Proposed design of LumiCal for a 3TeV CLIC

Iftach Sadeh

Tel Aviv University

Presenting a study which was conducted while enjoying the hospitality of the CLIC-LCD group at CERN

FCAL Collaboration
High precision design

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sadeh@alzt.tau.ac.il

Overview

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

2. **Luminosity measurement**;
using Bhabha scattering as the gauge process, dependence of the cross section on the size of LumiCal and the subsequent statistical bias on the measurement.

3. **Intrinsic properties of LumiCal**;
fiducial volume, energy resolution, bias in the luminosity measurement 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.

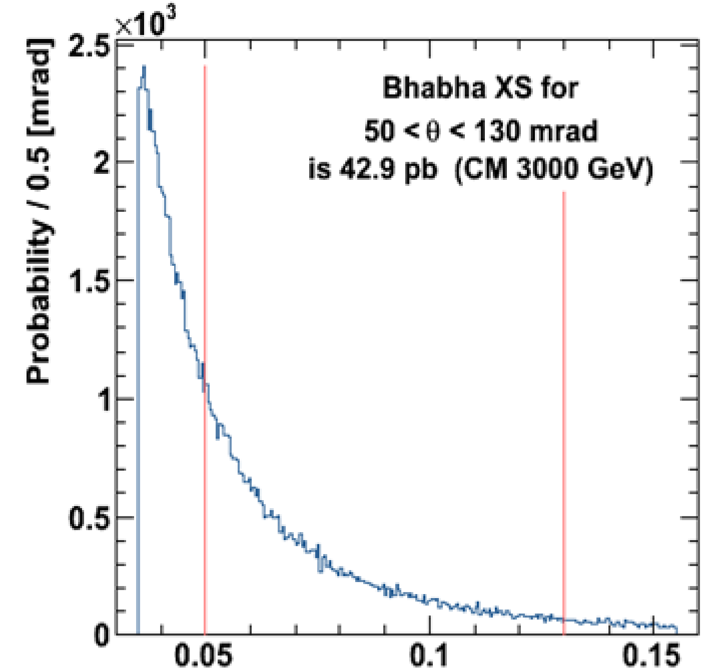
LumiCal design parameters

- **Placement and dimensions:**
  - Positioned 2.27m from the IP.
  - Inner to outer radii are 10 →35cm.
- **Transverse segmentation:**
  - 48 divisions in the azimuthal direction (cell size of 7.5deg).
  - 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

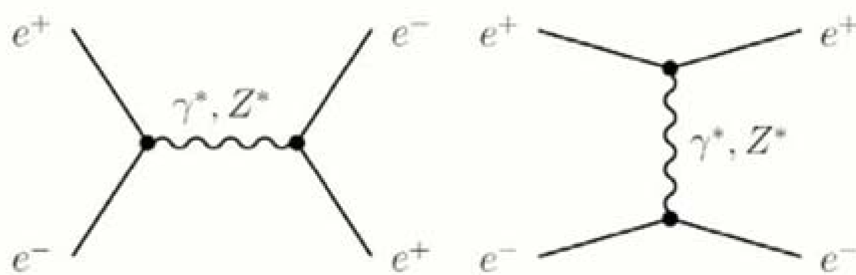
- The luminosity is measured by counting the number of Bhabha scattering events in a well defined angular and energetic region.

- 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.



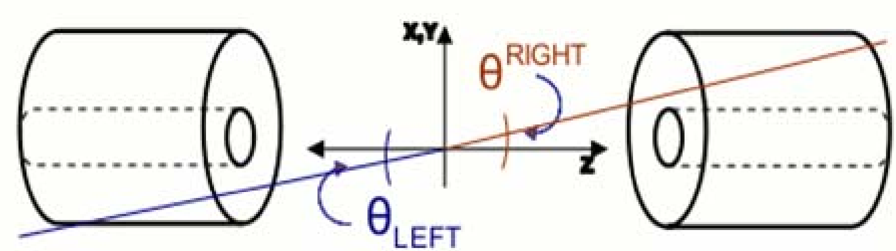
(Luminosity for this plot = 10.4 [1/nb])

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



(a) s channel (b) t channel

Compare angles & energy

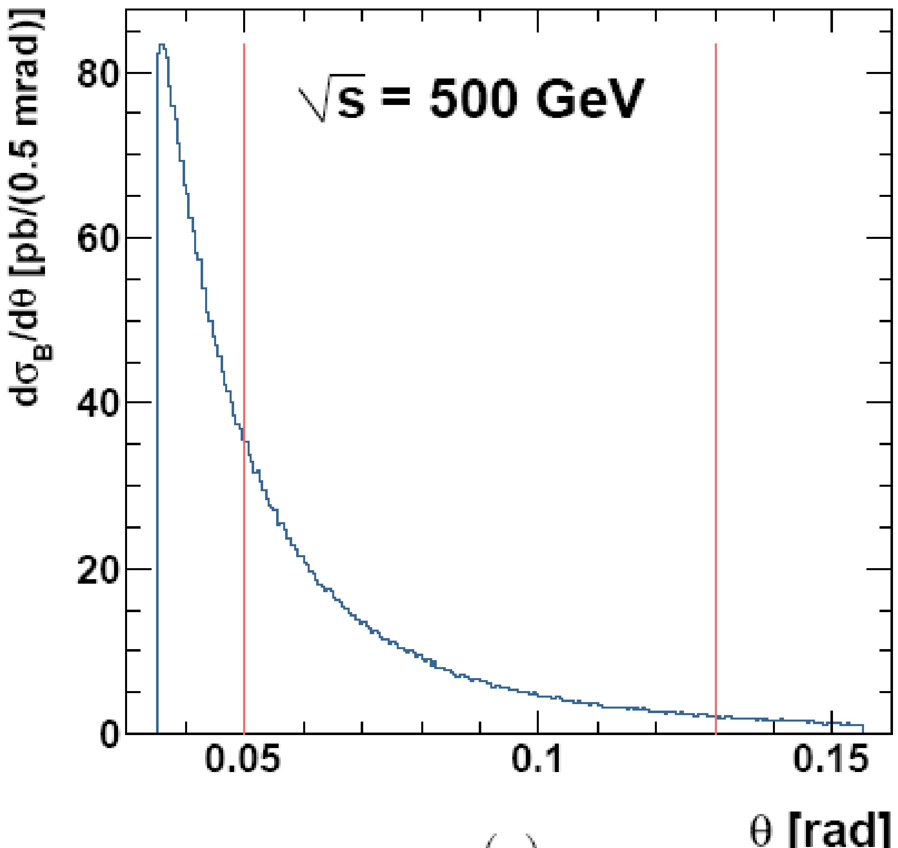


$$\Delta\theta \equiv \theta_{RIGHT} - \theta_{LEFT}$$

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

Bhabha cross-section

$$R:\ 10 \rightarrow 35\ \text{cm} \quad , \quad 44 < \theta^{\text{physical}} < 153\ \text{mrad} \quad , \quad 500\,\text{fb}^{-1}\ (4\,\text{years})$$

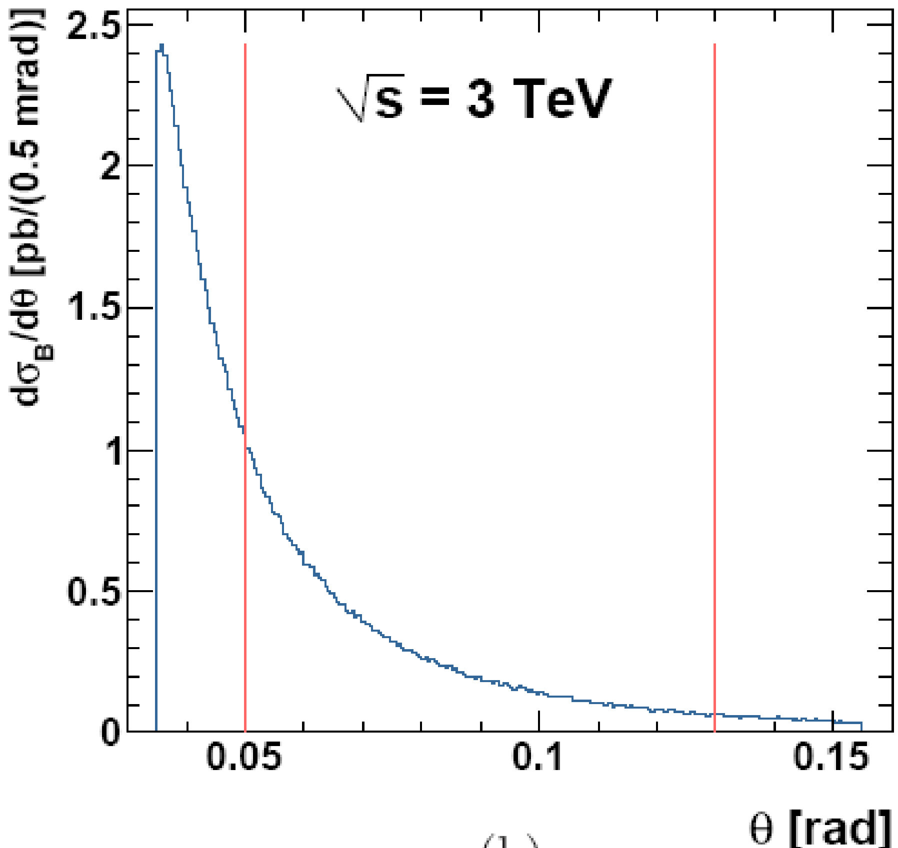


(a)

$$50 < \theta^{\text{fiducial}} < 130\ \text{mrad}$$

$$\rightarrow\ 1460.6\,\text{pb}$$

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



(b)

