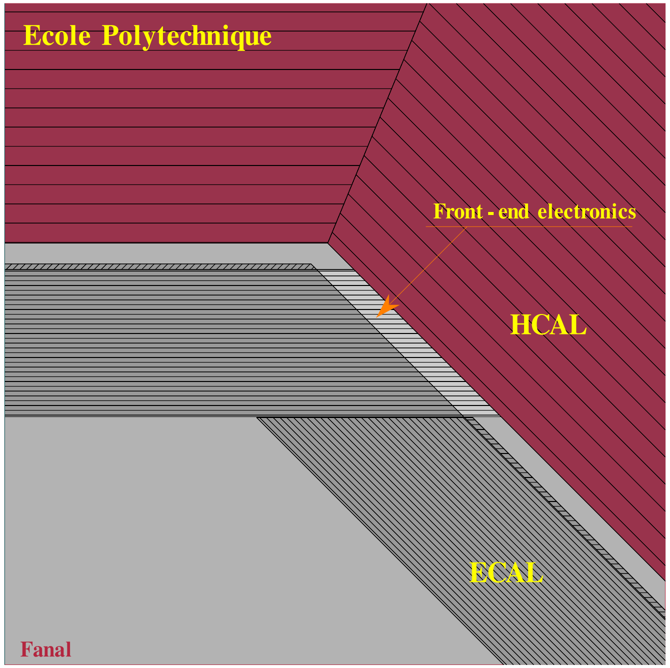


Shashlik Calorimeter

Si/W Calorimeter

- Original idea from SDC
- Used successfully for Lum. monitors at SLD/LEP
- Suited for Energy Flow
- Easily Segmented (5mm – 15mm), $\sim$ 50M pixels
- Si cost is expensive

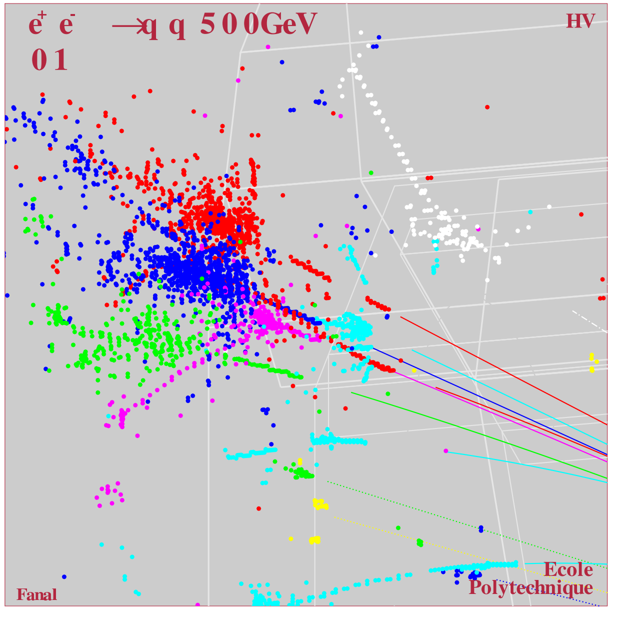


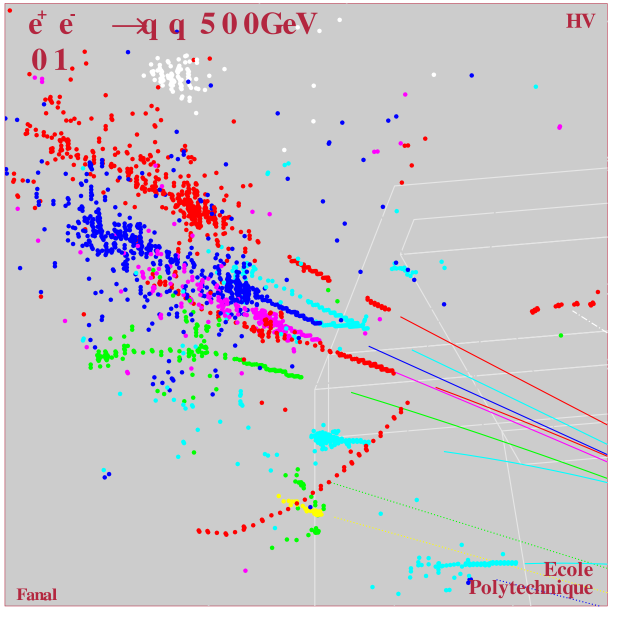


Barrel Calorimeter of TESLA

"Digital" Calorimeter

- "Imaging/Tracking Calorimeter" for Energy Flow measurement
- Cheap, highly-segmented detectors (1cm$\times$1cm)
- 1 (2?) bit readout
- Number of hit cells $\longrightarrow$ Energy





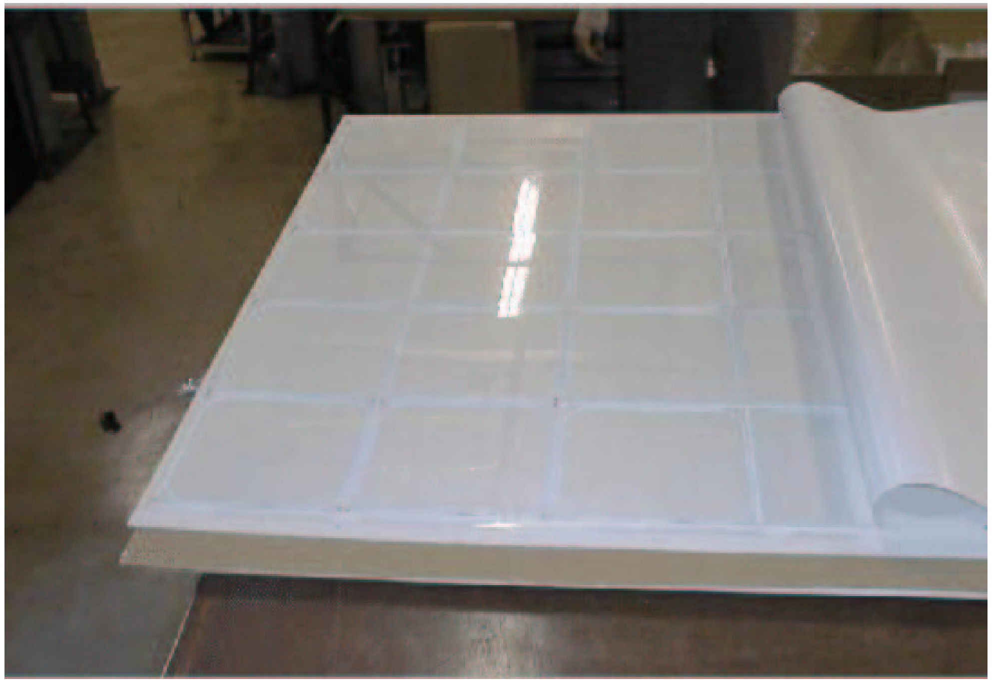
Same Di-jet for digital-steel(left) and for digital-tungsten(right) HCAL
hep-ex/0202004 (TESLA)

“Digital” Calorimeter (cont.)

- Energy resolution: similar to analog readout
- Active medium candidates
  RPCs (Resistive Plate Chambers)
  GEMs (Gas Electron Multipliers)
- under study
  - depth
  - MIP recognition
  - Algorithm : Software compensation (π^0 recognition)
- No experience. Need verification

Tile/Fiber Sampling Calorimeter

- Hardware Compensation Possible
- Design Flexibility
- Reasonable cost
- Well-established technology
- Sufficient granularity for EMCAL ?



