Cerenkov Events Seen by the TALE Air Fluorescence Detector

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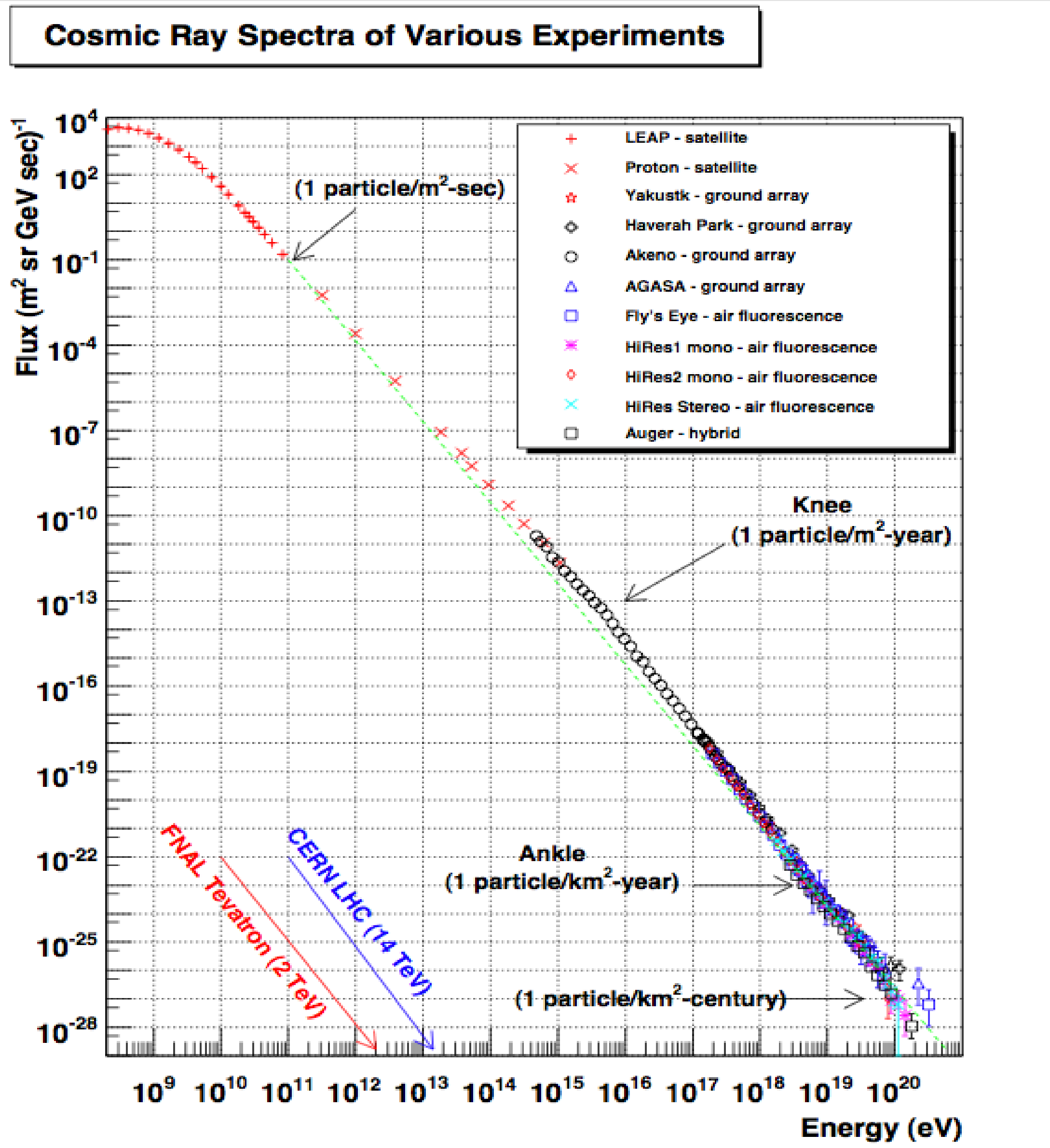
Outline

- **TA L**ow **E**nergy extension (TALE) Fluorescence Detector.
- Cerenkov Events
- Reconstruction Method / Performance
- Data Set / Data-MC comparison
- Preliminary Energy Spectrum using Cerenkov events
- Summary.

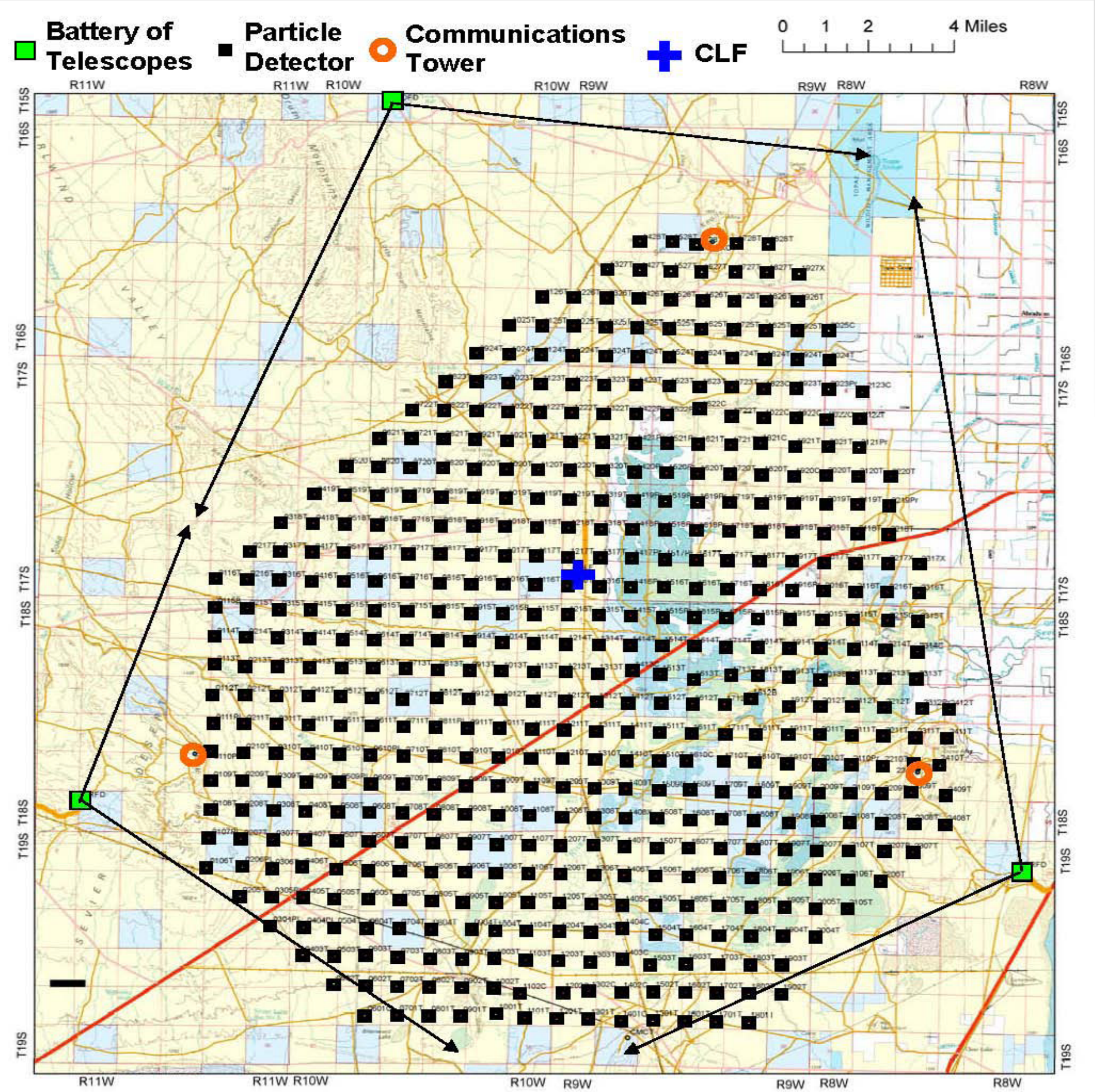
Telescope Array Experiment

- The Telescope Array (TA) experiment was originally designed for the study of ultra high energy (above ~**1x10**^{18} eV) cosmic rays.
- TA is a follow up experiment to AGASA/HiRes experiments with the goal of improving on both.
- TA Low Energy extension (TALE) aims to lower the energy threshold of the experiment to well below **10**^{17} eV.



Telescope Array Experiment

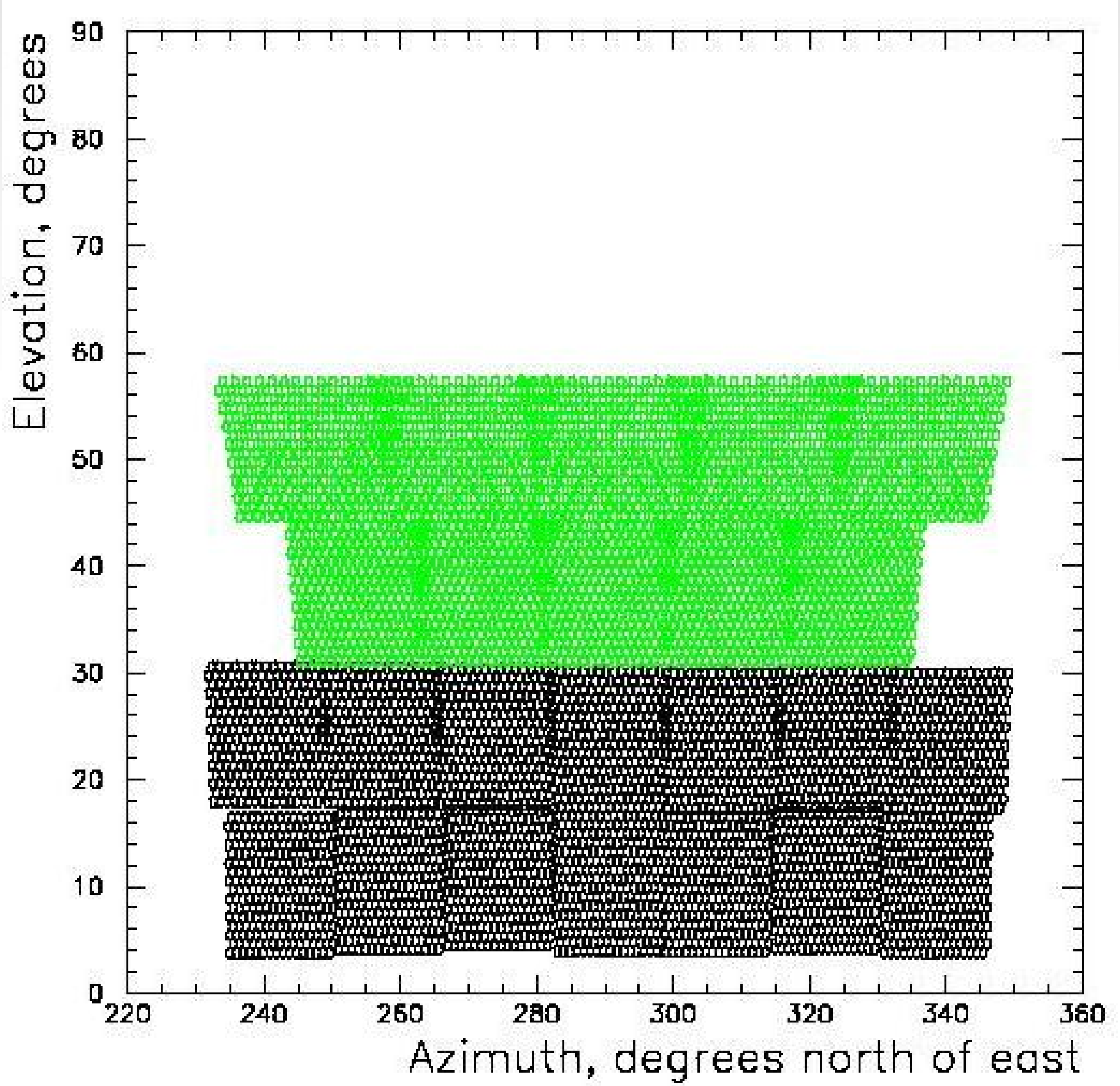
- TA is located in Millard County, Utah, ~200 km southwest of Salt Lake City.
- Surface Detector: 507 scintillation counters 1.2 km spacing.
- Three Fluorescence Detectors overlooking SD:
  - **Middle Drum (MD)**
  - Black Rock (BR)
  - Long Ridge (LR)



Middle Drum TALE Observatory Site (14+10 Telescopes)

Middle Drum TA/TALE Viewing Range

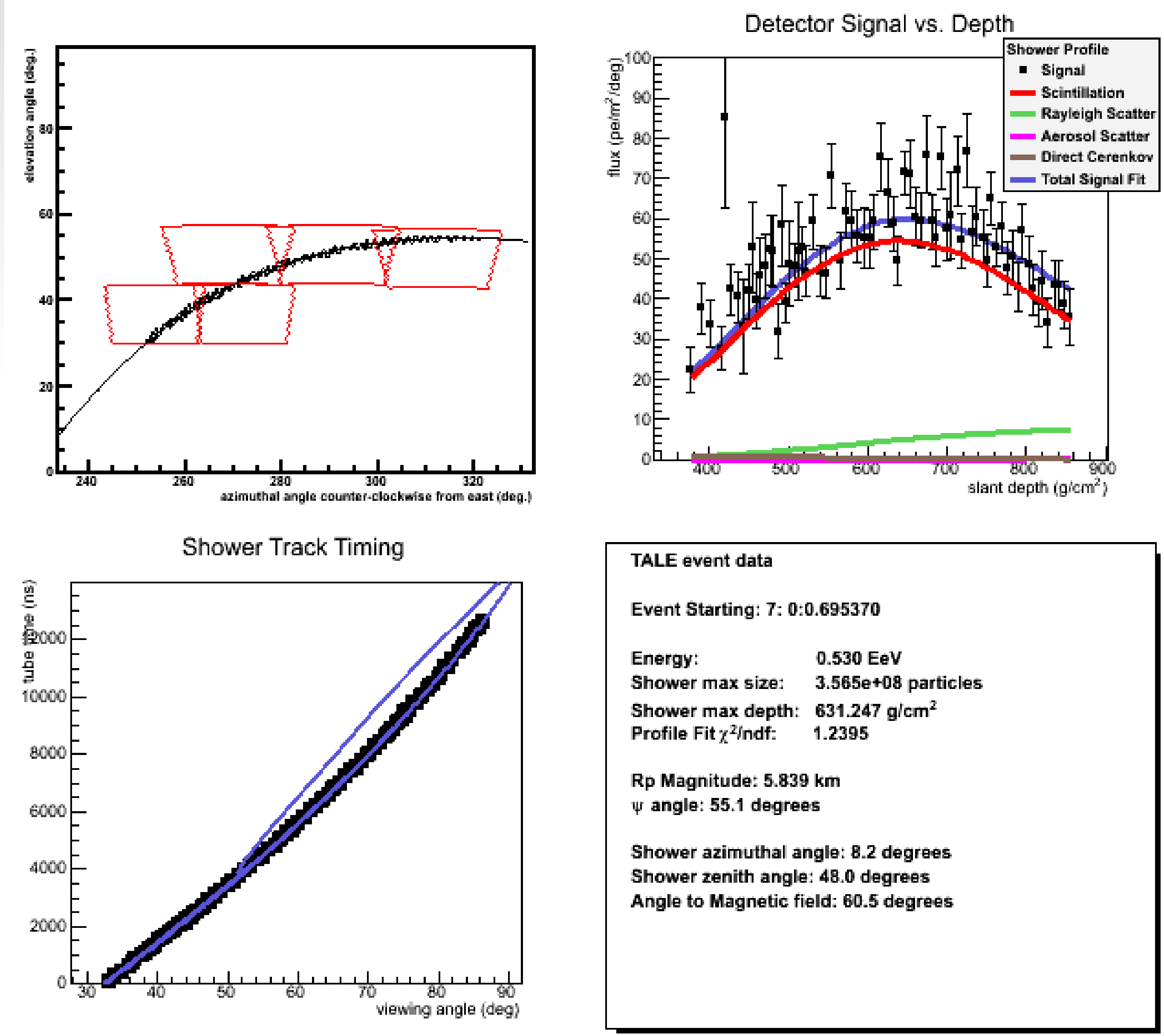
- TAMD + TALE
- 14 lower pointing telescopes make up TA (Middle Drum) Detector.
- 10 higher pointing telescopes make up the TA-Low Energy extension Detector.
- TALE telescopes equipped with (HiRes2) FADC electronics.



