LHAASO 高海拔宇宙线观测站 Large High Altitude Air Shower Observatory

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Measurement of cosmic-ray electrons with LHAASO KM2A-WCDA synergy

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On behalf of the LHAASO Collaboration

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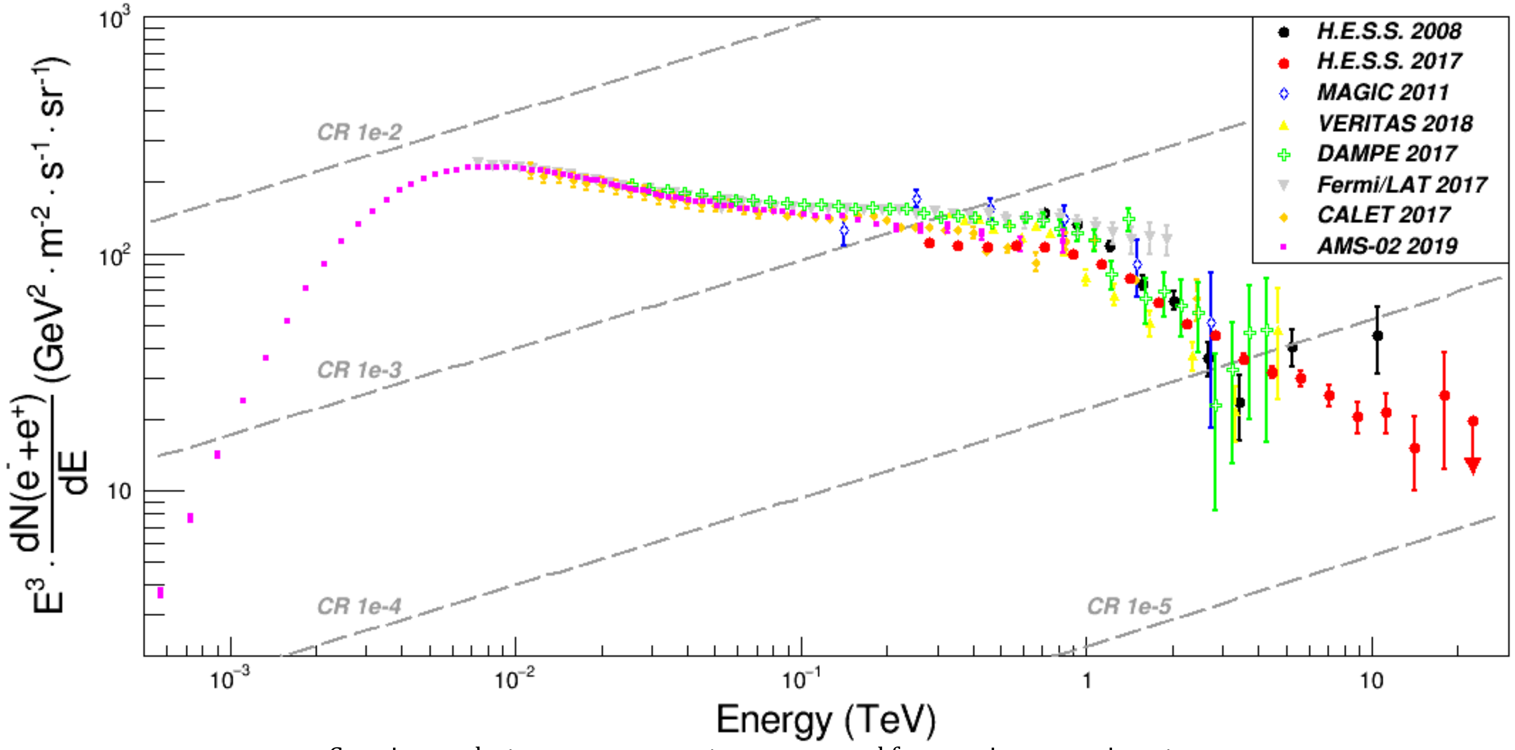
I. Motivation for this Study



Cosmic-ray electrons energy spectrum measured from various experiments

DAMPE Nature 552 7683 (2017): 63-66.
Fermi/LAT Physical Review D 95.8 (2017): 082007.
CALET Phys. Rev. Lett. 119.18 (2017): 181101.
AMS-02 Phys. Rev. Lett. 122.10 (2019): 101101.

H.E.S.S. Phys. Rev. Lett. 101.26 (2008): 261104.
MAGIC 32nd ICRC Beijing,China, 2011
VERITAS Phys. Rev. D 98.6 (2018): 062004.
H.E.S.S. 35th ICRC Busan, Korea, 2017

- Below 1 TeV, satellite-based instruments measure cosmic-ray electron (CRE) ***directly***.
  DAMPE up to 4.6 TeV !
- Above 1 TeV, ***the CRE flux is very low.*** Ground-based Cherenkov telescopes have ***large effective areas*** and ***background rejection power.***
  H.E.S.S up to 20 TeV !
  20 TeV needs $1{\times}10^5$ ***CR rejection power***

I. Motivation – Overview of LHAASO

- ➢ ***½ KM2A achieves $\mathbf{4\times10^3}$ γ/p rejection power over 100 TeV***
  Chinese Phys. C 2021,45(8) 025002

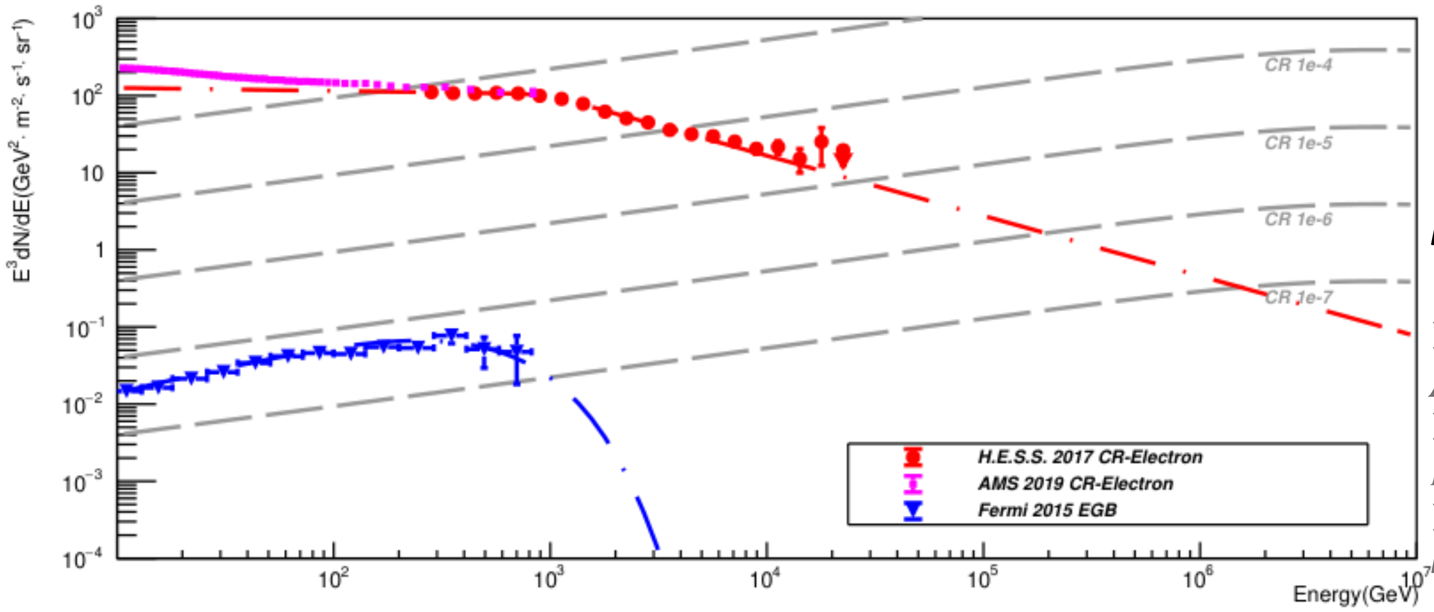
- ➢ ***LHAASO unveils a dozen of ultrahigh-energy gamma-ray sources***
  LHAASO, Science 373 (2021) 425–430
  LHAASO, Nature 594 (2021) 427 33–36

- ➢ ***LHAASO observes A tera–electron volt afterglow of GRB221009A***
  LHAASO, Science (2023) 360 1390-1396.

