Initial proposal for the design of the luminosity calorimeter at a 3TeV CLIC

Iftach Sadeh

Tel Aviv University

March 6th 2009

sadeh@alzt.tau.ac.il

Overview

1. **Basic design** of the calorimeter.

2. **Luminosity measurement**;
using Bhabha scattering as the gauge proccess, dependance of the cross section on the size of LumiCal and the subsequent statistical error of the measurement.

3. **Intrinsic properties of LumiCal**;
fiducial volume, energy resolution, error in the luminosity measureemnt due to reconstruction of the polar angle of showers, Moliere radius, dynamical range of the signal and justification for the selected segmentation scheme (number of radial segmentations and number of layers).

4. **Beam background**;
energy deposits in LumiCal due to beamstrahlung pairs and backscattering from LumiCal.

5. **Physics background** at 3TeV.

LumiCal design parameters

- **Placement and dimensions:**

  a. Positioned 2.27m from the IP.

  b. Inner to outer radii are 10 $\rightarrow$ 35cm.

- **Transverse segmentation:**

  a. 48 divisions in the azimuthal direction (cell size of 7.5deg).

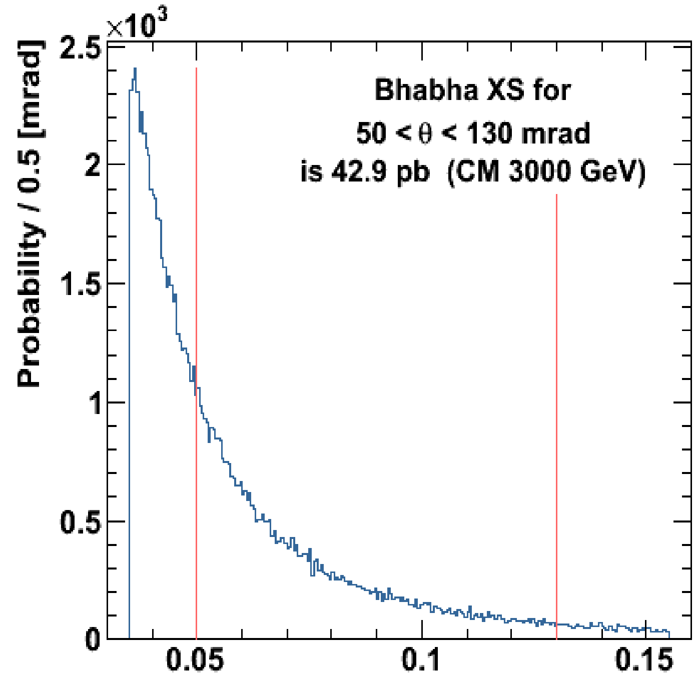
  b. 50 divisions in the radial direction (cell size of 2mrad).

- **Longitudinal segmentation** - 40 layers, which are made up of: 3.5mm tungsten, 0.3mm silicon sensors, 0.1mm free space for electronics, 0.6mm ceramic support.

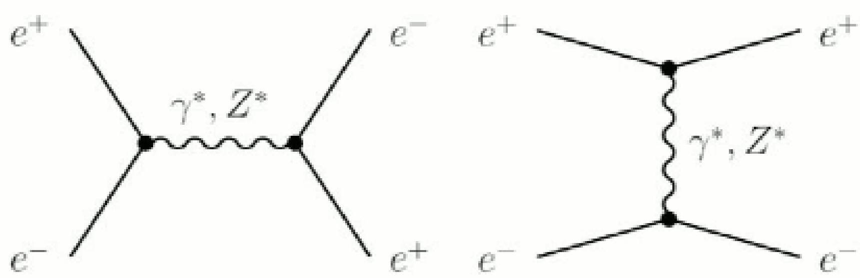
Luminosity measurement

- The luminosity is measured by counting the the number of Bhabha scattering events in a well defined angular (and energetic) region.

- The events are distinguished from the background by applying selection cuts, which constrain the difference in shower energy and angle between the two arms of LumiCal.



(Luminosity for this plot = 10.4 [1/nb])

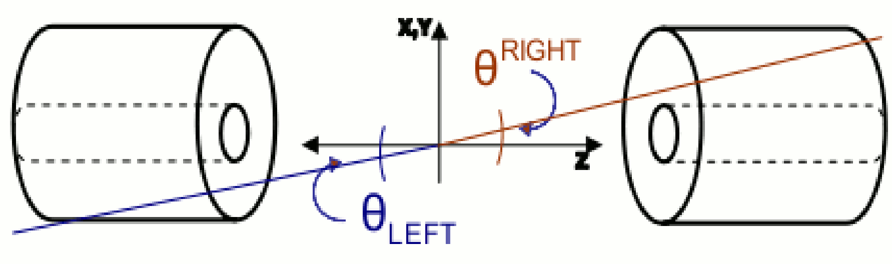


(a) s channel (b) t channel

$$\frac{d\sigma_B}{d\theta} \propto \frac{1}{\theta^3}$$

Compare angles & energy

$$L = \frac{N_B}{\sigma_B} \quad , \quad \frac{\Delta L}{L} = \frac{\Delta N_B}{N_B} = \frac{N_{rec} - N_{gen}}{N_{gen}}\Bigg|_{\theta_{min}}^{\theta_{max}}$$

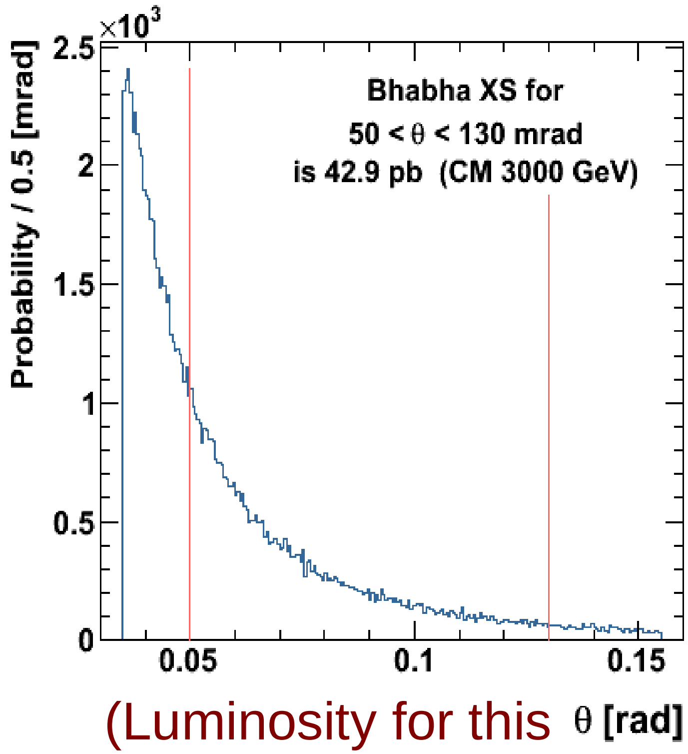


$$\Delta\theta \equiv \theta_{RIGHT} - \theta_{LEFT}$$

Cross section calculation

In order to simulate Bhabha scattering the BHWIDE generator was used with different center-of-mass energies.

The scattering angles of the leptons were constrained within the physical volume of LumiCal ($44 < \theta < 154$ mrad).
The cross section was computed for the fiducial volume of LumiCal ($50 < \theta < 130$ mrad) due to the fact that this is the region within which Bhabha scattering can be measured.



(Luminosity for this plot = 10.4 [1/nb])

The statistical error in luminosity due to the counting of the number of Bhabha scattering events, N, is:

$$\frac{\Delta N}{N} = \frac{1}{\sqrt{N}}$$

Bhabha statistics in with "ILC" size (Inner to outer radius: ΔR = 12 cm)

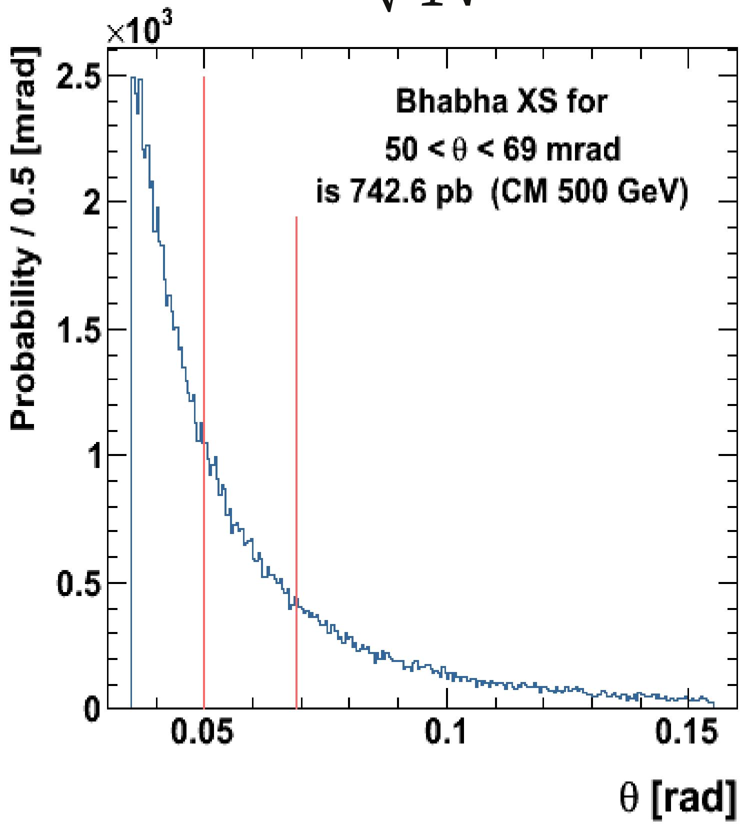
$$Radius: 10 \rightarrow 22\,cm \;\Rightarrow\; \theta: 44 \rightarrow 153\,mrad$$

(estimated fiducial volume)

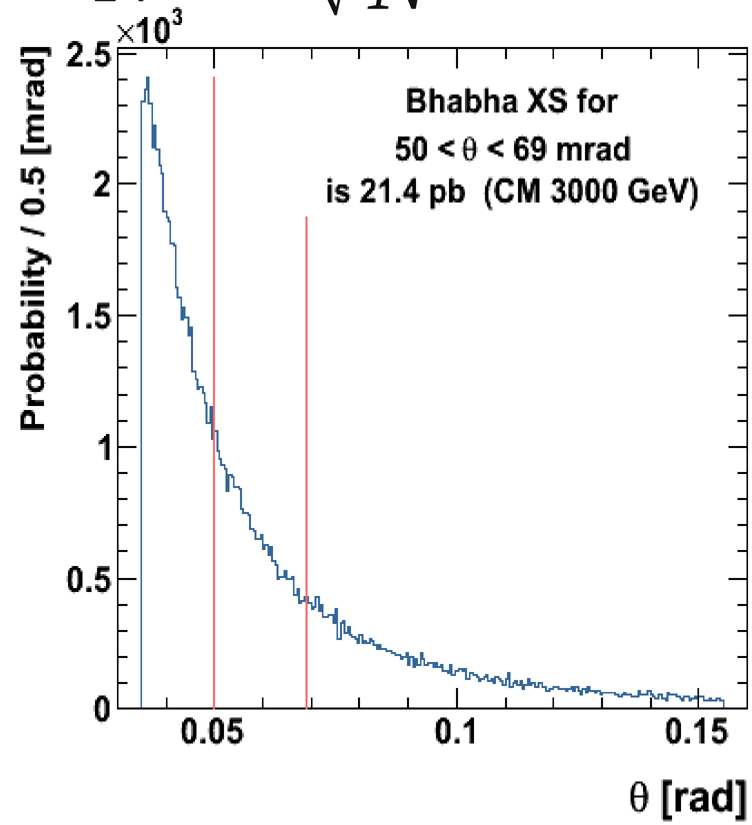
(500 [1/fb] – 4 years)

$$\frac{\Delta N}{N} = \frac{1}{\sqrt{N}} = 5.2 \cdot 10^{-5}$$

$$\frac{\Delta N}{N} = \frac{1}{\sqrt{N}} = 3 \cdot 10^{-4}$$



(Luminosity for this plot = 0.3 [1/nb])



(Luminosity for this plot = 10.4 [1/nb])

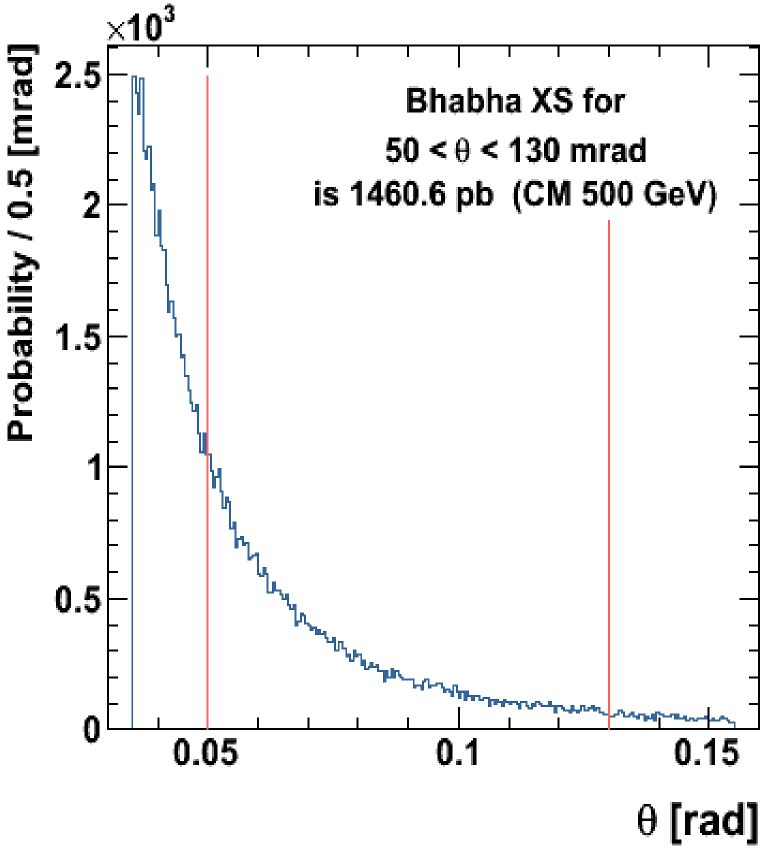
Bhabha statistics in with larger fiducial volume

$$Radius: 10 \rightarrow 35\, cm \quad \Rightarrow \quad \theta: 44 \rightarrow 153\, mrad$$

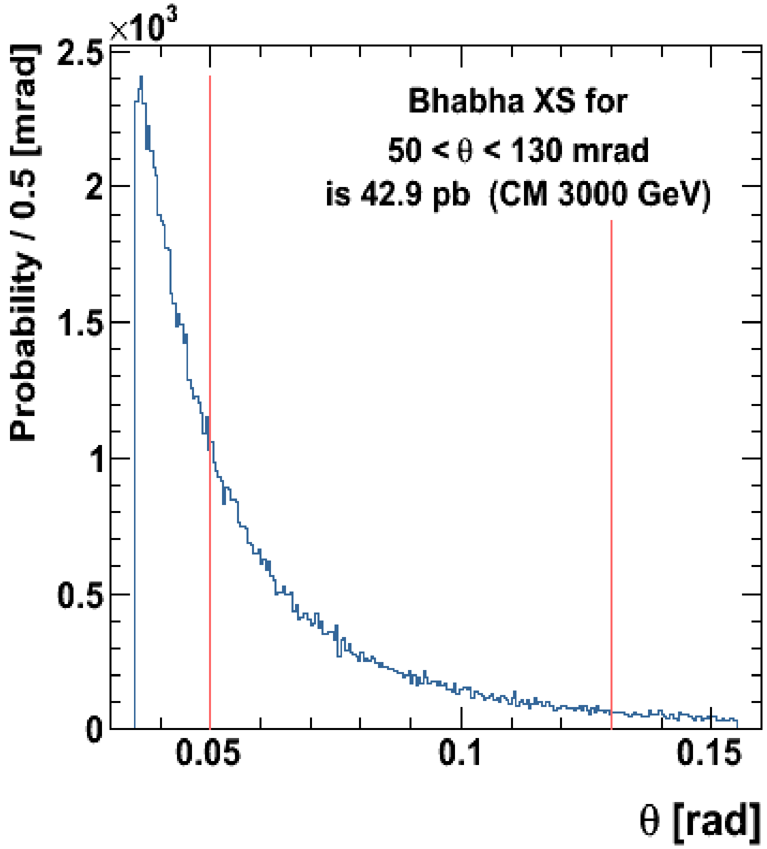
(500 [1/fb] – 4 years)

$$\frac{\Delta N}{N} = \frac{1}{\sqrt{N}} = 3.7 \cdot 10^{-5}$$

$$\frac{\Delta N}{N} = \frac{1}{\sqrt{N}} = 2.2 \cdot 10^{-4}$$



(Luminosity for this plot = 0.3 [1/nb])

