High Energy Physics Group: Imperial College

6 March 2019

Recent results on Astrophysics and Particle Physics from studies of cosmic rays with the Pierre Auger Observatory

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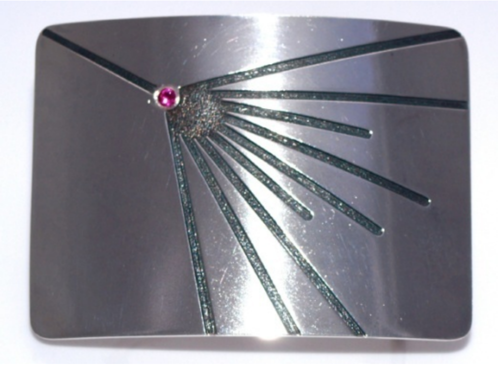
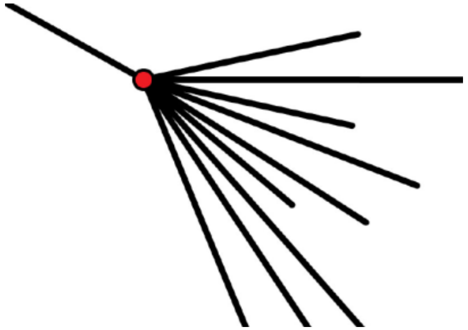




Outline:

- **Goals of UHECR (> 10^{18} eV, or 1 EeV) research**
- **Pierre Auger Observatory**
- **Energy Spectrum**
- **Arrival Directions – to show that we too get 5 σ results**
- **Hadronic models needed to get Mass Composition – limitation of conclusions so far**

  (no discussion of photon, neutrino or monopole searches: best limits available)

- **p-p cross-section up to 57 TeV centre-of-mass**
- **Anomalies between muon data and predictions**

Astrophysical Questions at the highest energies

- What are the sources?
- How are the particles accelerated?
- Does the energy spectrum terminate?

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

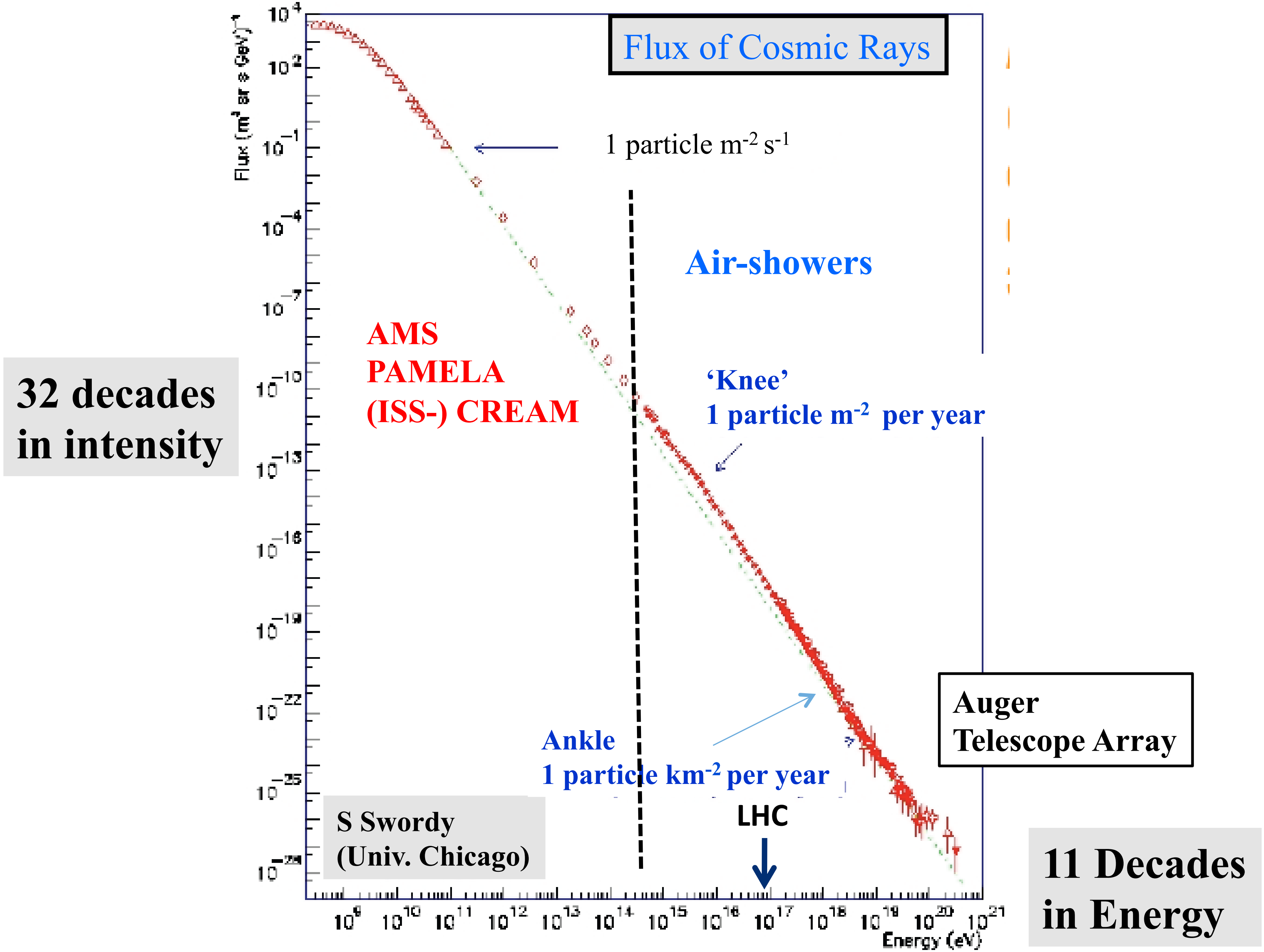
and

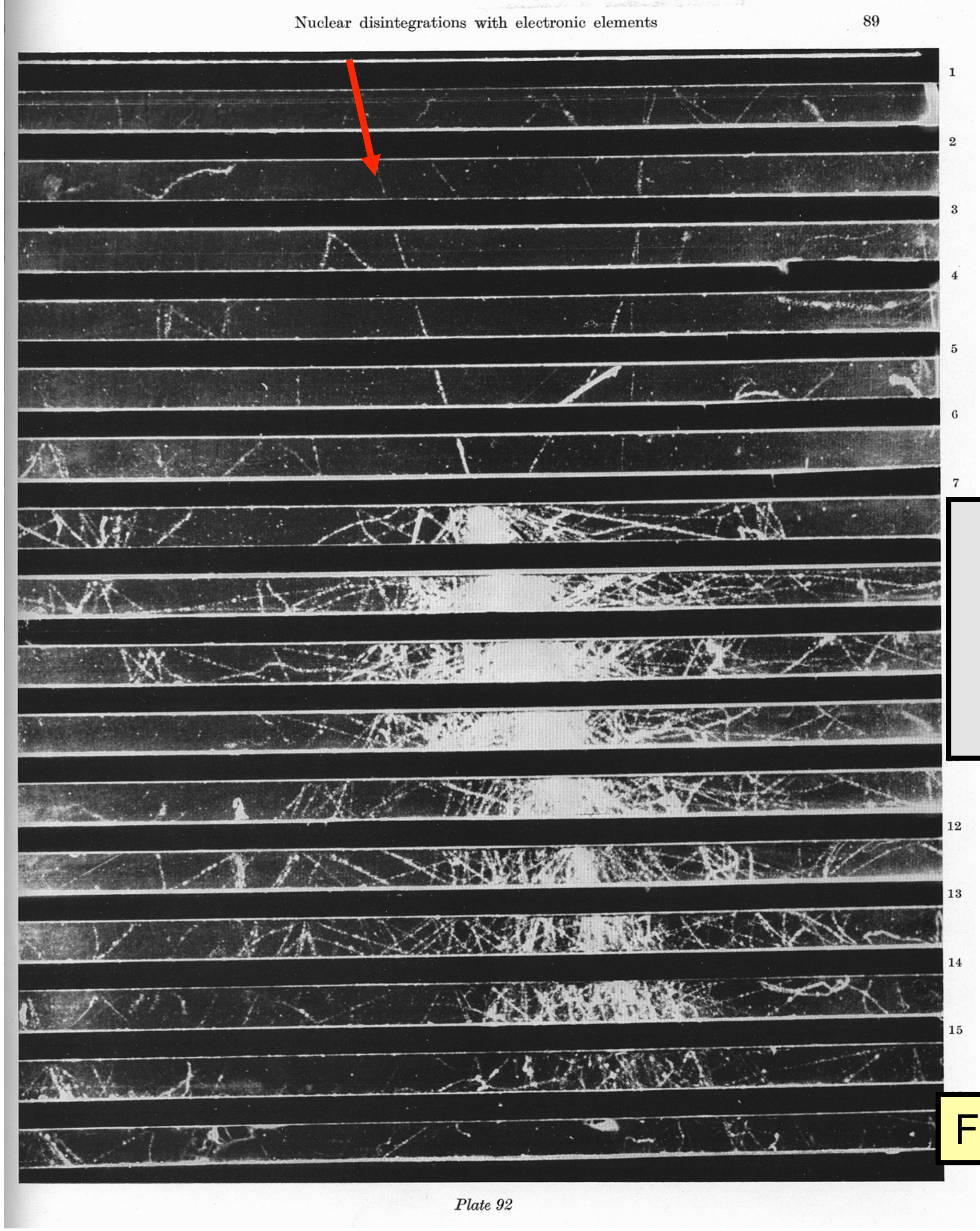
$$\gamma_{IR/2.7\,K} + A \rightarrow (A - 1) + n$$

Prediction of steepening (GZK effect) around 50 EeV

- What is the mass of the particles?

Lack of knowledge of hadronic physics is main limitation here


Flux of Cosmic Rays
1 particle m-2 s-1
Air-showers
AMS
PAMELA
(ISS-) CREAM
'Knee'
1 particle m-2 per year
Ankle
1 particle km-2 per year
LHC
Auger
Telescope Array
S Swordy
(Univ. Chicago)
32 decades
in intensity
11 Decades
in Energy
Flux (m² sr s GeV)⁻¹
Energy (eV)



1.3 cm Pb

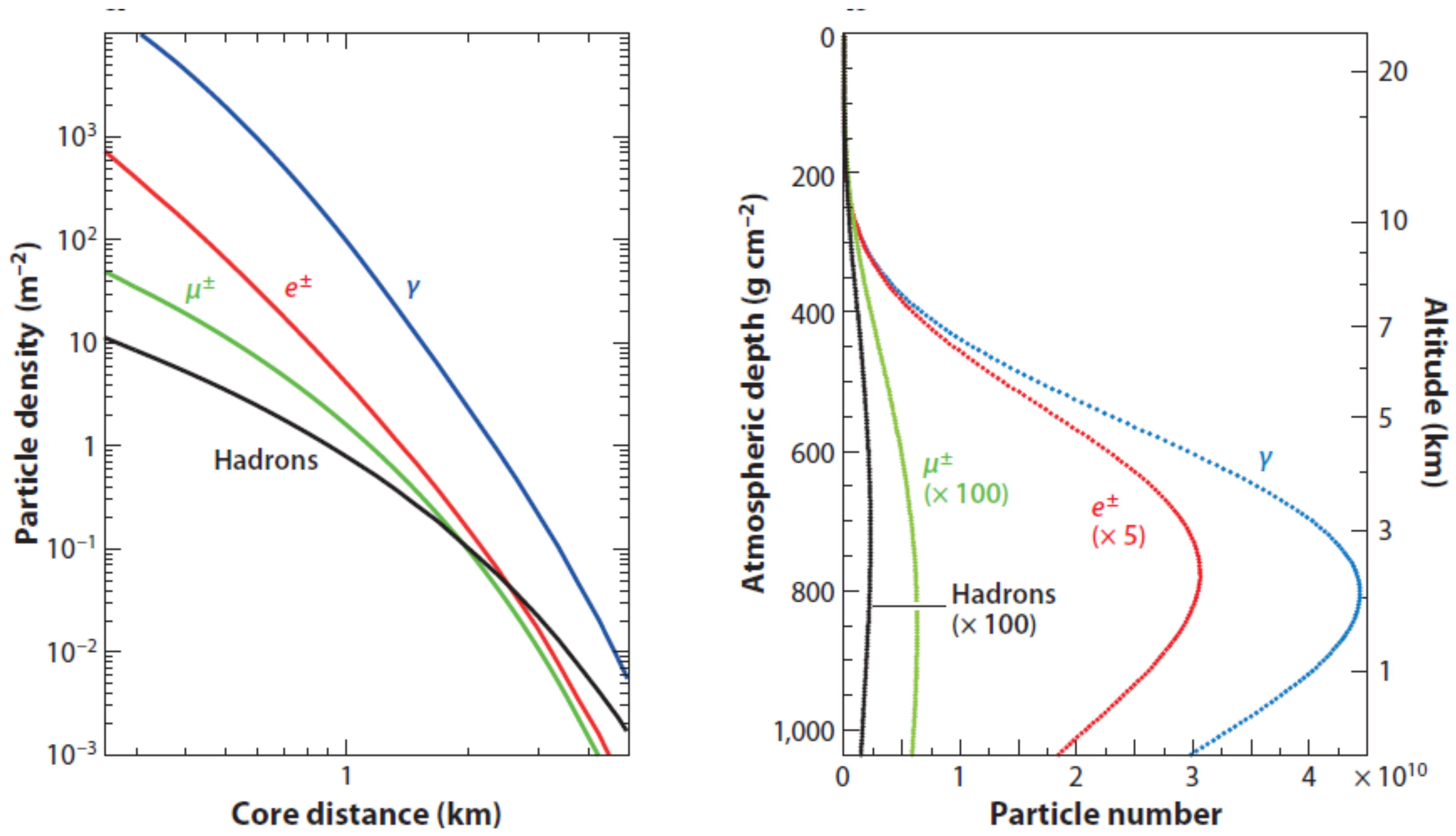
10 GeV proton

Shower initiated by proton in lead plates of cloud chamber

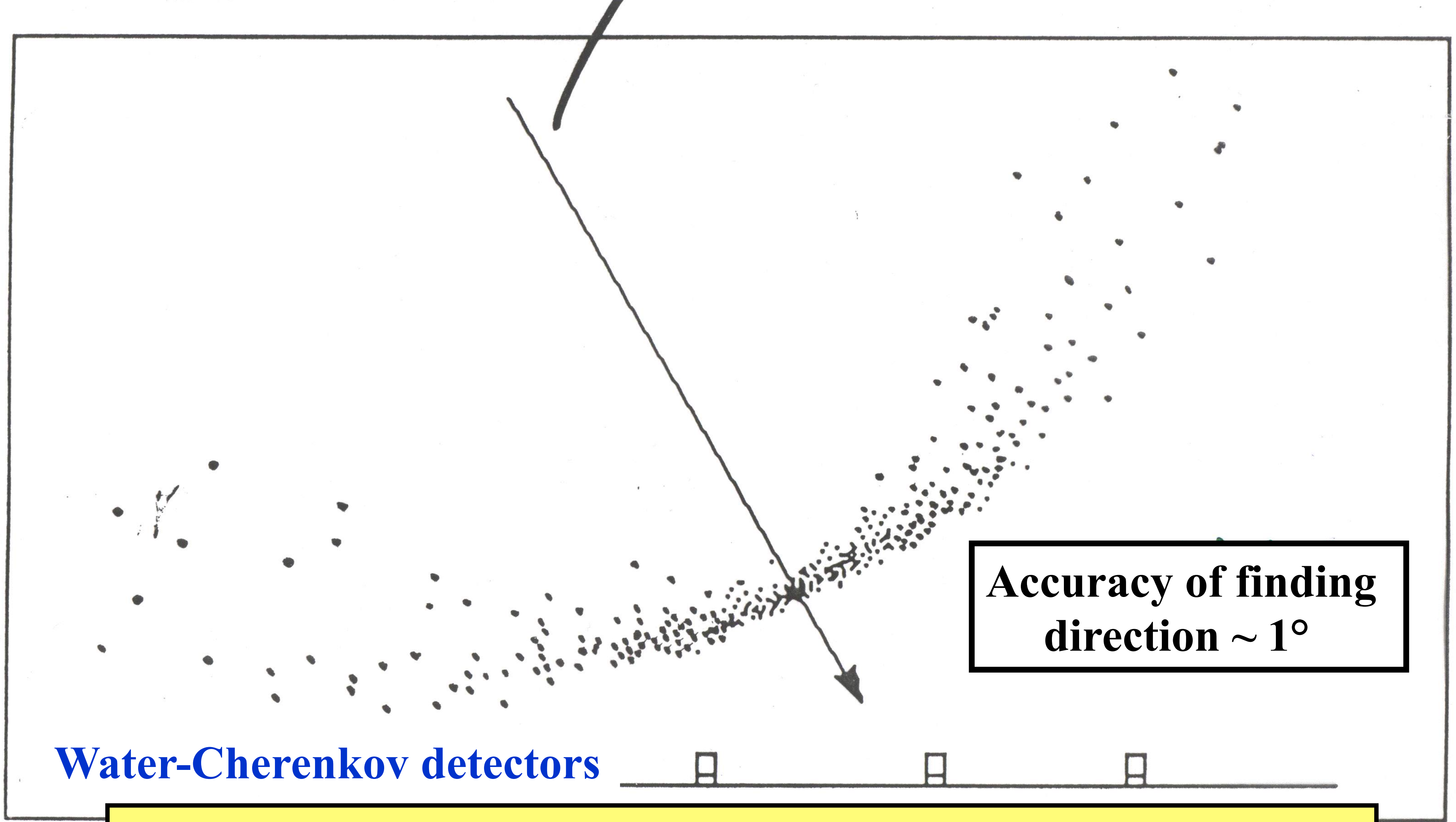
Detectors can find particle number and arrival times

Fretter: Echo Lake, 1949

Shower components as a function of distance and depth



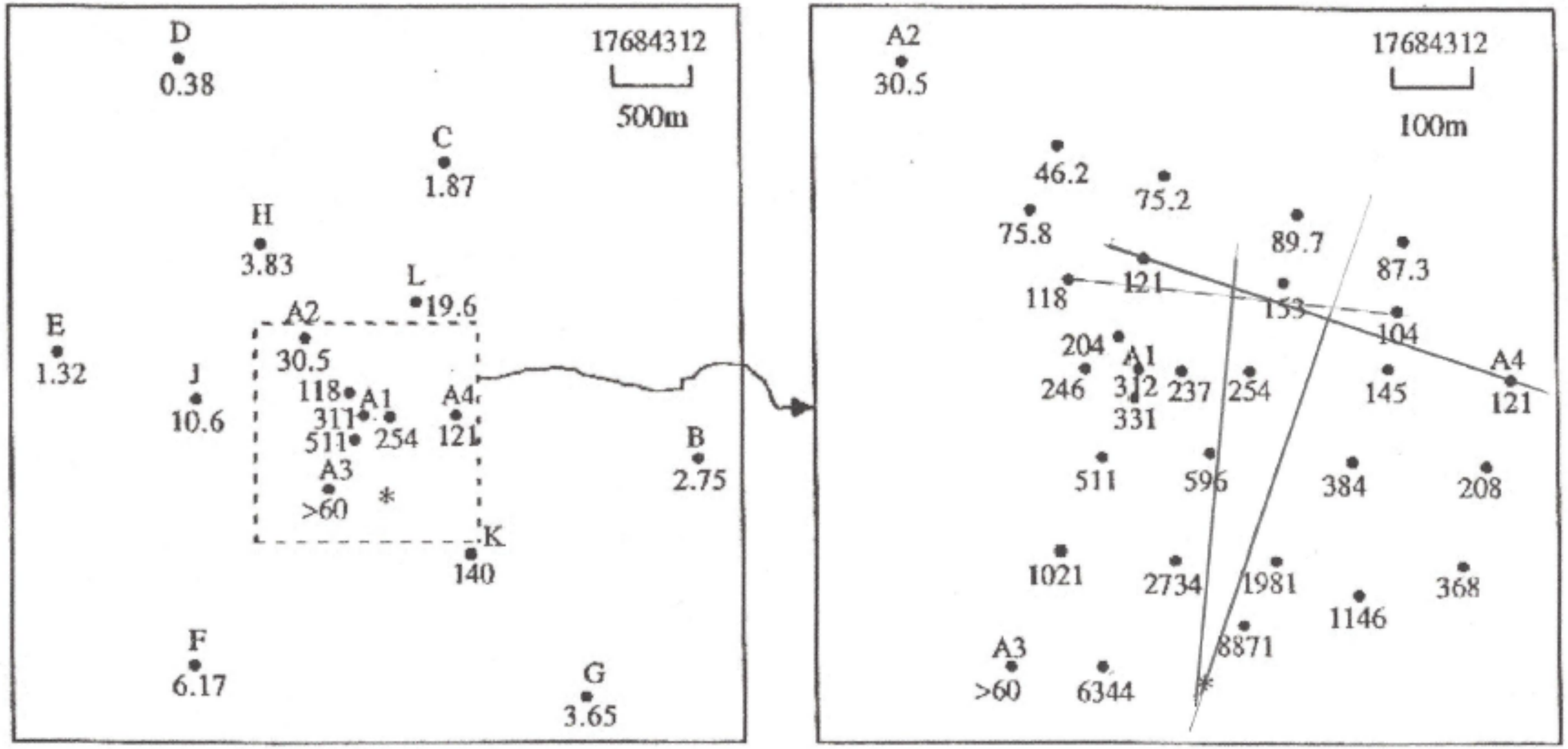
Engel et al. Ann Rev NPS 2011

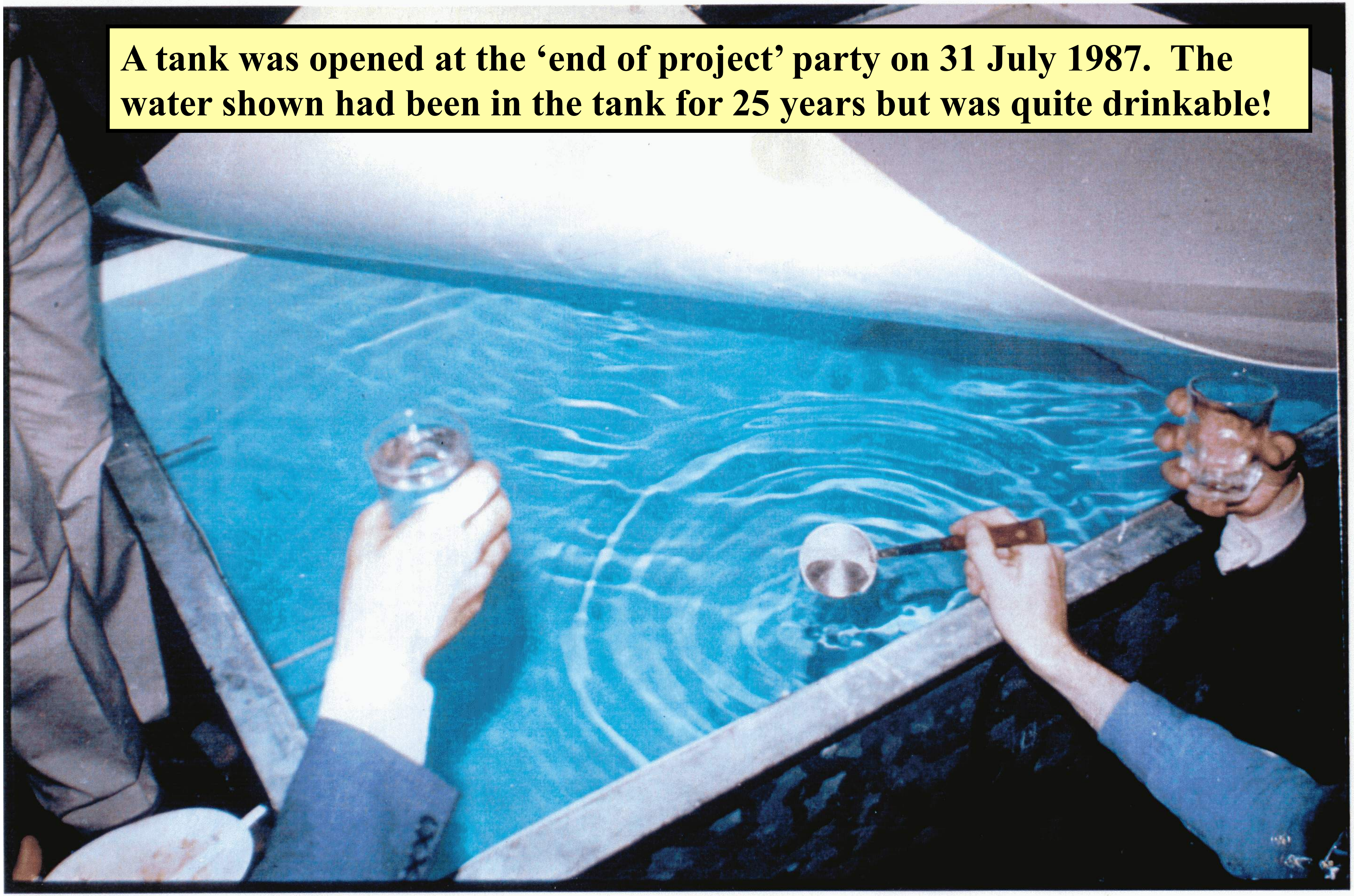


‘Fast timing’ gives the direction:

