LINEAR COLLIDER COLLABORATION

World-Wide Studies of ILC Physics and Detectors

FCAL Collaboration High precision design

Optimization of the BeamCal Design (simulation studies)

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on behalf of the FCAL collaboration

HELMHOLTZ | ASSOCIATION

LCWS'14 | Vinca Institute, Belgrad | 9 October 2014

DESY

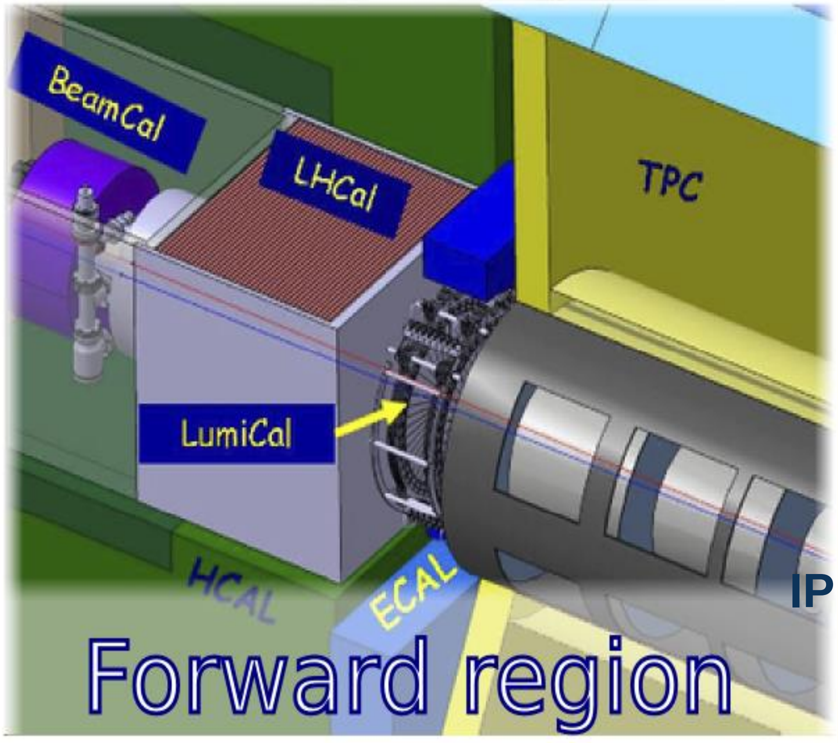
The Aim and Content

The Aim: compare performance of BeamCal for 2 types of segmentation, investigate signal digitization

Content:

- Introduction
- Simulation studies
  - reconstruction algorithm
  - fake rate
  - efficiency
  - energy resolution
- Signal digitization
- New BeamCal design proposal based on sapphire sensors
- Summary

Beam Calorimeter at ILC

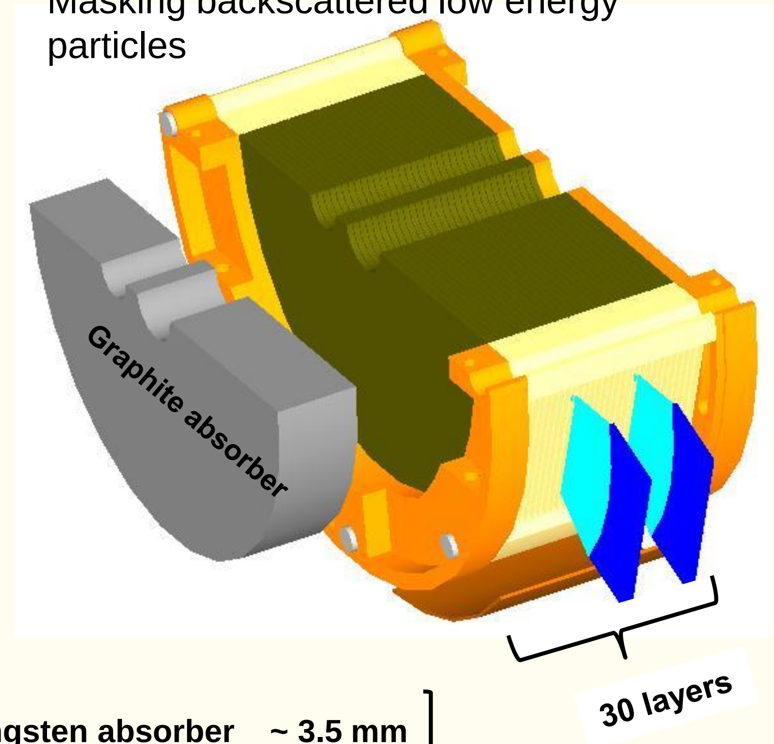


Beam parameters from the ILC Technical Design Report (November 2012)

- Nominal parameter set
- Center-of-mass energy 1 TeV

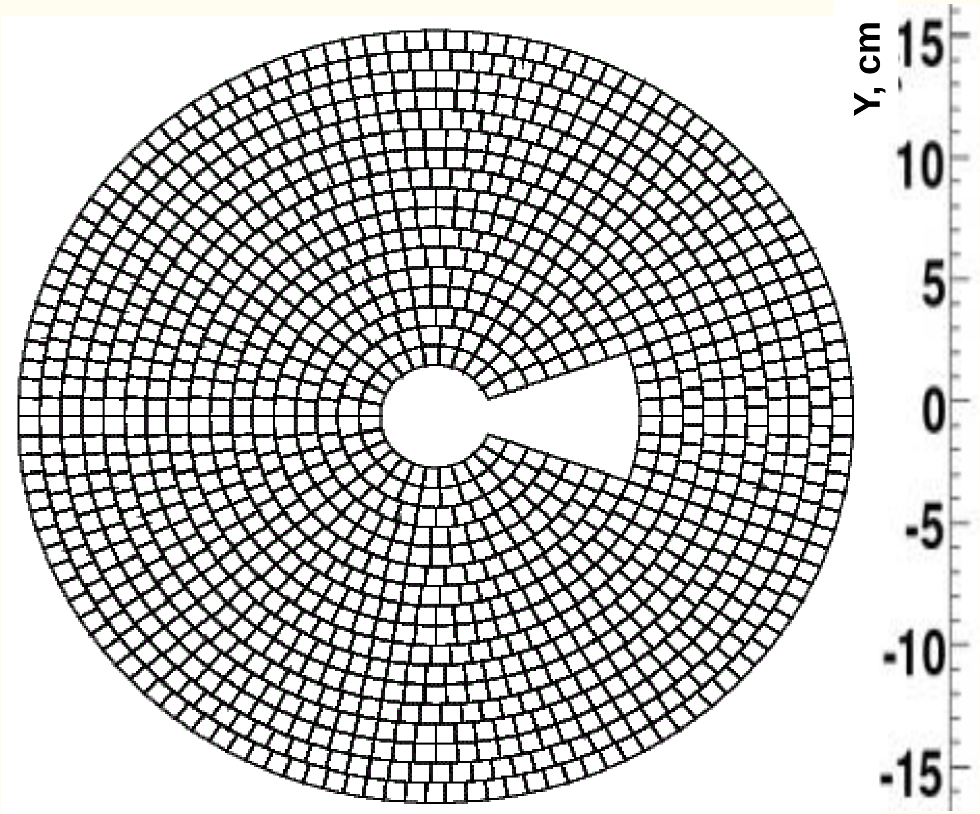
Purposes of BeamCal:

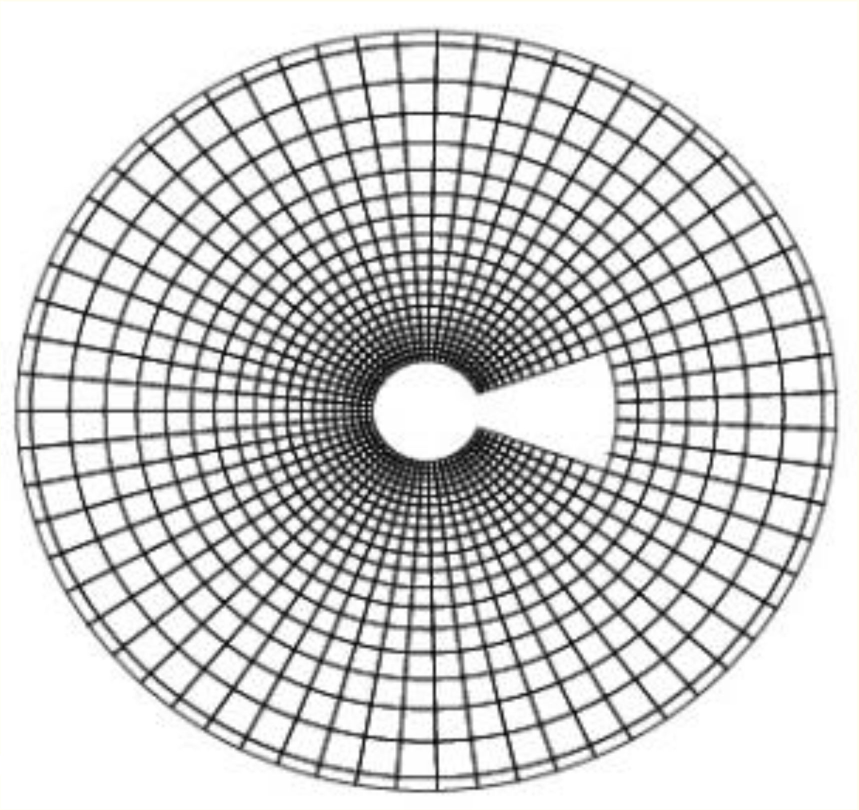
- Detect showers(SH) from single high energy electrons on the top of the background (BG)
- Determine Beam Parameters
- Masking backscattered low energy particles



Tungsten absorber	**~ 3.5 mm**	**1 X_0**
Sensor	**~ 0.3 mm**	
Readout plane	**~ 0.2 mm**	

BeamCal Segmentation





Uniform Segmentation (US)

