Analysis of atmospheric attenuation using the Telescope Array central laser data (Influence on Cosmic Rays Measurements)

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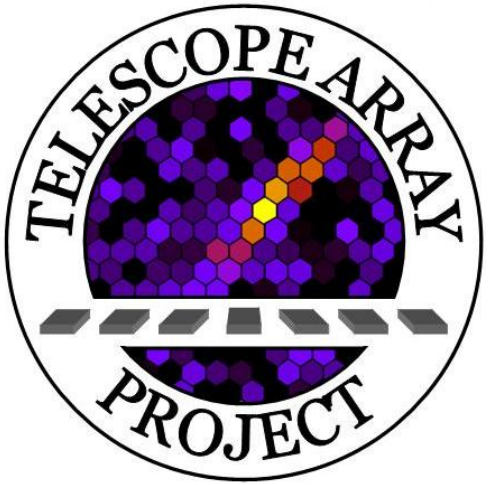
for
The Telescope Array Collaboration



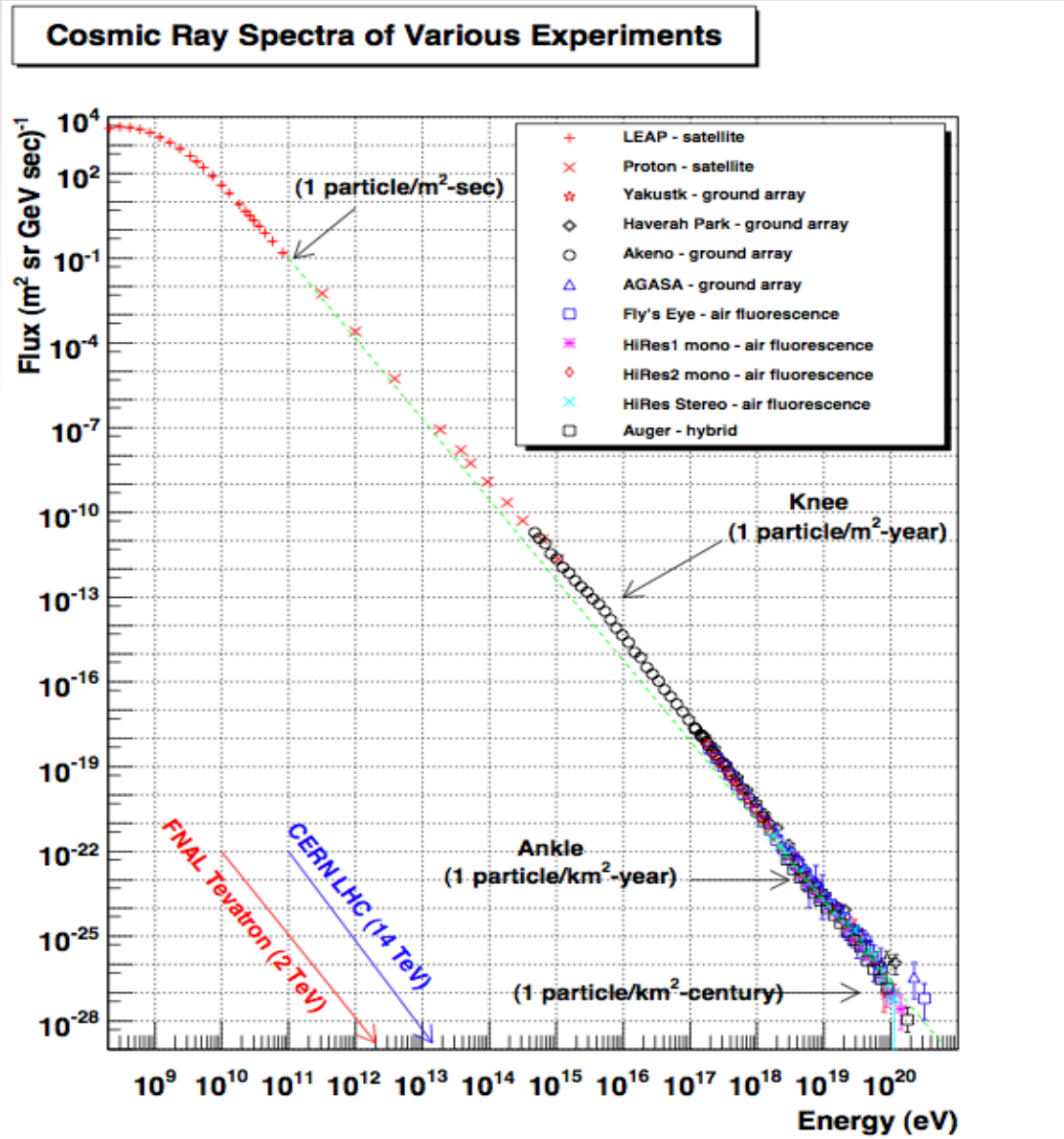
AtmoHEAD 2018 Meeting
9/24/2018

Outline

- **TA** and **TA L**ow **E**nergy extension (TALE) Detectors.
- Aerosols Measurements using the CLF.
- Effect of Aerosols on Shower Energy and Xmax reconstruction.
- Effect of Aerosols on Data Rates (TALE)
- 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 Low Energy extension (TALE) built to lower the energy threshold of the experiment to well below **10^{17}** eV.
- TALE FD threshold ~ 10^{15} eV



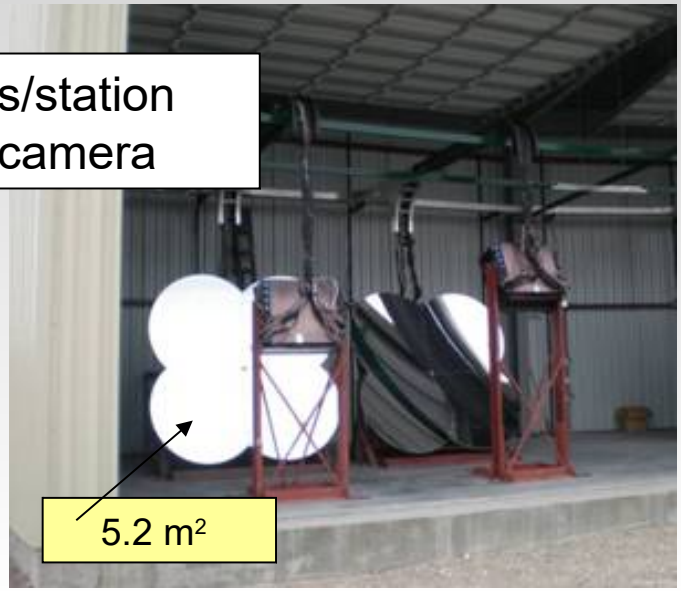
TA Fluorescence Detectors

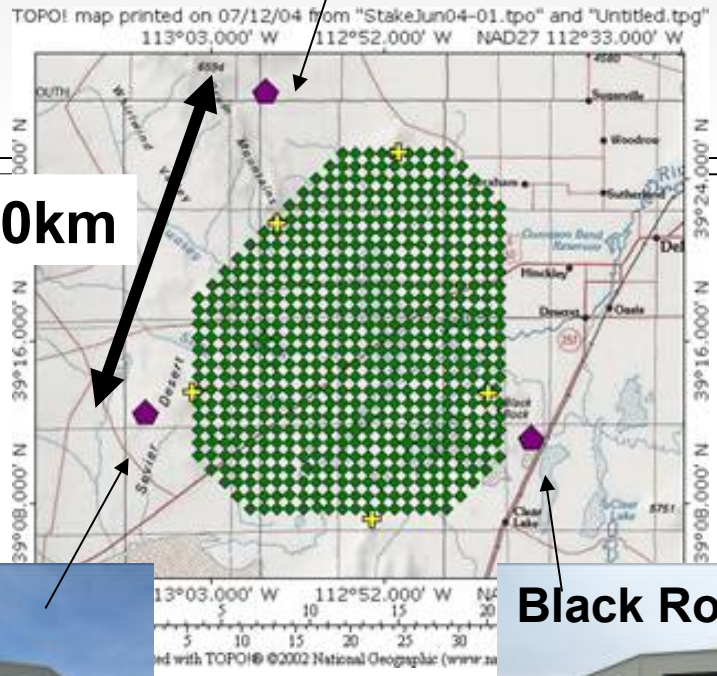
Refurbished from HiRes

Observation started Dec. 2007

Middle Drum

14 cameras/station
256 PMTs/camera





Observation started Nov. 2007

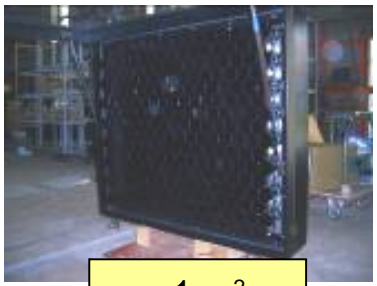
New FDs

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

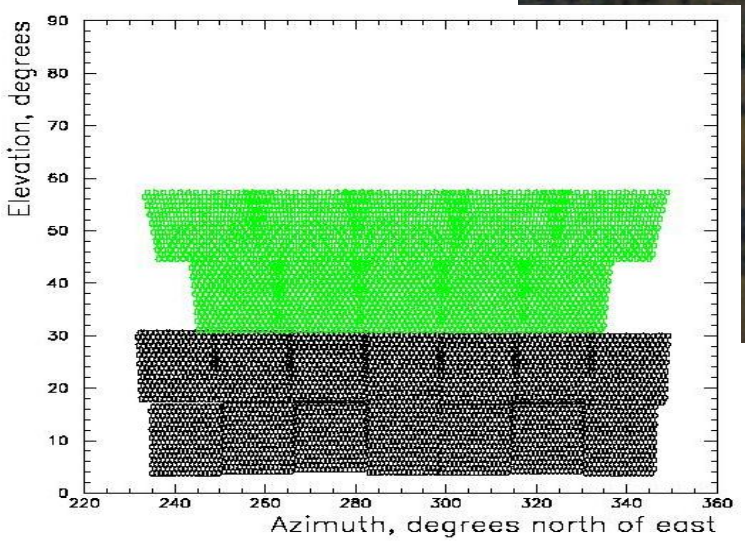
Long Ridge

Observation started Jun. 2007

Black Rock Mesa

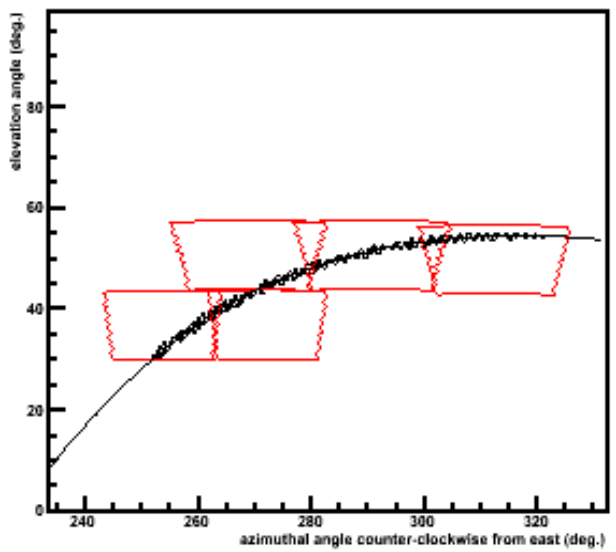


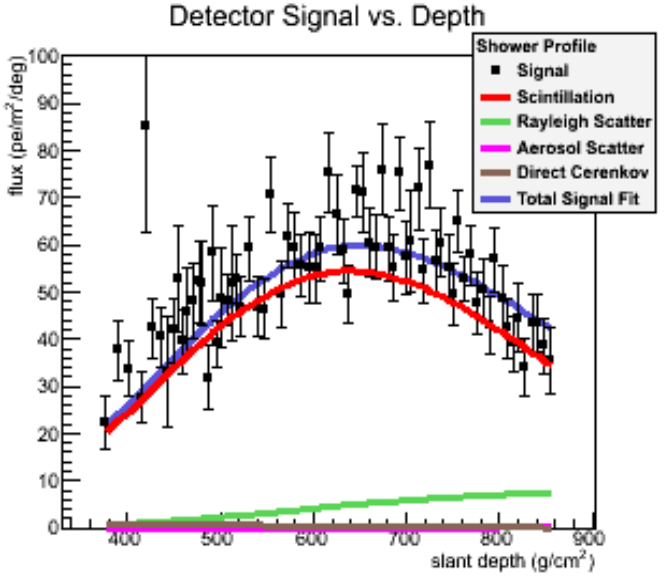
Middle Drum TALE Observatory Site (14+10 Telescopes)