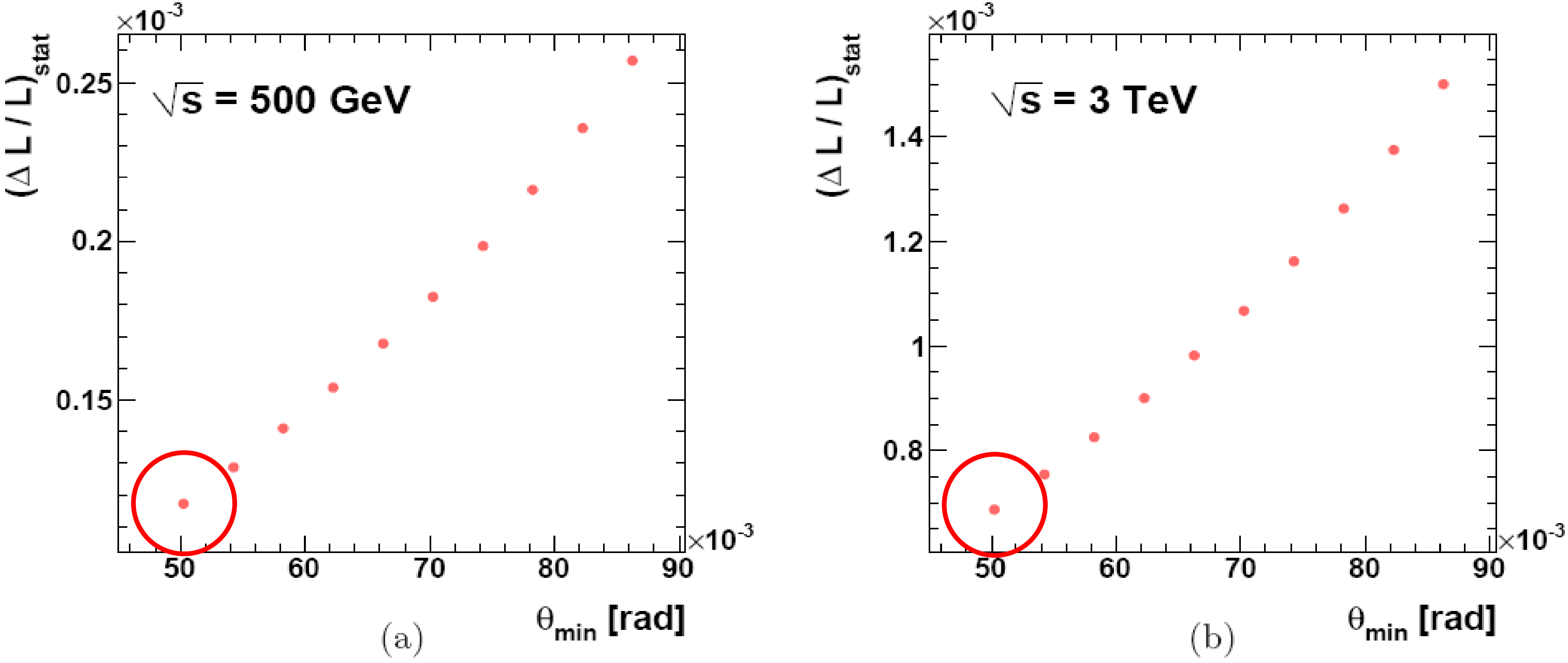
$$50 < \theta^{\text{fiducial}} < 130\ \text{mrad}$$

$$\rightarrow\ 42.9\,\text{pb}$$

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

Statistical error in the luminosity

$$\left(100\,\text{fb}^{-1}\ \text{and 50\% selection efficiency}\right)$$

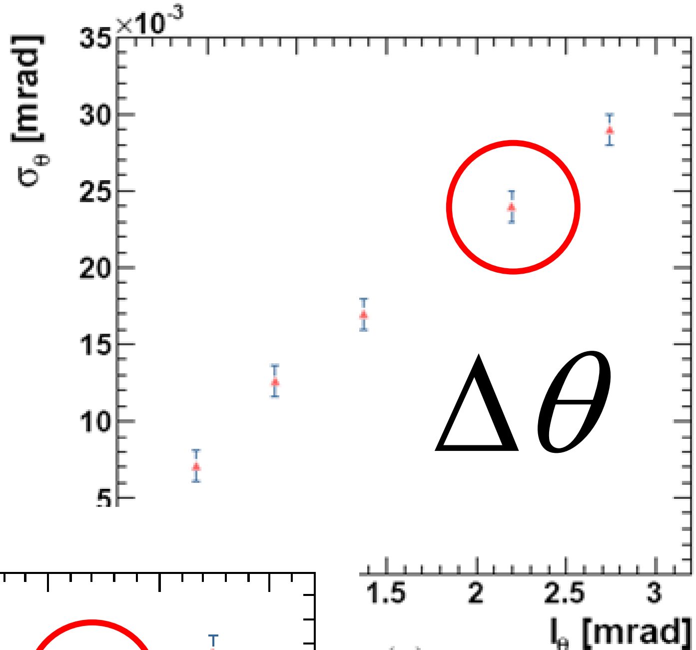


$$\left(50 < \theta^{\text{fiducial}} < 130\ \text{mrad}\right)$$

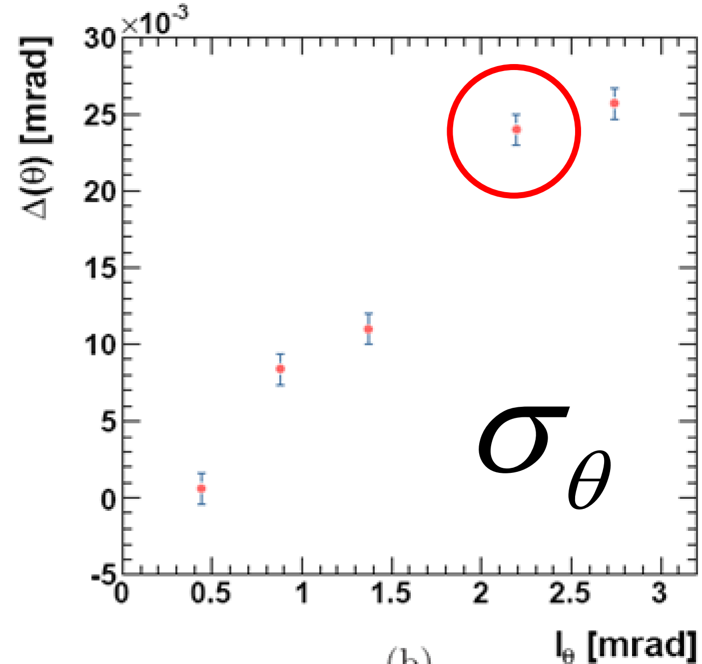
$$\left(\frac{\Delta L}{L}\right)_{stat} = \frac{1}{\sqrt{N_B}} < 0.01\%$$

Polar bias ($\Delta\theta$) and resolution (σ_θ) as a function of the angular cell size.

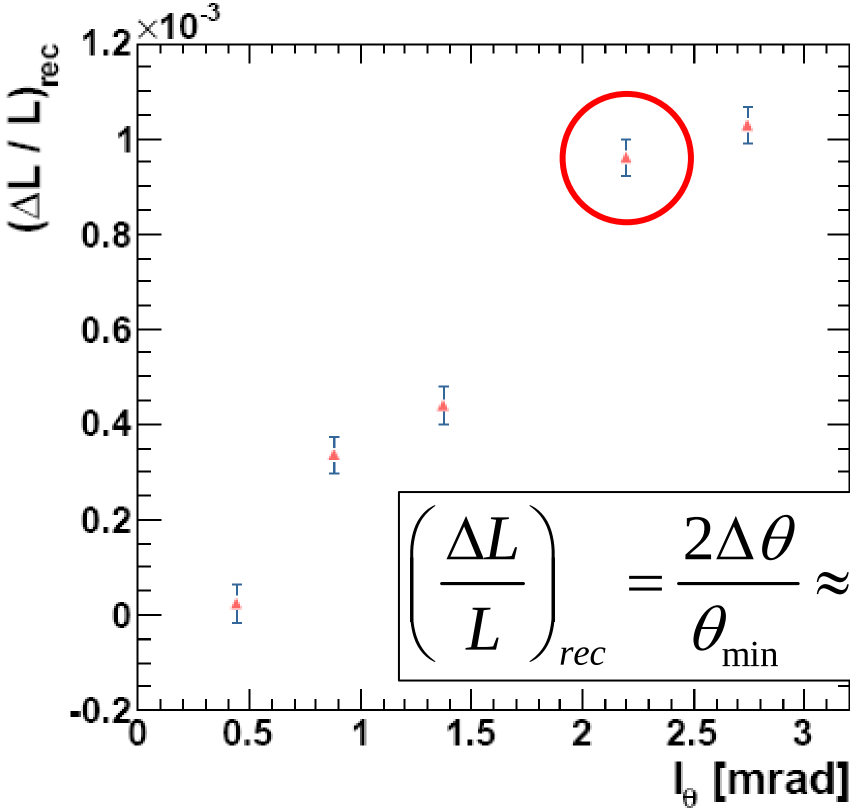
Polar bias may cause a shift in the luminosity. The bias depends on the angular cell size.



(a)



(b)



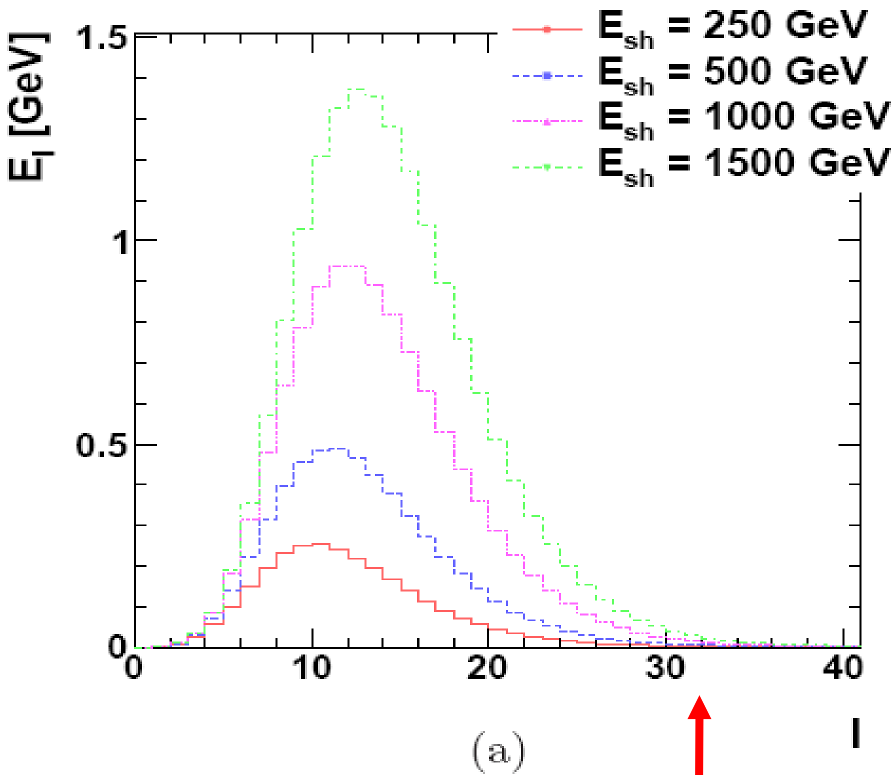
$$\left(\frac{\Delta L}{L}\right)_{rec} = \frac{2\Delta\theta}{\theta_{\min}} \approx 0.1\%$$

Polar angel reconstruction:

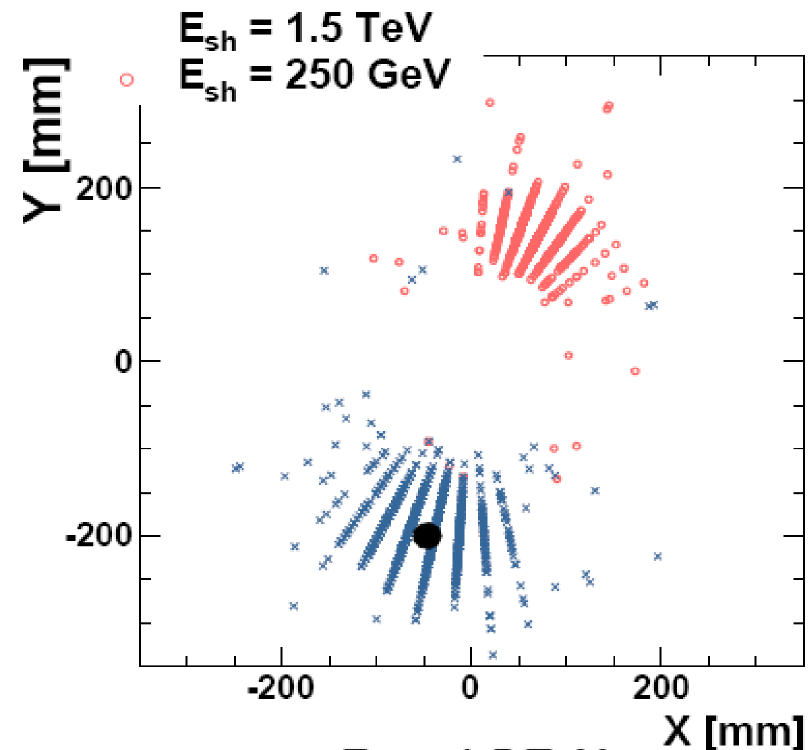
$$<\theta> = \frac{\sum_i \theta_i \cdot \mathcal{W}_i}{\sum_i \mathcal{W}_i}$$

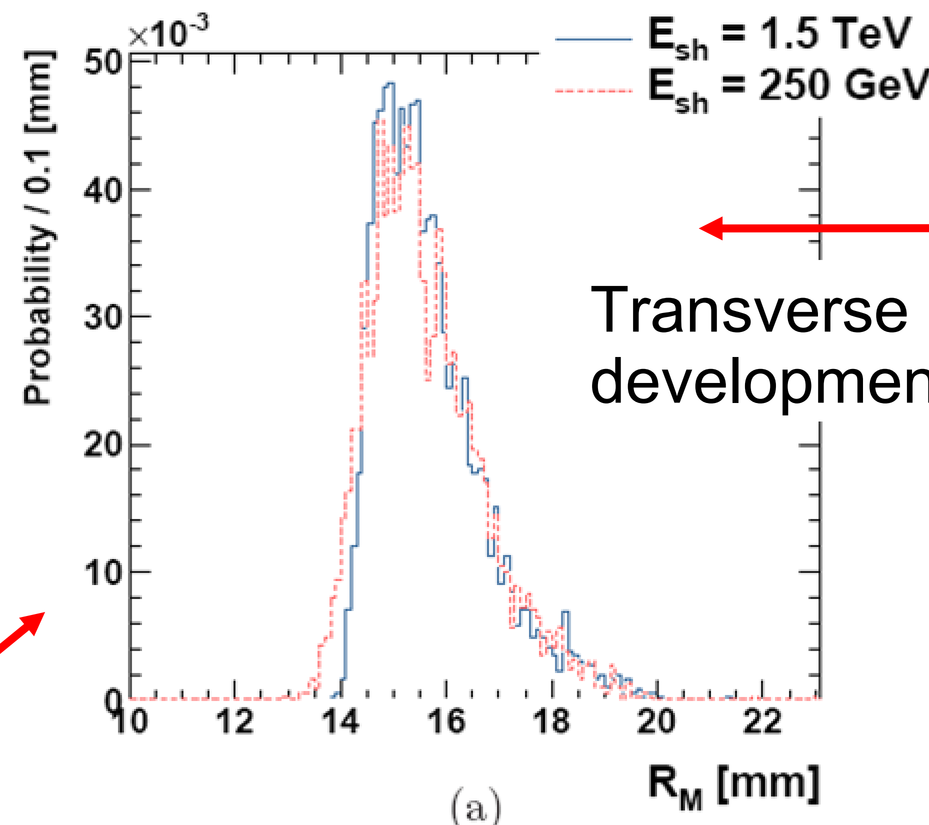
$$\mathcal{W}_i = \max\{\ 0\ ,\ \mathcal{C} + \ln\frac{E_i}{E_{tot}}\}$$

Shower development



Longitudinal development



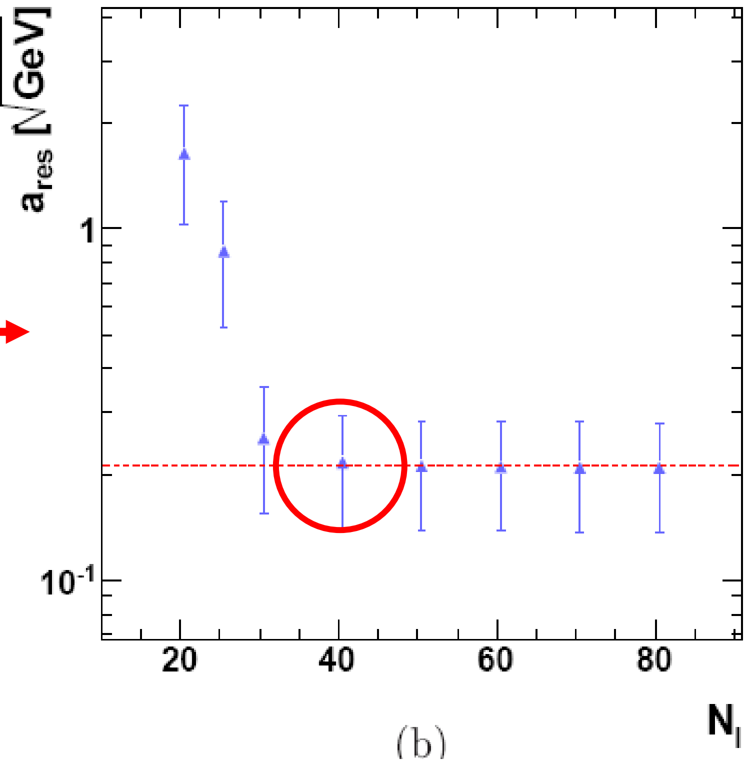


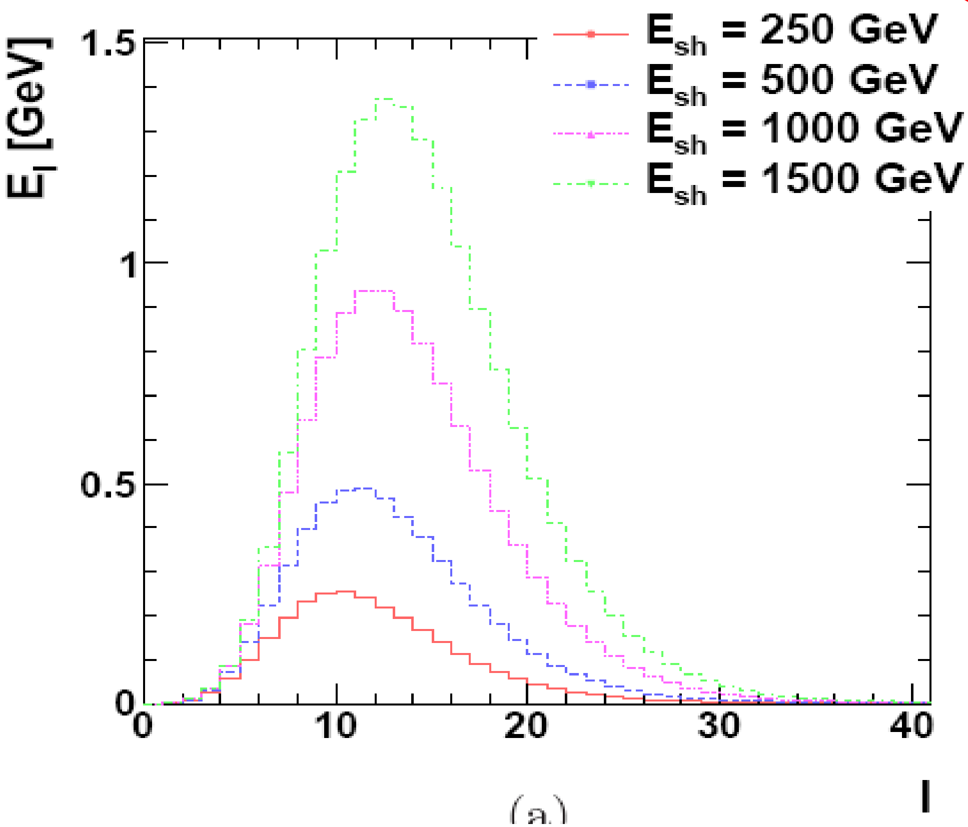
Transverse development

90% of the energy is within 15mm of the center of the shower, independent of the shower energy.

