Telescope Array Experiment Highlights on Composition and Anisotropy

For the Telescope Array Collaboration

Charlie Jui, University of Utah, Jan 23, 2018

"SuGAR 2018: Searching for the sources of galactic and extra galactic cosmic rays"

Outline

- Latest Hybrid Xmax measurements from TA FD
  - Xmax Distributions vs MC simulation for 4 pure primaries
  - <Xmax> vs LogE
  - σ(Xmax) vs <Xmax>
  - Interpretation of Results: Shape Analysis
- Anisotropy
  - Global anisotropy
  - Hotspot
  - Coldspot
  - Large Scale Structure
  - Anisotropy in the spectrum
  - Small scale Anisotropy
- Ralph says I have to show the TALE spectrum

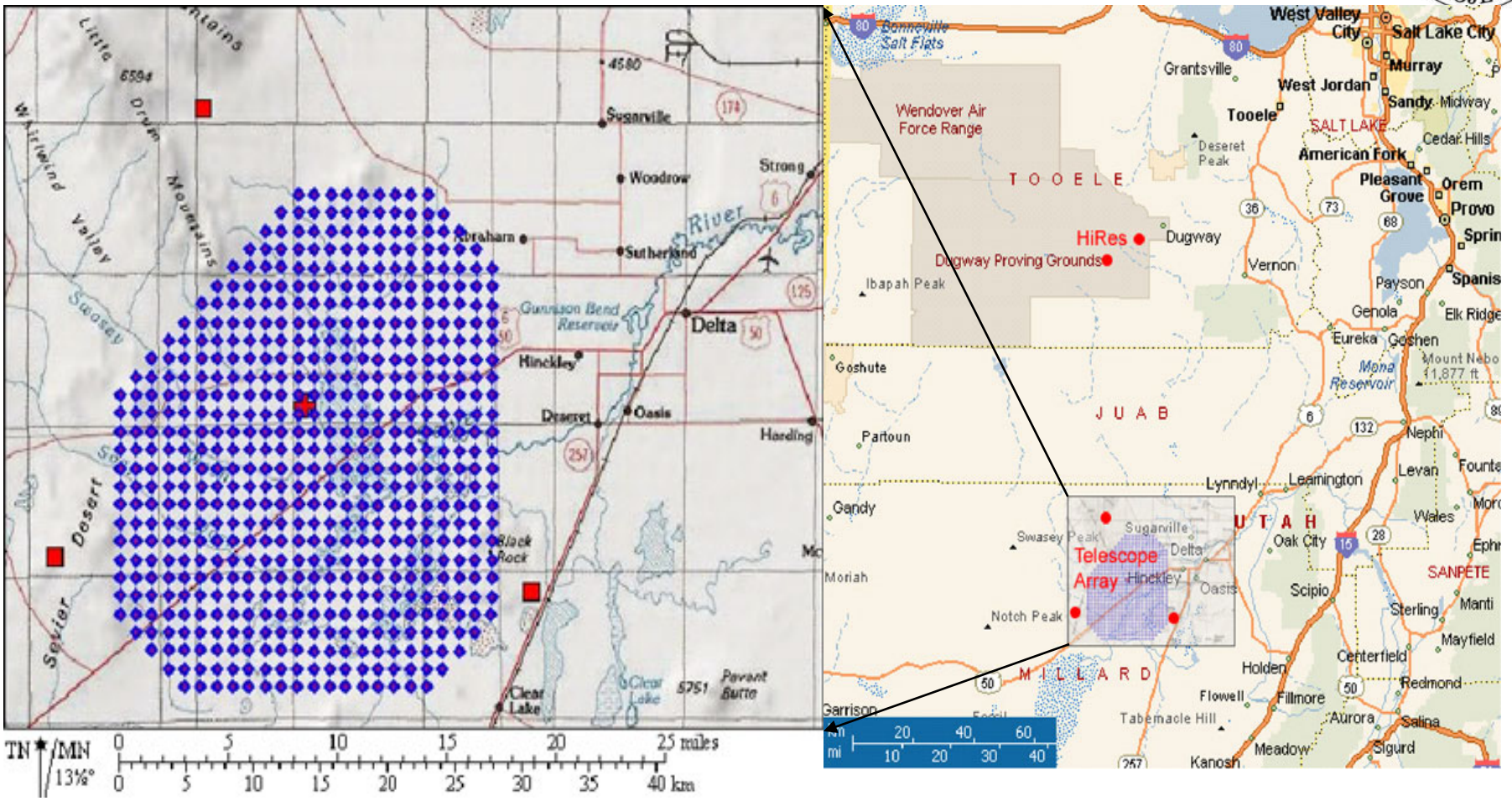
Temporarily
~~Open~~
~~Closed~~
Open?

R.U. Abbasi,[1] M. Abe,[2] T. Abu-Zayyad,[1] M. Allen,[1] R. Azuma,[3] E. Barcikowski,[1] J.W. Belz,[1] D.R. Bergman,[1] S.A. Blake,[1] R. Cady,[1] M.J. Chae,[4] B.G. Cheon,[5] J. Chiba,[6] M. Chikawa,[7] W.R. Cho,[8] T. Fujii,[9] M. Fukushima,[9,10] T. Goto,[11] W. Hanlon,[1] Y. Hayashi,[11] N. Hayashida,[12] K. Hibino,[12] K. Honda,[13] D. Ikeda,[9] N. Inoue,[2] T. Ishii,[13] R. Ishimori,[3] H. Ito,[14] D. Ivanov,[1] C.C.H. Jui,[1] K. Kadota,[15] F. Kakimoto,[3] O. Kalashev,[16] K. Kasahara,[17] H. Kawai,[18] S. Kawakami,[11] S. Kawana,[2] K. Kawata,[9] E. Kido,[9] H.B. Kim,[5] J.H. Kim,[1] J.H. Kim,[19] S. Kitamura,[3] Y. Kitamura,[3] V. Kuzmin,[16] Y.J. Kwon,[8] J. Lan,[1] S.I. Lim,[4] J.P. Lundquist,[1] K. Machida,[13] K. Martens,[10] T. Matsuda,[20] T. Matsuyama,[11] J.N. Matthews,[1] M. Minamino,[11] Y. Mukai,[13] I. Myers,[1] K. Nagasawa,[2] S. Nagataki,[14] T. Nakamura,[21] T. Nonaka,[9] A. Nozato,[7] S. Ogio,[11] J. Ogura,[3] M. Ohnishi,[9] H. Ohoka,[9] K. Oki,[9] T. Okuda,[22] M. Ono,[23] A. Oshima,[24] S. Ozawa,[17] I.H. Park,[25] M.S. Pshirkov,[16,26] D.C. Rodriguez,[1] G. Rubtsov,[16] D. Ryu,[19] H. Sagawa,[9] N. Sakurai,[11] L.M. Scott,[27] P.D. Shah,[1] F. Shibata,[13] T. Shibata,[9] H. Shimodaira,[9] B.K. Shin,[5] H.S. Shin,[9] J.D. Smith,[1] P. Sokolsky,[1] R.W. Springer,[1] B.T. Stokes,[1] S.R. Stratton,[1,27] T.A. Stroman,[1] T. Suzawa,[2] M. Takamura,[6] M. Takeda,[9] R. Takeishi,[9] A. Taketa,[28] M. Takita,[9] Y. Tameda,[12] H. Tanaka,[11] K. Tanaka,[29] M. Tanaka,[20] S.B. Thomas,[1] G.B. Thomson,[1] P. Tinyakov,[30,16] I. Tkachev,[16] H. Tokuno,[3] T. Tomida,[31] S. Troitsky,[16] Y. Tsunesada,[3] K. Tsutsumi,[3] Y. Uchihori,[32] S. Udo,[12] F. Urban,[30] G. Vasiloff,[1] T. Wong,[1] R. Yamane,[11] H. Yamaoka,[20] K. Yamazaki,[28] J. Yang,[4] K. Yashiro,[6] Y. Yoneda,[11] S. Yoshida,[18] H. Yoshii,[33] R. Zollinger,[1] and Z. Zundel[1]

[1] *High Energy Astrophysics Institute and Department of Physics and Astronomy, University of Utah, Salt Lake City, Utah, USA*
[2] *The Graduate School of Science and Engineering, Saitama University, Saitama, Saitama, Japan*
[3] *Graduate School of Science and Engineering, Tokyo Institute of Technology, Meguro, Tokyo, Japan*
[4] *Department of Physics and Institute for the Early Universe, Ewha Womans University, Seodaemun-gu, Seoul, Korea*
[5] *Department of Physics and The Research Institute of Natural Science, Hanyang University, Seongdong-gu, Seoul, Korea*
[6] *Department of Physics, Tokyo University of Science, Noda, Chiba, Japan*
[7] *Department of Physics, Kinki University, Higashi Osaka, Osaka, Japan*
[8] *Department of Physics, Yonsei University, Seodaemun-gu, Seoul, Korea*
[9] *Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba, Japan*
[10] *Kavli Institute for the Physics and Mathematics of the Universe (WPI), Todai Institutes for Advanced Study, the University of Tokyo, Kashiwa, Chiba, Japan*
[11] *Graduate School of Science, Osaka City University, Osaka, Osaka, Japan*
[12] *Faculty of Engineering, Kanagawa University, Yokohama, Kanagawa, Japan*
[13] *Interdisciplinary Graduate School of Medicine and Engineering, University of Yamanashi, Kofu, Yamanashi, Japan*
[14] *Astrophysical Big Bang Laboratory, RIKEN, Wako, Saitama, Japan*
[15] *Department of Physics, Tokyo City University, Setagaya-ku, Tokyo, Japan*
[16] *Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia*
[17] *Advanced Research Institute for Science and Engineering, Waseda University, Shinjuku-ku, Tokyo, Japan*
[18] *Department of Physics, Chiba University, Chiba, Chiba, Japan*
[19] *Department of Physics, School of Natural Sciences, Ulsan National Institute of Science and Technology, UNIST-gil, Ulsan, Korea*
[20] *Institute of Particle and Nuclear Studies, KEK, Tsukuba, Ibaraki, Japan*
[21] *Faculty of Science, Kochi University, Kochi, Kochi, Japan*
[22] *Department of Physical Sciences, Ritsumeikan University, Kusatsu, Shiga, Japan*
[23] *Department of Physics, Kyushu University, Fukuoka, Fukuoka, Japan*
[24] *Engineering Science Laboratory, Chubu University, Kasugai, Aichi, Japan*
[25] *Department of Physics, Sungkyunkwan University, Jang-an-gu, Suwon, Korea*
[26] *Sternberg Astronomical Institute, Moscow M.V. Lomonosov State University, Moscow, Russia*
[27] *Department of Physics and Astronomy, Rutgers University – The State University of New Jersey, Piscataway, New Jersey, USA*
[28] *Earthquake Research Institute, University of Tokyo, Bunkyo-ku, Tokyo, Japan*
[29] *Graduate School of Information Sciences, Hiroshima City University, Hiroshima, Hiroshima, Japan*
[30] *Service de Physique Théorique, Université Libre de Bruxelles, Brussels, Belgium*
[31] *Department of Computer Science and Engineering, Shinshu University, Nagano, Nagano, Japan*
[32] *National Institute of Radiological Science, Chiba, Chiba, Japan*
[33] *Department of Physics, Ehime University, Matsuyama, Ehime, Japan*

5 nations, 33 institutions, 124 members

Telescope Array



507 scintillation counters surface detector (SD): Area: ~700 km^2.

3 fluorescence detector (FD) stations

In operation since 2008

TA Fluorescence Detectors

Refurbished from HiRes-I

Observations since ~10/2007

Middle Drum

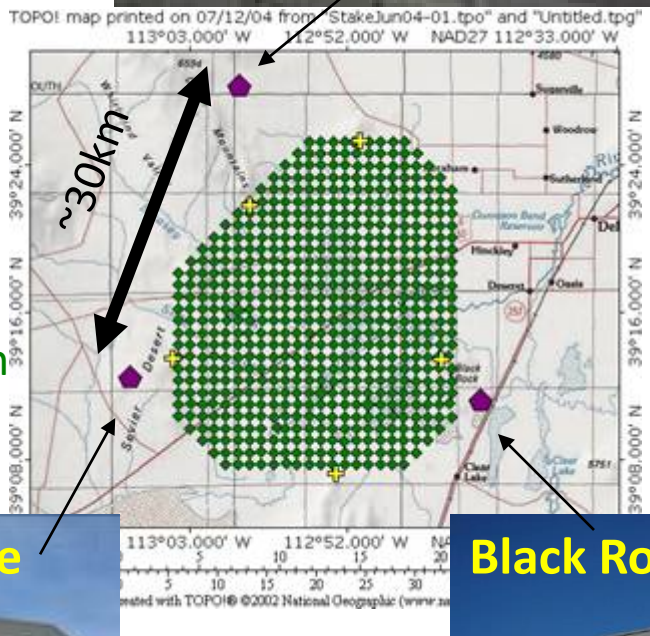
14 telescopes@station
256 PMTs/camera

5.2 m^2

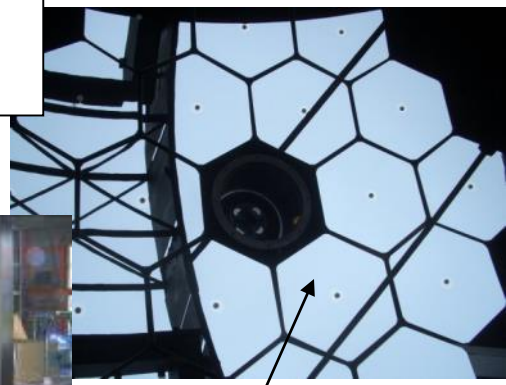
1° pixels

New FDs

Observation since ~11/2007



12 telescopes/station
256 PMTs/camera
Hamamatsu R9508
FOV~15x18deg



6.8 m^2

Long Ridge

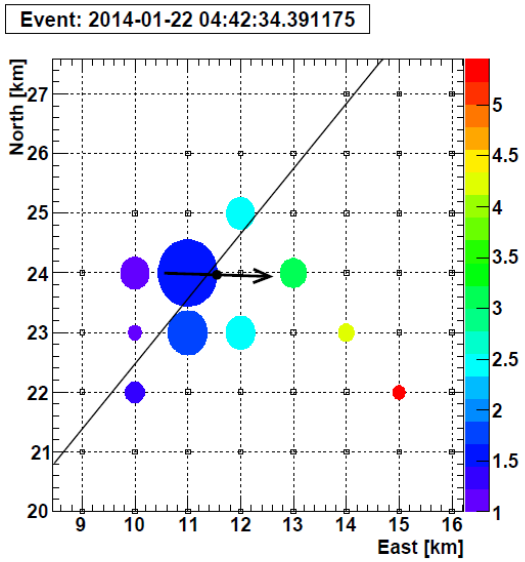
Observation since ~6/2007

Black Rock Mesa

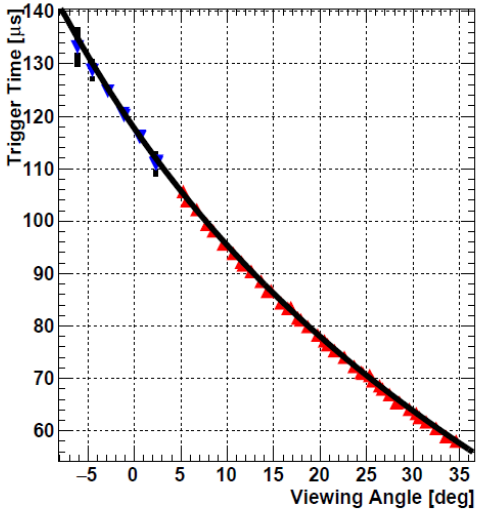
~1 m^2

Latest Composition: FD Xmax; shower geometry: timing fit including SD

Event Display: SD



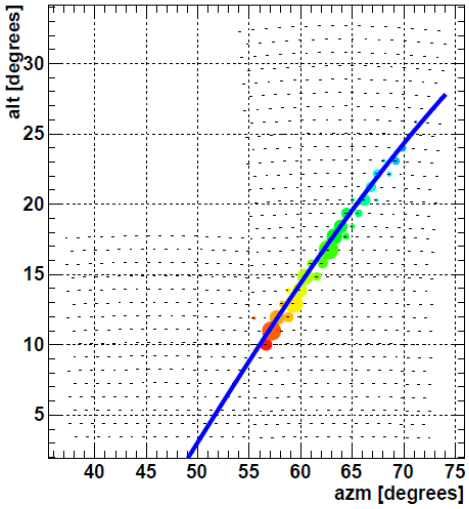
(a) Surface detector display.



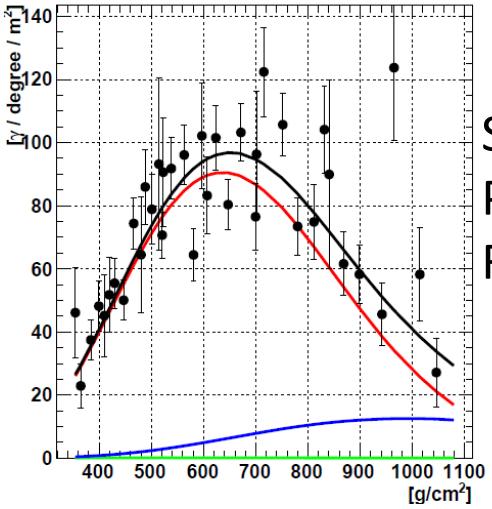
(b) Time vs angle fit.

Timing Geometry Fit (blue points are from SD)

Event Display: FD



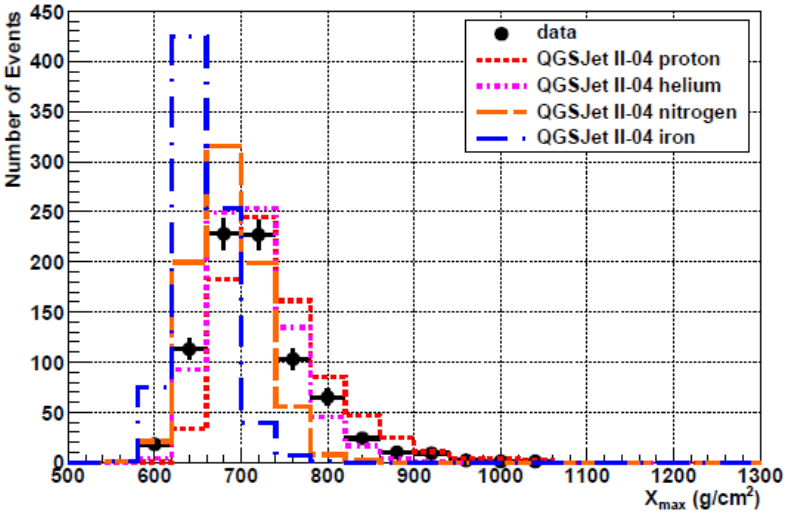
(c) Fluorescence detector display.



