ILC DETECTOR WORKSHOP
MAR 4, 2005.

Calorimeter Optimization by GEANT4

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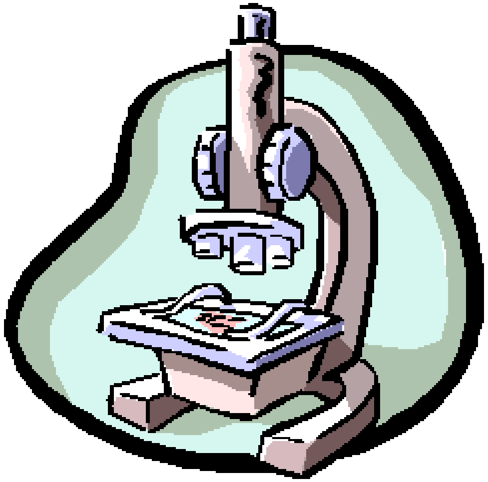
- Motivation
- ECAL
  - Sampling Ratio
  - Reset Range Cut
  - Energy Deposit
  - Energy Resolution
  - Data vs. MC

Motivation

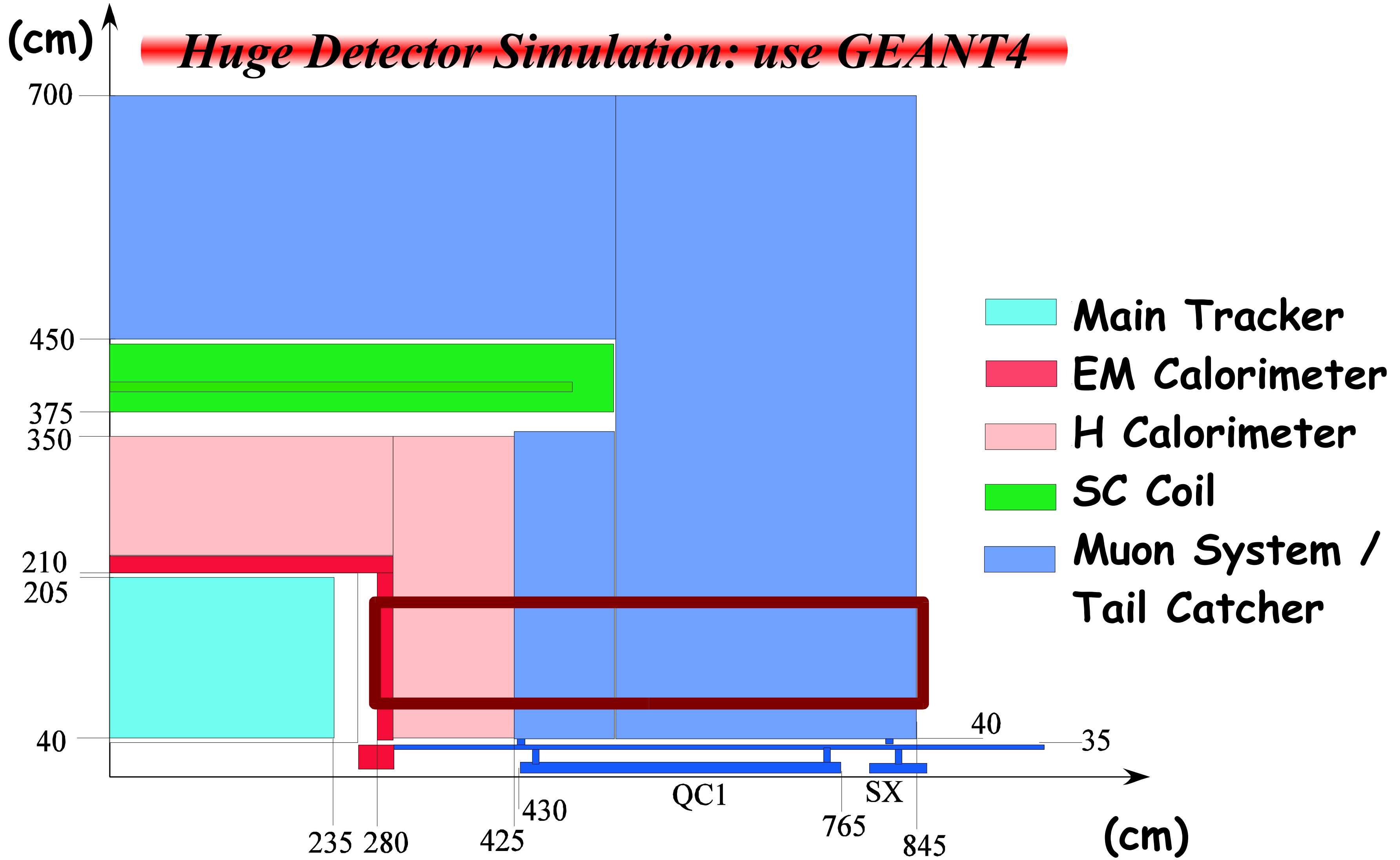


- Physics Motivation for Linear Collider:
  - Precise Measurement of Higgs mass
- Needed:
  - Excellent momentum resolution
- Jet Physics:
  - Event reconstruction need excellent jet recontruction
  - Seperate WW and ZZ jets
- Current Study:
  - "Particle Flow"
  - Assuming perfect seperation of particles
  - $\sigma(\mathrm{Jet}) = \sqrt{\sum \epsilon_T^2 E_i^4 + \sum \epsilon_{ECAL}^2 E_i + \sum \epsilon_{HCAL}^2 E_i}$
  - Energy resolution is dominated by HCAL
- Excellent spatial resolution of ECAL and HCAL can maximaze the shower tracking

ECAL+HCAL+TC Study

- Get benifit from the high luminosity → Well-separated W and Z.

Huge Detector Simulation: use GEANT4



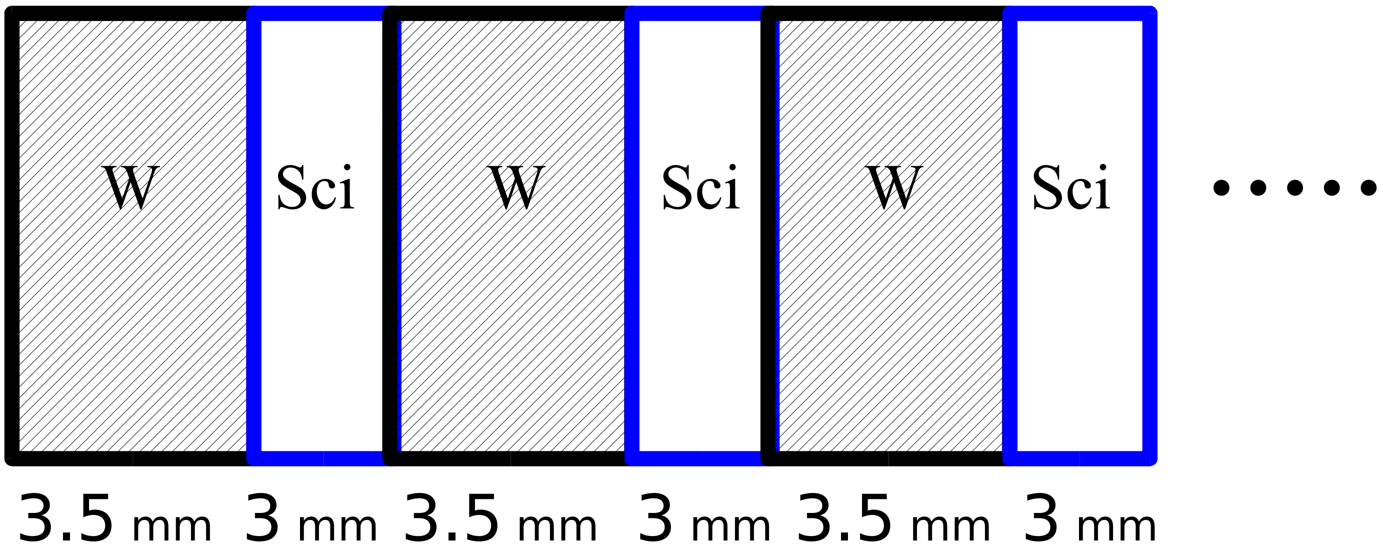
Y. Sugimoto @ 7th ACFA

ECAL Study: sampling calorimetry

▶ Absorber Layers sandwiched with the active media

ECAL Construction

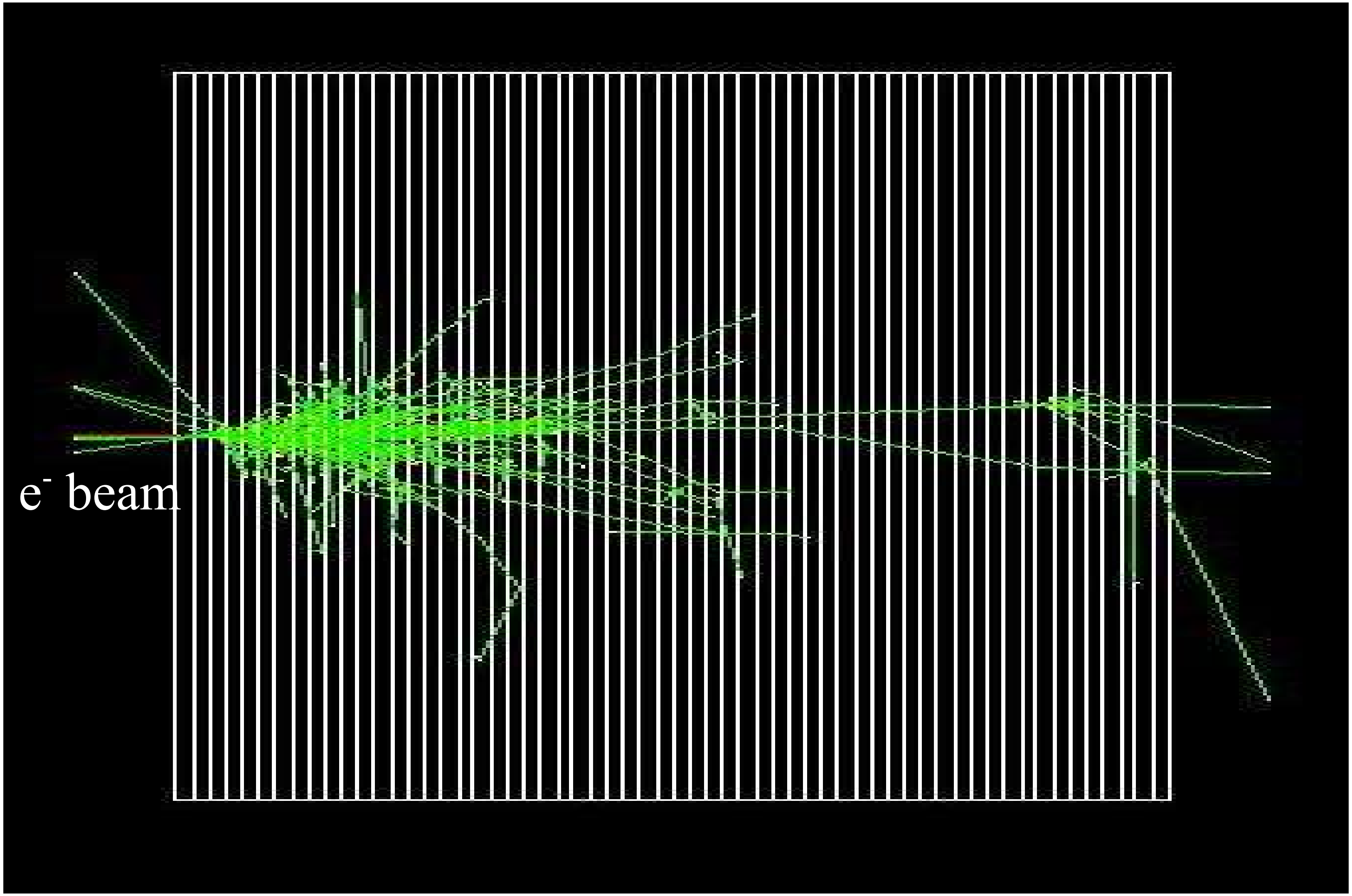
- Material
  - W (Tungsten)-Scintillator Sandwich
- Thickness
  - W: 3.5 mm/layer (2 mm/layer and 1 mm/layer)
  - Sci: 3.0 mm/layer (4 mm/layer and 5 mm/layer)
- Layers
  - 30 layers → (3.5+3)x30 = 195 mm – thickness
  - 100 m x 100 m – interaction surface



