Calorimeters of the Very Forward Region

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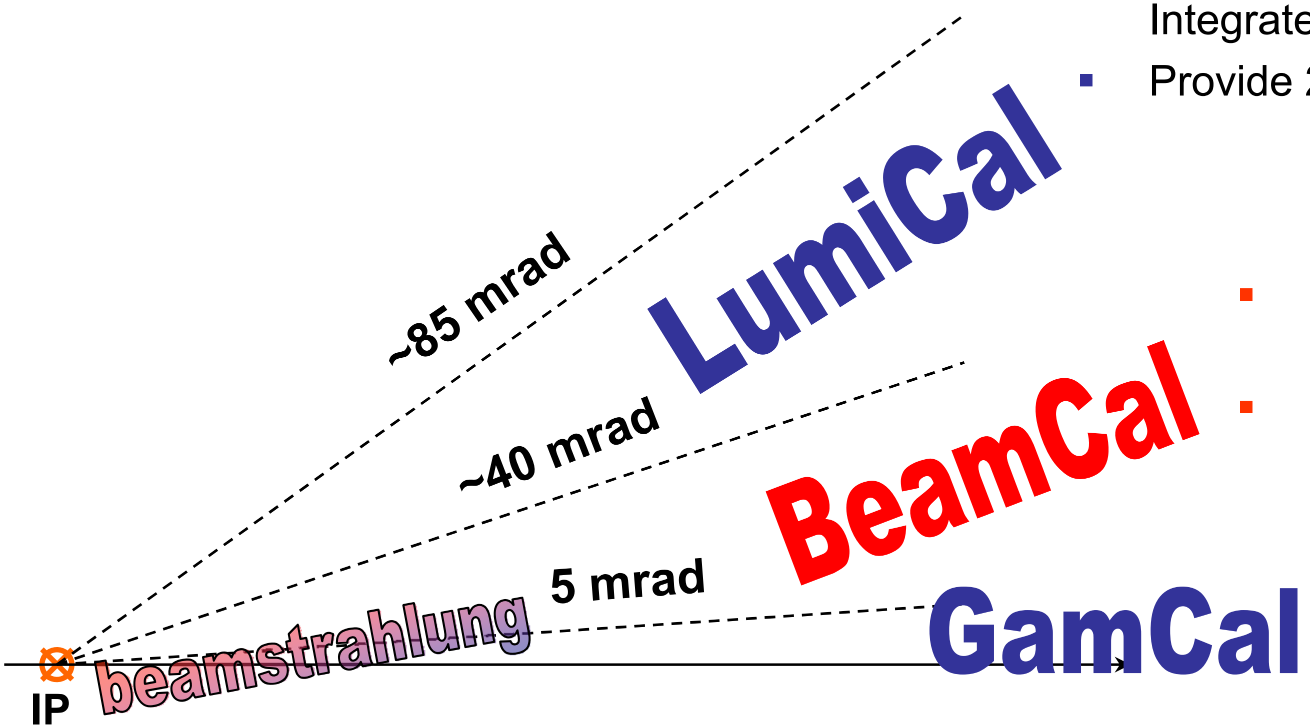
DESY

FCAL Collaboration
High precision design

March 5th 2008

Layout of the Forward Region

ECal and Very Forward Tracker
acceptance region.



~85 mrad

~40 mrad

5 mrad

IP

beamstrahlung

LumiCal

- Precise measurement o the Integrated Luminosity ($\Delta L/L \sim 10^{-4}$).
- Provide 2 photon veto.

BeamCal

- BeamDiagnostics using beamstrahlung pairs.
- Provide 2 photon veto.

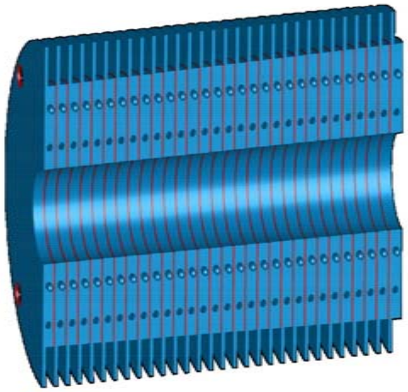
GamCal

- BeamDiagnostics using beamstrahlung photons.

Challenges:
High precision, high occupancy,
high radiation dose, fast read-out!

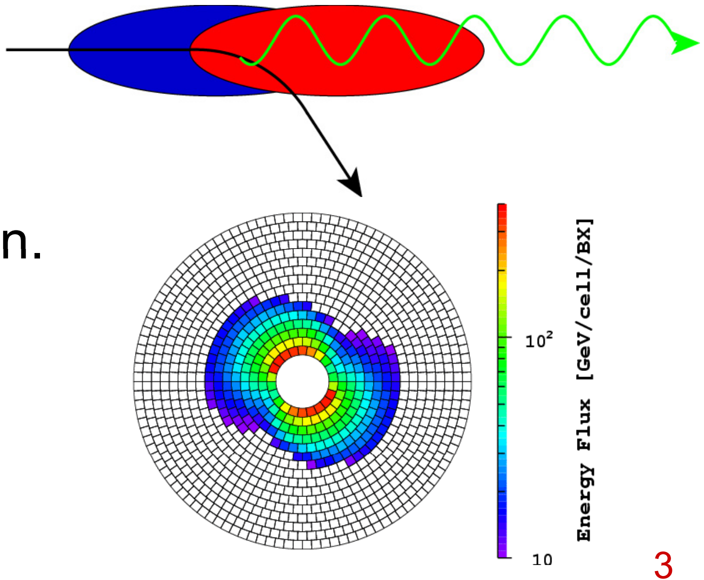
BeamCal: Overview

- **Compact EM calorimeter with sandwich structure**:
  1. 30 layers of 1 X_0 : 3.5 mm W and 0.3 mm sensor.
  2. Angular coverage from ~ [5,40] mrad
  3. Moliére radius (R_M) ~ 1 cm
  4. Segmentation between 0.5 and 0.8 x $R_{M.}$



- **Functionality**:
  1. Provide electron veto.
  2. Perform beam diagnostics for a feedback loop on luminosity optimization.
  3. Shield the inner part of the detector from upstream backscattered particles..

Beamstrahlung



Pair depositions

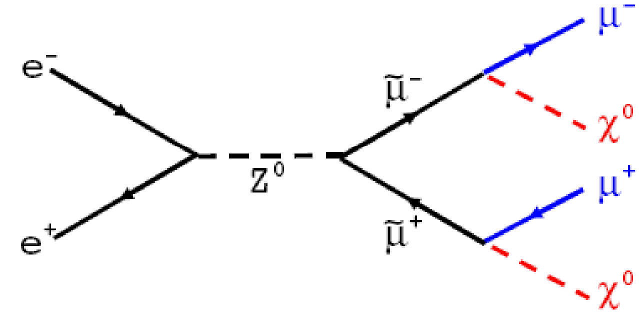
BeamCal: Electron veto

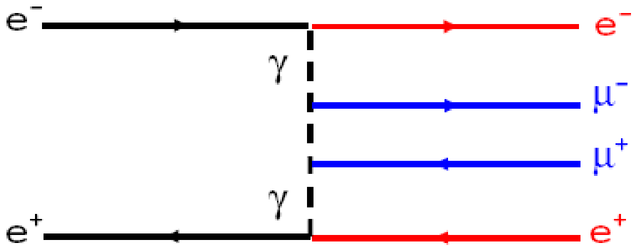
- Two photon events constitute the most serious background for many search channels which are characterized by missing energy and missing momentum.
- **Example**: stau/smuon production:
  1. Large SM background:

     $\gamma^*\gamma^* \rightarrow \tau^+\tau^-$ ($E_t > 4.5$GeV) $\sigma \sim 4.3 \cdot 10^5$ fb
     $\rightarrow \mu^+\mu^-$ ($E_t > 2$GeV) $\sigma \sim 5.2 \cdot 10^6$ fb
     $\rightarrow$ WW

     $e^+e^- \rightarrow \mu^+\mu^-$, $\tau^+\tau^-$ $\sigma \sim 1.0 \cdot 10^3$ fb
     $\rightarrow$ WW
  2. Some cuts based on event topology & kinematics help, but are not enough due to the high background cross-section.
  3. Missing energy (the neutralino (LSP?)).
  4. The difference between SUSY and the SM background is the final state electron.

SUSY

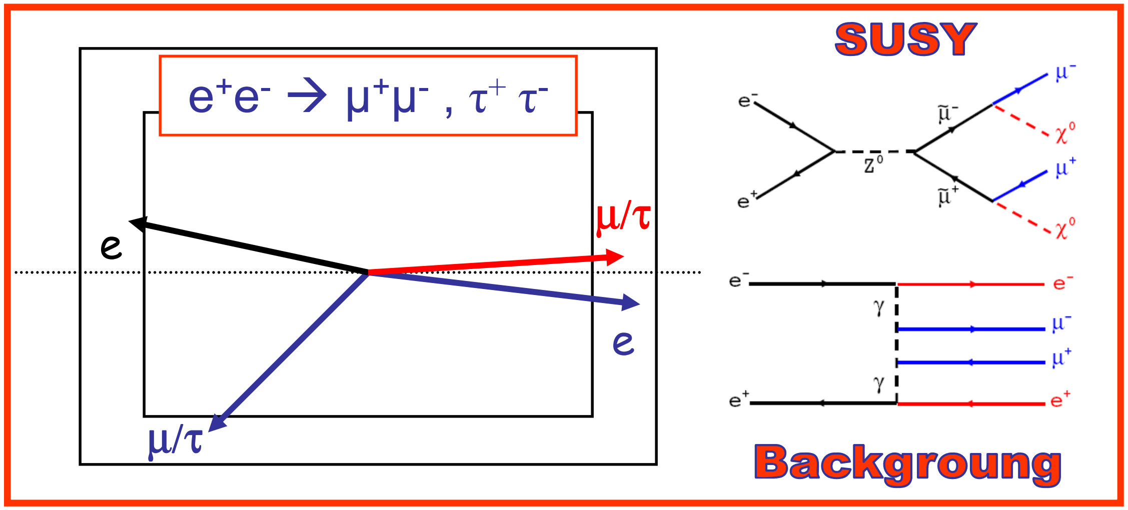


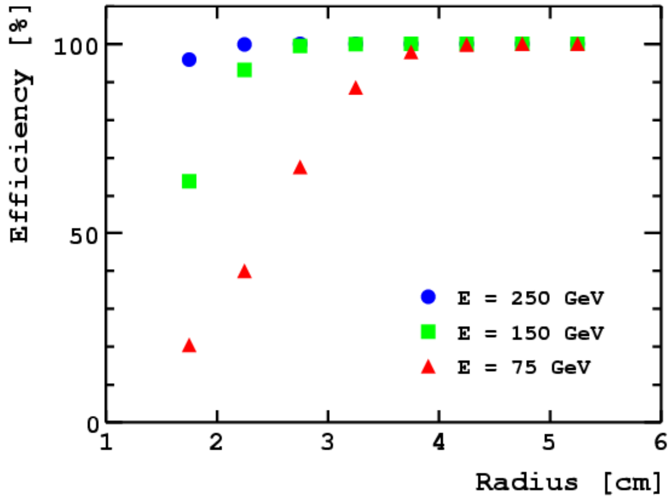


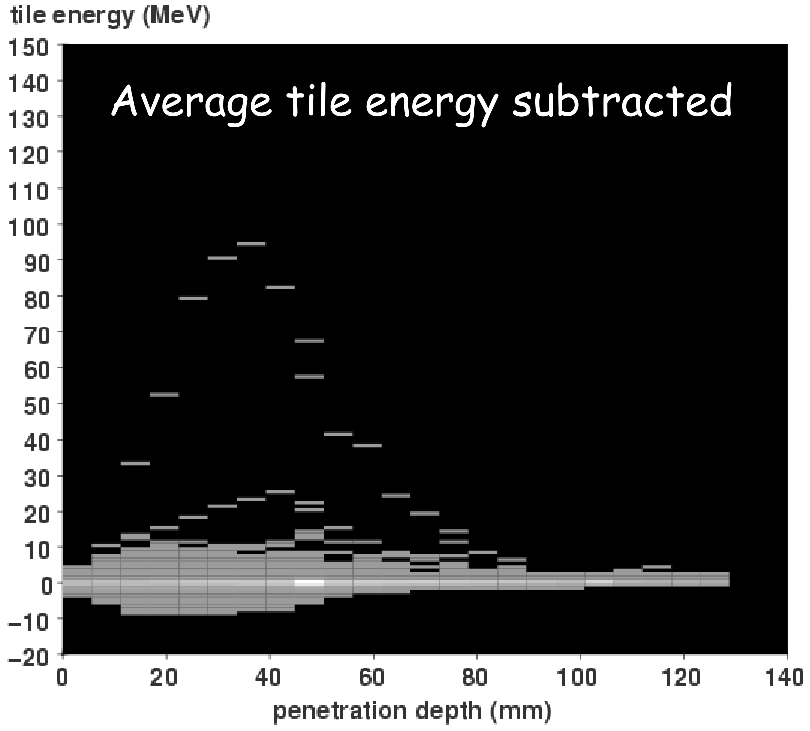
Backgroung

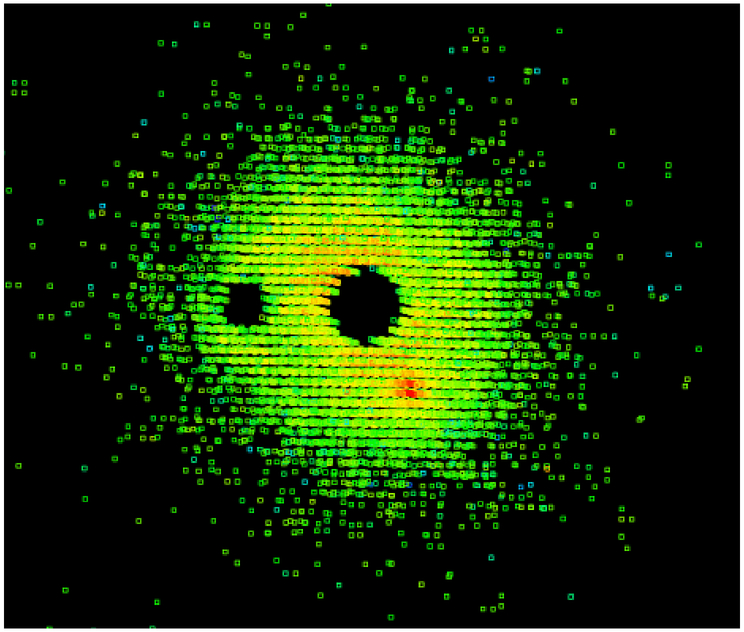
(Talk by Z. Zhang , FCAL Collaboration Meeting , October 2007, http://events.lal.in2p3.fr/conferences/FCAL07/)