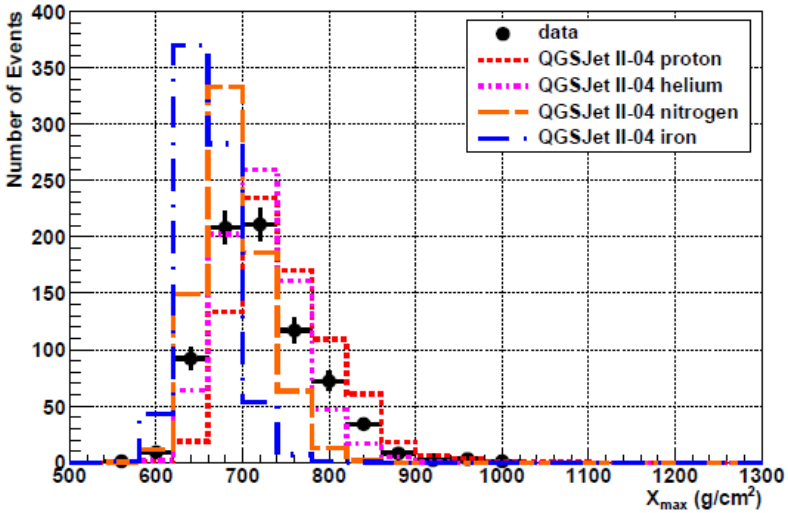
(d) Measured flux.

Shower Profile Fit.

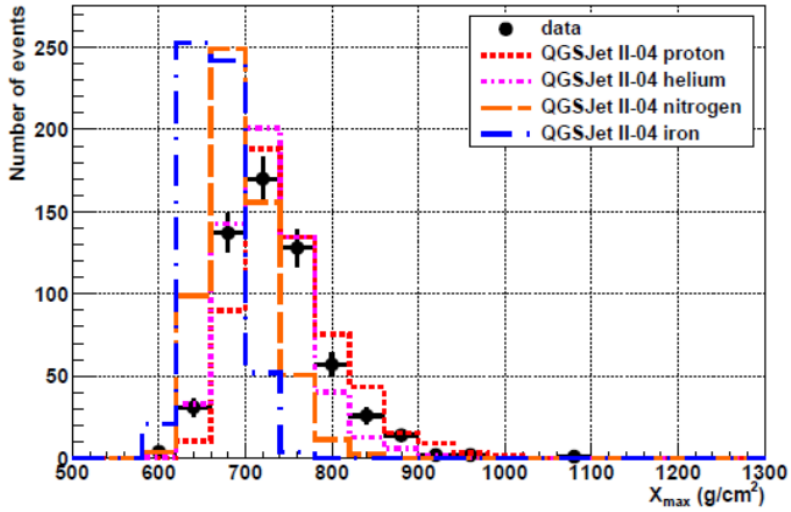
Xmax Distributions vs MC



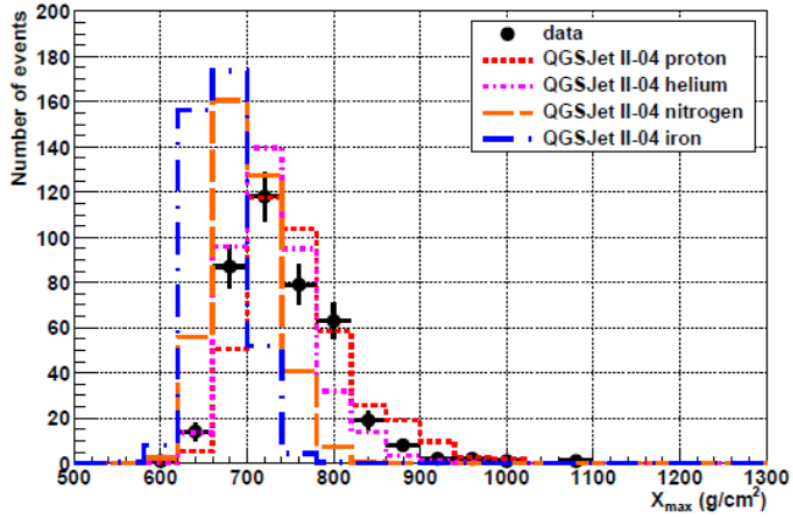
(a) $18.2 \leq \log_{10}(E/\mathrm{eV}) < 18.3$



(b) $18.3 \leq \log_{10}(E/\mathrm{eV}) < 18.4$

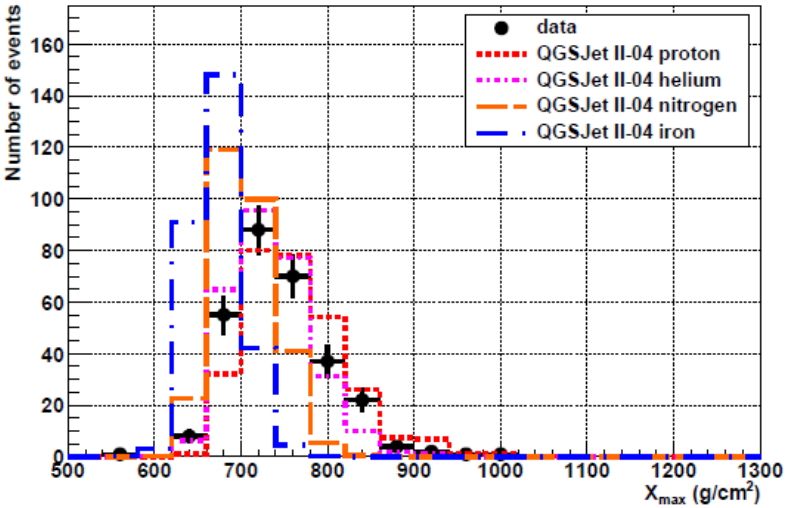


(c) $18.4 \leq \log_{10}(E/\mathrm{eV}) < 18.5$

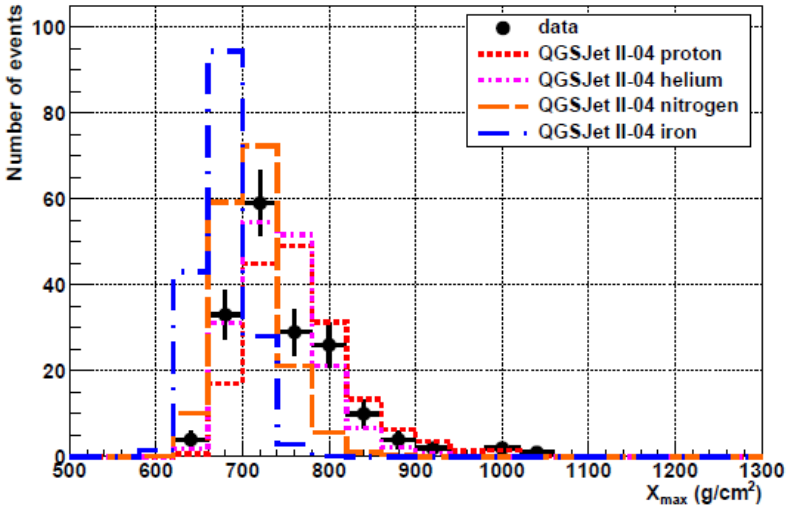


(d) $18.5 \leq \log_{10}(E/\mathrm{eV}) < 18.6$

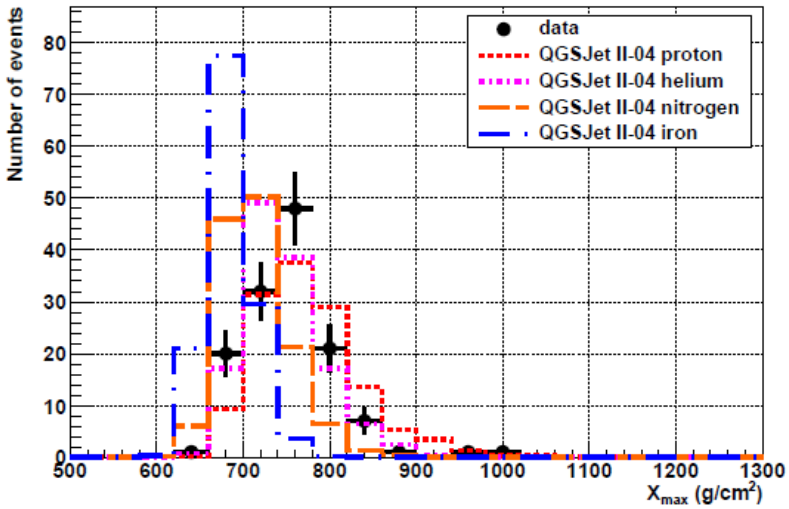
Xmax Distributions vs MC



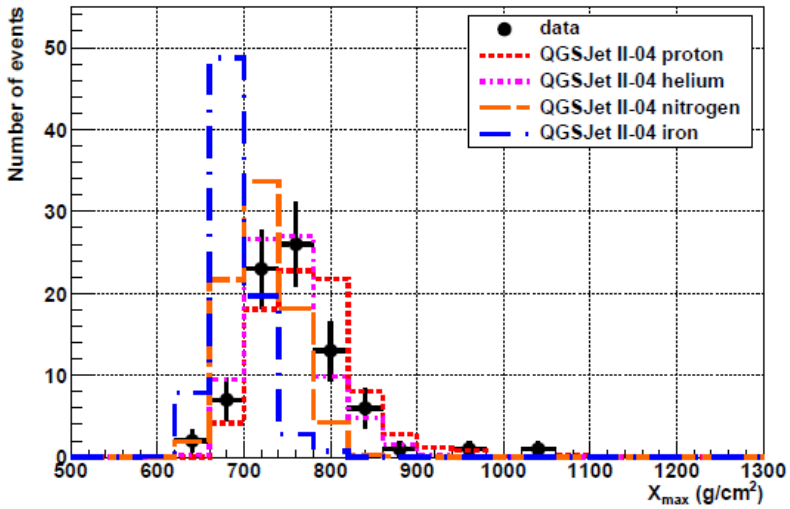
(e) $18.6 \leq \log_{10}(E/\mathrm{eV}) < 18.7$



(f) $18.7 \leq \log_{10}(E/\mathrm{eV}) < 18.8$

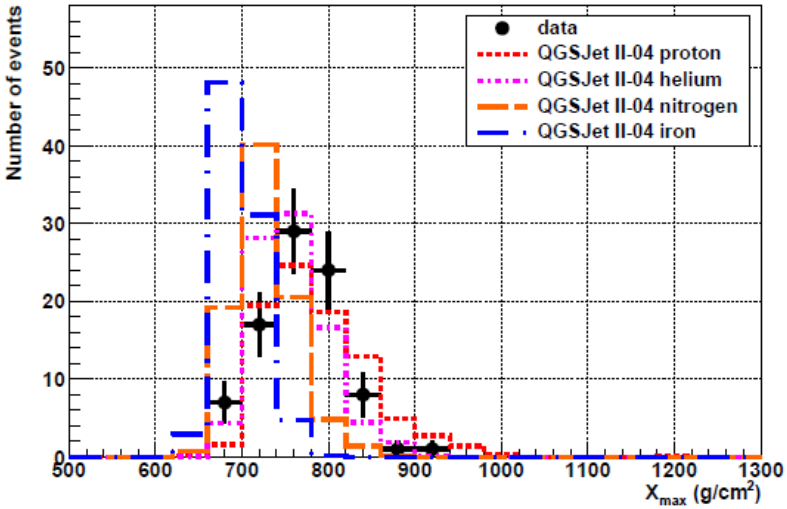


(a) $18.8 \leq \log_{10}(E/\mathrm{eV}) < 18.9$

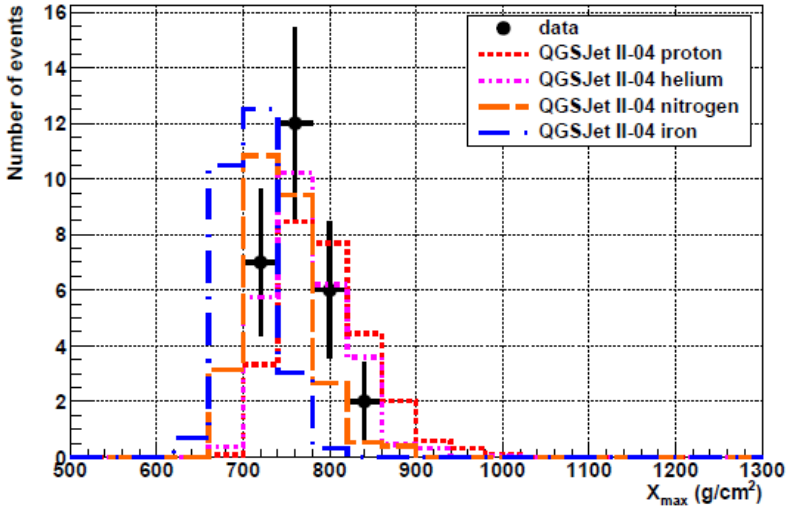


(b) $18.9 \leq \log_{10}(E/\mathrm{eV}) < 19.0$

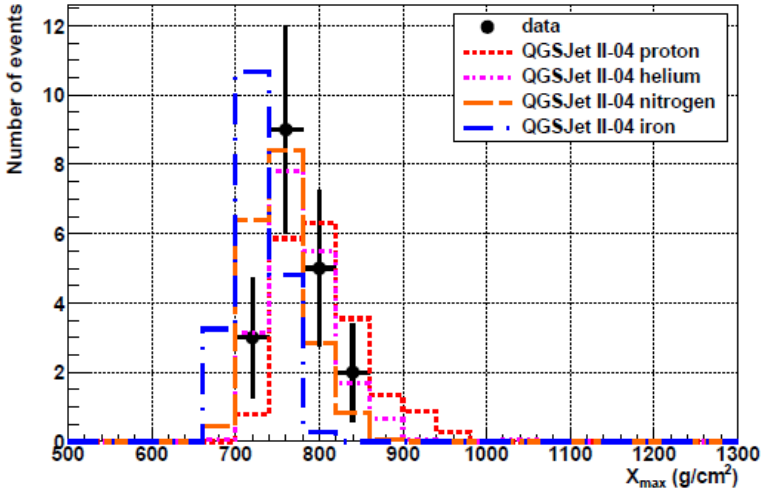
Xmax Distributions vs MC



(c) $19.0 \leq \log_{10}(E/\mathrm{eV}) < 19.2$

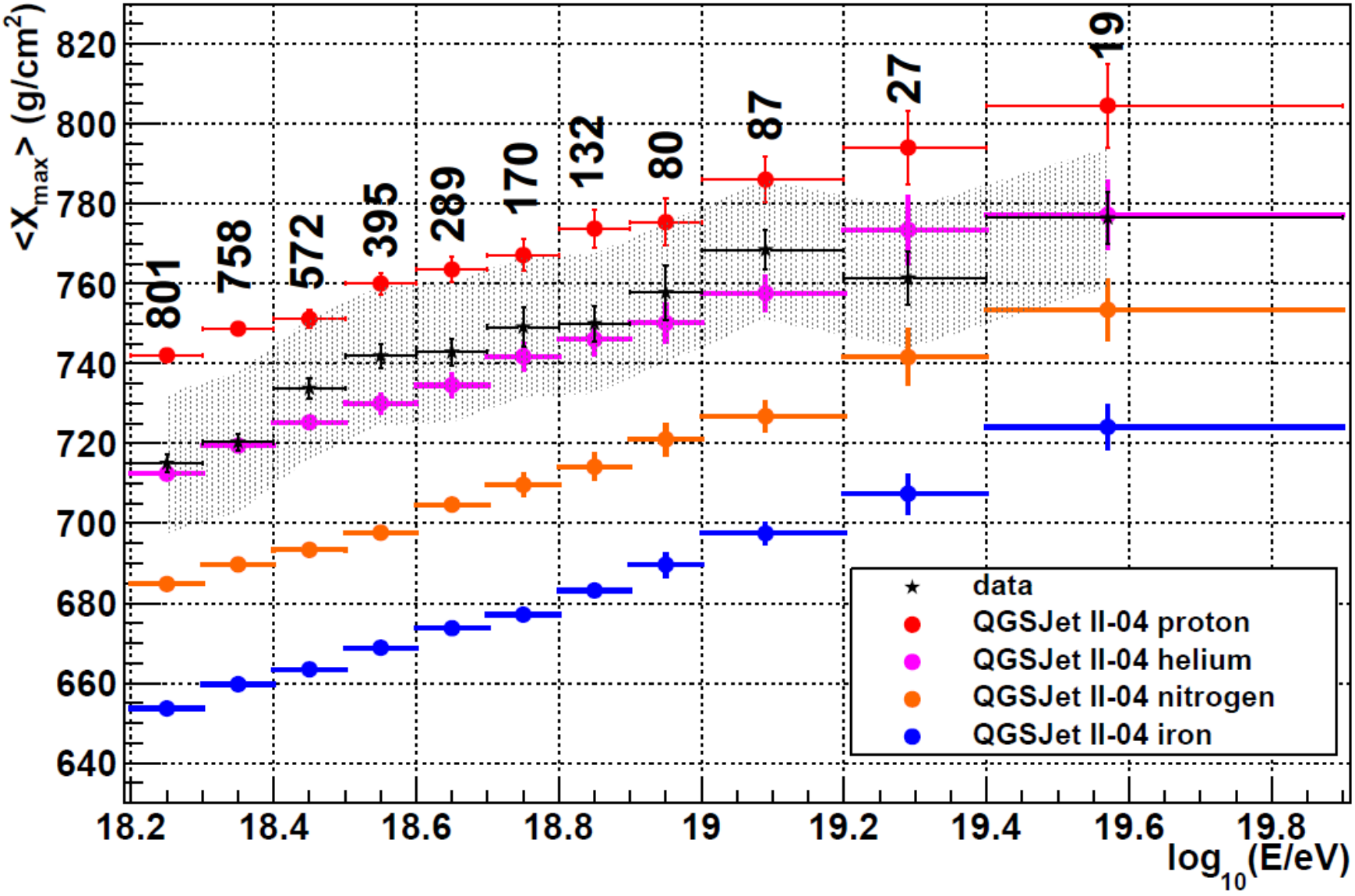


(d) $19.2 \leq \log_{10}(E/\mathrm{eV}) < 19.4$



(e) $19.4 \leq \log_{10}(E/\mathrm{eV}) < 19.9$

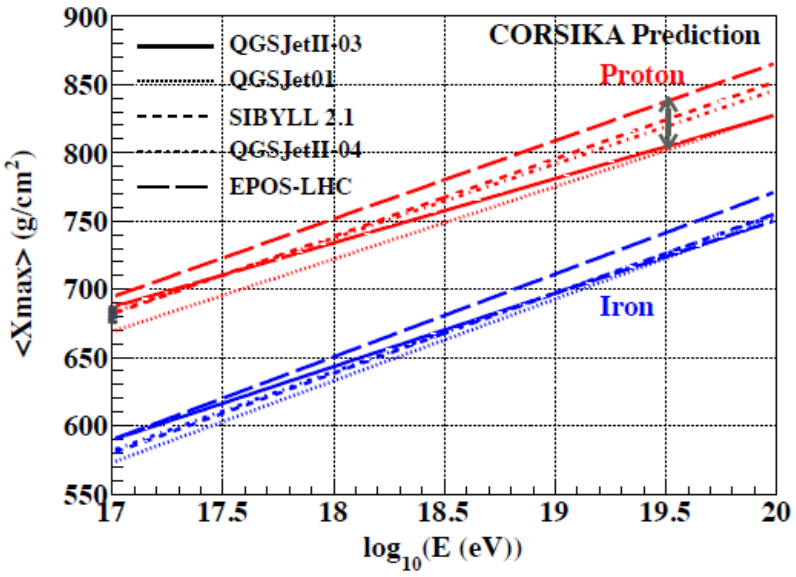
<Xmax> vs logE


$\langle X_{max} \rangle$ (g/cm^2)
820
800
780
760
740
720
700
680
660
640
801
758
572
395
289
170
132
80
87
27
19
18.2
18.4
18.6
18.8
19
19.2
19.4
19.6
19.8
log$_{10}$(E/eV)
data
QGSJet II-04 proton
QGSJet II-04 helium
QGSJet II-04 nitrogen
QGSJet II-04 iron

