Particle Physics Group, Rutherford Lab

7 February 2018

Insights into hadronic physics beyond LHC energies from studies of cosmic rays with the Pierre Auger Observatory

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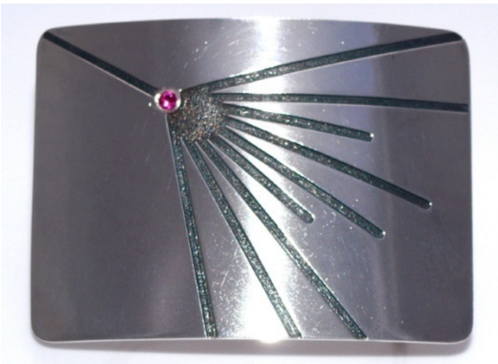
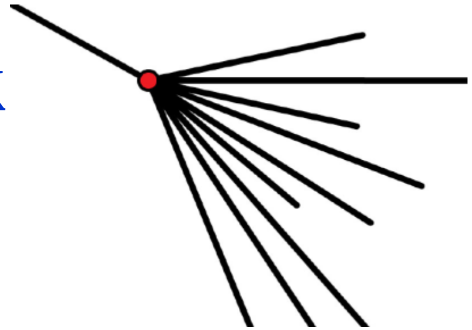




Bristol: Conference on Very High Energy Interactions, January 1963

AGS
33 GeV
CERN PS
28 GeV

Outline:

- **Goals of UHECR (> 10^{18} eV, or 1 EeV) research**
- **Pierre Auger Observatory**
- **Energy Spectrum – to show you how we work**
- **Mass Composition - to show what we need from you**
  (no discussion of photon or neutrino searches)
- **Arrival Directions – to show that we do get 5 σ results**
- **Hadronic physics models used**
- **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?

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

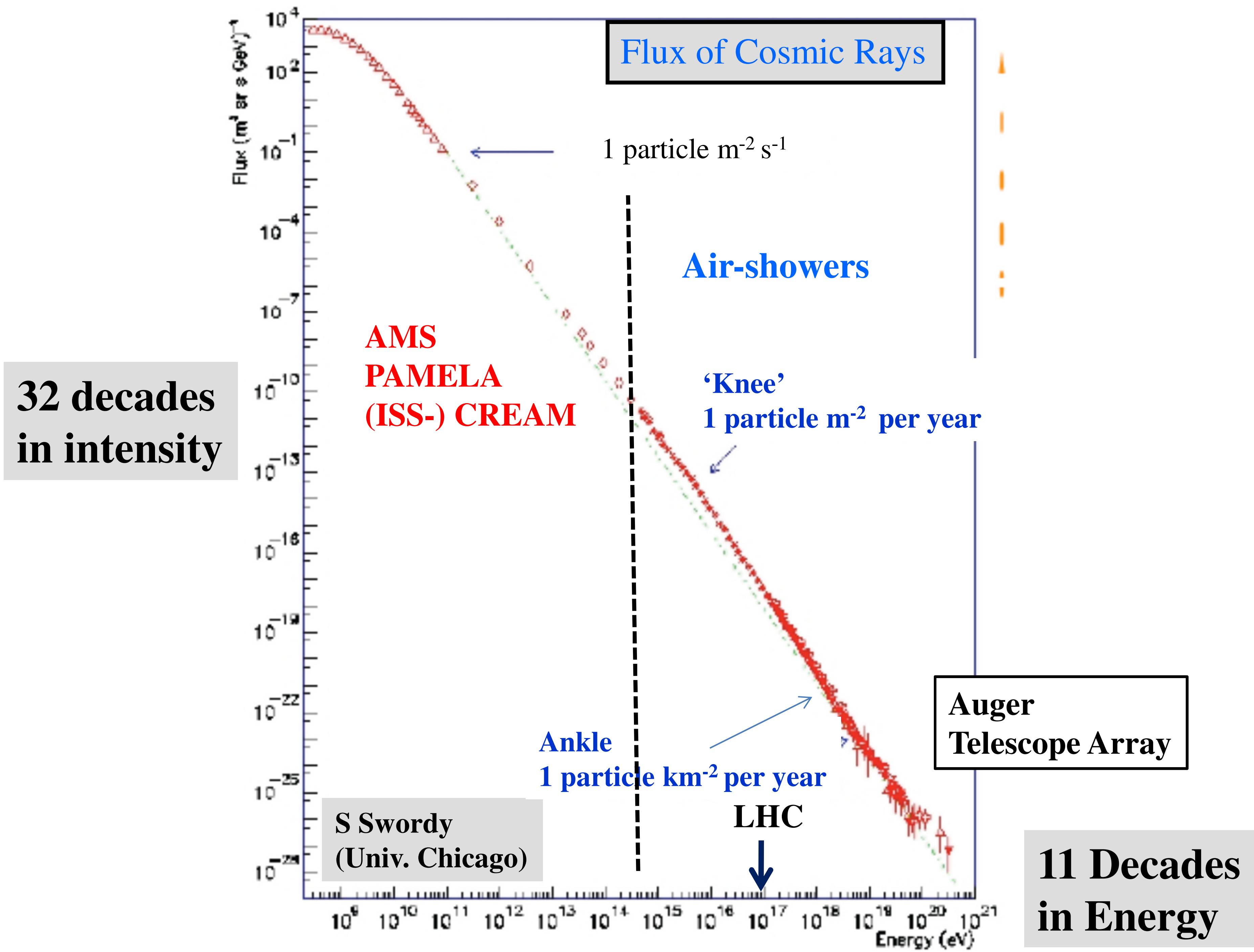
and

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

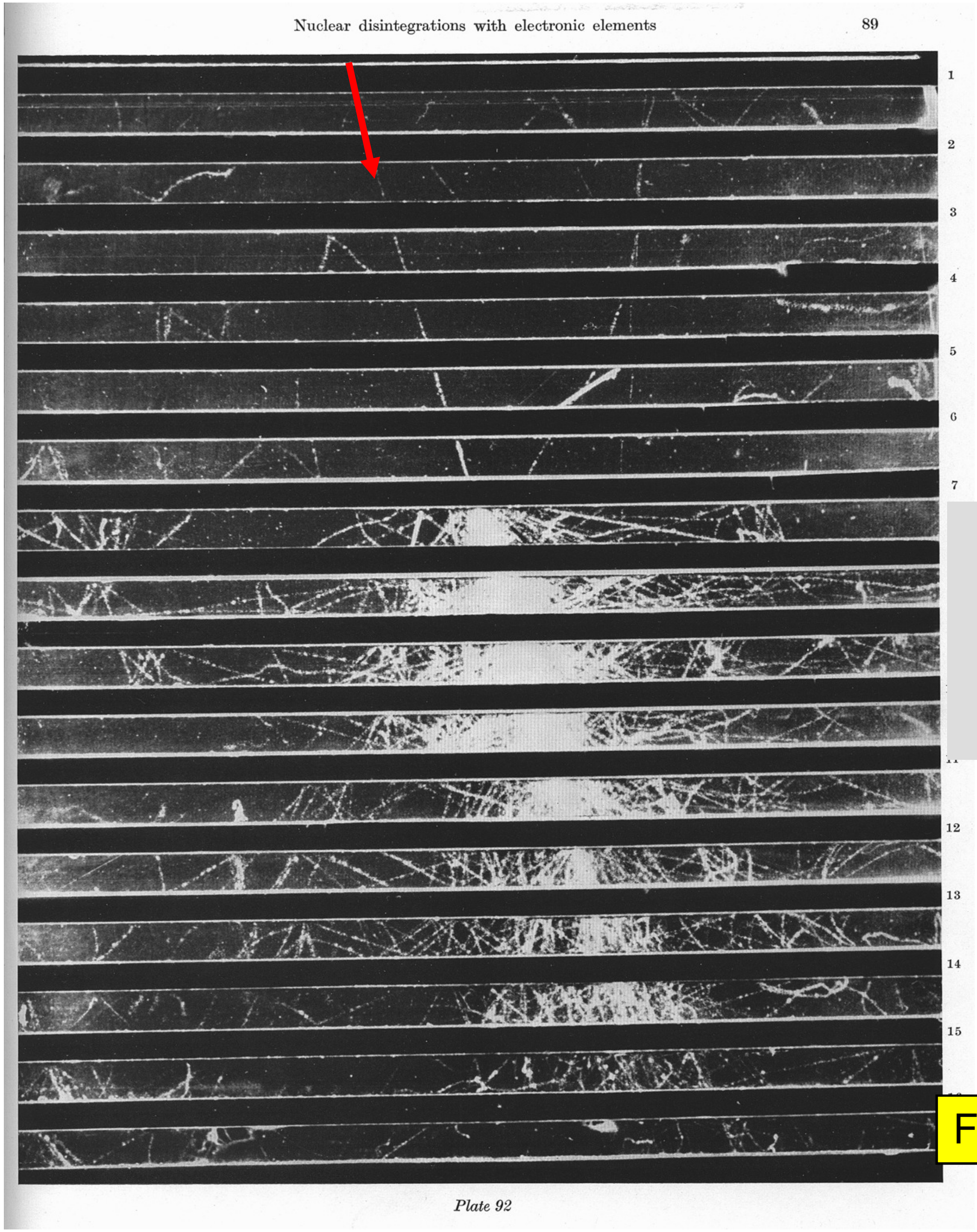
Prediction of steepening (GZK effect) around 50 EeV

What is the mass of the particles?

Lack of knowledge of hadronic physics is main limitation



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

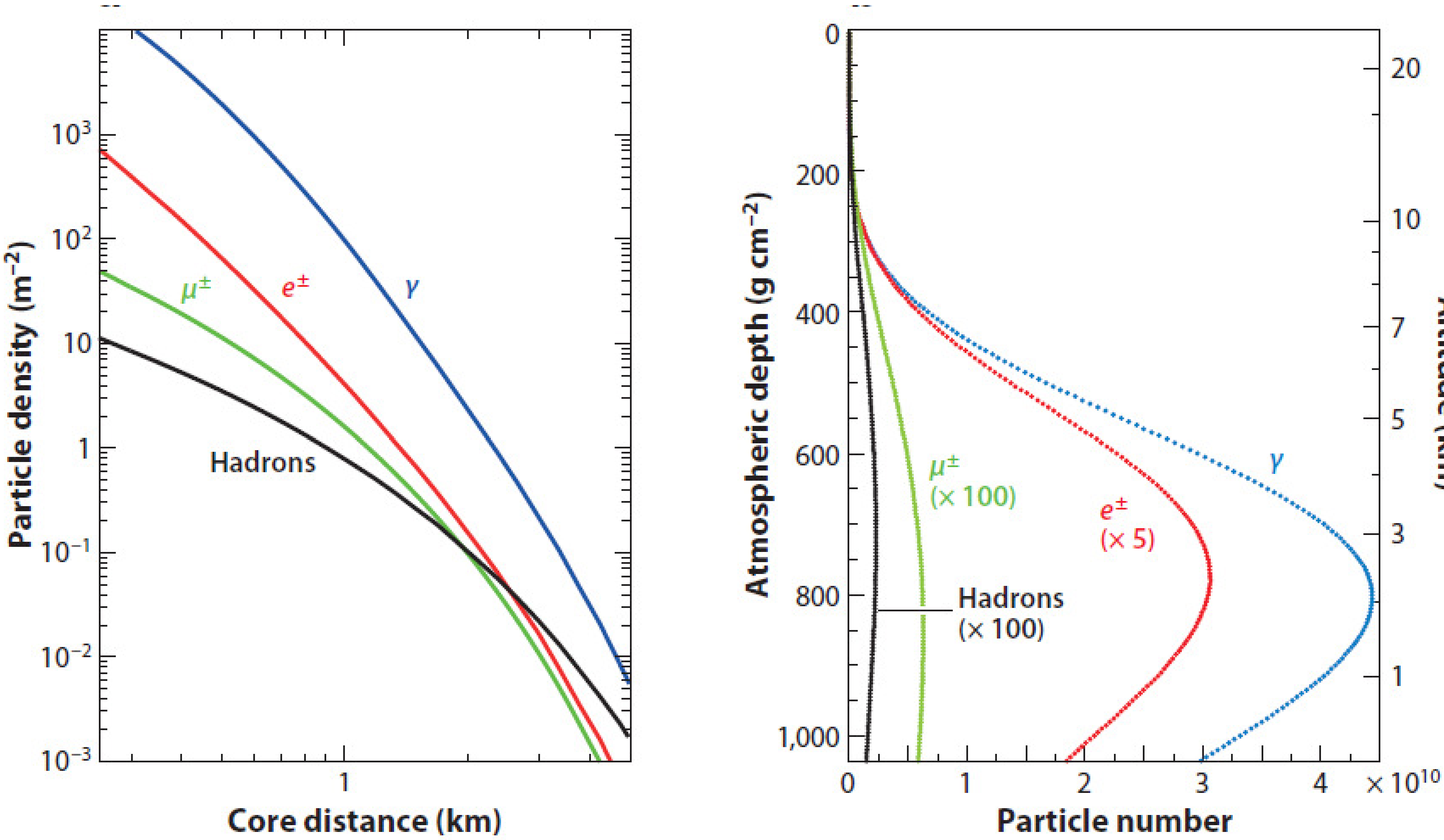
10 GeV proton

Shower initiated by proton in lead plates of cloud chamber

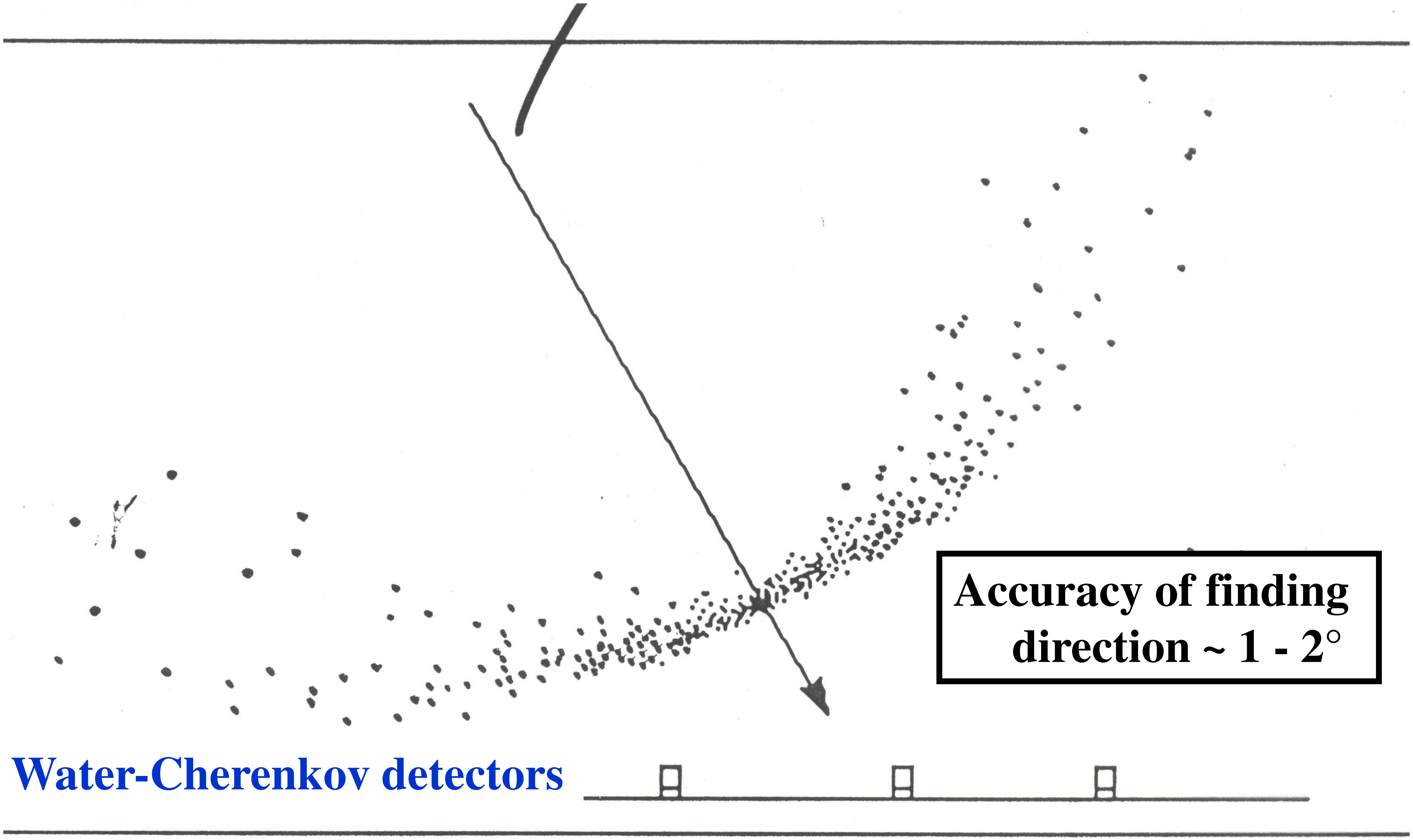
Detectors can find particle number and arrival times

