The Cosmic Ray Energy Spectrum between 2 PeV and 2EeV Observed with the TALE Detector in Monocular Mode.

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Currently visiting Jerusalem
for the TA Collab.
Presented by
Charlie Jui

Oct 9, UHECR 2018
Paris, France

Tareq's son Ziad from Jerusalem, Oct 8

Telescope Array collaboration

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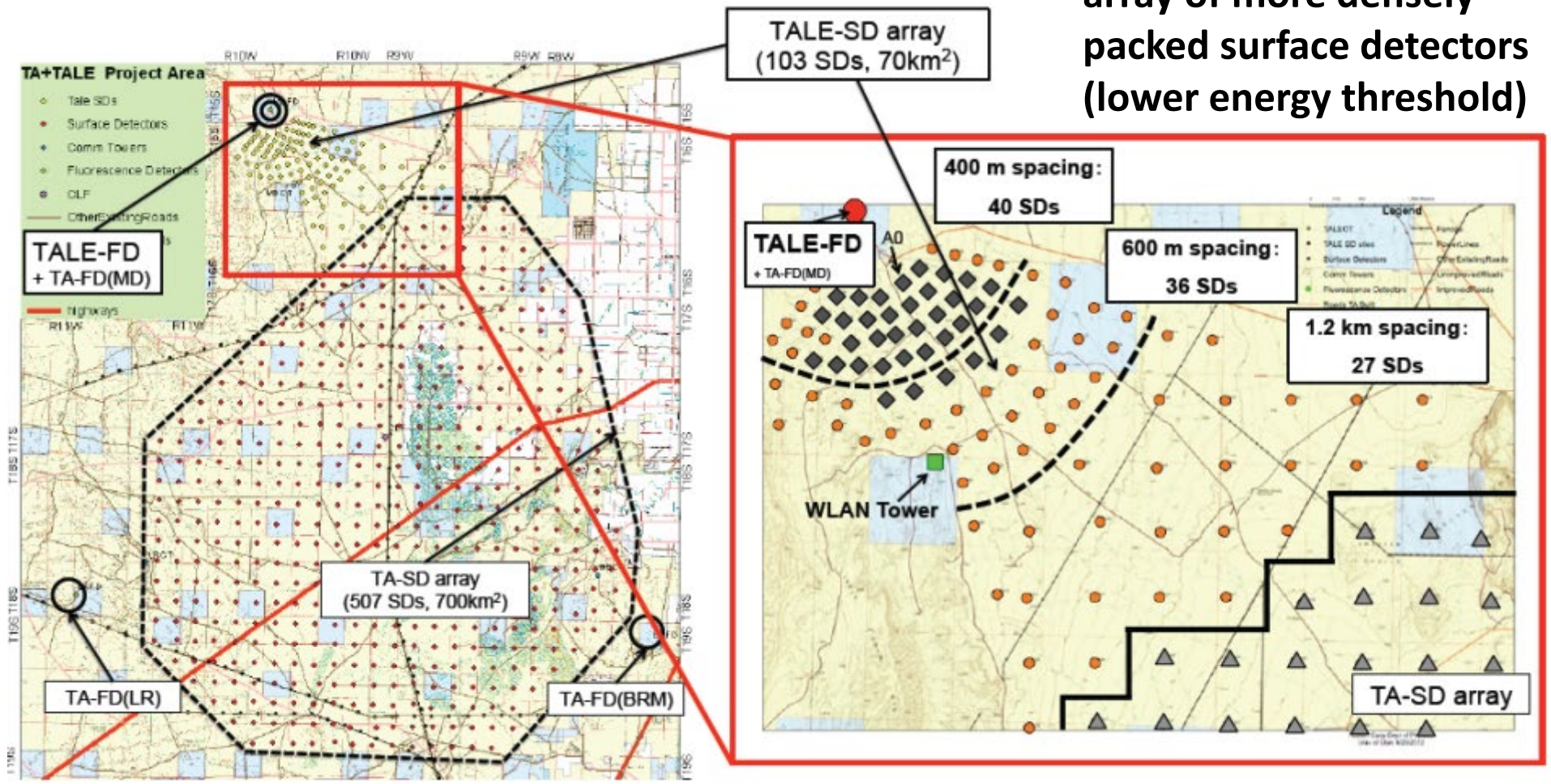
TA Low Energy Extension (TALE)

10 new telescopes to look higher in the sky (31-59^o) to see shower development to much lower energies

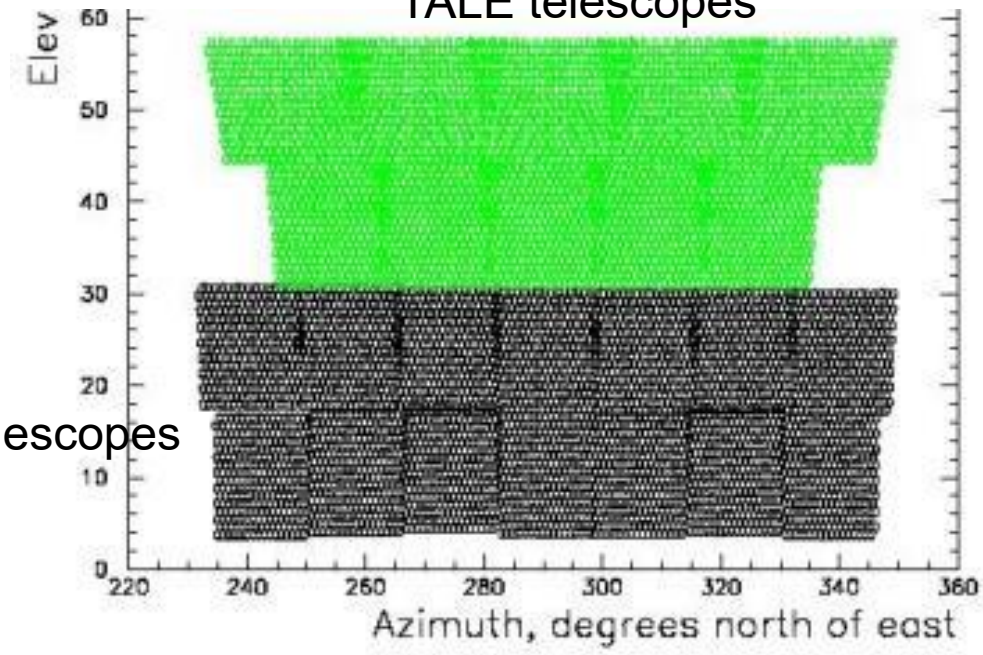
Infill surface detector array of more densely packed surface detectors (lower energy threshold)



- All 10 TALE FD telescopes installed in 2013.
  - Shake-down 2013-2014
  - **Stable operation since fall 2014**
- **103 TALE SD counters deployed as of fall 2017**

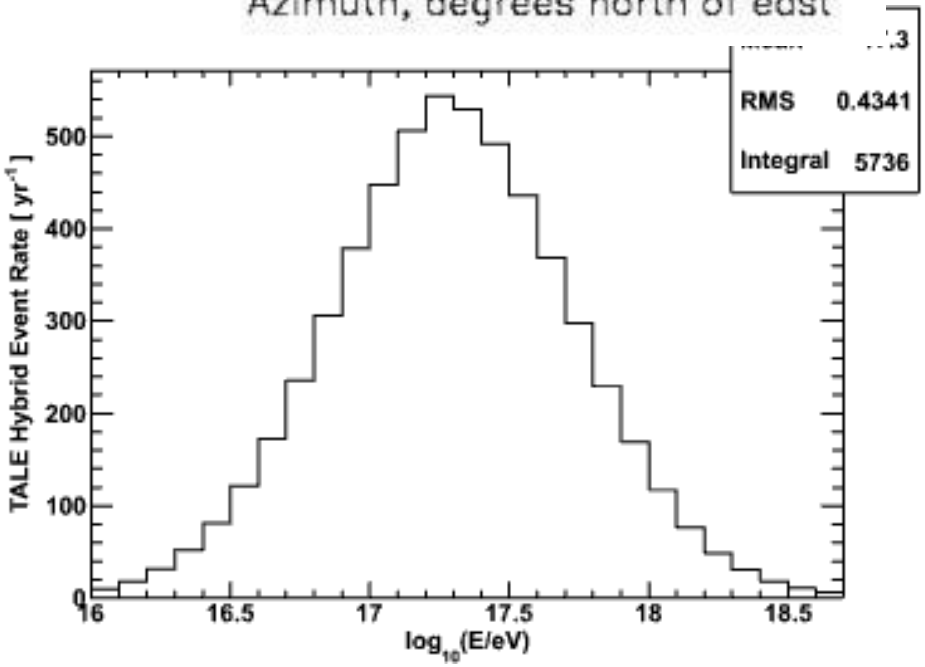
TALE Fluorescence Detector

TALE telescopes



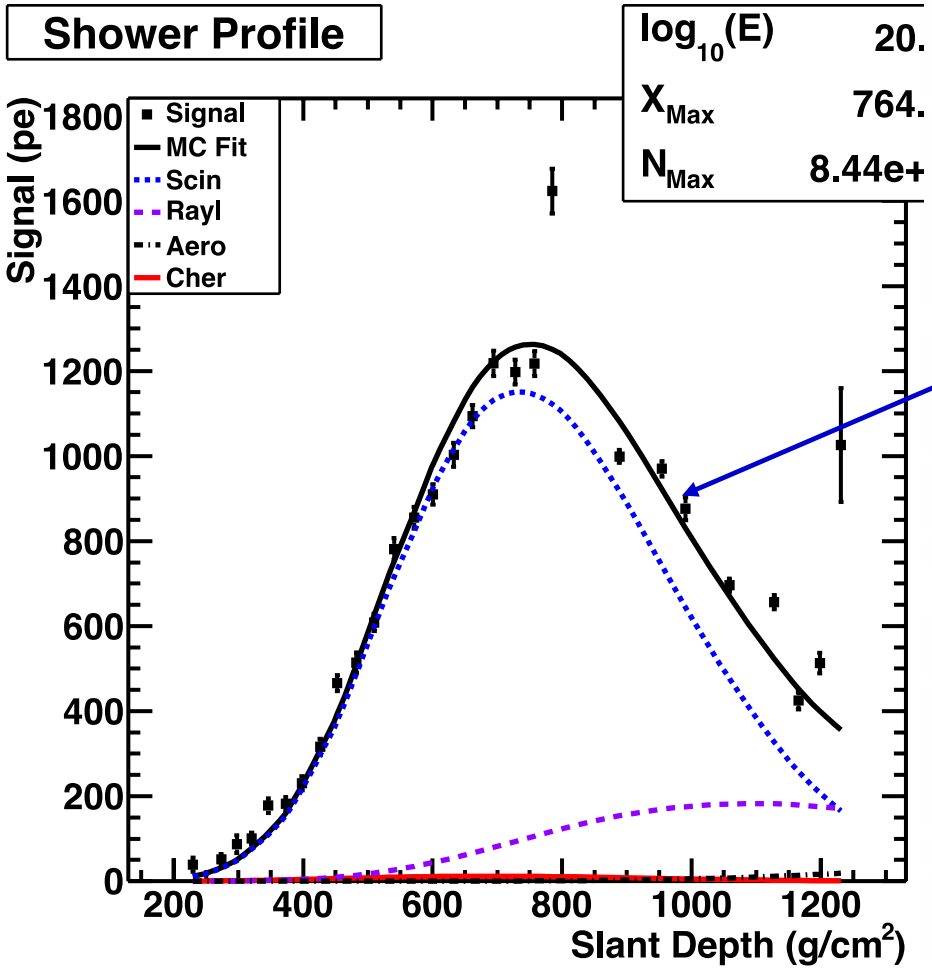
TA MD telescopes

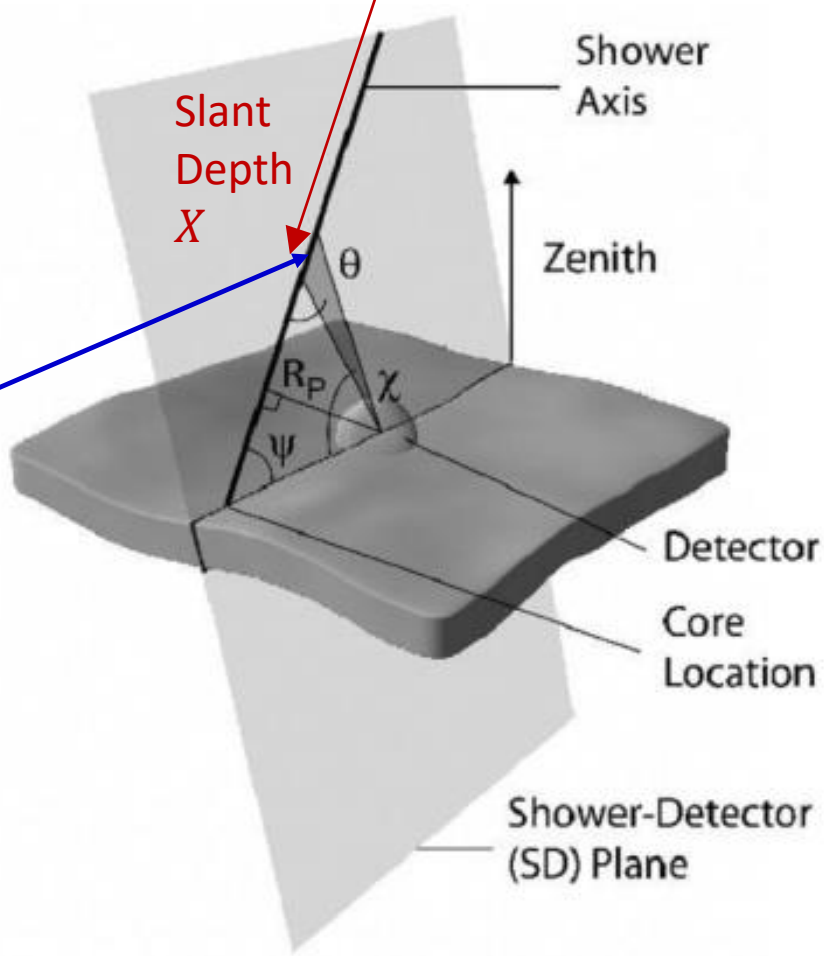
- 10 high-elevation telescopes at the Middle Drum site, looking from 31°-59° in elevation.
- Originally designed for monocular and hybrid observations down to ~$10^{16.5}$eV.



