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Measurement of VHE diffuse gamma-ray emission from $|b| < 5$ degree of Galactic plane with LHAASO-WCDA

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Outline

- ◆ Introduction
- ◆ Data and analysis method
- ◆ Results
- ◆ Summary

Sky maps of Gamma-Rays

◆ Different Origins of Gamma-Rays

- ◆ Resolved Sources
- ◆ Large-scale extensive sources
- ◆ Galactic Diffuse Gamma-ray Emission(GDE)

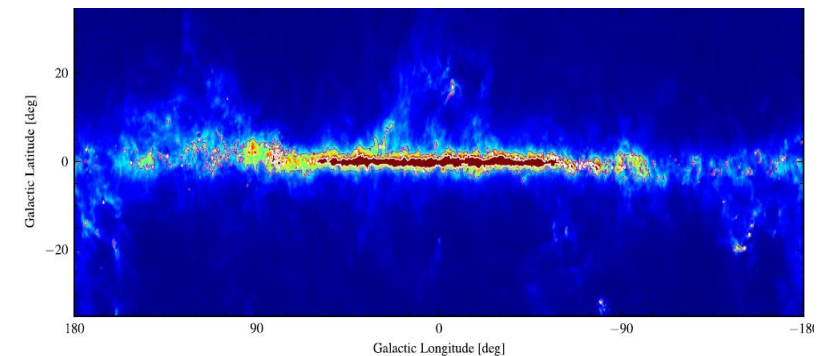
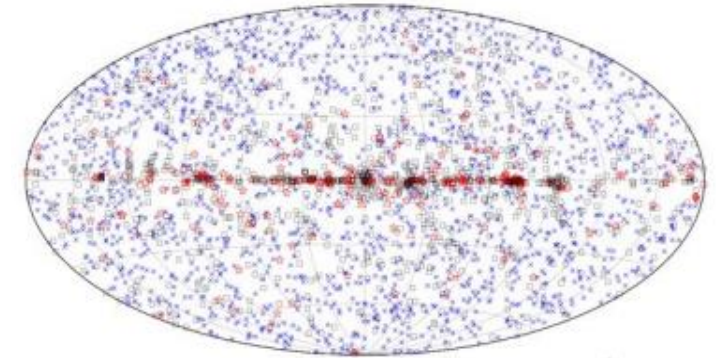
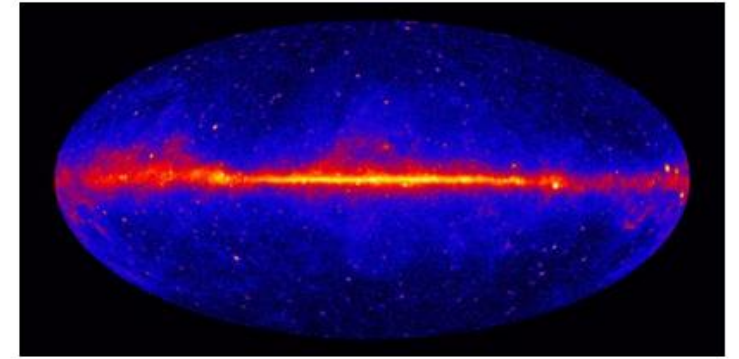
$$p, \alpha + \text{ISM} \rightarrow \pi^0 \rightarrow 2\gamma$$

$$e + \text{ISM} \rightarrow \gamma \quad \text{bremsstrahlung}$$

$$e + \text{ISRF} \rightarrow \gamma \quad \text{Inverse Compton scattering}$$

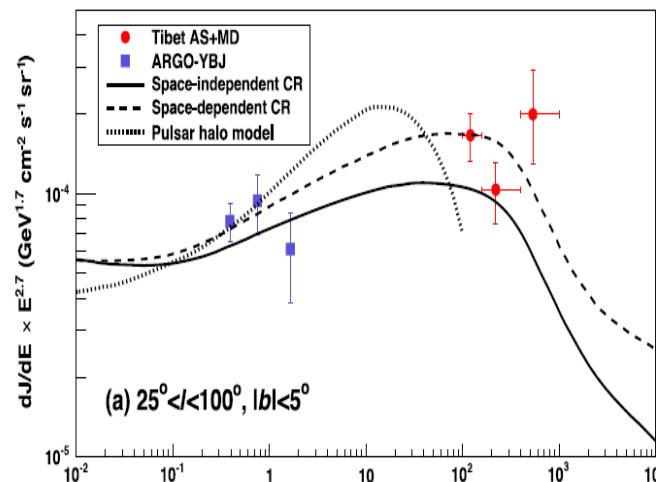
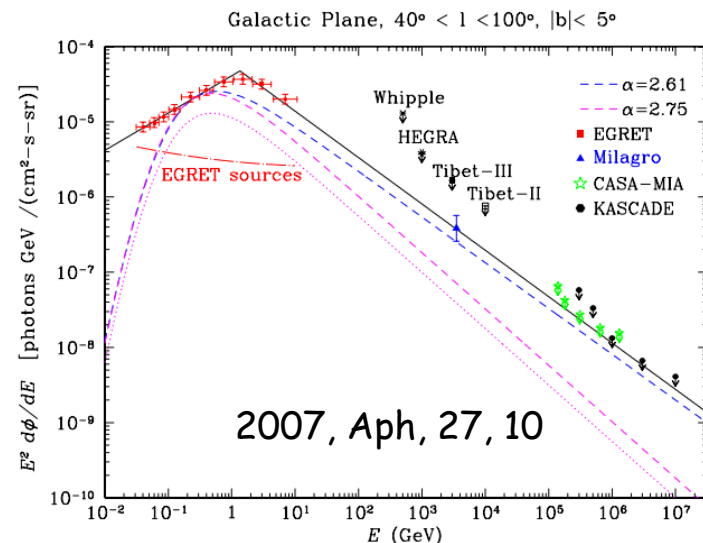
◆ An indirect way to study CRs & DM

- ◆ The GDE is a direct measurement of CR distribution in the Milky Way
- ◆ more important information of the production and propagation of CRs
- ◆ Propagating & Acceleration
- ◆ Origin of "Knee" in SED of CRs
- ◆ Dark Matter annihilation signal



