



# Optimizing LHAASO-KM2A Performance at Large Zenith Angles

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01

Scientific Motivation

# ◆ Galactic Center: A Forbidden Treasure

## Zenith Angle Limitation

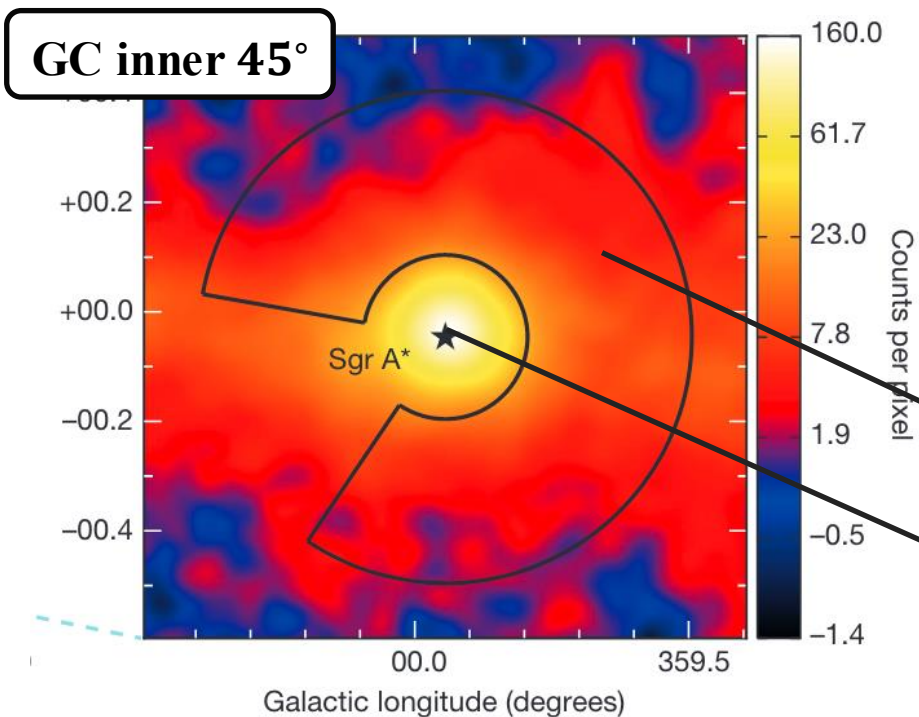
Standard LHAASO analysis restricts zenith angles to below  $50^\circ$ , excluding the scientifically rich Galactic Center region from observation.

## Key Astrophysical Targets

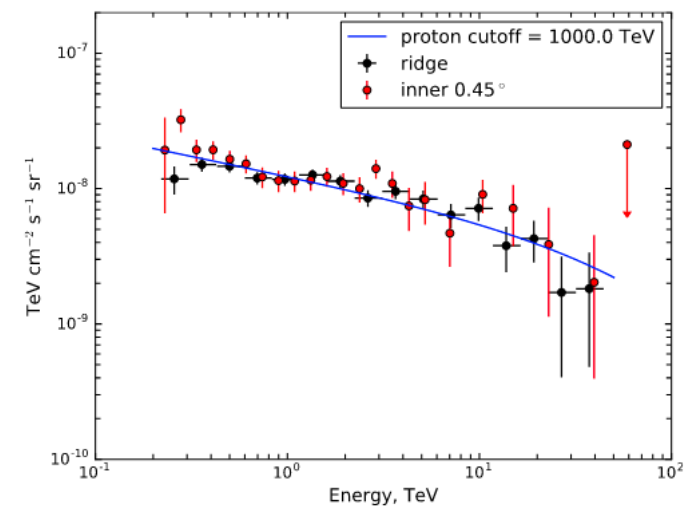
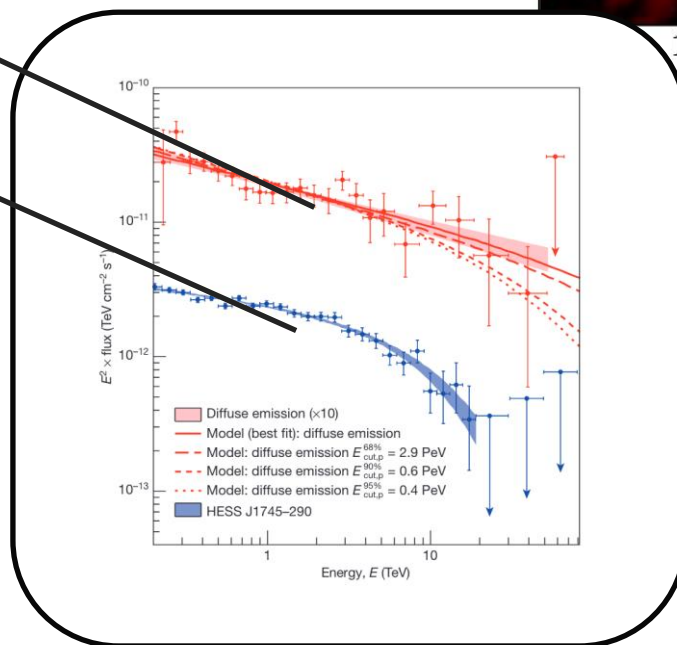
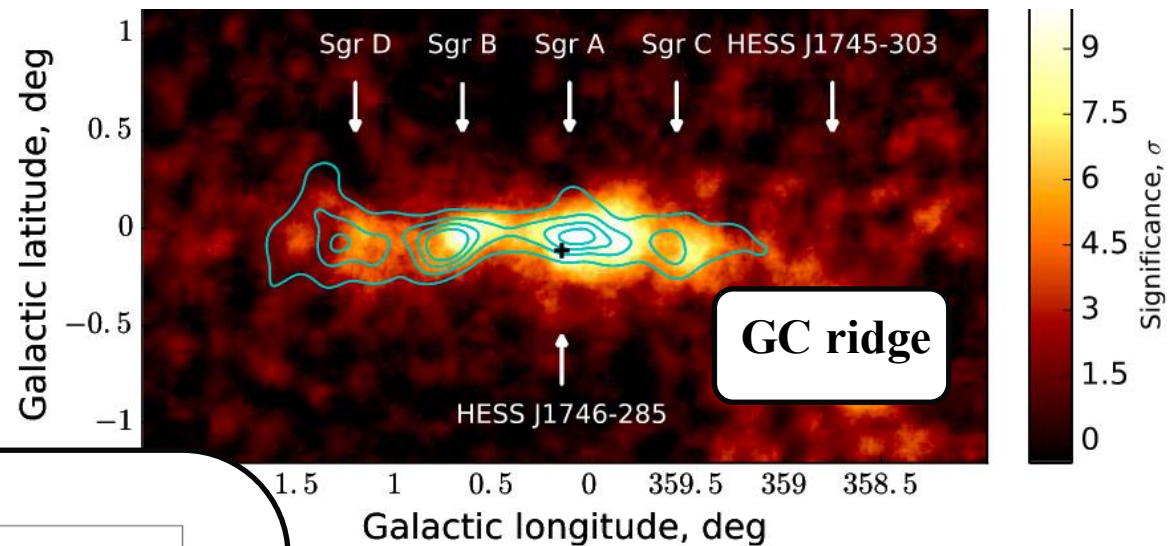
The Galactic Center contains Sgr A\* supermassive black hole, Central Molecular Zone, and supernova remnant G0.9+0.1, crucial for high-energy astrophysics research.

# Galactic Center: A Forbidden Treasure

H.E.S.S. collaboration. 2018



H.E.S.S. collaboration. 2016



# ◆ Other sources in large zenith angle region

Some examples:

Source	Type	RA [°]	Dec [°]	Time [h] ( $\theta < 50^\circ$ )	Time [h] ( $\theta < 65^\circ$ )	Increase
LS I +61 303	Binary	40.14	61.24	7.9	12.1	53%
LS 5039	Binary	276.56	-14.85	3.2	6.6	104%
W28(SNR G006.4-00.1)	SNR/MC	270.43	-23.34	0.0	5.3	new
V4641 Sgr	Binary	274.84	-25.41	0.0	4.9	new
SNR G000.9+00.1	SNR/PWN	266.85	-28.15	0.0	4.2	new
Galactic Center	SMBH	266.42	-29.01	0.0	4.0	new
SNR G353.6-0.7	SNR/Shell	263.01	-34.76	0.0	1.5	new

< 5 >

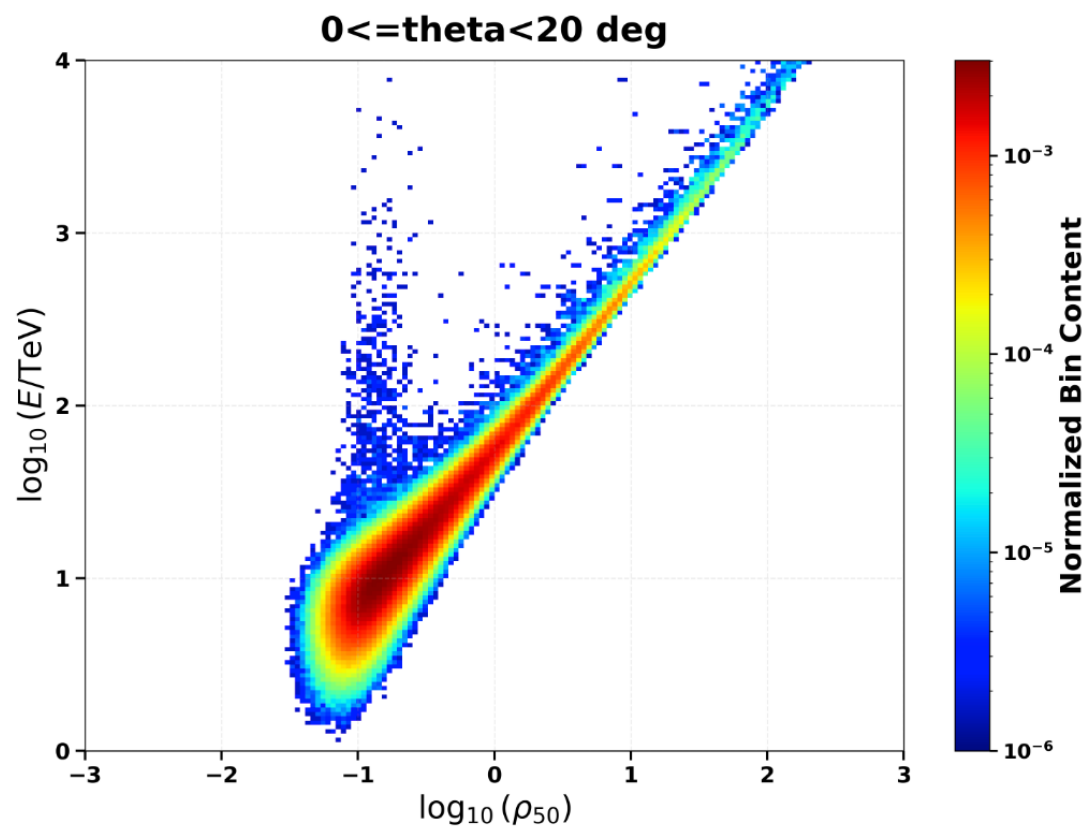
Provided by Wenlian Li



02

Energy Reconstruction

# Standard Energy Reconstruction Framework



$\rho_{50}$  vs  $E_{true}$

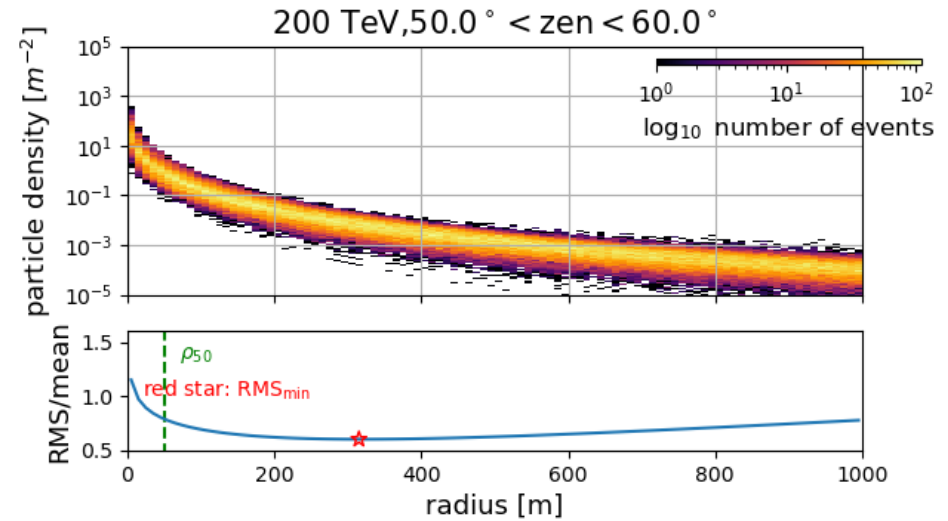
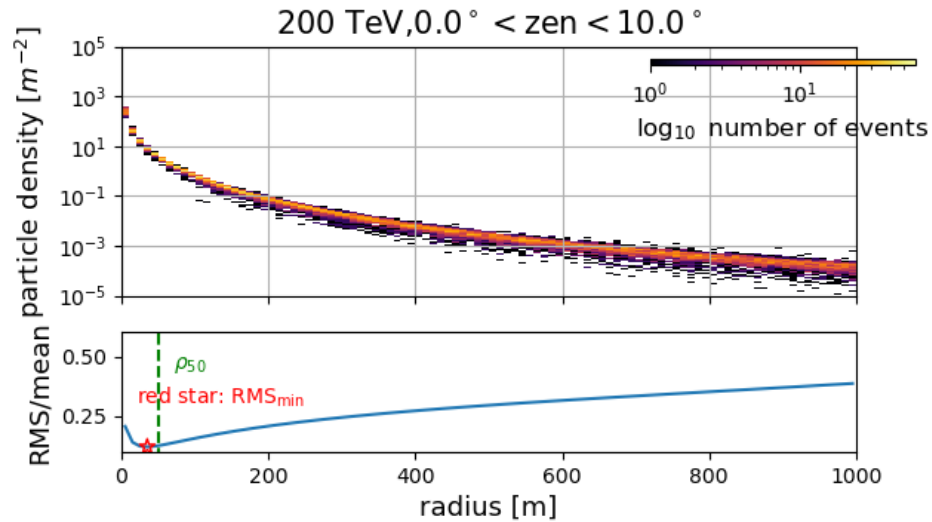
## Quadratic Reconstruction Formula

Standard method uses particle density at 50m ( $\rho_{50}$ ) as estimator:

$$\log(E_{rec}/\text{TeV}) = a(\theta) \cdot (\log(\rho_{50}))^2 + b(\theta) \cdot \log(\rho_{50}) + c(\theta)$$

Coefficients are zenith-dependent and fitted from MC simulations of  $\rho_{50}$  versus  $E_{true}$  distributions.

# Optimal Distance for Density Measurement



## Density Fluctuation Analysis

Particle density fluctuations vary with core distance; larger angles show different radial characteristics.

## Stability at Extended Distance

Measurements at 150m demonstrate significantly reduced fluctuations compared to 50m reference point.

## Revised Energy Estimator

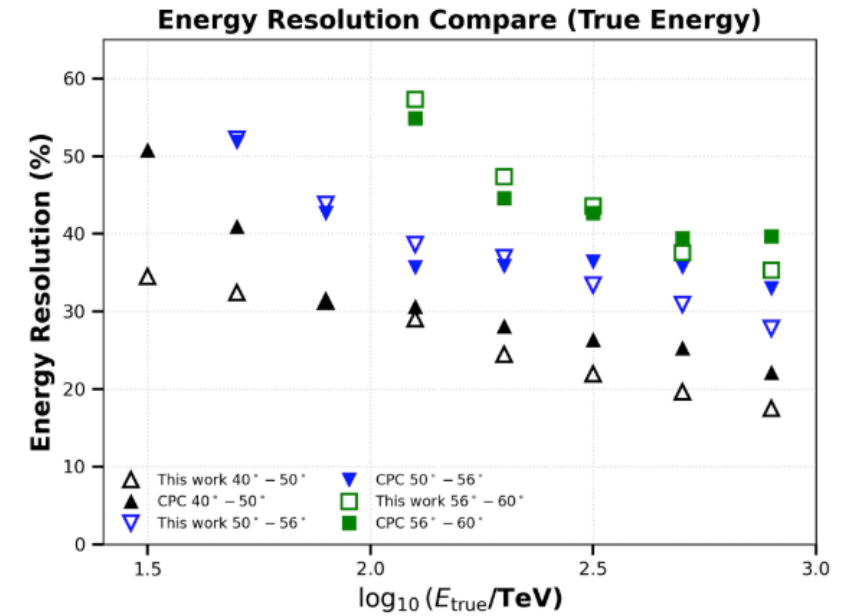
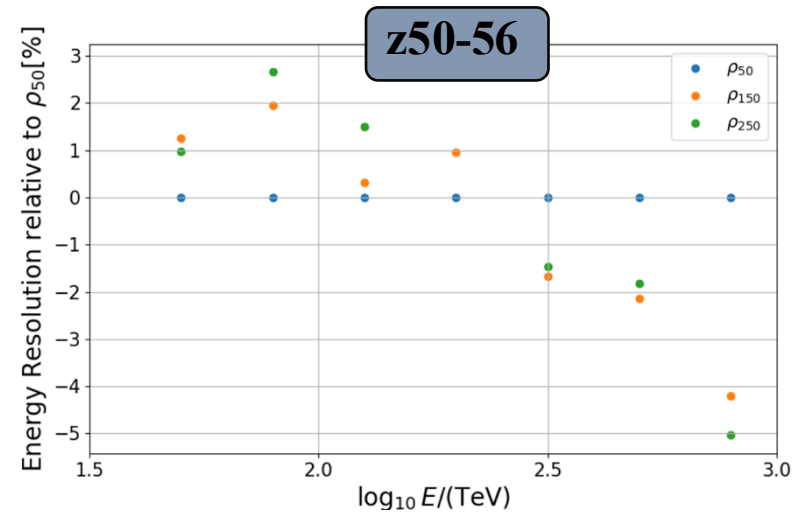
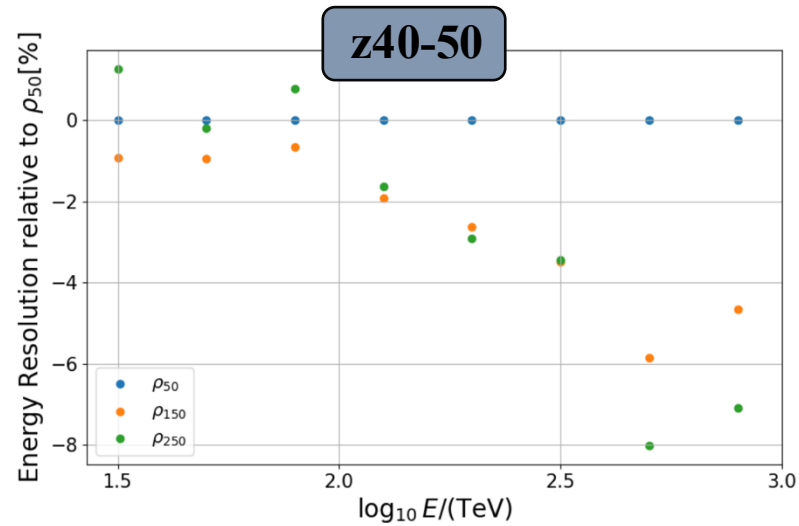
Energy reconstruction reoptimized using  $\rho_{150}$  with recalibrated quadratic parameters for large zenith angles.

