Geant 4 simulation of the DEPFET beam test

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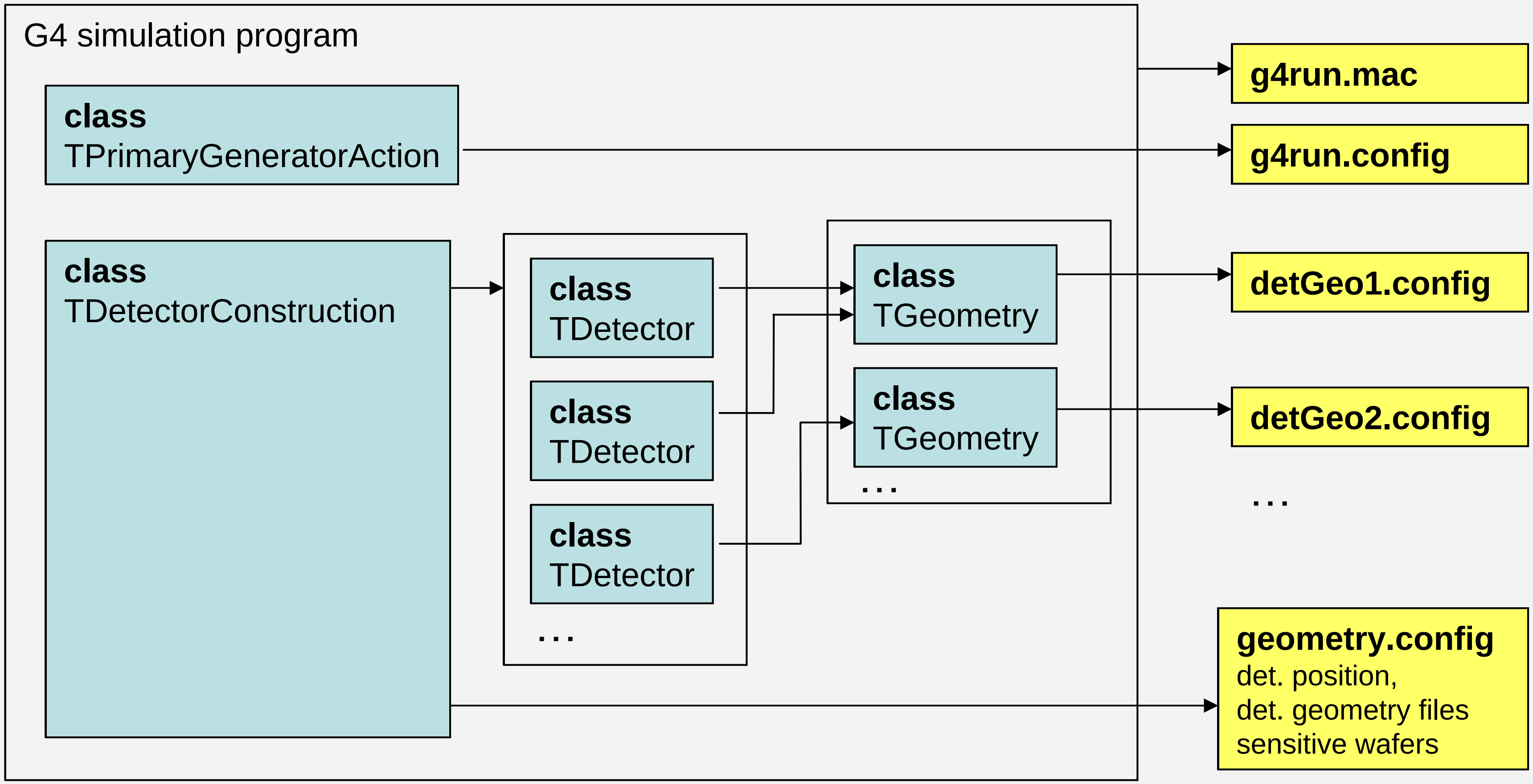
Index

- Geant 4 simulation program
- Model validation
- Geometry of the beam test
- Unscattered particles
- Electron beam simulation
  - Residual plots for 2 different geometries
  - Residual plots for 3 different window thickness
- CERN 180 GeV pion beam simulation
- The latest results
- Conclusions

Geant 4 simulation program

- More about Geant 4 framework at **www.cern.ch/geant4**
- C++ object oriented architecture
- Parameters are loaded from files



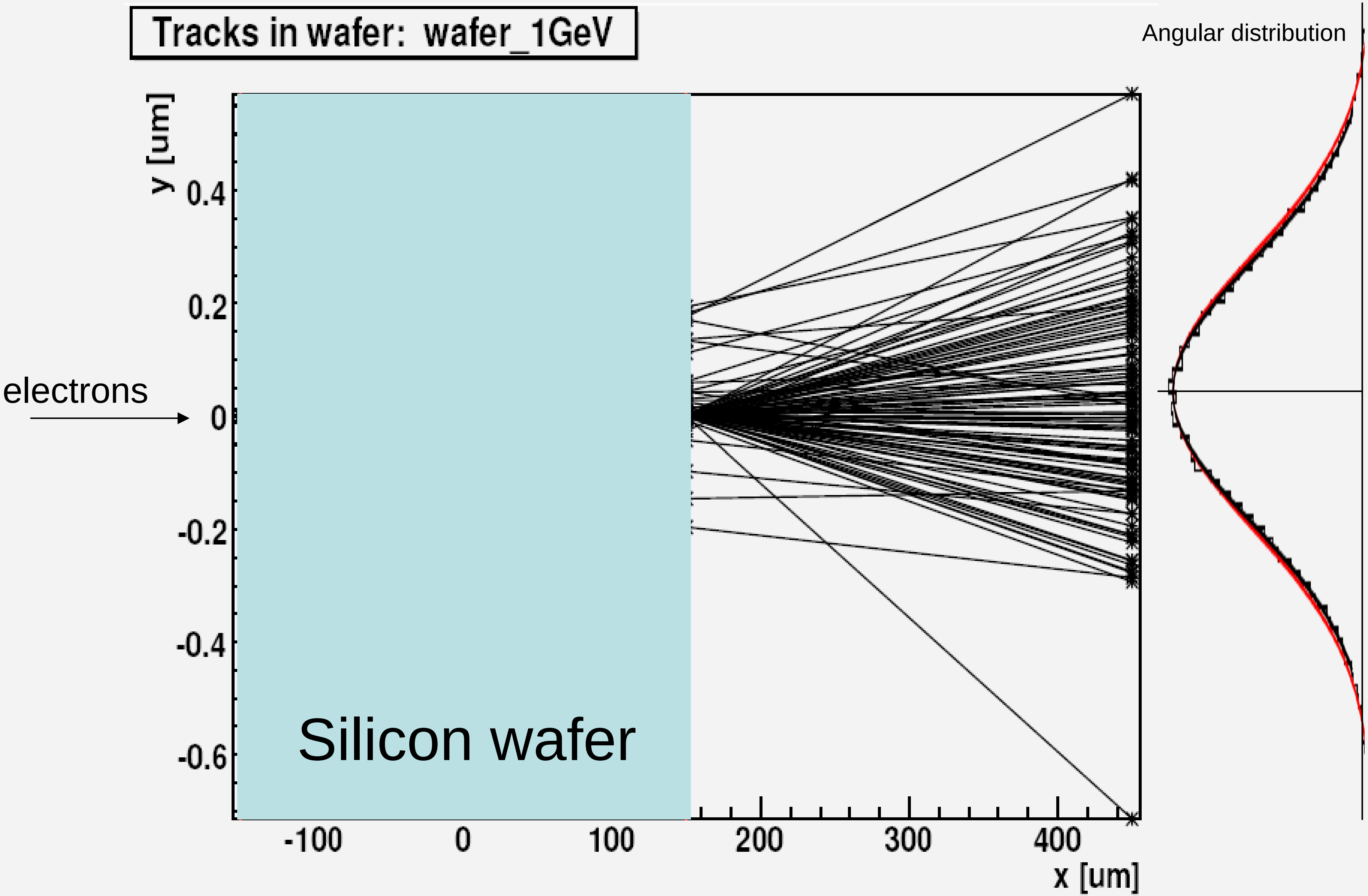
Model validation

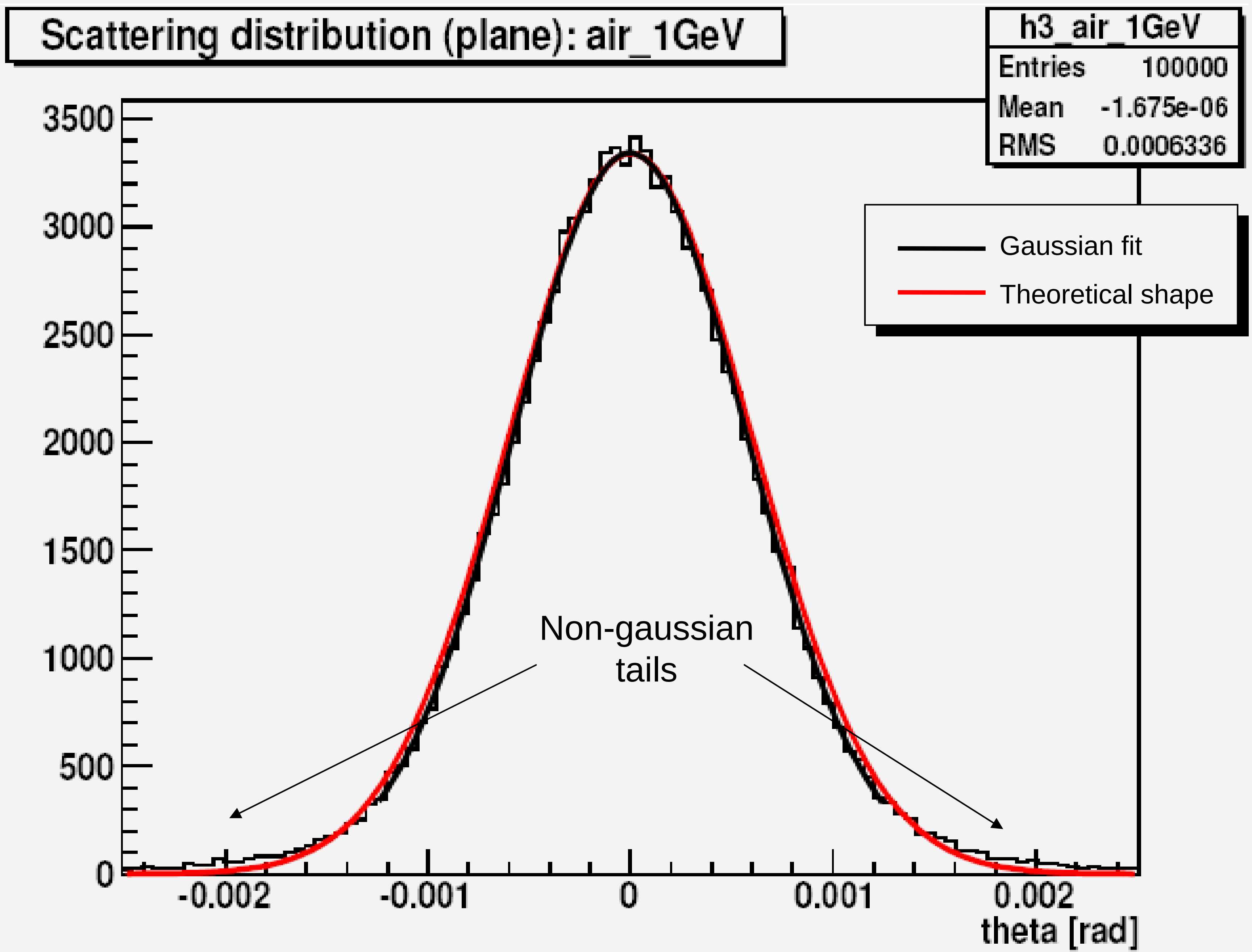
- Simulation of an electron scattering in the 300 μm silicon wafer
- Angular distribution histogram
- Comparison with a theoretical shape of the distribution. According to the Particle Physics Review it is approximately Gaussian with a width given by the formula:

$$\theta_0 = 13.6\text{MeV}\, z\sqrt{\frac{x}{X_0}}\left(1 + 0.038\ \ln\left(\frac{x}{X_0}\right)\right)\beta^{-1}c^{-1}p^{-1}$$

where *p*, β and *z* are the momentum, velocity and charge number, and x/X_0 is the thickness in radiation length. Accuracy of θ_0 is 11% or better.