Fretter: Echo Lake, 1949

Shower components as a function of distance and depth



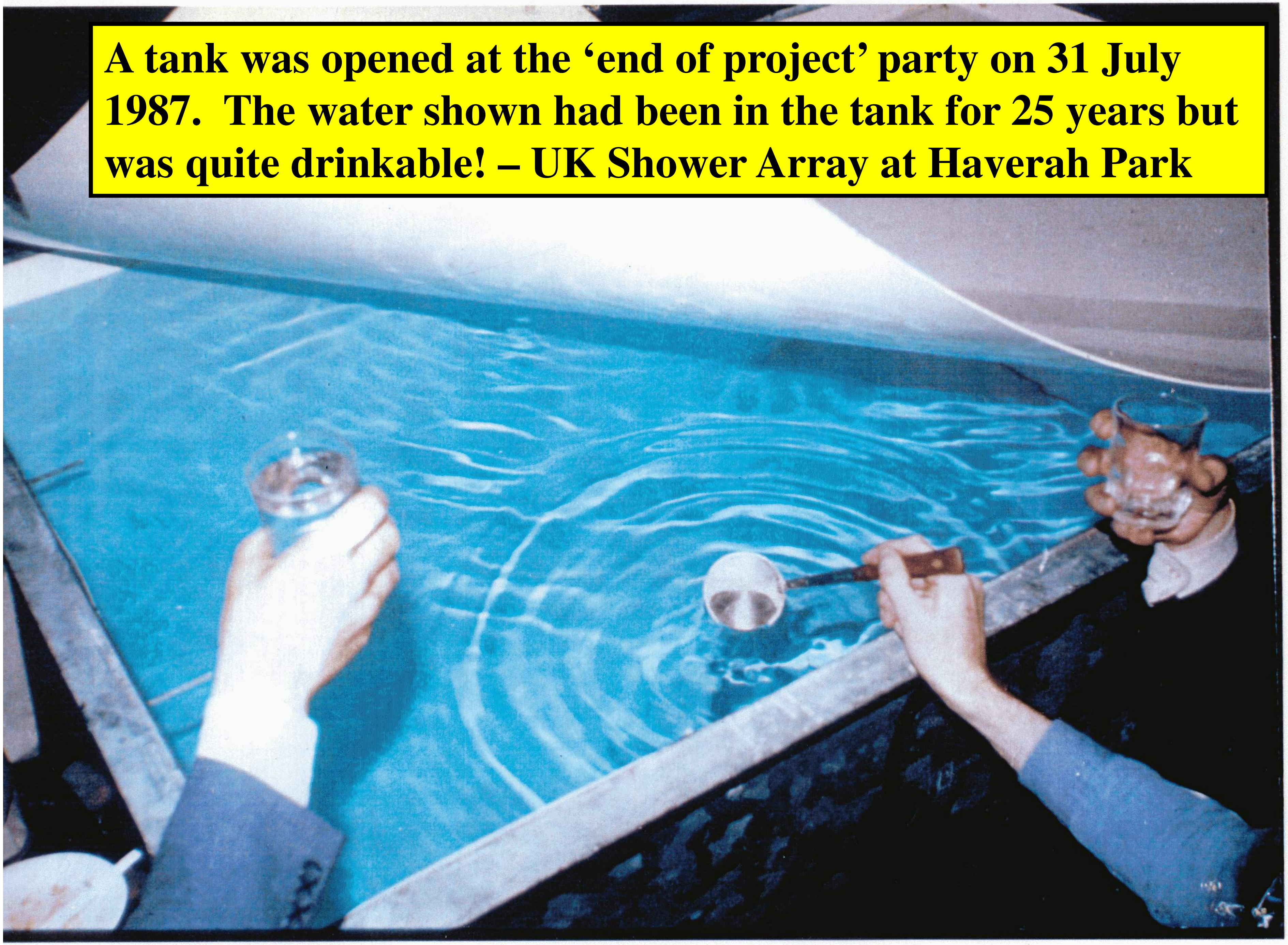
Engel et al. Ann Rev NPS 2011

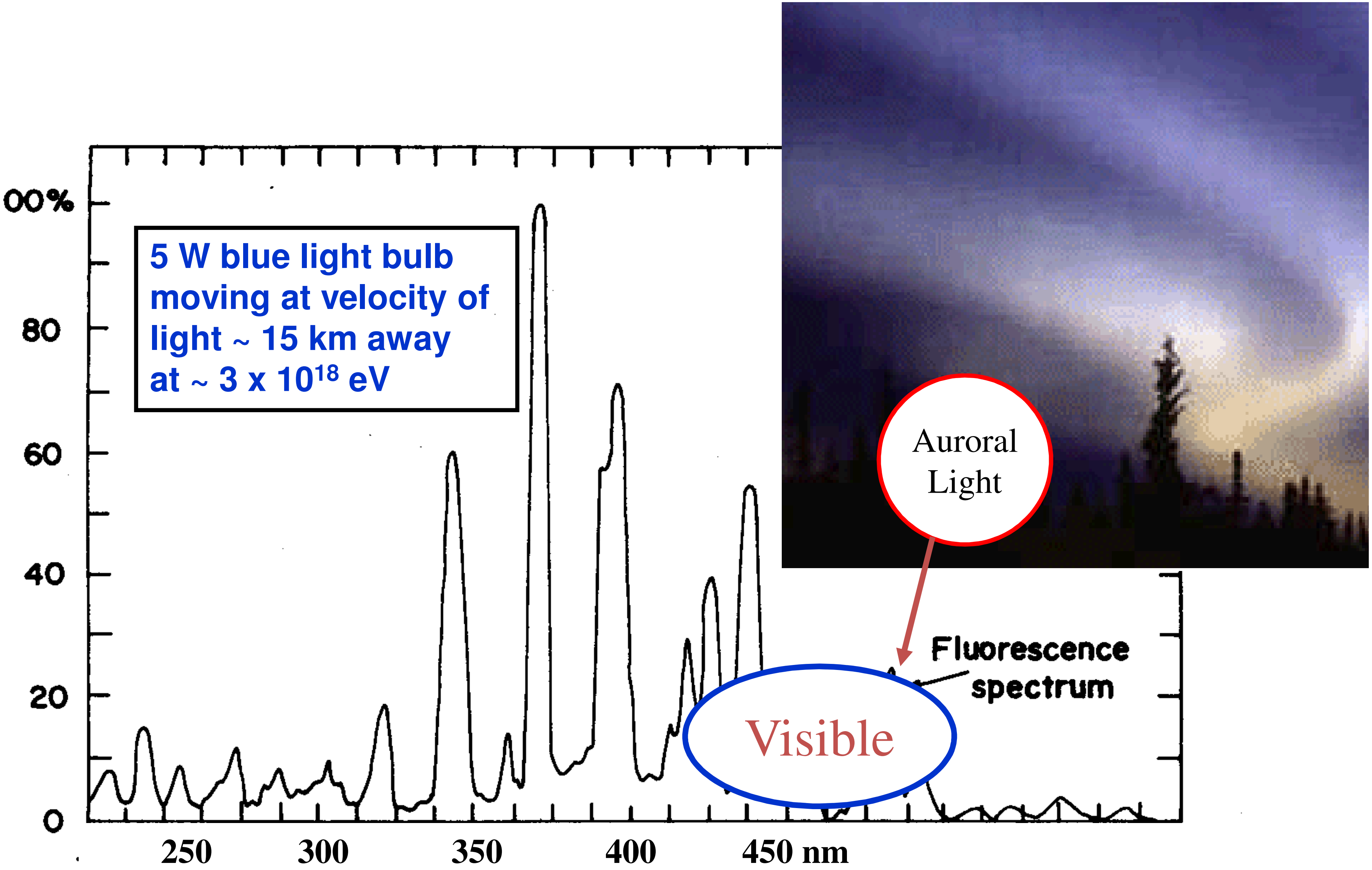


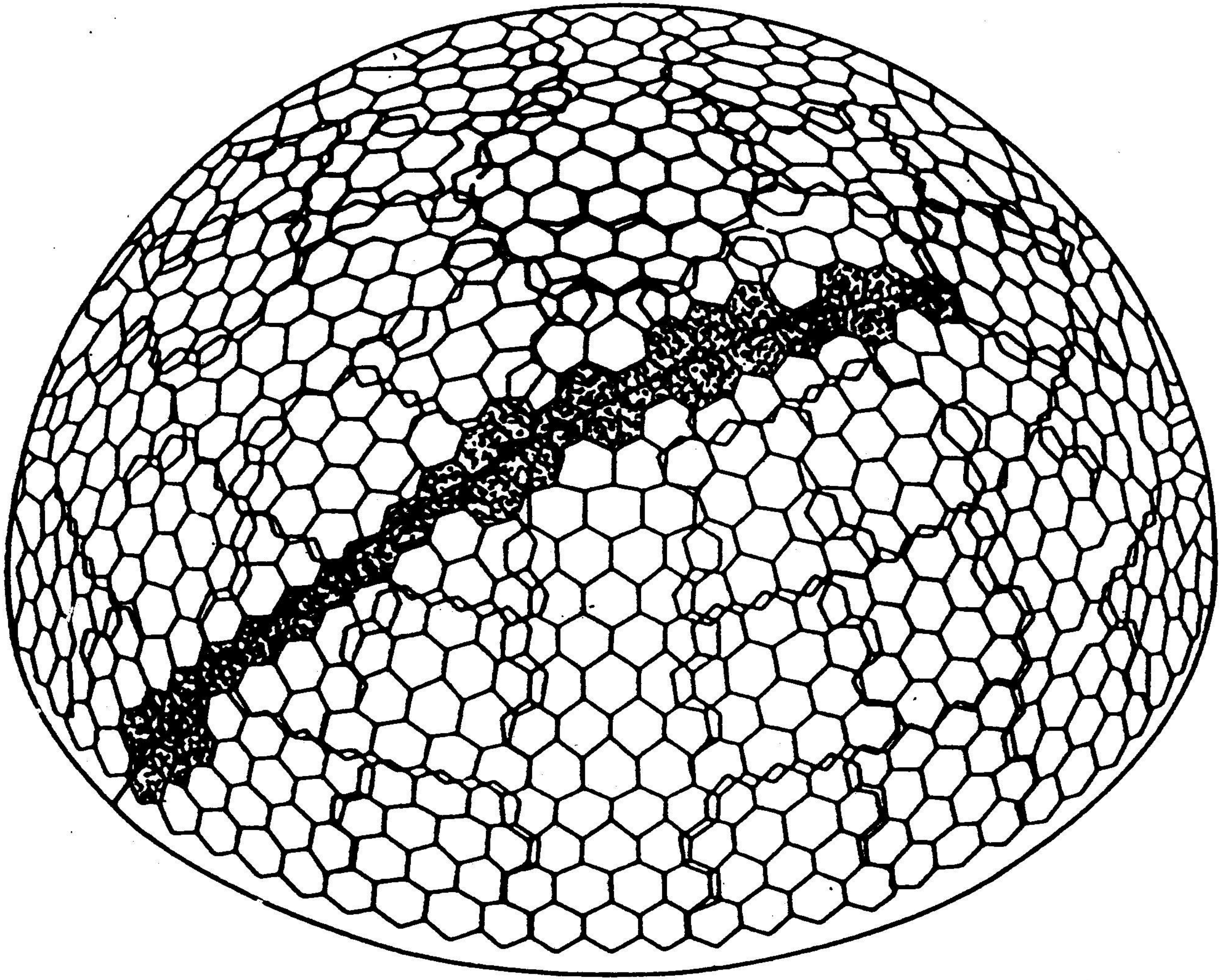
Accuracy of finding direction ~ 1 - 2°

'Fast timing' gives the direction

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! – UK Shower Array at Haverah Park

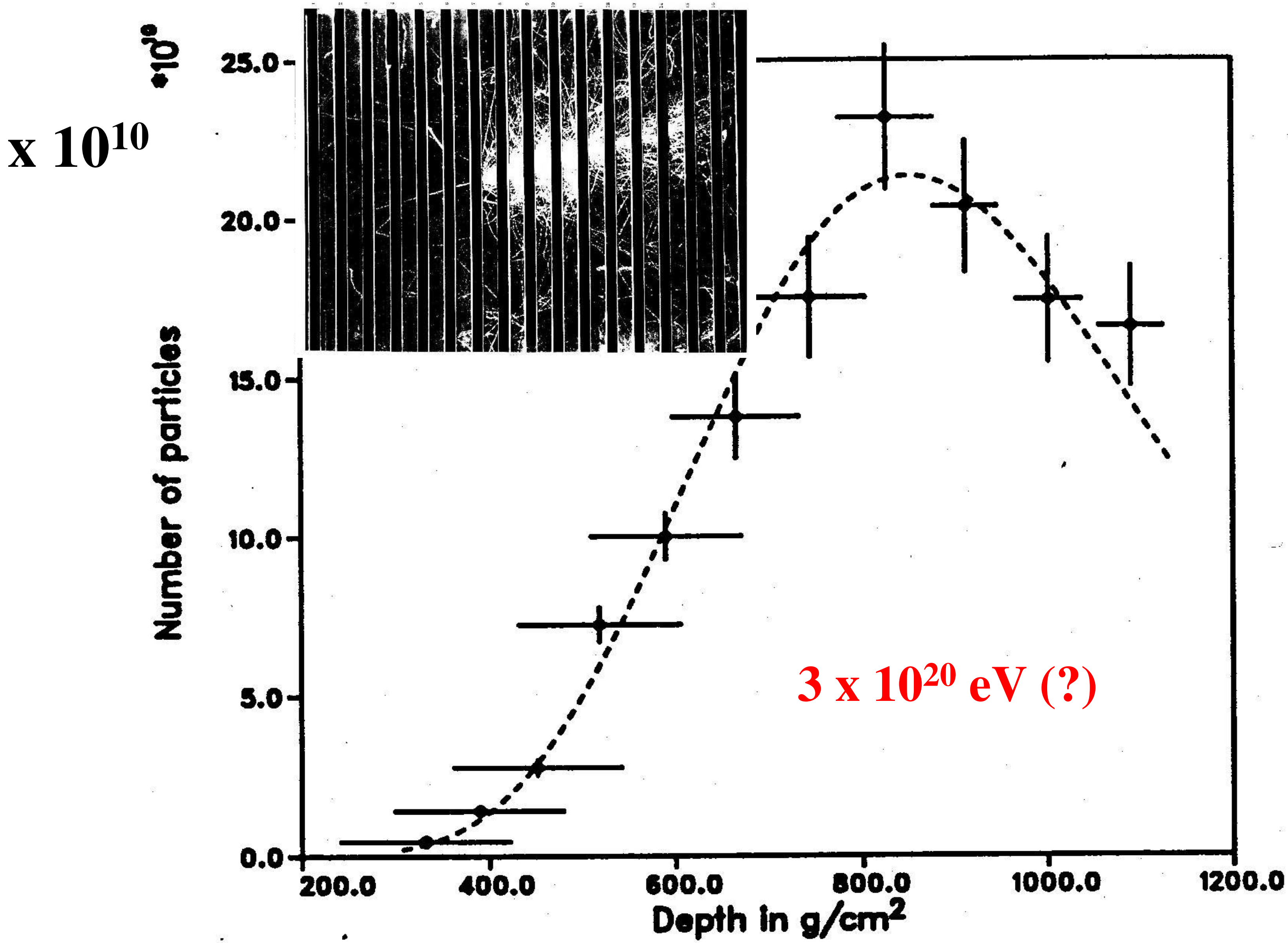



5 W blue light bulb moving at velocity of light ~ 15 km away at ~ 3 x 10^18 eV
Auroral Light
Visible
Fluorescence spectrum
00%
80
60
40
20
0
250
300
350
400
450 nm



Idea of Fly's Eye Detector (University of Utah): 880 photomultipliers

A Fluorescence Detector of the Utah University Group



x 10^10
*10^9
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/cm2
3 x 10^20 eV (?)

~1990: different techniques gave different results –

- all 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 (University of 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

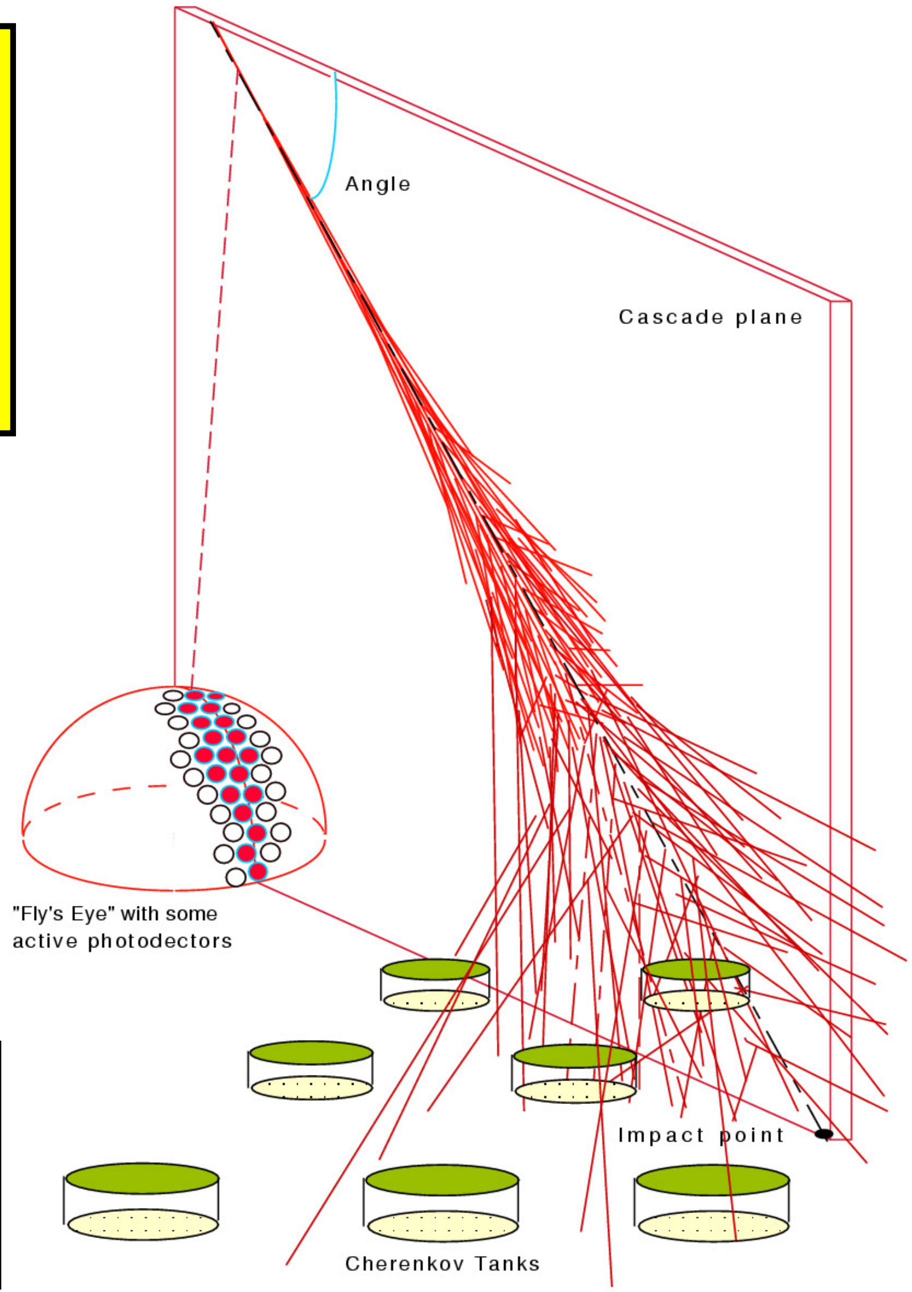
The Design of the Pierre Auger Observatory marries the two techniques

the 'HYBRID' technique

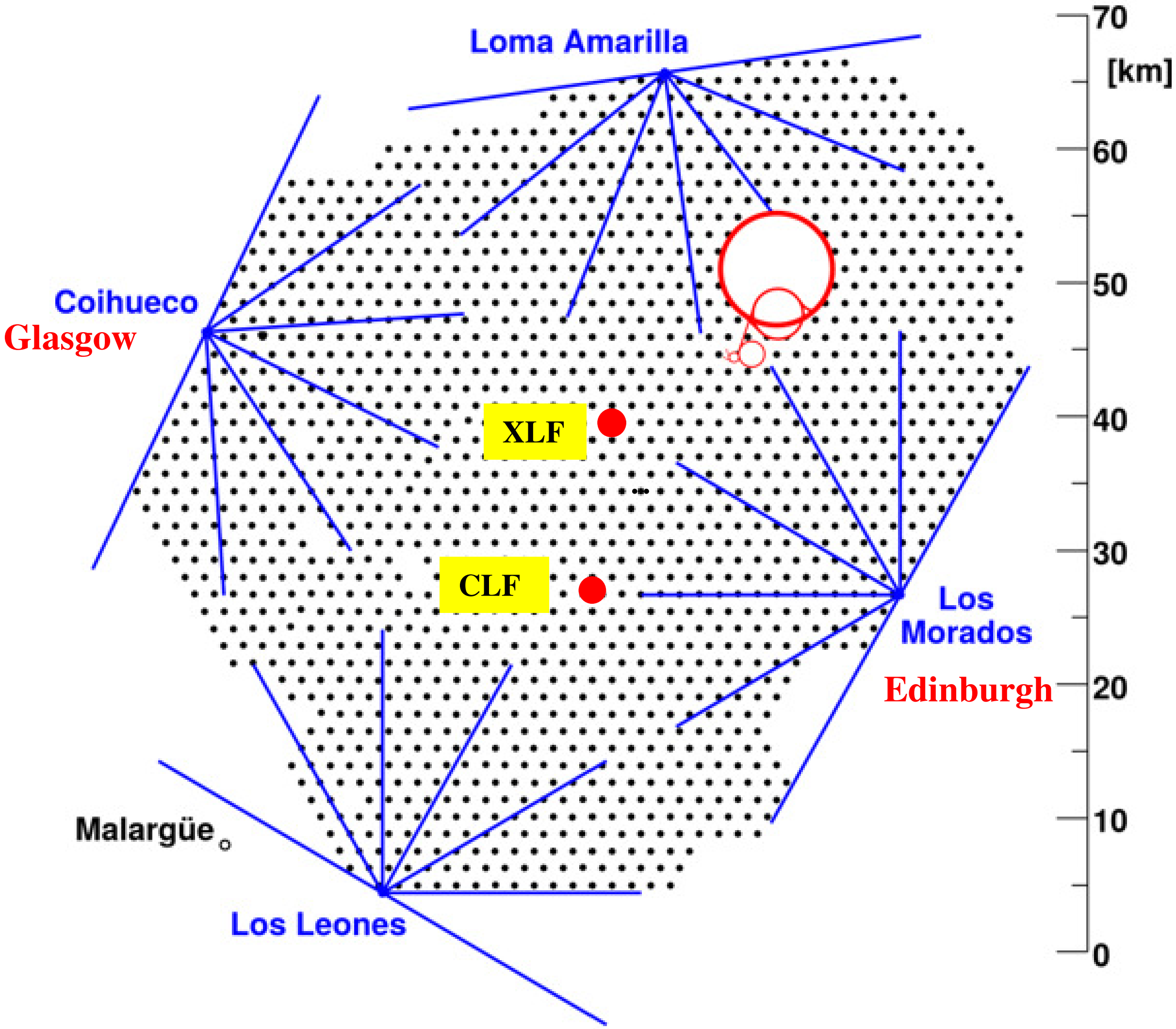
Fluorescence →

AND

Array of water-Cherenkov detectors →



The Pierre Auger Observatory: Malargüe, Argentina

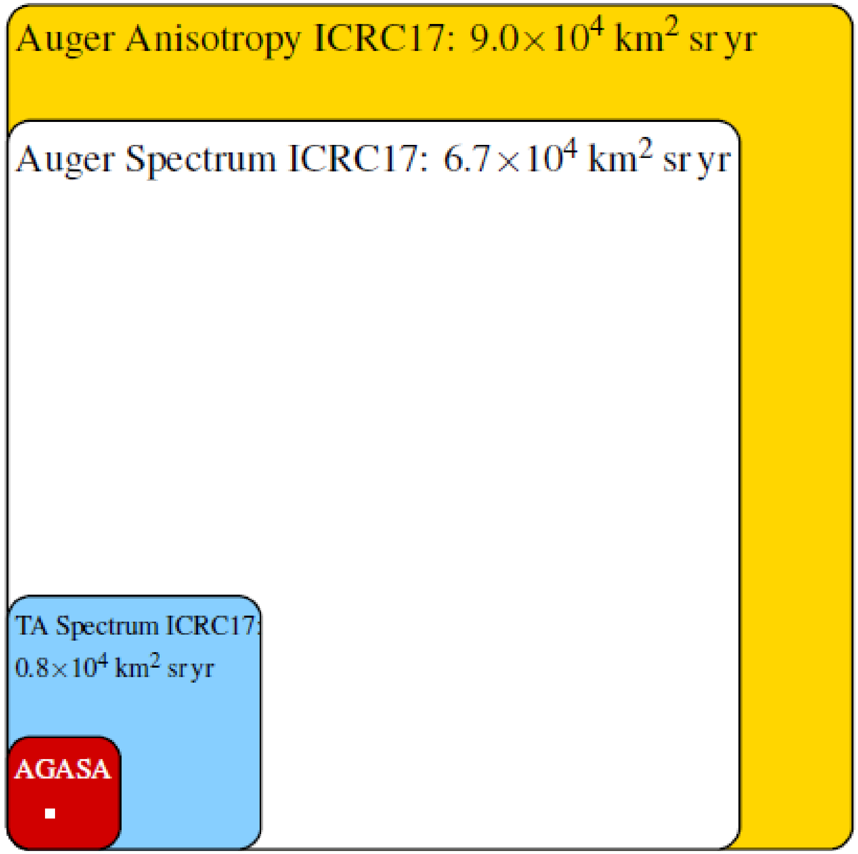


- 1600 water-Cherenkov detectors: 10 m² x 1.2 m
- 3000 km²
- Fluorescence detectors at 4 locations
- Two laser facilities for monitoring atmosphere and checking reconstruction
- Lidars at each FD site
-