$$\log(E_{\text{rec}}/\text{TeV}) = a(\theta) \cdot (\log(\rho_{150}))^2 + b(\theta) \cdot \log(\rho_{150}) + c(\theta)$$



# Resolution

## Energy resolution variation along $\rho$



- Best energy estimator changes along energy & zenith angle



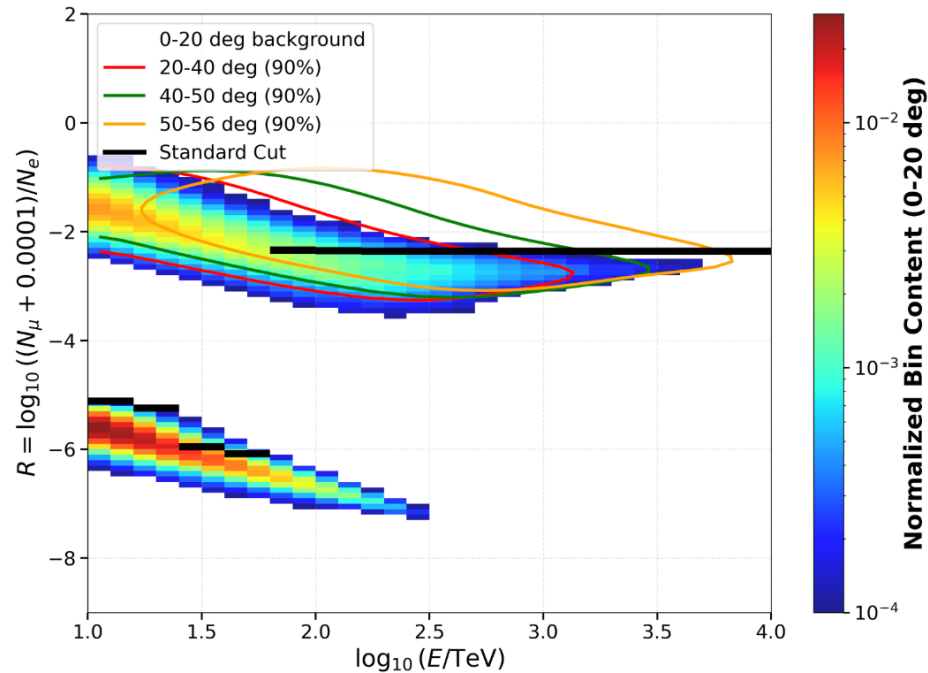
03

Particle identification

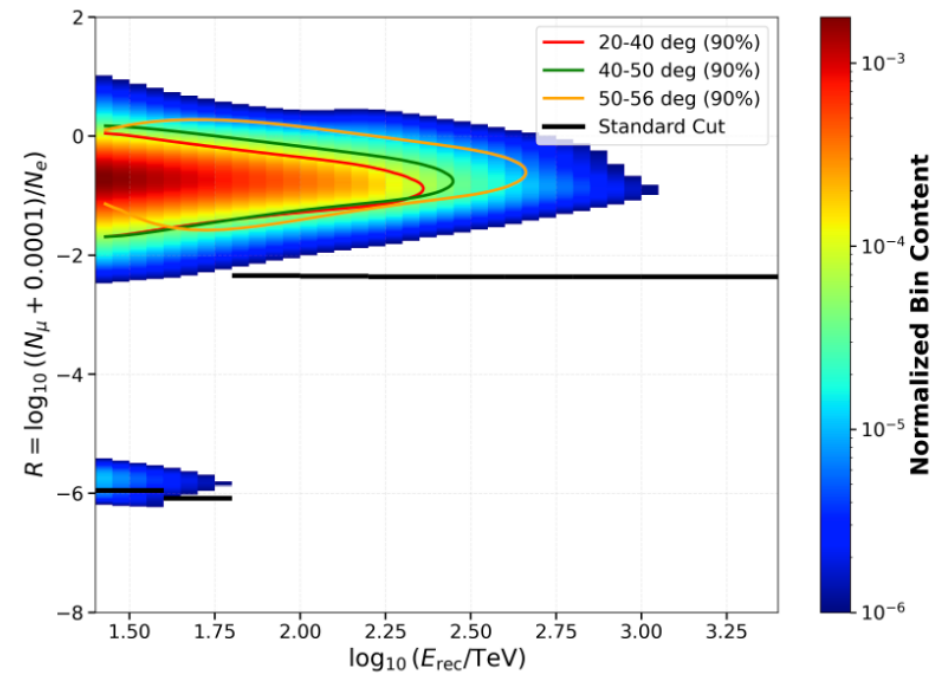
# Zenith-Dependent Particle Identification Evolution

## R profile

### Gamma-rays from Monte Carlo



### Cosmic rays from experimental data in mask region (up to end of 2024)

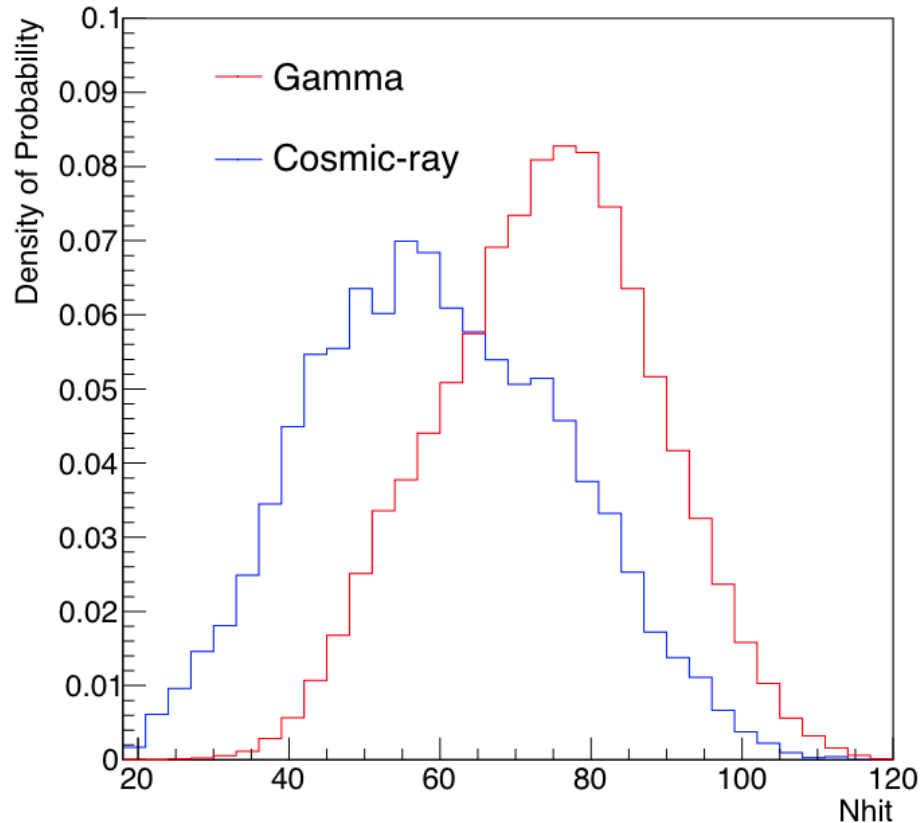


- R distribution shifts systematically upward with zenith angle.
- Uniform selection thresholds severely suppress valid gamma-ray events at large angles, making reevaluation essential.

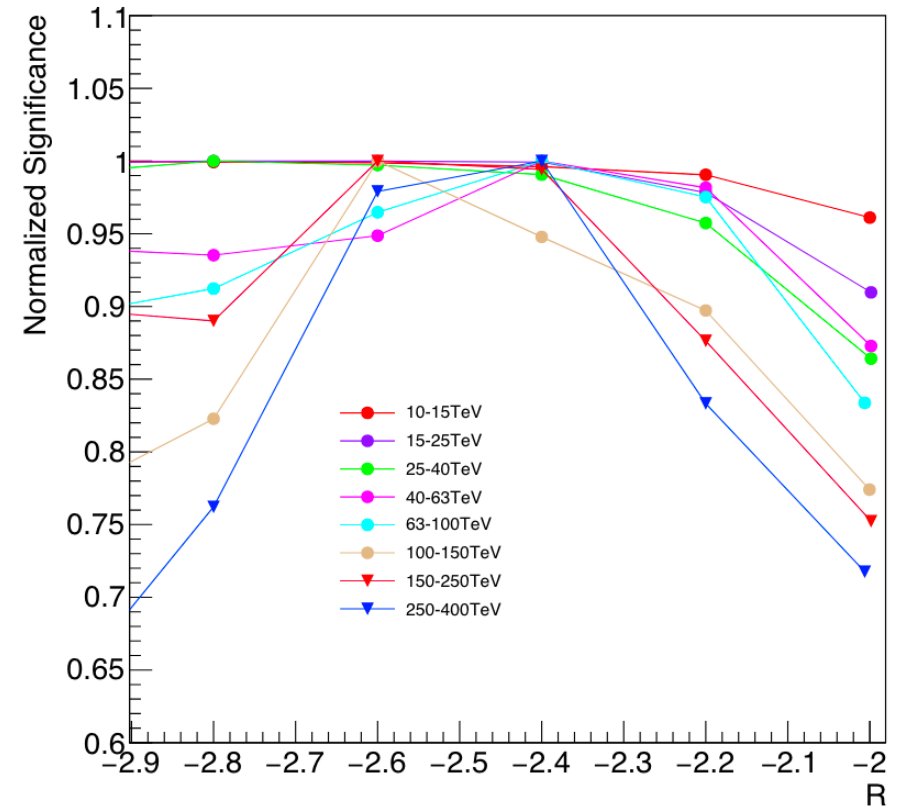


# Optimization threshold of Nhit and R

39.8TeV to 63.1TeV



Cao et al. 2024



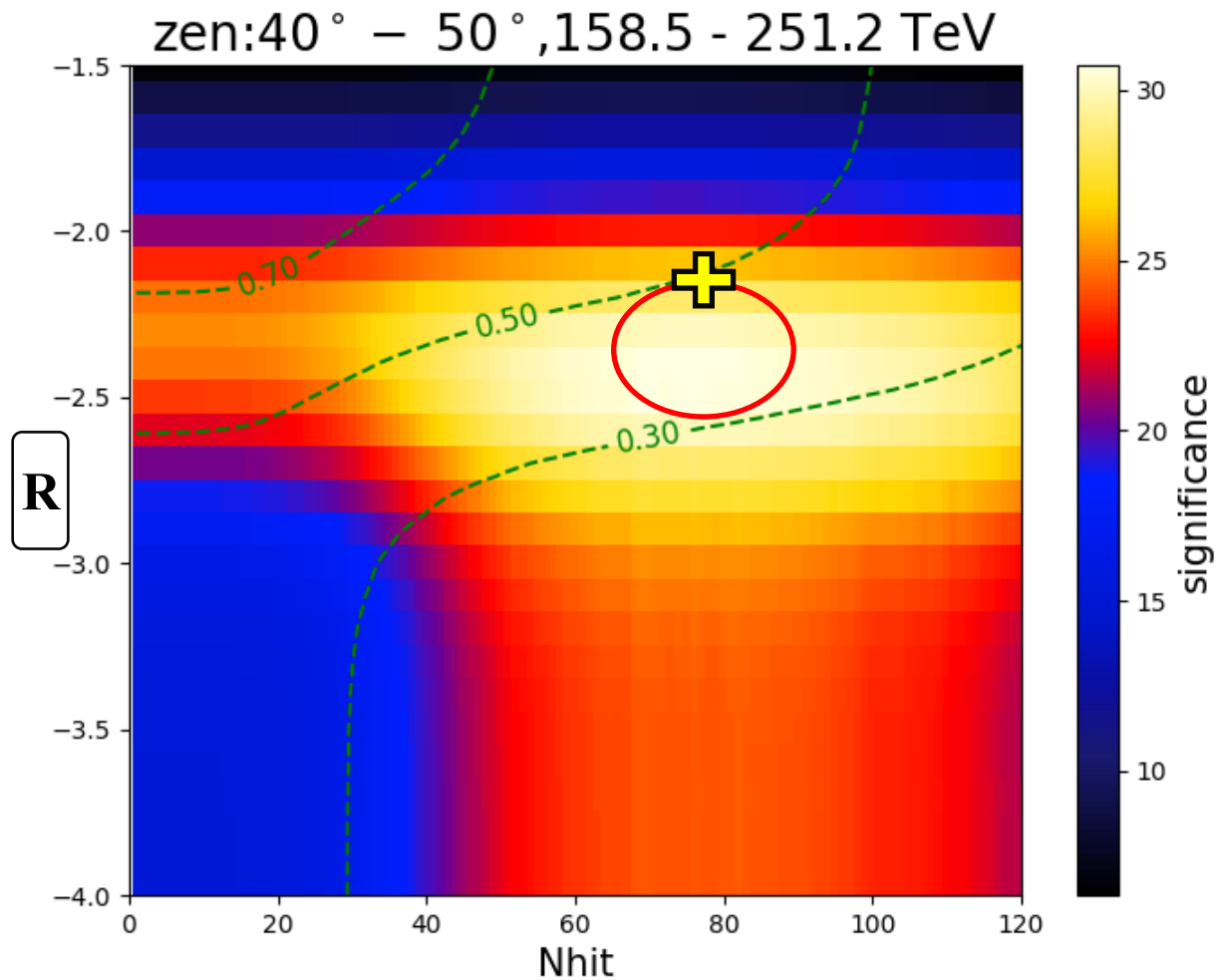
- **Nhit provides strong  $\gamma$ /CR separation complementary to R parameter**
- **Energy dependent Nhit a constant R thresholds derive a maximum significance of Crab Nebula**

# ◆ Simulation-Based Optimization Strategy

## Artificial Source Injection Method

- **Due to lack of bright standard candles (e.g., Crab Nebula) at large angles, artificial source ( $\sim$ tens of  $\sigma$  point source) is injected into MC data.**
- **Optimization performed across  $40^\circ$ - $50^\circ$ ,  $50^\circ$ - $56^\circ$ , and  $56^\circ$ - $60^\circ$  bins, significance of the injected source as performance metric for establishing optimal selection criteria.**

# Optimized Selection Criteria Results



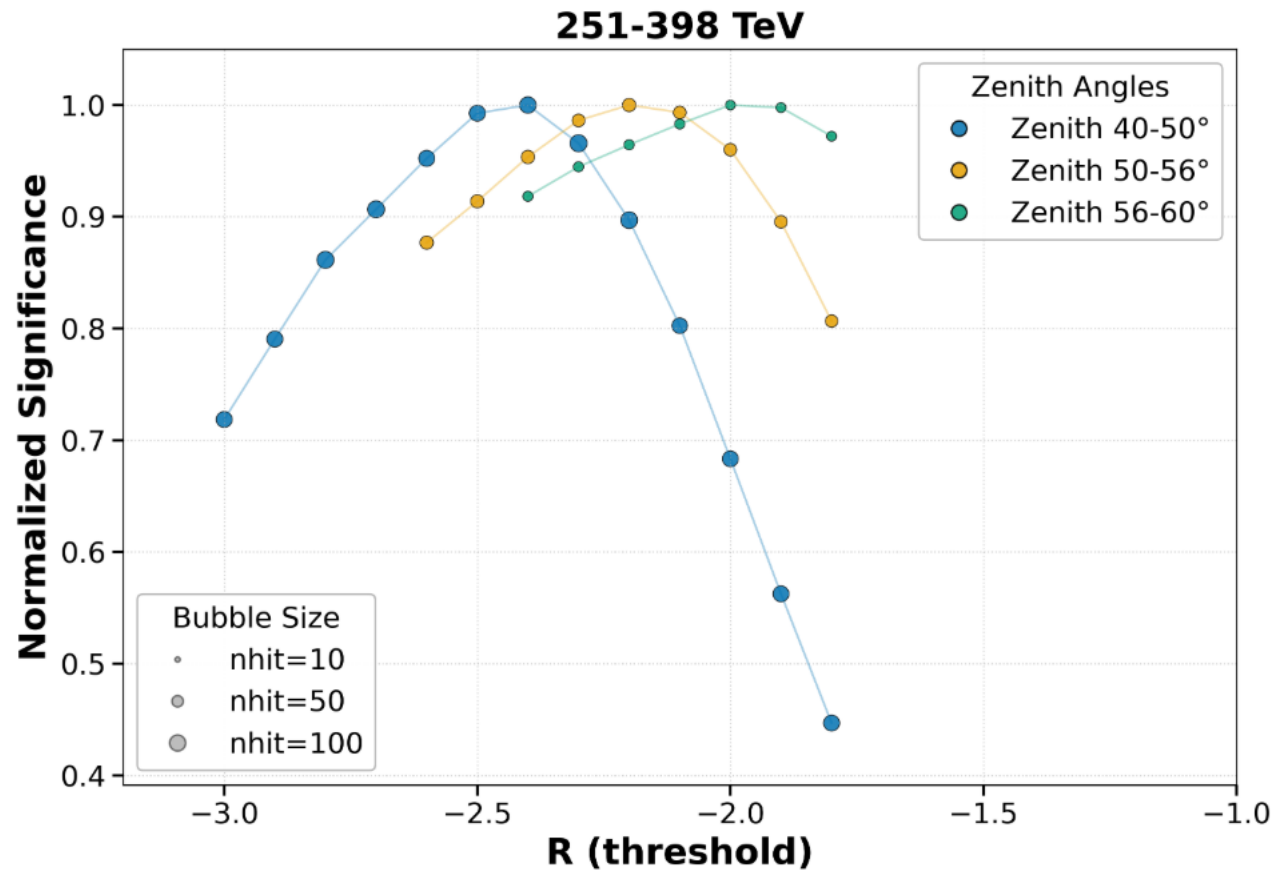
- **Green line: Keep enough gamma-rays survival**
- **Significance of fake source as a judgement**



