The trouble with UHECRs

Seeming contradictions have interesting Implications…

Glennys R. Farrar
NYU

With special thanks to J. Allen, A. Berlind, R. Jansson, C. Lage, I. Zaw and members of the Pierre Auger Collaboration

Contradictions?

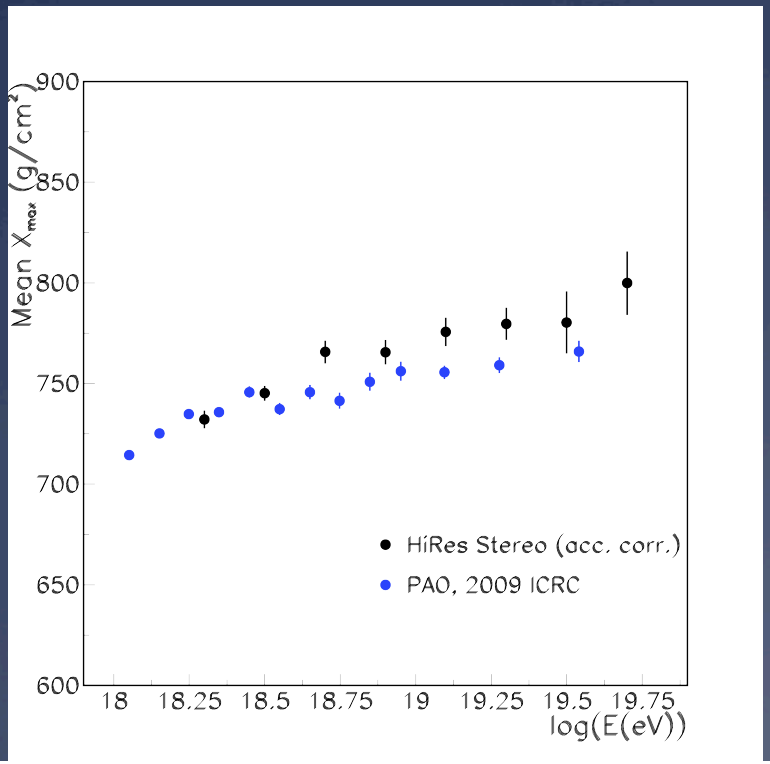
- Experimental? Interpretational?
- Consider:
  - Composition
  - Correlations
- HiRes versus Auger
- "Auger versus Auger" – Is there any consistent interpretation of all the data?

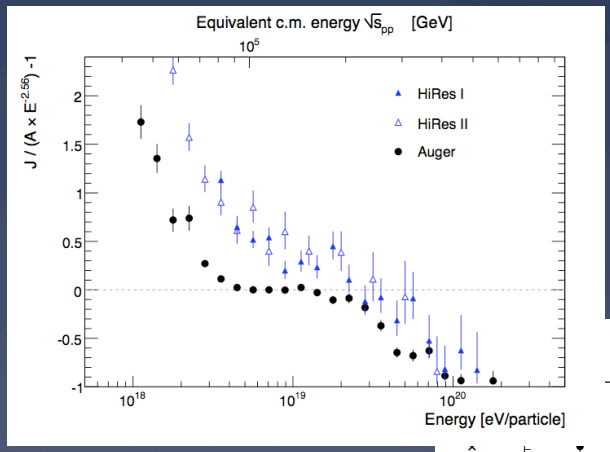
Can both HiRes and Auger be right about composition?

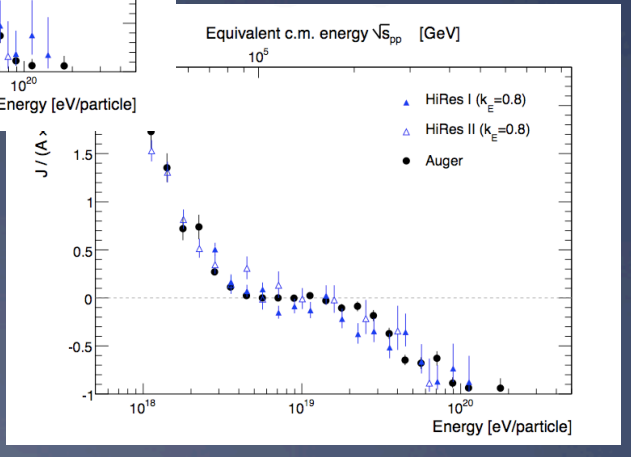
Yes!....

Both see the "Auger break"

- X-max distributions have same shapes:
  - become consistent, when shift HiRes by -0.1 in log E, and systematic shift in Xmax.
  - => break and flattening in Elongation Rate from (astro)physics

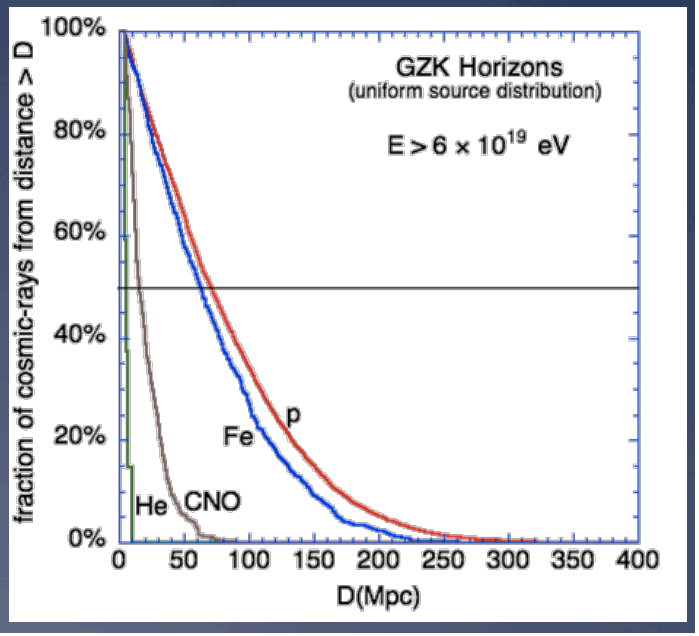






But could HiRes and Auger be *seeing* different compositions?

- In principle yes, because see different sky:
  - Intermediate mass nuclei ⇔ nearby source
  - Distant sources only => bimodal composition (heavy & light)
- Only Auger sees Cen A (4 Mpc)
- Nearest obvious source for HR is Virgo (20 Mpc)
- But doesn't fit other evidence…



Most straightforward interpretation of X_{max} data:

* Both HiRes and Auger see the "Auger break"

=> either

1) Composition is becoming heavier at higher energy
2) Or, particle physics is changing at higher energy…
3) (or both!)

