CRIS 2016: Ischia 4 – 8 July 2016

Indirect Measurements of High Energy Cosmic Rays – the Air-Shower Regime: *some random thoughts*

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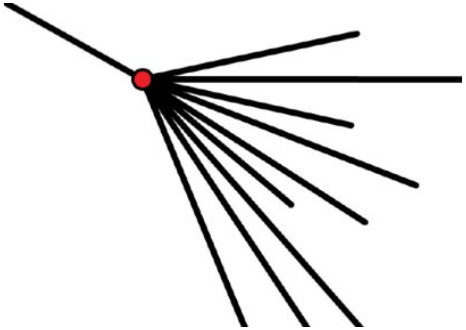
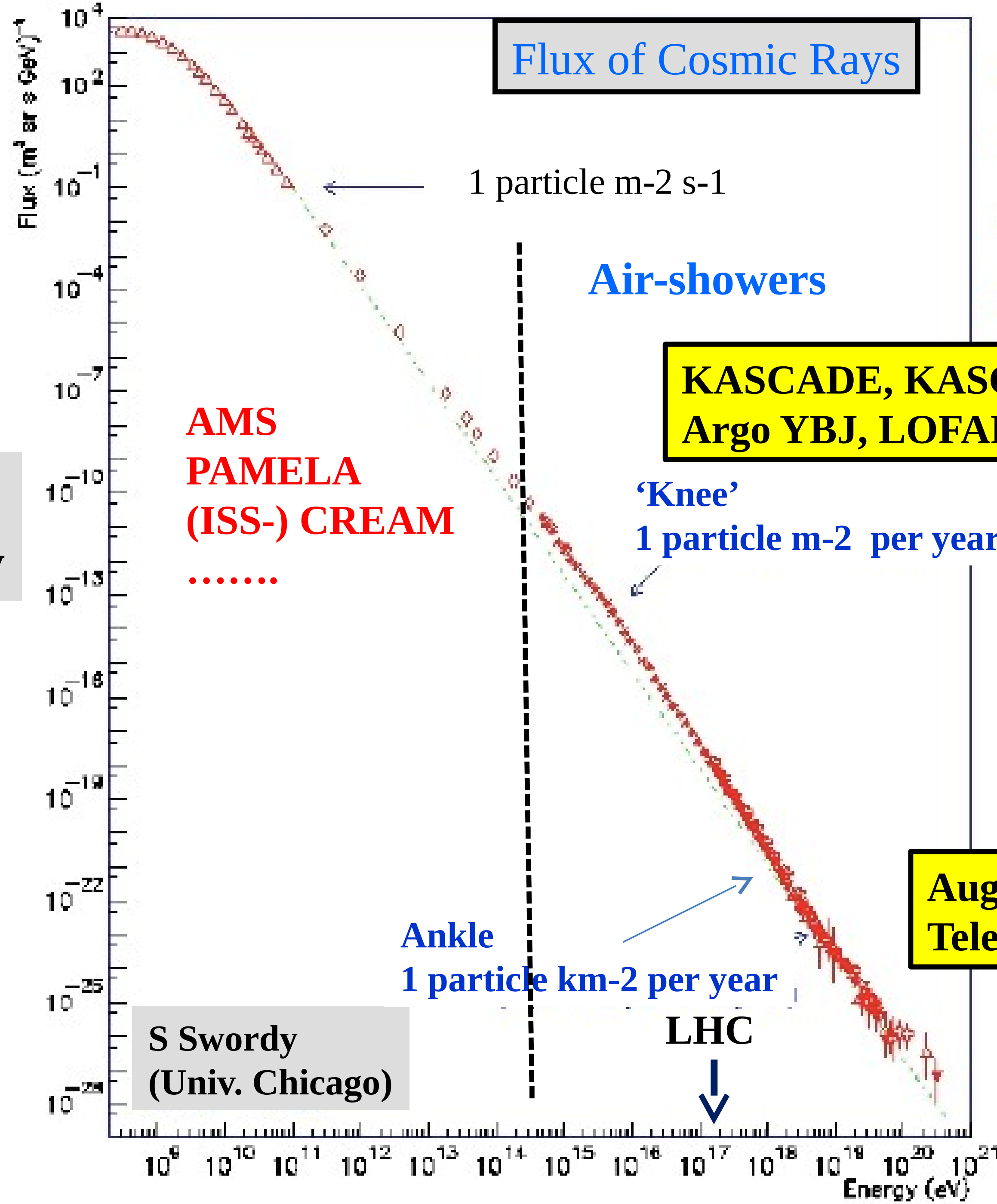


32 decades in intensity



11 Decades in Energy

Outline:

- What we need to know about high energy interactions – a systematic uncertainty that is difficult to assess
- Tensions between data from IceCube/IceTop, Auger Observatory and DELPHI and predictions from hadronic models
- Astrophysical conclusions we can draw despite these tensions

  Arrival Direction Distributions

  Energy Spectrum – relatively modest effect and *LESS* at high energies
- Exploration of Origin of Dip from neutrino and gamma-ray information
- Comments on some models of cosmic ray origin
- Prospects for the future

Bristol: Conference on Very High Energy Interactions, January 1963

Trying to get information about particle interactions from studying extensive-air showers is like trying to get information about the workings of the British Cabinet by reading the

Bild? Novella 2000?

J G Wilson

- **Information from LHC is relatively weak at large x (but LHCf)**
- **Need information on cross-section, inelasticity, multiplicity and, *very importantly*, pion-nucleus interactions**
- **One approach to testing the validity of the hadronic models is to see whether the mass composition, deduced from data, are consistent from method-to-method**
- **One method, common to Auger Observatory and Telescope Array**
- **Different approach from the IceCube/IceTop installation**
- **Three other methods have been explored at the Auger Observatory where the use of water-Cherenkov detectors allows the study of showers at large zenith angle**

The Designs of the Pierre Auger Observatory and Telescope Array marry the two established techniques.

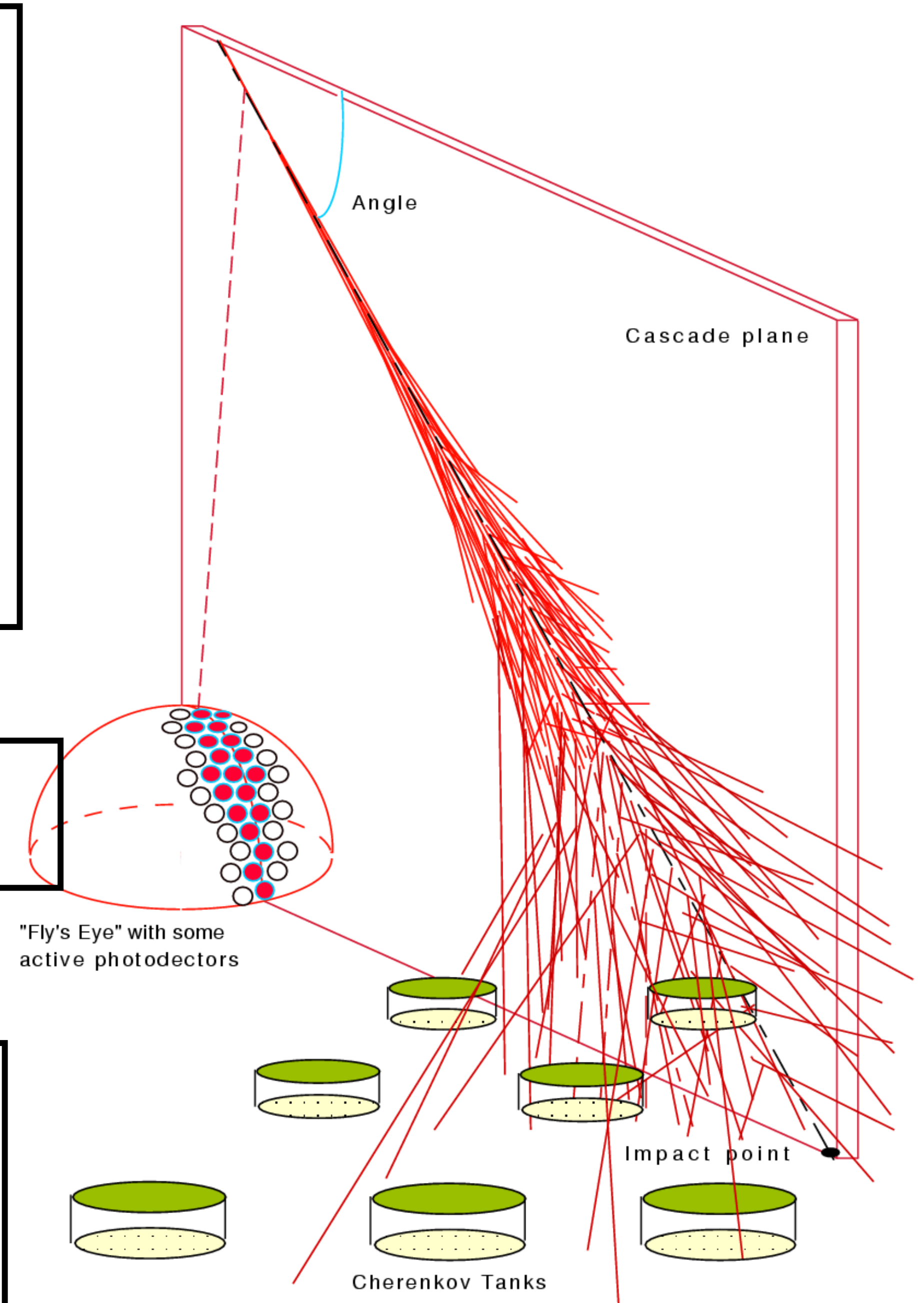
Water-Cherenkov detectors or scintillators are operated in tandem with fluorescence detectors

the 'HYBRID' technique

Fluorescence →

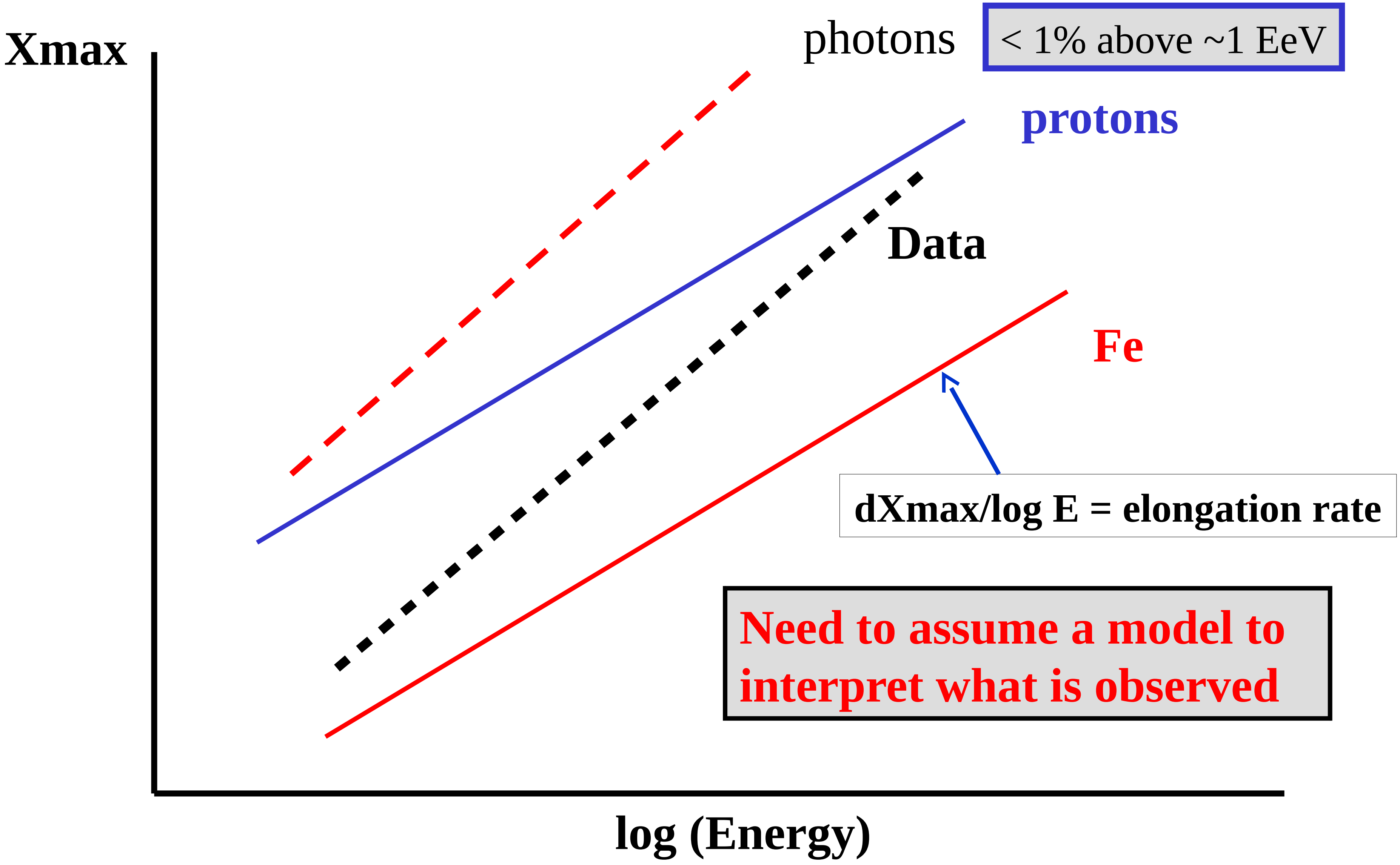
AND

Array of water-Cherenkov detectors or scintillators →



Enrique Zas, Santiago de Compostela

One method to try to infer the variation of mass with energy



Results on mass from depth of maximum with fluorescence detectors

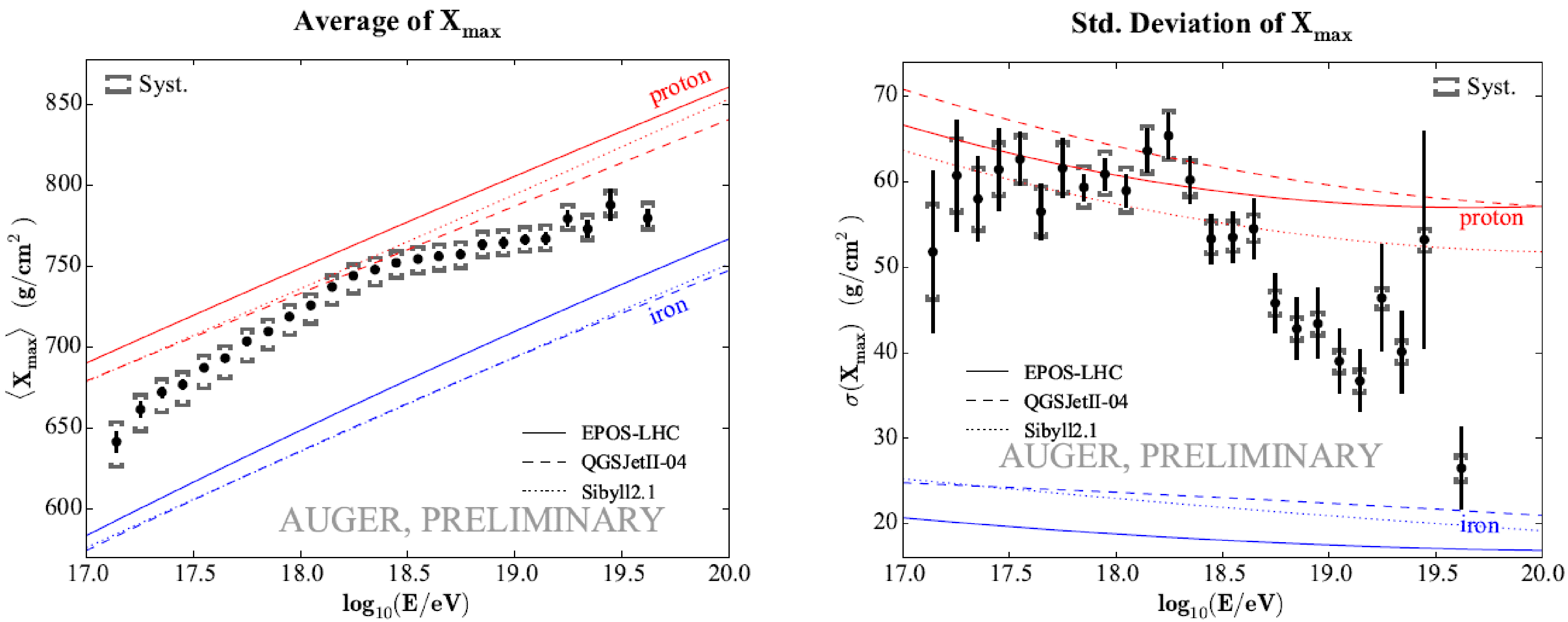
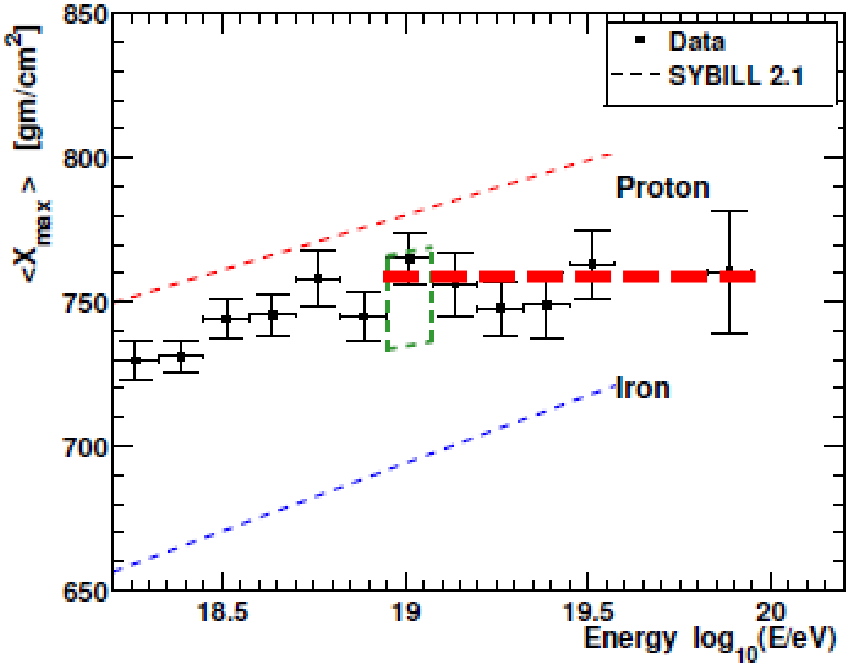


Figure 3: The mean (left) and the standard deviation (right) of the measured X_{max} distributions as a function of energy compared to air-shower simulations for proton and iron primaries.

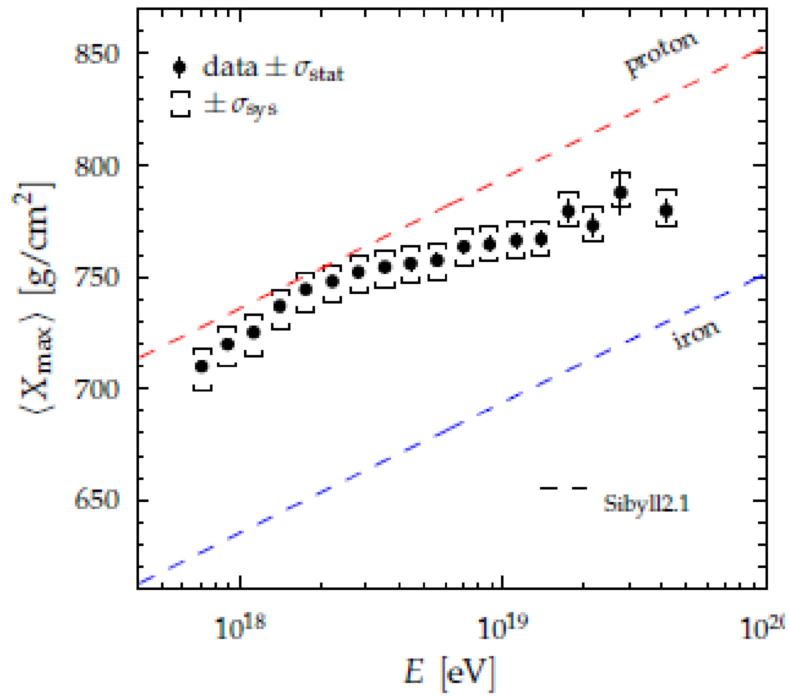
Predictions from Sibyl model lie between those with QGSjet and EPOS-LHC

Comparison of TA and Auger results against a single model

– Michael Unger



Telescope Array Collaboration, APP **64** (2014) 49



Pierre Auger Collaboration, PRD **90** (2014) 12, 122005

- **New Sybil model moves depth of maximum DEEPER into atmosphere and thus *pure proton claims become harder to sustain***

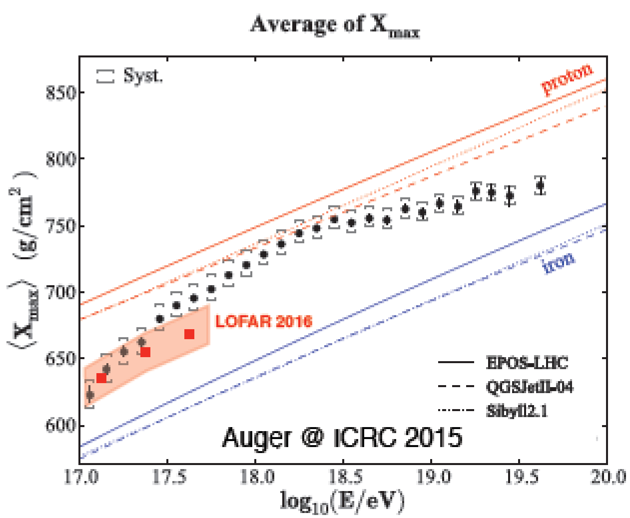
- **Change of elongation rate seen in BOTH data sets**

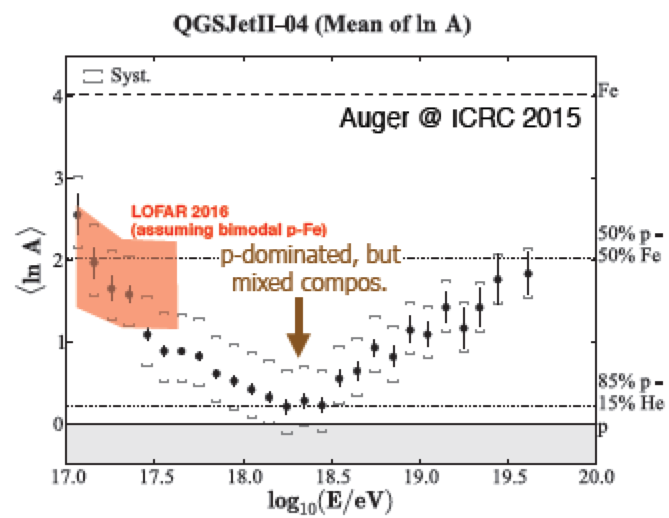
  Martina Bohacova and Daisuke Ikeda for more discussion

Additional Support from the Radio Technique

A look at lower energies: Auger-LOFAR

Auger Collaboration, ICRC2015, arXiv:1509.03732





S. Buitnik et al (LOFAR), Nature 531 (2016) 70

Talk by Benedikt Zimmermann to follow

lux

e of

composition that we measured in the 10^{17}–$10^{17.5}$ eV range.

