The Performance of Strip-Fiber EM Calorimeter
- Linearity, Energy Resolution –

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Introduction
Calorimeter
Test beam
Gain calibration
Linearity
Energy resolution
Summary
Introduction

- Requirements for LC EMCAL
  - Energy resolution
    \[ \frac{\sigma_E}{E} = \frac{15\%}{\sqrt{E}} \oplus 1\% \]
  - Linearity
    - 1%
  - Fine granularity
    - particle flow analysis
- Scintillator strip array EMCAL
  - Fine granularity
Calorimeter

Module design for test beam
- $1 \times 20\text{cm} \times 2\text{mm}$-thick Sci. strip
  - effective cell size: $1\text{cm}^2$
- WLS fiber + clear fiber
- 1 layer
  - Lead (4mm-thick)
  - X-strips $\times 20$
  - Y-strips $\times 20$
- Total 24 layers
  - 17 $X_0$
  - 6 super layers
    - 1 SL = 4 layers
Test beam

- KEK PS Mar 2004
  - Unseparated beams (e, pi, mu)
  - 1 - 4 GeV
- EMCAL on movable stage
- Scintillation counters
- Electron-ID with Cherenkov counters
- Tracking with drift chambers

**T545 beamline**
Gain Calibration
Cuts for MIP events

- Inclusive trigger (T1&T2)
- All upstream and downstream superlayers of the target should have signals above the pedestals.
  - \( \text{ped} + 3 \sigma_{\text{ped}} < \text{p.h.} \)
- Signals of all other strips in the same superlayer as the target should be consistent with pedestal.
  - \( \text{ped} + 5 \sigma_{\text{ped}} > \text{p.h.} \)
MIP pulse height

- Fit function: asymmetric-gauss
  \[ f = \begin{cases} 
  p_0 \exp\left(-\frac{1}{2} \left( \frac{x-p_1}{p_2} \right)^2 \right) & (x < p_1) \\
  p_0 \exp\left(-\frac{1}{2} \left( \frac{x-p_1}{p_3} \right)^2 \right) & (x > p_1) 
  \end{cases} \]

- Fit range: \( \text{ped+3 } \sigma_{\text{ped}} < \text{p.h. } < \text{mean+3}p_3 \)
- Binning: 5 counts/bin
- Constant:
  \[ \mu = \frac{\int_{-\infty}^{+\infty} xf dx}{\int_{-\infty}^{+\infty} f dx} = p_1 + \sqrt{\frac{2}{\pi}} (p_3 - p_2) \]
- Error:
  \[ \sigma^2_{\mu} = \sum_{i=0}^{3} \sum_{j=0}^{3} \frac{\partial \mu}{\partial p_i} \frac{\partial \mu}{\partial p_j} \text{cov}(i, j) \]
  \[ = \sigma_1^2 + \frac{2}{\pi} \sigma_2^2 + \frac{2}{\pi} \sigma_3^2 - 2\sqrt{\frac{2}{\pi}} \sigma_{12} + 2\sqrt{\frac{2}{\pi}} \sigma_{13} - 2\frac{2}{\pi} \sigma_{23} \]

- Mean = 68.37 ± 0.50
Relative errors

- Less than 1% for most strips
- about 0.3% in the central region
Linearity
Energy Resolution
Cuts for electron events

- Electron trigger (T1&T2&C1&C2)
- T1, T2
  - Consistent with one MIP
- Cherenkov
  - High enough to separate from pions and muons
- MU
  - Consistent with pedestal
Energy distribution

- Fit function: gauss
- Fit range: mean ± 2σ
- Binning: 0.4MIPs/bin

![Graphs showing energy distribution for 1 GeV, 2 GeV, 3 GeV, and 4 GeV with fit functions and ranges.]
Systematic uncertainty

- Calibration uncertainty
- Pedestal uncertainty
- PMT gain drift
- Binning of energy distribution
- Beam momentum bite
  - 0.08%

Uncertainties at 4 GeV (all strips) [%]

<table>
<thead>
<tr>
<th></th>
<th>statistical</th>
<th>systematic</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>calibration</td>
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<tr>
<td>energy</td>
<td>0.09</td>
<td>0.04</td>
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<tr>
<td>resolution</td>
<td>1.5</td>
<td>0.5</td>
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</table>
Linearity

Energy Deposit [MIPs] vs Beam Momentum [GeV/c]

- **X strips**: 30.39 ± 0.03 MIPs/GeV
- **Y strips**: 30.23 ± 0.03 MIPs/GeV
- **All strips**: 60.68 ± 0.06 MIPs/GeV
- **Simulation (X strips)**: 32.78 ± 0.02 MIPs/GeV
- **Simulation (Y strips)**: 31.91 ± 0.02 MIPs/GeV
- **Simulation (all strips)**: 64.70 ± 0.03 MIPs/GeV

Deviation [%] vs Beam Momentum [GeV/c]

- **X strips**
- **Y strips**
- **All strips**
- **Simulation (X strips)**
- **Simulation (Y strips)**
- **Simulation (all strips)**
Energy resolution

- Resolution parameters
  \[ \frac{\sigma_E}{E} = \sigma_{\text{stochastic}} \sqrt{E} \oplus \sigma_{\text{constant}} \]

- All strips
  - Stochastic: 13.10 ± 0.12%
  - Constant: 0.00 ± 0.72%

- Simulation
  - + Photo statistics
  - + Noise effect

Simulation:
- \( X : \sigma_{\text{sto}} = 14.79 \pm 0.07 \)
- \( \sigma_{\text{const}} = 0.00 \pm 0.07 \)
- \( Y : \sigma_{\text{sto}} = 14.38 \pm 0.19 \)
- \( \sigma_{\text{const}} = 1.14 \pm 1.14 \)
- all : \( \sigma_{\text{sto}} = 12.63 \pm 0.10 \)
- \( \sigma_{\text{const}} = 0.00 \pm 1.08 \)
Parameter decomposition

- **Stochastic term**
  - sampling fluctuation
  - track length fluctuation
  - photo statistics

- **Constant term**
  - calibration uncertainty
  - non-uniformity

- **Noise effect**
  - pedestal fluctuation

\[ \sigma_E = \sigma_{\text{sampling}} \oplus \sigma_{\text{track}} \oplus \sigma_{\text{photo}} \oplus \sigma_{\text{noise}} \]

\( \text{at 1GeV} \)
### Parameter decomposition

<table>
<thead>
<tr>
<th>Parameter</th>
<th>all strips (%)</th>
<th>x(y) strips (%)</th>
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<tbody>
<tr>
<td>Resolution</td>
<td>13.1%</td>
<td>14.7%</td>
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<td>Noise effect</td>
<td>4.2%</td>
<td>5.0%</td>
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<td>Photo statistics (9.2 pes/MIP)</td>
<td>4.2%</td>
<td>6.0%</td>
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<tr>
<td>Subtracted $\sigma_{\text{noise}}$ and $\sigma_{\text{photo}}$</td>
<td>11.7%</td>
<td>12.4%</td>
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<tr>
<td>Track length fluctuation</td>
<td>4.2%</td>
<td>6.0%</td>
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<td>Sampling</td>
<td>10.9%</td>
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$$\sigma_{\text{track}}^{\text{all}} = \sigma_{\text{track}}^{x(y)} / \sqrt{2}$$

The difference = track length fluctuation.
Summary

- Scintillator strip-array EMCAL was tested with test beam
  - Good linearity
    1% level
  - Good energy resolution
    - stochastic: $13.10 \pm 0.12\%$
    - constant: $0.00^{+0.72}_{-0.00}\%$

- Granularity -> next speaker