The Luminosity Calorimeter

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Desy

(On behalf of the FCAL collaboration)

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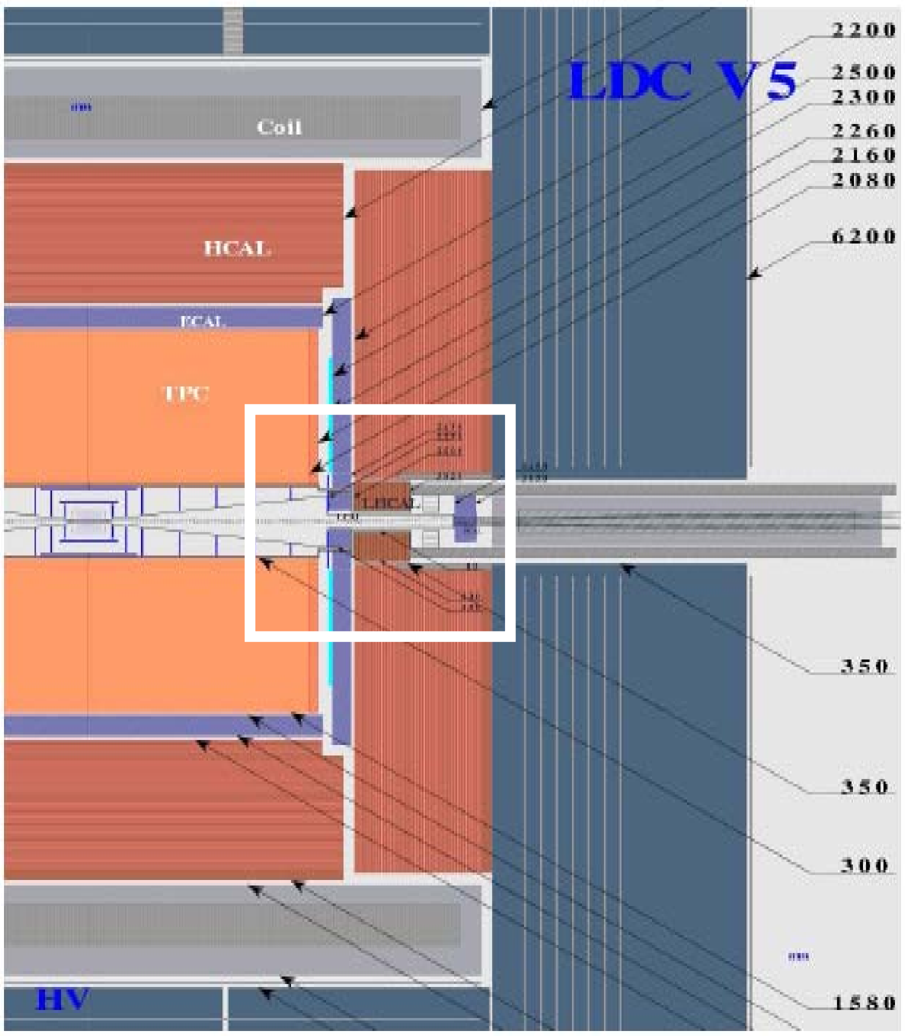
Overview

1. Intrinsic properties of LumiCal:
   - Luminosity measurement.
   - Design of LumiCal.
   - Performance of LumiCal.
2. Event reconstruction:
   - Bhabha scattering.
   - Clustering in LumiCal - Algorithm design and performance.



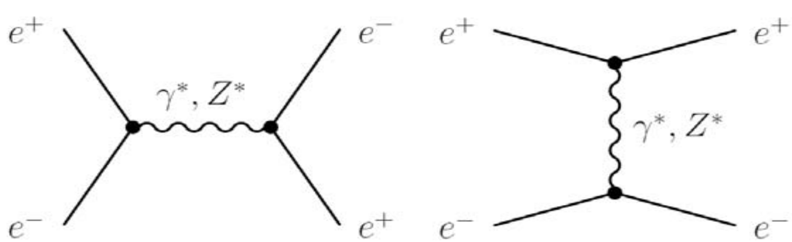
Performance requirements

1. Required precision is: $\frac{\Delta L}{L} < 10^{-3}$, GigaZ (hadronic Z decays) 10^9 / year

   $\frac{\Delta L}{L} \sim 10^{-3}$, $e^+ e^- \to W^+ W^-$ 10^6 / year

   $\frac{\Delta L}{L} \sim 10^{-3}$, $e^+ e^- \to q^+ q^-$ 10^6 / year

2. Measure luminosity by counting the number of Bhabha events (N_B):

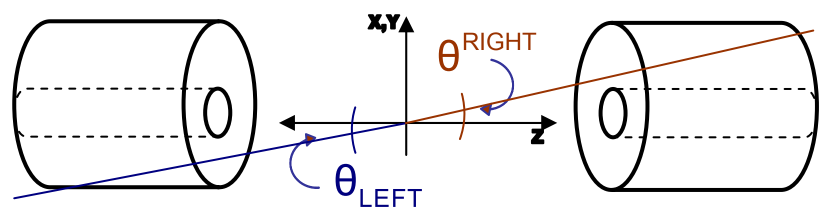


(a) s channel (b) t channel

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

Compare angles & energy

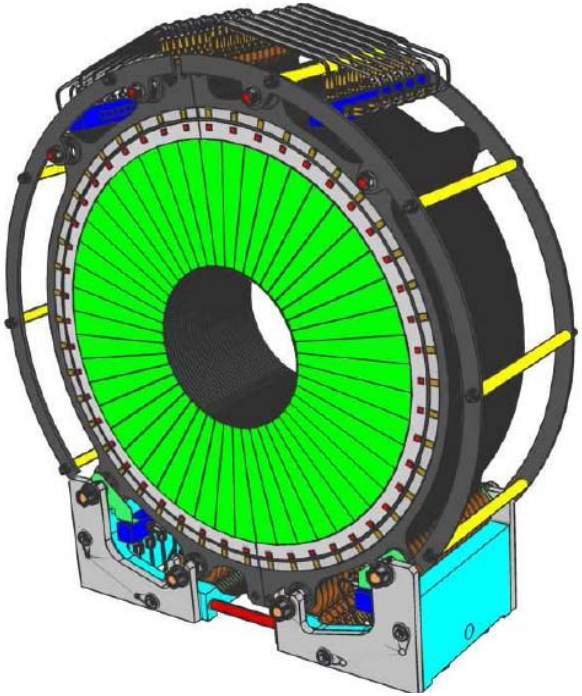
$$L = \frac{N_B}{\sigma_B} \quad , \quad \frac{\Delta L}{L} = \frac{\Delta N_B}{N_B} = \left. \frac{N_{rec} - N_{gen}}{N_{gen}} \right|_{\theta_{min}}^{\theta_{max}}$$

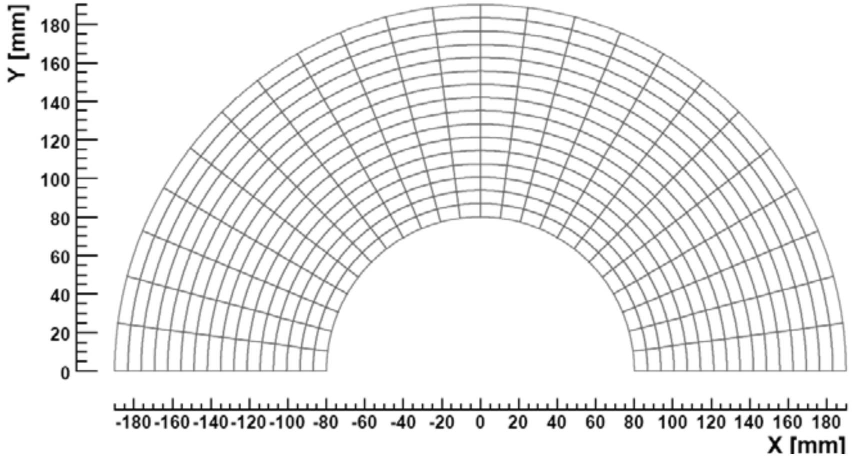


$\Delta\theta \equiv \theta_{RIGHT} - \theta_{LEFT}$

Design parameters

1. **Placement:**
   - 2270 mm from the IP
   - Inner Radius - 80 mm
   - Outer Radius - 190 mm
2. **Segmentation:**
   - 48 azimuthal & 64 radial divisions:
   - Azimuthal Cell Size - 131 mrad
   - Radial Cell Size - 0.8 mrad

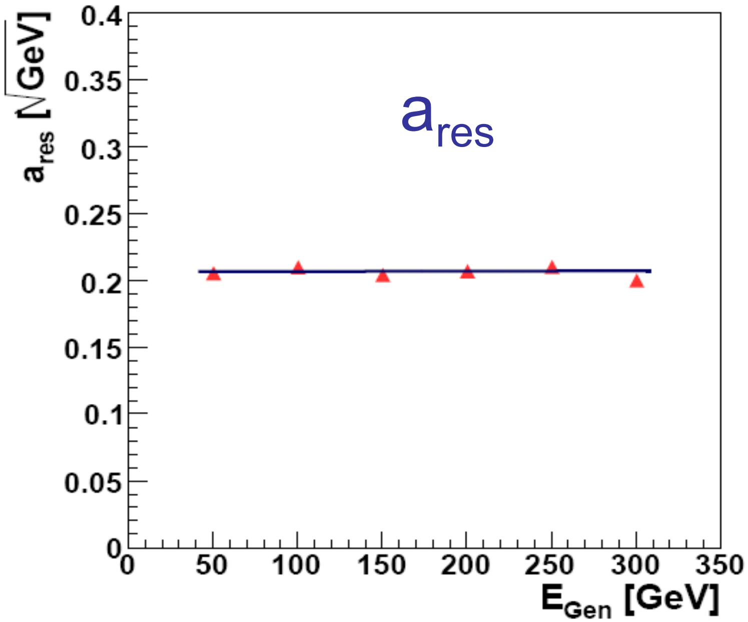




(every fourth radial segment is drawn)

3. **Layers:**
   - Number of layers - 30
   - Tungsten Thickness - 3.5 mm
   - Silicon Thickness - 0.3 mm
   - Elec. Space - 0.1 mm
   - Support Thickness - 0.6 mm

Intrinsic parameters



- Relative energy resolution:

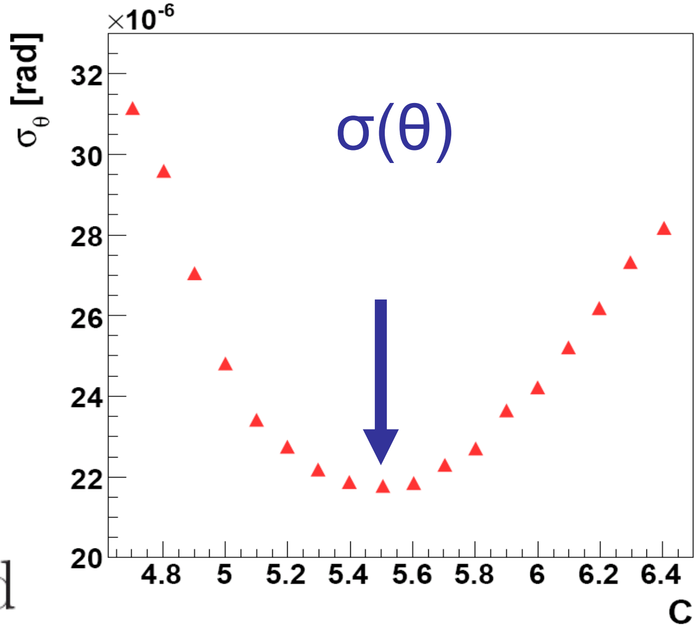
$$\frac{\sigma_E}{E} = \frac{a_{res}}{\sqrt{E_{beam}\ (\mathrm{GeV})}}$$

$$a_{res} \approx 0.21\ \sqrt{(\mathrm{GeV})}$$

- Position reconstruction (polar angle):

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

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

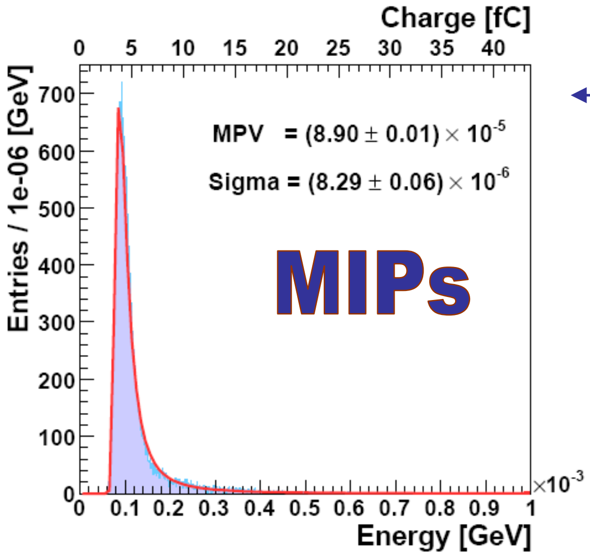


Bias $\Delta\theta = (3.2 \pm 0.1) \cdot 10^{-3}$ mrad

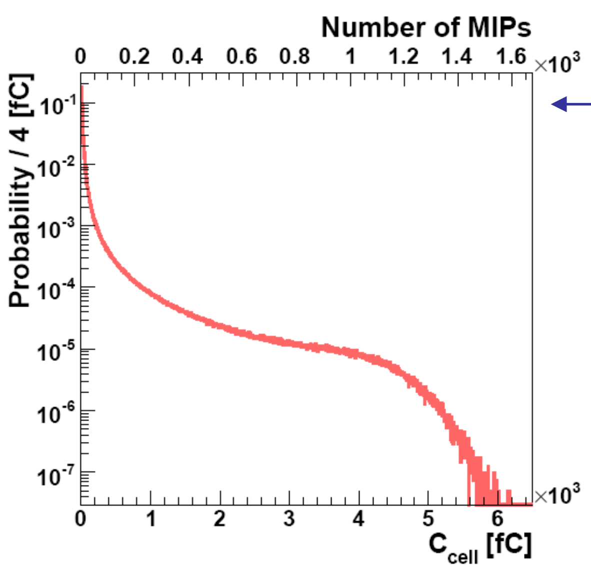
Resolution $\sigma_\theta = (2.18 \pm 0.01) \cdot 10^{-2}$ mrad

Logarithmic constant

Detector signal

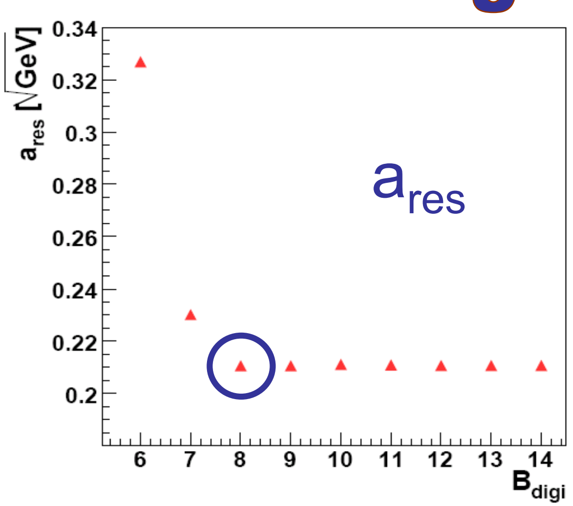


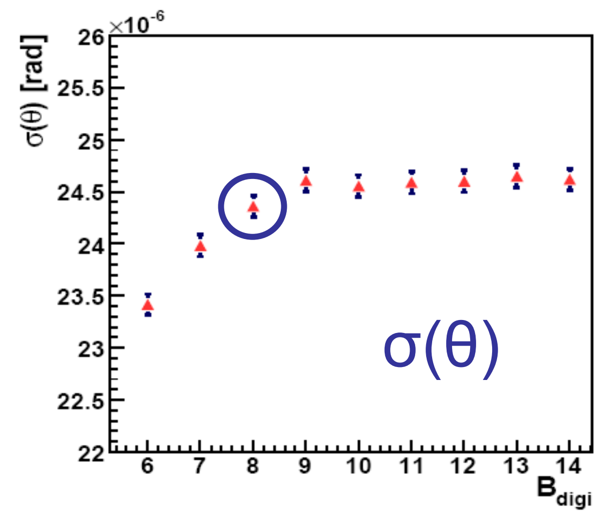
- Distribution of the deposited energy spectrum of a **MIP** (using 250 GeV muons): **MPV** of distribution **= 89 keV ~ 3.9 fC**.
- Distributions of the charge in a single cell for **250 GeV electron showers**.
- The influence of digitization on the energy resolution and on the polar bias.



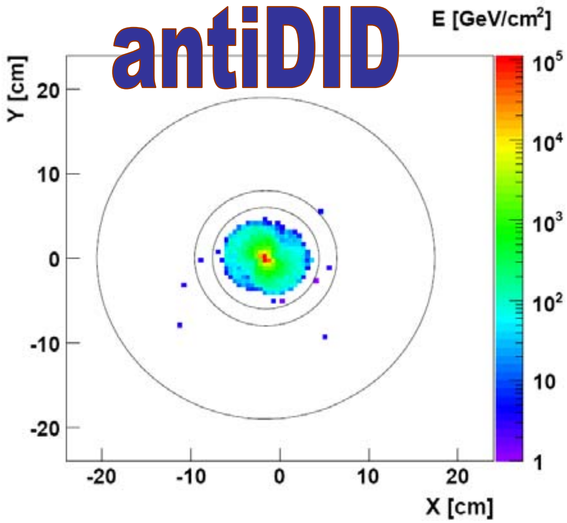
Signal distribution

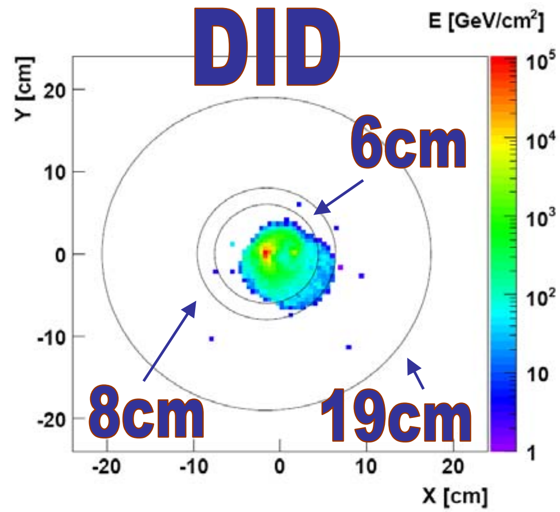
Digitization





LumiCal Performance





- Beamstrahlung spectrum on the face of LumiCal (14 mrad crossing angle): For the antiDID case R_{min} must be larger than 7cm.

$$a_{res} \approx 0.21 \sqrt{(\mathrm{GeV})}$$

$$\frac{d\sigma_B}{d\theta} = \frac{2\pi\alpha^2}{s} \frac{\sin\theta}{\sin^4(\theta/2)} \approx \frac{32\pi\alpha^2}{s} \frac{1}{\theta^3}$$

$$\int_{\theta_{min}}^{\theta_{max}} \frac{d\sigma_B}{d\theta} d\theta = 1.23 \text{ nb}$$

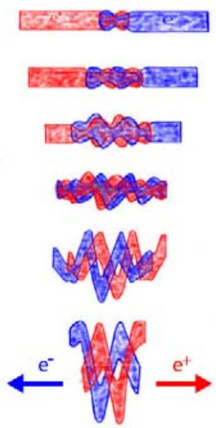
$$\left(\frac{\Delta\mathcal{L}}{\mathcal{L}}\right)_{rec} \approx 2\frac{\Delta\theta}{\theta_{min}} = 1.5 \cdot 10^{-4}$$

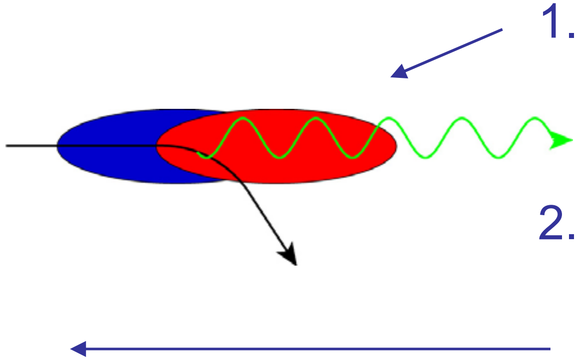
$$(\Delta\theta = 3.2 \cdot 10^{-6} \text{ rad})$$

$$\left(\frac{\Delta\mathcal{L}}{\mathcal{L}}\right)_{stat} = \frac{\Delta N_B}{N_B} = \frac{\sqrt{N_B}}{N_B} = \frac{1}{\sqrt{N_B}} = 4 \cdot 10^{-5}$$

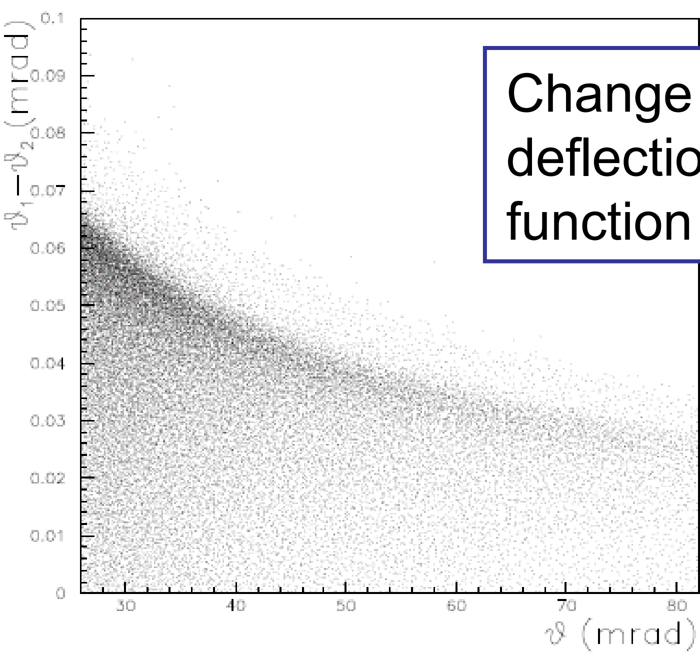
$$(500\ fb^{-1})$$

Beam-Beam effects at the ILC





1. High beam-beam field (~kT) results in energy loss in the form of synchrotron radiation (beamstrahlung).
2. Bunches are deformed by electromagnetic attraction: each beam acting as a focusing lens on the other.