* Correlation data favors 2)

Correlations

	AGASA*	HiRes	Auger
multiplets	yes	no	some
BL-Lacs	no	yes	[no]@
AGNs	….	no	yes
Ursa Major Cluster	3	2	can't see
Large Scale Structure	??	??	yes

Need more data to clarify correlations

COSMIC VARIANCE in SCAN METHOD is large (GRF et al in prep)

*AGASA angular resolution much worse than HiRes or Auger => AGASA correlation studies are less sensitive

@ Auger angular resolution insufficient to exclude BL-Lac correlation with photon-like events, at the HiRes level.

Ursa Major Cluster

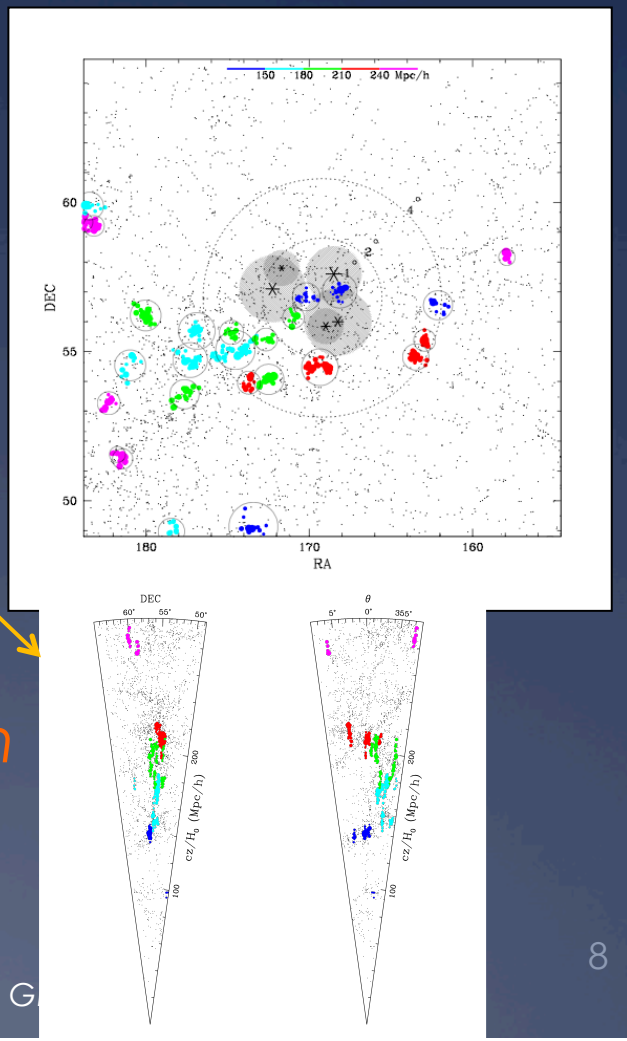
- 4 events in AGASA + HiRes (94 total) *HiRes+GRF 05*
  Same position within < 1°,
  Chance probability: $2\ 10^{-3}$ *GRF 05*
  Not in Auger field of view!

- SDSS => foreground empty!
  Extragalactic magnetic deflection low
  "confusion" problem reduced
  GRF, Berlind, Hogg 06