ECAL Study

- Calorimetry works because T $\propto$ E (the energy of the particle)

Track Length (T) = sum of tracks of all charged particles in a shower

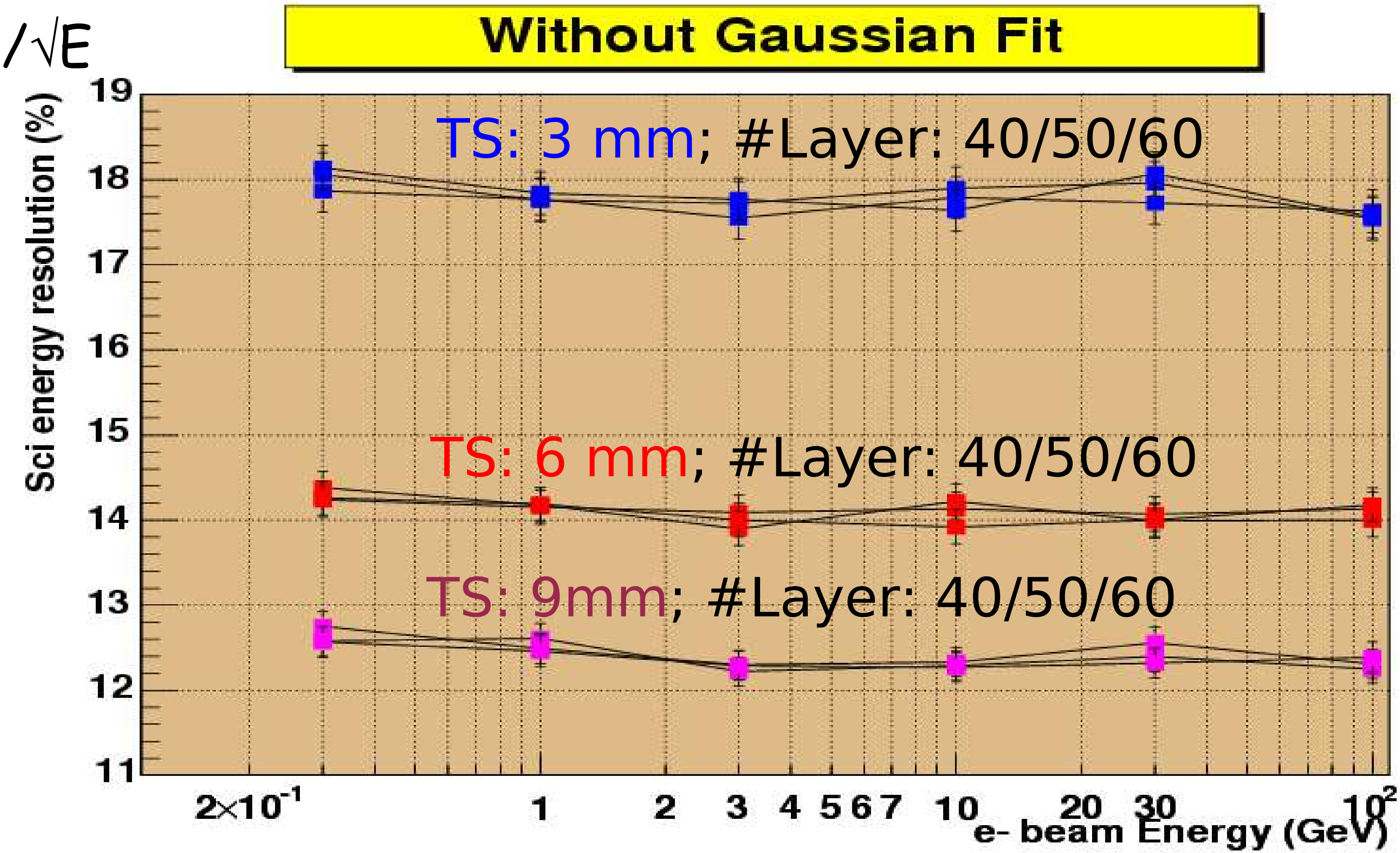


ECAL Study: absorber/sci thickness?

- 0.3 GeV ~ 100 GeV e- beam test; 10,000 events
- Thickness of W: 3.5 mm

Thickness of Sci: 3 mm
Thickness of Sci: 6 mm
Thickness of Sci: 9mm

RMS/√E



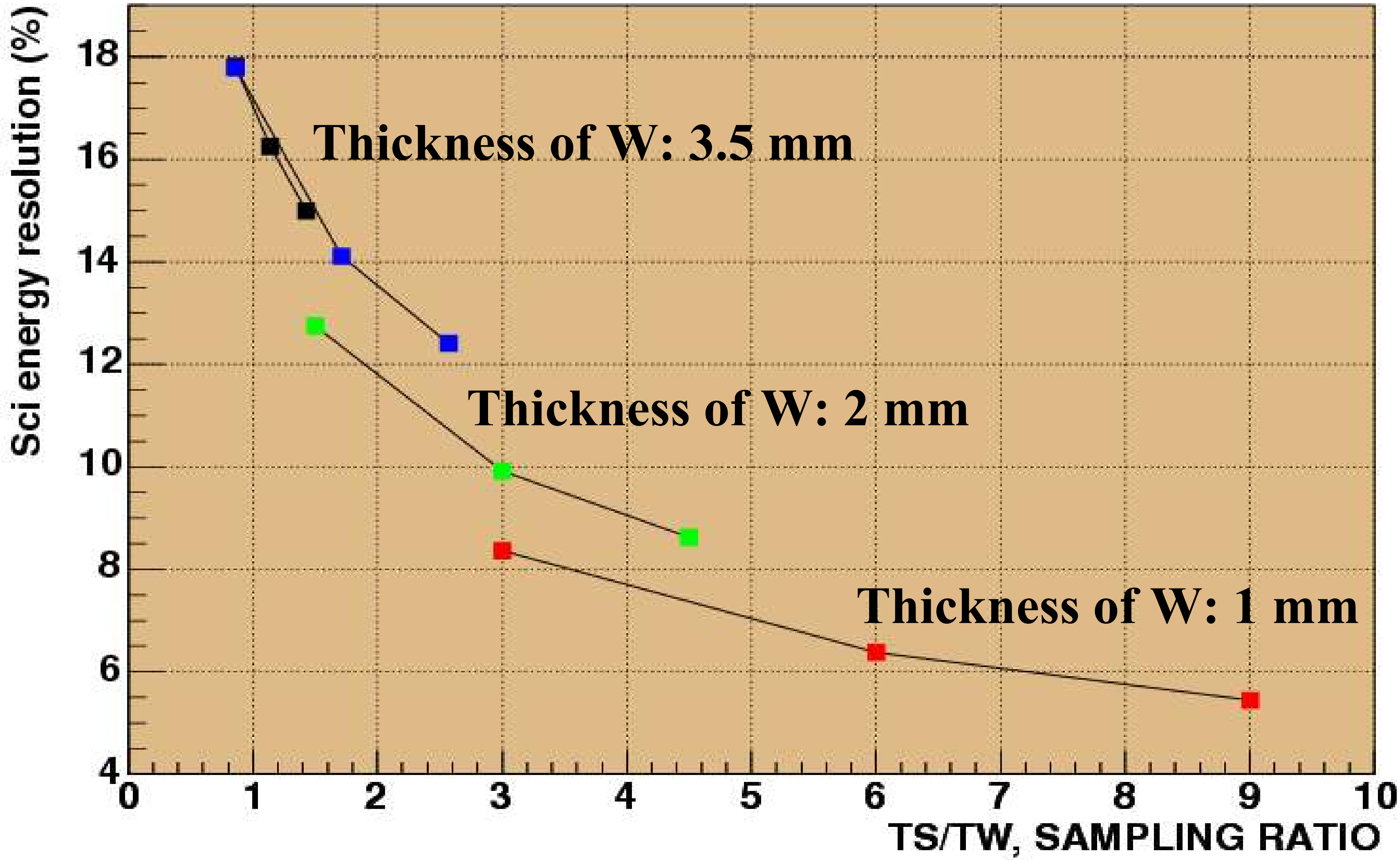
ECAL Study: absorber/sci thickness?