# Optimized Selection Criteria Results

## Optimized Thresholds

e.g., @ 251 – 398 TeV



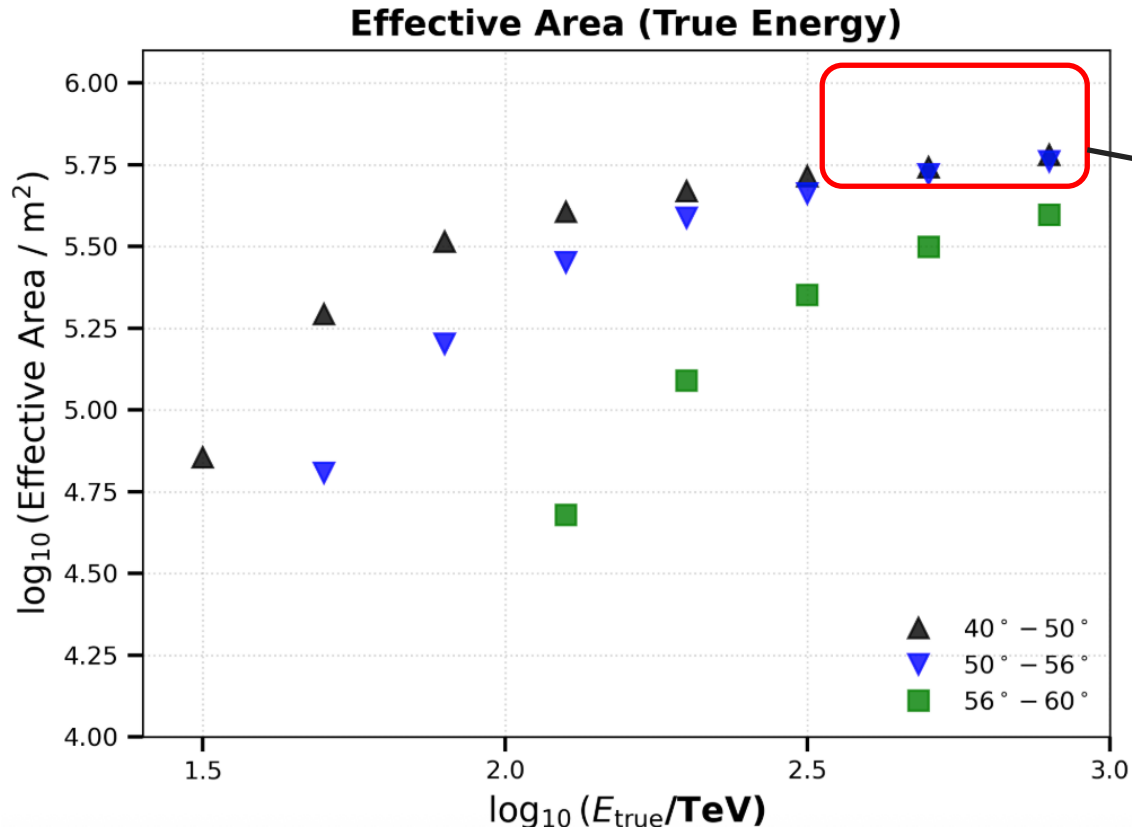
- **Results align with Cao et al. 2024 findings : energy- dependent Nhit thresholds and constant R thresholds maximize detection significance.**
- **Nhit and R thresholds is looser as zenith angles increase .**



04

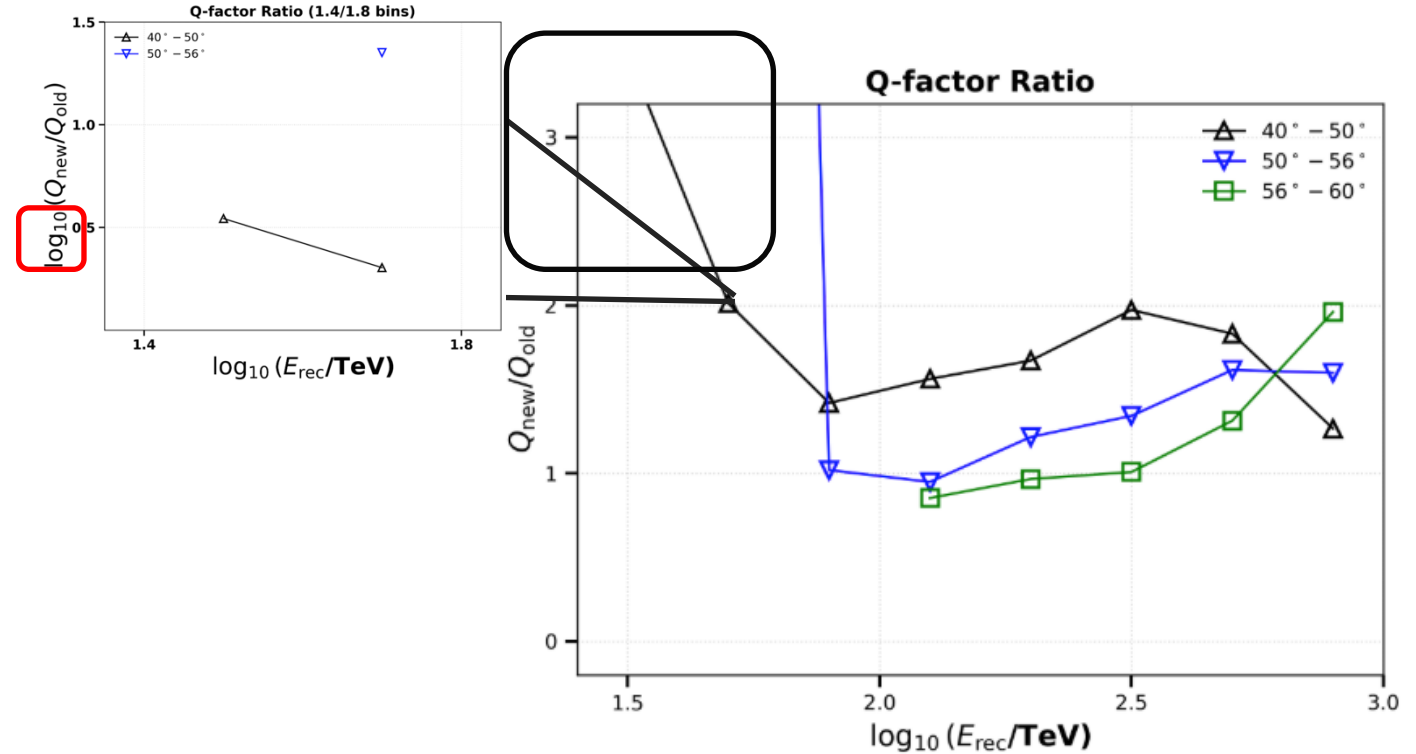
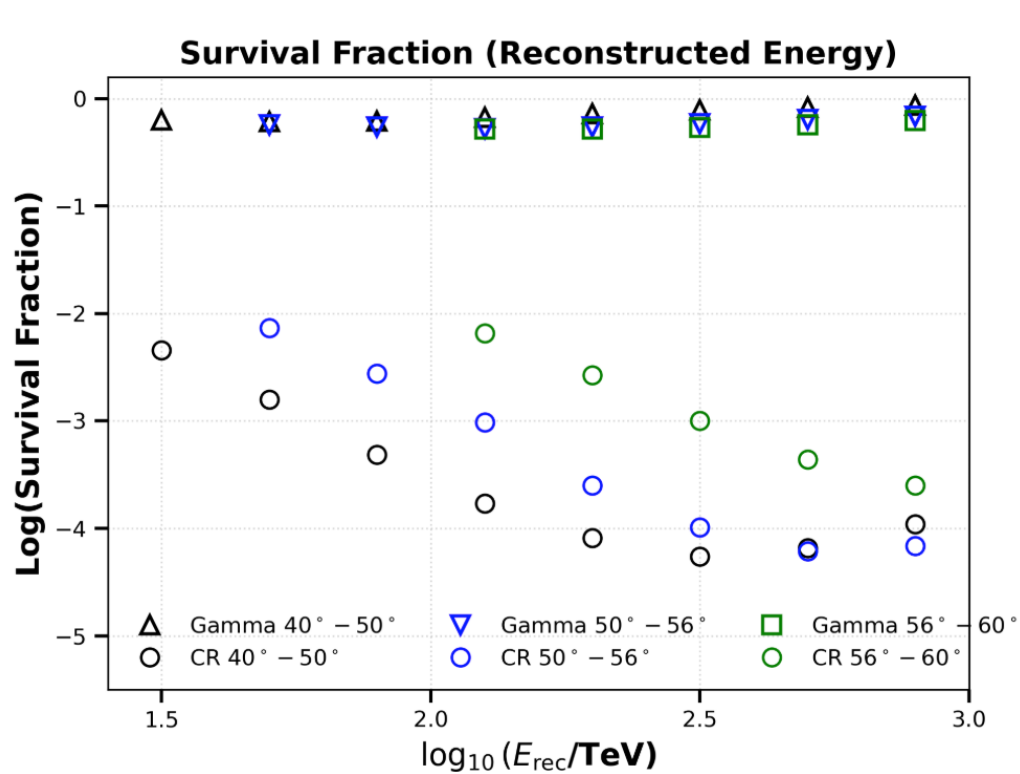
Detection Performance

# Effective area & efficiency cut



- **10% efficiency peak efficiency (27%) at zenith 40-50 cut is applied to filter the data with bad performance**

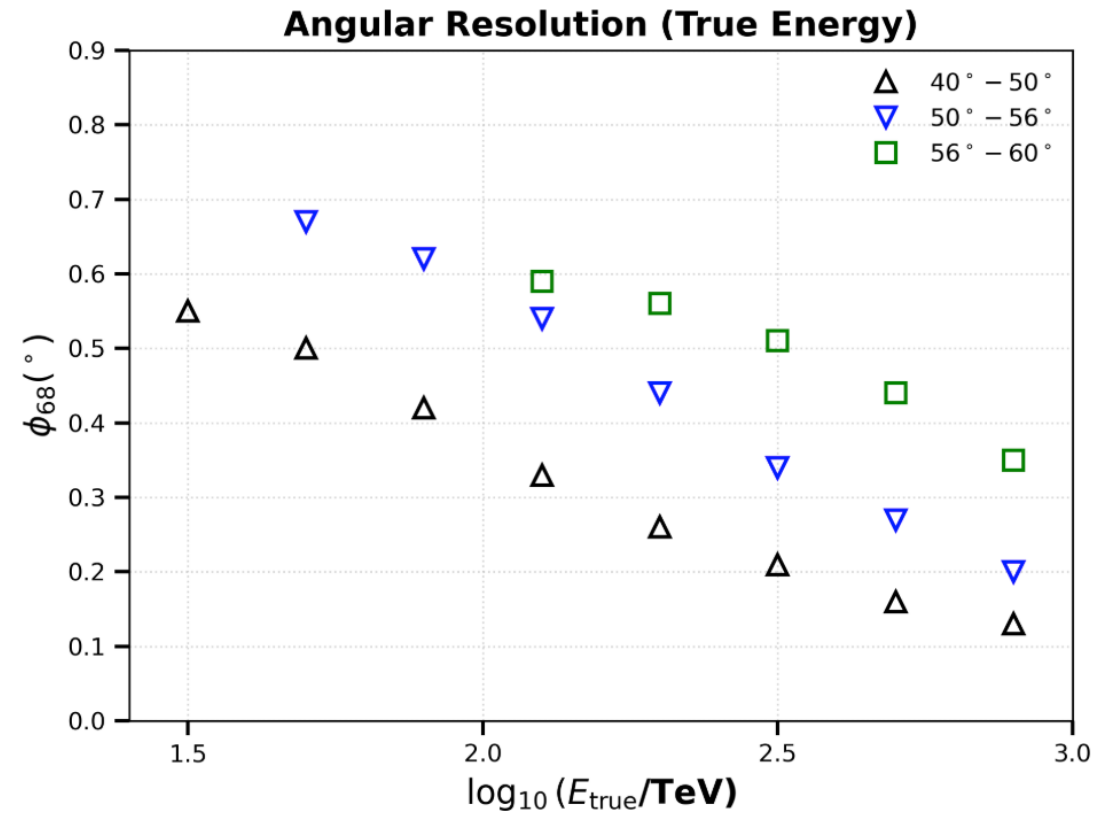
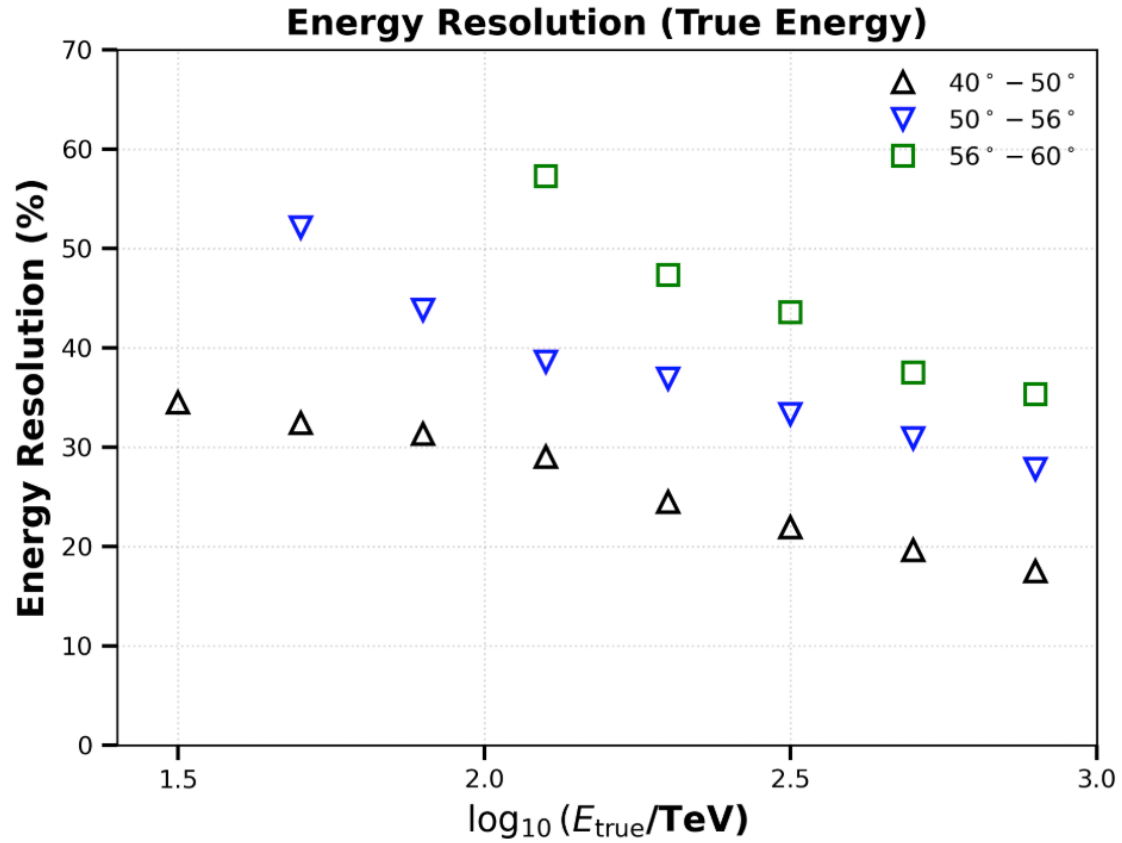
# Survival fraction & Q-factor [Rcut+Nhit]



- **Great Q-factor improvement in the energy range below  $10^{1.8}$  TeV, due to the increase of survival fraction of Gamma ray at large zenith angle**



# Resolution





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Experimental Verification

# ◆ Spectral Validation

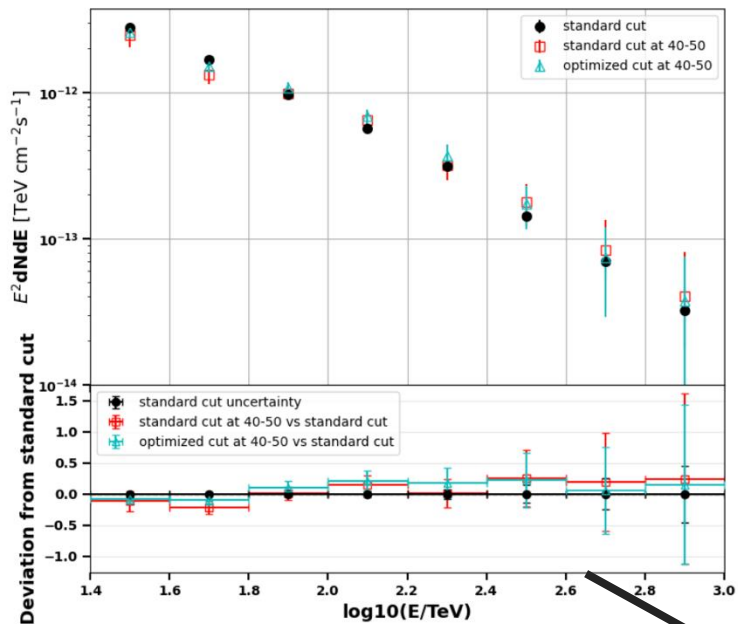
## Standard Candle Verification

Crab Nebula corresponding to a  $\sim 6$   $\sigma$  significance above 25 TeV at zenith angle  $> 50^\circ$  (Cao et al. 2025), the validation of optimization can be tested.

