Recent Developments for BeamCal

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on behalf of the FCAL collaboration

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Outline

I Beamstrahlung(BS) pairs study for BeamCal concerning L* change

II Deposited energy and collected charge in Diamond and GaAs sensors

III Updates on performance of sapphire BeamCal

IV Technological prototype of sapphire BeamCal

I. BS studies: Guinea Pig files

MC program Guinea Pig (GP) generates particles after beam collision

Guinea Pig produces files:

- "beam1" and "beam2" - *files, containing particles of the beams after collision*
- "Beamstrahlung photon" - *contains beamstrahlung photons*
- "Pair" output file - *contains secondary particles coming from incoherent pair creation or from compton scattering*
- "Lumi" output files – *contain energies of colliding particles*
- "Hadron" output file - *contain colliding photons that produced a hadronic event*

For BG simulation in BeamCal files "Pair" were used. They contain data about BS e-e+ pairs at the IP line by line in the format: Edep [GeV], Vx/c, Vy/c, Vz/c, Xo, Yo, Zo [nm]

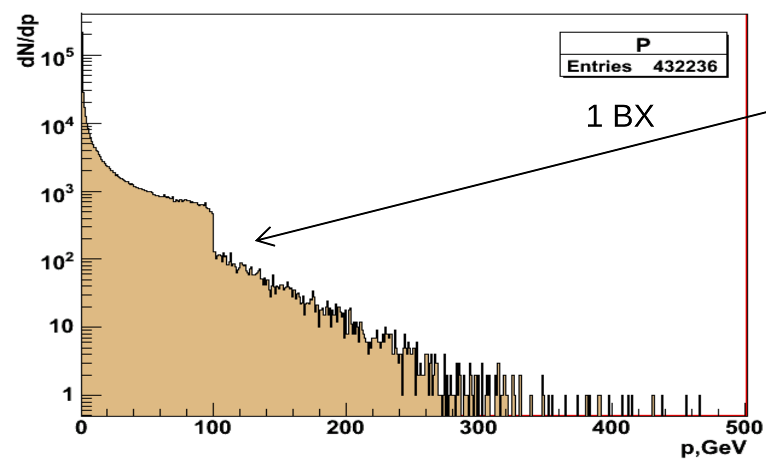
In total each file, that correspond each BX, contains ~430 000 particles

Beam parameter set is „Upgrades 1000 B1b" –> 1TeV in cm

For the next plots one file Pair.dat (Number 500) was used as an example

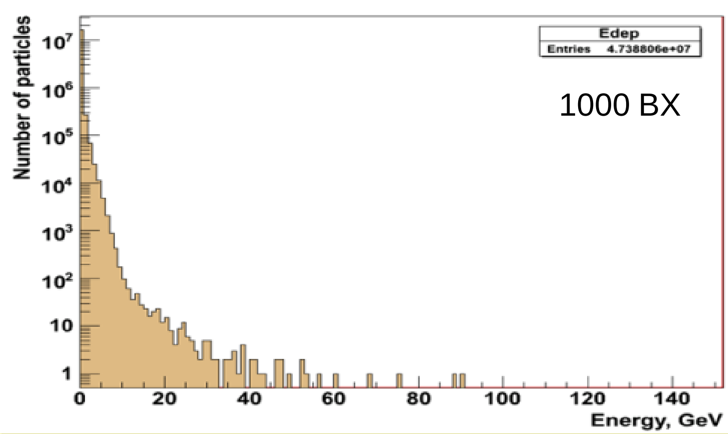
I. BS studies: Energy distributions of BS particles

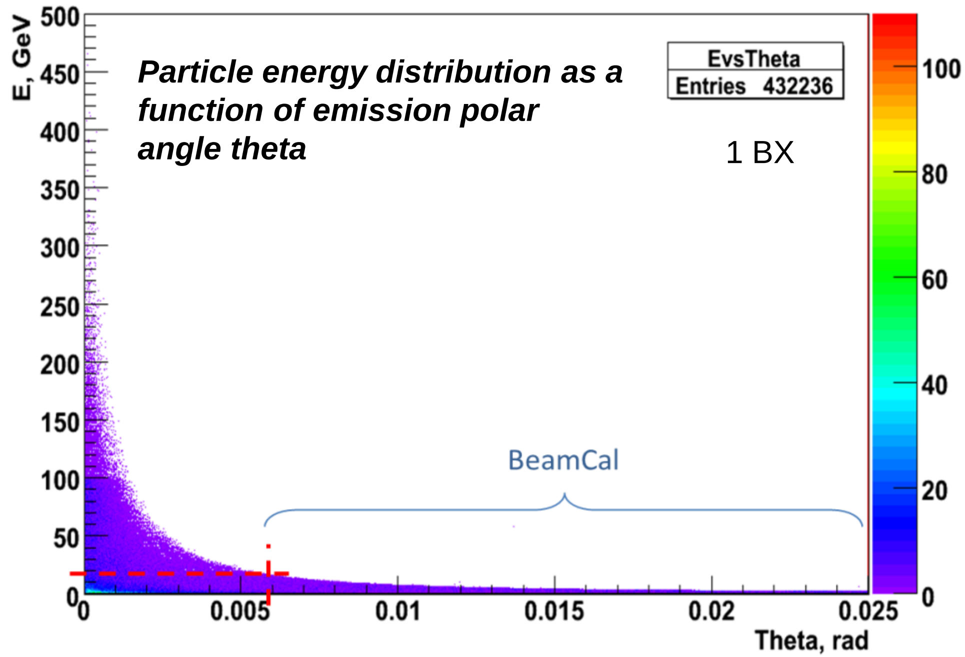
Momentum distribution of all e-e+ pairs



Cut on 100 GeV for Compton electrons made on a production level of GP, but particles with energies bigger then 100 GeV fly to the beam pipe anyway and not relevant for this study

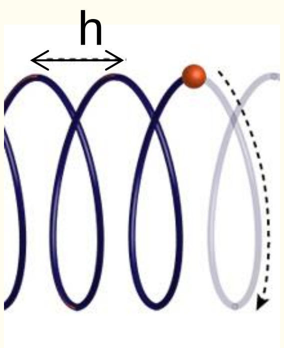
Energy distribution of beamstrahlung pairs from 1000 bunch crossings that hit BeamCal.

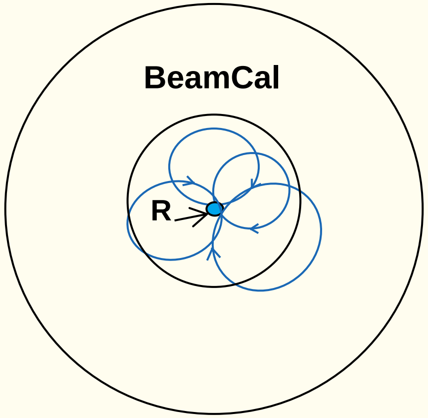




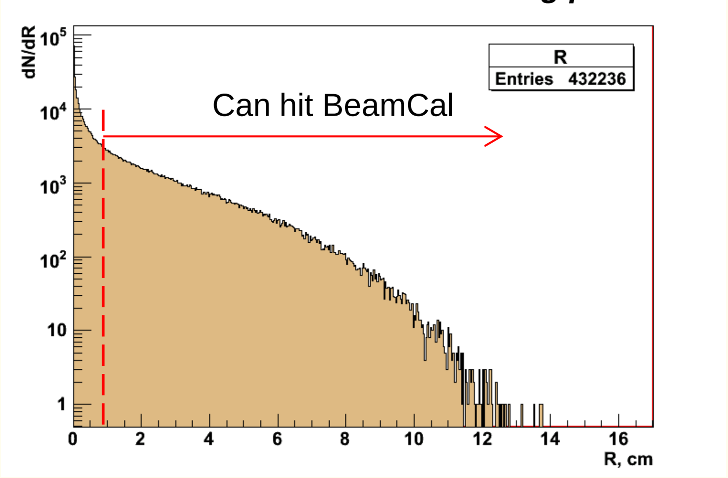
I. BS studies: Radius and Step of curling

Produced e-e+ curling in magnetic field B = 4T (field map antiDID)



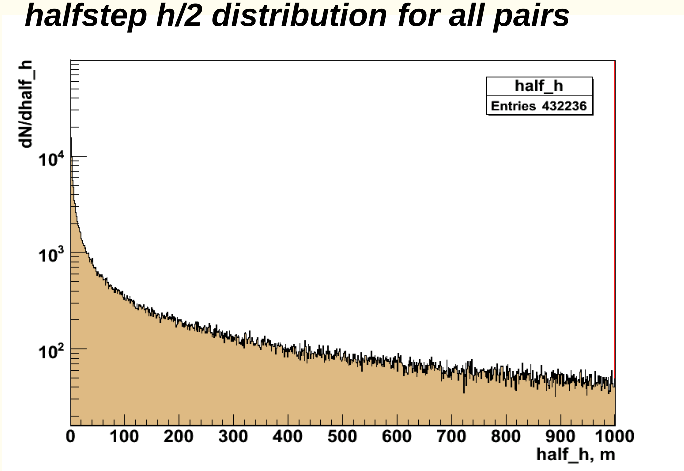


Distribution of radii of all curling particles

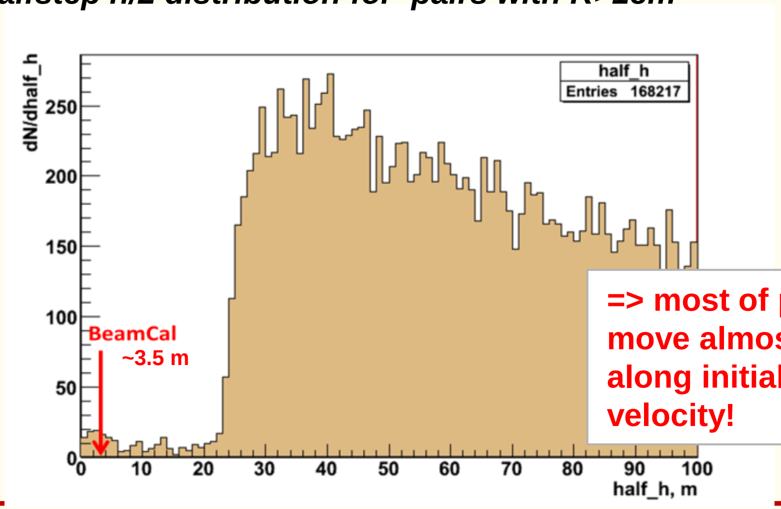


Whether particle hit BeamCal or not also depend on step of curling h
*** On a half-step particle has maximal deviation from beam axis.**

halfstep h/2 distribution for all pairs



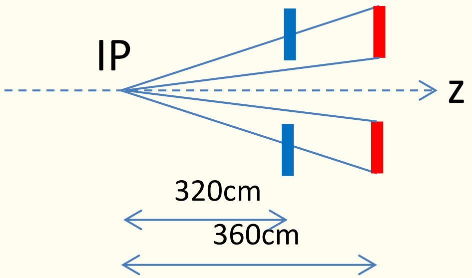
halfstep h/2 distribution for pairs with R>1cm



=> most of particles will move almost straight along initial vector of velocity!

