Shower Reconstruction with the Telescope Array Fluorescence Detector

I. Shower Reconstruction
II. Analysis in Monocular Mode

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+ Telescope Array Collaboration

Telescope Array Experiment

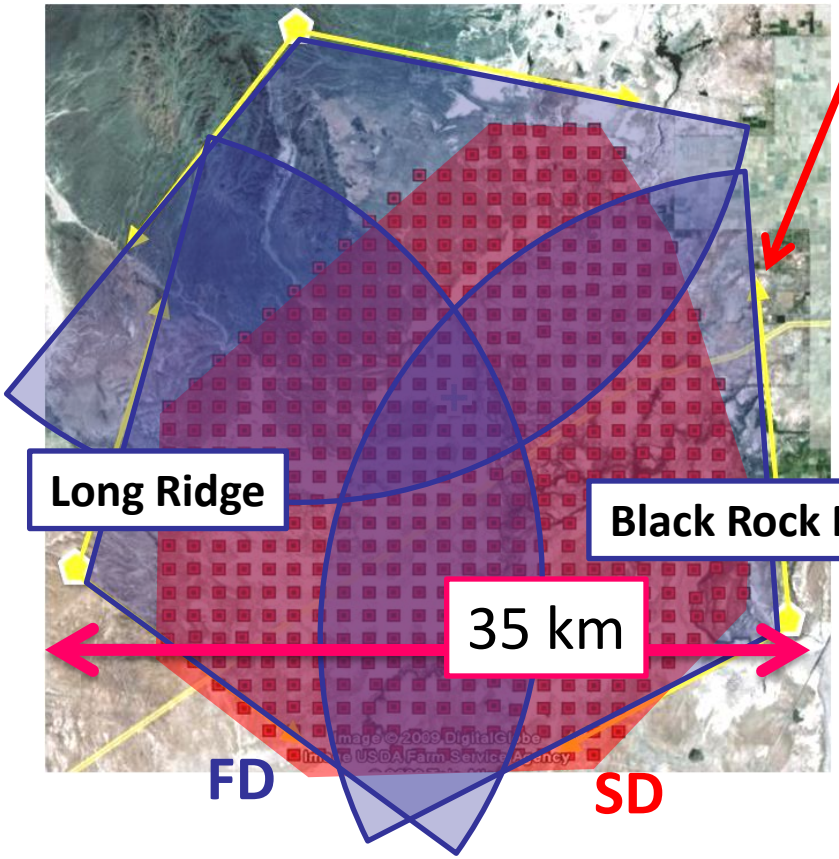
Middle Drum

507 Surface detectors（SD）

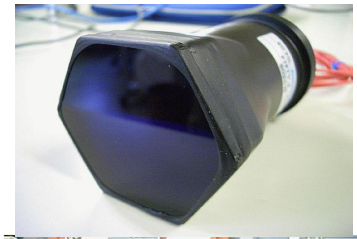
- Utah, US
- The largest detector in northern hemisphere ~700 km^2

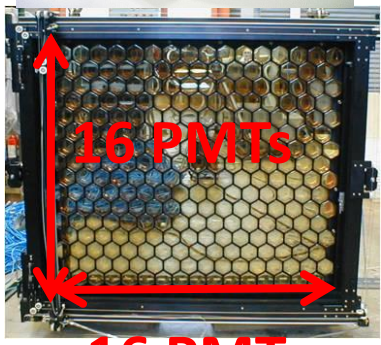
Fluorescence Detector (FD)

