Ultra High Energy Cosmic Ray Spectrum Measured by HiRes Experiment

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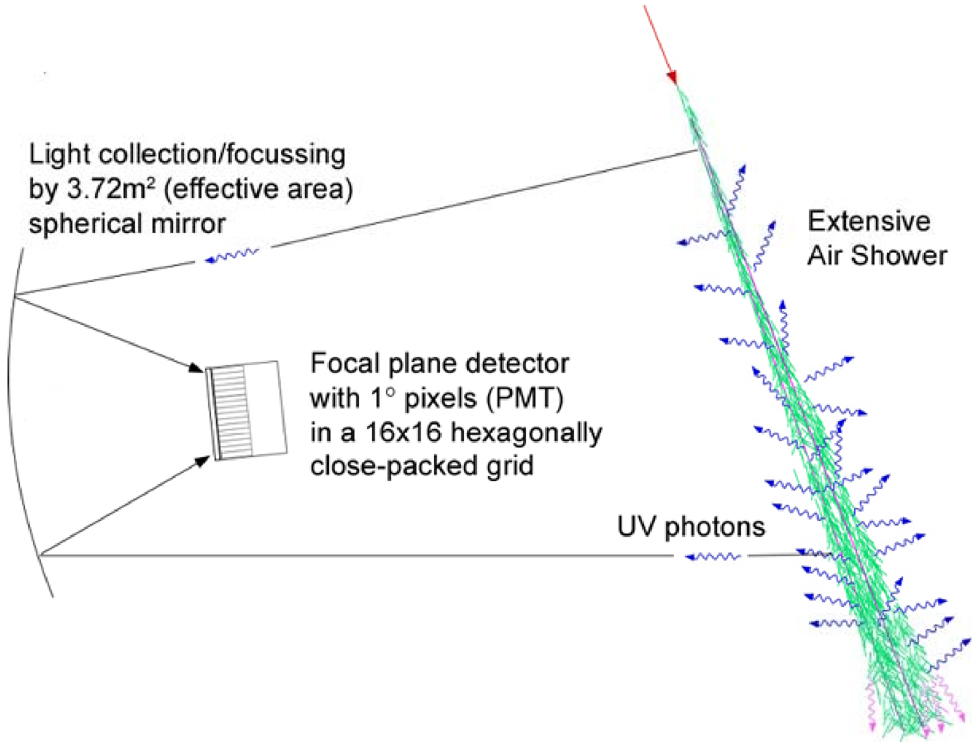
Outline

- Introduction
- Detector Calibration
- Detector Simulation
- Detector Resolution
- Aperture estimation
- Energy Spectrum
- Uncertainty study
- Conclusion

Introduction

HiRes

- Each HiRes detector unit ("*mirror*") consists of:
  - spherical mirror w/ 3.72m^2 unobstructed collection area
  - 16x16 array (hexagonally close-packed) of PMT pixels each viewing 1° cone of sky



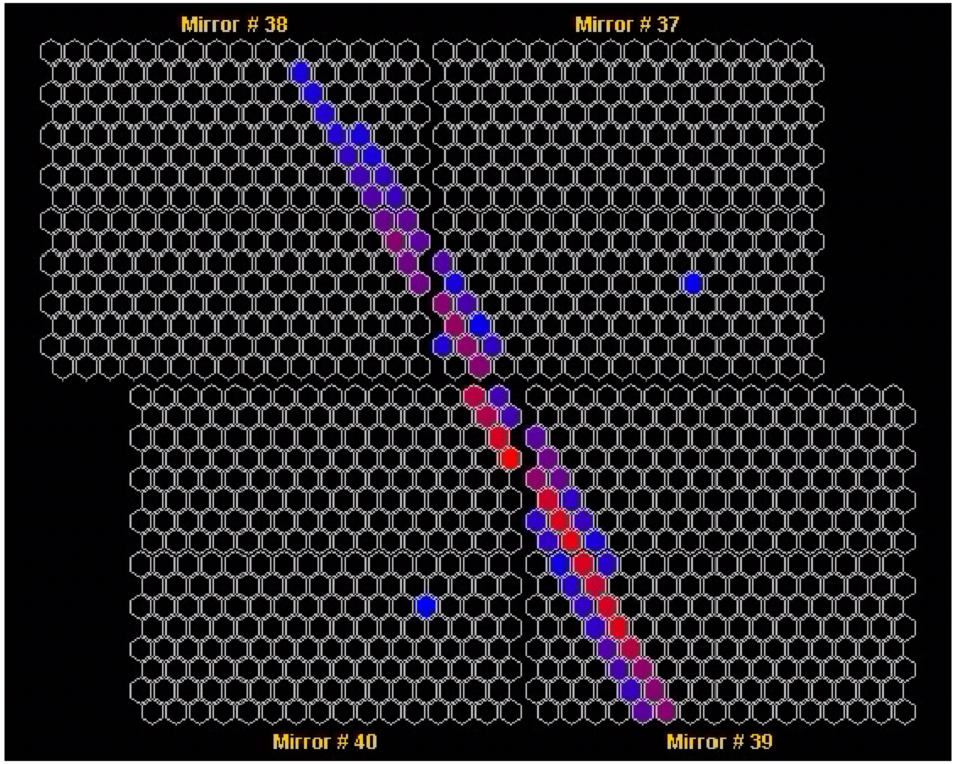
HiRes

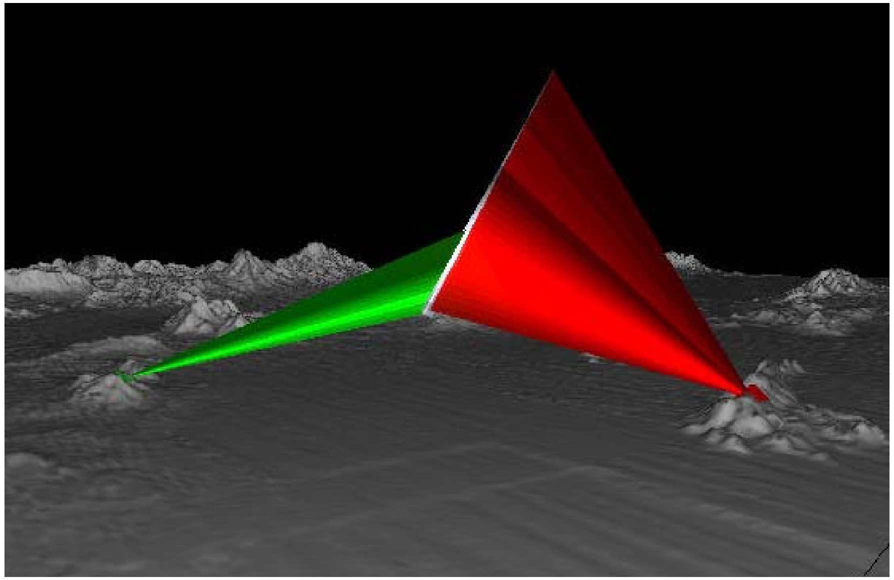
- HiRes-1 site re-used HiRes prototype PMT and electronics
  - began operation in June, 1997
- HiRes-2 site uses new FADC system developed at Columbia Univ.
  - Stereo observation began Dec 1999.

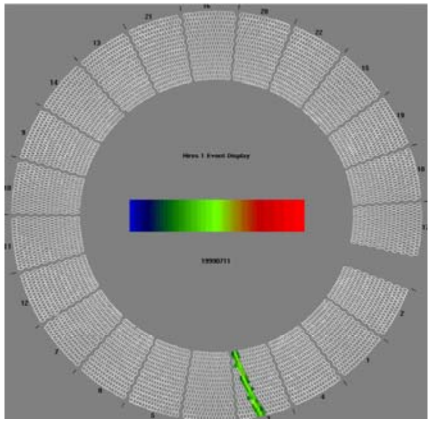
HiRes-1

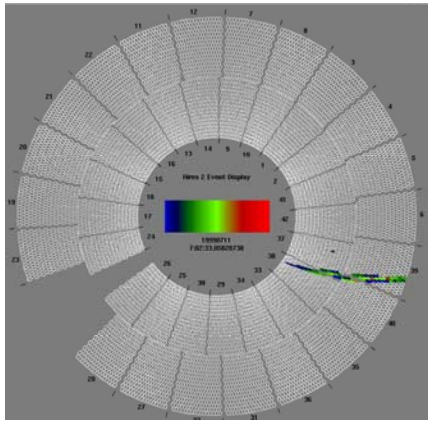
HiRes-2

Typical HiRes Event



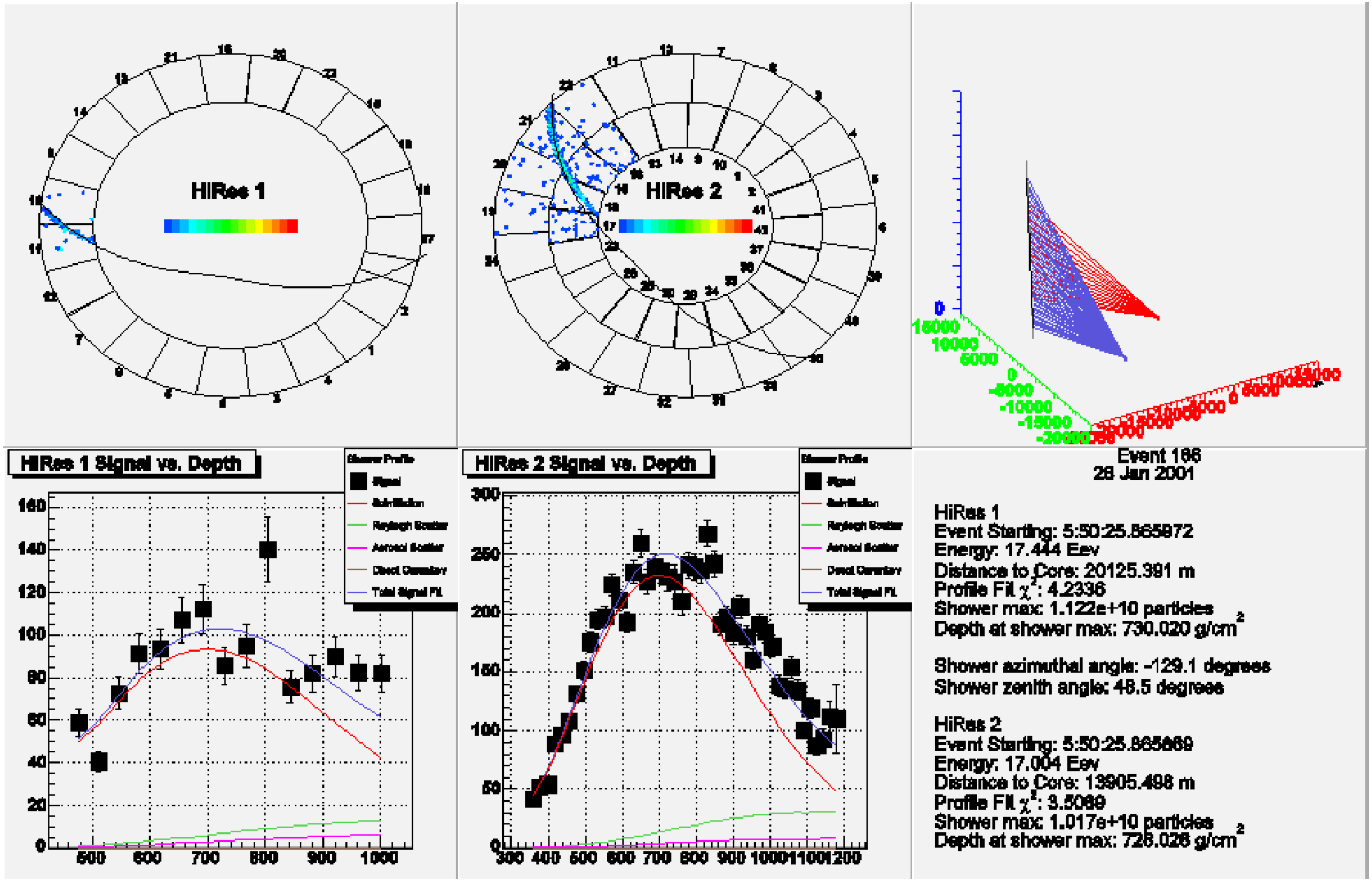






- ~2 × 10^9 eV events seen in 1999
- 1/500,000 speed playback of "movie"

An example event



Stereoscopic Operational Facts

- 719 operational nights: $T=1.3\times10^{7}$ sec

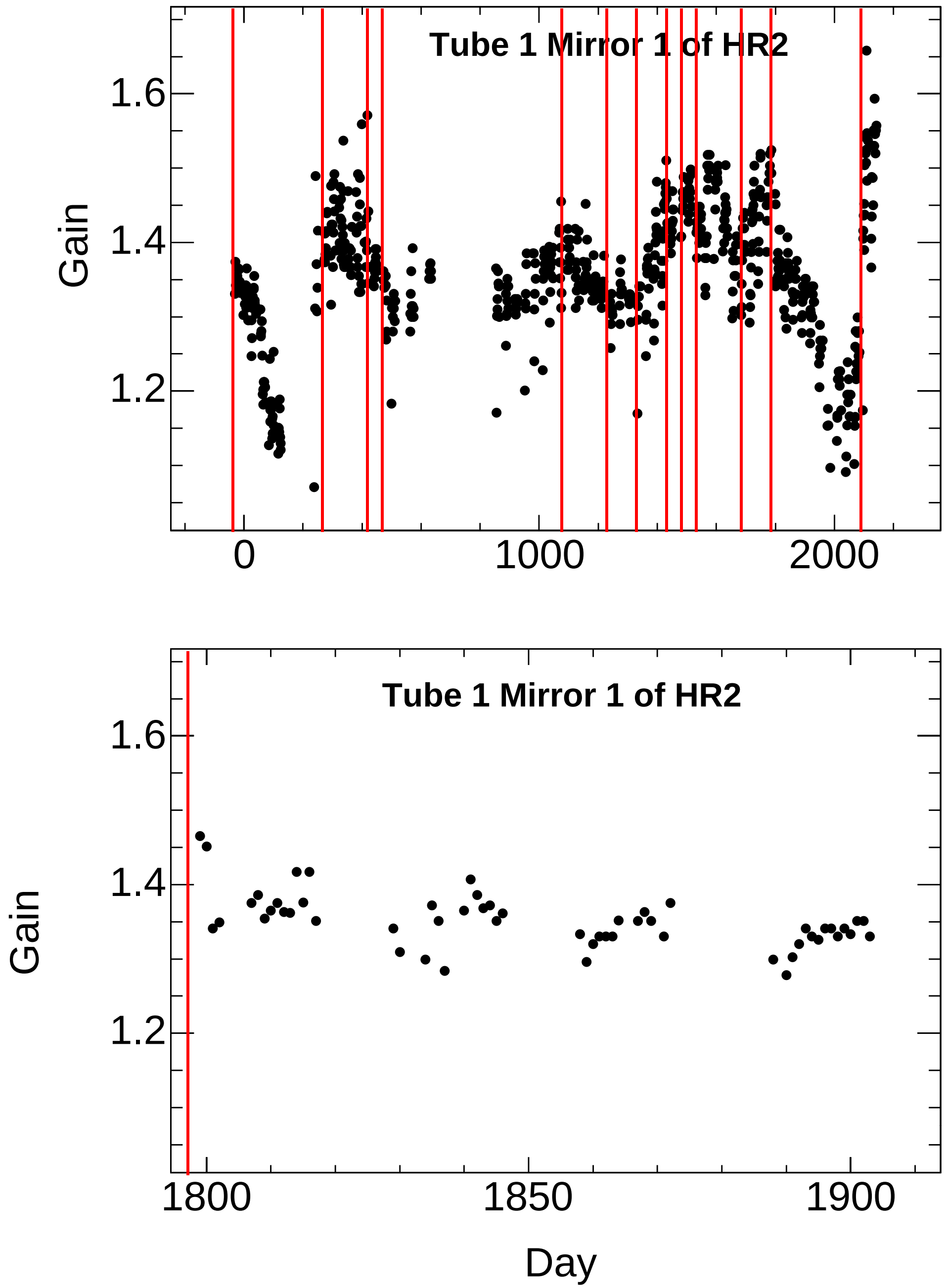
  effective duty cycle: 6.5%
- # of reconstructed events : 16473

  after all cuts:
- # of events in the spectrum analysis: 1256
- # of events below $E_{th}=3\times10^{18}$ eV: 1033