BeamCal: Electron veto





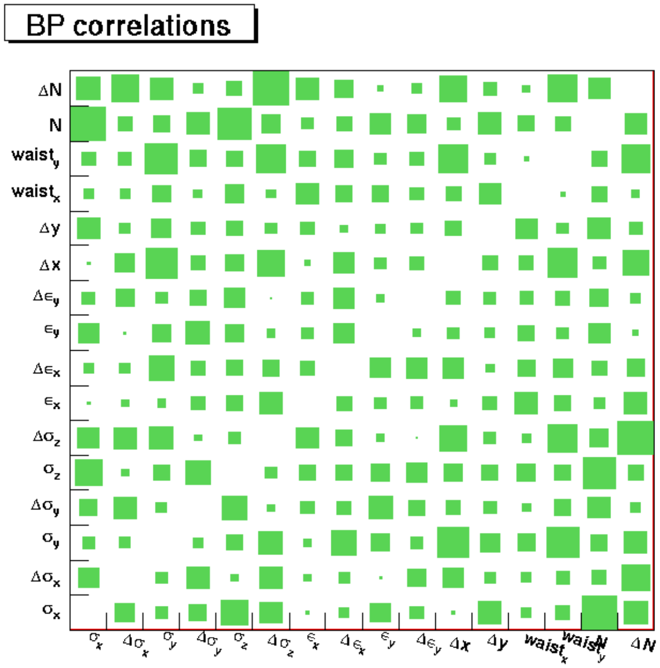




BeamCal: Beam diagnostics

- **Beam parameters:**

  beam sizes (σx, σy and σz)
  emittances (εx and εy)
  offsets (Δx and Δy)
  waist shifts (wx and wy)
  angles and rotation (αh, αv and φ)
  Particles per bunch (Nb)



- **Observables:**

  total energy
  first radial moment
  thrust value
  angular spread
  E(ring ≥ 4) / Etot
  r-φ observables T1, T2
  E / N
  l/r, u/d, f/b asymmetries

Moore Penrose Method

$$\begin{pmatrix}\text{Observables}\end{pmatrix} = \begin{pmatrix}\text{Observables}\end{pmatrix}_{\text{nom}} + \begin{pmatrix}\text{Taylor}\\ \text{Matrix}\end{pmatrix}\begin{pmatrix}\Delta\ \text{BeamPar}^{*}\end{pmatrix}$$

"Diagnostics of Colliding Bunches from Pair Production and Beam Strahlung at the IP"
– Achim Stahl (LC-DET-2005-003)

LumiCal: Performance requirements

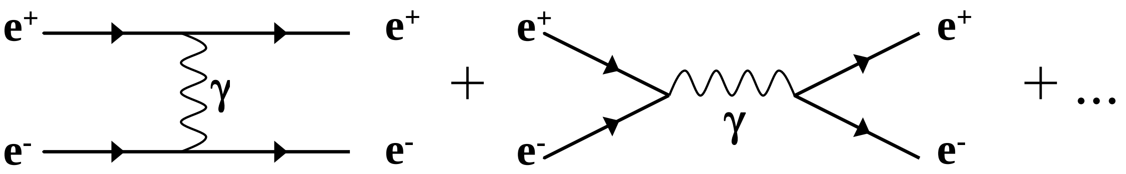
1. Required precision is: $\frac{\Delta L}{L} \sim 10^{-4}$, $\text{GigaZ (hadronic Z decays)} \quad 10^{9}\,/\,\text{year}$

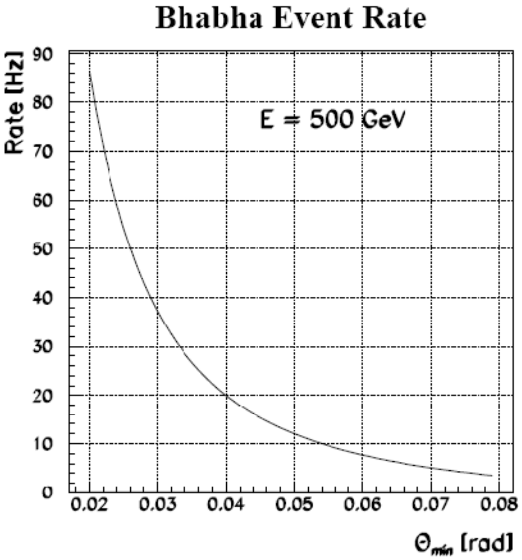
   $\frac{\Delta L}{L} \sim 10^{-3}$, $e^{+}e^{-} \rightarrow W^{+}W^{-} \quad 10^{6}\,/\,\text{year}$

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

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

$$e^{+}e^{-} \rightarrow e^{+}e^{-}(\gamma)$$





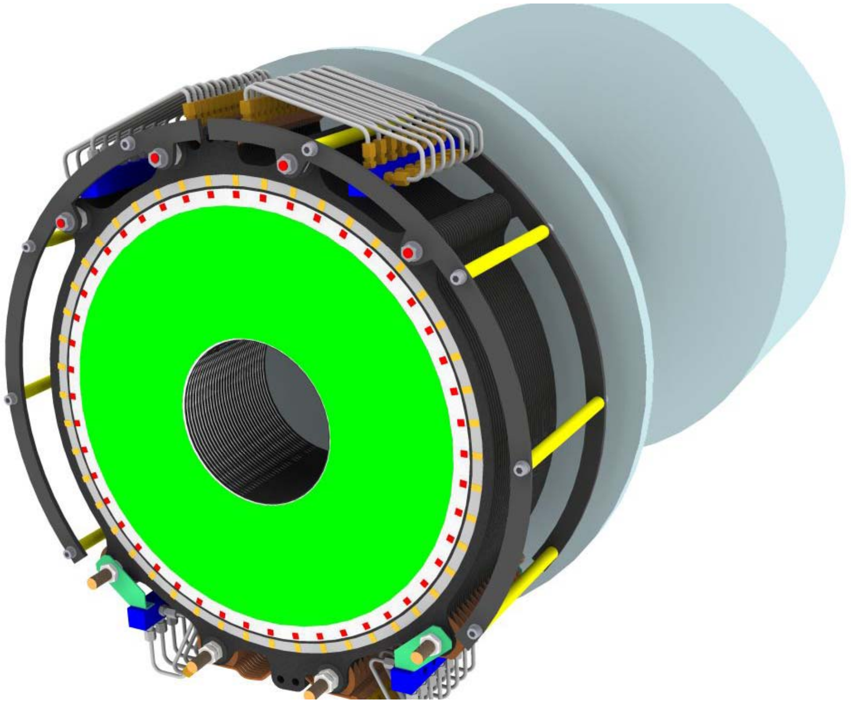
$$N = \frac{L}{\sigma} \qquad \frac{d\sigma_{Bhabha}}{d\theta} \propto \frac{1}{\theta^{3}} \qquad \frac{\Delta L}{L} = \frac{\Delta N}{N} = \left. \frac{N_{rec} - N_{gen}}{N_{gen}} \right|_{\theta_{\min}}^{\theta_{\max}}$$

LumiCal: Design parameters

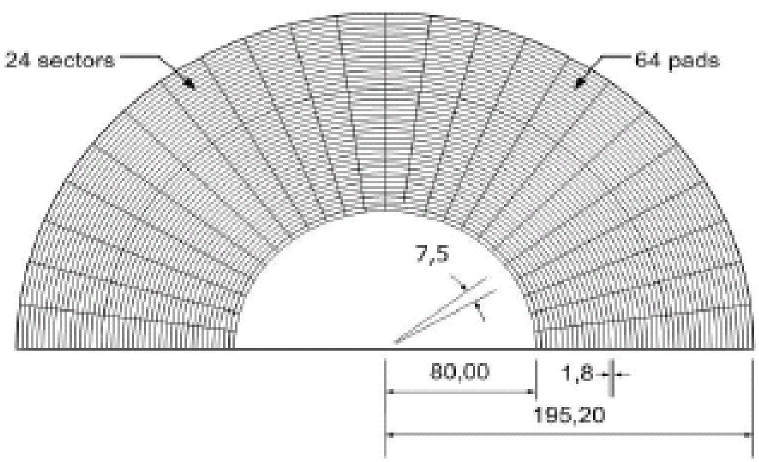
1. **Placement:**
   - 2270 mm from the IP.
   - Inner Radius - 80 mm
   - Outer Radius - 190 mm
2. **Segmentation:**
   - 48 sectors & 64 cylinders:

     Azimuthal Cell Size - 131 mrad

     → Radial Cell Size - 0.8 mrad



Silicon sensor half plane



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

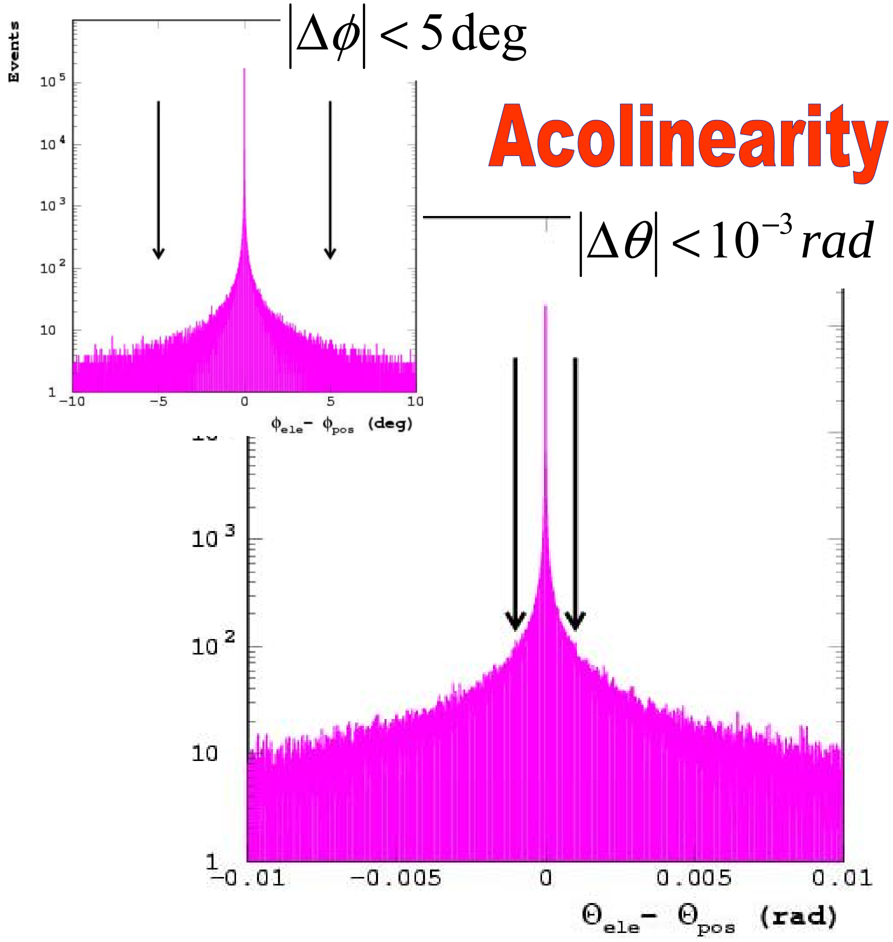
LumiCal: Selection of Bhabha events

Acoplanarity

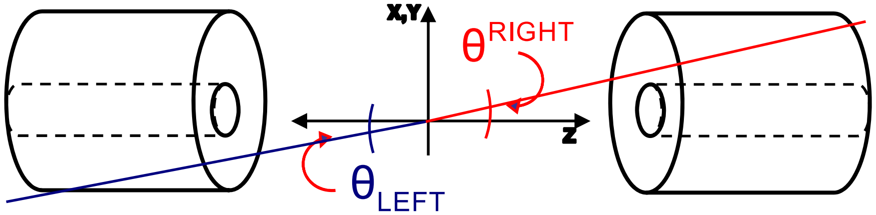
$$|\Delta\phi| < 5\,\mathrm{deg}$$

Acolinearity

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



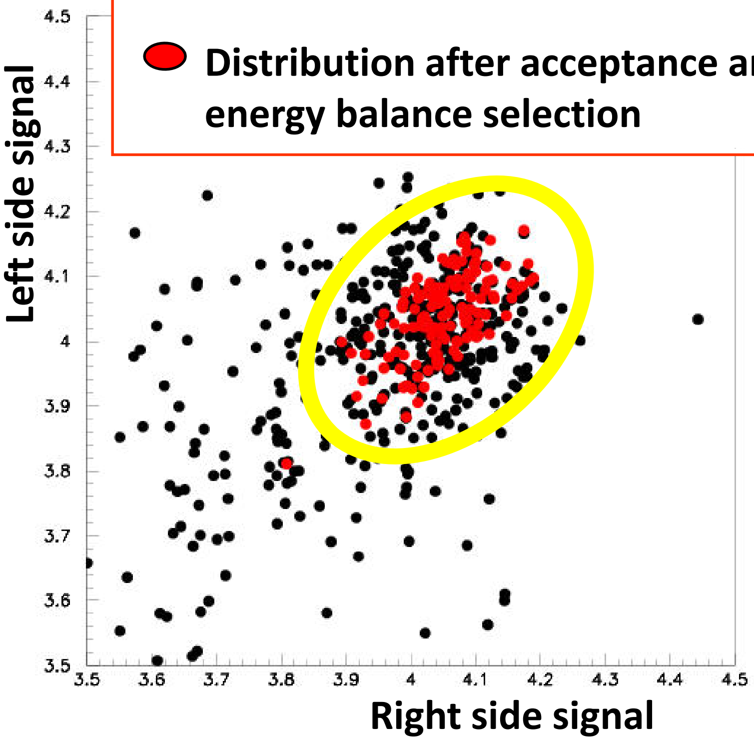
Compare Angles



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

● **Simulation distribution**

● **Distribution after acceptance and energy balance selection**



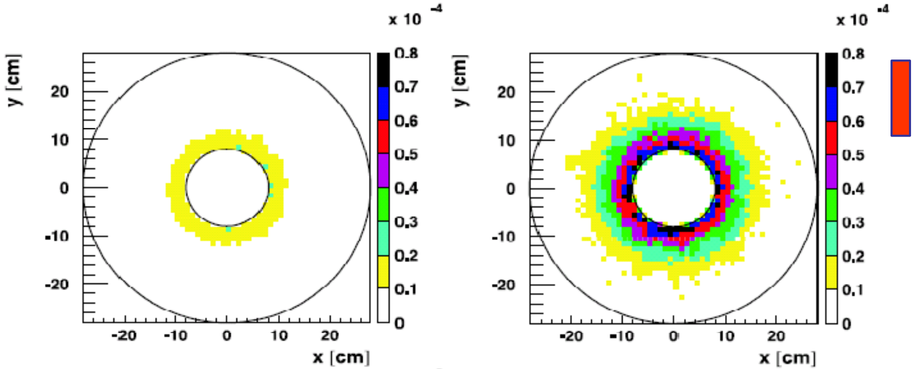
Energy Balance

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

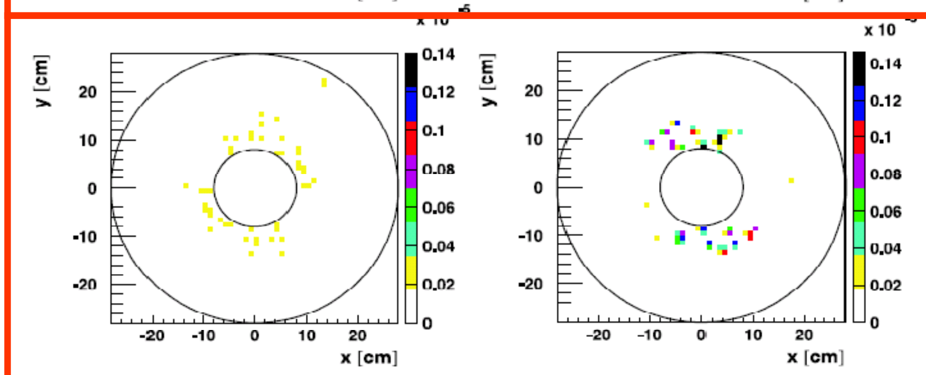
LumiCal: Physics Background

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

BEFORE ⇨ AFTER cut



leptonic

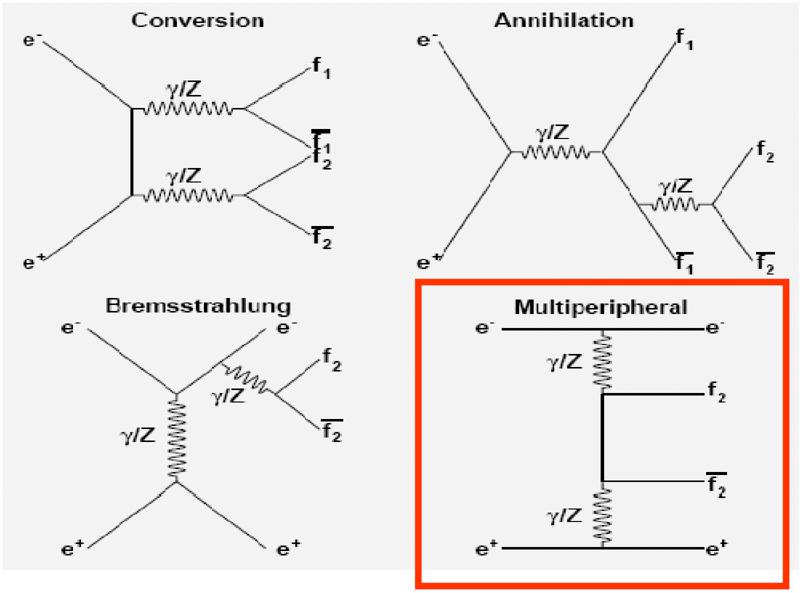


hadronic

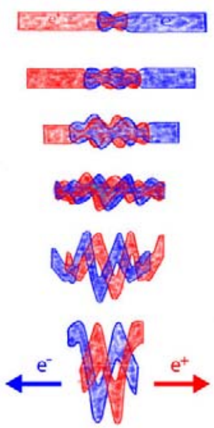
The cuts reduce the background to the level of 10^{-4}

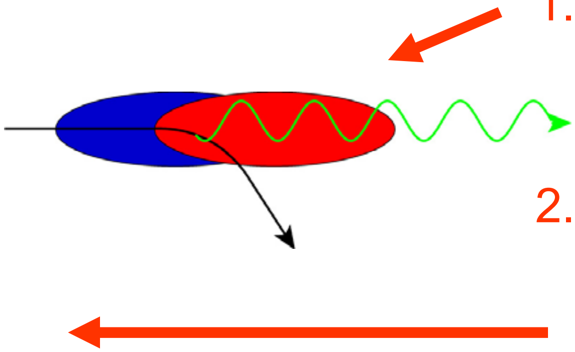
Four-fermion processes

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

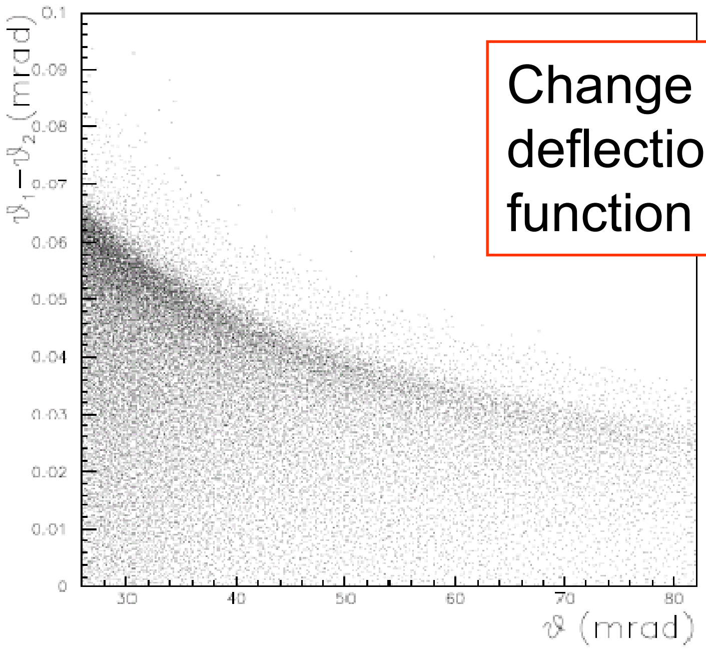


LumiCal: Beam-Beam effects at the ILC





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.



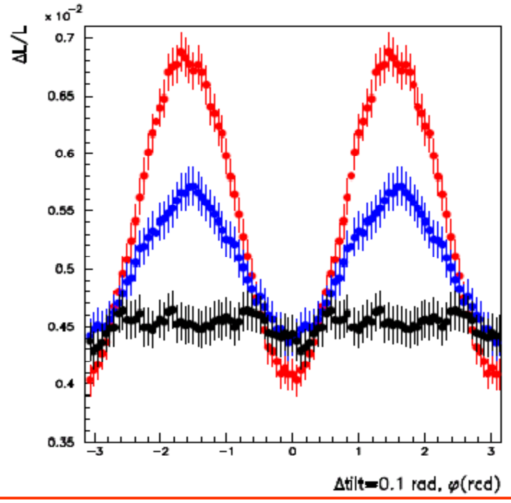
Change in the final state polar angle due to deflection by the opposite bunch, as a function of the polar angle at production.

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

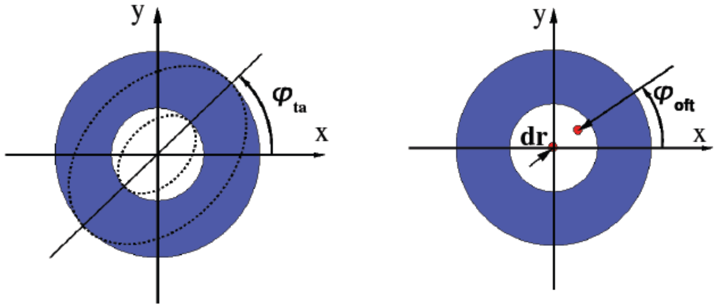
“Impact of beam-beam effects on precision luminosity measurements at the ILC”

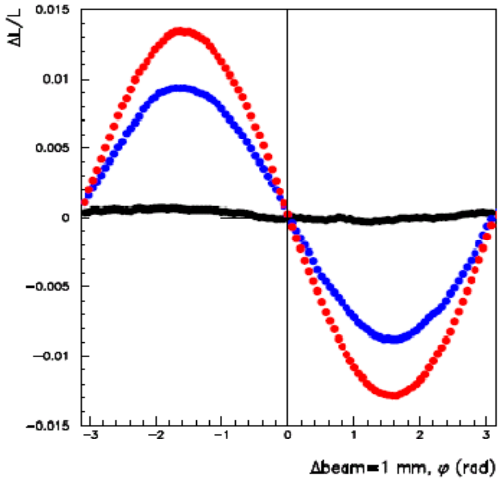
– C. Rimbault et al. (http://www.iop.org/EJ/abstract/1748-0221/2/09/P09001/)

LumiCal: Systematic Effects – Placement

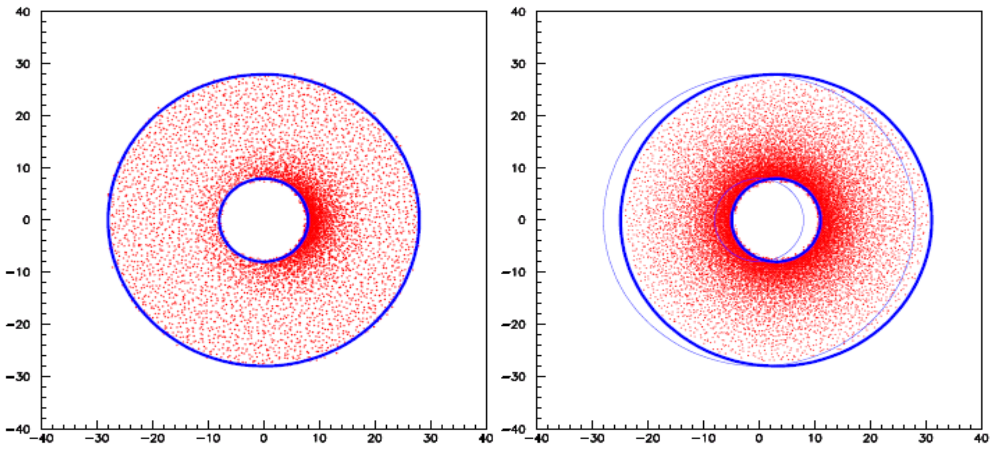


Radial beam axis tilts/shifts





- ● **Headon**, 14,20 mrad X-angle outgoing beam
- ● **14 mrad** X-angle detector axis
- ● **20 mrad** X-angle detector axis

