Reconstruction of charge number of heavy cosmic rays using Cherenkov Light

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Lateral Photon Distribution Method

- New reconstruction method, fitting received DC photons to known Lateral Distribution Function.
- Aim is to improve reconstruction of Charge.

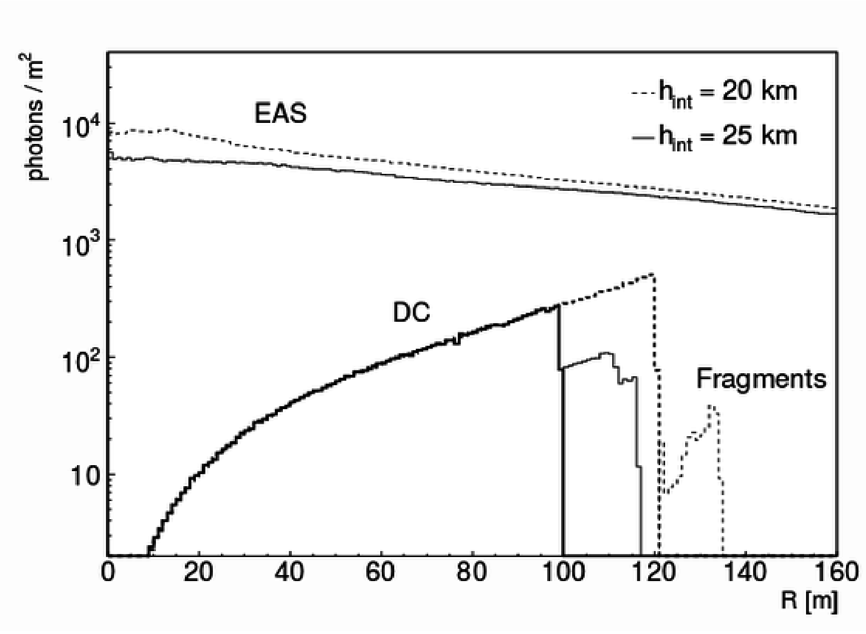


FIG. 2: Simulated intensity distribution on the ground for the EAS-light and DC-light of an individual 50 TeV iron nucleus, as a function of distance from the shower core, for two different first interaction heights (the shower core is defined as the intersection point of the shower axis on the ground). The zenith angle is 0°. The drop in DC-intensity at 100/120 m reflects the first interaction height. The low intensity tail at larger radii is caused by Cherenkov light from fragments of the primary nucleus.

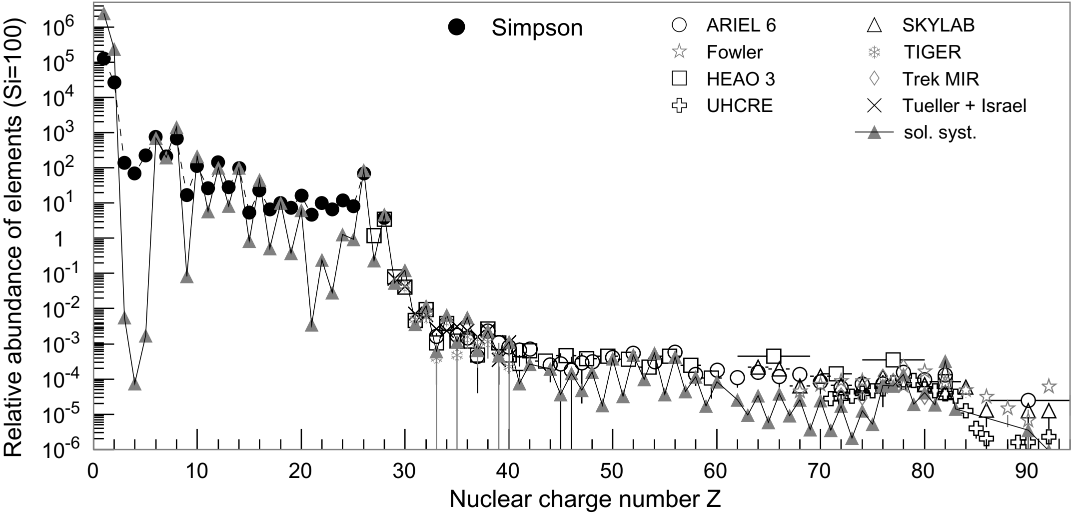


Fig. 3. Abundance of elements in cosmic rays as function of their nuclear charge number Z at energies around 1 GeV/n, normalized to Si = 100. Abundance for nuclei with $Z \leqslant 28$ according to Simpson (1983). Heavy nuclei as measured by ARIEL 6 (Fowler et al., 1987), Fowler et al. (1977), HEAO 3 (Binns et al., 1989), SKYLAB (Shirk and Price, 1978), TIGER (Lawrence et al., 1999), TREK/MIR (Weaver and Westphal, 2001), Tueller et al. (1981), as well as UHCRE (Donelly et al., 1999). In addition, the abundance of elements in the solar system is shown according to Lodders (2003).