Example of an electron scattering




Scattering distribution (plane): air_1GeV
h3_air_1GeV
Entries 100000
Mean -1.675e-06
RMS 0.0006336
Gaussian fit
Theoretical shape
Non-gaussian tails
3500
3000
2500
2000
1500
1000
500
0
-0.002
-0.001
0
0.001
0.002
theta [rad]

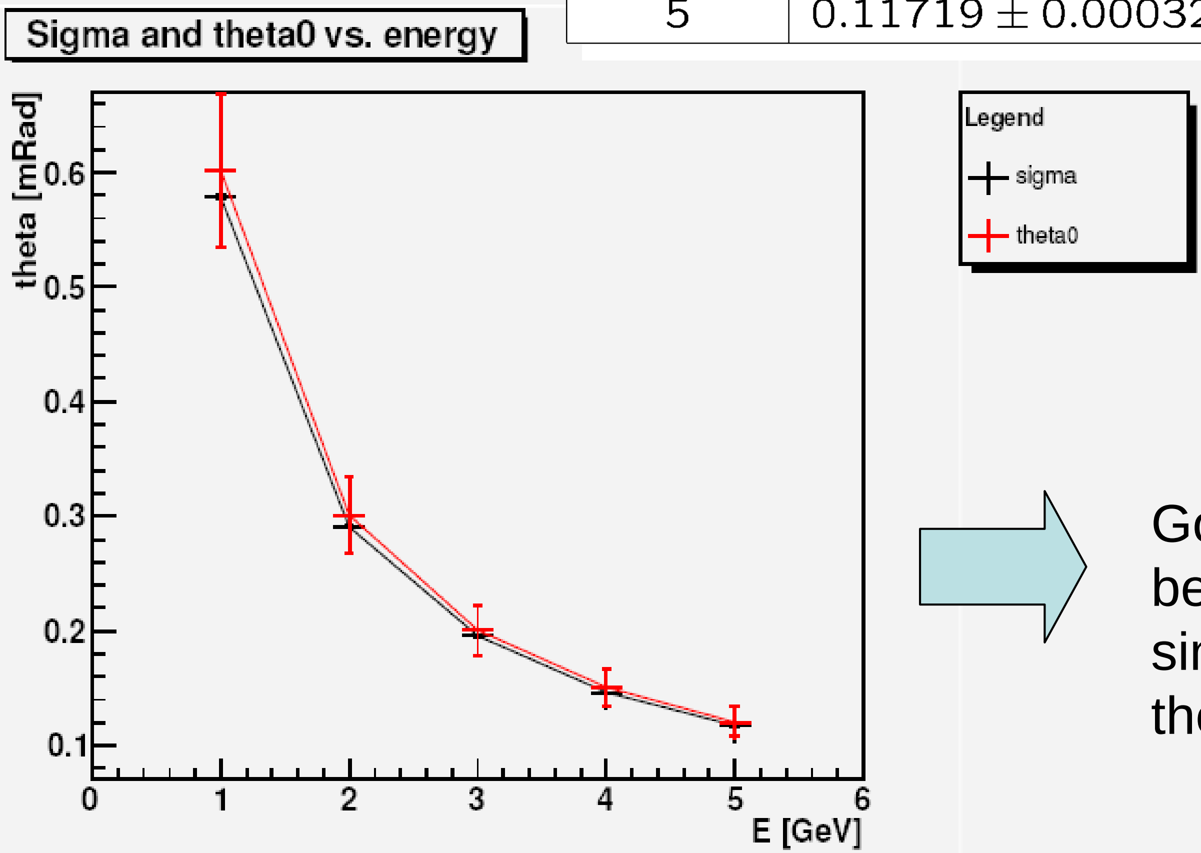
Results: simulation vs. theory

ϑ_0... width of the theoretical Gaussian distribution

σ...width of the fitted Gaussian

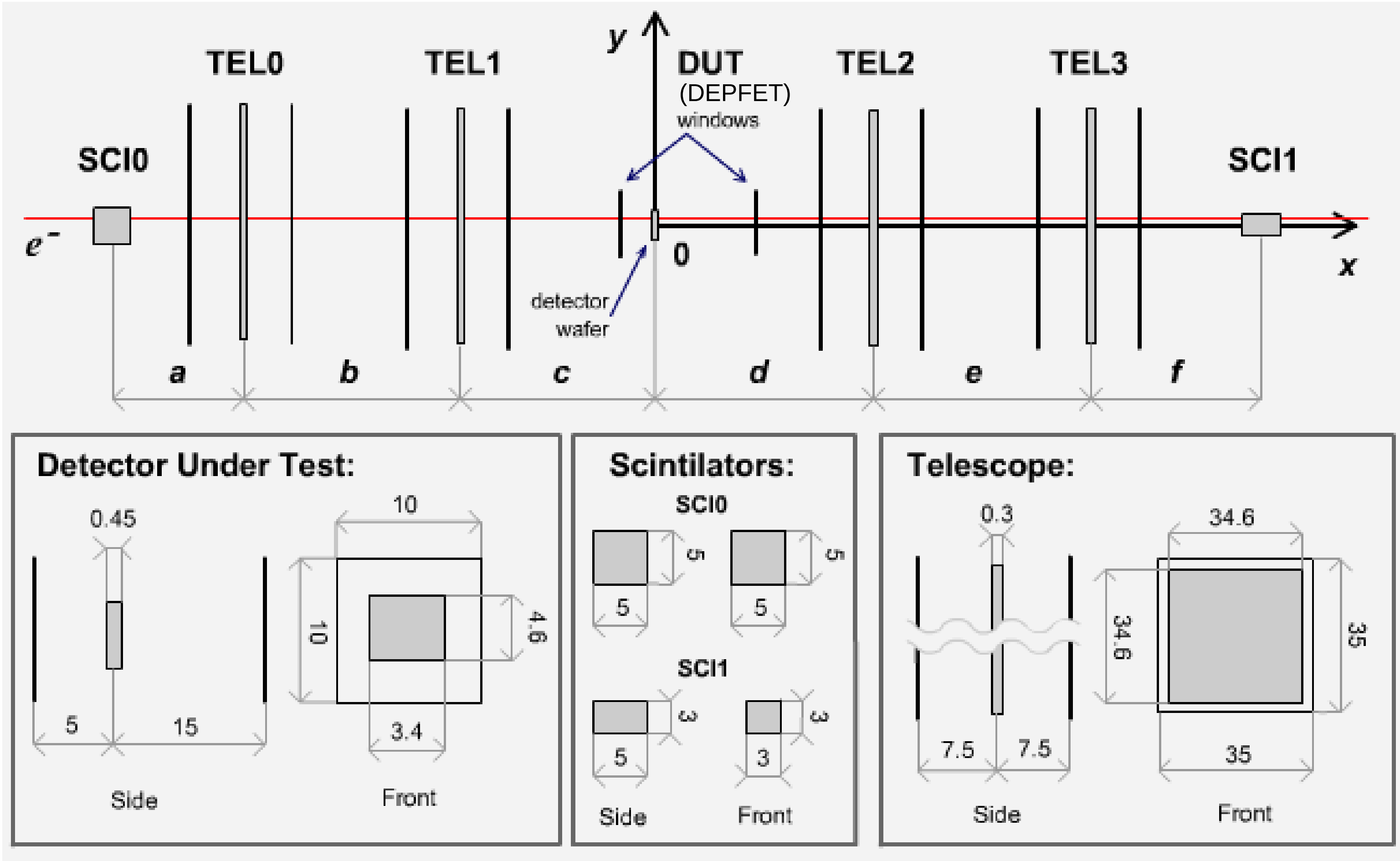
accuracy of ϑ_0 parametrisation (theory) is 11% or better

	Simulation	Theory	
E [GeV]	σ [mRad]	ϑ_0 [mRad]	ϑ_0/σ
1	0.57905 ± 0.00191	0.602 ± 0.066	0.96
2	0.29061 ± 0.00087	0.301 ± 0.033	0.97
3	0.19550 ± 0.00055	0.201 ± 0.022	0.97
4	0.14610 ± 0.00041	0.150 ± 0.017	0.97
5	0.11719 ± 0.00032	0.120 ± 0.013	0.97



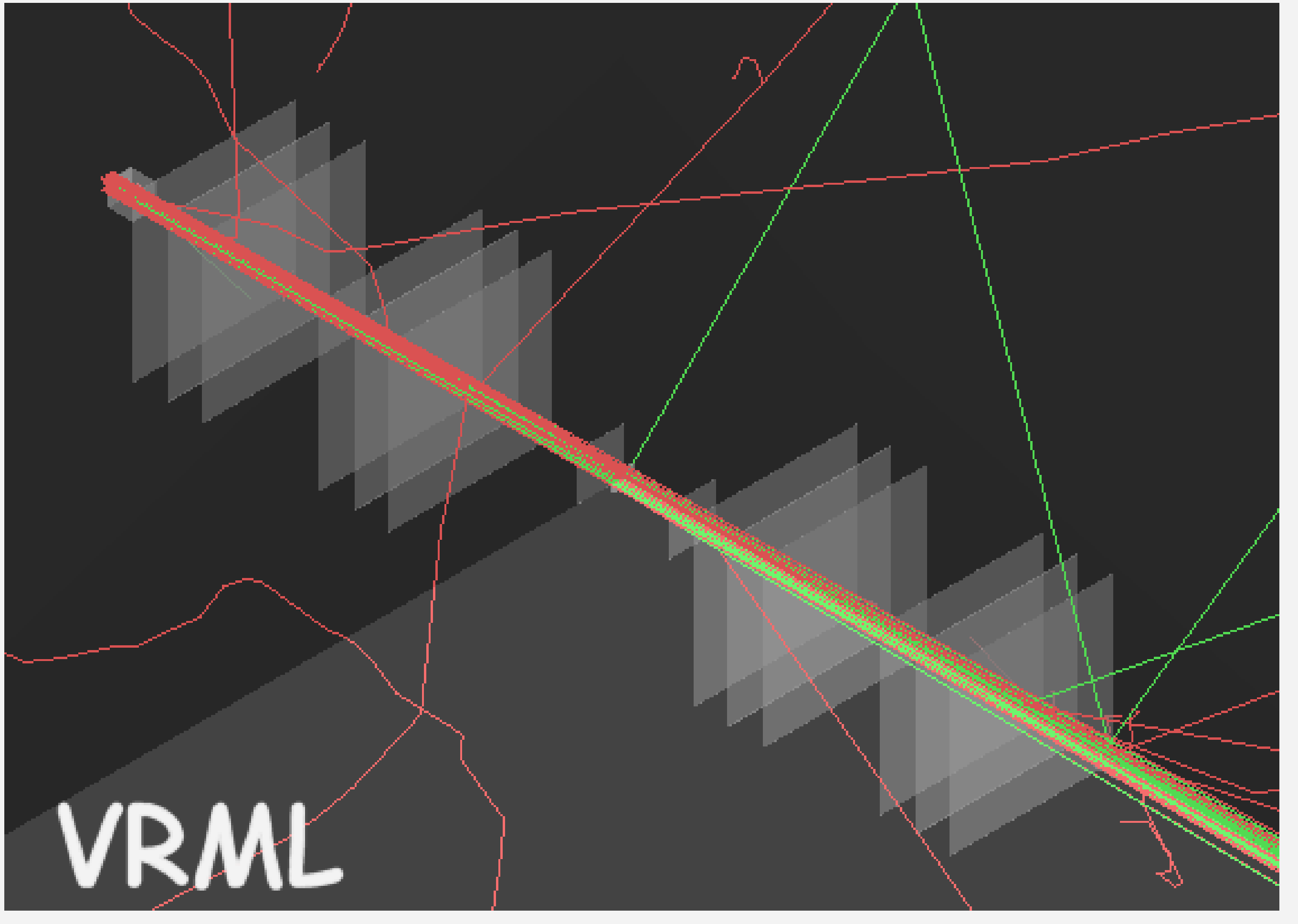
Good agreement between the G4 simulation and the theory

