チベット高原での高エネルギー宇宙線の研究

川田 和正 (東京大学宇宙線研究所)

For the Tibet ASγ Collaboration

2024年度チベット実験関連採択課題

F8. チベット高原での高エネルギー宇宙線の研究(継続)
(瀧田正人 東京大学宇宙線研究所)

F9. チベット空気シャワーアレイによる10TeV宇宙線強度の恒星時日周変動の観測 (継続)
(宗像一起 信州大学理学部)

F10. Knee領域一次宇宙線組成の研究(継続)
(片寄祐作 横浜国立大学大学院工学研究院)

F11. 宇宙線による太陽の影を用いた太陽周辺磁場の時間変動の研究(継続)
(西澤正己 国立情報学研究所情報社会相関研究系)

チベットグループ経費執行状況

研究費: 申請額 800万円 → 配分額 180万円
Tibet空気シャワー観測装置、YAC空気シャワーコア観測装置、
地下ミューオン観測装置の維持・運転
に必要な経費の一部に使用。

旅費: 申請額 900万円 → 配分額 200万円
中国出張や宇宙線研での研究打ち合わせ等に使用。

ご支援、どうもありがとうございました。

Tibet ASγ Experiment Research Activities

International Conferences:

- TeV Particle Astrophysics (TeVPA2024), Chicago, US, August 2024 — 1 talk
- Theory Meeting Experiment 2025 (TMEX2025), Quy Nhon, Vietnam, January 2025 — 1 invited talk
- Searching for the Sources of Galactic Cosmic Rays (SuGAR2024), Wisconsin Madison, US, October 2024 — 1 invited talk
- XXXIIth International Astronomical Union General Assembly, Cape Town (Online), August 2024 — 1 talk
- 22nd International Symposium on Very High Energy Cosmic Ray Interactions (ISVHECRI 2024), Puerto Vallarta, Mexico, July 2024 — 1 invited talk
- 21st Asia Oceania Geosciences Society (AOGS2024), Pyeongchang, South Korea, June 2024 — 1 invited talk
- 8th Heidelberg International Symposium on High-Energy Gamma-Ray Astronomy, Milano, Italy, September 2024 — 1 talk
- ASTRONUM 2024 - the 16th International Conference on Numerical Modeling of Space Plasma Flows at La Rochelle, France, 1-5 July, 2024 — 1 invited talk
- COSPAR2024 45 Scientific Assembly, Busan, Korea, Jul 13-Jul 21, 2024 — 1 talk

Domestic Conferences

- 日本物理学会, 第79回年次大会, 北海道大学(札幌キャンパス), September 2024 — 2 talks
- 日本物理学会, 2025年春季大会, オンライン, March 2025 (予定) — 2 talks
- 日本天文学会秋季大会, 関西学院大学, September 2024 — 1 talk
- 「宇宙線学」の共創研究会2024, 大阪公立大学, May 2024 — 1 talk
- 名大ISEE共同研究集会「太陽地球環境と宇宙線モジュレーション」, February 2025 (予定) — 1 talk

Tibet ASγ Experiment Research Activities

Refereed Papers:

- S. Kato et al., Quantitative Constraint on the Contribution of Resolved Gamma-Ray Sources to the Sub-PeV Galactic Diffuse Gamma-Ray Flux Measured by the Tibet ASγ Experiment, The Astrophysical Journal Letters, 977, id.L3, 8 pp (2024).
- S. Kato et al, On the Source Contribution to the Galactic Diffuse Gamma Rays above 398 TeV Detected by the Tibet ASγ Experiment, The Astrophysical Journal Letters, 961, id.L13, 4 pp (2024).
- S. Okukawa et al., Neural networks for separation of cosmic gamma rays and hadronic cosmic rays in air shower observation with a large area surface detector array, Machine Learning: Science and Technology, 5, id.025016, 21 pp (2024).
- S. Kato, "Gamma Rays in the 100 TeV Region from Potential Galactic PeVatron Candidates", Springer Theses (2024), doi: https://doi.org/10.1007/978-981-97-1643-2 (Book)
- H. Tsuchiya, "Characteristics of temporal variability of long-duration bursts of high-energy radiation associated with thunderclouds on the Tibetan plateau", Progress in Earth and Planetary Science, 11, article id.26 (2024)
- M. Amenomori et al, Modeling of TeV Galactic Cosmic-ray Anisotropy based on Intensity Mapping in an MHD Model Heliosphere, Journal of Physics: Conference Series, 2742, id.012014, 7 pp (2024).

Tibet ASγ Collaboration

M. Amenomori[1], S. Asano[2], Y. W. Bao[3], X. J. Bi[4], D. Chen[5], T. L. Chen[6], W. Y. Chen[4], Xu Chen[4,5], Y. Chen[3], Cirennima[6], S. W. Cui[7], Danzengluobu[6], L. K. Ding[4], J. H. Fang[4,8], K. Fang[4], C. F. Feng[9], Zhaoyang Feng[4], Z. Y. Feng[10], Qi Gao[6], A. Gomi[11], Q. B. Gou[4], Y. Q. Guo[4], Y. Y. Guo[4], Y. Hayashi[2], H. H. He[4], Z. T. He[7], K. Hibino[12], N. Hotta[13], Haibing Hu[6], H. B. Hu[4], K. Y. Hu[4,8], J. Huang[4], H. Y. Jia[10], L. Jiang[4], P. Jiang[5], H. B. Jin[5], K. Kasahara[14], Y. Katayose[11], C. Kato[2], S. Kato[15], I. Kawahara[11], T. Kawashima[15], K. Kawata[15], M. Kozai[16], D. Kurashige[11], Labaciren[6], G. M. Le[17], A. F. Li[4,9,18], H. J. Li[6], W. J. Li[4,10], Y. Li[5], Y. H. Lin[4,8], B. Liu[19], C. Liu[4], J. S. Liu[4], L. Y. Liu[5], M. Y. Liu[6], W. Liu[4], X. L. Liu[5], Y.-Q. Lou[20,21,22], H. Lu[4], X. R. Meng[6], Y. Meng[4,8], K. Munakata[2], K. Nagaya[11], Y. Nakamura[15], Y. Nakazawa[23], H. Nanjo[1], C. C. Ning[6], M. Nishizawa[24], R. Noguchi[11], M. Ohnishi[15], S. Okukawa[11], S. Ozawa[25], L. Qian[5], X. Qian[5], X. L. Qian[26], X. B. Qu[27], T. Saito[28], Y. Sakakibara[11], M. Sakata[29], T. Sako[15], T. K. Sako[15], T. Sasaki[12], J. Shao[4,9], M. Shibata[11], A. Shiomi[23], H. Sugimoto[30], W. Takano[12], M. Takita[15], Y. H. Tan[4], N. Tateyama[12], S. Torii[31], H. Tsuchiya[32], S. Udo[12], H. Wang[4], Y. P. Wang[6], Wangdui[6], H. R. Wu[4], Q. Wu[6], J. L. Xu[5], L. Xue[9], Z. Yang[4], Y. Q. Yao[5], J. Yin[5], Y. Yokoe[15], N. P. Yu[5], A. F. Yuan[6], L. M. Zhai[5], C. P. Zhang[5], H. M. Zhang[4], J. L. Zhang[4], X. Zhang[3], X. Y. Zhang[9], Y. Zhang[4], Yi Zhang[33], Ying Zhang[4], S. P. Zhao[4], Zhaxisangzhu[6], X. X. Zhou[10] and Y. H. Zou[4,8]

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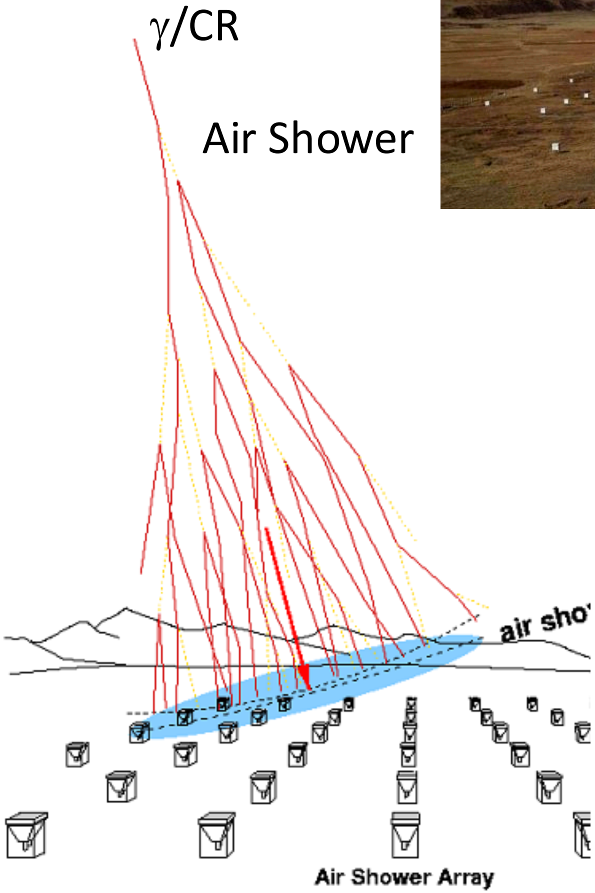
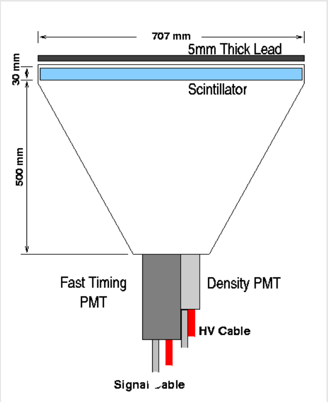
Tibet Air Shower Array



☐ Site: Tibet (90.522°E, 30.102°N) 4,300 m a.s.l.