Cerenkov Events

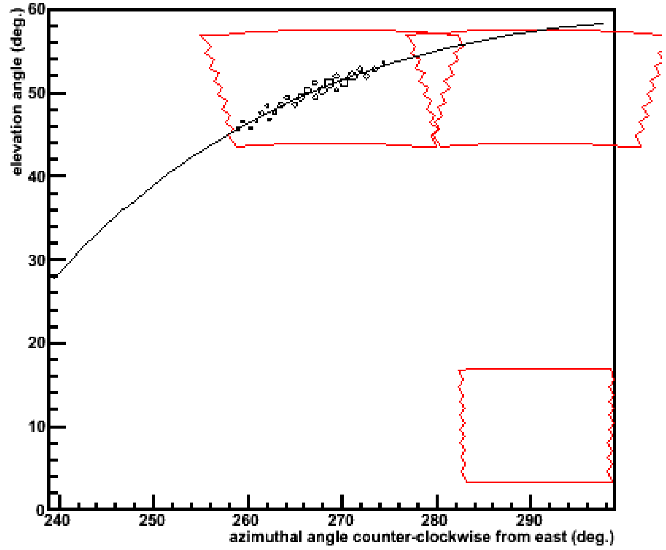
Example Fluorescence event seen by TALE FD

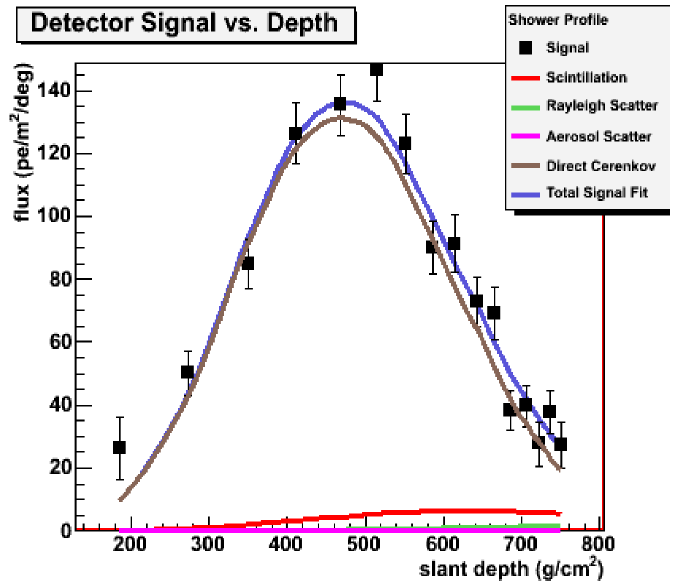
- Five telescope (eight with ring 1-2 mirrors) event.
- Event duration ~ few micro-seconds
- Long angular extent
- Likely to trigger ground array
- Threshold ~3e16 eV

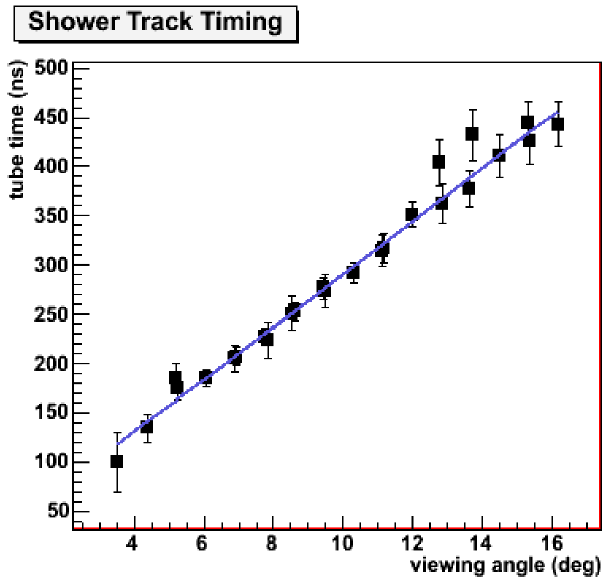


Example Cerenkov event seen by TALE FD

- Most C'kov events are single telescope
- Event duration ~100ns - ~600 ns
- Short angular extent
- Unlikely to trigger surface detector
- Threshold ~3e15 eV







TALE event data

Event Starting: 0: 0:0.139663747441801

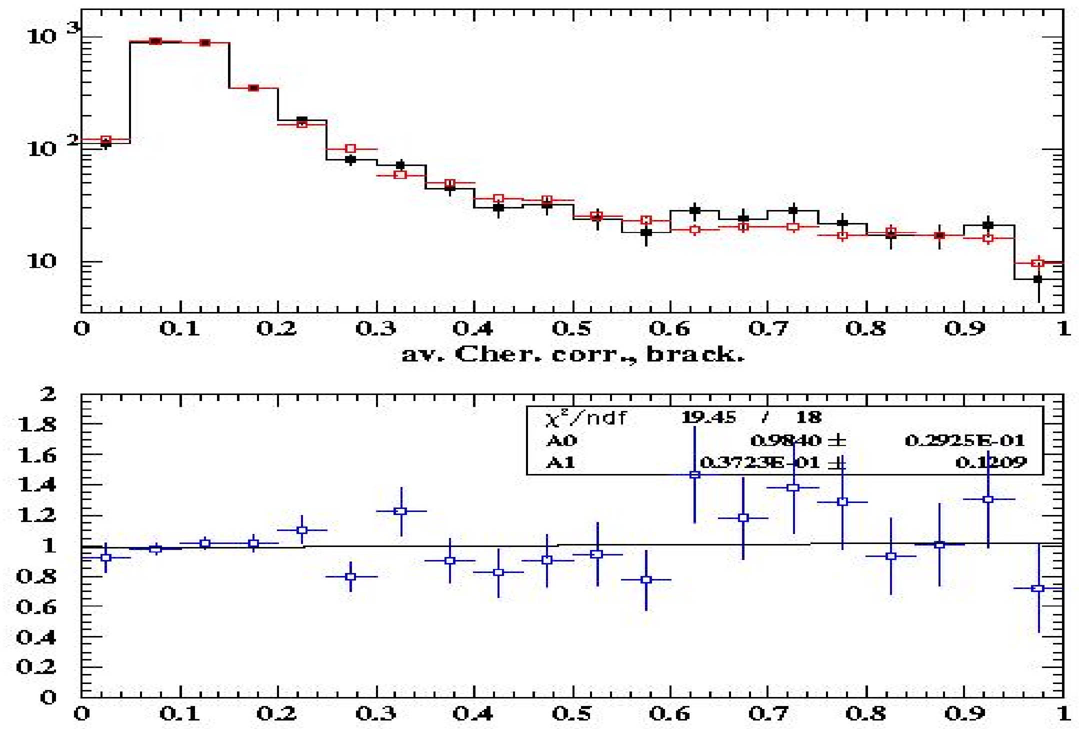
Energy: 9.241 PeV
Shower max size: 6.143e+06 particles
Shower max depth: 605.810 g/cm^2
Profile Fit χ^2/ndf: 0.7362

Rp Magnitude: 0.912 km
ψ angle: 106.9 degrees

Shower azimuthal angle: -80.1 degrees
Shower zenith angle: 35.0 degrees

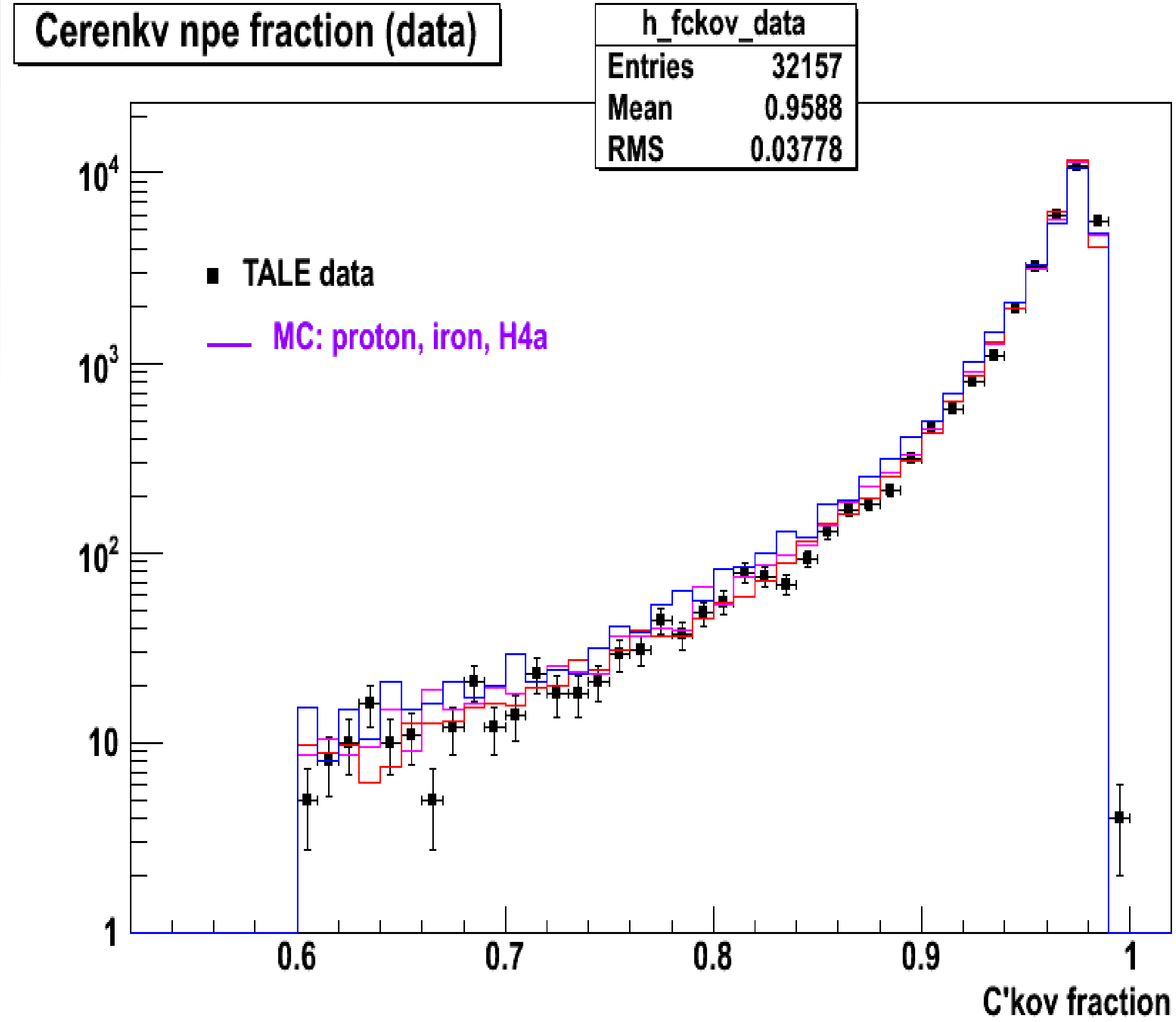
Cerenkov Contribution to Detected Signal

- HiRes-II event set.
- Most events have less than 20% contribution from direct ***and*** scattered Cerenkov light.



Cerenkov Contribution to Detected Signal

- TALE Cerenkov event set.
- Most events have more than 90% contribution from ***direct*** Cerenkov light.



Event Reconstruction / Performance

TALE Event Reconstruction

- Event reconstruction entails reconstructing:
  - Shower geometry
  - Shower profile/energy.
- Cerenkov events are reconstructed as *monocular* events.
- Profile constrained Geometry Fit (PCGF) method (developed and used for the HiRes-I analysis) is adapted for TALE:
  - Unlike for HiRes-I, the shower *xmax* parameter is fixed ***only*** at the start of the fit but is turned into a ***free fit parameter*** at a later step in the reconstruction process.

TALE Corsika-IACT MC

- Corsika / IACT (arXiv:0808.2253 [astro-ph])
  - Full 3D MC shower development
  - Cerenkov photons production
  - Cerenkov photons detection (sphere surrounding telescope mirror)
- Modified Detector MC to use Corsika/IACT output instead of parametrized calculation of direct Cerenkov light:
  - Number of C'kov photons, arrival times, which (if any) PMT is hit are all pre-determined by the Coriska/IACT simulation.
- We can test our reconstruction code ***against an external 3D simulation***.

TALE Corsika-IACT MC

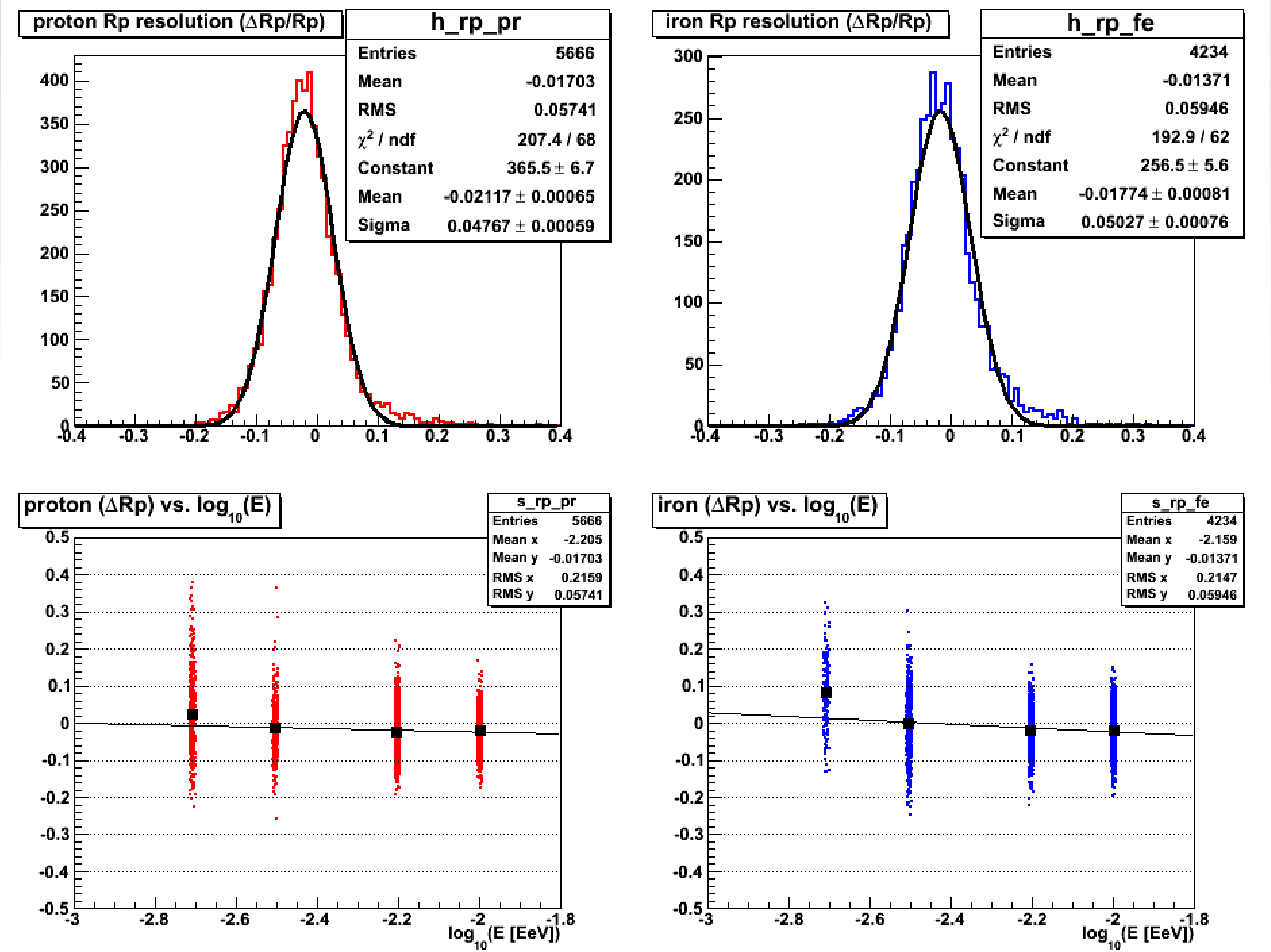
- Simulation specific to TALE telescopes.
- MD coordinates origin, magnetic filed.
- TA "typical" atmosphere
- Wavelength range
- Each Corsika shower is resampled 100 times at different core locations surrounding origin
- Mirror positions in rotated coordinate system (Corsika coordinates)

```
OBSLEV   1.586655e5                          observation level (in cm) (MD - 2Radius)
MAGNET   21.95 46.40                         magnetic field (TA .. Middle Drum)

ATMOSPHERE 11  F                             !TAZ external atmos model (TA Typical)

CERSIZ   5.0                                 !TAZ bunch size Cherenkov photons
CWAVLG   300. 420.                           !TAZ Cherenkov wavelength band

CSCAT    100 2.5e5 0.                        !TAZ scatter Cherenkov events

ARRANG   0.0                                 !TAZ rotation of array to north
TELESCOPE    1848.30     -1635.03      251.03      129.54   !TAZ CT 1 =TALE mir 15
TELESCOPE    2137.39     -1629.84      251.84      129.54   !TAZ CT 2
TELESCOPE    2576.55     -1959.19      252.47      129.54   !TAZ CT 3
TELESCOPE    2849.93     -2053.28      253.05      129.54   !TAZ CT 4
TELESCOPE    3226.95     -2463.69      253.37      129.54   !TAZ CT 5
TELESCOPE    3297.67     -2744.10      253.07      129.54   !TAZ CT 6
TELESCOPE    3588.58     -3209.51      253.05      129.54   !TAZ CT 7
TELESCOPE    3559.09     -3497.11      252.46      129.54   !TAZ CT 8
TELESCOPE    3673.34     -4033.99      251.83      129.54   !TAZ CT 9
TELESCOPE    3547.29     -4294.15      251.02      129.54   !TAZ CT10
```

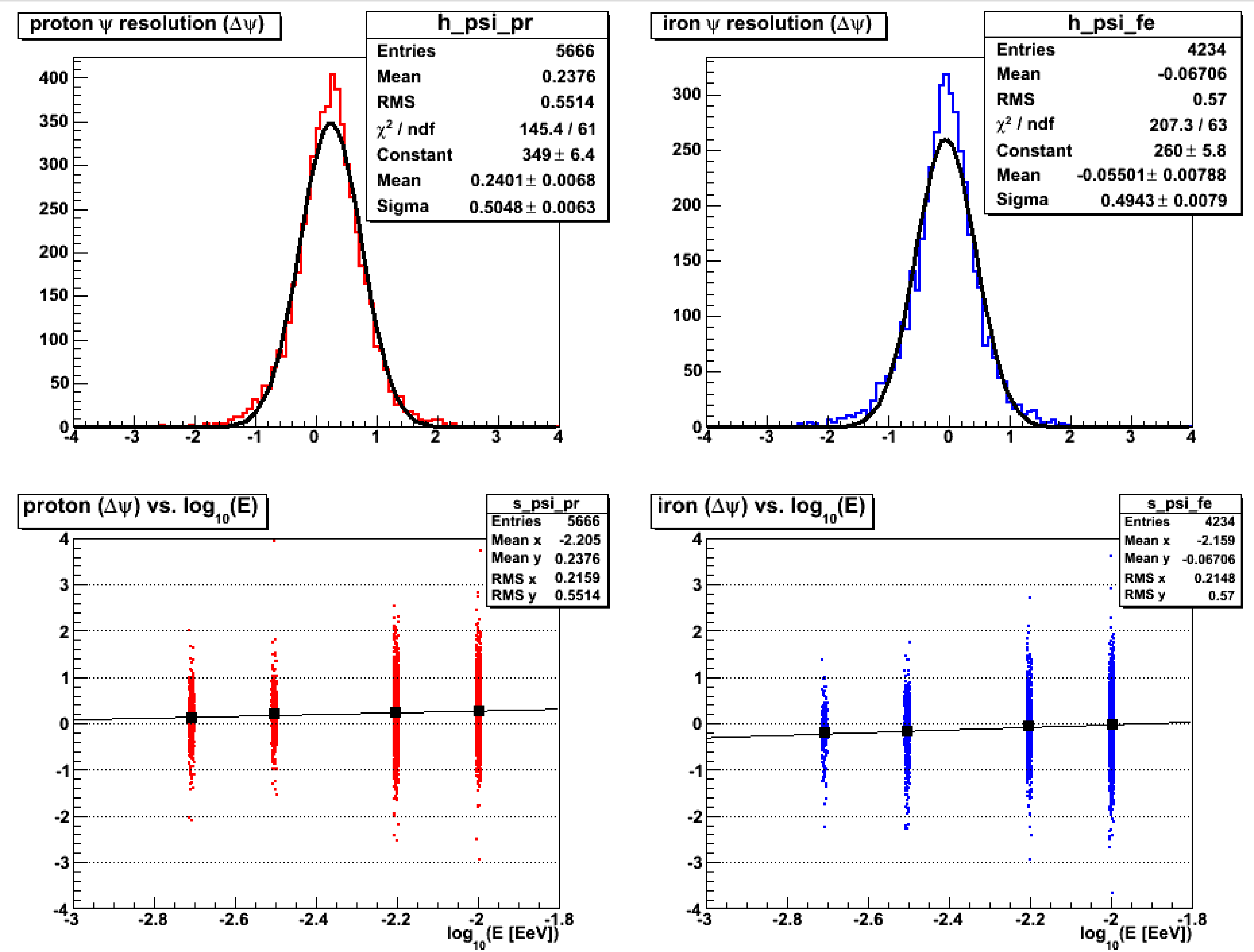
Corsika-IACT simulation results

- Look at bias and resolution of reconstruction of MC generated with both options.
- Simulation energies: 2, 3, 5, and 10 PeV
  - **NOTE:** Our spectrum measurement is for E > 4 PeV
- Primaries: Proton (red) & Iron (blue)