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

HP →

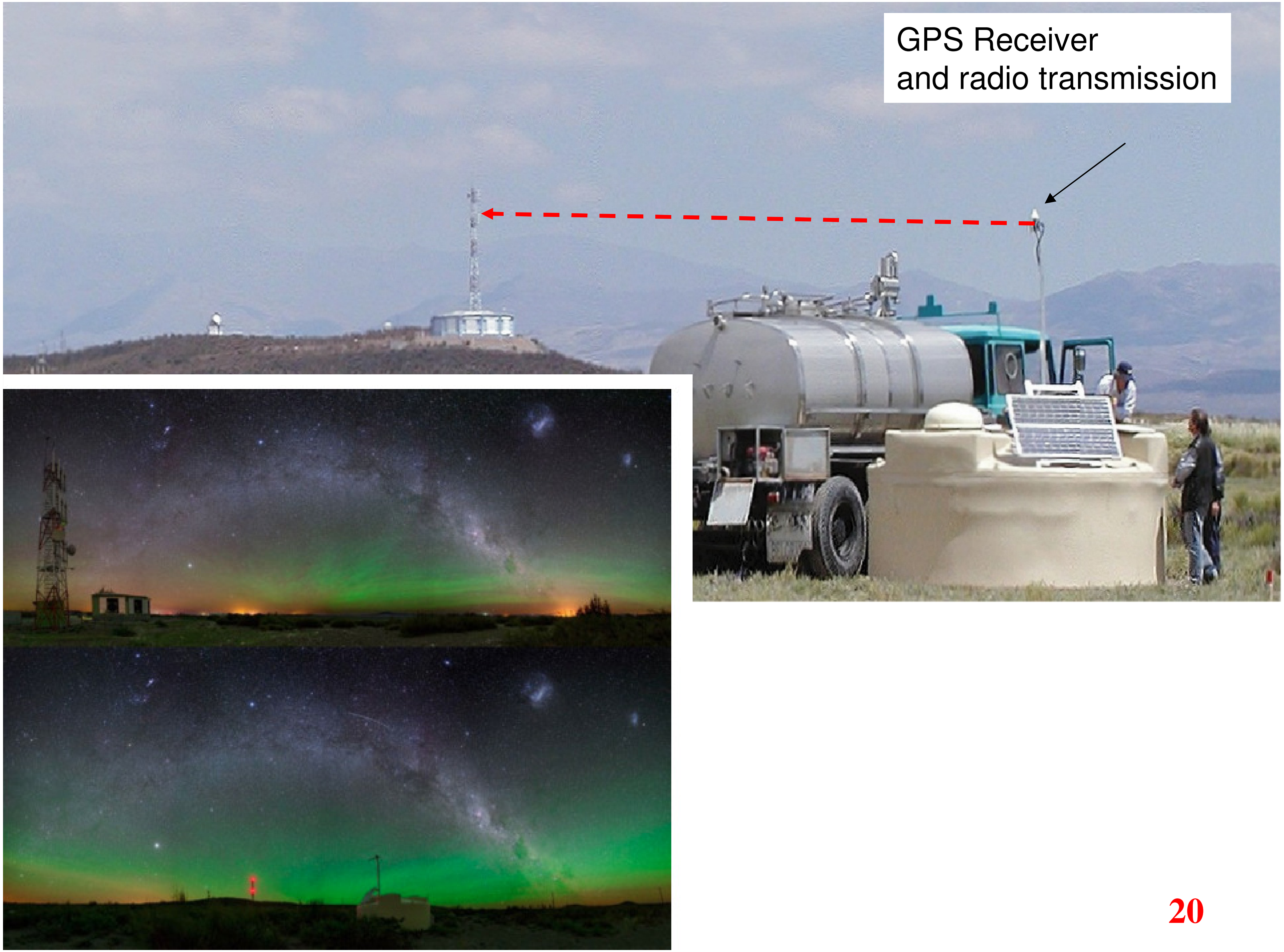


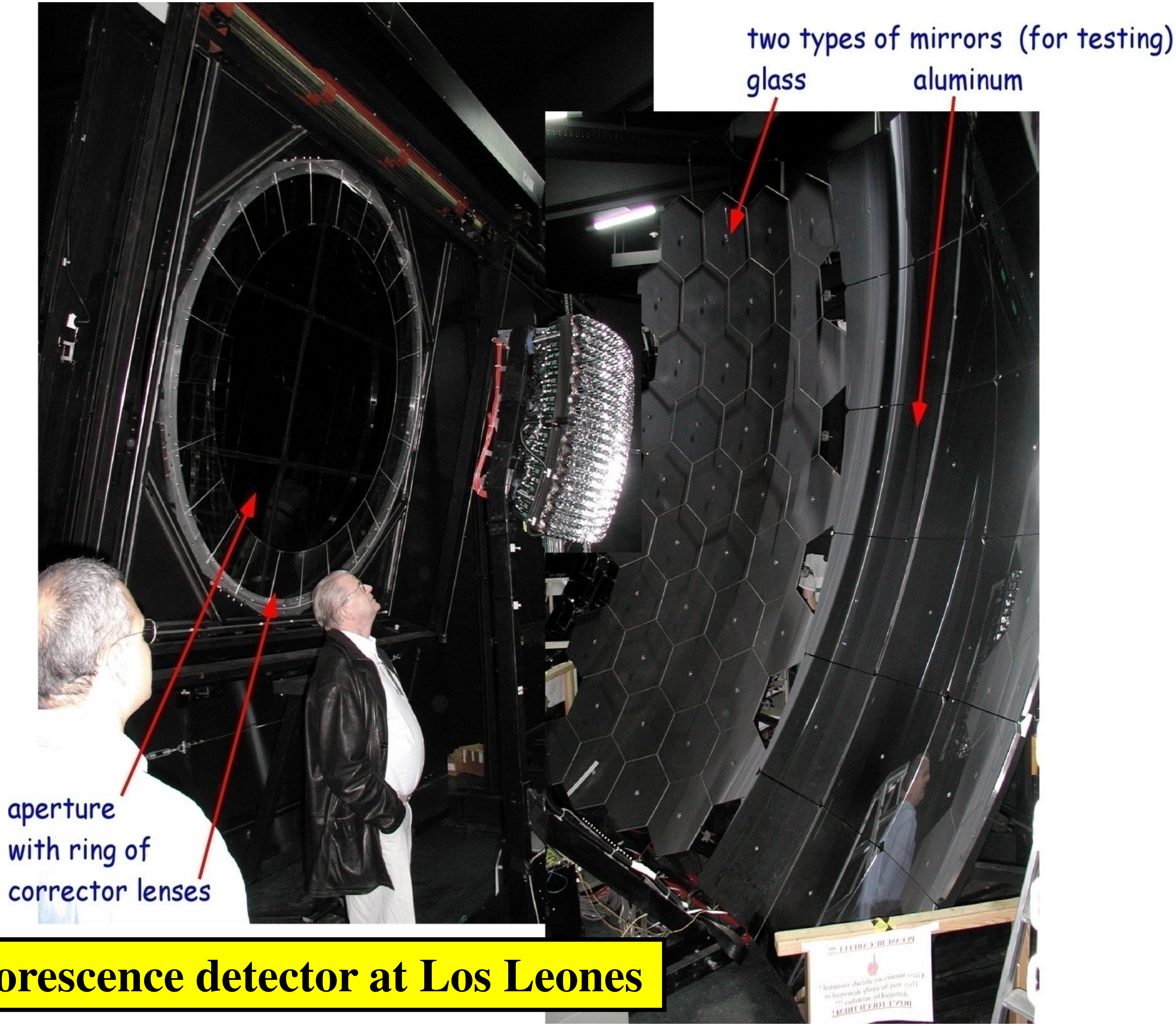
After Michael Unger 2017

The Auger Observatory Campus in Malargüe

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

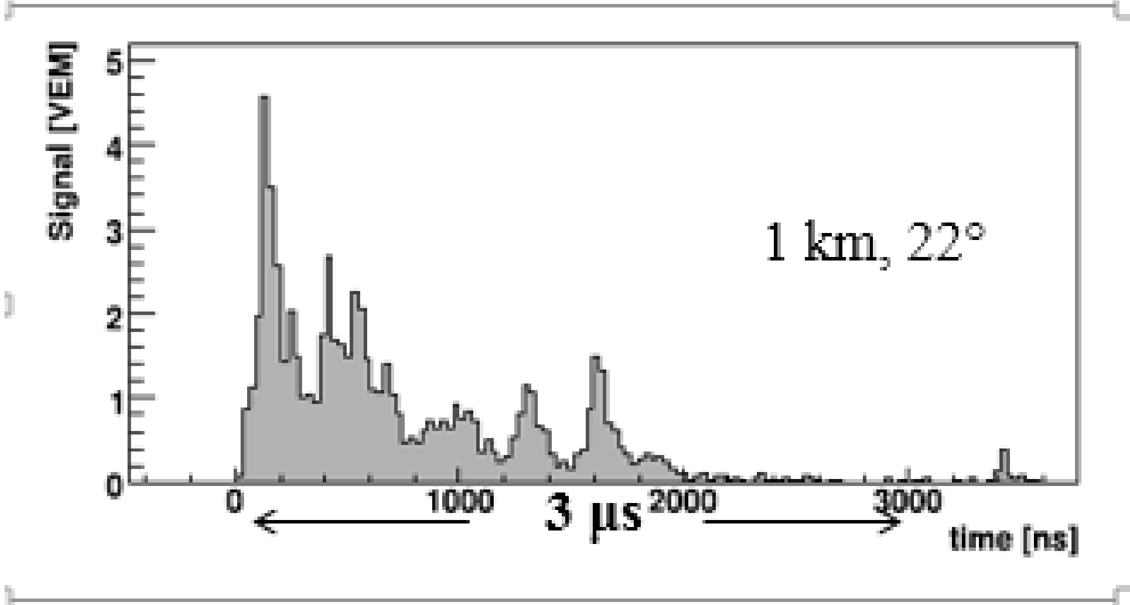

29. 6. 1999


GPS Receiver
and radio transmission

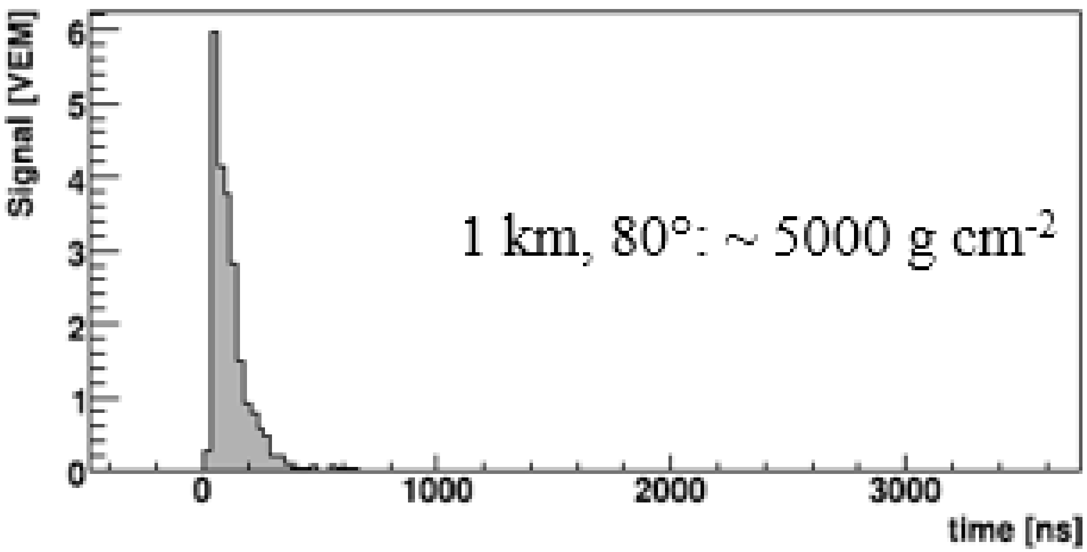


Fluorescence detector at Los Leones

Examples of signals from water-Cherenkov detectors

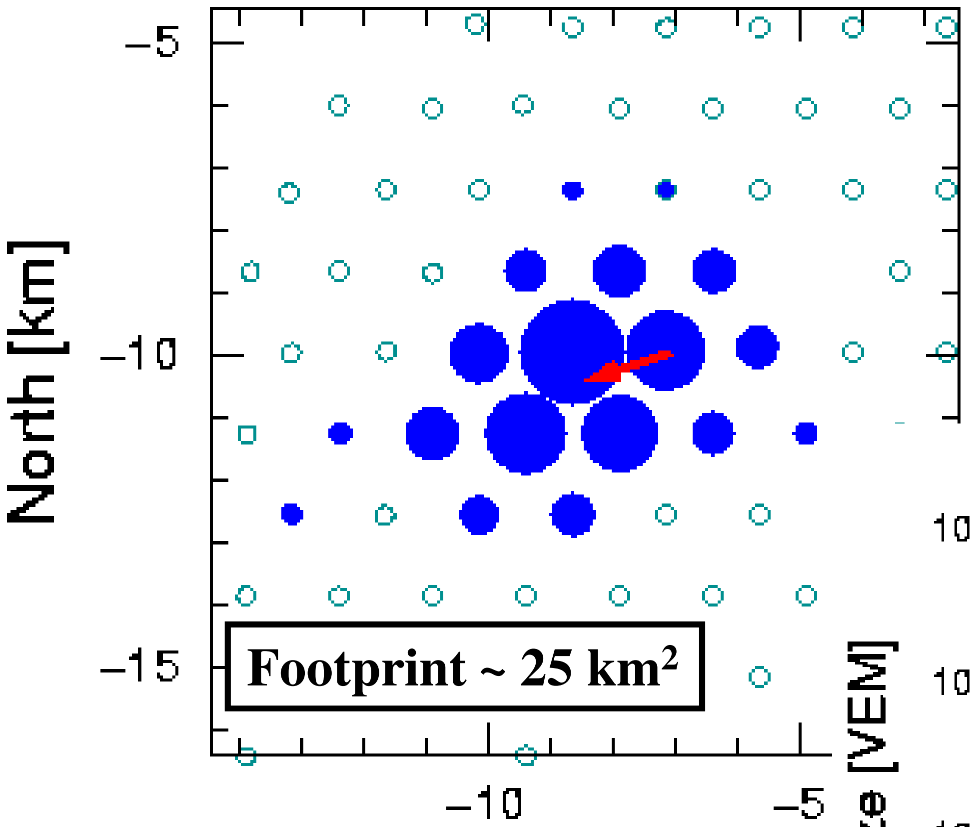


μ, γ, e

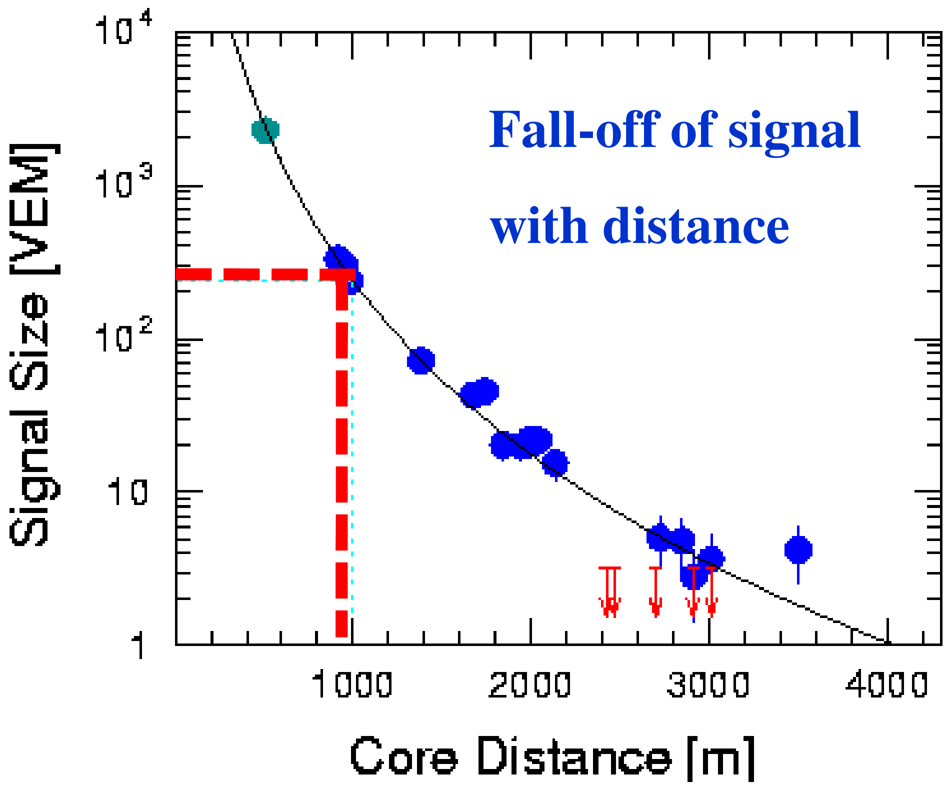


μ

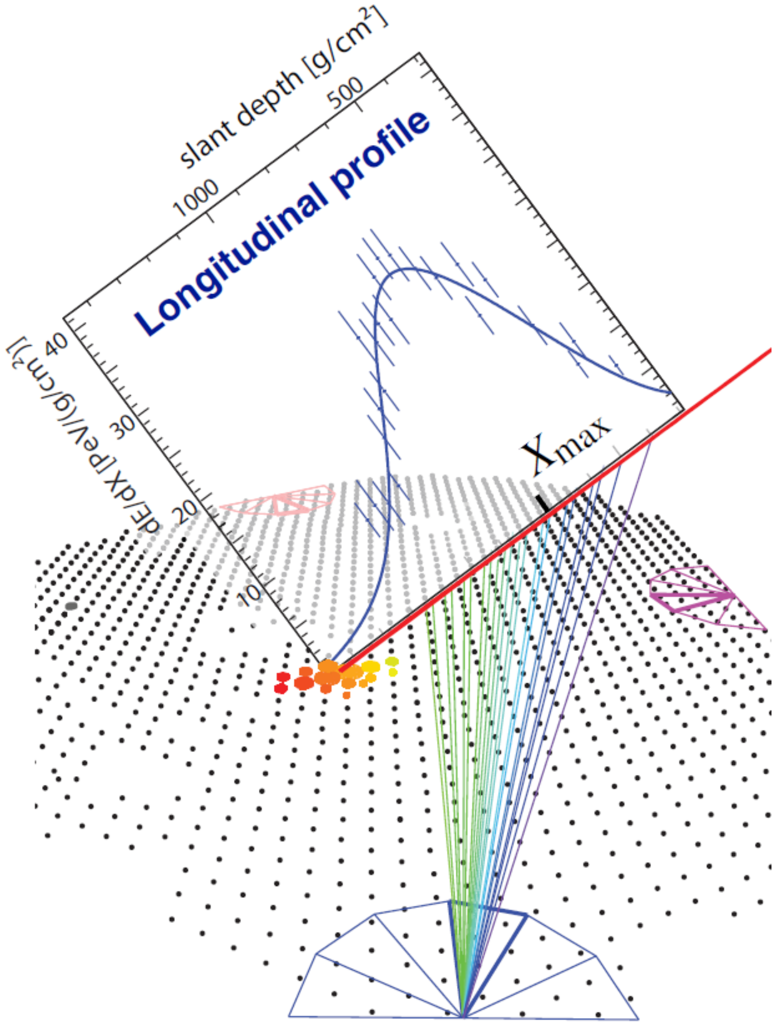
A large event: 7 x 10^{19} eV



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



Energy from fluorescence measurements

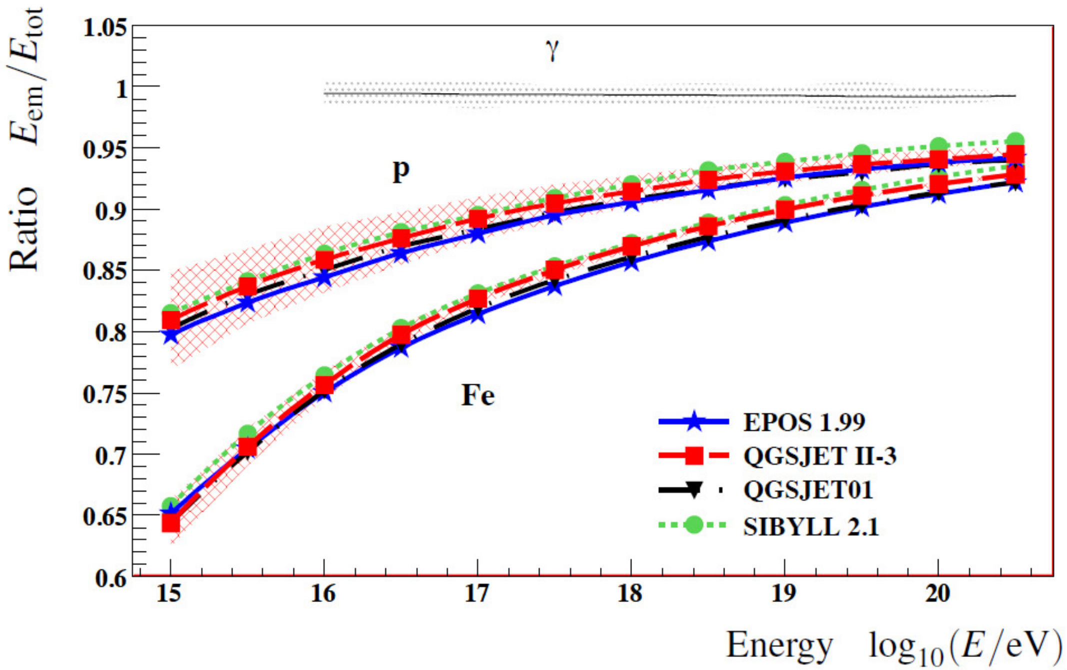


Example: event observed with Auger Observatory

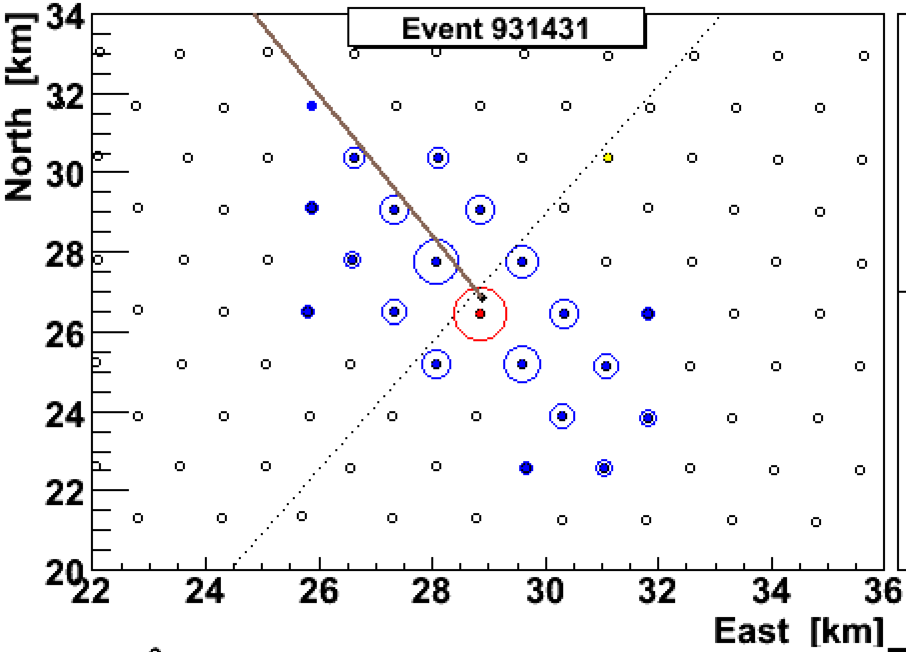
Electrons:

$$E_{\text{em}} = \int \left. \frac{dE_{\text{ion}}}{dX} \right|_{\text{meas.+extrap.}} dX$$