<u>Present Performance</u>

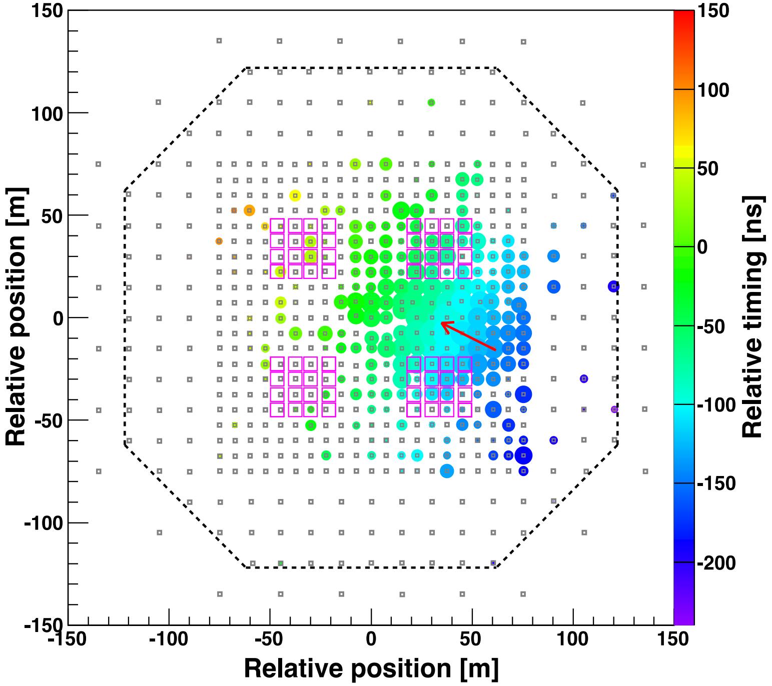
✓	# of detectors	0.5 m^2 x 597
✓	Covering area	~65,700 m^2
✓	Angular resolution	~0.5° @10TeV γ
		~0.2° @100TeV γ
✓	Energy resolution	~40%@10TeV γ
		~20%@100TeV γ



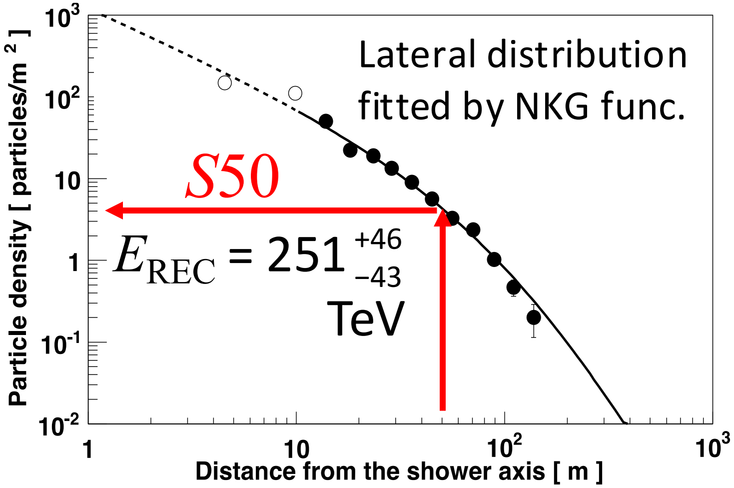
→Observation of secondary (mainly $e^{+/-}$,γ) in AS
Primary energy : 2^{nd} particle densities
Primary direction : 2^{nd} relative timings

Air Shower Reconstruction

Gamma-ray candidate event



Amenomori +, PRL ***123****, 051101 (2019)*



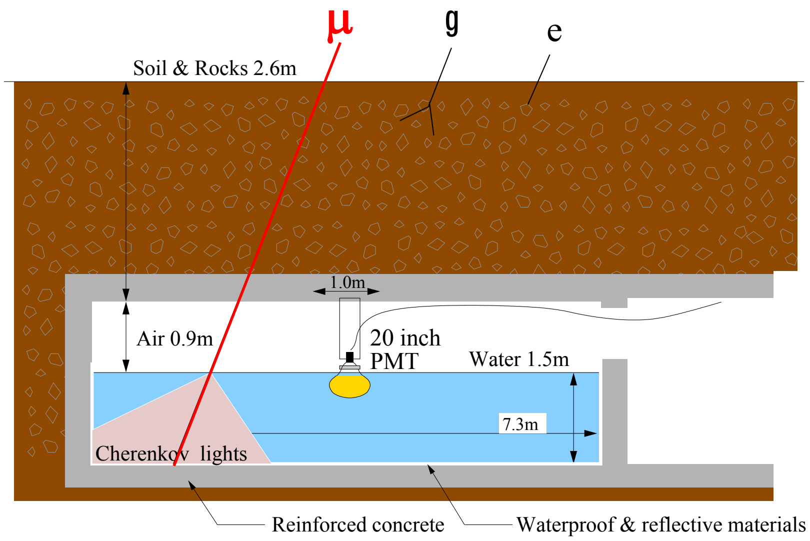
S50 improves *E* resolutions (10 - 1000 TeV)
→ ~40%@10 TeV , ~20%@100 TeV

Kawata+, Experimental Astronomy ***44****, 1 (2017)*

circle size ∝ log(# of detected particles)
circle color ∝ relative timing [ns]

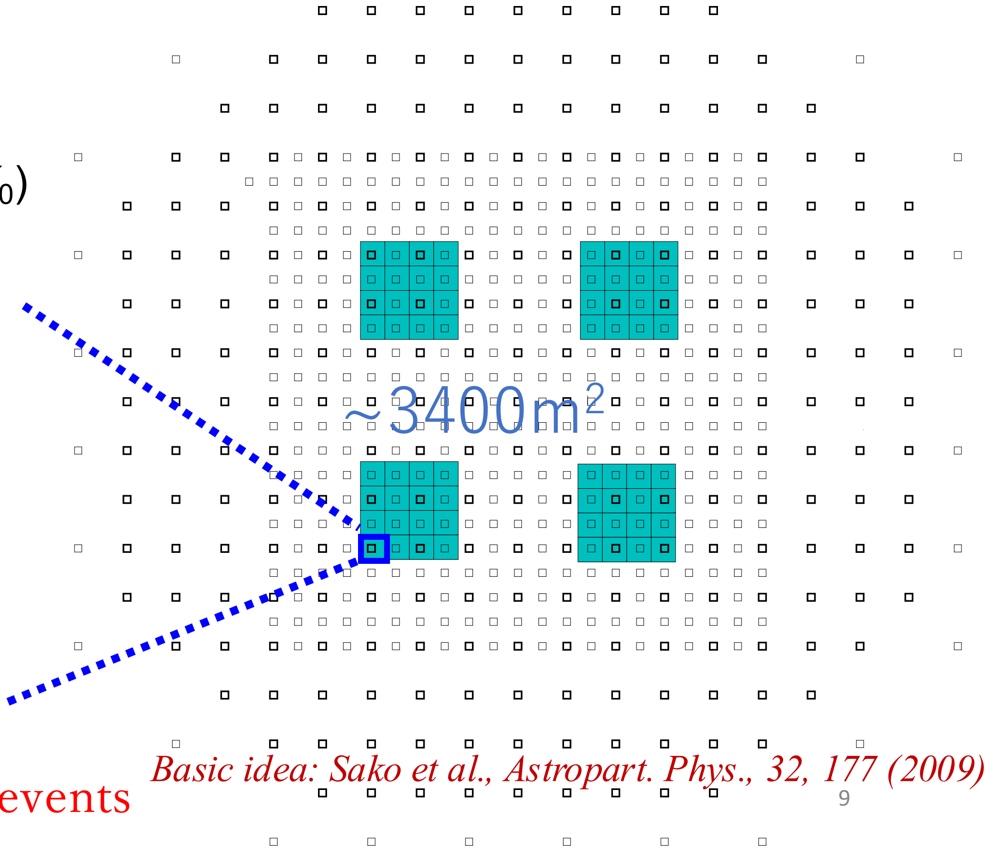
Underground WC Muon Detectors

- ✓ 4 pools, 16 units / pool
- ✓ 54 m^2 in area × 1.5m in depth / unit
- ✓ 20”ΦPMT (HAMAMATSU R3600)
- ✓ Concrete pools + white Tyvek sheets
- ✓ 2.4m soil overburden (~515g/cm^2 ~9X_0)



