Digital ECAL: Lecture 1

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DECAL lectures summary

- Lecture 1 – Ideal case and limits to resolution
    - Digital ECAL motivation and ideal performance compared with AECAL
    - Shower densities at high granularity; pixel sizes
    - Effects of EM shower physics on DECAL performance
- Lecture 2 – Status of DECAL sensors
    - Basic design requirements for a DECAL sensor
    - Current implementation in CMOS technology
    - Characteristics of sensors; noise, charge diffusion
    - Results from first prototypes; verification of performance
- Lecture 3 – Detector effects and realistic resolution
    - Effect of sensor characteristics on EM resolution
    - Degradation of resolution due to sensor performance
    - Main issues affecting resolution
    - Remaining measurements required to verify resolution

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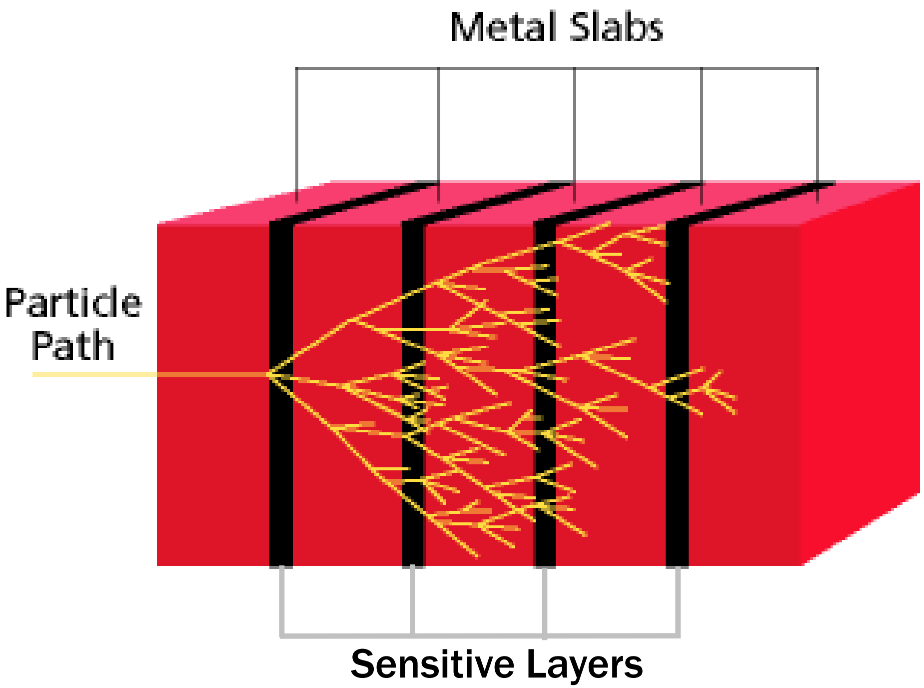
DECAL: basics

- Requirements for linear collider ECAL
  - Highly granular to allow particle flow
  - Reasonable EM shower resolution
- Covers range of energies relevant to hadronic jets; 1-100 GeV
  - Take typical energy as 10GeV
- Effect of DECAL on PFA not yet studied in detail
  - Complex optimisation; depends on detector details
- Compared to analogue ECAL, DECAL presented here may have
  - Improved energy resolution
  - Improved position resolution
  - Lower cost
- Assume this cannot harm PFA

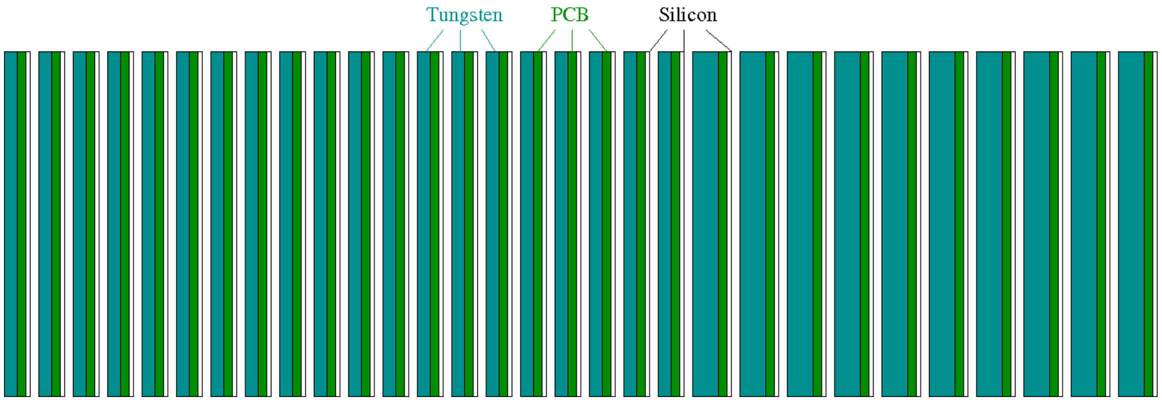
DECAL: Motivation



- Average number of charged particles in an EM shower $\propto$ incident energy
  - Fluctuations around the average occur due to statistical nature of the shower
- Average energy deposited in the sensitive layers $\propto$ number of charged particles
  - Fluctuations around the average occur due to angle of incidence, velocity and Landau spread
- Number of particles is a better measure than energy deposited of the shower energy

Simulation study of concept

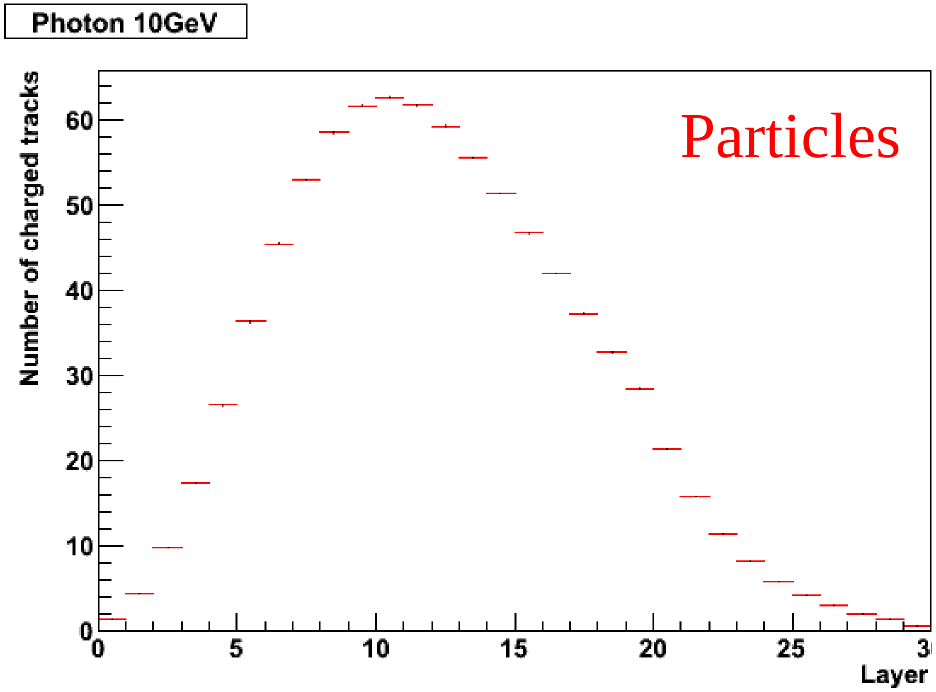
- Use simplified "typical" ILC calorimeter geometry
  - 30 layers of silicon-tungsten
  - $20 \times 0.6X_0 + 10 \times 1.2X_0$ giving $24X_0$ total
- 500μm thick silicon to give analogue energy deposit
  - No electronics, noise, etc, effects included; "ideal" analogue case
- Count number of particles emerging from back of each silicon sensor
  - DECAL energy measure

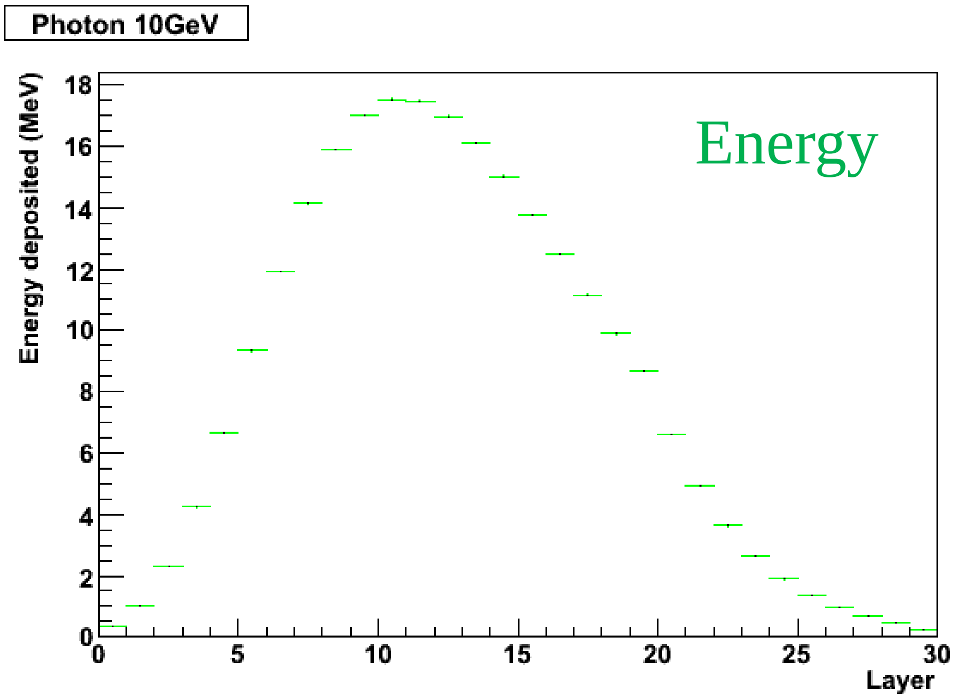


$20 \times 0.6X_0 + 10 \times 1.2X_0$

Shower depth dependence

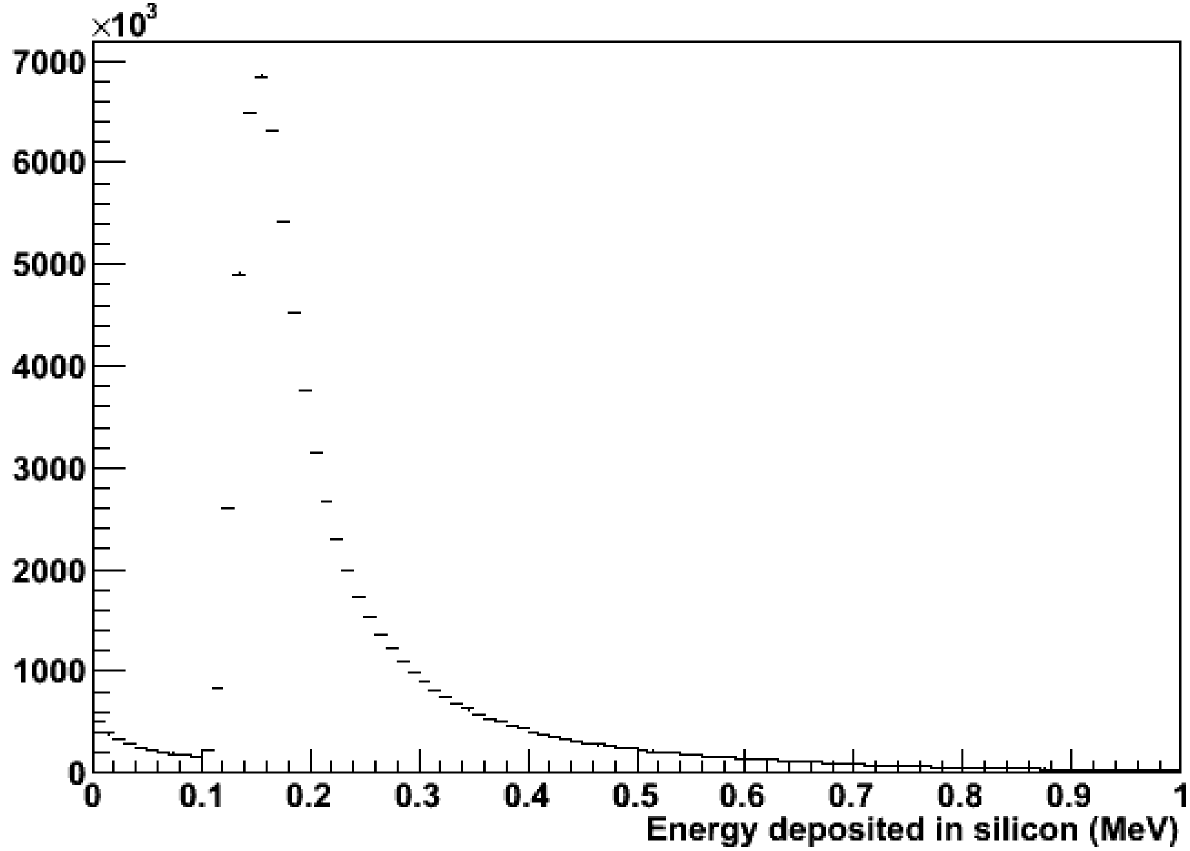
- Number of particles and energy deposited closely related; both peak at layer ~11
- Proportional with ~ 0.26MeV/particle





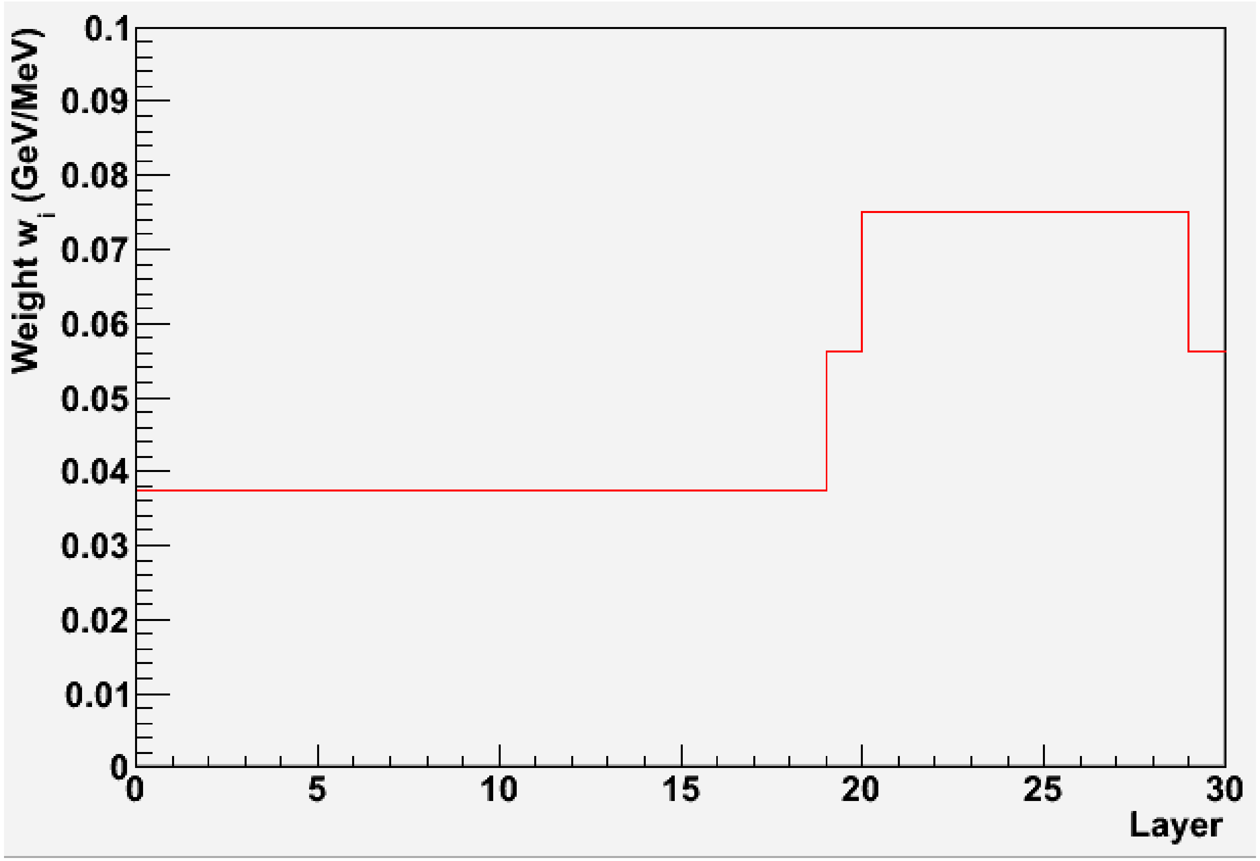
Energy spread per particle

- 0.26MeV is not a constant but an average
- Energy has extra spread due to fluctuations
- Dominated by Landau contribution
- Does not affect number of particles



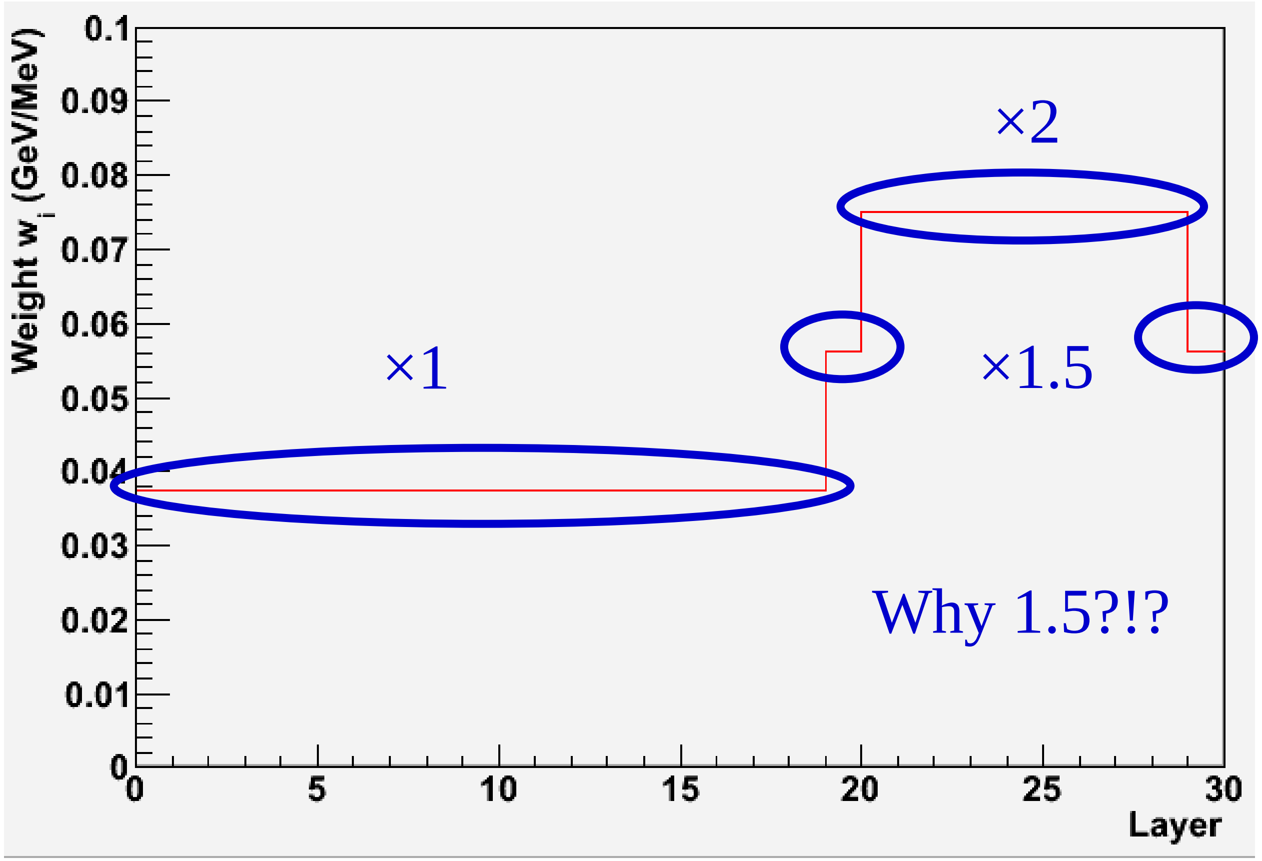
Reconstruction of total shower energy

$E_{total} = \sum_{i=0,29} w_i\ E_i$



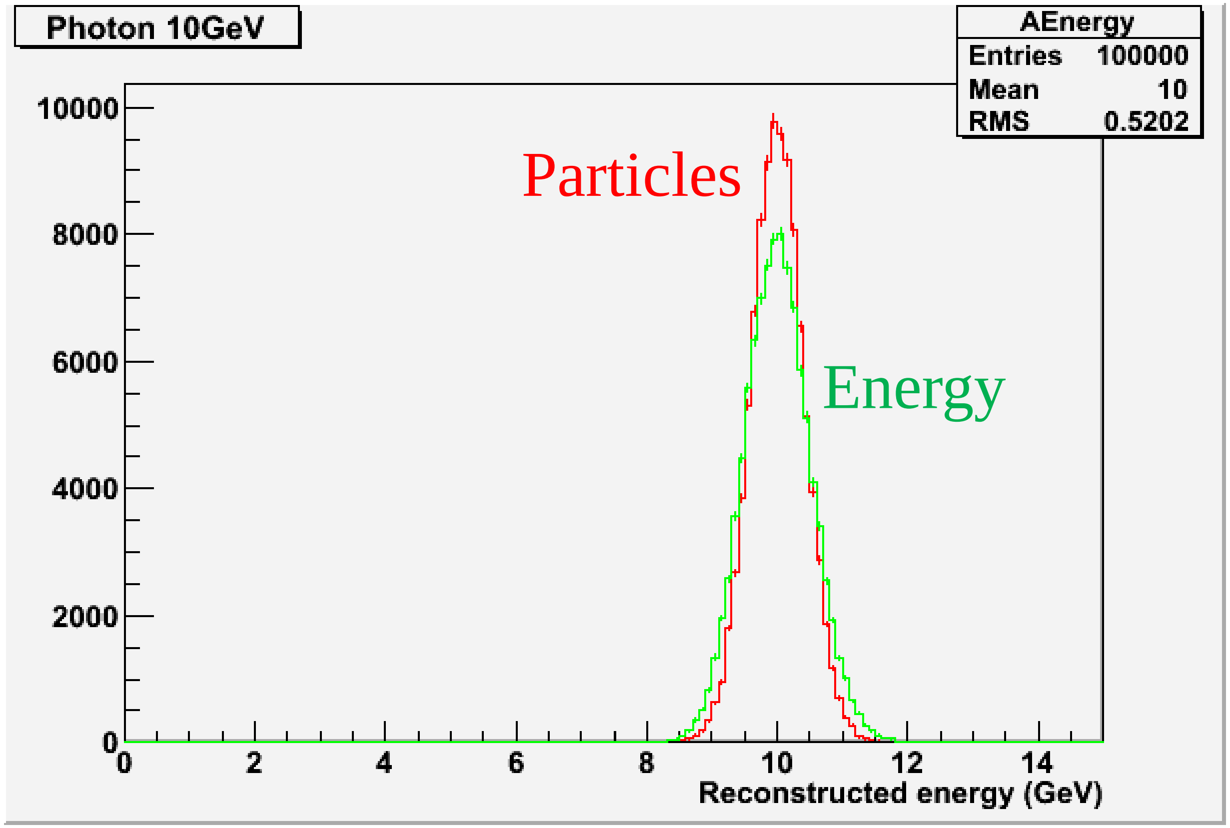
Reconstruction of total shower energy

$E_{total} = \sum_{i=0,29} w_i \, E_i$



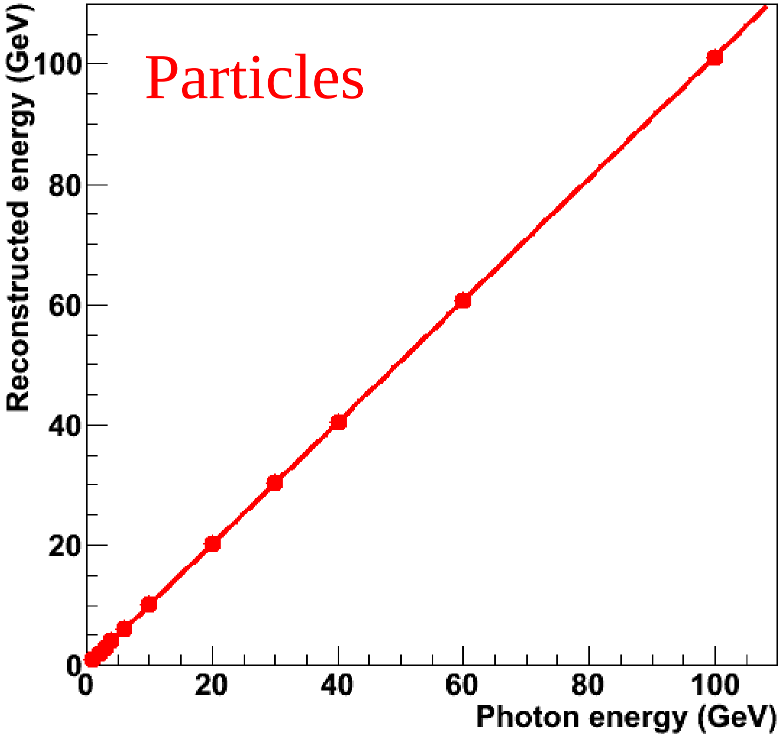
Example resolution

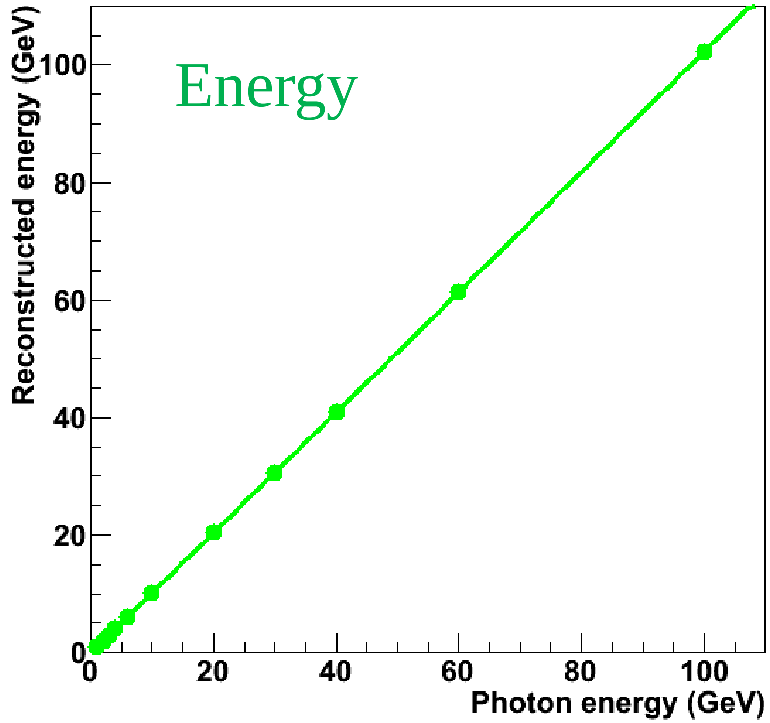
- E_{total} for 10 GeV photons
- Counting particles gives better resolution
- Find mean and width for many different photon energies



