The Cosmic Ray Spectrum above 10^{17} eV Measured by the Telescope Array and TALE Fluorescence Telescopes

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PhD defense

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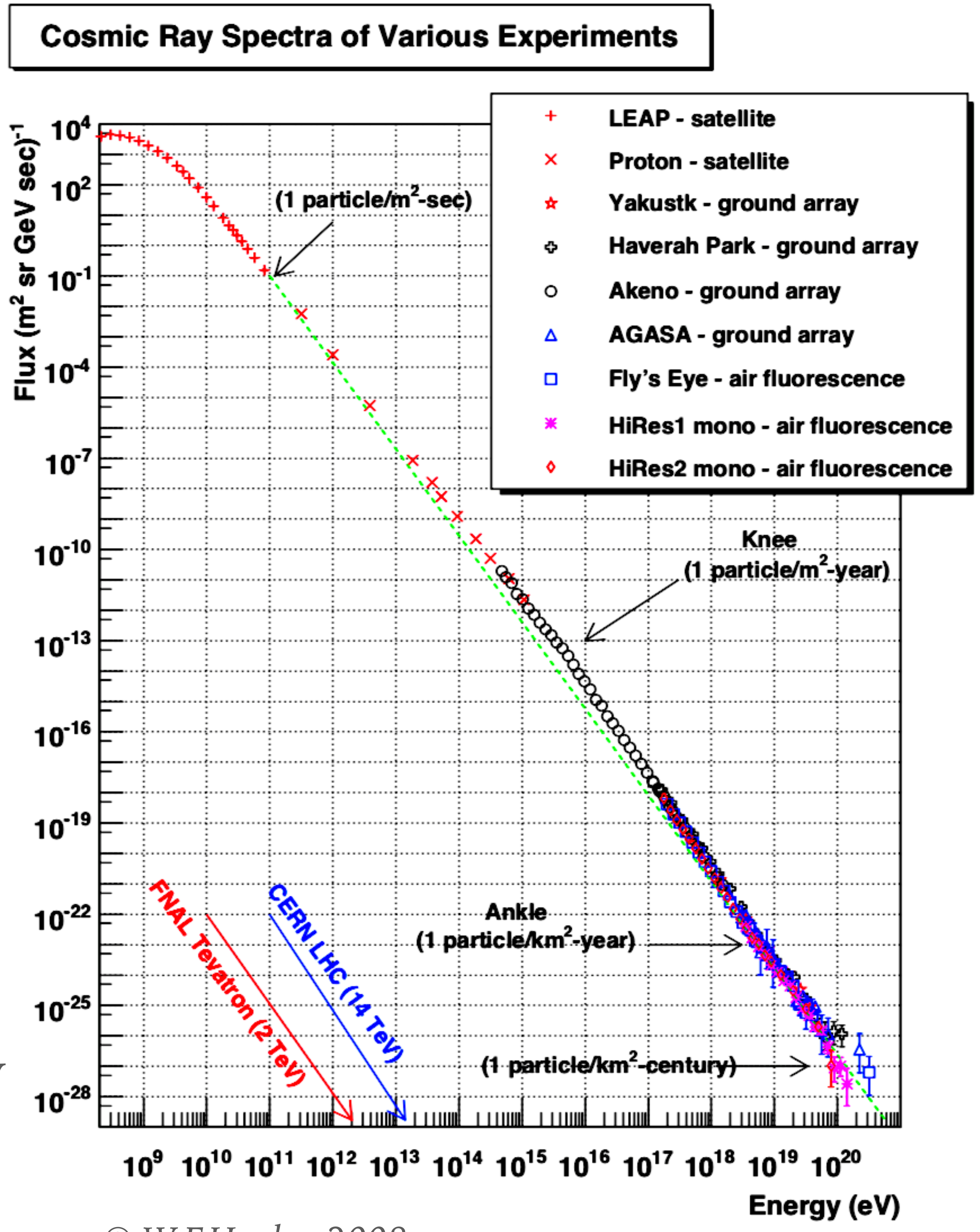
OUTLINE

- Introduction - Cosmic Rays
- Telescope Array and TALE Experiments
- Extensive Air Shower
- Monte Carlo Simulation
- Event Reconstruction
- Data/MC Comparison
- Energy Spectrum Measurement
- Conclusions (take-home message)

INTRODUCTION – COSMIC RAYS

- Cosmic rays : Energetic particles accelerated by astrophysical sources.

- Solar cosmic rays below ~ a few 10^9 eV
- Galactic cosmic rays below ~10^{17} eV, extragalactic cosmic rays above
- Ultra-High Energy Cosmic Rays (UHECRs) above 10^{18} eV
  - In 1991, Fly's Eye Experiment observed 3.2×10^{20} eV
  - At present, Large Hadron Collider (LHC) reaches 1.3×10^{13} eV



INTRODUCTION – COSMIC RAY MEASUREMENTS

There are three main topics of cosmic ray research:

- **Cosmic Ray Energy Spectrum**

  - Flux follows a simple power law : Flux(E) $\sim E^{-\gamma}$, γ is spectral index

  - Spectral features where spectral indices change

- **Cosmic Ray Composition**

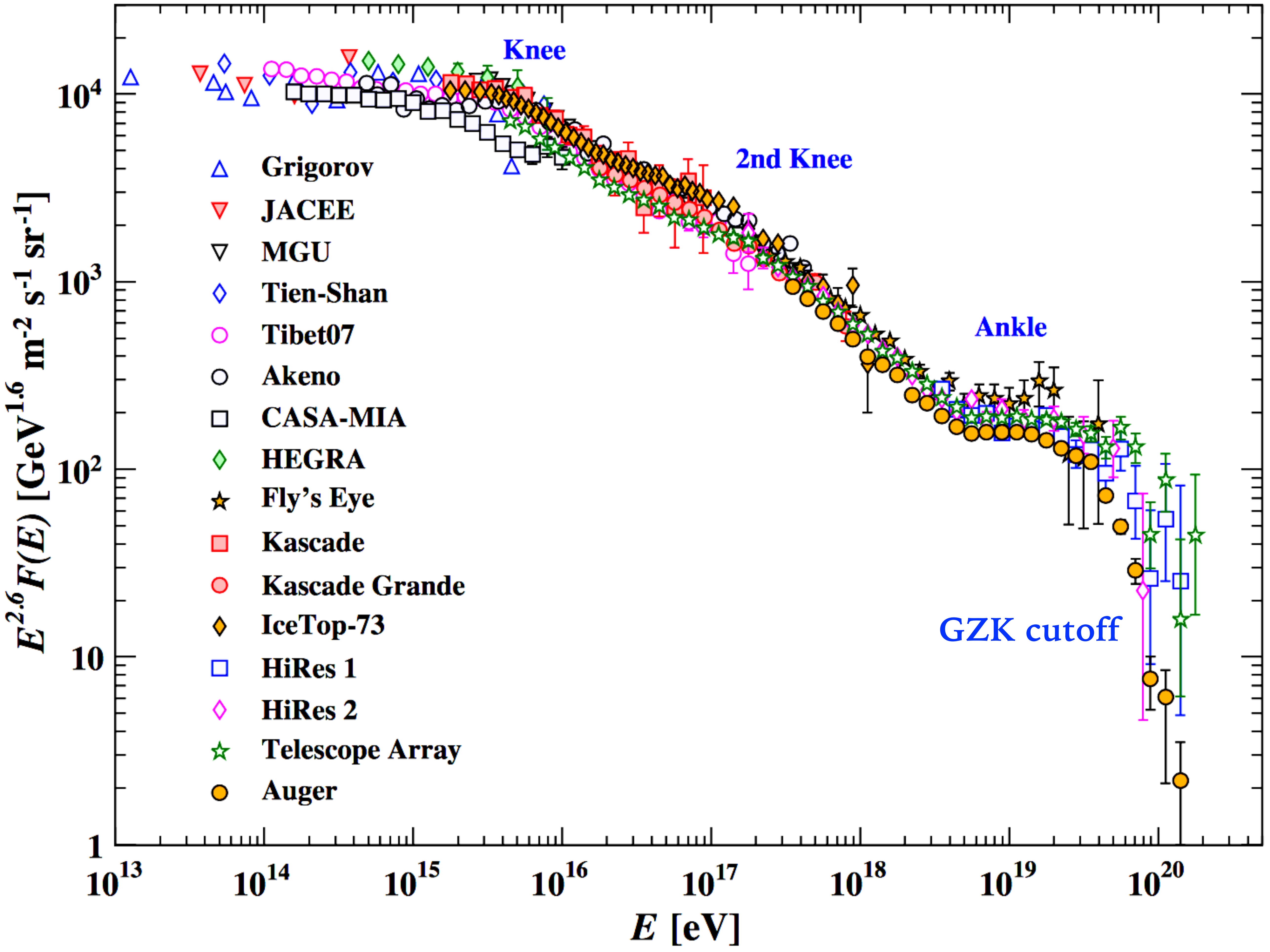
  - Chemical composition of cosmic rays: nuclei type

- **Cosmic Ray Sources**

  - Arrival direction of cosmic rays and correlation with possible sources

INTRODUCTION – COSMIC RAY ENERGY SPECTRUM

- Near E ~ $10^{15.6}$ eV, **"Knee"**
  γ changes from 2.7 to 3.0
- Near E ~ $10^{16.2}$ eV, **"Dip"**
- Above 10^{17} eV,
  "2nd Knee" or **"Iron Knee"**
- At E ~ $10^{18.7}$ eV, **"Ankle"**
  becomes less steep
- At E ~ $10^{19.8}$ eV, **"GZK cutoff"**
  flux drops dramatically



INTRODUCTION - COSMIC RAY ENERGY SPECTRUM

- “**Knee**”, $E \sim 10^{15.6}$ eV

  - Associated with galactic sources: Supernova Remnants (SNRs); shock fronts

  - Maximum energy of galactic cosmic ray protons

  - Acceleration through magnetic fields, rigidity dependent

$$E_{max}(Z) = Ze \times R_c = Z \times E_{p\ max}, \quad \text{where } R_c = E/Ze$$

  - **Rigidity-dependent effect**: heavy charged nuclei can achieve Z times higher energy than a proton when accelerated in a magnetic field

- “**2nd Knee**” or “**Iron Knee**”, $E \sim 10^{17.1}$ eV

  - 10^{17} decade in energy region may be a transition from galactic cosmic rays to extragalactic cosmic rays (heavy nuclei to light nuclei)

INTRODUCTION – COSMIC RAY ENERGY SPECTRUM

- **"Ankle"**, E ~ $10^{18.7}$ eV

  - Dip in the flux of cosmic ray particles; origin not yet fully resolved

    1. Pair production from ultra-high energy protons : $p + \gamma_{CMB} \rightarrow p + e^- + e^+$
    2. Galactic/extragalactic transition
    3. Rigidity-dependent cycle

- **"GZK cutoff"**, E ~ $10^{19.8}$ eV

  - Theoretical upper limit on energy of cosmic rays coming from sources: 5-6$\times 10^{19}$ eV

  - Cosmic rays traveling over distances > 50 Mpc likely collide and form Δ resonance

$$p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow p + \pi^0 \quad \text{or} \quad p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow n + \pi^+$$

INTRODUCTION – COSMIC RAY MEASUREMENTS

There are three topics of cosmic ray research:

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  - Flux follows a simple power law : Flux(E) $\sim E^{-\gamma}$, γ is spectral index

  - Spectral features where spectral indices change

- Cosmic Ray Composition

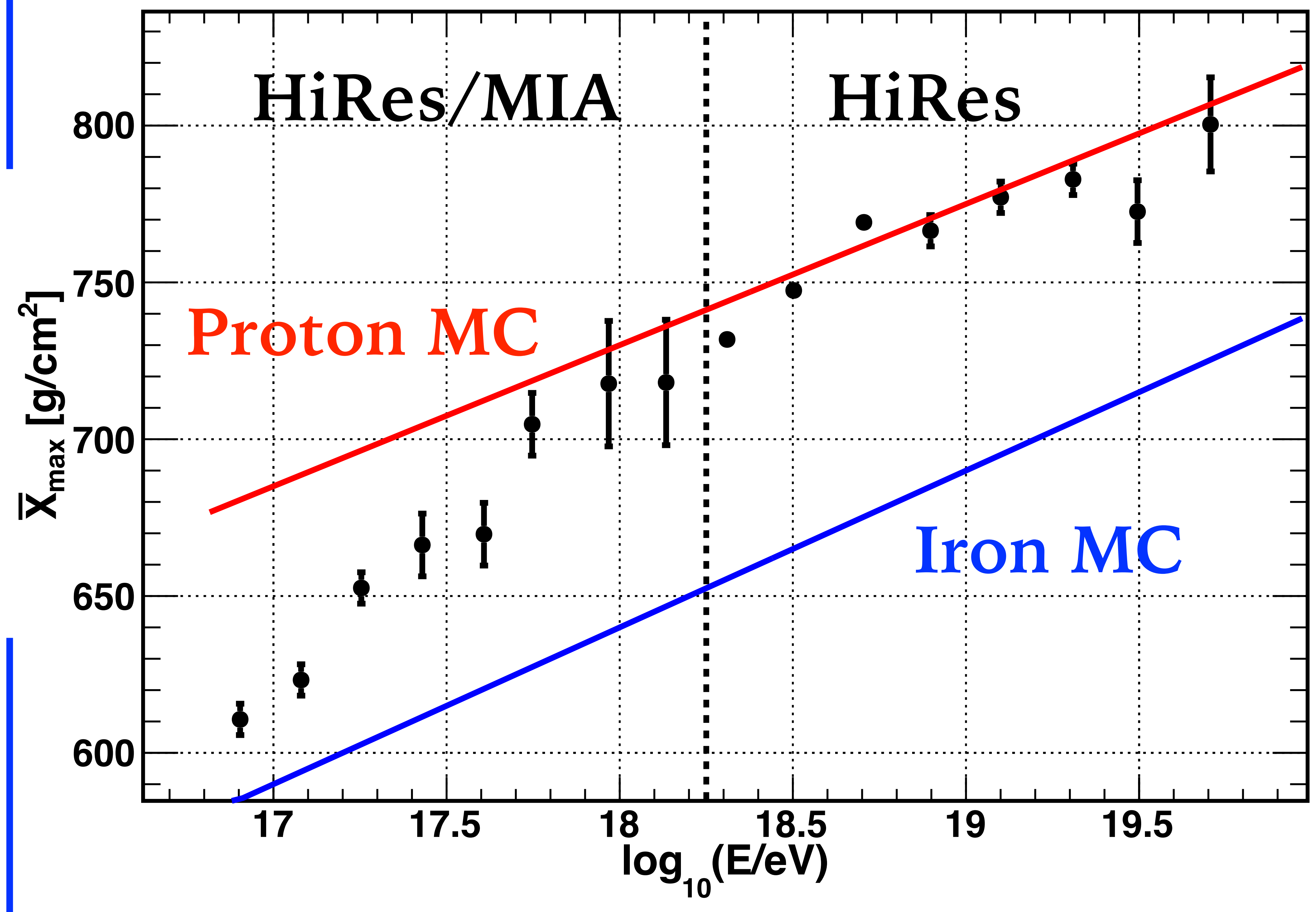
  - Chemical composition of cosmic rays: nuclei type

- Cosmic Ray Sources

  - Arrival direction of cosmic rays and correlation with possible sources

INTRODUCTION – COSMIC RAY COMPOSITION

Close to ground



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Close to top of atmosphere

- Study depth of shower max, X_{max}, maximum number of charged particles, in extensive air shower
- Chemical composition determines average characteristics of the shower development

  - Proton penetrates deeper

  - Iron interacts w/ air molecules earlier (superposition of 56 nucleons)

- **Previous composition result will be used for my study**

INTRODUCTION – COSMIC RAY MEASUREMENTS

There are three topics of cosmic ray research:

- ➤ **Cosmic Ray Energy Spectrum**

  - Flux follows a simple power law : Flux(E) $\sim E^{-\gamma}$, γ is spectral index

  - Spectral features where spectral indices change

- ➤ **Cosmic Ray Composition**

  - Chemical composition of cosmic rays: nuclei type

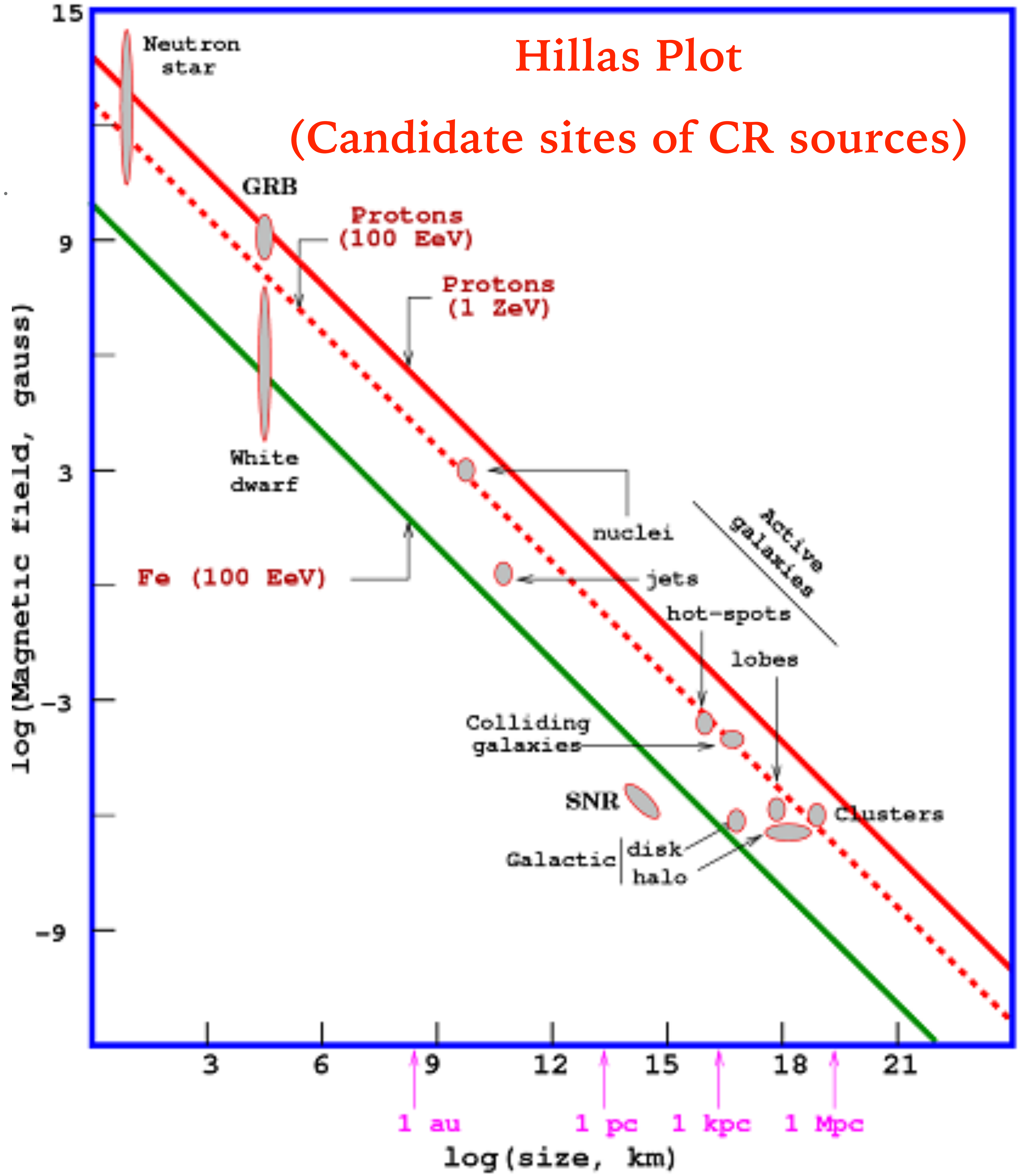
- ➤ **Cosmic Ray Sources**

  - Arrival direction of cosmic rays and correlation with possible sources

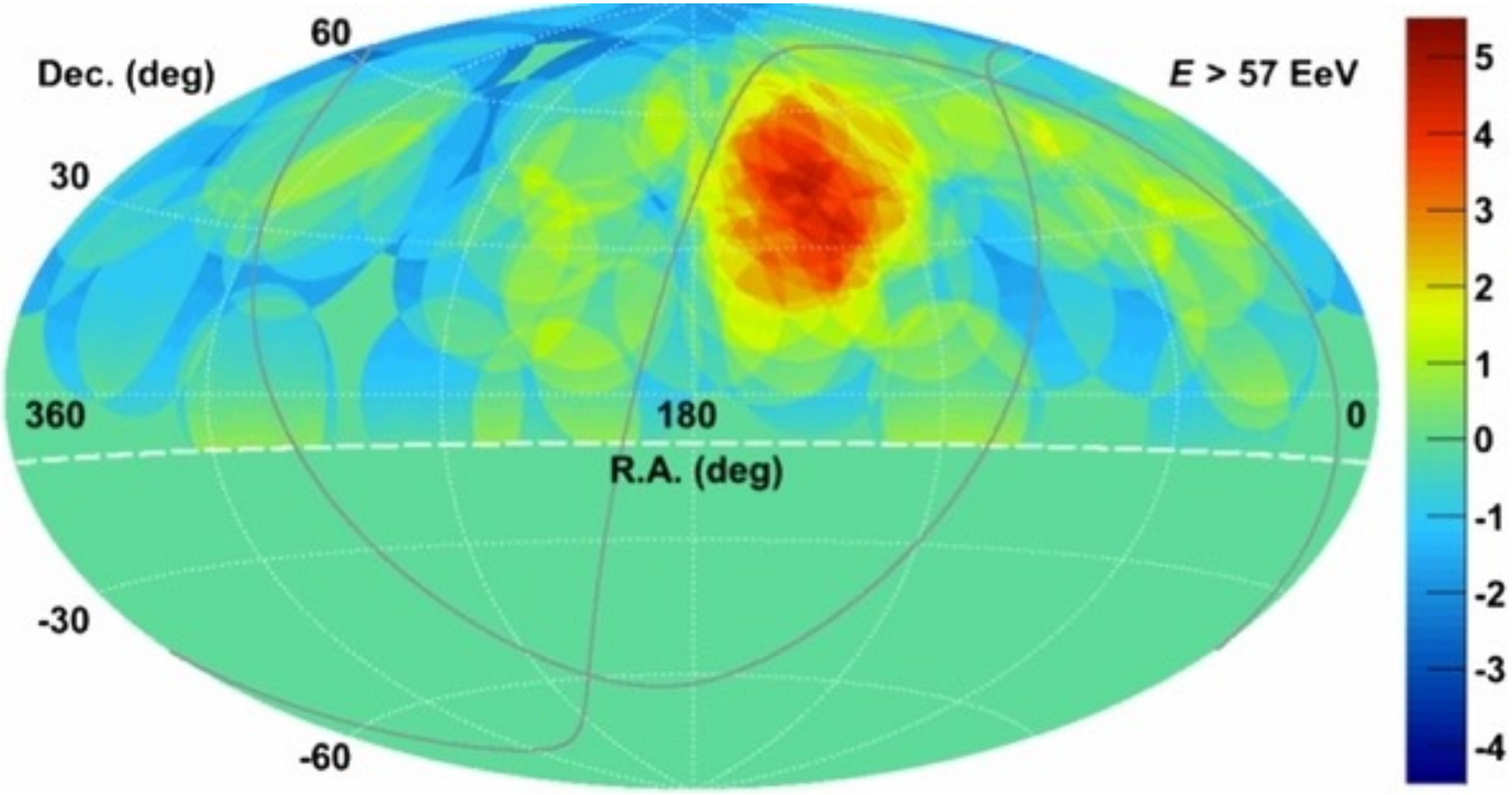
INTRODUCTION – COSMIC RAY SOURCES

- Ultra-high energy cosmic ray sources remain unknown
- Strong magnetic fields and large size to accelerate particles over longer periods of time required to get to Ultra-high energy
- Possible sources:

Super Massive Black Hole, Gamma Ray Burst, Star Burst Galaxies, etc



INTRODUCTION – COSMIC RAY SOURCES



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- Energy range : 10^{18} to $10^{18.5}$