Scintillator tiles arranged as 5 $\times$ 5 segmentation

JLC Calorimeter: Design Concept

- **Hardware Compensation for excellent hadron energy resolution and linearity**

$$\frac{\sigma_E}{E} = \frac{15\%}{\sqrt{E}} + 1\% \qquad (e/\gamma)$$

$$\frac{\sigma_E}{E} = \frac{40\%}{\sqrt{E}} + 2\% \qquad \text{(hadron)}$$

- **Fine Granularity for precise topological reconstruction**
- **Whole Calorimeter system inside the solenoid**

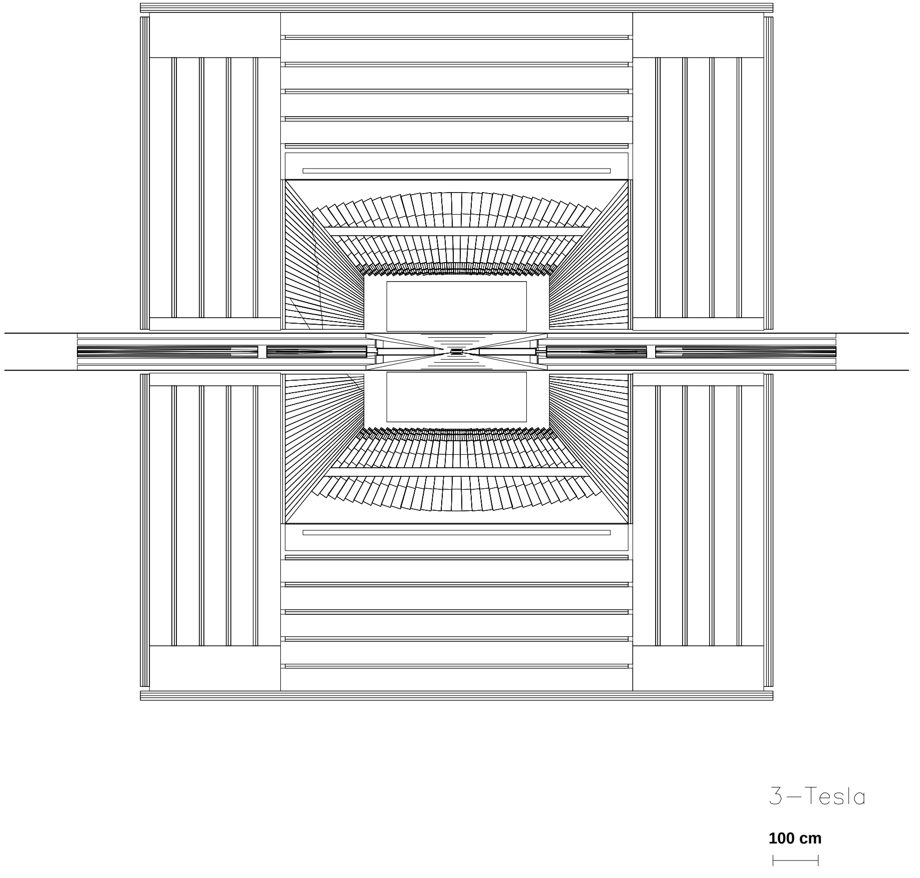
No software compensation
No extremely-fine granularity

Technology Choice

$\Longrightarrow$ **Tile/Fiber Sampling Calorimeter**

Calorimeter Configuration

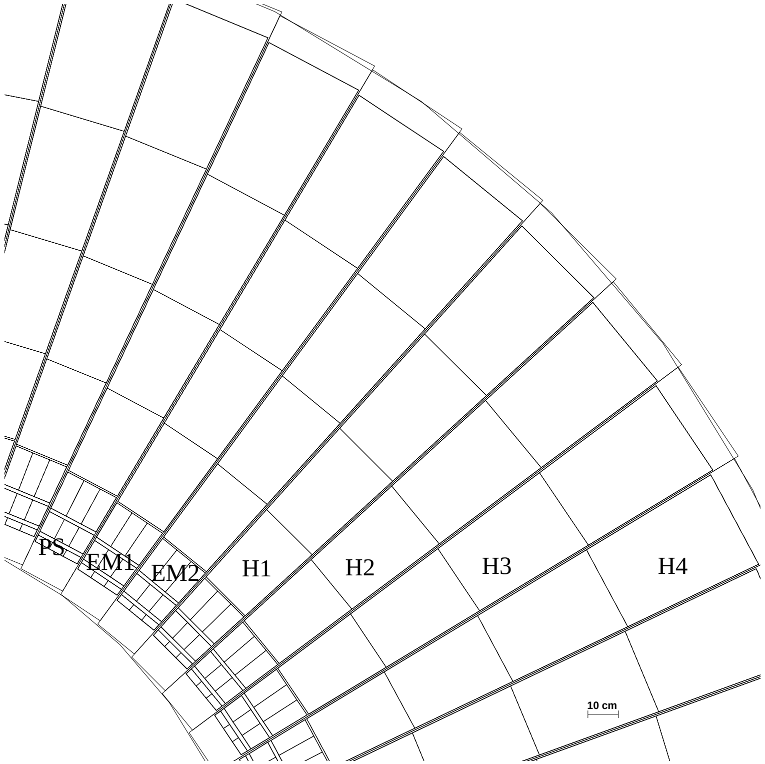
Calorimeter is in the 3 Tesla B-Field
Tower Structure
Crackless Hermeticity



JLC Detector

Basic Parameters

Barrel Inner Radius	160 cm
Barrel Outer Radius	340 cm
Angular Coverage (full)	$\lvert\cos\theta\rvert < 0.966$
(partial)	$\lvert\cos\theta\rvert < 0.991$
SHmax scheme	scintillator strip (1 cm-wide) Option = Si-pad (1cm $\times$ 1cm)
Granularity	
PreSH/EMCAL transverse	4 cm $\times$ 4 cm (24 mrad)
longitudinal	3 sections (6+12+20 layers)
HCAL transverse	12 cm $\times$ 12 cm (72 mrad)
longitudinal	4 sections (25+30+35+40 layers)
Thickness	
PreSH	$4X_0$
EMCAL	$23X_0$
HCAL	$6.5\lambda_0$

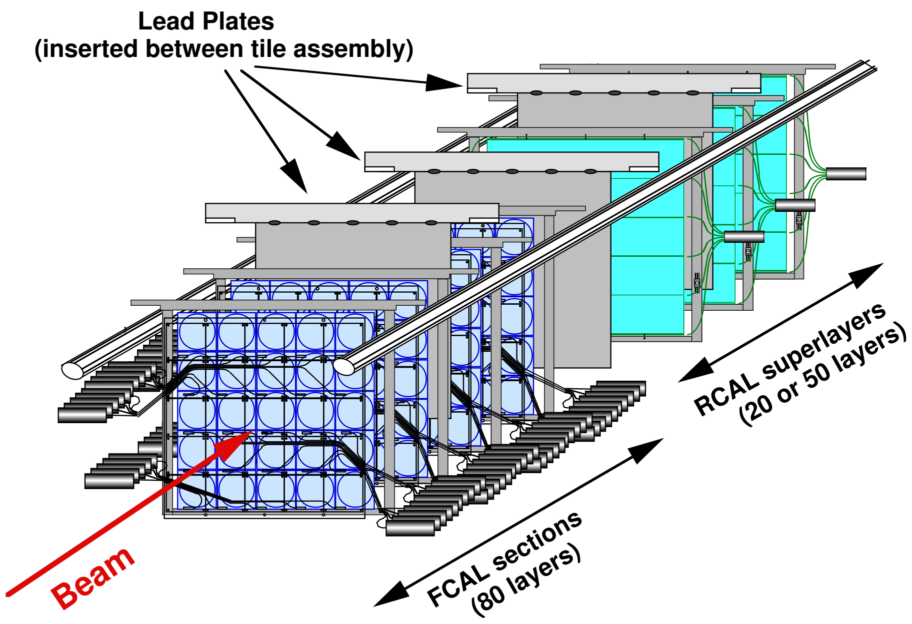


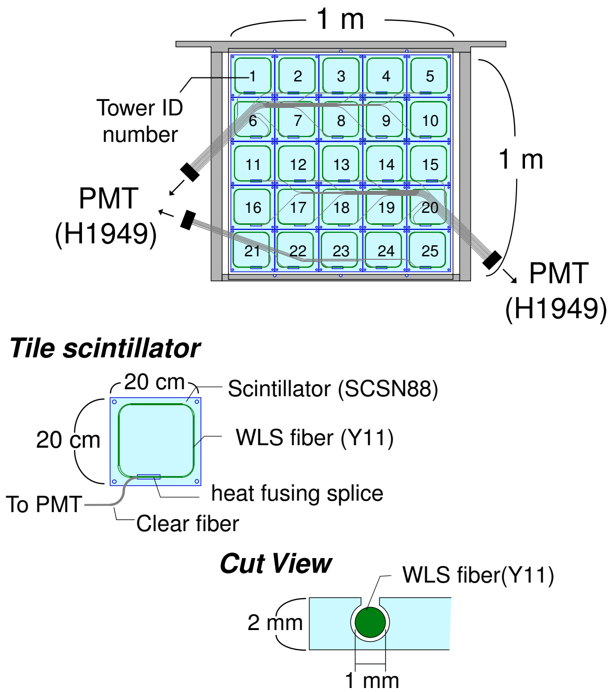
Configuration of Baseline Barrel Calorimeter