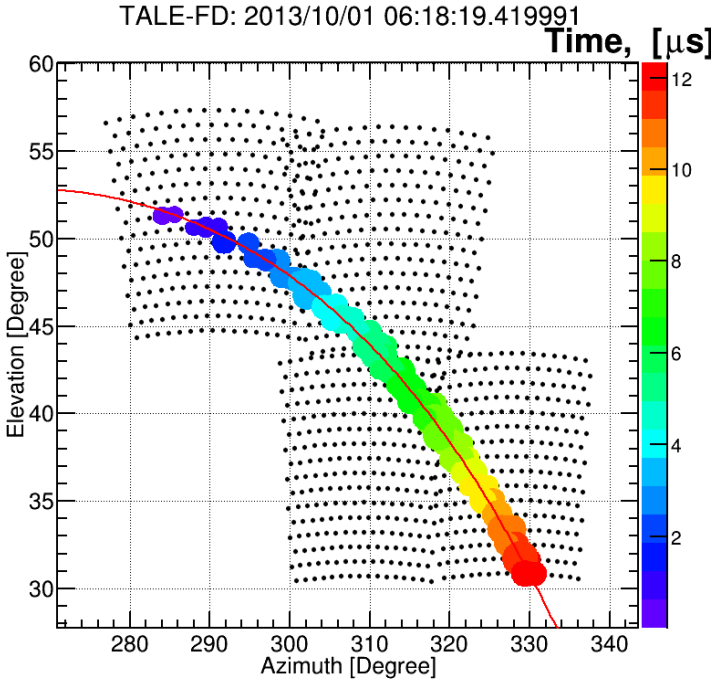
Expected TALE hybrid events per year

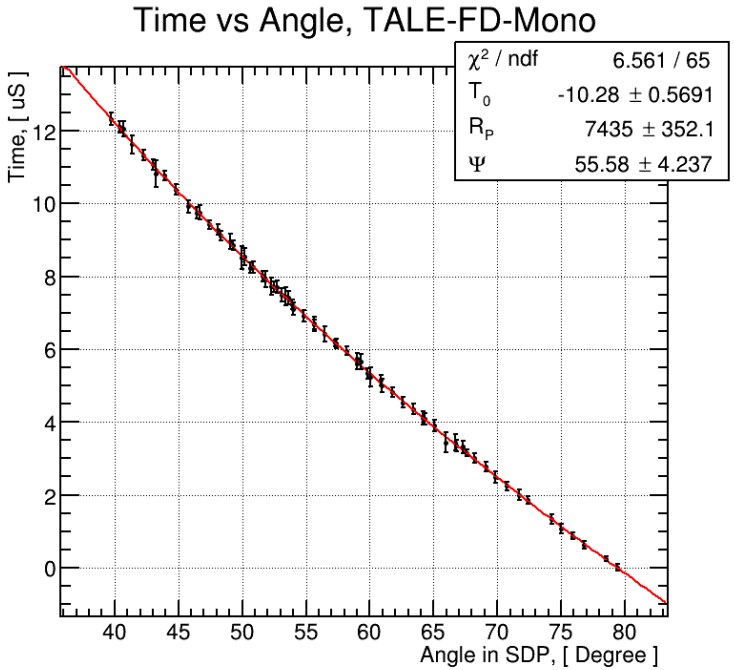
Combined Tim-Profile Fit





TALE FD Event

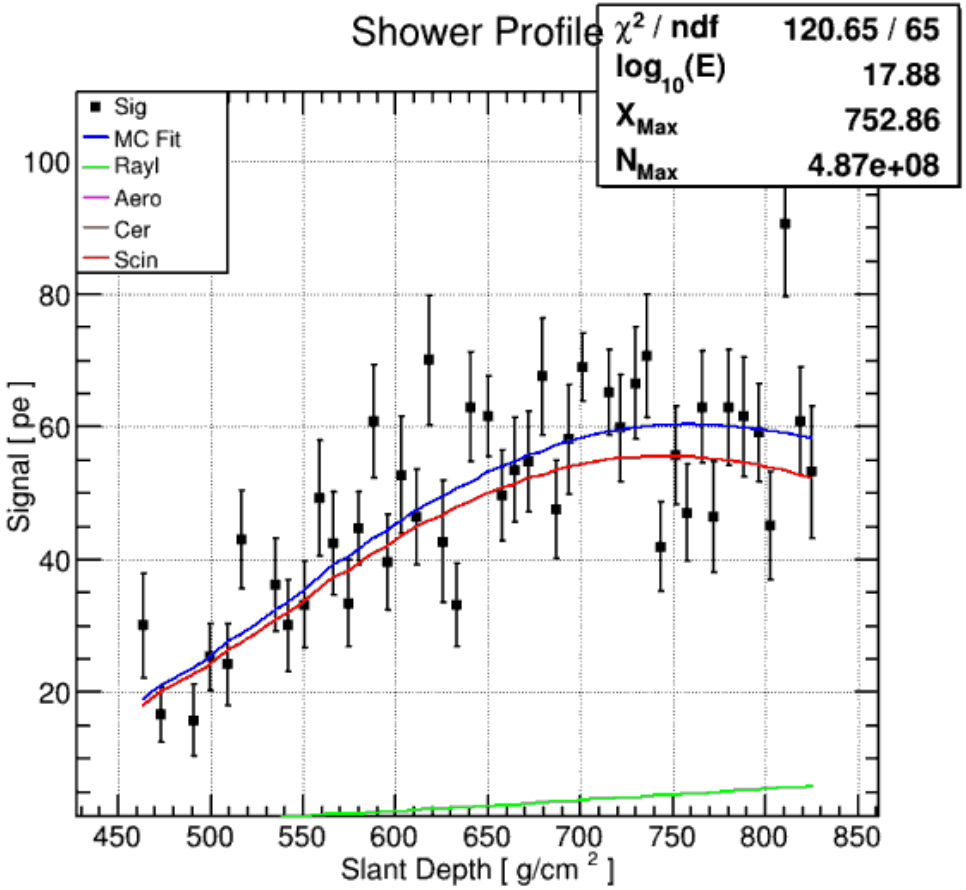




For TALE FD reconstruction: we combined the time and profile fit: simultaneous

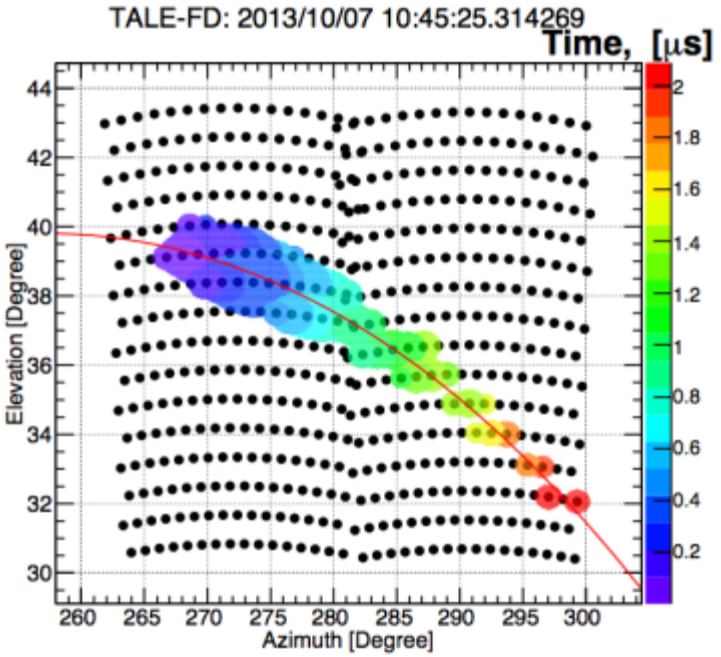
Profile Constrained Geometry Fit (PCFG)

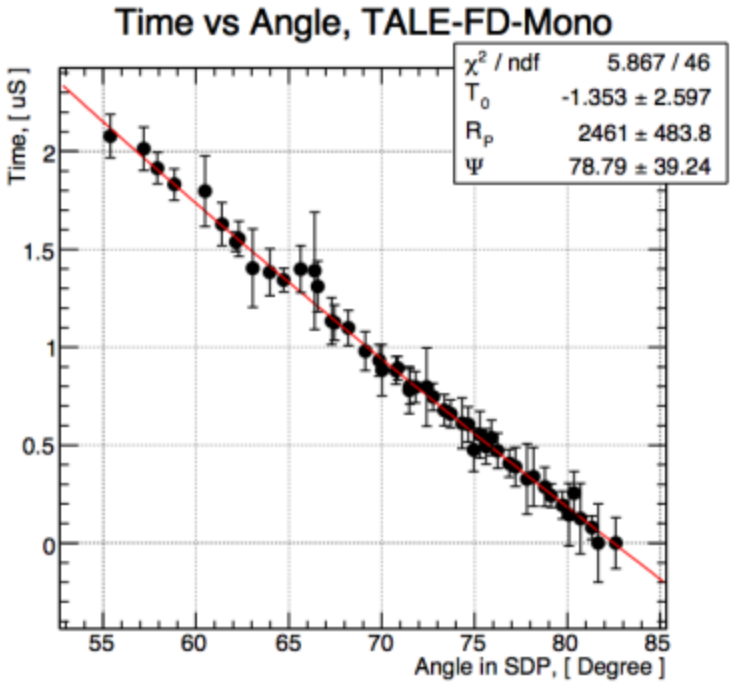
originally developed for HiRes monocular analysis

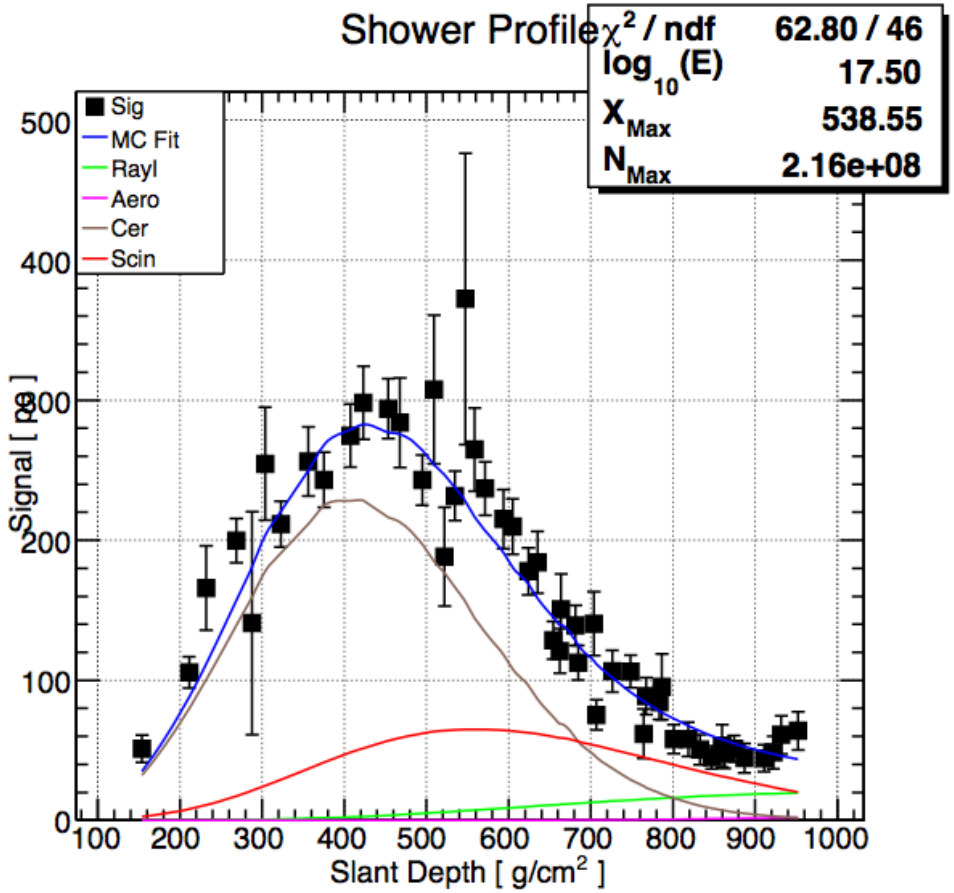


TALE Cherenkov Event

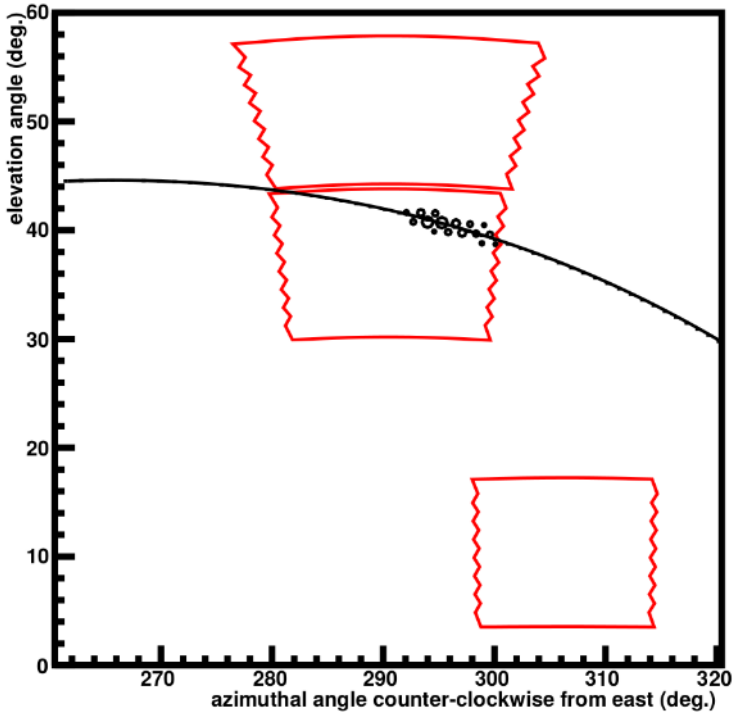
PCGF turns out to work very well on **Cherenkov light dominated events**



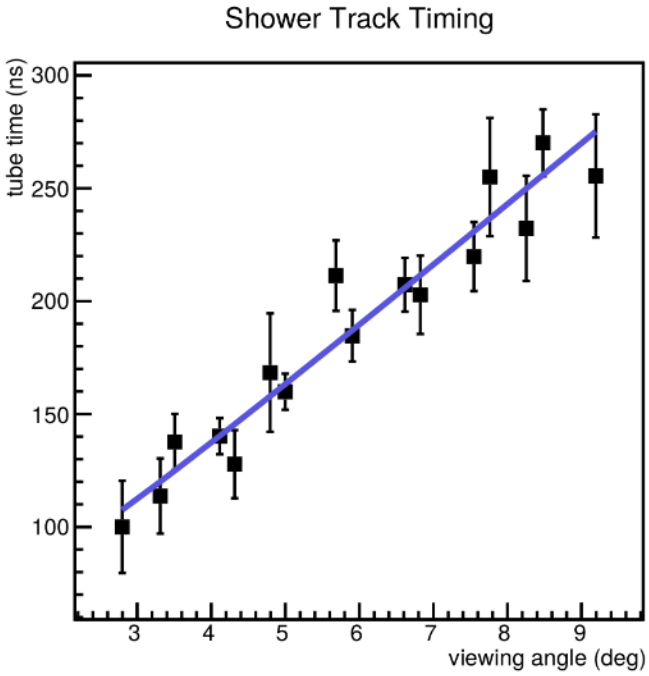




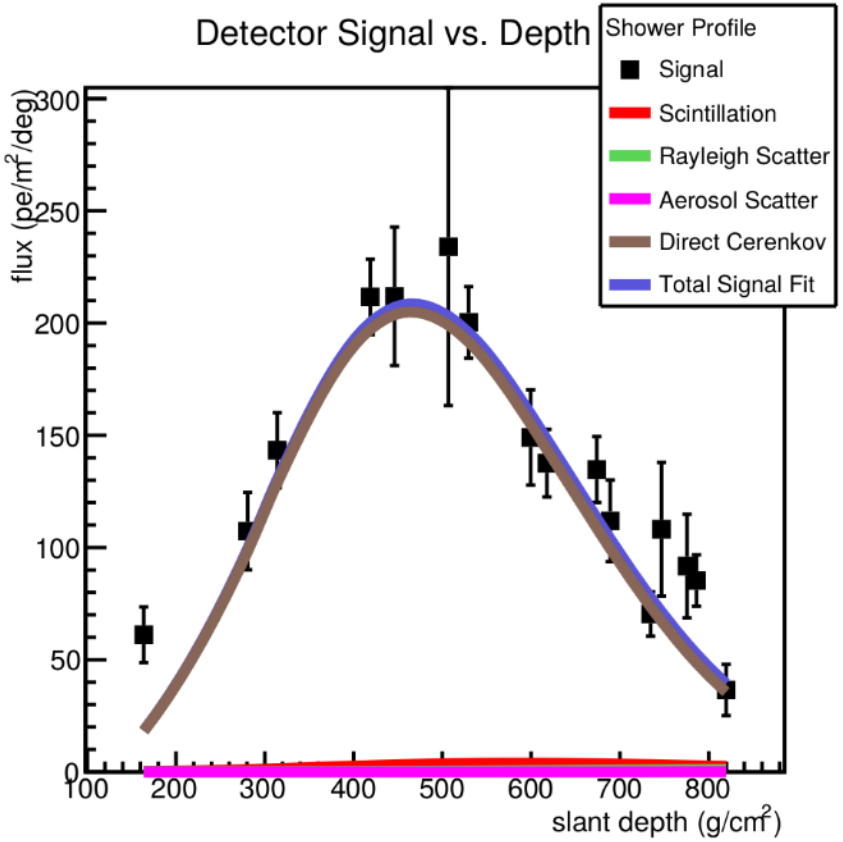
TALE Cherenkov Event



Cherenkov light dominated events allowed TALE to reach more than another **decade lower in energy than designed: Down to $10^{15.3}$ eV**



$10^{15.6}$ eV Event



Events

Between June 2014 and March 2016 TALE collected

220 173 events between $10^{15.5}$ and $10^{16.0}$ eV

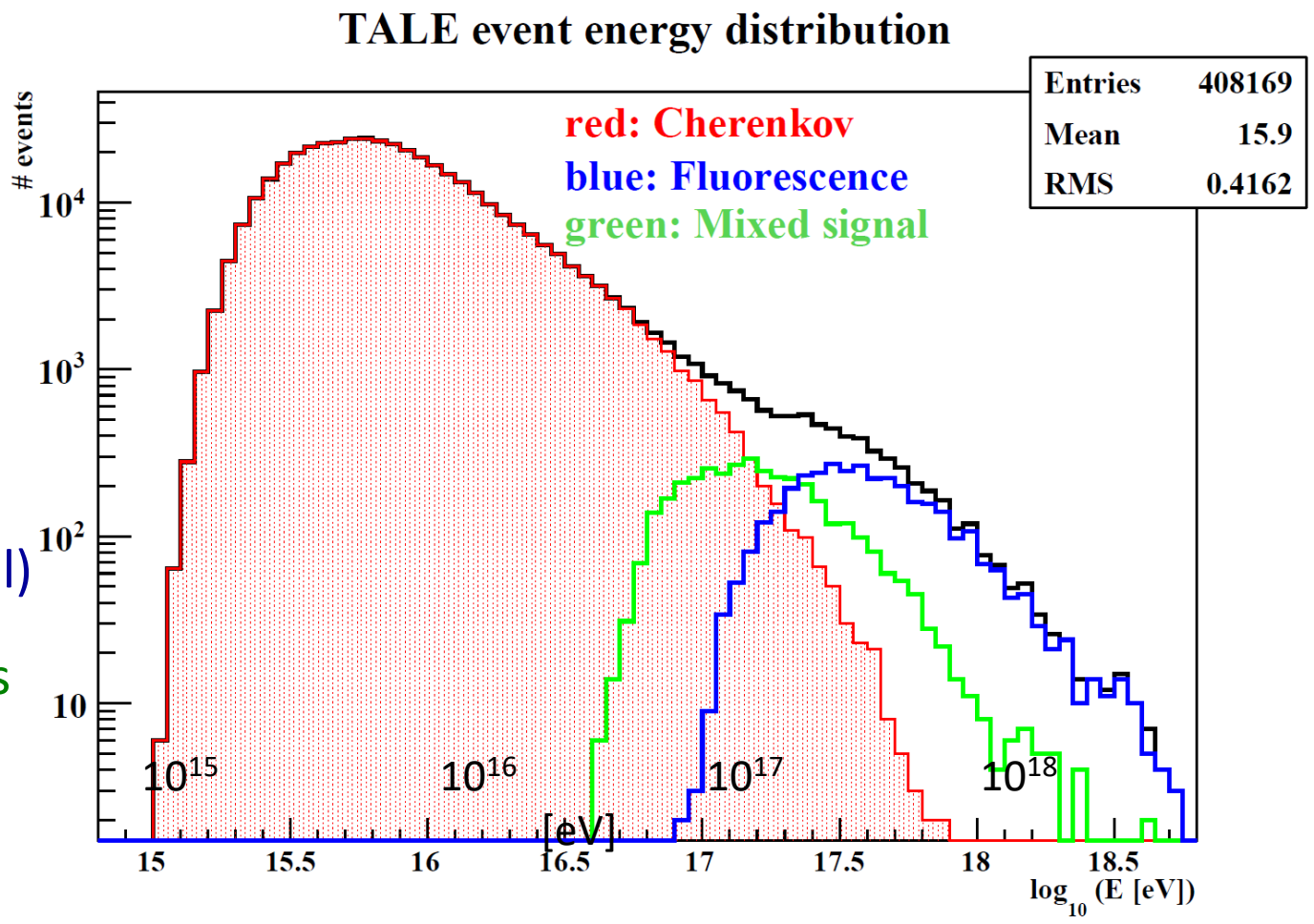
98 677 events between $10^{16.0}$ and $10^{16.5}$ eV

23 285 events between $10^{16.5}$ and $10^{17.0}$ eV

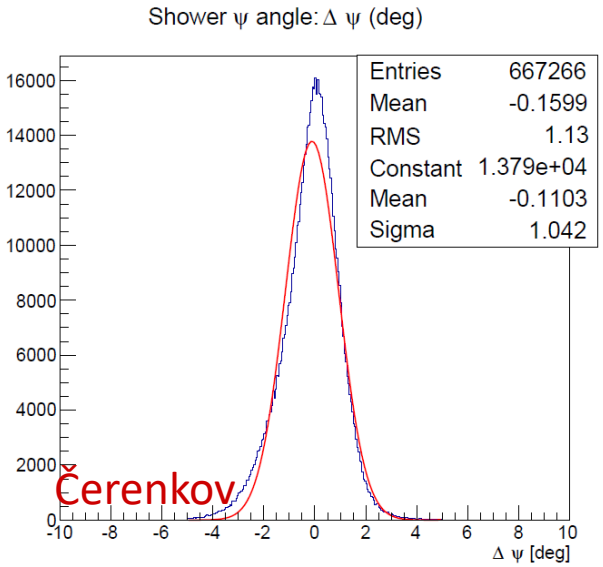
Cherenkov dominated events (C'kov > 75% of total)