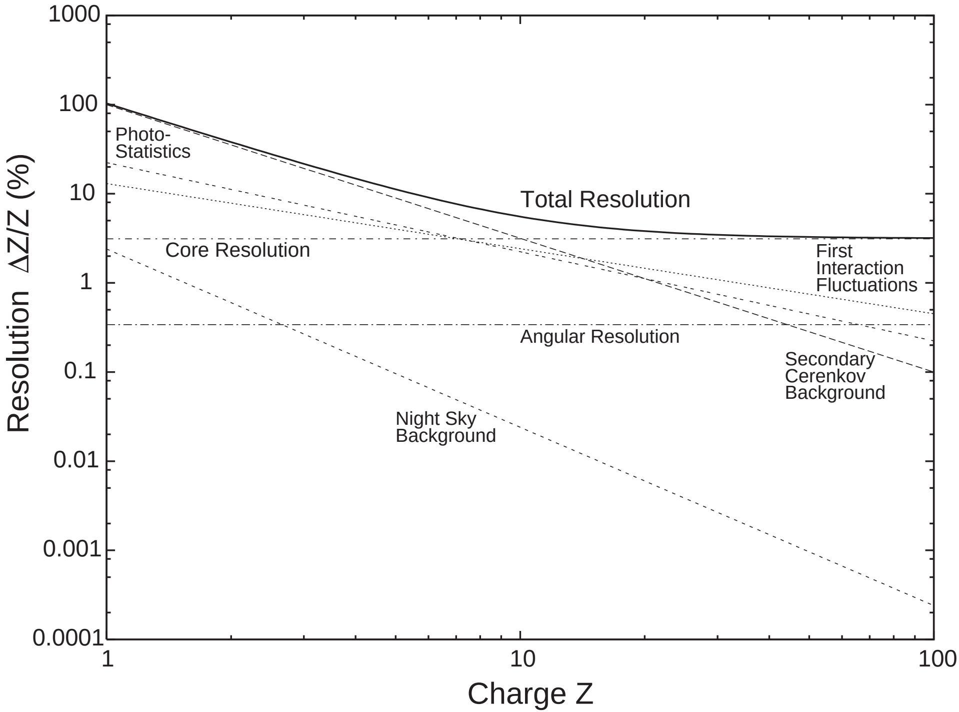
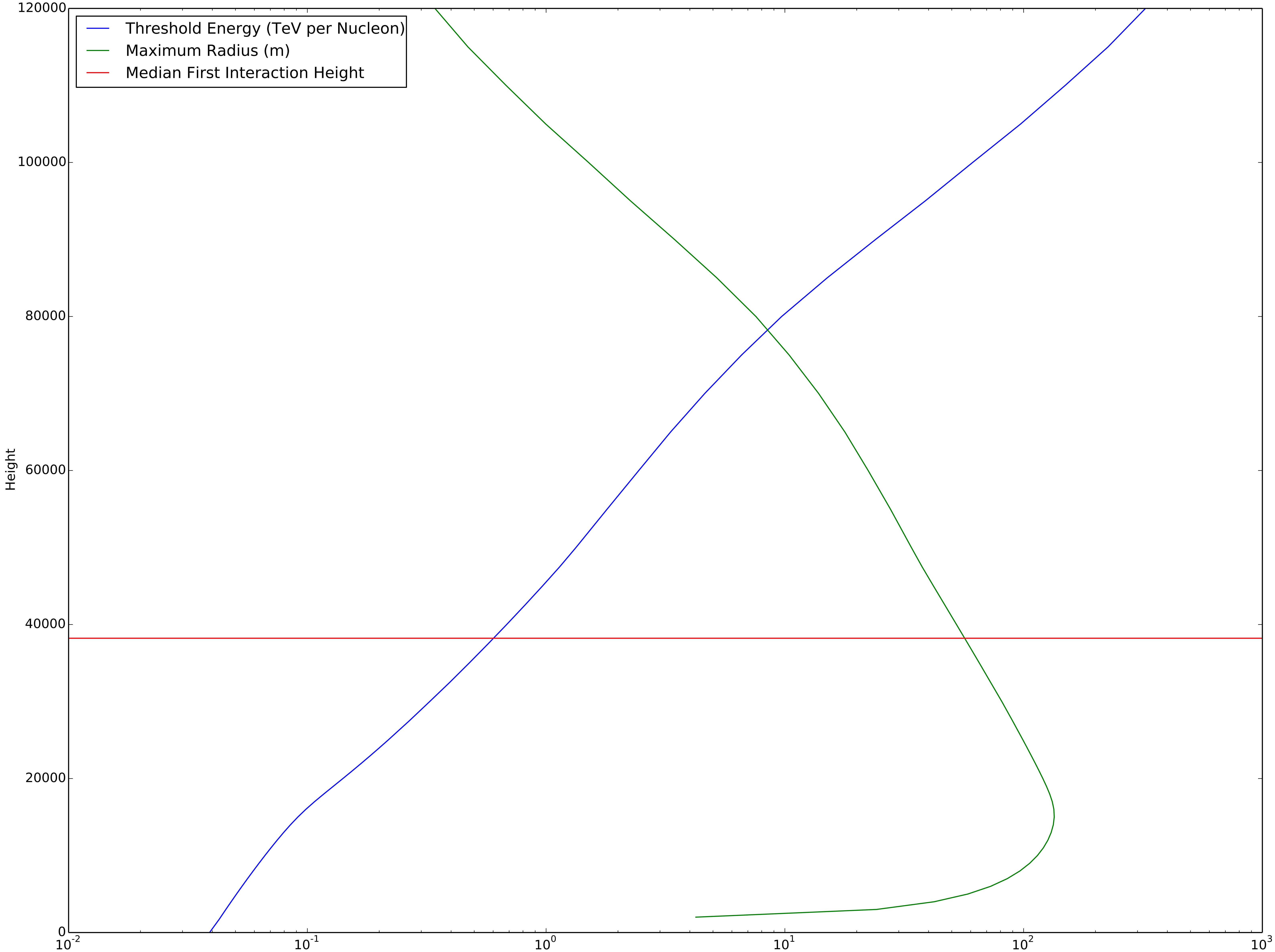


Fig. 11. The expected charge resolution $\Delta Z/Z$ for a detector of effective area 100 m^2 and core position resolution 5 m. Horizontal Axis: Primary Charge Z. Vertical Axis: Charge Resolution $\Delta Z/Z(\%)$