- Galactic magnetic deflection

$$\Delta\theta \sim 1^\circ\ Z/E_{100}$$

Evidence for proton composition



Time development of CRs from bursting source, with GZK

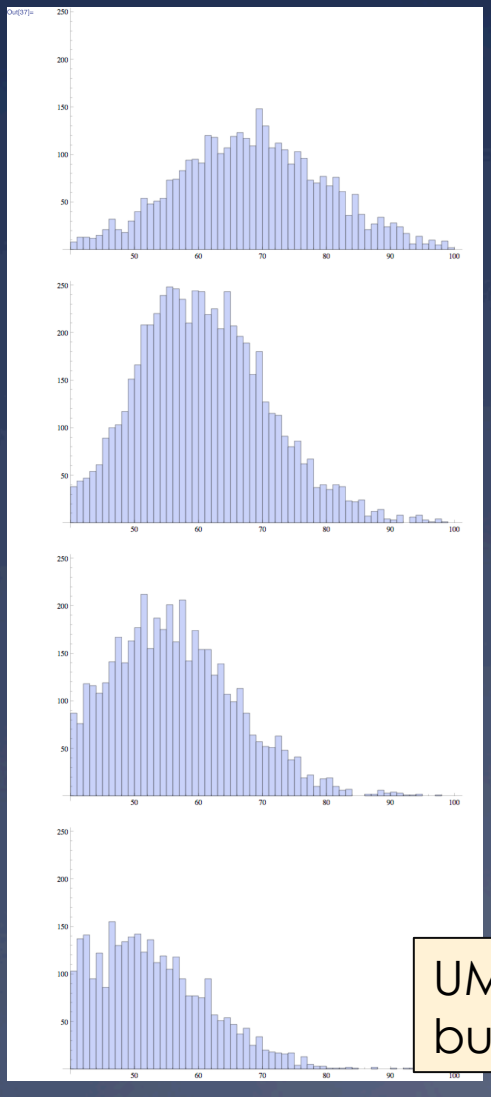
GRF 07 & in prep

T=0-3kyr

T=30-31kyr

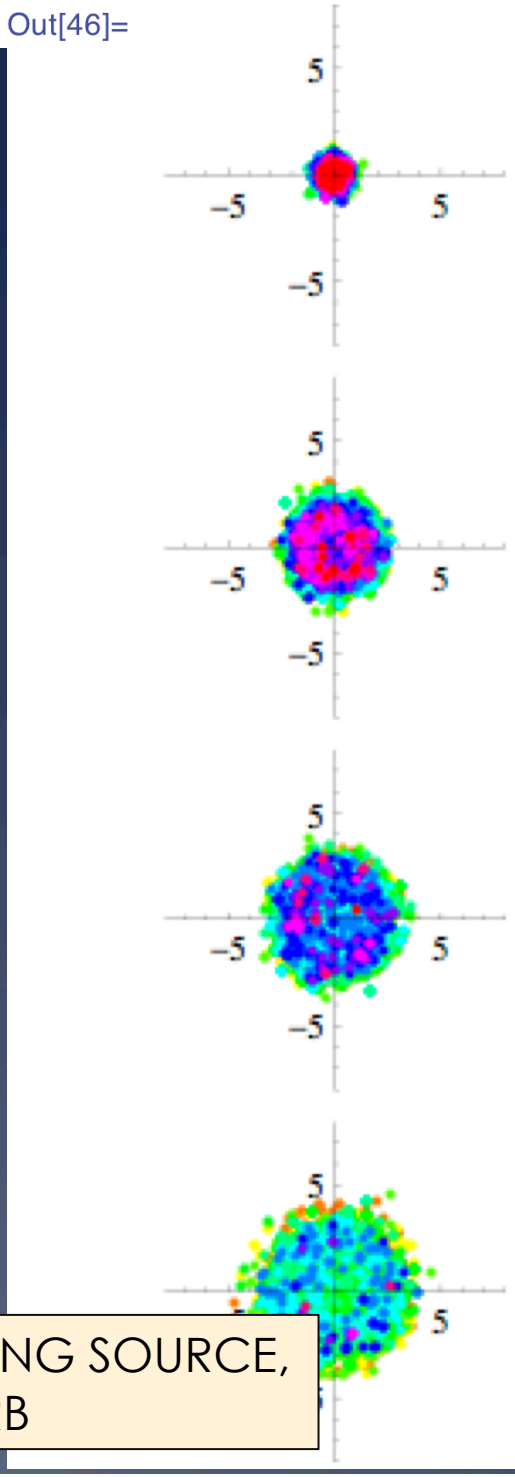
T=60-61kyr

T=90-91kyr



←Spectrum (E^{-2} at source)

Arrival Directions→



UM CR Energies:

38, 53, 55, 77 EeV

+ 1 event in HiRes < 30 EeV

$E_{UHECR} \approx 10^{49}$ erg $(D_{200})^3$ f_{GZK}

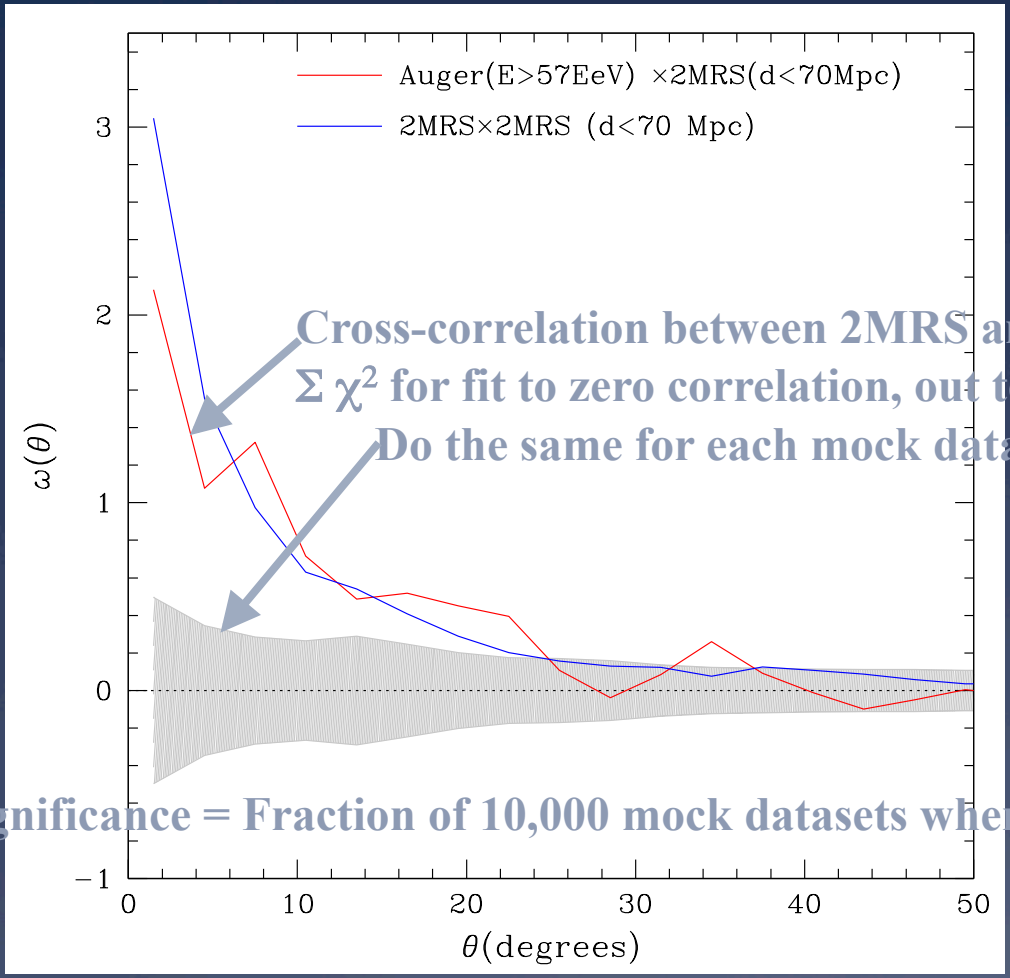
Too low for GRB

UM Cluster FAVORS BURSTING SOURCE, but not so powerful as GRB

UHECR correlation with Large Scale Structure

- X-correlate with nearby galaxies
- Traditional method in cosmology
- Application to published UHECRs: A. Berlind + GRF ICRC09 & in prep (presented here)
- Application to Auger data: presented by C. Lage for the Auger Collaboration, Washington APS Feb, 2010