Geometry of the beam test



Electron beam: 3x3 mm^2, homogenous, parallel with x-axis

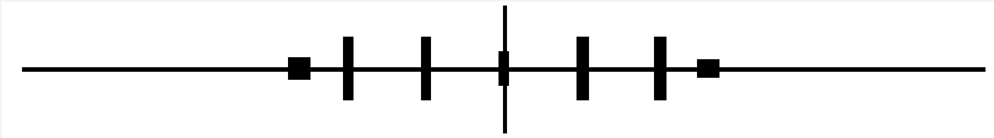
Geometry of the beam test: example



Configurations used for the simulation

as planned for January 2006 TB – info from Lars Reuen, October 2005

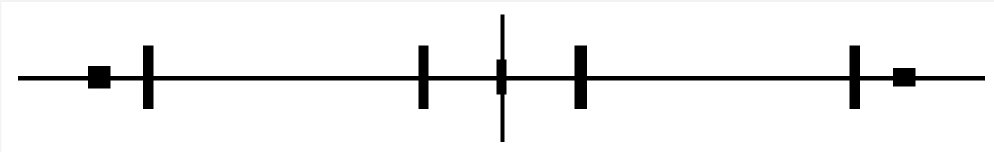
Geometry 1



a [mm]	b [mm]	c [mm]	d [mm]	e [mm]	f [mm]
15	40	40	40	40	15

Module windows:
- 50 μm copper foils
- no foils
- 150 μm copper foils

Geometry 2



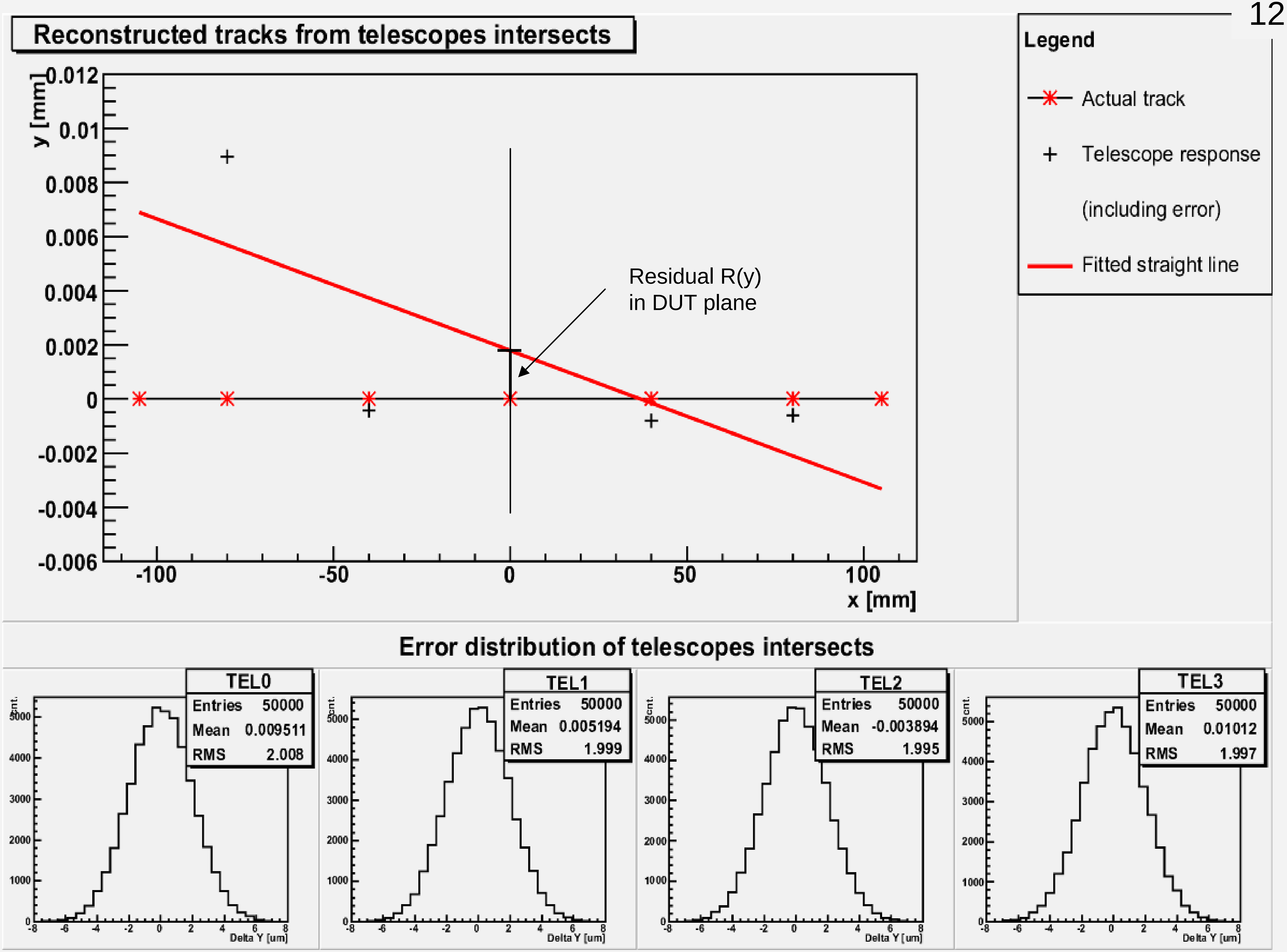
a [mm]	b [mm]	c [mm]	d [mm]	e [mm]	f [mm]
15	140	40	40	140	15

Module windows:
- 50 μm copper foils

Unscattered particle
(geometry only)

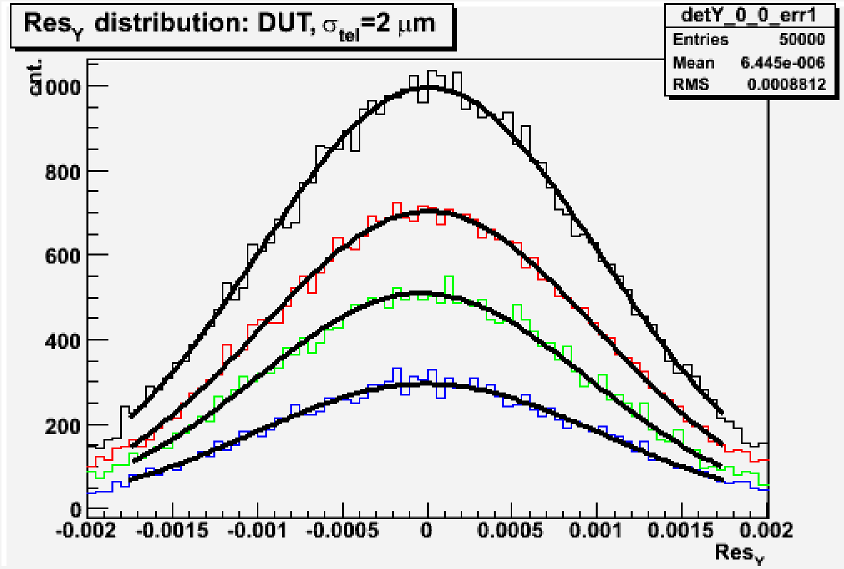
- Intersects of an unscattered particle lie on a straight line.
- A resolution of telescopes is approximately

  pitch/(S/N) ~ 2 μm.
- Positions of intersects in telescopes plane were blurred with a Gaussian to simulate telescope resolution.
- These points were fitted by a straight line.



Reconstructed tracks from telescopes intersects
y [mm]
x [mm]
Residual R(y)
in DUT plane
Legend
Actual track
Telescope response
(including error)
Fitted straight line
Error distribution of telescopes intersects
TEL0
Entries 50000
Mean 0.009511
RMS 2.008
TEL1
Entries 50000
Mean 0.005194
RMS 1.999
TEL2
Entries 50000
Mean -0.003894
RMS 1.995
TEL3
Entries 50000
Mean 0.01012
RMS 1.997
Delta Y [um]