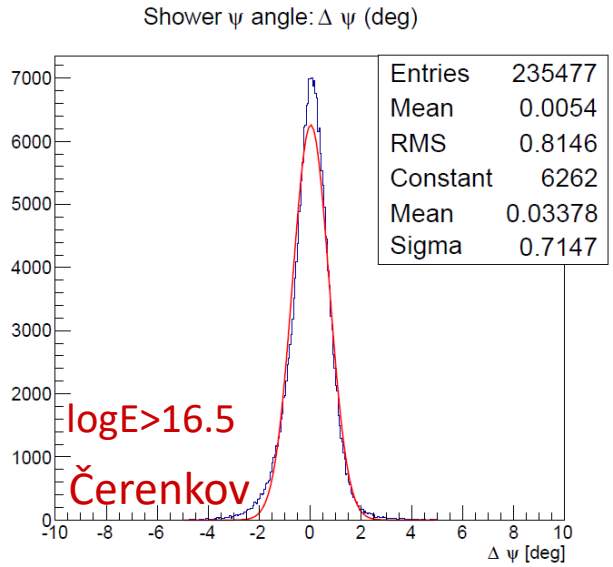
Fluorescence dominated events (Scin. > 75% of total)

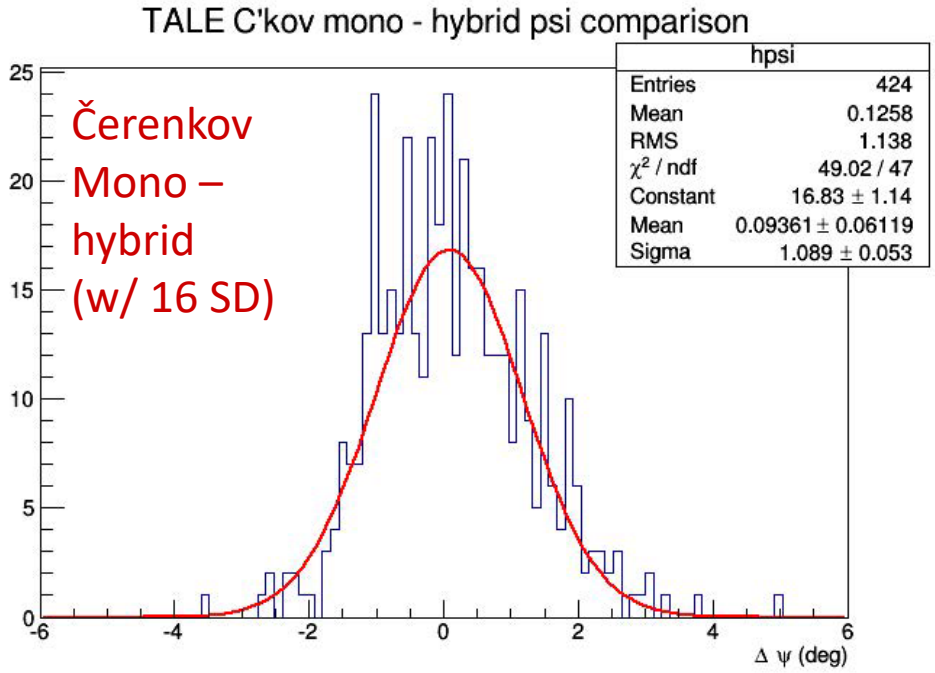
Mixed signal events



Verification of monocular Ψ resolution

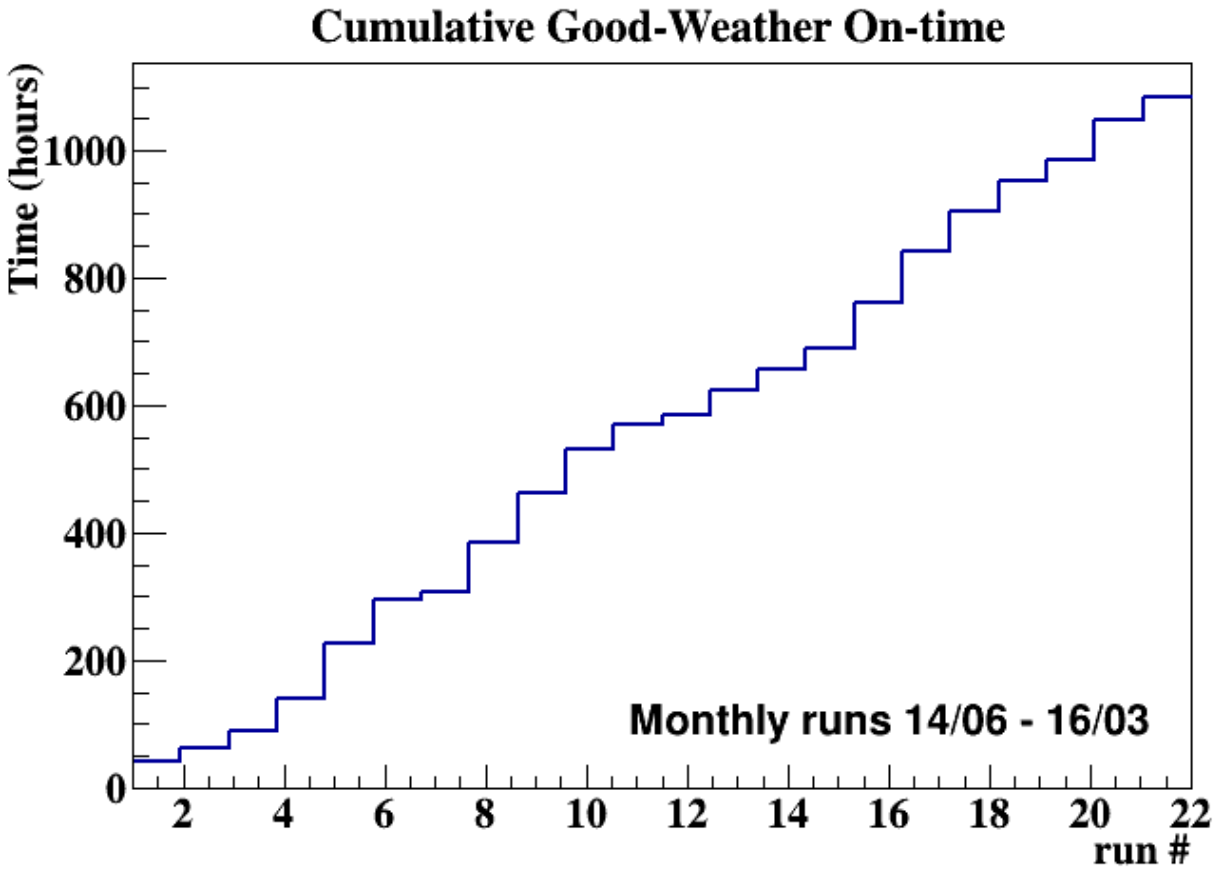




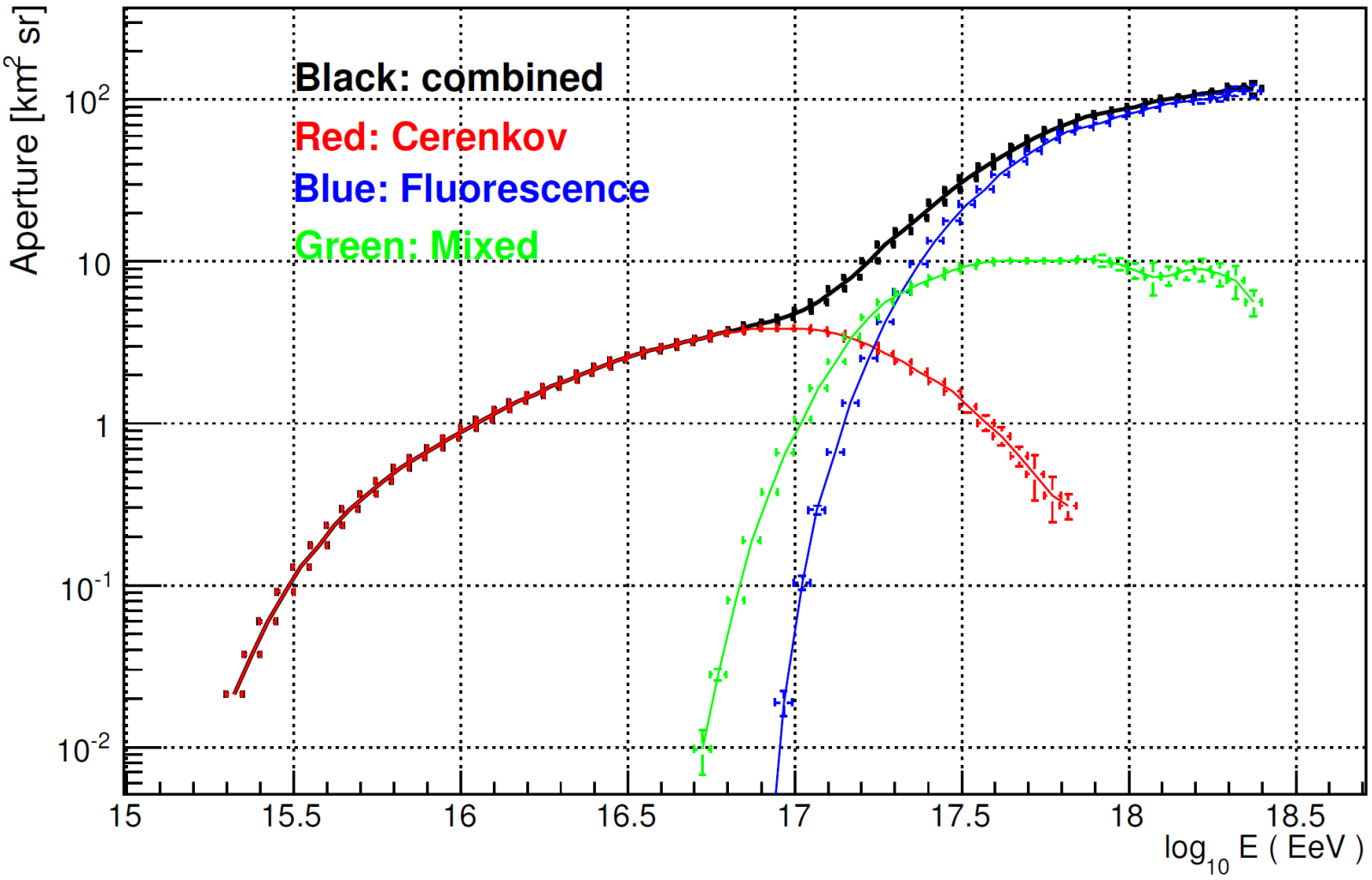


Exposure

- TALE FD data collected from 06/20/2014 to 03/31/2016 (***22 months***).
- Only **good weather** data:
- **Total on-time 1080.0 hours.**

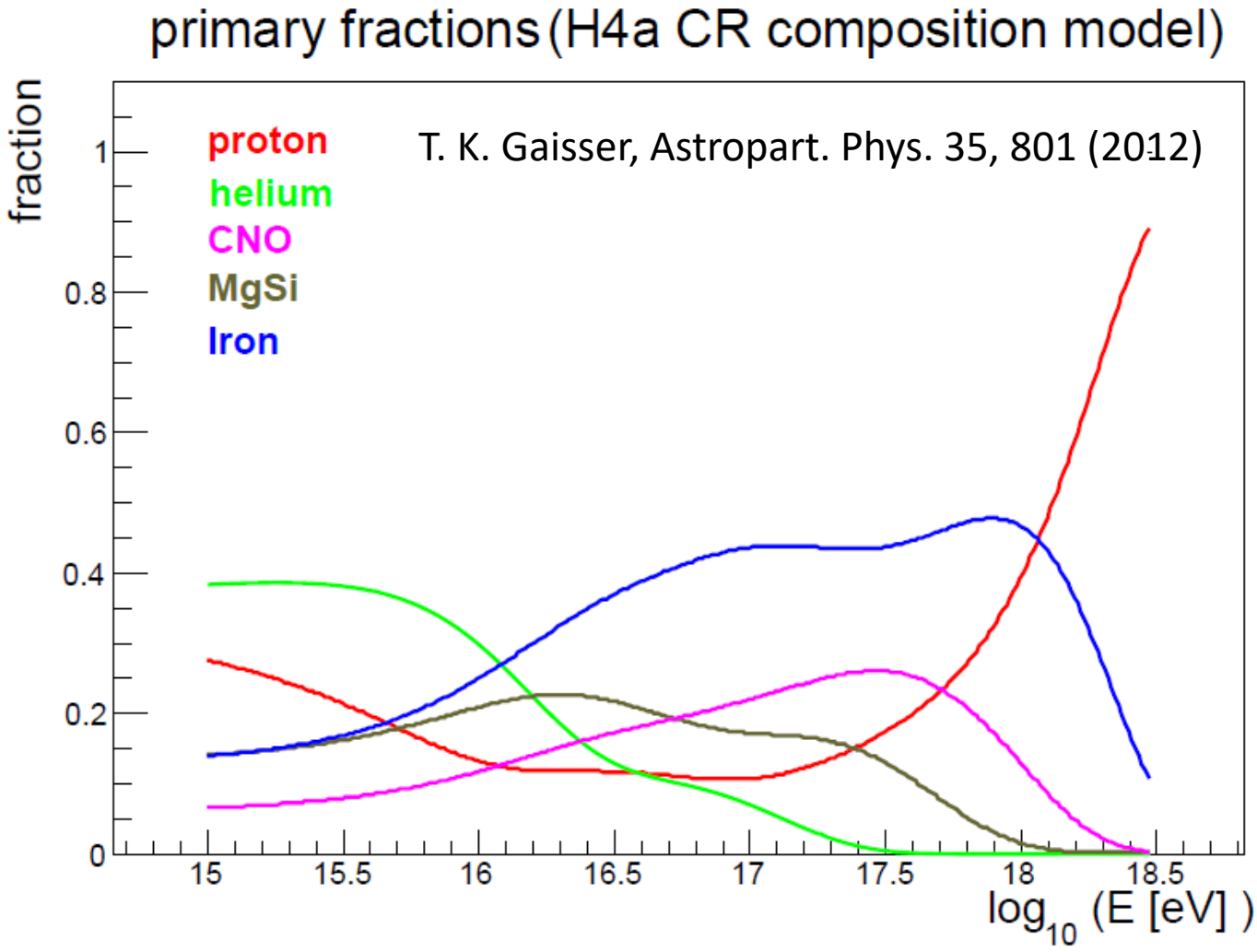


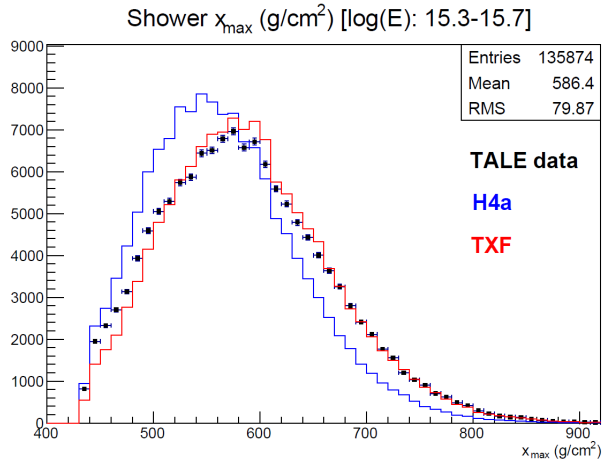
Aperture

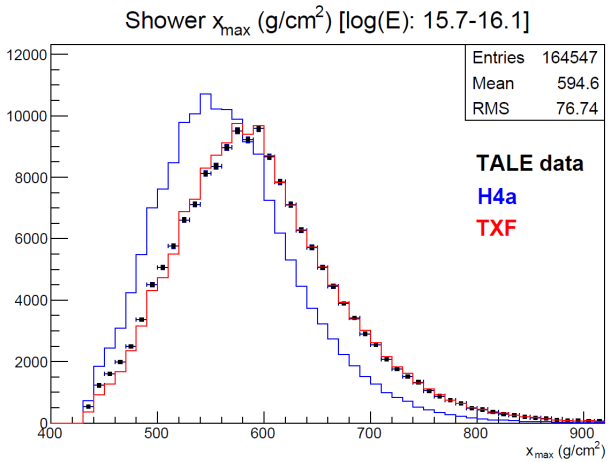

Black: combined
Red: Cerenkov
Blue: Fluorescence
Green: Mixed
Aperture [km² sr]
10²
10
1
10⁻¹
10⁻²
15
15.5
16
16.5
17
17.5
18
18.5
log₁₀ E (EeV)

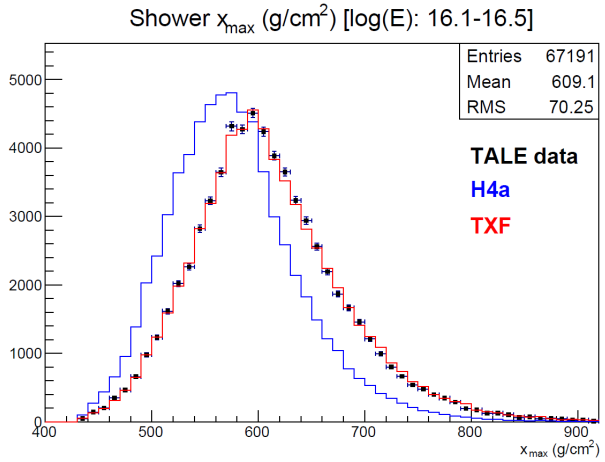
Composition?

