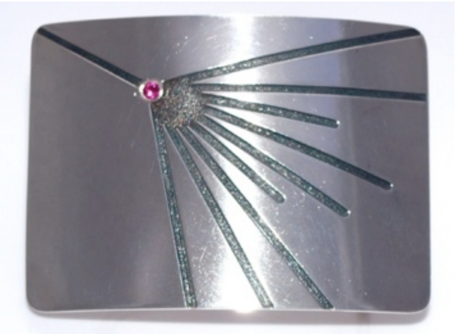
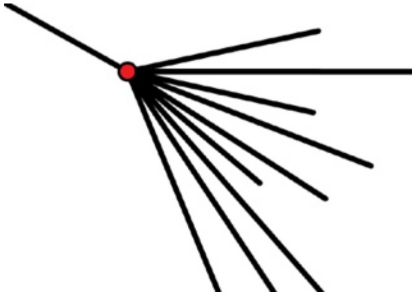
Trevorfest: Tuscon, 26 October 2013

Recent Results from the Pierre Auger Observatory

Alan Watson
University of Leeds, UK





Bristol, UK: Conference on Very High Energy Interactions, January 1963

Bristol, UK: Conference on Very High Energy Interactions, January 1963

Important names in ground-based gamma-ray astronomy:
Jelley, Galbraith, Porter, Hillas and Weekes

Bristol, UK: Conference on Very High Energy Interactions, January 1963

Important names in ground-based gamma-ray astronomy: Jelley, Galbraith, Porter, Hillas and Weekes

Bristol, UK: Conference on Very High Energy Interactions, January 1963

Important names in ground-based gamma-ray astronomy:
Jelley, Galbraith, Porter, Hillas and Weekes

574 Nuclear Instruments and Methods in Physics Research A301 (1991) 574–578
North-Holland

Measurement of the angular resolution of an extensive air shower array using a Cherenkov light detector

A. Walker [a,†], A.M. Hillas [b], M.A. Pomerantz [a], P.T. Reynolds [c], J.C. Perrett [a], J.T.P.M. van Stekelenborg [a], A.A. Watson [b] and T.C. Weekes [c]

[a] *Bartol Research Institute, University of Delaware, 217 Sharp Laboratory, Newark, DE 19716, USA*
[b] *University of Leeds, Leeds LS2 9JT, England, UK*
[c] *Smithsonian Institution, Fred Lawrence Whipple Observatory, Astrophysical Observatory, Amado, AZ 85645-0097, USA*

Received 2 October 1990

We describe a method which has been used to evaluate the pointing accuracy and angular resolution of the South Pole air shower array. It makes use of coincidences between the air shower array and a very simple air Cherenkov detector of small aperture. The alignment of the array is shown to be known to be within $\pm 0.2°$ for the zenith direction and $\pm 0.5°$ for the azimuth direction. Additionally the angular resolution has been measured at energies below 200 TeV, lower than those at which the subarray comparison technique can be applied. At higher energies conclusions drawn previously from subarray comparisons are confirmed: the angular resolution, as described by the root mean square uncertainty in zenith angle, of showers produced by primaries of 200 TeV is found to be $0.8°$ for showers incident at about $20°$ from the vertical.

Cherenkov Light Detector: Pair of pmts and a Fresnel lens

5 citations

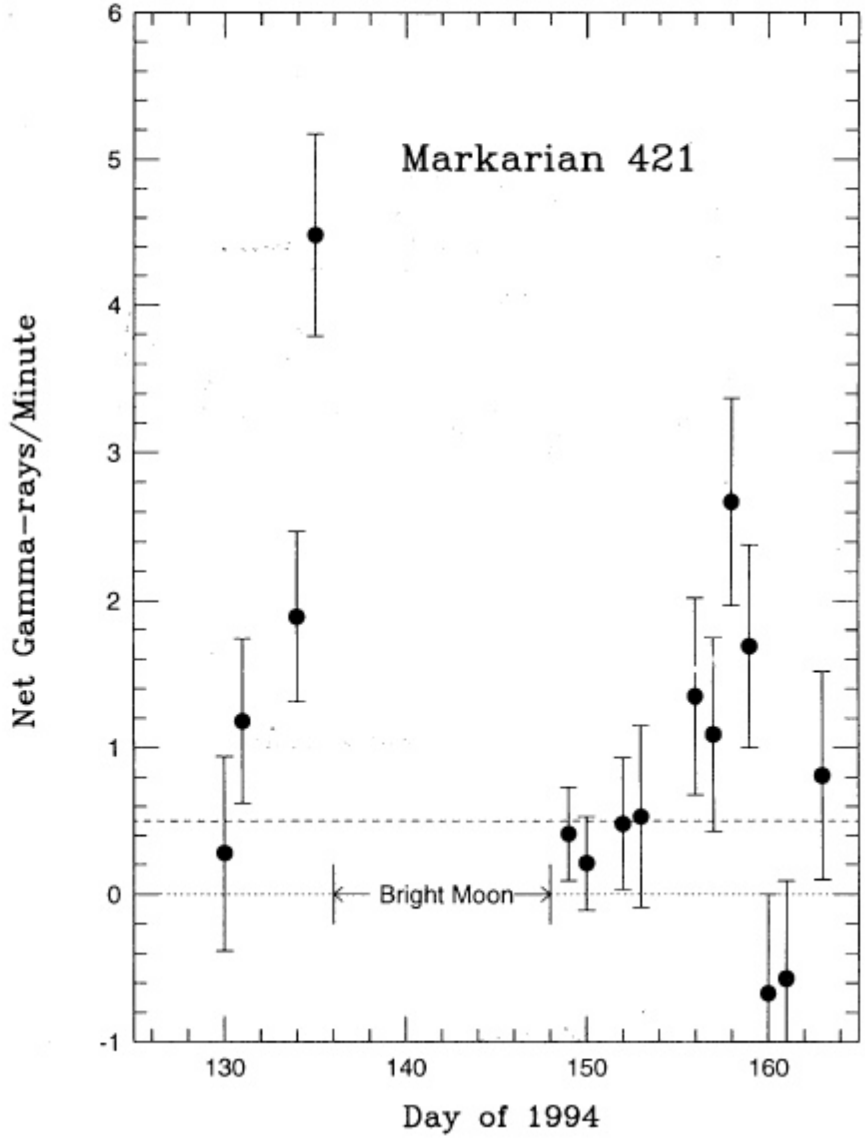
Visit to Whipple: April – May 1994 Smithsonian Visiting Fellow

Visit to Whipple: April – May 1994 Smithsonian Visiting Fellow

Observing Markarian 421 with Julie McHenry

Visit to Whipple: April – May
1994 Smithsonian Visiting Fellow

Observing Markarian 421 with Julie McHenry



Visit to Whipple: April – May
1994 Smithsonian Visiting Fellow

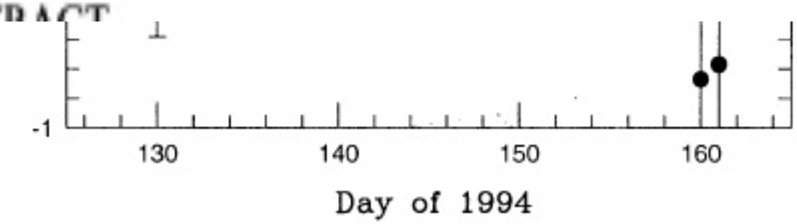
Observing Markarian 421 with Julie McHenry

THE ASTROPHYSICAL JOURNAL, 438: L59–L62, 1995 January 10

OUTBURST OF TeV PHOTONS FROM MARKARIAN 421

A. D. KERRICK,[1] C. W. AKERLOF,[2] S. D. BILLER,[3] J. H. BUCKLEY,[4] M. F. CAWLEY,[5] M. CHANTELL,[4]
V. CONNAUGHTON,[6] D. J. FEGAN,[6] S. FENNELL,[6] J. A. GAIDOS,[7] A. M. HILLAS,[3] R. C. LAMB,[1]
D. A. LEWIS,[1] D. I. MEYER,[2] J. MCENERY,[6] G. MOHANTY,[1] J. QUINN,[6] A. C. ROVERO,[4]
H. J. ROSE,[3] M. S. SCHUBNELL,[2] G. SEMBROSKI,[7] M. URBAN,[8] A. A. WATSON,[3]
T. C. WEEKES,[4] M. WEST,[3] C. WILSON,[7] AND J. ZWEERINK[1]
Received 1994 September 15; accepted 1994 October 21

Over 70 citations



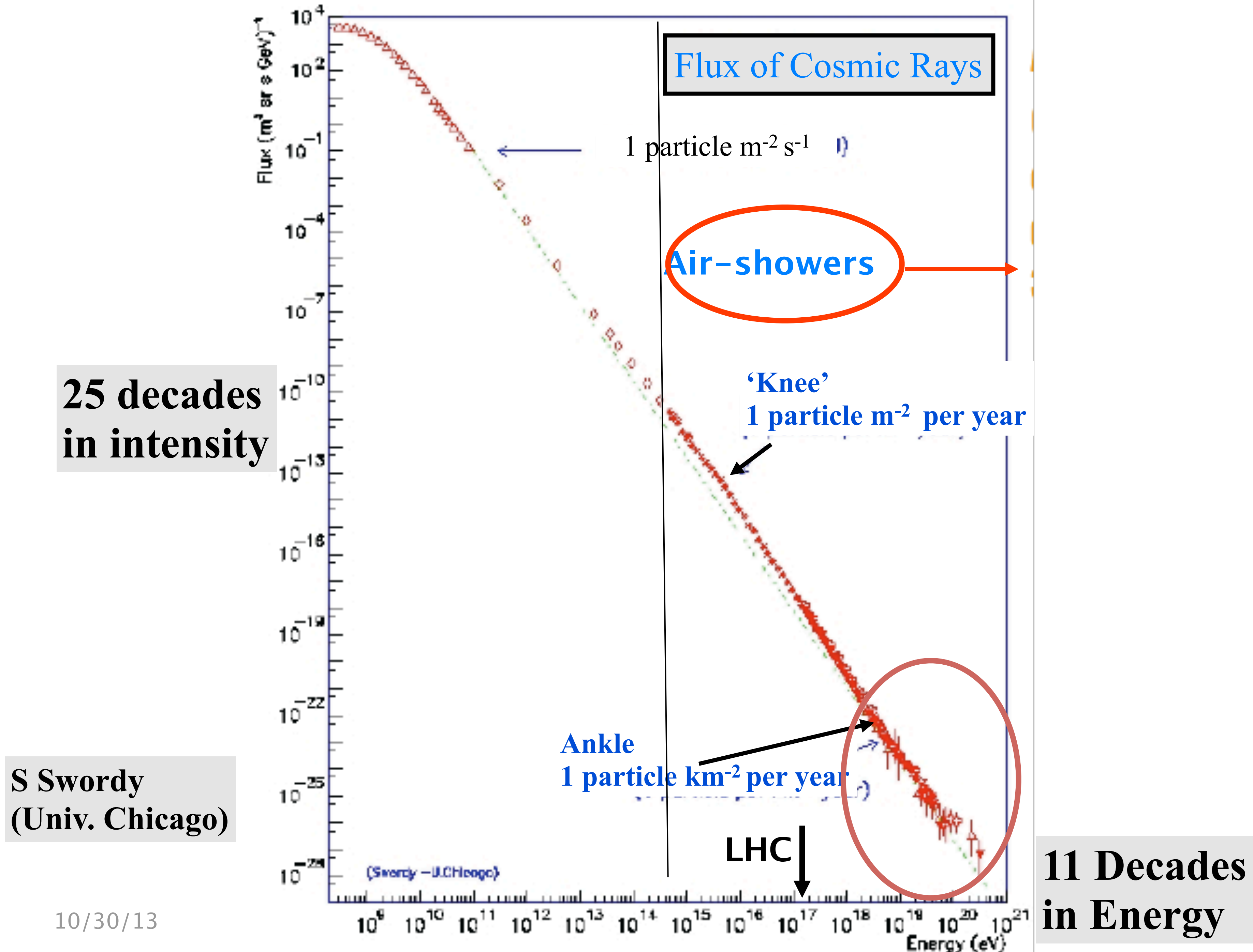
SAGENAP Committee

Three awful meetings in 1997 - 98

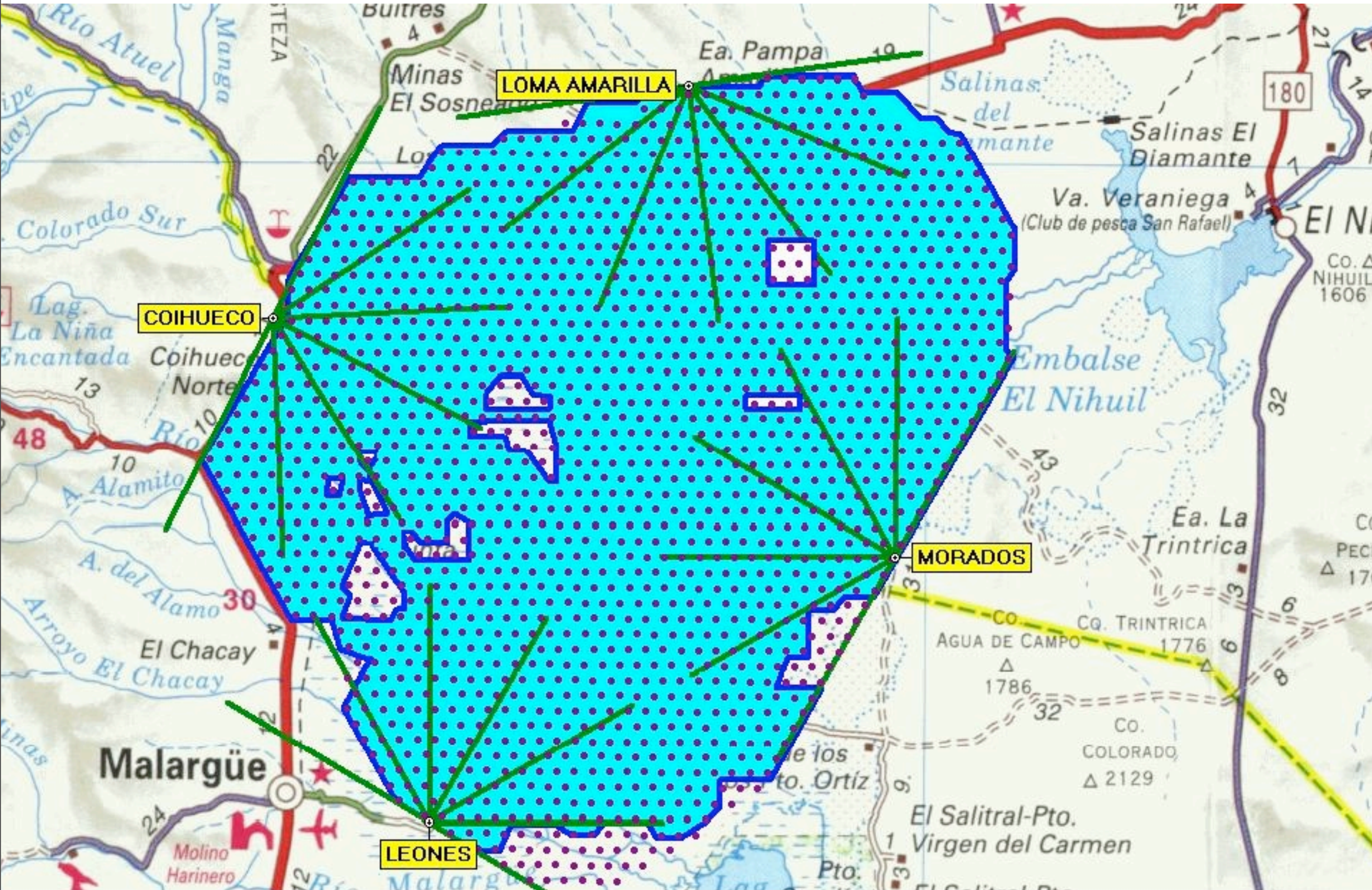
Trevor was one of the Auger Champions

Outline

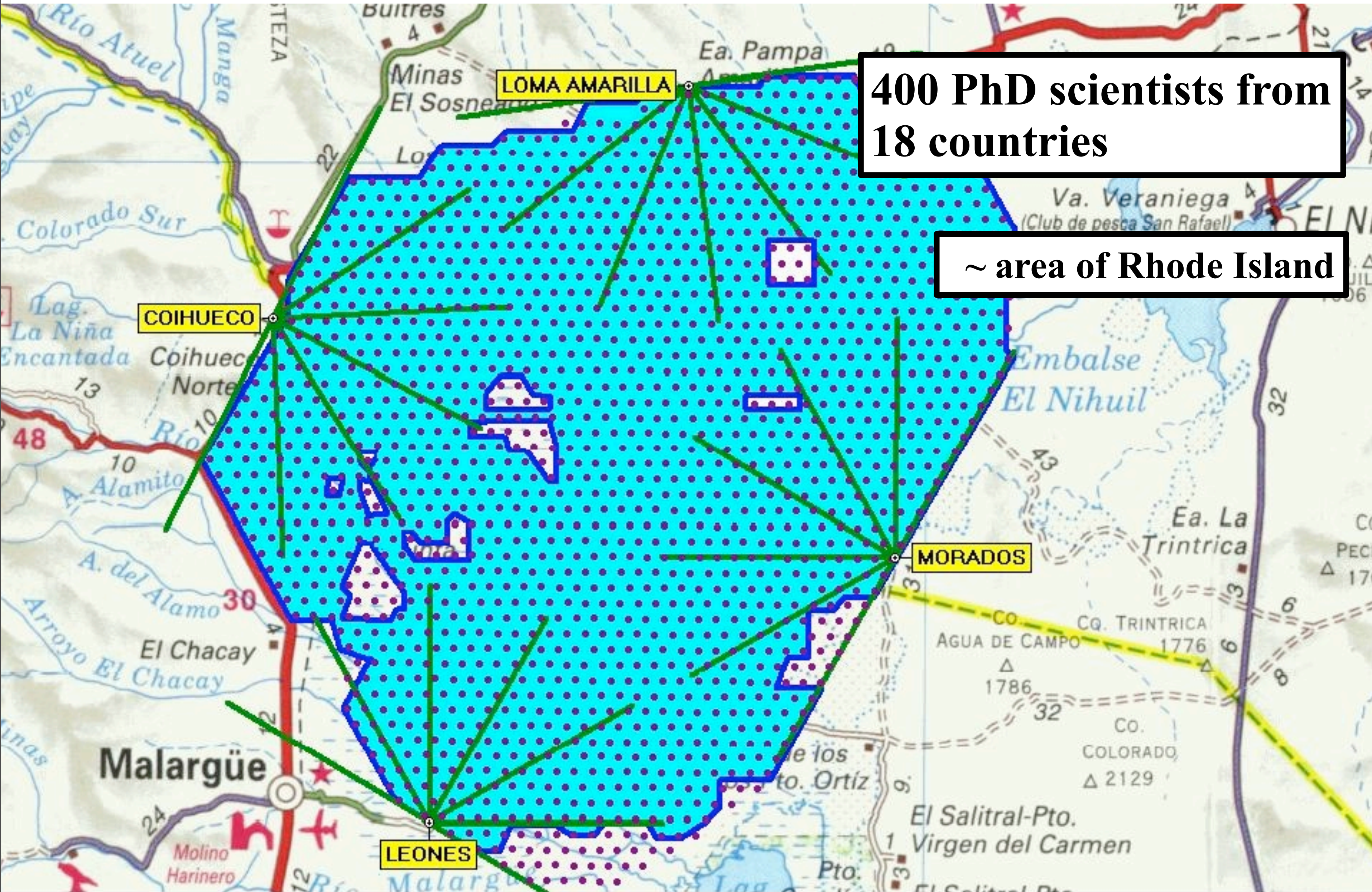
- The Auger Observatory
- Mass Composition and influence of hadronic interactions on interpretation
- Spectrum
- Some conclusions


Flux of Cosmic Rays
1 particle m-2 s-1
Air-showers
'Knee'
1 particle m-2 per year
Ankle
1 particle km-2 per year
LHC
25 decades
in intensity
11 Decades
in Energy
S Swordy
(Univ. Chicago)
Flux (m² sr s GeV)⁻¹
Energy (eV)
(Swordy - U.Chicago)