Interpretation of <Xmax>?
Extrapolation Uncertainties for <Xmax>

Ulrich, Engel and Unger arXiv:1010.4310v1 [hep-ph] 20 Oct 2010)
Thomson and Abbasi, arXiv:1605.05241v1 [hep-ex] 17 May 2016)

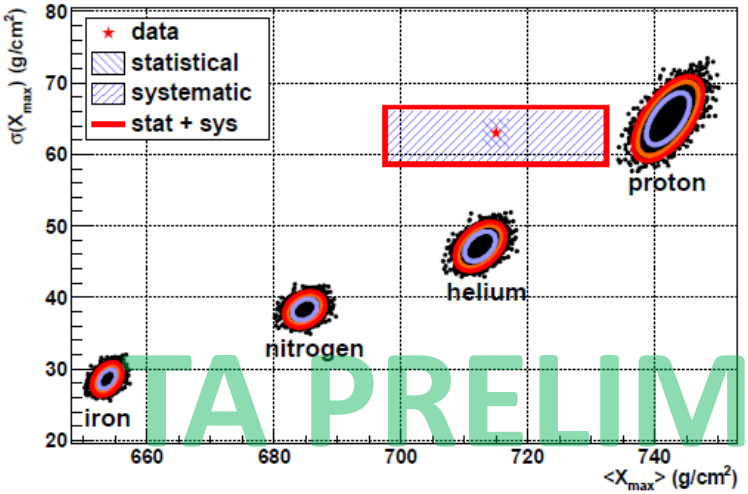
Model	<Xmax> uncertainty 10^{17}eV	<Xmax> uncertainty $10^{19.5}$eV
SIBYLL2.1	±3 g/cm2	±18 g/cm2
QGSJETII4	±3.5 g/cm2	±16 g/cm2
QGSJET01	±3 g/cm2	±18 g/cm2
EPOS-LHC	±3 g/cm2	±18 g/cm2



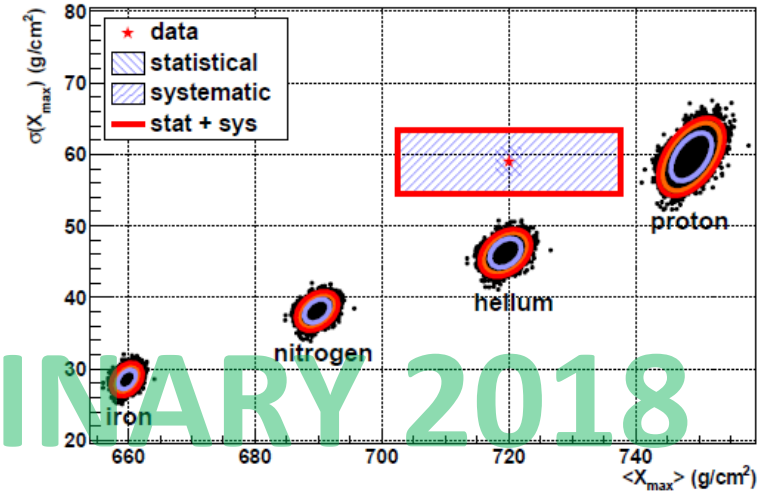
Uncertainty at 250 TeV (= $10^{19.5}$ eV) encompasses all the models at the ± 1σ level; smaller at 10^{17} eV.

But the uncertainty is less for RMS(Xmax).

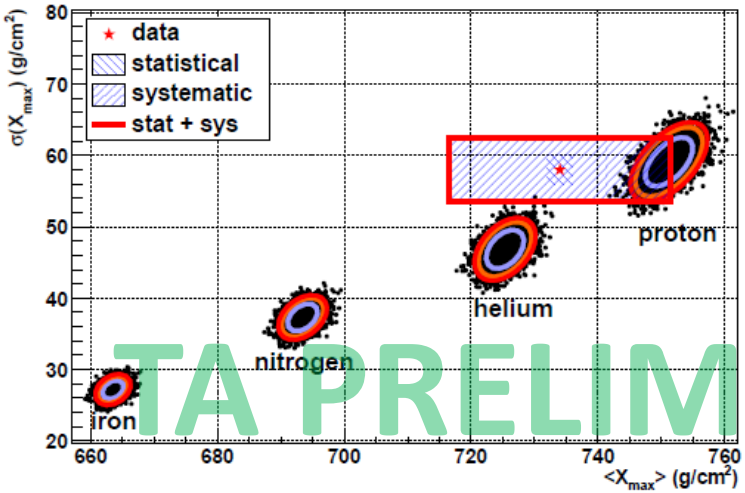
Data/MC: σ(Xmax) vs <Xmax>



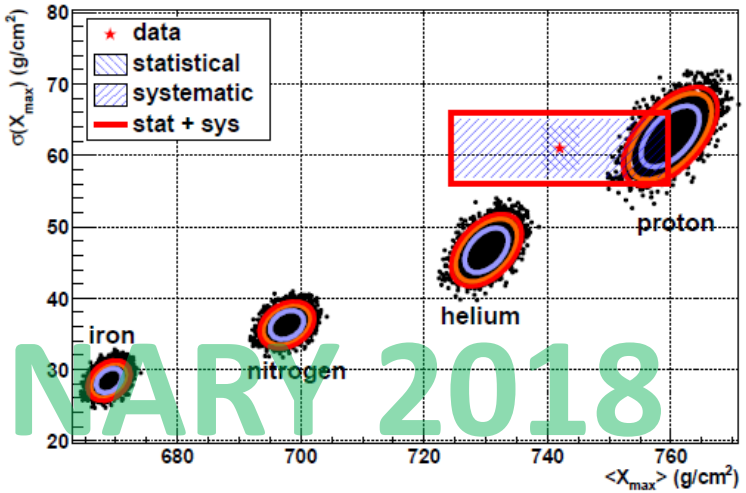
(a) $18.2 \leq \log_{10}(E/\mathrm{eV}) < 18.3$



(b) $18.3 \leq \log_{10}(E/\mathrm{eV}) < 18.4$



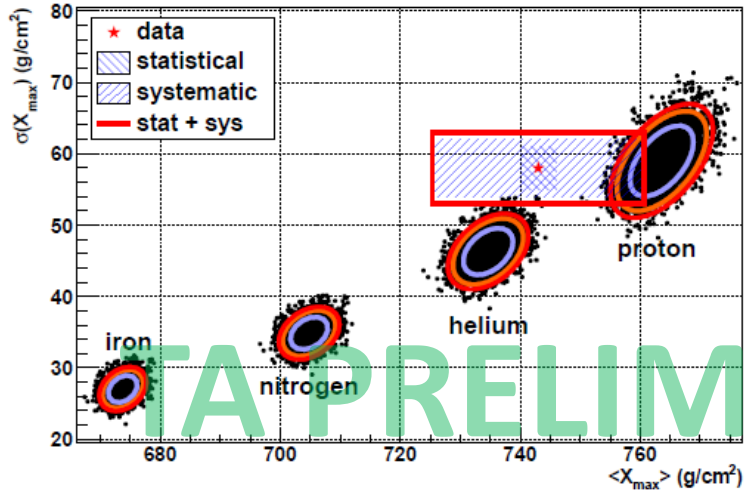
(c) $18.4 \leq \log_{10}(E/\mathrm{eV}) < 18.5$



(d) $18.5 \leq \log_{10}(E/\mathrm{eV}) < 18.6$

Dots: Resampled MC with same no. of events as data; with contours 68.3% (blue), 90% (orange), and 95% (red) confidence intervals

Data/MC: σ(Xmax) vs <Xmax>



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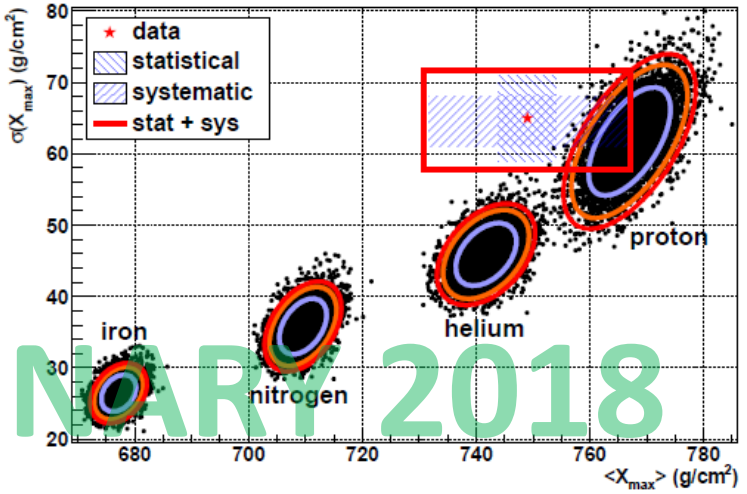
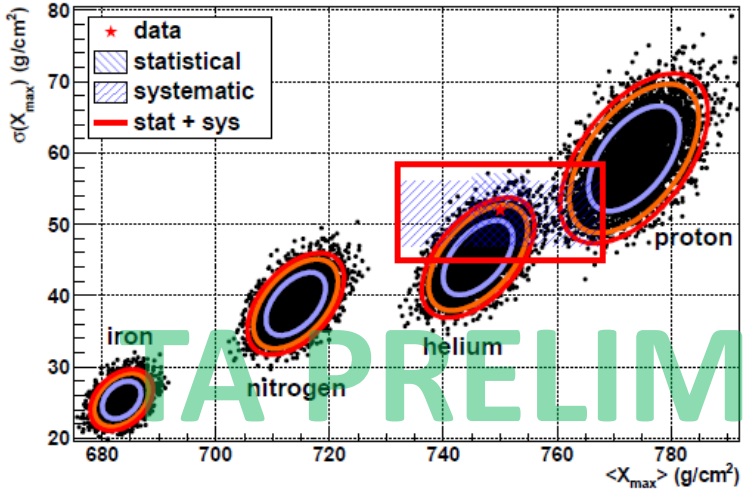
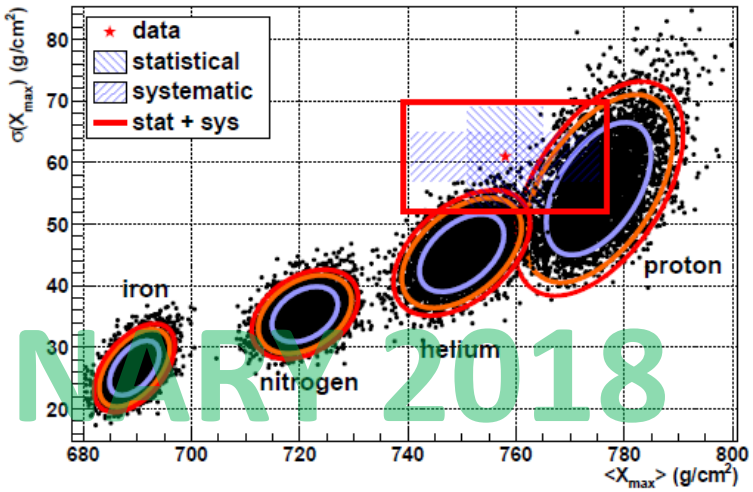


(f) $18.7 \leq \log_{10}(E/\mathrm{eV}) < 18.8$



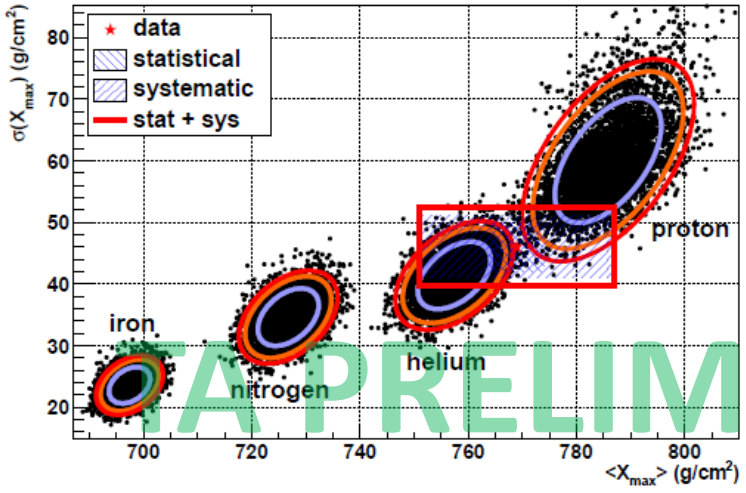
(a) $18.8 \leq \log_{10}(E/\mathrm{eV}) < 18.9$



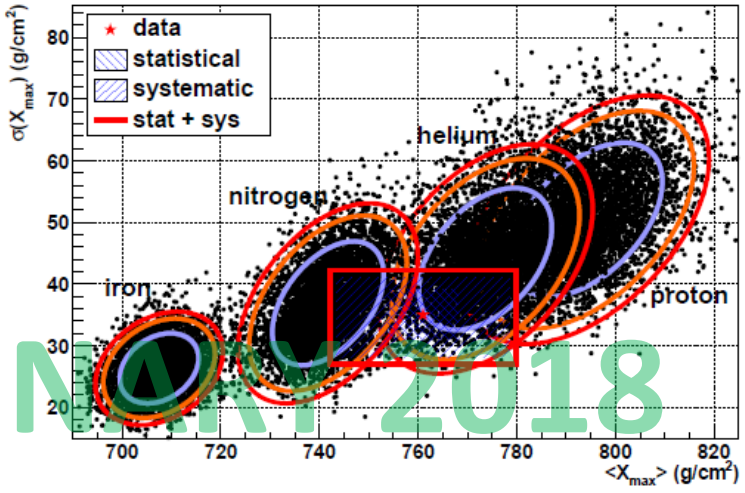
(b) $18.9 \leq \log_{10}(E/\mathrm{eV}) < 19.0$

Dots: Resampled MC with same no. of events as data; with contours 68.3% (blue), 90% (orange), and 95% (red) confidence intervals

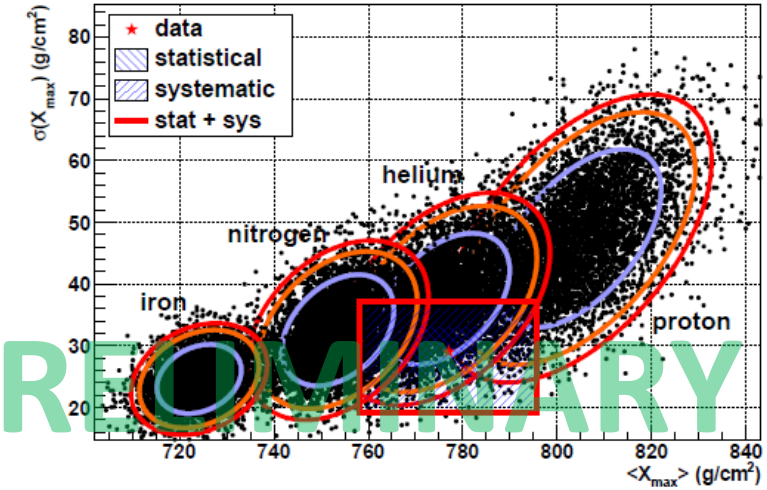
Data/MC: σ(Xmax) vs <Xmax>



(c) $19.0 \leq \log_{10}(E/\mathrm{eV}) < 19.2$



(d) $19.2 \leq \log_{10}(E/\mathrm{eV}) < 19.4$

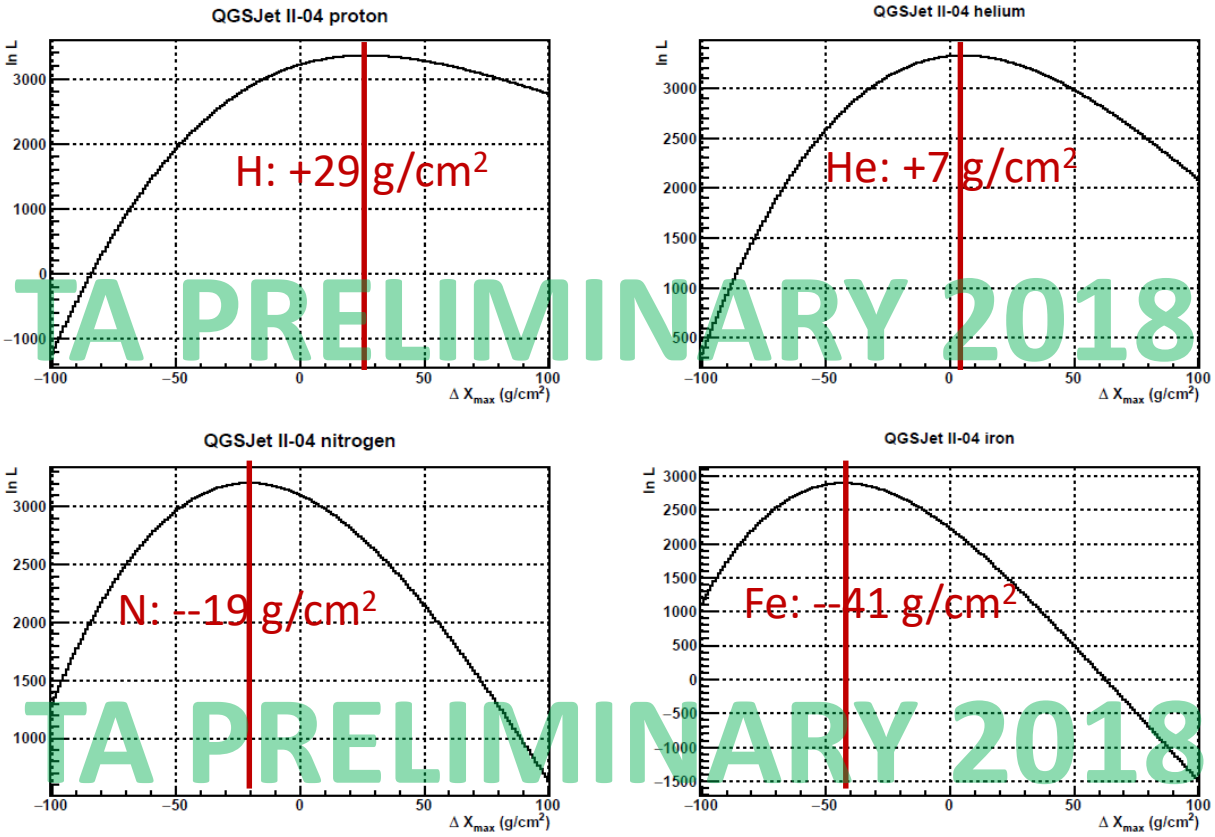


(e) $19.4 \leq \log_{10}(E/\mathrm{eV}) < 19.9$

Limited Statistics above 10^{19}eV!