  Isotropic - no excess along the galactic plane

- E > 5.7×10^{19} eV, The HotSpot

  - A local cluster of high energy events (26% of events fall in 6% of visible sky)

  - Near Ursa Major

INTRODUCTION – COSMIC RAY ENERGY SPECTRUM IS FOCUS OF MY DISSERTATION

- This analysis focused on particles $10^{17} < E < 10^{18}$ eV

  - Transition region

  - Heavy galactic component dying off/leaking out

  - Light extragalactic particles starting to leak in to the galaxy

- Technique - 4 ring* analysis: combined TA MD and TALE telescope data (Optimal)

  *ring : a set of telescopes shared the same elevation

  - FOV:

    - Elevation : 3- 59°

    - Azimuthal : 115°

    Observation full shower development

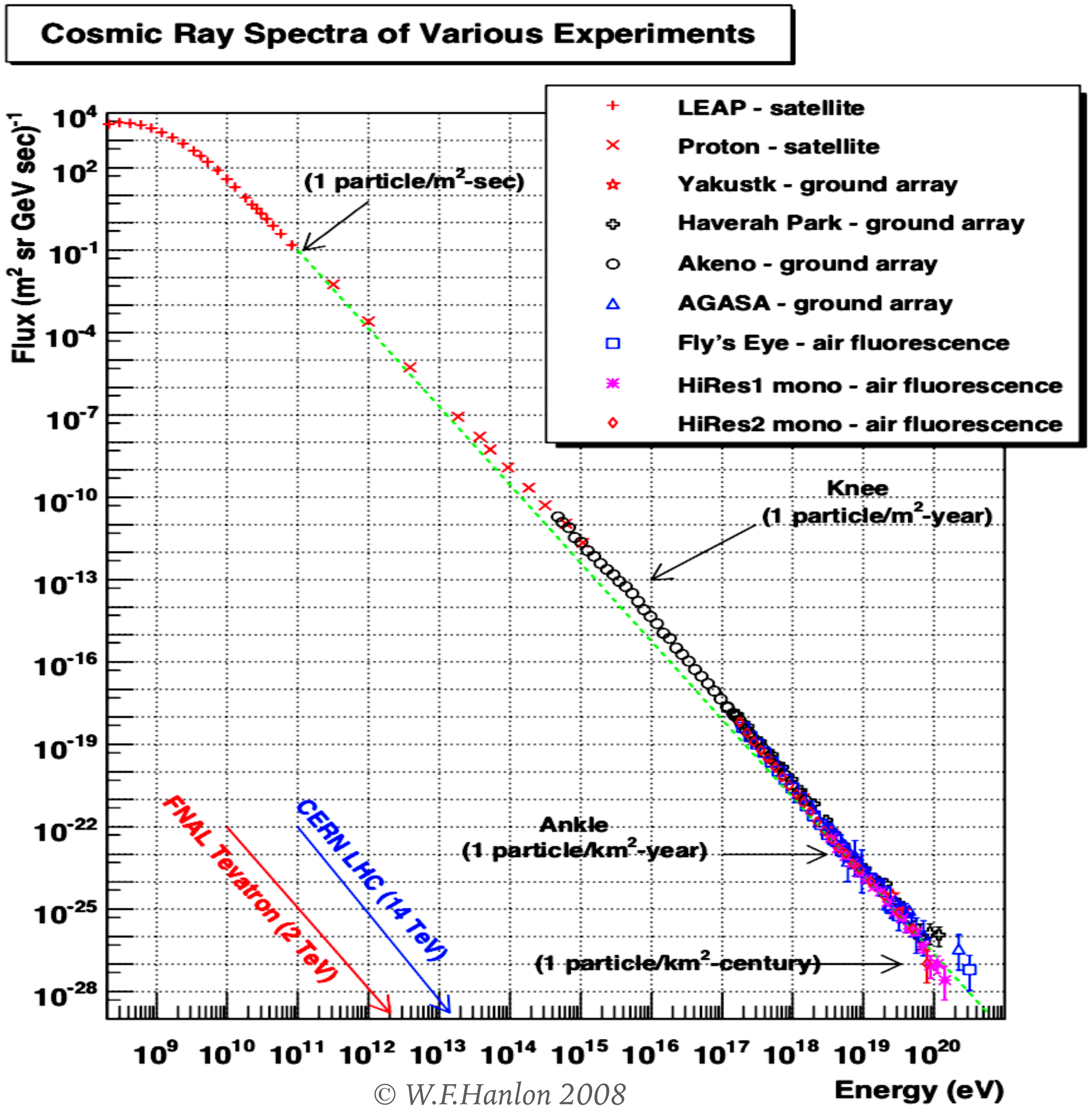
INTRODUCTION – COSMIC RAY ENERGY SPECTRUM

- Steep spectrum
- Near E ~ $10^{15.6}$ eV, "**Knee**"

  1 particle/m²/year
- At E ~ $10^{18.7}$ eV, "**Ankle**"

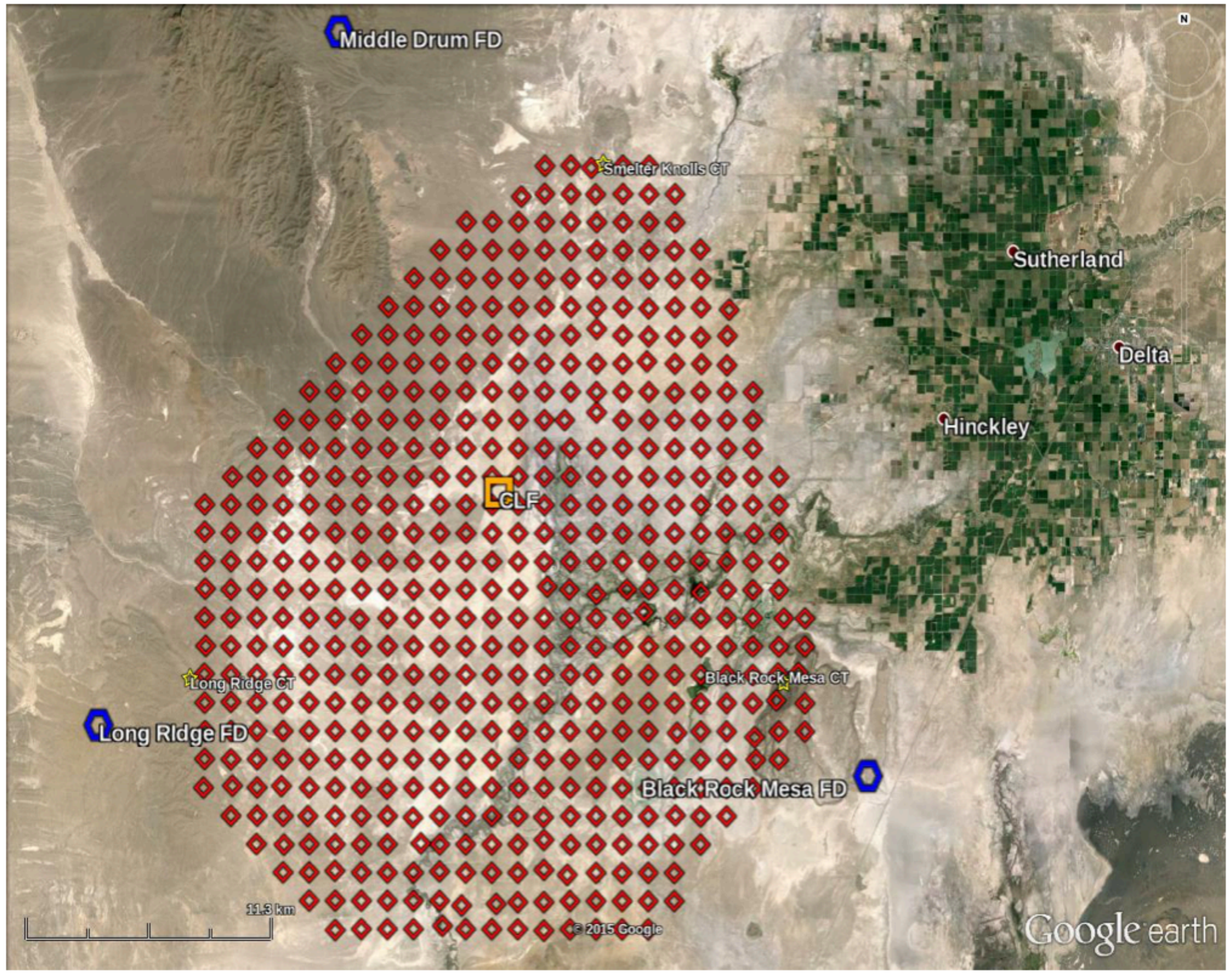
  1 particle/km²/year
- At E ~ $10^{19.8}$ eV, "**GZK cutoff**"

  1-2 particle(s)/km²/century



EXPERIMENT – TELESCOPE ARRAY (TA)

- **Telescope Array** - Largest cosmic ray observatory in the Northern hemisphere
- West Desert, Millard County, Utah - About 2.5 hrs south of UofU



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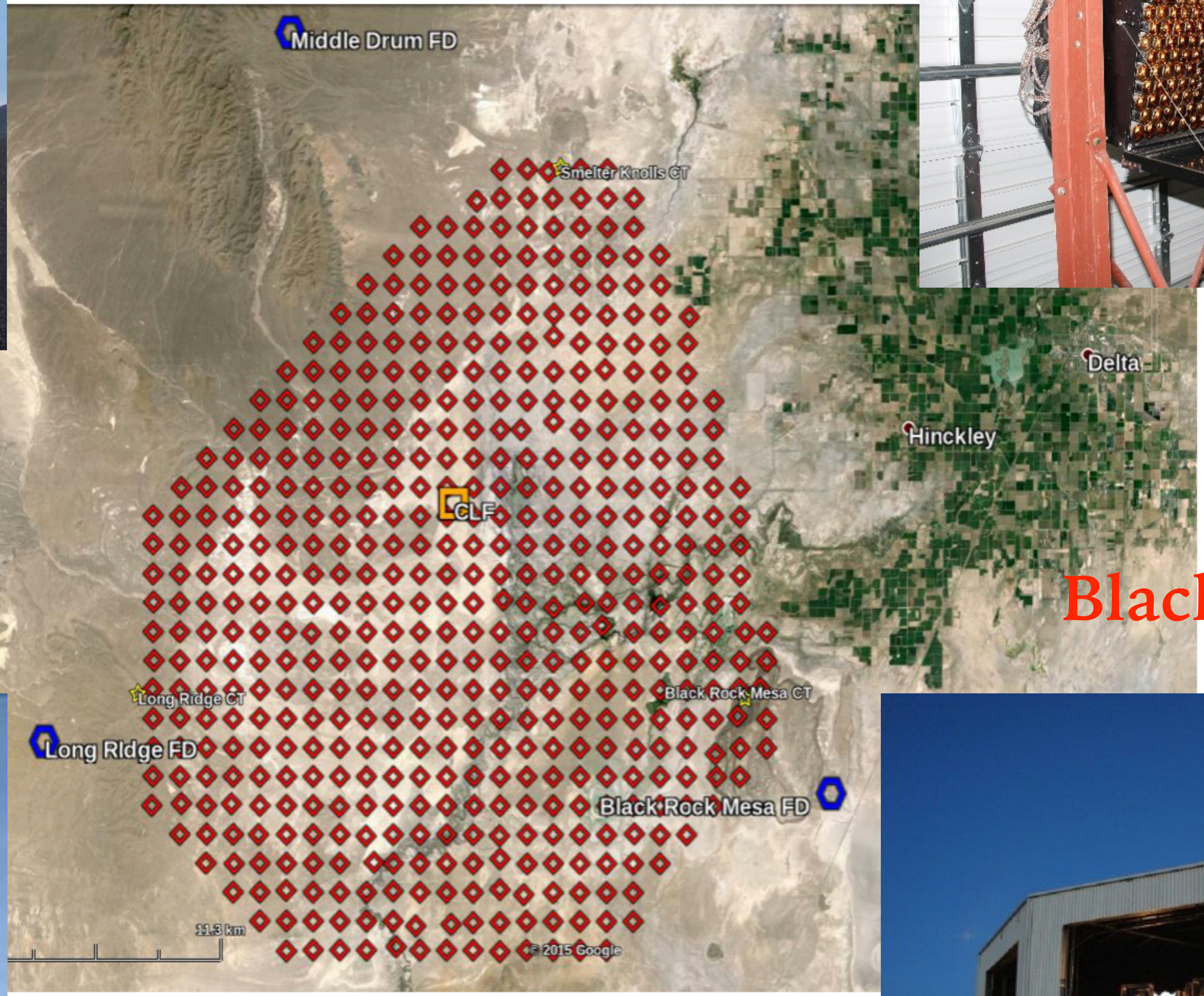
- International Collaboration: US, Japan, Korea, Russia, Belgium (130 people)
- Observes cosmic rays E > 10^{19} eV
  - 3 telescope stations (⬡)
  - overlooking an array of 507 scintillator surface detectors (◇)
  - Central Laser Facility (□) (Atm calib)
  - Area : ~ 700 km² (300 mi²)

EXPERIMENT – TA FLUORESCENCE DETECTOR (FD)

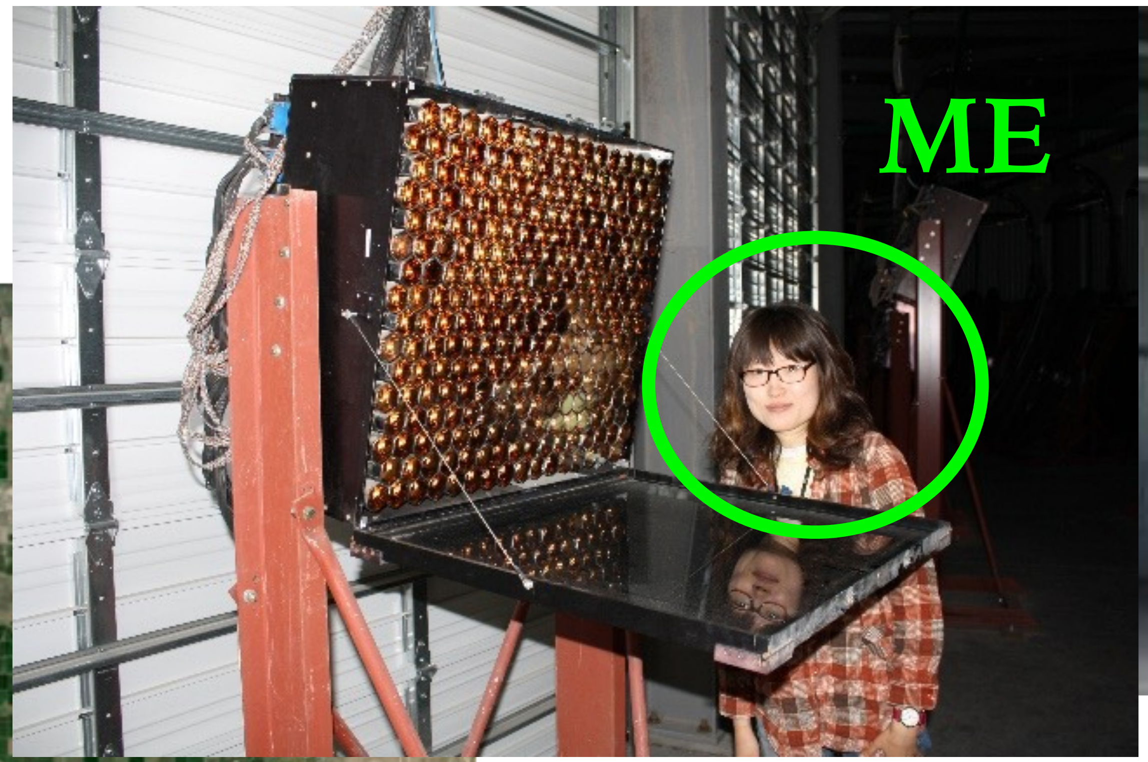
Middle Drum (MDFD)

Long Ridge (LRFD)

14 telescopes @ station
Reutilized from HiRes-1

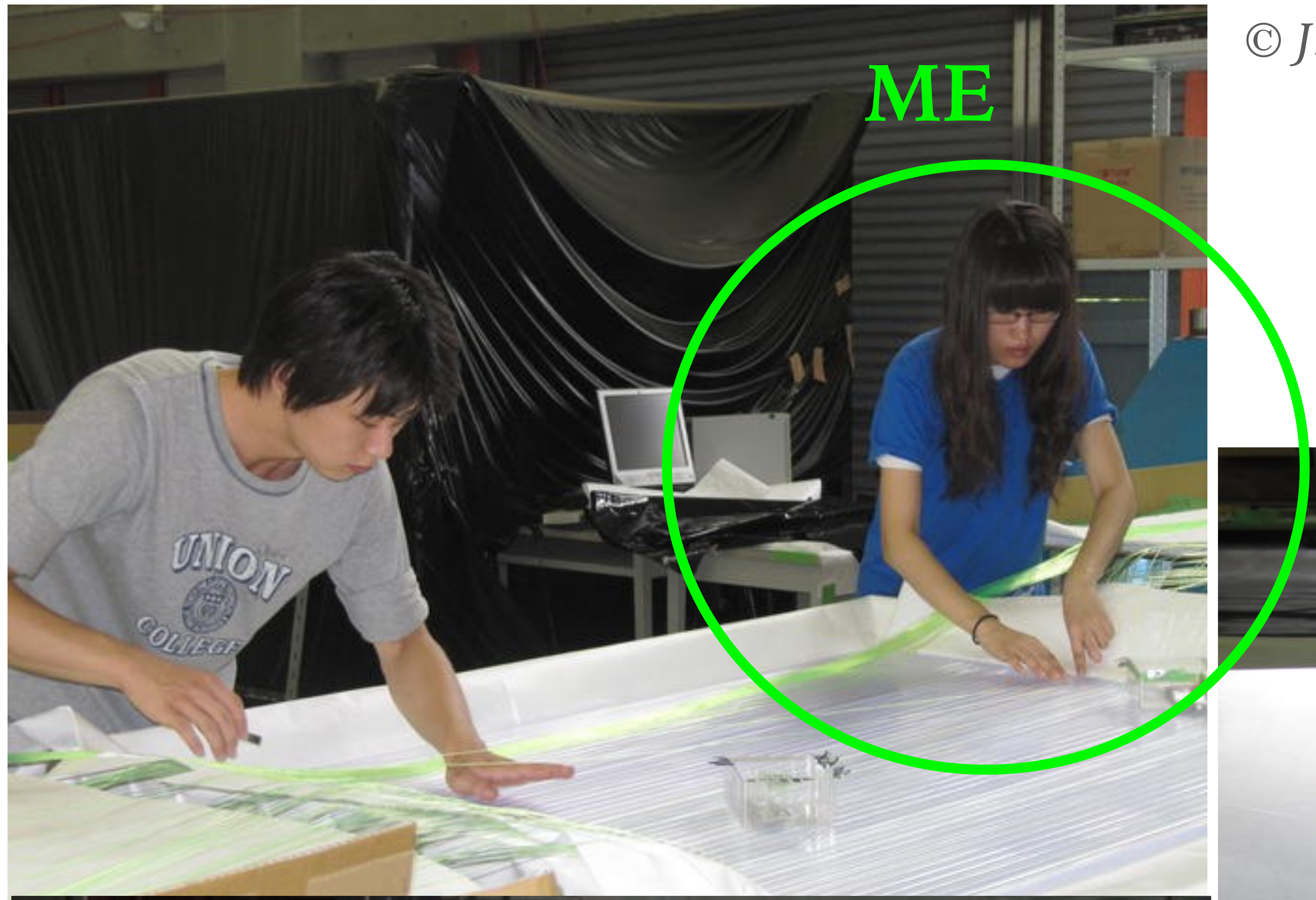


12 telescopes @ station
new telescopes



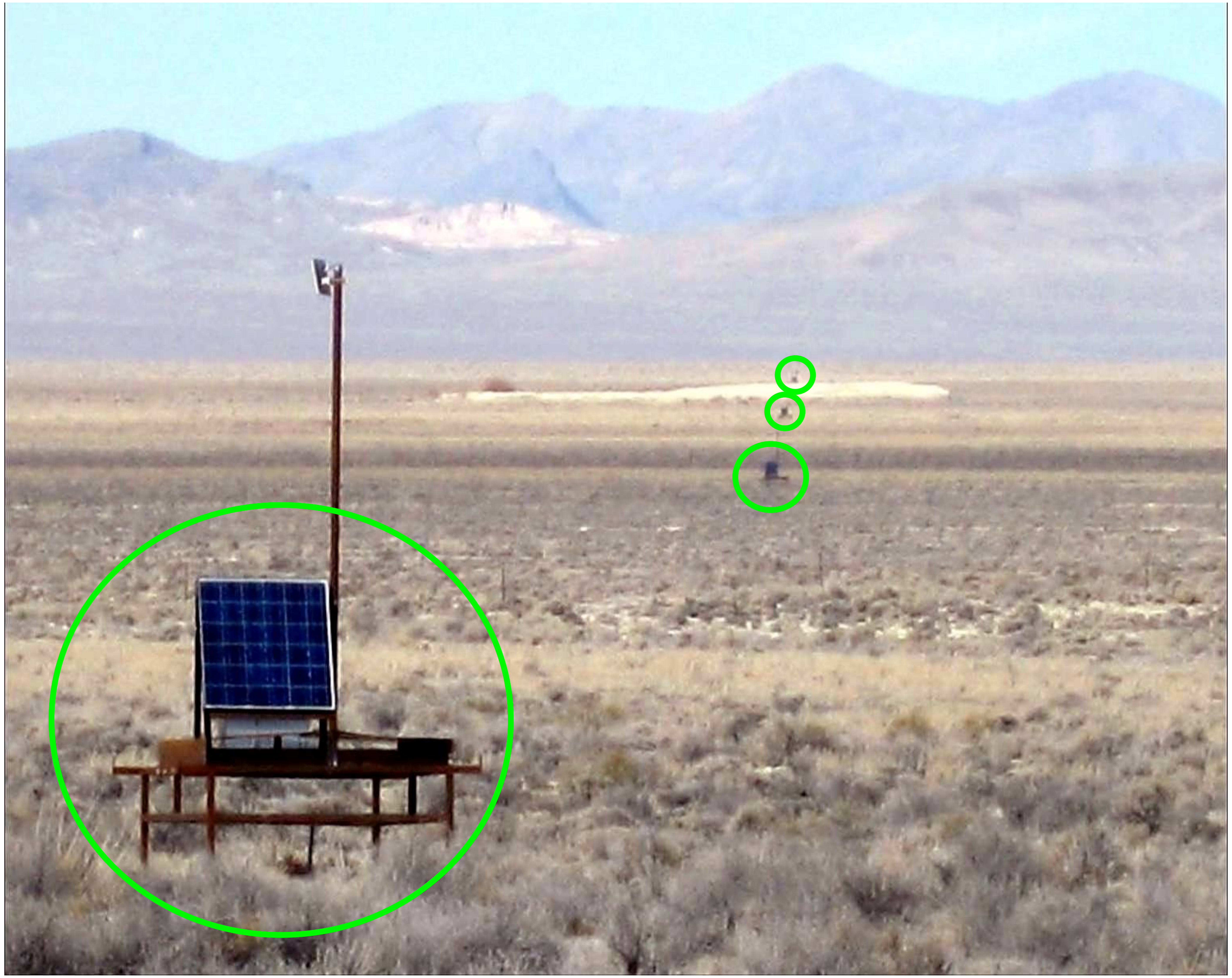
Black Rock Mesa
(BRFD)

EXPERIMENT – TA SURFACE DETECTOR (SD)



2 layers scintillator
1.25 cm thick, 3 m² area
Optical fibers to PMTs

EXPERIMENT – TA SURFACE DETECTOR (SD)



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1.2 km spacing
radio communication/trigger
Solar/Battery power
24/7 operation

