Observation of TeV gamma ray emissions from PeV sources with the LHAASO-WCDA

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Outline

- Introduce
- Significance estimate
- Data and method validation
- Significance of some sources
- LHAASO J1908+0621
- LHAASO J2226+6057

Introduce

Twelve gamma ray sources have been detected **above 100 TeV** by half array of the LHAASO-**KM2A**

Revealing that many **PeVatrons** exist in the galaxy.

LHAASO-**WCDA** turns **more sensitive** than KM2A **at TeV energy range**

source name	R.A. (°)	dec (°)	Significance (σ) above 100 TeV	E_{Max} (PeV)	Flux (± error) (CU) at 100 TeV
LHAASO J0534+2202	83.55	22.05	17.8	0.88 ± 0.11	1.00(0.14)
LHAASO J1825-1326	276.45	-13.45	16.4	0.42 ± 0.16	3.57(0.52)
LHAASO J1839-0545	279.95	-5.75	7.7	0.21 ± 0.05	0.70(0.18)
LHAASO J1843-0338	280.75	-3.65	8.5	$0.26\ ^{+0.16}_{-0.10}$	0.73(0.17)
LHAASO J1849-0003	282.35	-0.05	10.4	0.35 ± 0.07	0.74(0.15)
LHAASO J1908+0621	287.05	6.35	17.2	0.44 ± 0.05	1.36(0.18)
LHAASO J1929+1745	292.25	17.75	7.4	$0.71\ ^{+0.16}_{-0.07}$	0.38(0.09)
LHAASO J1956+2845	299.05	28.75	7.4	0.42 ± 0.03	0.41(0.09)
LHAASO J2018+3651	304.75	36.85	10.4	0.27 ± 0.02	0.50(0.10)
LHAASO J2032+4102	308.05	41.05	10.5	1.42 ± 0.13	0.54(0.10)
LHAASO J2108+5157	317.15	51.95	8.3	0.43 ± 0.05	0.38(0.09)
LHAASO J2226+6057	336.75	60.95	13.6	0.57 ± 0.19	1.05(0.16)

•Wider spectral measurements provide more information to determine the nature of the source

Significance estimate

WCDA-1 sensitivity(>1TeV): $8\%I_{crab}$

Most of sources could be observed for one year operation of WCDA

Source	$Zen_{\min}$	Flux($E^{-1}cm^{-2}s^{-1}$)	Significance 1pool ,2pool,3pool
Crab	7	$2.79*10^{-13}(\frac{E}{7TeV})^{-2.675-0.082*\log(\frac{E}{7TeV})}$	(60, 250, 416)
LHAASO J1825-1326	42	$1.72*10^{-11}(\frac{E}{1.16TeV})^{-2.38}$	(36, 151, 251)
LHAASO J1839-0545	35	$2.0*10^{-11}(\frac{E}{0.95TeV})^{-2.54}$	(23.5, 97.9, 162)
LHAASO J1843-0338	32	$9.14*10^{-12}(\frac{E}{1.87TeV})^{-2.15}$	(6.32, 26.3, 43.8)
LHAASO J1849-0003	29	$7.66*10^{-14}(\frac{E}{2.74TeV})^{-1.97}$	(1.21, 5.0,8.4)
LHAASO J1908+0621	23	$2.06*10^{-12}(\frac{E}{2.06TeV})^{-2.26}$	(18.4,76.8, 127)
LHAASO J1929+1745	12	$1.28*10^{-13}(\frac{E}{1.7TeV})^{-2.59}$	(0.73, *, *)
LHAASO J2018+3651	7	$7*10^{-14}(\frac{E}{10TeV})^{-2}\cdot\exp(-E/29Tev)$	(21.8, 91.15, 151)
LHAASO J2032+4102	12	$2.*10^{-14}(\frac{E}{10TeV})^{-3.22}$	(36.9, 154, 256)

*Flux of sources is obtained by looking at the relevant article on the TeVCat website.

Data and method validation

Data:

wcda-1,201906-202002, live time: 190day
Reconstruction of version: Rc

Cut **:** compactness>16 for Y/P identification

Method :

Background estimation: equal zenith Angle method

Signal calculation : maximum likelihood

SED method : forward unfolding $\chi^2=\sum_i^n(\frac{N_i^{obs}-N_i^{sim}}{\sigma_i^{obs}})^2$

Data and method validation

Signal calculation

Signal model: gaus2D (Ns, position, sigma)
Background model: hist2D obtained by equal zenith angle method

ML:

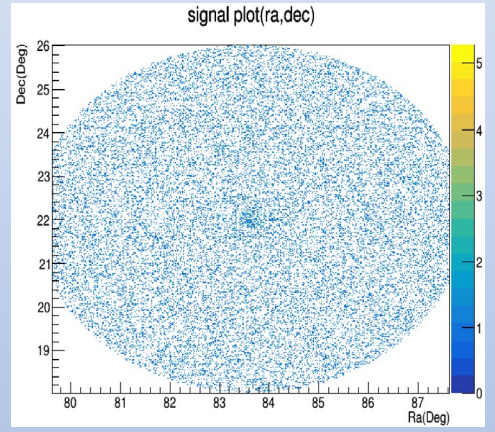
$$P_i = \frac{\lambda_i^{n_i}}{n_i!} e^{\lambda_i}$$

$$n_i = n_s + n_b$$

$$\lambda_s = N_s' \frac{n_b^{i'} * \left(\sum_j^n (\frac{dP}{d\Omega}(r) * n_b^{j'} \right)}{N_b^2 f_b^2} \frac{dP}{d\Omega}(r) \quad (\textit{assumption } \frac{n_b^{i'}}{n_b^i} = k \frac{n_s^{i'}}{n_s^i})$$

(*signal model correction*)

$$L = \prod Pi \xrightarrow{\text{Minimize -2lnL}} \textbf{Get Ns ,position, extension}$$