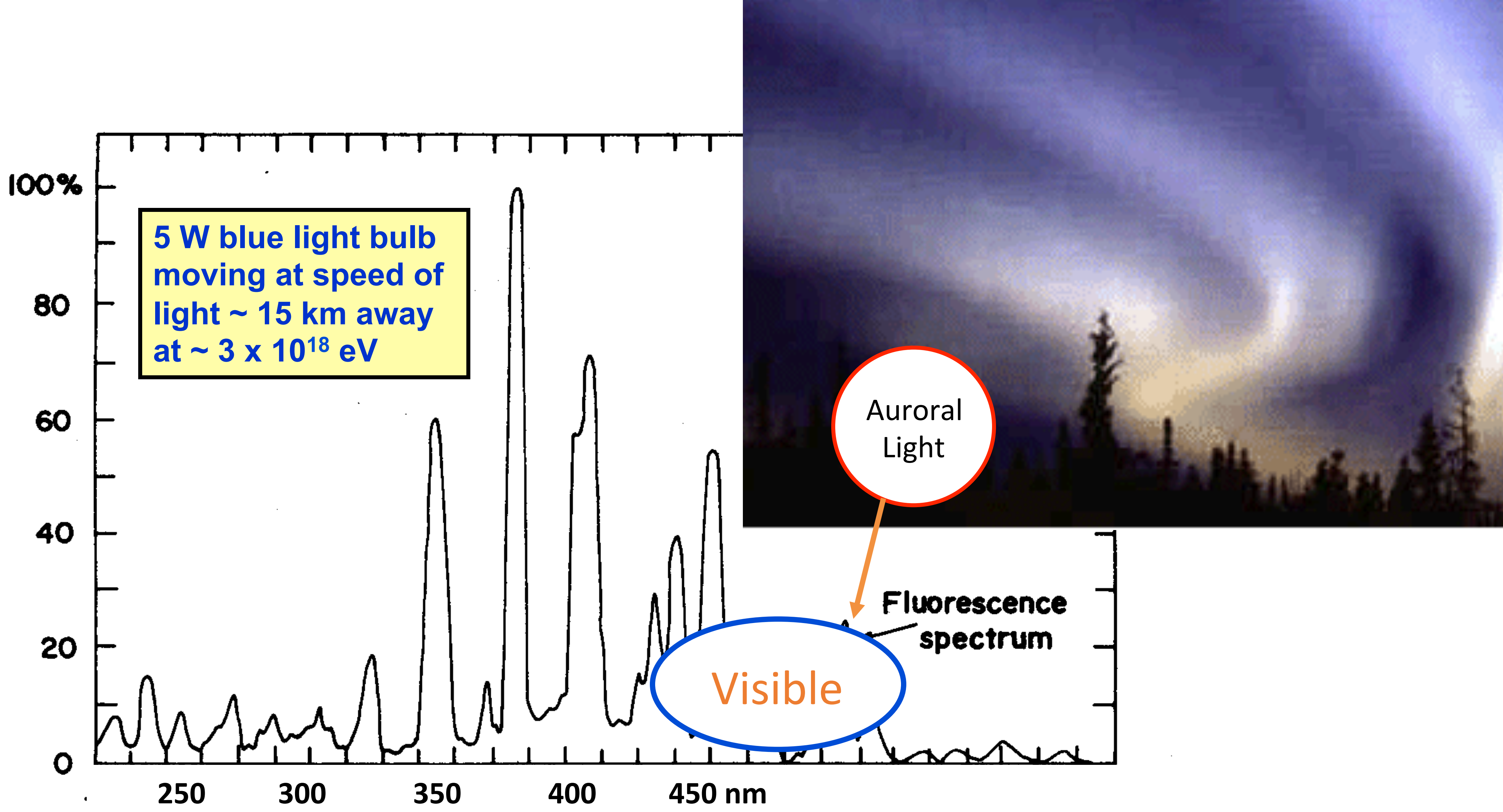
This is crucial when trying to establish the origin of the particles which travel across magnetic fields

Event with energy of ~ 8 x 10^{19} eV recorded at UK Array, Haverah Park

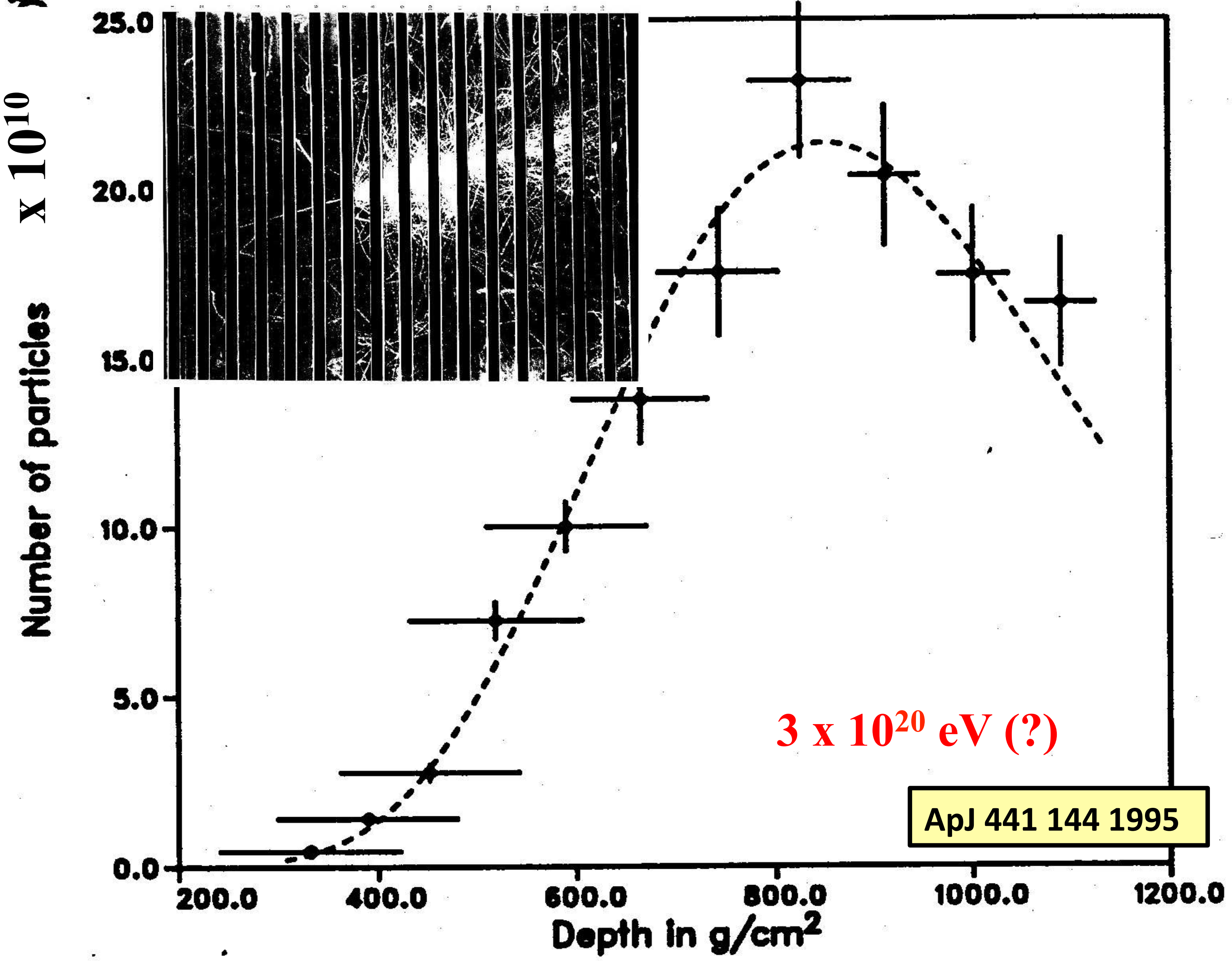




A tank was opened at the ‘end of project’ party on 31 July 1987. The water shown had been in the tank for 25 years but was quite drinkable!


5 W blue light bulb moving at speed of light ~ 15 km away at ~ 3 x 10^18 eV
100%
80
60
40
20
0
250
300
350
400
450 nm
Auroral Light
Fluorescence spectrum
Visible

A Fluorescence Detector of the Utah University Group



x 10^{10}
Number of particles
25.0
20.0
15.0
10.0
5.0
0.0
200.0
400.0
600.0
800.0
1000.0
1200.0
Depth in g/cm^2
3 x 10^{20} eV (?)
ApJ 441 144 1995

~1990: different techniques gave different results –

- but agreed that rate is low:

~ 1 per km^2 per century at 10^{20} eV
(~ 10/min on earth's atmosphere)

- 1990: Need larger areas > 1000 km^2

- 1991: Started working with Jim Cronin (Chicago)
to form a collaboration to design and
build such an instrument, and to raise the money

- Our efforts helped create the Pierre Auger Observatory
~ 400 scientists from 17 countries

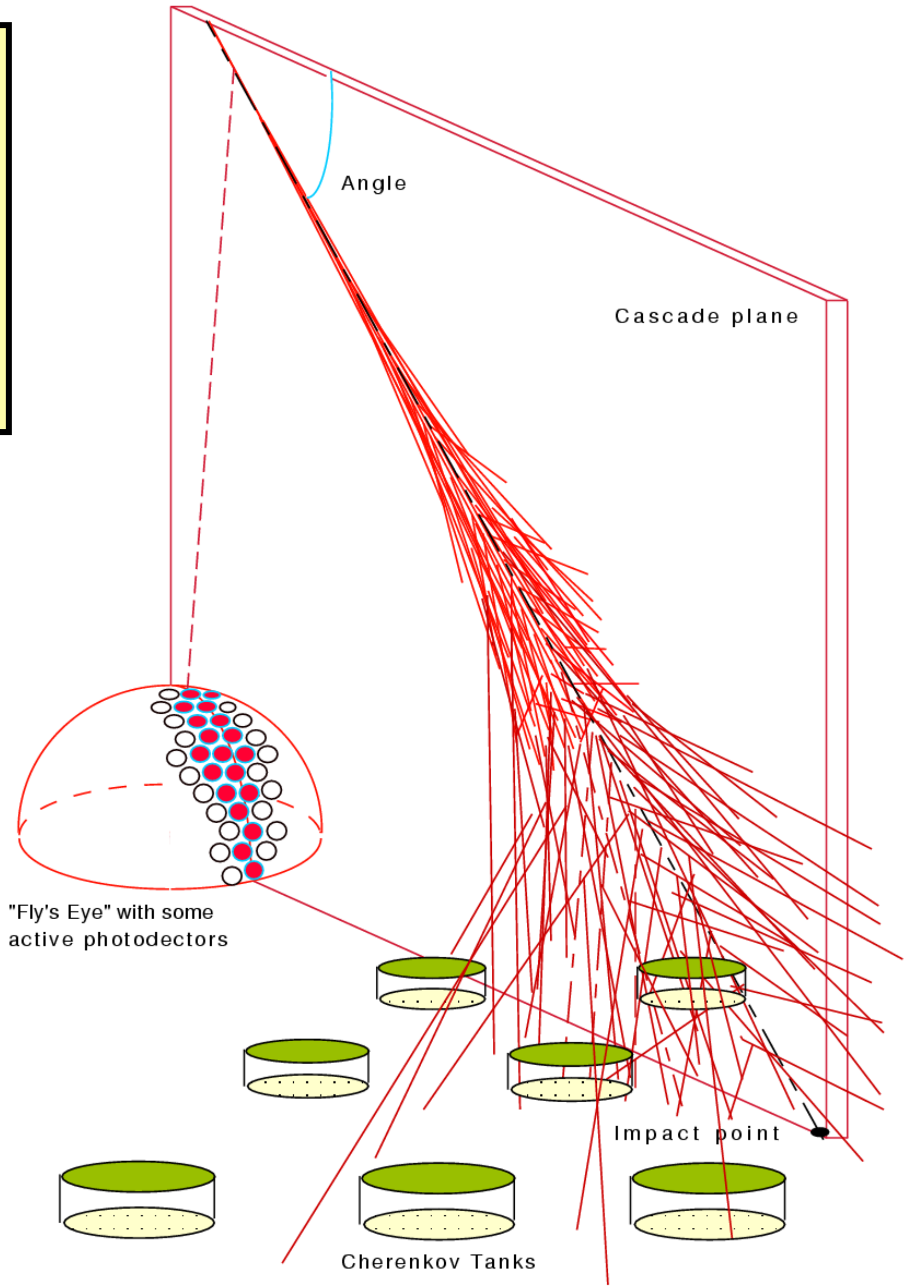
The Design of the Pierre Auger Observatory marries the two techniques

the 'HYBRID' technique

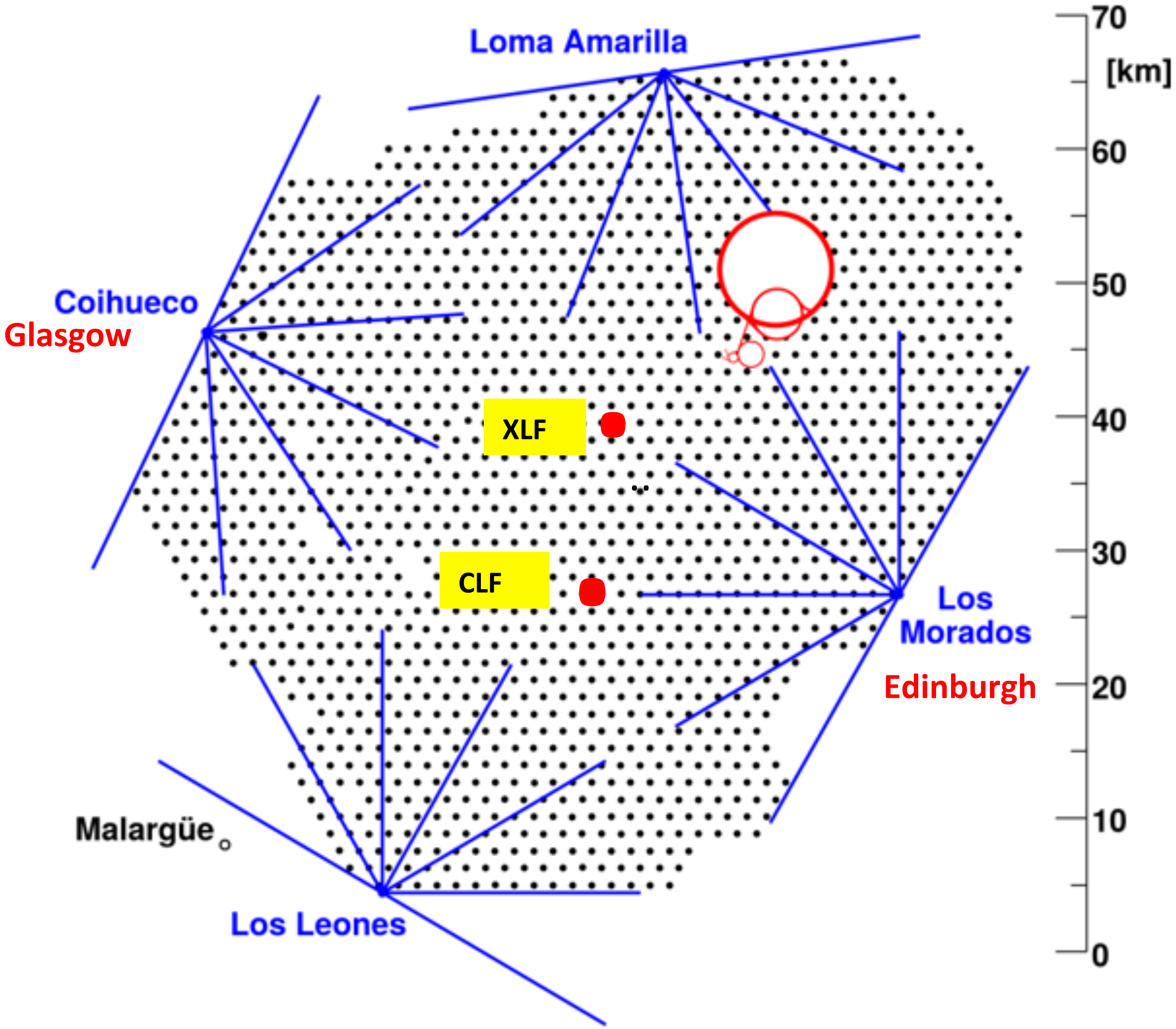
Fluorescence →

AND

Array of water-Cherenkov detectors →



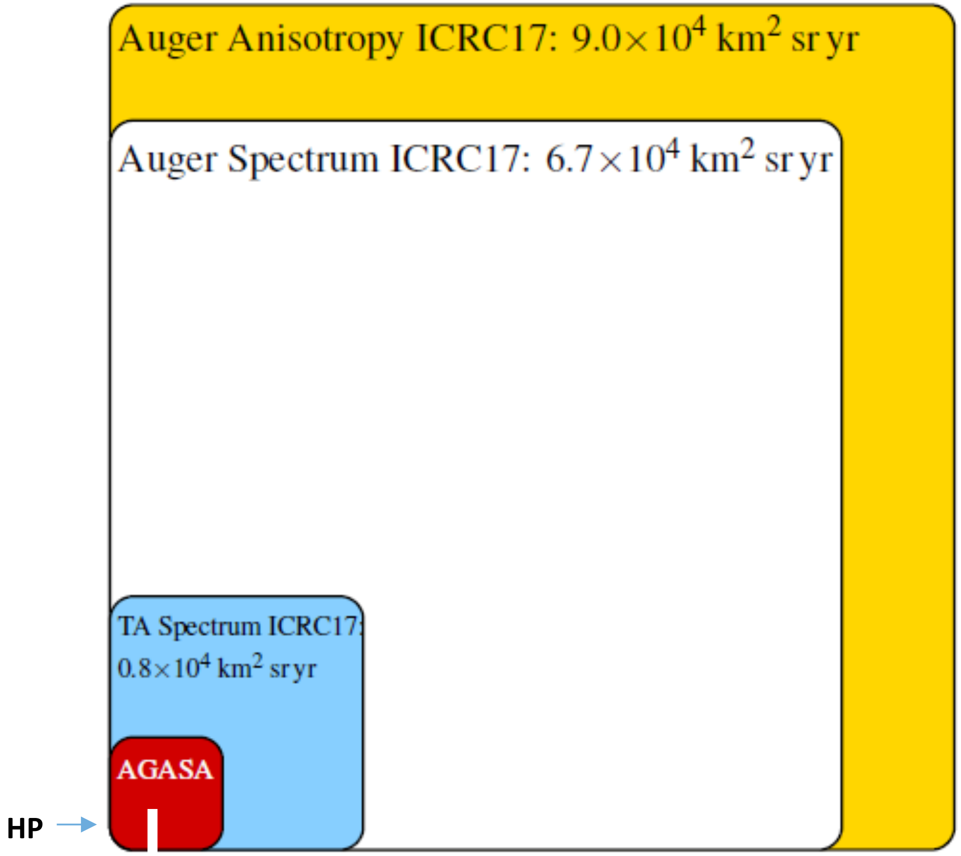
The Pierre Auger Observatory: Malargüe, Argentina



- 1600 water-Cherenkov detectors: 10 m^2 x 1.2 m
- 3000 km^2
- Fluorescence detectors at 4 locations
- Two laser facilities for monitoring atmosphere and checking reconstruction
- Lidars at each FD site

2004: **Data taking started with about 200 water-Cherenkov detectors and two fluorescence telescopes - 13 years after first discussions**

Soon surpassed the exposure at Haverah Park accrued in 20 years – now over 67,000 km^2 sr years

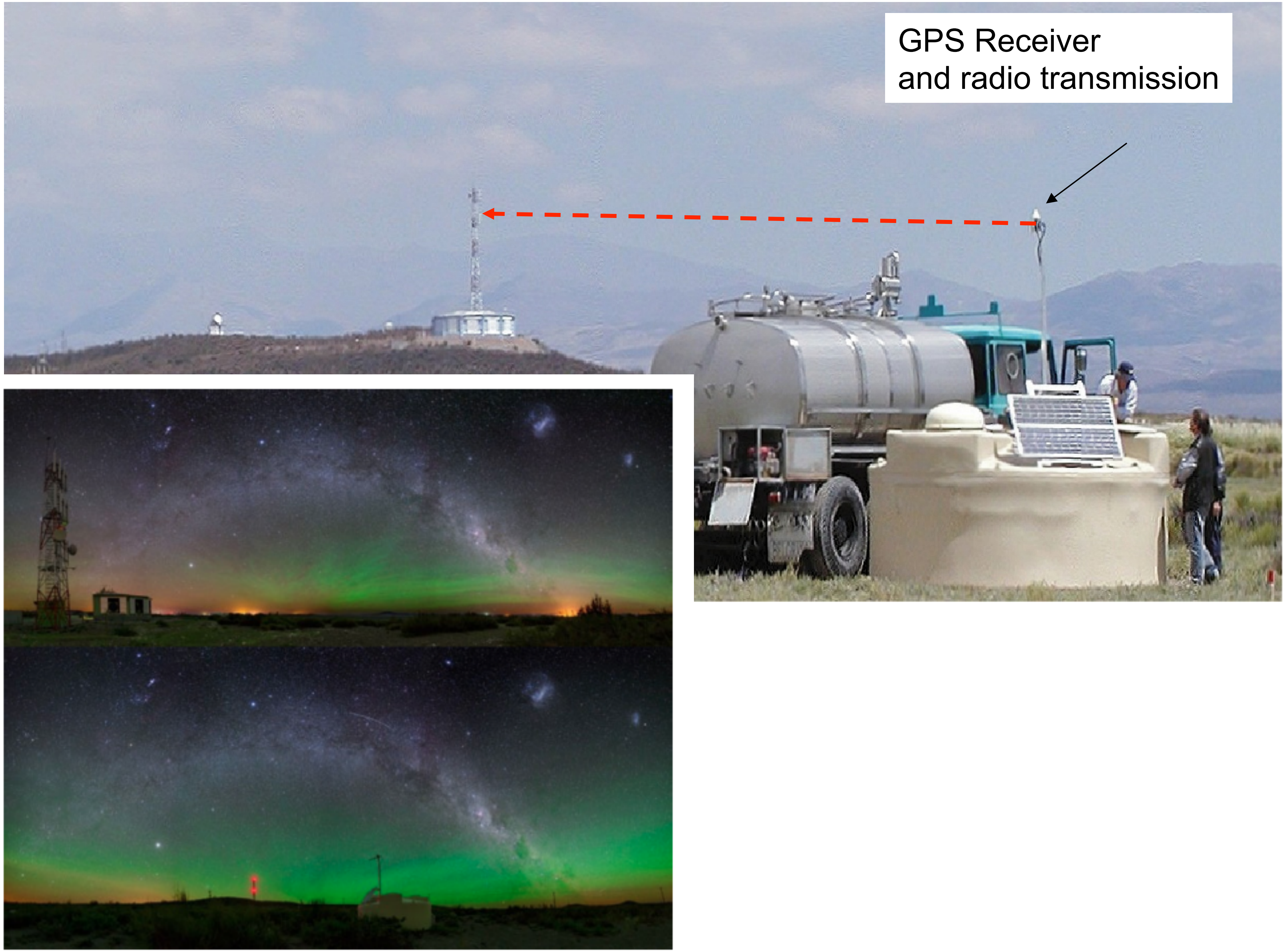


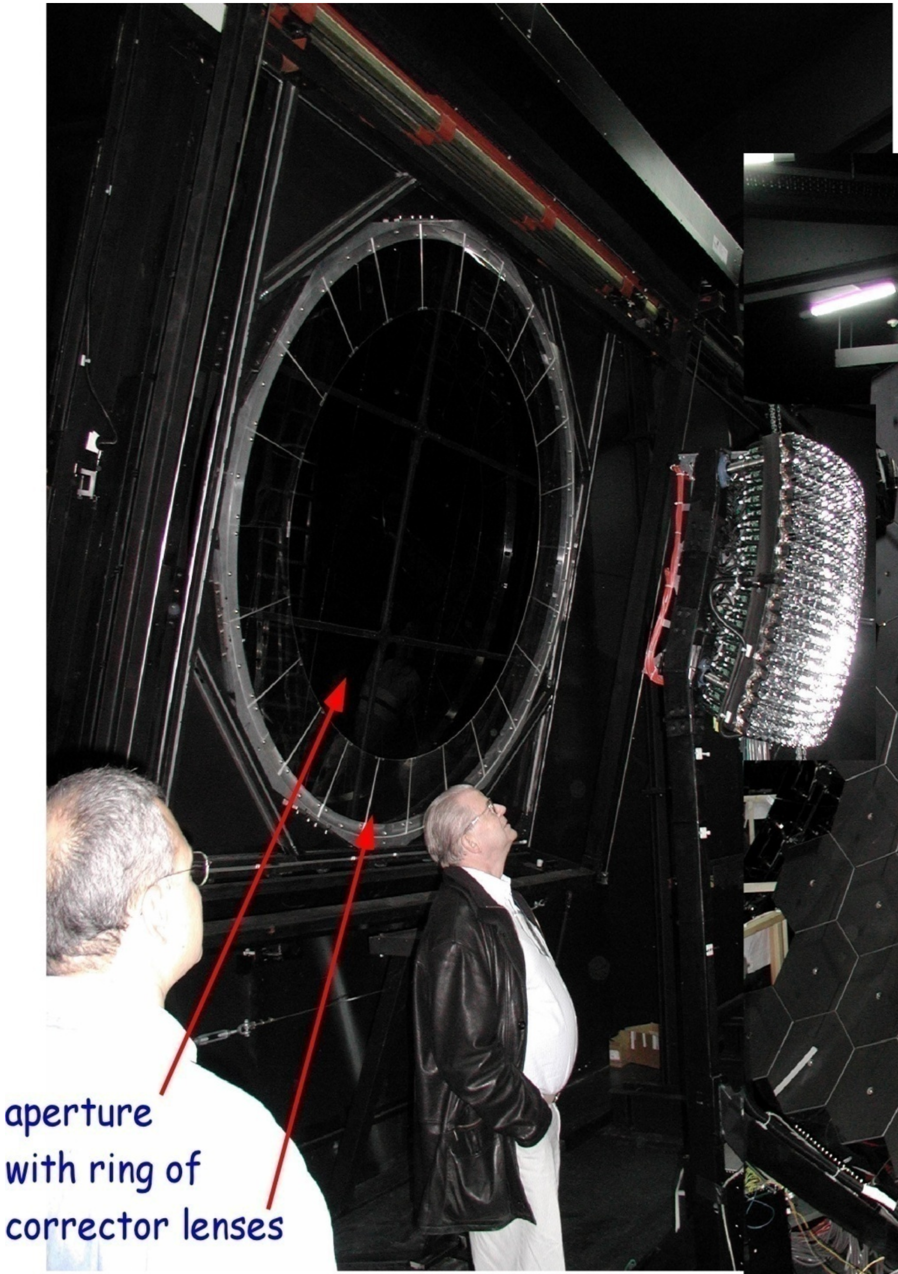
After Michael Unger 2017

The Auger Observatory Campus in Malargüe

The Office and Assembly Buildings in Malargüe
- funded by the University of Chicago ($1M)