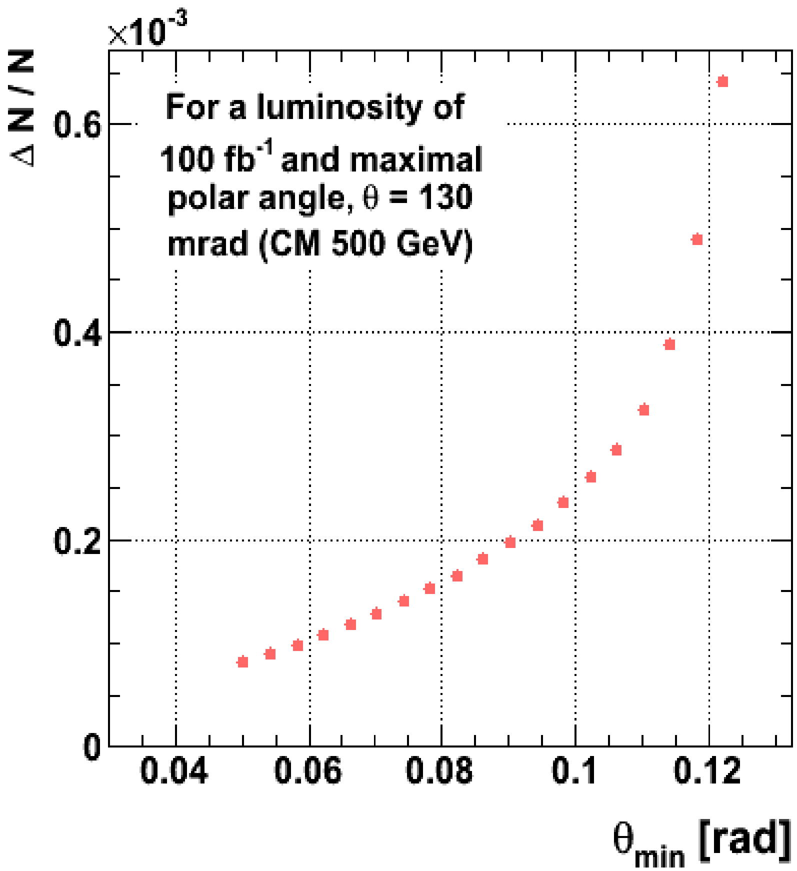


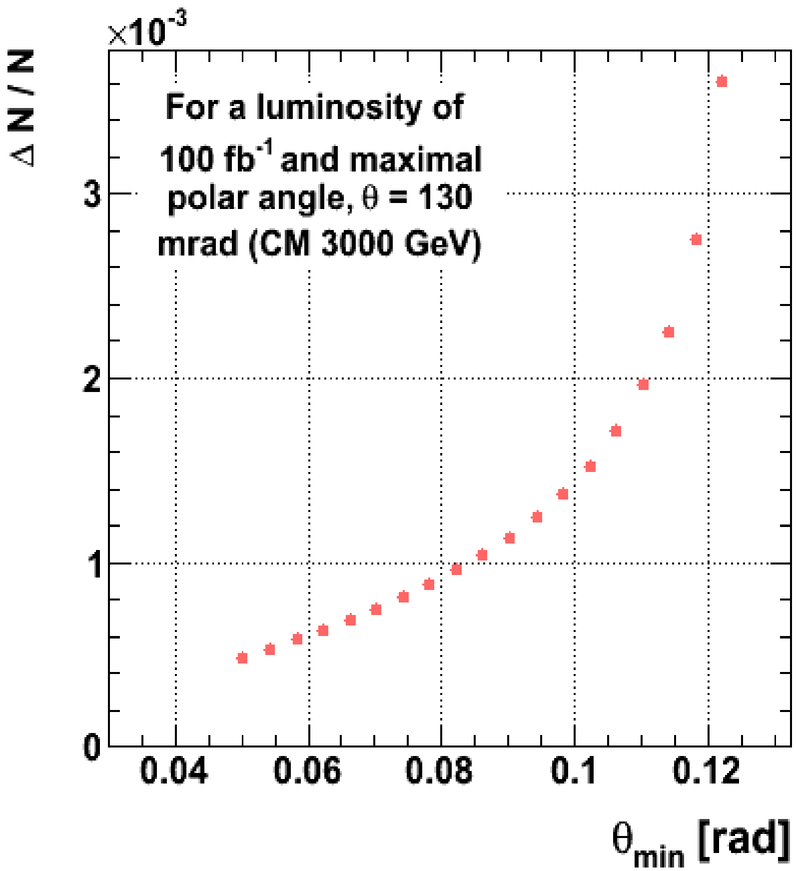
(Luminosity for this plot = 10.4 [1/nb])

Statistical error in luminosity as a function of the minimal polar angle of the fiducial volume

We change the minimal polar angle for reconstruction (keeping the outer angle constant) and check the statistical error for one year of running (100 [1/fb], for a 1/3 year active machine)

$$(\,?<\theta<130\,mrad\,)$$



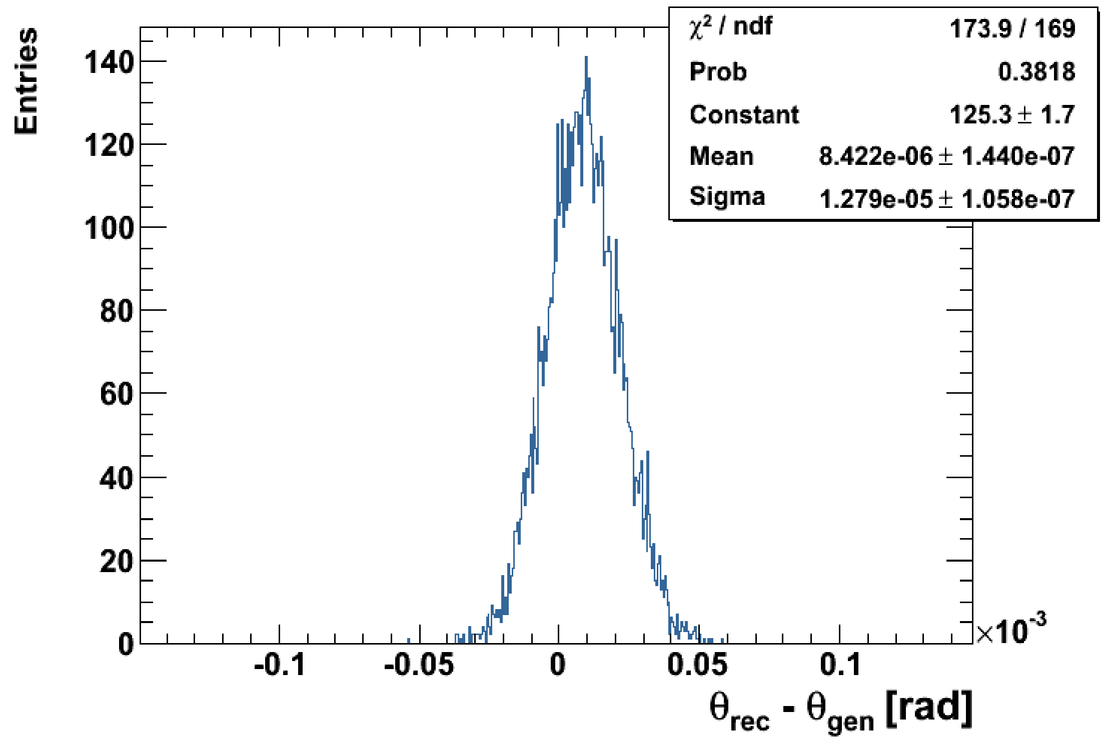


Reconstruction of the polar angle

In order to count the number Bhabha events in LumiCal in a given angular range, it is necessary to reconstruct the polar angle of showers with great precision. This is done by means of the so called logarithmic method.

$$\mathcal{W}_i = \max\{\ 0\ ,\ \mathcal{C} + \ln \frac{E_i}{E_{tot}}\} \qquad < \theta > = \frac{\sum_i \theta_i \cdot \mathcal{W}_i}{\sum_i \mathcal{W}_i}$$

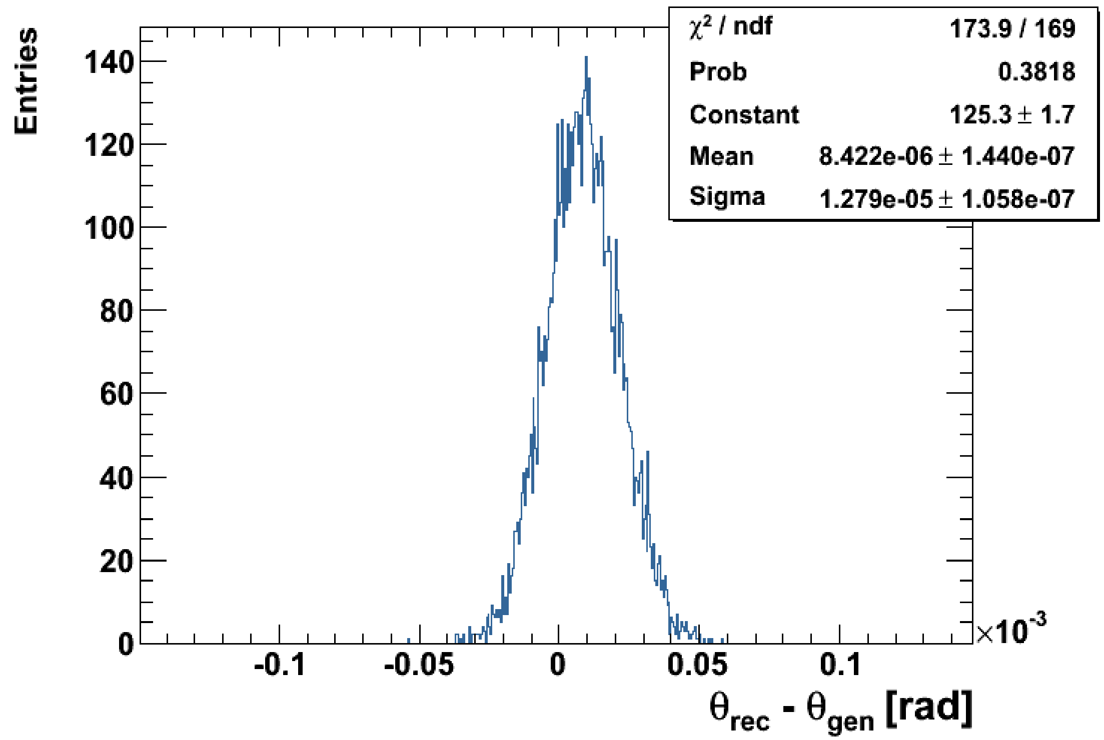
The **polar bias** is defined as the mean of the distribution of the difference between the reconstructed and the generated polar angle of showers.
The **polar resolution** is the width of the distribution.



Reconstruction of the polar angle

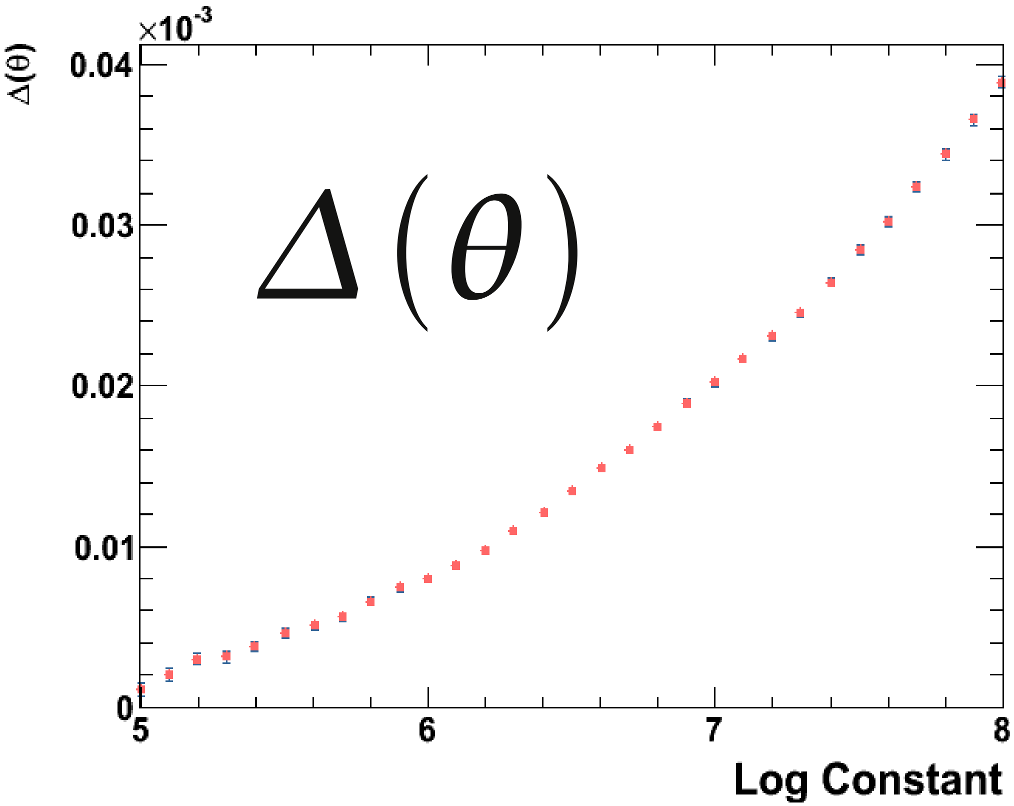
The reconstruction induces an intrinsic polar bias, due to the non-linear transformation from the xy coordinates of the detector to the polar symmetric coordinates of the acceleration reference frame.
The bias cam be determined by simulation and measured by test-beam.
For different logarithmic weighting constants the bias changes. A good way to get a consistent reconstruction method is to always choose the constant which minimizes the angular resolution.

- In general the polar bias decreases when the angular resolution improves (angular cell size decreases).
- The logarithmic constant must be re-optimized if the cell size is changed.
- The logarithmic constant also has a week dependance on the energy of the reconstructed shower.

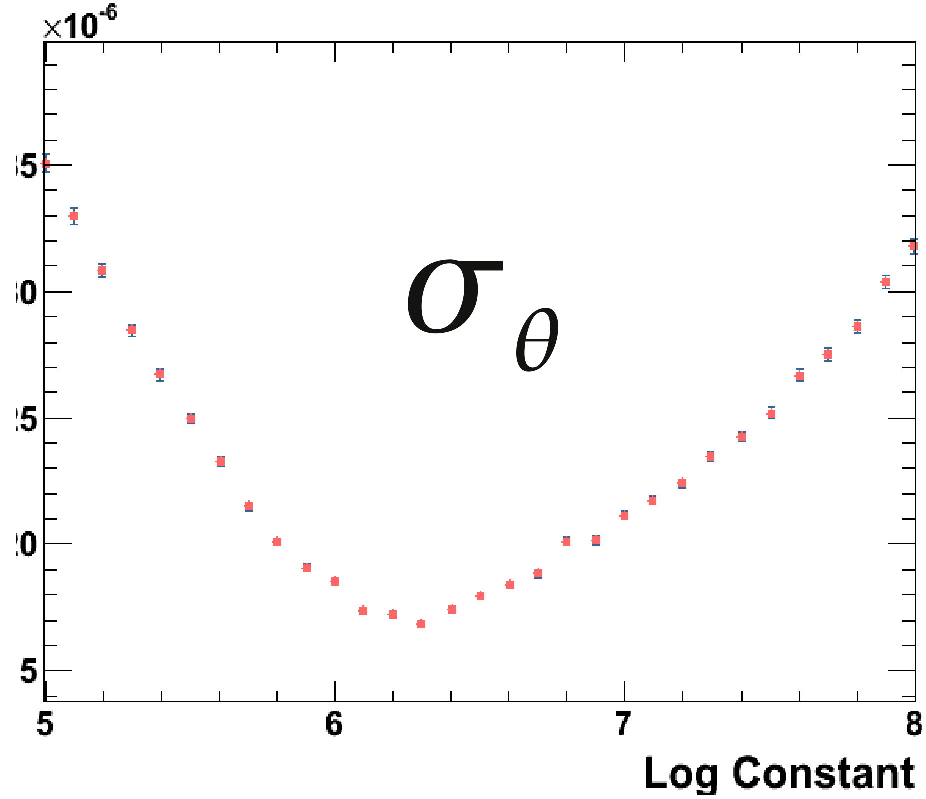


Reconstruction of the polar angle

Polar bias



Polar resolution



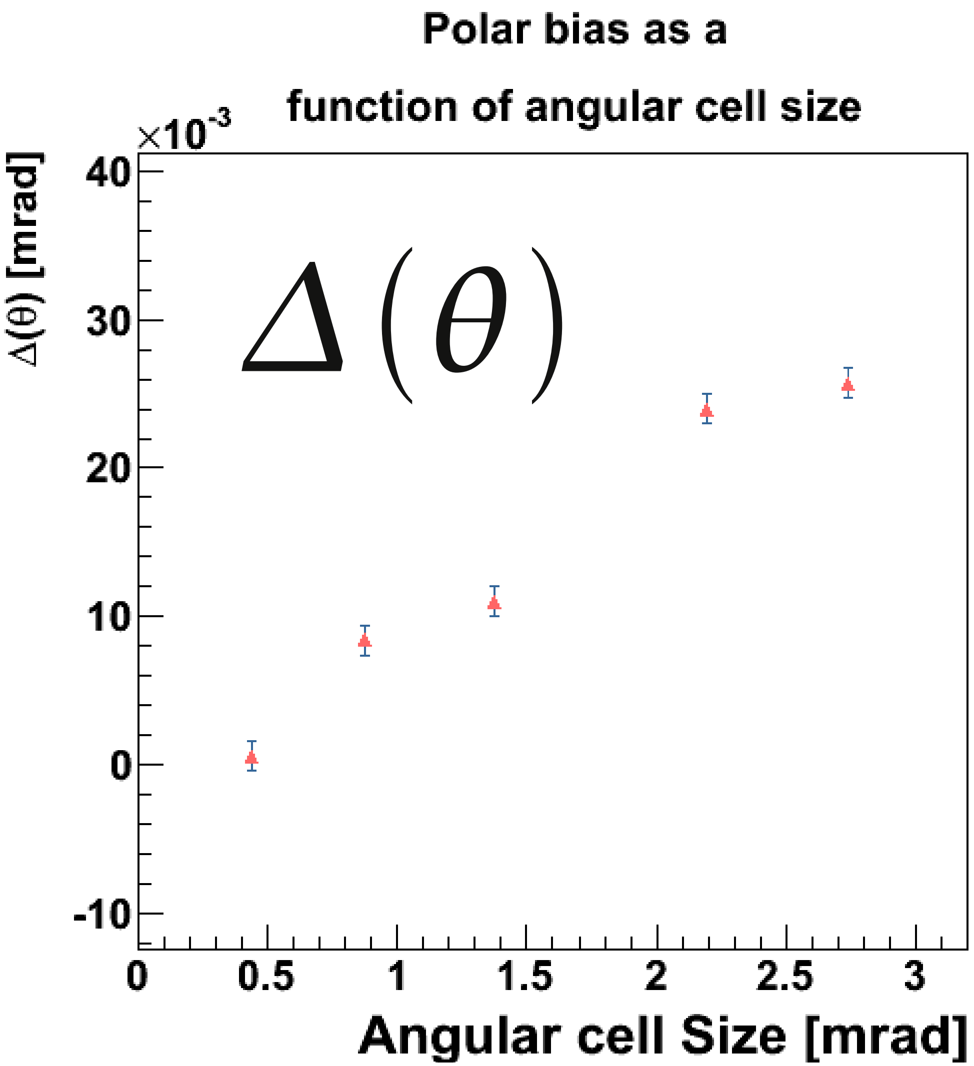
1. Minimize the polar resolution and determine the subsequent polar bias (in this example the lumical cell-size is 1.3mrad).
2. The polar bias determines the error in the luminosity.