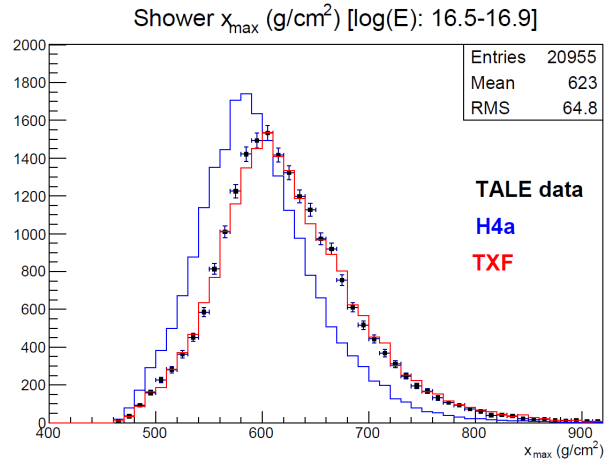
Initial Assumption

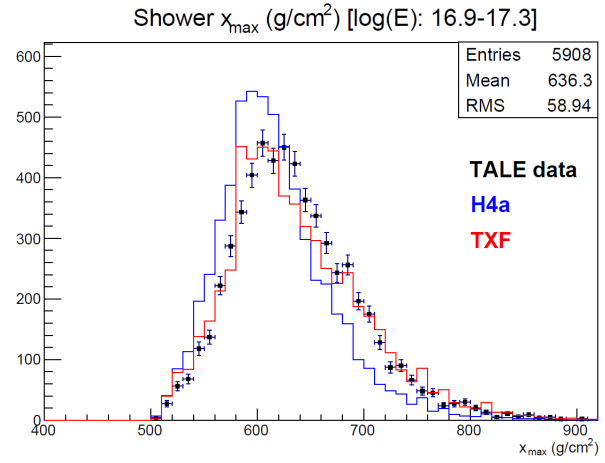


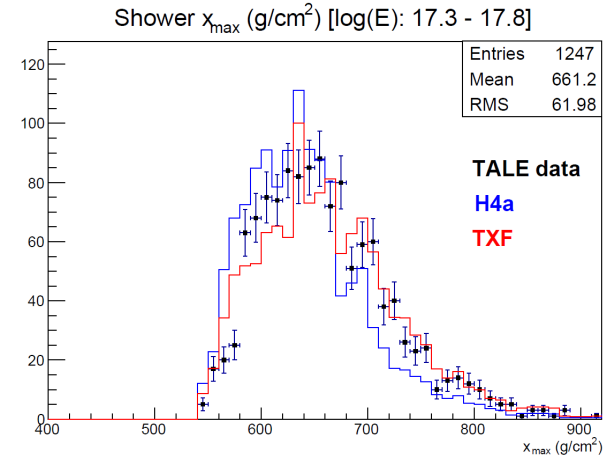










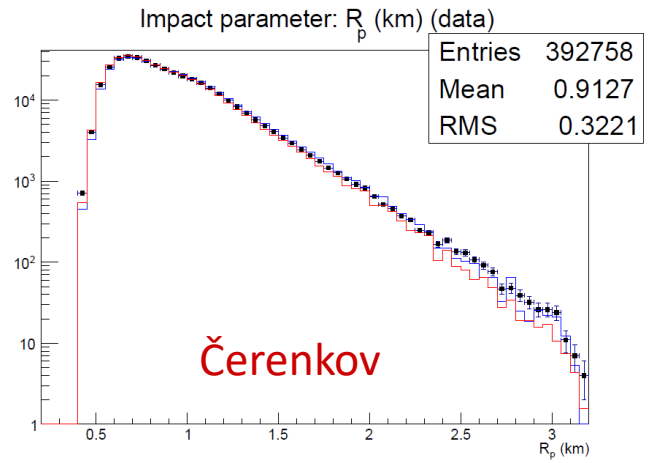


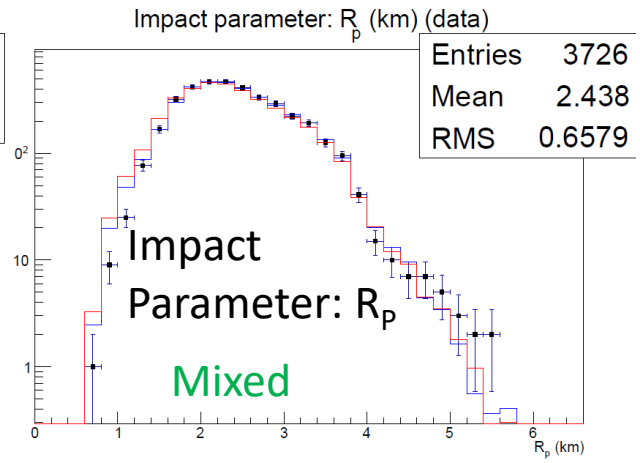
Xmax MC/Data Comparison

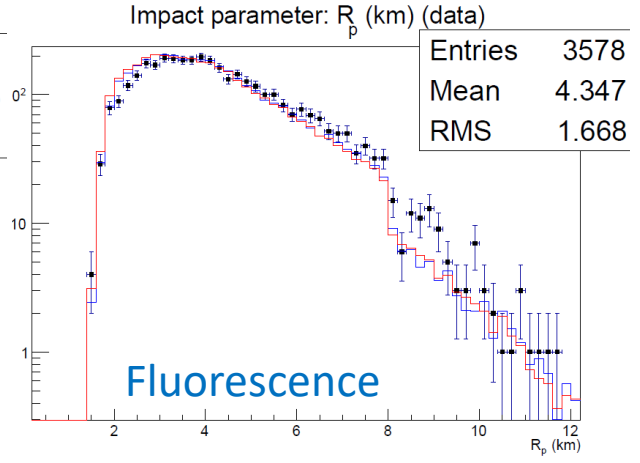
Originally assumed **H4A** Composition (interpreted using QGS_jet II.3) gives an Xmax distribution appeared to be too high in the sky.

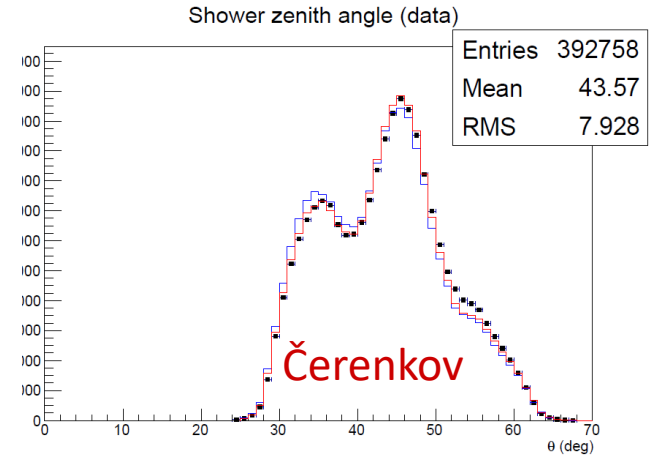
Adjusted Xmax dist. (a 4-component fit to QGS-Jet II.3) to better match TALE FD data: call this Tale Xmax Fit (**TXF**)

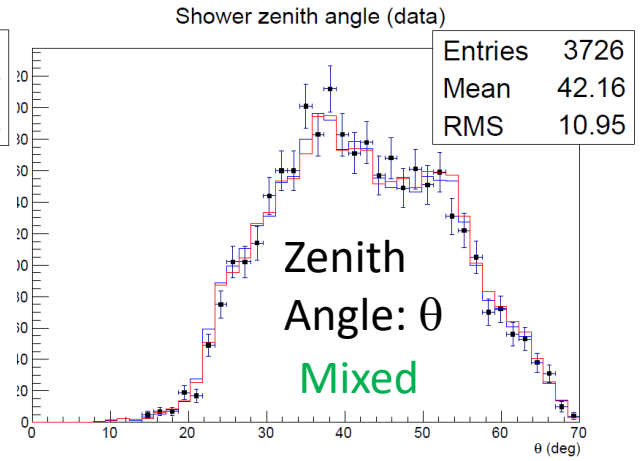
MC/Data Comparison

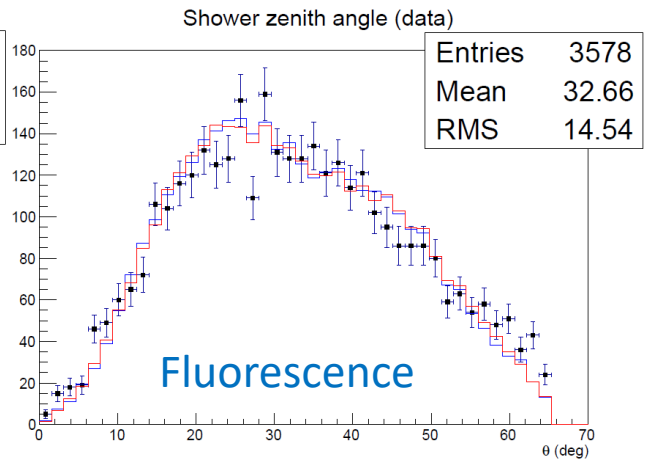








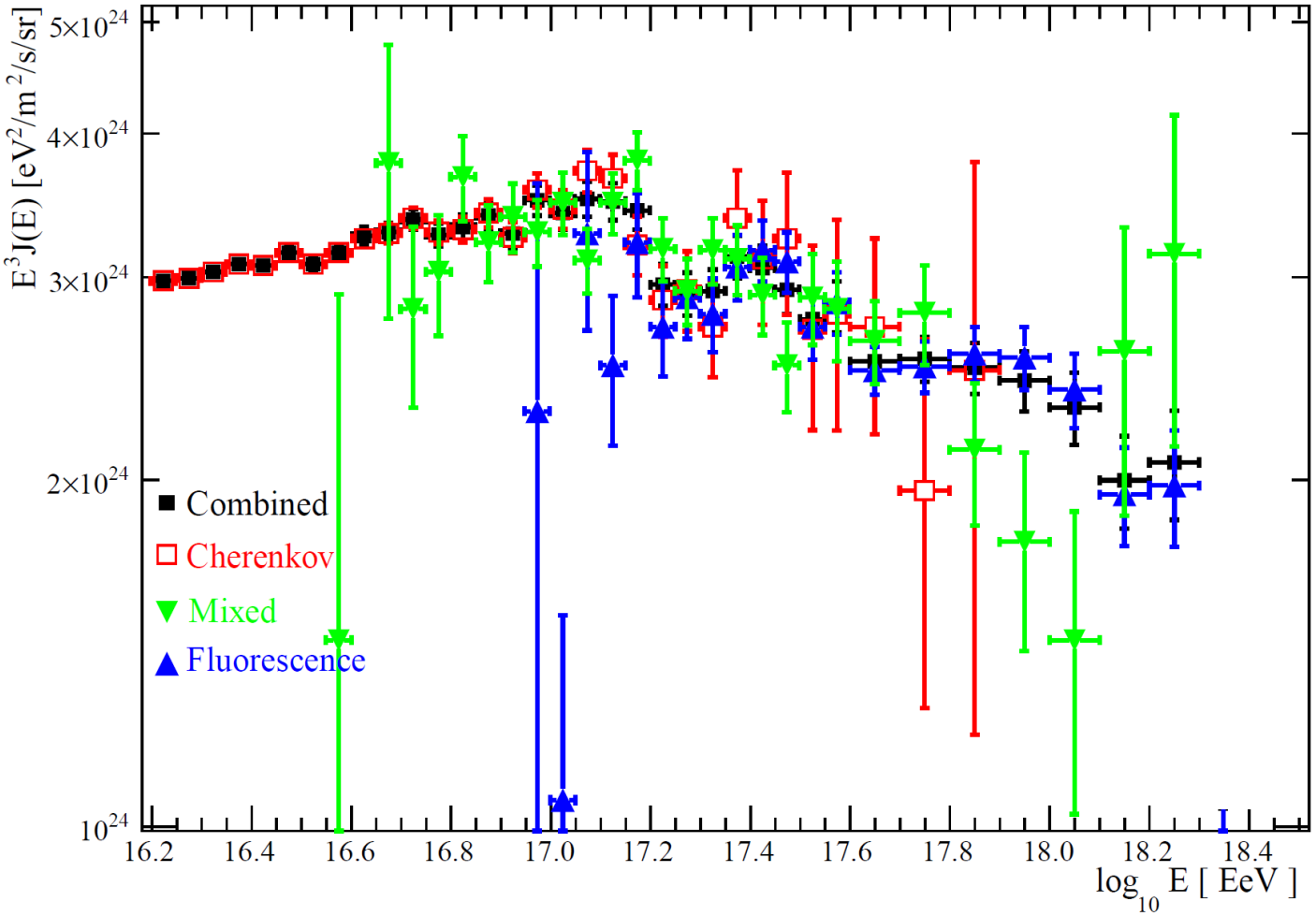




H4A **TXF**

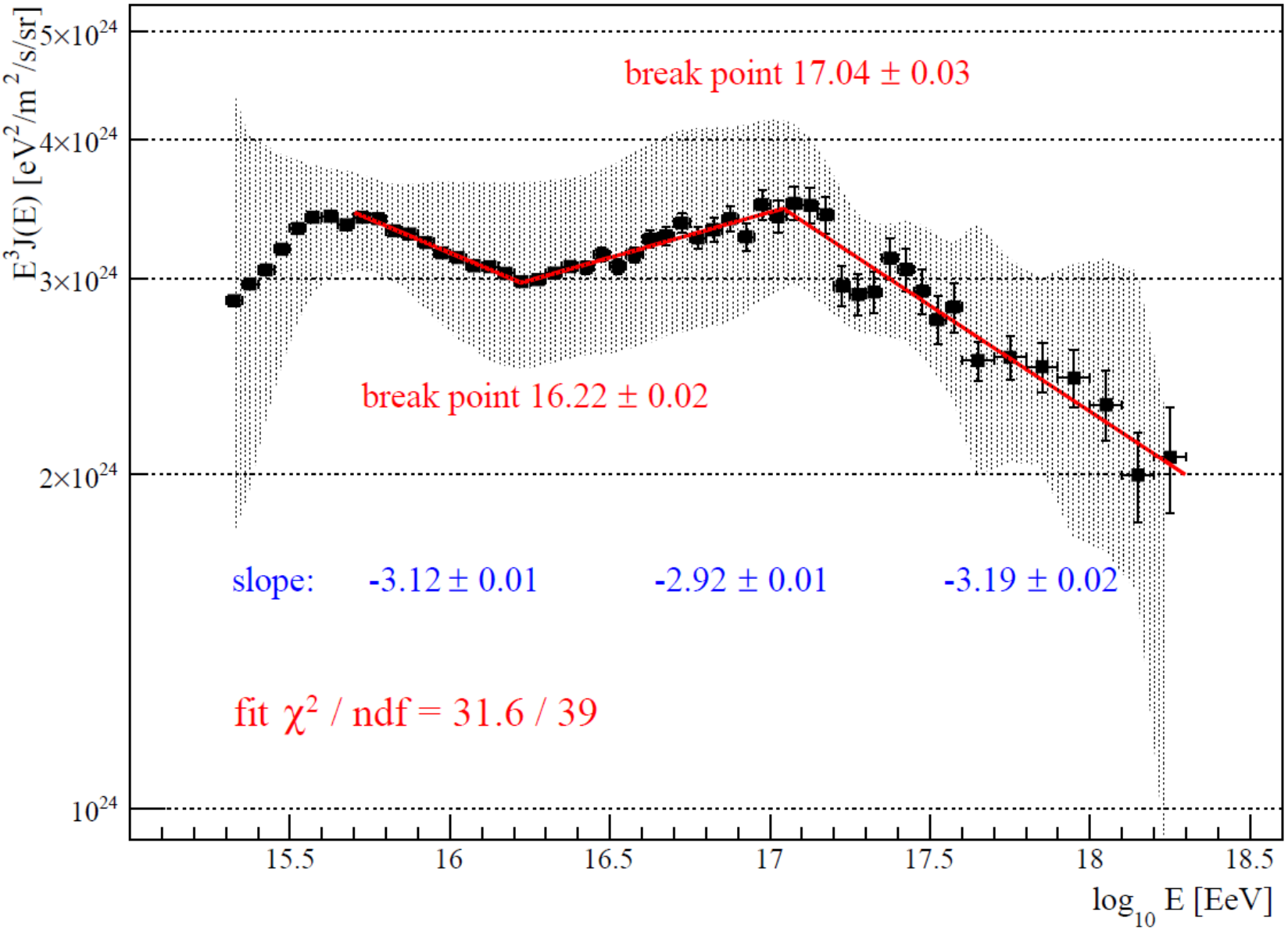
Validation of Aperture Calculation

Consistency

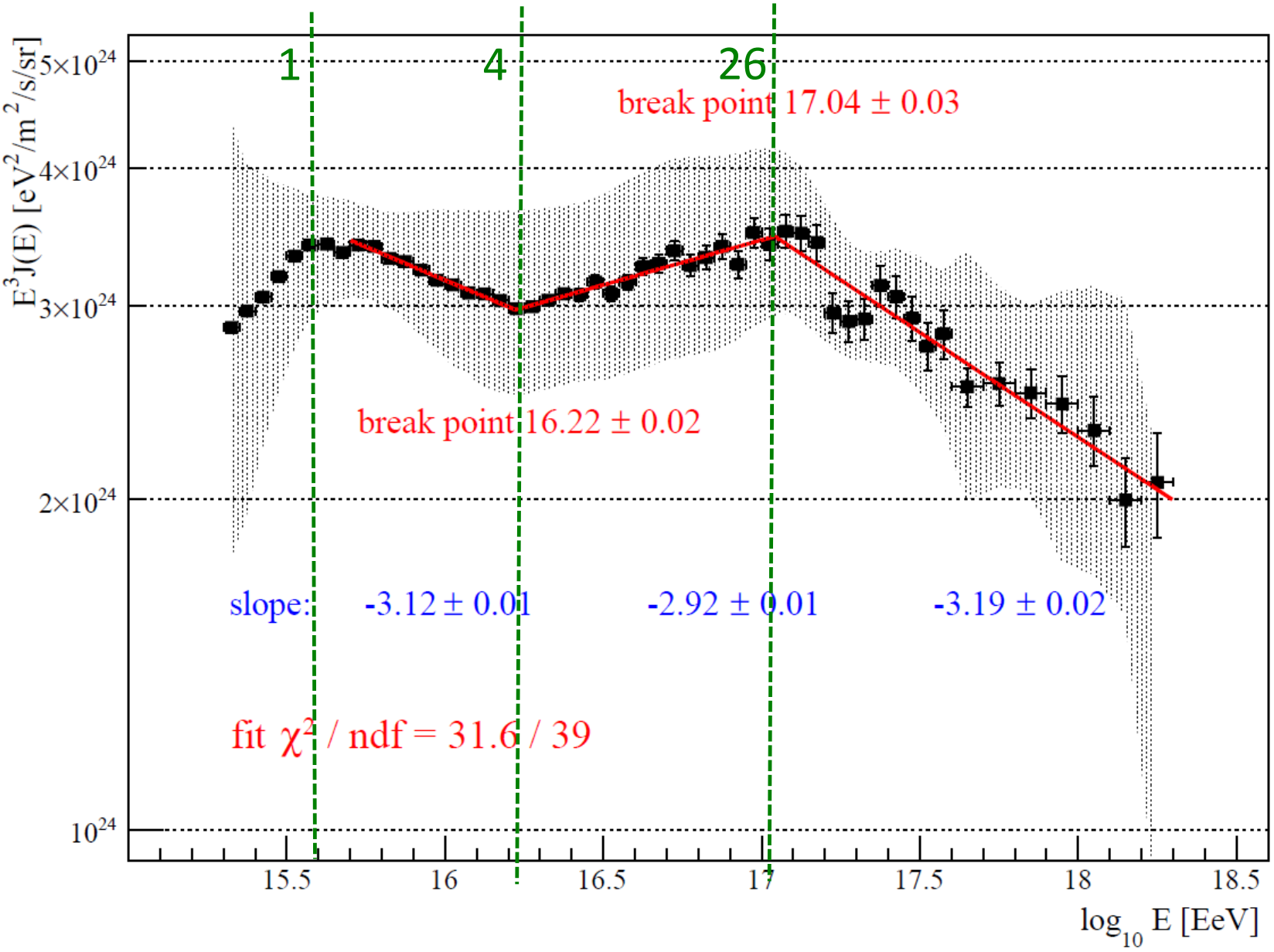


Spectra obtained from the three classifications of events appear to be consistent