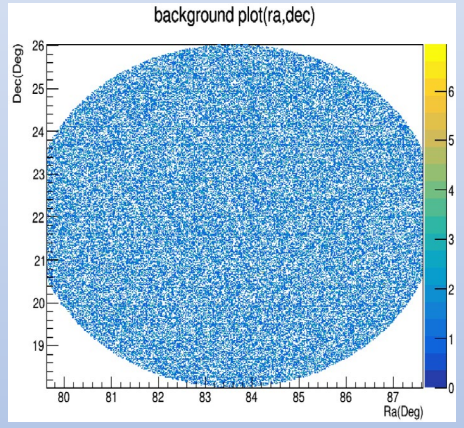
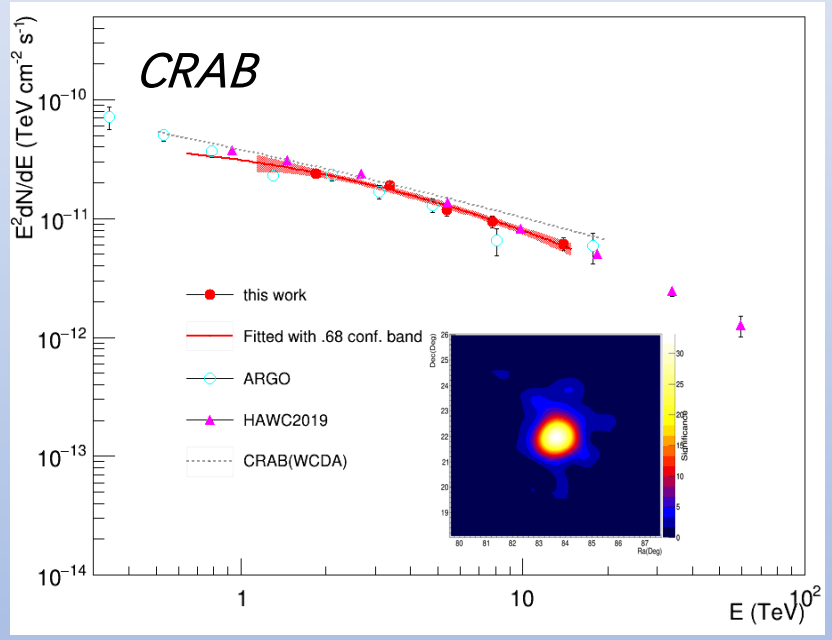


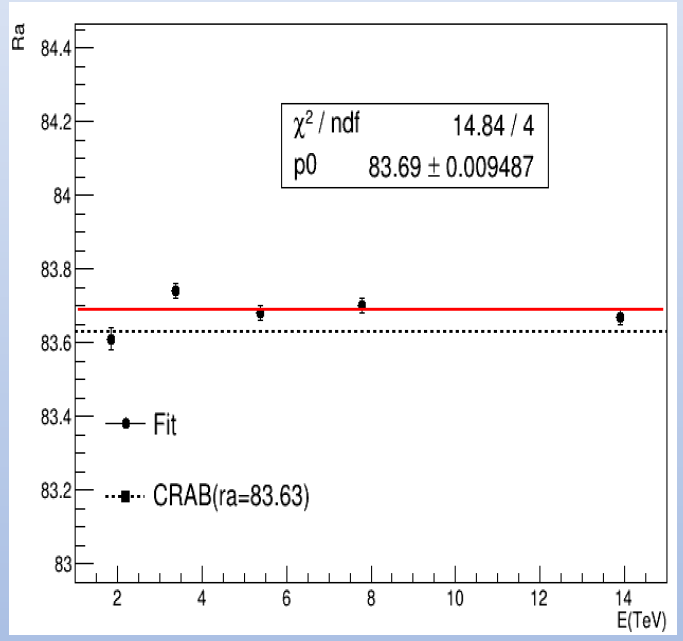
Fig. Data for fitting

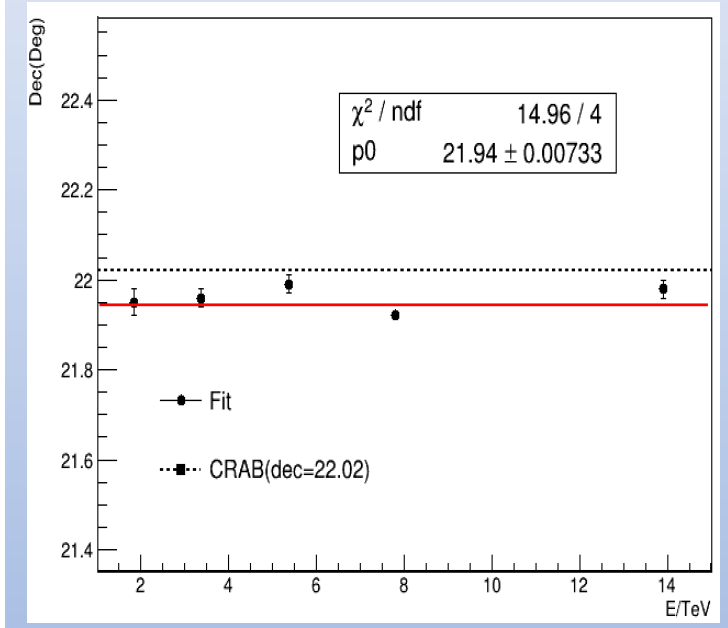
Data and method validation

method validation

Data:201911-202002,Rc



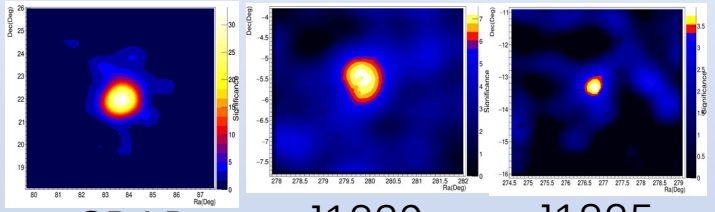




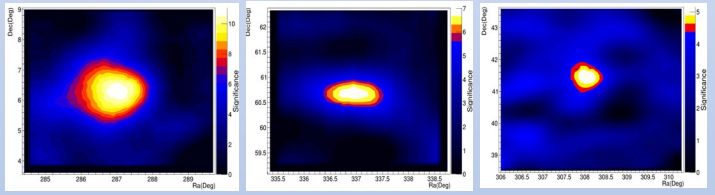
Significance

Cut: ndetc>100&&compactness>16

Source	Ra(Deg)	Dec (Deg)	$\sqrt{TS}$
CRAB	83.67 +/- 0.02	21.97 +/- 0.01	*33.0
J1908+0621	286.72 +/- 0.11	6.23 +/- 0.11	13.1
J2226+6057	336.95 +/- 0.13	60.67 +/- 0.06	7.0
J1839-0545	279.99 +/- 0.13	-5.47 +/- 0.17	7.5
J2032+4102	308.04 +/- 0.06	41.71 +/- 0.03	5.1
J1825-1326	276.83 +/- 0.03	-13.14 +/-0.04	3.9