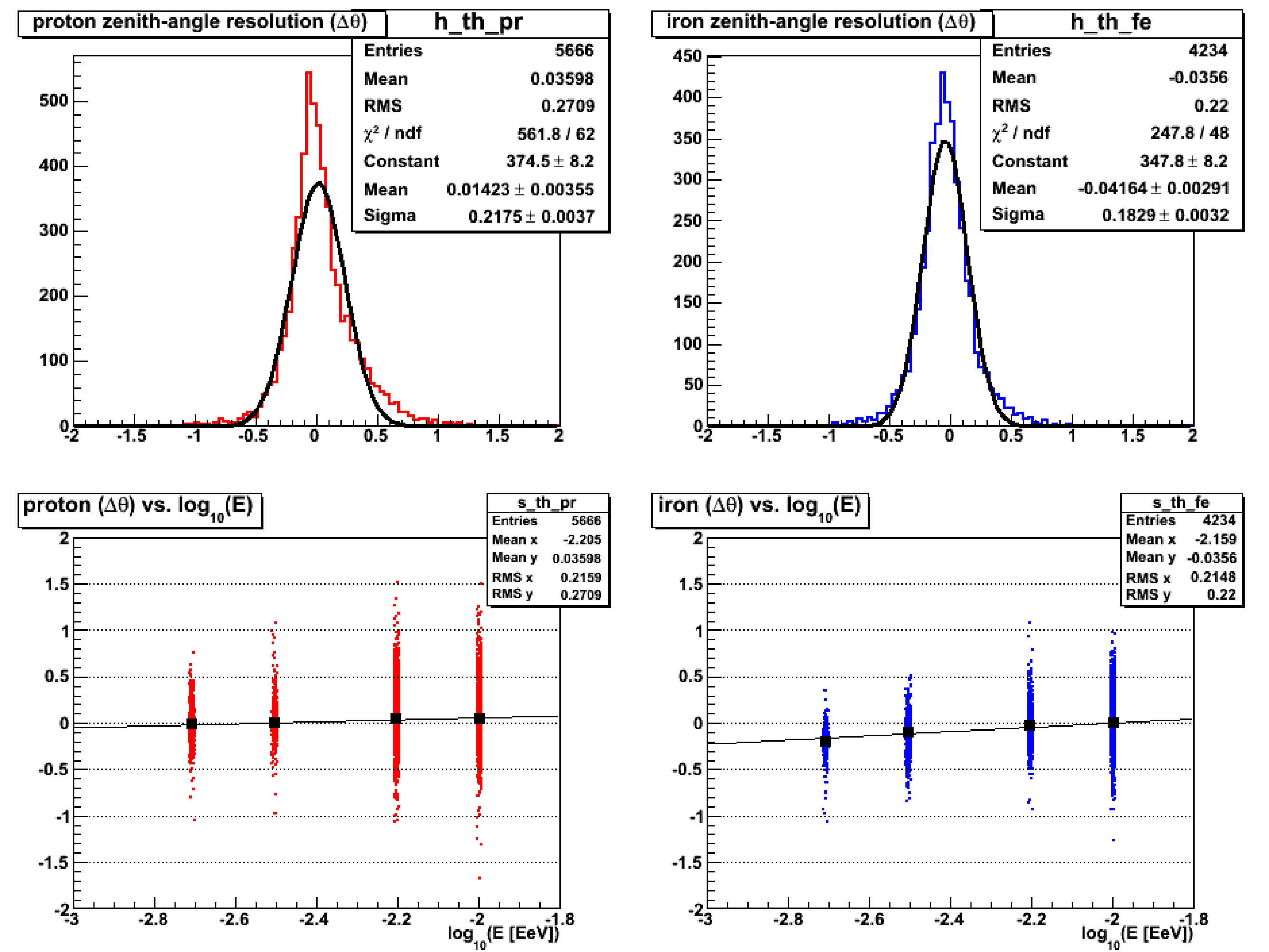
Geometrical Resolution



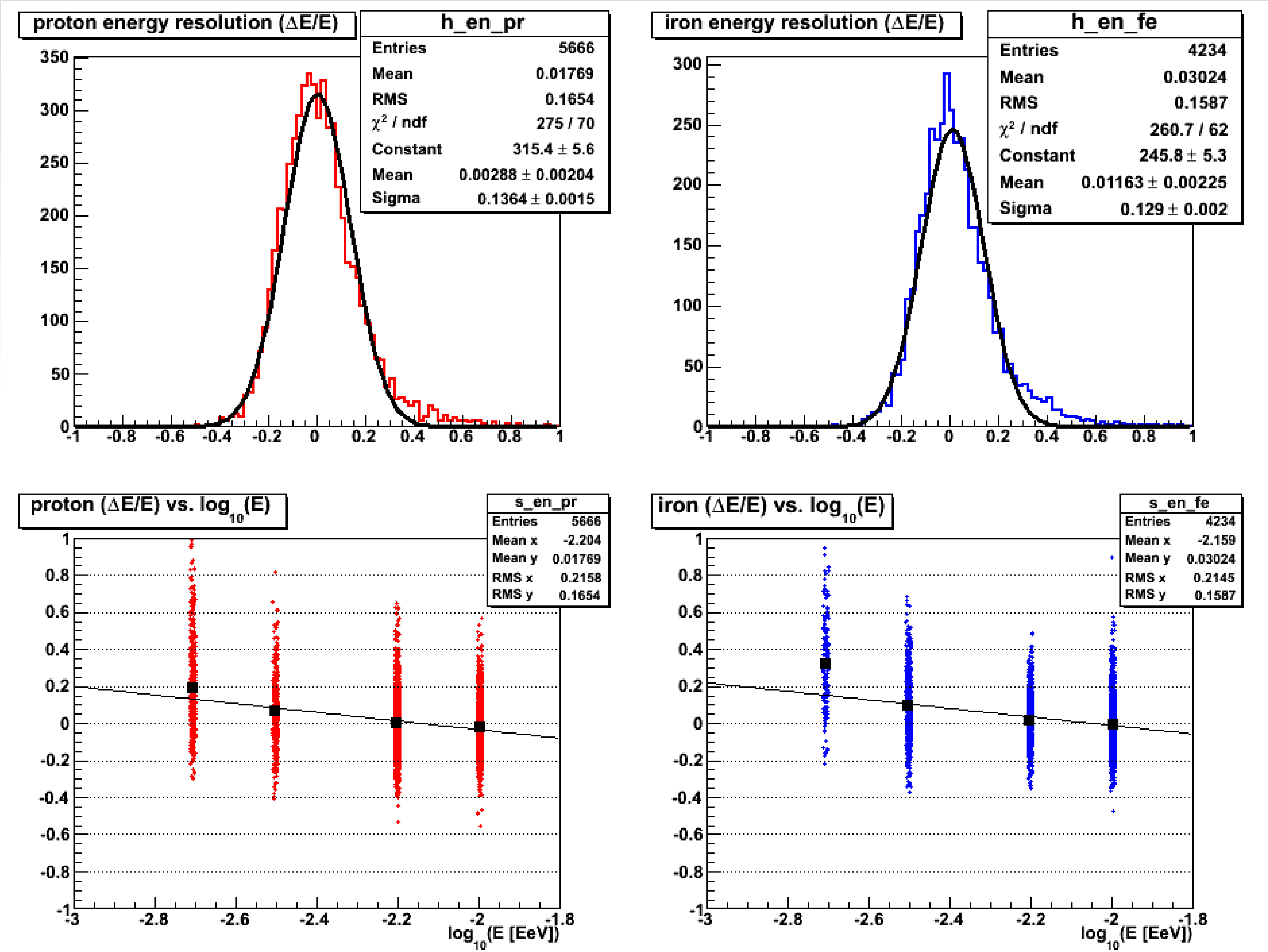
Geometrical Resolution



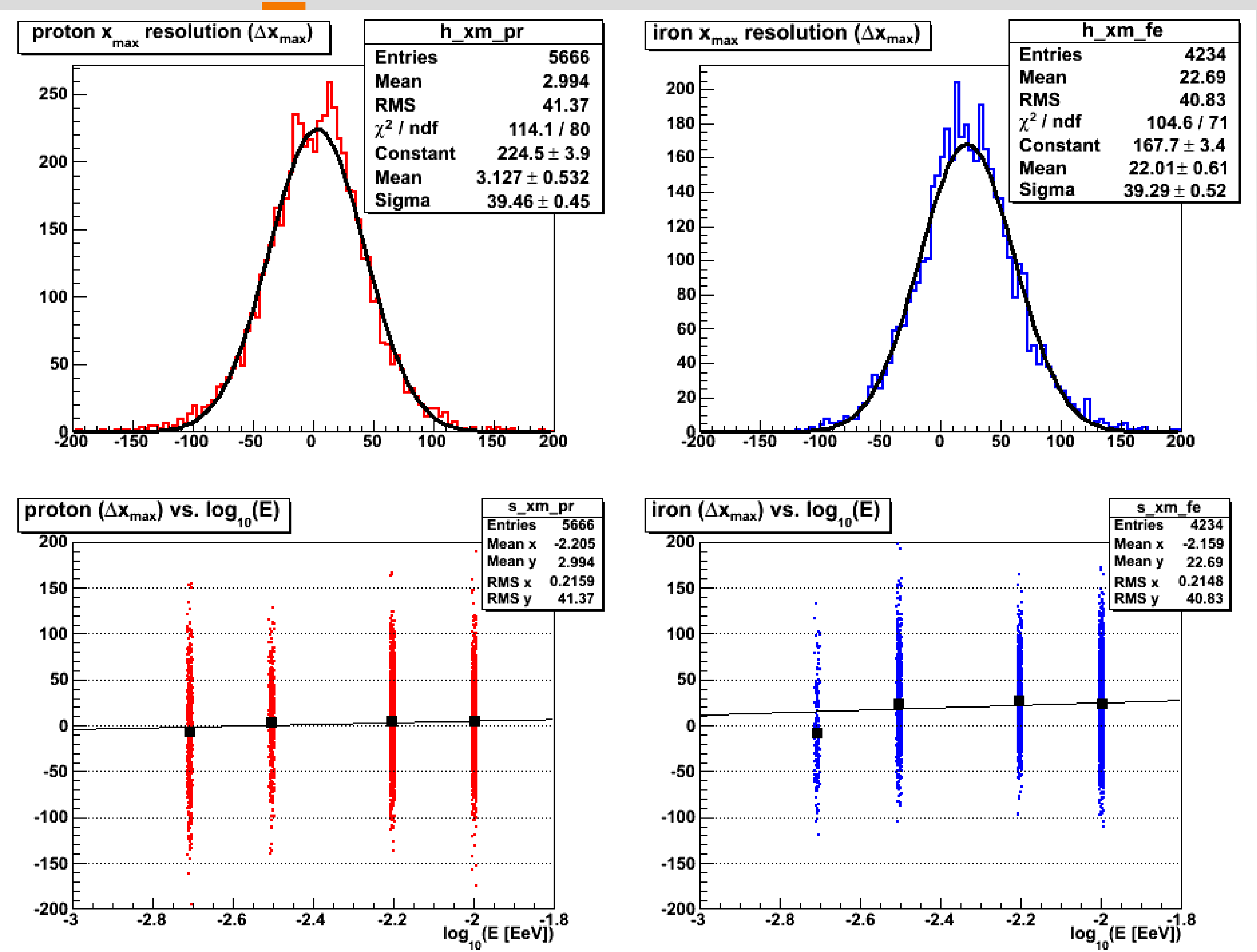
Geometrical Resolution



Energy Resolution



x_max Resolution



Spectrum Calculation

Spectrum Calculation

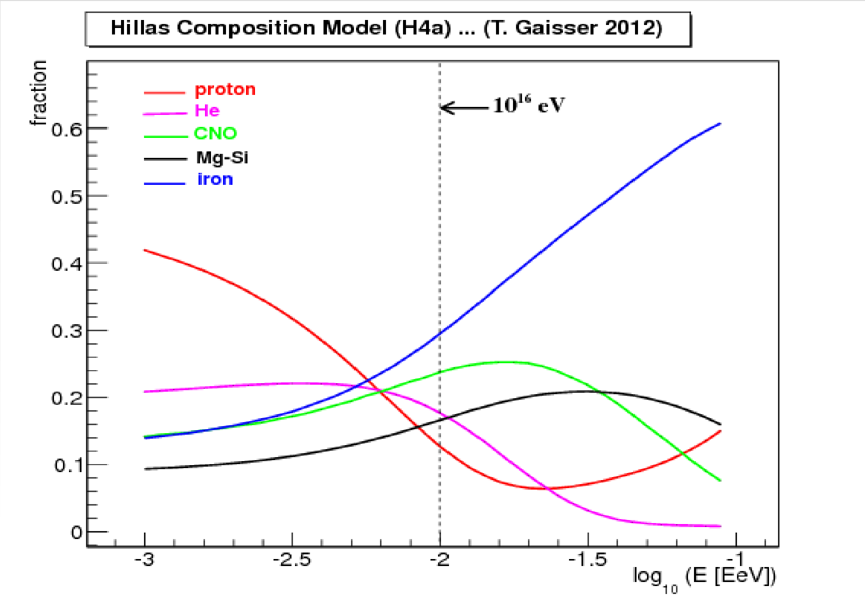
- Data set goes from 09/06/2013 to 01/06/2014
- Good weather selection “clear overhead”
- Total ontime 225. hours
  - Note that previously we calculated an effective ontime for a full detector. In the this treatment we calculate the actual time the detector was run regardless of how many live mirrors participated in the data taking.
- Simulation: For each primary type (pr, fe, h4a):
  - 2X data set starting at 2x10^15 eV
  - 5X data set starting at 4x10^16 eV

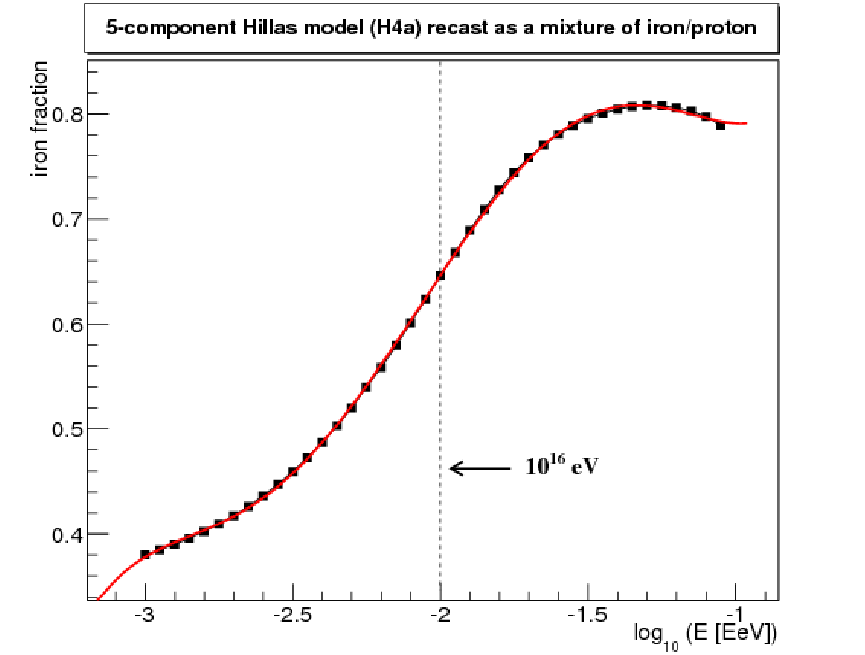
Spectrum Calculation

- Detector simulation sets:
  - Nightly atmospheric profile
  - Actual Mirror live-times (for each data part)
  - 5-component H4a composition model
    - Primary fraction as a function of energy
  - Also proton and iron sets.
  - Shower Library using
    CONEX with QGSJetII-4

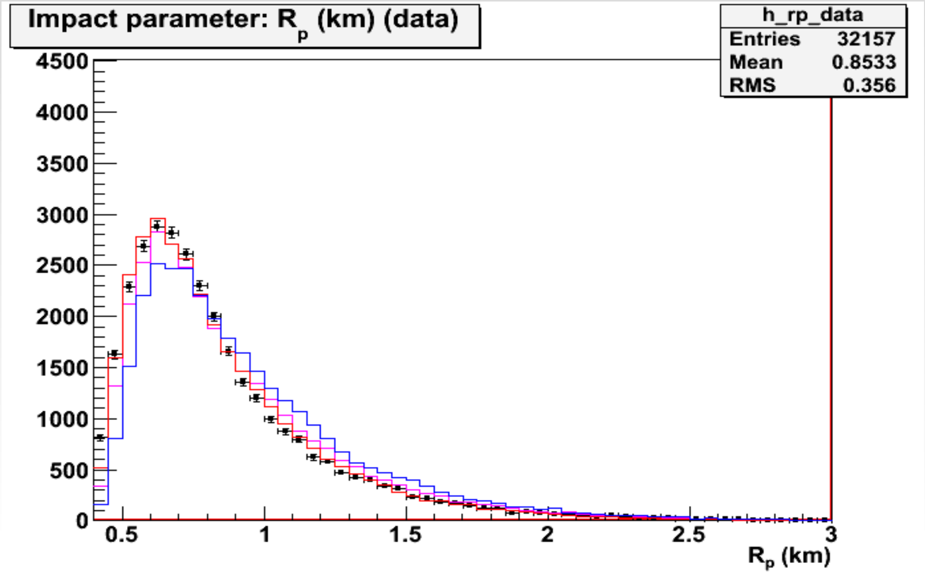
Composition Assumption

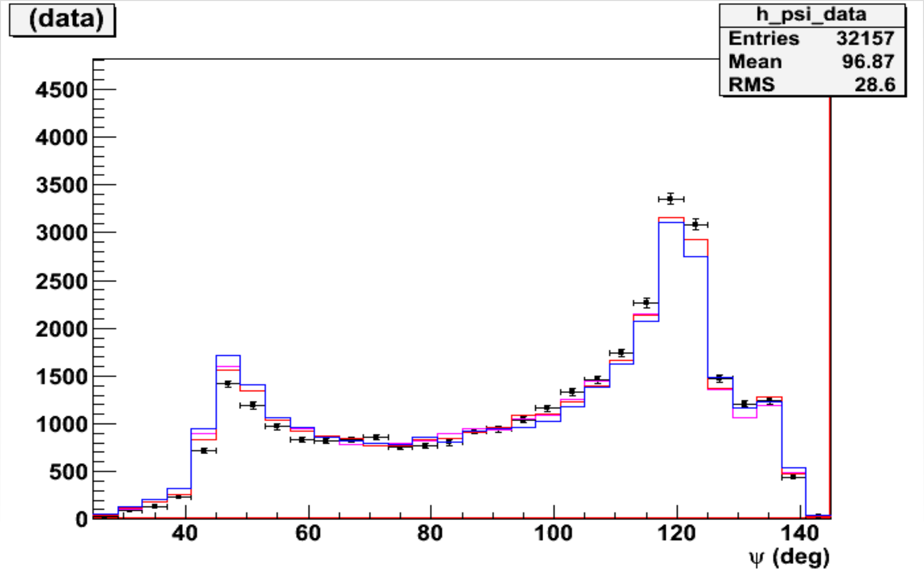
- H4a composition model by T. Gaisser [arXiv:1111.6675v2]
- In the second plot intermediate nuclei are assigned to either proton or iron components based on their atomic mass.