- ➢ **The Large High Altitude Air Shower Observatory (LHAASO) Experiment**
  [CRI6–01] Performances of the LHAASO detectors

- **KM2A - $1km^2$, 5242 EDs + 1181 MDs; @30 TeV – 10 PeV →** Full-array started from July 2021.
- **WCDA - 78000 m^2, 3120 cells; @100 GeV – 30 TeV →** Full-array started from March 2021.
- **WFCTA – 18 Cherenkov telescopes**

II. KM2A performance analysis



CRE spectrum Given by ***H.E.S.S. 2017*** > 1TeV

$$E^3\left(\frac{dN}{dE}\right) = N_0\left(\frac{E}{1TeV}\right)^{3-\Gamma_1}\left(1+\left(\frac{E}{E_b}\right)^{\frac{1}{\alpha}}\right)^{-(\Gamma_1-\Gamma_2)\alpha}$$

Required 10^5 background rejection power over 20 TeV

- CRE lower energy band AMS

AMS-02 Phys. Rev. Lett. 122.10 (2019): 101101.

- CRE higher energy band HESS

H.E.S.S. 35th ICRC Busan, Korea, 2017

- EGB From Fermi/LAT

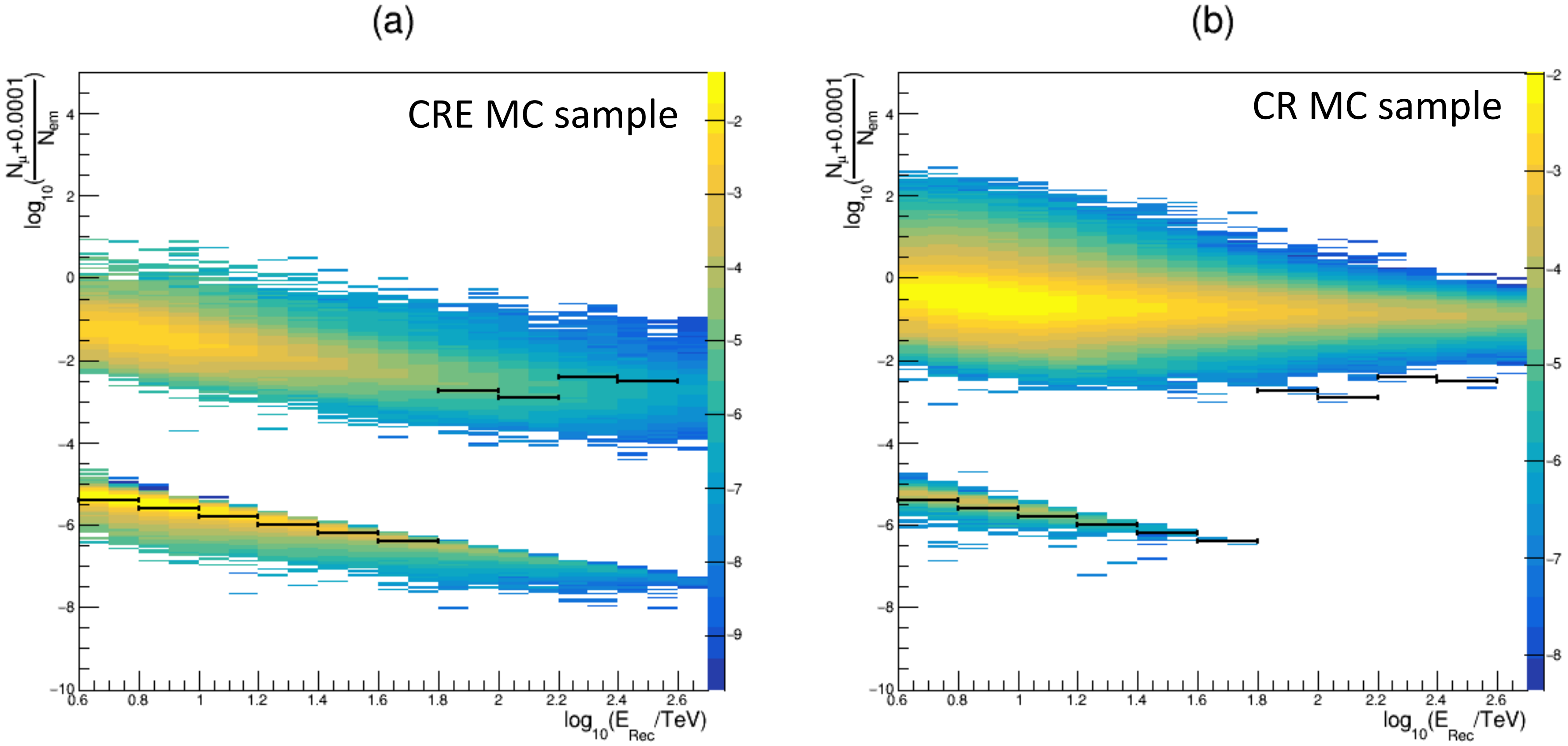
Fermi/LAT The Astrophysical Journal 799.1 (2015): 86.

- ***LHAASO Simulation Data:***
  - ***CRE:***
    - E^{-2} spectrum 10^{12}eV - 10^{16}eV
    - zenithal angle 0 – 70°
    - radius 0 – 1000 m
    - 2.222×10^8 in total
    - Reweighted to H.E.S.S. fit spectrum
  - ***CR background:***
    - E^{-2} spectrum 10^{12}eV - 10^{16} eV
    - zenithal angle 0 – 40°
    - radius 0 – 1000 m
    - 5.555×10^8 in total (Proton, Helium, CNO, MgAlSi, Iron)
    - Reweighted to Gaisser and Hörandel model.

II. KM2A performance analysis

➢ ***Preliminary Result of the CRE/CR rejection power of full-KM2A:***

25% CRE signal survival at least!