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



A Hybrid Event



Core location

Easting 468693 ± 59

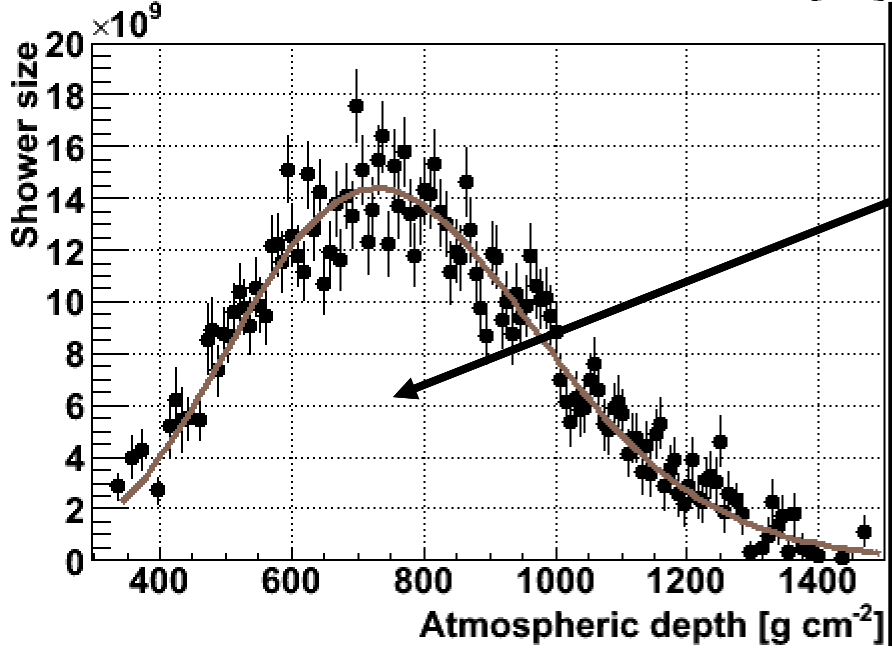
Northing 6087022 ± 80

Altitude = 1390 m a.s.l.

Shower Axis

$\theta = (62.3 \pm 0.2)^\circ$

$\phi = (119.7 \pm 0.1)^\circ$

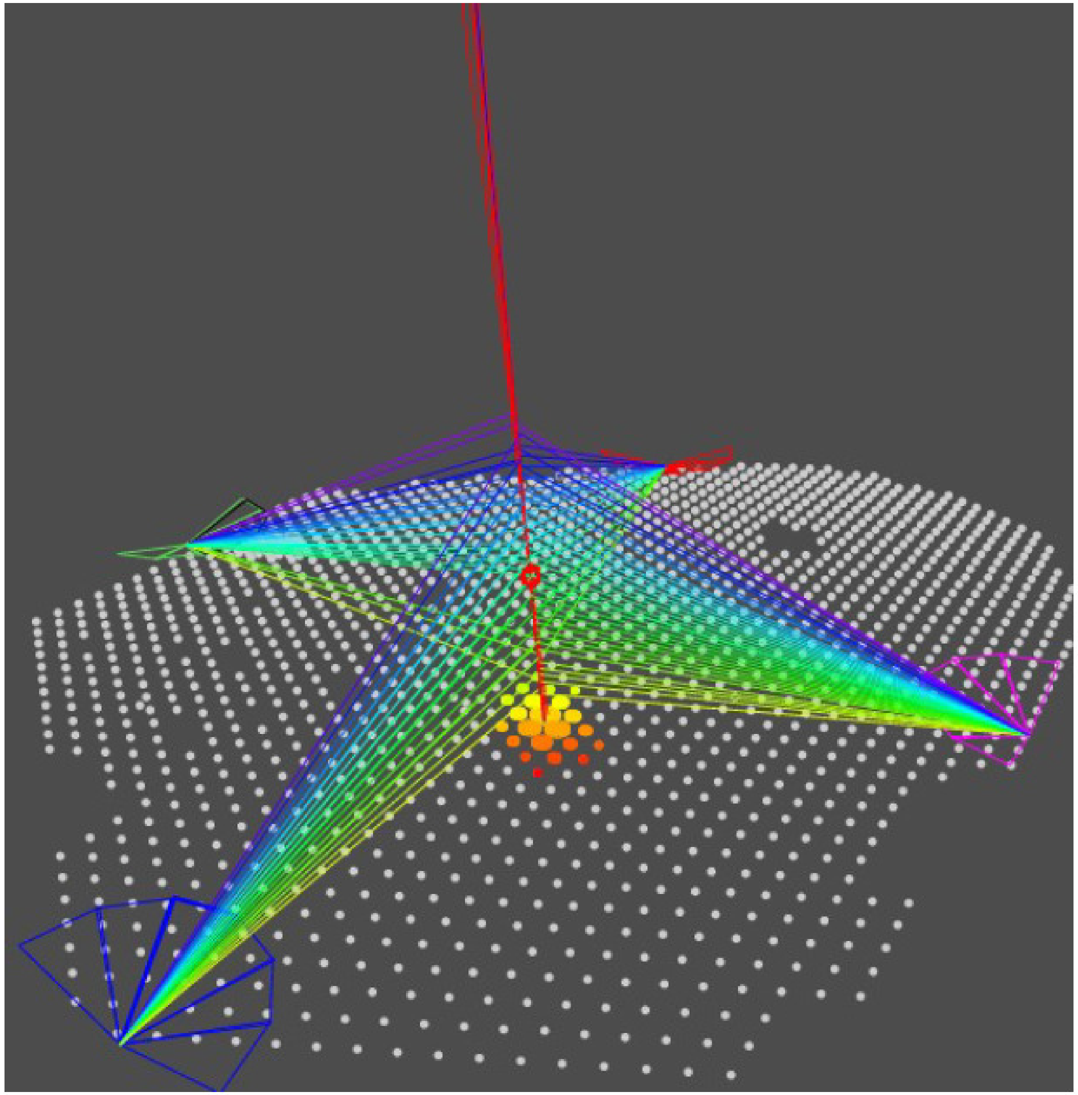


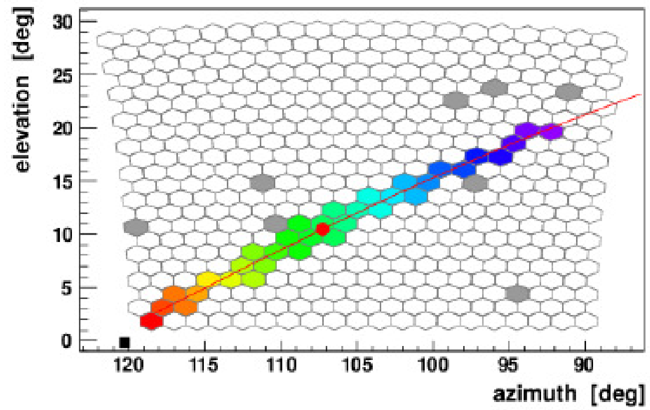
Energy Estimate
- from area under curve

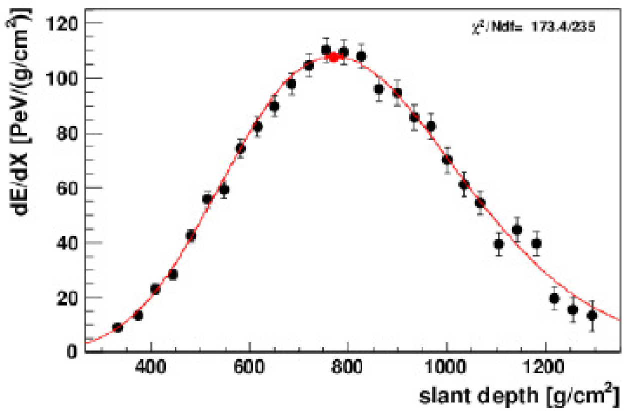
$(2.1 \pm 0.5) \times 10^{19}$ eV

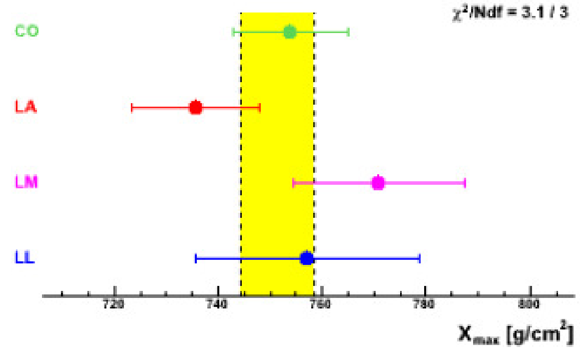
must account for 'missing energy'

Getting the Energy and X_{max}

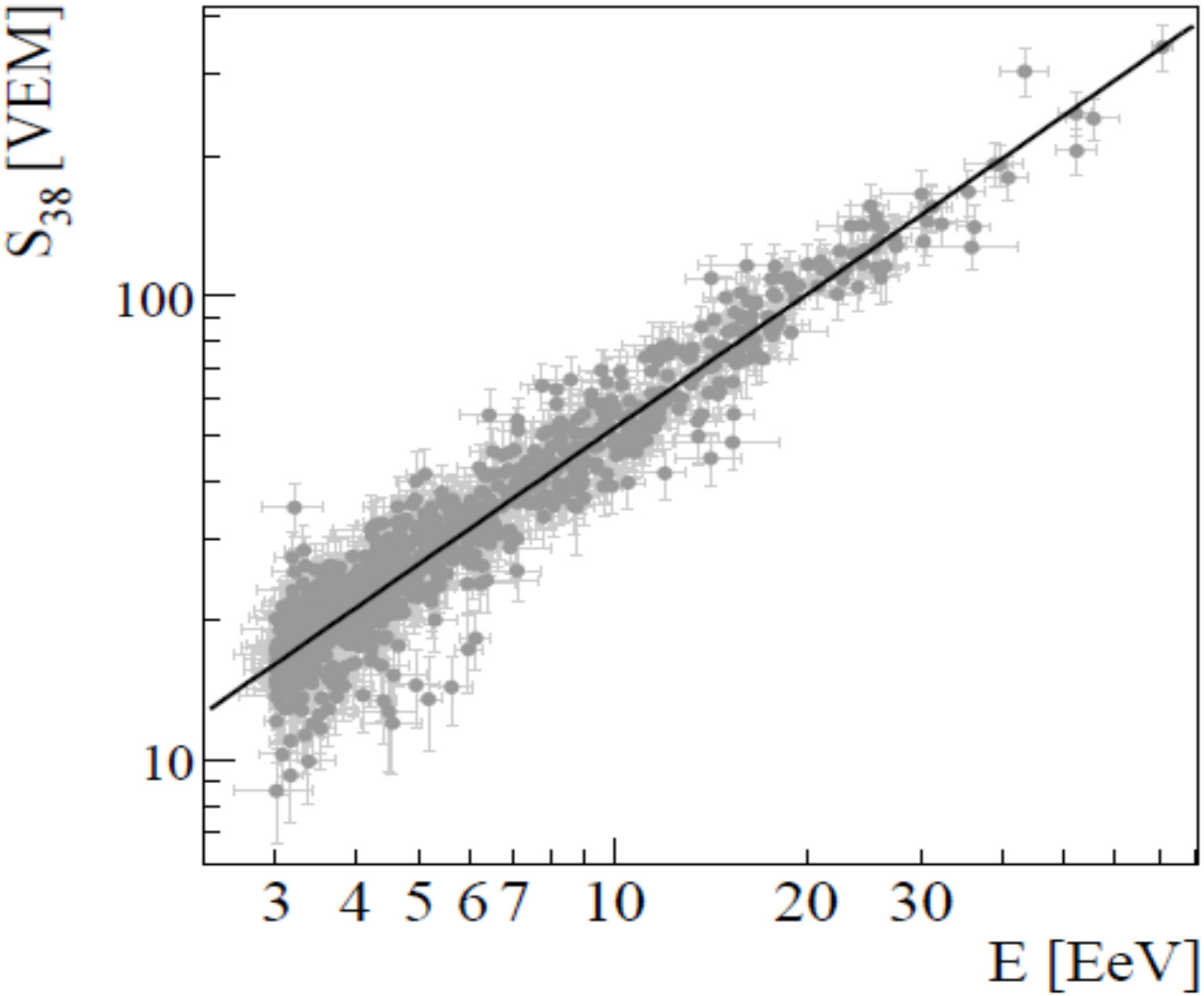








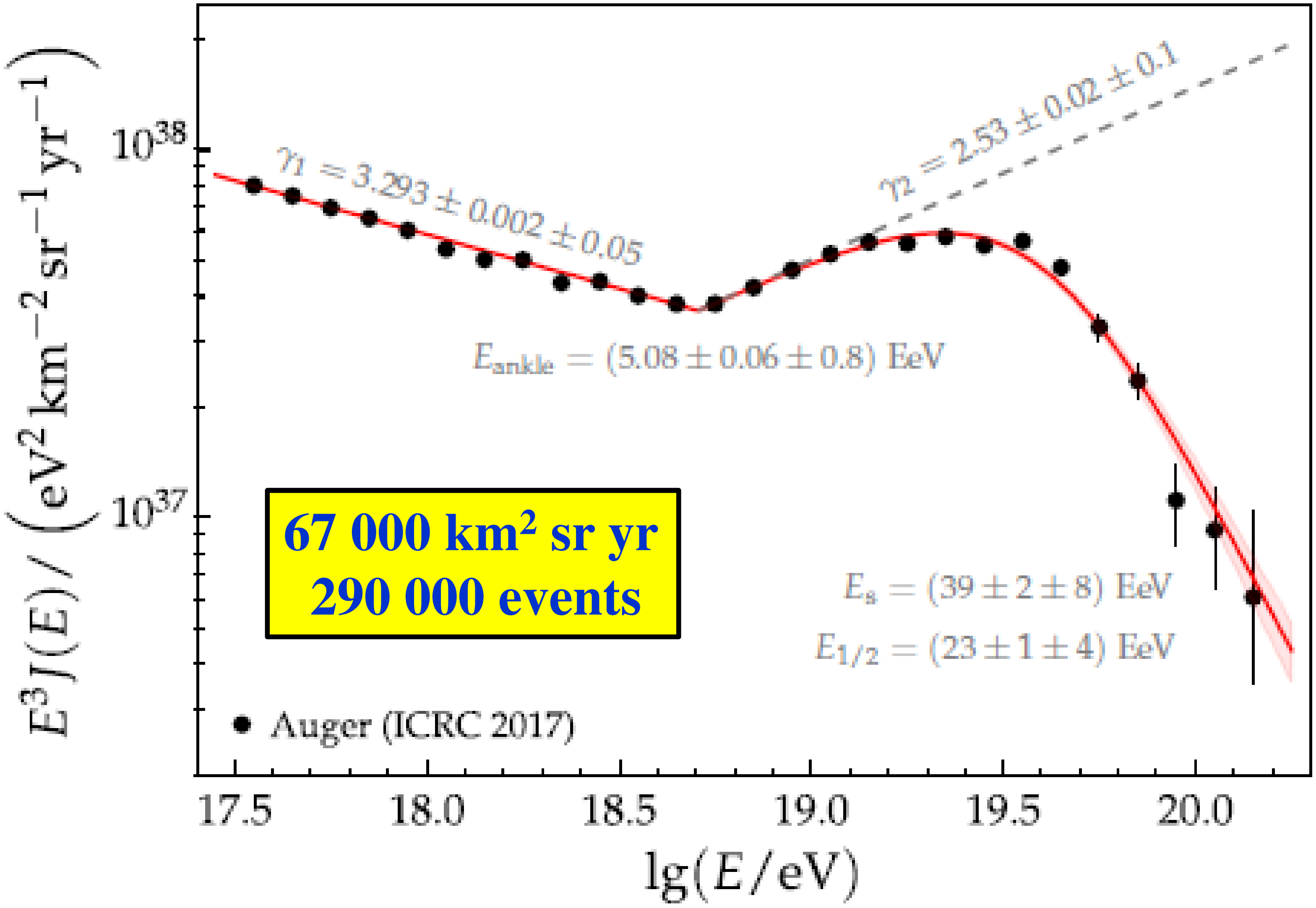
$E = 7.1 \pm 0.2\ 10^{19}$ eV - $X_{max} = 752 \pm 7$ g/cm^2



839 events

7.5 x 10^{19} eV

Auger Energy Calibration



$E^3 J(E) / (eV^2 km^{-2} sr^{-1} yr^{-1})$
10^{38}
10^{37}
$\gamma_1 = 3.293 \pm 0.002 \pm 0.05$
$\gamma_2 = 2.53 \pm 0.02 \pm 0.1$
$E_{ankle} = (5.08 \pm 0.06 \pm 0.8)$ 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)
17.5
18.0
18.5
19.0
19.5
20.0
$\lg(E/eV)$

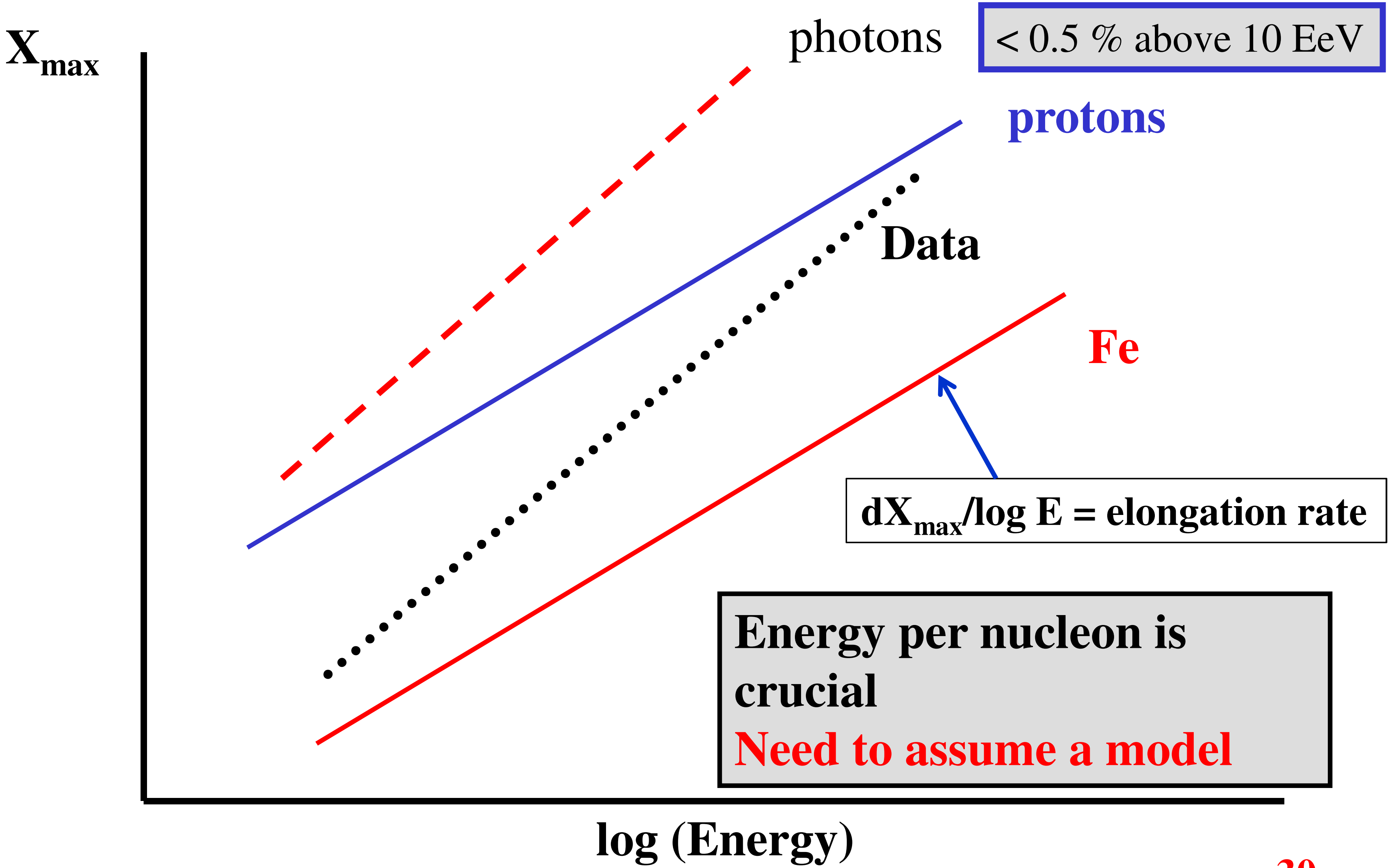
However the steepening itself is INSUFFICIENT for us to claim that we have seen the Greisen-Zatsepin-Kuz'min effect

It might simply be that the sources cannot raise particles to energies as high as 10^{20}eV – Nature could be teasing us!