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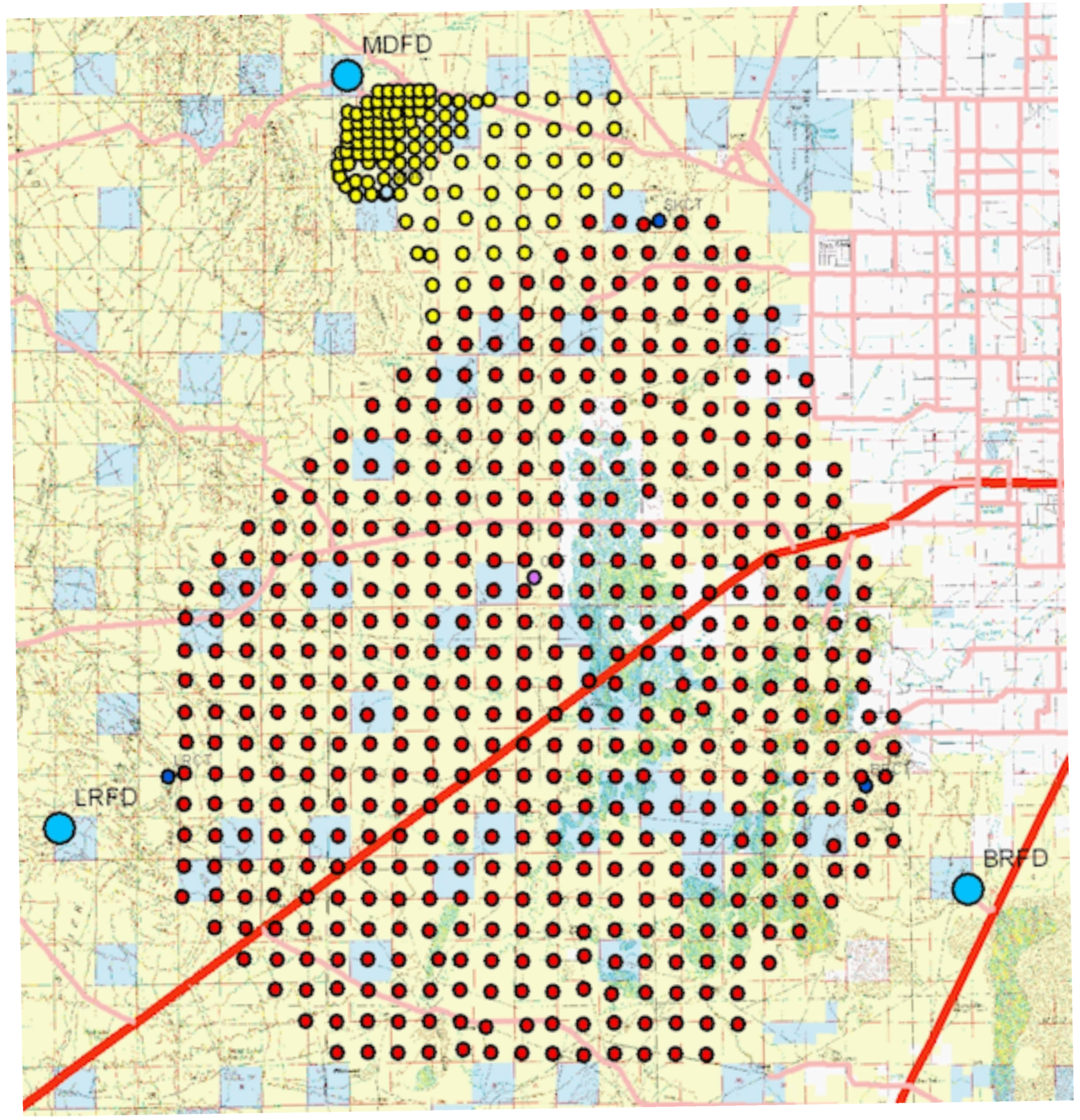
EXPERIMENT – TA SURFACE DETECTOR (SD)

TALE SD (103) Deployment

TAx4 SD (560) Site Staking

EXPERIMENT - TA + TA LOW ENERGY EXTENSION (TALE)

- Low energy particles are not as bright - closer
- Low energy particles develop higher up



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- 10 new telescopes looking higher in the sky at MDFD site
- 103 surface detectors (●)

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EXPERIMENT - TA + TA LOW ENERGY EXTENSION (TALE)

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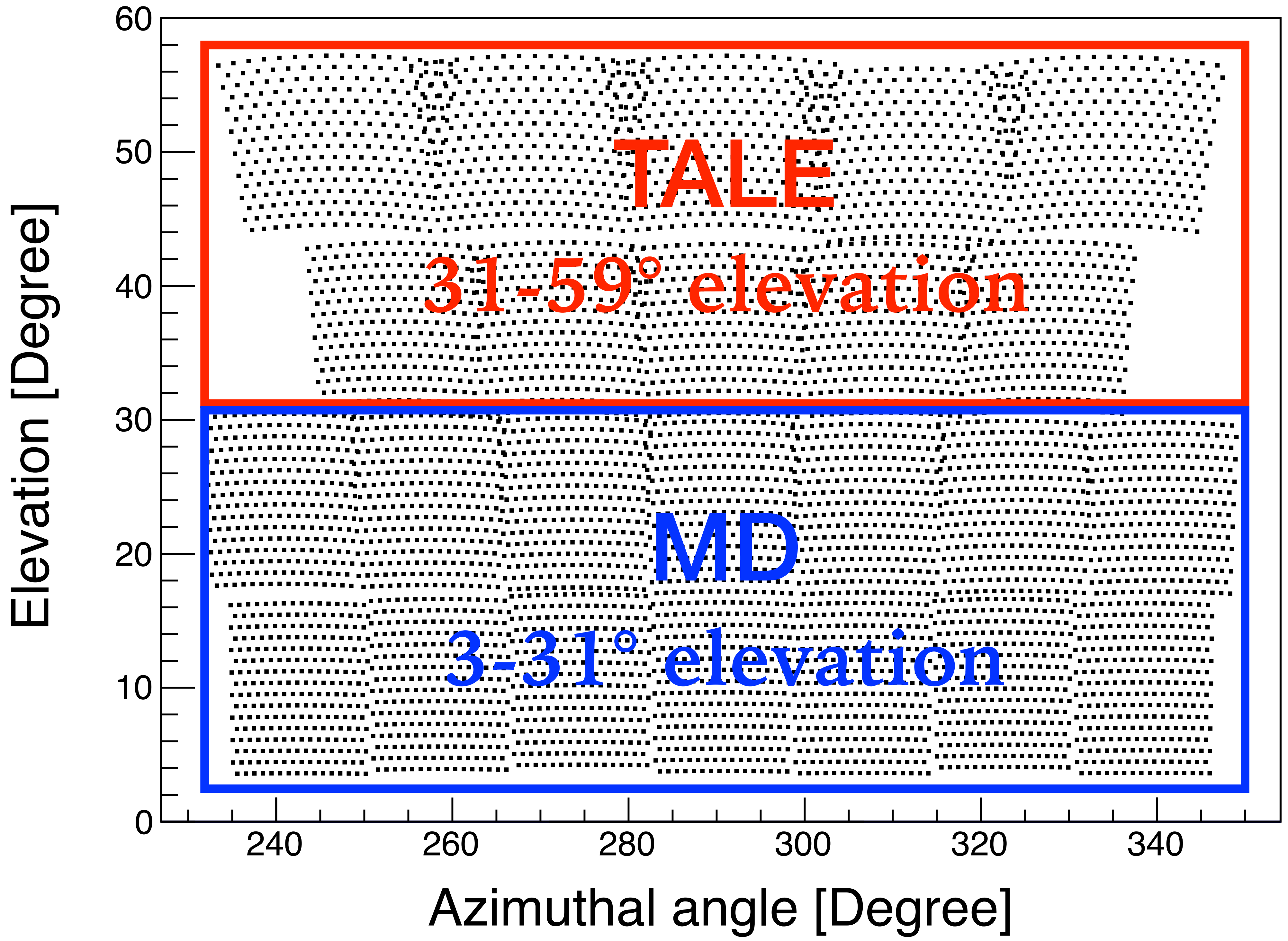
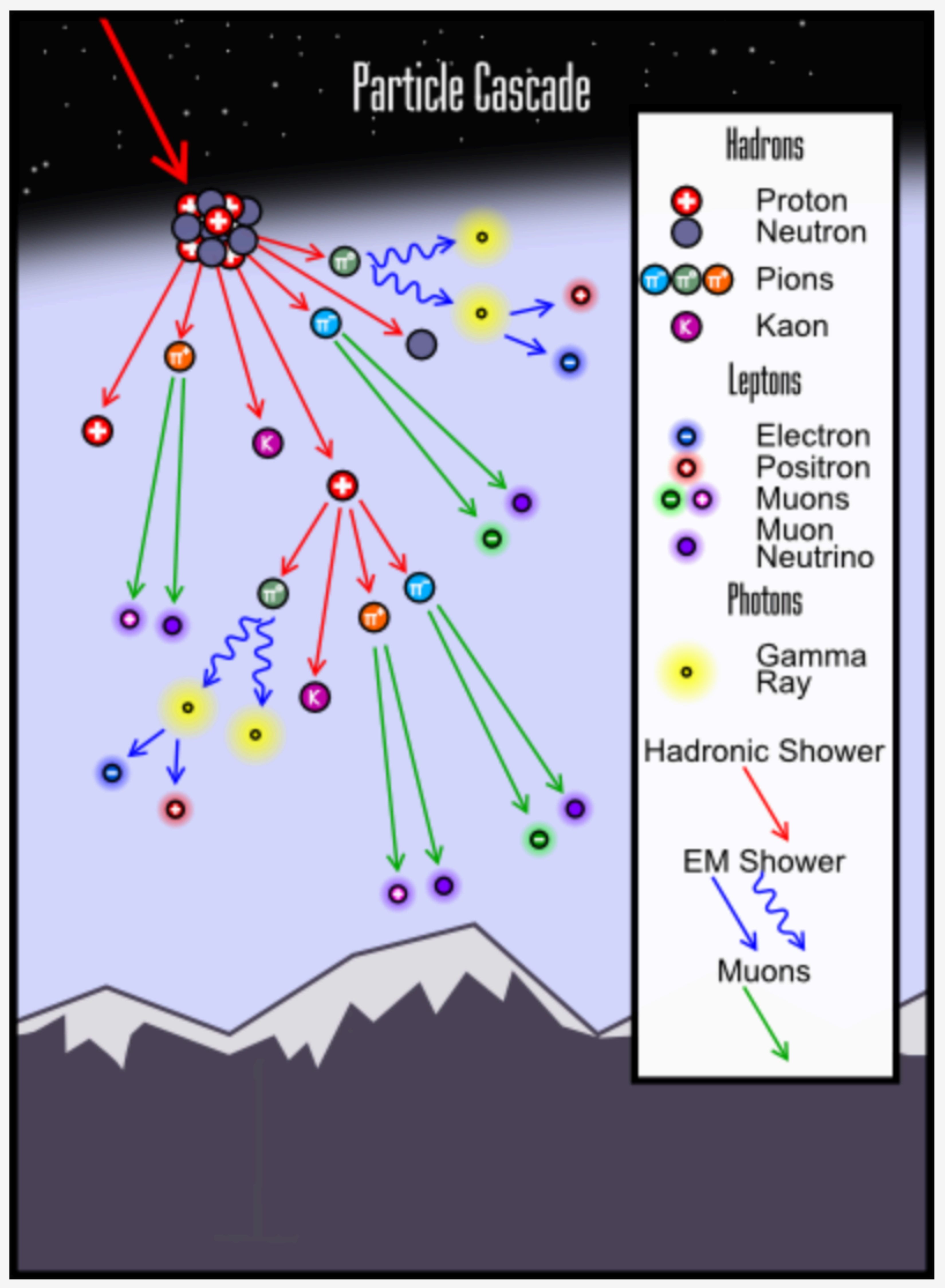
- Monocular reconstruction of combined MD and TALE telescope data
  - MD (**2 rings**) and TALE (**2 rings**) FDs
  - Enable us to observe the full development of showers

Field of View



EXTENSIVE AIR SHOWER (EAS)



- ➤ High Energy Cosmic Rays induce a cascade of secondary particles when they collide with air molecules high in the atmosphere. Called as Extensive Air Shower (EAS)
- ➤ For 10^{19} eV, about 10^{10} charged particles are created at shower maximum

  - 85% of total energy ($e^{\pm}$ and γ)
  - 10% of total energy ($\mu^{\pm}$)
  - 4% of total energy ($\pi^{\pm}$)
  - the remainder (ν)

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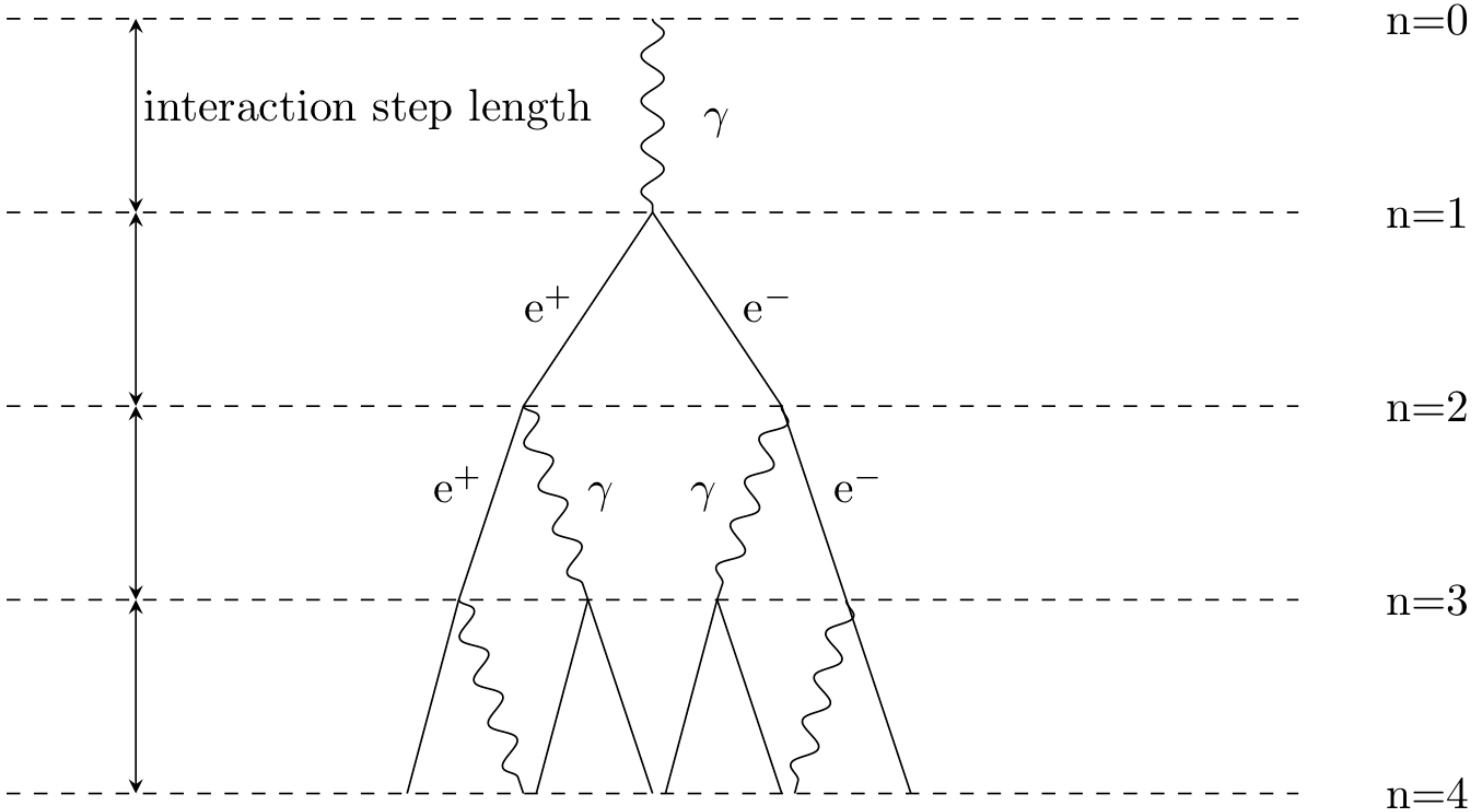
EXTENSIVE AIR SHOWER - ELECTROMAGNETIC SHOWERS



- Heitler model: **very simple model**
- Only $e^{\pm}$ and γ

  $e^{\pm}$: bremsstrahlung

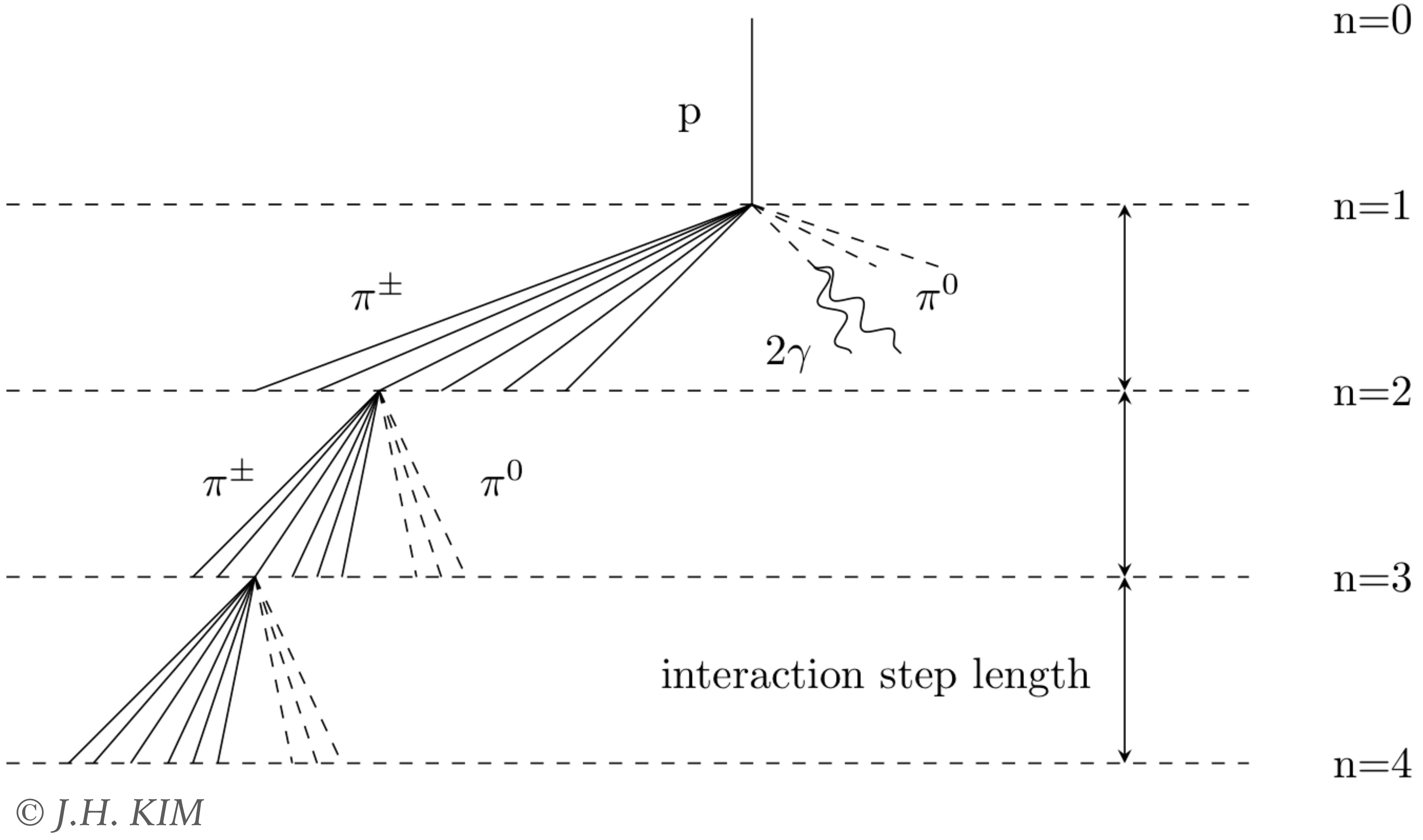
  γ : pair production
- Each interaction

  - # of particles doubled

  - energy of particles divided equally

- # of particles at shower maximum : $N_{max} = E_0/\varepsilon_c$ (ε_c : critical energy)
- Depth of shower maximum : $X_{max} = X_0 \ln(E_0/\varepsilon_c)$

EXTENSIVE AIR SHOWER – HADRONIC SHOWERS



- Heitler-like model: **very simple model**
  - Cosmic ray proton with a total energy, E_0, collides with air molecule
  - Each interaction
    - N_{ch} of $\boldsymbol{\pi}^{\pm}$ & 1/2 N_{ch} $\boldsymbol{\pi}^{0}$
    - $\boldsymbol{\pi}^{\pm}$ (2/3 E_0) and $\boldsymbol{\pi}^{0}$ (1/3 E_0)
- $\boldsymbol{\pi}^{0} \rightarrow 2\gamma$ (electromagnetic sub showers), while a few $\boldsymbol{\pi}^{\pm}$ decay to μ and $\boldsymbol{\nu}_{\mu}$
- X_{max} for a nuclei with mass number A : $X_{max} = X_{p\ max} - X_0 \ln(A)$; higher than proton
- Iron showers : ~40% more muons than proton showers

  $\langle X_{max} \rangle$: 80-100 g/cm^2 shallower

MONTE CARLO (MC) SIMULATION

- For Fluorescence Detector (FD) measurement, the aperture depends significantly on energy

  High energy events - more particles/brighter, seen from greater distances

  Lower energy events only visible nearby

- Aperture (AΩ)

$$A\Omega = \frac{N_{\text{Reconstructed}}(E)}{N_{\text{Thrown}}(E)} \times A_0\Omega_0$$

$N_{\text{Reconstructed}}(E)$ # of reconstructed MC events

$N_{\text{Thrown}}(E)$ # of thrown MC events

A_0 effective area

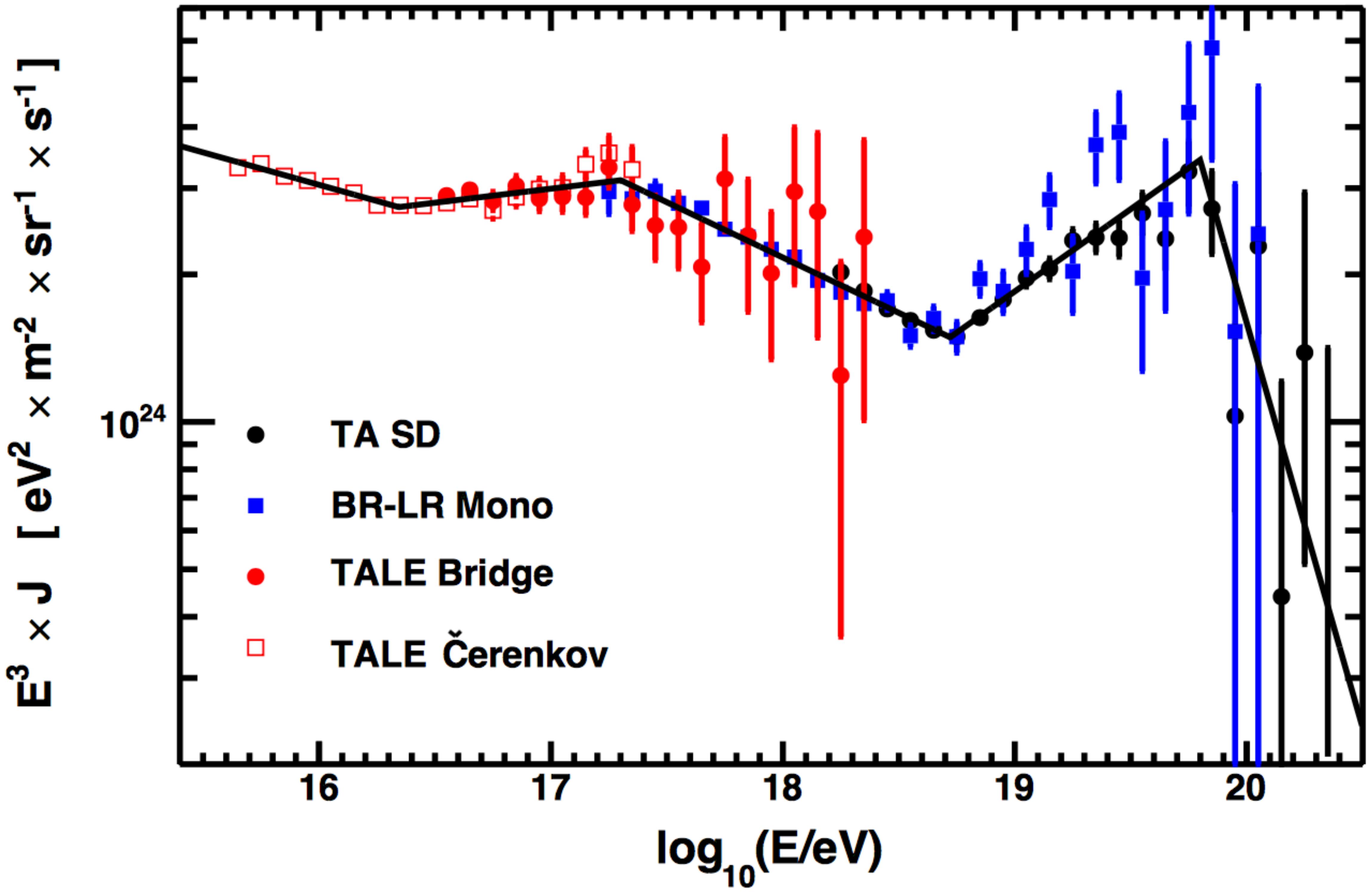
Ω_0 solid angle

MONTE CARLO (MC) SIMULATION

1. Input previous measurement such as the energy spectra and compositions
2. Generate showers using CORSIKA (COsmic Ray Simulations for KAscade) program
3. Undergo light generation, atmospheric scattering and light transmission
4. Detector response, trigger, and readout then write MC events into the same format as the data
5. Analyze MC event with the exact same programs as are used for data analysis
6. Compare analyzed data with the analyzed MC.