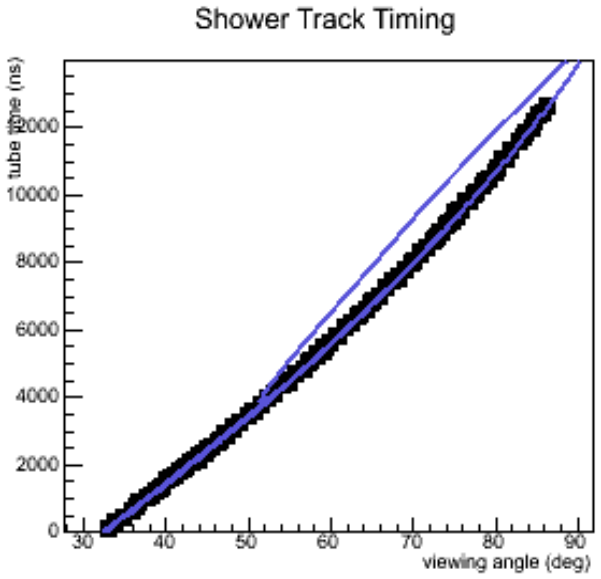


TALE Air Fluorescence Events

- Example Air Fluorescence event seen by TALE FD
- Threshold ~1e17 eV
- Mostly close by (Rp < 10 km)
- Aerosols attenuation correction expected to be small due to smaller Rp but should be qualitatively similar to other TA FDs.







TALE event data

Event Starting: 7: 0:0.695370

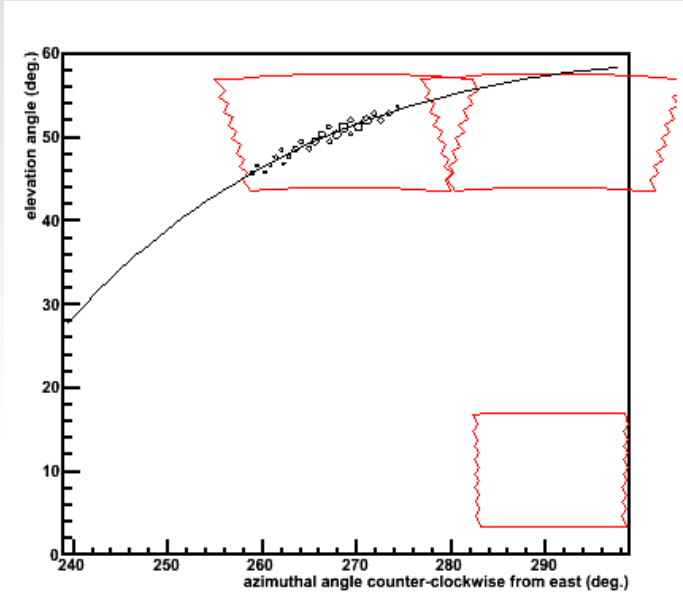
Energy:	**0.530 EeV**
Shower max size:	**3.565e+08 particles**
Shower max depth:	**631.247 g/cm^2**
Profile Fit χ^2/ndf:	**1.2395**

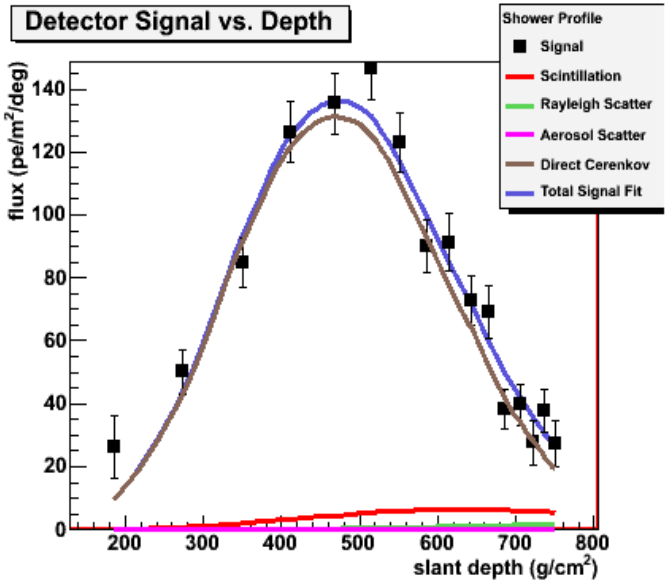
Rp Magnitude: 5.839 km
ψ angle: 55.1 degrees

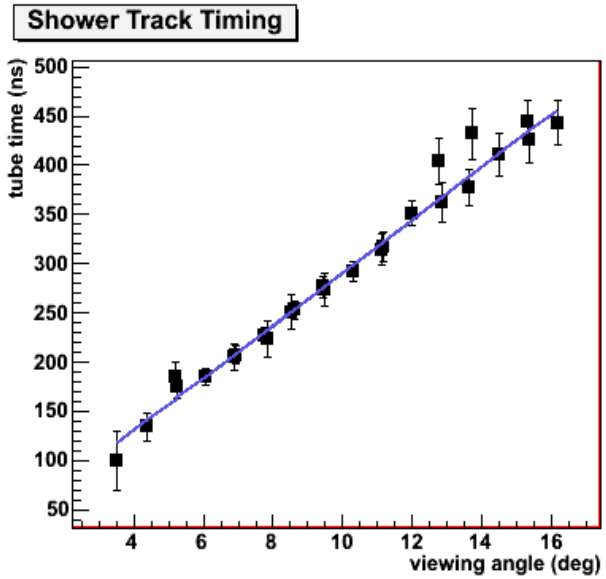
Shower azimuthal angle: 8.2 degrees
Shower zenith angle: 48.0 degrees
Angle to Magnetic field: 60.5 degrees

TALE Cherenkov Events (2)

- Example Cherenkov event seen by TALE
- Threshold ~1e15 eV
- Very close by (Rp < 3km)
- "Fully develops above the ground aerosols layer?"
- Aerosols attenuation correction expected to be small.







TALE event data

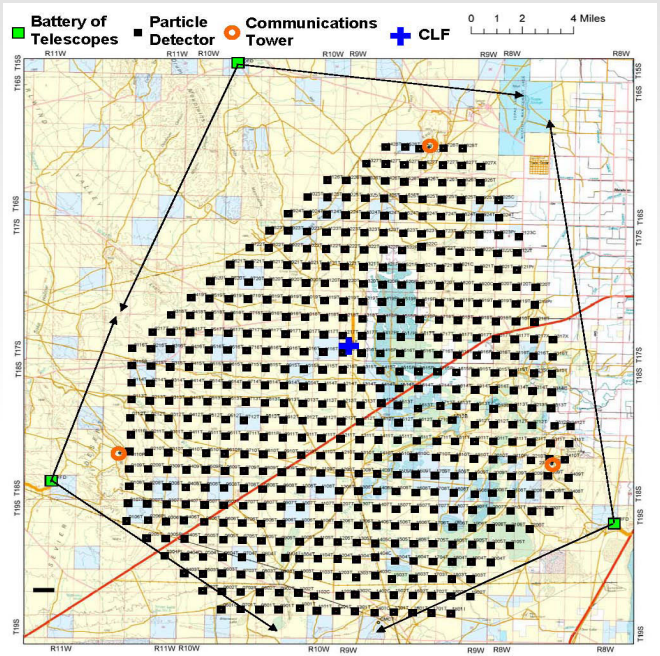
Event Starting: 0: 0:0.139663747441801

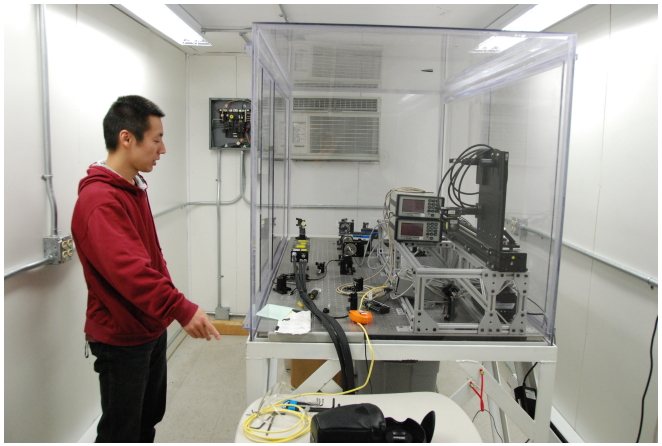
Energy: 9.241 PeV
Shower max size: 6.143e+06 particles
Shower max depth: 605.810 g/cm²
Profile Fit χ^2/ndf: 0.7362

Rp Magnitude: 0.912 km
ψ angle: 106.9 degrees

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

TA FD's and CLF





- TA FD's located at three sites:
  - Black Rock (BR)
  - Long Ridge (LR)
  - Middle Drum (MD)
- Central Laser Facility equidistant to all three at (20.85 km)
- Note: TALE FD located at MD site.