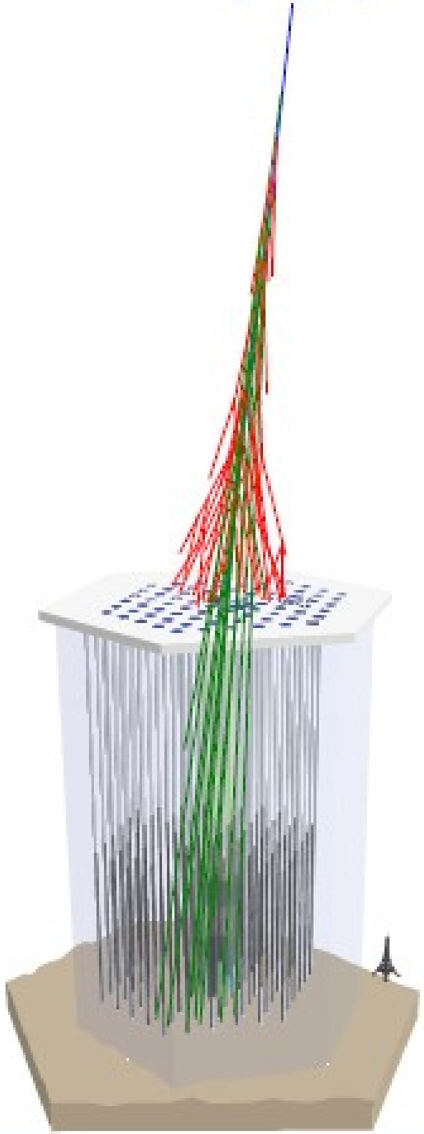
Auger; arXiv:1509.03732

Correlations of Xmax and shower-size

⇒ mixed composition at ankle, i.e. no pure p-beam

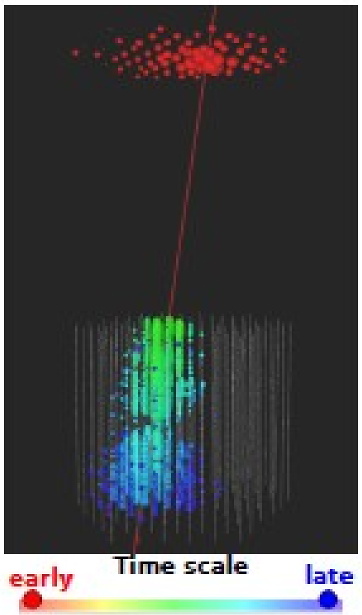
⇒ dip-model (e+e- pair prod. in CMB) ruled out: subm. to PRD

Cosmic ray physics with the IceCube Neutrino Observatory

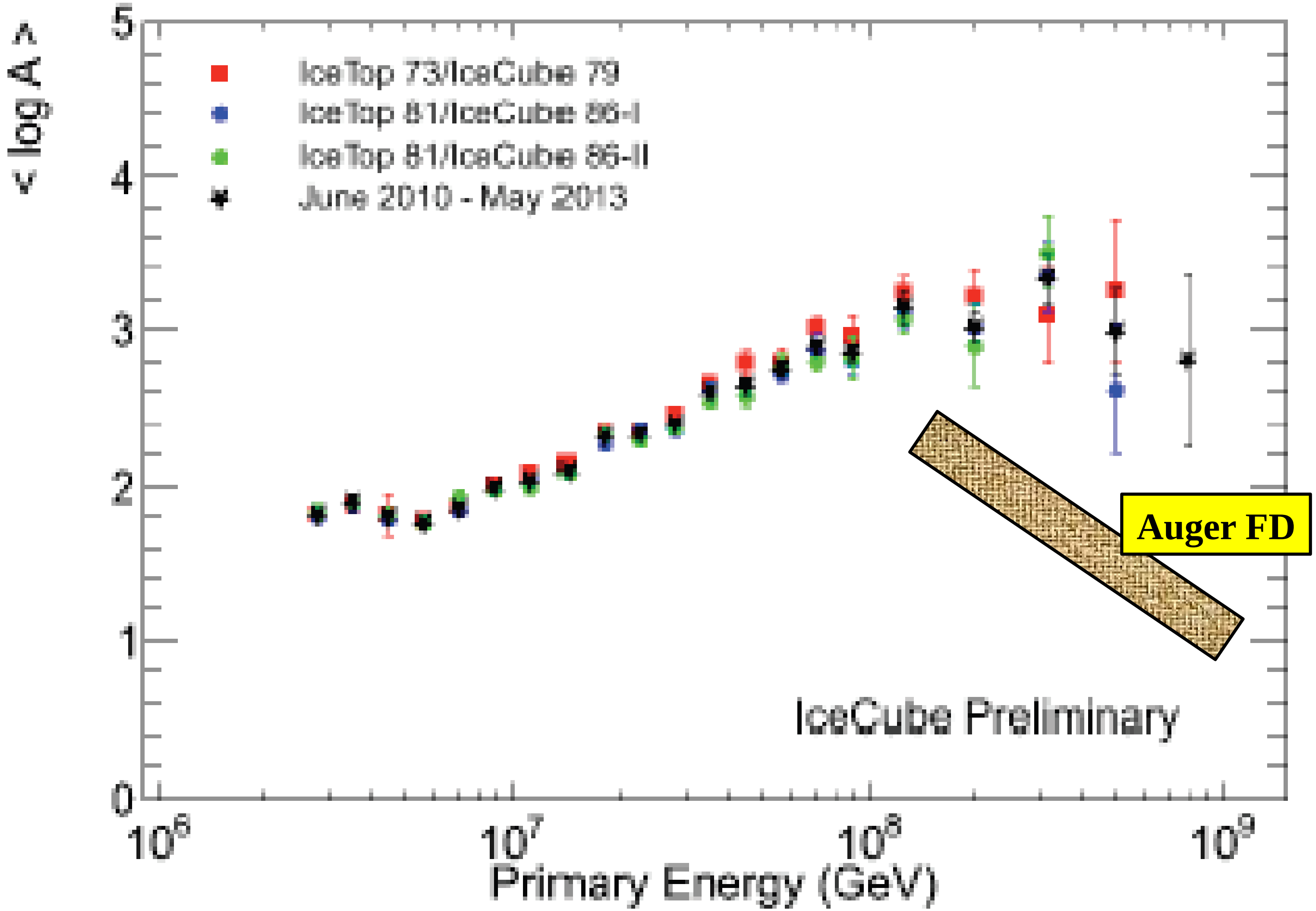


Coincident analysis:

- IceTop stations detect the electromagnetic component (and low-energy muons): sensitive to the energy of the shower.
- High-energy muon bundles travel down to the IceCube detector:



- Minimal muon energy: ~ 275 GeV.
- Multiplicity: 1 - 1000s.
- Created high in the atmosphere.
- Typical radius: $\sim 20 - 50$ m
- Ionization + radiative, stochastic energy loss.



Gaisser for IceCube: Summary talk, Karlsruhe Composition meeting, October 2015

A method of testing models:
Muon Production Depth (MPD)
PRD 90 012012 2014

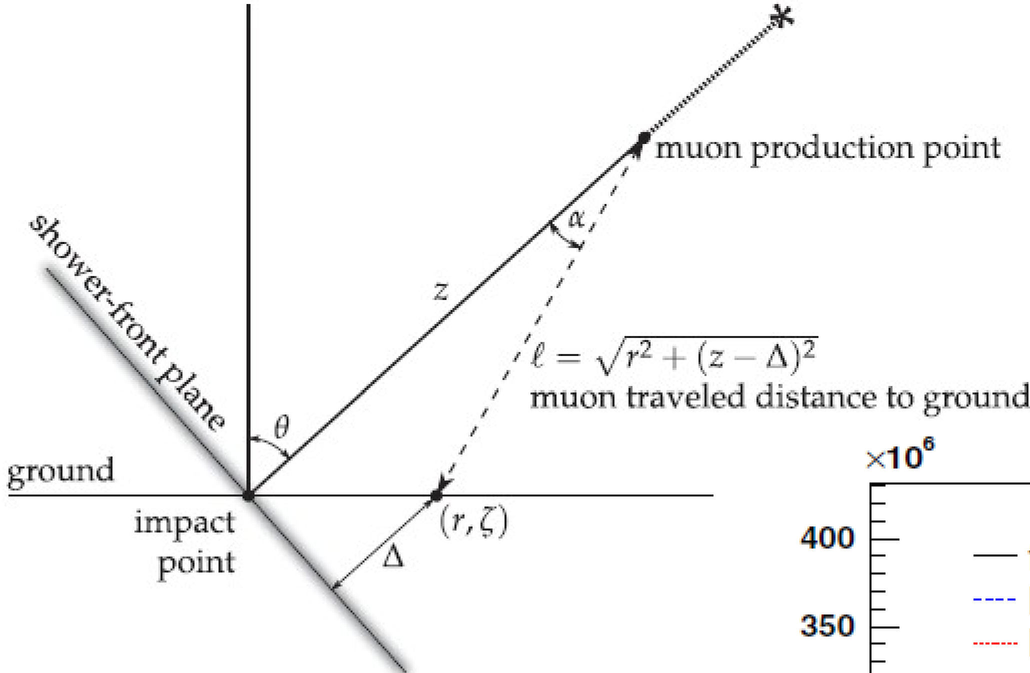
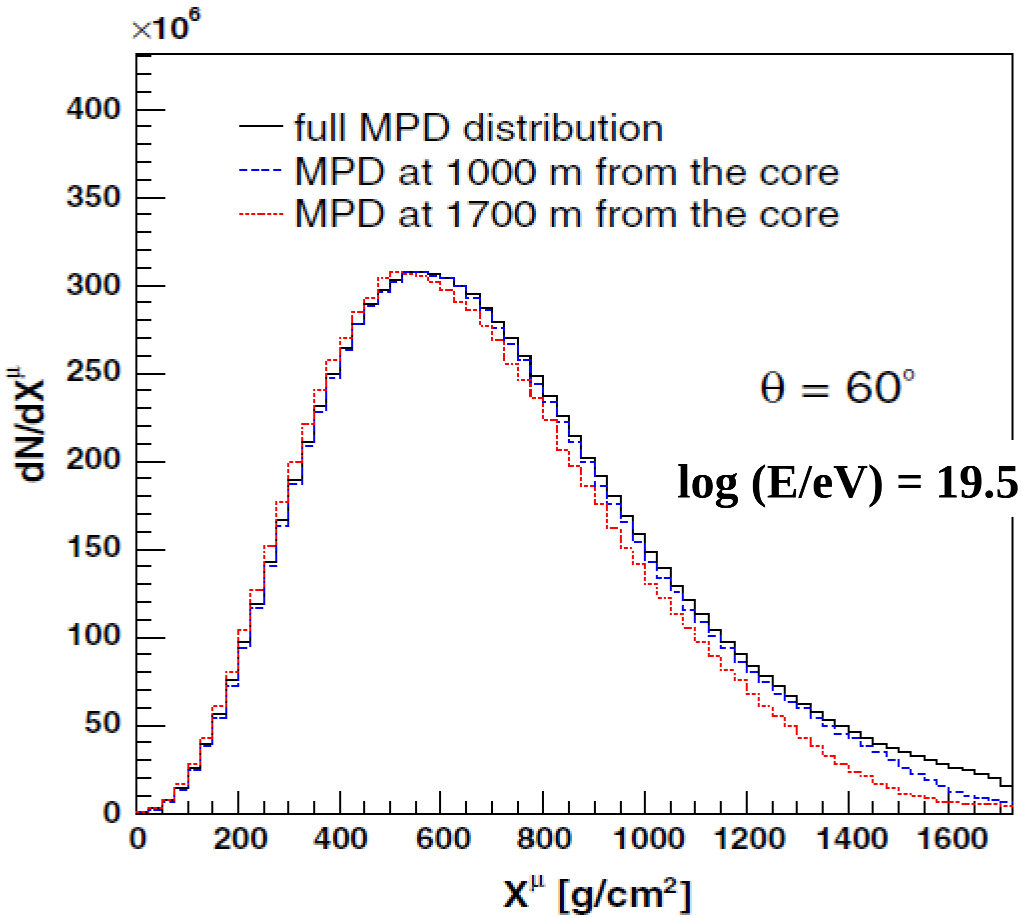
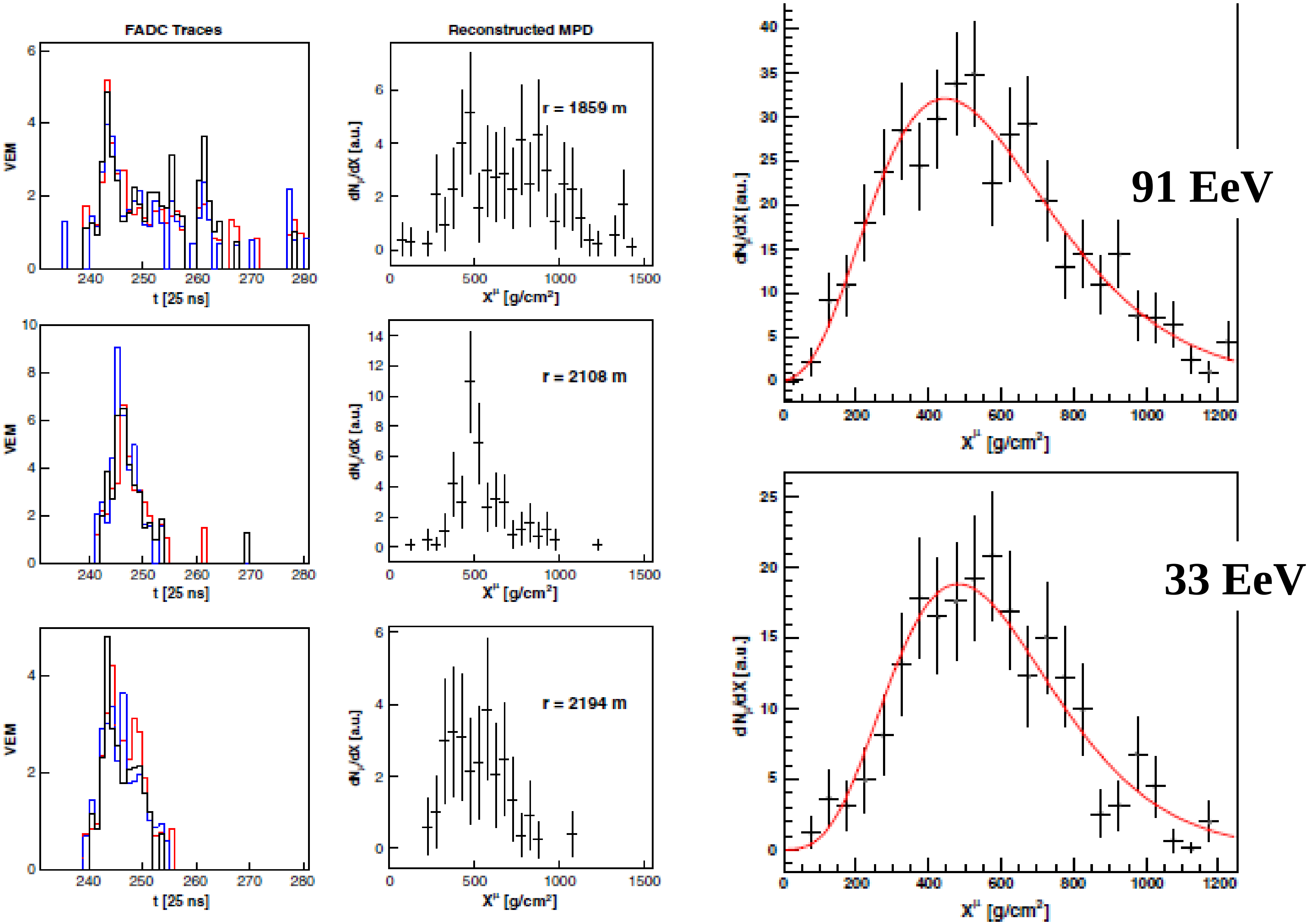


FIG. 1. Geometry used to obtain the muon t
the time delay.