Diffuse γ -ray measurements

2021, PRL, 27, 10

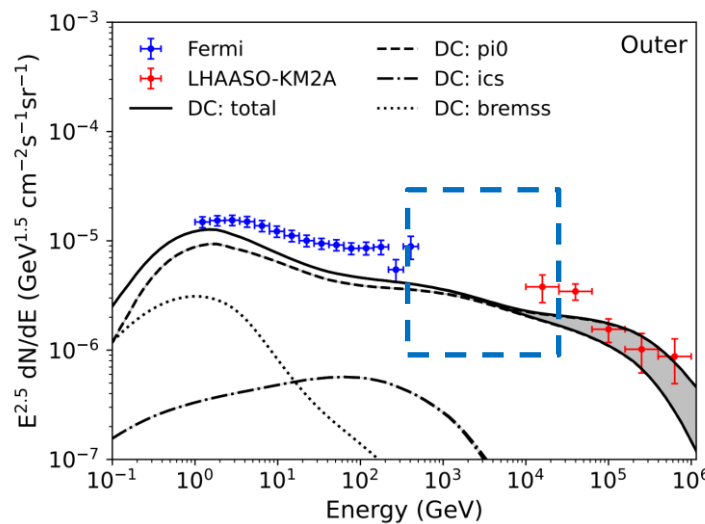
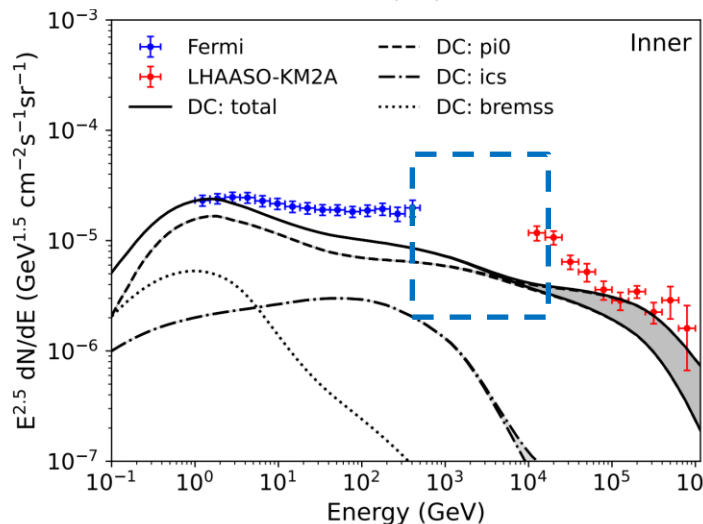


- ◆ EGRET and Fermi measured diffuse emission below 1TeV.

- ◆ Milagro, ARGO-YBJ, Tibet-ASy provide measurements for some sky regions.

- ◆ KM2A measured diffuse emission up to PeV.

- ◆ The energy range of WCDA from sub-TeV to 20 TeV, well bridge Fermi and KM2A.



R. Zhang et al.(arXiv:2305.06948)

Z. Cao et al.(arXiv.2305.05372)

LHAASO-WCDA (4410meter a.s.l.)

2021.03
Fullarray

2023.10
32 months

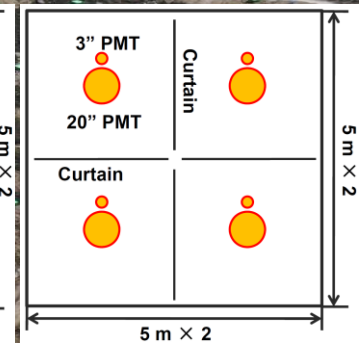
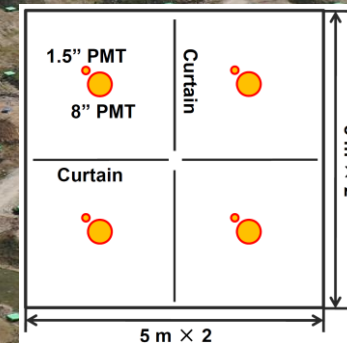
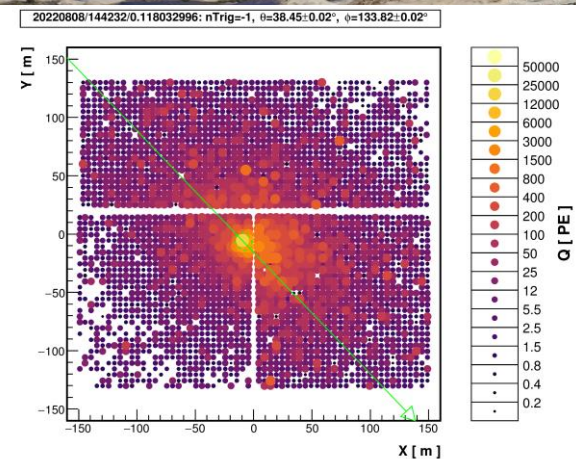
Water Cherenkov Detector Array

Ground-based detector array

- Large area : 78000 m^2 , 3120 units
- Angular resolution: $\sim 0.4^\circ @ 3 \text{ TeV}$
- Gamma/Proton discrimination: $Q > 10$
- $\sim 100 \text{ GeV} - \sim 30 \text{ TeV}$ gamma-ray astronomy

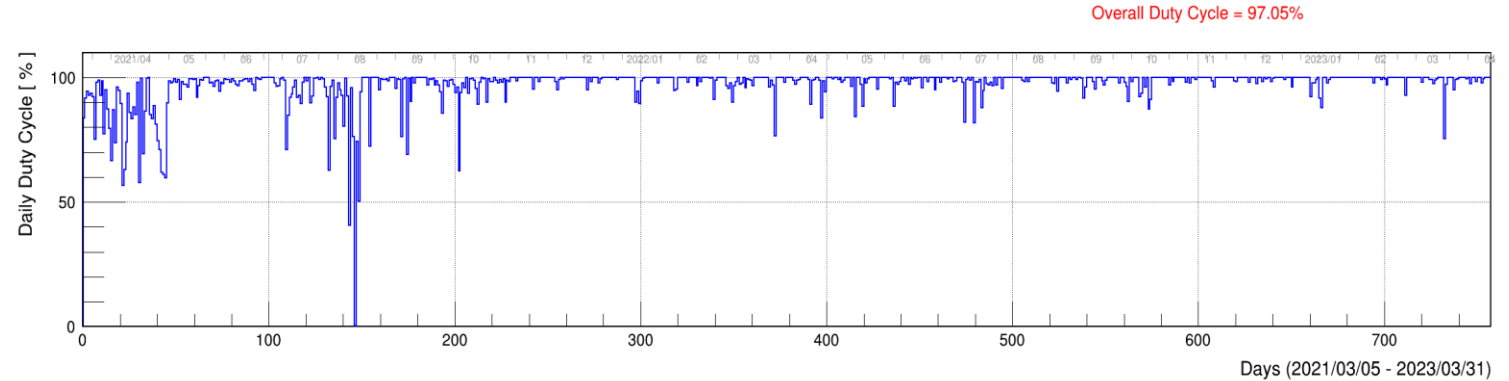
→ high sensitivity

- Wide field of view: $\sim 2 \text{ sr}$
- Duty cycle: $> 95\%$

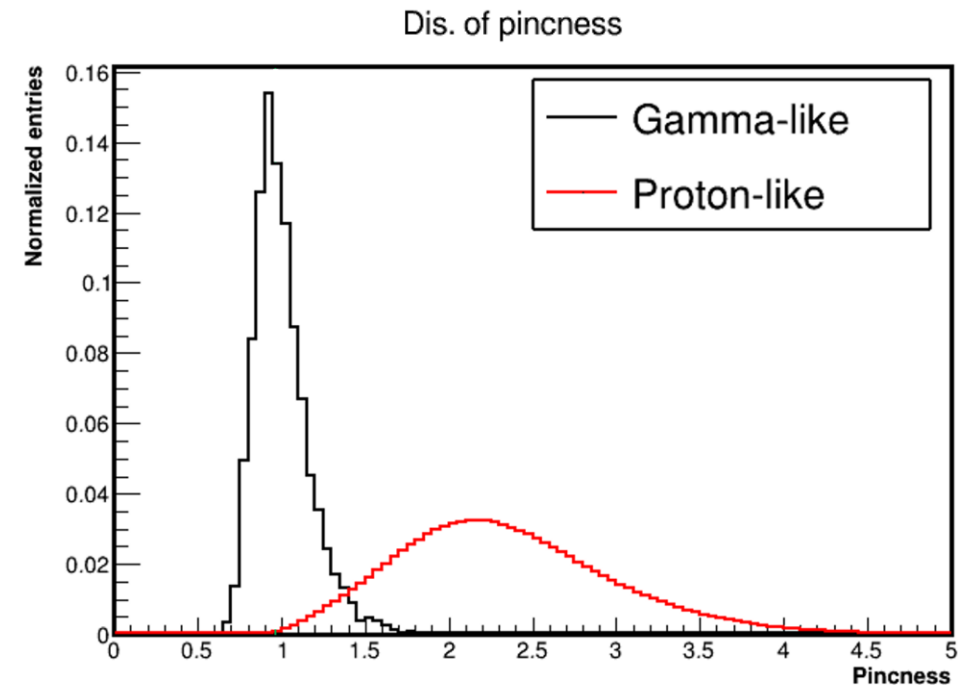


Data and event selection

- ◆ Full array data
 - ◆ 20210305-20230331
 - ◆ Livetime: ~686 days



- ◆ Event selection
 - ◆ Reconstructed zenith angle : $zen < 50^\circ$
 - ◆ Gamma/CR discrimination: $Pincness < 1.1$
 - ◆ N_{hit} : 60-100-200-300-500-2000