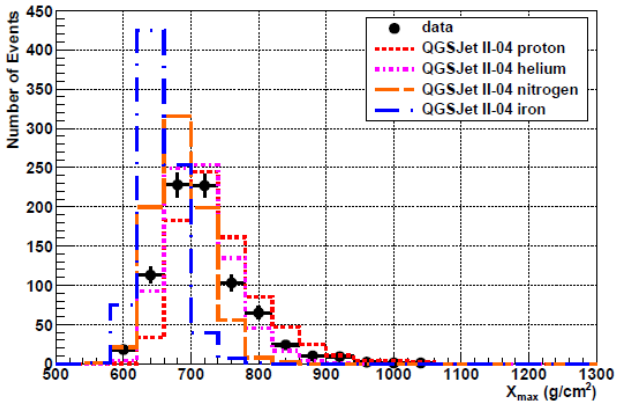
Dots: Resampled MC with same no. of events as data; with contours 68.3% (blue), 90% (orange), and 95% (red) confidence intervals

Shape Analysis: 1st bin



TA PRELIMINARY 2018

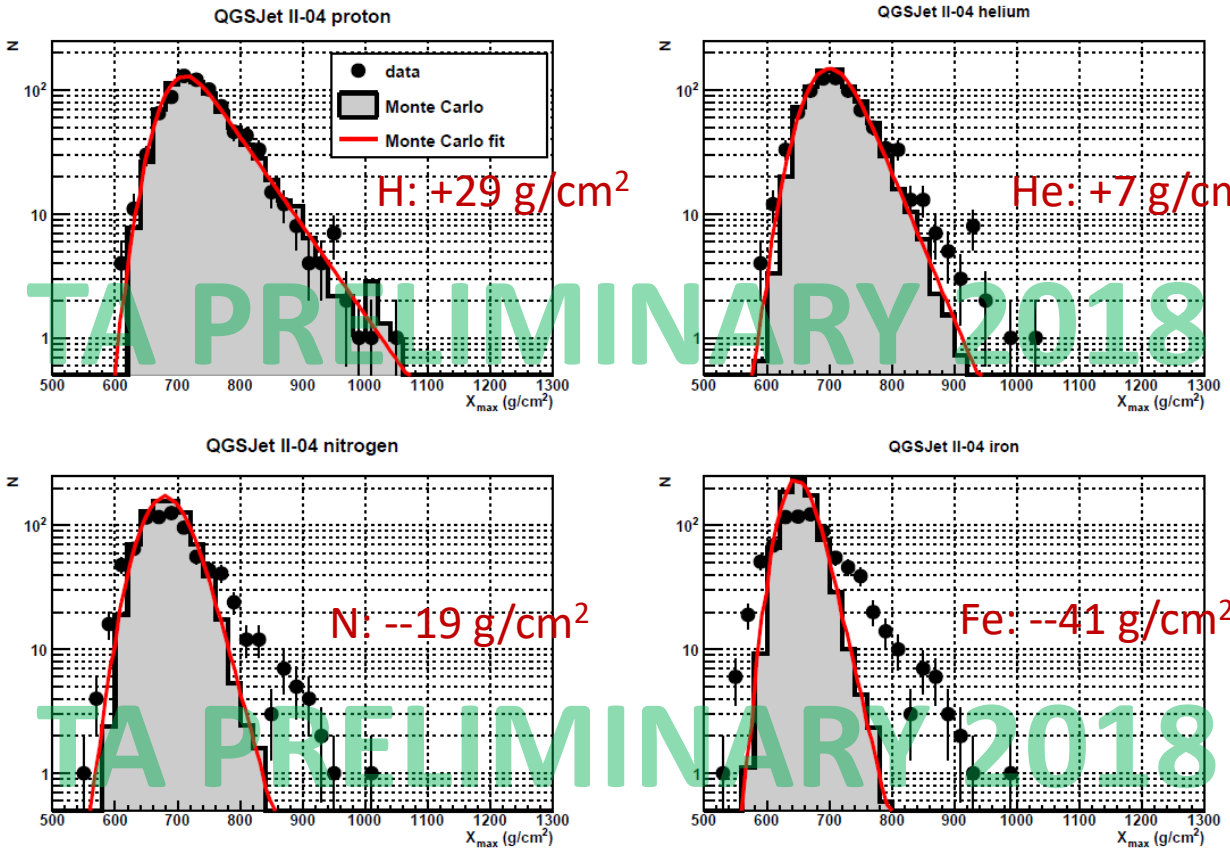
$18.2 \leq \log_{10}(E/\mathrm{eV}) < 18.3$



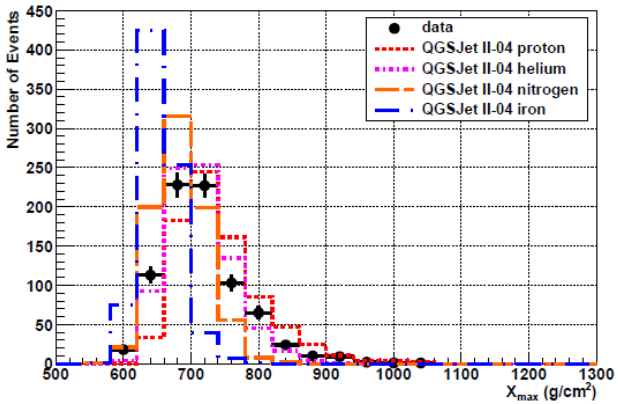
(a) $18.2 \leq \log_{10}(E/\mathrm{eV}) < 18.3$

- Likelihood function, L ($\log L$ is shown), is constructed for the data against the MC event set (fitted to a Gaussian + exponential tail), vs. shift ΔXmax in data
- $\log L$ is interpreted as a measured of how much the data resembles the MC
- Max value of $\log L$ is a measure of how much the shifted data resembles MC

Comparing Shifted data to MC



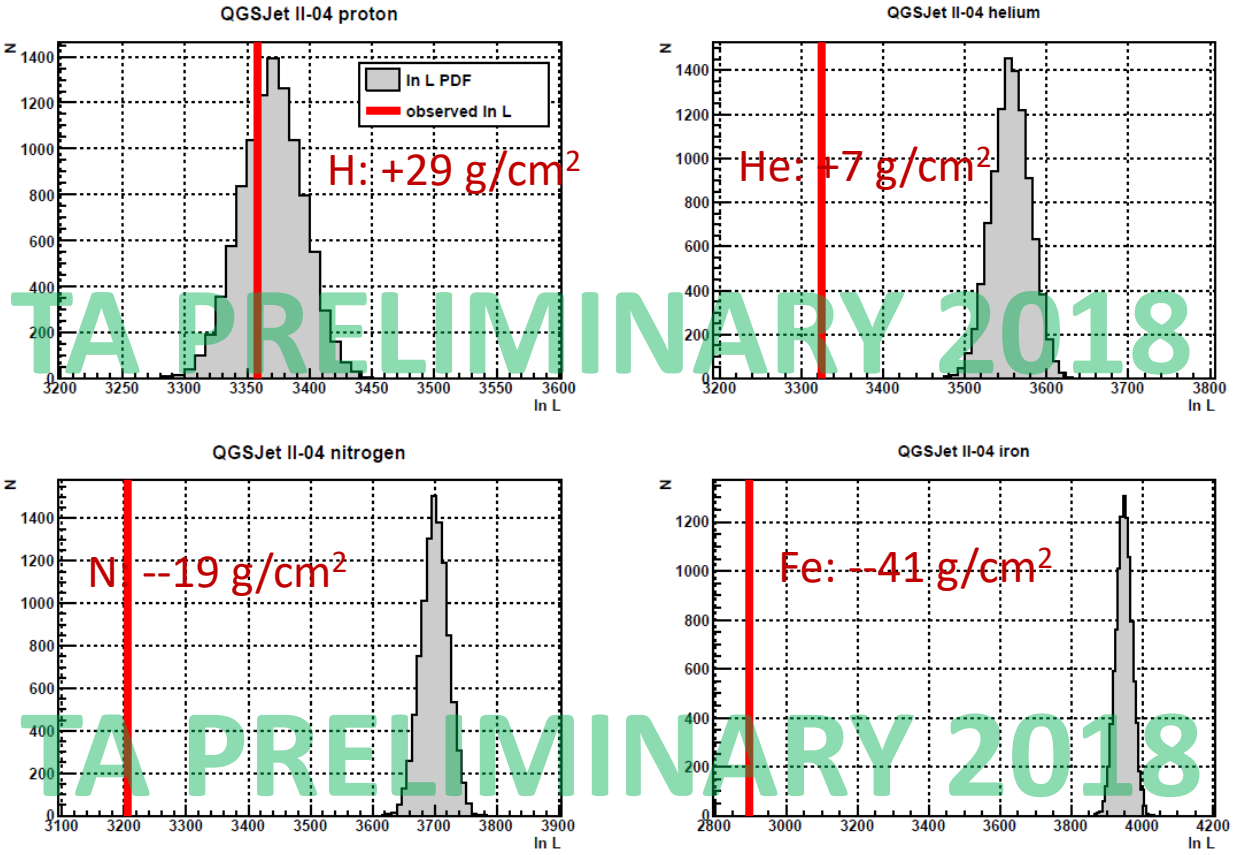
$18.2 \leq \log_{10}(E/\mathrm{eV}) < 18.3$



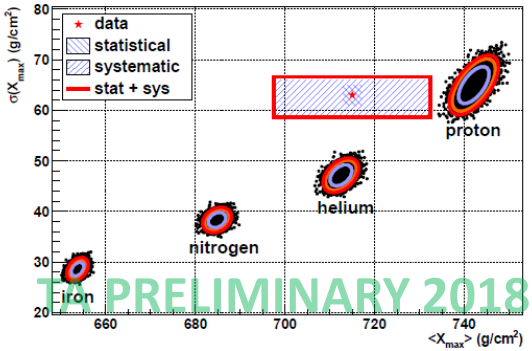
(a) $18.2 \leq \log_{10}(E/\mathrm{eV}) < 18.3$

- Likelihood function, L ($\log L$ is shown), is constructed for the data against the MC event set (fitted to a Gaussian + exponential tail), vs. shift ΔXmax in data
- $\log L$ is interpreted as a measured of how much the data resembled the MC
- Max value of $\log L$ is a measured of how much the shifted data resembled MC

Compare Shifted data to resampled MC



$18.2 \leq \log_{10}(E/\mathrm{eV}) < 18.3$



(a) $18.2 \leq \log_{10}(E/\mathrm{eV}) < 18.3$

- Resample MC (same no. of events as data in each resample)
- Find ΔXmax from max. log$L$. The max value of log$L$ is then histogrammed and the resulting distribution is fitted to a Gaussian – interpreted as a PDF
- Find p value that one of the resample gives max. log$L$ further away from data

Repeat for each energy bin: Result

	proton		helium		nitrogen		iron	
energy	$\Delta X_{\rm max}$	p-val	$\Delta X_{\rm max}$	p-val	$\Delta X_{\rm max}$	p-val	$\Delta X_{\rm max}$	p-val
18.2-18.3	29 ± 2	0.32	7 ± 2	—	-19 ± 1	—	-41 ± 1	—
18.3-18.4	30 ± 2	0.59	6 ± 2	2×10^{-18}	-19 ± 1	—	-43 ± 1	—
18.4-18.5	19 ± 2	0.50	-2 ± 2	9×10^{-11}	-28 ± 2	—	-53 ± 1	—
18.5-18.6	19 ± 2	0.65	-2 ± 2	2×10^{-11}	-33 ± 2	—	-54 ± 2	—
18.6-18.7	22 ± 3	0.38	-1 ± 3	3×10^{-7}	-25 ± 2	—	-52 ± 2	—
18.7-18.8	20 ± 4	0.55	2 ± 3	6×10^{-6}	-24 ± 3	—	-53 ± 2	—
18.8-18.9	20 ± 4	0.97	2 ± 3	0.027	-27 ± 3	3×10^{-6}	-51 ± 2	—
18.9-19.0	21 ± 5	0.30	1 ± 5	0.0010	-25 ± 4	1×10^{-14}	-42 ± 3	—
19.0-19.2	10 ± 5	0.98	-7 ± 4	0.059	-34 ± 4	1×10^{-5}	-57 ± 3	—
19.2-19.4	26 ± 8	0.98	9 ± 8	0.93	-18 ± 7	0.71	-50 ± 5	0.027
19.4-19.9	19 ± 8	0.98	-3 ± 8	0.93	-23 ± 7	0.81	-50 ± 6	0.26

"—" : p-value < $7.6\ 10^{-24}$ (significance > 10σ). $X_{\rm max}$ shifts are measured in g/cm^2.

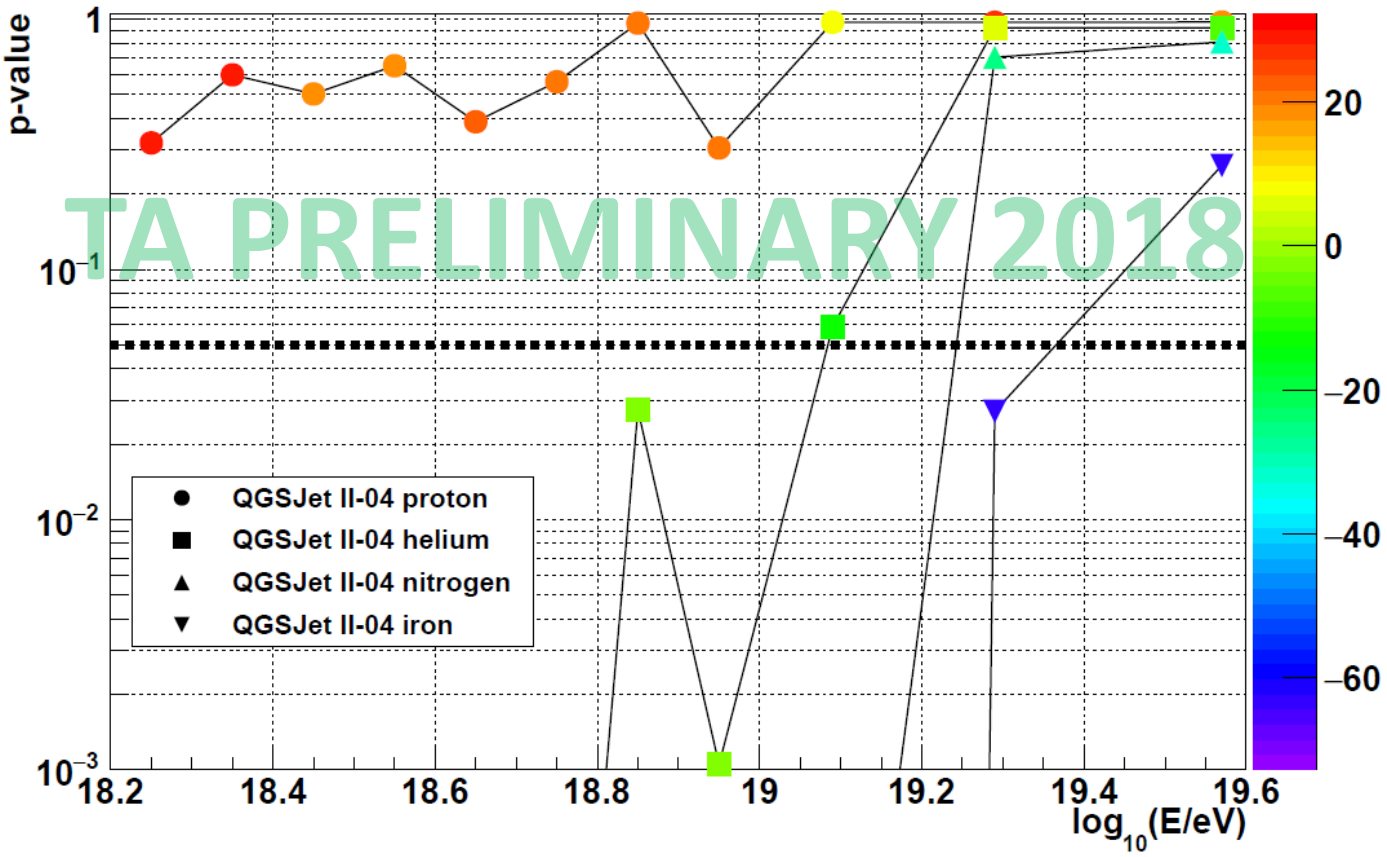
$E<10^{19.0}$eV

- max. log$L$ derived p rejects (at 95% C.L.) all species except H

$E>10^{19.2}$eV

- max. log$L$ derived p FAILS to reject (at 95% C.L.) any species

Graphing the Results



Color indicates the amount of shift in Xmax applied to data for best fit to MC (in g/cm^2)

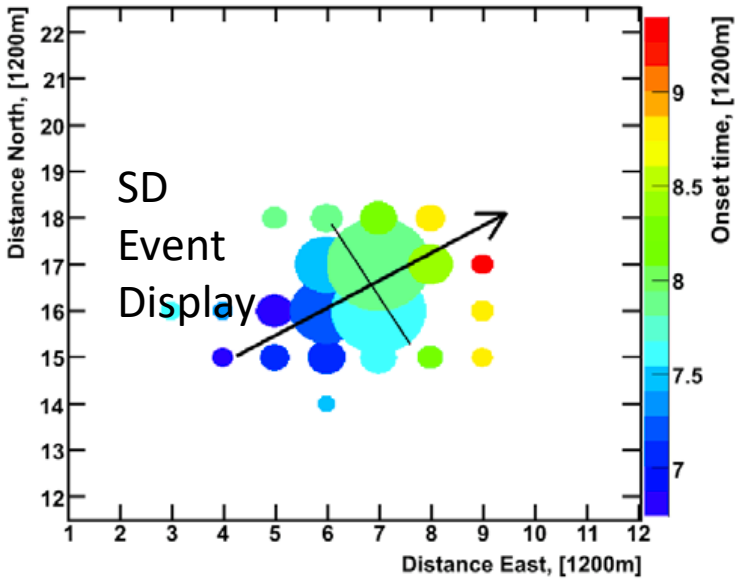
$E<10^{19.0}$eV

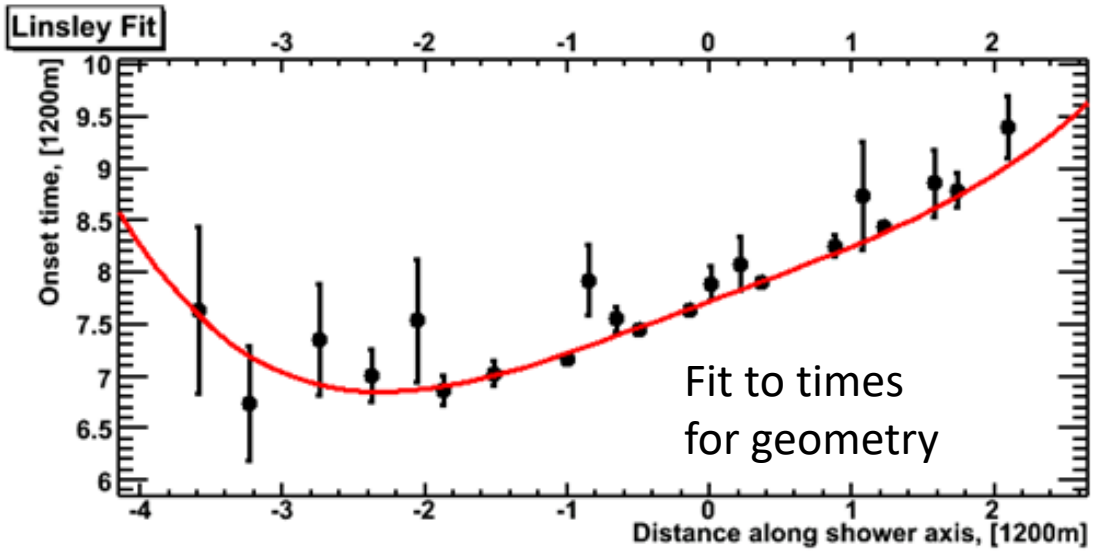
- max. log$L$ derived p rejects (at 95% C.L.) all species except H