Change in the final state polar angle due to deflection by the opposite bunch, as a function of the production polar angle.

- Since the beamstrahlung emissions occur asymmetrically between e+ and e^-, the acolinearity is increased resulting in a bias in the counting rate.

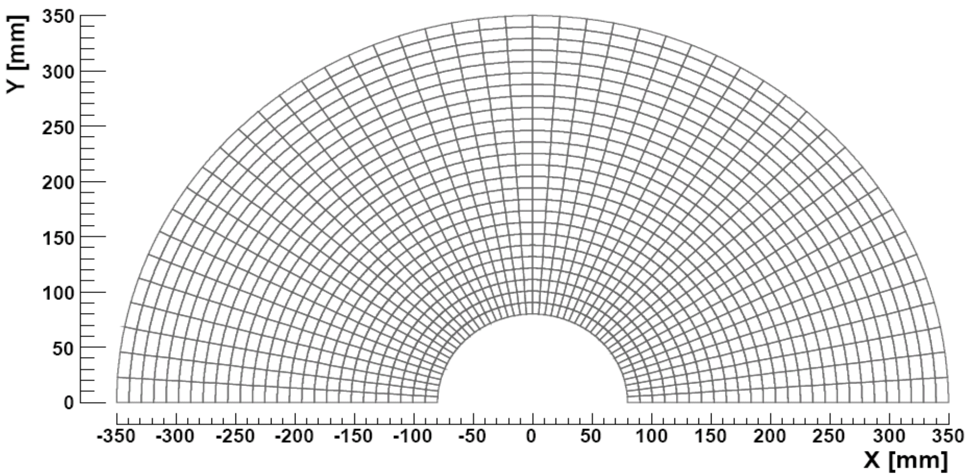
"Impact of beam-beam effects on precision luminosity measurements at the ILC"

– C. Rimbault et al. (http://www.iop.org/EJ/abstract/1748-0221/2/09/P09001/)

Clustering - Detector simulation

1. **Placement:**
   - 2270 mm from the IP
   - Inner Radius - 80 mm
   - Outer Radius - **350 mm**
2. **Segmentation:**
   - 96 azimuthal & 104 radial divisions:
   - Azimuthal Cell Size - **65.5 mrad**
   - Radial Cell Size - **1.1 mrad**

- The clustering algorithm was tested for the **previous version of LumiCal**:
  1. Larger radius.
  2. Smaller azimuthal cell size.
  3. Larger radial cell size.

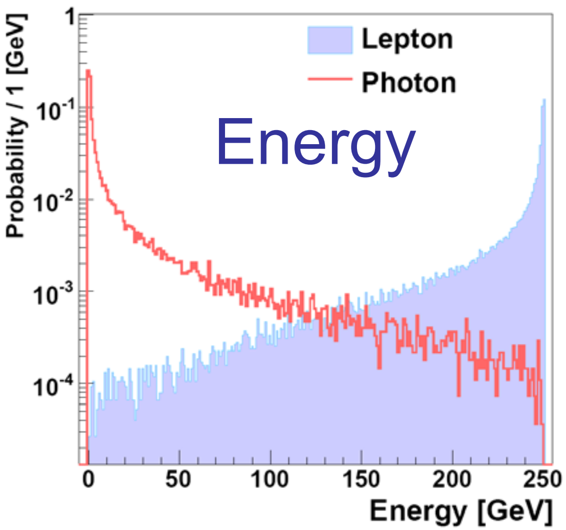


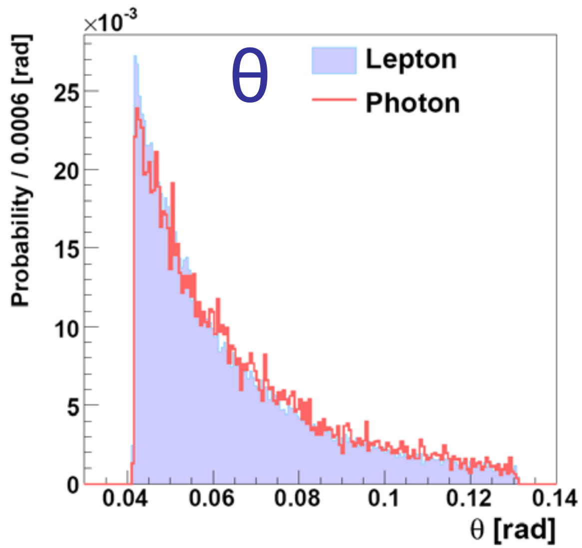
(every fourth radial segment is drawn)

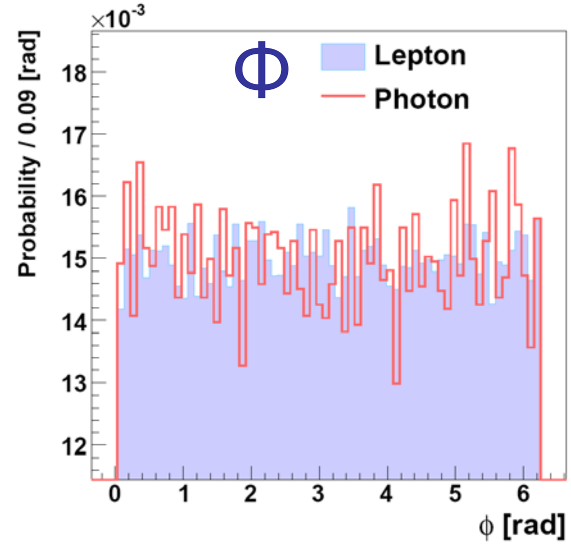
3. **Layers:**
   - Number of layers - 30
   - Tungsten Thickness - 3.5 mm
   - Silicon Thickness - 0.3 mm
   - Elec. Space - 0.1 mm
   - Support Thickness - 0.6 mm

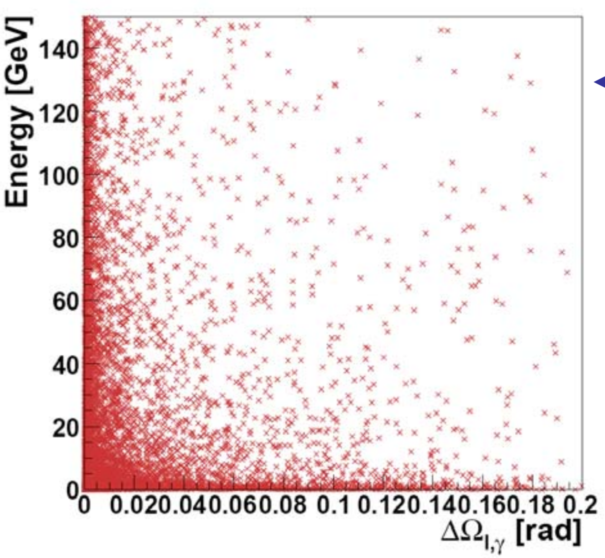
Topology of Bhabha scattering

- (3·10⁴ events of) Bhabha scattering with √s = 500 GeV

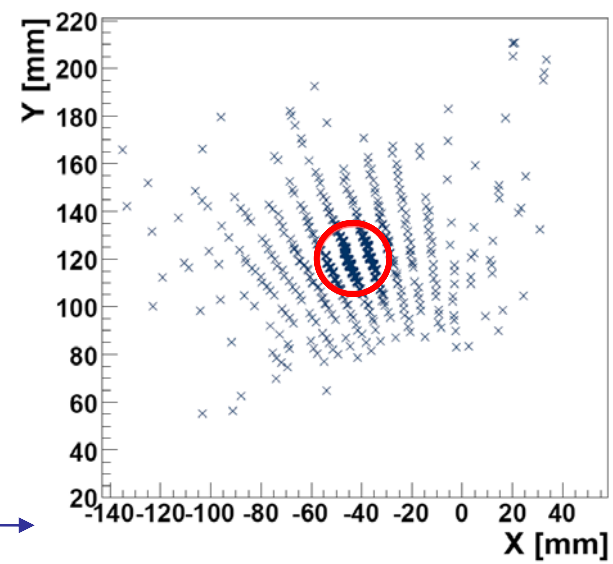








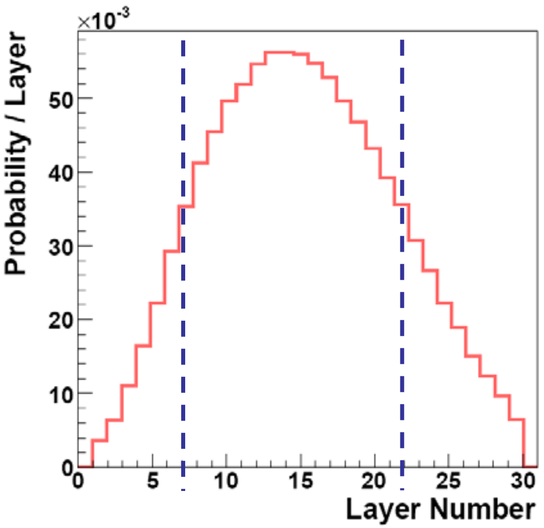
- Separation between photons and leptons, as a function of the energy of the low-energy particle.
- Shower profile in LumiCal - The Moliere radius is indicated by the red circle.