Epn Statistics for 20.0 hours



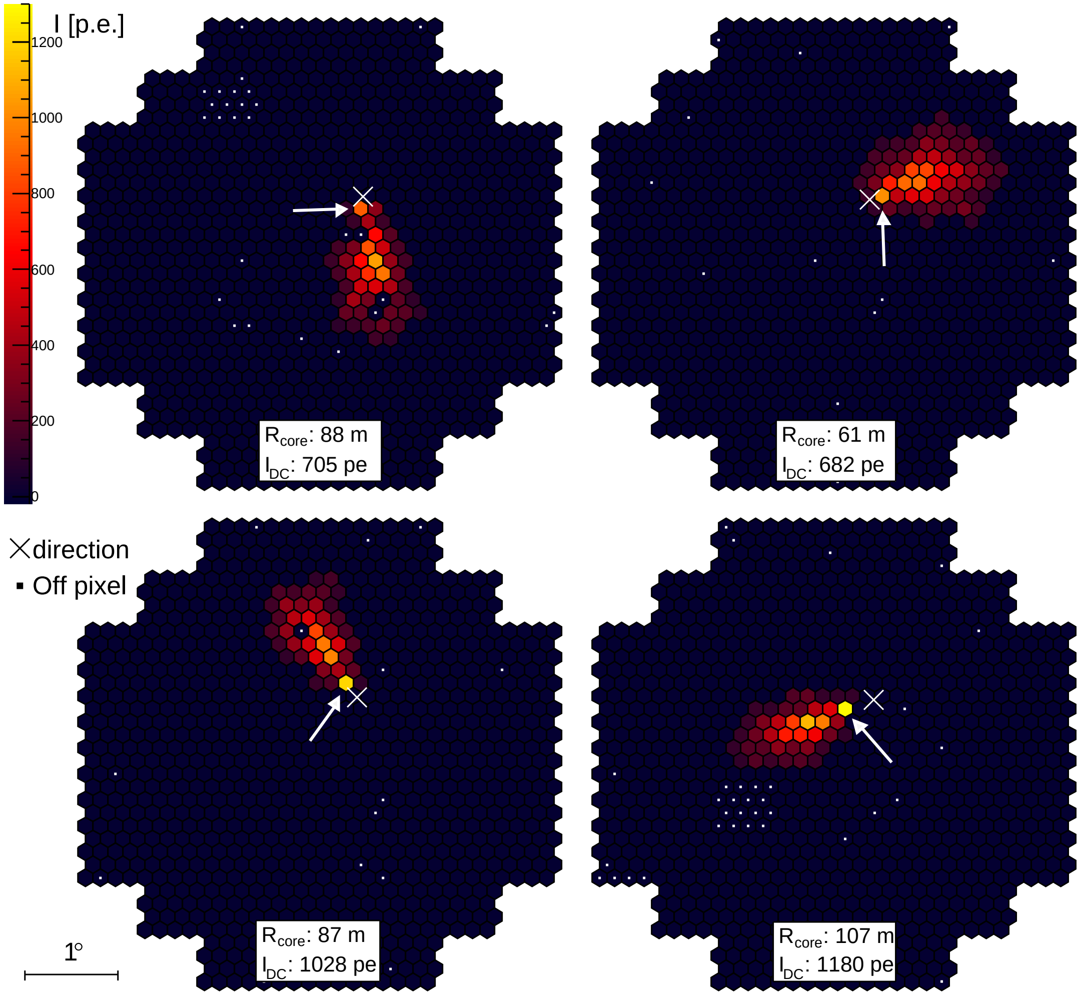
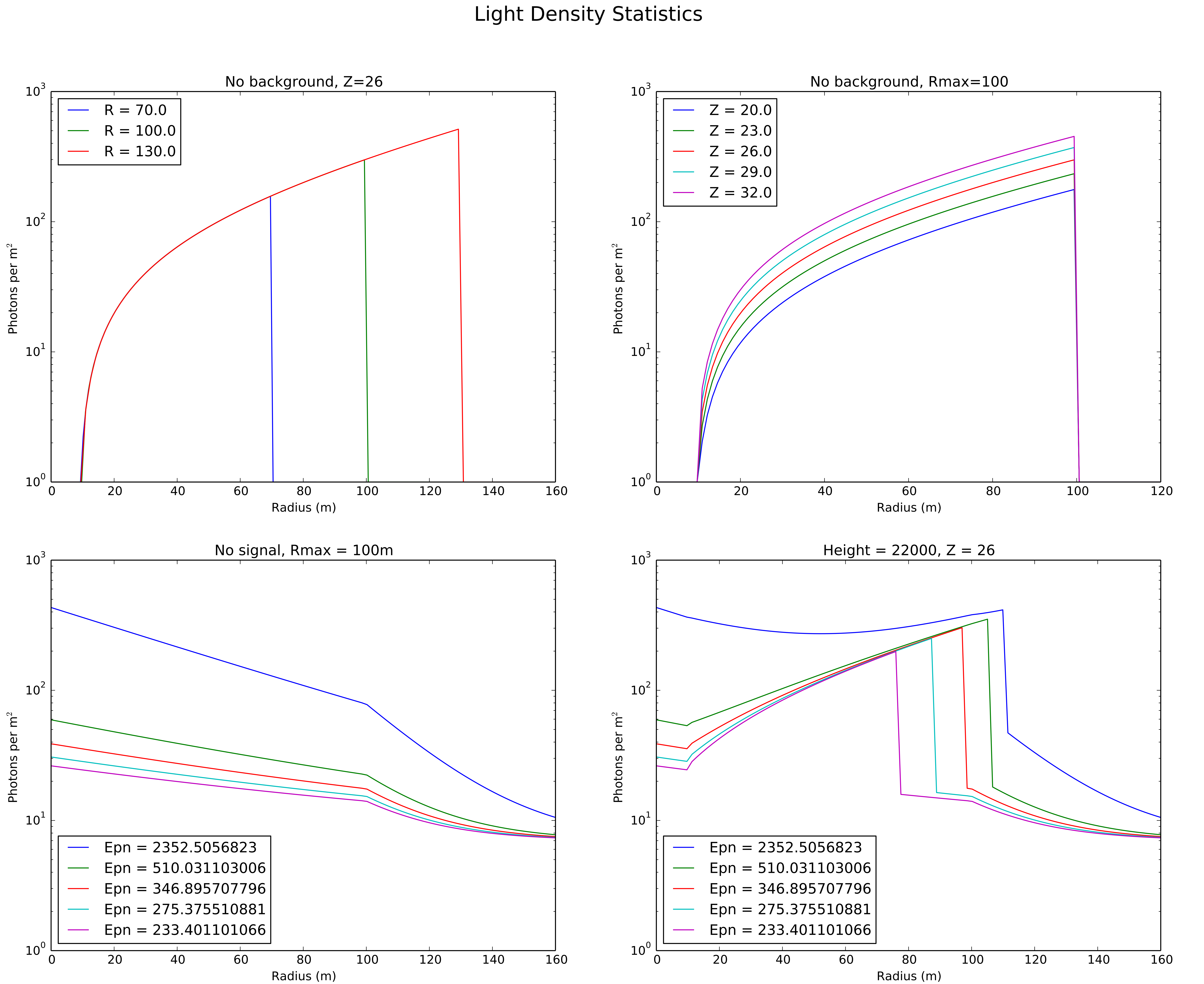


FIG. 5: A measured event with indications of DC-light in all four cameras images (indicated by arrows), after high threshold image cleaning. The reconstructed shower direction is shown by a cross ($\times$) in each image. The reconstructed energy of this event is 50/48 TeV based on QGSJET/SIBYLL simulations. The reconstructed impact parameter and DC-light intensity for each telescope are shown in the lower panels in each image. The energy and impact parameter resolutions are $\approx$20% and $\approx$20 m, respectively. The white points mark disabled pixels.



Light Density Statistics
No background, Z=26
R = 70.0
R = 100.0
R = 130.0
No background, Rmax=100
Z = 20.0
Z = 23.0
Z = 26.0
Z = 29.0
Z = 32.0
No signal, Rmax = 100m
Height = 22000, Z = 26
Epn = 2352.5056823
Epn = 510.031103006
Epn = 346.895707796
Epn = 275.375510881
Epn = 233.401101066
Photons per m^2
Radius (m)

Fitting and event reconstruction

- Five variables to reconstruct:
  - x/y Core Position,
  - First Interaction Height,
  - Energy per Nucleon
  - Charge.

