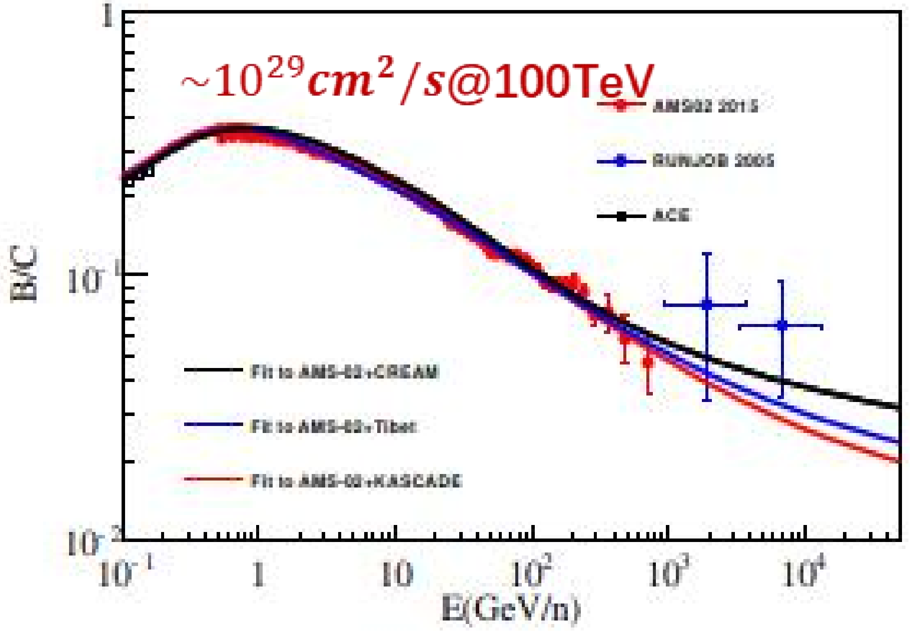
On the energy-dependent morphology and spectra around Geminga and Monogem with LHAASO-KM2A

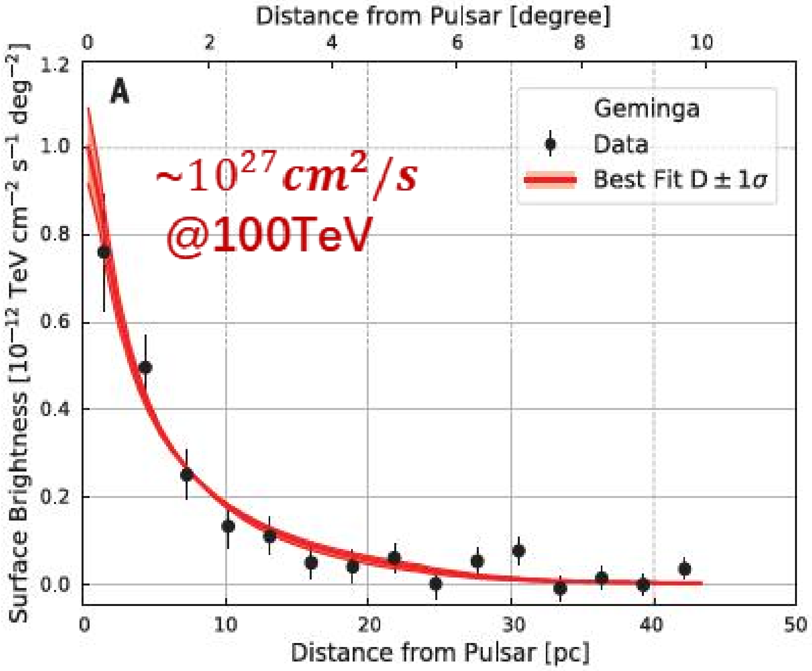
Reporter: Yingying Guo[2]

Collaborator: Yi Zhang[2,1], Qiang Yuan[2], Hongbo Hu[1], Ensheng Chen[1], Xiaojun Bi[1]

1. Institute of High Energy Physics(IHEP)
2. Purple Mountain Observatory

The discovery of inefficient diffusion





B/C ratio constrains diffusion coefficient, and extrapolates to higher energy

The measurement of diffusion coefficient

- How does diffusion depend on energy?
- The shape of injected electron spectrum?

Abeysekara et al., Science 358, 911–914 (2017) 17 November 2017

Content

- Data introduction
- Background estimation (equi-zenith angle method)
- Significance of Geminga and Monogem
- Morphology evolution with energy measured by
  - (1) 1/2KM2A
  - (2)3/4KM2A
  - (3) 1/2KM2A and 3/4KM2A
- Source spectra
- Implication on electron spectrum

Data introduction

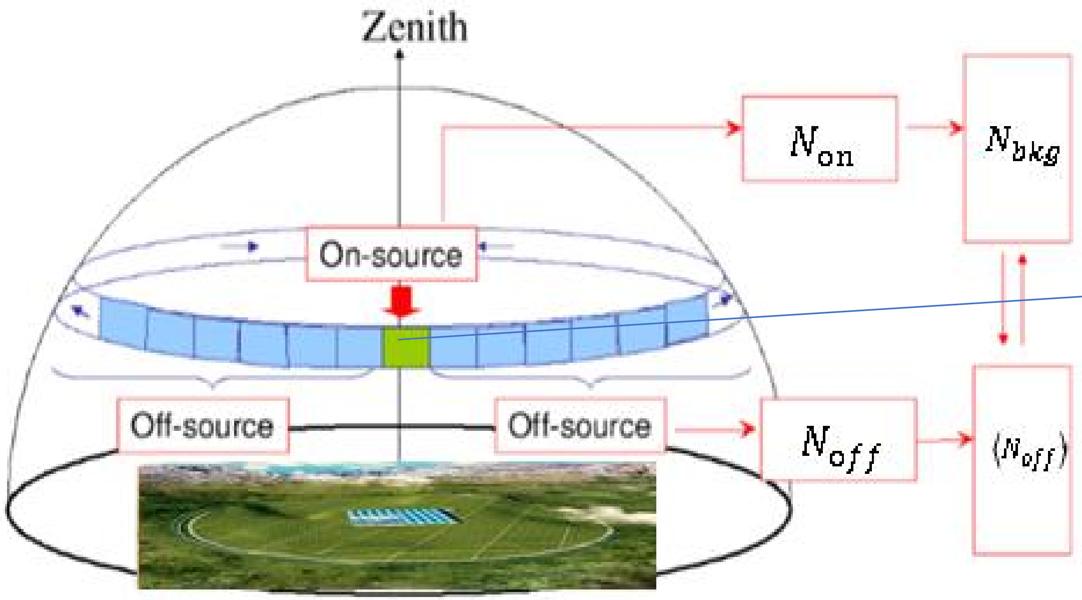
➢Duration:

- ½ KM2A： 27 Dec. 2019 – 30 Nov. 2020
- ¾ KM2A： 1 Dec. 2020 – 19 Jul. 2021

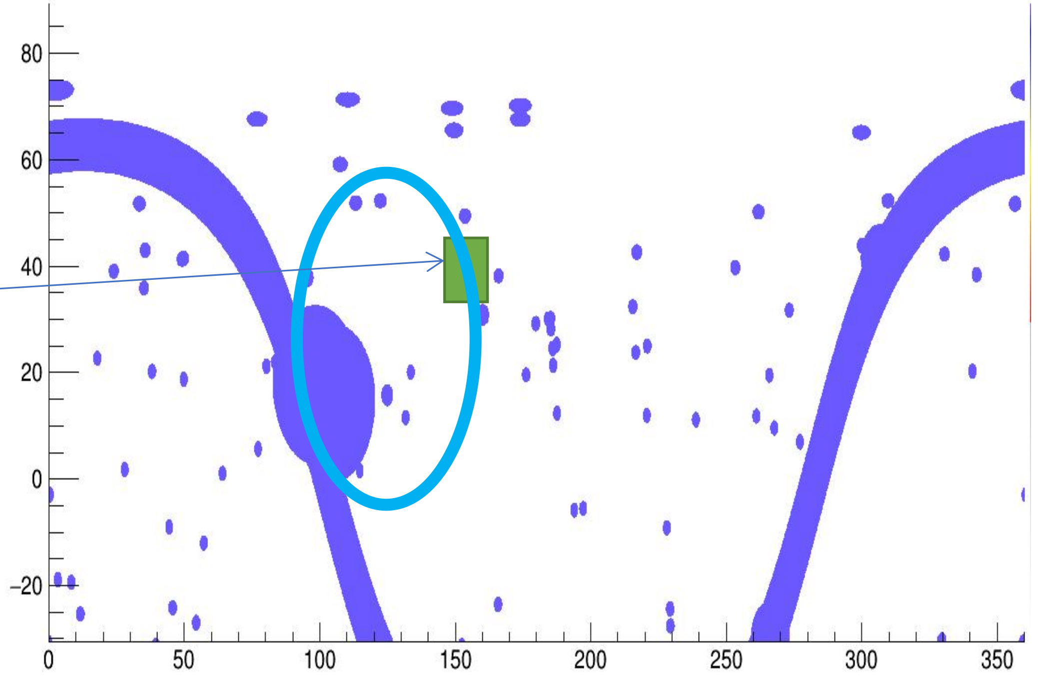
➢Data selection criteria are the same as Crab(zenith angle is 10-50deg).

F. Aharonian et al 2021 Chinese Phys. C 45 025002

Background estimation

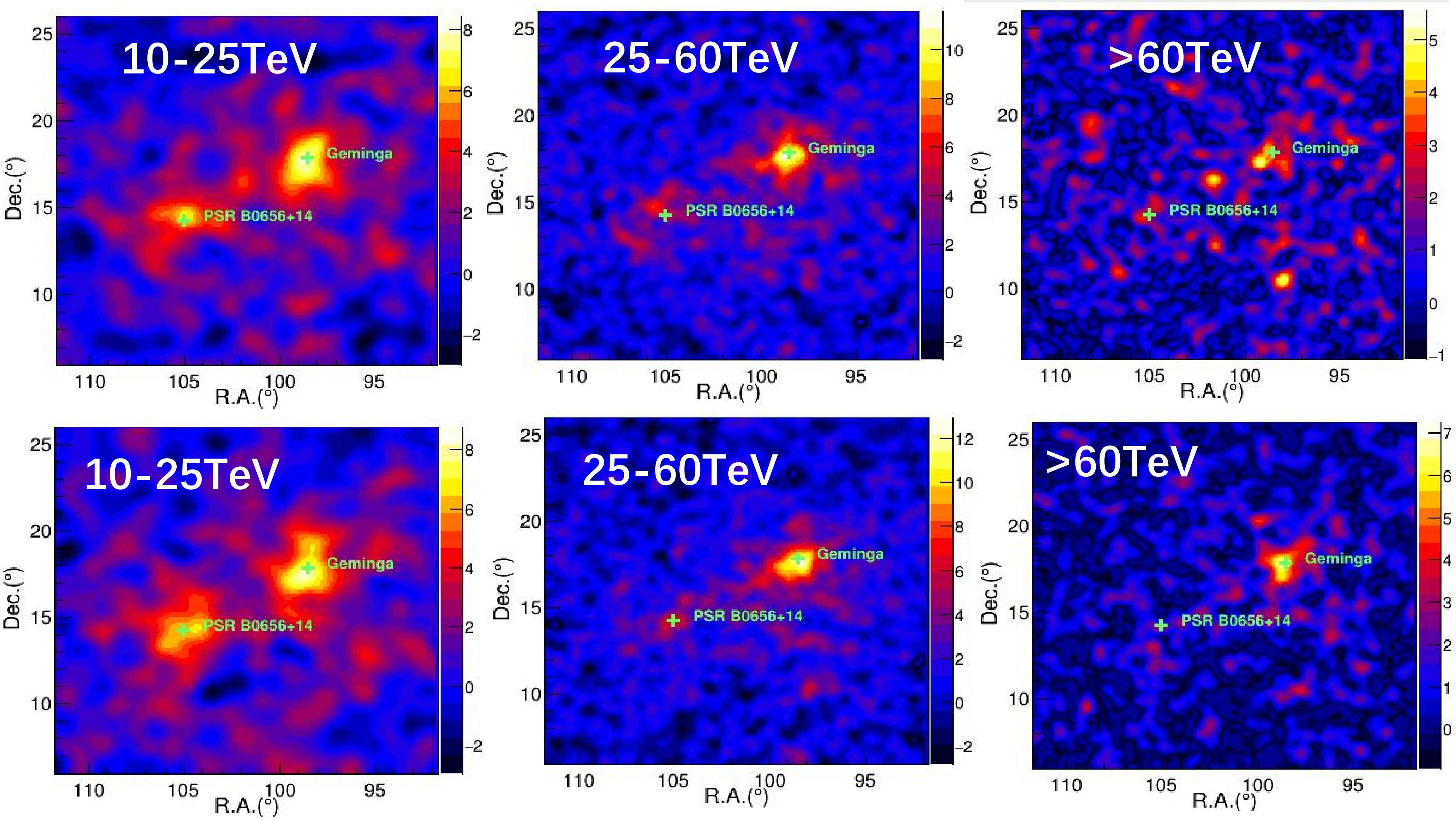


equi-zenith angle method



Mask region:
Galactic plane and sources in TeVCat
Mask radius for Geminga and Monogem is 15 degree.