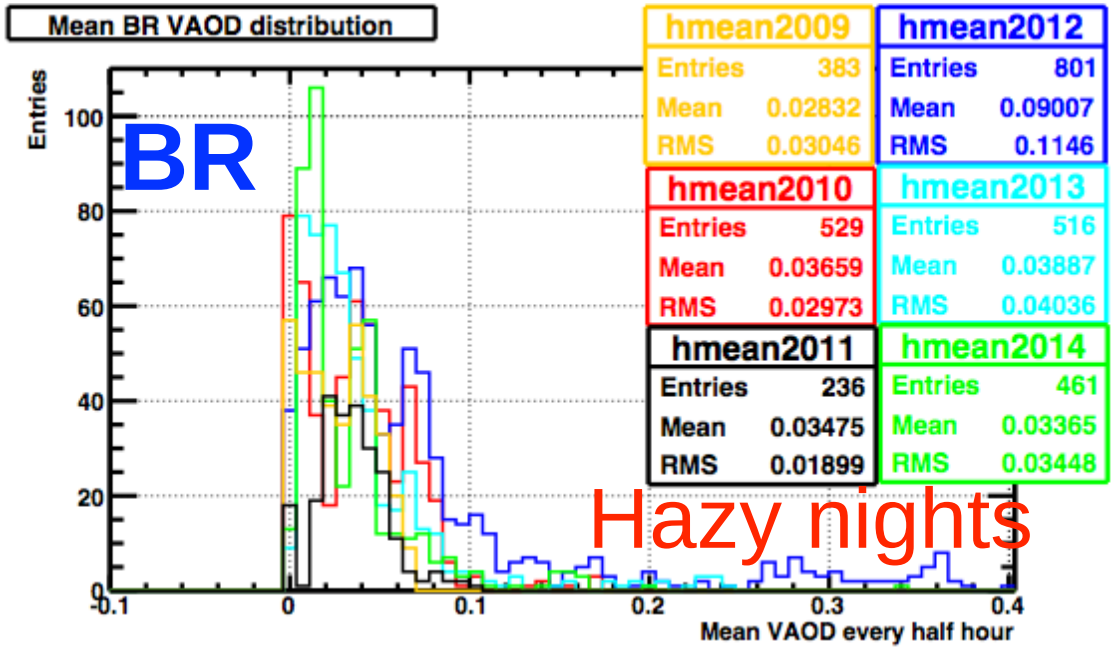
Aerosols Measurements using the CLF

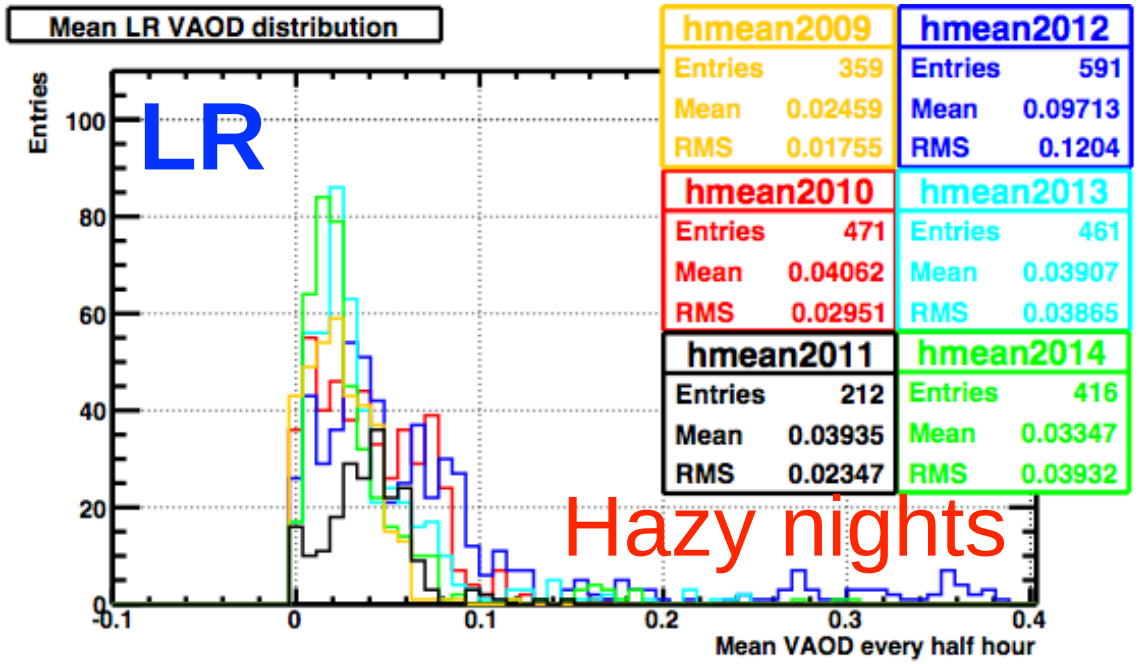
- CLF laser is operated nightly; data taken every 30 minutes.
- Multiple Analyses are carried out to measure Aerosols distributions on an hourly basis . …
  - I will show results from one.
- An average Aerosols distribution is used in the cosmic rays data analyses.
- This average is characterized by a single number: **V**ertical **A**erosols **O**ptical **D**epth (VAOD)
  - Or, two numbers for use in simulation/reconstruction codes.

Results of Aerosols Study by J. Kim

- A UofU Graduate Student, Jihee Kim, working with Prof. Gordon Thomson measured the **V**ertical **A**erosols **O**ptical **D**epth (VAOD) using data from three FD sites.
- Started with data from BR and LR sites.
- Extended study to MD.
- Calculated yearly averages.

VAOD measurement for 6 yrs

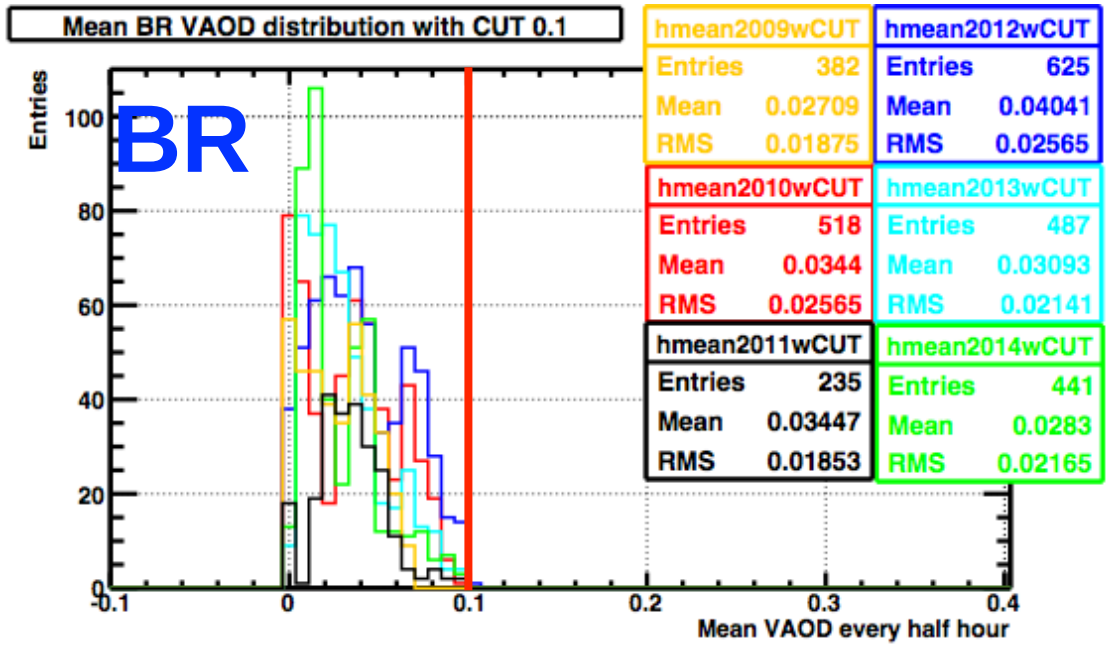


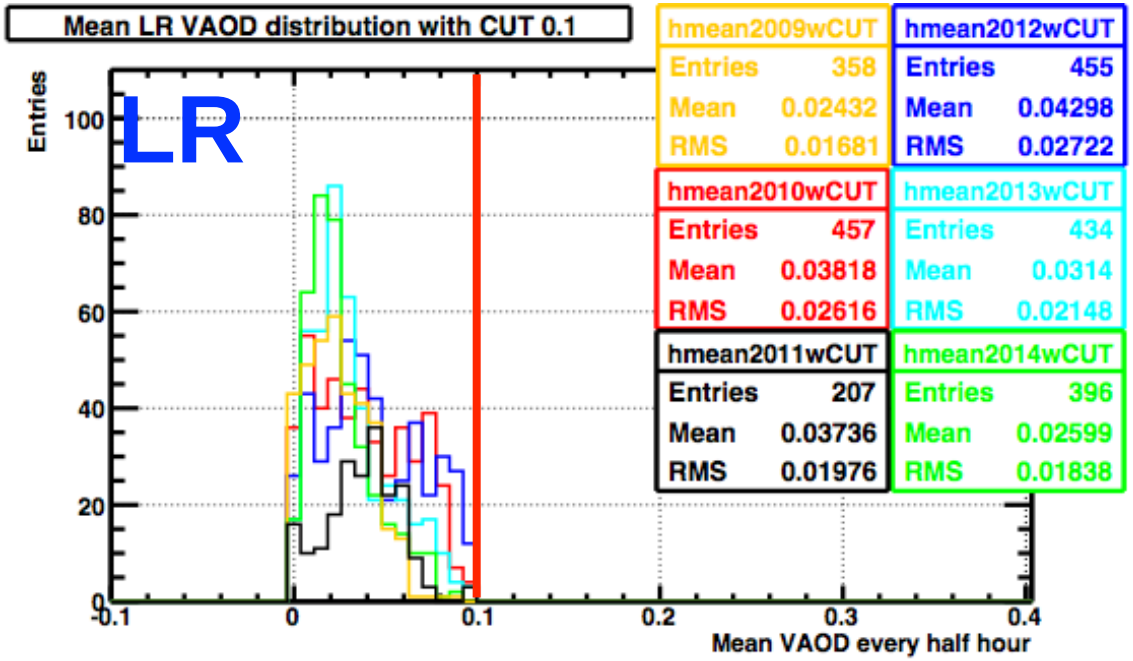


	Mean VAOD	
	BR	LR
2009	0.028	0.025
2010	0.037	0.040
2011	0.035	0.039
2012	0.090	0.097
2013	0.039	0.039
2014	0.034	0.033

Many wild fires

Remove Hazy Nights (6 yrs)