Measurement of # of μ in AS → γ/CR discrimination

DATA: February 2014 - May 2017 Live time: 719 days

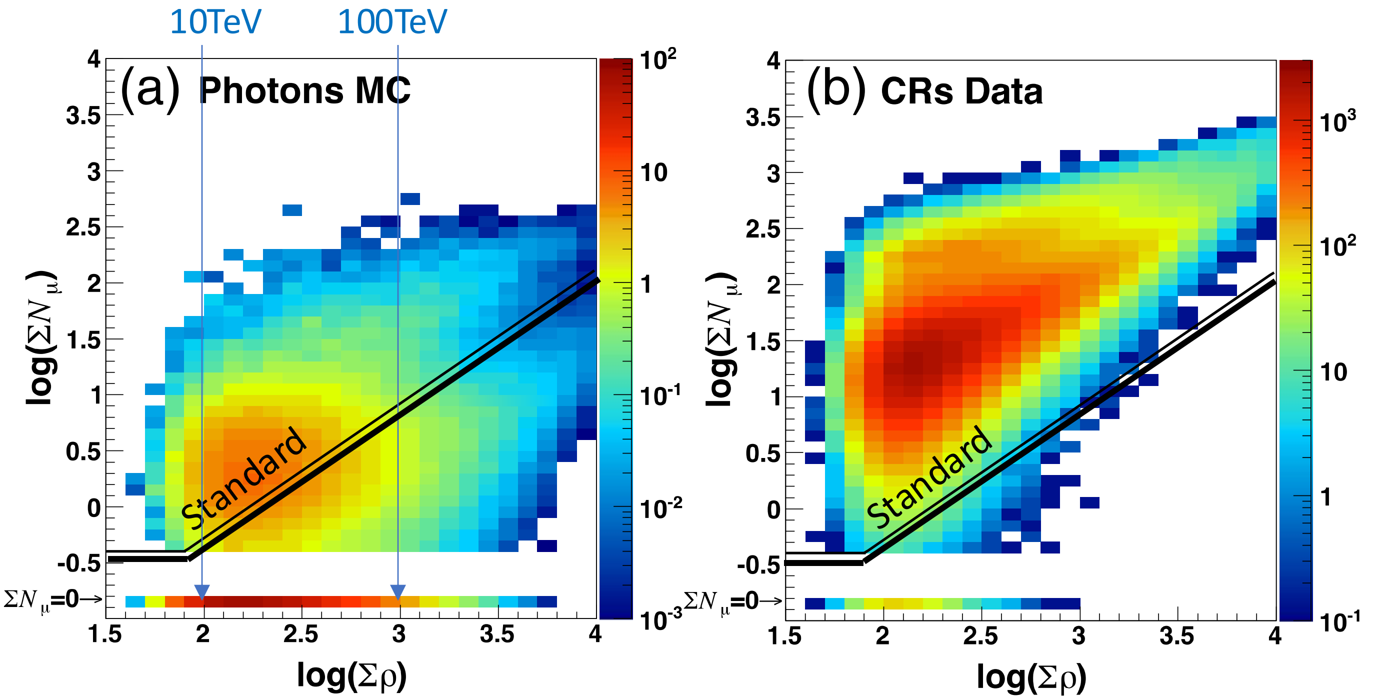


→Succeeded in rejecting by >99.9% CR events

Basic idea: Sako et al., Astropart. Phys., 32, 177 (2009)

Muon Cut Condition (Standard)

Standard muon cut : $\Sigma N\mu < 2.1 \times 10^{-3}\ \Sigma\rho^{1.2}$ → Optimized for the gamma-ray point-like source

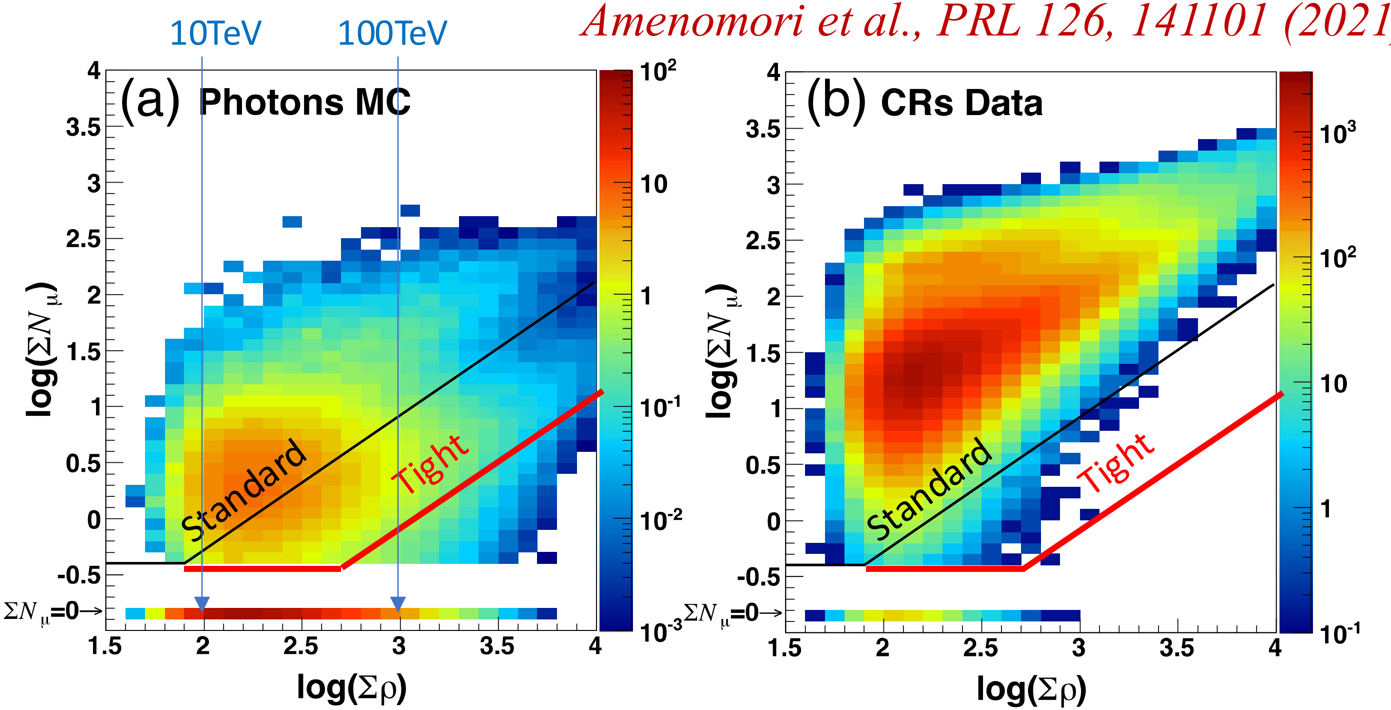


Gamma Survival ratio : ~90% by MC sim (>100TeV)   CR Survival ratio : ~10^{-3} (>100TeV)

Muon Cut Condition (Tight) for Diffuse γ

Tight muon cut : $\Sigma N\mu < 2.1 \times 10^{-4}\ \Sigma\rho^{1.2}$ → One order magnitude tighter than the Crab analysis

Amenomori et al., PRL 126, 141101 (2021)



Gamma Survival ratio : ~30% by MC sim (>398TeV) CR Survival ratio : $\sim 10^{-6}$ (>398TeV=$10^{2.6}$TeV)