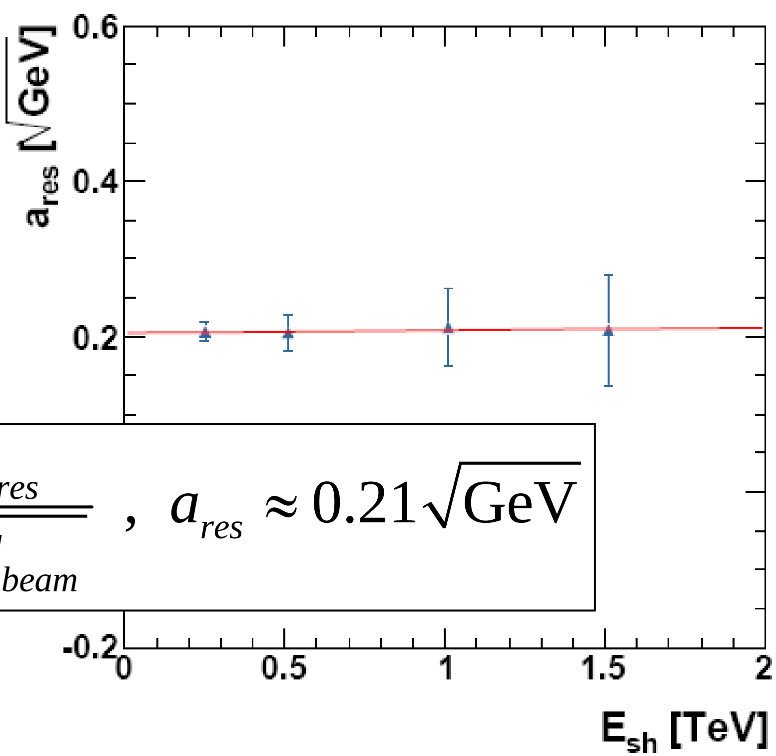
Energy resolution

Energy resolution as a function of
- The number of layers
- The shower energy



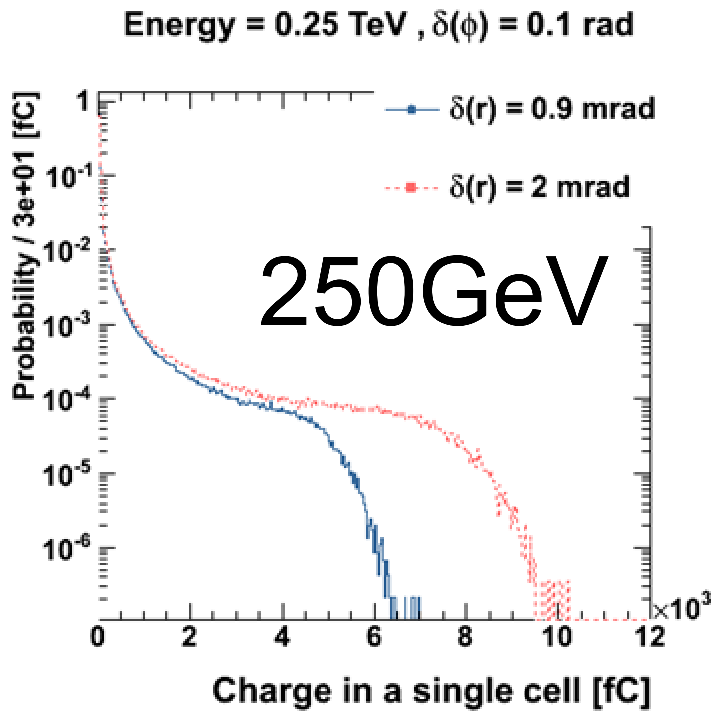


Longitudinal shower profile



$$\frac{\sigma_E}{E} = \frac{a_{res}}{\sqrt{E_{beam}}} \;,\; a_{res} \approx 0.21\sqrt{\mathrm{GeV}}$$

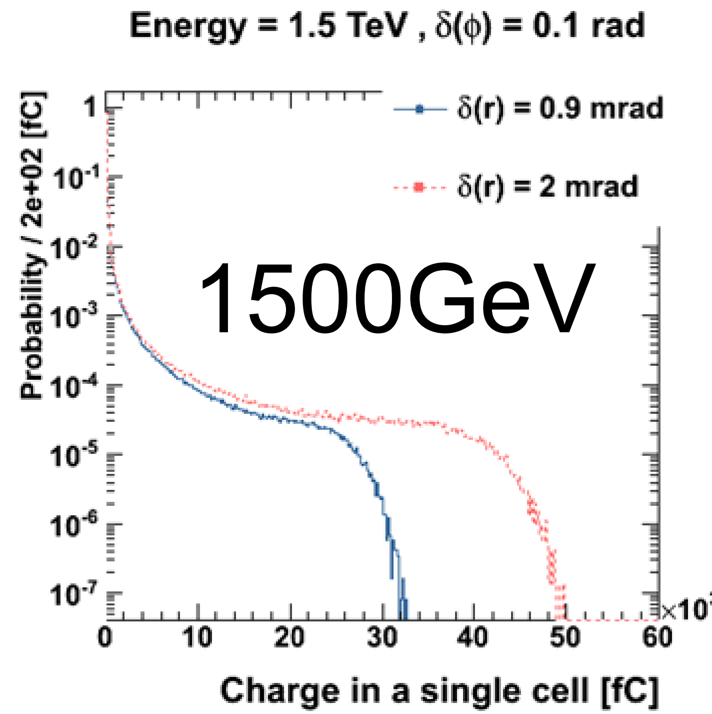
Signal (charge) in a single cell

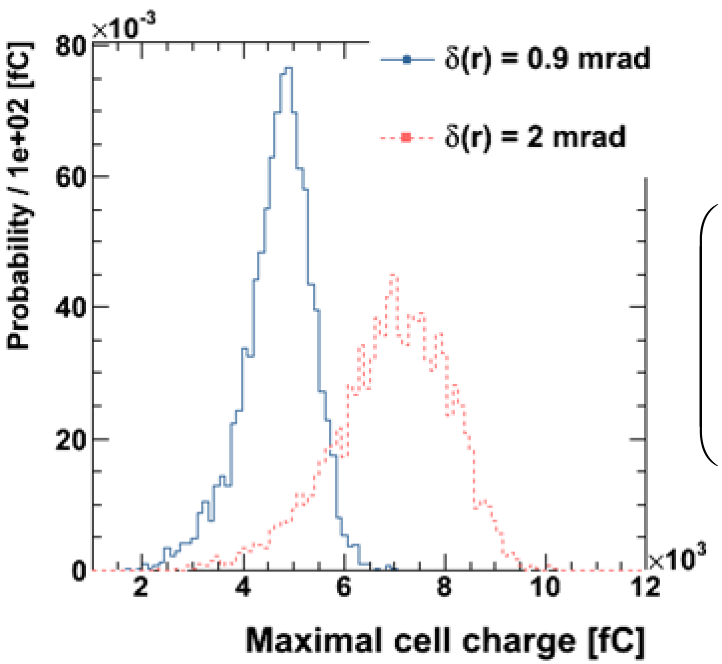


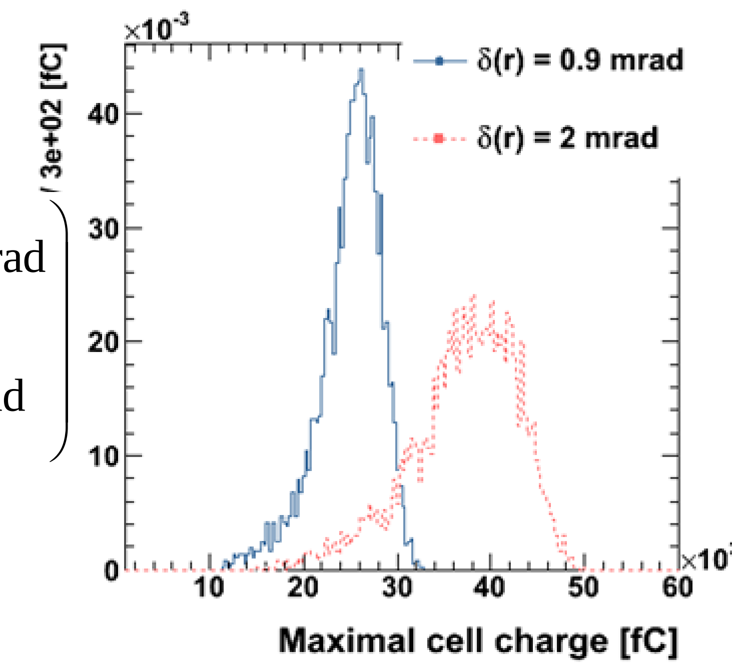
The charge in a single cell for two lumical cell division schemes:

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

$$\begin{pmatrix} \left(\frac{\Delta L}{L}\right)_{rec} = 0.5\cdot 10^{-3}\ , \ \ell_{\theta} = 0.9\,\mathrm{mrad} \\ \left(\frac{\Delta L}{L}\right)_{rec} = 1\cdot 10^{-3}\ , \ \ell_{\theta} = 2.2\,\mathrm{mrad} \end{pmatrix}$$







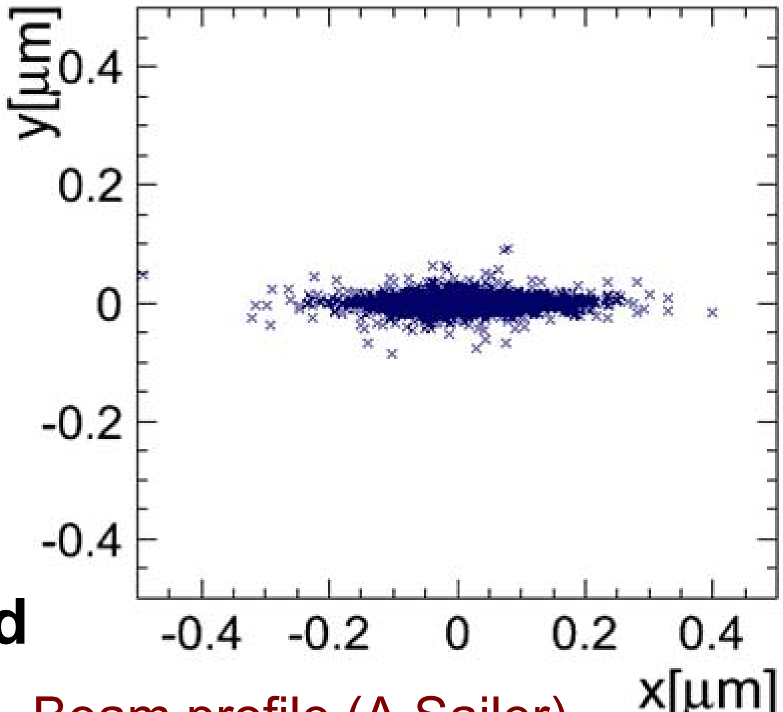
Beamstrahlung pair distribution at 3TeV with input beam information

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.