Proportional Segmentation (PS)

pad sizes are the same

pad sizes are proportional to the radius

number of channels almost the same

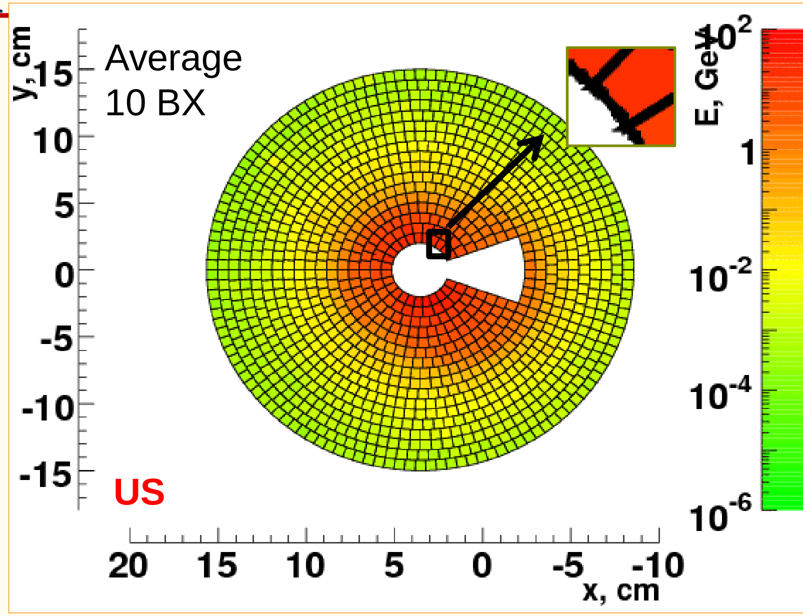
Energy Deposition due to Beamstrahlung

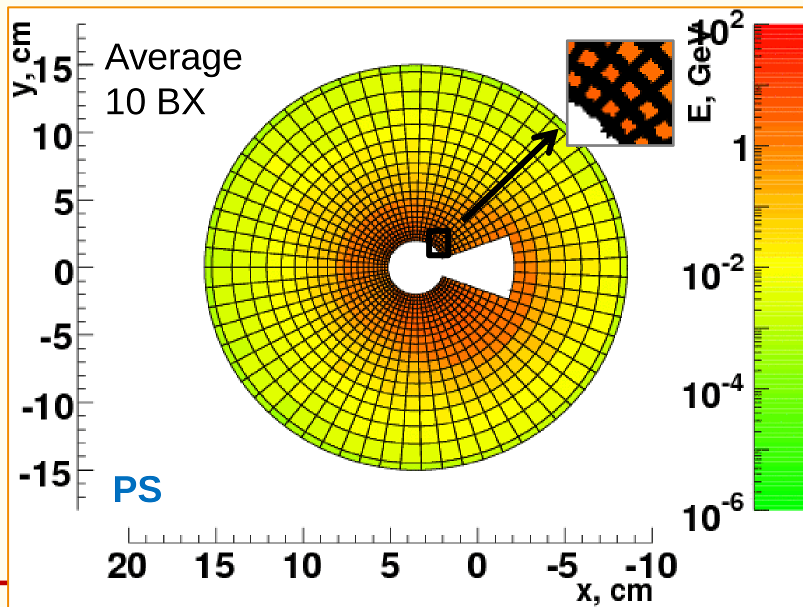
- Beamstrahlung (BS) pairs generated with Guinea Pig
- Energy deposition (E_dep) in BeamCal sensors from BS simulated with Geant4

  ⟶ *considered as a Background*
- RMS of the averaged BG

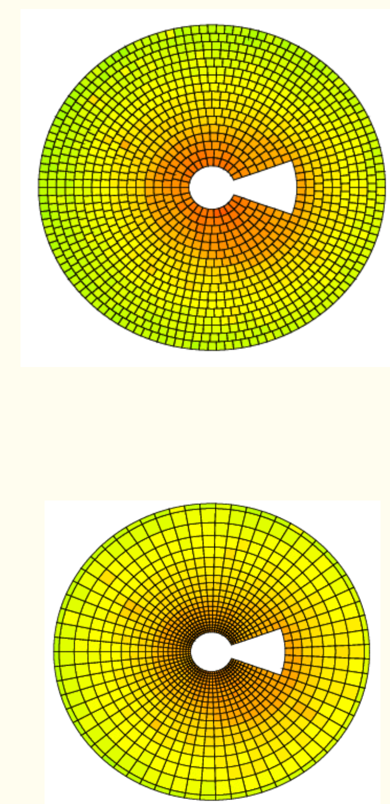
  ⟶ *used for energy threshold calculation*

E_{dep} is the same, but E_{dep}/pad is different!





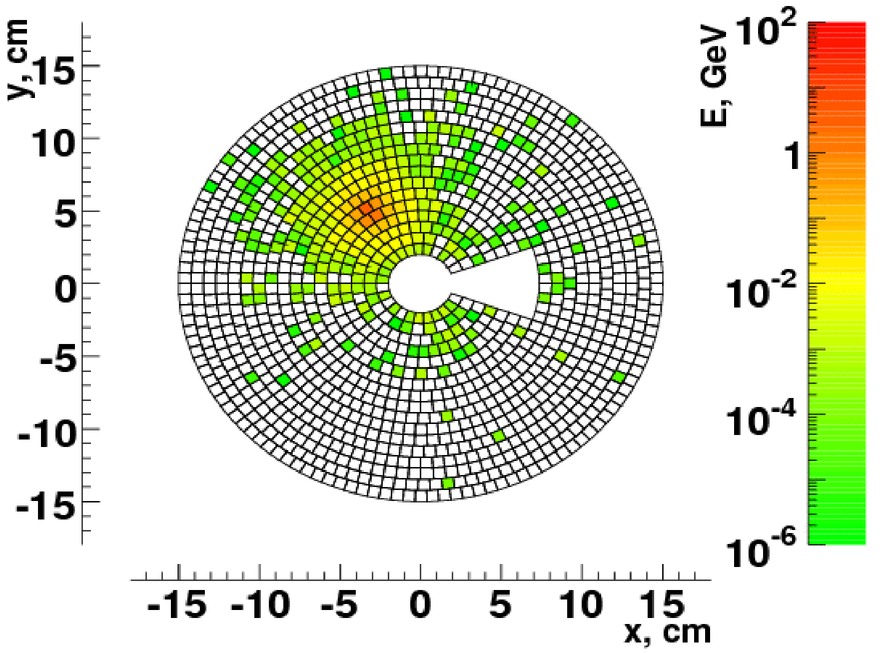
RMS



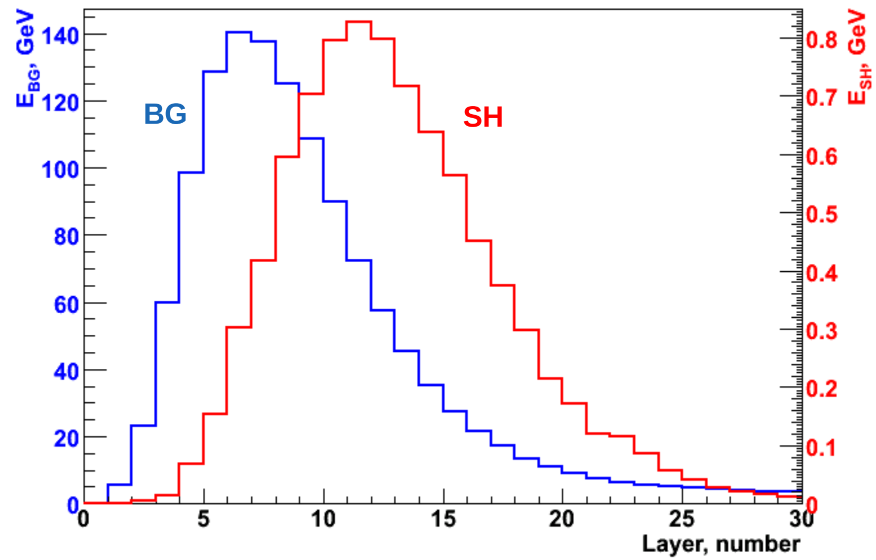
Figures show sum of all layers

Example of 500GeV SH. Longitudinal E_{dep} for SH&BG

Shower from 500 GeV electron



Longitudinal distributions of energy deposition in whole calorimeter from background and 500 GeV shower



- ***At some areas BG energy deposition is several times higher than deposition from the electron***
- ***But due to the relatively low energy of BS pairs, the background and shower have different longitudinal distributions***

Reconstruction Algorithm

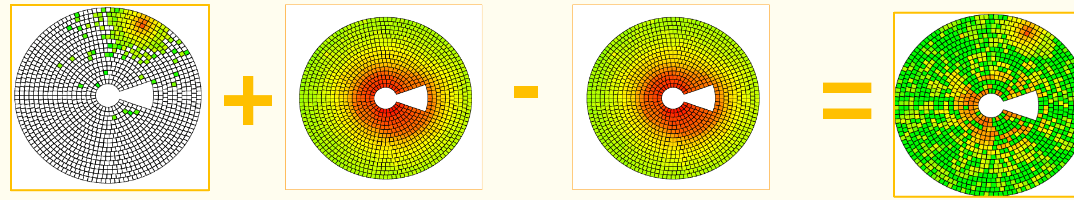
With BG

Without BG

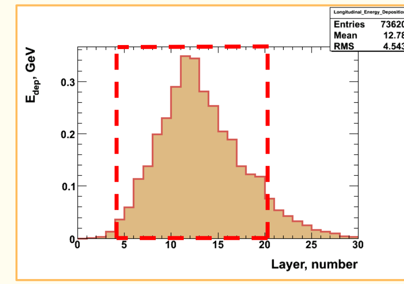
1. SH + BG – average by 10th previous BXs BG
2. Consider layers from **5th** to **20th**
3. Select pads with energy above threshold energy , **3** RMS, and combine them to towers
4. Search tower with max number of pads
   * if there ≥ **9** pads (not necessarily consecutive) – consider this tower as shower core
5. Search for neighbor towers
   * if in neighbor ≥ **6** pads & at least 1 neighbor => shower defined
   * Neighbor towers are considered to shower within Rm=1.2 cm or at least 8 towers around core
6. For each shower calculated
   - R_{COG}, φ_{COG}, E_{sh}