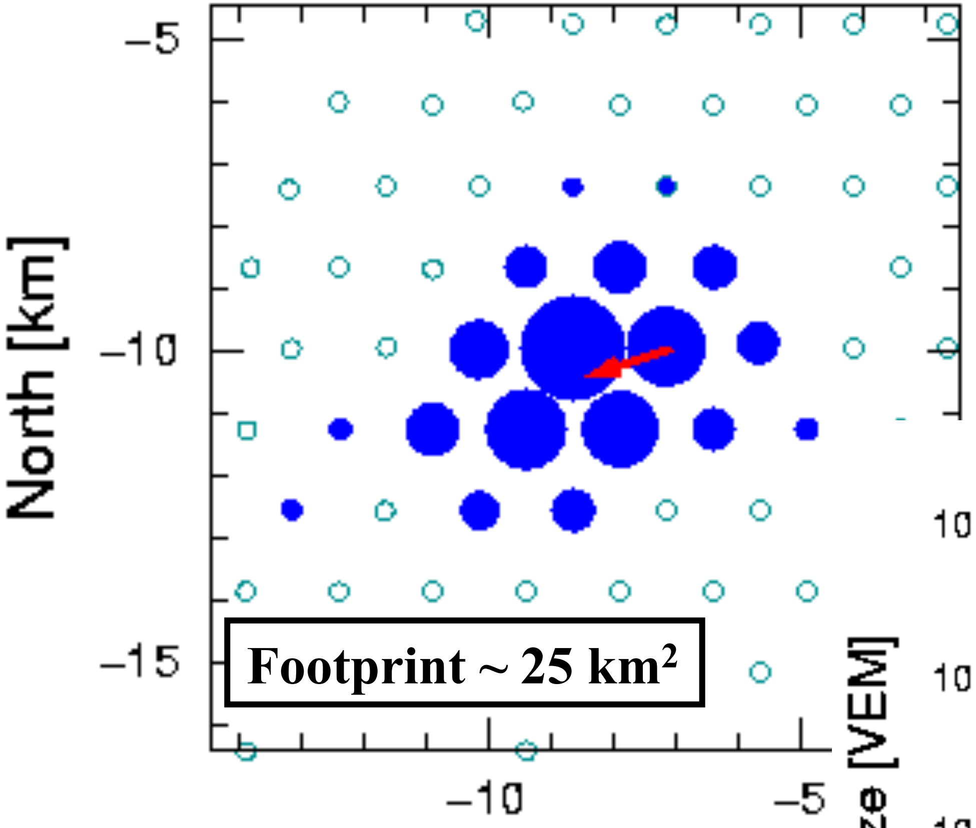

29. 6. 1999


GPS Receiver
and radio transmission

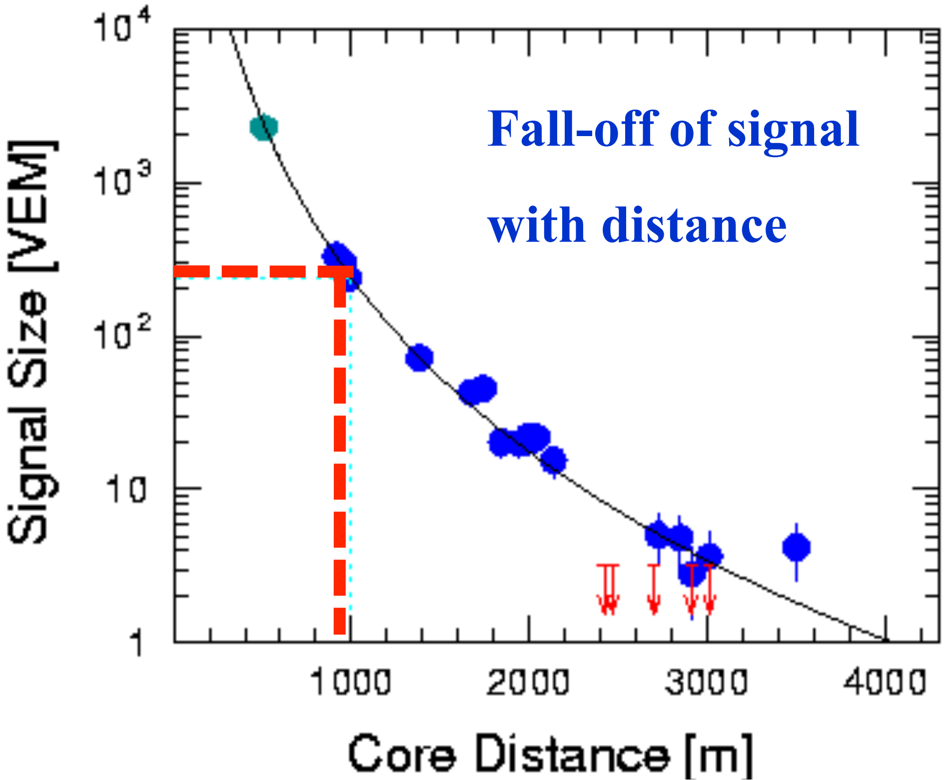


Fluorescence detector at Los Leones

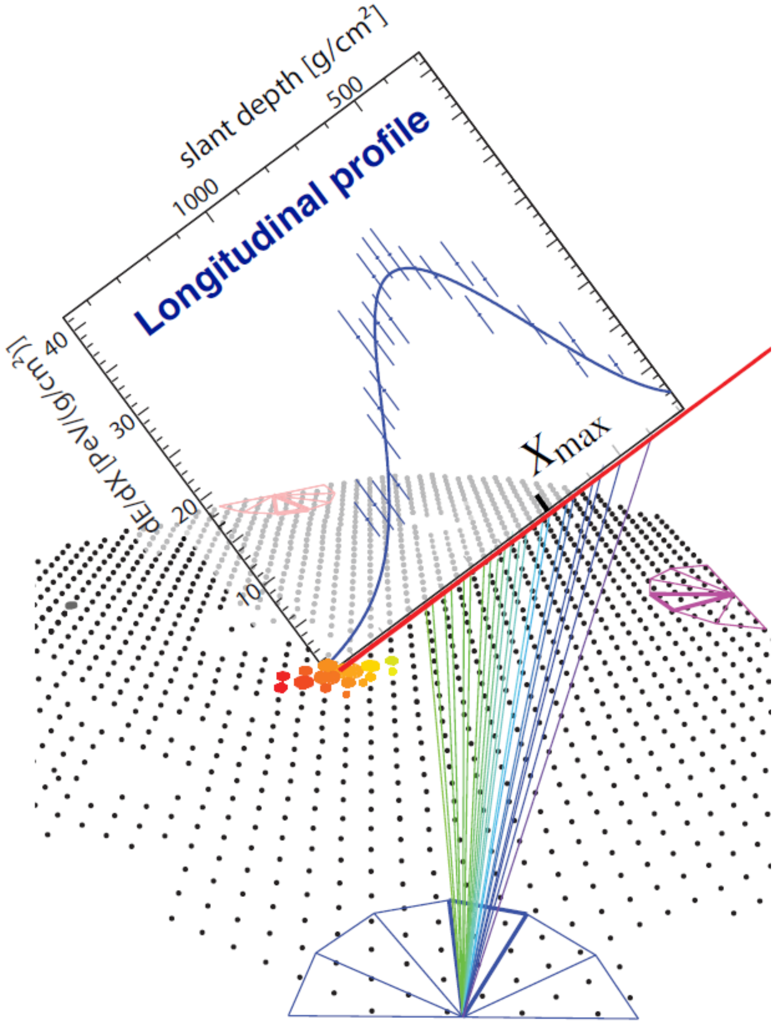
A large event: 7 x 10^{19} eV



Signal at 1000 m from densest part of shower is chosen to define the 'size' of the shower



Energy from fluorescence measurements

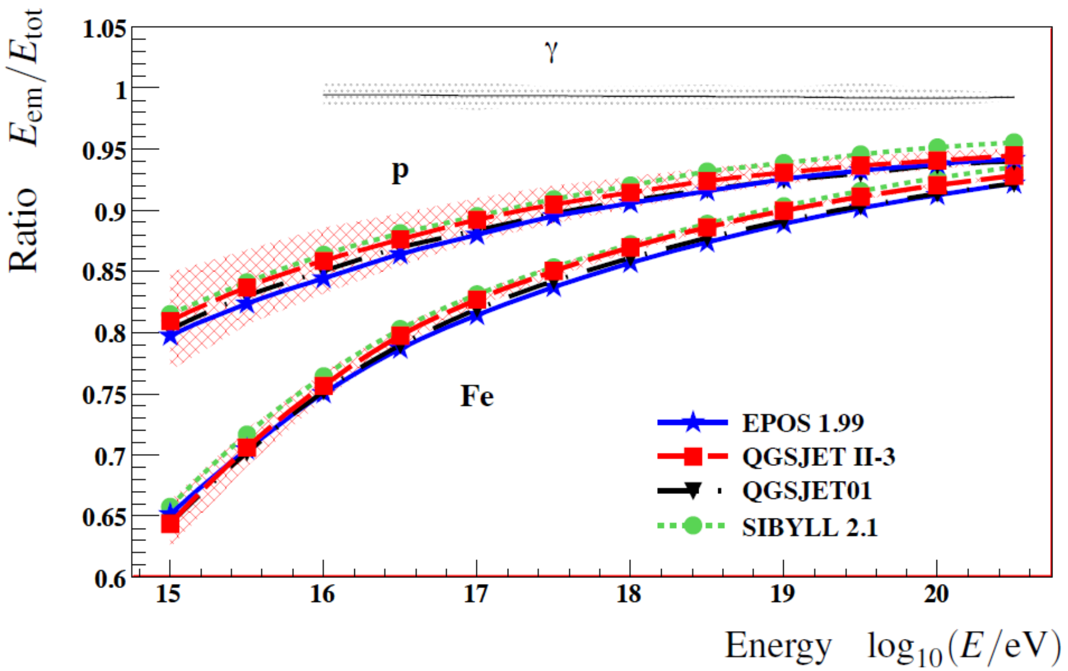


Example: event observed with Auger Observatory

Electrons:

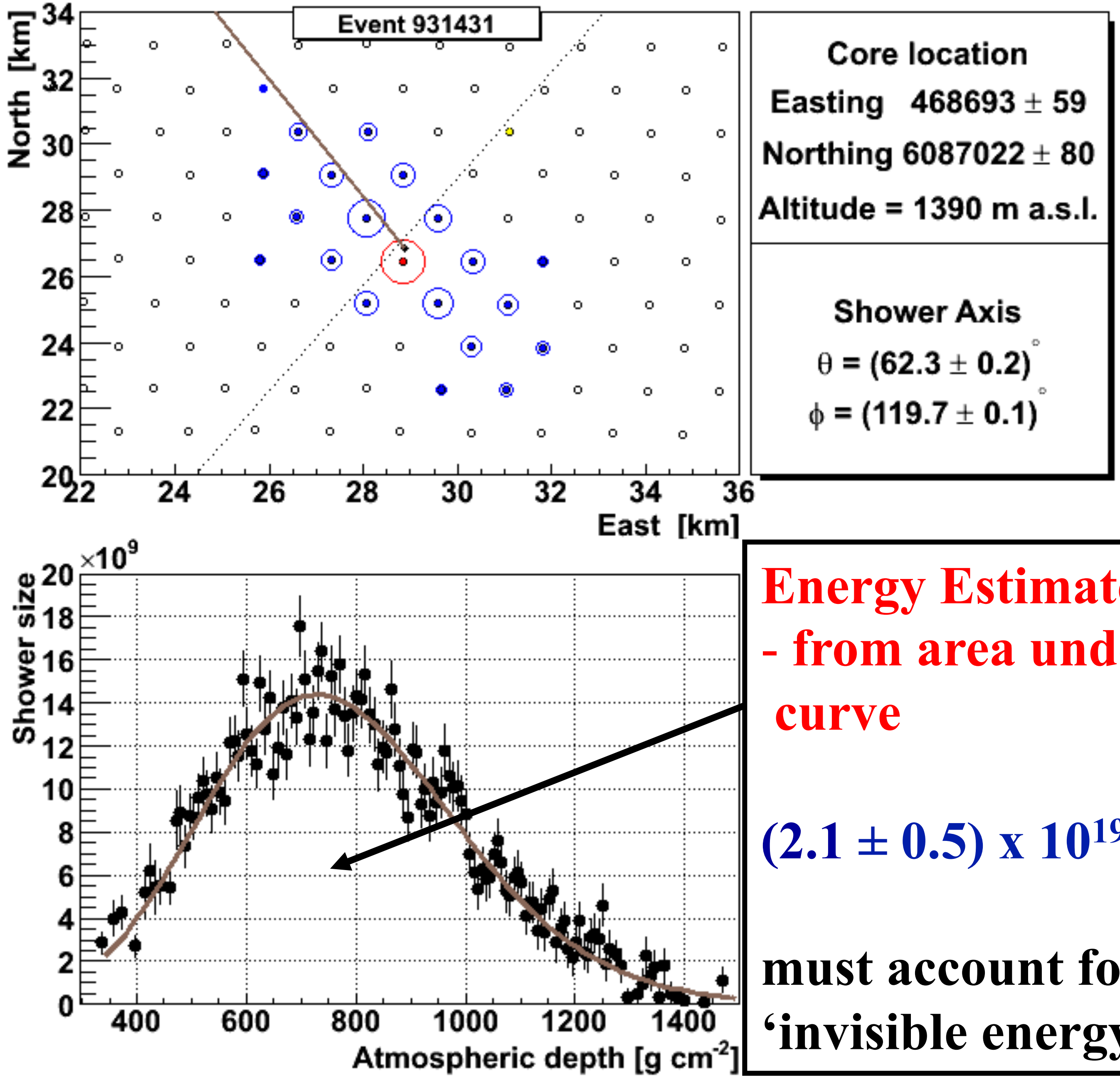
$$E_{\mathrm{em}} = \int \left. \frac{\mathrm{d}E_{\mathrm{ion}}}{\mathrm{d}X} \right|_{\mathrm{meas.+extrap.}} \mathrm{d}X$$

$$E_{\mathrm{tot}} = (1 + f_{\mathrm{cor}})\, E_{\mathrm{em}}$$



Correction for invisible energy

A Hybrid Event

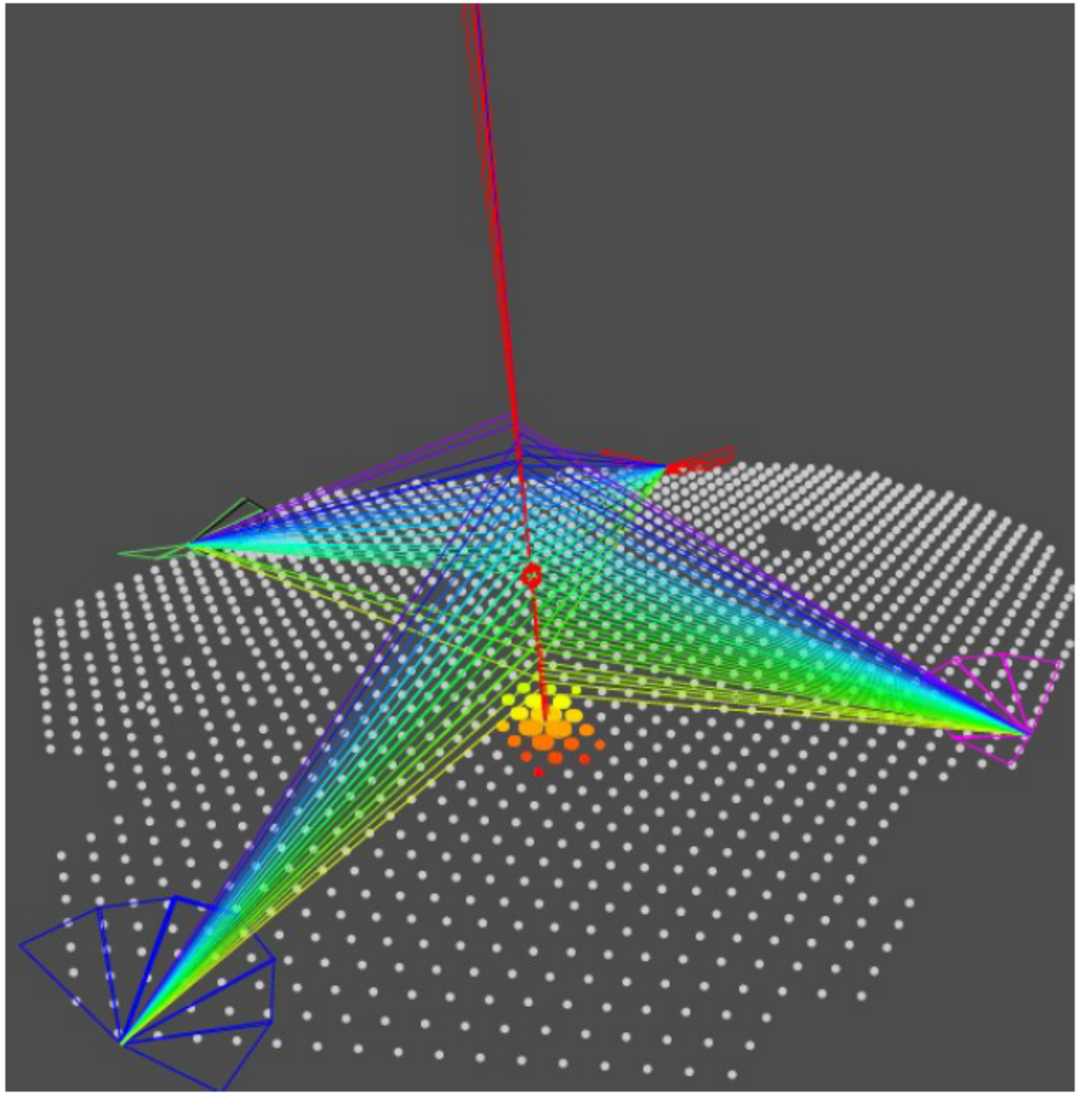


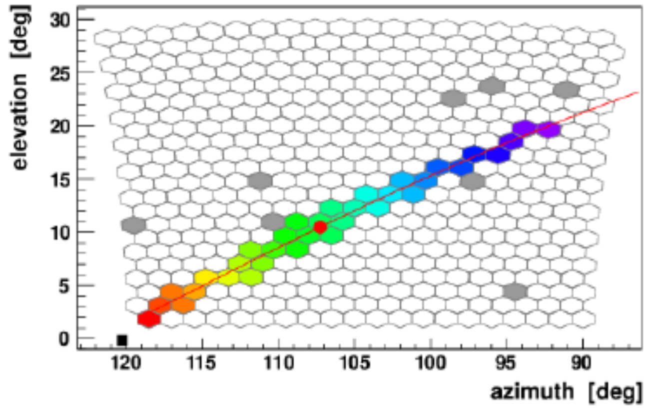
Energy Estimate
- from area under curve

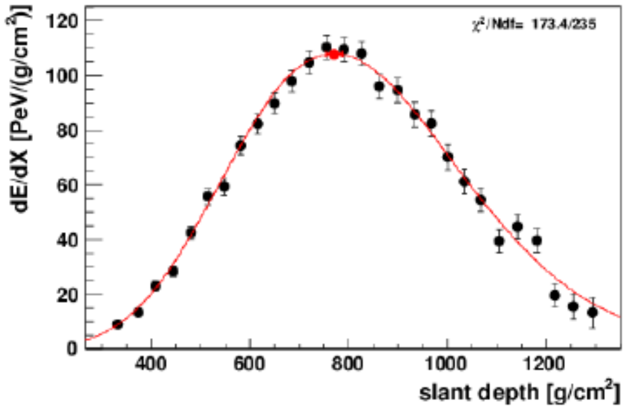
$(2.1 \pm 0.5) \times 10^{19}$ eV

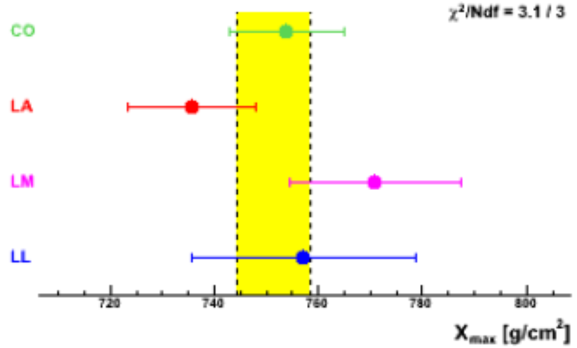
must account for 'invisible energy'

