TA Recent Results and Prospects
VULCANO-2014

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Outline

- Ultra-High Energy Cosmic Rays
- The TA detector
- Spectrum
- Composition - New result from hybrid analysis
- Composition – New preliminary result on spectrum from "imaging Cherenkov" mode.
- Anisotropy – New result on evidence for hotspot

If time permits:

- TARA – Bistatic radar detection of Cosmic Rays
- NICHE – Cherenkov array for low energy studies

Why UHECR?

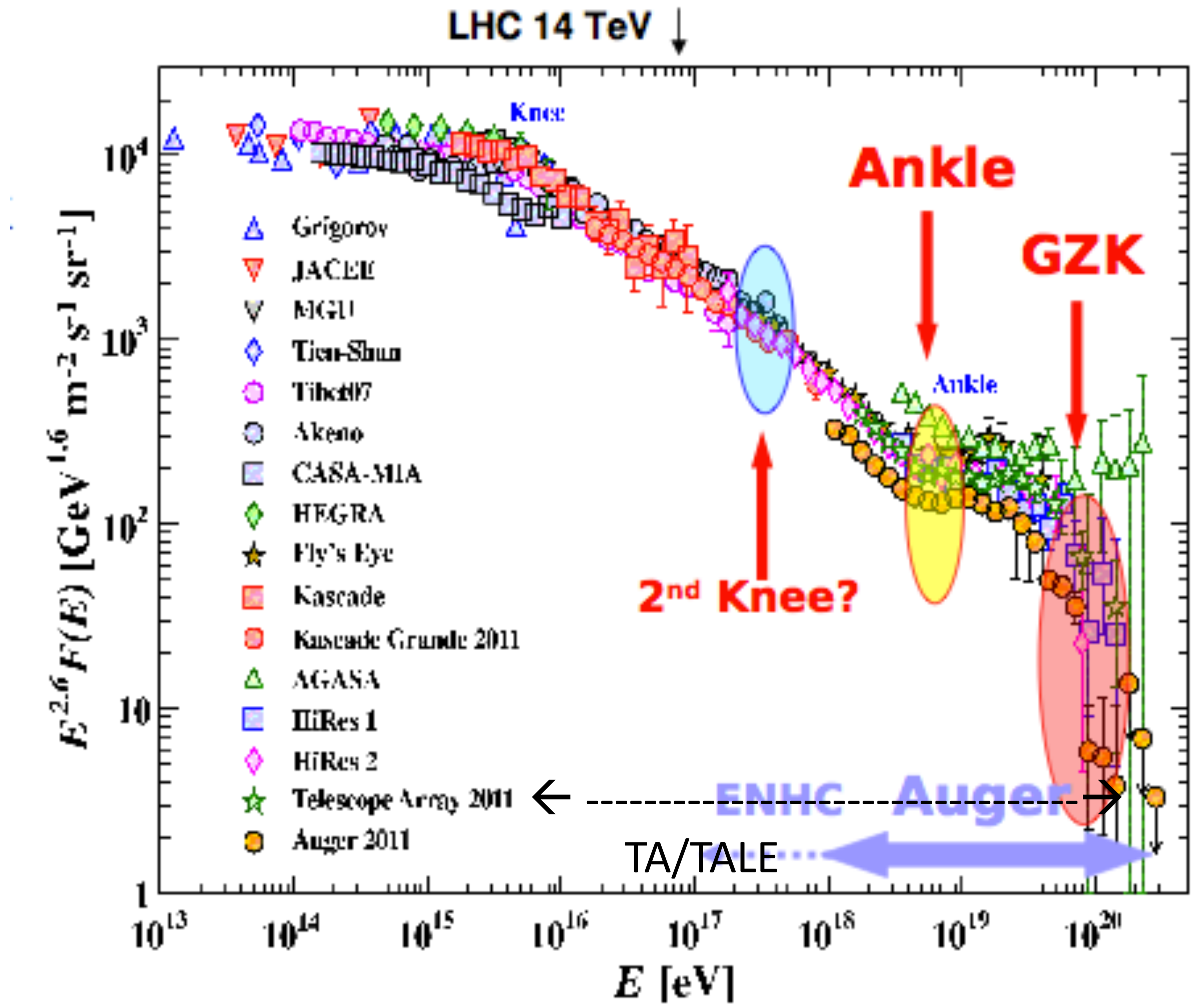
- Highest energy particles in Universe – 10^{20} eV ~ 10 Joules/nucleon – rate ~ 1/km^2/century
- Acceleration mechanism and sources unknown
- Interactions with 2.7 deg BB background – characteristic signature (GZK cutoff)
- Elucidate by studying spectrum, composition and anisotropy from 10^{17} to 10^{20} eV.

UHECR nature and origin

- Are they predominantly galactic or extra-galactic?
- What is the acceleration mechanism?

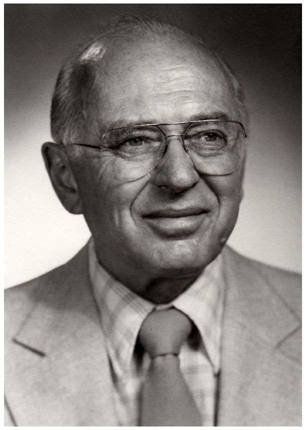
  SN, galactic wind, AGN jets, decays of super-heavy primordial objects
- What is the composition of the cosmic rays?
- What is the effect of propagation thru space ?

  Interactions with relic BB radiation, starlight, dust, etc.; effect of magnetic fields on trajectories



Reasonable agreement considering energy scale uncertainties –many structures imply variety of sources and acceleration mechanisms

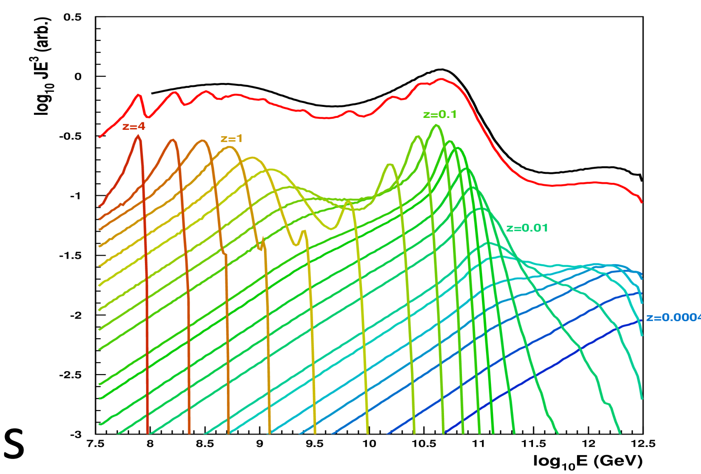
Are things simpler at the highest energies?



- Propagation effects are striking

for distant sources

- – Cut off due to relic BB photons (GZK).
- – Simplification of composition to protons
- – and Fe
- \- Effect of magnetic fields is minimized
- – protons should point back to their sources



How to detect very rare events? Utilize secondary interations

The Hybrid Concept

Surface Detector Array

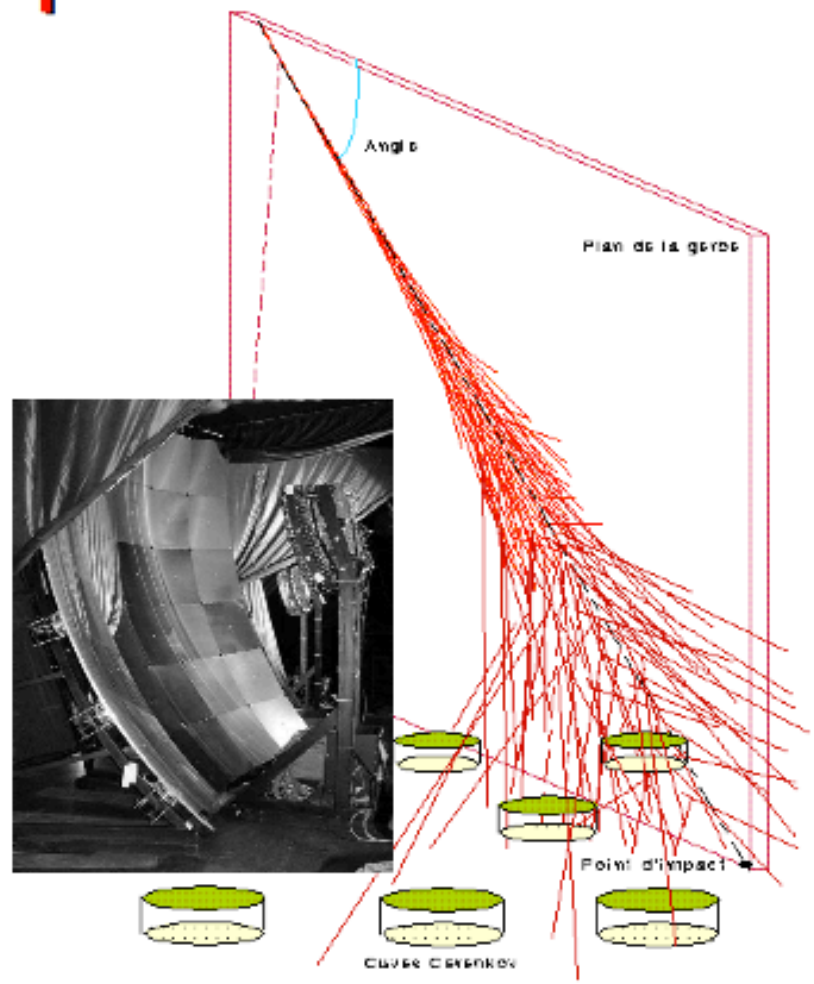
lateral distribution, 100% duty cycle

Air Fluorescence Detectors

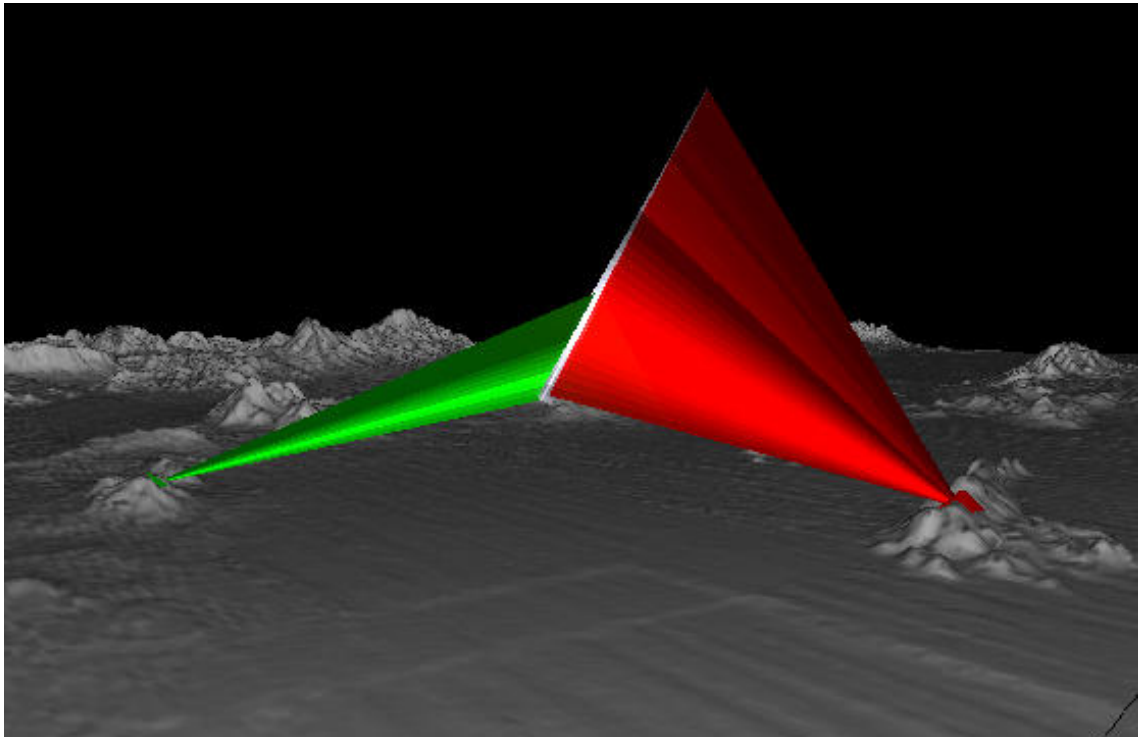
Longitudinal profile, calorimetric energy measurement, ~15% duty cycle

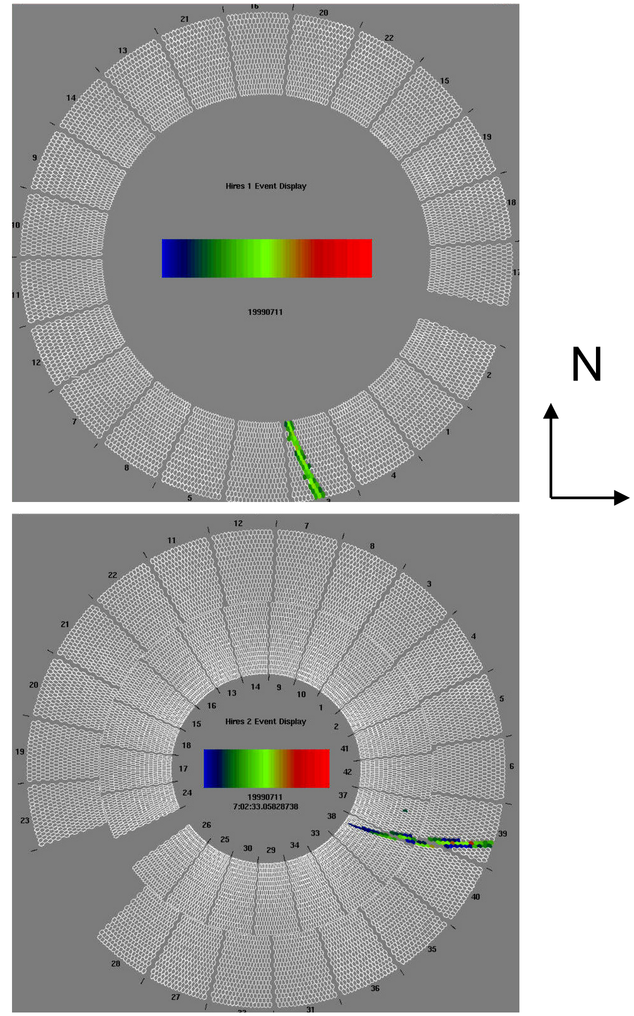
accurate energy and direction measurement

mass composition studies in a complementary way



Typical HiRes Stereo Event





- ~2×10^{19} eV event
- (3× vertical scale)

Telescope Array Collaboration

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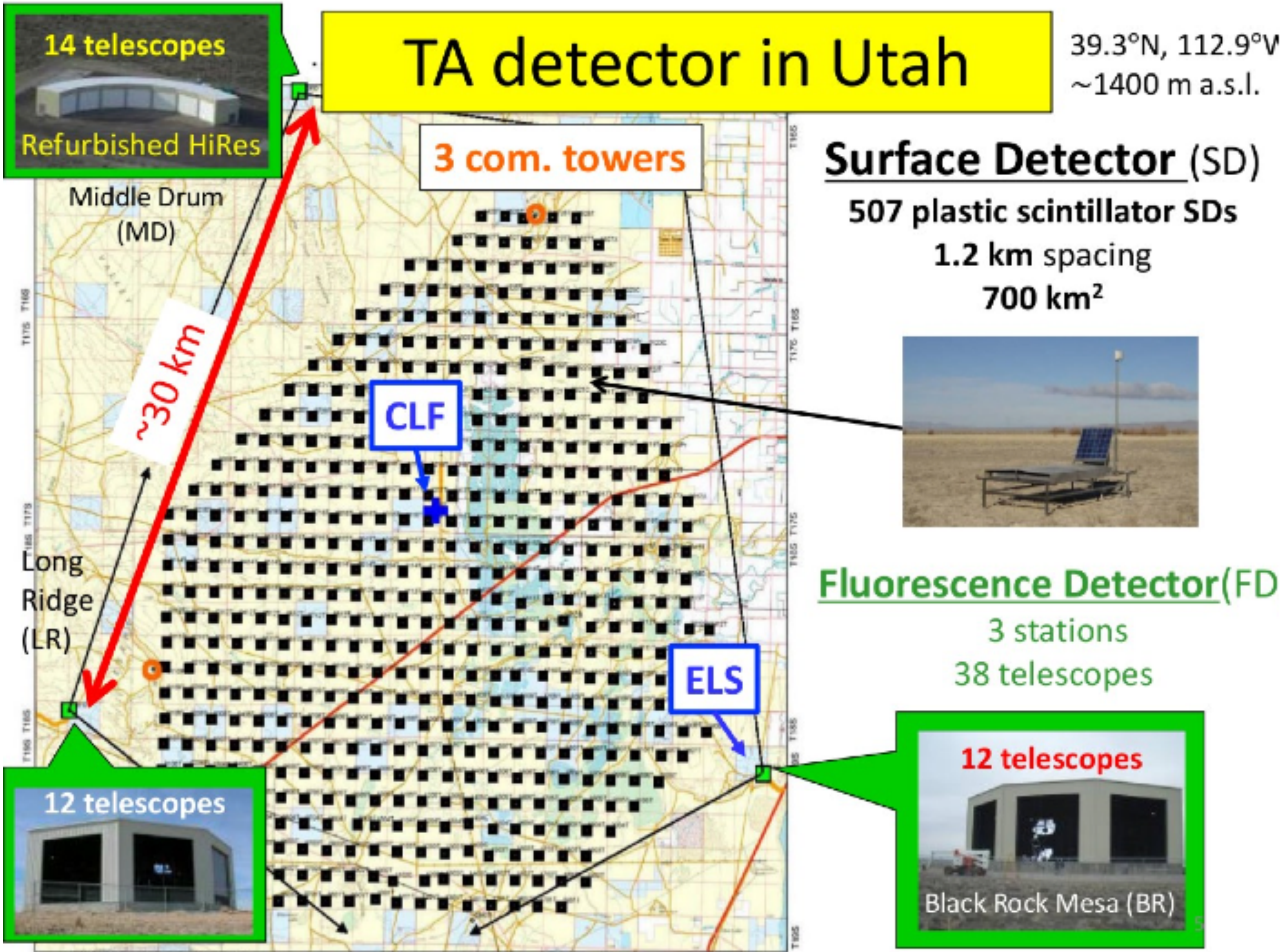
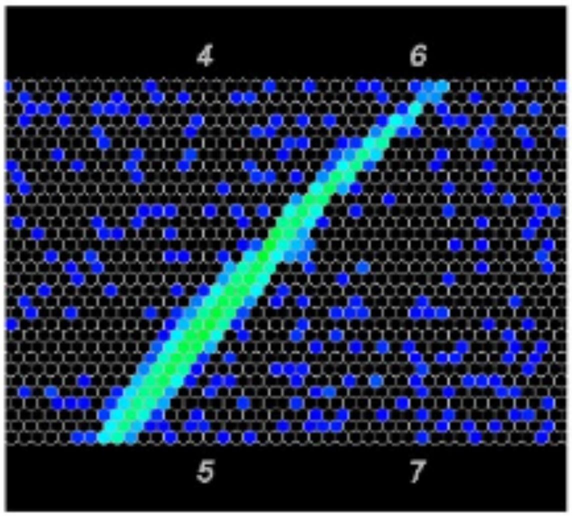
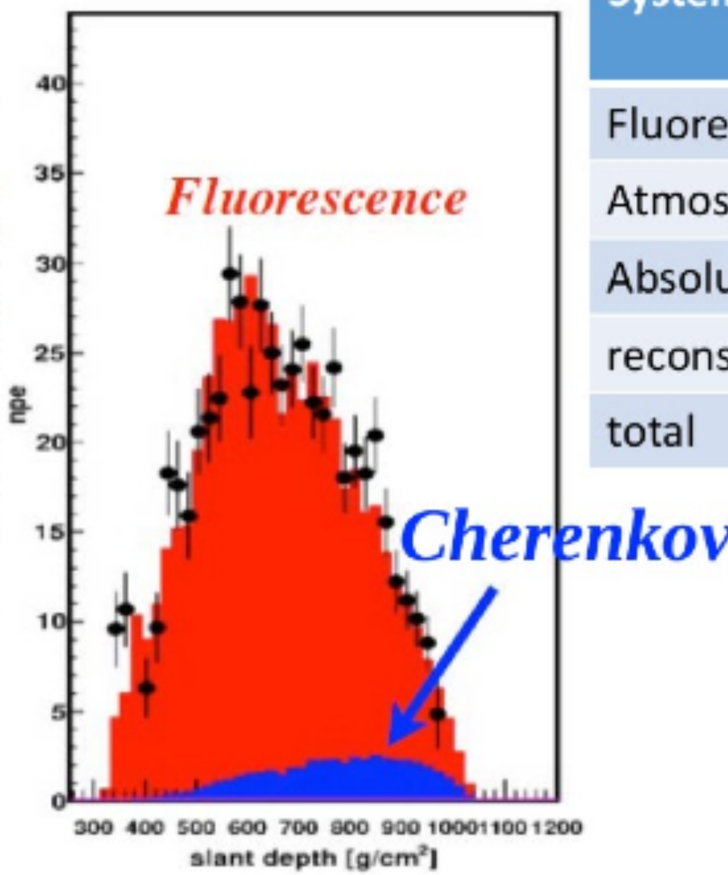

TA detector in Utah
39.3°N, 112.9°W
~1400 m a.s.l.
14 telescopes
Refurbished HiRes
Middle Drum
(MD)
3 com. towers
~30 km
CLF
Long
Ridge
(LR)
ELS
12 telescopes
Surface Detector (SD)
507 plastic scintillator SDs
1.2 km spacing
700 km²
Fluorescence Detector(FD)
3 stations
38 telescopes
12 telescopes
Black Rock Mesa (BR)

TA shower analysis with FD

An example of an air shower
the camera view

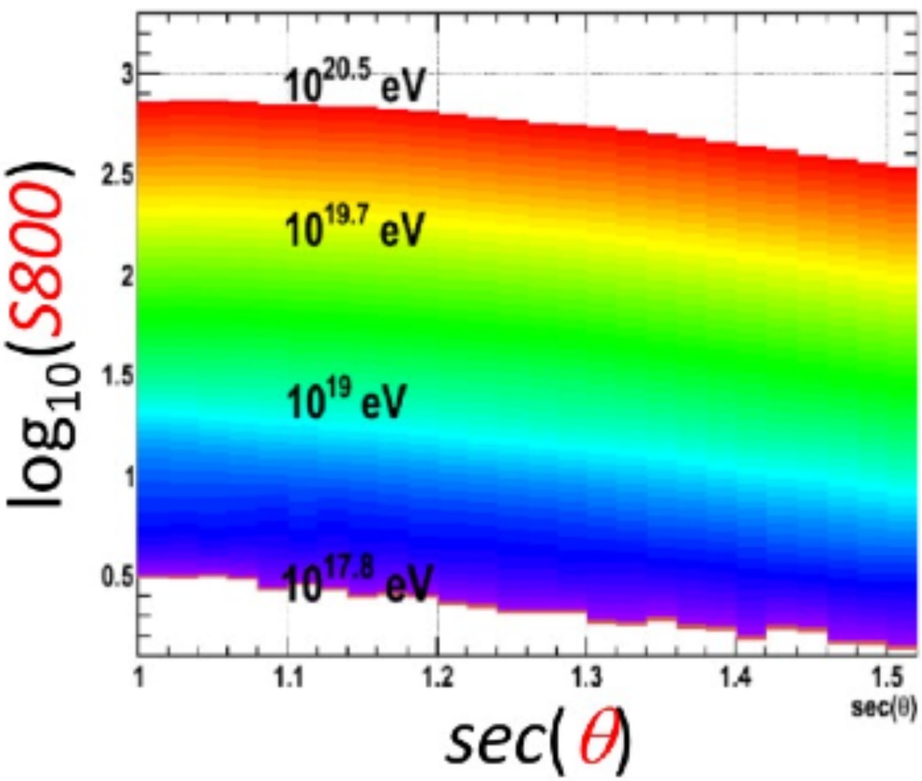


Longitudinal shower profile

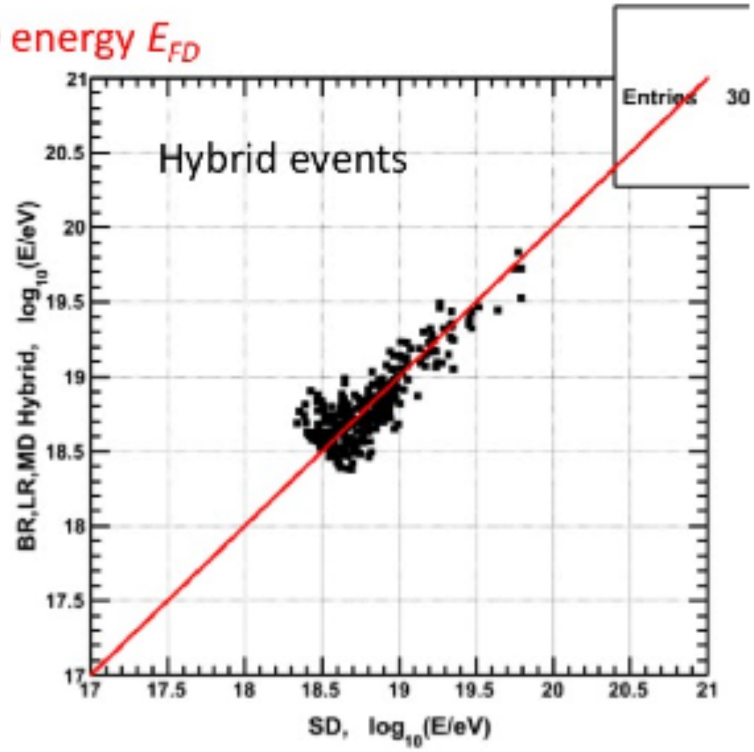


Systematic uncertainty in energy determination	
Fluorescence yield	11%
Atmospheric attenuation	11%
Absolute detector calib.	10%
reconstruction	10%
total	21%