10/30/13



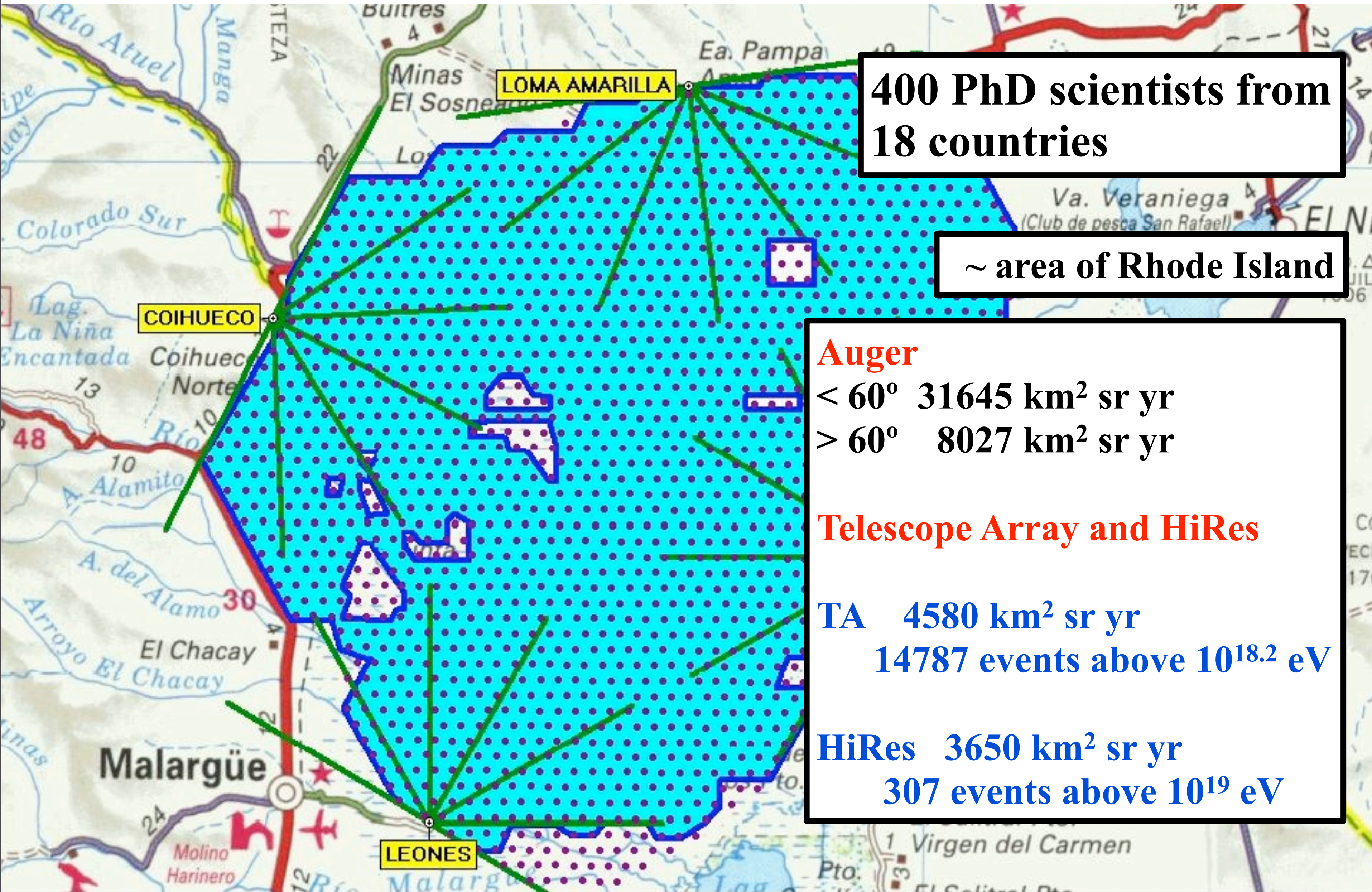
1390 m above sea level: 875 g cm^{-2}



400 PhD scientists from 18 countries

~ area of Rhode Island

1390 m above sea level: 875 g cm^{-2}



400 PhD scientists from 18 countries

~ area of Rhode Island

Auger

< 60° 31645 km² sr yr

> 60° 8027 km² sr yr

Telescope Array and HiRes

TA 4580 km² sr yr

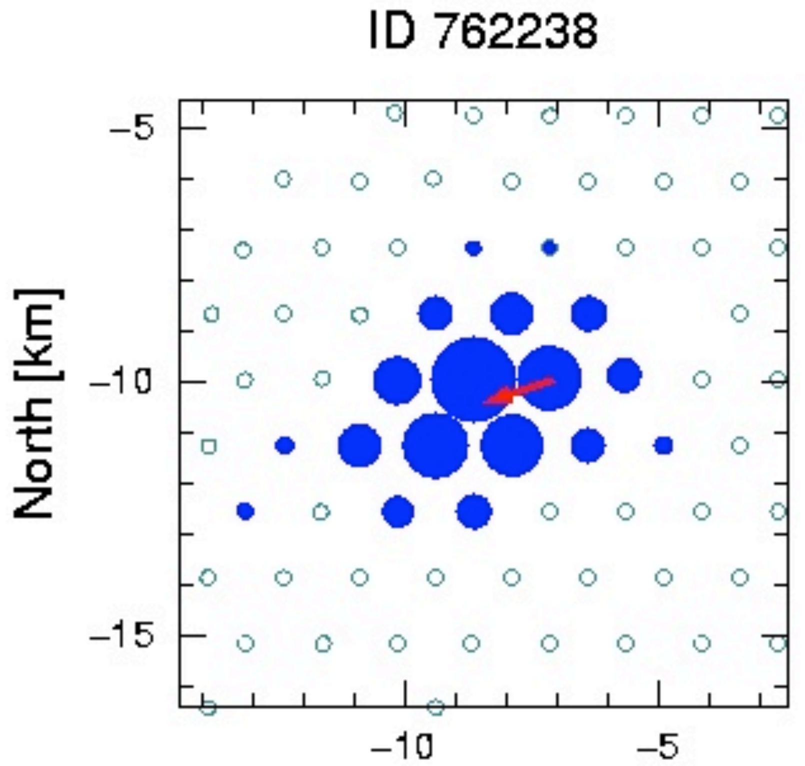
14787 events above $10^{18.2}$ eV

HiRes 3650 km² sr yr

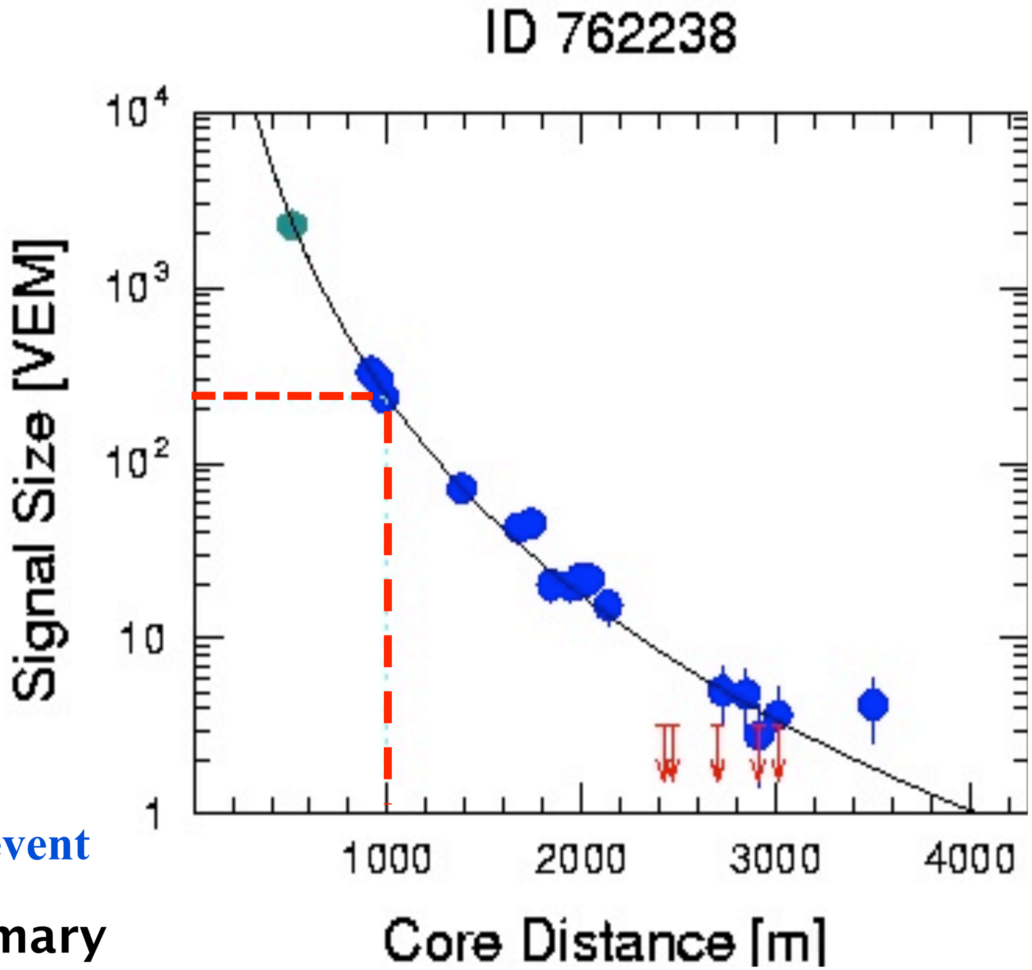
307 events above 10^{19} eV

1390 m above sea level: 875 g cm^{-2}

The Auger energy scale is determined from the data and does not depend on a knowledge of interaction models or of the primary composition – except at level of few %.



Zenith Angle ~ 48^0 Energy ~ 7×10^{19} eV



The detector signal at 1000 m from the shower core

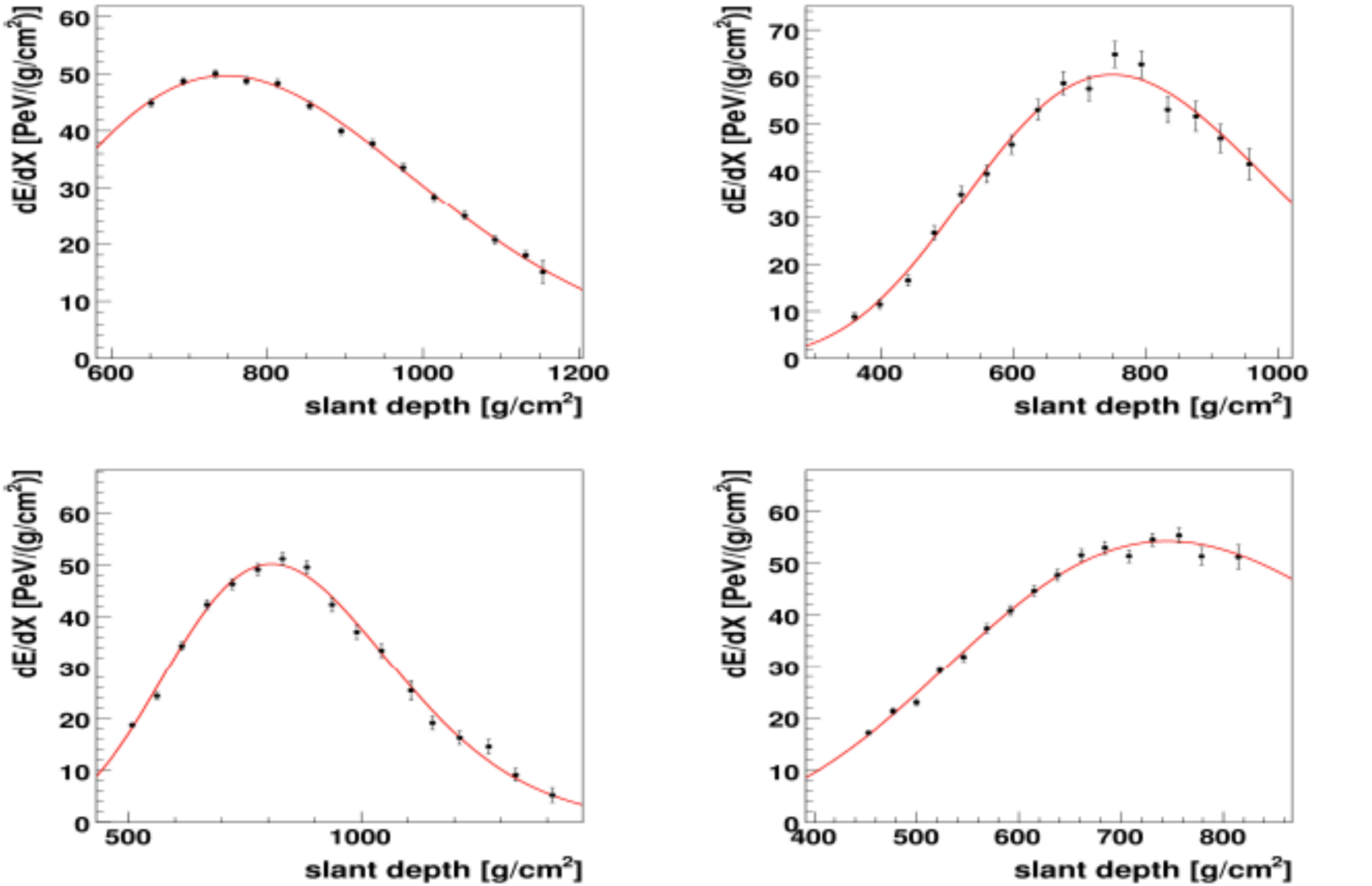
– S(1000)

- determined for each surface detector event

S(1000) is proportional to the primary energy

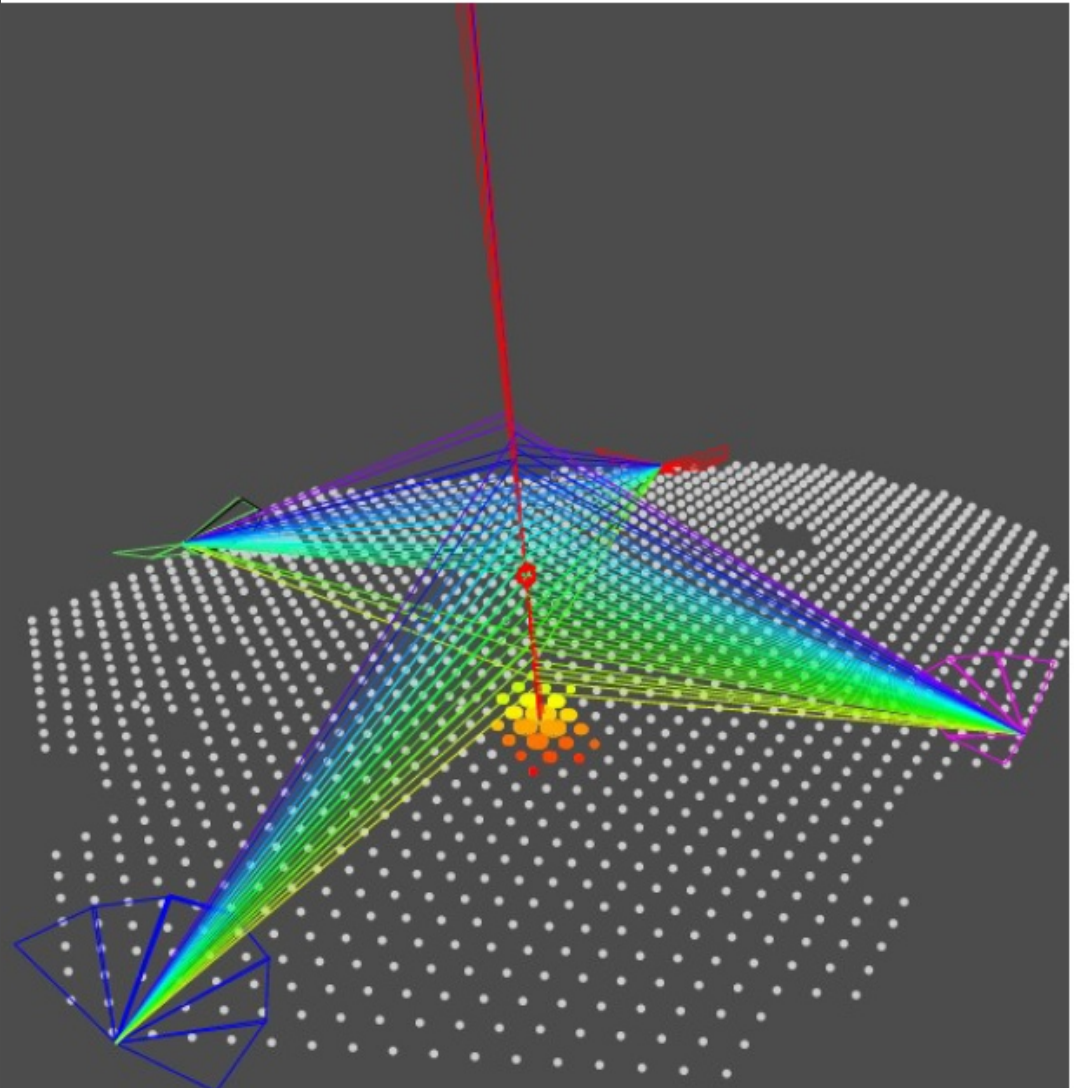
Some Longitudinal Profiles measured with Auge

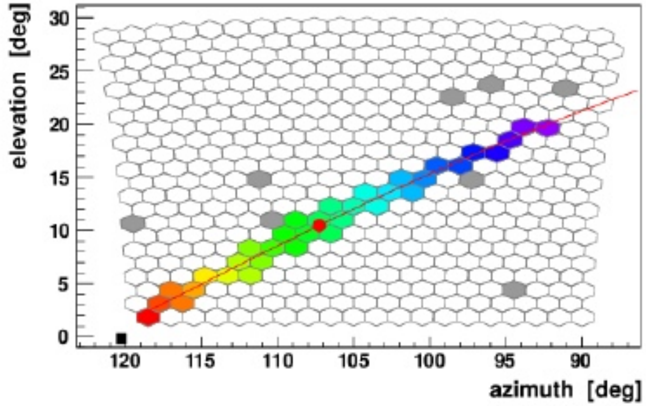
1000 g cm^{-2} = 1 Atmosphere ~ 1000 mb

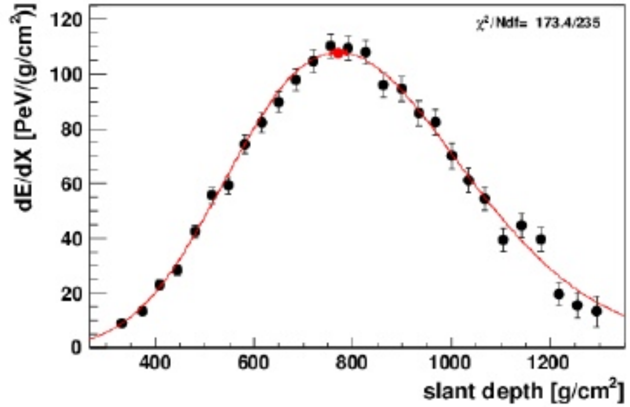


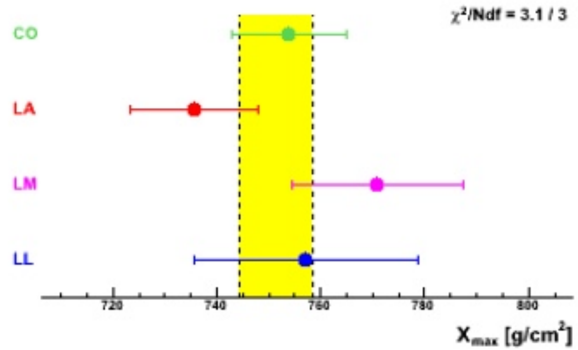
rms uncertainty in X_{max} = 20 g cm^{-2} from stereo-measurements