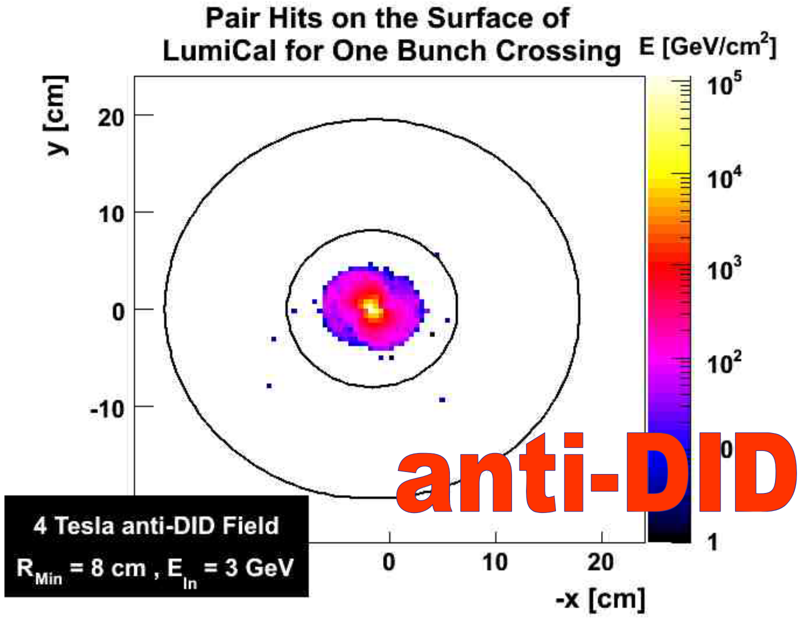


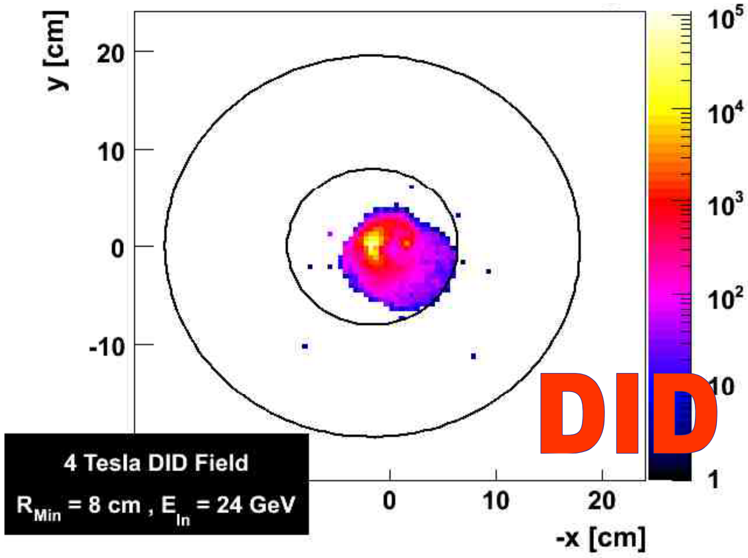
Detector axis **Outgoing beam**

- Small tilts/shifts cause large φ-dependant errors in the Luminosity measurement.
- Azimuthal symmetry is lost when LumiCal is placed along the detector axis

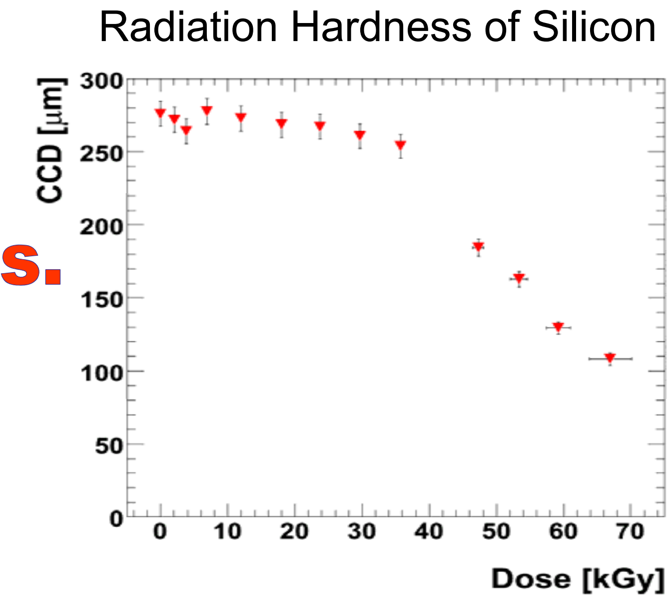
→ Choose the **outgoing beam** option.

LumiCal: Machine background (Magnetic Field)



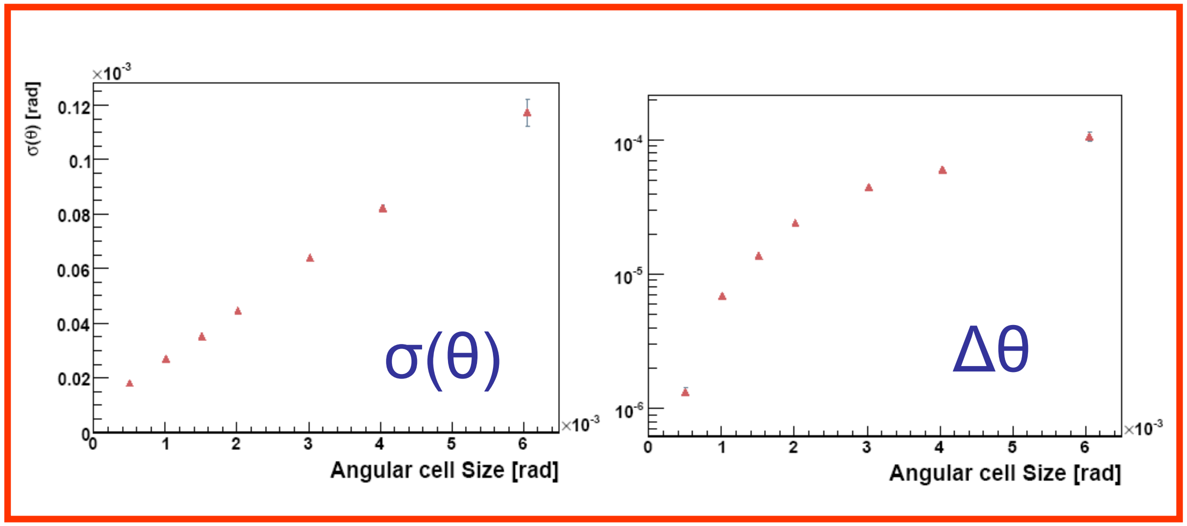


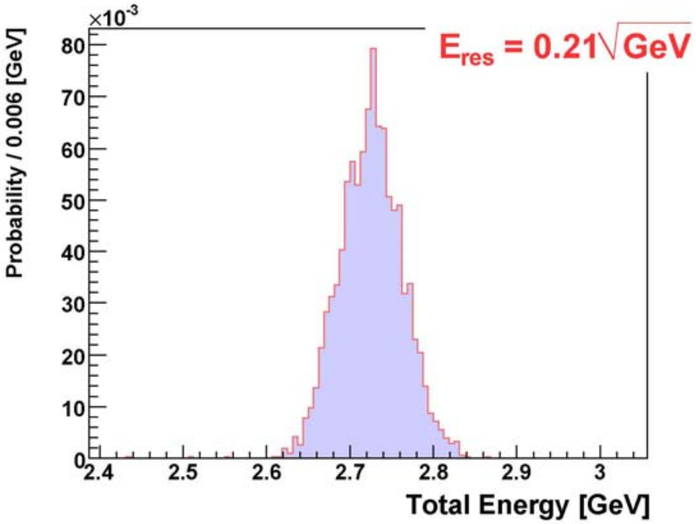
CCD vs. Dose



- Negative effect of grazing LumiCal with the pair distribution:
  1. Radiation damage to the silicon sensors ~O(MGy/year).
  2. Detrimental to the Luminosity measurement.
  3. Backscattering to the inner part of the detector.

LumiCal: Detector Performance





Cell size [mrad]	# Radial divisions	σ(θ) [mrad]	Δθ [mrad]	$2\cdot\Delta\theta/\theta_{min}$
0.5	96	$1.8 \cdot 10^{-2}$	$1.3 \cdot 10^{-3}$	$0.6 \cdot 10^{-4}$
0.8	64	$2.3 \cdot 10^{-2}$	$3.4 \cdot 10^{-3}$	$1.7 \cdot 10^{-4}$
1	48	$2.7 \cdot 10^{-2}$	$6.9 \cdot 10^{-3}$	$3.1 \cdot 10^{-4}$
1.5	32	$3.5 \cdot 10^{-2}$	$13.7 \cdot 10^{-3}$	$6.2 \cdot 10^{-4}$
2	24	$4.4 \cdot 10^{-2}$	$24 \cdot 10^{-3}$	$10.9 \cdot 10^{-4}$

$$\frac{\Delta L}{L} \approx \frac{2\Delta\theta}{\theta_{\min}}$$

$$\sqrt{s} = 500\,\mathrm{GeV}$$

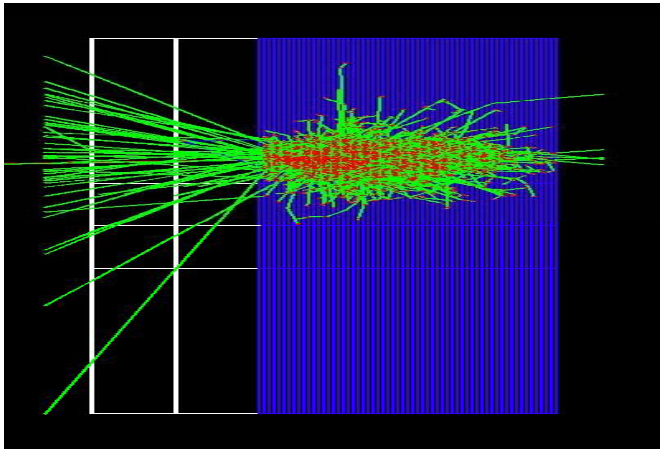
$$L = 500\,\mathrm{fb}^{-1}$$

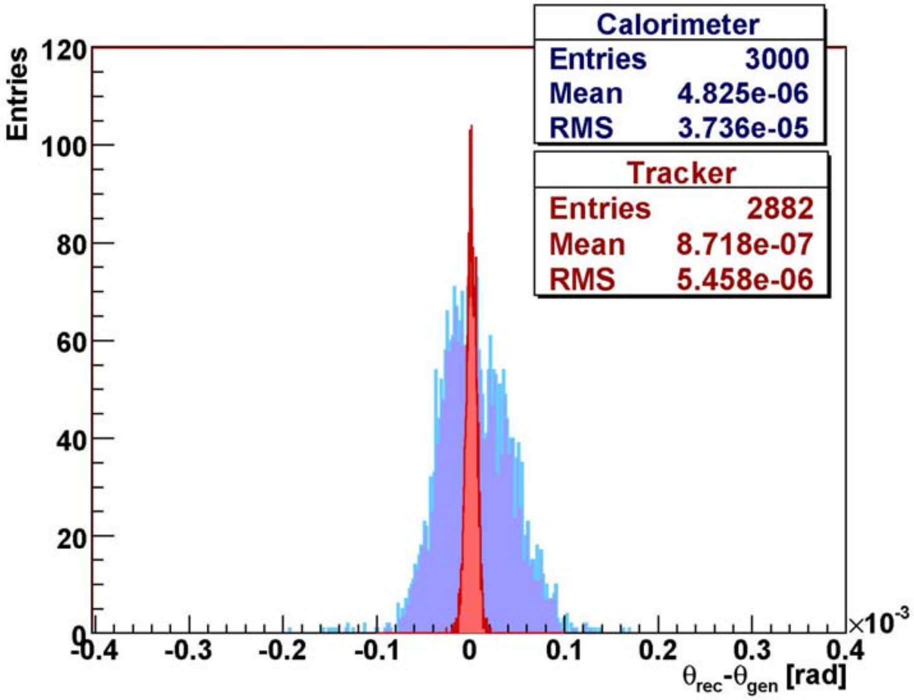
$$\sigma = 1.23\,\mathrm{nb}$$

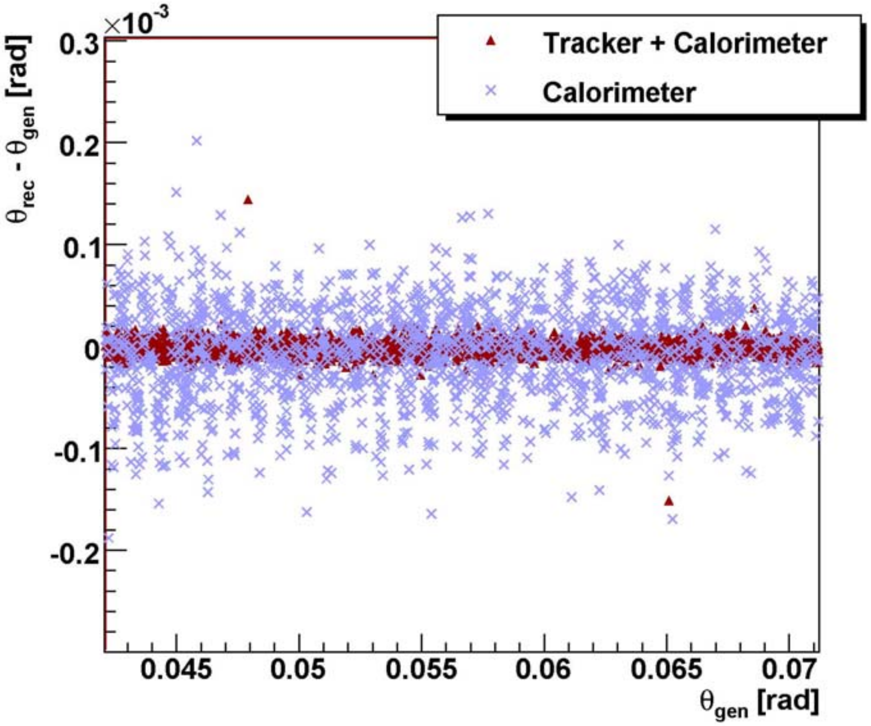
$$\frac{\Delta N}{N} = 4 \cdot 10^{-5}$$