Getting the Energy and X_{max}

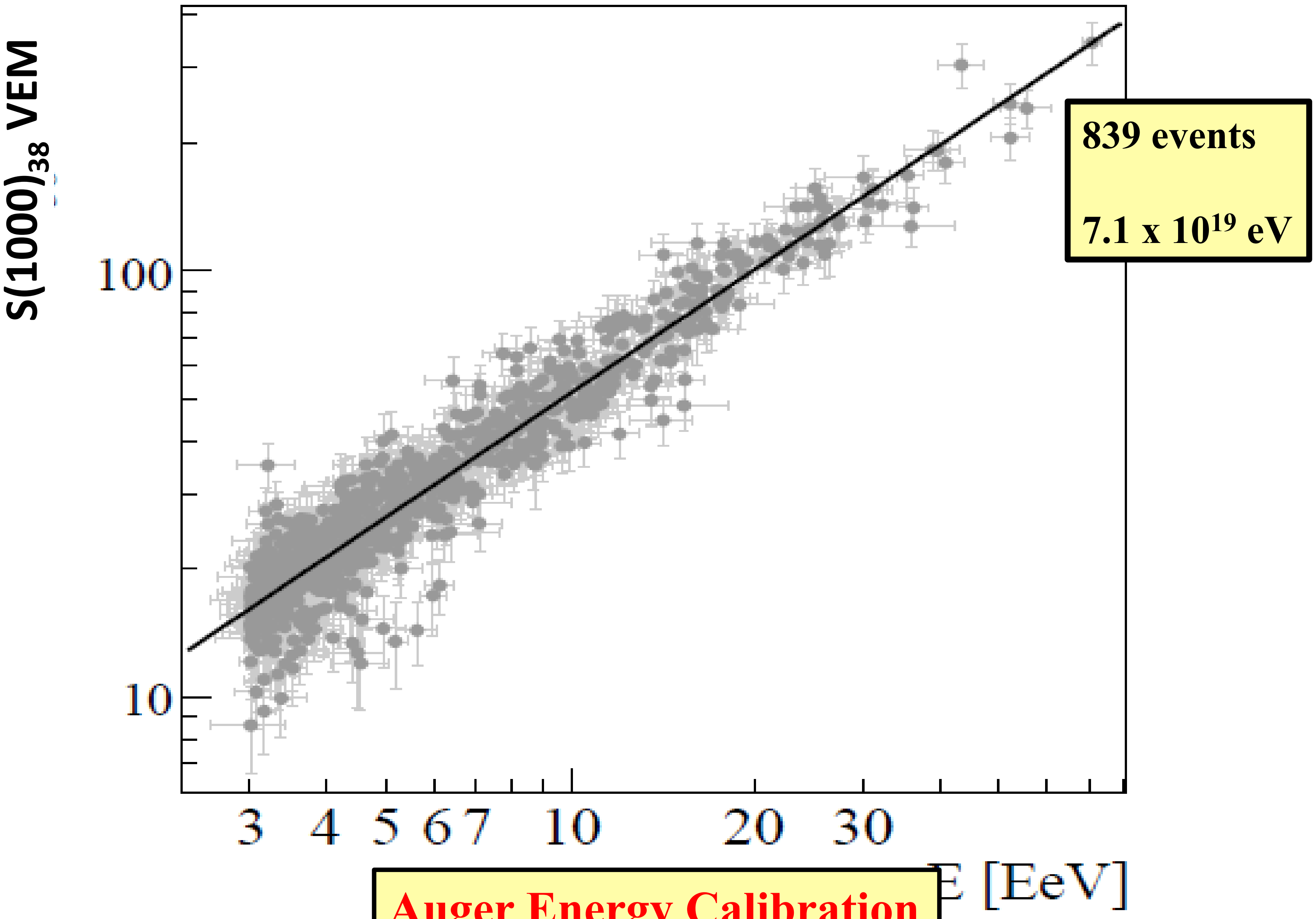




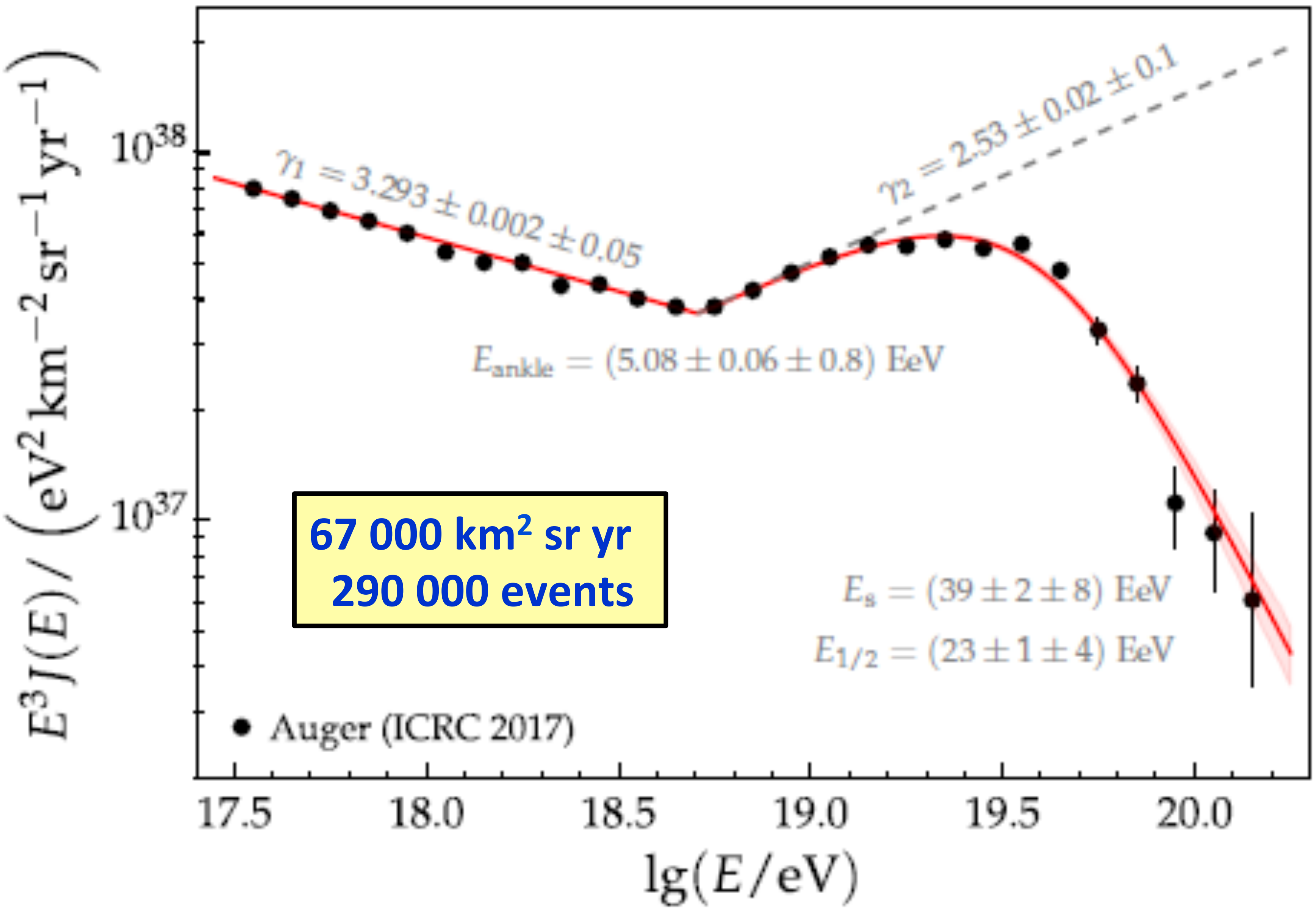




$E = 7.1 \pm 0.2\ 10^{19}$ eV - $X_{max} = 752 \pm 7$ g/cm^2



Auger Energy Calibration



$\gamma_1 = 3.293 \pm 0.002 \pm 0.05$
$\gamma_2 = 2.53 \pm 0.02 \pm 0.1$
$E_{ankle} = (5.08 \pm 0.06 \pm 0.8)$ EeV
$E_s = (39 \pm 2 \pm 8)$ EeV
$E_{1/2} = (23 \pm 1 \pm 4)$ EeV
67 000 km^2 sr yr
290 000 events
Auger (ICRC 2017)
10^{38}
10^{37}
$E^3 J(E) / (\mathrm{eV}^2 \mathrm{km}^{-2} \mathrm{sr}^{-1} \mathrm{yr}^{-1})$
17.5
18.0
18.5
19.0
19.5
20.0
$\lg(E/\mathrm{eV})$

What might the steepening mean?

Rigidity-limited **Photo-disintegration effects**

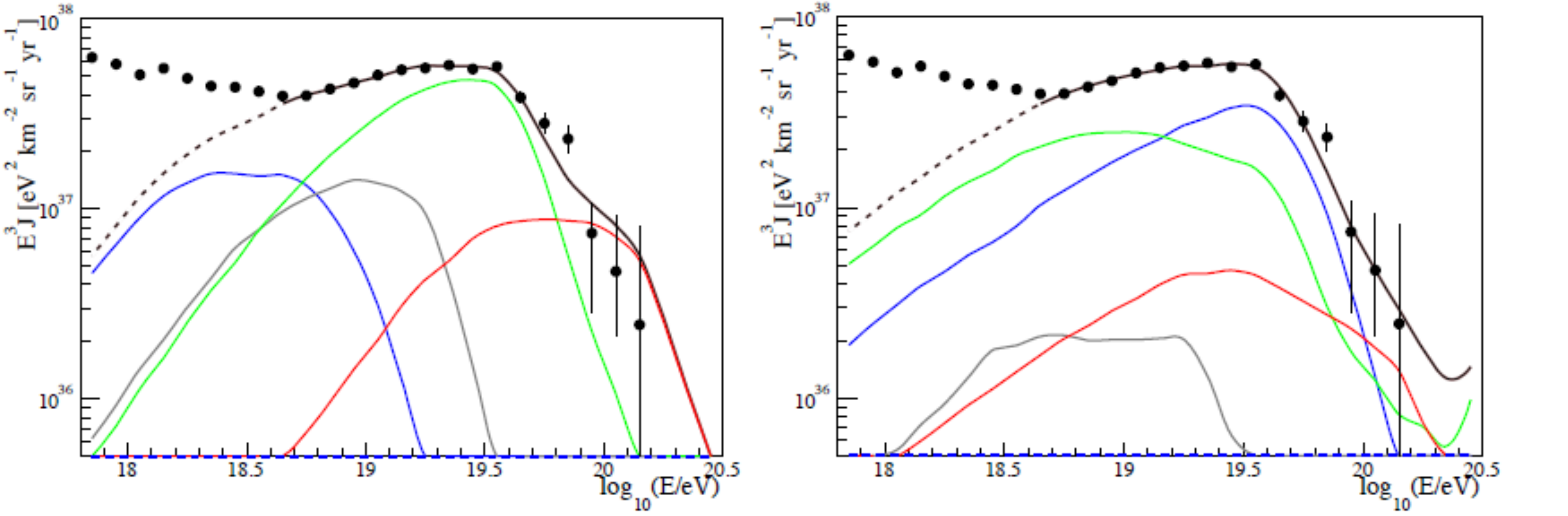
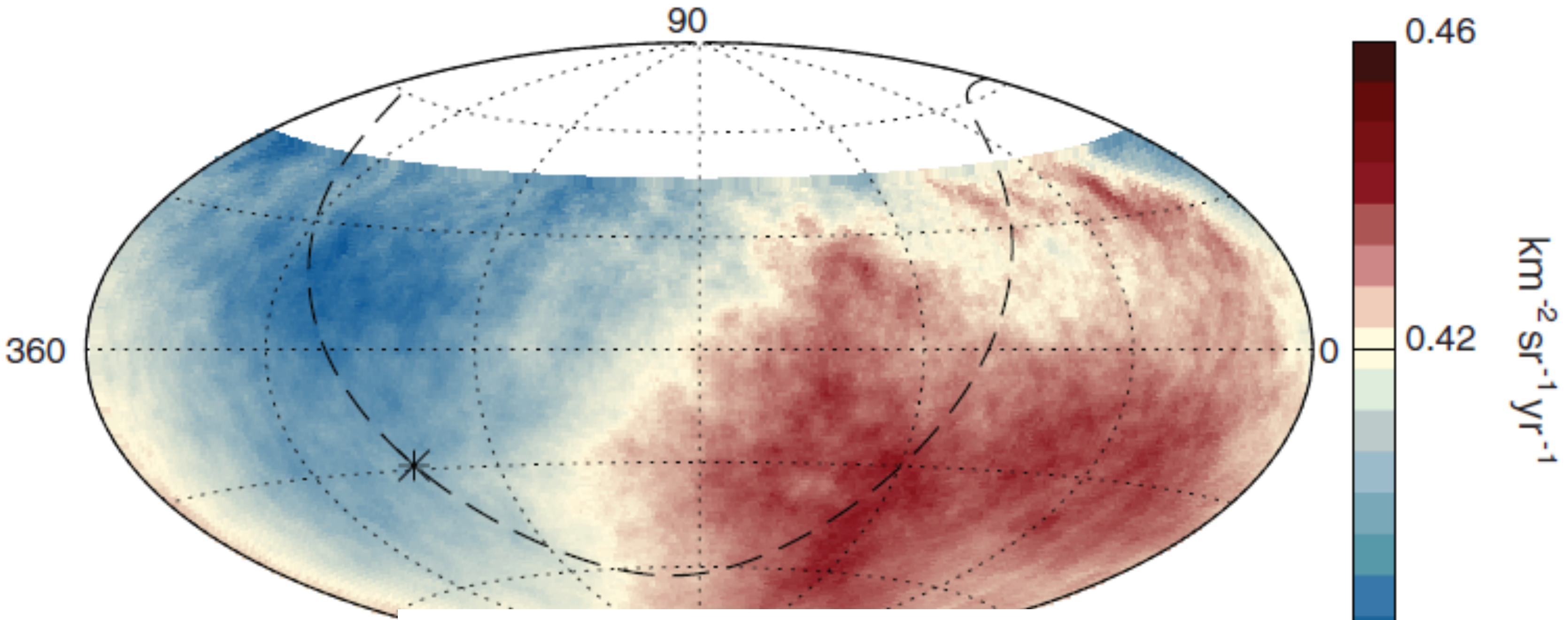
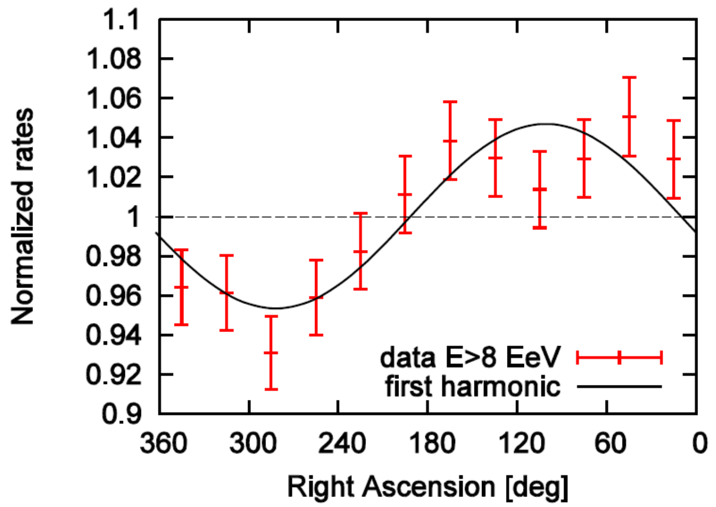


Figure 2.10: Examples of fluxes of different mass groups for describing the Auger spectrum and composition data. Shown are the fluxes of different mass groups that are approximations of one maximum-rigidity scenario (left panel) and one photo-disintegration scenario (right panel). The col-

p He N Fe

Cosmic rays with energies above 8 EeV come from outside of our Galaxy: Science 22 September 2018





physicsworld TOP 10 BREAKTHROUGH 2017

Significance ~ 5.2 sigma

Auger/TA all sky survey at high energies

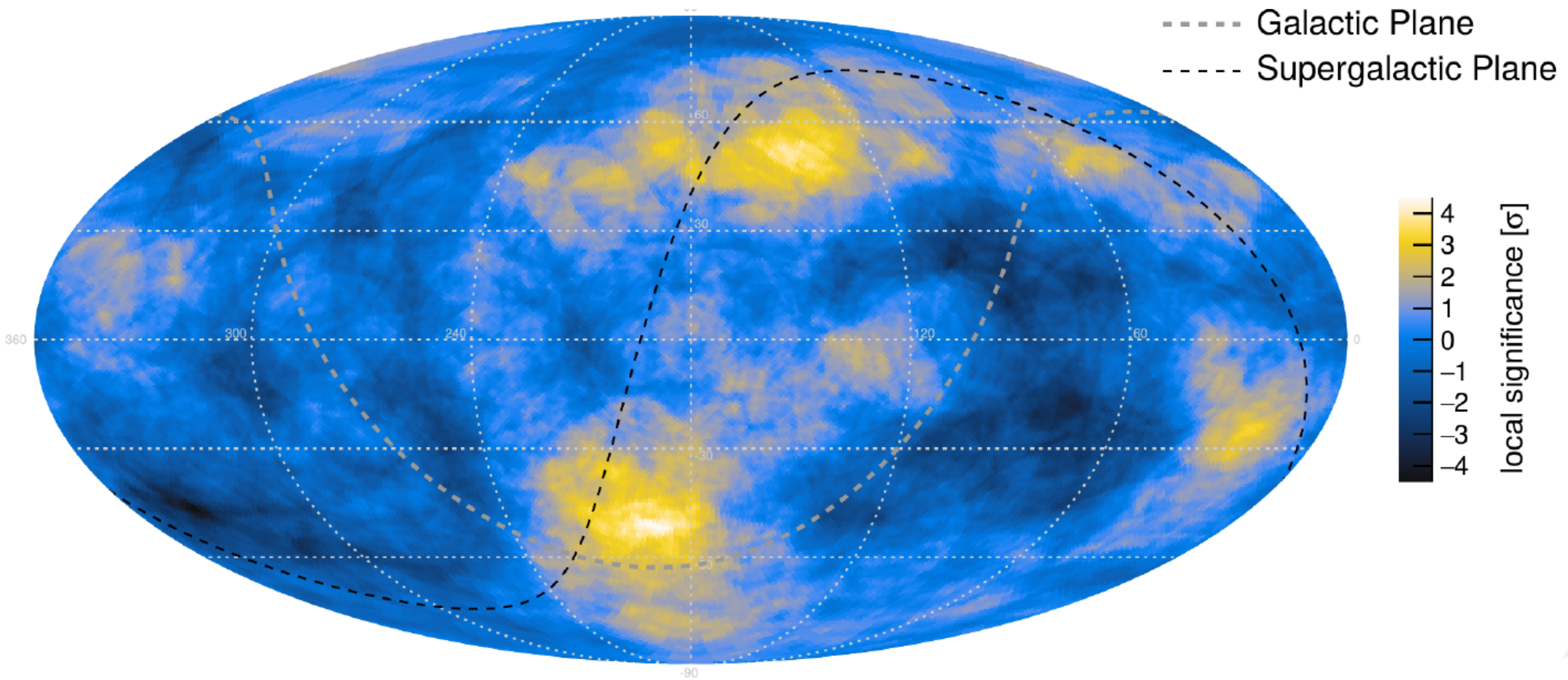
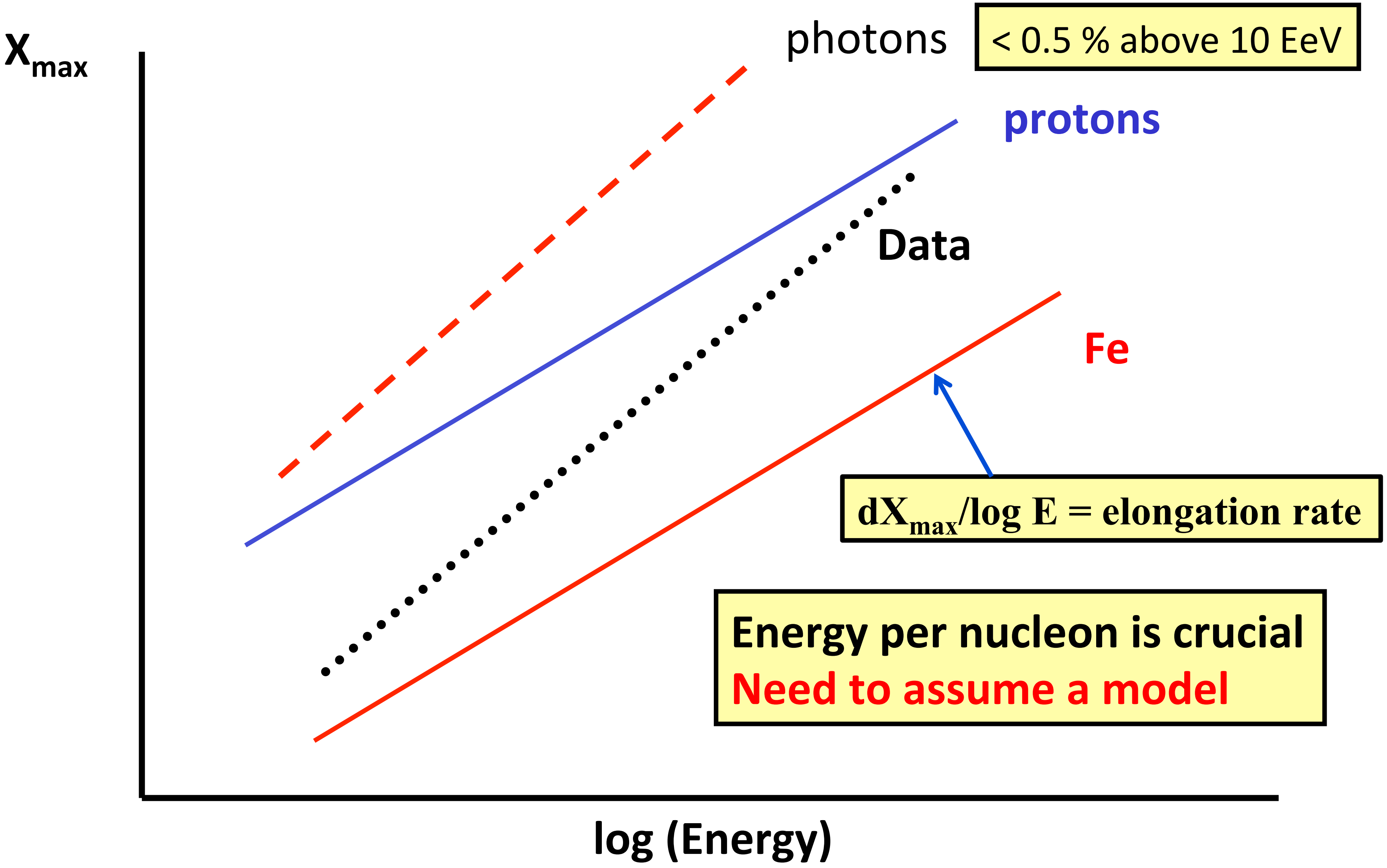


Figure 2: Sky map, in equatorial coordinates, of local over- and under-densities in units of standard deviations of UHECRs above 47 ± 7 EeV.

The variation of mass with energy



Given the necessity of using models, an important question is

"Are the cosmic-ray models adopted sensible?"

Here, the LHC results have proved an excellent test-bed

- **to evaluate three different models -All within Gribov's Reggeon Field Theory framework**

- **EPOS: parton-based Gribov-Regge Theory**

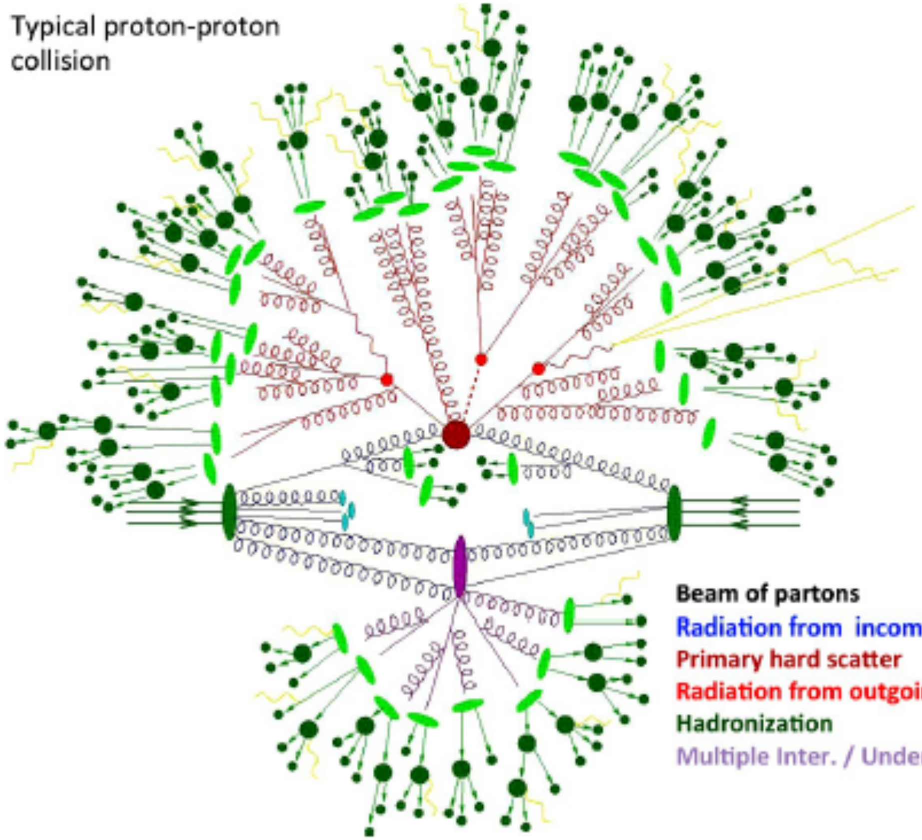
- **QGS: quark-gluon string model – multi-pomeron amplitudes calculated to all orders**

- **Sibyll: based on Dual-parton model – mini-jet model**

- **Each model has a different but self-consistent assumptions to describe hadronic interactions.**
  This is ALL I really can tell you about the details of the models!

Hadronic Monte Carlos for LHC collisions

- Proton-proton collisions in PYTHIA, HERWIG,...



- Theoretical basis:
  - Perturbative QCD (LO + K-factor): PDFs, matrix-elements.
  - Leading-log parton shower.
  - Multiparton interactions.
  - Saturation-based infrared p_T cut-off

- Non-pQCD modeling:
  - String fragmentation (Lund model).
  - Beam-remnants.
  - Diffraction.