MONTE CARLO (MC) SIMULATION – INPUT SPECTRUM

- To make the MC events more realistic
- As the spectral reference, we used Telescope Array energy spectrum which presented in the International Cosmic Ray Conference (ICRC) 2015.
- Including 2nd knee, ankle, and GZK cutoff above 10^{16} eV.



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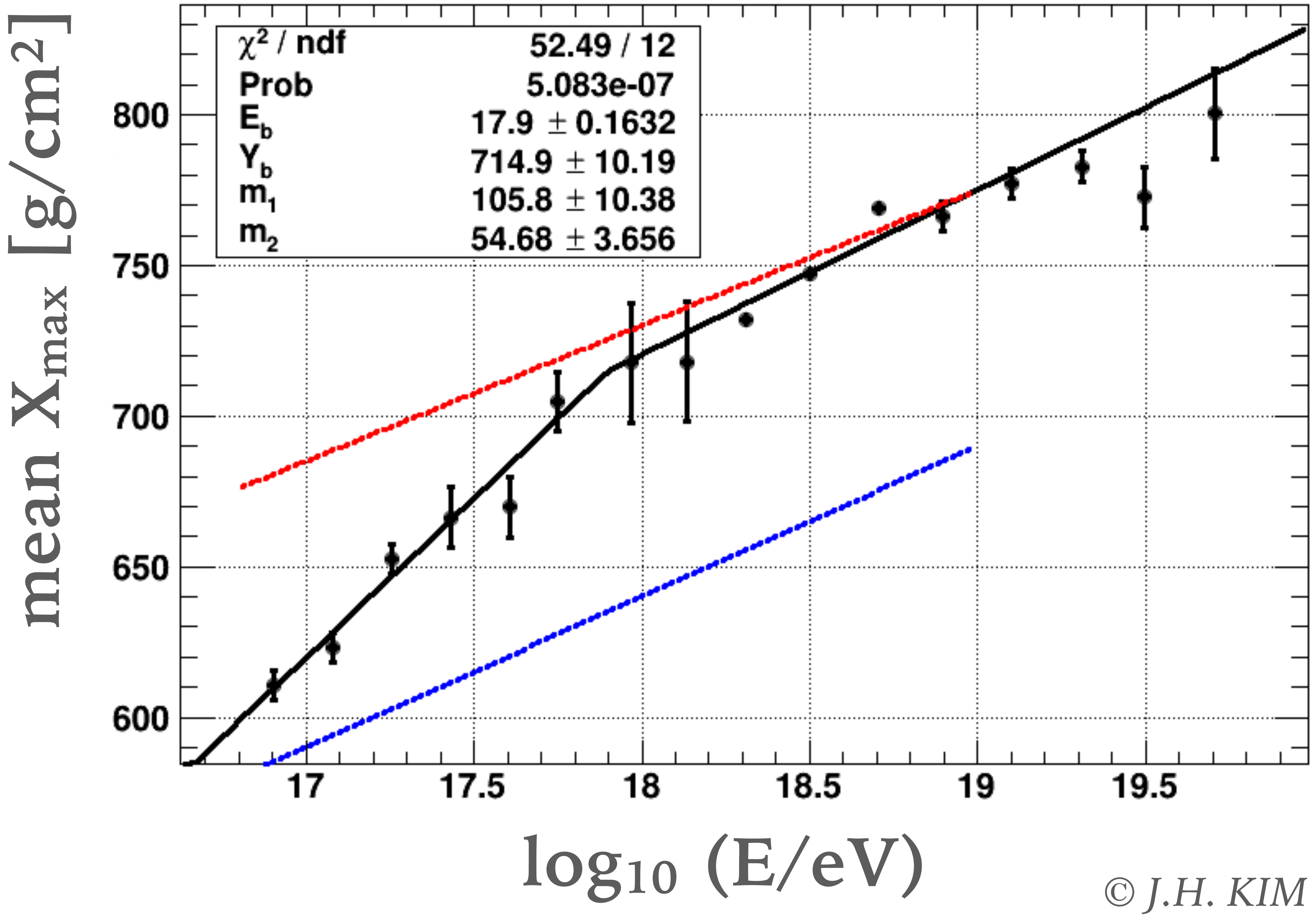
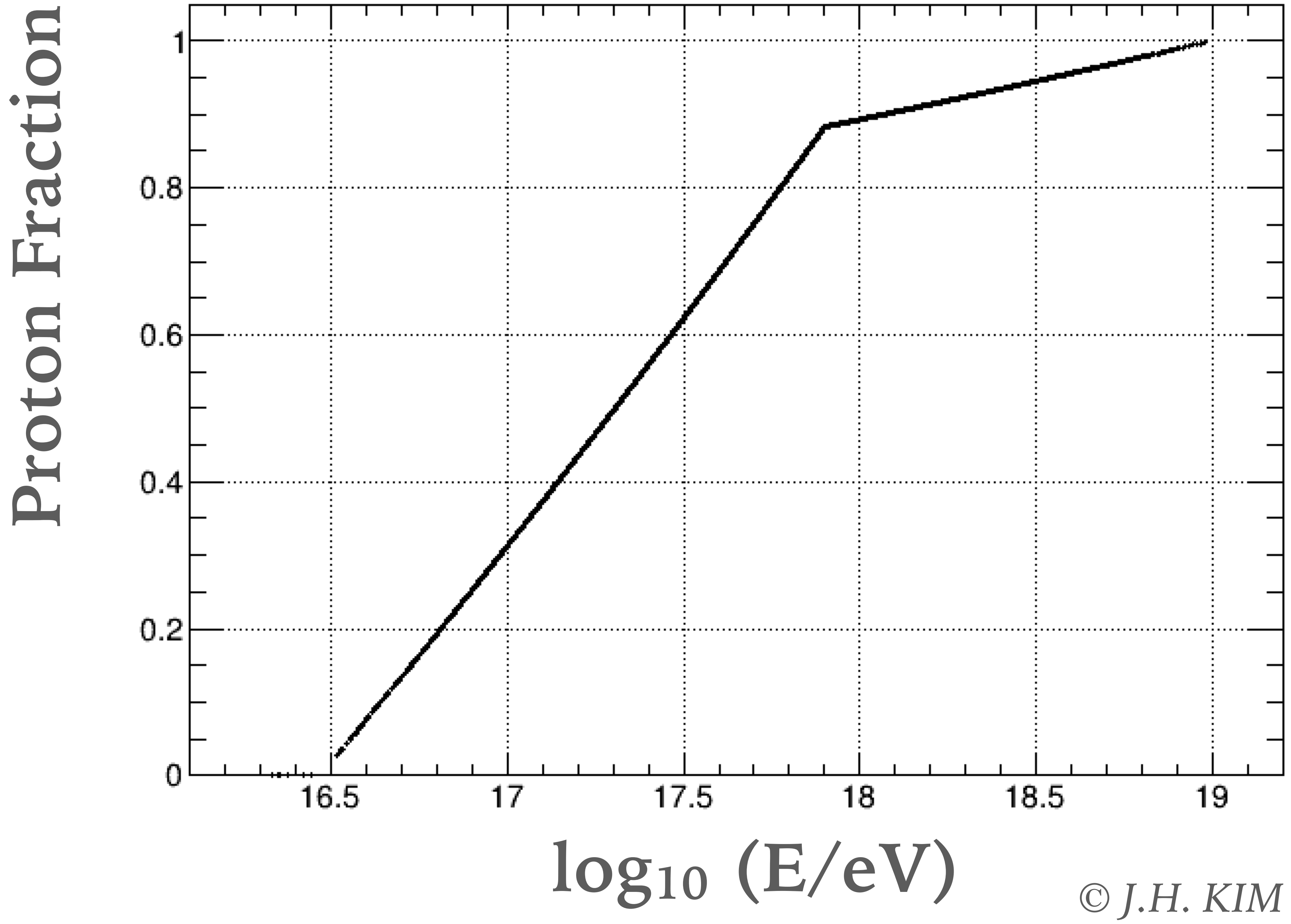
MONTE CARLO (MC) SIMULATION – INPUT COMPOSITION

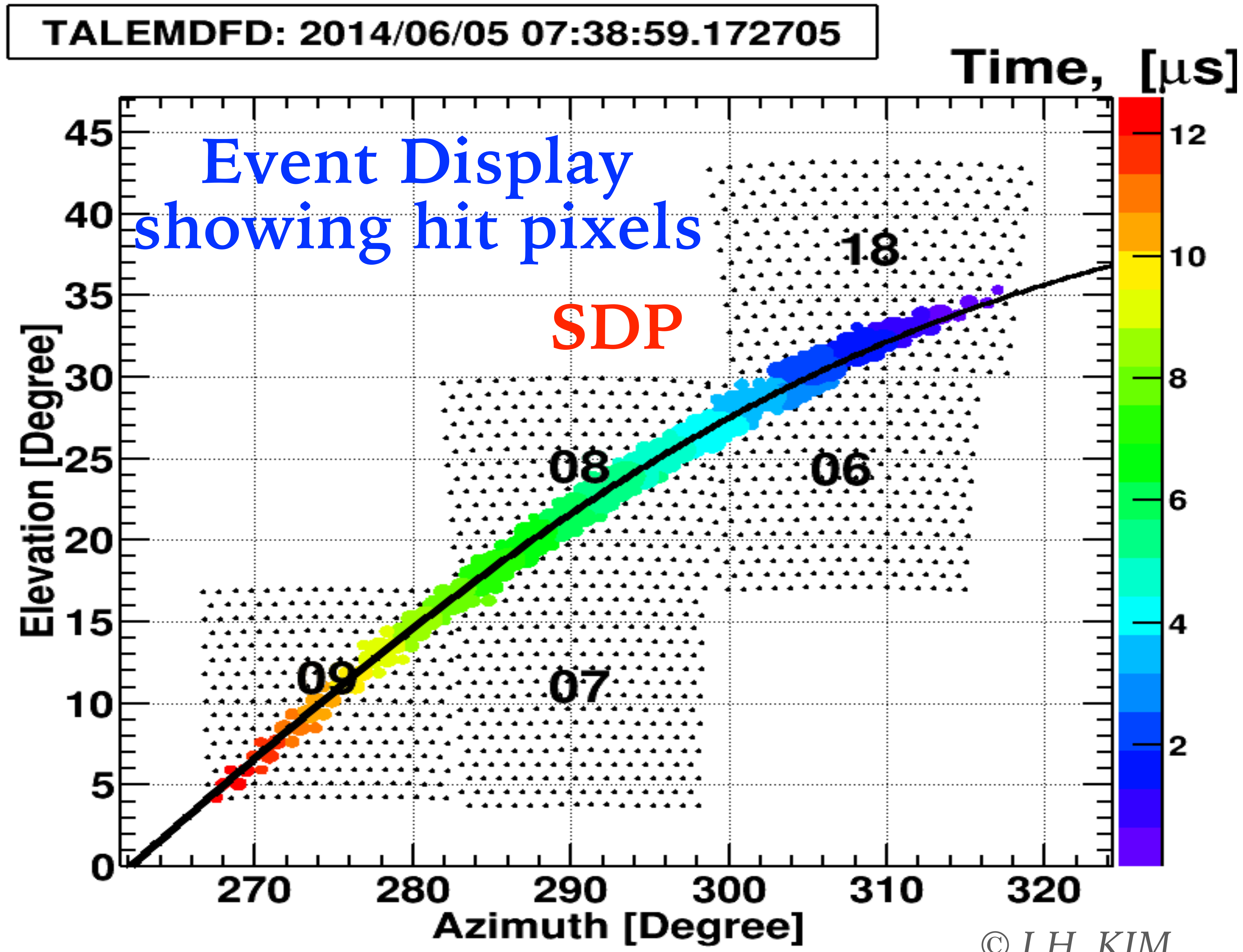
- To make the MC events more realistic
- As a composition reference, HiRes/MIA and HiRes X_{max} results
- Translated to proton fraction as a function of energy





EVENT RECONSTRUCTION – GEOMETRY OF EXAMPLE EVENT

- To determine a shower detector plane
  - Triggered tube's pointing direction
  - Detector position



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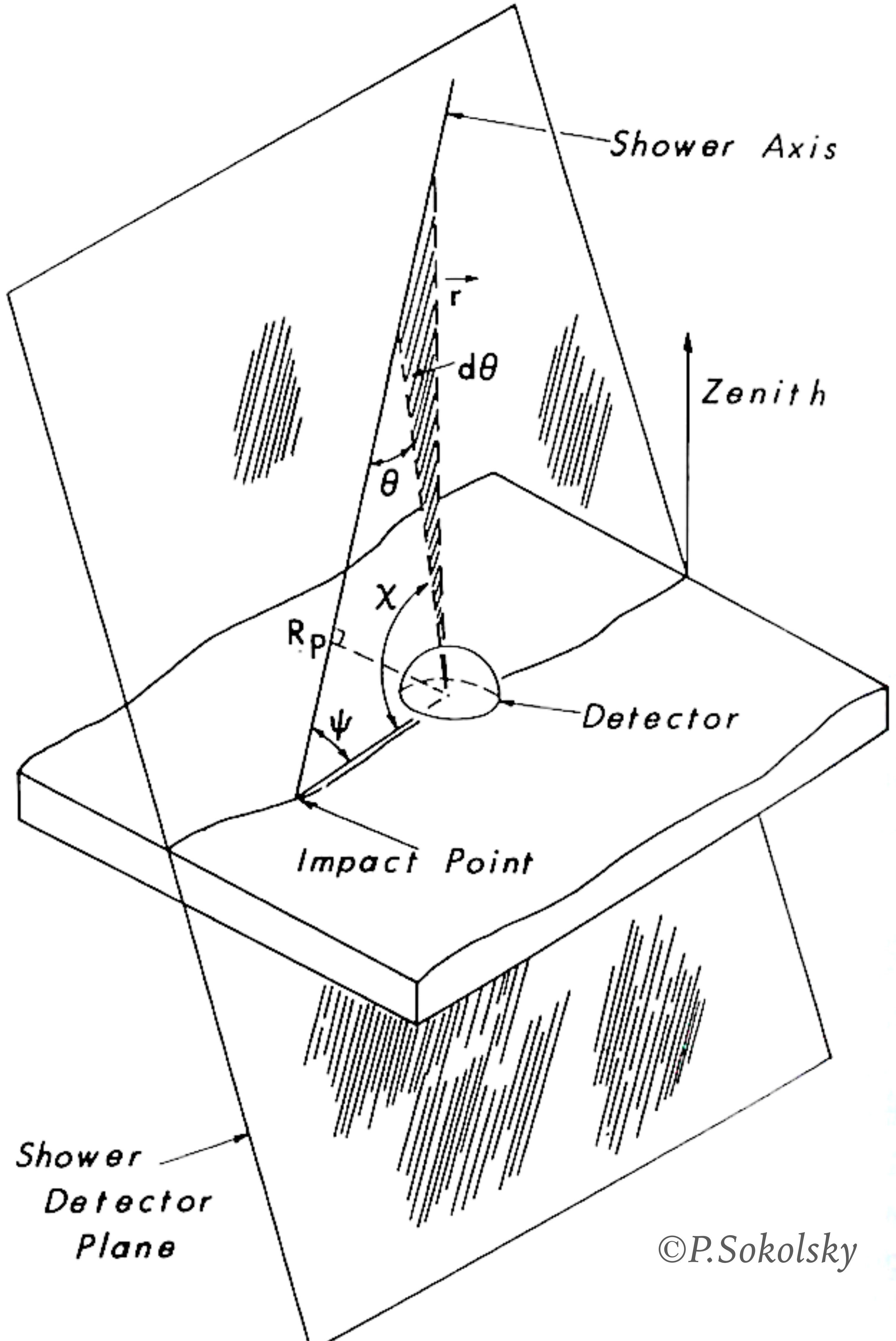
Top of atmosphere



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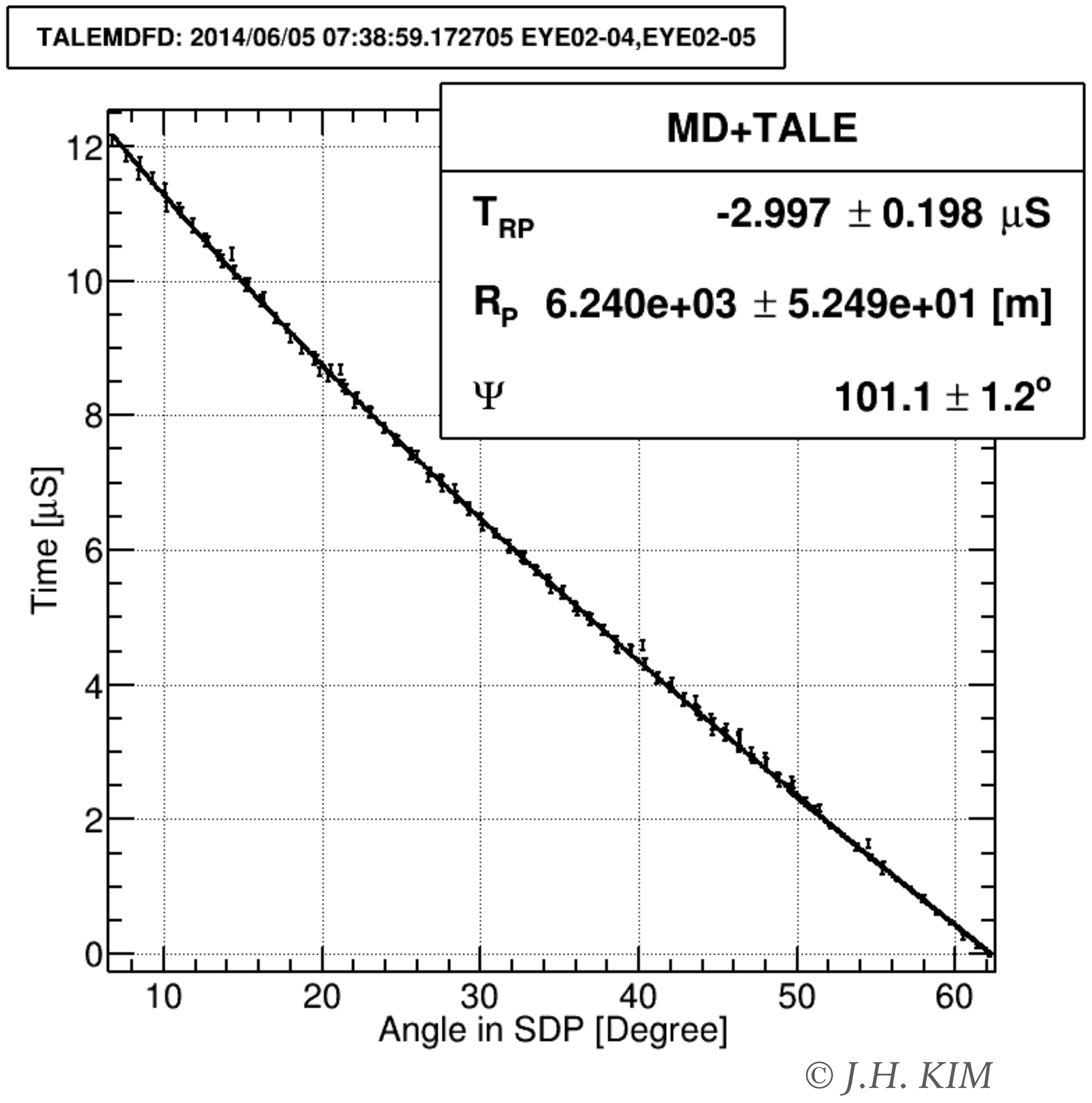
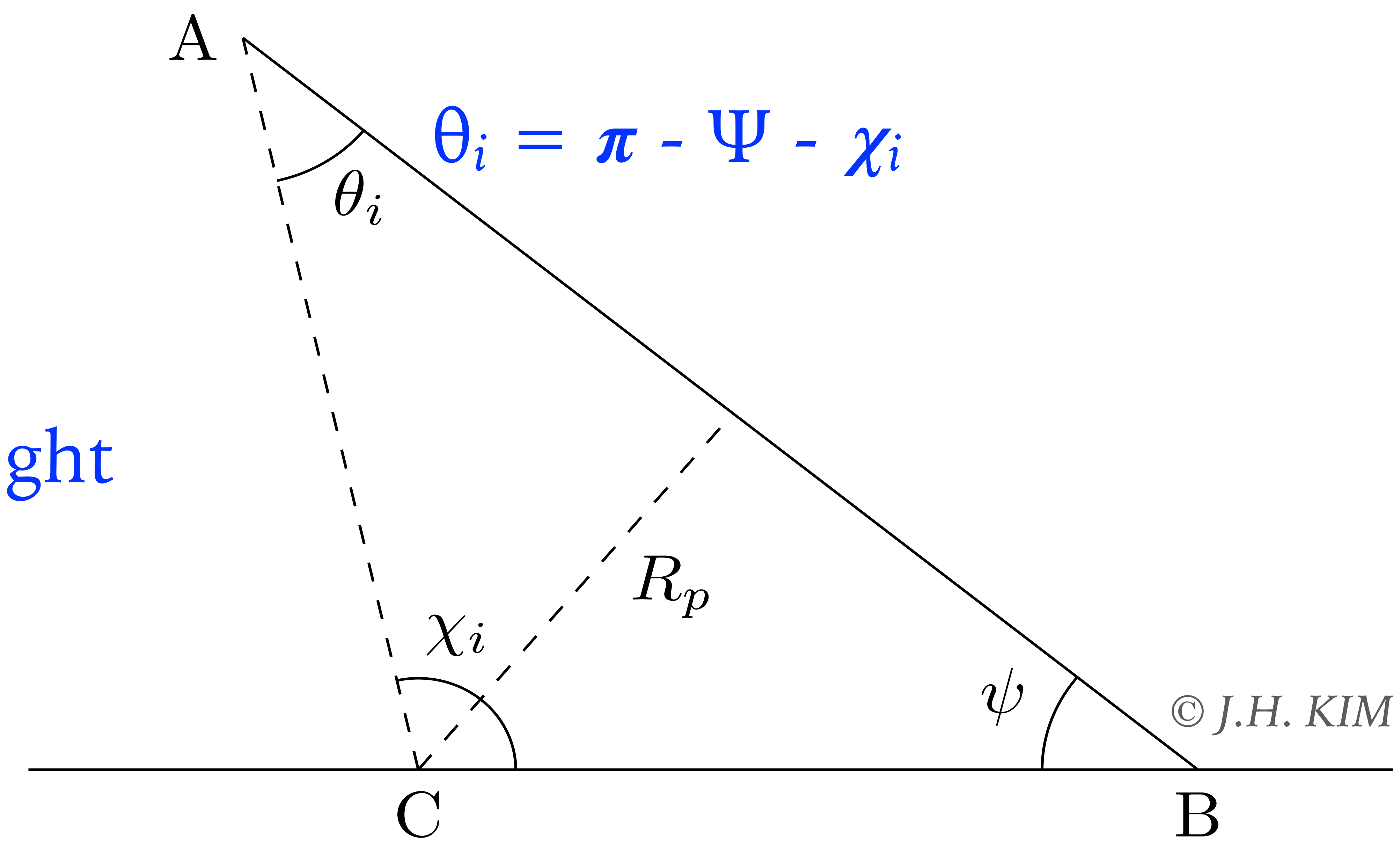
EVENT RECONSTRUCTION – GEOMETRY OF EXAMPLE EVENT