➢ ***Discrimination parameter, R***

$$R = \log_{10}\left(\frac{N_\mu + 0.0001}{N_{em}}\right)$$

N_{em} EM particles by KM2A-EDs

N_μ Muons by KM2A-MDs

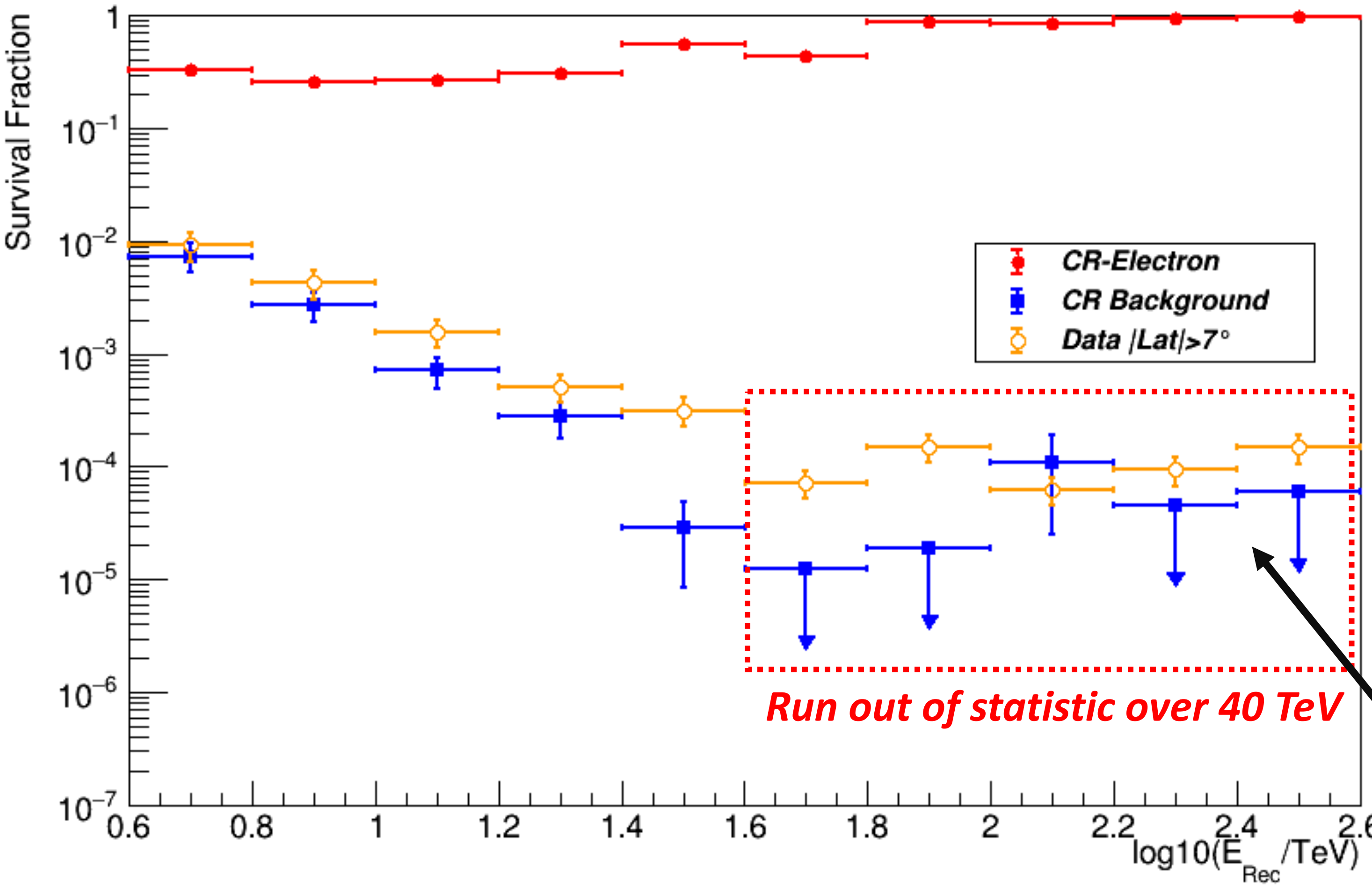
➢ ***Discrimination parameter is optimized for Significance:***

$$\text{Sig} = \frac{N_{CRE,MC} \cdot \epsilon_e}{\sqrt{\left(N_{CR,MC} \cdot \epsilon_{CR} + N_{CRE,MC} \cdot \epsilon_e + \left(\delta \cdot N_{CR,MC} \cdot \epsilon_{CR}\right)^2\right)}}$$

Absolute CR flux uncertainty is under 20%,
We take $\delta = 20\%$ here.
EPJ Web of Conferences. Vol. 210. EDP Sciences, 2019.

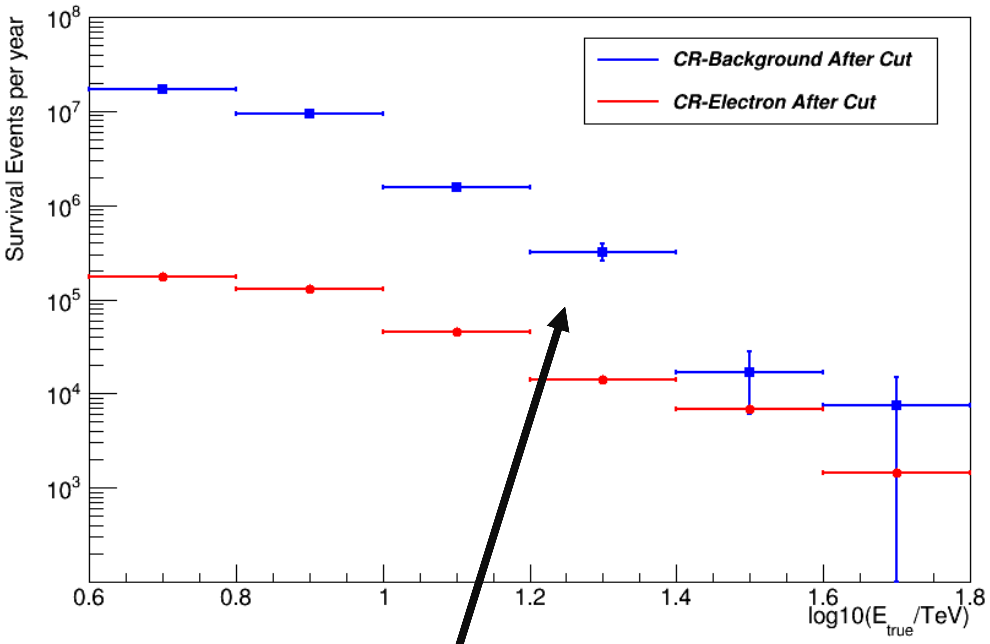
II. KM2A performance analysis

- ***Survival Fraction and Survival Events:***



The survival fraction of simulated CRE, CR-background, and observed events in different energy bins after the discrimination cuts.

The survival events of CRE and CR-background events (according to simulation) in different energy bins after the discrimination cuts.