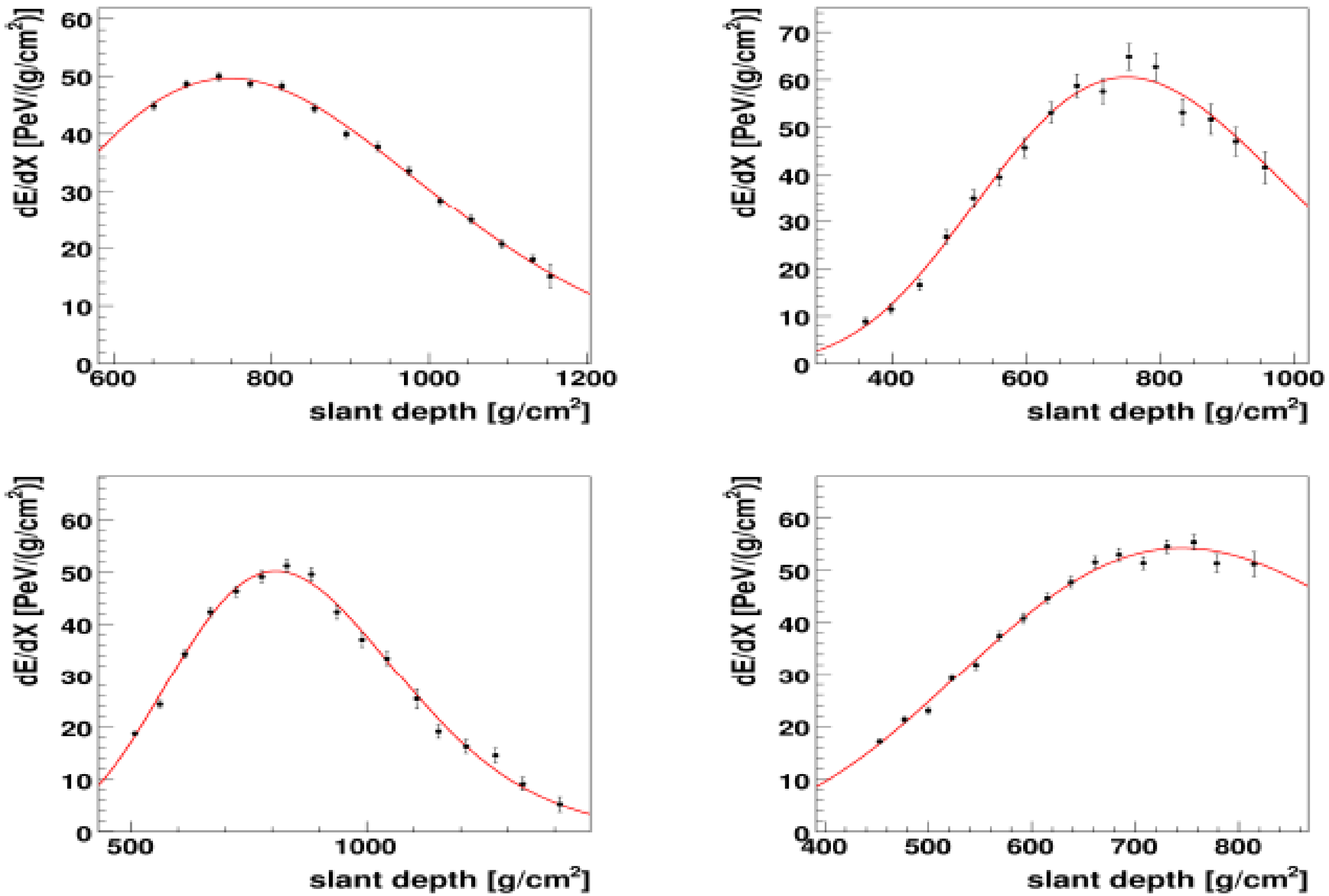
- Model parameters:
  - *O*(100) parameters
  - Multiples tunes to many collider measurements.

- No p-A, A-A available (yet). But PYTHIA comparable to EPOS/QGSJET via:
  - Constructing a CONEX hydrogen atmosphere with same density as air.
  - Running PYTHIA-6 proton-hydrogen with varying MC tunes to LHC data.

More later

Some Longitudinal Profiles measured with Auger

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



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

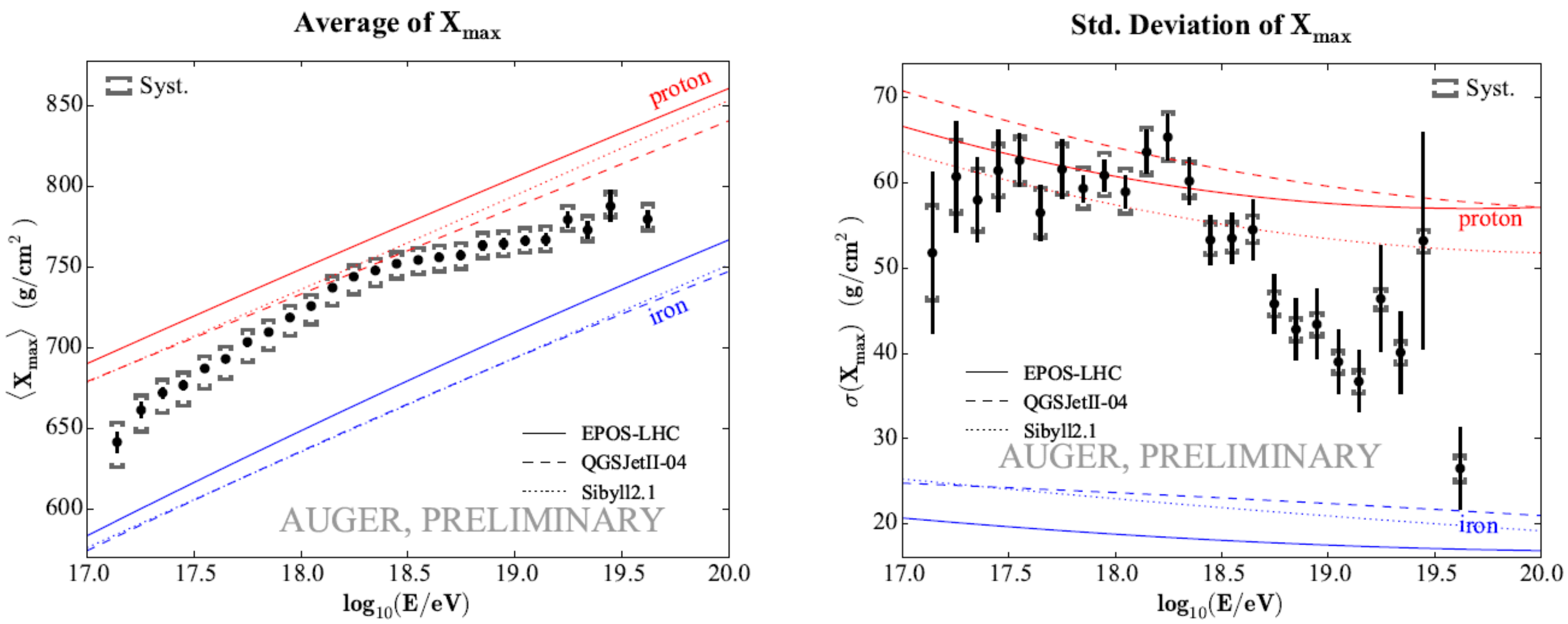


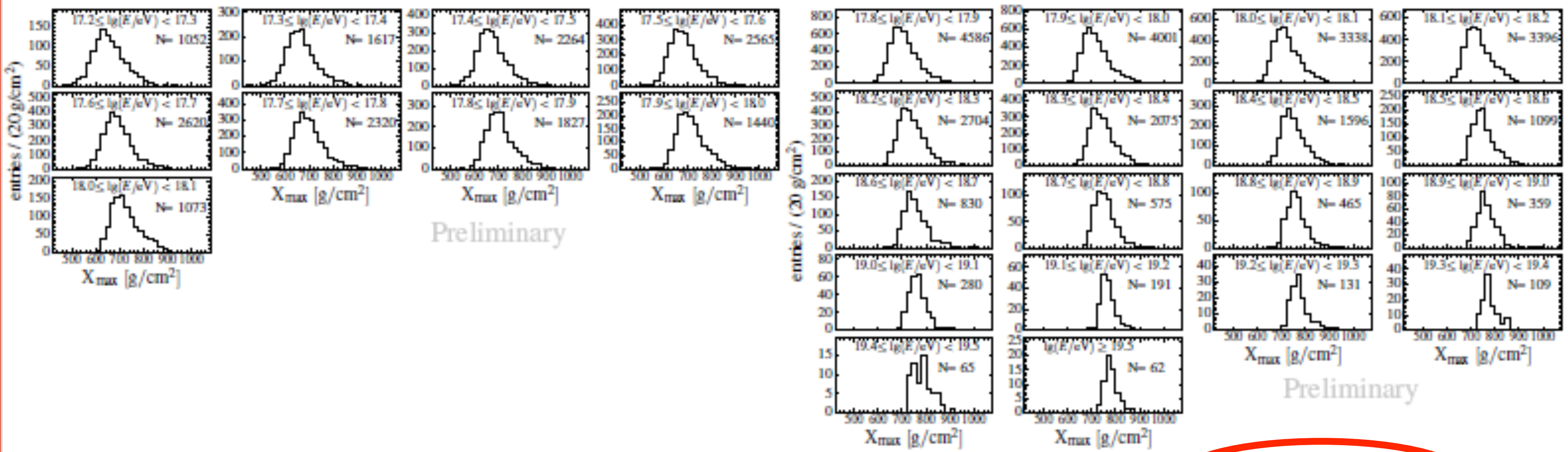
Figure 3: The mean (left) and the standard deviation (right) of the measured X_{max} distributions as a function of energy compared to air-shower simulations for proton and iron primaries.

(p-He-N-Fe)-fit of X_{max} Distributions

FD data:

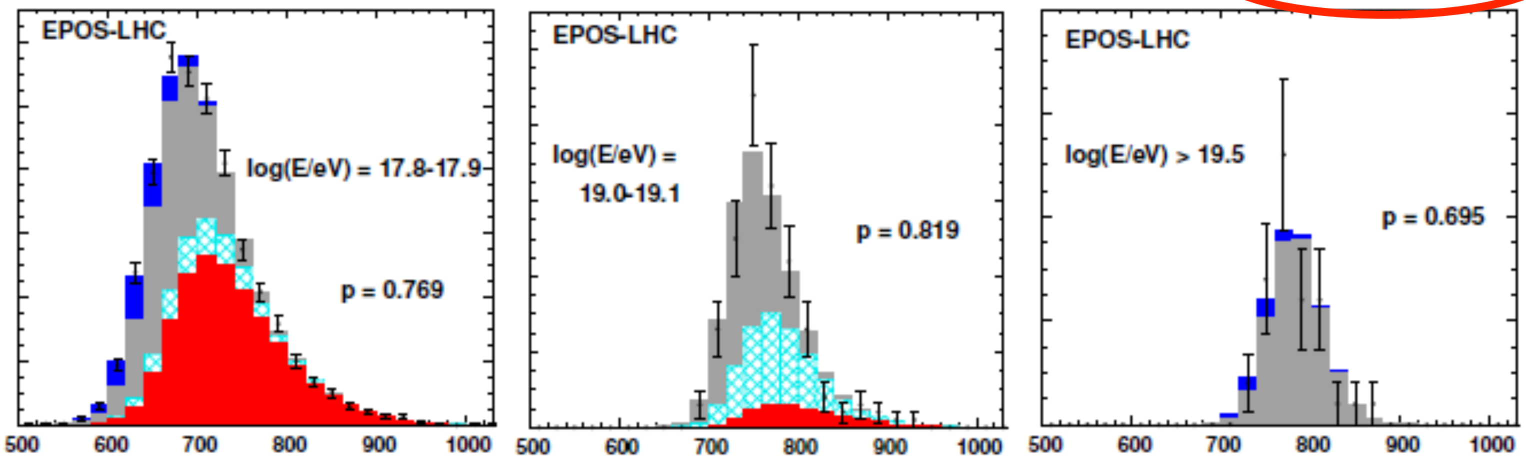
$\lg(E/\mathrm{eV}) = 17.2 \ldots 18.1$

$\lg(E/\mathrm{eV}) = 17.8 \ldots > 19.5$

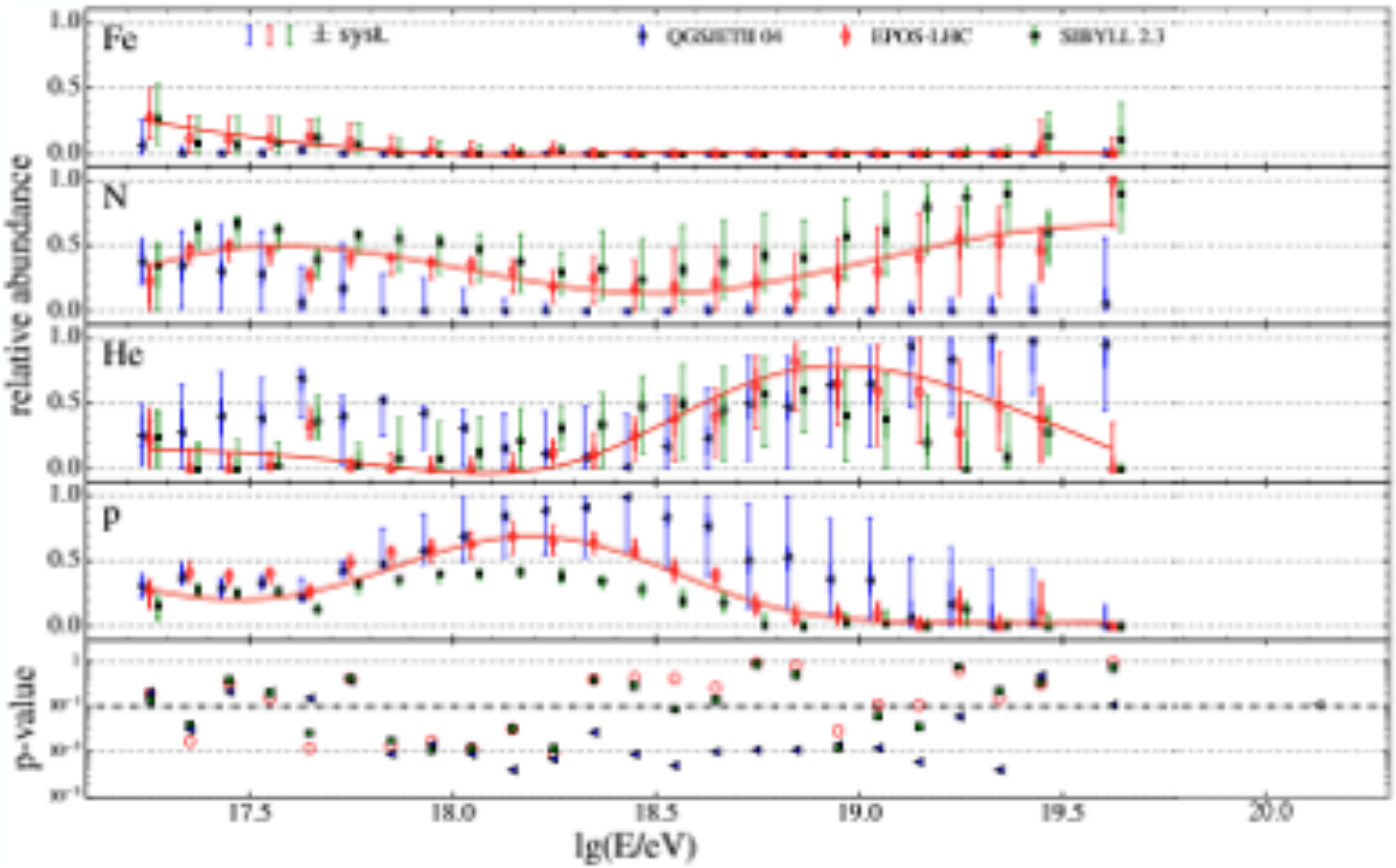


Examples of 4-component fit:

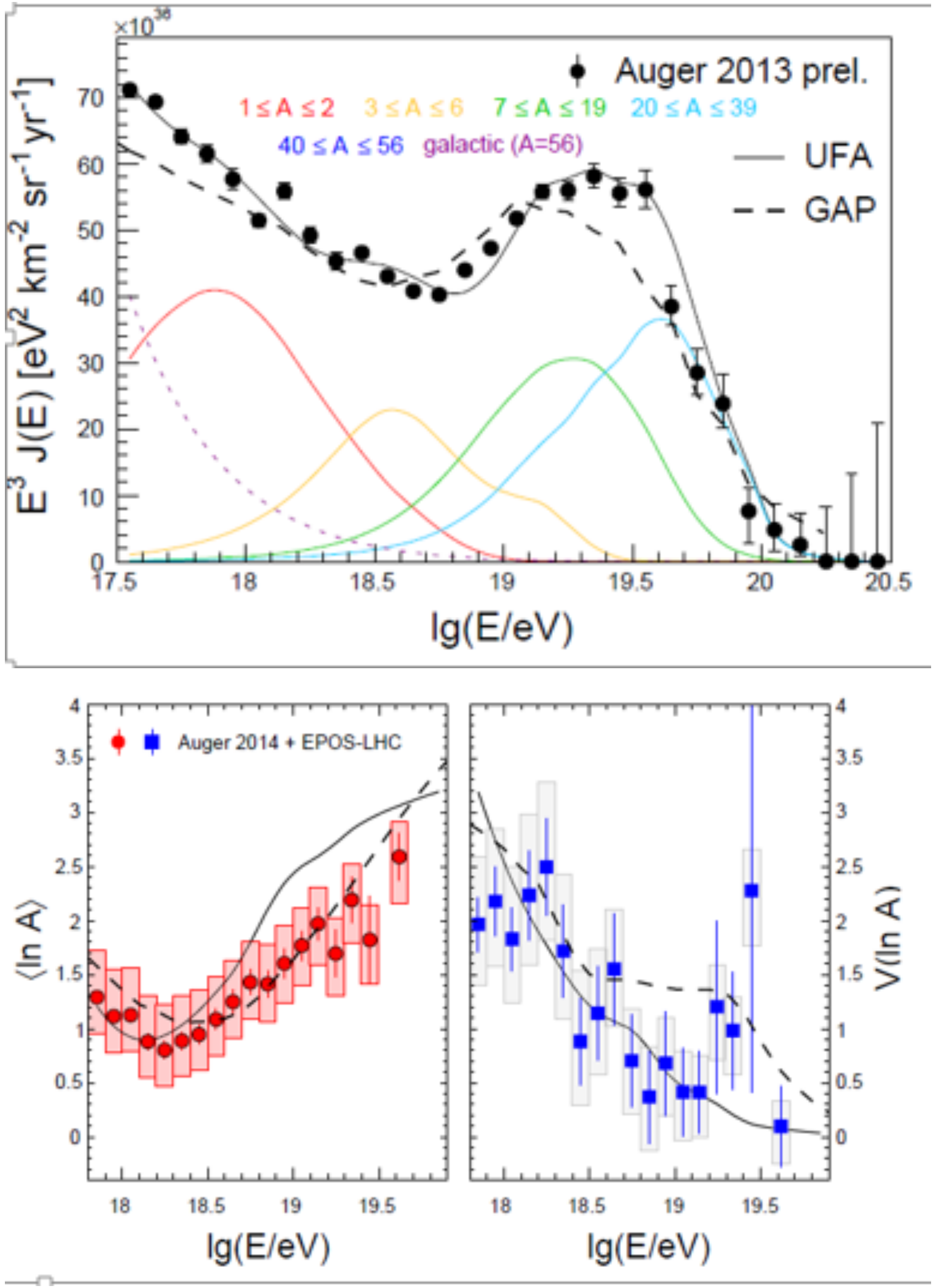
p He N Fe



Fraction of p, He, N and Fe as function of energy



(Bellido ICRC 2017)



Many models have been devised to explain data

Appealing ones have acceleration of 'normal' range of masses which are photo-disintegrated close to source.

Neutrons escape and their decay gives protons around 1 EeV

Unger et al. arXiv 1505.02153
Globus et al. arXiv 1505.01377

Hadronic Interactions

Some success

- and of some problems

Auger Design Study (1995): virtually no mention

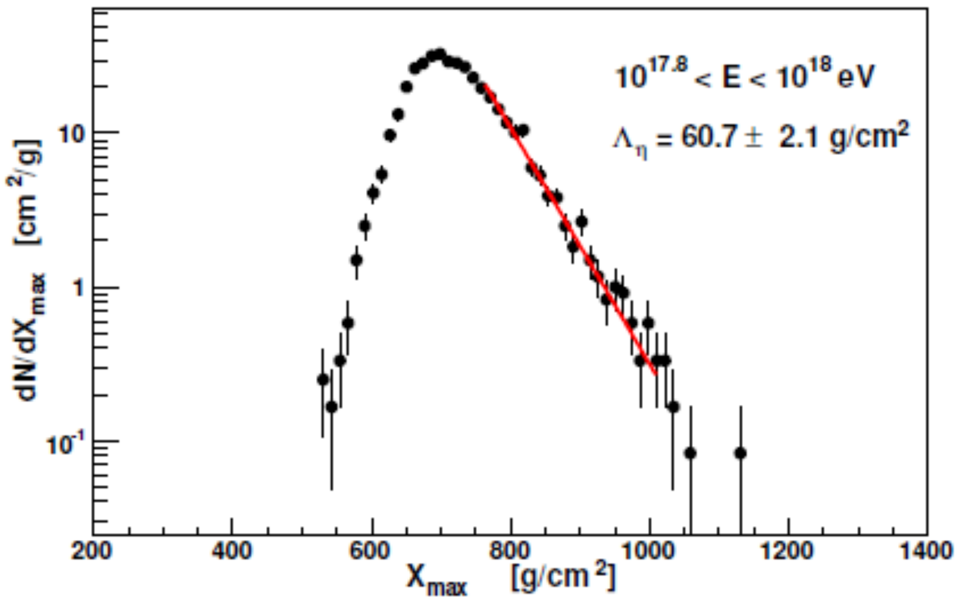
Rather, argued how well we would do *without* detailed knowledge of hadronic physics!

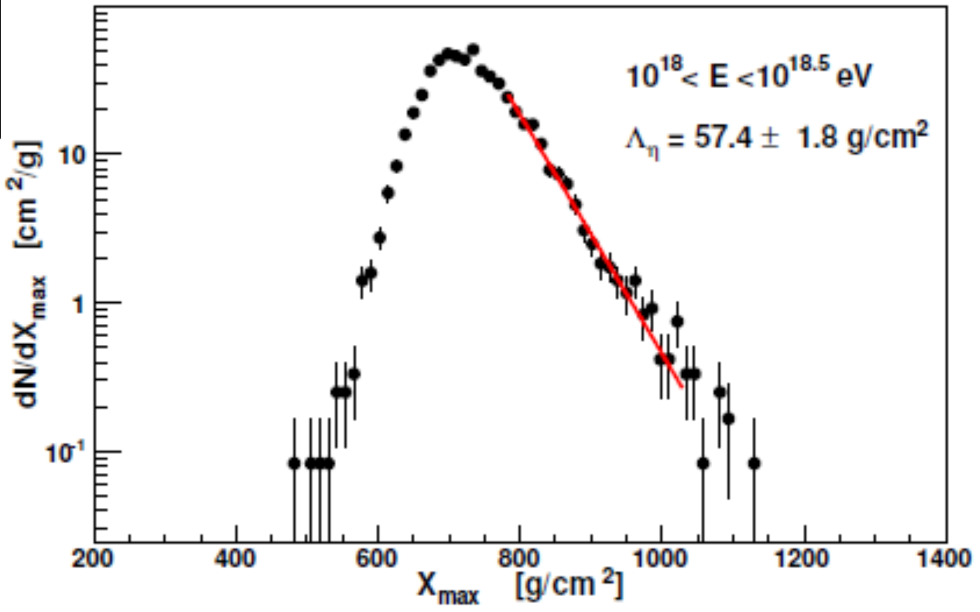
Bristol: Conference on Very High Energy Interactions, January 1963

AGS
33 GeV
CERN PS
28 GeV

Distribution of X_{max} for two energy ranges ICRC 2015

Measure Λ_η

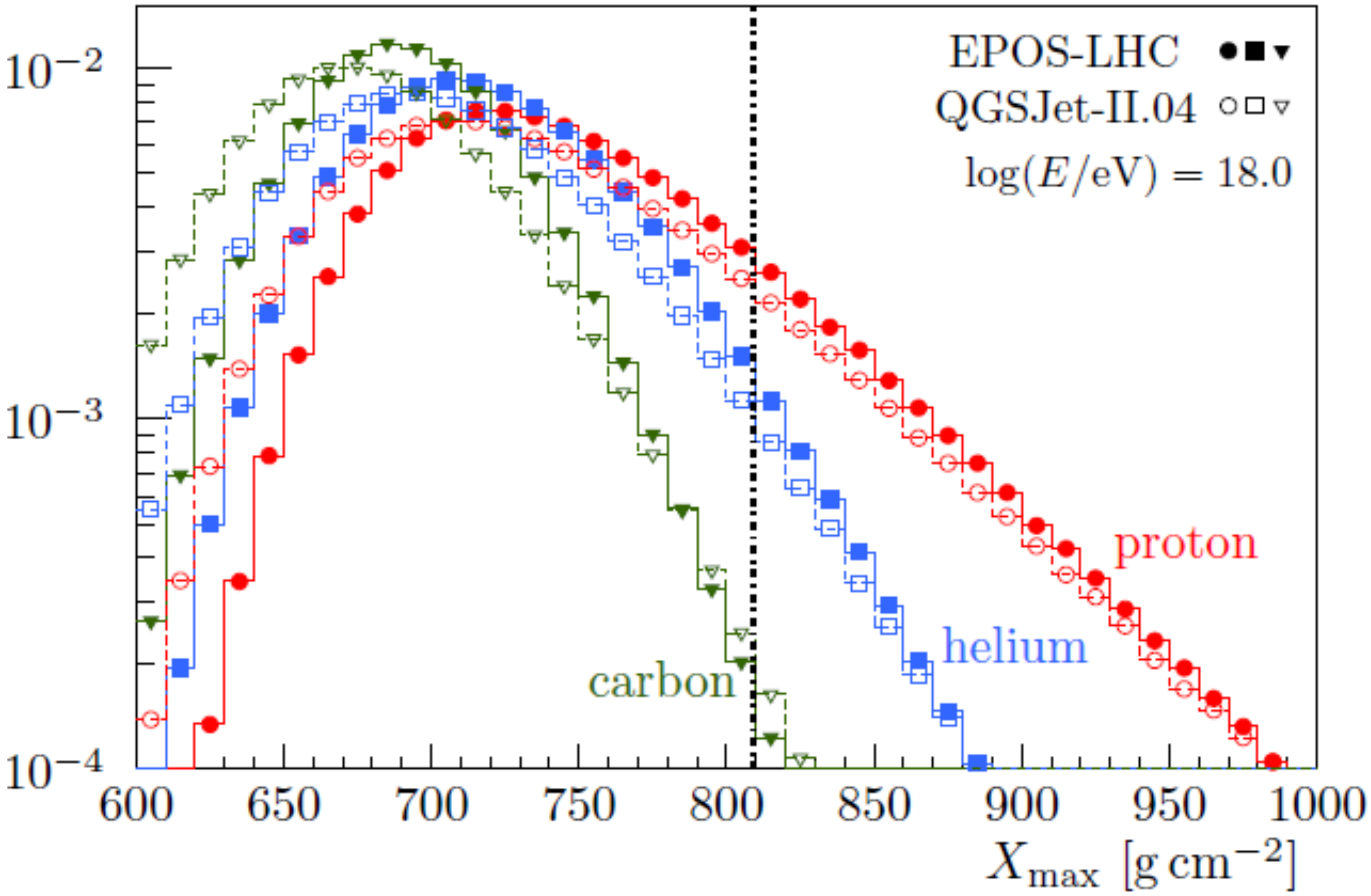




Λ_η, the attenuation length, is found from the 20% most penetrating events

<u>1196</u>/18090

<u>1384</u>/21270



EPOS-LHC
QGSJet-II.04
log(E/eV) = 18.0
proton
helium
carbon
10−2
10−3
10−4
600
650
700
750
800
850
900
950
1000
Xmax [g cm−2]