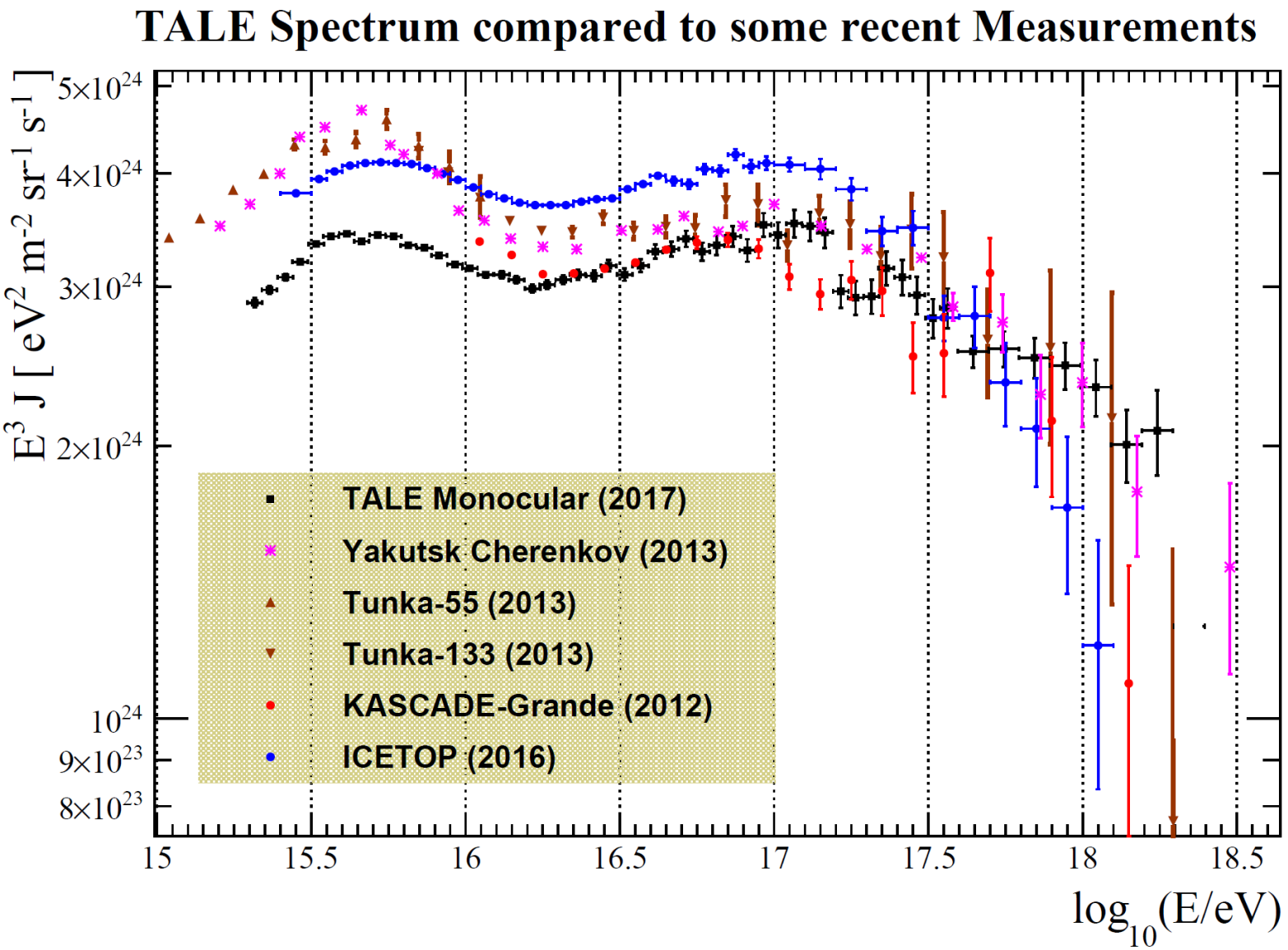
TALE Spectrum



TALE Spectrum



Comparison to other experiments



Summary

- We have measured the cosmic ray energy spectrum in the range $10^{15.3}$-$10^{18.3}$ eV
  - Published 2018 September 24. The Astrophysical Journal, Volume 865, Number 1
  - Three spectral features are seen: Knee, “dip”, “second knee” at energies at $10.^{15.6}$eVm $10^{16.22}$eV and $10^{17.04}$eV
  - The energies of the three features are approximately in the ratio of 1:4:26 (??? proton: beryllium: iron ???)
- Composition results in the near future
- TALE surface detector now operational
  - FD to SD trigger now running

End

Reserve Slides

Systematic Errors

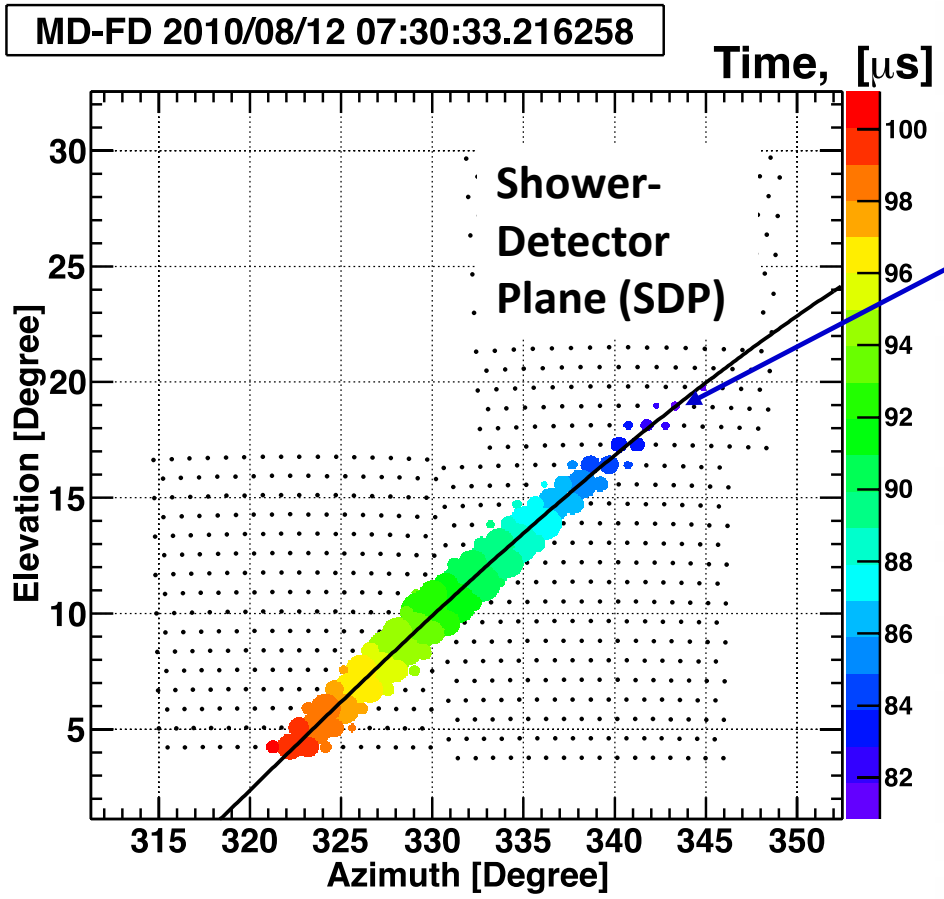
Table 5. Estimates of systematic uncertainties in the TALE FD energy scale and spectrum measurement. This uncertainty is approximately constant as a function of energy *[Explanation of change: Added entry: Cherenkov model]*

Energy	Source	value	contribution to spectrum
$< 10^{17}$ eV	photonic scale	10%	20%
$< 10^{17}$ eV	missing energy	10%	20%
$< 10^{17}$ eV	atmosphere	0	0
$< 10^{17}$ eV	Cherenkov model	5%	10%
$< 10^{17}$ eV	fluorescence yield	0	0
$< 10^{17}$ eV	composition (X_{max})	3%	6%
10^{18} eV	photonic scale	10%	20%
10^{18} eV	missing energy	5%	10%
10^{18} eV	atmosphere	2%	4%
10^{18} eV	Cherenkov model	0	0
10^{18} eV	fluorescence yield	10%	20%
10^{18} eV	composition (X_{max})	3%	6%
$< 10^{17}$ eV	total	15%	31%
10^{18} eV	total	15%	31%

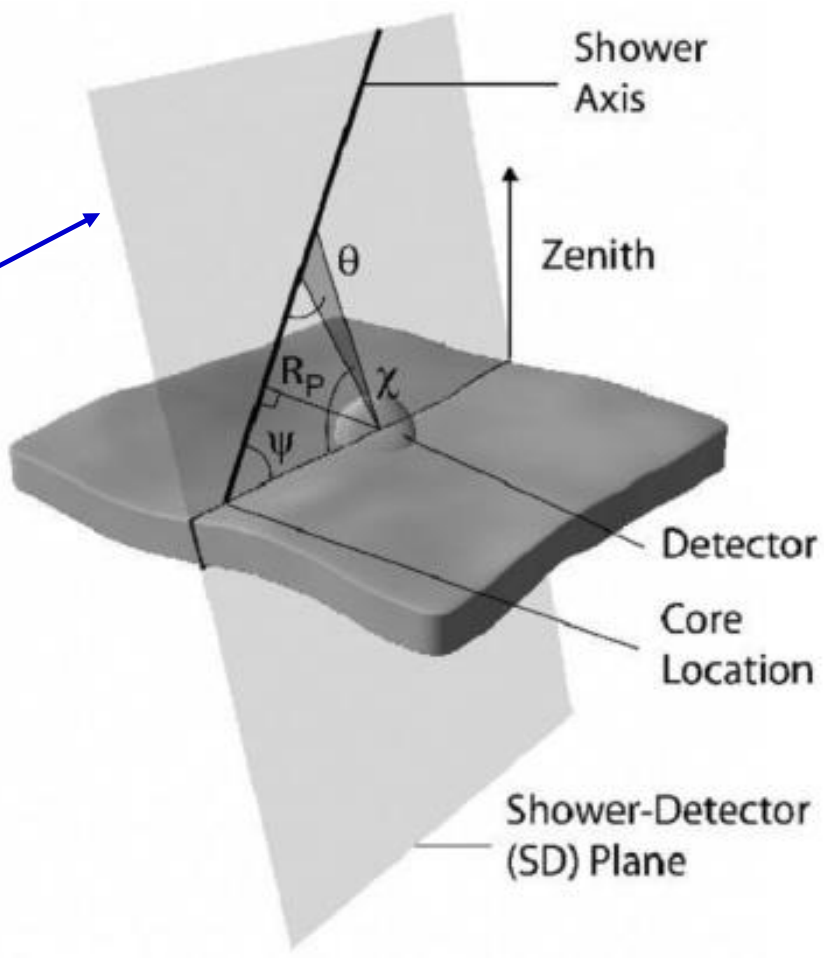
Outline

- Introduction to TALE
- TALE Events and Reconstruction
- Detector Resolutions
- Aperture and Data/MC Comparisons
- Spectrum
- Interpretation of Spectrum
- Continuing work on TALE FD and SD

“Reconstruction” of an air shower

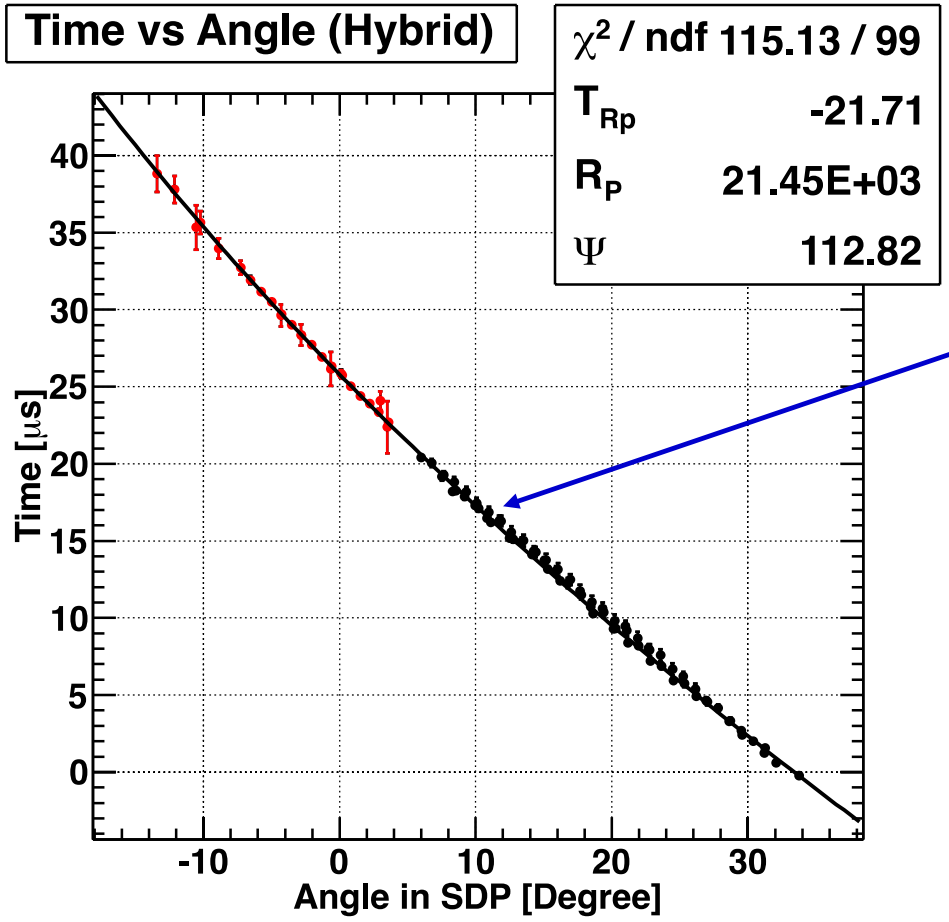


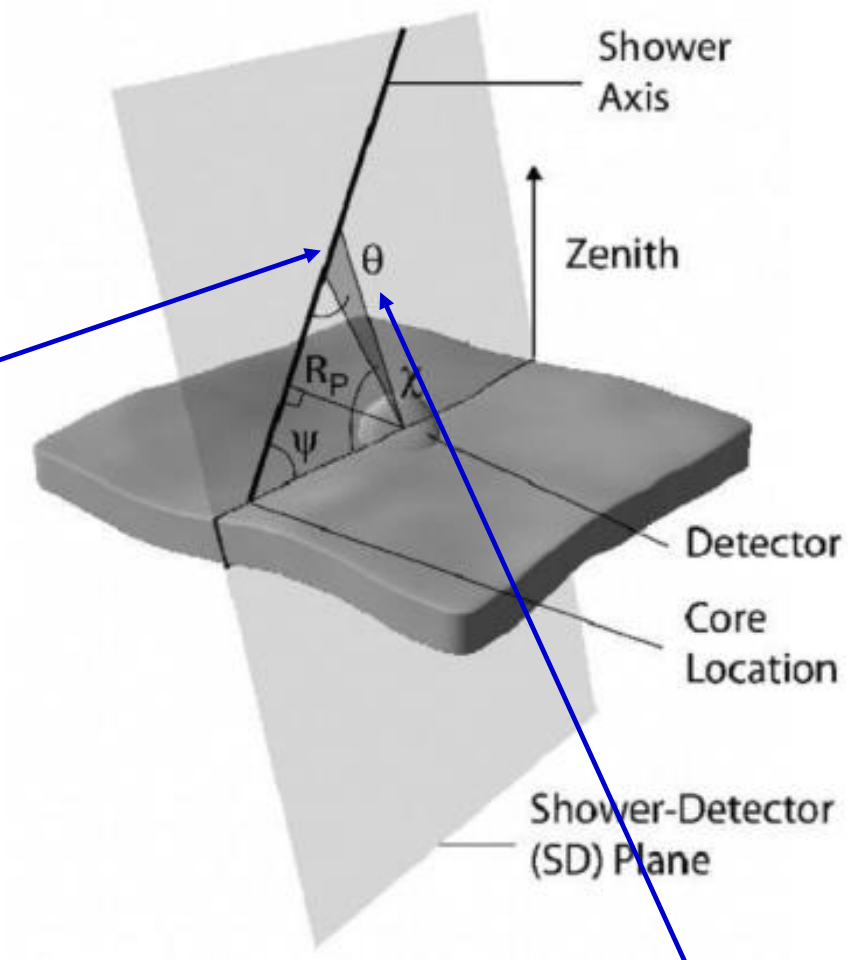
Event Display showing pattern of hit pixels



Direction of hit pixels fitted to a shower-detector plane (SDP)