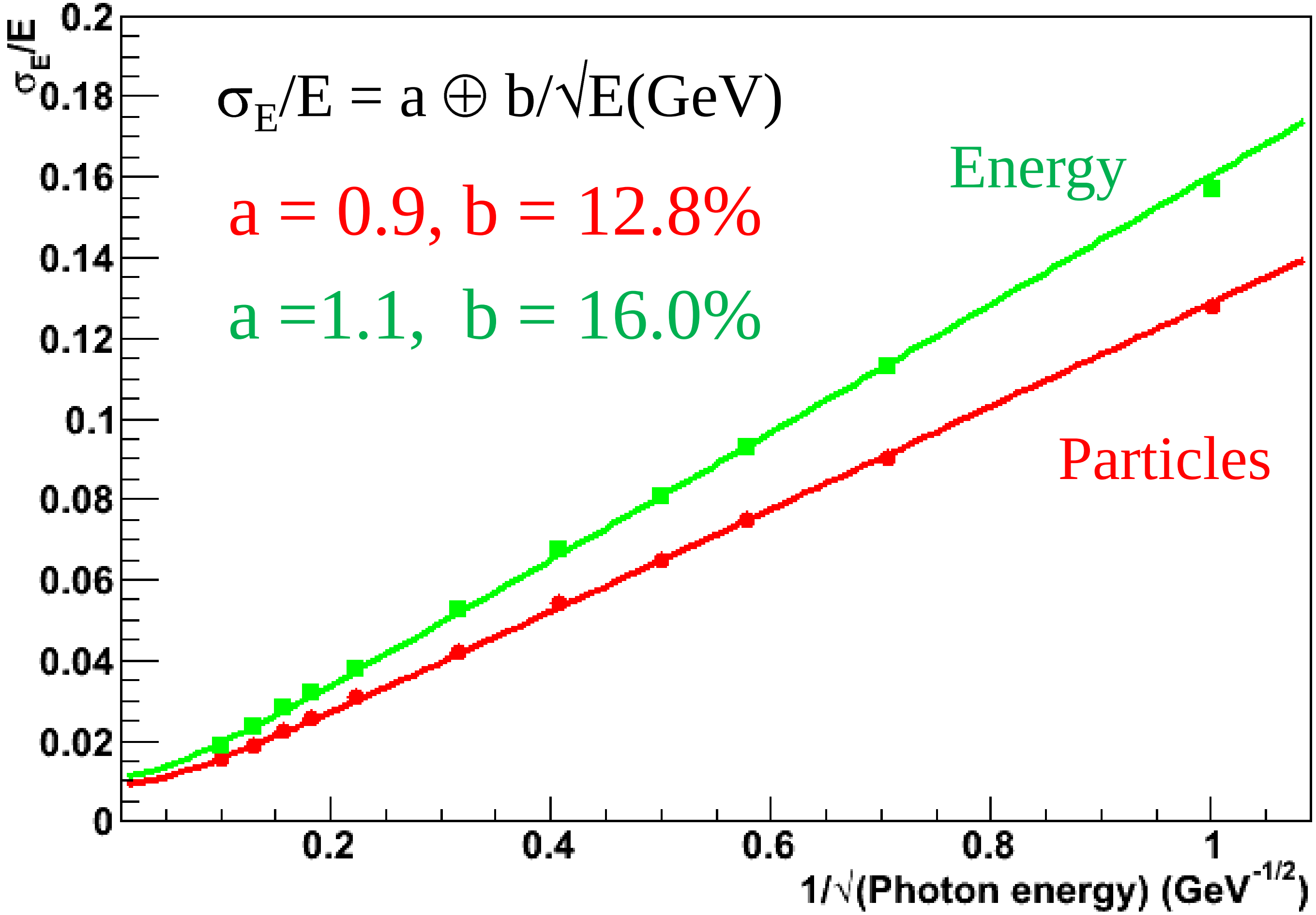
EM shower mean = linearity

- Both number of particles and energy deposited show good linearity





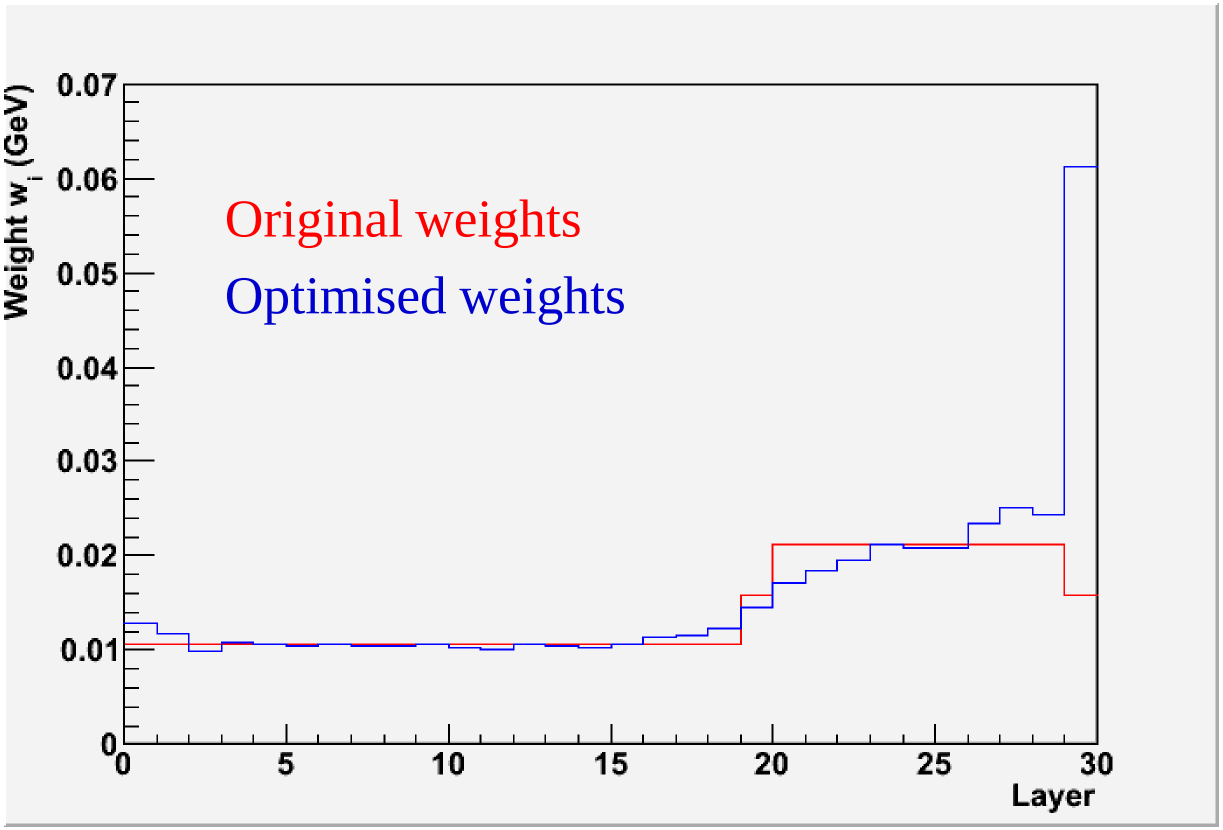
EM shower width = resolution



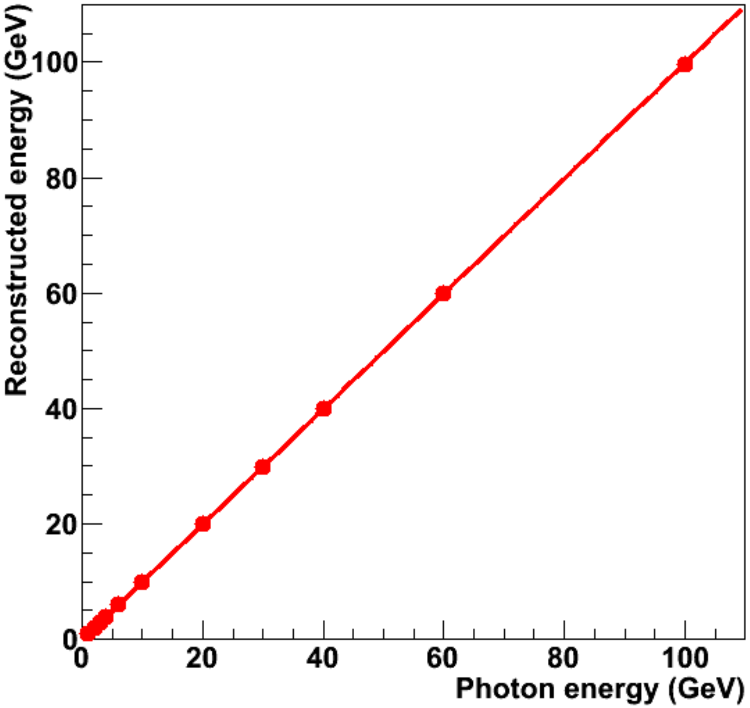
$20\times0.6X_0 + 10\times1.2X_0$

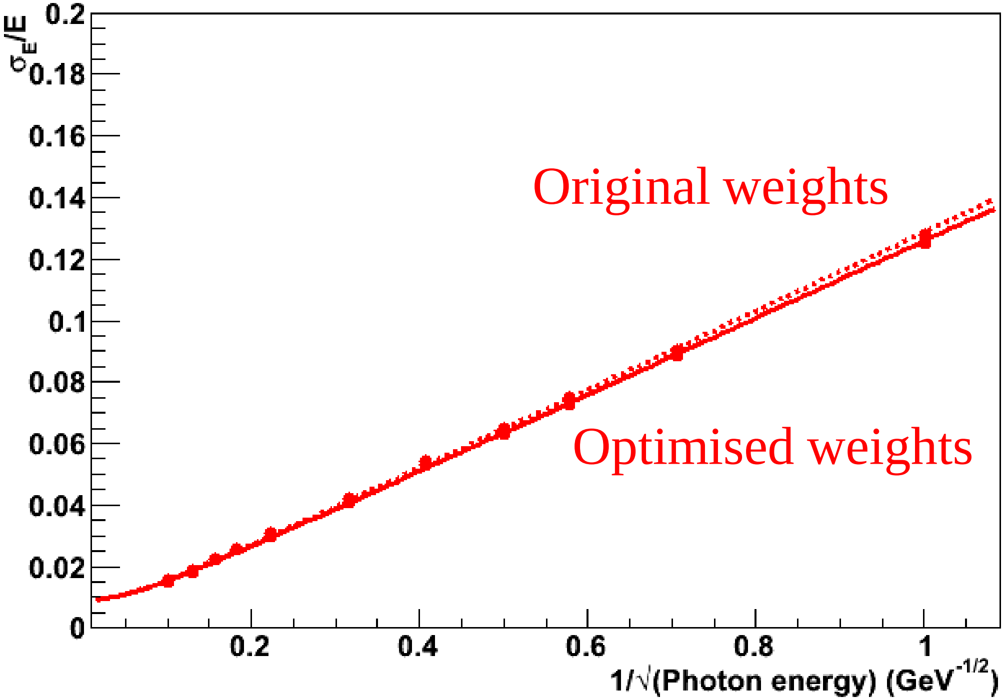
Aside: Fischer discriminant

- Linear weighted combination of N variables
- Take number of particles per layer (or energy per layer) as 30 variables and find weights which minimise resolution



Fischer discriminant: resolution

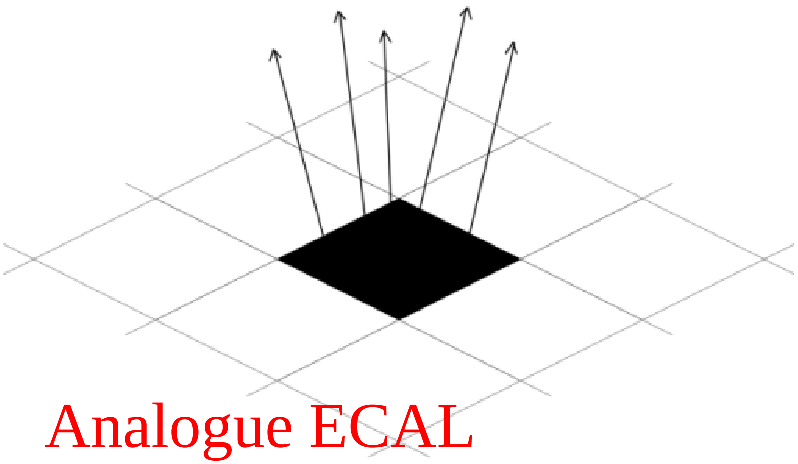




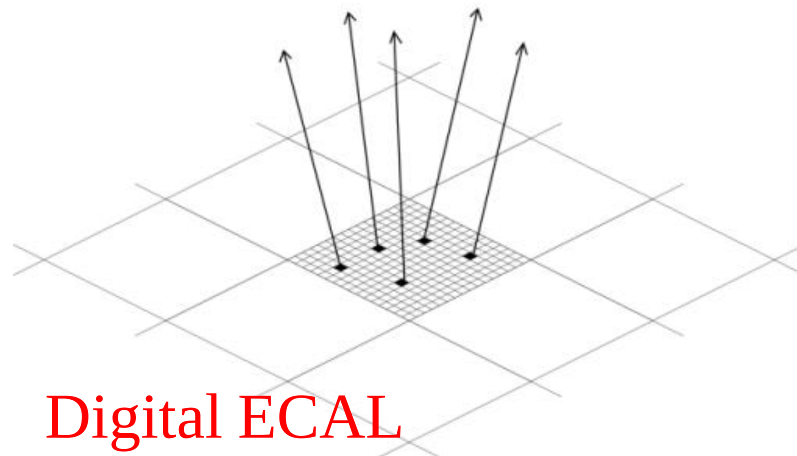
Only minor improvement...

Digital ECAL concept

- How can we measure the number of charged particles???
- Make pixellated detector with small pixels and count pixels
- Probability of more than one charged particle per pixel must be small
- Allows binary (digital) readout = hit/no hit



Analogue ECAL

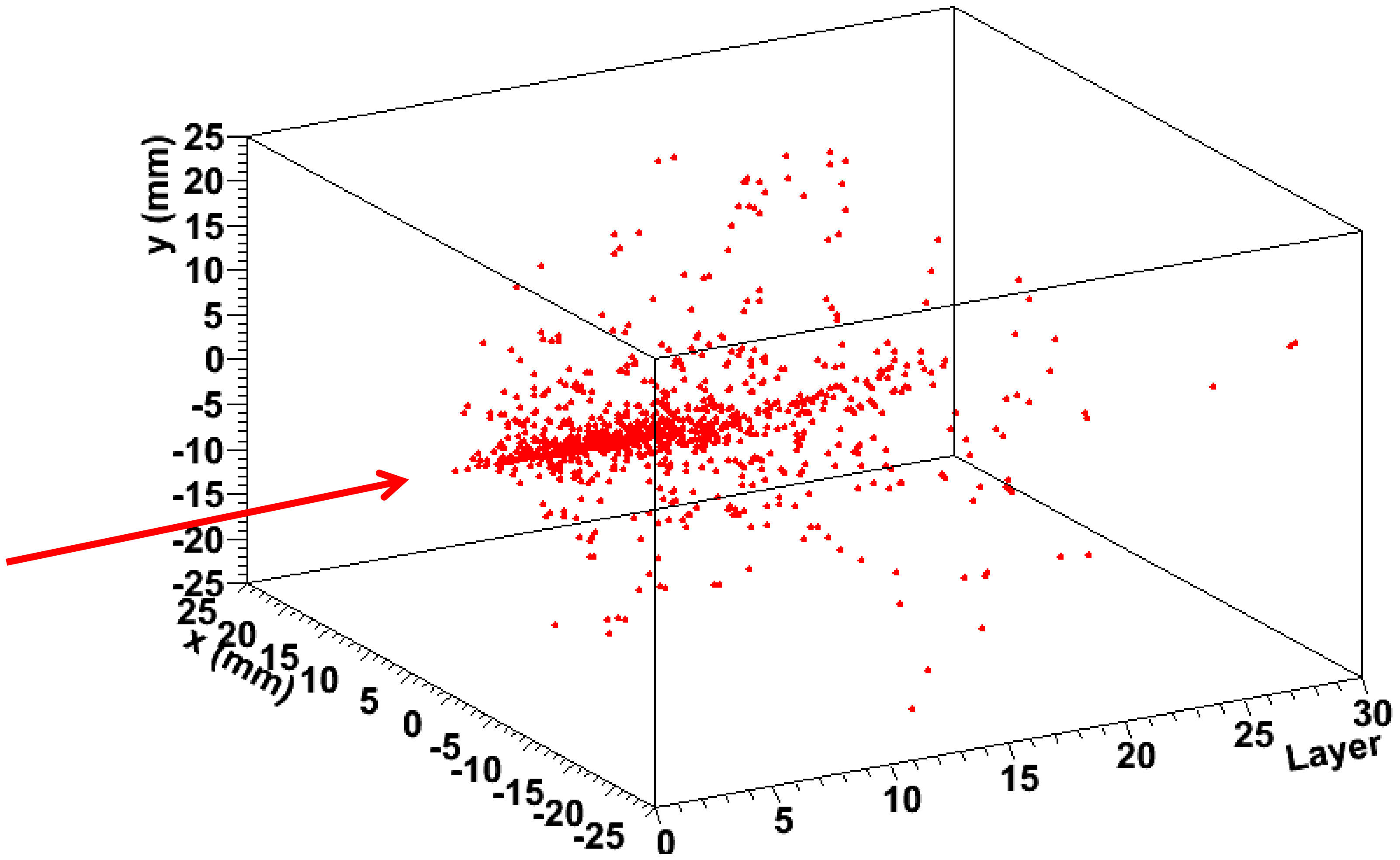


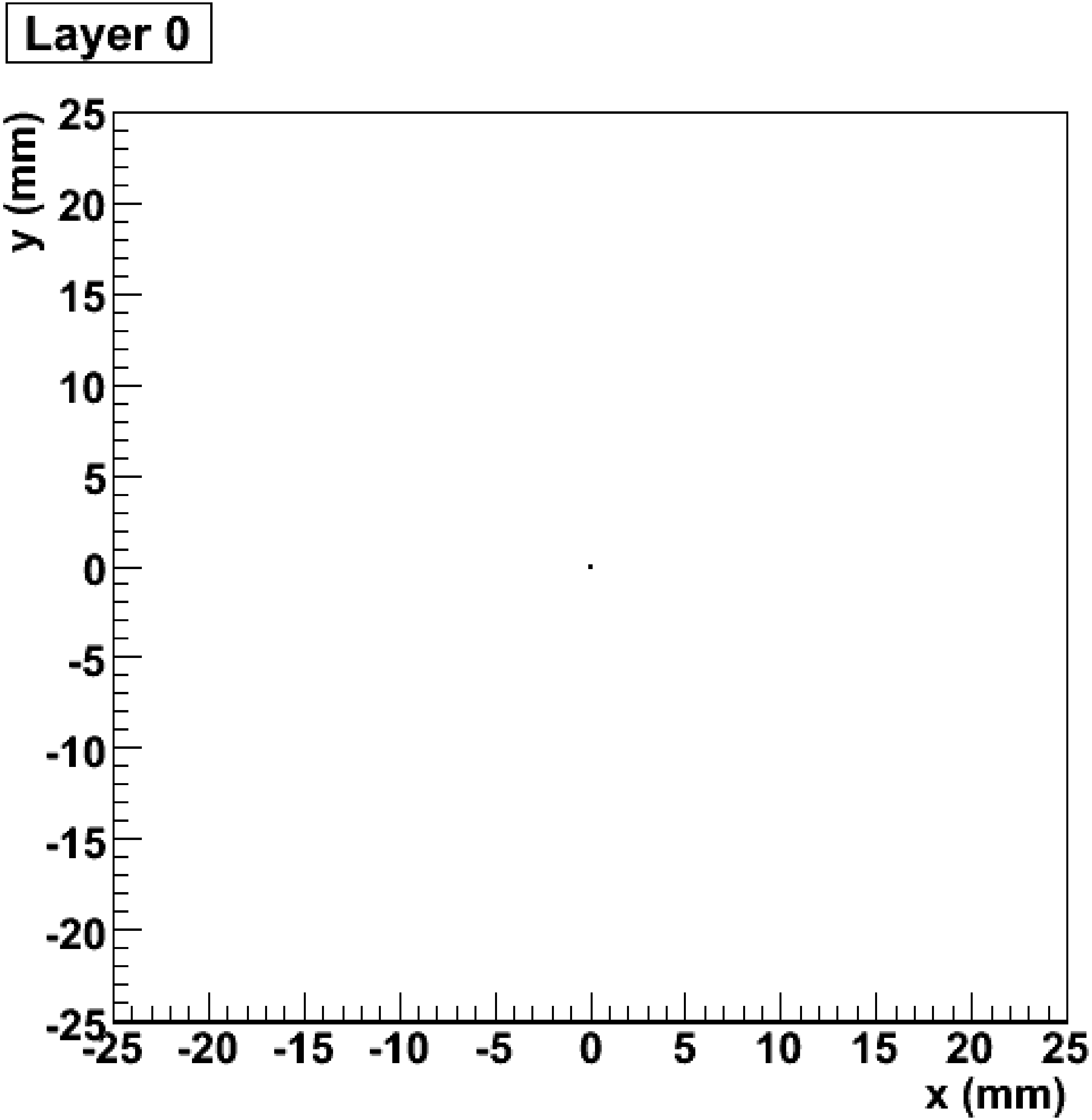
Digital ECAL

Pixel size

- Any realistic sensor has to be pixellated
- With digital (binary) readout, each pixel gives a single bit
- Two particles within one pixel will lead to undercounting and non-linearity
  - Analogous to saturation effects in SiPMs and DHCAL
- How small do the pixels need to be? Compromise
  - Non-linearity minimised by smaller pixels
  - Channel count and power minimised by larger pixels
- Critical quantity is density of particles within EM showers
  - Go for largest pixel size which does not harm resolution