γ-ray-like event Distribution

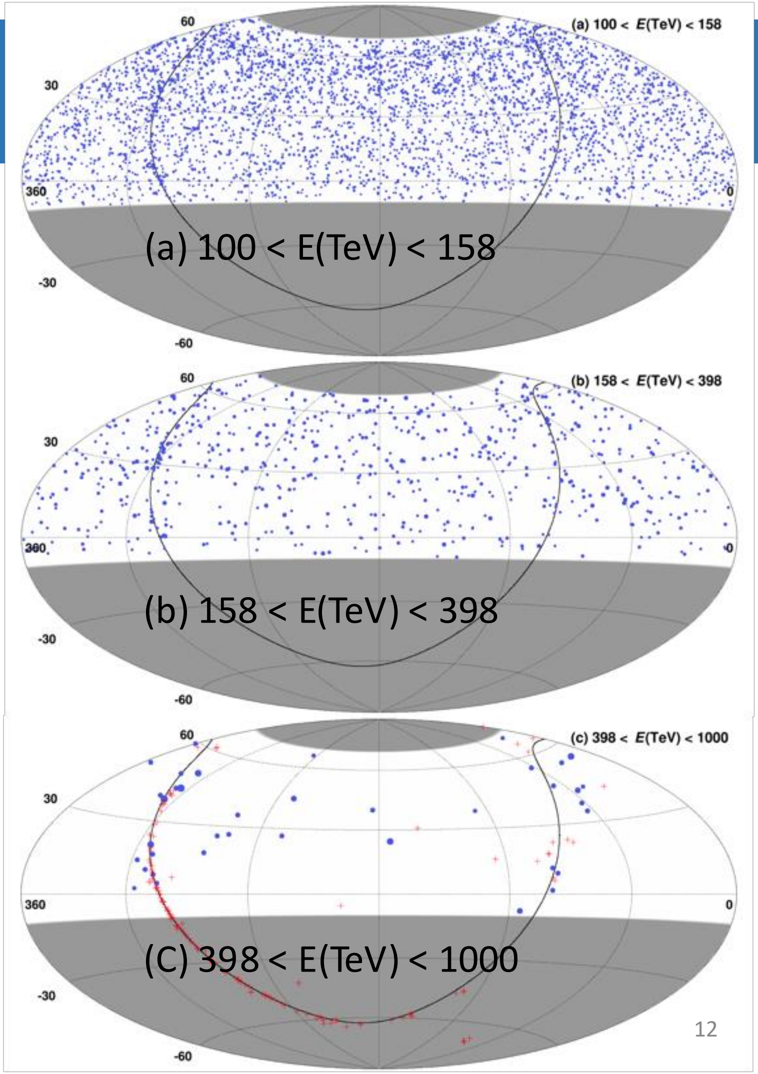
Amenomori et al., PRL 126, 141101 (2021)

Gamma-ray-like events
after the tight muon cut
in the equatorial coordinates

Blue points:
Experimental data

Red plus marks:
known Galactic TeV sources

>398 TeV ($10^{2.6}$ TeV)
38 events in our FoV
23 events in $|b| < 10^{o}$
16 events in $|b| < 5^{o}$



Latitude Profile

Amenomori et al., PRL 126, 141101 (2021)

Red points:
experimental data across our FoV ($22^o < l < 225^o$)
including source contribution

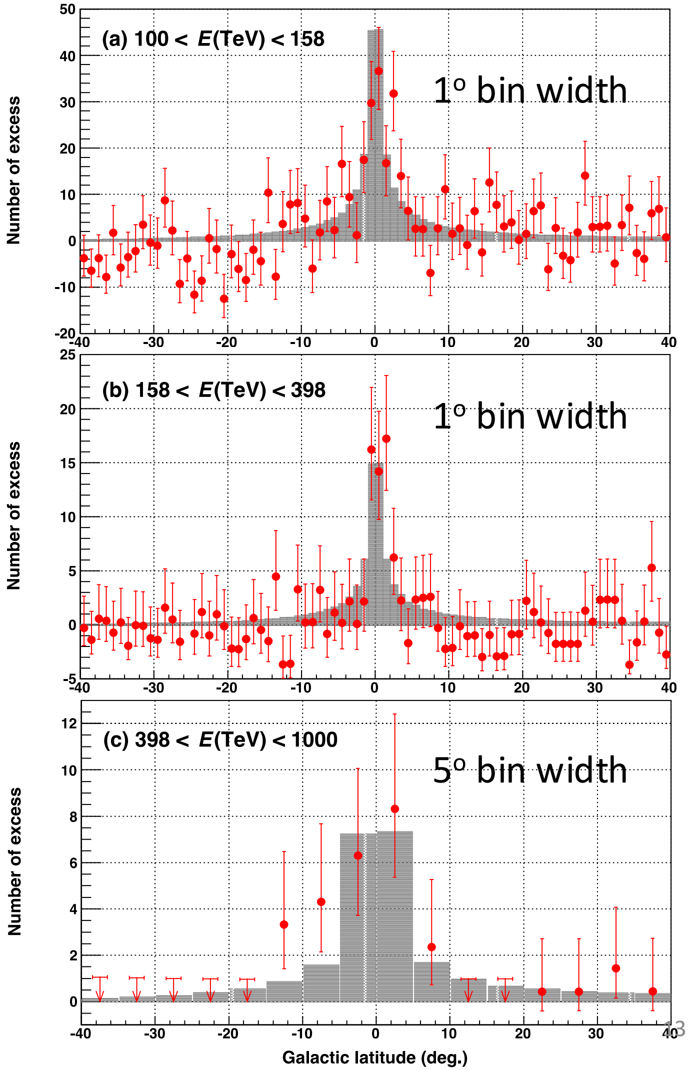
Gray shade histogram:
Model by Lipari and Vernetto

Lipari & Vernetto, PRD 98, 043003 (2018)

6.6σ

5.1σ

5.9σ



Energy Spectrum of UHE Diffuse γ Rays

Amenomori et al., PRL 126, 141101 (2021)

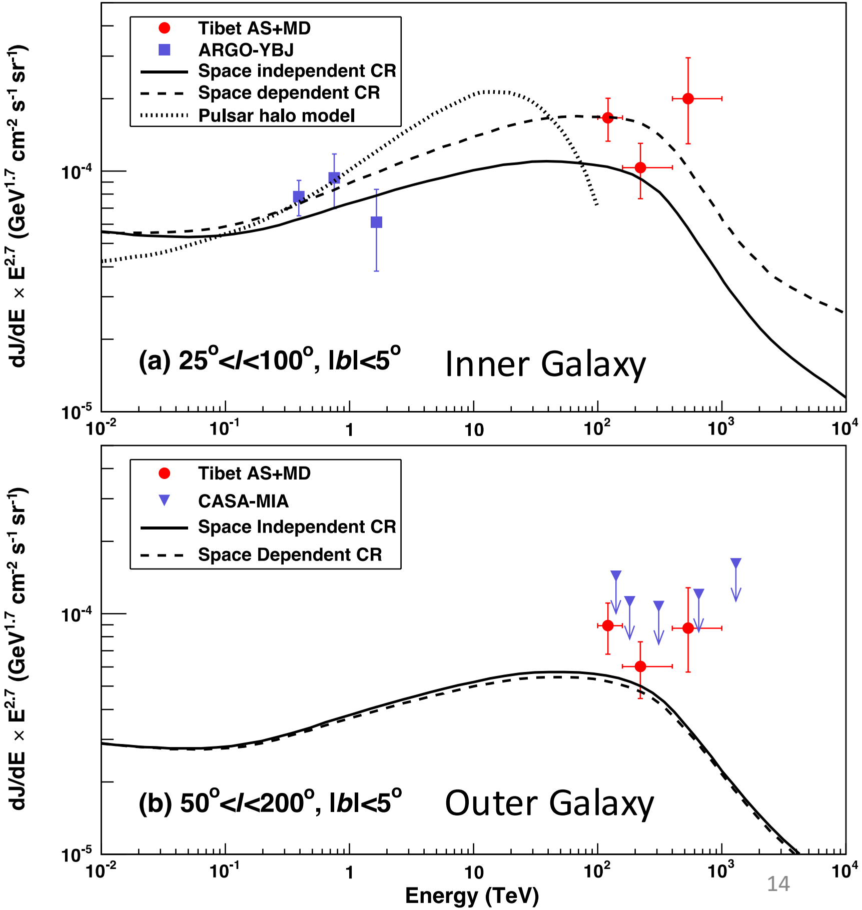
After excluding the contribution from the known TeV sources (within 0.5 degrees) listed in the TeV source catalog

↓

The measured fluxes are overall consistent with Lipari's diffuse gamma model assuming the hadronic cosmic ray origin.

$$\mathrm{CR} + \mathrm{ISM} \rightarrow X\text{'s} + \pi^0 \ldots \rightarrow 2\gamma$$

Lipari & Vernetto, PRD 98, 043003 (2018)