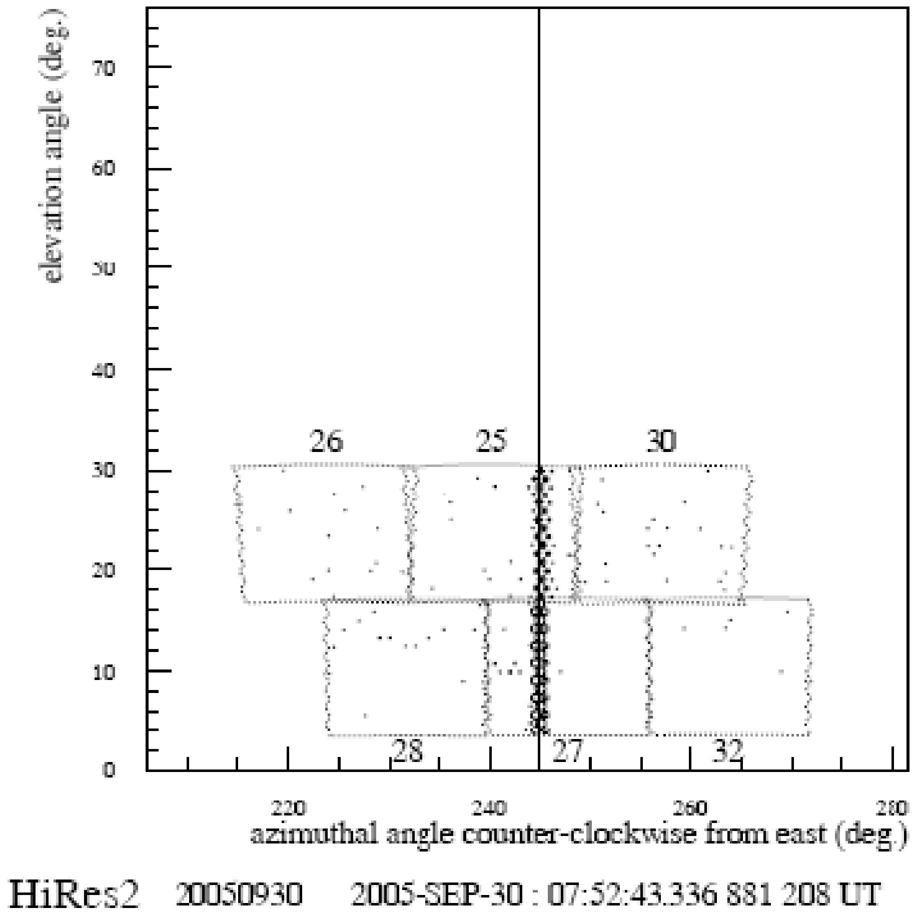
Calibration

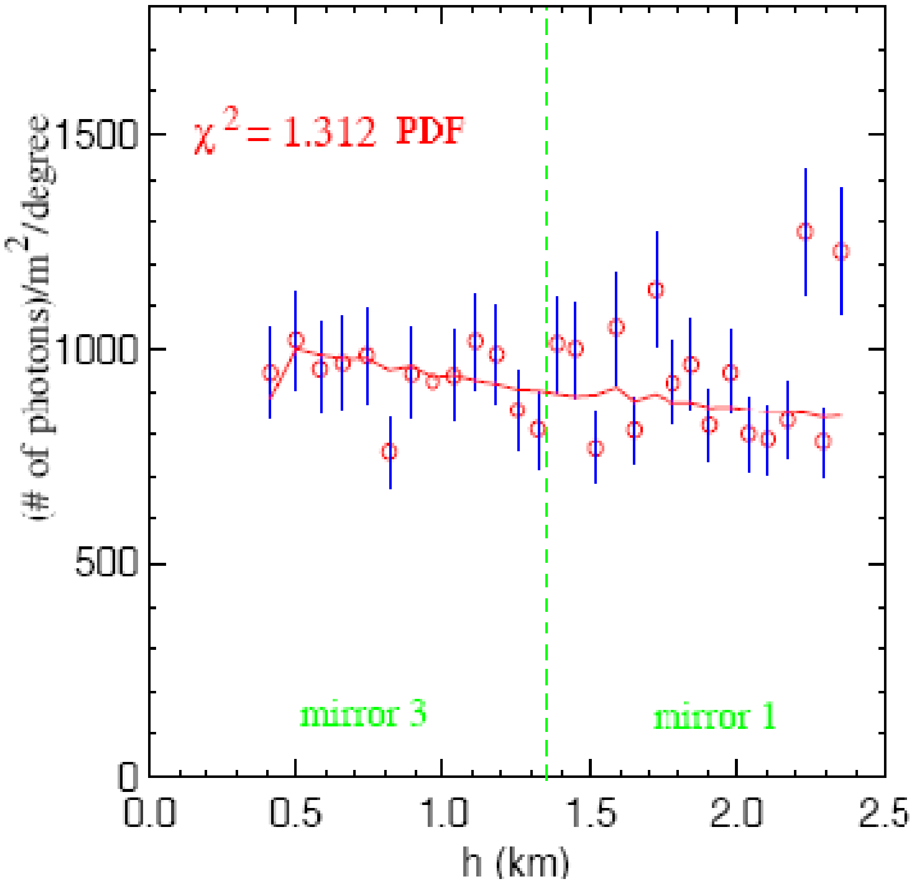
1. Roving Xenon Flasher
2. YAG laser monitoring (daily gain database)
3. End-to-end using roving N_2 laser
4. Hourly atmospheric transmission
5. Mirror reflectivity (m,λ)

Gains are calibrated using roving xenon flasher (red lines) & monitored using YAG laser+fiber-bundle



"end-to-end" absolute Calibration using N_2 laser@4km





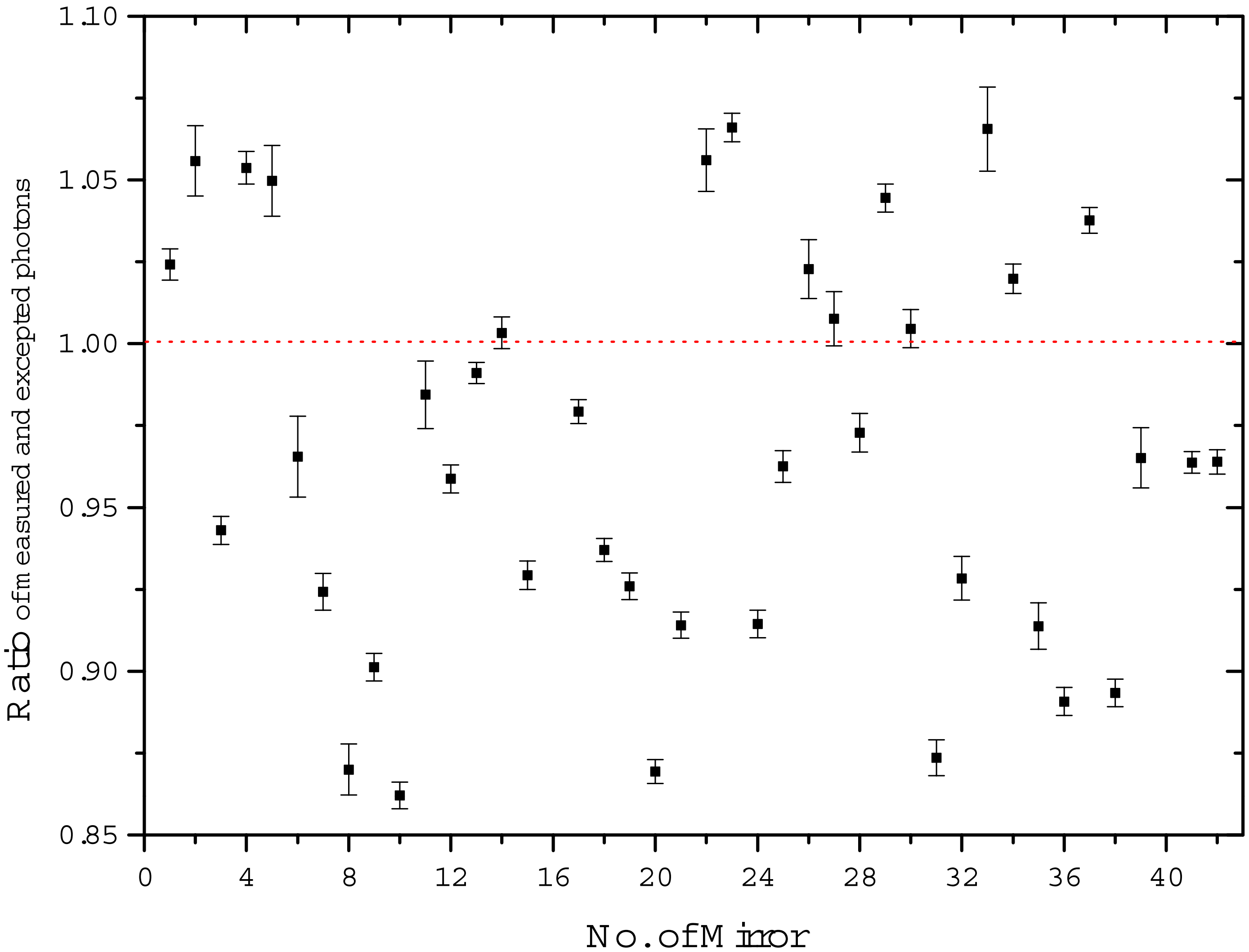
Average energy scale of each mirror (HR2)

Most of mirrors are in ±10%

mir 1,2,3,4 are right on the boundary

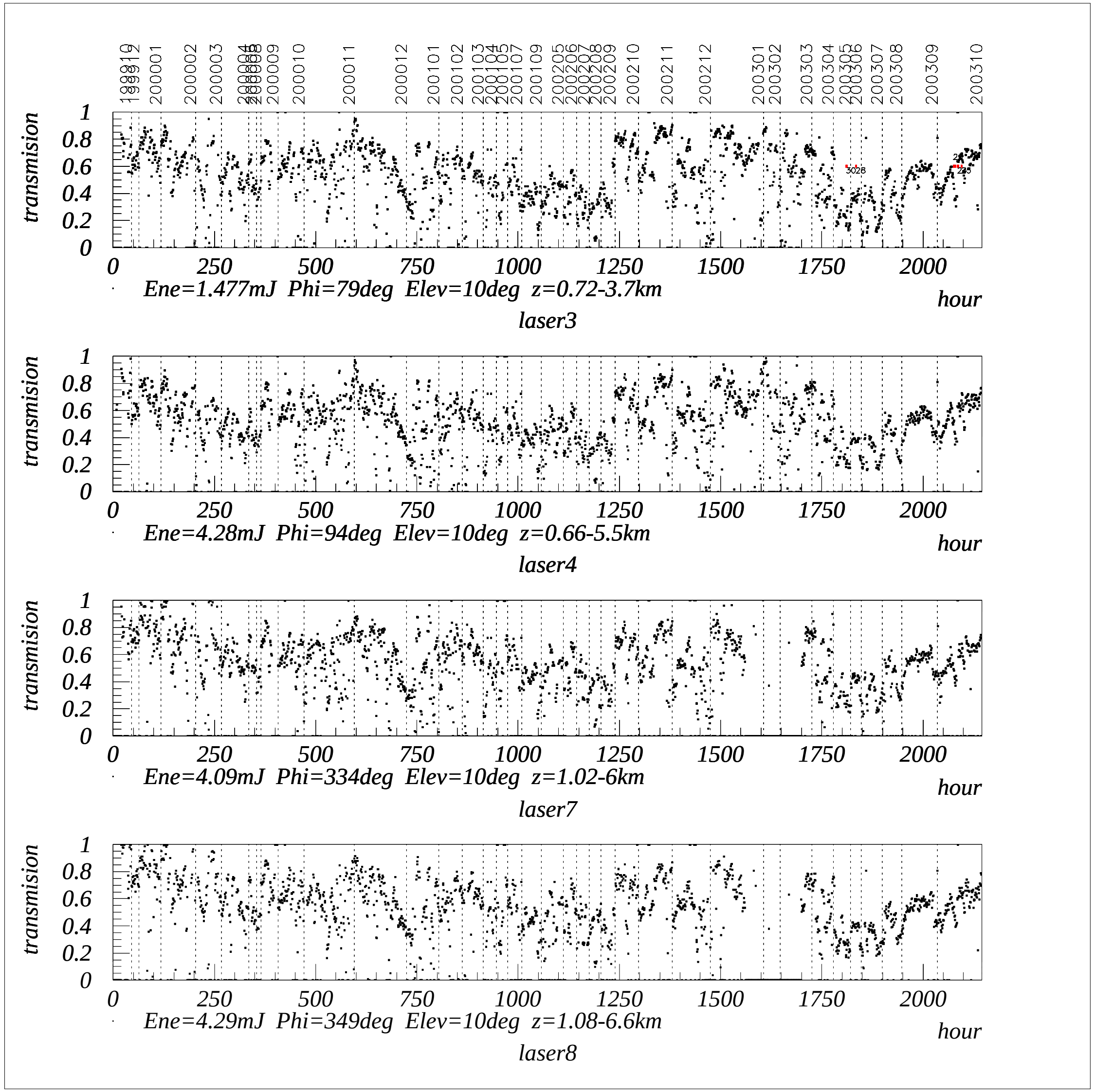
mir 8 is too far away from the laser (>6km)