LumiCal: Silicon Tracker

- **Tracker parameters** (still being optimized…): 2 silicon layers, 5 cm gap between layers, 0.3 mm silicon thickness, 1000 azimuthal divisions , 1600 radial divisions.
- Use Tracker information to correct the Calorimeter reconstruction of the polar angle, θ.







LumiCal: MIP (muon) Detection

- Many physics studies demand the ability to detect muons (or the lack thereof) in the Forward Region.
- **Example**: Discrimination between super-symmetry (SUSY) and the universal extra dimensions (UED) theories may be done by measuring the smuon-pair production process. The observable in the figure, $\boldsymbol{\theta_\mu}$, denotes the scattering angle of the two final state muons.

UED:

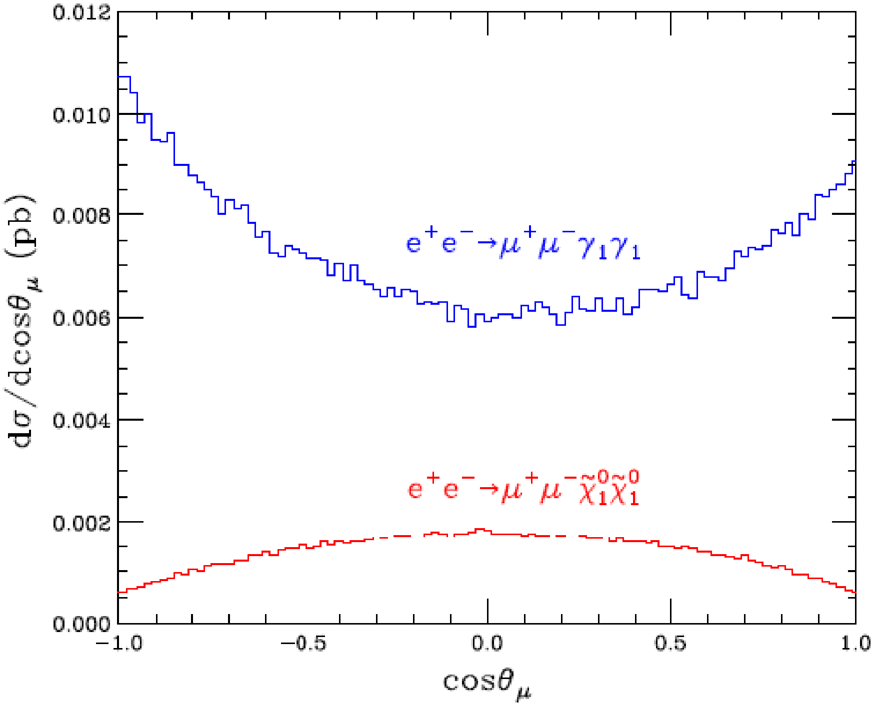
$$e^+ e^- \to \mu_1^+ \mu_1^- \to \mu^+ \mu^- \gamma_1 \gamma_1$$

$$\frac{d\sigma}{d\cos\theta} \sim 1 + \cos^2\theta$$

SUSY:

$$e^+ e^- \to \tilde{\mu}^+ \tilde{\mu}^- \to \mu^+ \mu^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$$

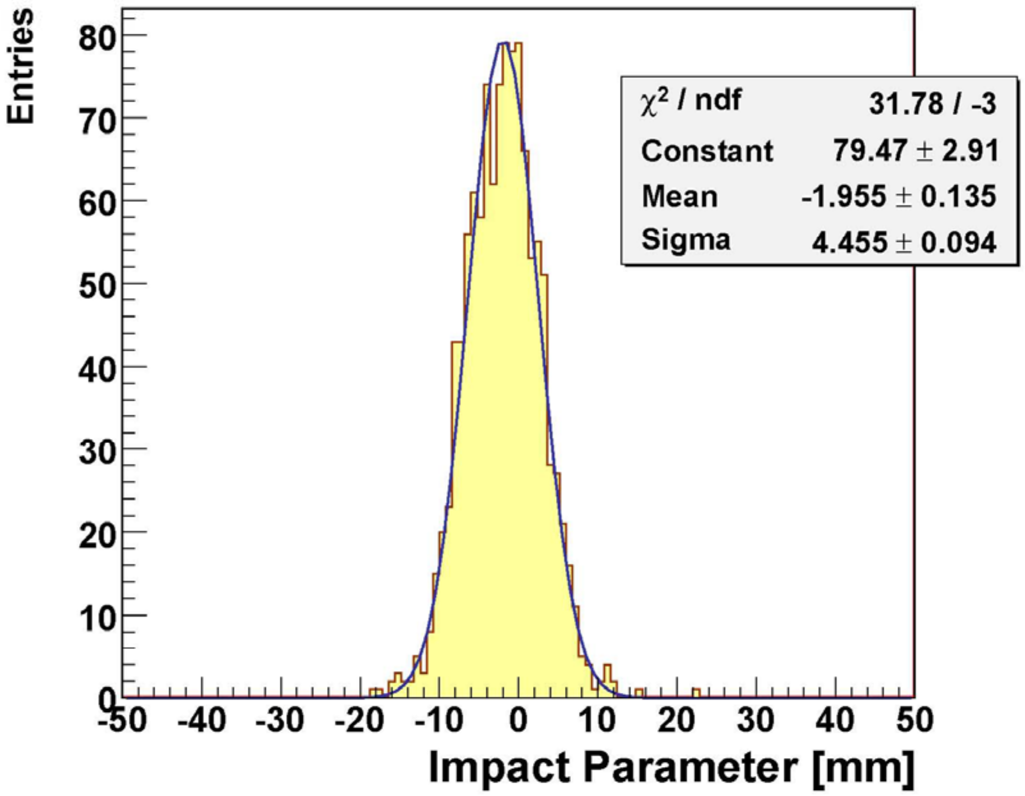
$$\frac{d\sigma}{d\cos\theta} \sim 1 - \cos^2\theta$$



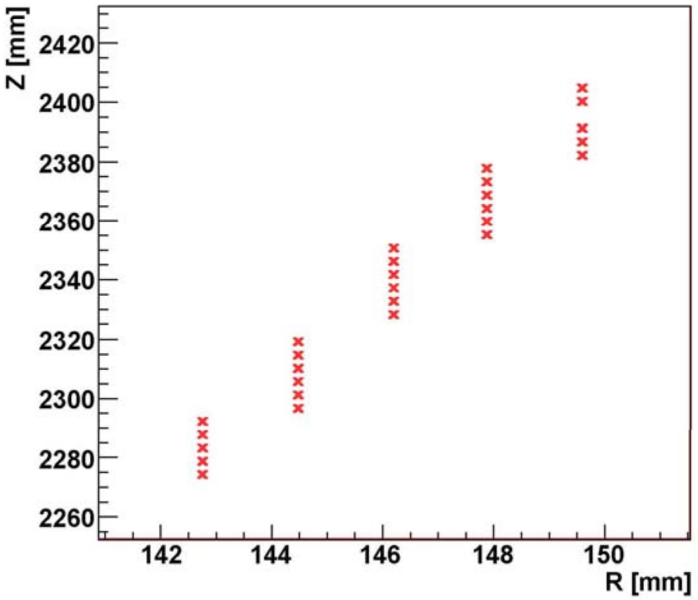
“Contrasting Supersymmetry and Universal Extra Dimensions at Colliders”
– M. Battaglia et al. (http://arxiv.org/pdf/hep-ph/0507284)

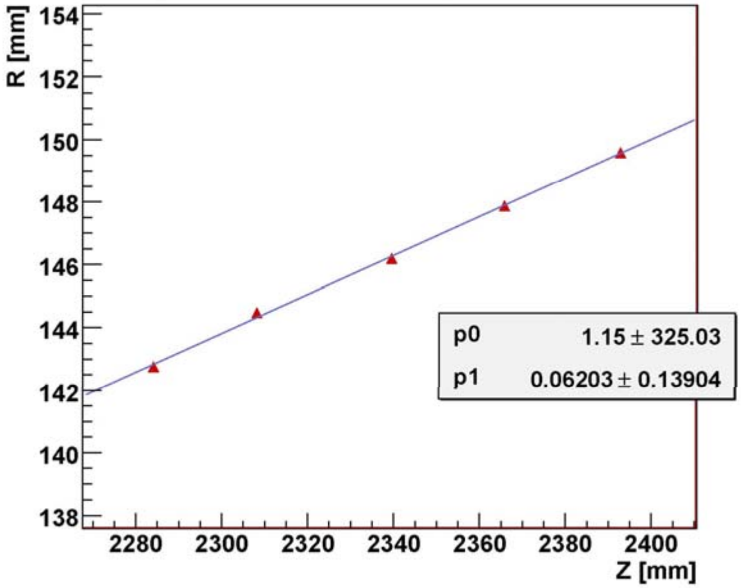
LumiCal: MIP (muon) Detection

- Multiple hits for the same radius (non-zero cell size).
- After averaging and fitting, an extrapolation to the IP (z = 0) can be made.