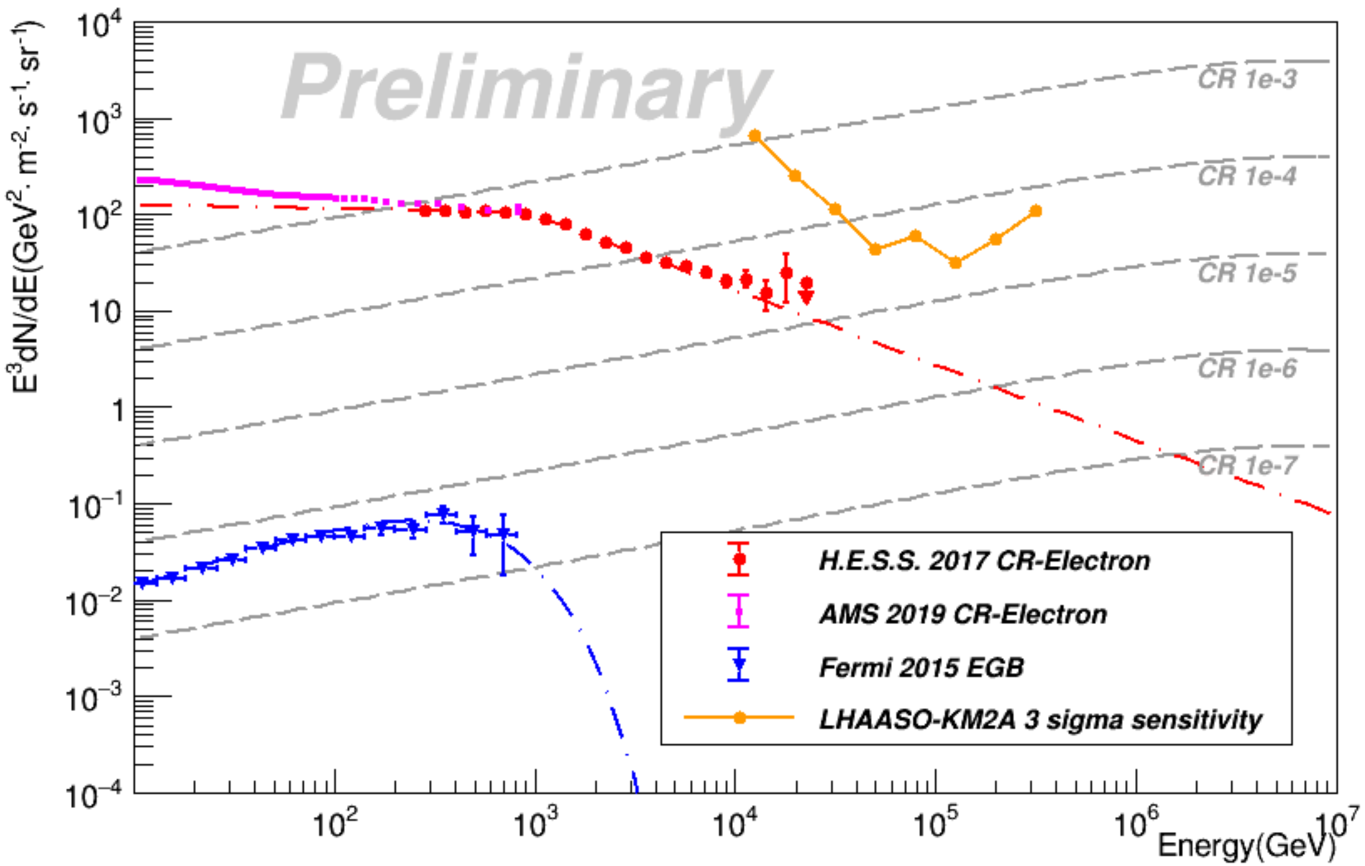
Overwhelming background and observe events are expected to be background.

Insufficient MC data will ***overestimate background rejection power!!***

Same Selection Cut adapted to our observation; we will discuss Data |Lat|>7° later.

II. KM2A performance analysis

- ***Sensitivity of KM2A to CRE:***



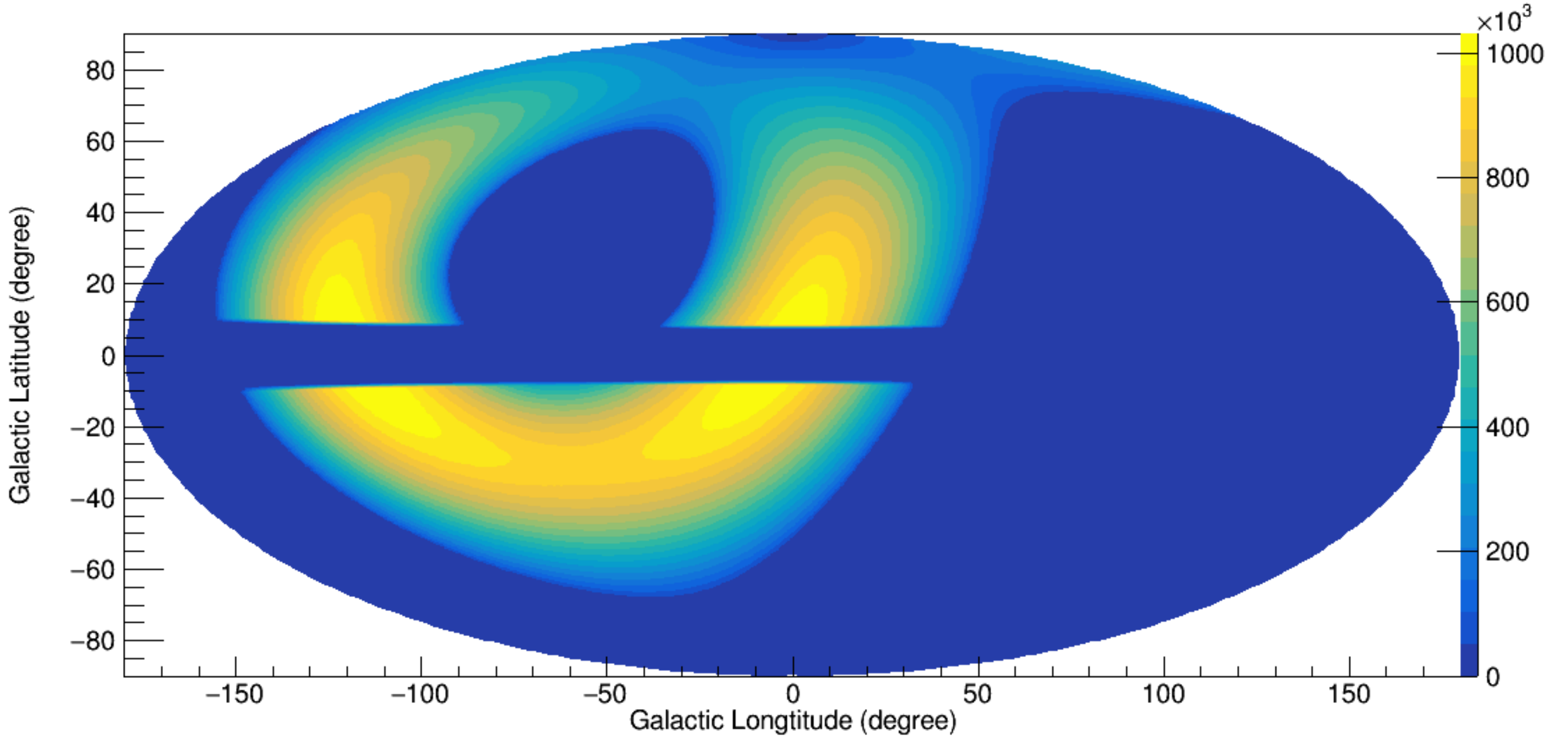
The one-year 3-sigma sensitivity of LHAASO-KM2A for Cosmic-ray electrons

Take the ***survival fraction of CR based on observation*** as a conservative value.

$$F_{\mathrm{CRE},3\sigma} = \frac{N_{CRE,sur,3\sigma}}{N_{CRE,sur,1yr}} \cdot f_{HESS}$$

$$N_{\mathrm{CRE,sur},3\sigma} = \frac{9}{2} + \sqrt{9 \cdot \left(N_{\mathrm{CR,sur,1yr}} + \delta^2 \cdot N^2_{\mathrm{CR,sur,1yr}}\right) + \frac{81}{4}}$$

II. KM2A performance analysis



The LHAASO Field of View with additional cut for Galactic Latitude (|b|>7 °) for CRE observation

➢ ***LHAASO Observation Data:***

- Full-array KM2A with developed reconstruction algorithm.
- 2021.07.20 – 2022.8.18, 383 days in total. (3.22e+07s)
- Additional cut on galactic latitude (|b|>7 °) to discard the gamma astrophysical sources on the galactic plane.
- EGB is existed but negligible over TeV.