FADC Traces
Reconstructed MPD
VEM
t [25 ns]
dN/dX [a.u.]
X^μ [g/cm²]
r = 1859 m
r = 2108 m
r = 2194 m
91 EeV
33 EeV

Another method of testing models

Asymmetry of Risetime
Aab et al, Phys Rev D 93 072006 2016

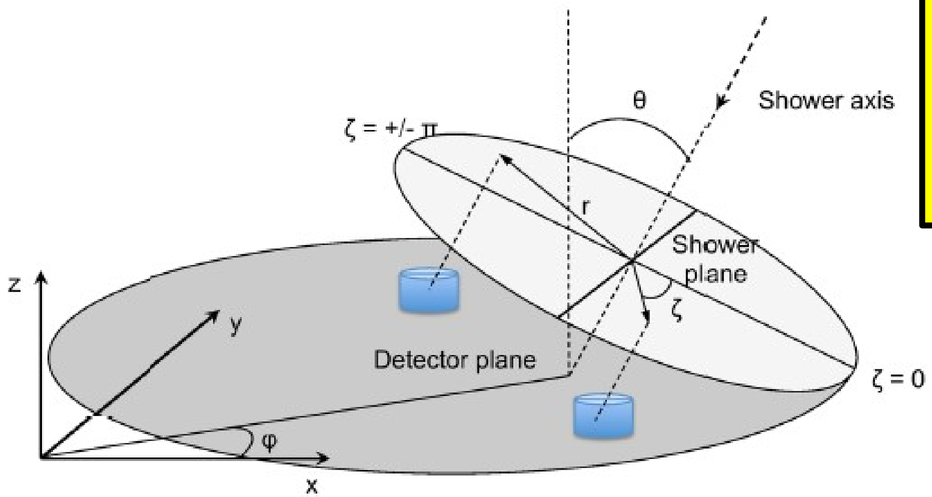
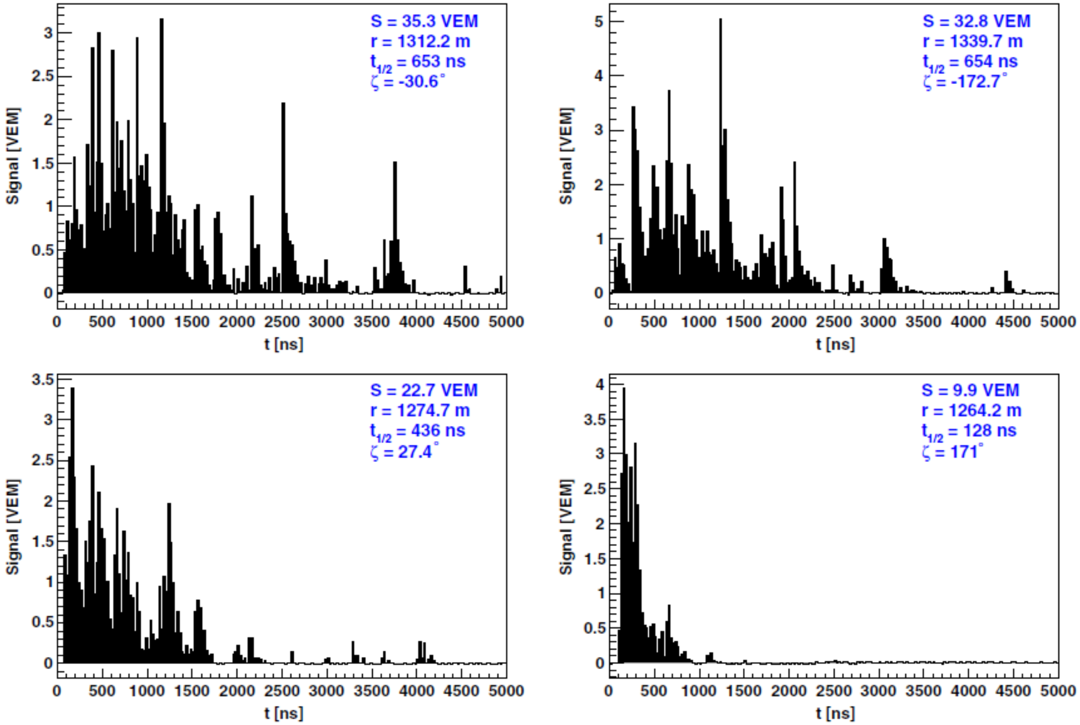
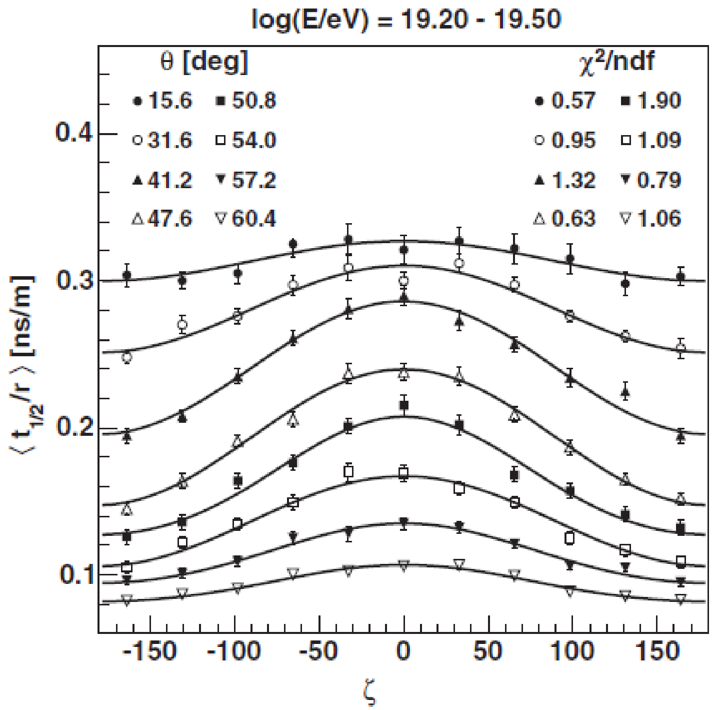
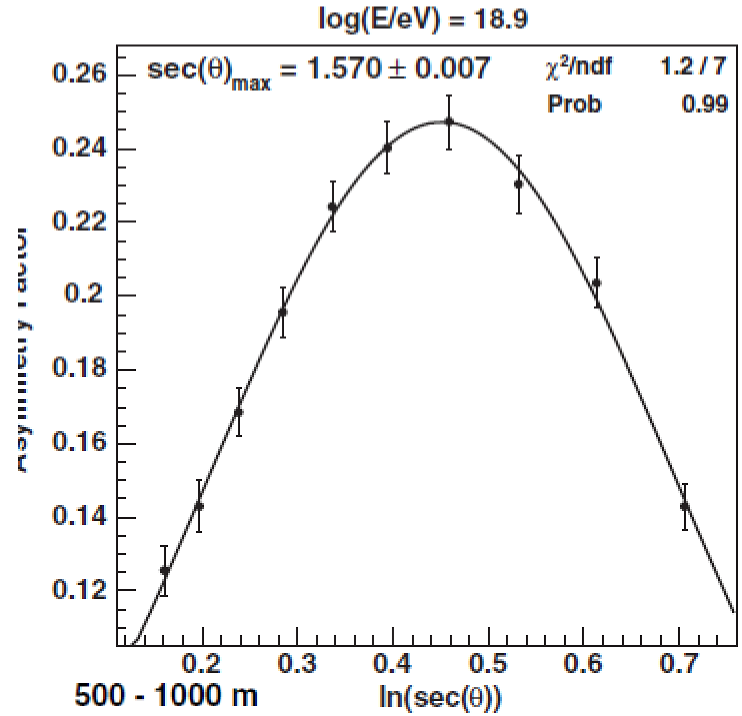
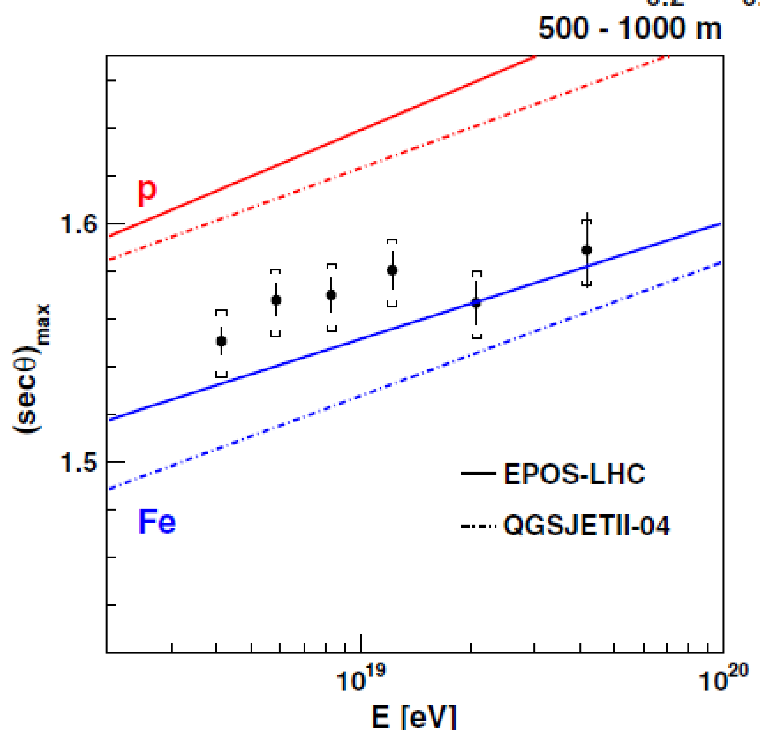


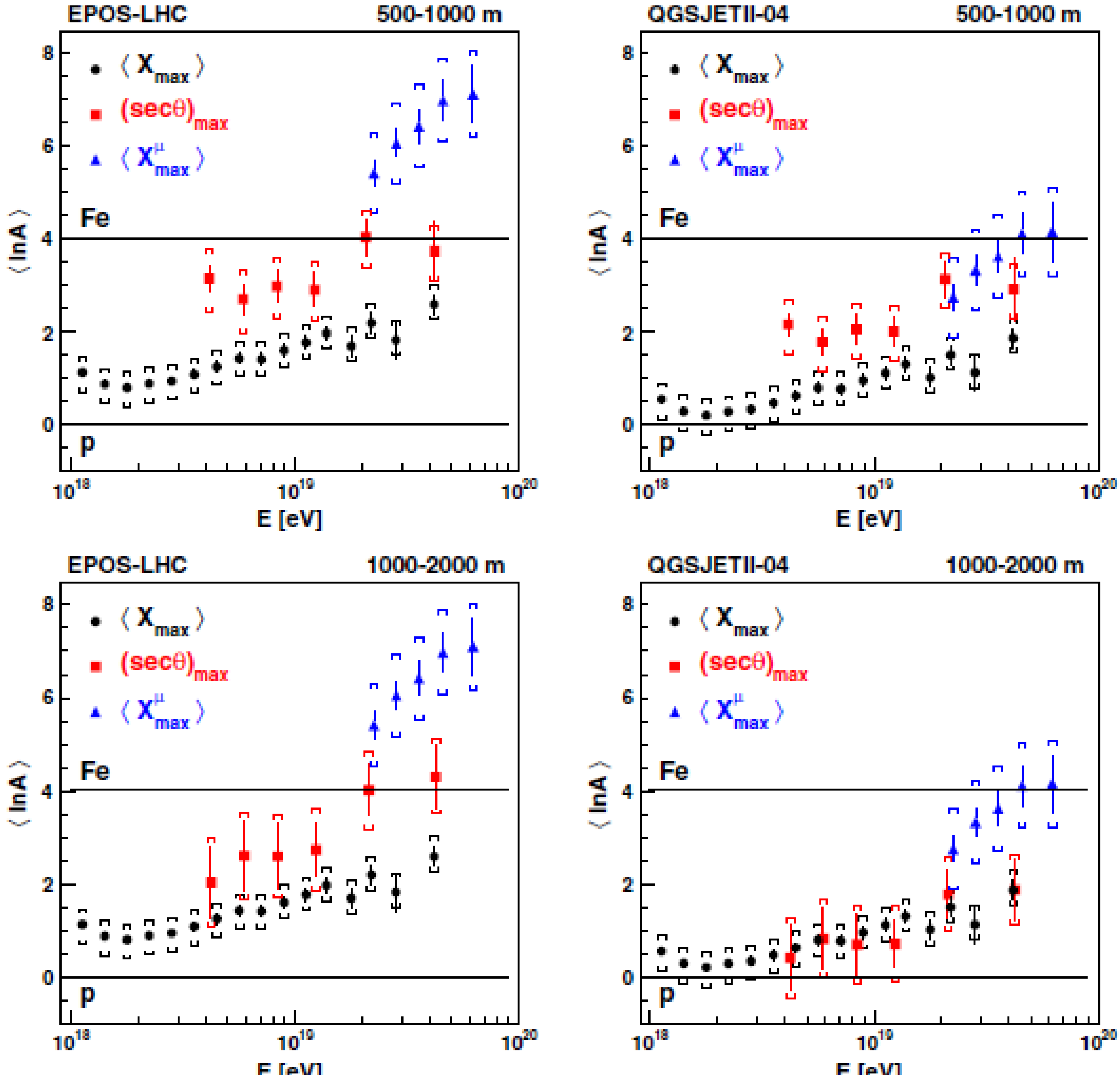
FIG. 1. Schematic view of the shower geometry. The incoming direction of the primary particle defines two regions, "early" ($|\zeta| < \pi/2$) and "late" region ($|\zeta| > \pi/2$) amount of atmosphere traversed by the p detectors in each region.




log(E/eV) = 19.20 - 19.50
θ [deg]
χ²/ndf
15.6
50.8
31.6
54.0
41.2
57.2
47.6
60.4
0.57
1.90
0.95
1.09
1.32
0.79
0.63
1.06
⟨ t_{1/2}/r ⟩ [ns/m]
ζ

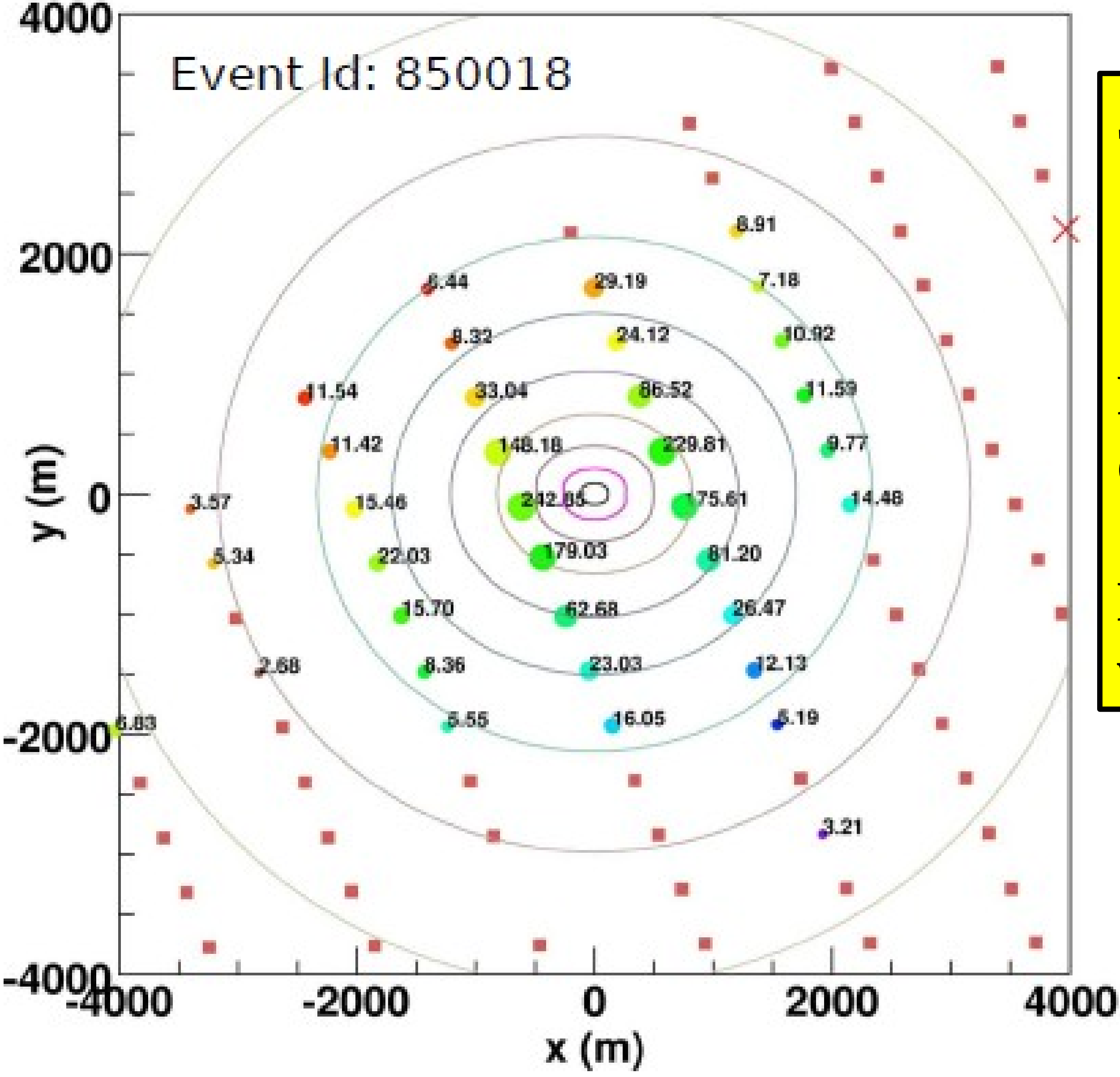

log(E/eV) = 18.9
sec(θ)_max = 1.570 ± 0.007
χ²/ndf 1.2 / 7
Prob 0.99
ln(sec(θ))


500 - 1000 m
p
Fe
(secθ)_max
EPOS-LHC
QGSJETII-04
E [eV]



EPOS-LHC
500-1000 m
QGSJETII-04
1000-2000 m
⟨ X_{max} ⟩
$(\sec\theta)_{max}$
⟨ X^{μ}_{max} ⟩
Fe
p
⟨ lnA ⟩
E [eV]

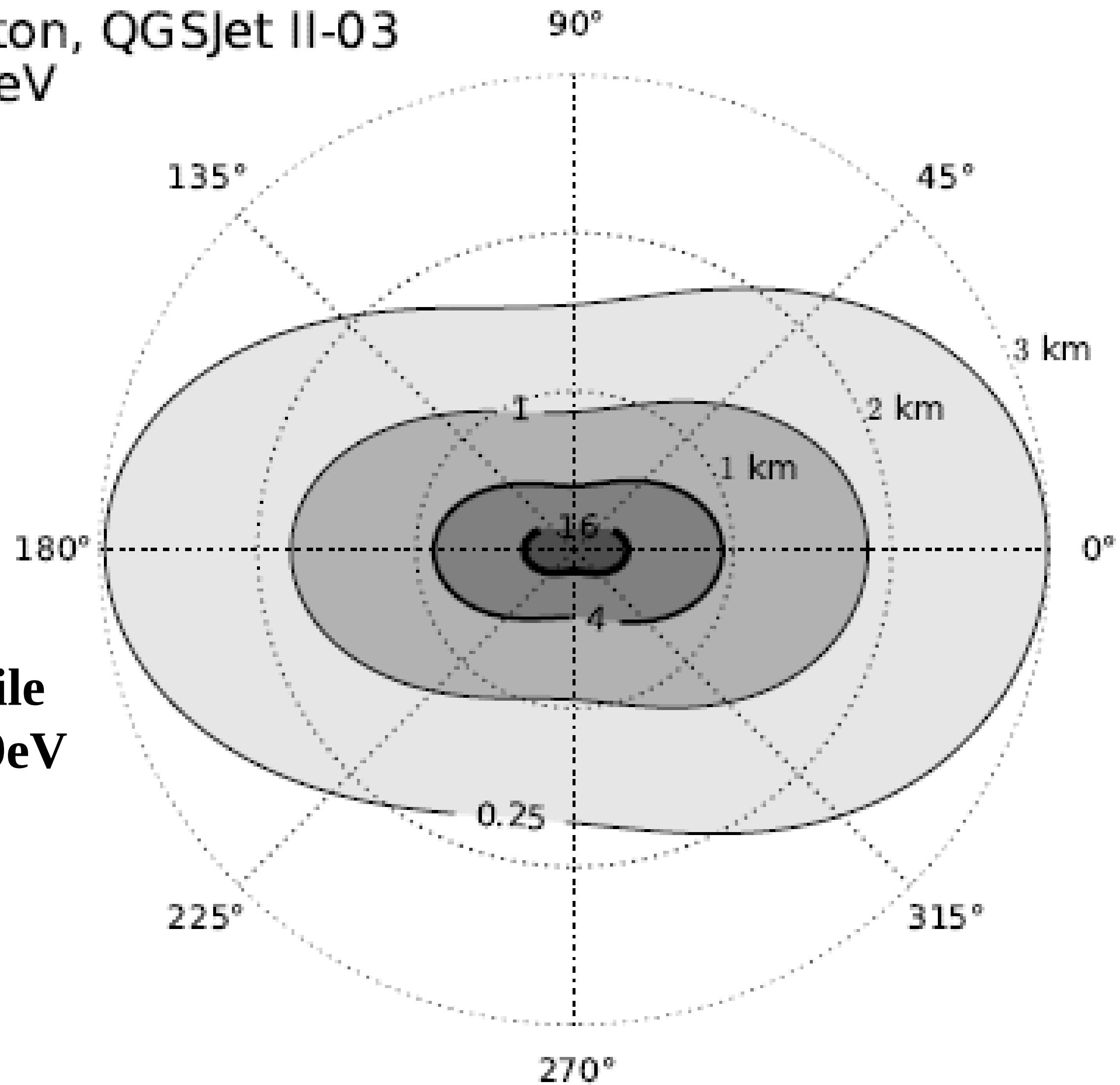
Muon content can be measured directly in inclined showers