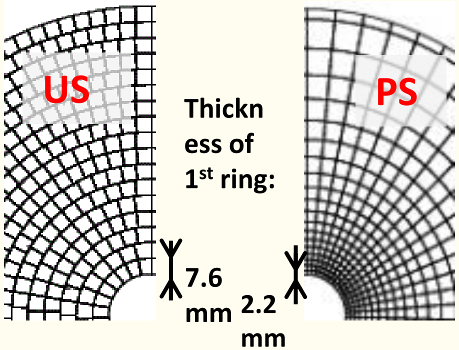
I. BS studies: deposited in BeamCal energy from BS

Moving BeamCal closer to IP it covers bigger polar angles (both: inner and outer angle), hence deposited energy from beamstrahlung pairs will be smaller

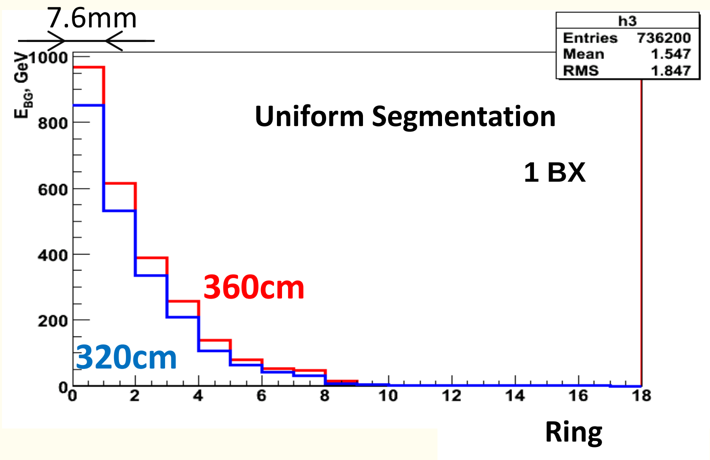


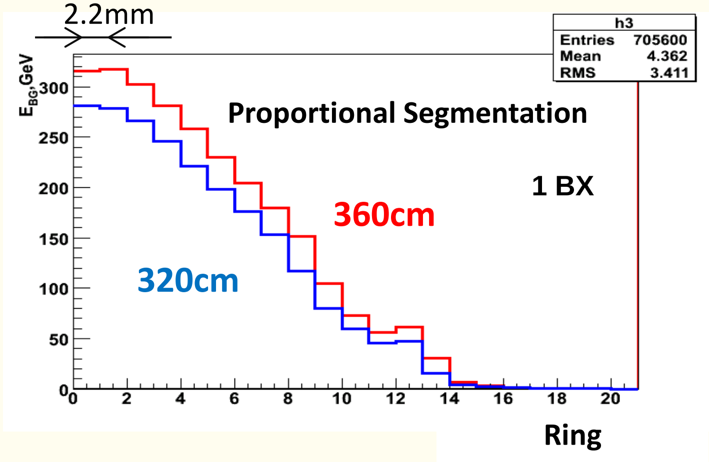
-> Deposited energy per ring for 320cm distance is ~14% smaller then for 360cm.

-> In the same time polar angle is getting ~13% bigger



Average E_{dep} versus rings over all azimuthal angles and over all layers



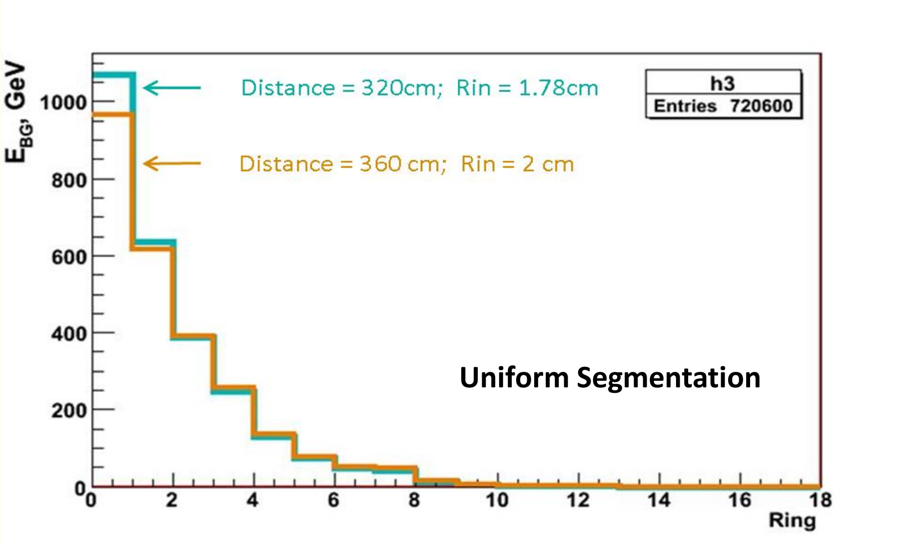


I. BS studies: Remarks

- Note! when Rin of BeamCal stays unchanged on 320 cm, it allows easier to reconstruct showers having less BG, but from other side BeamCal aimed on masking QD0, which is situated directly after BeamCal around the beam pipe. => it is needed to decrease Rin of BeamCal to 1,78 cm to cover the same polar angle θ_{in} as on 360 cm

- Then pad of the same area on 320 cm distance will cover bigger solid angle, then on 360 cm distance, therefore energy deposition per pad will be bigger (see fig.)

- Thus, when changing L* to 4 m and moving BeamCal closer to IP, while keeping inner polar angle θ_{in} the same, the density of BG according to the area will be slightly increased and it motivates us even more to move to another segmentation (f.e. PS) where SNR is better

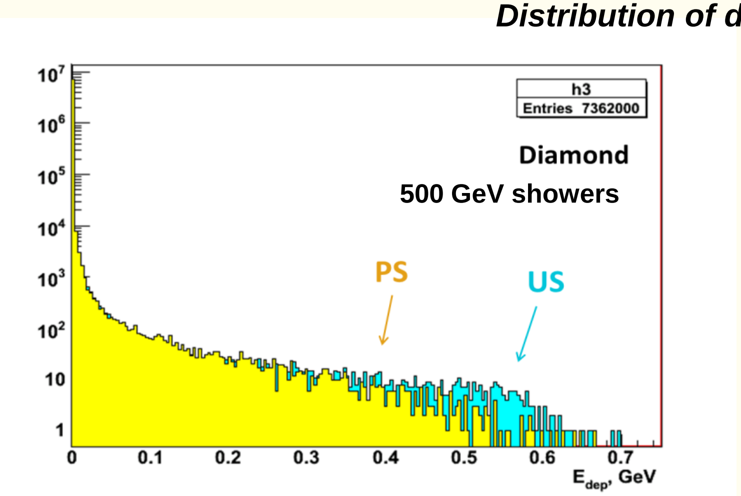


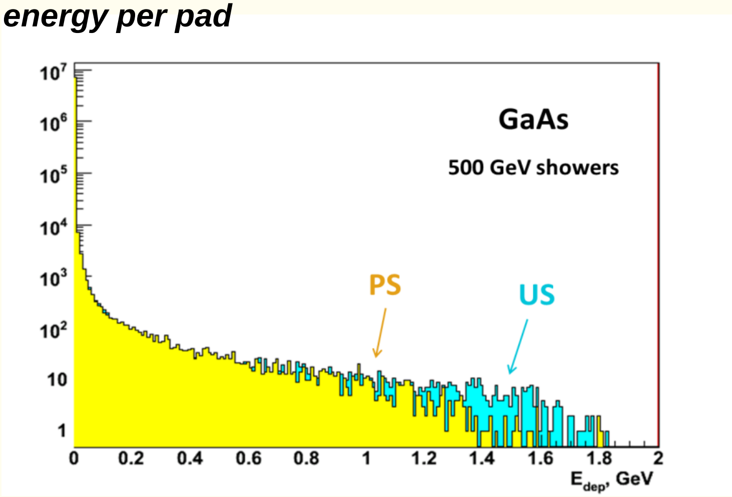
- Also, moving BeamCal closer to IP the picture of backscattered particles from first layers of BeamCal will be changed as well. I expect to see bigger occupancy of backscattered particles around beam axis, when move BeamCal closer to IP and keeping polar angle . To see this distributions it is needed to make full simulations, but to estimate relative changes to use BeCaS is sufficient

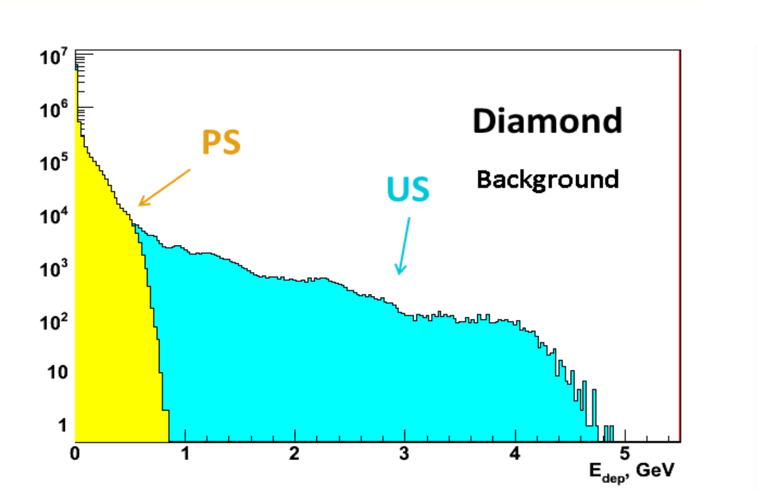
II. E_{dep} & Q_{coll} in Sensors: E_{dep} for SH and BG

Distance to IP 355 cm, Rin=2cm
Sensor thickness 300 µm

Distribution of deposited energy per pad







Deposited energy in sensor pads in Diamond and in GaAs sensors was obtained by simulations.

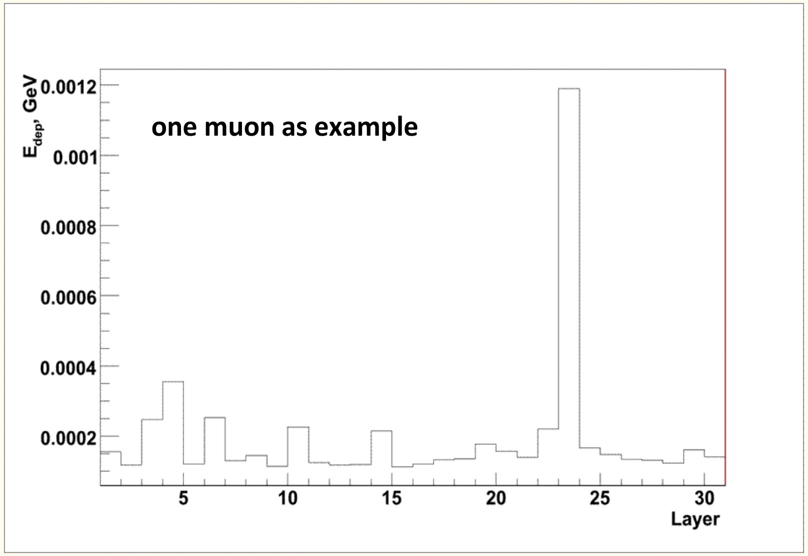
Collected charge Qcoll calculated by formula:

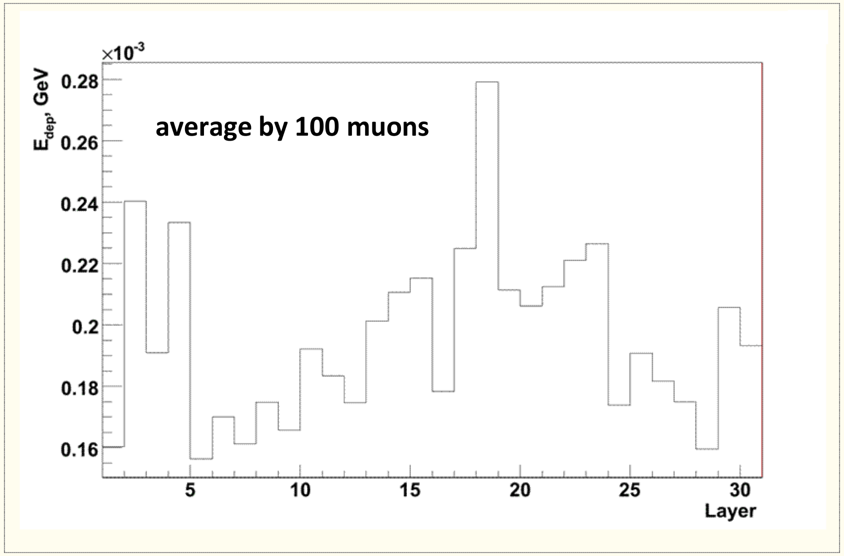
Diamond: $\mathbf{Q_{coll}\ (Diamond) = \frac{E_{dep}}{E_{e-h}} \cdot q_e}$,   Ee-h (Diamond) = 13.1 eV

GaAs: $\mathbf{Q_{coll}\ (GaAs) = \frac{1}{2} \cdot \frac{E_{dep}}{E_{e-h}} \cdot q_e}$,   Ee-h (GaAs) = 4.57 eV

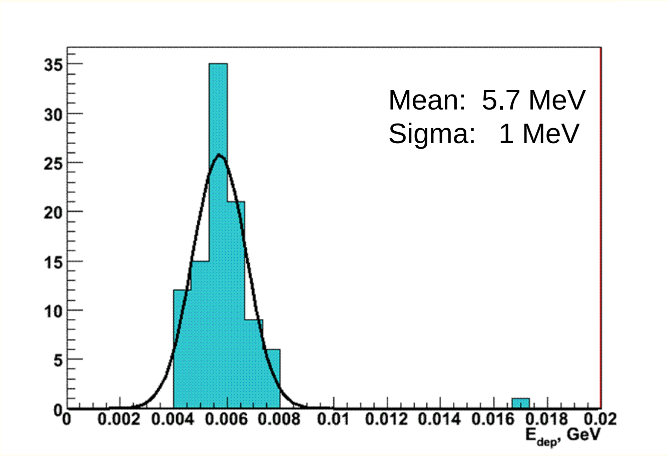
II. E_{dep} & Q_{coll} in Sensors: E_{dep} from Muons