LHAASO Diffuse Gamma Rays

Z. Cao et al. (LHAASO Collob.) PRL, 131, 151001 (2023)

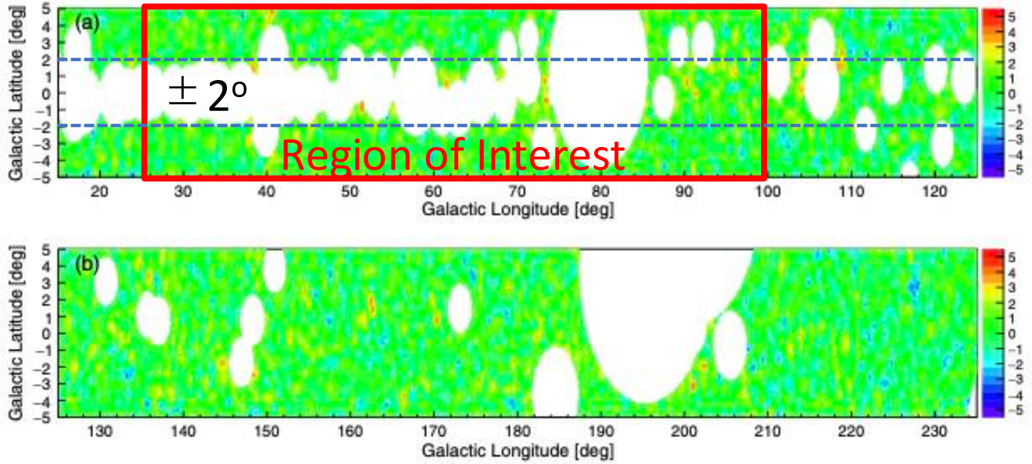
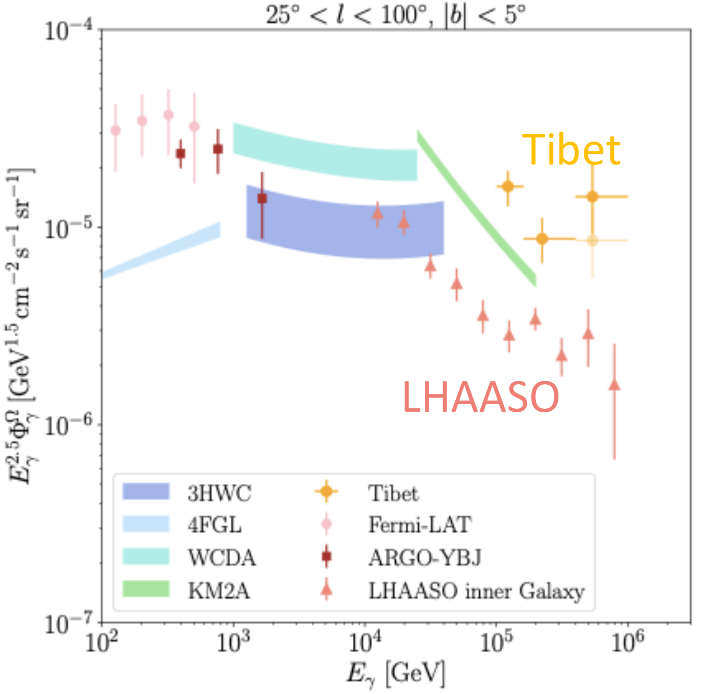


FIG. 1. The significance maps in Galactic coordinate of the inner Galaxy region [panel (a)] and outer Galaxy region [panel (b)] above 25 TeV after masking the resolved KM2A and TeVCat sources.

K. Fang & K. Murase, ApJ, 957, L6 (2023)



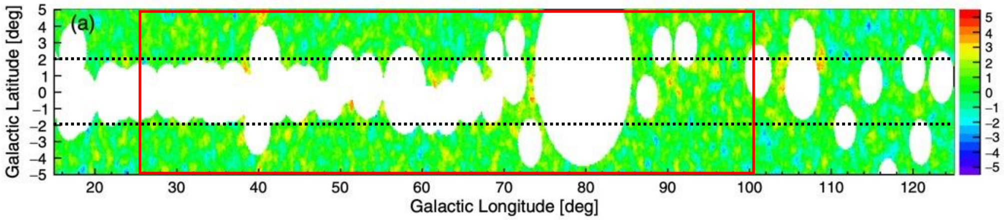
LHAASO flux is a few times lower than Tibet flux, LHAASO conservatively masks most of region $l \pm 2^o$.
→ This discrepancy can be explained assuming diffuse gamma ray latitude profile.

LHAASO Diffuse Gamma Rays

$$\frac{\text{Tibet GDE } (25^\circ<l<100^\circ, |b|<5^\circ) - \text{Source}}{\text{LHAASO GDE}^{1}\ (15^\circ<l<125^\circ, |b|<5^\circ)} = 3,\ 2,\ \&\ 7\ @\ 120\text{TeV},\ 220\text{TeV},\ \&\ 530\text{TeV}$$

Kato et al. ApJ, 977, L3 (2024)

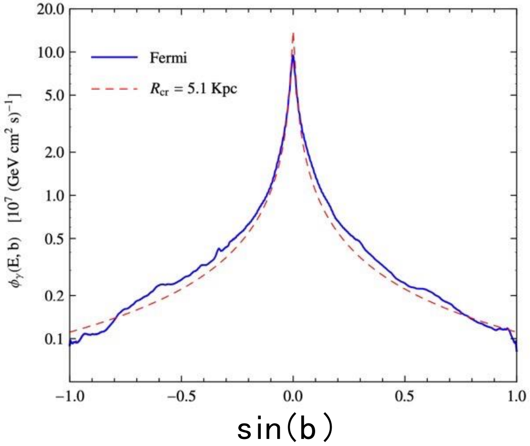
LHAAASO masking in the inner Galaxy[1]



: Tibet region A (25° < l < 100° & |b| < 5°)

LHAASO masks most of the region w/i |b| < 2°

1. Cao et al., PRL 131, 151001 (2023)
2. Lipari & Vernetto, PRD 98, 043003 (2018)



GDE latitudinal distribution*by Lipari & Vernetto (2018)[2]

*The distribution is Integrated over |l| < 180°

Using the theoretical prediction,

<u>Flux(|b|<5°)</u> ÷<u>Flux(2°<|b|<5°)</u> ~ 3

~ Tibet region A   ~ LHAASO inner Gal. plane

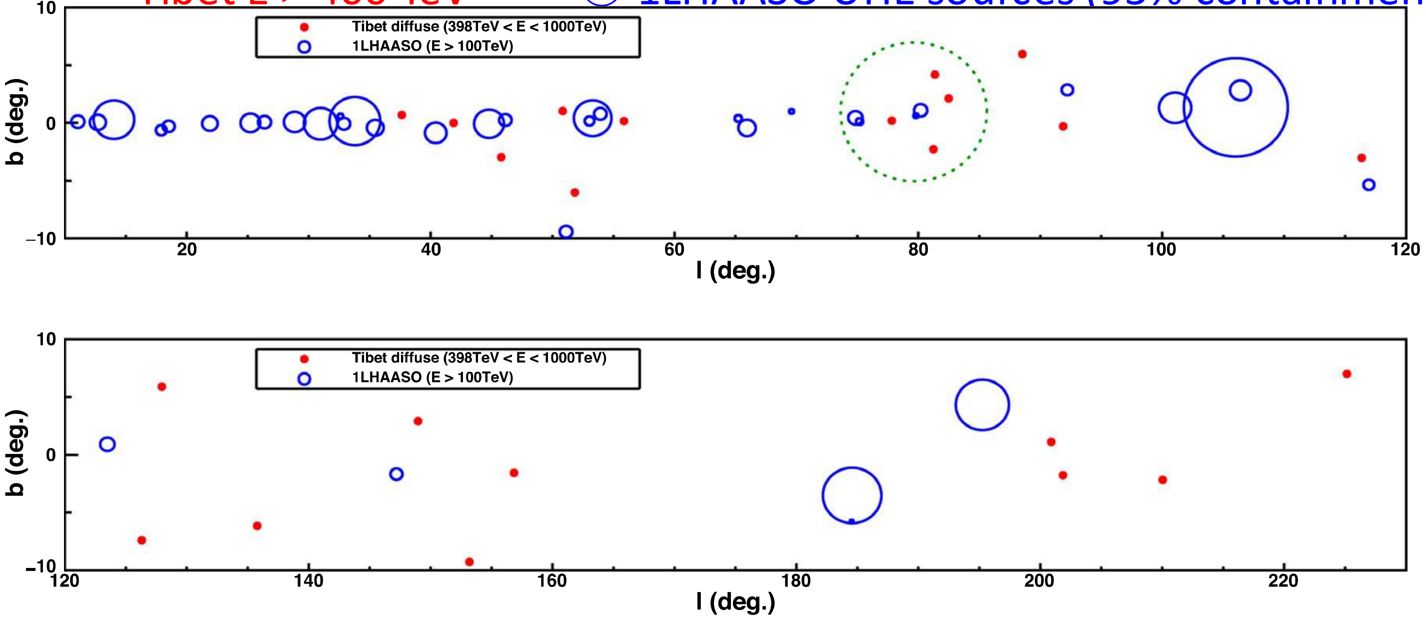
The following scenario can explain the difference:

They observe hadronic GDE, <u>but in the different Galactic latitudinal regions due to their different masking schemes</u>

1LHAASO Catalog and Tibet UHE Diffuse Events

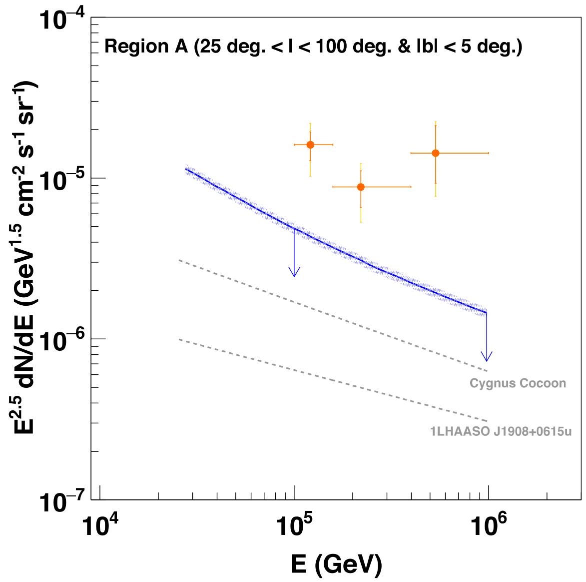
Kato et al. ApJ, 961, L13 (2024)