Residual distribution in DUT: unscattered particle



χ^2 cut : width

100% : σ =0.9912 μm

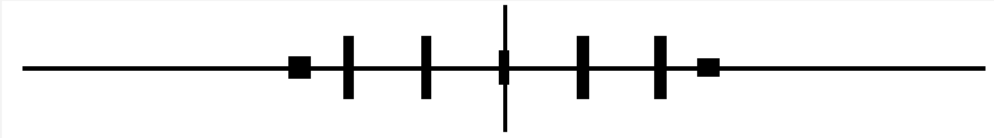
70% : σ =0.9928 μm

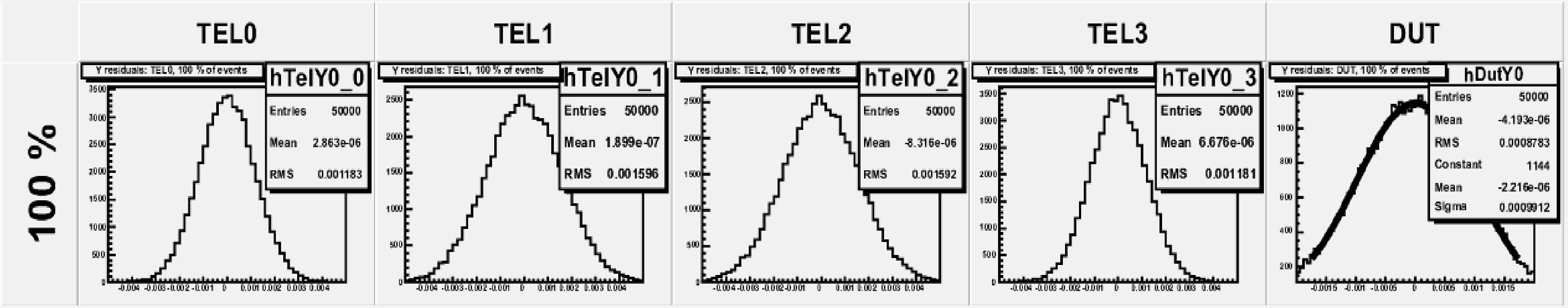
50% : σ =0.9918 μm

30% : σ =0.9852 μm

Unscattered particles: residual plots

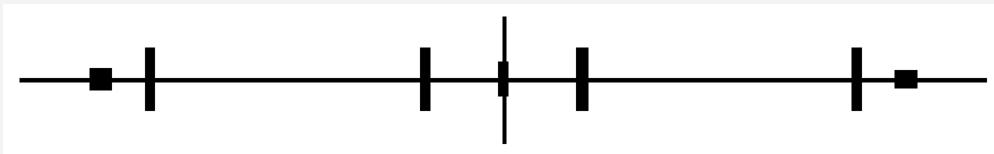
Geometry 1

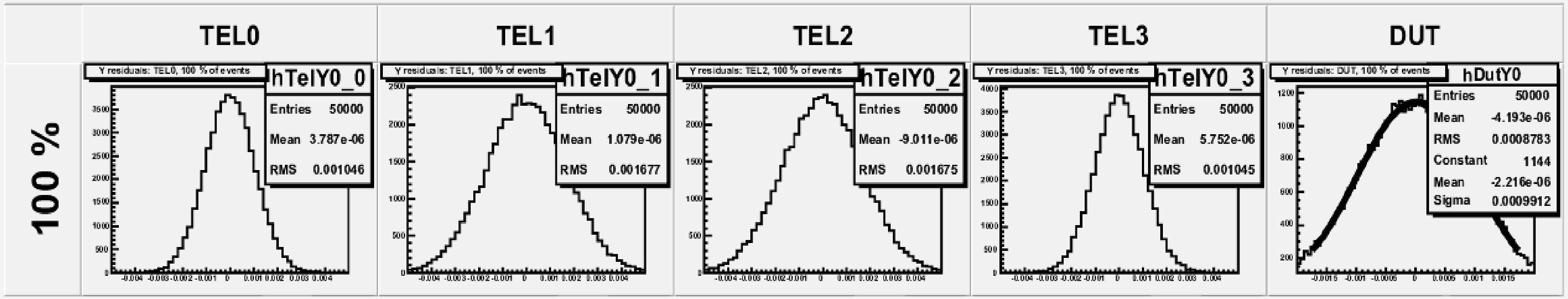




σ = 1.19 μm σ = 1.60 μm σ = 1.60 μm σ = 1.18 μm σ = 0.99 μm

Geometry 2



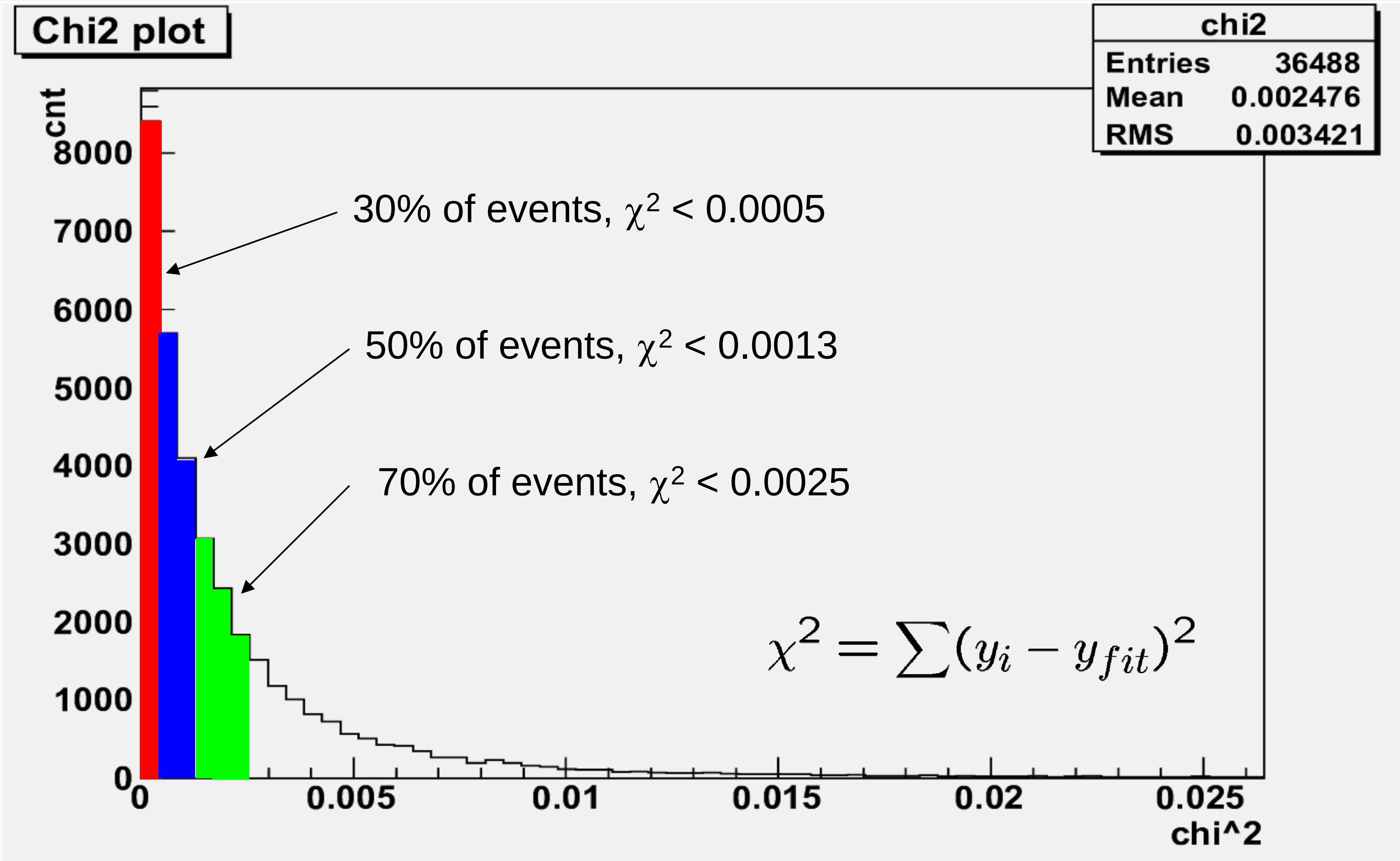


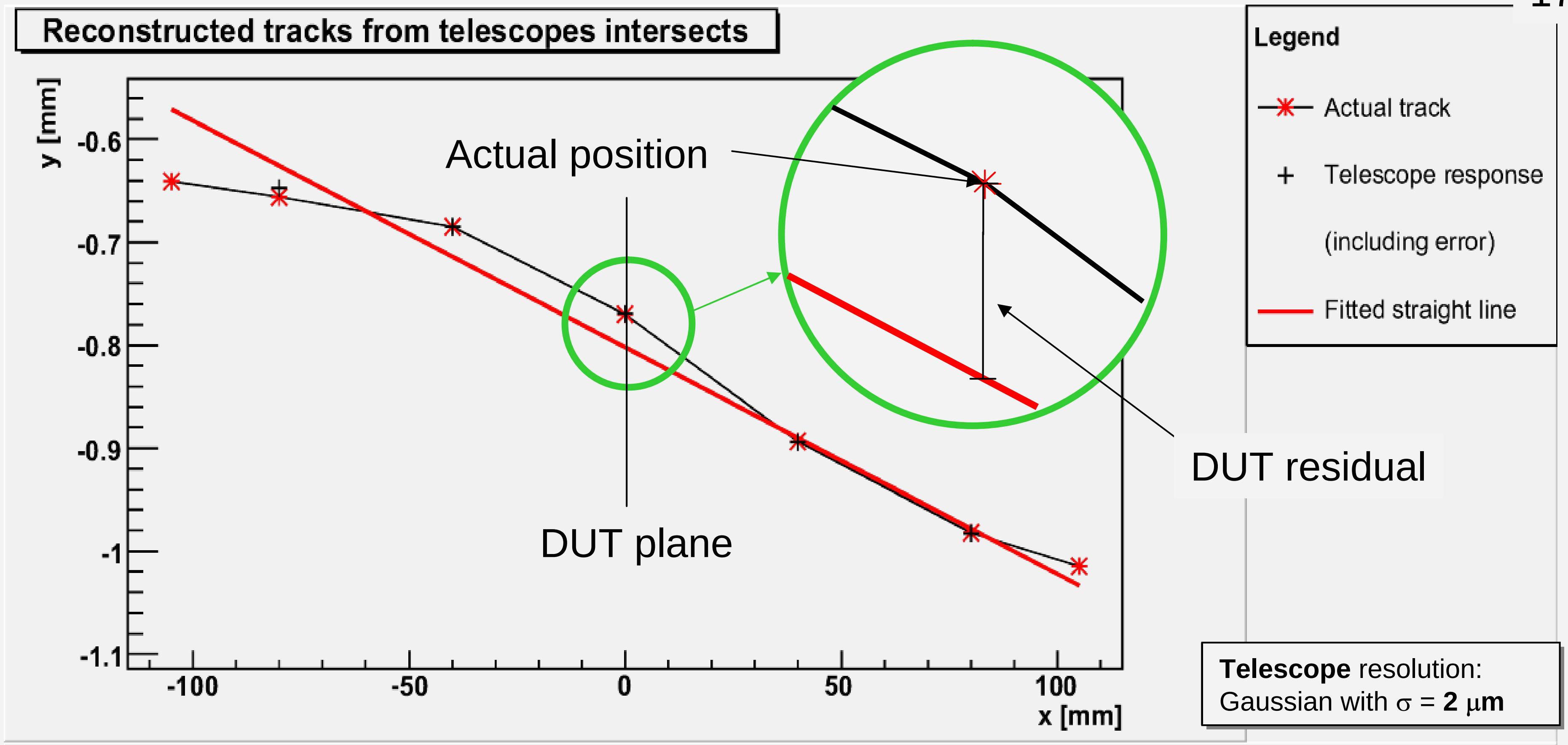
σ = 1.05 μm σ = 1.68 μm σ = 1.68 μm σ = 1.05 μm σ = 0.99 μm

Electron beam simulation

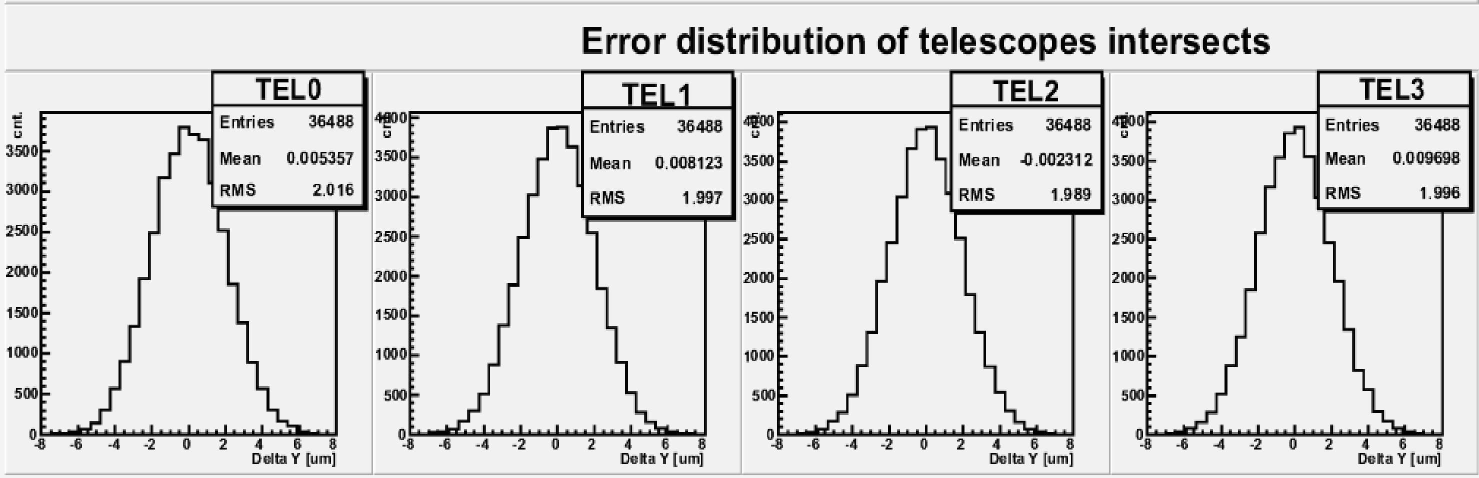
- There are 2 main contributions to the residual plots RMS:
  - Multiple scattering
  - Telescope resolution
- Simulation was done for 1 GeV to 5 GeV electrons, 50000 events for each run
- Particles that didn’t hit the both scintillators were excluded from the analysis
- χ^2 cuts were applied to exclude bad fits