SH BG Average BG

1

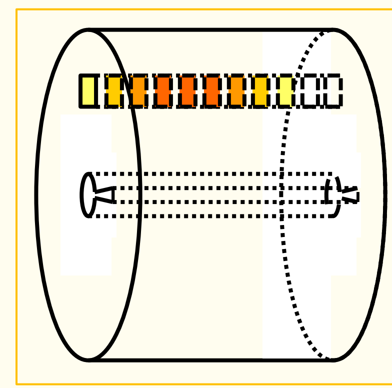


2



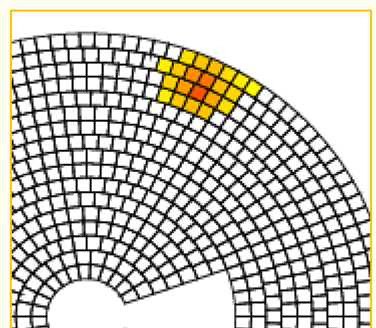
Tower

3



Reconstructed SH

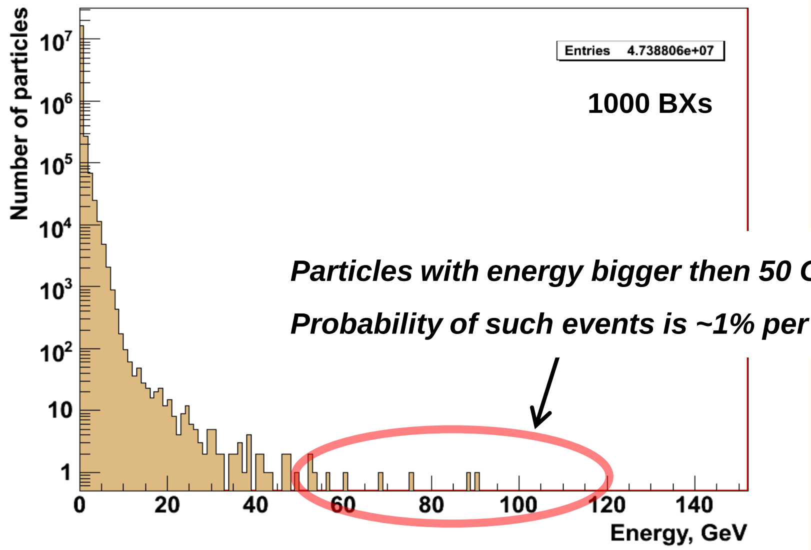
6



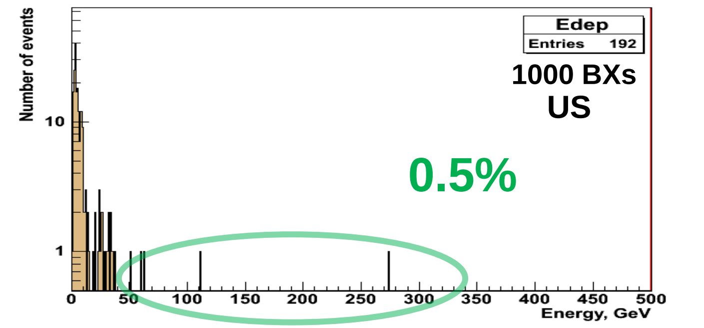
The parameters of algorithm (red numbers) have gotten from optimization

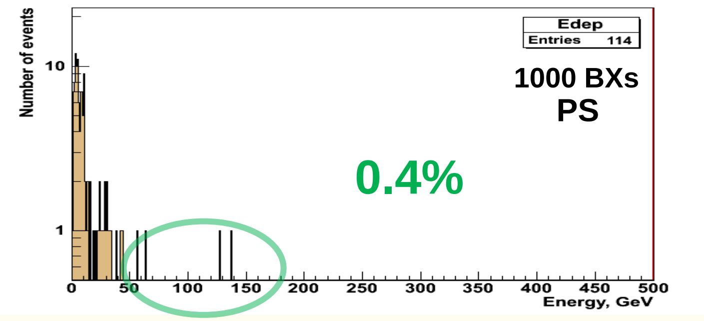
Beamstrahlung (BS) Energy Distribution & Fake Rate

Energy distribution of BS pairs that hit BeamCal



Energy distribution of reconstructed showers from pure background





⇒ *Some part of high energetic particles from Beamstrahlung, which hit BeamCal, can cause "fake showers"*

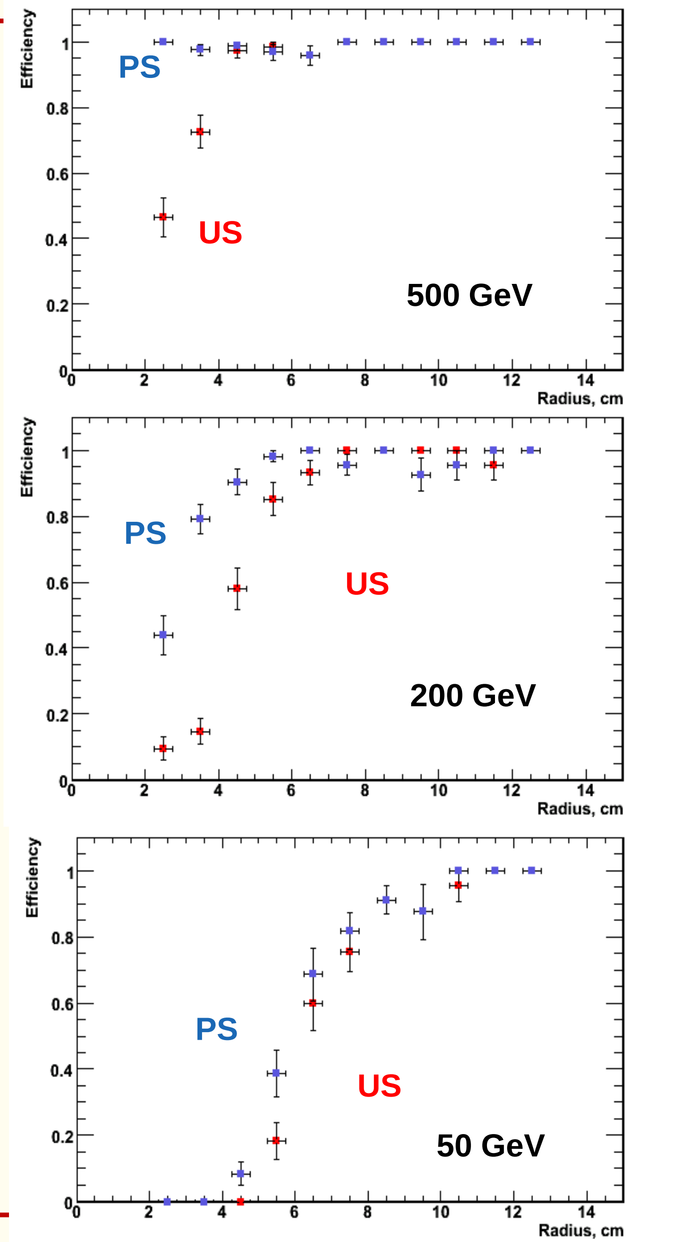
⇒ *Also fluctuations of background can be recognized as a shower by reconstruction algorithm*

Efficiency of shower reconstruction as a function of radius

Shower is considered as correctly reconstructed if:

- distance

$$| (X,Y)_{true} - (X,Y)_{reco} | \leq R_{moliere}$$

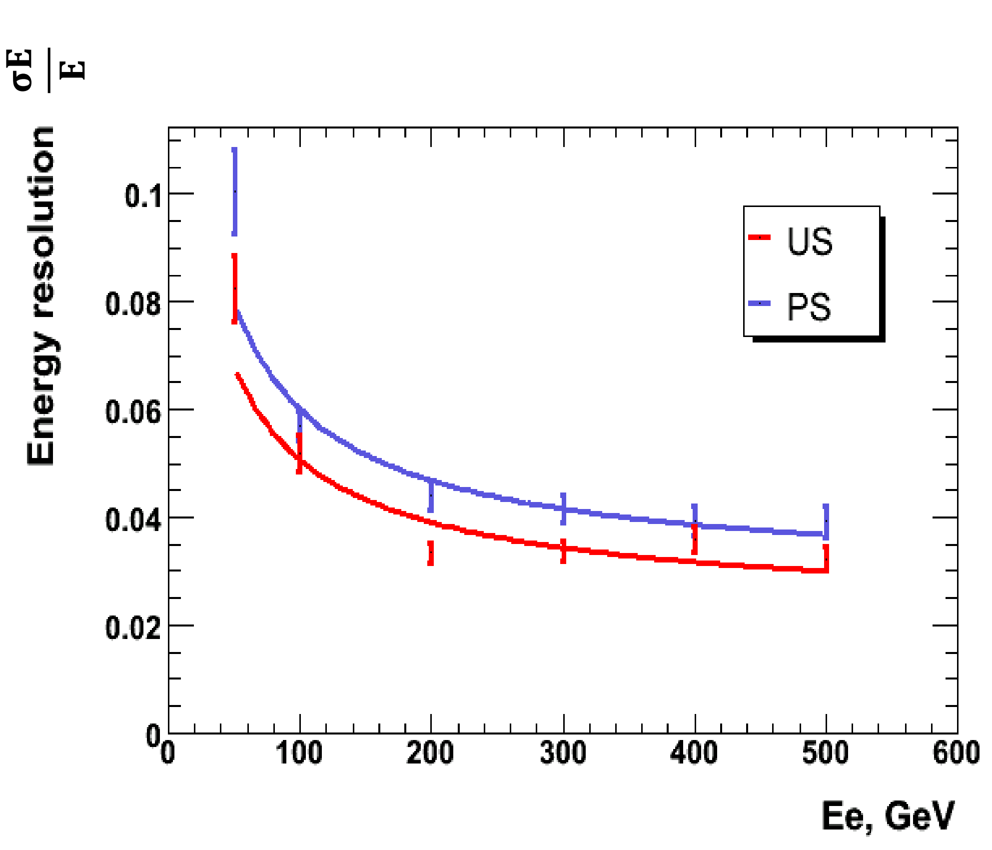


Number of events 500

- 500 GeV electrons detected with 100% efficiency by PS even at high background area, while US detects efficient, but concede at this area
- 200 GeV electrons can be efficiently detected at radii larger then ~4 cm, while PS performs better
- 50 GeV electrons can be efficiently detected only at R ≥ 7cm