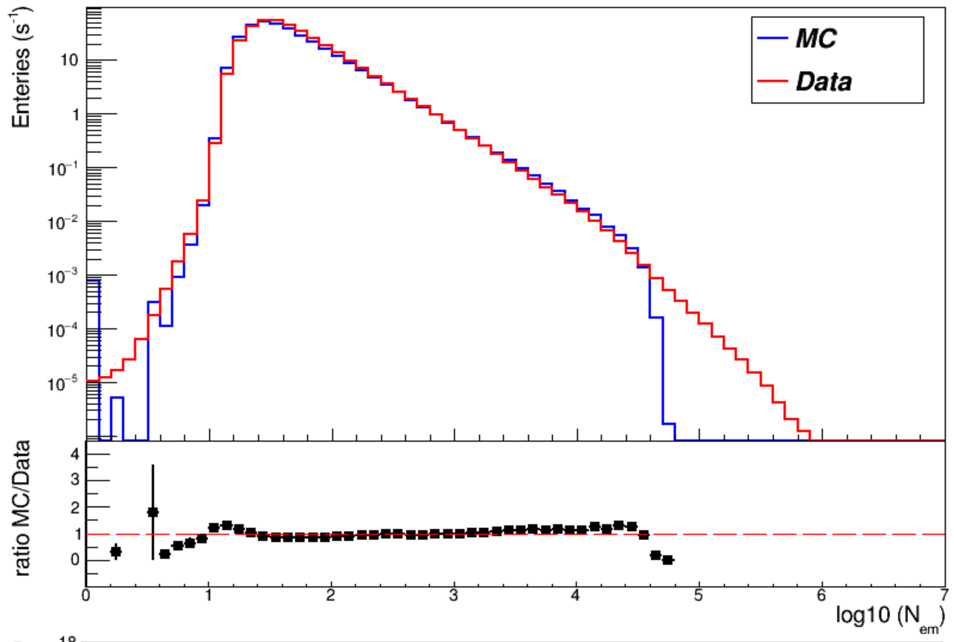
➢ ***Data Selection:***

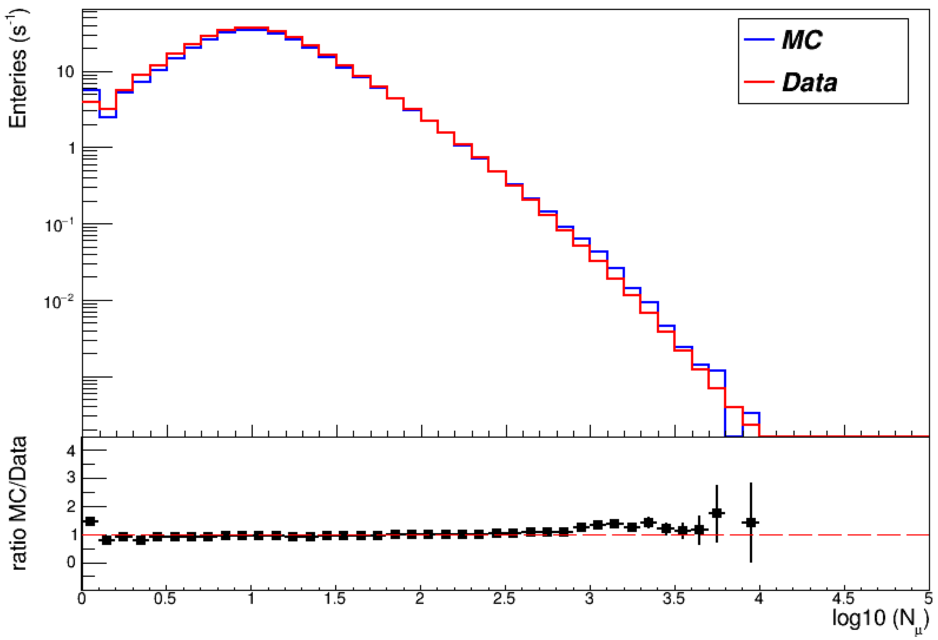
- Fire KM2A-EDs after noise-filter ≥ 10.
- CoreR>=320m && CoreR<=420m.
- Rec zenith angle ≤ 30°.
- Rec energy ≥ 4 TeV.
- Galactic Latitude (|b|>7 °) for observation.

II. KM2A performance analysis

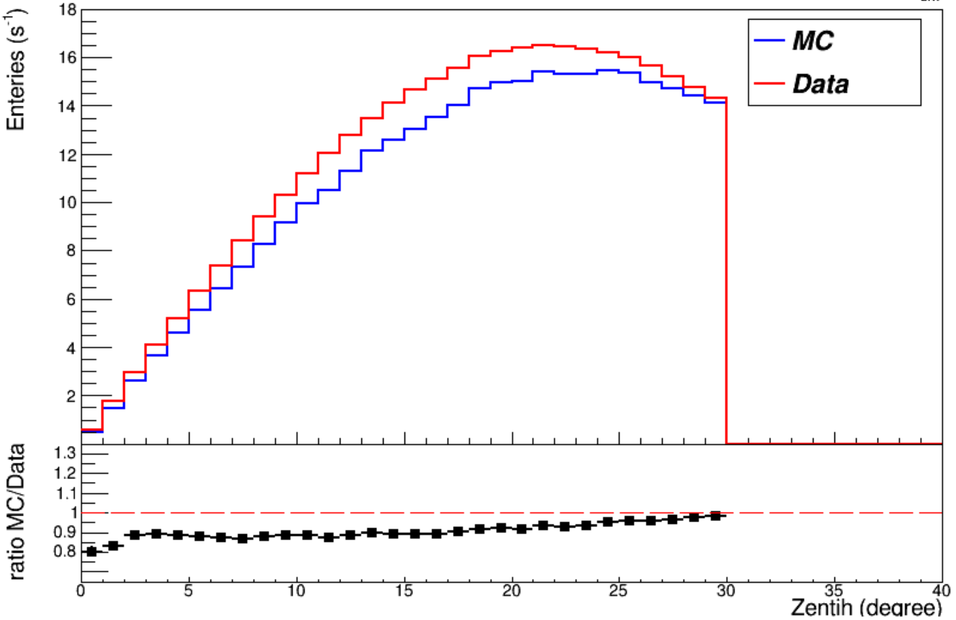
The simulation has been tested for its validity by comparing the distributions of several shower parameters with the measured in the observation.