Timing Fit

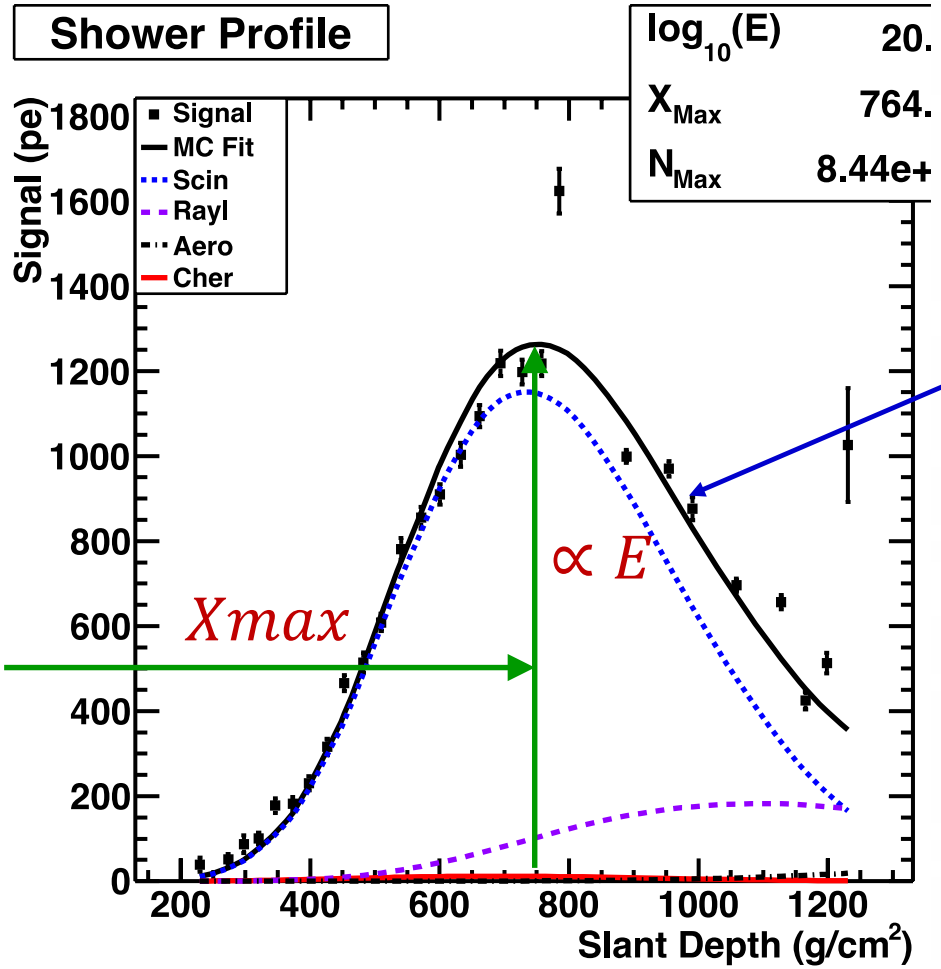


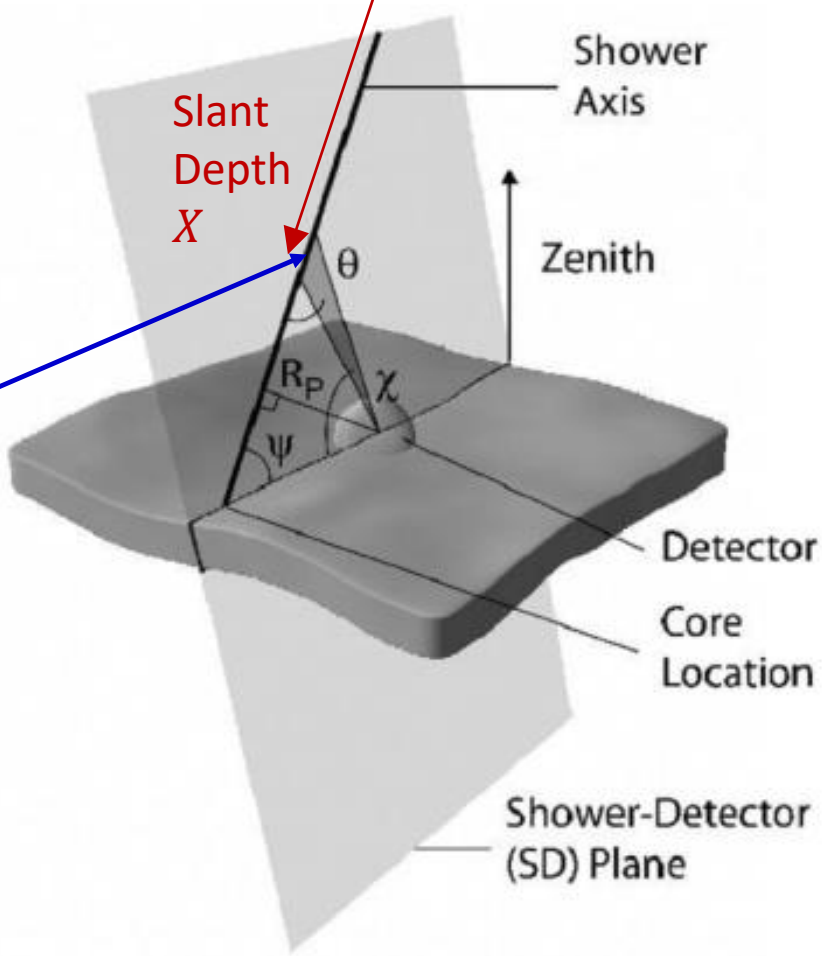


Arrival times of signal light in each pixel is fitted as a function of the SDP θ angles: **Gives direction of primary cosmic ray**

$$t_i = t_0 + \frac{R_P}{c} \tan\frac{\theta_i}{2}$$

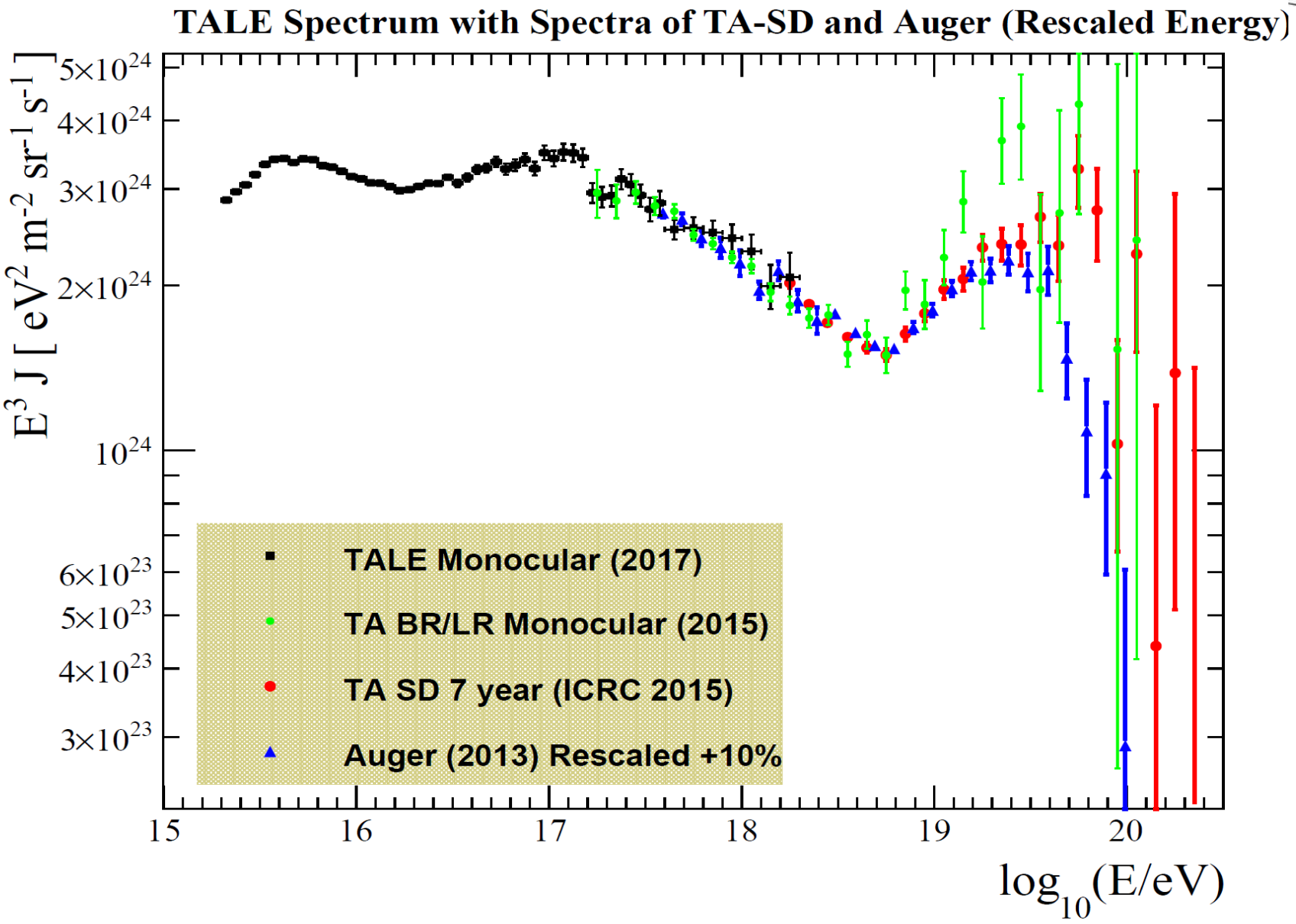
Shower Profile Fit



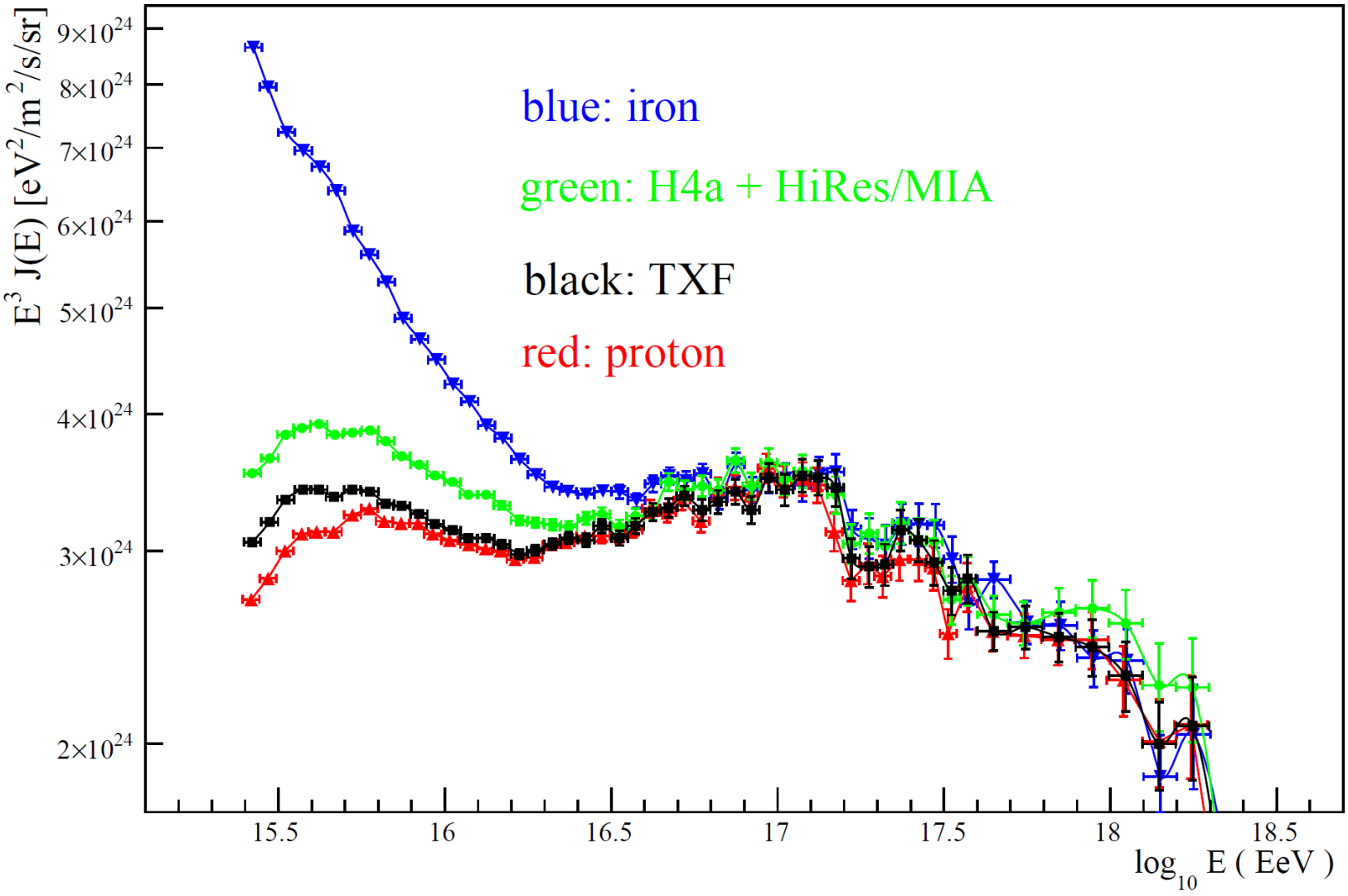


SDP θ angles converted to slant depth.
Light signal fitted to depth to give energy E and $Xmax$ (depth of maximum)

TA Energy Spectrum

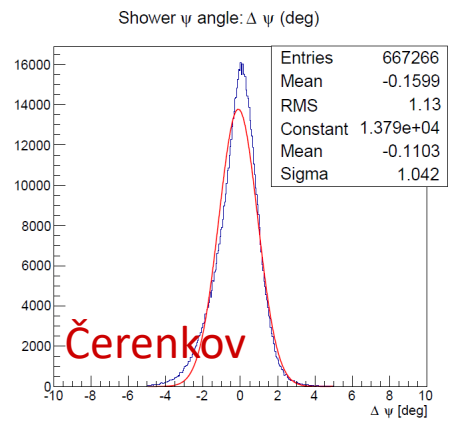


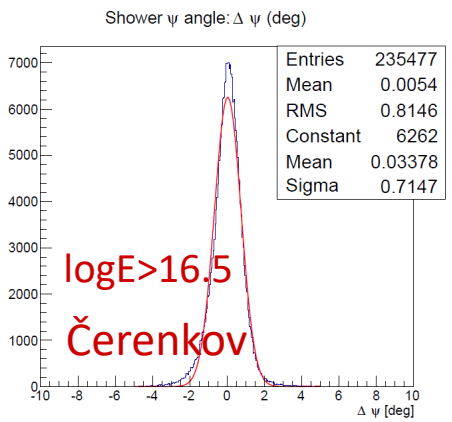
Dependence on Xmax Distribution

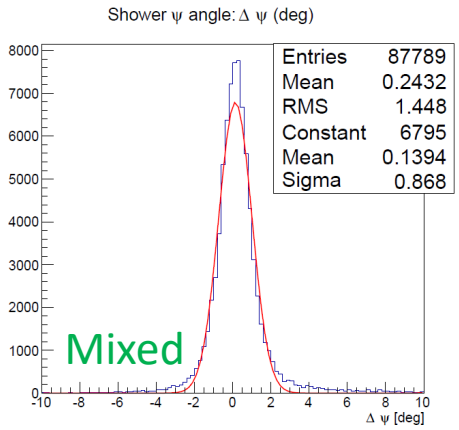


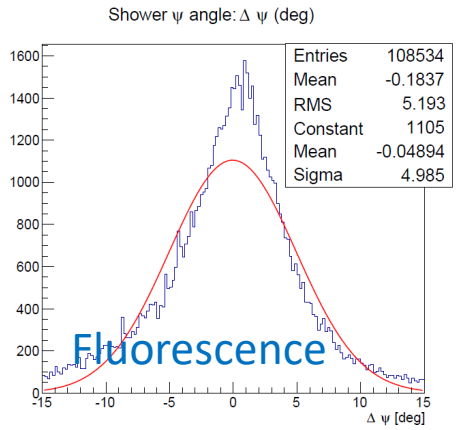
Reconstruction Resolution (1/2)

Ψ Angle

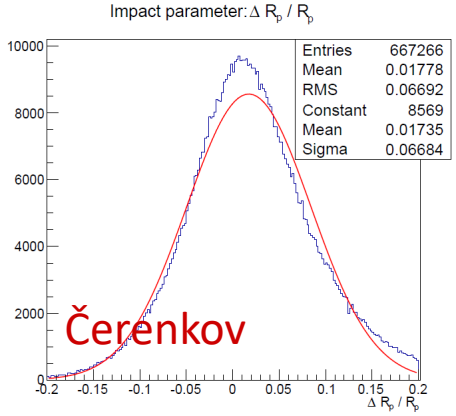


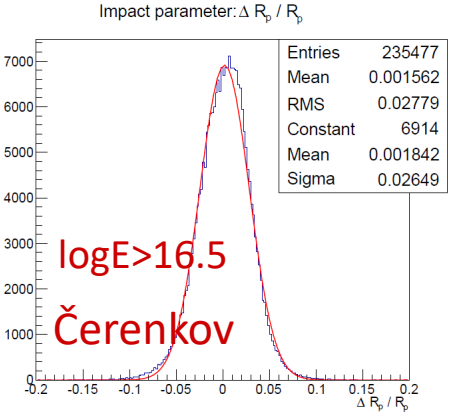


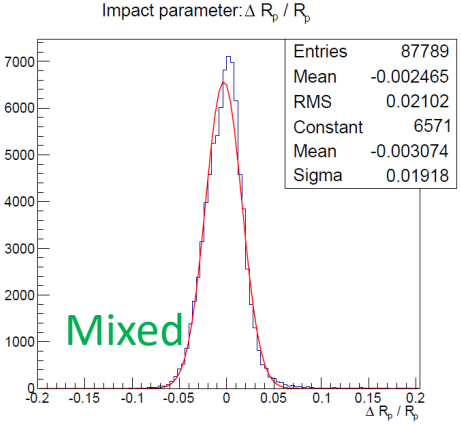


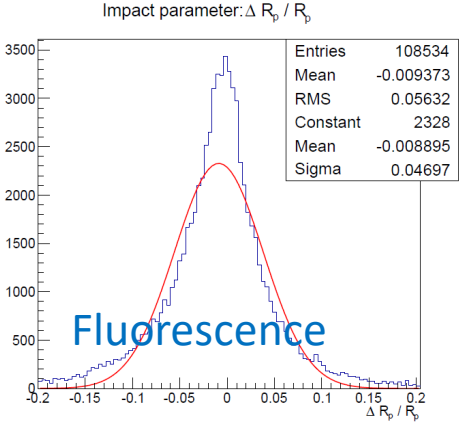


R_P



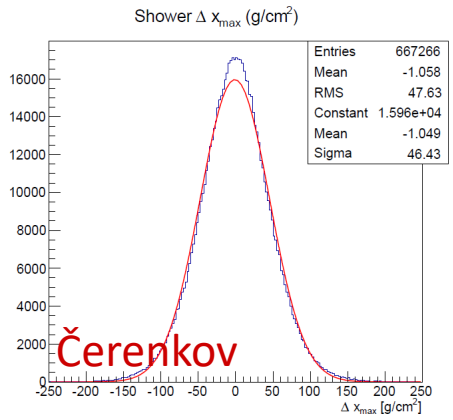


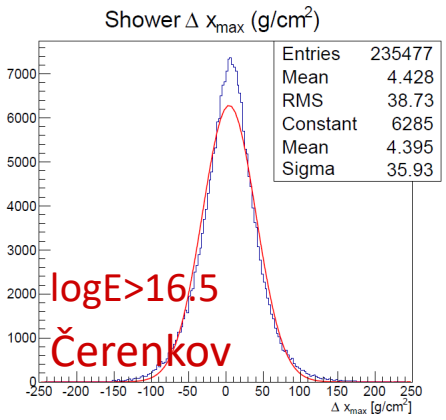


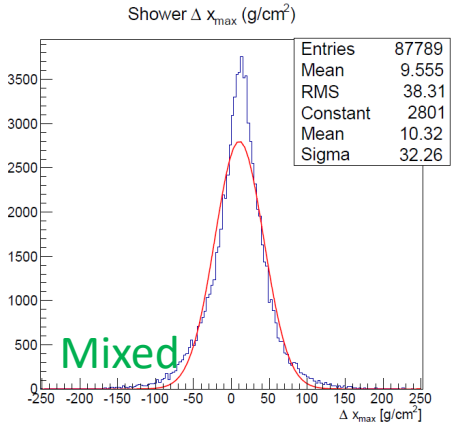


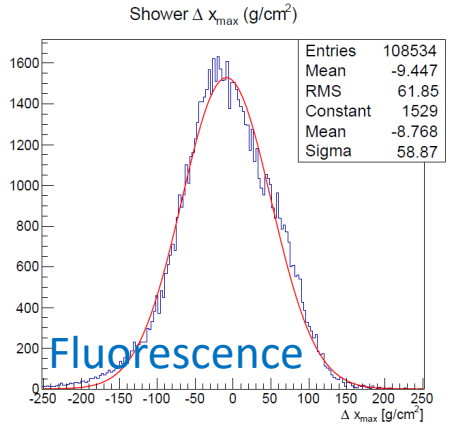
Reconstruction Resolution (2/2)