background estimation

◆ Method

- Direct integral method
- Integral time: 4 + 10 hours
(4 hr step and +/-5 hr window)

- SED: Forward-folding
- Maximization: 3D likelihood

◆ Masked region

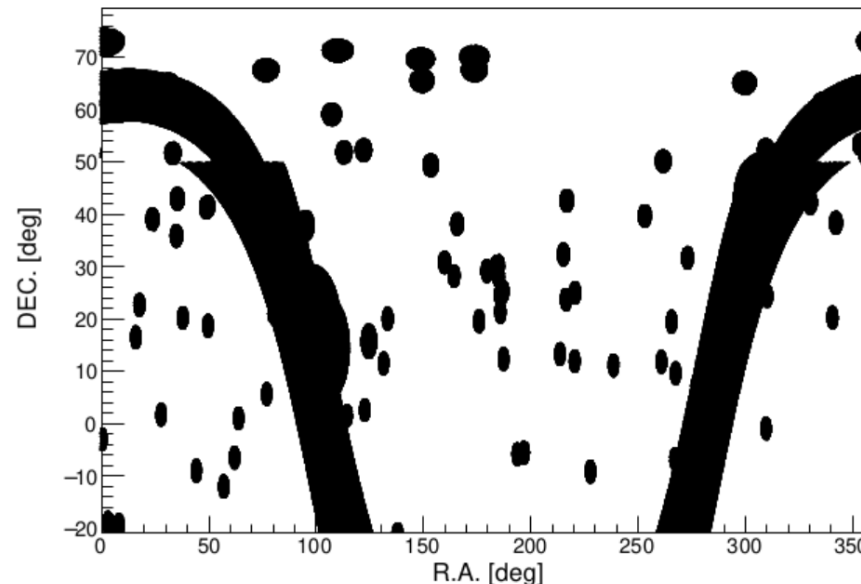
◆ Galactic plane:

- ◆ $-5^\circ < b < 5^\circ$ (if dec $> 50^\circ$)
- ◆ $-10^\circ < b < 10^\circ$ (if dec $< 50^\circ$)

◆ Resolved sources:

- ◆ TeV Catalog

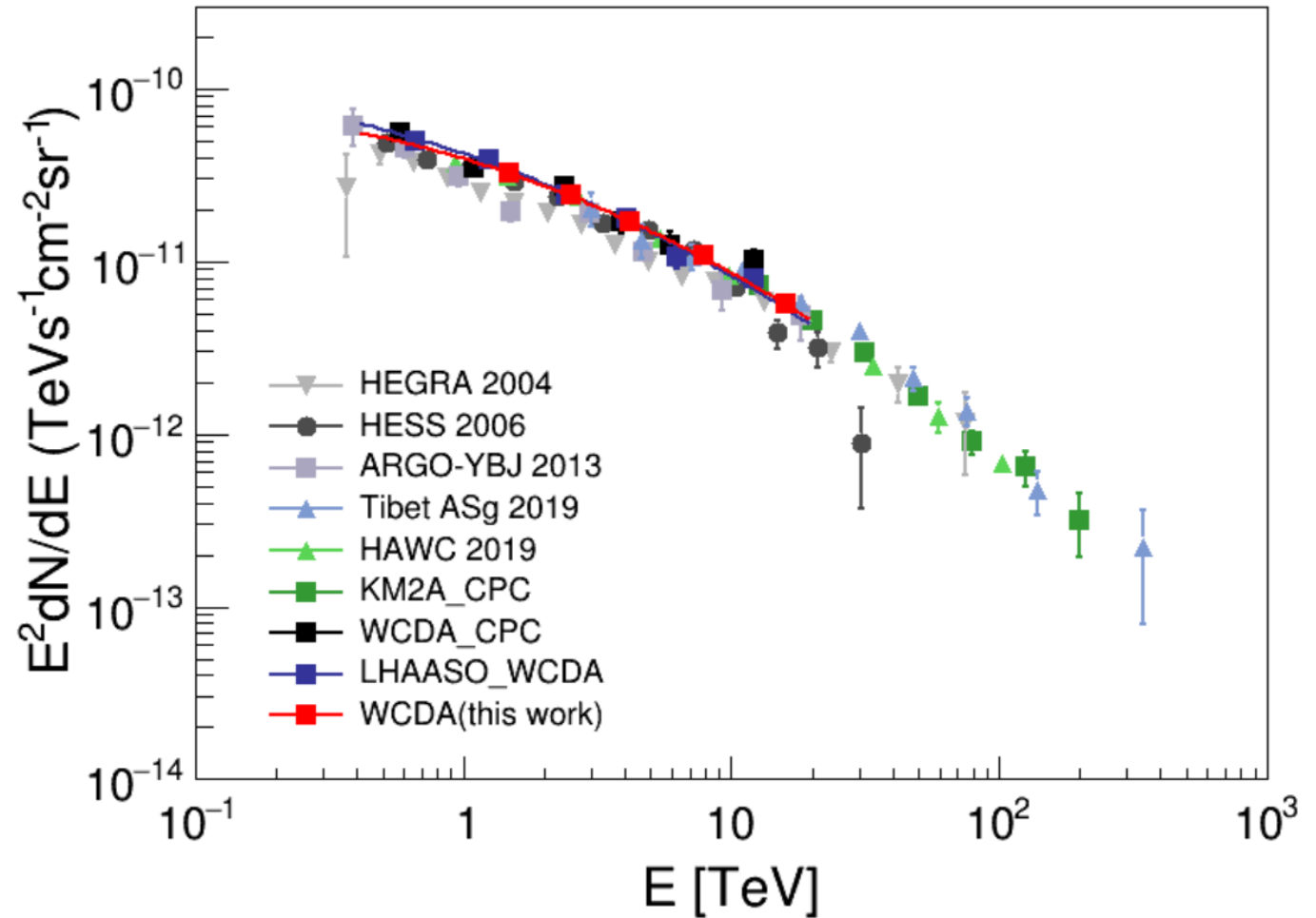
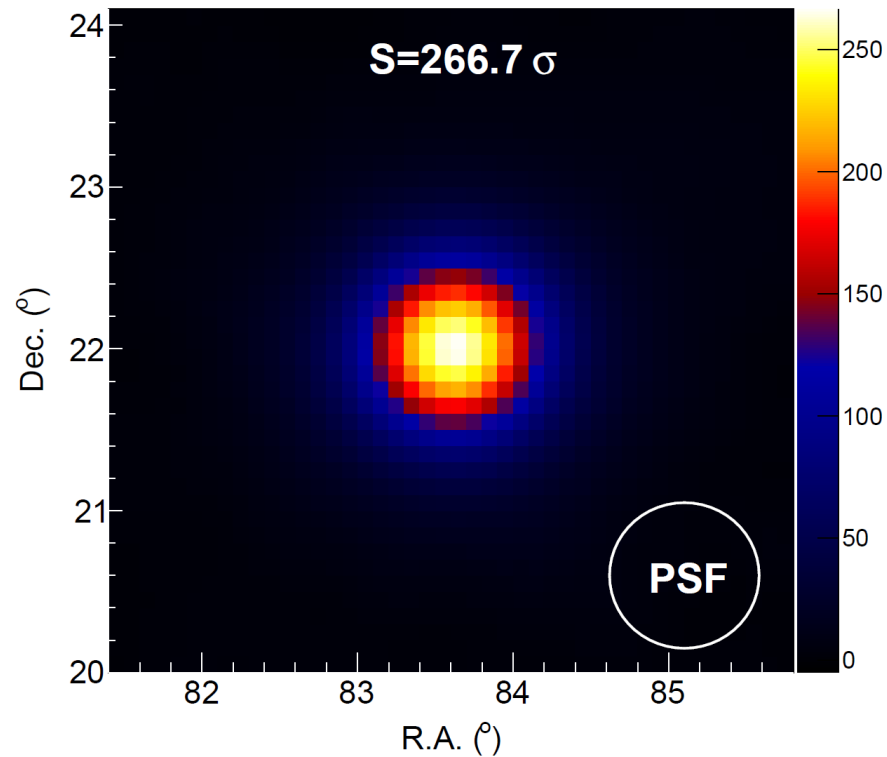
- ◆
$$R_{\text{mask}} = 5 \times \sqrt{\sigma_{\text{psf}}^2 + \sigma_{\text{ext}}^2}$$