HCAL beam tests

Beam tests done at KEK (1–4 GeV) and at FNAL (10-200 GeV) to prove

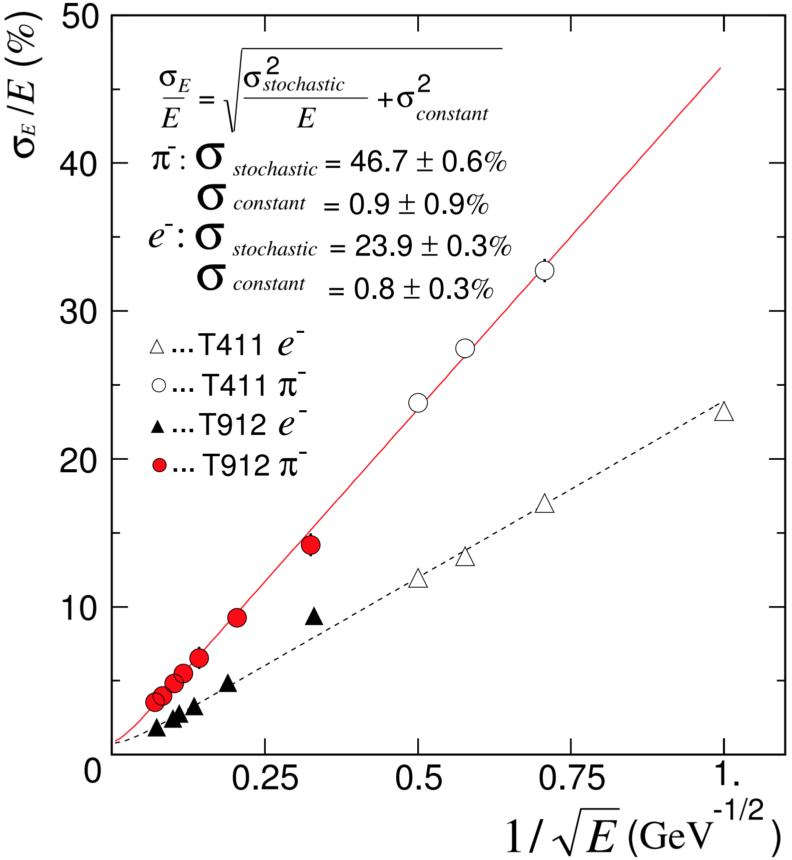
- Energy Resolution / Hardware compensation
- Linearity / Dynamic Range
- Tower Boundary Uniformity
- e/π Separation Capability

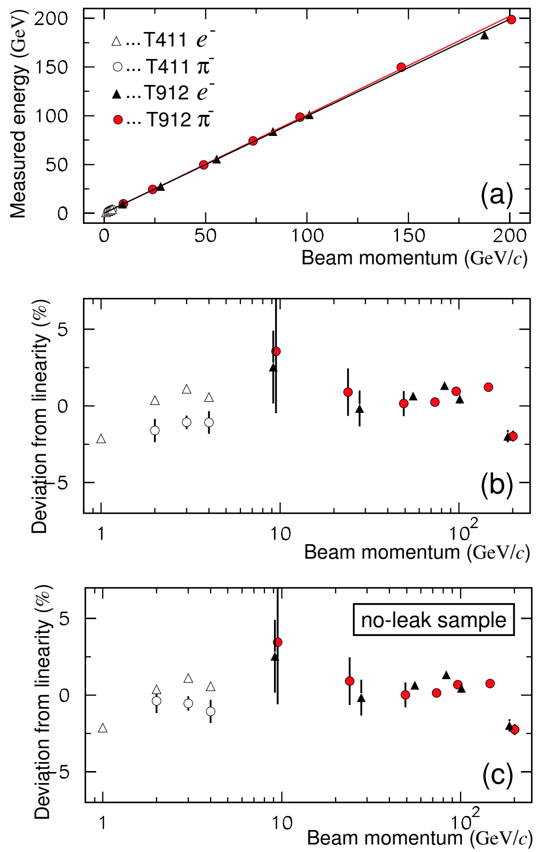




Schematic view of HCAL test module with Tile/Fiber configuration

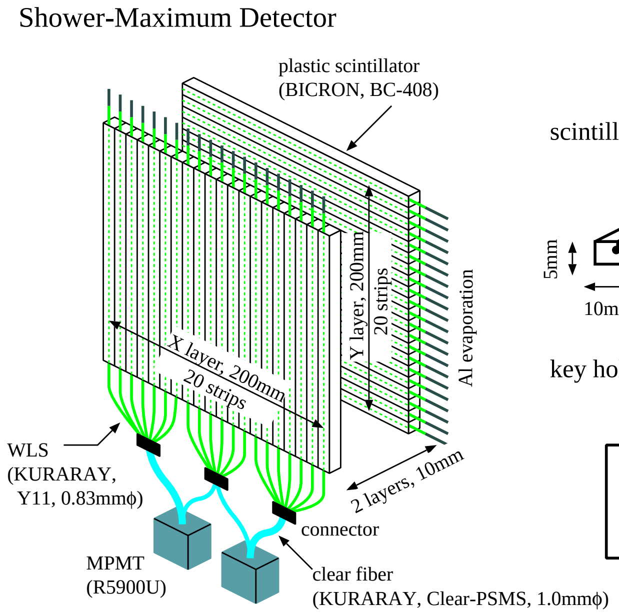
Energy Resolution & Linearity



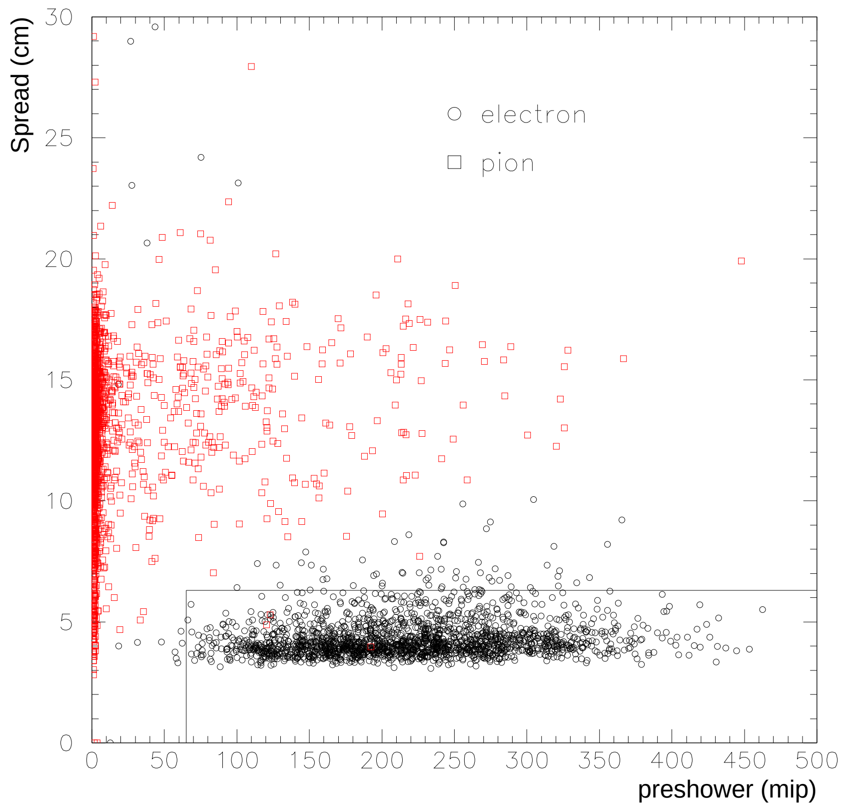


- π energy resolution is worse than design due to "fiber-routing" acryl plate
  $\longrightarrow$ should be OK but needs verification
- Linearity is good thanks to hardware compensation

e/π Separation with PreSH/SHmax



Shower MAX detector



- **pion rejection $\sim$ 1/1400**
- **efficiency for electron $\sim$ 98 %**
- **position resolution 2$\sim$3 mm**
  due to noise/cross-talk
  needs improvements