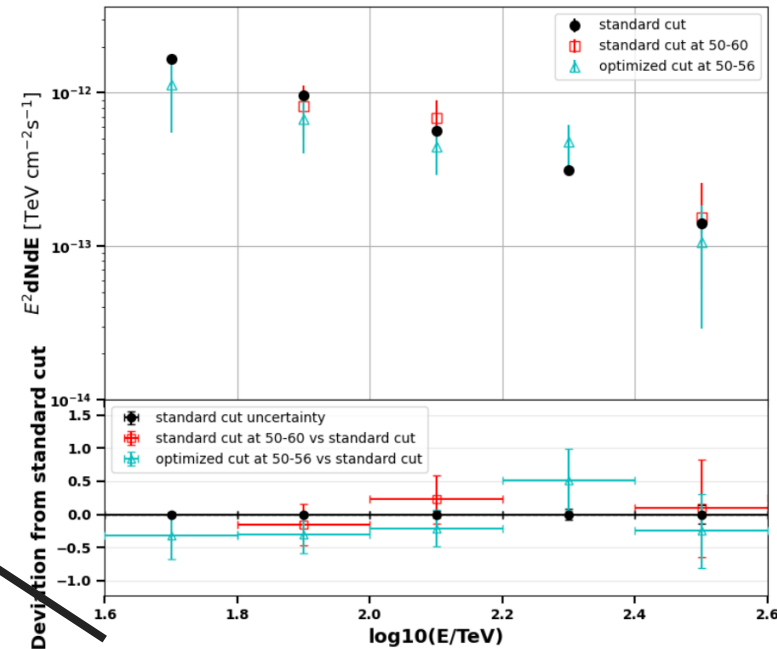
## J1825 region

J1825 region hosts in galactic plane with a significant detection significance even at a relative zenith angle ( $\sim 42^\circ$ ), due to complex environment (3 sources + DGE), spatial model at large zenith angle is assumed as a single gaussian source and fixed as the parameter measured at  $40^\circ - 50^\circ$ .

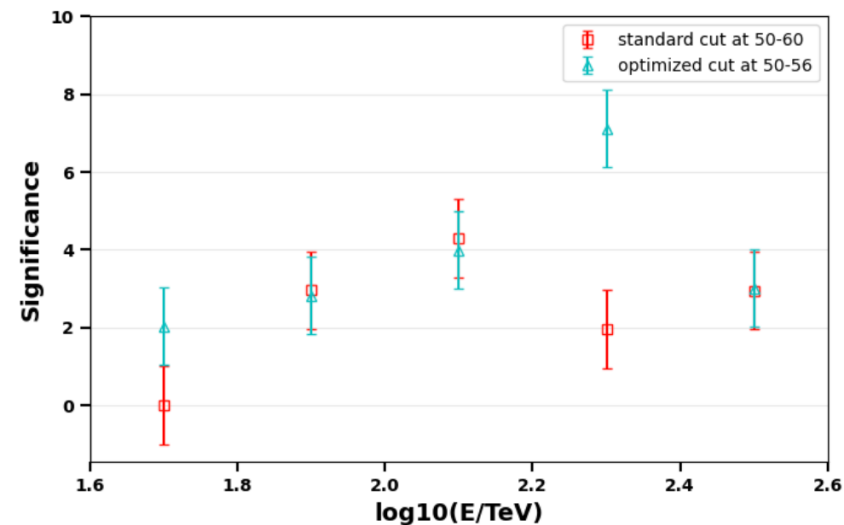
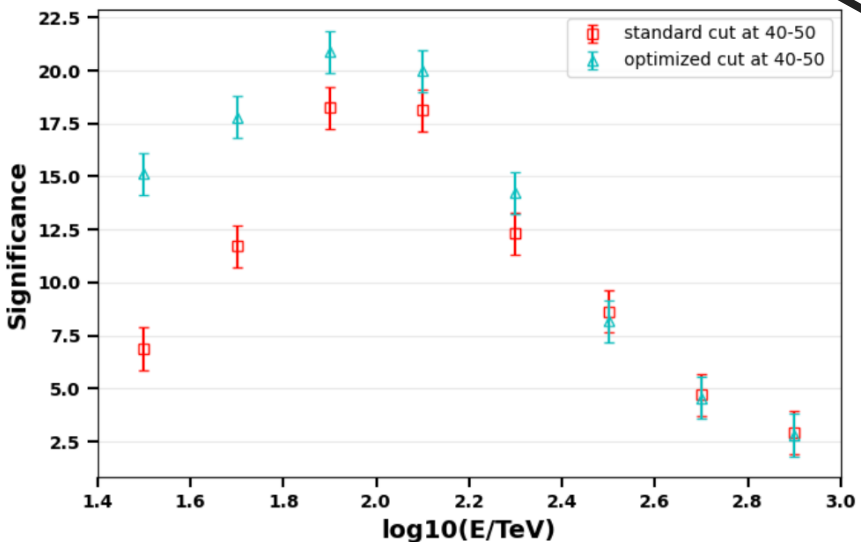
# Crab Nebula Spectral Validation



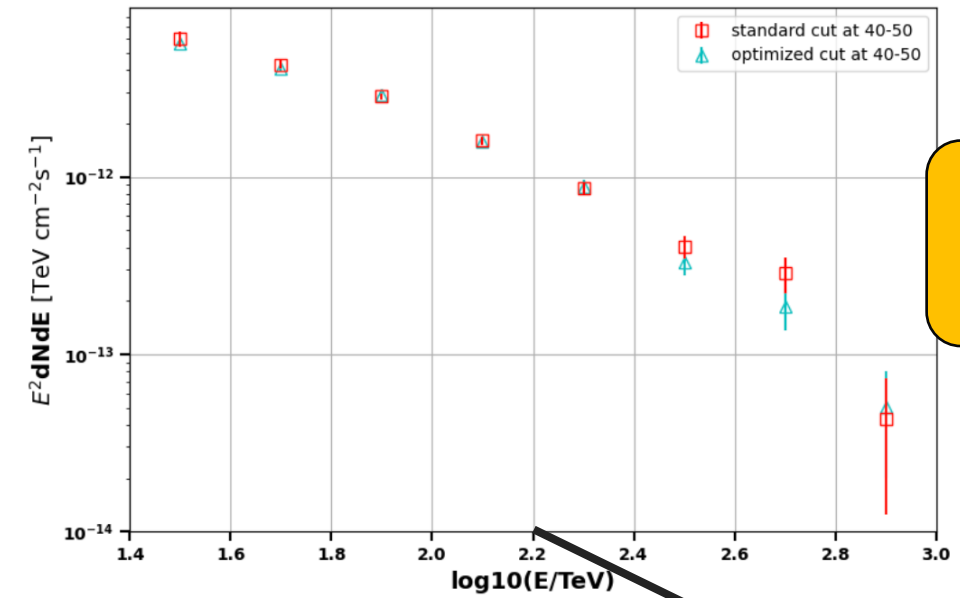
**z 50-56**  
**> 40 TeV red-> cyan**  
**TS: ~41->~78**



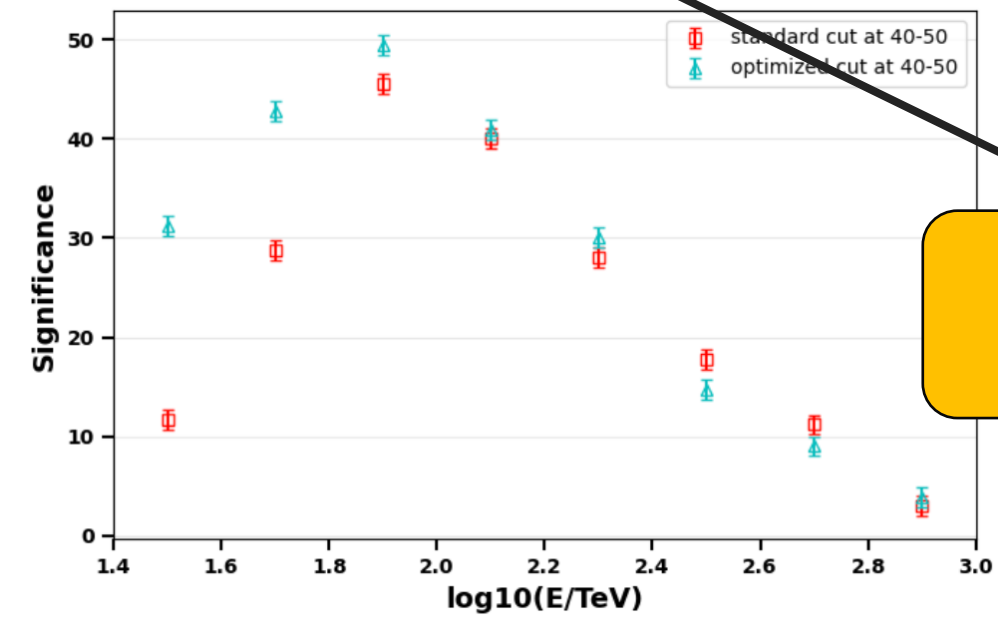
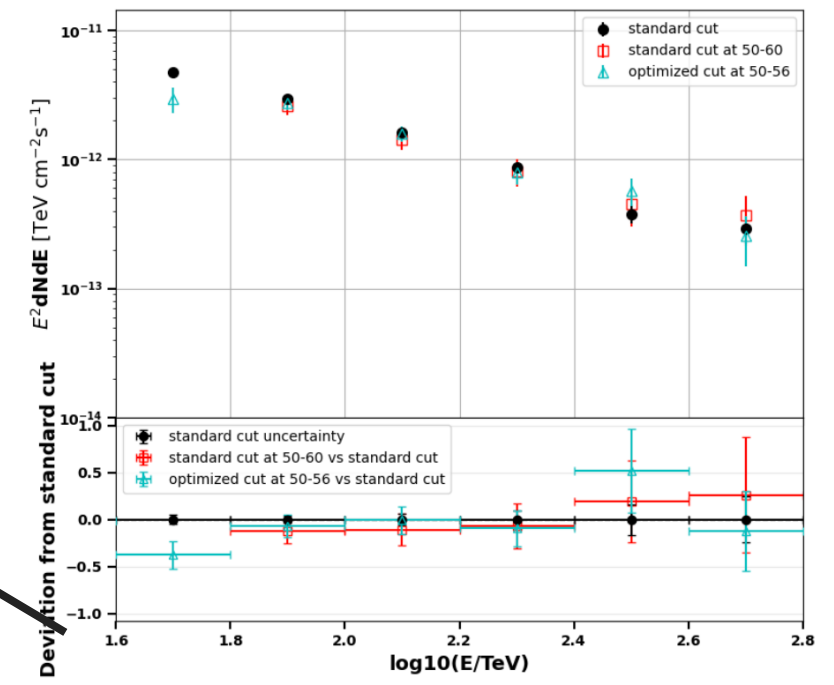
**z 40-50**  
**> 25 TeV : red-> cyan**  
**TS: ~1098->~1673**



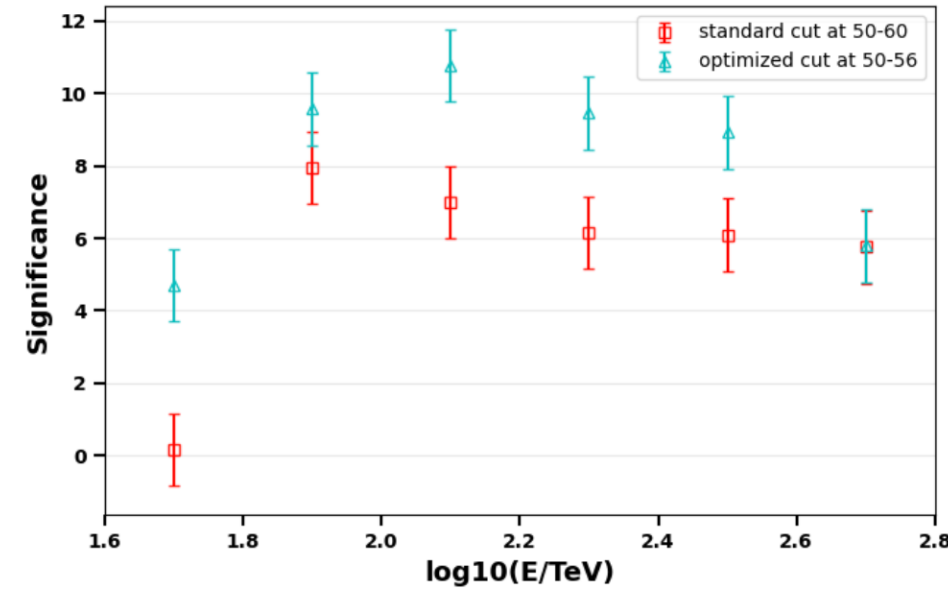
# J1825 region Spectral Validation



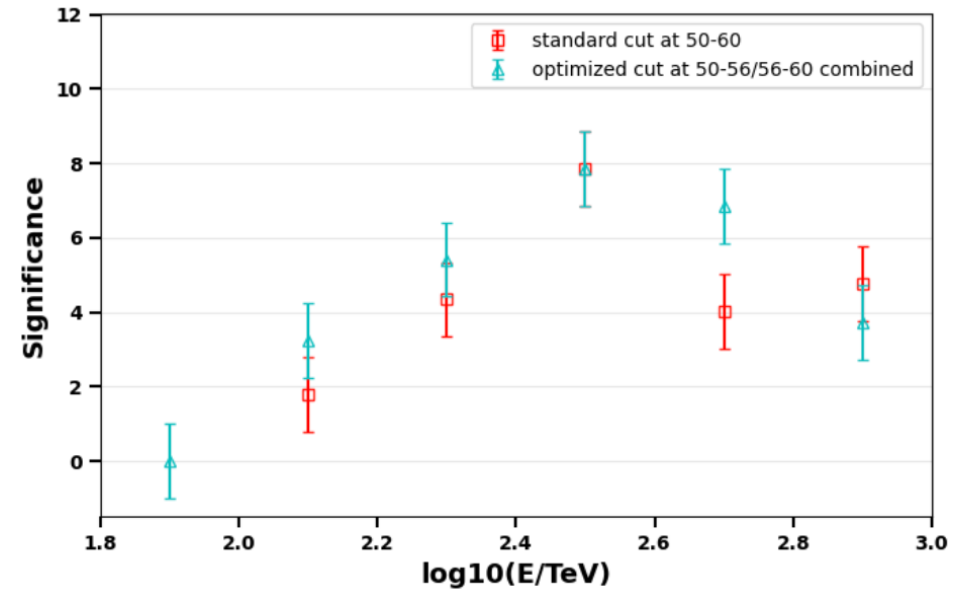
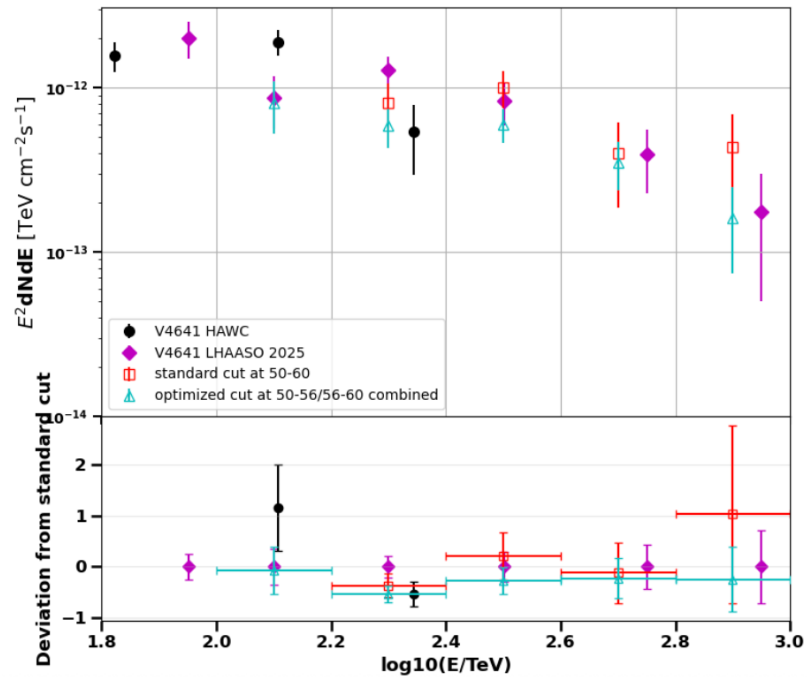
**z 50-56**  
**> 40 TeV red-> cyan**  
**TS: ~216->~443**



**z 40-50**  
**> 25 TeV red-> cyan**  
**TS: ~5859->~6902**



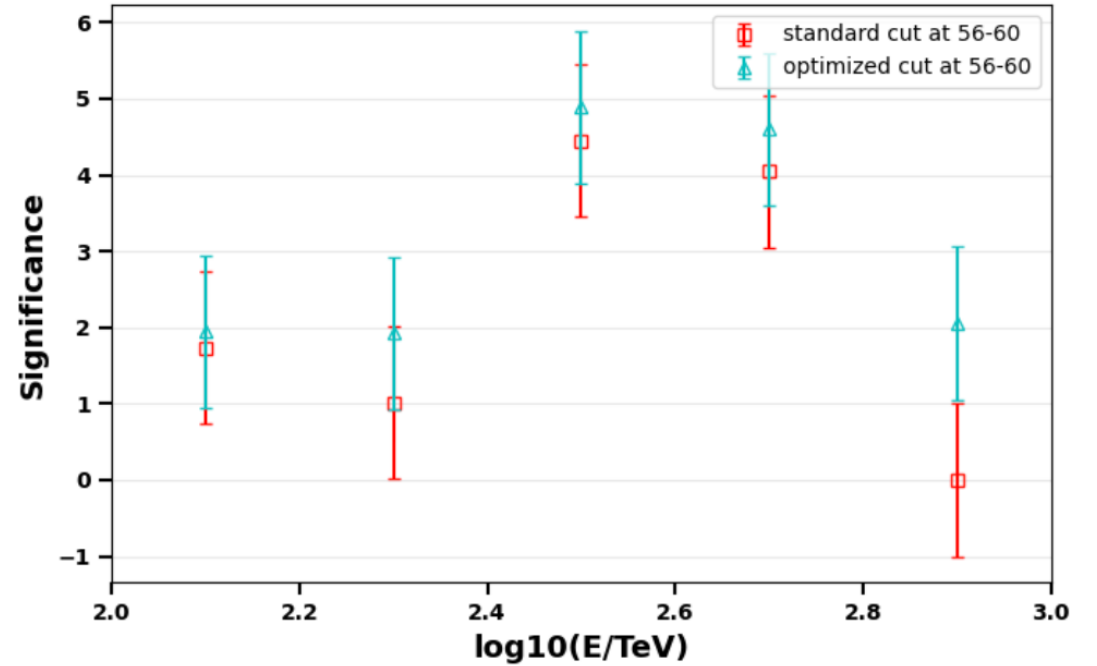
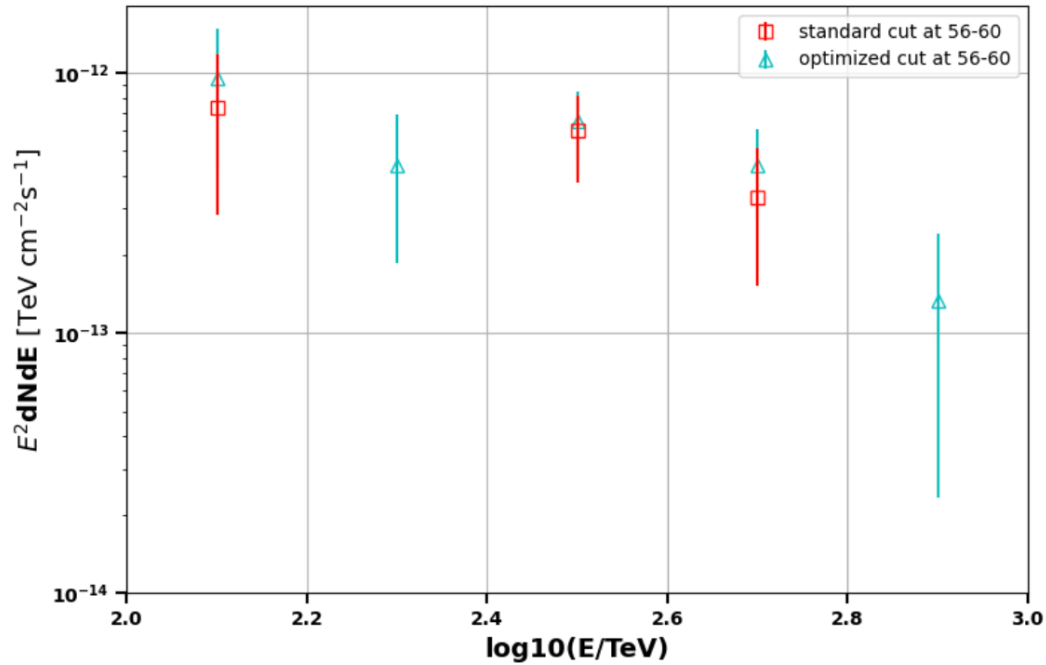
# ◆ Bright Source V4641 sgr as an additional test