Energy resolution vs Energy of Electron for low BG area

7<R<14 [cm]



Relative energy resolution parameterized as

$$\frac{\sigma E}{E} = \frac{A}{\sqrt{E}} \oplus \mathbf{B}$$

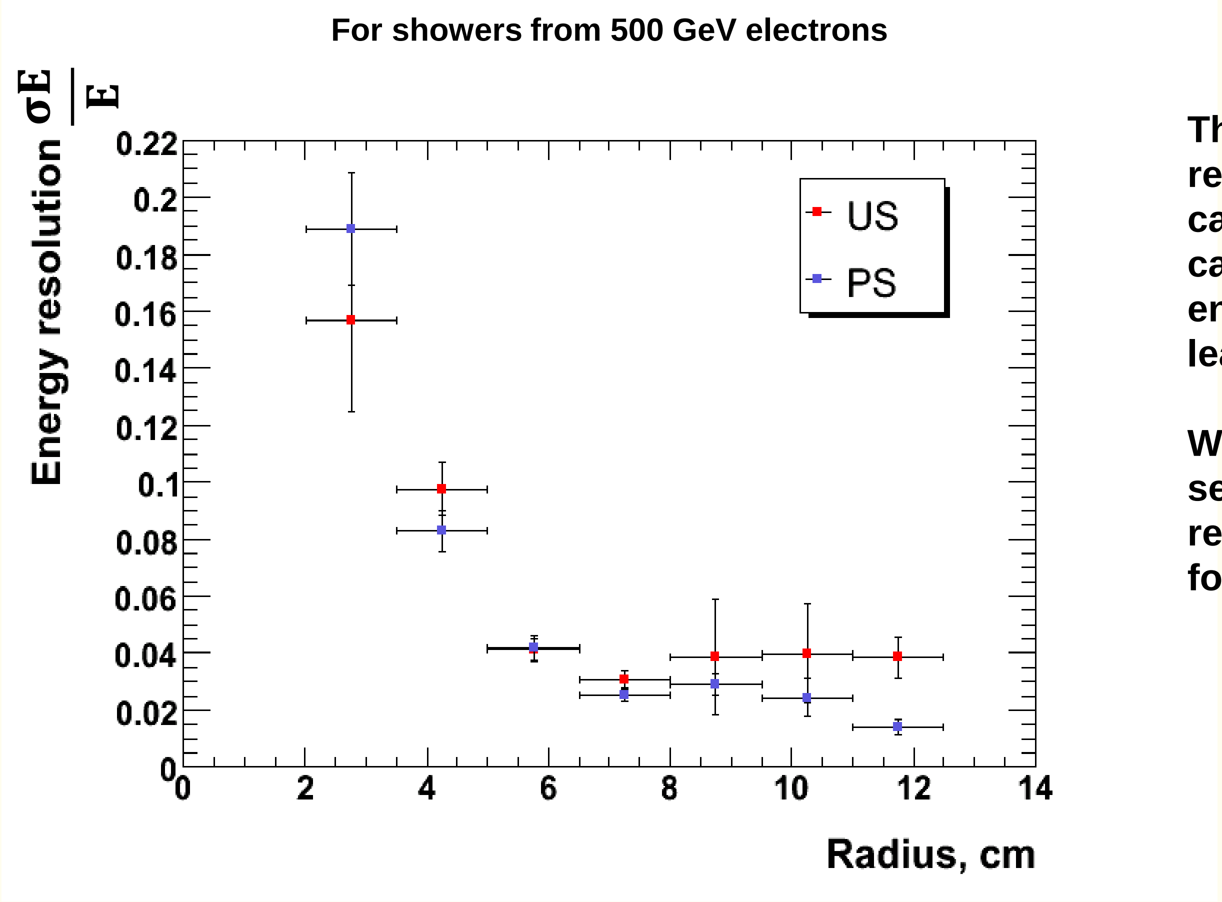
For the ideal case (without BG) A ~ 0.2

For reconstructed showers on top of the background :

$$A_{US} \sim 0.46 \qquad B_{US} \sim 0.02$$
$$A_{PS} \sim 0.53 \qquad B_{PS} \sim 0.03$$

The energy resolution for PS is worse, because the Edep along radius varies more for PS then for US

E resolution vs Radius



The large values of the energy resolution in the first 2 cm of calorimeter (R<4cm) are caused by the high background energy density and the shower leakage

Within errors both segmentations give similar resolution as function of radius for the 500 GeV electrons

Energy resolution of the BeamCal varies significantly over the radius, depending on the background energy density

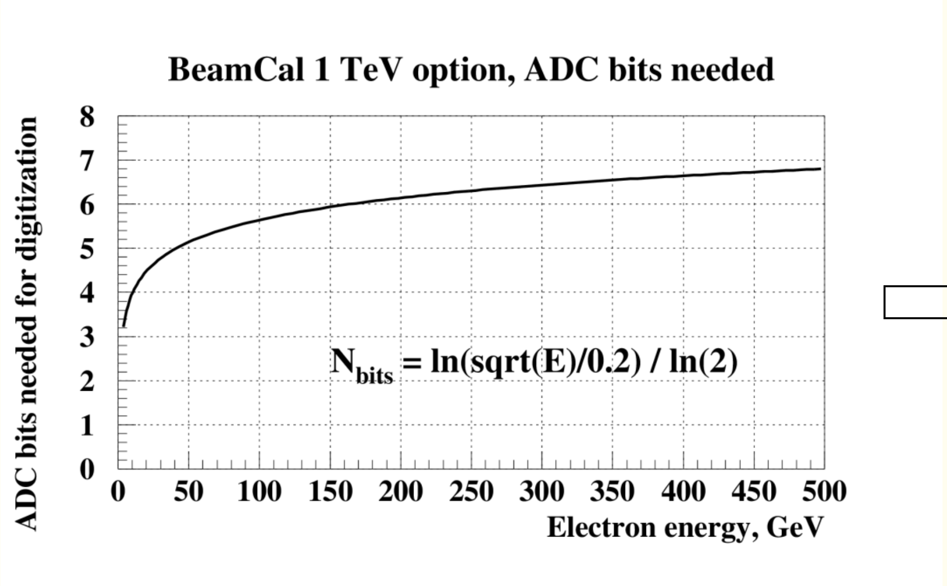
ADC bits needed to measure shower energy

- **Energy resolution of the sampling calorimeter :** $$\frac{\sigma E}{E} = \frac{A}{\sqrt{E}}$$

  For the BeamCal for ideal case (no BG) A ~ 0.2: $$\frac{\sigma E}{E} = \frac{0.2}{\sqrt{E}}$$

- **Ratio of the signal E to the absolute error σE gives number of bits N_{bits} that are necessary for charge measurement:** $$\frac{E}{\sigma E} = 2^{N_{bits}}$$

$$N_{bits} = \frac{\ln\frac{\sqrt{E}}{0.2}}{\ln 2}$$



- **7-bit number gives enough precision even at high energies**
- **Max E_{dep} from BG similar to 500GeV electron E_{dep} => need factor of 2 extension of the energy range => 8-bits**

BeamCal calibration. Estimates of charge range

- We want to calibrate sensors by MIPs during ILC operation
- Also MIPs can be used for estimation of degradation of sensors after irradiation

⇨ Electronics should be sufficiently precise for low signals

GaAs sensors, 300 micron thickness:

		Max collected charge per pad
MIP		4.3 fC
500 GeV electron		20 pC
BG	PS	20 pC
	US	120(!) pC

$$\frac{Q_{max}}{Q_{min}} = \frac{Q_{500GeV\ electron}}{Q_{MIP}} \sim 4500$$

=> 12-13 –bit ADC is needed

Note: this inner area of calorimeter with US is not effective!

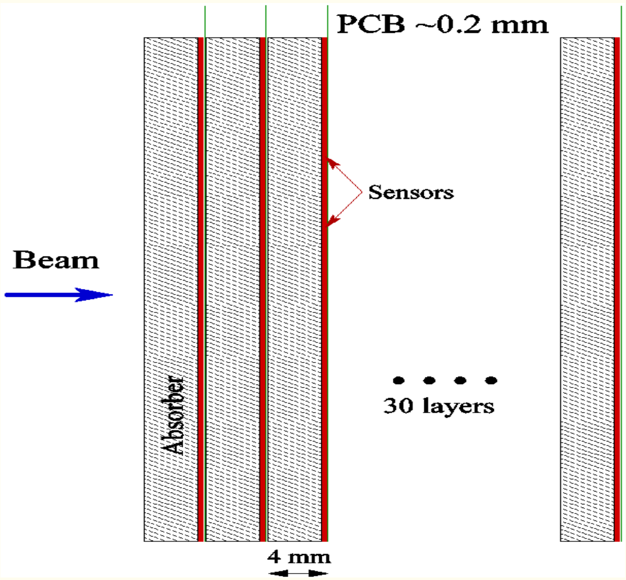
Solutions

- 2 channels from each pad: with low and high gain
  Reading either both together or only one channel chosen by threshold energy
- to turn sensors along beam direction (see next slides)