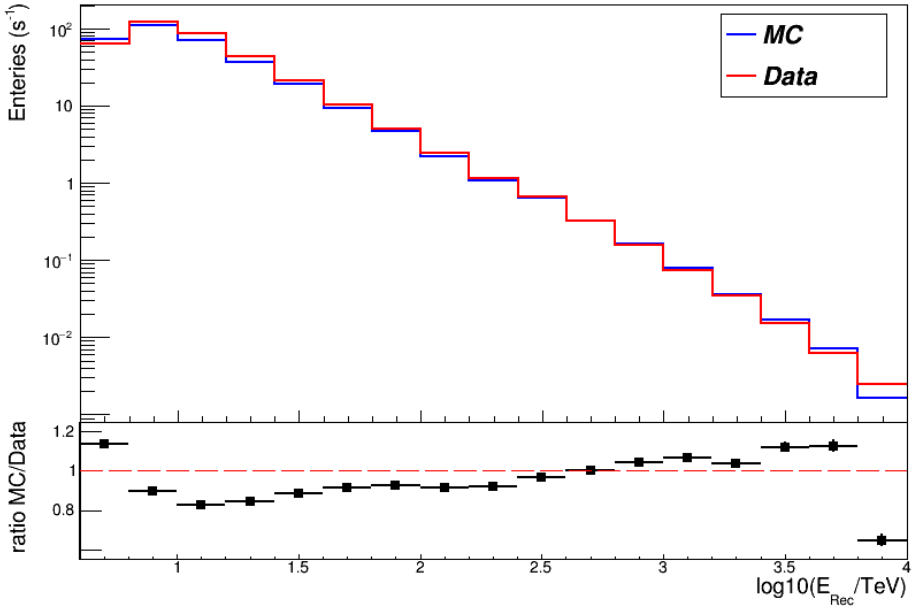
➢ ***Comparison between MC and Data:***





$\log10(N_{em})$	$\log10(N_{\mu})$
Rec_Zentih	$\log10(\frac{E_{rec}}{TeV})$





➢ ***Event Rate***

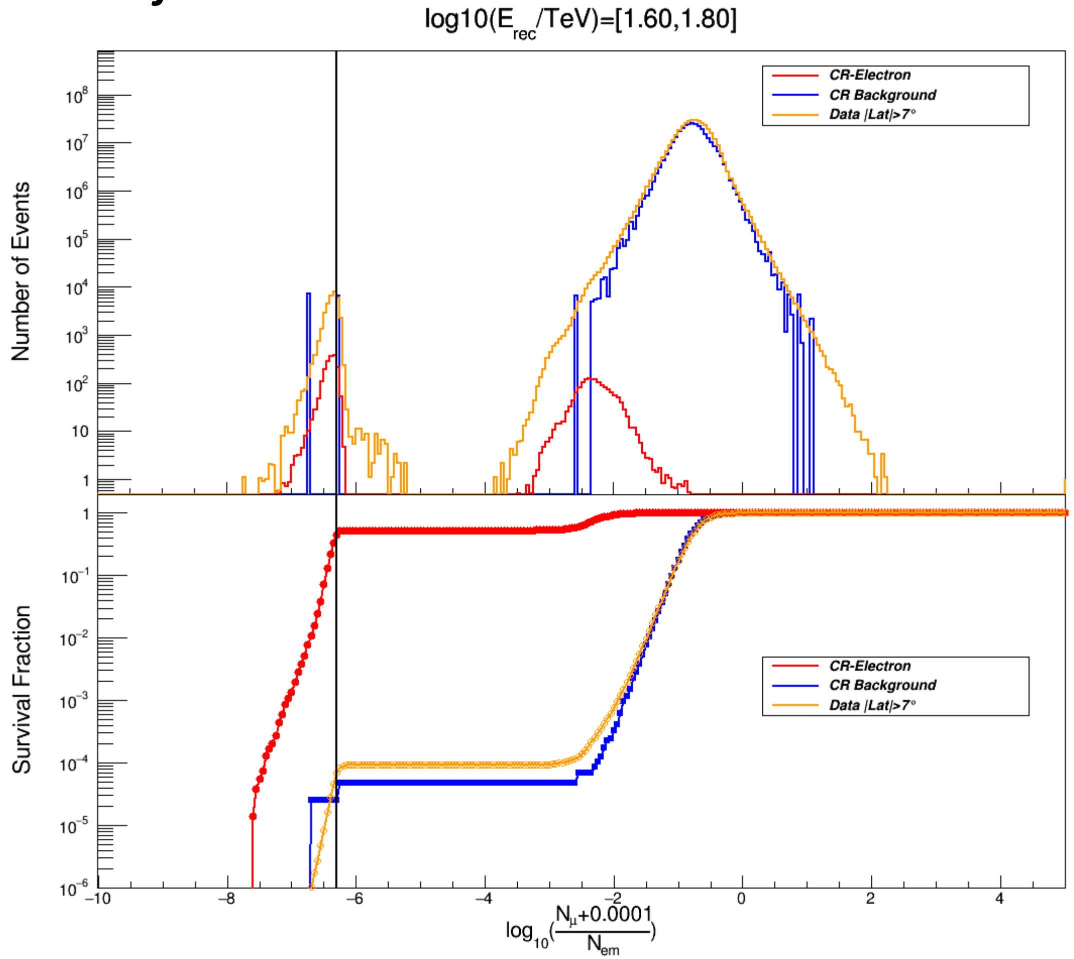
Data=355.617 Hz

MC= 326.205 Hz

Difference ~9.0%

II. KM2A performance analysis

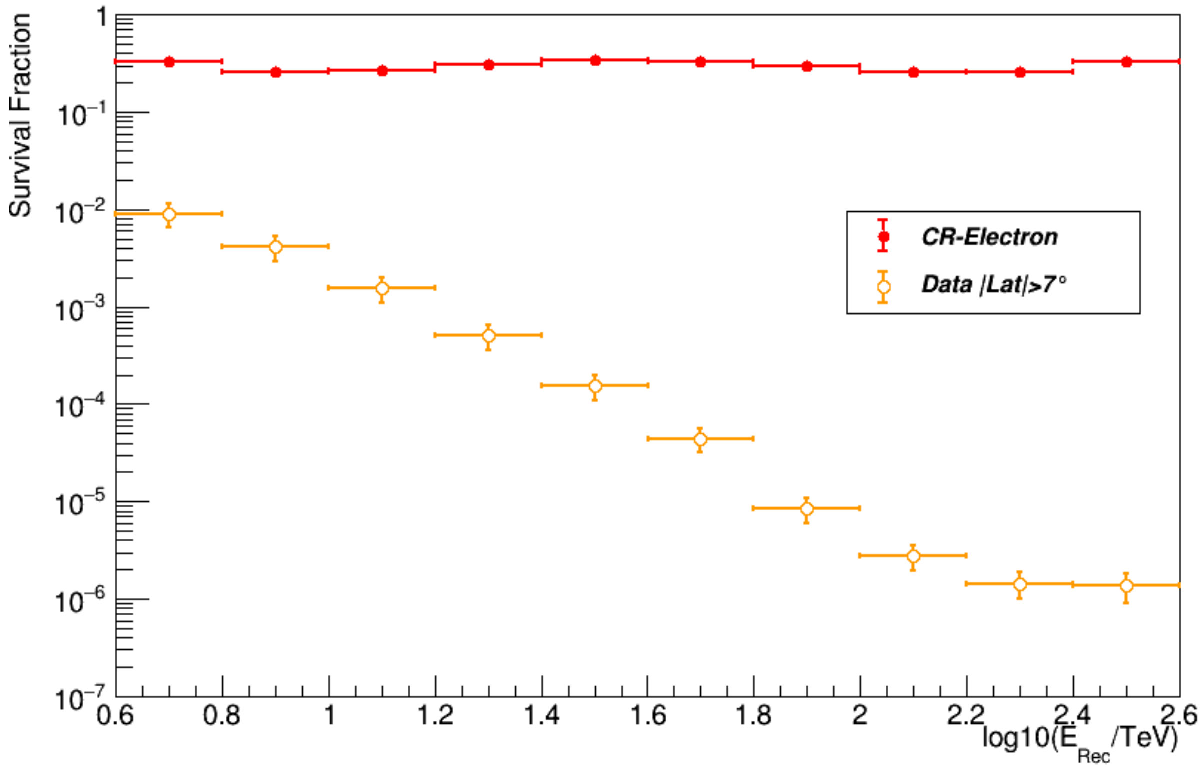
- ***Survival fraction overestimation issue:***



The distribution of number of events and survival fraction of simulated CRE, CR and measured events are plotted. The black solid line is the optimized discrimination cut based on Monte Carlo samples.