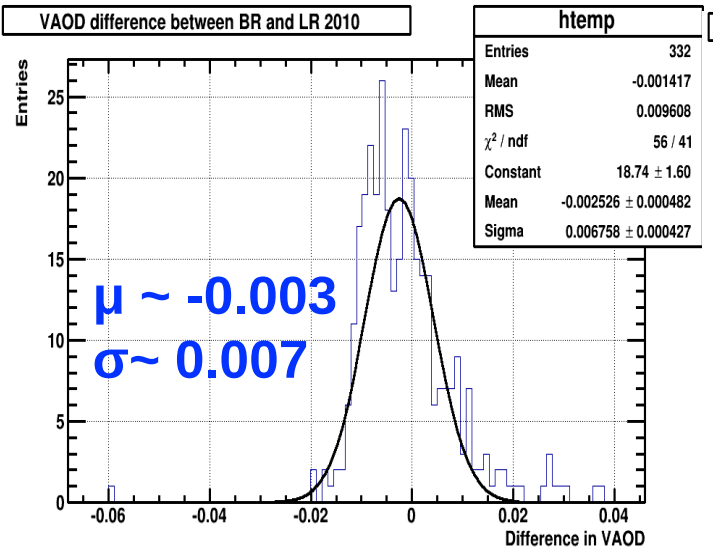


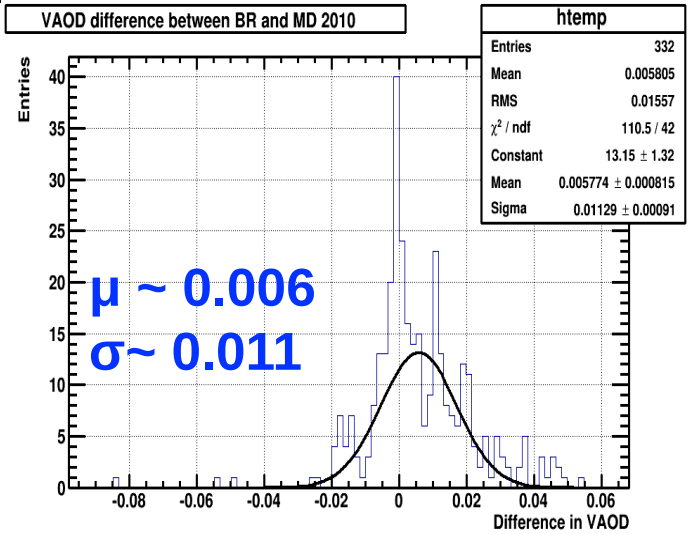


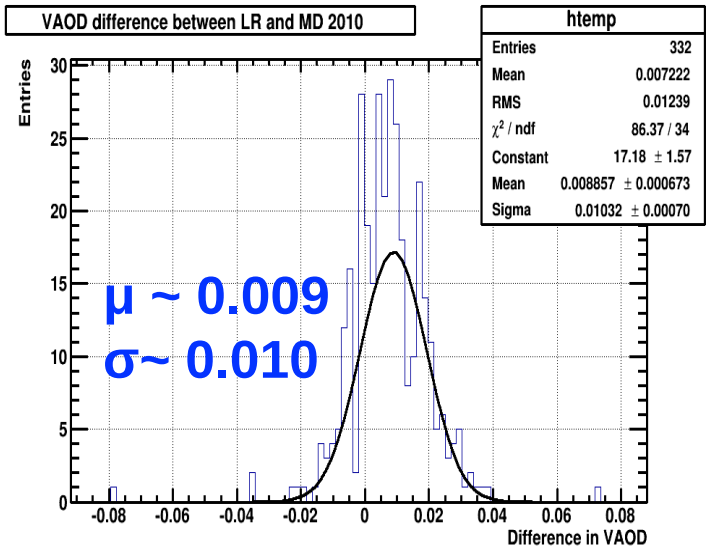
Put a cut VAOD <0.1

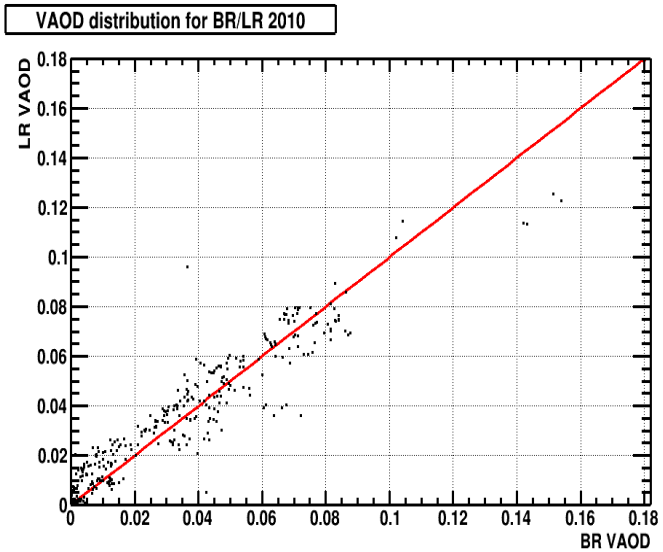
	Mean VAOD	
	BR	LR
2009	0.027	0.024
2010	0.034	0.038
2011	0.034	0.037
2012	0.040	0.043
2013	0.031	0.031
2014	0.028	0.026

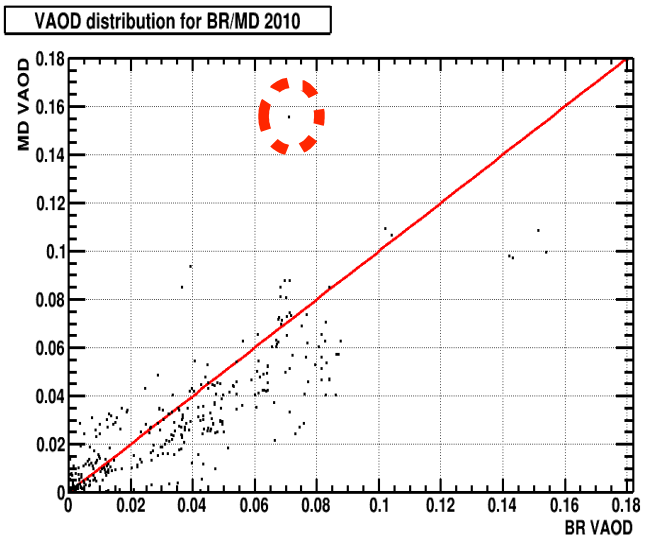
VAOD difference when 3 stations are present (2010)

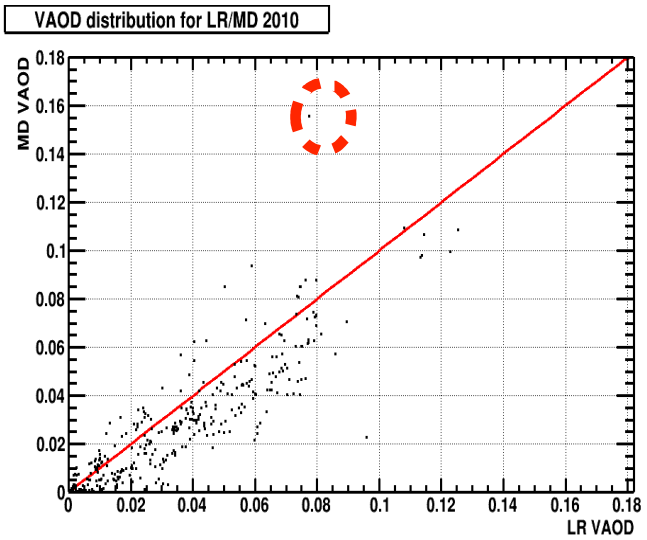












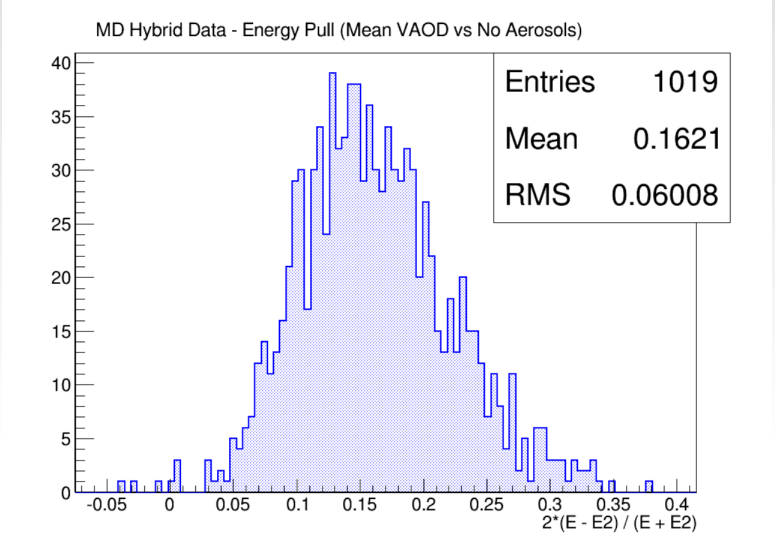
Influence on Cosmic Rays Measurements

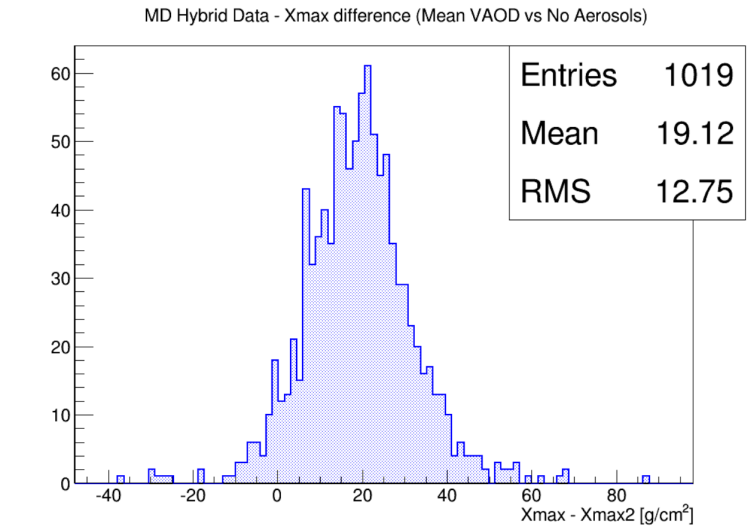
Effect of Aerosols on Energy and Xmax Reconstruction

- Aerosols distributions, and therefore light attenuation due to aerosols can change on time scales of days or even hours.
- Yet we use an average Aerosols model in our data analyses.
- Two questions regarding reconstructed shower energies and Xmax:
  - What is the effect of using an average vs hourly correction?
  - What is the effect of using the wrong average?
- Also, how dependent are the effects on cosmic rays energies:
  - TAFD: ~3 EeV and higher
  - TALE: ~3 PeV and higher

MD Hybrid Data

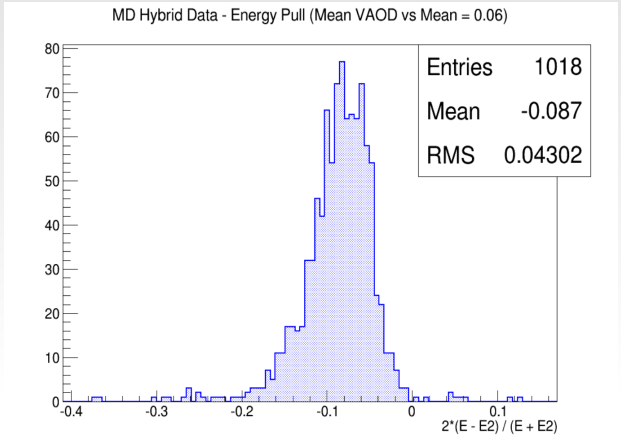
- MD Hybrid data Set used for composition measurement. (ref.)
- Mean VAOD = 0.04
- Unrealistic, but ...
- Remove aerosols scattering from reconstruction:
  - E lower by 16 %
  - Xmax smaller by 19 g/cm2

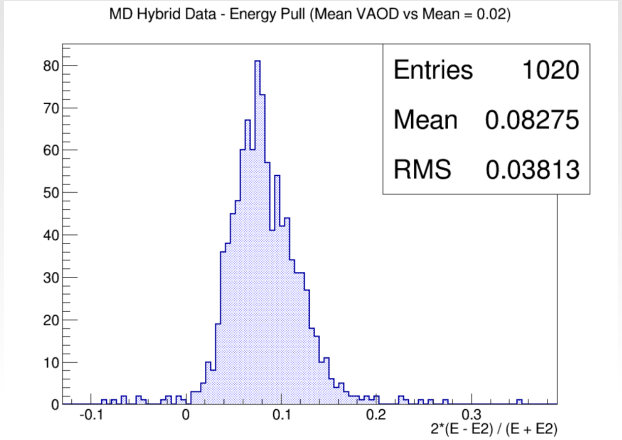


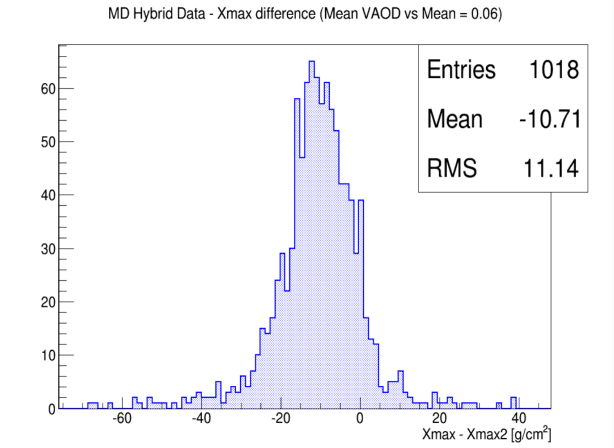


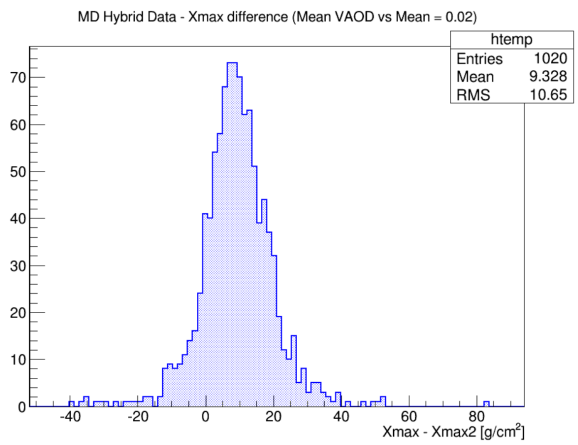
MD Hybrid Data

- MD Hybrid data Set
- Reconstructed with Mean VAOD = 0.04
- Change Mean VAOD to 0.02 or 0.06 in reconstruction:
  - E range +/- 8.5 %
  - Xmax range +/- 10 g/cm^2