- Time vs. Angle Fit $$t_i = t_{R_p} + \frac{R_p}{c} \cdot \tan\left(\frac{\pi - \psi - \chi_i}{2}\right)$$

t_i trigger time of tube i
χ_i pointing direction of tube i
Ψ in-plane angle
R_p impact parameters
c speed of light
t_{Rp} time at R_p



Arrival times of light fit vs angle



EVENT RECONSTRUCTION – PROFILE FIT

- The **Gaisser-Hillas** parameterization formula

$$N_e(x) = N_{\max} \cdot \left[\frac{x - X_0}{X_{\max} - X_0}\right]^{\frac{X_{\max}-X_0}{\lambda}} \cdot e^{\frac{X_{\max}-x}{\lambda}}$$

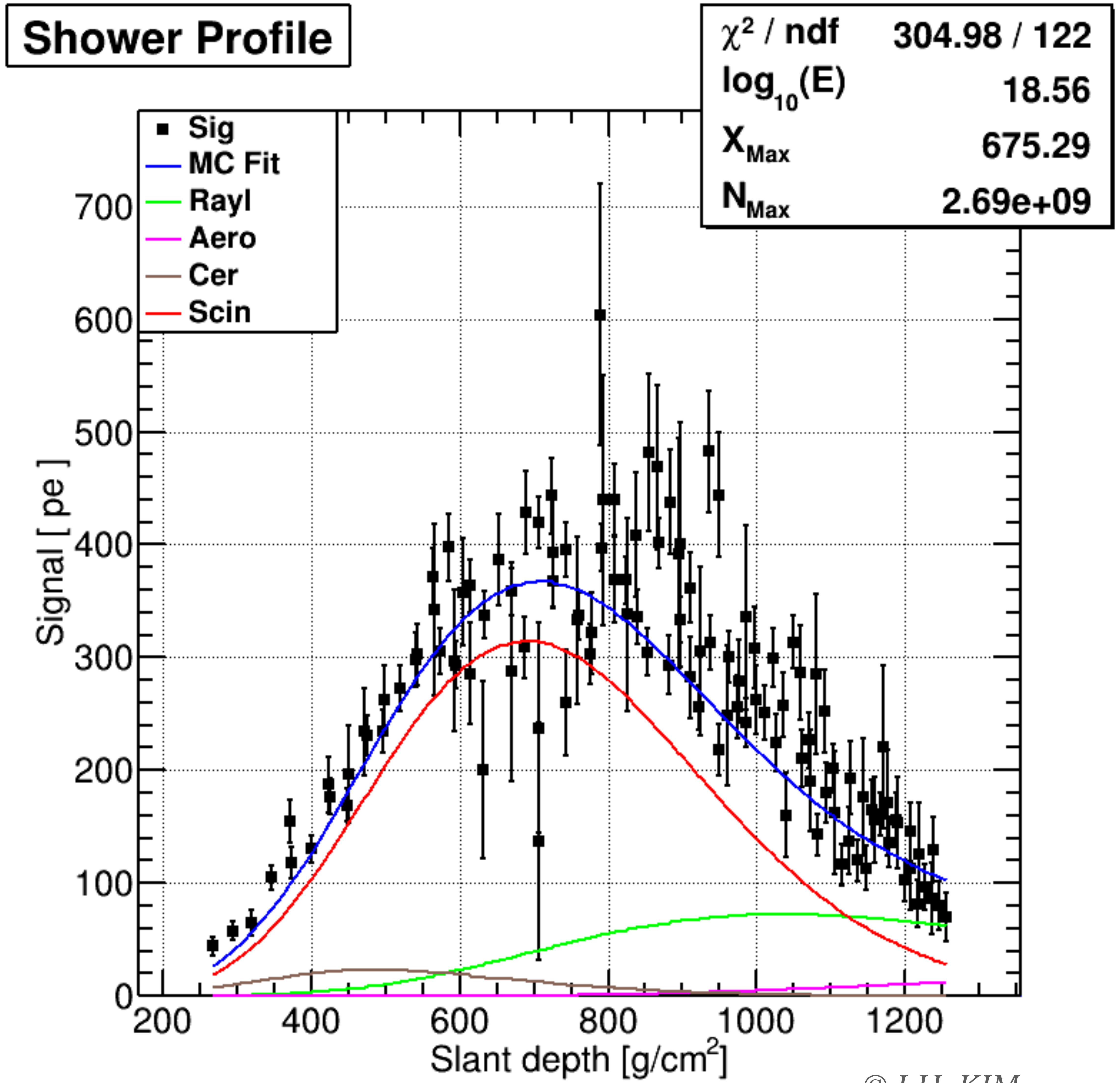
$N_e(x)$ # of charged particles at given depth, x
X_{max} depth of shower max, g/cm^2
N_{max} max # of particles
X_0 related to depth of the first interaction (X_0 = -100 g/cm^2 set)
λ related to width of the shower profile (λ = 70 g/cm^2 set)

- The mean energy deposit parameterization (light generated/particle)
- Integrating Gaisser-Hillas parameterization with mean energy deposition, **estimate calorimetric energy of visible part of shower**

EVENT RECONSTRUCTION – PROFILE FIT OF EXAMPLE EVENT

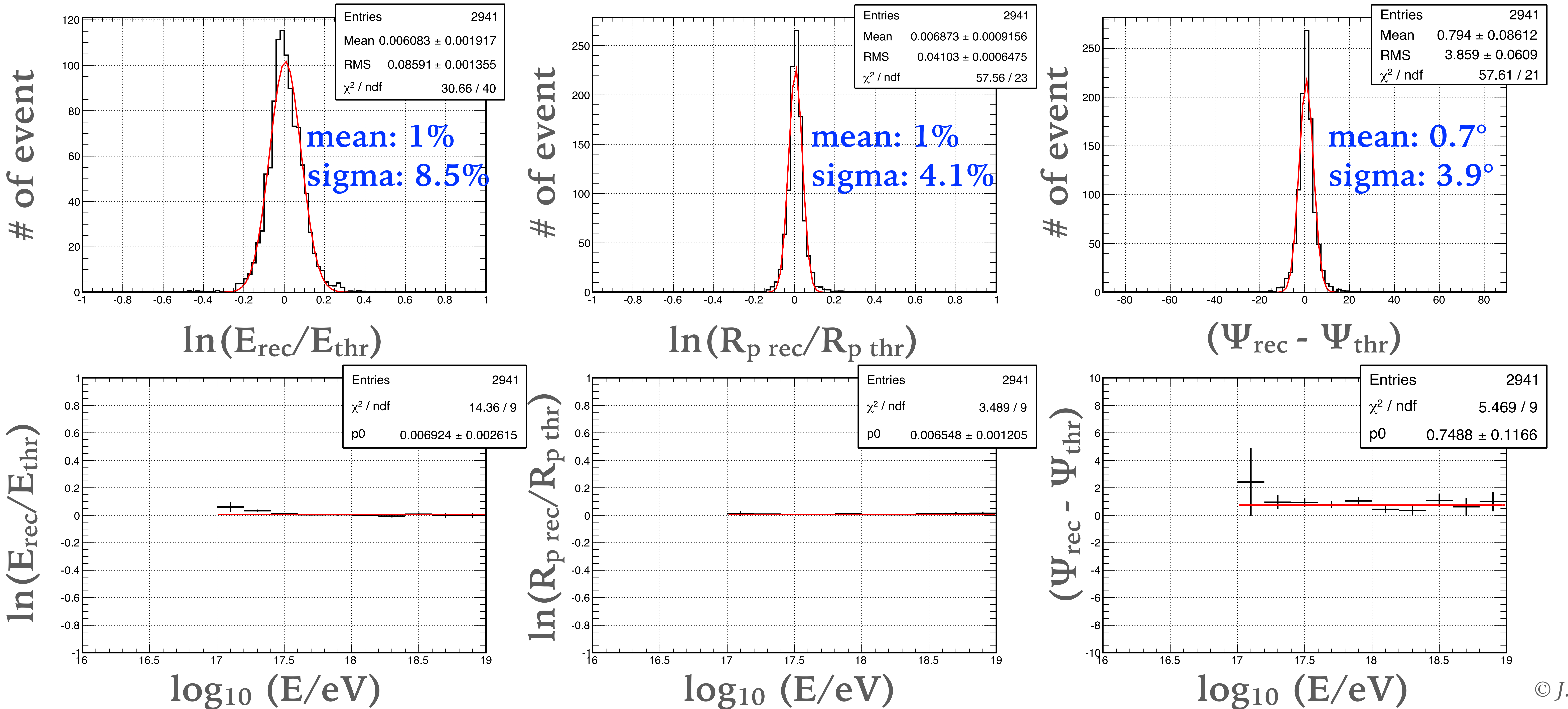
- Light signal fit vs slant depth to determine energy and depth of shower maximum, X_{max}

Black: data
Blue: fit to total signal
Red: scintillation
Green: Rayleigh scattering
Magenta: Aerosol scattering
Grey: Direct Cherenkov



MONTE CARLO (MC) SIMULATION – RESOLUTIONS

Total Energy (E_{tot}) | Impact parameter (R_p) | In-plane angle (Ψ)



EVENT RECONSTRUCTION – QUALITY CUT

	TALE	MD	TALE and MD
Cut level 1	Down-going events only, Both MD and TALE running, Good weather		
Cut level 2	$\theta < 70°$		
Cut level 3	$E_{rec\_tot} > 10^{16.5}$ eV		
Cut level 4	No track length cut		
Cut level 5	Crossing time > 2 μs	Crossing time > 6 μs	Crossing time > 4 μs
Cut level 6	No number of good tubes cut		
Cut level 7	An event must be successfully reconstructed (profile fit)		
Cut level 8	χ^2/ndf of profile fit < 10		
Cut level 9	**X_{max} bracketing** ($X_{first} > 200$ g/cm², $(X_{last}-X_{first}) > 150$ g/cm², **$X_{first} < X_{max} < X_{last}$**)		
Cut level 10	$S_{fraction} > 1.05$	$S_{fraction} > 1.05$	$S_{fraction} > 1.20$
Cut level 11	$S_{peak} > 50.0$	$S_{peak} > 80.0$	$S_{peak} > 50.0$, $S_{peak} \times R_p^2 > 3.2 \times 10^8$
Cut level 12	$d\Psi < 20°$	$d\Psi < 12°$	$d\Psi < 15°$
Cut level 13	$\Psi < 120°$		

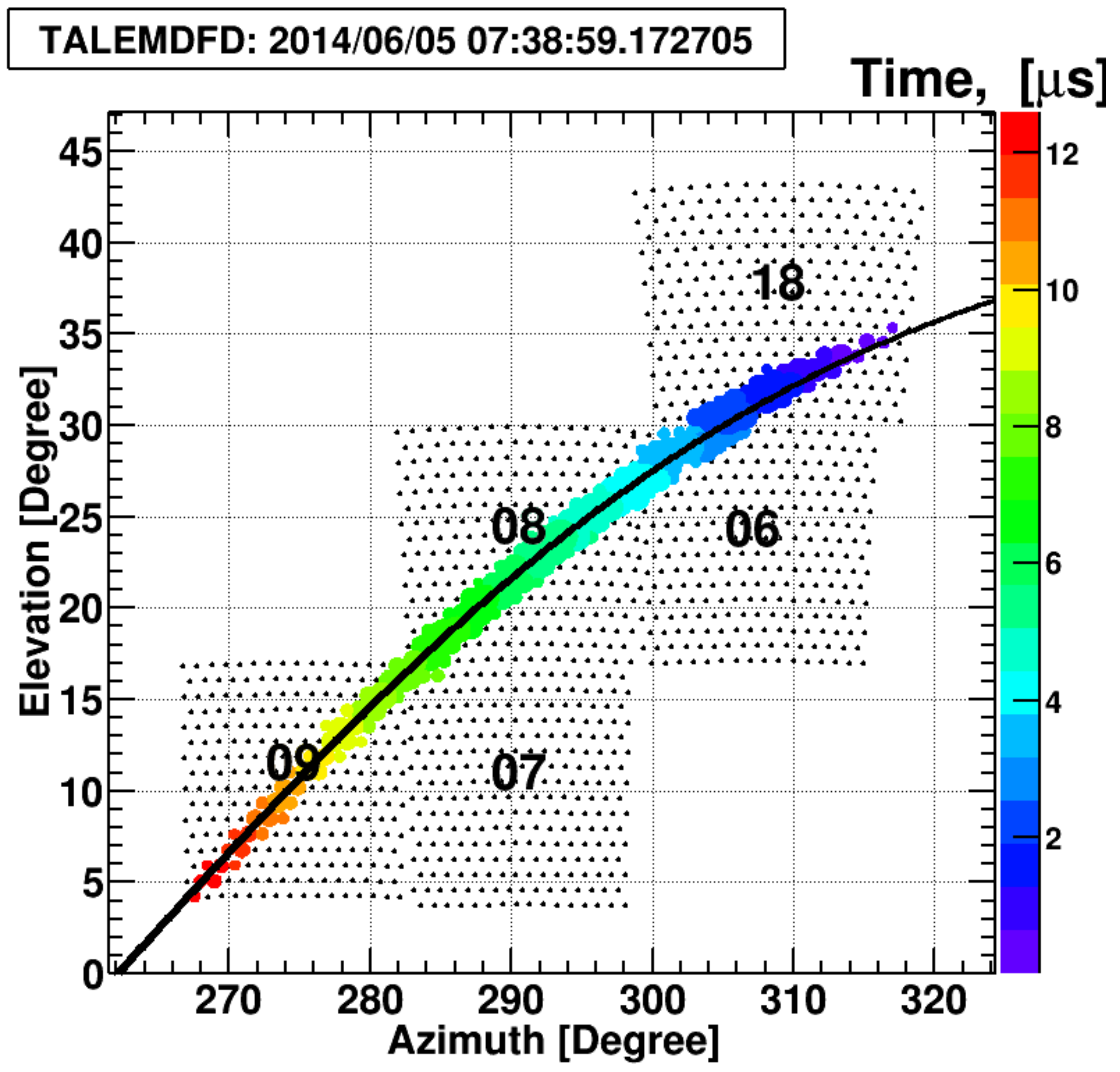
EVENT RECONSTRUCTION – # OF DATA EVENTS AFTER QUALITY CUT

	TALE	MD	TALE and MD
Cut level 1	112642	9608	4034
Cut level 2	43810	5099	3177
Cut level 3	30439	4754	2805
Cut level 4	-	-	-
Cut level 5	428	1291	1113
Cut level 6	-	-	-
Cut level 7	375	1270	1109
Cut level 8	350	1223	1084
Cut level 9	144	935	886
Cut level 10	83	682	492
Cut level 11	71	139	461
Cut level 12	65	123	461
Cut level 13	65	118	455