mir 16 not clear why



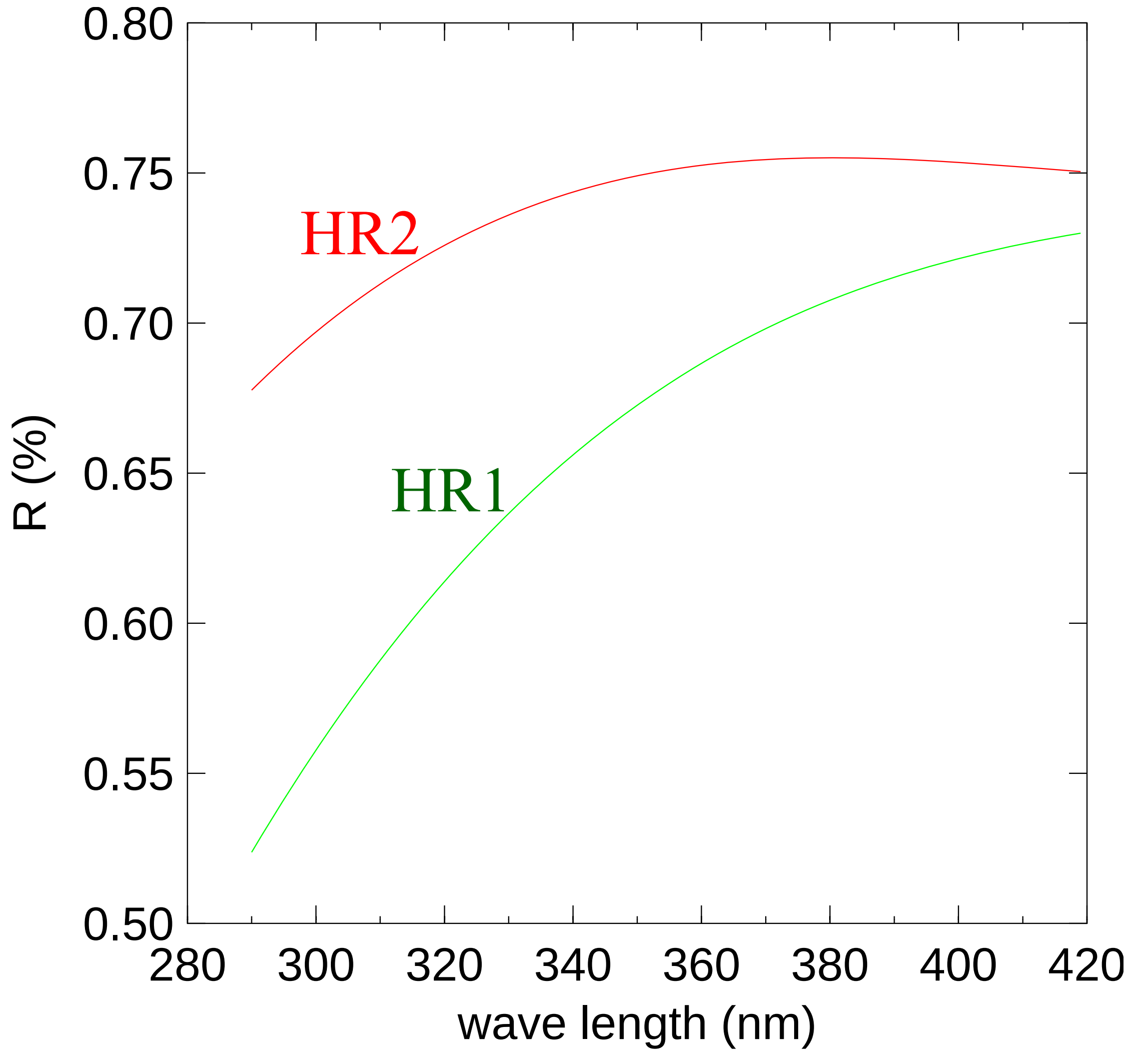
Aerosol transmission

- Entire data taking period



Reflectivity of Mirrors

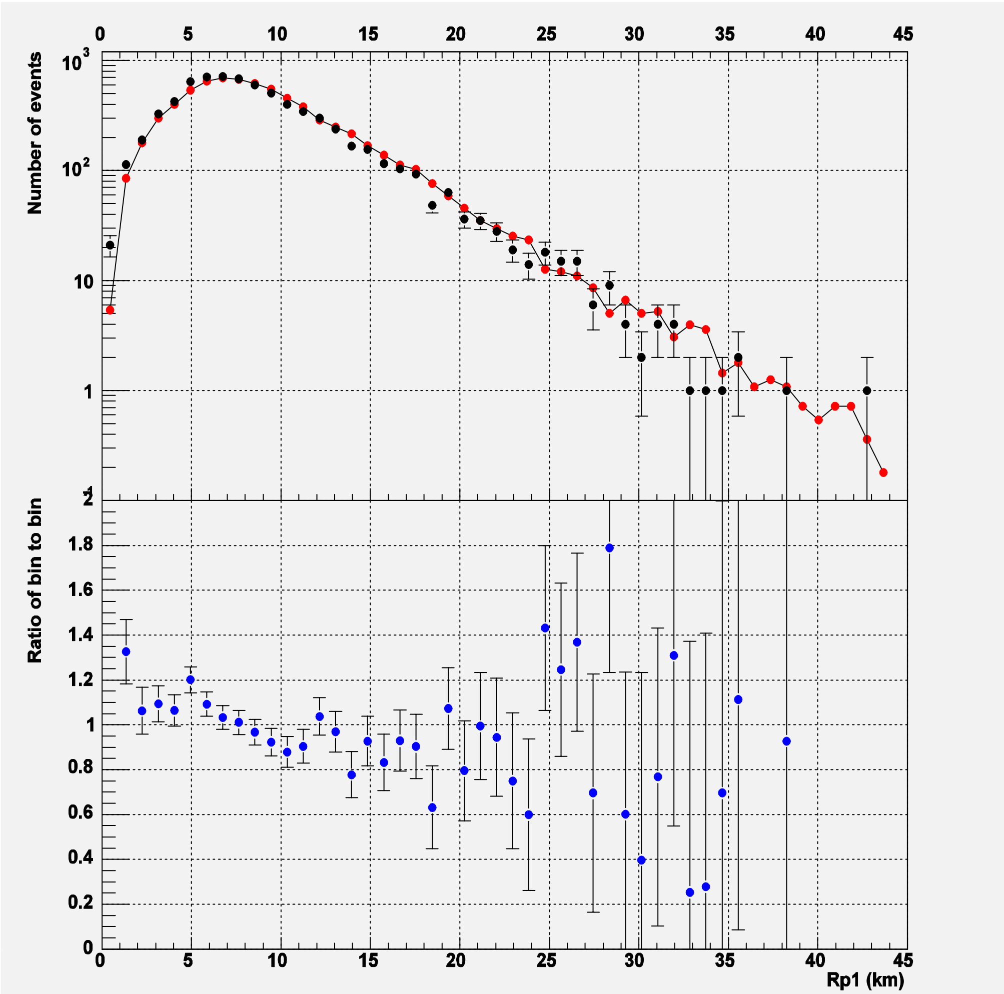
Relative reflectivities for different mirror is within ±6%



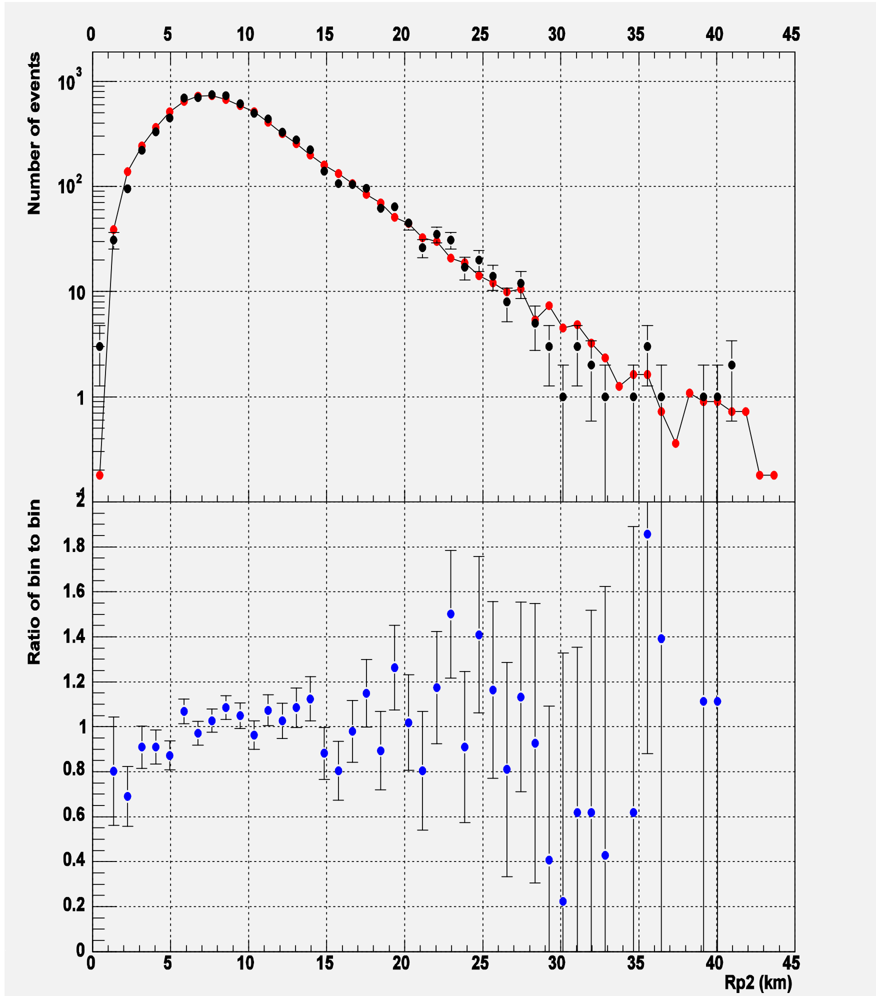
Detector Simulation and Comparison with Data

1. Corsika shower driven simulation
2. Light production and propagation
3. Detector response and trigger
4. Fully reconstructed

MC vs. Data: Rp distribution (proton)



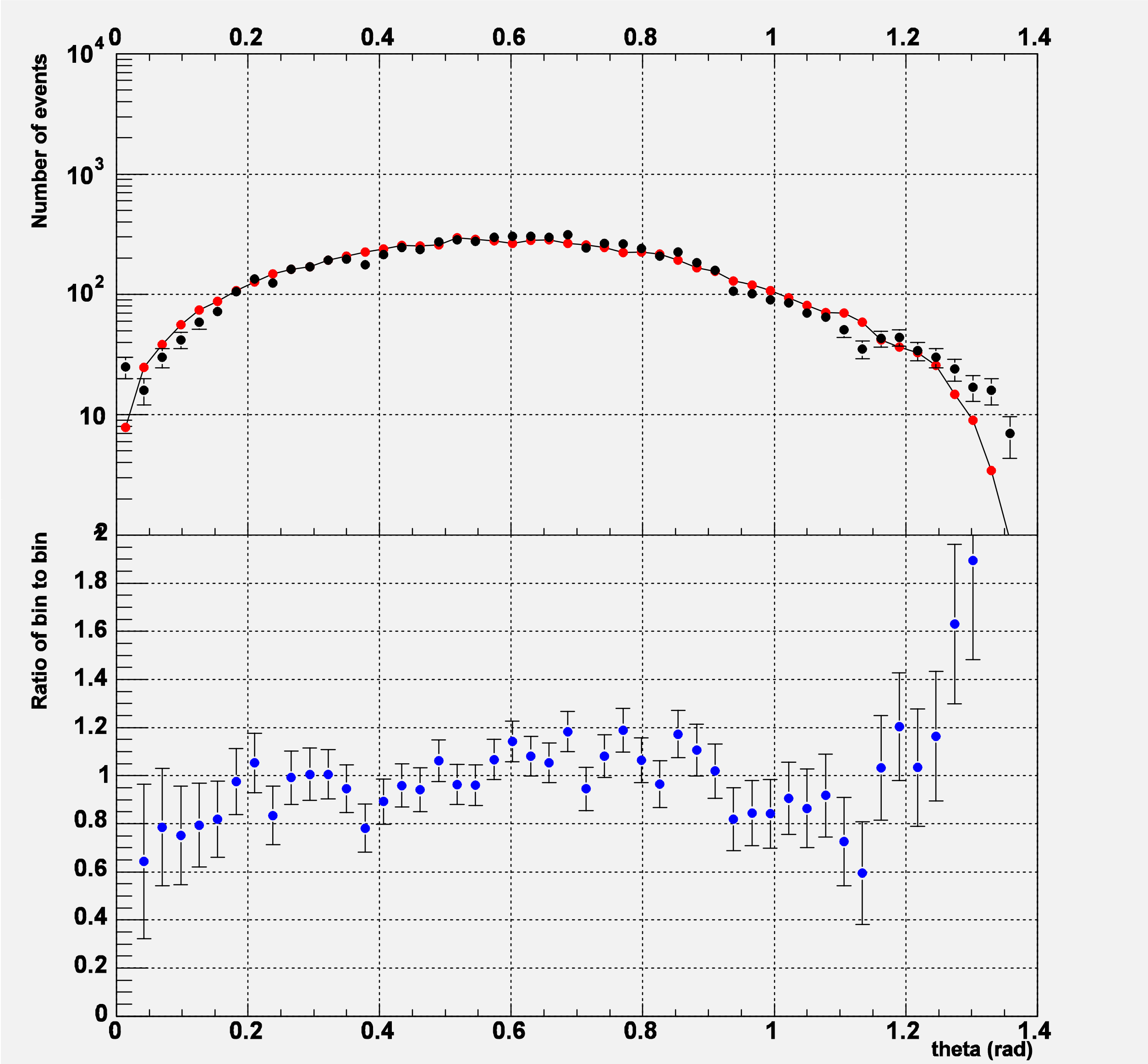
Rp1 (km)



Rp2 (km)

MC vs. Data: zenith angle distribution

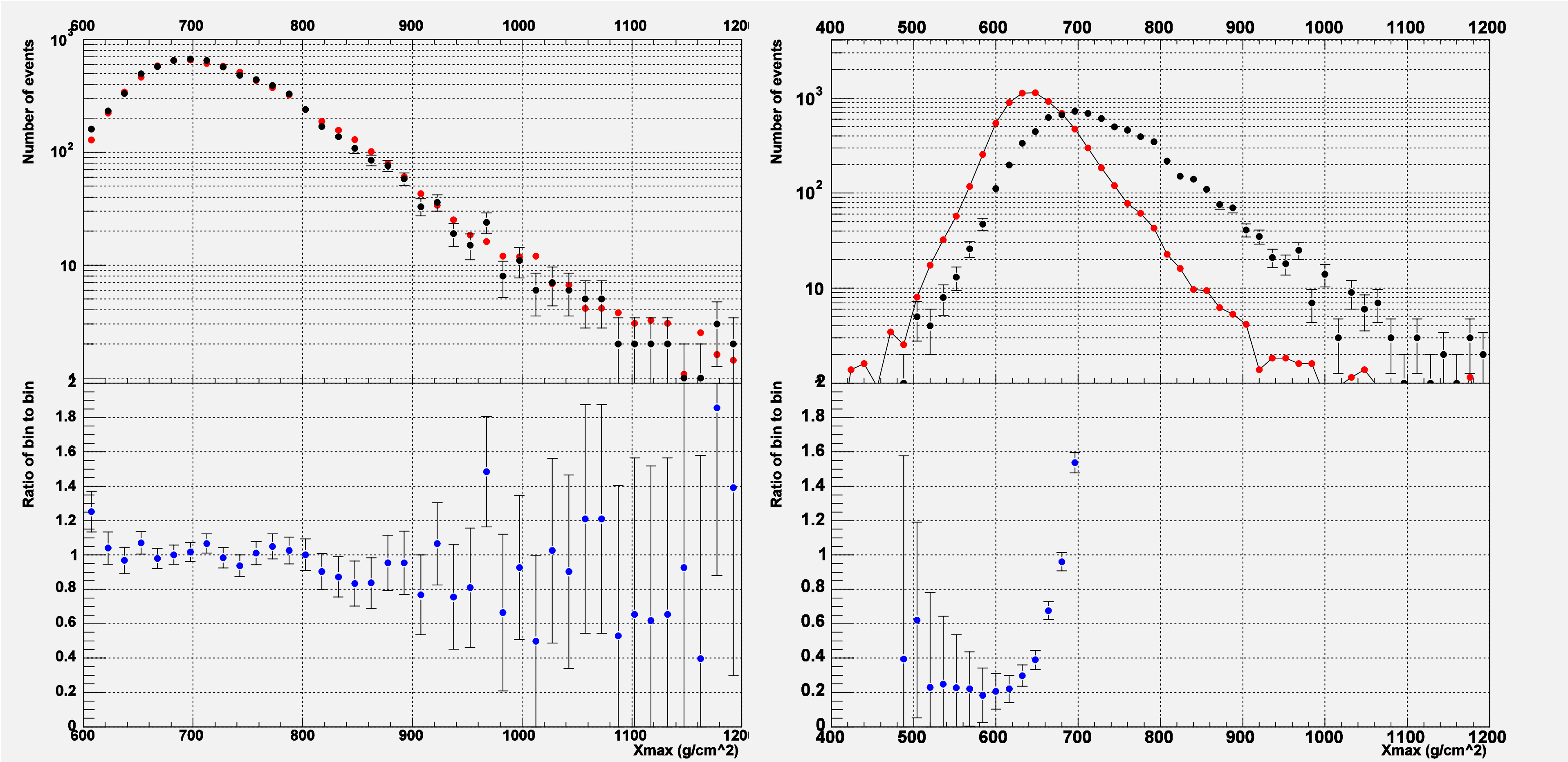
Iron



θ (rad)

MC vs. Data: Xmax distribution

Data seems to favor proton

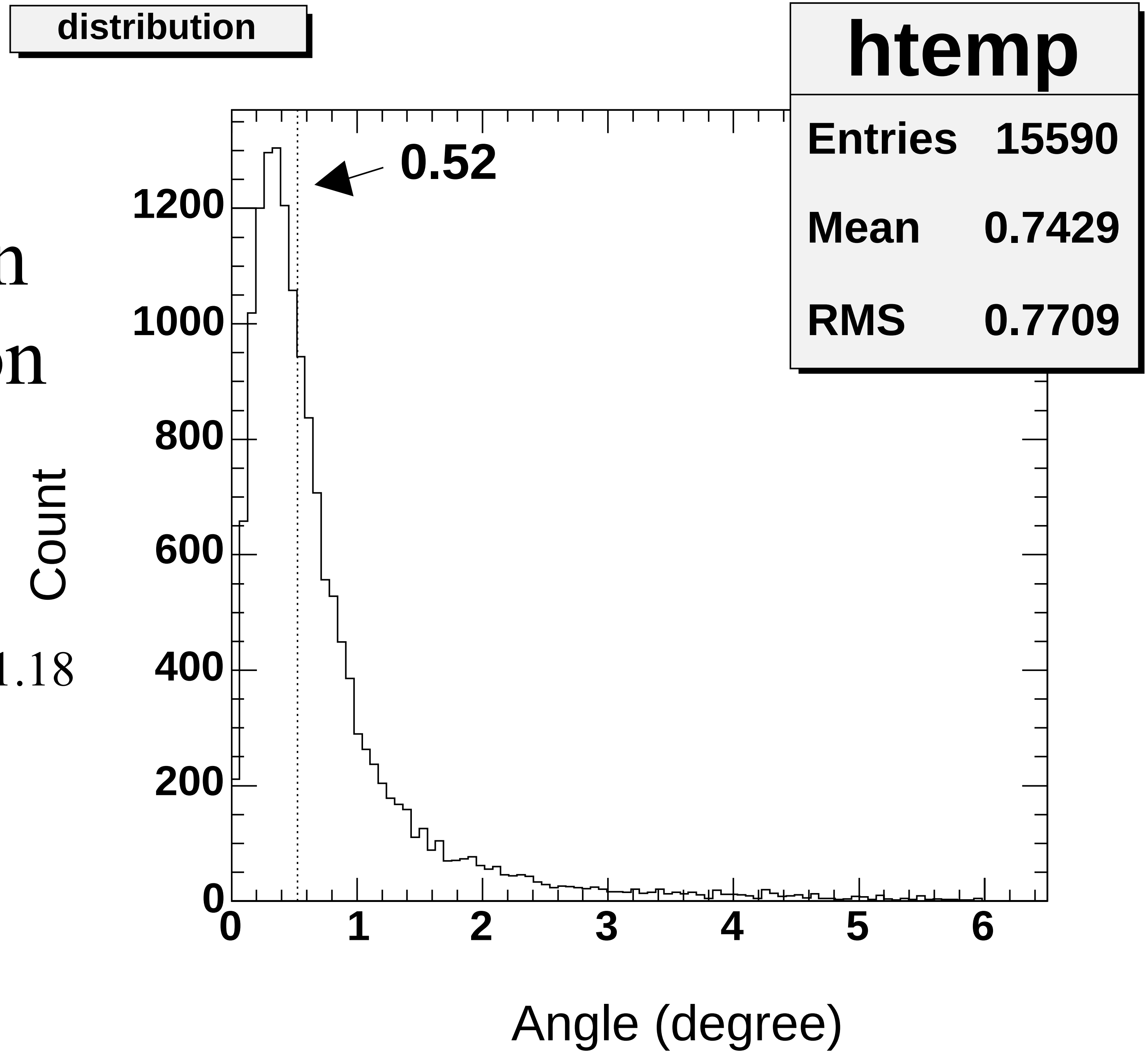


Xmax (g/cm^2)