Energy densities of CMB, galactic magnetic field, cosmic rays and starlight are very similar – this may be another coincidence

Knowing the mass composition is really essential
– but for this we need to extrapolate key features of
hadronic interactions to high energies
cross-section, multiplicity, inelasticity, pion collisions…

The variation of mass with energy



Given the necessity of using models, an important question is

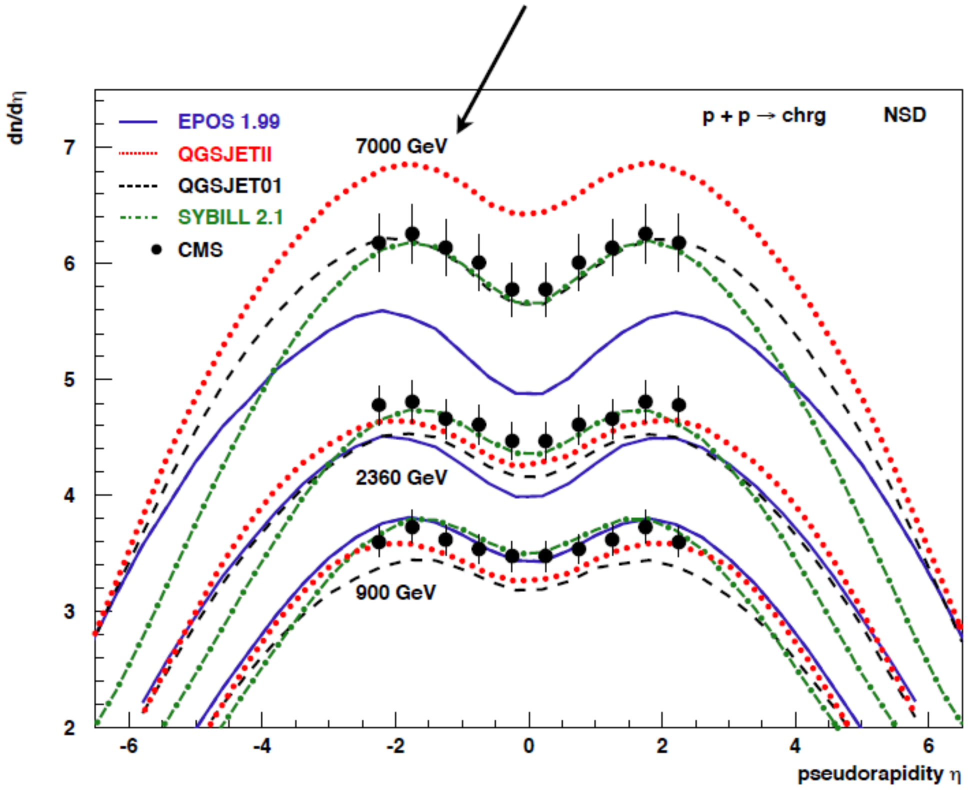
"Are the cosmic-ray models adopted sensible?"

Here, the LHC results have proved an excellent test-bed to evaluate three different models

- **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 set of phenomenological and theoretical assumptions to describe hadronic interactions**
- ***This is ALL I really can tell you about the details of the models!***

Charged particle distribution in pseudorapidity

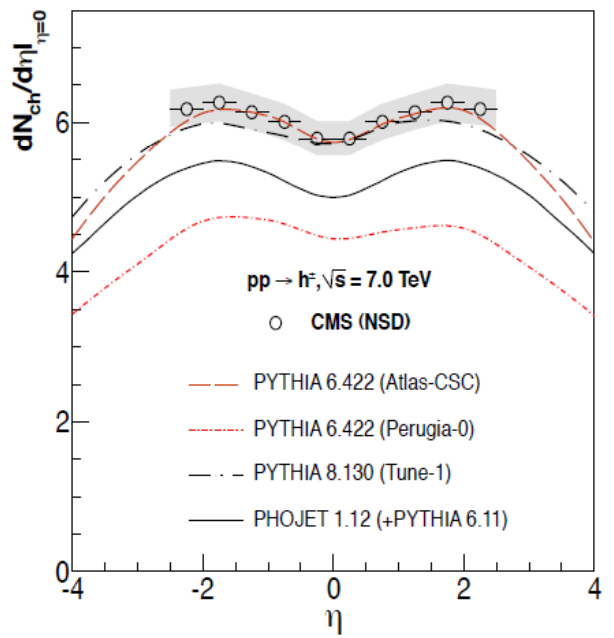
Protons: E_{lab} = 3 x 10^{16} eV



(data from all LHC experiments, CMS shown as example)

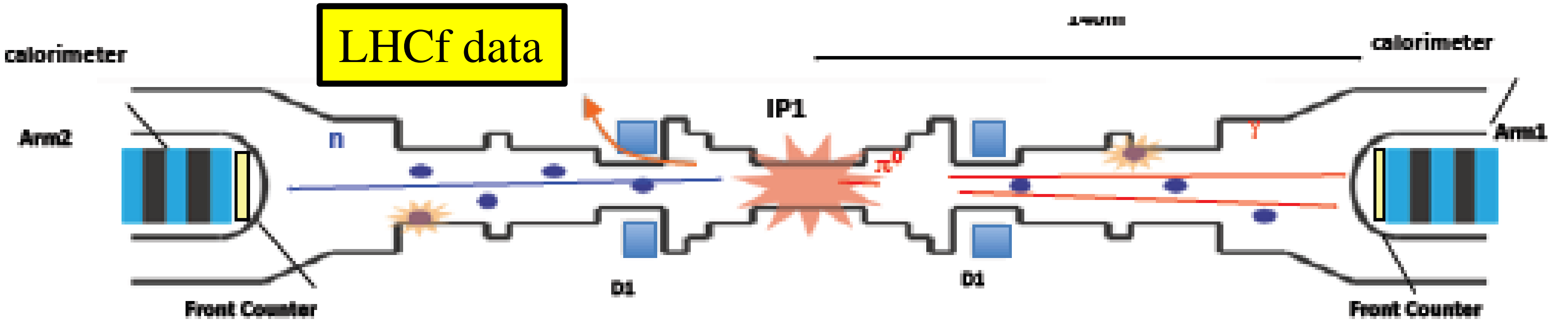
Detailed LHC comparison

(D'Enterria et al., Astropart. Phys. 35, 2011)

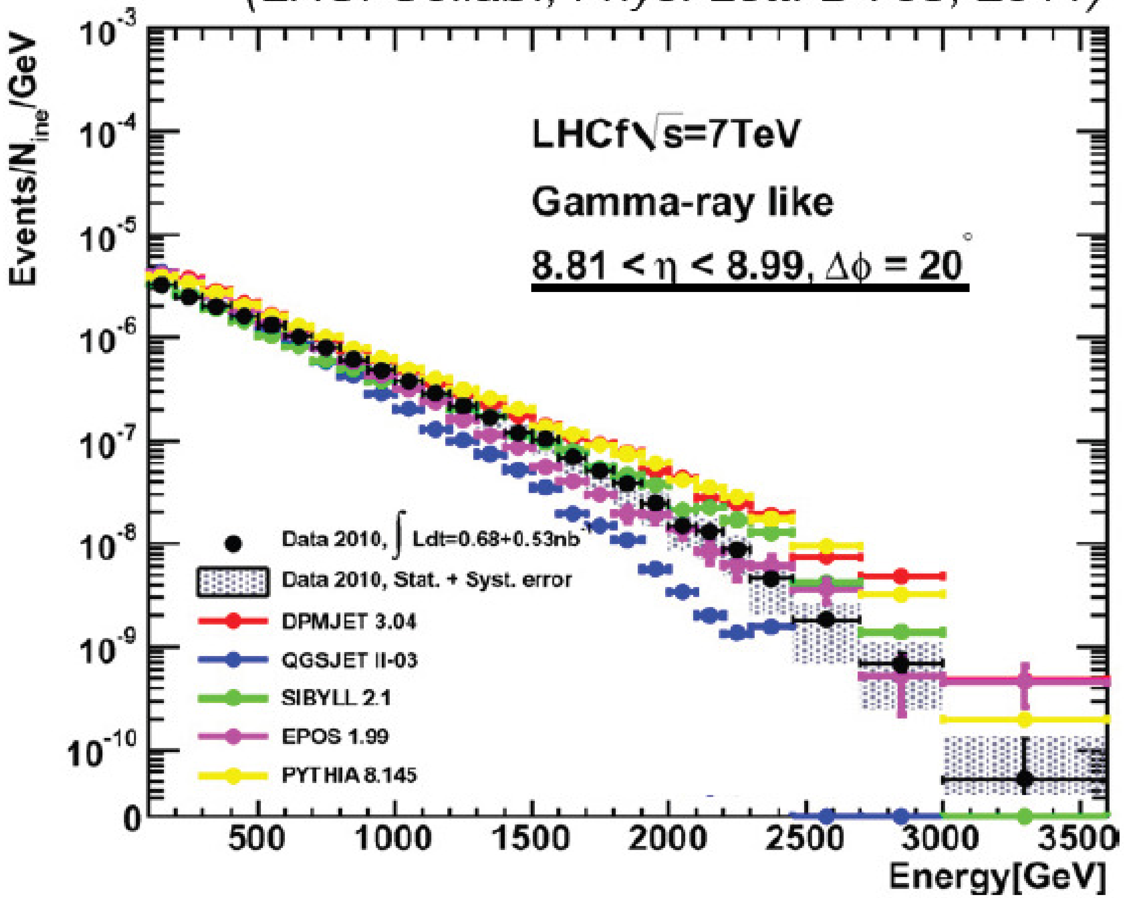


The first data from the LHC agreed better with CR models than with PYTHIA and PHOJET

LHCf data

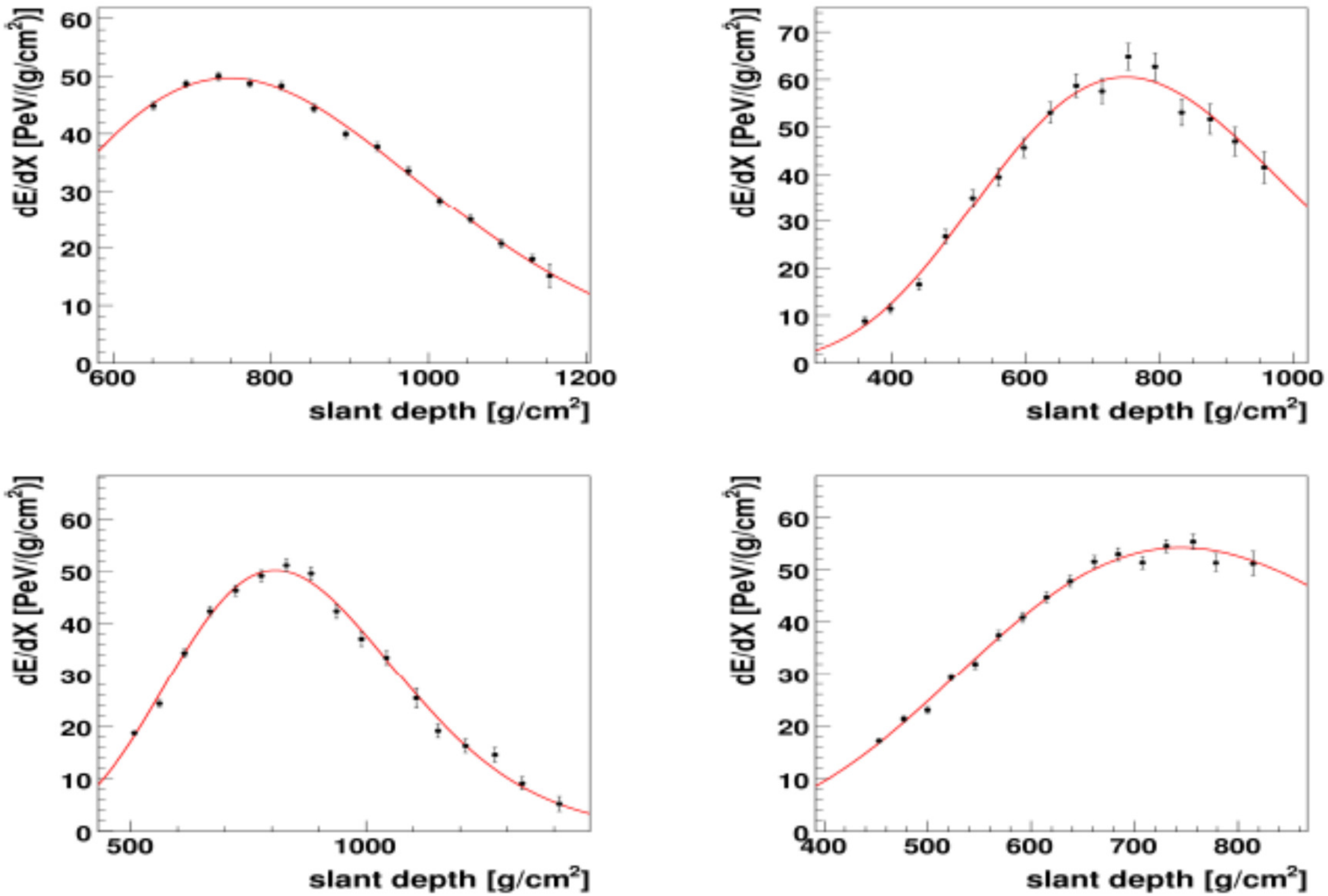


(LHCf Collab., Phys. Lett. B 703, 2011)



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

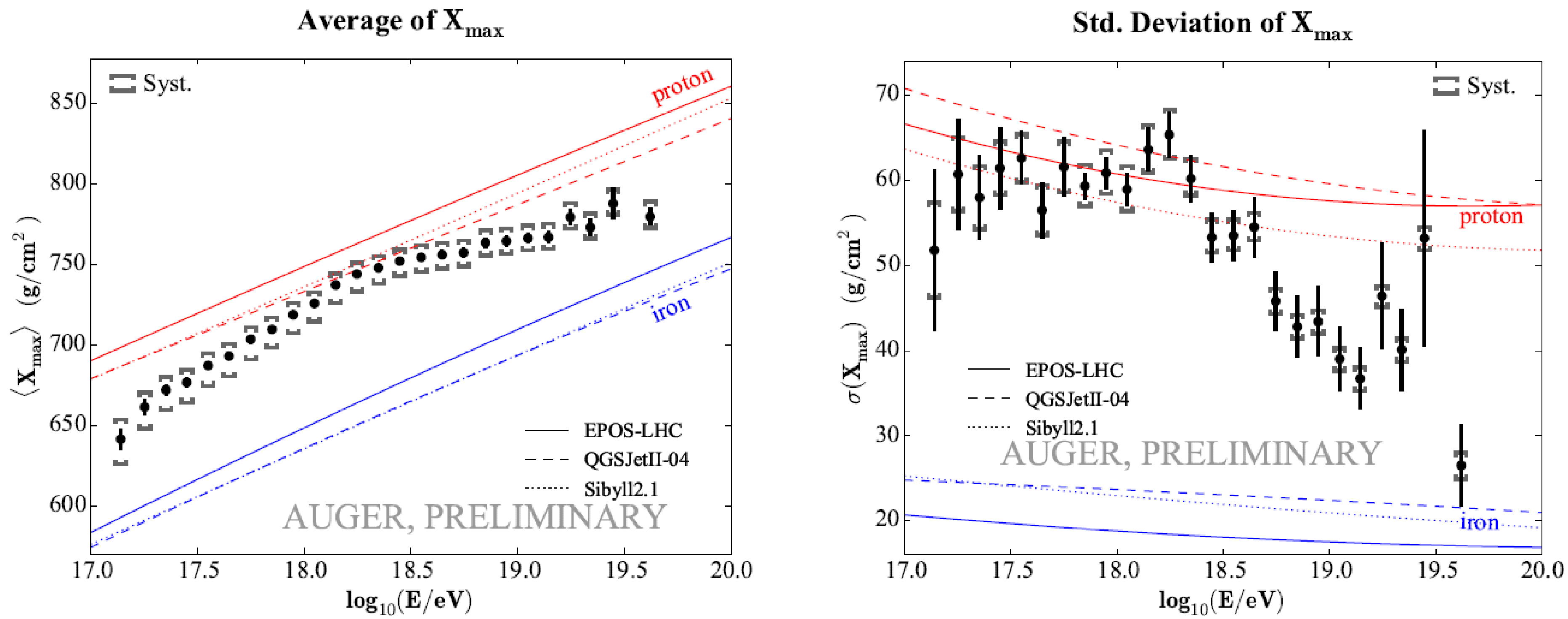


Figure 3: The mean (left) and the standard deviation (right) of the measured X_{max} distributions as a function of energy compared to air-shower simulations for proton and iron primaries.

Distribution of X_{max} as function of energy

PRD 90 1220005 2014

19759 events above 6 x 10^{17} eV

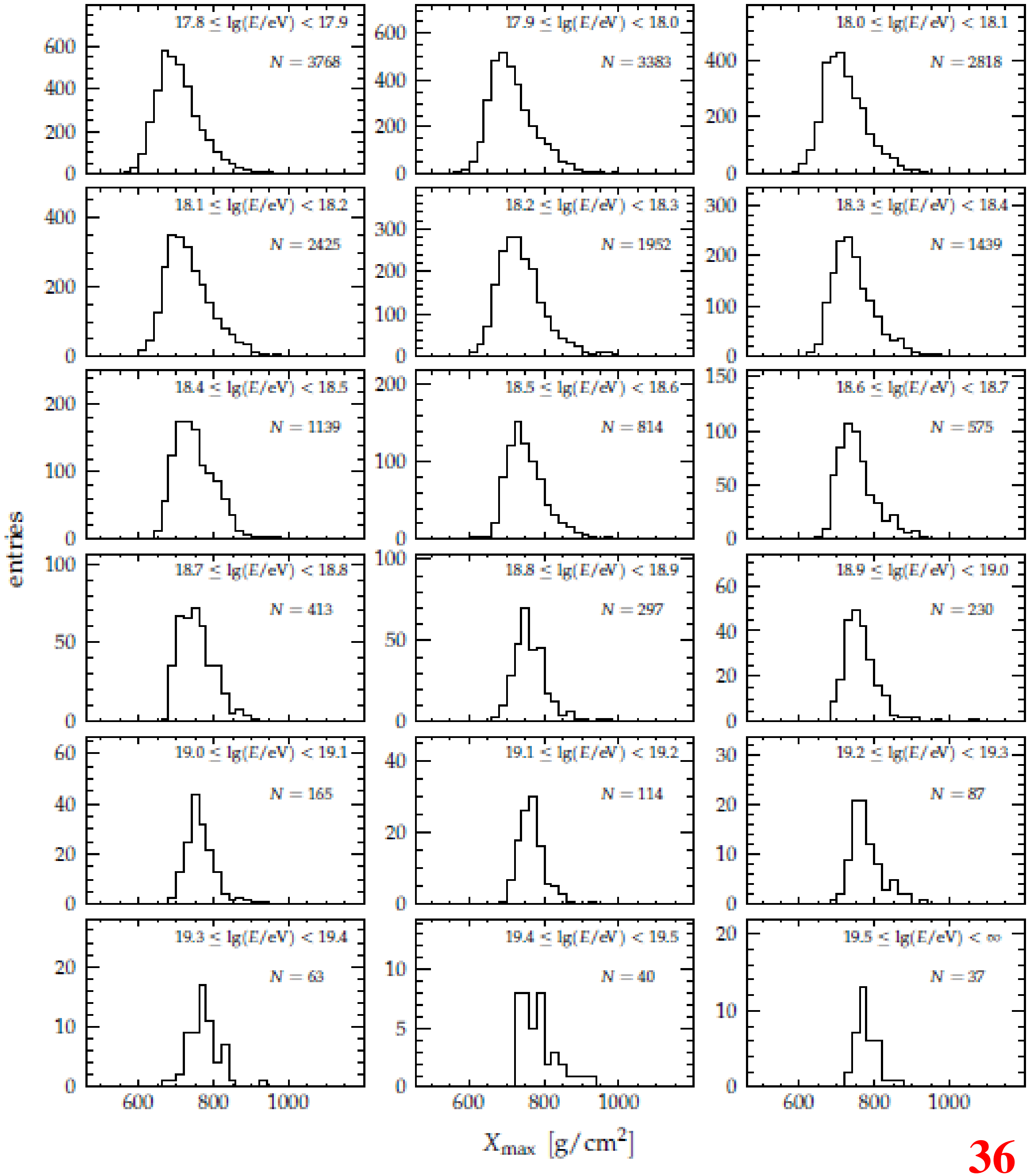
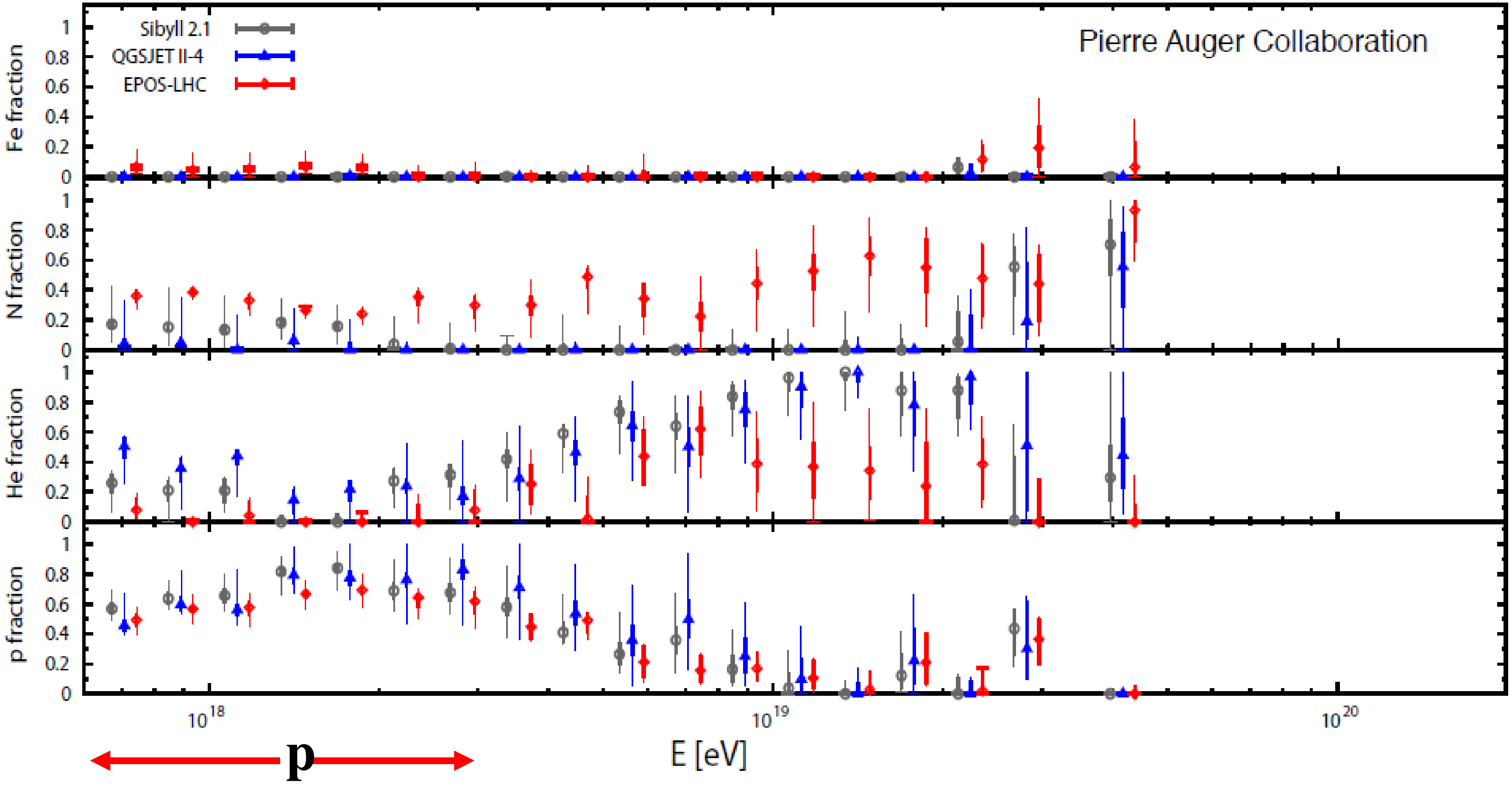


Figure 8: X_{max} distributions for different energy intervals.