N_μ events induced by the CR sample would ***consume large computing resources*** due to its tiny proportion.

- ***Survival Fraction and Survival Events based on observation data:***



The survival fraction of simulated CRE and observed events (subtracting CRE MC sample) in different energy bins after the discrimination cuts.

II. KM2A performance analysis

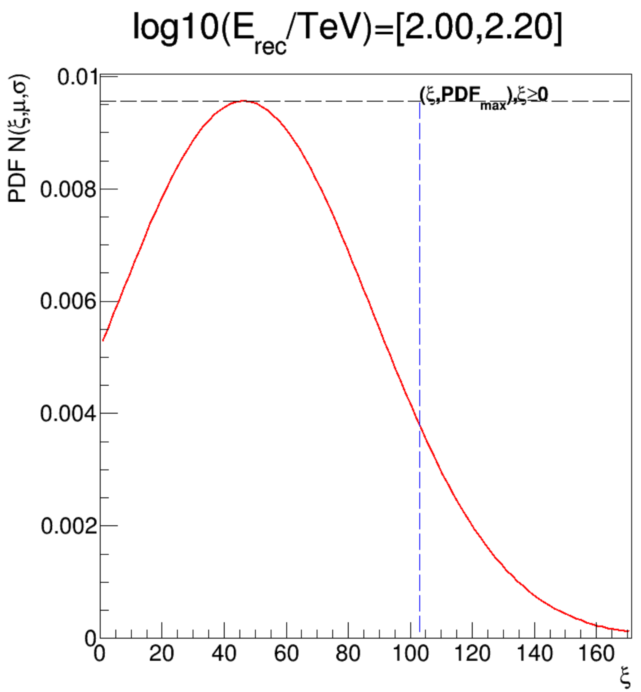
- ***Calculate the 90% C.L. upper limit on N_{CRE} for each energy bin***

$\xi < 0$*, non-physical!*

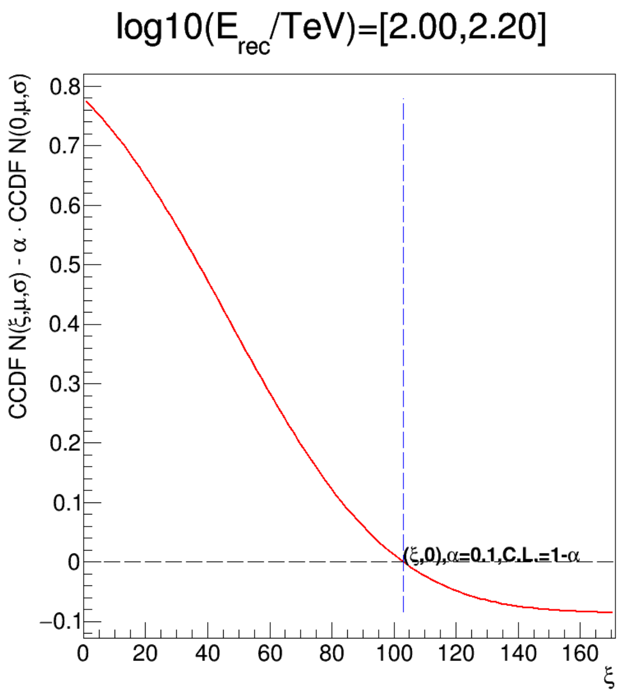
Total number of event:
1.14e+10
Number of electron-like events after all cuts:
4.39e+7

After all cuts, we supposed:

$N_{obs} \sim$ ***Gaussian distribution***
$N_{CR} \sim$ ***Gaussian distribution***



The probability density function of ξ



To solve the 90% C.L. Upper Limit of ξ

The expectation number of CRE after all cuts (**ξ**) in each energy bin, ***can be approximated with Gaussian distribution***

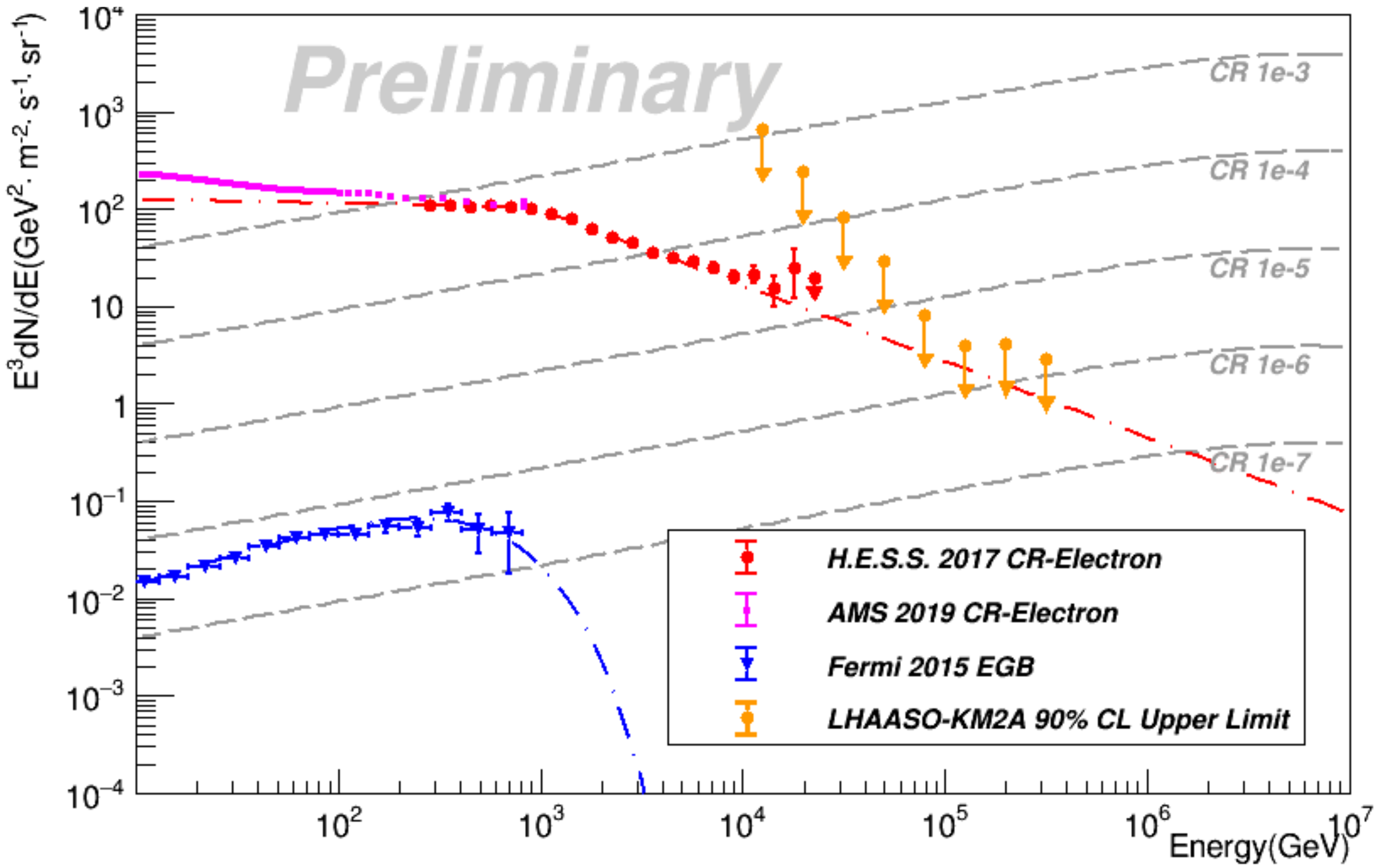
$$\hat{\xi} = N_{obs} - N_{CR}$$
$$\sigma_{\xi}^2 = \sigma_{N_{obs}}^2 + \sigma_{N_{CR}}^2 + (\delta \cdot N_{CR})^2$$