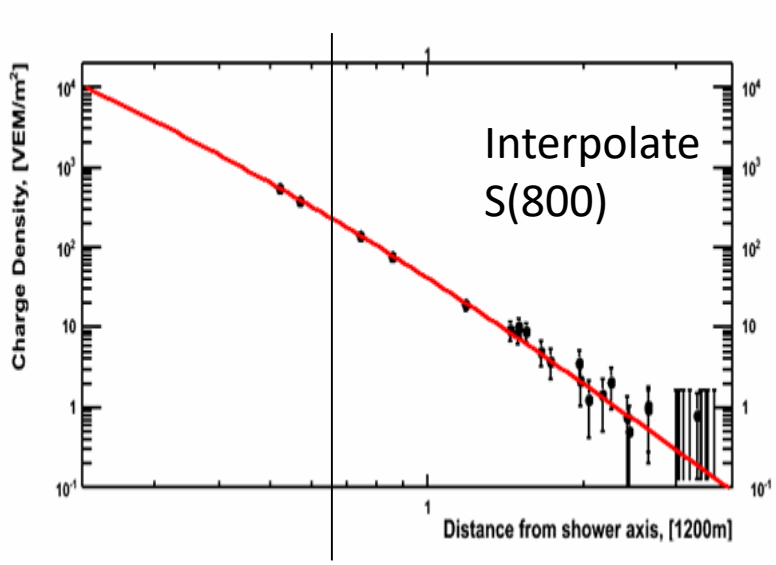
$E>10^{19.2}$eV

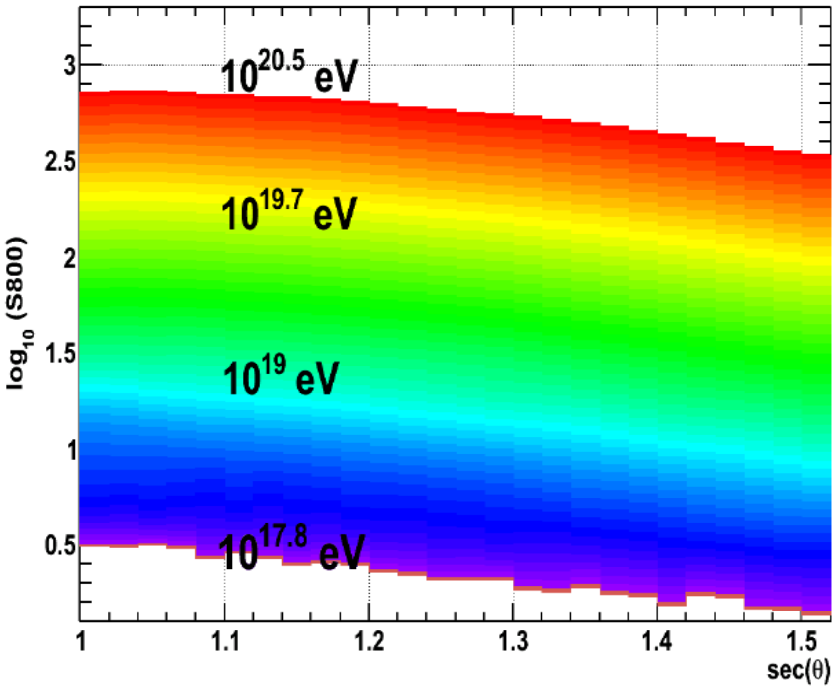
- max. log$L$ derived p FAILS to reject (at 95% C.L.) any species

Anisotropy Result:Based on SD Data





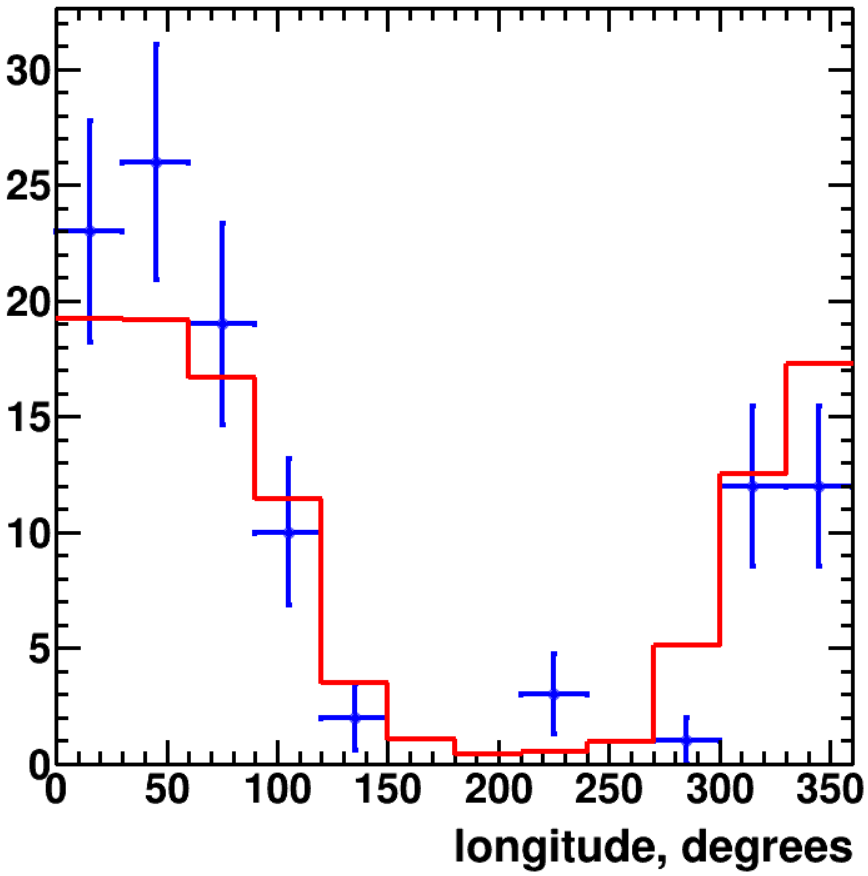


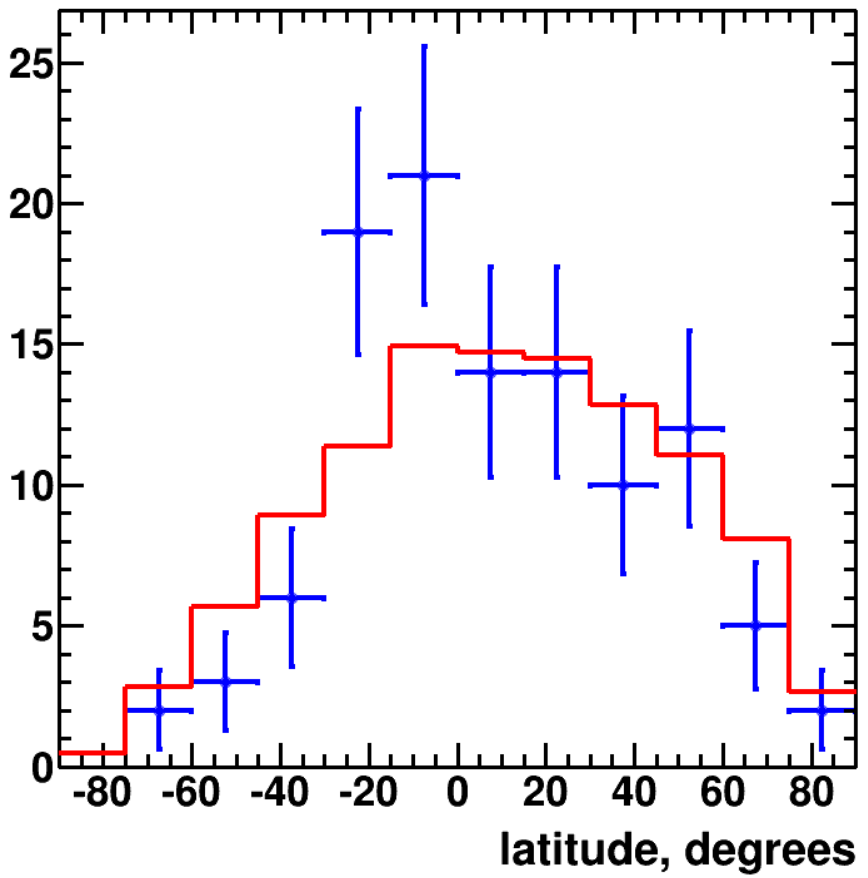


Read off
Energy from
MC Table

 r = 800m

Supergalactic Coordinates

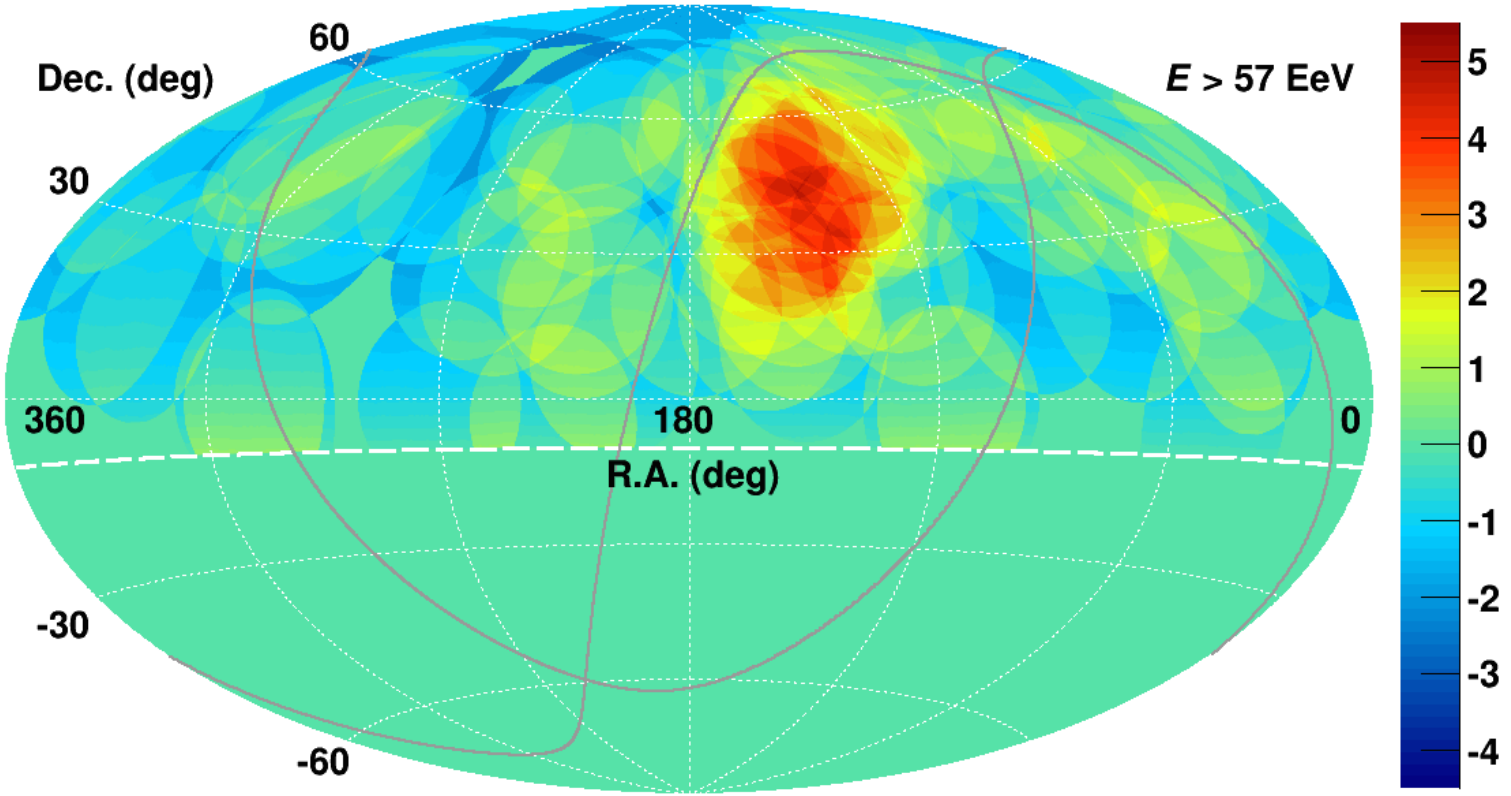




Kolmogorov-Smirnov p-value = 0.01 for SG latitude, E>57 EeV

other thresholds/coordinates = isotropic

Hot Spot (2014)



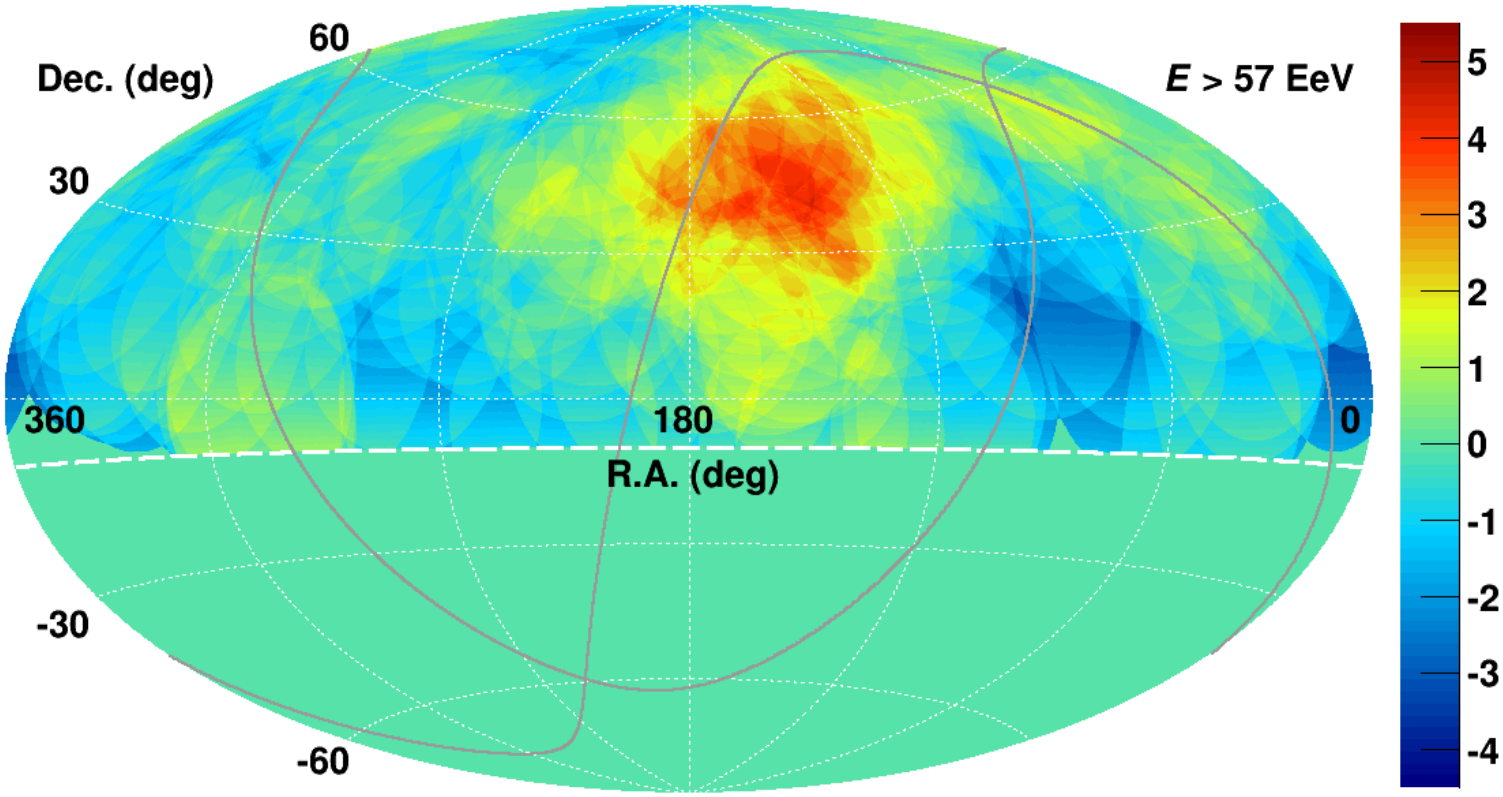
Total events: 72
Observed: 19
Expected : 4.5

Best circle center: RA=146.7°, Dec=+43.2°
Best circle radius: 20°
Local significance : 5 σ
Global significance : 3 σ

Hot Spot (2017)