Extrapolation of a muon track to the IP

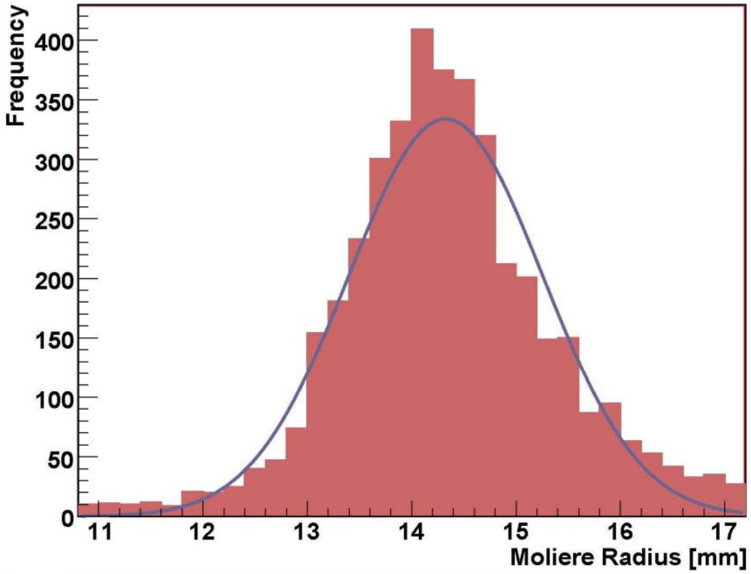




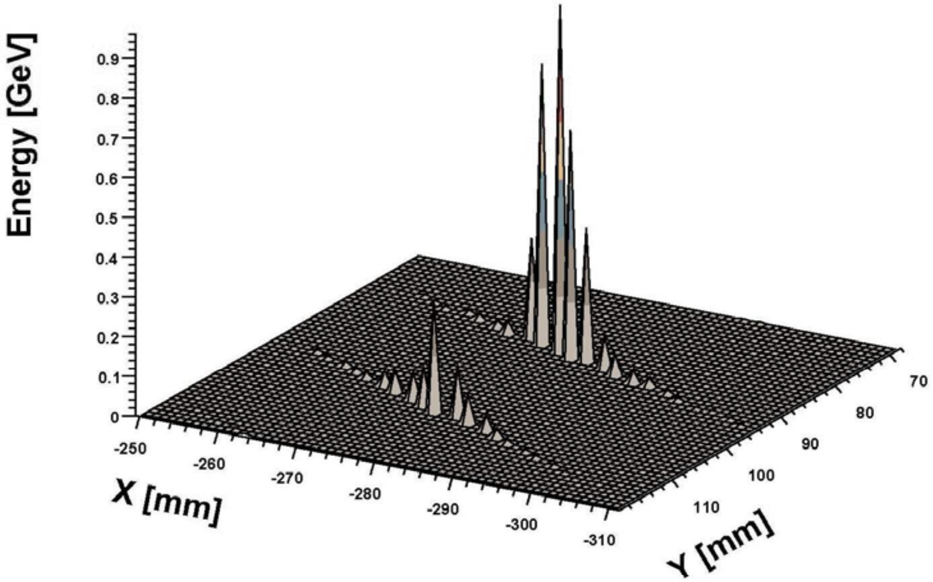
R(Z) - Energy-averaged Z position

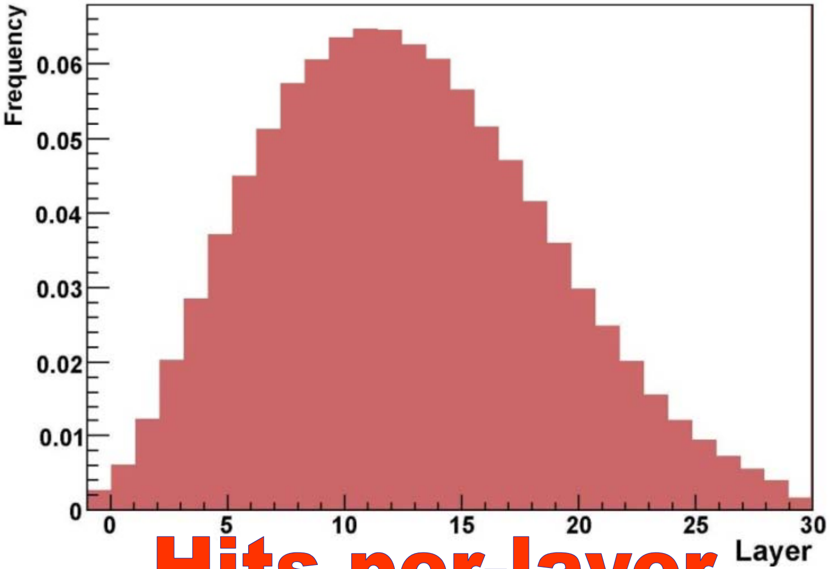
LumiCal: EM Shower Properties

Moliere radius

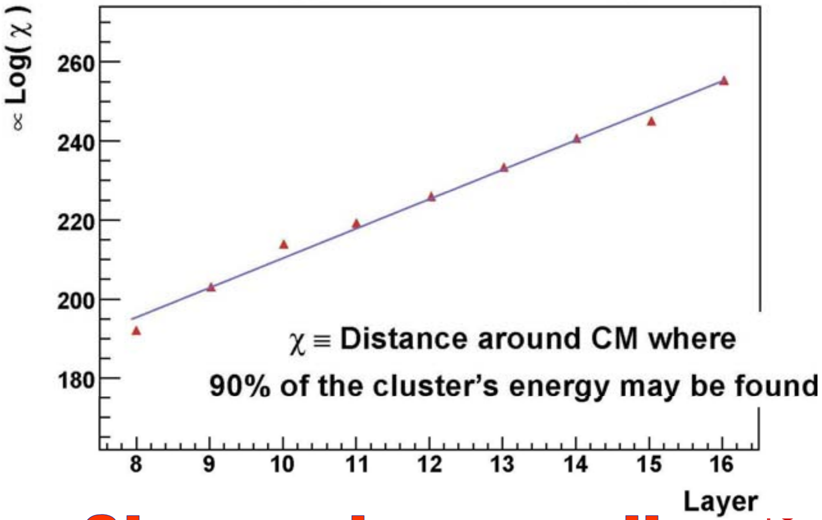


Double-shower energy profile





Hits per-layer



χ ≡ Distance around CM where 90% of the cluster's energy may be found

Shower layer-radius

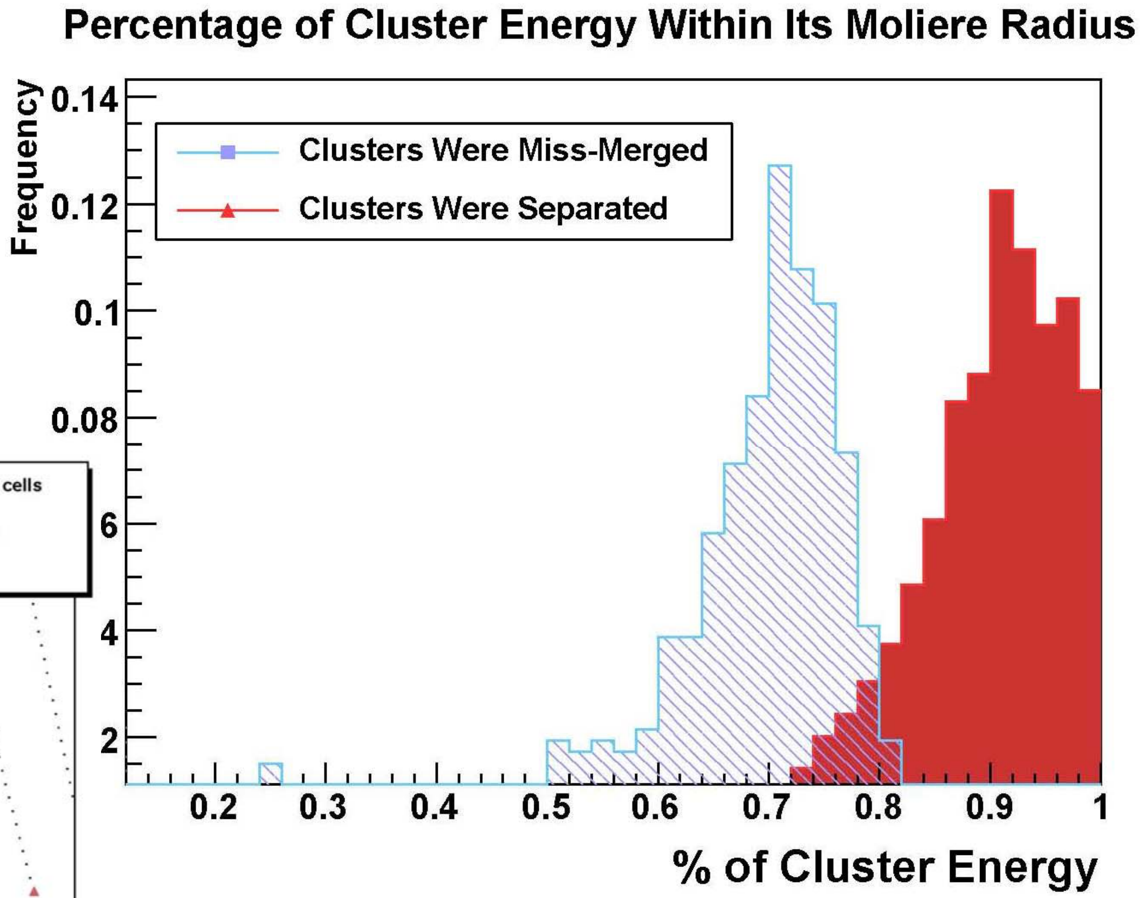
LumiCal: Bhabha reconstruction - Clustering

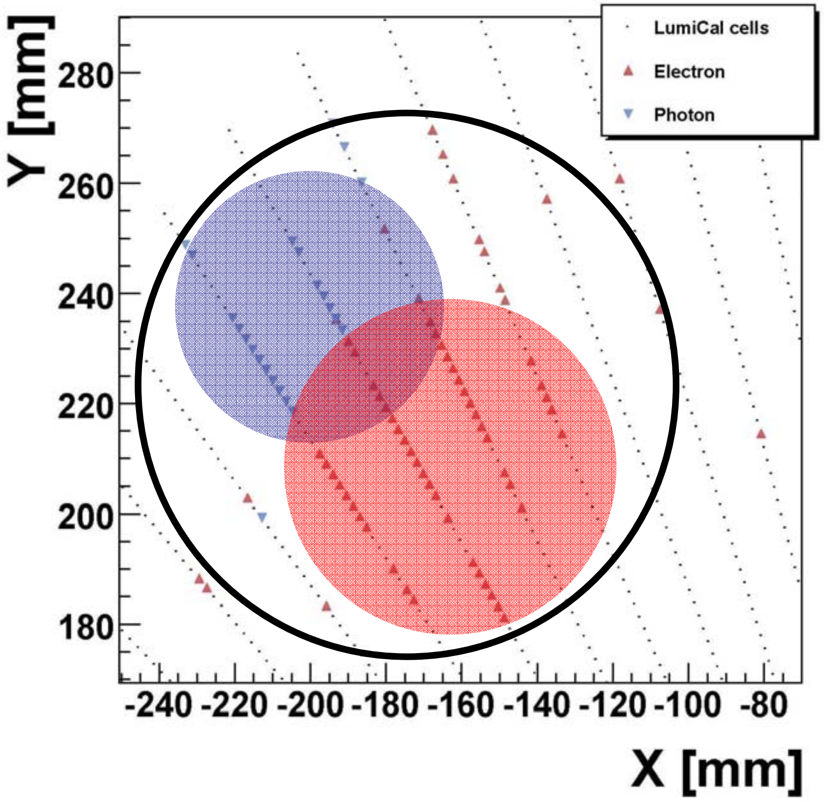
1. Perform initial 2D clustering in shower-peak layers.
2. Extrapolate “virtual cluster” CMs in non shower-peak layers, and build real clusters accordingly.
3. Build (global) 3D “super clusters” from all 2D layer clusters.
4. Check cluster properties (e.g. percentage of energy within a Molière Radius), and (attempt to) re-cluster if needed.
5. Correct cluster-energy distributions.

- Events were generated with **BHWIDE**(1.04) and simulated by **Mokka**(v06-05-p02) using **Geant4**(v4-09-00-patch-01). The super-driver LumiCalX of the LDC(00-03Rp) model was used to build LumiCal in Mokka.
- The clustering algorithm was written as a Marlin processor, using **Marlin**(v00-09-08).

LumiCal: Clustering - Molière Radius corrections

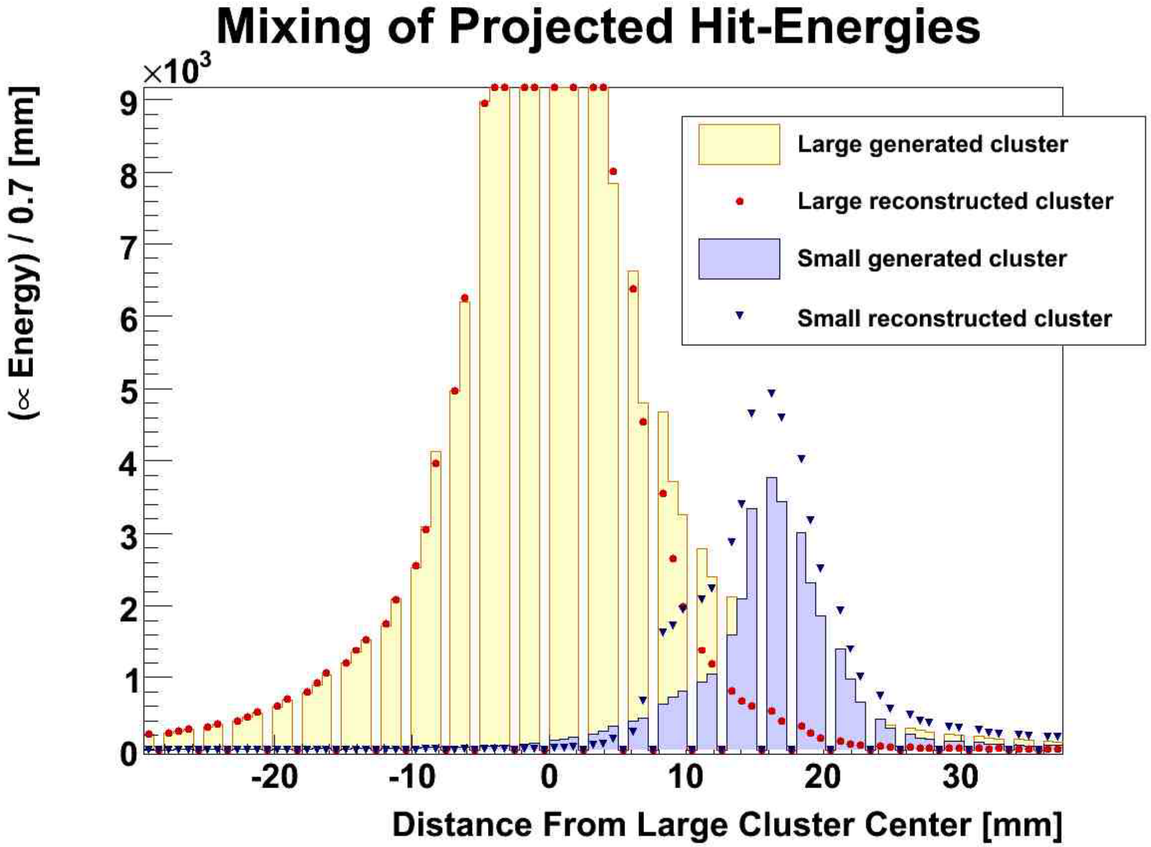
- Inside a cluster’s Molière radius should be found ~90% of the cluster’s total energy.