Crab results

➤ Data

- 508 days
- 1TeV - 25TeV @ Crab spectrum
- Zenith angle < 50 deg



Resolved source mask

◆ Inner Galaxy Plane

- $(-5^\circ < b < 5^\circ, 15^\circ < l < 125^\circ)$

◆ Outer Galaxy Plane

- $(-5^\circ < b < 5^\circ, 125^\circ < l < 235^\circ)$

◆ Exceptions for very large sources

- Cygnus cocoon : 6°
- Geminga : 6°
- Monogem : 8°

The first LHAASO Catalog
arXiv:2305.17030v1

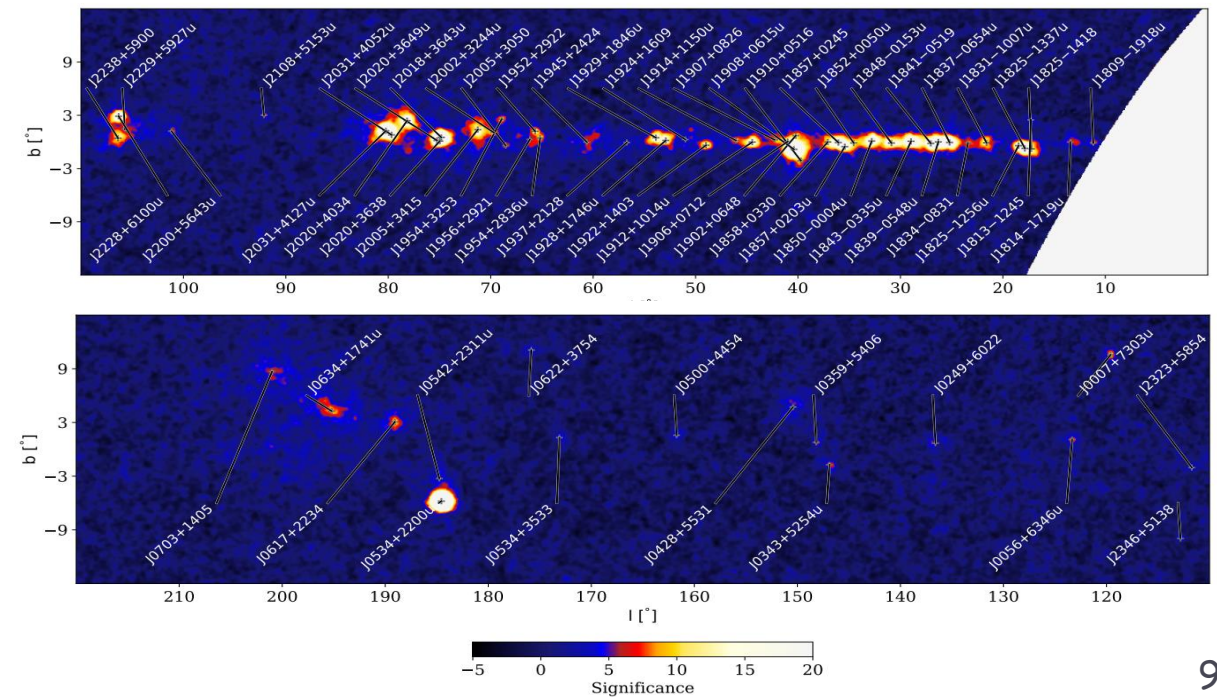
◆ Resolved source Mask:

- WCDA Catalog + TeV Catalog
- For overlapping sources, WCDA parameters are used

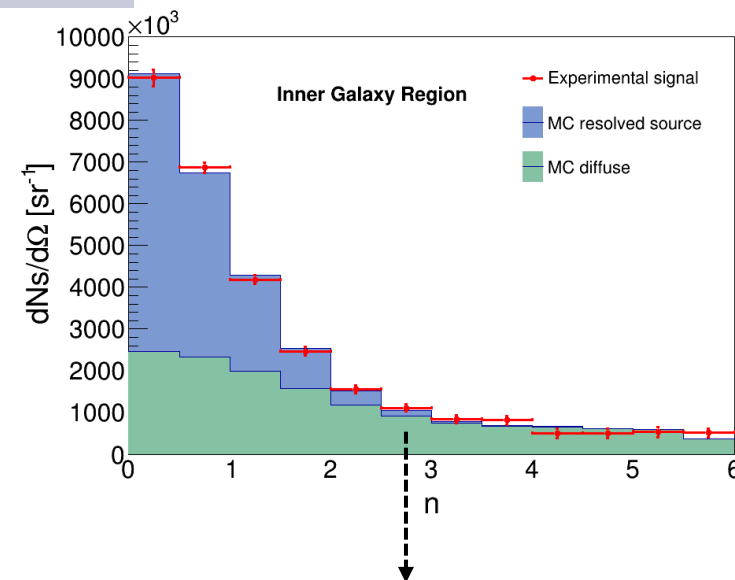
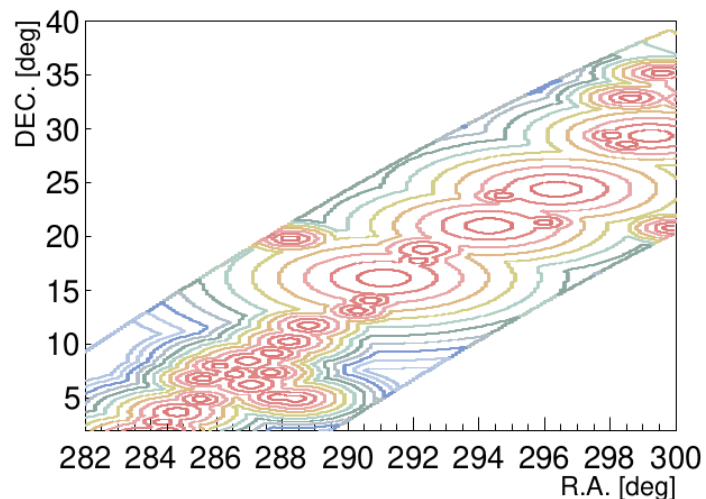
$$R_{\text{mask}} = n \times \sqrt{\sigma_{\text{psf}}^2 + \sigma_{\text{ext}}^2}$$