Typical shower particles; 10GeV photon




Layer 0
y (mm)
x (mm)
25
20
15
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0
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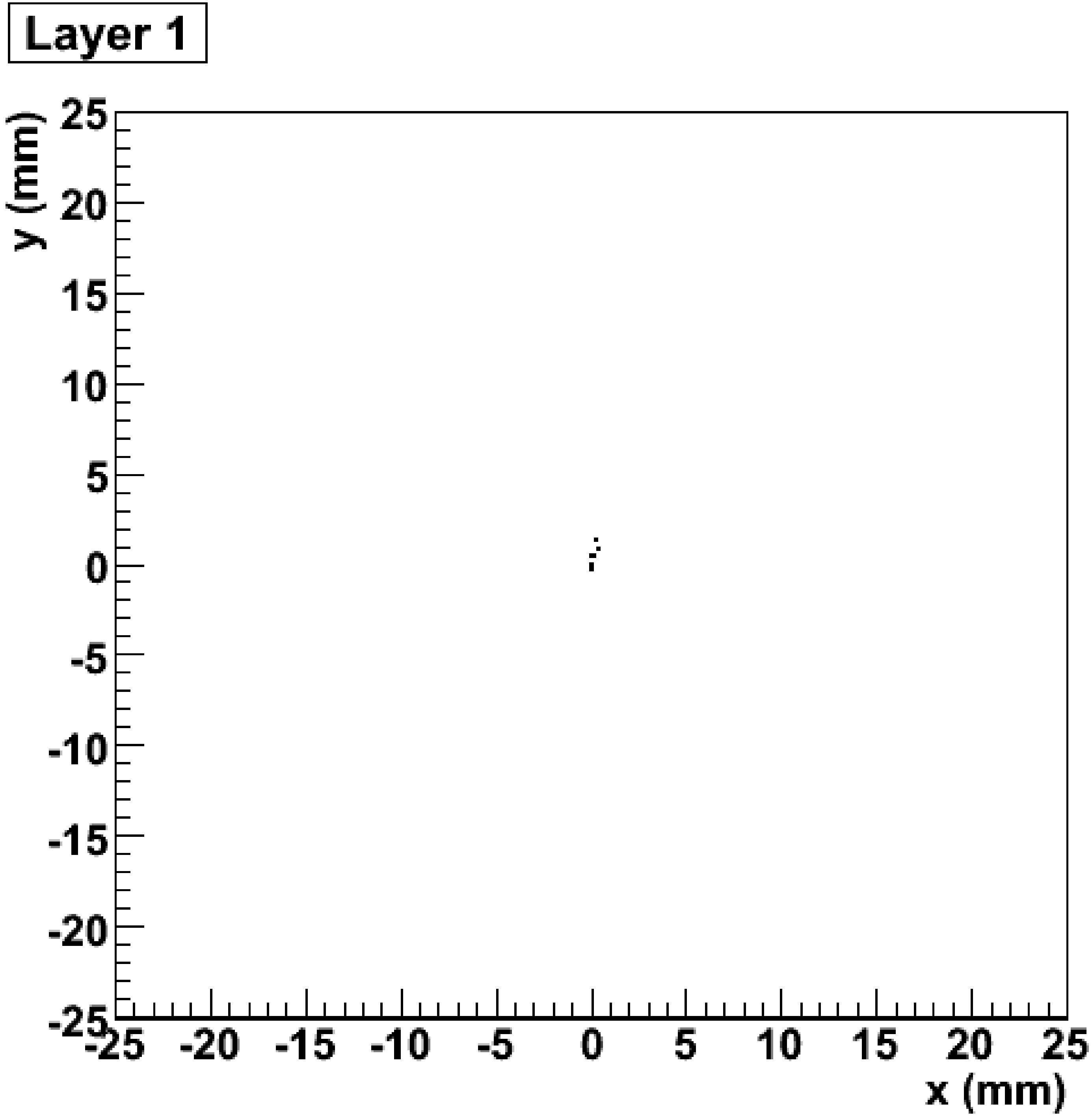
-25
-25 -20 -15 -10 -5 0 5 10 15 20 25


Layer 1
y (mm)
25
20
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-15
-10
-5
0
5
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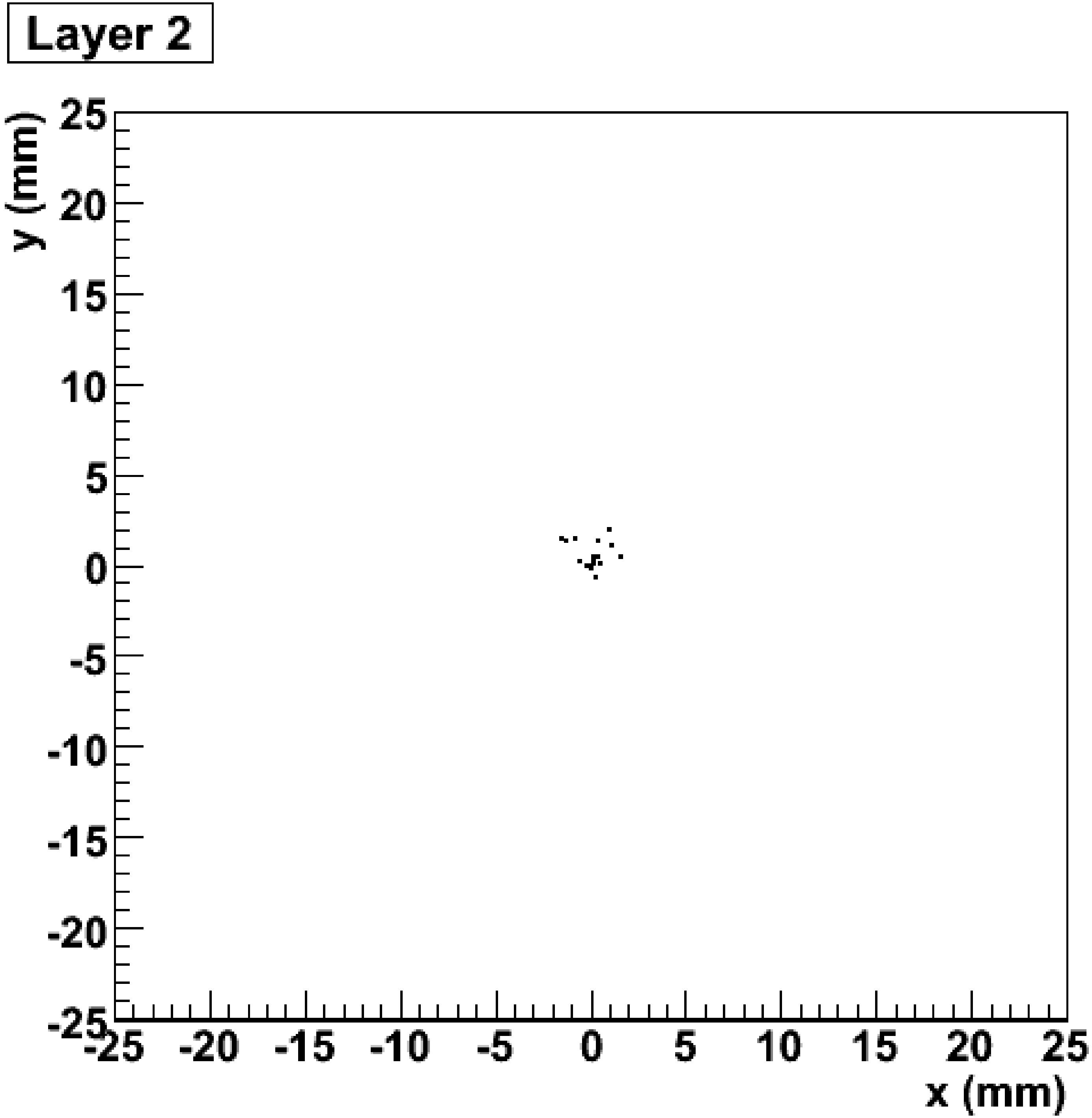
15
20
25
x (mm)


Layer 2
y (mm)
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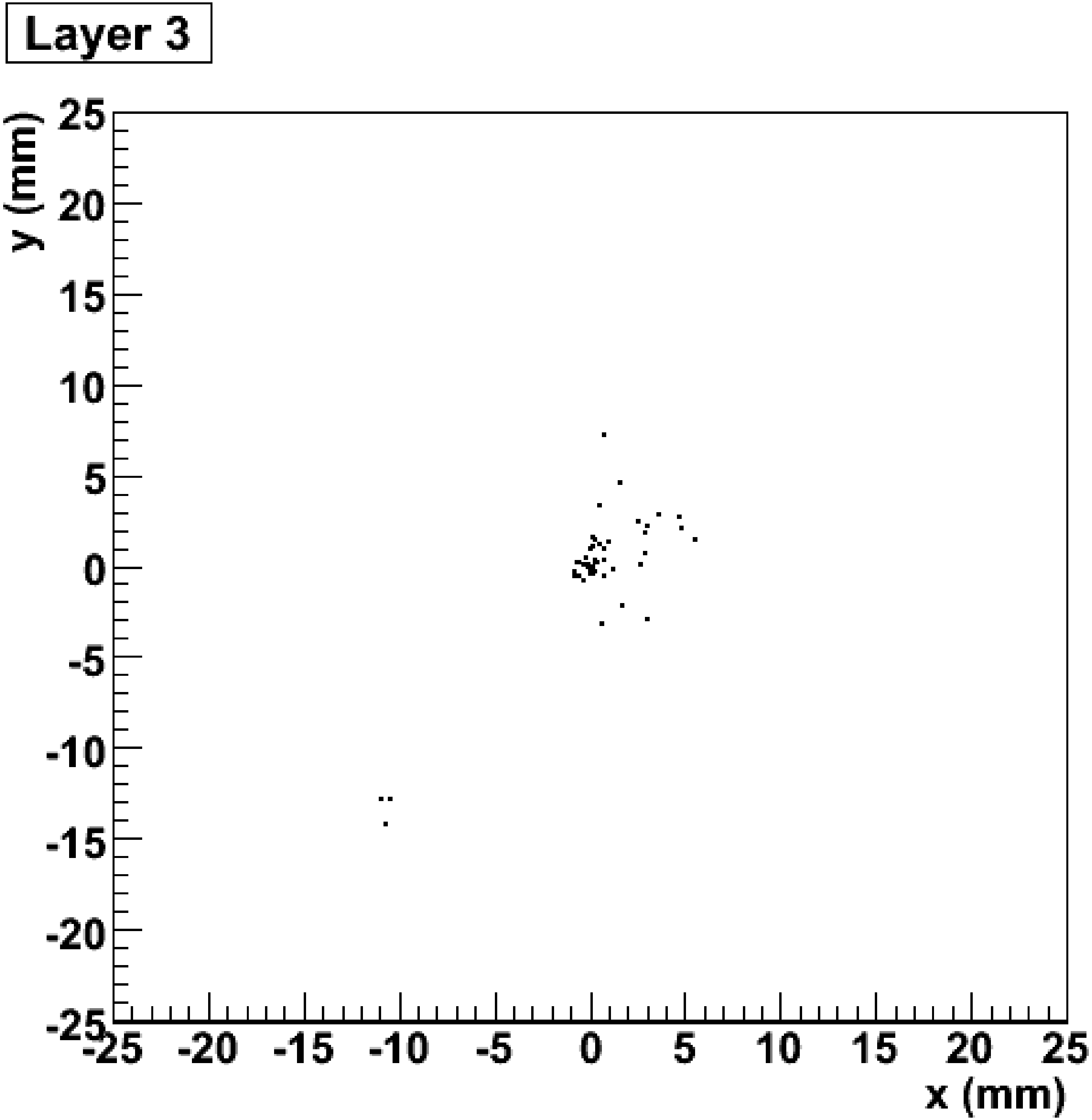
-20
-25
-25 -20 -15 -10 -5 0 5 10 15 20 25
x (mm)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y (mm)
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0
-5
-10
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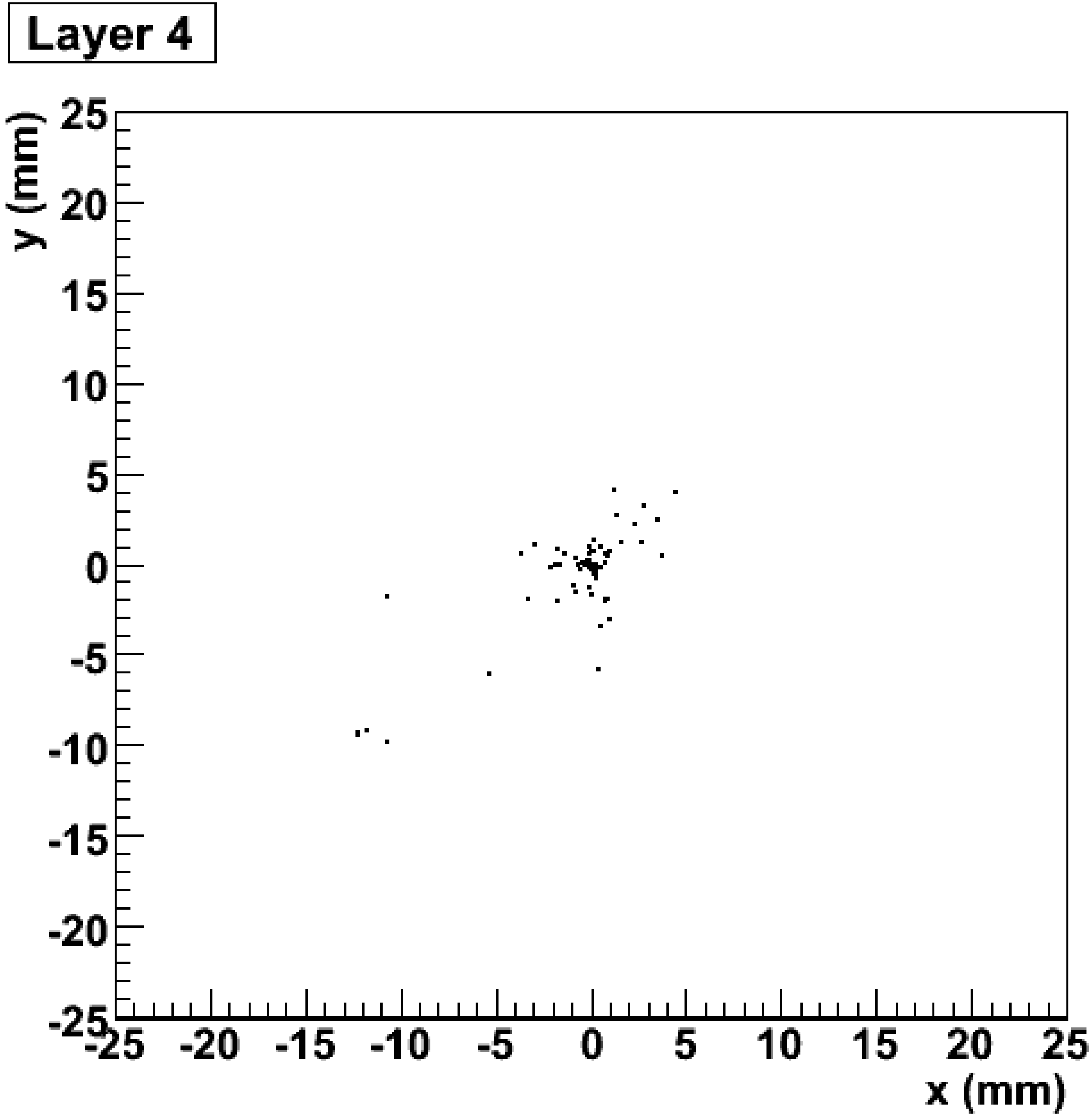
-20
-25
-25
-20
-15
-10
-5
0
5
10
15
20
25
x (mm)



Layer 4
y (mm)
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20
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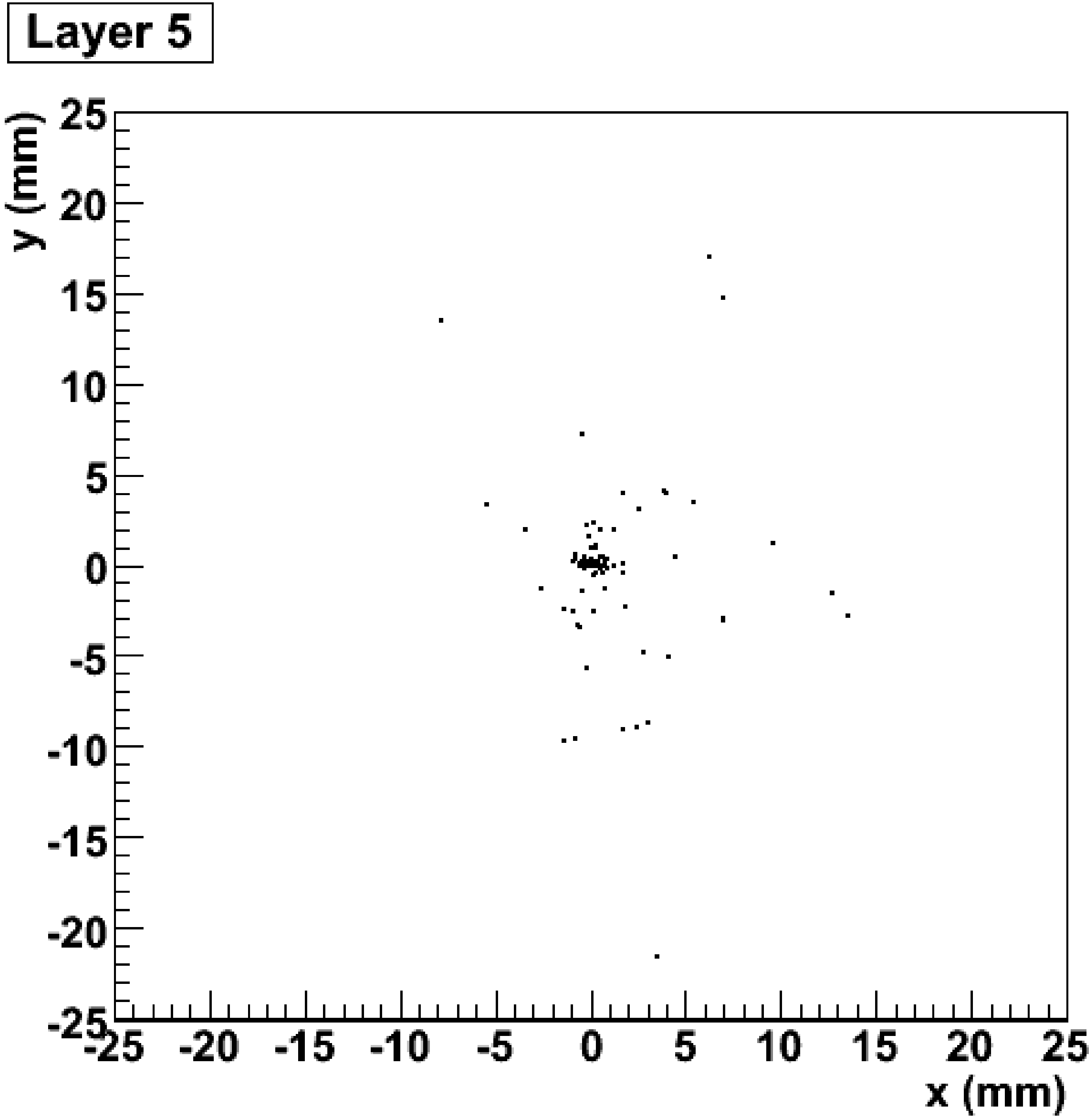
-5
-10
-15
-20
-25
-25
-20
-15
-10
-5
0
5
10
15
20
25
x (mm)


Layer 5
y (mm)
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10
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-5
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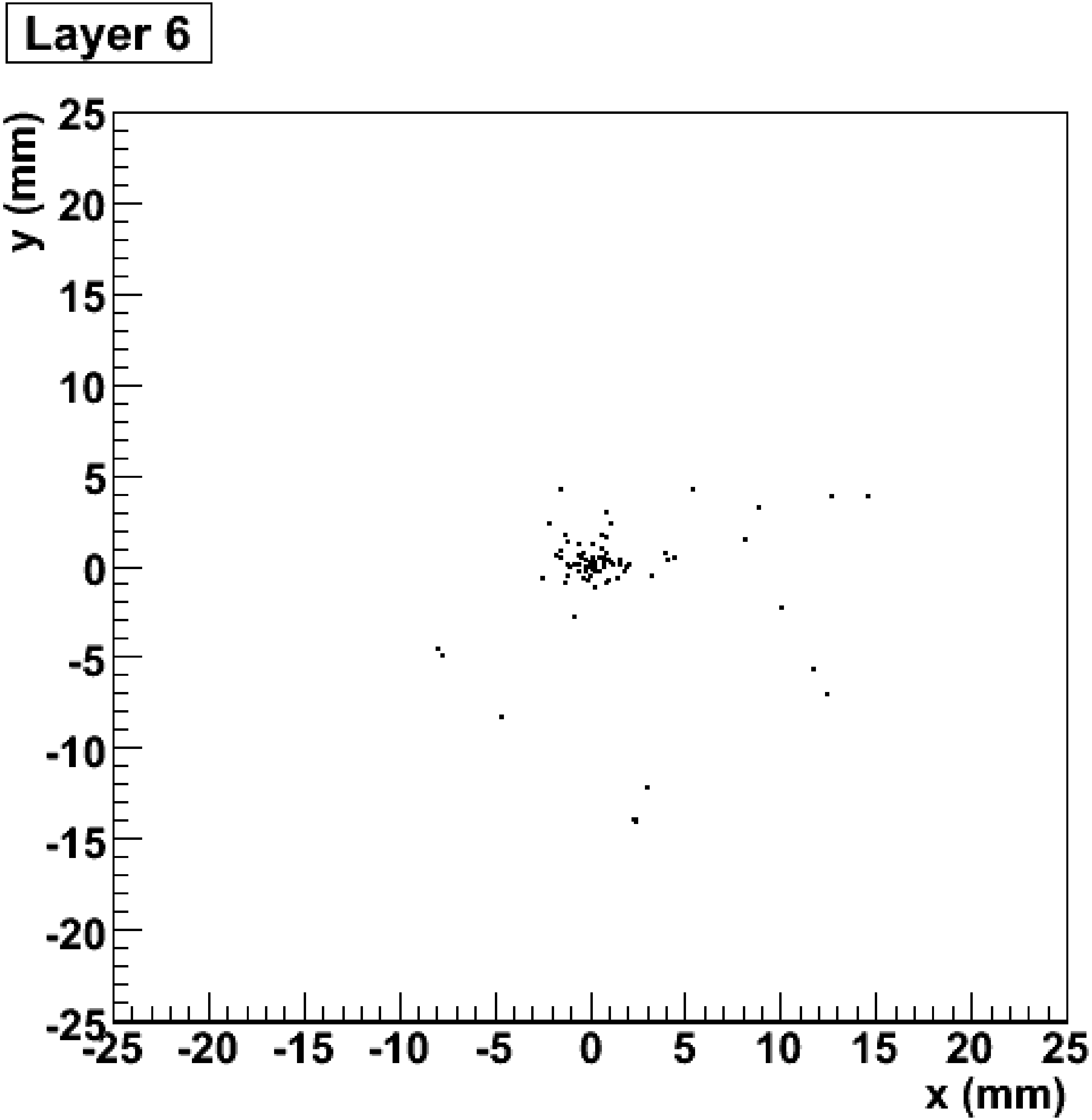
-20
-15
-10
-5
0
5
10
15
20
25
x (mm)