**z 50-60**  
**> 100 TeV red-> cyan**  
**TS:~115->~168**

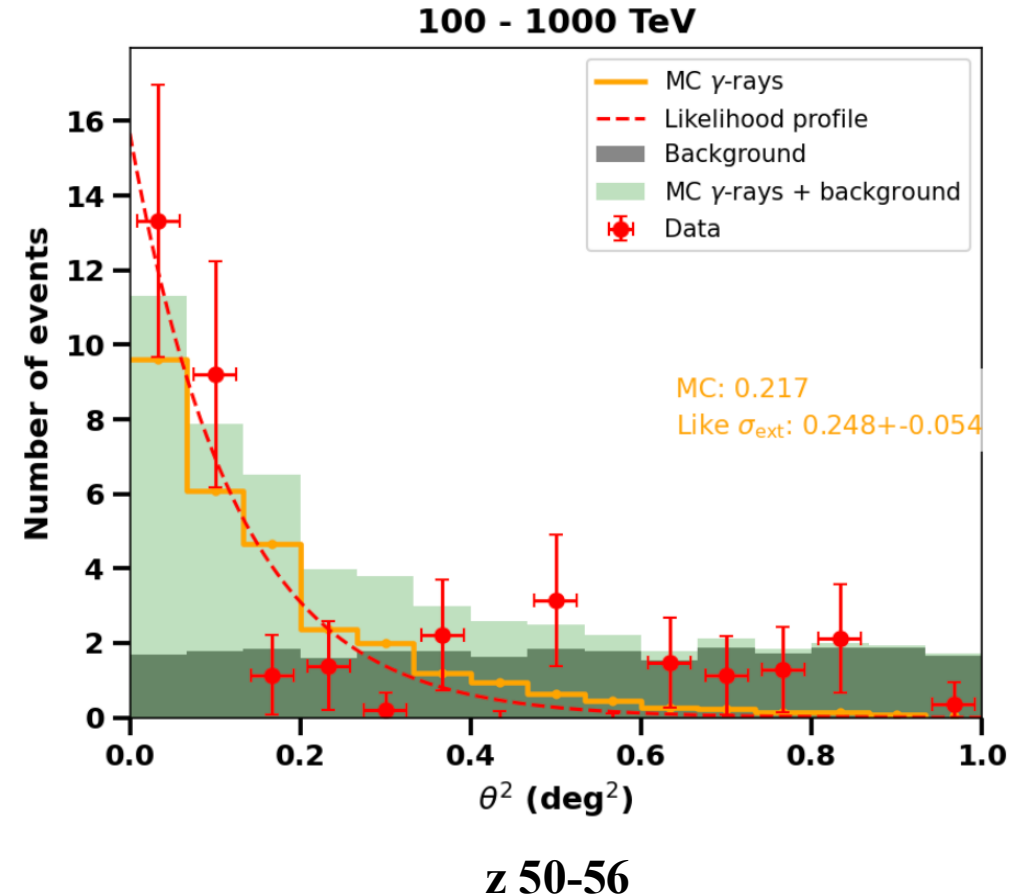
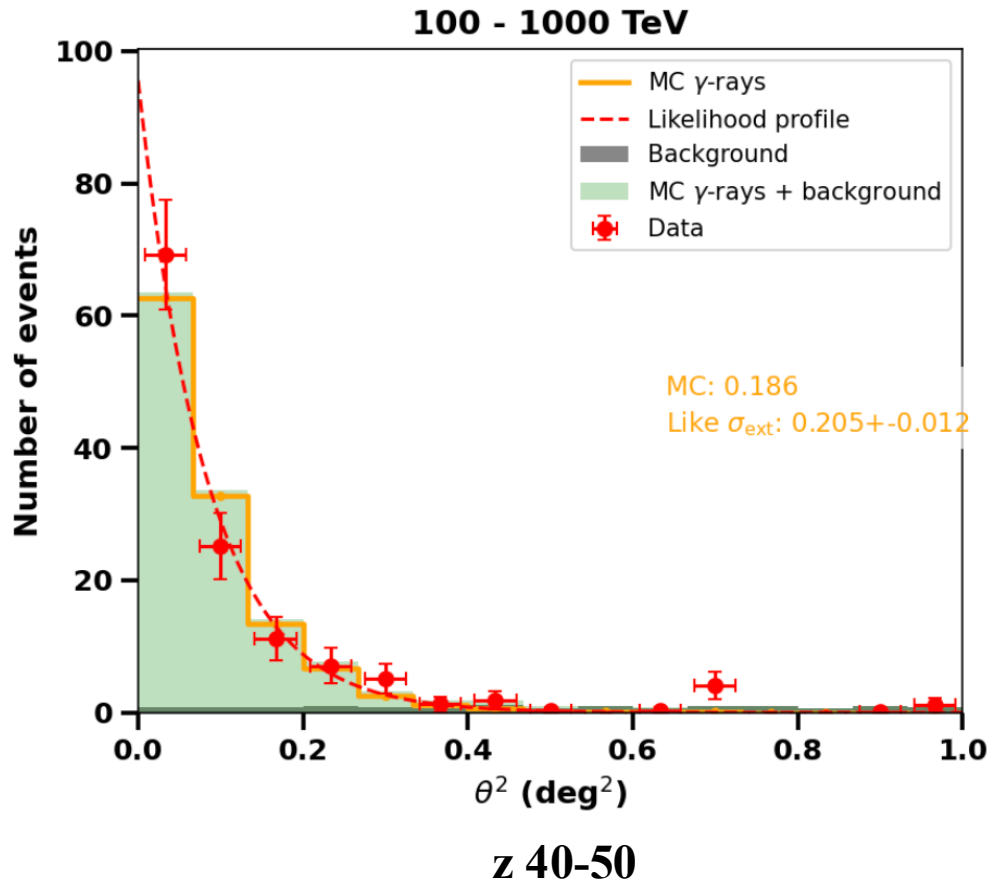
- **Data at 56-60 is applied to analysis as a separation dataset to avoid the higher background discrimination due to a tighter cut**

# ◇◇ V4641 at higher zenith angle



**z 56-60**  
**> 100 TeV red-> cyan**  
**TS:~34->~55**

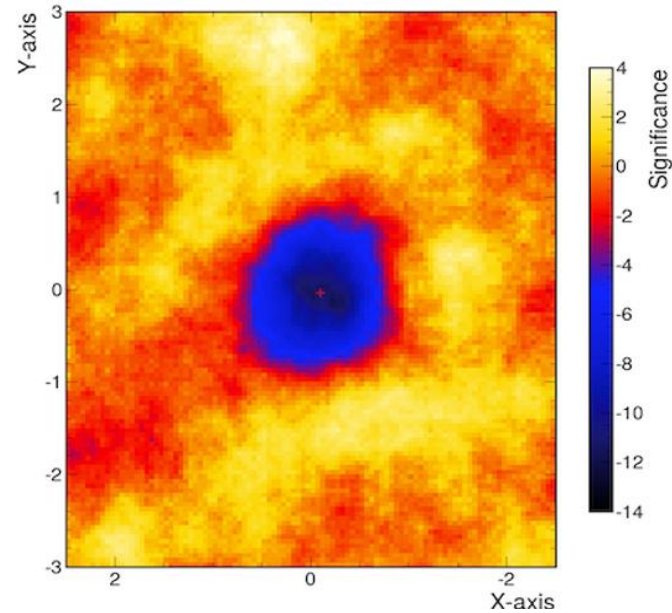
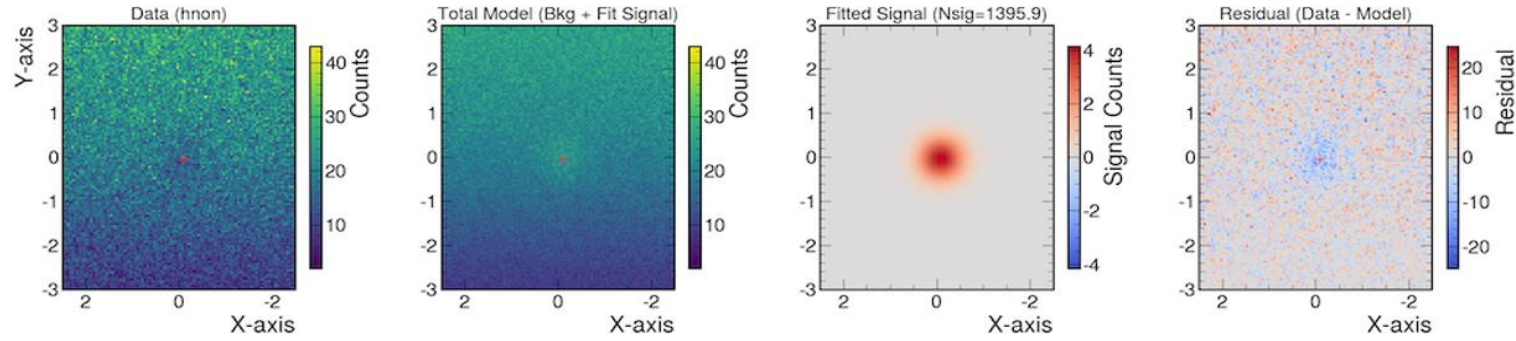
# PSF from experimental from Crab



- PSF is consistent between the Monte Carlo & experimental data in Crab region



# Moon shadow



$$\underline{\text{mean\_x}} = -0.094 \pm 0.036$$

$$\underline{\text{mean\_y}} = -0.033 \pm 0.046$$



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Conclusions

## Conclusions

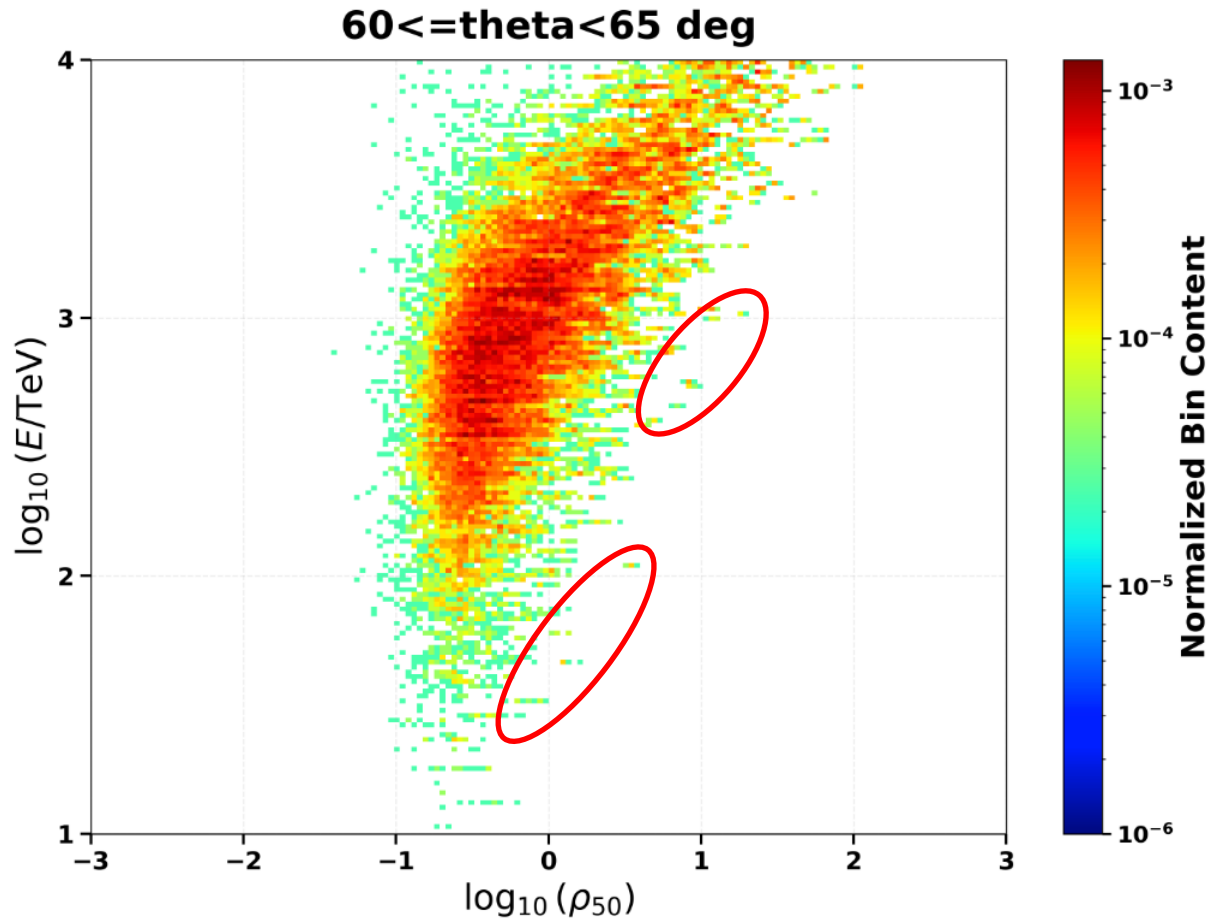
- **Energy Reconstruction is redefined by  $\rho_{150}$  for LZA data.**
- **PID is optimized by R & Nhit thresholds, which are zenith angle and energy dependent values**
- **Spectral measurement and psf between monte carlo and experiment is consistent within the uncertainties.**
- **TS values is improved compared to baseline cut at small angle due to the zenith angle dependent profile of R distribution by applied to standard gamma-ray sources.**



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Anomalous shower

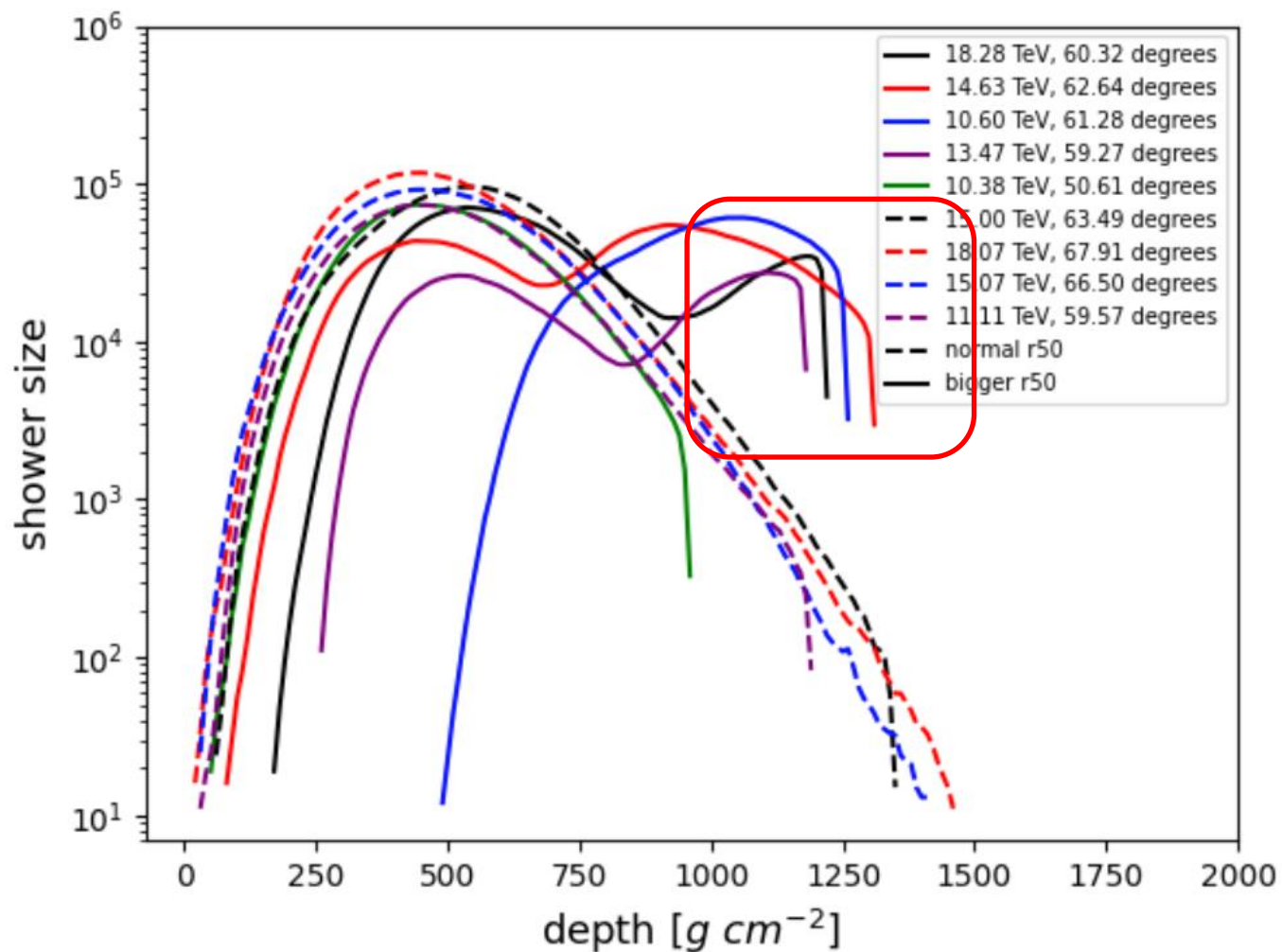
# ◆ Anomalous Distribution at Large Angles