CRAB J1839 J1825

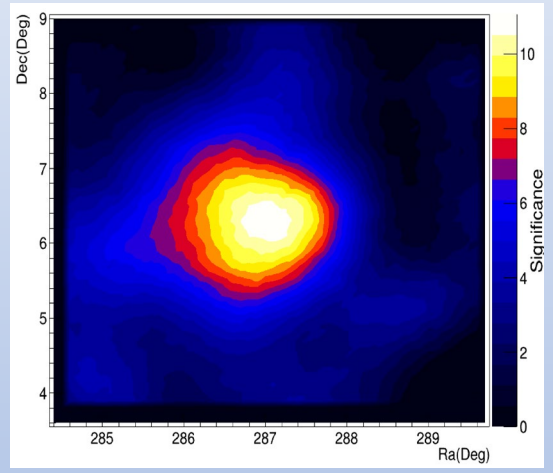


J1908 J2227 J2032

- As the statistics increase, some sources are expected to be seen

LHAASO J1908+0621

1.Signal



ndetc>100,Sqrt(TS)=13

100<ndetc<300 *300<ndetc<500* *500<ndetc<800*

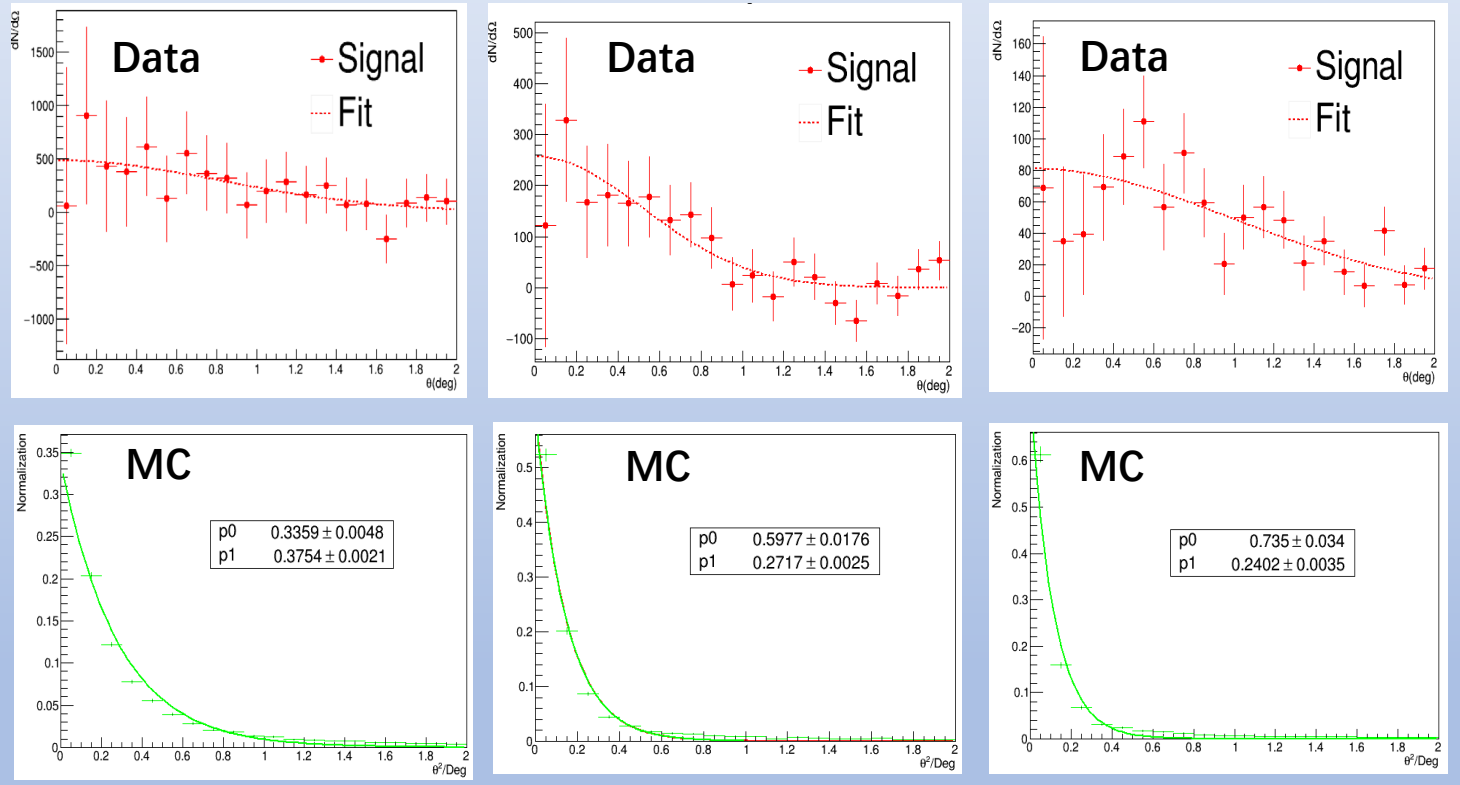
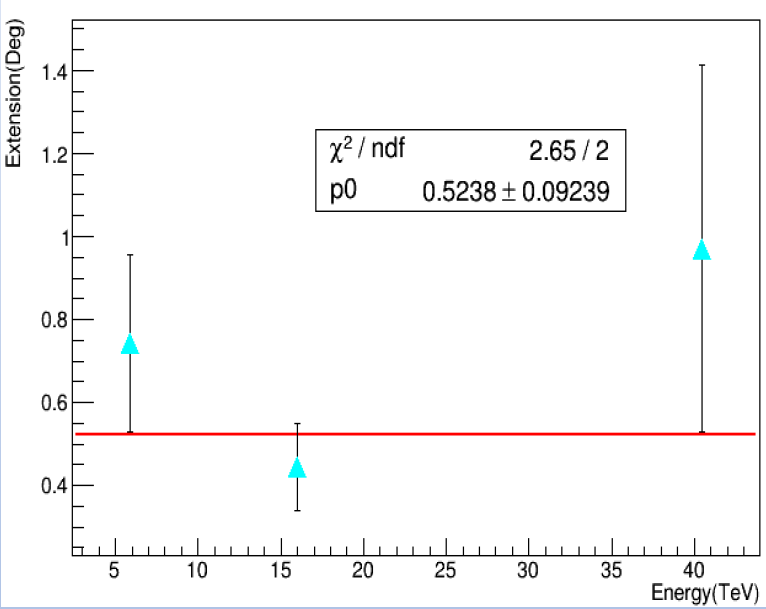