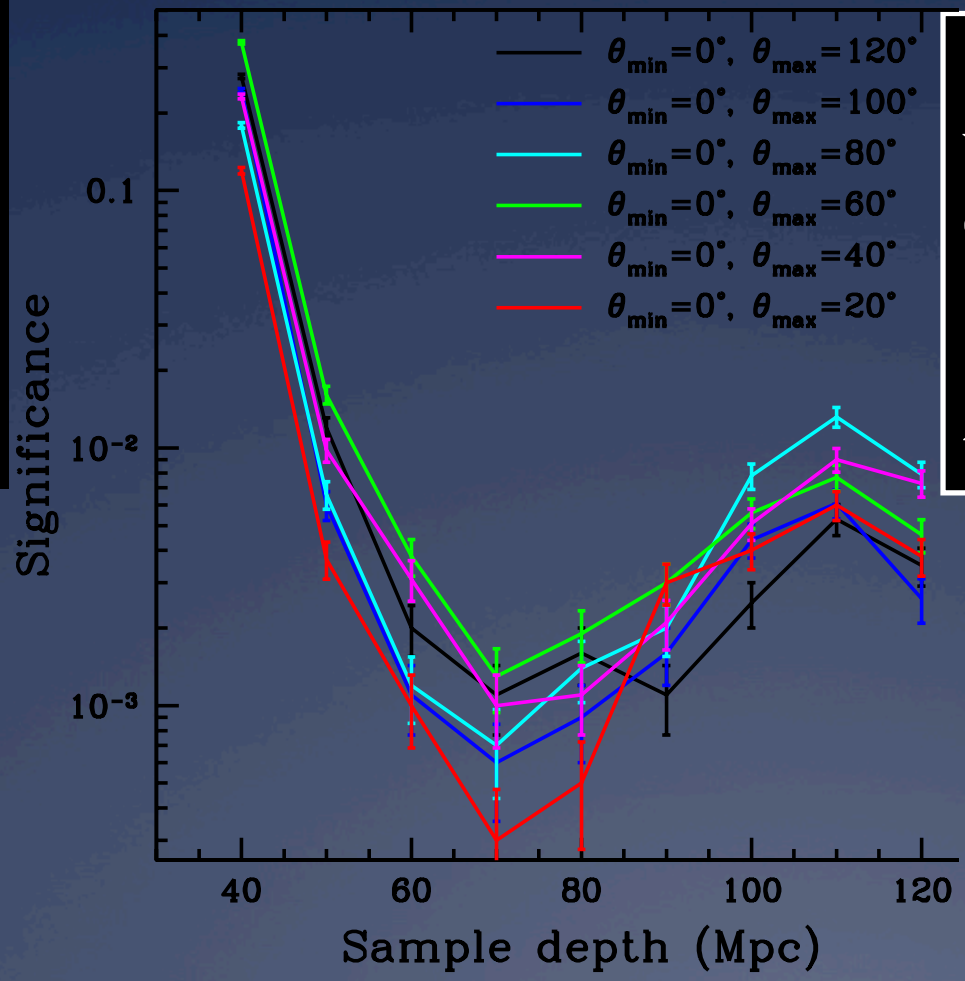
Significance Level Calculation



Cross-correlation between 2MRS and Real Data =>
$\Sigma\ \chi^2$ for fit to zero correlation, out to some Θ_{max}
Do the same for each mock data set => 1-sigma range

Significance = Fraction of 10,000 mock datasets where χ^2 > real dataset.

Impact of galaxy sample depth and angular separation



- **Broad minimum with respect to Galaxy depth**
- **Relatively insensitive to Θ_{max}**

Conclusions from UHECR-galaxy cross-correlation

(A. Berlind & GRF using published events)

- **UHECR arrival directions are inconsistent with an isotropic distribution at the 3σ level, and appear correlated with locations of nearby galaxies.**

- **Strongest correlations are seen at UHECR energies of E > 55 EeV, and galaxy depths D <= 70 Mpc.**

- **The observations are consistent with external galaxies as the source of UHECRs, moderate deflections and the GZK model.**

- See C. Lage, for the Auger Collaboration, Washington APS, Feb. 2010 for results with full dataset

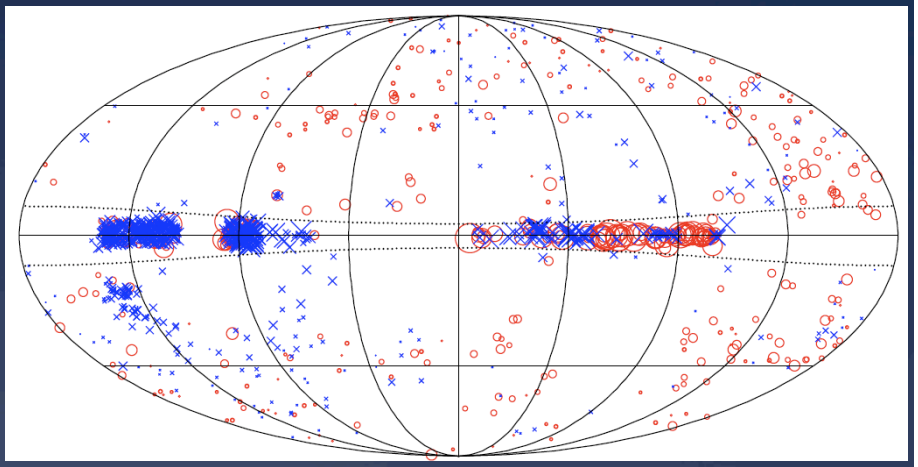
Cen A & Galactic deflections

R. Jansson, GRF, I. Feain & B. Gaenssler, in prep

Fit Galactic magnetic field

R. Jansson, GRF, Waelkens, Ensslin 09

WMAP5 22.8 GHz, Q&U + RMs



Stokes Q

Constraining models of the large scale Galactic magnetic field 5

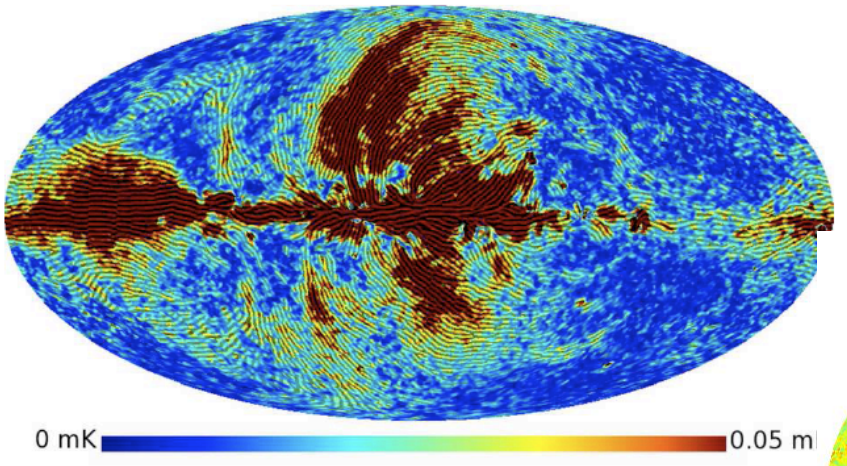
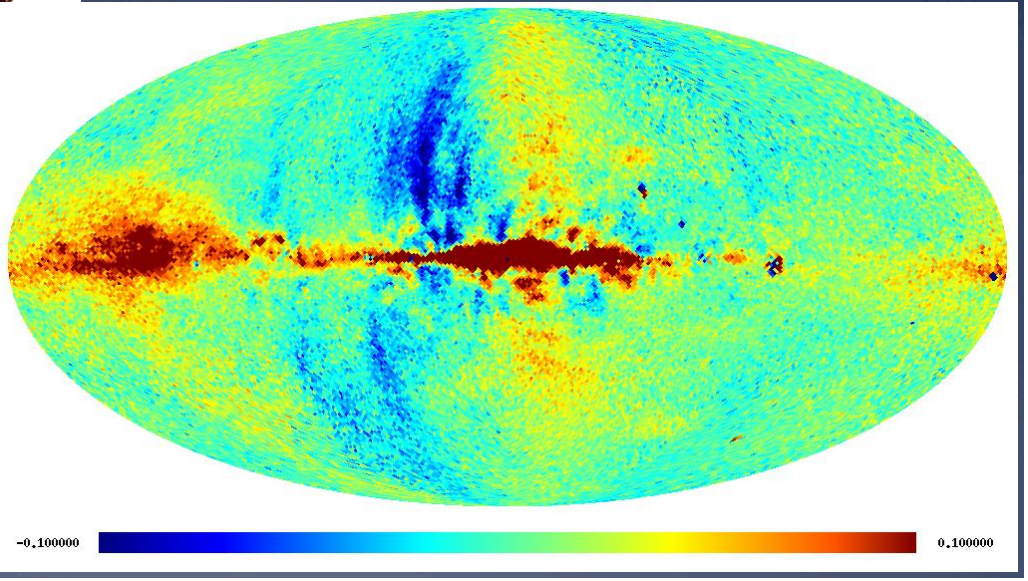