SD/FD Energy Scale

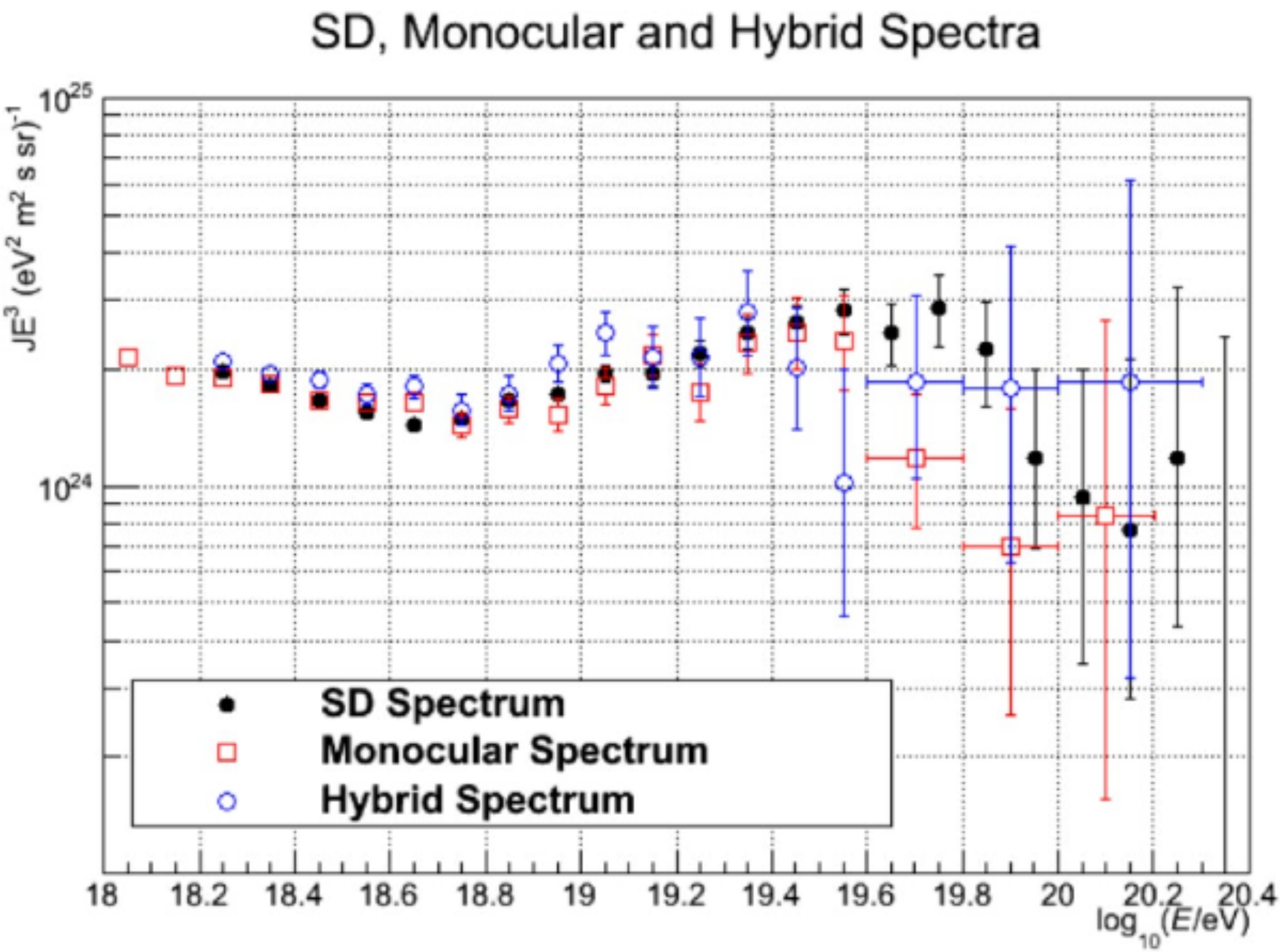


First estimate of SD Energy: MC lookup table

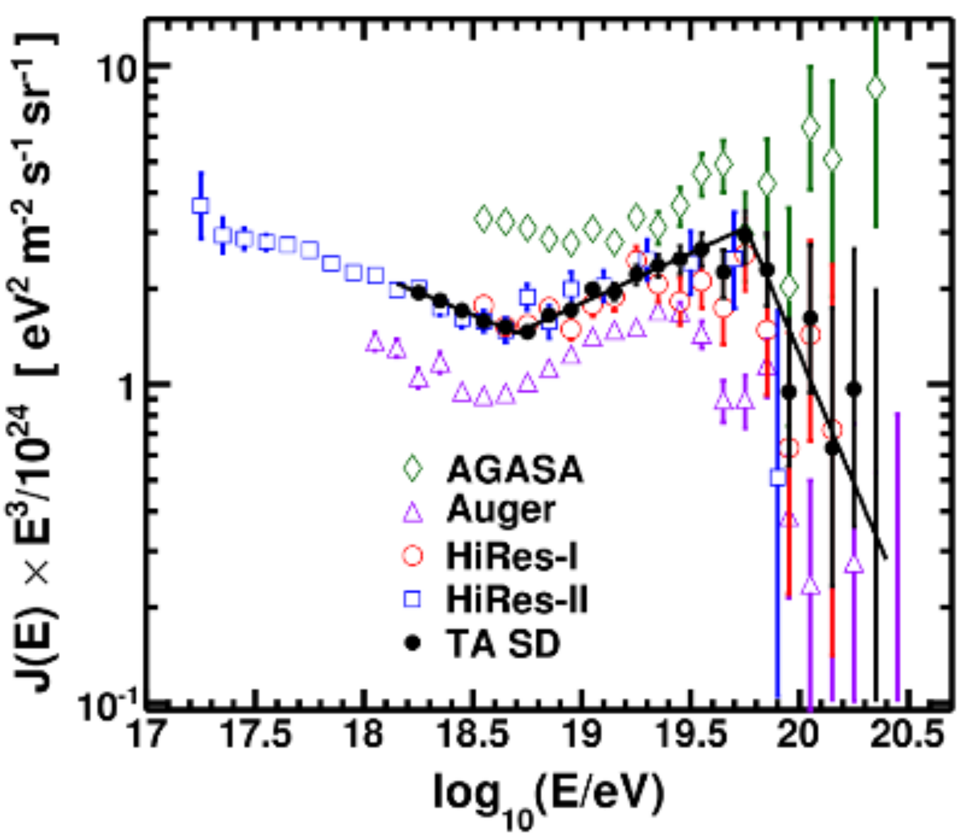


$E_{SD} = E'_{SD}/1.27$

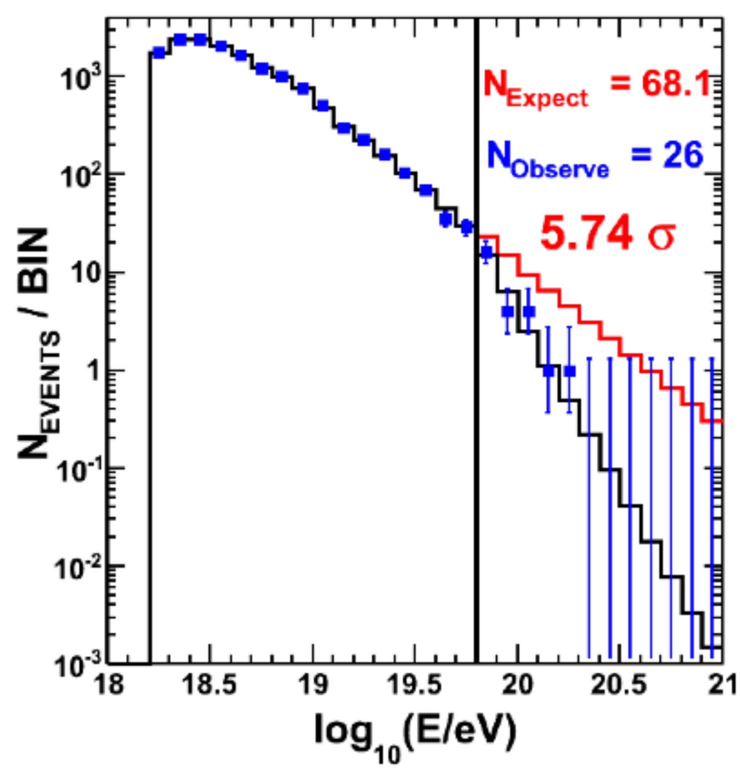
Spectrum overview



Comparison with other experiments and significance



Significance of suppression



Status of GZK Cutoff

- Now observed with multiple methods
- HiRes – Fluorescence – 5 sigma
- PAO – Cherenkov water + Fluorescence > 20sig
- TA – Plastic scintillator + Fluroescence > 5 sig
- Energy within 20% of each other – within systematics
- TA SD is 1.27 x higher energy than FD. Explains AGASA normalization.
- What is the composition?

GZK-suppression clearly exists
But …

- Is this suppression due to onset of inelastic pion photoproduction (protons), nuclear spallation on relic microwave background, or a reflection of the injection spectrum of the sources?
- Composition of cosmic rays needs to be determined.

Composition

- Simulate p, CNO, Fe interactions using:

Hadronic models QGS-Jet, Sybill, etc..

Generate simulated data – Corsika + detector simulator

Assume a mass compostion

Compare simulated data to real data

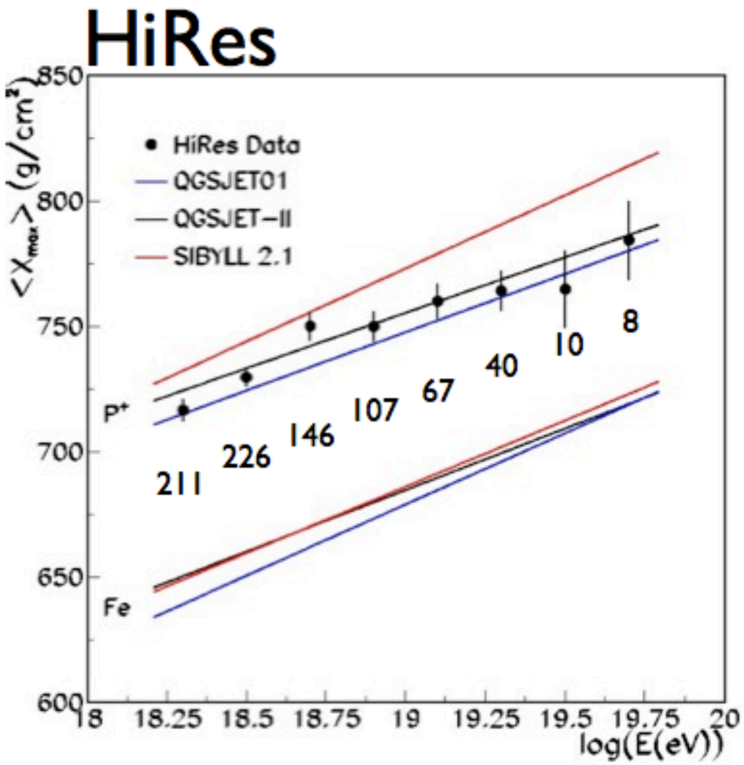
Xmax distribution, mean and fluctuations

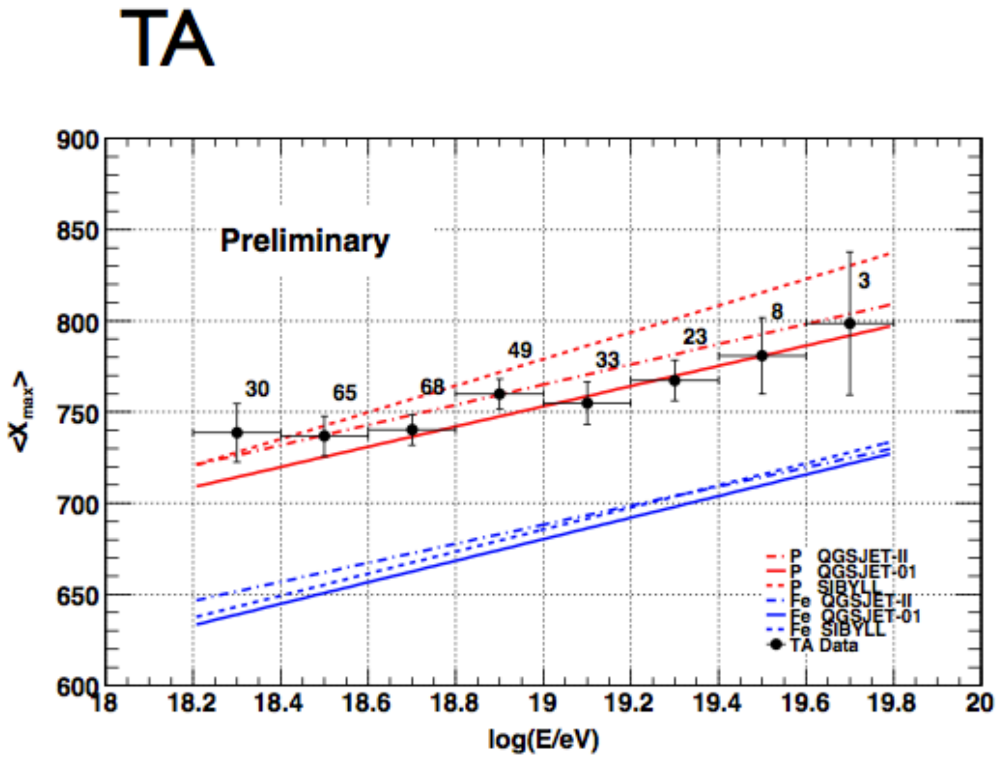
All carry composition information

Composition Strategy

- Because the Xmax technique is subject to significant experimental and theoretical model systematics, measurement in various modes is an important check.
- Compare HiRes (stereo), TA (stereo), TA MD (HiRes-like) + SD hybrid, TA BR+LR (new FD) + SD hybrid with results from PAO (FD + H2O Cherenkov)
- Here we present TA MD hybrid results.

Composition – Elongation Rate from Stereo measurements





Composition –North/South Difference?

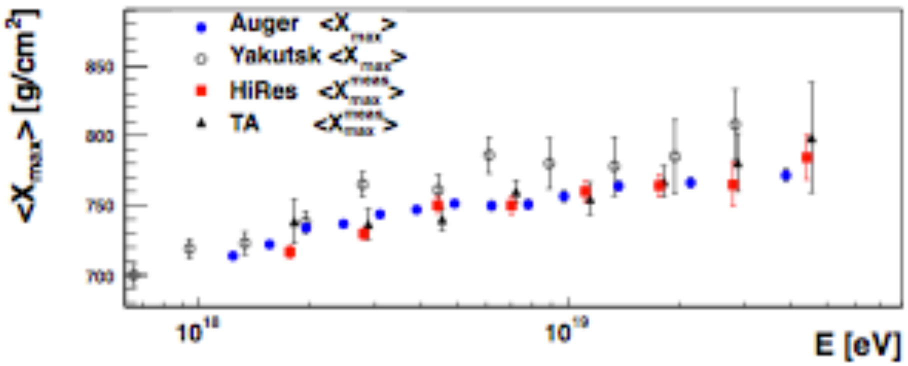
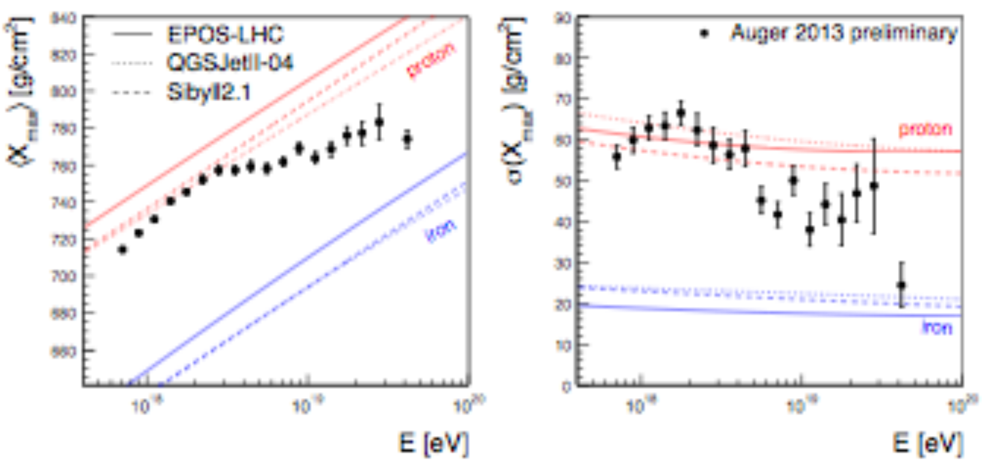
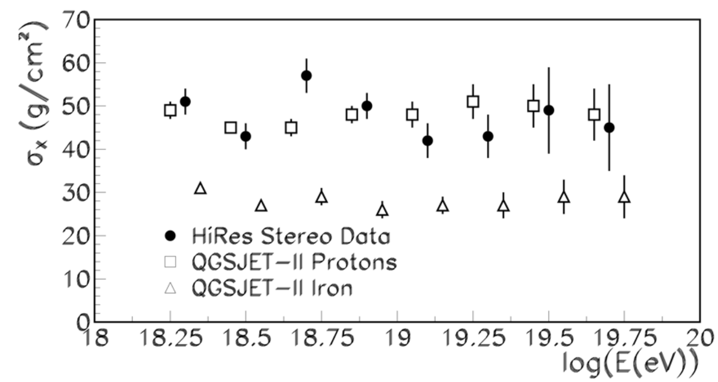


Fig. 2. $\langle X_{\max}\rangle$ measured by Auger and Yakutsk, together with the $\langle X_{\max}^{\mathrm{meas}}\rangle$ as measured by HiRes and TA. Data points are shifted to a common energy scale (text for details).



Most recent
PAO result



HiRes Stereo

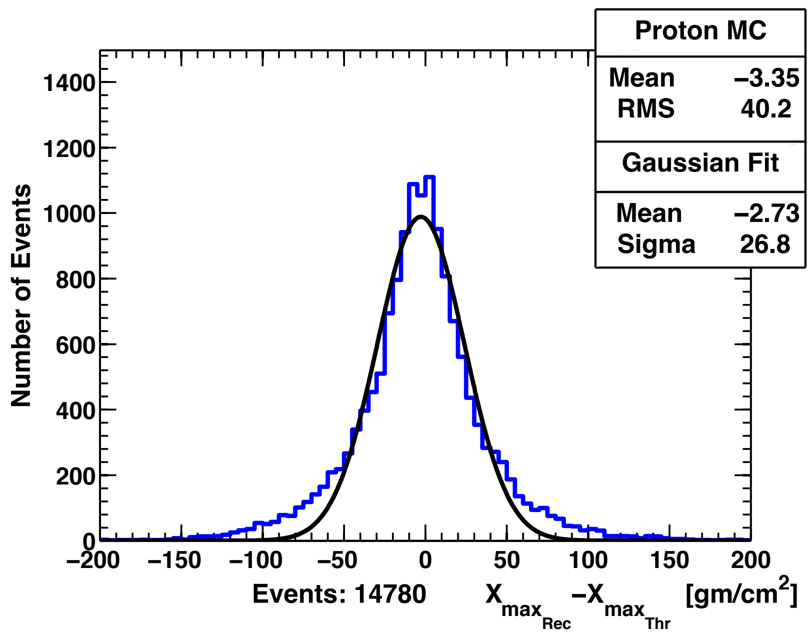
Summary of differences

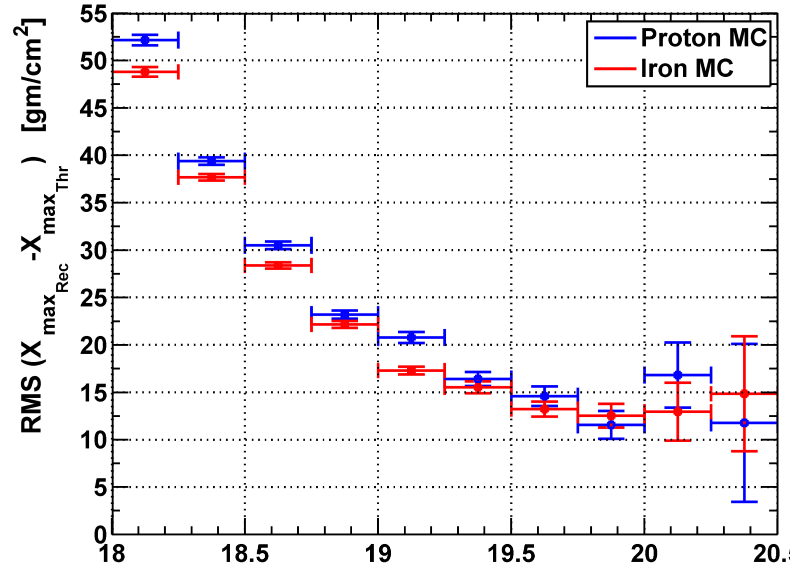
- Elongation rate data is ~ consistent
- Interpretation in terms of composition different (acceptance issues?)
- Width in PAO changes from ~ 60 gm/cm2 < 6x10^18 to ~ 40 gm/cm2 > 6x10^18 eV. Not supported by HiRes stereo?
- Resolution and acceptance in Xmax are important issues