Fig .Distribution of excess event

LHAASO J1908+0621

2.Extension



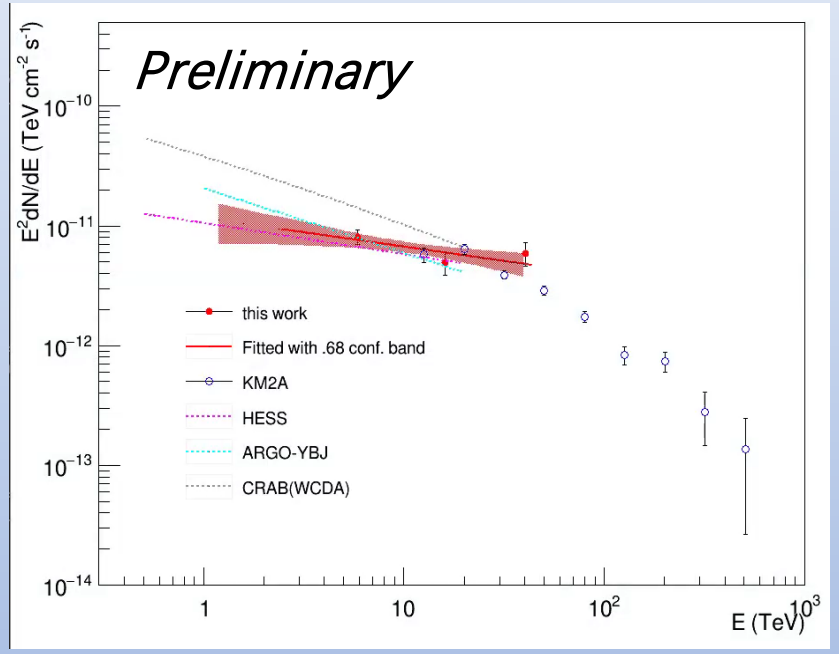
Spatial model : gaussian

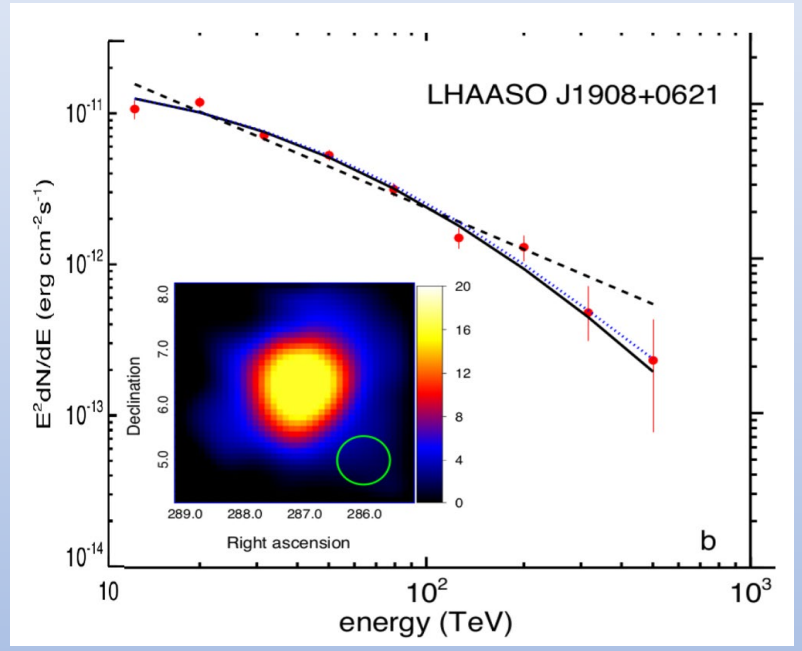
Energy/TeV	Sigma(fit)/Deg	Sigma(psf)/Deg	Extension/Deg
5.87	0.83+/-0.19	0.37+/-0.01	0.74+/-0.21
15.98	0.52+/-0.09	0.27+/-0.01	0.44+/-0.10
40.47	1.00+/-0.43	0.24+/-0.01	0.97+/-0.44

Intrinsic extension: 0.52+/-0.09 deg 0.49±0.22(Argo)

LHAASO J1908+0621

1.Spectrum





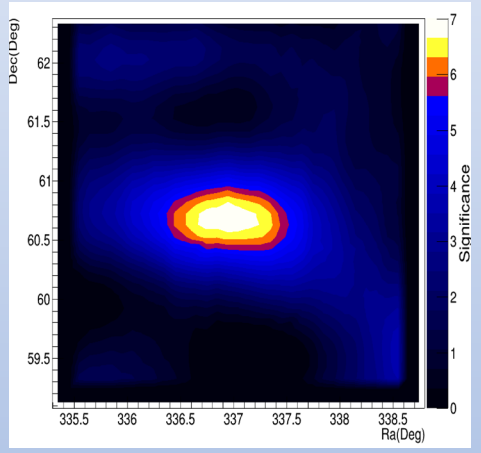
$$f(E) = (1.49 \pm 0.19) * 10^{-13}(E/7)^{-2.24\pm0.16}$$