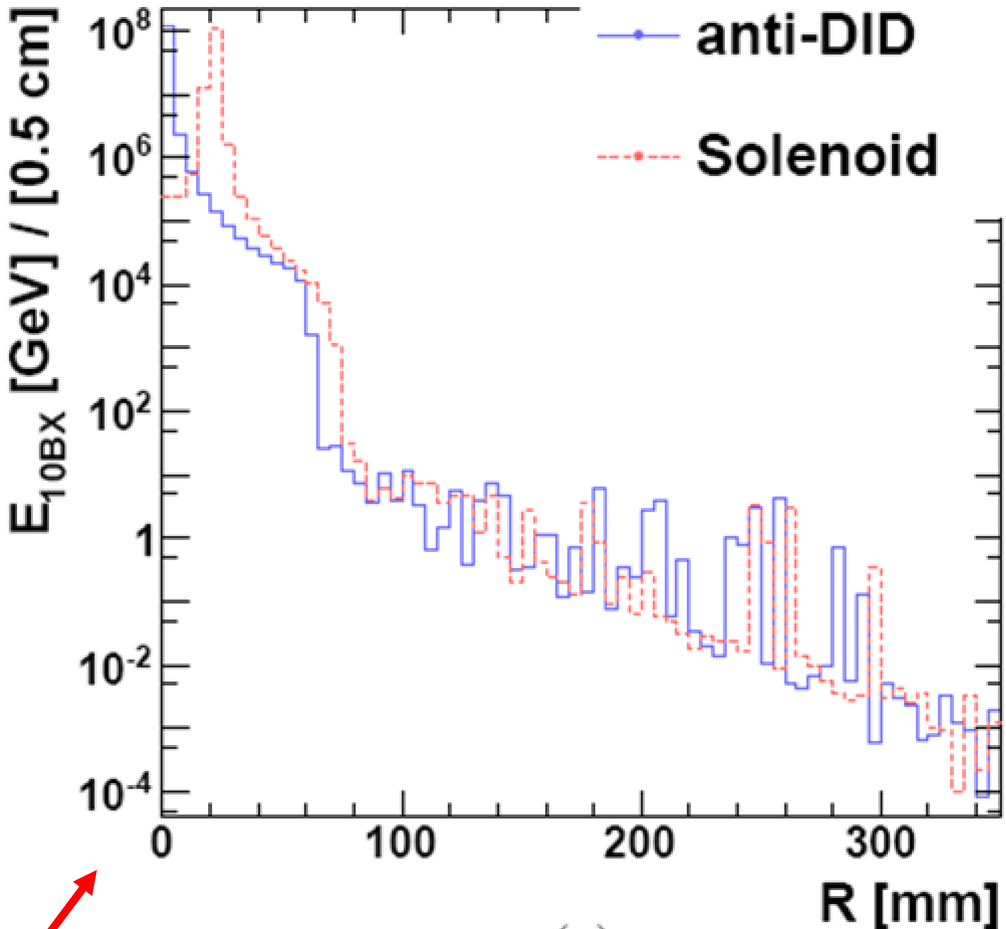
Important acc.dat parameters:
n_x=64; n_y=128; n_z=25;
n_t=1; n_m=150000;
grids=7;
do_pairs=1;
do_compt=0;
charge_sign=-1.0;

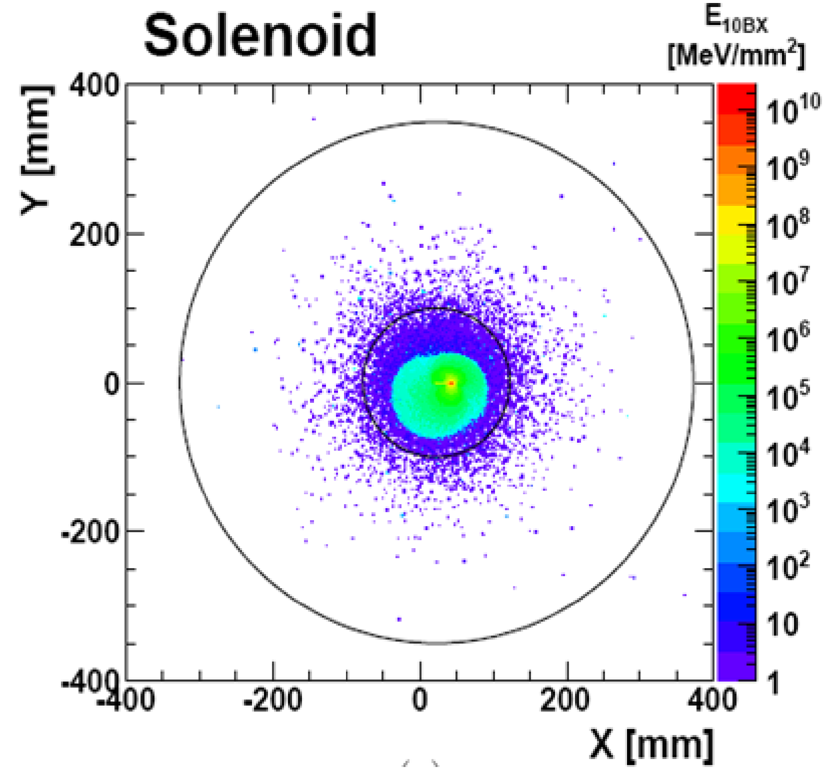
The pairs were run through MOKKA with a crossing angle of 20 mrad and a 4 T magnetic field.

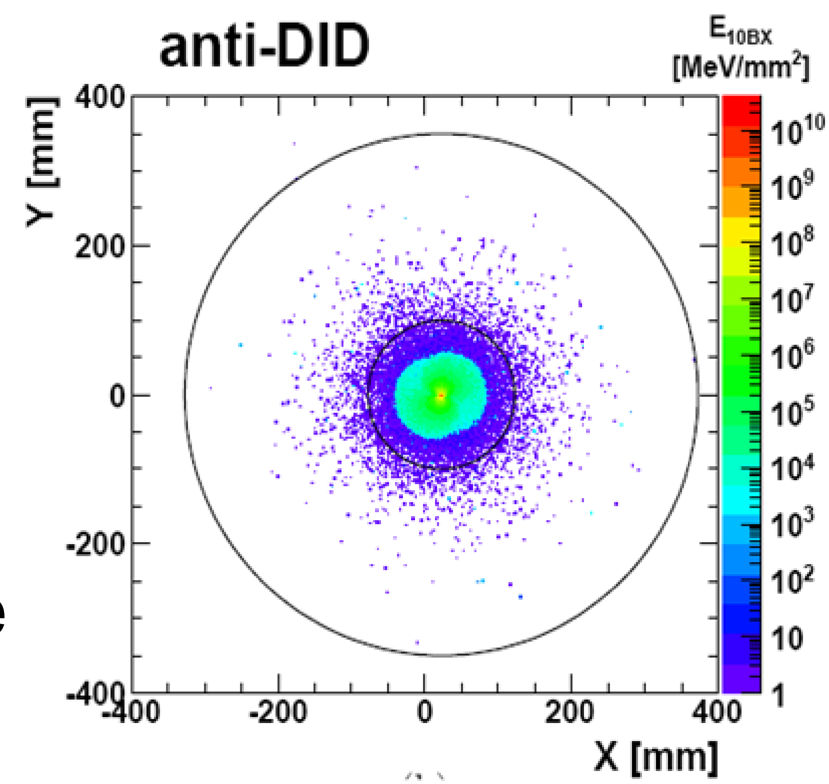


Beam profile (A.Sailer)

Pair distribution at √s = 3 TeV



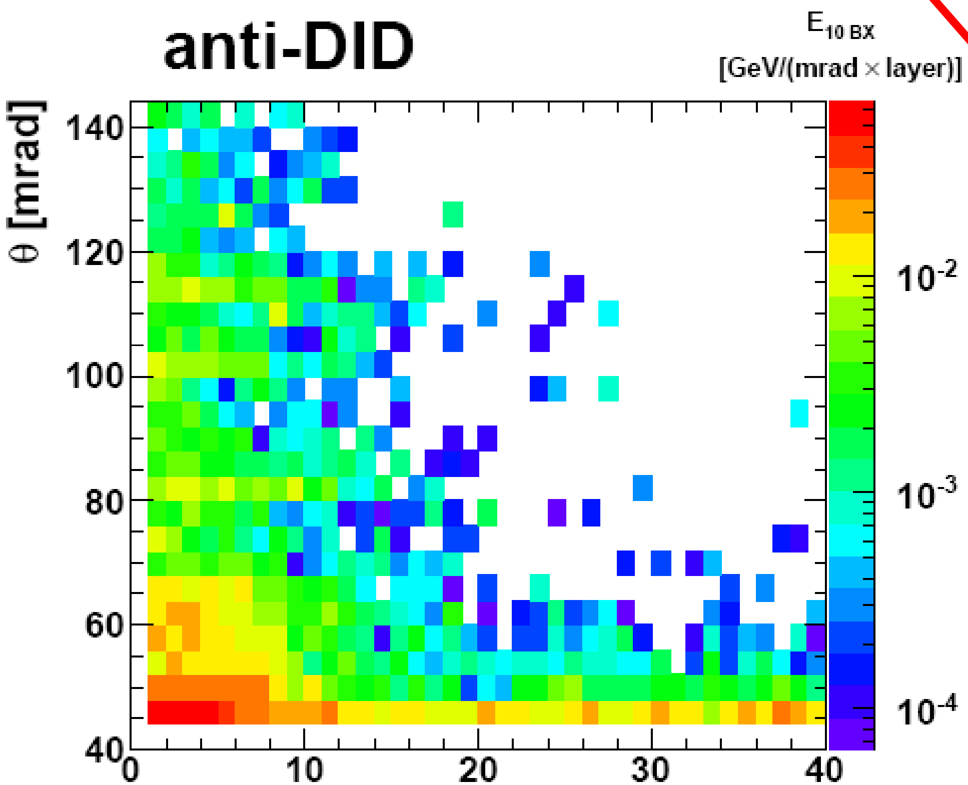




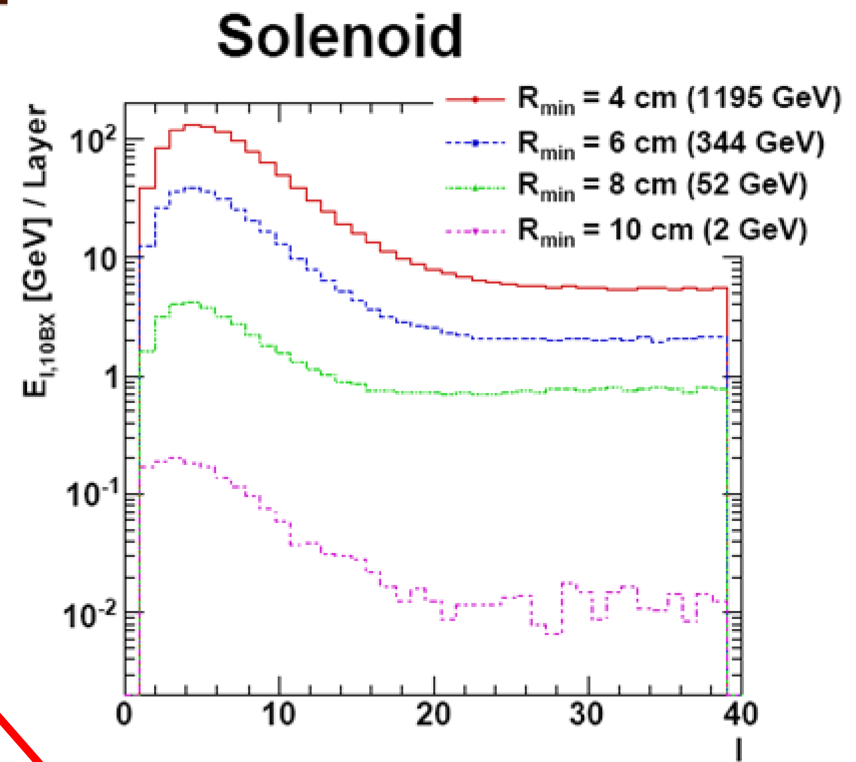
Energy for 10BX (bunch-crossings) as a function of the distance from the center of LumiCal (R_{min}=10 cm).