E>57 EeV - Years 1-9 excess map

TA preliminary



Total events: 143

Observed: 34

Expected : 13.5

Best circle center: RA=144.3°, Dec=+40.3°

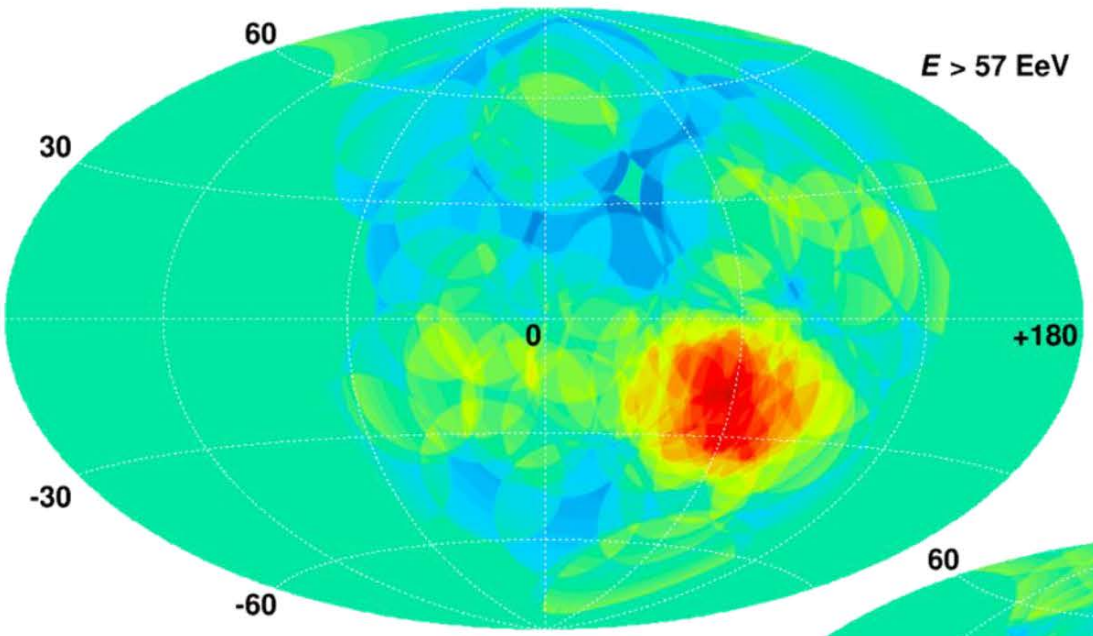
Best circle radius: 25°

Local significance : 5 σ

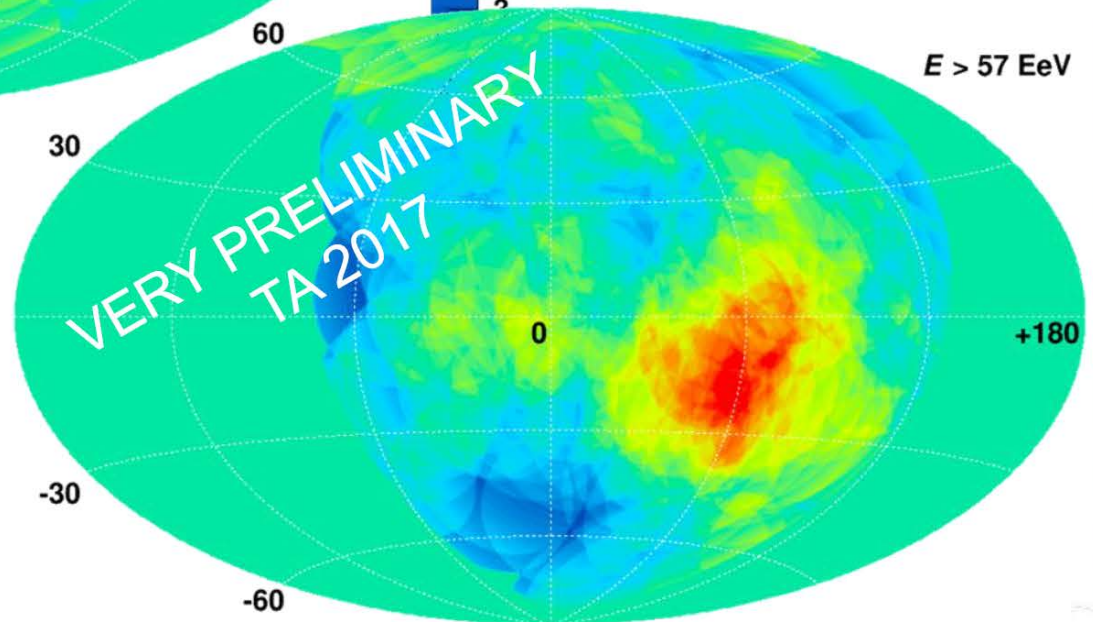
Global significance : 3 σ

Hot Spot

In **Supergalactic** coordinates

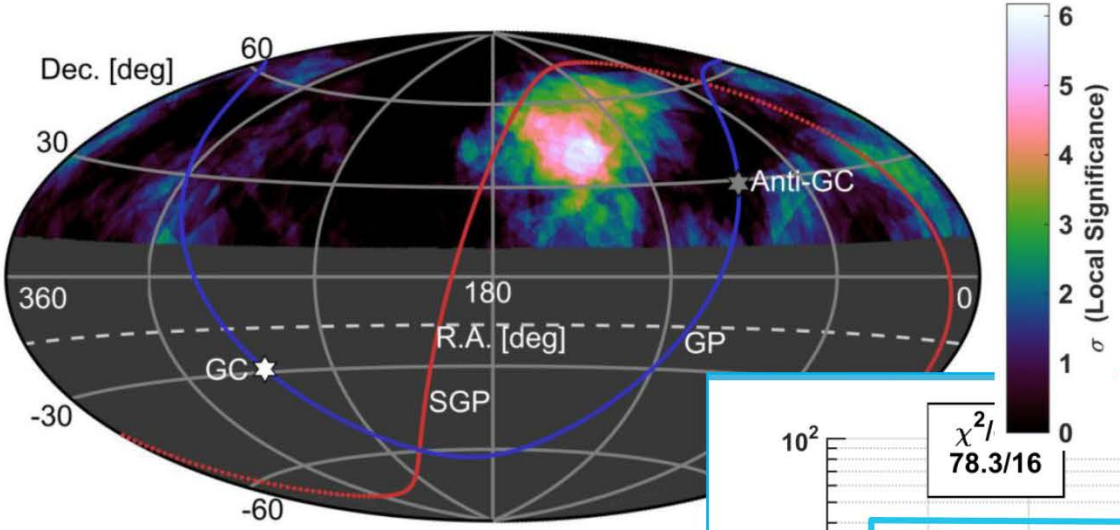


years 1-5
20° circles

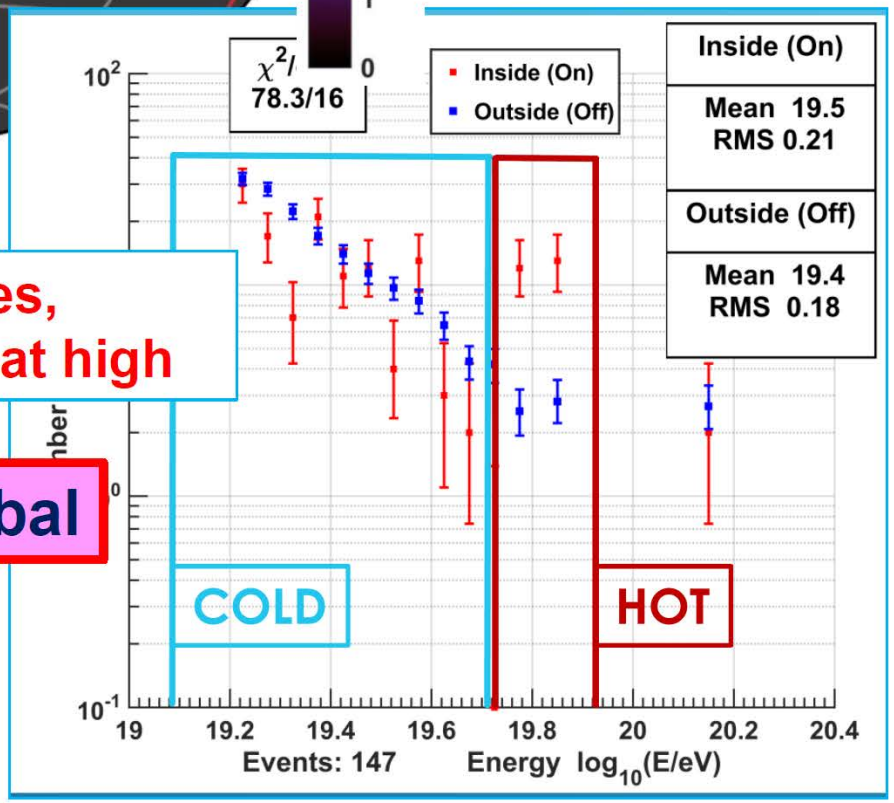


years 1-9
25° circles

Cold Spot



$E \geq 10^{19.2}$ eV

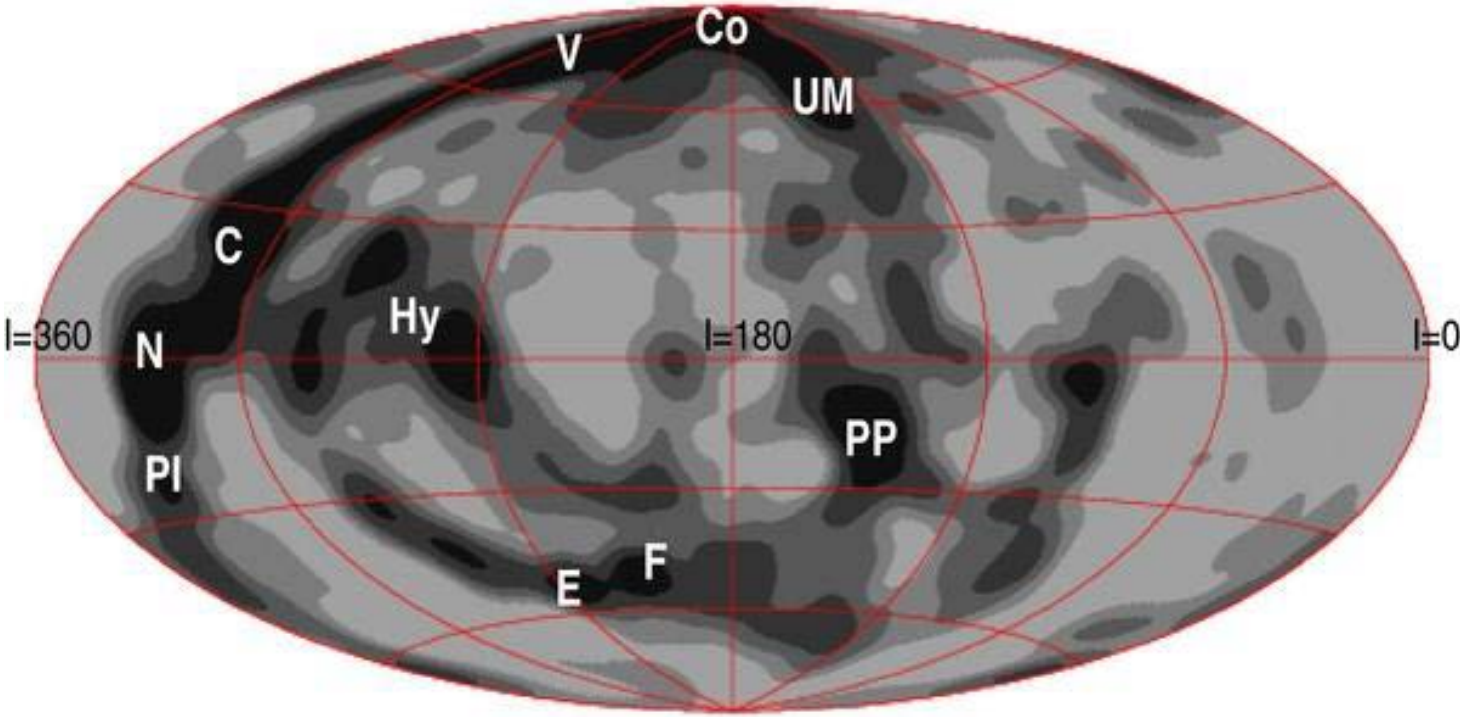


"cold spot" at lower energies, same place as the hot spot at high

3.7σ global

Lundquist talk CRI 231

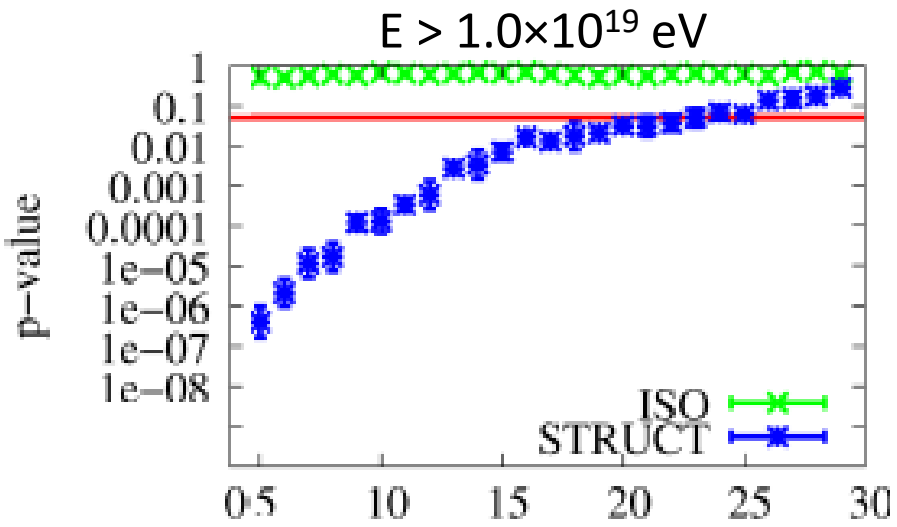
Large-Scale Structure

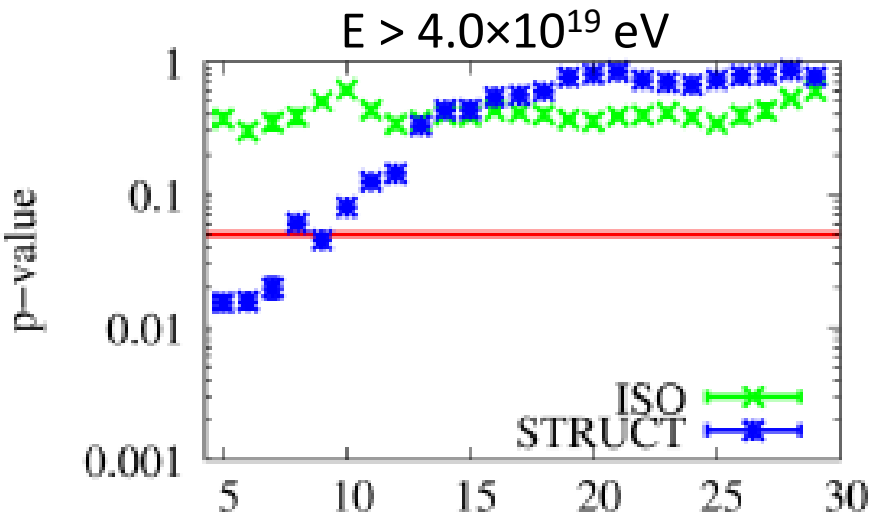


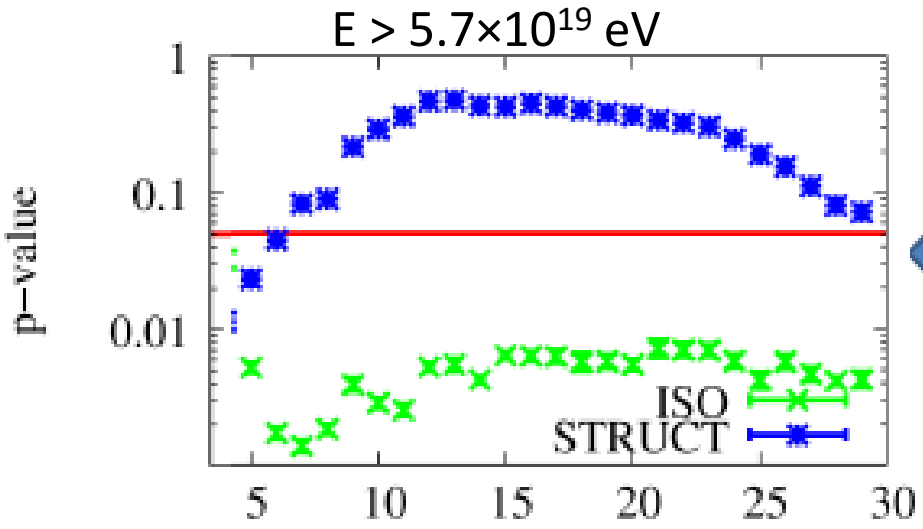
C: Centaurus SCl (60 Mpc); Co: Coma Cl (90 Mpc); E: Eridanus Cl (30 Mpc); F: Fornax Cl (20 Mpc); Hy: Hydra SCl (50 Mpc); N: Norma SCl (65 Mpc); PI: Pavo-Indus SCl (70 Mpc); PP: Perseus-Pisces SCl (70 Mpc); UM: Ursa Major Cl (20 Mpc); and V: Virgo Cl (20 Mpc).

- **Sky map of expected flux at *E* > 57 EeV (Galactic coordinates)**;
- smearing angle is 6°.