37 stations
71°
54 EeV

Fit made to density distribution

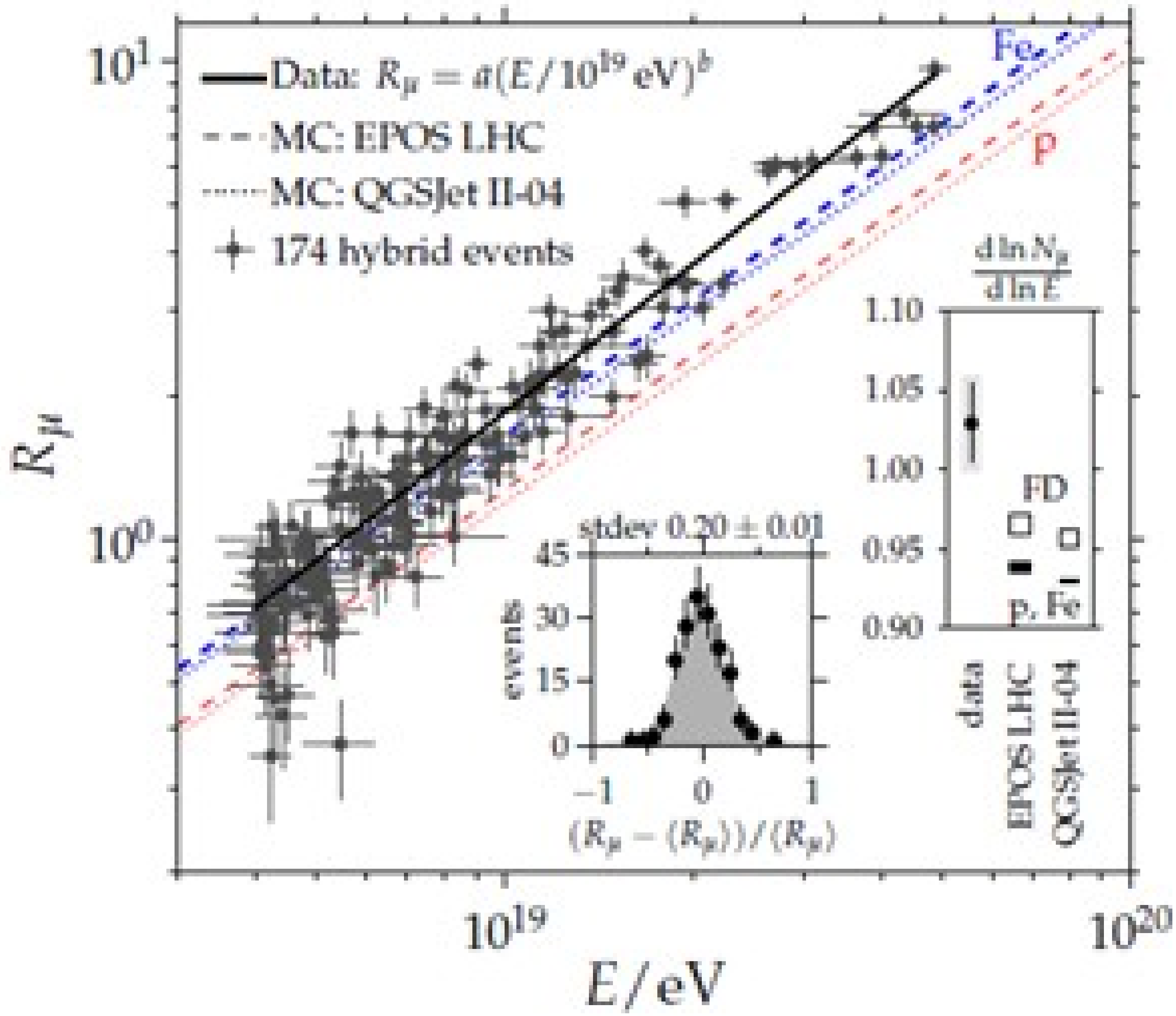
Energy measured with ~20 % accuracy



$$\rho_\mu(\vec{r}) = N_{19}\rho_{\mu,19}(\vec{r};\theta,\phi)$$

Average muon density profile of simulated-proton of 1019eV

Maps such as these are compared and fitted to the observations so that the number of muons, Rμ, can be obtained



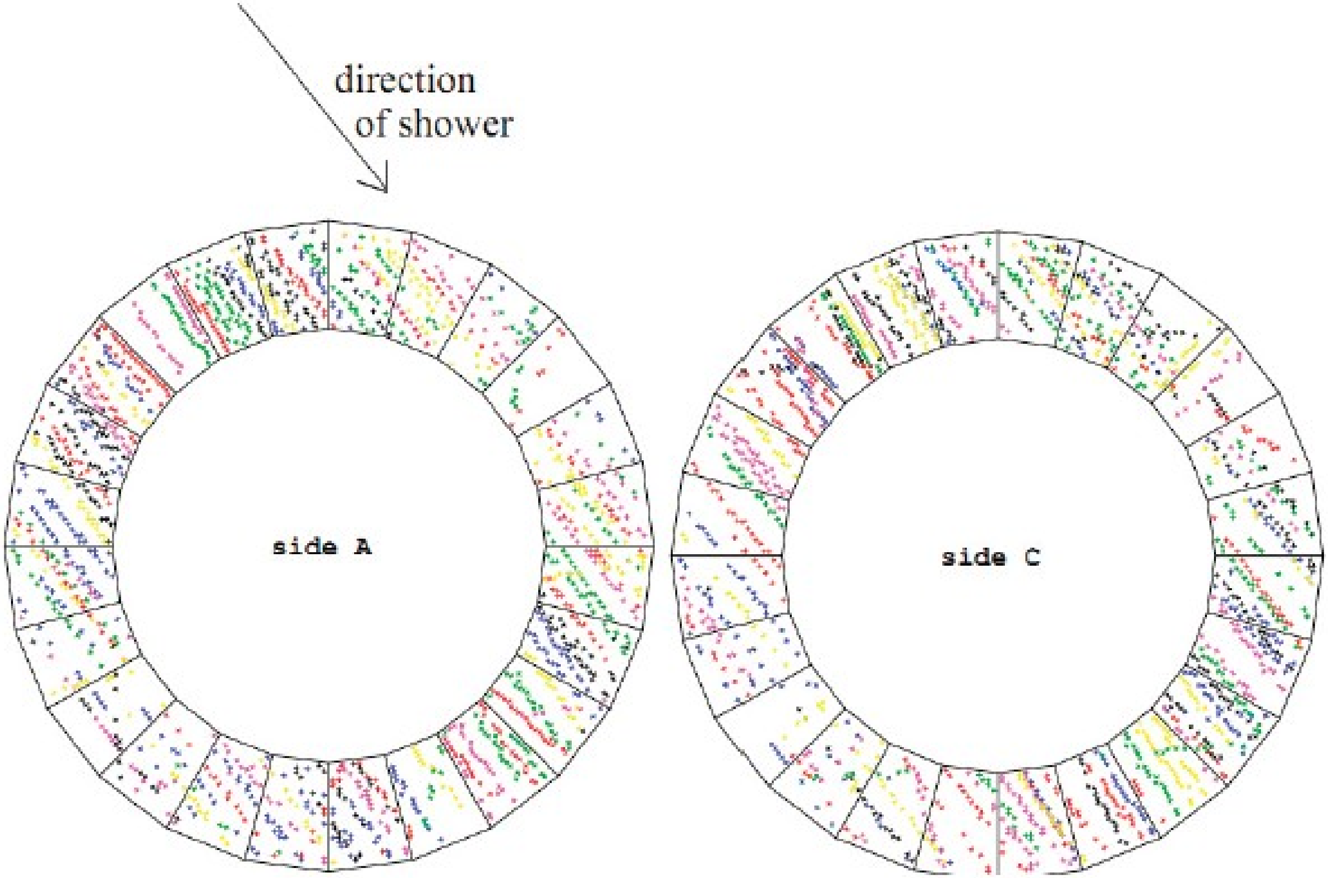
There seem to be more muons than expected in large showers

DELPHI as a cosmic ray detector

- rock overburden: vertical cutoff ~ 52 GeV
- cosmic measurement in concurence with normal run: effective uptime ~ 18 days

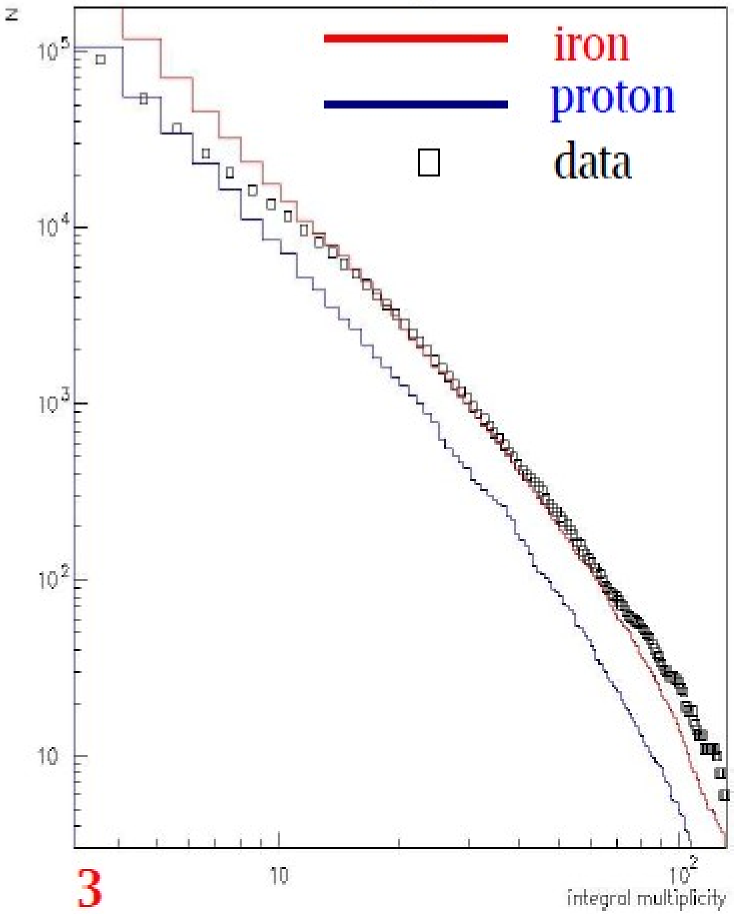
Bundles of parallel tracks in HCAL

- not every muon reconstructed (shadowing, saturation, non-active areas)
- high-multiplicity events mainly from EAS between 10^{15}–$10^{17.5}$ eV
- excess w.r.t contemporary simulations

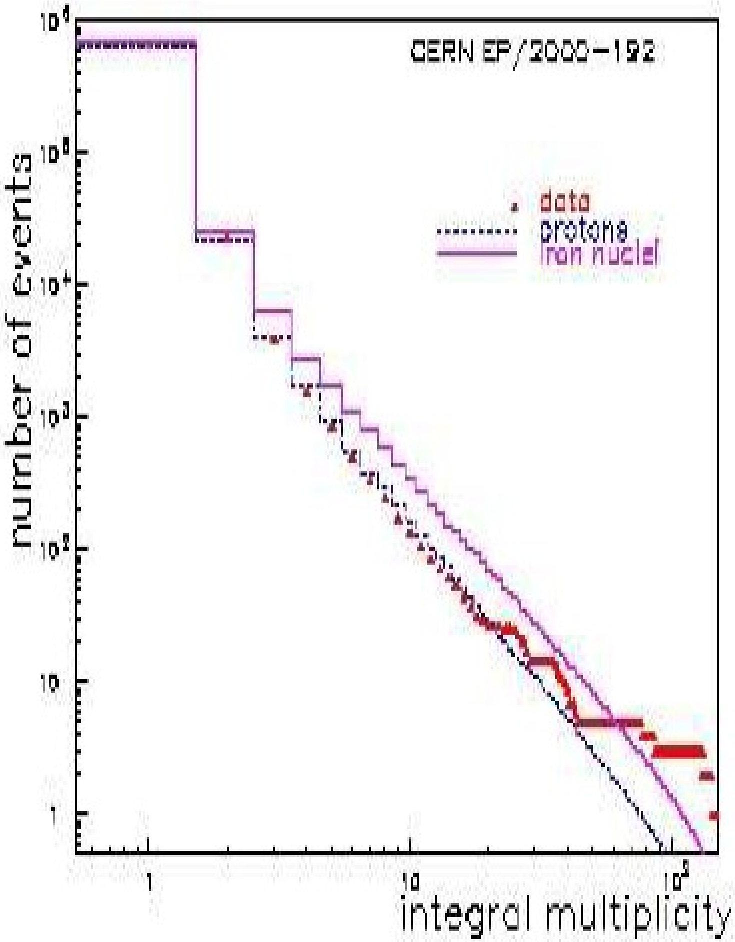


Results

Delphi



Aleph



Summary

There is e ... **ube/IceTop and the Auger Ob** ... **ers,** ***where the muon*** ... **lict with predictio** ... **onic physics (ALICE r** ...

What doe ... **air-shower measuren** ...

Clearly o ... **matic uncertainty** ***(which in*** ... **still a lot that we can learn** ...

Arrival Direction studies

- **The cosmic-ray sky is remarkably isotropic, even at the very highest energies**
- **This probably reflects the high charge of the particles and magnetic fields that lie between us and the sources – or there could be a huge number of sources**
- **There may be hot-spots in the sky at the highest energies**
- **There is evidence for a dipole anisotropy 8 EeV**
- **What is seriously lacking is an ability to look for anisotropies as a function of particle charge**

This should be a strong motivation for future experiments

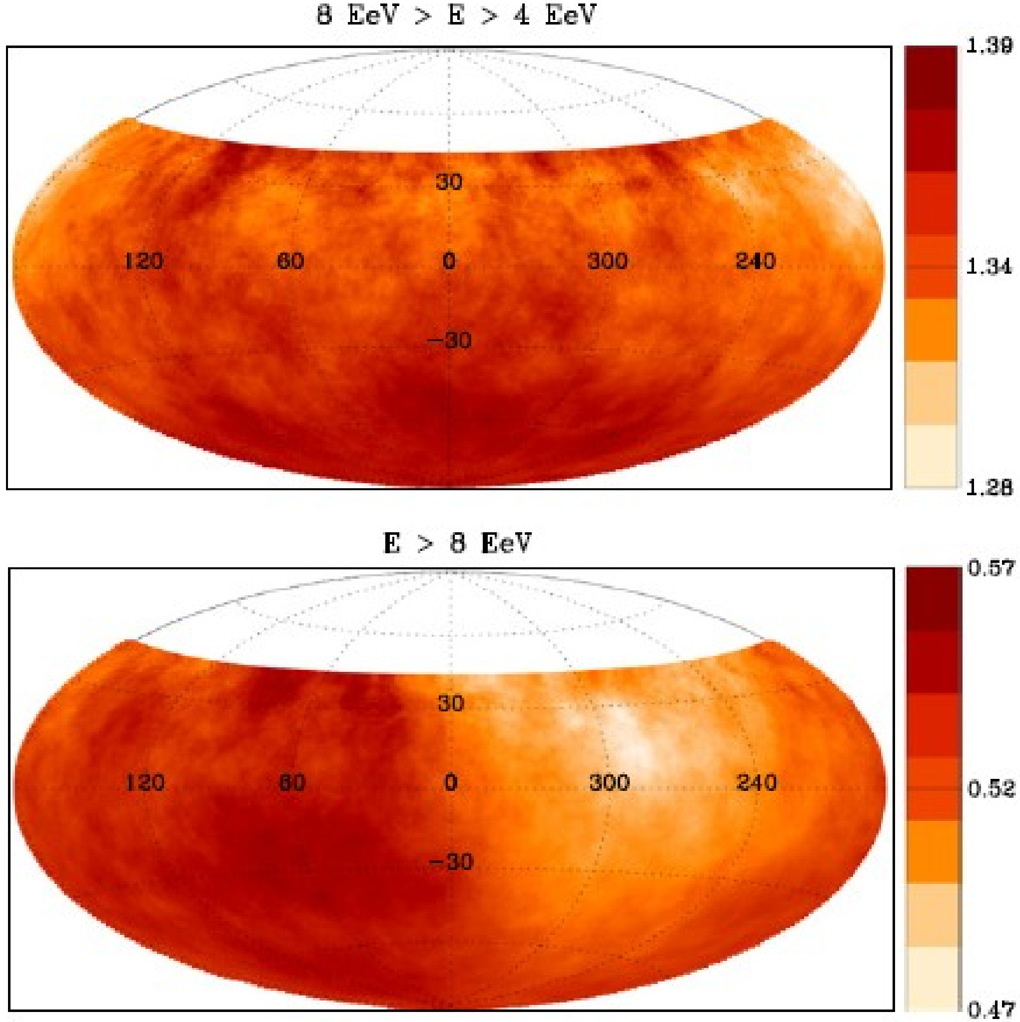
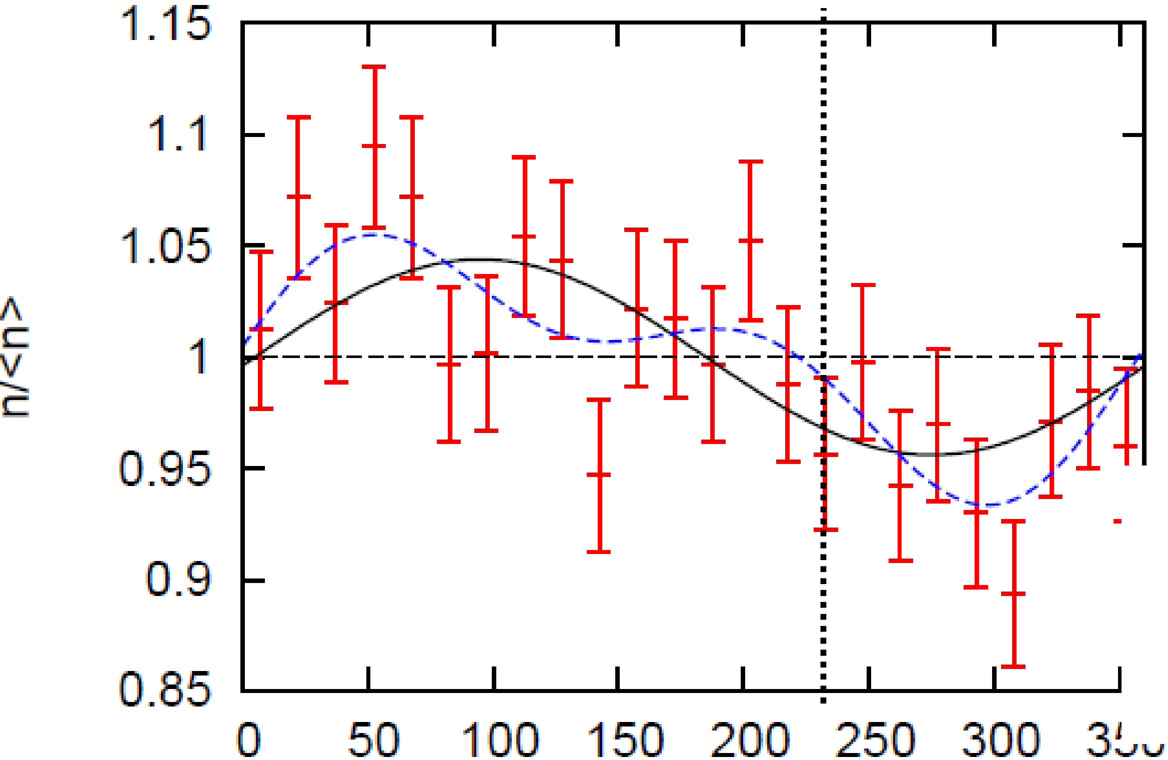


Figure 3. Sky map in equatorial coordinates of flux, in $km^{-2}\ yr^{-1}\ sr^{-1}$ units, smoothed in angular windows of 45° and for the two energy bins.



4% excess is in anti-centre Direction above 8 EeV

Auger Collaboration

Ap J 802 111 2015

Table 2
First Harmonic Analysis in Solar and Antisidereal Frequencies

	E (EeV)	r_1	φ_1 (h)	$P(\geqslant r_1)$
Solar	4–8	0.0110 ± 0.0063	14	0.21
…	>8	0.005 ± 0.010	17	0.86
Antisidereal	4–8	0.0046 ± 0.0063	8	0.76
…	>8	0.017 ± 0.010	13	0.24

Table 1: Rayleigh analysis in right ascension

E [EeV]	N	k	a_k^α	b_k^α	r_k^α	φ_k^α	$P(\geq r_k^\alpha)$
4 – 8	50,417	1	0.0020 ± 0.0062	0.0008 ± 0.0062	0.0021	15°	0.88
						99°	0.98
> 8	19,797	1	-0.004 ± 0.010	0.044 ± 0.010	0.044	95°	6.4×10^{-5}
		2	0.009 ± 0.010	0.027 ± 0.010	0.028	36°	0.021

Evidence of extragalactic origin above 8 EeV?
Harari et al.: arXiv 1507.06585

Measuring the energy spectrum at higher energies

- **At energies below around 30 PeV, the energy spectrum is model dependent**

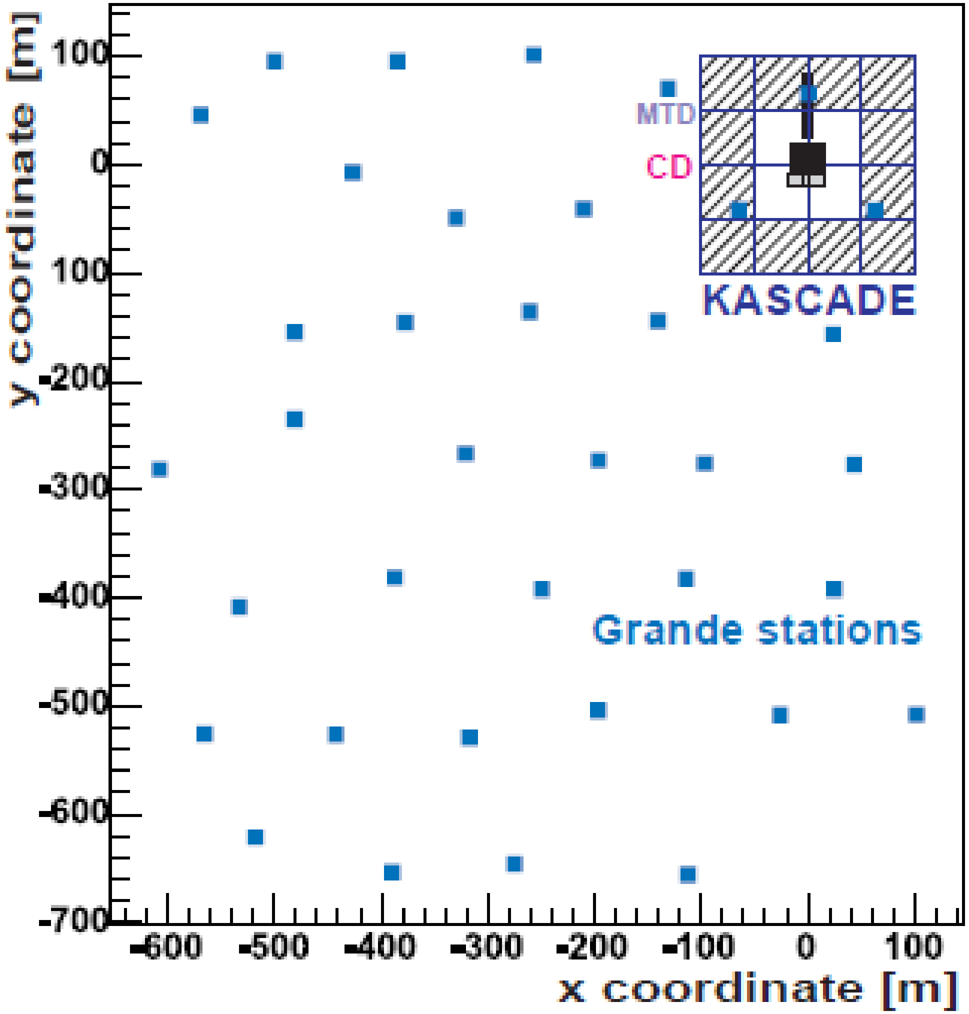
However, features can be identified with skilful use of the basic data using common sense (KASCADE and KASCADE-Grande)