Granularity Optimization

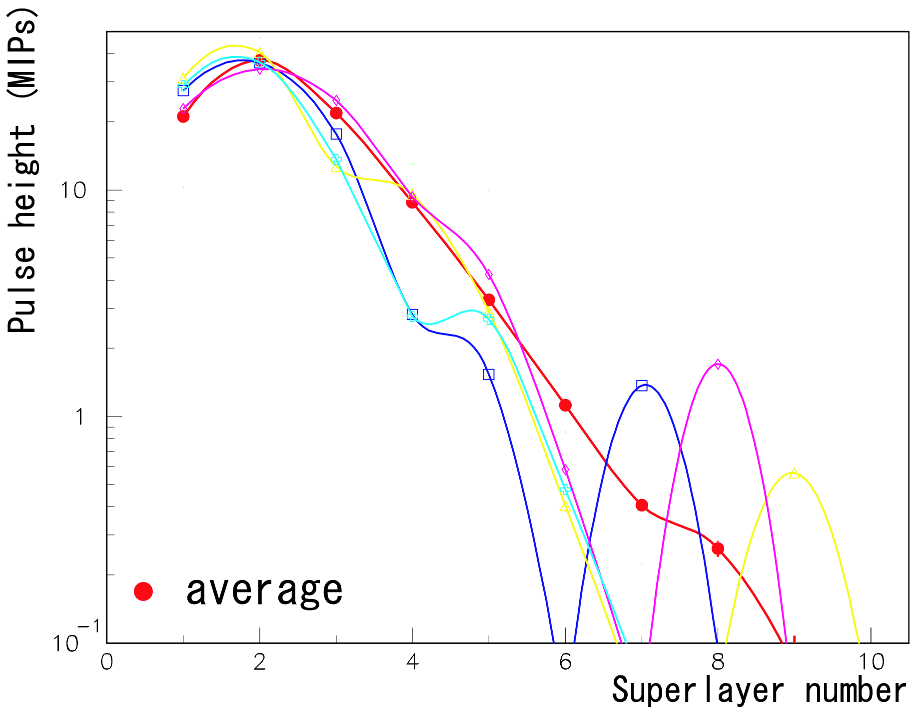
Optimization with full simulator based on GEANT3

- **Hadron shower clustering algorithm under study**
  2D-JADE, 2/3D-contiguous : not working well
  Larger spatial fluctuation in hadron shower development
  → Split a cluster in two (or more)
- **Cluster-track association algorithm under study**

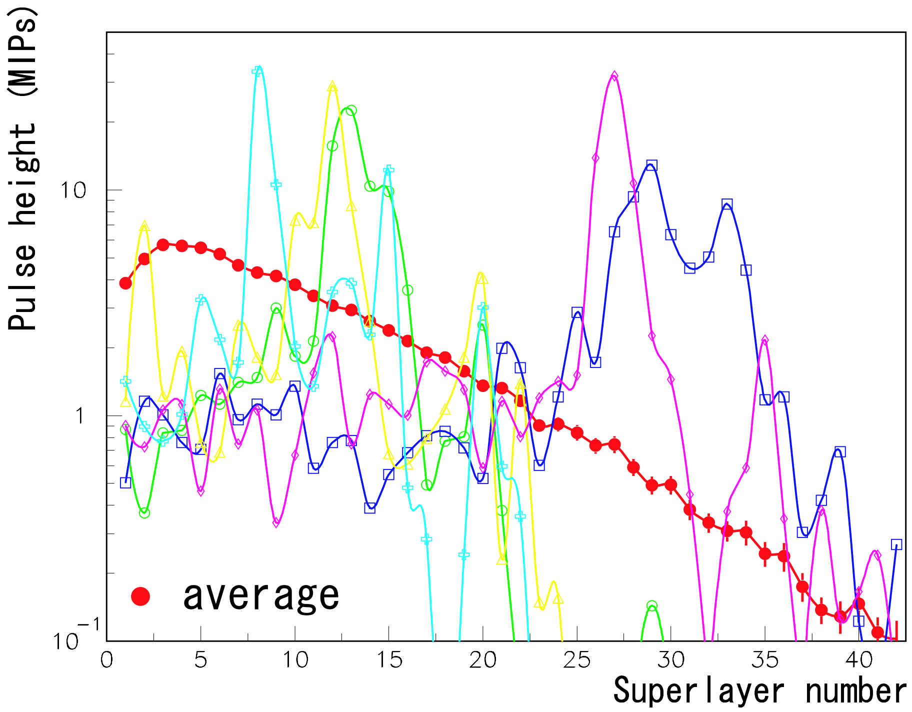
Simulation study is severely behind schedule

Longitudinal Shower profile

- Longitudinal shower profile and event-by-event fluctuation for hadron shower
  - Improve hadron energy resolution
  - Implementation of hadron shower generator
  - e/π separation capability