- Mirror Area: 6.8 m^2 (5.2 m^2)
- Camera: 16 × 16 PMTs
- 12+12+14 telescopes



38 Fluorescence detector（FD）





Shower Reconstruction Procedure

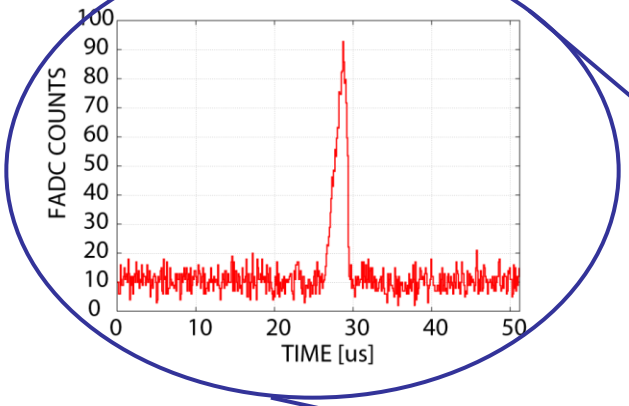
I. PMT Selection

II. Geometry Reconstruction
- Monocular Mode
- Stereo Mode
- Hybrid Mode

III. Shower Profile Reconstruction
- Inverse Monte Carlo

PMT selection

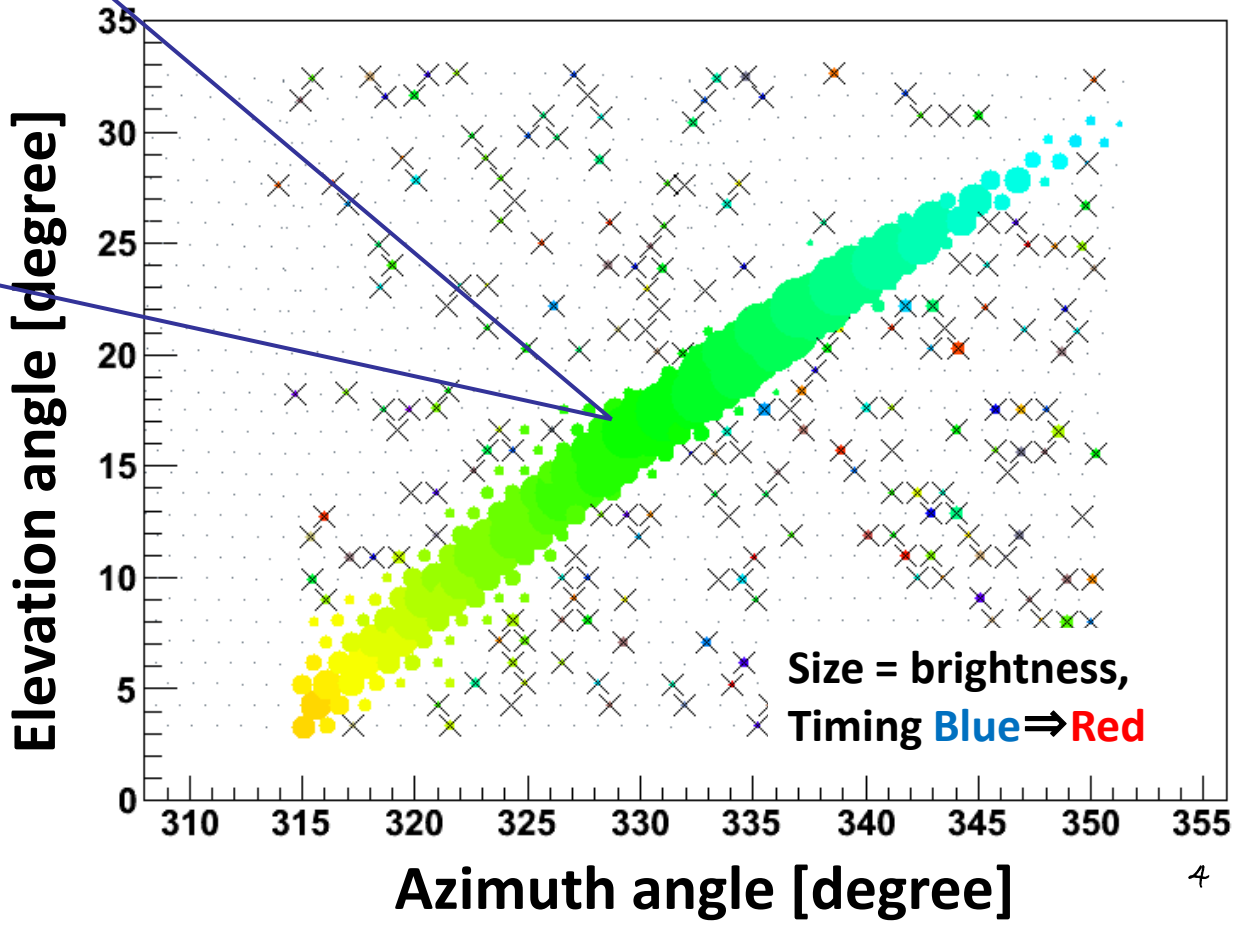
Waveform



If include the many noise PMTs, the resolution is lower.

Air shower signal should be sequential distribution in a track and signal timing

I. Geometrical distribution
II. Signal timing distribution



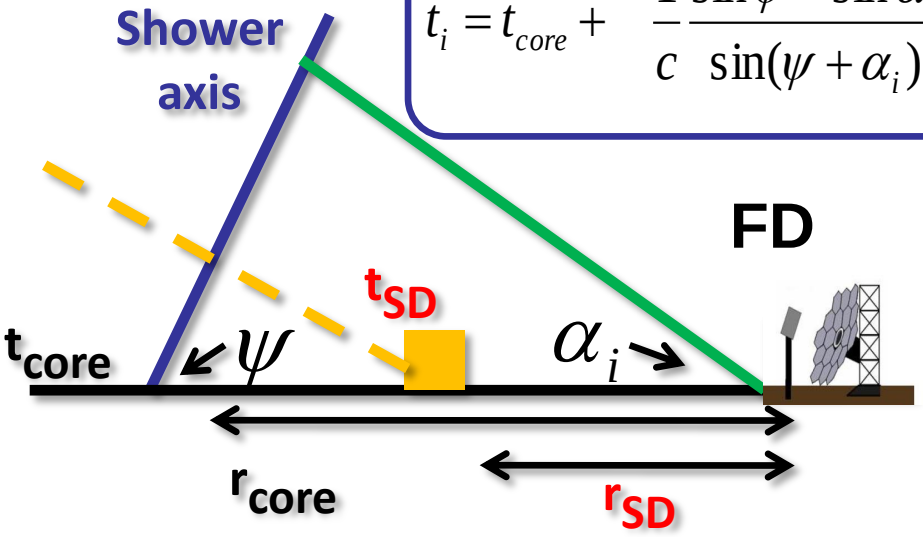
Geometry Reconstruction

Monocular Mode

◆Only 1 FD station

Timing Fit

$$t_i = t_{core} + \frac{1}{c}\frac{\sin\psi - \sin\alpha_i}{\sin(\psi + \alpha_i)} r_{core}$$

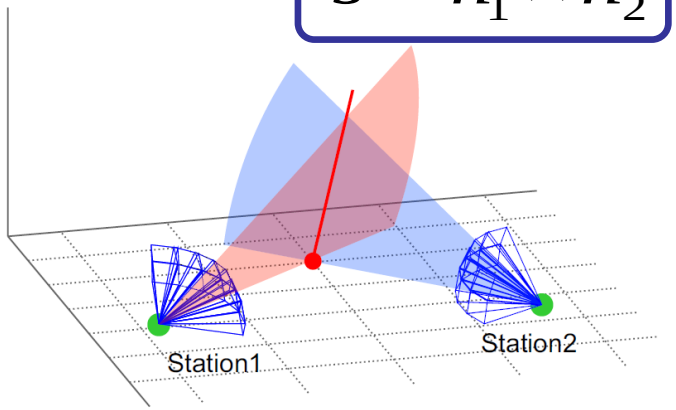


Stereo Mode

◆2 FD stations

Intersection of Shower Detector Planes

$$s = n_1 \times n_2$$



Hybrid Mode

Timing Fit by FD and SD

◆FD station + SD

◆Best resolution < 1°

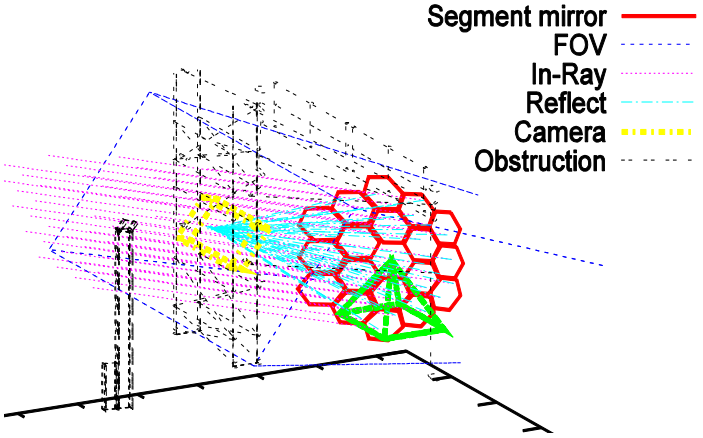
$$t_i = t_{core} + \frac{1}{c}\frac{\sin\psi - \sin\alpha_i}{\sin(\psi + \alpha_i)} r_{core}$$