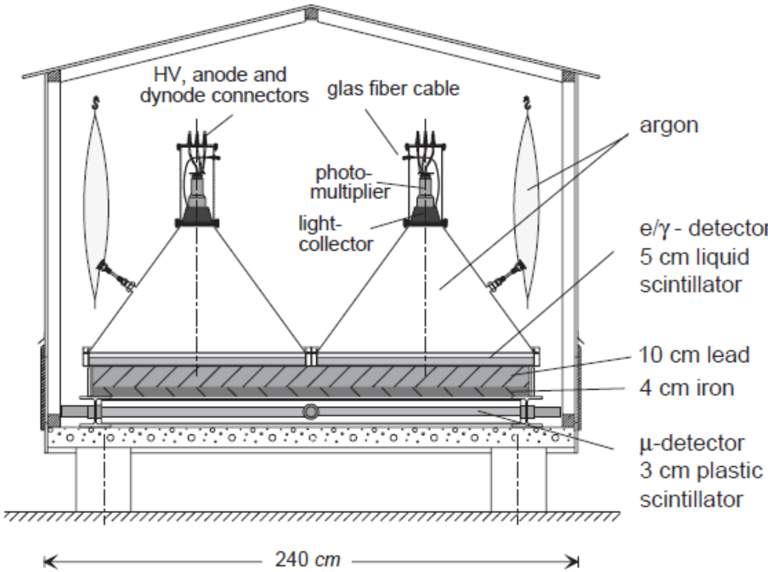
- **The dependence on models becomes SMALLER as one moves to higher energies**

  Above ~ 0.3 EeV fluorescence radiation acts as a calibration tool

  There is a dependence on models but this is relatively small

  This is an advantage of the hybrid technique used at Auger Observatory and TA (see later talks)

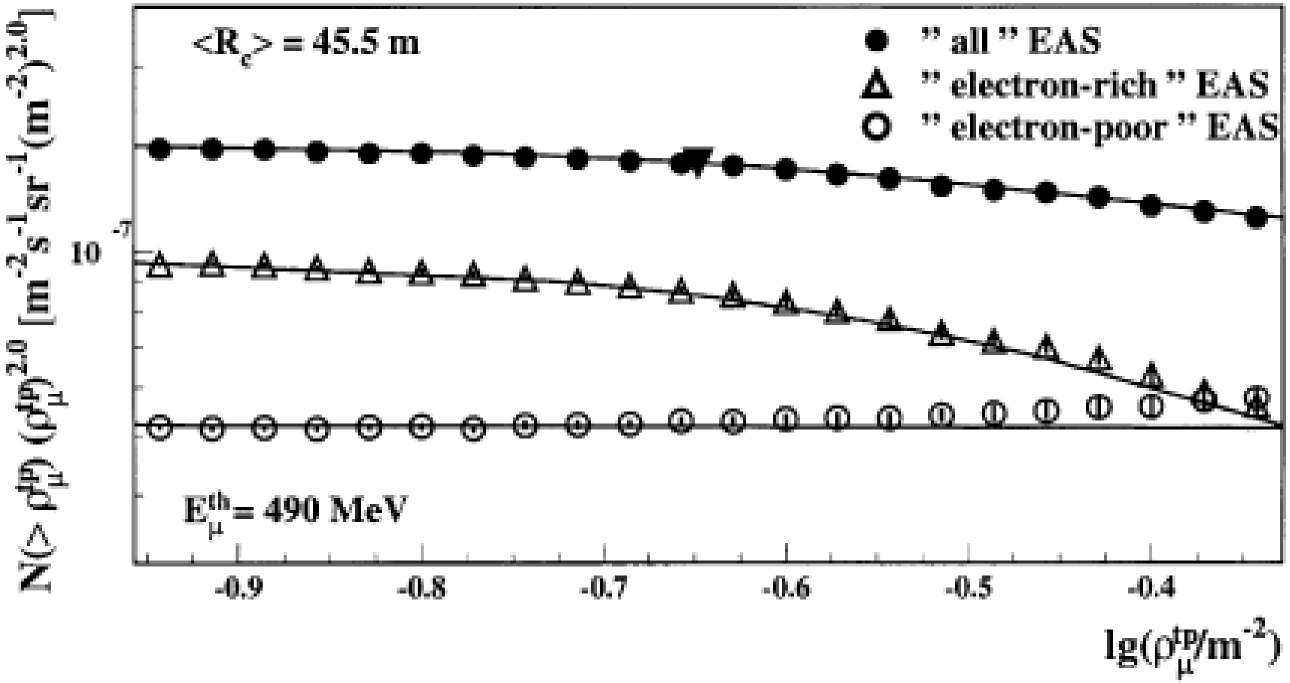


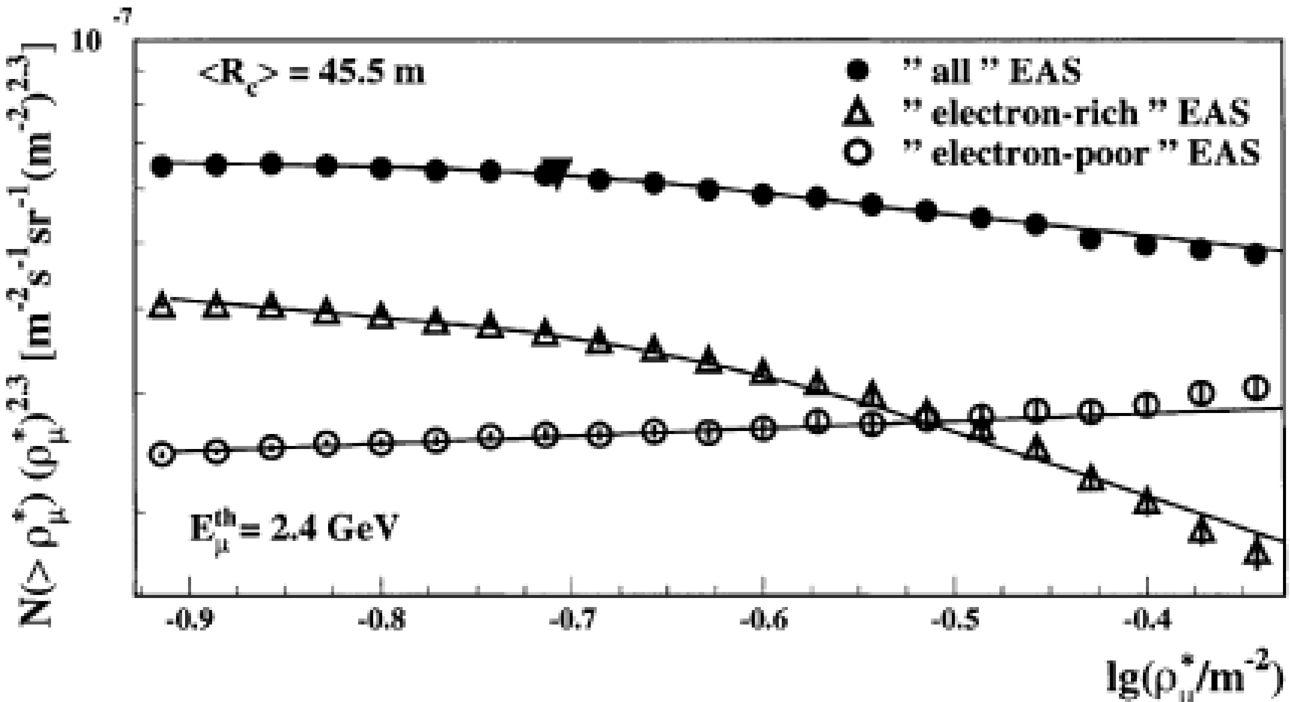


KASCADE and KASCADE-Grande

Data on first and second knees

Model-free analysis of KASCADE data showed that knee was a 'light' nucleus feature





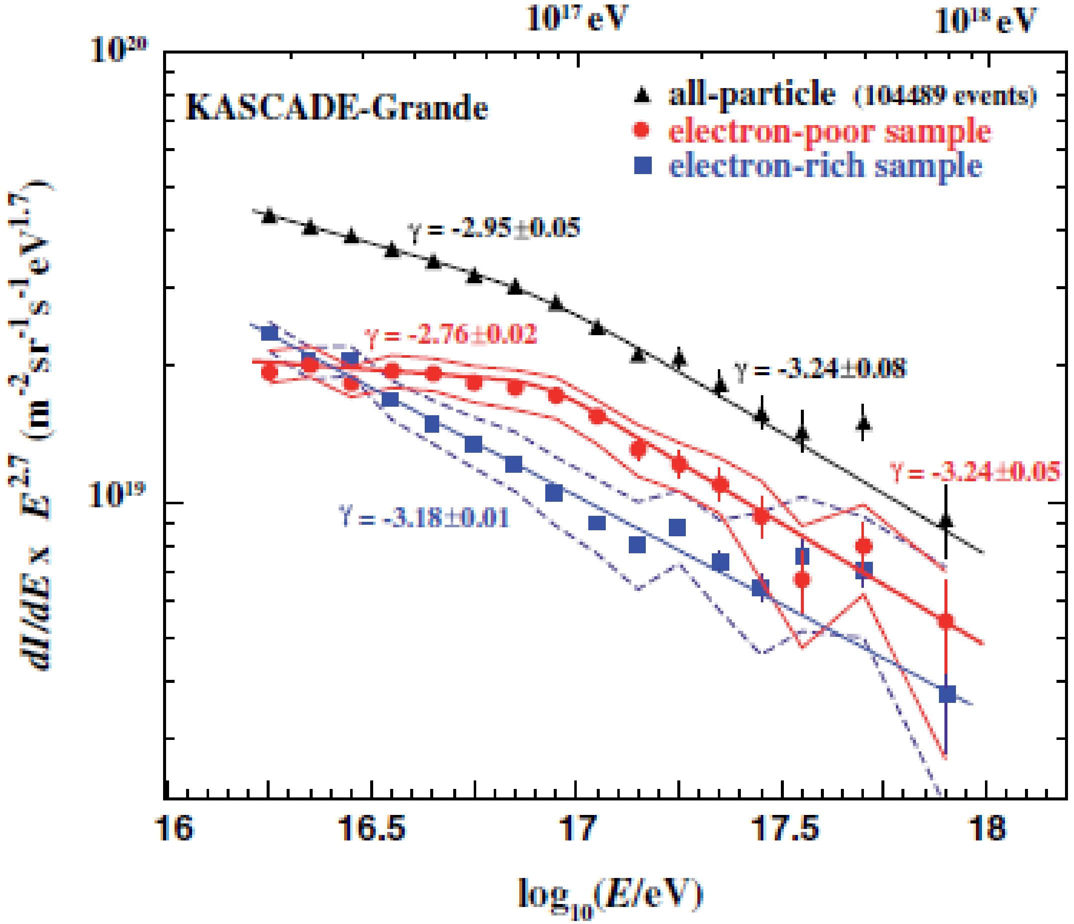
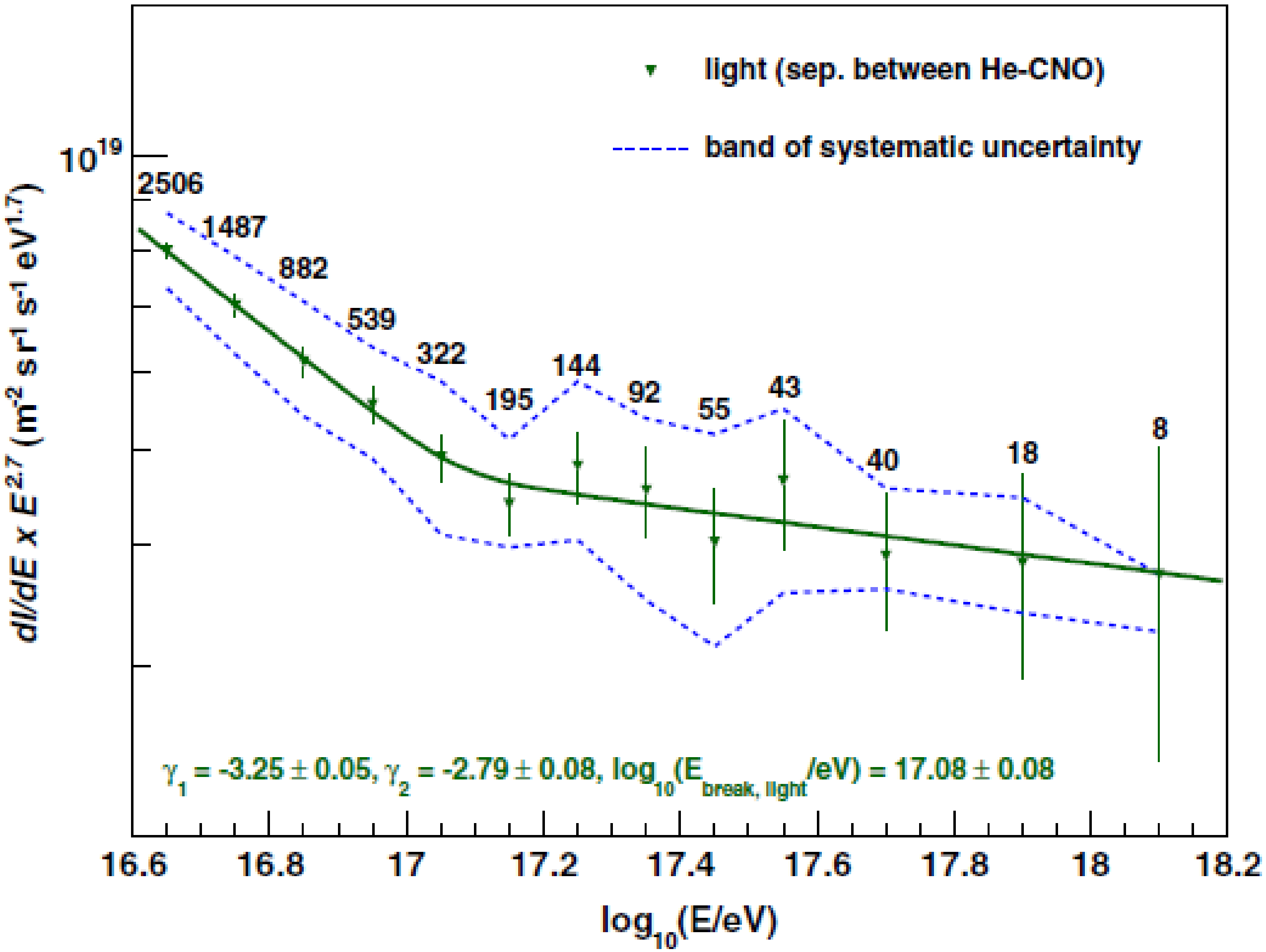


FIG. 4 (color online). Reconstructed energy spectrum of the electron-poor and electron-rich components together with the all-particle spectrum for the angular range 0°–40°. The error bars show the statistical uncertainties; the bands assign systematic uncertainties due to the selection of the subsamples. Fits on the spectra and resulting slopes are also indicated.

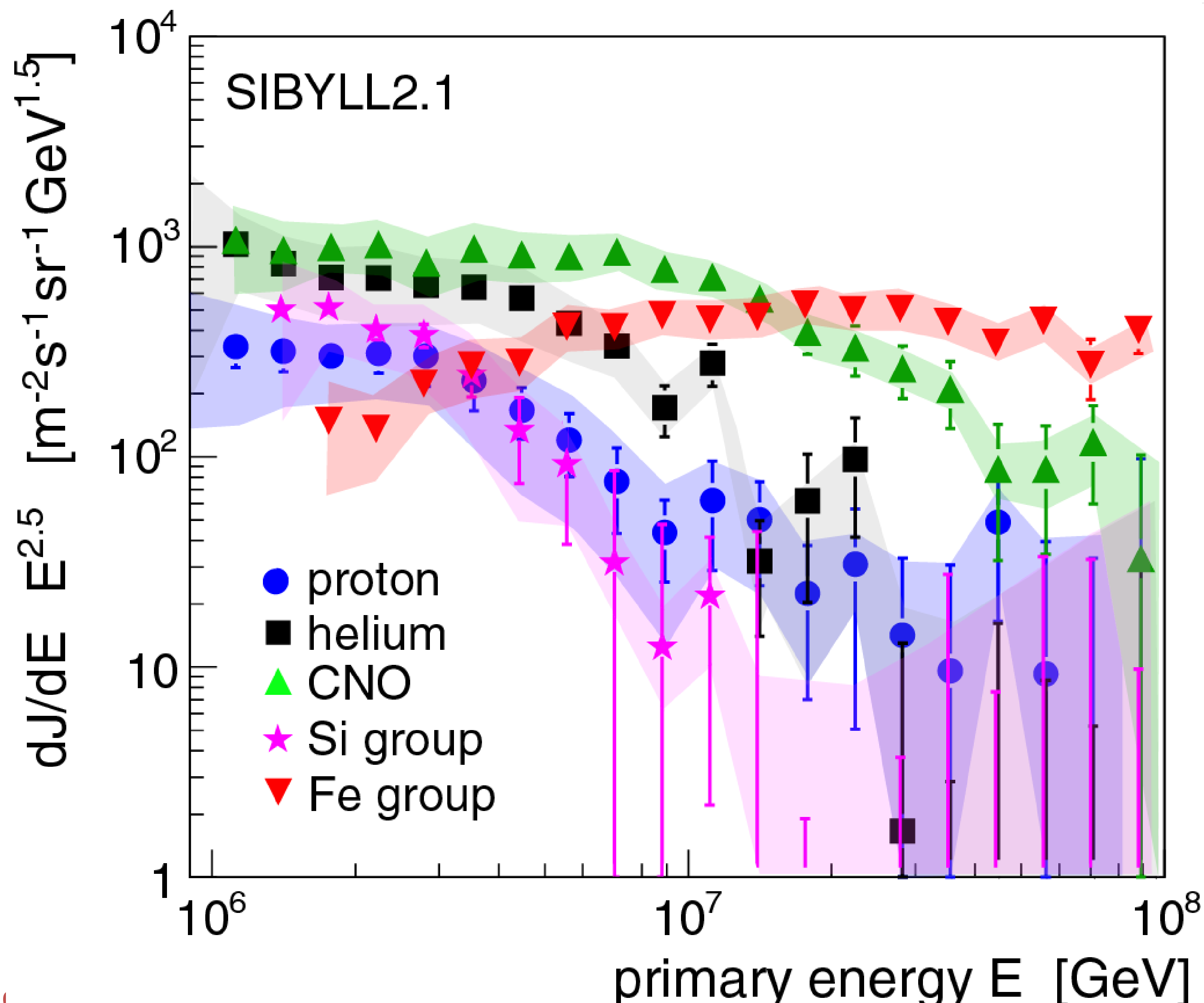
PRL 107 171104 2011



With more events

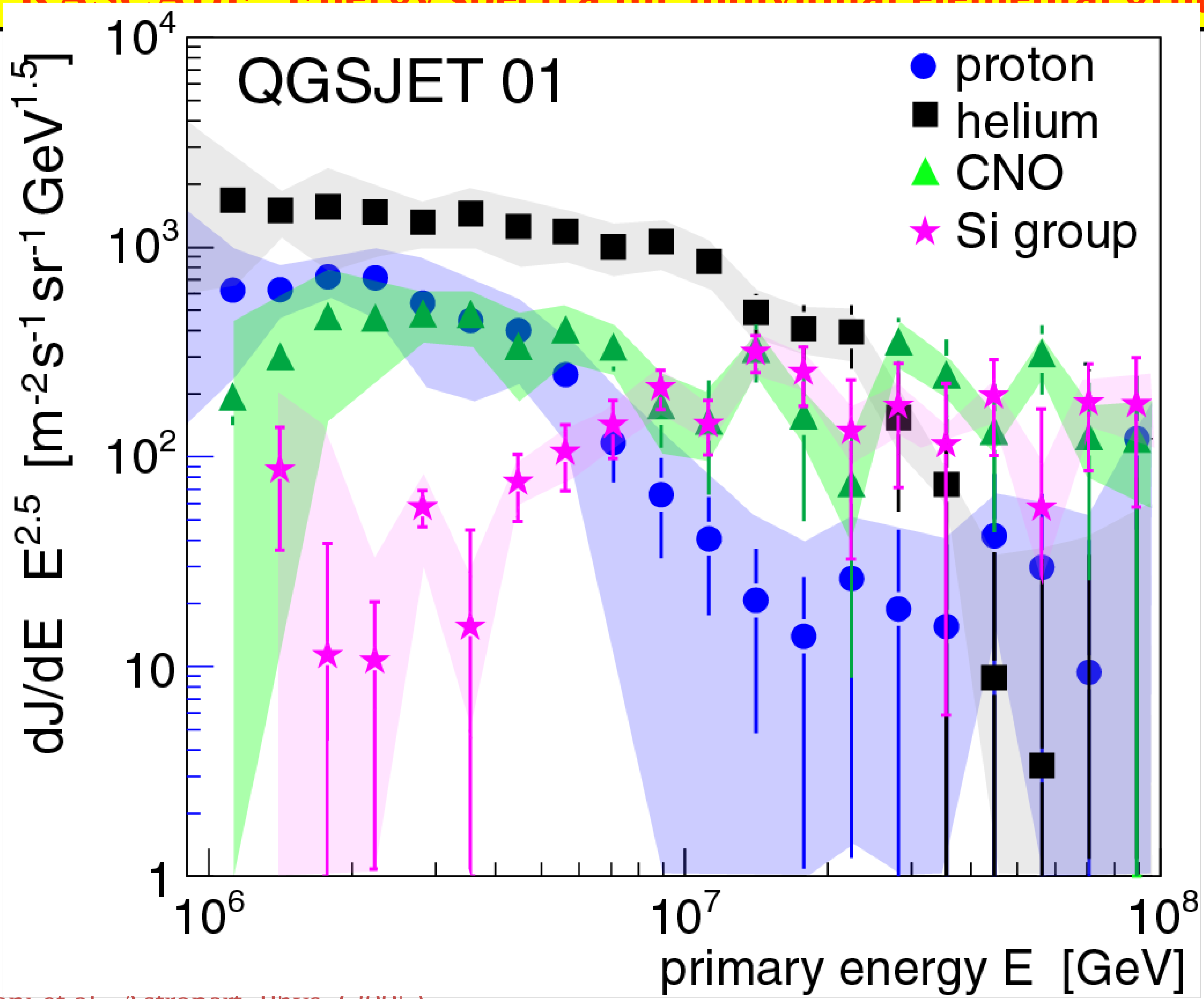
FIG. 5 (color online). The reconstructed energy spectrum of the light mass component of cosmic rays. The number of events per energy bin is indicated as well as the range of systematic uncertainty. The error bars show the statistical uncertainties.