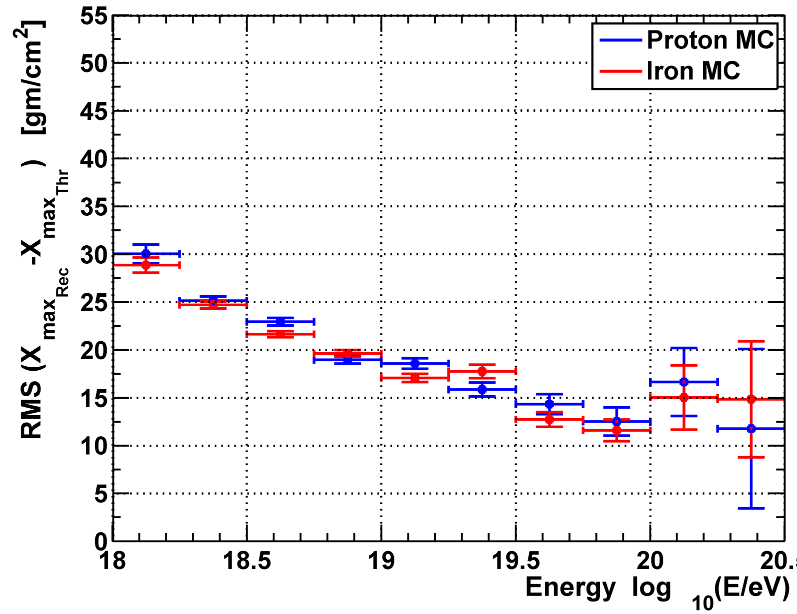
TA MD (HiRes-like) hybrid analysis

- FD + SD coincidences found by timing
- Use geometrical cuts after reconstruction similar to "HiRes cuts".
- Resultant data in good agreement with MC predictions from QGS-Jet II proton model – zenith, Rp, tracklength etc.
- Xmax resolution is energy dependent over 10^{18} to 10^{20} eV range (50 – 15 gm/cm^2)
- Train pattern recognition program to find "good resolution events" – clear rise and fall of signal
- After pattern recognition, Xmax resolution has much slower energy dependence (30 – 15 gm/cm^2)

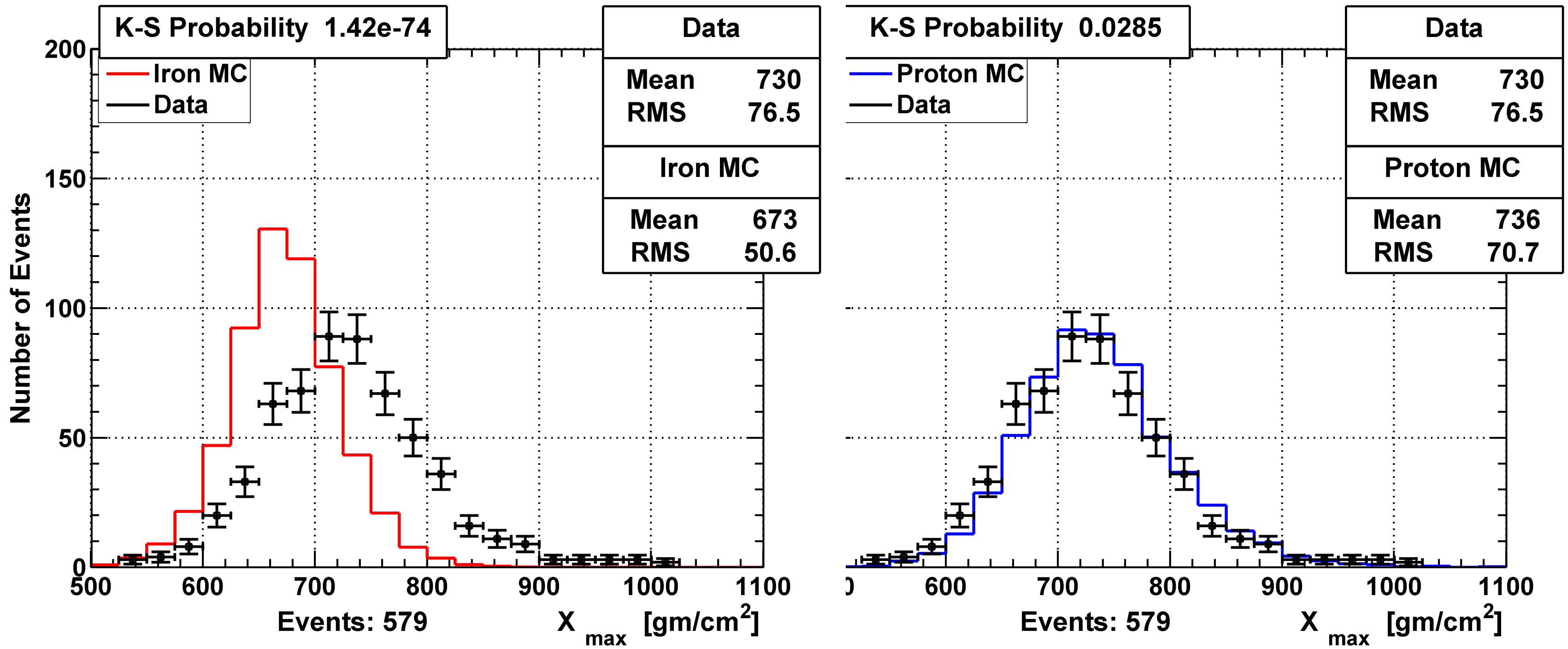
Xmax resolution “HiRes type cuts” and pattern rec. cuts



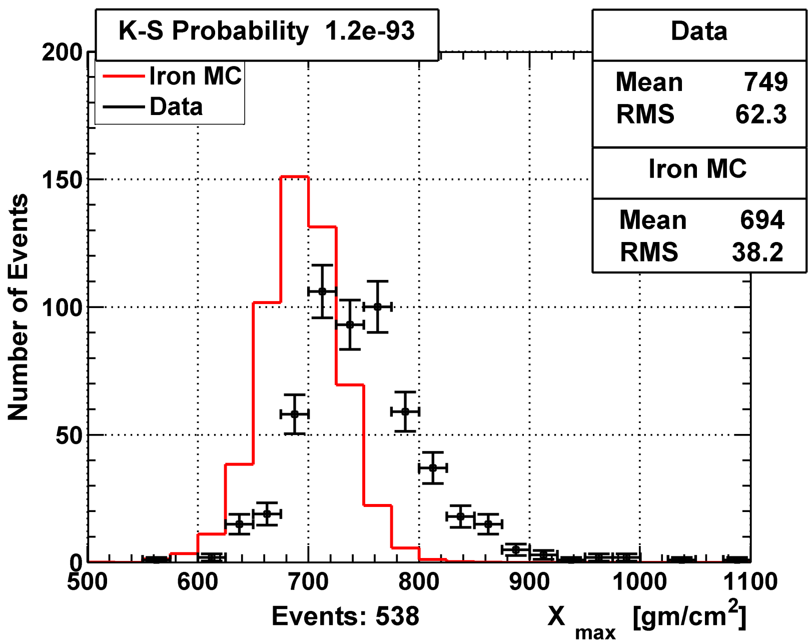


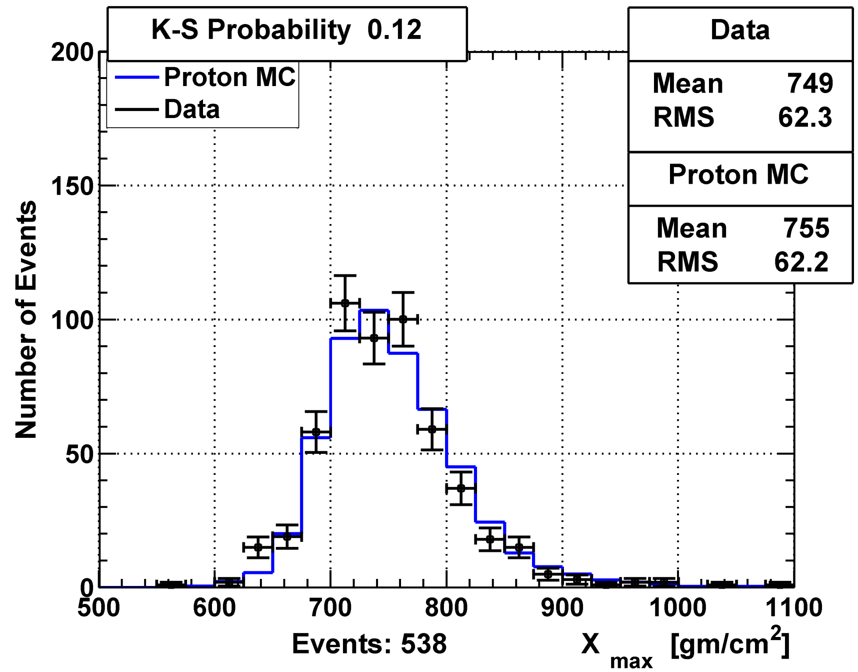


HiRes type cuts < 18.4



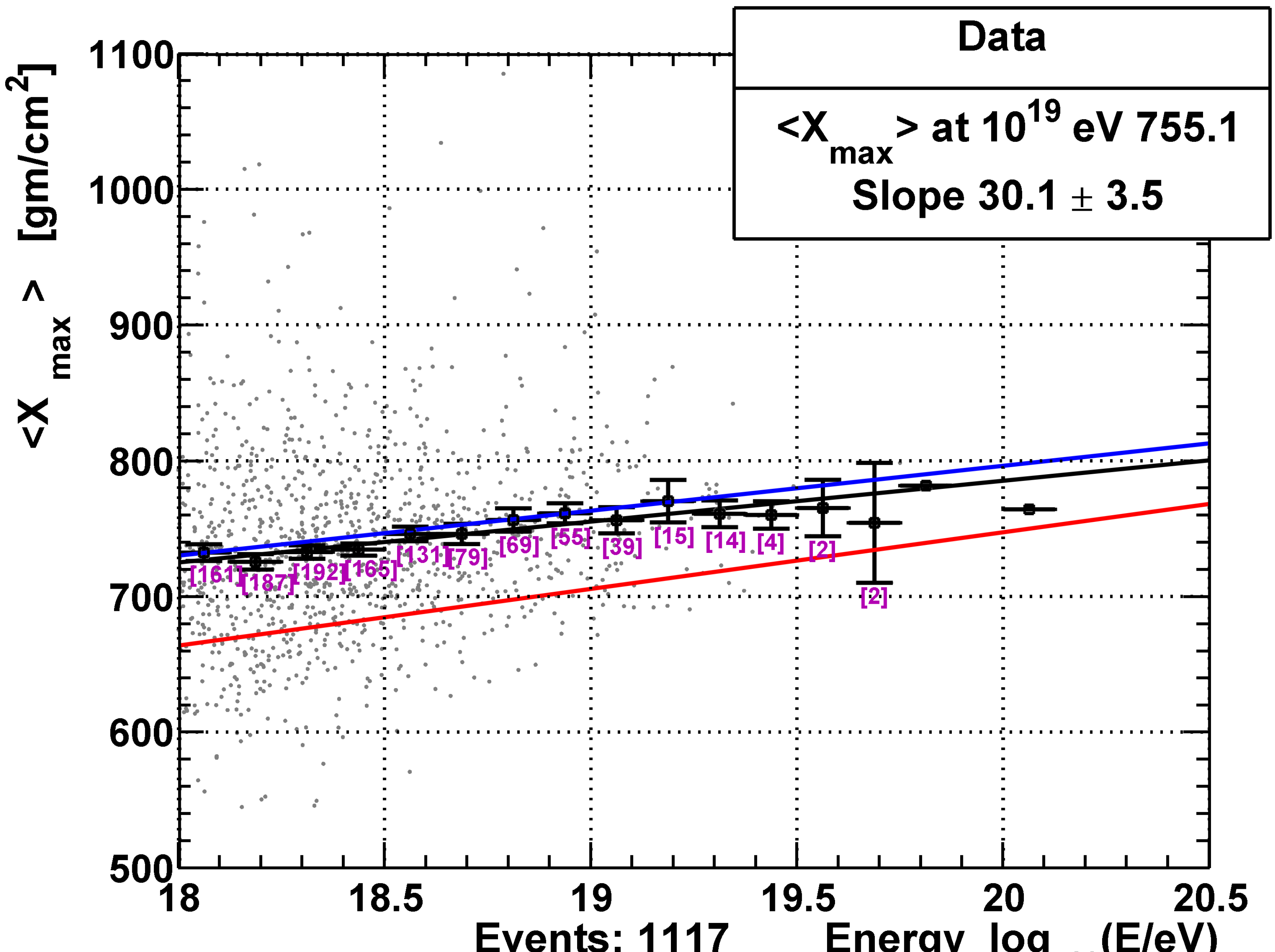
HiRes type cuts > 18.4



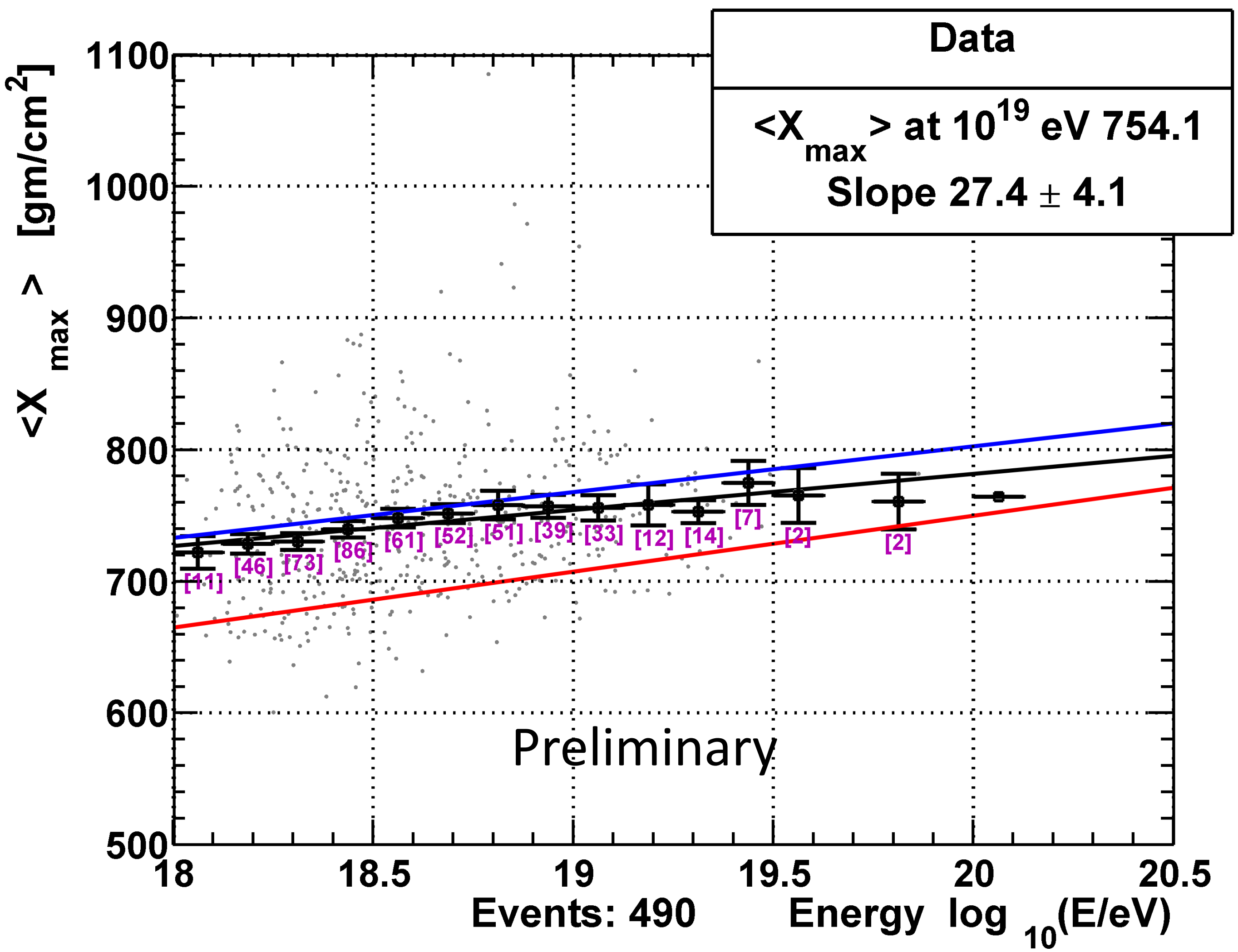


Even with poorer resolution, MC using proton QGS-Jet is "High Fidelity" in app measured Parameters.