Example of χ^2 cuts

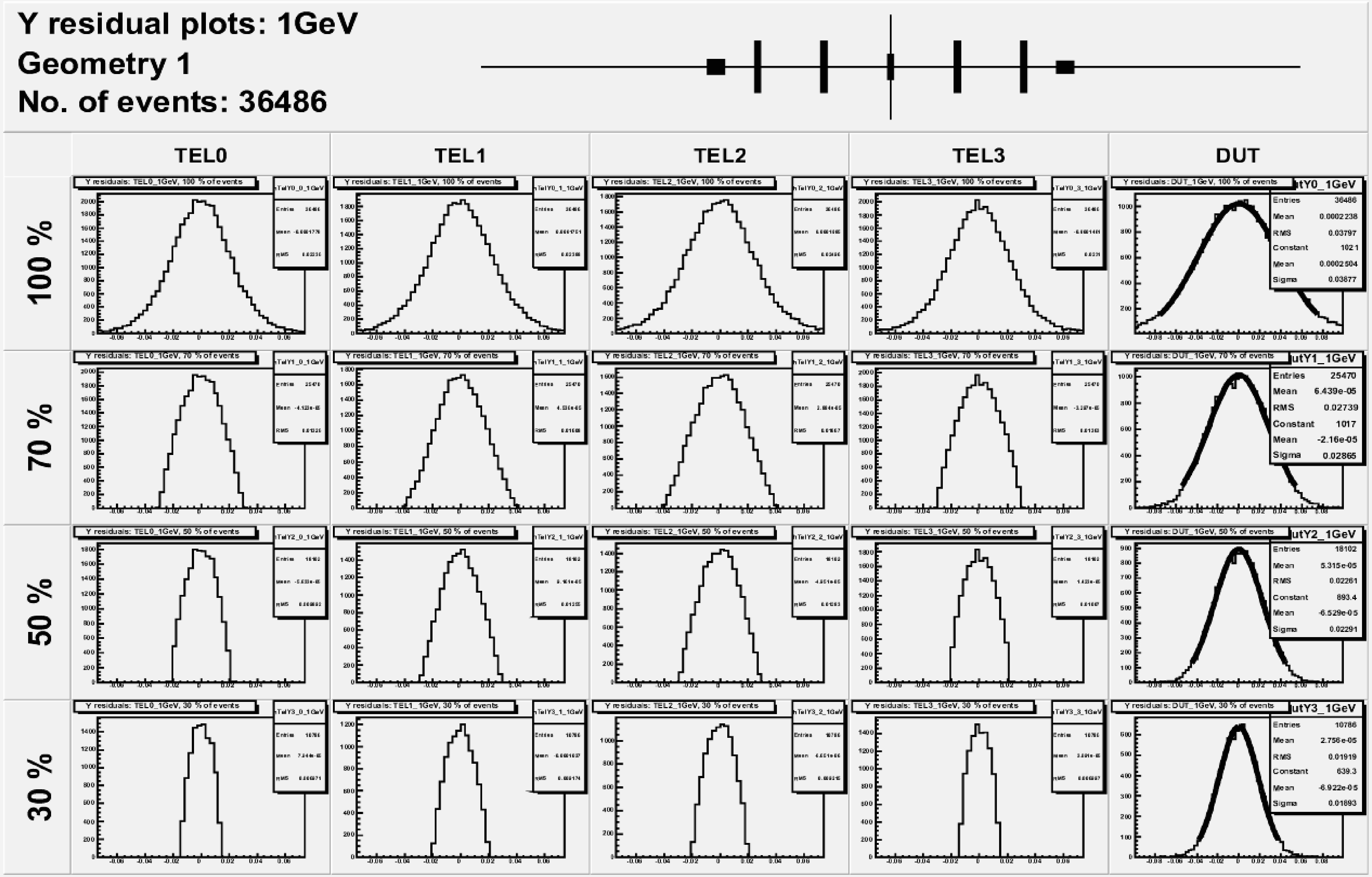




Telescope resolution:
Gaussian with σ = **2** μ**m**



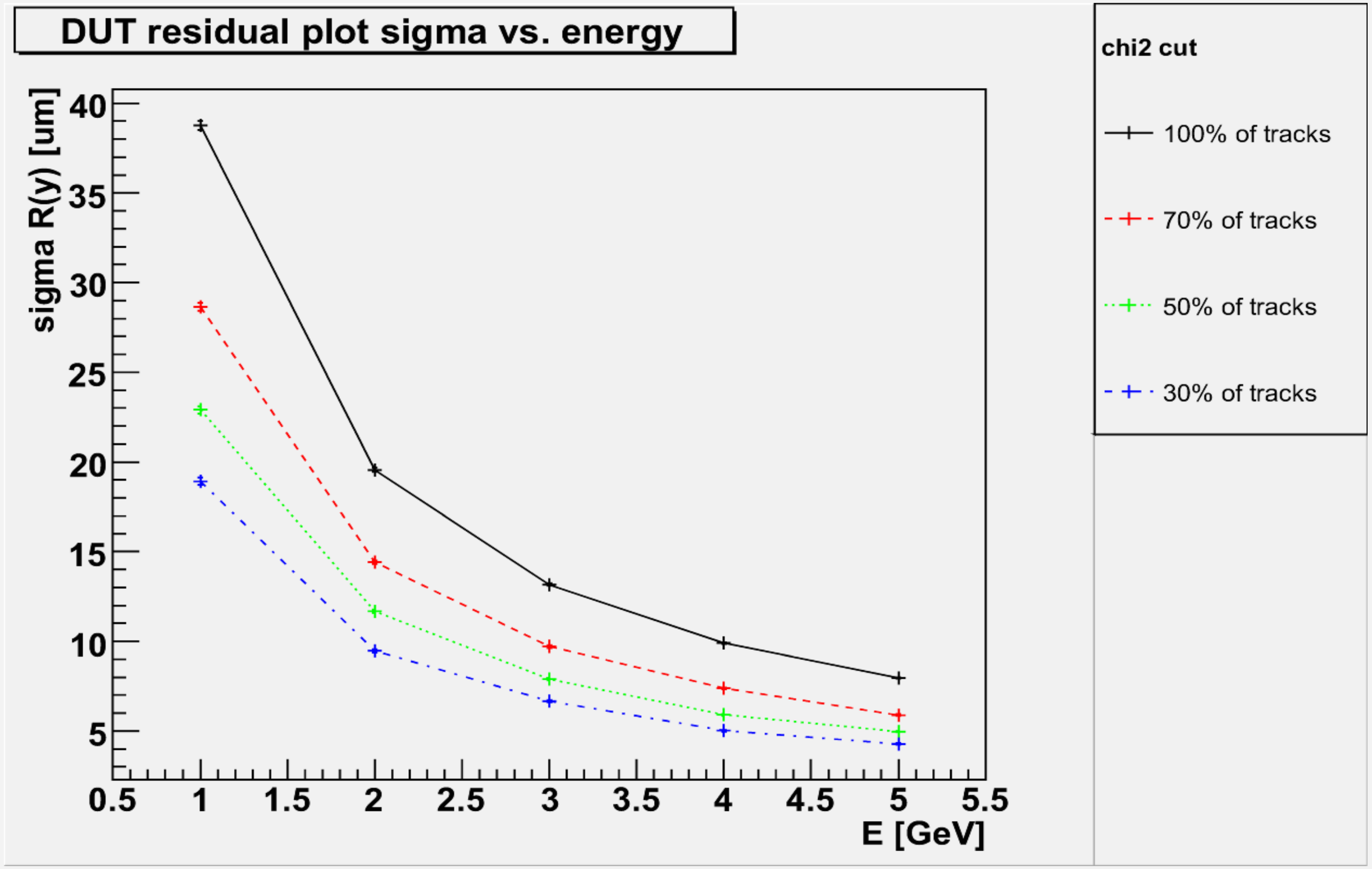
Electron beam simulation: residual plots



Electron beam simulation: residual plots

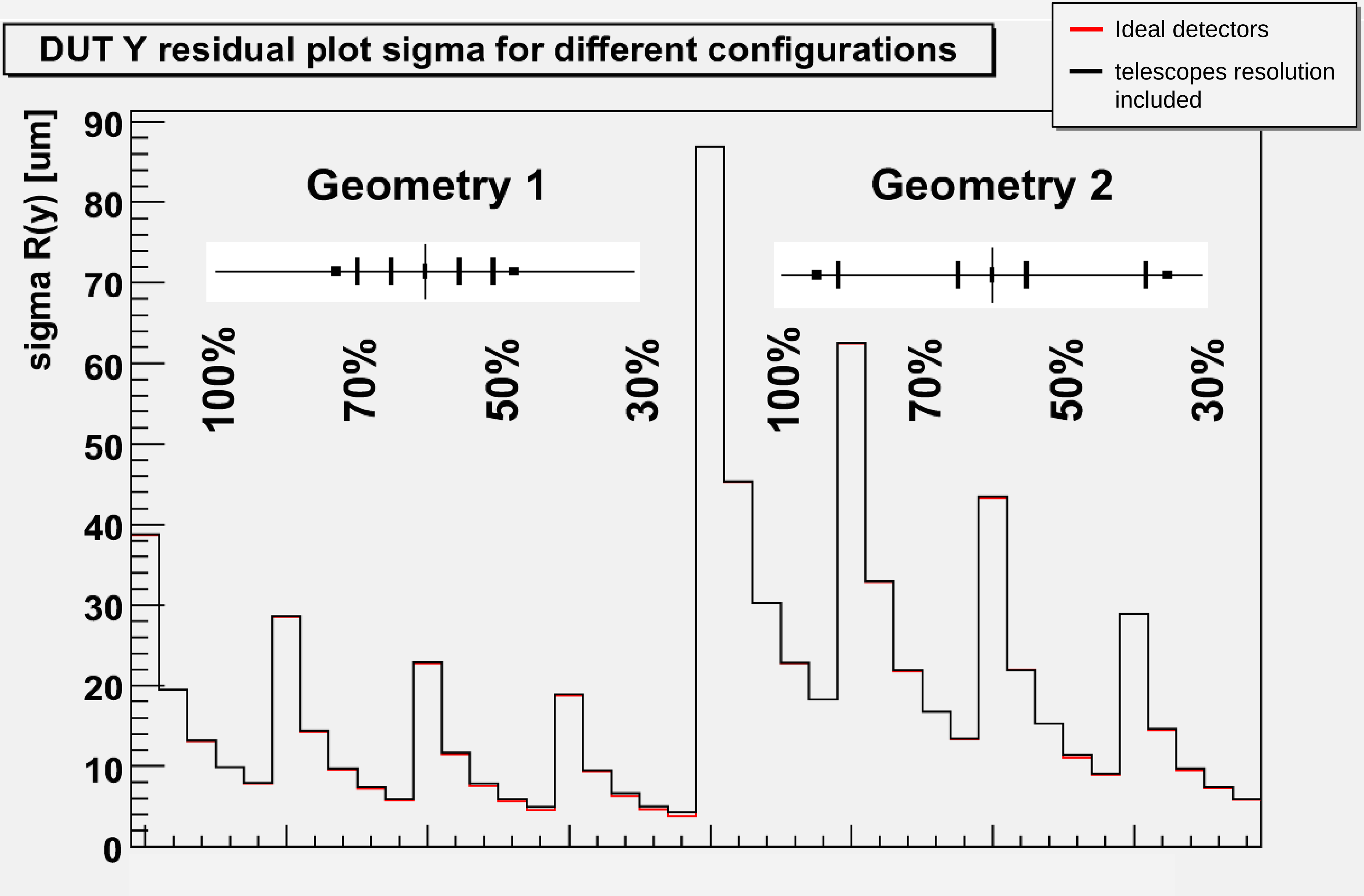
Energy: 1 GeV, no. of events: 36486						
χ^2 cut [mm^2]		TEL0	TEL1	TEL2	TEL3	DUT
	$\sigma R(y)$ [μm]	22.36 ± 0.08	23.88 ± 0.09	24.96 ± 0.09	23.10 ± 0.09	38.8 ± 0.2
100%	$\sigma R(z)$ [μm]	22.32 ± 0.08	23.68 ± 0.09	24.94 ± 0.09	22.96 ± 0.09	38.3 ± 0.2
0.0025	$\sigma R(y)$ [μm]	13.26 ± 0.06	16.08 ± 0.07	16.67 ± 0.07	13.63 ± 0.06	28.6 ± 0.2
70%	$\sigma R(z)$ [μm]	13.21 ± 0.06	15.99 ± 0.07	16.63 ± 0.07	13.60 ± 0.06	28.4 ± 0.2
0.0013	$\sigma R(y)$ [μm]	9.89 ± 0.05	12.55 ± 0.07	12.83 ± 0.07	10.07 ± 0.05	22.9 ± 0.2
50%	$\sigma R(z)$ [μm]	9.93 ± 0.05	12.53 ± 0.07	12.79 ± 0.07	10.10 ± 0.05	22.9 ± 0.2
0.0006	$\sigma R(y)$ [μm]	6.97 ± 0.05	9.17 ± 0.06	9.21 ± 0.06	7.00 ± 0.05	18.9 ± 0.2
30%	$\sigma R(z)$ [μm]	6.97 ± 0.05	9.15 ± 0.06	9.17 ± 0.06	6.98 ± 0.05	18.8 ± 0.2