Proposal of new BeamCal design based on Sapphires

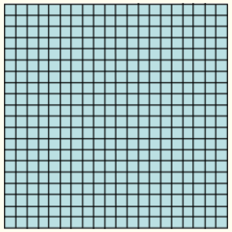
For comparison 2 designs of BeamCal models are considered:

baseline



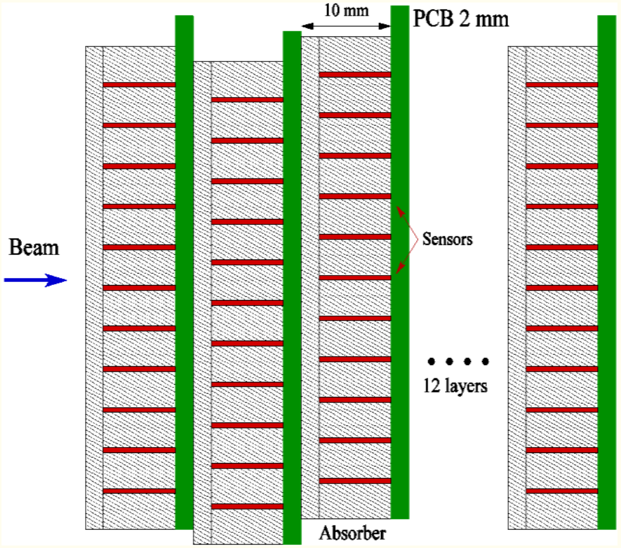
Transverse view:

150 x 150 mm



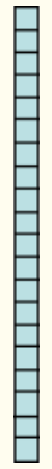
pads 7.5 x 7.5 mm

new



Sensor strip in depth:

7.5 x 150 mm



pads 7.5 x 7.5 mm

- **The main idea of the new design is to increase response of sensors to the MIPs, shifting calibration signal up in the "physical" working range, thus additional calibration mode is not needed anymore**
- **Longitudinal and transverse sizes for both designs are kept the same**
  Number of readout channels is 12000 for baseline design and 8880 for new one
- **Note: new design leaves much more space for electronics between layers ~10mm compare to 4mm at baseline design and fanout PCB could be made using standard multilayer technology**
- **In connection with new design new sapphire sensors are investigated. They are very cheap! very radiation resistant! and "small signal" down point is solved by turning sensors =>**

Cool!

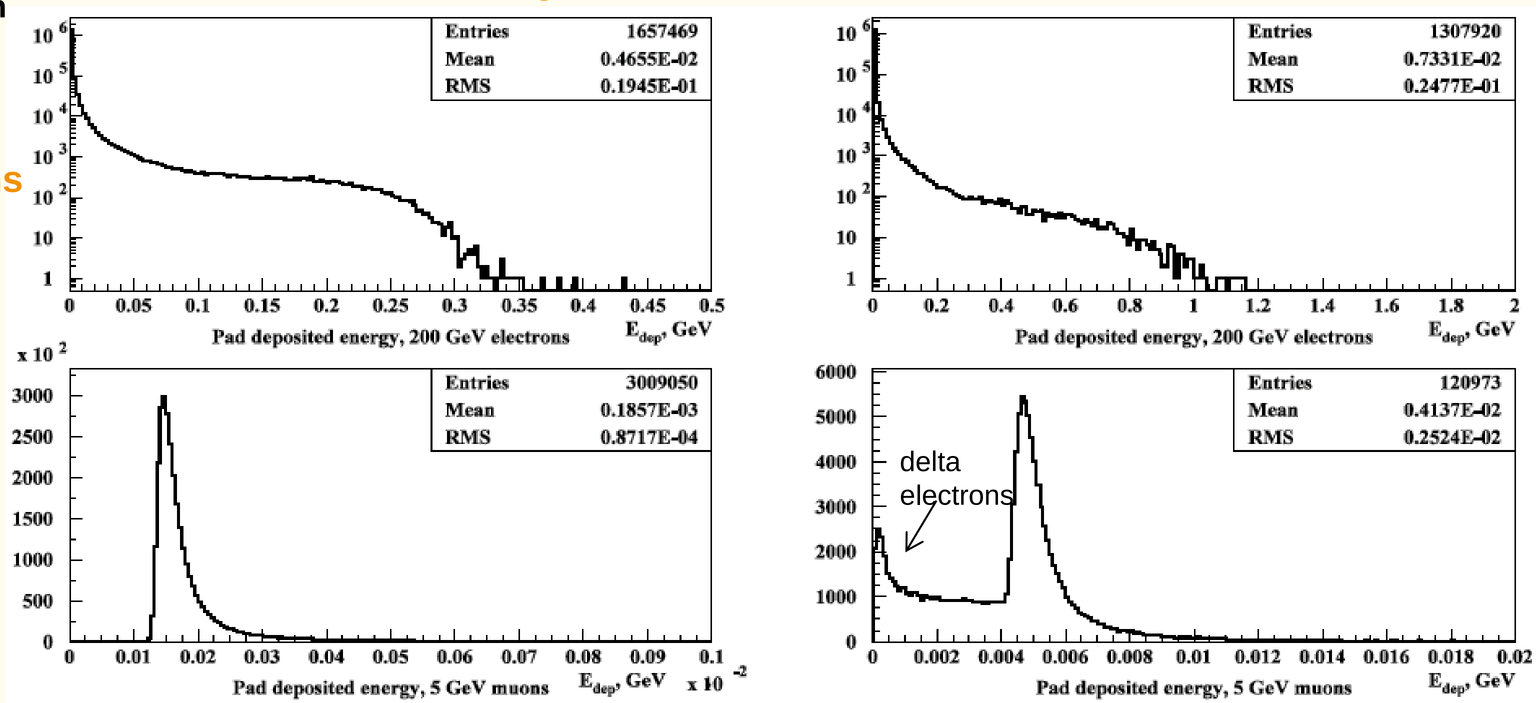
Testing new design: energy deposition in pads

Distribution of energy deposition per pad from:

Baseline design | **New sapphire design**

200 GeV electrons

5 GeV muons (MIPs)



2300 | 220

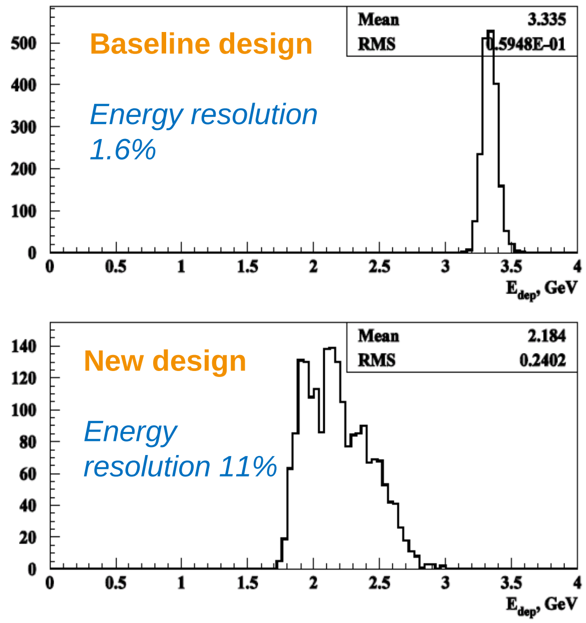
Dynamic range of the readout $= \frac{\textit{end point of 200 GeV } e^{-} \textit{ spectra}}{\textit{MPV of MIPs peak}}$

Due to sensors orientation for new design for the calibration 15 times more statistics is needed

From the other side, for new design no special runs are needed!

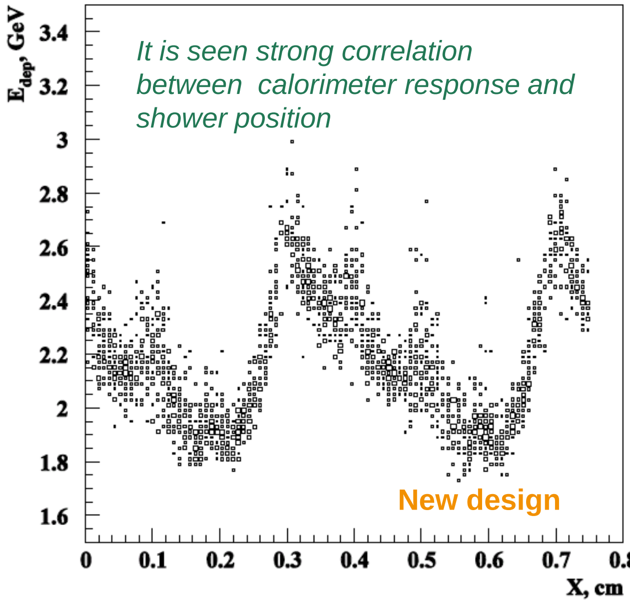
Testing new design: energy and spatial resolutions

Distribution of total sensors energy deposition for 200 GeV electrons:



Poor energy resolution for new design is caused by highly non-uniform sensors distribution in the transverse direction

Sensor energy deposition sum for 200 GeV electrons as a function of transverse coordinate X, which is perpendicular to sensor strips:



- ***Further optimization should include hardware compensation of non-uniformity (optimization of layers displacement) and software correction of the measured energy, based on the shower position determination***
- ***Spatial resolution of the new design is expected to be similar to the baseline one along the strips, and could be higher in perpendicular strips direction(higher sampling frequency)***