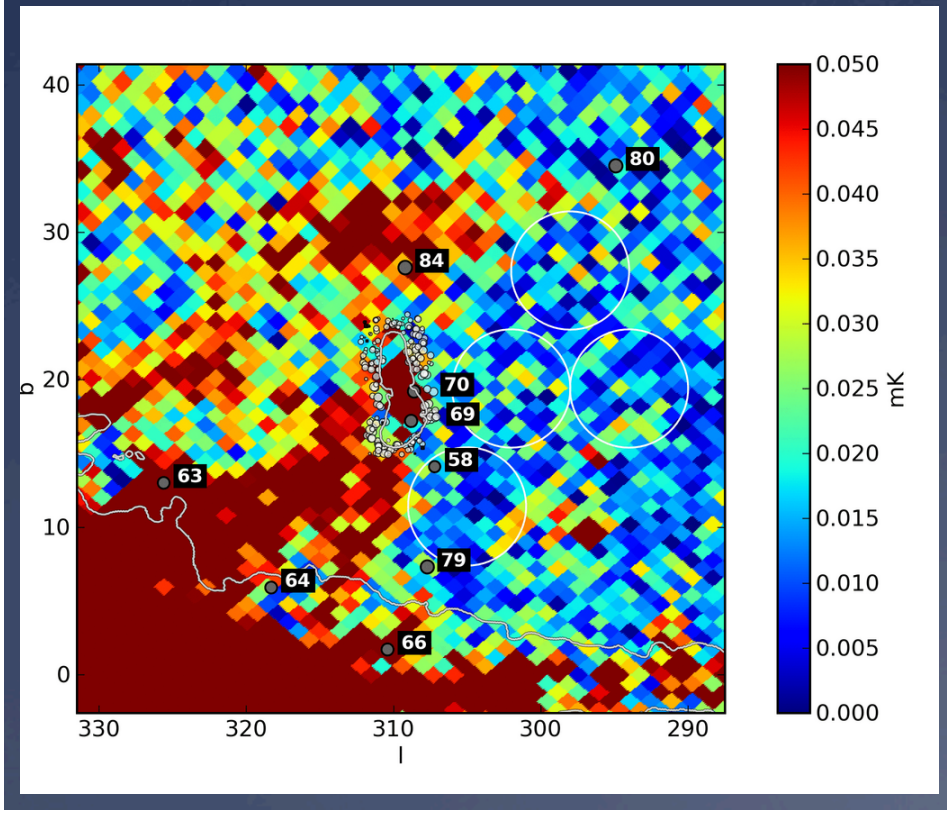
Figure 2. Polarized synchrotron intensity (color), overlaid with a texture showi
the magnetic field directions (i.e., the observed polarization angle rotated by 90°
Image created using the line integral convolution code, ALICE, written by Dav
Larson.



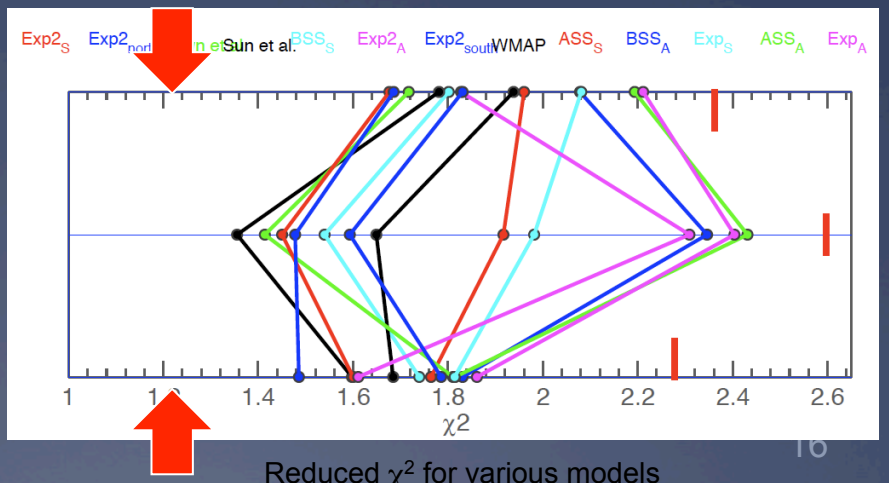
Dedicated Cen A study of GMF

RJ, GRF, I Feain, B Gaelssler in prep

* 166 new RMs surrounding lobes (Feain & Gaenssler)



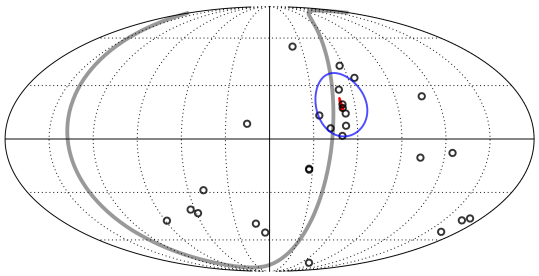
* New GMF model (RJ+GF) adding
  * Random and striated fields
  * Out-of-plane component
* Gives MUCH BETTER fit to Q,U & RMs
  * Global fit, with halo and disk



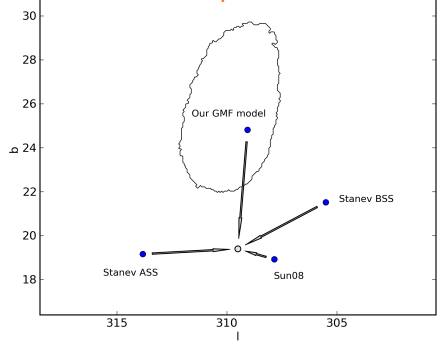
Reduced χ^2 for various models

Interpretation of Cen A excess requires good GMF model!