4 GeV e^- (beam test)

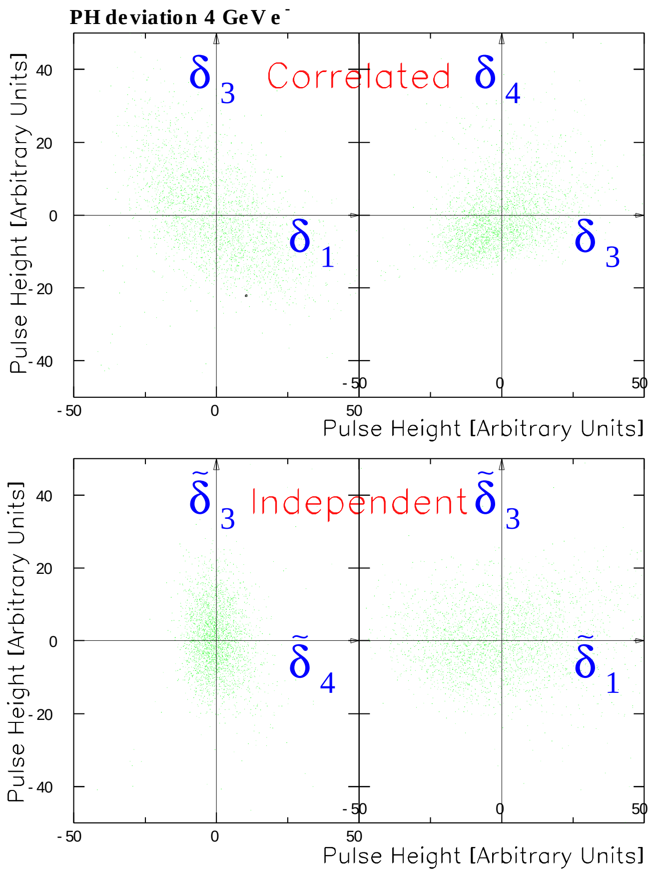


4 GeV π^- (beam test)

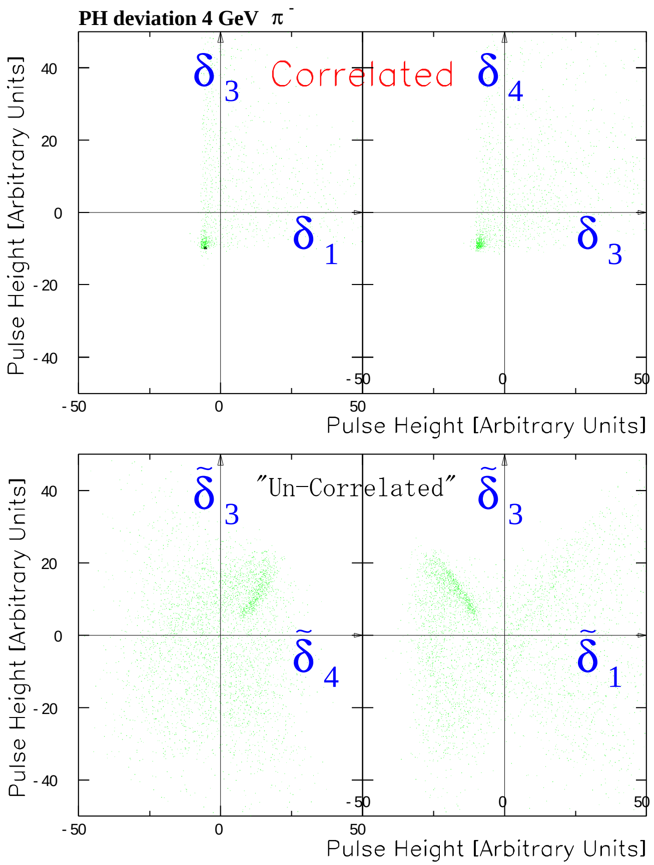
Longitudinal Shower profile (cont.)

$\delta_i^{(k)} = ph_i^{(k)} - \overline{ph_i}$ at i-th super-layer of k-th event

$\tilde{\delta}_i^{(k)}$: Orthogonalized $\delta_i^{(k)}$



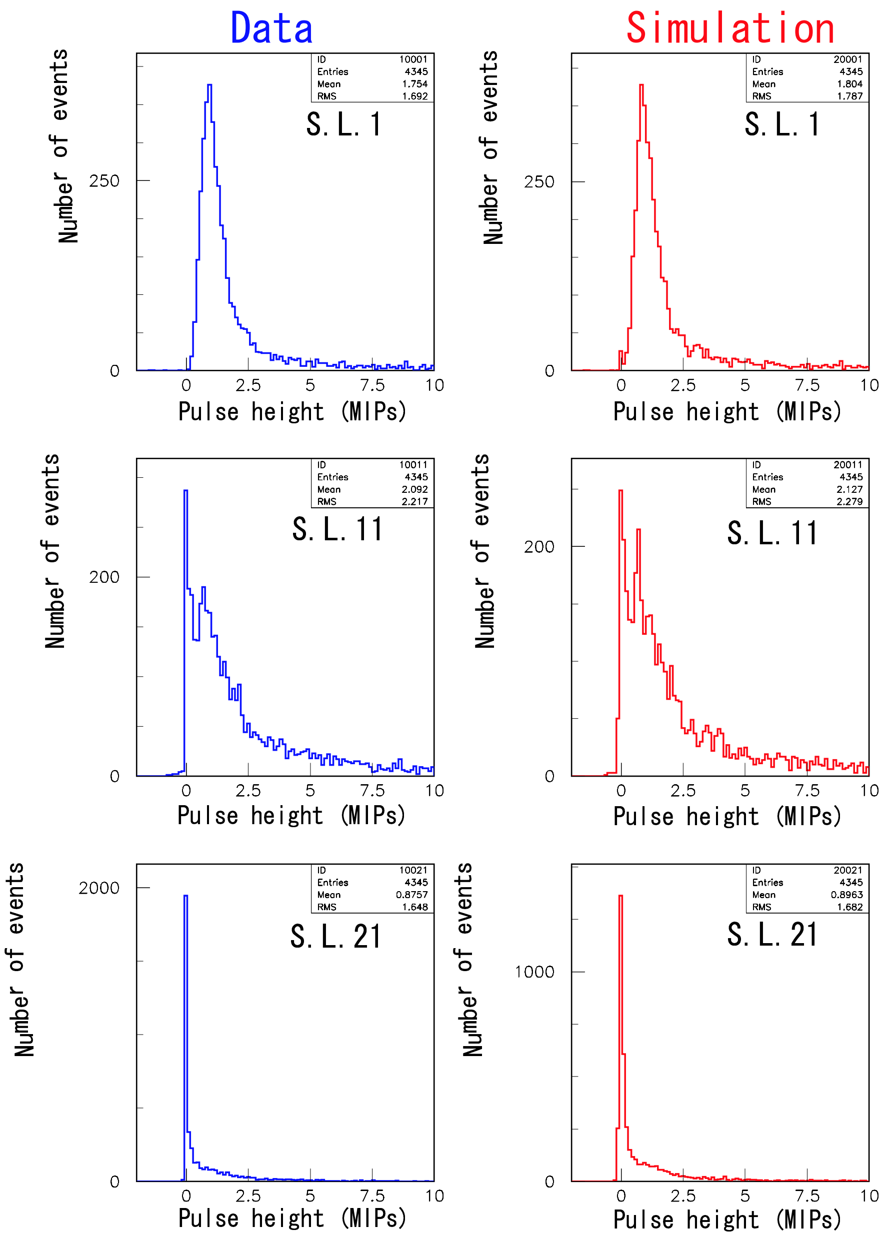
Correlated fluctuation for EM

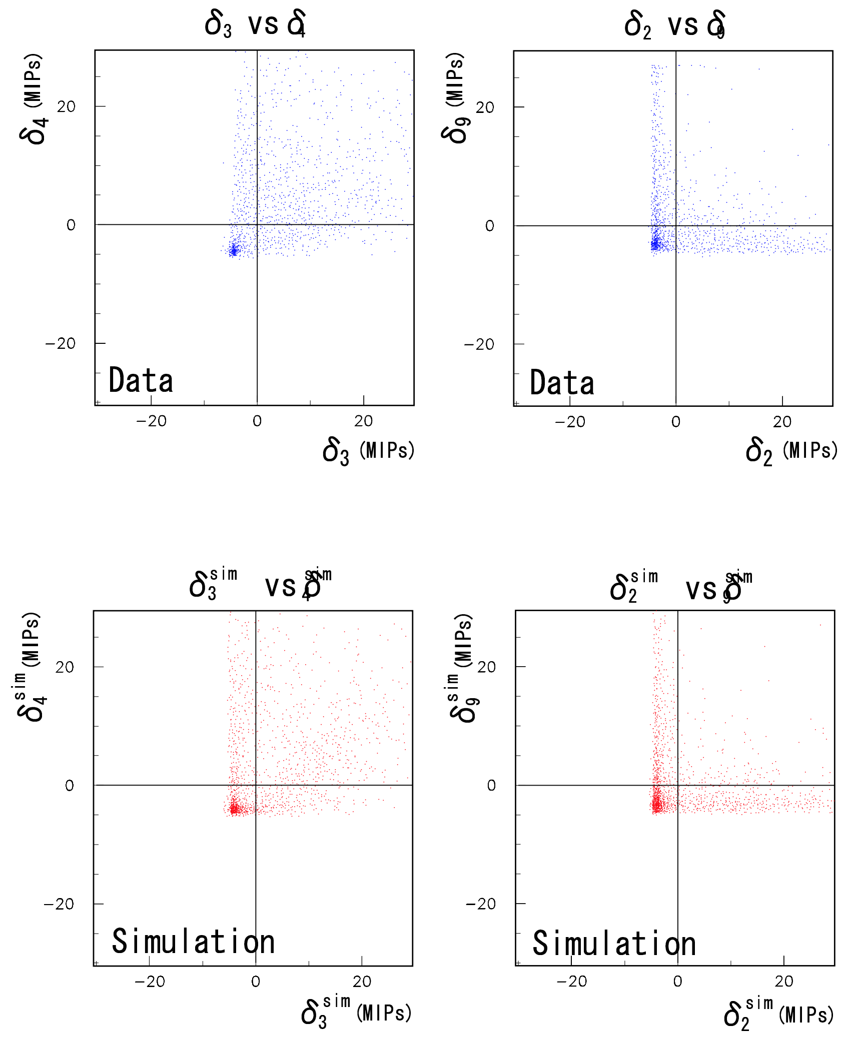


Un-correlated fluctuation for hadrons

Orthogogonalization unsuccessful for hadrons

Longitudinal Shower profile (cont.)