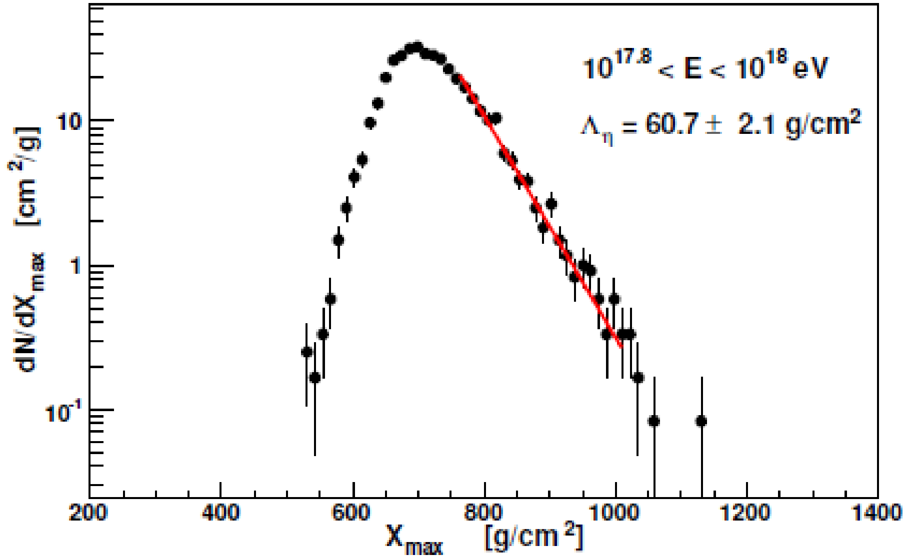


Proton-dominance

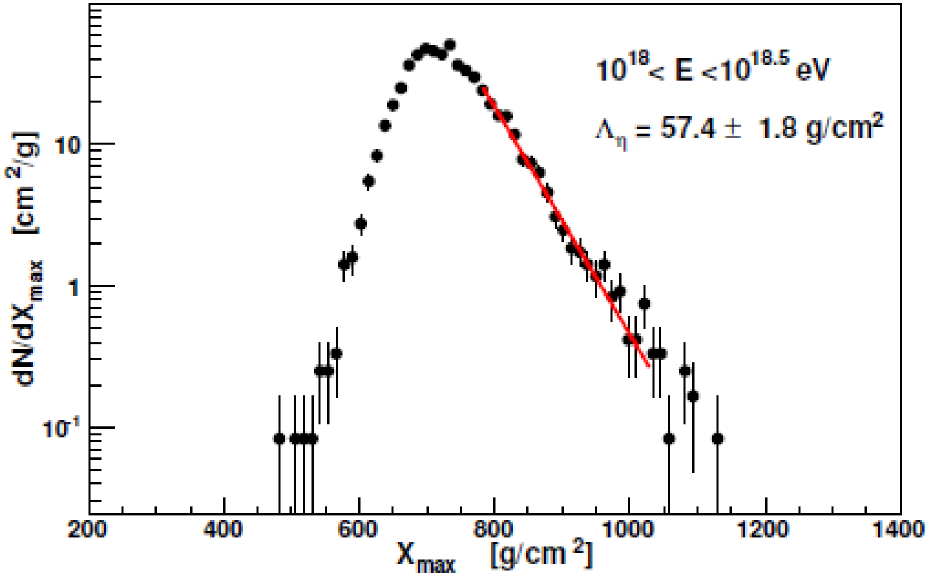
Demonstrations of some success
- and of some problems

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

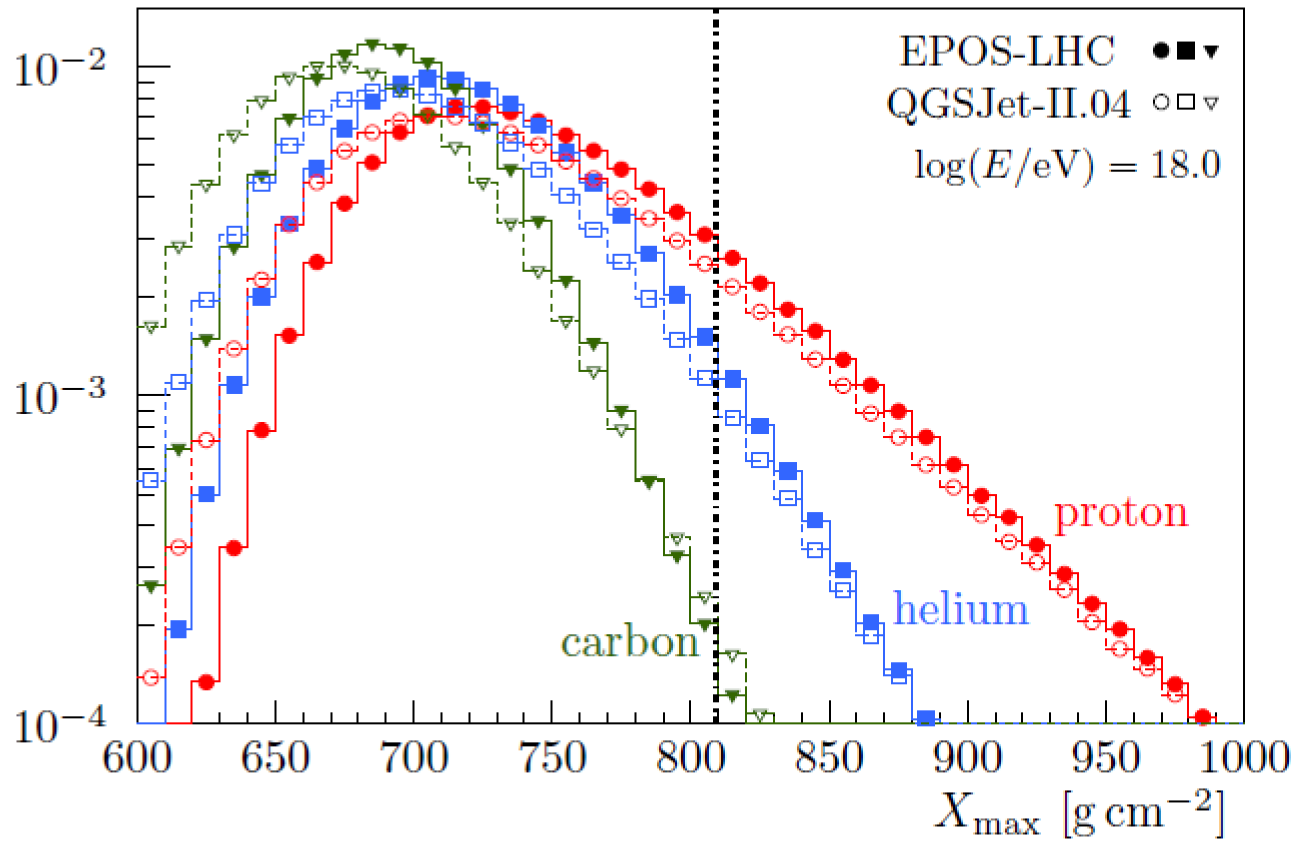
Λ_η ,the attenuation length, is found from the top 20% of events



<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

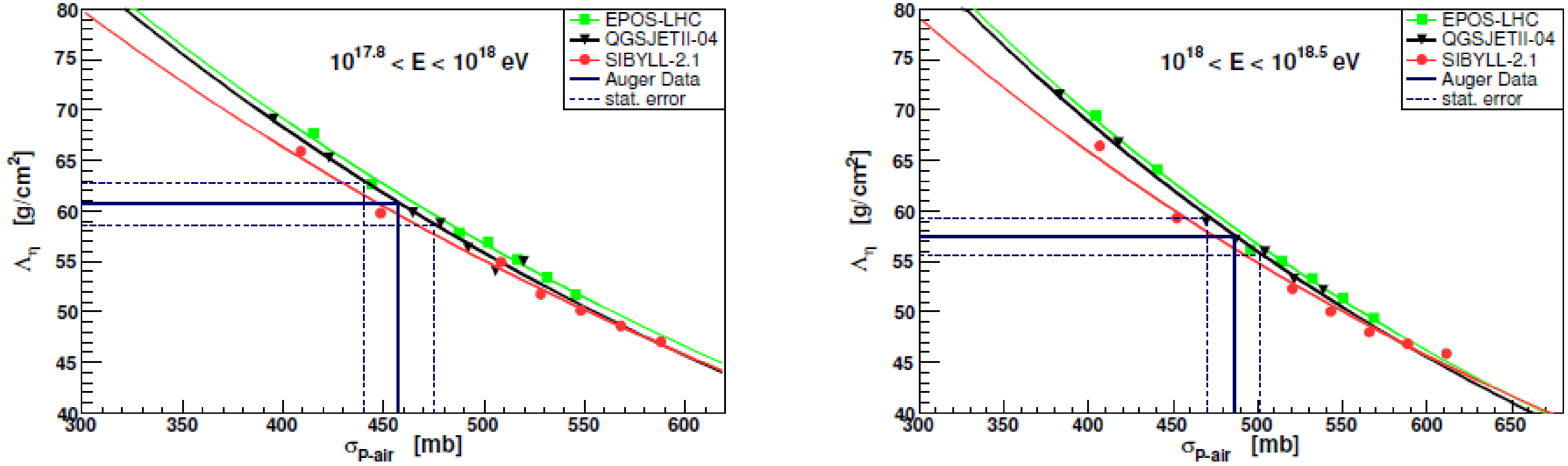
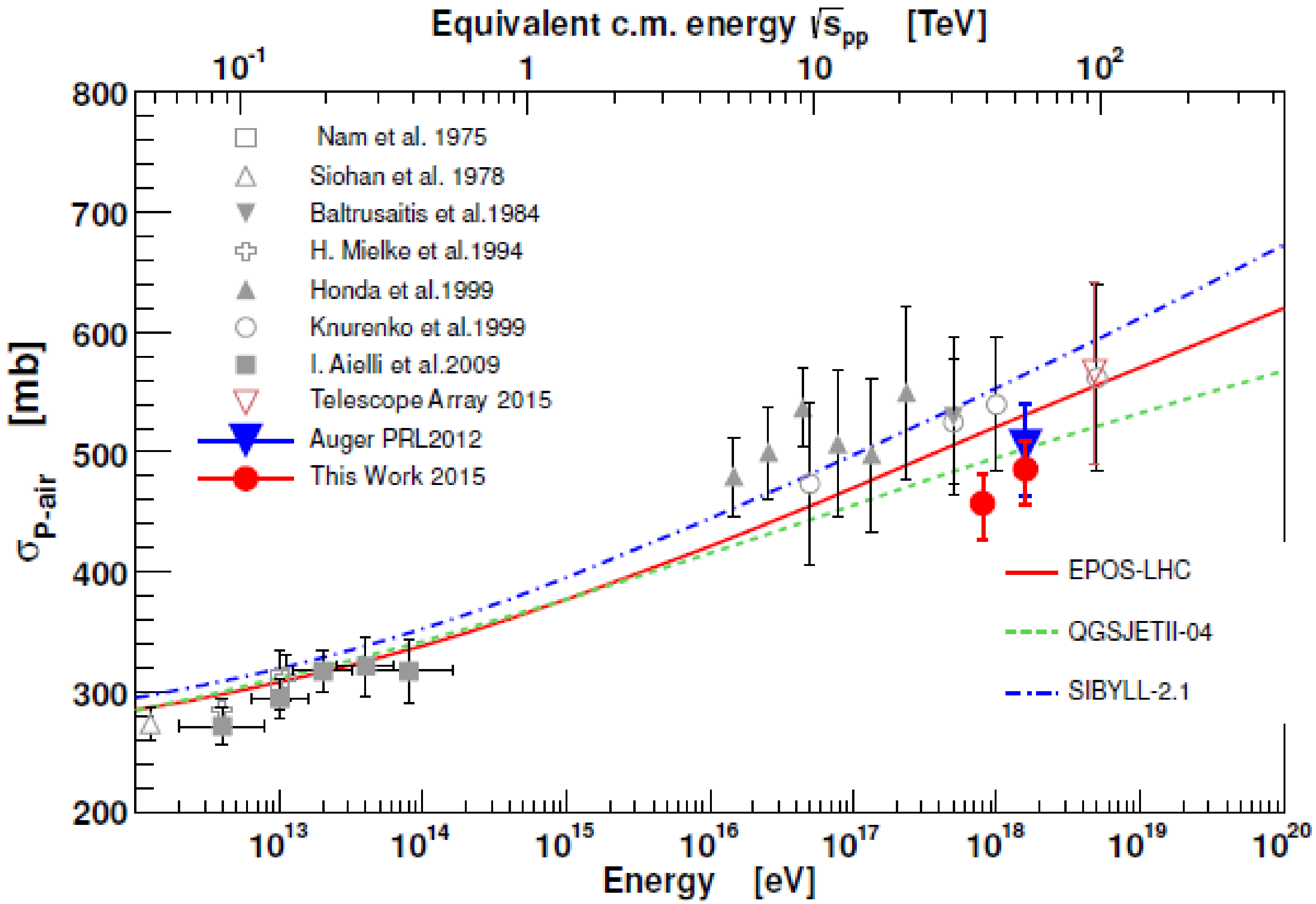


Figure 2: Conversion of Λ_η to σ_{p-air}. The simulations includes all detector resolution effects, while the data is corrected for acceptance effects. The solid and dashed lines show the Λ_η measurement and its projection to σ_{p-air} as derived using the average of all models.

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

Proton-air cross-section as function of energy

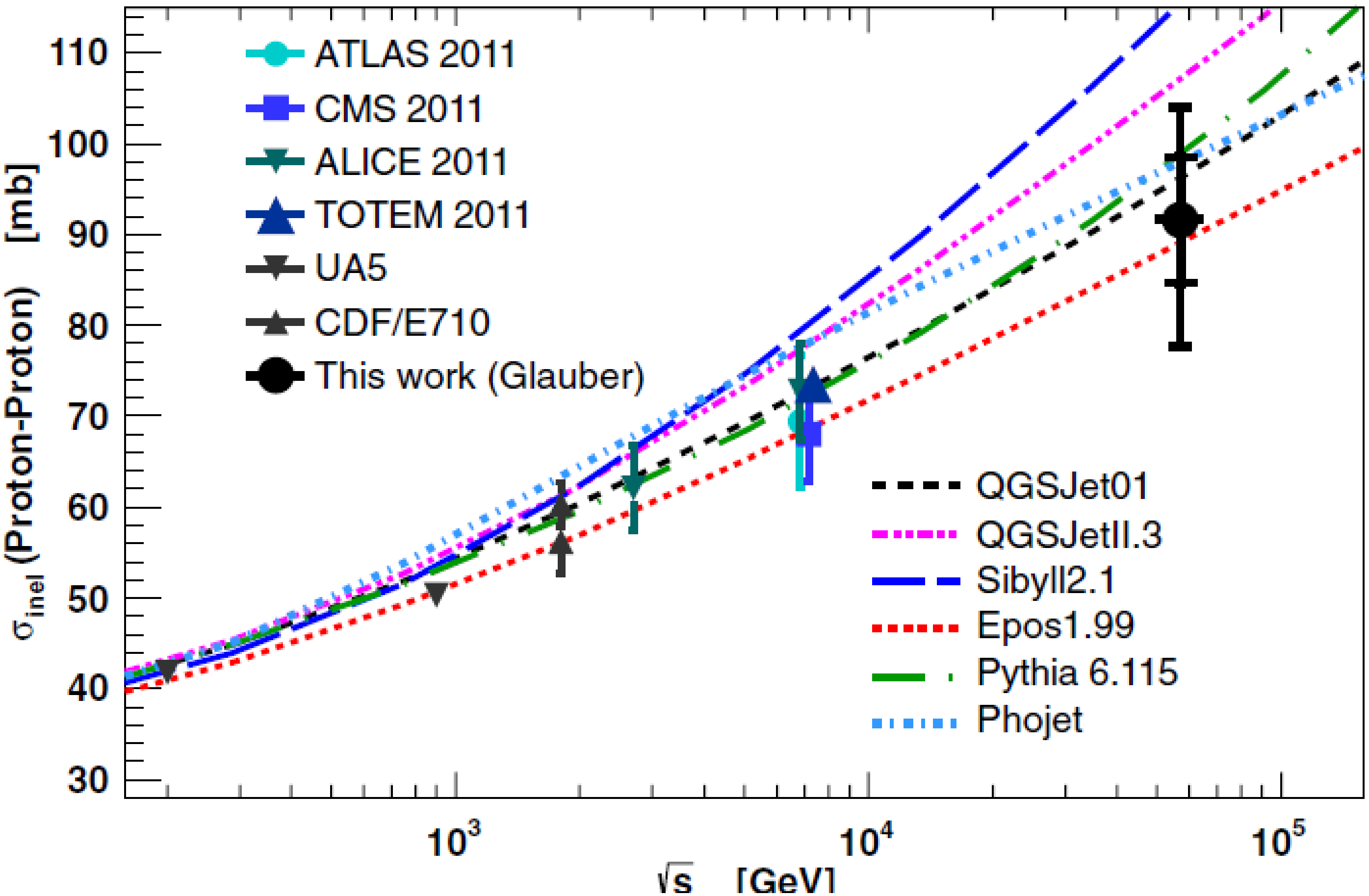


Impact of 25% He is included as systematic uncertainty (- 16 mb)

Photons have been shown to be < 0.5% at energies of interest:

contamination would raise σ by ~ 4.5 mb

p-p inelastic cross-section: PRL 109 062002 2012



$$\sigma_{pp}^{\rm inel} = [92 \pm 7({\rm stat})^{+9}_{-11}({\rm syst}) \pm 7({\rm Glauber})]\ {\rm mb},$$

$$\sigma_{pp}^{\rm tot} = [133 \pm 13({\rm stat})^{+17}_{-20}({\rm syst}) \pm 16({\rm Glauber})]\ {\rm mb}.$$