Layer 6
y (mm)
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20
15
10
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0
-5
-10
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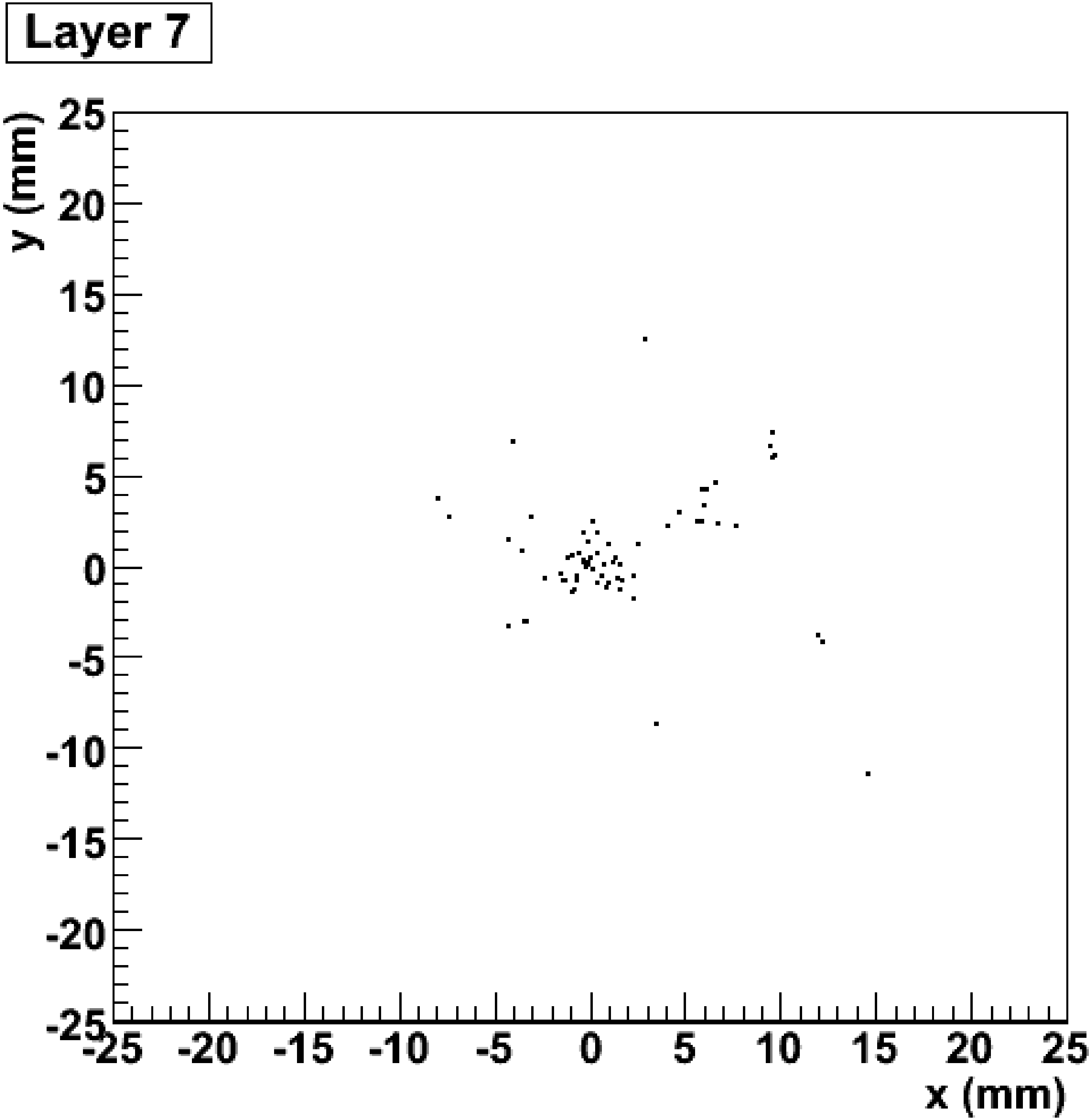
-25
-25
-20
-15
-10
-5
0
5
10
15
20
25
x (mm)


Layer 7
y (mm)
x (mm)
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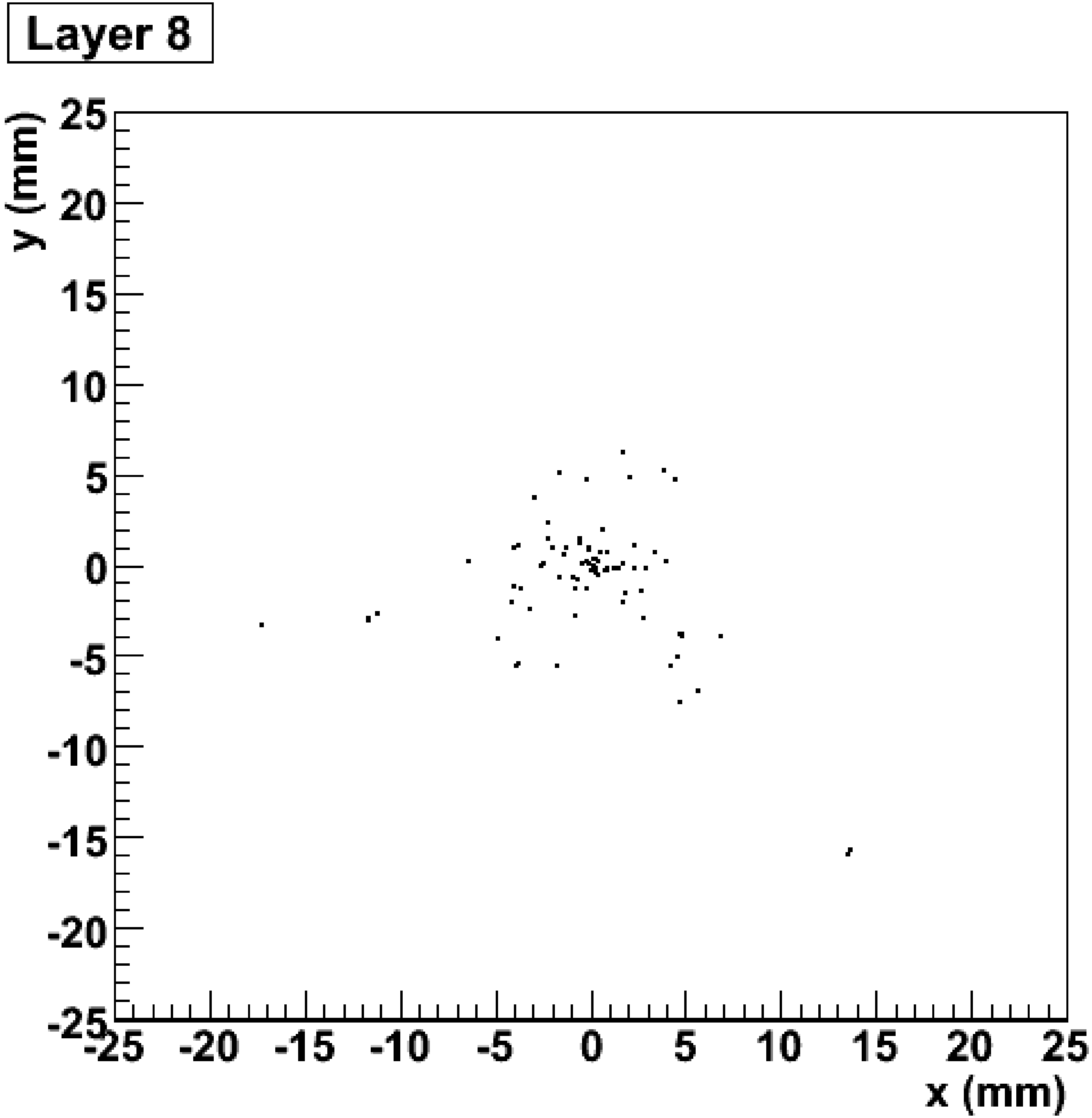
-5
0
5
10
15
20
25


Layer 8
y (mm)
x (mm)
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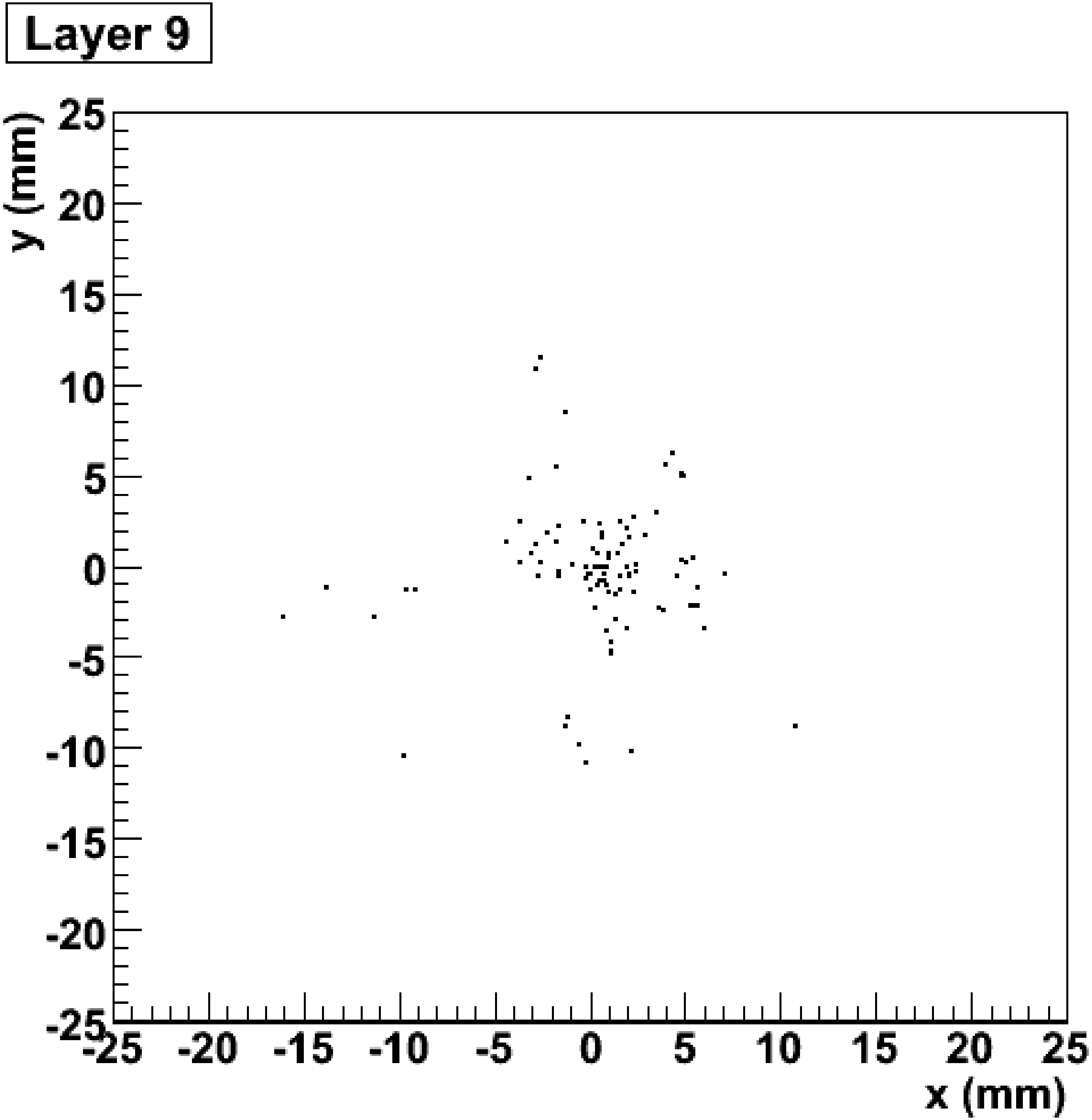
-5
-10
-15
-20
-25


Layer 9
y (mm)
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10
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-5
-10
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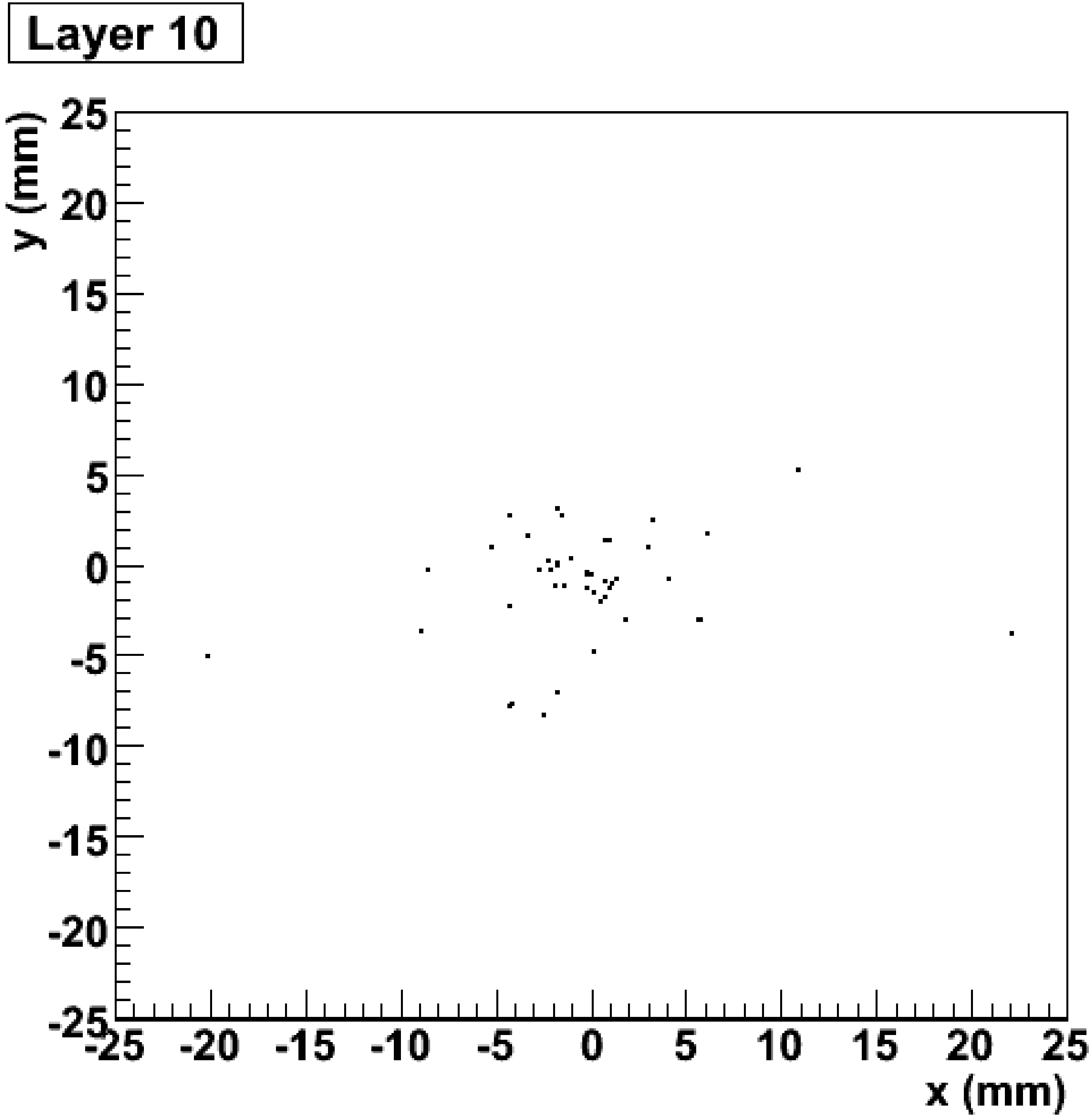
-20
-25
-25
-20
-15
-10
-5
0
5
10
15
20
25
x (mm)


Layer 10
y (mm)
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-5
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-25
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-15
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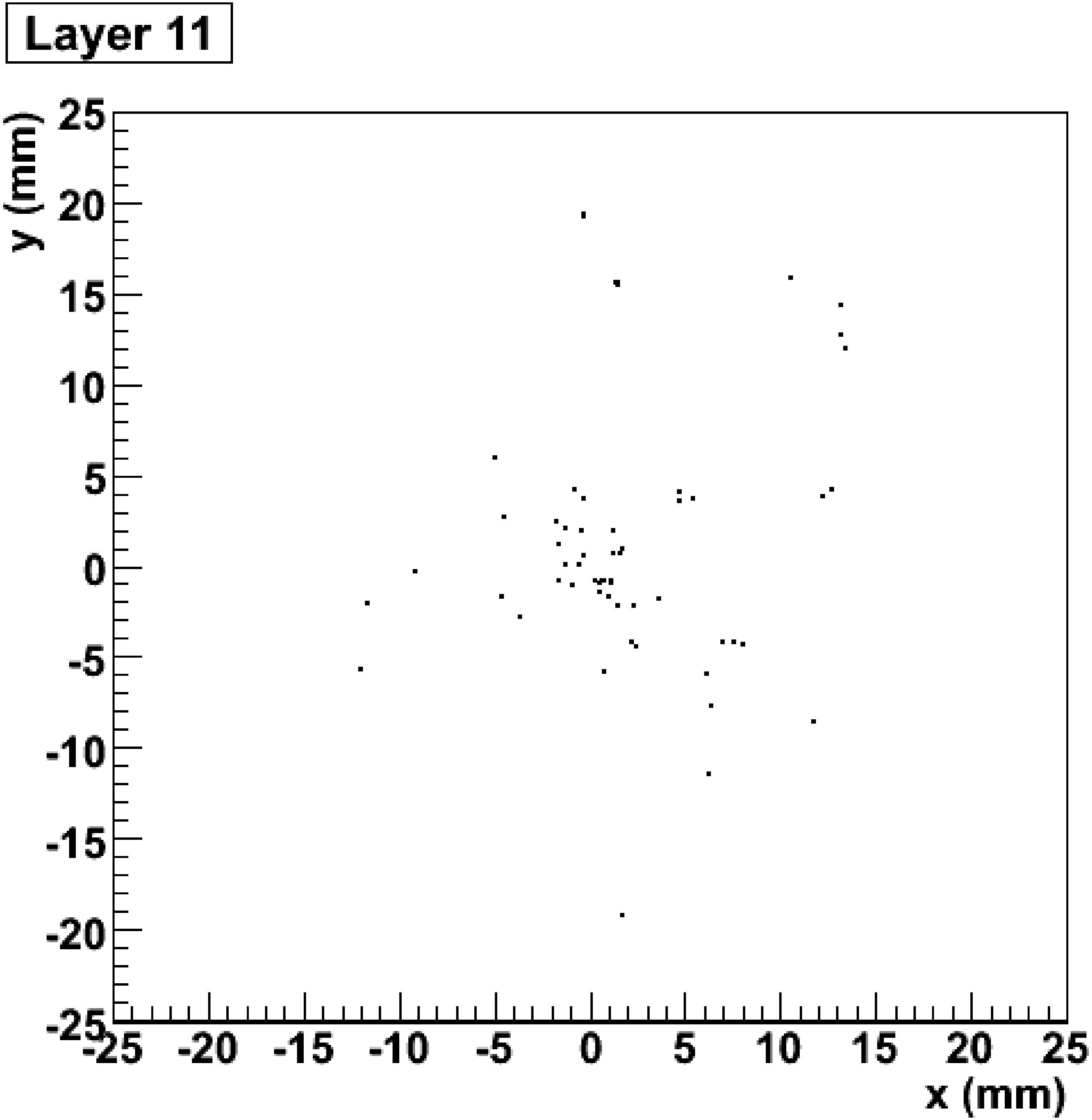
0
5
10
15
20
25
x (mm)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y (mm)
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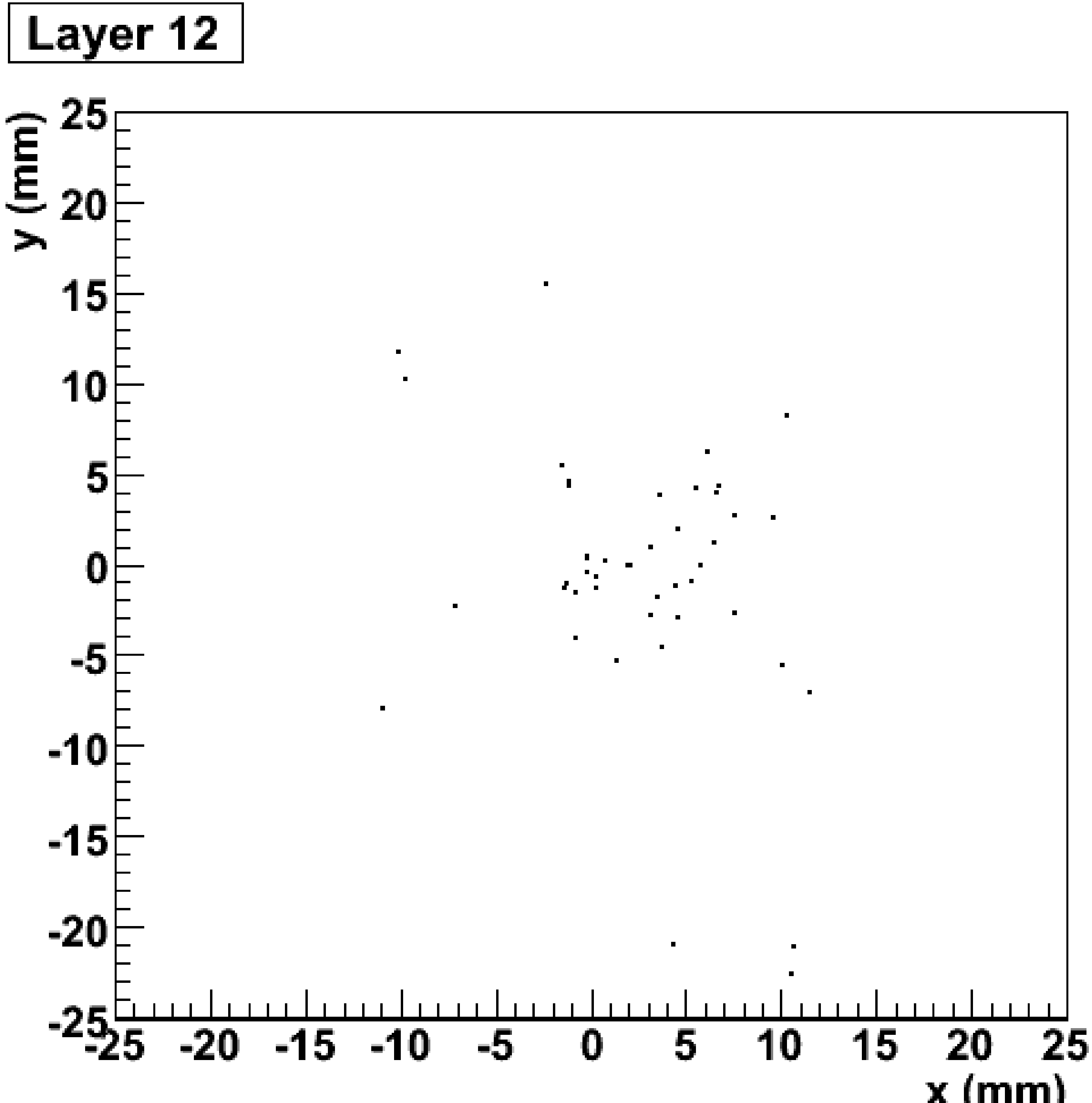
15
20
25
x (mm)