Detector Resolution

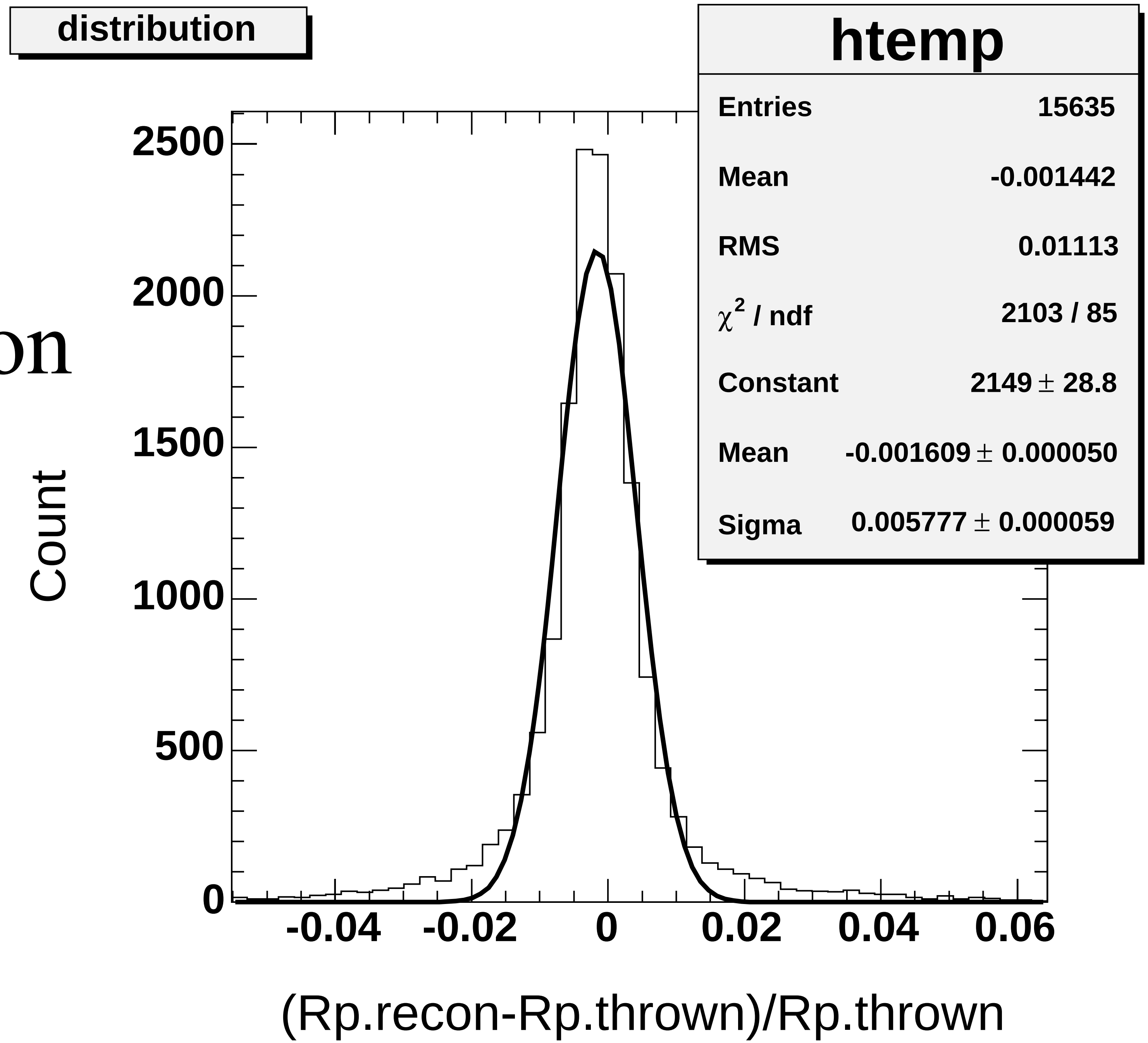
1. Geometrical reconstruction
2. Shower development