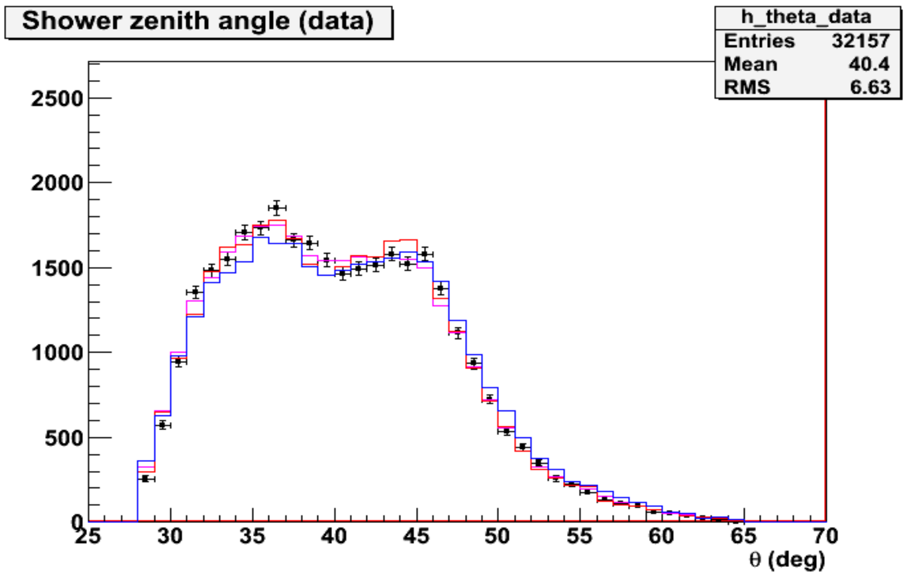


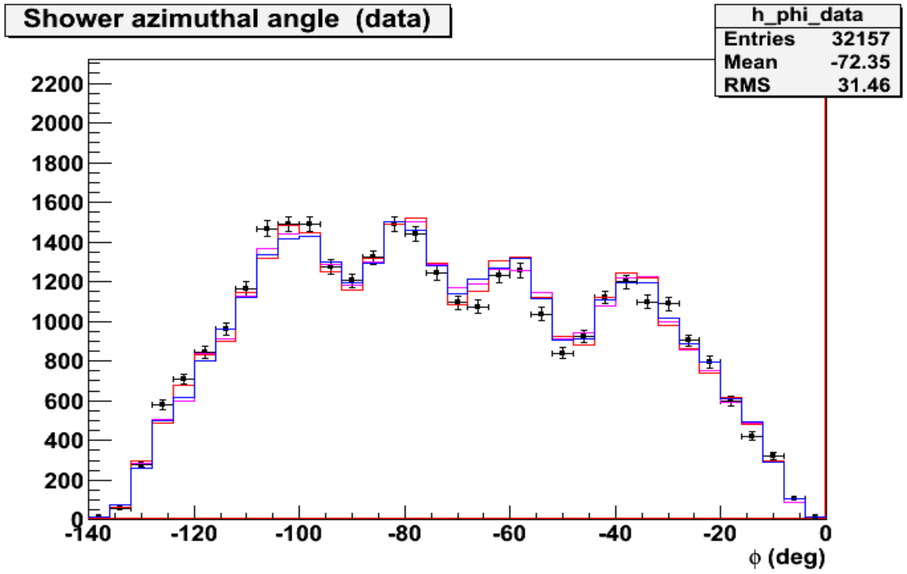


Data-MC comparison



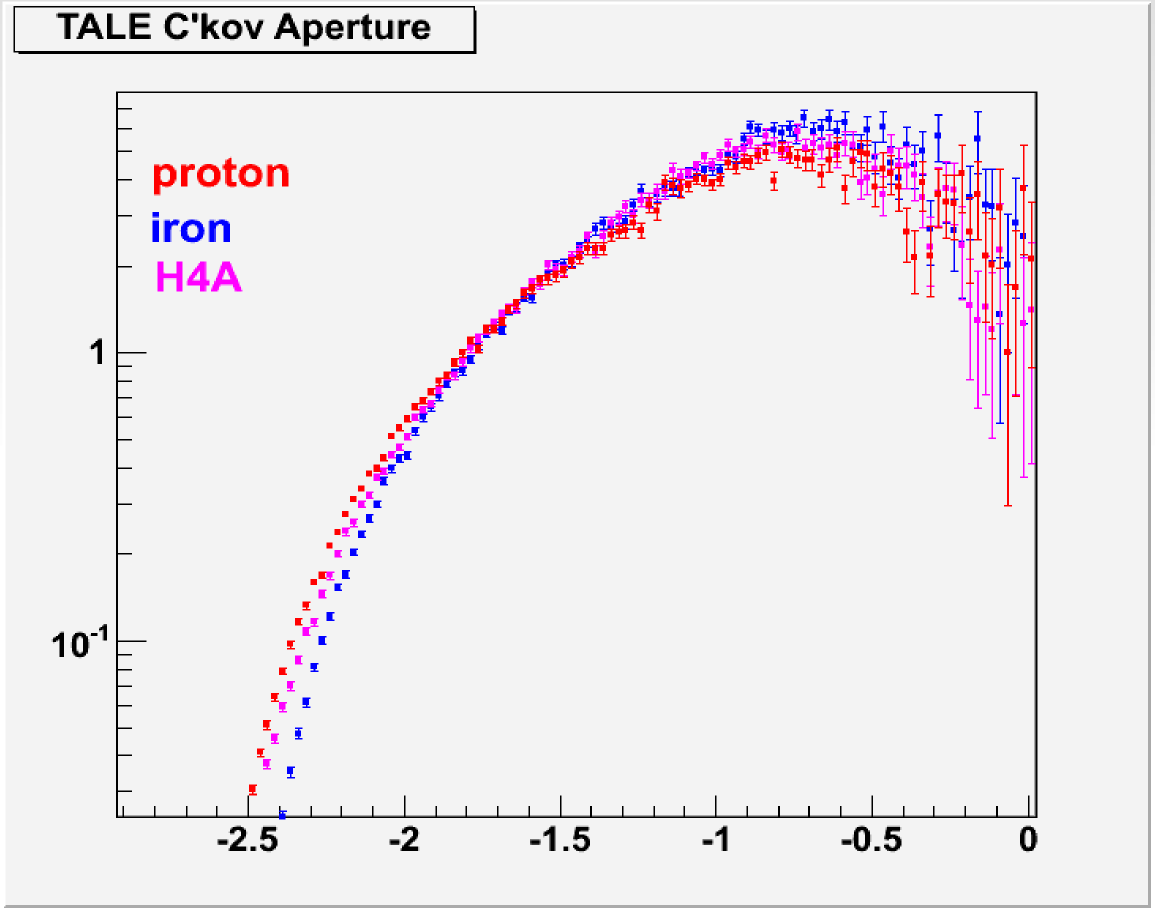


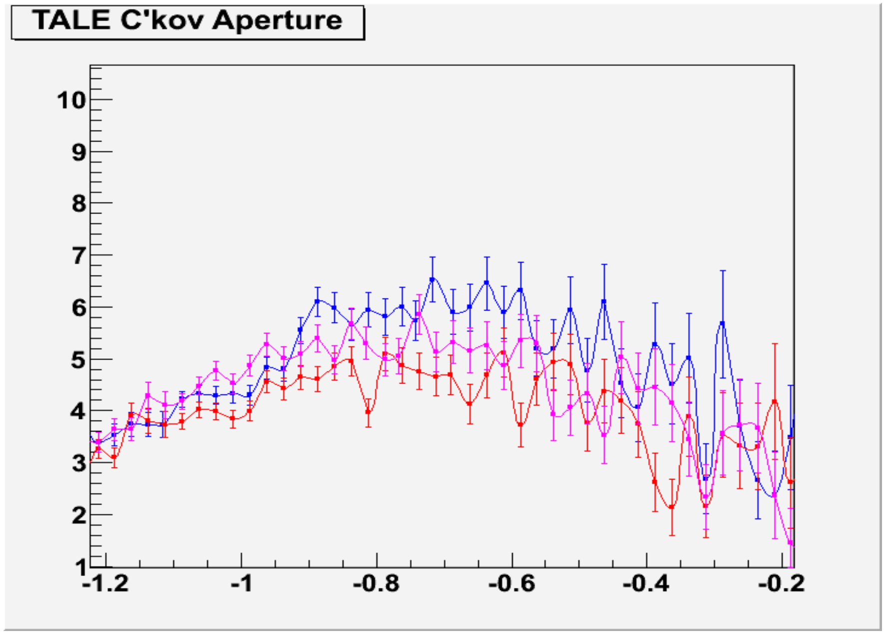




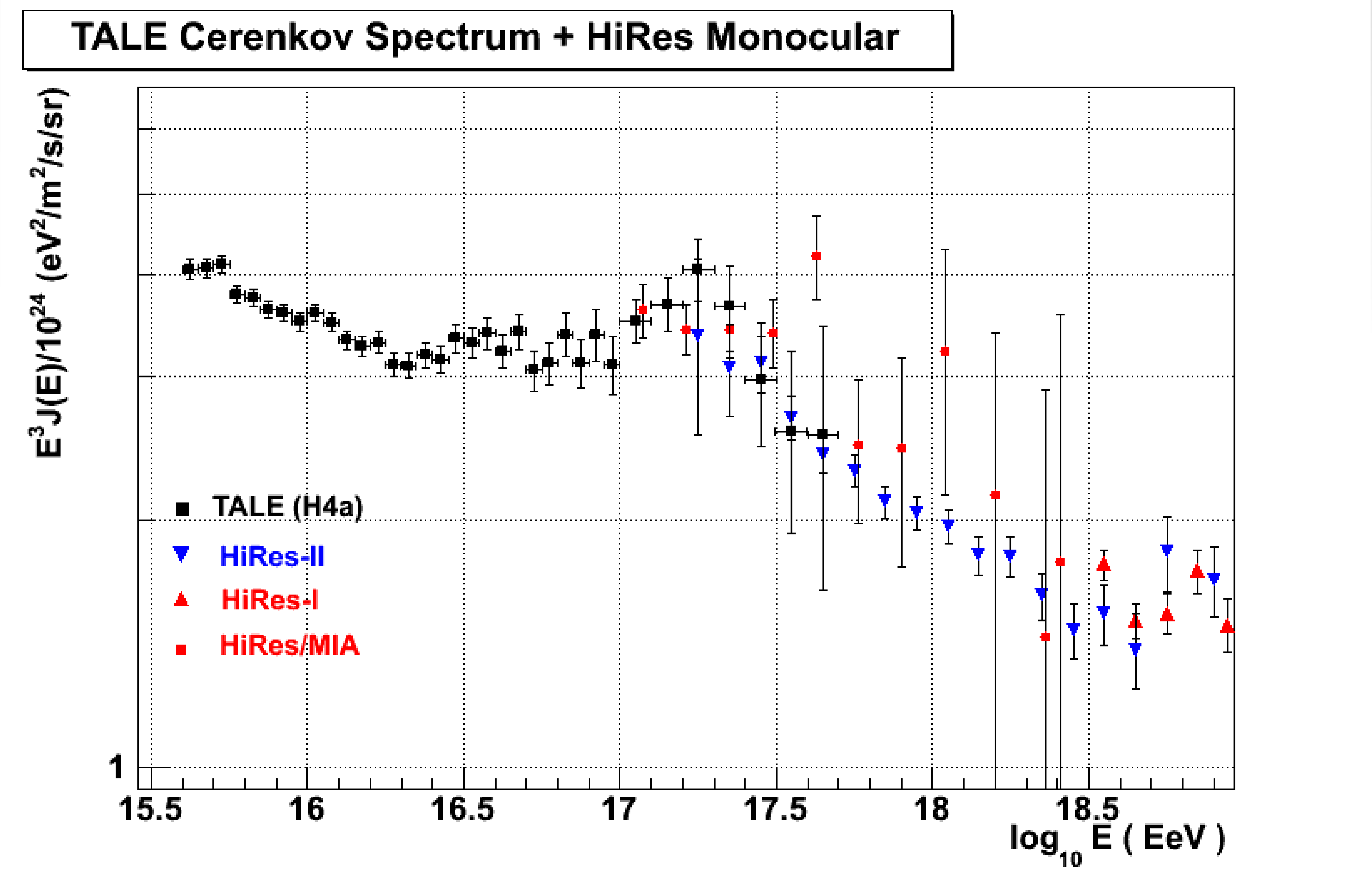
TALE C'kov Aperture

- X-axis: $\log_{10}$(E [EeV])
- Y-axis Reconstructible aperture [km^2 sr]
- Bottom plot: zoom in at higher energies

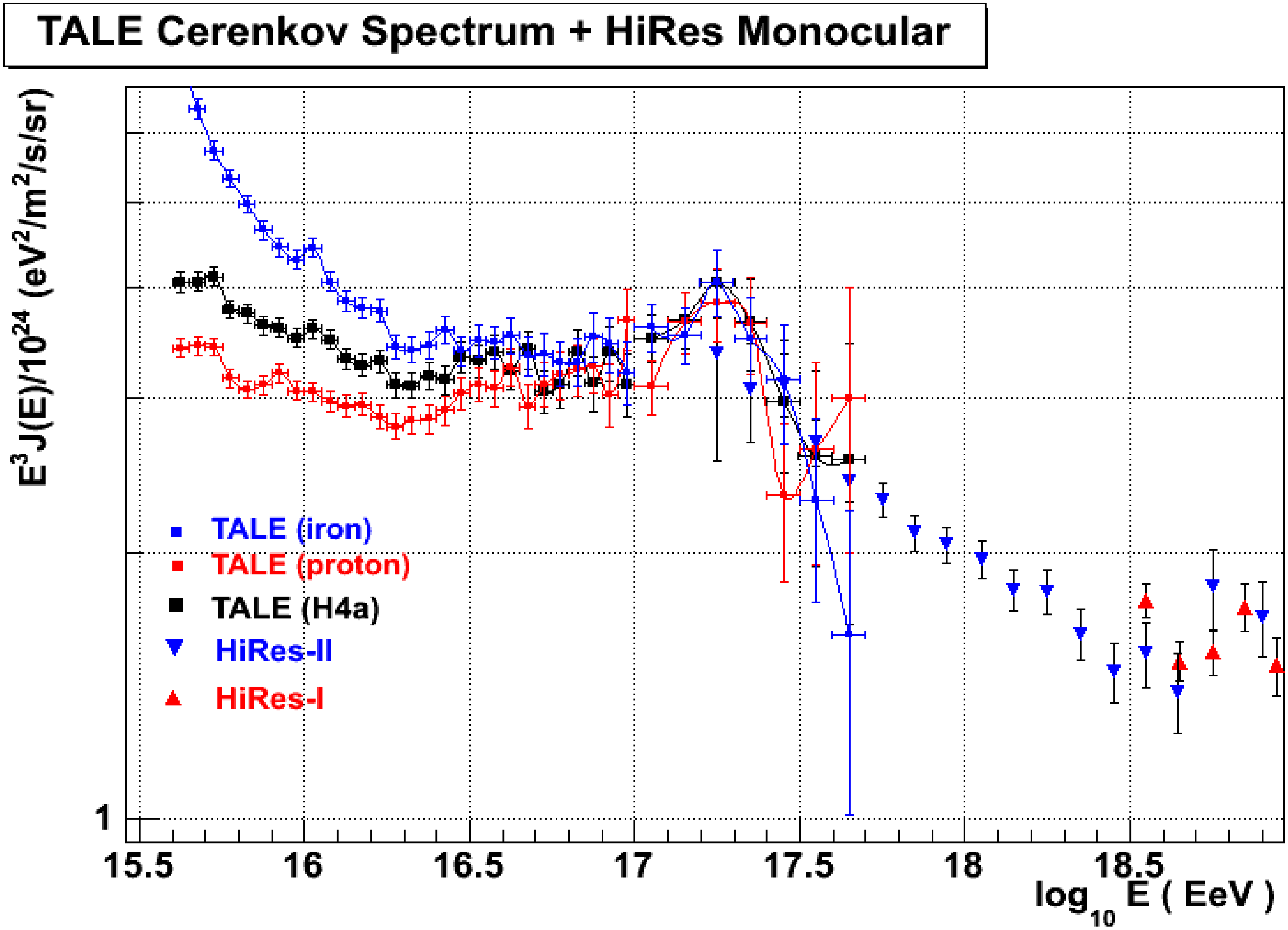




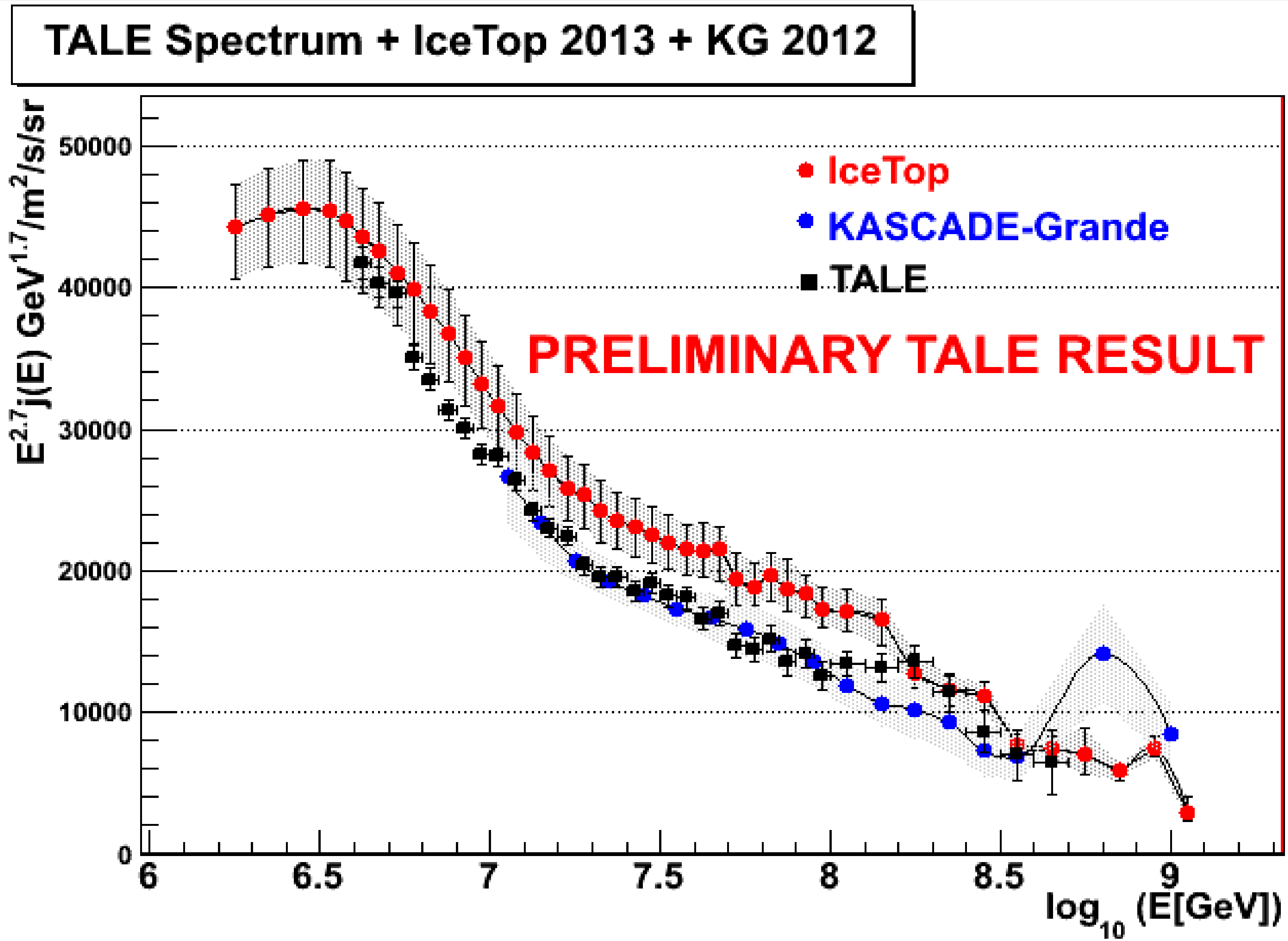
TALE spectrum with HiRes



TALE spectrum (2)