X_{MAX}

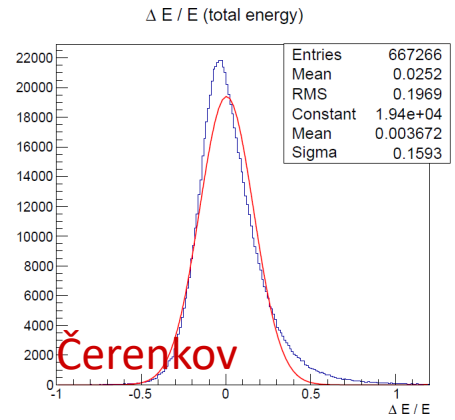


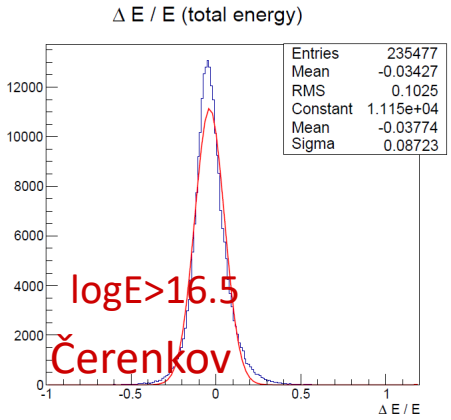


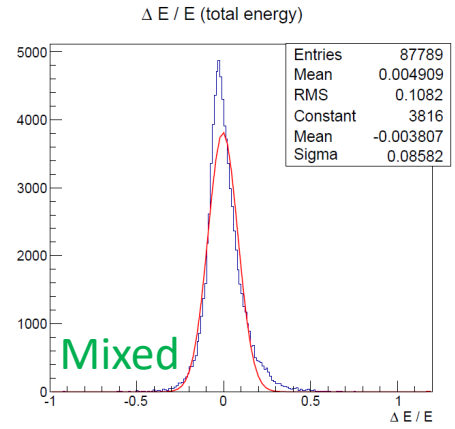


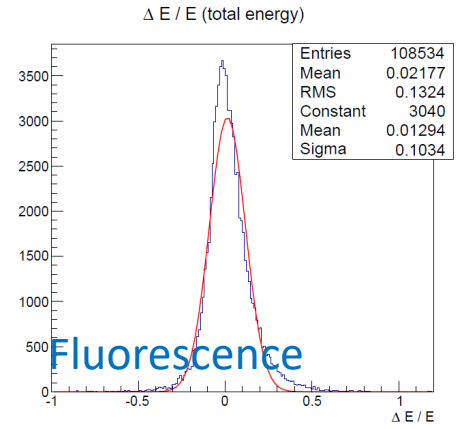


Energy



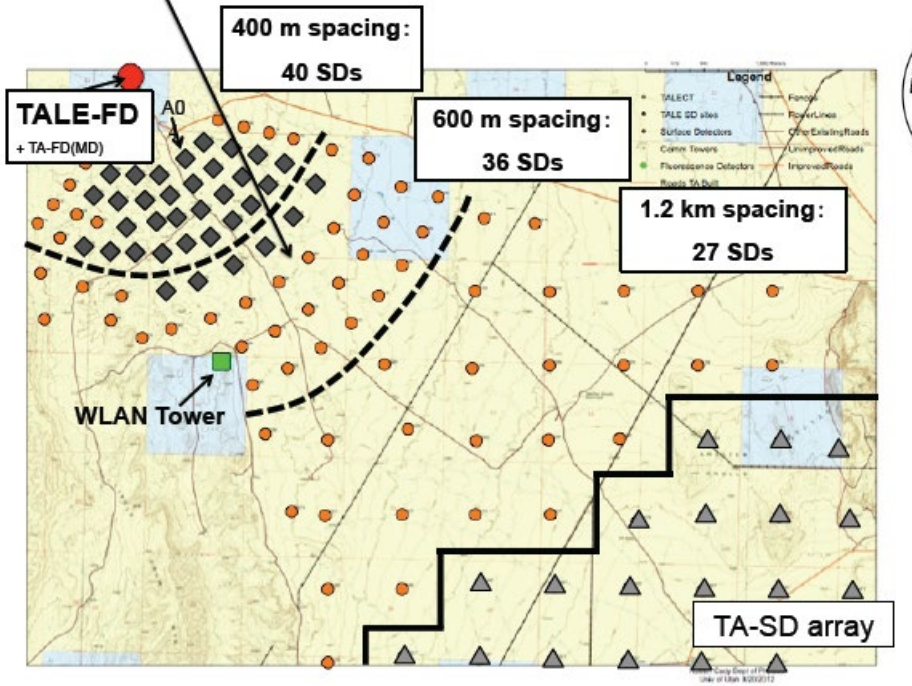


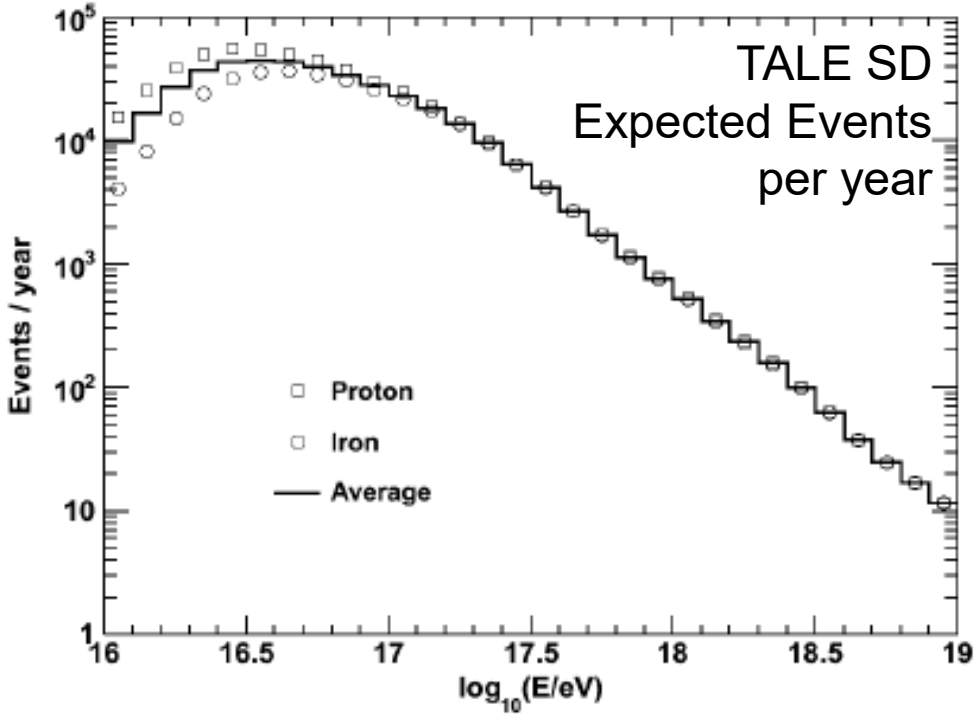




TALE "Infill" Surface Detector

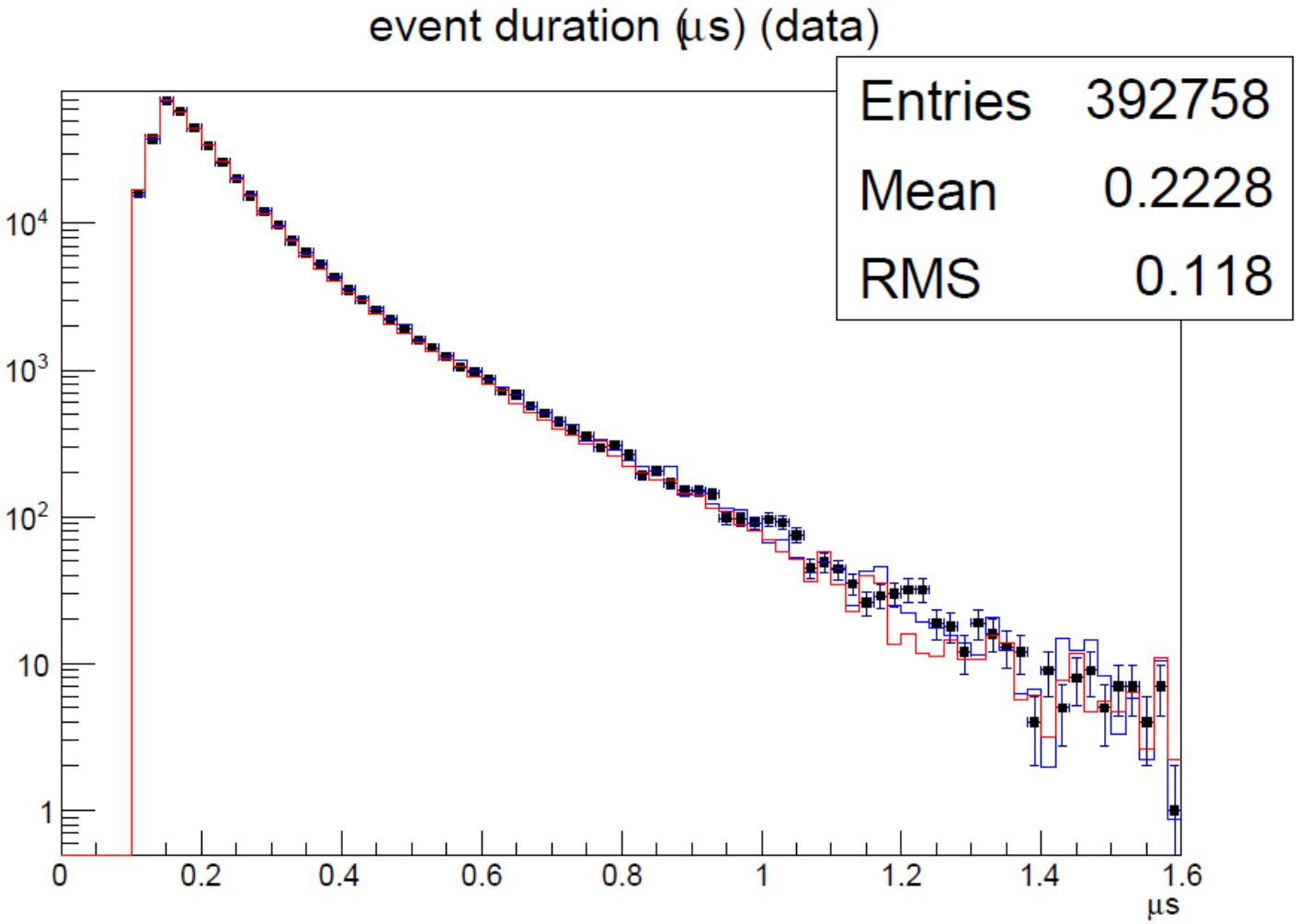
- Construction and deployment funded by the Gov't of Japan
- Add infill array (400m and 600m spacing) for hybrid and stand-alone observation.
- Also add counters to build out main TA SD array (1200m separation).

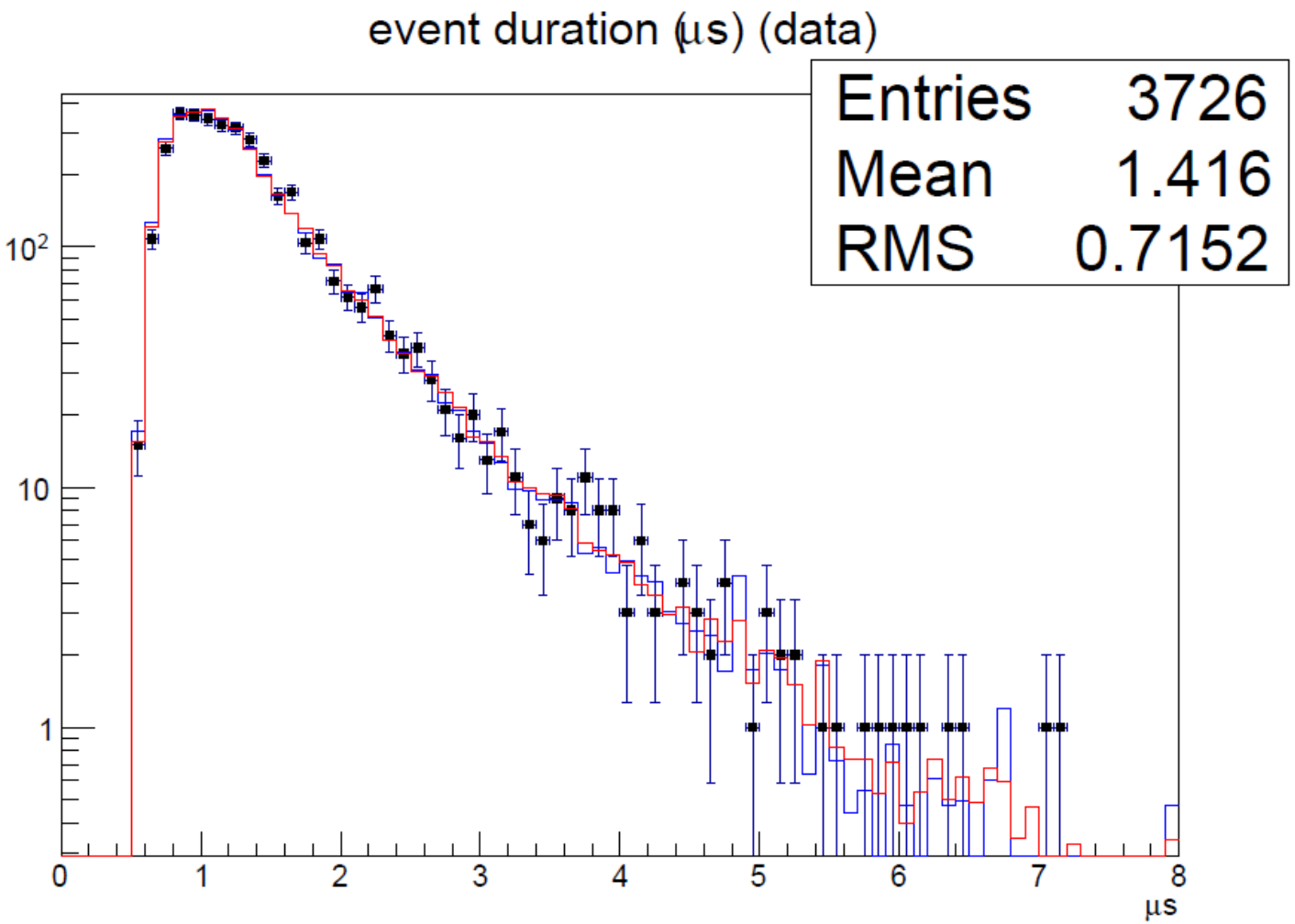




TALE Deployment: Summer 2017

- 103 counters are in place as of fall, 2017
- TALE SD is in shake-down mode


event duration (μs) (data)
Entries 392758
Mean 0.2228
RMS 0.118
10^4
10^3
10^2
10
1
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
μs


event duration (μs) (data)
Entries 3726
Mean 1.416
RMS 0.7152
10²
10
1
0
1
2
3
4
5
6
7
8
μs