$$t_{core} = t_{SD} + \frac{1}{c}(r_{core} - r_{SD})\cos\psi$$

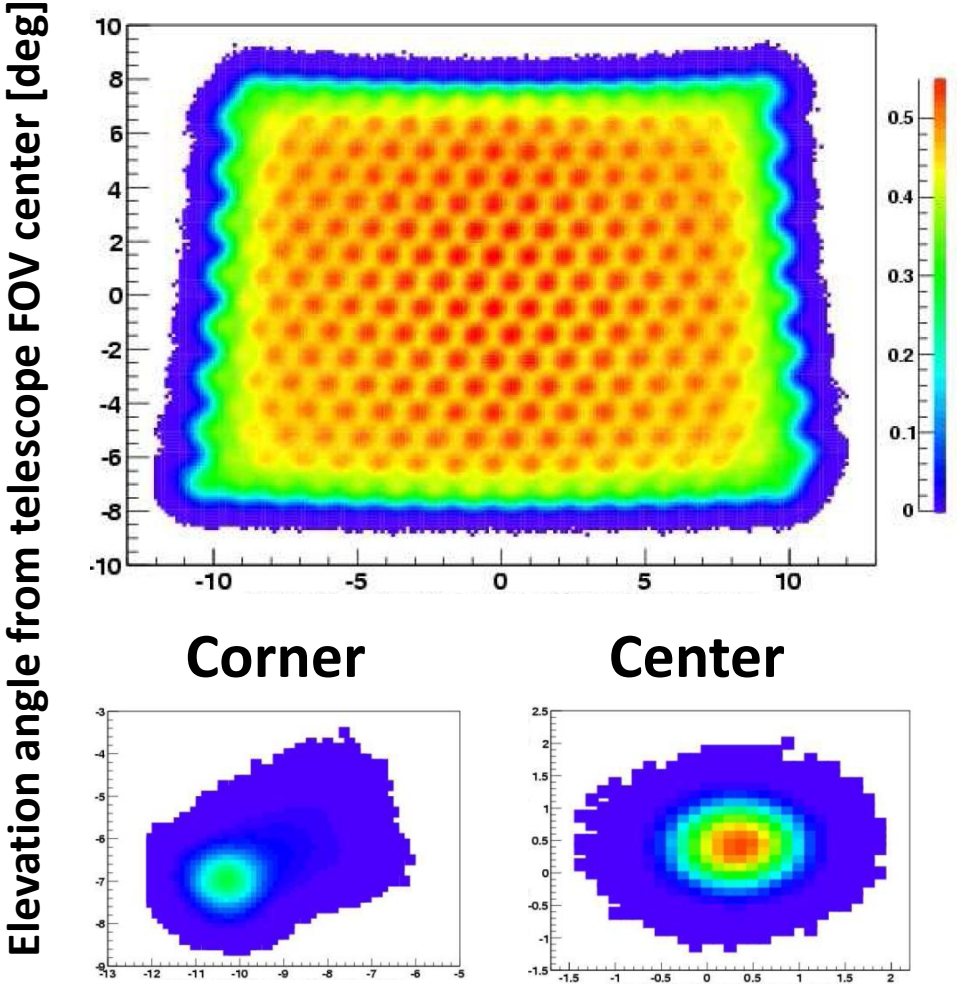
Database of directional sensitivity

- RayTrace **parallel photons** for each direction
- Consider the following effects
  - ✓Detector configuration and shadow
  - ✓PMT non-uniformity

(NOT depend on time)



Directional sensitivity of telescope

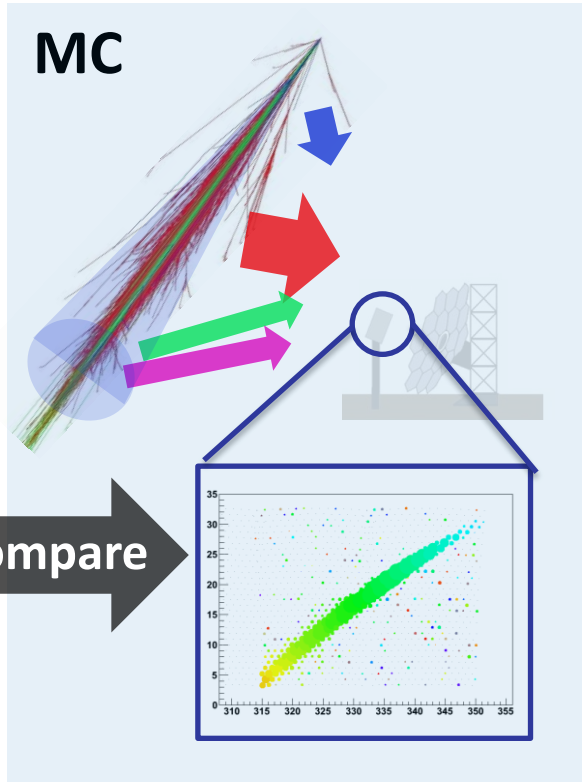


Filter transmittance and mirror reflectance = 100%

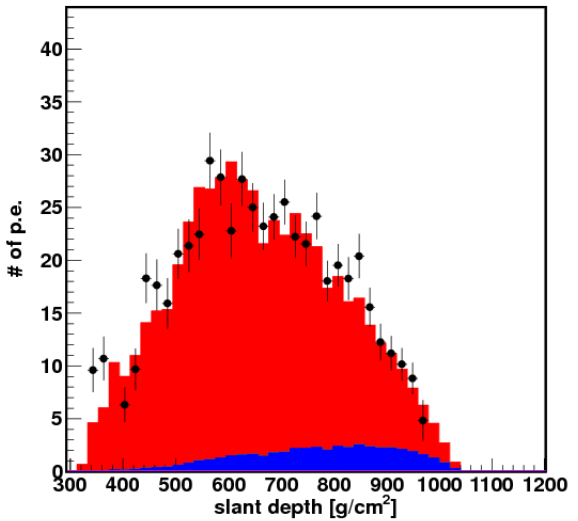
The Concept of Inverse Monte Carlo (IMC)