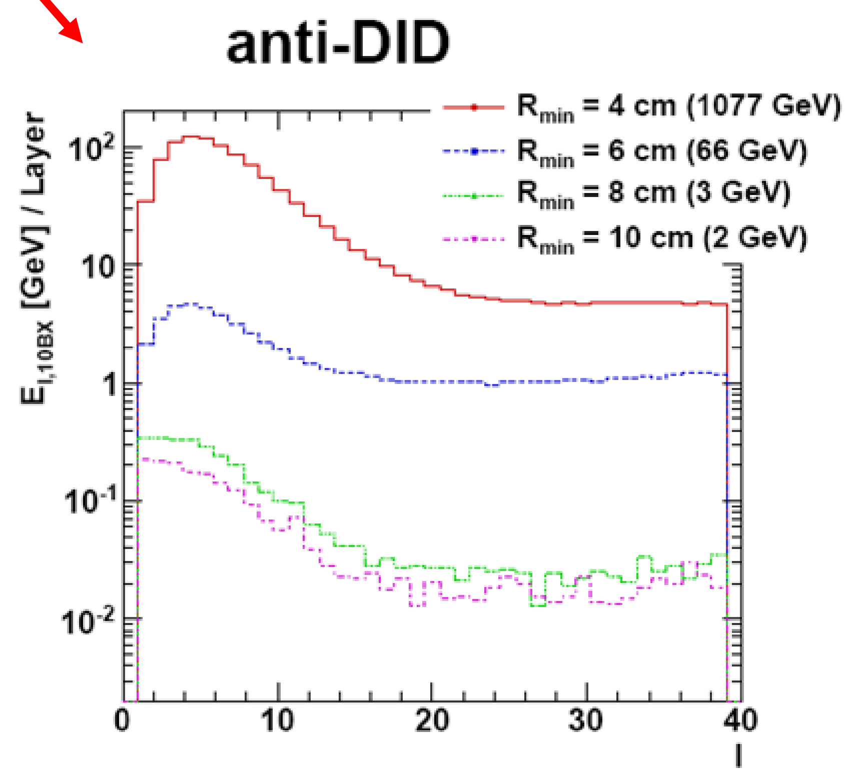
Pair deposits at $\sqrt{s}$ = 3 TeV

Deposited energy in LumiCal as a function of the layer number for 10BX. Different inner radii (R_{min}) were simulated.

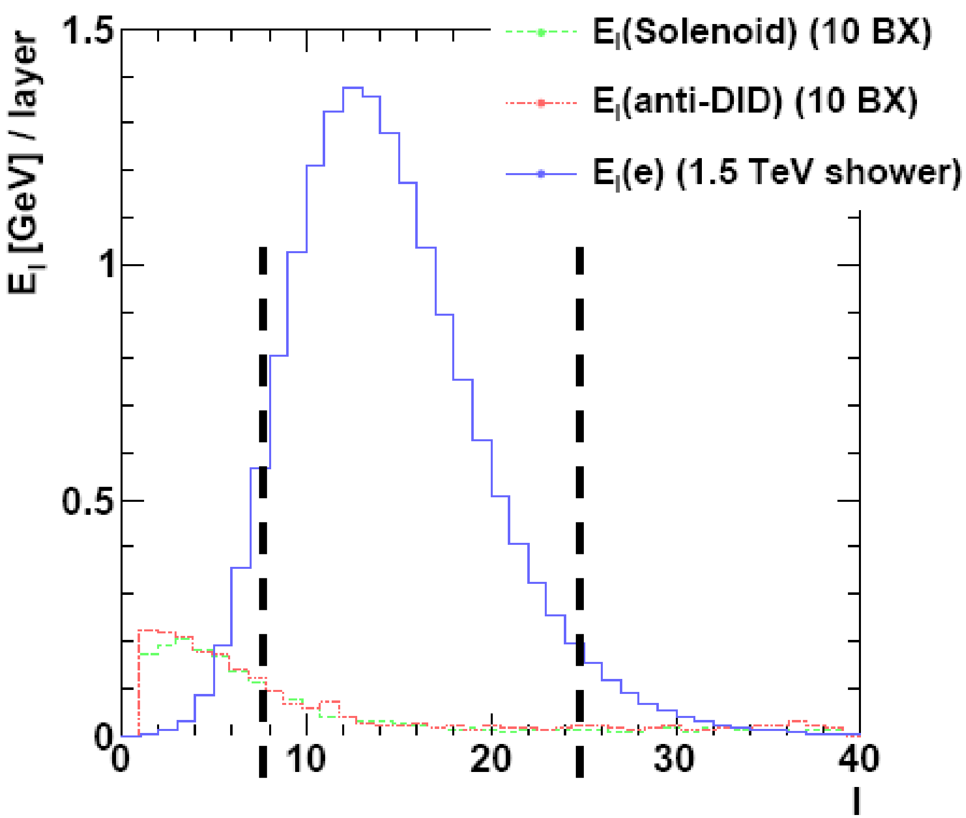


Deposited energy in LumiCal as a function of the layer number and of the polar angle for 10BX and R_{min}=10 cm.





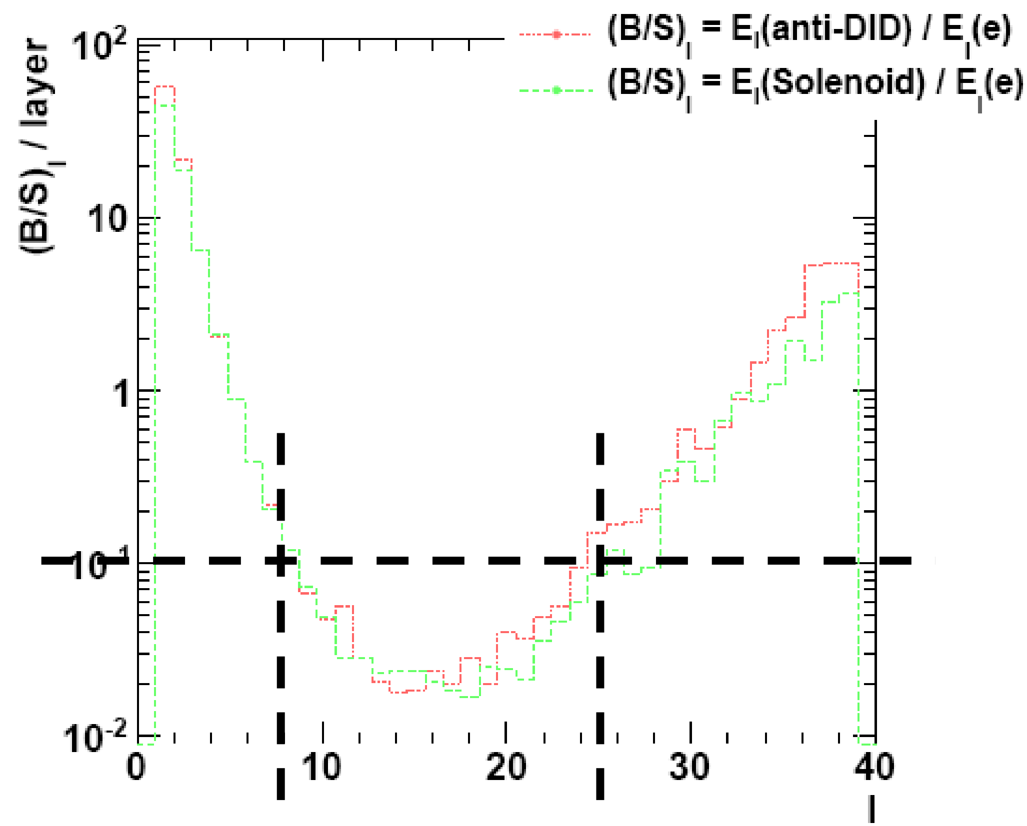
Pair deposits at $\sqrt{s}$ = 3 TeV



Deposited energy in LumiCal as a function of the layer number for 10BX and R_{min}=10 cm.

Background to signal ratio as a function of the layer number:

- Signal = 1.5 TeV electron shower
- Background = pair deposits for 10BX

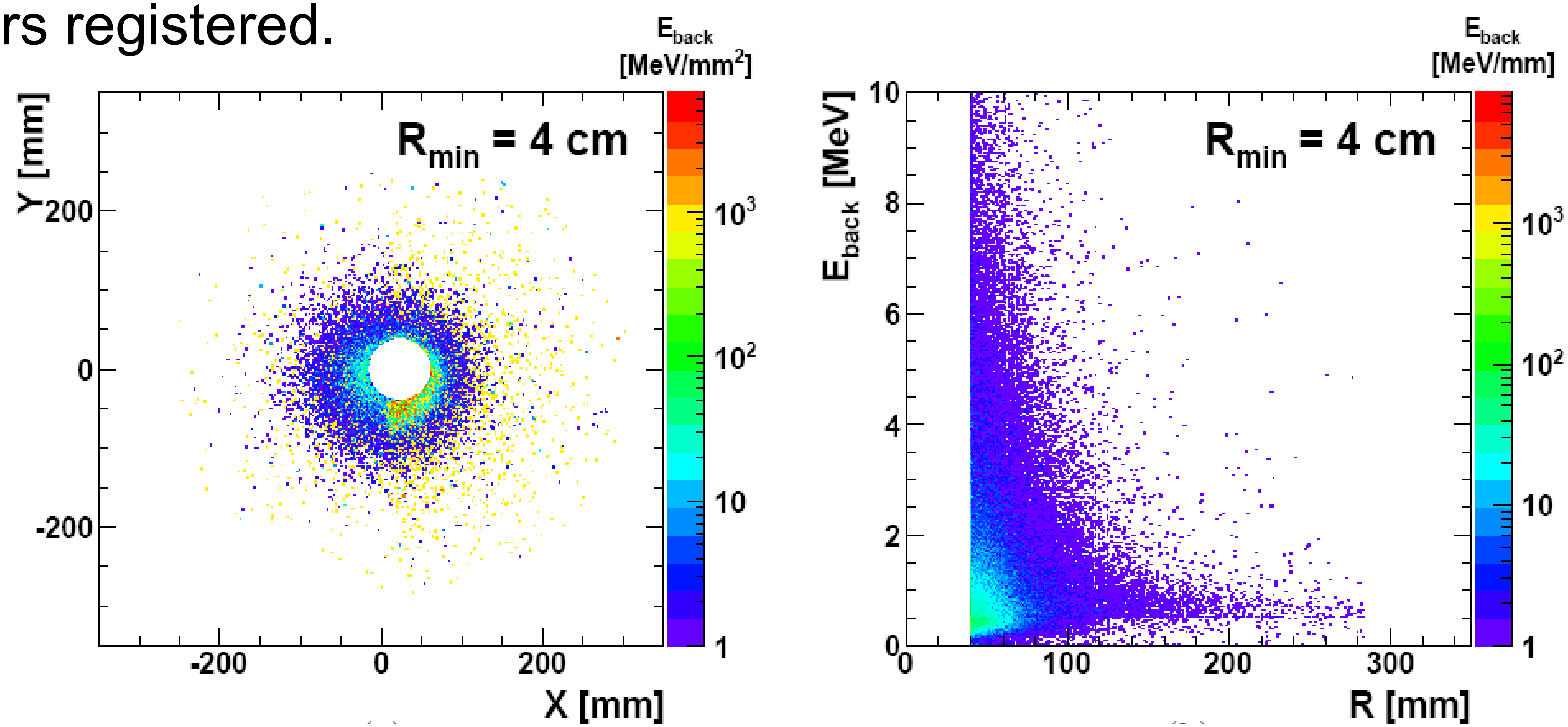


- Between layers 8 and 25 the shower peaks, and the background to signal ratio is smaller than 10%.