Relationship between Λ_η and proton-air cross-section

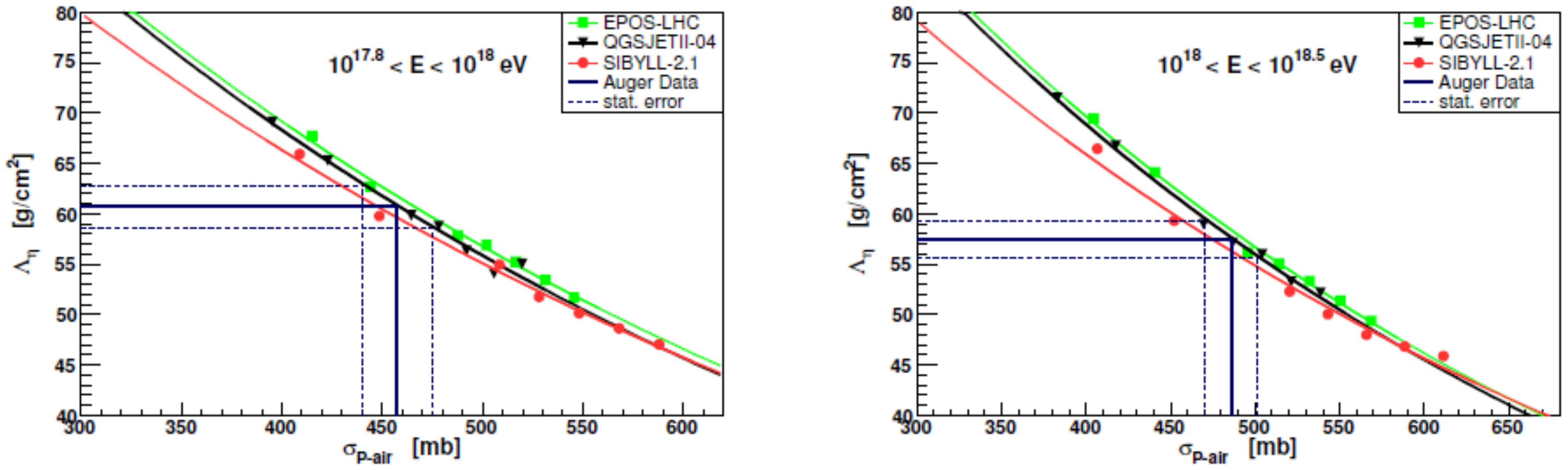
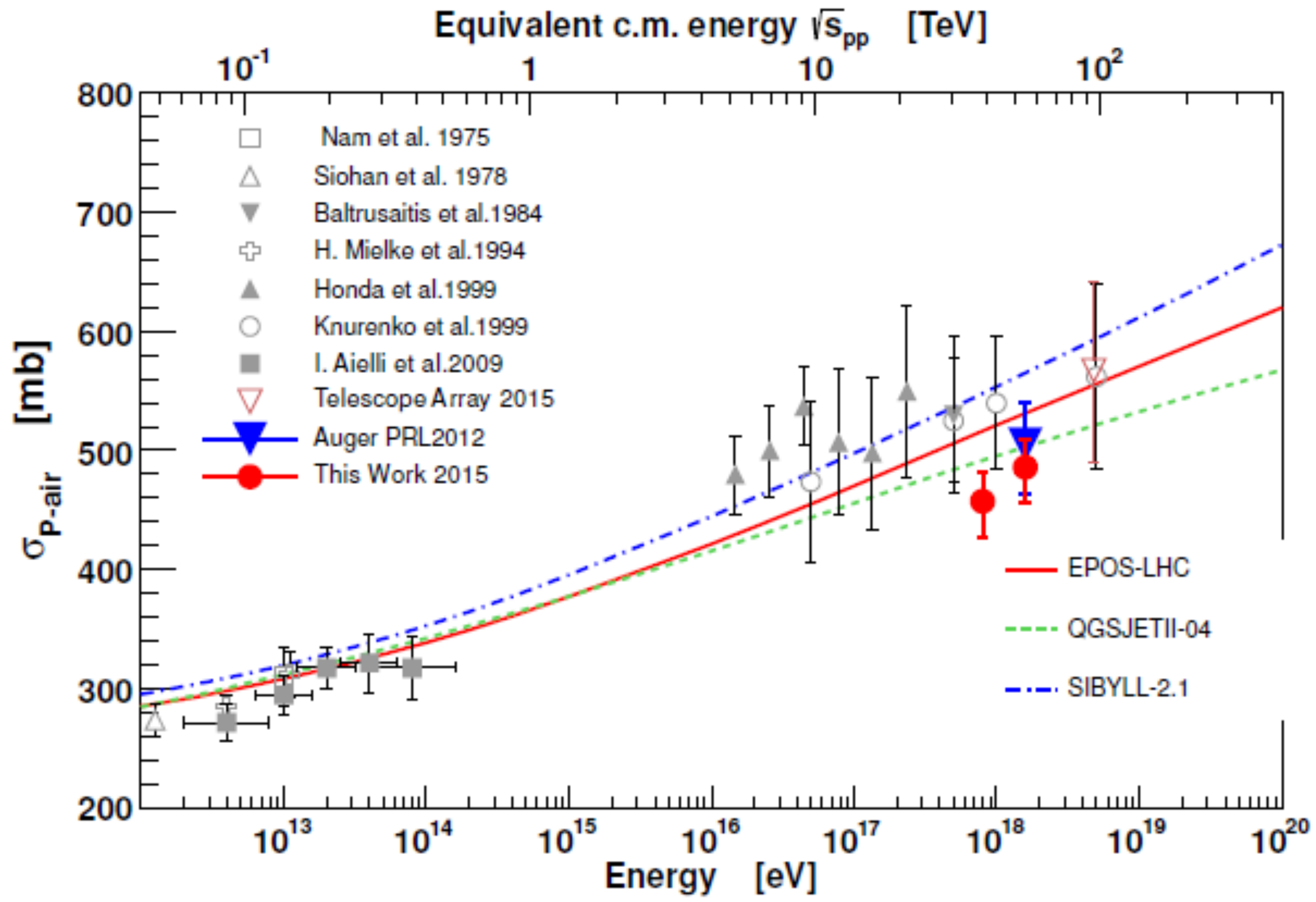


Figure 2: Conversion of Λ_η to σ_{p-air}. The simulations includes all detector resolution effects, while the data is corrected for acceptance effects. The solid and dashed lines show the Λ_η measurement and its projection to σ_{p-air} as derived using the average of all models.

25% Helium contamination: σ reduced by -17 and – 16 mb

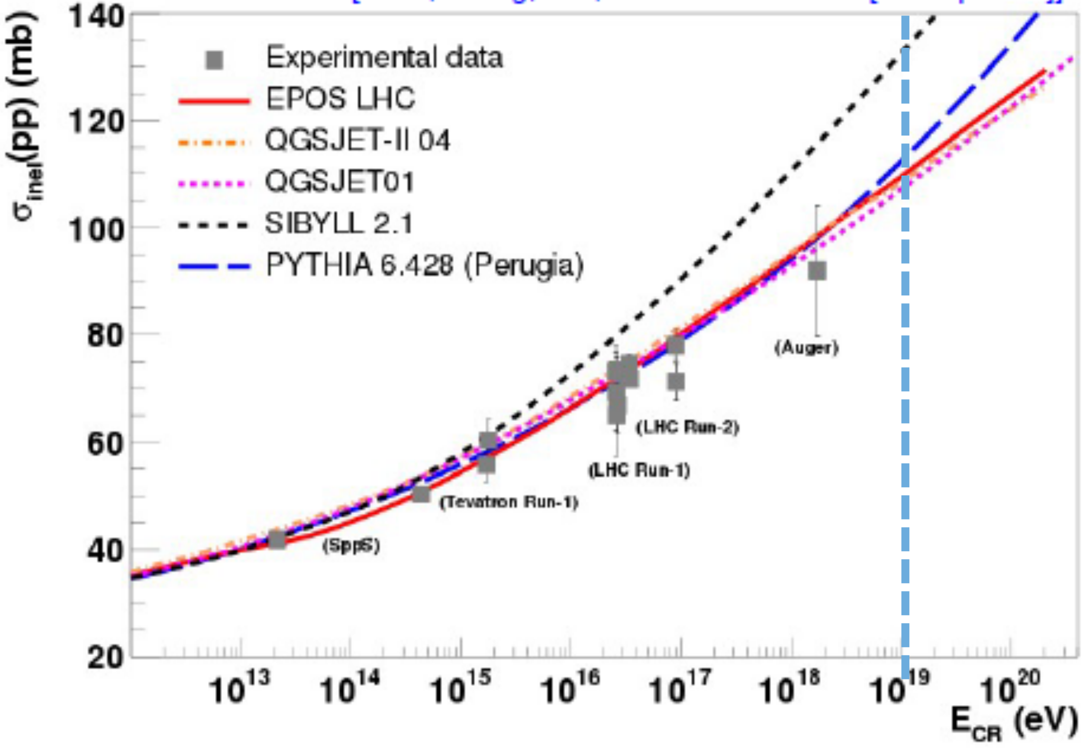
Proton-air cross-section as function of energy

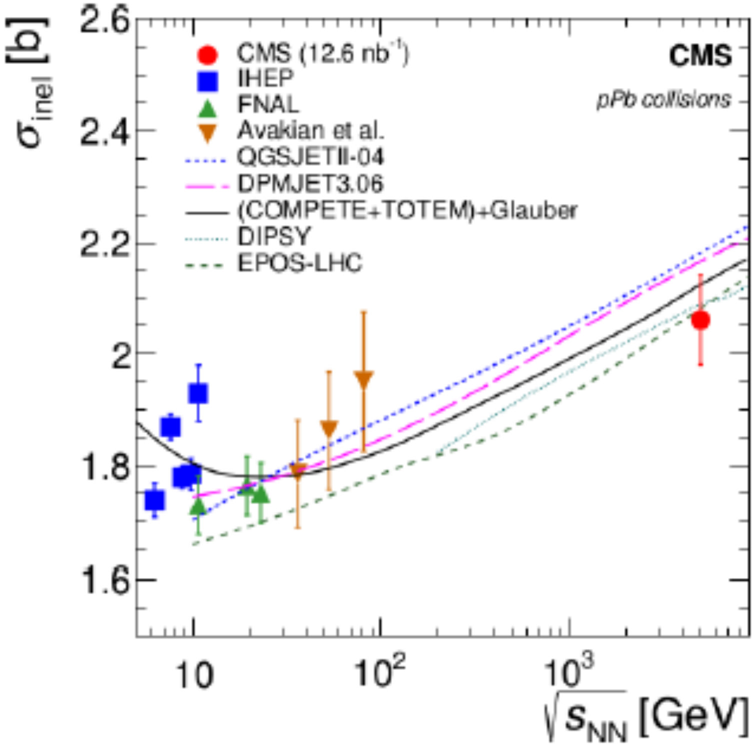


Impact of 25% He is included as systematic uncertainty (- 16 mb)
Photons have been shown to be < 0.5% at energies of interest:
contamination would raise σ by ~ 4.5 mb

Inelastic p-p, p-Pb cross sections (LHC)

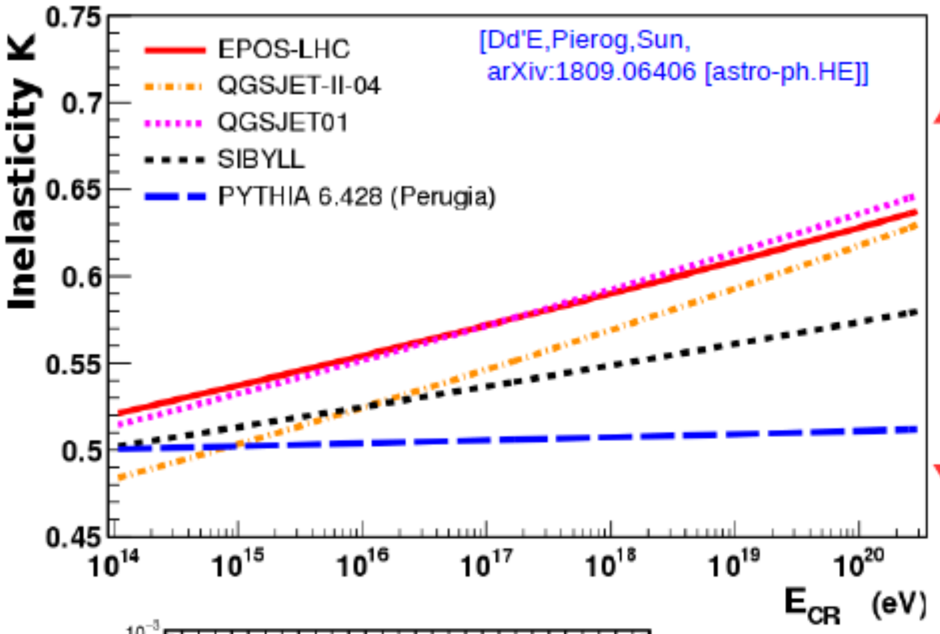
[Dd'E,Pierog,Sun, arXiv:1809.06406 [astro-ph.HE]]





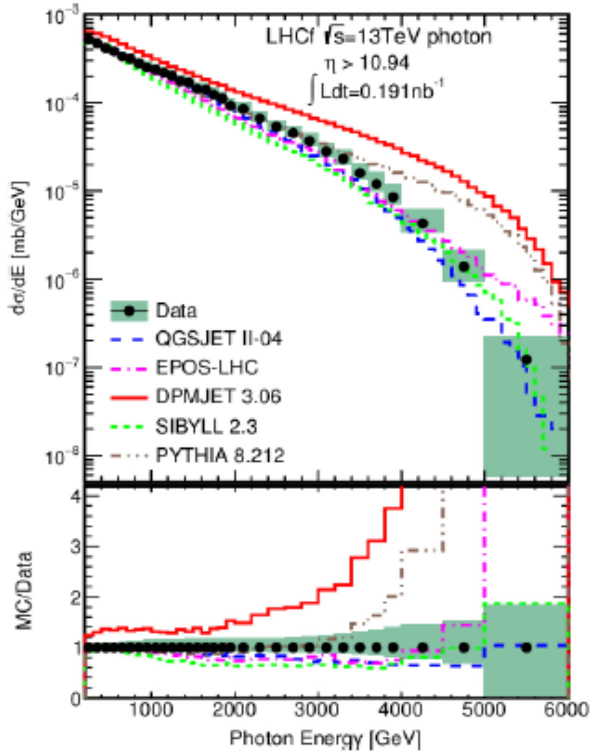
- All retuned MCs predictions are now ~consistent up to GZK cutoff.
- Measured σ(p-Pb) at 5.16 TeV confirms Glauber-scaling of σ(p-p) to σ(p-Air)
- Measured σ(p-p) at LHC, slightly below pre-LHC MC predictions, leads to reduced σ(p-Air): Deeper shower X_{max} position.

arXiv: 1902.09505



Less energy goes to very forward particle production
(Faster shower development: Smaller X_{max})

More energy goes to very forward particle production.
(Slower shower development: Larger X_{max})



For very forward particles all models need retuning though CR models slightly better

arXiv:1902.09505

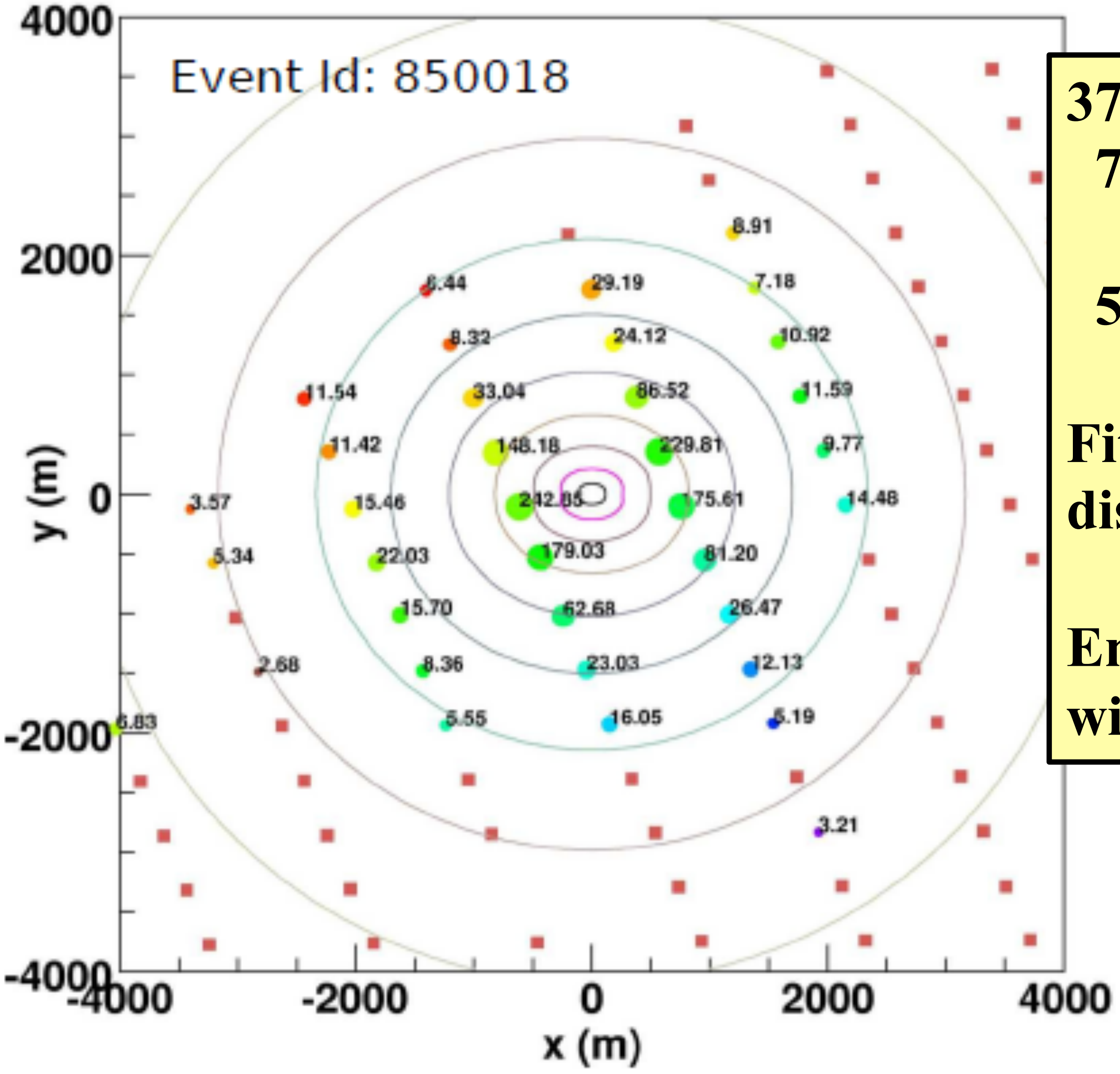
‘The Muon Problem’

$$N_\mu = A\left(\frac{E/A}{\epsilon_c}\right)^\beta,$$

β = 0.9
ε_c = energy at which pion interaction becomes less probable than decay (~10 GeV)