Layer 12
y (mm)
x (mm)
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10
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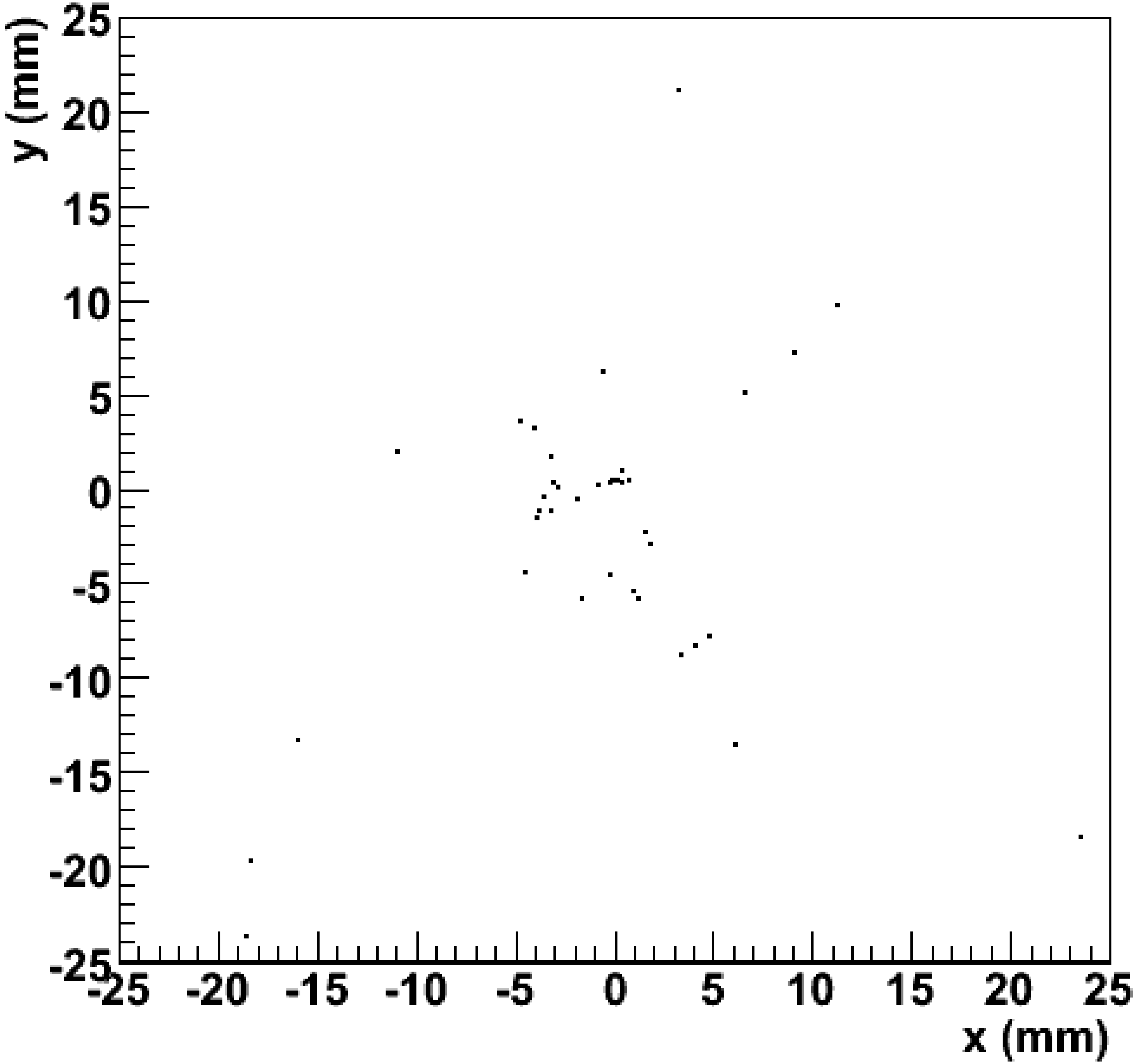
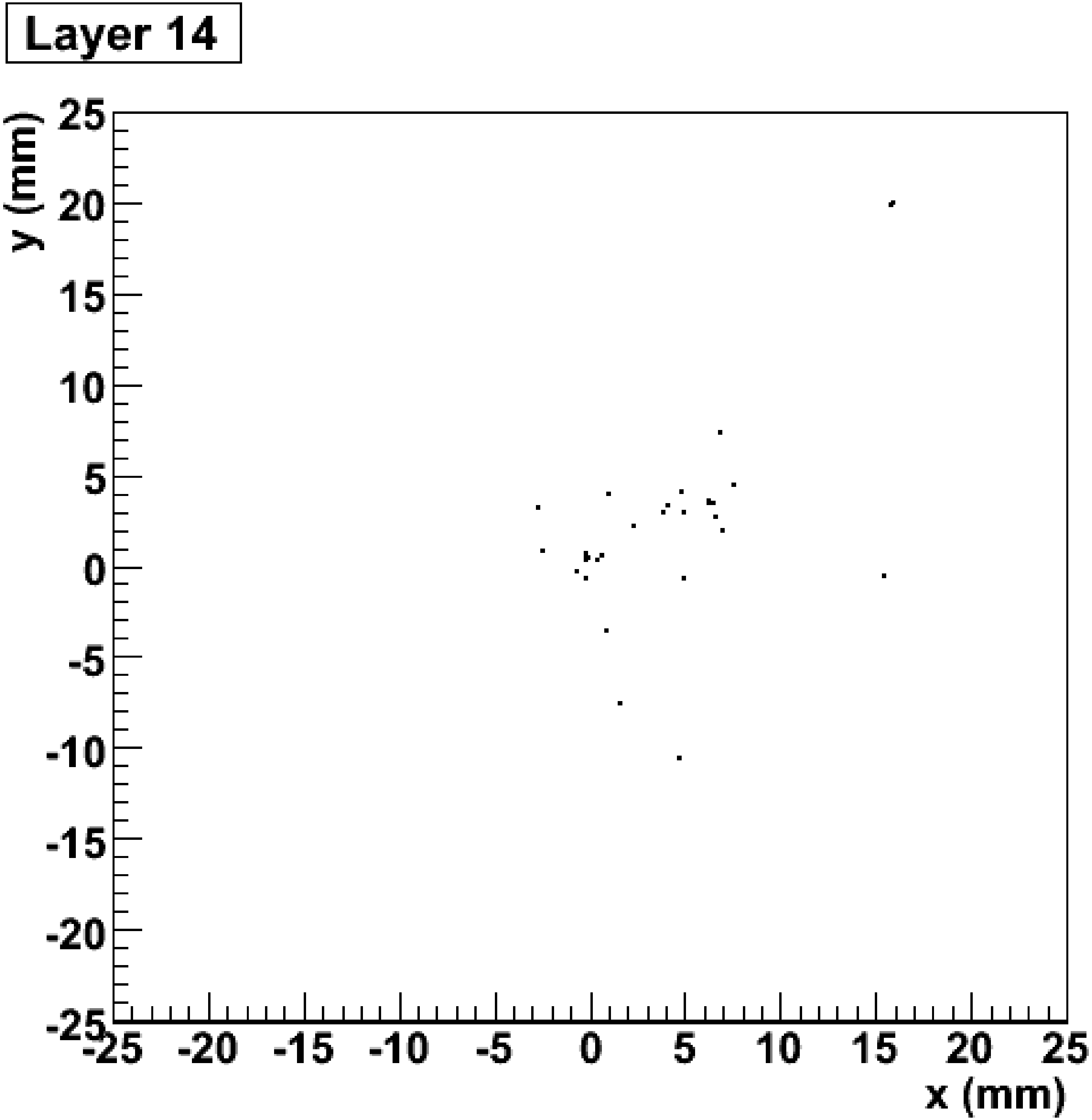
0
-5
-10
-15
-20
-25

Layer 13





Layer 14
y (mm)
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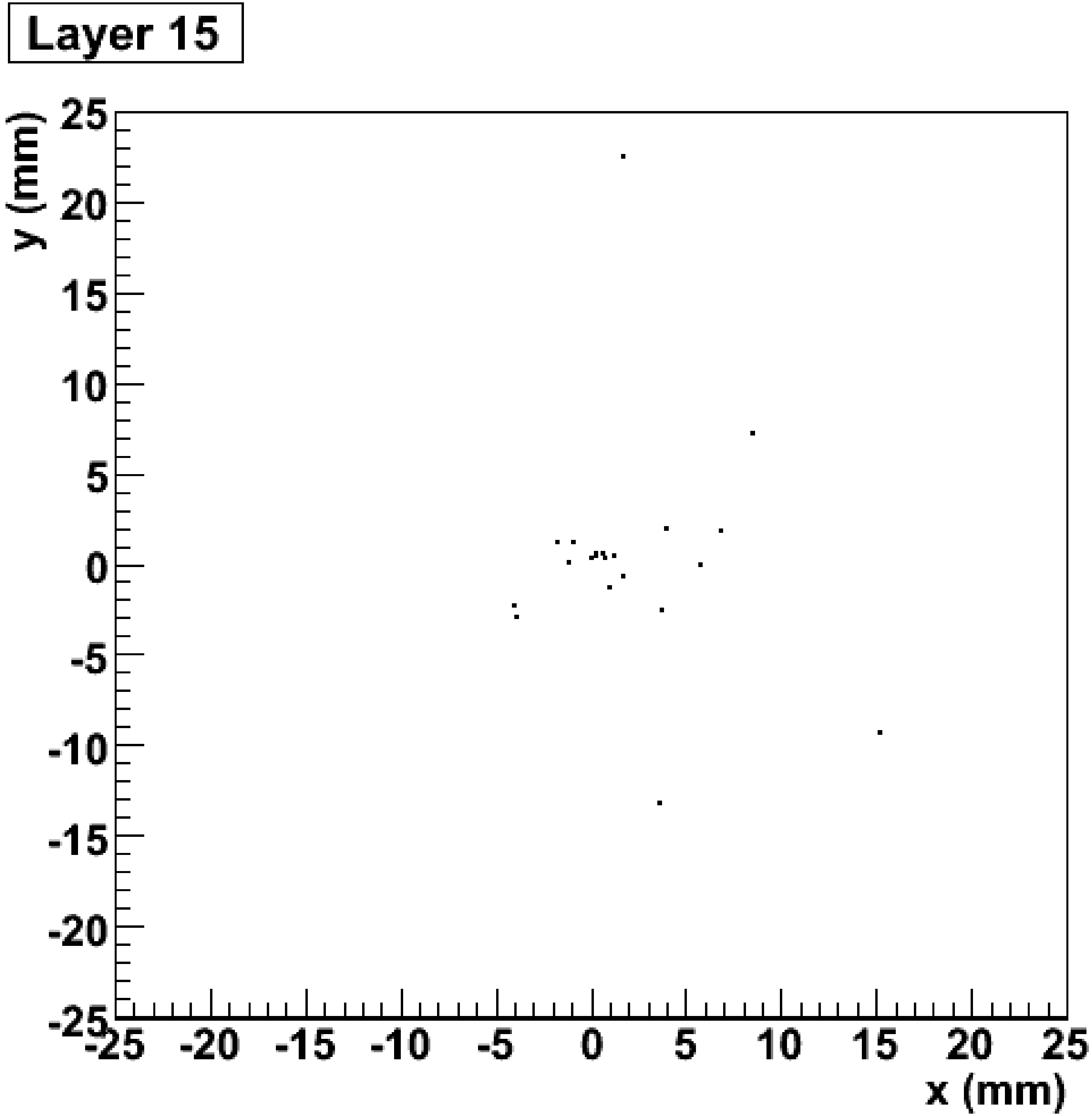
x (mm)


Layer 15
y (mm)
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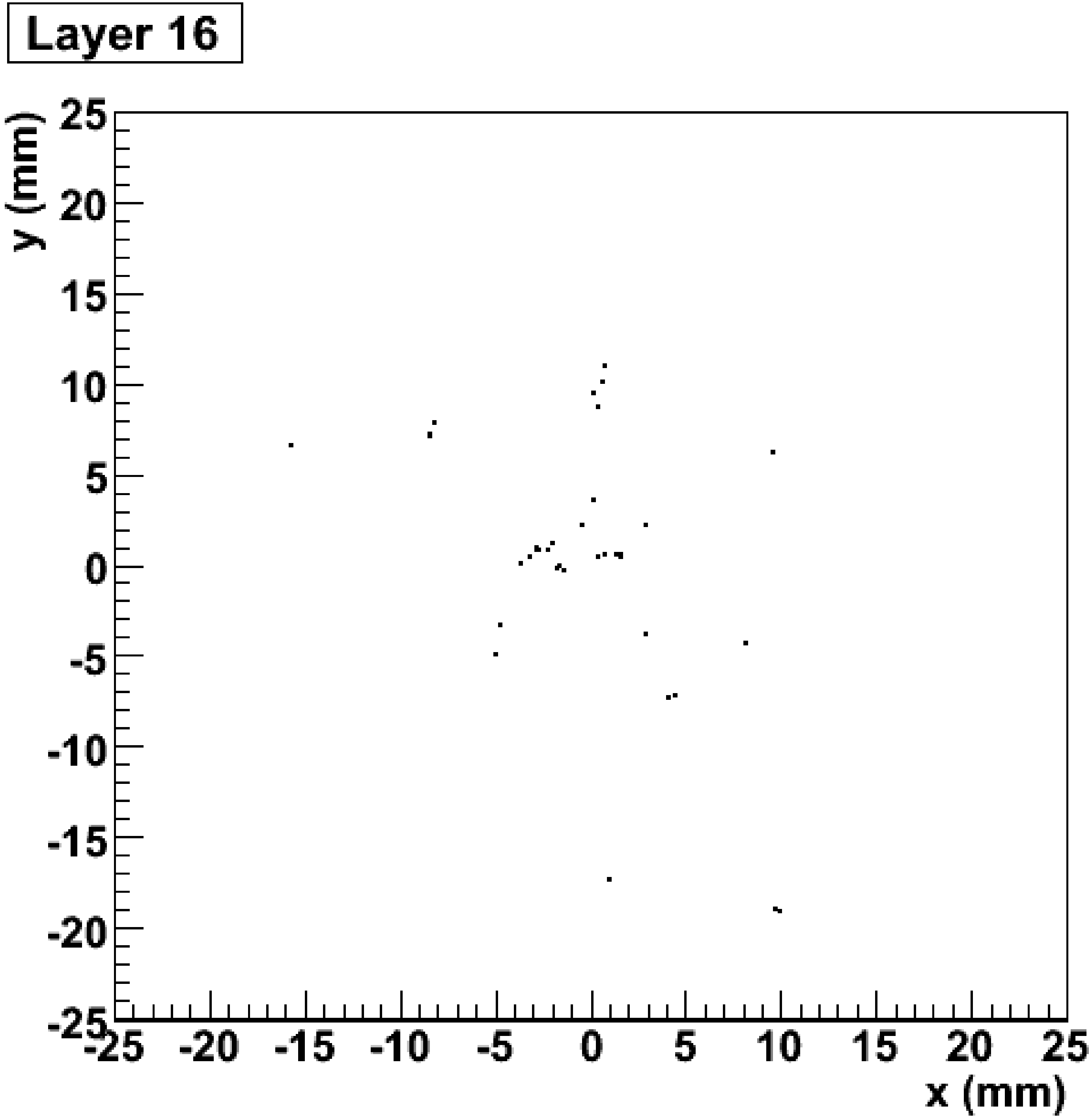
-25 -20 -15 -10 -5 0 5 10 15 20 25
x (mm)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y (mm)
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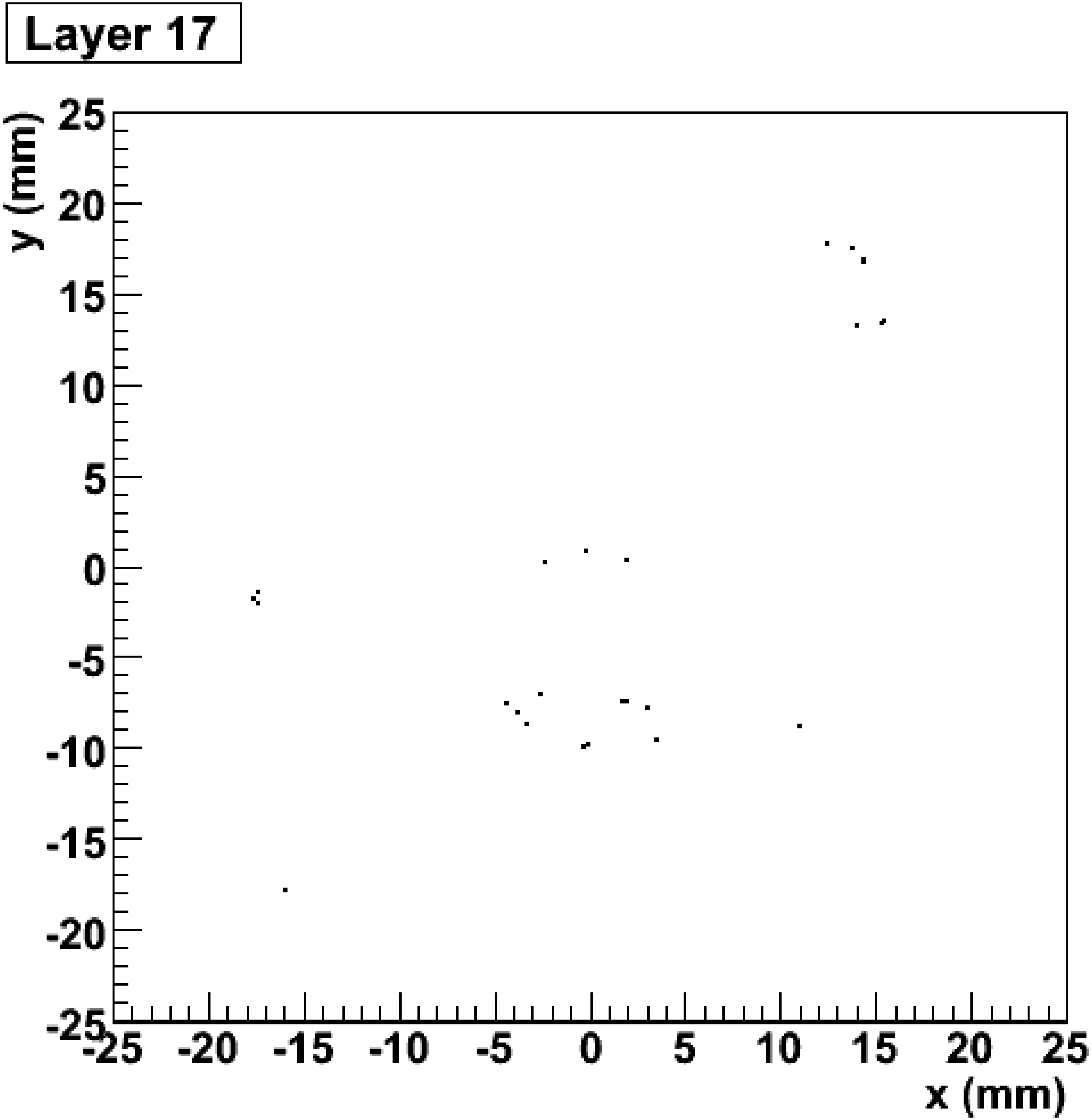
0
5
10
15
20
25
x (mm)



Layer 17
y (mm)
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-20
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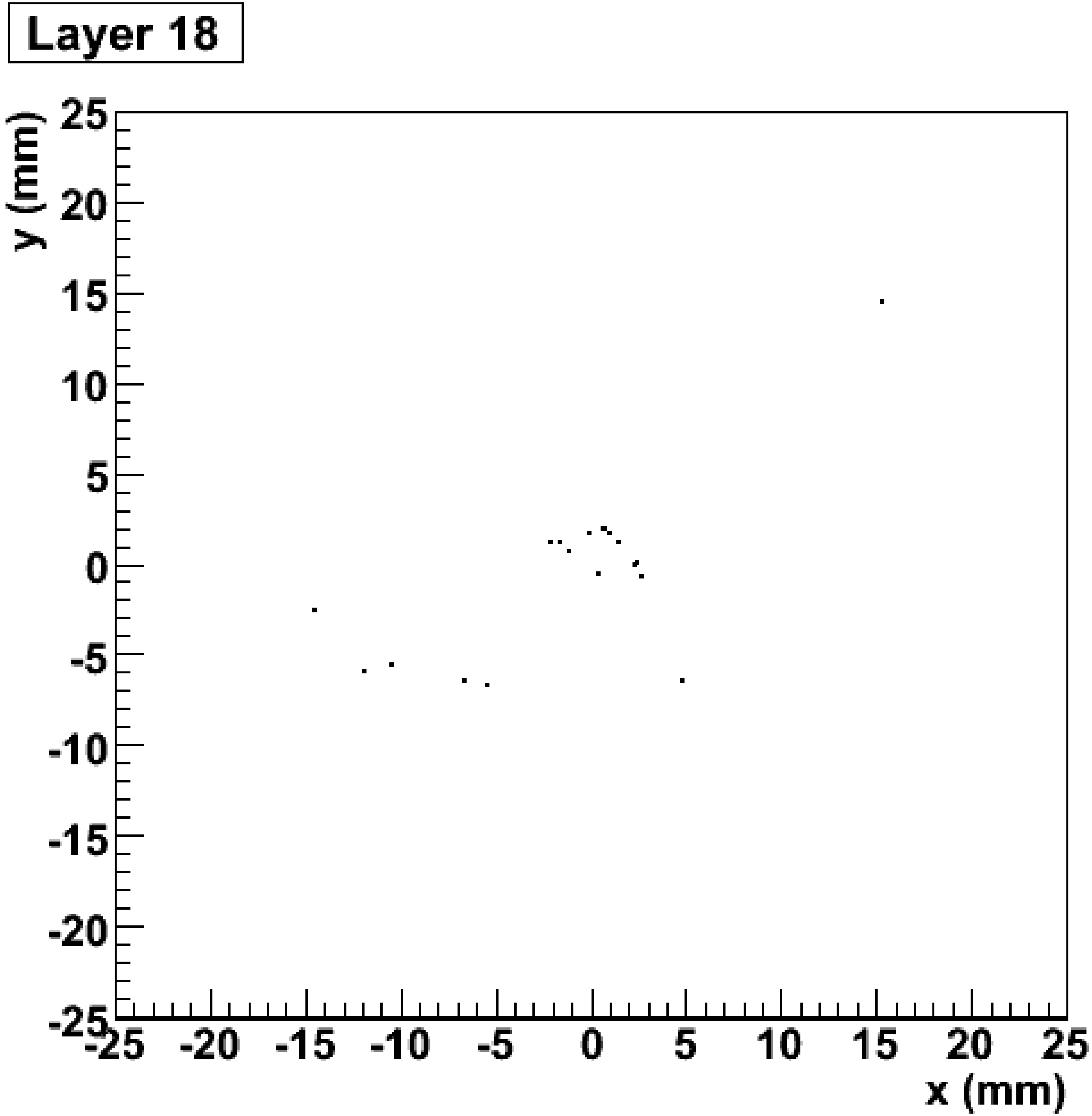
-25 -20 -15 -10 -5 0 5 10 15 20 25
x (mm)