Excellent check on the Energy





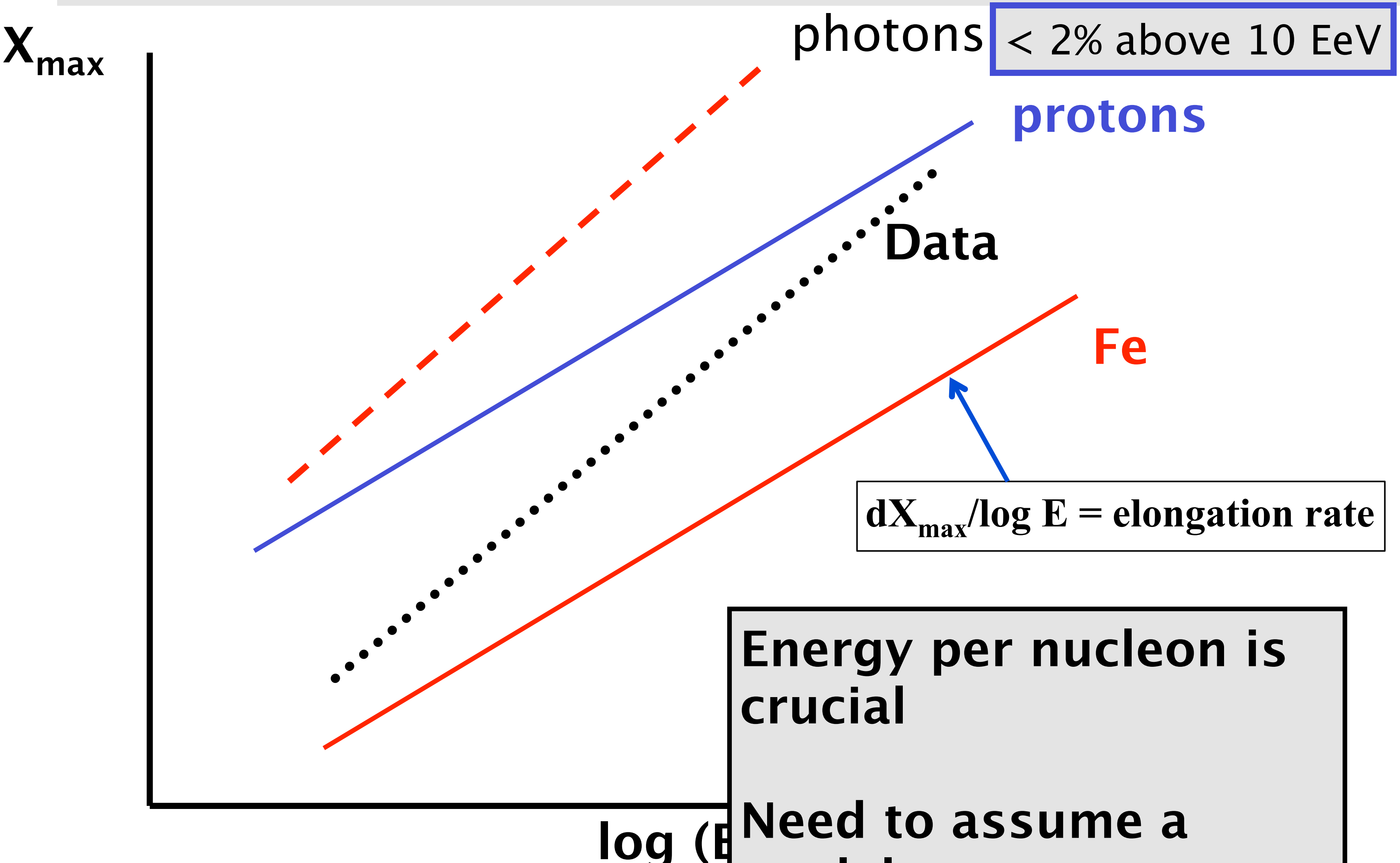




$E = 7.1 \pm 0.2\ 10^{19}$ eV - $X_{max} = 752 \pm 7$ g/cm^2

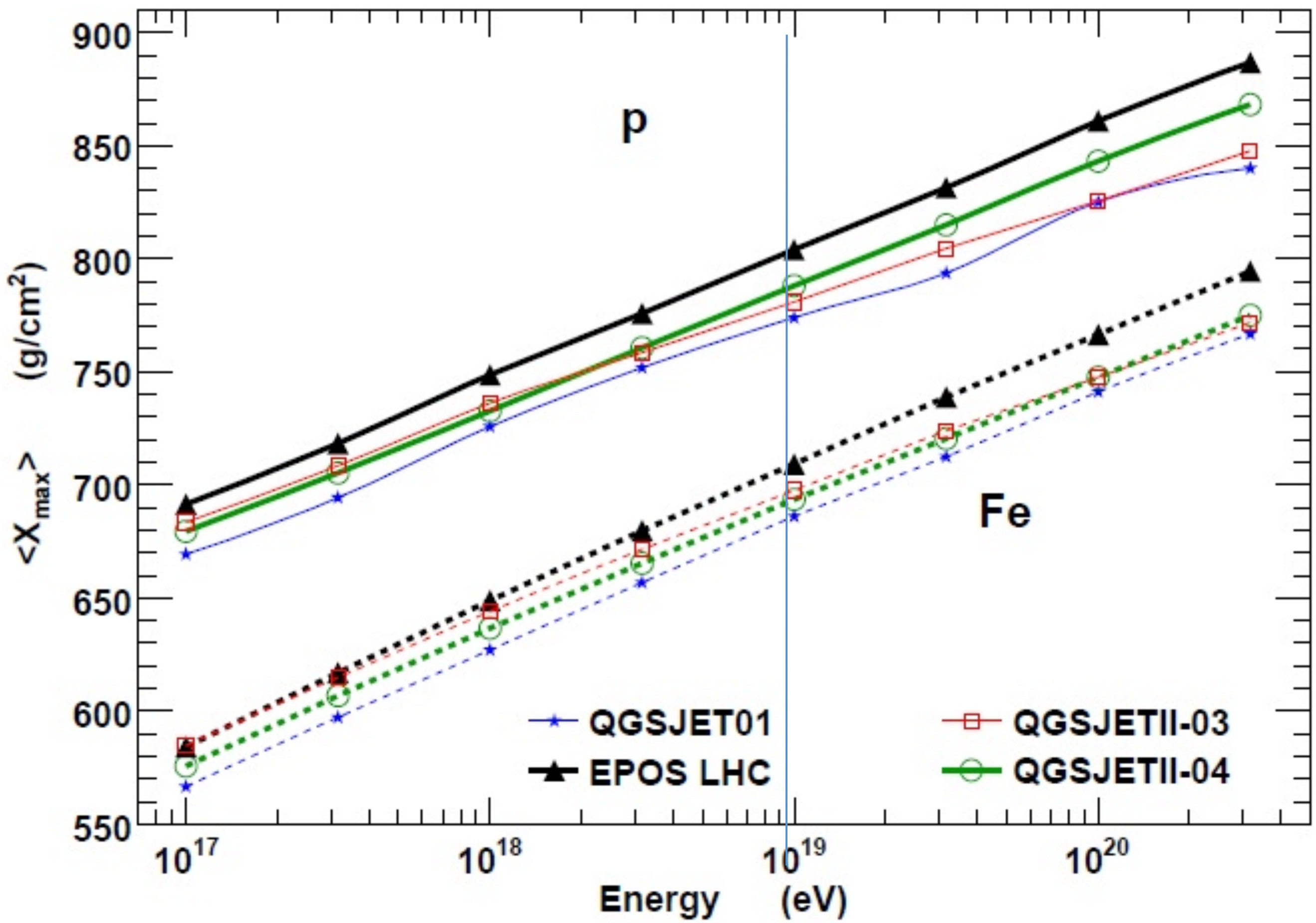
Mass Composition

How we try to infer the variation of mass with energy

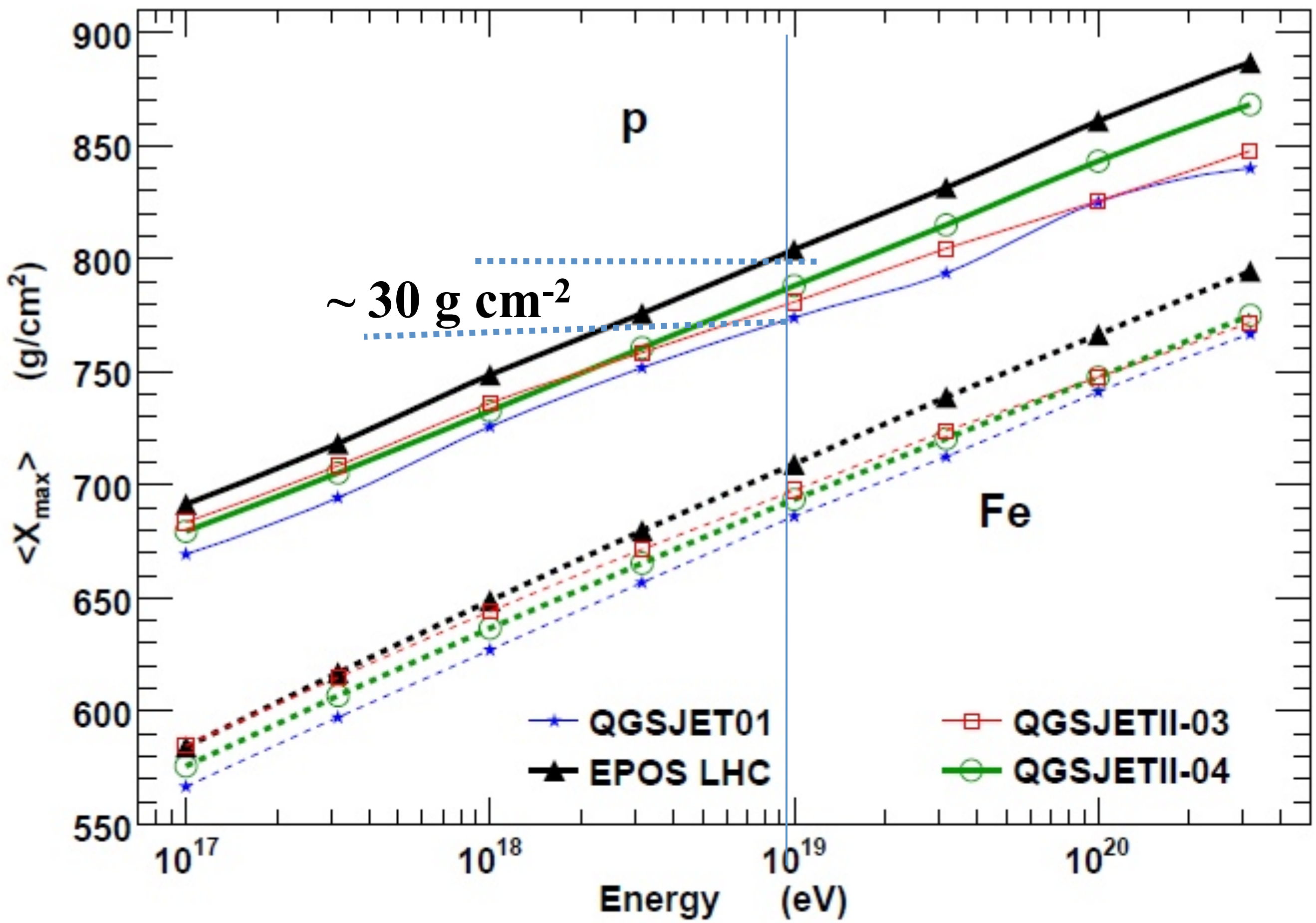


Energy per nucleon is crucial

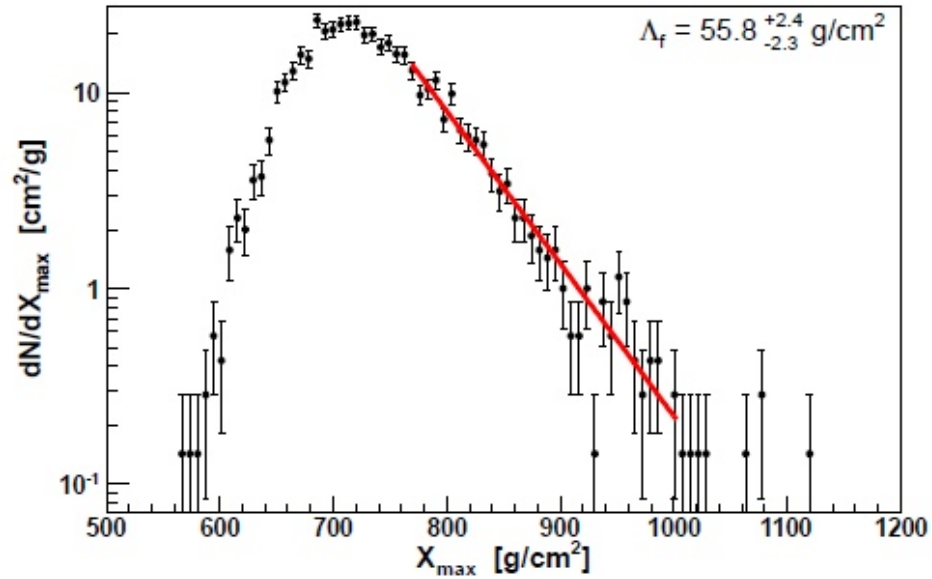
Need to assume a model



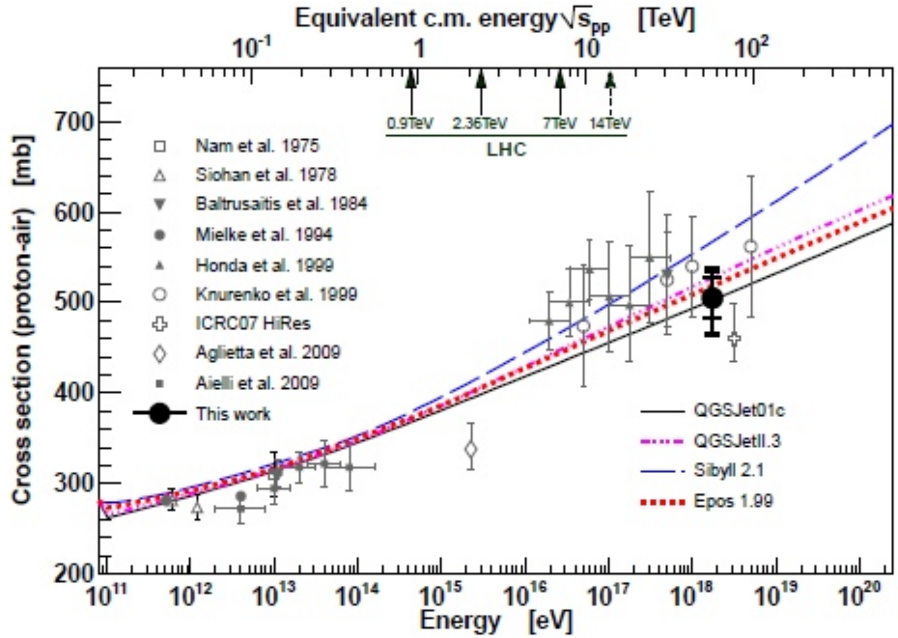
after Tanguy Pierog



after Tanguy Pierog

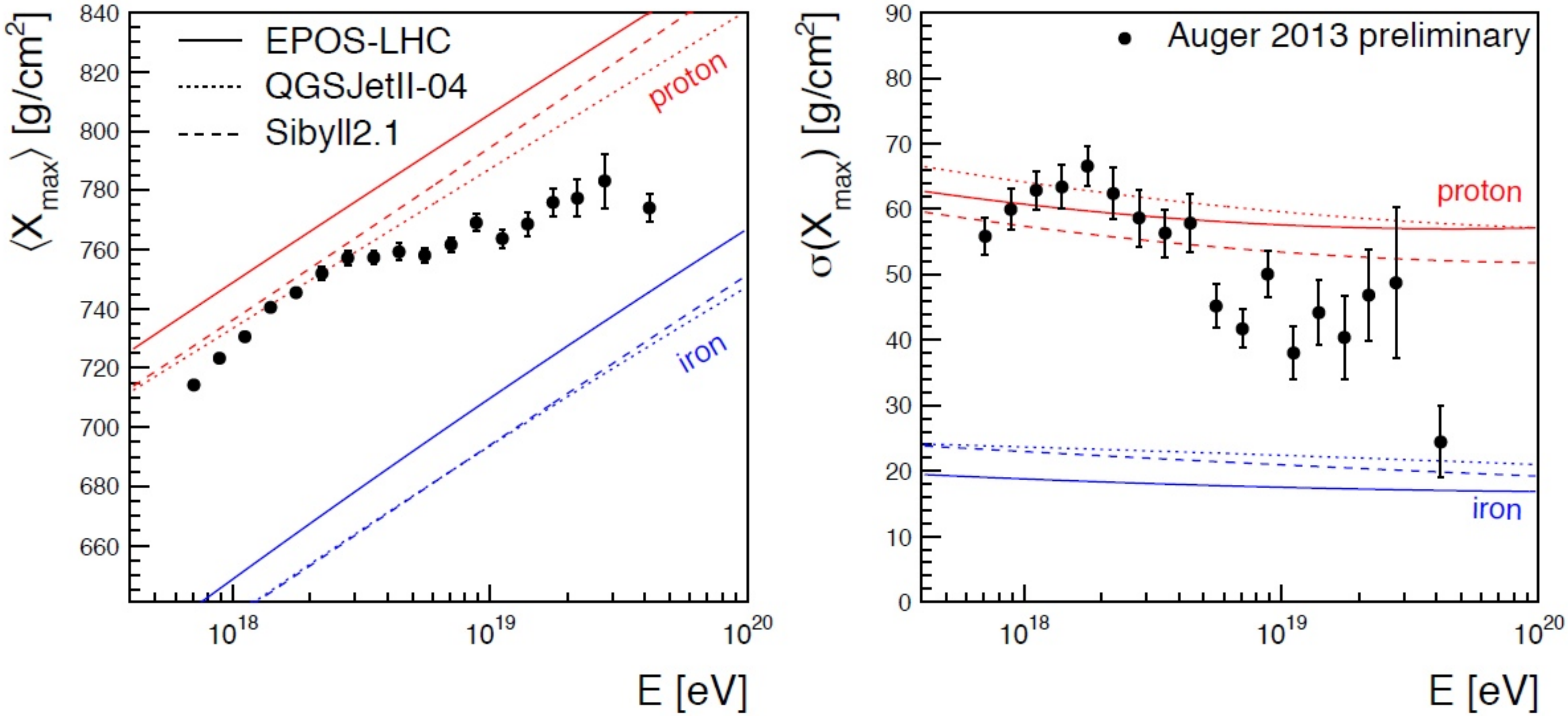


$\Lambda_f = 55.8^{+2.4}_{-2.3}$ g/cm^2
dN/dX$_{max}$ [cm^2/g]
X$_{max}$ [g/cm^2]



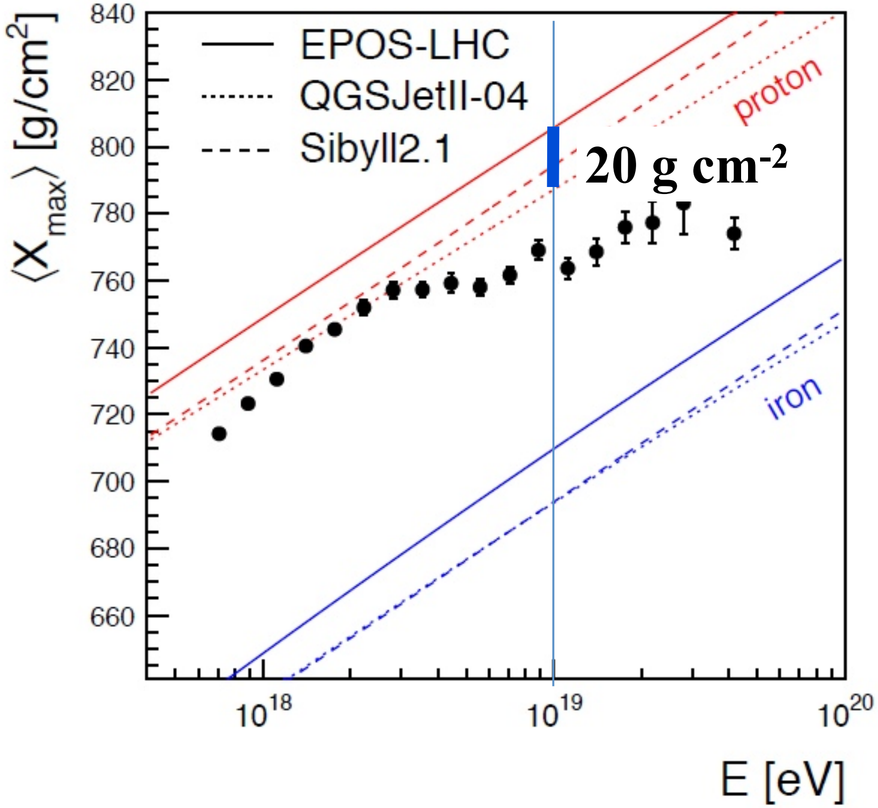
Equivalent c.m. energy $\sqrt{s}_{pp}$ [TeV]
0.9TeV
2.36TeV
7TeV
14TeV
LHC
Nam et al. 1975
Siohan et al. 1978
Baltrusaitis et al. 1984
Mielke et al. 1994
Honda et al. 1999
Knurenko et al. 1999
ICRC07 HiRes
Aglietta et al. 2009
Aielli et al. 2009
This work
QGSJet01c
QGSJetII.3
Sibyll 2.1
Epos 1.99
Cross section (proton-air) [mb]
Energy [eV]

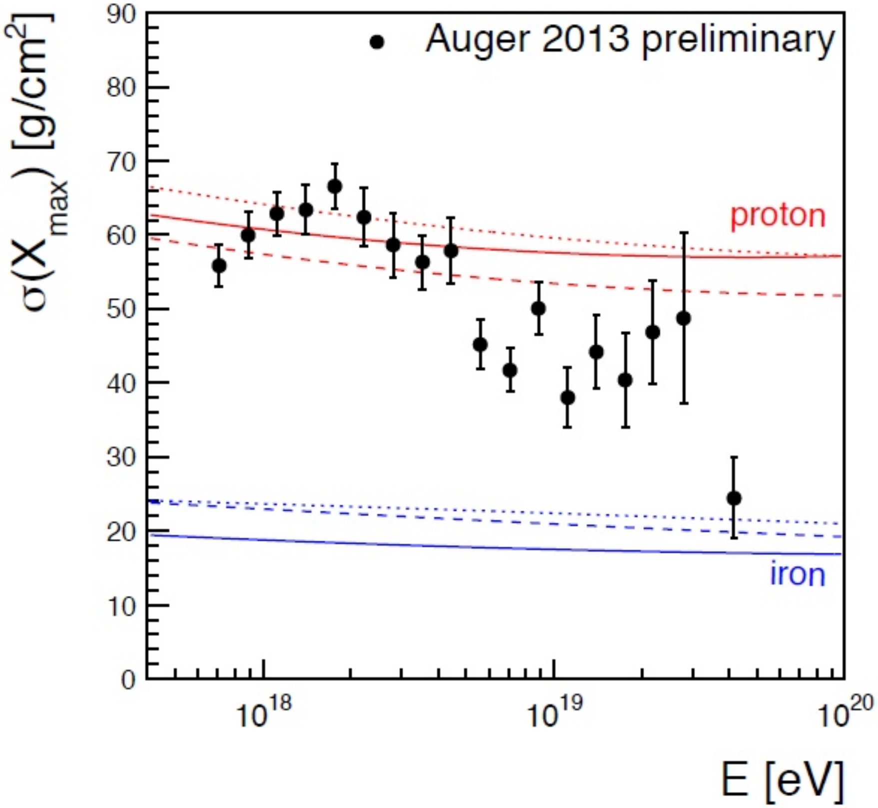
(ICRC 2013)



Change from a mixed/light composition to a heavier one, Sigma relatively small
(RMS of 50% p and 50% Fe would be higher than proton-only fluctuations)

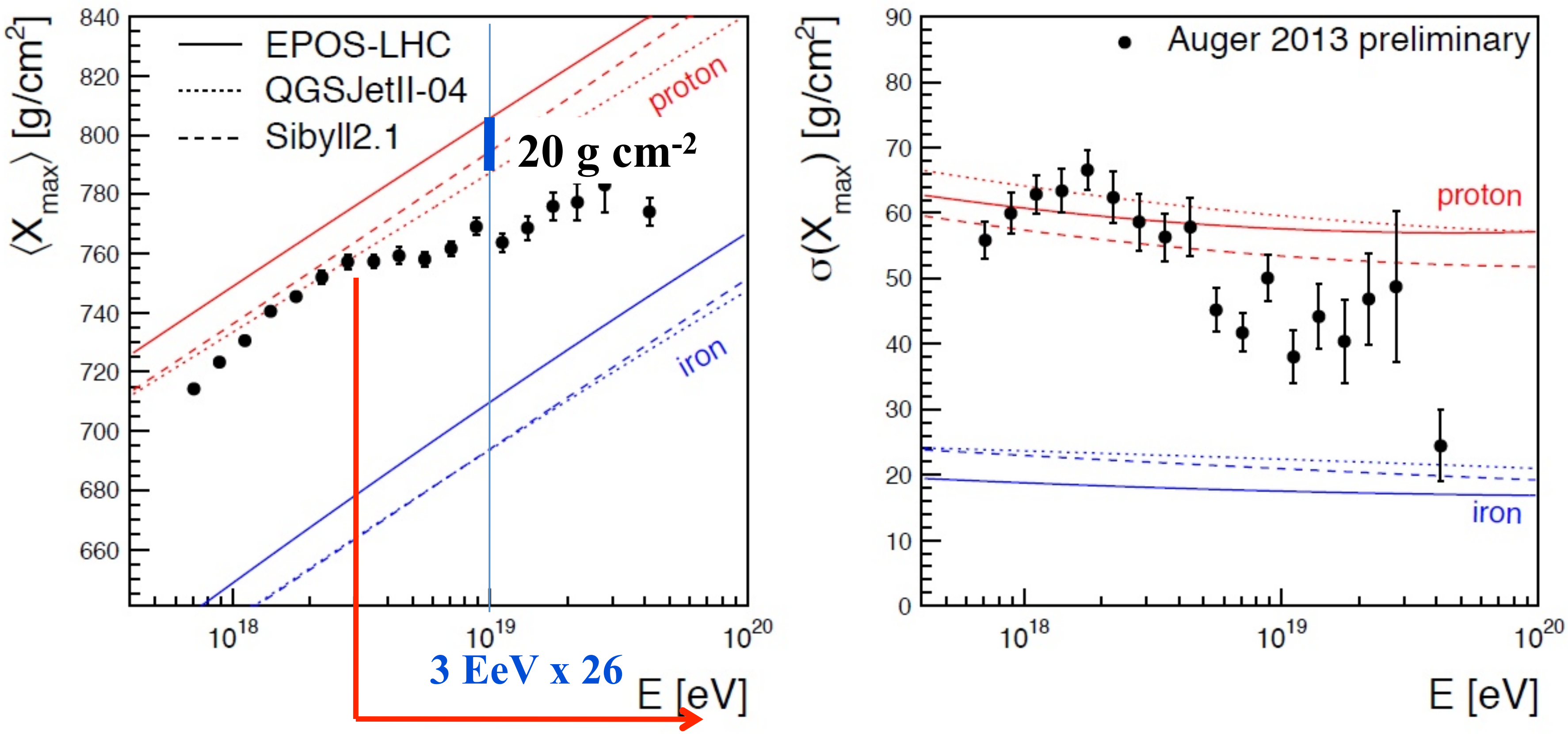
(ICRC 2013)





Change from a mixed/light composition to a heavier one, Sigma relatively small
(RMS of 50% p and 50% Fe would be higher than proton-only fluctuations)

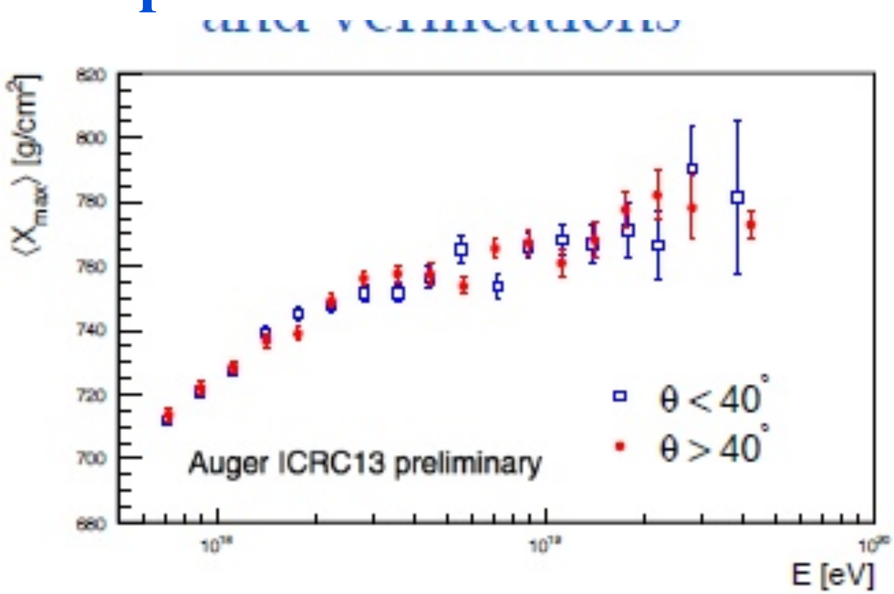
(ICRC 2013)



Change from a mixed/light composition to a heavier one, Sigma relatively small

(RMS of 50% p and 50% Fe would be higher than proton-only fluctuations)

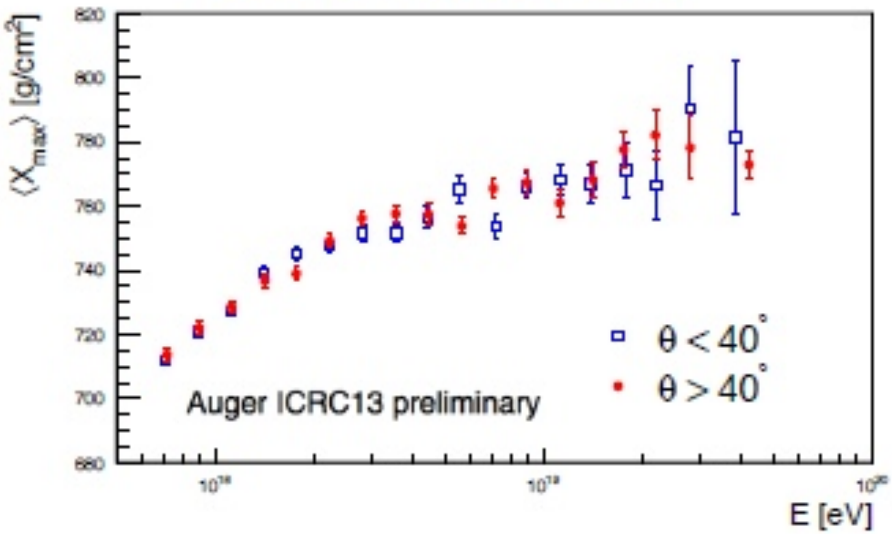
Extensive Cross-checks and Verifications
Zenith and declination dependencies