Simulation successfully reproduces same distribution as real data

R & D on EMCAL and SHmax

EMCAL :

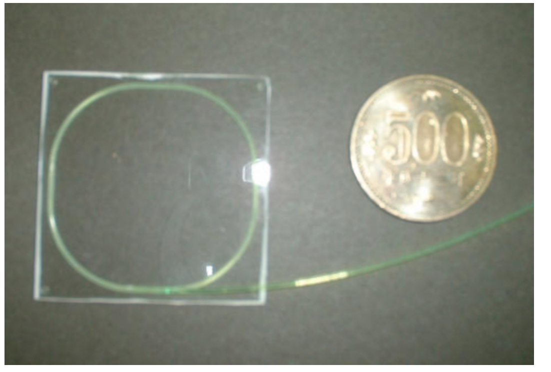
- **Scint. Tile of 4cm $\times$ 4cm $\times$ 1mm**
  - 4cm is limited by fiber curvature in the tile
- **Scint. Strip of 1cm $\times$ 20cm $\times$ 2mm**
  - finer granularity
  - crossed-strip layout like SHmax
  - needs super multi-channel photo detectors
  - ghost-rejection capability by full simulation

Staggered fiber layout on every other layer
$\longrightarrow$ Reduce non-uniformity

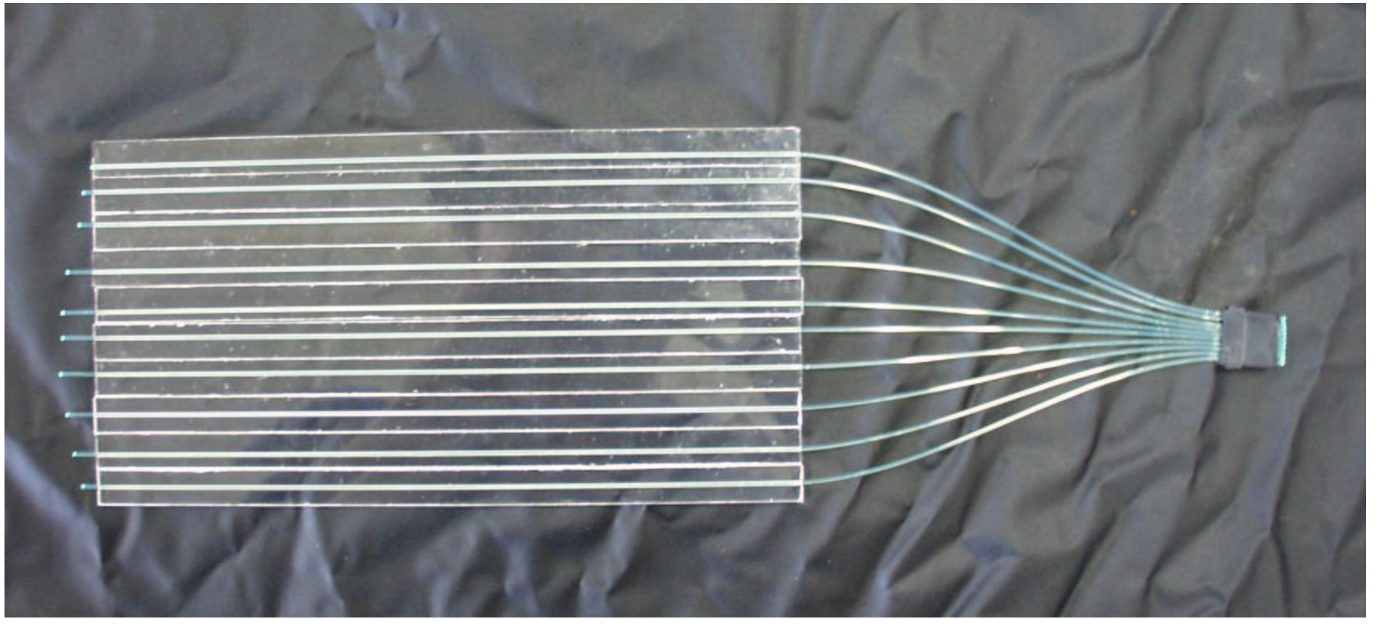
SHmax :

- **Scint. Strip of 1cm $\times$ 20cm $\times$ 1cm**
  - WLS fiber + multi-channel Photon detector
  - high-gain APD attached directly at the end of Scint. strip