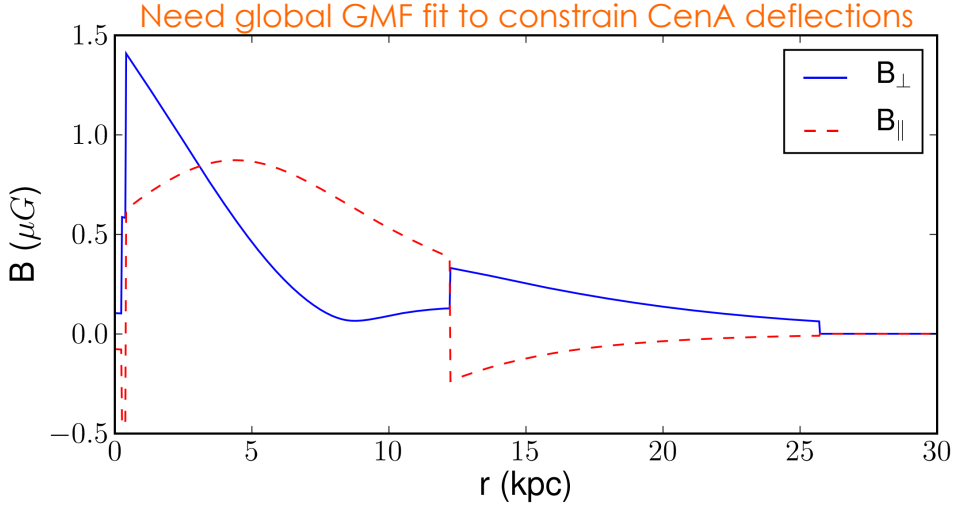
27 Auger events with 18° circle @ CenA



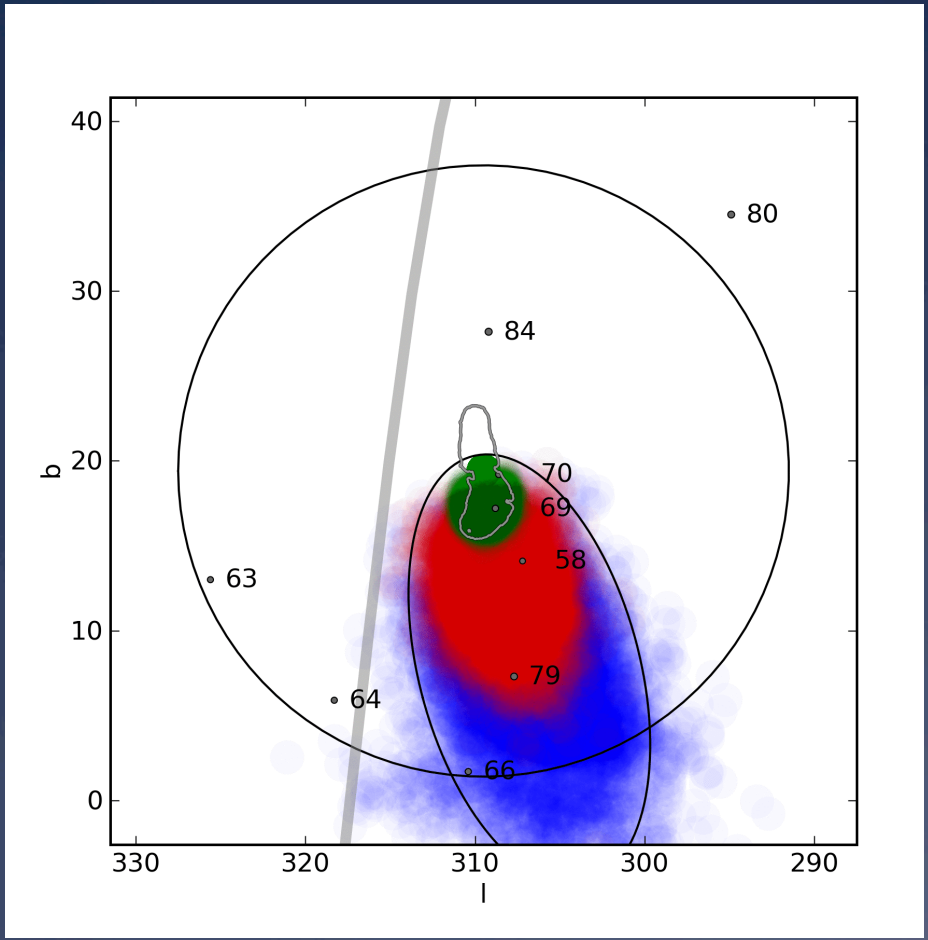
~~Deflection depends on GMF~~



Need global GMF fit to constrain CenA deflections



5 of 27 published Auger CRs are most likely protons from Cen A



- Define Cen A locus
- Contains 5 events
- Fraction of Auger exp in locus = 0.009
- 27 events => expect 0.25
- Probability to find ≥ 5 by chance = $7\ 10^{-6}$
- No scan penalty… what "idea penalty"???

$$f_{\mathrm{CenA}} = 0.18^{+0.07}_{-0.08}$$

Implication of Correlations

- Protons are a major component of UHECRs even above 50 EeV
- Reconciliation with Auger-HiRes "X-max break"
  - Requires σ_{tot} increases faster with E than in models, hint of some break or acceleration
- But, need to get consistency also with ground signal!