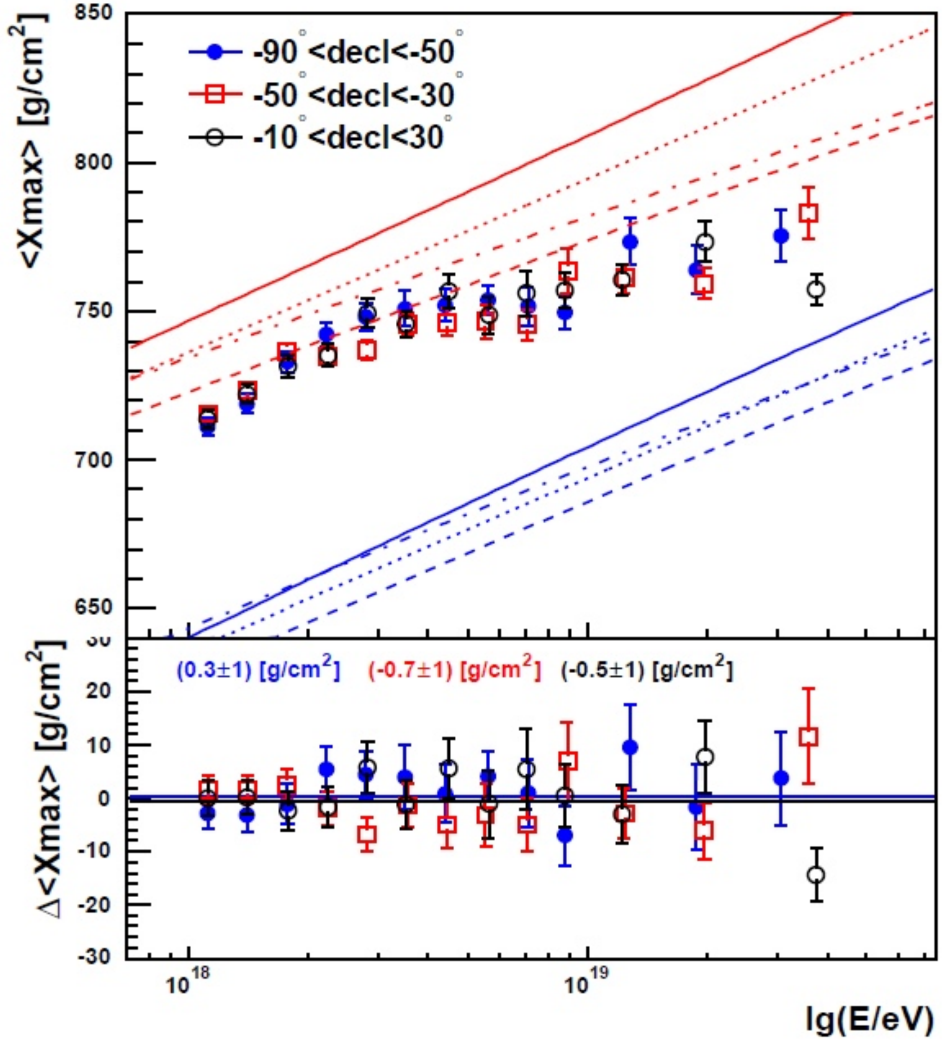


For detailed discussion of method see paper by de Souza at Rio ICRC

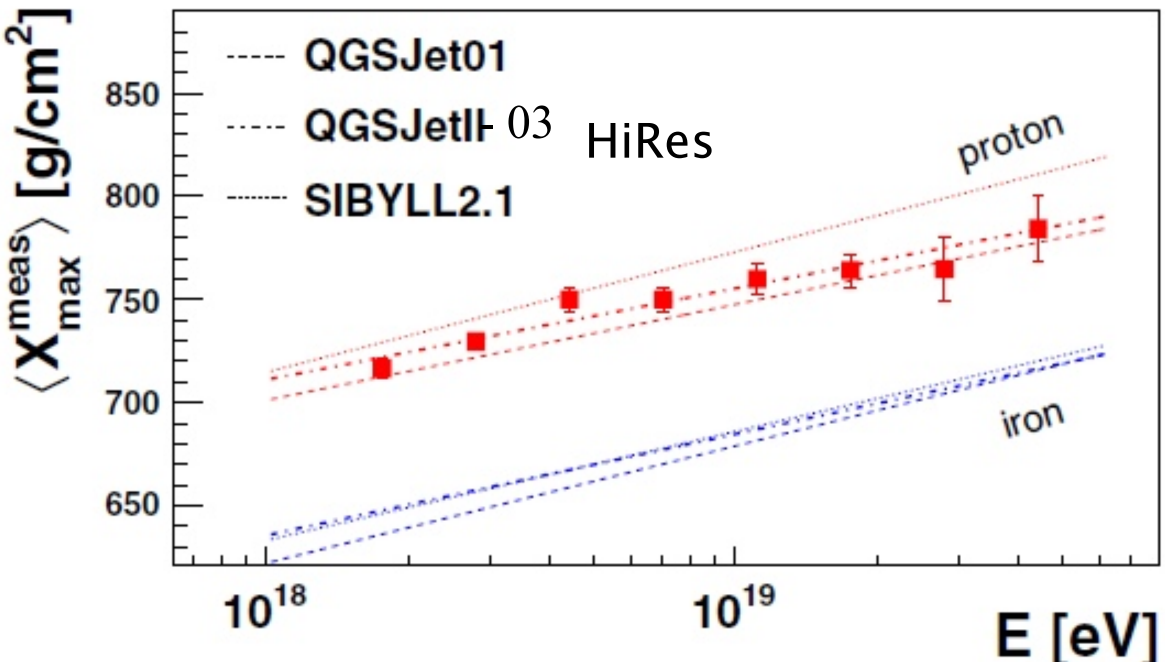
Extensive Cross-checks and Verifications

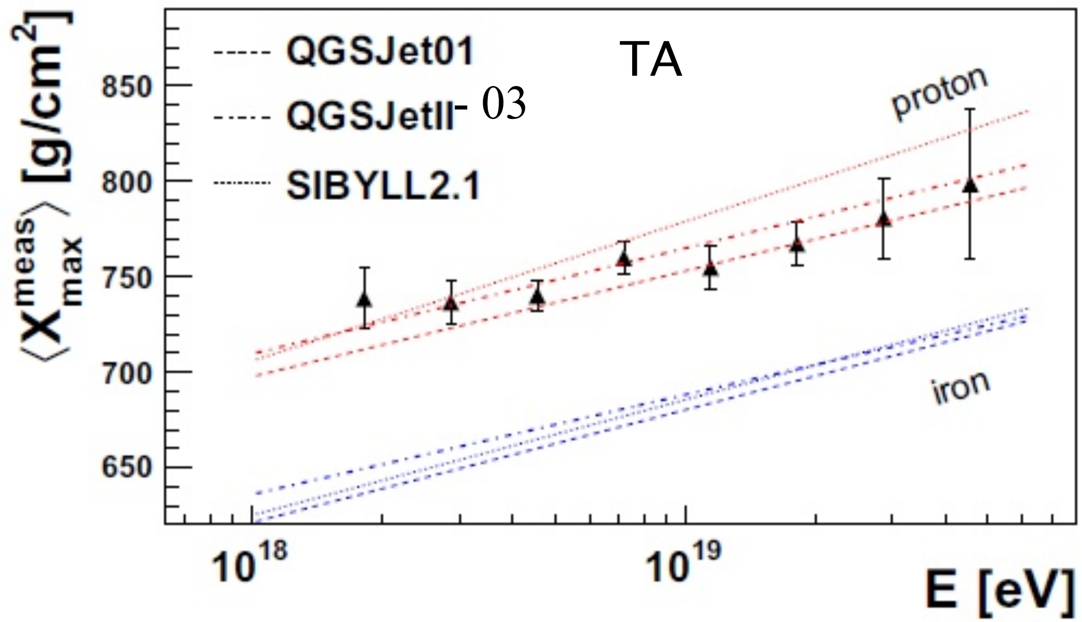
Zenith and declination dependencies



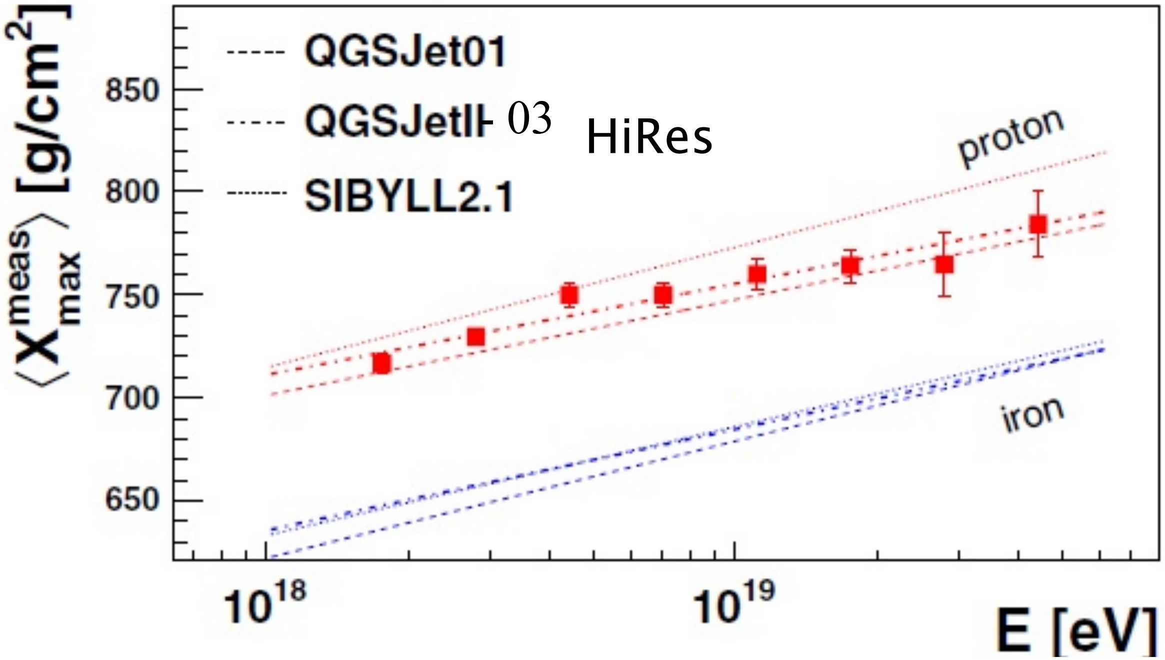


For detailed discussion of method see paper by de Souza at Rio ICRC

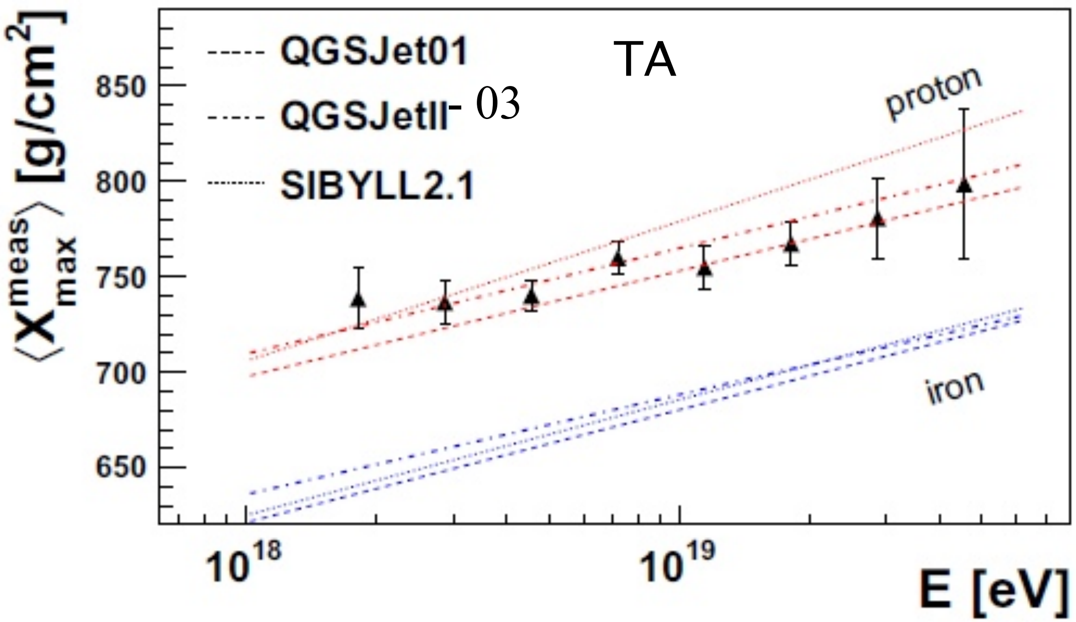

QGSJet01
QGSJetII- 03
SIBYLL2.1
HiRes
proton
iron
$\langle X_{max}^{meas} \rangle$ [g/cm^2]
850
800
750
700
650
10^{18}
10^{19}
E [eV]


QGSJet01
QGSJetII- 03
SIBYLL2.1
TA
proton
iron
$\langle X_{max}^{meas} \rangle$ [g/cm^2]
850
800
750
700
650
10^{18}
10^{19}
E [eV]

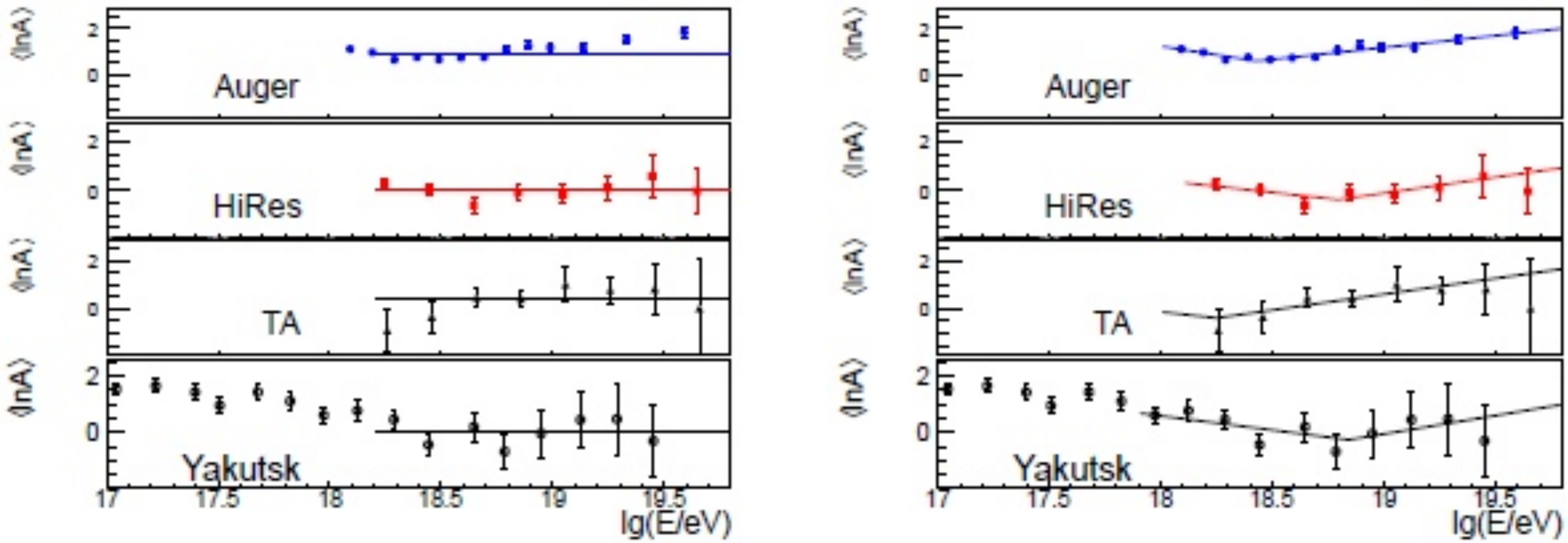
.3



Elongation Rate Compatibility?



.3



(a) fit to a horizontal line (constant composition). (b) fit to a broken line (changing composition).

	Auger	HiRes	TA	Yakutsk
First Slope	-1.0 ± 0.3	-1.0	-1.0	-1.0
Second Slope	1.3 ± 0.1	1.3	1.3	1.3
$\lg(E_{break}/eV)$	18.43 ± 0.04	18.65 ± 0.07	18.26 +0.14/-∞	18.62 ± 0.14
$\langle\ln(A)\rangle_{break}$	0.75 ± 0.05	0.26 ± 0.10	0.05 +0.22/-∞	0.08 ± 0.15
χ^2/ndf	7.4/9	1.23/6	3.37/6	4.22/8

Auger/HiRes/TA/Yakutsk Joint Working Group: CERN 2012, arXiv1306.4430

Cosmic Ray Energy Spectrum: Does the spectrum terminate?

Greisen-Zatsepin-Kuz'min – GZK effect (1966)

$$\gamma_{2.7\,K} + p \rightarrow \Delta^+ \rightarrow n + \pi^+ \text{ or } p + \pi^o$$

and

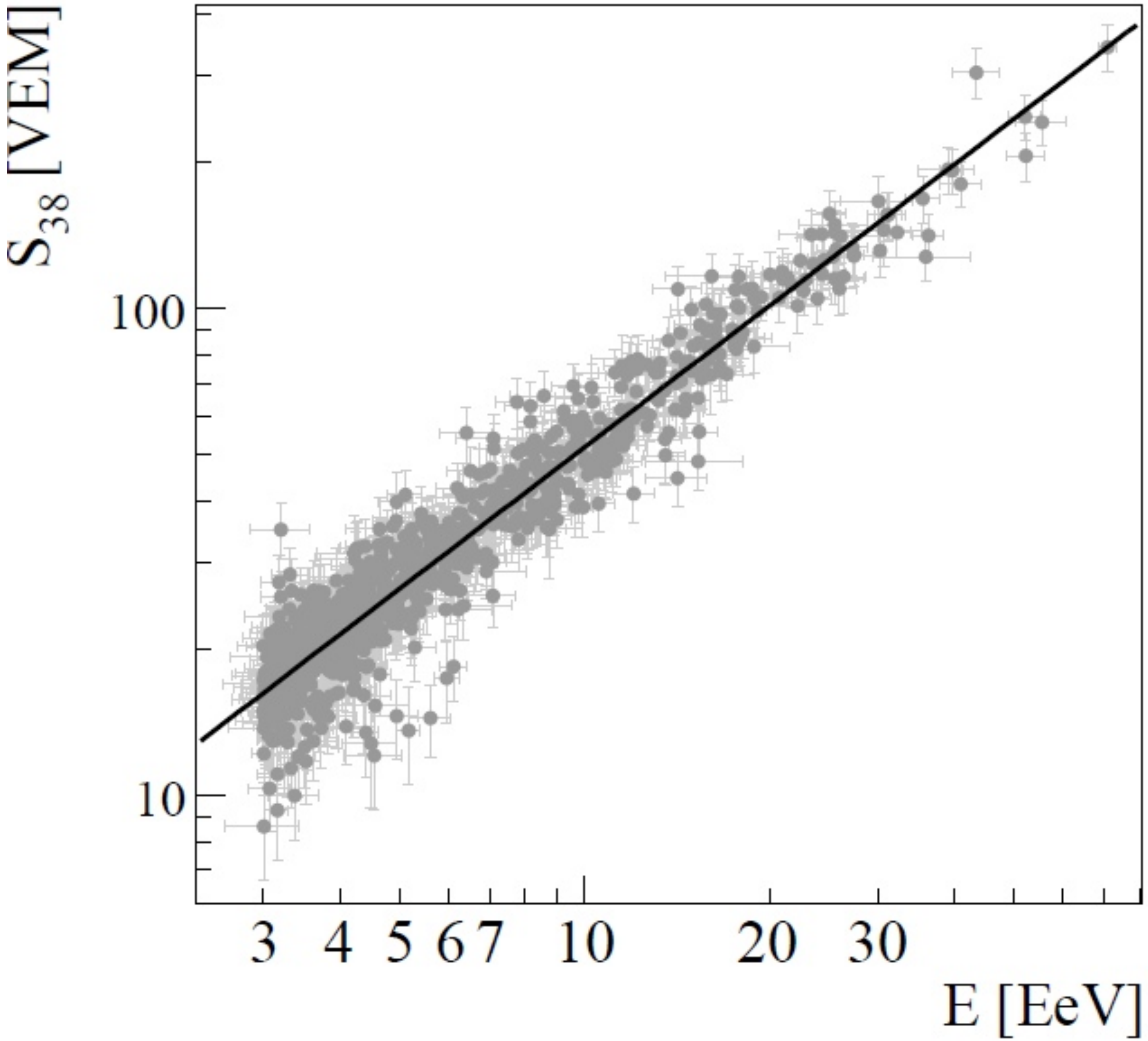
$$\gamma_{IR/2.7\,K} + A \rightarrow (A - 1) + n$$

Sources must lie within about 100 Mpc

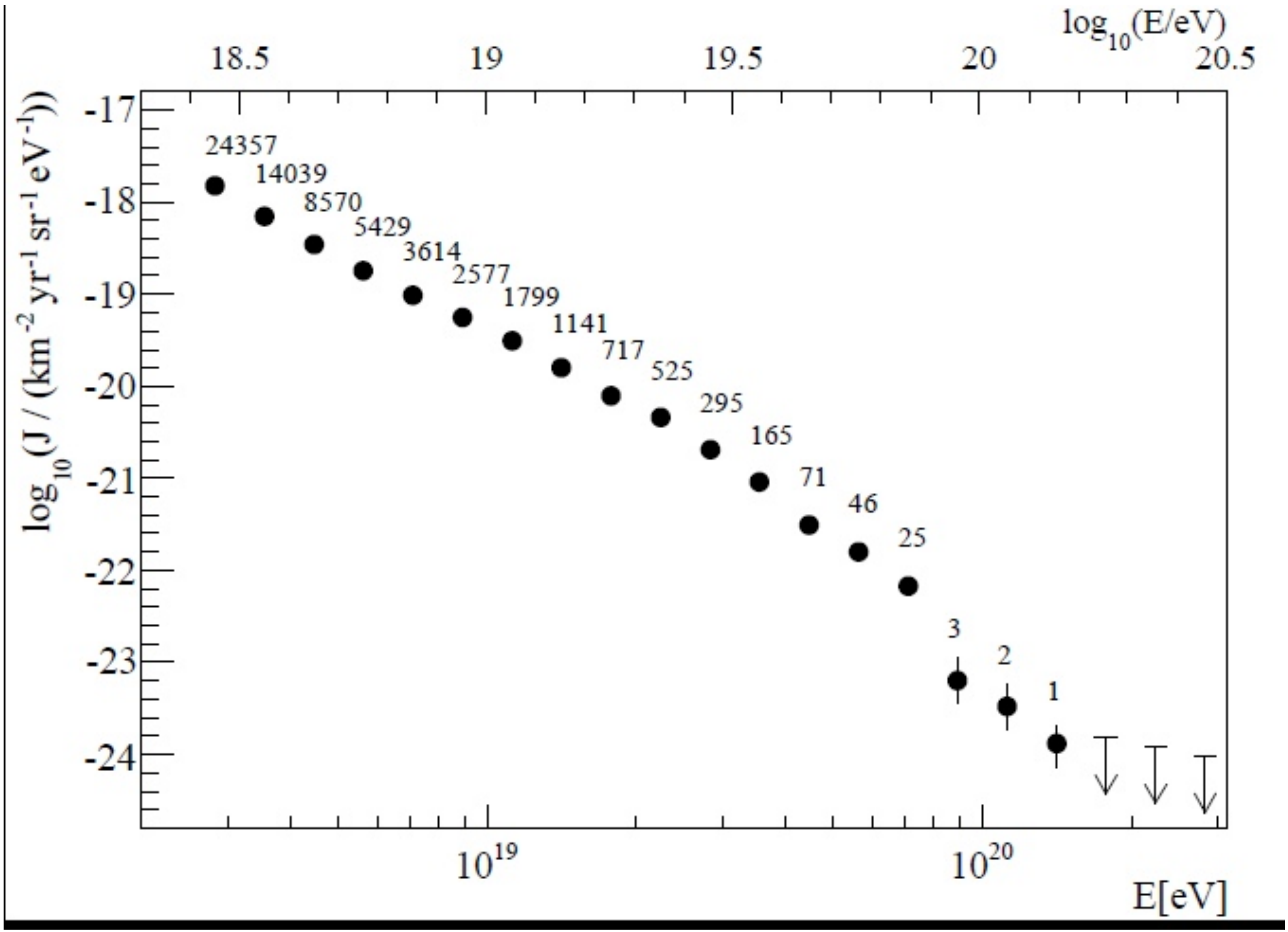
Approach introduced by Auger Collaboration:-