Residual-plot sigma vs. particle energy



E [GeV]	1	2	3	4	5
100%	38.8 ± 0.2	19.6 ± 0.1	13.17 ± 0.07	9.90 ± 0.05	7.96 ± 0.04
70%	28.6 ± 0.2	14.41 ± 0.10	9.71 ± 0.06	7.38 ± 0.05	5.89 ± 0.04
50%	22.9 ± 0.2	11.69 ± 0.09	7.89 ± 0.06	5.90 ± 0.04	4.98 ± 0.04
30%	18.9 ± 0.2	9.48 ± 0.09	6.66 ± 0.06	5.02 ± 0.05	4.28 ± 0.04

Residual plots: two geometries



Residual plots: two geometries

E [GeV]	1	2	3	4	5
100%	38.8 ± 0.2	19.6 ± 0.1	13.17 ± 0.07	9.90 ± 0.05	7.96 ± 0.04
70%	28.6 ± 0.2	14.41 ± 0.10	9.71 ± 0.06	7.38 ± 0.05	5.89 ± 0.04
50%	22.9 ± 0.2	11.69 ± 0.09	7.89 ± 0.06	5.90 ± 0.04	4.98 ± 0.04
30%	18.9 ± 0.2	9.48 ± 0.09	6.66 ± 0.06	5.02 ± 0.05	4.28 ± 0.04

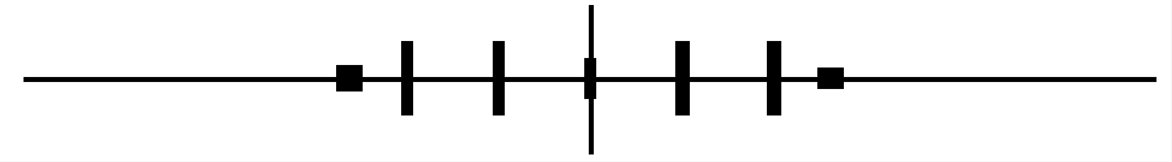
E [GeV]	1	2	3	4	5
100%	86.9 ± 0.6	45.4 ± 0.3	30.3 ± 0.2	22.8 ± 0.1	18.3 ± 0.1
70%	62.6 ± 0.6	33.0 ± 0.3	21.9 ± 0.2	16.8 ± 0.1	13.4 ± 0.1
50%	43.5 ± 0.5	21.9 ± 0.2	15.2 ± 0.1	11.47 ± 0.10	9.08 ± 0.08
30%	29.0 ± 0.4	14.7 ± 0.2	9.7 ± 0.1	7.44 ± 0.07	5.94 ± 0.06

E [GeV]	1	2	3	4	5
100%	38.7 ± 0.2	19.5 ± 0.1	13.11 ± 0.07	9.85 ± 0.05	7.90 ± 0.04
70%	28.5 ± 0.2	14.28 ± 0.10	9.56 ± 0.06	7.16 ± 0.05	5.76 ± 0.04
50%	22.8 ± 0.2	11.55 ± 0.09	7.57 ± 0.06	5.65 ± 0.04	4.60 ± 0.03
29%	18.8 ± 0.2	9.35 ± 0.09	6.30 ± 0.06	4.66 ± 0.05	3.75 ± 0.04

E [GeV]	1	2	3	4	5
100%	86.9 ± 0.6	45.3 ± 0.3	30.3 ± 0.2	22.8 ± 0.1	18.2 ± 0.1
70%	62.5 ± 0.6	32.9 ± 0.3	21.7 ± 0.2	16.7 ± 0.1	13.3 ± 0.1
50%	43.3 ± 0.5	21.9 ± 0.2	15.3 ± 0.1	11.07 ± 0.09	8.91 ± 0.07
30%	28.9 ± 0.4	14.5 ± 0.2	9.54 ± 0.10	7.29 ± 0.07	5.85 ± 0.07

Three windows thicknesses for the geometry 1

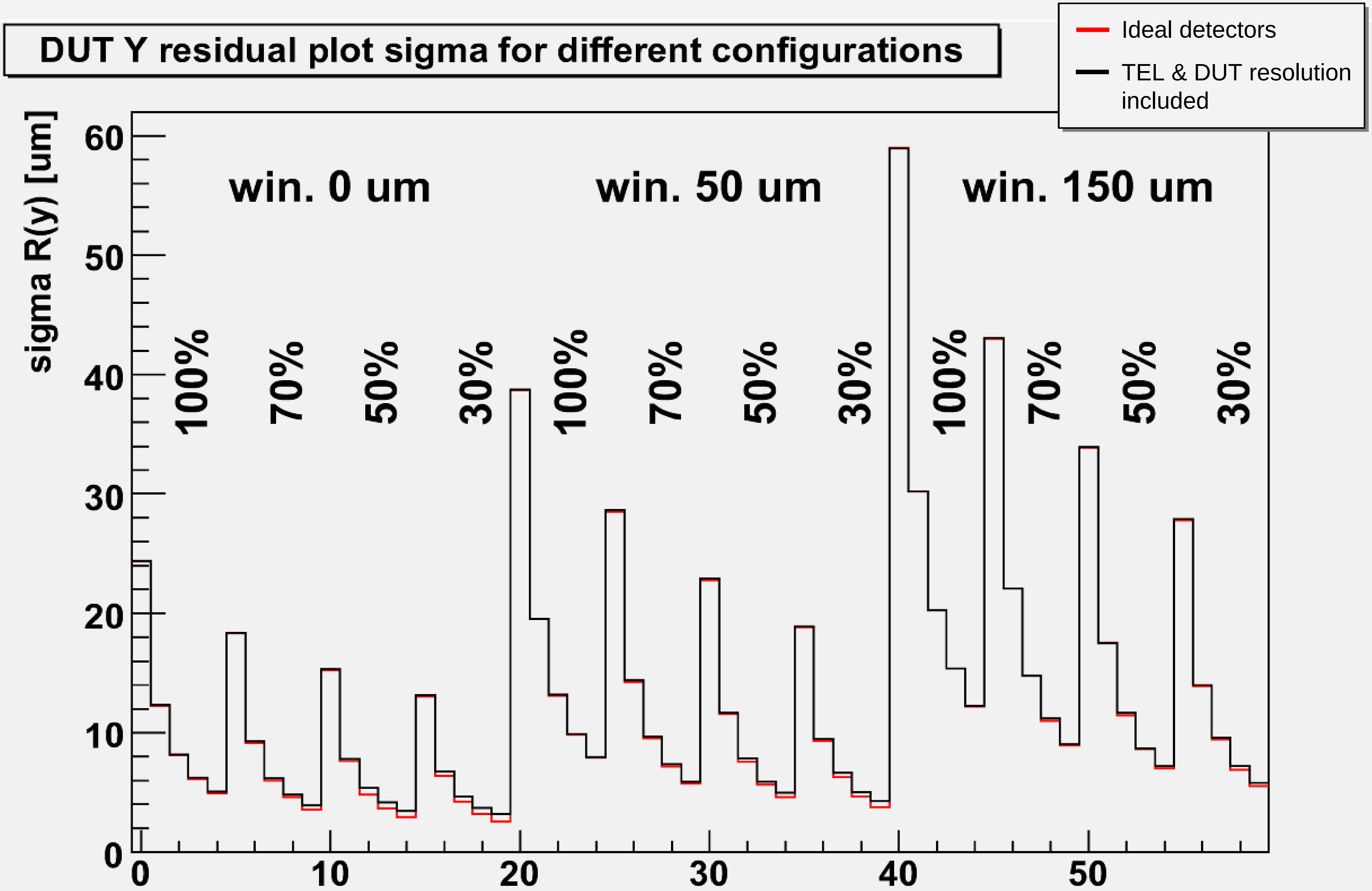
Geometry 1



Module windows:

- no foils
- 50 μm copper foils
- 150 μm copper foils

Residual plots: three thicknesses



Residual plots: three thicknesses

E [GeV]	1	2	3	4	5
100%	24.4 ± 0.1	12.32 ± 0.07	8.19 ± 0.04	6.25 ± 0.03	5.08 ± 0.02
70%	18.4 ± 0.1	9.30 ± 0.06	6.17 ± 0.04	4.83 ± 0.03	3.94 ± 0.03
50%	15.3 ± 0.1	7.82 ± 0.06	5.38 ± 0.04	4.17 ± 0.03	3.48 ± 0.03
29%	13.2 ± 0.1	6.77 ± 0.07	4.67 ± 0.05	3.73 ± 0.04	3.20 ± 0.03

E [GeV]	1	2	3	4	5
100%	58.9 ± 0.4	30.2 ± 0.2	20.2 ± 0.1	15.38 ± 0.08	12.24 ± 0.06
70%	43.1 ± 0.3	22.1 ± 0.1	14.75 ± 0.09	11.23 ± 0.07	9.04 ± 0.06
50%	33.9 ± 0.3	17.5 ± 0.1	11.66 ± 0.09	8.69 ± 0.07	7.23 ± 0.05
30%	27.9 ± 0.3	14.0 ± 0.1	9.6 ± 0.1	7.21 ± 0.08	5.79 ± 0.06

E [GeV]	1	2	3	4	5
100%	38.8 ± 0.2	19.6 ± 0.1	13.17 ± 0.07	9.90 ± 0.05	7.96 ± 0.04
70%	28.6 ± 0.2	14.41 ± 0.10	9.71 ± 0.06	7.38 ± 0.05	5.89 ± 0.04
50%	22.9 ± 0.2	11.69 ± 0.09	7.89 ± 0.06	5.90 ± 0.04	4.98 ± 0.04
30%	18.9 ± 0.2	9.48 ± 0.09	6.66 ± 0.06	5.02 ± 0.05	4.28 ± 0.04

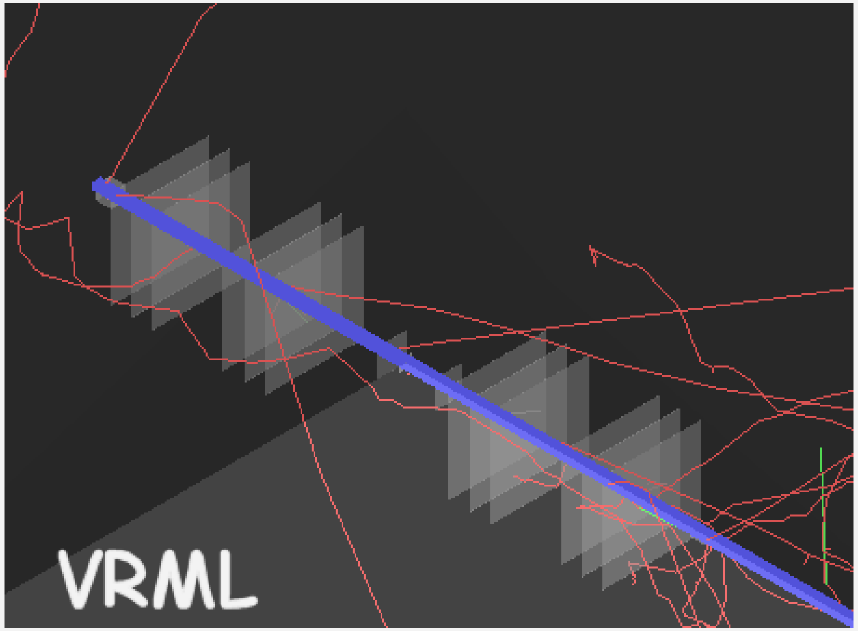
E [GeV]	1	2	3	4	5
100%	24.3 ± 0.1	12.22 ± 0.06	8.14 ± 0.04	6.16 ± 0.03	4.94 ± 0.02
70%	18.3 ± 0.1	9.16 ± 0.06	5.99 ± 0.04	4.61 ± 0.03	3.58 ± 0.02
50%	15.2 ± 0.1	7.62 ± 0.06	4.84 ± 0.04	3.66 ± 0.03	2.93 ± 0.02
30%	13.0 ± 0.1	6.38 ± 0.06	4.23 ± 0.04	3.19 ± 0.03	2.55 ± 0.03