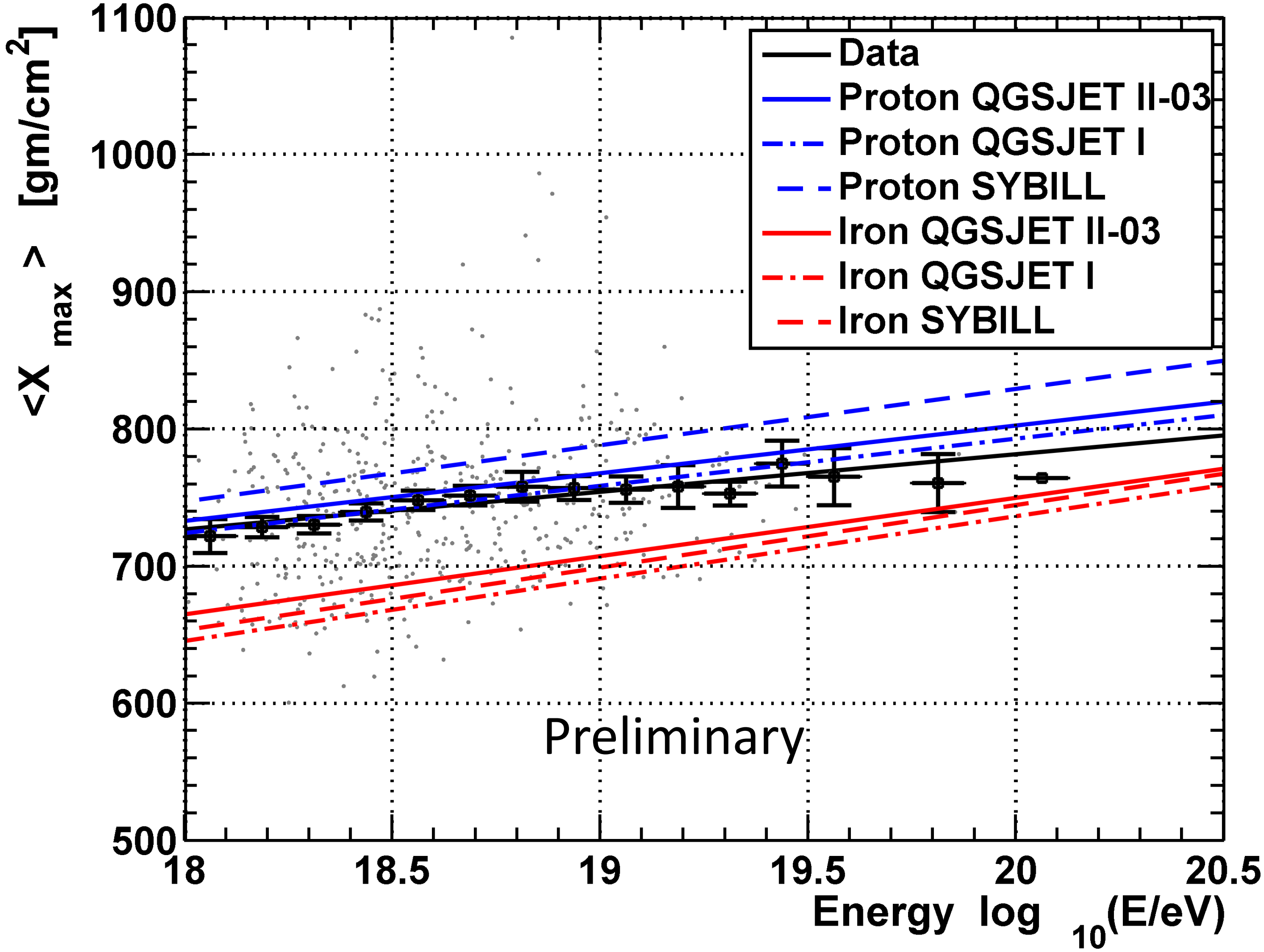
HiRes type cuts



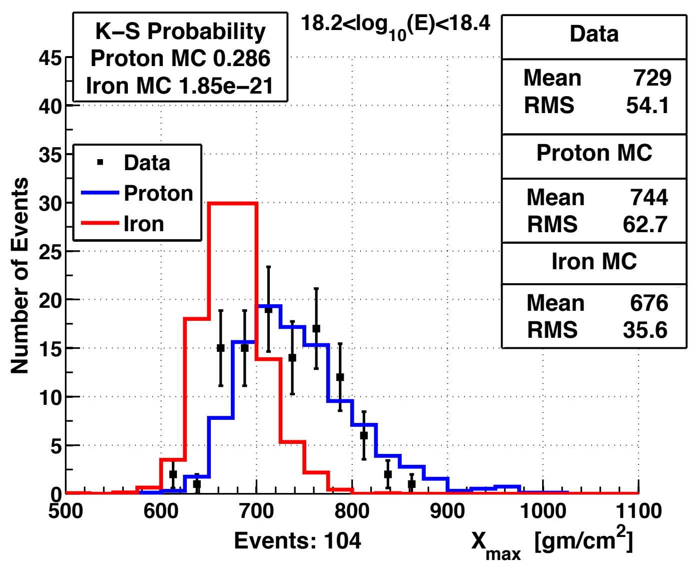
Pattern recognition cuts

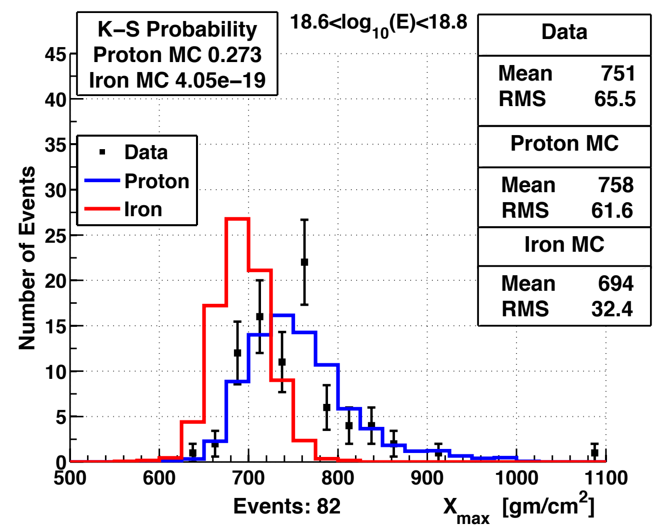


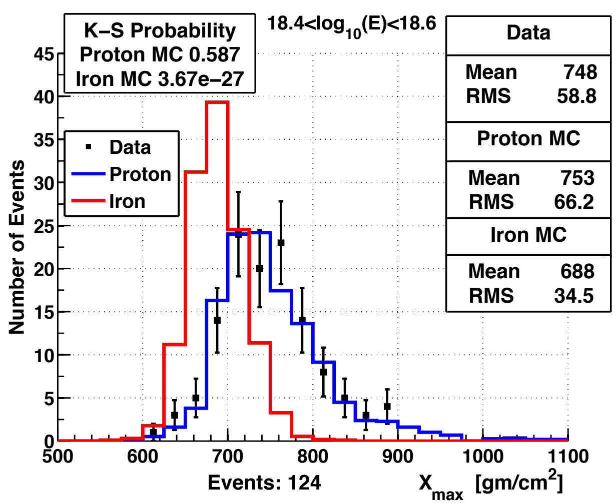
Hadronic model dependence

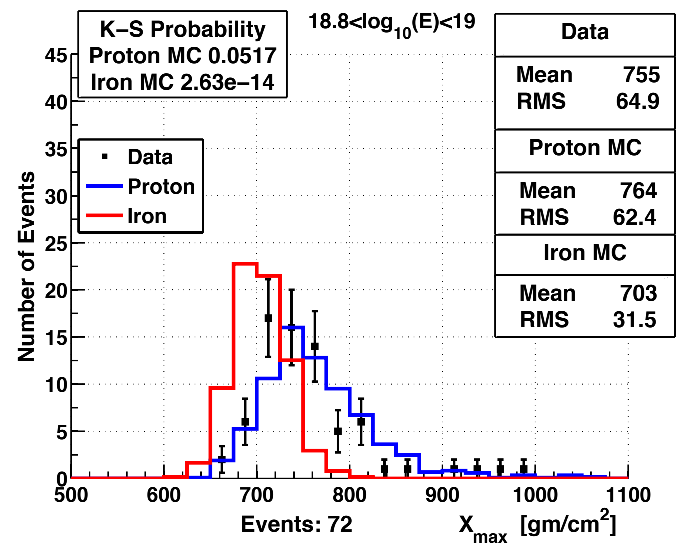


Xmax distributions – pattern rec. cuts Preliminary



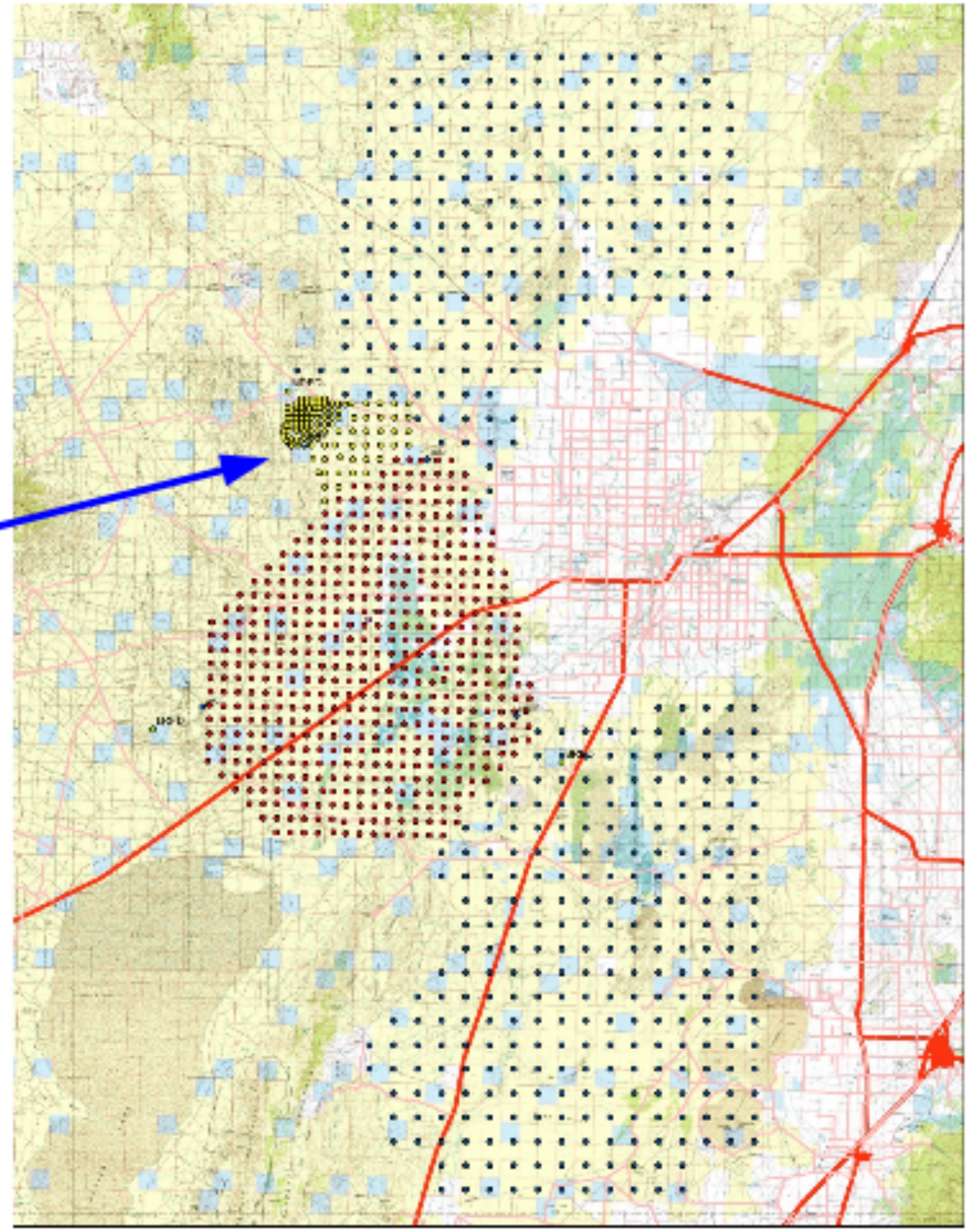




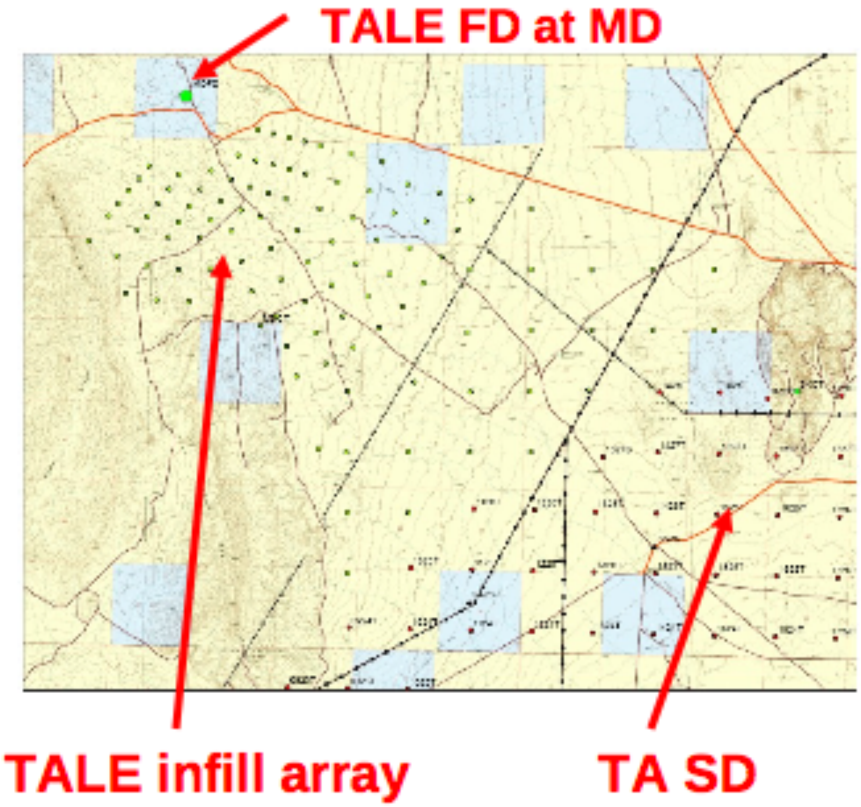


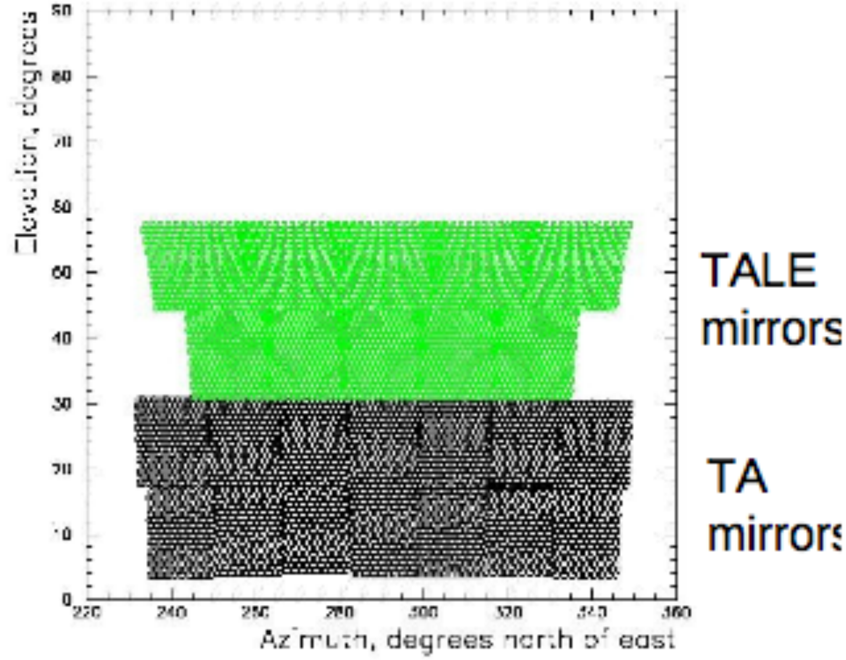
TA Upgrades

- Low-energy extension; TALE

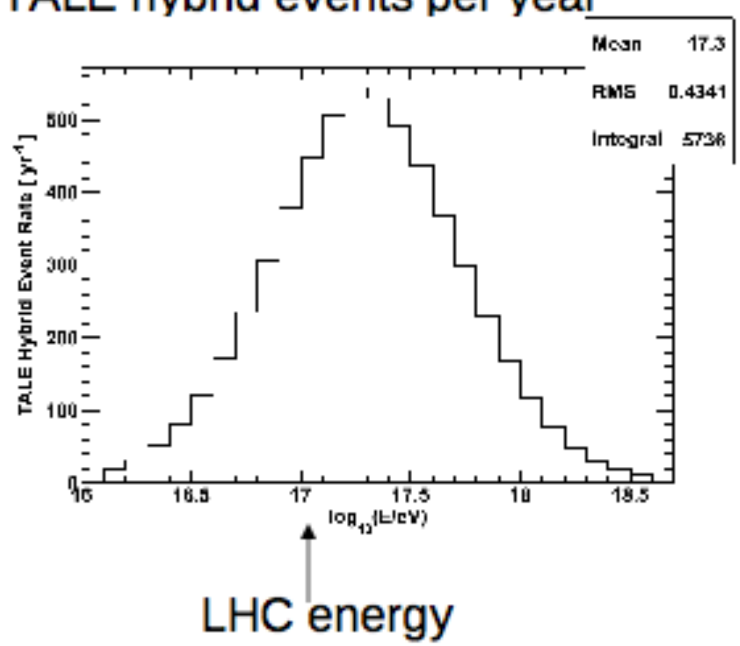


TALE Detectors are being deployed.





TALE hybrid events per year



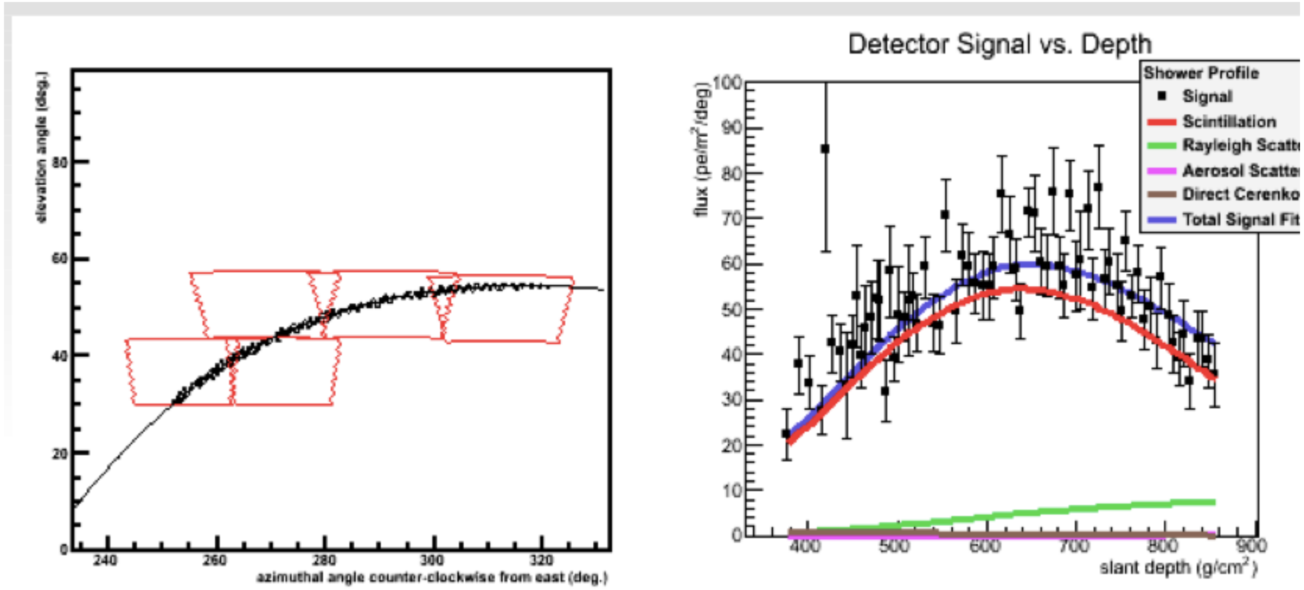
TALE is now taking data

- 10 TALE FDs:
  - refurbished HiRes-II telescopes
  - installed and running.

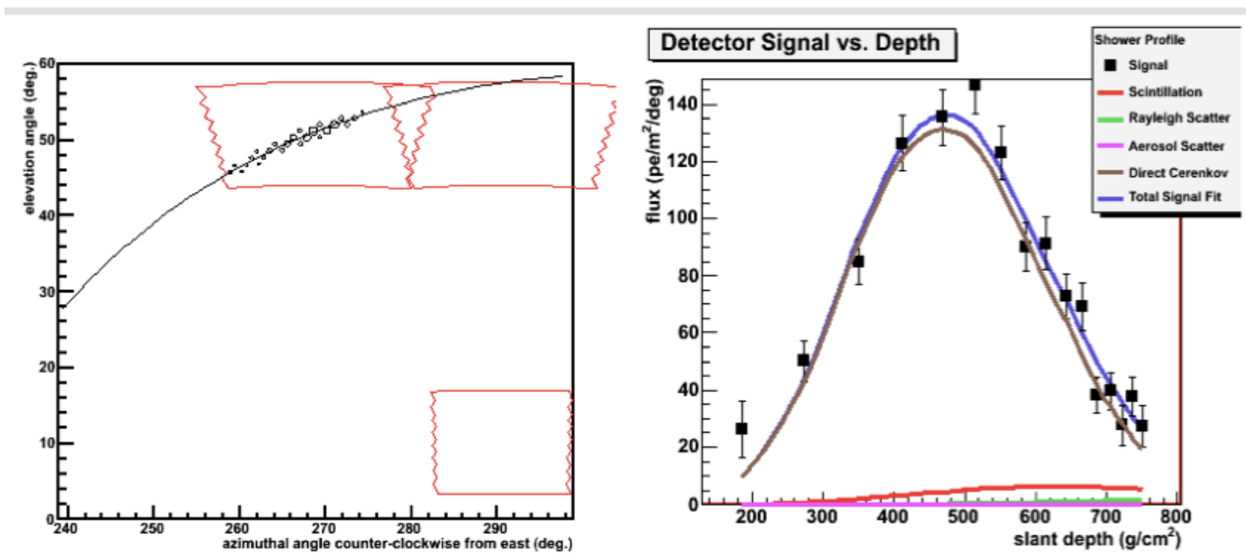
- TALE SDs
  - 35 TALE SDs were deployed among 101 SDs.
  - 16 in operation

Cherenkov Events in TALE

- Method being developed to study “dominantly Cherenkov light” events.
- Extend energy range to lower energies
- Study “second knee region” and composition
- Method under development: similar to imaging Cherenkov used by CTA -preliminary results



Fluorescence dominated event

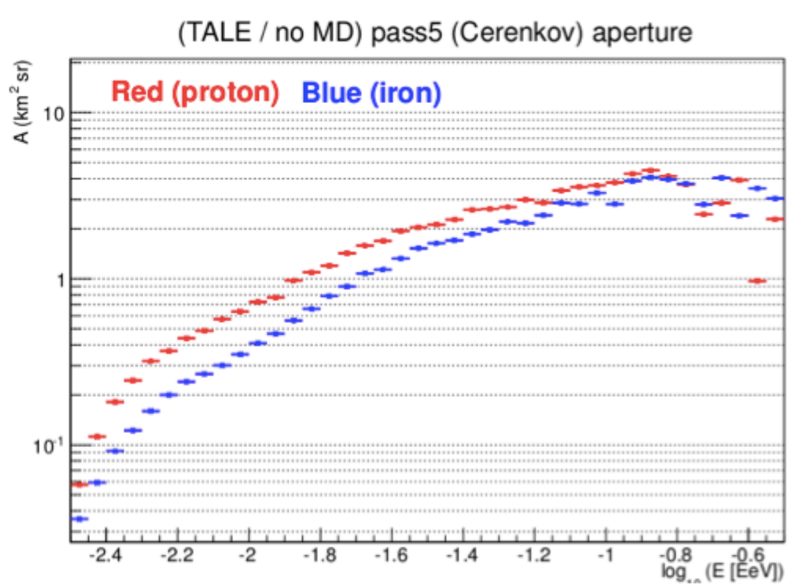


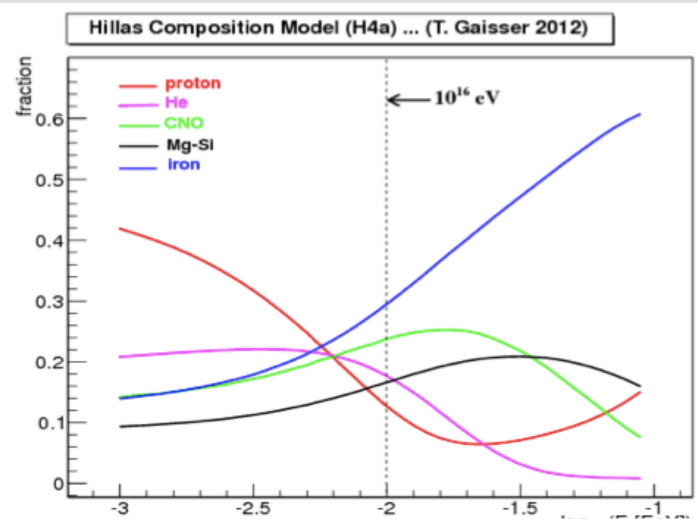
Cherenkov dominated event

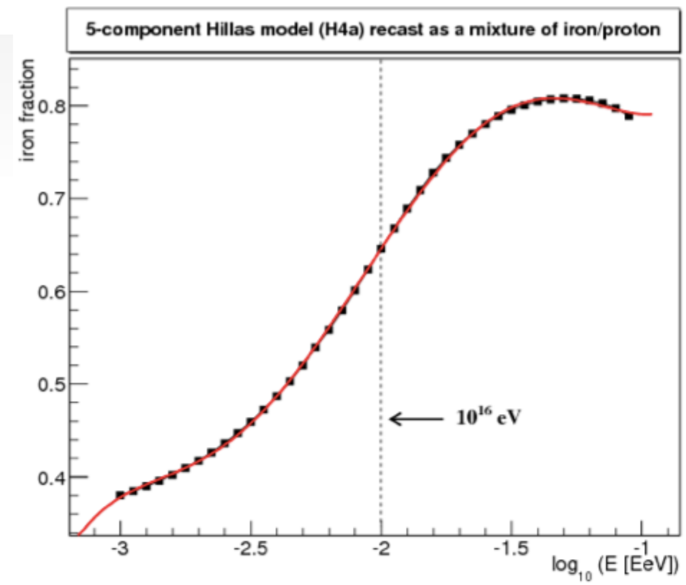
Reconstruction uses "profile constrained technique": profile+timing

- Corsika / IACT (arXiv:0808.2253 [astro-ph])
  - Full 3D MC shower development
  - Cerenkov photons production
  - Cerenkov photons detection (sphere surrounding telescope mirror)
- We can test our reconstruction code (and parameterizations) ***against an external, "true MC" simulation***.