$$f(E)=\alpha\left(\frac{E}{10TeV}\right)^{-a-blog(E/10TeV)}$$

$$a = 2.40, b = 0.47\ VS\ \Gamma = 2.89$$

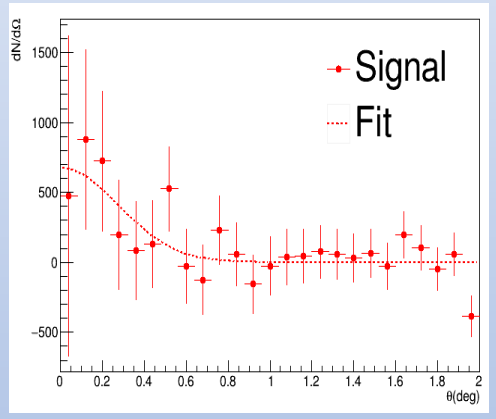
LHAASO J2226+6057

1.Signal

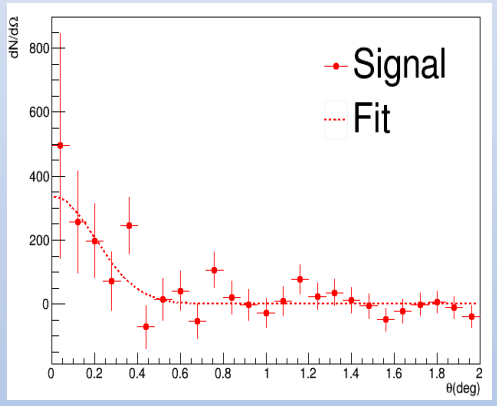


ndetc>100,Sqrt(TS)=7

100<ndetc<300



300<ndetc<500



500<ndetc<800

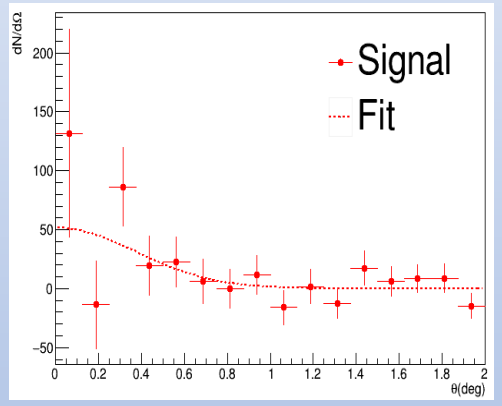
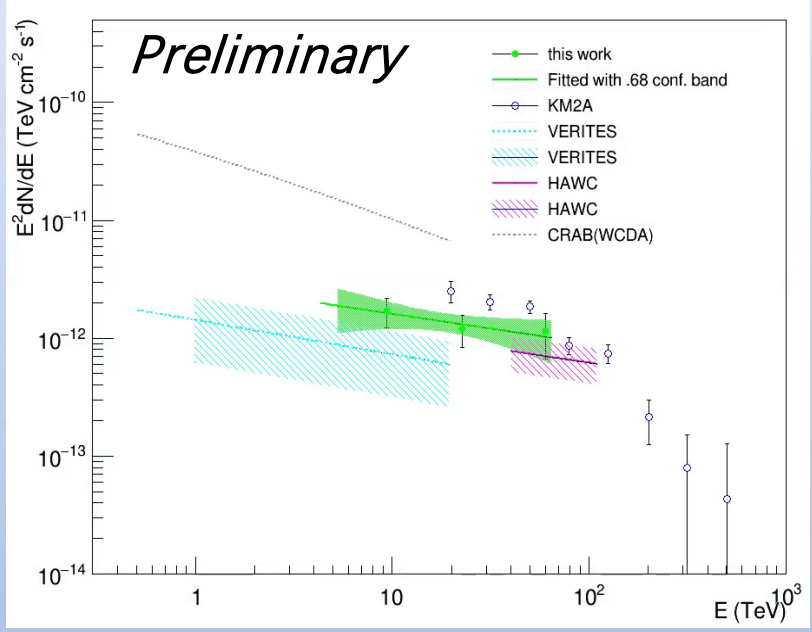
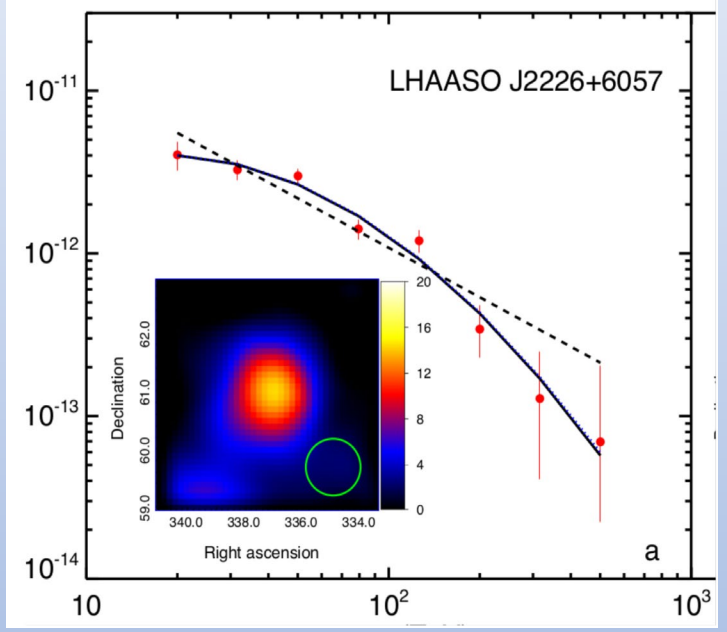


Fig .Distribution of excess event

LHAASO J2226+6057

2.Spectrum





$$f(E) = (0.36 \pm 0.12) * 10^{-13}(E/7)^{-2.25\pm0.29}$$

$$f(E)=\alpha\left(\frac{E}{10TeV}\right)^{-a-blog(E/10TeV)}$$

$$a = 1.84, b = 0.87\ VS\ \Gamma = 3.01$$

Summary and outlook

- Four sources have been observed around 190 days with more than 5 sigma statistical significance at TeV energy.

- Preliminary Energy spectrum of J1908-0621 and J2227+0607 has been measurement, it's spectral indices is -2.24, -2.25 respectively.

- Next step

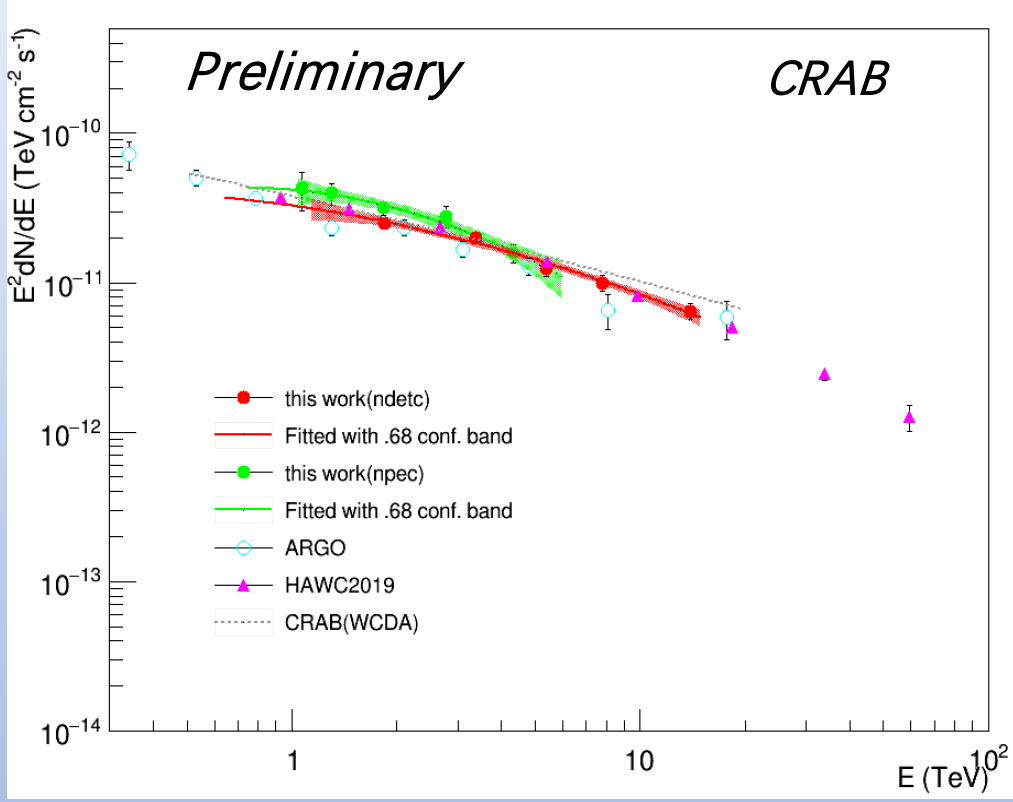
  1. Further analysis using data from 20200314 to 20210228 of wcda-1
     (another data set : wcda-1 and wcda-2 20201101-20210228)
  2. Extended energy spectrum measurement using NPE parameter

Thanks!