Significance map



½ KM2A

¾ KM2A

Morphology analysis method

- Morphology model:

$$f(\theta) = \frac{A}{\theta_d(\theta + 0.085\theta_d)} \exp[-1.54(\theta/\theta_d)^{1.52}],$$

Diffusion property is the same around two source, ie.
$\theta_{d,geminga} \times Dist_{geminga} = \theta_{d,monogem} \times Dist_{monogem}$

- Detected signal distribution

$$N^{\mathrm{source}}(\theta) = f(\theta_d) \otimes PSF$$

- Likelihood Analysis

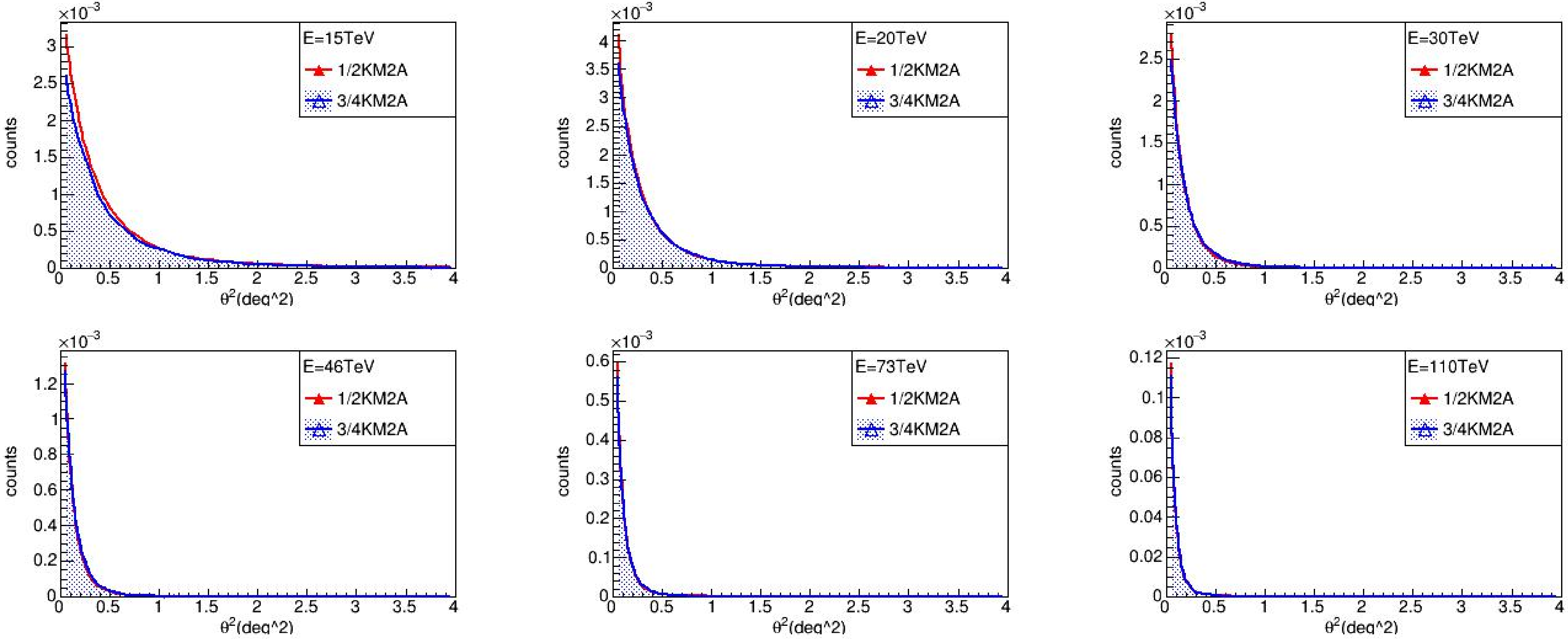
The signals from Geminga and Monogem, respectively

$$\Delta \ln \mathcal{L} = \sum_{j=1}^{n} \ln \left[\frac{P\left(N_j^{\mathrm{obs}}, N_j^{\mathrm{bkg}} + N_j^{\mathrm{G}} + N_j^{\mathrm{M}}\right)}{P\left(N_j^{\mathrm{obs}}, N_j^{\mathrm{bkg}}\right)} \right]$$

The observed number of events in the j^{th}-pixel

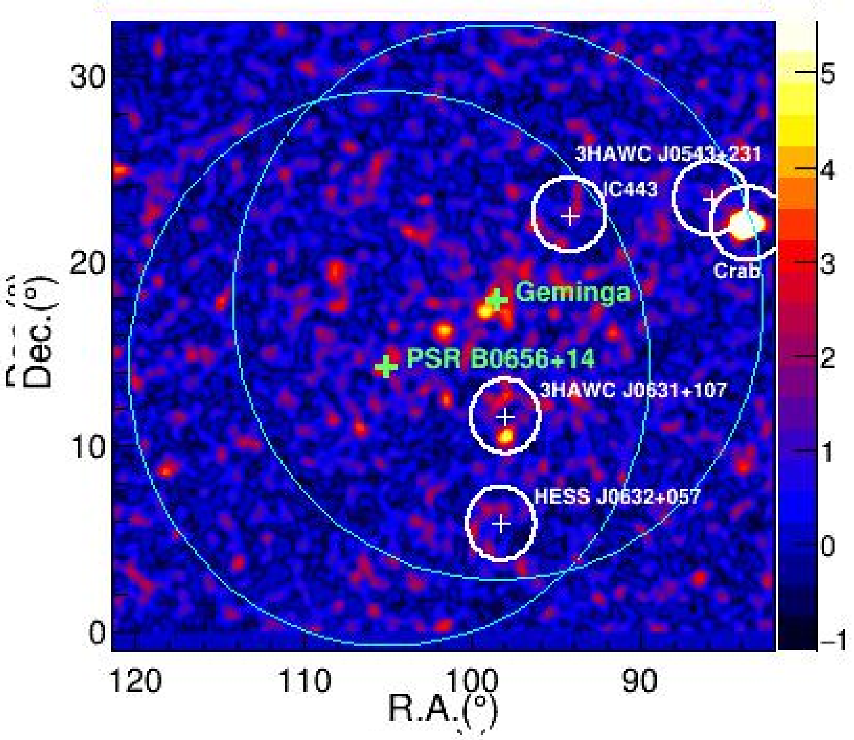
The estimated background

The PSF around sources

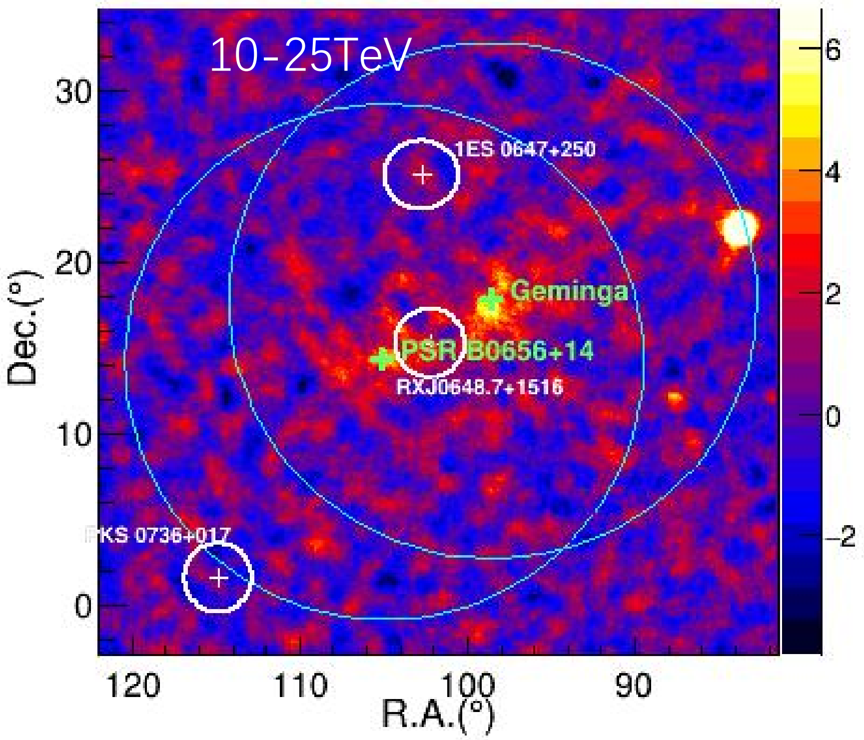


The PSFs are obtained from Geminga simulation.

Region of Interest—exclude known sources



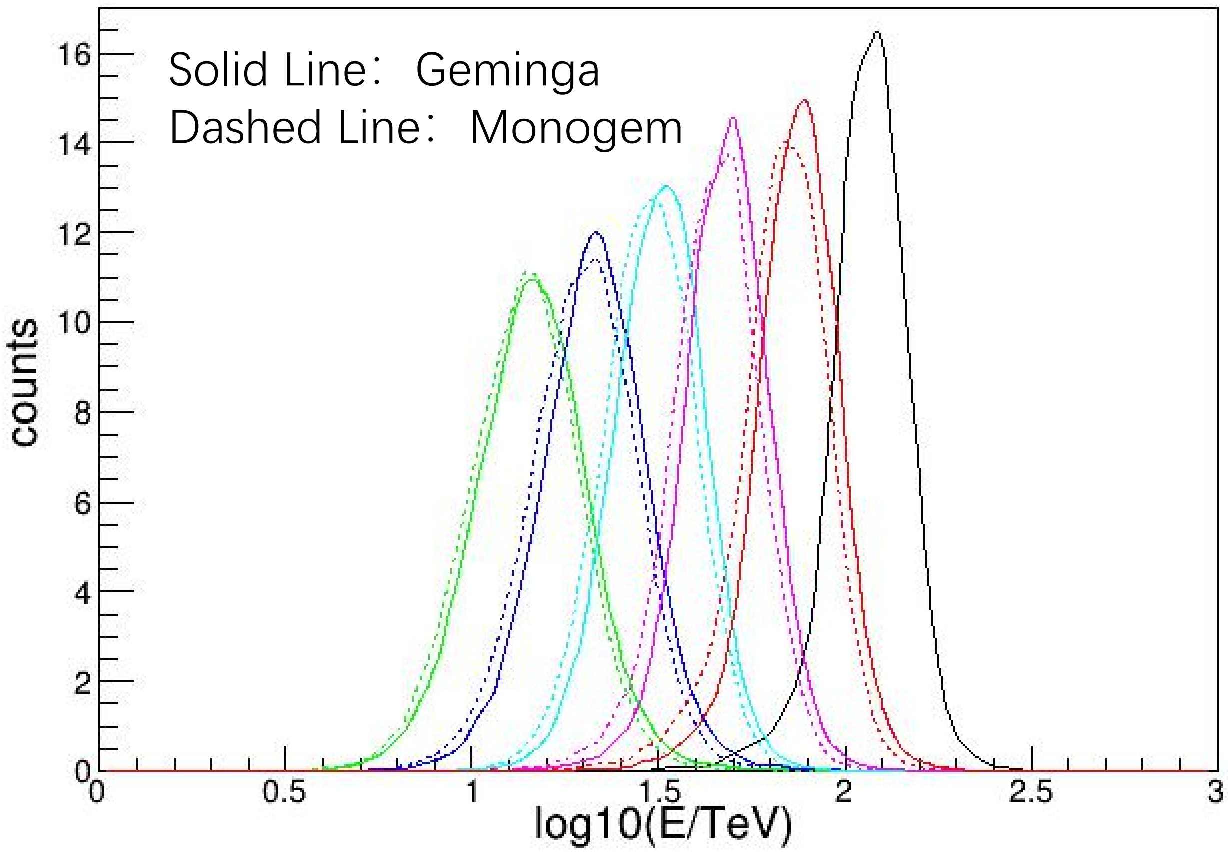
The white circles are the exclusion domain: the Galactic TeV source with a radius of 2 degrees.