Reconstructed Shower Geometry

Repeatedly calculate shower images using **Database** with changing longitudinal development parameters



Signal at camera



Plot: Data
Histogram(Red): Fluorescence MC
Histogram(Blue): Cherenkov MC

Size = brightness, Timing Blue⇒Red

The detail calculation of IMC

1. Xmax (shower shape)

Search for the optimum Xmax in the repeated MC, maximized the following likelihood (X_0 = 0.0 g/cm^2, Nmax = 1.0, fixed)

$$L = \sum_{\mathrm{PMT}} \left\{ N_{\mathrm{pe,data}}^{\mathrm{PMT}} \log \left(\frac{N_{\mathrm{pe}}^{\mathrm{PMT}}}{N_{\mathrm{pe}}^{\mathrm{station}}} \right) \right\}$$

$$N_{\mathrm{pe}}^{\mathrm{station}} = \sum_{\mathrm{PMT}} N_{\mathrm{pe}}^{\mathrm{PMT}}$$

N_{pe}^{PMT} : # of photo-electrons for each PMT (MC)

$N_{pe}^{station}$: # of photo-electrons of station (MC)

$N_{pe,data}^{PMT}$: # of photo-electrons from Data

2. Nmax

Data(Nmax)

$$N_{\mathrm{pe,data}}^{\mathrm{station}} = \sum_{\mathrm{PMT}} N_{\mathrm{pe,data}}^{\mathrm{PMT}}$$

MC(Nmax=1.0)

$$N_{\mathrm{pe,Nmax=1}}^{\mathrm{station}} = \sum_{\mathrm{PMT}} N_{\mathrm{pe,Nmax=1}}^{\mathrm{PMT}}$$

Calculate the sum of p.e. of one station for MC(Nmax=1.0) and Data. Nmax is a ratio between these values.

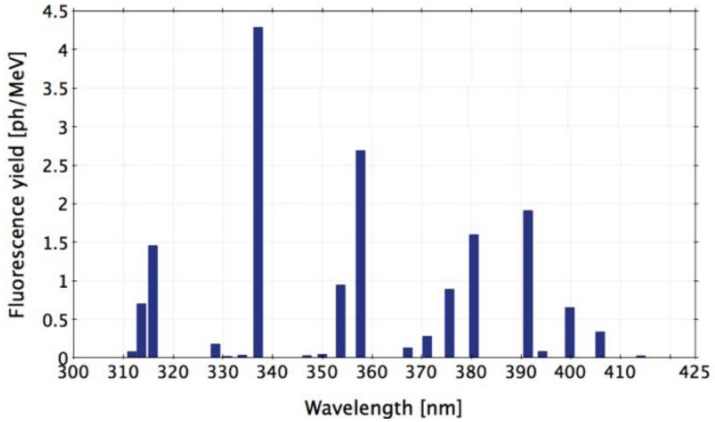
$$Nmax = \frac{N_{\mathrm{pe,data}}^{\mathrm{station}}}{N_{\mathrm{pe,Nmax=1}}^{\mathrm{station}}}$$

3. Energy

Integrate energy deposit and correct invisible energy

$$E_{cal} = \left\langle \frac{dE}{dX} \right\rangle \int_X N(X : X_{\max}, N_{\max}, X_0) dX$$

Energy Systematic Uncertainty (Hybrid Mode)



Fluorescence Yield 11%

Spectrum: FLASH

Abbassi *et al., Astropart. Phys.,* **29** 77-86 (2008)

Absolute: Kakimoto *et al.*

Kakimoto *et al., NIM A,* **372** 527-533 (1996)

Source	$\Delta E/E$
Fluorescence yield	11%
Calibration	10%
Atmosphere	11%
Reconstruction	10%
Total	**21%**