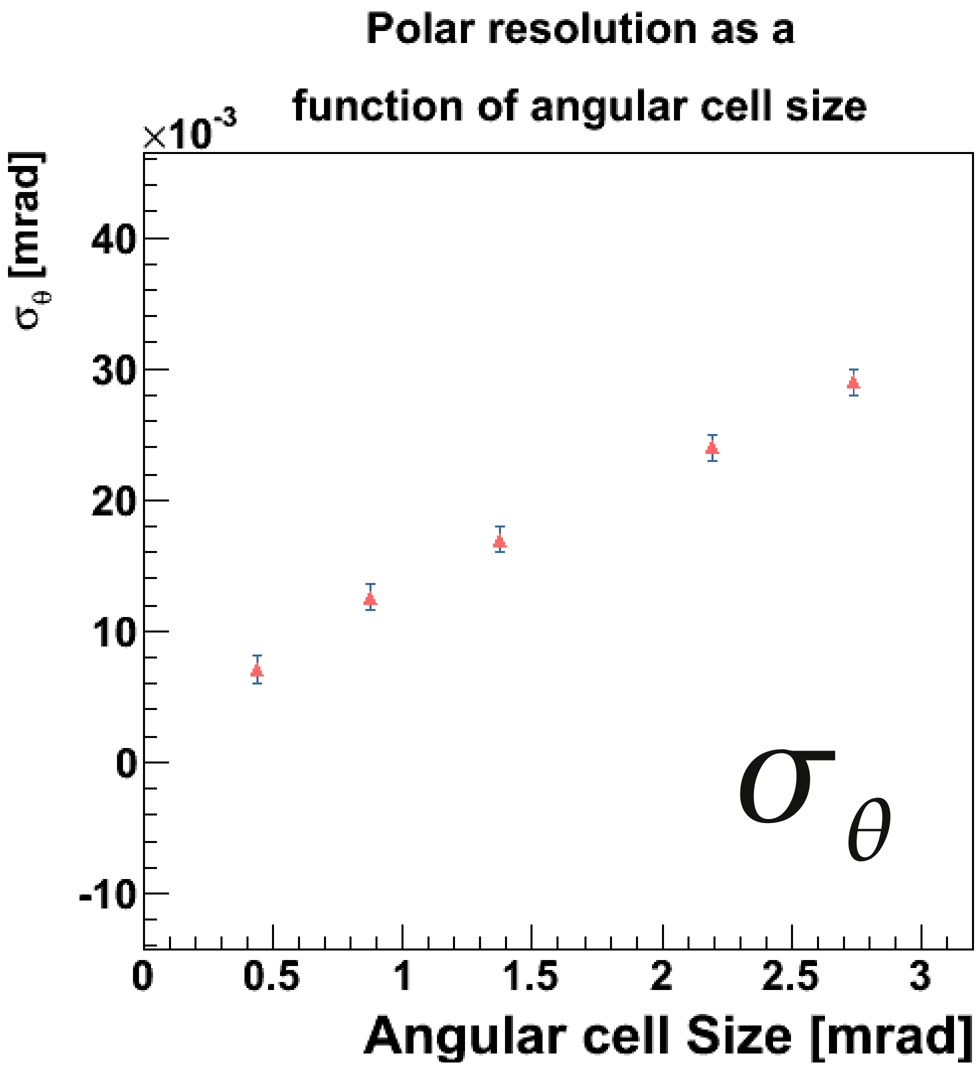
$$<\theta> = \frac{\sum_i \theta_i \cdot \mathcal{W}_i}{\sum_i \mathcal{W}_i}$$

$$\mathcal{W}_i = \max\{\ 0\ ,\ \mathcal{C} + \ln\frac{E_i}{E_{tot}}\}$$

Reconstruction of the polar angle

The resolution and bias increase linearly with the cell-size.

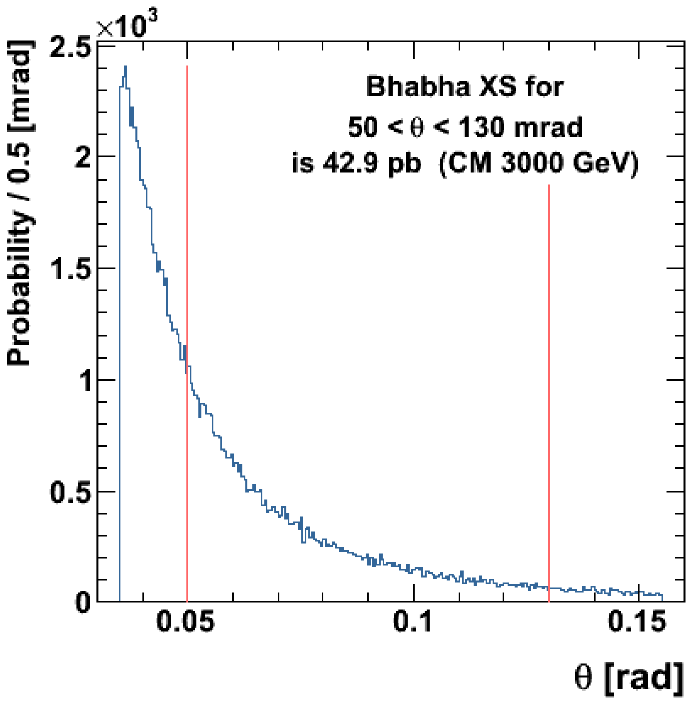


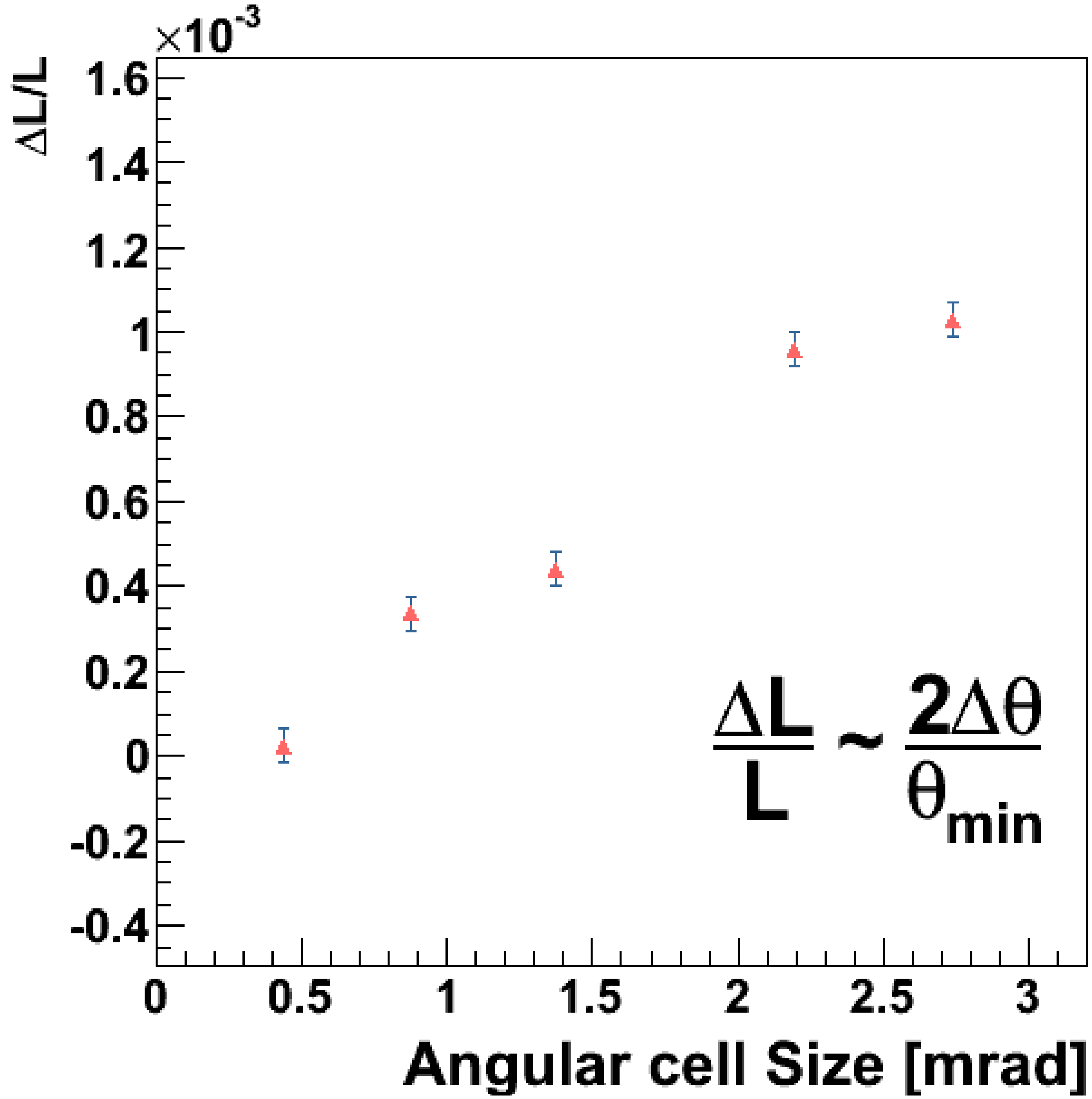


* High statistics are needed in order to determine the linear relations better...

Reconstruction error in luminosity as a function of the (polar) angular cell size

The error in the luminosity depends on the cell size, since for finer granulation the position reconstruction increases. Therefore, the number of Bhabha events in the fiducial volume is counted with higher precision.



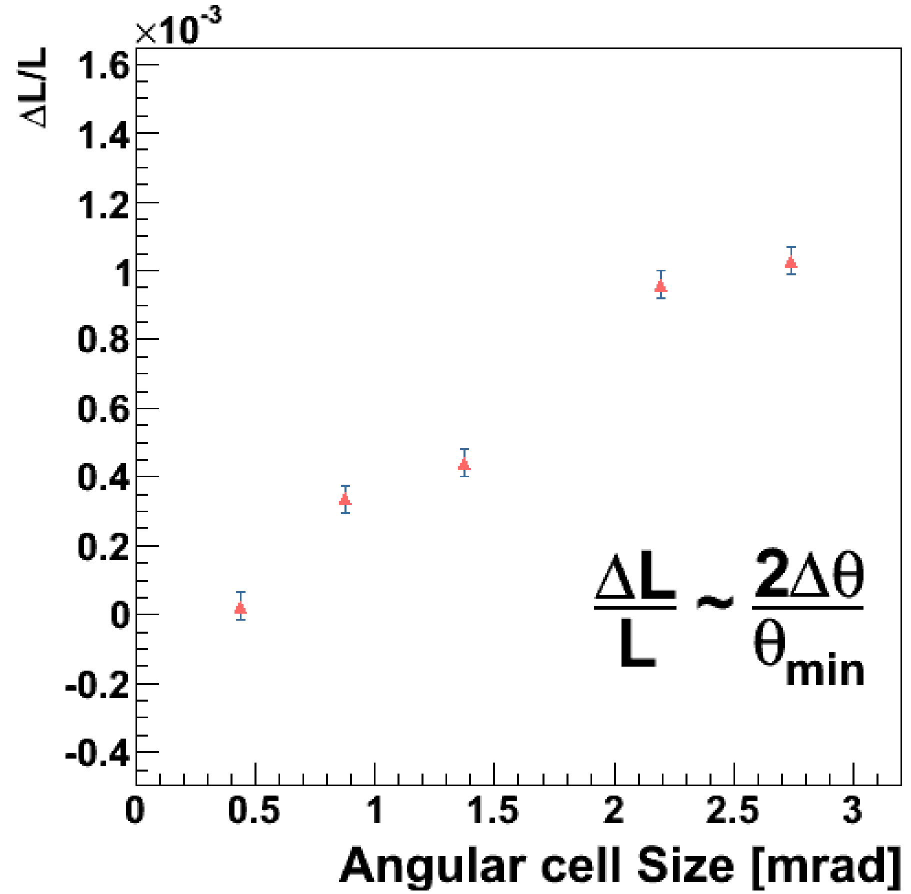


* High statistics are needed in order to determine the linear relation better...

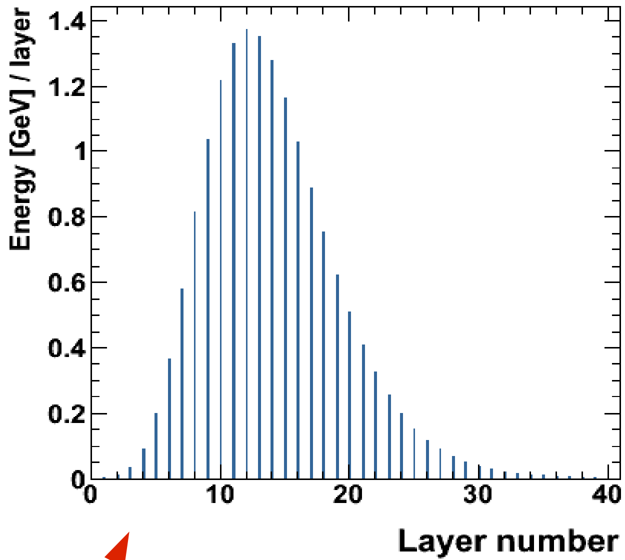
Reconstruction error in luminosity as a function of the (polar) angular cell size

The polar segmentation is chosen such that the luminosity error is within the acceptable error.

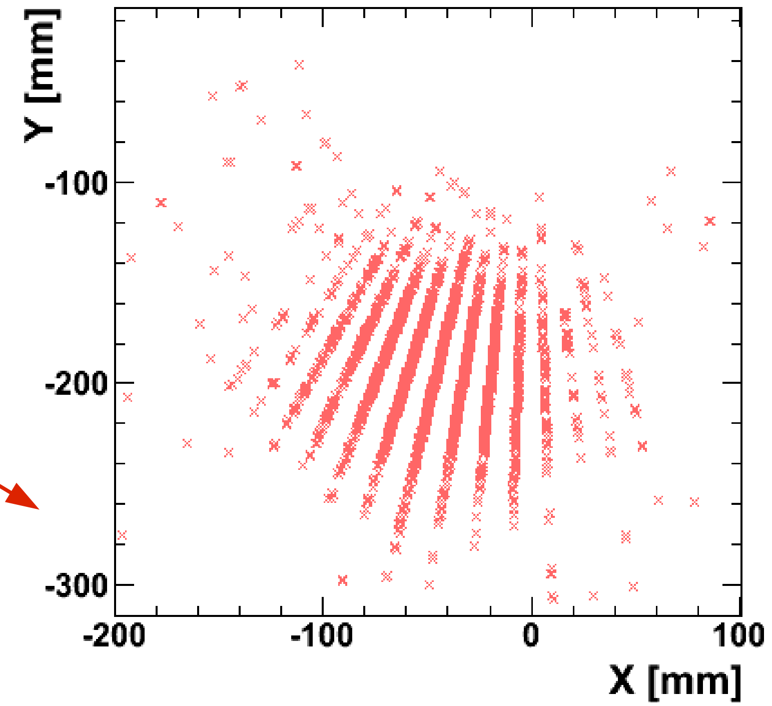
For the requirement that the relative error in luminosity be < 1% , it is sufficient to have at least 50 radial divisions in a 25cm (minimal to maximal radii length) LumiCal. This cell size corresponds to 2.2mrad.