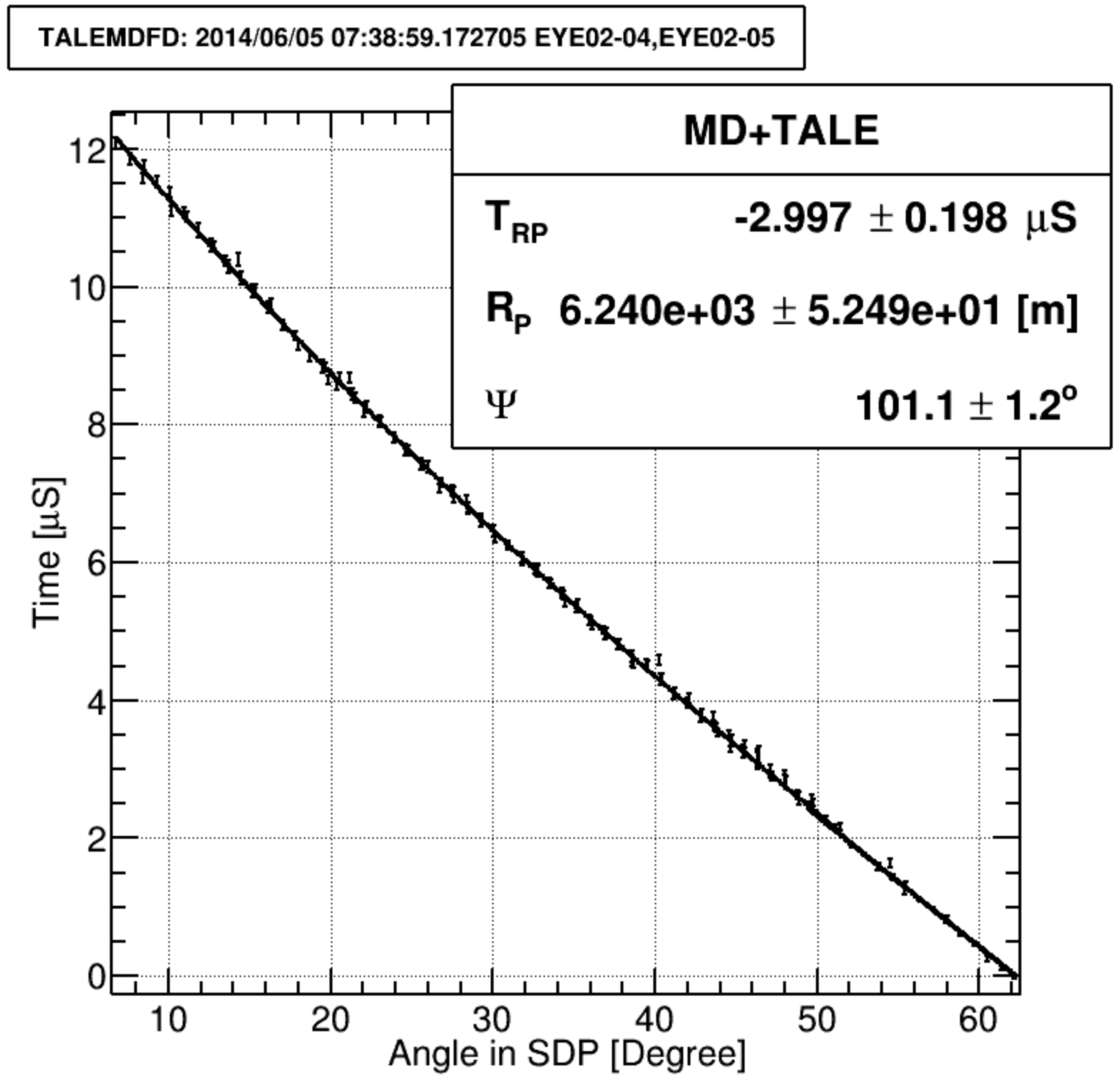
EVENT RECONSTRUCTION – EXAMPLE EVENT

- An example of the data event triggered both Middle Drum and TALE telescopes

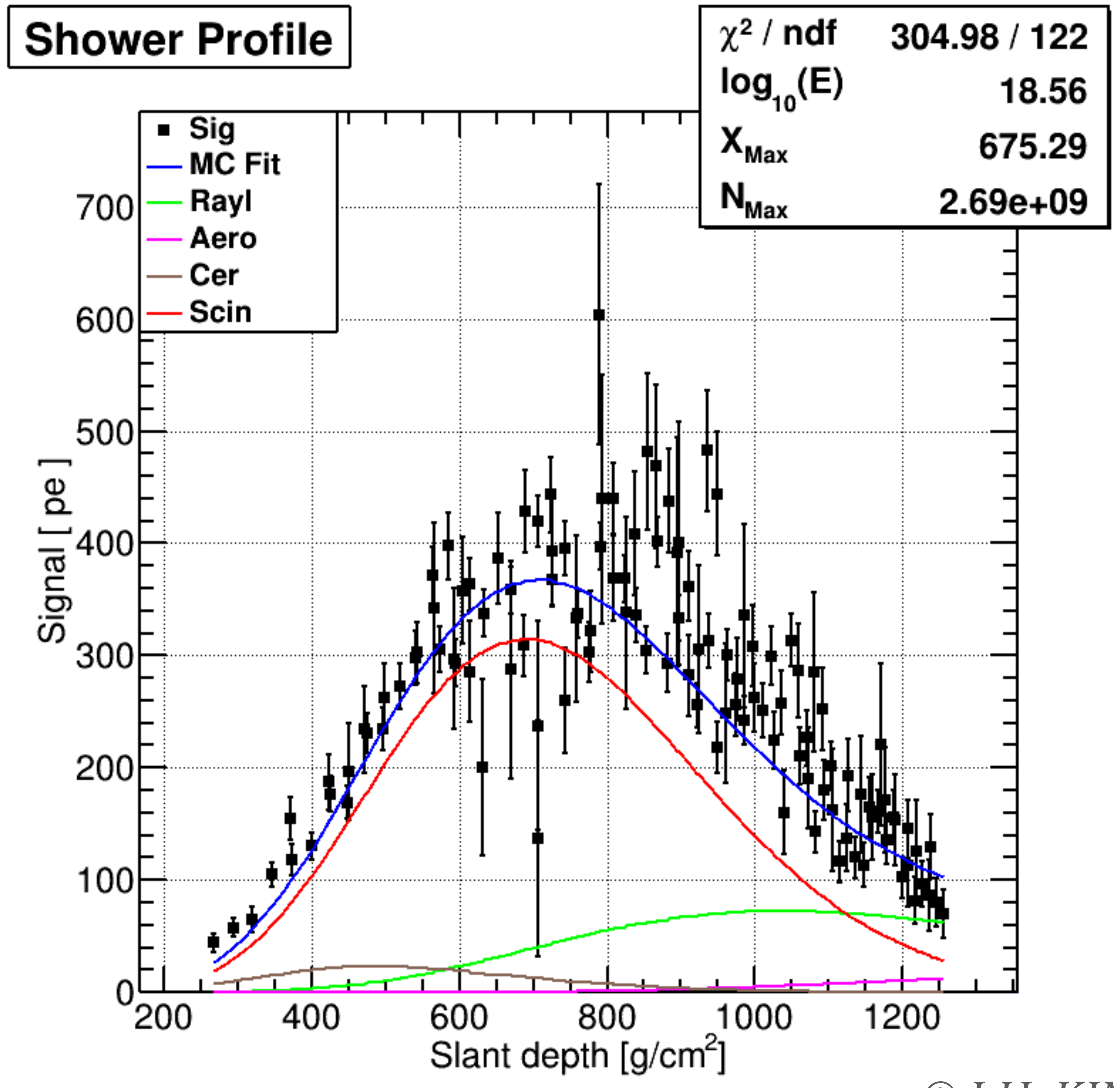
Event Display



Time vs. Angle Fit



Profile Fit



DATA/MC COMPARISON (1/5) – GEOMETRY CHECK

(Top) **Data** and **MC** distributions
(Bottom) Ratio of Data to MC

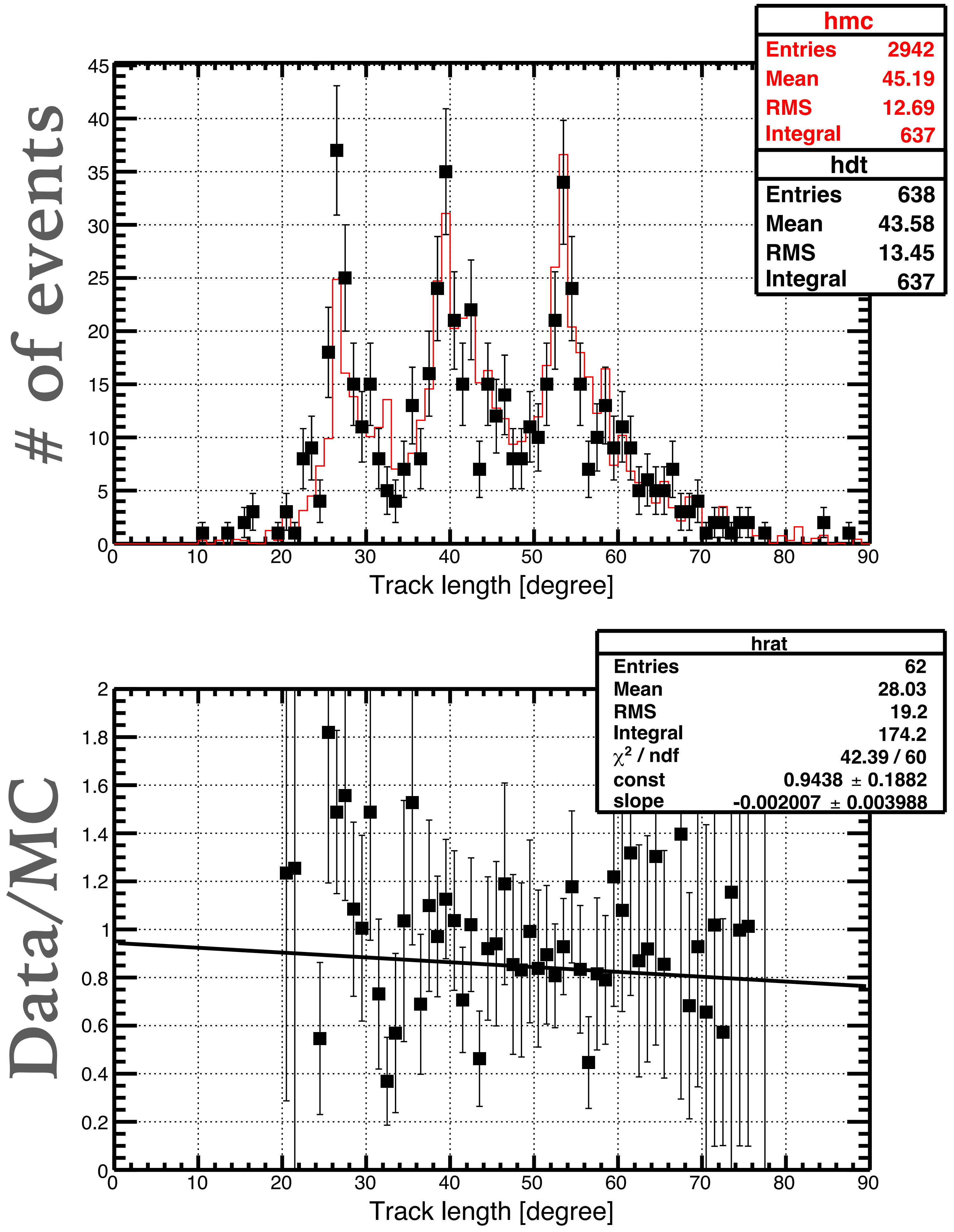
- Track length

  Three peaks corresponding to 2,3, & 4 telescope events

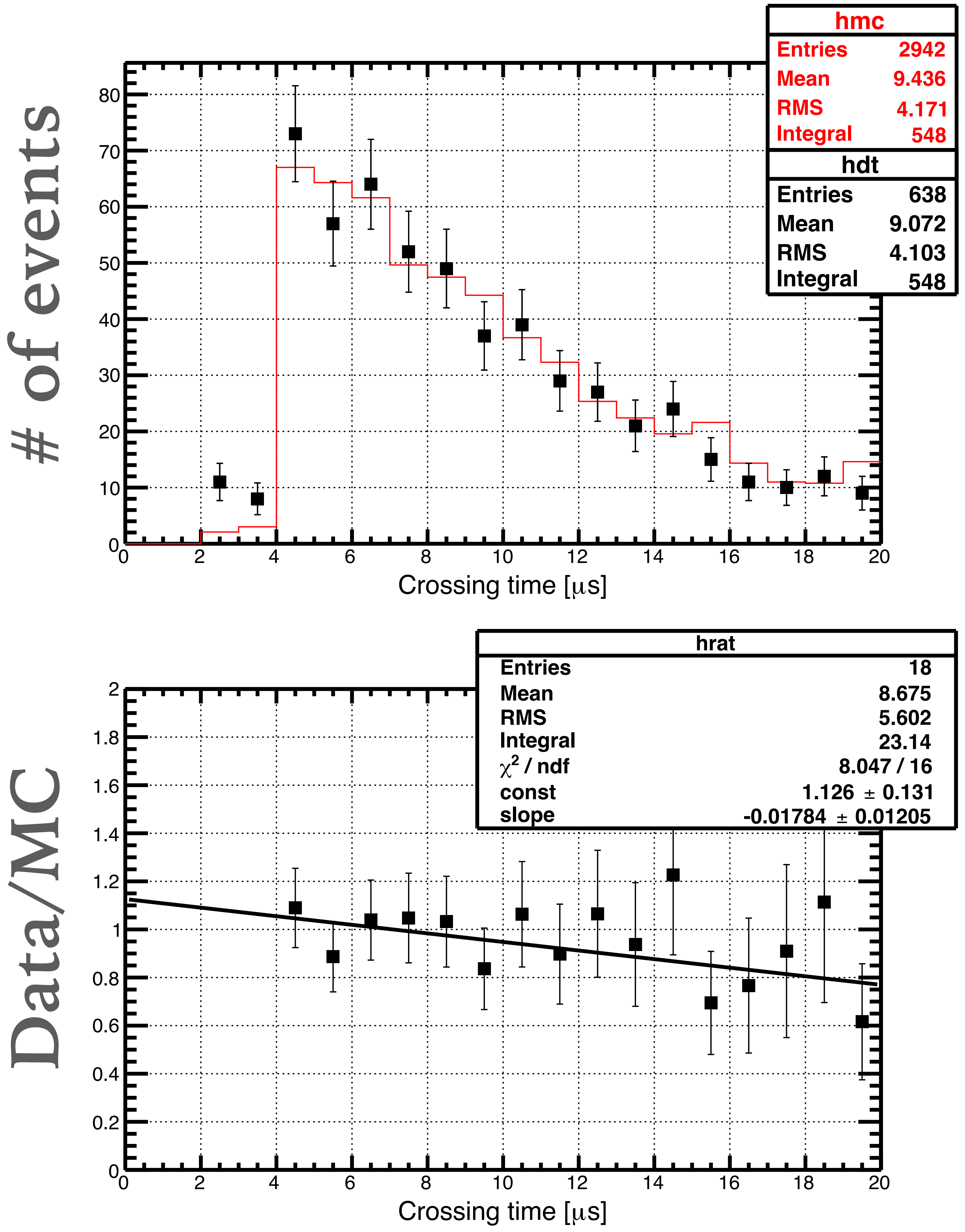
- Crossing time

  Time first to last tube triggered

Track length



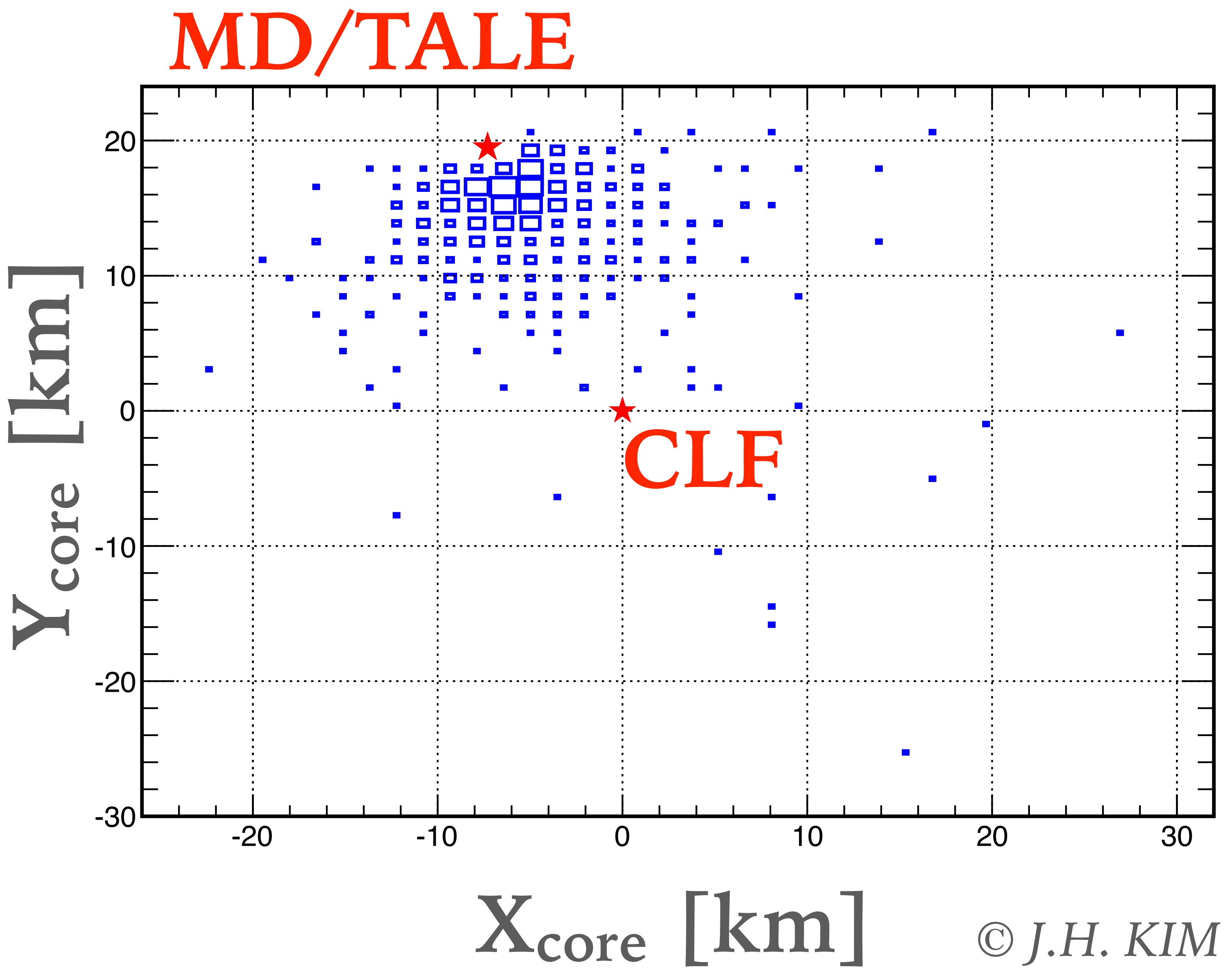
Crossing time



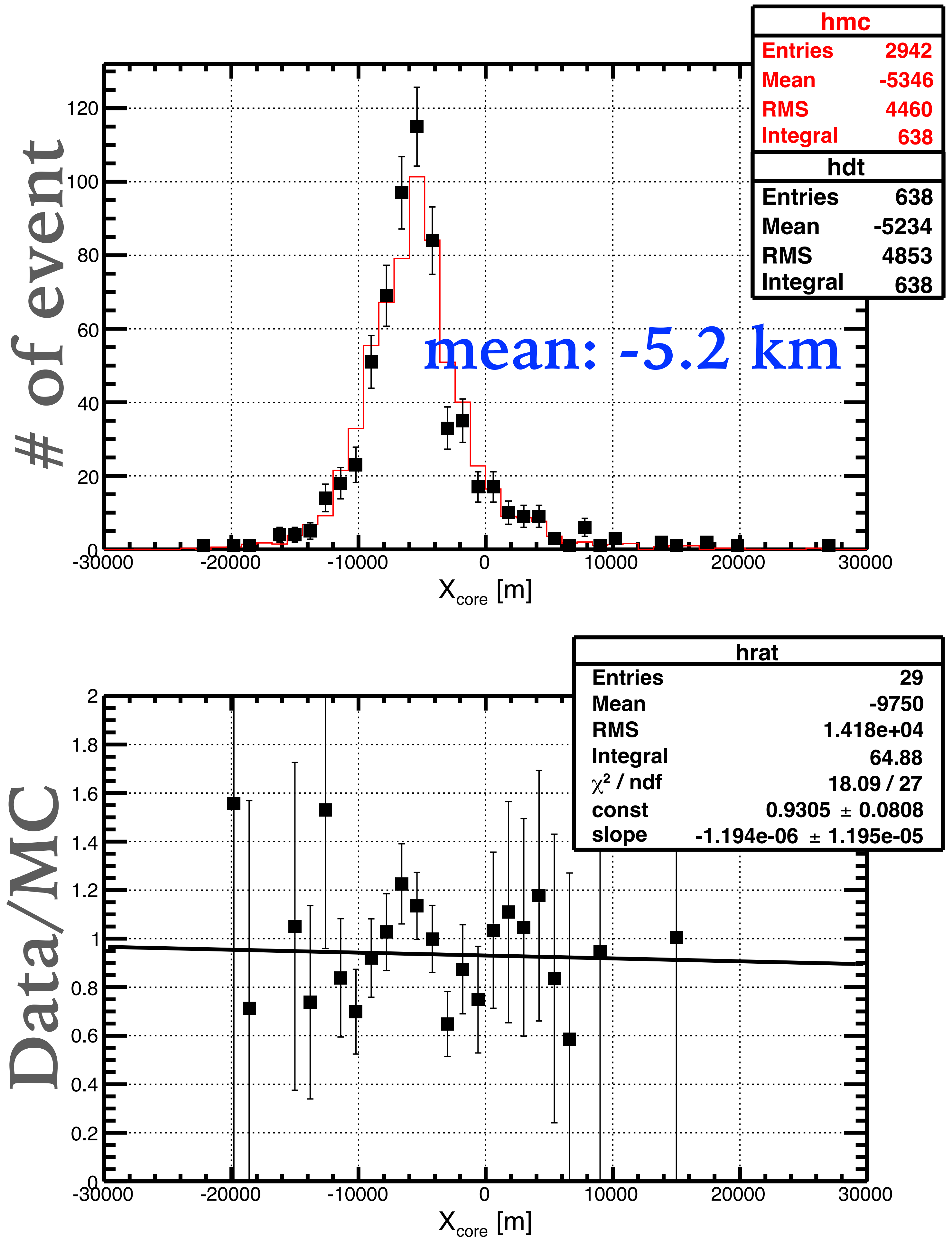
DATA/MC COMPARISON (2/5) – GEOMETRY CHECK

(Top) **Data** and **MC** distributions
(Bottom) Ratio of Data to MC

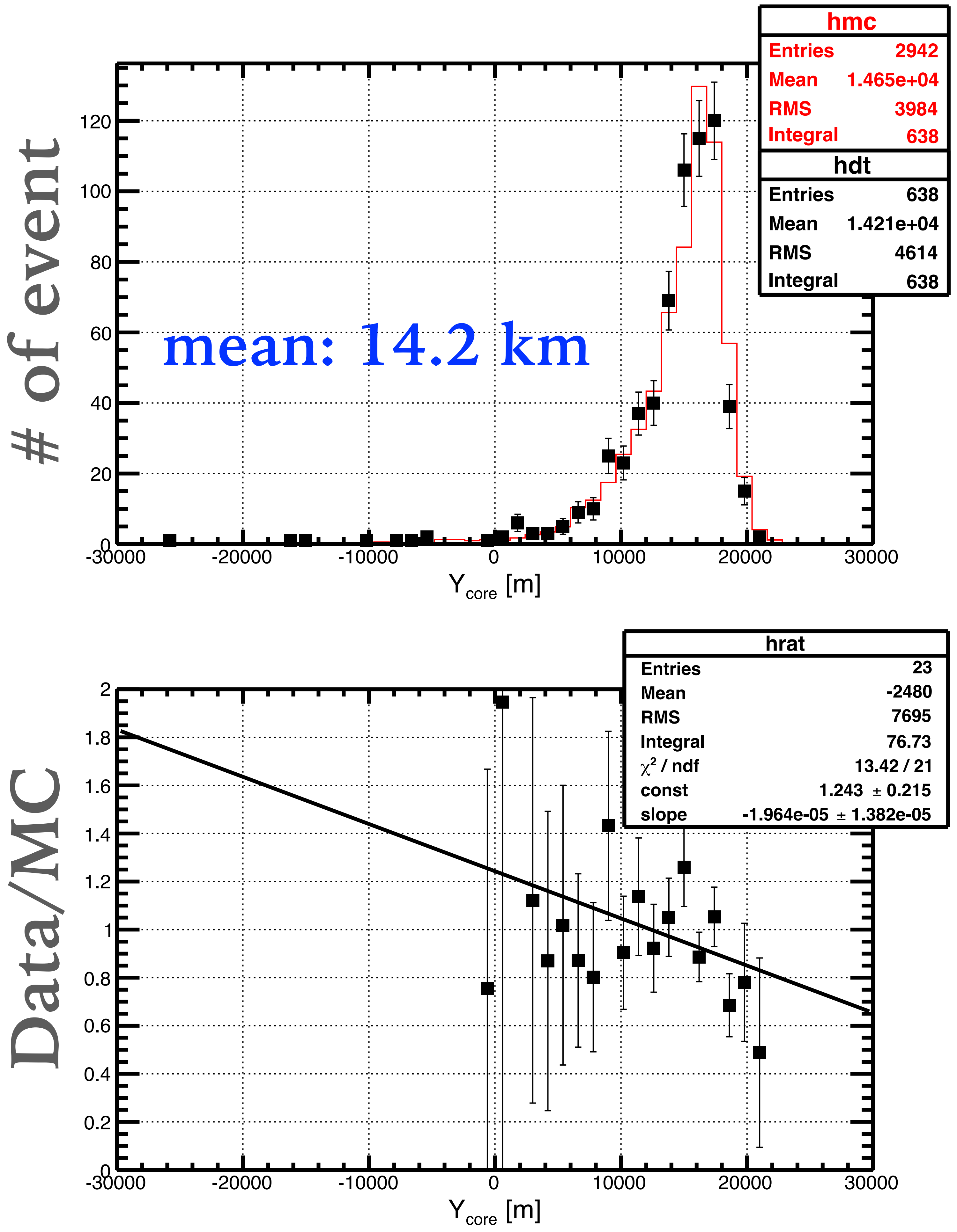
- Shower core position [km] in CLF coordinate



X_{core}



Y_{core}



DATA/MC COMPARISON (3/5) – APERTURE CHECK

(Top) **Data** and **MC** distributions
(Bottom) Ratio of Data to MC

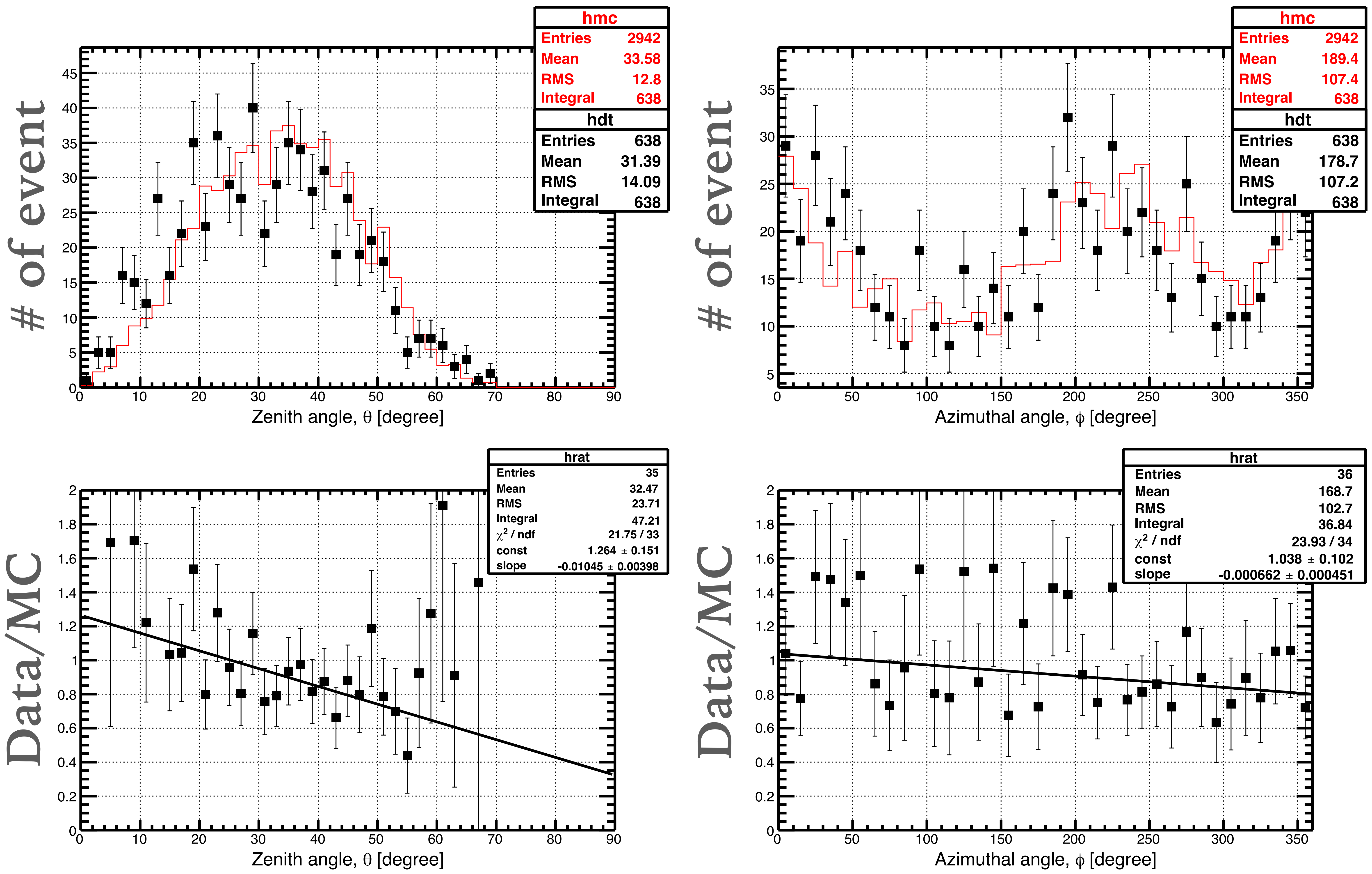
- Zenith angle

  Inclined of shower

- Azimuthal angle

  Degrees N of E

Zenith angle (θ) | Azimuthal angle (ϕ)