Calibrate the surface detector measurements with a sample of hybrid events

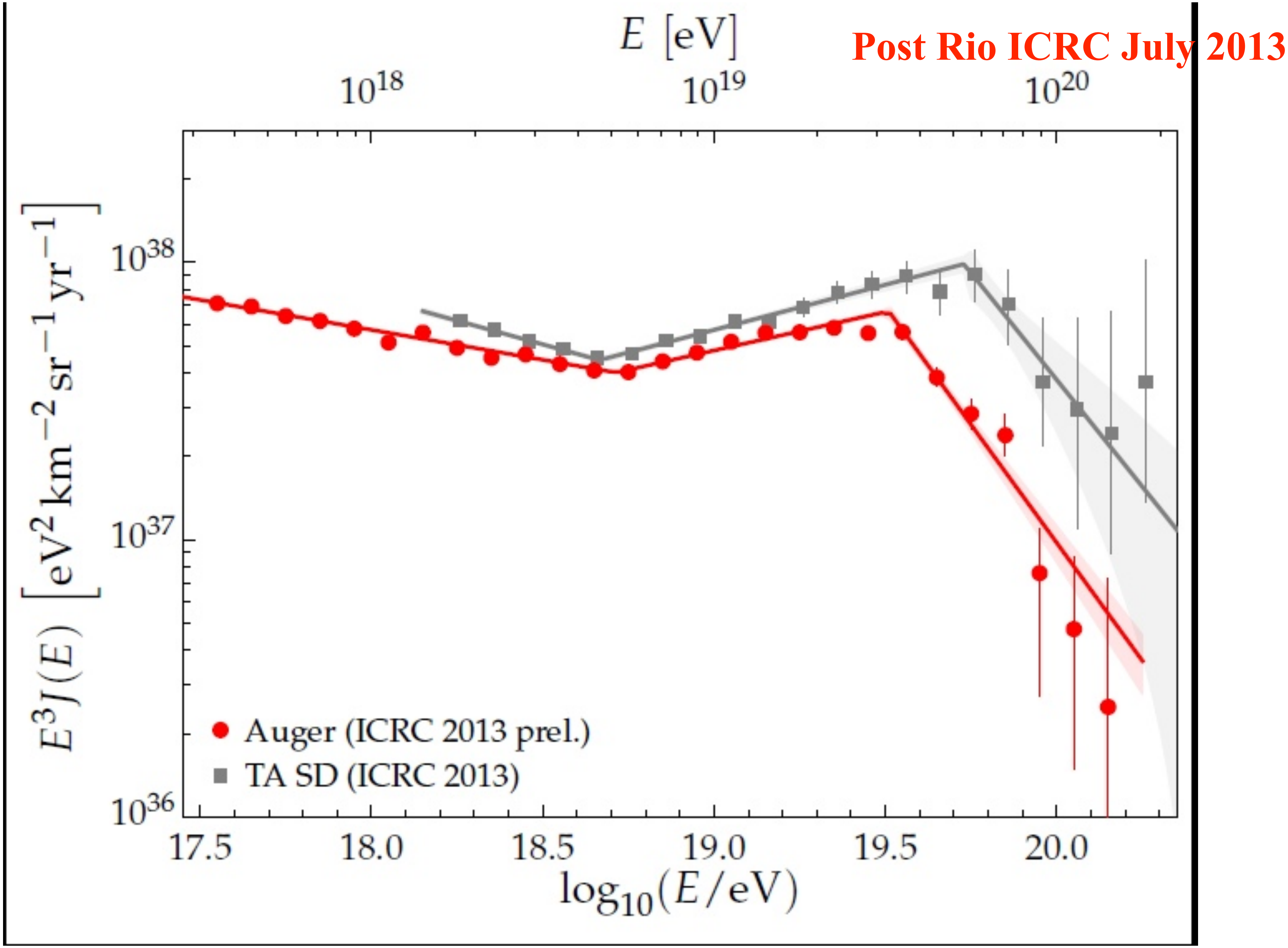
Many surface events at various angles combined using a very well-established method – the constant intensity approach



S38 [VEM]
100
10
3
4
5
6
7
10
20
30
E [EeV]

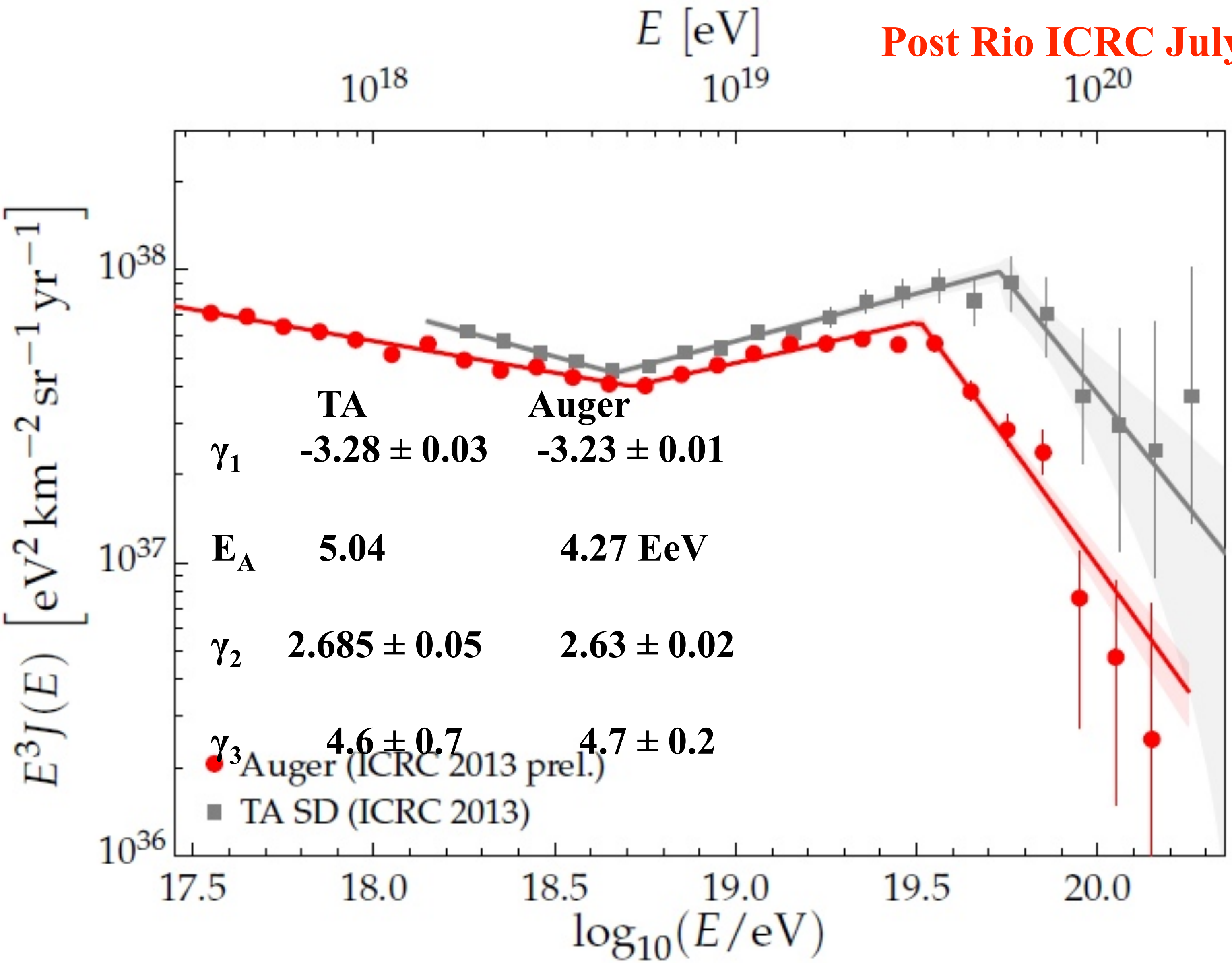


log10(E/eV)
18.5
19
19.5
20
20.5
-17
-18
-19
-20
-21
-22
-23
-24
log10(J / (km-2 yr-1 sr-1 eV-1))
24357
14039
8570
5429
3614
2577
1799
1141
717
525
295
165
71
46
25
3
2
1
10^19
10^20
E[eV]



Thanks to Alex Schulz

Post Rio ICRC July 2013



	TA	Auger
γ_1	-3.28 ± 0.03	-3.23 ± 0.01
E_A	5.04	4.27 EeV
γ_2	2.685 ± 0.05	2.63 ± 0.02
γ_3	4.6 ± 0.7	4.7 ± 0.2

Thanks to Alex Schulz

At ICRC in Rio there was some speculation that the differences might be a N-S effect.

Likely?

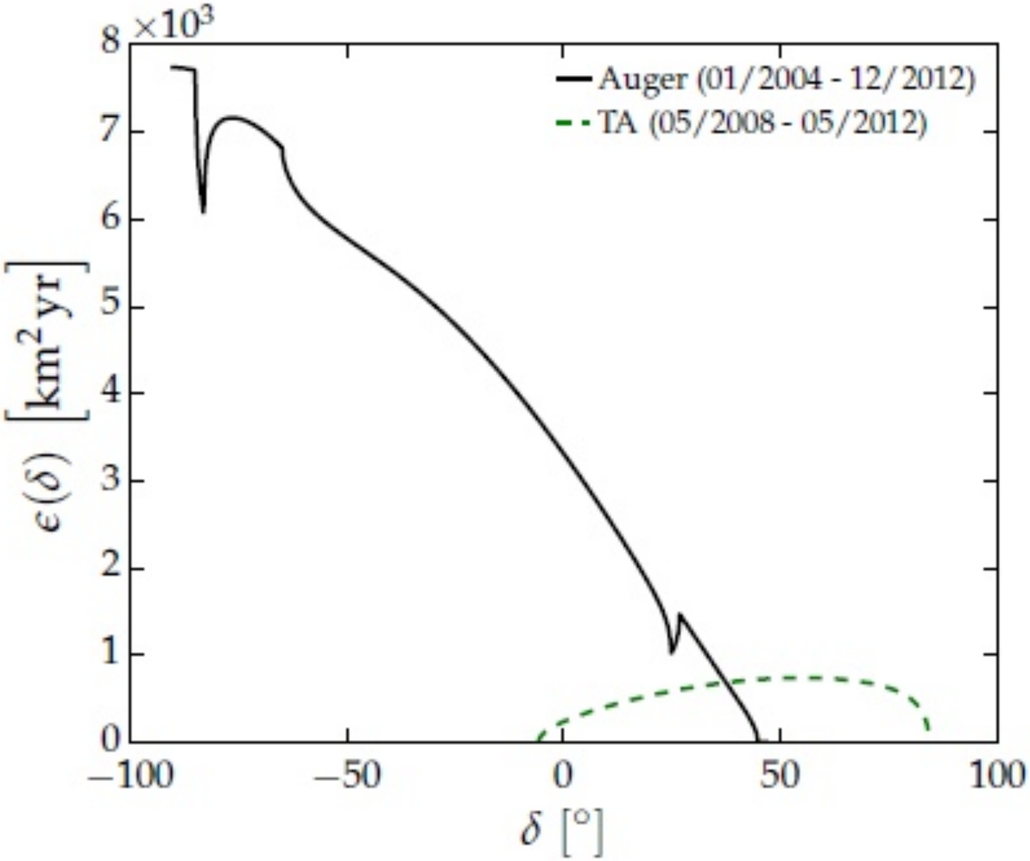
Would depend on source distribution and particular sources

BUT

Different 'invisible energy' corrections used
Different assumptions about mass composition
Different fluorescent yields used

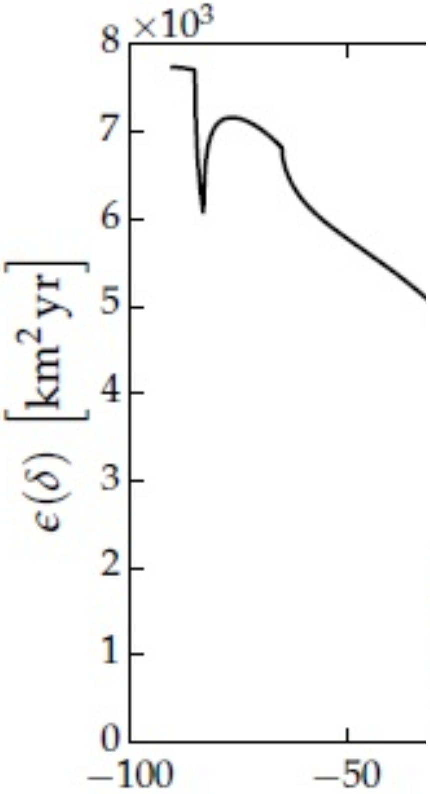
Key test would be to look at overlap region of sky - statistics

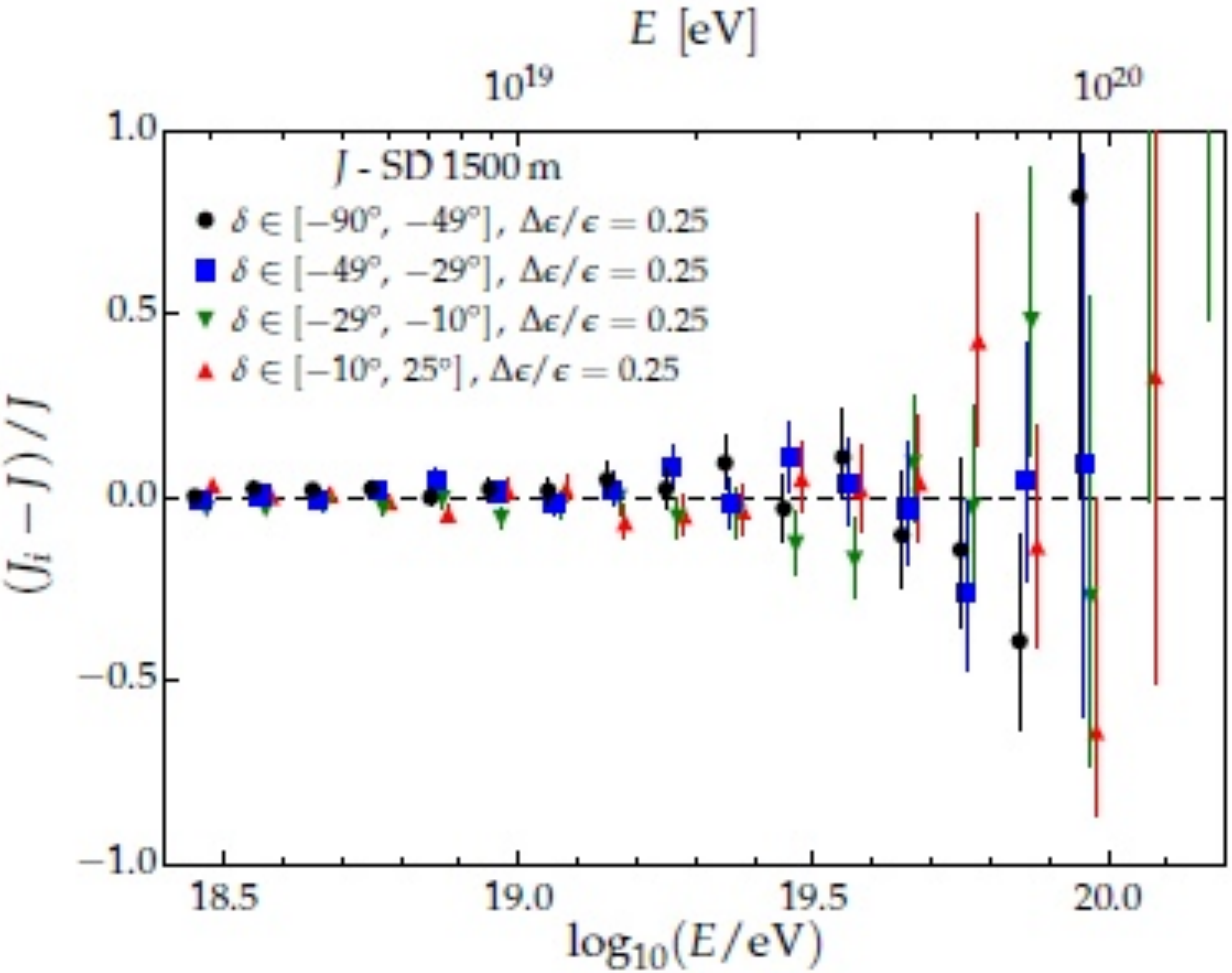
With inclined showers Auger Observatory sees up to declination +36^0



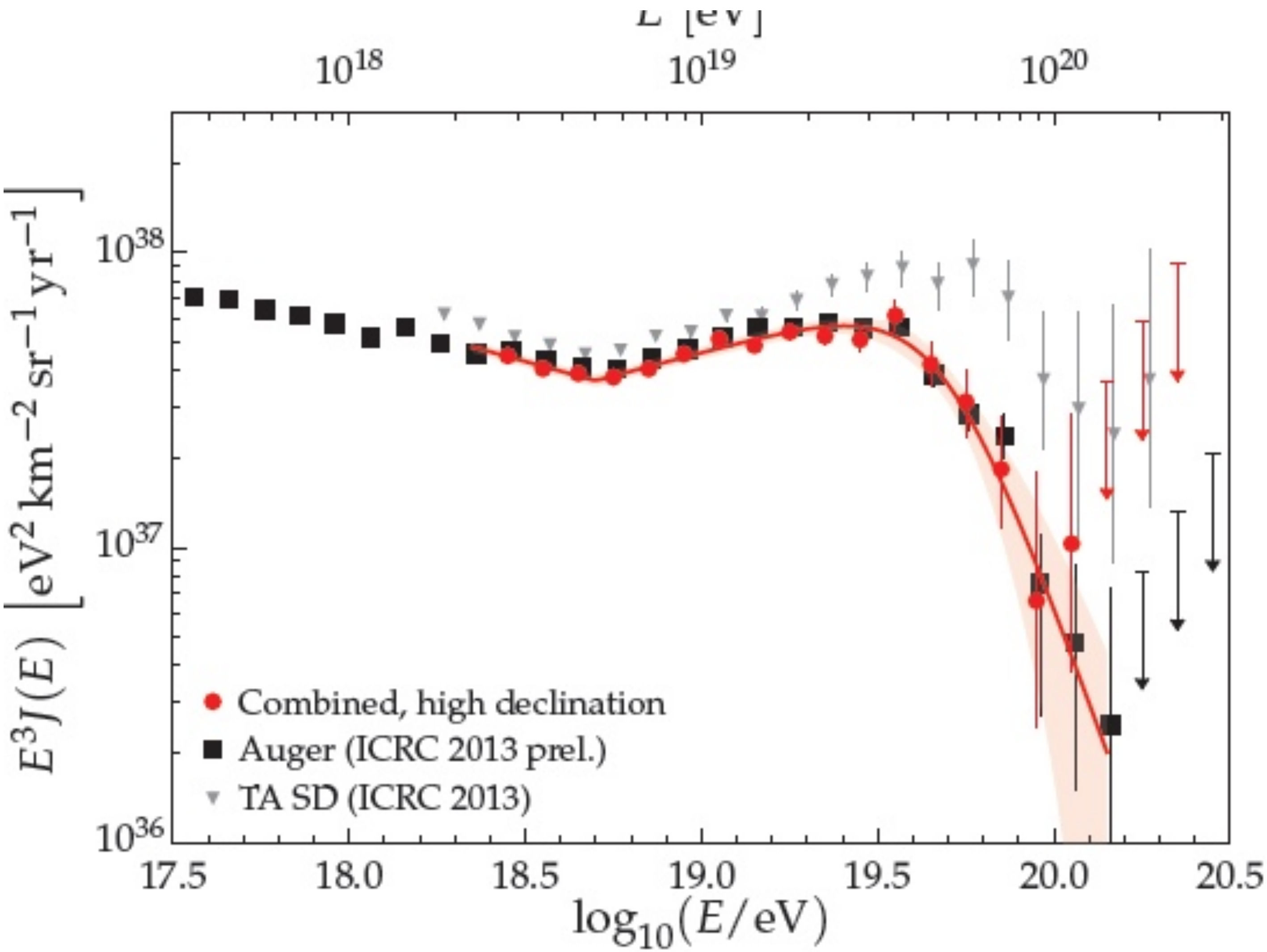
Wednesday, October 30, 13

Vertical - 1500m





Spectrum in a band of $\delta \in [0, 45°]$

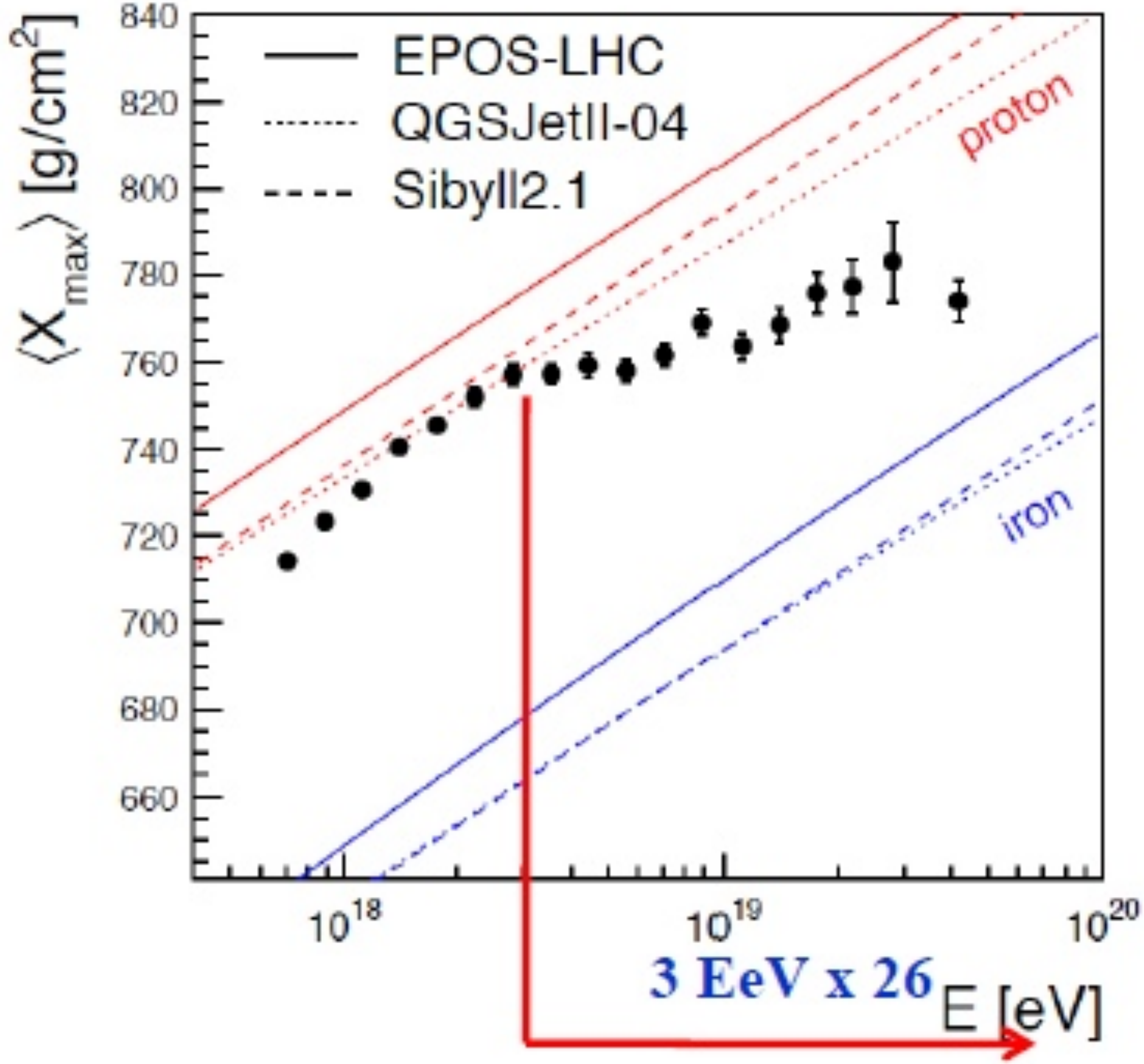


Origin Models

1. Cen A a major source?
   - might lead to N/S differences (role of M87?)
   - but only at high declinations

2. Galactic Source (Dermer and Holmes, 2005 and Calvez et al 2010)
   GRB within our galaxy 10^5
   needs extensive magnetic field