Arrival direction resolution

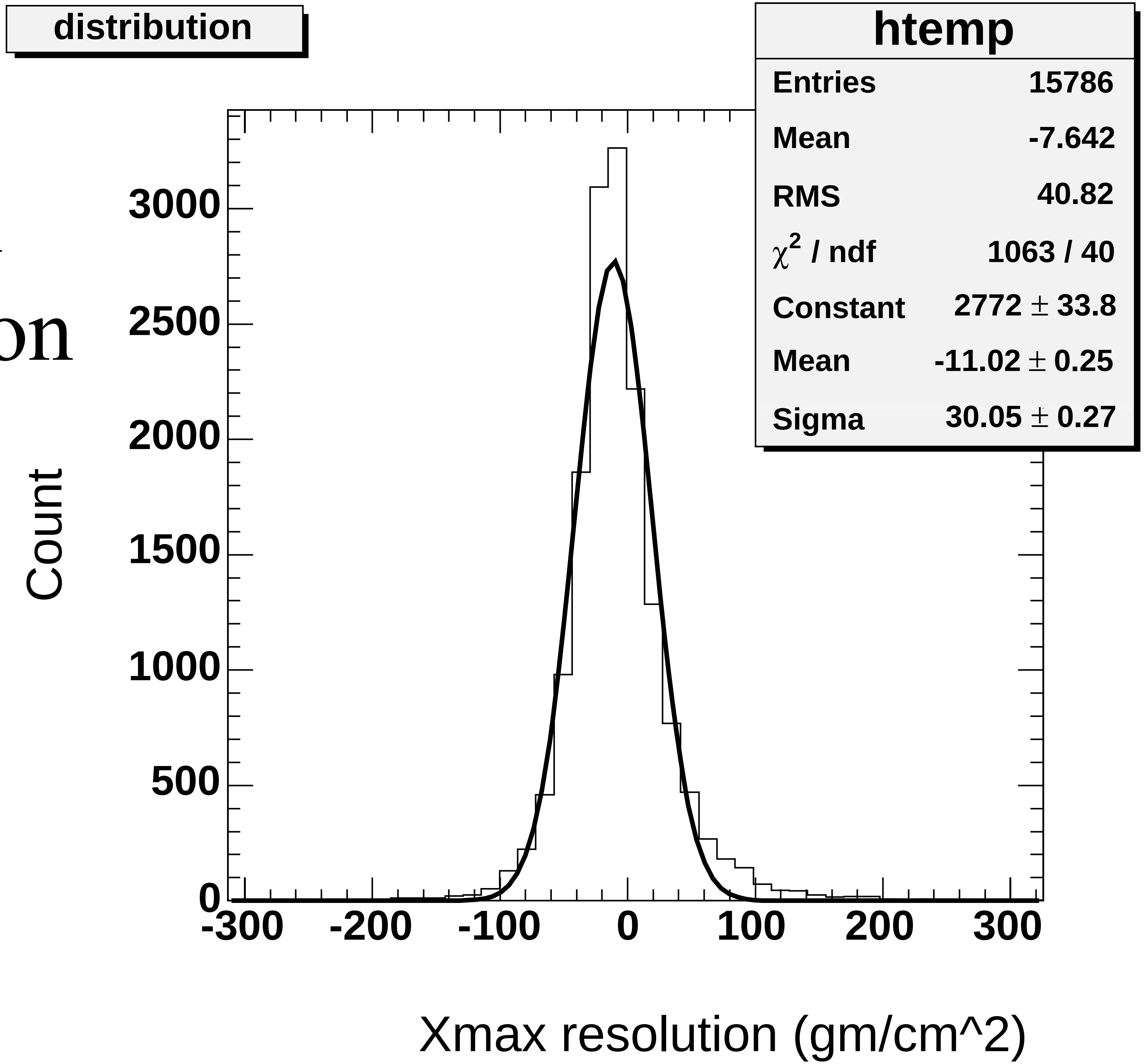


Resolution
= 0.52 degree /1.18
= 0.44 degree

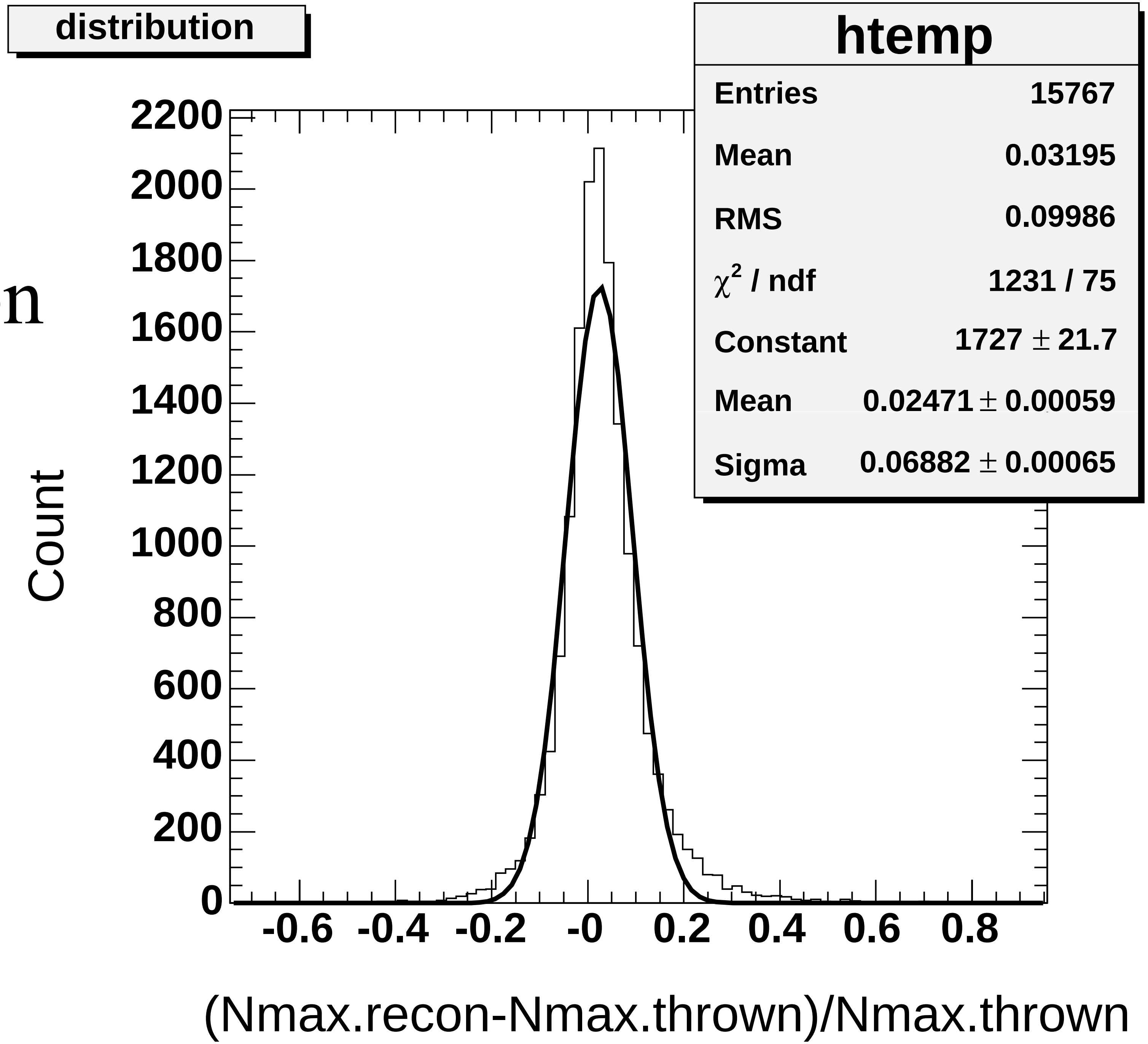
Rp resolution



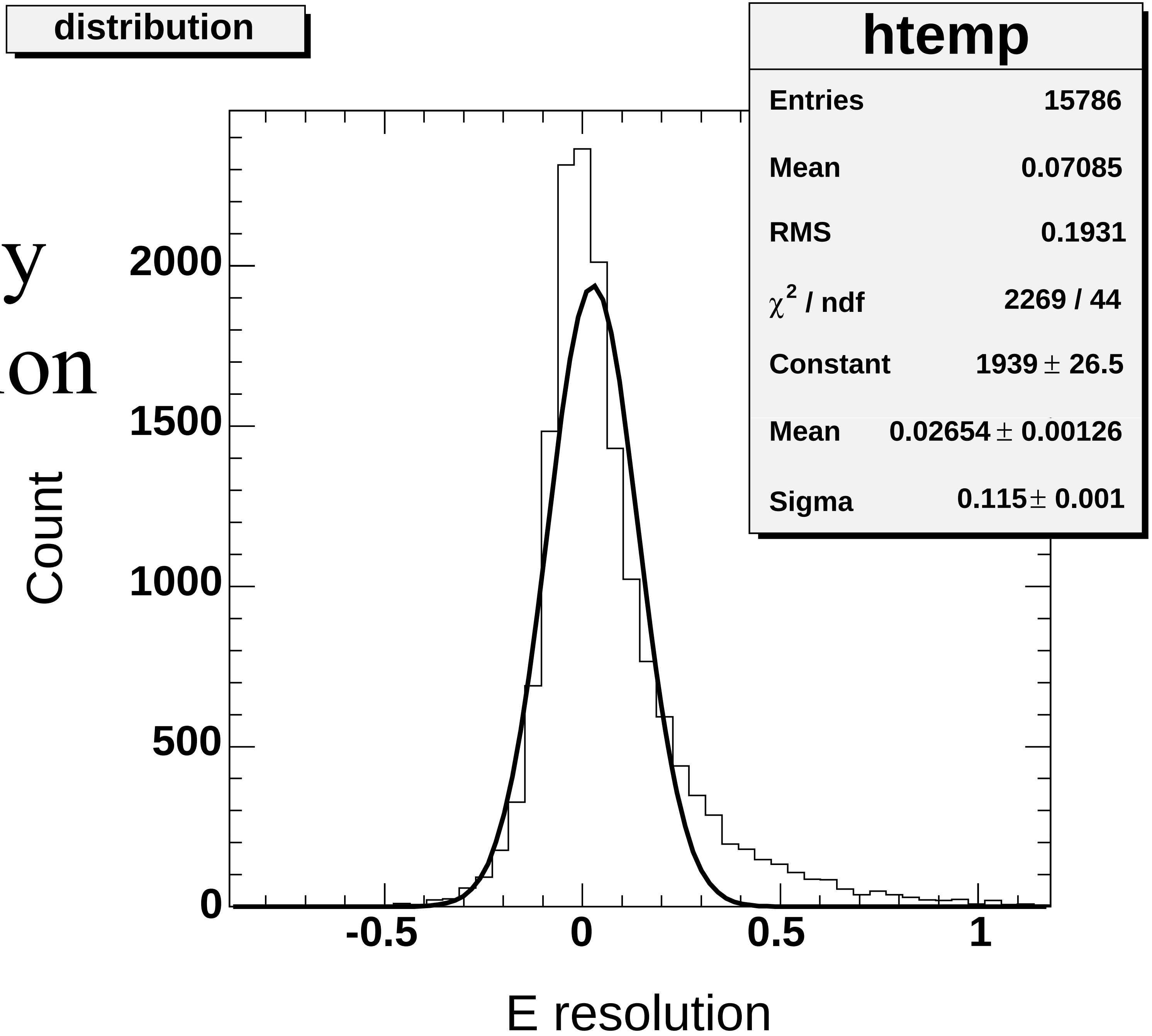
Xmax resolution



Nmax resolution

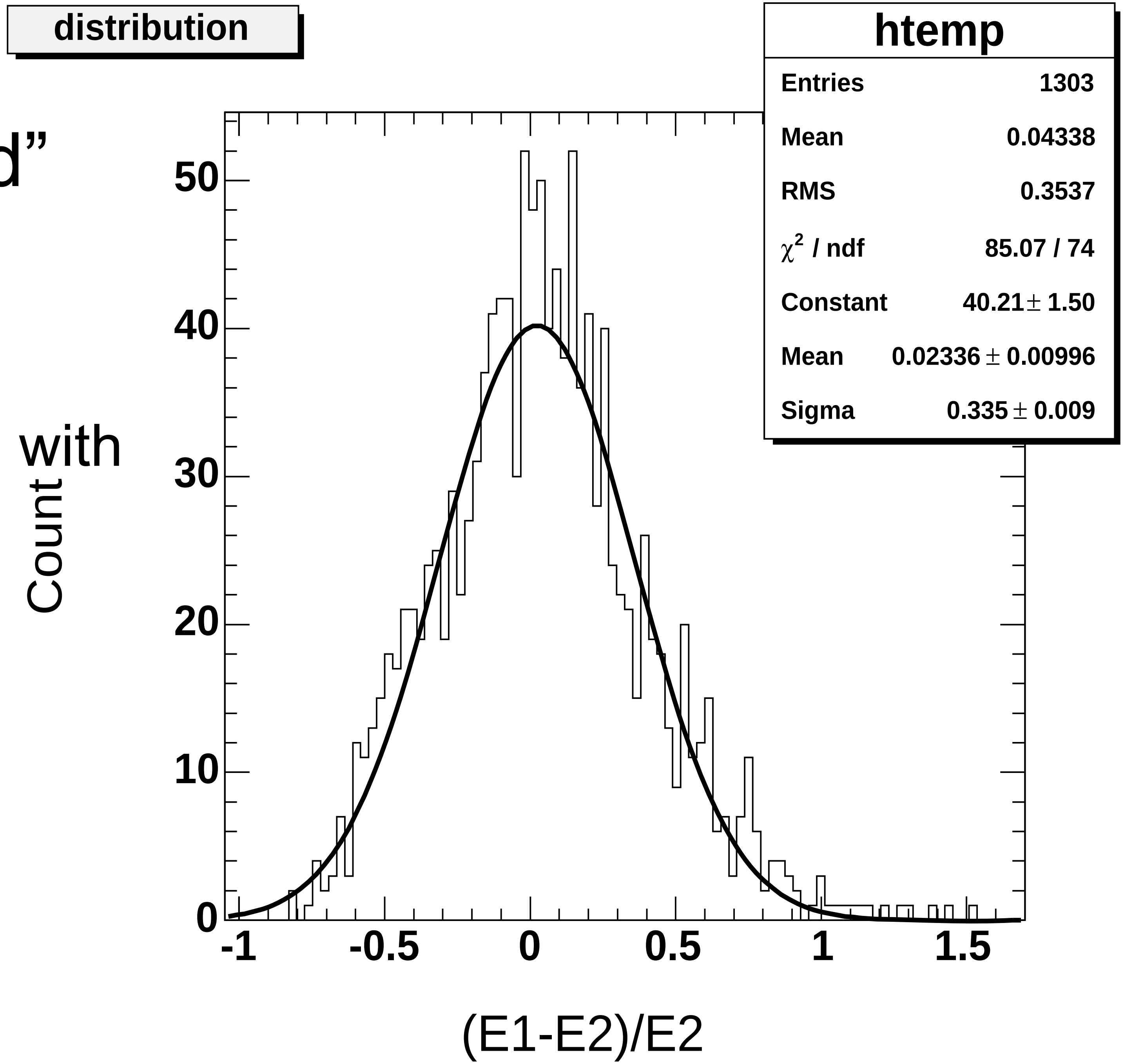


Energy resolution



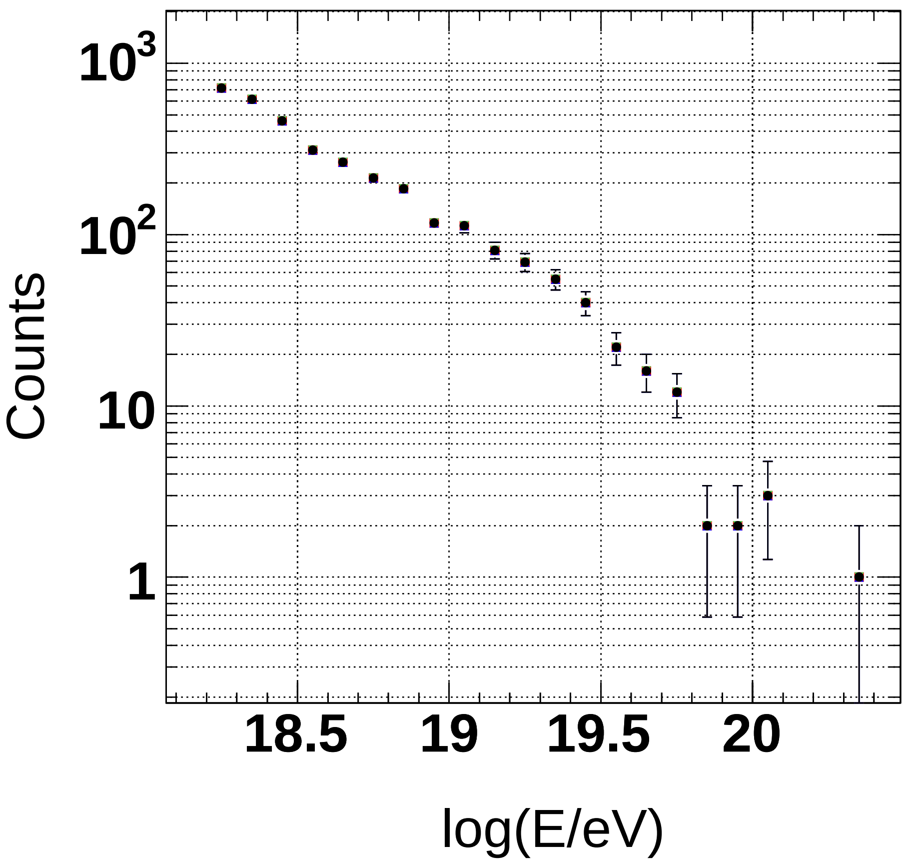
“measured” resolution

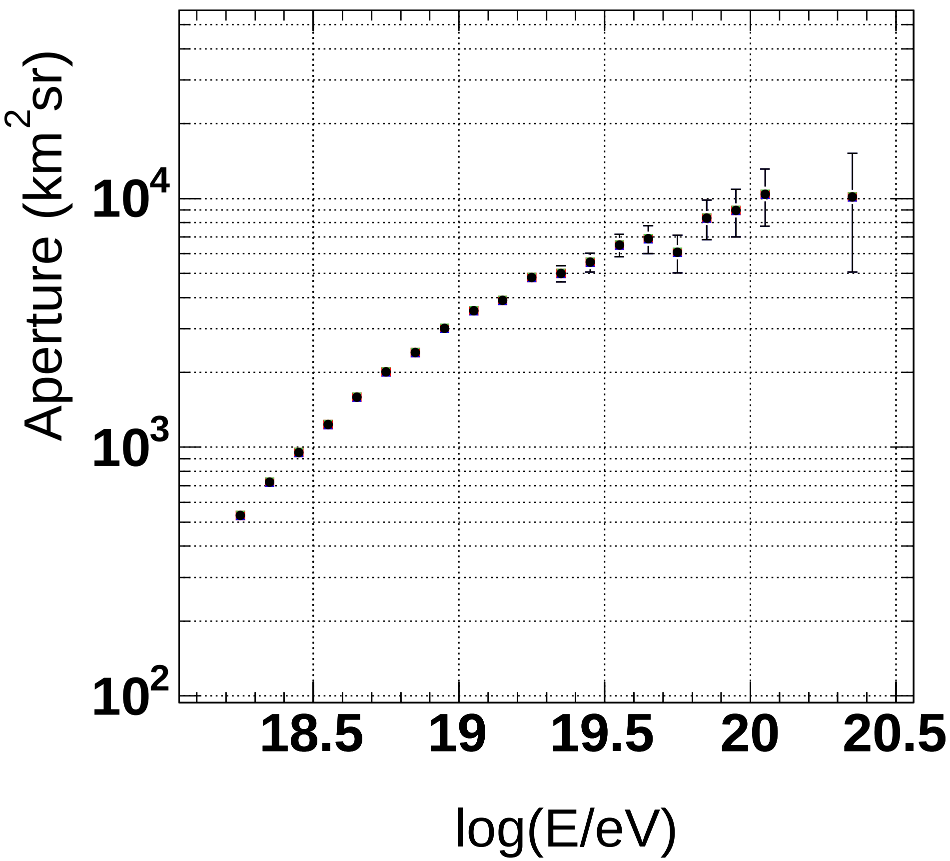
of 33%
is consistent with
σ_2~12%
σ_1~30%



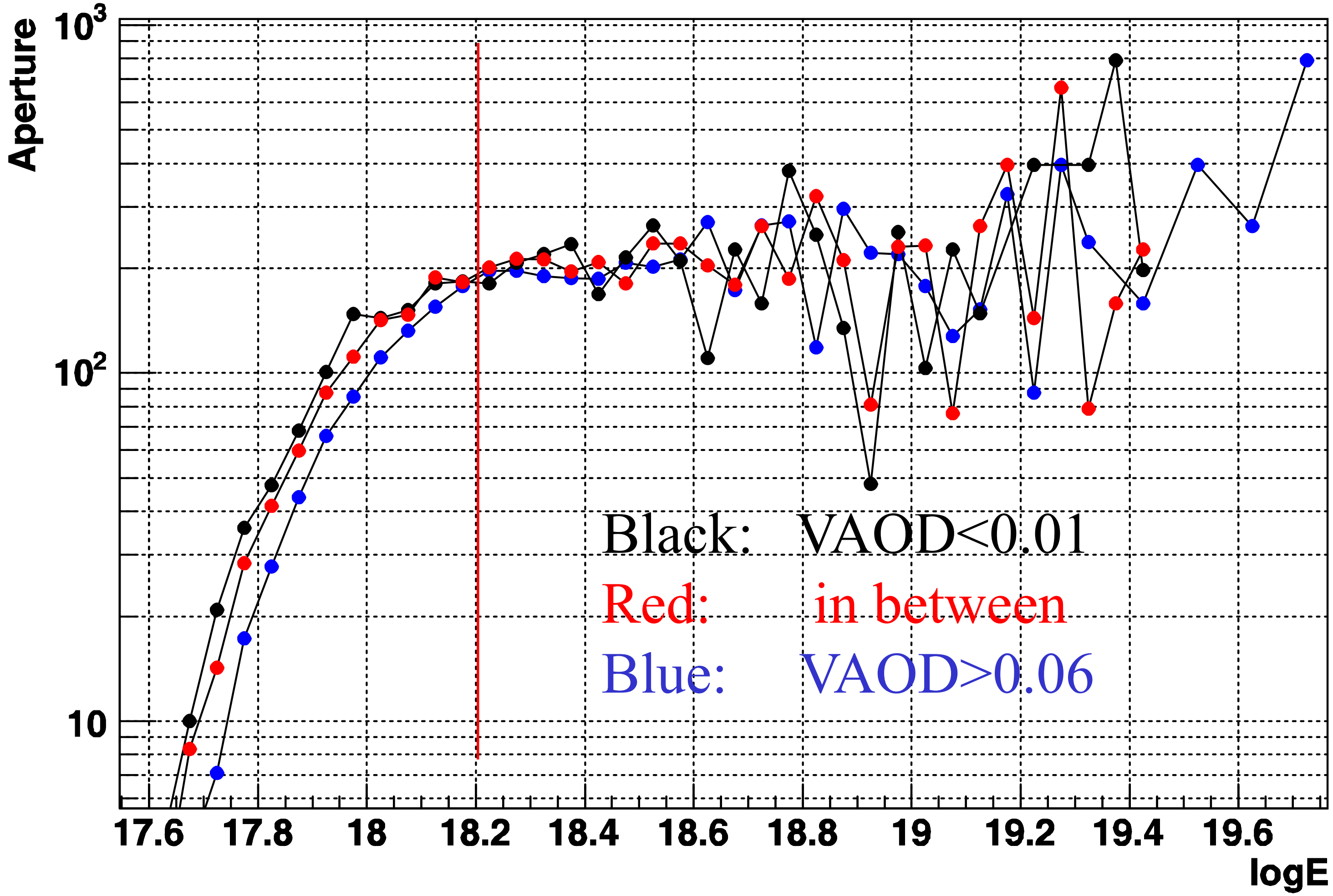
Detector Aperture Estimate

Energy distribution & HiRes Aperture





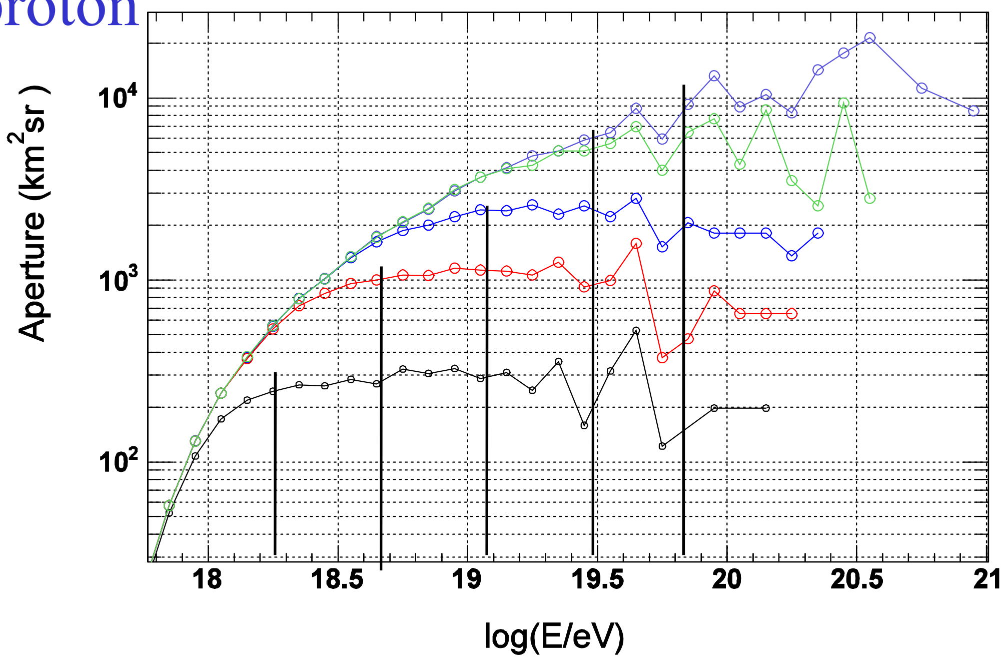
Stable Aperture with minimized aerosol effect Rp<10km



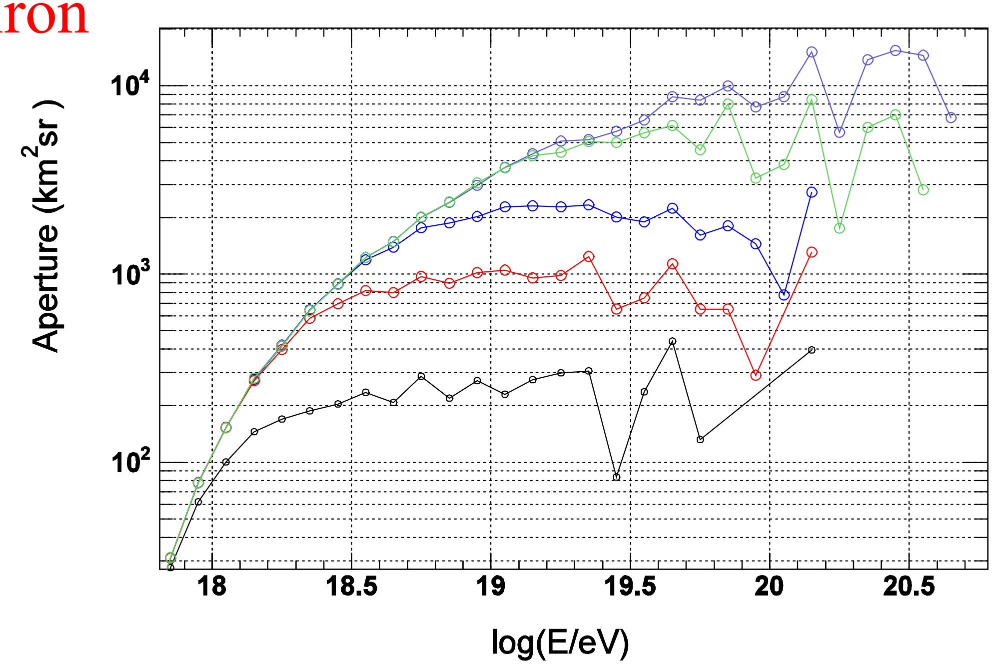
Geo constrained Aperture: minimizing weather & boundary eff.