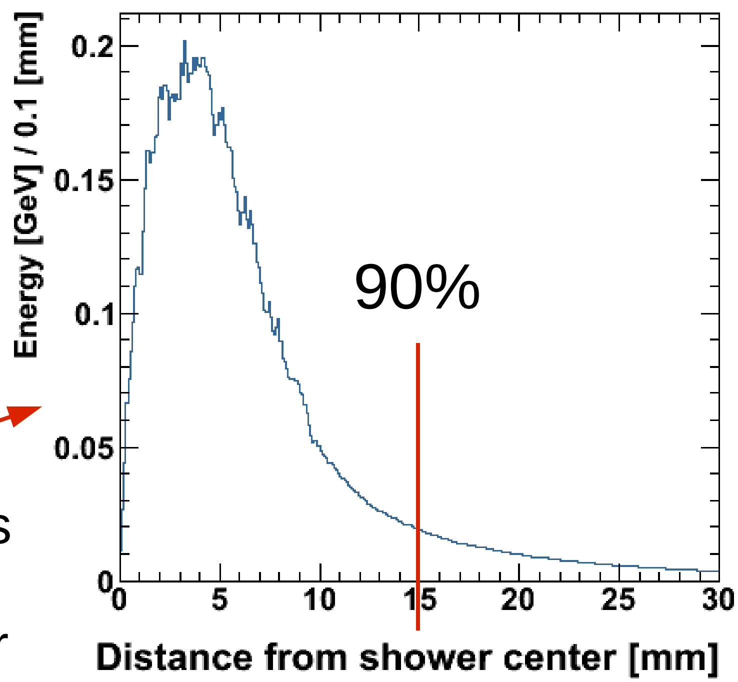
Shower development (1.5TeV electron shower)

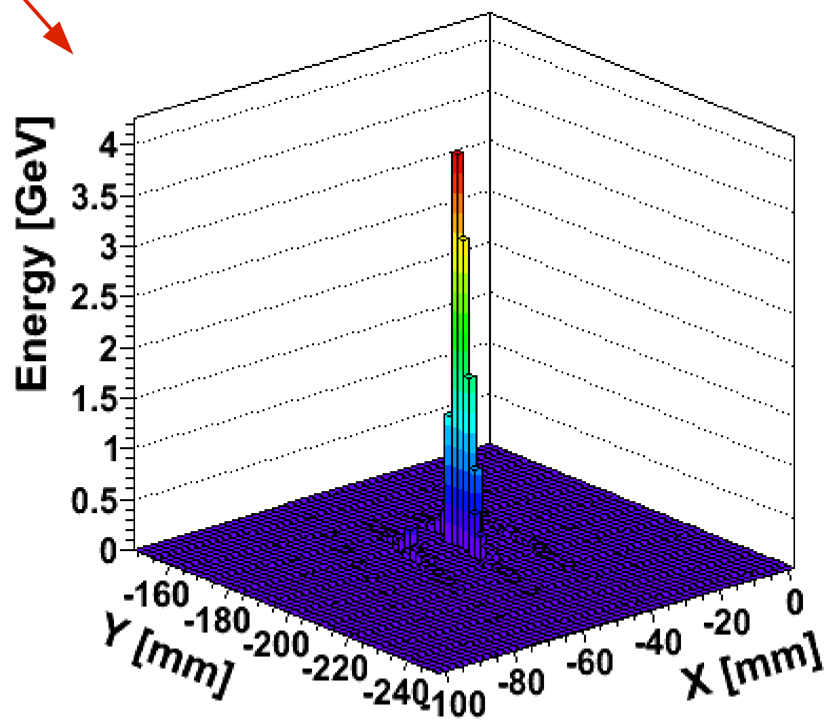


Transverse development



Longitudinal development

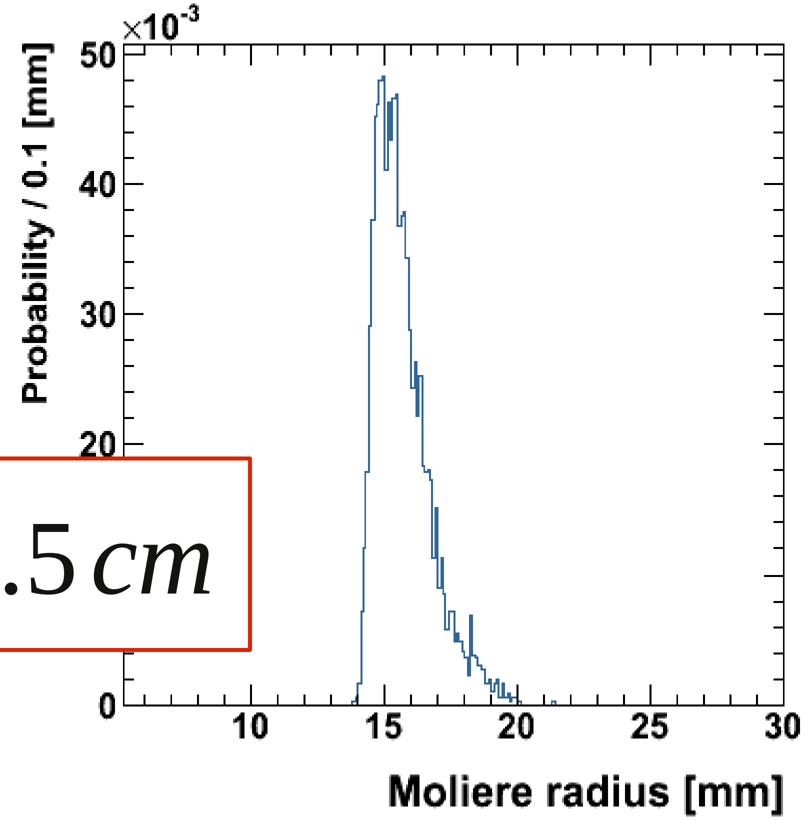




90% of the energy is within 15mm of the center of the shower

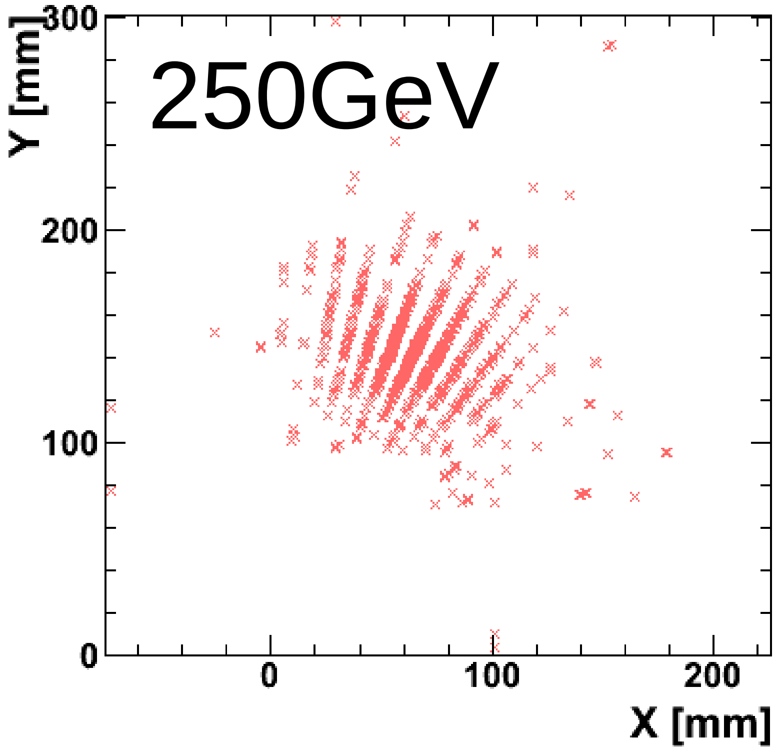
Moliere radius

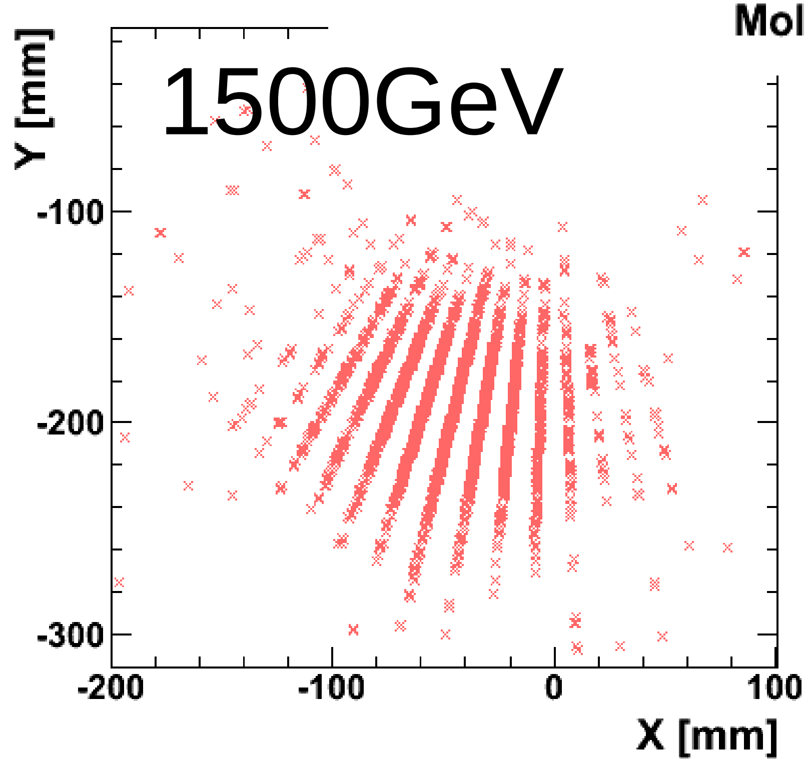
Distribution of the Moliere radius (90% of the shower's energy is inside the Moliere radius) - Does not depend on the energy !



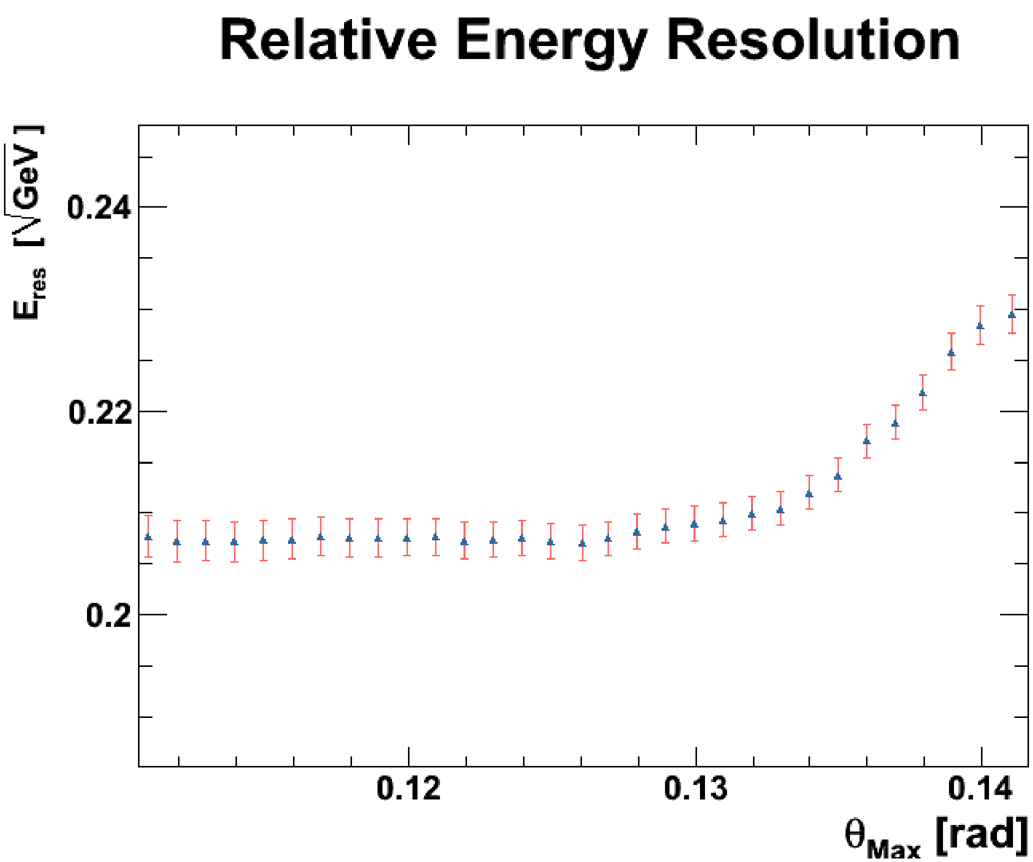
$$R_M = 1.5\,cm$$

Transverse shower development





Fiducial volume at 3TeV



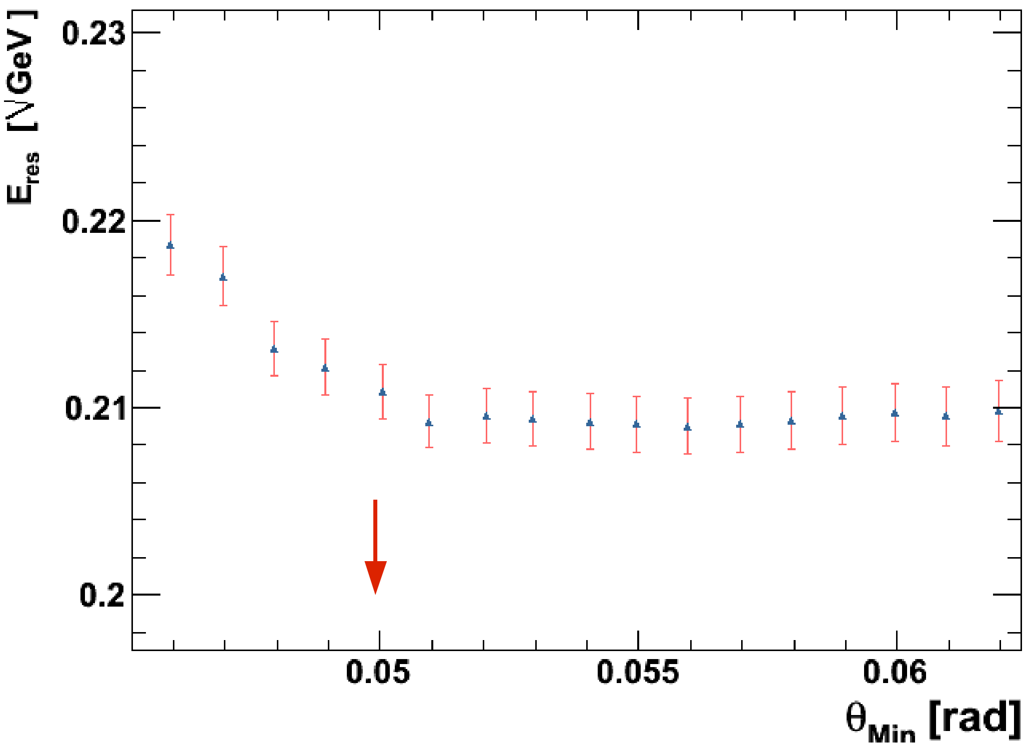
$$E_{res} \equiv \frac{\sigma_E}{E}\sqrt{E_{beam}}$$

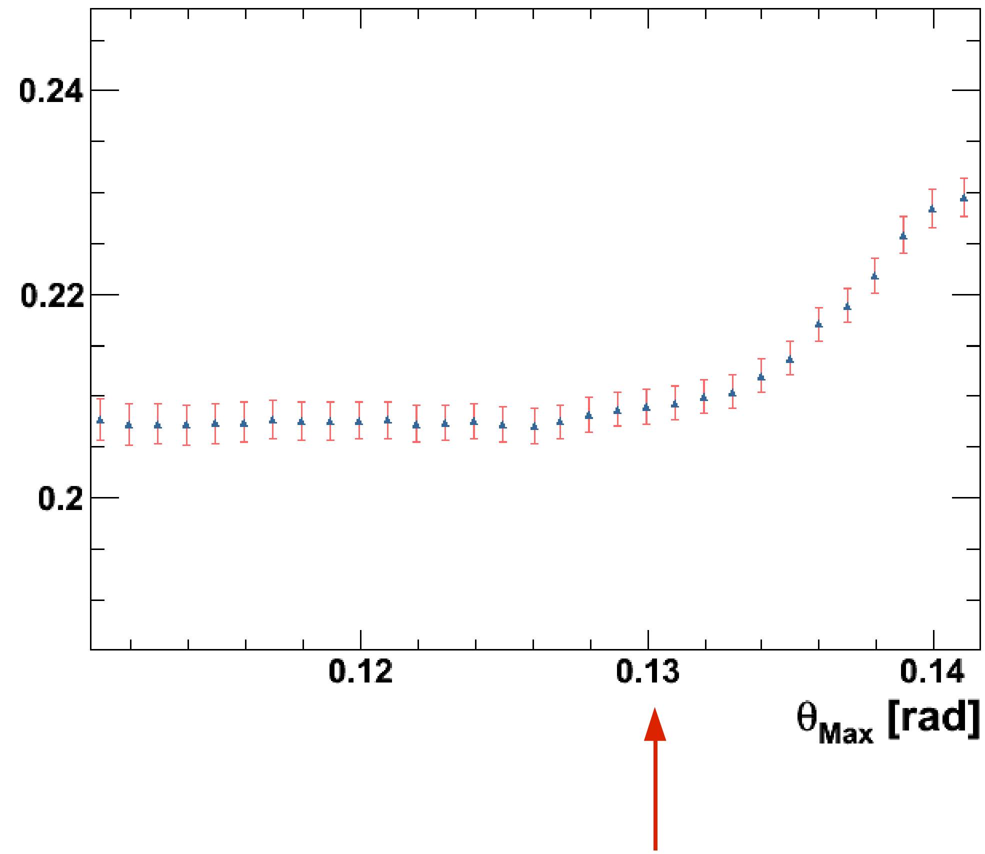
- In order to prevent leakage from the sides of LumiCal, one may determine the minimal and maximal allowed polar angles for shower by determining the energy resolution of showers. When energy leaks out of the calorimeter, the energy resolution degrades.
- These minimal and maximal angles define the fiducial volume of LumiCal.