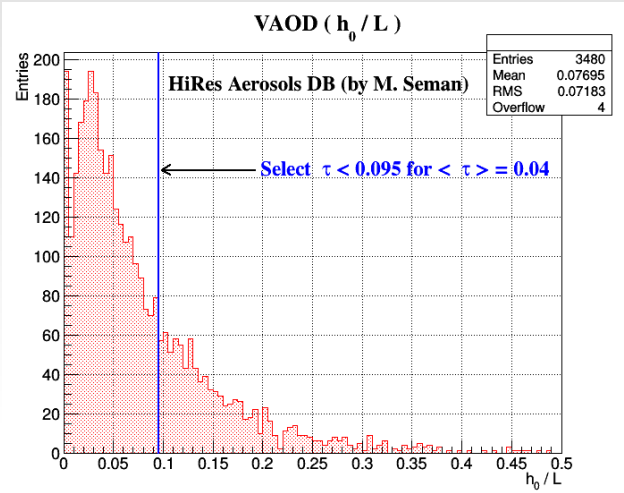


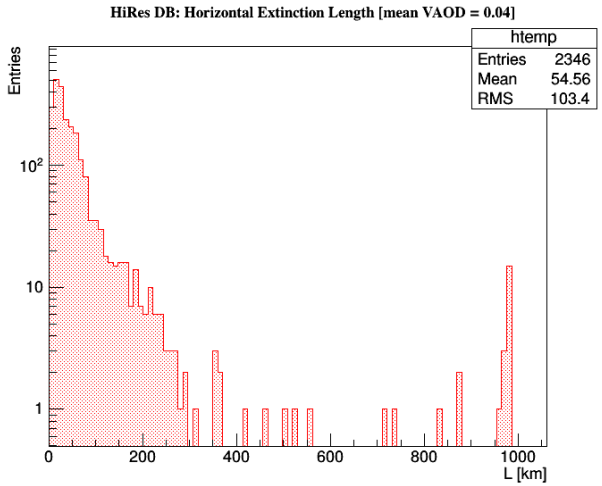
Simulation Study

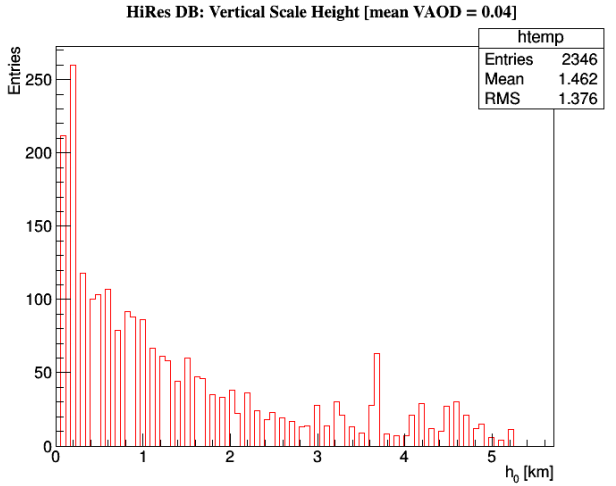
- MD for high energy E >= 3 EeV, E <= 100 EeV
- TALE for low energy E >= 3 PeV, E <= 100 PeV
- Use “Random” Aerosols model parameters sampled from HiRes Atmospheric Database … (For convenience, already built in simulation code).
- Reconstruct events using either same model parameters as in simulation or using mean values
- Compare results.

HiRes Aerosols Data Base

- Aerosols modeling:
  - Mixing Layer height above ground: h_m
  - Scale height: h_0
  - Horizontal extinction length (@ 334 nm): L
- VAOD = $(h_m + h_0) / L$
- In practice,we set $h_m = 0$
- Avg. Aerosols: $h_0 = 1$ km, L = 25 km.
- DB Aerosols: h_0 and L are extracted from atmospheric monitoring data

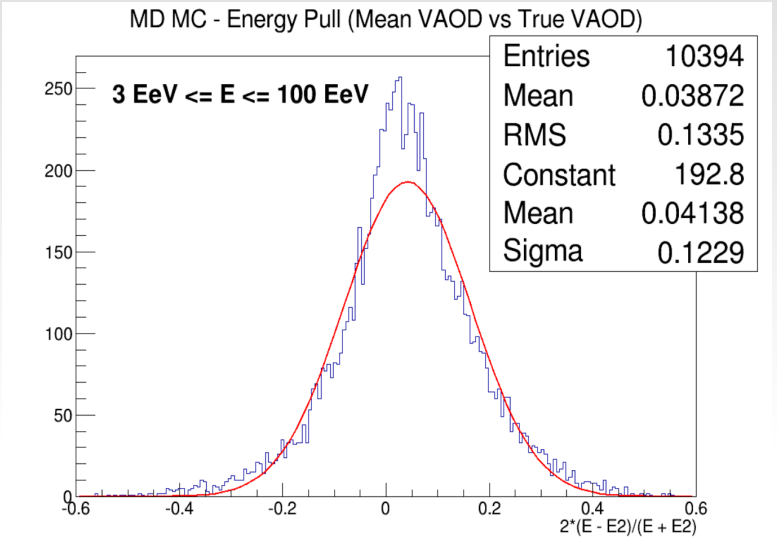


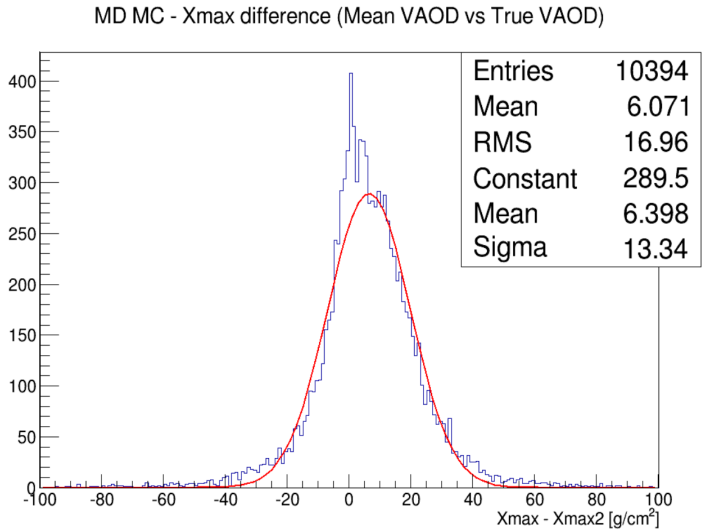




MD MC

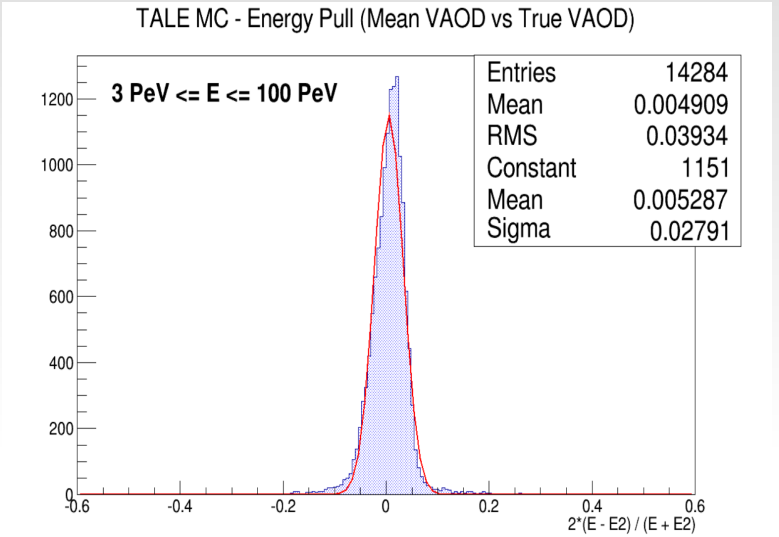
- MD FD Simulation set.
- Mono energetic showers
- Sampled DB Aerosols Parameters.
- Recon with Mean VAOD = 0.04
- Recon with same VAOD as thrown
- Minimal QC's for event selection
- Compare Recon results:
  - Energy: sigma 12%
  - Xmax: sigma 13 g / cm^2

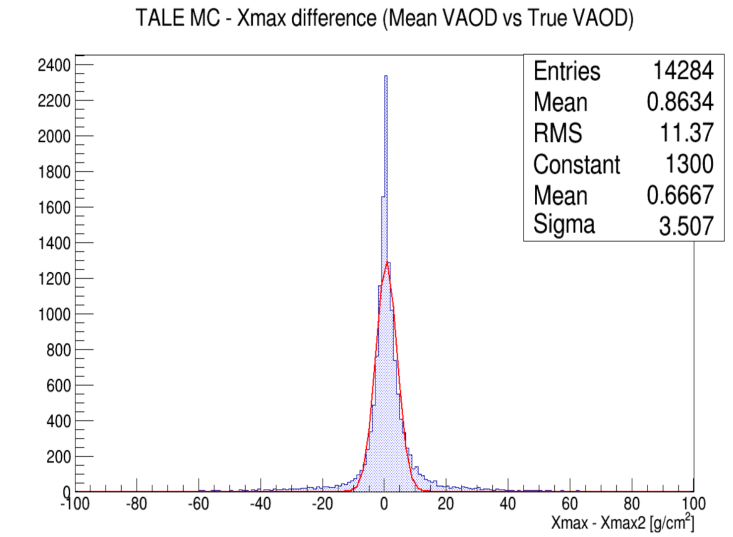




TALE MC

- TALE FD Simulation set.
- Mono energetic showers
- Sampled DB Aerosols Parameters.
- Recon with Mean VAOD = 0.04
- Recon with same VAOD as thrown
- Minimal QC's for event selection
- Compare Recon results:
  - Energy: sigma 3%
  - Xmax: sigma 3.5 g / cm^2





TALE Event Rates

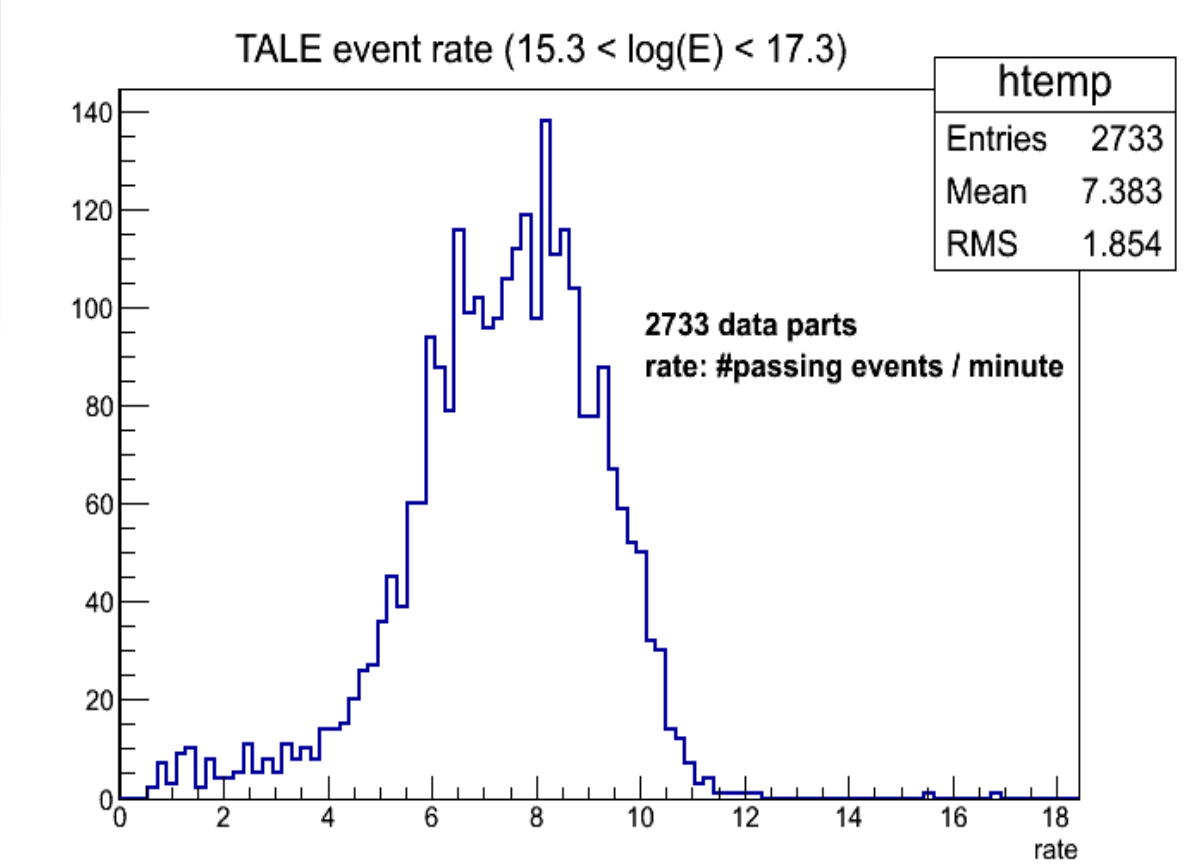
- Flux measurement depends on assumed atmospheric transparency
- Event rates: Number of reconstructed events in some predefined time window.
- Rates are energy dependent; a first approximation is to look at a wide energy range and use an average. … Avg. calculated by a fit (pol0)
- In the following we used an energy range of $15.3 < \log10(E\ [eV]) < 17.3$