KASCADE: Energy spectra for individual elemental groups



T. Antoni

KASCADE: Energy spectra for individual elemental groups



T. Antoni et al., Astropart. Phys. (2005)

Comparison of features at the knee
ALL PARTICLE SPECTRUM

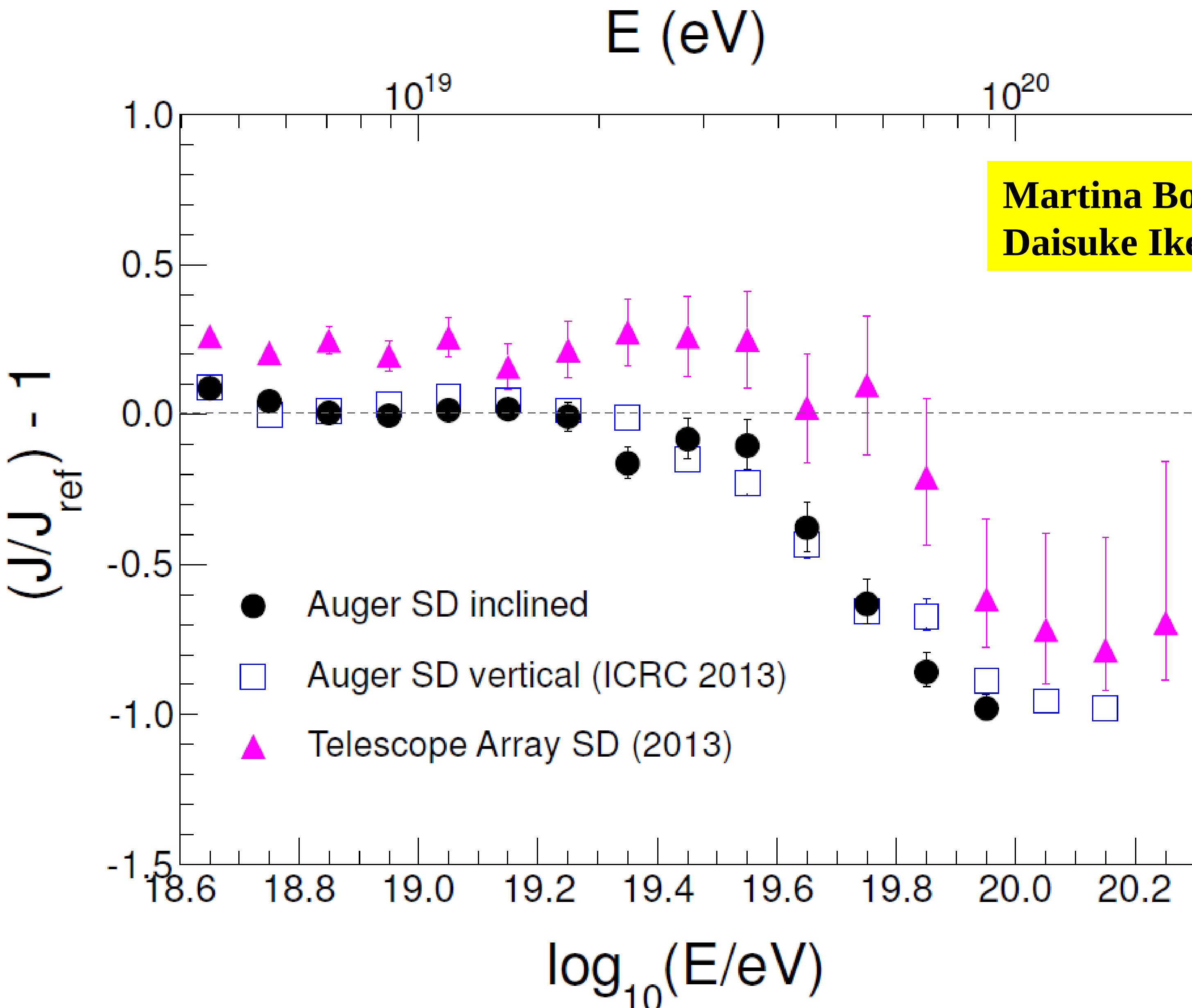
	Knee	$\gamma 1$	$\gamma 2$
QGSJET01	**4.0 +/-0.8 PeV**	**-2.70 +/- 0.01**	**-3.10 +/- 0.07**
Sibyll 2.1	**5.7 +/- 1.6 PeV**	**-2.70 +/- 0.06**	**-3.14 +/- 0.06**

This gives a strong warning about the sensitivity of spectral details to mass and models – and this is at LOW energies

Should be considered when predicting photons from hadronic processes – should show systematic uncertainties in predicted flux from hadronic processes

Comparison of two Auger Spectra with Telescope Array

Martina Bohacova
Daisuke Ikeda



Auger and Telescope Array spectra

- Auger spectrum is now measured up to a declination of 25.3°N, well into Telescope Array range – inter-group studies on-going

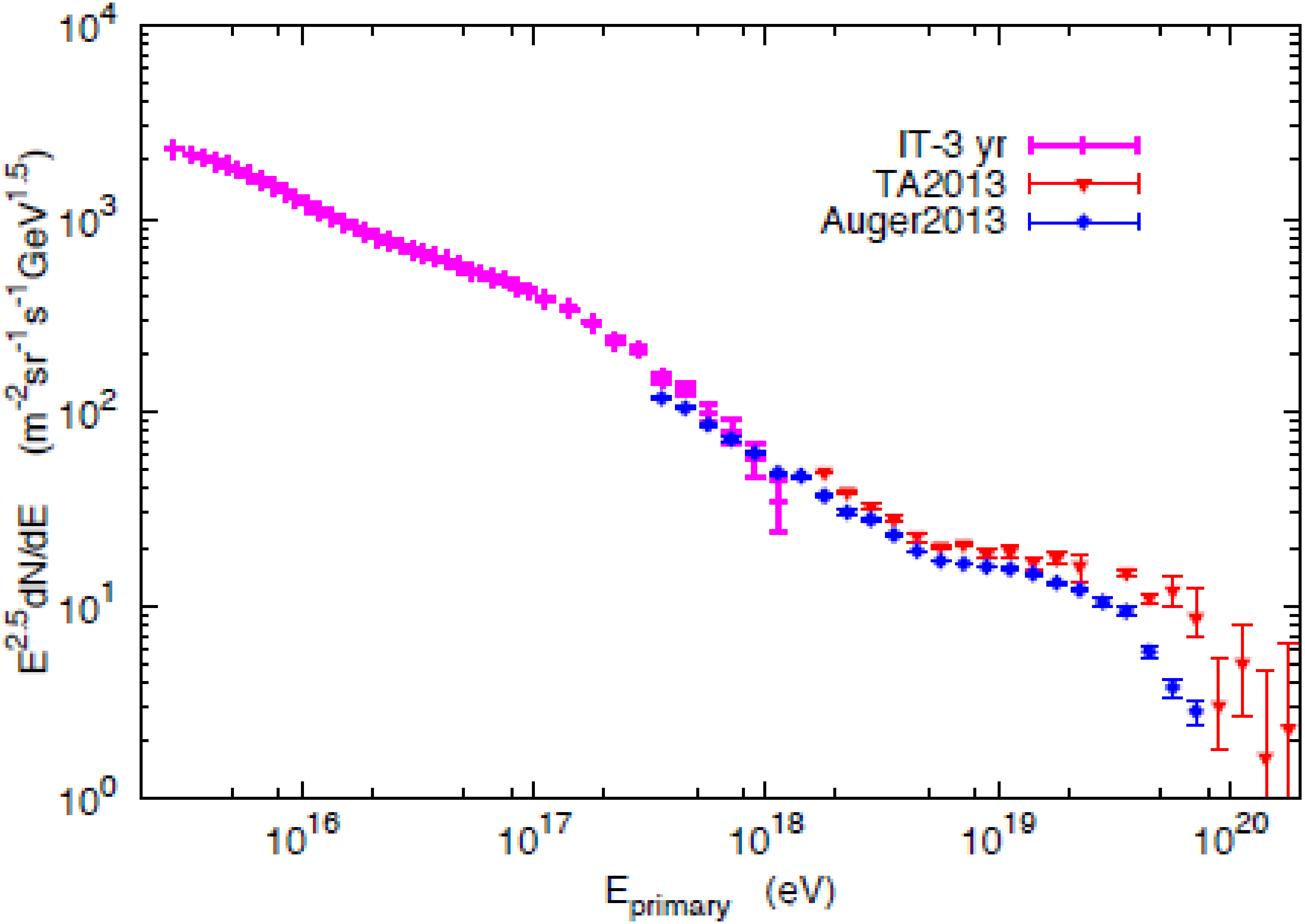
- Up to suppression region, TA and Auger spectra agree quite well
  Average TA residual is 23%.

- In suppression region the differences are large and may be due to

  Anisotropy effects
  Atmospheric (Vertical aerosol depth as function of height)

- Energy and mass dependence of model used by TA in conversion

  Different assumptions about composition
  invisible energy
  fluorescence yield



Summary by Gaisser, KIT October 2016

Search for UHE neutrinos at the Auger Observatory

ELSEVIER Astroparticle Physics 8 (1998) 321–328

On the detection of ultra high energy neutrinos with the Auger observatory

K.S. Capelle [a], J.W. Cronin [a], G. Parente [b], E. Zas [b]

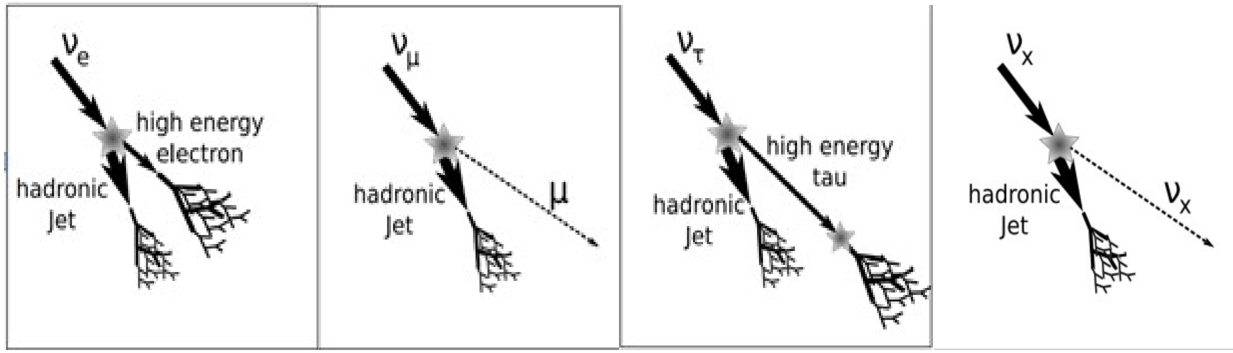
Parente and Zas: Venice Meeting 1996, arXiv 960609

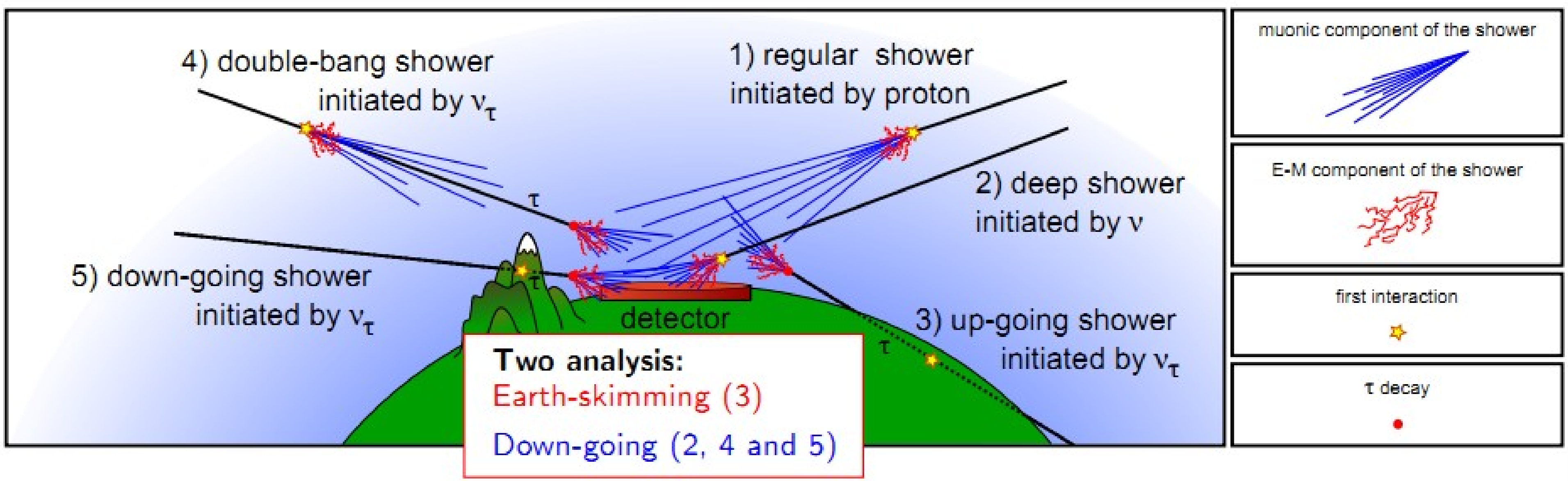
τ at EeV may decay before reaching the ground
→ Secondary shower (Double Bang event)

Also interactions in mountains or upward-going in earth

Letessier-Selvon A 2001 *AIP Conf. Proc.* **566** 157 (*Preprint* astro-ph/0009444)
Fargion D 2002 *Astrophys. J.* **570** 909 (*Preprint* astro-ph/0002453)
Fargion D 2003 *Proc. Int. Conf on Neutrino Telescopes, Venice* vol 2, pp 433–55 (*Preprint* hep-ph/0306238)

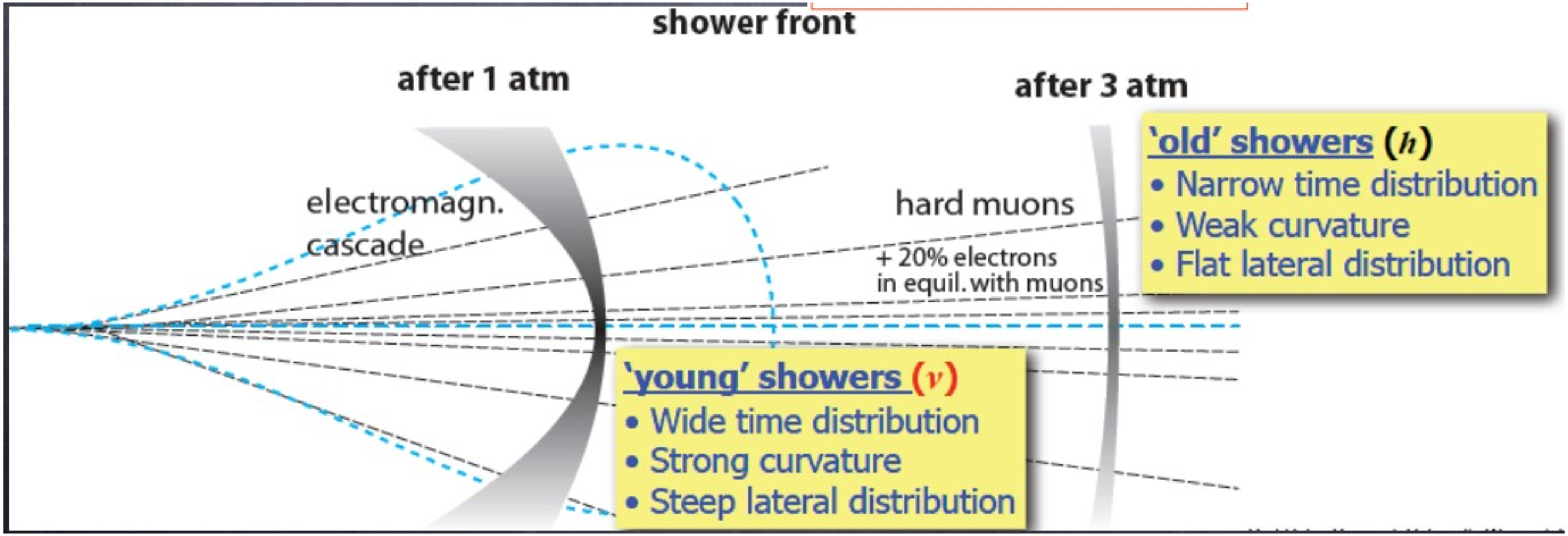
$$p + \gamma_{CMB} \longrightarrow \pi \longrightarrow \nu$$