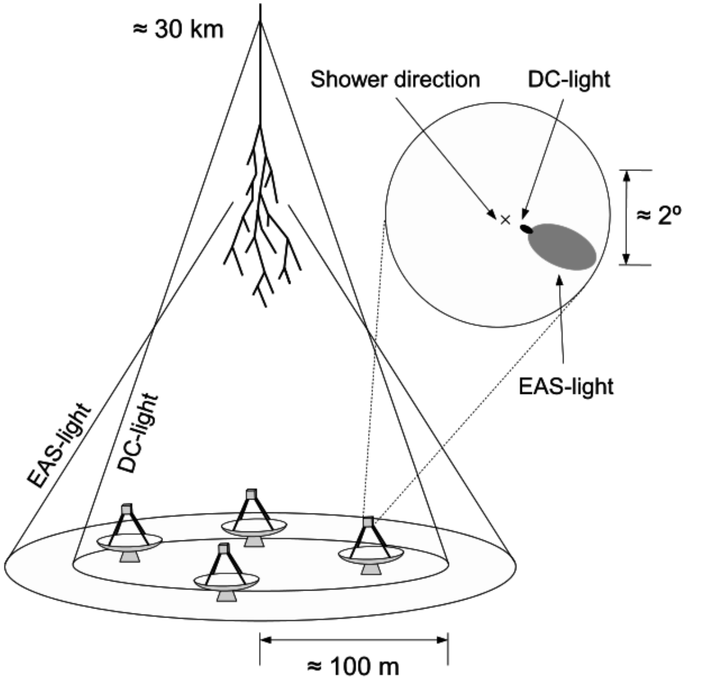


FIG. 1: Schematic representation of the Cherenkov emission from a cosmic-ray primary particle and the light distribution on the ground and in the camera plane of an IACT.

Likelihood

Poisson Distribution

$$P_i(N_{i,Received}|X,Y,Z,height,Epn)=\frac{e^{-\lambda_i}\times\lambda_i^{N_i}}{N_i!}$$

+

Stirling's Approximation

$$\ln(N!)\approx N\ln(N)-N+\frac{1}{2}\ln(2\Pi N)$$

=

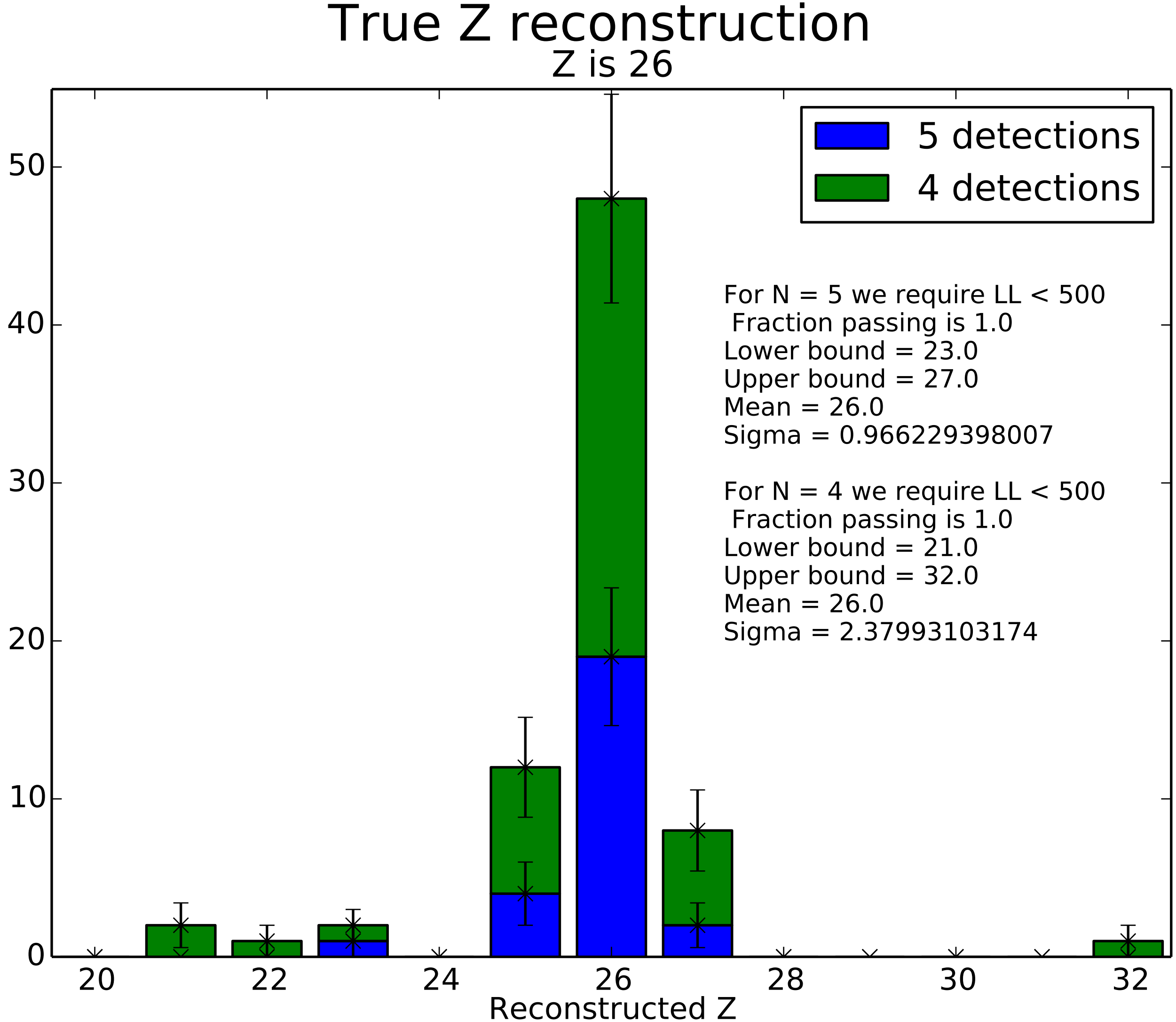
$$-\ln(L)=-\sum_i \ln(P_i)=\sum_i \lambda_i-N_i\ln(\lambda_i)+N_i\ln(N_i)-N_i+\frac{1}{2}\ln(2\Pi N_i)$$