DATA/MC COMPARISON (4/5) – APERTURE CHECK

(Top) **Data** and **MC** distributions
(Bottom) Ratio of Data to MC

- In-plane angle

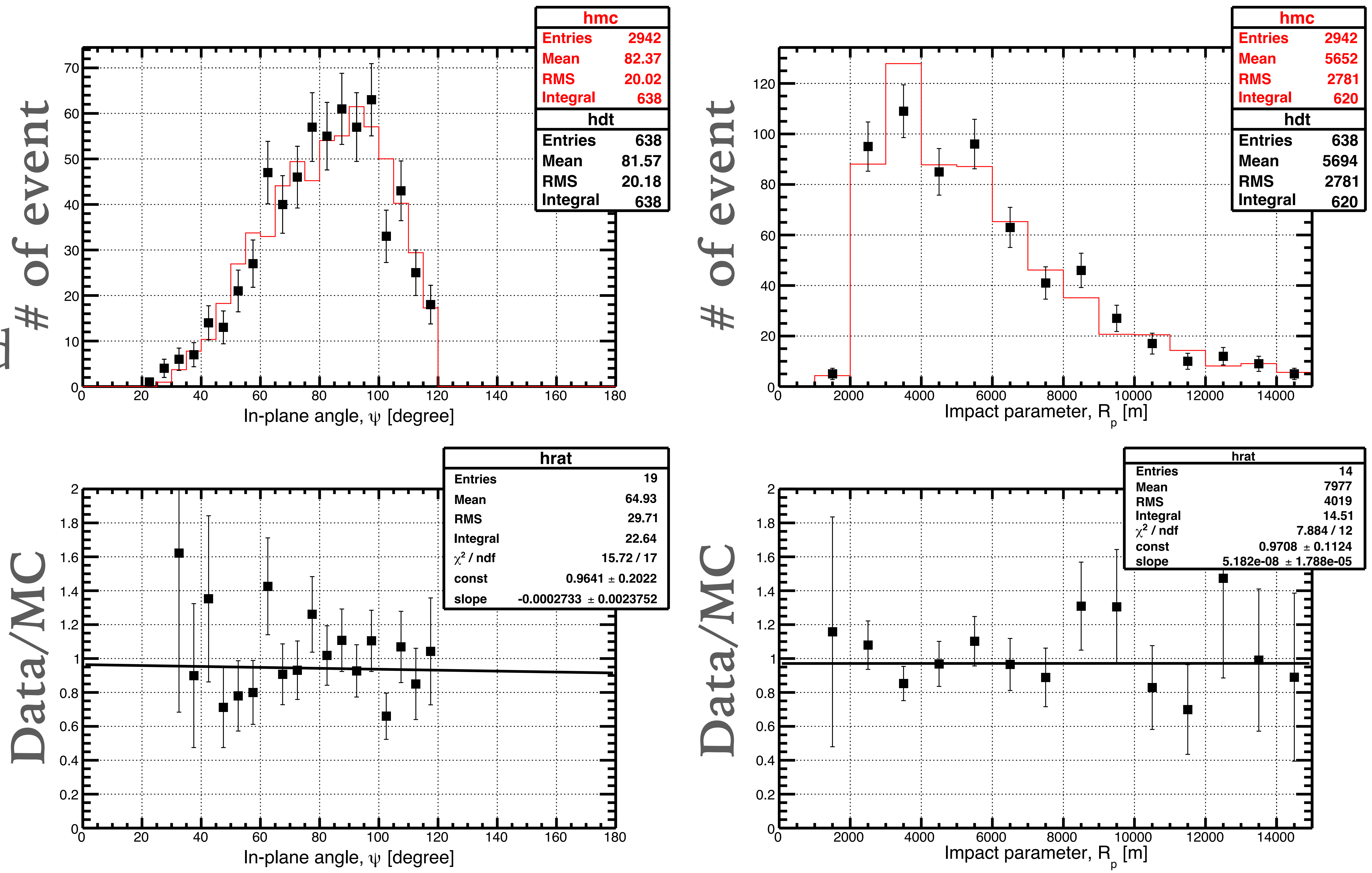
  Going away or Coming toward

- Impact parameter

  Distance at closet approach

In-plane angle (Ψ)

Impact parameter (R_p)



DATA/MC COMPARISON (5/5) – SENSITIVITY CHECK

(Top) **Data** and **MC** distributions
(Bottom) Ratio of Data to MC

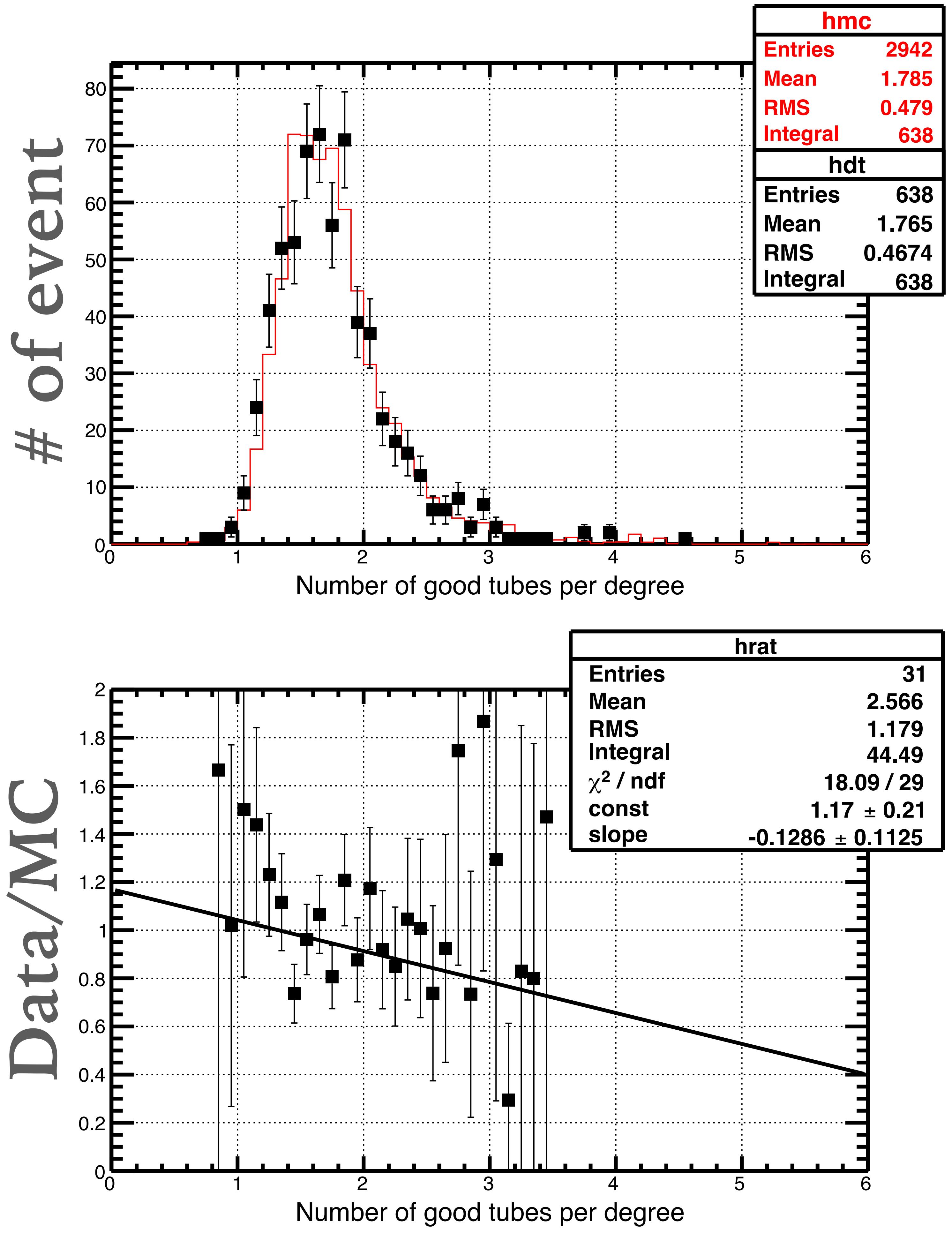
- # of good tubes per degree

  how wide or how near

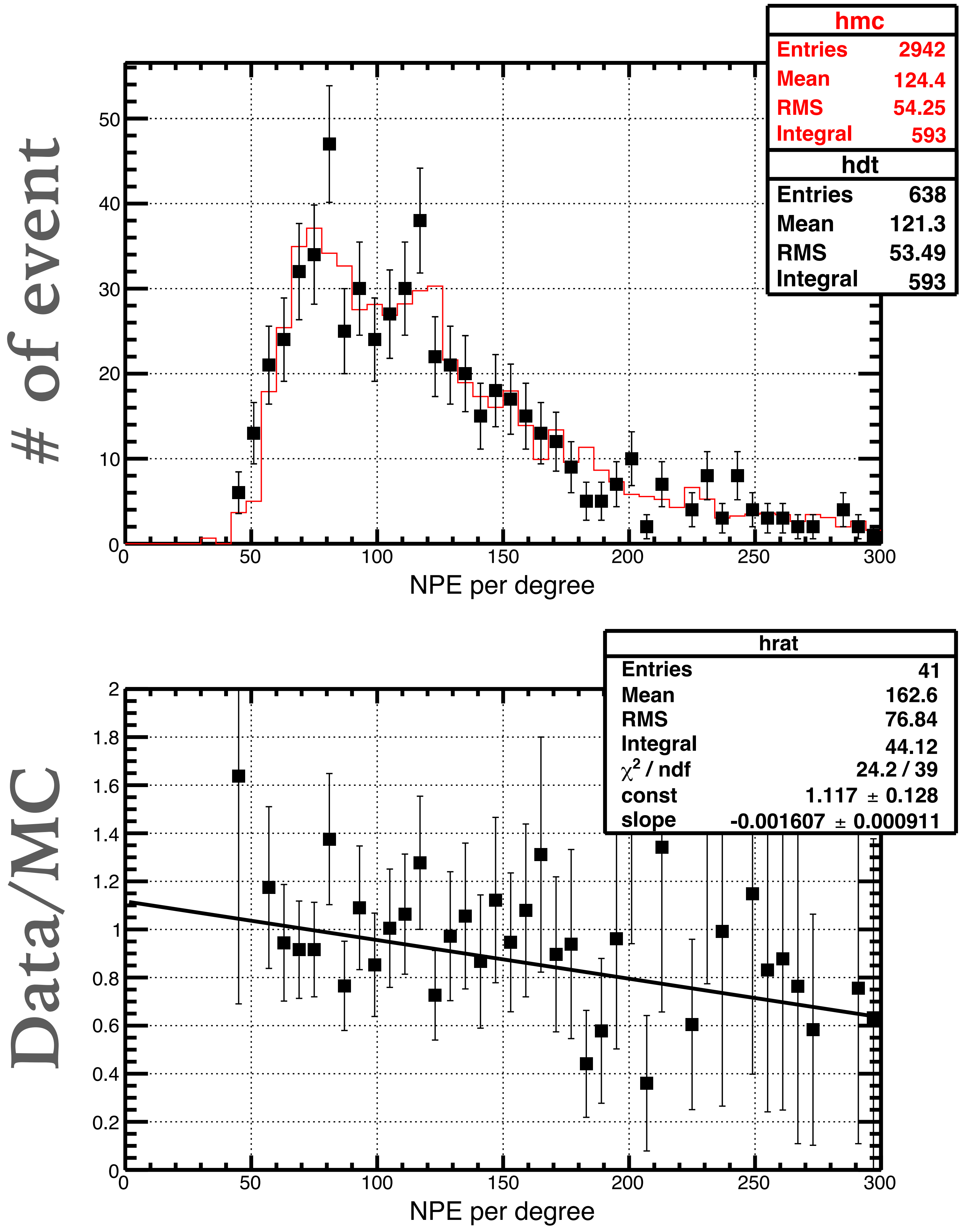
- NPE per degree

  signal size per track

of good tubes per degree



NPE per degree



ENERGY SPECTRUM MEASUREMENT

- Energy spectrum

$$J(E_i) = \frac{N(E_i)}{A\Omega(E_i) \times T \times \Delta E_i}$$

$J(E_i)$ flux of comic rays
$N(E_i)$ # of observed cosmic rays
$A\Omega(E_i)$ energy dependent aperture
T detector on-time
E_i width of energy bin

- Data set:

- 1 June 2014 - 31 January 2015 (about 8 months; on-time 537 hrs)

  - 1 June 2014 = start of stable operation

  - 31 January 2015 = change in trigger (require different MC)

- Good weather 470 hrs

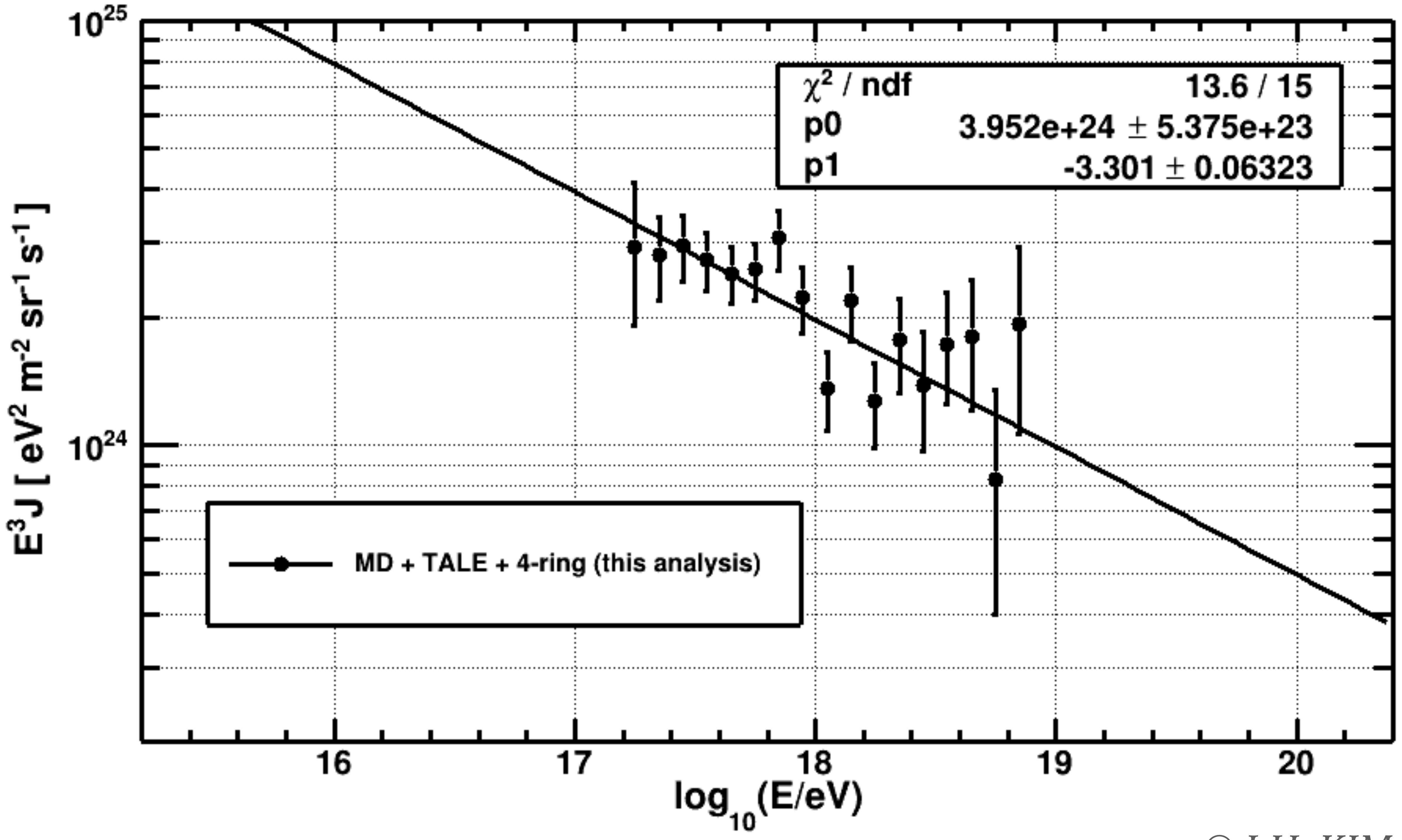
- 638 events after quality cuts

- Events seen by MD or TALE or both

ENERGY SPECTRUM

- Middle Drum and TALE monocular energy spectrum
- Fit between 2nd knee and ankle to a power law:

-3.30±0.06 spectral index



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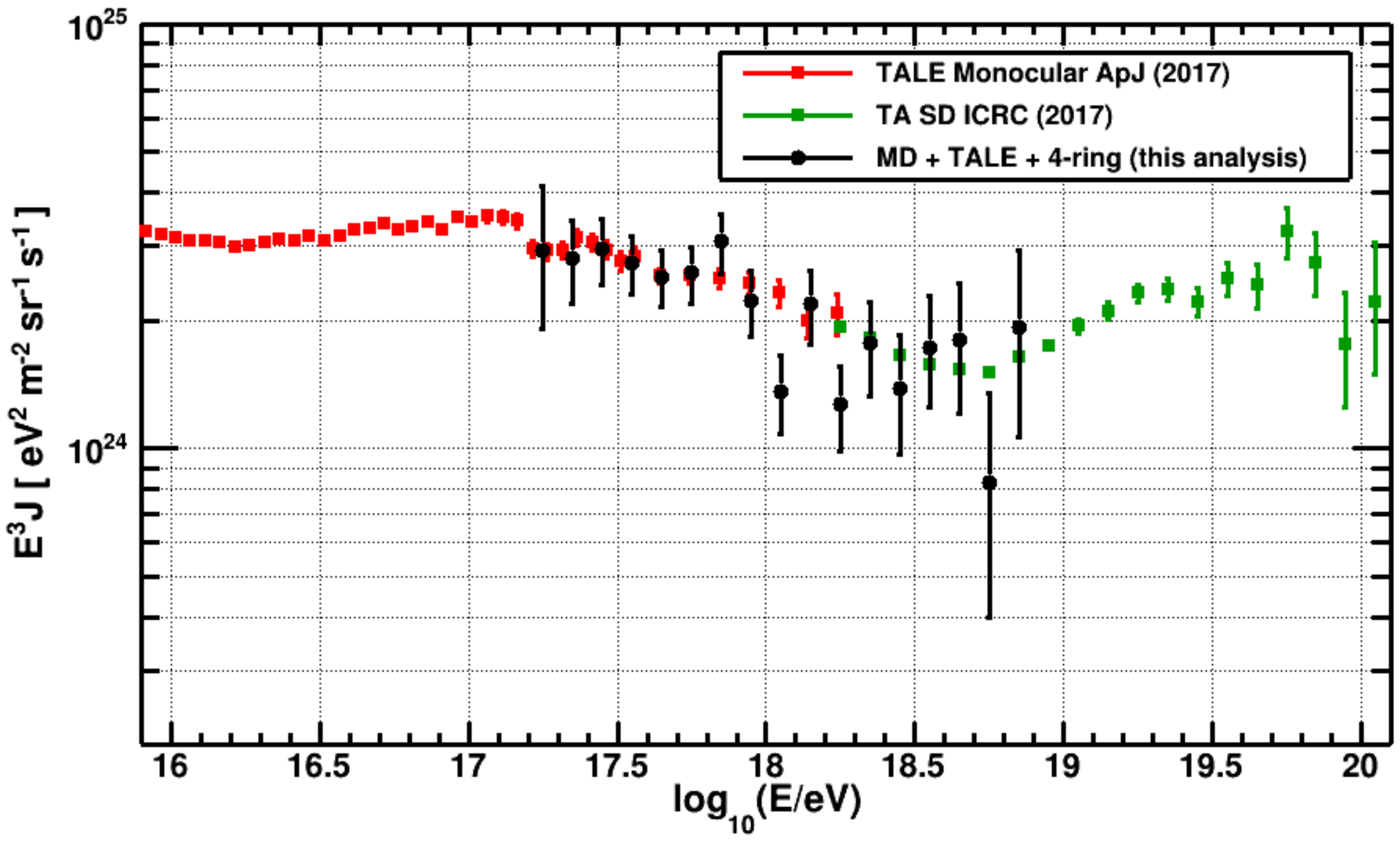
Energy log10(E/eV)	Number of Events
17.25	12
17.35	33
17.45	52
17.55	67
17.65	72
17.75	71
17.85	70
17.95	53
18.05	33
18.15	43
18.25	28
18.35	26
18.45	17
18.55	20
18.65	15
18.75	5
18.85	8

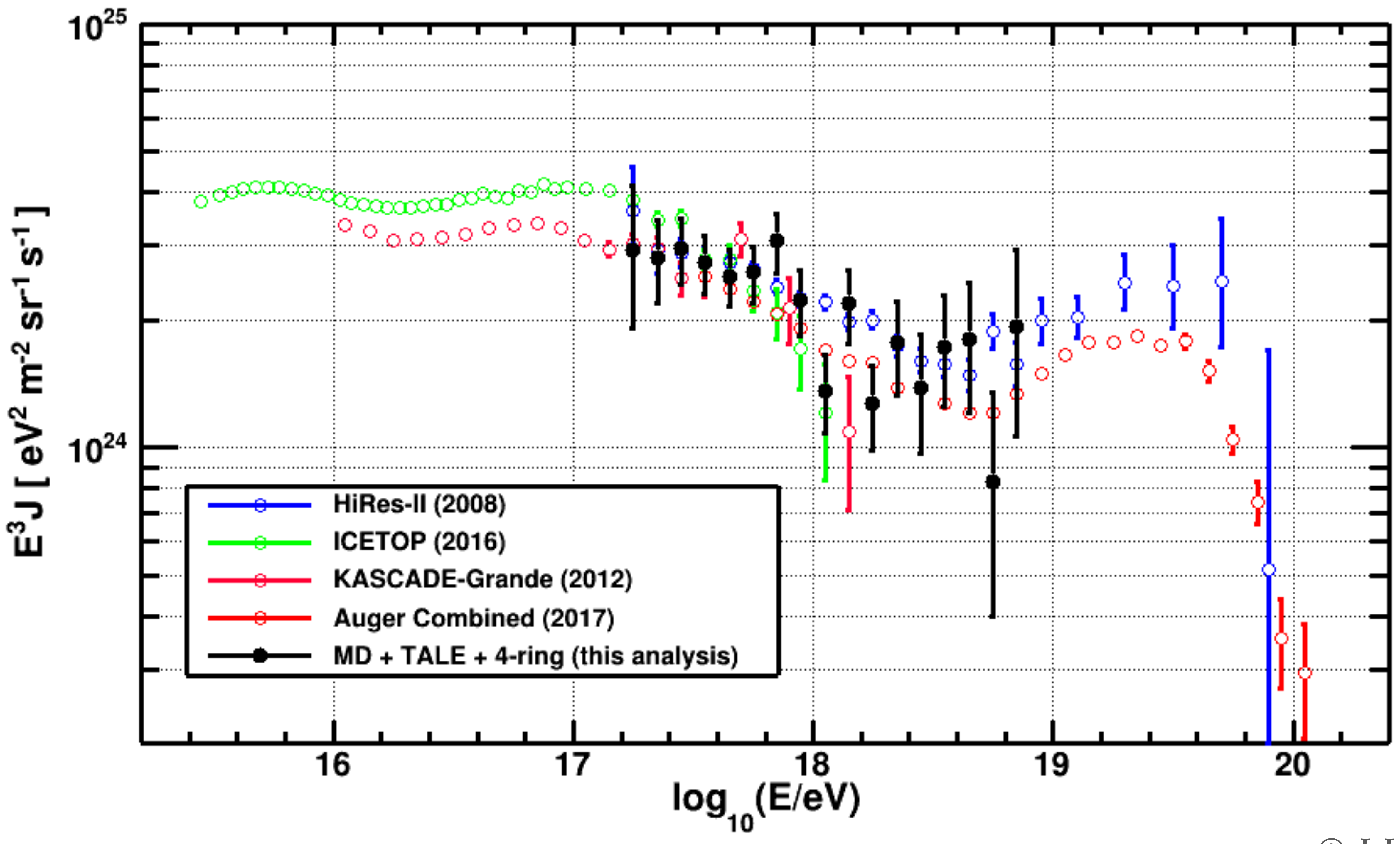
ENERGY SPECTRUM

- (Left) A bridge between TALE only detector (Red) and Surface detector spectra (Green)
- (Right) HiRes-2 (Blue), Icetop (Green), KASCADE-Grande (Orange), and Auger (Red)

w/ other TA energy spectra



w/ other external energy spectra



CONCLUSIONS (TAKE-HOME MESSAGE)

- Monocular Cosmic Ray Energy spectrum Measurement

  MD telescope - High Energy

  TALE telescope - Low Energy

- Joint measurement of Cosmic rays using both MD and TALE telescopes

  - 4 ring analysis : optimal technique for this energy region

- Transition from heavy galactic to light extra galactic cosmic rays
- **Spectral slope, -3.30±0.06 in the energy range $10^{17.2}$ to 10^{19} eV**