E [GeV]	1	2	3	4	5
100%	59.0 ± 0.4	30.2 ± 0.2	20.2 ± 0.1	15.37 ± 0.08	12.20 ± 0.06
70%	43.0 ± 0.3	22.1 ± 0.1	14.8 ± 0.1	11.01 ± 0.07	8.96 ± 0.06
50%	33.9 ± 0.3	17.5 ± 0.1	11.48 ± 0.09	8.61 ± 0.06	7.00 ± 0.06
30%	27.8 ± 0.3	13.9 ± 0.1	9.44 ± 0.10	6.93 ± 0.07	5.55 ± 0.06

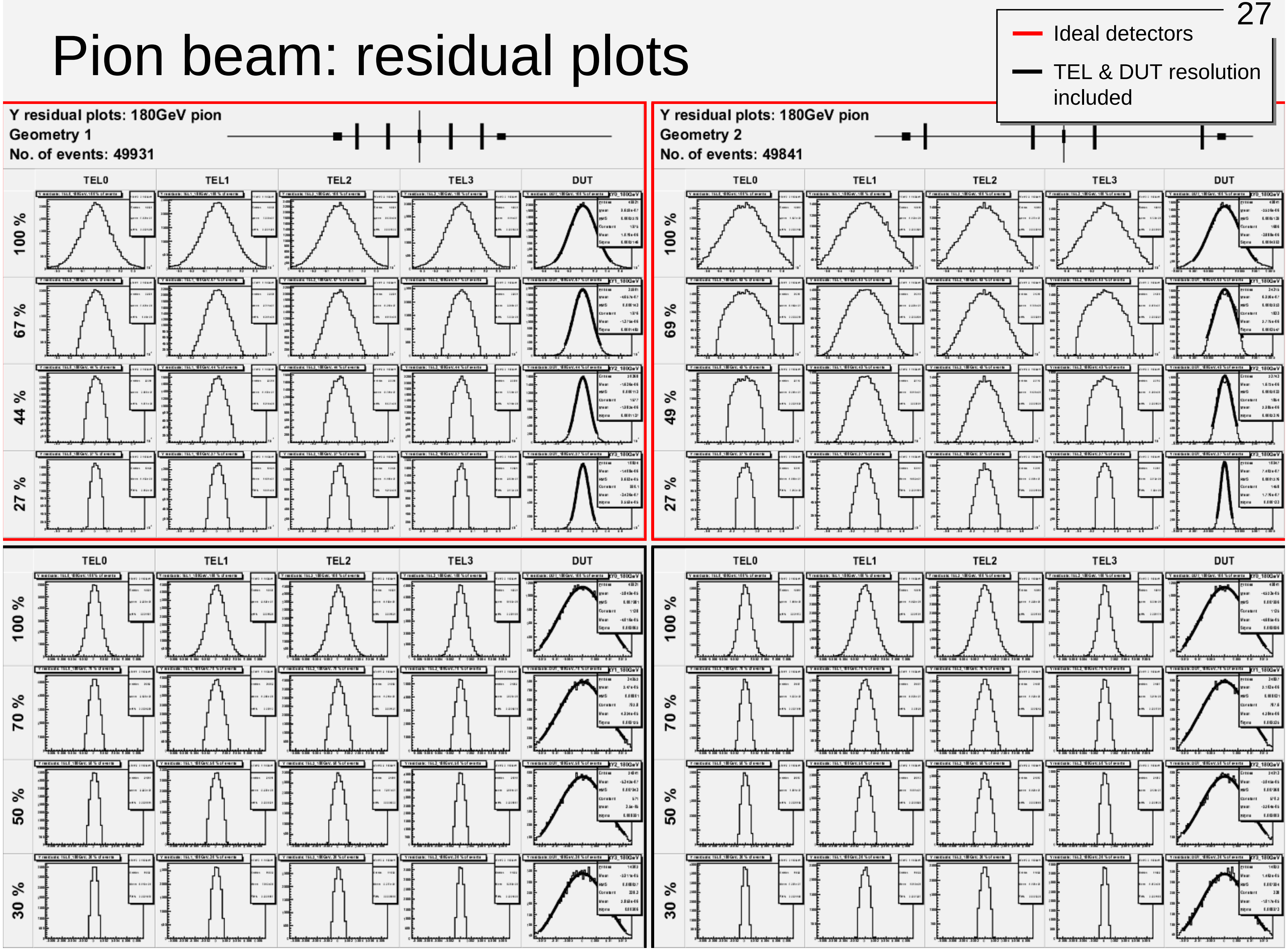
E [GeV]	1	2	3	4	5
100%	38.7 ± 0.2	19.5 ± 0.1	13.11 ± 0.07	9.85 ± 0.05	7.90 ± 0.04
70%	28.5 ± 0.2	14.28 ± 0.10	9.56 ± 0.06	7.16 ± 0.05	5.76 ± 0.04
50%	22.8 ± 0.2	11.55 ± 0.09	7.57 ± 0.06	5.65 ± 0.04	4.60 ± 0.03
29%	18.8 ± 0.2	9.35 ± 0.09	6.30 ± 0.06	4.66 ± 0.05	3.75 ± 0.04

Pion beam simulation

- CERN 180 GeV pion beam was simulated
- Geometries 1 and 2 were tested



Pion beam: residual plots



Pion beam: residual plots

Energy: 1 GeV, no. of events: 49931		
χ^2 cut [mm^2]		DUT
100%	$\sigma R(y)$ [μm]	0.215 ± 0.001
	$\sigma R(z)$ [μm]	0.214 ± 0.001
0.0000 67%	$\sigma R(y)$ [μm]	0.1482 ± 0.0009
	$\sigma R(z)$ [μm]	0.1482 ± 0.0009
0.0000 44%	$\sigma R(y)$ [μm]	0.1137 ± 0.0009
	$\sigma R(z)$ [μm]	0.1131 ± 0.0009
0.0000 27%	$\sigma R(y)$ [μm]	0.0956 ± 0.0010
	$\sigma R(z)$ [μm]	0.0954 ± 0.0010

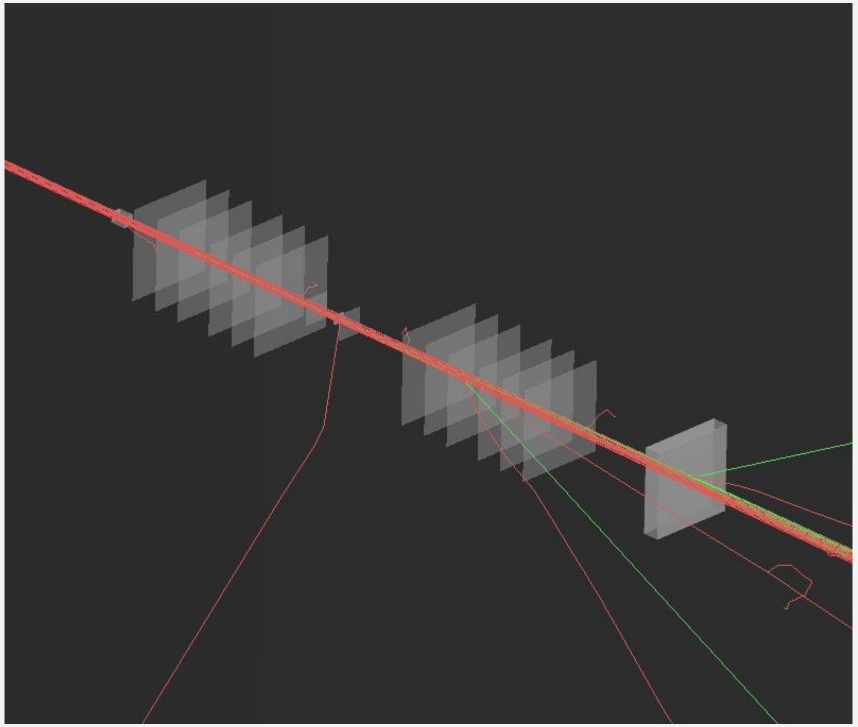
Energy: 1 GeV, no. of events: 49841		
χ^2 cut [mm^2]		DUT
100%	$\sigma R(y)$ [μm]	0.499 ± 0.003
	$\sigma R(z)$ [μm]	0.491 ± 0.002
0.0000 69%	$\sigma R(y)$ [μm]	0.355 ± 0.003
	$\sigma R(z)$ [μm]	0.358 ± 0.003
0.0000 49%	$\sigma R(y)$ [μm]	0.238 ± 0.002
	$\sigma R(z)$ [μm]	0.248 ± 0.002
0.0000 27%	$\sigma R(y)$ [μm]	0.133 ± 0.001
	$\sigma R(z)$ [μm]	0.134 ± 0.001

Energy: 1 GeV, no. of events: 49931		
χ^2 cut [mm^2]		DUT
100%	$\sigma R(y)$ [μm]	1.020 ± 0.006
	$\sigma R(z)$ [μm]	1.020 ± 0.006
0.0000 70%	$\sigma R(y)$ [μm]	1.025 ± 0.007
	$\sigma R(z)$ [μm]	1.026 ± 0.007
0.0000 50%	$\sigma R(y)$ [μm]	1.024 ± 0.009
	$\sigma R(z)$ [μm]	1.017 ± 0.008
0.0000 30%	$\sigma R(y)$ [μm]	1.02 ± 0.01
	$\sigma R(z)$ [μm]	1.00 ± 0.01

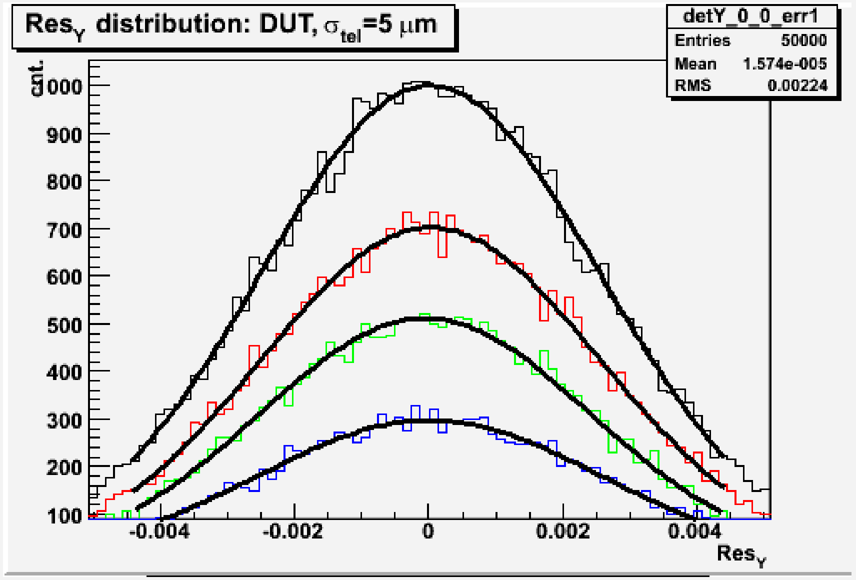
Energy: 1 GeV, no. of events: 49841		
χ^2 cut [mm^2]		DUT
100%	$\sigma R(y)$ [μm]	1.138 ± 0.007
	$\sigma R(z)$ [μm]	1.126 ± 0.006
0.0000 70%	$\sigma R(y)$ [μm]	1.127 ± 0.008
	$\sigma R(z)$ [μm]	1.118 ± 0.007
0.0000 50%	$\sigma R(y)$ [μm]	1.132 ± 0.009
	$\sigma R(z)$ [μm]	1.111 ± 0.009
0.0000 30%	$\sigma R(y)$ [μm]	1.12 ± 0.01
	$\sigma R(z)$ [μm]	1.10 ± 0.01

The latest results

- Final beam test geometry: similar to the Geometry 1
- DUT is shifted to the front side
- The resolution of telescopes ~ 5 μm