Iterative Minimisation

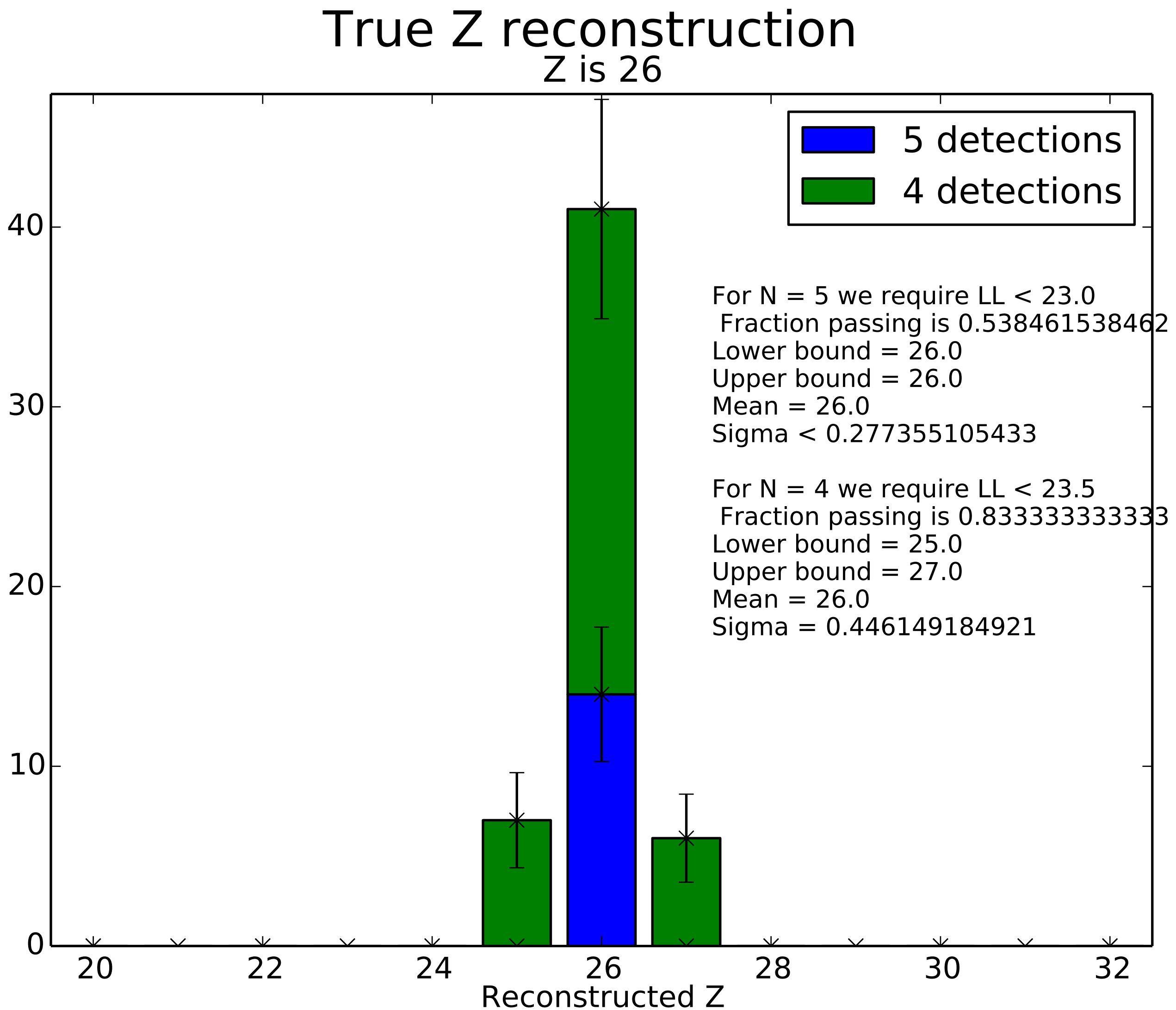
- Iterate over integer Z
- Select a ~100m² region
- Scan valid Height/Energy combinations

  - 13 Z values
  - 10 positions
  - 51 Epn/Height Combos
  - 13 x 10 x 51 = 6630

- **Candidate with smallest log likelihood of the 6630 runs is selected**



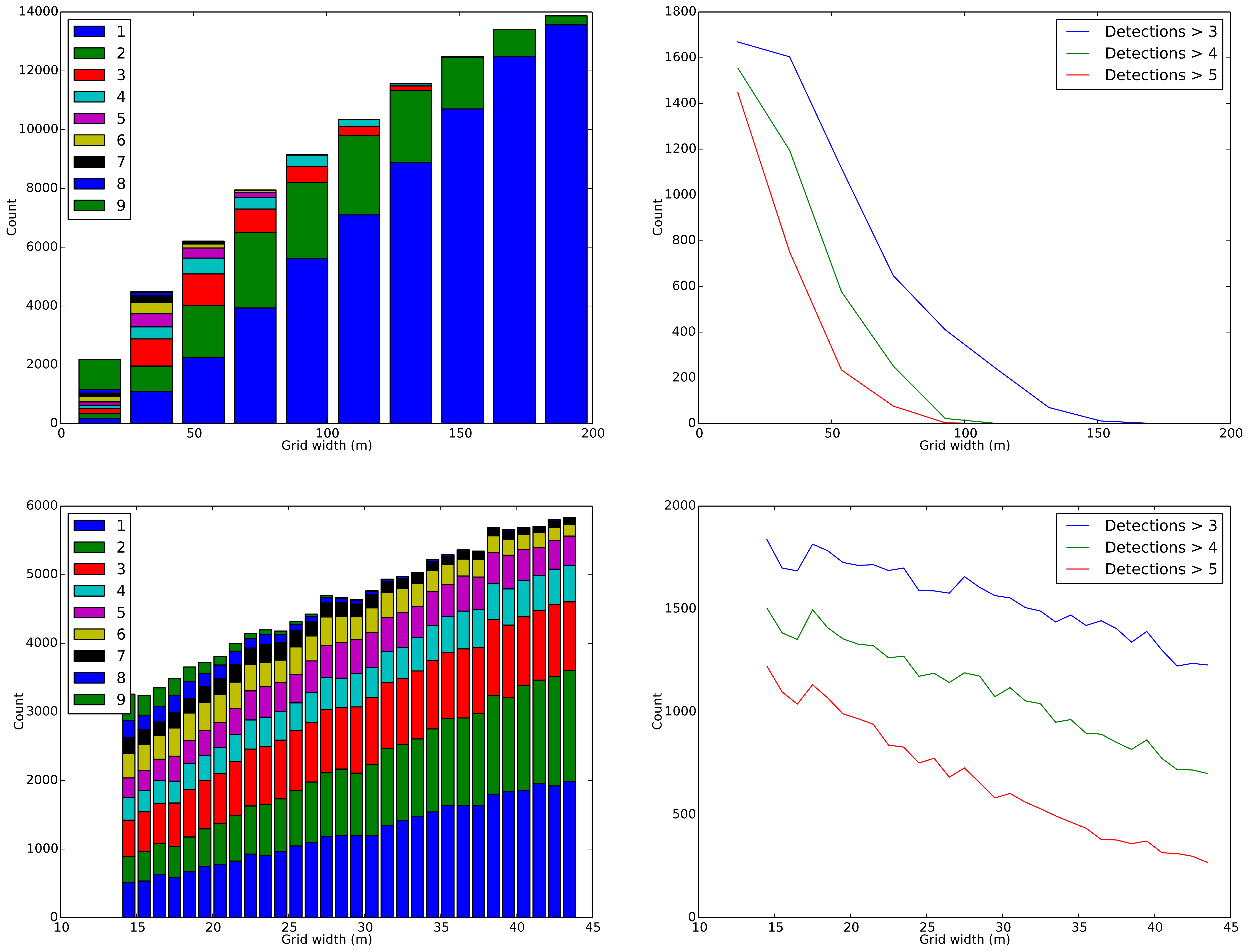
True Z reconstruction
Z is 26
5 detections
4 detections
For N = 5 we require LL < 500
Fraction passing is 1.0
Lower bound = 23.0
Upper bound = 27.0
Mean = 26.0
Sigma = 0.966229398007
For N = 4 we require LL < 500
Fraction passing is 1.0
Lower bound = 21.0
Upper bound = 32.0
Mean = 26.0
Sigma = 2.37993103174
0
10
20
30
40
50
20
22
24
26
28
30
32
Reconstructed Z