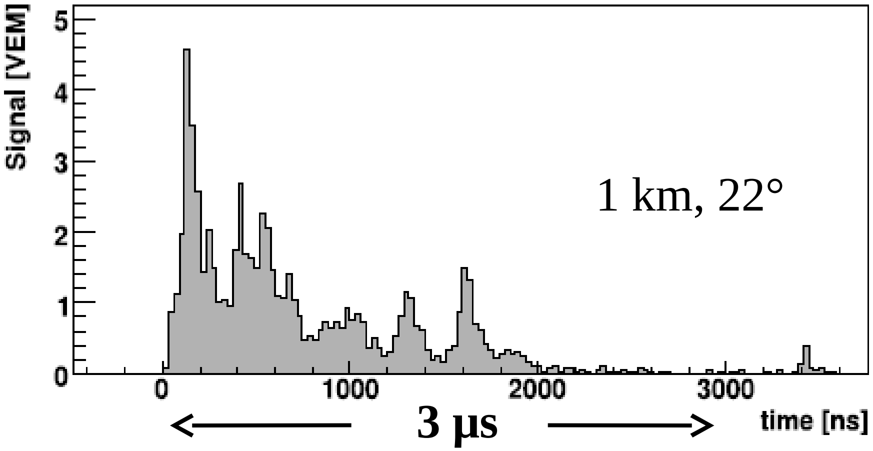


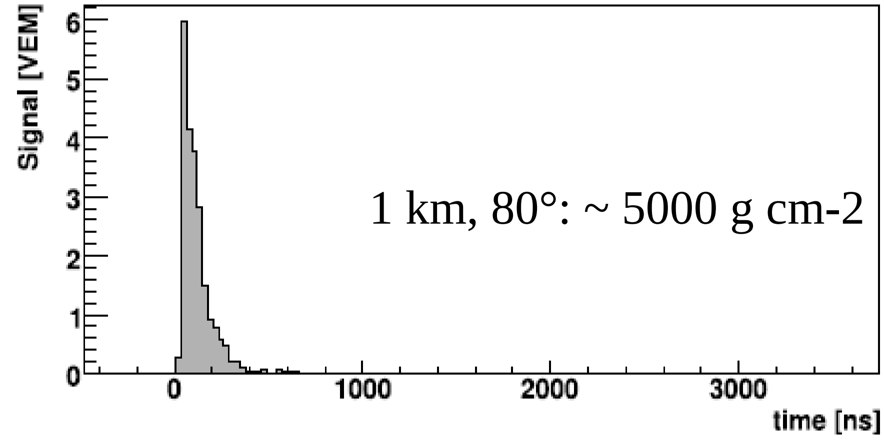
Search Method for neutrinos

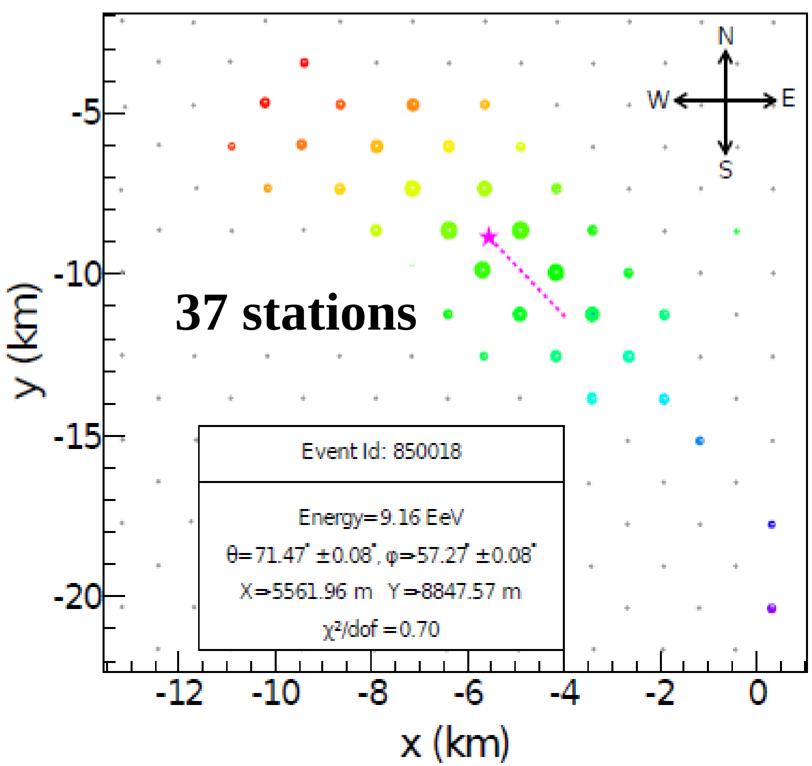
Look for inclined, BUT young, showers

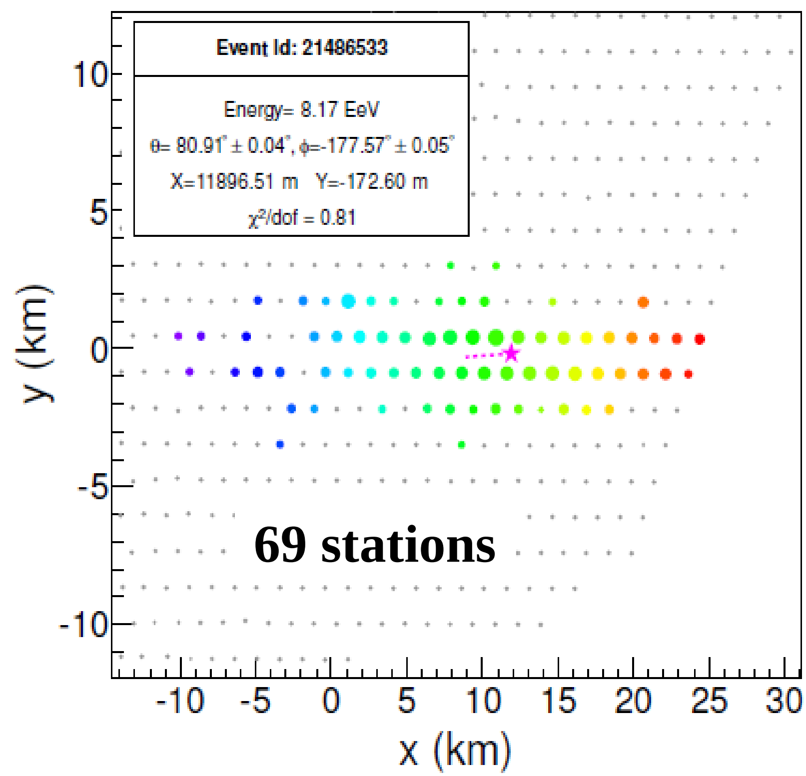


Using inclined showers to look for neutrinos









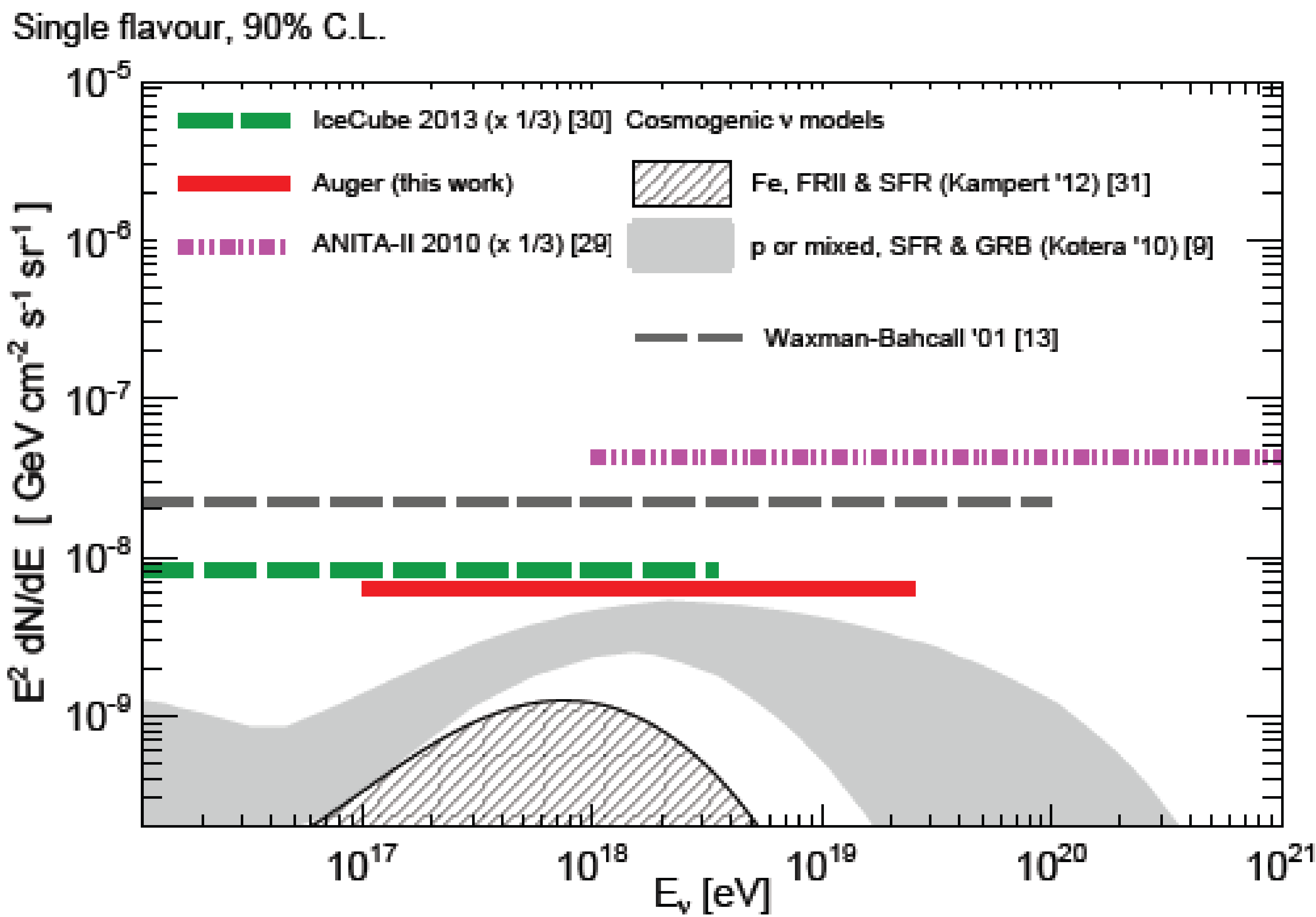


Figure 4. Top panel: Upper limit (at 90% C.L.) to the nor-
malization of the diffuse flux of UHE neutrinos as given in
Eqs. (2) and (3), from the Pierre Auger Observatory. We

Summary of experimental data discussed above

- **Knee features are seen in p, He, C and Fe spectra**
- **Flattening of proton spectrum at about 1017 eV**
- **Ankle at ~ 4 EeV and steepening at ~ 50 EeV clearly established**
- **Mass composition getting heavier above the ankle (still some dispute)**
- **Strong evidence for dipole anisotropy in Auger data above 8 EeV**
- **No neutrinos seen (at level similar to IceCube)**

Exploring the ‘dip’ model of the ankle

Does it arise from pair-production by extragalactic protons?

There has been a long-standing belief, pushed very strongly by Venya Berezinsky and colleagues, that the ankle is indicative of a bite being taken out of source proton-spectrum because of pair-production

$$p + \gamma\mathrm{CMB} \rightarrow e^{+} + e^{-} + p$$

Theory predicts almost pure protons in ankle region

What would be the resultant neutrino flux?

There will also be a diffuse photon flux at Fermi energies from UHECR

Implications of mass result for detection of cosmogenic neutrinos

(Ave, Busca, Olinto, aaw, Yamamoto 2005; Hooper, Taylor and Sarkar 2005)

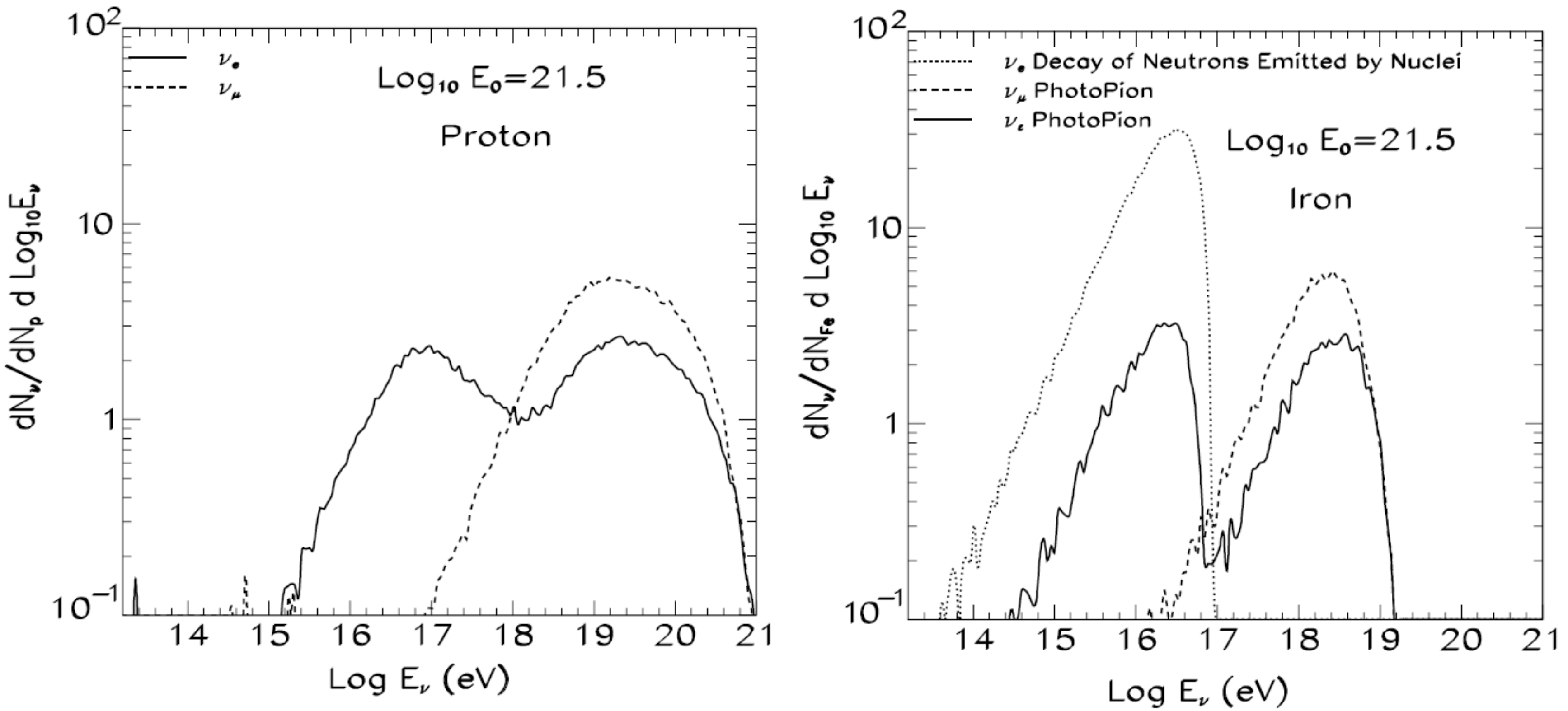


Figure 1: The neutrino yield for a proton primary (left) and an iron primary (right). In each case the initial energy was chosen as $10^{21.5}$ eV and the propagation distance was 300 Mpc. The different origins of the neutrinos are shown. The dotted line in the right-hand diagram shows the neutrino flux that arises from the decay of neutrons from photodisintegration processes. The figure is from [3].

Neutrino argument and the Ankle Region:
Heinze et al. arXiv 1512.05988 (HBBW)

Assume that the TA spectrum measurement and interpretation of pure protons is correct

Scan simultaneously over

- **Spectral index at injection**
- **Source Evolution**
- **Maximum proton energy**

Predict the neutrino flux and compare with IceCube

3D best fit: log (Emax/GeV) = 10.7 +0.3 /0.1; **m = 4.3** +0.4/-0.8; **γ = 1.52** +0.35/-0.20

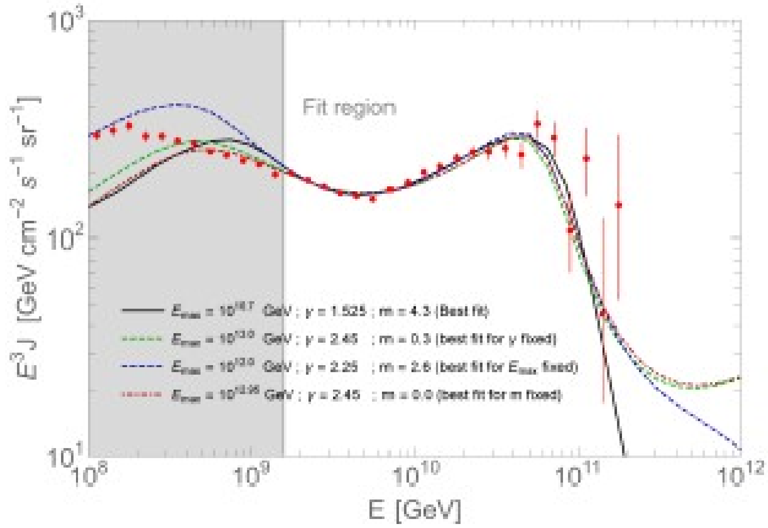


FIG. 3: Best-fit UHECR spectra for 3D scan (solid curve) and 2D scans (dashed/dotted curves), superimposed on the TA 7-year data [2, 66]. Here the energy scale of the data points is fixed while that of the models is for each one shifted by the best fit value.

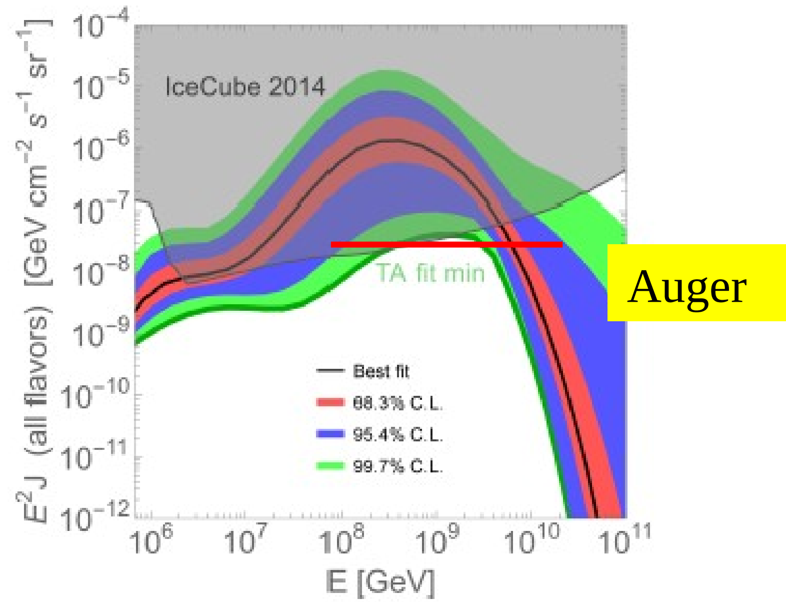


FIG. 4: All-flavor flux of cosmogenic neutrinos predicted by the 3D fit to the TA 7-year UHECR spectrum reported in Sec. III. The IceCube experimental upper limit is taken from Ref. [63].

	ν events
Best fit	180.6
68.3% C.L. min flux	62.7
95.4% C.L. min flux	12.4
99.7% C.L. min flux, **TA fit min**	4.9

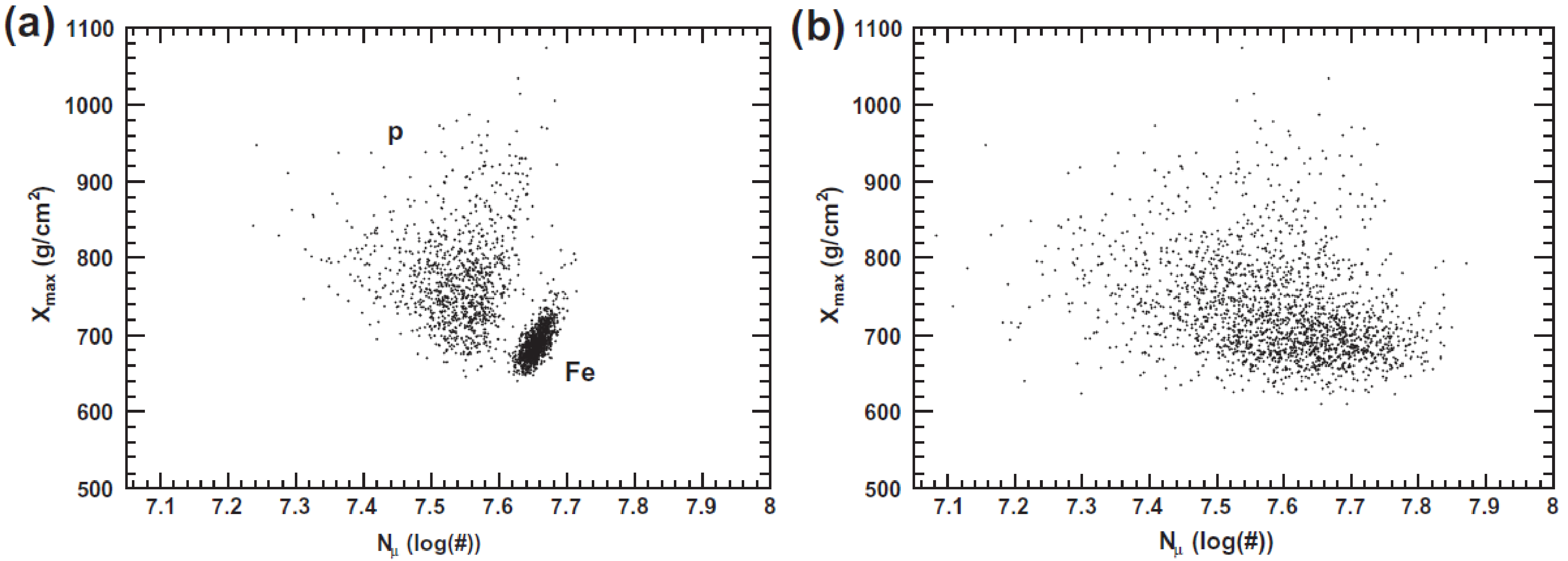
TABLE I: Expected number of cosmogenic neutrino events in IceCube, corresponding to the 7-year UHECR TA best-fit, and to the minimal fluxes within the 68.3%, 95.4%, 99.7% C.L.