The white circles are the AGNs: the redshifts of which are all greater than 0.15 and do not need to be deducted

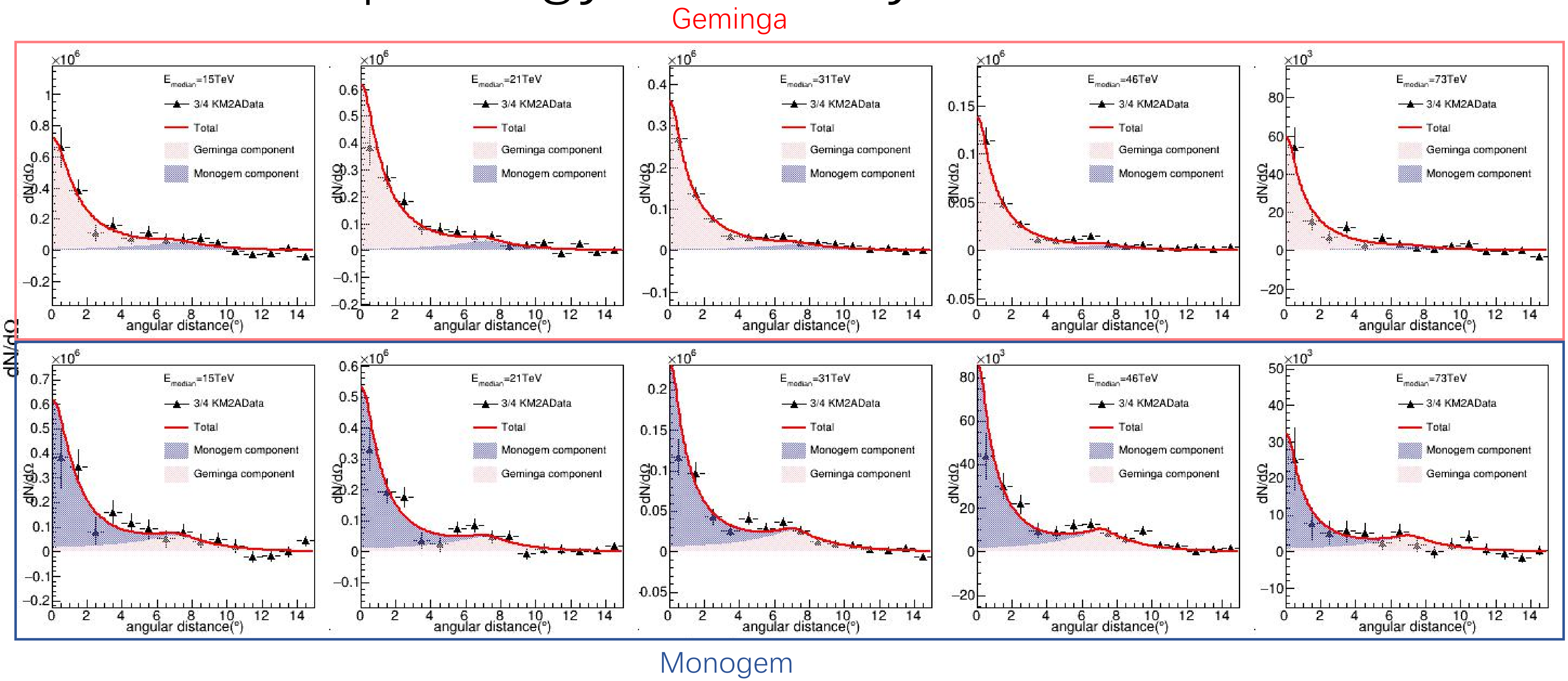
- The fitted range is a 15-degree circles centered on both sources.

The photon energy distribution of both sources

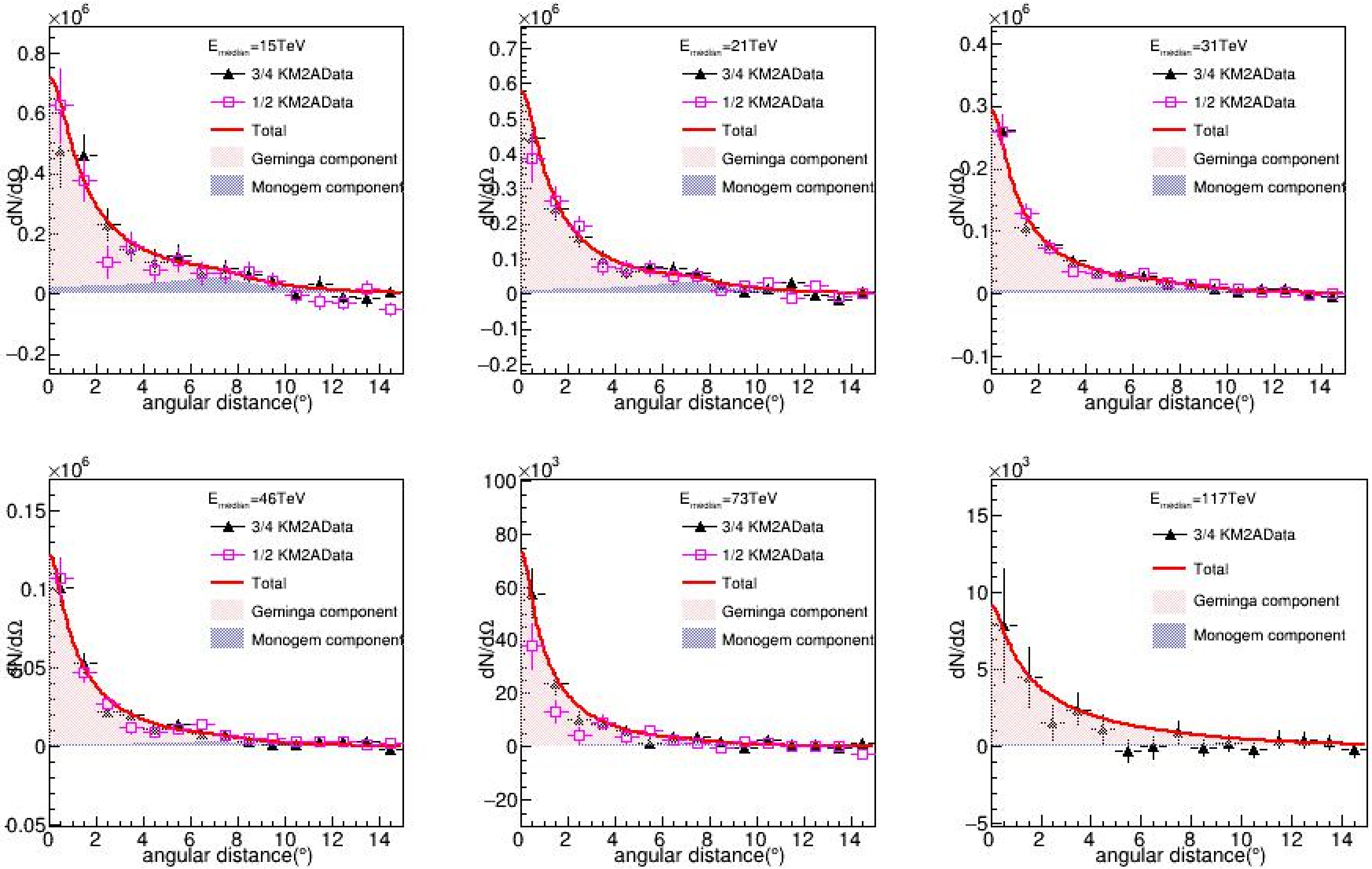


- ✓ The spectra of both source are considered.
- ✓ The pivot energy of γ-rays are:15,21,31,46,73,117TeV

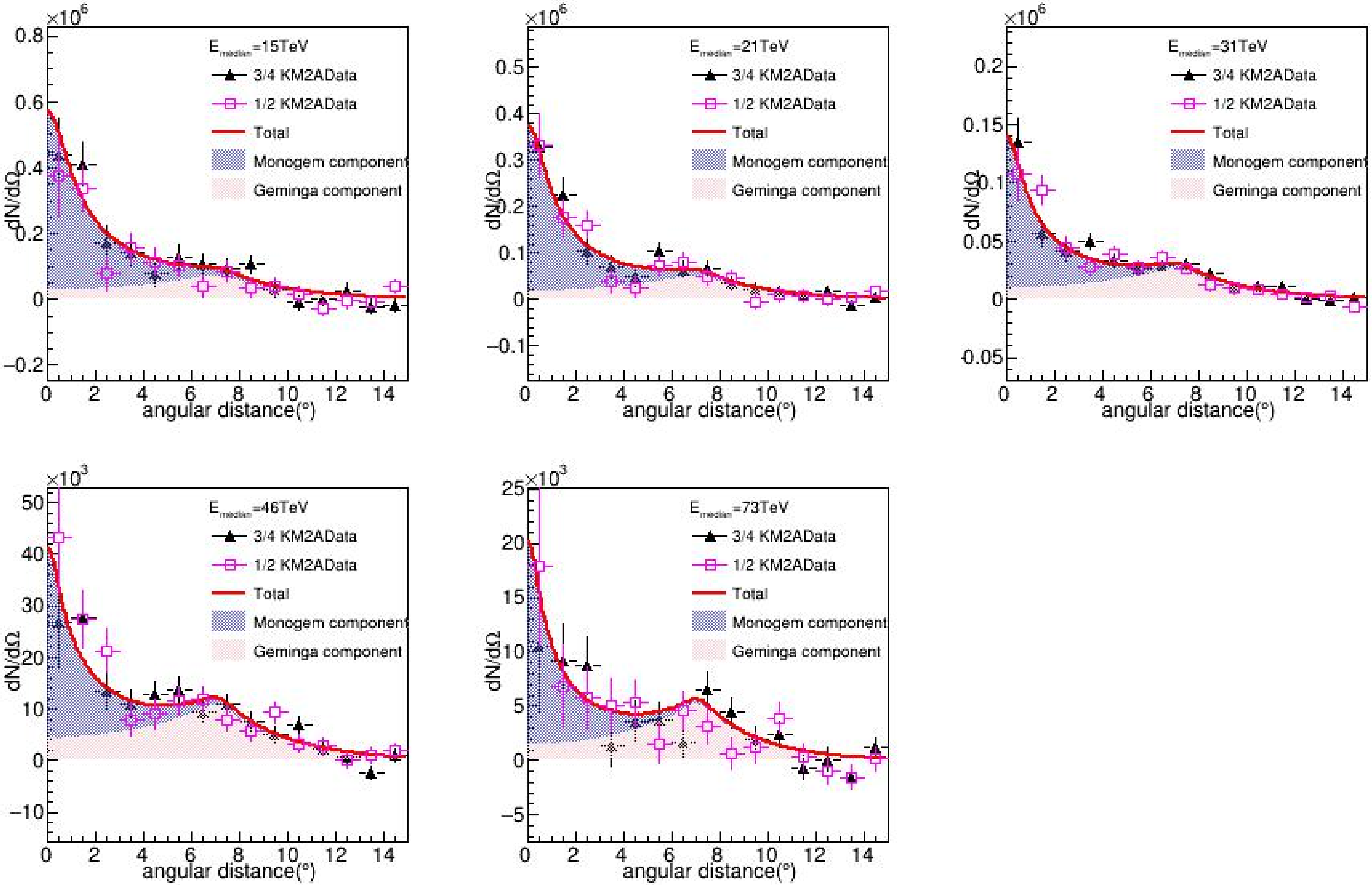
The Morphology results by ½ KM2A



Morphology of Gemingna by ¾ KM2A



Morphology of Monogem by ¾ KM2A



The energy-dependent morphology

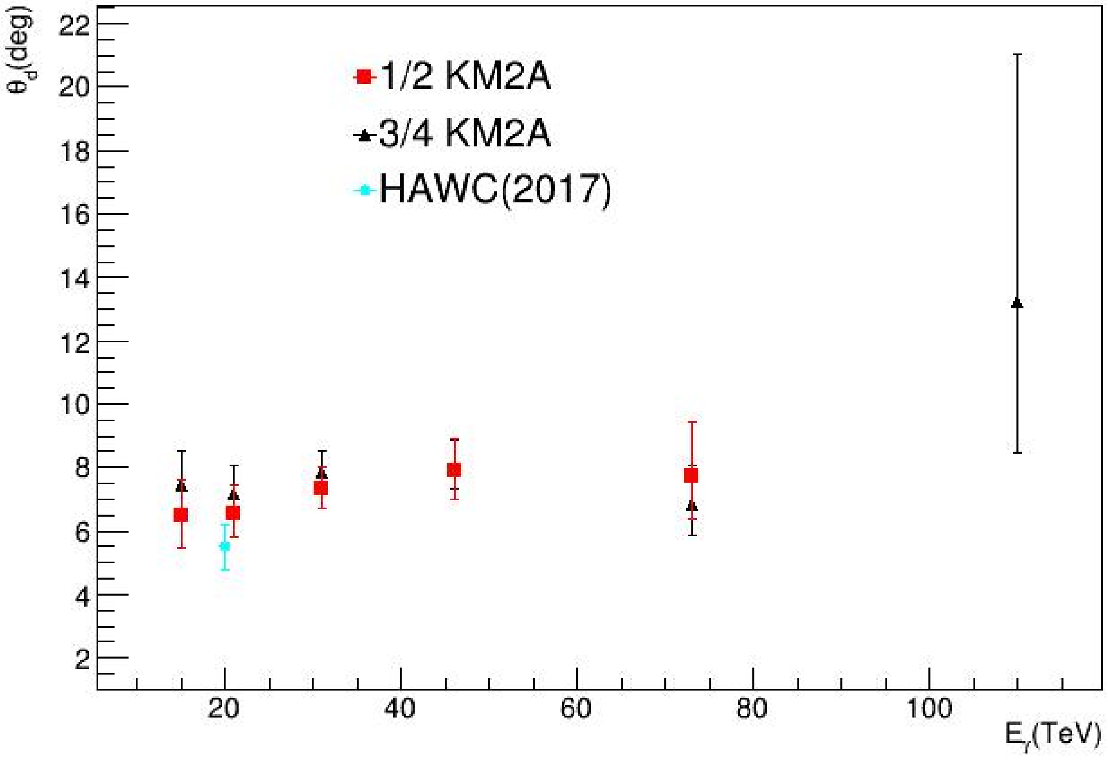


TABLE I. Diffusion coefficients in different energy bins. The E_γ is the median energy of each analysis bin, E_e is the parent electron or positron mean energy, θ_d is the typical diffusion extension of Geminga, the extension of PSR B0656+14 equals to $\theta_d \times 250/288$ due that the distance of Geminga (PSR B0656+14) is 250 (280) parseconds.

