Photons:
Energy Resolution and Linearity

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Analysis

- Can we use simulations to design a detector with good response to photons?
- Start by investigating the intrinsic detector characteristics:
  - Energy linearity
  - Energy resolution
- Analyze the response to single photons.

Simple Geant4 study (TB analog)

- Generate simple sampling calorimeters composed of tungsten-silicon sandwiches.
- Create stacks sufficiently large to contain the full particle showers.
- Vary thicknesses of tungsten and silicon to study the impact on the energy resolution.
- Simulate the response to single photons of varying energy.
- Sum energy deposited in silicon and plot energy resolution as a function of tungsten and silicon thickness.

Resolution as $f^{\underline{n}}(d_W, d_{Si})$

- Generate 400 detectors in 20 x 20 space of tungsten thickness (d_W) & silicon thickness (d_{Si}).
- 2000 events @ 1, 2, 5,10, 20 & 50 GeV
  - ~5 million events analyzed.
- Resolution fits well to the plane:

  h(x,y) = a*x + b*y + c

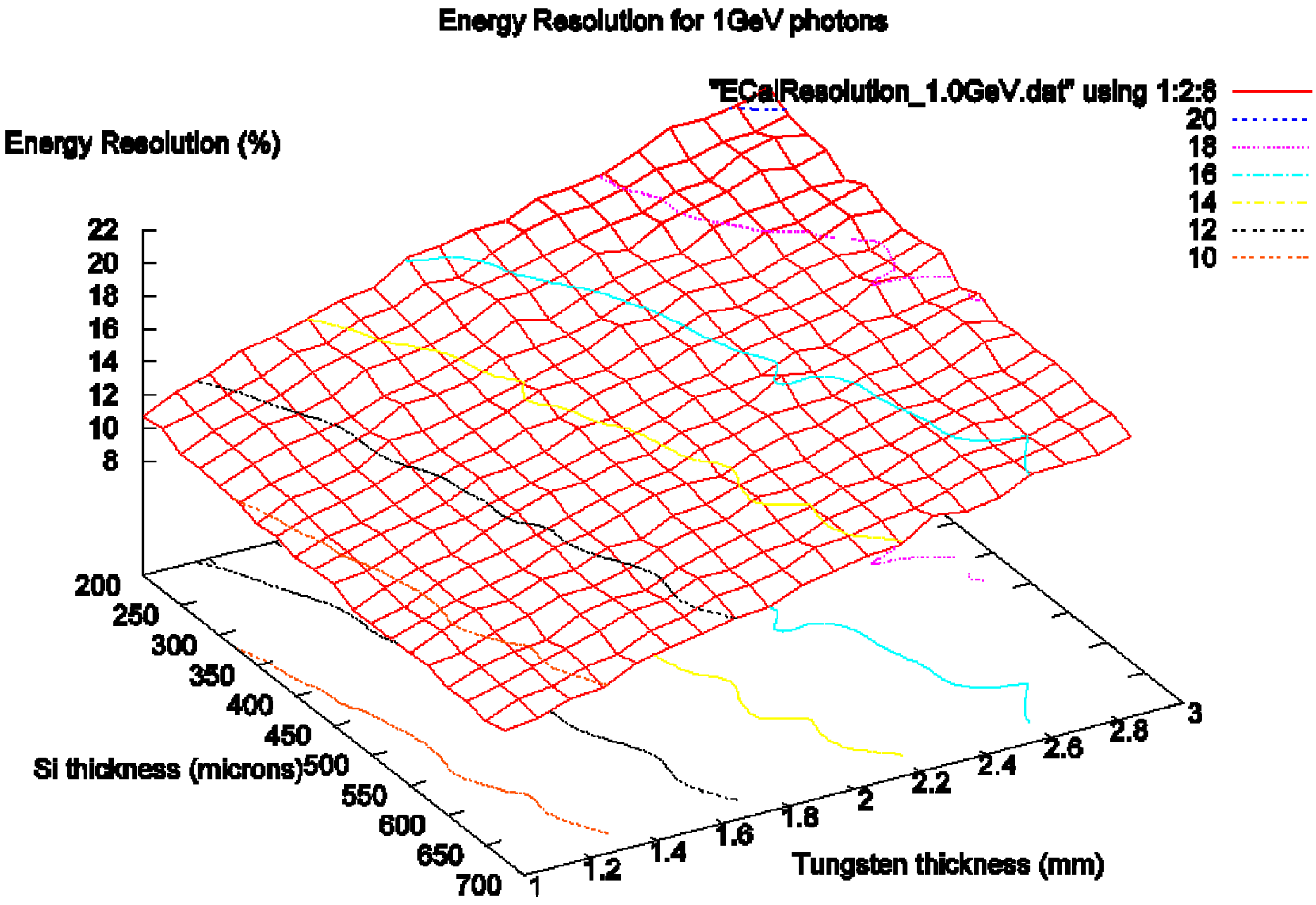
  x is the silicon thickness in microns

  y is the tungsten thickness in mm

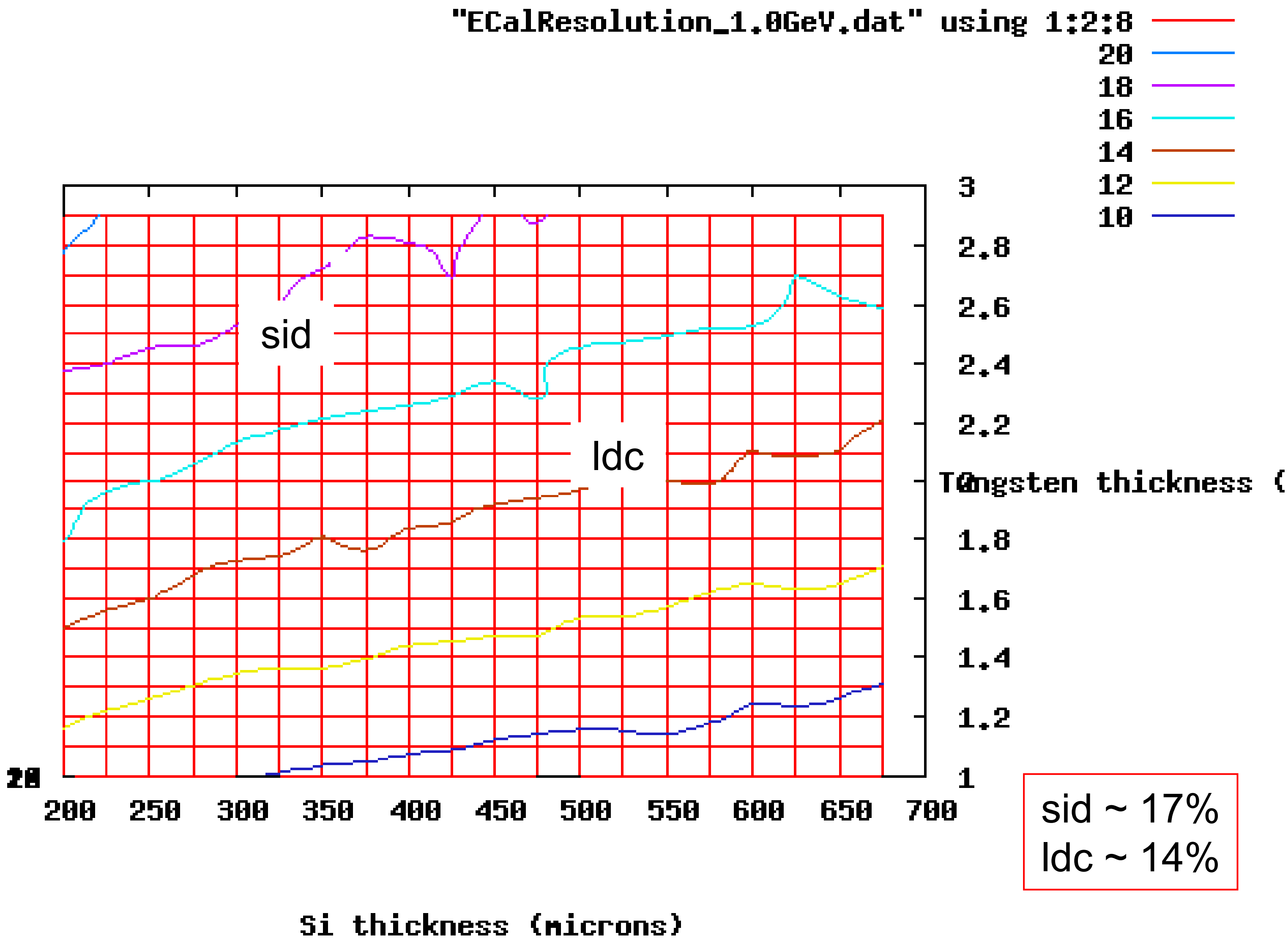
  h is the energy resolution in %
- With parameters:

a = -0.00614792	+/- 0.0001221	(1.986%)
b = 4.57985	+/- 0.03052	(0.6665%)
c = 8.02729	+/- 0.08189	(1.02%)