Summary

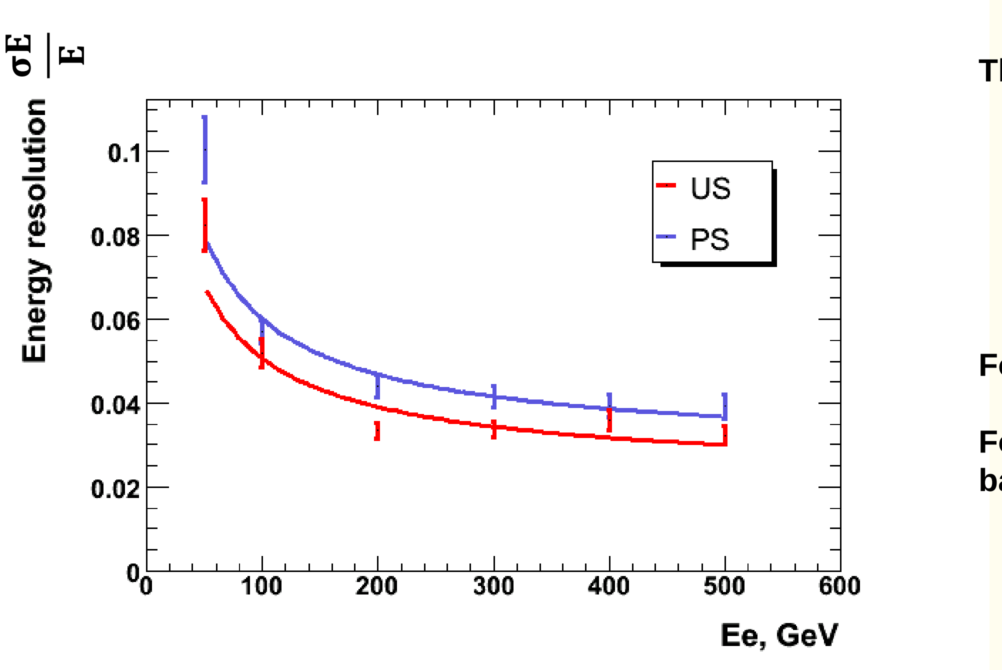
- Performance of BeamCal for two different sensor segmentations (US and PS) was compared by applying optimized reconstruction algorithm
  - The fake rate per BX for reconstructed showers E_{sh} > 50 GeV is 0.5% for US and 0.4% for PS. Energies below 50 GeV unreasonable to consider for reconstruction, since amount of such BS pairs is too big
  - 50 GeV showers can be efficiently reconstructed only at low BG area (R>7cm) . For higher energies showers can be reconstructed at most radii and PS performs better then US
  - Energy resolution for showers 200-500 GeV is around 4% and for lower energies it increases up to 10%.
  - Energy resolution as function of radius doesn't differ significant for both segmentations
- For the BeamCal calibration electronics should be sufficiently precise for low signals as well as for high signals. Solutions can be: reading signal from 2 channels with low and high gain or to turn sensors along beam direction
- New model of BeamCal with new sapphire sensors placed in parallel to the beam looks very promising
  - It reduces the dual gain requirement of the front-end
  - It is under study yet but it promising performance similar to baseline design

Thank you for your attention!

Backup slides

Energy resolution vs Energy of Electron for low BG area

7<R<14 [cm]



The relative energy resolution parameterized as

$$\frac{\sigma E}{E} = \frac{A}{\sqrt{E}}$$

For the ideal case (without BG) A~0.2

For reconstructed showers on top of the background :

$$A_{US} \sim 0.5$$
$$A_{PS} \sim 0.6$$

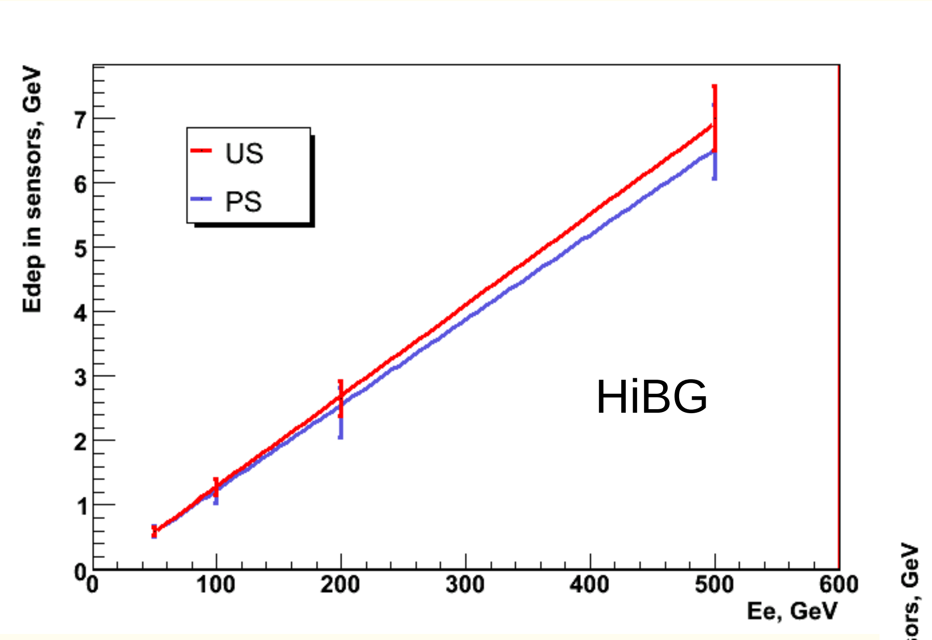
The energy resolution for PS is worse on low BG area because pads are bigger there

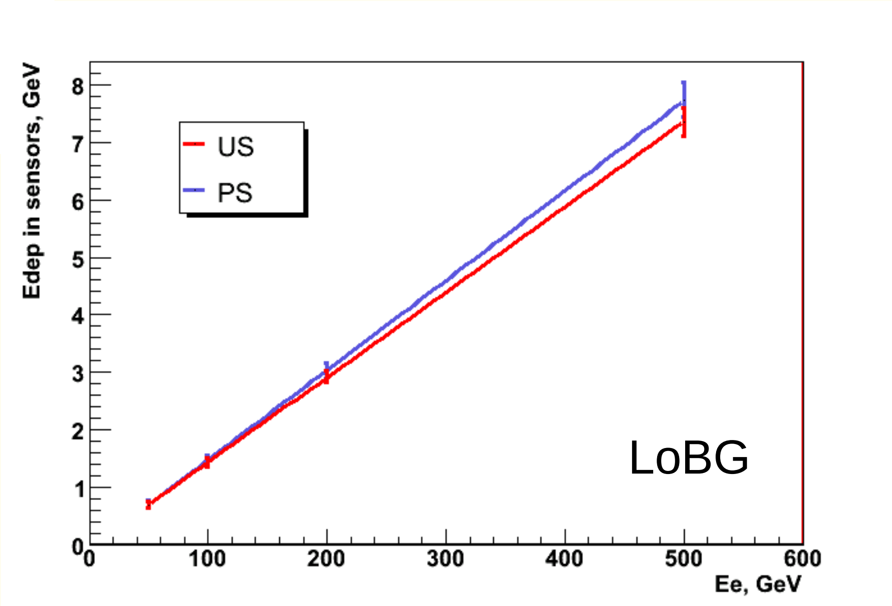
Spatial Resolution

$\frac{\sigma R}{R}$

For showers from
500 GeV electrons

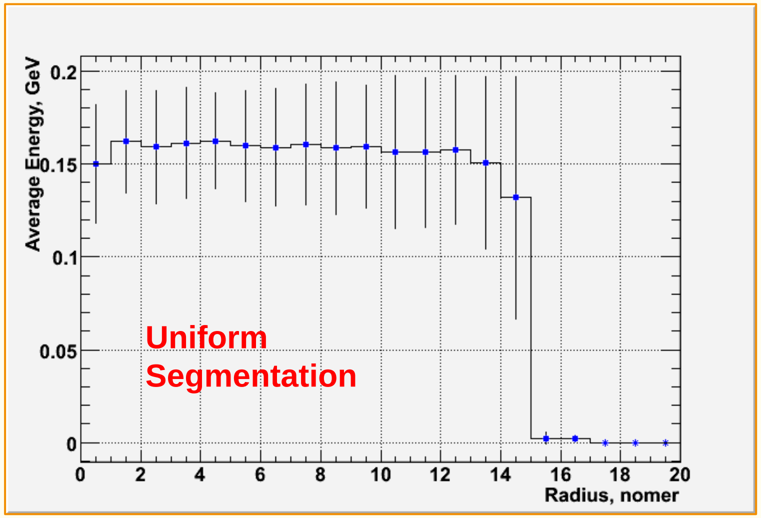
Energy Deposition in sensors vs Energy of Electron

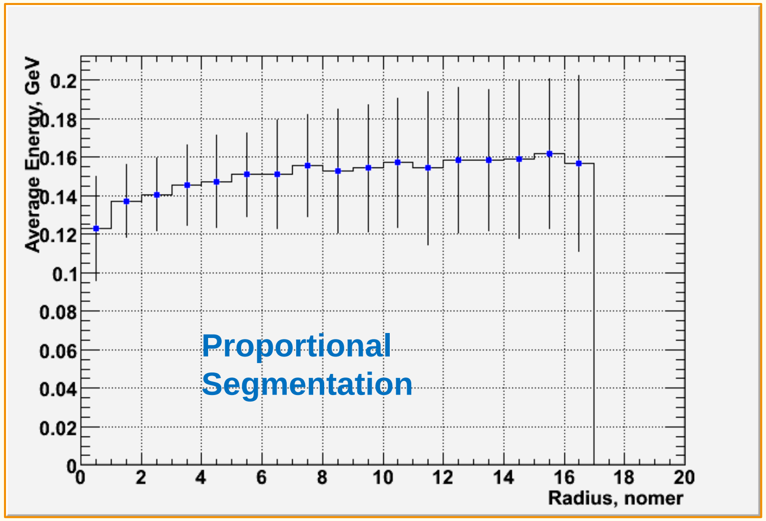




Signal and RMS for both Segmentations

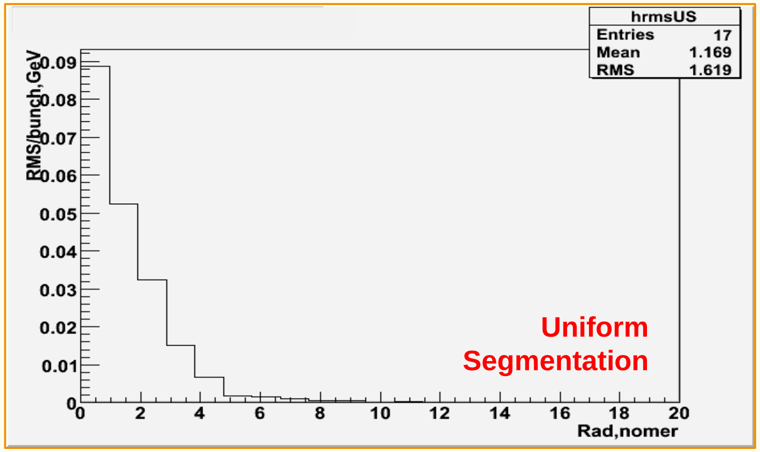
Core signal in layer of shower maximum (10th layer for 100 GeV)

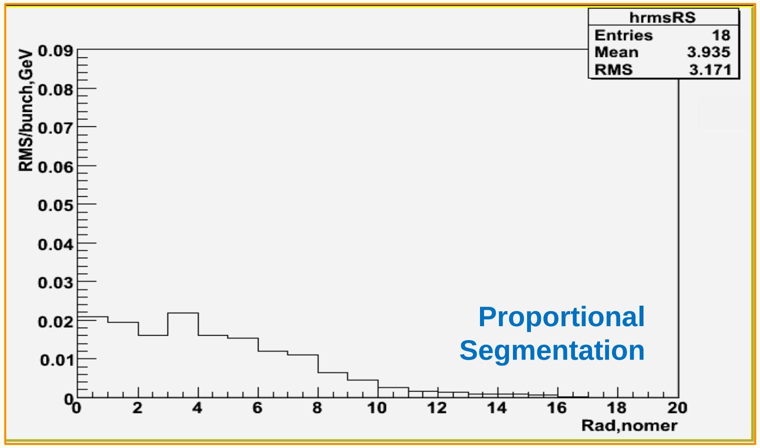




Signal nearly segmentation-independent!