$E_\gamma(TeV)$	$\theta_d(^\circ)$ $\frac{3}{4}$KM2A	TS	$\theta_d(^\circ)$ $\frac{1}{2}$KM2A	TS
15	$7.44^{+1.09}_{-0.94}$	185.7	$6.67^{+1.2}_{-1.02}$	127.8
21	$7.18^{+0.89}_{-0.78}$	267.3	$6.86^{+0.91}_{-0.79}$	217.3
31	$7.86^{+0.66}_{-0.6}$	662.5	$7.5^{+0.68}_{-0.61}$	544.7
46	$8.04^{+0.81}_{-0.73}$	539	$7.92^{+1.03}_{-0.9}$	412.8
73	$6.85^{+1.22}_{-0.99}$	206.3	$7.75^{+1.7}_{-1.39}$	87.8
117	$13.11^{+2.66}_{-2.07}$	43.3	-	-

$$f(\theta) = \frac{A}{\theta_d(\theta + 0.085\theta_d)} \exp[-1.54(\theta/\theta_d)^{1.52}]$$

The two sets of data are consistent with each other.

Combined morphology analysis method with two data sets

- Morphology model:

$$f(\theta) = \frac{A}{\theta_d(\theta + 0.085\theta_d)} \exp[-1.54(\theta/\theta_d)^{1.52}],$$

- Detected signal distribution

$$N^{\text{source}}(\theta) = f(\theta_d) \bigotimes PSF$$

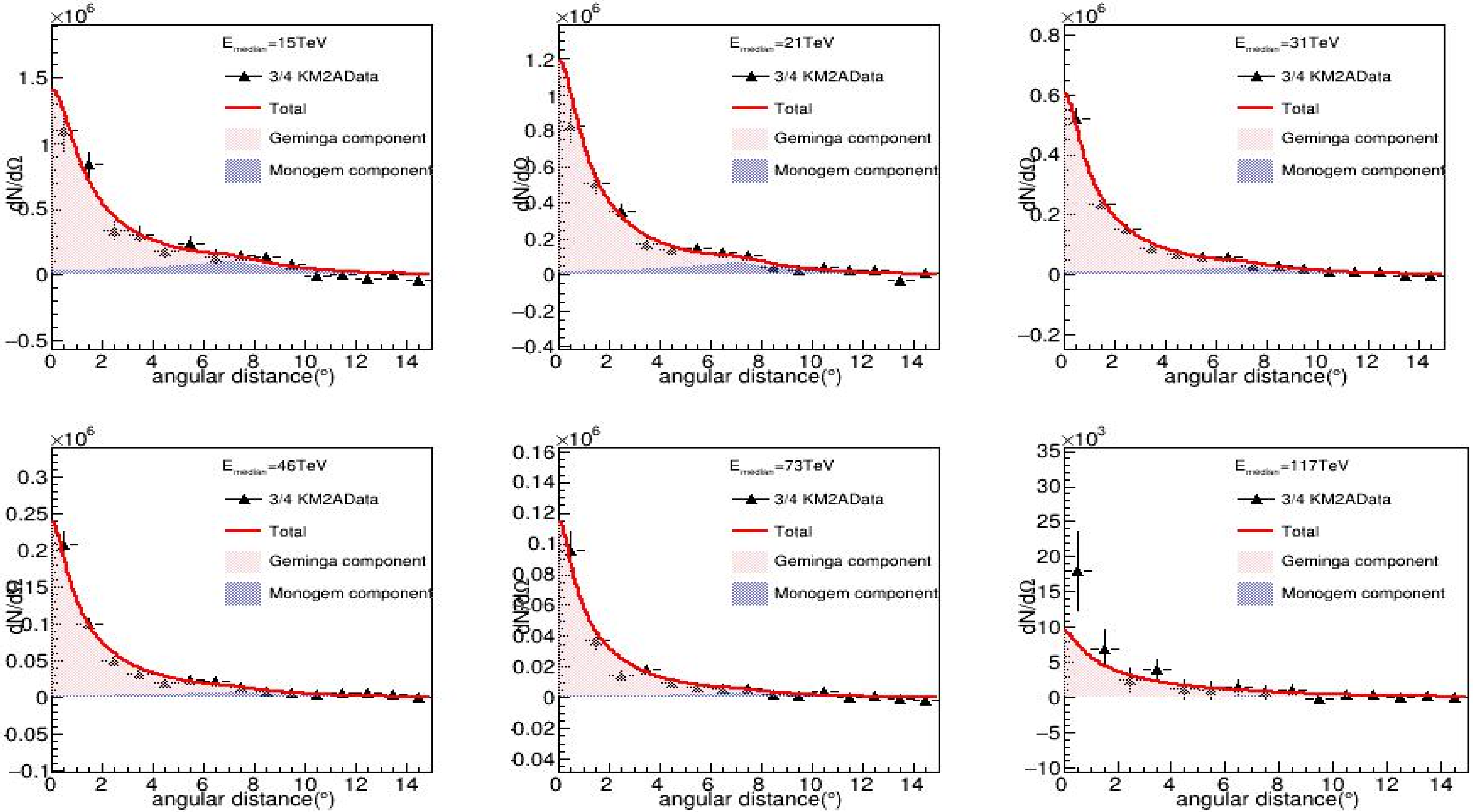
- Likelihood Analysis

$$\Delta \ln \mathcal{L} = \sum_{j=1}^{n} \left(\ln \left[\frac{P\left(N_j^{\text{obs}}, N_j^{\text{bkg}} + N_j^{\text{G}} + N_j^{\text{M}}\right)}{P\left(N_j^{\text{obs}}, N_j^{\text{bkg}}\right)} \right]_{1/2KM2A} + \ln \left[\frac{P\left(N_j^{\text{obs}}, N_j^{\text{bkg}} + N_j^{\text{G}} + N_j^{\text{M}}\right)}{P\left(N_j^{\text{obs}}, N_j^{\text{bkg}}\right)} \right]_{3/4KM2A} \right)$$