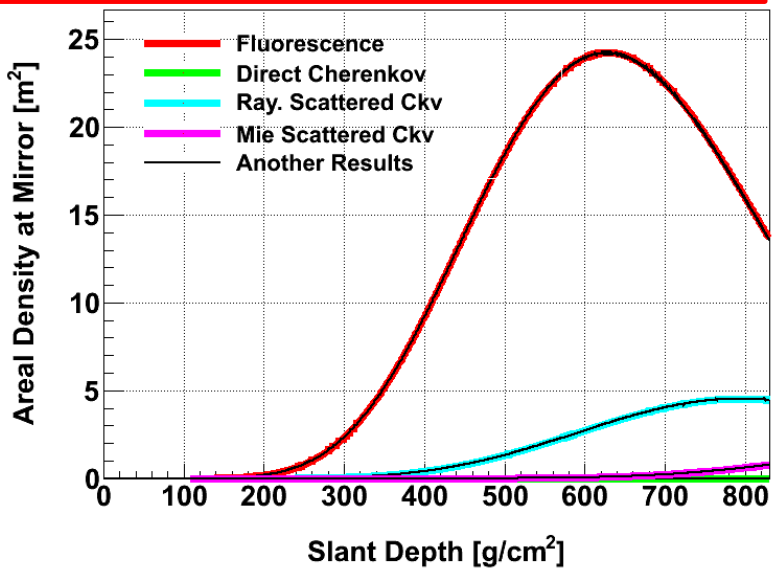
Cross check with another software

Compare with another independently developed software

Cross Check 1

◆Generate the perfectly identified air shower in both simulations

Photon density at mirror is completely agreement

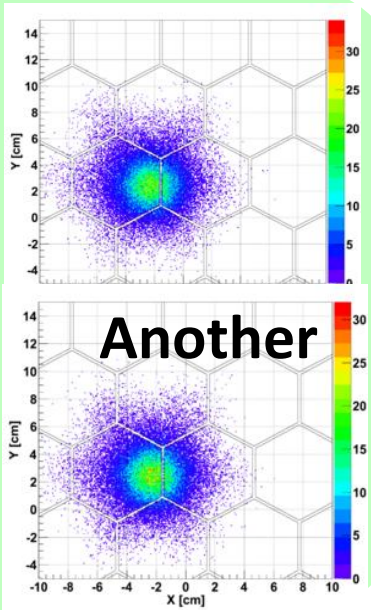


Cross Check 2

Raytrace from Point source

- ➢Detector configuration
- ➢Detector Shadow

Good agreement < 2%



Cross Check 3

data analysis independently

- ➢PMT selection
- ➢Geometry reconstruction
- ➢Shower profile reconstruction

Reconstructed Energy is good agreement < 4%

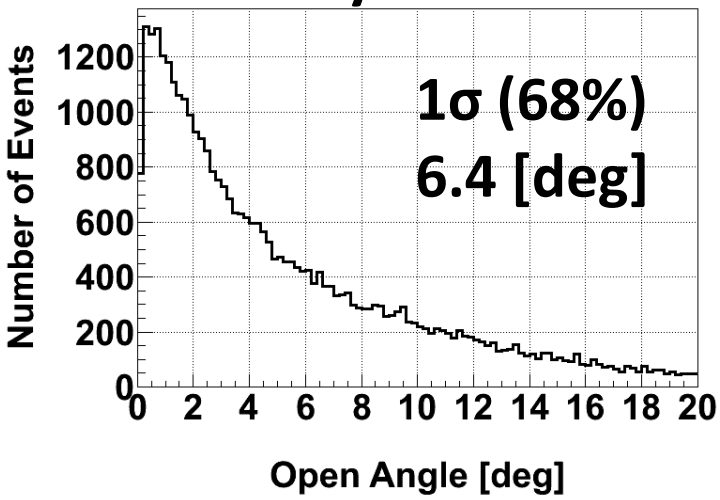
FD Analysis in Monocular Mode

MC study: Resolution in Monocular Mode

Monocular analysis

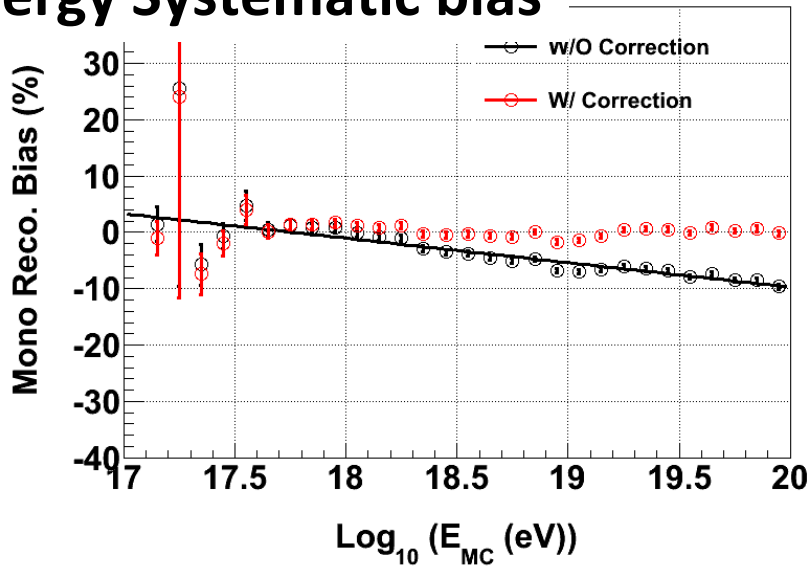
- Corsika QGSJET-II **Proton**
- LogE: 17.0 - 20.0
- Spectrum index = -1.0
- Zen: 0-65 deg, Azi: 0-360 deg
- Core: less than 35 km from TA Center