Resolution as $f^{\underline{n}}(d_W, d_{Si})$



Resolution as $f^{\underline{n}}(d_W, d_{Si})$



Results

- For a simple W-Si sampling calorimeter, the energy resolution is given by:

$$\frac{\sigma}{E} \simeq \left[11.5\left(\frac{d_W}{2.5mm} \right) - 1.8\left(\frac{d_{Si}}{300\mu m} \right) + 8 \right]\%$$

  - Doubling silicon thickness to 600μm would reduce resolution by 1.8%
  - Decreasing tungsten thickness by 5% would reduce resolution by 1.4%
- Would like to see some of this space explored in testbeam:
  - Ideally with wafers of different thicknesses.
  - Could also use thick silicon and vary effective sensitive thickness (depletion depth) with bias voltage.

Full Simulation Detectors

- Use full detector simulations to study energy resolution with “realistic” designs.
- Benchmark electromagnetic calorimeter setup:
  - <slice material = "TungstenDens25" thickness = "0.271*cm" />
  - <slice material = "Silicon" thickness = "0.032*cm" sensitive = "yes" />
  - <slice material = "Copper" thickness = "0.005*cm" />
  - <slice material = "Kapton" thickness = "0.030*cm" />
  - <slice material = "Air"   thickness = "0.033*cm" />
- Study mixed EM designs, saturation due to cell segmentation, punchthrough to HCal

Full Simulation Detectors

- acme0605
  - 20 layers of .271cm W, 320μm Si
  - 10 layers of .543cm W, 320μm Si
  - HCal: .75cm W, .5cm scintillator
- acme0605_30layerecal
  - 30 layers of .271cm W, 320μm Si
- acme0605_40layerecal
  - 40 layers of .271cm W, 320μm Si
- acme0605_steel_scint
  - 20 layers of .271cm W, 320μm Si
  - 10 layers of .543cm W, 320μm Si
  - HCal: 2.0cm Steel, .5cm scintillator