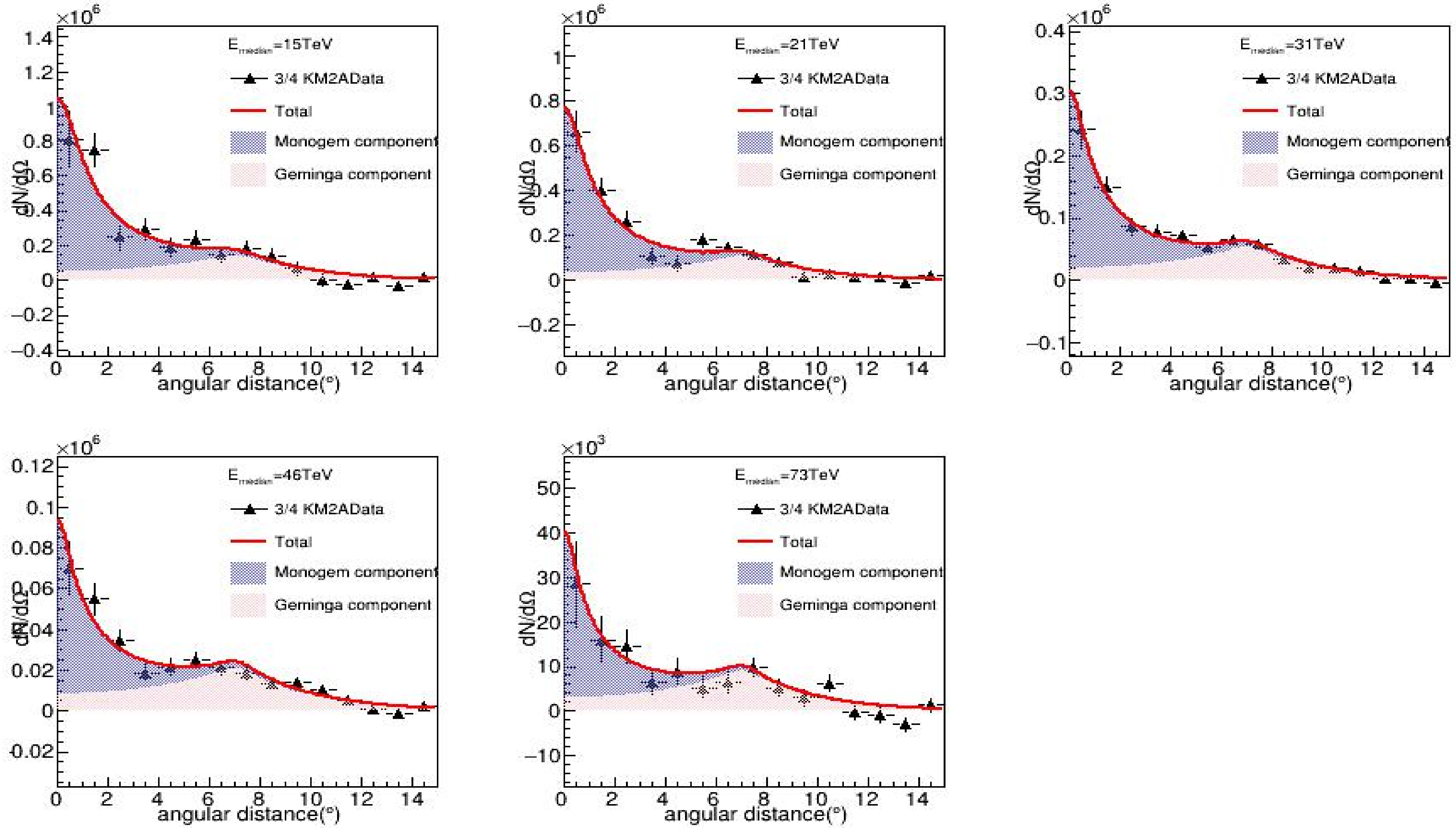
1/2KM2A Likelihood

3/4KM2A Likelihood

Morphology of Gemingna by ¾ KM2A and ½KM2A



Mophology of Monogem by ¾ KM2A and ½KM2A



The joint fitting morphology with two data sets

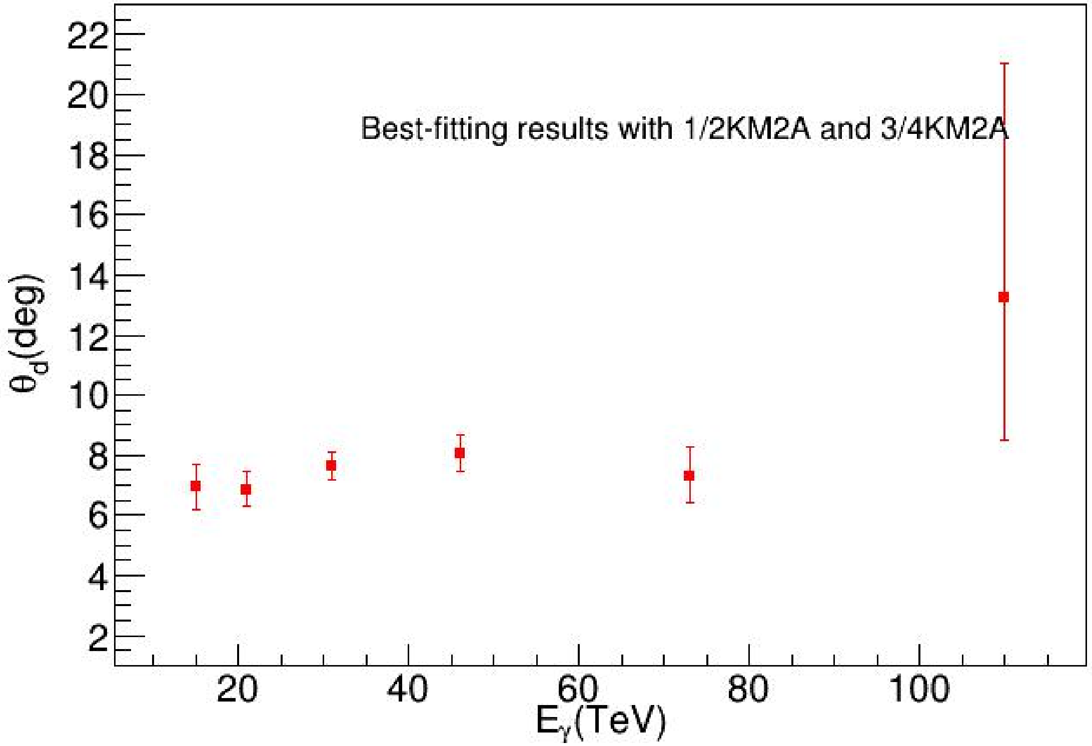
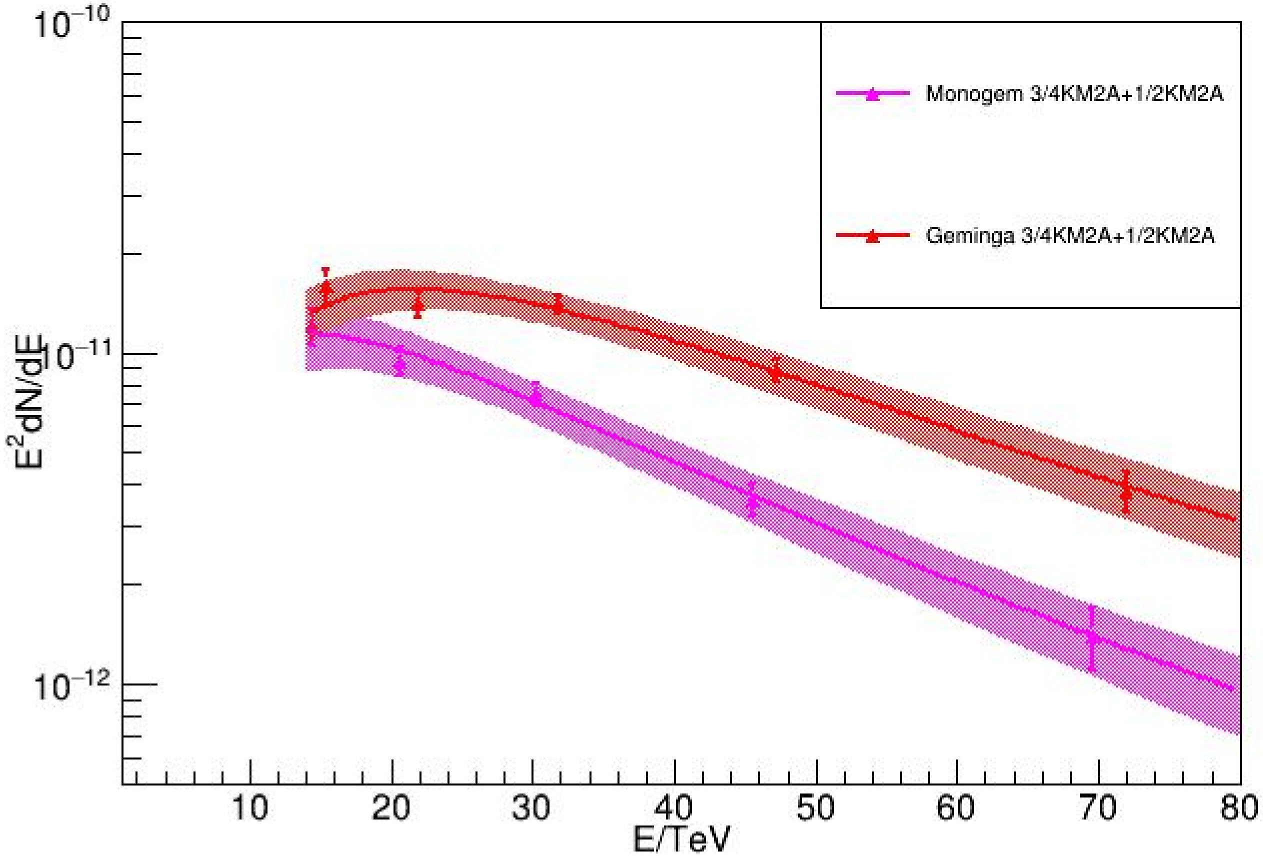


TABLE III. Diffusion angle measured by two data sets.

$E_\gamma(TeV)$	$\theta_d(^\circ)$	TS
15	$6.92^{+0.79}_{-0.7}$	302
21	$6.85^{+0.61}_{-0.56}$	484.3
31	$7.63^{+0.46}_{-0.43}$	1200.3
46	$8.04^{+0.63}_{-0.58}$	944.2
73	$7.3^{+0.99}_{-0.86}$	274
117	$13.23^{+7.82}_{-4.75}$	43.3

$$f(\theta) = \frac{A}{\theta_d(\theta + 0.085\theta_d)} \exp[-1.54(\theta/\theta_d)^{1.52}]$$

The joint fitting spectra with two data sets



The shading area denotes the 1σ statistic error.

- The spectra according to diffusion model:

$$\frac{dN}{dE} = (1.57 \pm 0.09_{\mathrm{stat}}) \times 10^{-14}\ (\mathrm{TeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}) \times (E/30TeV)^{-2.62 \pm 0.10_{\mathrm{stat}} - (0.94 \pm 0.20_{\mathrm{stat}}) \ln(E/30TeV)}$$

$$\frac{dN}{dE} = (0.80 \pm 0.06_{\mathrm{stat}}) \times 10^{-14}\ (\mathrm{TeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}) \times (E/30TeV)^{-3.24 \pm 0.12_{\mathrm{stat}} - (0.84 \pm 0.24_{\mathrm{stat}}) \ln(E/30TeV)}$$

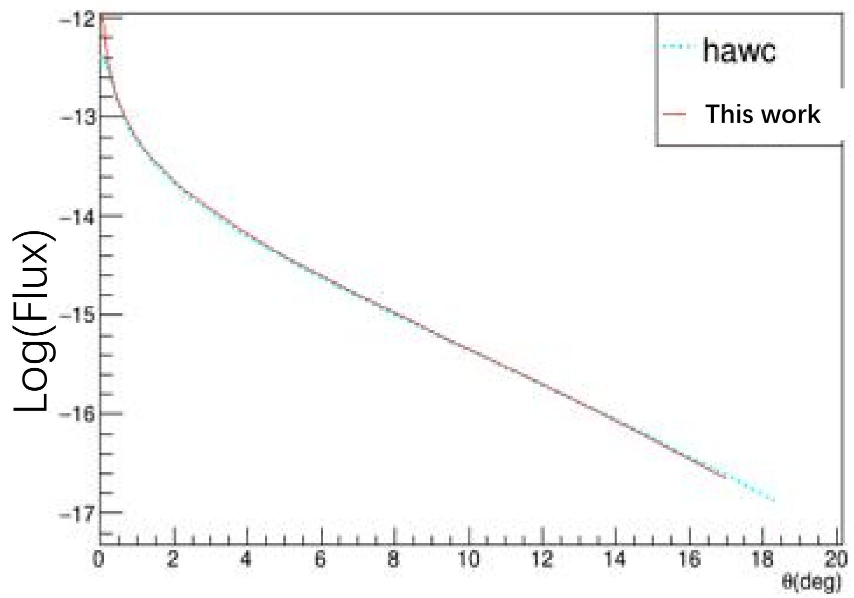
Research on Diffusion coefficient

-The global fit of electron spectrum and diffusion coefficient

the diffusion equation → Numerical solution → The theoretical γ-ray spectrum and morphology. → Detector response → Likelihood model

Q: injected electron spectrum
D: diffusion coefficient

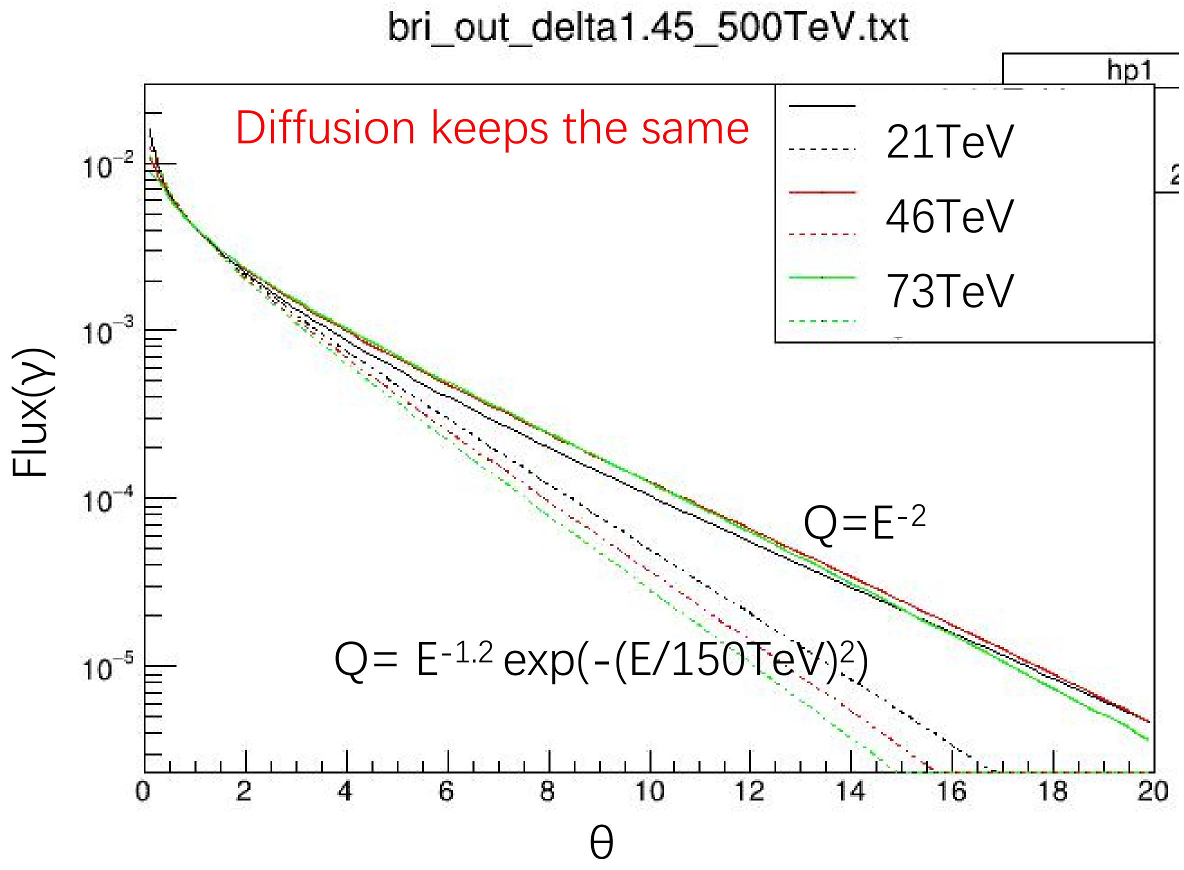
$$\frac{\partial f}{\partial t} = \frac{D}{r^2}\frac{\partial}{\partial r}r^2\frac{\partial f}{\partial r} + \frac{\partial}{\partial \gamma}(Pf) + Q,$$



The consistency of γ (20TeV) profile with hawc model.

Find Best-fitting Q and D

The influence of injected spectrum on morphology



- Diffusion keeps the same.
- Changing the injected electron spectrum
  - solid line: $Q=E^{-2}$
  - dashed line: $Q= E^{-1.2} \exp(-(E/150\text{TeV})^2)$
- The energy-dependent morphology also changed.

Both the injected spectrum and diffusion process decide the morphology of γ rays.

Check the method by simulation

- Generate simulated signals:

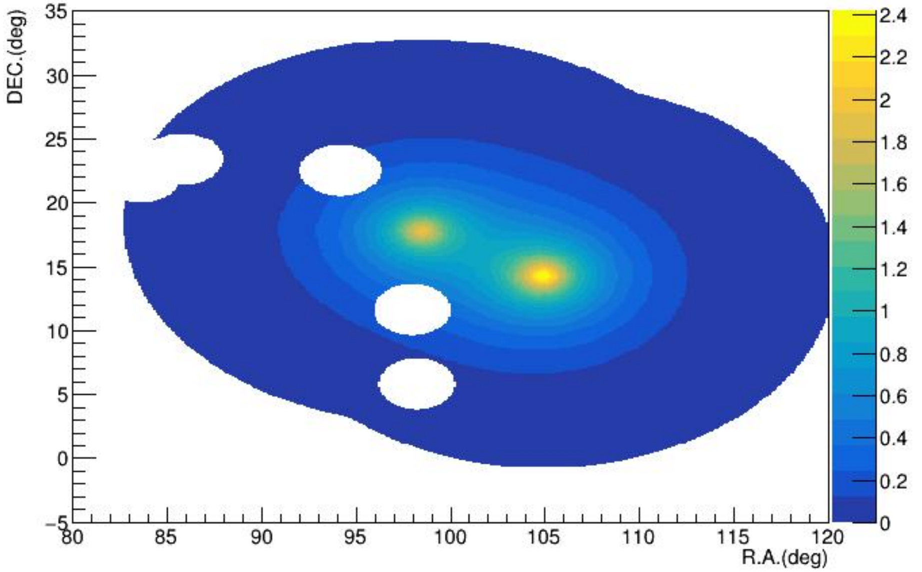
Input parameter: flux of Gemigna and Monogem; diffusion