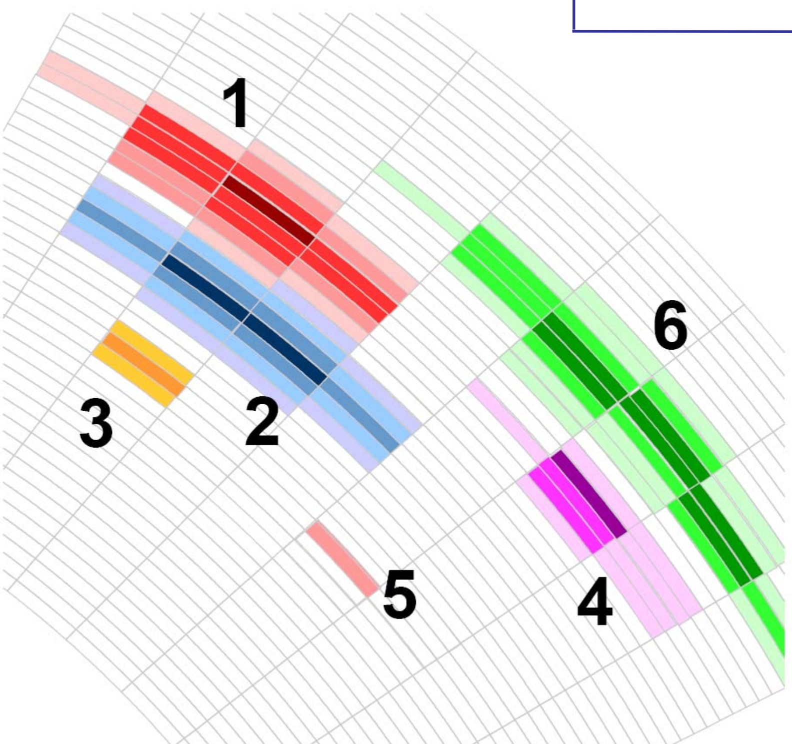
Clustering - Algorithm

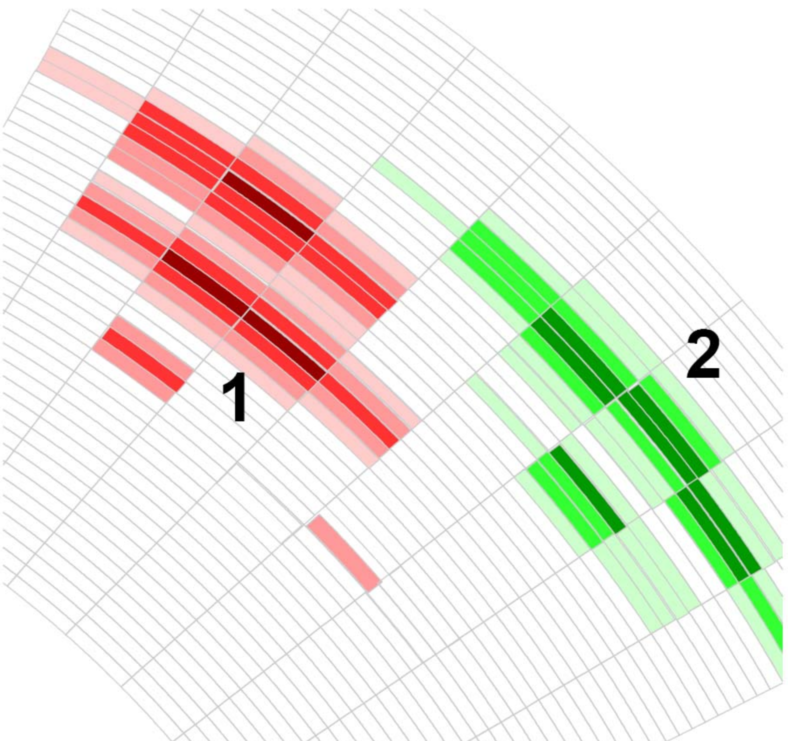
- **Phase I:**
  Near-neighbor clustering in a single layer.

- Longitudinal shower shape.

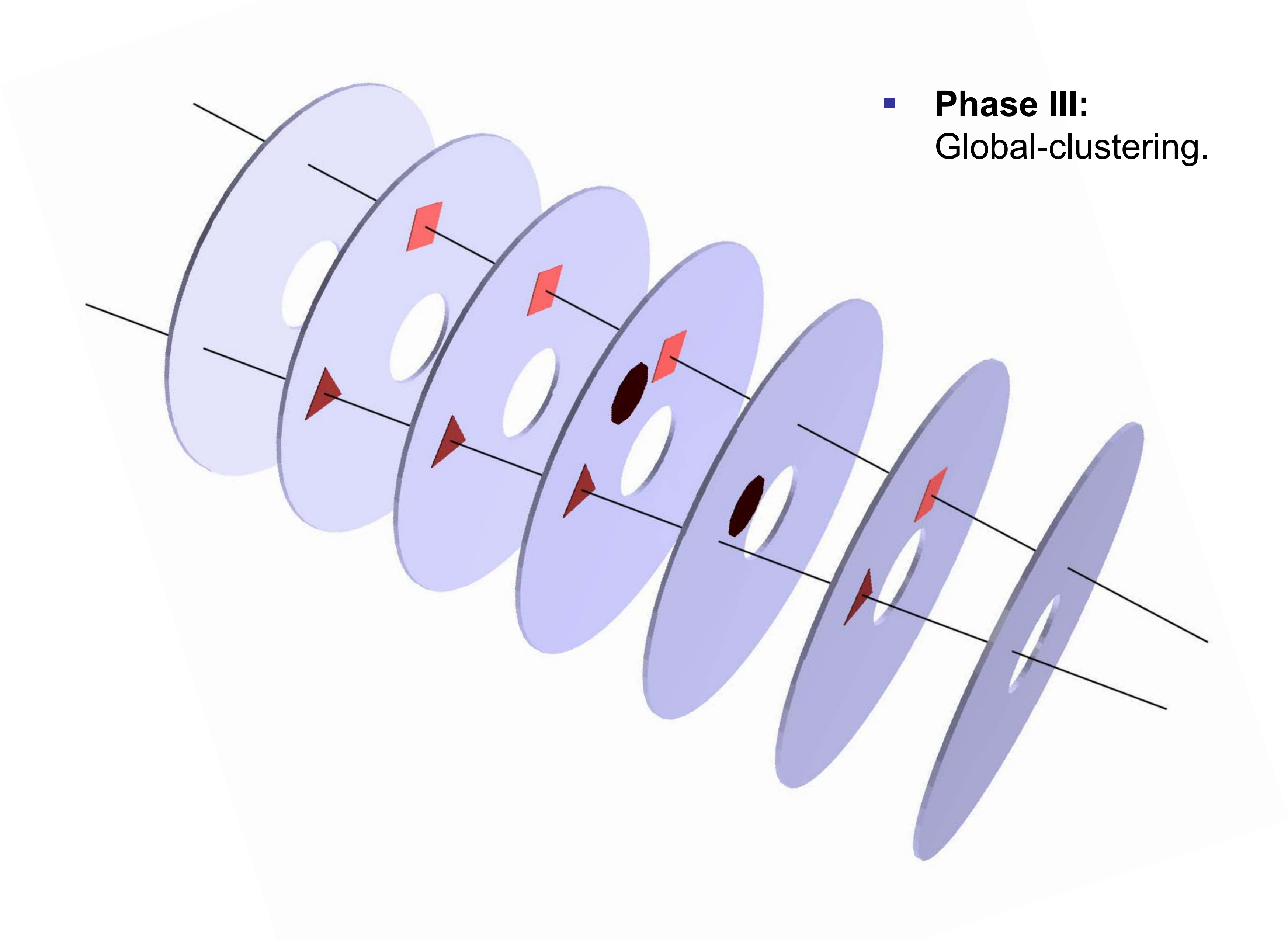


- **Phase II:**
  Cluster-merging in a single layer.





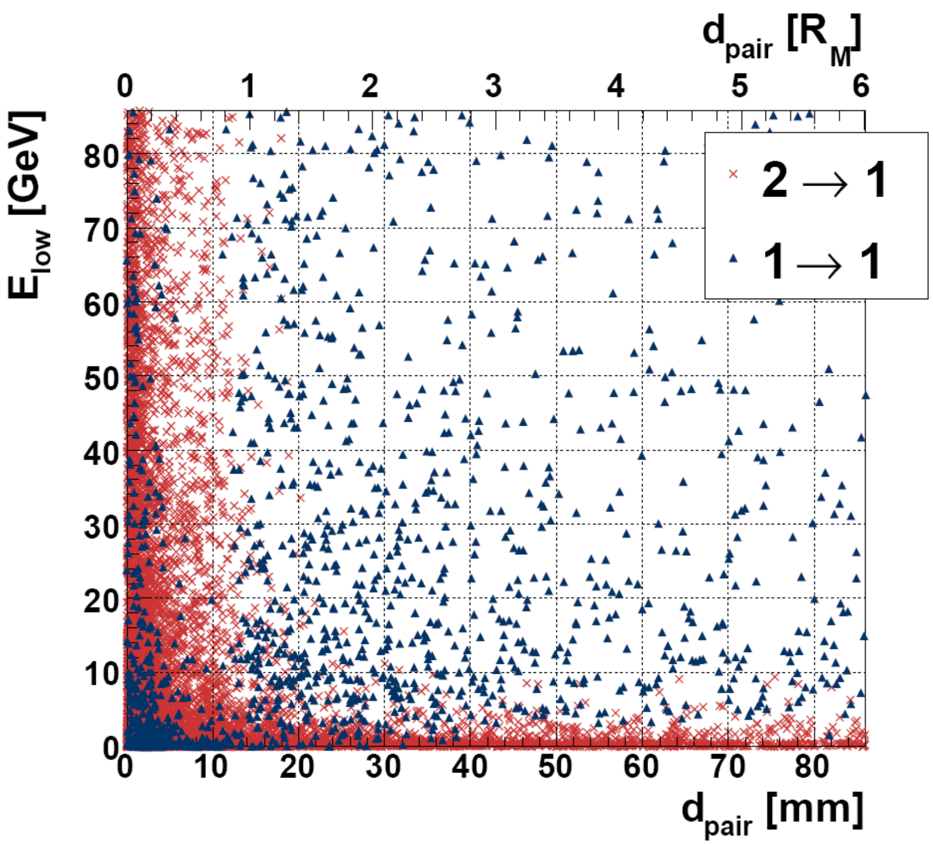
Clustering - Algorithm

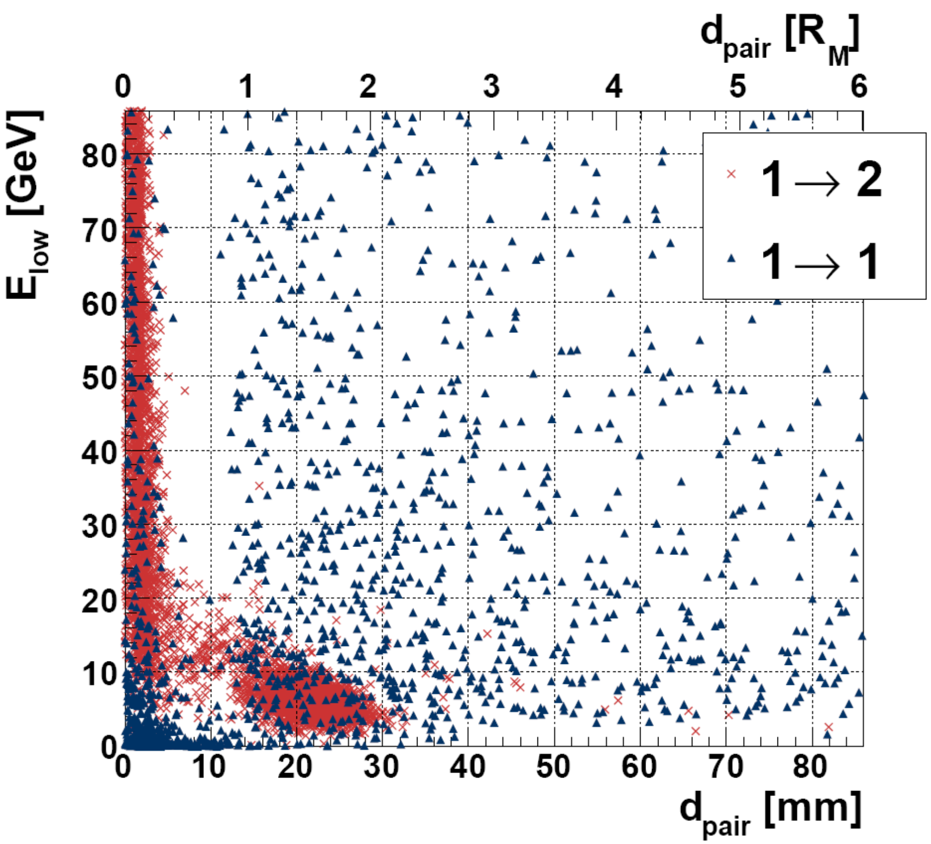


- **Phase III:**
  Global-clustering.