- $\sigma_{\text{psf}} = 0.5^\circ$ is chosen

- σ_{ext} : the source extension



Residual source contamination



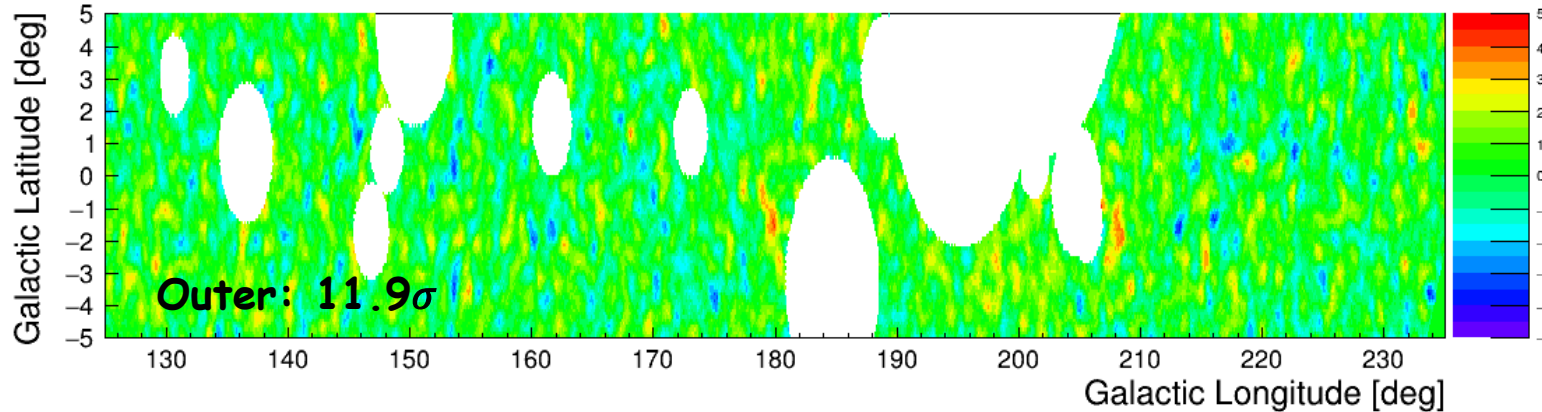
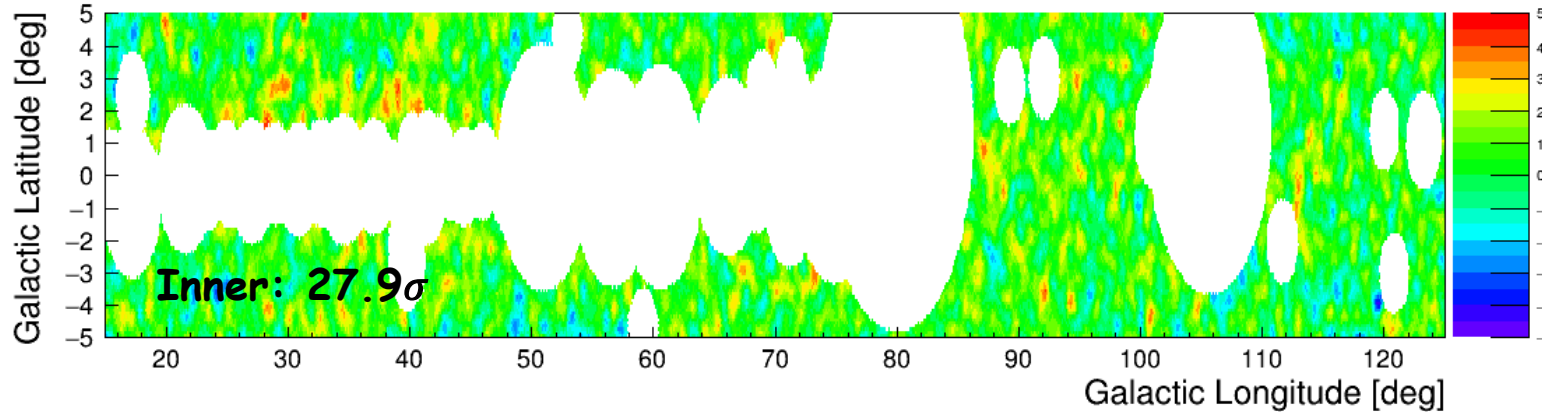
- ◆ $R_{\text{mask}} = n \times \sqrt{\sigma_{\text{psf}}^2 + \sigma_{\text{ext}}^2}$
- ◆ MC resolved source
 - WCDACat + TeVCat - counterpart
- ◆ The contamination proportion(%)

$$f_{\text{cont}} = \frac{N_{\text{src}}}{(N_{\text{src}} + N_{\text{DGE}})},$$

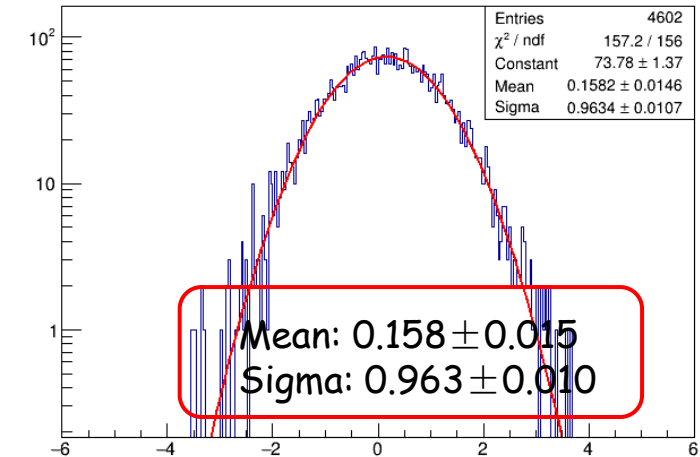
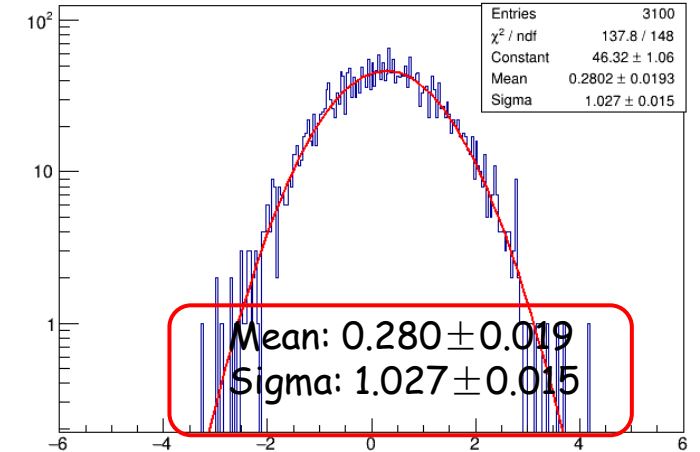
nhit	Inner galaxy region (%)
100-200	6.03 ± 0.16
200-300	3.11 ± 0.18
300-500	2.60 ± 0.19
500-800	2.32 ± 0.26
>800	3.50 ± 0.62