Sampling Ratio vs. Energy Resolution

Default Range Cut

Without Gaussian Fit

RMS/√E



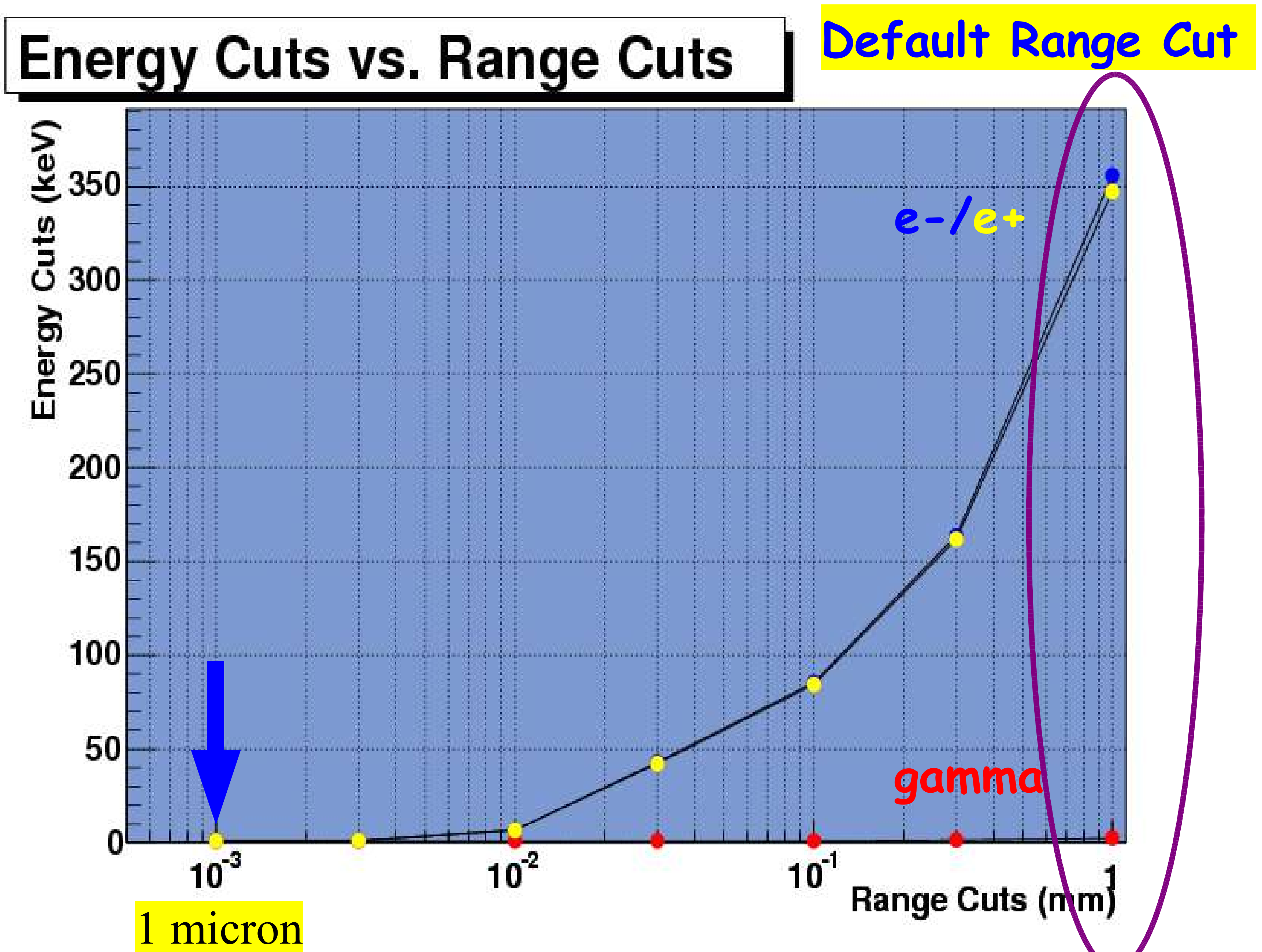
ECAL Study: absorber/sci thickness?

Short Summary

- Reduce the thickness of W or Increase the thickness of Sci, the energy resolution BECOMES BETTER.
- <u>Even the same sampling ratio, the thinner W will lead to better energy resolution.</u>

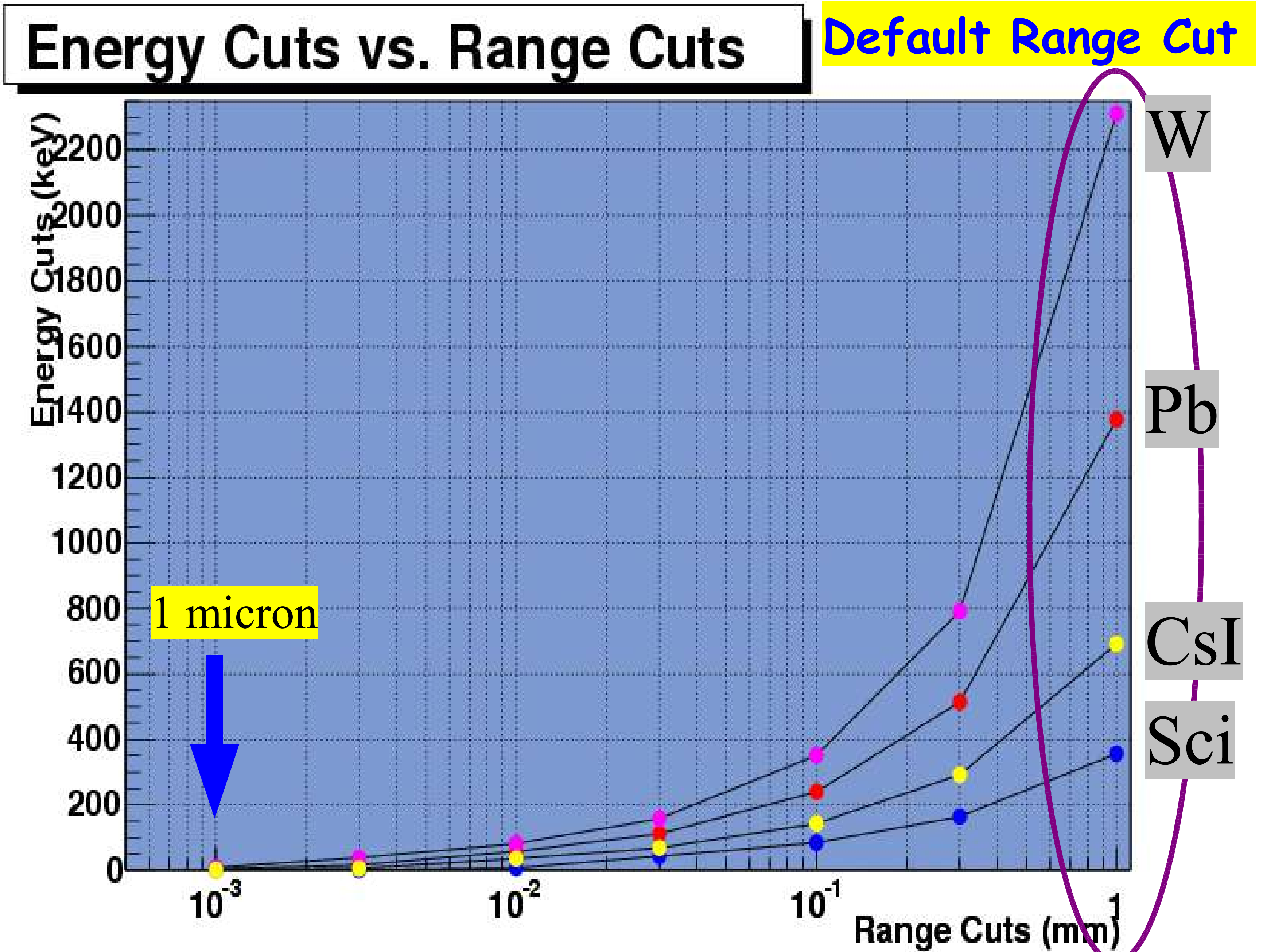
ECAL Study: range cut?

Inside Scintillator



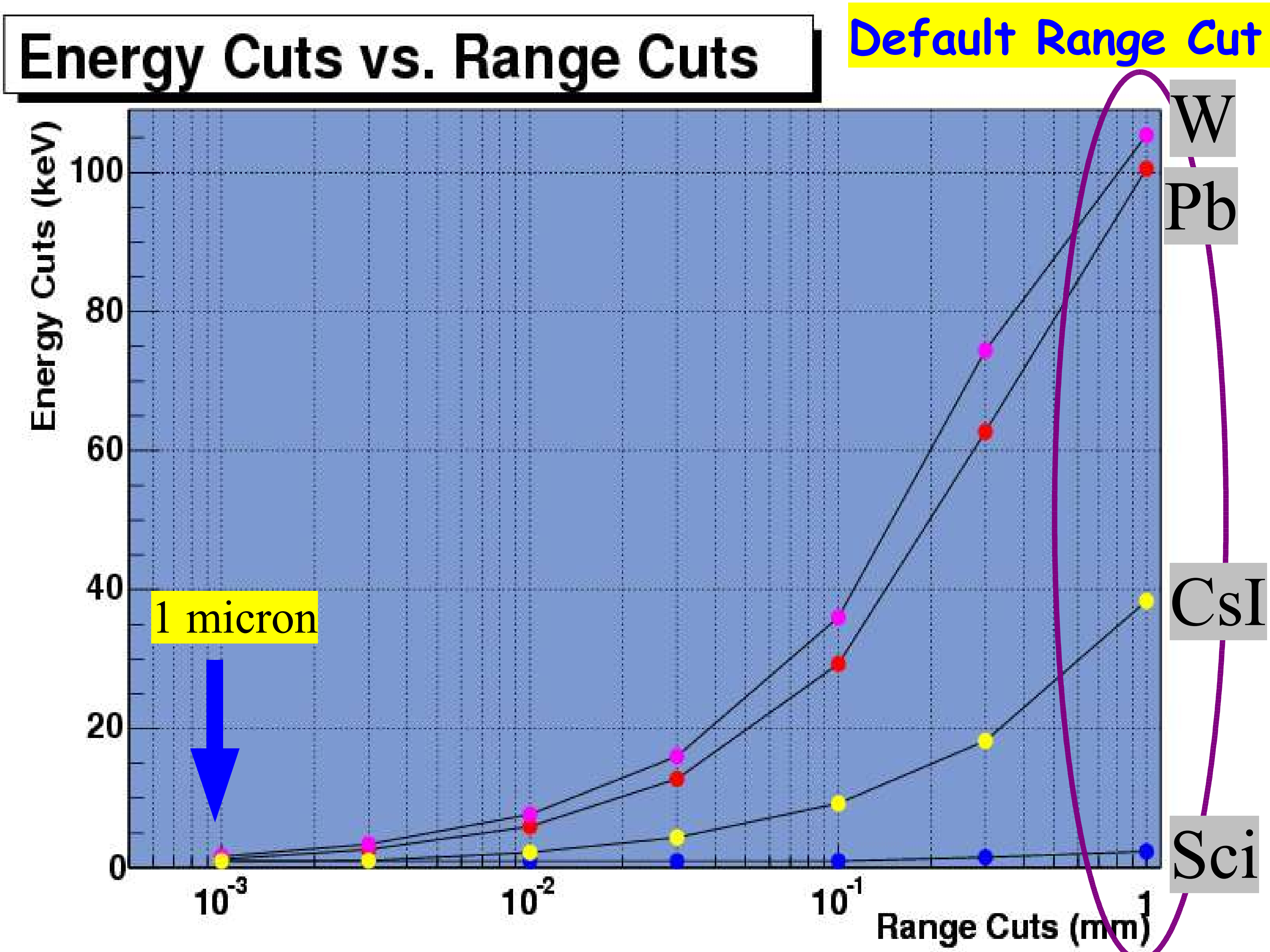
ECAL Study: range cut?