Fiducial volume at 3TeV

Physical radius: $10 \rightarrow 35\, cm$

$\Rightarrow$ Fiducial volume: $50 < \theta < 130\, mrad$

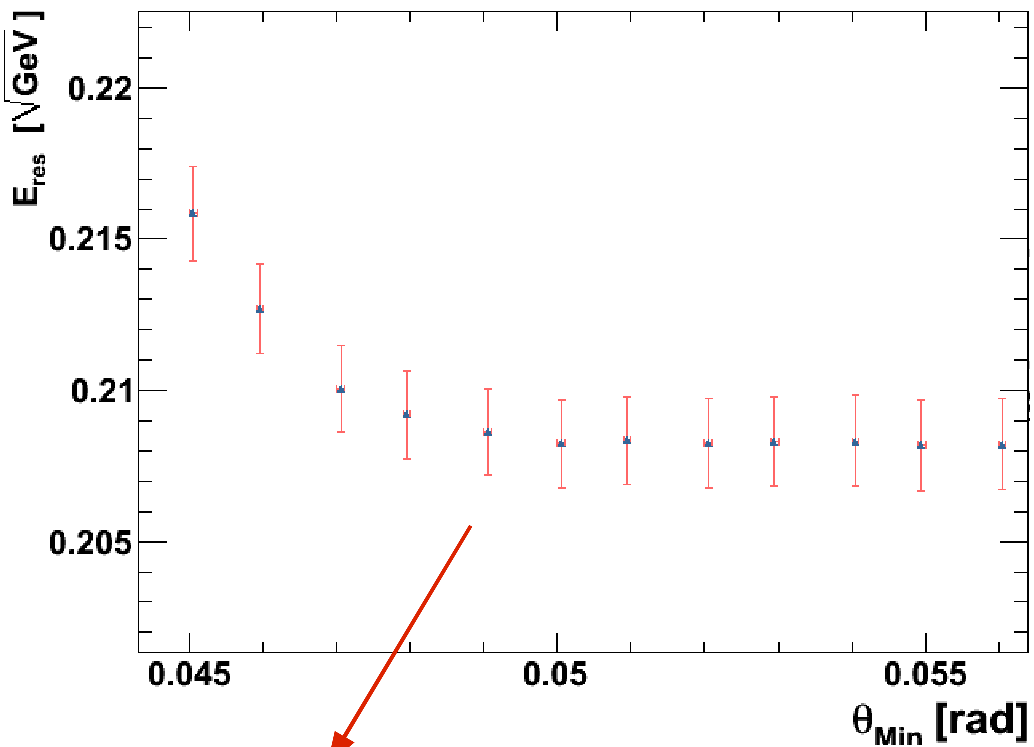


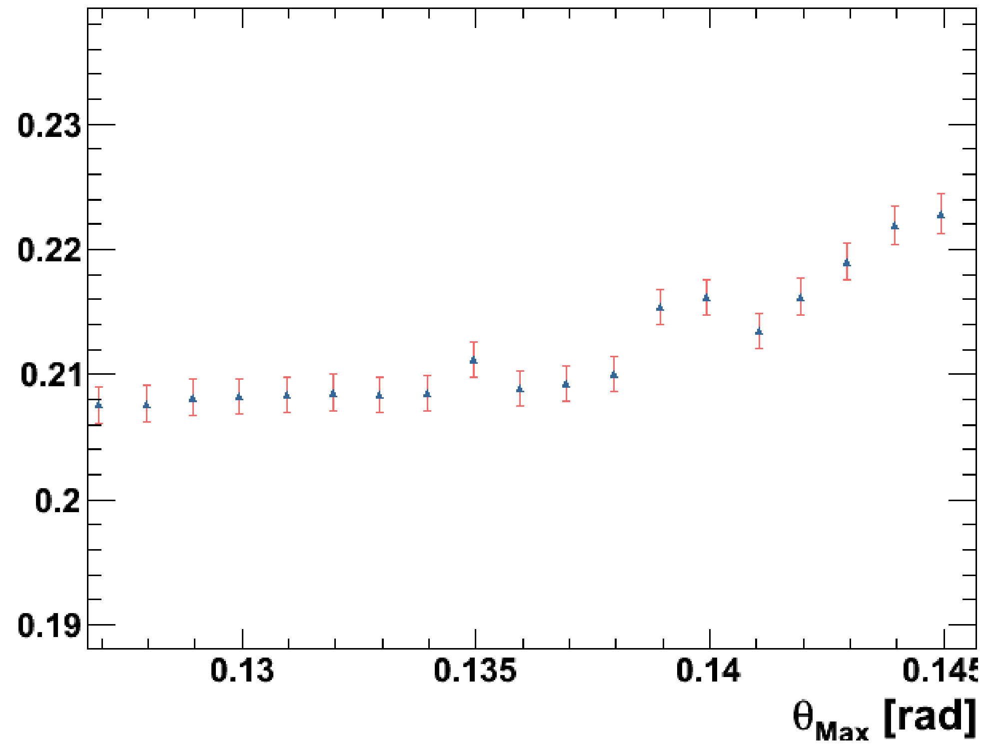


$$E_{res} \equiv \frac{\sigma_E}{E}\sqrt{E_{beam}} \approx 0.21\%$$

Fiducial volume at 500GeV

$$\text{Physical radius: } 10 \rightarrow 35\,cm$$
$$\Rightarrow \text{ Fiducial volume: } 50 < \theta < 130\,mrad$$

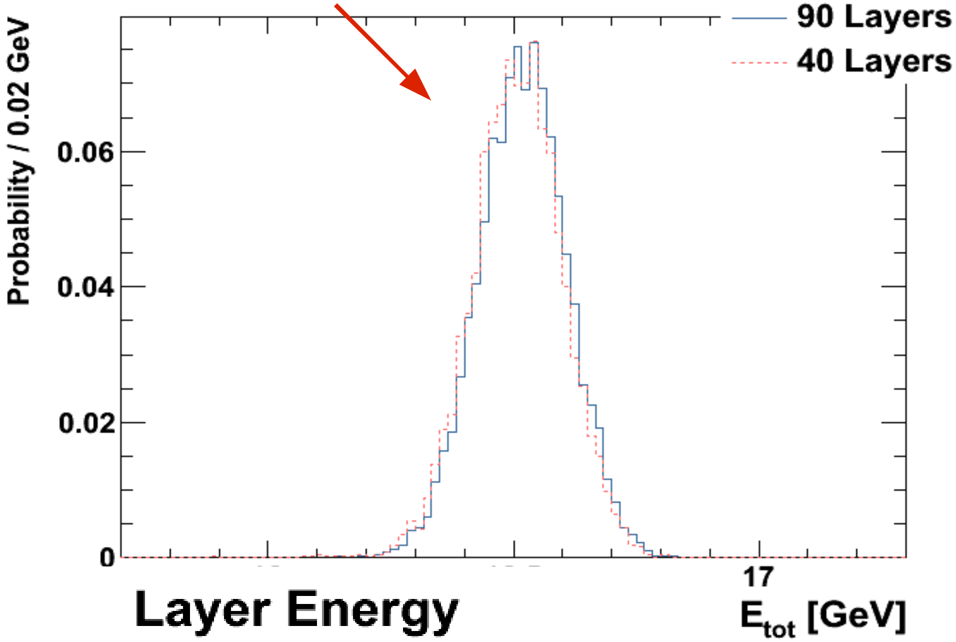


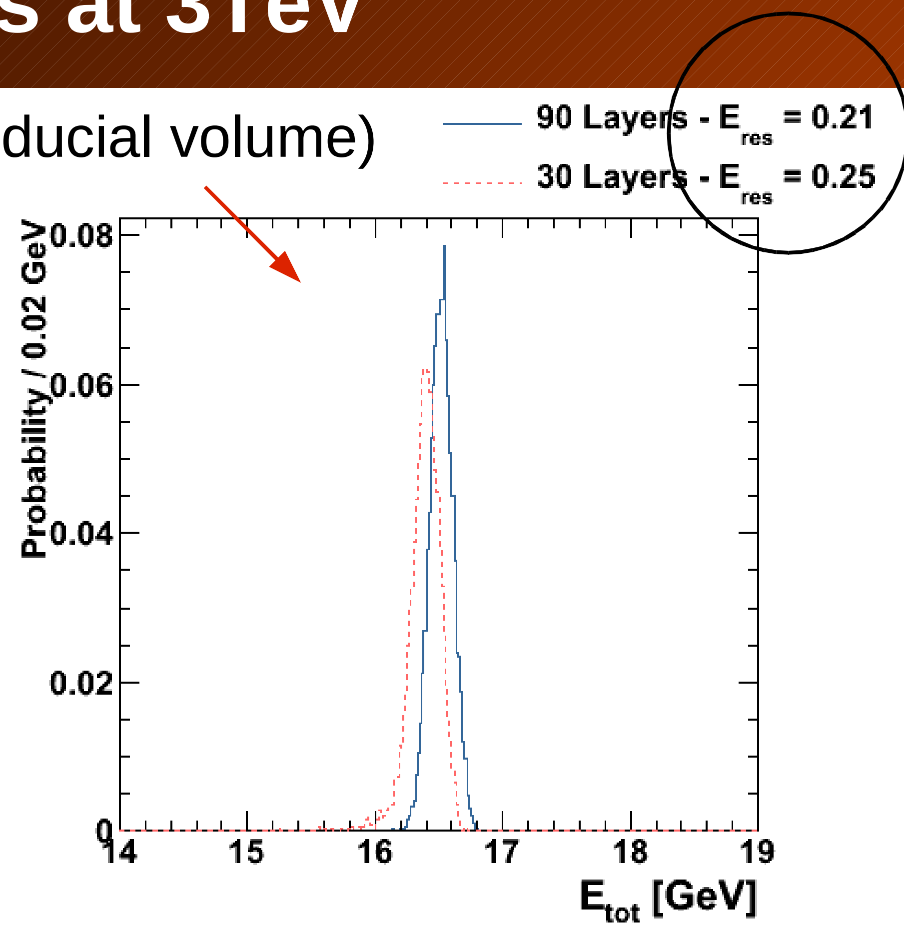


Basically the same as for 3TeV, as the Moliere radius does not depend strongly on the energy of showers.

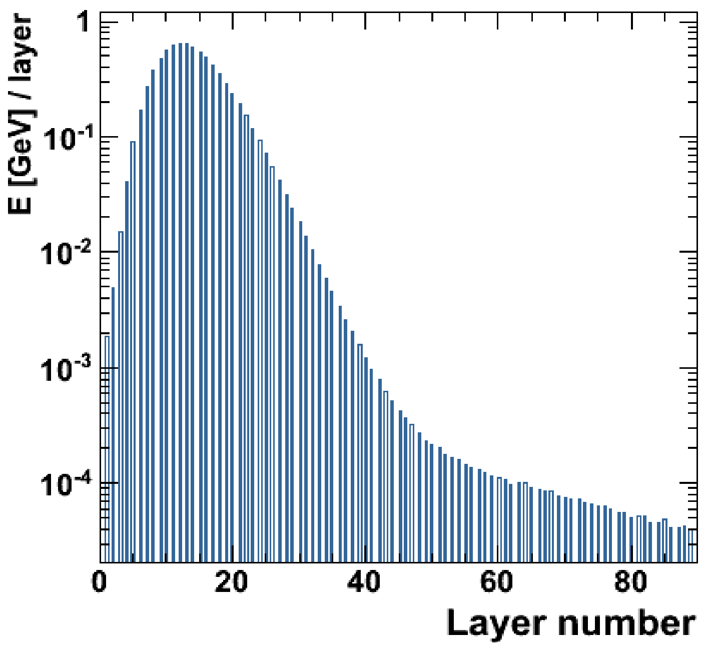
Number of layers at 3TeV

(total energy in an event in the fiducial volume)





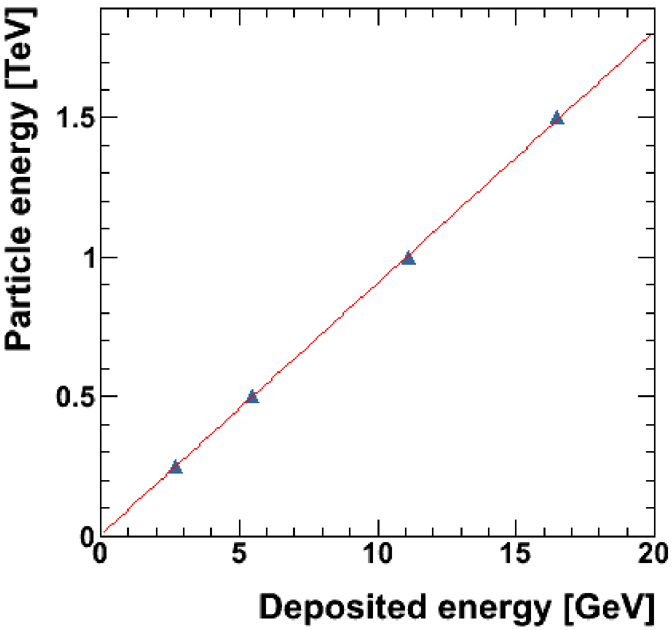
Layer Energy

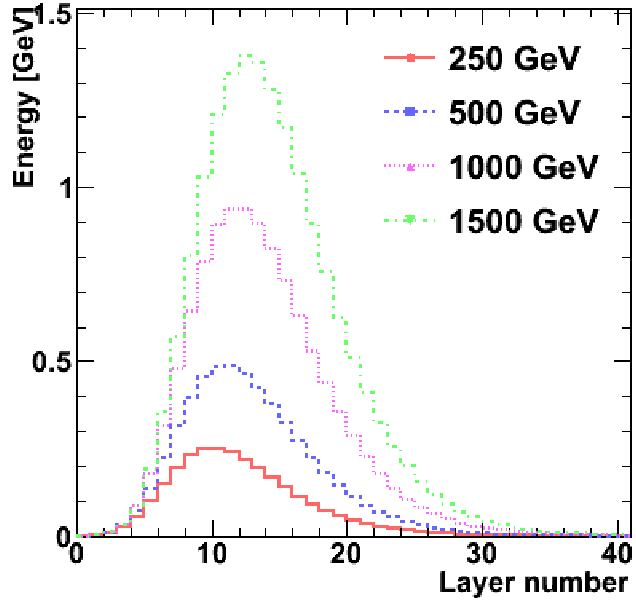


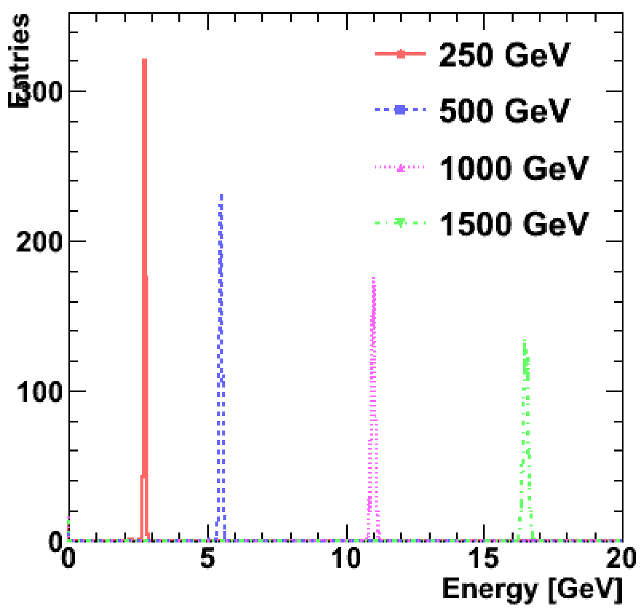
- Each layer is 1 radiation length thick (3.5 mm of tungsten).
- 40 layers are needed for containment.