- ◆ **$n = 2.5$ to balance resolved source contamination and residual sky area**

Results: Significance map



$(-5^\circ < b < 5^\circ, 15^\circ < l < 125^\circ)$

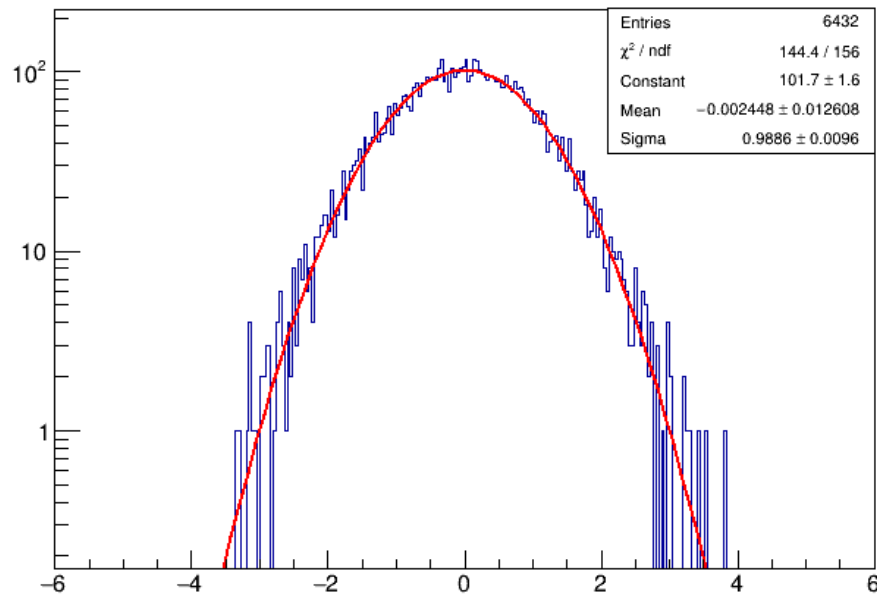


$(-5^\circ < b < 5^\circ, 125^\circ < l < 235^\circ)$

- ◆ The total significance of the inner (outer) Galaxy region is 27.9σ (11.9σ).
- ◆ After the mask, no significant point-like sources are present in the significance maps.
- ◆ The positive mean values indicate the presence of diffuse emission in these regions.

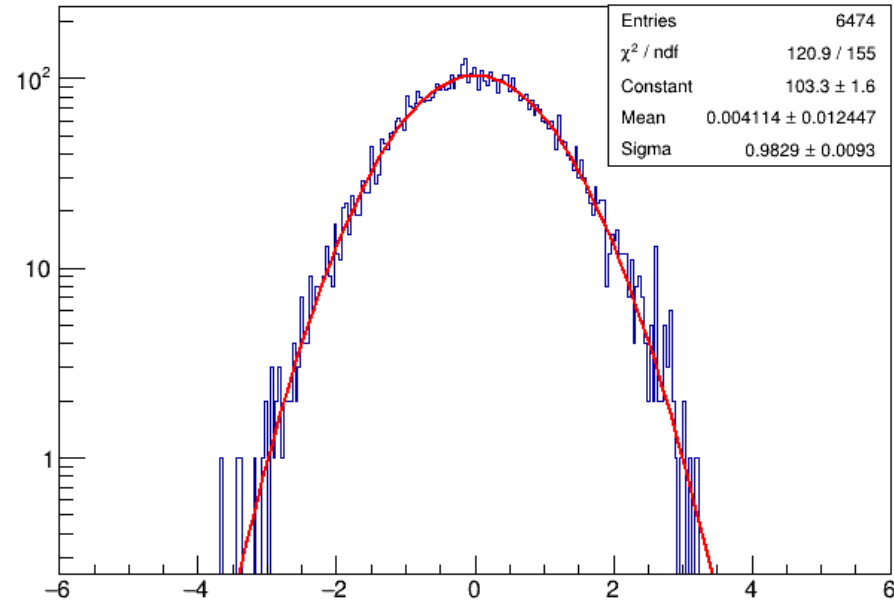
The other regions

$(15^\circ < b < 25^\circ, 15^\circ < l < 125^\circ)$



Mean: -0.002 ± 0.013
Sigma: 0.989 ± 0.010

$(15^\circ < b < 25^\circ, 125^\circ < l < 235^\circ)$



Mean: -0.004 ± 0.012
Sigma: 0.983 ± 0.009

- ◆ The significance distributions of the other two regions are consistent with the standard Gaussian distribution expected for the background distribution.

The Spectrum Fitting

- Forward-Folding: power law $\phi(E) = \phi_0 (E/E_0)^{-\alpha}$, $E_0=3\text{TeV}$

- Maximizing $\frac{\mathcal{L}_{s+b}}{\mathcal{L}_b} = \frac{\prod_{i=1}^n \text{Poisson}(N_i^{\text{obs}}, N_i^{\text{sig}}(\phi_0, \alpha) + N_i^{\text{bkg}})}{\prod_{i=1}^n \text{Poisson}(N_i^{\text{obs}}, N_i^{\text{bkg}})}$