Compare the e-/e+ energy cuts



ECAL Study: range cut?

Compare the gamma energy cuts



ECAL Study: range cut?

Short Summary

- We can't use the default range cut, because
  - The thickness of scitillator is about 1 mm
  - The minimum energy cut for e-/e+ is too high
  - Set the range cut at 1 micron is better

How Range Cut works?

When the range of the particle for the next step is calculated to be less than the range cut, Geant4 kills the particle there and deposits all of its energy there.

a secondary particle is not acutually created if its range is less than the range cut.

ECAL Study: range cut effect?

Same Radiation Length

Test A: ECAL+HCAL

- ECAL: (8mm Pb + 2mm Sci) x 18 Layers
- HCAL:(16mm Pb + 4mm Sci)x 60 Layers

Test B: ECAL+HCAL

- ECAL: (5mm W + 2mm Sci) x 18 Layers
- HCAL:(10mm W + 4mm Sci)x 60 Layers

Same Sampling Ratio

Test C: ECAL+HCAL

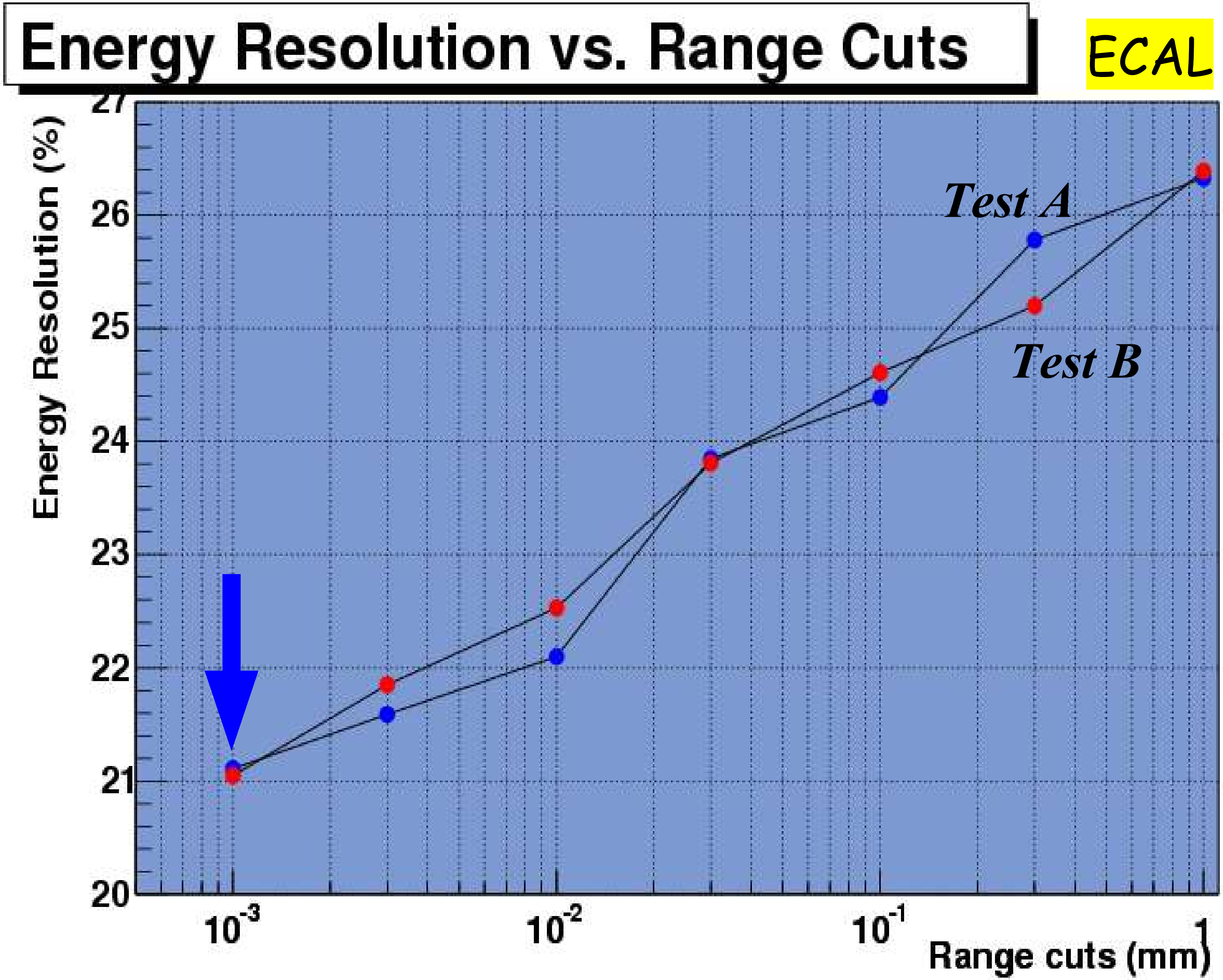
- ECAL: (4mm Pb + 1mm Sci) x 36 Layers
- HCAL:(8mm Pb + 2mm Sci)x 120 Layers

Jupiter setting

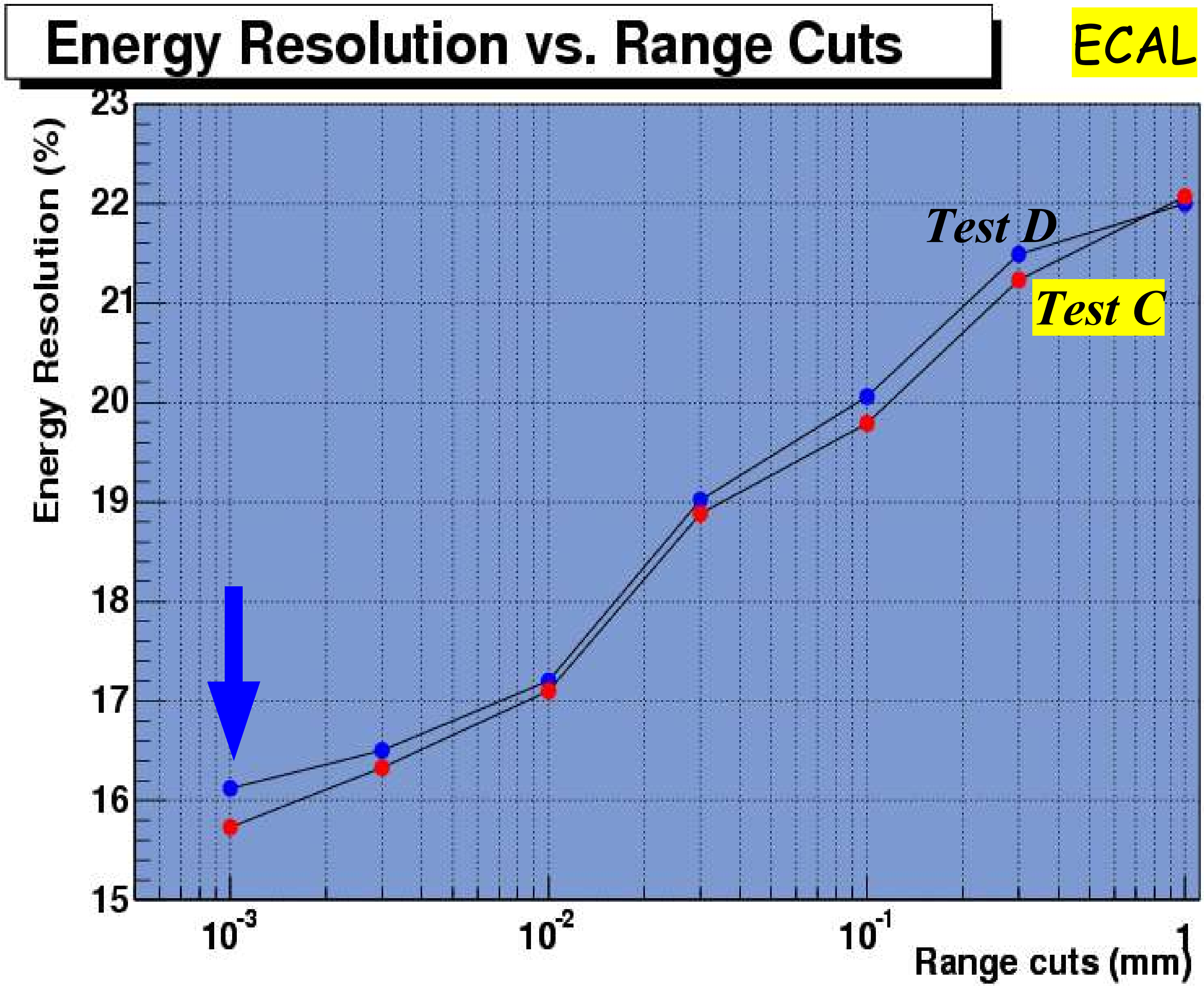
Test D: ECAL+HCAL

- ECAL: (2.5mm W + 1mm Sci) x 36 Layers
- HCAL:(5.0mm W + 2mm Sci)x 120 Layers

ECAL Study: range cut effect?



ECAL Study: range cut effect?



ECAL Study: Cost?