Eenrgy deposition in layers (Diamond, US) of Beamcal from 5 GeV muon





Distribution of total deposited energy in Diamond sensors from 100 5-GeV-muons



mean energy deposition per pad is ~0.19 MeV

II. E_{dep} & Q_{coll} in Sensors: Table

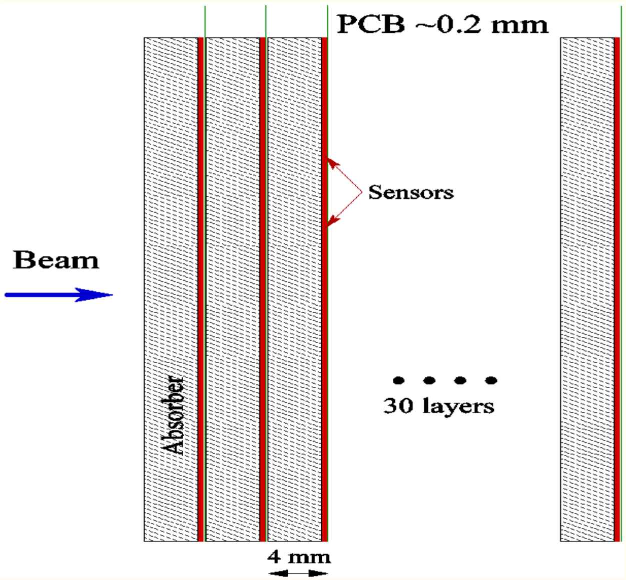
		Diamond		GaAs		Comments
		US	PS	US	PS	
MIP - 5 GeV muon (mean deposited energy per pad)	E_{dep}	0.19 MeV		*0.5 MeV*		
	Q_{coll}	*2.3 fC*		*8.7 fC*		
500 GeV e- (max deposition/pad)	E_{dep}	0.7 GeV		1.8 GeV		in GaAs max E dep is ~**2.6** times bigger
	Q_{coll}	*8.6 pC*		*31 pC*		in GaAs max collected charge is ~**3.6** times bigger
500 GeV e- (mean value of total deposited energy in sensors)	E_{dep}	8.5 GeV		22 GeV		This koeff used for other calculations of Edep in GaAs
	Q_{coll}	*105 pC*		*383 pC*		
BG (max deposition/pad)	E_{dep}	4.9 GeV	0.85 GeV	*13 GeV*	*2.2 GeV*	!! Diamond: max E dep at US is ~5.8 times bigger then at PS
	Q_{coll}	*60 pC*	*10.5 pC*	*230 pC*	*38 pC*	

- *Not italic numbers – obtained from simulations*
- *Italic numbers – calculated*

III. Sapphire prototype: construction

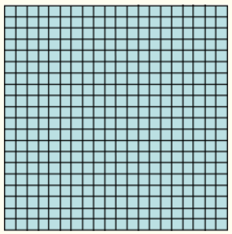
For comparison 2 designs of BeamCal models are considered:

baseline



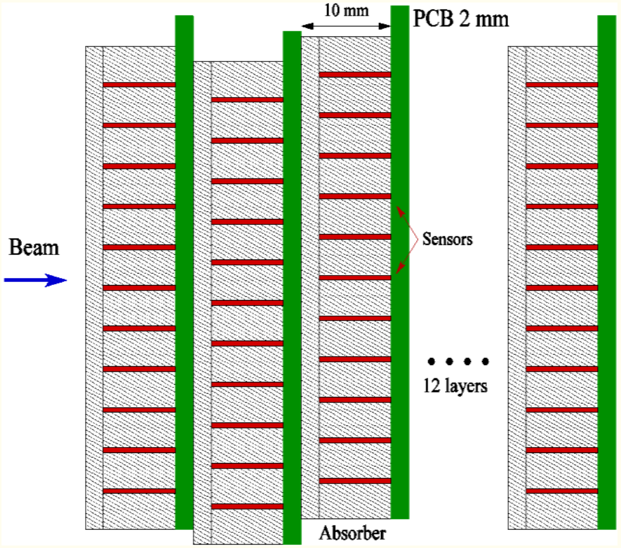
Transverse view:

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**

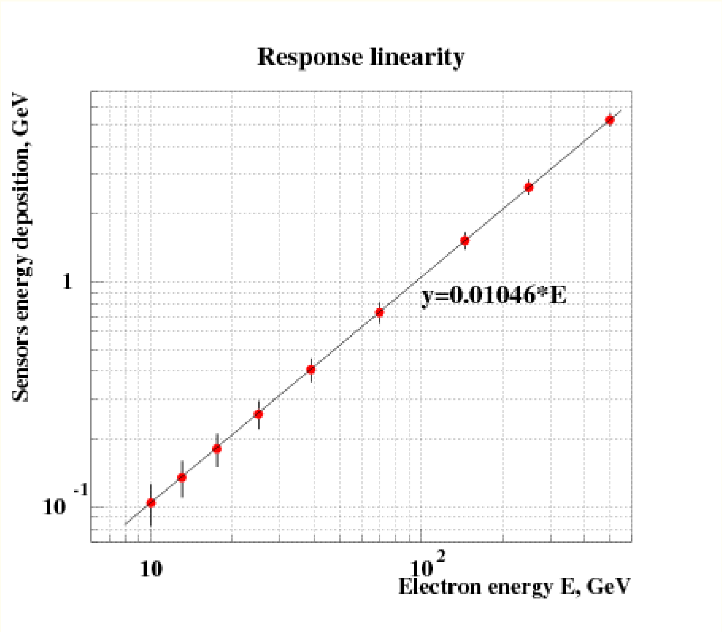
- **Longitudinal and transverse sizes for both designs are kept the same**
  Number of readout channels is 12000 for baseline design and 8880 for new one

- **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!**

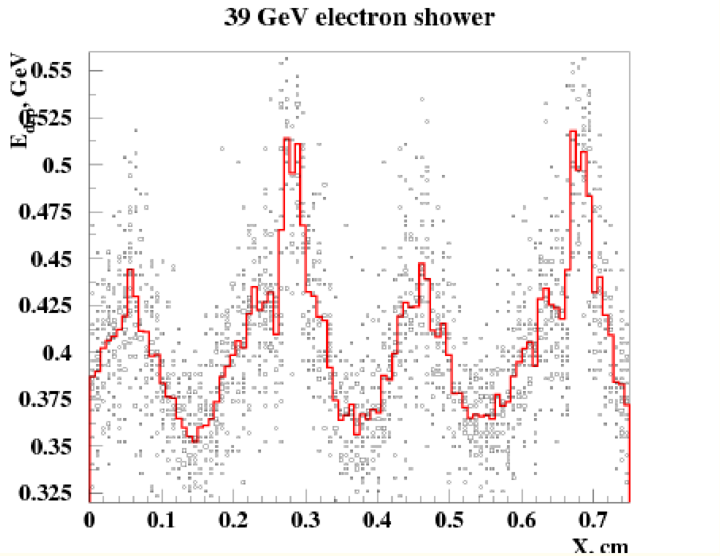
III. Sapphire prototype: performance updates

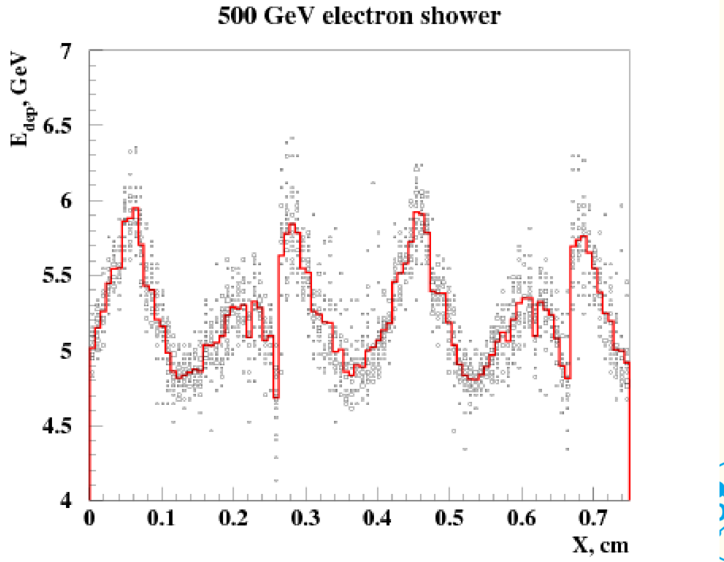
For study used several energy values: from 10 to 500 GeV



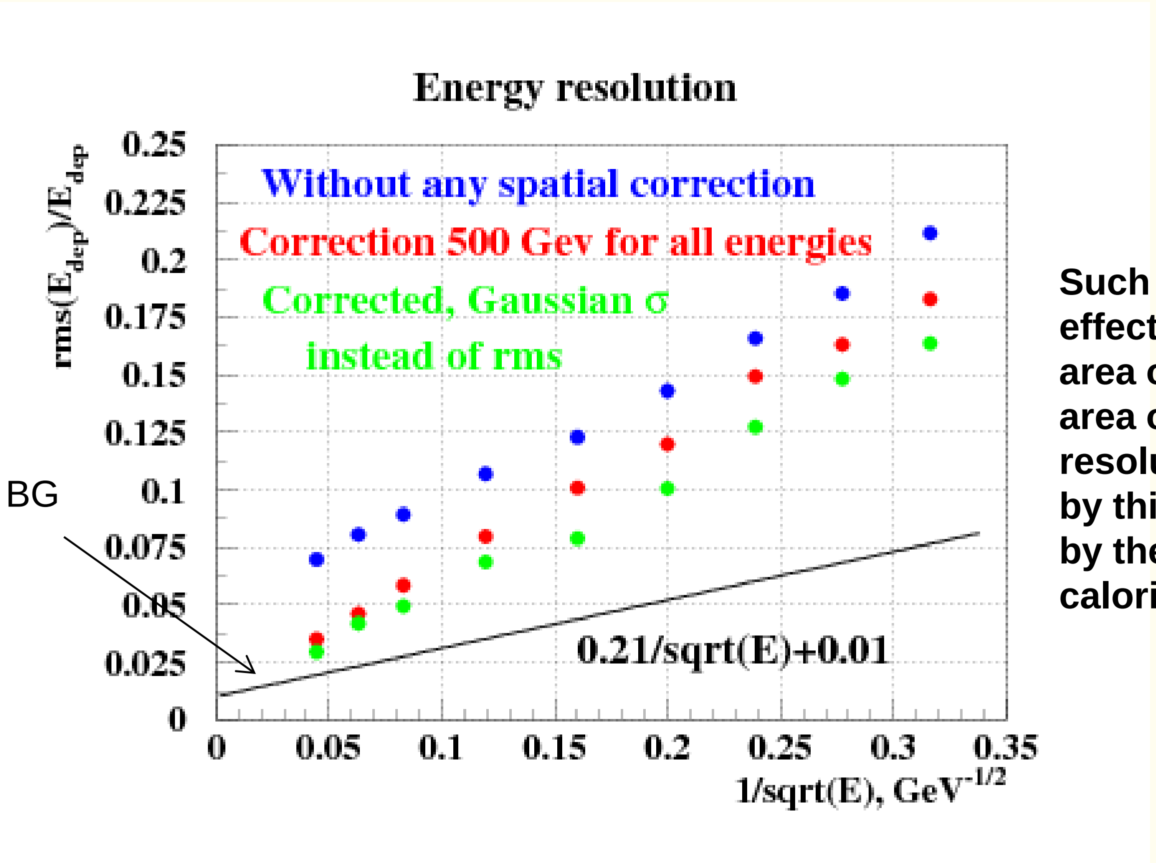
$$E_{dep,\ corrected} = \frac{E_{dep}}{\langle E \rangle|_{x_i}} \cdot \langle E \rangle|_{all\ x}$$

Full energy deposition from shower as a function of transverse coordinate X, which is perpendicular to sensor strips:





III. Sapphire prototype: energy resolution



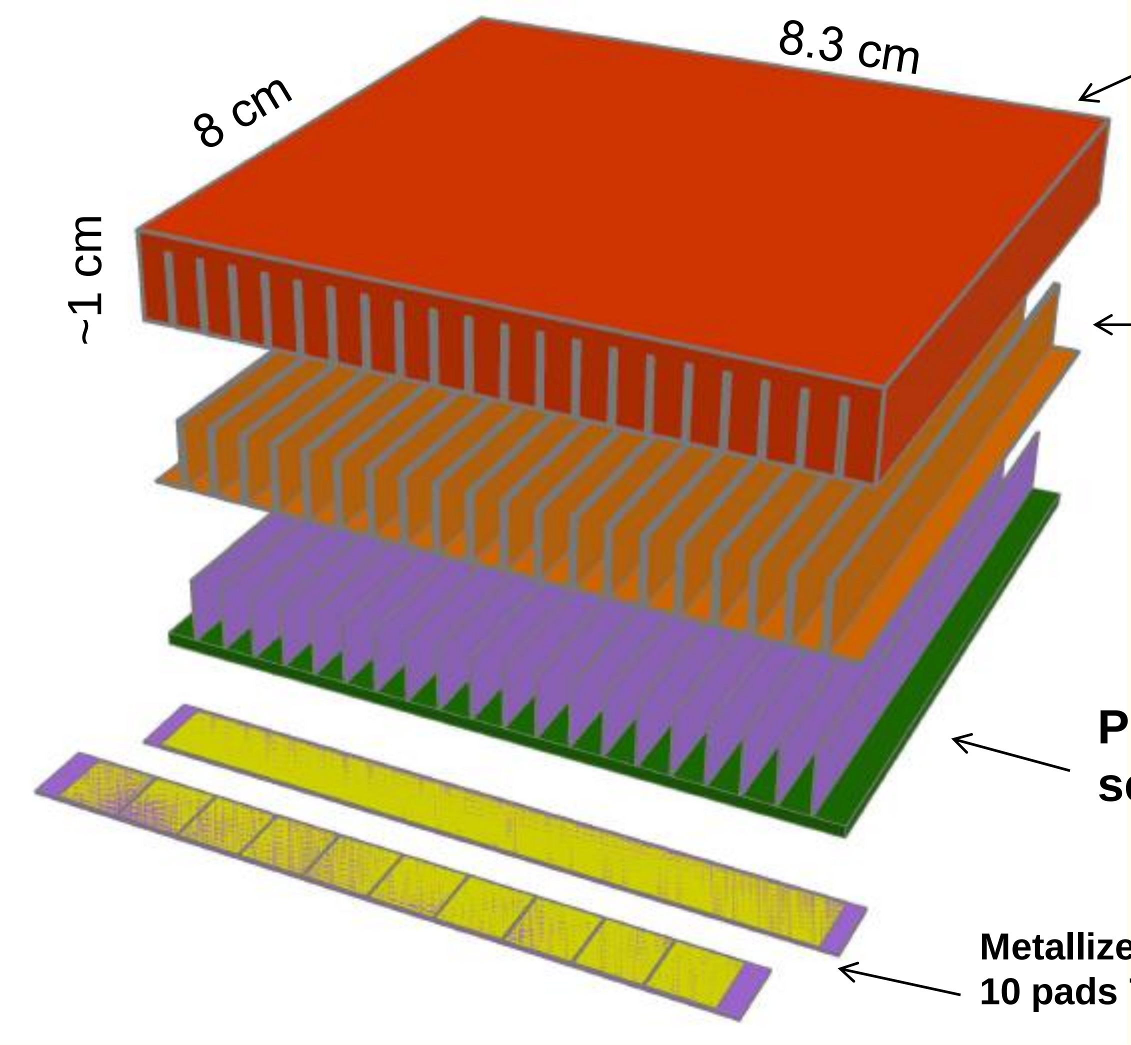
baseline design – ideal case without BG -> Gaussian σ in calculations

Such correction can effectively work only in area of low BG, and in area of high BG energy resolution will be defined by this BG itself, but not by the quality of calorimeter.

Thus, study on the performance of new sapphire design is going on and continuing be promising!

IV. Technological prototype of sapphire BeamCal layer for TB

* Idea is to put this layer in a shower maximum (after several Tg planes)



Absorber

brass for the first prototype as cheaper material (vs Tg) and can be done in our WS

Preformed kapton foil (50 µm)

to isolate absorber from sensors

200 R/O channels

PCB with 20 sapphire sensor strips

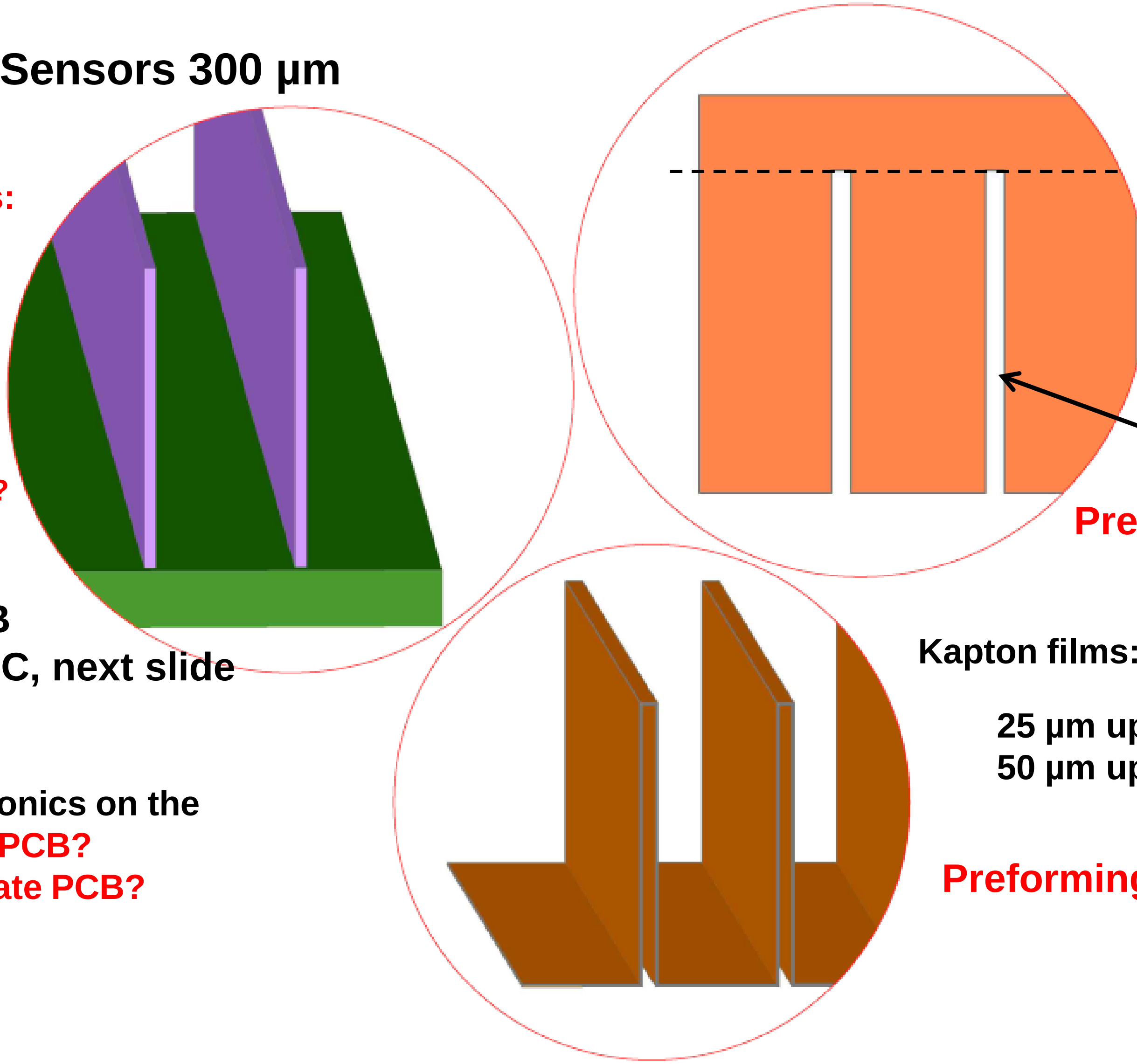
Metallized sapphire strips
10 pads 7.5 x 7.5 mm^2

IV. Prototype of sapphire BeamCal: design

Sensors 300 µm

Pad contacts: conductive glue?

HV
Out or inside?



PCB
LTCC, next slide

R/O elecronics on the
- same PCB?
- separate PCB?

Brass – machined from one piece,

Tungsten – glued rectangular pieces

0.5 mm slots

Precise assembly?

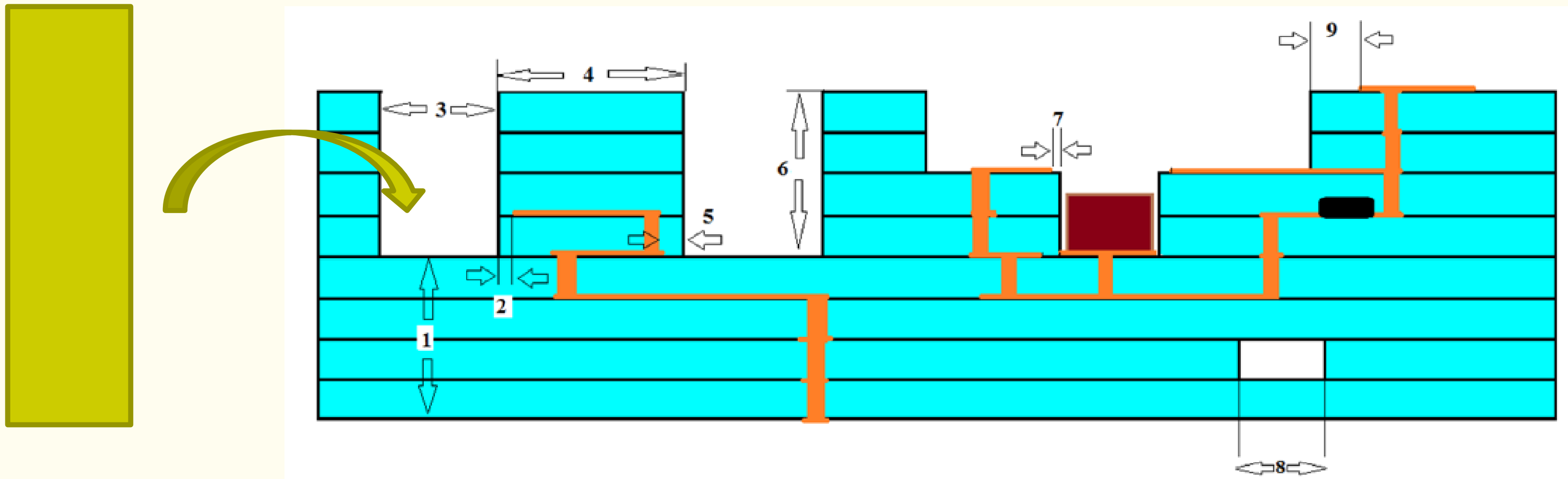
Kapton films:

25 µm up to 7 kV
50 µm up to 13 kV

Preforming technology?

IV. Prototype of sapphire BeamCal: Ceramic PCB

LTCC systems – Low Temperature Co-fired Ceramic

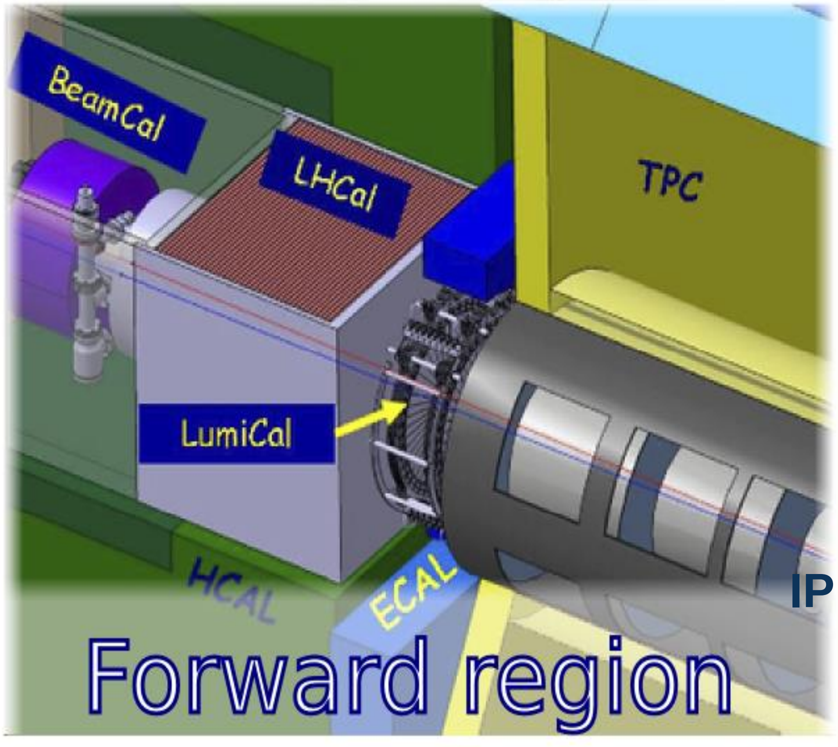


BASIC DESIGN RULES	Standard	Special
		On request
cavity/windows shape	rectangular, square	circular, others
1- cavity floor thickness in µm	≥ 400	< 400
2- inner conductor-cavity spacing in µm	200	125
3- min. cavity/windows/ size in µm	400	< 400
min. channel width and height in µm max channel width and height in µm	100*100 600*400	Others Others
4- min. distance between cavities in mm	≥2.0	< 2.0
5- via center-cavity spacing in µm	325	225
6- cavity depth in µm	≤ 800	> 800

Thank you for your attention!