3. 'Disappointing model' of Aloisio, Beresinzky and Gazizov (2010)



⟨X_max⟩ [g/cm²]
840
820
800
780
760
740
720
700
680
660
EPOS-LHC
QGSJetII-04
Sibyll2.1
proton
iron
10^18
10^19
10^20
E [eV]
3 EeV x 26

Final Remarks:-

Hadronic models presently available do not fit data

Mass composition appears to become heavier as energy increases
No evidence of dependence on Declination for $\delta < 30°$

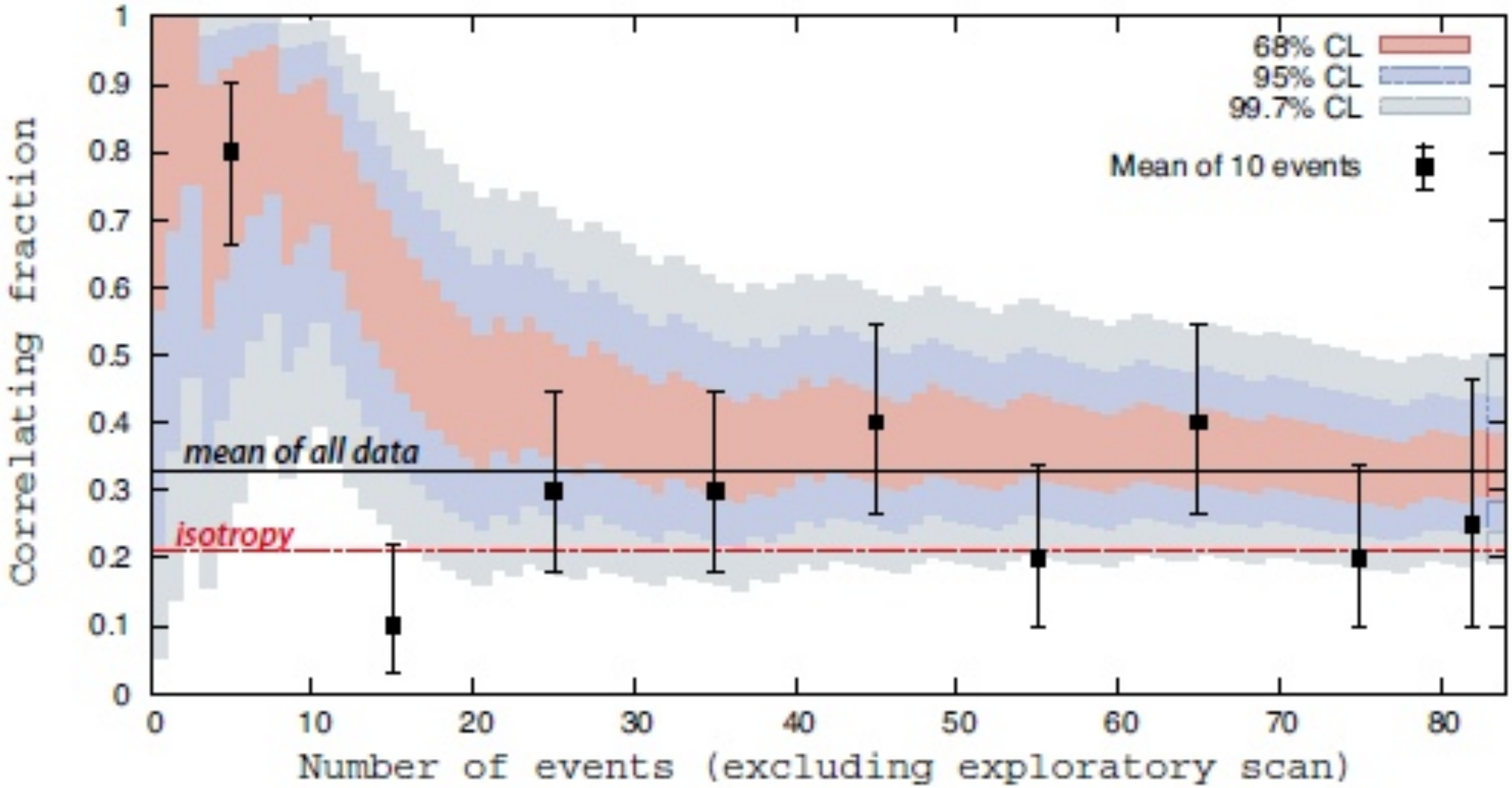
Spectrum shows evidence of steepening at ~ 40 EeV

Steepening at highest energies may be due to limit reached by accelerators
Sensible in context of heavy-nuclei: need to know mass better

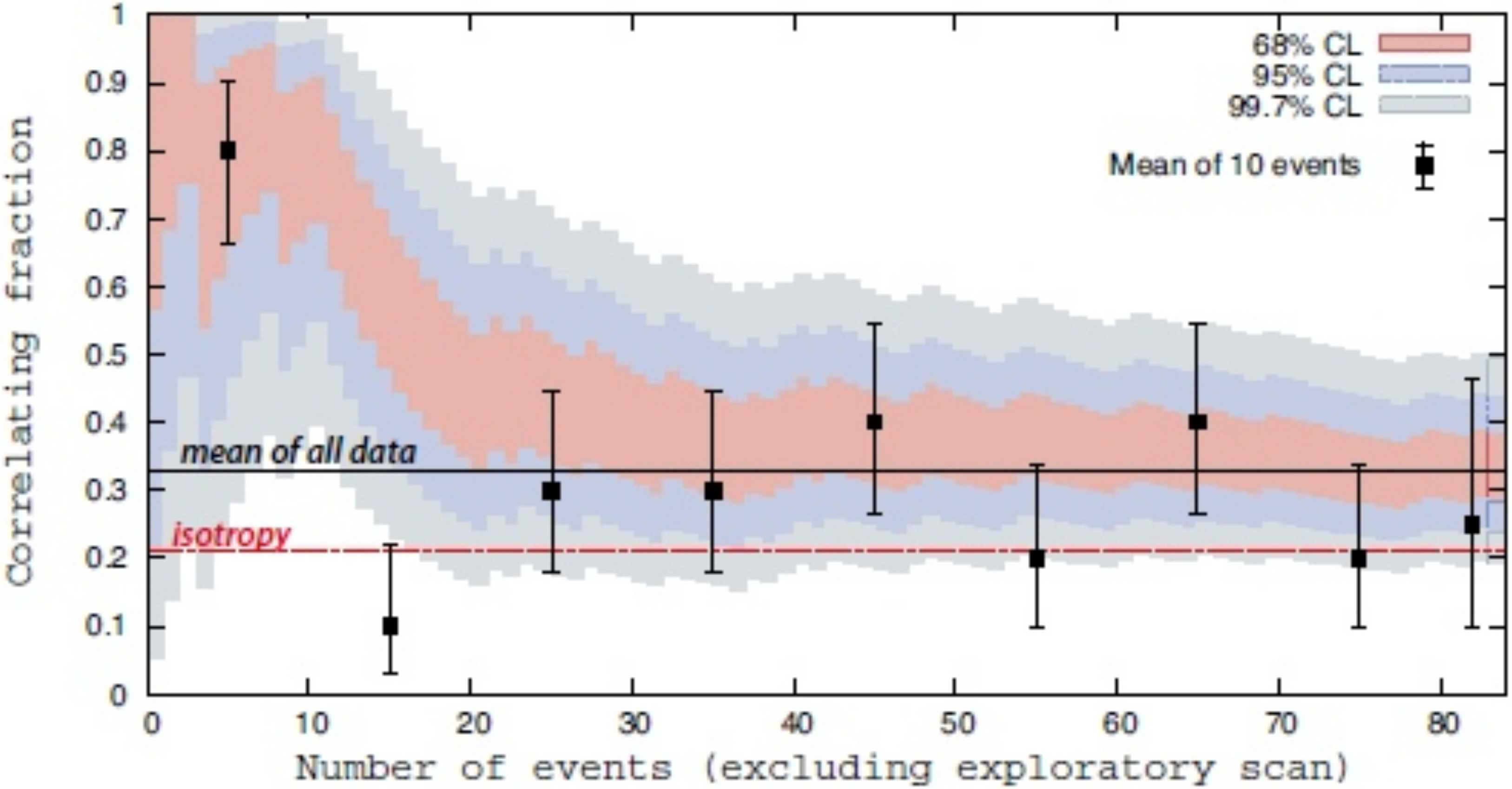
N-S differences at highest energies will be settled by JEM-EUSO (despite relatively poor energy resolution) and by OVERLAP STUDIES
but look rather improbable – unless at $\delta >\sim 40°$

Arrival Direction Distributions

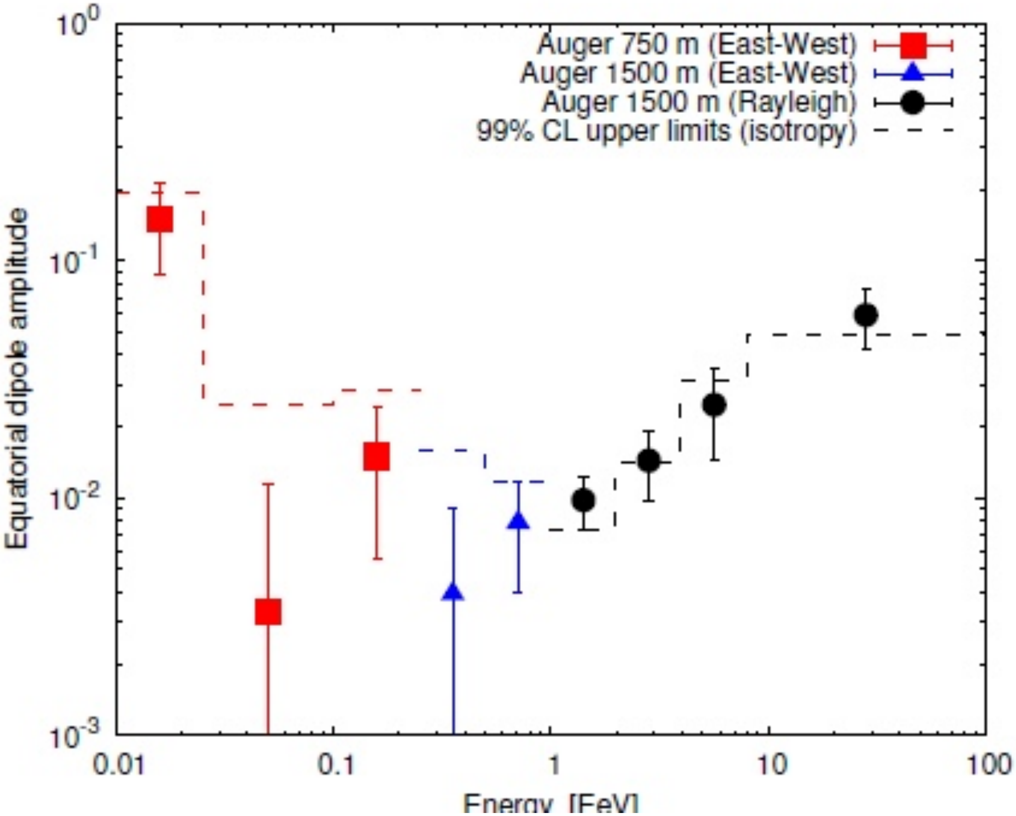
Events above 50 EeV



Events above 50 EeV

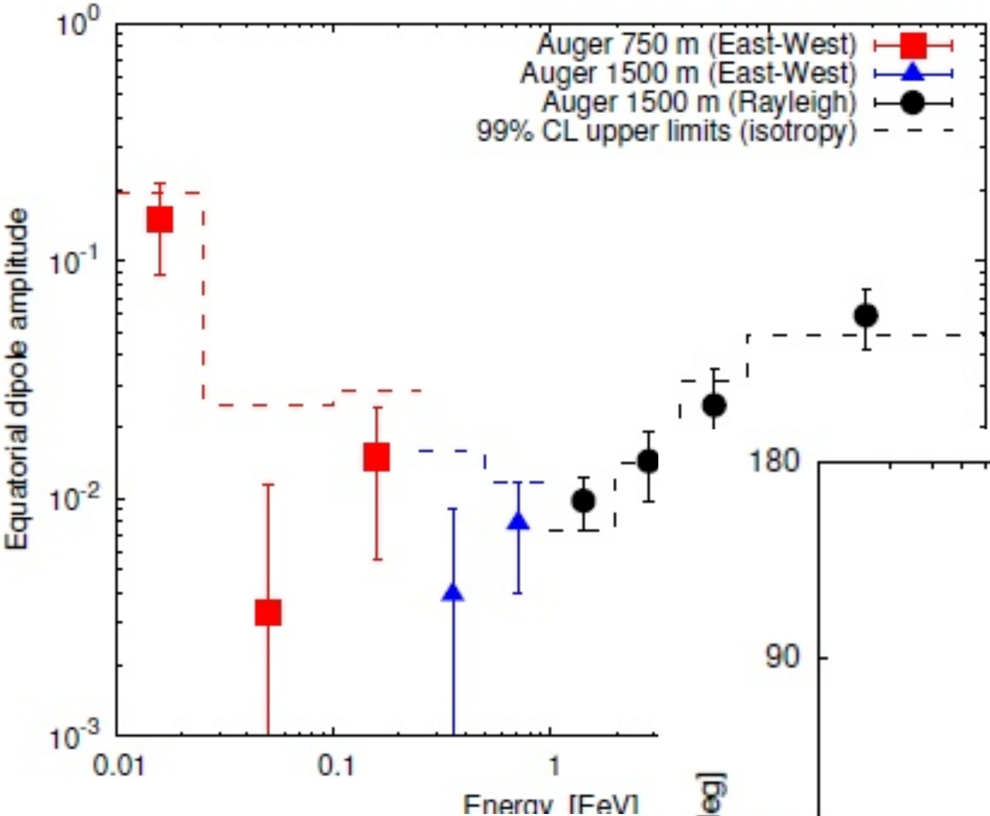


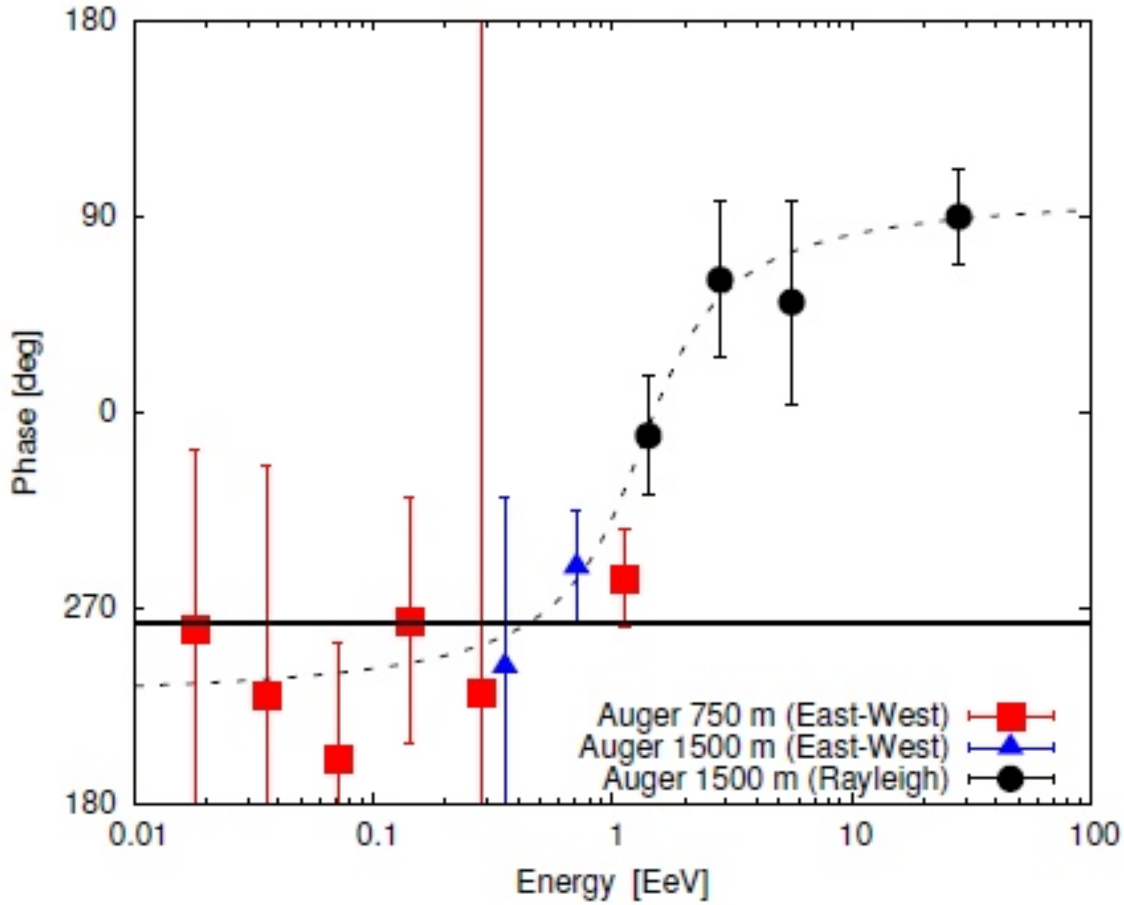
New results from TA do not contradict this effect



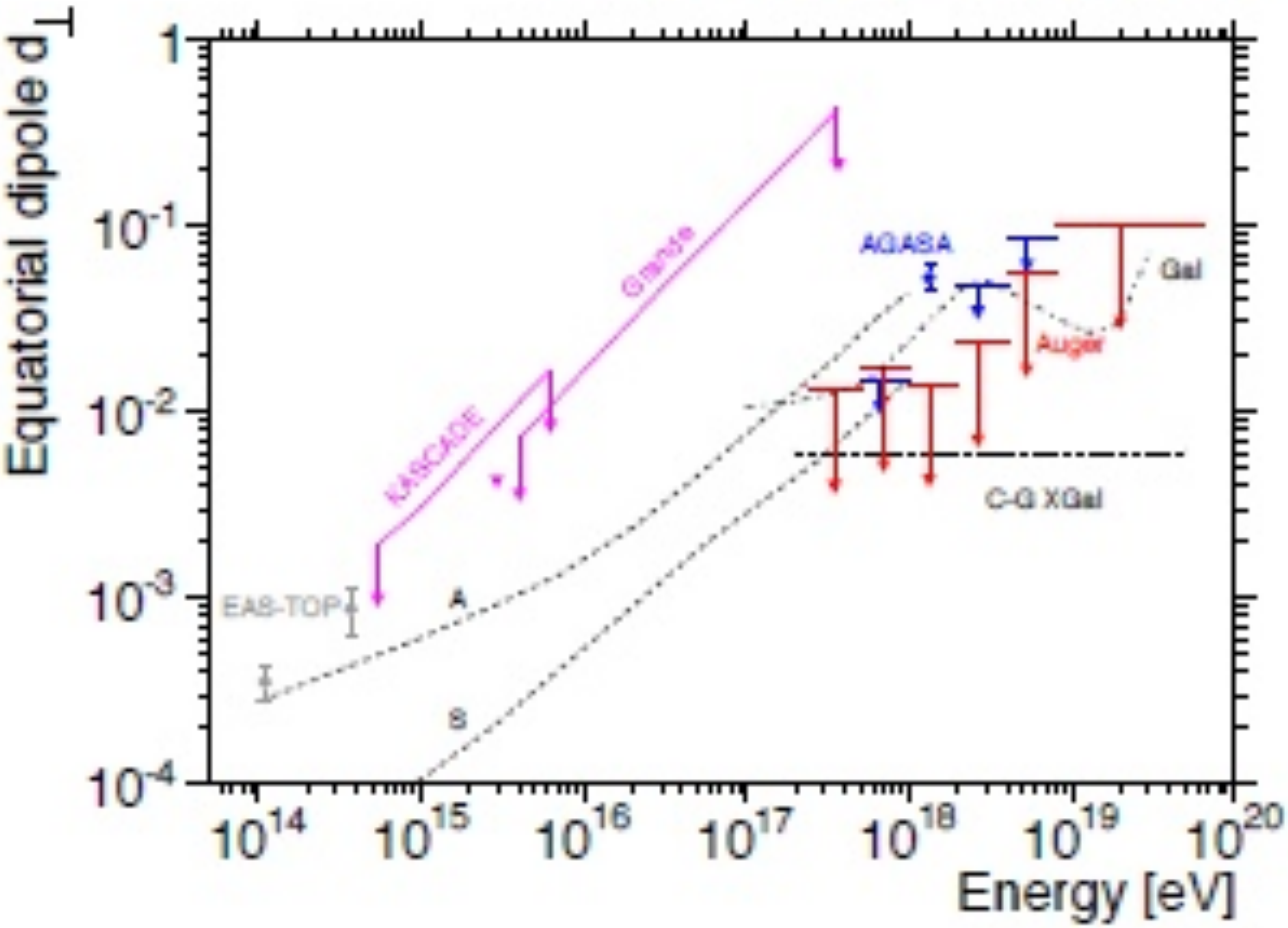
Amplitudes and Phases from Auger

Amplitudes and Phases from Auger





(Astropart. Phys. 34 (2011) 627)