Prototype

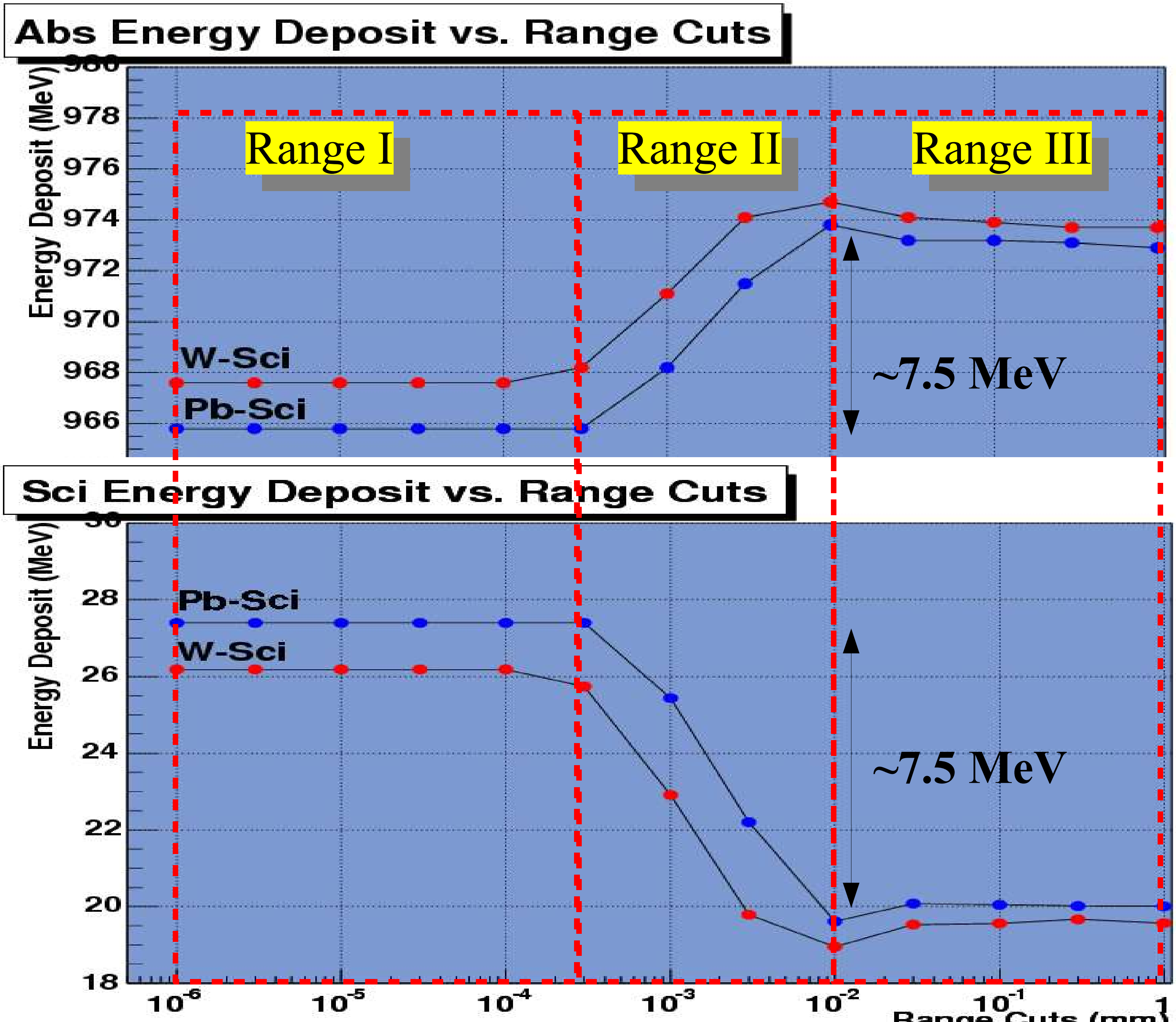
- ECAL: (4mm Pb + 1mm Sci) x 36 Layers
- ECAL: (2.5mm W + 1mm Sci) x 36 Layers
- Surface: 1m x 1m
-
- **First Calculation Results**
- Pb with 99.99%, 36 pcs, ~ 1700kg, 774,000 yen
- W , ~ 1,500,000 yen
- For the total ECAL in the future "Huge Detector", the price is
  - Pb: ~774,000,000 yen (7 億 yen or US$ 7M)
  - W: ~1,500,000,000 yen (15 億 yen or US $15M)
- We have to include the Sci, readout SiPM (or PMTs), readout electronics, and manpower, ... I will keep update the price issues.

ECAL Study: range cut effect?

Short Summary

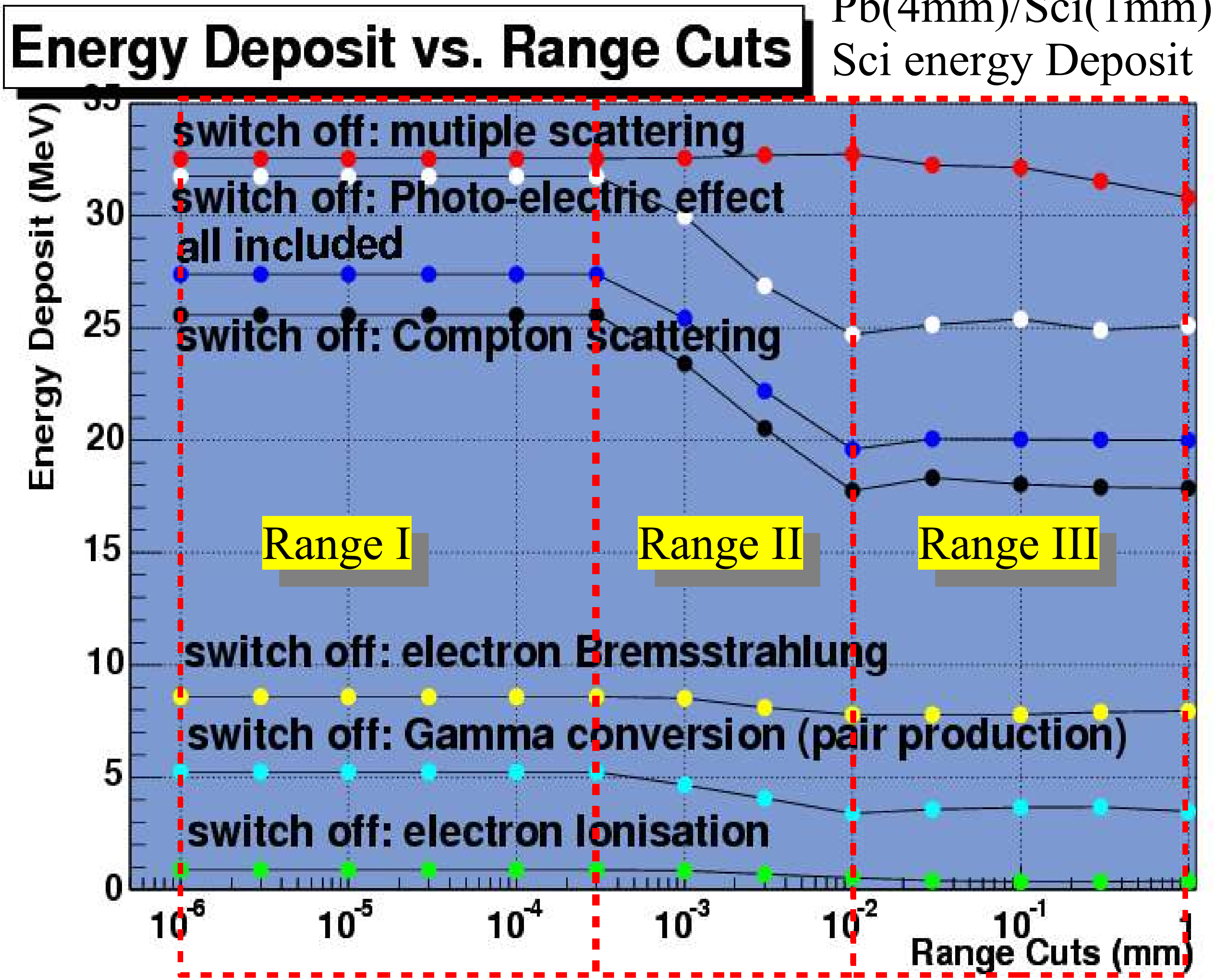
- Test A vs. Test B (same as Test C vs. Test D):
  - The energy resolution between them are very close to each other while with the same radiation length configuration.
  - Pb:Sci = 4:1 ~ W:Sci = 2.5 :1
- Test A vs. Test C (same as Test B vs Test D):
  - Even with the same sampling ratio, the thinner absorber will lead to better energy resolution.