TALE Spectrum (3)



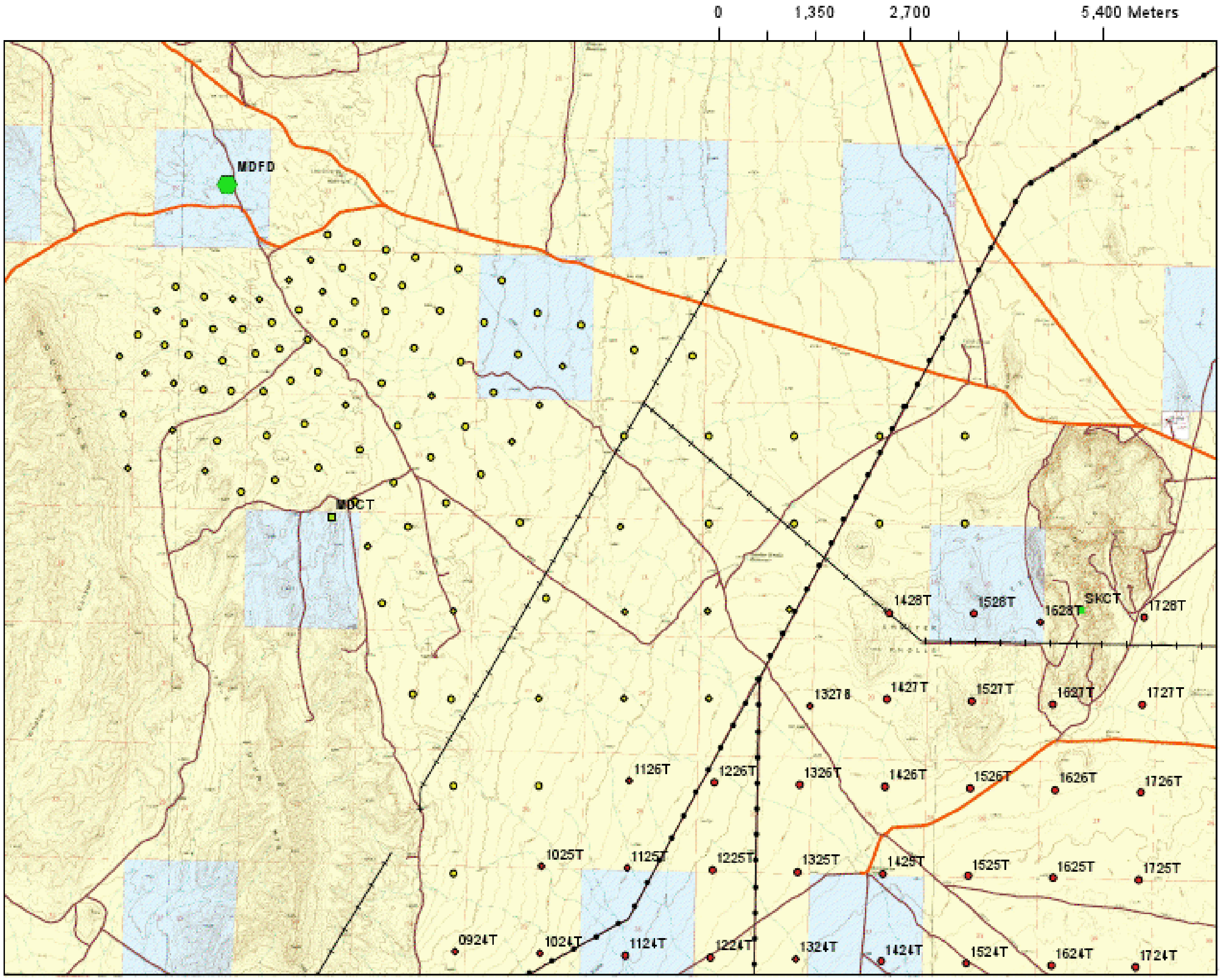
Summary

- We developed a new event reconstruction technique which allows us to use TALE as an Imaging Air Cerenkov Telescope.
- TALE as a Cerenkov detector can reach energies lower than 10^{16} eV with high statistics.
- We performed a calculation of the cosmic rays energy spectrum using TALE data from the first four months of operation.
- We observe a hardening of the spectrum at an energy of ~$10^{16.2}$ eV consistent with other experiments.

Backup Slides

TALE Surface Detector Infill Array

- Infill Array operates 24/7.
- However, when FD is on, we get the opportunity for hybrid observation.