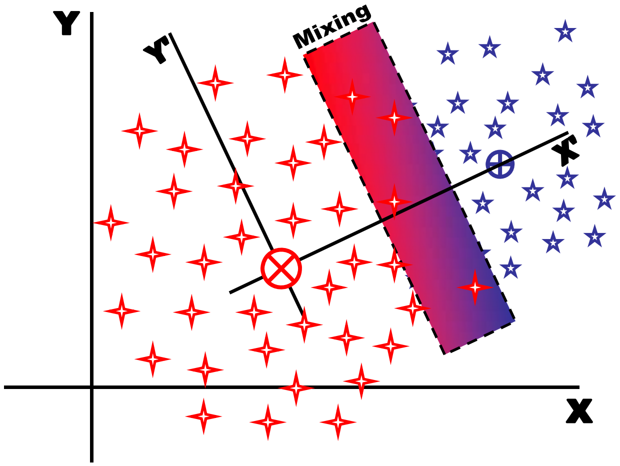


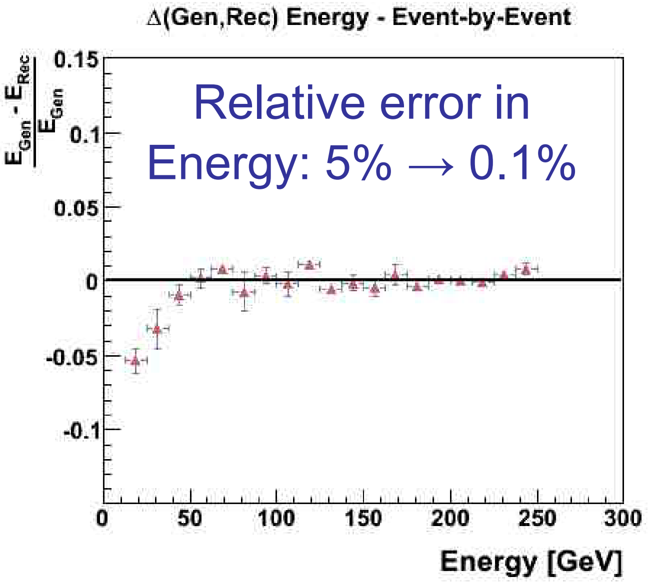


- Two clusters (blue & red full circle) are merged by mistake (black hallow circle).

LumiCal: Clustering – Energy Corrections





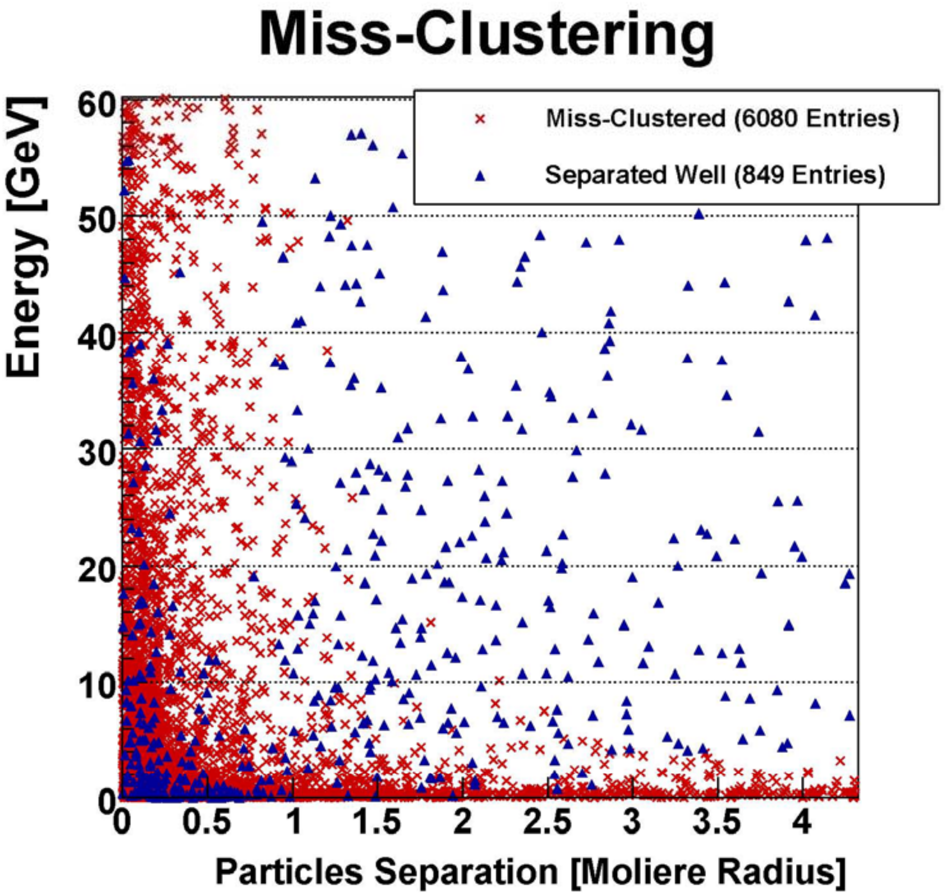


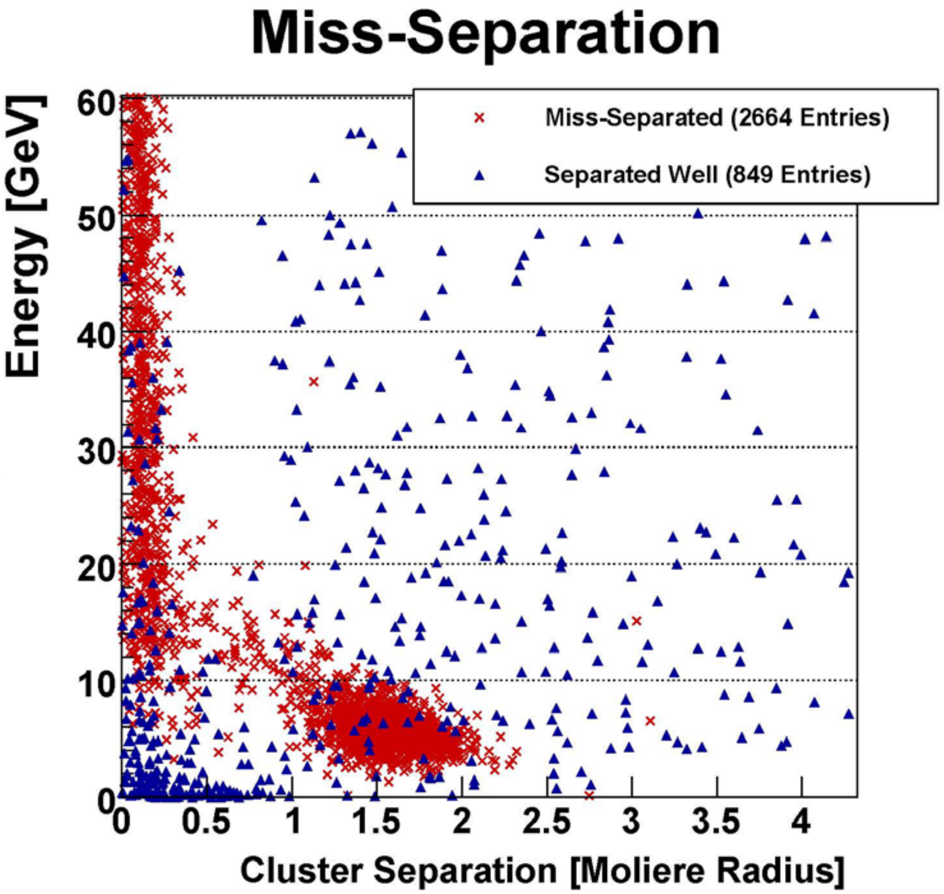
Relative error in Energy: 5% → 0.1%

- Hits from either cluster are projected into a coordinate system where the X-axis connects the two cluster centers.
- The difference between the reconstructed and generated clusters is apparent in the area where the two clusters are inter-mixed.

LumiCal: Clustering – Algorithm performance

- Photons which were not found.





- Fake photons.

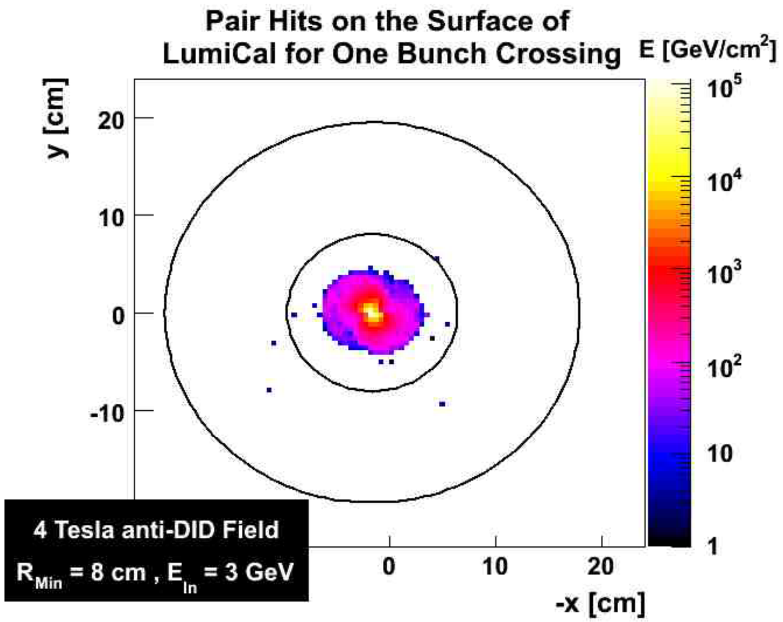
LumiCal: Clustering – Algorithm performance

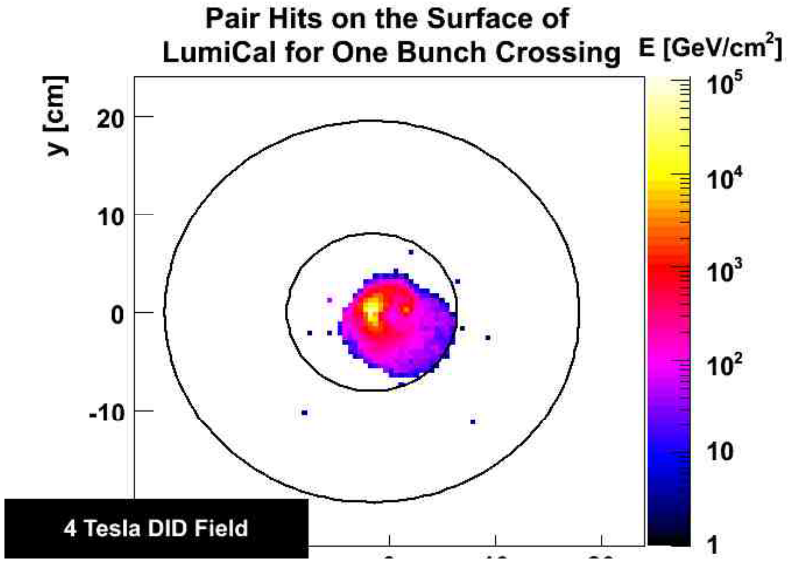
Cut		Photons which are available for reconstruction [%]	Relative errors		
Moliere radius [%]	Minimal Energy [GeV]		Miss Separating [%]	Miss Clustering [%]	Total error for 500 fb^{-1}
75	20	5.4	$7.6 \cdot 10^{-2}$	15.5	$7.0 \cdot 10^{-5}$
75	25	4.7	$6.0 \cdot 10^{-2}$	15.7	$7.6 \cdot 10^{-5}$
150	20	4.5	$4.0 \cdot 10^{-2}$	0	$5.8 \cdot 10^{-7}$
100	20	5.3	$7.1 \cdot 10^{-2}$	3.8	$4.0 \cdot 10^{-5}$
100	25	4.6	$5.6 \cdot 10^{-2}$	4	$4.4 \cdot 10^{-5}$

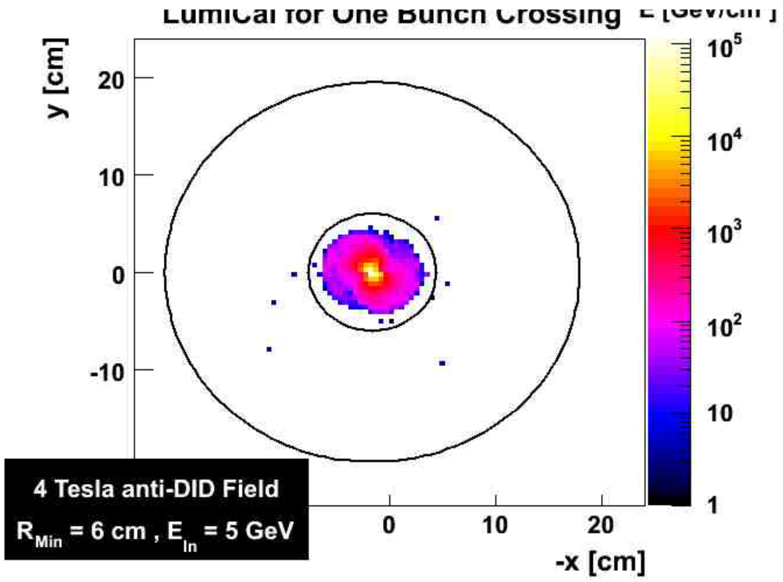
- Selection of different cuts on minimal cluster energy and on separation distance between the cluster pair results in different counting errors.