ECAL Study: range cut



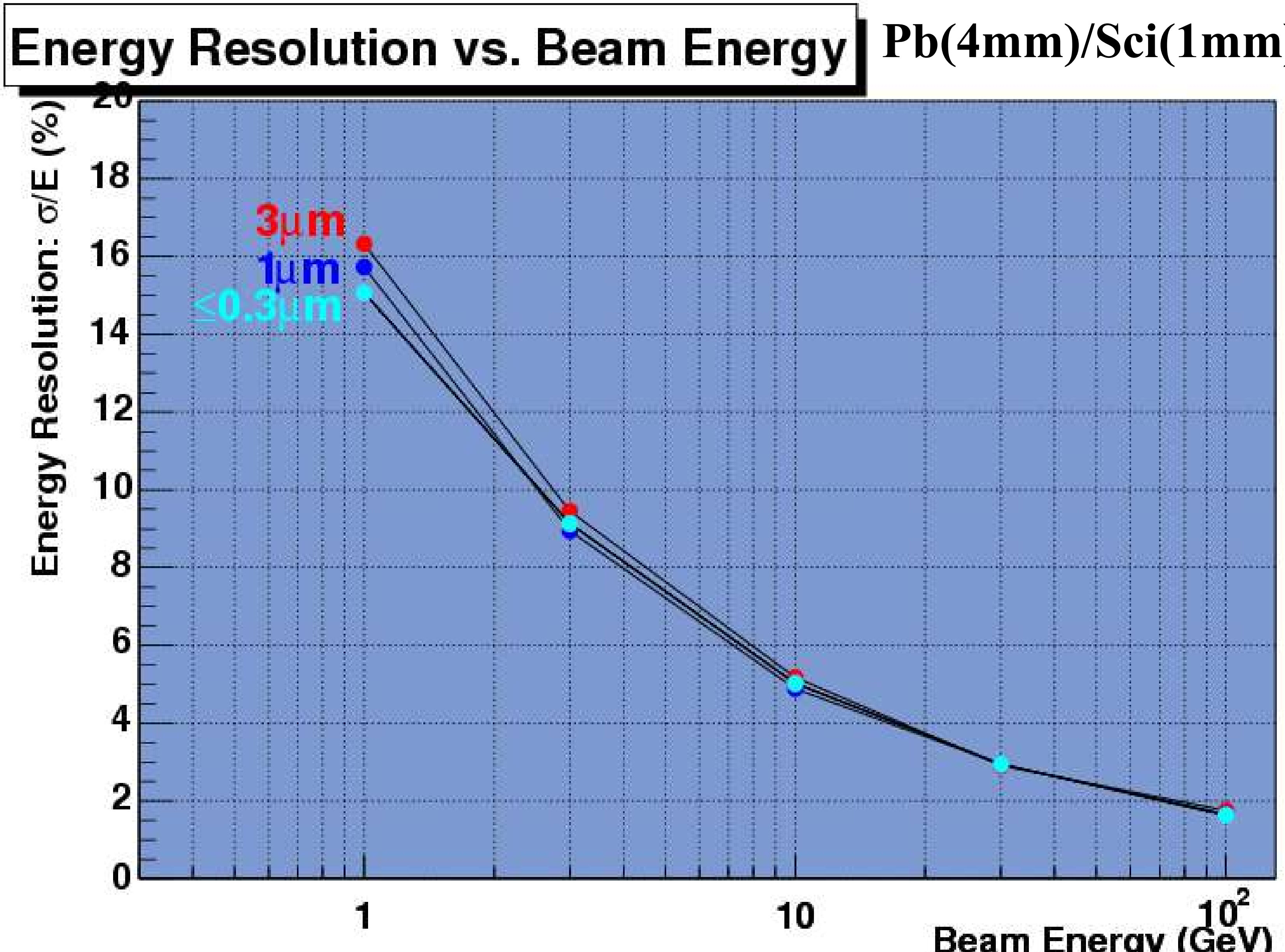
ECAL Study: range cut

Pb(4mm)/Sci(1mm),
Sci energy Deposit



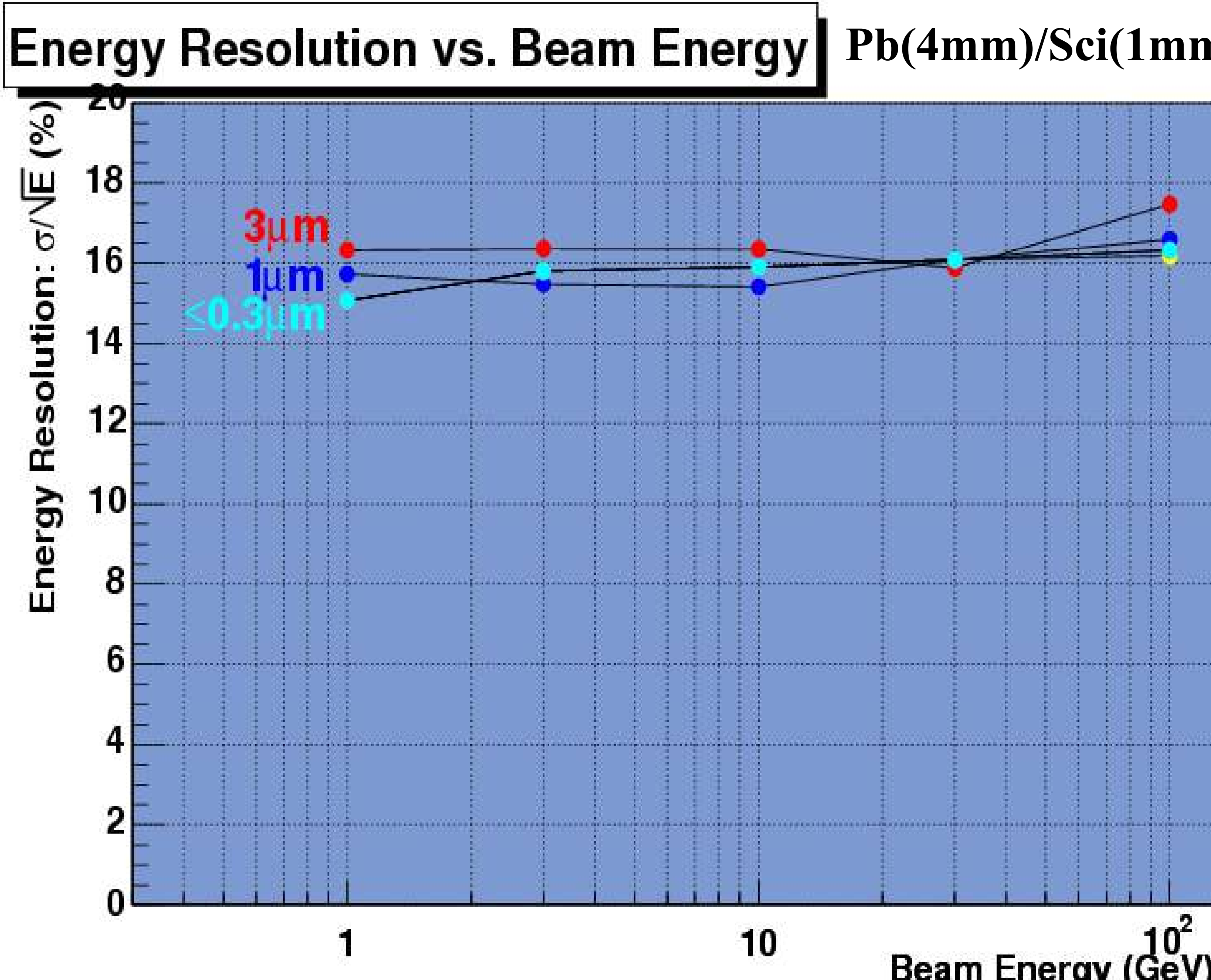
ECAL Study: range cut effect?

Pb(4mm)/Sci(1mm)



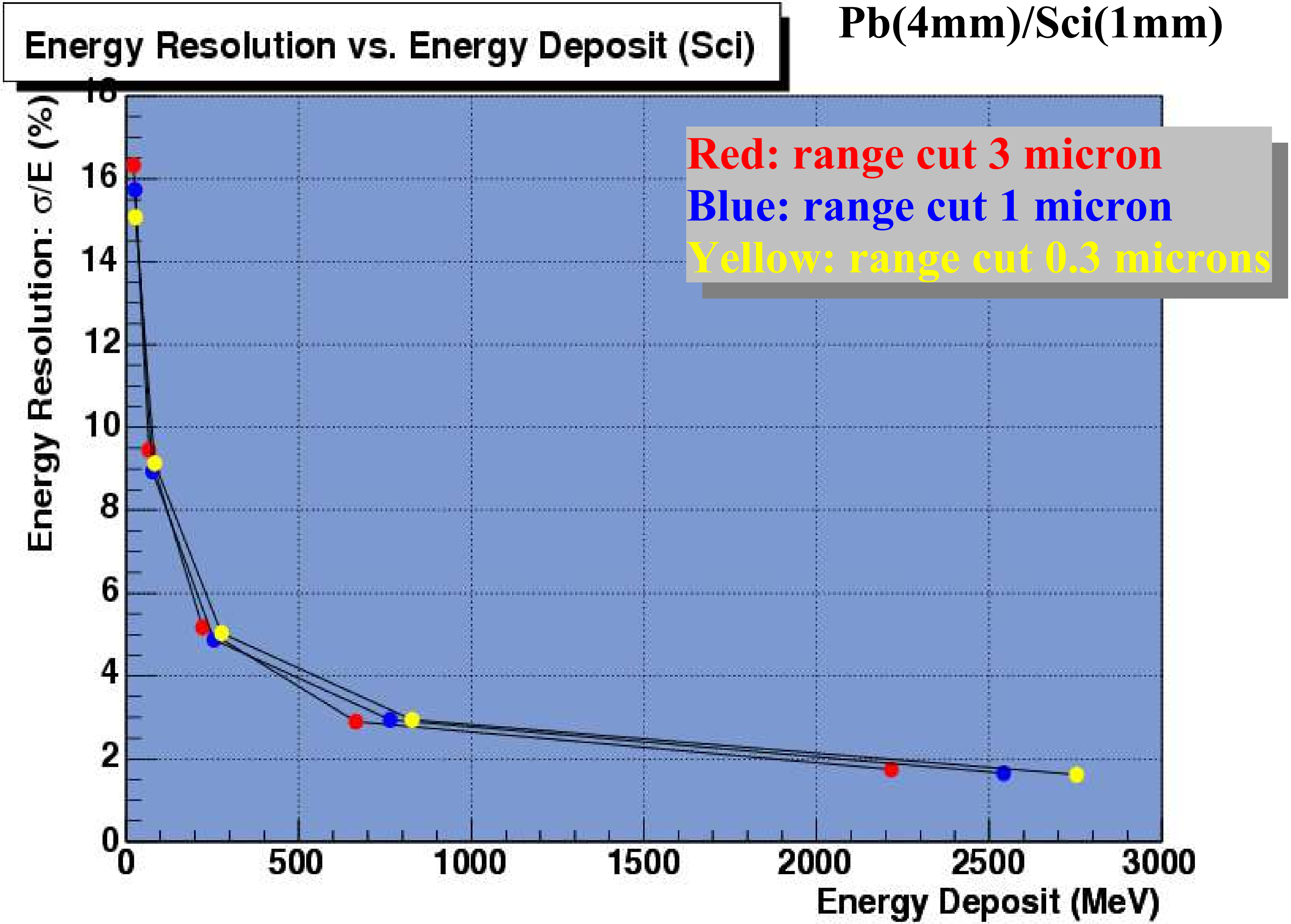
ECAL Study: range cut effect?