N_μ increases with energy
increases with A at given energy

Inclined showers are useful to test models – muons dominate



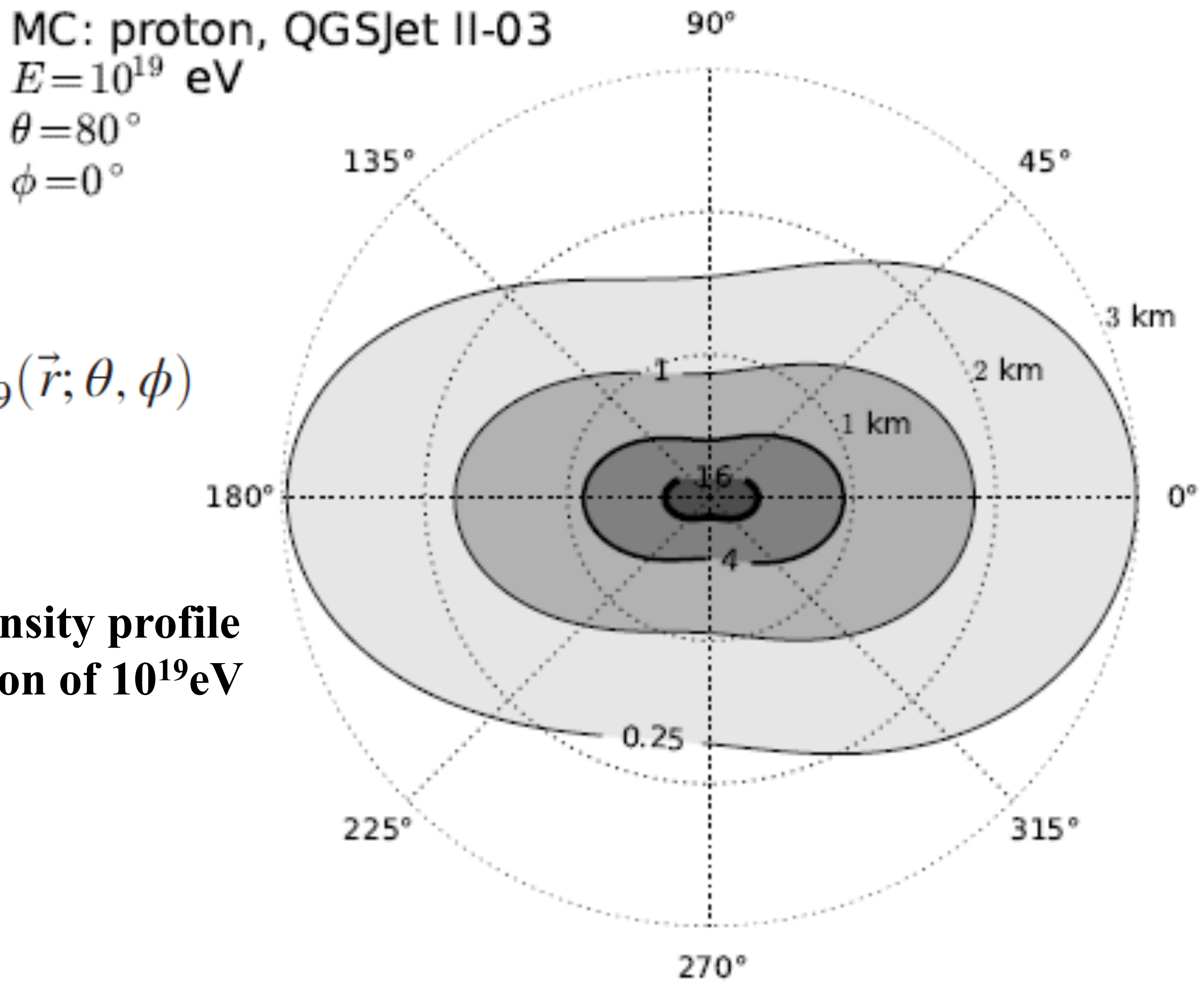
37 stations
71°
3200 g cm^{-2}
54 EeV

Fit made to density distribution

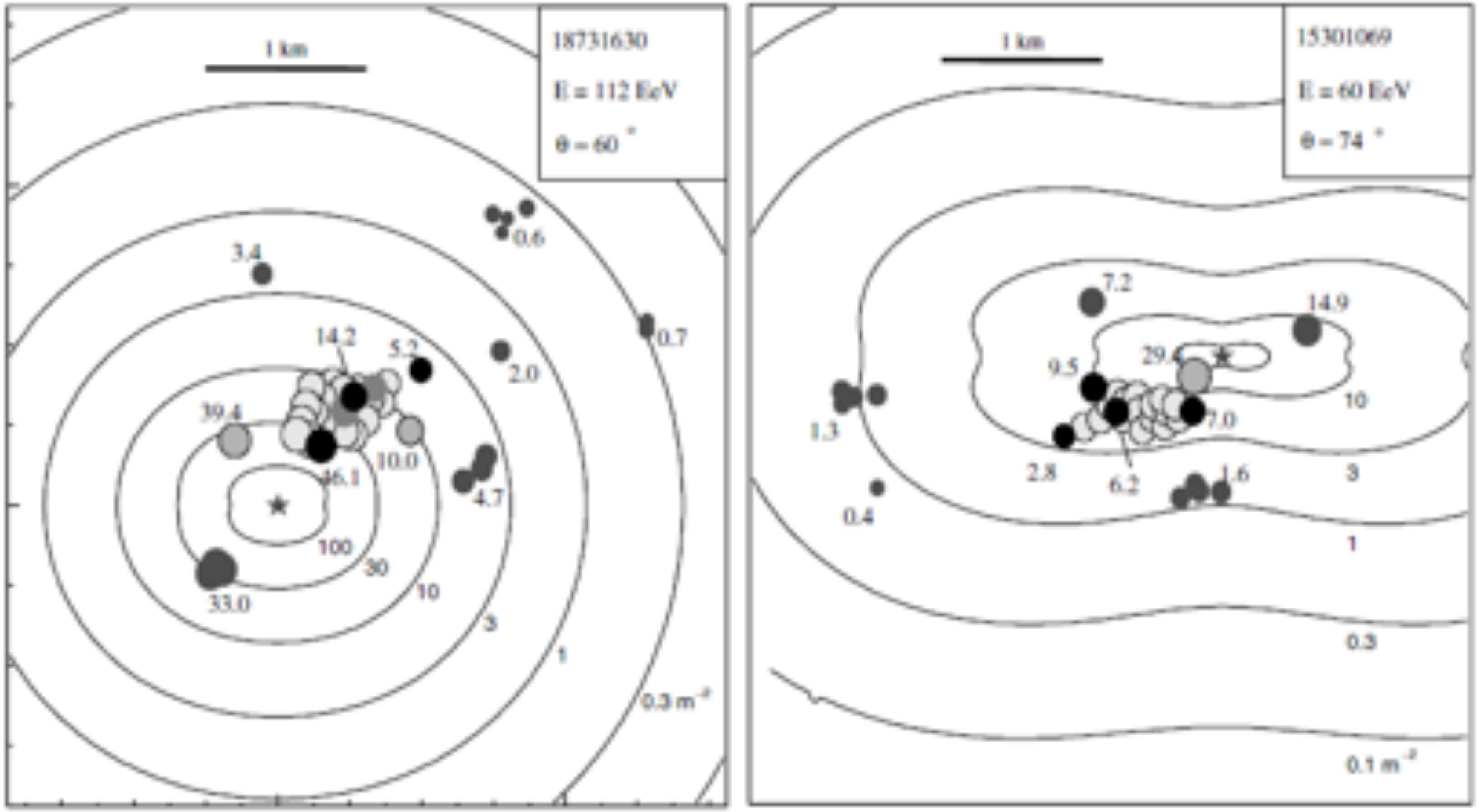
Energy measured with ~20 % accuracy

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

Average muon density profile of simulated-proton of 10^{19}eV



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



G. 1. Density maps of two events in the plane perpendicular to the shower axis. Recorded muon densities are shown as circl

R_μ in highly inclined events

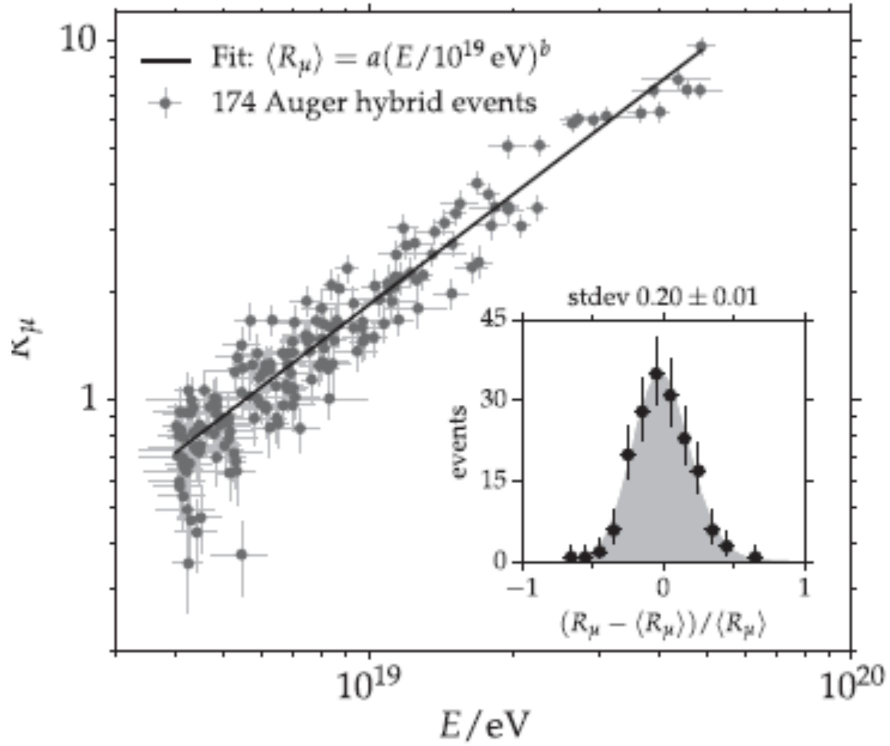
$$N_\mu = A\left(\frac{E/A}{\xi_c}\right)^\beta \qquad R_\mu = \frac{N_\mu^{data}}{N_{\mu,19}^{MC}}$$

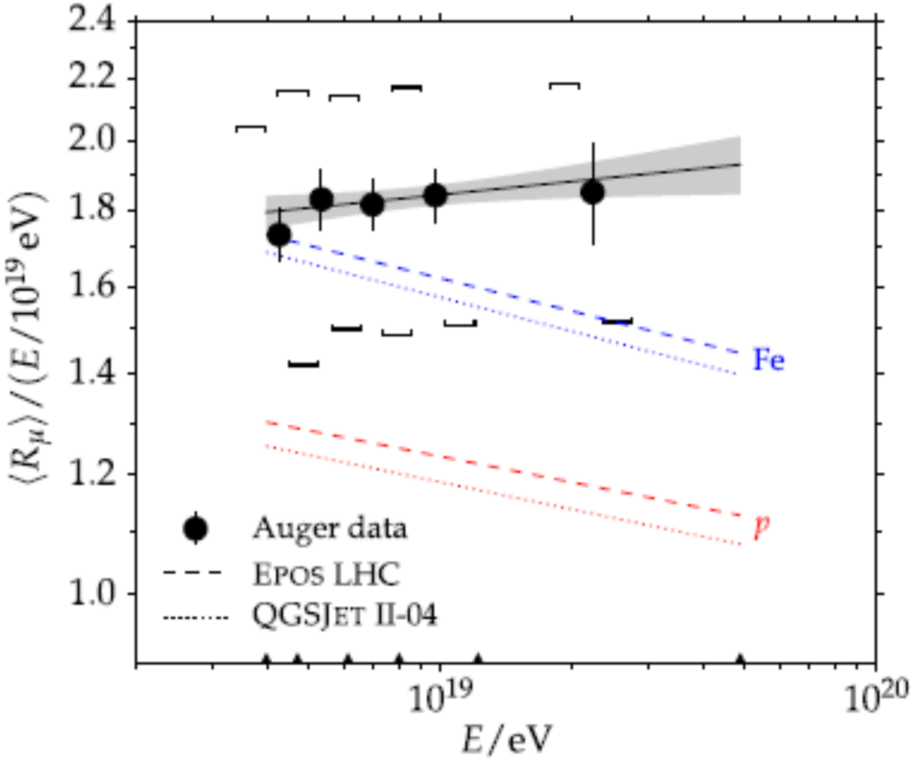
$$\langle R_\mu \rangle = a(E/10^{19}\ \mathrm{eV})^b$$

$$a = \langle R_\mu \rangle (10^{19}\ \mathrm{eV}) = (1.841 \pm 0.029 \pm 0.324(\mathrm{sys})),$$

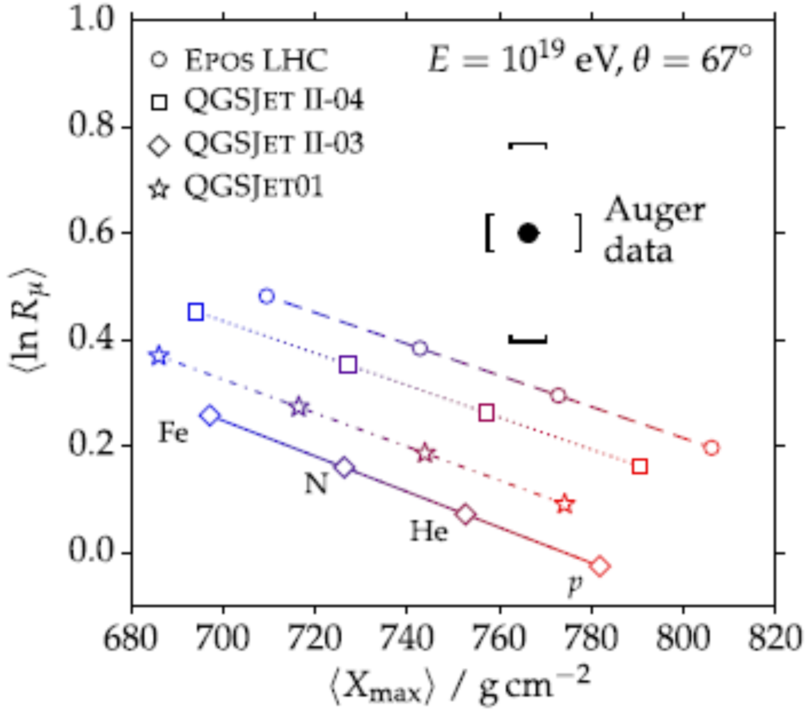
$$b = \mathrm{d}\langle \ln R_\mu \rangle / \mathrm{d} \ln E = (1.029 \pm 0.024 \pm 0.030(\mathrm{sys})),$$

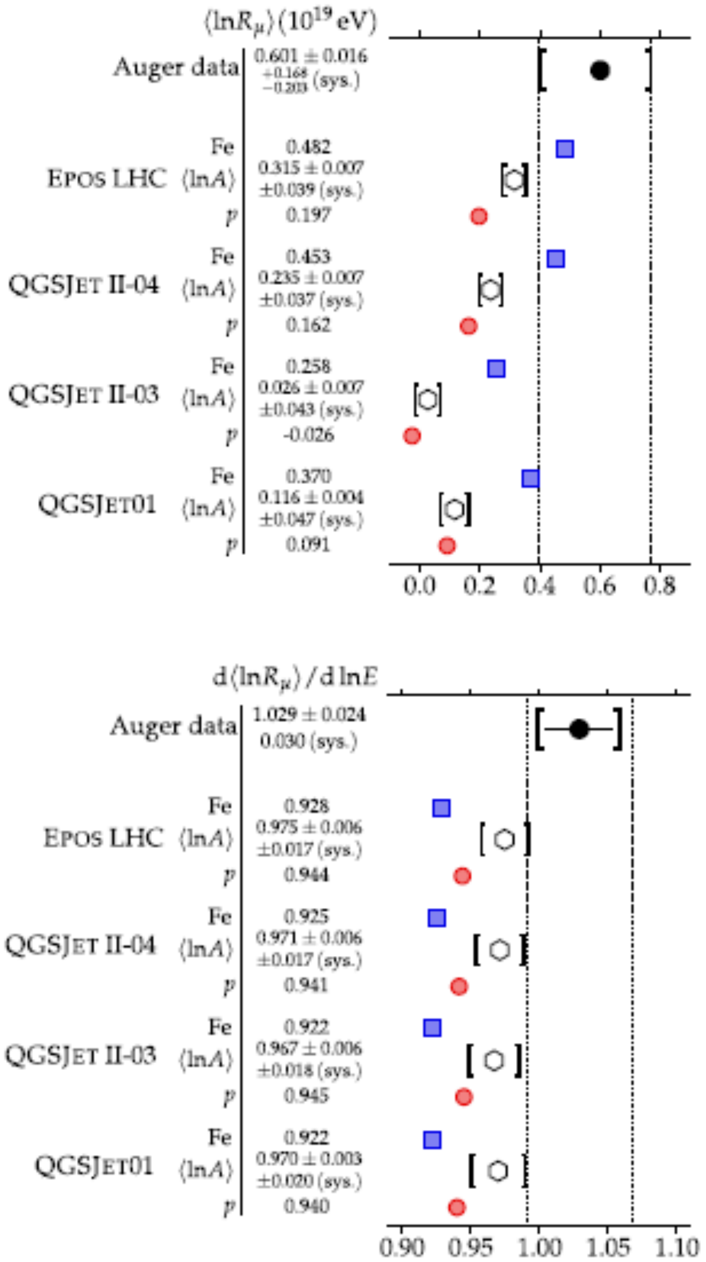
$$\sigma[R_\mu]/R_\mu = (0.136 \pm 0.015 \pm 0.033(\mathrm{sys})).$$





Results on $\langle \ln R_\mu \rangle$

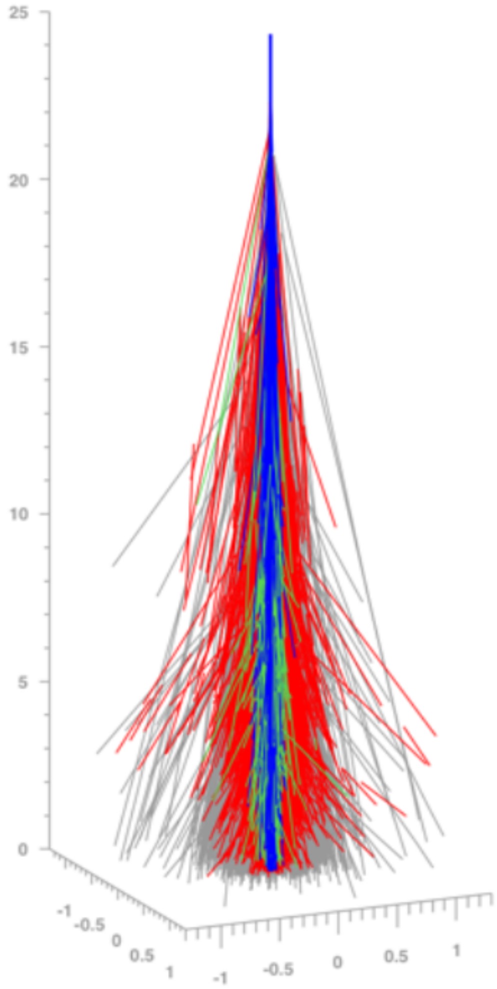


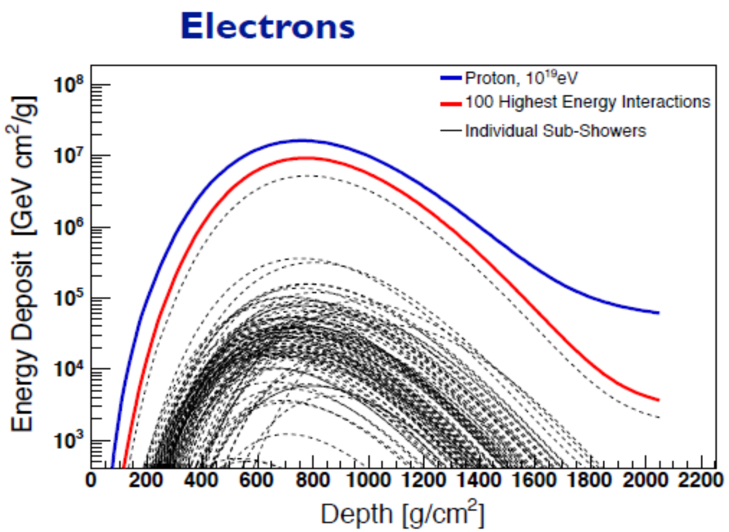


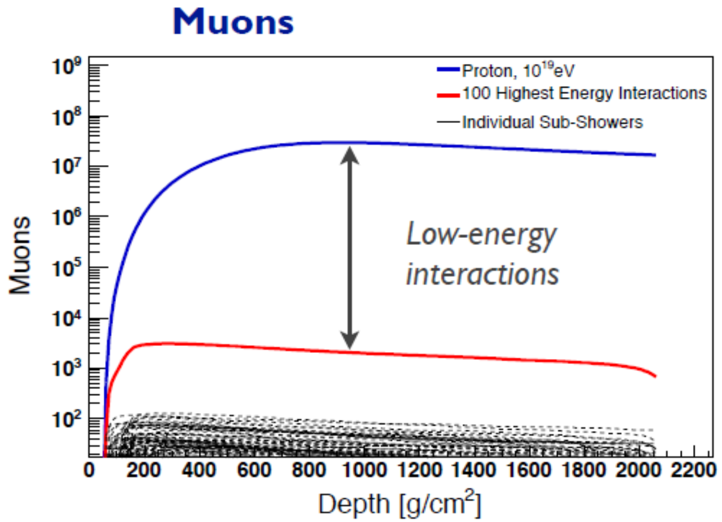
Muon deficit in sims,
and also deficit on
energy derivative (muon gain)

Predicted muon numbers are under-estimated by 30 to 80% (20% systematic)

Importance of different interaction energies







Shower particles produced in 100 interactions of highest energy

Electrons/photons: high-energy interactions

(Ulrich, APS 2012)

Muons/hadrons: low-energy interactions

Muons: majority produced in low energy interactions (**30-200 GeV** lab.)

- Data suggest few leading neutral pions in meson interactions

$$\pi^{\pm} + p \not\to \pi^0_{\text{lead}} + X$$

Instead

$$\pi^{\pm} + p \to \rho^0_{\text{lead}} + X$$

NA62/SHINE

Pion-Carbon Interactions Measured by NA61/SHINE Alexander E. Hervé

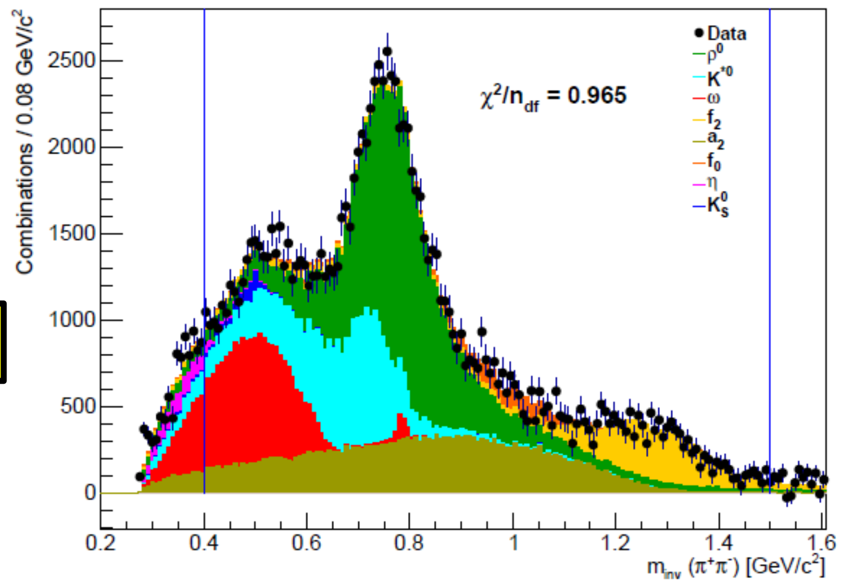


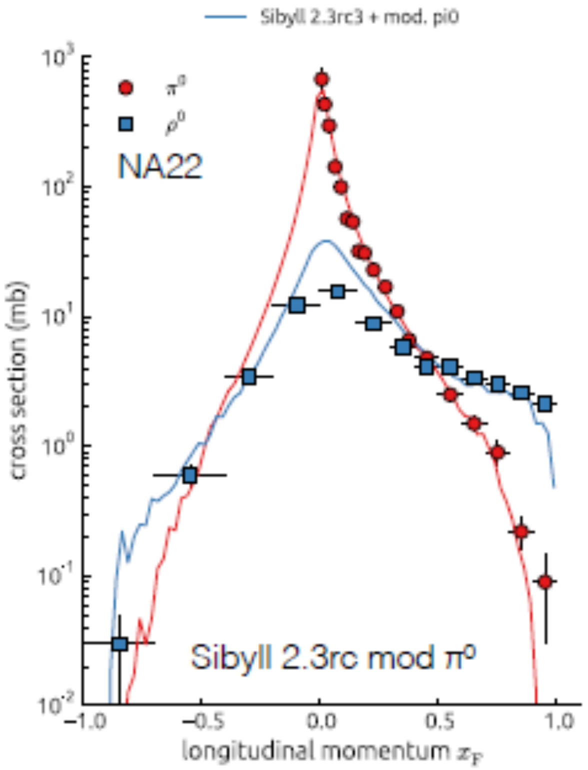
Figure 4: $\pi^+\pi^-$ mass distribution in π^-+C interactions at 158 GeV/c in the range $0.4 < x_F < 0.5$. Dots with error bars denote the data and the fitted resonance templates are shown as filled histograms. The vertical lines indicate the range of the fit.