Layer 18
y (mm)
x (mm)
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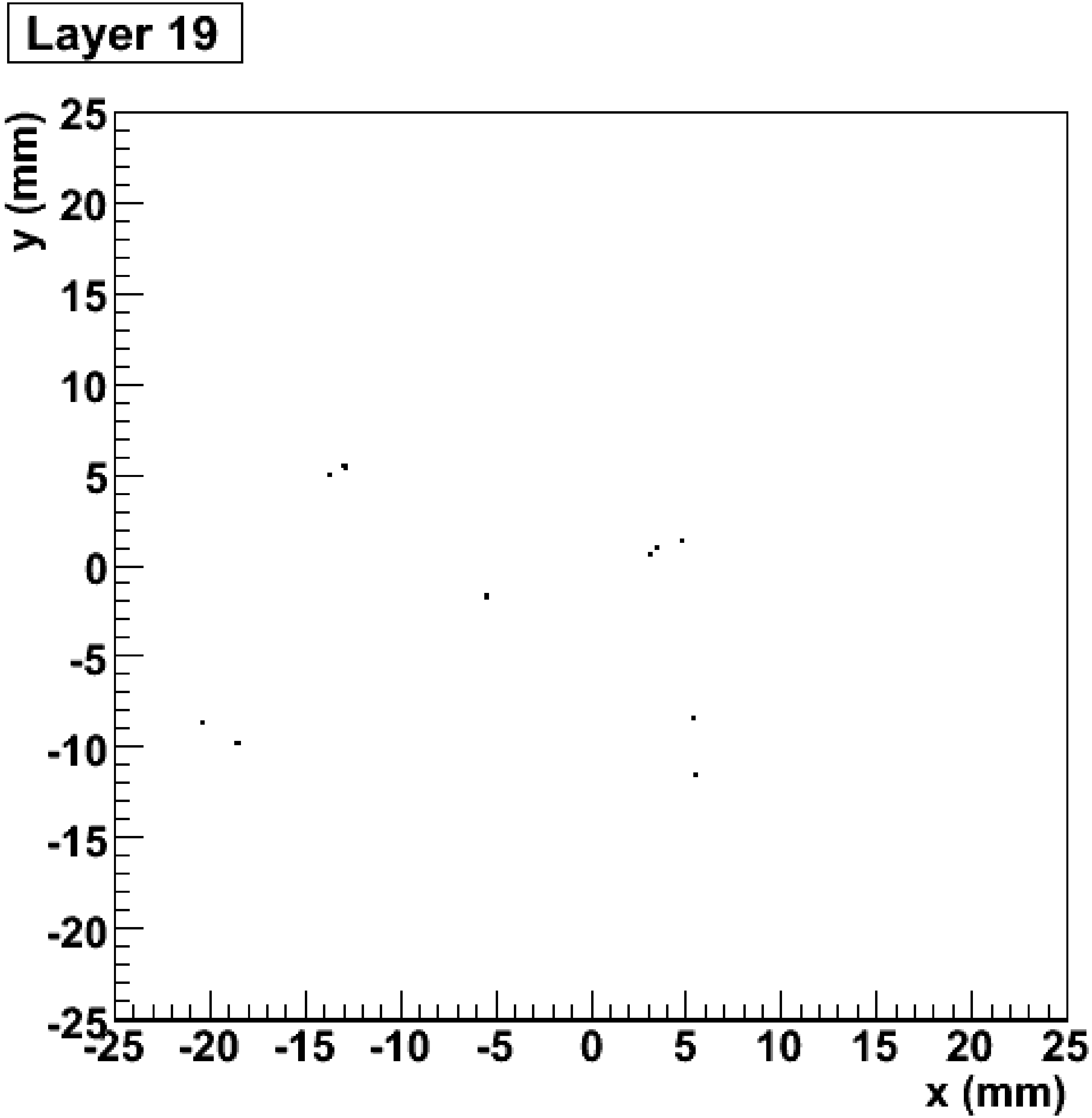
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y (mm)
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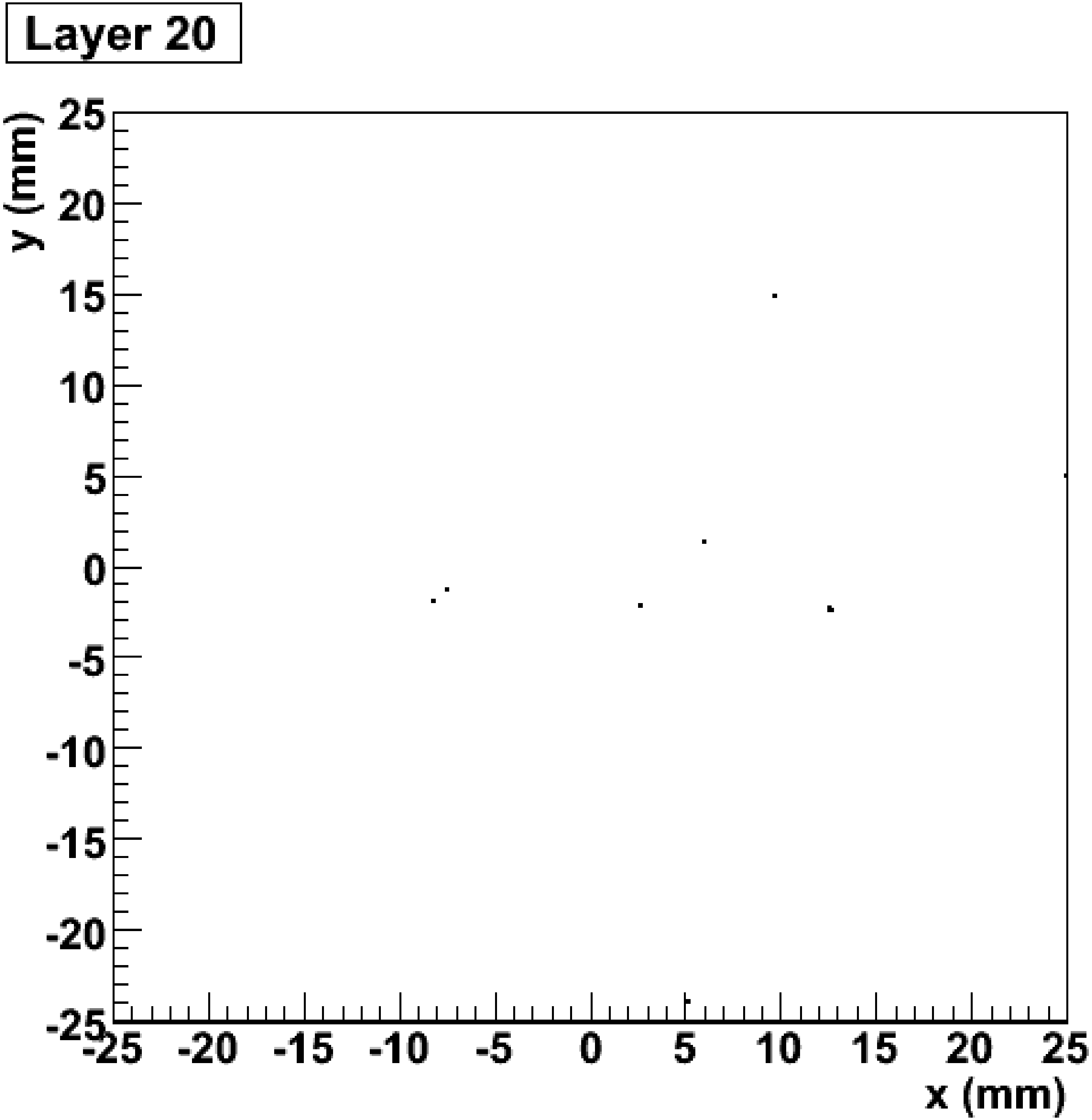
20
25
x (mm)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y (mm)
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-15
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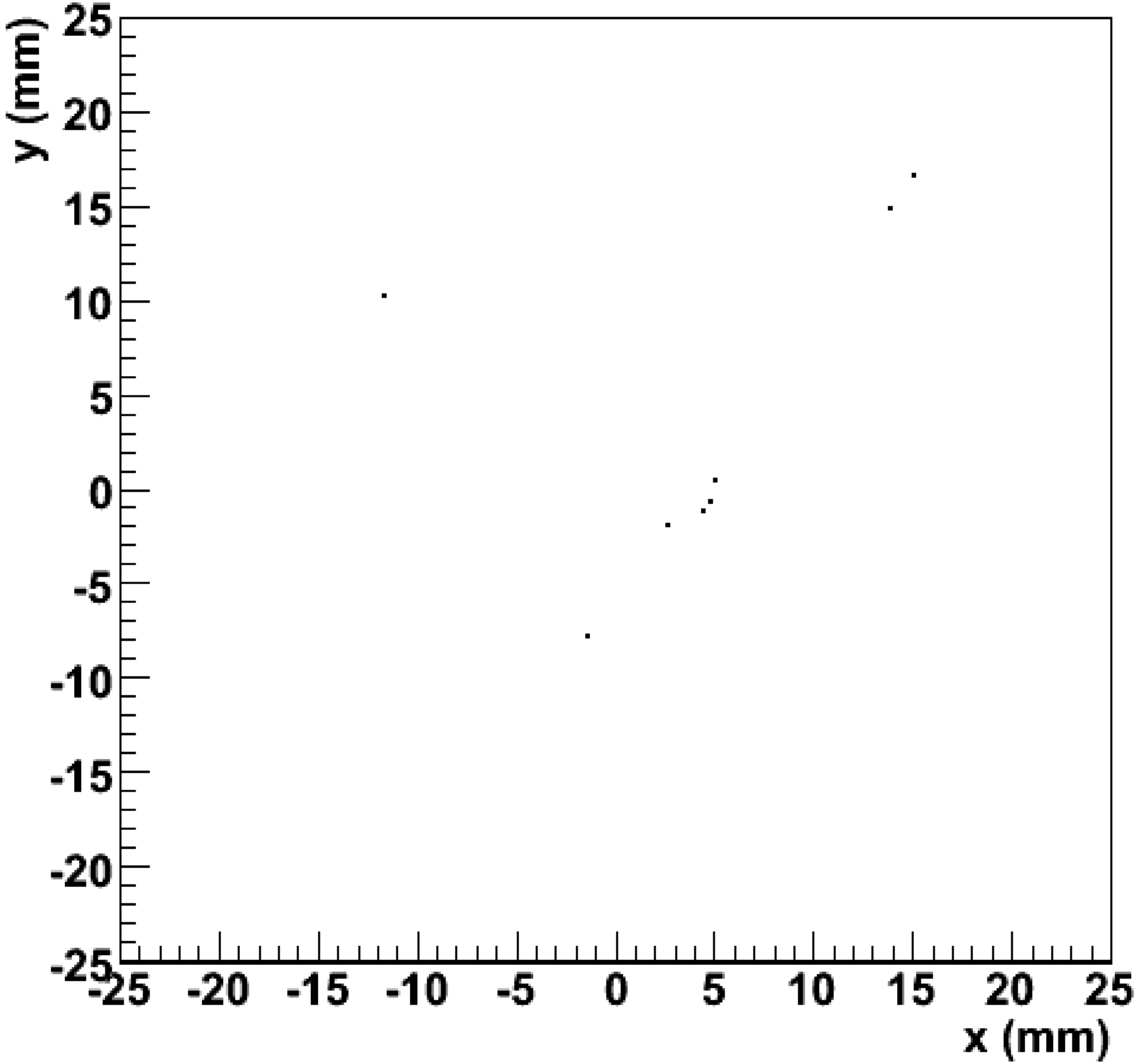
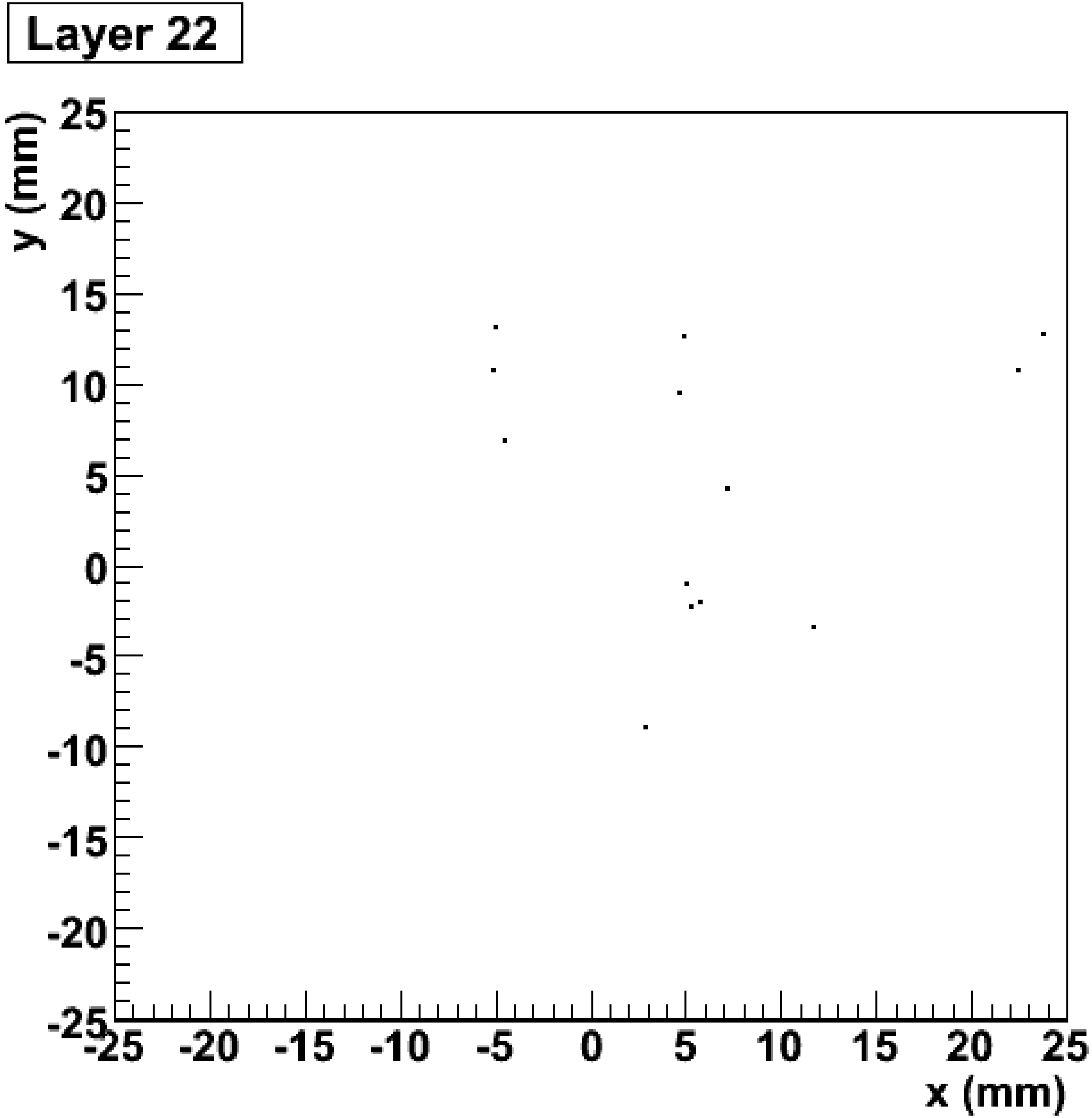
-5
0
5
10
15
20
25
x (mm)

Layer 21




Layer 22
y (mm)
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-5
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-15
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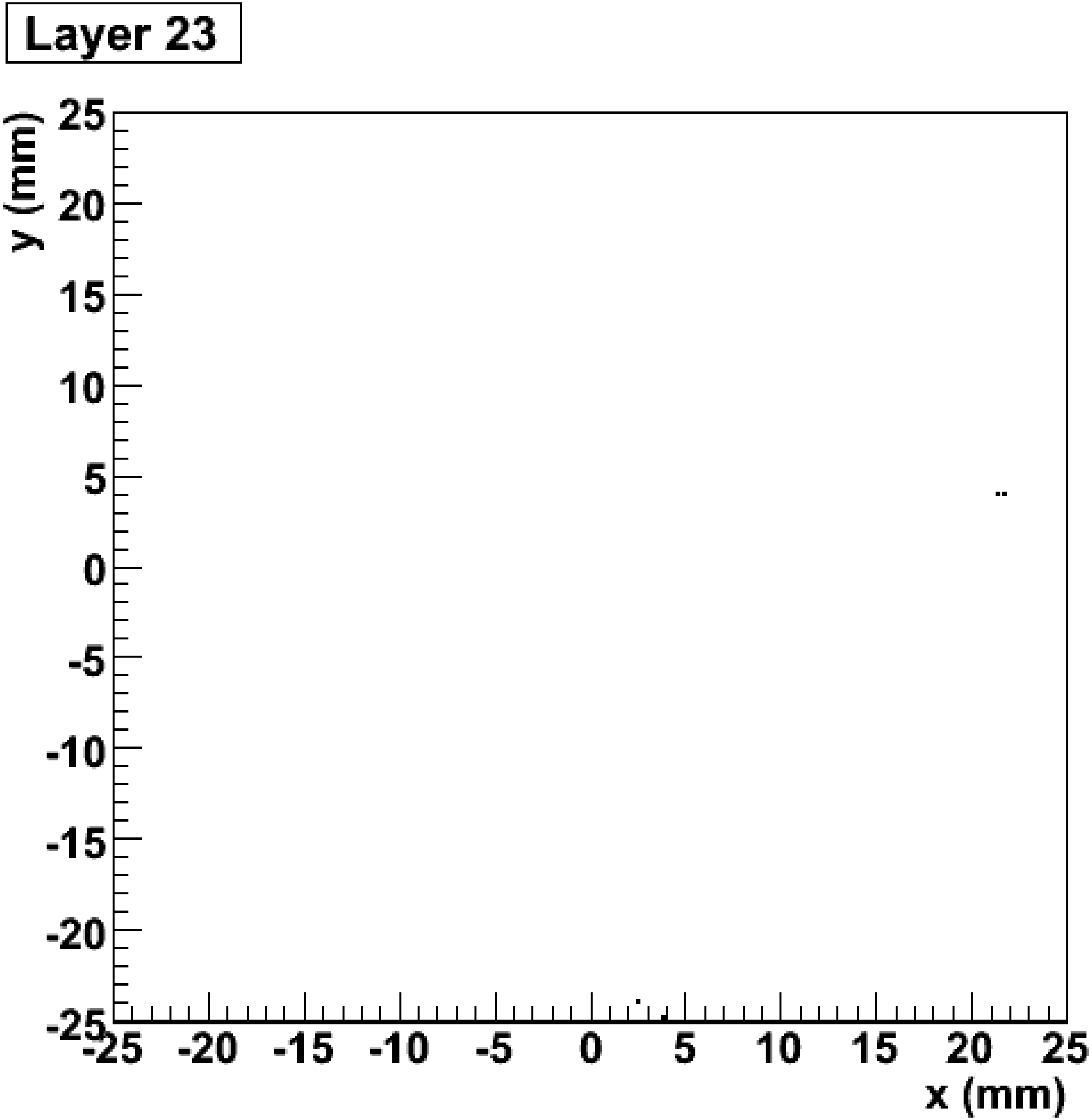
-25
-20
-15
-10
-5
0
5
10
15
20
25
x (mm)


Layer 23
y (mm)
25
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15
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-5
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-25
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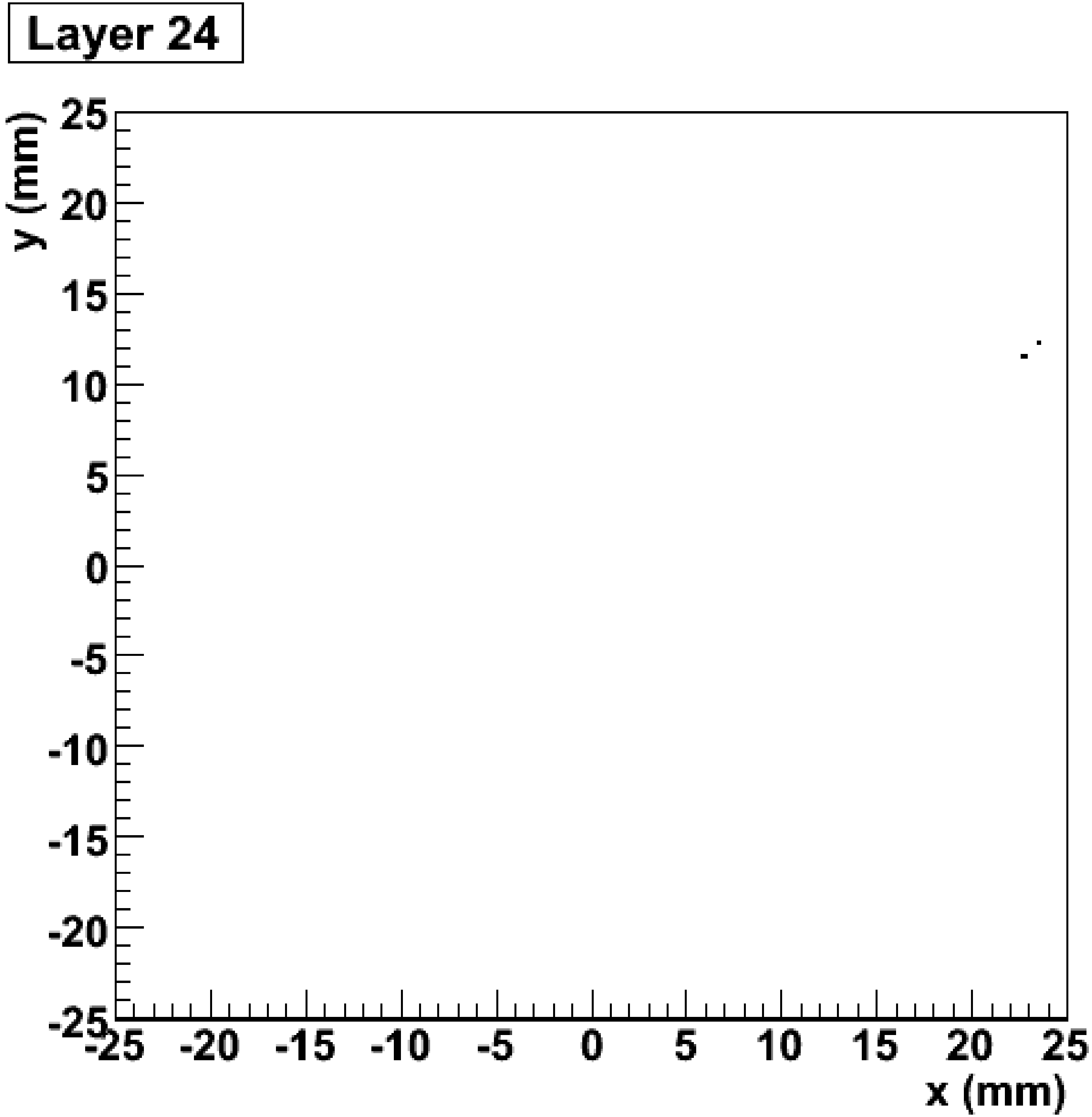
-20
-15
-10
-5
0
5
10
15
20
25
x (mm)