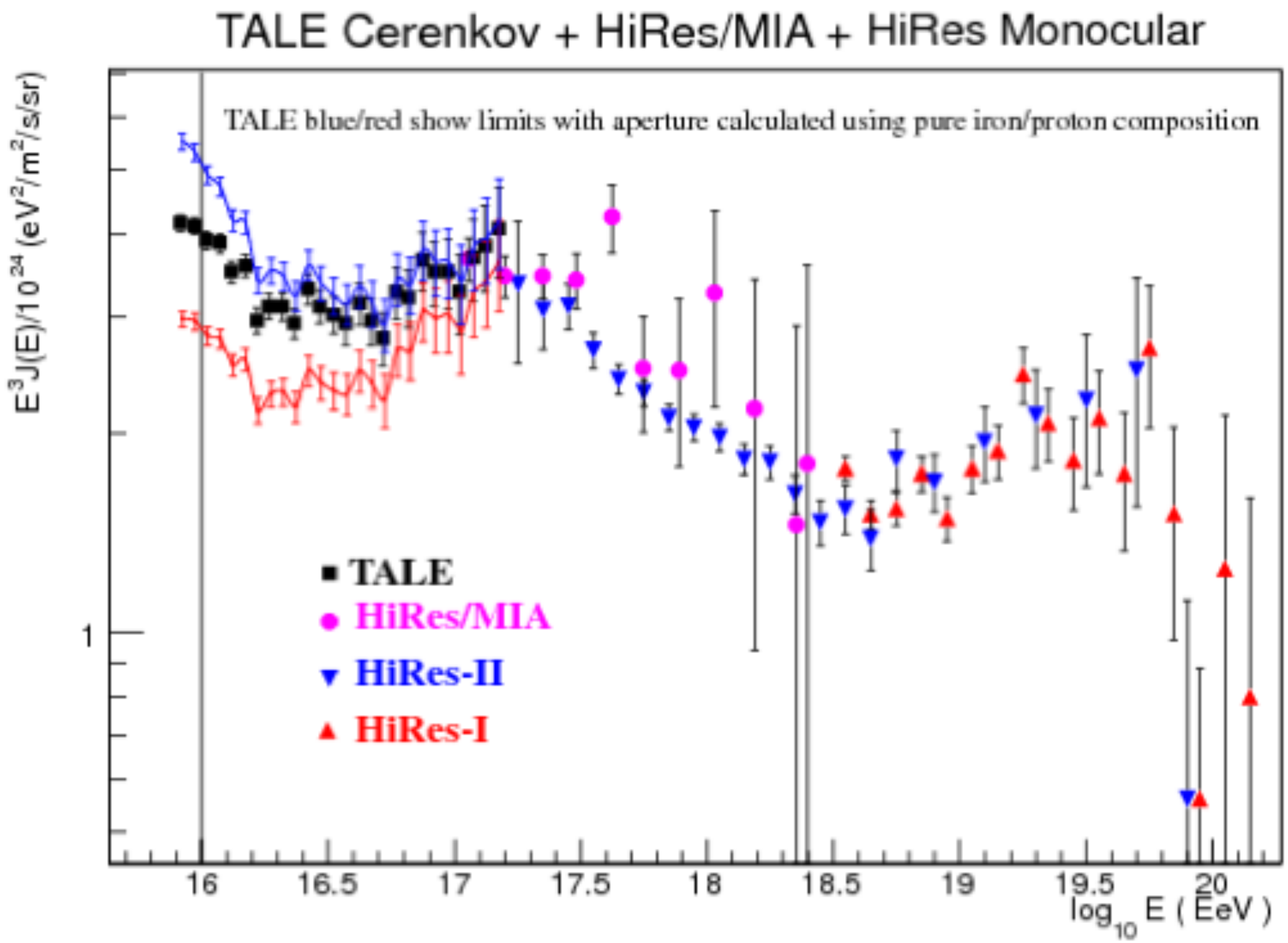
Aperture is composition dependent



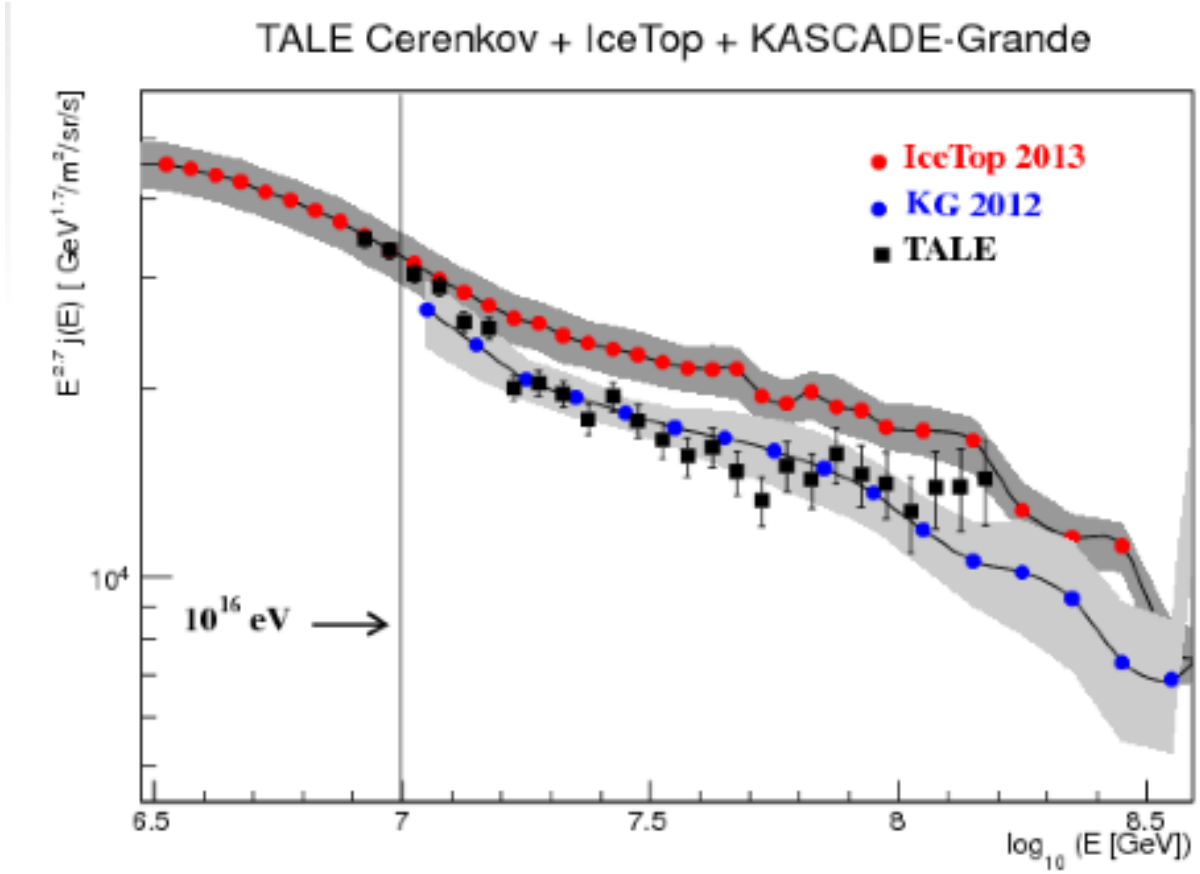




Preliminary spectrum



Comparison to other experiments



Local LSS as source of UHECR

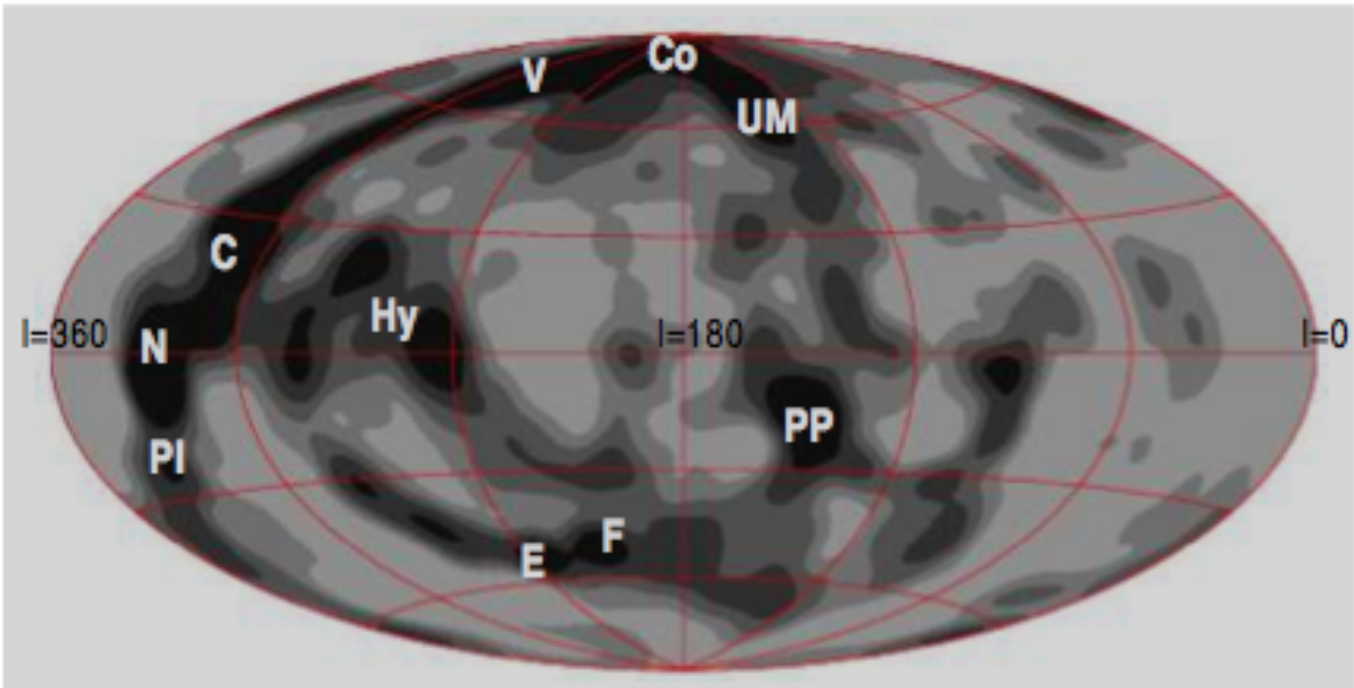
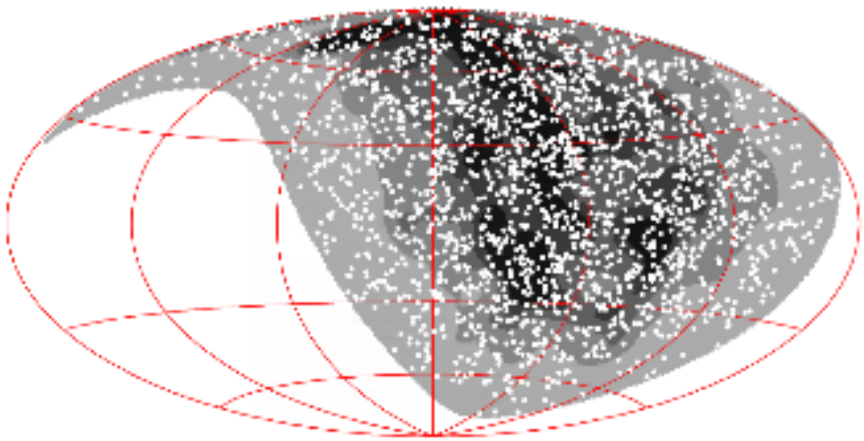


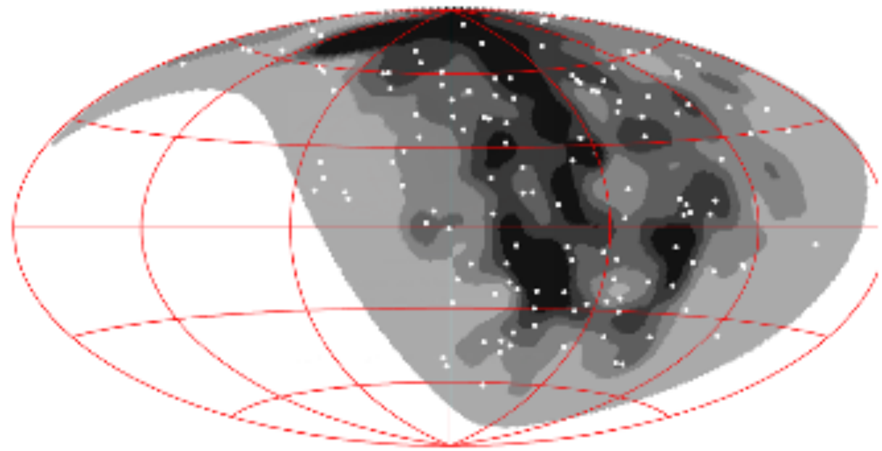
FIG. 5.— Sky map of expected flux at $E > 57$ EeV (Galactic coordinates). The smearing angle is $6°$. Letters indicate the nearby structures as follows: **C**: Centaurus supercluster (60 Mpc); **Co**: Coma cluster (90 Mpc); **E**: Eridanus cluster (30 Mpc); **F**: Fornax cluster (20 Mpc); **Hy**: Hydra supercluster (50 Mpc); **N**: Norma supercluster (65 Mpc); **PI**: Pavo-Indus supercluster (70 Mpc); **PP**: Perseus-Pisces supercluster (70 Mpc); **UM**: Ursa Major (20 Mpc); **V**: Virgo cluster (20 Mpc).

Correlations with LSS

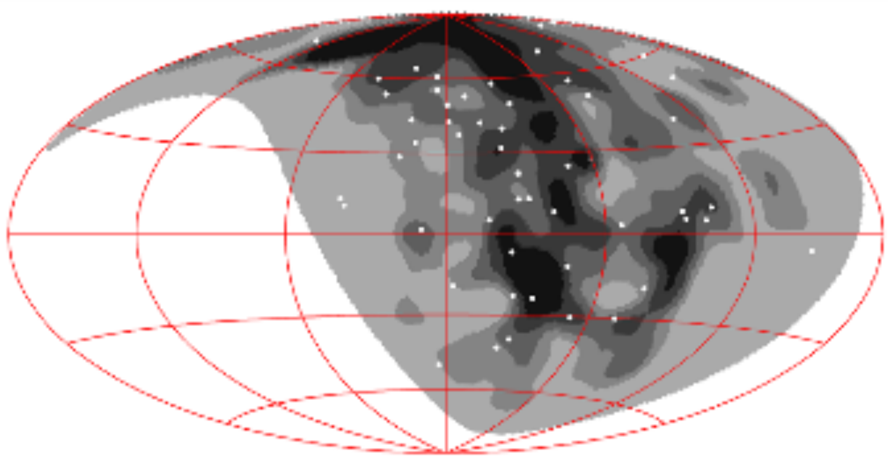
E > 10 EeV: 2130 ev.



E > 40 EeV: 132 ev.



E > 57 EeV: 52 ev.

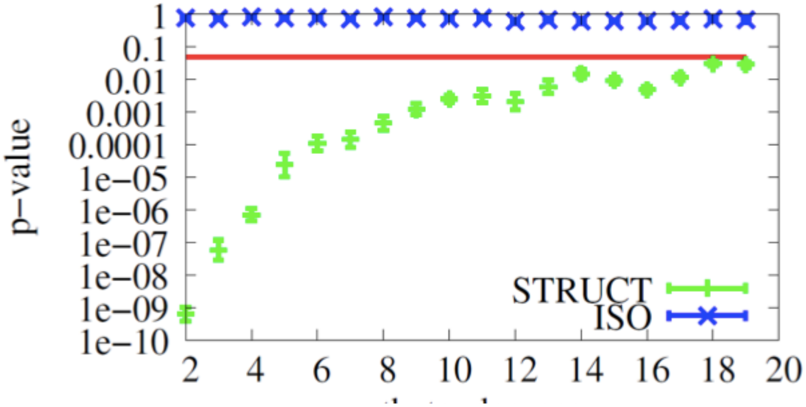


White dots: TA data with zenith angle < 5!

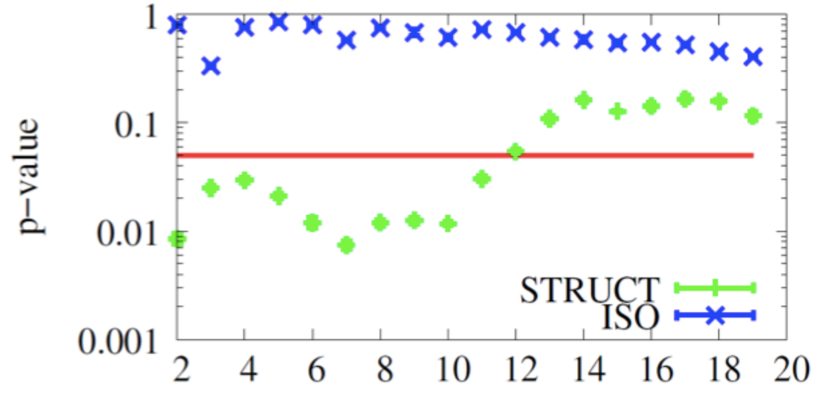
Gray patterns:
expected flux density from proton LSS
2MASS Galaxy Redshift catalog (XSCz)

Blue- isotropic, green -LSS

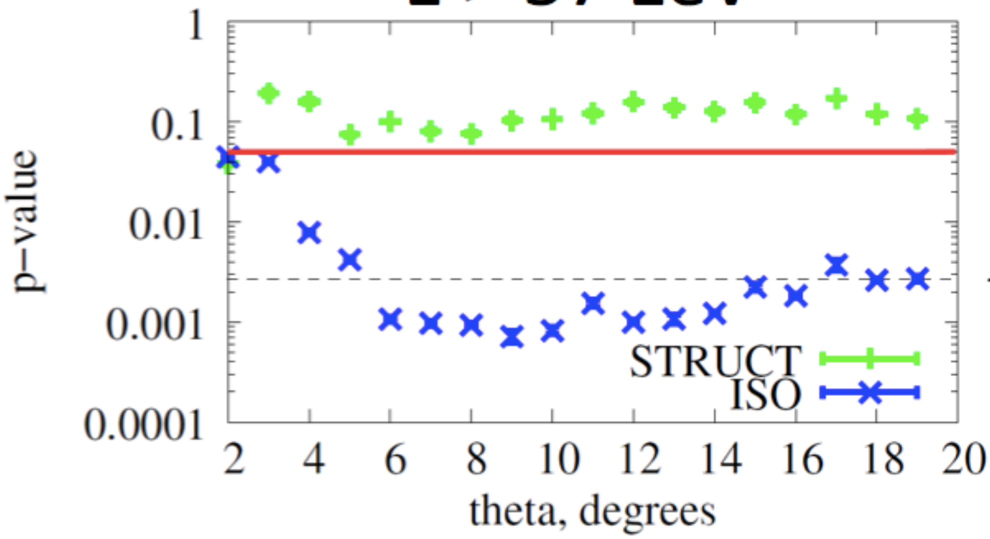
E > 10 EeV



E > 40 EeV



E > 57 EeV



~3σ (pre-trial)

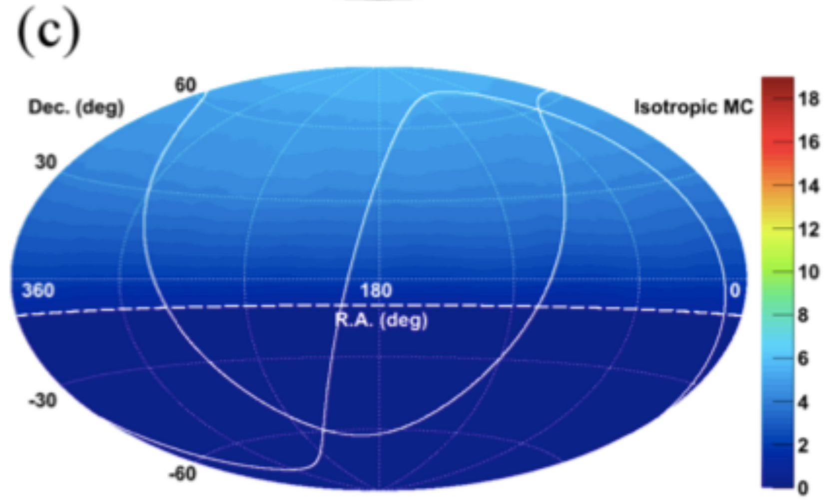
Theta: deflection angle

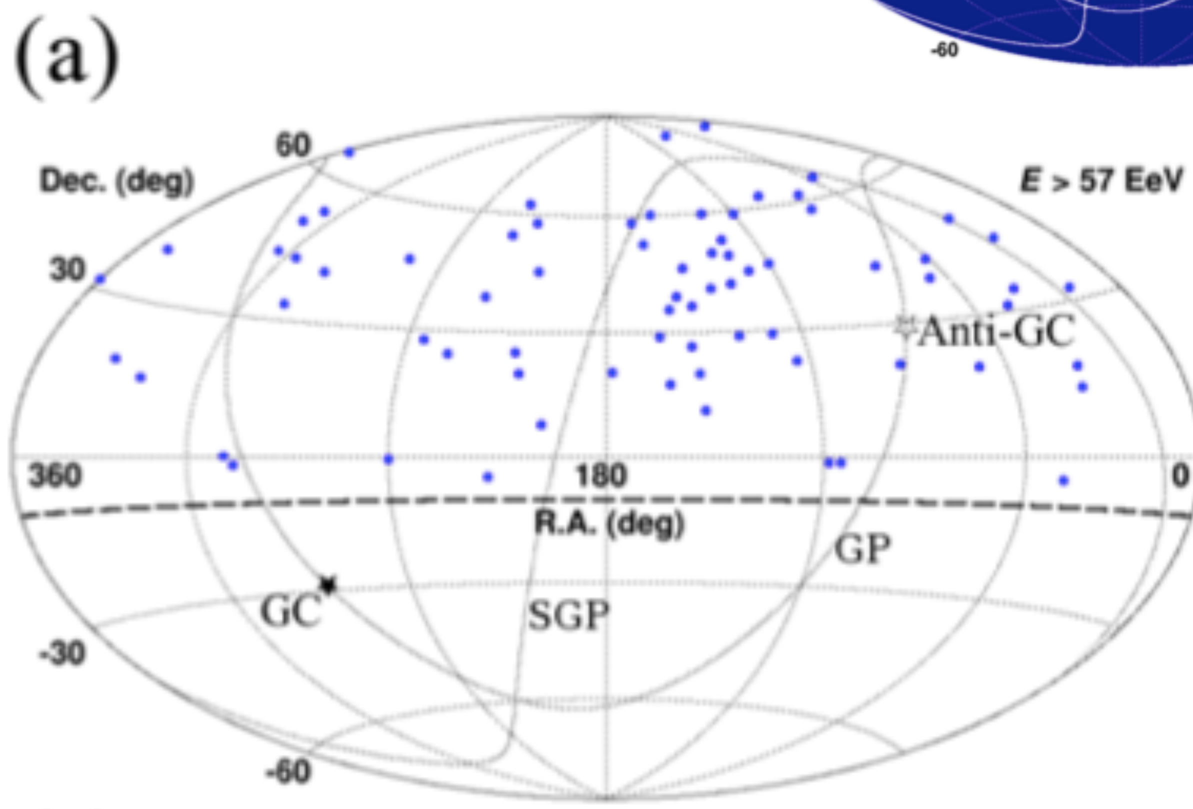
Search for intermediate scale enhancements (hot-spots)

- AGASA heritage choice of 20 degree integration circles
- Evaluate enhancements relative to background (Li-Ma N – sigma)
- Throw isotropic sets to estimate probability of > N – sigma by chance
- Data set uses looser cuts than LSS analysis: 72 events above 57 EeV. **arXiv:1404.5890**

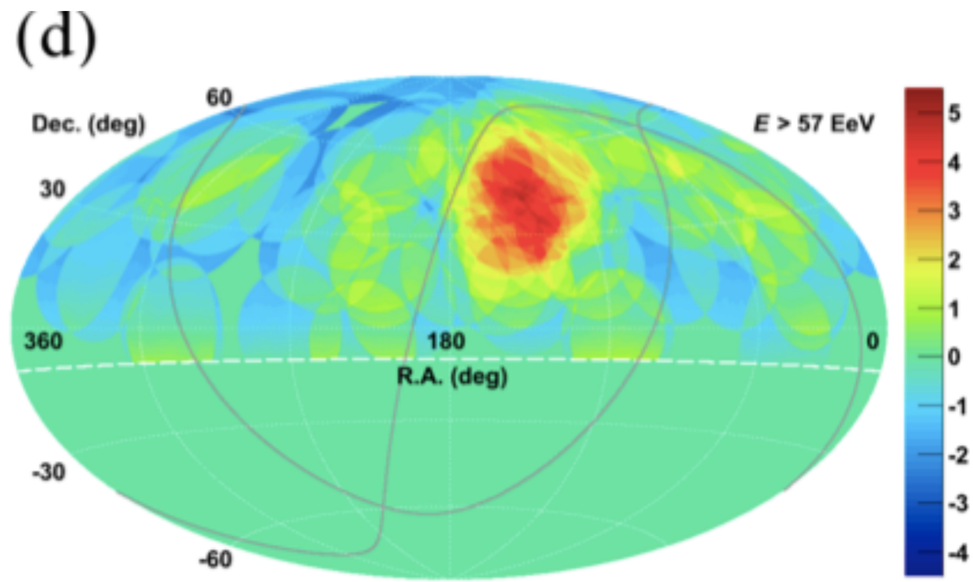
Events > 57 EeV (72)
TA SD detector

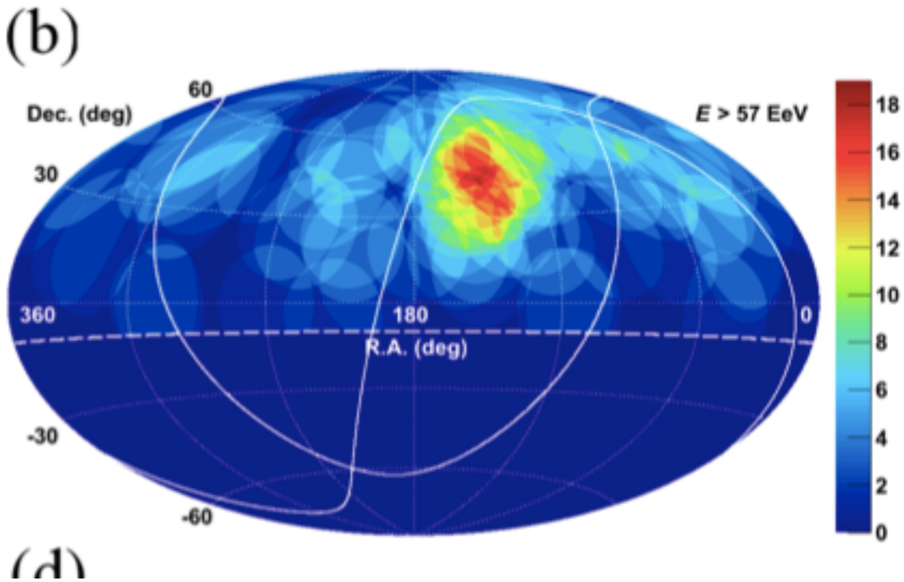
TA SD isotropic background





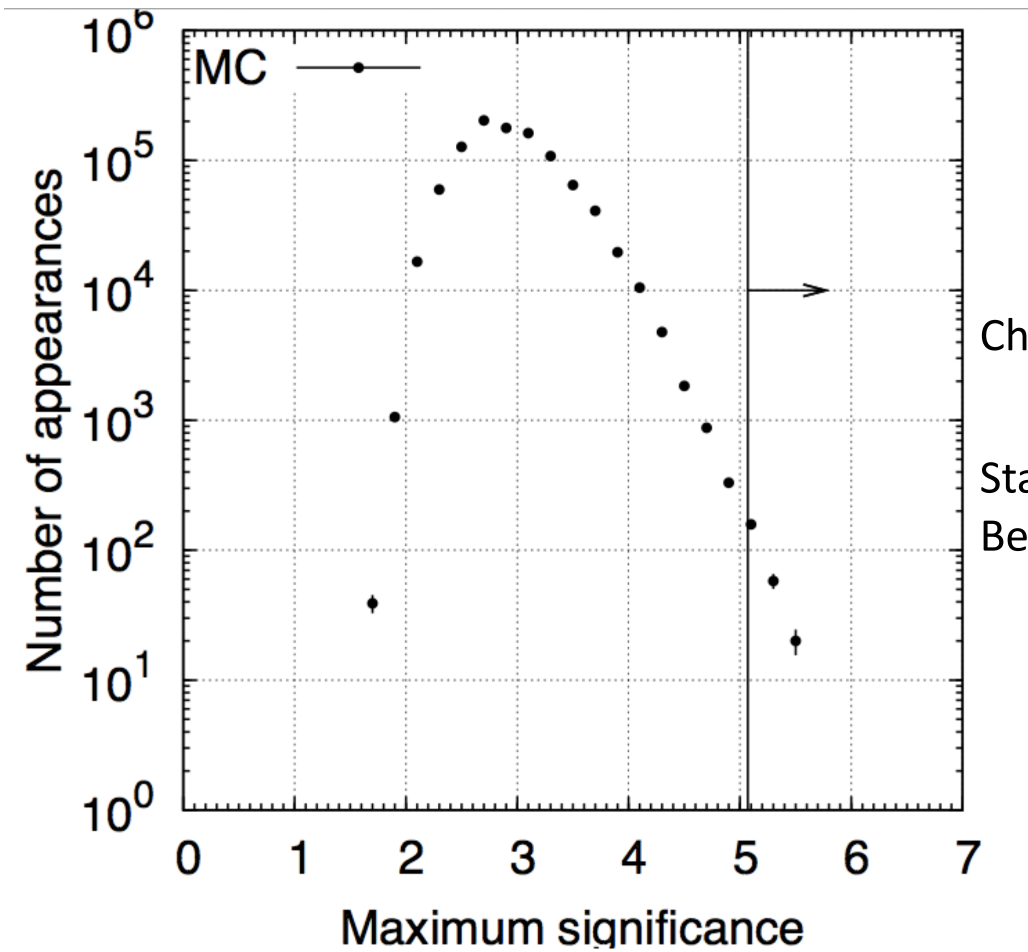
Events > 57 integrated over 20 degree circles and Li-Ma significance