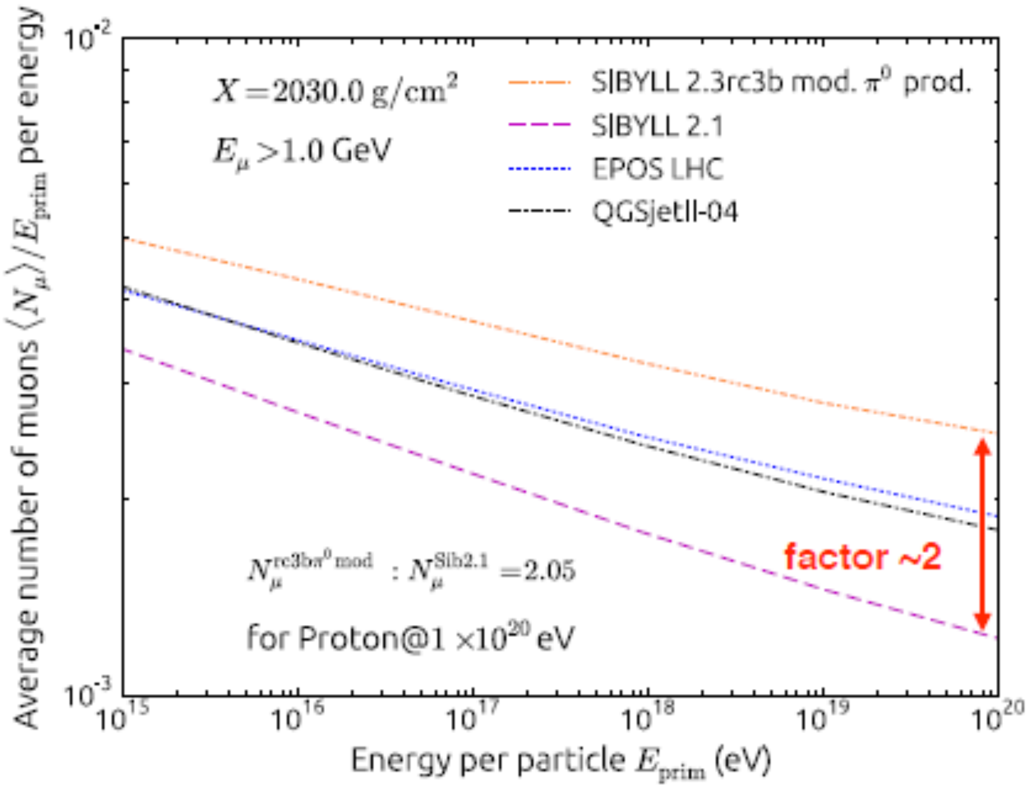
$$\rho^0 \longrightarrow \pi^+ + \pi^-$$

Thus there is a channel to enhance muon production

Taking energy out of electromagnetic channel will raise depth of shower maximum - slightly lighter primaries

Rho production in pion-proton interactions (iii)



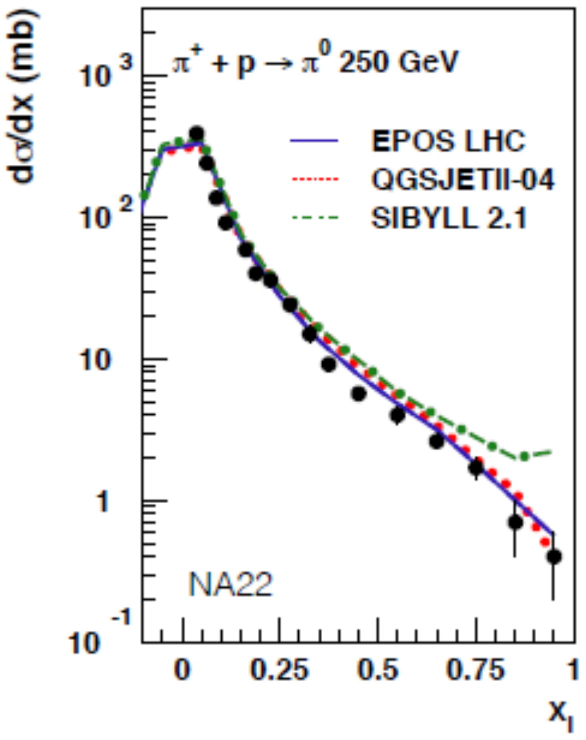


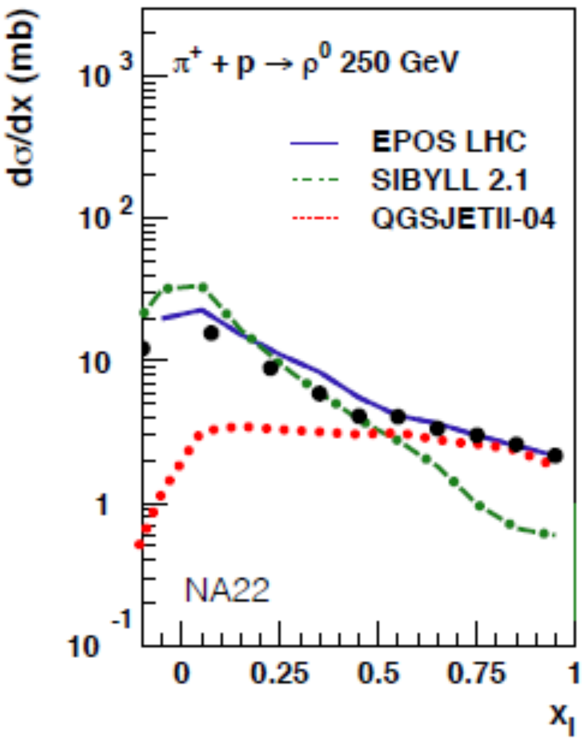
Ad hoc modified ρ^0 and π^0 production

Sibyll 2.3rc mod π^0

(Riehn et al., ICRC 2015)

Open questions related to rho production



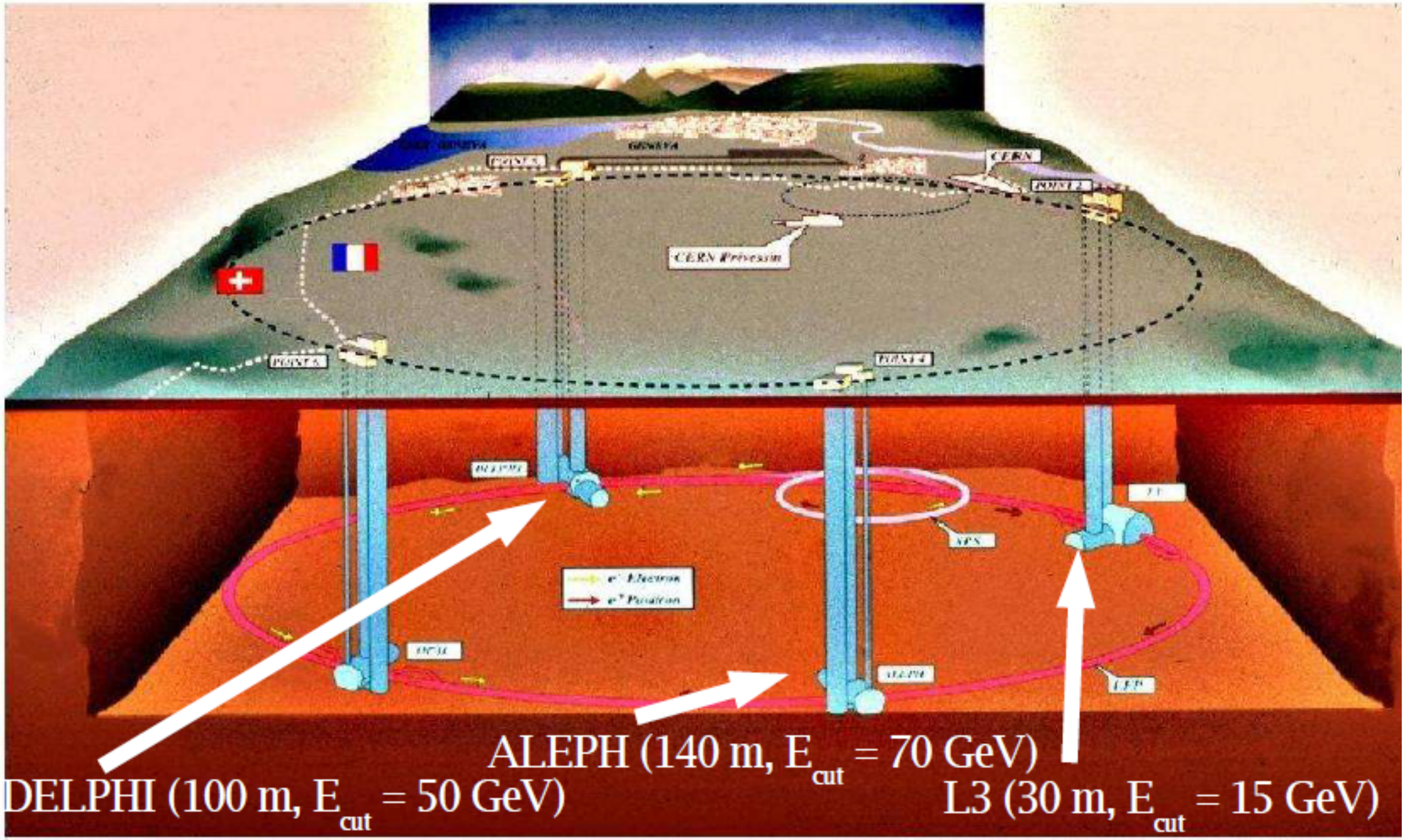


- EPOS and QGSJet tuned to reproduce π-p data
- Apparently origin of rho production not understood
- Suppression of π^0 production rather strong
- Energy dependence of these effects could be important

(Pierog 2015)

Was a similar muon problem seen with LEP detectors?

Detection of CR by LEP experiments

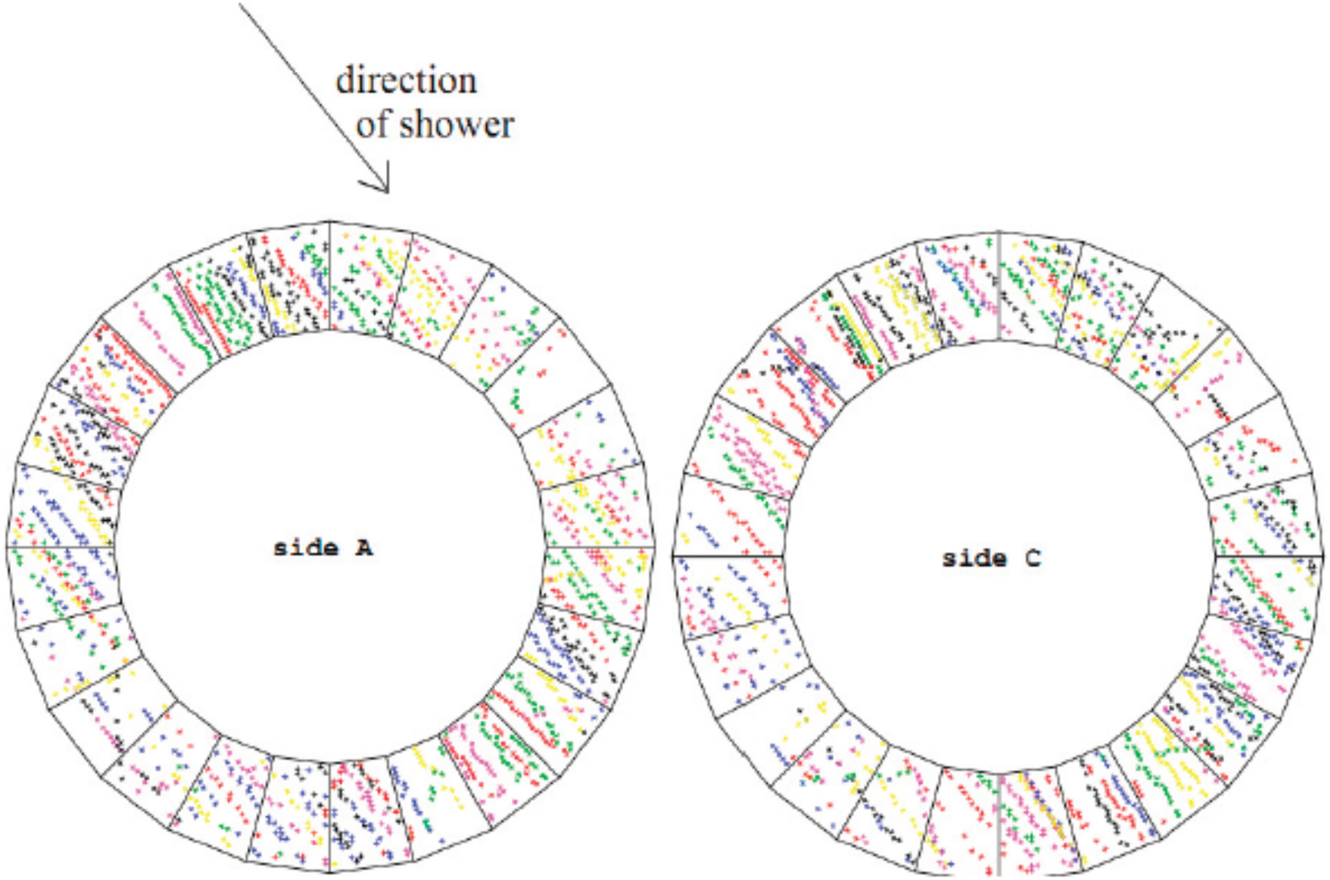


DELPHI as a cosmic ray detector

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

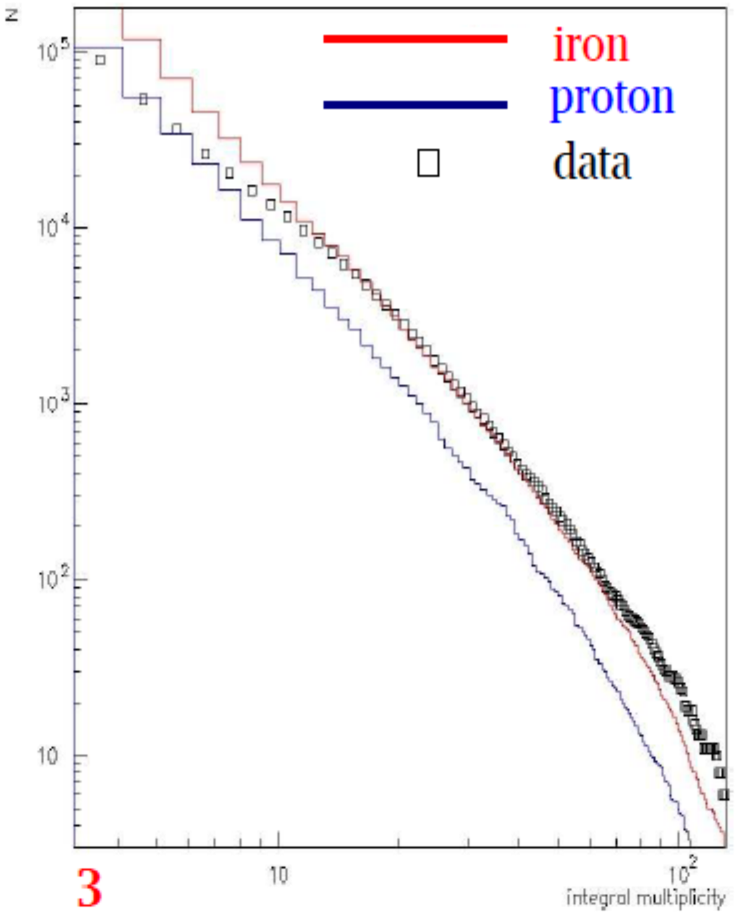
Bundles of parallel tracks in HCAL

- 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

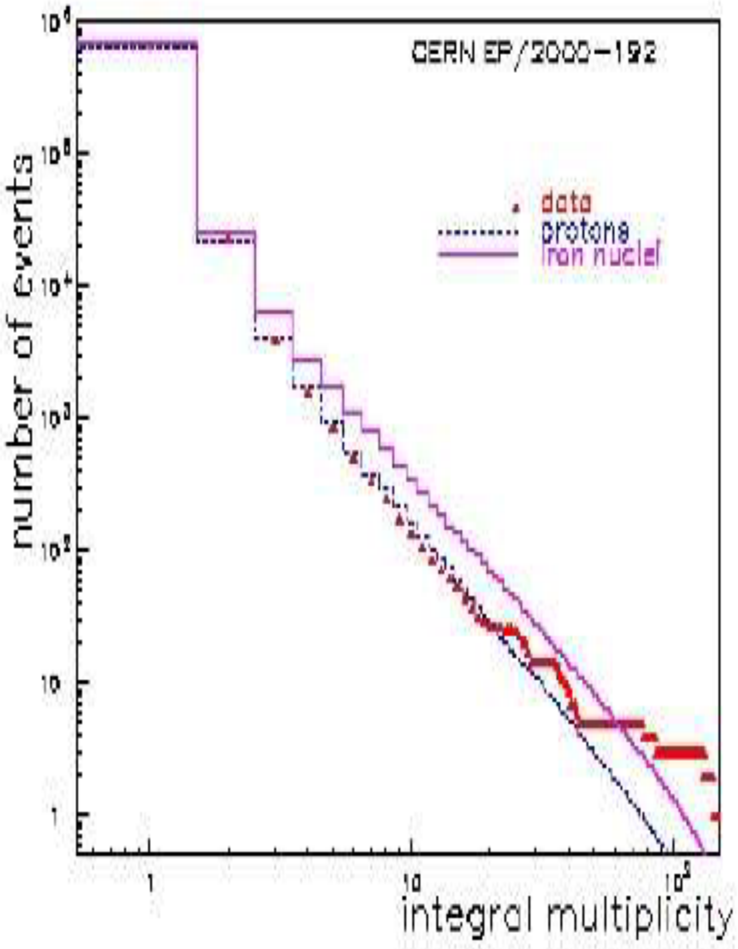


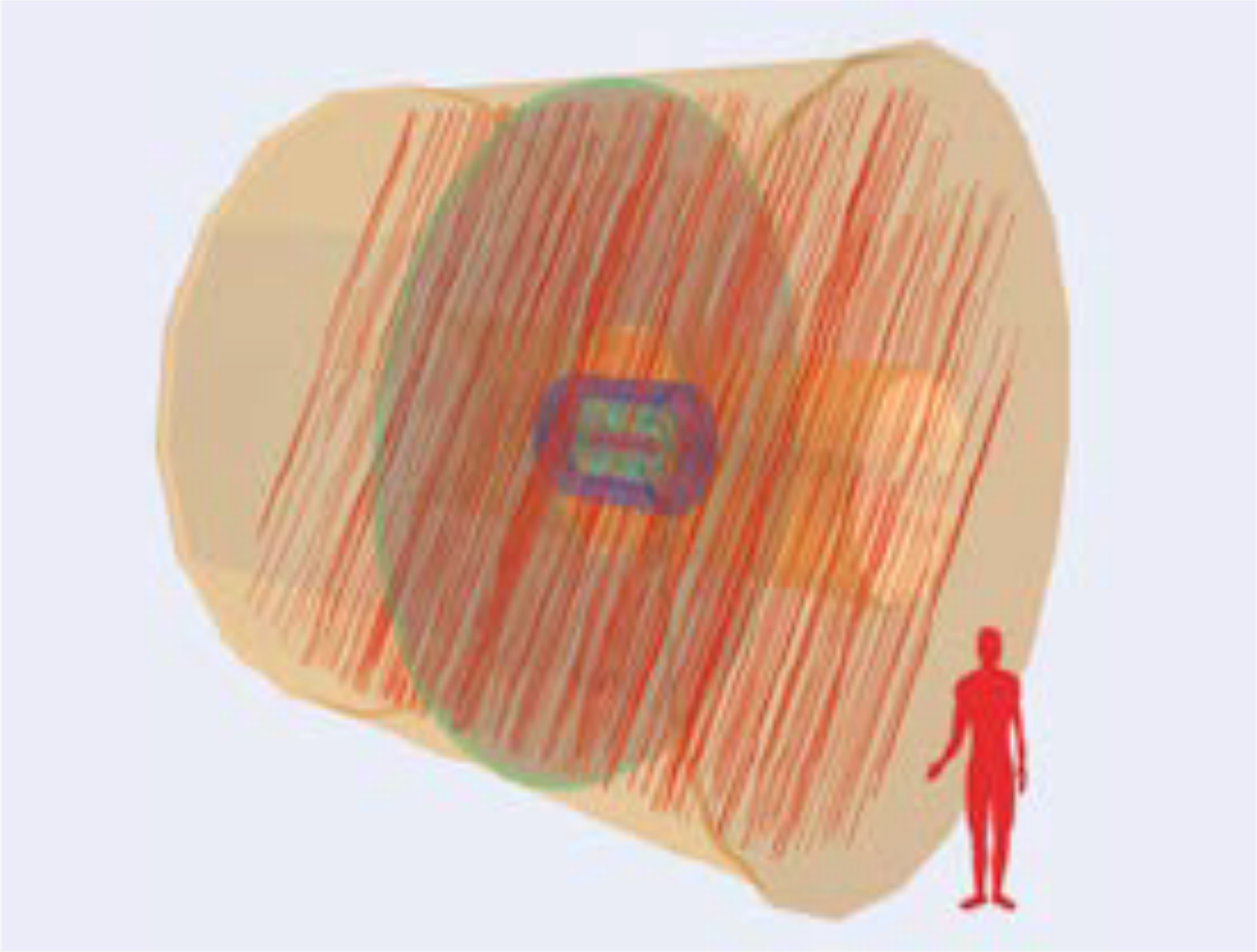
Results

Delphi



Aleph





Event display of a multi-muon event with 276 reconstructed muons crossing the TPC.

CERN Courier
December 2015

ALICE

Study of cosmic ray events with high muon multiplicity using the ALICE detector at the CERN Large Hadron Collider

JCAP 01 032 2016

ALICE

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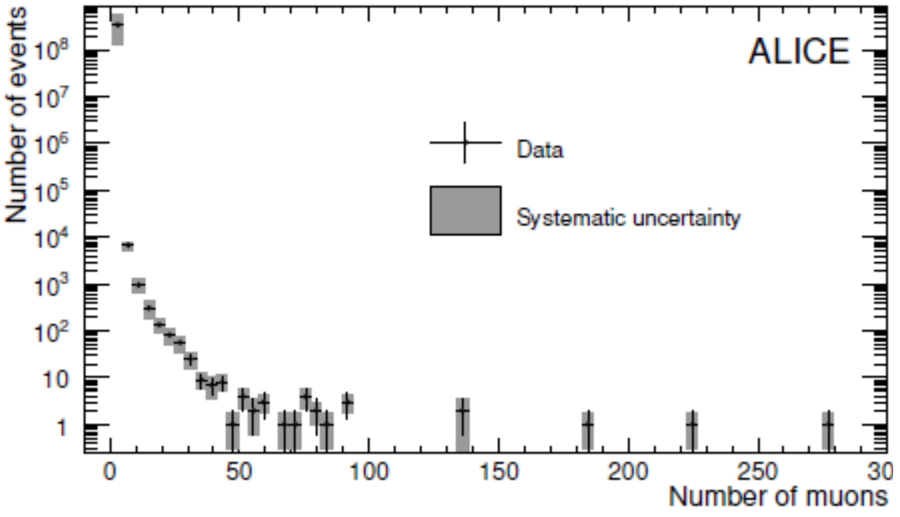
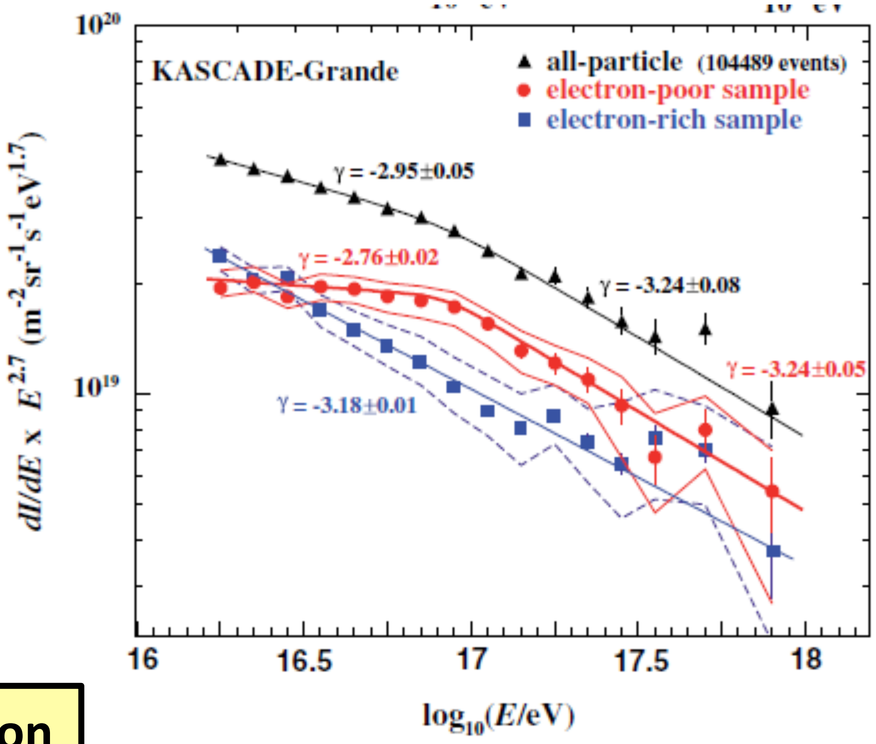
Received August 7, 2015
Accepted December 17, 2015
Published January 19, 2016

Abstract. ALICE is one of four large experiments at the CERN Large Hadron Collider near Geneva, specially designed to study particle production in ultra-relativistic heavy-ion collisions. Located 52 meters underground with 28 meters of overburden rock, it has also been used to detect muons produced by cosmic ray interactions in the upper atmosphere. In this paper, we present the multiplicity distribution of these atmospheric muons and its comparison with Monte Carlo simulations. This analysis exploits the large size and excellent tracking capability of the ALICE Time Projection Chamber. A special emphasis is given to the study of high multiplicity events containing more than 100 reconstructed muons and corresponding to a muon areal density $\rho_\mu > 5.9\ \mathrm{m}^{-2}$. Similar events have been studied in previous underground experiments such as ALEPH and DELPHI at LEP. While these experiments were able to reproduce the measured muon multiplicity distribution with Monte Carlo simulations at low and intermediate multiplicities, their simulations failed to describe the frequency of the highest multiplicity events. In this work we show that the high multiplicity events observed in ALICE stem from primary cosmic rays with energies above 10^{16} eV and that the frequency of these events can be successfully described by assuming a heavy mass composition of primary cosmic rays in this energy range. The development of the resulting air showers was simulated using the latest version of QGSJET to model hadronic interactions. This observation places significant constraints on alternative, more exotic, production mechanisms for these events.



Iuon multiplicity distribution of the whole sample of data (2010-2013)



Conclusion in ALICE paper makes assumption about mass composition, in contradiction with cosmic ray data

(color online). Reconstructed energy spectrum of the
n-poor and electron-rich components together with the
ticle spectrum for the angular range 0°–40°. The error

High muon multiplicity events were observed in the past by experiments at LEP but without satisfactory explanation. Similar high multiplicity events have been observed in this study with ALICE. Over the 30.8 days of data taking reported in this paper, 5 events with more than 100 muons and zenith angles less than 50° have been recorded. We have found that the observed rate of HMM events is consistent with the rate predicted by CORSIKA 7350 using QGSJET II-04 to model the development of the resulting air shower, assuming a pure iron composition for the primary cosmic rays. Only primary cosmic rays with an energy $E > 10^{16}$ eV were found to give rise to HMM events. This observation is compatible with a knee in the cosmic ray energy distribution around 3×10^{15} eV due to the light component followed by a spectral steepening, the onset of which depends on the atomic number (Z) of the primary.

Summary:

- Energy spectrum shows two features:

  Flattening at ~ 4 x 10^{18} eV

  Steepening at about 4 x 10^{19} eV

- Mass is proton-dominated near 10^{18} eV and then gets heavier as energy rises (details are model-dependent)

- Arrival direction data show evidence of anisotropies

- While cosmic-ray models fit some data reasonably well, there are problems in fitting the muon features: too many muons?

- p-p cross-section at 57 TeV

- May be excess of production of ρ^0 in p-C collisions

- Need data on pion-A collisions and p-A collisions