Layer 24
y (mm)
25
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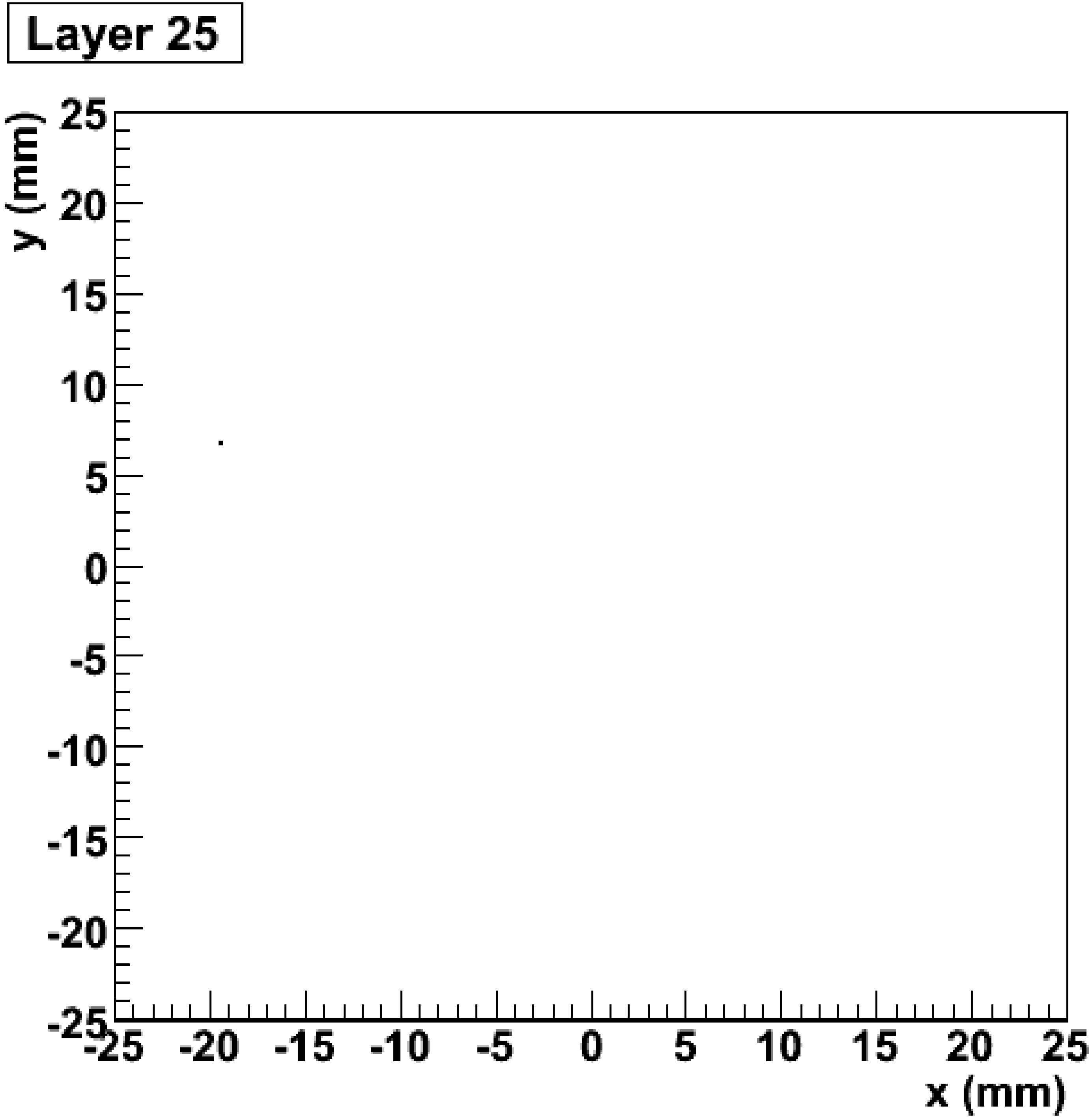
-5
-10
-15
-20
-25
-25 -20 -15 -10 -5 0 5 10 15 20 25
x (mm)


Layer 25
y (mm)
25
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-5
-10
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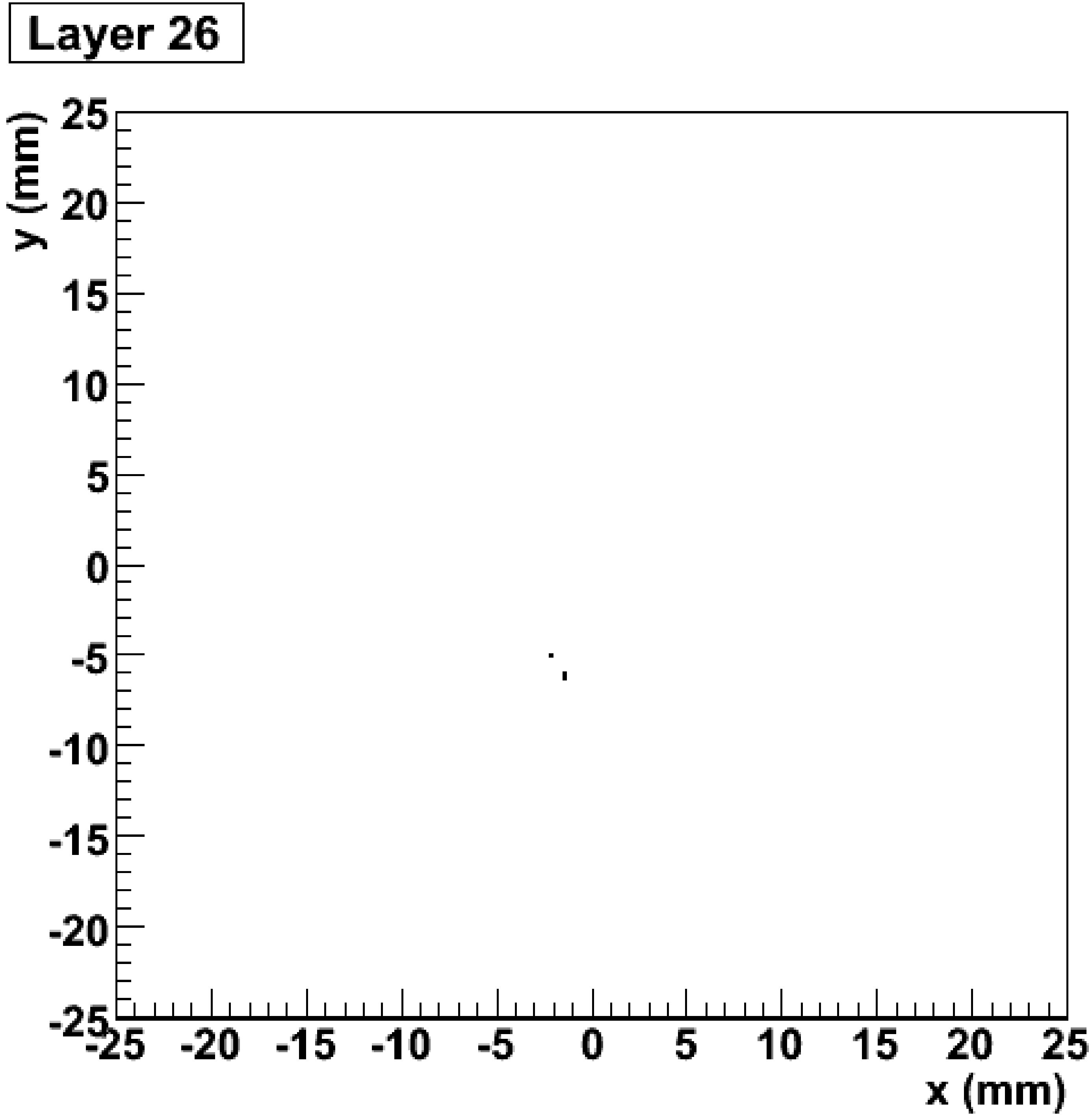
-25
-20
-15
-10
-5
0
5
10
15
20
25
x (mm)


Layer 26
y (mm)
25
20
15
10
5
0
-5
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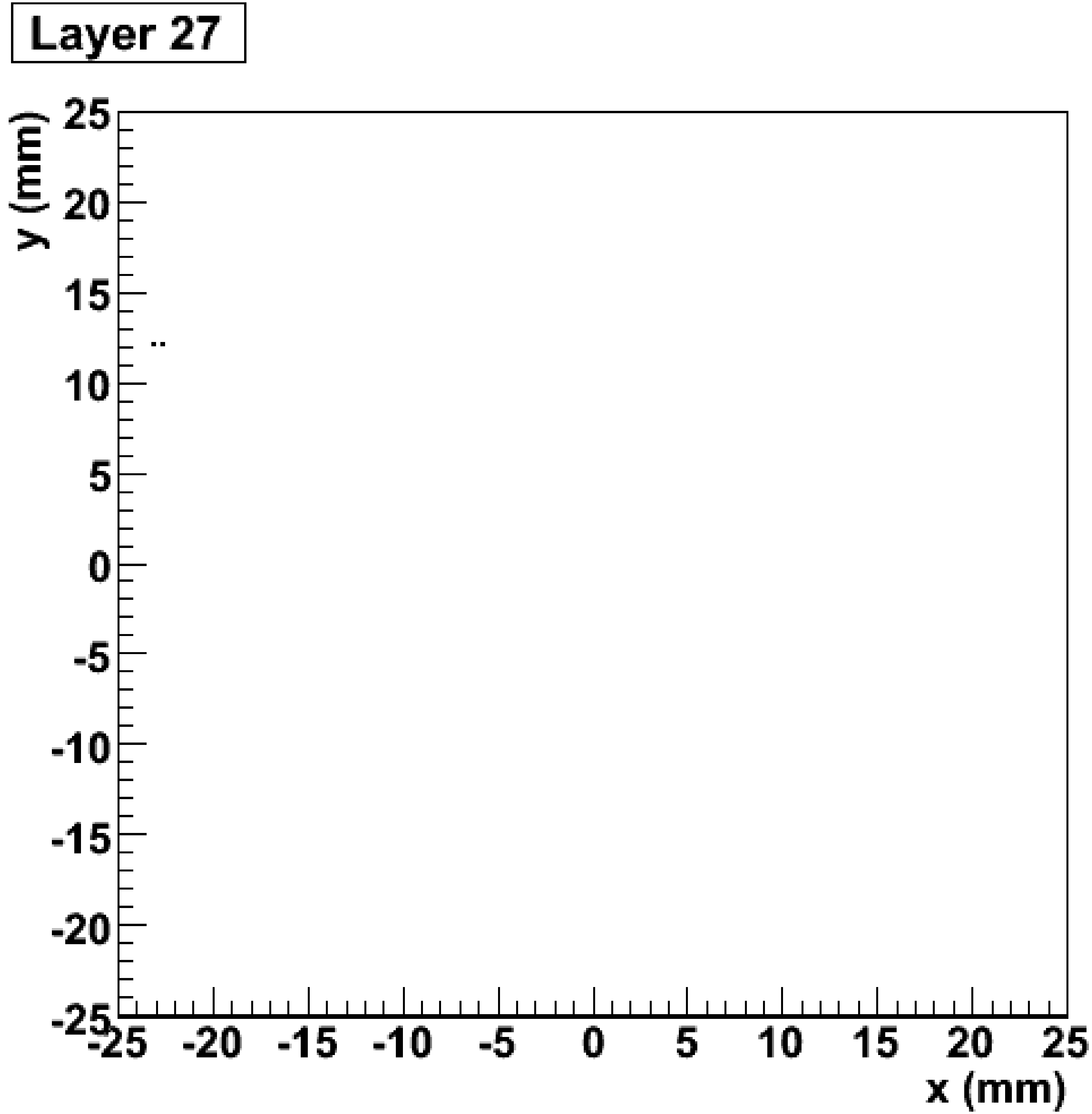
-10
-5
0
5
10
15
20
25
x (mm)


Layer 27
y (mm)
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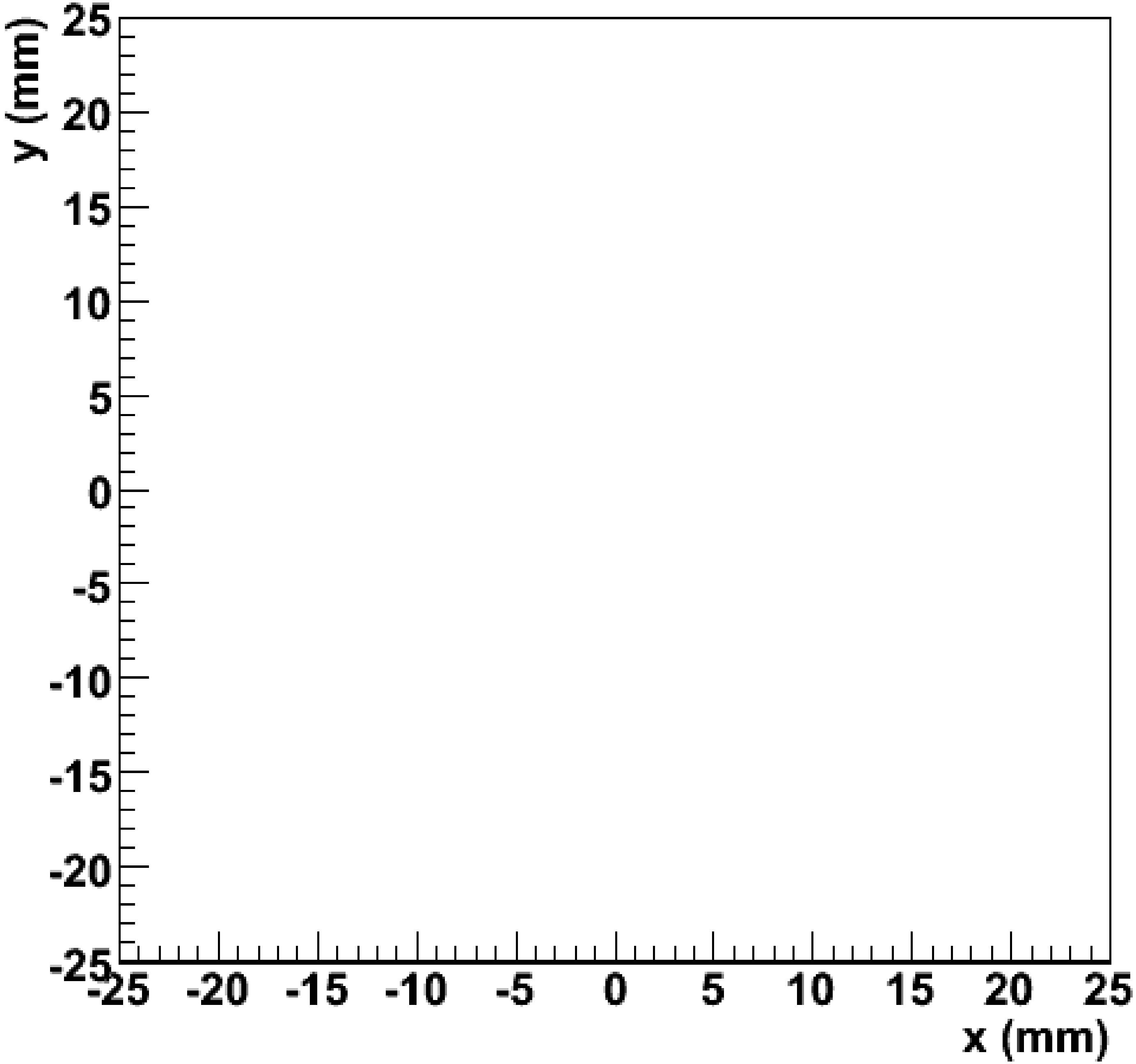
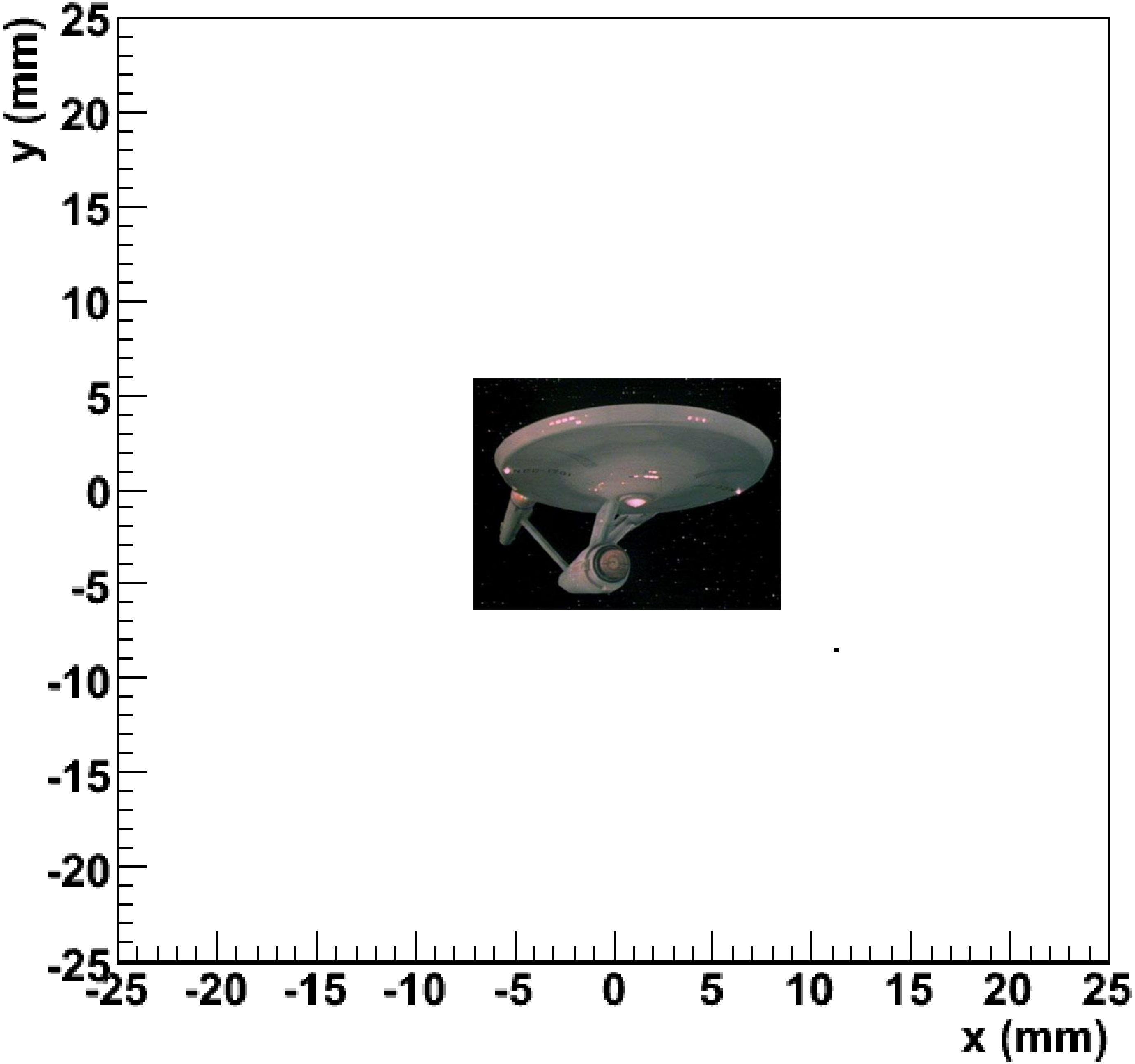
-20
-15
-10
-5
0
5
10
15
20
25
x (mm)

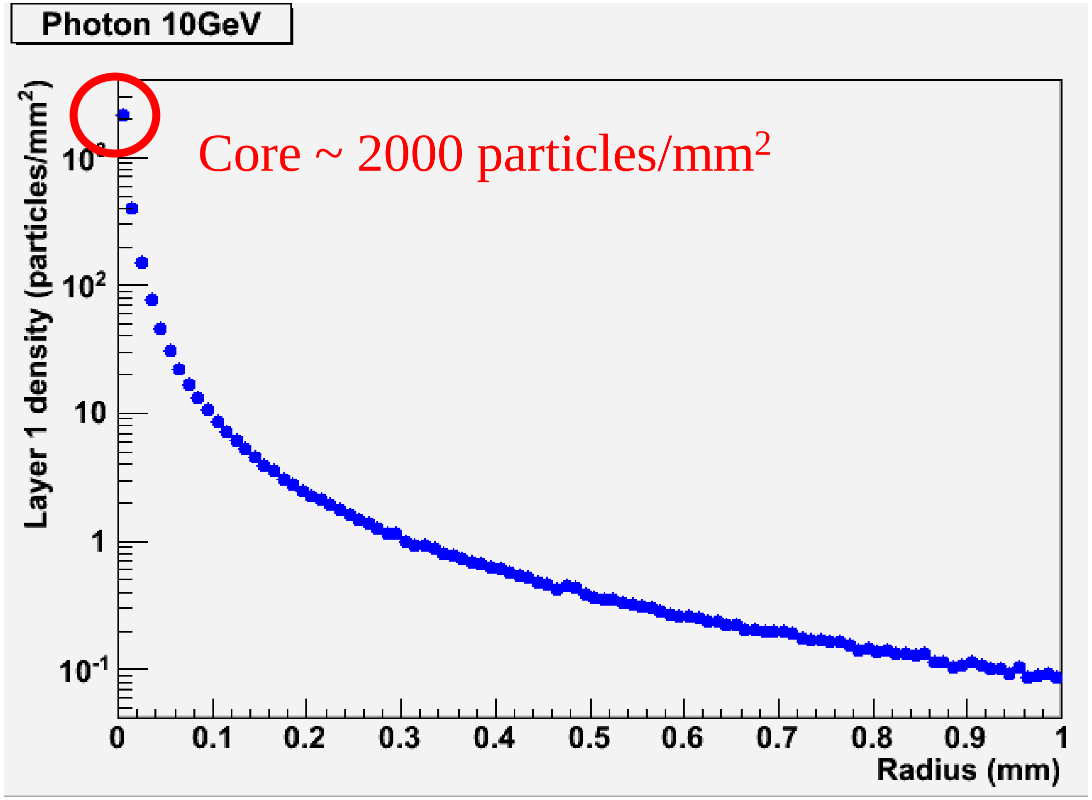
Layer 28



Layer 29

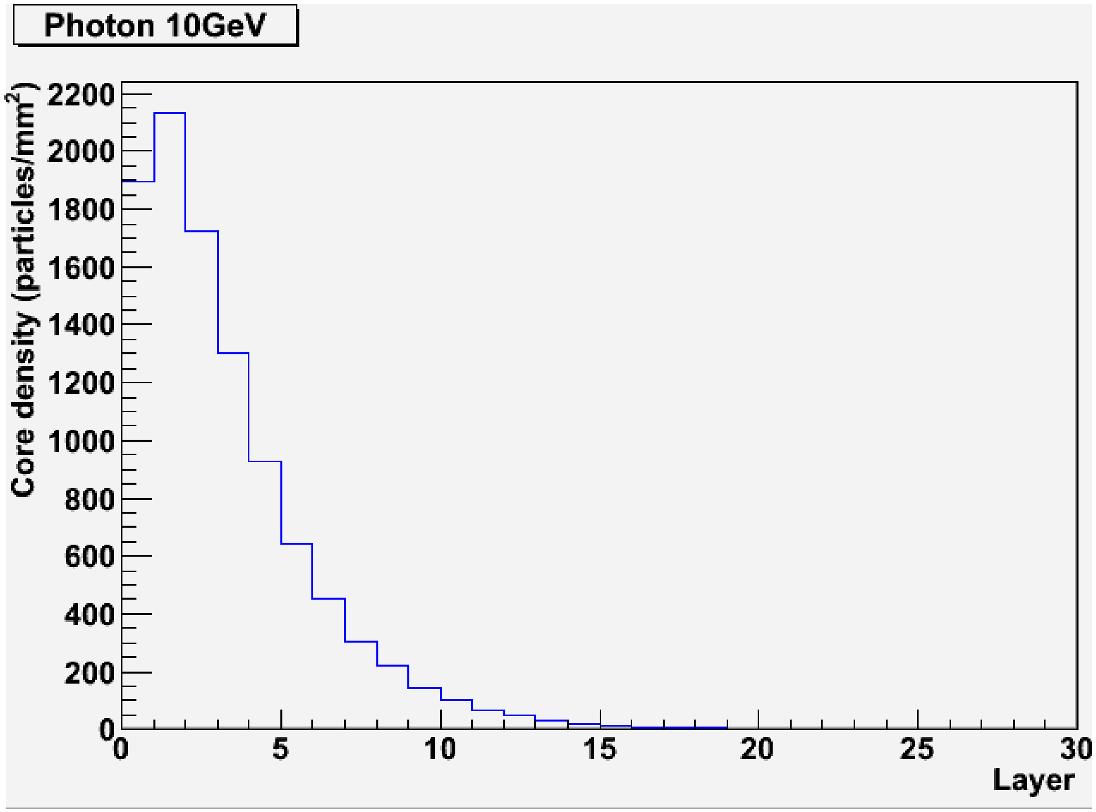


Particle density vs radius



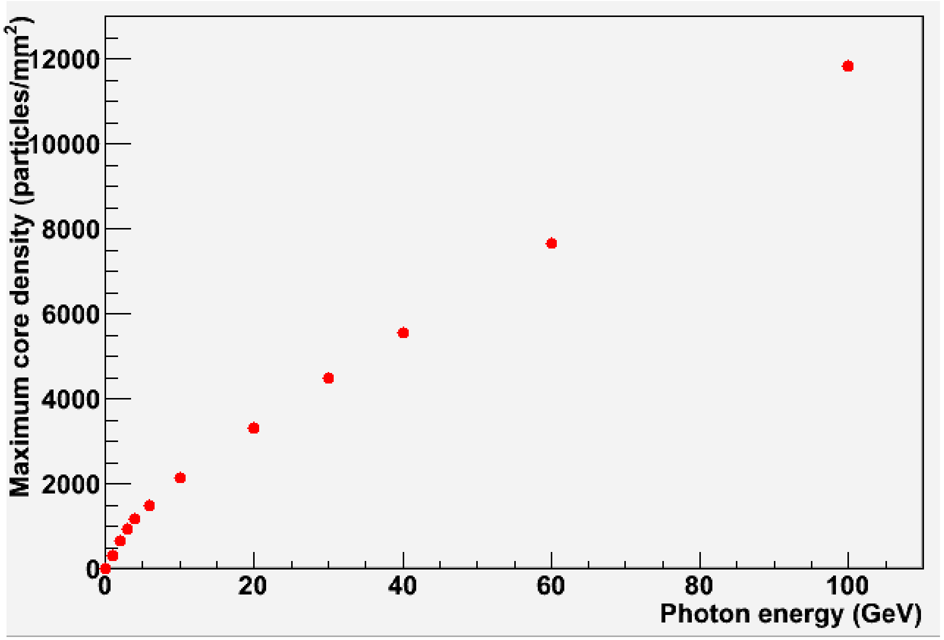
- Area of first bin $\pi r^2 \sim 3\times10^{-4}$ mm^2
- Only ~0.6 particles/event in this bin
- Density in other bins falls off exponentially