True Z reconstruction
Z is 26
5 detections
4 detections
For N = 5 we require LL < 23.0
Fraction passing is 0.538461538462
Lower bound = 26.0
Upper bound = 26.0
Mean = 26.0
Sigma < 0.277355105433
For N = 4 we require LL < 23.5
Fraction passing is 0.833333333333
Lower bound = 25.0
Upper bound = 27.0
Mean = 26.0
Sigma = 0.446149184921
0
10
20
30
40
20
22
24
26
28
30
32
Reconstructed Z

Optimised Telescope Array

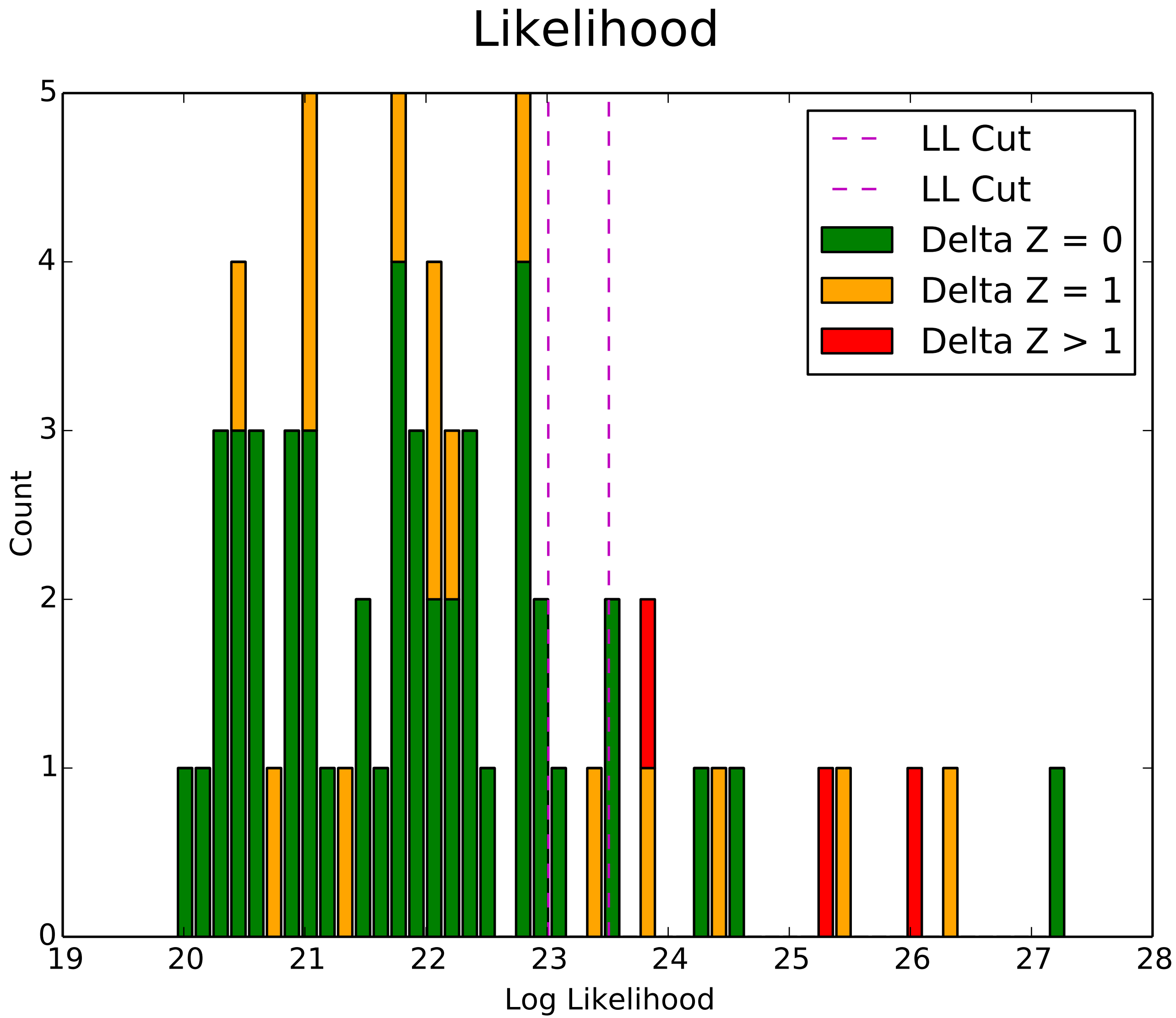
- Grid of 3 x 3 telescopes (12m Diameter)
- Expected counts for 50 hours run time
- Minimise σ_z by balancing competing effects