Unscattered particle



Telescope resolution 5 μm

χ^2 cut : width

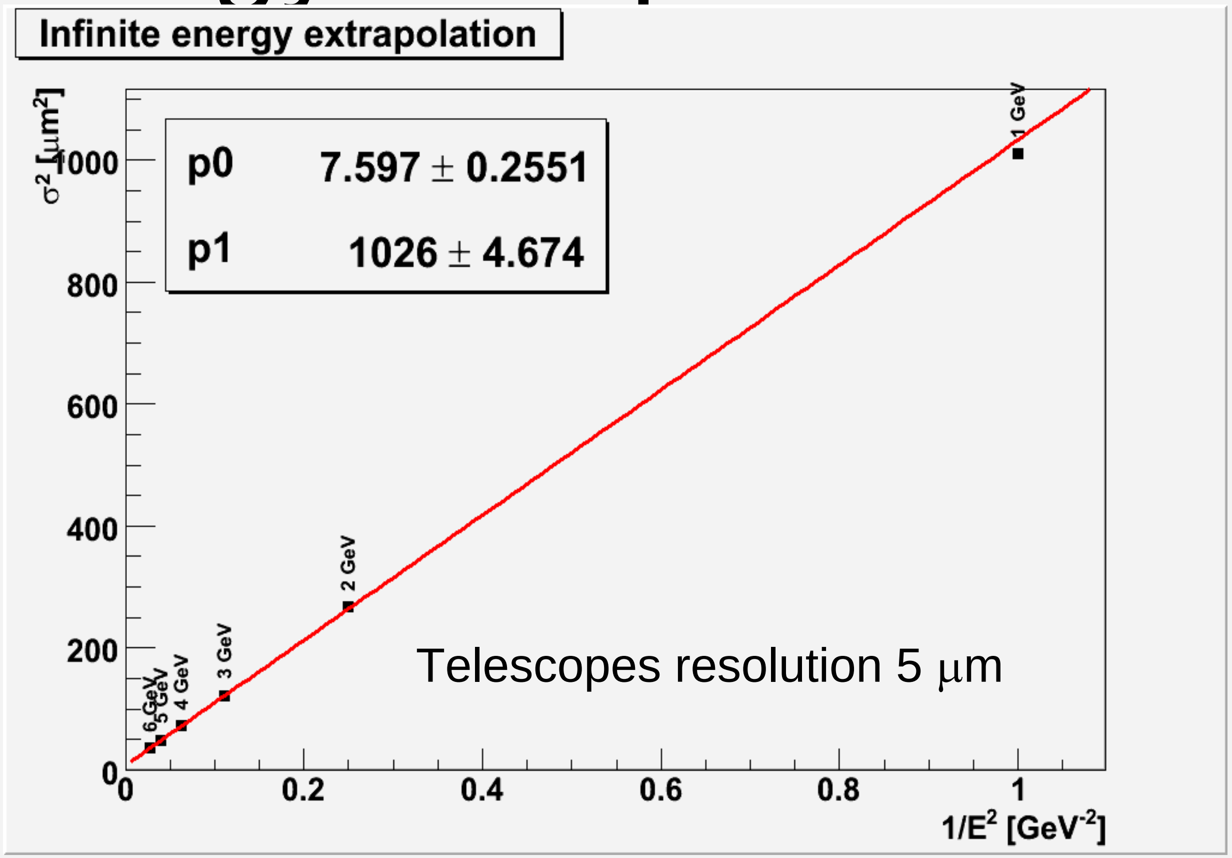
100% : σ =2.53 ± 0.02 μm

70% : σ =2.53 ± 0.02 μm

50% : σ =2.49 ± 0.02 μm

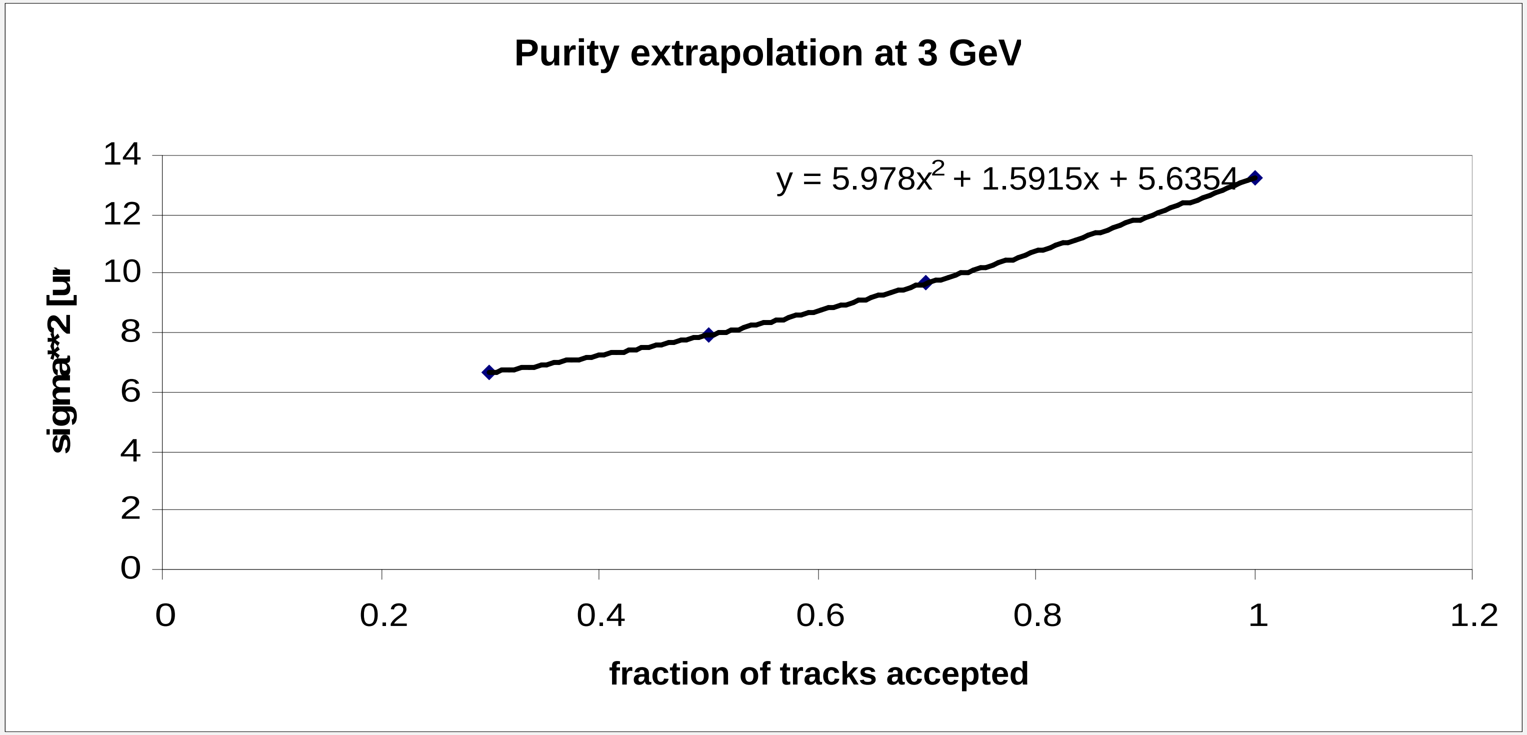
30% : σ =2.56 ± 0.02 μm

Infinite energy extrapolation



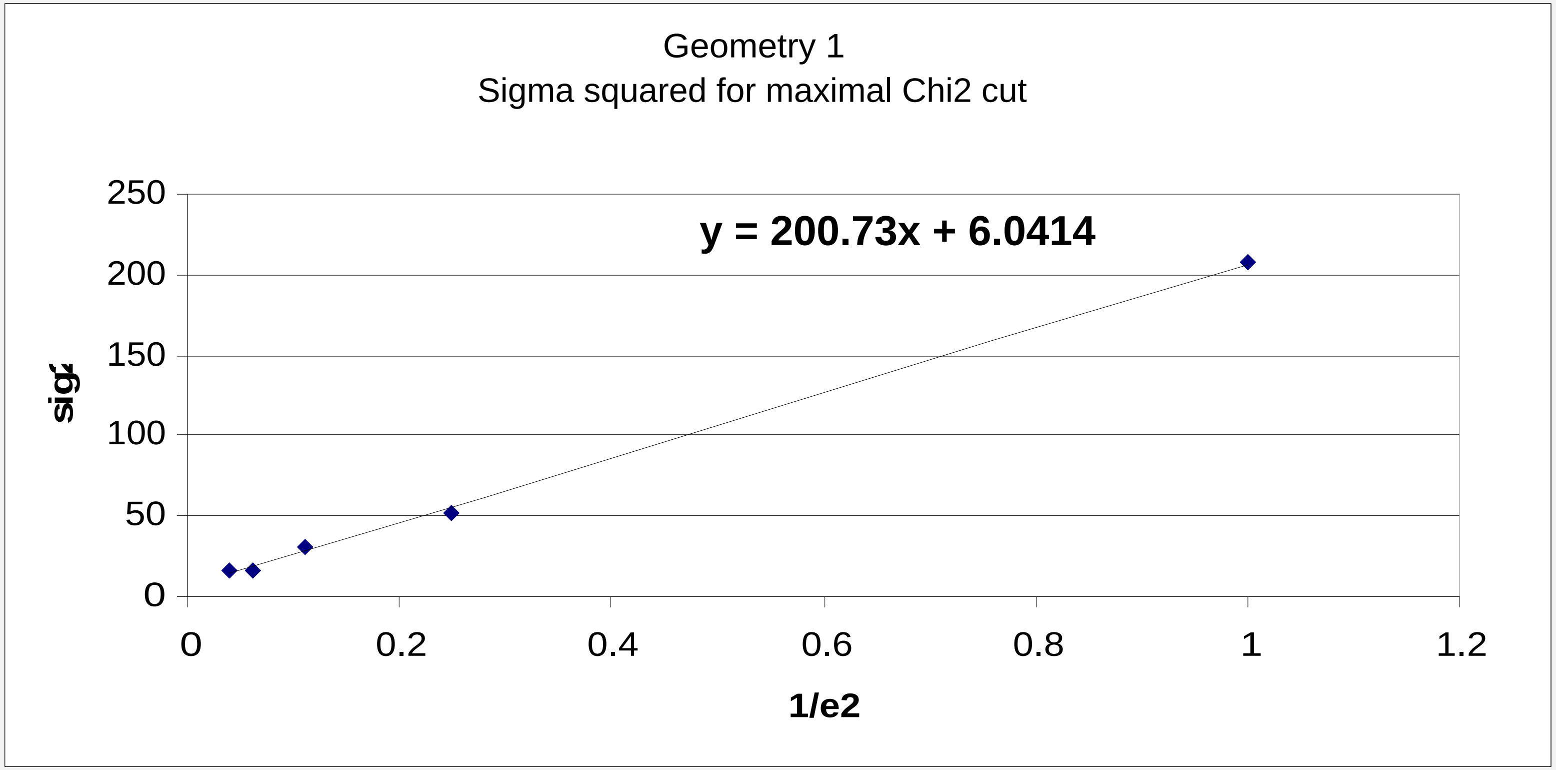
- Plot σ^2 vs. $1/E^2$
- Angular distribution width σ due to a multiple scattering is proportional to $1/E$

Infinite purity extrapolation



Attempt to exclude scattered tracks by Chi2 cut – infinite purity

Infinite purity and energy extrapolation



Even the most stringent cut cannot eliminate multiple scattering effects

Conclusions

- Software for a simulation and data analysis has been created. Now it's not a problem to run it all again with different parameters.
- There is no significant difference between the geometry 1 and 2 for unscattered particles.
- We can improve the resolution by excluding bad fits.
- Geometry 2 gives wider residual plots due to a multiple scattering. For 5 GeV electrons and 30% χ^2 cut σ = **4.28 μm** for the Geometry 1 and σ = **5.94 μm** for the Geometry 2.

Conclusions

- For 5 GeV electrons and 30% χ^2 cut there is approximately 1 μm difference between simulations with no module windows and 50 μm copper windows.
- CERN 180 GeV pion beam has a significantly lower multiple scattering. The main contribution to its residual plot width come from the telescopes intrinsic resolution.