R.A 146.7 deg, dec 43.2 deg, 5.1 sigma

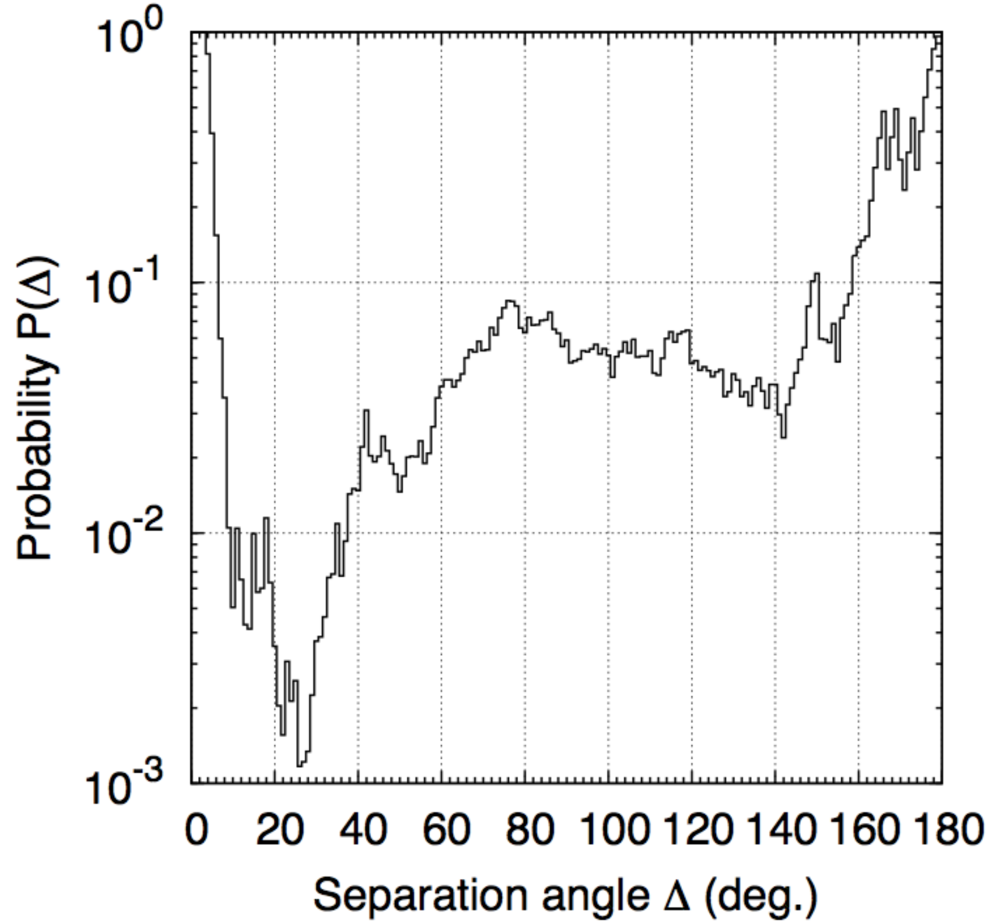
Distribution of isotropic distributions



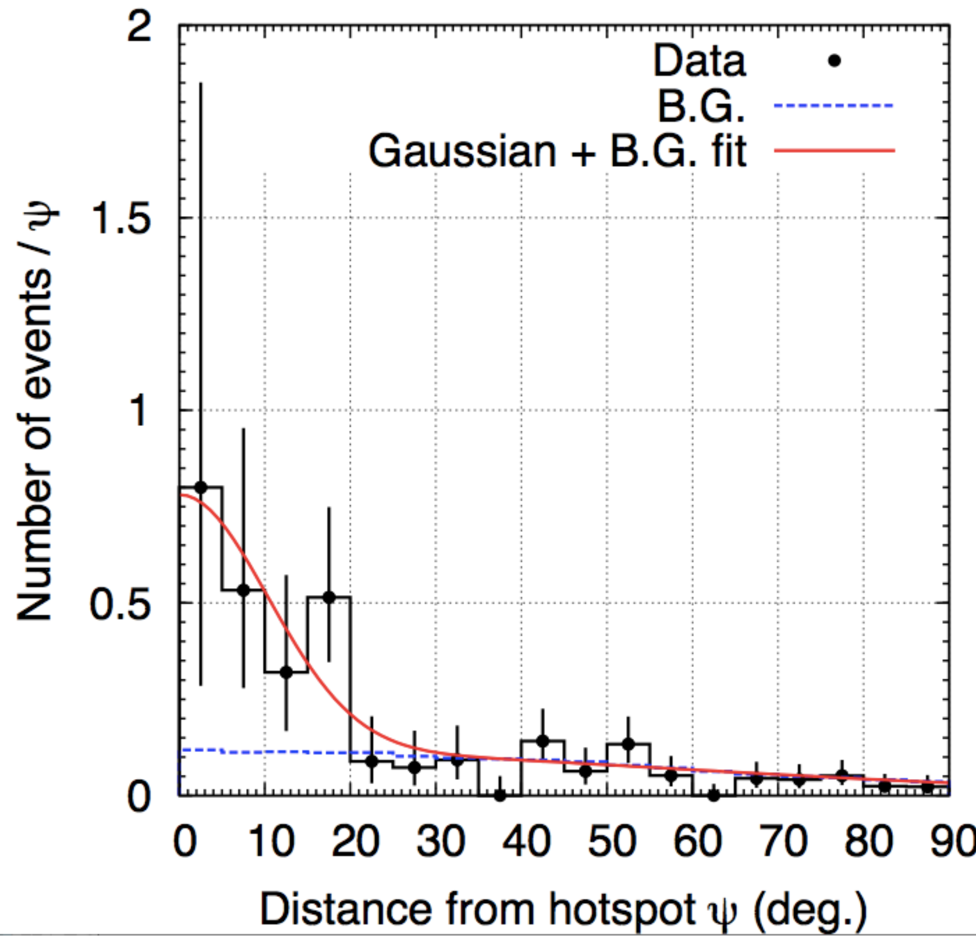
Chance Prob 1.4 $x10^{-4}$

Statistical significance
Becomes ~ 3.6 sigma

Autocorrelation Probability

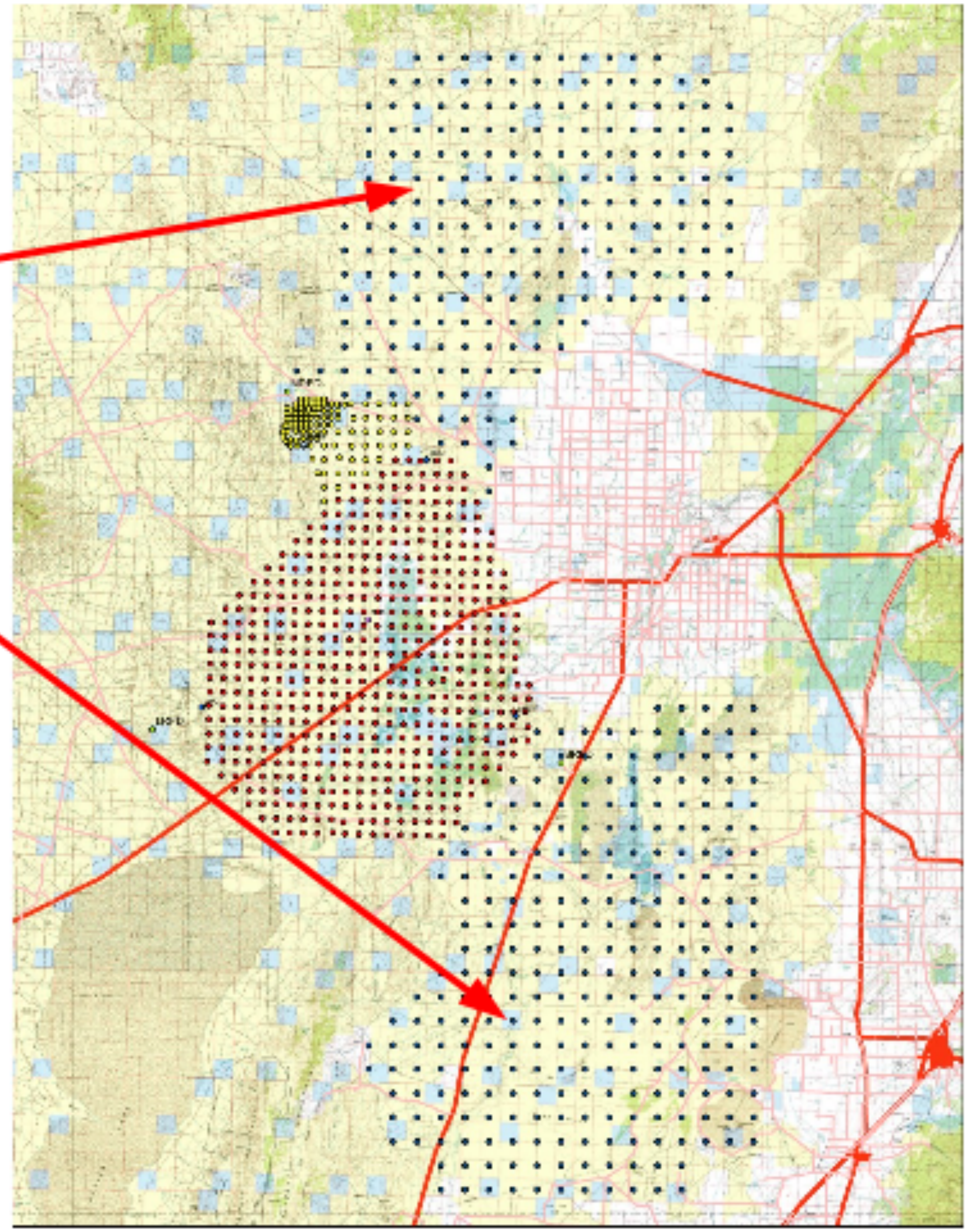


Angular spread of “hot spot”



TA Upgrades

- TA x 4
- 3,000 km^2
  - 500 SD's, 2 km spacing
  - 1 new FD (HiRes refurbished)
- Proposals fall 2013
- Anisotropy: 20 TA-SD years by 2019



Conclusions (Physics)

- GZK cutoff confirmed by TA at > 5 sigma level with AGASA-like SD array calibrated with FD.
- Composition looks light, but detailed comparisons with PAO results in process.
- Interesting ~3 sigma correlation at highest energies with LSS within ~ 100 Mpc. Indications of a "hot spot" off the Super-galactic plane emerging.

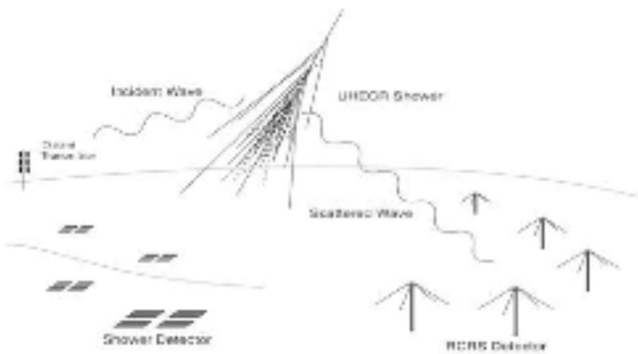
Prospect (optimistic)

- If hot spot is confirmed at 5 sigma (~ 2-3 years), North-South universality may not be valid – impact on composition at UHE
- TAx4 will allow much more precise determination of location and energy dependence of hot spot excess. Candidate sources?
- Joint TA/PAO anisotropy in progress – global anisotropy. First attempts at multipole analysis. Emergence of a dipole component?

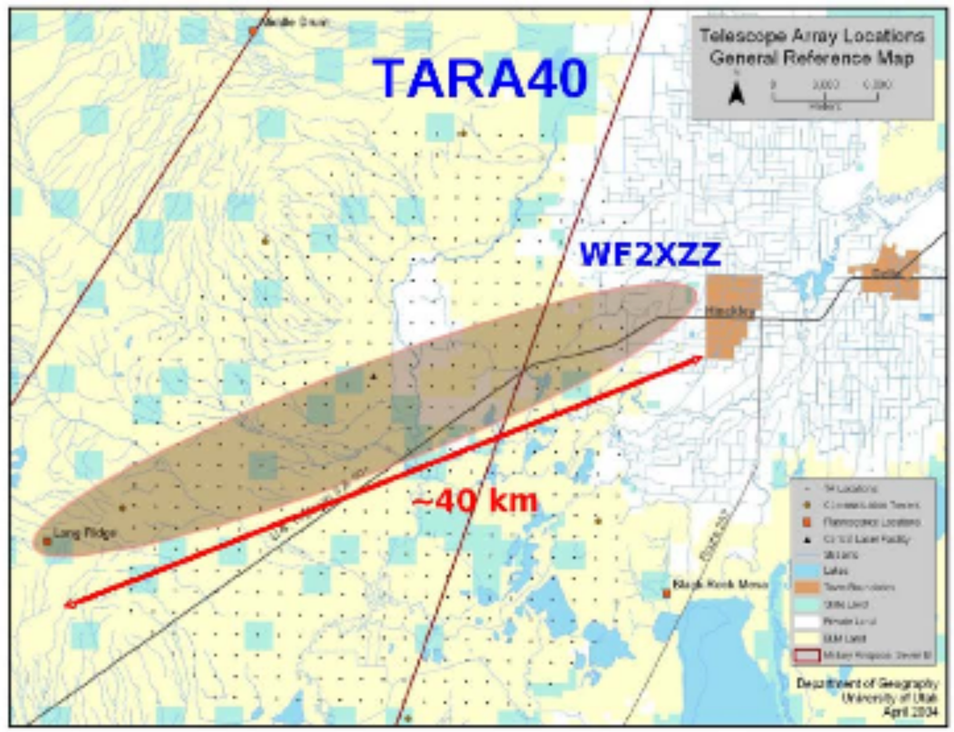
TARA (TA Radar)

J. Belz et al., oral 1192
I. Meyer et al., poster

- An R&D project to observe radar reflections form cosmic ray air showers

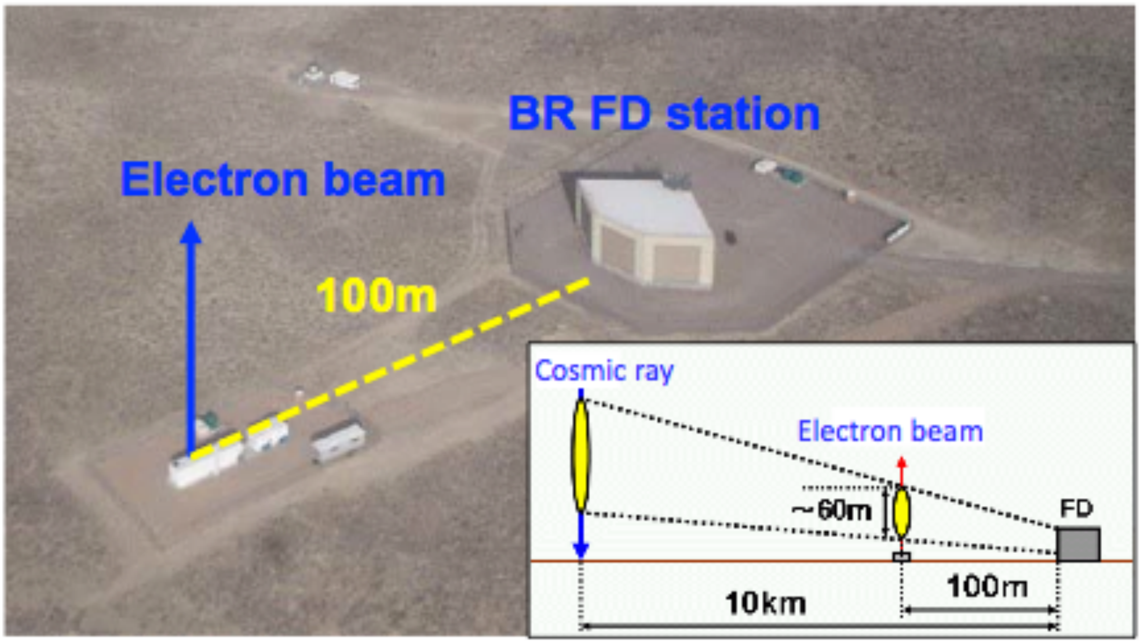


- TARA1.5
  - April 2011 to July 2012
  - 54.1 MHz @ 1.5 kW
- TARA40
  - Summer 2013~
  - 54.1 MHz @ 40 kW

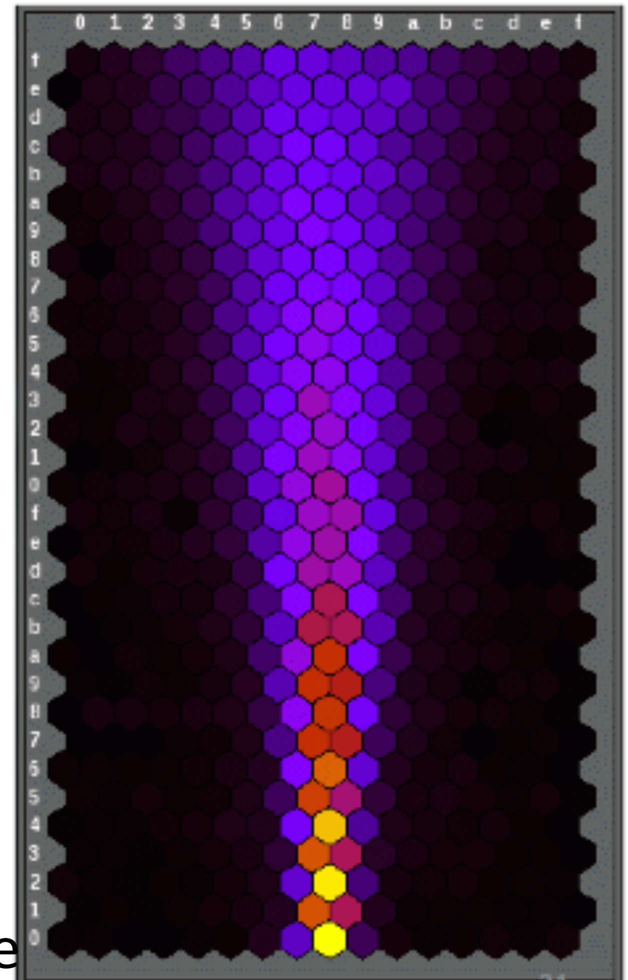


T. Shibata, oral 507

Electron Light Source (ELS)



An image of data
Measured with FD



- 40-MeV, 10^9 electrons (typical)
- End-to-end FD energy calibration

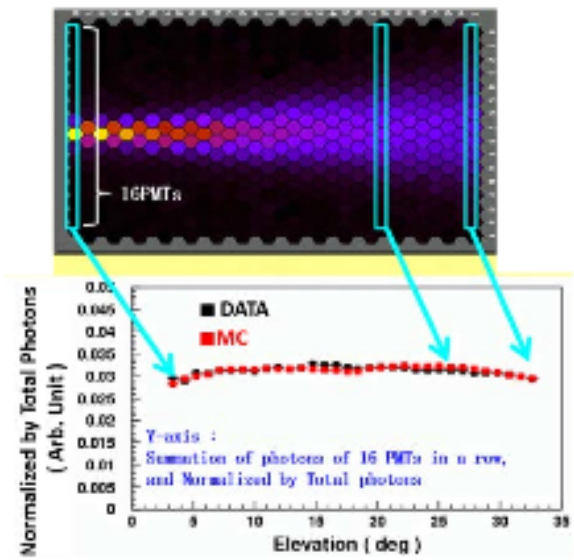
Used to calibrate JEM-EUSO detector module

ELS analysis

- Real data
  - ELS
    - Energy/beam current from monitor
    - FADC counts from FD

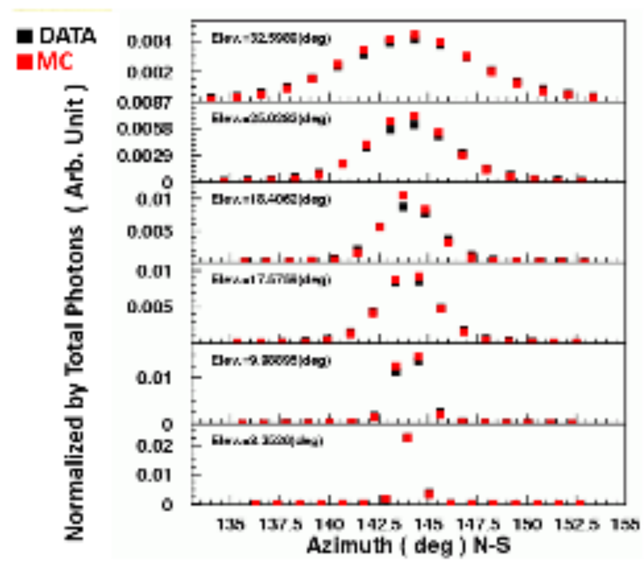
- MC data
  - Shower generation
    - Geant4.9.5 or 4.9.6
  - FD simulation
    - TA official software

Longitudinal distribution



Data/MC agreement: within 5%

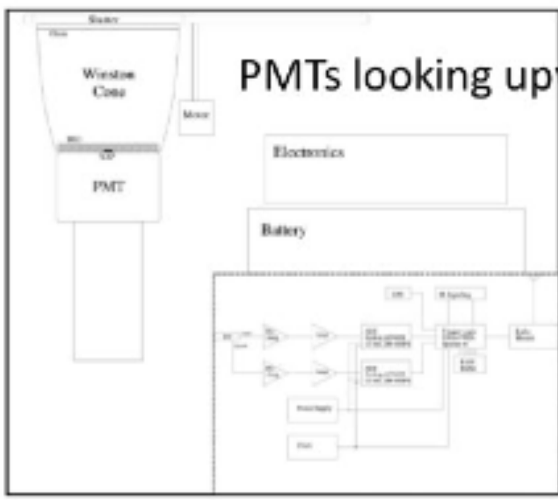
Lateral distribution



Good agreement

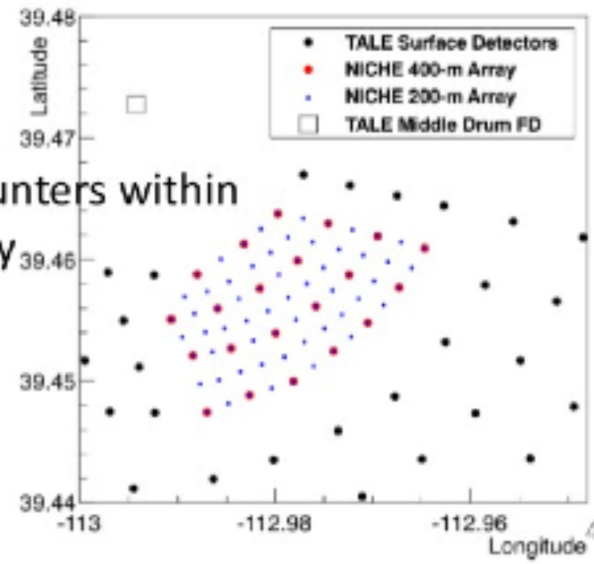
NICHE project

- Non-Imaging CHErenkov Array (NICHE)
- TA/TALE extension to measure the the energy and composition (Xmax) of very-high energy cosmic rays
  - E = $10^{15.5}$ to 10^{17} eV
  - Proposed but not yet funded



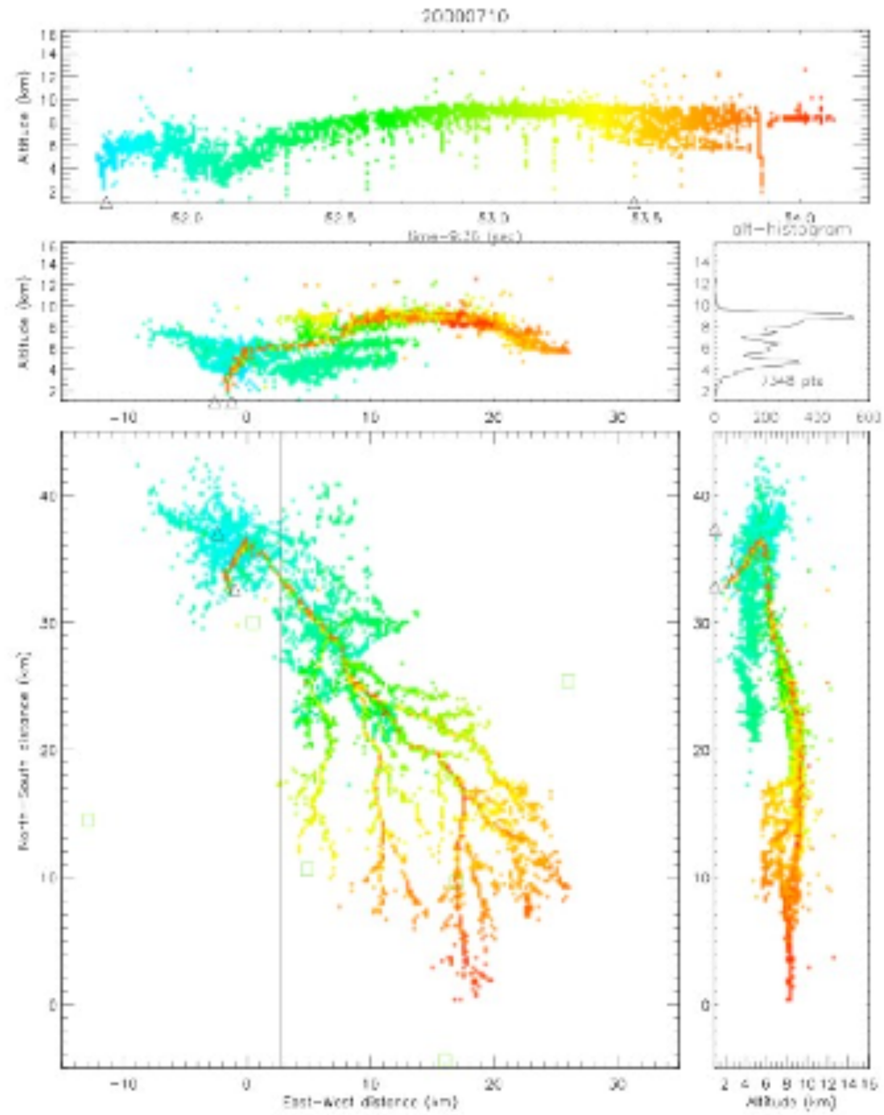
PMTs looking upwards

Cherenkov counters within TALE infill array



TA/LMA: Lightning Mapping

- Cosmic rays *may* trigger lightning strikes.
- Lightning *does* emit air shower-like bursts of particles.
- Proposing to deploy lightning mapping array (LMA) at TA to study these phenomena.