Simulated versus observed ground signal, with proton composition

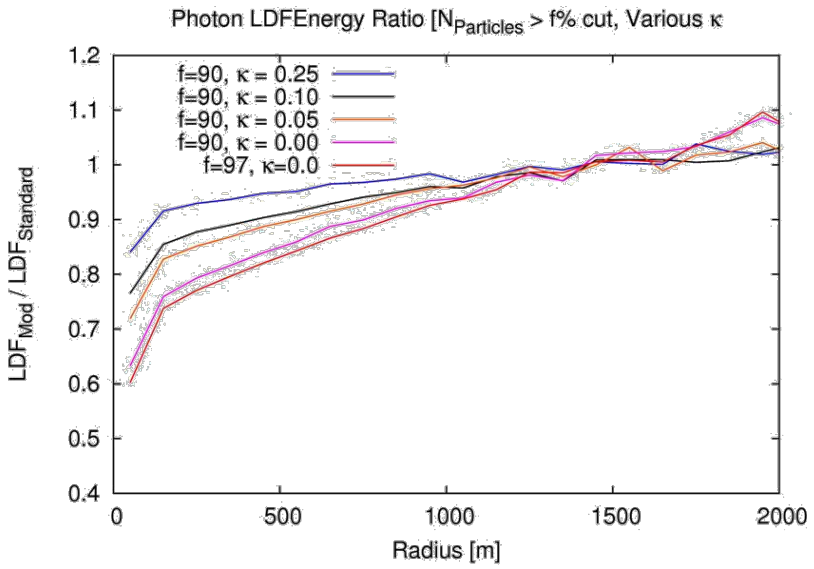
- Robust evidence that observed SD signal is too strong compared to model predictions
  - The "excess-muon problem"
  - Seen using many approaches, in both SD and Hybrid datasets
  - More info in next talk by M. Unger
- Present models have factor-2 deficiency with protons
  - Fe only increases muons by ~ 1/3, so
  - Factor-1.7 deficiency with Fe
- Hadronic models matter (Ulrich et al 0906.0418)

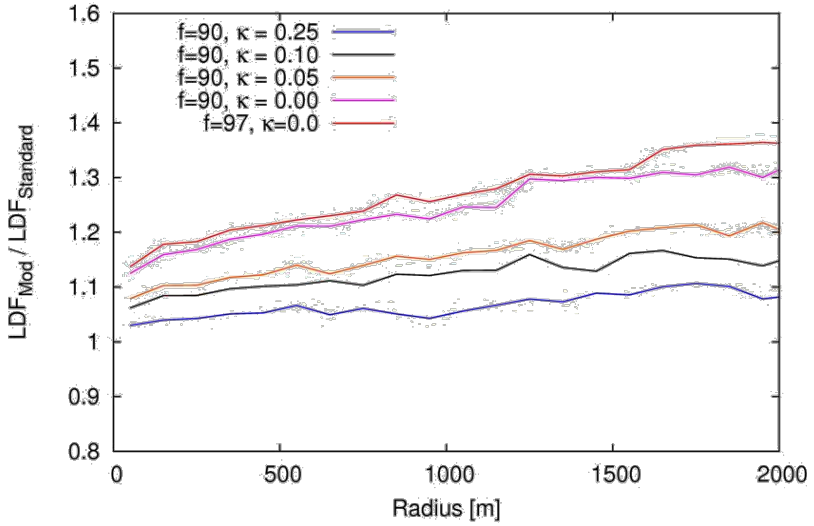
How can the "muon excess" be explained?

- Problem severe -- not solved by heavy composition
- Jeff Allen & GRF campaign to explore options:
  - Use QGSJet-2, Sybill, and EPOS
  - Vary total cross section, multiplicity distribution, photon fraction
  - "Accept" combos giving observed X-max distribution and strength and zenith average LDF
  - Are Golden Hybrid events well-described?

The Axe (1) -- Multiplicity

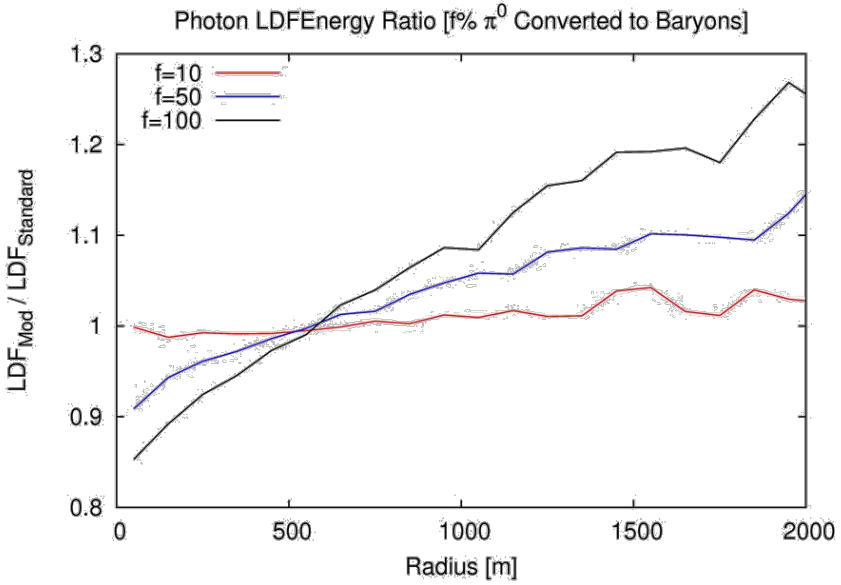
- Method: selective choose events generated by QII
- Make a multiplicity cut, only keep a fraction, κ, that fall below cut
  - Cut at the 90% threshold to see maximum effect possible
  - Cut is energy dependent
- Maximum effect of the "axe"
  - 10% reduction of EM signal
  - 25% increase in number of muons
  - Right direction, need more muons