IceCube and Auger predictions from 3D scan appears to exclude proton-dip model strongly

Heavier composition, *à la Auger*, is favoured
(or some additional component in ankle region)

Xmax and S(1000) correlation in the Ankle Region

Studies with simulations show that there is good separation between species in the Xmax- Nμ plane (Younk and Risse 2012)



But, in reality, we cannot measure Nμ

S(1000) can be used as a surrogate: ICRC 2015 Auger collaboration

Yushkov et al. (for Auger Collaboration) ICRC 2015 and submitted to Physics Letters B

Also demonstrates non-proton dominance in dip region

Data set used is that for composition studies

$18.5 < \log (E/eV) < 19.0$, $\theta < 65°$: 1376 events

Scaled to 38° and 10 EeV, using elongation rate of 58 g cm-2

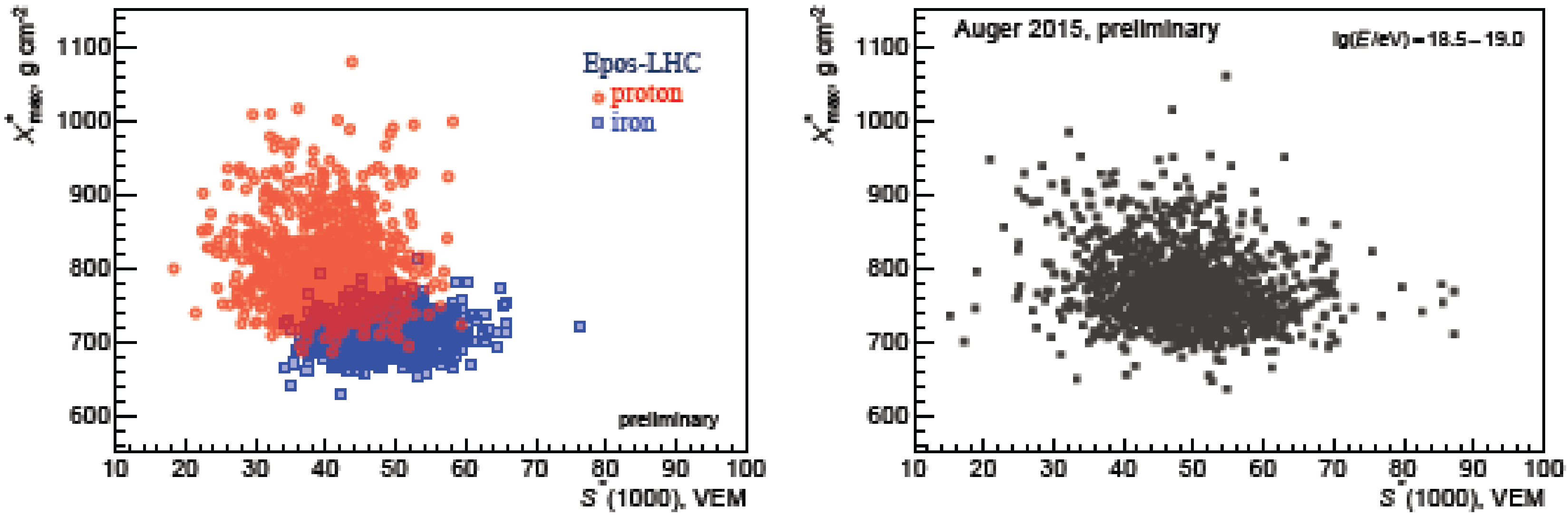


Figure 1: Scatter plot of X^*_{max} vs $S^*(1000)$ for protons and iron of Epos-LHC from full detector simulations (left) and for data (right) for $\lg(E/\text{eV}) = 18.5 - 19.0$.

Table 1: $r_G(X^*_{max}, S^*(1000))$ for data and for MC simulations of pure beams (preliminary). Statistical uncertainties on the MC values are $\sigma_{stat} \approx 0.01$.

data	-0.125 ± 0.024 (stat)		
	Epos-LHC	QGSJetII-04	Sibyll 2.1
p	0.00	0.08	0.07
He	0.08	0.15	0.15
O	0.09	0.15	0.14
Fe	0.08	0.12	0.12

Conclusion: Composition in this energy range is mixed, not pure

Astrophysical Models

There are many and the data are not very constraining

John von Neumann famously said

> With four parameters I can fit an e wiggle
> his trunk.

By this he meant that one should not be in data set well.
With enough parameters, you can fit any d

Truth ... is much too complicated to allow anything but approximations.

New York and Parisian Ideas: Extragalactic sources

Globus, Allard and Parizot: arXiv 1505.01377

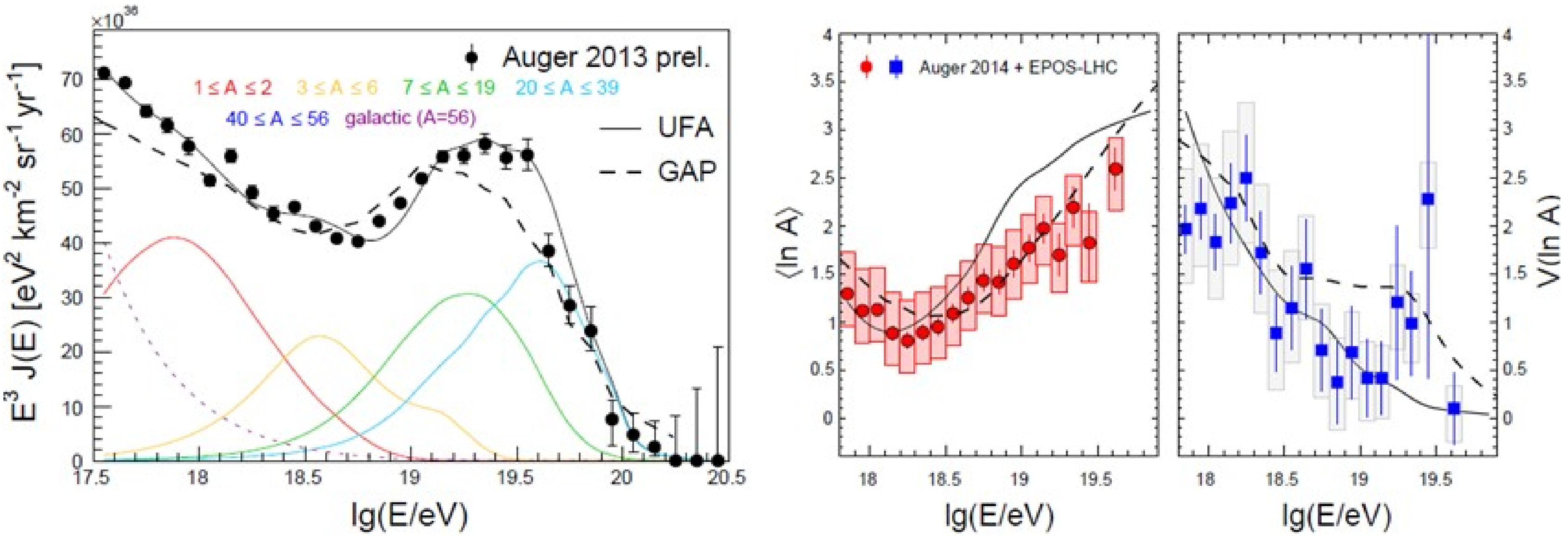
Unger, Farrar and Anchordoqui: arXiv 1505.02153

Acceleration in extragalactic sources surrounded by strong photon fields

Globus et al. Specific GRB model

Unger et al. More generic

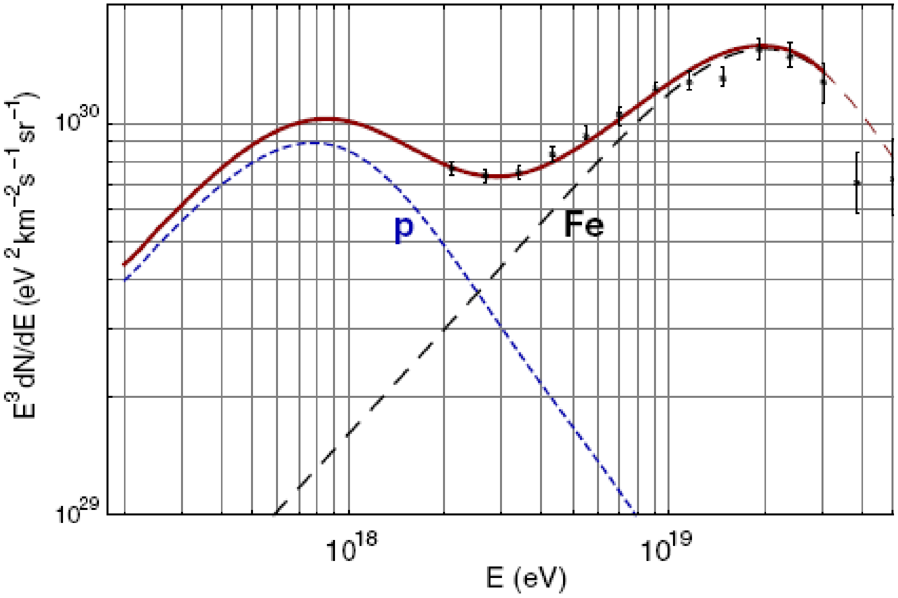
Fragmentation and propagation studied

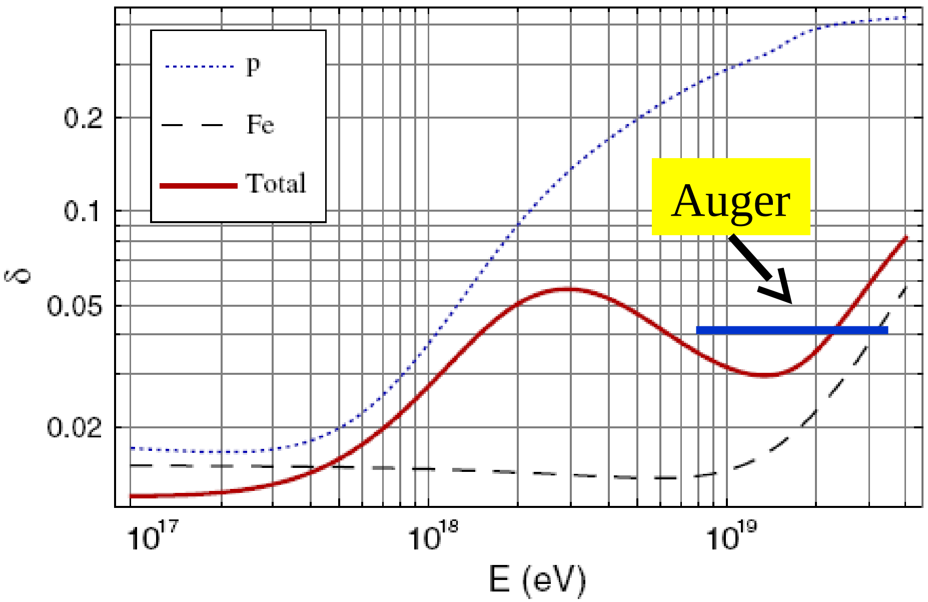


Auger 2013 prel.
1 ≤ A ≤ 2
3 ≤ A ≤ 6
7 ≤ A ≤ 19
20 ≤ A ≤ 39
40 ≤ A ≤ 56
galactic (A=56)
UFA
GAP
E^3 J(E) [eV^2 km^-2 sr^-1 yr^-1]
lg(E/eV)
Auger 2014 + EPOS-LHC
⟨ln A⟩
V(ln A)
lg(E/eV)
lg(E/eV)

Galactic Origin: Calvez et al. PRL 105 091101 2010

GRBs in our galaxy about every 105 years





Eichler et al: Galactic Origin? arXiv:1604.05721

Kumar and Eichler: ApJ 71 47 2014, arXiv:1311.1208

Argue that sources, such as GFBs, might be responsible and can keep the anisotropy low – but the magnetic fields seem contrived

But it is a measure of the need for better data that we cannot exclude such an idea

Need to be able to separate showers according to mass – *BUT IN LARGE NUMBERS*

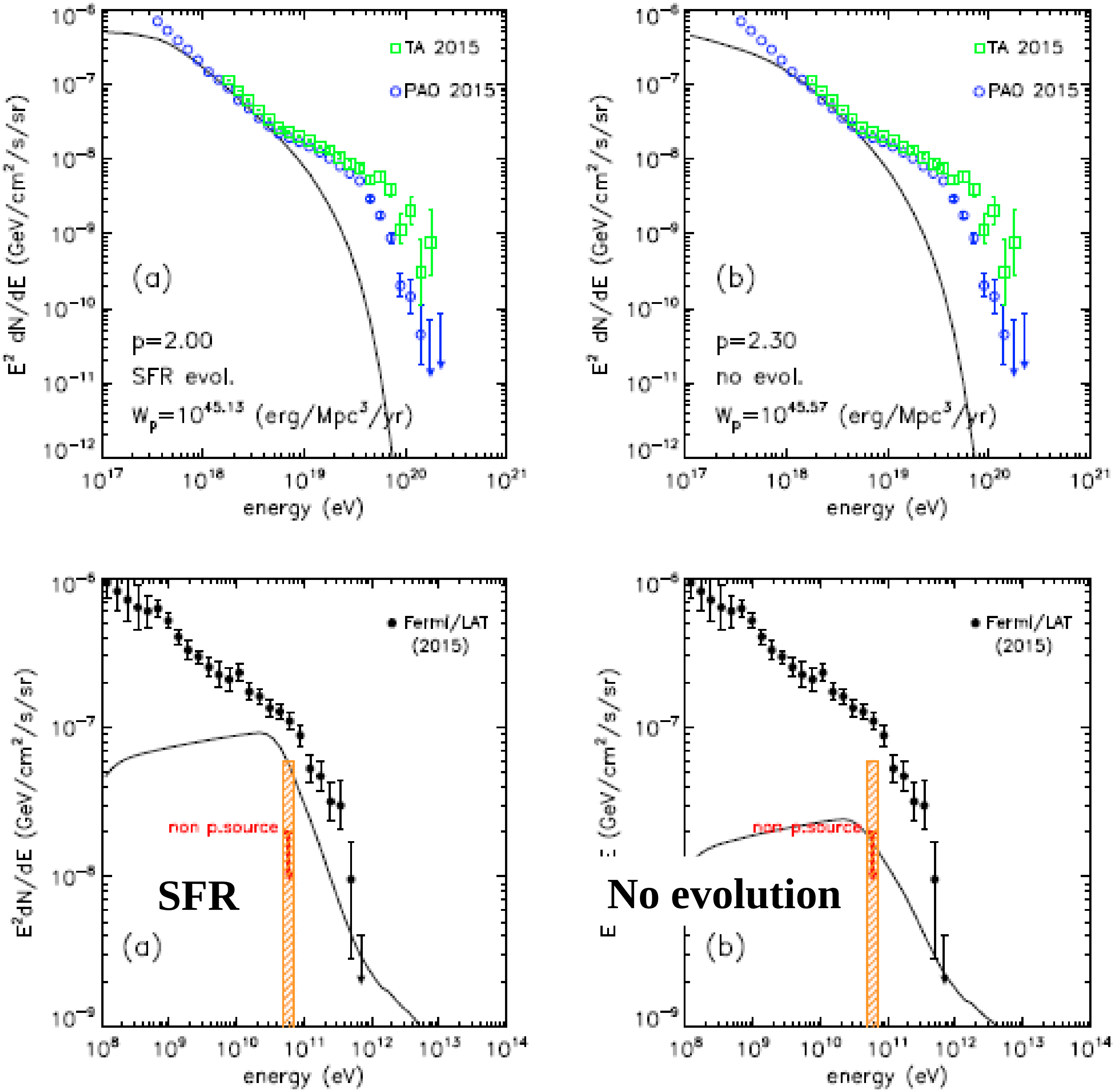
Will happen with Auger Prime at highest energies, and through more imaginative use of Surface Detector signals at lower energies, (talk by Gabriella Cataldi)

Many other ideas: A few from last 18 months…….

- **Repeated Peters' Cycle: Gaisser, Stanev and Tilav**
- **Electric Field acceleration near black holes: Manriquez**
- **'Disappointing model': Berezinsky et al**
- **Magnetars: Arons, Olinto and others**
- **Super-heavy dark matter: Olinto**
- **'Espresso Acceleration': Caprioli**
- **UHECR and black strings: de Souza et al**
- **Black Hole mergers: Kotera and Silk**
- **Magnetic Turbulence: Mezaros**

…………………..

Liu, Taylor, Wang and Aharonian: 1603:03223

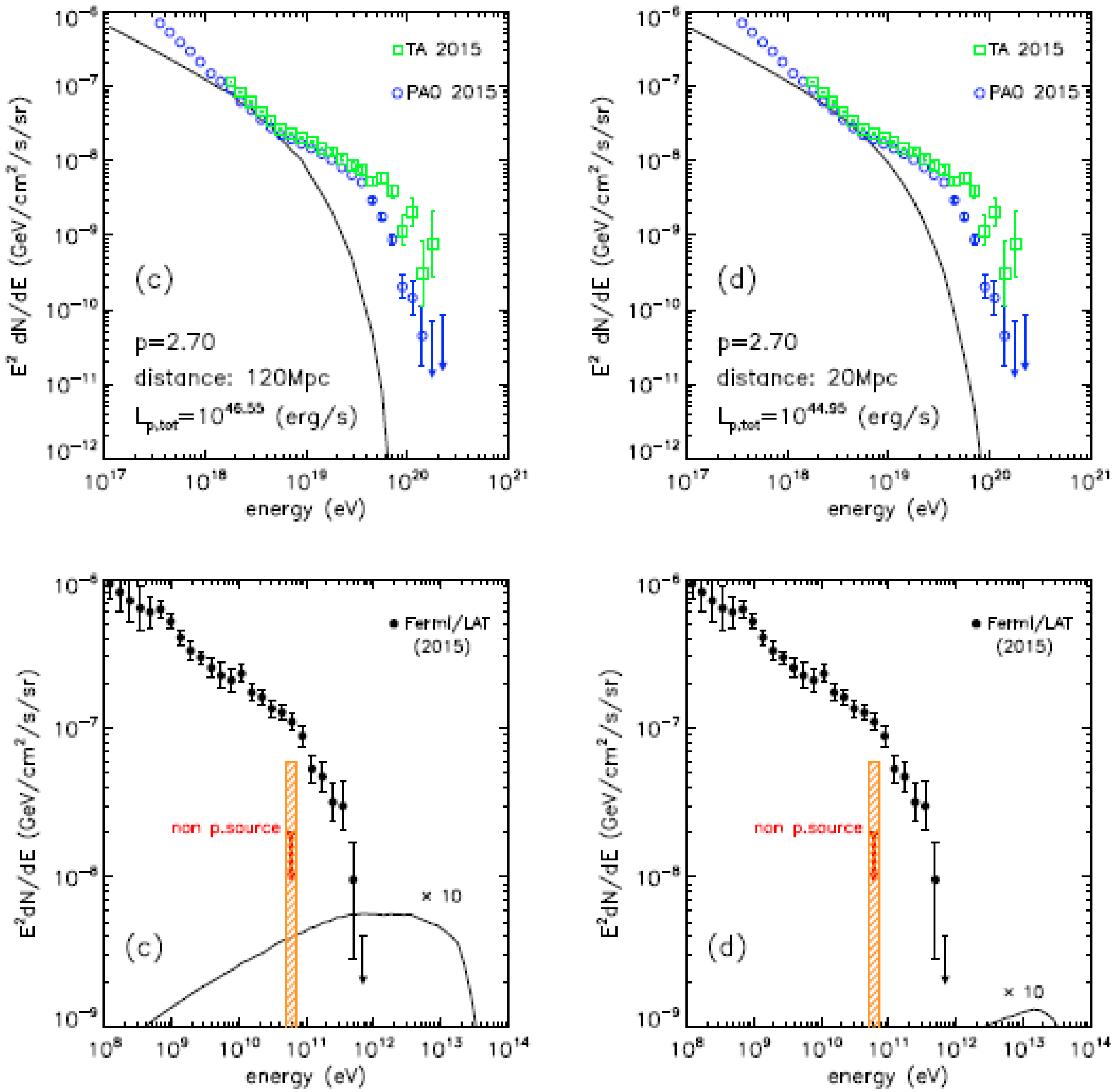


Uniform distribution of sources assumed

How does prediction of diffuse photon flux fit with Fermi data?

Gamma ray production can be reduced if sources are closer

120 Mpc



20 Mpc

Related analyses by Gavish and Eichler, arXiv 1603.04074

- favour SFR evolution

and by Berezinsky et al., arXiv 1606.09293 – not easy to follow

BUT - finds Aharonian et al. conclusions ‘rather extreme’!

The Future at the Highest Energies – immediate future

- **Separate particles as function of development for anisotropy studies:**
  FADC parameters with water-Cherenkov detectors
  Radio detection to measure Xmax , 24 hours per day
  (Benedikt Zimmermann)

- **Achieve greater exposures:**
  TA x 4 (Daisuke Ikeda)
  Continued operation of Auger Observatory
  JEM-EUSO and derivatives (Phillippe Gorodetsky)

- **Composition on shower-by-shower basis at highest energy with AugerPrime (Gabriella Cataldi)**

Long-term Future: private communication?

- **Auger Observatory is at least one-order of magnitude too small**

- **Planned space projects are very important: is there something interesting to measure beyond the present questions?**

Compare SPS and LEP

Young people working together and getting to know each other is necessary for any future World Observatory

Joint Working Groups – great success

How can a giant Observatory be created?

How can we take this concept forward?