Data Rates (data/MC)

- TALE MC is generated per data part.
  - 2X set; E^-2.92 spectrum, normalized to Kaskade-Grande at log(E) = 16.2
- The Atmosphere (GDAS) / Detector calibration are chosen according to actual run conditions.
- Exceptions:
  - MC run with average Aerosols
  - MC run with nominal sky-noise background levels
    - Minimal effect after filtering, reconstruction and QCs
- In the following plots, we count #events passing quality cuts (used for the spectrum calculation)

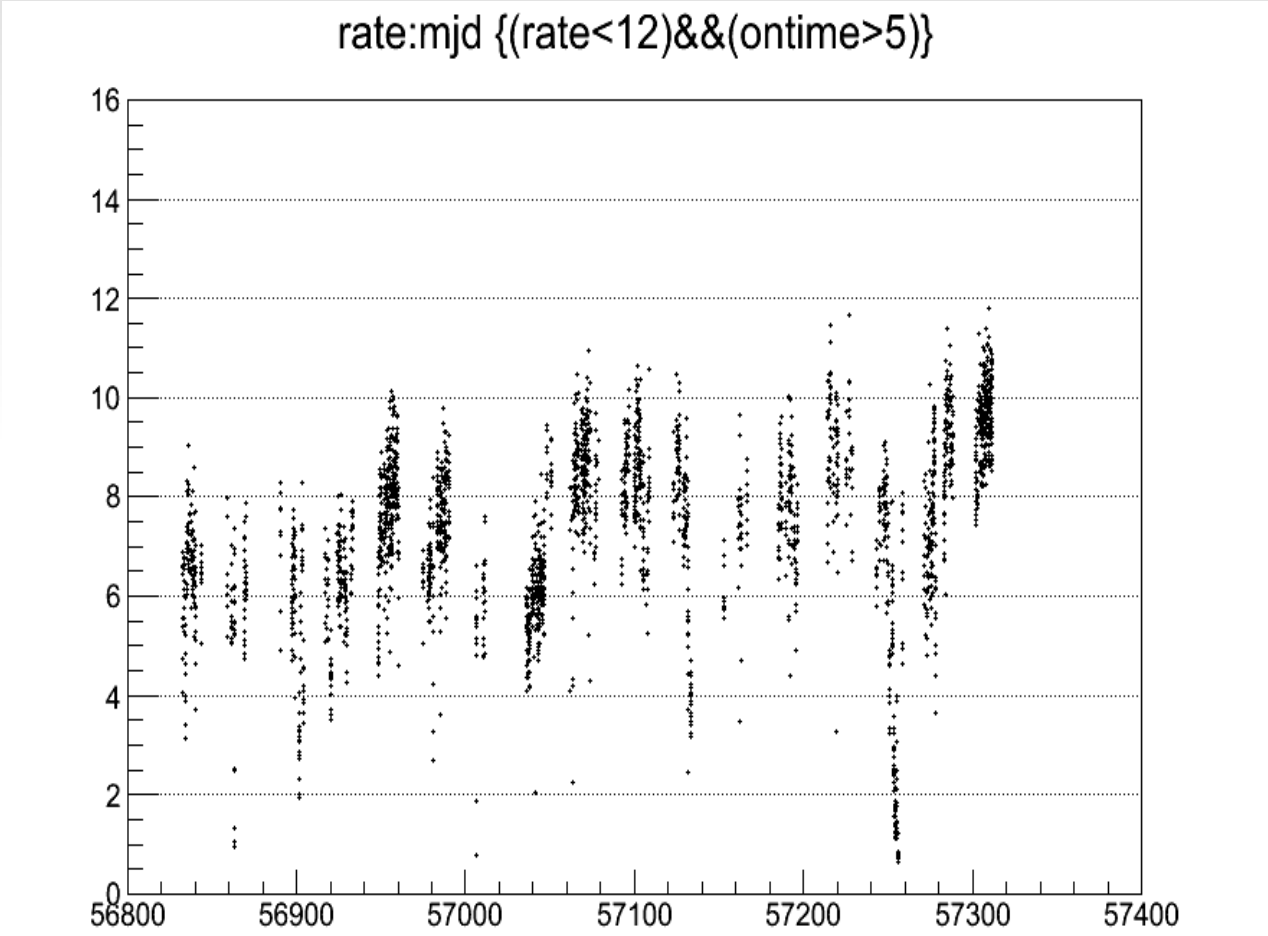
Data Rates

- Good weather selection based on cloud cover already applied
- Total of ~873 hrs in 2733 data parts.
- A typical data part is 20 minutes long.



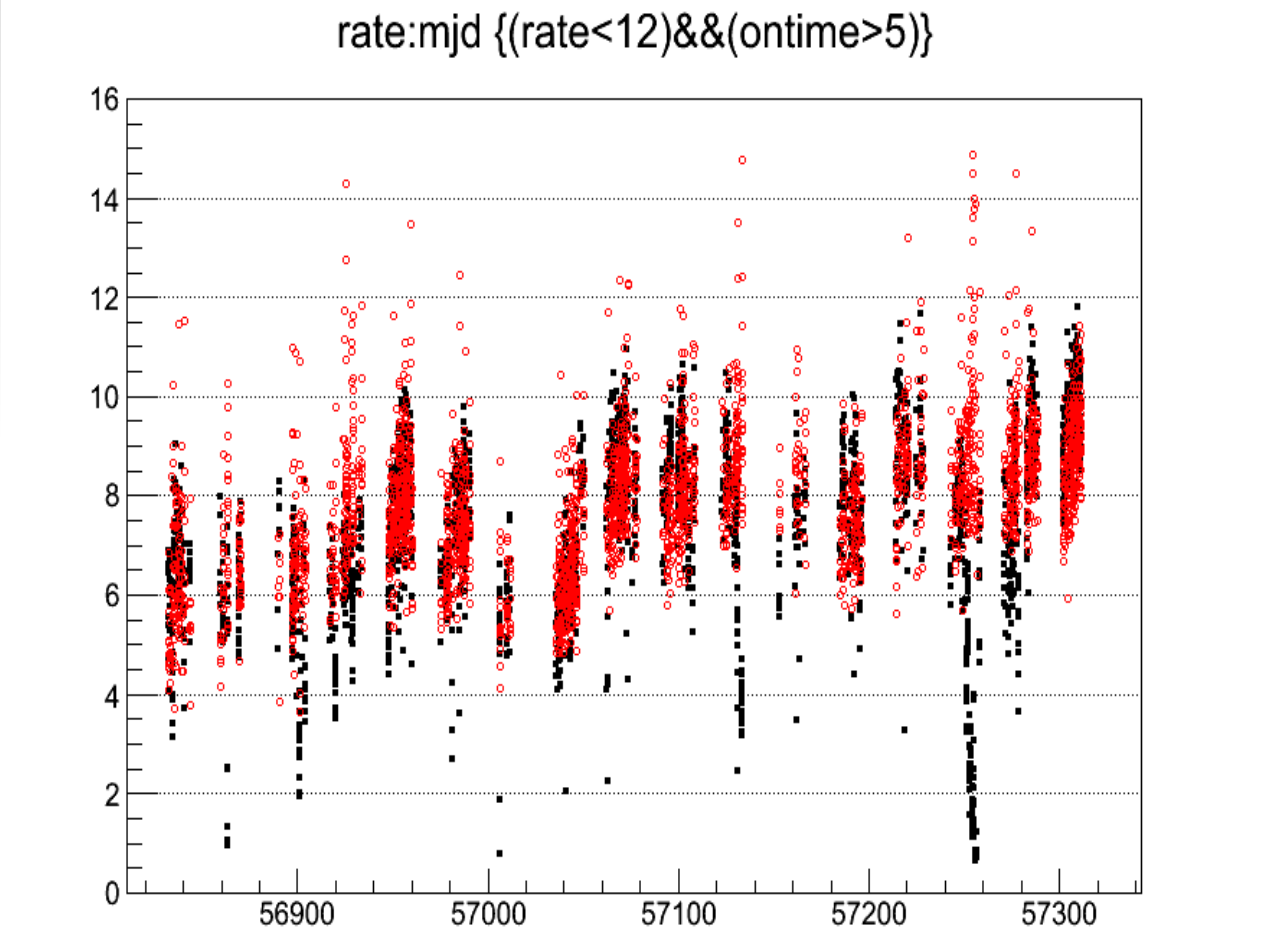
Data Rates

- TALE events vs. Modified Julian day
- First mjd with data corresponds to 06/24/2014
- Last entry is 10/16/2015



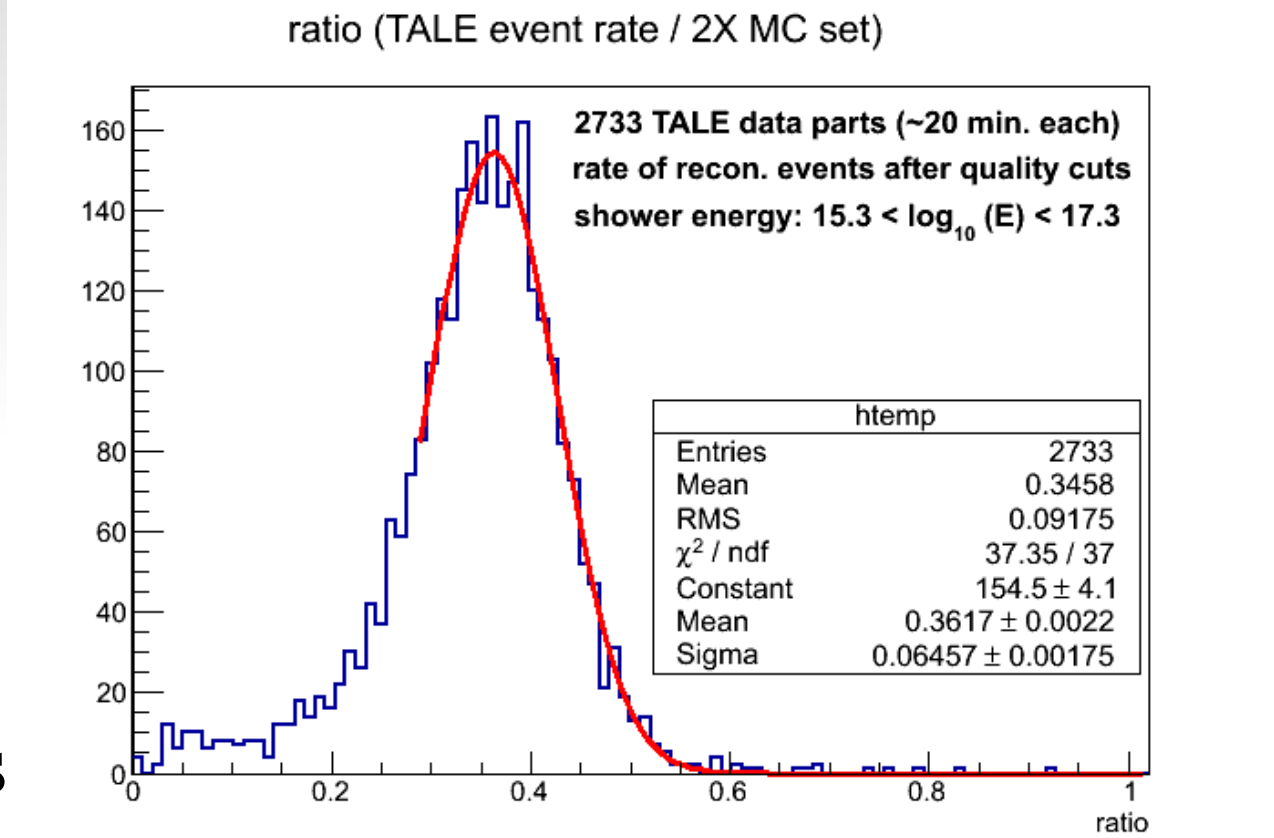
Data Rates (MC vs Real)

- TALE events vs. Modified Julian day
- First mjd with data corresponds to 06/24/2014
- Last entry is 10/16/2015
- Red points: MC prediction.