Scint. Tile & Strip

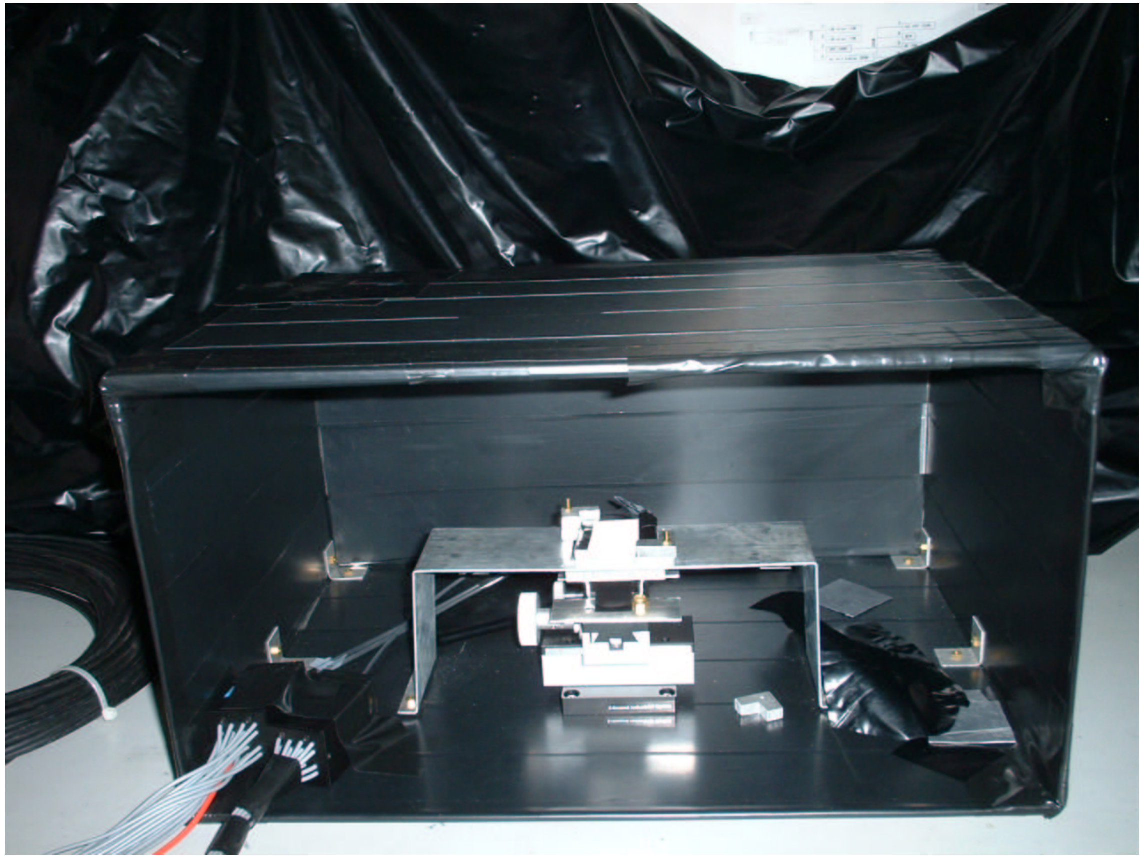


Scint. Tile with WLS fiber



Scint. Strips with WLS fibers

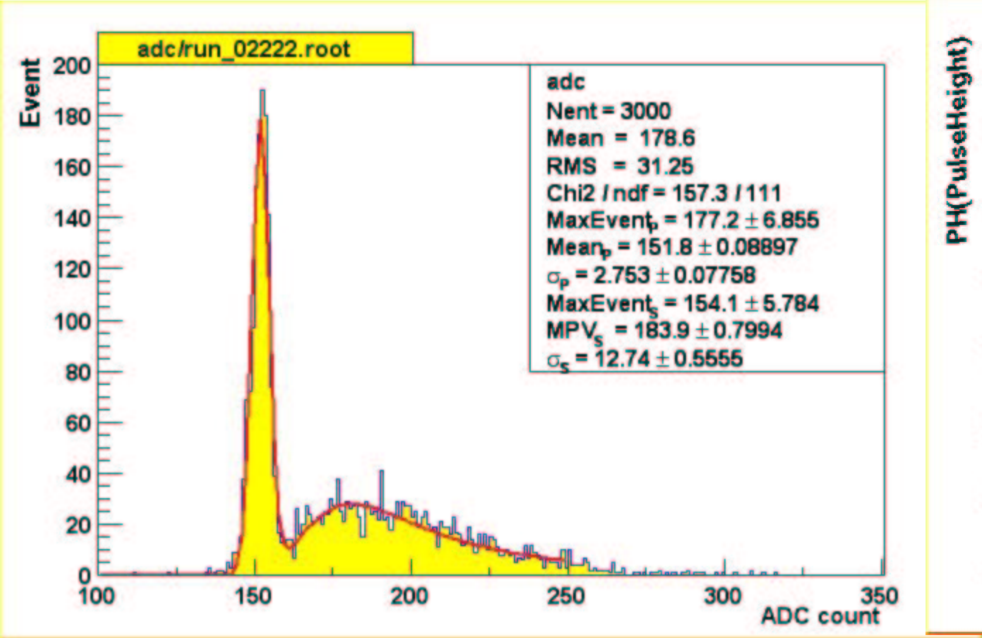
Bench Test: Tile/Fiber module



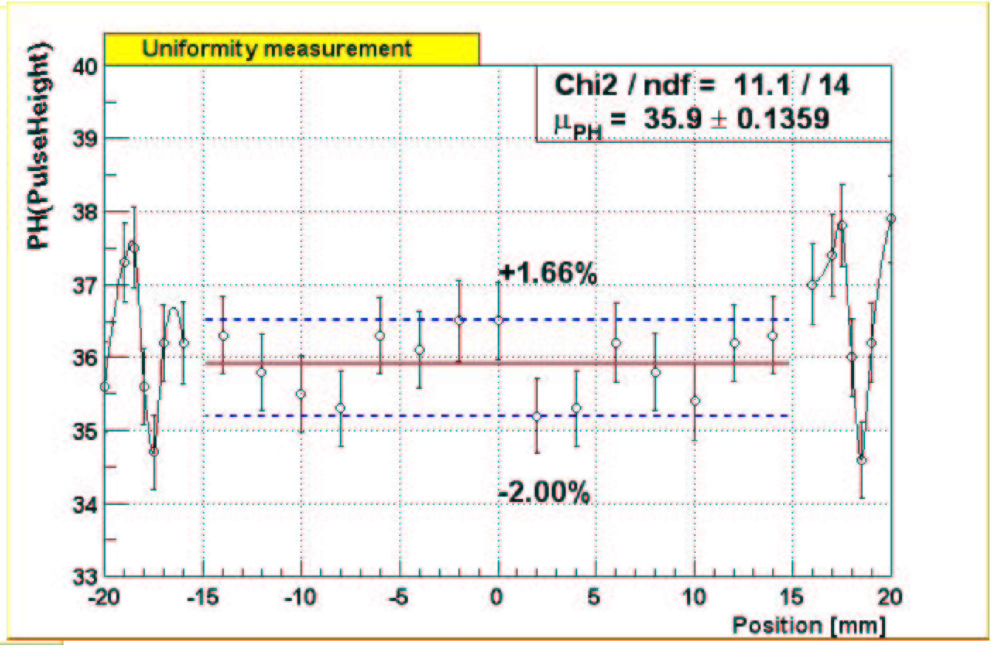
Bench Test:

- β rays from RI source
- Multi-Anode PMT

Bench Test: Tile/Fiber module (cont.)



ADC distribution



Uniformity check (1-dim.)

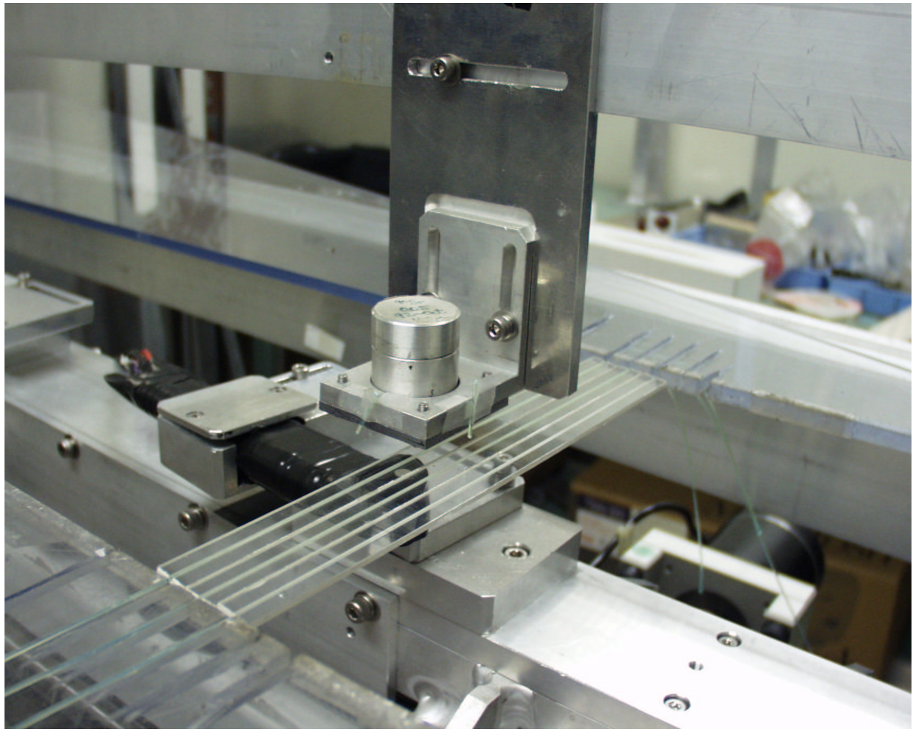
N_{pe} = 2.2

- Expect a factor of $\sim$ 1.6 improvement by polishing the fiber end and sputtering Al to it

Uniformity : $<$ 5%

$<$ 2% (inside fiber groove)