Clustering - Results

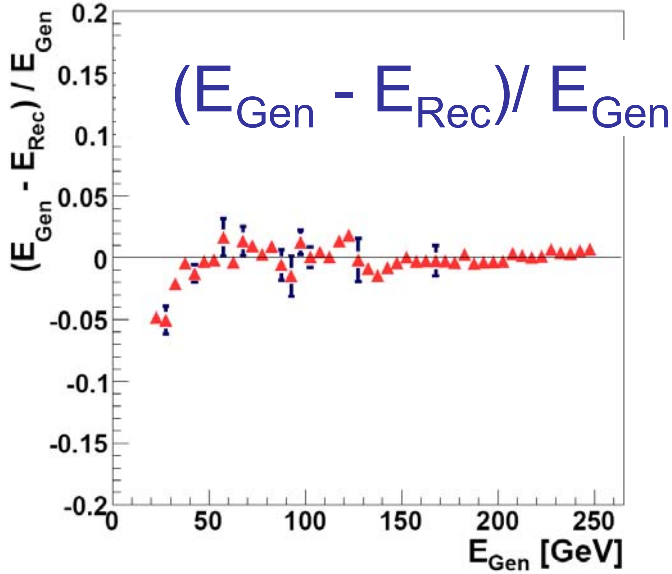
- **(2→1)**: Two showers were merged into one cluster.
- **(1→2)**: One shower was split into two clusters.
- The Moliere radius is $\mathbf{R_M}$ (= 14mm), $\mathbf{d_{pair}}$ is the distance between a pair of showers, and $\mathbf{E_{low}}$ is the energy of the low-energy shower.

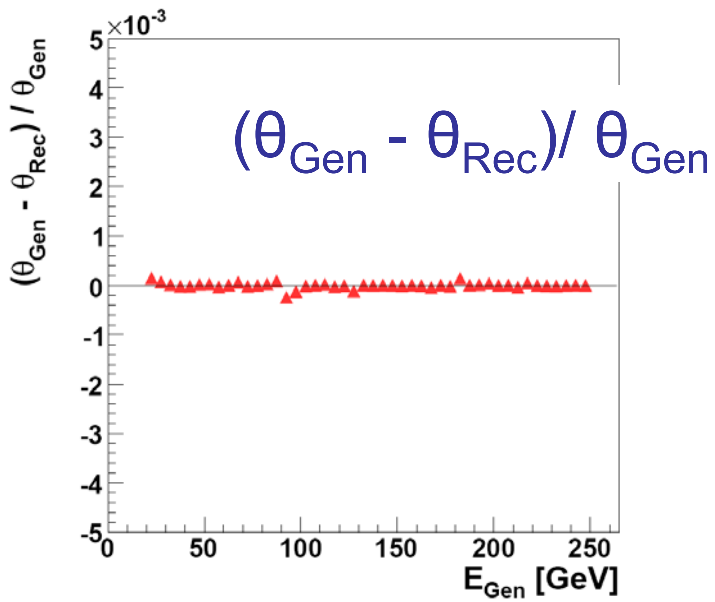


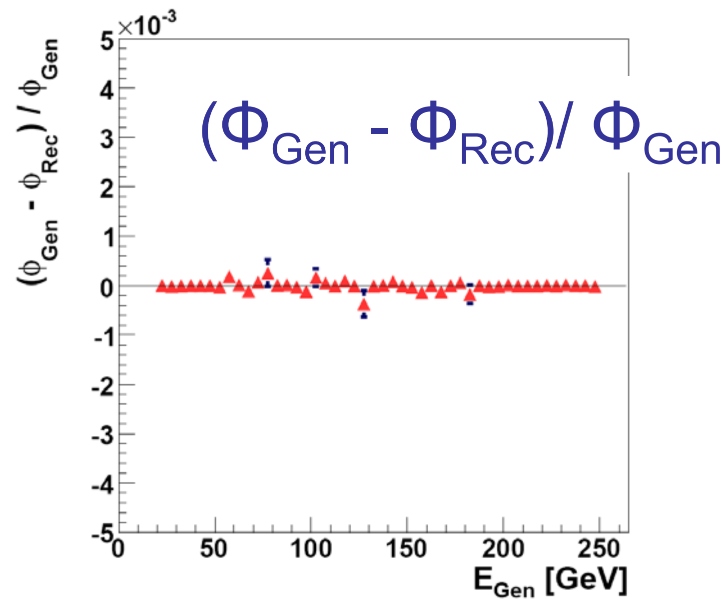


Clustering - Results (event-by-event)

- Event-by-event comparison of the energy and position of showers (GEN) and clusters (REC) as a function of **E_{Gen}**.







Clustering - Geometry dependence

$$\mathcal{A} = \frac{N_{1\to1}}{N_{1\to1} + N_{2\to1}}$$

$$\mathcal{P} = \frac{N_{1\to1}}{N_{1\to1} + N_{1\to2}}$$

$$\frac{\Delta N_{\ell,\gamma}}{N_{\ell,\gamma}} = \frac{\sqrt{N_{\ell,\gamma} pq}}{N_{\ell,\gamma}} = \sqrt{\frac{pq}{N_{\ell,\gamma}}}$$

$N_{1\to2} \rightarrow N_{\ell,\gamma} \to N_{\gamma}$

$N_{2\to1} \rightarrow N_{\ell,\gamma} \to N_{\ell}$

$$\frac{\Delta N_{tot}}{N_{tot}} = \left(\frac{\Delta N}{N}\right)_{1\to2} \oplus \left(\frac{\Delta N}{N}\right)_{2\to1} \qquad (500\ fb^{-1})$$

	Cell Length				$\mathcal{A}$ [%]	$\mathcal{P}$ [%]	$\frac{\Delta N_{tot}}{N_{tot}}$
	$\Delta\phi$ ($R_{min} \to R_{max}$)		Δr				
	[mrad]	[$R_{\mathcal{M}}$]	[mrad]	[$R_{\mathcal{M}}$]			
96 div	65.5	$0.37 \to 1.64$	0.38	0.06	99	94	$2.9 \cdot 10^{-5}$
			1.52	0.24	98	92	$3.5 \cdot 10^{-5}$
48 div	131	$0.74 \to 3.28$	0.38	0.06	94	79	$6.6 \cdot 10^{-5}$
			0.76	0.12	93	77	$7.5 \cdot 10^{-5}$
			1.52	0.24	90	84	$9.1 \cdot 10^{-5}$
24 div	262	$1.48 \to 6.56$	0.76	0.12	76	22	$11.1 \cdot 10^{-5}$

Summary

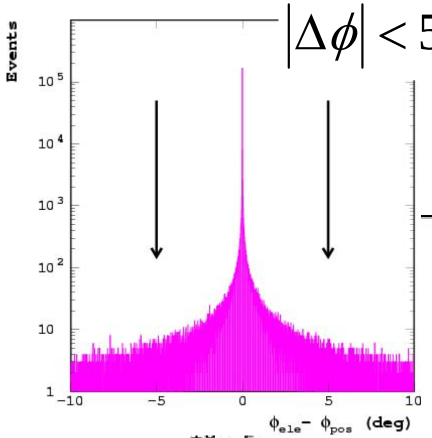
1. Intrinsic properties of LumiCal:
   - Energy resolution: $a_{res} \approx 0.21\ \sqrt{\text{GeV}}$.
   - Relative error in the luminosity measurement:
     $\Delta L/L = 1.5 \cdot 10^{-4} \oplus 4 \cdot 10^{-5}$ (at 500 fb^{-1}), where the theoretical uncertainty is expected to be $\sim 2 \cdot 10^{-4}$.
2. Event reconstruction (photon counting):
   - Merging-cuts need to be made on the minimal energy of a cluster and on the separation between any pair of clusters.
   - The algorithm performs with high efficiency and purity for both the previous and the new design of LumiCal.
   - The number of radiative photons within a well defined phase-space may be counted with an acceptable uncertainty.