RMS from Background (in 10th layer)





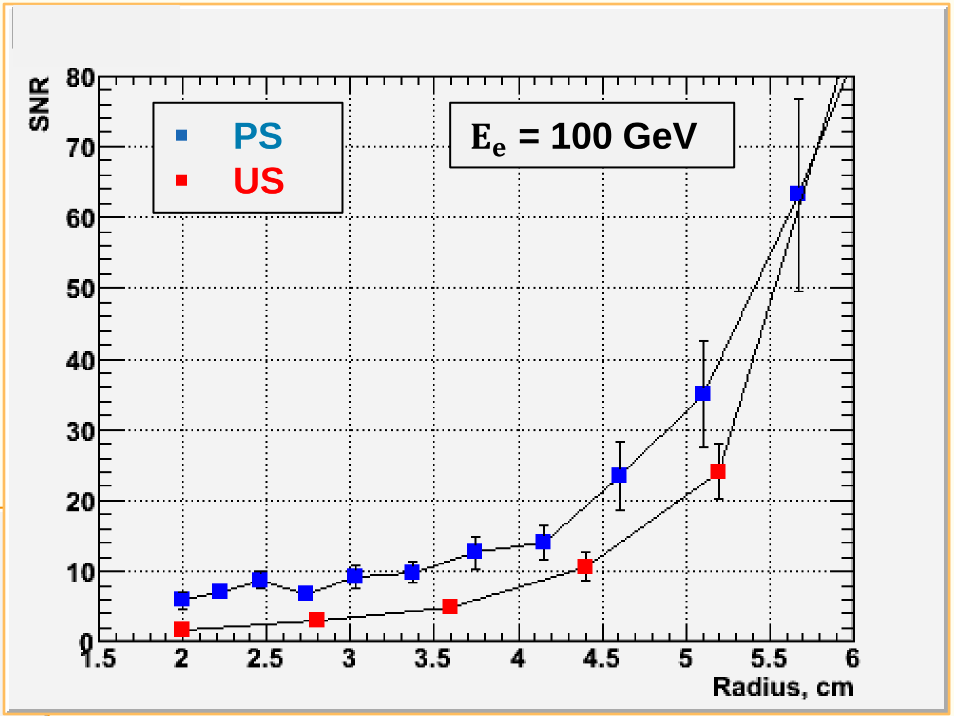
Different distributions!

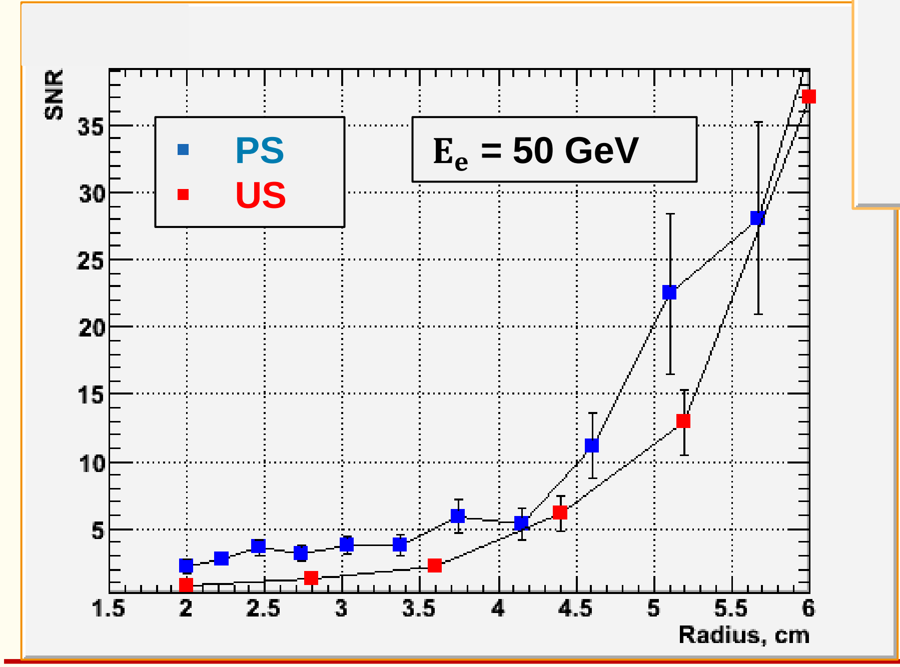
20 bunch crossings were given

SNR in cell with maximum E_dep

- <u>Signal</u> – is maximum energy deposition in cell from sHEe *(in the core of shower and in the maximum energy deposition layer)*

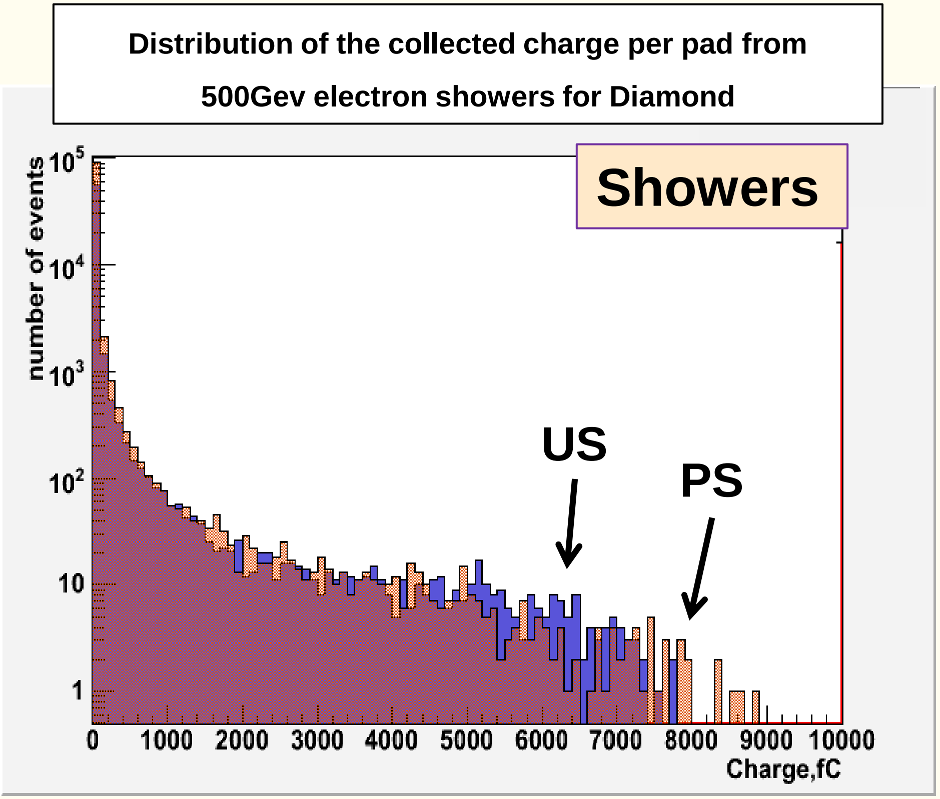
- <u>Noise</u> – is RMS of the averaged BG