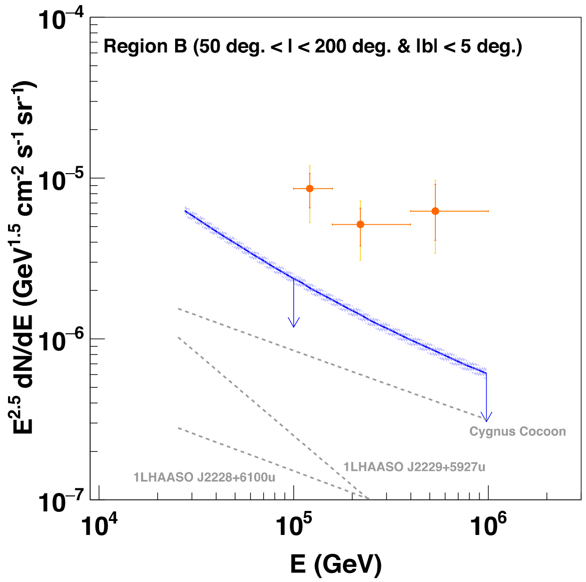
• Tibet E > 400 TeV ◯ 1LHAASO UHE sources (95% containment radius)



Tibet Galactic diffuse gamma rays above 400 TeV:
do NOT overlap with 1LHAASO UHE (>100 TeV) sources.
* Expected # of accidental overlap = 0.9 events

Source Contribution to the Tibet Diffuse





Integral flux of 1LHAASO sources (>100TeV) outside the Tibet Masked region

Kato et al. ApJ, 977, L3 (2024)

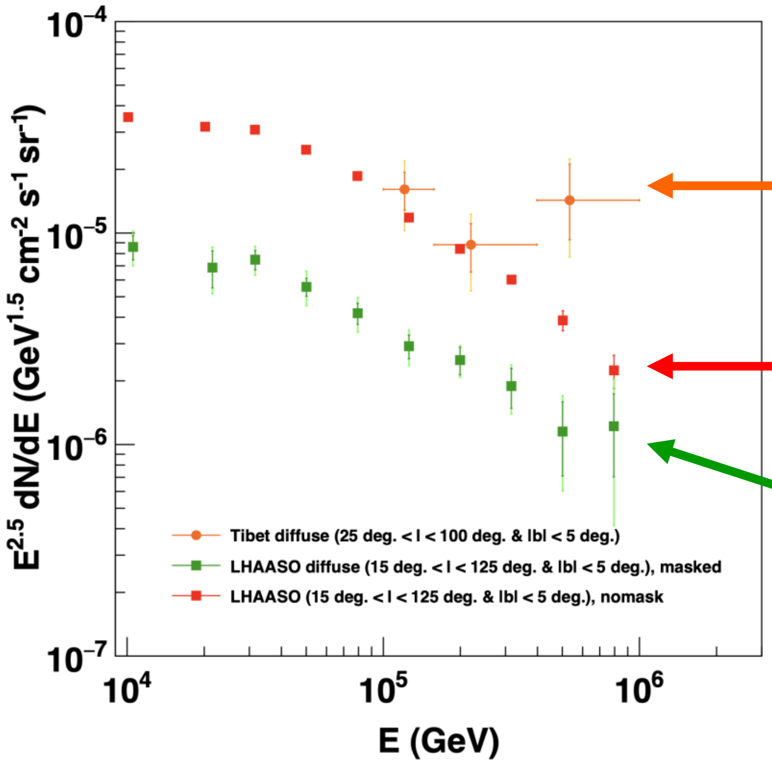
Source / Tibet GDE	Region A (25°<l<100° & |b|<5°)	Region B (50°<l<200° & |b|<5°)
121 TeV	< 26.9%±9.9%	< 24.1%±9.5%
220 TeV	< 34.8%±14.0%	< 27.4%±11.1%
534 TeV	$< 13.5\%^{+6.3\%}_{-7.7\%}$	$< 13.5\%^{+6.2\%}_{-7.6\%}$

Source Contribution is subdominant

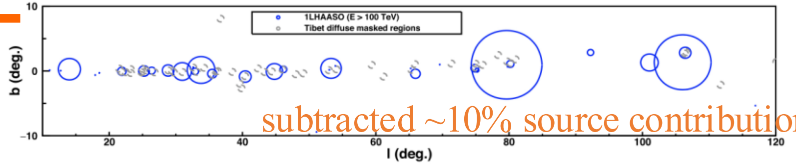
Comparison with LHAASO Non-Masked Flux

arXiv:2411.16021v2 (LHAASO Collabo.)
(Supplemental Material)

Measurement of Very-high-energy Diffuse Gamma-ray Emissions from the Galactic Plane with LHAASO-WCDA



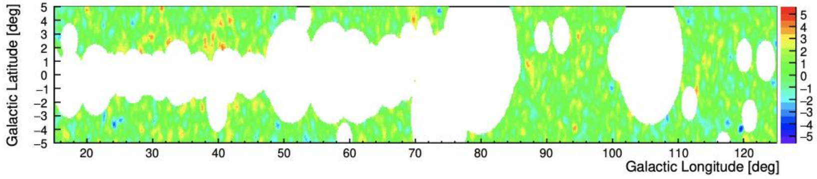
Tibet masked diffuse flux (PRL2021)



subtracted ~10% source contribution

LHAASO NON-masked flux (arXiv:2411.16021v2)

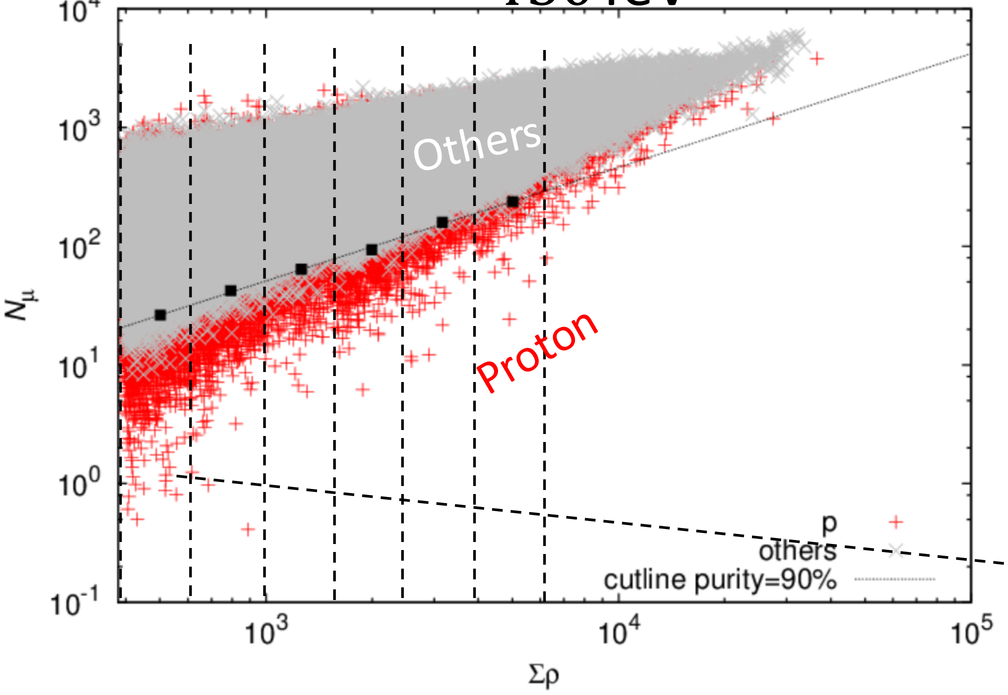
LHAASO masked diffuse flux (arXiv:2411.16021v2)



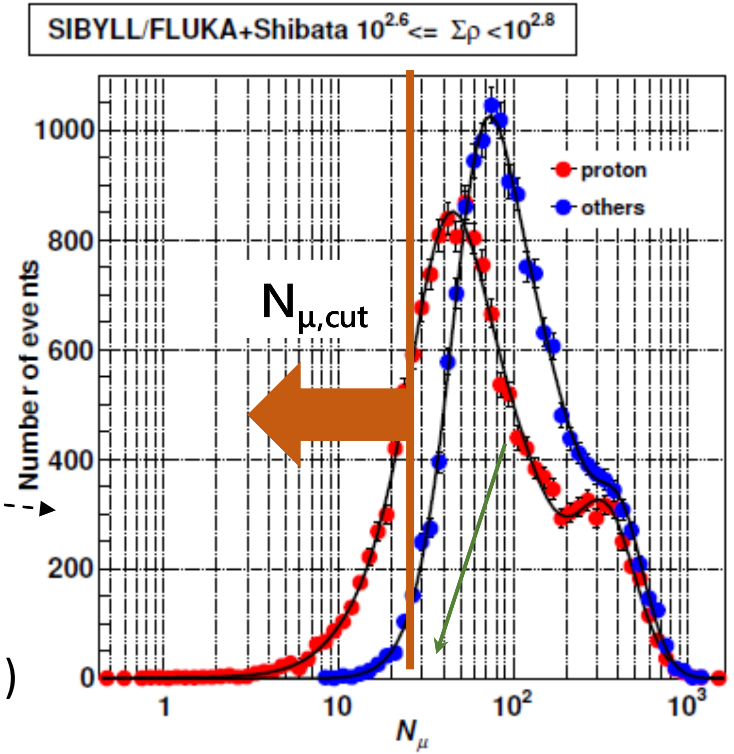
Proton Spectrum Study by Tibet AS+MD

Katayose et al., ICRC2023 etc.