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).

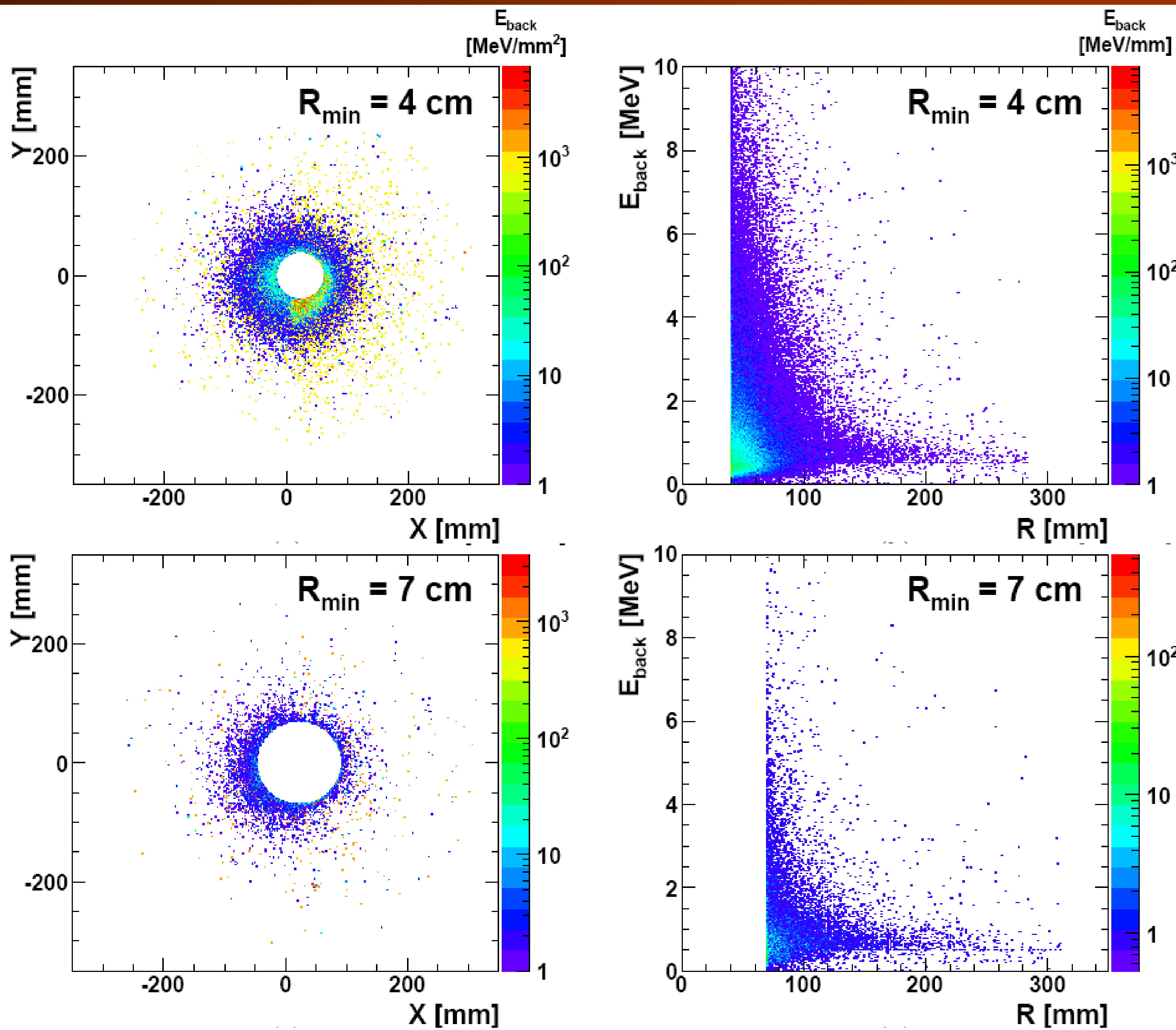
It must be noted that this is only a first step. In order to investigate this issue in full detail the entire detector must be simulated, and the hits in other sub-detectors registered.



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

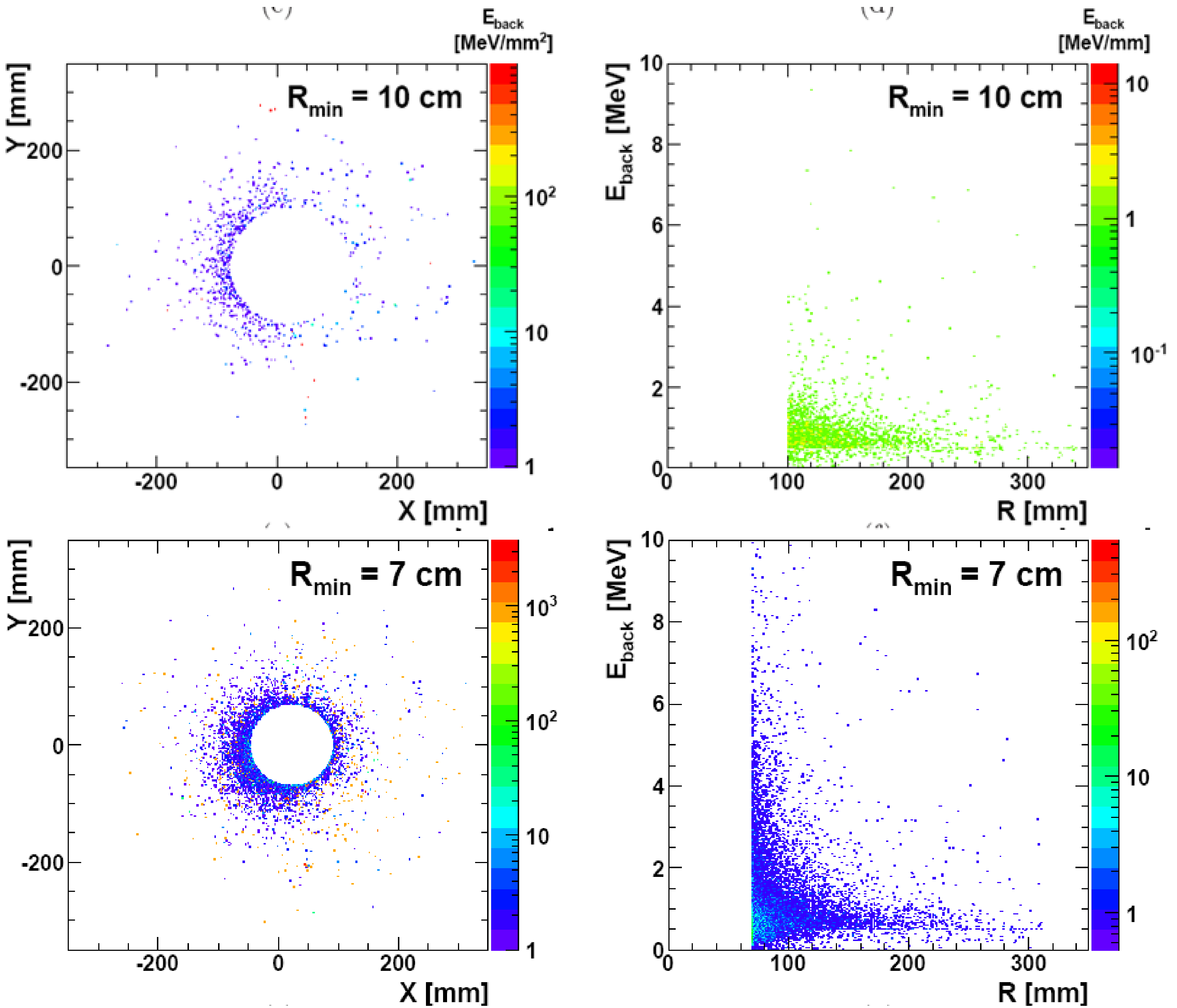
Backscattering from the front face of LumiCal

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



Backscattering from the front face of LumiCal

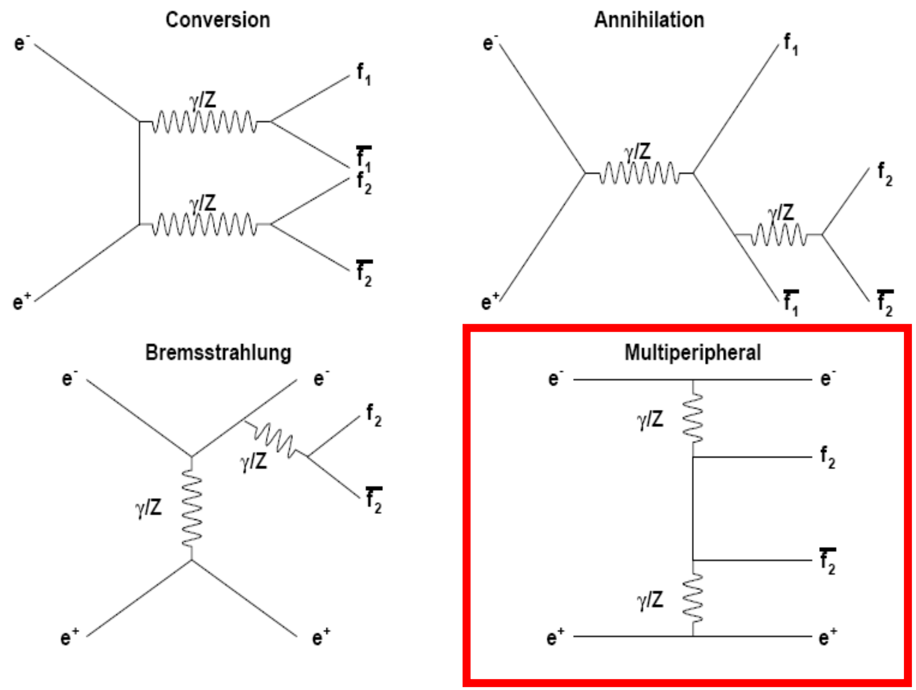
Simulation parameters:
- Solenoid field.
- 1.5 TeV beams.
- 20 mrad crossing angle.
- Integrated over 10 BX.
- Two minimal radii of LumiCal (10,7 cm).