Full Simulation Data Samples

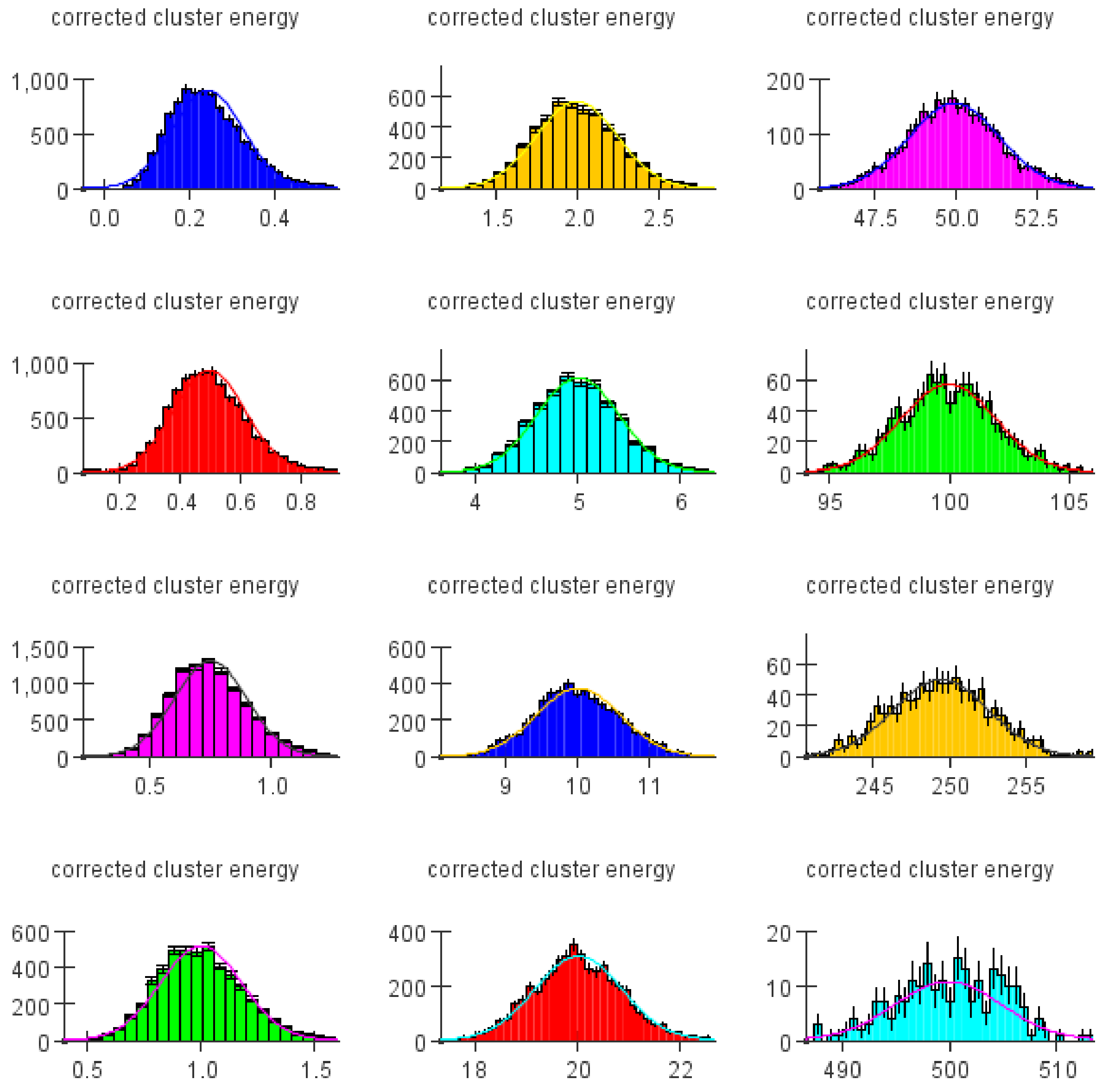
- Generated single particle events with photons at $\theta = 90°$ to the beam line, $0 < \varphi < 2\pi$, with discrete energies.
- Low Energy:
  - 100, 250, 500, 750 MeV
- Intermediate Energy:
  - 1, 2, 5, 10, 20, 50, 100 GeV
- High Energy (Bhabhas)
  - 250 and 500 GeV.
- Apply conservative fixed-cone clustering algorithm to clean up obvious outliers.

Analysis

- For simplicity's sake, only calculate three sampling fractions:
  - EM1(first 20 layers), EM2(remaining layers), HCal
- $E = \alpha * E_{EM1} + \beta * E_{EM2} + \gamma * E_{HCal}$
- Plot cluster energy for each energy point.
- Fit Gaussians to the distributions.
- Study energy linearity (mean vs MC Energy).
- Study energy resolution (sigma vs MC Energy).