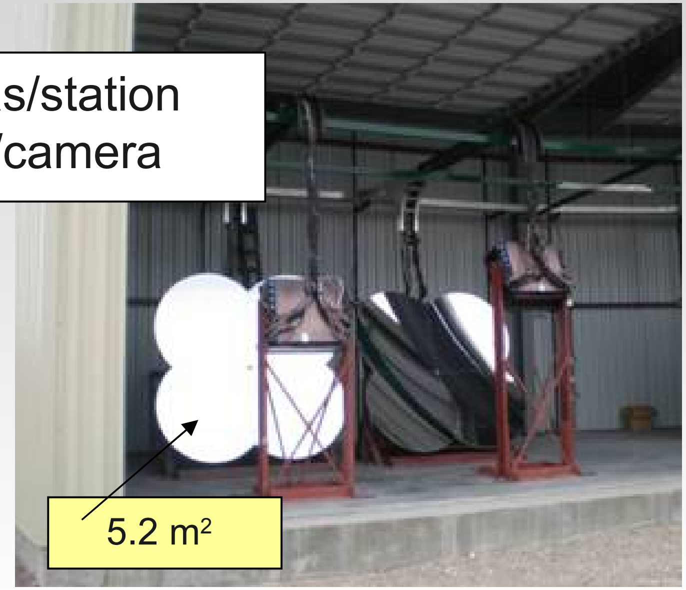
TA Fluorescence Detectors

Refurbished from HiRes

Observation started Dec. 2007

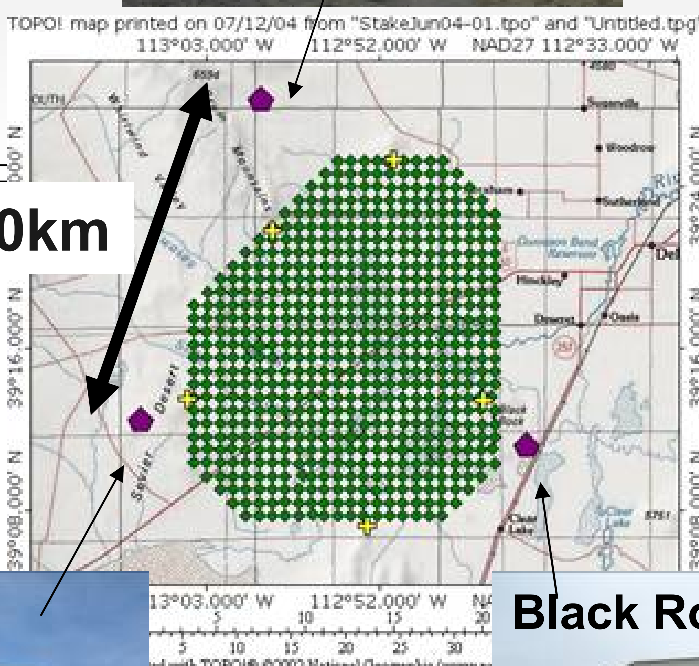
Middle Drum

14 cameras/station
256 PMTs/camera



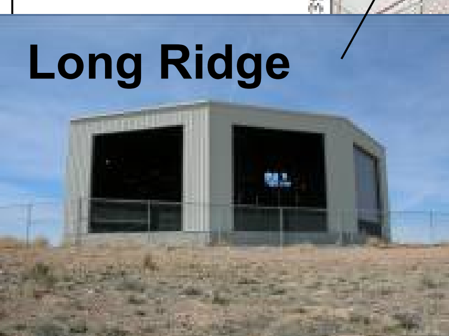
5.2 m²

~30km



Observation started Nov. 2007

Long Ridge



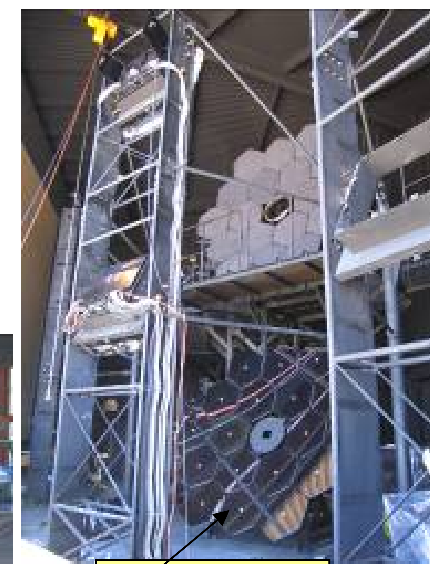
Observation started Jun. 2007

Black Rock Mesa

New FDs

256 PMTs/camera
HAMAMATSU R9508
FOV~15x18deg
12 cameras/station

~1 m²

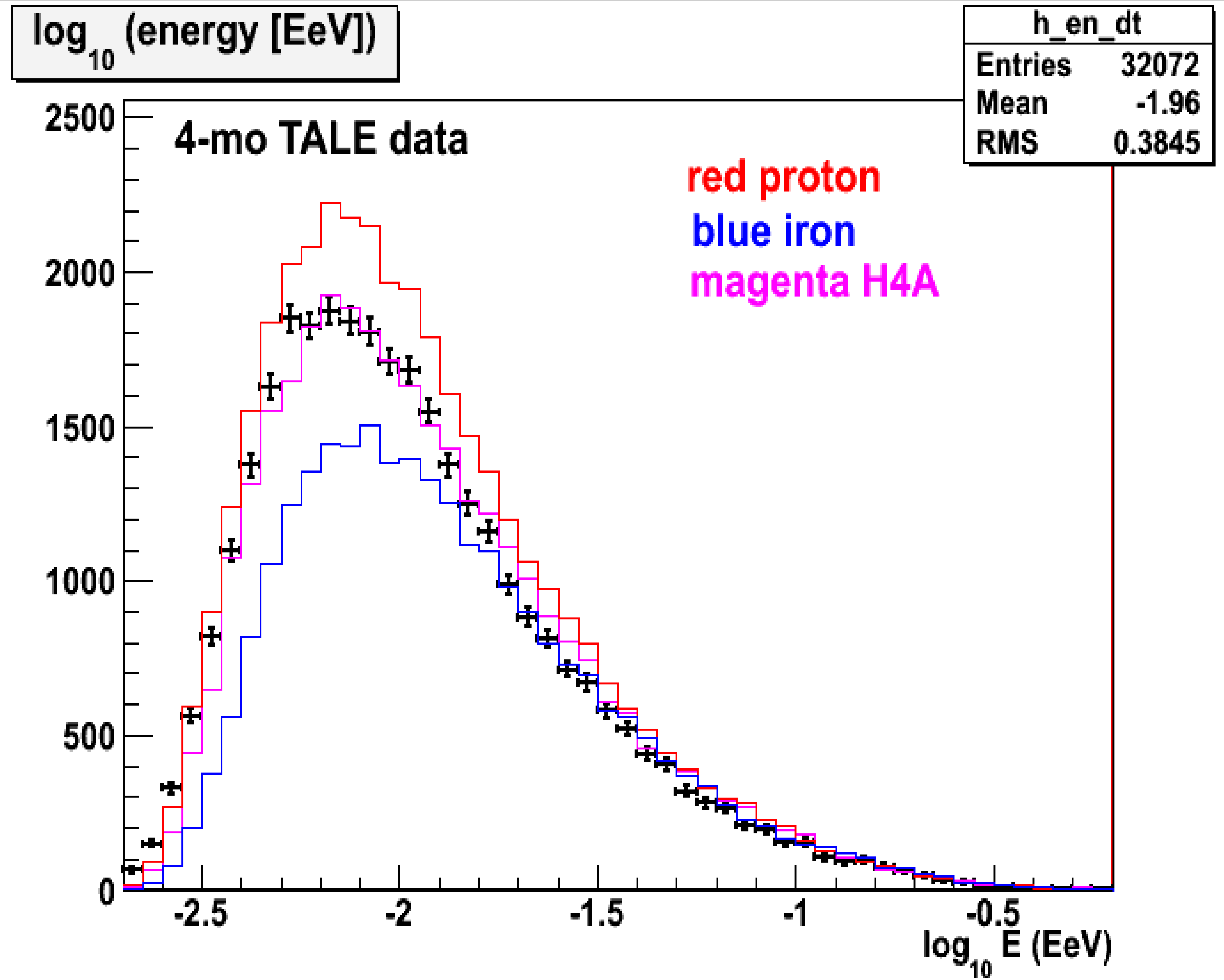


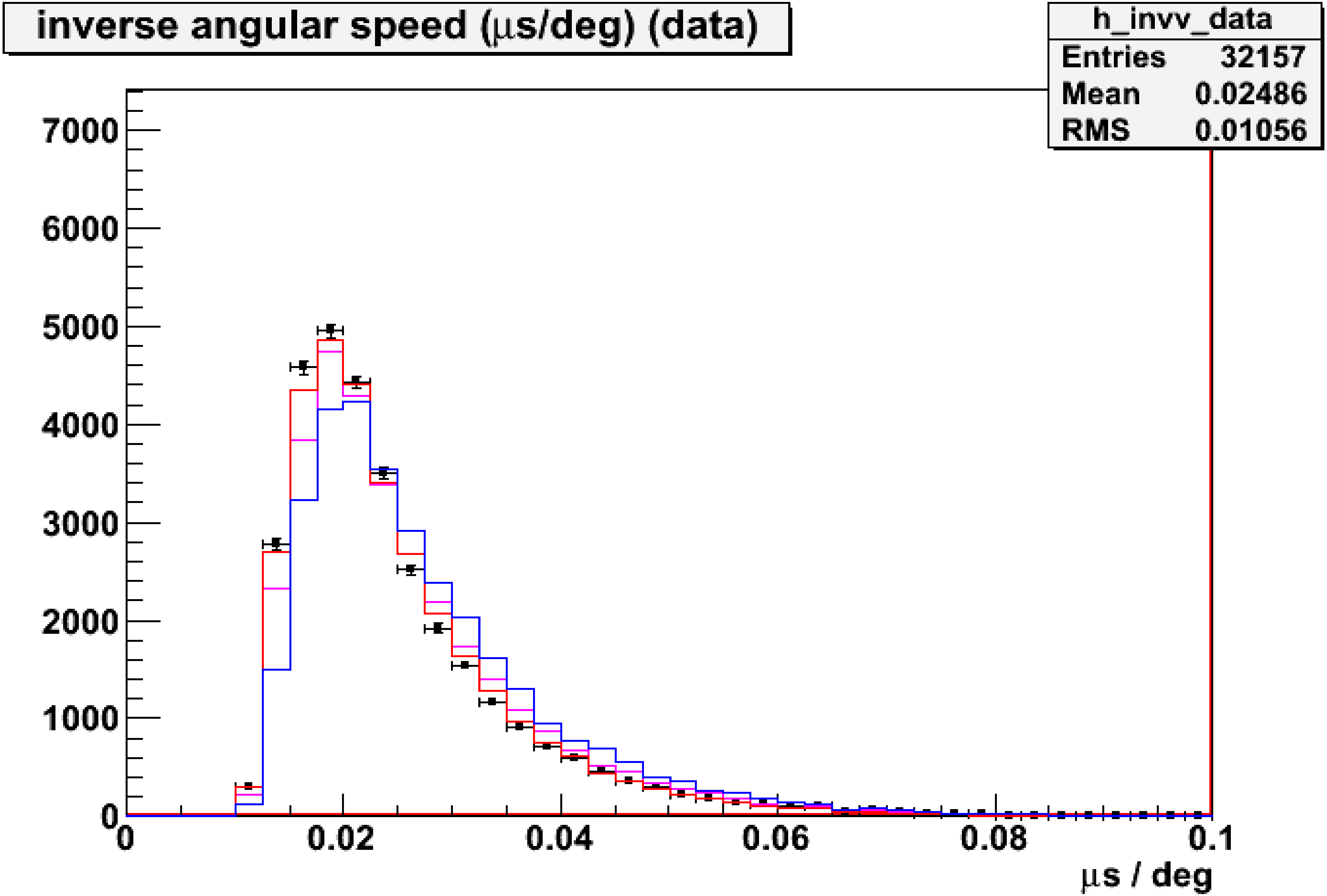
6.8 m²

TALE Corsika-IACT MC

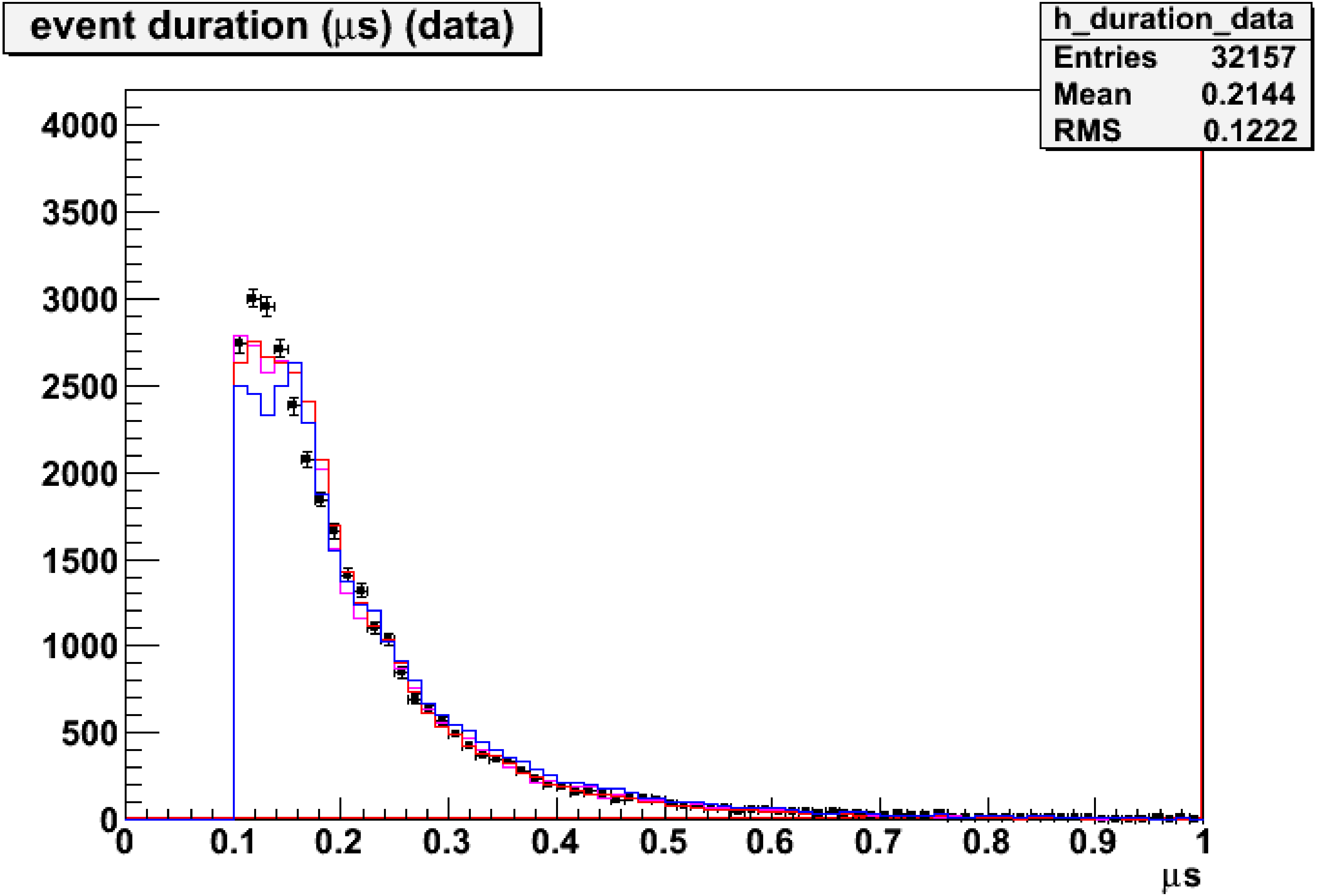
- Simulation fully determines:
  - number of photons
  - location of photon hits (before mirror Reflection)
  - arrival times at the detector

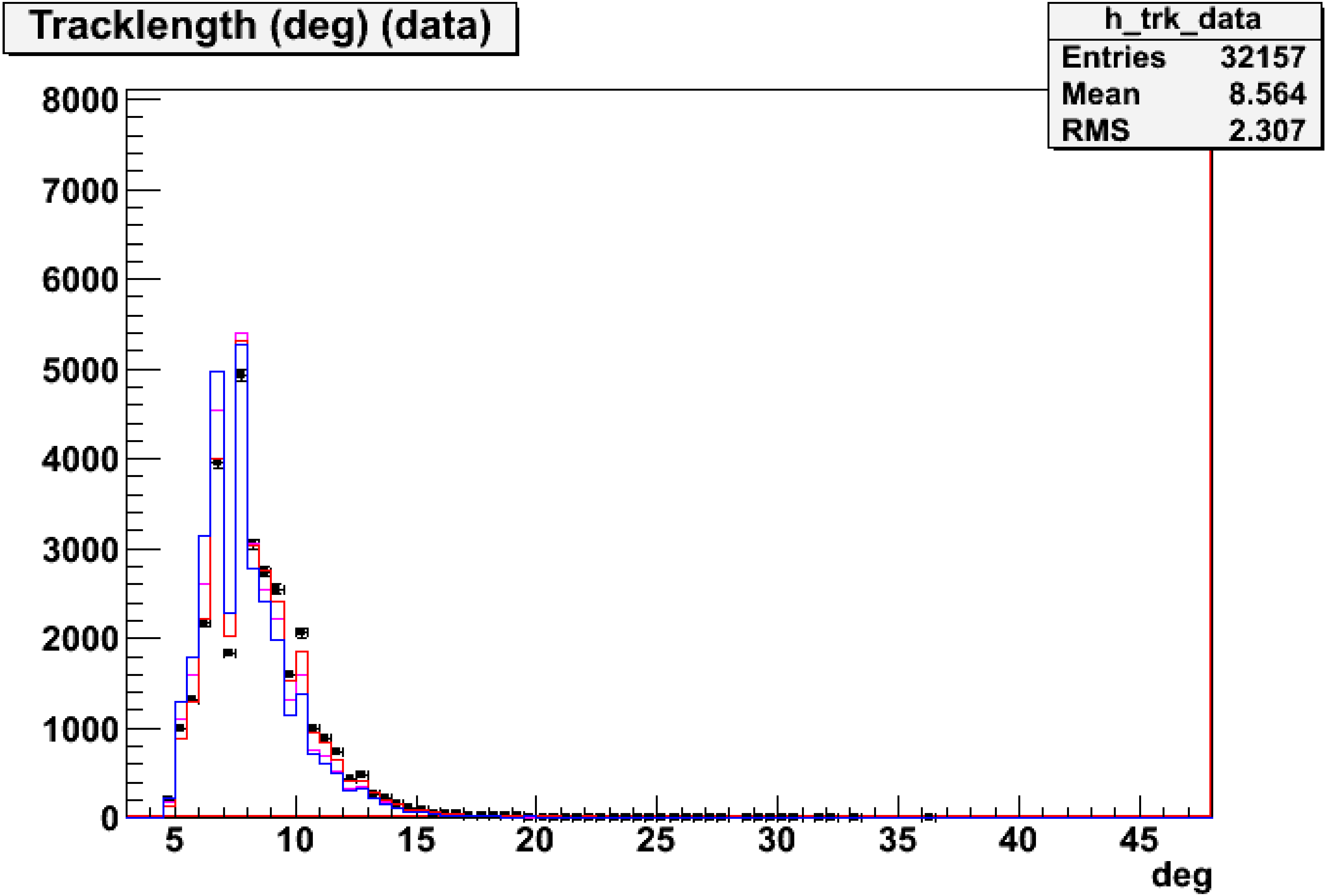
```
/**
 * Photons collected in bunches of identical direction, position, time,
 * and wavelength. The wavelength will normally be unspecified as
 * produced by CORSIKA (lambda=0).
*/

struct bunch
{
   float photons; /**< Number of photons in bunch */
   float x, y;    /**< Arrival position relative to telescope (cm) */
   float cx, cy;  /**< Direction cosines of photon direction */
   float ctime;   /**< Arrival time (ns) */
   float zem;     /**< Height of emission point above sea level (cm) */
   float lambda;  /**< Wavelength in nanometers or 0 */
};
```

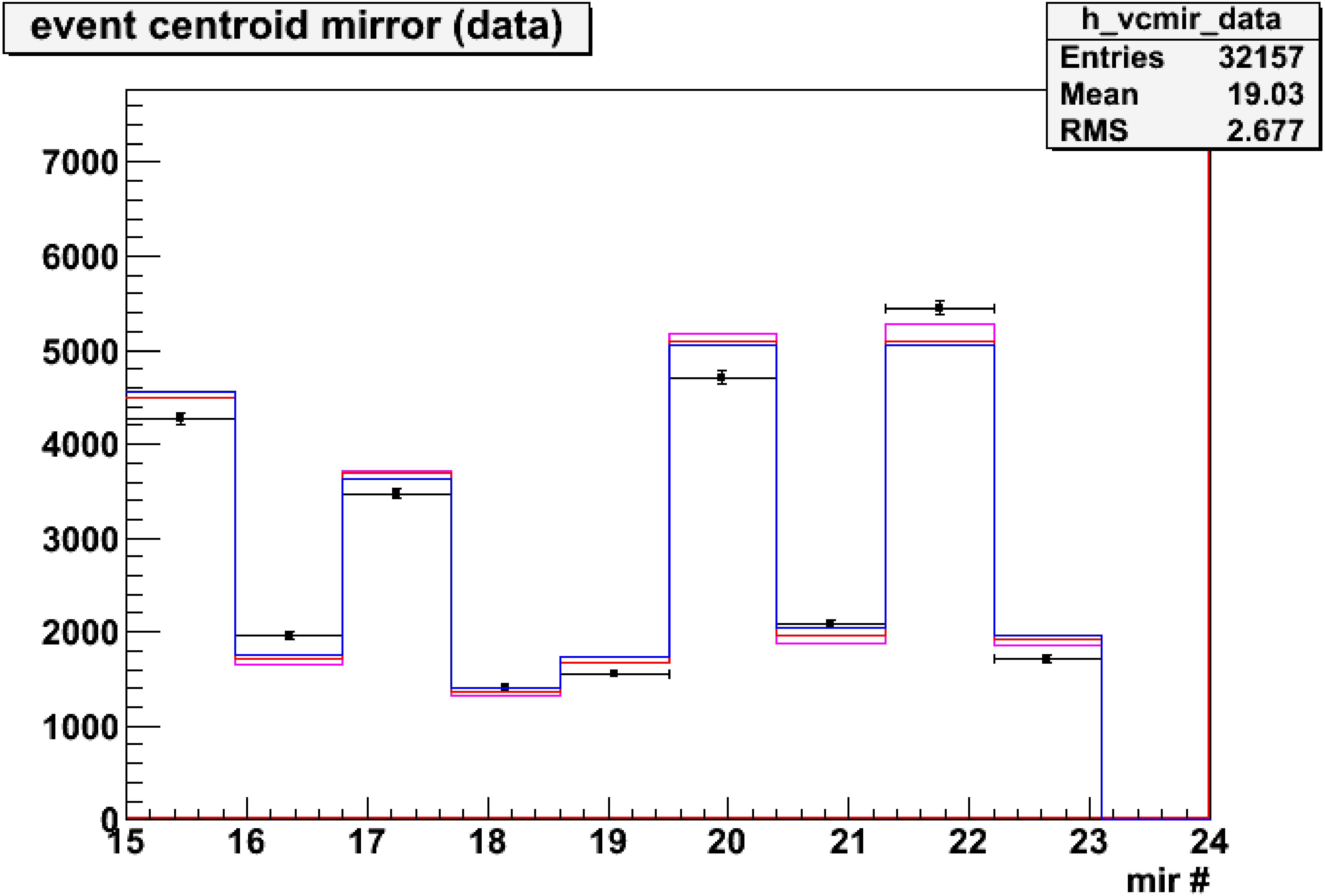

log10 (energy [EeV])
h_en_dt
Entries 32072
Mean -1.96
RMS 0.3845
4-mo TALE data
red proton
blue iron
magenta H4A
2500
2000
1500
1000
500
0
-2.5
-2
-1.5
-1
-0.5
log10 E (EeV)

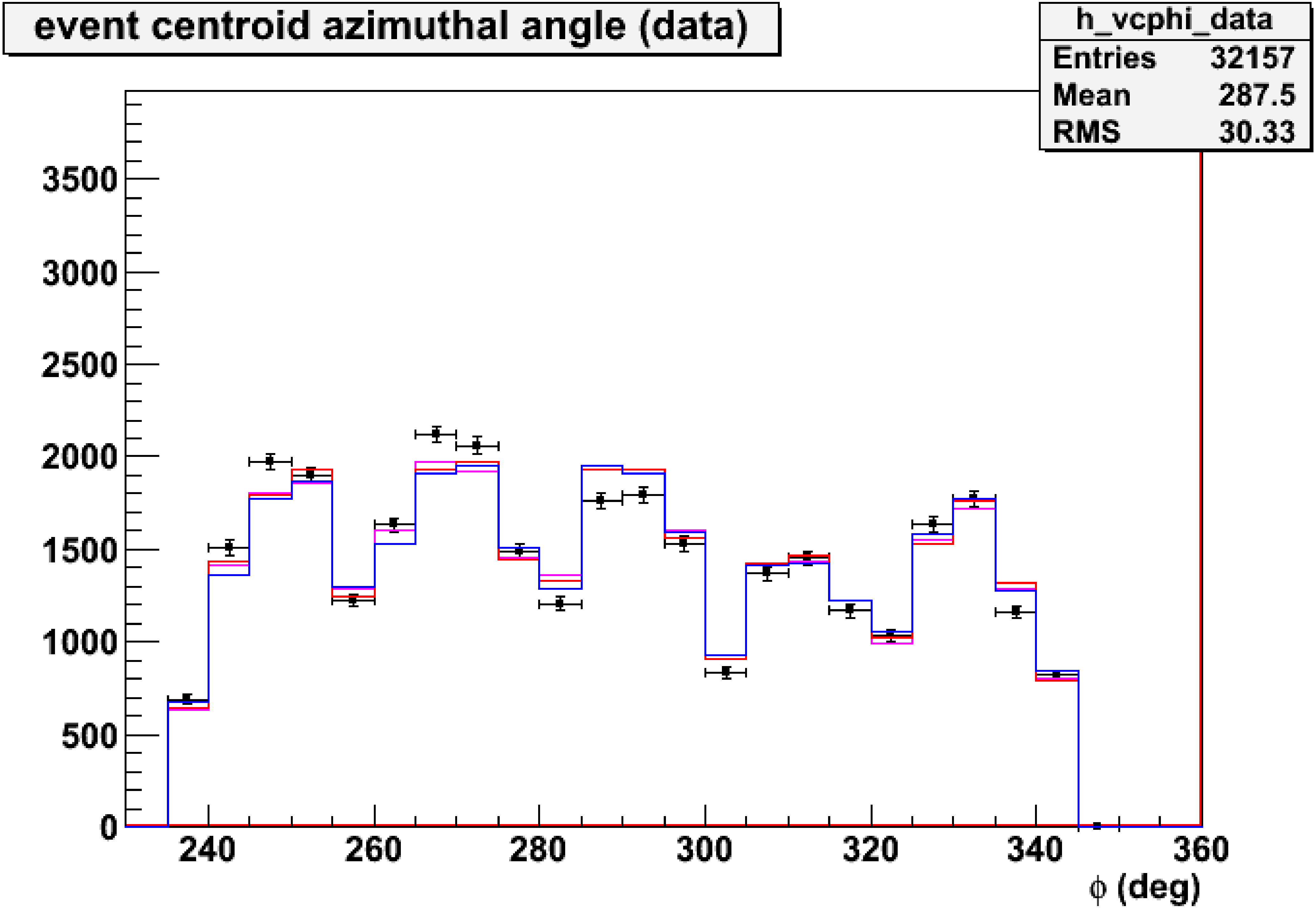


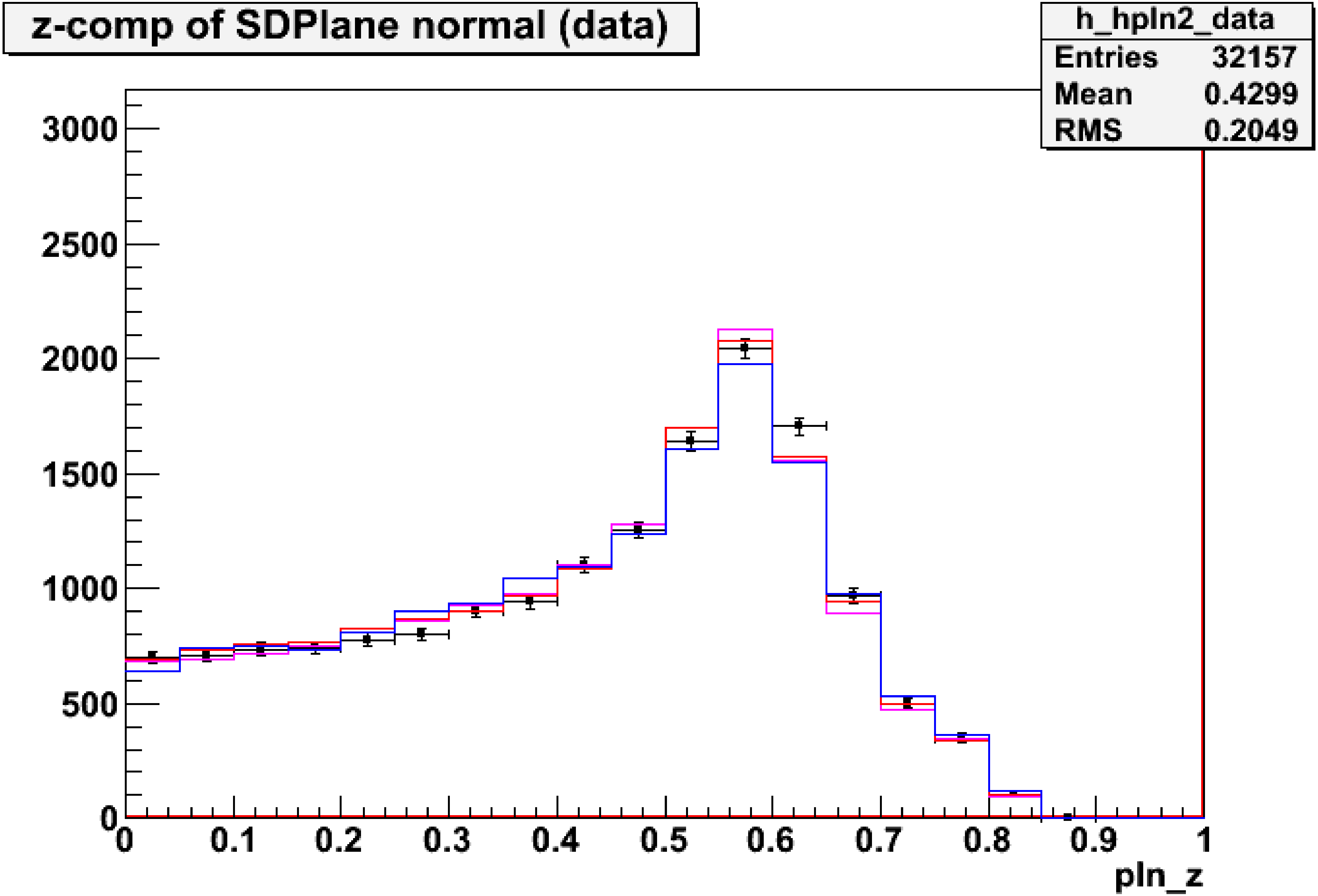
inverse angular speed (μs/deg) (data)
h_invv_data
Entries 32157
Mean 0.02486
RMS 0.01056
7000
6000
5000
4000
3000
2000
1000
0
0
0.02
0.04
0.06
0.08
0.1
μs / deg