(Rp<10,15,20,30 &55km)

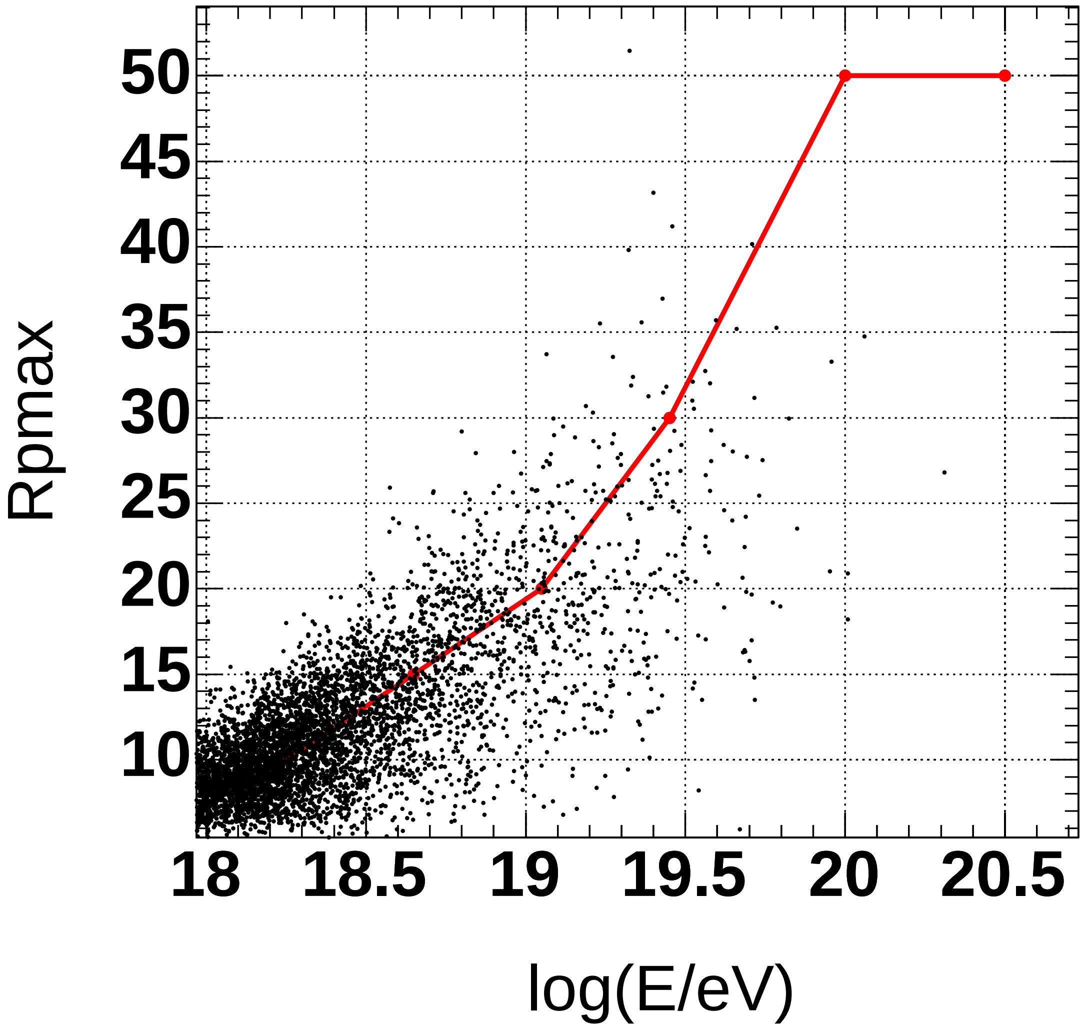
proton



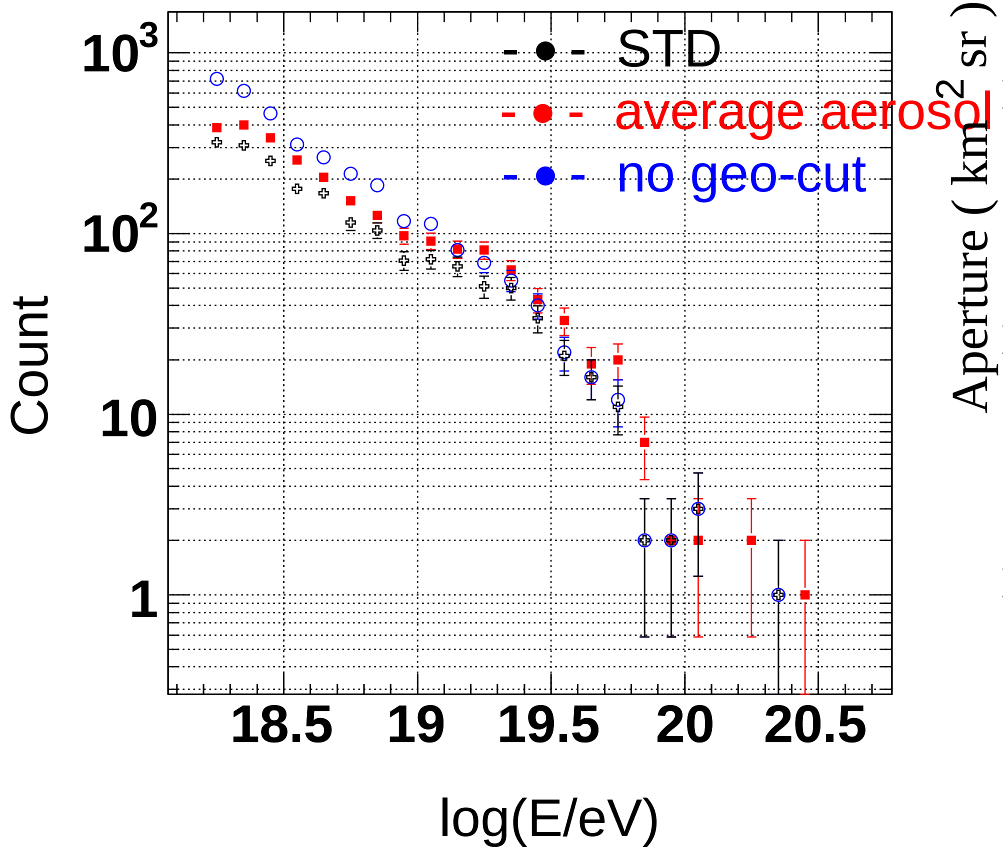
iron

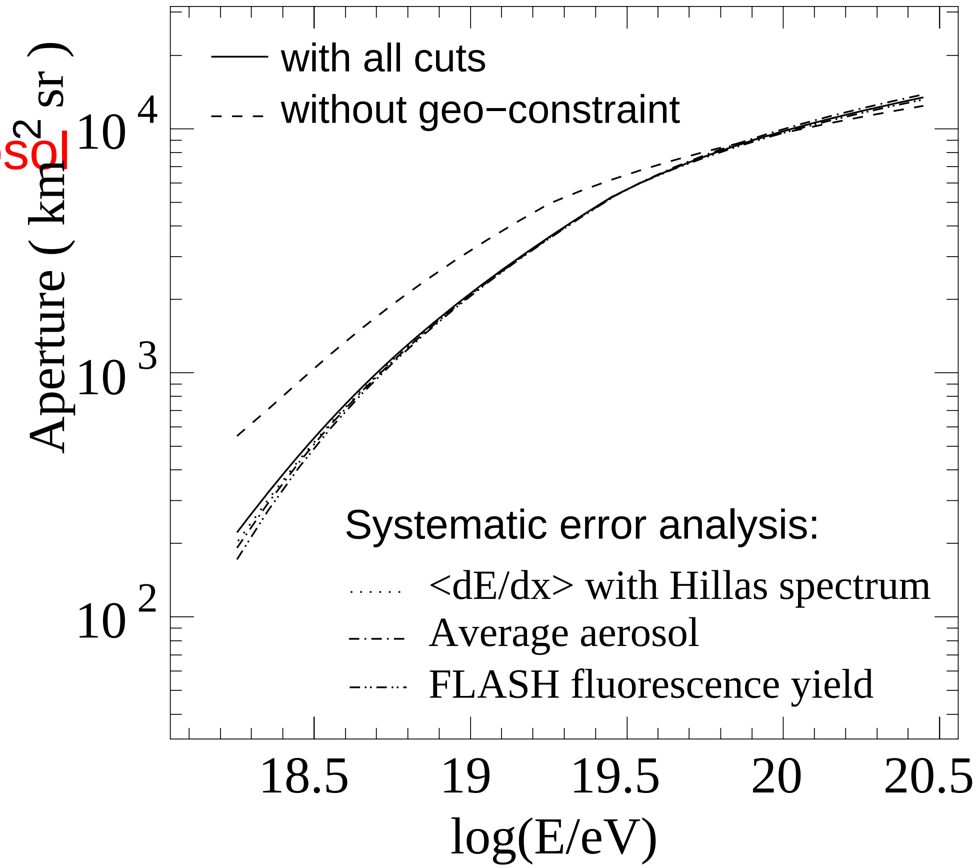


Geometrical constrained measurement

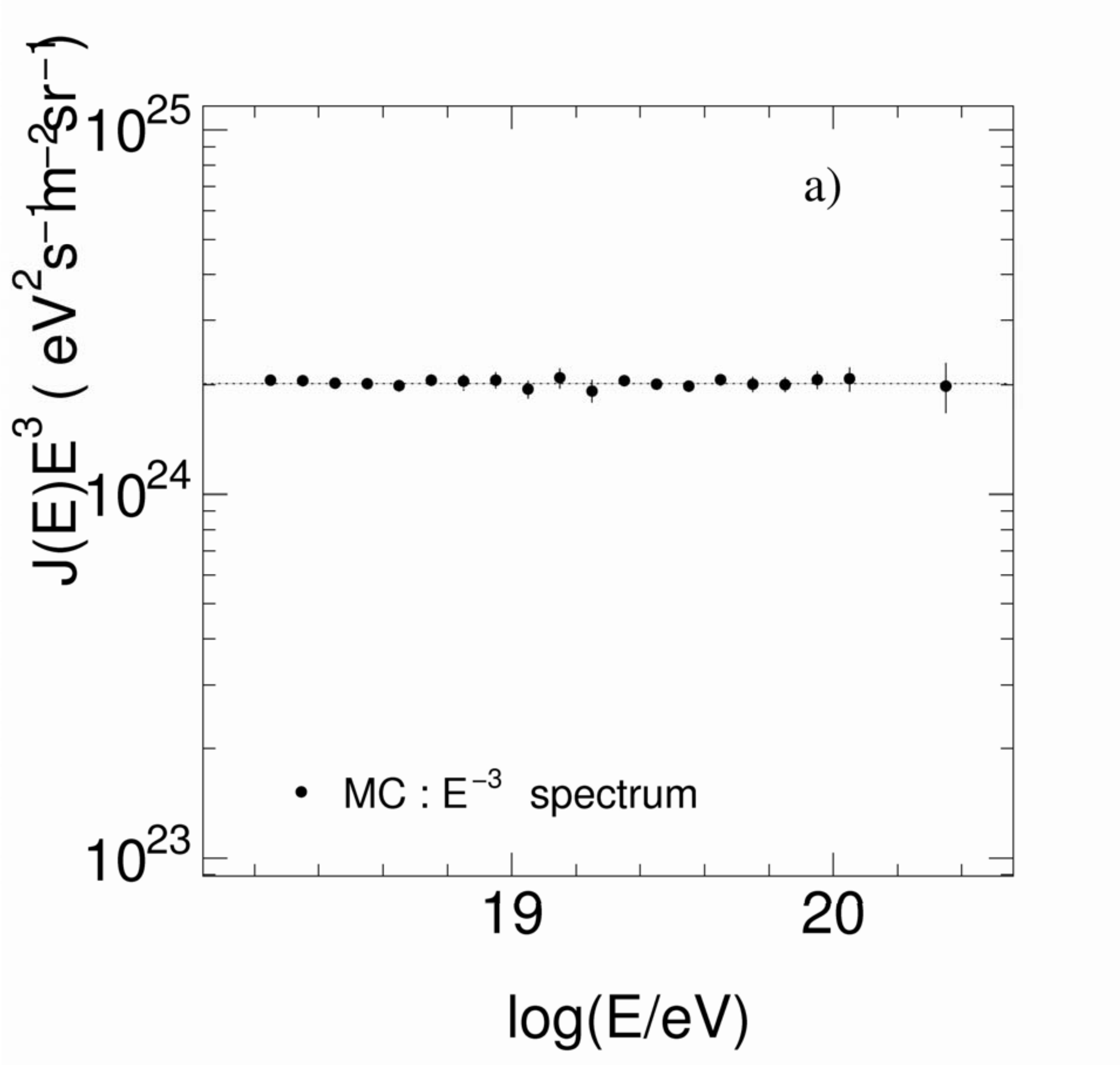


Stable and well defined
HiRes aperture





MC test on geo-constraints



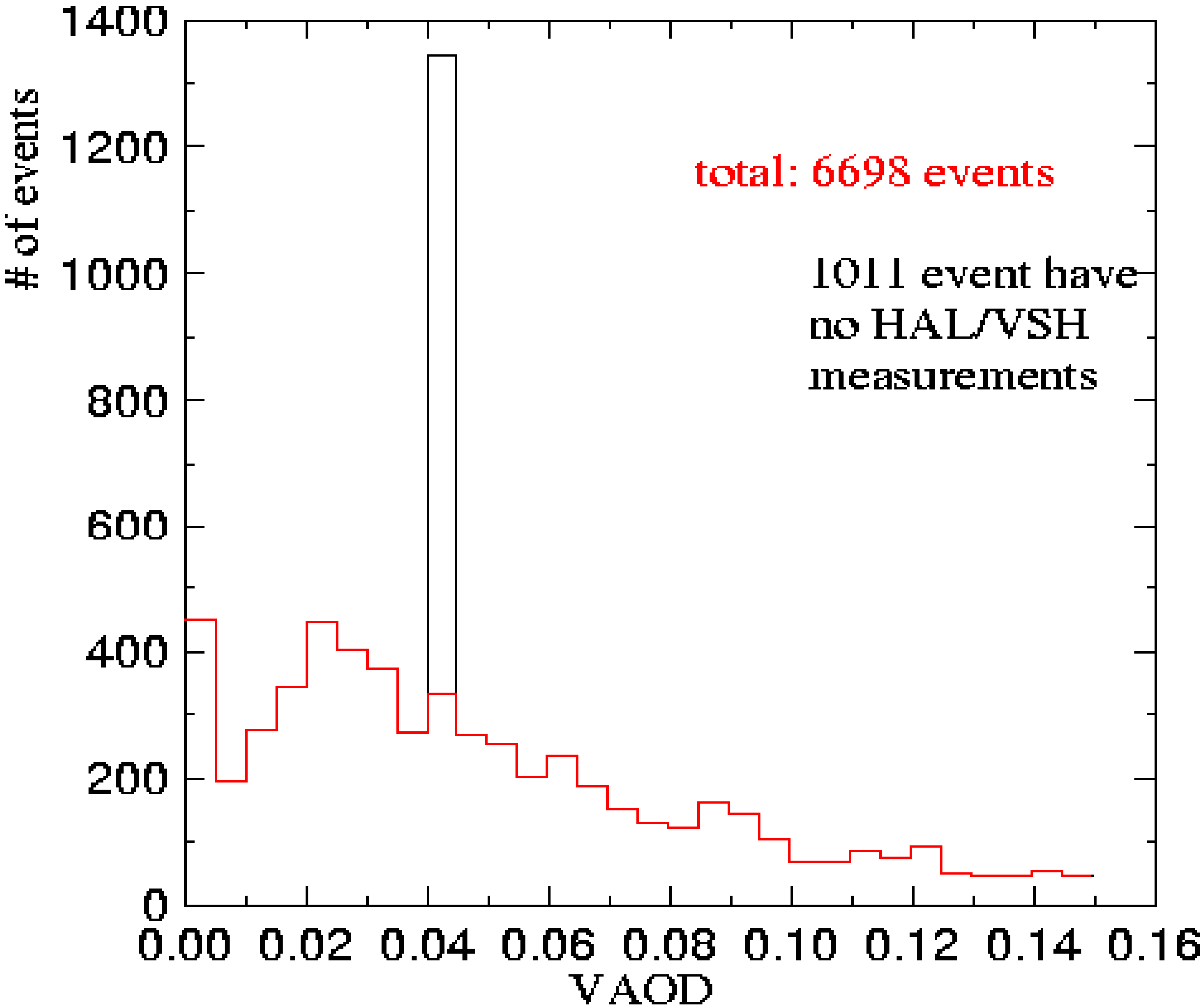
Energy Spectrum

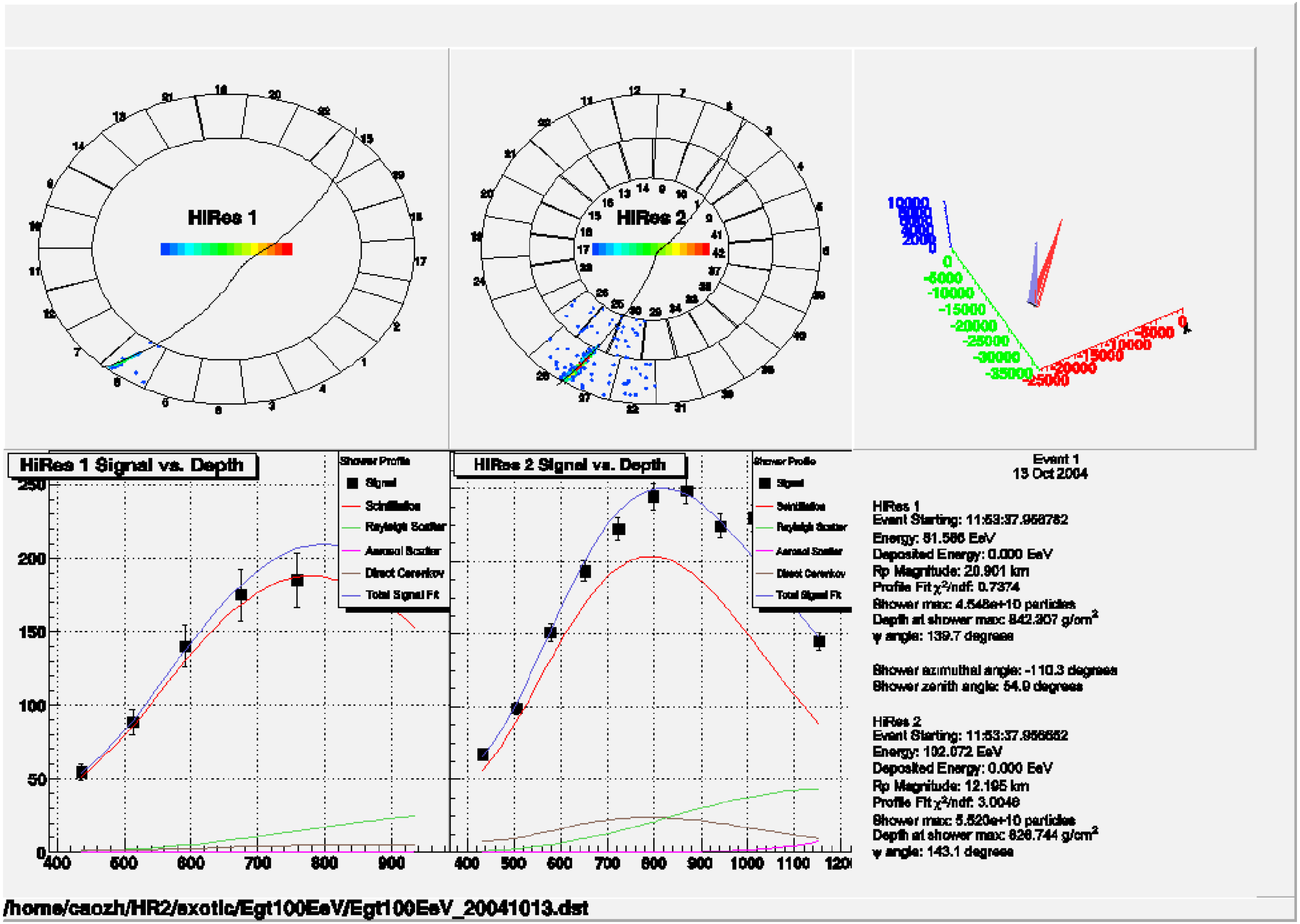
Cuts

16473 reconstructed events in total

- **Good Weather**: VAOD<0.1 &
  correction on bin signal<2) (12730)
- **Fitting Quality**: profiles with both rising and falling (6394)
- **Cerenkov contamination**: < 30% (6016)
- **Threshold@$10^{18.2}$eV**: stabilizing detecting efficiency (3300)
- **Minimizing atmospheric effects**: geometrical constraints (1844)
- **Clouds free**: (1256)

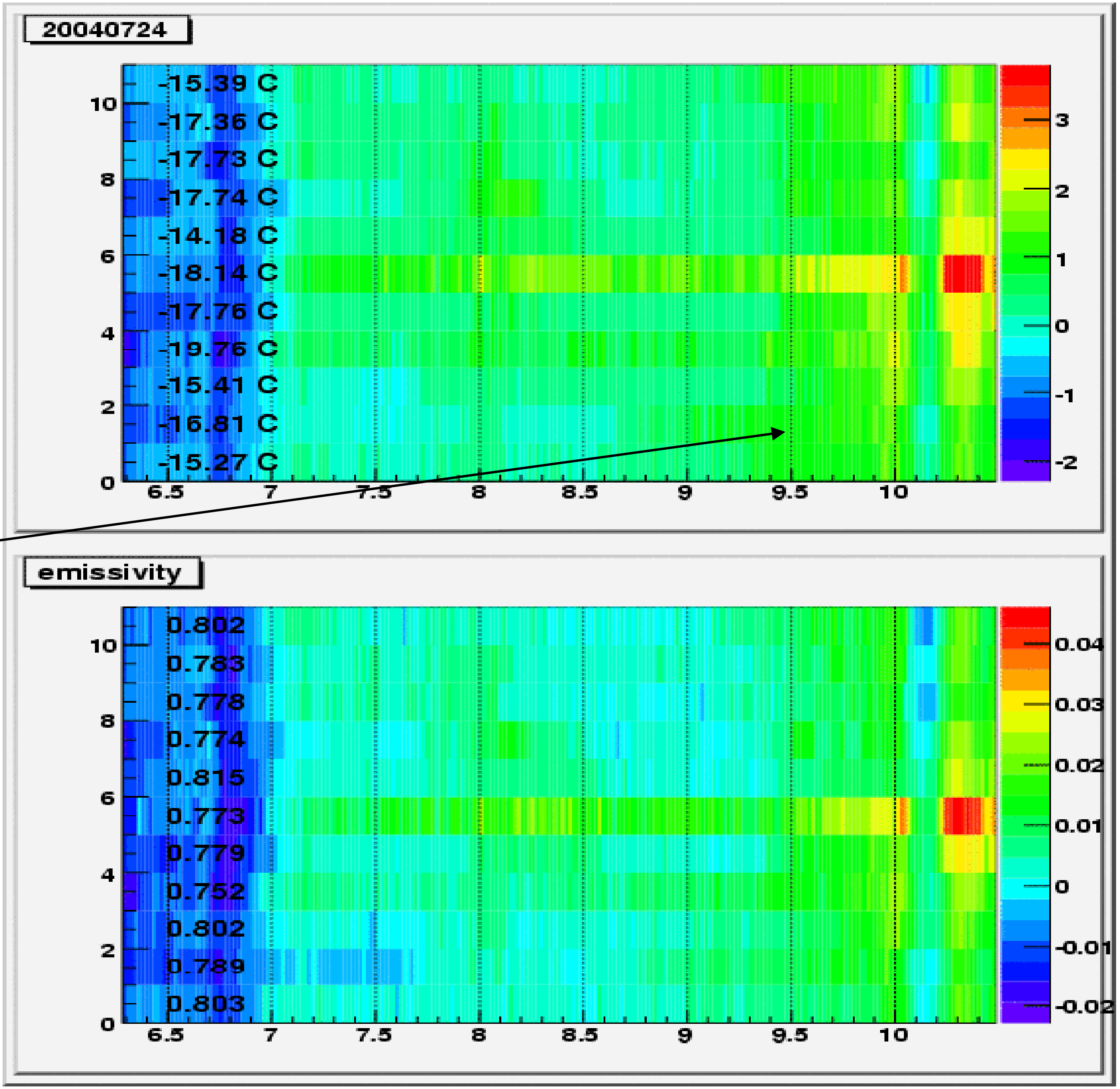
VAOD distribution




HiRes 1
HiRes 2
HiRes 1 Signal vs. Depth
HiRes 2 Signal vs. Depth
Shower Profile
Signal