$$Q(Geminga) = 7.9 \times 10^{-6}(\frac{E}{130TeV})^5 \times e^{-E/14TeV}$$

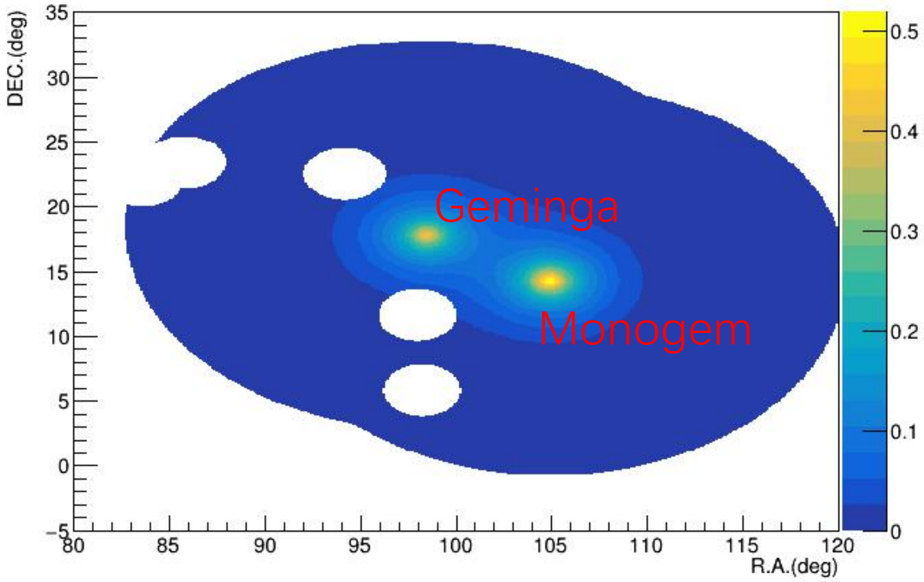
$$Q(Monogem) = 1.3 \times 10^{-6}(\frac{E}{130TeV})^5 \times e^{-E/14TeV}$$

$$D(E) = 1.1 \times 10^{28} E^{0.65}$$

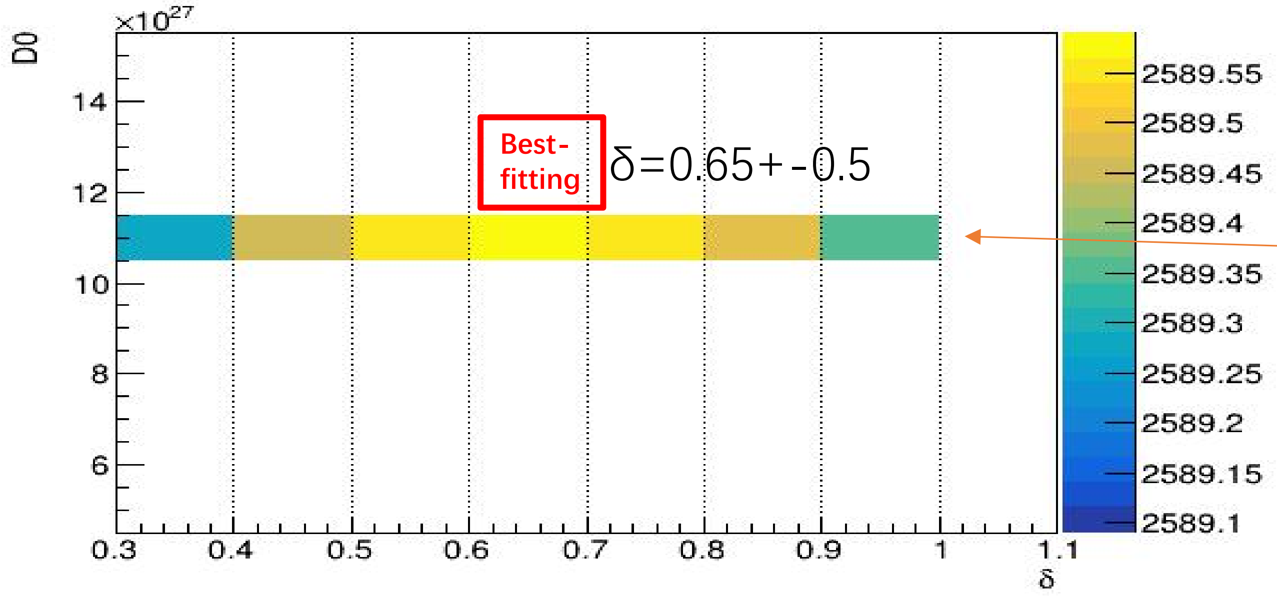
15TeV signal map

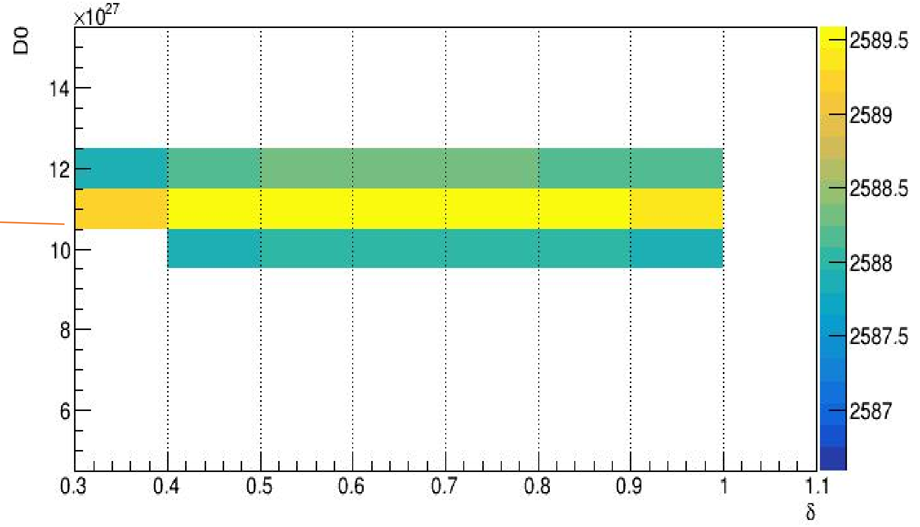


43TeV signal map



Check the method by simulation





- Best-Fiting results:

Geminga:
alpha: 7.9e-06 +- 3.7e-05 beta: 5 +- 3.36 Ecut: 14 +- 6.32
Monogem:
alphaM: 1.3e-06 +- 8.35e-06 betaM: 5 +- 3.87 EcutM: 14 +- 7.33
D=1.1e28*E^(0.65+-0.5)

- Input parameter:

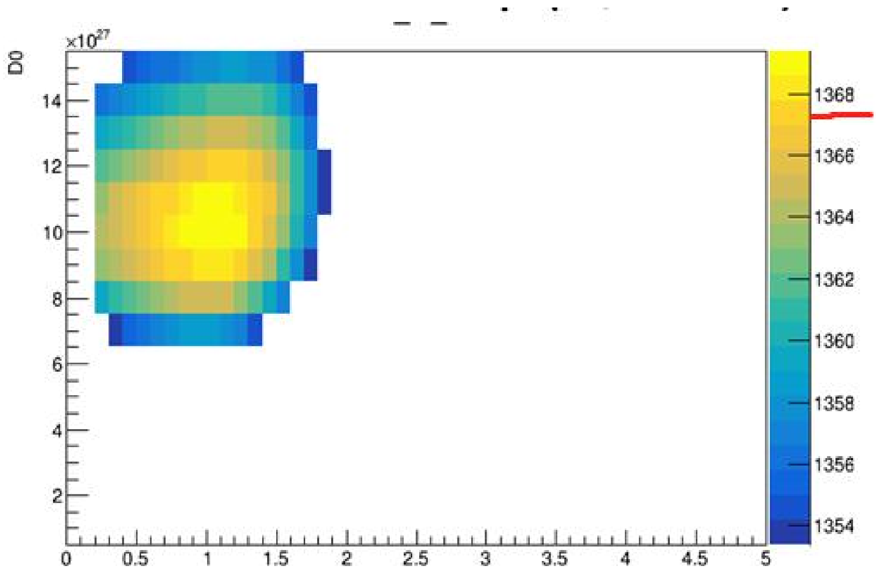
$$Q(Geminga) = 7.9 \times 10^{-6}(\frac{E}{130TeV})^5 \times e^{-E/14TeV}$$

$$Q(Monogem) = 1.3 \times 10^{-6}(\frac{E}{130TeV})^5 \times e^{-E/14TeV}$$

$$D(E) = 1.1 \times 10^{28} E^{0.65}$$

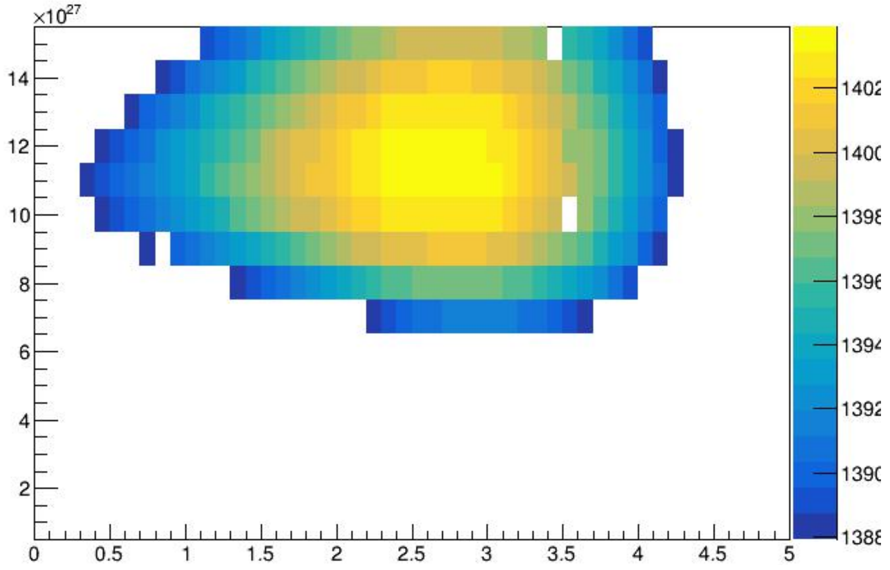
The injection spectrum influences the energy dependence of the diffusion coefficient

Fix Q=E^{-2}exp(E/Ecut)



Delta=1 TS=1368

Fix Q=E^{2}exp(-E/Ecut)



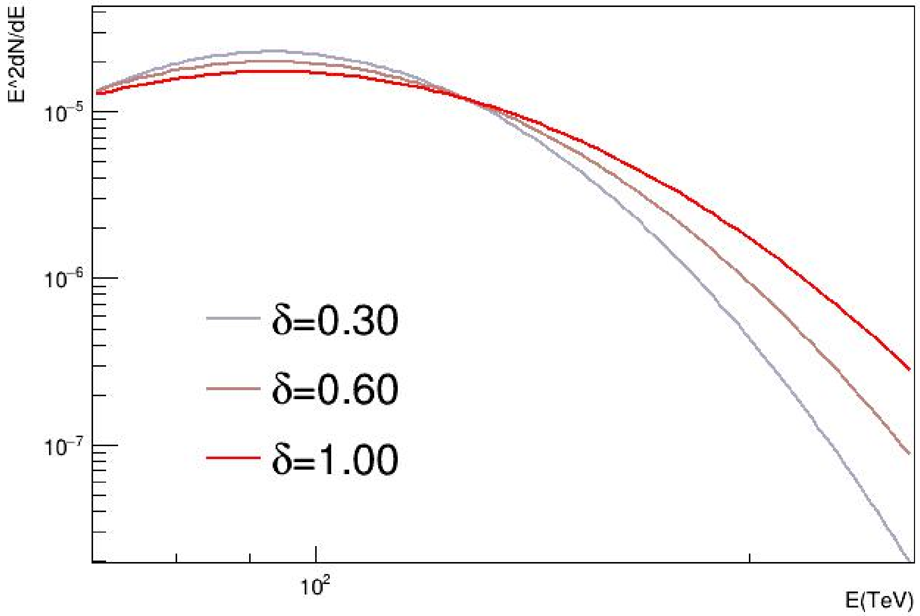
delta=2.6 TS=1402

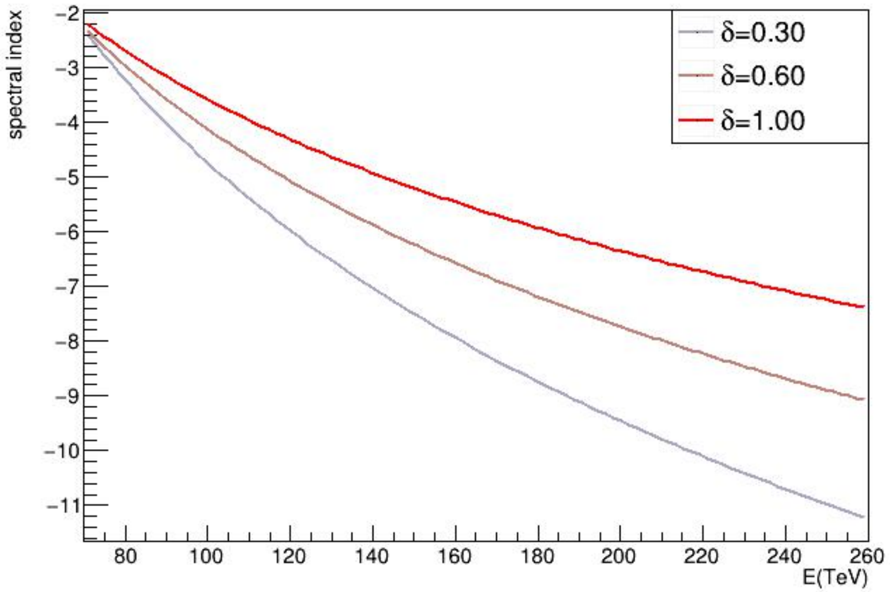
✓ The energy-dependence of diffusion coefficient is sensitive to the assumption of the electron spectrum.