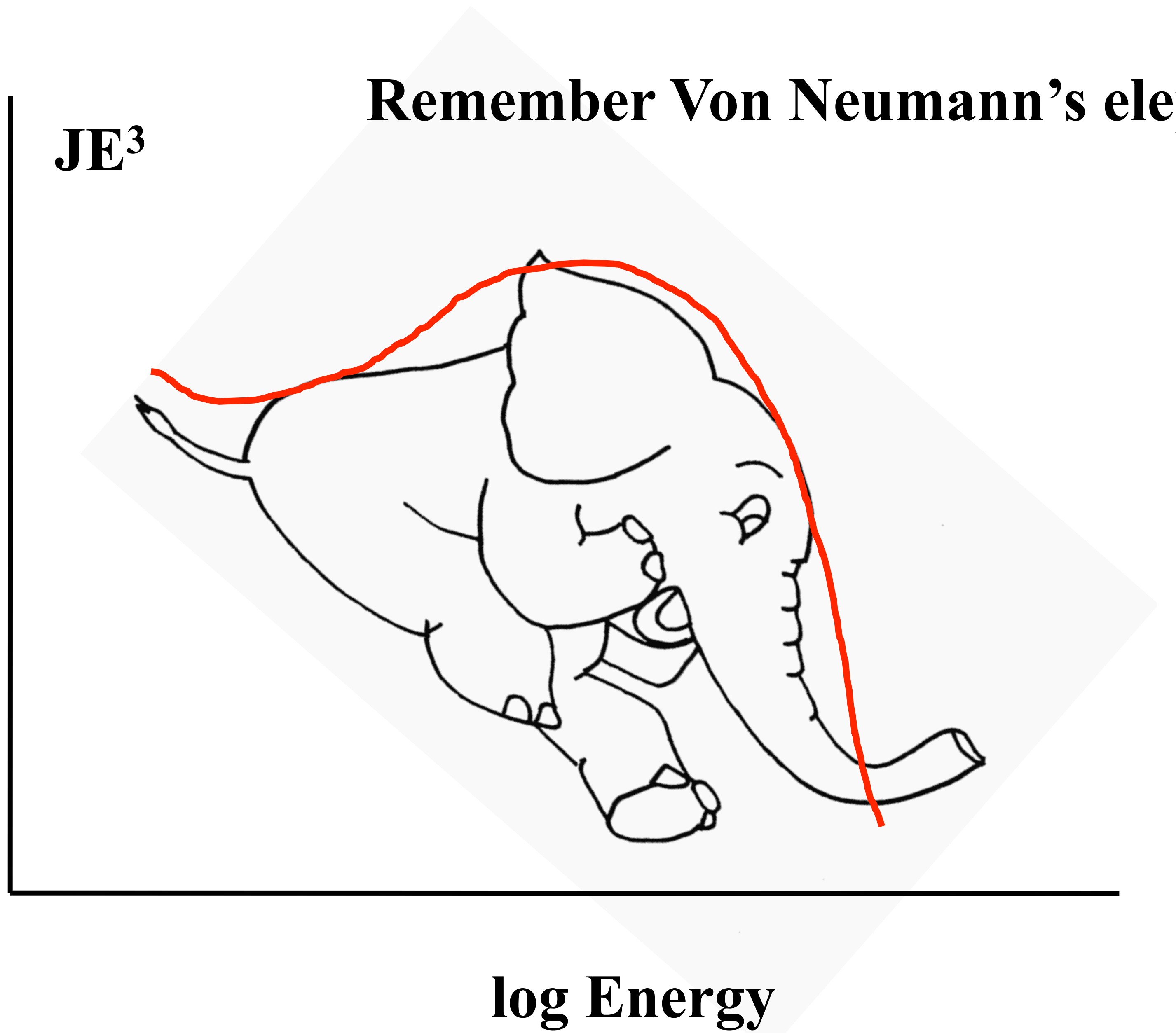


A and S:
Candia et al. 2003

Gal:
Calvez et al. 20110

C-G Xgal:
Kachelreiss and Serpico 2006

Remember Von Neumann's elephant



Hadronic Interactions

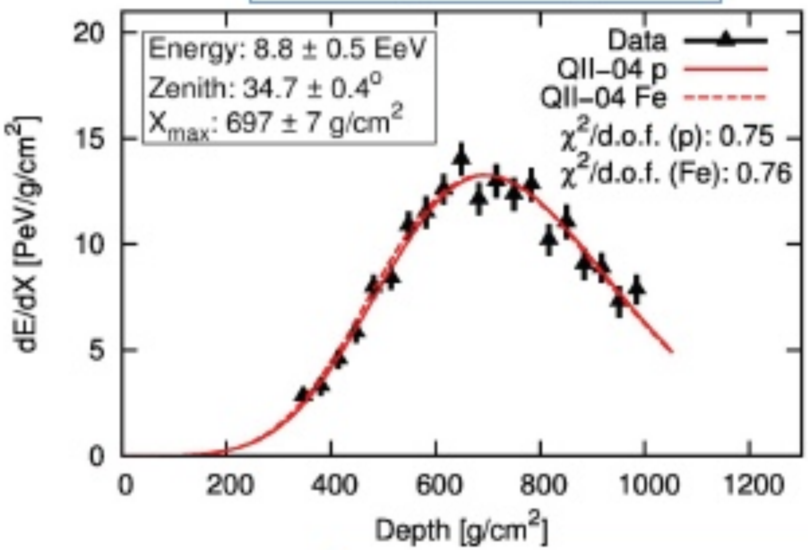
ONE example of a problem with extrapolation of particle physics

ONE example of a problem with extrapolation of particle physics

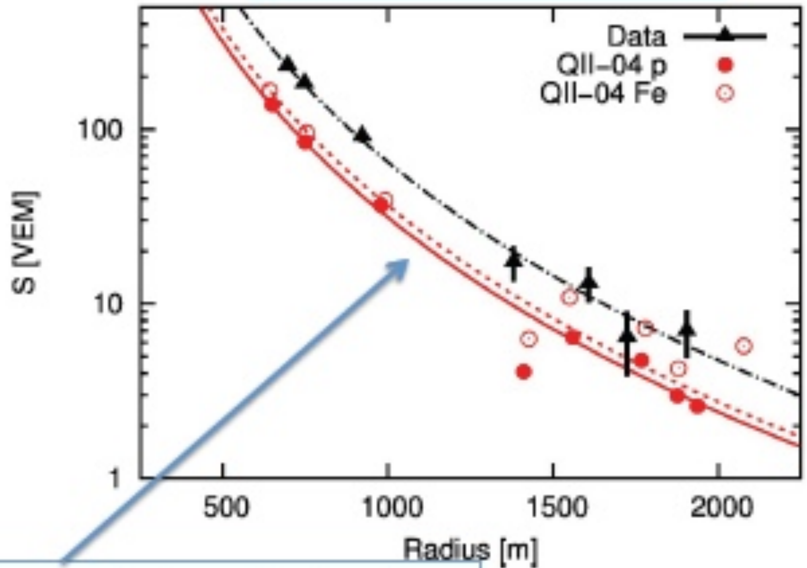
Can models match both FD and SD?

- Find simulations which match measured FD profile, ***for each event***
- Compare the ground signals between the simulations and data
- Rescale muon content so that simulated ground showers best-match observed ones.

FD: longitudinal profile



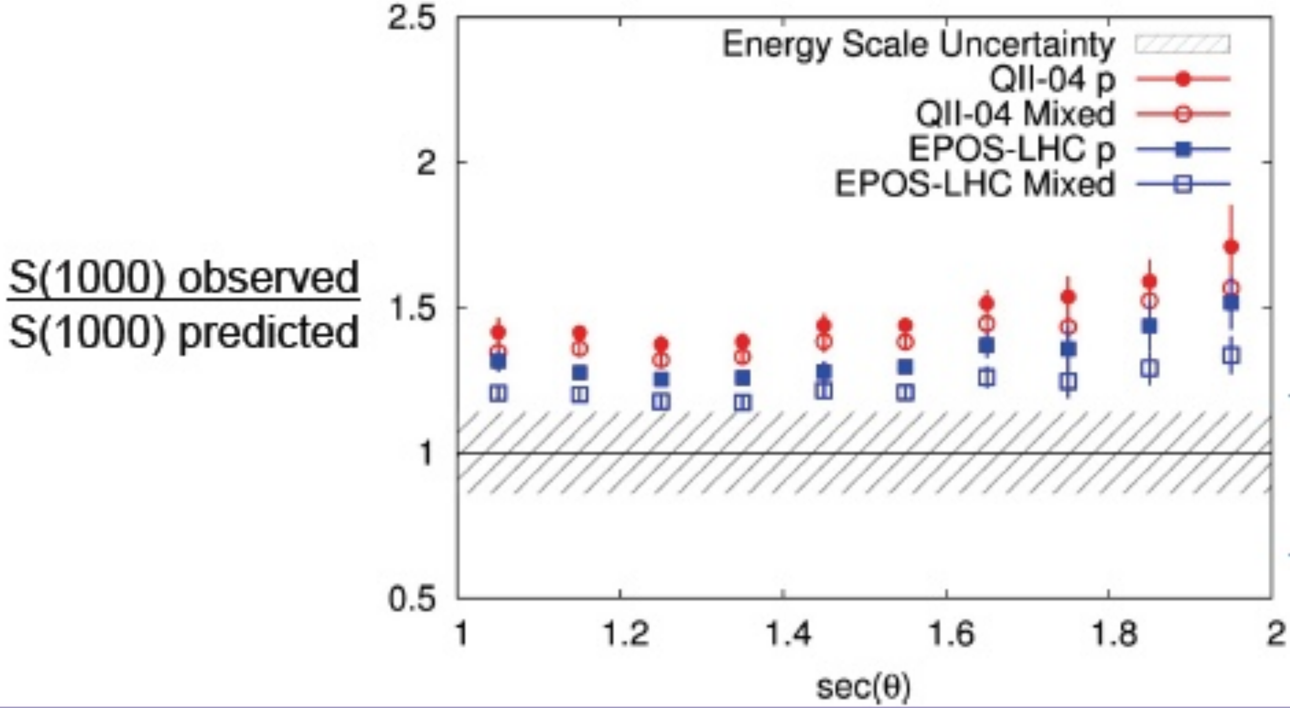
SD: lateral distribution



Typical example: model ground signal is too low

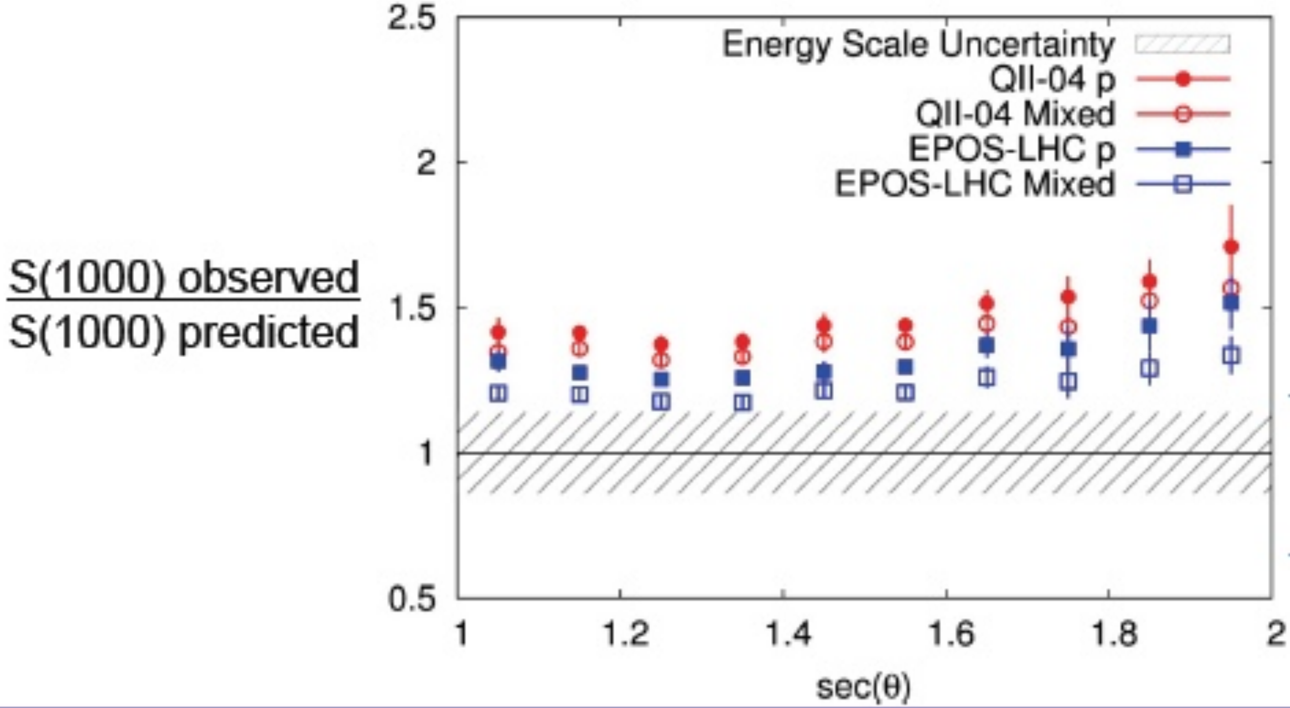
- Uses latest Hadronic Event Generators
  - EPOS-LHC and QGSJET-02-4
  - models tuned to LHC data
- Allows for mixed composition
  - p, He, N, Fe
- 411 Golden Hybrid Events
  - Jan 1, 2004 – Dec 31, 2012
  - $10^{18.8}$ to $10^{19.2}$ eV

- Find simulated events that match the FD shower, for
  - 4 different primaries (p, He, N, Fe)
  - QGSJET-II-04 and EPOS-LHC
- ***Simulated ground signal is too low; discrepancy grows with zenith angle***
  - For both models and for all composition mixes that fit X_{max} distribution



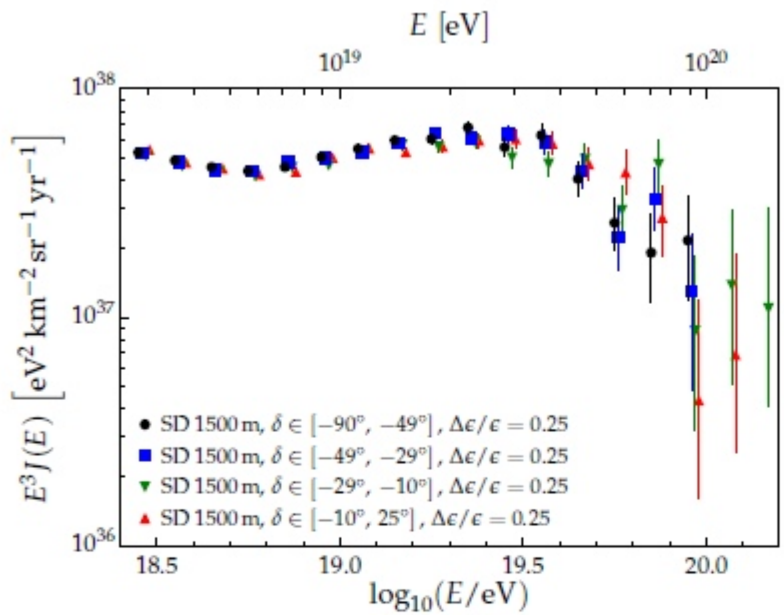
Hatched band is 14% FD systematic uncertainty

- Find simulated events that match the FD shower, for
  - 4 different primaries (p, He, N, Fe)
  - QGSJET-II-04 and EPOS-LHC
- ***Simulated ground signal is too low; discrepancy grows with zenith angle***
  - For both models and for all composition mixes that fit X_{max} distribution



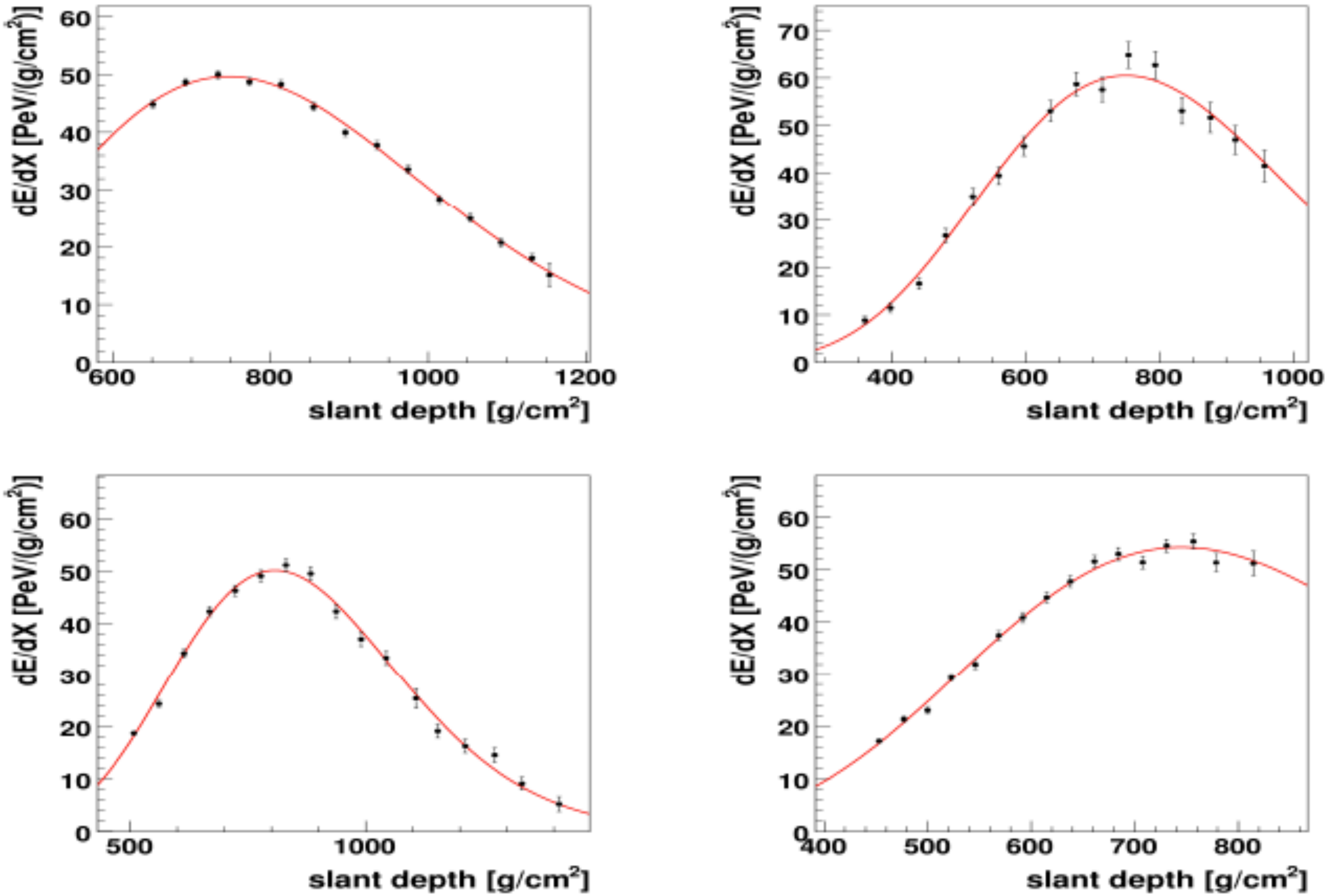
Hatched band is 14% FD systematic uncertainty

This is only ONE example of how the data and the models disagree: others from indirect measurement of muon content


E [eV]
10^19
10^20
10^38
10^37
10^36
E^3 J(E) [eV^2 km^-2 sr^-1 yr^-1]
SD 1500 m, δ ∈ [−90°, −49°], Δε/ε = 0.25
SD 1500 m, δ ∈ [−49°, −29°], Δε/ε = 0.25
SD 1500 m, δ ∈ [−29°, −10°], Δε/ε = 0.25
SD 1500 m, δ ∈ [−10°, 25°], Δε/ε = 0.25
18.5
19.0
19.5
20.0
log10(E/eV)

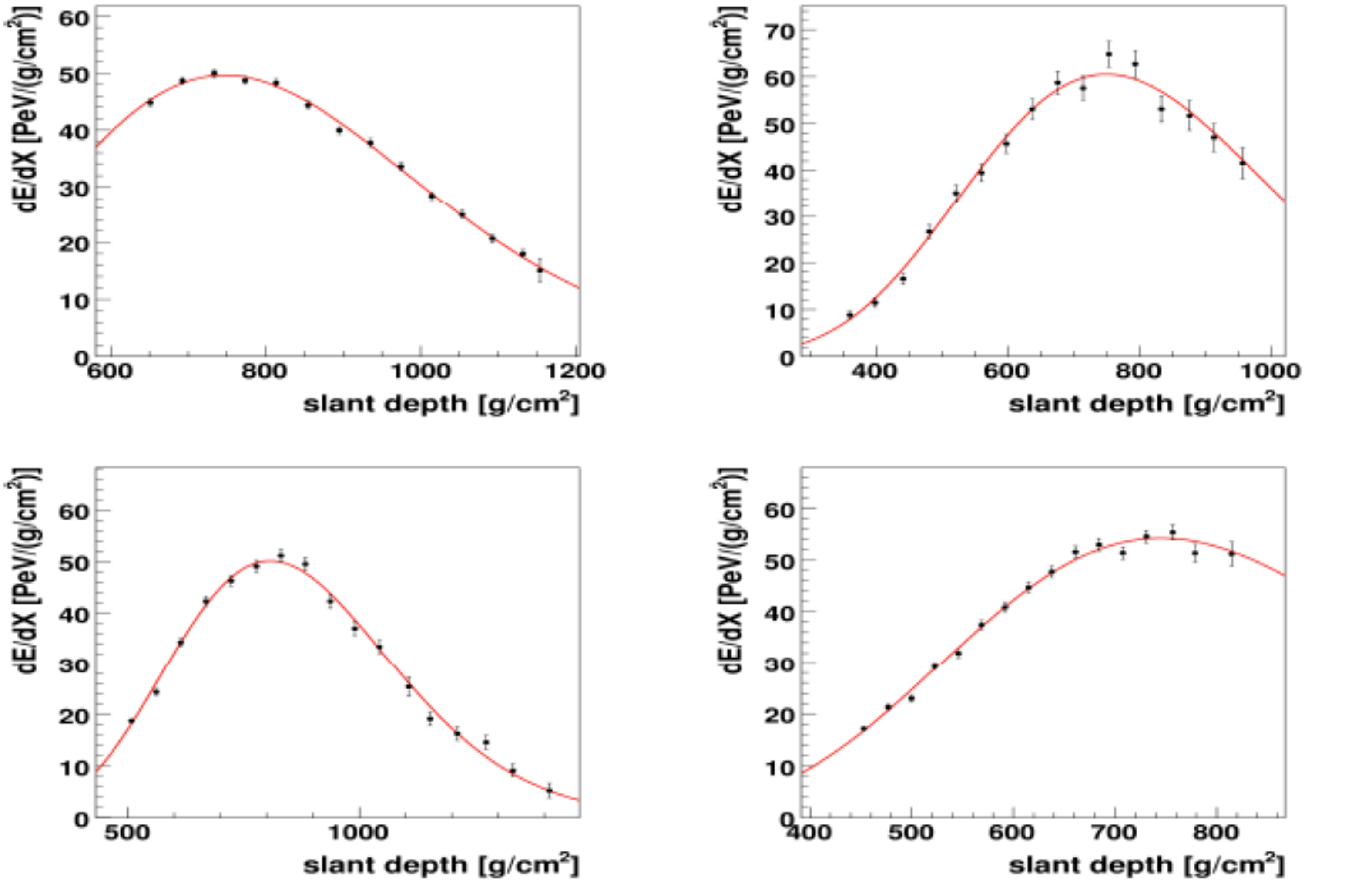
Some Longitudinal Profiles measured with Auge