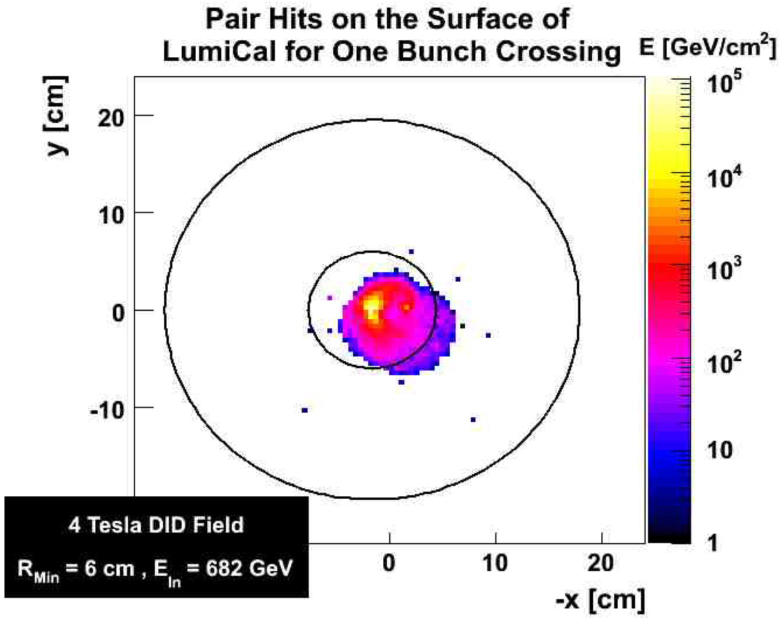
EXTRA
SLIDES

LumiCal: Systematic Effects









LumiCal: Geometry – Inner & outer radii

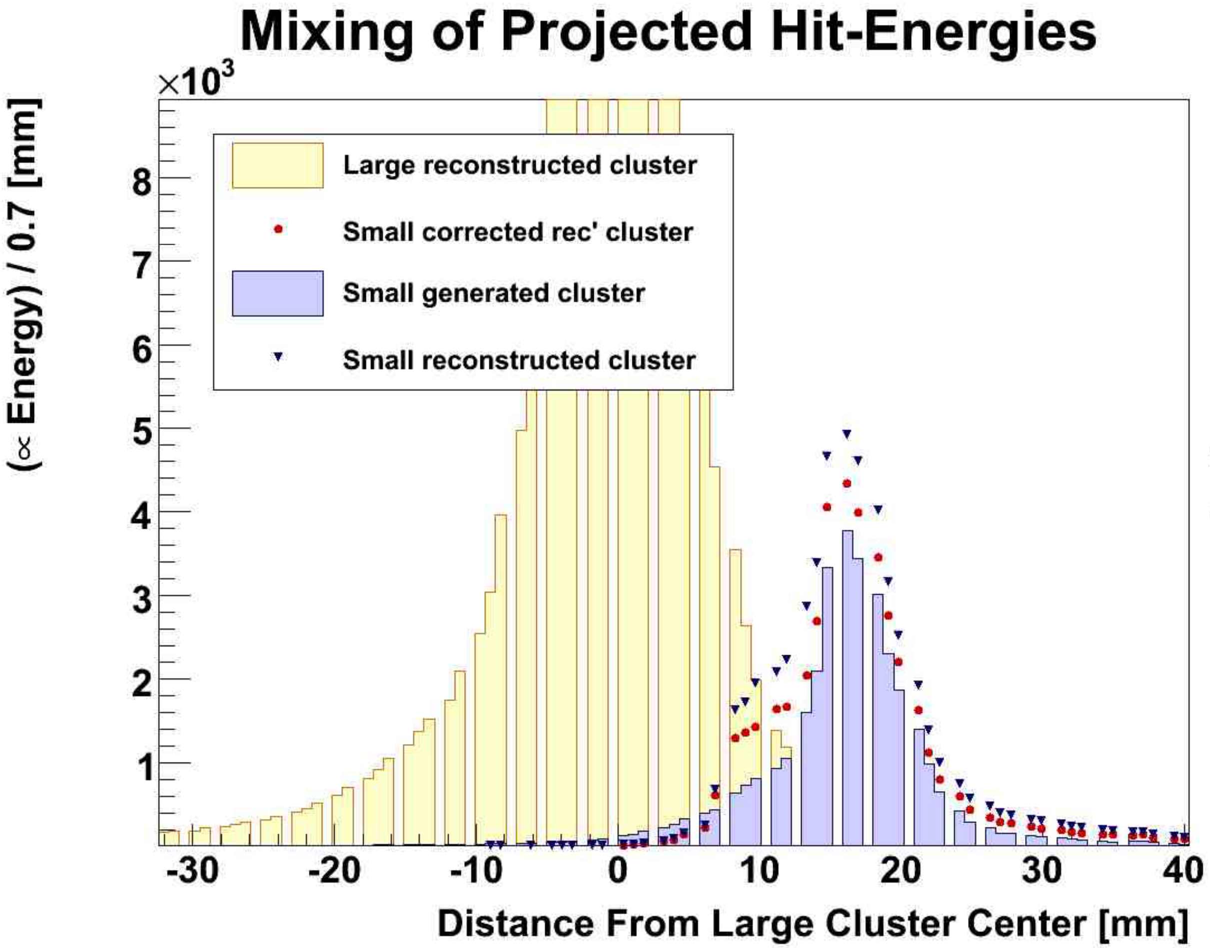
$R_{min} \rightarrow R_{max}$ [mm]	Fiducial volume		σ_{Bhabha} [nb]	Relative Error	
	θ_{min} [mrad]	θ_{max} [mrad]		$\Delta N/N$	$2\cdot\Delta\theta/\theta_{min}$
60 → 170	33	59	2.58	$2.8 \cdot 10^{-5}$	$2.1 \cdot 10^{-4}$
70 → 180	37	64	1.98	$3.2 \cdot 10^{-5}$	$1.8 \cdot 10^{-4}$
80 → 190	41	69	1.23	$4 \cdot 10^{-5}$	$1.7 \cdot 10^{-4}$
90 → 200	50	74	0.86	$4.8 \cdot 10^{-5}$	$1.4 \cdot 10^{-4}$

- The **fiducial volume sets bounds that prevent leakage** through the sides and back of LumiCal, thus insuring shower containment.

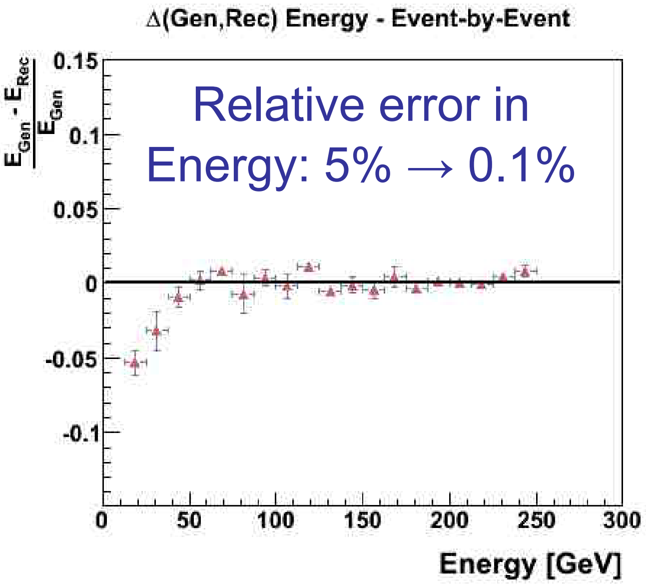
$$\sqrt{s} = 500 \text{ GeV}$$
$$L = 500 \text{ fb}^{-1}$$

$$, \quad L = \frac{N}{\sigma_{Bhabha}}$$

LumiCal: Clustering – Energy Corrections



- The relative error of the cluster energy for small-energy clusters is improved by a factor of 3.



Relative error in Energy: 5% → 0.1%

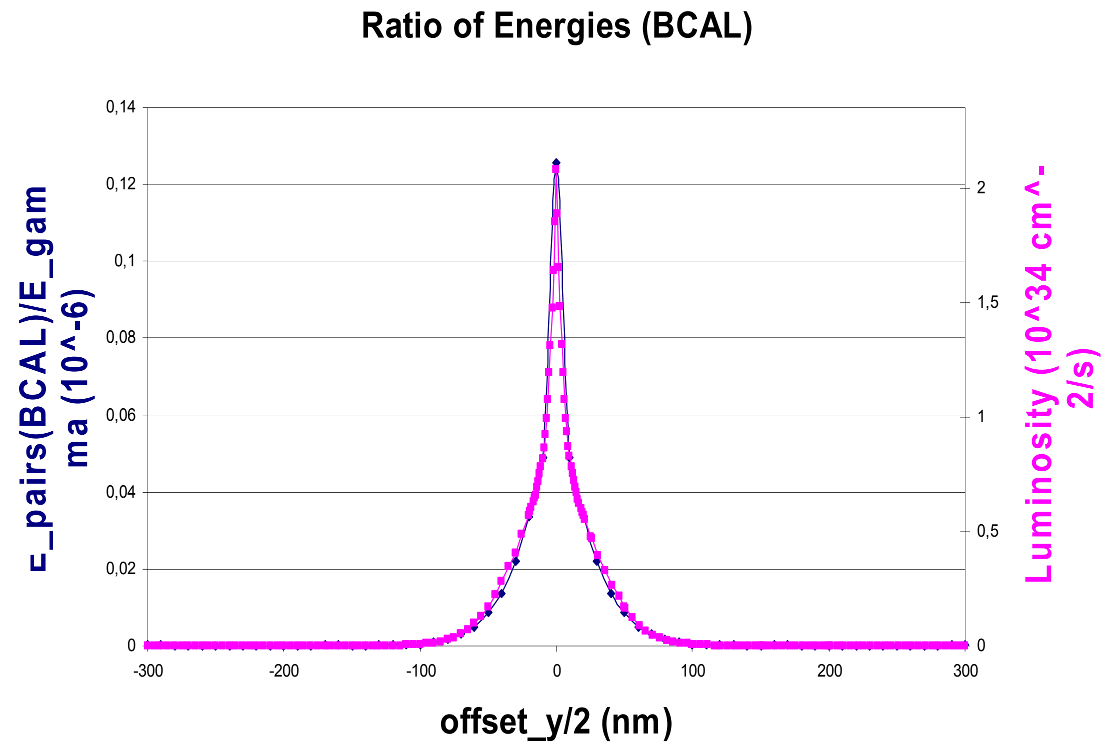
- **The procedure:** Some of the energy from hits which are associated with the small-energy cluster is allocated to the high-energy cluster. Exactly how much is determined according to the energy distribution of the large-energy cluster on the left (negative) side, where the cluster inter-mixing is negligible.

BeamCal: Instant Luminosity Measurement

- Use as much information about the collision as possible.
- BeamCal measures the energy of pairs originating from beamstrahlung.
- GamCal will measure the energy of the beamstrahlung photons.

- Define a robust signal proportional to the luminosity which can be fed to the feedback system.

- Ratio of E_pairs/E_gam vs offset_y is proportional to the luminosity.
- similar behaviour for angle_y, waist_y …



LumiCal: Clustering – Algorithm performance

Cuts		Acceptance [%]	Purity [%]	Efficiency [%]
Moliere radius [%]	Minimal Energy [GeV]			
75	20	84	96	88
75	25	84	96	87
150	20	100	97	1.03
100	20	96	96	100
100	25	96	97	99

Cut		Photons which are available for reconstruction [%]	Relative errors		
Moliere radius [%]	Minimal Energy [GeV]		Miss Separating [%]	Miss Clustering [%]	Total error for 500 fb^{-1}
75	20	5.4	$7.6 \cdot 10^{-2}$	15.5	$7.0 \cdot 10^{-5}$
75	25	4.7	$6.0 \cdot 10^{-2}$	15.7	$7.6 \cdot 10^{-5}$
150	20	4.5	$4.0 \cdot 10^{-2}$	0	$5.8 \cdot 10^{-7}$
100	20	5.3	$7.1 \cdot 10^{-2}$	3.8	$4.0 \cdot 10^{-5}$
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