(Energy in each layer for one event)

Energy calibration and resolution

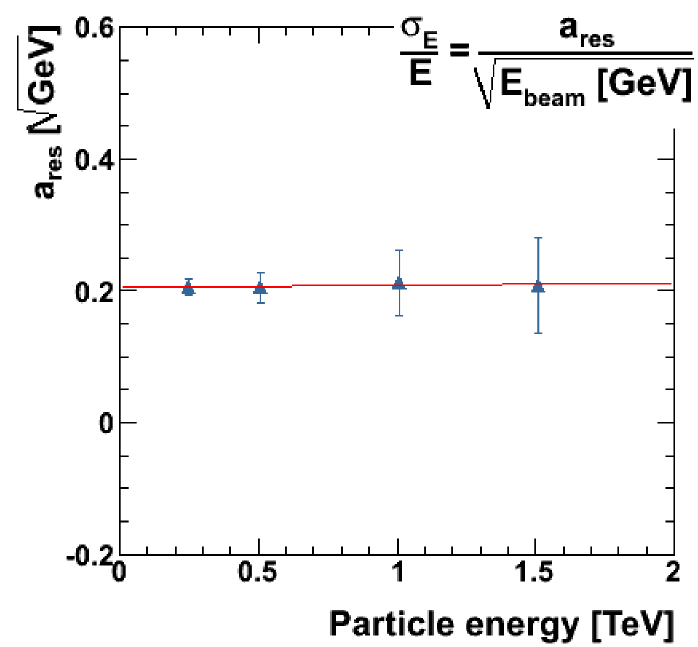






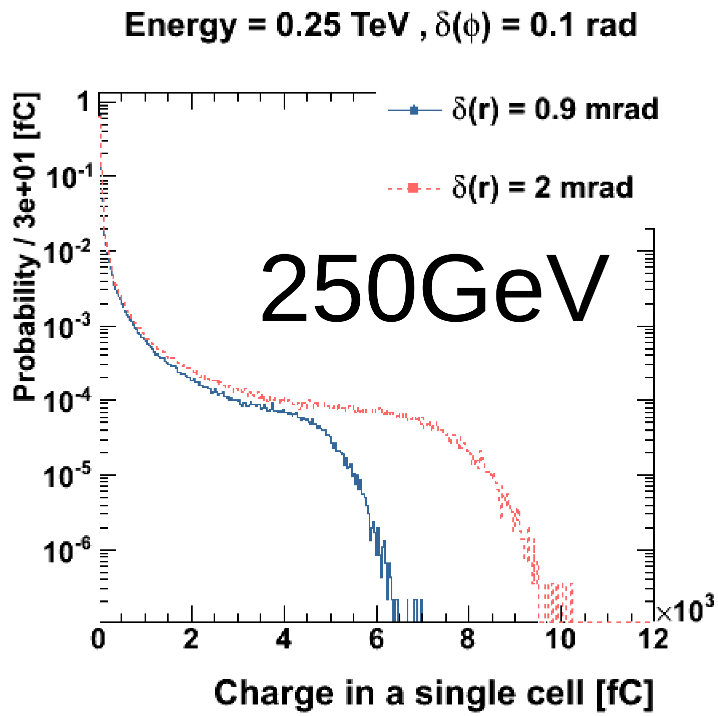
Layer energy and total deposited energy as a function of beam energy

Energy resolution as a function of beam energy



* High statistics are needed in order to get smaller error bars for the resolution...

Signal (charge) in a single cell

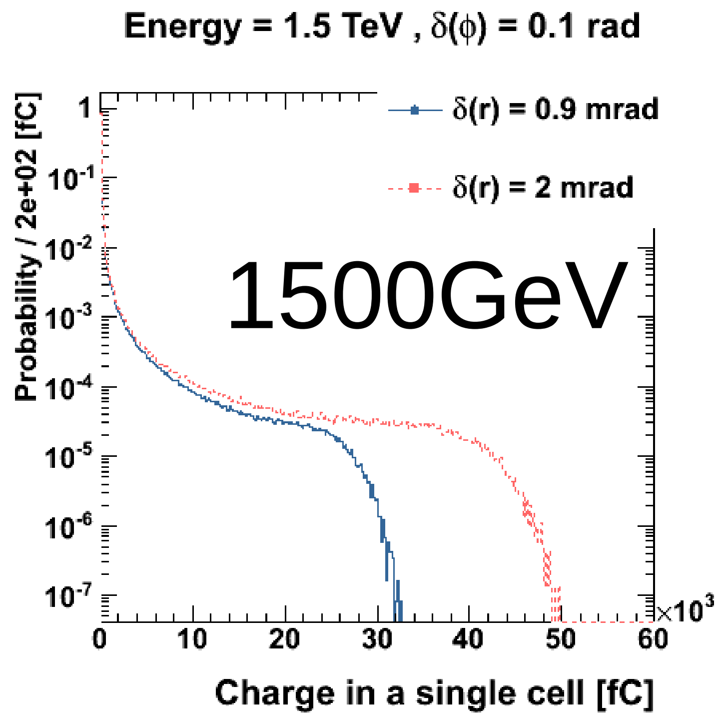


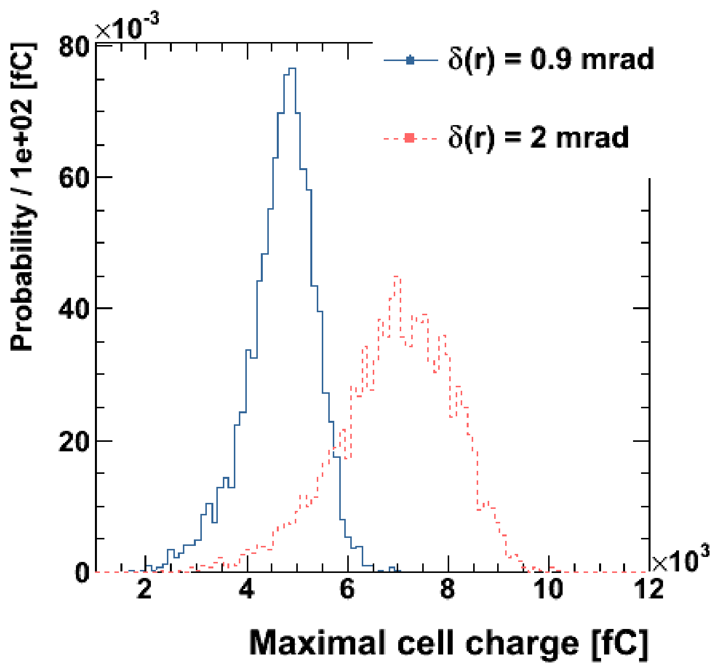
The charge in a single cell for two lumical cell division schemes:

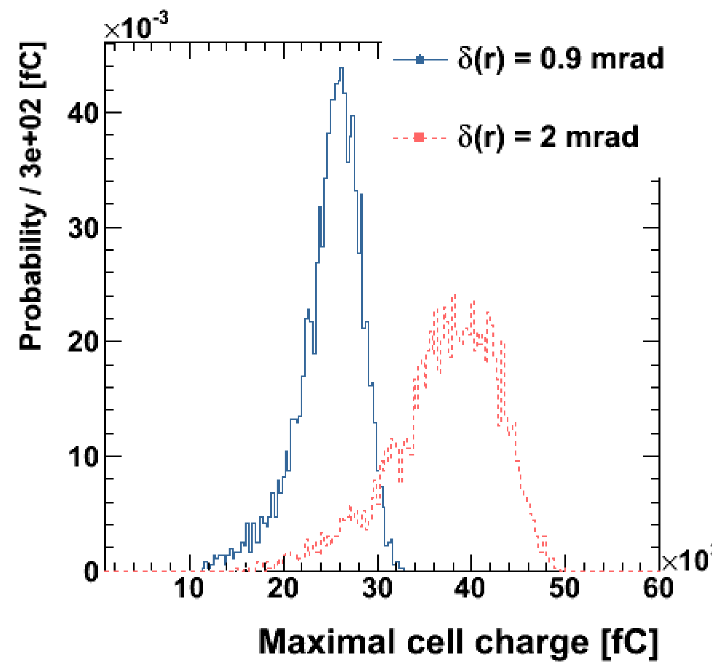
- The azimuthal cells are 0.13 rad wide in both cases.
- The radial cells are either 0.9 or 2 mrad wide.
- The error in luminosity for the two designs is:

$$\frac{\Delta L}{L}(\delta(r)=0.9)\approx\frac{1}{2}10^{-3}$$

$$\frac{\Delta L}{L}(\delta(r)=2)\approx 10^{-3}$$







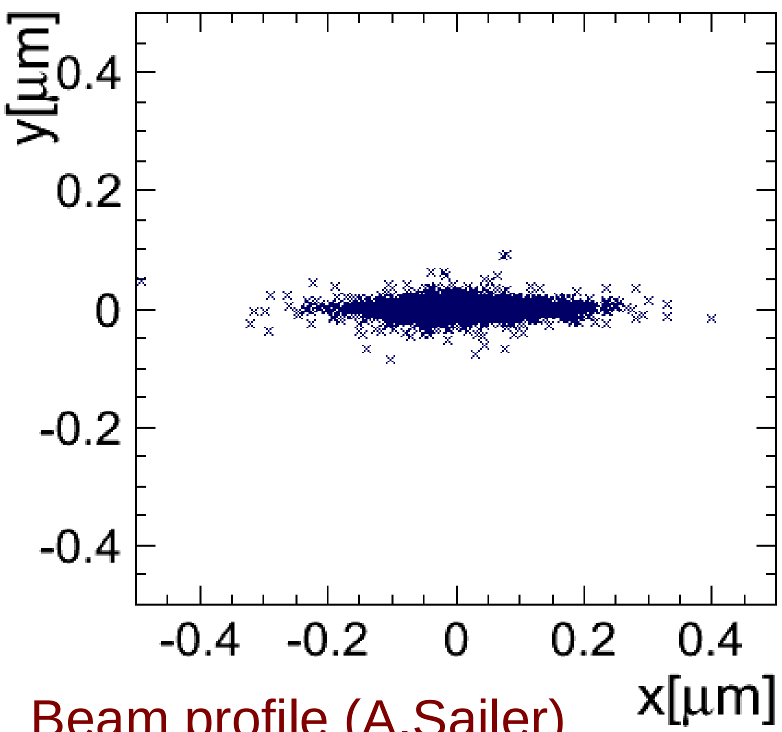
Pair distribution at 3TeV with input beam information

In order to estimate the beam background the GUINEAPIG generator was used.

- Input files describing the beam shape and charge distribution (electron.ini and positron.ini files) were provided by D.Schulte for the 3TeV CMS simulation.
- For the 500GeV case the program was run with input beam parameters in the standard acc.dat steering file.

Important acc.dat parameters:

n_x=64; n_y=128; n_z=25;
n_t=1; n_m=150000;
grids=7;
do_pairs=1;
do_compt=0;
charge_sign=-1.0;



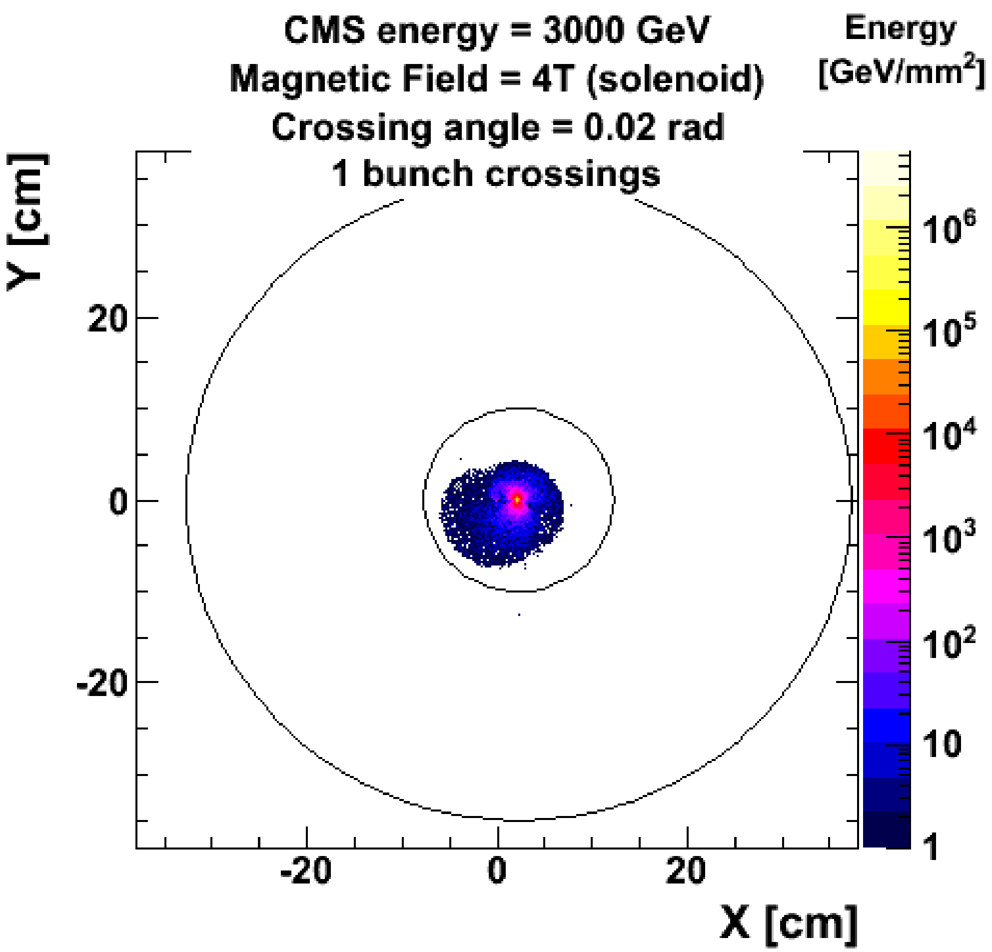
Beam profile (A.Sailer)

Pair distribution – Fast simulation

The pair distribution was analyzed using a fast simulation.

The position of particles on the front face of LumiCal were computed by making boosts according to a 20mrad crossing angle assuming the added influence of the magnetic field.

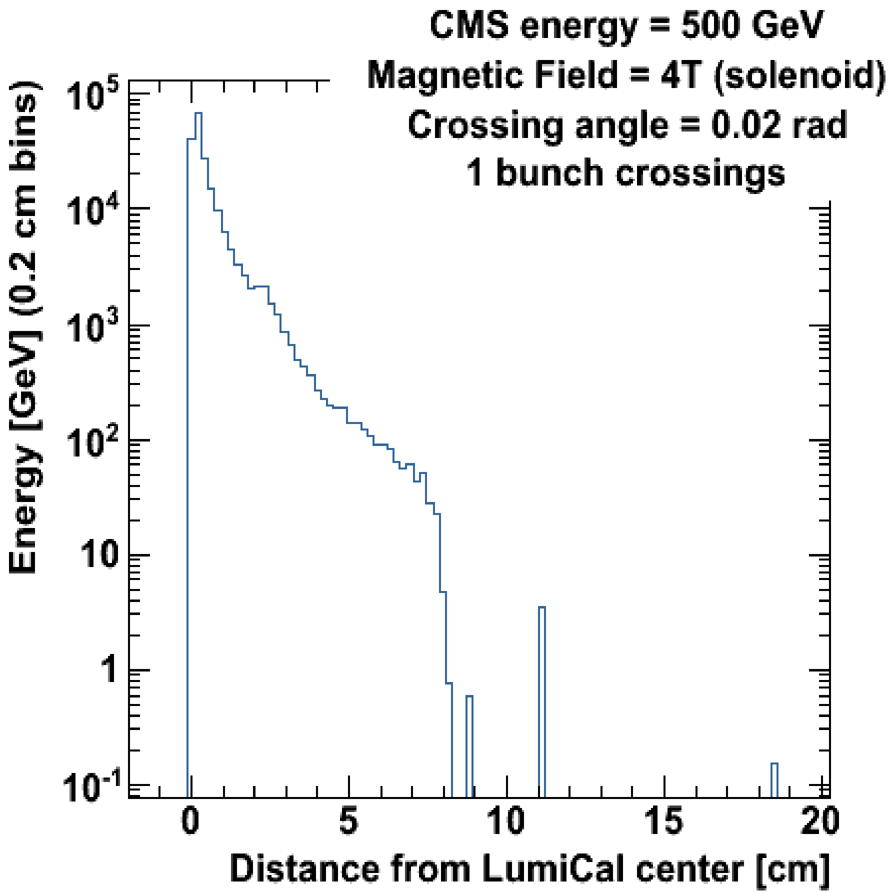
This was done for each energy (250 and 1500 GeV) for each magnetic field with configurations (Solenoid, anti-DID).