1000 g cm^{-2} = 1 Atmosphere ~ 1000 mb

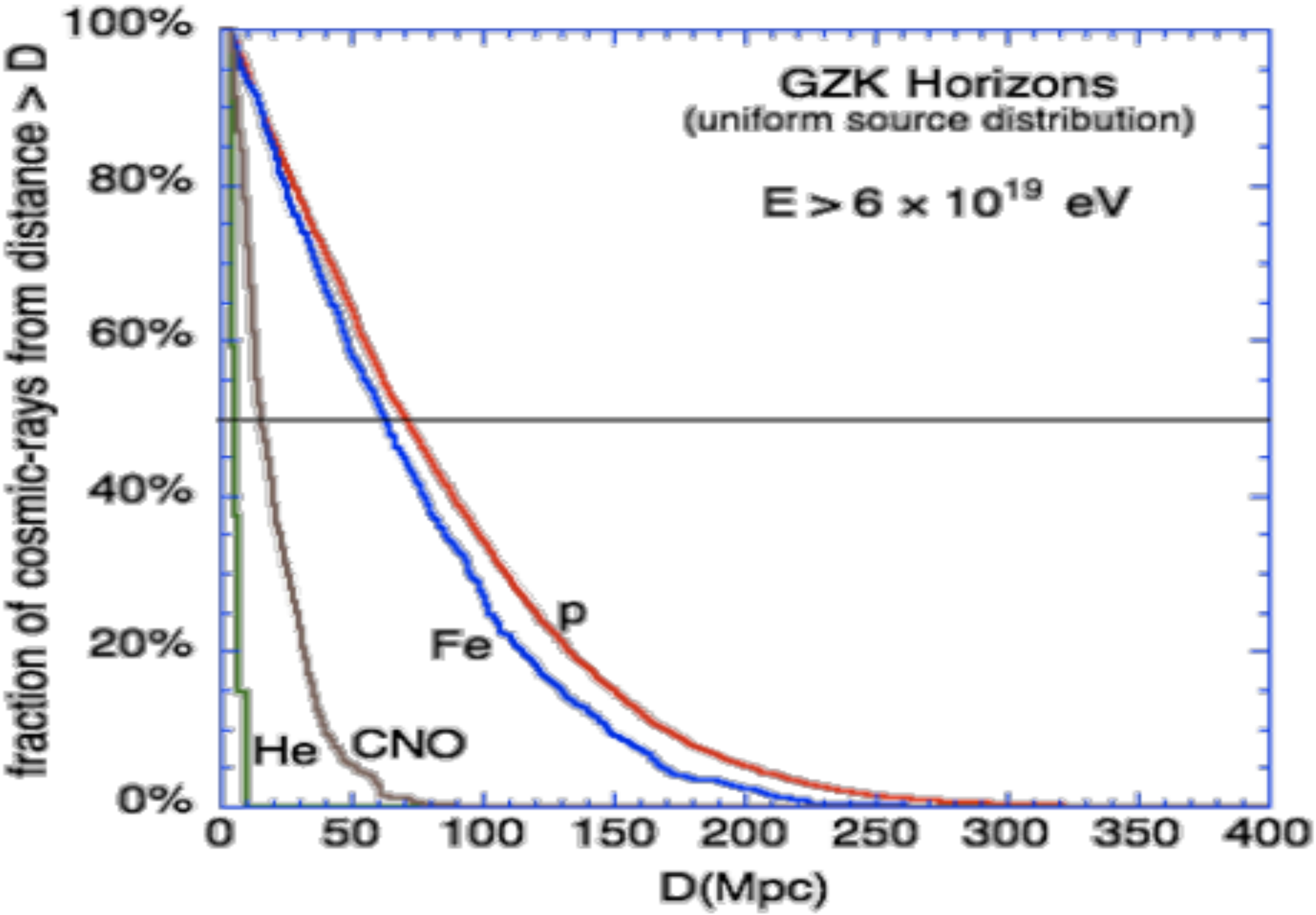


Some Longitudinal Profiles measured with Auge

1000 g cm^{-2} = 1 Atmosphere ~ 1000 mb



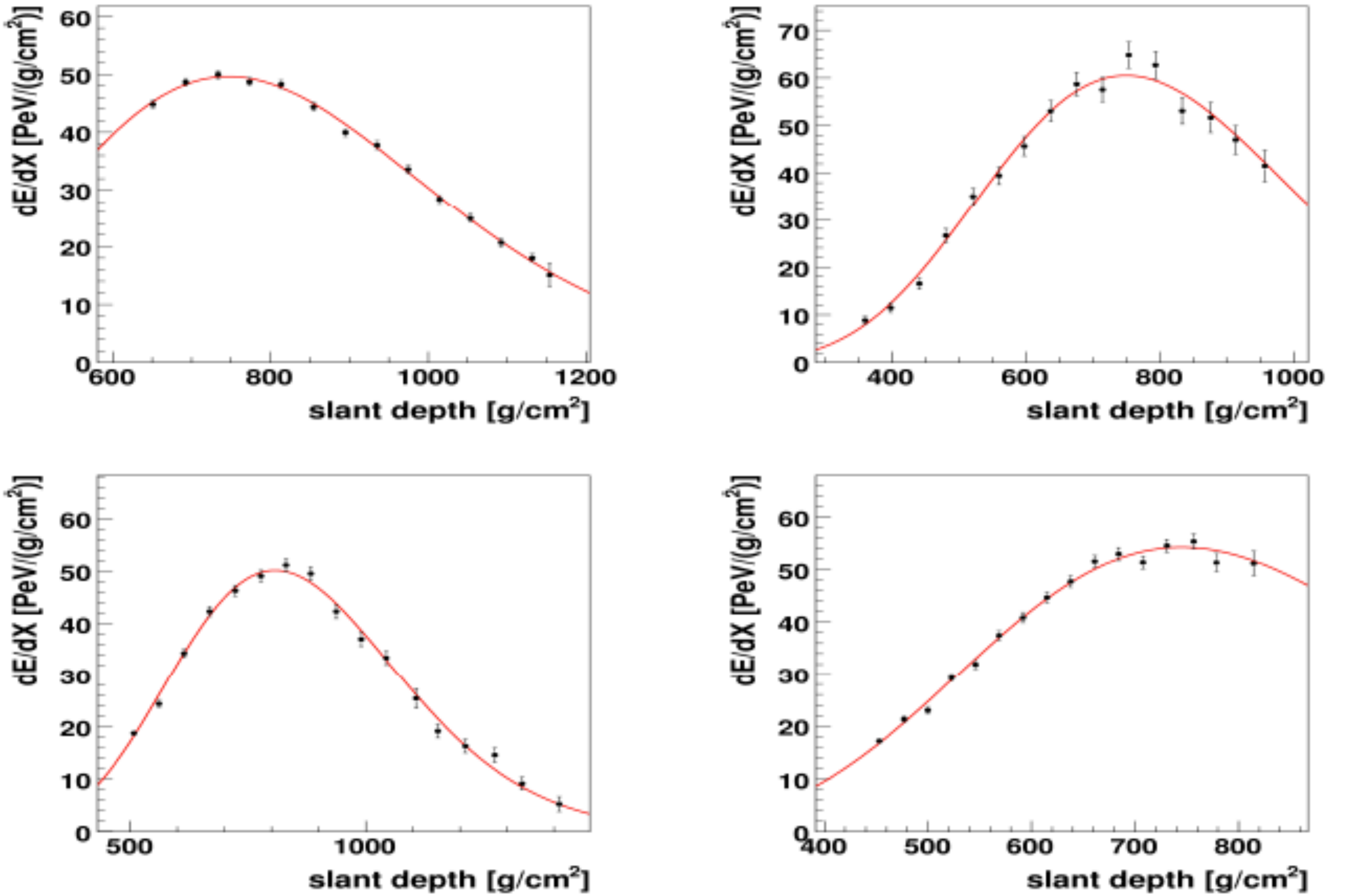
rms uncertainty in X_{max} = 20 g cm^{-2} from stereo-measurements



Allard and Parizot 2010

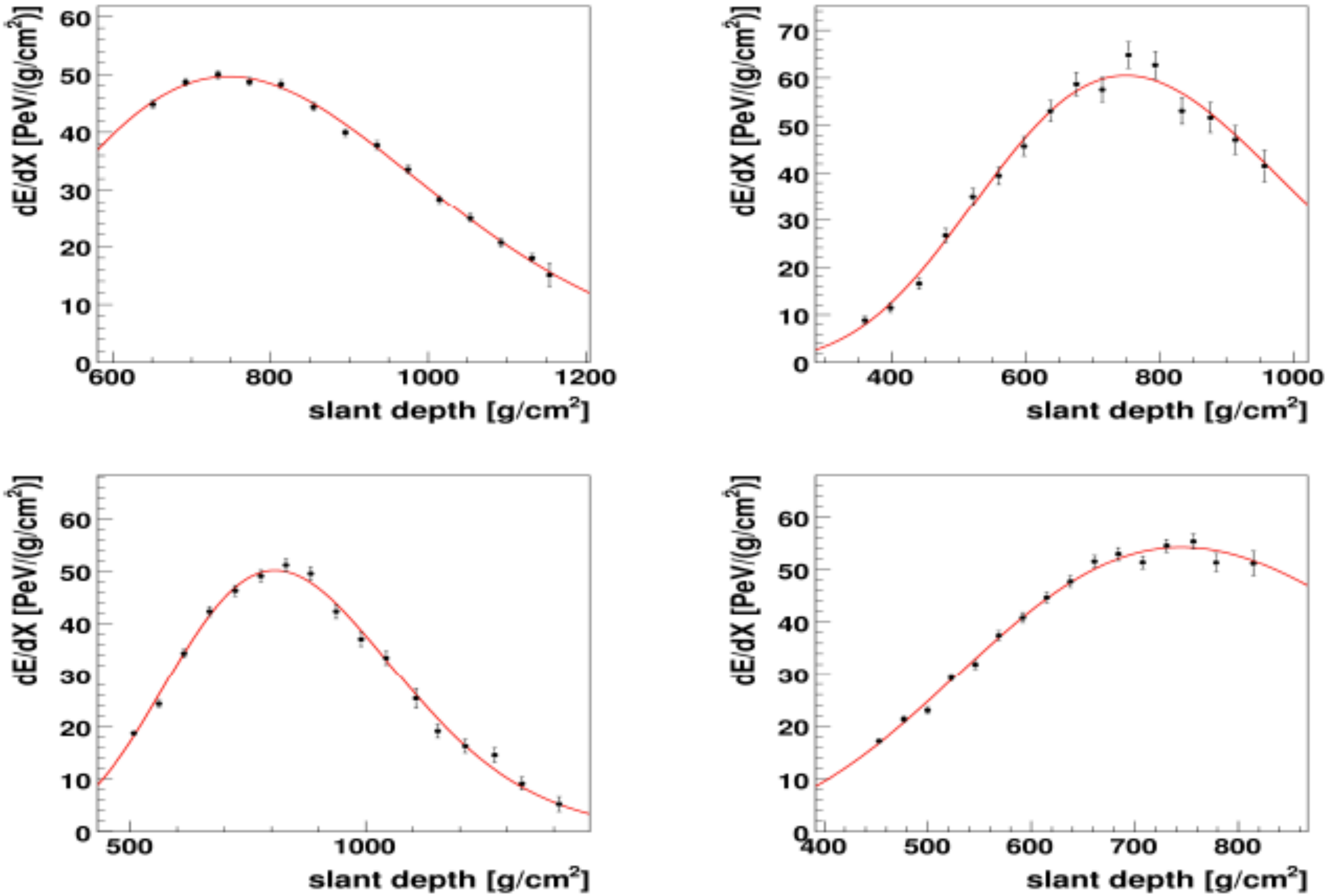
Some Longitudinal Profiles measured with Auge

1000 g cm^{-2} = 1 Atmosphere ~ 1000 mb



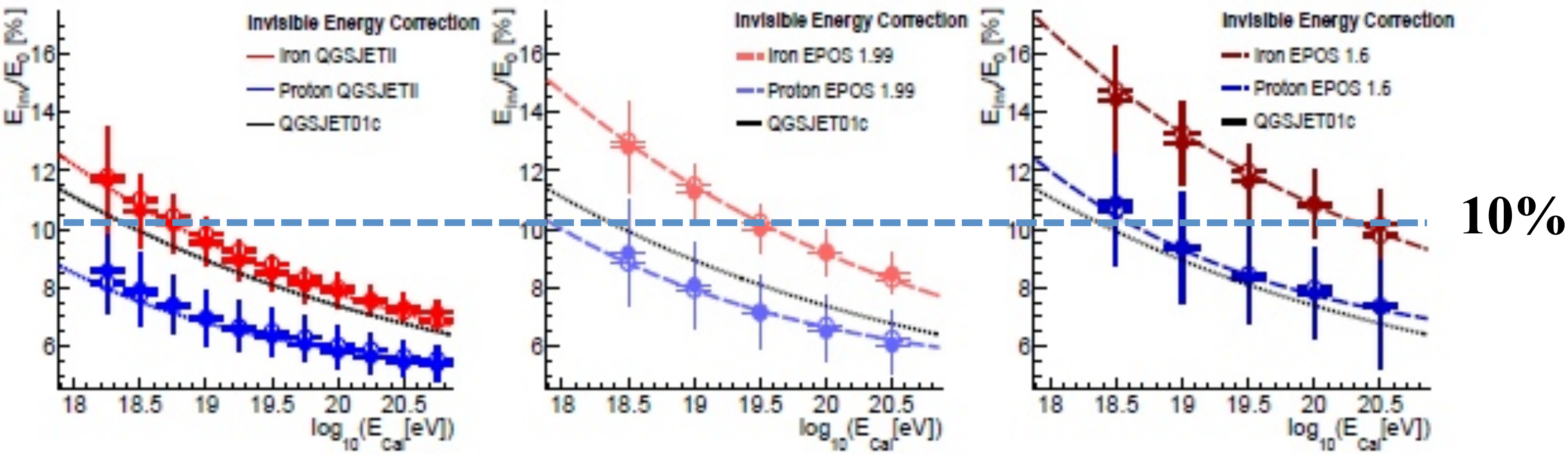
Some Longitudinal Profiles measured with Auge

1000 g cm^{-2} = 1 Atmosphere ~ 1000 mb

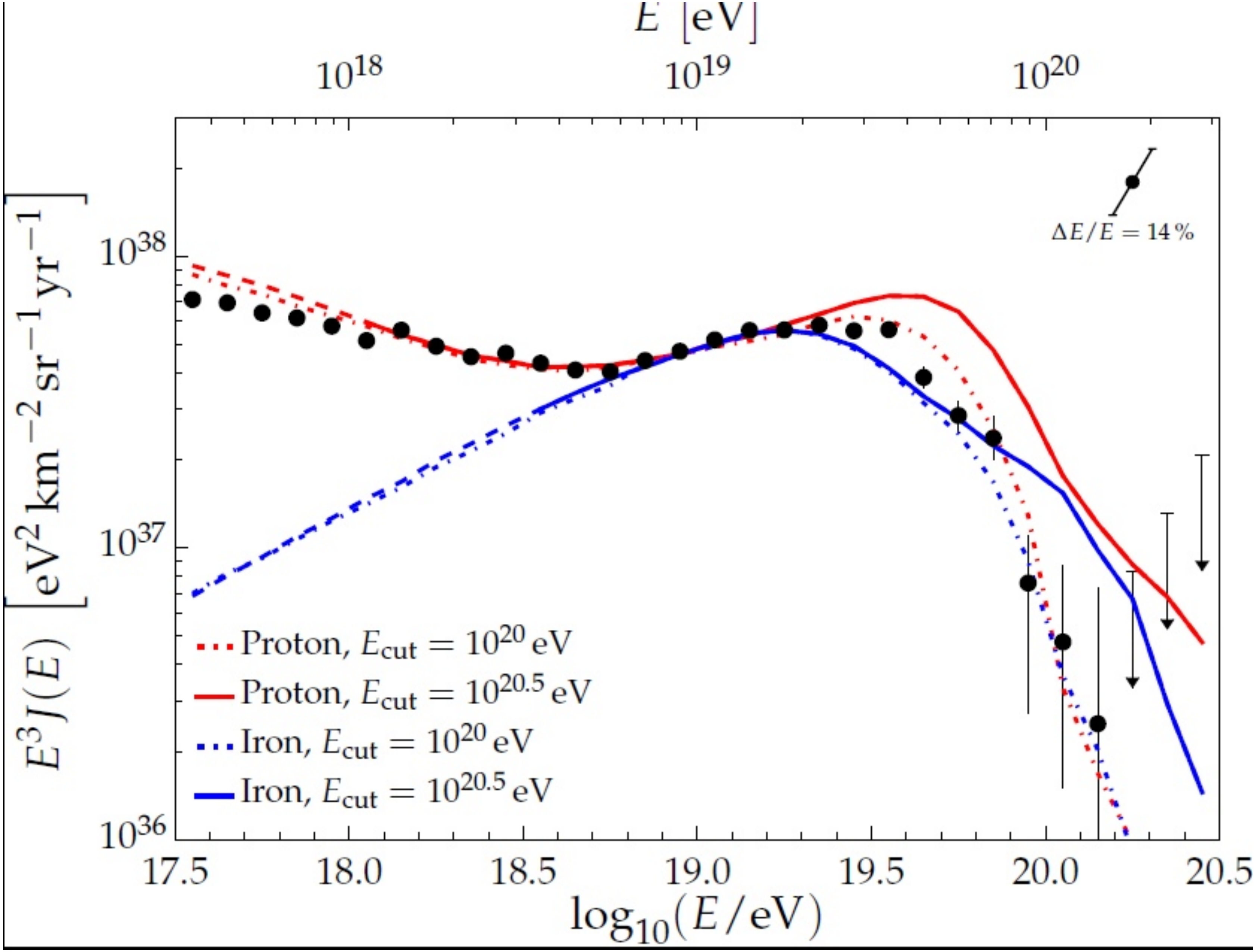


rms uncertainty in X_{max} = 20 g cm^{-2} from stereo-measurements

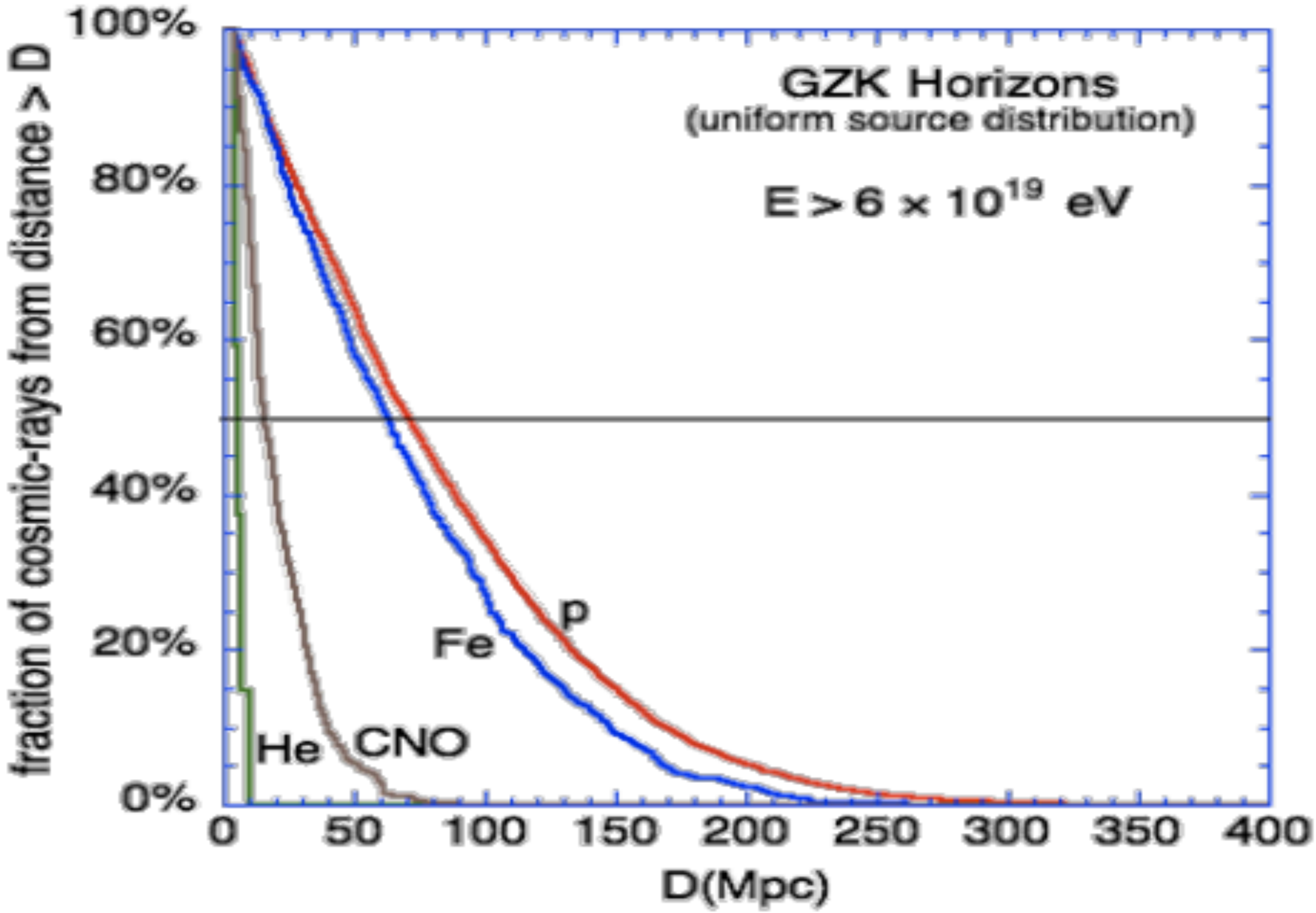
Invisible Energy Correction



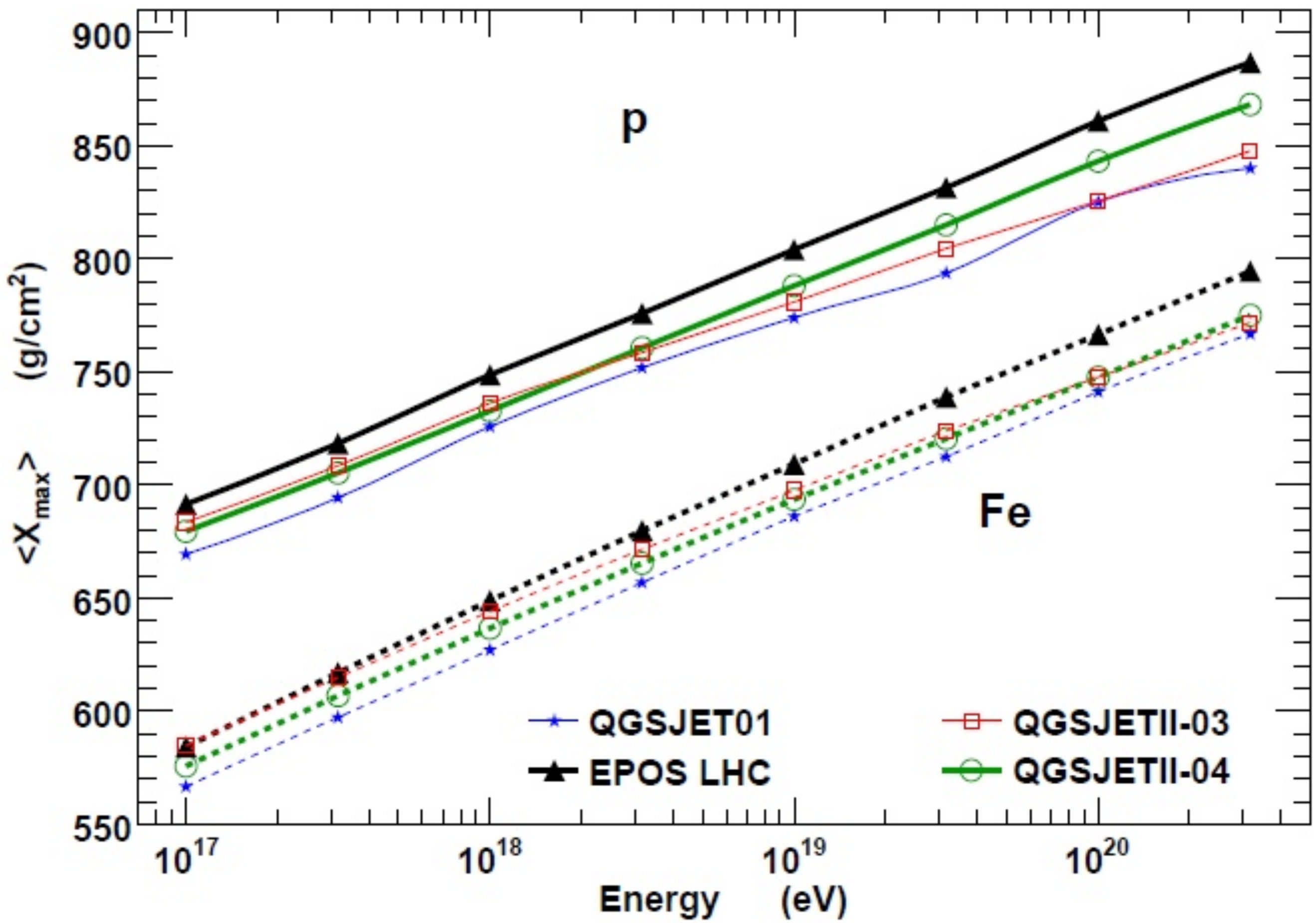
The Auger Collaboration have adopted 50/50 proton/ iron in making the invisible energy correction



E [eV]
10^18
10^19
10^20
ΔE/E = 14 %
10^38
10^37
10^36
E^3 J(E) [eV^2 km^-2 sr^-1 yr^-1]
Proton, E_cut = 10^20 eV
Proton, E_cut = 10^20.5 eV
Iron, E_cut = 10^20 eV
Iron, E_cut = 10^20.5 eV
17.5
18.0
18.5
19.0
19.5
20.0
20.5
log_10(E/eV)



Allard and Parizot 2010



Tanguy Pierog