Backup slides

Beam Calorimeter at ILC

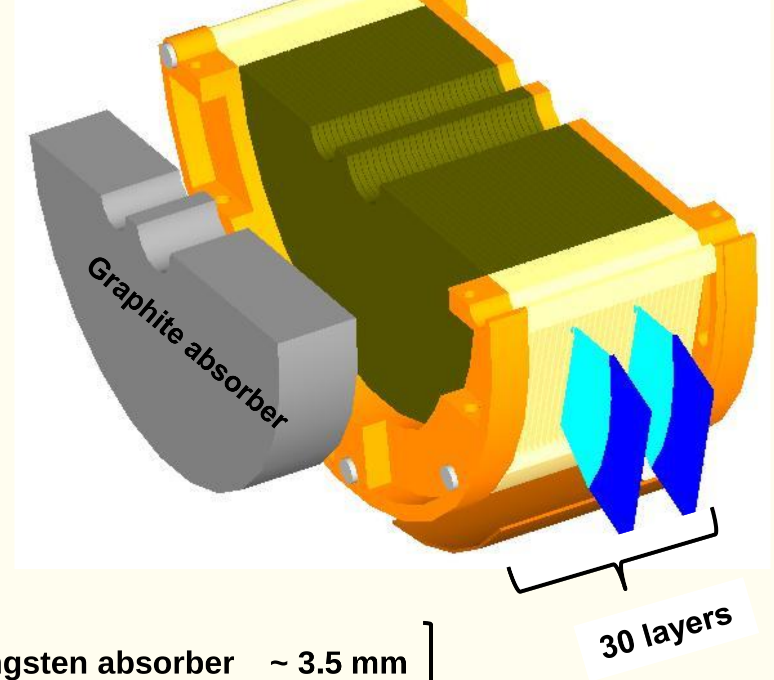


Beam parameters from the ILC Technical Design Report (November 2012)

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

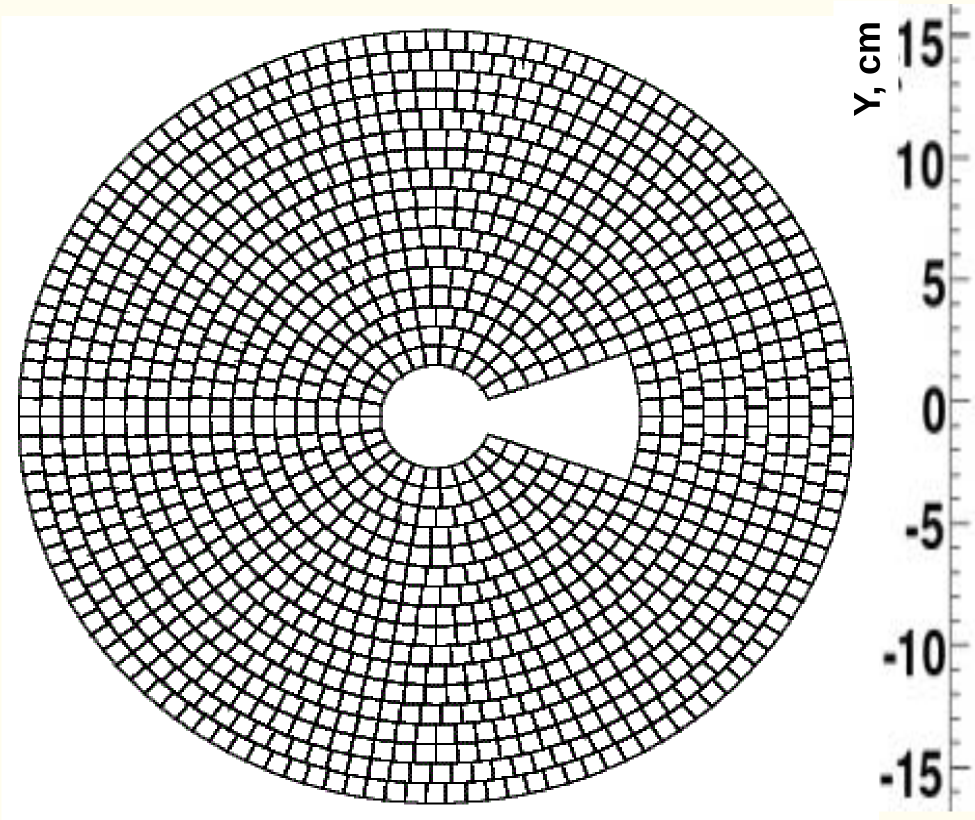
Purposes of BeamCal:

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



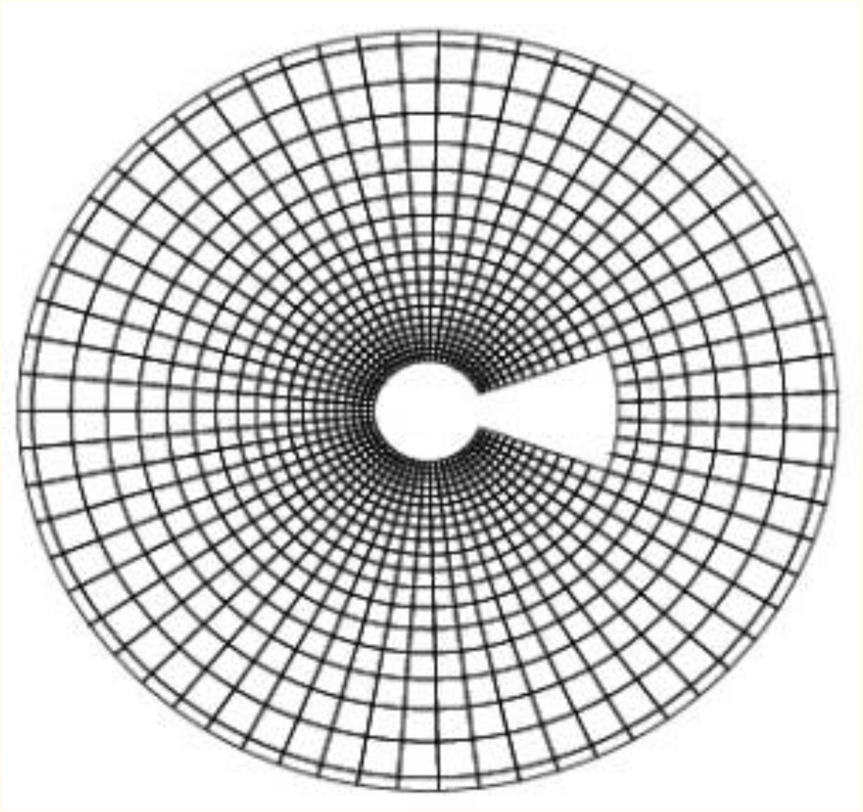
Tungsten absorber	**~ 3.5 mm**	
Sensor	**~ 0.3 mm**	**1 X_0**
Readout plane	**~ 0.2 mm**	

BeamCal Segmentation



Uniform Segmentation (US)

pad sizes are the same



Proportional Segmentation (PS)

pad sizes are proportional to the radius

number of channels almost the same

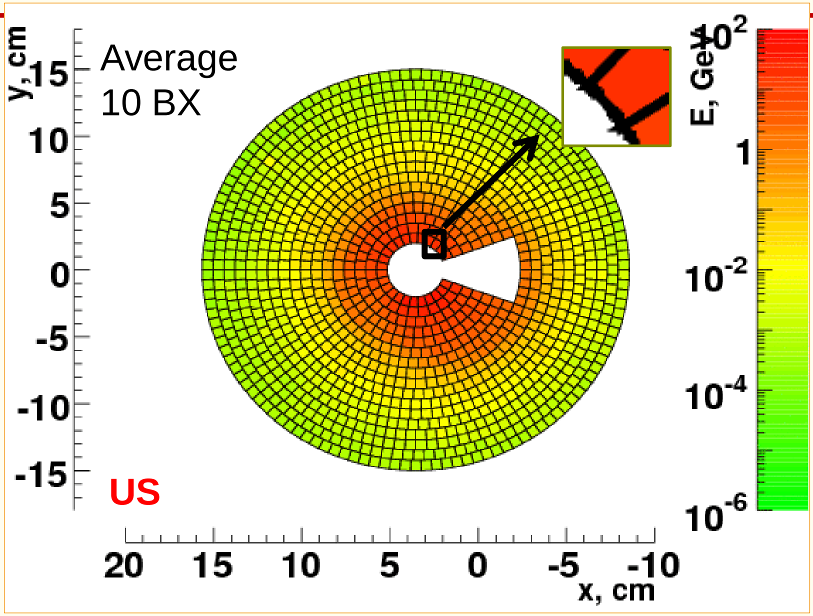
Energy Deposition due to Beamstrahlung

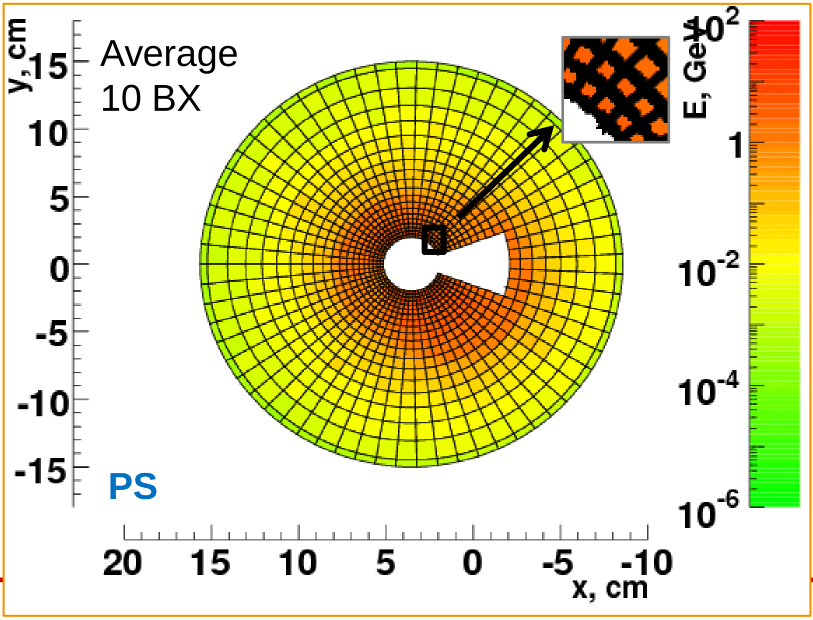
- Beamstrahlung (BS) pairs generated with Guinea Pig

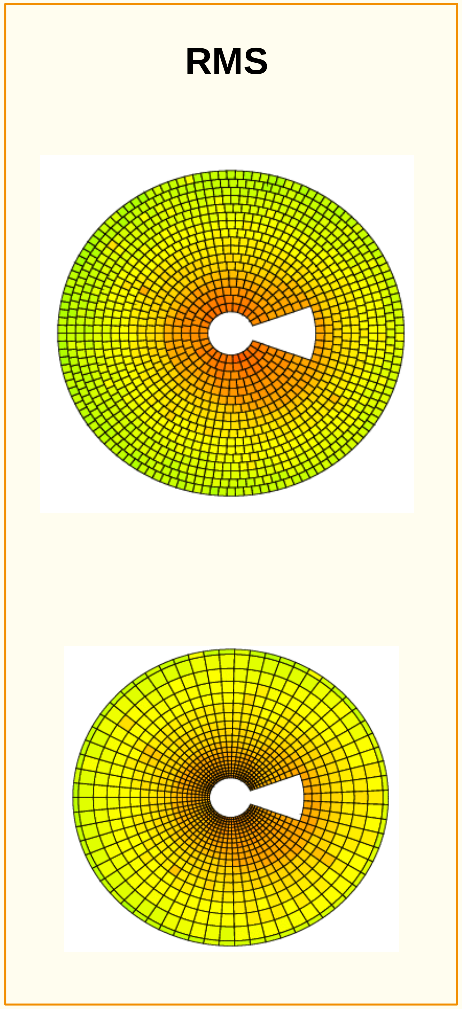
- Energy deposition (E_dep) in BeamCal sensors from BS simulated with Geant4
  $\longrightarrow$ *considered as a Background*