  - **Spectral slope : good agreement with other TA techniques**

- **Good agreement with other measurements (HiRes, IceTop, KASCADE)**

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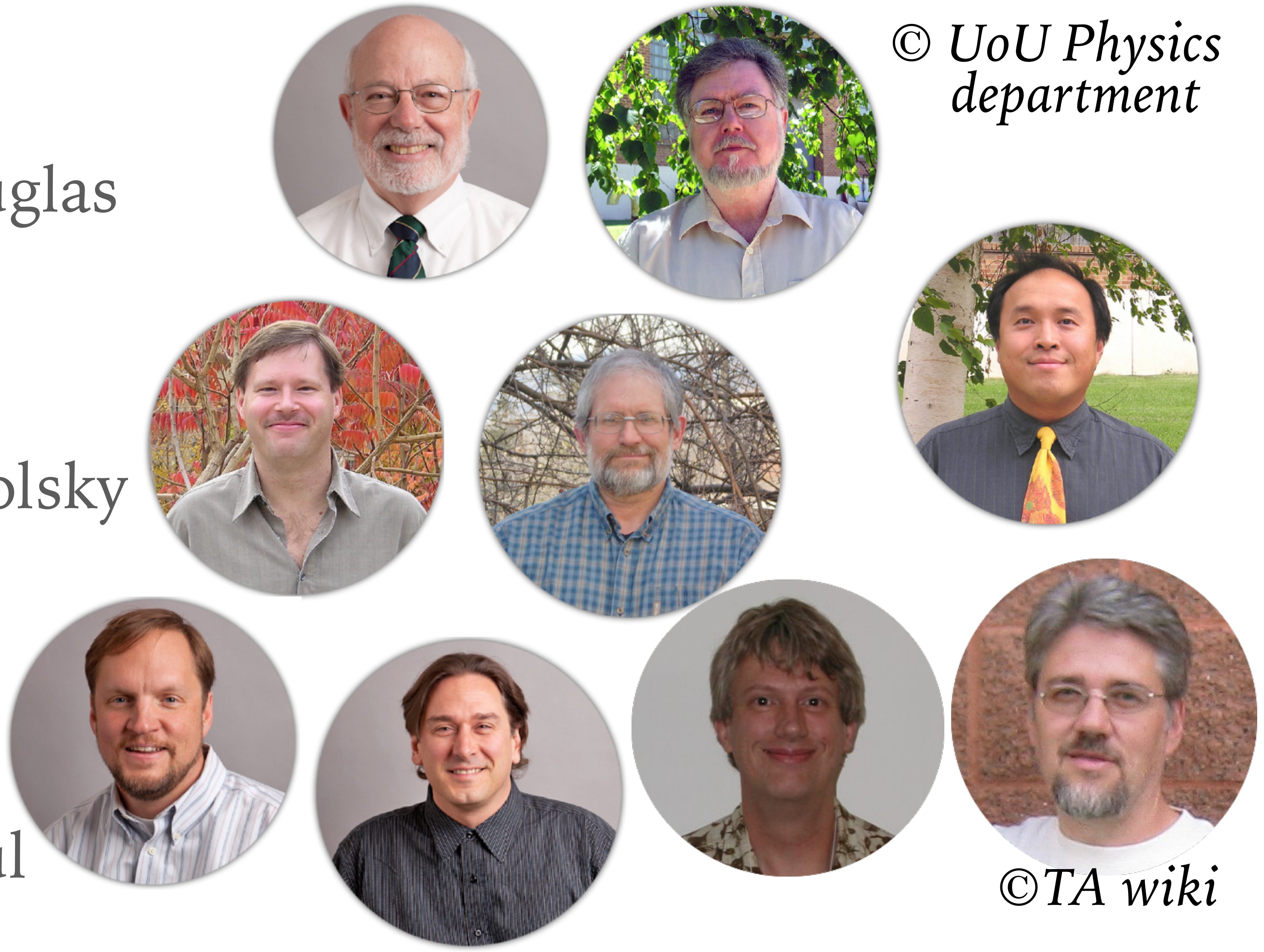
- Ganymede (Dog therapy while writing dissertation)



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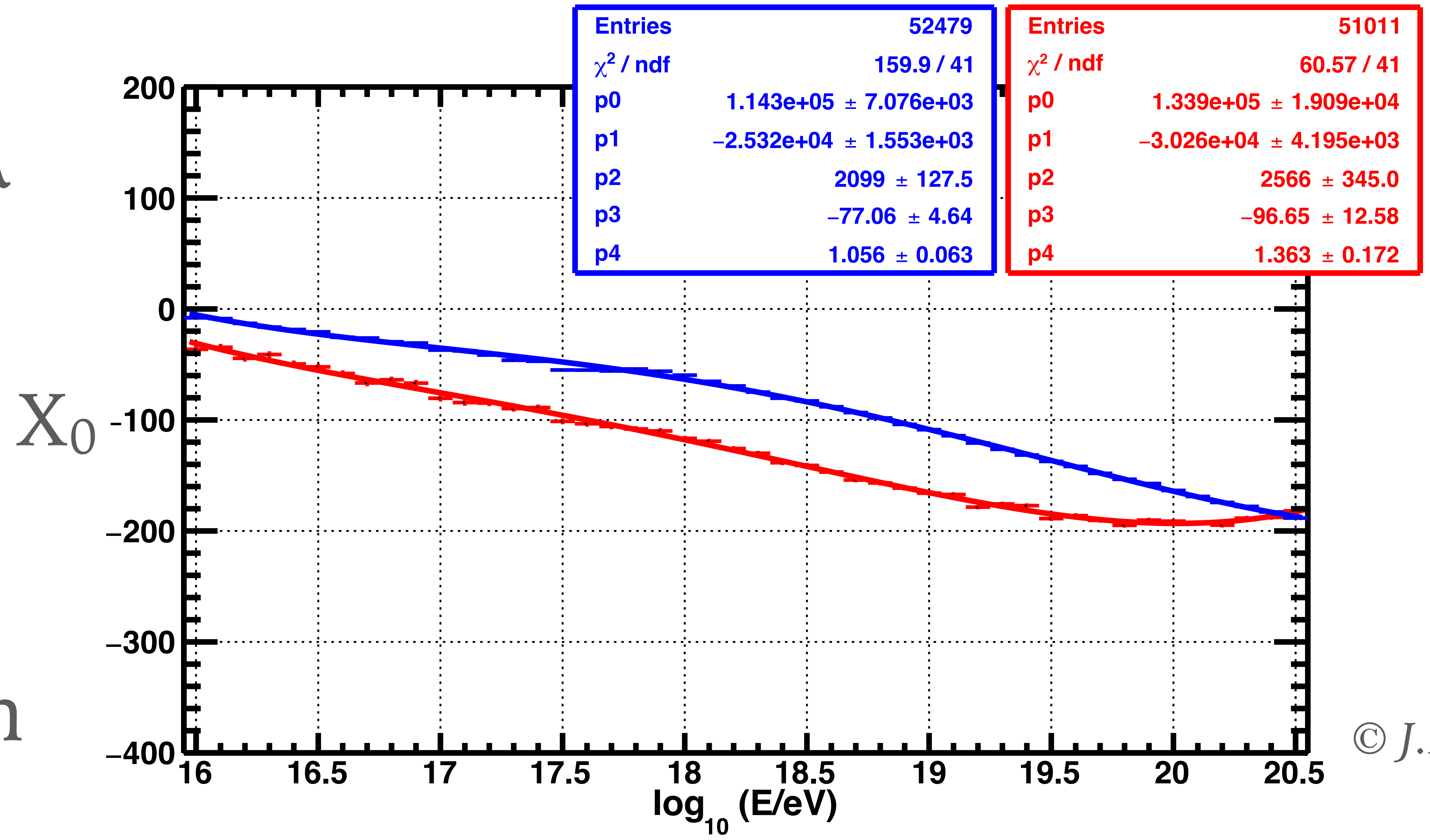
BACK UP SLIDES

NEXT

- Data Set 3, ~5 × statistics (change MC)
  - may gain 2-3 more data points at lower energy
  - may gain 2-3 more data points at higher energy
  - observation of ankle unlikely
- Extend to higher energy using MD

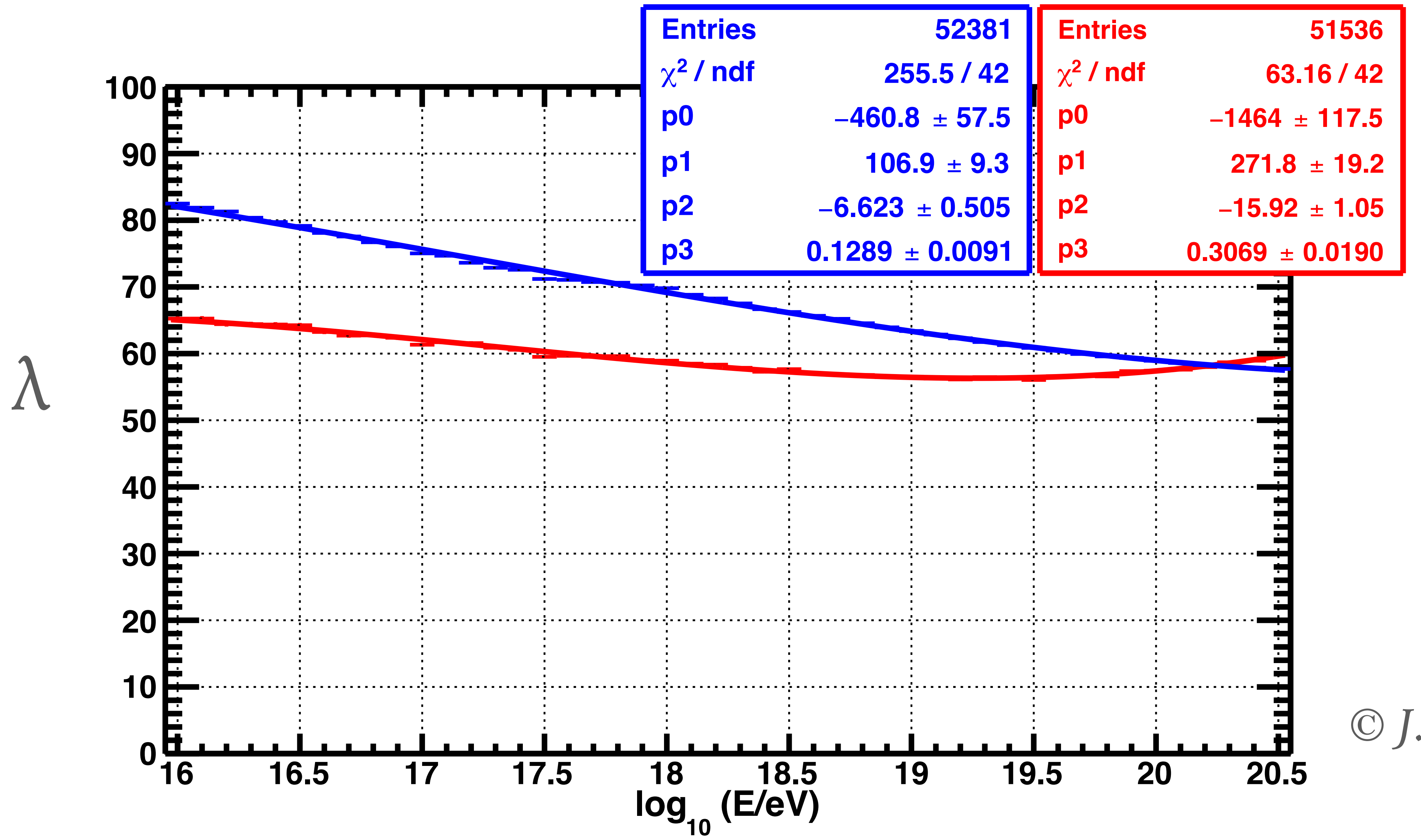
EVENT RECONSTRUCTION – PROFILE FIT

- Found I had an Energy bias when fixed X_0 and λ
- Generated look-up table of X_0 and λ from p/Fe CORSIKA events
- Corrected for variation in X_0 and λ with energy during analysis. Weighted based on composition as measured by the HiRes/MIA and HiRes experiments.



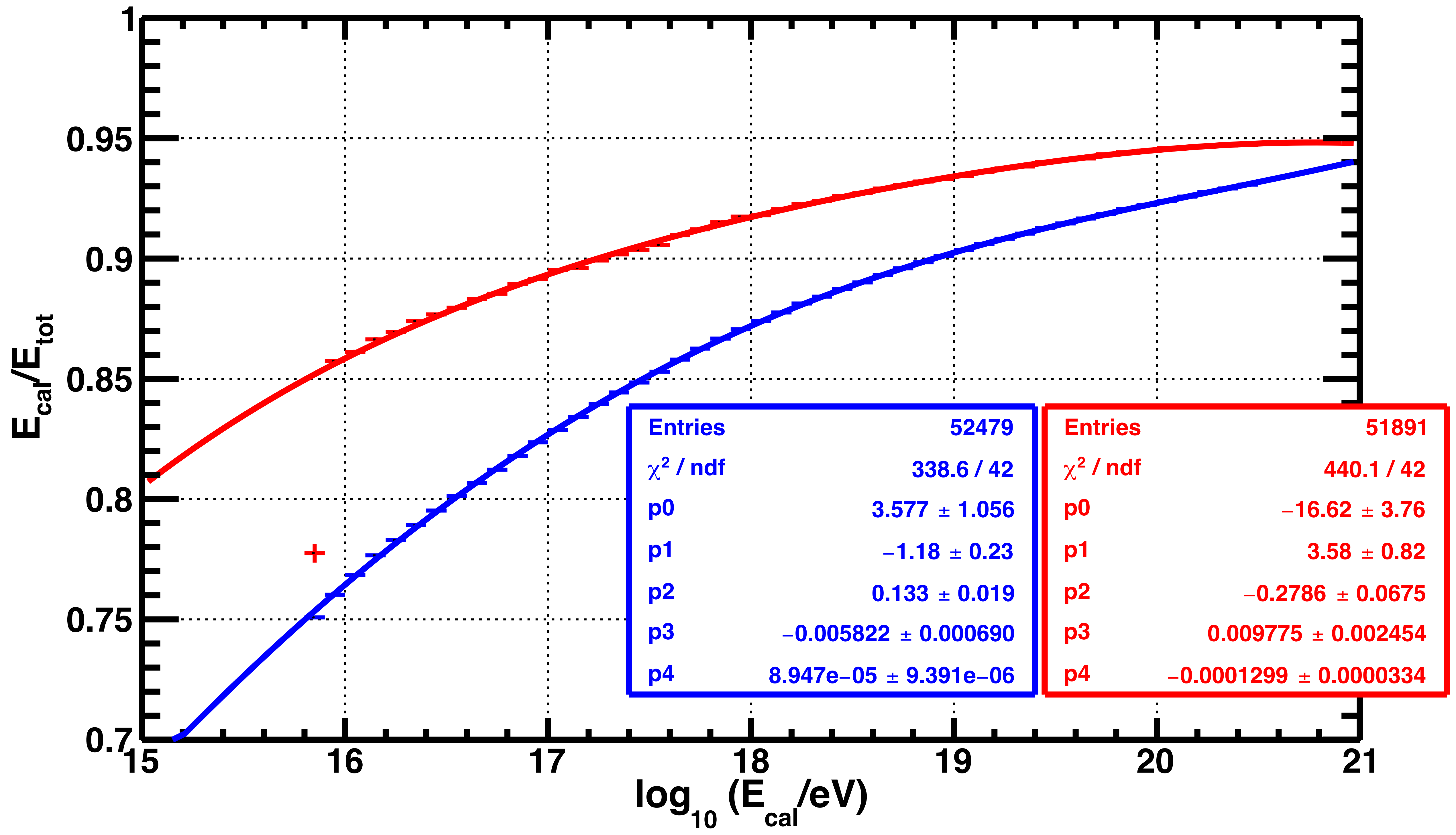
Red : Proton MC

Blue : Iron MC



EVENT RECONSTRUCTION – MISSING ENERGY CORRECTION

- Calorimetric/Visible energy by telescopes
- Energy carried by μ and *ν* missing
- As energy of primary cosmic rays (# of interactions) increases, the required missing energy correction decreases
- As # of interactions increases, energy transferred to electromagnetic/visible component



Red : Proton MC

Blue : Iron MC

DATA/MC COMPARISON

(Top) **Data** and **MC** distributions
(Bottom) Ratio of Data to MC

- # of participating rings

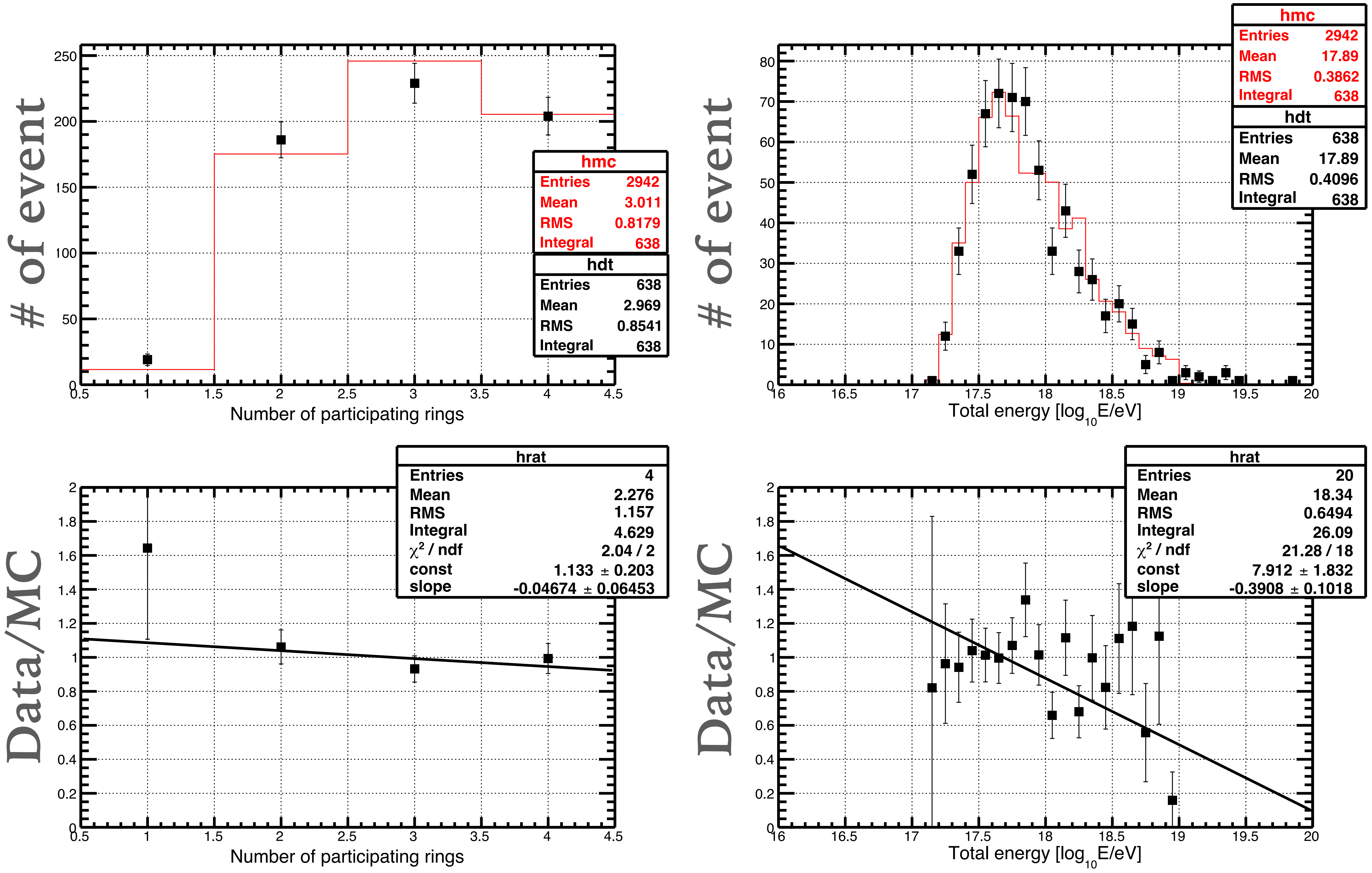
  1, 2, 3, and 4-ring

- Total energy

  Missing energy corrected

# of participating rings

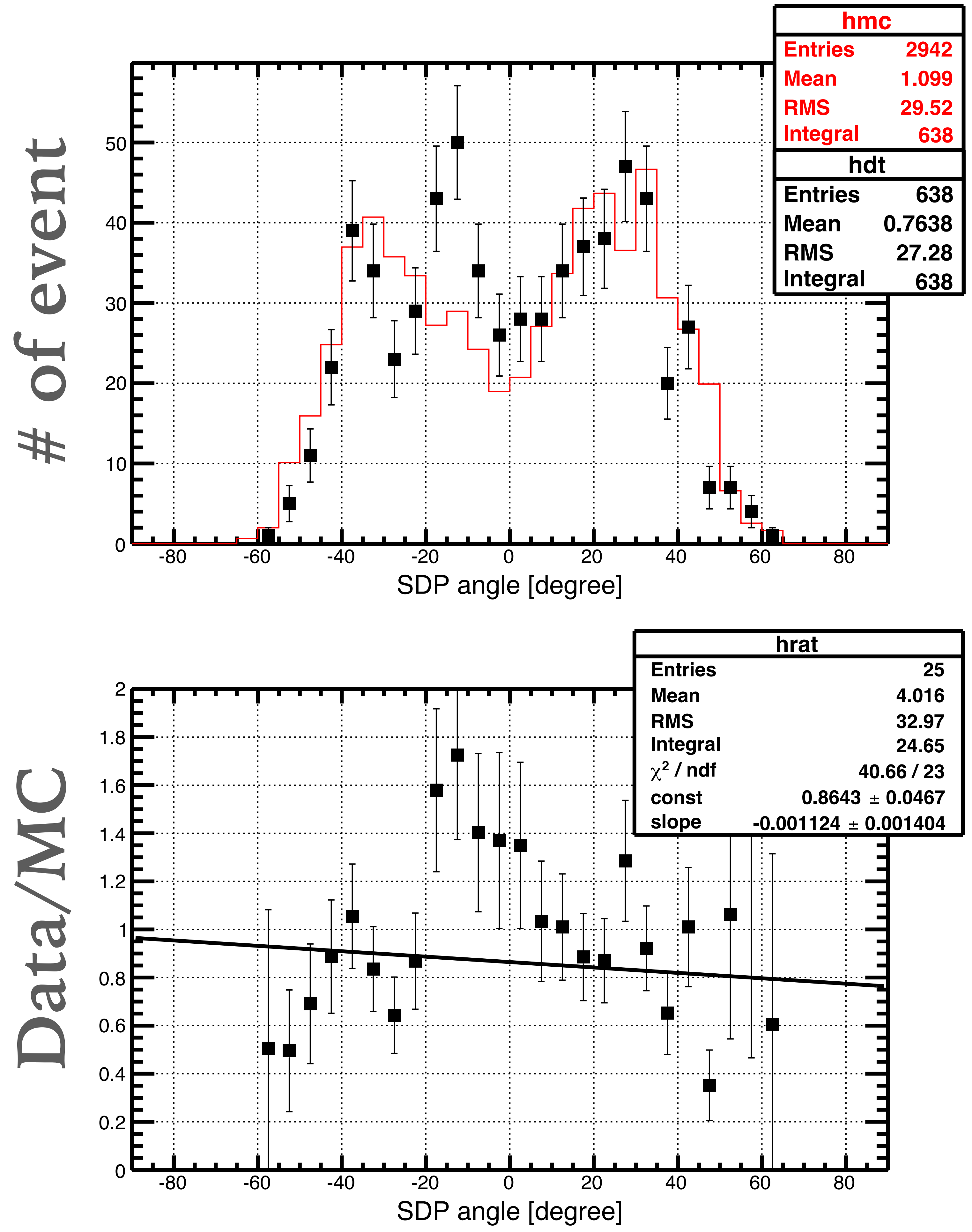
Total energy



DATA/MC COMPARISON

(Top) **Data** and **MC** distributions
(Bottom) Ratio of Data to MC

Shower Detector Plane angle



- SDP angle

  Dip structure around 0°

  Related to insensitivity in the trigger