~35TeV ~ 450TeV



N_μ distribuion



Number of muon particles in an AS + a cut value($N_{\mu,cut}$)

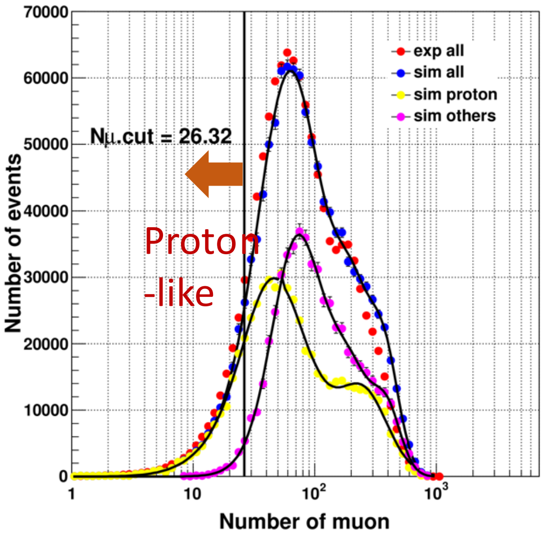
-> Protons are separated with a 90 % purity.

Proton Spectrum Study by Tibet AS+MD

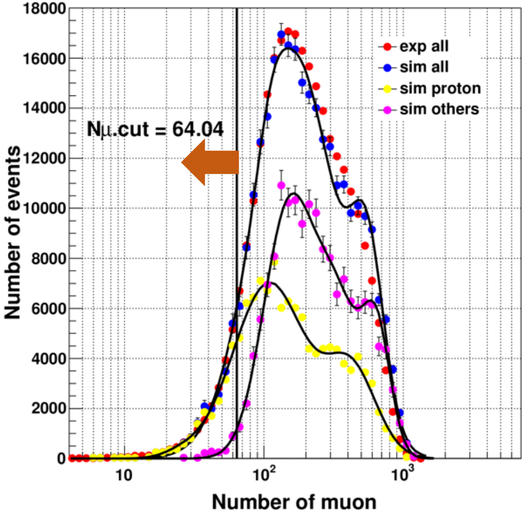
Katayose et al., ICRC2023 etc.

Red: Data(Data period: 12 days)
, Blue:Sim-all, Yellow: Sim-proton, Purple:Sim-others

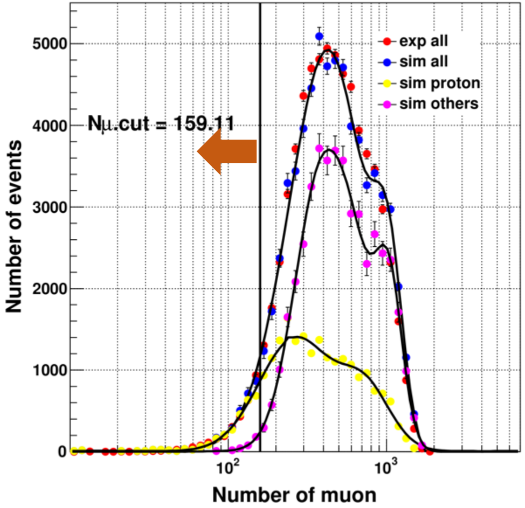
$10^{2.6} \leq \Sigma\rho < 10^{2.8}$



$10^{3.0} \leq \Sigma\rho < 10^{3.2}$



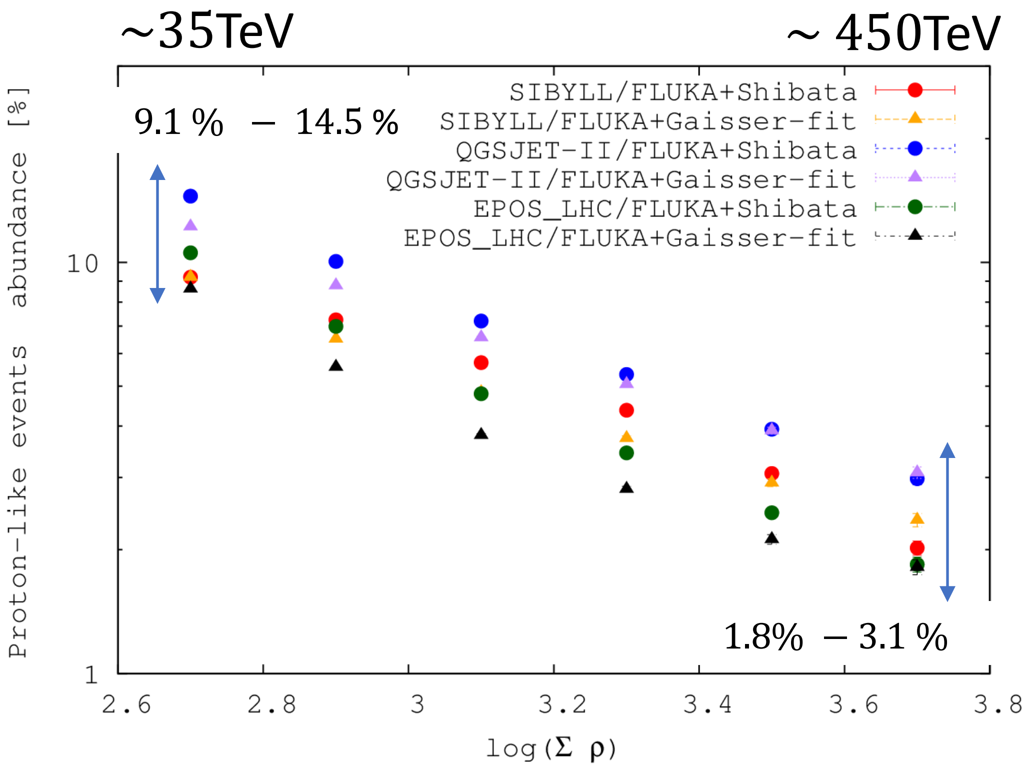
$10^{3.4} \leq \Sigma\rho < 10^{3.6}$



$N\mu$ distribution Data and MC(SIBYLL/FKUKA+Shibata)

Proton Spectrum Study by Tibet AS+MD

Katayose et al., ICRC2023 etc.



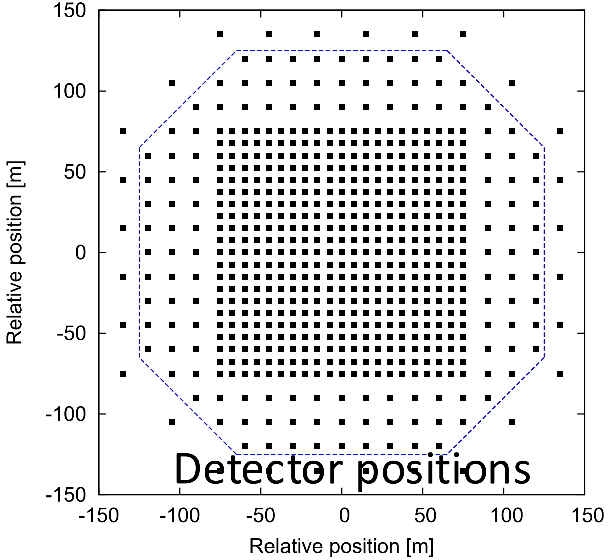
Ratio proton-like events to whole well-reconstructed events with different hadronic interaction models and Composition models

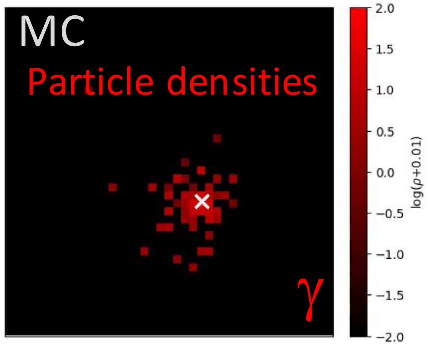
A detailed evaluation of systematic errors is currently underway