Pb(4mm)/Sci(1mm)



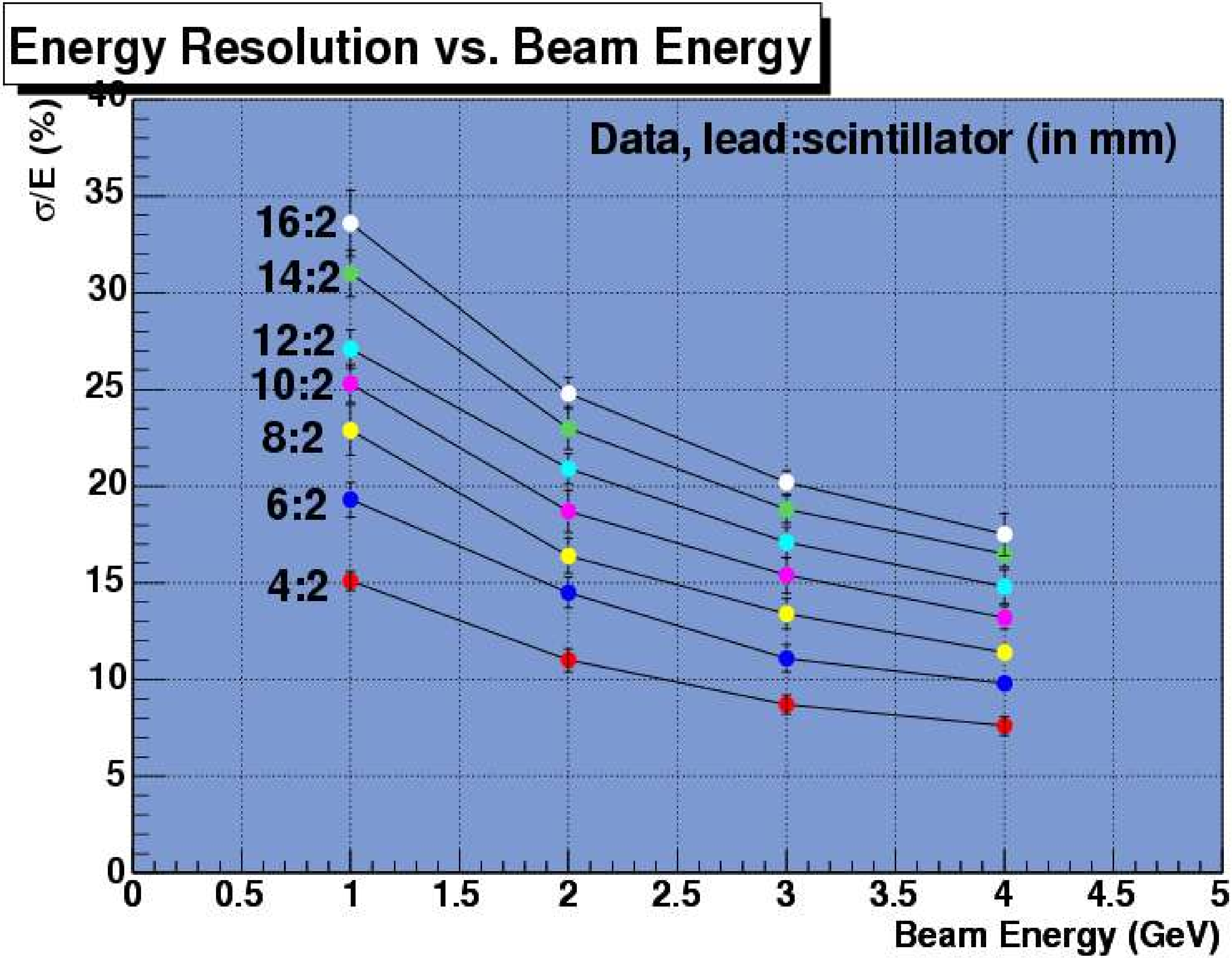
ECAL Study: e- beam, 1000 events/point

Pb(4mm)/Sci(1mm)



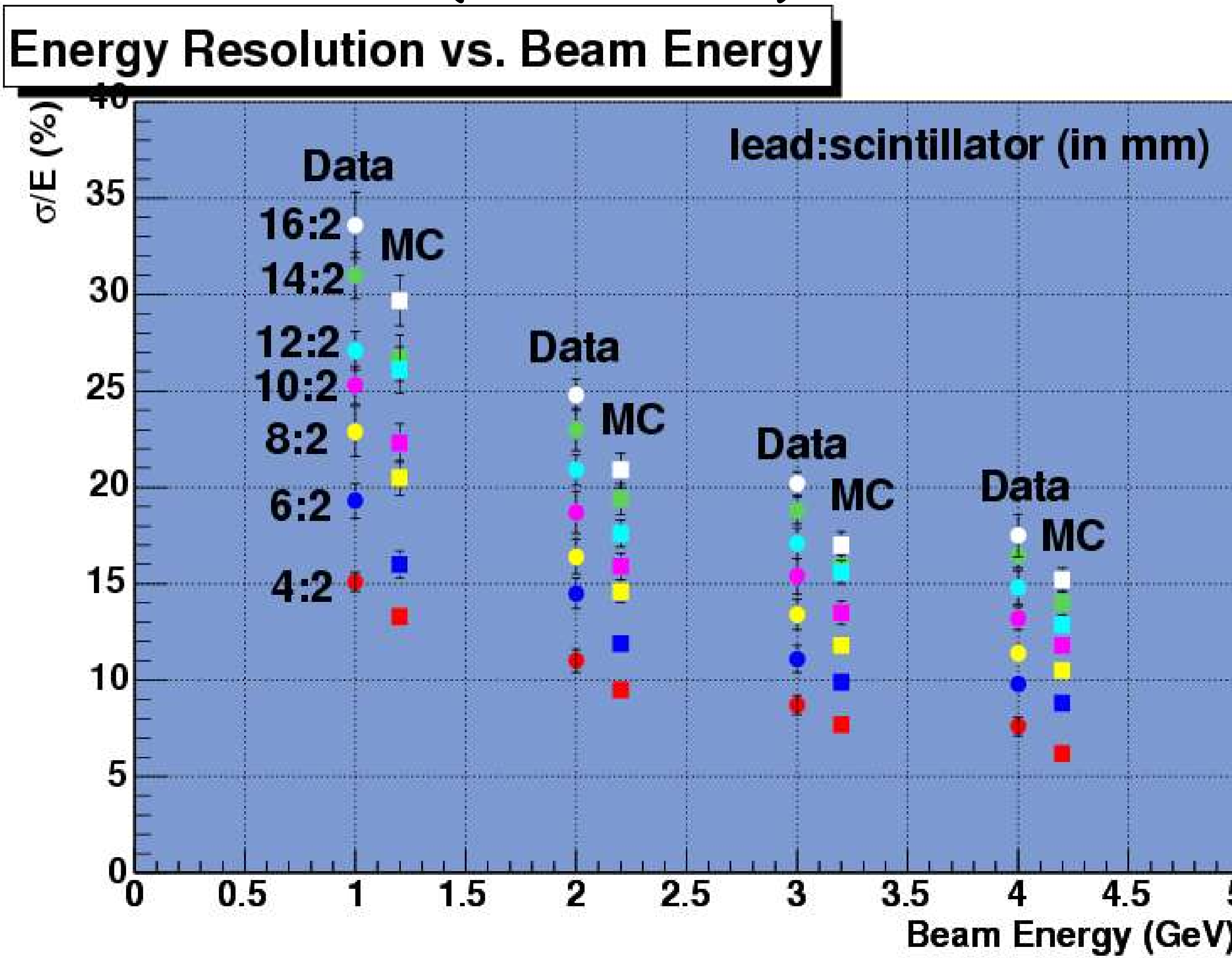
ECAL Study: NIMA paper

Data: Beam test (T405 & T411) at KEK in 1999



ECAL Study: data vs. MC

Data: Beam test (T405 & T411) at KEK in 1999



ECAL Study

Short Summary

- The comparsion between data and MC
  - Energy resolution sigma/E for electrons are done.
  - The results are close to each other, however, MC results are always lower than data.

Next

- Compare the energy resolution sigma/E for pions.
- Compare the e/pi ratio
- Finish the data vs. MC (NIMA 432, 48-65, 1999) comparsion.

Backup

EM Shower Model

Scitillator:

Layer → Tile (1 cm x 1 cm) x2 mm

1. Fast Simulation:

Based on the "<u>Berger and Seltzer approximation</u>"

Set:

Critical Energy Ec = 800 MeV/(Z + 1.2)

where Z = 3.6 for scintillator, C_9H_{10}

(6x9+1x10)/19 = 3.6

Z = 82 for Pb

ps. Different models may lead to different results, in general.

2. Mean longitudinal profile of the energy deposition in an EM shower is described by a gamma distribution.

3. Moliere radius R_M

Set:

$R_M = X_0 * 21$ MeV/Ec

Hadron Shower Model

Four kinds of the hadron shower models: (in PhysicsList)

- "LHEP" (fastest)
- QGSP
- QGSC
- FTFP

For neutral flux:

- LHEP_GN (fastest)
- QGSP_GN
- LHEP_HP
- QGSP_HP

Range Cut Study (Fujii-san's email)

1. How Range Cut Works:

A particle makes a step in Geant4 when a geometrical boundary is encountered or when some physics process is chosen to take process at some point along its trajectory.

When the range of the particle for the next step is calculated to be less than the range cut, Geant4 kills the particle there and deposits all of its energy there.

The same procedure applies to any secondary particles produced at the point of interaction: <u>a secondary particle is not acutually created if its range is less than the range cut</u>. Its energy will be deposited at the point of interaction, instead.

Range Cut Study (Fujii-san's email)

2. Range Cut and Multiple Scattering

The multiple scattering is the most frequent process that decides step points since it has usually the shortest mean free path.

When the range cut is larger than the mean free path for multiple scattering, those <u>low E particles near the Pb-Sci boundaries</u> which would have reached the active layers <u>will be lost</u> if their range values are less than the range cut.

Range III

The energy deposit will be independent of the range cut, once the range cut exceeds the mean free path significantly, since then the multiple scattering will be the <u>main stopper</u> near the Pb-Sci boundaries.

Range II

Range Cut Study (Fujii-san's email)

2. Range Cut and Multiple Scattering (continuum)

The mean free path decides a typical step size. If the mean free path is much smaller than the range cut value, Geant4 checks very frequently the condition for further propagation: range > the range cut.

Range III

"The mean free path controls the frequency of this assertion. "

This condition will hence be violated as soon as the range gets closer to the range cut value, resulting in a premature termination of particle propagation.

Range II

Range Cut Study (Fujii-san's email)

2. Range Cut and Multiple Scattering (continuum)

On the other hand, once the range cut value is reduced significantly below the mean free path for multiple scattering, the particles will keep propagating in the materical without any artificial interruption. Range I

When multiple scattering is completely switched off, there is no significant artificial stopper and the particles will keep propagating. Page 5

In addtion, the projected range to the shower axis will become longer, since transverse kick due to multiple scattering will be absent. The energy deposit in active layers will be thus significantly higher than the MS-on case.

Range Cut Study (Fujii-san's email)

3. Expected Energy Recovery for Short Enough Range Cut

The energy recovered when the range cut value is set significantly below the mean free path for multiple scattering is at most the energy which would have been deposited in the absober regions of about the mean free path thick (~10microns in Pb?) near the Pb-Sci boundary.

The energy fraction should then be at most 10microns/1mm of the energy deposited in the absorber layers.

Since the energy deposit in the absorber layers is O(10) times larger than that in the active layers, we may hence expect a (10/1000)xO(10)=O(10%) increase in the energy deposit in the active layers.

7.5 MeV/20 MeV = 37.5%

Sampling Calorimetry

Price?

- Usually, digital calorimeter is cheaper than analog calorimeter.

ECAL, Digital or Analog ?

- In our Jupiter setting, ECAL is an Analog calorimeter.

HCAL, Digital or Analog ?