- RMS of the averaged BG
  $\longrightarrow$ *used for energy threshold calculation*

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



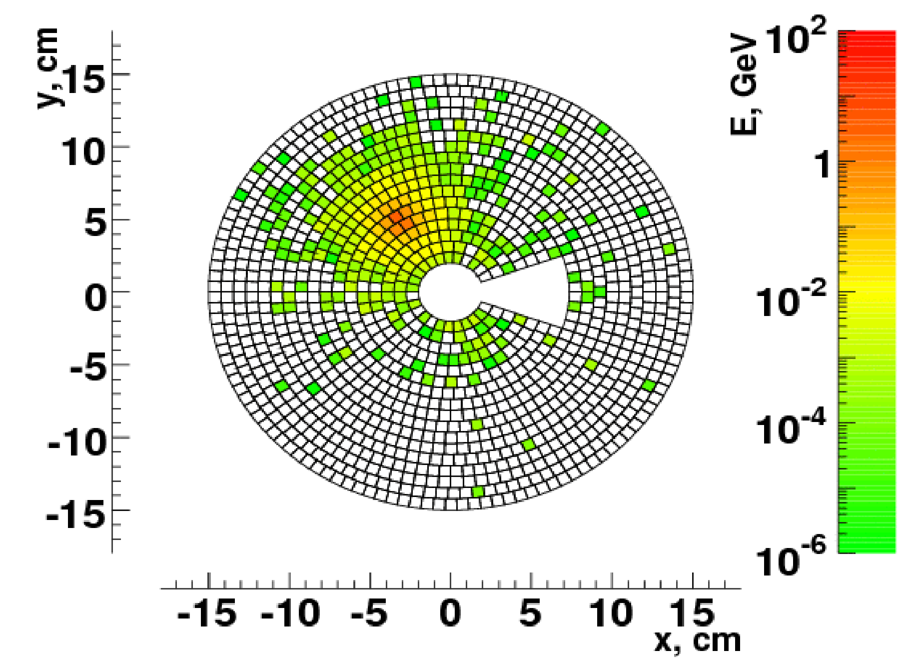




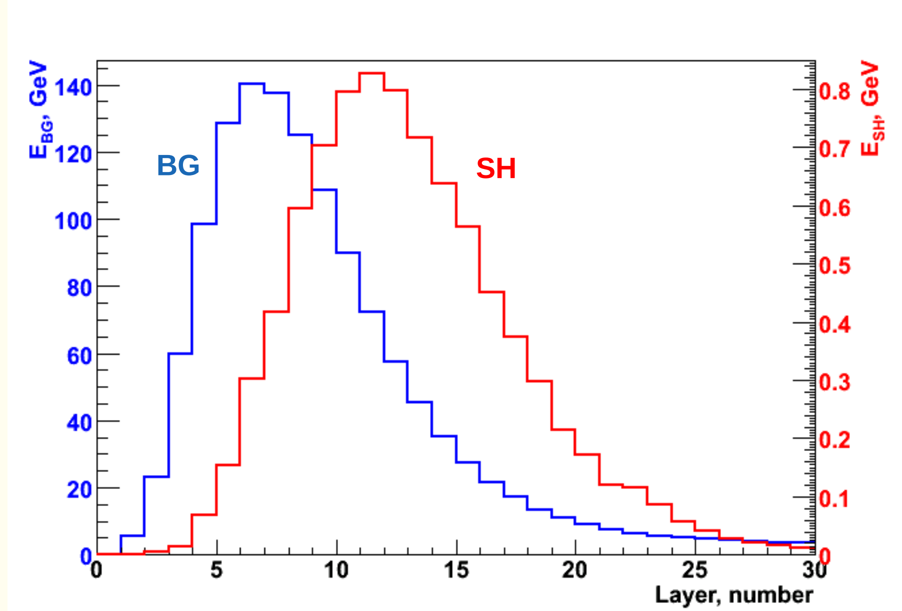
Figures show sum of all layers

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***

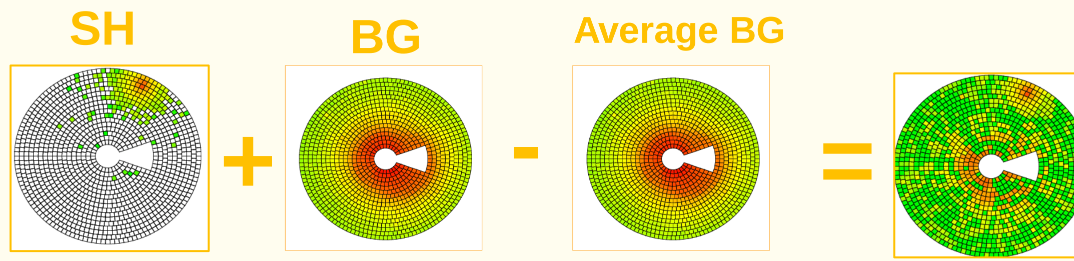
Reconstruction Algorithm

With BG

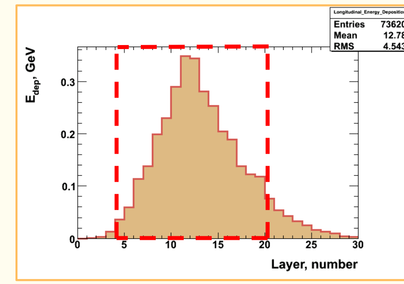
Without BG

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
   - $R_{COG}, \varphi_{COG}, E_{sh}$

1

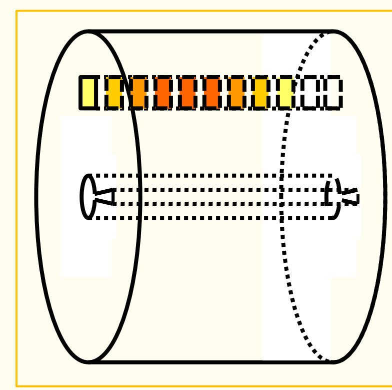


2



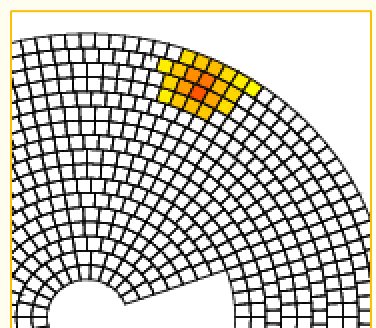
Tower

3



Reconstructed SH

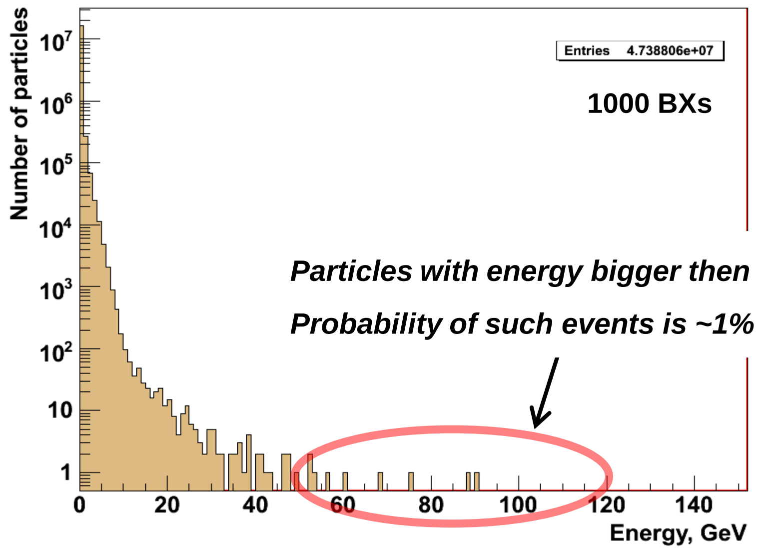
6



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

Beamstrahlung (BS) Energy Distribution & Fake Rate

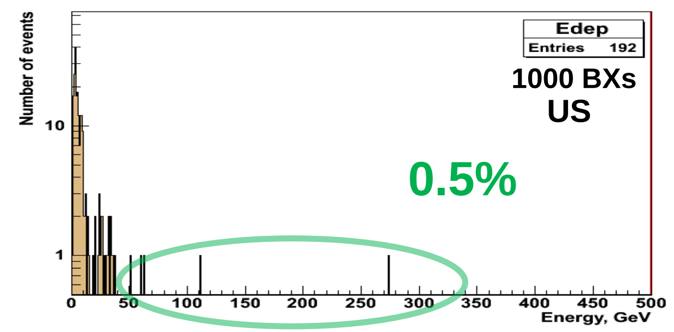
Energy distribution of BS pairs that hit BeamCal

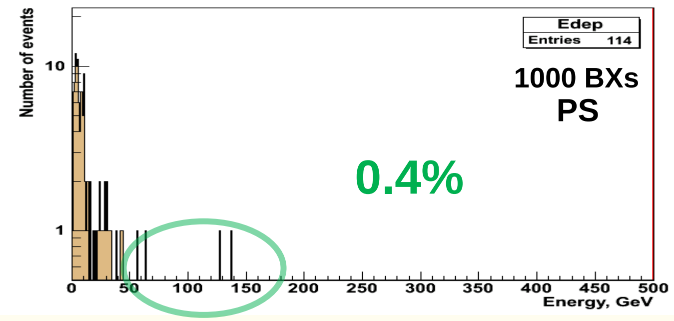


Particles with energy bigger then 50 GeV

Probability of such events is ~1% per BX

Energy distribution of reconstructed showers from pure background





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

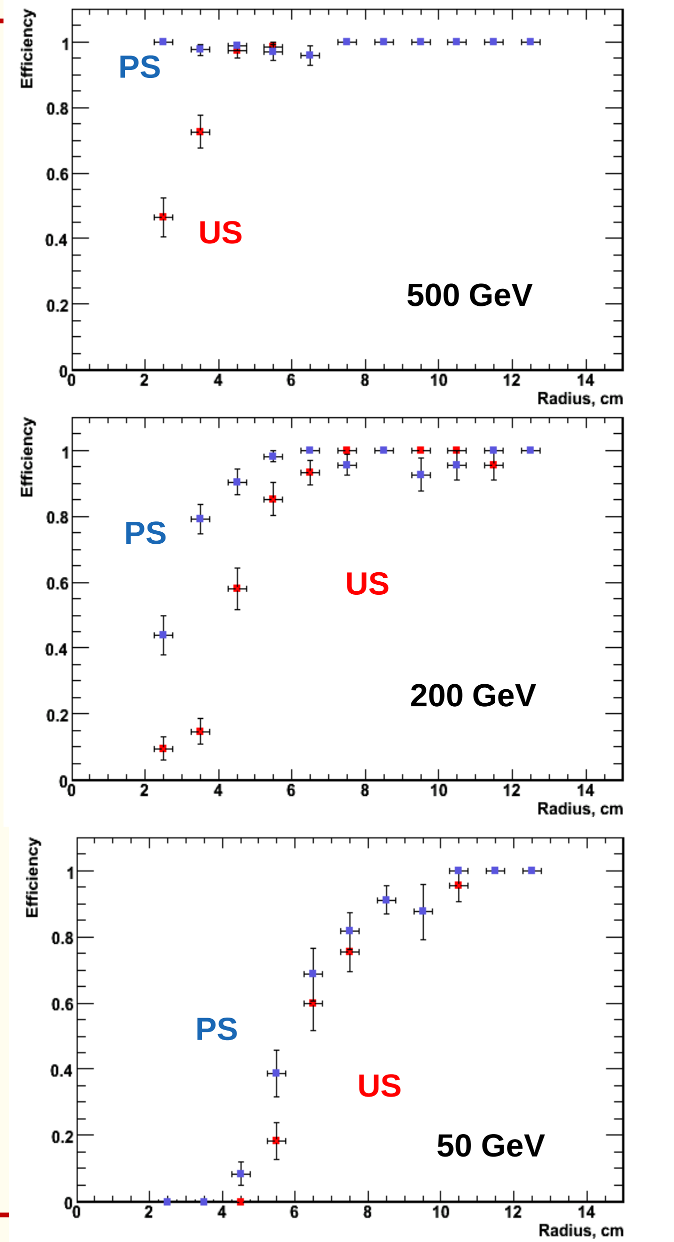
⇒ *Also fluctuations of background can be recognized as a shower by reconstruction algorithm*