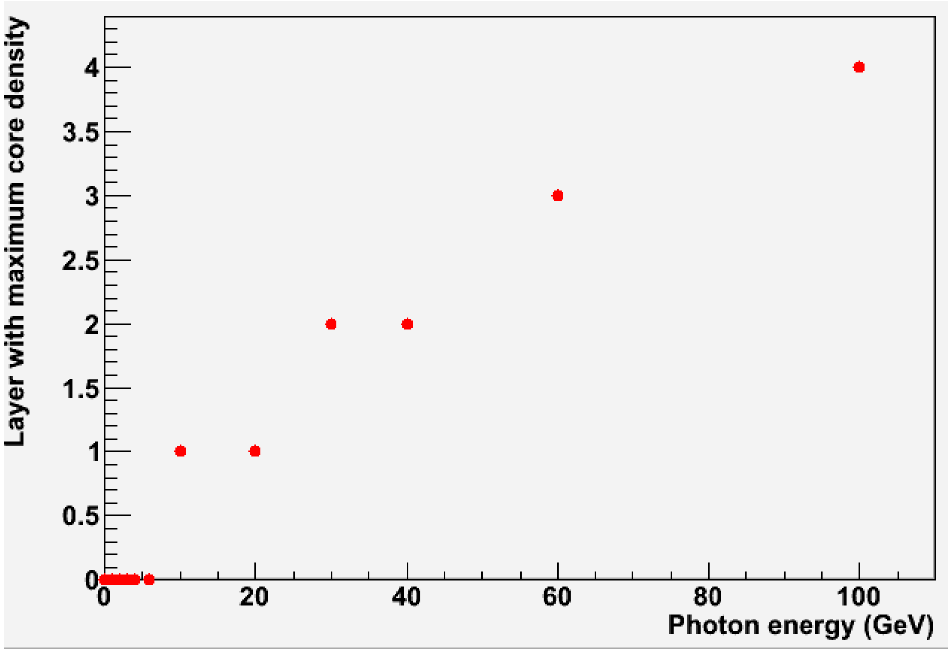
Core particle densities



- Core density is balance of
  - Increasing number of particles
  - Increasing transverse spread
- Spread wins; core density is highest in first few layers
  - Absolute number of particles is low here
- Note, peak in density is NOT at shower maximum, layer ~11

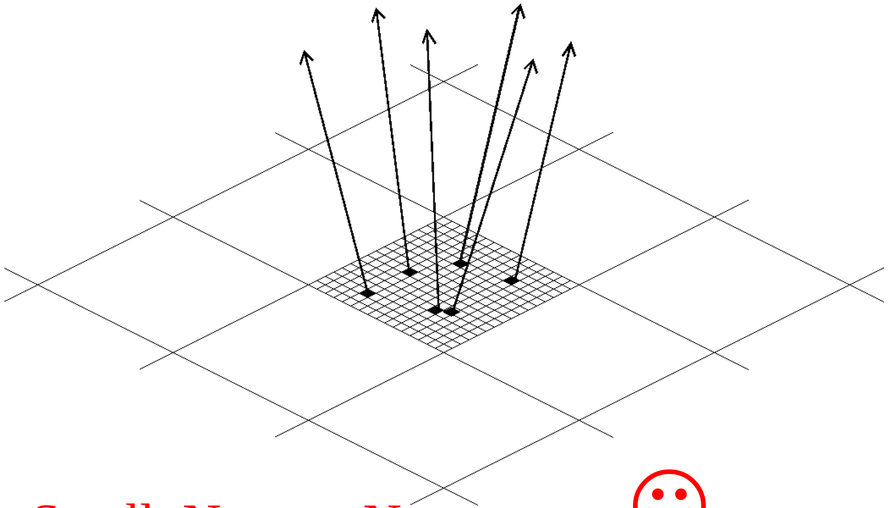
Core particle density vs energy



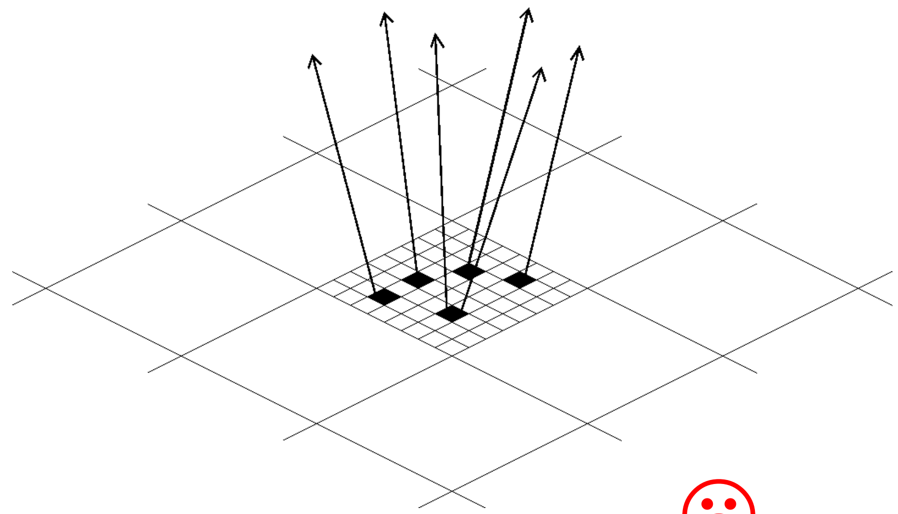


Effect of pixellation

- If pixels too big, probability of two particles in one pixel is higher



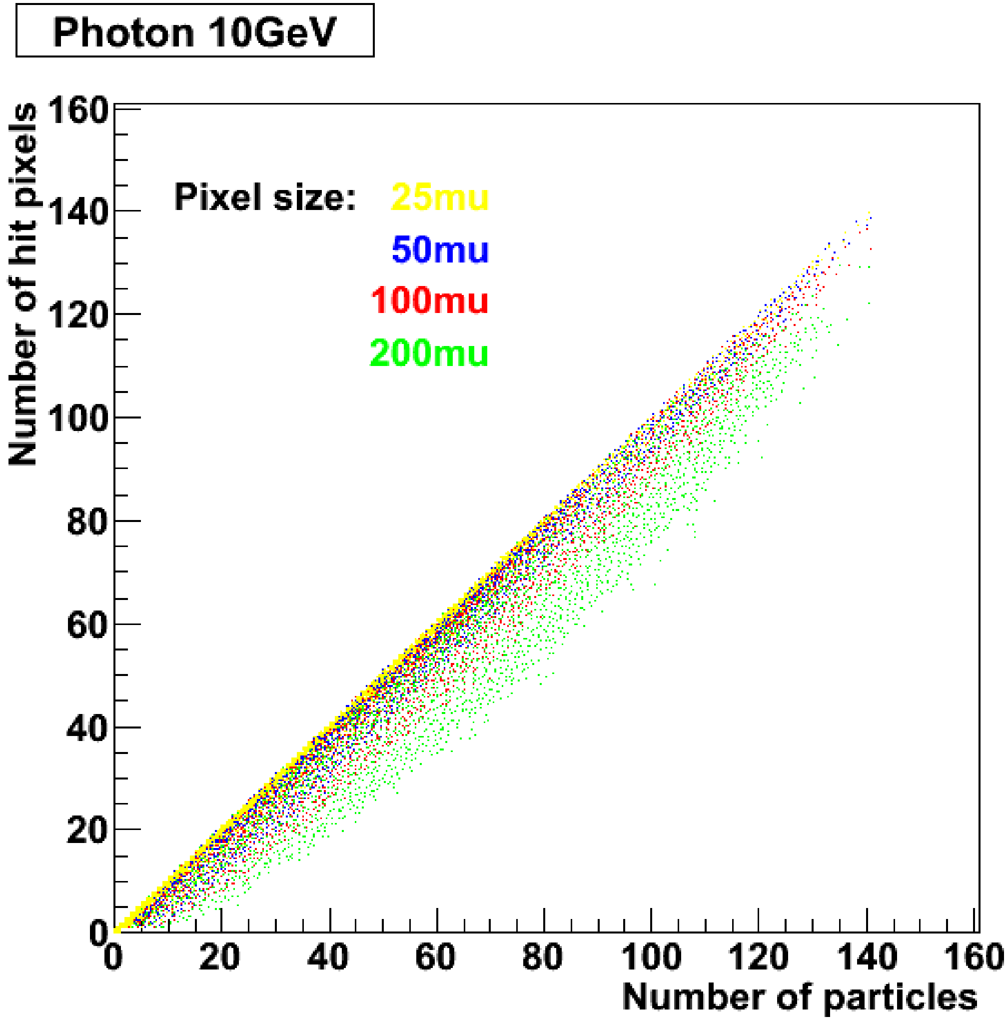
Small: $N_{pixels} = N_{particles}$ ☺



Big: $N_{pixels} < N_{particles}$ ☹

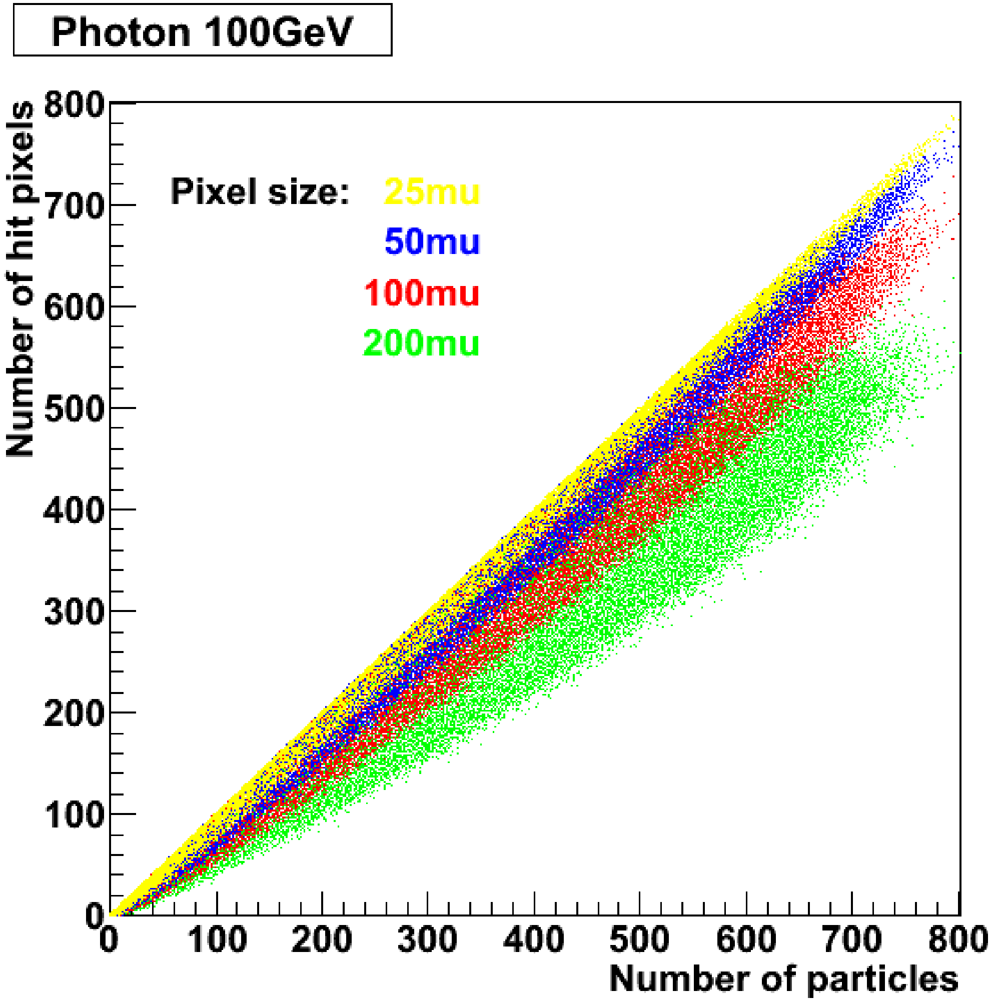
Effect of pixellation

- Compare original number of particles with number of hit pixels

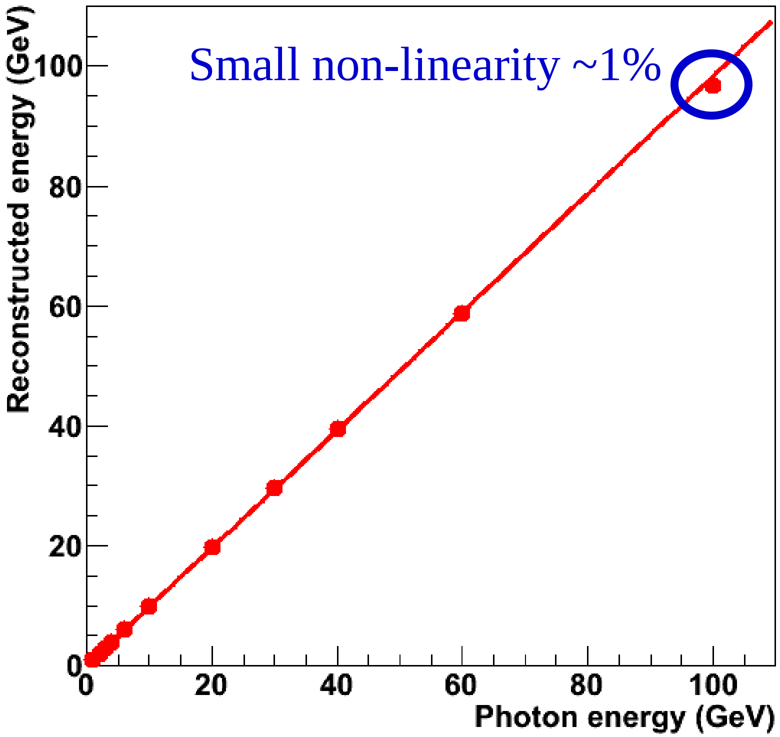


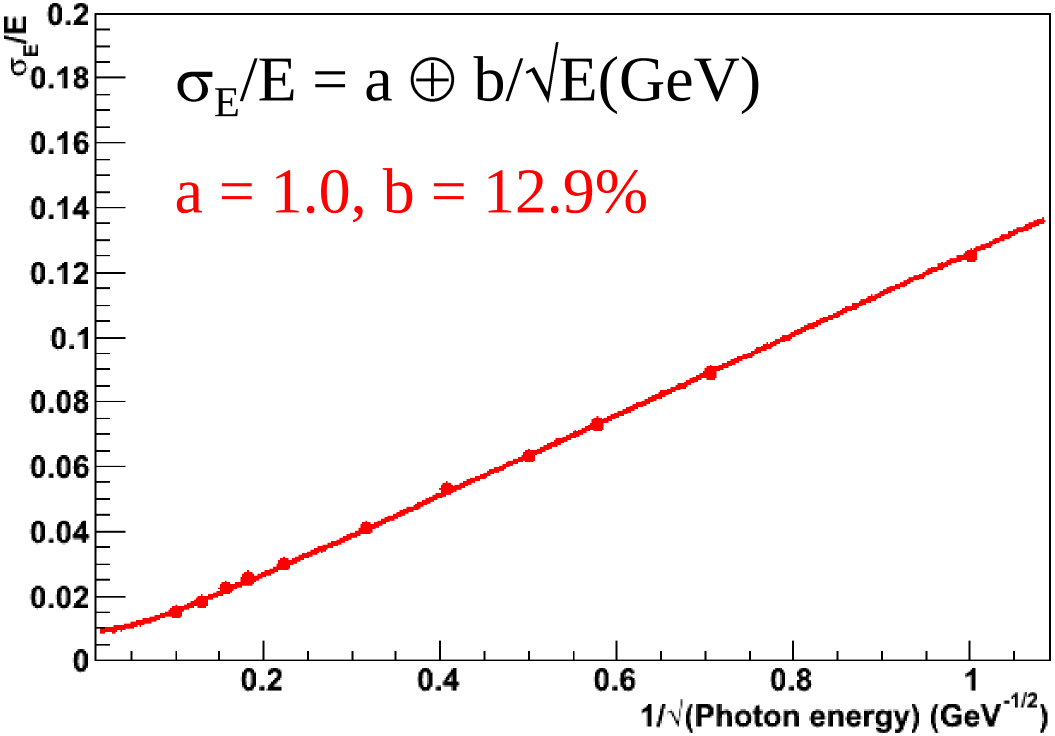
Effect of pixellation

- Conclusion: 50µm is sufficiently small
- Factor 100 smaller than AECAL cells of 5mm
- Cross-check
  - AECAL expects up to ~4000 particles per cell
  - Roughly ~0.4 particles per 50µm pixel
- Assume 50µm for rest of lectures



Pixellation effect: linearity and resolution

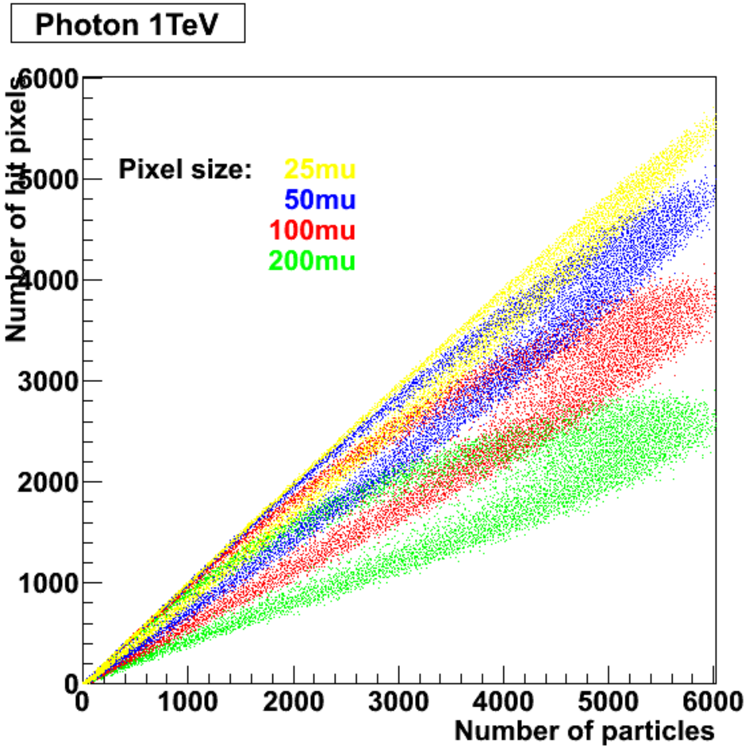


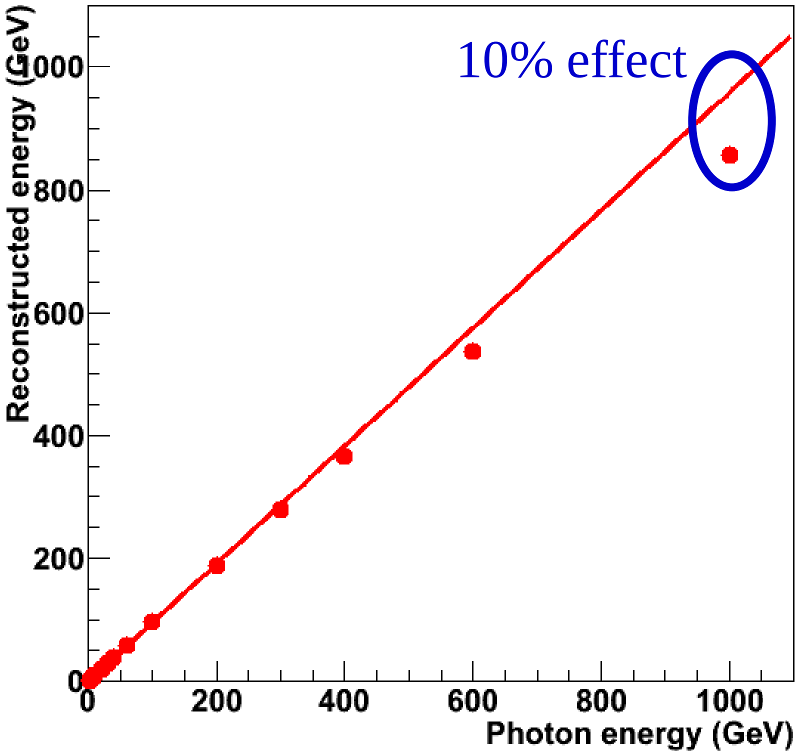


Effectively unchanged

CLIC energies

- Typical hadrons not 1TeV but for fun, see what happens at these energies...





Critical points

- Counting particles gives better resolution than energy deposited
- Core density is highest well before shower maximum
- Pixels of 50μm will give good performance up to at least 100GeV