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.

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



$$\sigma\left(e^+e^- \to e^+e^- l^+ l^-\right) = 1.62\cdot 10^5 \text{ fb}$$

$$\sigma\left(e^+e^- \to e^+e^- q^+ q^-\right) = 3.99\cdot 10^4 \text{ fb}$$

$$\sigma\left(e^+e^- \to e^+e^-\right) = 6.03\cdot 10^4 \text{ fb}$$

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

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

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 luminosity bias 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).

$$\frac{\Delta L}{L} = \frac{N_{rec} - N_{gen}}{N_{gen}} = \frac{N_{eell} + N_{eeqq} + N_{Bhabha} - N_{Bhabha}}{N_{Bhabha}}$$

$$= \frac{N_{eell} + N_{eeqq}}{N_{Bhabha}} = \frac{\text{Background}}{\text{Signal}} \equiv \left(B/S\right)_{cut}$$

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.

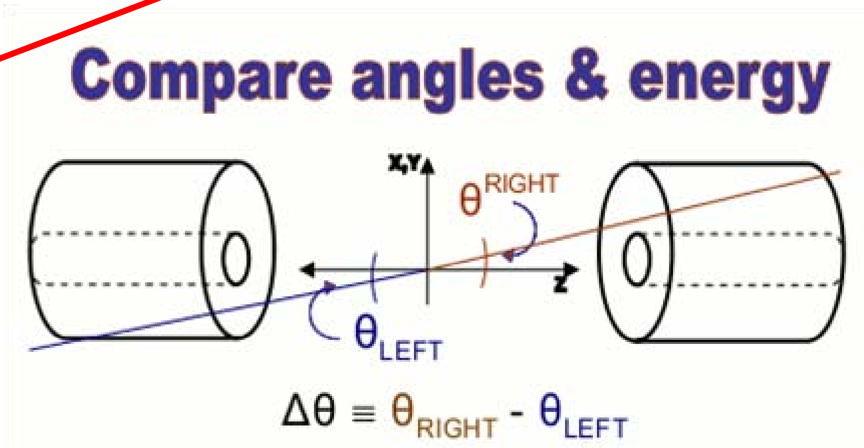
C. The re-scaled number of events for each sample was used in order to compute the error in the luminosity measurement (miss-counting of Bhabha events.)

Physics background – selection cuts

$$\frac{\Delta E_{r,l}}{E_{r,l}} \equiv \frac{|E_r - E_l|}{\min\{E_r, E_l\}} \quad , \quad C_E = \text{Relative energy cut} \quad , \quad C_\theta = \text{Polar angle cut}$$

$$\frac{\Delta E_{r,l}}{E_{r,l}} \le \mathcal{C}_E \quad , \quad |\theta_r - \theta_l| \le \mathcal{C}_\theta$$

$$\text{and} \quad \theta^f_{min} \le \theta_r, \theta_l \le \theta^f_{max} .$$



Background / Signal:

Number of background events which pass the cuts divided by the number of Bhabha events which pass the cuts.

Selection efficiency

Percentage of the number of Bhabha events which pass the cuts.

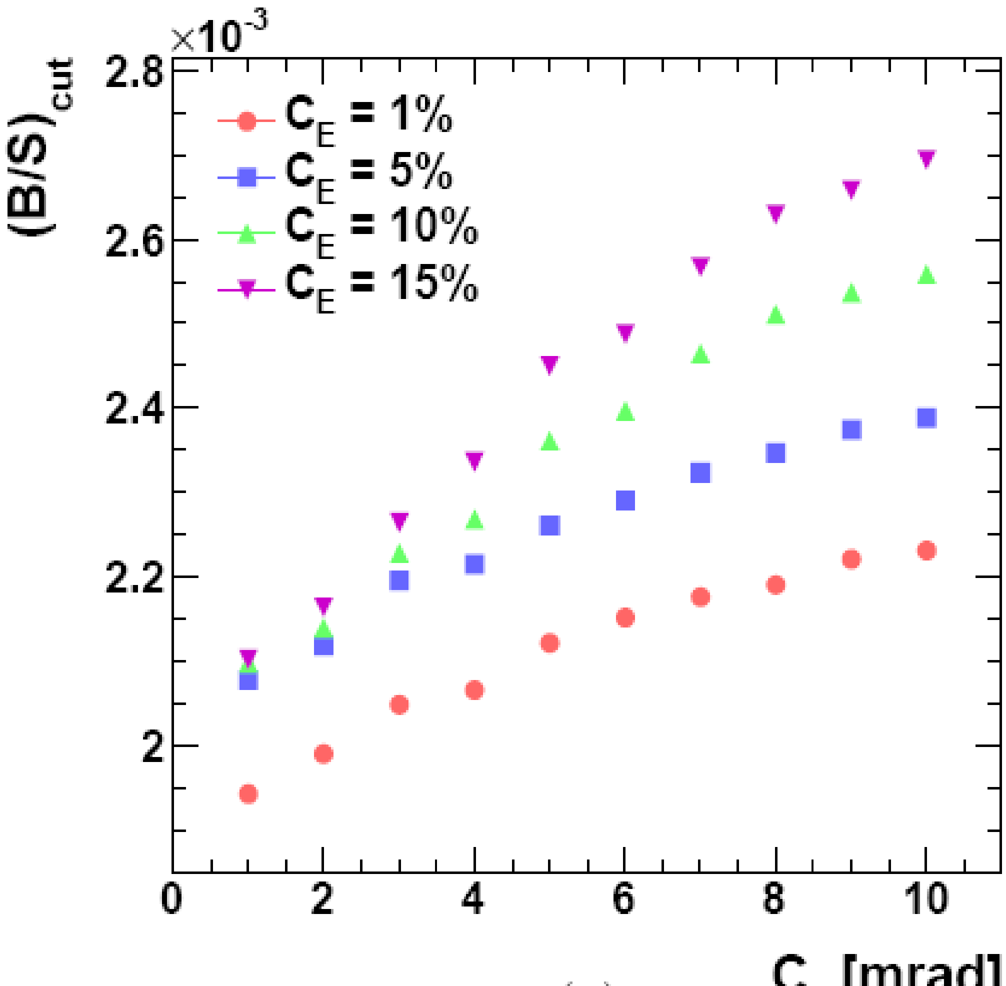
ε_{cut}

$(B/S)_{cut}$ ← This is in fact the **upper limit on the error in the luminosity measurement** due to the physics background.

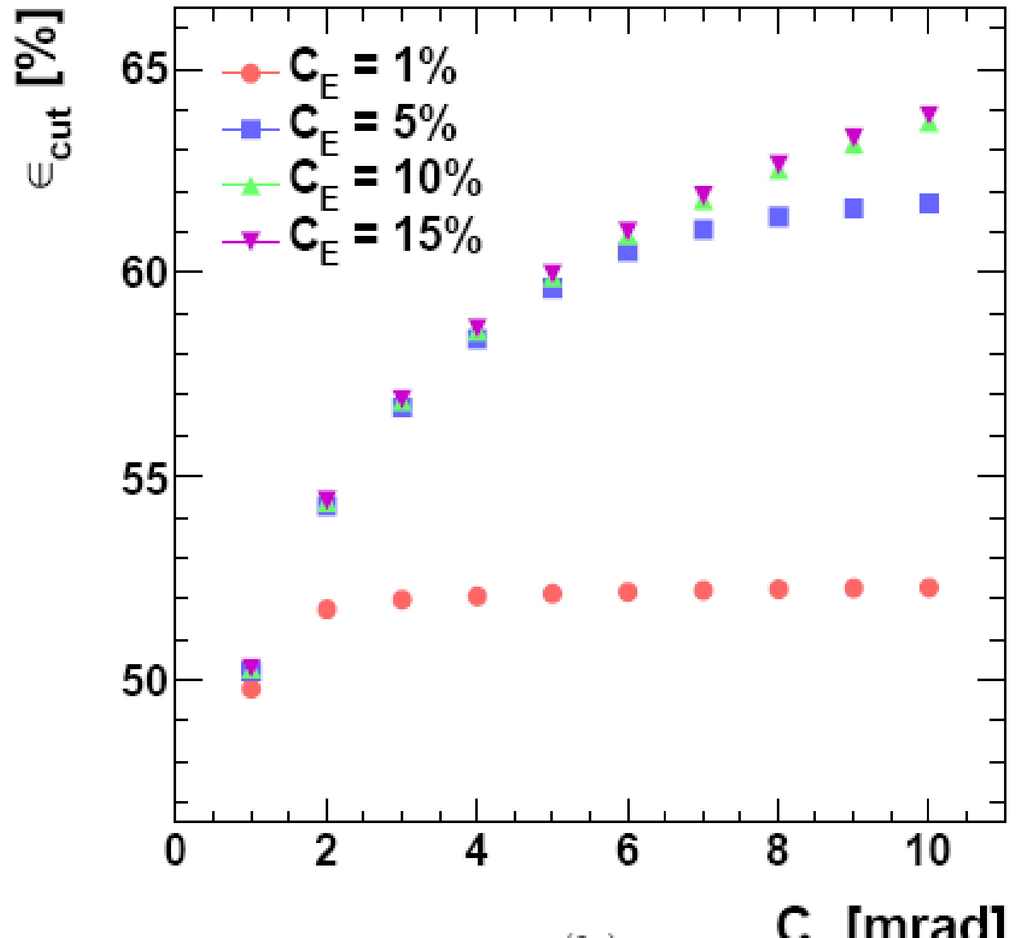
Physics background

Background / Signal

Selection efficiency



(a)



(b)

C_θ = Polar angle cut , C_E = Relative energy cut

Summary

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

2. In order to 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.
   - The selection cuts presented here do not take into account the beam-beam effects.