Scintillation
Rayleigh Scatter
Aerosol Scatter
Direct Cerenkov
Total Signal Fit
Event 1
13 Oct 2004
HiRes 1
Event Starting: 11:53:37.958782
Energy: 81.586 EeV
Deposited Energy: 0.000 EeV
Rp Magnitude: 20.901 km
Profile Fit χ^2/ndf: 0.7374
Shower max: 4.548e+10 particles
Depth at shower max: 842.307 g/cm^2
ψ angle: 139.7 degrees
Shower azimuthal angle: -110.3 degrees
Shower zenith angle: 54.9 degrees
HiRes 2
Event Starting: 11:53:37.958852
Energy: 102.072 EeV
Deposited Energy: 0.000 EeV
Rp Magnitude: 12.195 km
Profile Fit χ^2/ndf: 3.0049
Shower max: 5.520e+10 particles
Depth at shower max: 826.744 g/cm^2
ψ angle: 143.1 degrees
/home/caozh/HR2/exotic/Egt100EeV/Egt100EeV_20041013.dst

11
IR detectors are installed on HR1 mirror stands

IR images on 2004/07/24



Ankle:

$10^{18.2}$ eV to $10^{19.7}$ eV

$2.2 \times 10^{24} / E^3$

$(1/eV/s/m^2/sr)$

$\chi^2 = 32.66$

(DOF of 14)

CL:99.7%

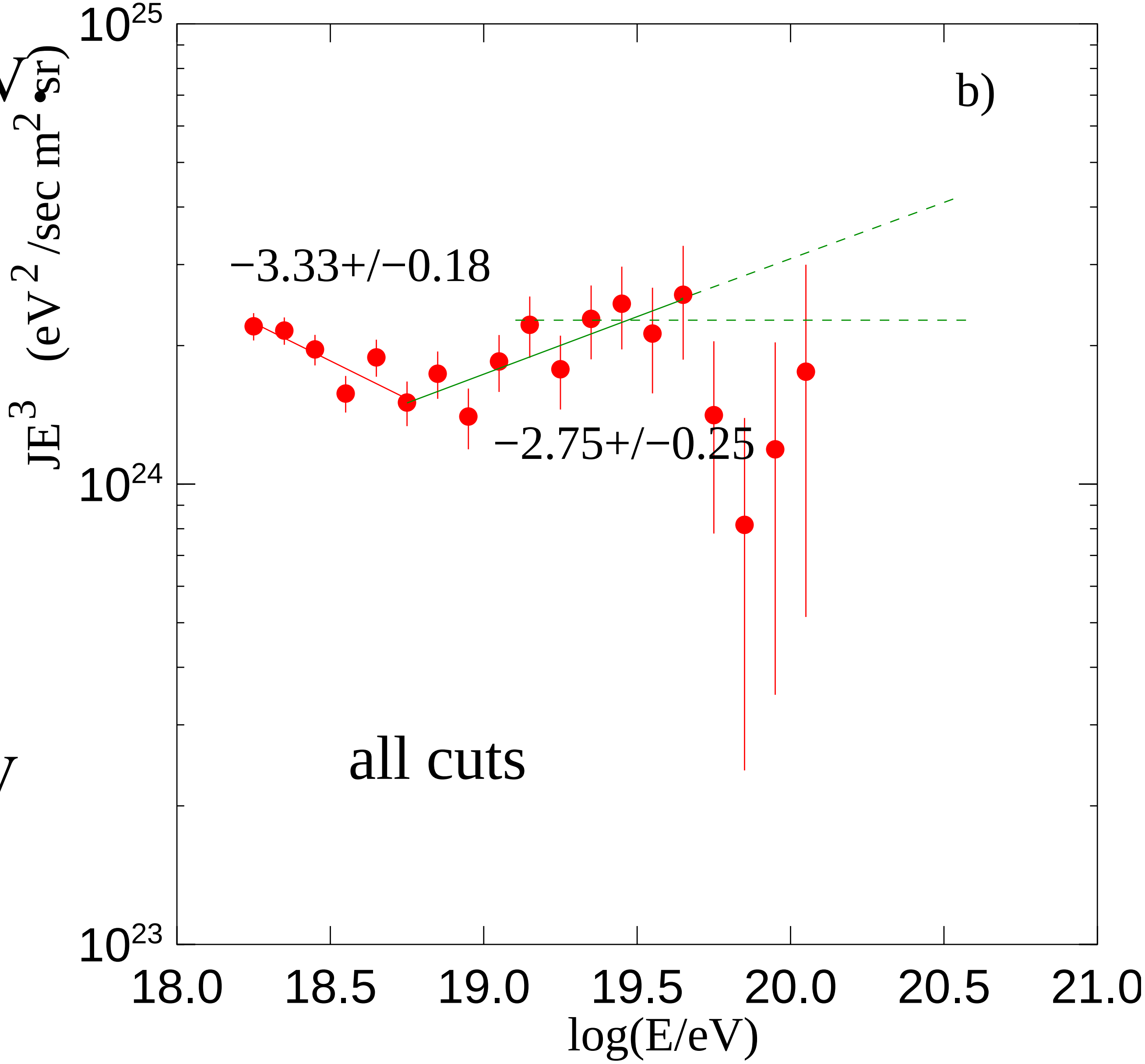
GZK cut-off:

11 above $10^{19.7}$ eV

out of

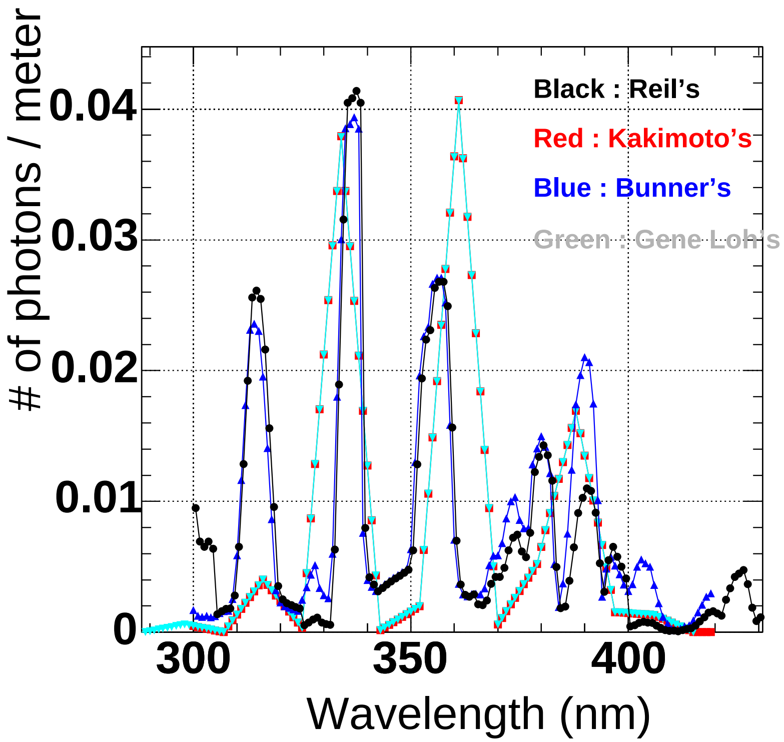
37.4 4.3σ

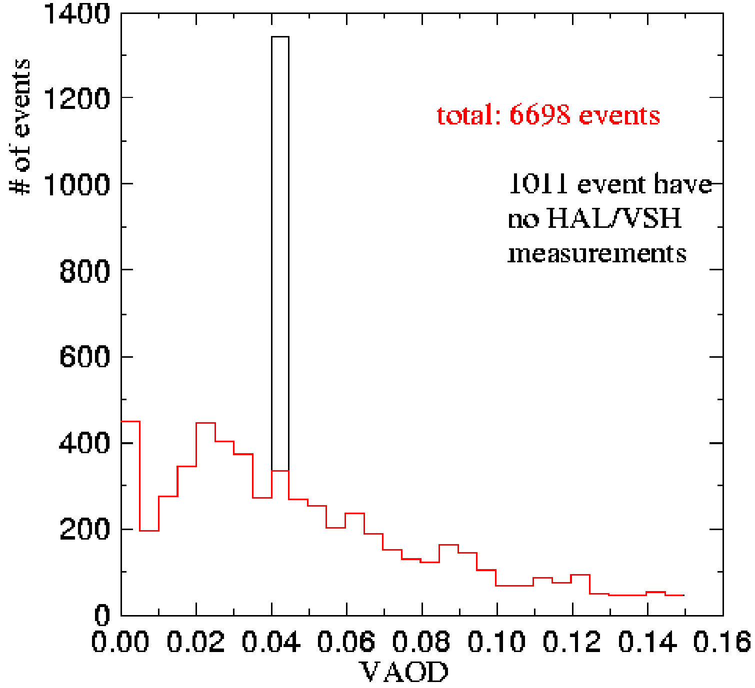
or 29.8 3.4σ

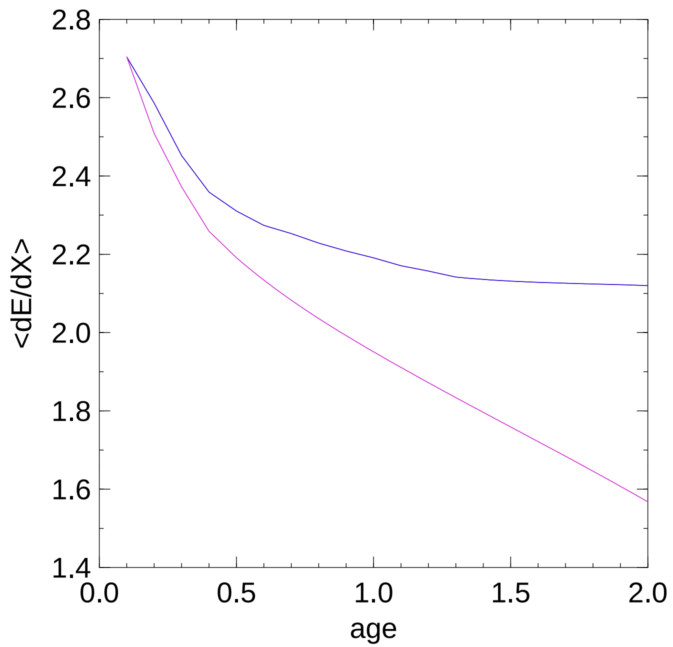


Systematical Uncertainties

1. Fluorescence yield
2. Aerosols
3. Spectra of shower charged particles
4. geo-constraint







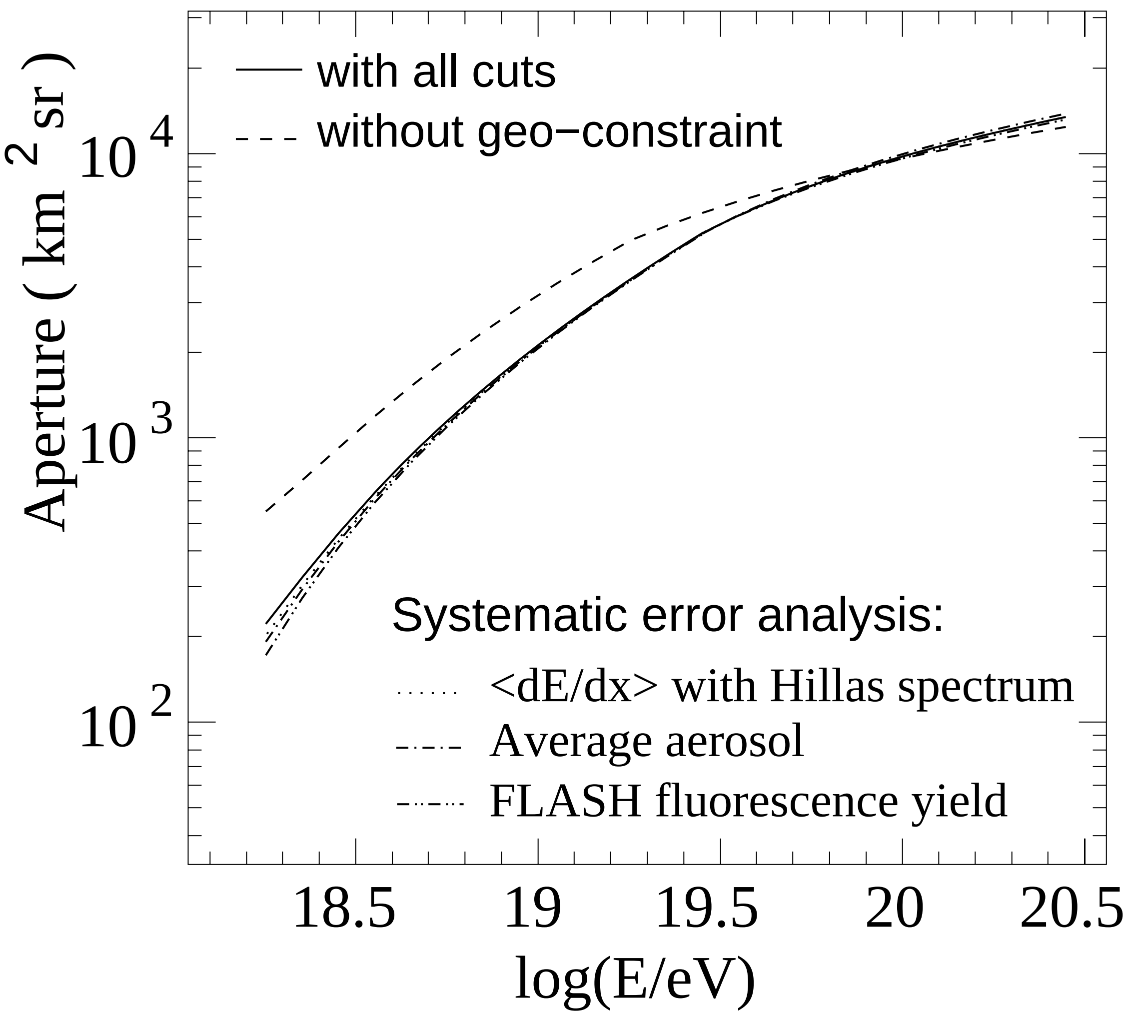
Fluorescence yields

Aerosols

<dE/dX> with different spectra

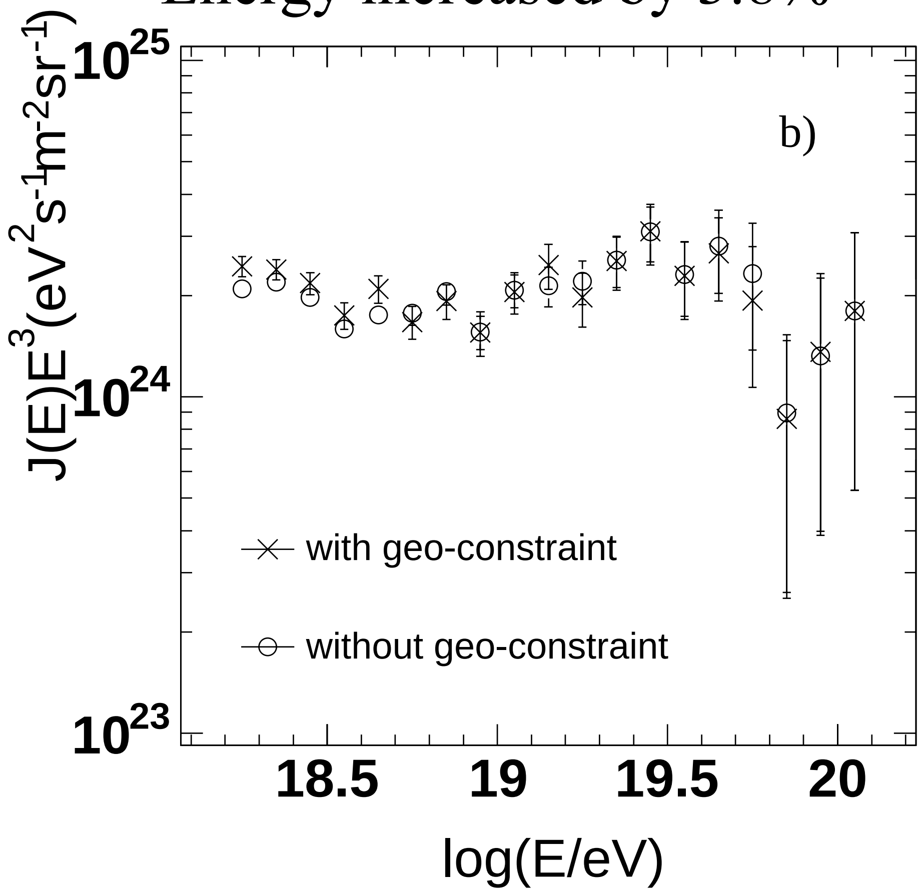
Geo-constraint

Aperture is essentially same after geometric constraint

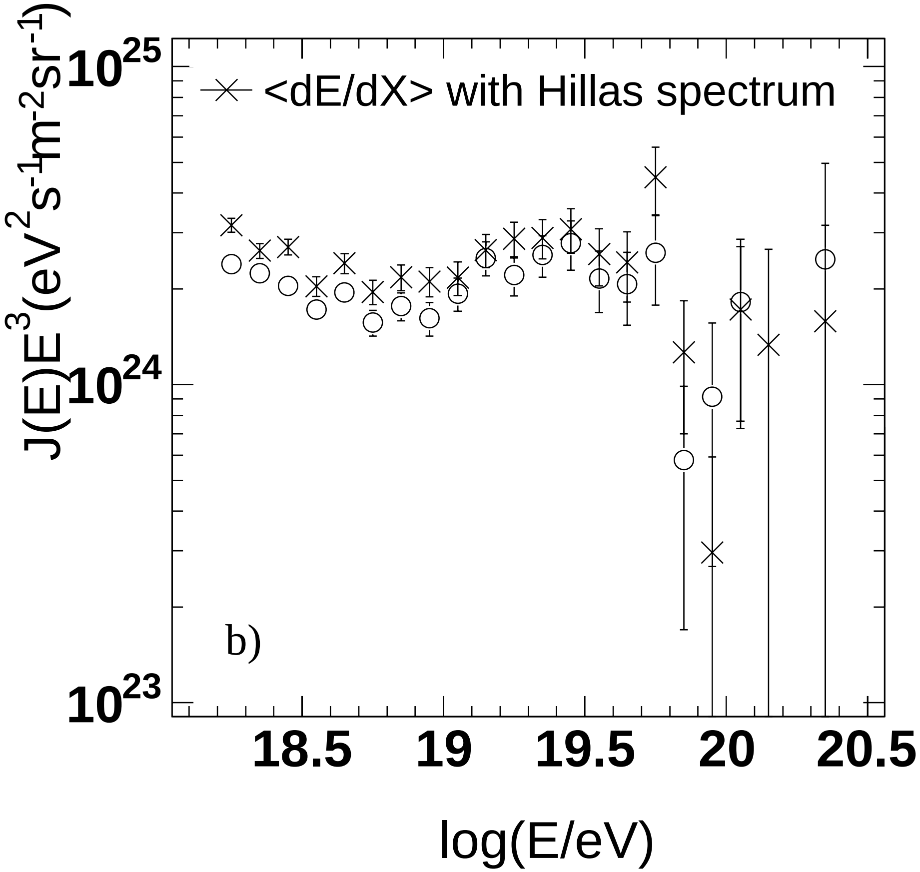


The largest uncertainty is due to spectra of shower electrons

Energy increased by 3.8%

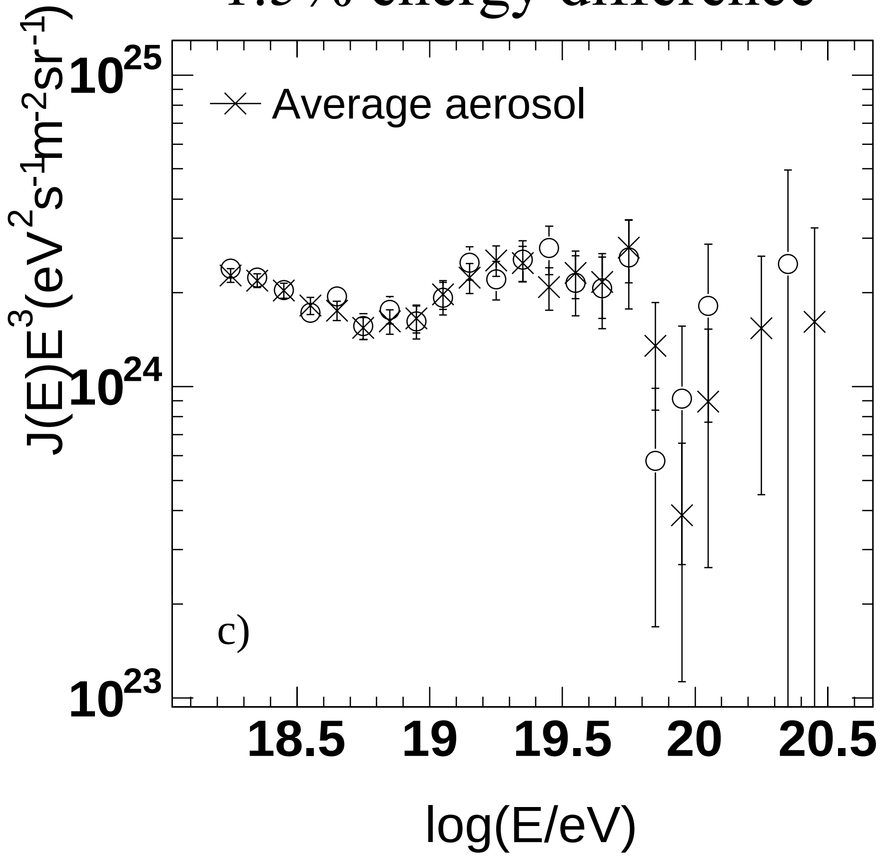


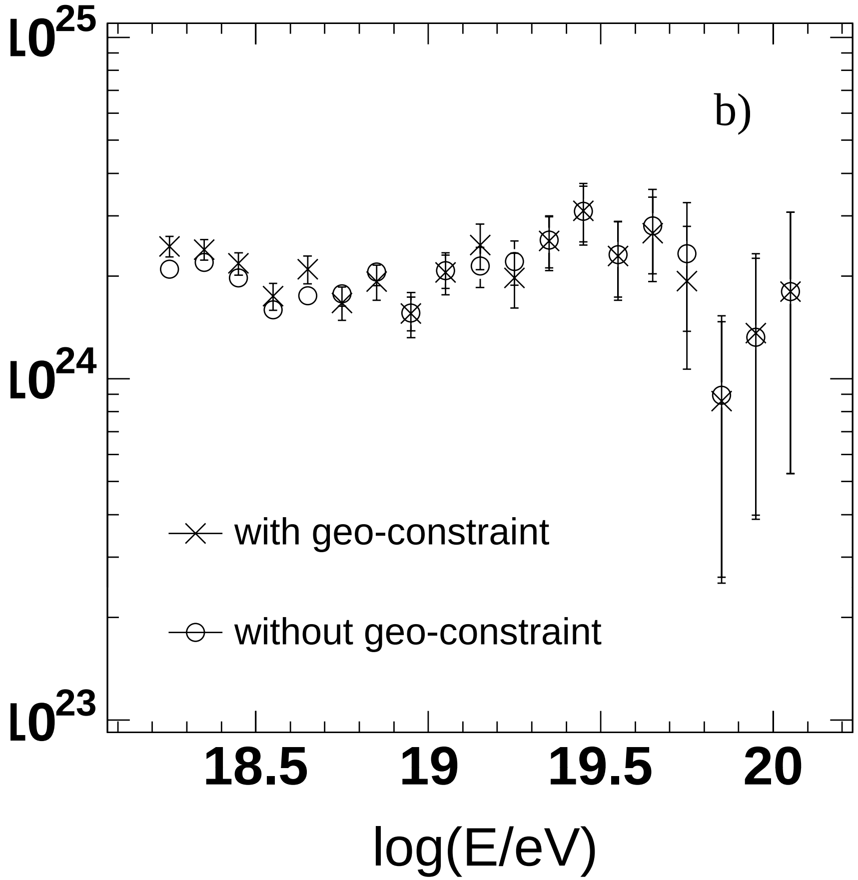
Energy increased by 10%



Aerosols do not affect the spectrum as expected geo-constr. does, but very small effect

1.5% energy difference





Conclusion

- HiRes Exp. 1999-2006 operation: 7% duty cycle
- Total number of events: 1256 ($E>10^{18.2}$eV)
- Stable aperture: 10^4 km^{2}sr @ 10^{20}eV
- Spectrum: dip@few EeV is well measured
  with CL=99.7%
  & GZK cut-off is observed with 4.3σ

  Status: to be **Published soon**
- Systematic Uncertainty: 11% in energy
  Aperture change by 2 with # of events as well,
  All spectrum features remain the same
  <10% in normalization of the flux

Comparing with monocular spectrum:

mono spectrum is confirmed