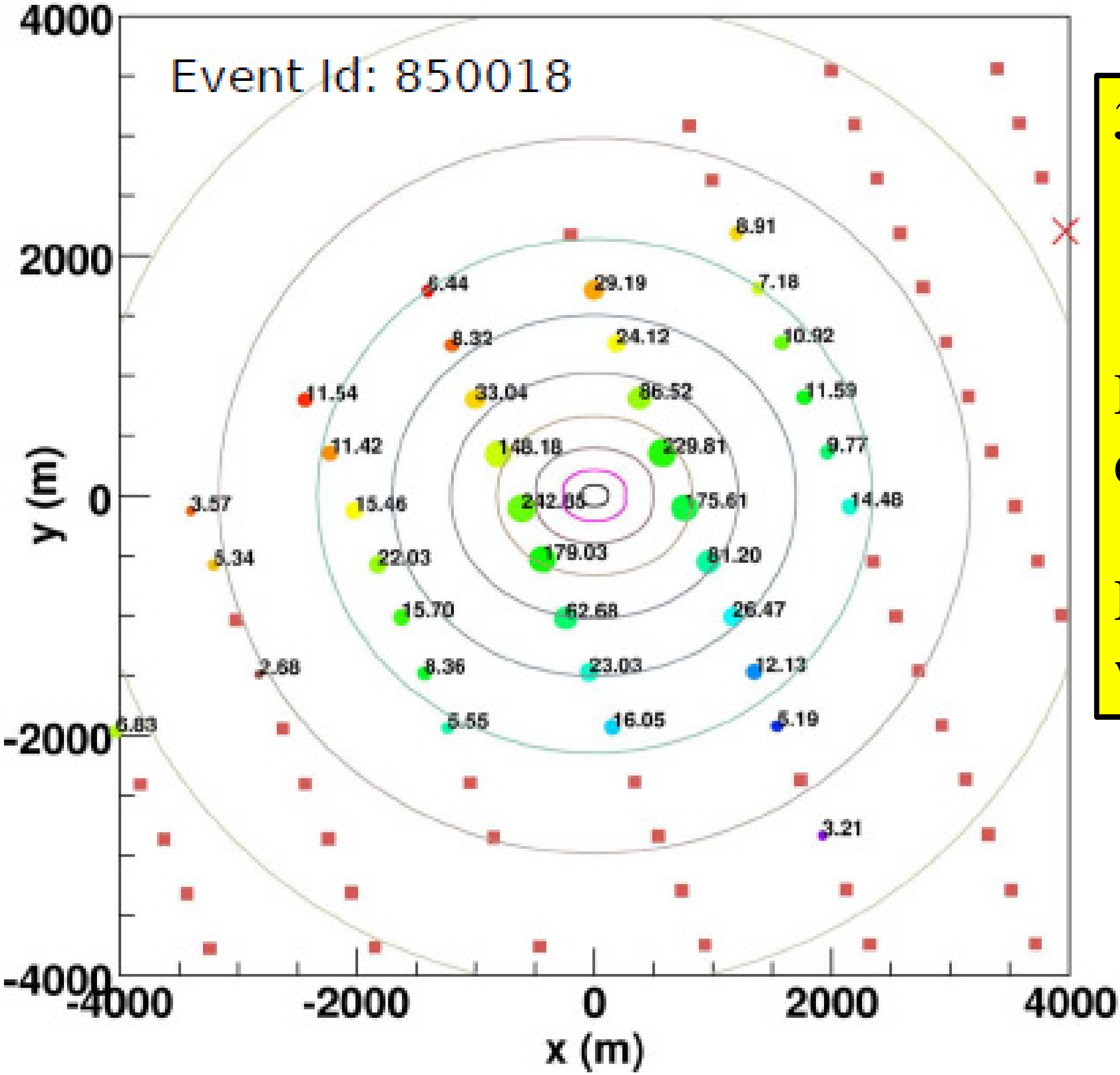
$$N_\mu = A \left(\frac{E/A}{\epsilon_c} \right)^\beta,$$

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

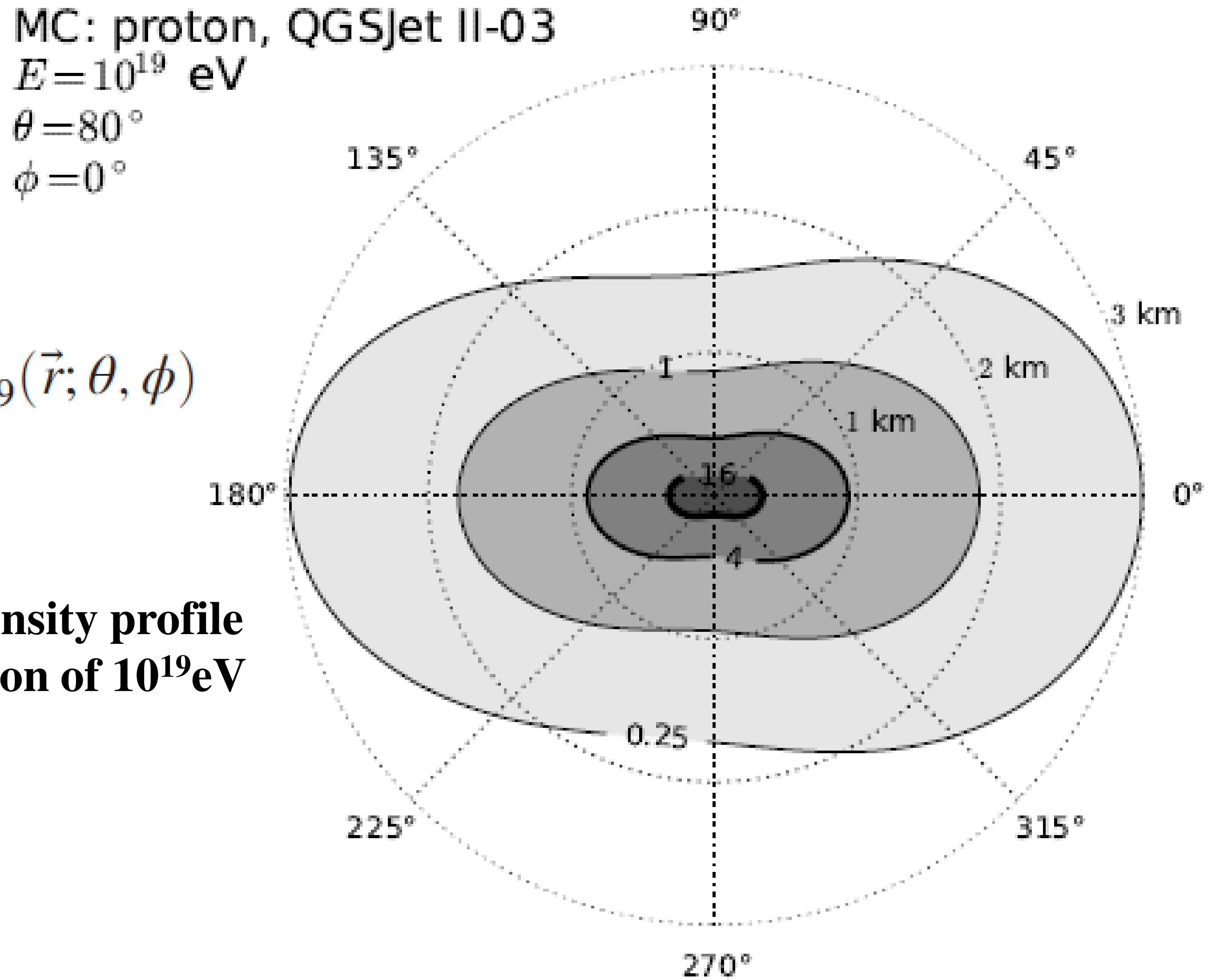
Inclined showers are useful to test models – muons dominate



37 stations
71°
54 EeV

Fit made to density distribution

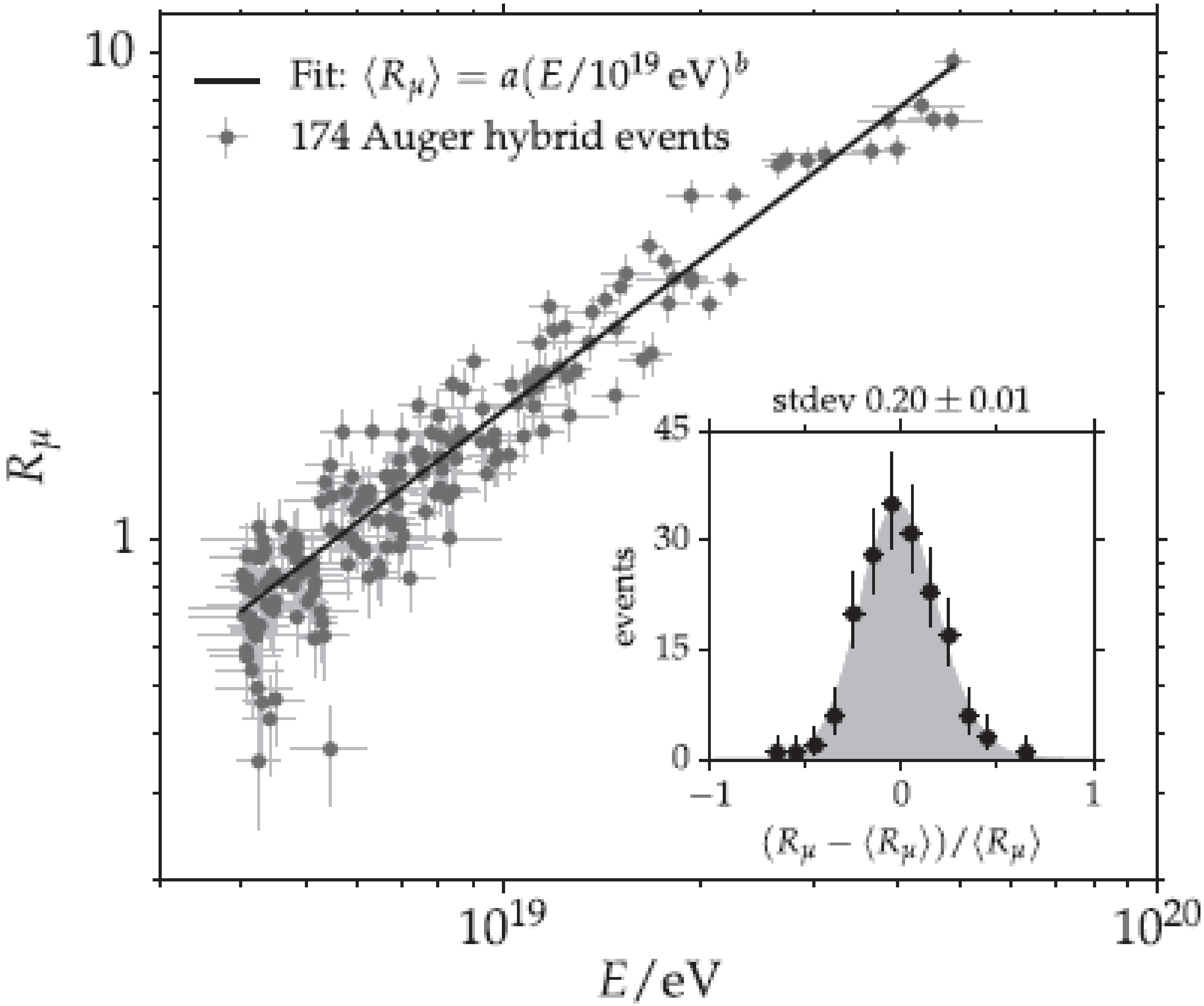
Energy measured with ~20 % accuracy



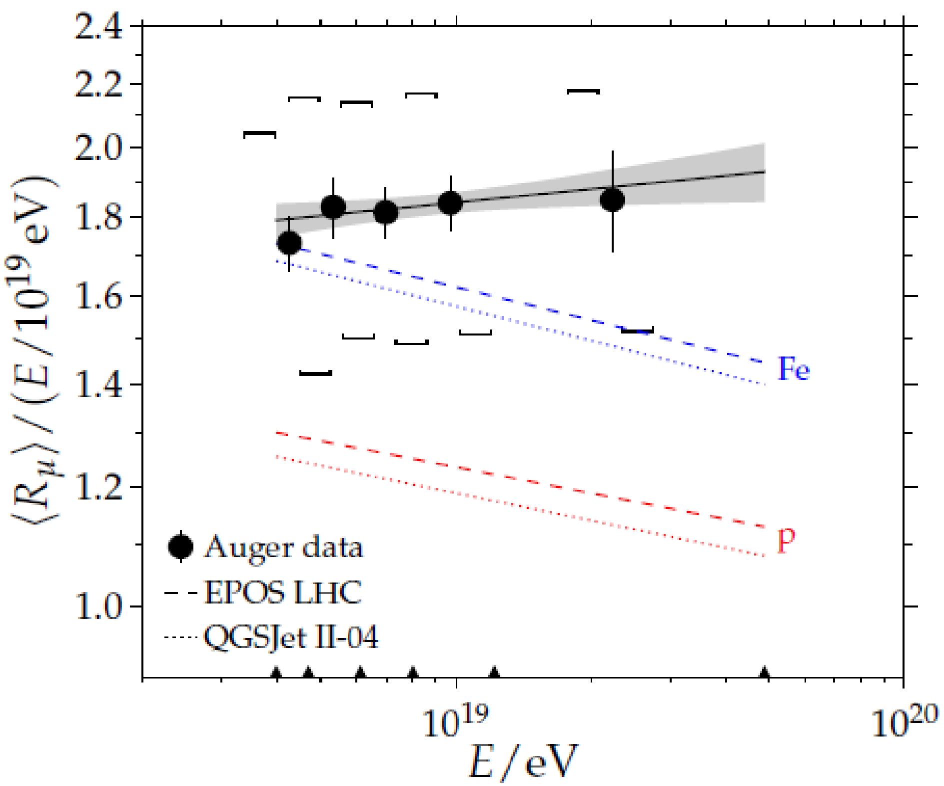
$$\rho_\mu(\vec{r}) = N_{19}\rho_{\mu,19}(\vec{r};\theta,\phi)$$

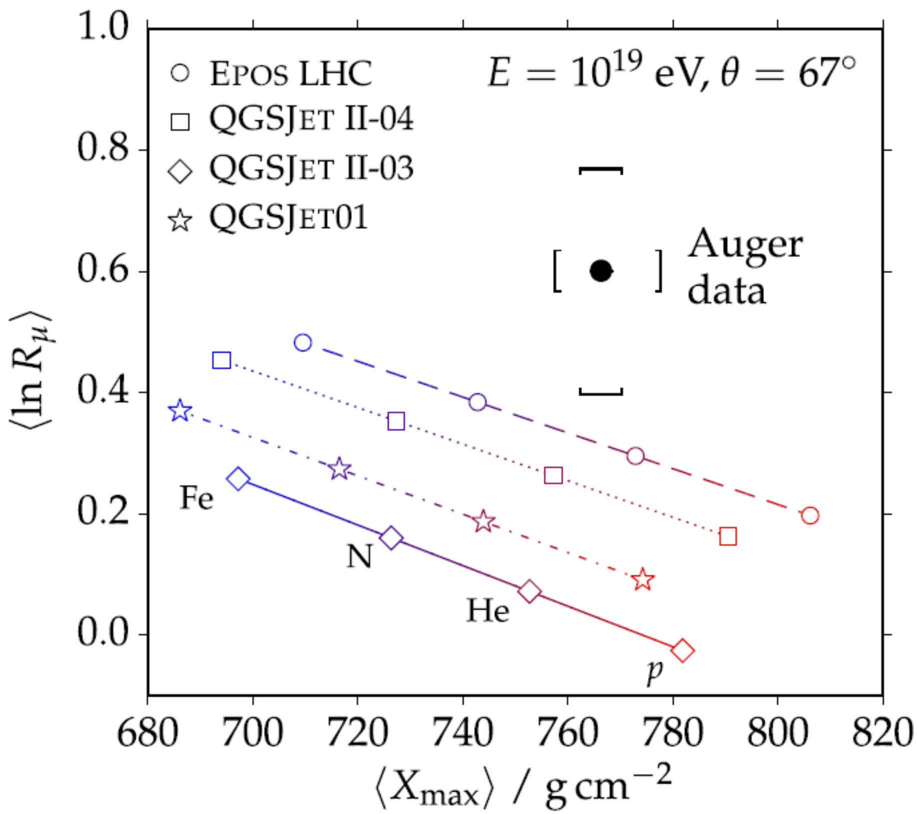
Average muon density profile of simulated-proton of 10^{19}eV

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

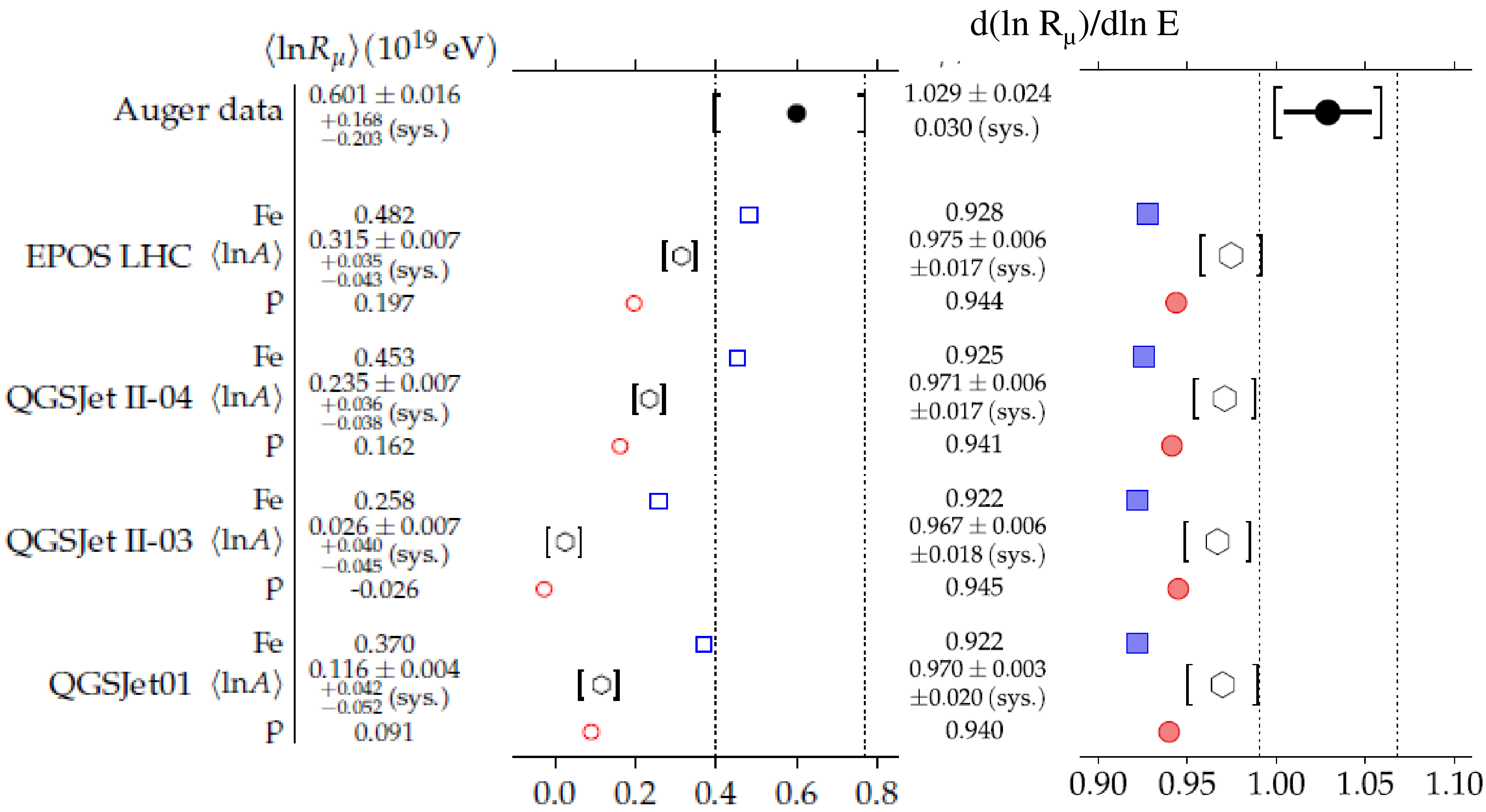


Fit: ⟨R_μ⟩ = $a(E/10^{19}$ eV$)^b$
174 Auger hybrid events
stdev 0.20 ± 0.01
45
30
15
0
events
−1
0
1
$(R_\mu - \langle R_\mu \rangle)/\langle R_\mu \rangle$
10
1
R_μ
10^{19}
10^{20}
E/eV





Muon numbers predicted by models are under-estimated by 30 to 80% (20% systematic)



⟨lnR_μ⟩ (10^{19} eV)
d(ln R_μ)/dln E
Auger data
0.601 ± 0.016
$^{+0.168}_{-0.203}$ (sys.)
1.029 ± 0.024
0.030 (sys.)
EPOS LHC ⟨ln$A$⟩
Fe
0.482
0.315 ± 0.007
$^{+0.035}_{-0.043}$ (sys.)
p
0.197
0.928
0.975 ± 0.006
± 0.017 (sys.)
0.944
QGSJet II-04 ⟨ln$A$⟩
Fe
0.453
0.235 ± 0.007
$^{+0.036}_{-0.038}$ (sys.)
p
0.162
0.925
0.971 ± 0.006
± 0.017 (sys.)
0.941
QGSJet II-03 ⟨ln$A$⟩
Fe
0.258
0.026 ± 0.007
$^{+0.040}_{-0.045}$ (sys.)
p
-0.026
0.922
0.967 ± 0.006
± 0.018 (sys.)
0.945
QGSJet01 ⟨ln$A$⟩
Fe
0.370
0.116 ± 0.004
$^{+0.042}_{-0.052}$ (sys.)
p
0.091
0.922
0.970 ± 0.003
± 0.020 (sys.)
0.940
0.0
0.2
0.4
0.6
0.8
0.90
0.95
1.00
1.05
1.10

Second method of testing models:

Muon Production Depth (MPD)