N_{obs} is the observed counts,

N_{bkg} is the background counts by **BKG-DI**,

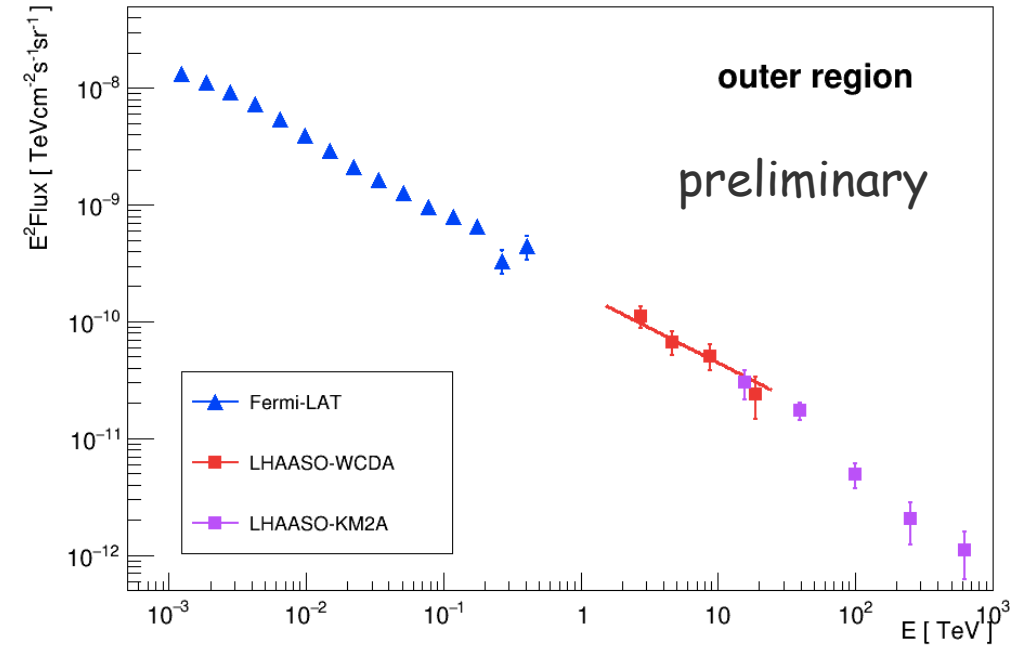
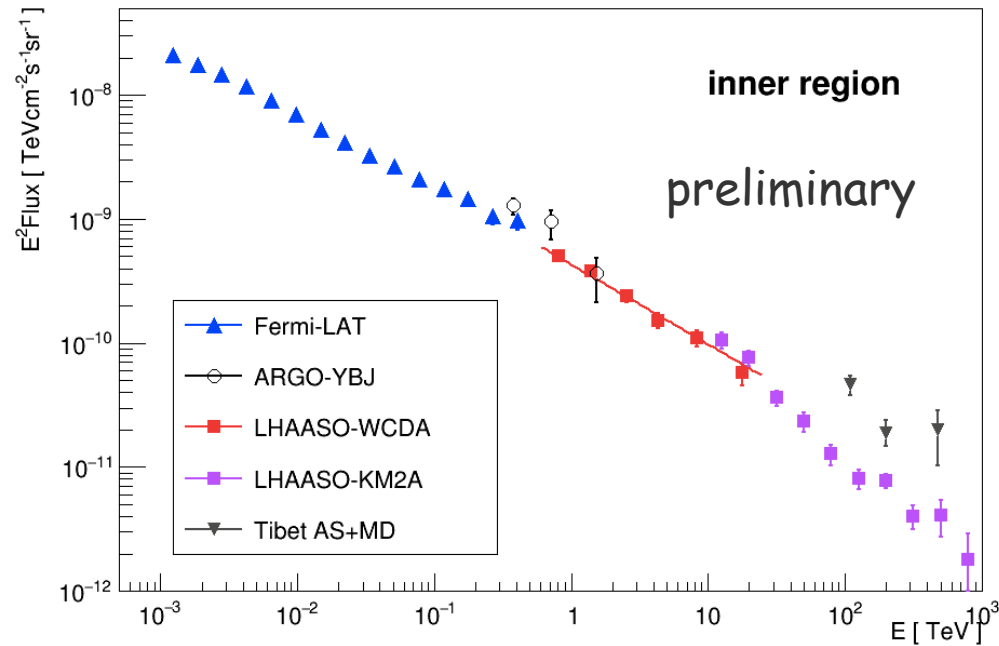
N_{sig} is the predicted counts from **Forward-folding**.

$$\text{TS} = -2 \ln (\mathcal{L}_{s+b}/\mathcal{L}_b)$$

$\mathcal{L}_{s+b}$: **Signal + background hypothesis**

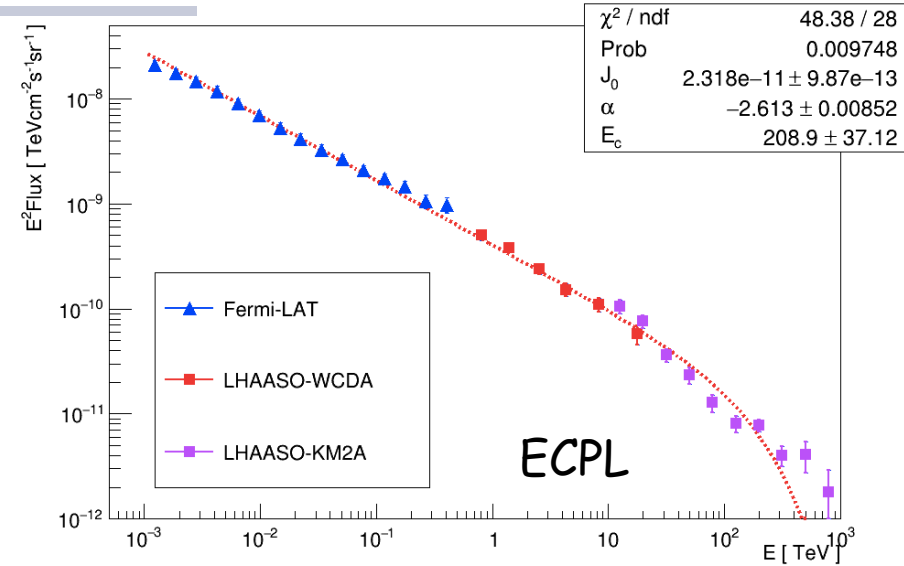
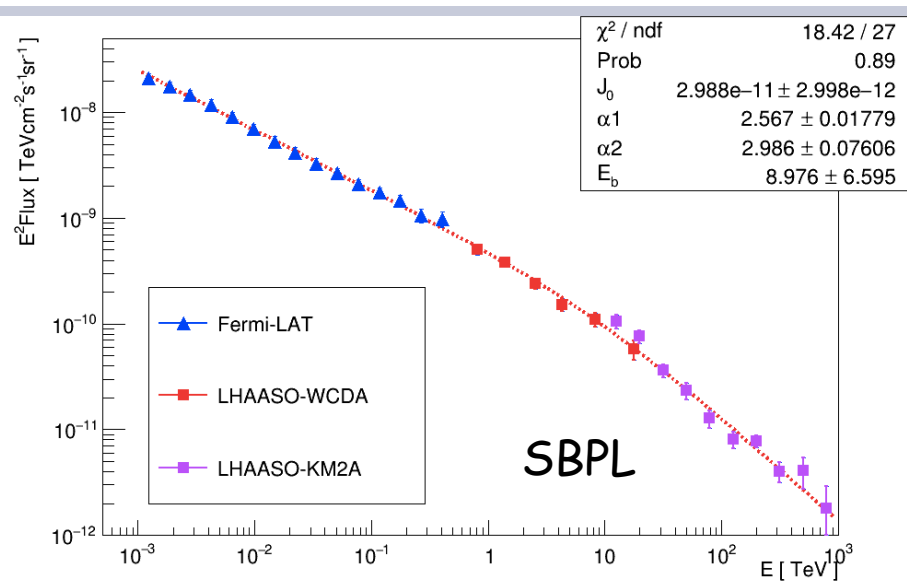
$\mathcal{L}_b$: **Only background hypothesis**

Results: SED

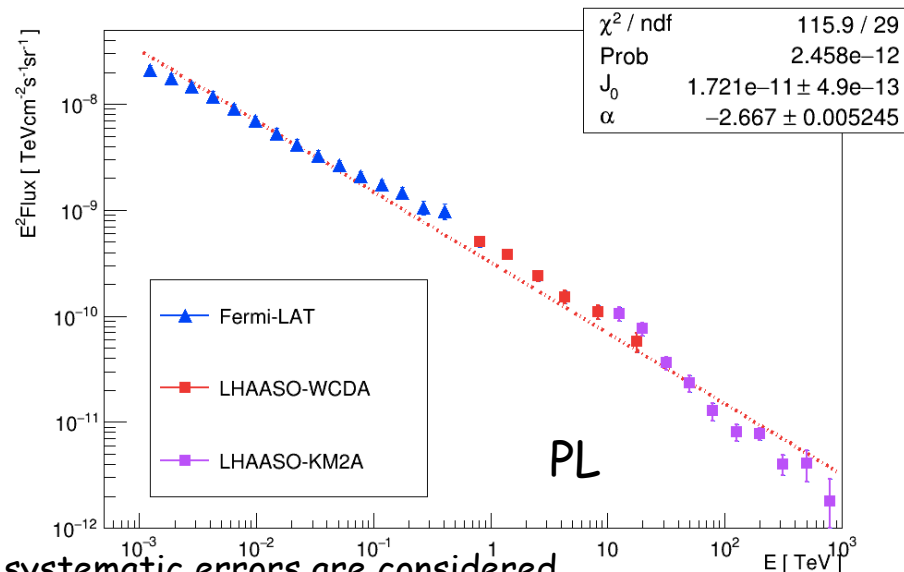


- ◆ Using a power-law function, index is 2.64 ± 0.04 and 2.60 ± 0.11 for the two regions.
- ◆ The SED is consistent with Fermi-LAT and KM2A, but, there are some subtle structures and differences in the connection.