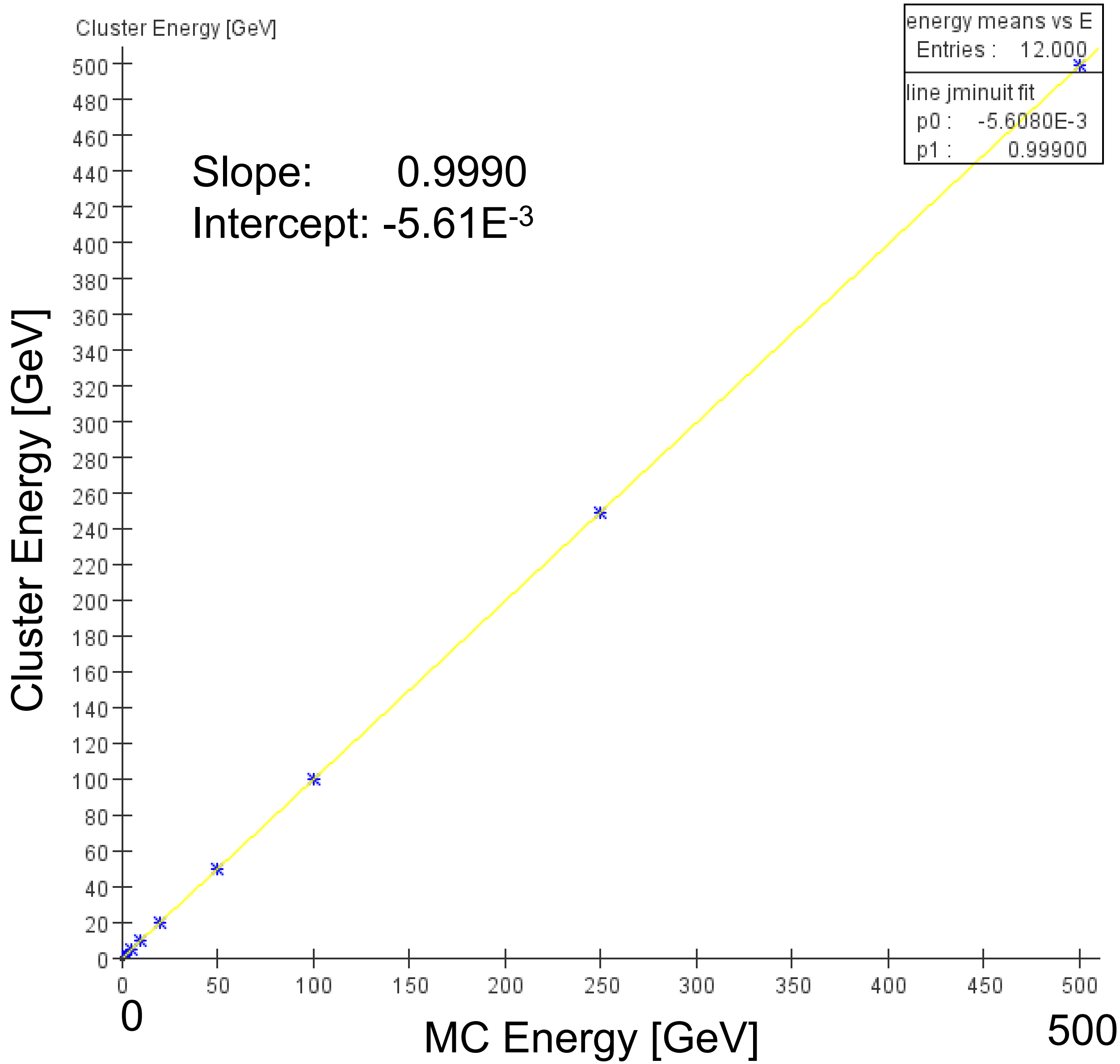
Plots: acme0605 Raw Data

250 MeV

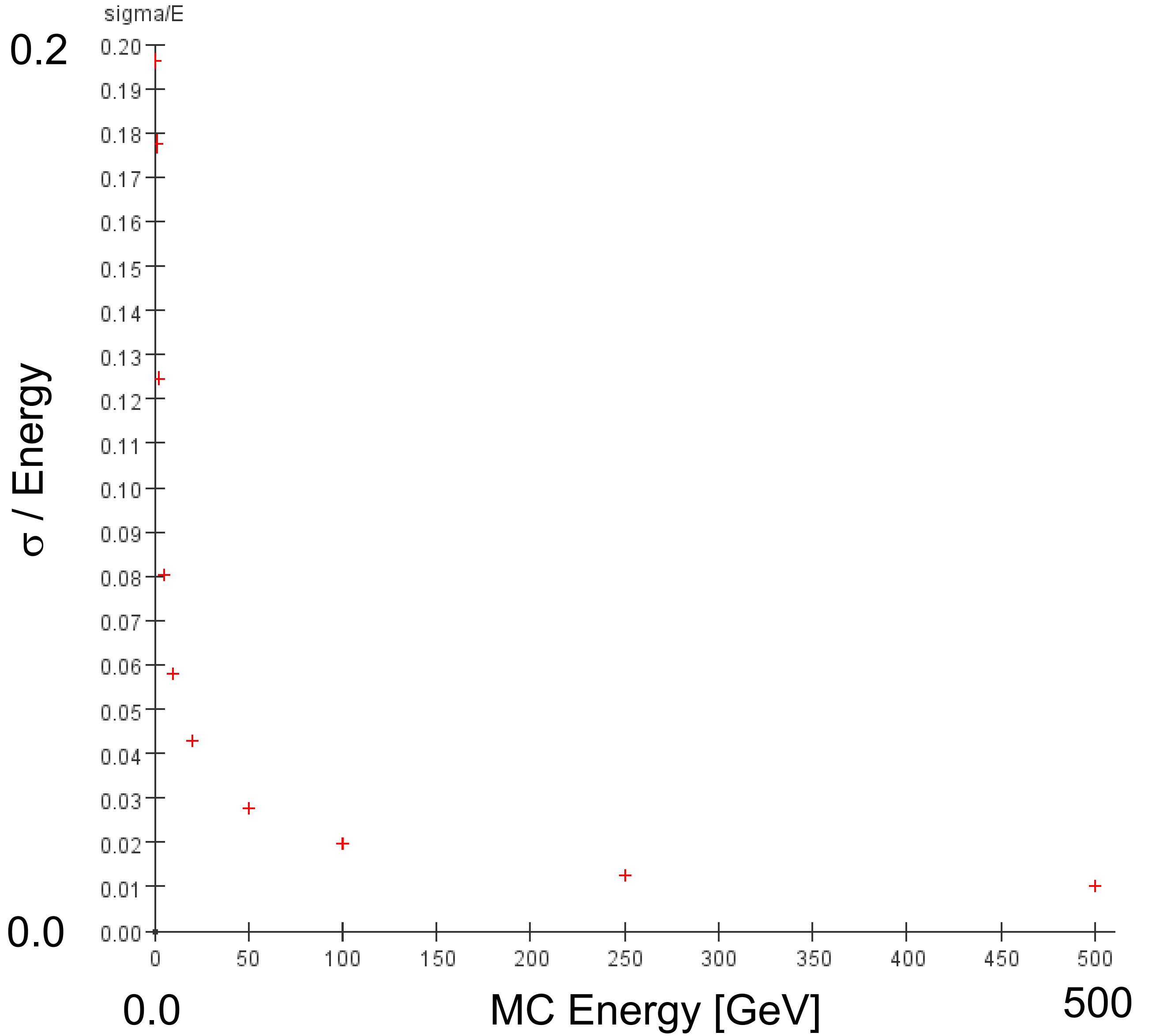


500 GeV

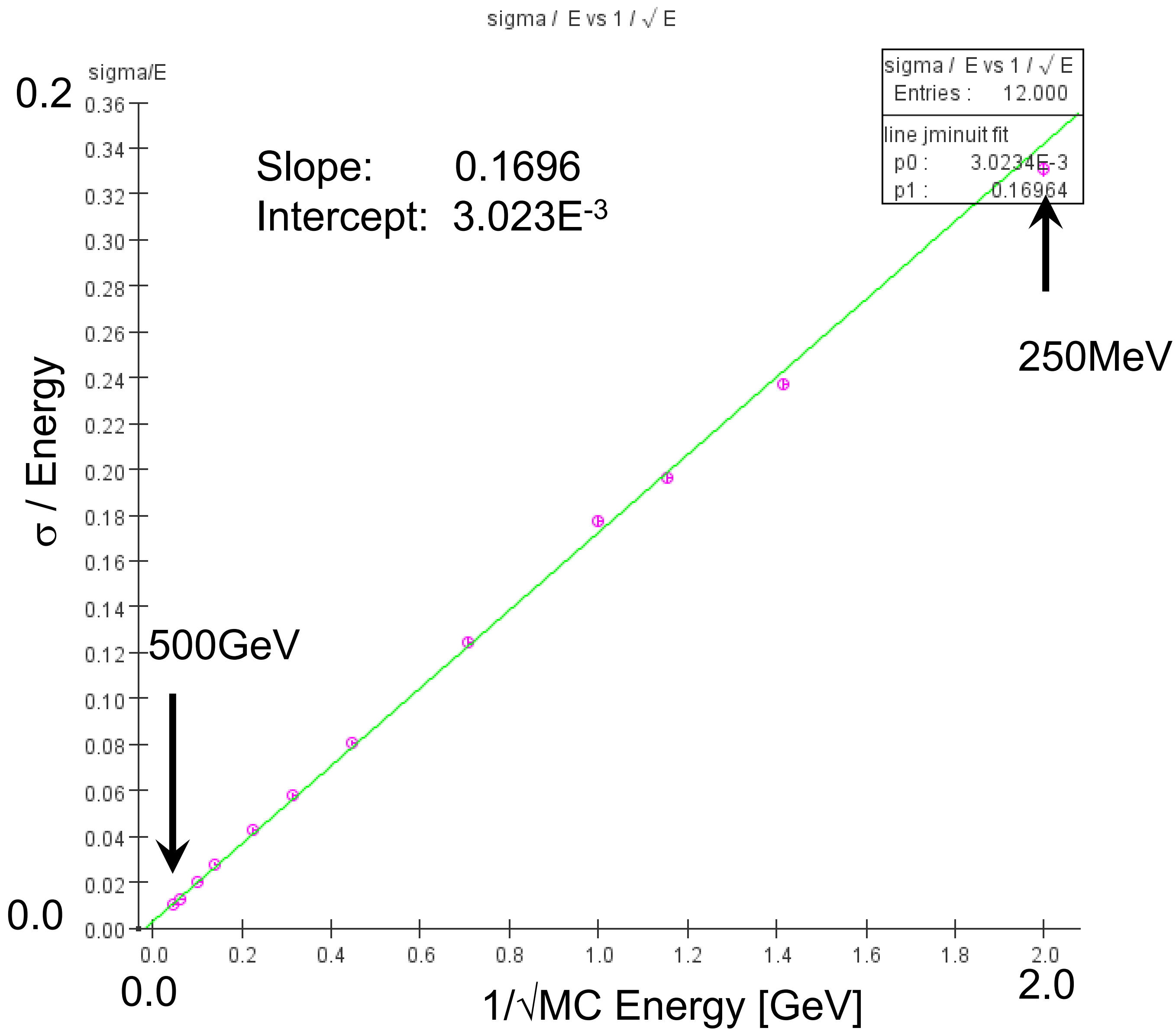
Plots: acme0605 Linearity



Plots: acme0605 Resolution



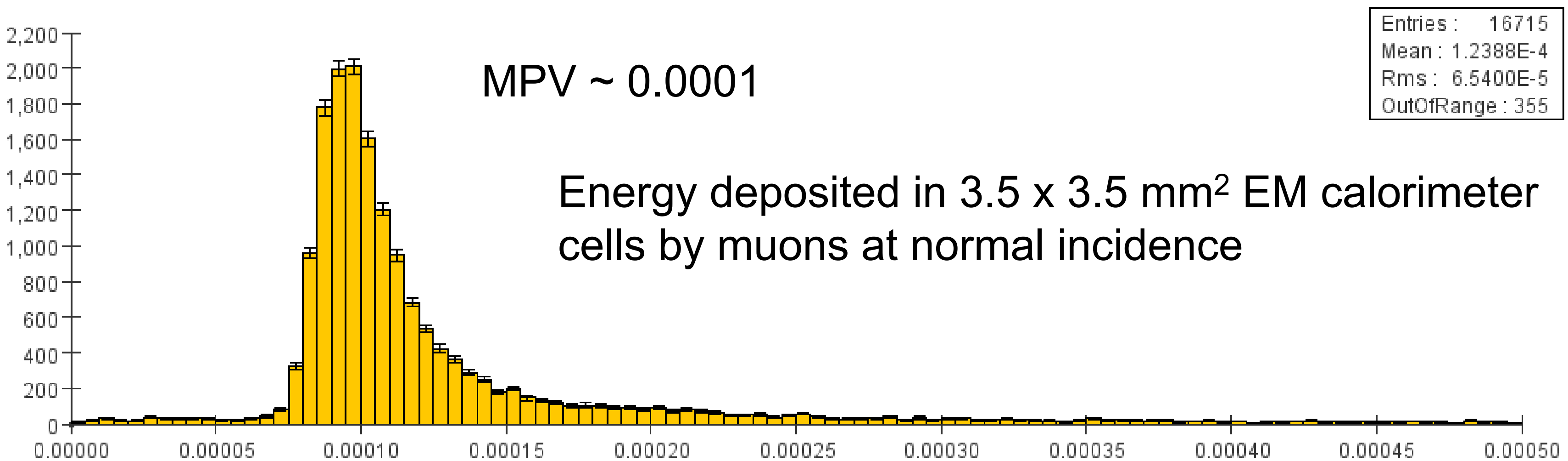
Plots: acme0605 Resolution

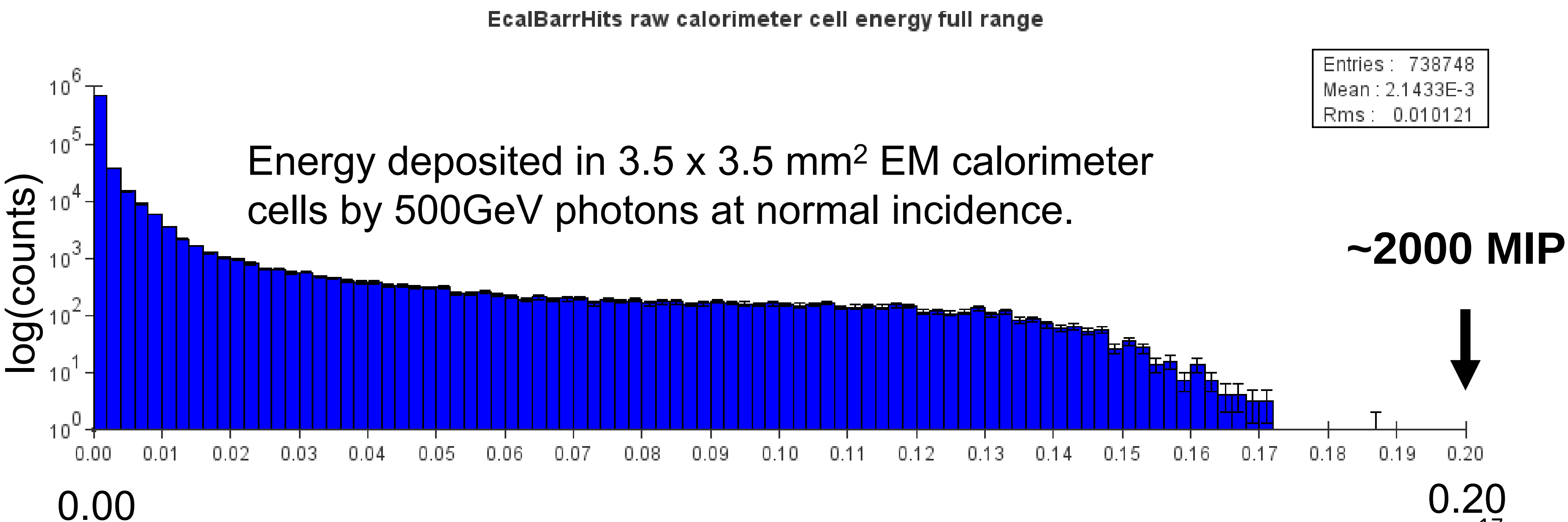


Results

- Sampling fractions can be obtained for all the detector designs (having analog HCal readout) which provide a linear response for photons with energies between 250 MeV and 500 GeV.
- The energy resolution is only slightly affected by the EM calorimeter designs:
  - acme0605: 17.1%
  - acme0605_40layerecal: 16.9%
  - acme0605_30layerecal: 17.2%