Auxiliary Slides

Selection of Bhabha events

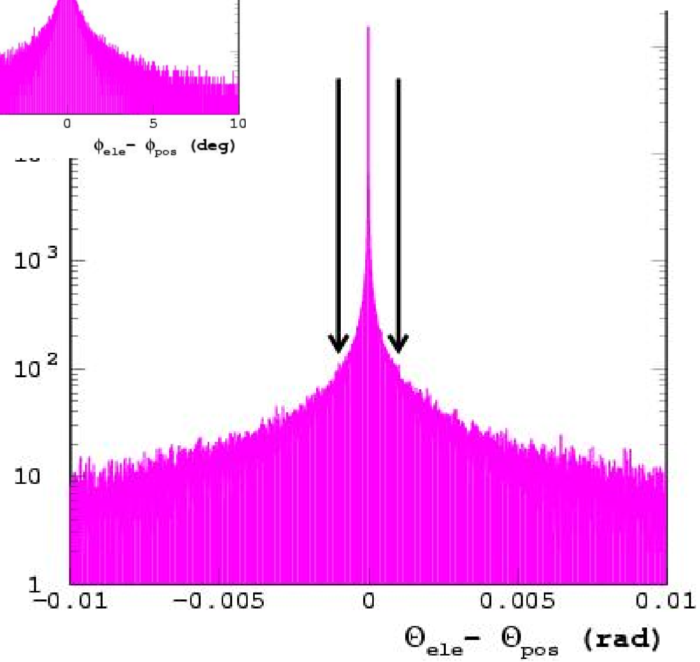
Acoplanarity

$$|\Delta\phi| < 5\,\text{deg}$$

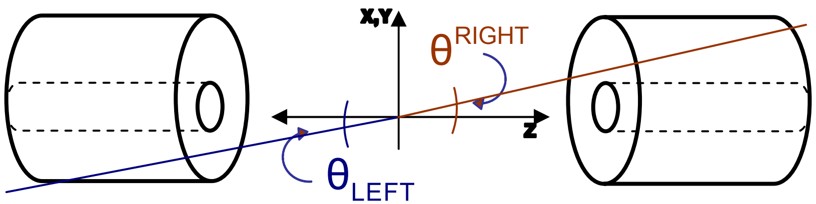


Acolinearity

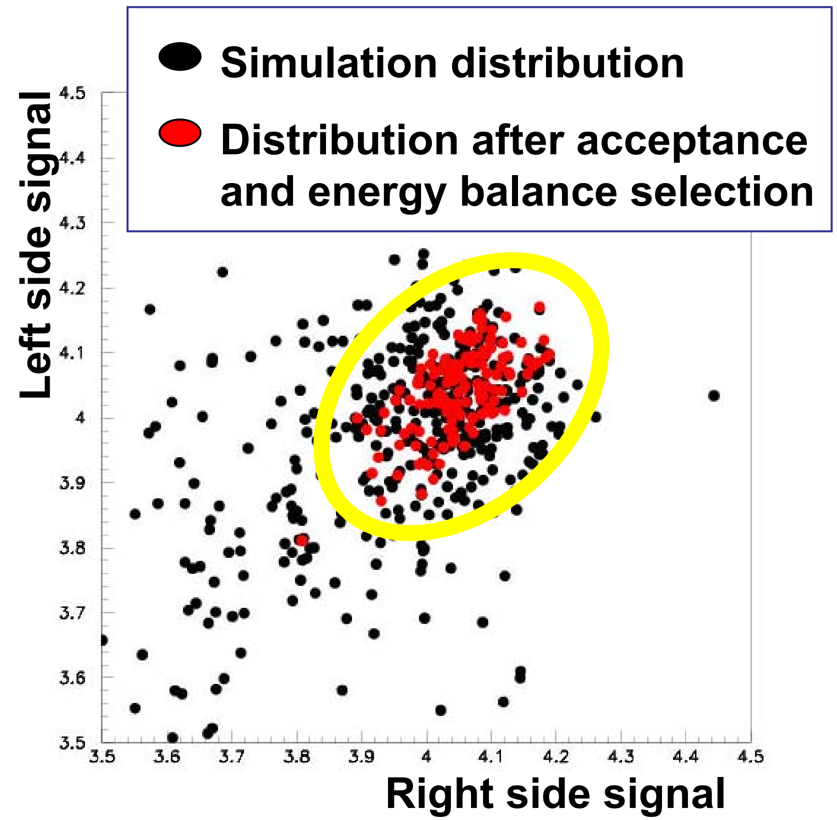
$$|\Delta\theta| < 10^{-3}\,rad$$



Compare angles & energy



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



Energy Balance

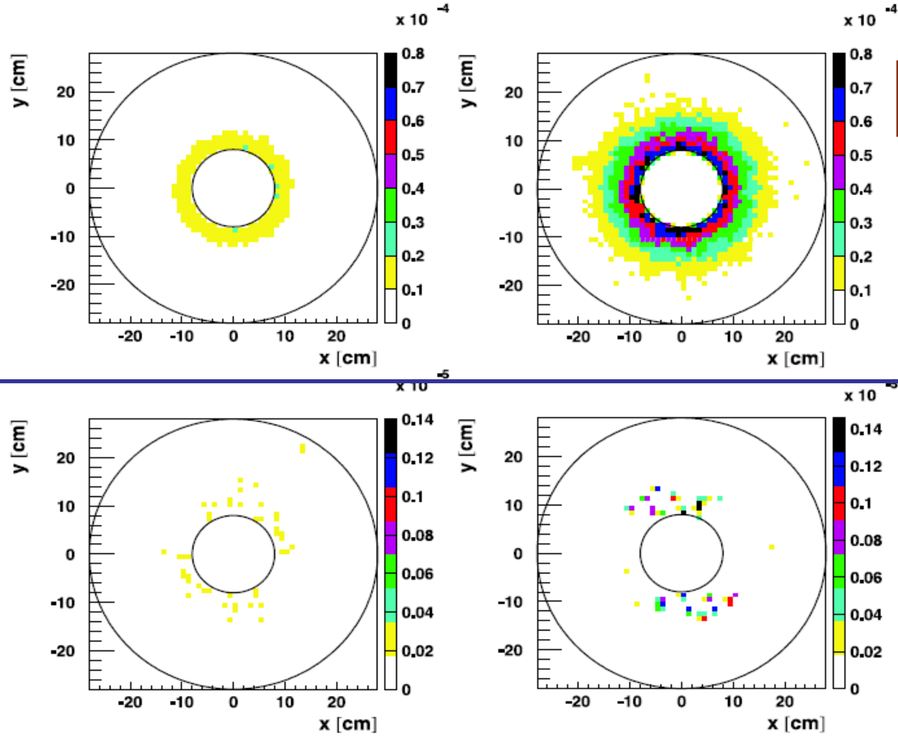
$$E_R - R_L \; < \; 0.1 \times \min(E_R, R_L)$$

Physics Background

- Four-fermion processes are the main background, dominated by two-photon events (bottom right diagram).

BEFORE → AFTER cut

leptonic

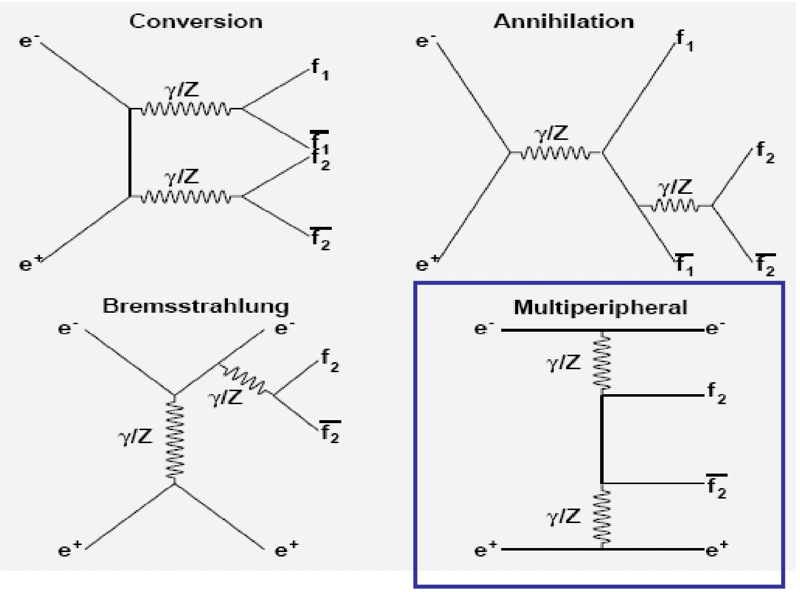


hadronic

The cuts reduce the background to the level of 10^{-4}

Four-fermion processes

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

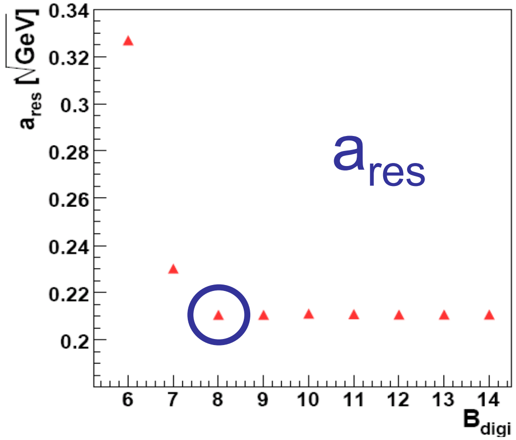


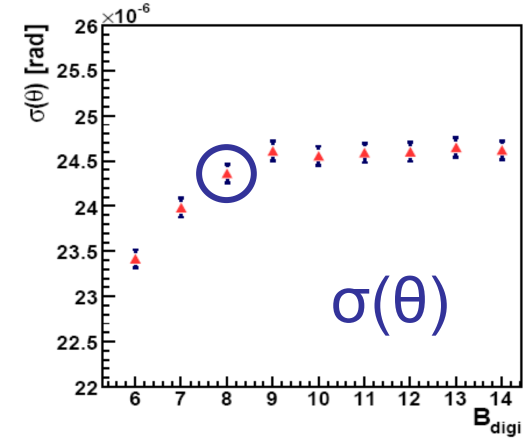
Digitization

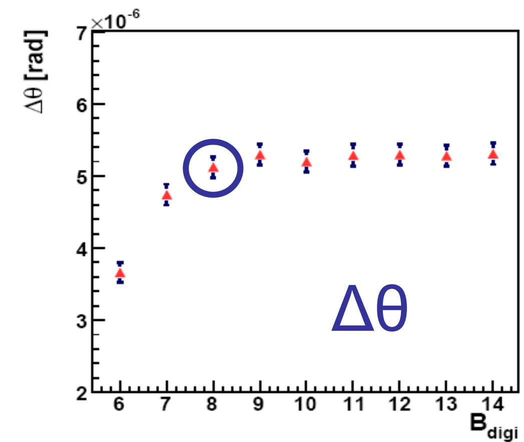
$$\sigma_{\mathrm{ADC}} \equiv q_{min} = \frac{q_{max}}{2^{\mathcal{B}_{digi}}}$$

	Calibration Mode	Physics Mode
q_{min}	0.8 fC (0.2 MIPs)	σ_{ADC}
q_{max}	0.8 fC $\times 2^{\mathcal{B}_{digi}}$	6 pC (1540 MIPs)

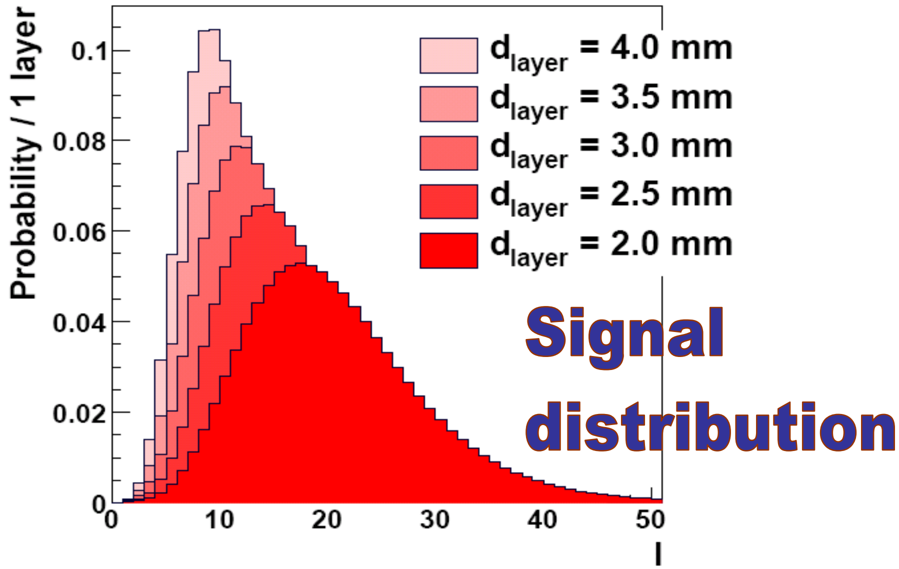
$\mathcal{B}_{digi}$ [bits]	q_{max} of Calibration Mode	q_{min} of Physics Mode
6	49.9 fC (13 MIPs)	93.7 fC (24 MIPs)
8	199.7 fC (52 MIPs)	23.4 fC (6 MIPs)
10	798.7 fC (205 MIPs)	5.9 fC (1.5 MIPs)
12	3.2 pC (819 MIPs)	1.5 fC (0.4 MIPs)
14	12.8 pC (3277 MIPs)	0.4 fC (0.1 MIPs)