Backup

- Trying using NPE to reconstruct energy spectrum in combination with small PMT

- More accurate spectral analysis with WCDA union data



Backup

天图接收度修正

(a)假设背景原分布 $\mathbf{dP/d\Omega = C}$=1/Ω

信号原分布： dP/dΩ=1/2Pi/sigma/sigma*Exp(-r*r/2/sigma/sigma)（也可用非对称高斯）

背景事例数：N_{b}

信号事例数：N_{s}

每一个格子背景事例数：$n_b^i = N_{\mathrm{b}} * C * \Delta\Omega_i$　　期望观测背景事例数$n_b^{i'} = N_b' * P_b^{i'}$

每一个格子信号事例数：$n_s^i = N_s * (\mathrm{dP/d\Omega}) * \Delta\Omega_i$　　期望观测信号事例数 $n_{\mathrm{s}}^{i'} = N_s' * P_s^{i'}$

设探测效率：　$\varepsilon_{\mathrm{s}} = k1 * \varepsilon_{\mathrm{b}} = k1 * \frac{N_b'}{N_{\mathrm{b}}} = \frac{N_s'}{N_s}$

(b)假设不同位置处，　$\boldsymbol{\varepsilon_s^i = k2 * \varepsilon_b^i}$　即 $\frac{n_b^{i'}}{n_b^i}$=1/k2* $\frac{n_{\mathrm{s}}^{i'}}{n_{\mathrm{s}}^i}$

$\frac{N_b' * P_b^{i'}}{N_{\mathrm{b}} * P_b^{\mathrm{i}}}$=1/k2* $\frac{N_s' * P_s^{i'}}{N_s * P_s^{\mathrm{i}}} \Rightarrow \frac{N_b' * P_b^{i'}}{(N_b'/\varepsilon_{\mathrm{b}}) * P_b^{\mathrm{i}}}$=1/k2* $\frac{N_s' * P_s^{i'}}{(N_s'/\varepsilon_{\mathrm{s}}) * P_s^{\mathrm{i}}} \Rightarrow \frac{N_b' * P_b^{i'}}{N_b' * P_b^{\mathrm{i}}}$=k1/k2* $\frac{P_s^{i'}}{P_s^{\mathrm{i}}} = \frac{n_b^{i'}}{N_b' * P_b^{\mathrm{i}}}$

$\mathrm{k1} = \frac{\varepsilon_{\mathrm{s}}}{\varepsilon_{\mathrm{b}}} = \frac{(\sum_i^n n_{\mathrm{s}}^{i'})/N_s}{(\sum_i^n n_b^{i'})/N_{\mathrm{b}}} =$

$\frac{(\sum_i^n n_{\mathrm{s}}^i * \varepsilon_s^i)/N_s}{(\sum_i^n n_b^i * \varepsilon_{\mathrm{b}}^i)/N_{\mathrm{b}}} = \frac{\sum_i^n \mathrm{p}_{\mathrm{s}}^i * \varepsilon_s^i}{\sum_i^n P_b^i * \varepsilon_{\mathrm{b}}^i} = k2 * \frac{\sum_i^n \mathrm{p}_{\mathrm{s}}^i * \varepsilon_b^i}{\sum_i^n P_b^i * \varepsilon_{\mathrm{b}}^i} =$

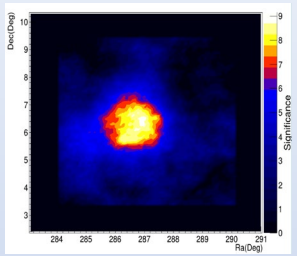
$k2 * \frac{\sum_i^n \mathrm{p}_{\mathrm{s}}^i * \frac{n_b^{i'}}{N_{\mathrm{b}} * \mathrm{p}_b^i}}{\frac{\sum_i^n P_b^i * n_b^{i'}}{N_{\mathrm{b}} * \mathrm{p}_b^i}} = \mathrm{k2} * \frac{\sum_i^n \mathrm{p}_{\mathrm{s}}^i * \frac{n_b^{i'}}{\mathrm{p}_b^i}}{\sum_i^n n_b^{i'}}$

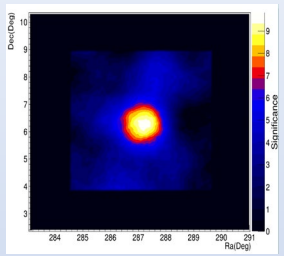
可得到 $n_{\mathrm{s}}^{i'} = N_s' * P_s^{i'}$ =(k1/k2) $* N_s' * (\frac{n_b^{i'}}{N_b' * P_b^{\mathrm{i}}} * P_s^{\mathrm{i}}) = N_s' * \frac{n_b^{i'} * (\sum_j^n (\frac{dP}{d\Omega}(r) * n_b^{j'}))}{(N_b' C)^2} * \frac{dP}{d\Omega}(r)$

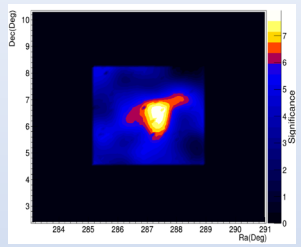
注意拟合区域内$\frac{dP'}{d\Omega}$(r)**不需要归一! 另外对bin依赖也减弱(依赖于统计量,nbin/nbin_all>30%)!**