Efficiency of shower reconstruction as a function of radius

Shower is considered as correctly reconstructed if:

- distance

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

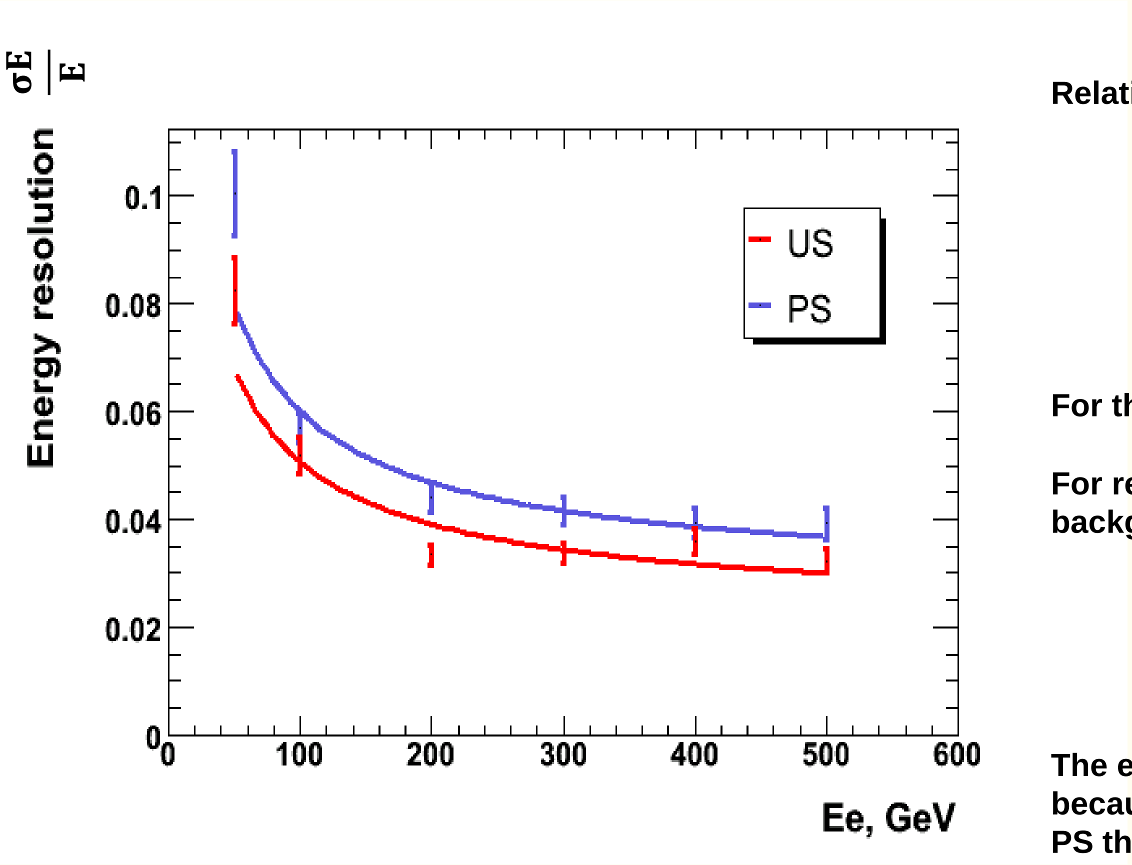


Number of events 500

- 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

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

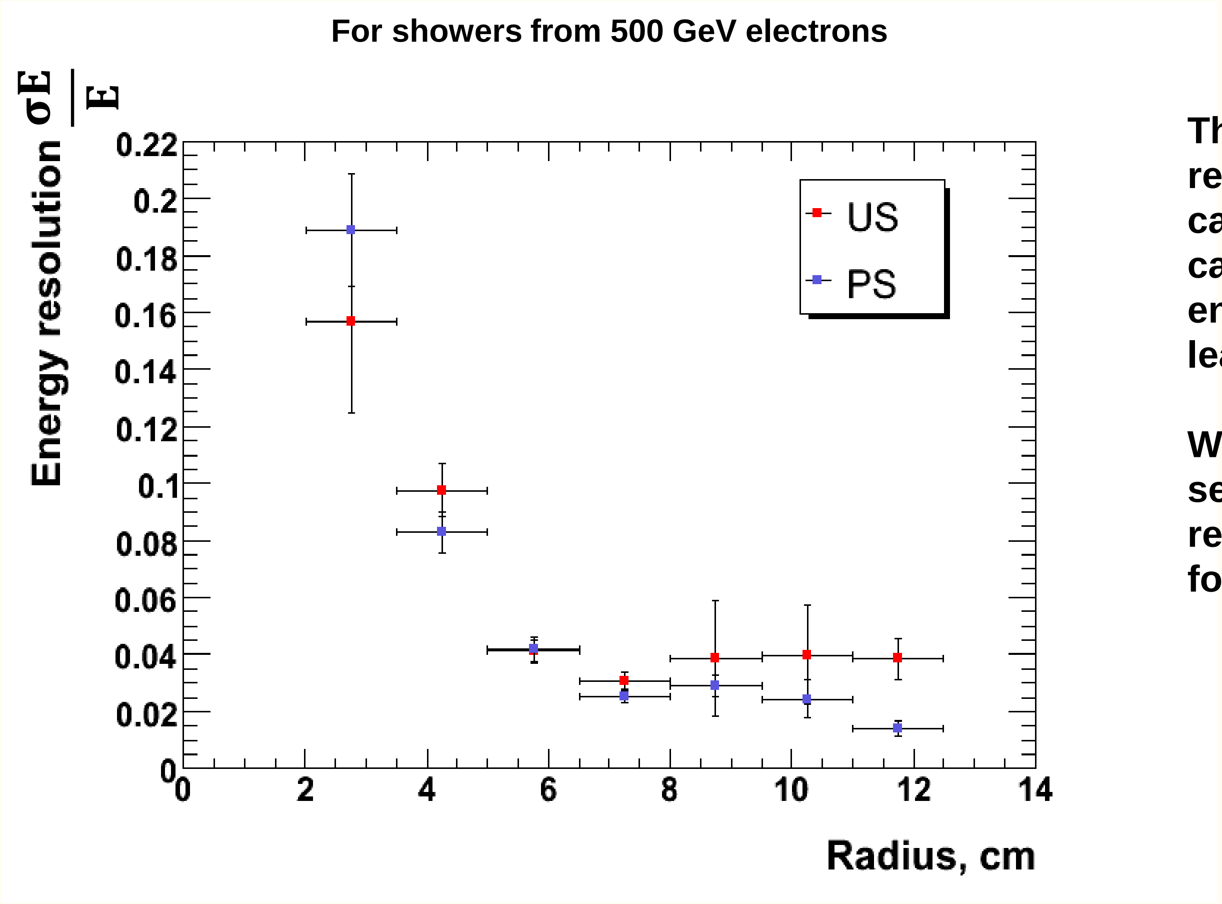
For the ideal case (without BG) A ~ 0.2

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

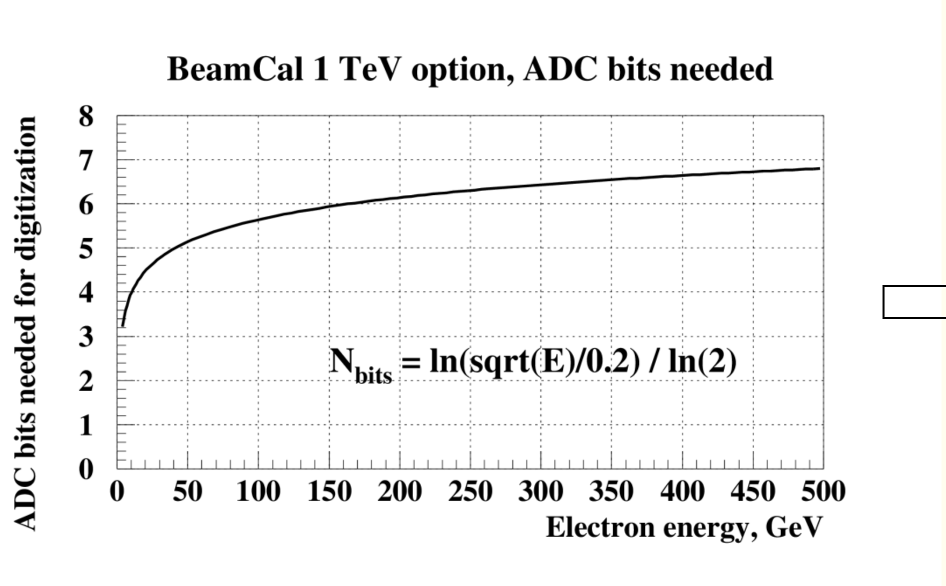
ADC bits needed to measure shower energy

- **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

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

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

=> 12-13 –bit ADC is needed

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)**

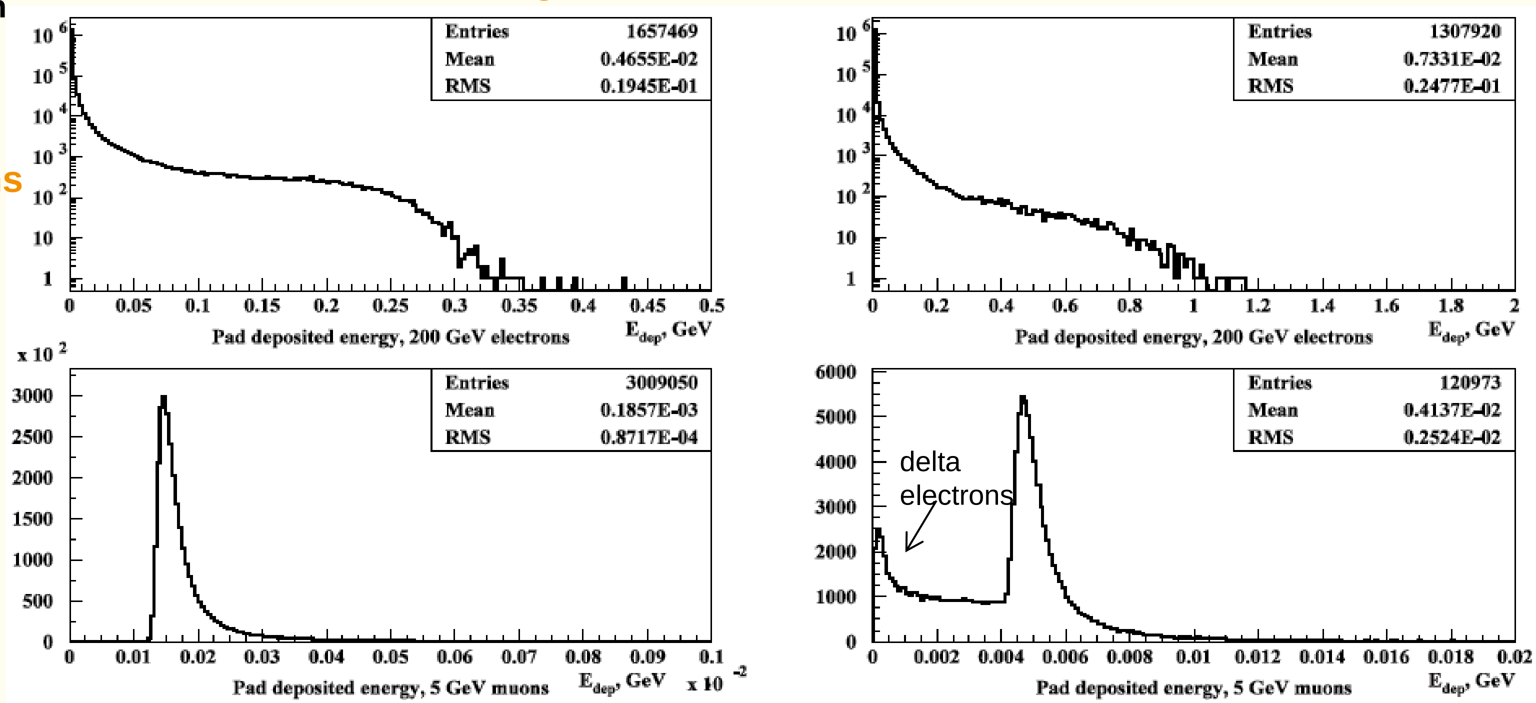
Testing new design: energy deposition in pads

Distribution of energy deposition per pad from:

Baseline design | **New sapphire design**

200 GeV electrons

5 GeV muons (MIPs)



2300 | **220**

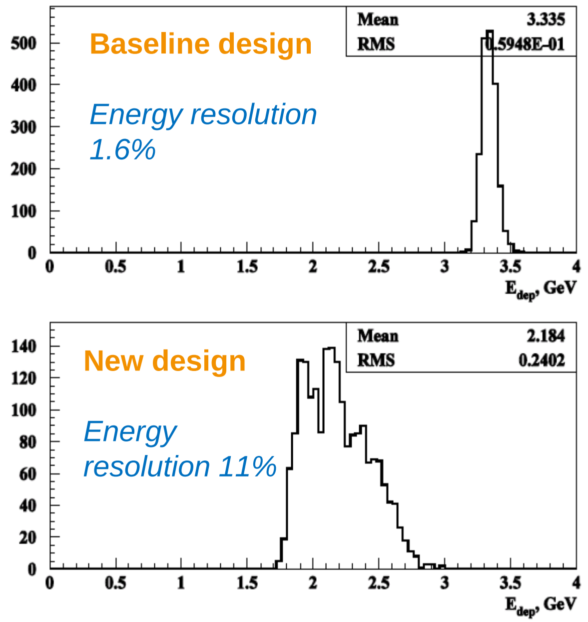
Dynamic range of the readout $= \dfrac{\textit{end point of 200 GeV } e^{-} \textit{ spectra}}{\textit{MPV of MIPs peak}}$

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!