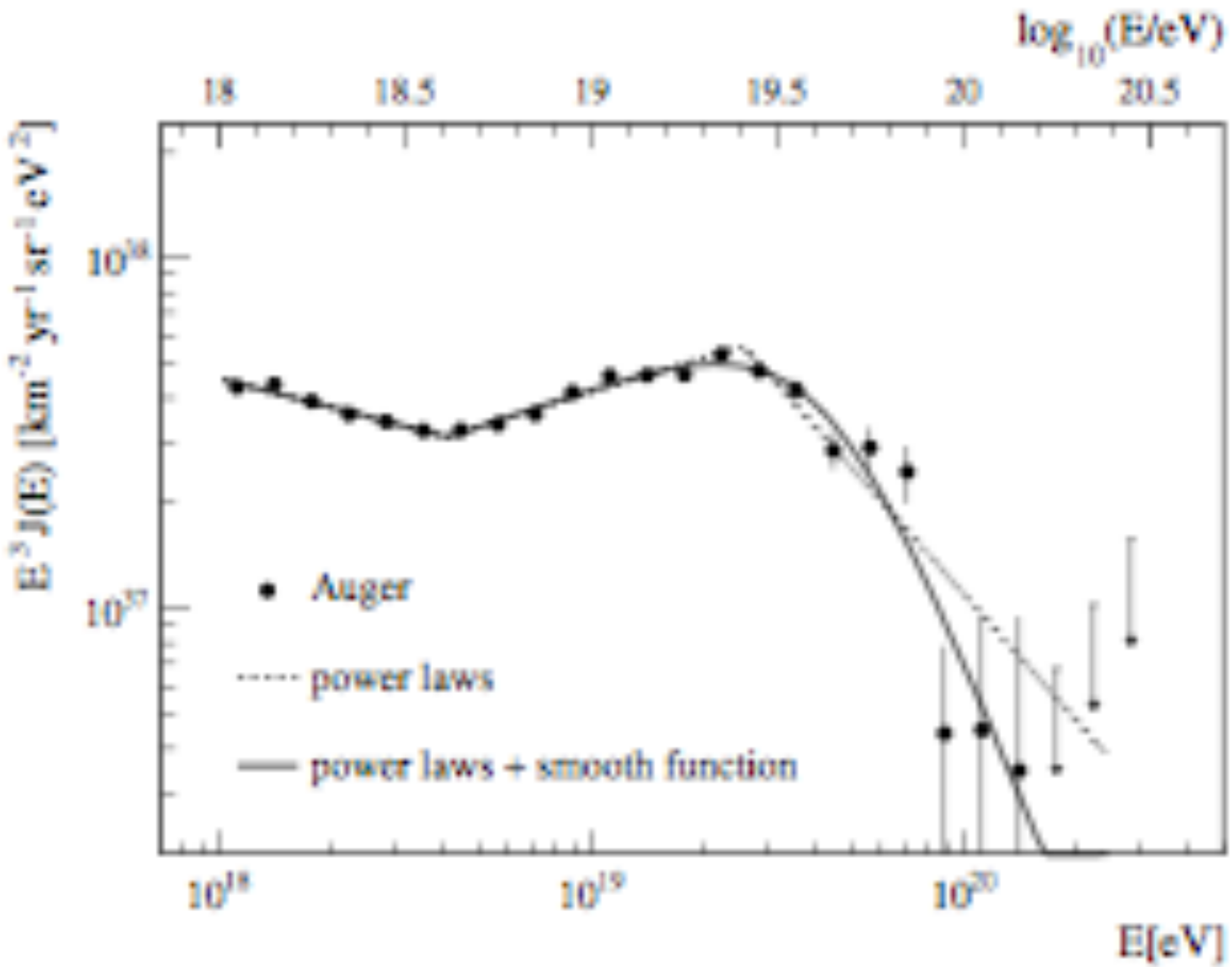


Conclusions (projects)

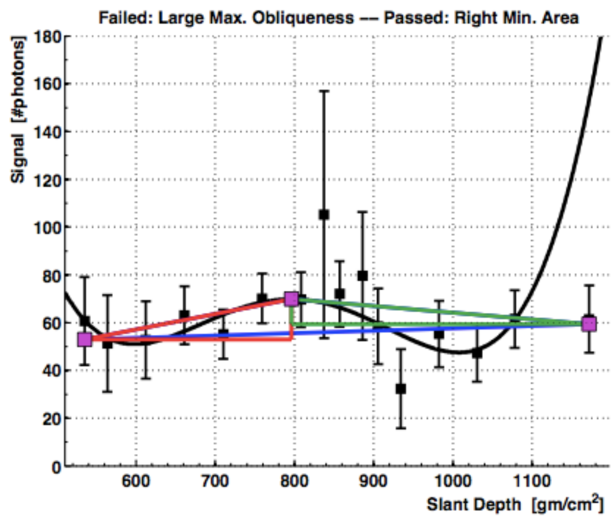
- Major expansion of SD to TAx4 proposed.
- Full power TARA is now taking data
- ELS providing end-to-end calibration and valuable resource for radio/fluorescence and JRM-EUSO calibration
- Low energy extensions – TALE currently in test data taking
- NICHE and TALMA in proposal/prototype stage

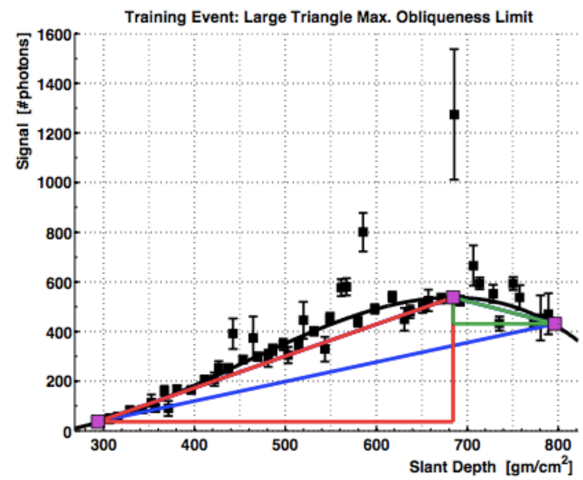

Thank You

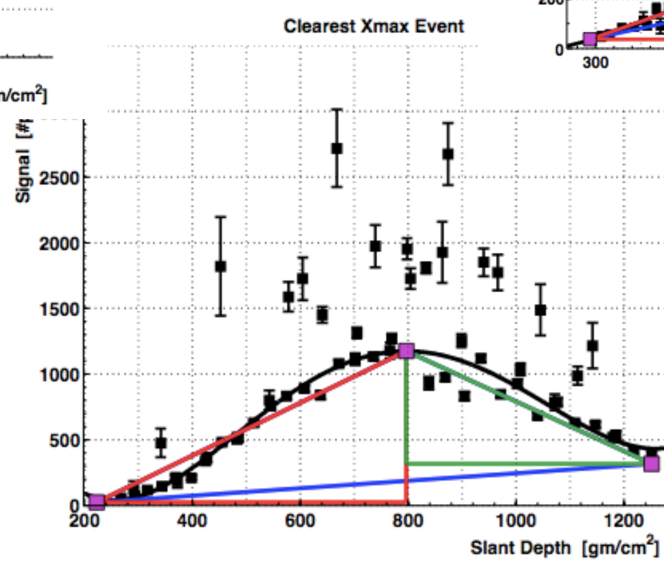
PAO Spectrum



Pattern recognition – triangle approximation







Training set – eye scan of all data and sample of p and Fe MC
Define most sensitive "triangle" parameters
Boolean decision tree to find successful candidates
~98% efficiency – apply to all MC data and real data
Data and MC distributions in geometrical variables are in excellent agreement after pattern recognition cuts

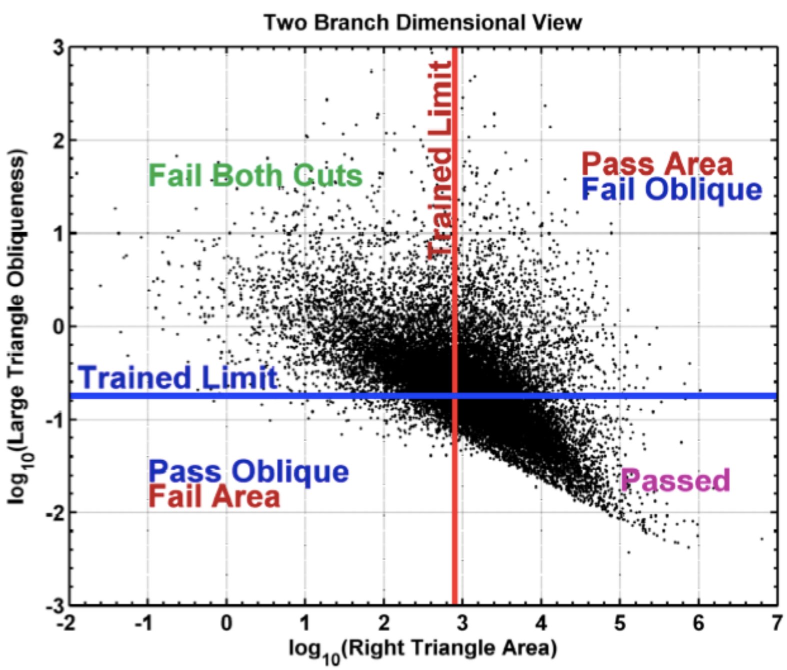


Figure 10: Dimensional View of Two Branches

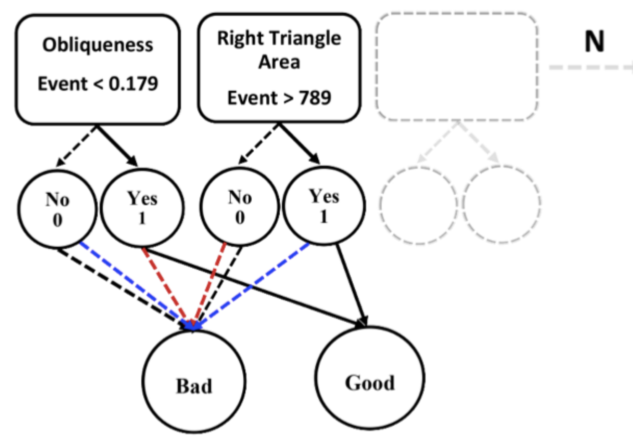
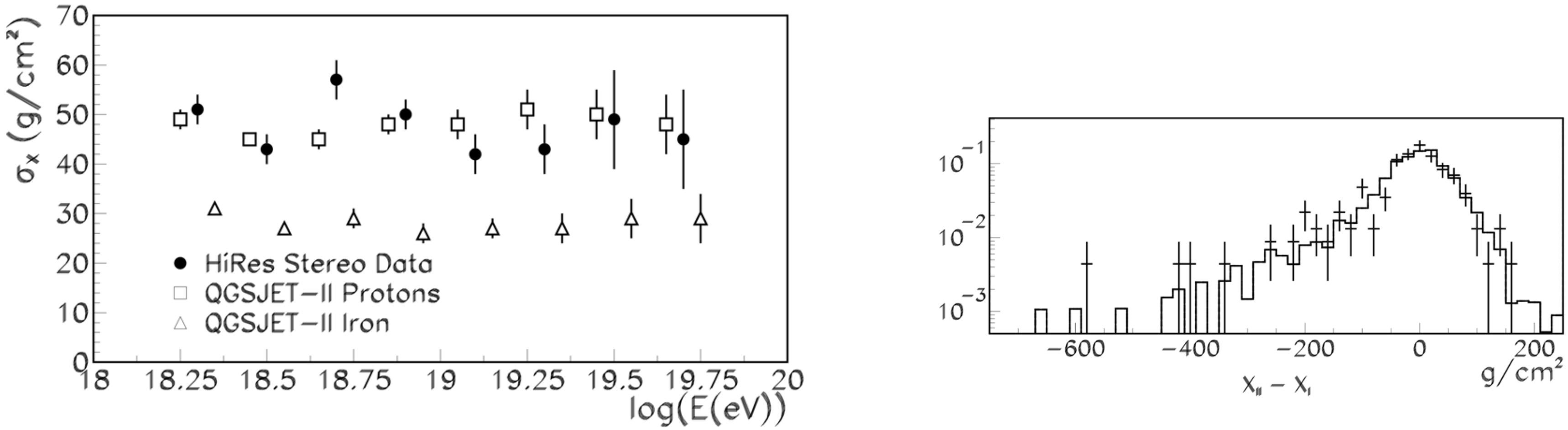
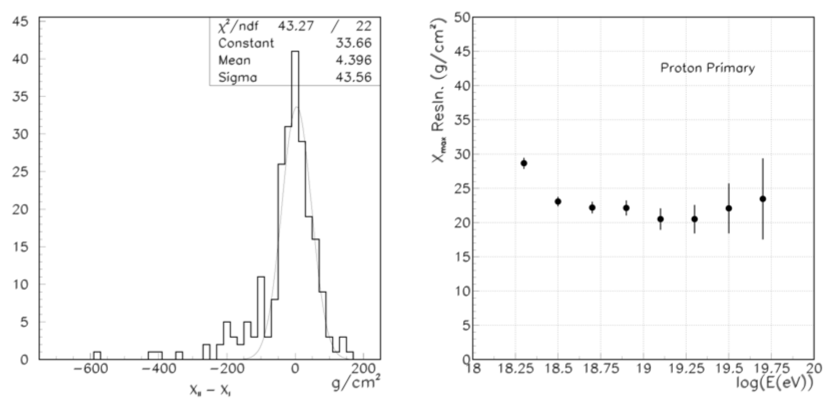