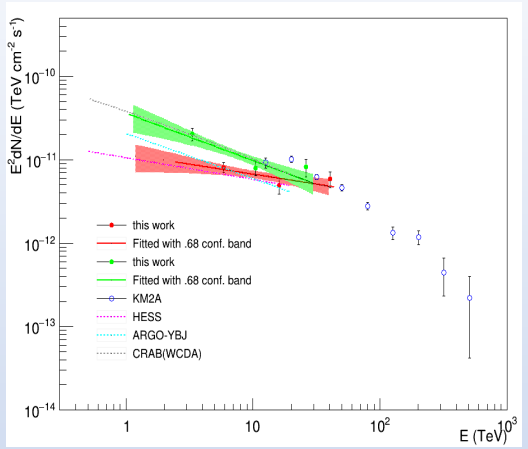
Backup

1.J1908(ra=287.05 dec=6.35)

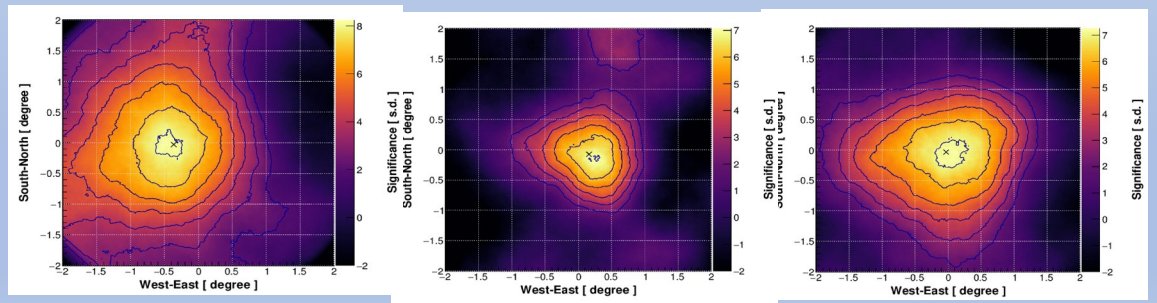








ndetc(1)	Energy(TeV)	Ra(deg)	Dec(deg)	$\sqrt{TS}$	Excess	sigma
100-300		286.54 +/-0.15	6.21 +/- 0.15	11.11	4652.99 +/-811.55	1.10 +/- 0.12
300-500		287.17 +/-0.11	6.28 +/- 0.10	8.62	642.01 +/- 121.64	0.60 +/- 0.09
500-800		287.10 +/-0.17	6.30 +/- 0.17	7.74	324.87 +/- 78.17	0.85 +/- 0.13

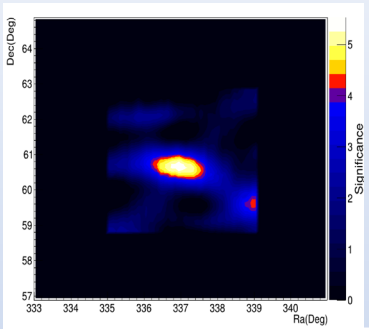


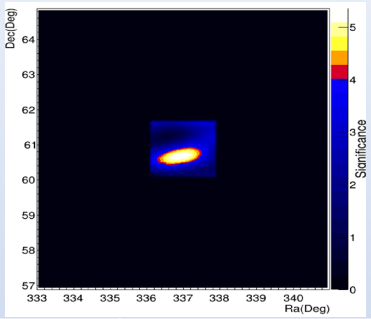
excess[npoint]={2494.71,499.986,296.062};
error[npoint]={0.140396*2494.71,0.208858*499.986,296.062*0.220652};

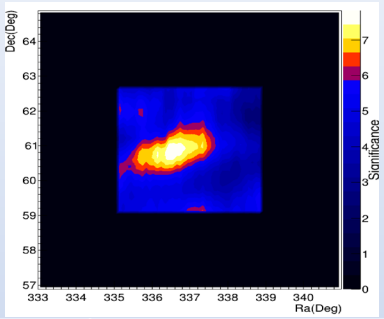
8.23 s.d. at (-0.47,-0.01) 7.06 s.d. at (0.31,-0.13) 7.26 s.d. at (0.09,-0.17)

Backup

1.J2226(ra=336.996 dec=60.8769)

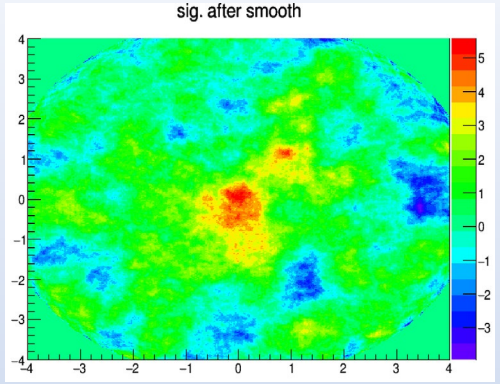




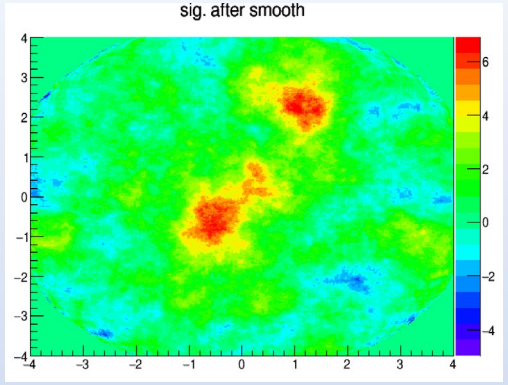


ndetc(1)	Energy(TeV)	Ra(deg)	Dec(deg)	$\sqrt{TS}$	Excess	sigma
100-300		336.95 +/- 0.20	60.64 +/- 0.08	4.84	469.01 +/- 130.20	0.30 +/- 0.06
300-500		337.07 +/- 0.15	60.70 +/- 0.06	4.85	113.54 +/- 34.09	0.20 +/- 0.04
500-800		336.76 +/-0.27	60.88 +/- 0.13	3.90	55.47 +/- 22.91	0.31 +/- 0.10

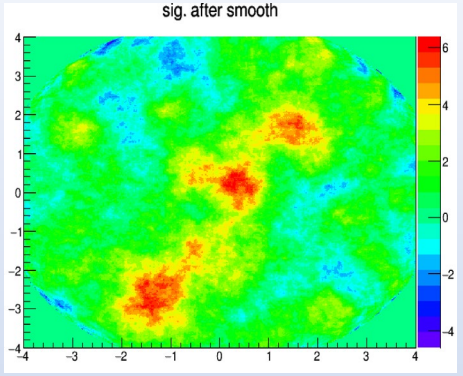
Ndetc>100&&&compactness>15



J1825-1326



J1839-0545



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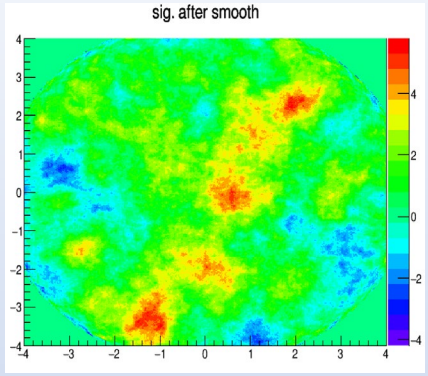