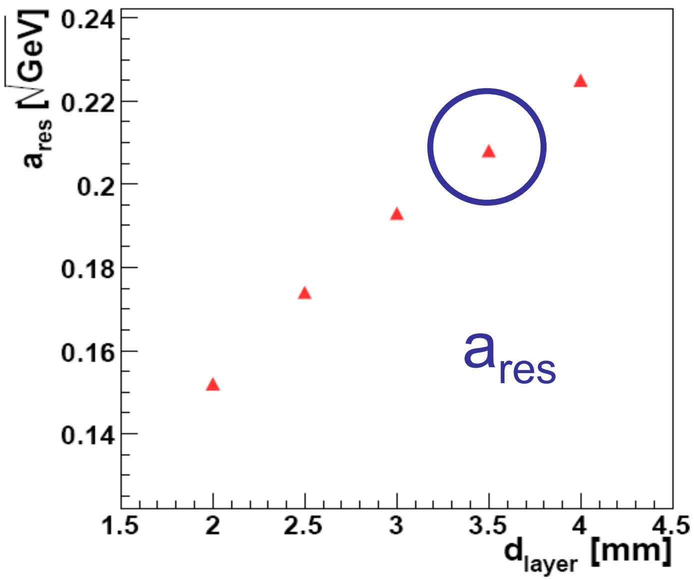


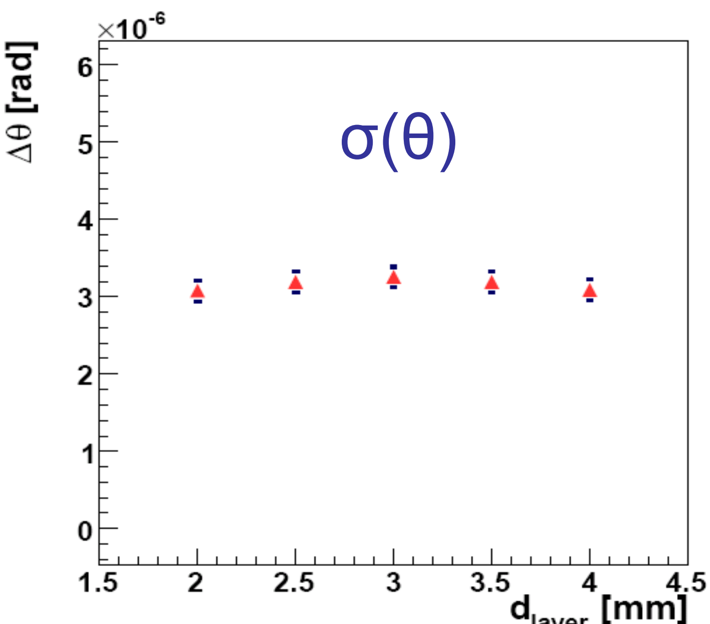


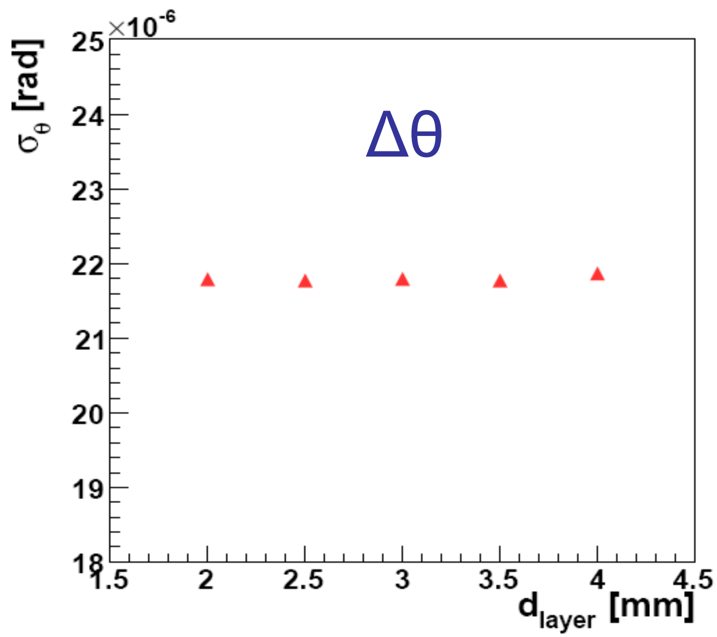


Thickness of the tungsten layers (d_{layer})





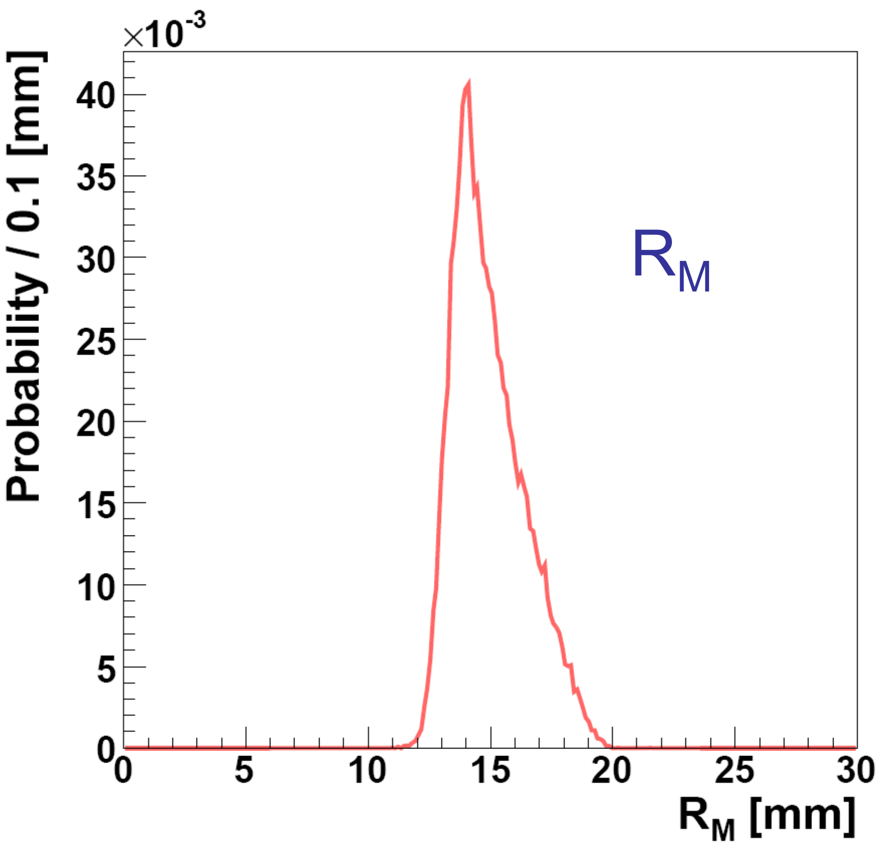


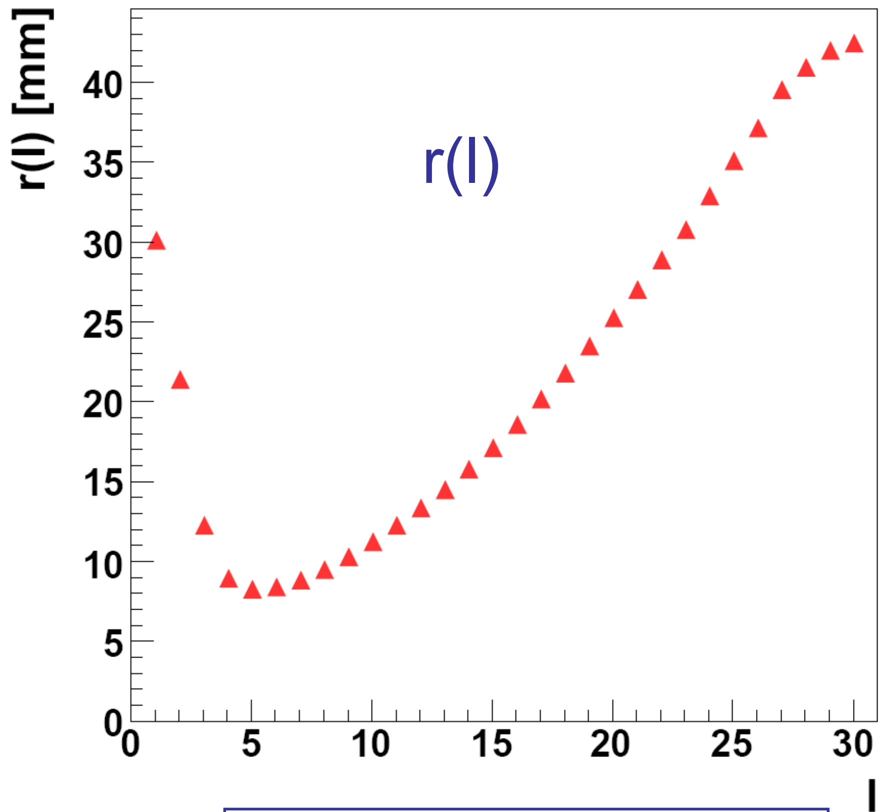


Effective layer-radius, $r_{eff}(l)$ & Moliere Radius, R_M

- Dependence of the layer-radius, r(l), on the layer number, l.

- Distribution of the Moliere radius, R_M.