- ***Calculate the $1 - \alpha$ C.L. upper limit of ξ :***

$$\Phi(\xi; \mu, \sigma) = \int_{\xi}^{\infty} \mathrm{Gauss}(x; \mu, \sigma) dx$$
$$\alpha = \frac{\Phi(\xi_{\mathrm{limit}})}{\Phi(0)}$$

II. KM2A performance analysis

➢ ***LHAASO-KM2A 90% C.L. Upper Limit on CRE:***



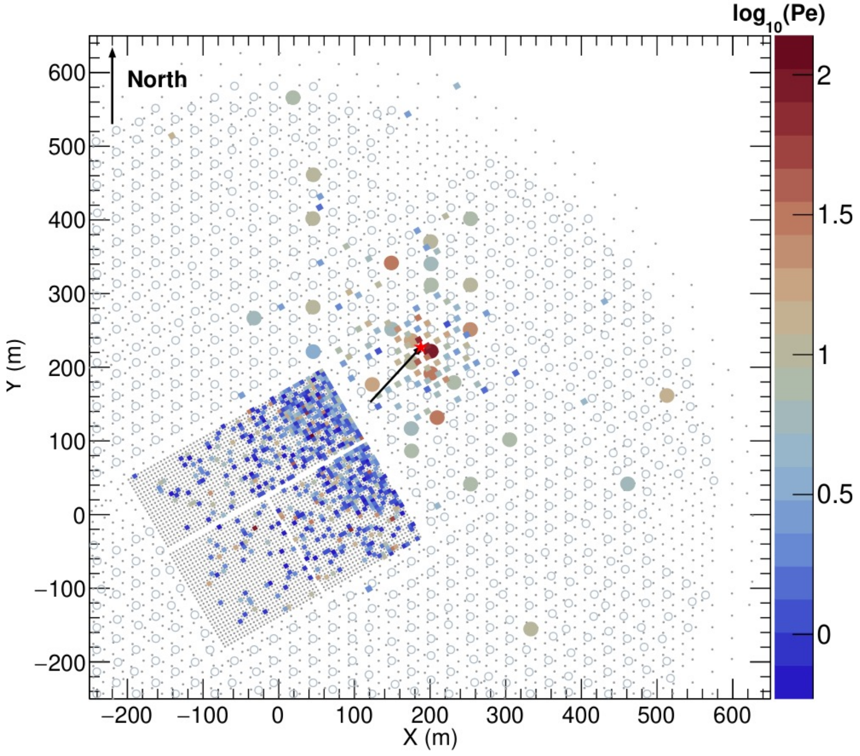
The 90% Upper limit of CRE spectrum has ***no conflict*** with the extrapolation of H.E.S.S. fitting spectrum

$$F_{\text{CRE Limit}} = \frac{N_{CRE,sur,3\sigma}}{N_{CRE,sur,1yr}} \cdot f_{HESS}$$

III. KM2A + WCDA synergy

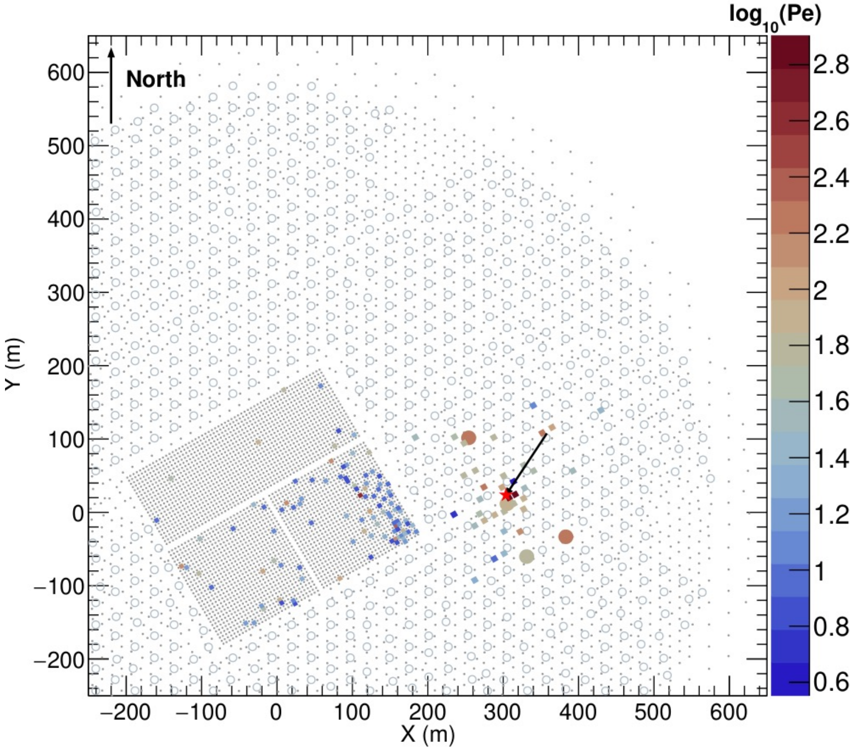
Please refer to ICRC 2023 Poster [PCRI1-13] Method to measure muon content of extensive air showers with LHAASO KM2A-WCDA synergy

The LHAASO observatory has achieved the simultaneous measurement of the same shower by KM2A and WCDA with the help of DAQ calibration!



An observed shower event with reconstructed primary energy of 45.99 TeV.

The simulation of the KM2A-WCDA synergy is under development. To utilize WCDA as a muon counter to enhance the rejection power in the future.



A simulated shower event with reconstructed energy of 14.8 TeV with primary energy of 26.1 TeV

IV. Summary

From our analysis：

- KM2A has the capability of measurement of CRE at ***3σ sensitivity given the 20% CR absolute flux in one year*** observation according to current simulation data.
- The LHAASO-KM2A 90% C.L. upper limit for cosmic-ray electron spectrum [10TeV, 1PeV] has ***no conflict*** with the extrapolation of H.E.S.S fitting spectrum so far.
- The KM2A simulation data applied for CRE is insufficient.

In the future:

- It is necessary to accumulate the simulation data at the energy ranges of [25TeV, 40TeV], [40TeV, 64TeV], [64TeV, 100TeV], [100TeV,160TeV], where are the most likely to measure CRE via the LHAASO experiment.
- The optimization selection adapted for the full KM2A in CRE/CR separation is about to release, which will contribute to further depress the background of cosmic-ray events.
- A method to utilize WCDA as a muon counter to measure the muon content in EAS with LHAASO KM2A-WCDA synergy released may help to improve the background rejection power of LHAASO above 20 TeV.

Thank you!

Back up

➢ ***Preliminary Result of the CRE/CR rejection power of full-KM2A:***