Implication on the electron spectrum by ½KM2A

➢Find the best-fitting injection spectrum

when fixing D0 at 1.1e28 and δ at 0.3/0.6/1.0/2.0, respectively.





- Injected spectrum of Geminga under different assumptions of

$$\delta = 0.3 Q(E) = (6.40 \pm 0.89) \times 10^{10} (E/130TeV)^{(-6.53\pm3.06)+(-6.80\pm5.86)ln(E/130TeV)}$$

$$\delta = 0.6(E) = (6.60 \pm 0.79) \times 10^{10} (E/130TeV)^{(-5.49\pm2.06)+(-5.21\pm3.92)ln(E/130TeV)}$$

$$\delta = 1.0 Q(E) = (6.70 \pm 0.80) \times 10^{10} (E/130TeV)^{(-4.63\pm1.32)+(-3.99\pm2.50)ln(E/130TeV)}$$

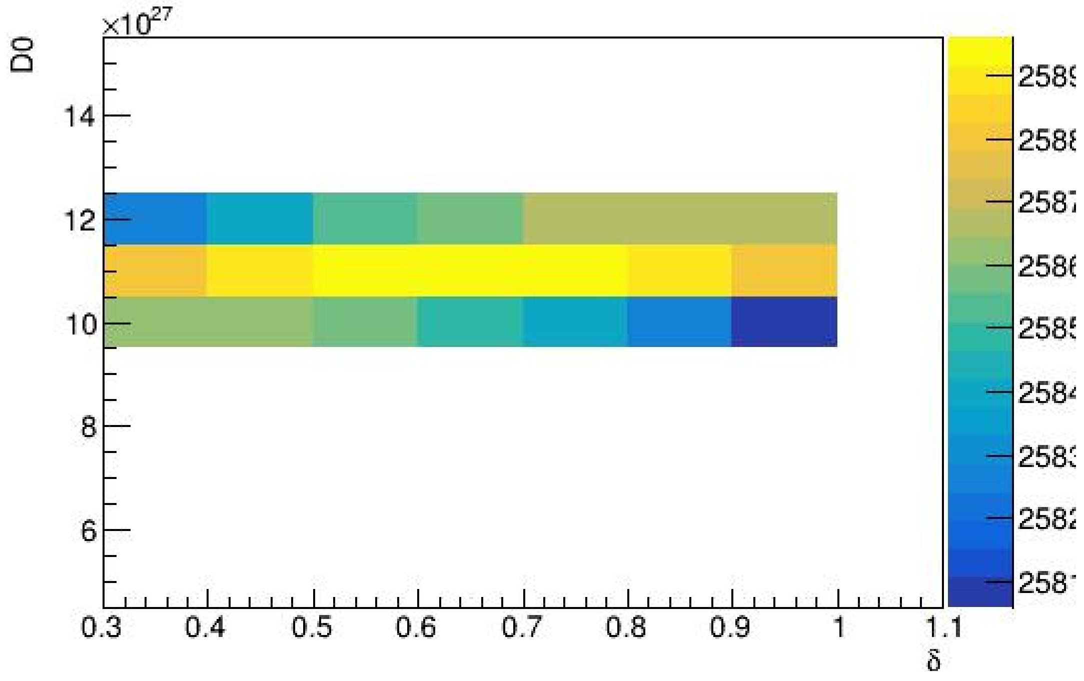
- Injected spectrum of Geminga under different assumptions of δ

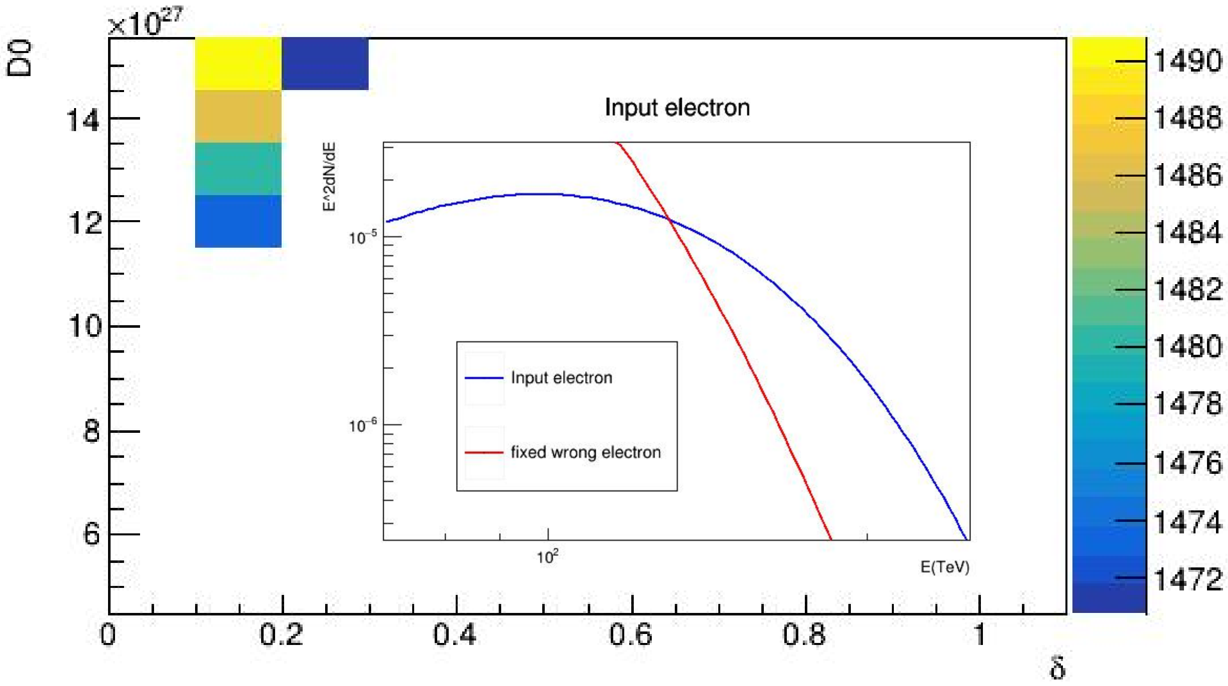
Injected spectra index=-4 @ 100TeV

Conclusion

- The data of ¾KM2A are consistent with the analysis results of ½KM2A
- The morphology of the two sources does not vary significantly from 15 to 73 TeV
- Measured Geminga morphology at 110 TeV with ¾Km2A
- The energy-dependence of diffusion coefficient is sensitive to the assumption of the electron spectrum.
- The shape of the electron spectrum is relatively narrow, regardless of $\delta=0.3/0.6/1$.