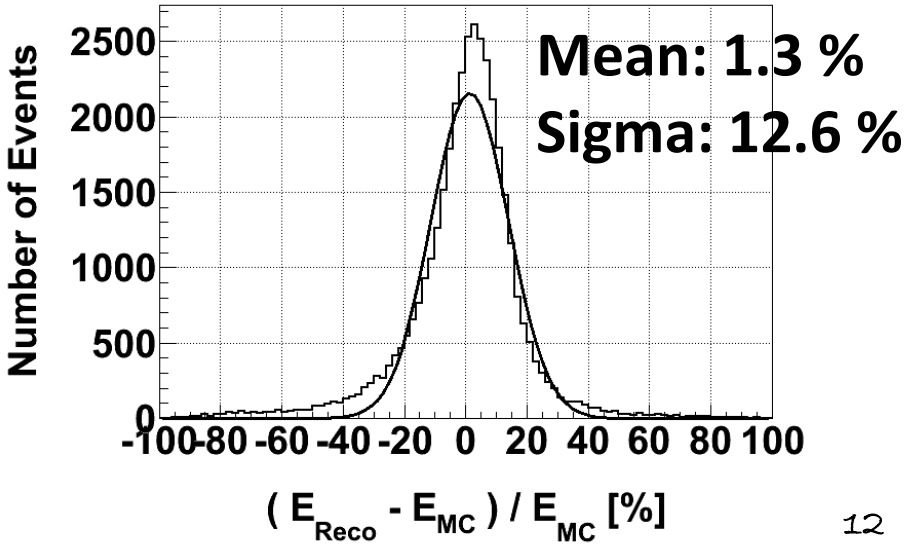
Geometry Resolution



Energy Resolution

Energy Systematic bias





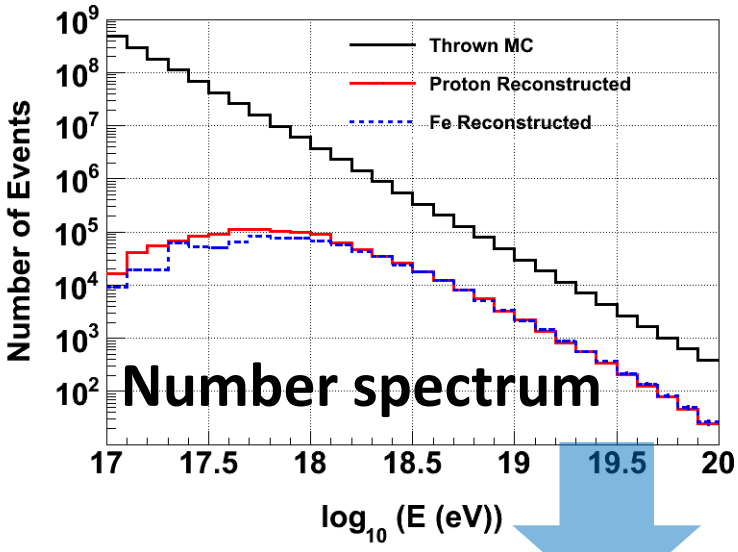
Aperture calculation in Monocular Mode

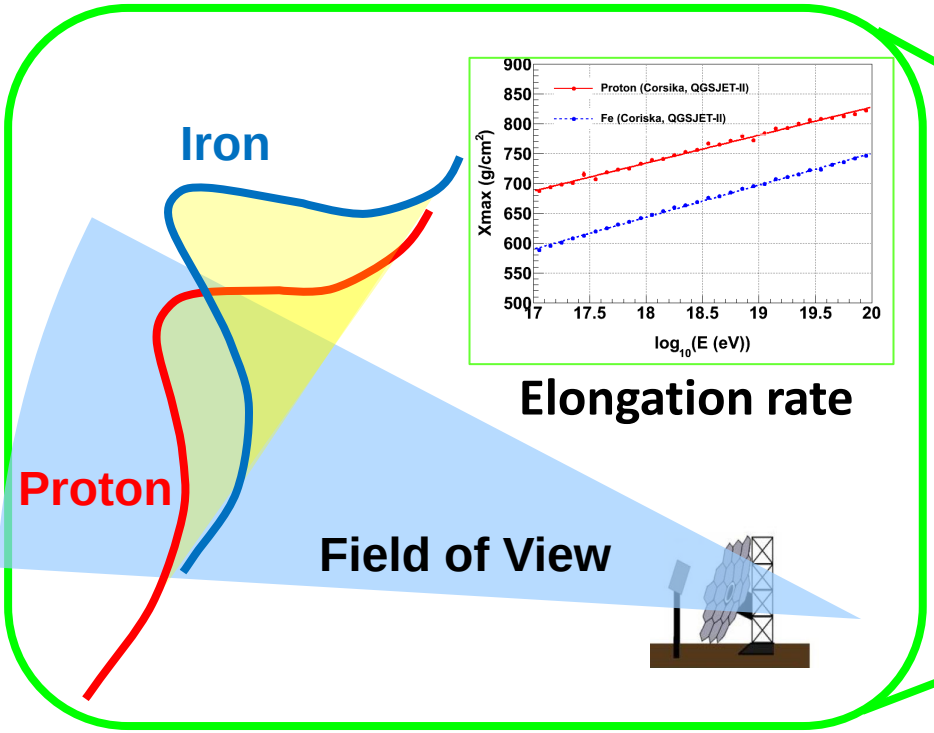
Model: Corsika (QGSJET-II)