## Anomalous Population

**Some events exhibit small true energy but abnormally large  $\rho_{50}$ , causing severe energy overestimation.**

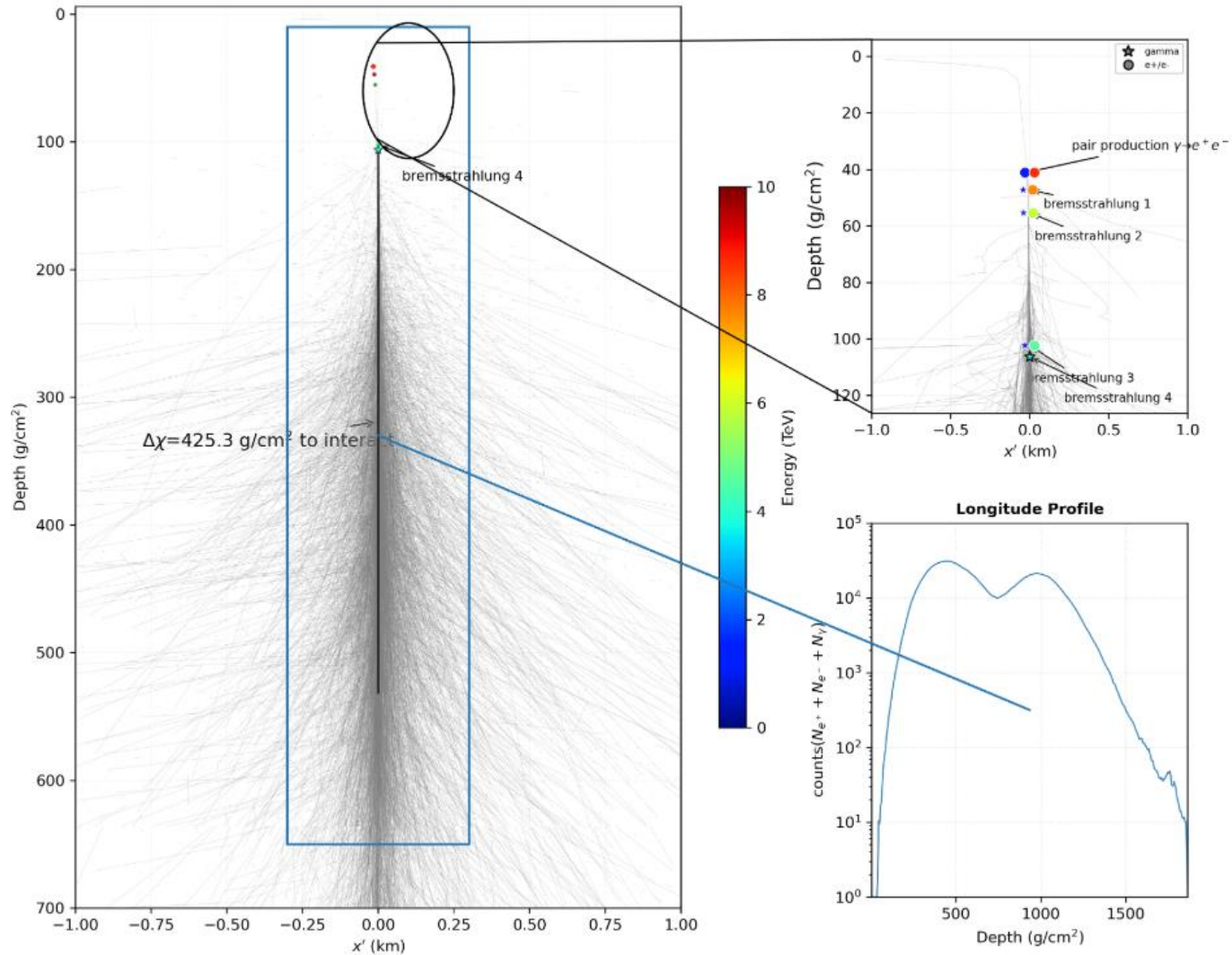
# Multi-Maxima Shower & Late Shower



**Longitude distribution of corsika shower**

# Multi-Maxima Shower Phenomenon

zenith=60°, E=10TeV  $\gamma$



High-energy photon traveled through several interaction lengths before interacting & initiating a new shower maximum.

## ◆◆ Possibility of double maximum shower

Electron-proton cross-section of bremsstrahlung for electrons with energy  $> 10\text{MeV}$

$$\frac{d\sigma}{d\epsilon_\gamma}(\epsilon_\gamma, \gamma_e) = \frac{4r_0^2\alpha}{\epsilon_\gamma} \left[ 1 + \left( \frac{1}{3} - \frac{\epsilon_\gamma}{\gamma_e} \right) \left( 1 - \frac{\epsilon_\gamma}{\gamma_e} \right) \right] \left\{ \log_e \left[ \frac{2\gamma_e(\gamma_e - \epsilon_\gamma)}{\epsilon_\gamma} - \frac{1}{2} \right] \right\} \quad (\text{Baring et al., 1999})$$

Electron energy vs depth:  $E = E_0 \exp\left(-\frac{x}{\chi_1}\right)$ ,  $\chi_1 = 37 \text{ g cm}^{-2}$   $E_0=10\text{TeV}$

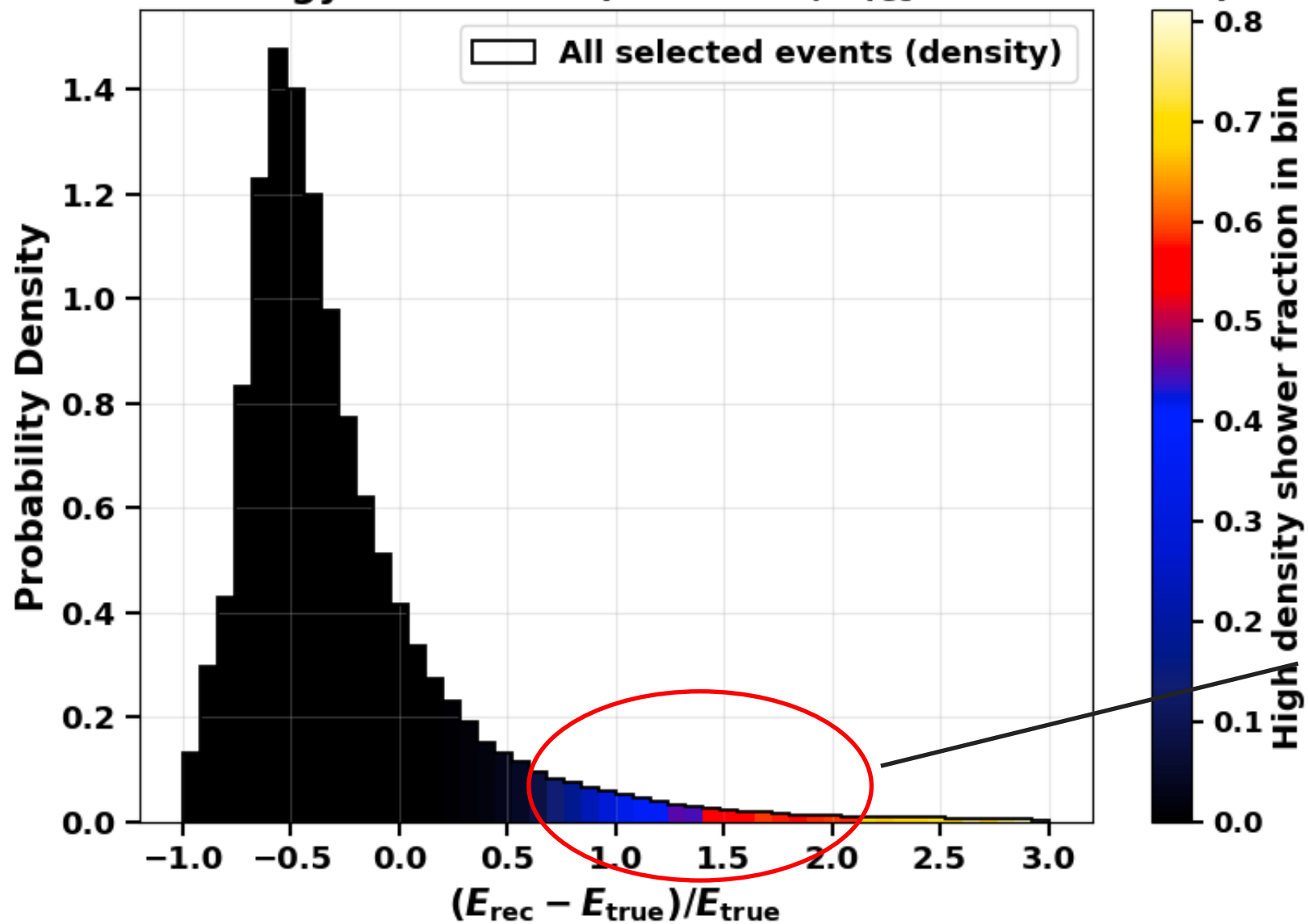
Counts rate for energy at bin  $d\epsilon_\gamma$ :  $N_{\epsilon_\gamma} = \int_0^{25 \text{ g cm}^{-2}} \frac{N_A}{A} \frac{d\sigma(E(x), \epsilon_\gamma)}{d\epsilon_\gamma} dx d\epsilon_\gamma$

Probability of a  $>5 \text{ TeV}$  gamma-ray traveling through  $>200 \text{ g/cm}^2$  of air:  $\int_{200 \text{ g cm}^{-2}}^{+\infty \text{ g cm}^{-2}} \int_{5 \text{ TeV}}^{10 \text{ TeV}} N_{\epsilon_\gamma} \frac{1}{\chi_2} \exp\left(-\frac{x}{\chi_2}\right) d\epsilon_\gamma dx$   
,  $\chi_2 = 47 \text{ g cm}^{-2}$

**$\sim 1.2/1000$ , in corsika  $\sim 2/1000$**

**Multi maximum + late shower  $\sim 37\%$ (Etrue:10-20TeV)  $\sim 3\%$ (Etrue:90-100TeV) in trigged(rec) data**

# Relative Energy Difference ( $\theta$ : 50-60°, $E_{\text{rec}}$ : 100-200 TeV)



> ~50% events with  
↑  $\delta E/E$  come from  
↑ density shower



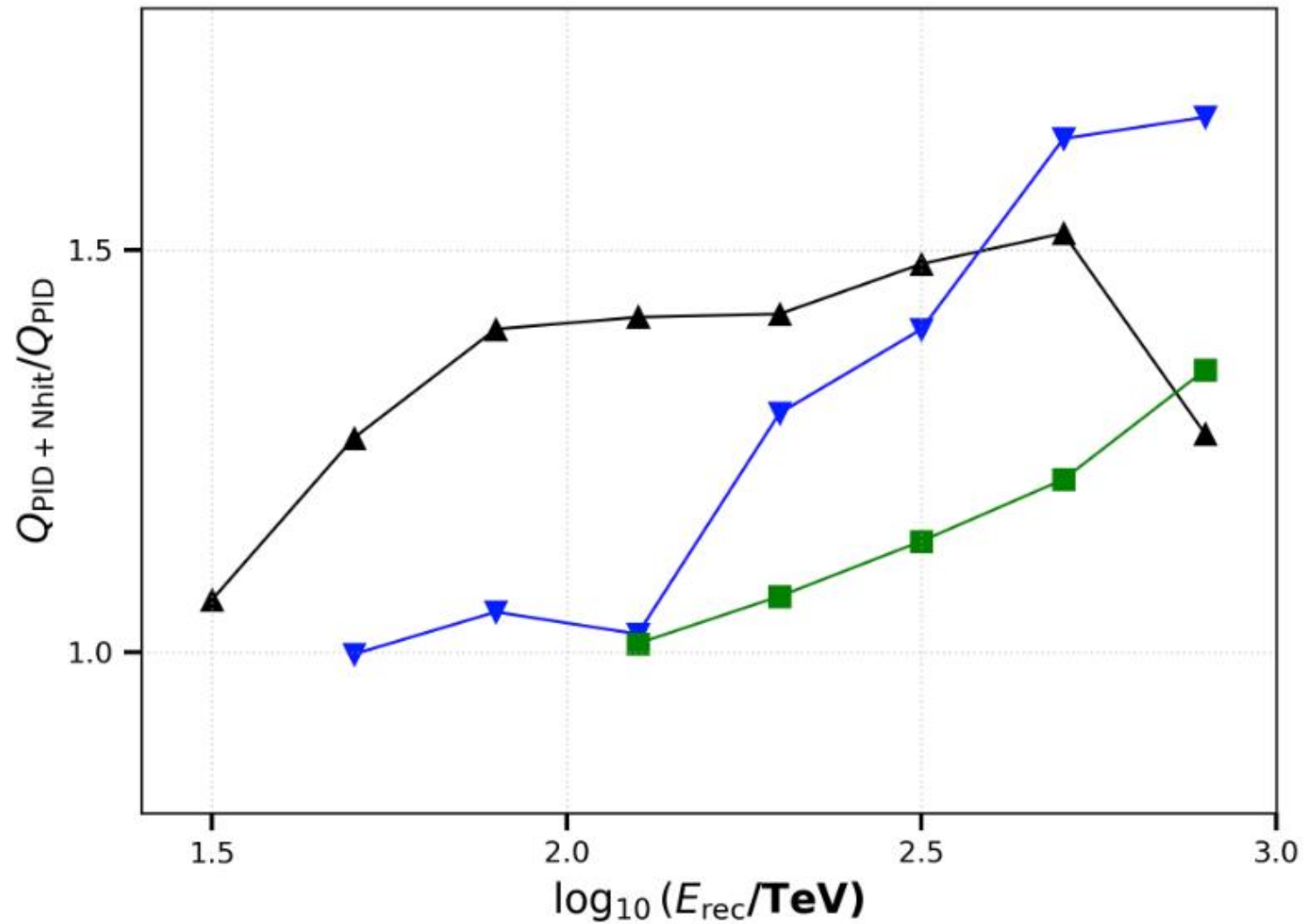
THANK YOU FOR WATCHING



08

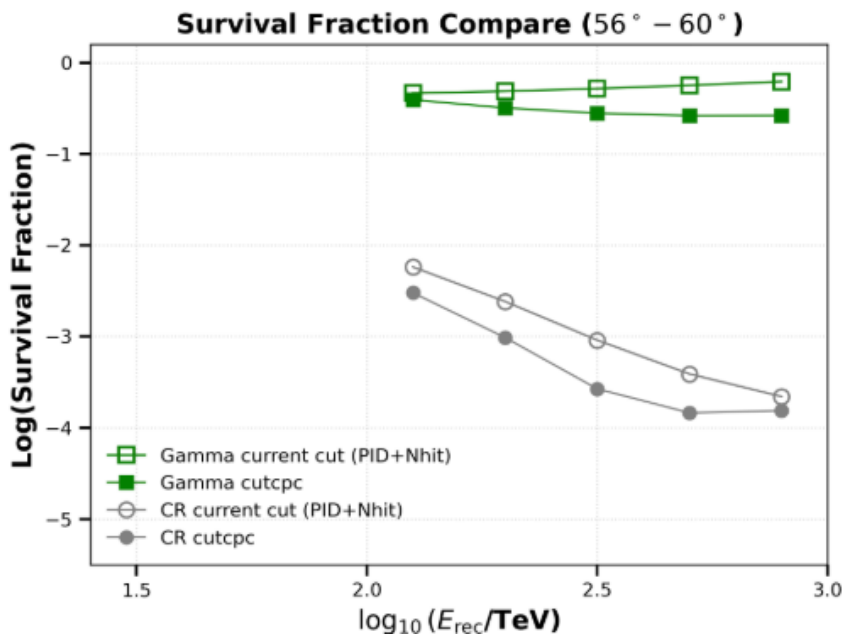
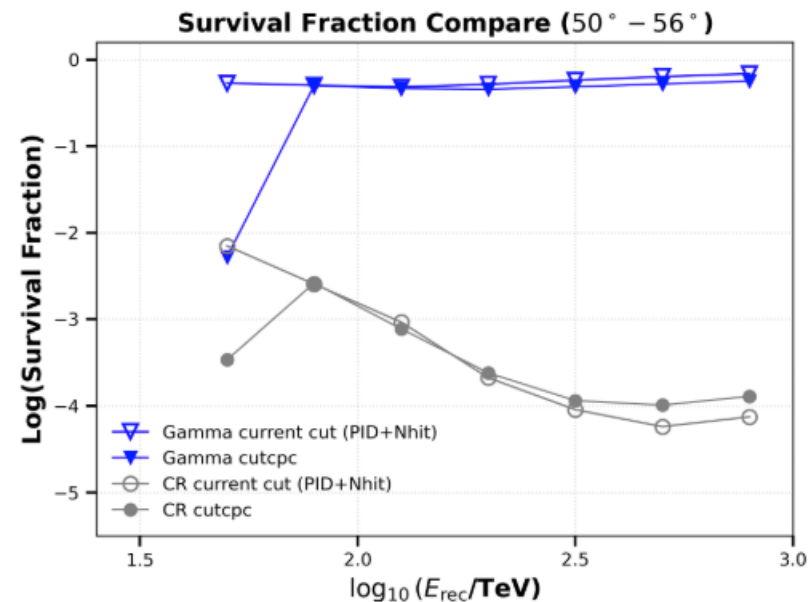
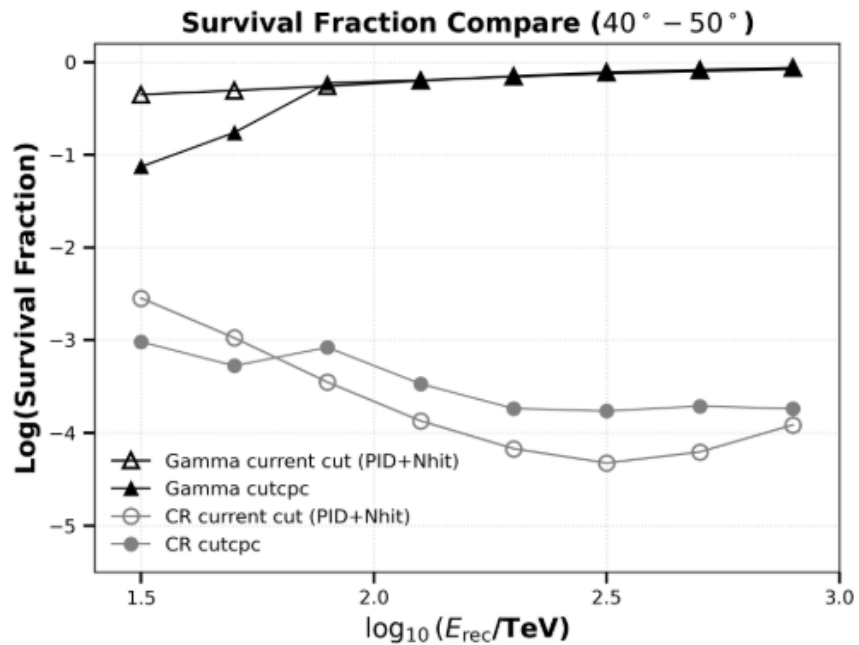
Backups