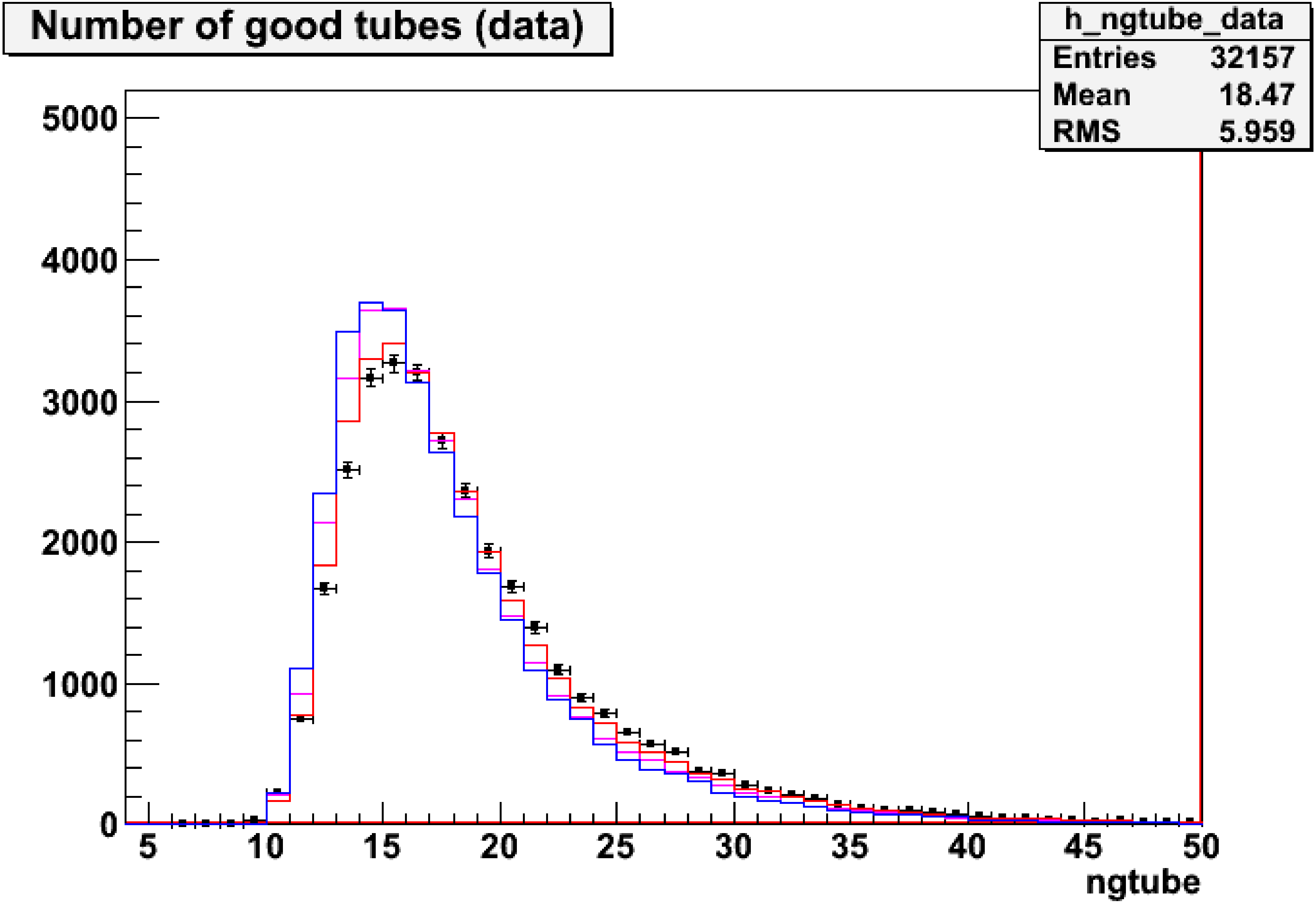

event duration (µs) (data)
h_duration_data
Entries 32157
Mean 0.2144
RMS 0.1222
4000
3500
3000
2500
2000
1500
1000
500
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
µs

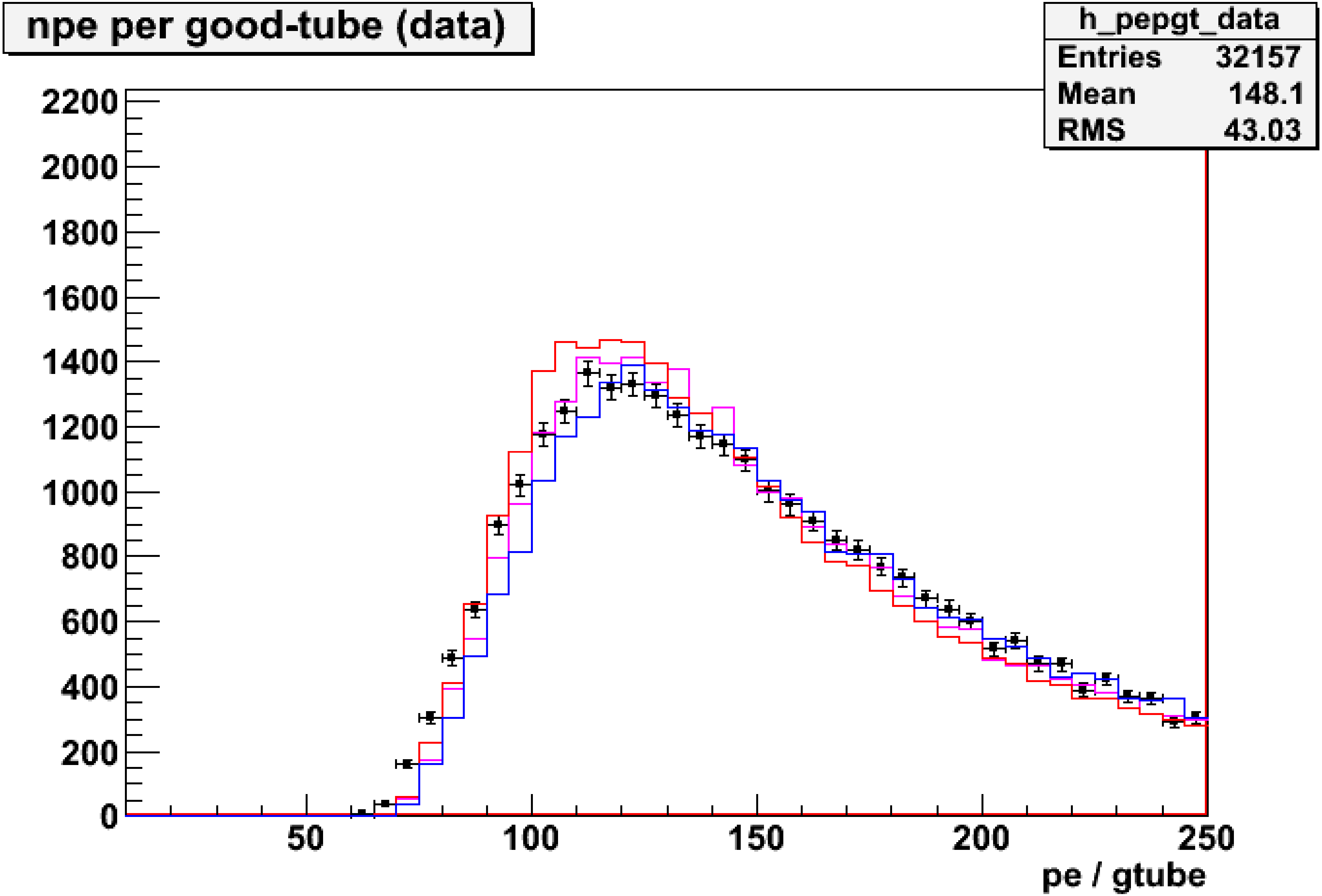

Tracklength (deg) (data)
h_trk_data
Entries 32157
Mean 8.564
RMS 2.307
8000
7000
6000
5000
4000
3000
2000
1000
0
5
10
15
20
25
30
35
40
45
deg

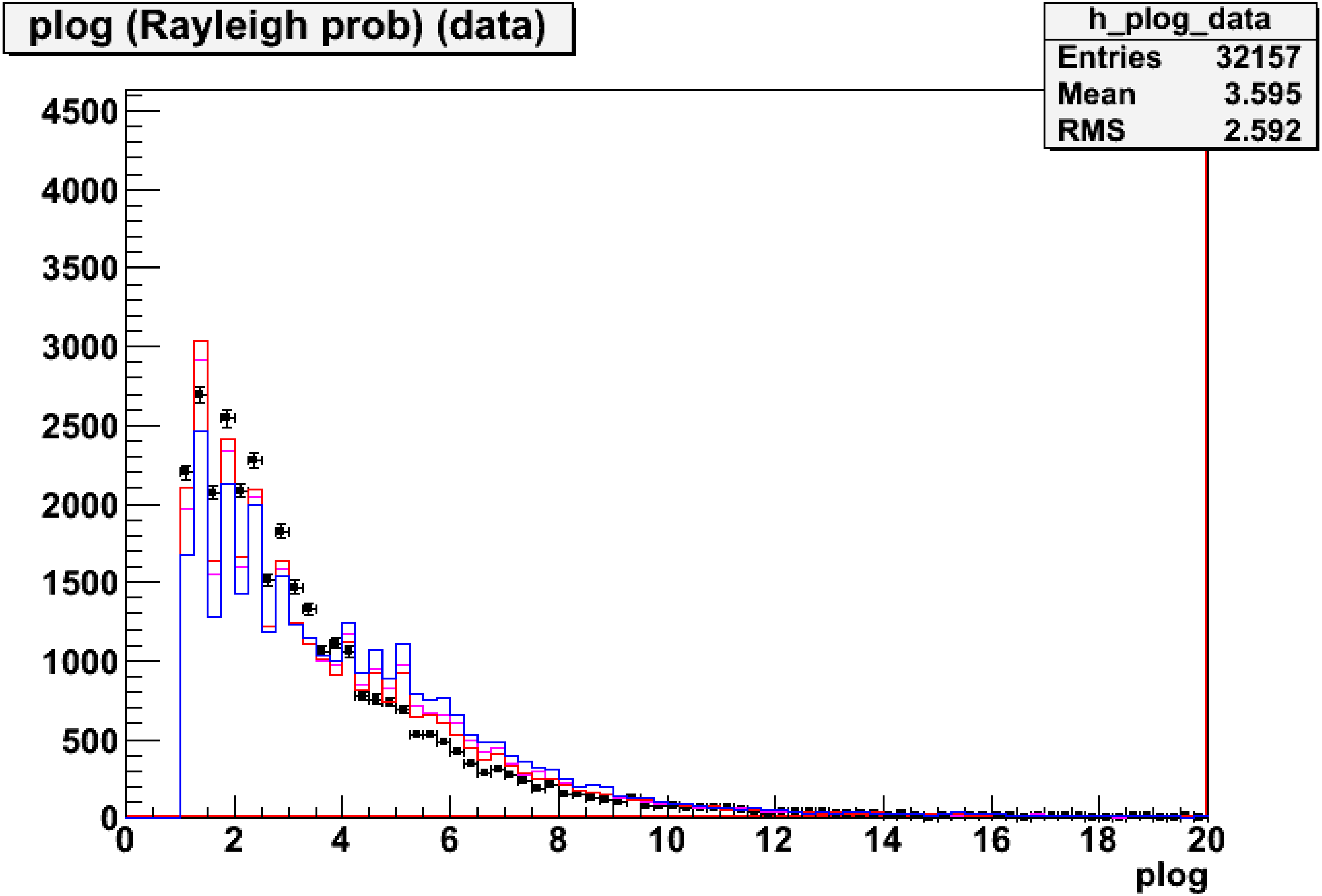

event centroid mirror (data)
h_vcmir_data
Entries 32157
Mean 19.03
RMS 2.677
7000
6000
5000
4000
3000
2000
1000
0
15
16
17
18
19
20
21
22
23
24
mir #

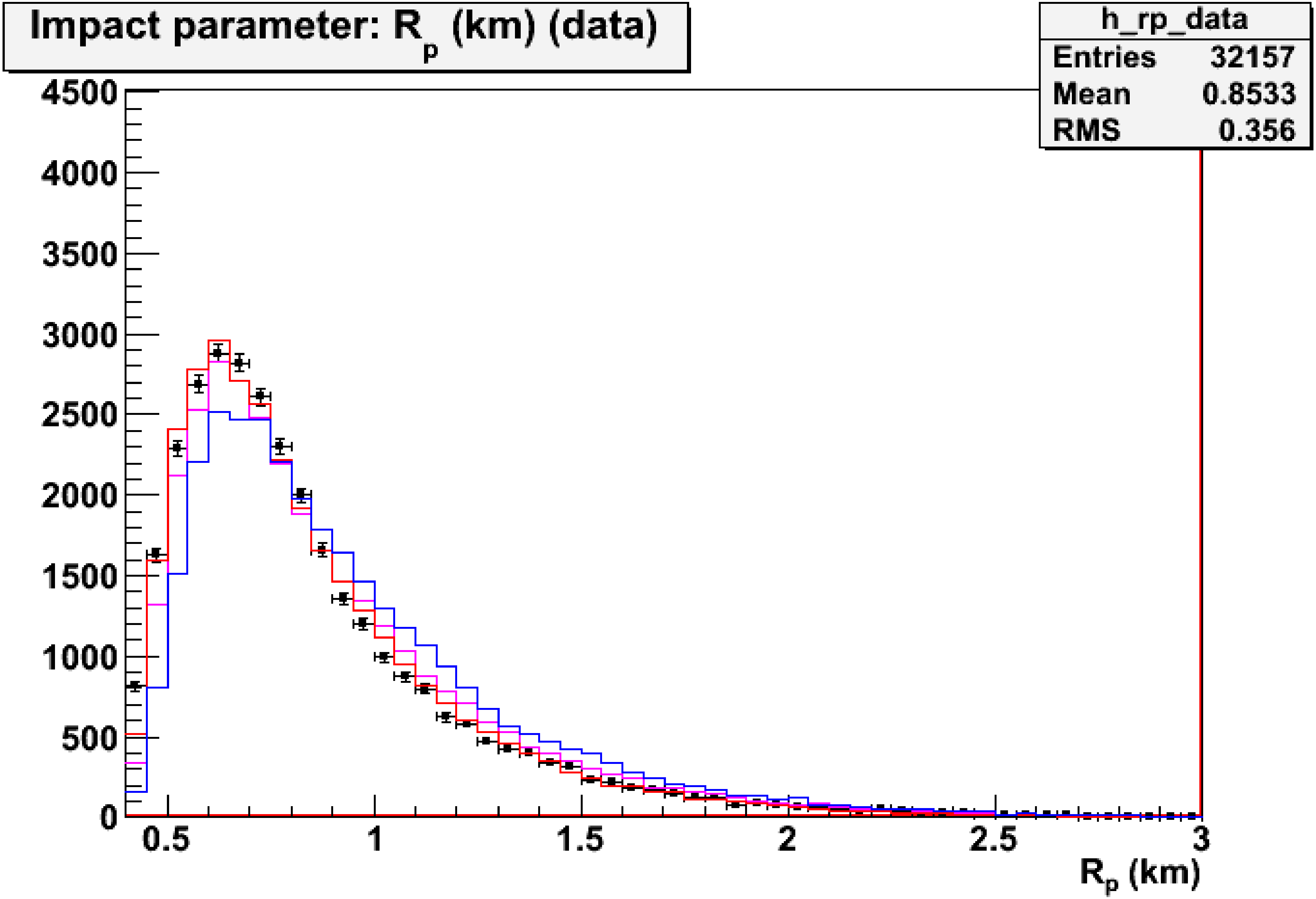

event centroid azimuthal angle (data)
h_vcphi_data
Entries 32157
Mean 287.5
RMS 30.33
3500
3000
2500
2000
1500
1000
500
0
240
260
280
300
320
340
360
φ (deg)


z-comp of SDPlane normal (data)
h_hpln2_data
Entries 32157
Mean 0.4299
RMS 0.2049
3000
2500
2000
1500
1000
500
0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
pln_z