Telescope Observations for 50 hours

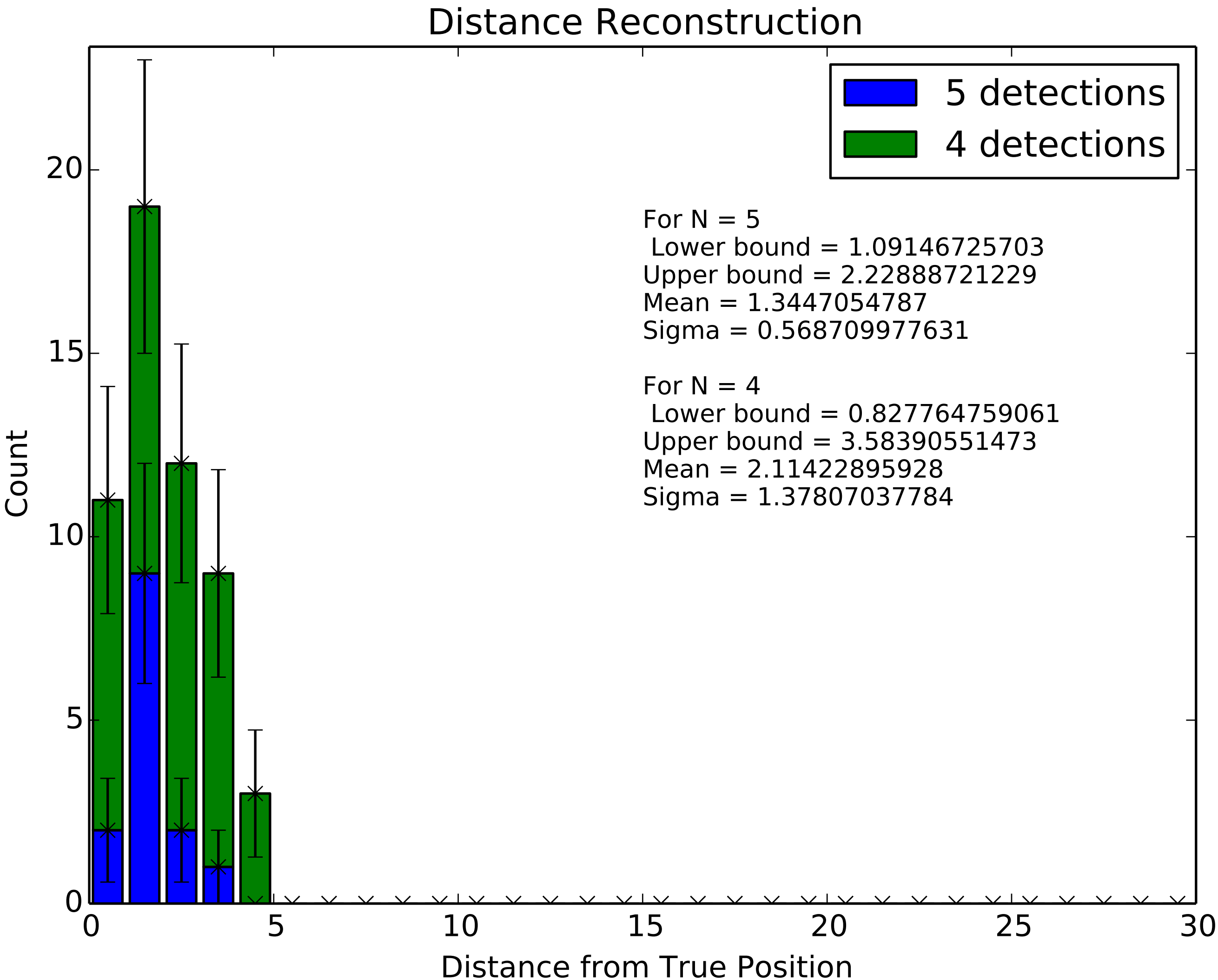


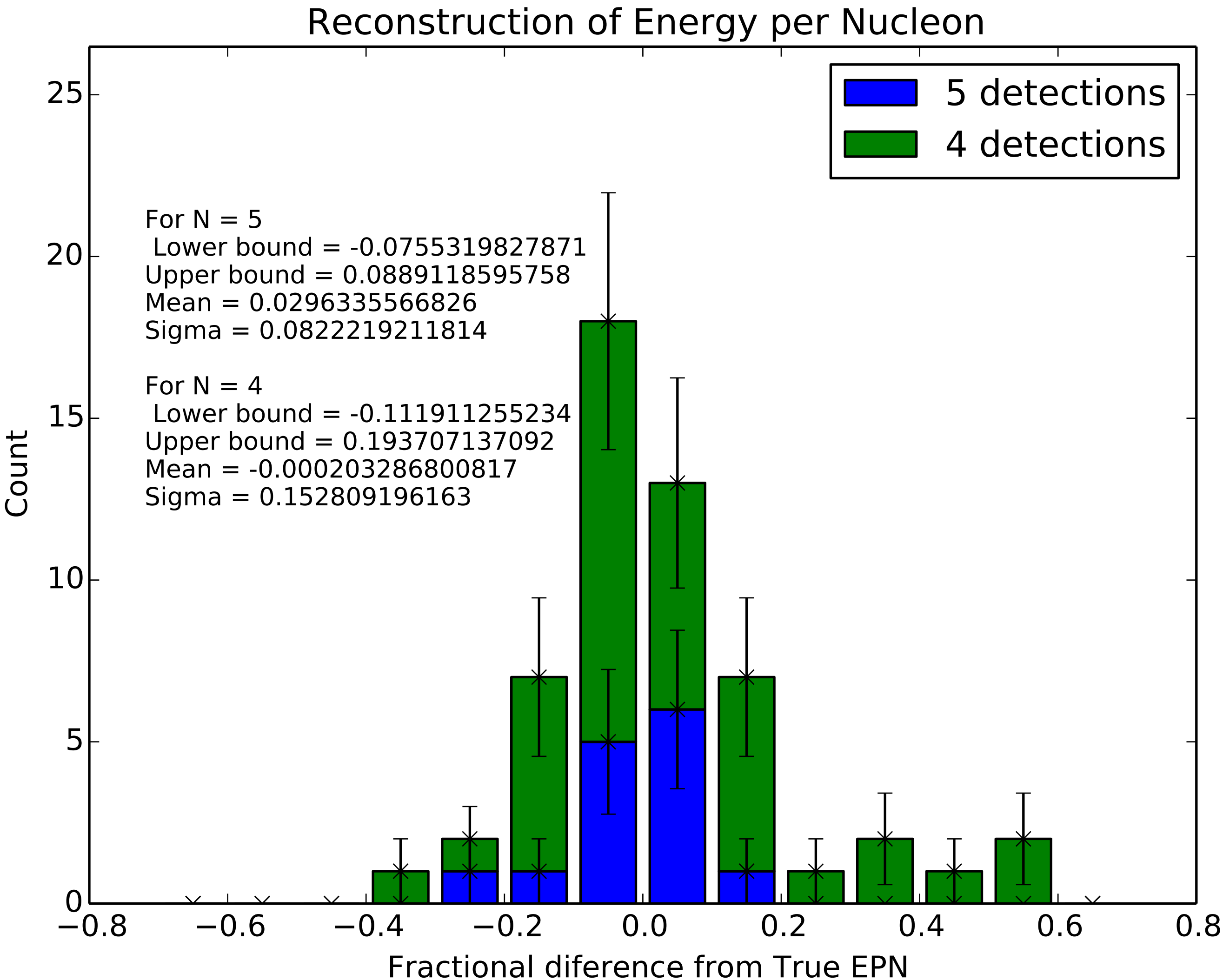
Summary

- New Technique for Charge Reconstruction, valid for both current and future IACT systems.
- Simulation with HESS-type layout yields a much improved core reconstruction.
- Charge resolution of $\sigma_Z < 0.3$ for five telescope events.
- Ideal future CT experiment would have 9 telescopes with a grid spacing of ~20-40m.
- Consequent event rate would be ~15 events per hour observed by 5 or more telescopes.

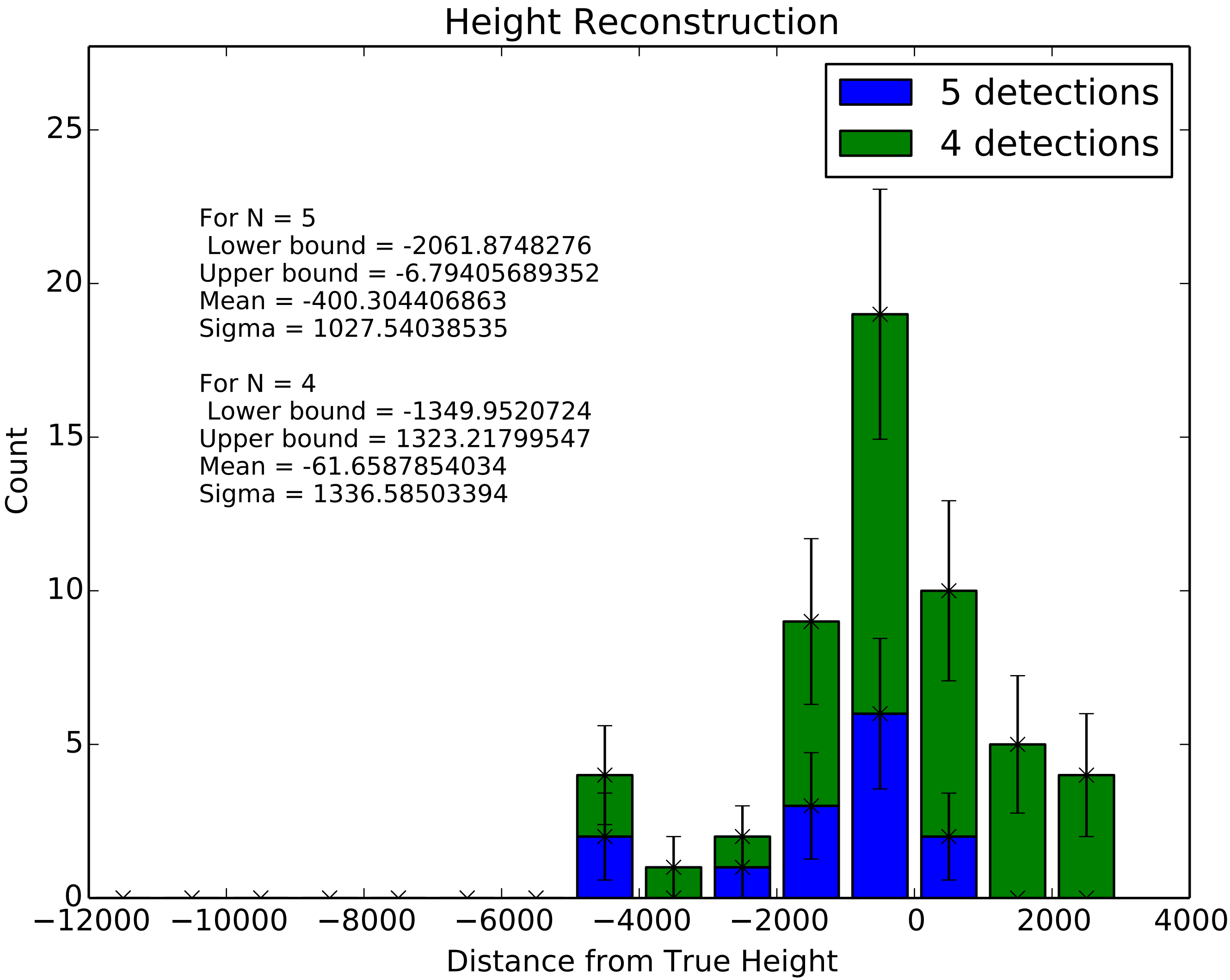


Likelihood
LL Cut
LL Cut
Delta Z = 0
Delta Z = 1
Delta Z > 1
Count
Log Likelihood
0
1
2
3
4
5
19
20
21
22
23
24
25
26
27
28


Distance Reconstruction
5 detections
4 detections
For N = 5
Lower bound = 1.09146725703
Upper bound = 2.22888721229
Mean = 1.3447054787
Sigma = 0.568709977631
For N = 4
Lower bound = 0.827764759061
Upper bound = 3.58390551473
Mean = 2.11422895928
Sigma = 1.37807037784
Count
0
5
10
15
20
25
30
Distance from True Position



Reconstruction of Energy per Nucleon
5 detections
4 detections
For N = 5
Lower bound = -0.0755319827871
Upper bound = 0.0889118595758
Mean = 0.0296335566826
Sigma = 0.0822219211814
For N = 4
Lower bound = -0.111911255234
Upper bound = 0.193707137092
Mean = -0.000203286800817
Sigma = 0.152809196163
Count
Fractional diference from True EPN


Height Reconstruction
5 detections
4 detections
For N = 5
Lower bound = -2061.8748276
Upper bound = -6.79405689352
Mean = -400.304406863
Sigma = 1027.54038535
For N = 4
Lower bound = -1349.9520724
Upper bound = 1323.21799547
Mean = -61.6587854034
Sigma = 1336.58503394
Count
Distance from True Height
0
5
10
15
20
25
−12000
−10000
−8000
−6000
−4000
−2000
0
2000
4000