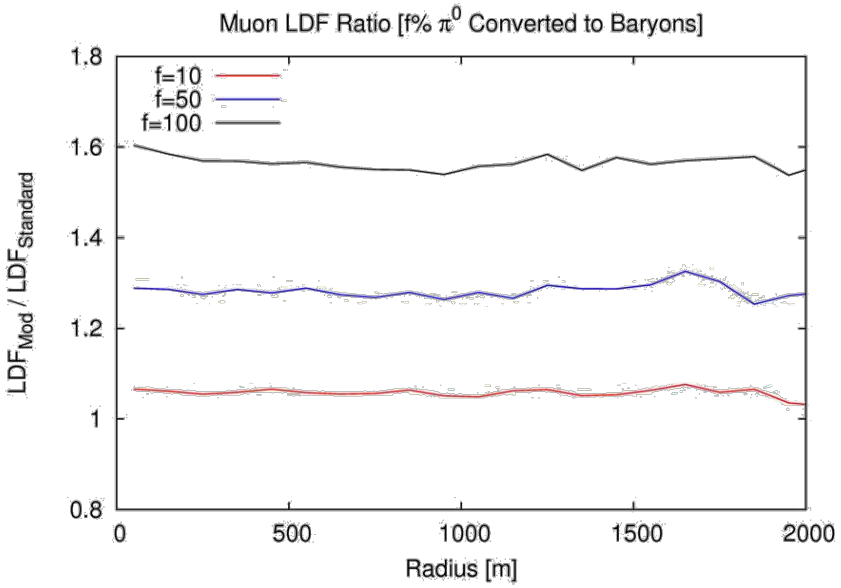




The axe (2) -- π^0 Conversion

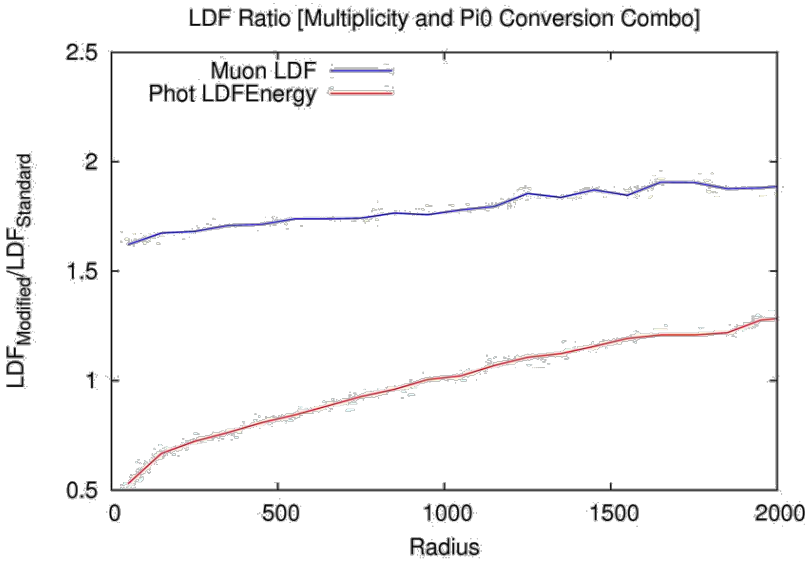
- Convert π^0's of QII events into baryons
- f is fraction of π^0 to convert at 10 EeV, with logarithmic E dependence
- Maximum effect:
  - 10% increase in EM signal
  - 60% increase in muonic signal
  - Still need more muons

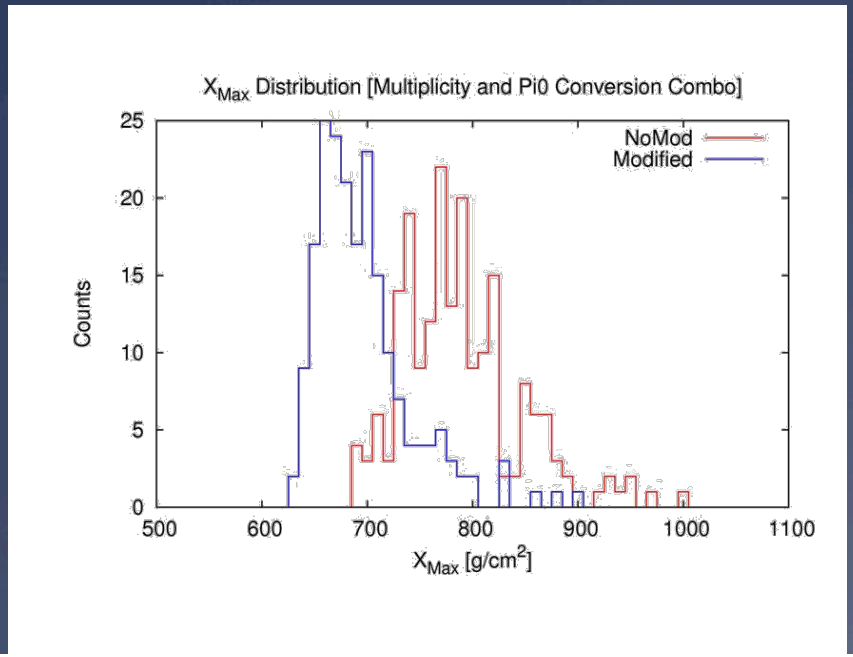


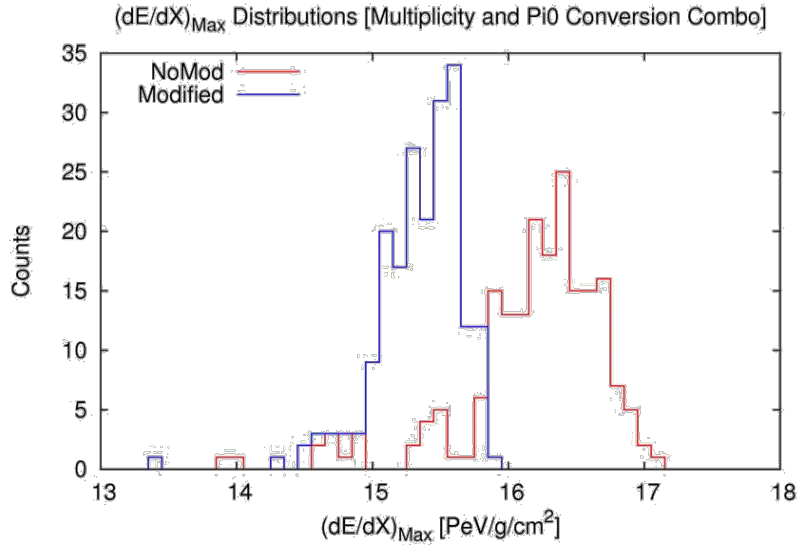


π^0-Multiplicity Combination

- Multiplicity cut
  - 90 % threshold
  - K = 0.0
- π^0 mod f=100%
- Maximum effect
  - No change in EM
  - 80% increase in muons
  - 8% reduction in LP
  - $\langle X_{Max} \rangle$ dramatically reduced
- Still not enough muons!
- Still too much EM ground signal!
- Getting a doubling of number of muons is non-trivial







The Axe -- Conclusions

- Drastic increase in multiplicity improves LDF muon signal
- Drastic conversion of pi-0's to other hadrons improves LDF
- VERY hard to get observed muon and EM signals
- Modification of total cross section fixes X-max distribution but doesn't impact muon problem
- Evidence of new physics?

Conclusions (very personal)

- UHECRs are perplexing, but not daunting.
- Present evidence favors predominantly proton composition, and drastic modifications to final states of hadronic collisions at energies > EeV.
- Promising directions:
  - bursting sources -- produce correlations with large scale structure but not individual source classes.
  - Improve GMF modeling for better-constrained reconstructions; use more sophisticated recontruction methods.
  - Improve astro source catalogs; start combining HiRes/TA and Auger data for all-sky correlation studies.