Figure 9: Decision Tree Pictogram

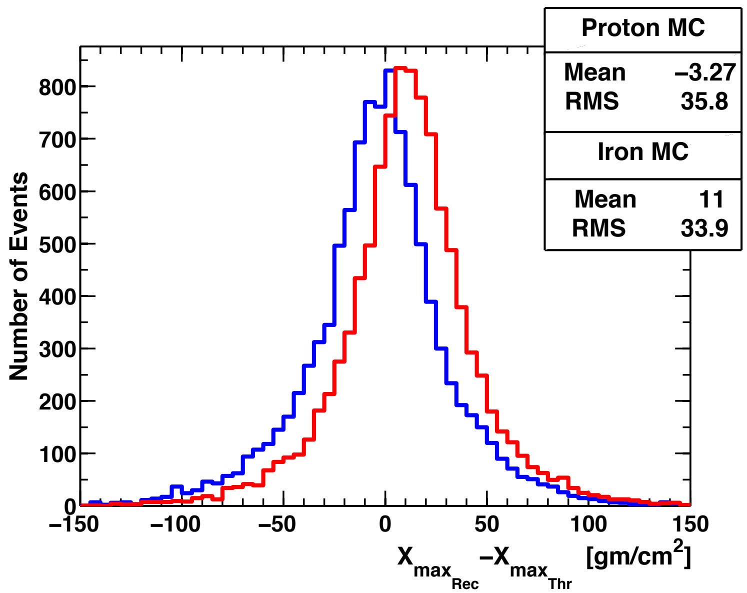


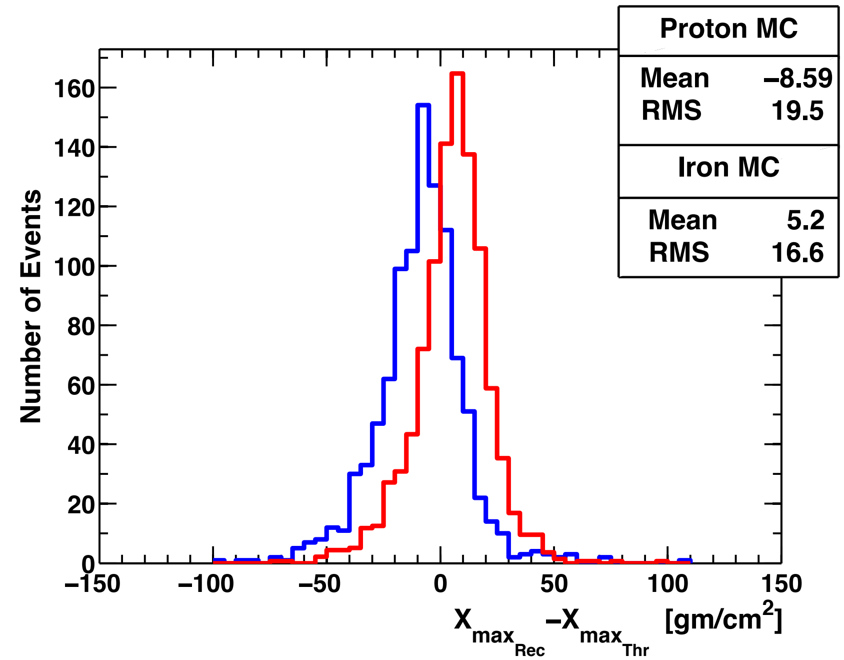
HiRes Xmax Fluctuation Study



Xmax resolution well understood

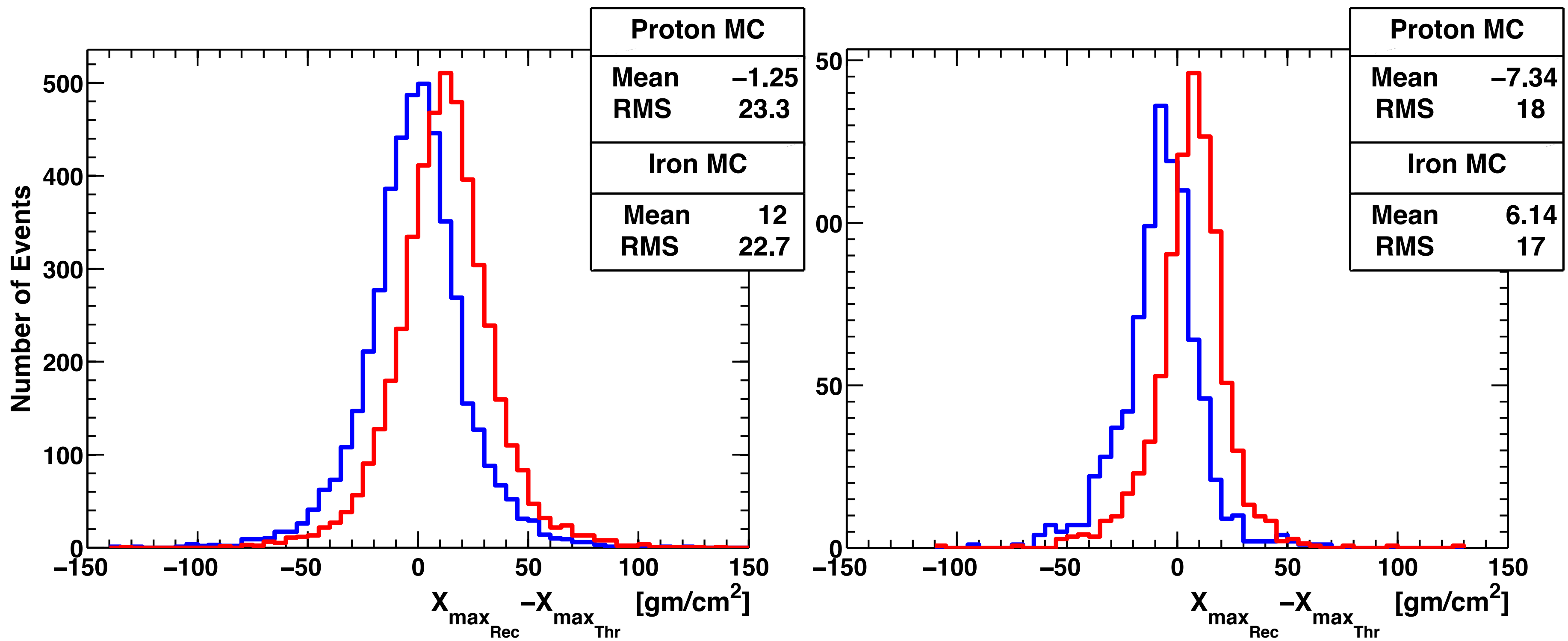
“HiRes” cut





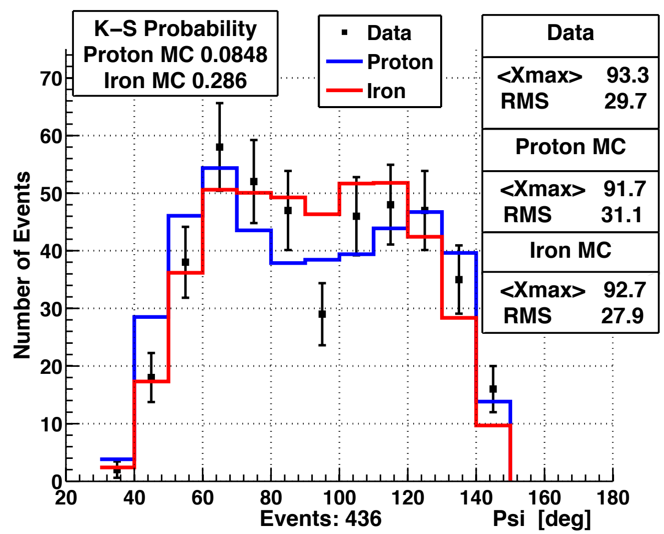
Below and Above 19.0

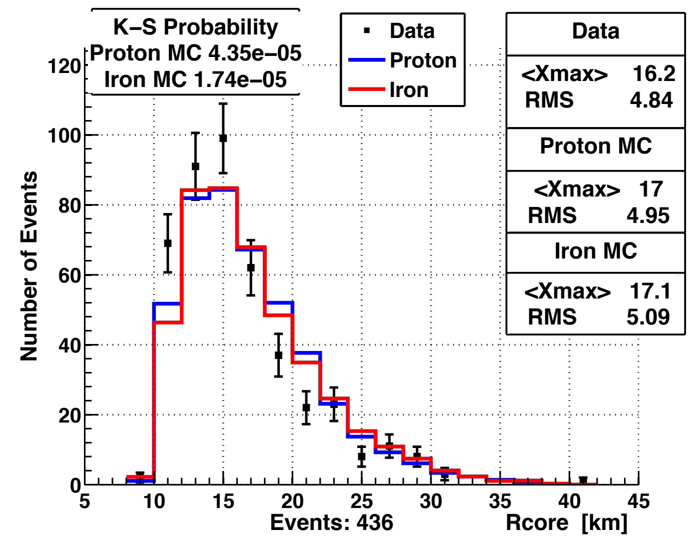
Pattern recognition cuts

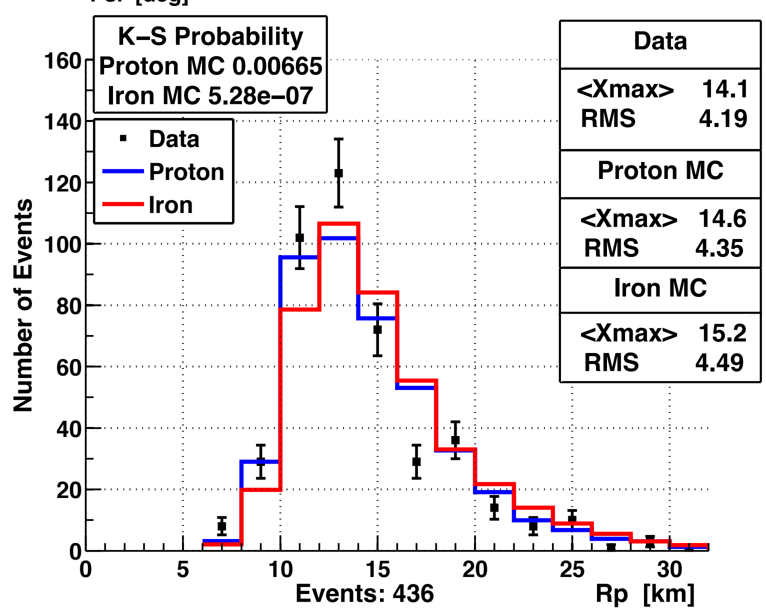


Below and above 19.0

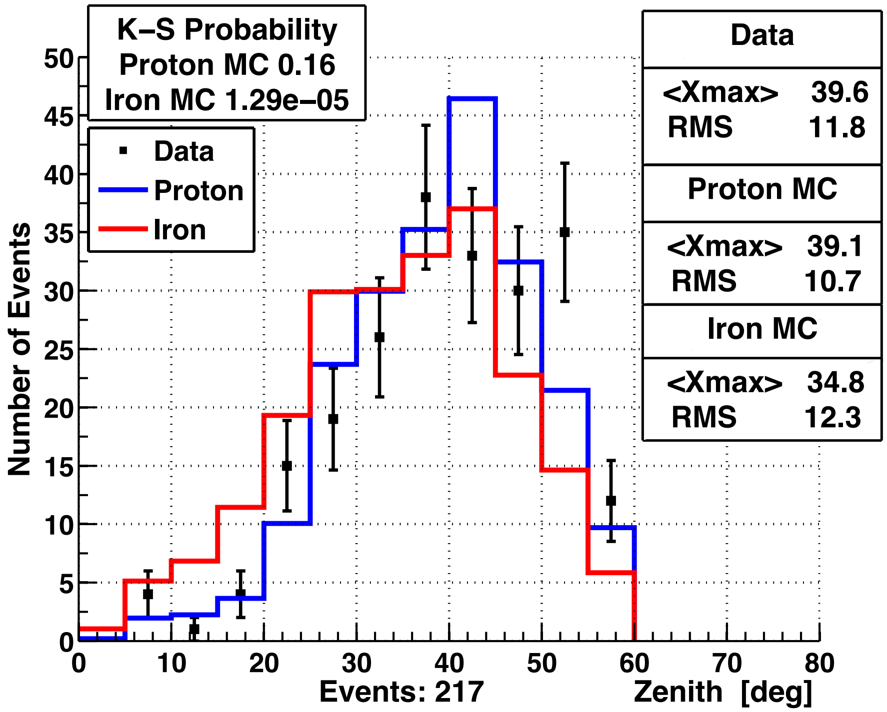
Data/MC comparisons – pattern rec.

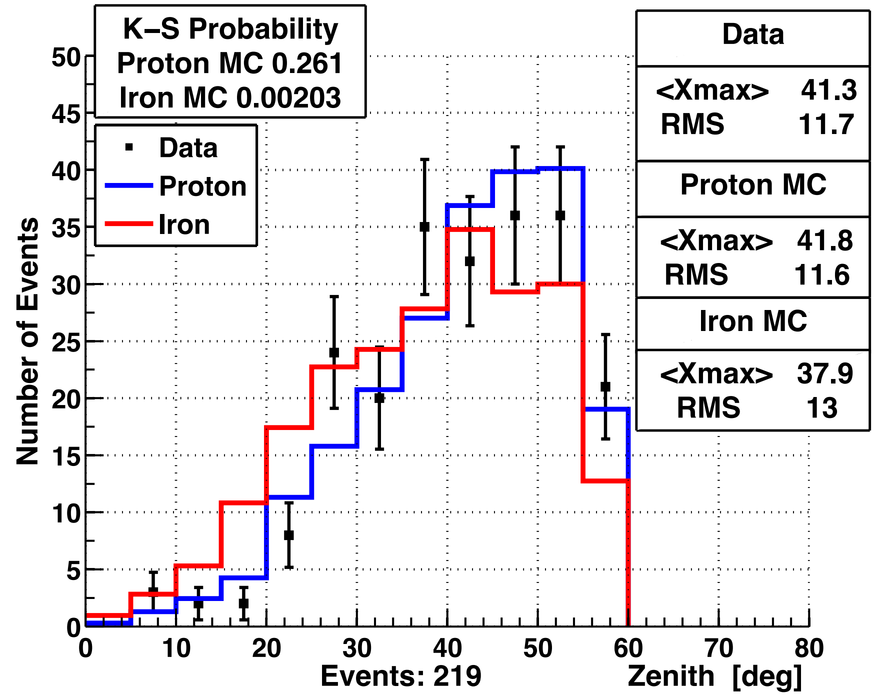






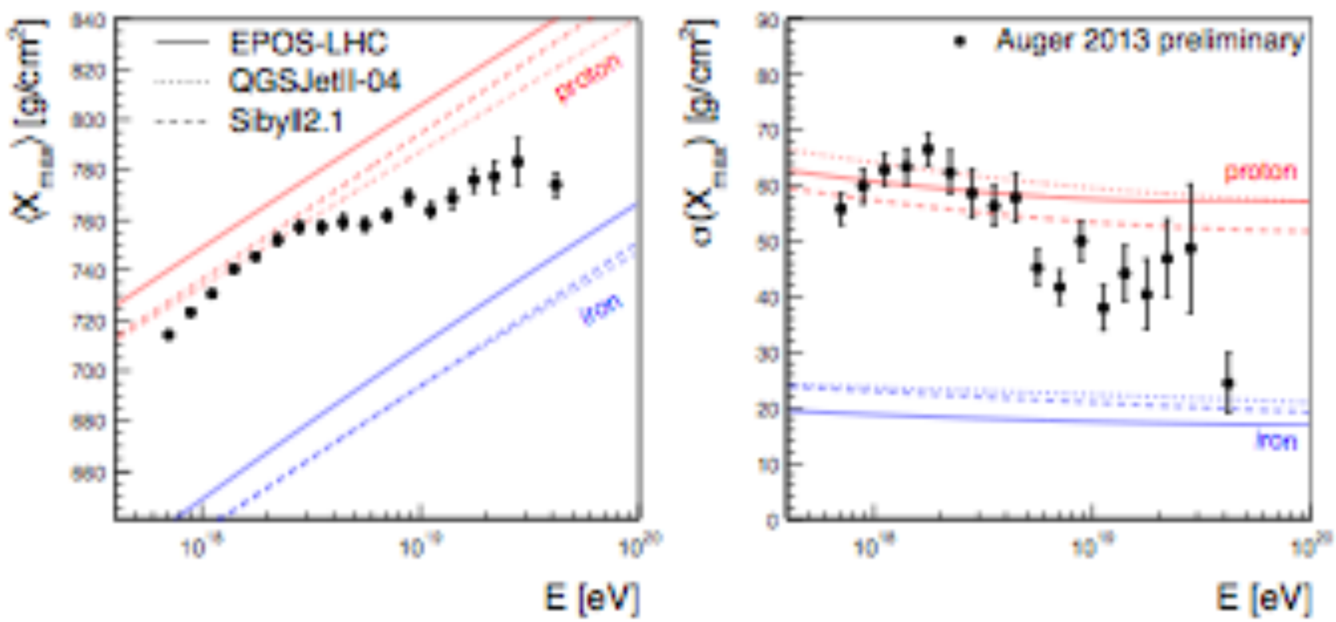
Data/MC comparison -zenith

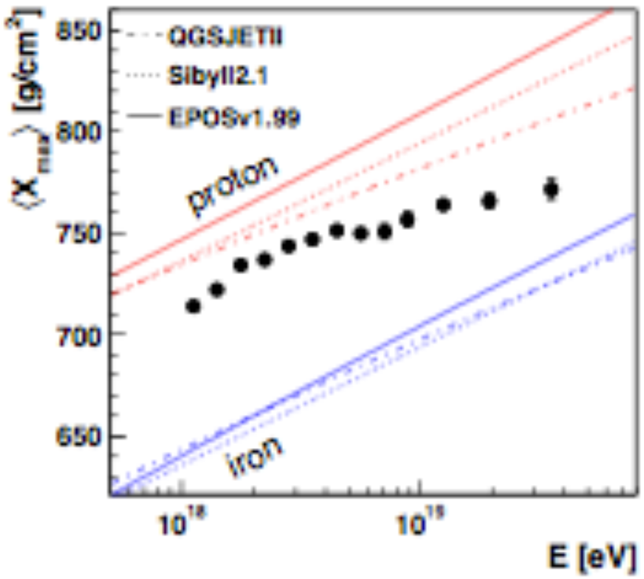


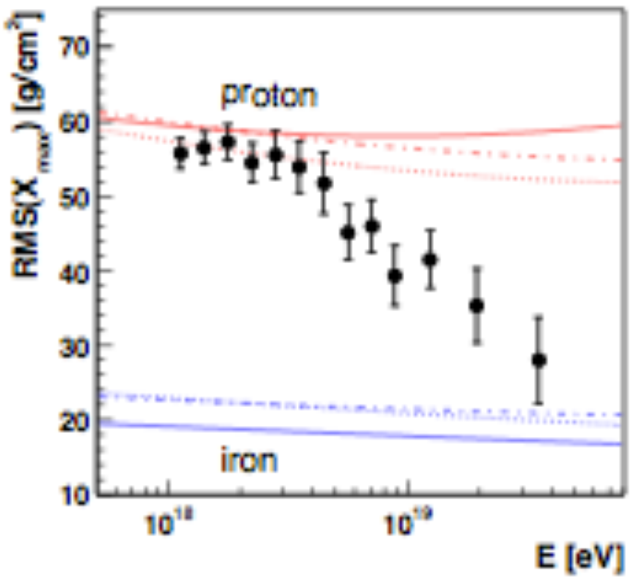


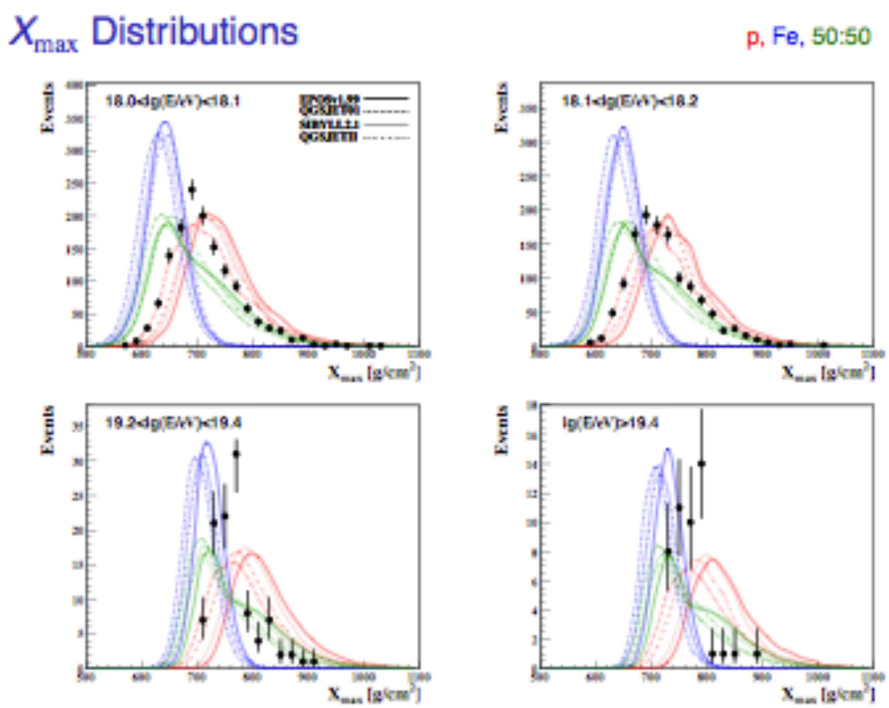
Below and Above 18.5

PAO Composition



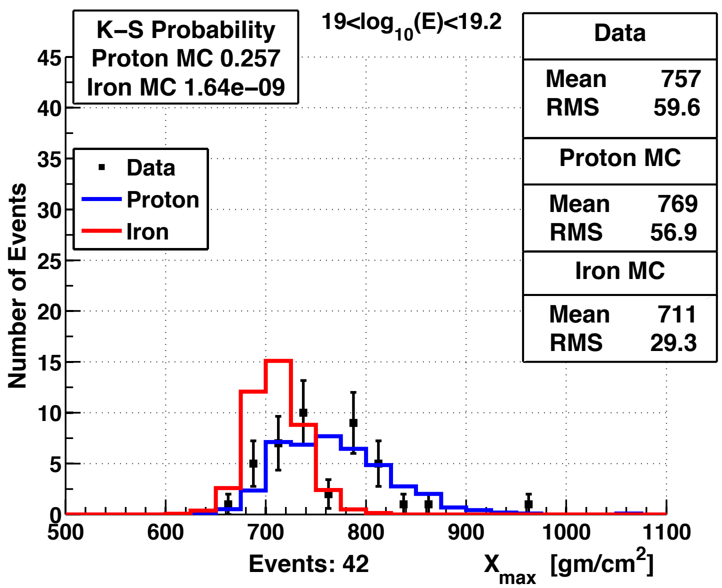


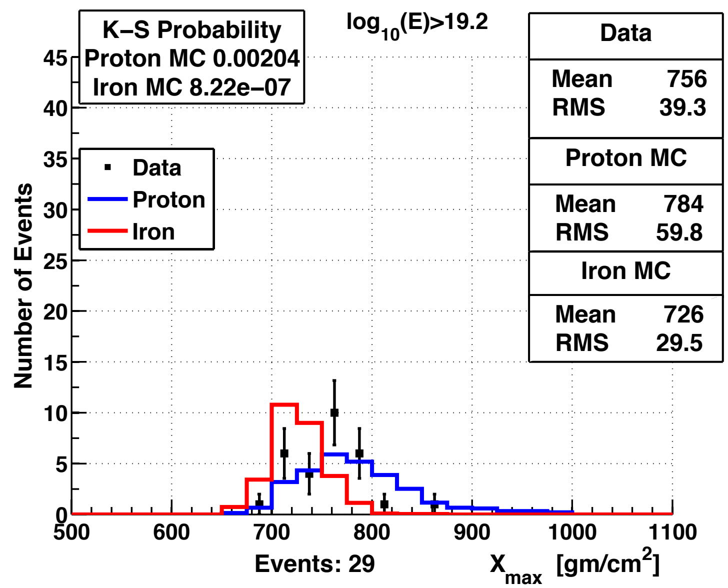




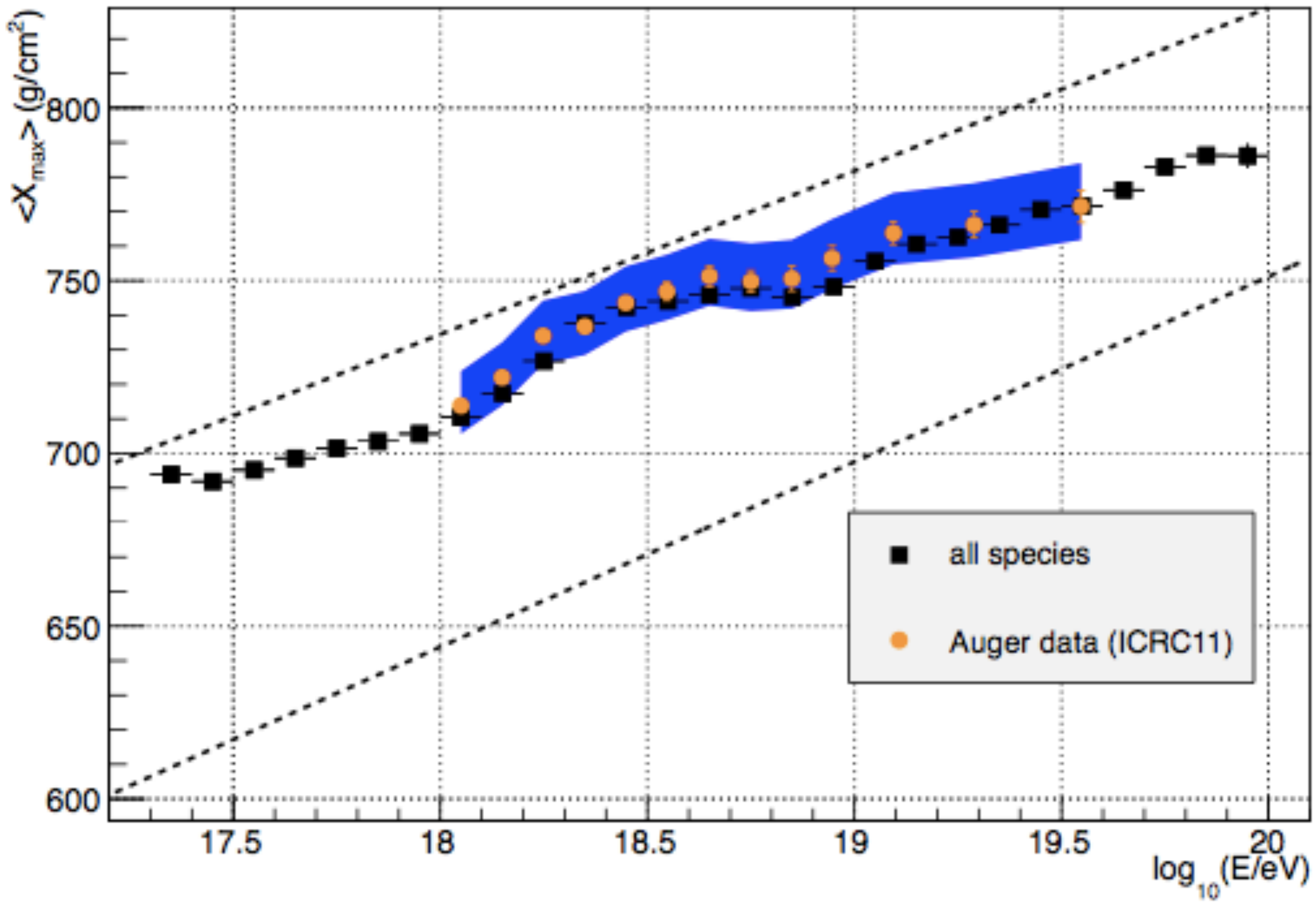
PAO elongation rate and fluctuation
rms
Note: no bias expected for data so
Prediction rails uncorrected
HiRes/TA data should be shifted by
~20 gm/cm2 deeper if QGSJET p.

Xmax dist, cont.

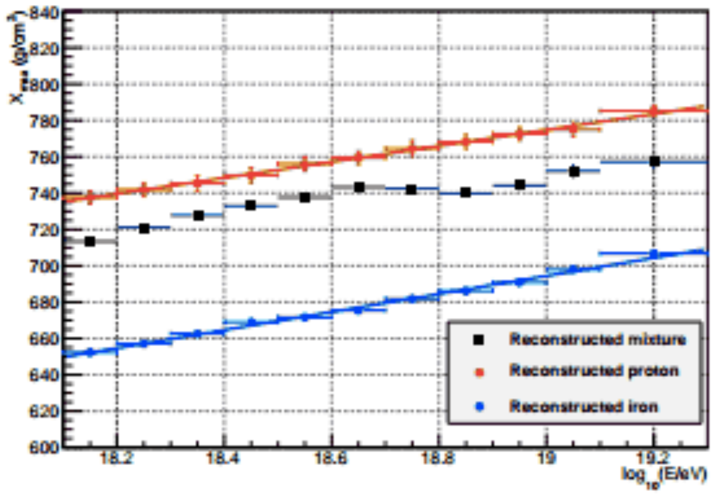


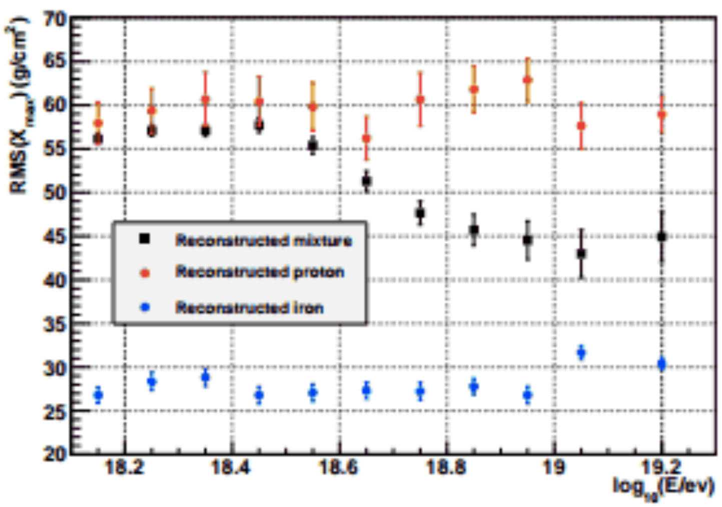


Auger-TA Composition Working Group
Development of TA-hybrid prediction model



Predictions for BR+LR hybrid





Reconstructed hybrid TA simulated
Data for pure protons, PAO mix and
Pure Iron, for both mean Xmax
And RMS of Xmax distribution – including
All acceptance and resolution effects.

TA hybrid will be able to cleanly
Distinguish between these three
hypotheses

TA hybrid comparison is expected
In near future

TA Low Energy Extension (TALE)

- Study 10^{16} and 10^{17} eV decades in hybrid
- Astrophysics
  - End of “knee”
  - Second knee
  - Galactic-Extragalactic Transition
- High-energy physics: Cross-section measurements overlapping LHC