# ◆◆ Quality factor including Nhit filter



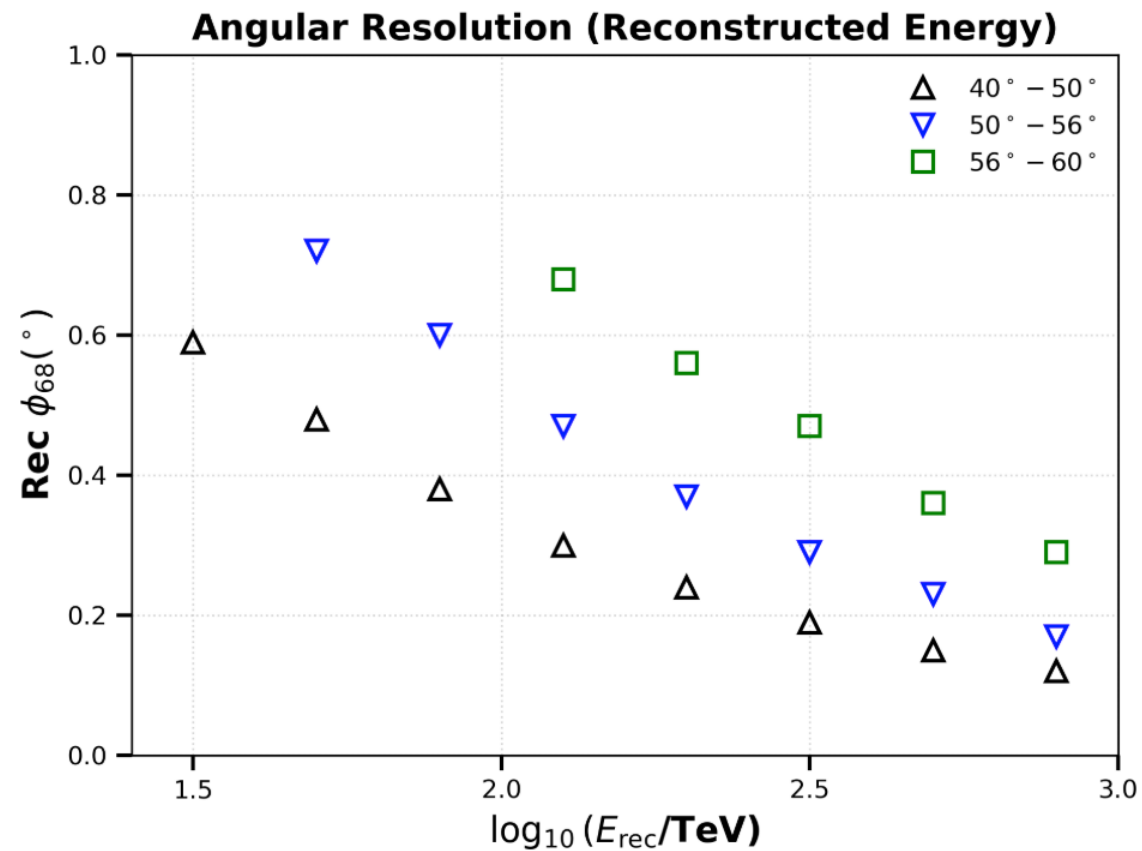
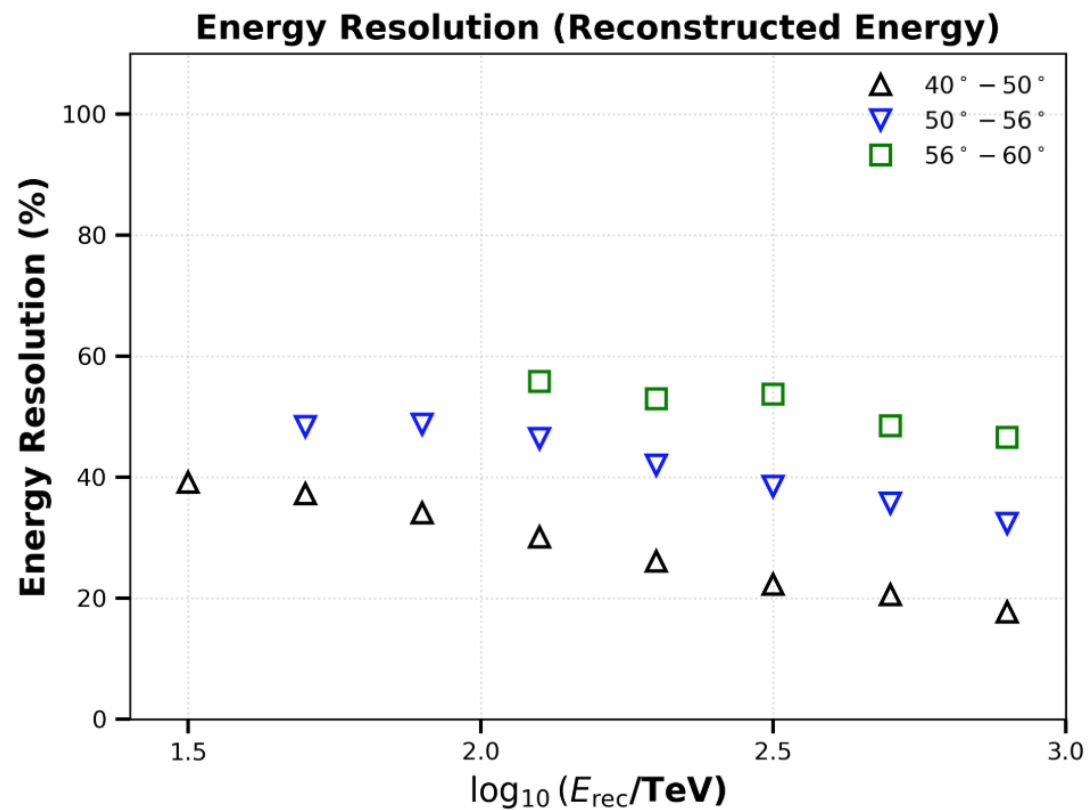


# Survival fraction vs zenith angle



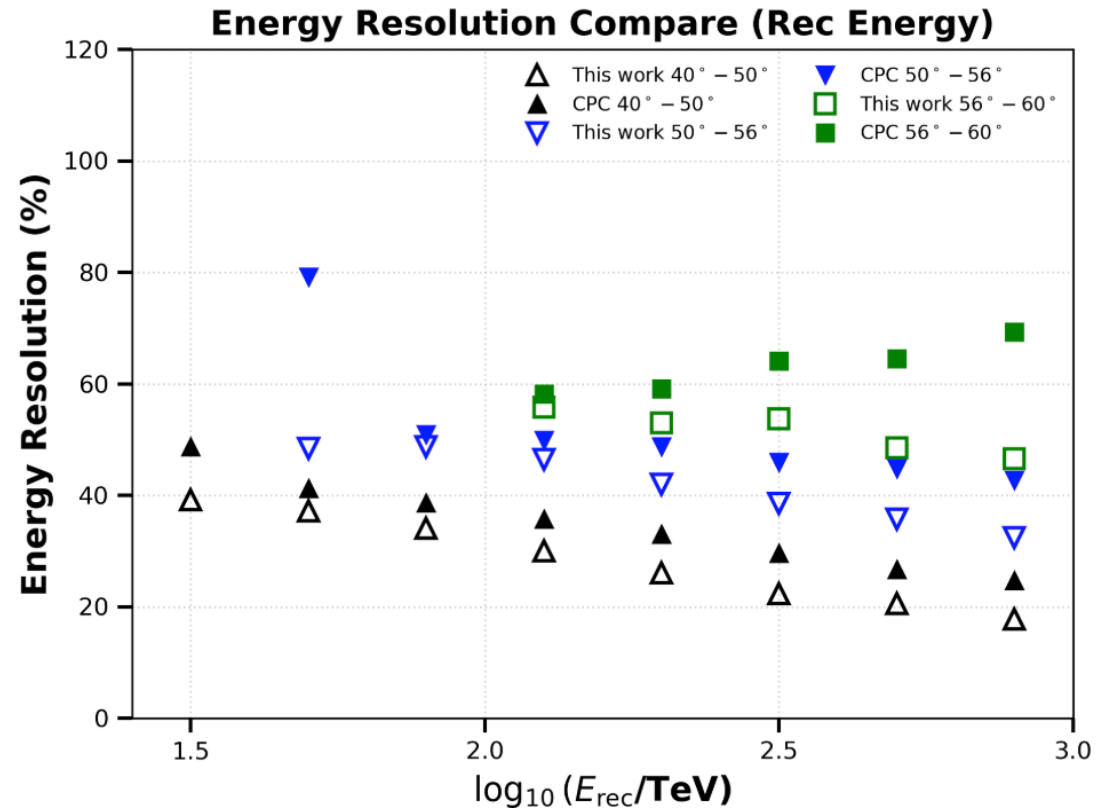


# Resolution



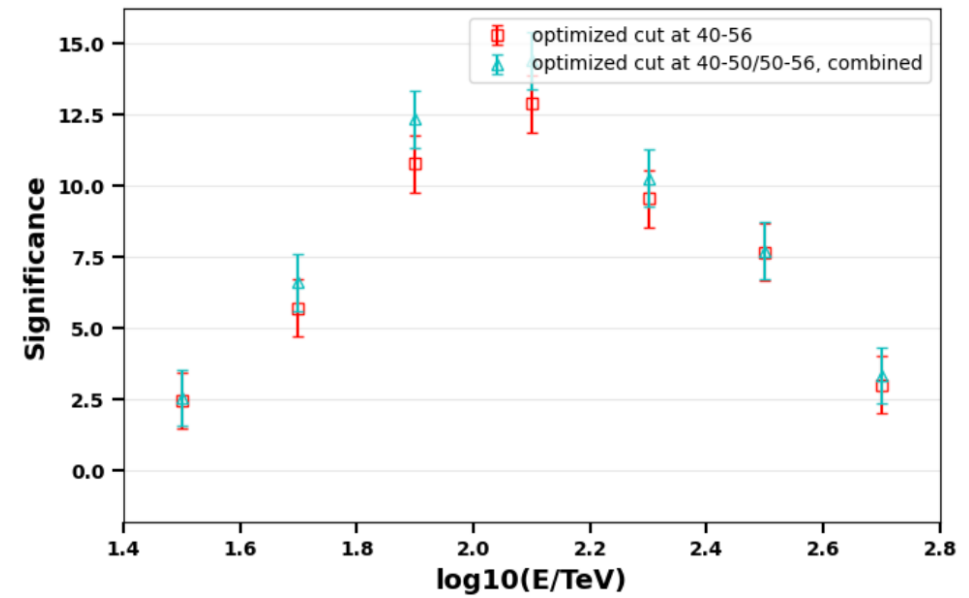
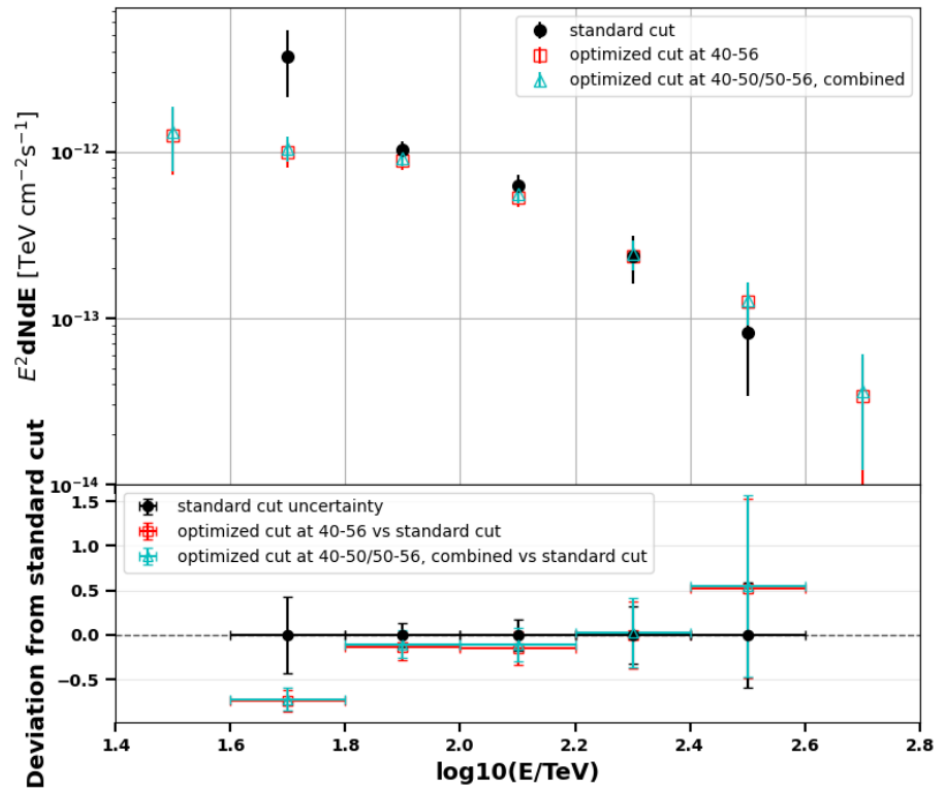


# Resolution





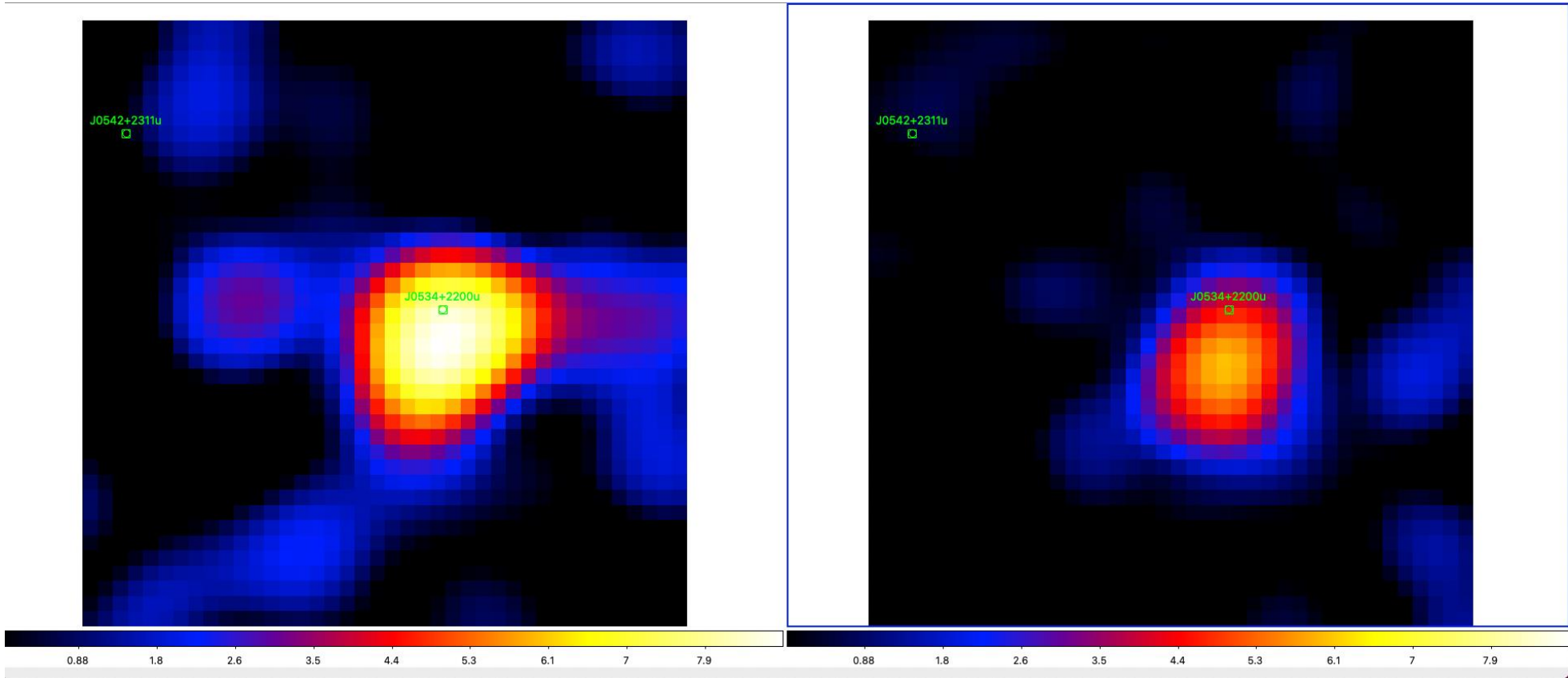
# Combined data at different zenith angles