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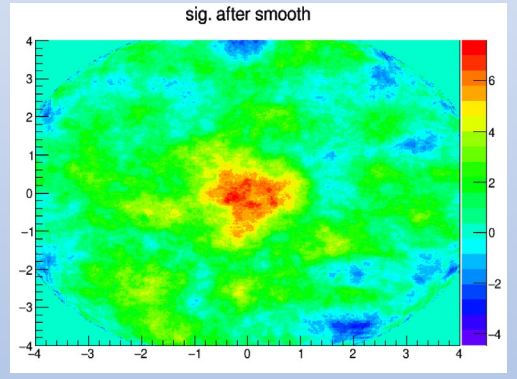

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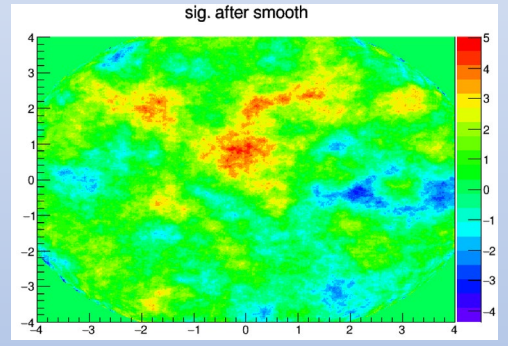

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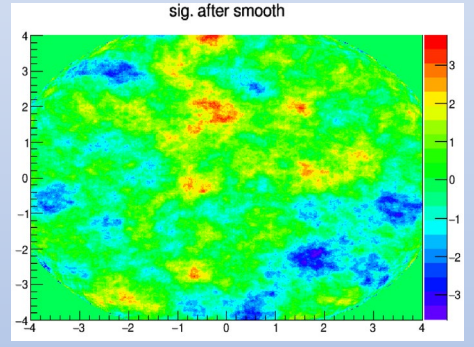

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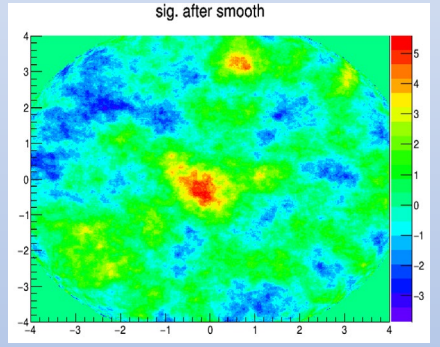

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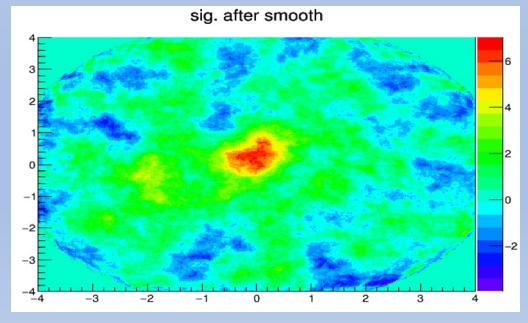

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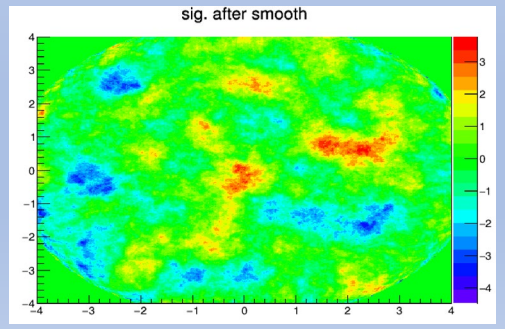

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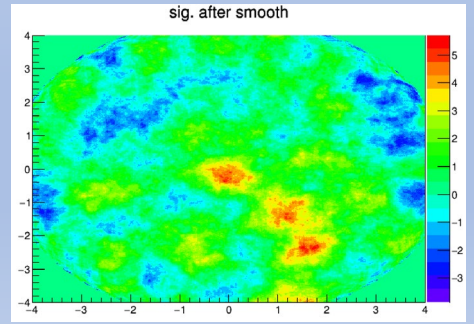

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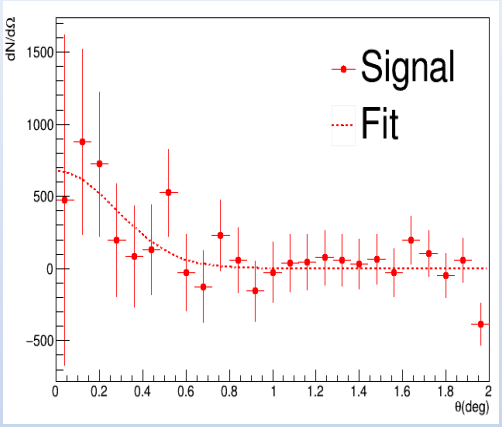
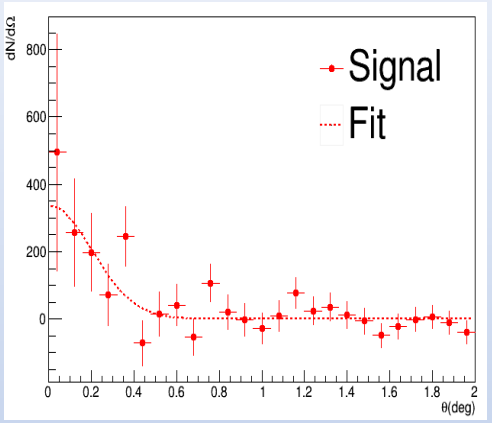
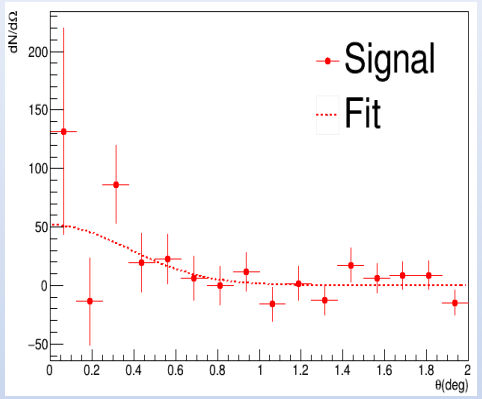
Backup

J2226







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