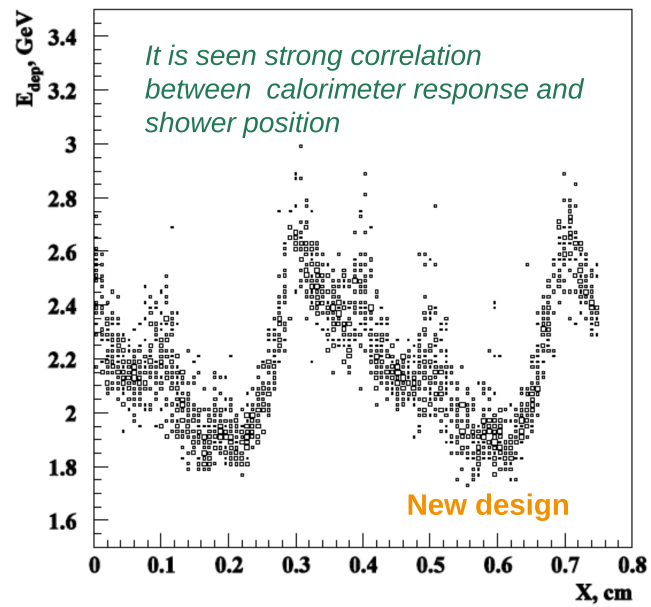
Testing new design: energy and spatial resolutions

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

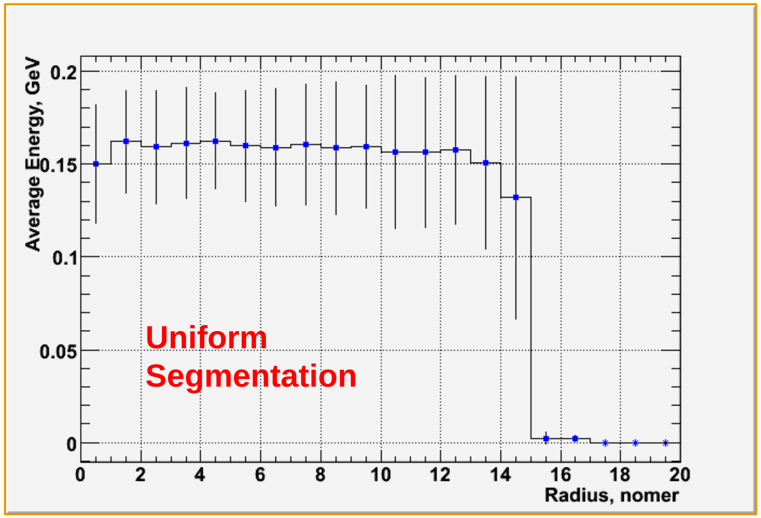
Sensor energy deposition sum for 200 GeV electrons as a function of transverse coordinate X, which is perpendicular to sensor strips:

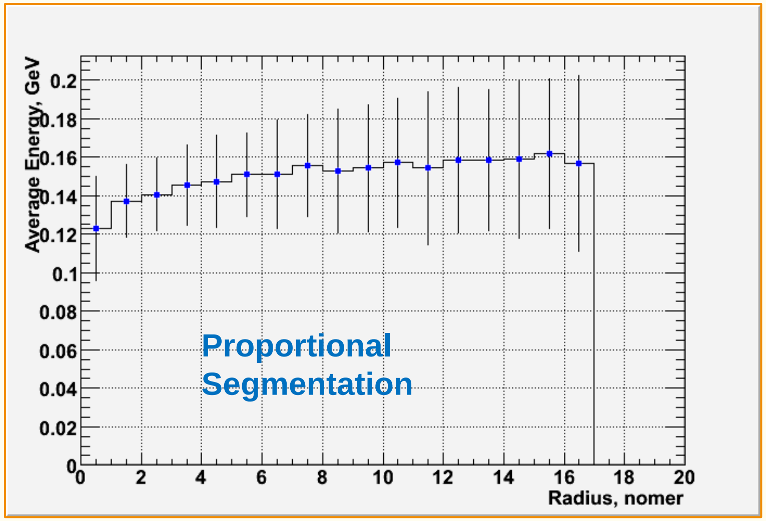


- ***Further optimization should include hardware compensation of non-uniformity (optimization of layers displacement) and software correction of the measured energy, based on the shower position determination***
- ***Spatial resolution of the new design is expected to be similar to the baseline one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

Signal and RMS for both Segmentations

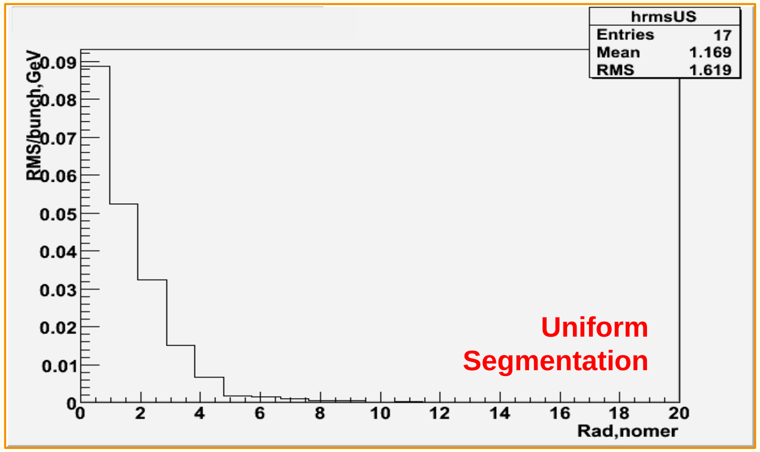
Core signal in layer of shower maximum (10th layer for 100 GeV)

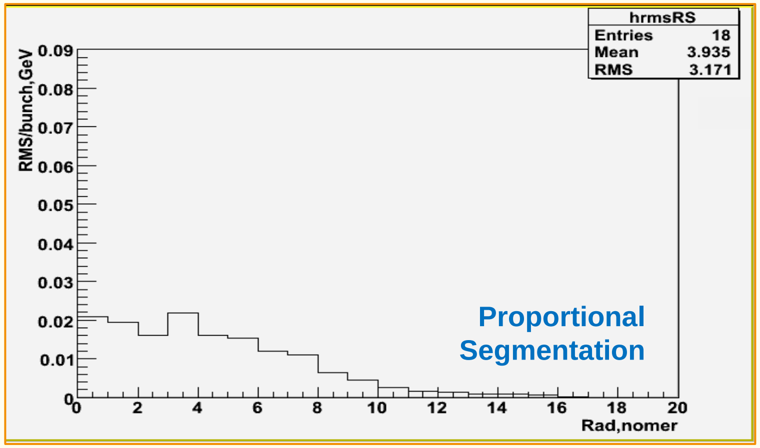




Signal nearly segmentation-independent!

RMS from Background (in 10th layer)



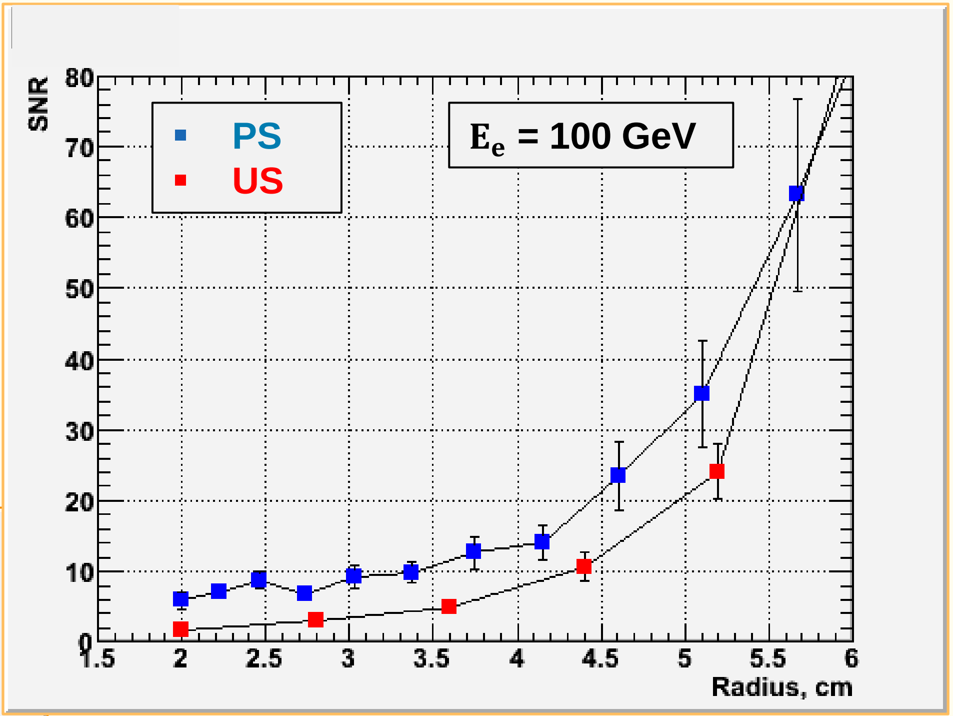


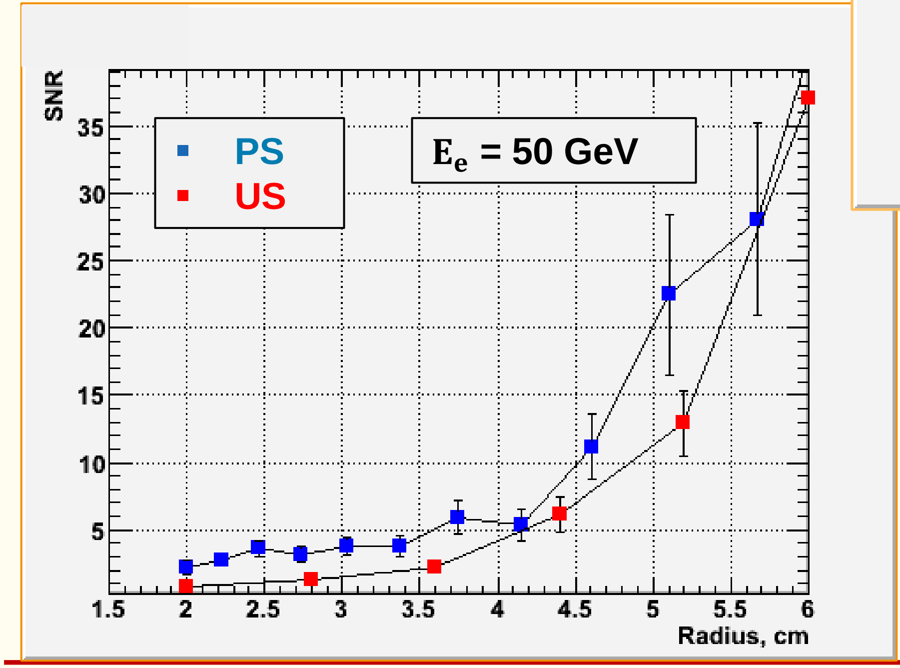
Different distributions!

20 bunch crossings were given

SNR in cell with maximum E_dep

- Signal – is maximum energy deposition in cell from sHEe *(in the core of shower and in the maximum energy deposition layer)*
- Noise – is RMS of the averaged BG





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