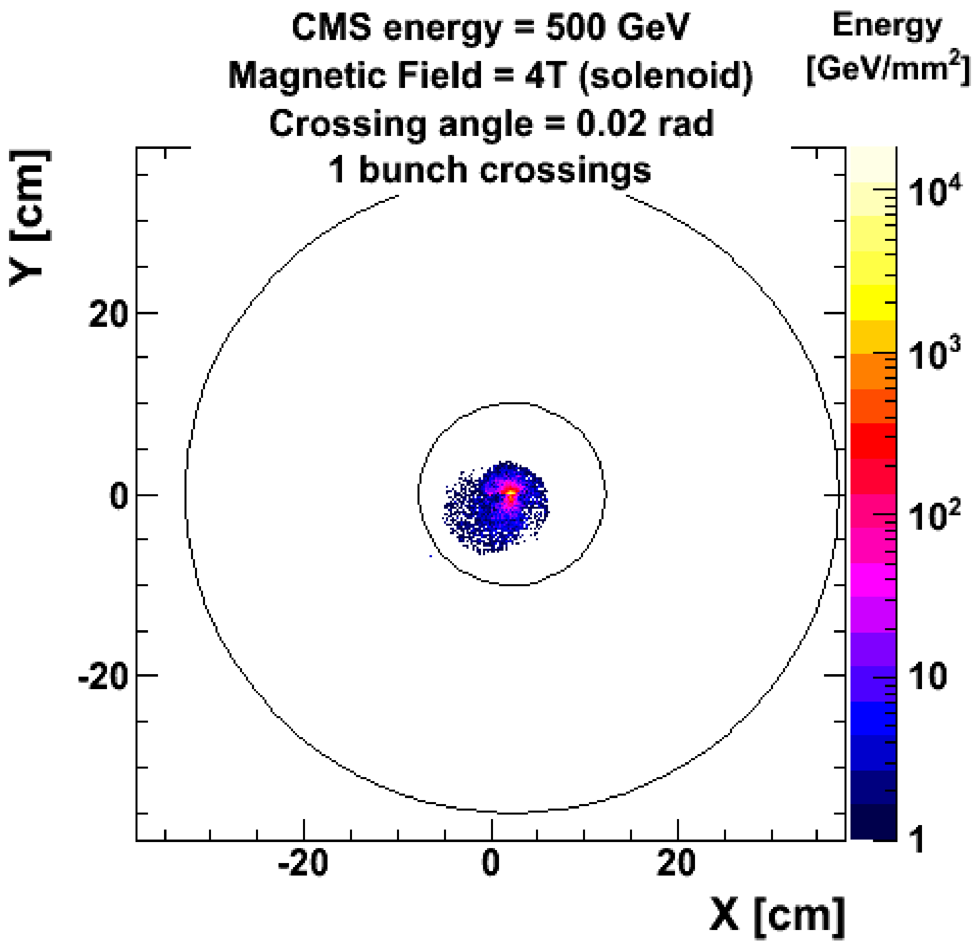


(3 TeV, Solenoid field)

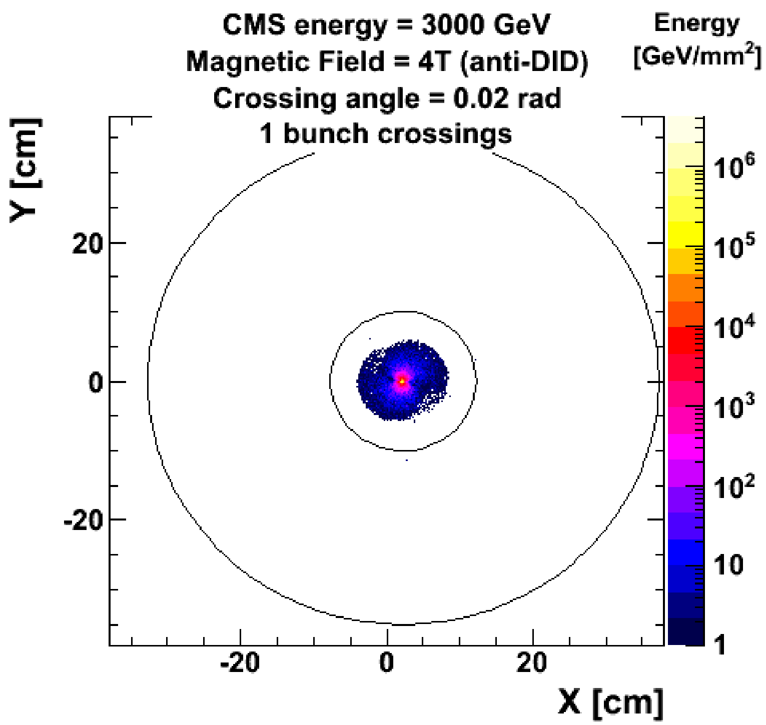
Pair distribution at 500GeV – Fast simulation

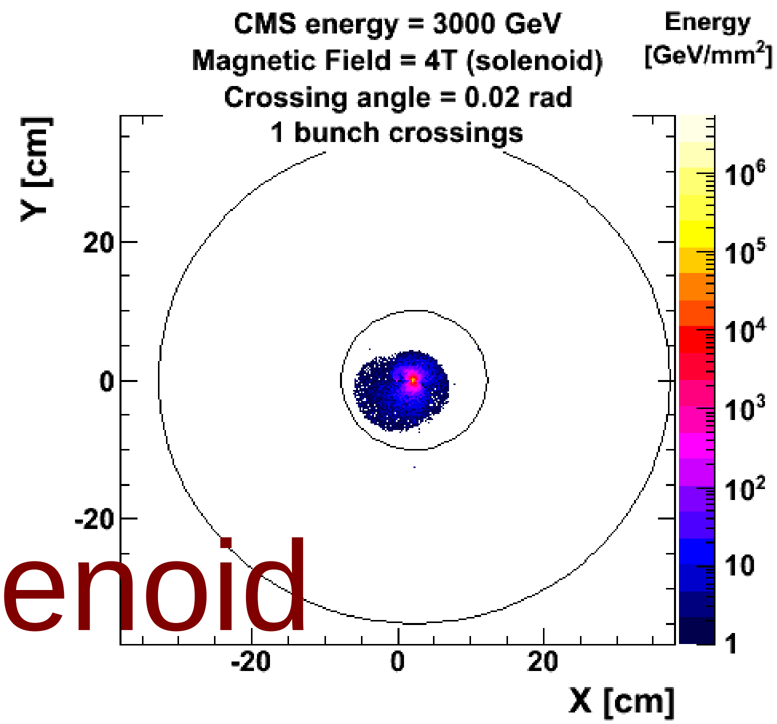
(Solenoid field)



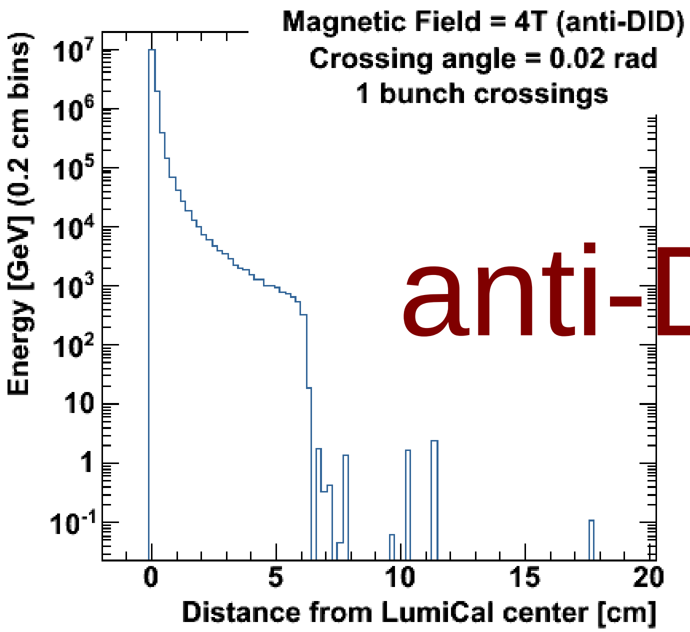


Pair distribution at 3TeV – Fast simulation

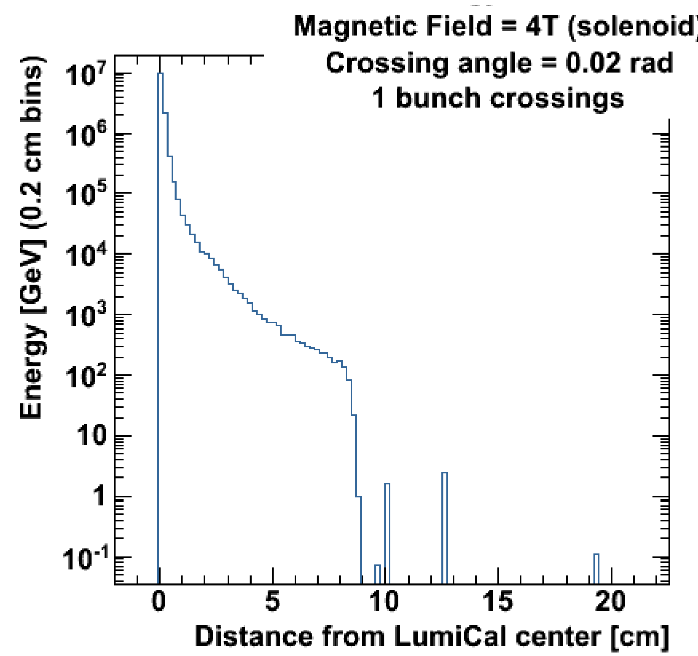




Solenoid



anti-DID



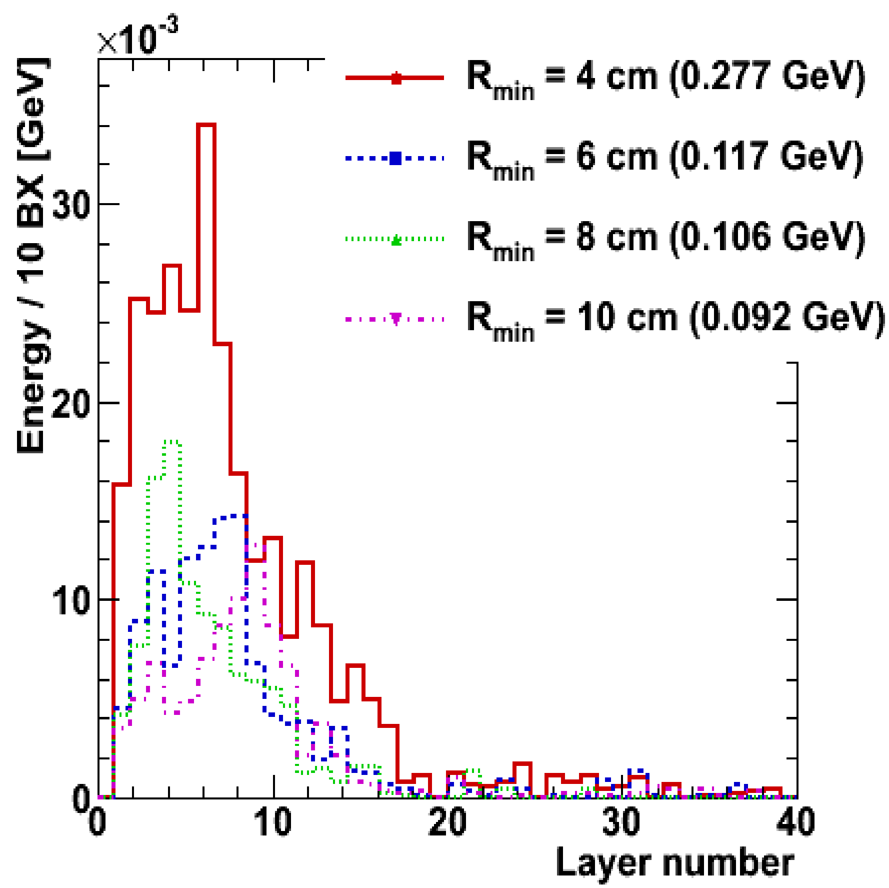
Pair deposits in LumiCal at 3TeV – Full simulation

Te response of LumiCal to the pairs was simulated in Mokka, and the deposited energy was measured for different geometries of the calorimter. The changing parameter was the inner radius of LumiCal. For lower inner radii the amount of radiation which enters the calorimeter increases.

- Deposited energy due to pairs in LumiCal for;
  - 10 BX,
  - 3TeV beam-energy,
  - 4T solenoid field,
  - 20 mrad crossing angle.

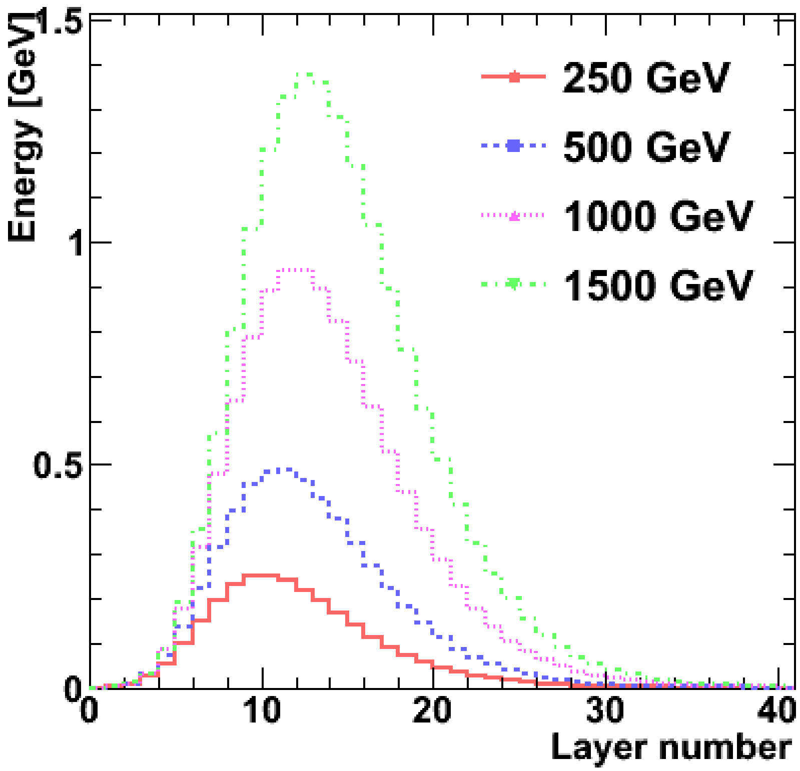
- Various inner radii of LumiCal were used (for instance, 10 cm corresponds to an angular range: 44 < θ < 154 mrad).

- The total deposited energy in each case is presented in the brackets.

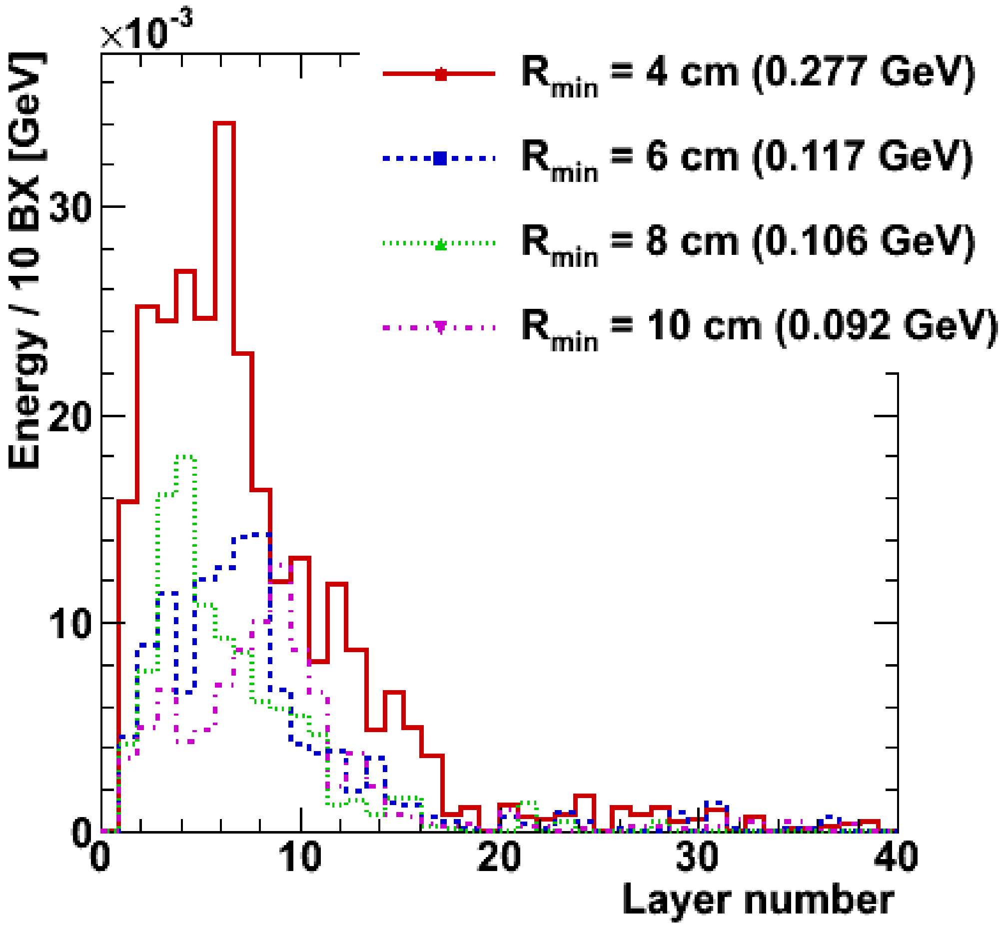


Pair deposits for 3TeV

- The deposited energy is small compared to the energy of electron showers. This will probably not affect the position reconstruction of showers, but the energy resolution may be impaired, and the amount of backscattering from LumiCal may be significant...
- More statistics are needed in any case...



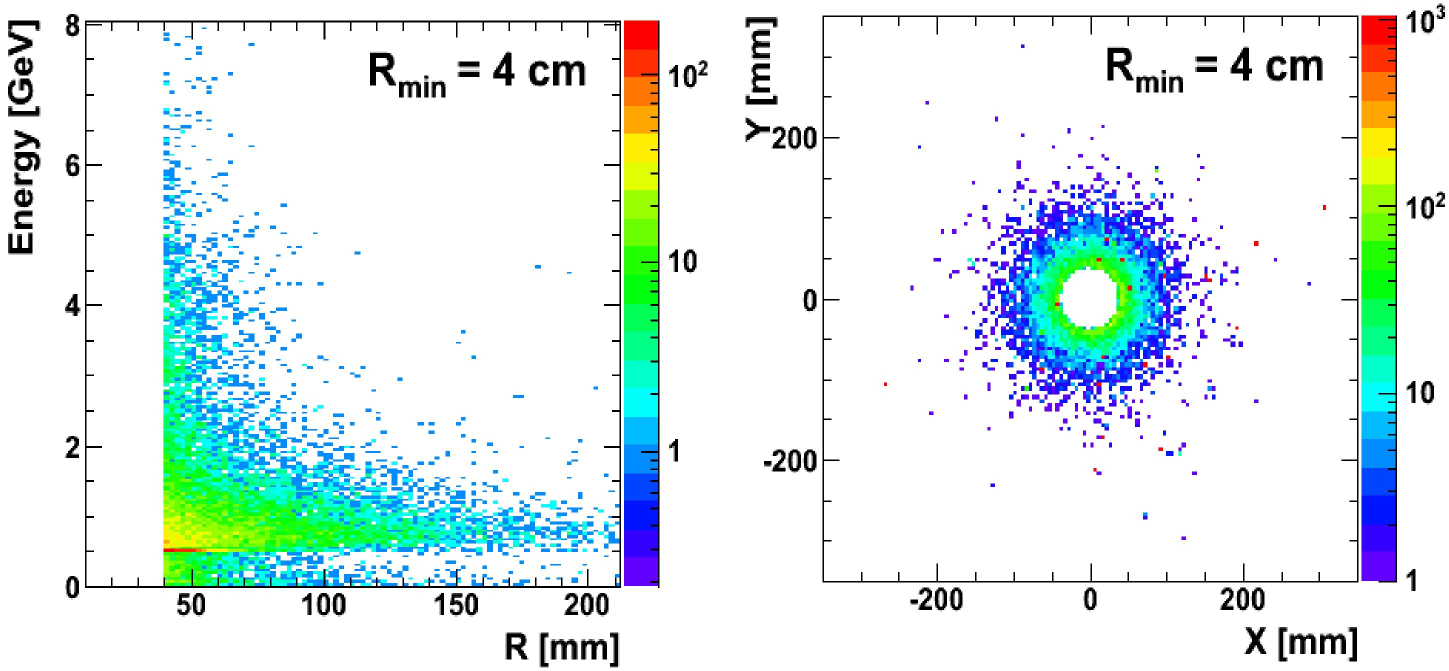
Deposited energy due to electron showers in LumiCal.