- In our Jupiter setting, HCAL can be an Analog or a Digital calorimeter.

Analog Readout

- Energy Deposit in the scitillator tiles

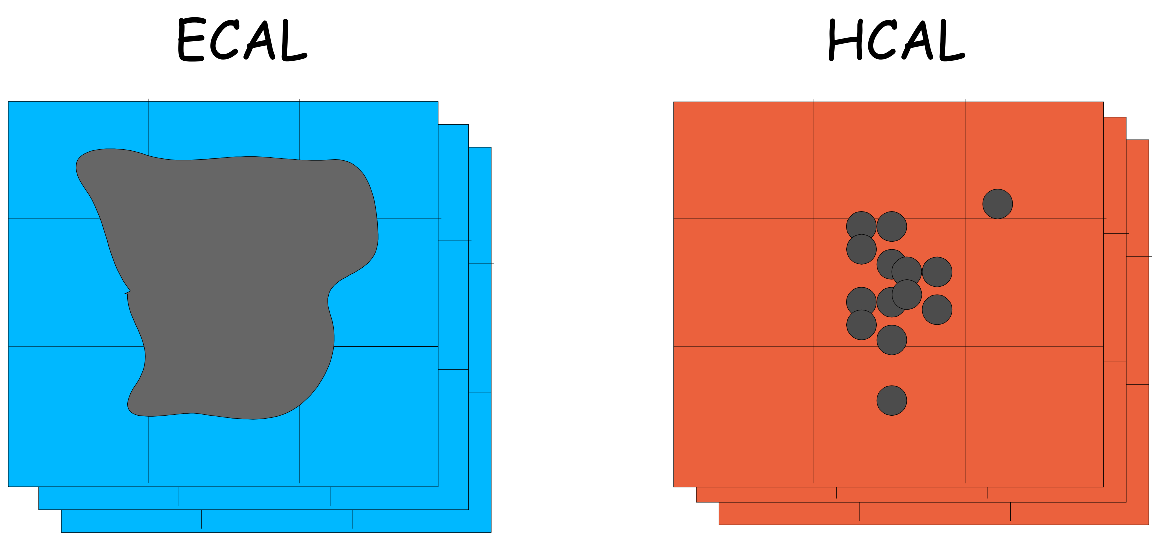
Digital Readout

- Number of Hits in the scitillator tiles

Particle Flow Algorithm (PFA)

Density-Based PFA (Energy Flow)

- Density-based clustering in both ECAL and HCAL
- Clusters matched to tracks are replaced by their generated momentum
- For ECAL, clusters use energy of associated cells
- For HCAL, clusters use nHit based energy estimate



Particle Flow Algorithm (PFA)

Track-First PFA

ANL, SLAC

1st step - Track extrapolation through Calorimeter

- substitute for Calorimeter cells (mip + ECAL shower tube + HCAL tube; reconstruct linked mip segments + density-weighted hit clusters)

- Calorimeter granularity/segmentation optimized for separation of charged/neutral clusters

2nd step - Photon finder

- use analytic long./trans. energy profiles, ECAL shower max, etc.

3rd step - Jet Algorithm

- tracks + photons + remaining Calorimeter cells (neutral hadron contribution)

- Calorimeter clustering not needed → Digital HCAL?

Particle Flow Algorithm (PFA)

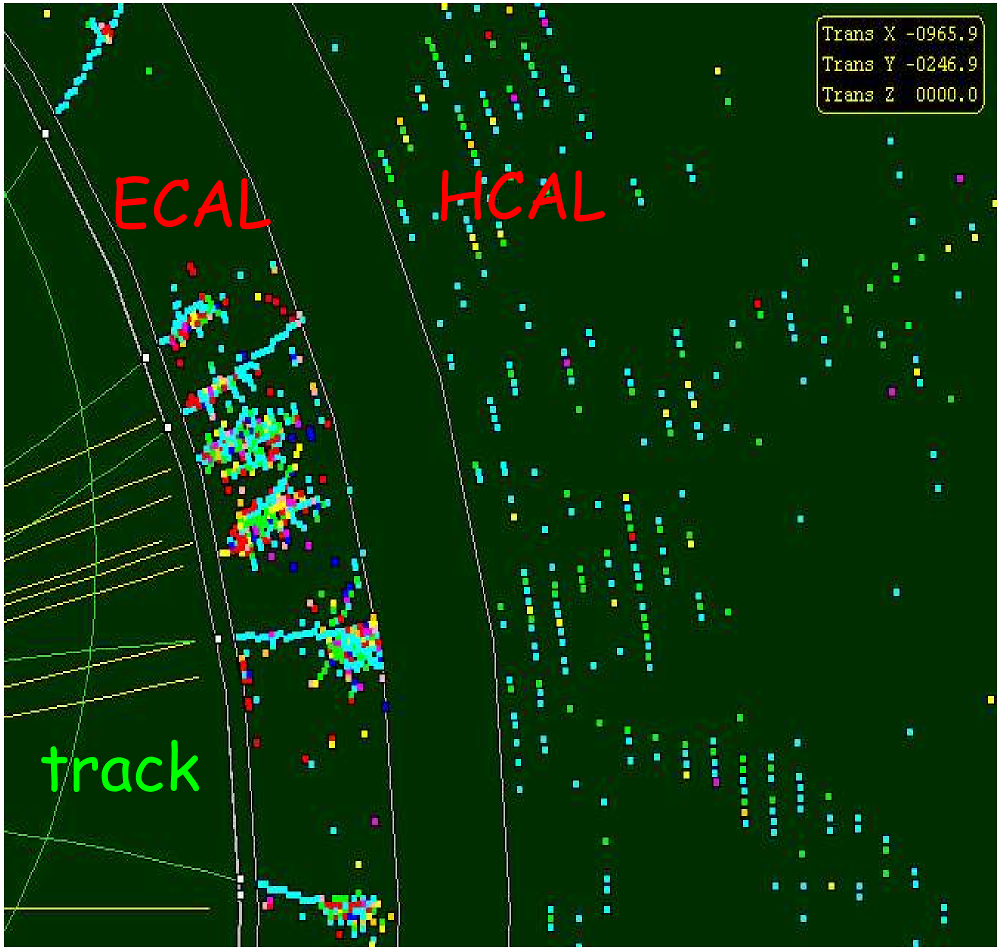
Motivation for Track-First PFA

ANL, SLAC

Charged particles
~ 62% of jet energy
→ Tracker $\sigma/p_T \sim 5 \times 10^{-5}\, p_T$
~190 MeV to 100 GeV jet energy resolution

Photons
~ 25% of jet energy
→ ECAL $\sigma/E \sim 15\text{-}20\%/\sqrt{E}$
~900 MeV to energy resolution

Neutral Hadrons
~ 13% of jet energy
→ HCAL with $\sigma/E \sim 80\%/\sqrt{E}$
~3 GeV to energy resolution

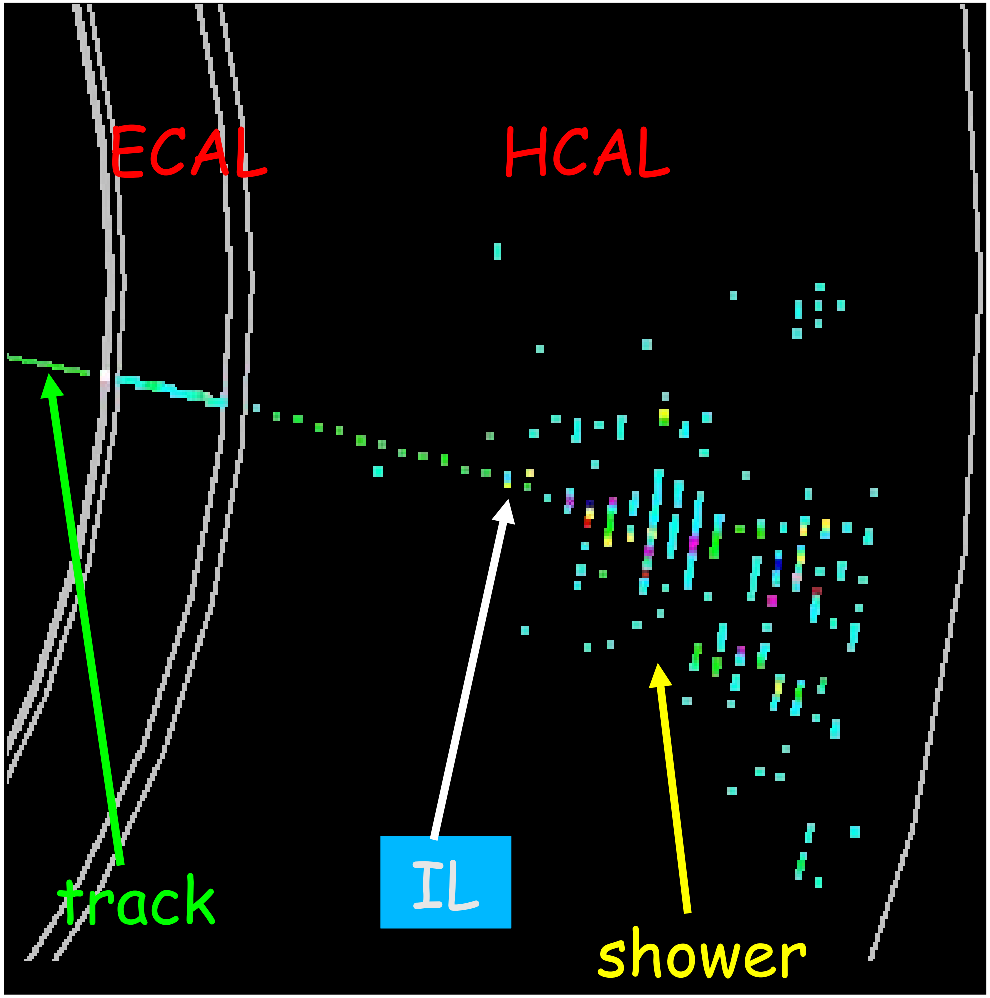


Also, since ECAL is dense, hadrons are optimally separated from photons (starting point of shower longitudinally)
→ 75% of hadrons shower after photon shower-max in ECAL

Particle Flow Algorithm (PFA)

Shower Reconstruction

ANL, SLAC



Mip reconstruction :

Extrapolate track through CAL layer-by-layer

Search for "Interaction Layer"

→ Clean region for photons

Shower reconstruction :

Define tubes for shower in ECAL, HCAL after IL

Optimize, iterating tubes in E,HCAL separately (E/p test)

Particle Flow Algorithm (PFA)

Single 10 GeV Pion – event display comparison

ANL, SLAC