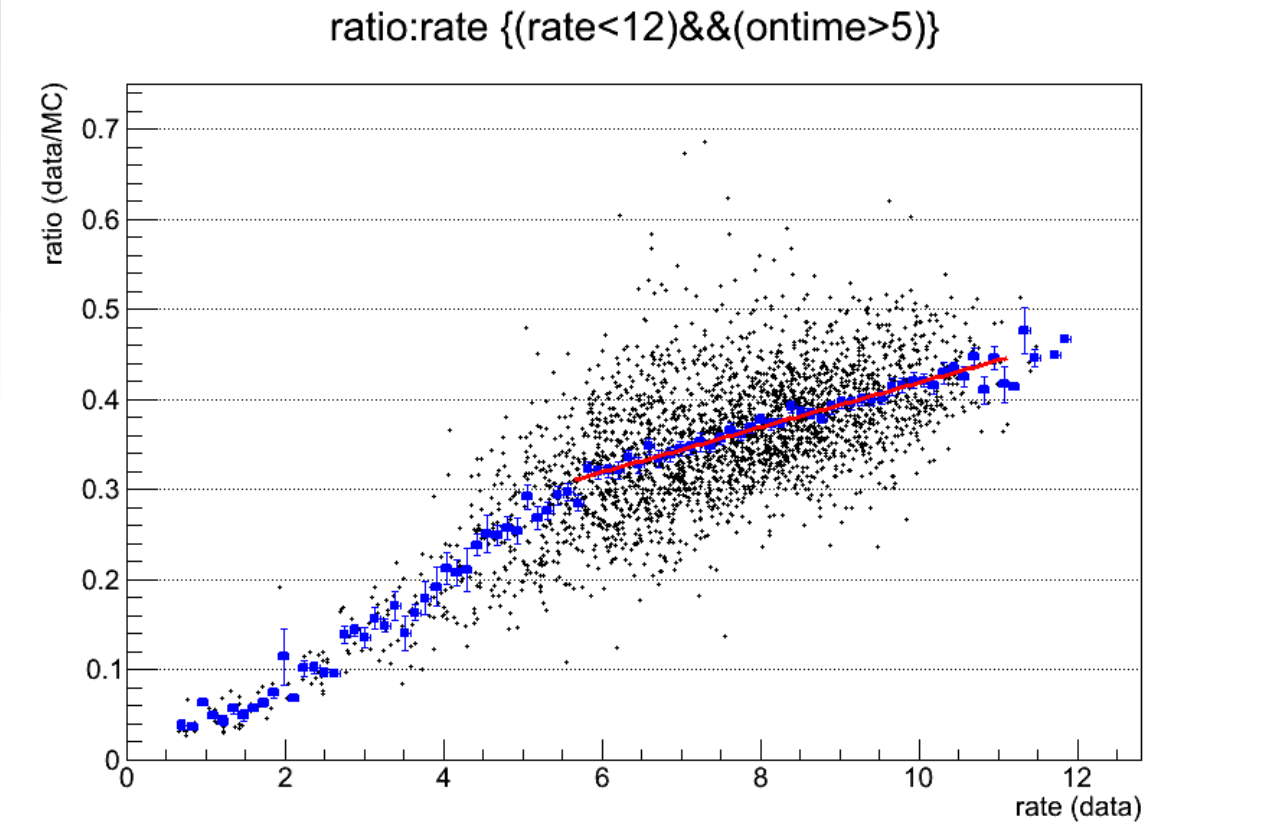
Data Rates (Ratio)

- Data/MC Events are histogrammed.
- Histograms divided and fit to pol0 function to calculate ratio.
- MC at E < $10^{15.6}$ is over-weighted! This makes the mean value of the ratio smaller than expected.



Data Rates (Ratio)

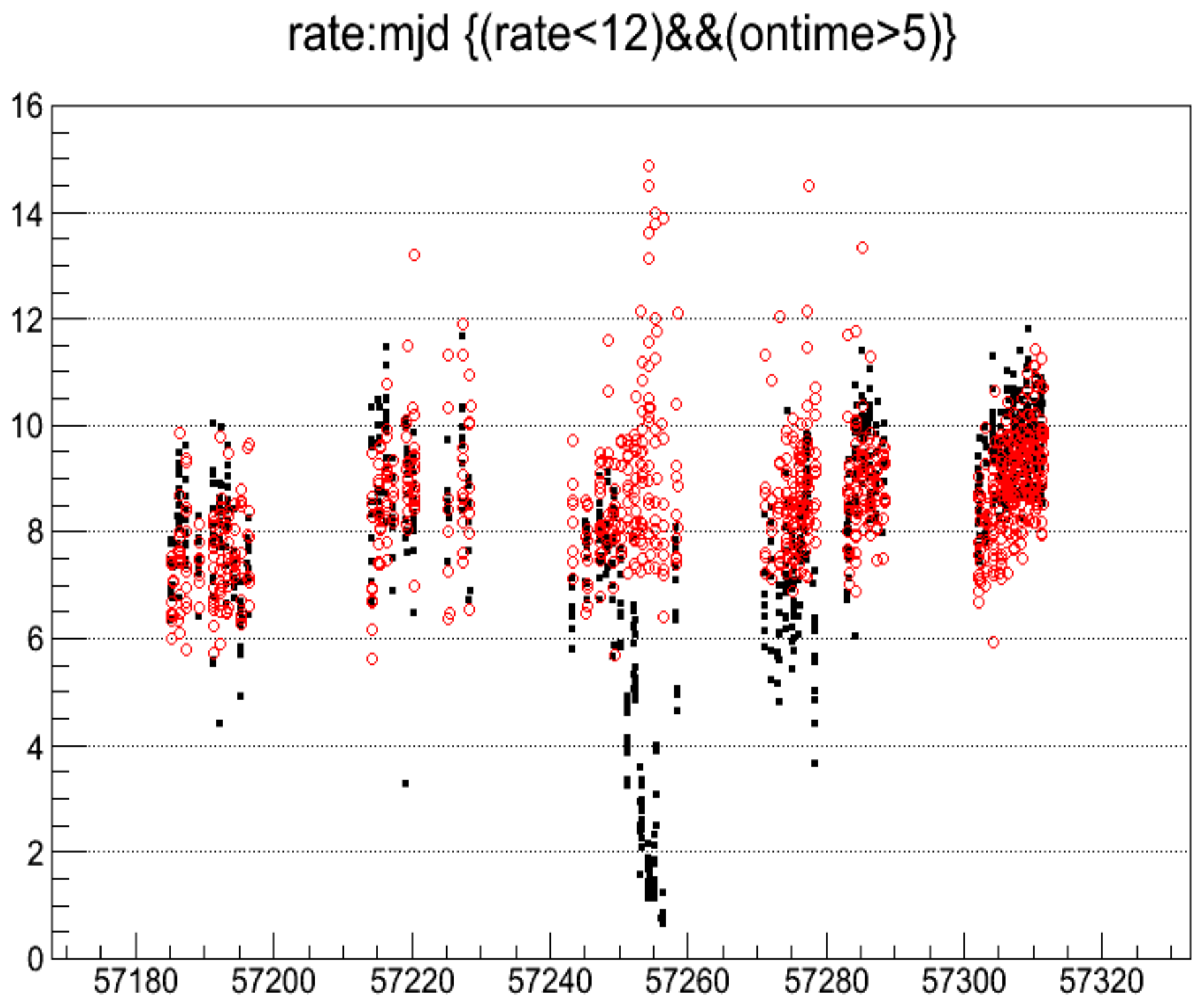
- Ideally, red line in the plot should be flat.
- Expect the difference to be due to the use of average aerosols in the simulation.
- Points were the rate is less than 4.5 mostly come from a few nights with more **haze** than typical.
- These nights are removed from the data set (~34 hrs)



Summary

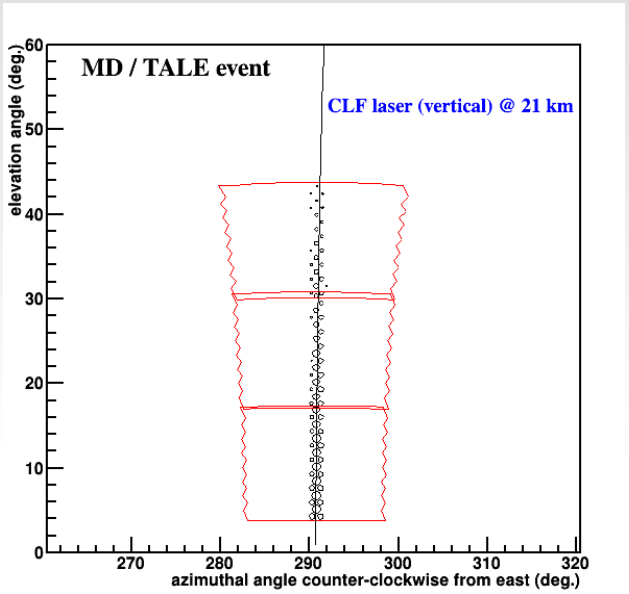
- Average VAOD measurement using the TA Central shows a mean of ~ 0.034 over a number of years.
- The nightly variation of VAOD around the mean is examined for its effect on reconstructed shower parameters (Energy and Xmax)
  - First by looking at data from MD site
  - Next by looking at simulations of MD & TALE FD's
- TALE event rates, i.e. predicted flux has some dependence (not yet fully quantified) on Aerosols. But overall effect should be small once "hazy" nights are removed from the analysis.

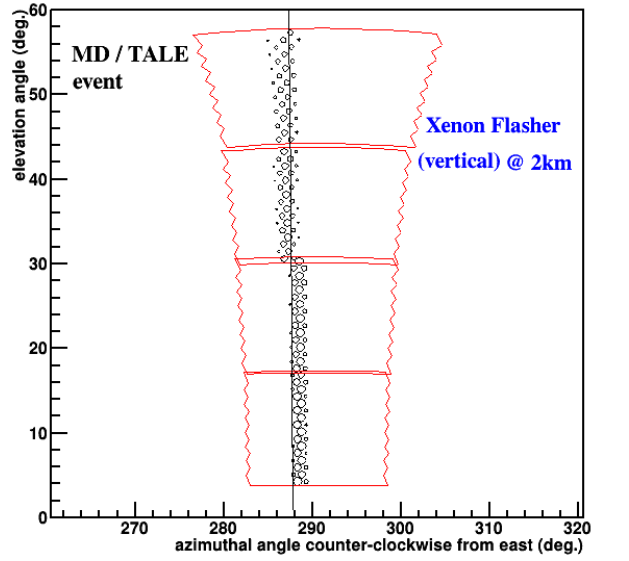
BACKUP SLIDES


rate:mjd {(rate<12)&&(ontime>5)}
16
14
12
10
8
6
4
2
0
57180
57200
57220
57240
57260
57280
57300
57320

CLF Laser seen in MD/TALE

- CLF shots seen in MD and TALE (ring 3)
- Xenon flashers were run for most of TALE operating period; located at a few km's from site.
- Data from BR and LR and MD (ring 1 & 2) sites used for Aerosols measurements.