Backscattering from the front face of LumiCal – Full simulation in Mokka, including LumiCal only.

Mokka was used in order to simulate the backscattering from the front face of LumiCal. Each particle which exited LumiCal was registered. The amount of backscattering depends on the inner radius of LumiCal (since this determines the amount of particles which are incident on LumiCal).

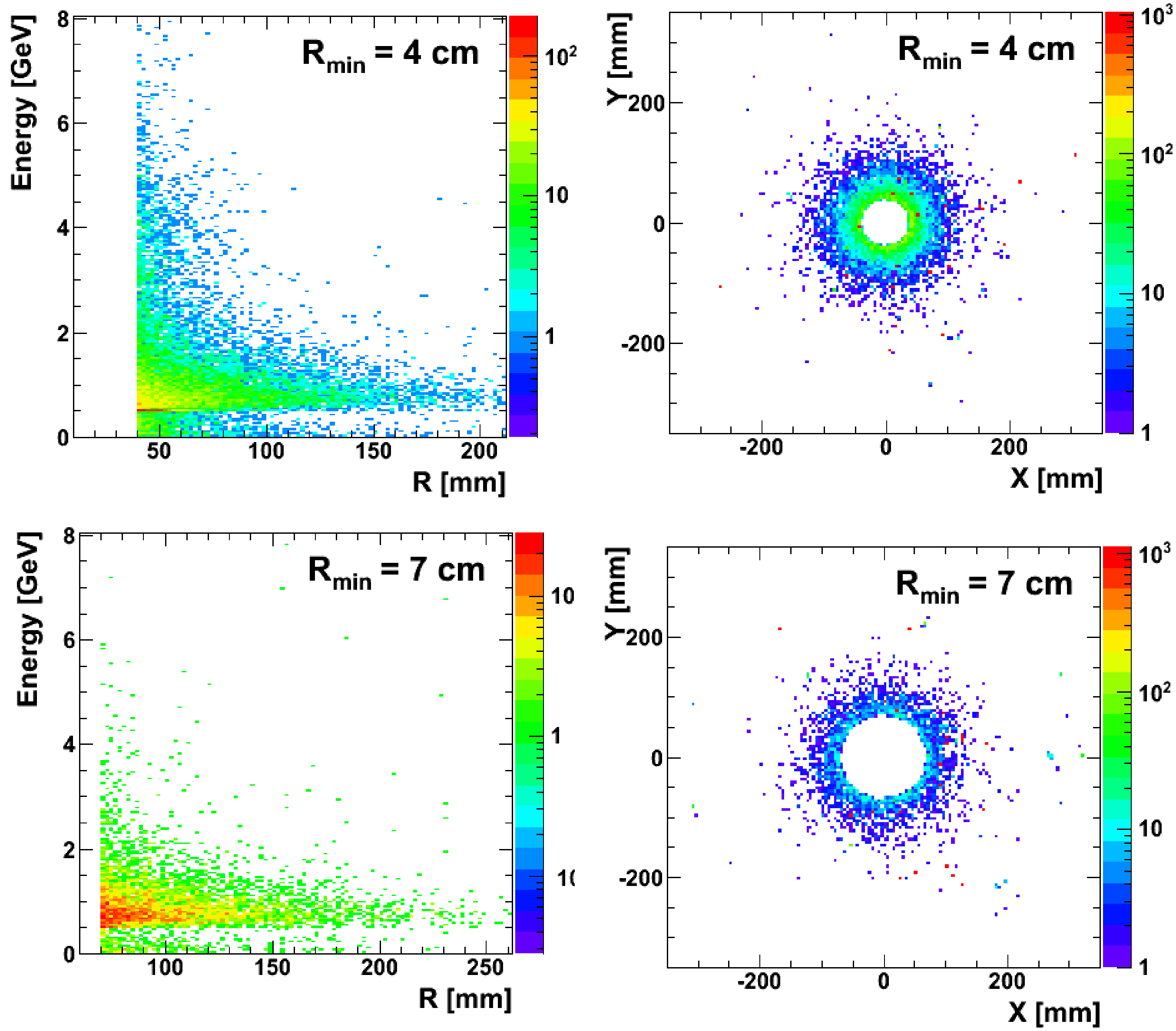
It must be noted that this is only a first step. In order to investigate this issue in full detail the entire detector must be simulated, and the hits in other sub-detercors registered.



Distribution of backscattered particles from the front face of LumiCal, assuming an inner radius of 4cm.

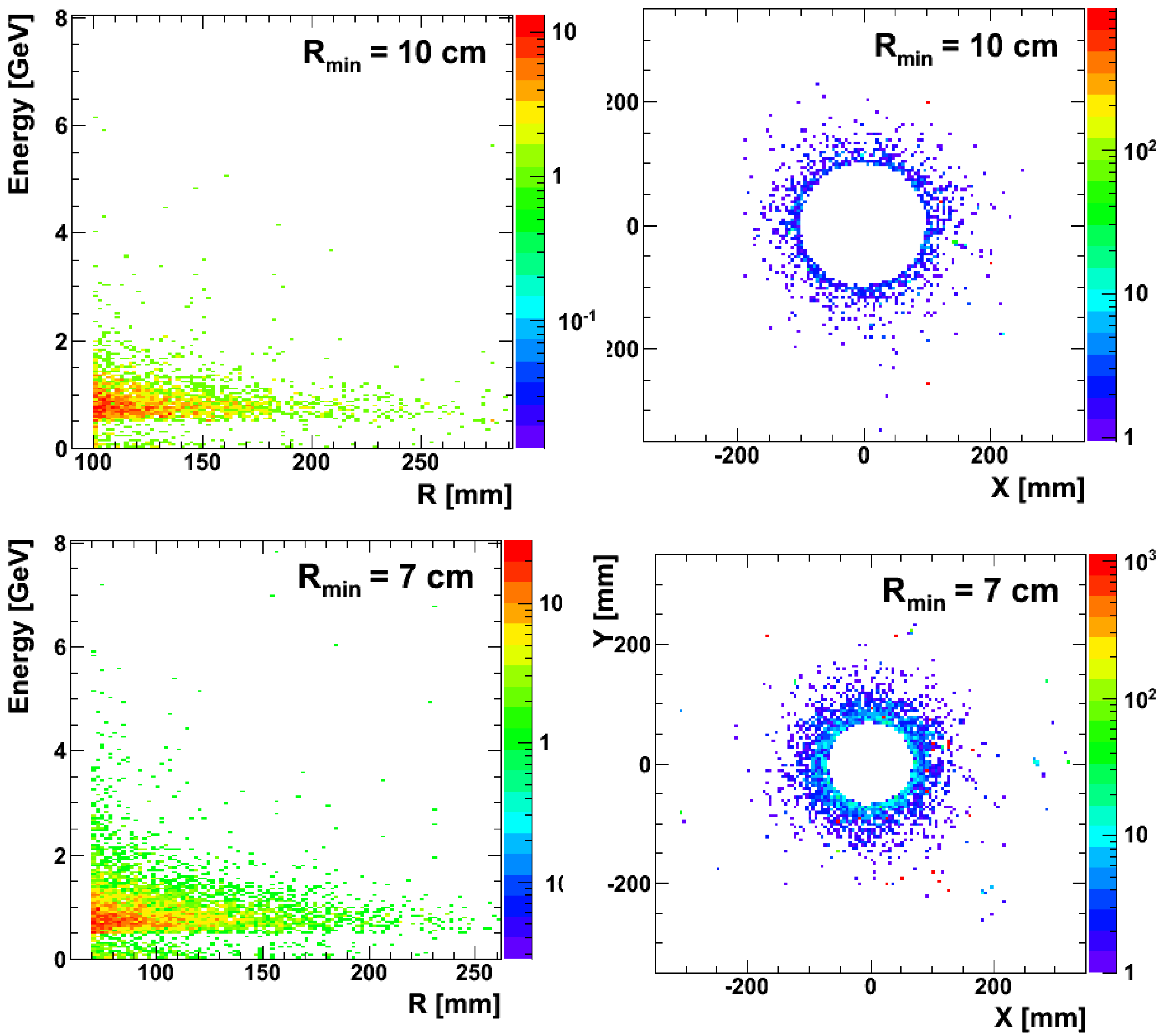
Backscattering from the front face of LumiCal

Simulation parameters:
- Solenoid field.
- 1.5 TeV beams.
- 20 mrad crossing angle.
- Integrated over 10 BX.
- Tow minimal radii of LumiCal (4,7 cm).



Backscattering from the front face of LumiCal

Simulation parameters:
- Solenoid field.
- 1.5 TeV beams.
- 20 mrad crossing angle.
- Integrated over 10 BX.
- Tow minimal radii of LumiCal (10,7 cm).

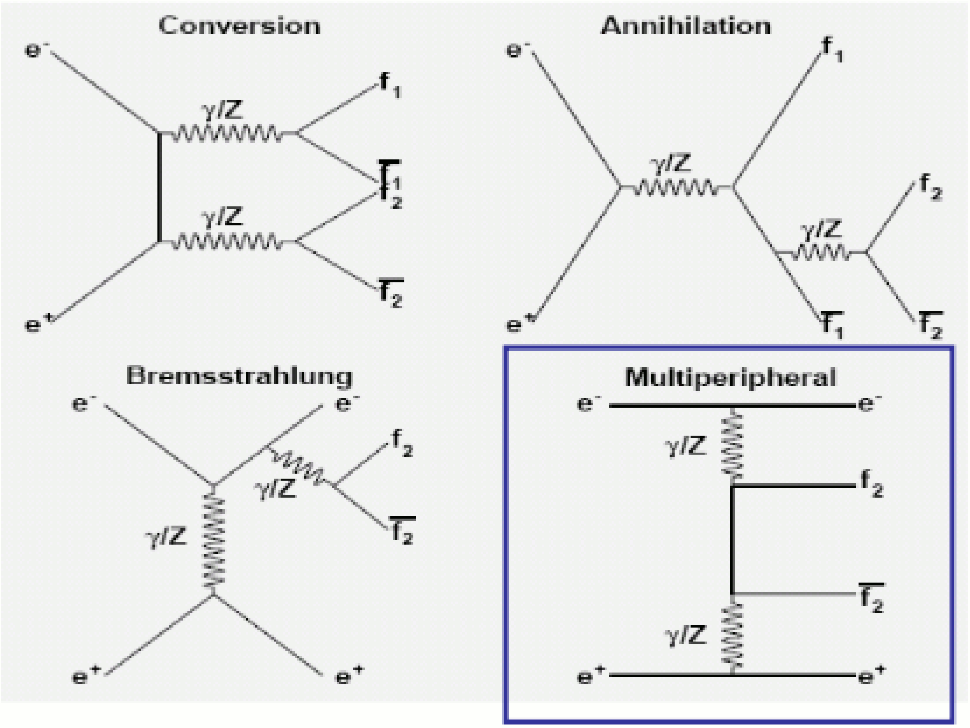


Physics background

The main physics background to Bhabha scattering is two-photon exchange. In order to have a high purity of Bhabha events one needs to apply topological selection cuts.

Four-fermion processes

$$e^+ e^- \rightarrow e^+ e^- f^+ f^-$$



The following event samples were generated using the WHIZARD generator, as well as 1M Bhabha scattering events, using BHWIDE (at 3TeV):

$$10^6: \quad e^+ e^- \rightarrow e^+ e^- l^+ l^- \quad , l = (e, \mu)$$

$$10^5: \quad e^+ e^- \rightarrow e^+ e^- q^+ q^- \quad , q = (u, d, s, c, b)$$

Physics background – selection strategy

In order to estimate the error in luminosity due to the background processes, one needs to count the number of Bhabha events which pass the cuts and compare this to the number of background processes which pass the cuts.

The error is the difference between the number of events one expects, N_{gen}, (the number of Bhabha events after the cuts) and the number one ends up counting, N_{rec} , due to background events which fake Bhabha scattering (pass the selection cuts).

$$\frac{\Delta L}{L} = \frac{N_{rec} - N_{gen}}{N_{gen}}$$

$$= \frac{(N_{eell} + N_{eeqq} + N_{Bhabha}) - N_{Bhabha}}{N_{Bhabha}} = \frac{N_{eell} + N_{eeqq}}{N_{Bhabha}}$$

Physics background – selection strategy

A. The selection cuts were applied in a fast simulation, according to the following procedure:

1. The event samples were generated using WHIZARD and BHWIDE and a center-of-mass energy of 3TeV.

2. For each event sample the 4-vectors of all particles within the fiducial volume of LumiCal ($50 < \theta < 130$ mrad) were integrated within each arm of the calorimeter. This produced an 'effective particle' in the following manner:

   a. An average polar angle was computed using energy weights.

   b. The energy was integrated.

3. The polar angle and the energy of the effective particles for the two arms of LumiCal were compared according to the selection cuts.

B. The number of events which passed the selection cuts in each sample was re-scaled according to the luminosity, with which the respective event sample was generated.

C. The re-scaled number of events for each sample was used in order to compute the error in the luminosity measurement (miss-counting of Bhabha events.)

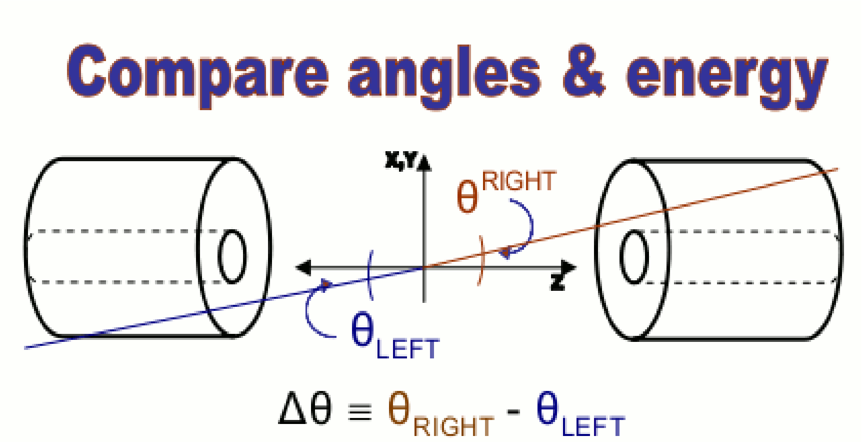
Physics background (very preliminary results)

Cross sections:

$$\sigma(e^+e^- \rightarrow e^+e^- l^+ l^-) = 1.62 \cdot 10^5 \pm 5 \cdot 10^3 \text{ fb}$$
$$\sigma(e^+e^- \rightarrow e^+e^- q^+ q^-) = 3.99 \cdot 10^4 \pm 6 \cdot 10^2 \text{ fb}$$
$$\sigma(e^+e^- \rightarrow e^+e^-) = 6.03 \cdot 10^4 \pm 5 \text{ fb}$$

Selection cuts:

$$\theta_r - \theta_l \leqslant 1 \text{ mrad}$$
$$E_r, E_l > 0$$
$$\frac{E_r - E_l}{E_r + E_l} \geqslant 1\ \%$$



Relative luminosity error:

$$\frac{\Delta L}{L} = \frac{N_{rec} - N_{gen}}{N_{gen}} = \frac{N_{eell} + N_{eeqq}}{N_{Bhabha}}$$
$$\frac{\Delta L}{L} = 1.9 \cdot 10^{-3} \pm 3 \cdot 10^{-7}$$

Where the numbers N represent the number of events out of each sample, which passed the selection cuts.

Summary

1. It has been shown that it is possible to design a tungsten-silicon sandwich luminosiy calorimeter which will **measure the luminosity with the required precision < 1%**.
Both the statistical error of counting Bhabha scattering events and the reconstruction error of the polar angle of showers in LumiCal were taken into account.

2. In order avoid absorbing and backscattering of the bulk of the **beamstrahlung background**, it is necessary to set the inner radius of LumiCal at 10cm or higher.

3. A preliminary set of selection cuts was tested, indicating that it should be possible to suppress the **physics background** to Bhabha scattering to within the required background to signal ratio.

Next steps...

1. Pair background in LumiCal in a full simulation:

    a. Need to perform simulation with large statistics in order to determine the occupancy in LumiCal.

    b. Check backscattering spectrum in the rest of the detector, using a ful simulation.

    c. Try to decrease backscattering by introducing a layer of graphite in front of LumiCal.

3. Testing different selection cuts on the physics background and on the Bhabha spectrum and getting the S/N ratio, the luminosity error and the selection efficiency.

4. Full simulation of the selection cut scheme (with reconstruction of showers, energy calibration etc.).