**z 40-56**  
**> 100 TeV red-> cyan**  
**TS:~464->~570**



# Skymap in crab region



New cut at z50-56

Cpc cut at 50-60



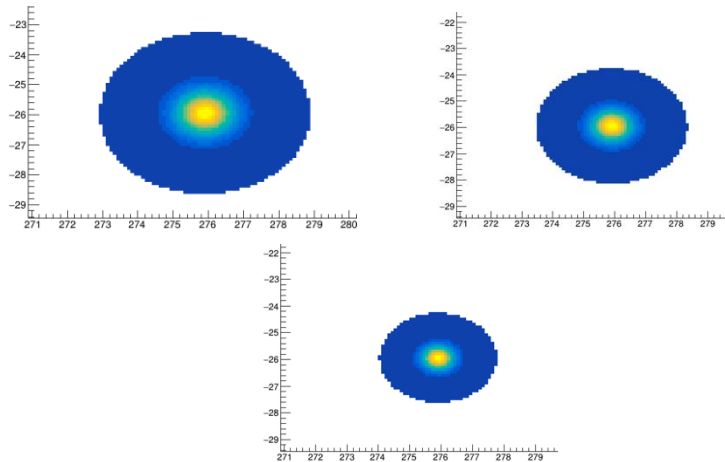
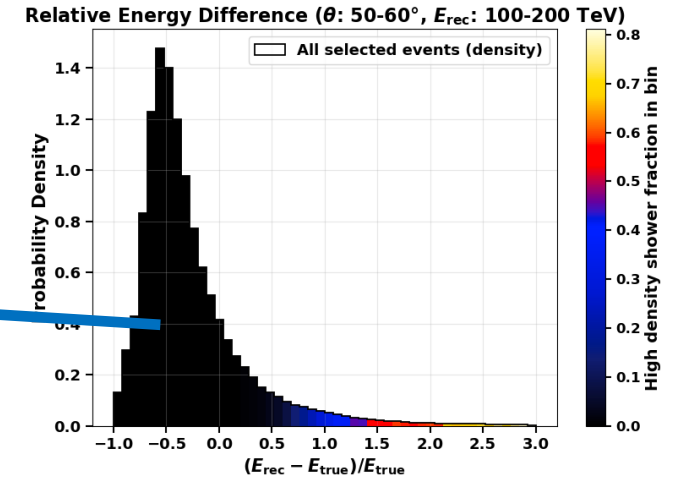
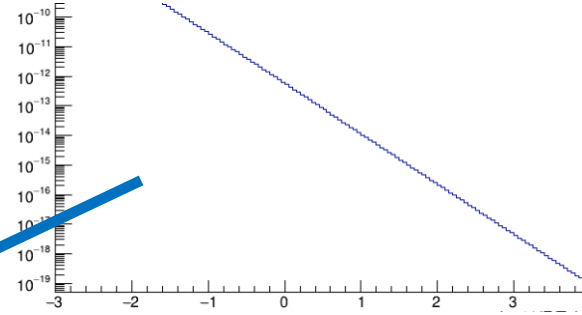
# Source analysis pipeline

Origin spectrum & trace of source

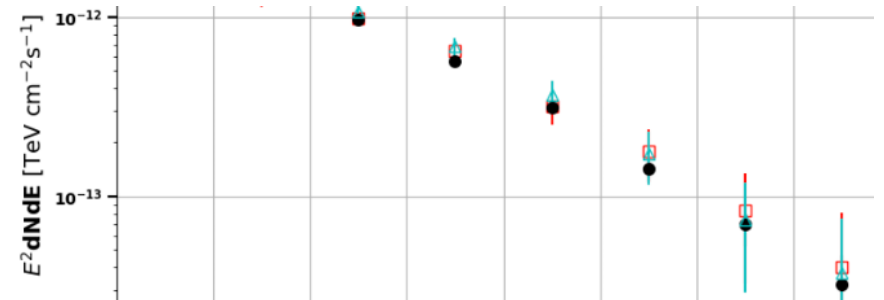
Weighting

Reconstructed MC data

( ~ spectrum convolving response  
e.g., **energy resolution** )



Fitting by scanning source  
[by reweighting spectrum distribution  
& spatial parameter]

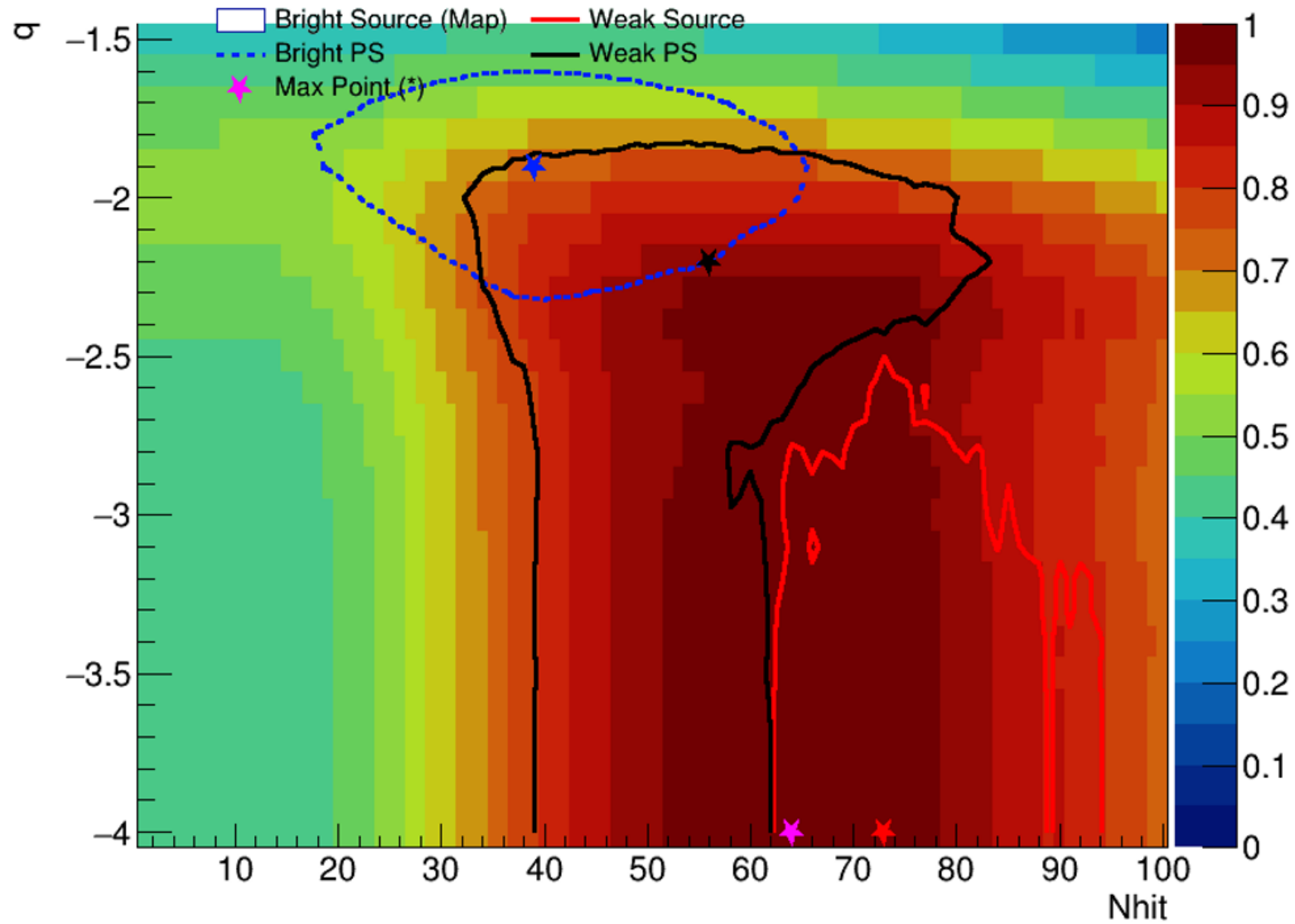


Expected source distribution (spatial/energy)  
at observed data

Best-fit spectrum with statistics  
uncertainties (**including energy  
resolution**)



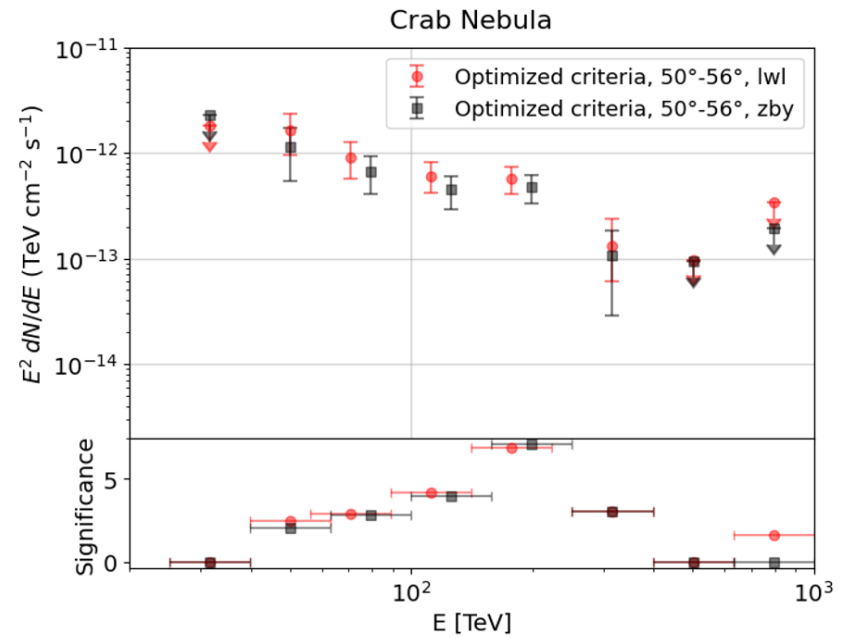
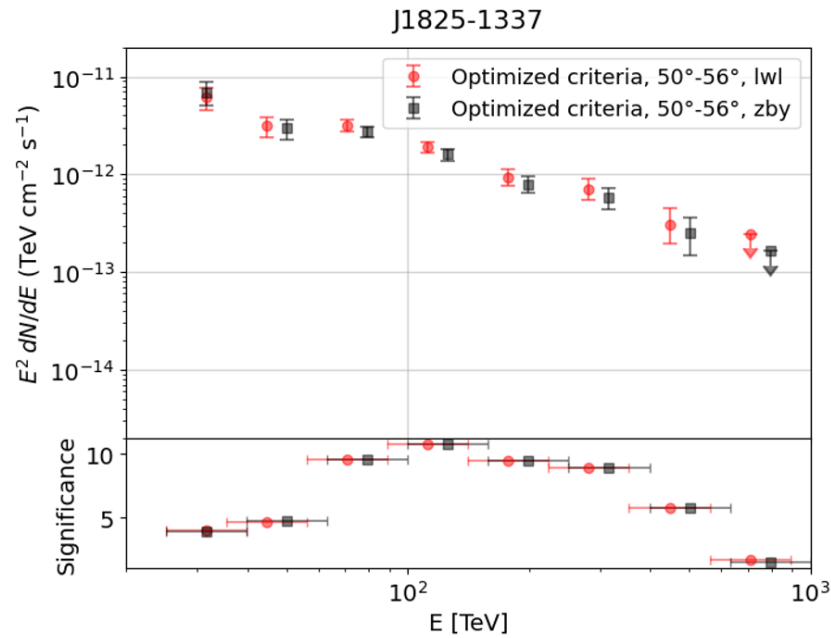
# Spatial & strength of fake source





# Double check for spectral measurement

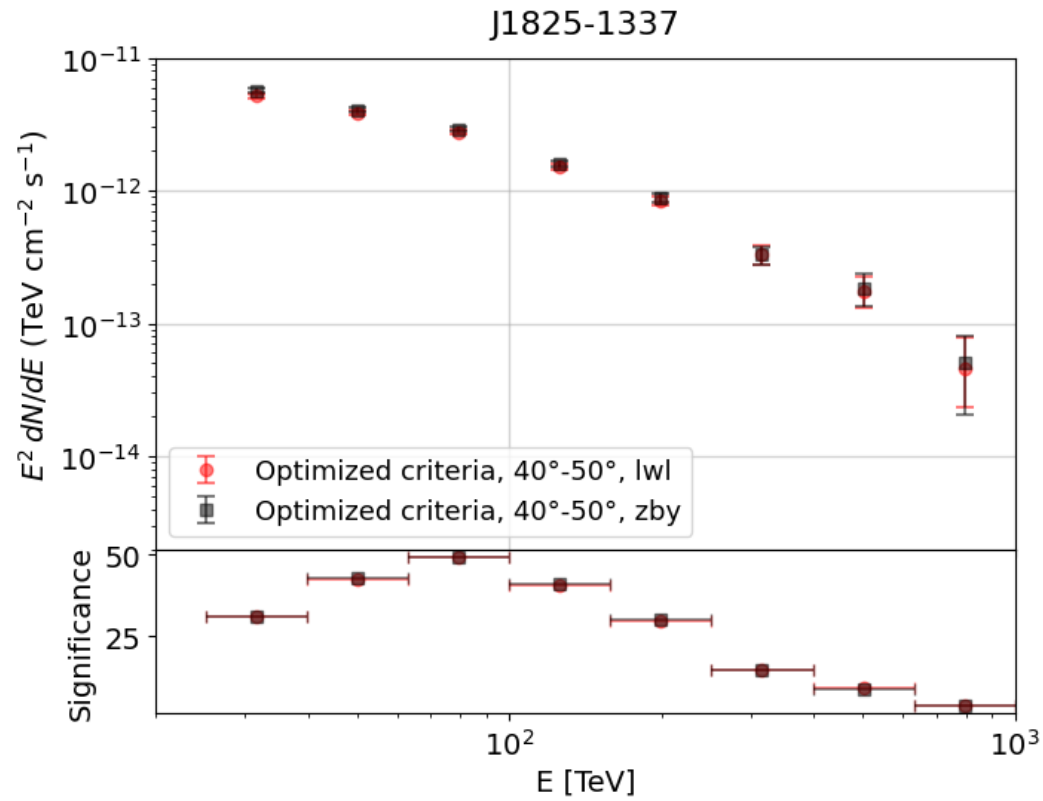
z 50-56



Provided by Wenlian Li



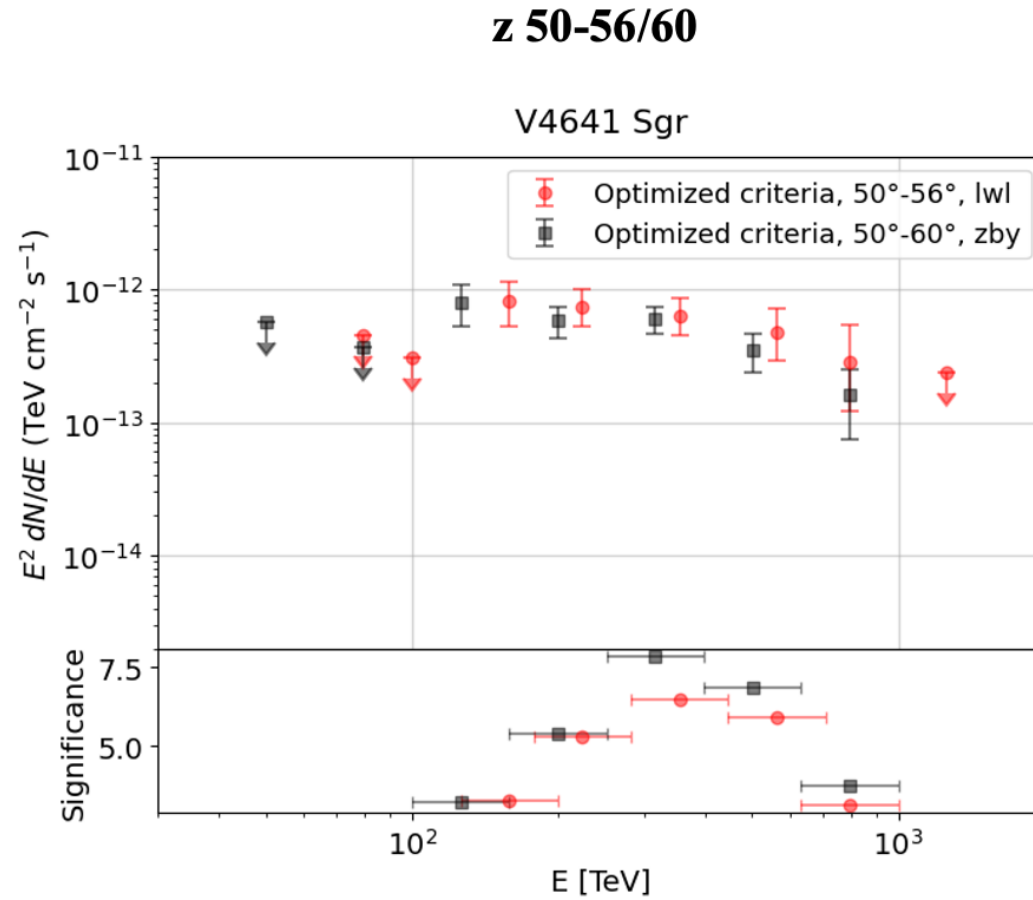
# Double check for spectral measurement



**z 40-50**



# Double check for spectral measurement

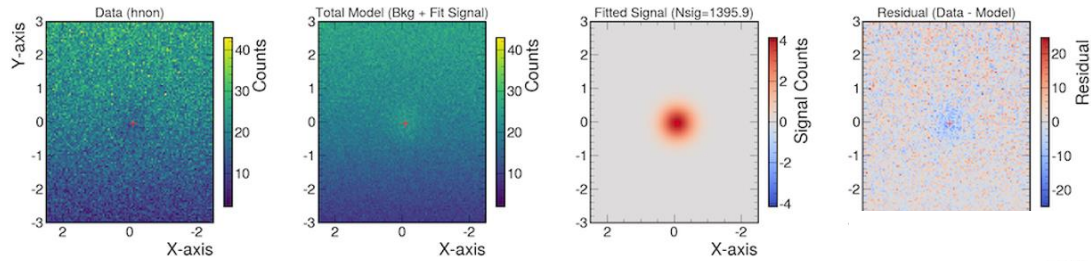


Provided by Wenlian Li

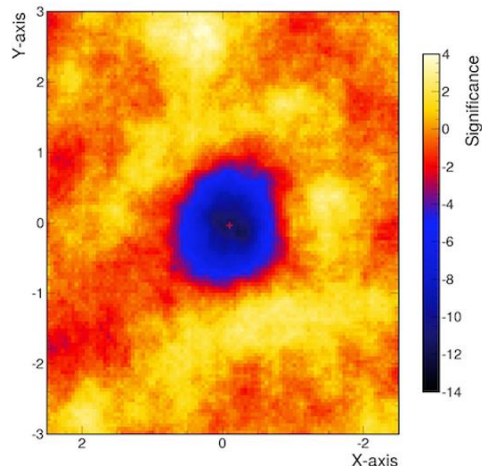




# Double check for Moon shadow



Provided by Xiajie



## 2D Elliptical Gaussian Fit Result (Normalized)