Large-Scale Structure

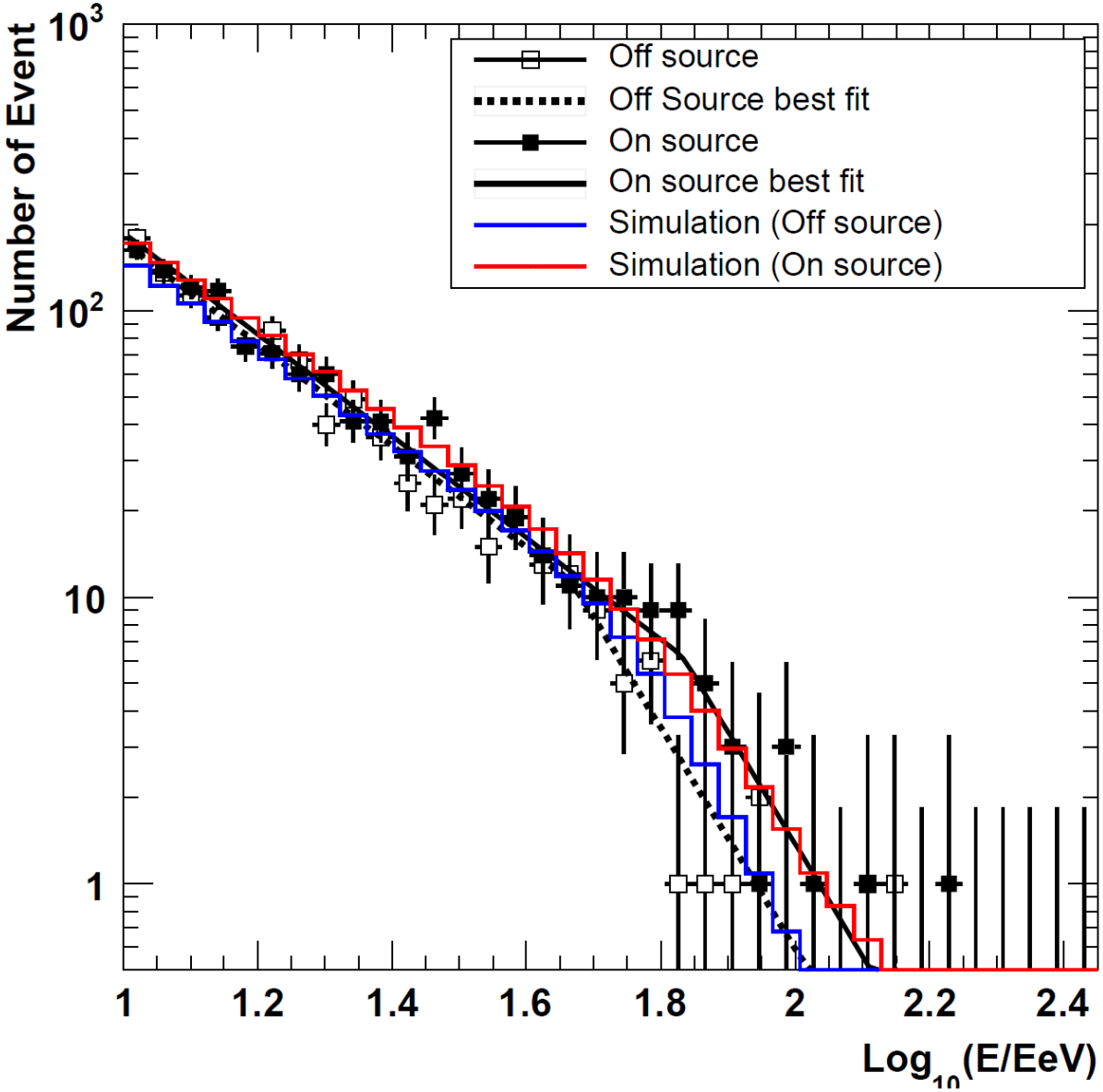




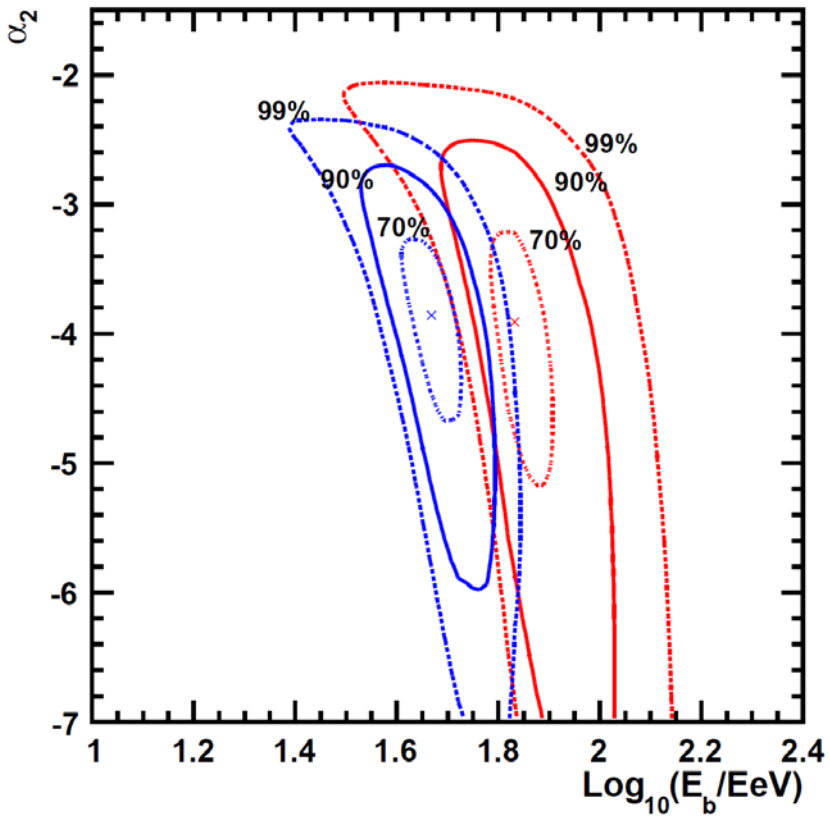


E>5.7×10^19 eV
Consistent with LSS
Inconsistent with isotropy

Hint of enhancement along SGP



- Source: Within 30° of the Supergalatic Plane (SGP)
- Simulation: using the large-scale structure model shown previously, assuming proton primaries



Difference between on-source and Off-source

Each spectrum fit to broken power law with:

(1) Power Law Index of no. of events vs logE before break: α_1

(2) Break point energy = E_b:

(3) Power Law Index of no. of events vs logE before break: α_1

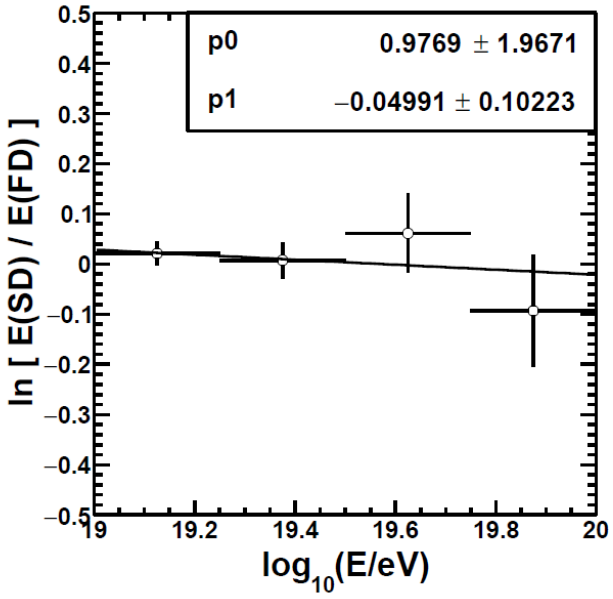
arXiv:1707.04967v3 [astro-ph.HE] 11 Aug 2017

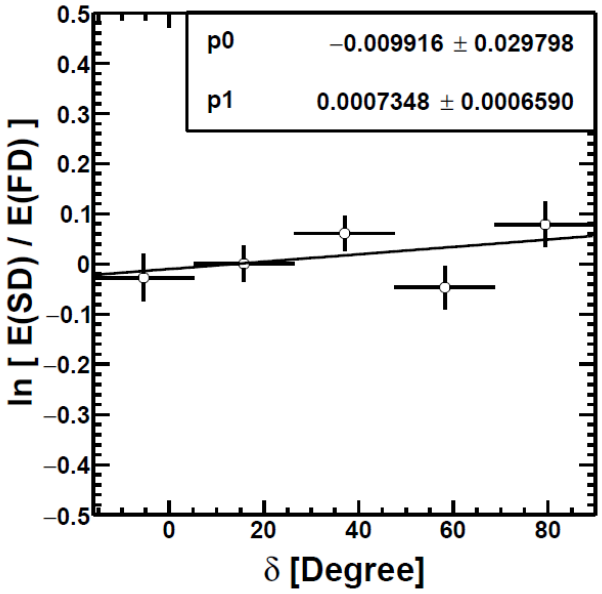
Region	C_o	α_1	$\log_{10}(E_b/EeV)$	α_2
All	$2.14^{+0.34}_{-0.30} \times 10^{+4}$	$-1.775^{+0.053}_{-0.053}$	$1.778^{+0.040}_{-0.068}$	$-3.91^{+0.64}_{-0.66}$
On source	$(1.1128 \times 10^{+4})$	(-1.775)	$1.832^{+0.069}_{-0.041}$	$-3.91^{+0.70}_{-1.30}$
Off source	$(1.0286 \times 10^{+4})$	(-1.775)	$1.668^{+0.052}_{-0.053}$	$-3.86^{+0.58}_{-0.82}$

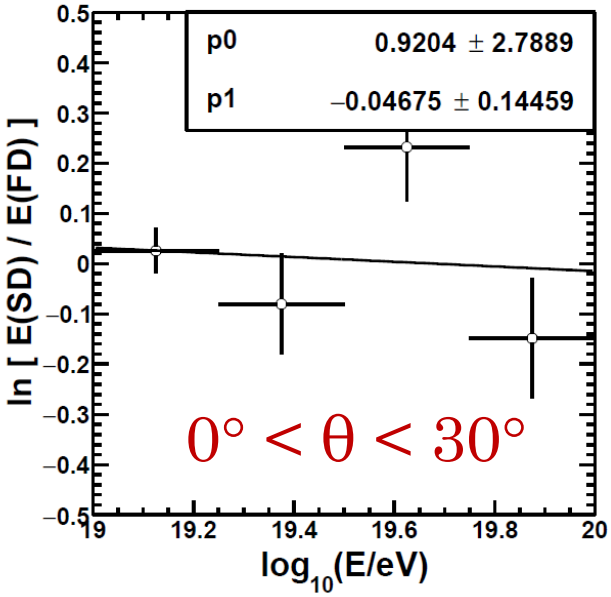
TABLE I. Parameters of the best fit broken power law in the SGP case.

Global Chance Probability/Significance : p = 6.2×10^{-4} (3.2σ)

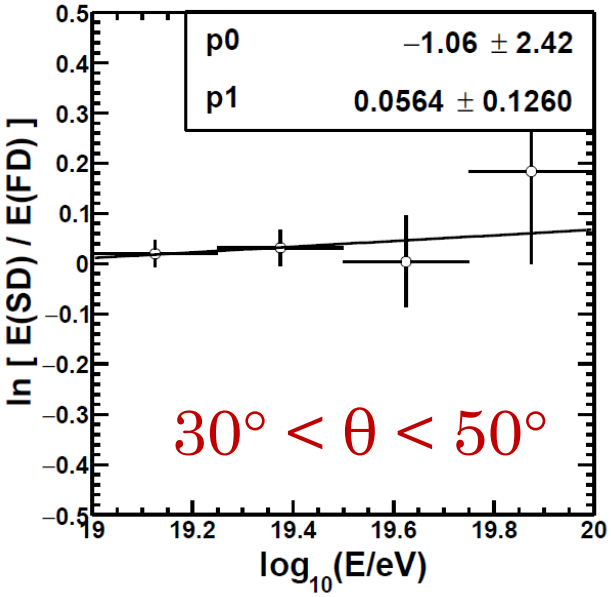
Systematic Checks of Energy Scale





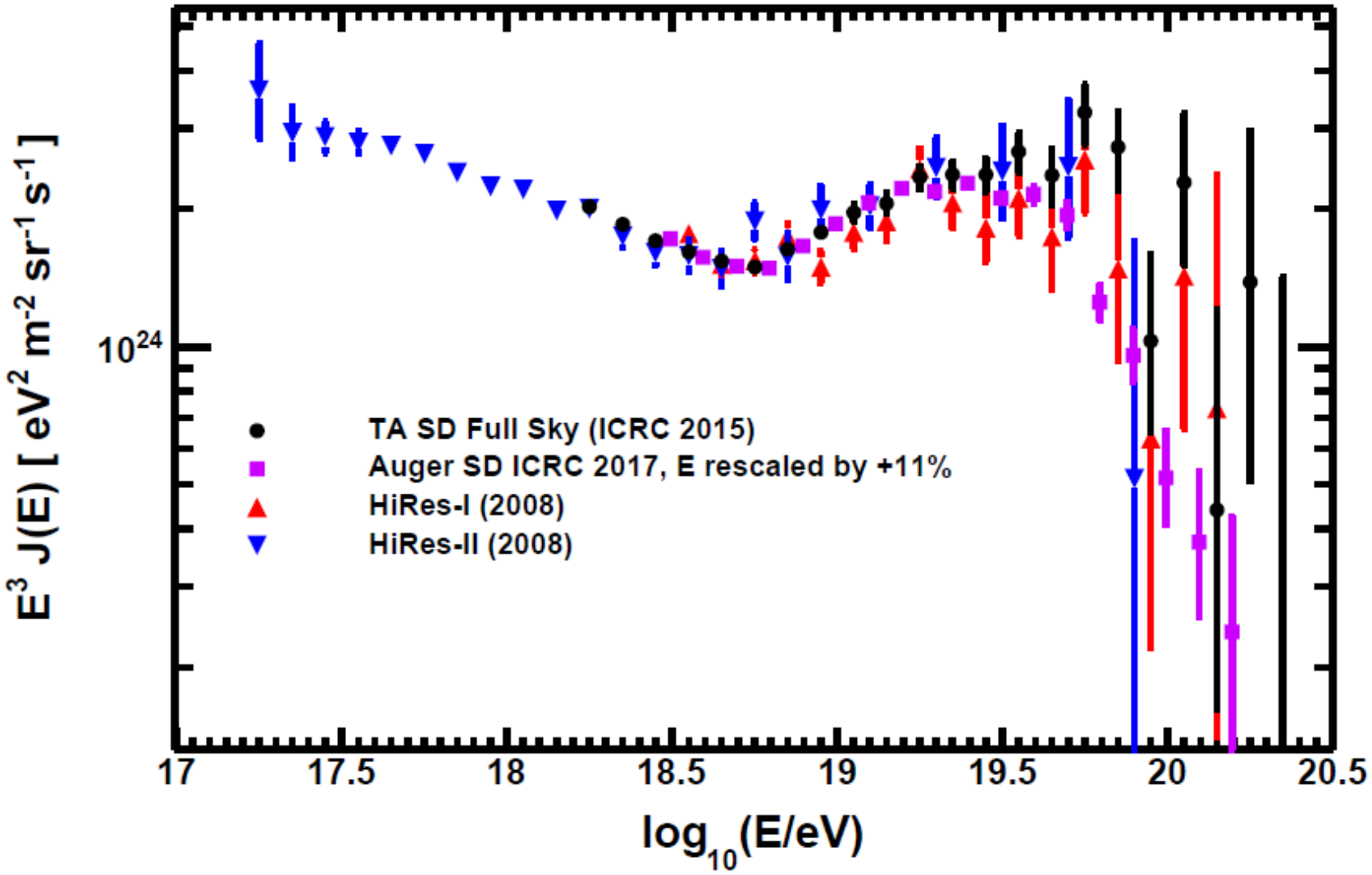


(a)

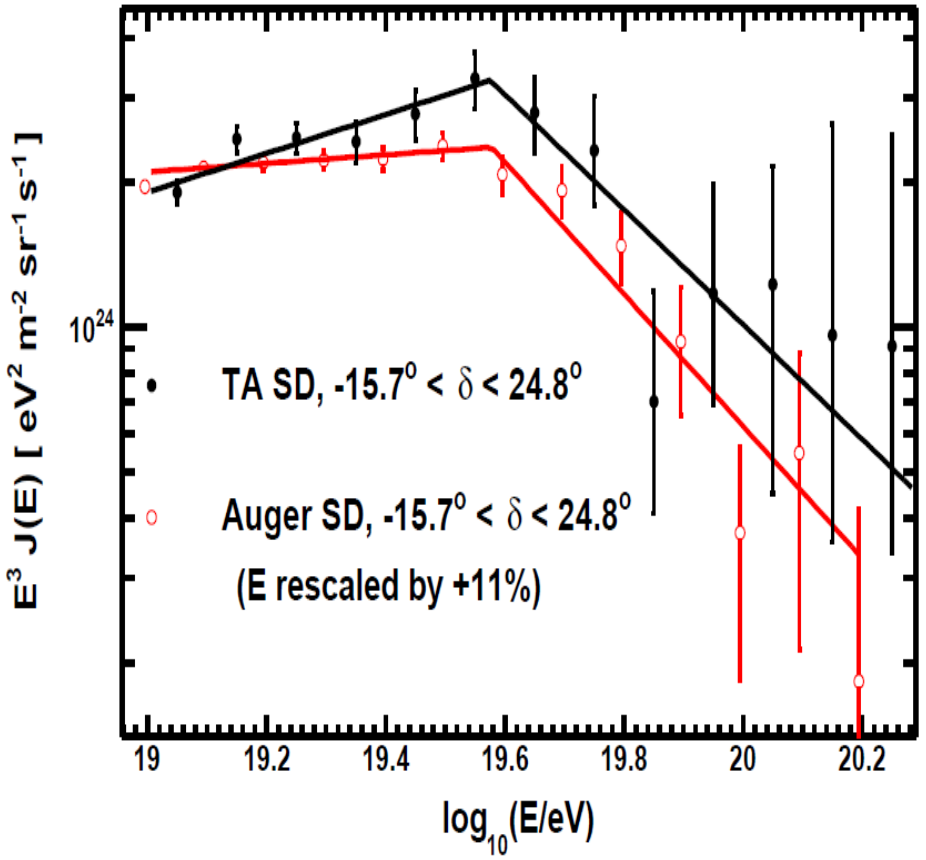


(b)

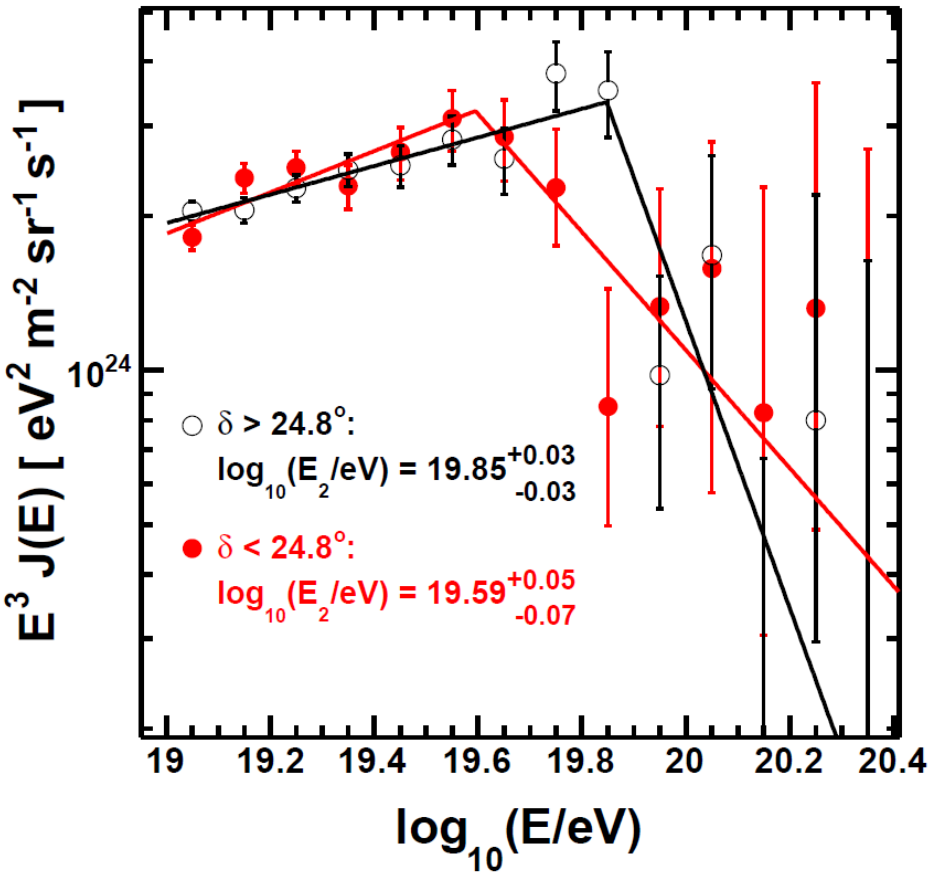
TA spectrum is harder than AUGER at the highest energies