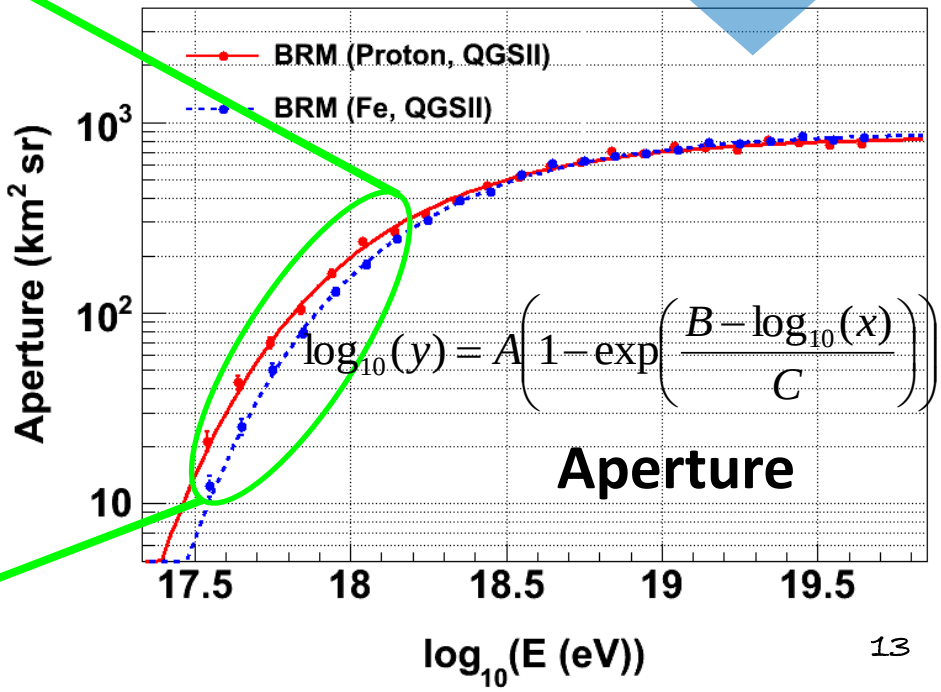
Proton and Iron

$$Aperture = Area^{MC} \times \frac{\#reco.}{\#MC}$$

Weight: $J(E) \propto E^{-3.1}$

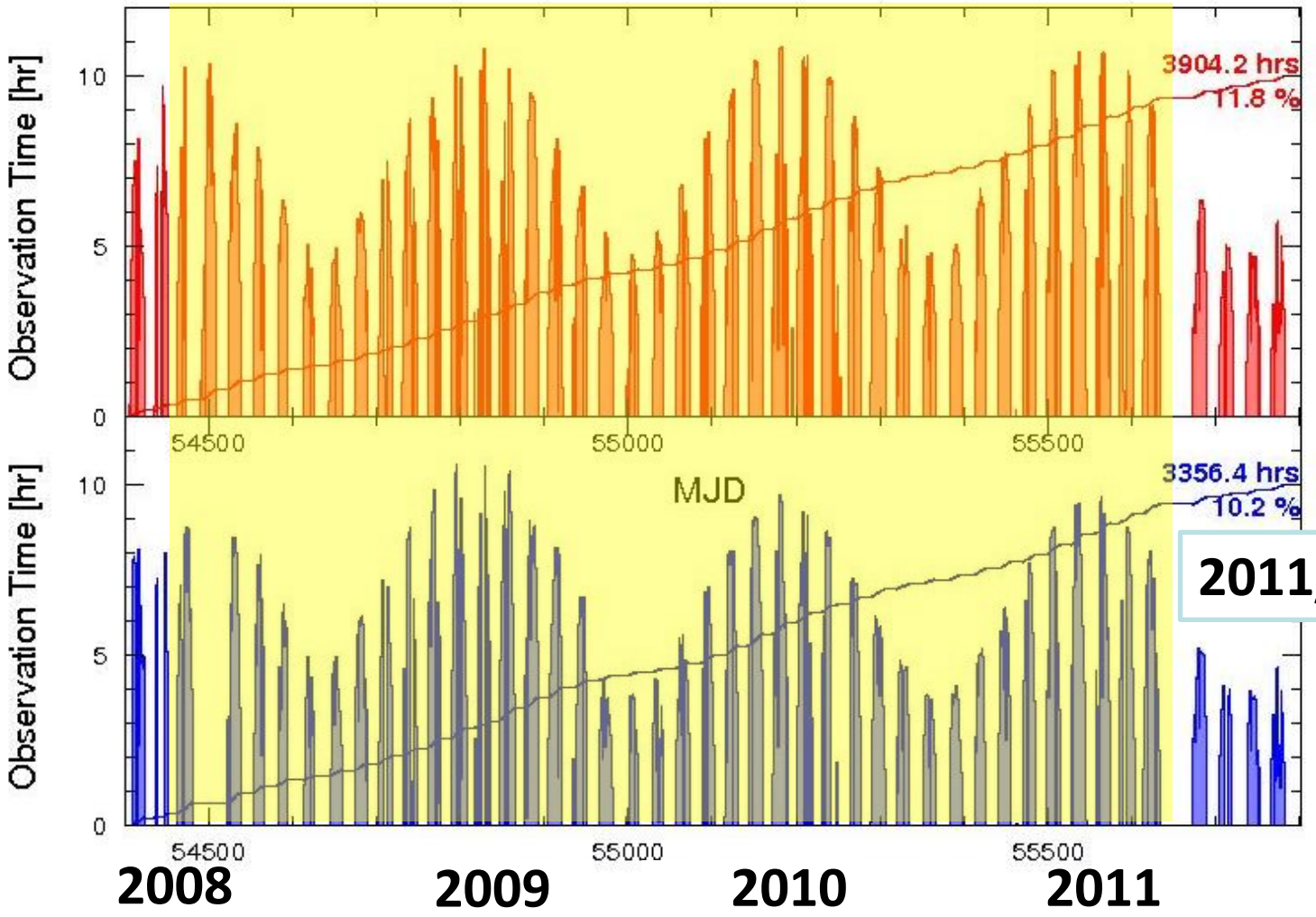






Data Analysis in Monocular Mode

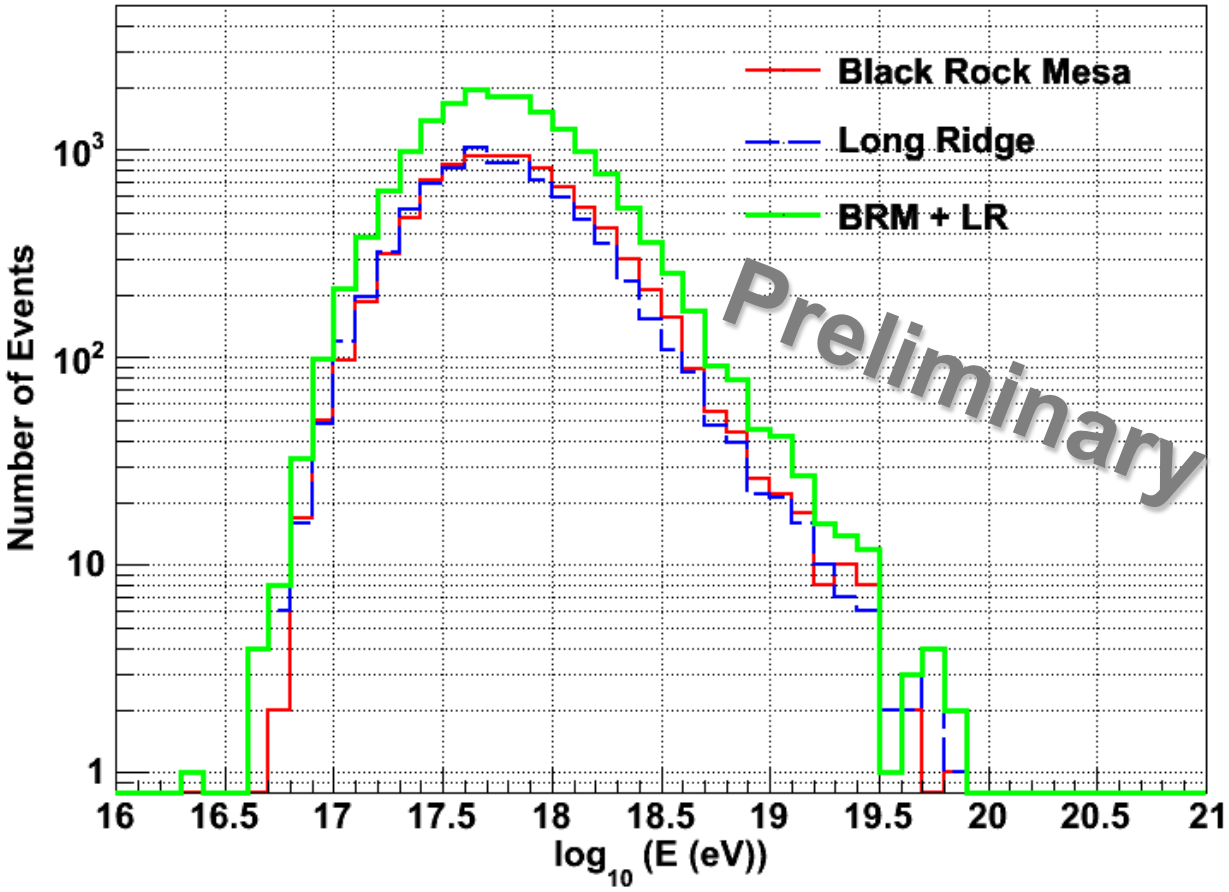
Observation Time and Data Set



2008/Jan/01 ~ 2011/Mar/13 3.3 yrs (Monocular analysis)

BRM: 2280 hrs LR: 1974 hrs (cloud cut and dead time subtracted)