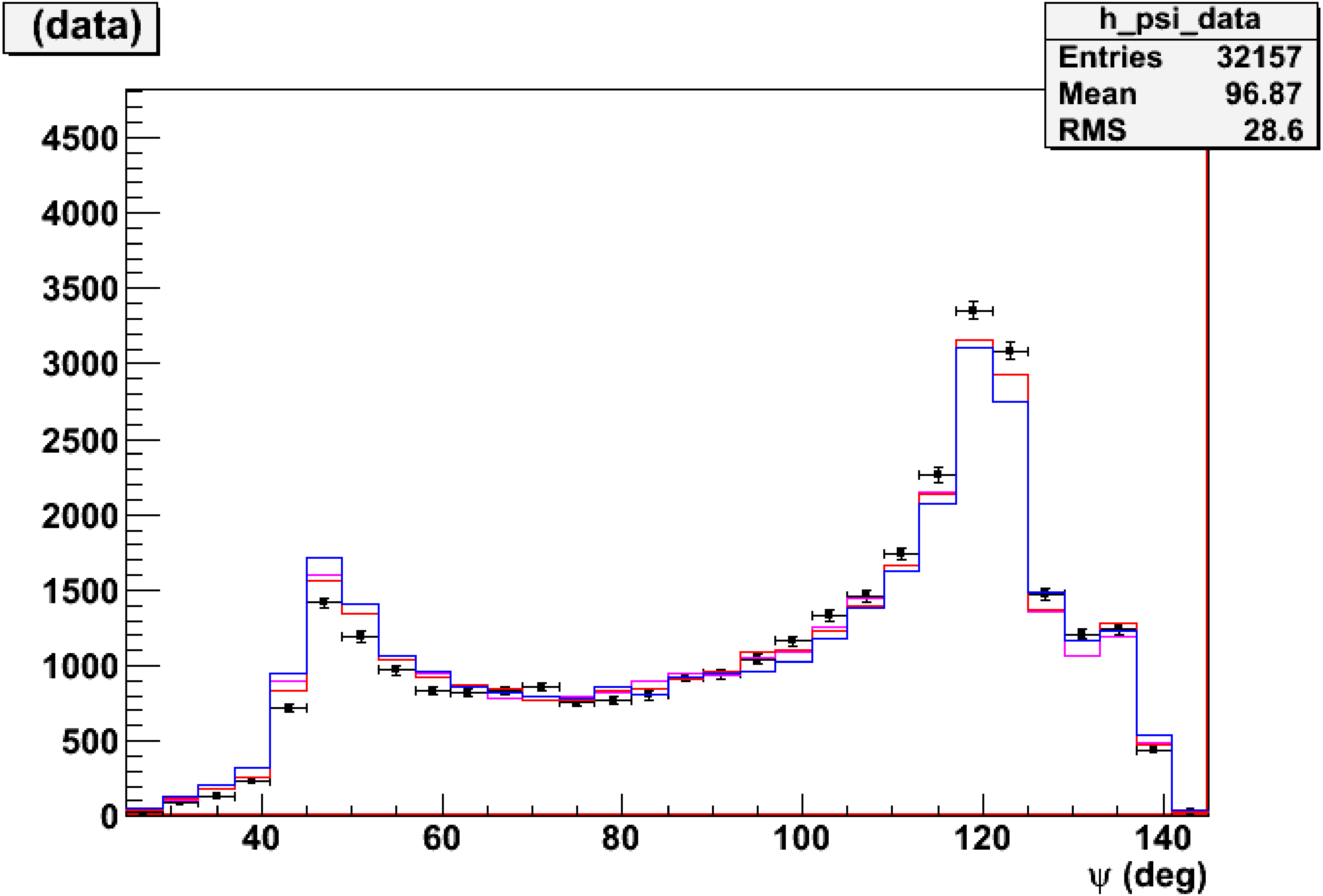

Number of good tubes (data)
h_ngtube_data
Entries 32157
Mean 18.47
RMS 5.959
5000
4000
3000
2000
1000
0
5
10
15
20
25
30
35
40
45
50
ngtube

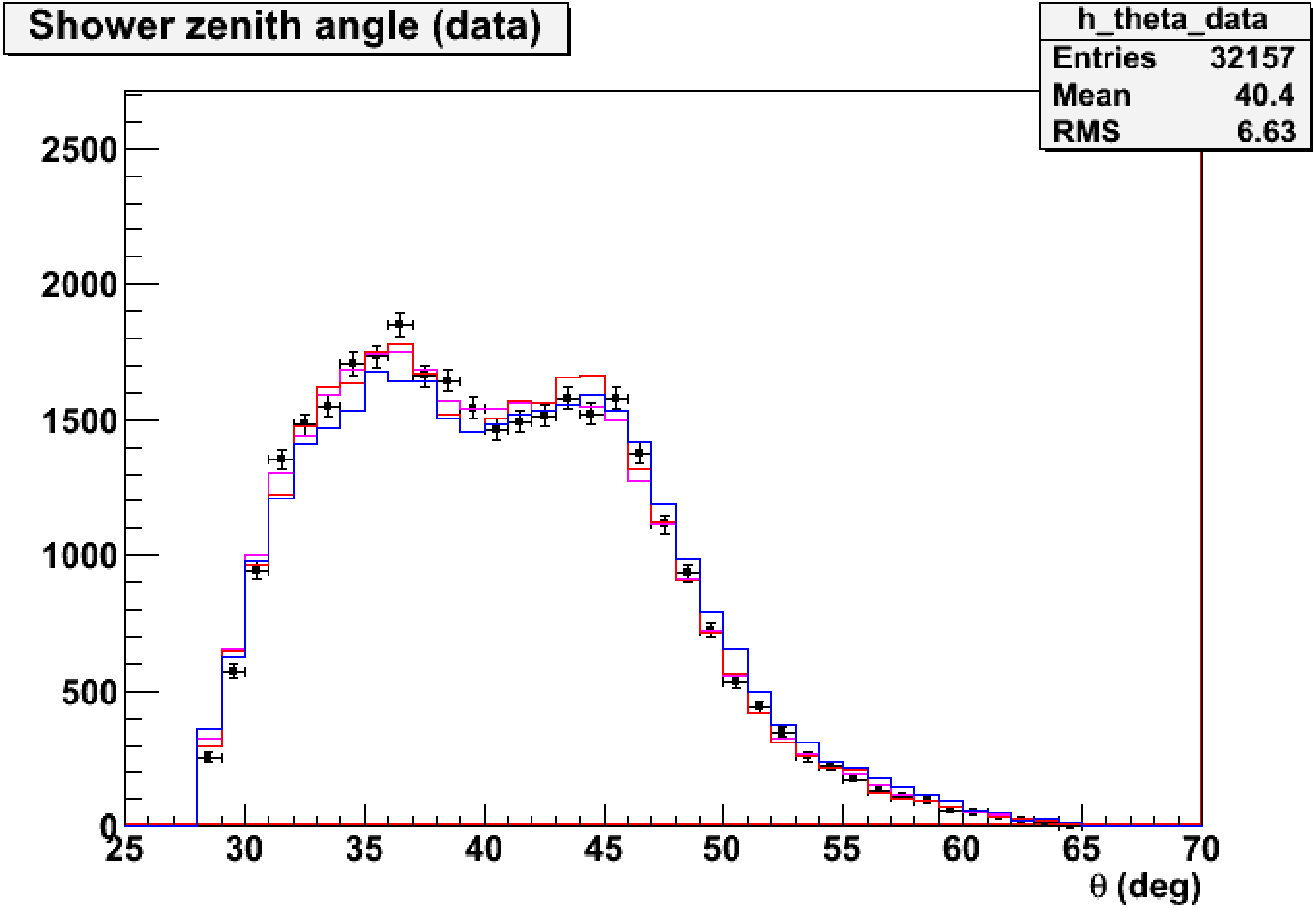

npe per good-tube (data)
h_pepgt_data
Entries 32157
Mean 148.1
RMS 43.03
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
50
100
150
200
250
pe / gtube

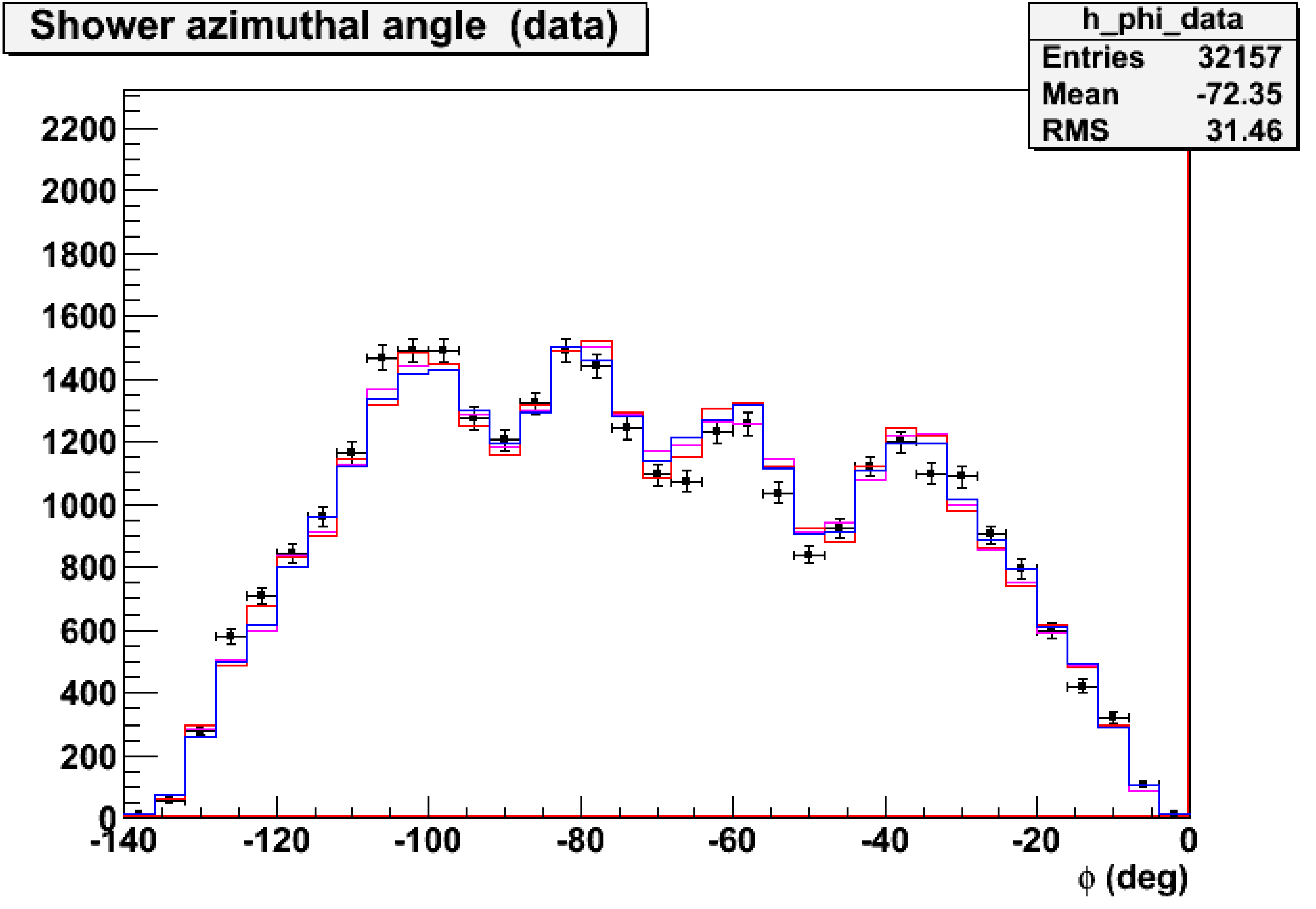

plog (Rayleigh prob) (data)
h_plog_data
Entries 32157
Mean 3.595
RMS 2.592
0
500
1000
1500
2000
2500
3000
3500
4000
4500
0
2
4
6
8
10
12
14
16
18
20
plog



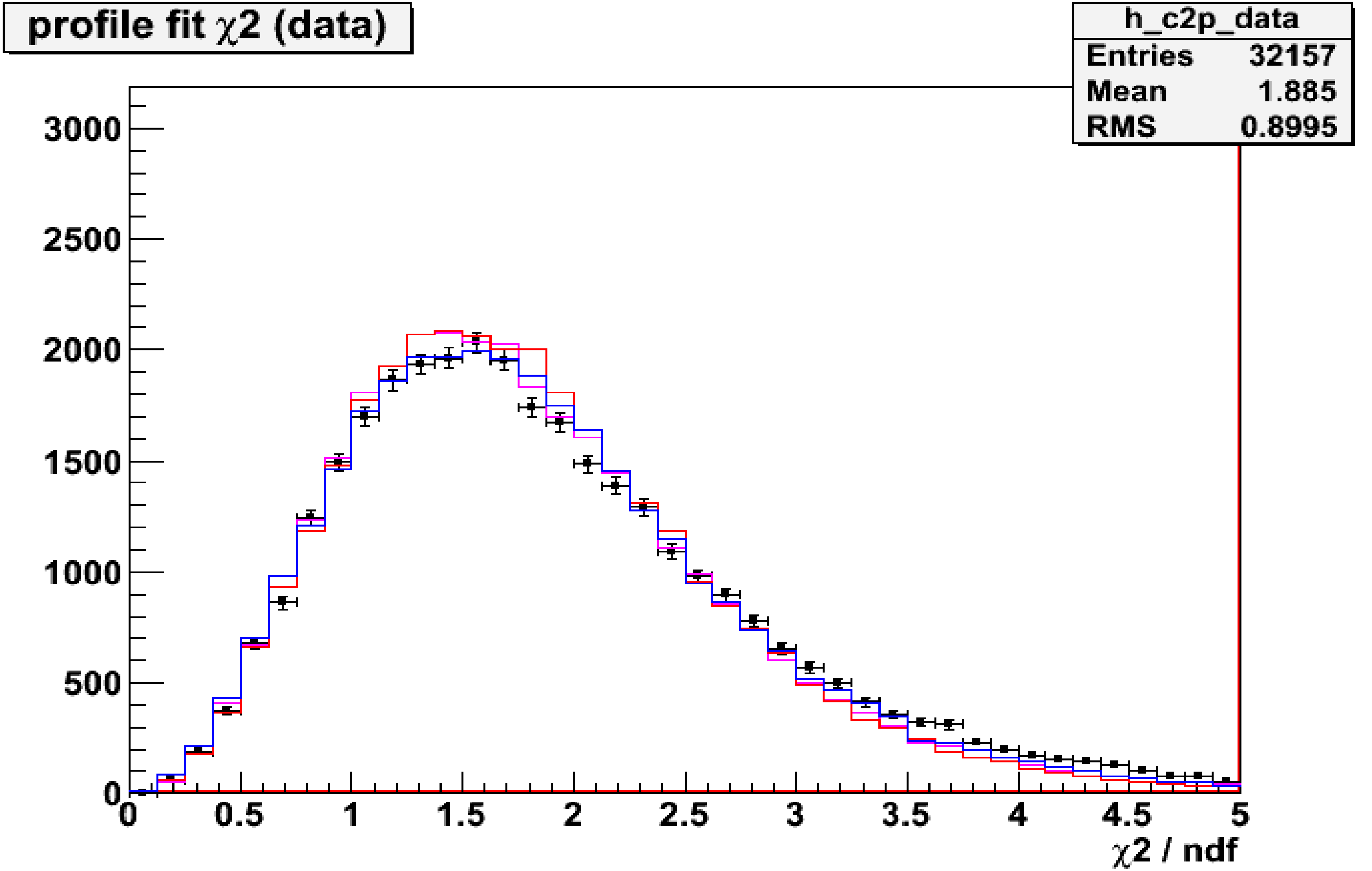
Impact parameter: R
p
(km) (data)
h_rp_data
Entries 32157
Mean 0.8533
RMS 0.356
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0.5
1
1.5
2
2.5
3
R
p
(km)


(data)
h_psi_data
Entries 32157
Mean 96.87
RMS 28.6
4500
4000
3500
3000
2500
2000
1500
1000
500
0
40
60
80
100
120
140
ψ (deg)

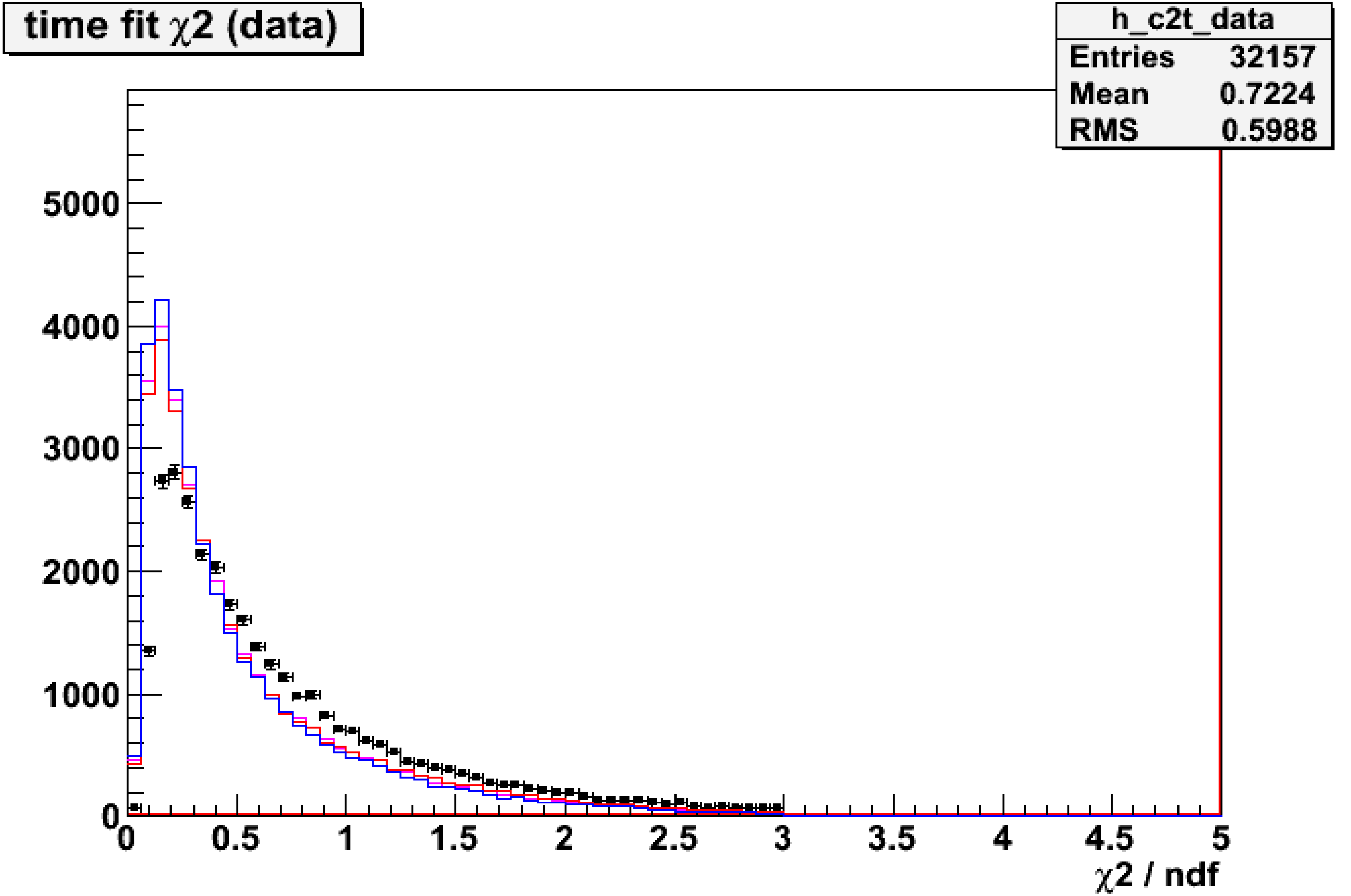

Shower zenith angle (data)
h_theta_data
Entries 32157
Mean 40.4
RMS 6.63
0
500
1000
1500
2000
2500
25
30
35
40
45
50
55
60
65
70
θ (deg)



Shower azimuthal angle (data)
h_phi_data
Entries 32157
Mean -72.35
RMS 31.46
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
-140
-120
-100
-80
-60
-40
-20
0
φ (deg)



- MC scaled up by 1.6



- MC scaled up by 1.6