Bench Test: Scint. Strip module



Setup of bench test

β rays from ^{90}Sr, mapping by X-Y stage

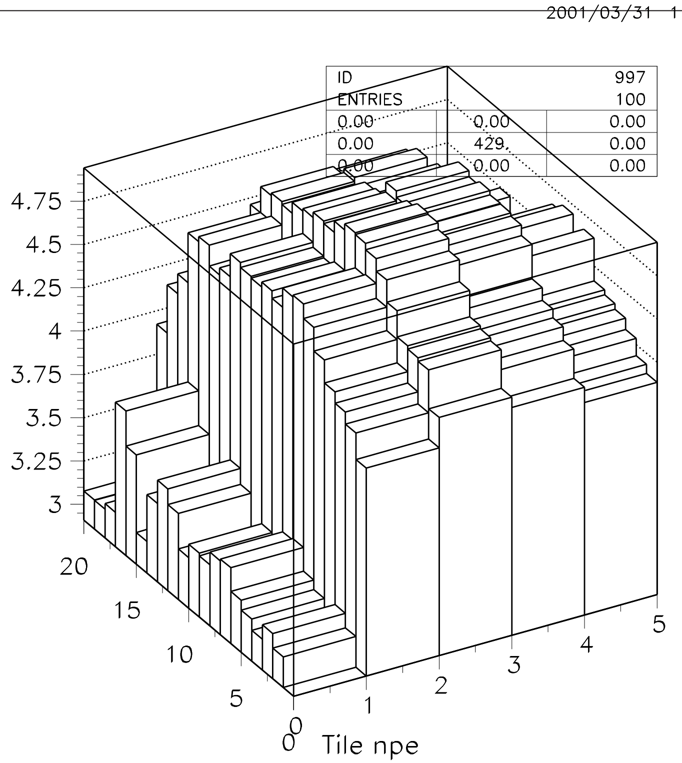


Photo-electron yield over a strip

Non-uniformity $\sim$ 4.8 %

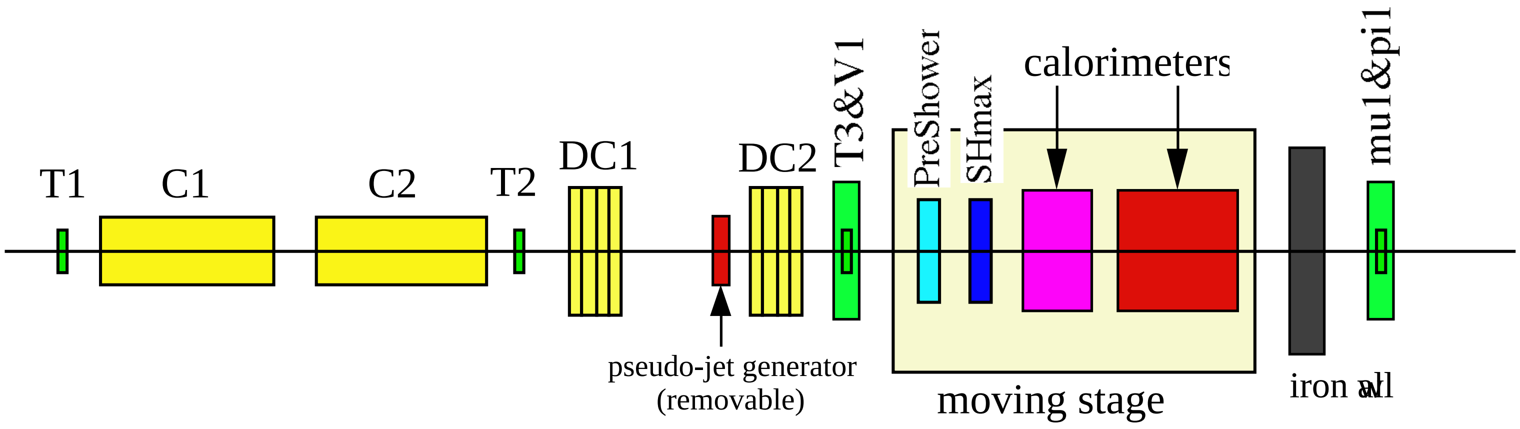
Similar to square tiles

Plan for Beam Tests: EMCAL

Aims of the beam test:

- **Uniformity**
- **Ghost rejection capability**
- **Energy Resolution for electron**
- **Input for simulation study**
- **New SHmax scheme**

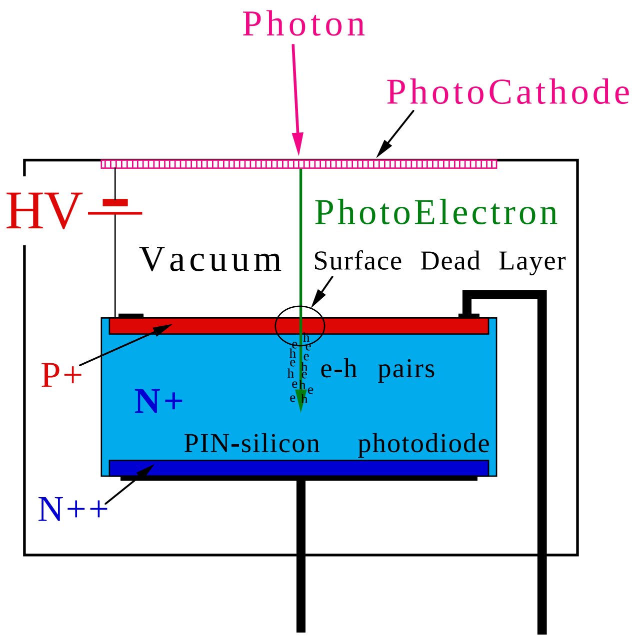
November 2002: π2 beam line at KEK



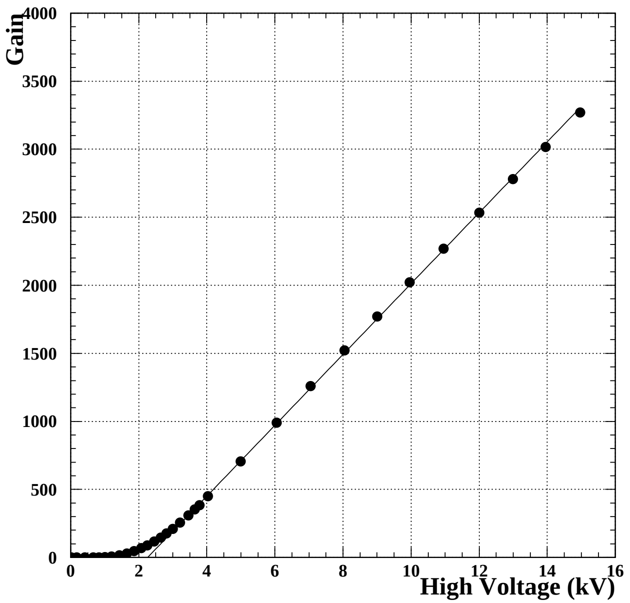
Photon Detectors

Photon detectors used in 3 Tesla Magnetic Field

- **Multi-channel(61ch) Hybrid Photo Diodes (HPDs) :**
  - promising (cost-down needed)
- **Hybrid Avalanche Photo Diodes (HAPDs) :**
  - difficult to make multi-pixel HAPDs



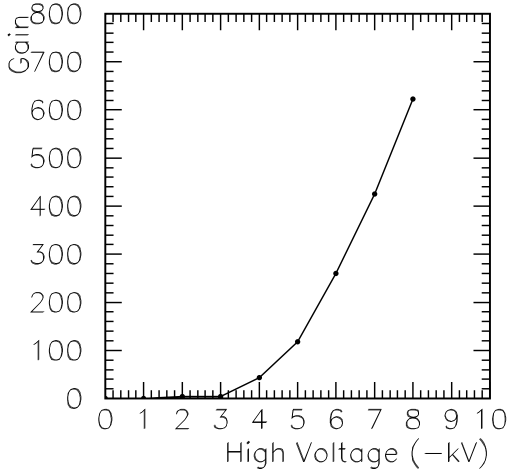
Schematic view of the HPD structure



HPD gain as a function of HV
$\sim$ 3000 at 14 kV

Photon Detectors (cont.)

- **For Scintillator-strip EMCAL/SHmax :**
  - **Electron-Bombarded CCD (EBCCD)**
    Ultra-multi-pixel devices, single-photon sensitivity
    Higher gain is needed.



Gain vs. Photo-cathode voltage for proximity-focused EBCCD

- **Si-Photomultipliers (Si-PM's) : study at Moscow**
  - output signal is proportional to # of pixels fired
  - sensitive to single photon

Summary

JLC Calorimeter :

- **Well-established technology: Tile/Fiber scheme**
- **High Performance: Hermeticity, Resolution, Linearity**
- **Reasonable Cost: Casting enables further cost reduction**

Verification in progress :

- **EMCAL/SHmax**
  Beam tests in 2002,2003
- **Granularity optimization, Clustering Algorithm**
  needs Full Simulation
- **Photon Devices**