Number Spectrum (Data)



Black Rock Mesa: 8905 events, Long Ridge 8378 events, BRM+LR 17208 events

(selected the result with a larger number of photo-electrons)

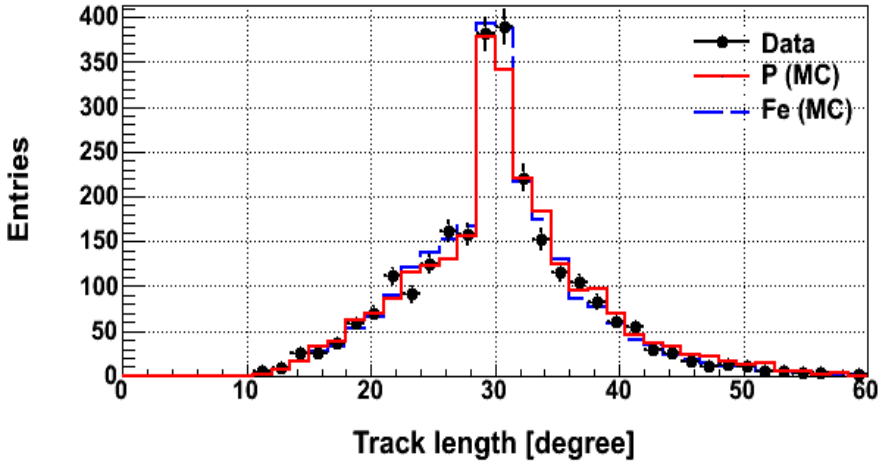
1 station: 1 air shower for every 15 min.

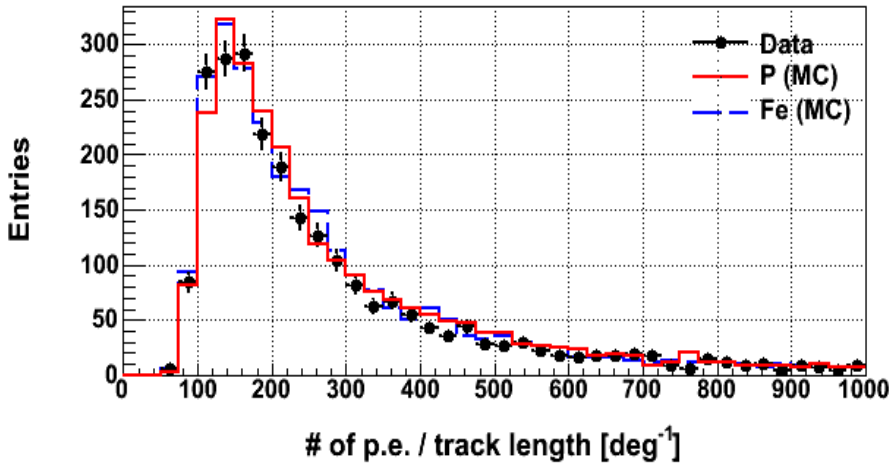
Data/MC comparison

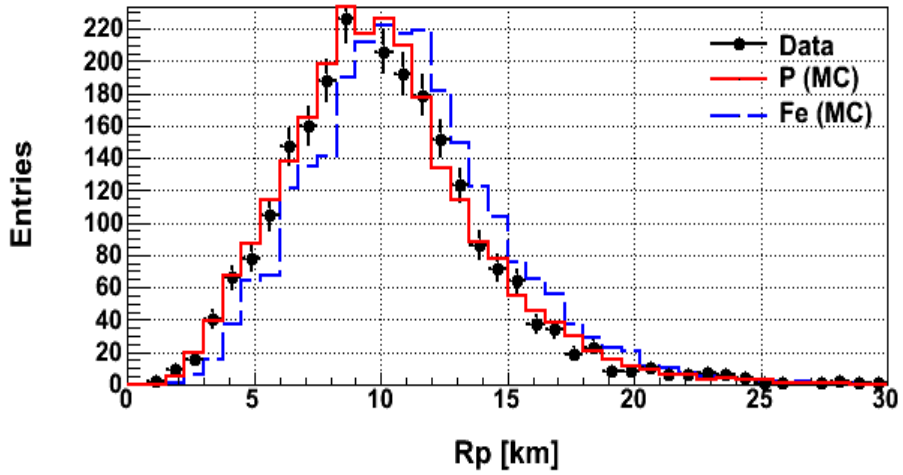
Black Rock Mesa

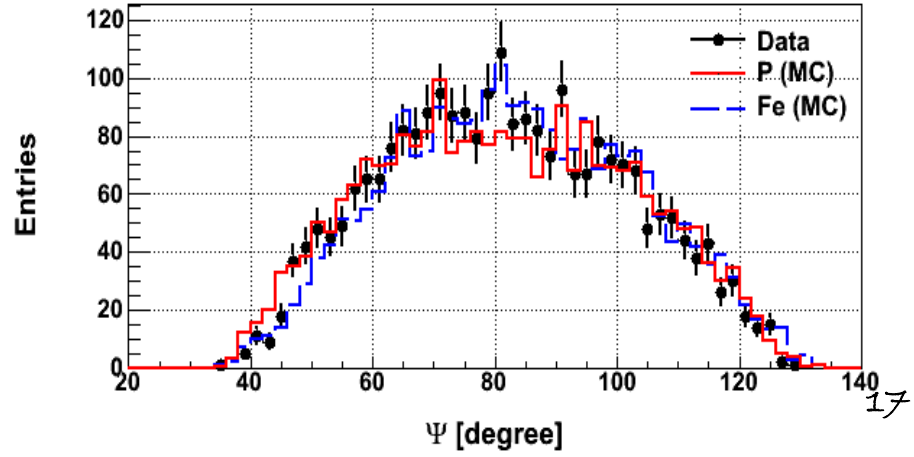
Energy > 10^{18}eV

Histogram(Red): Proton MC
Histogram(Blue): Fe MC
Plot: Data









Summary

- FD analysis in Monocular Mode
  - Resolution :
    - Arrival direction 6.4 [deg]
    - Energy: 12.6%
- Good agreement for cross check with another independently developed software
- BRM and LR data analysis during 3.3 yrs in Monocular Mode
- Data/MC comparison is very consistent

Future plans

- Energy spectrum, mass composition