some drafts



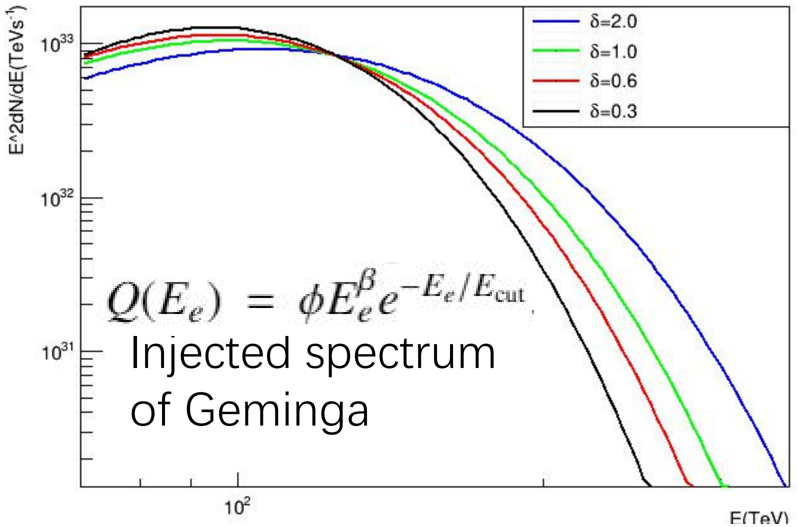


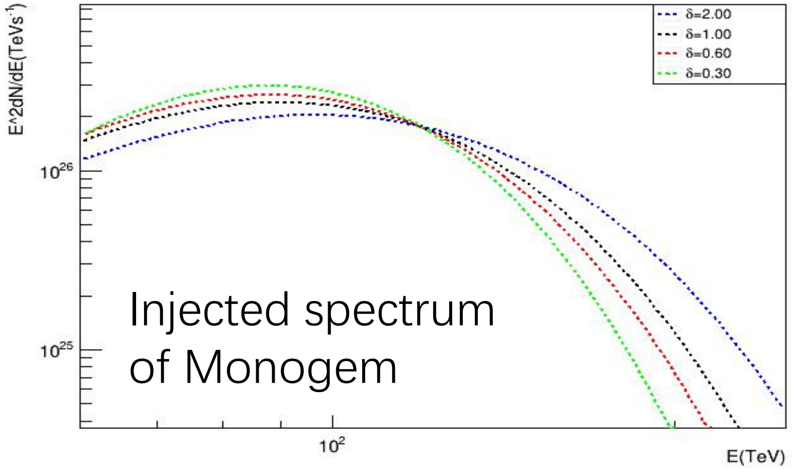
能谱固定为输入能谱时D0 VS δ 分布
δ=0.65+-0.25

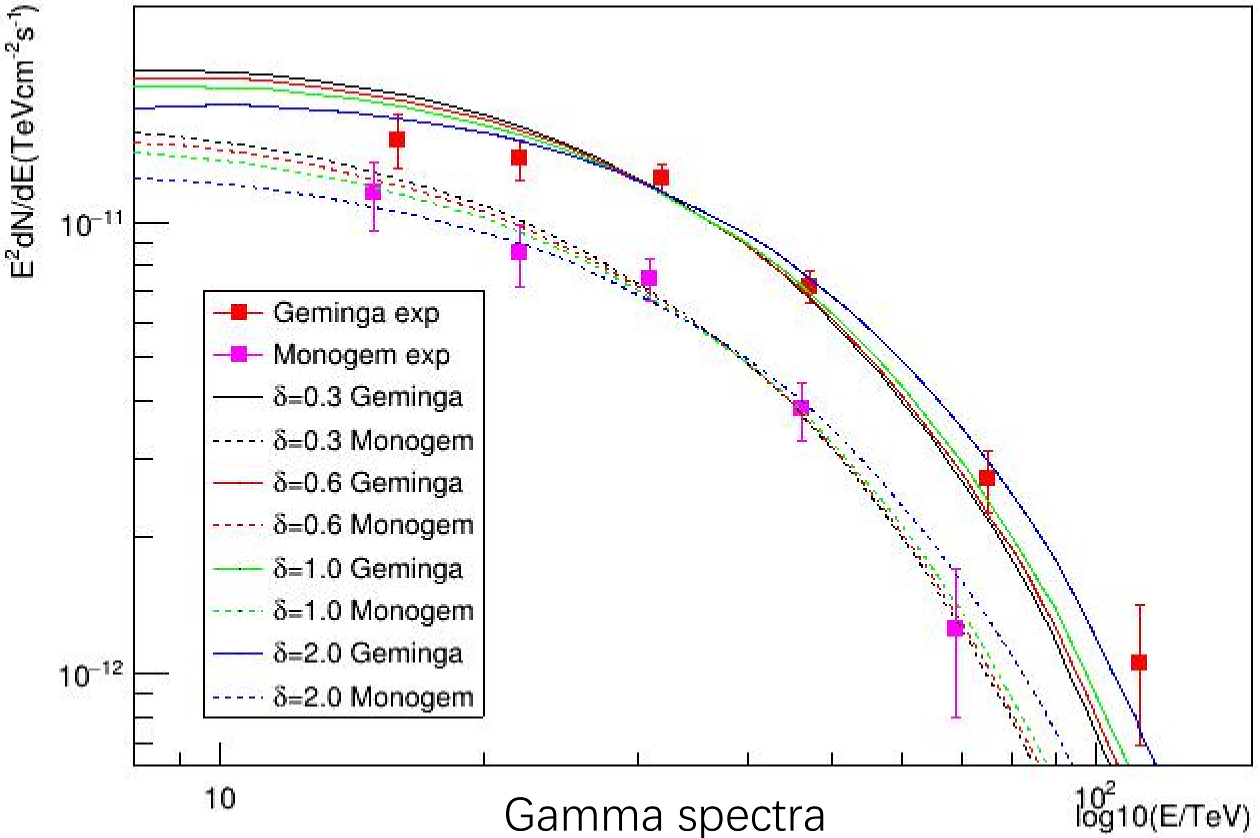
能谱固定为一个错误的能谱时:
D0 VS δ 分布 δ=0.15

Implication on the electron spectrum by ½KM2A

通过固定扩散系数的能量依赖δ=0.3/0.6/1 来推测电子注入谱



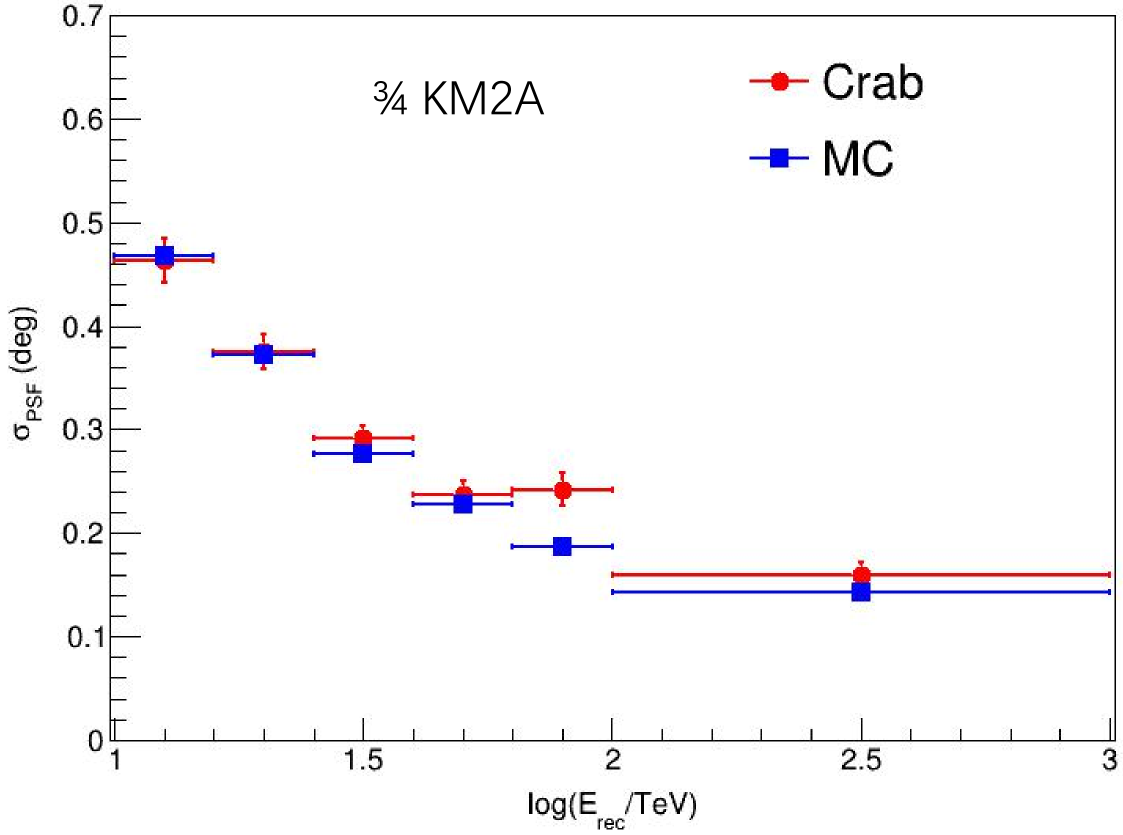


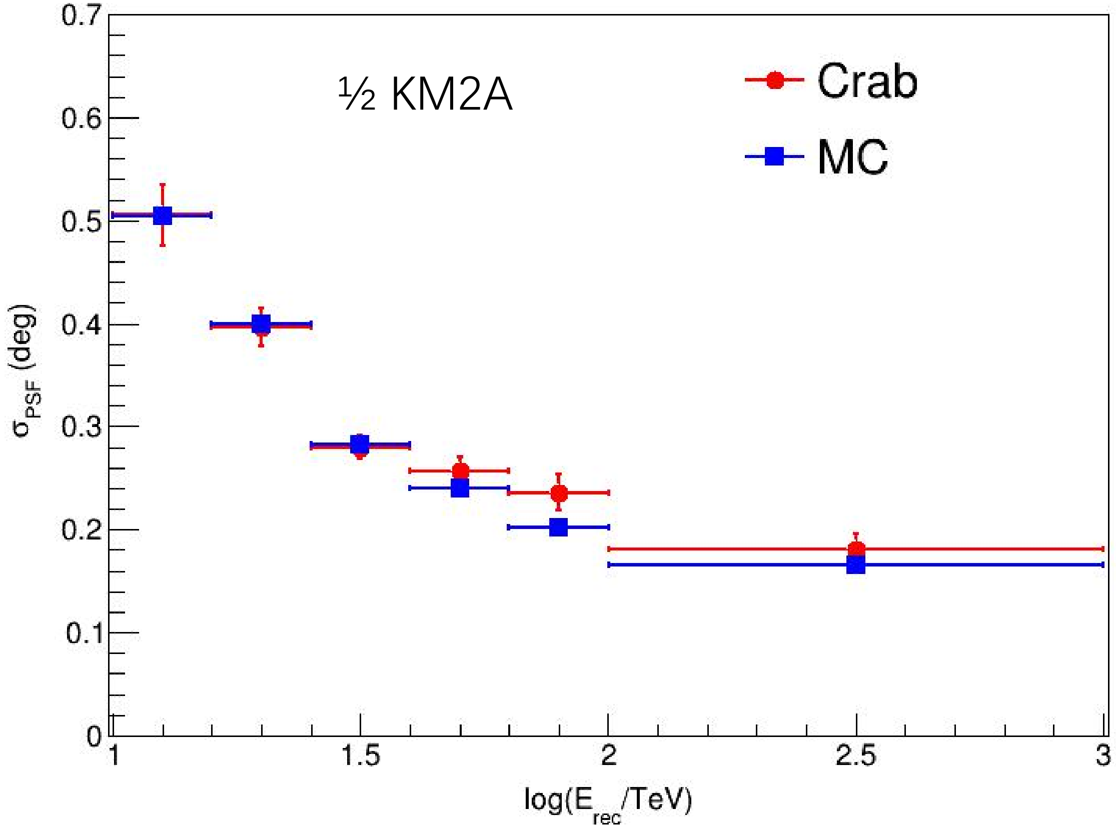


Gamma spectra

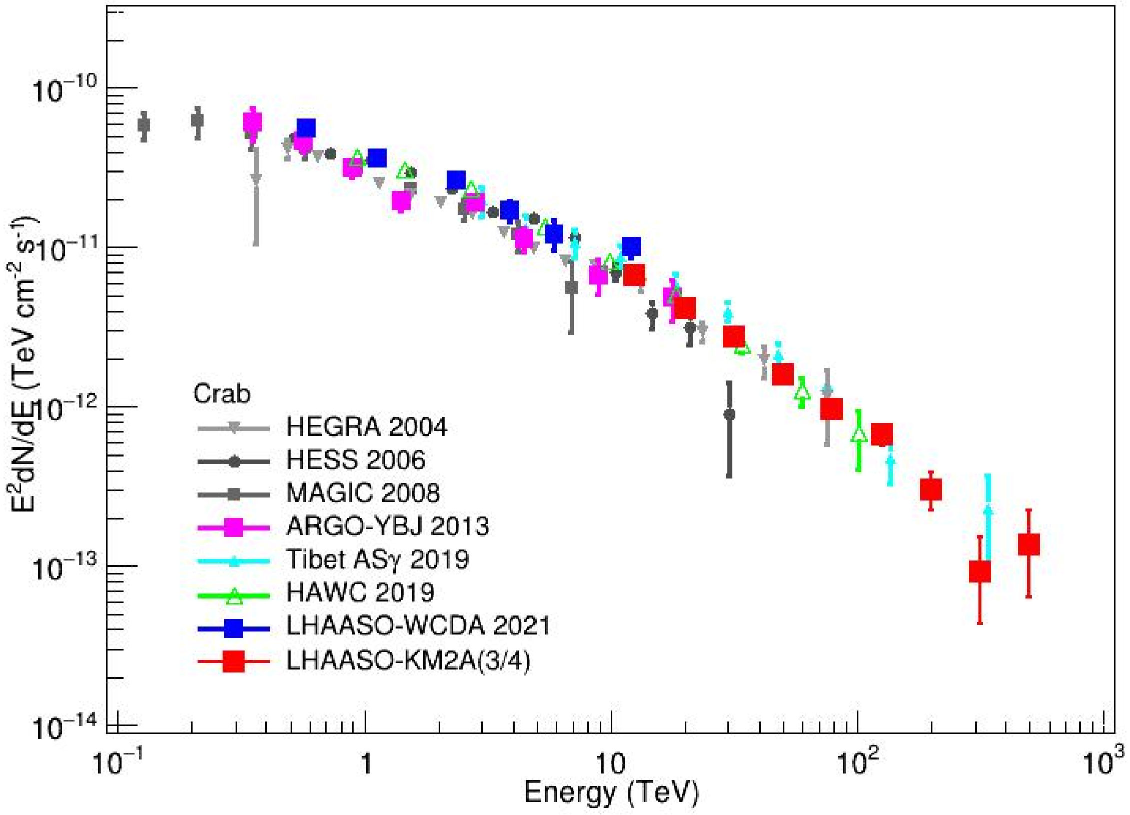
- Find the best-fitting injection spectrum when fixing D0 at 1.1e28 and δ at 0.3/0.6/1.0/2.0, respectively. $D(E_e) = D_0(E_e/130\ \mathrm{TeV})^{\delta}$
- Injected spectrum: $Q(E_e) = \phi E_e^{\beta} e^{-E_e/E_{\rm cut}}$
- β~4，Ecut ~ 10TeV

Crab analysis with ¾ KM2A --PSF

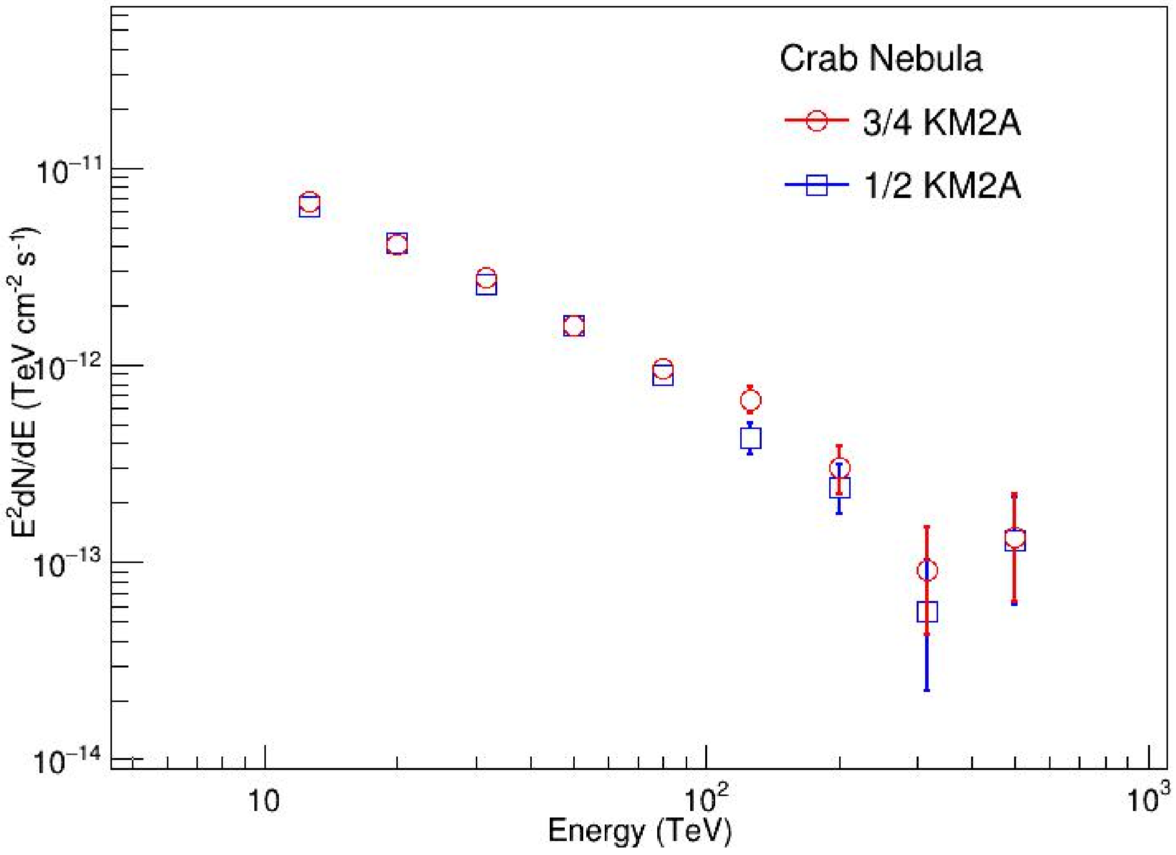




Crab analysis with ¾ KM2A -- SED



$$f(E) = (1.06 \pm 0.03) \times 10^{-14} \cdot \left(\frac{E}{20\mathrm{TeV}} \right)^{-3.08 \pm 0.04}$$



The spectra of Crab are consistent.