γ/p Separation with the Machine Learning

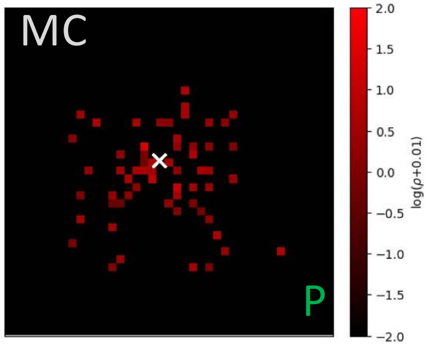
2D image-like data from
the positions of each detector
and the particle densities

Okukawa et al., Machine Learning: Science and Technology, 5, id.025016 (2024)



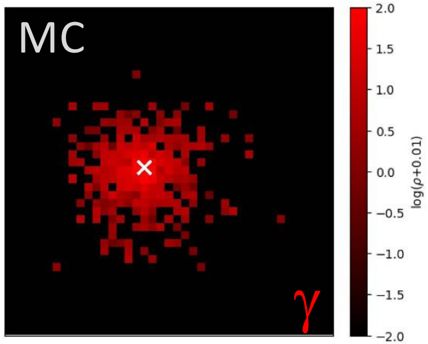


(a) 10 TeV gamma ray

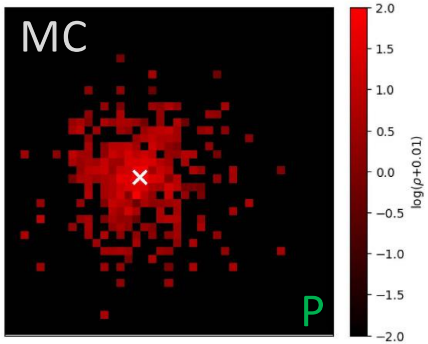


(b) 21 TeV proton

Air showers generation: CORSIKA (Version 7.6400)
Detector simulation: based on GEANT4.10.02



(c) 100 TeV gamma ray



(d) 165 TeV proton

γ/p Separation with the Machine Learning

We constructed a CNN architecture consisting of consecutive processes, referencing the *Inception-v3* image recognition model.

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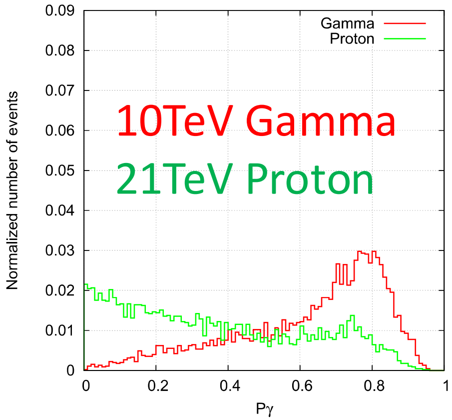
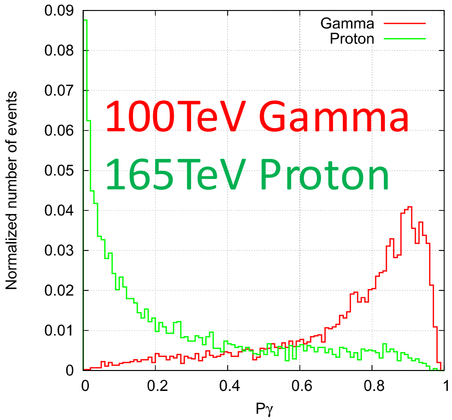
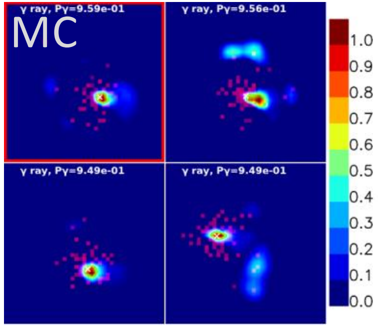


(a) 10 TeV gamma rays, 21 TeV protons

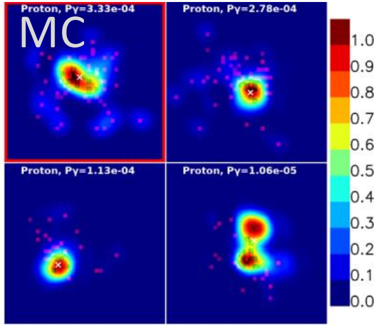


(b) 100 TeV gamma rays, 165 TeV proton

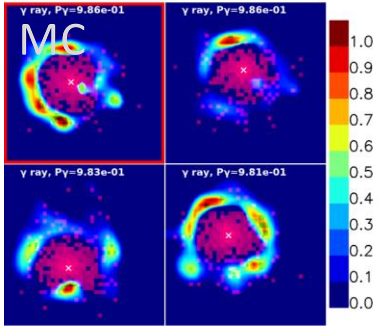
Heatmaps analyzed by Grad-CAM.



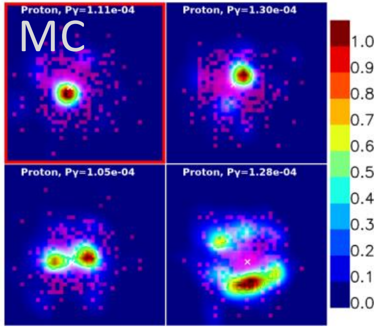
(a) 10 TeV gamma rays



(b) 21 TeV protons



(c) 100 TeV gamma rays



(d) 165 TeV protons

γ/p Separation with the Machine Learning

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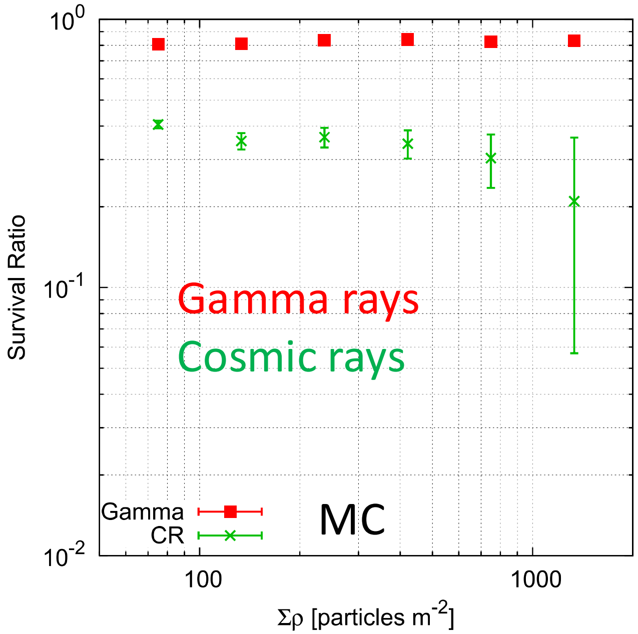
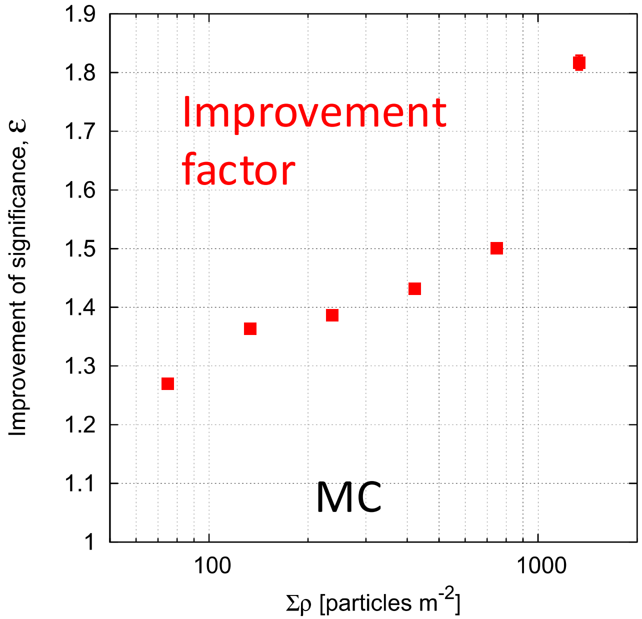
MC simulation assuming the Crab Nebula orbit

→ How much sensitivity is improved for gamma-ray sources?

→ The method can be applied to all the past data recorded without MD.





Summary

- ✓ Tibet ASγ experiment successfully observed Galactic diffuse gamma rays between 100 TeV and 1 PeV for the first time.
- ✓ Tibet UHE events (>400 TeV) do not originate from LHAASO UHE (>100 TeV) sources. Possible source contribution from LHAASO UHE sources is less than 20-30%.
- ✓ Tibet UHE Diffuse gamma-ray spectrum (subtracted ~10% source contribution) is compatible with the non-masked LHAASO spectrum within uncertainties.
- ✓ Studies of the proton spectrum/abundance in the energy range between 40 TeV and a few hundred TeV with the Tibet AS+MD are underway.
- ✓ The method of γ/p separation using only the particle density distribution measured by the Tibet AS array has been developed with the convolutional neural network (CNN).