Declination Dependence of TA Spectrum



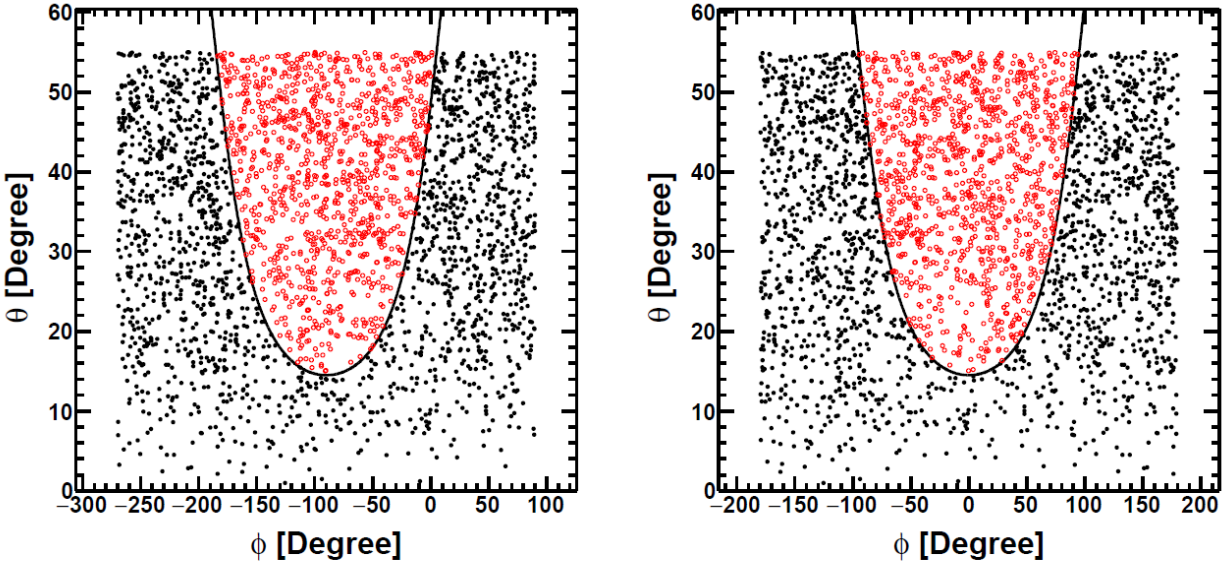
Energy spectra of TA and Auger in the common declination band. They agree at about 1σ level



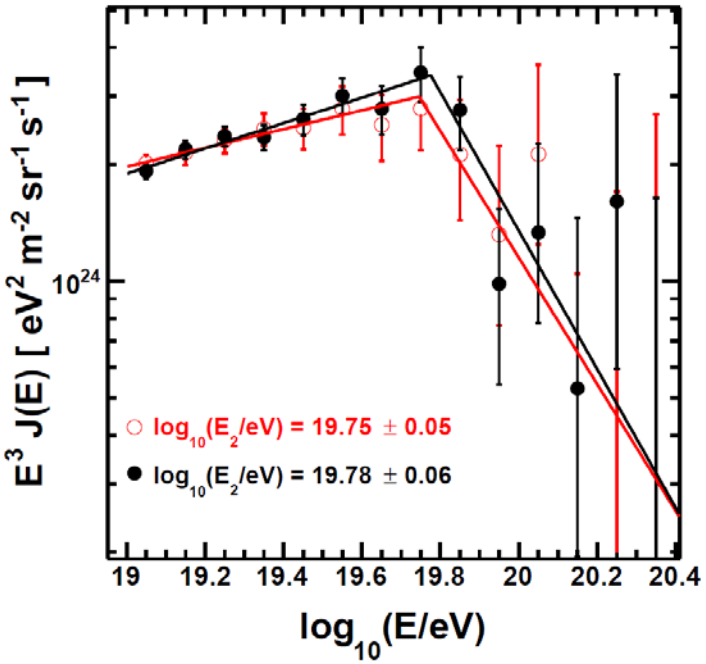
Energy spectra of TA above and below δ=24.8° They disagree at ~4σ level

Global Significance ~ 3.2 σ

Turning the detector 90 deg.



(a)



Local Angular Coordinates

Small-Scale Anisotropy

Autocorrelations: E> (1.0, 4.0, 5.7)×10^{19} eV

scan over [small] angles -> NO significant clustering

Coincidence with PAO

- At high E -> small deflections,

  spread determined by angular resolution

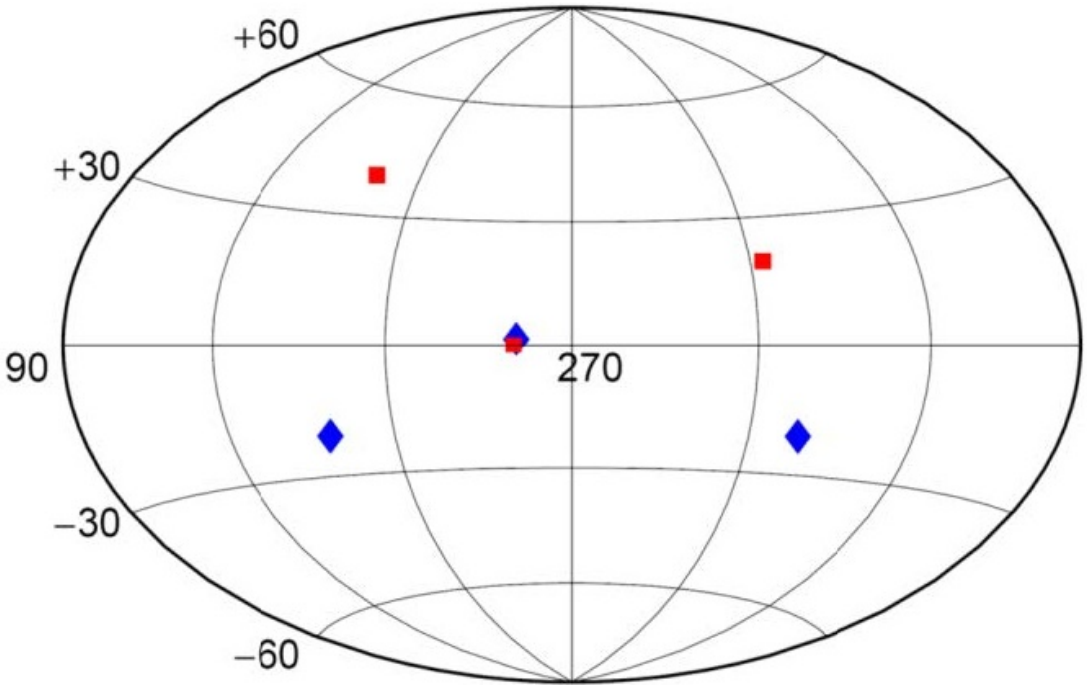
- doublet in TA/Auger joint dataset of 6 events [ST 2012]
- became a triplet(2TA + 1PAO) with more TA data

  [TA 2014]

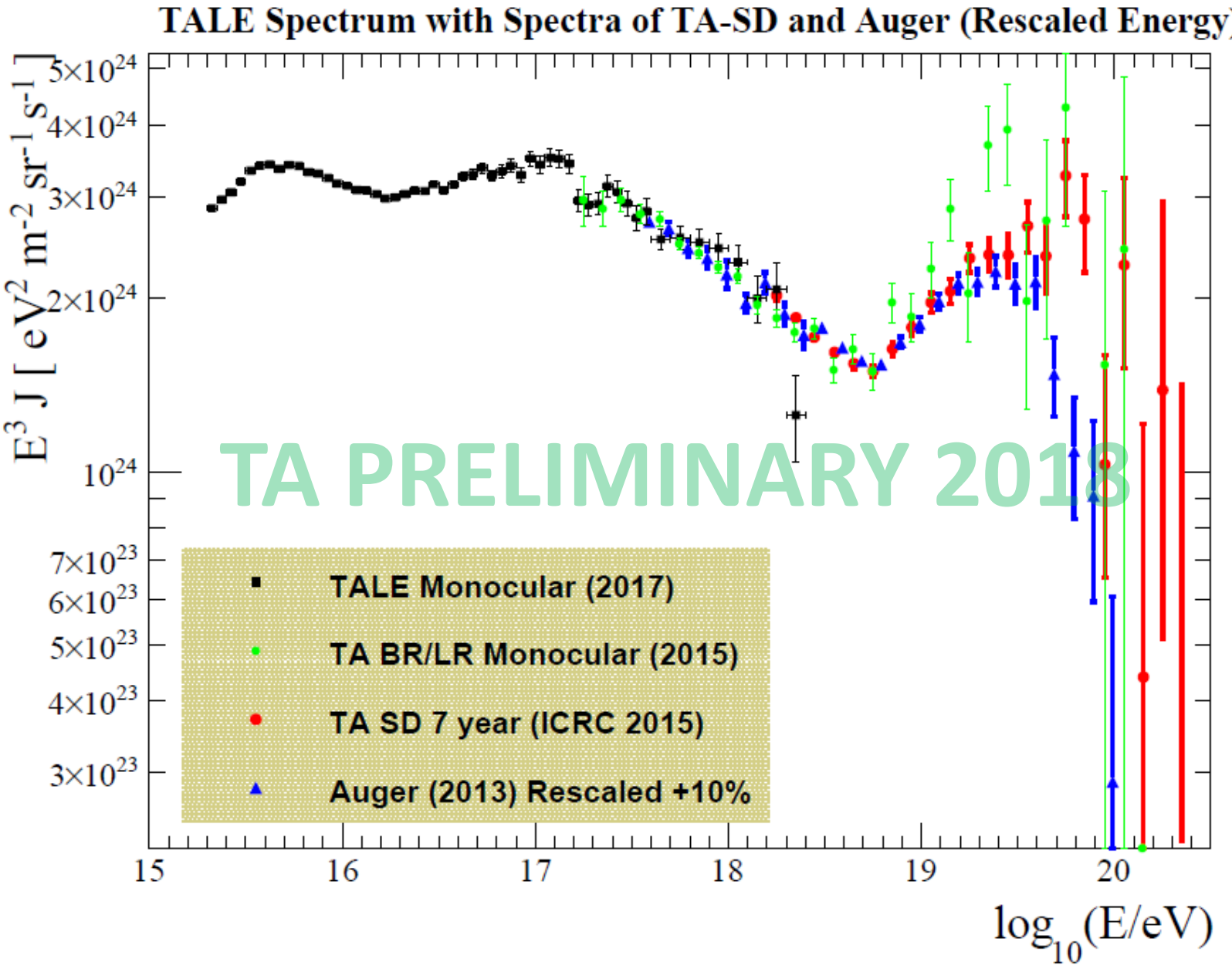
- E> 100 EeV, resolution = 1°,

  pre-determined angle

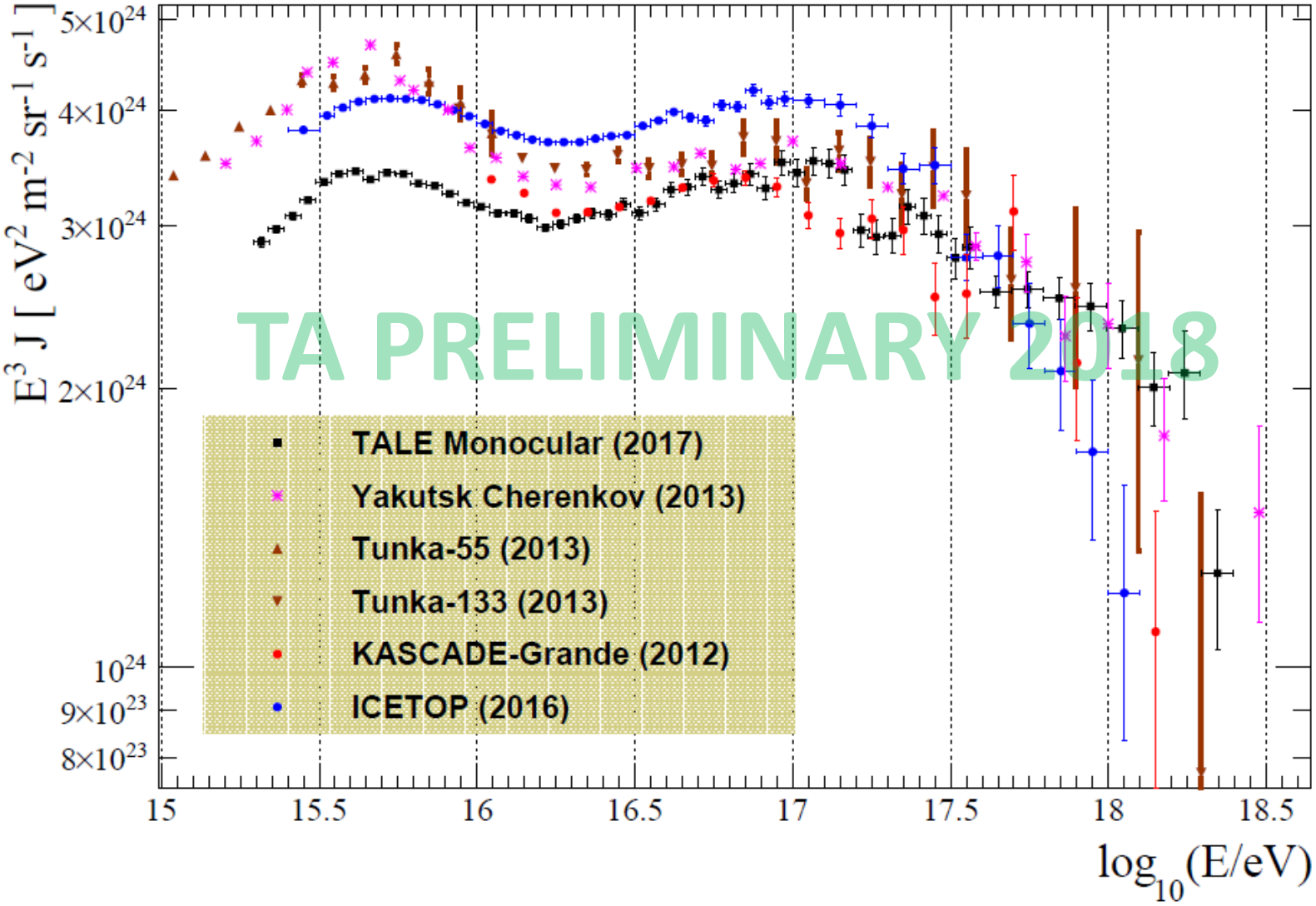
  = $\sqrt{2}$ × resolution



Equatorial Coordinates


TALE Spectrum with Spectra of TA-SD and Auger (Rescaled Energy)
E³ J [eV² m⁻² sr⁻¹ s⁻¹]
5×10²⁴
4×10²⁴
3×10²⁴
2×10²⁴
10²⁴
7×10²³
6×10²³
5×10²³
4×10²³
3×10²³
TA PRELIMINARY 2018
TALE Monocular (2017)
TA BR/LR Monocular (2015)
TA SD 7 year (ICRC 2015)
Auger (2013) Rescaled +10%
15
16
17
18
19
20
log₁₀(E/eV)

TALE Spectrum compared to some recent Measurements



Conclusions: Composition

- <Xmax> Result compatible with either helium or hydrogen – statement is model-dependent (and extrapolation uncertainties)
- Get around the problem by comparing the shape of the Xmax distribution (in energy bins) to MC predictions for four primaries (H, He, N, Fe)
- Shift <Xmax> using maximum likelihood method on the Xmax distribution
- Use Max. logL as a measure of compatibility between data shape and MC
- **Compatible with ONLY protons < 10^{19}eV**
- **Insufficient statistics to rule out any primary >10^{19}eV**

NEED MORE DATA! (TAx4)

- **We will be studying composition with TALE**

Conclusions: Anistropy

Hints of large-scale anisotropy at E>57 EeV

- ✓ Supergalactic latitude distribution
- ✓ Supergalactic plane spectrum
- ✓ Large-scale structure correlations
- ✓ declination dependence of the spectrum

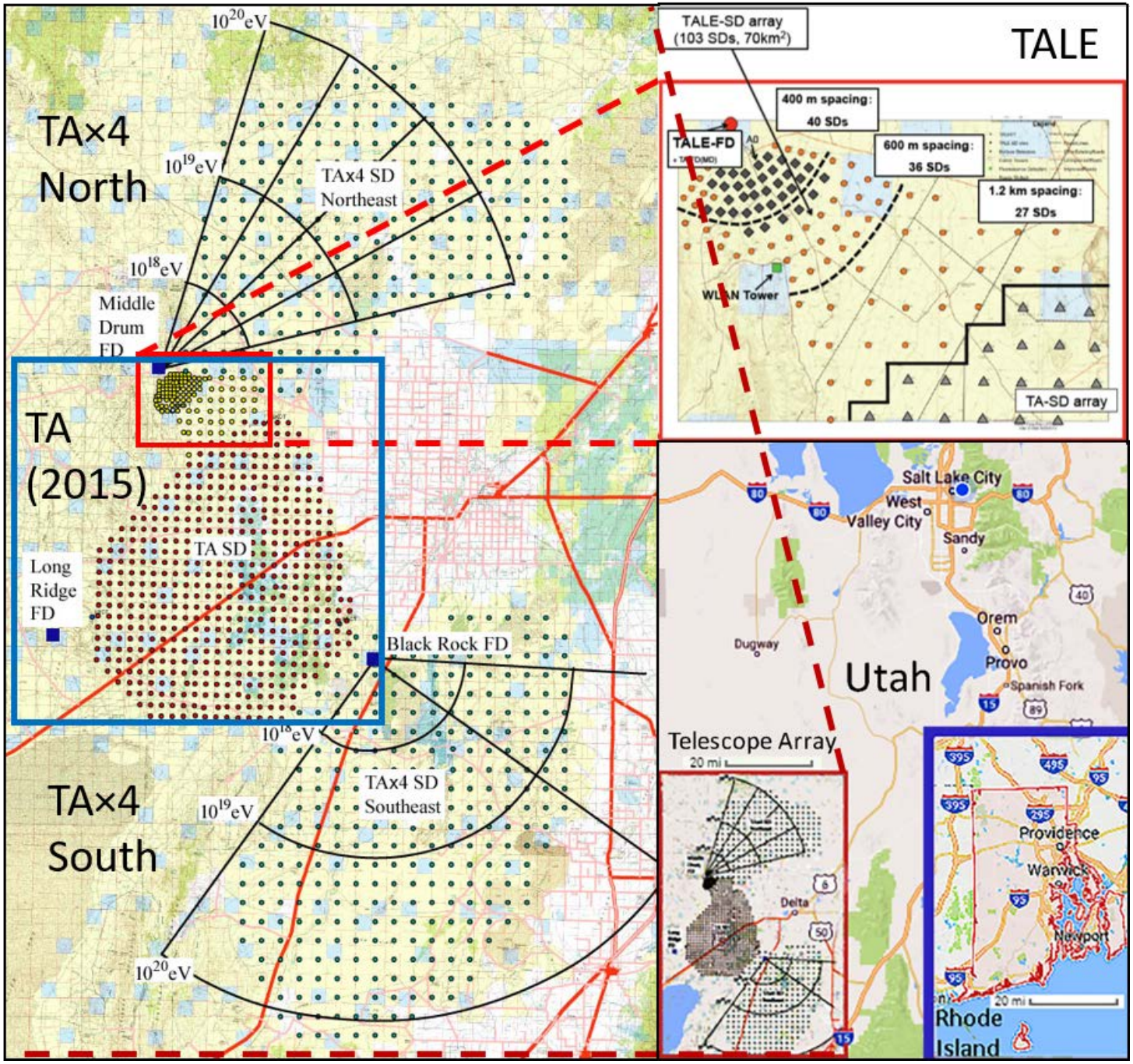
Medium-scale anisotropy at E>57 EeV

- ✓ hot spot larger and closer to supergalactic plane (9 years)
- ✓ cold spot at lower energies in the same place

Small-scale

- Doublets at $E>10^{20}$ eV, not significant

ALL POSTITIVE HINTS IN THE NORTHERN SKY OCCUR AT THE HIGHEST ENERGIES: NEED MORE DATA! (TAx4)



TAx4 now under construction:

Will double TA data sample by mid-2021