  - acme0605_steel_scint: 17.7%

Saturation


MPV ~ 0.0001
Energy deposited in 3.5 x 3.5 mm² EM calorimeter cells by muons at normal incidence
Entries : 16715
Mean : 1.2388E-4
Rms : 6.5400E-5
OutOfRange : 355
2,200
2,000
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
0.00000
0.00005
0.00010
0.00015
0.00020
0.00025
0.00030
0.00035
0.00040
0.00045
0.00050


EcalBarrHits raw calorimeter cell energy full range
Entries : 738748
Mean : 2.1433E-3
Rms : 0.010121
Energy deposited in 3.5 x 3.5 mm² EM calorimeter cells by 500GeV photons at normal incidence.
~2000 MIP
log(counts)
10^6
10^5
10^4
10^3
10^2
10^1
10^0
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
0.11
0.12
0.13
0.14
0.15
0.16
0.17
0.18
0.19
0.20
0.00
0.20

Results

- Saturation, even for highest energy electromagnetic showers (Bhabhas at a 1 TeV machine), is not a problem with the default design of 3.5 x 3.5 mm^2 cells read out using the KPiX chip.

Summary

- The tools are available to design a system of calorimeters with good energy resolution and linearity of response to photons.
- A default set of sampling fractions can be determined which gives excellent linearity for photons with energies between 250 MeV and 500 GeV.
- The energy resolution and linearity could be improved by introducing energy-dependent sampling fractions.
  - Physical reason for this is that the electromagnetic shower composition changes as a function of energy and longitudinal depth of the shower.
- The baseline silicon detector calorimeters provide an energy resolution of:

$\sigma/E \sim 17\%/\sqrt{E}$ with small constant term.

Future work

- Present study has concentrated on energy linearity and resolution with analog HCal.
  - extend to digital: $E = \alpha * E_{EM1} + \beta * E_{EM2} + \gamma * N_{HCal}$
- Investigate lateral shower spread.
  - Molière radius as function of gap thickness.
- Study position and pointing resolution.
- Apply to photons in physics events.
  - Study impact of clustering schemes and local particle densities on resolution, etc.
- Get feedback from physics groups on requirements.
- Study this in testbeam!