How to measure VAOD

- Look at events with no clouds visible

  ➔ height = 4.3 km above CLF

- Observe N_{pe} by FD and know E_{laser} [mJ] at CLF

$$N_{pe}/E_{laser}\,(h) = f \cdot \underbrace{e^{-VAOD(1+\sec(\theta))}}_{\text{effect of aerosol scattering}} \cdot \underbrace{e^{-VROD(1+\sec(\theta))}}_{\text{effect of Rayleigh scattering}}$$

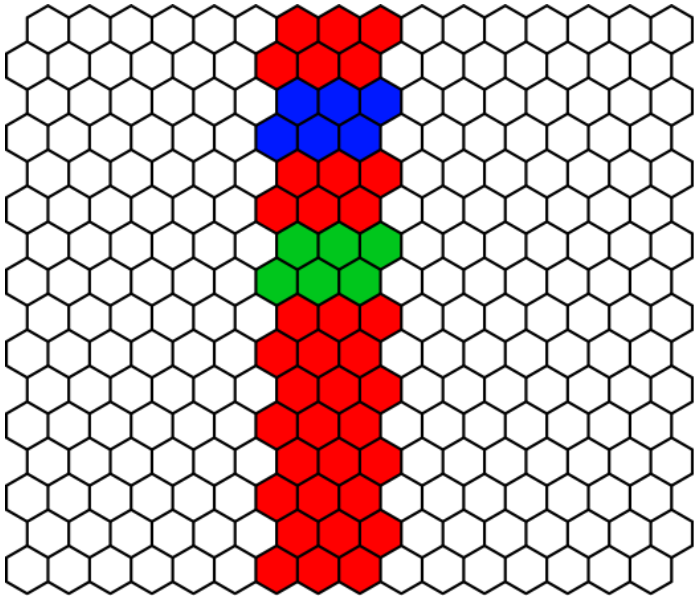
- Find Rayleigh nights, for which VAOD ≈ 0

Quality Cuts

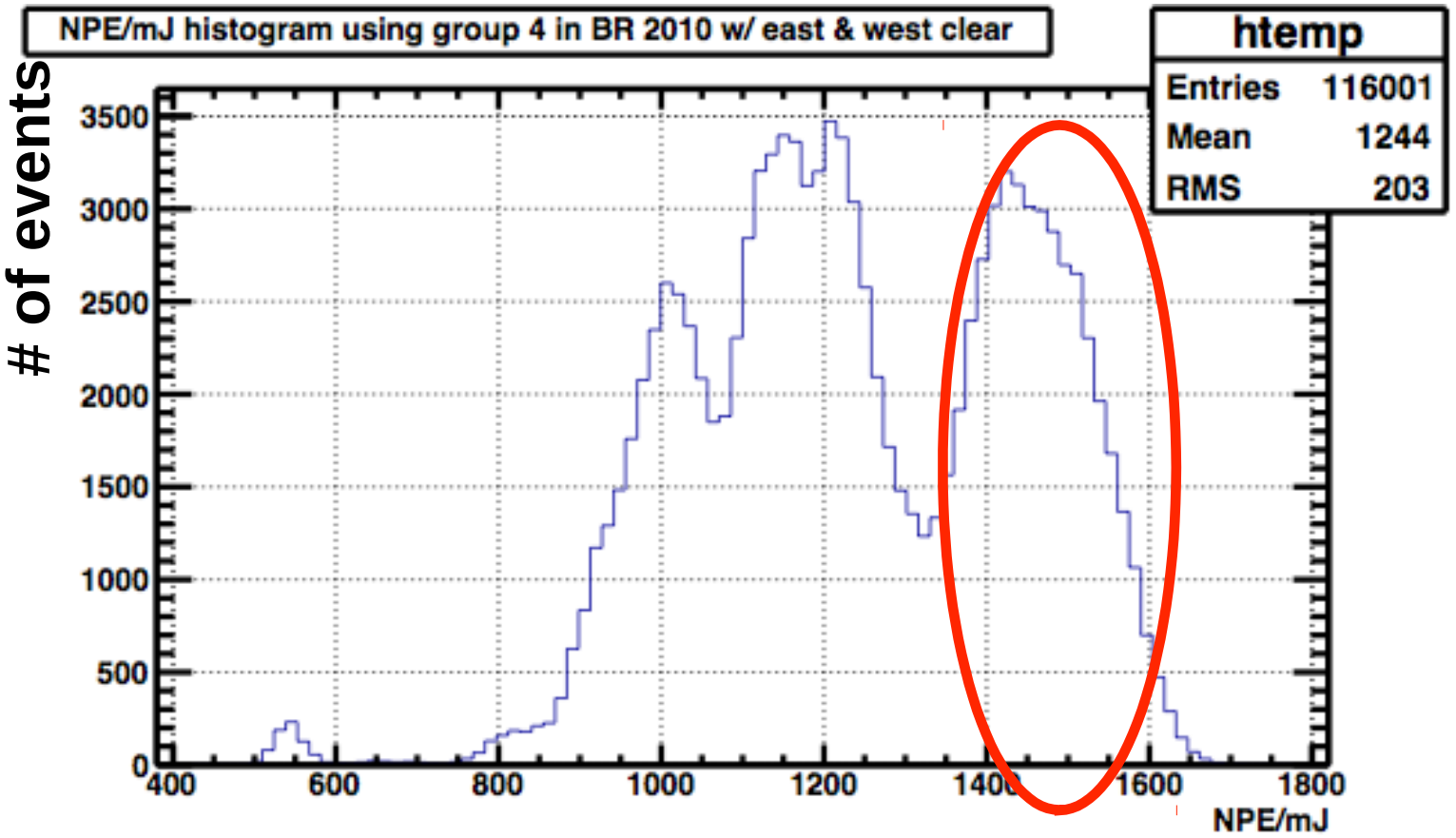
1. laser energy between 1 mJ and 10 mJ
2. To get rid of events with **clouds,** mushroom cut*; scattered by clouds
3. Sum of npe in each group* greater than 100 npe

Laser shots are on the central 3 ▶ columns (Red).

*group: 6 tubes (ex. Green or Blue)

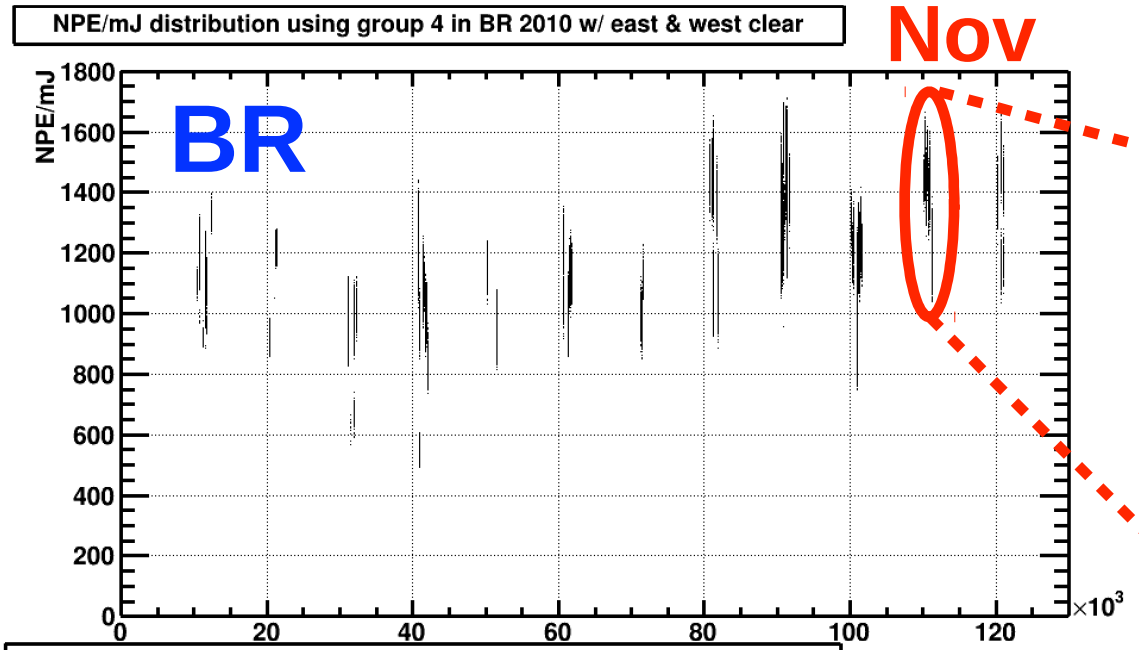


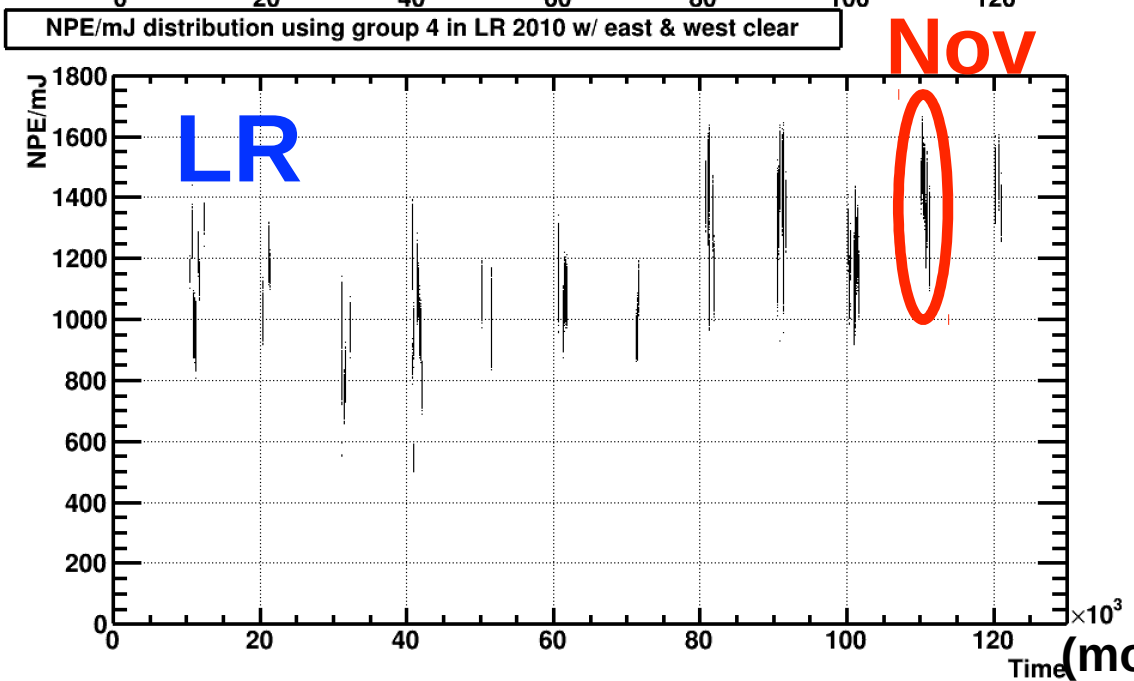
2010 Data: NPE/mJ histogram



Largest signal for Rayleigh nights

2010 Data: NPE/mJ vs Time





Nov. 3rd Entire night Perfect

Found the Rayleigh night