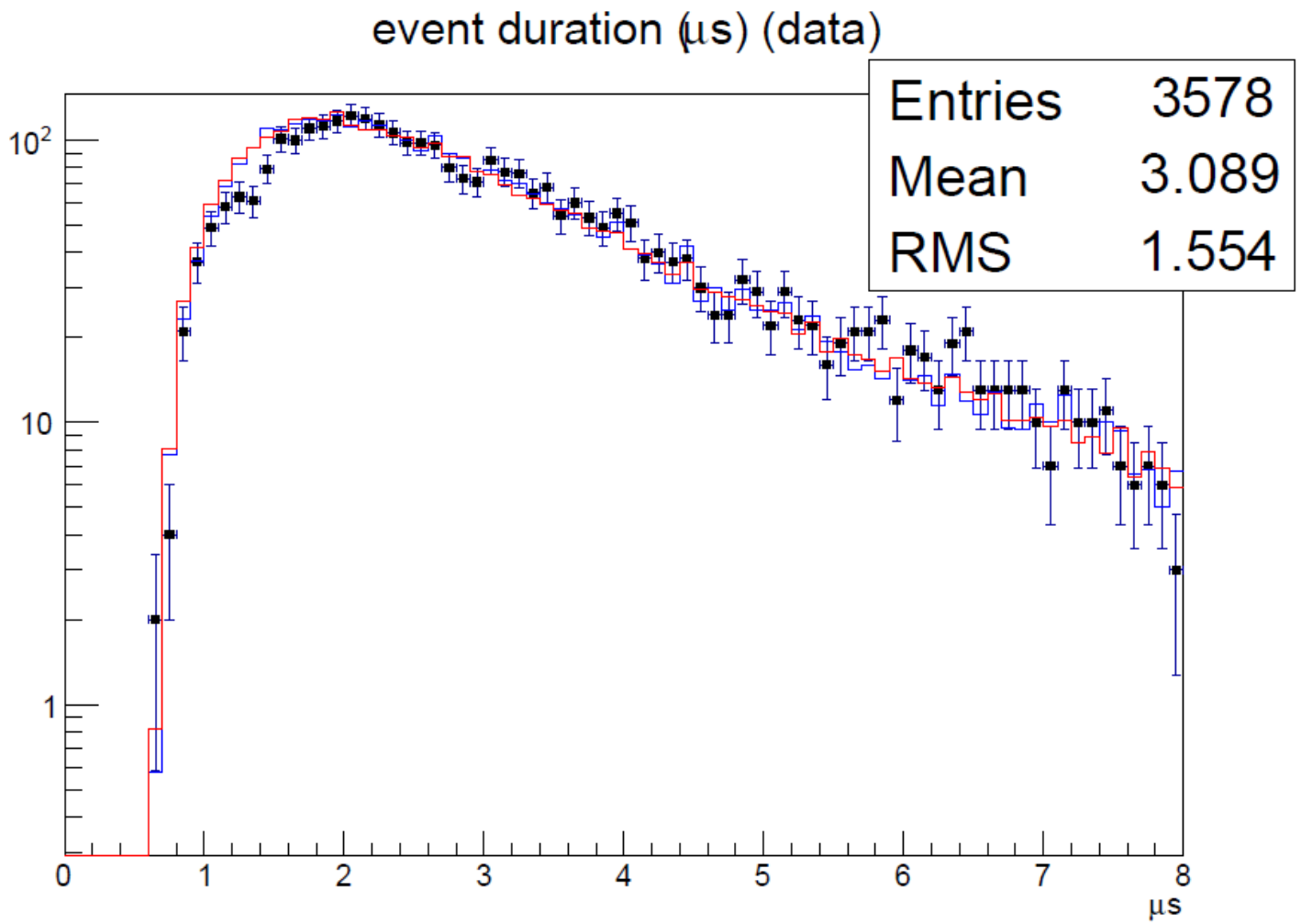
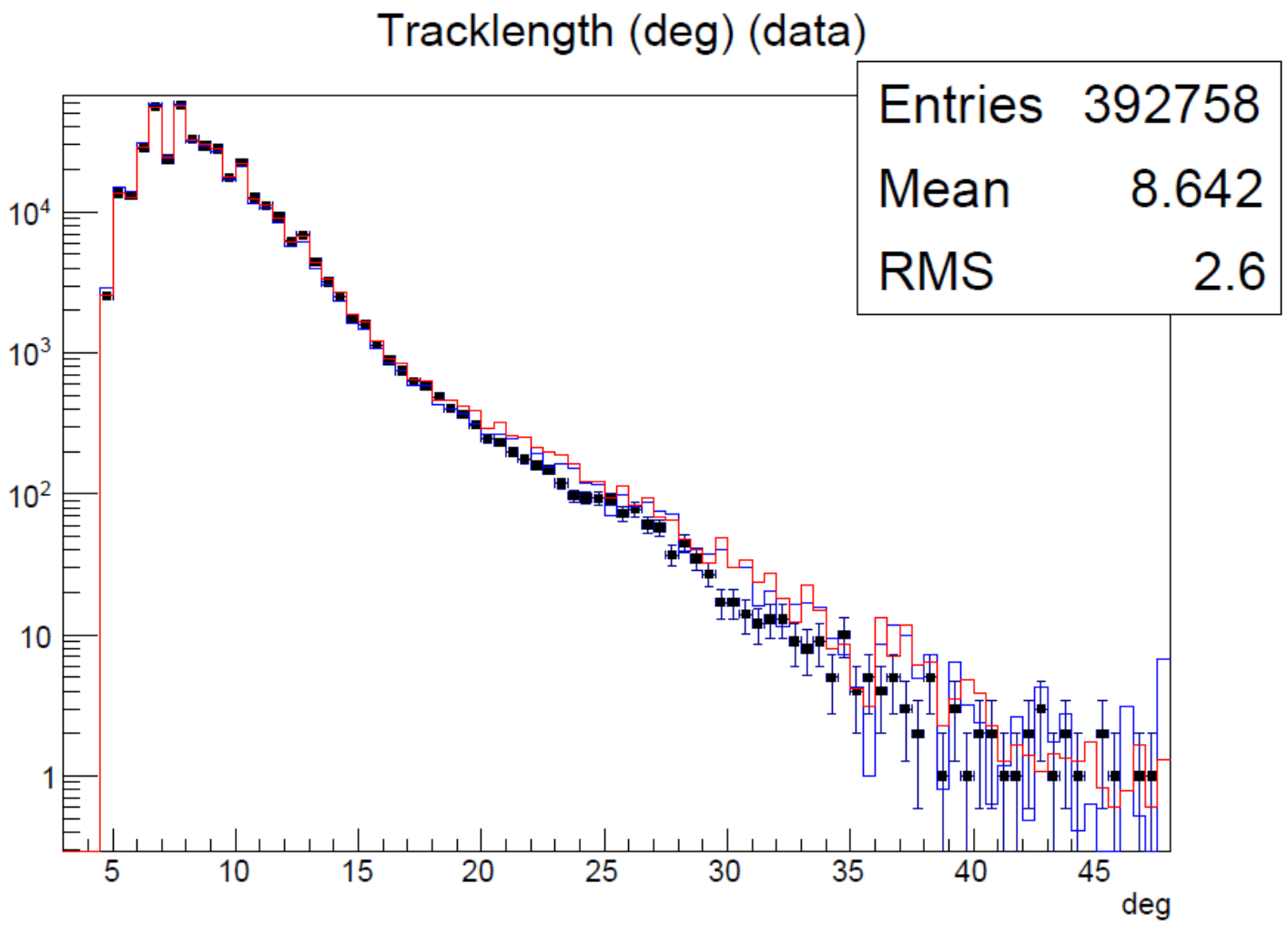
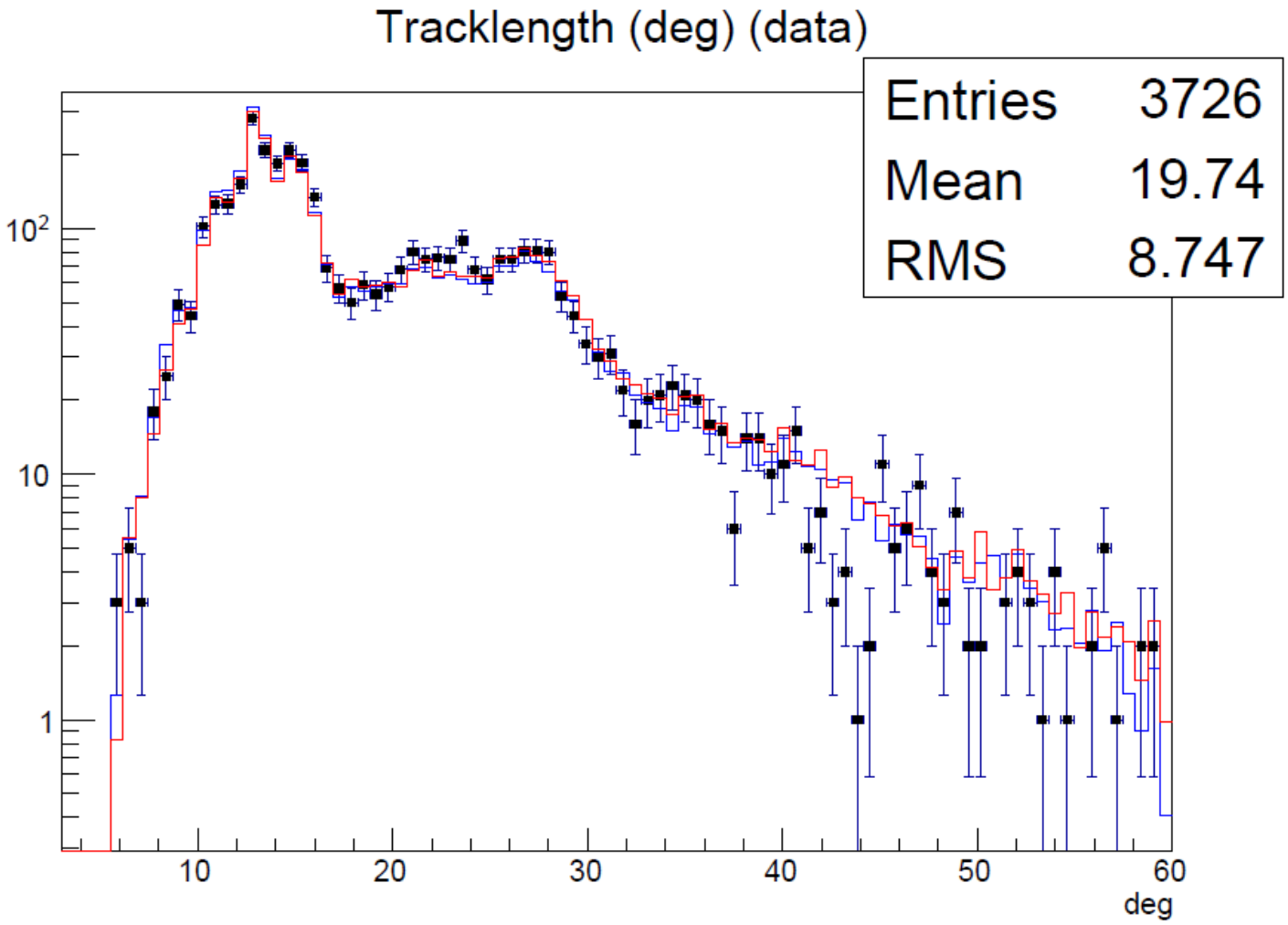


Figure 13: Total event duration (μs), for Cherenkov (left), Mixed (center), and fluorescence events (right). Black points are
data, blue / red histograms are MC with mixed composition (H4a / TXF respectively).


Tracklength (deg) (data)
Entries 392758
Mean 8.642
RMS 2.6
10^4
10^3
10^2
10
1
5
10
15
20
25
30
35
40
45
deg


Tracklength (deg) (data)
Entries 3726
Mean 19.74
RMS 8.747
10^2
10
1
10
20
30
40
50
60
deg

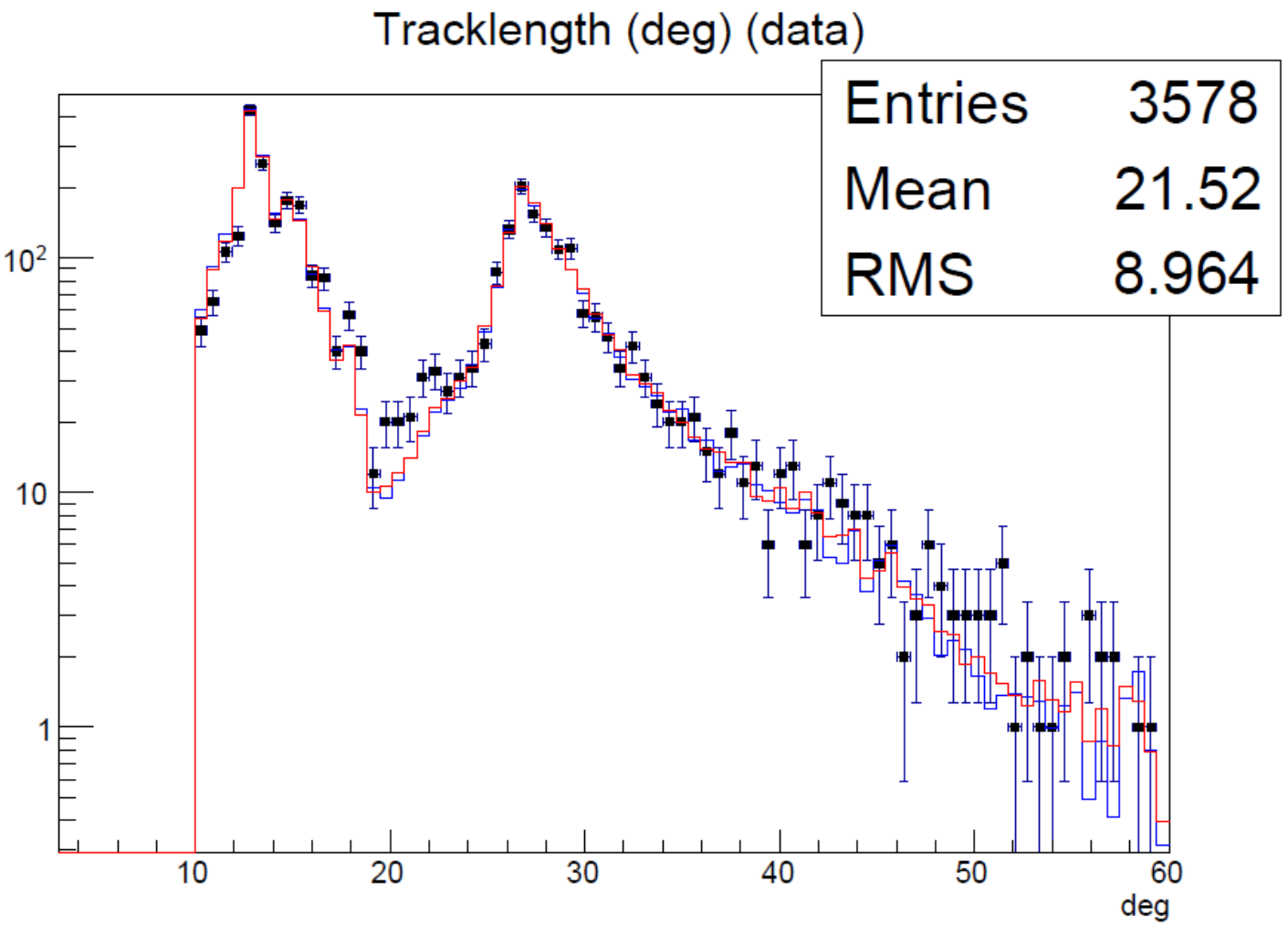


Figure 14: Angular track-length (deg), for Cherenkov (left), Mixed (center), and fluorescence events (right). Black points are data, blue / red histograms are MC with mixed composition (H4a / TXF respectively).

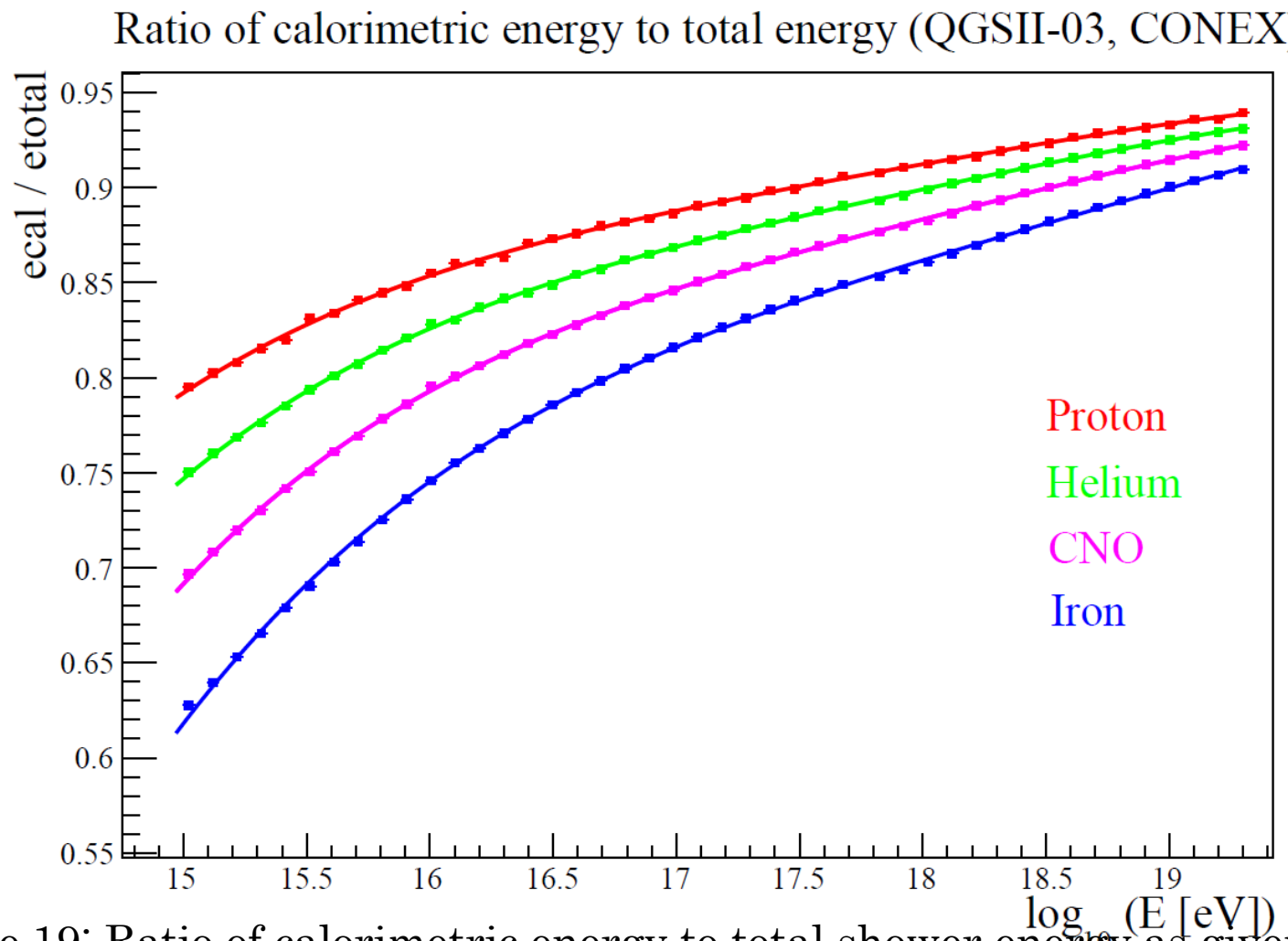


Figure 19: Ratio of calorimetric energy to total shower energy as given by Conex simulations. Simulation sets of mono-energetic showers were used to calculate the ratio. Each point in the figure represents a simulation set and the curves represent a 4-th degree polynomial fit to the point