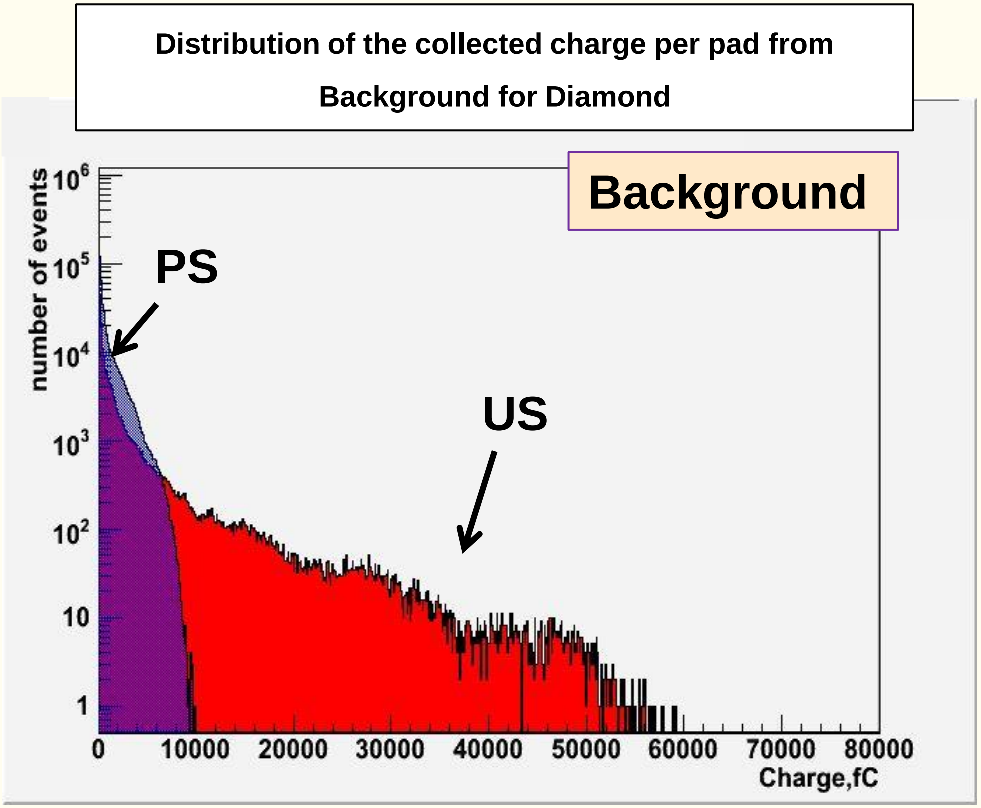




$$SNR = \frac{\text{signal from HE electron}}{\text{RMS from background}}$$

Charge Range Estimate



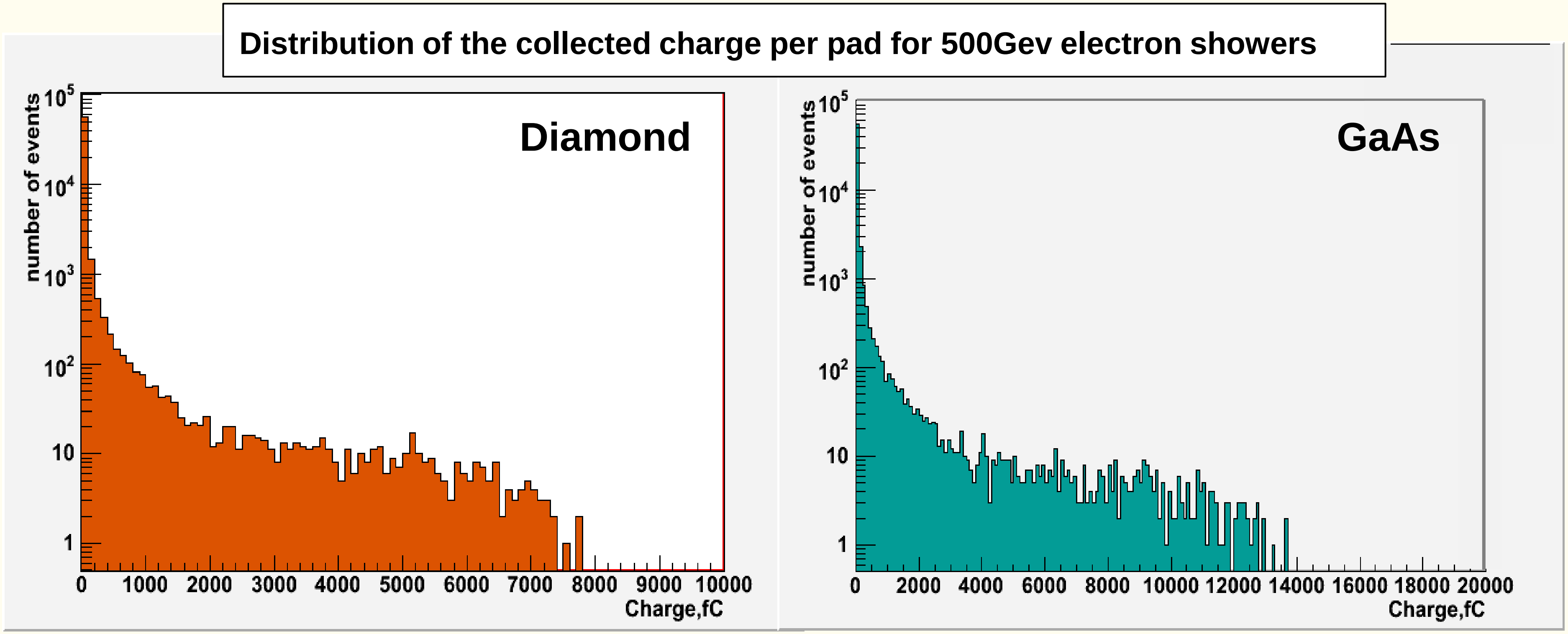


For Diamond sensor pad thickness 300 µm:

- **Charge collected from MIP: 2.44 fC**
- **Maximum charge collected – for shower from 500 GeV electron: 12214 fC**

(correspond to about 5000 MIPs)

Charge range estimate



For Diamond sensor pad thickness 300 μm:

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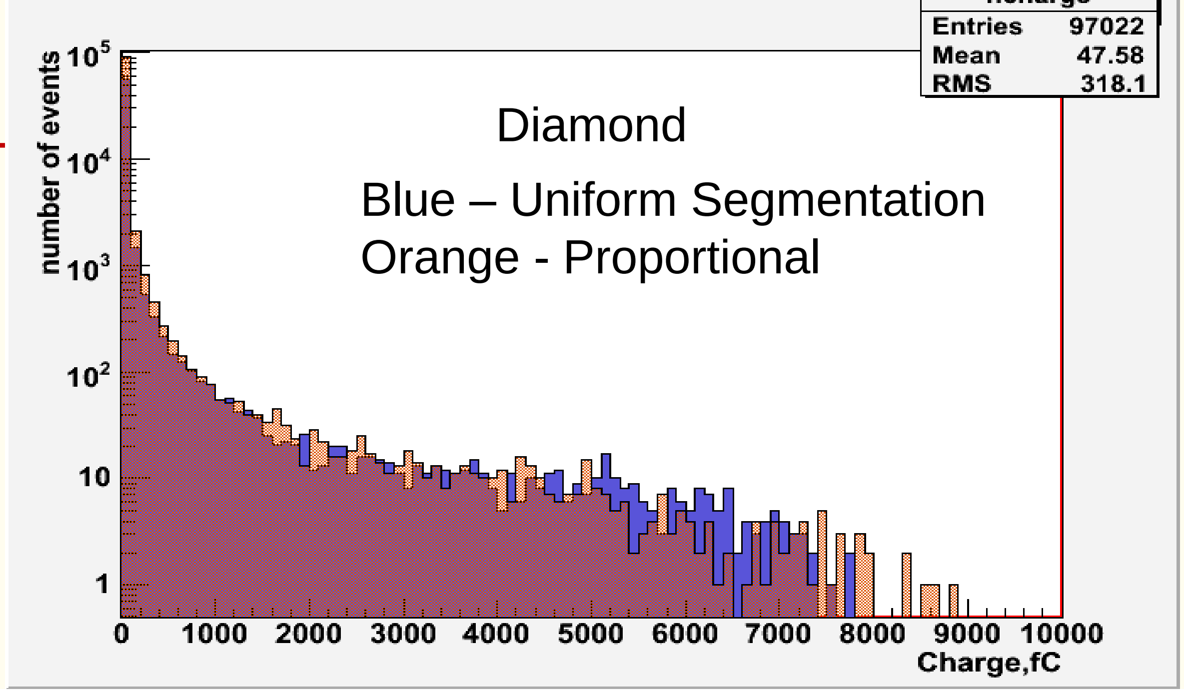
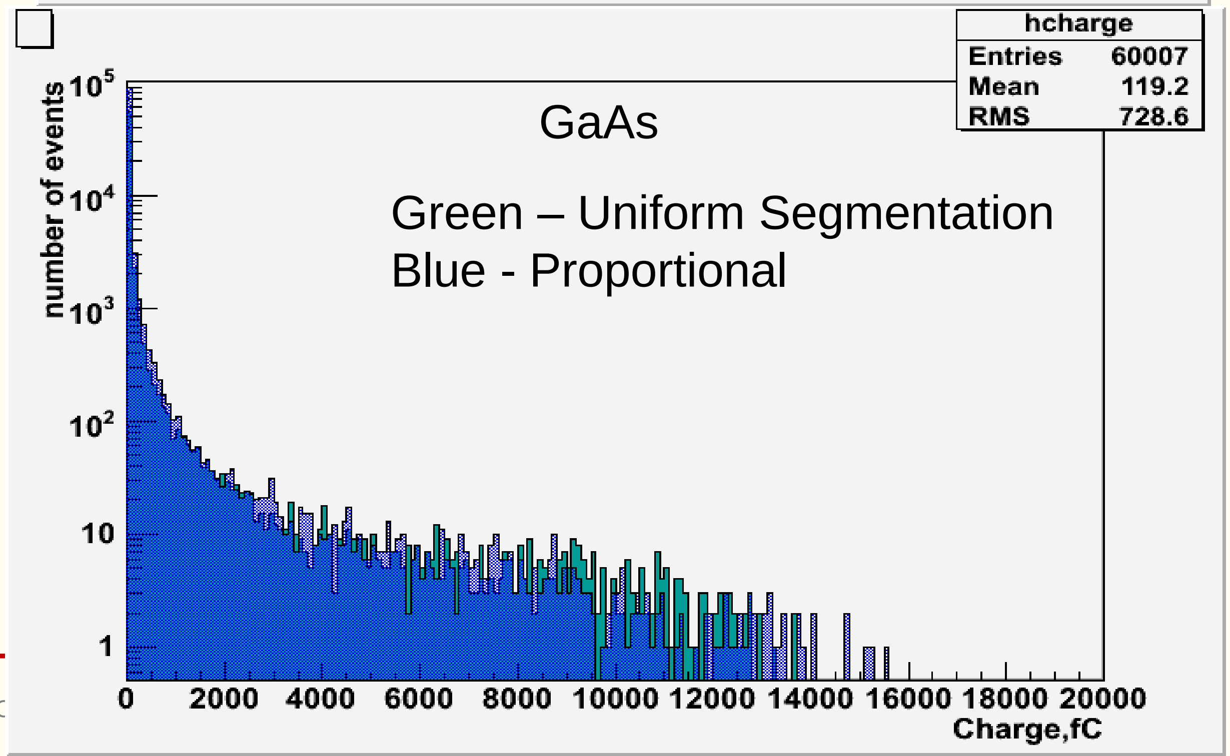
(correspond to about 5000 MIPs)

Distribution of the collected charge per pad for 500Gev electron showers





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- Considered new model of BeamCal with new sapphire sensors placed in parallel to the beam looks very promising
  - It solves problem with signal digitization
  - It is under study yet but promising has similar to baseline design performance