Discussion: Broadband Spectral Fit

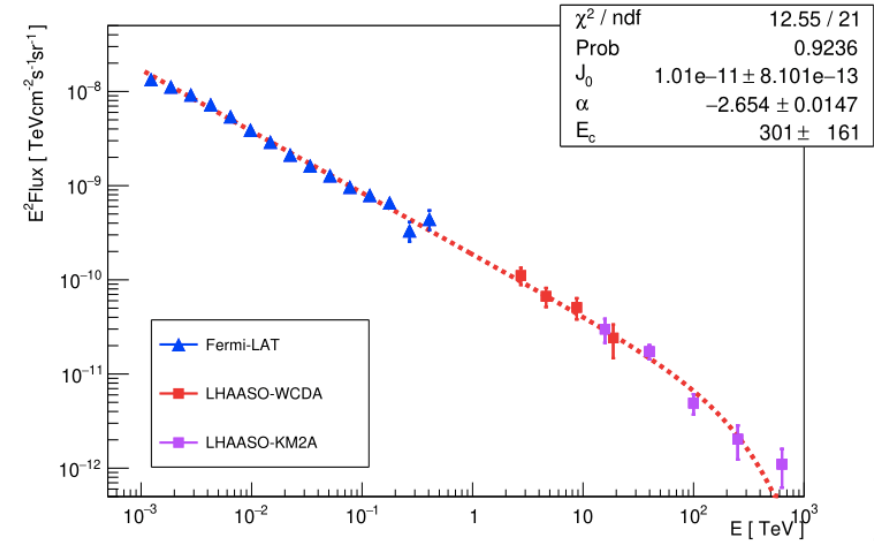
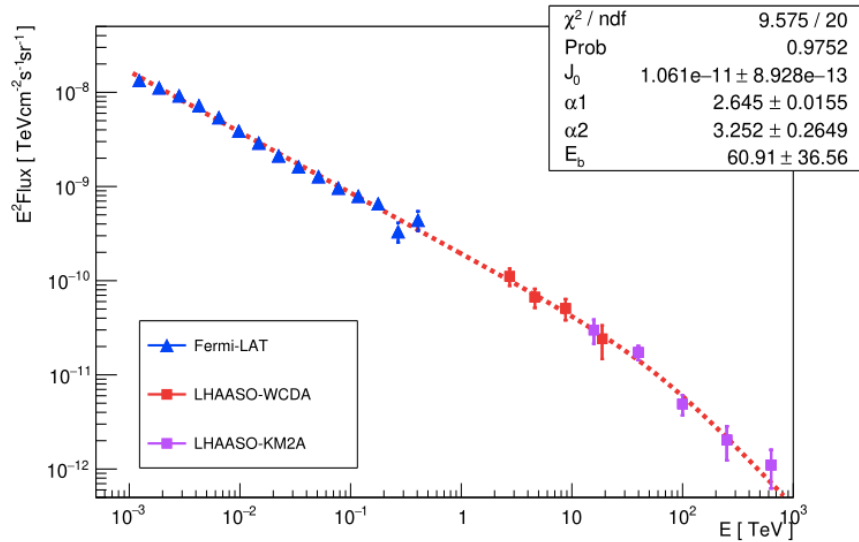


Spectral Model	Formula	Parameter values	χ^2 / ndf
SBPL	$N_0(E/E_0)^{-\gamma_1} (1 + (E/E_b)^{\frac{\gamma_2 - \gamma_1}{\beta}})^{-\beta}$	$\gamma_1 = 2.57 \pm 0.02$ $\gamma_2 = 2.99 \pm 0.08$ $E_b \text{ (TeV)} = 9.0 \pm 6.6$	18.4/27
ECPL	$N_0(E/E_0)^{-\gamma} \exp(-E/E_c)$	$\gamma = 2.61 \pm 0.008$ $E_c \text{ (TeV)} = 208.9 \pm 37.1$	48.4/28
PL	$N_0(E/E_0)^{-\gamma}$	$\gamma = 2.67 \pm 0.005$	115.9/29

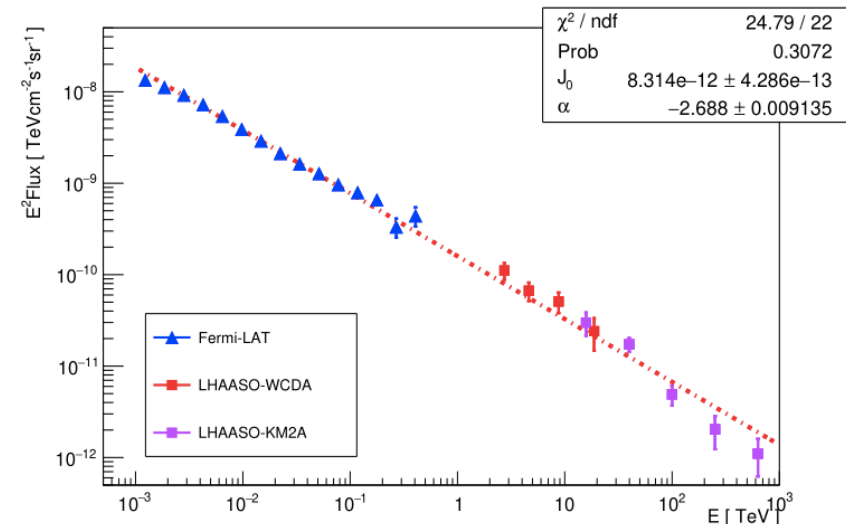


The SBPL model is therefore favored over when statistical and systematic errors are considered.

Discussion: Broadband Spectral Fit



Spectral Model	Formula	Parameter values	χ^2 / ndf
SBPL	$N_0(E/E_0)^{-\gamma_1} (1 + (E/E_b)^{\frac{\gamma_2 - \gamma_1}{\beta}})^{-\beta}$	$\gamma_1 = 2.65 \pm 0.02$ $\gamma_2 = 3.25 \pm 0.26$ $E_b \text{ (TeV)} = 60.9 \pm 36.6$	9.6/20
ECPL	$N_0(E/E_0)^{-\gamma} \exp(-E/E_c)$	$\gamma = 2.65 \pm 0.01$ $E_c \text{ (TeV)} = 301 \pm 161$	12.5/21
PL	$N_0(E/E_0)^{-\gamma}$	$\gamma = 2.69 \pm 0.009$	24.8/22



There was no significant difference between the three models by the current data.

Summary

- ◆ Diffuse gamma emission from two regions of the Galactic plane is measured with high significance by LHAASO-WCDA.
- ◆ SED of two region well bridge Fermi and KM2A. Spectral indices of the two regions are 2.64 and 2.60.
- ◆ Broadband Spectral Fit: The SBPL model is favored.

Thank you!