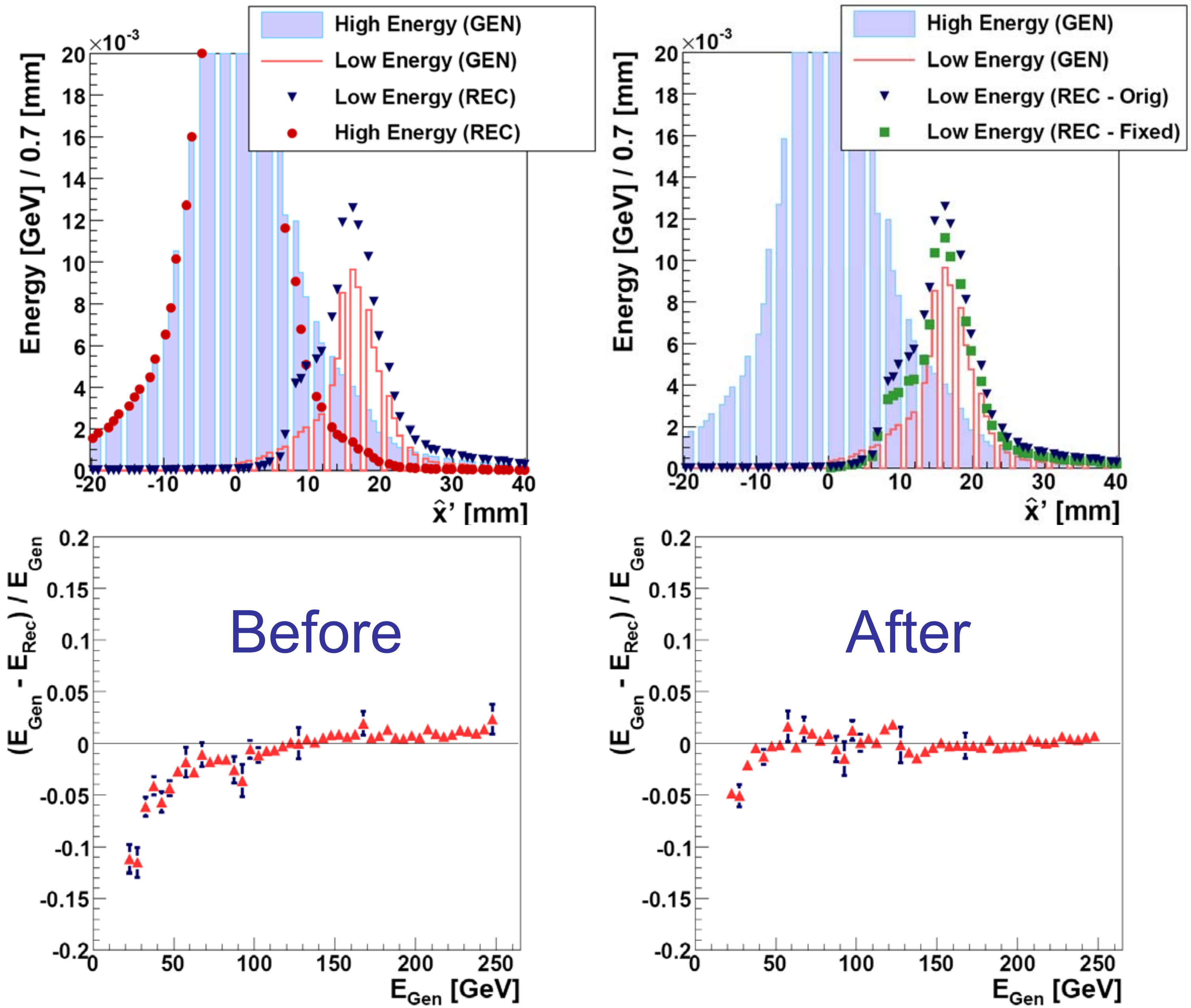




$$r_{eff}(\ell) \equiv r(6 \leq \ell \leq 24)$$
$$\approx 5 + 0.23 \cdot \ell + 0.04 \cdot \ell^2$$

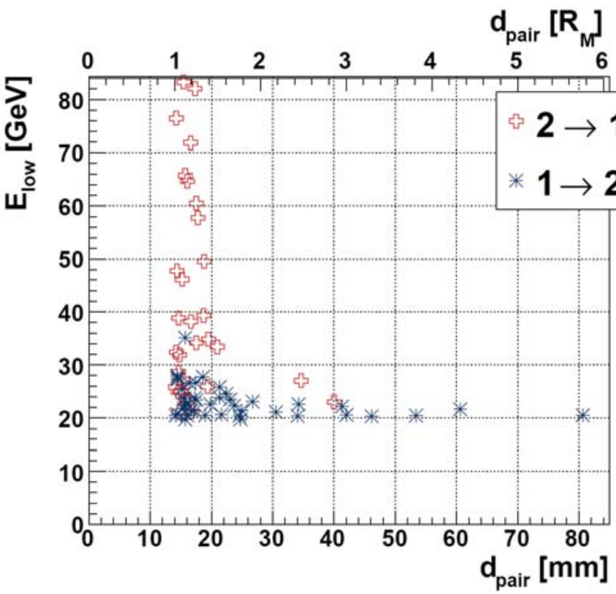
Clustering - Energy density corrections

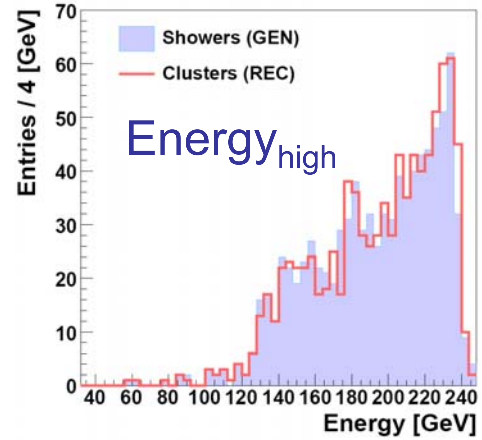
- Event-by-event comparison of the energy of showers (GEN) and clusters (REC).

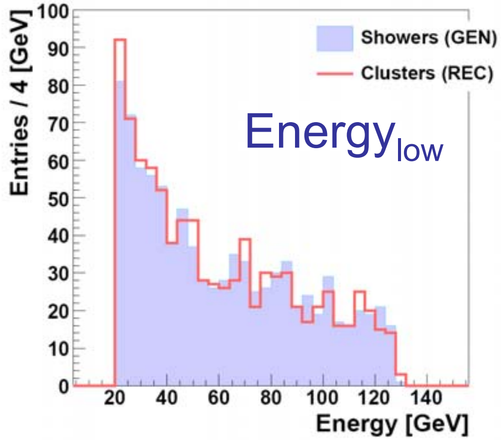


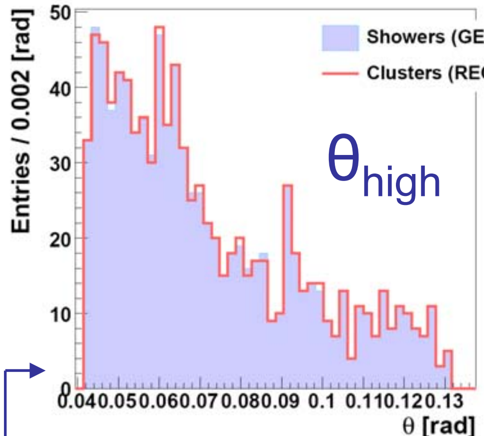
Clustering - Results (measurable distributions)

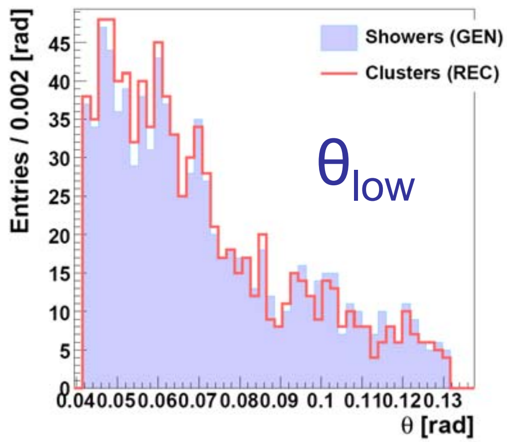
- **Merging-cuts:**
  $E_{low} \geq 20$ GeV , $d_{pair} \geq R_M$

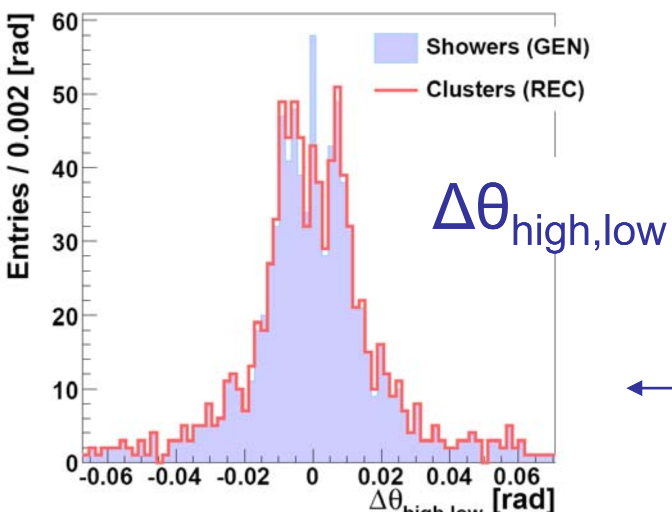








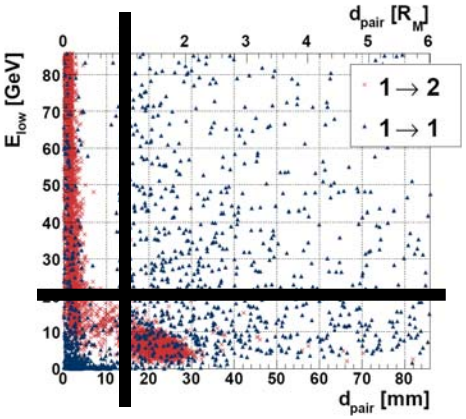


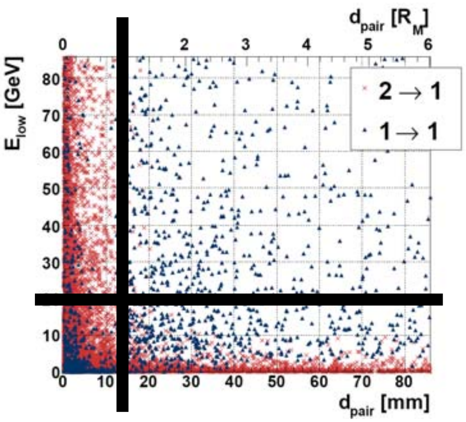


- Energy and polar angle (θ) of high and low-energy clusters/showers.
- Difference in θ between the high and low-energy clusters/showers.

Clustering - Results (relative errors)

- Dependence on the merging-cuts of the errors in counting the number of single showers which were reconstructed as two clusters ($N_{1\to2}$), and the number of showers pairs which were reconstructed as single clusters, ($N_{2\to1}$).





Cuts		$\frac{\Delta N_{1\to2}}{N_{1\to2}}$	$\frac{\Delta N_{2\to1}}{N_{2\to1}}$	$\frac{\Delta N_{tot}}{N_{tot}}$
d_{pair} [$R_{\mathcal{M}}$]	E_{min} [GeV]			
0.5	25	$4.2\cdot10^{-4}$	$31.5\cdot10^{-2}$	$10.3\cdot10^{-5}$
0.75	20	$7.6\cdot10^{-4}$	$14.6\cdot10^{-2}$	$7.5\cdot10^{-5}$
0.75	25	$5.4\cdot10^{-4}$	$14.6\cdot10^{-2}$	$8\cdot10^{-5}$
1	15	$12.9\cdot10^{-4}$	$6.3\cdot10^{-2}$	$5.1\cdot10^{-5}$
1	20	$7\cdot10^{-4}$	$4.6\cdot10^{-2}$	$4.9\cdot10^{-5}$
1	25	$5.1\cdot10^{-4}$	$5.2\cdot10^{-2}$	$5.3\cdot10^{-5}$
1.5	20	$3.2\cdot10^{-4}$	$0.5\cdot10^{-2}$	$1.8\cdot10^{-5}$