PRD 90 012012 2014

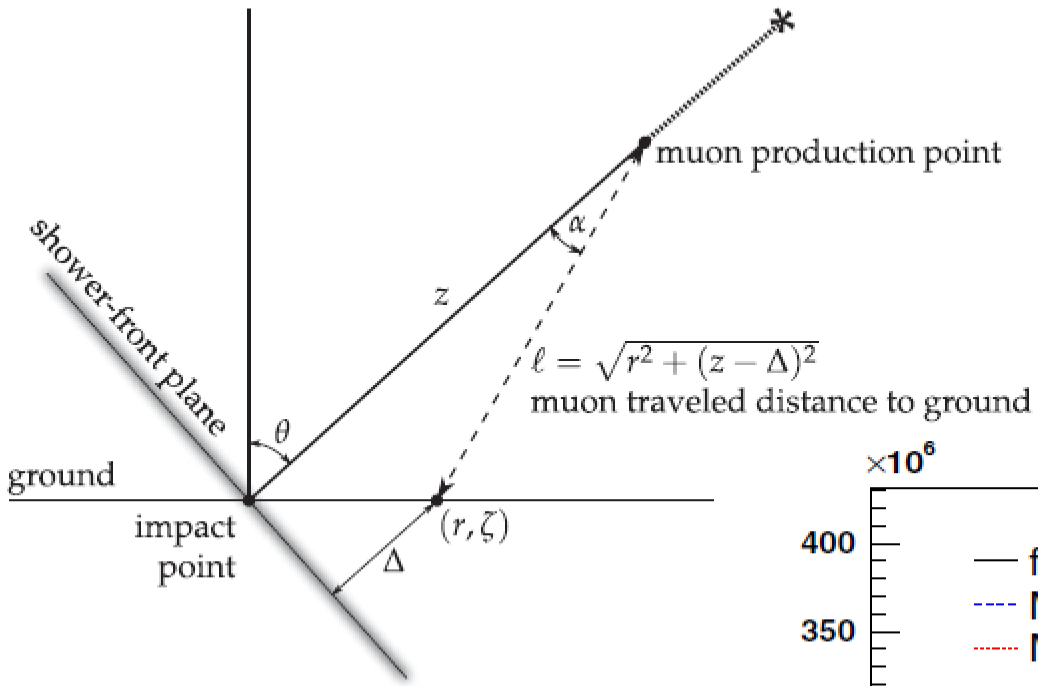
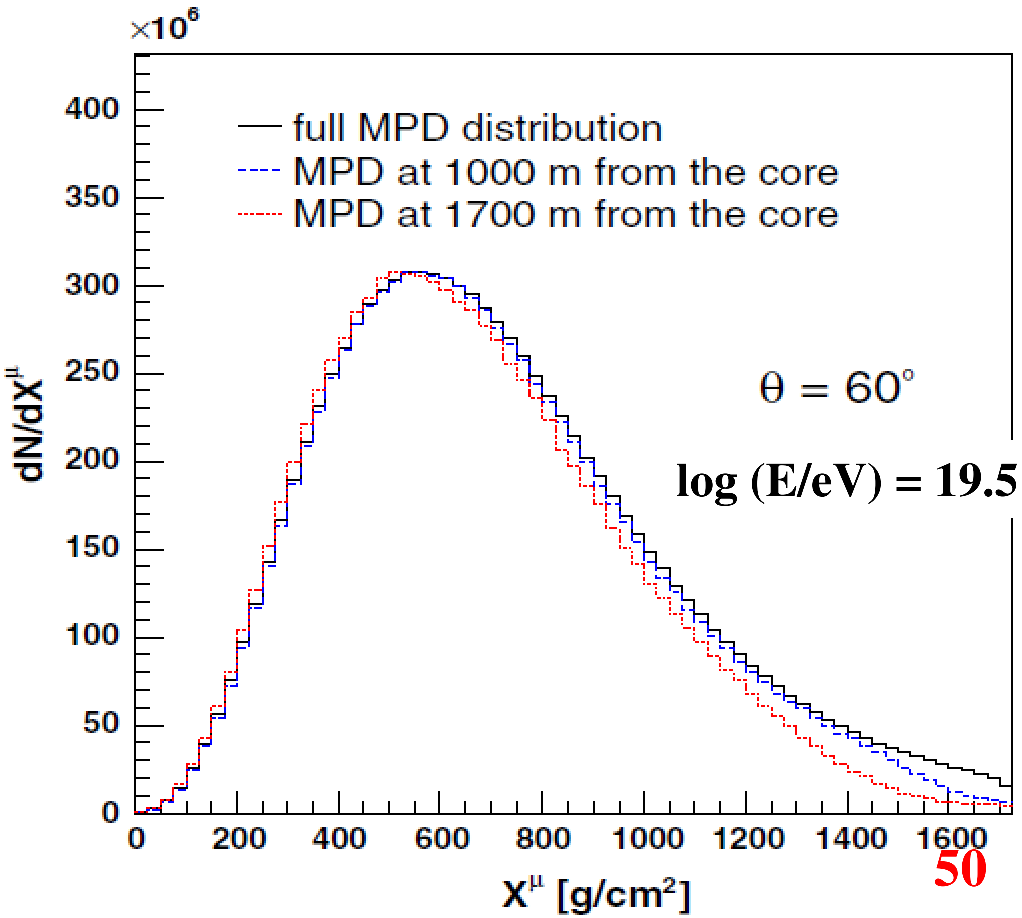
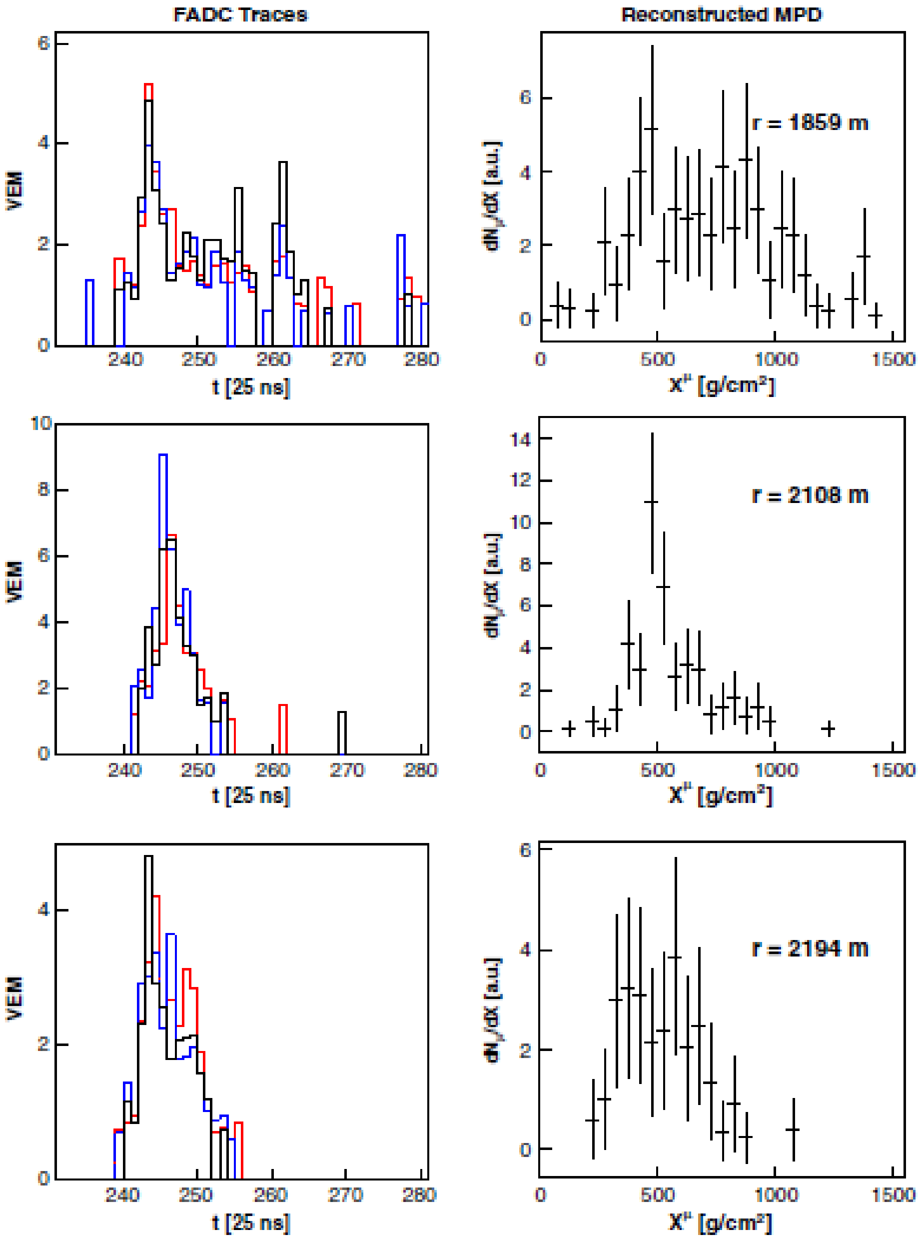
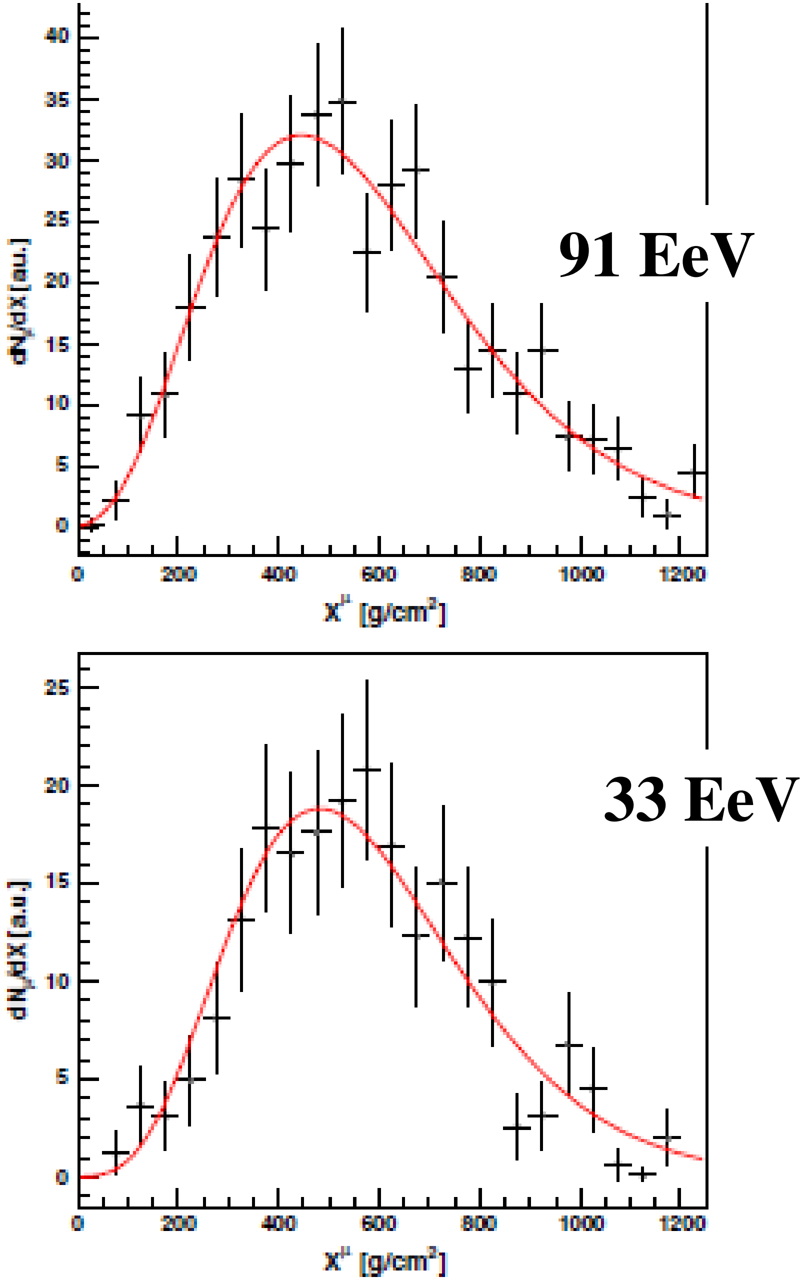


FIG. 1. Geometry used to obtain the muon t
the time delay.




FADC Traces
Reconstructed MPD
VEM
t [25 ns]
dN$_\mu$/dX [a.u.]
X$^\mu$ [g/cm^2]
r = 1859 m
r = 2108 m
r = 2194 m


91 EeV
33 EeV
dN$_\mu$/dX [a.u.]
X$^\mu$ [g/cm^2]

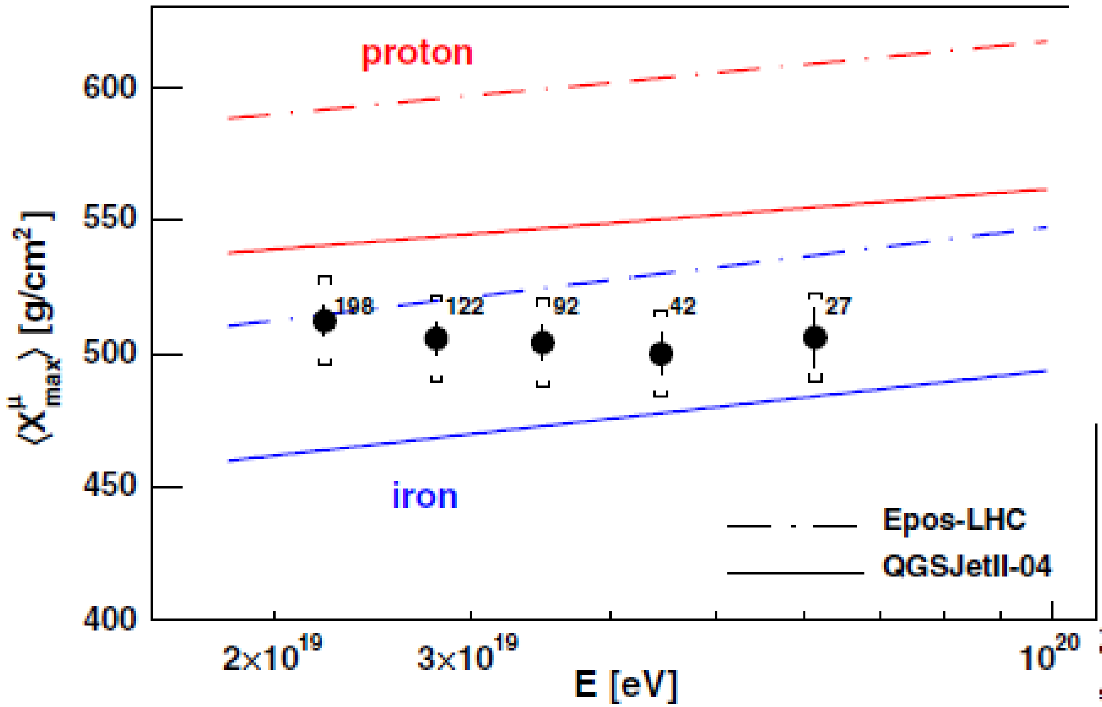
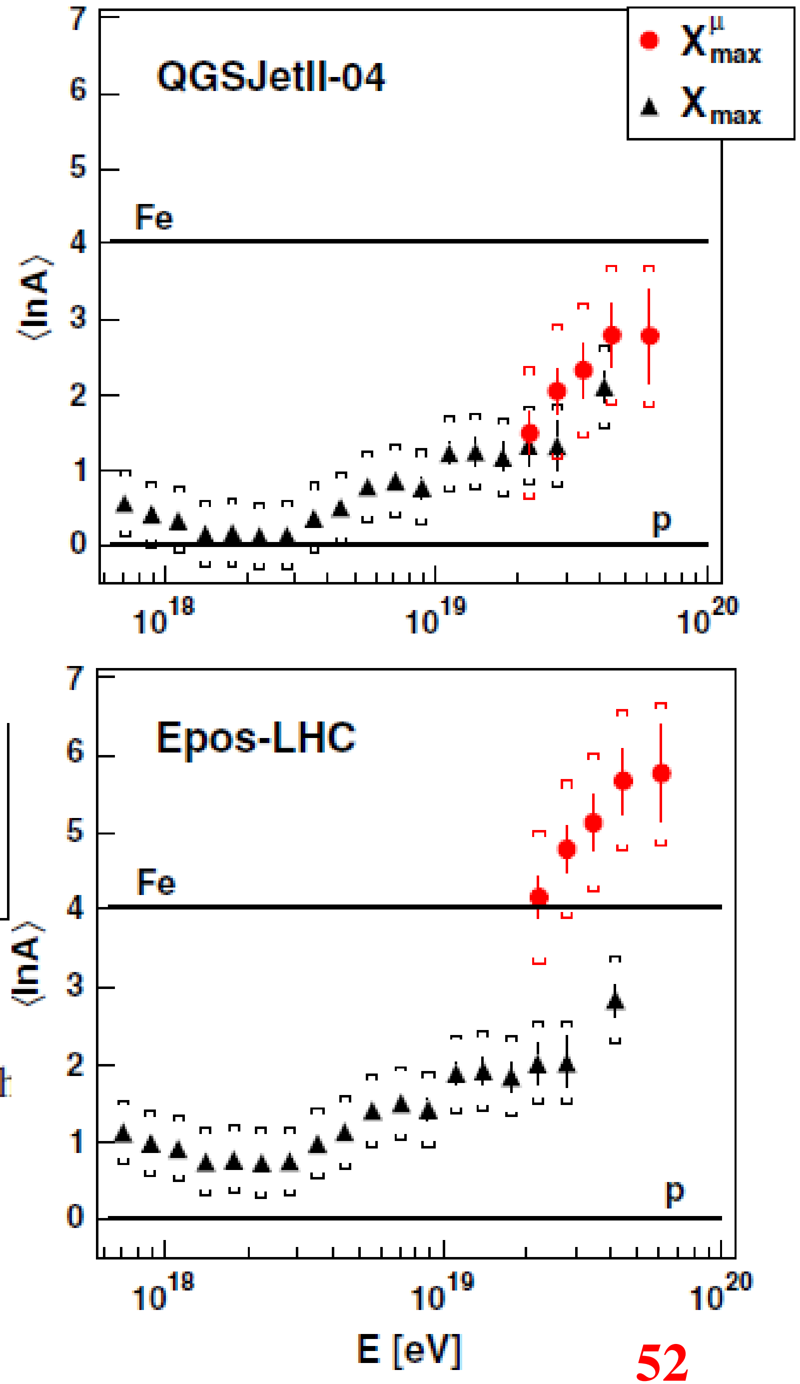
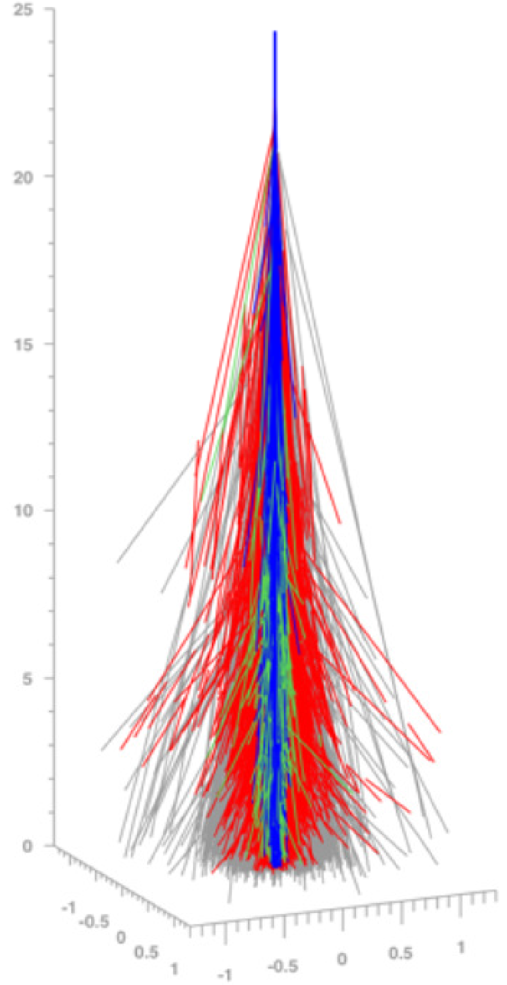


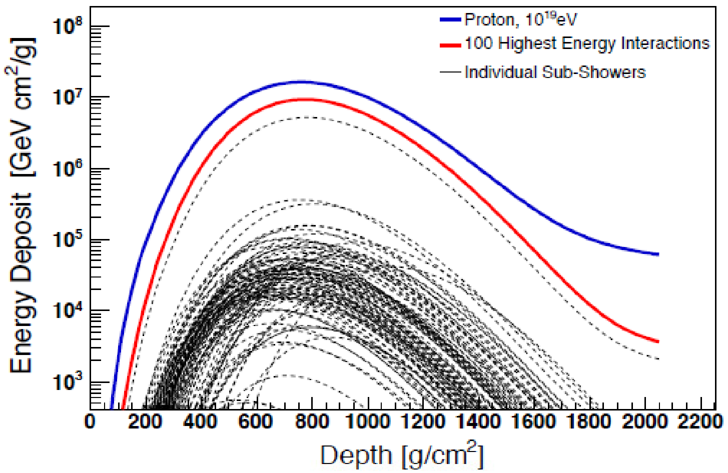
FIG. 8 (color online). $\langle X^{\mu}_{\rm max} \rangle$ as a function of energy. Th



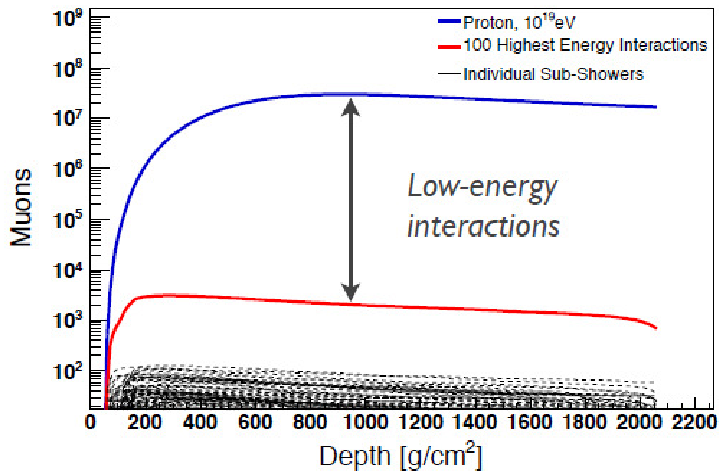
Importance of different interaction energies



Electrons



Muons



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

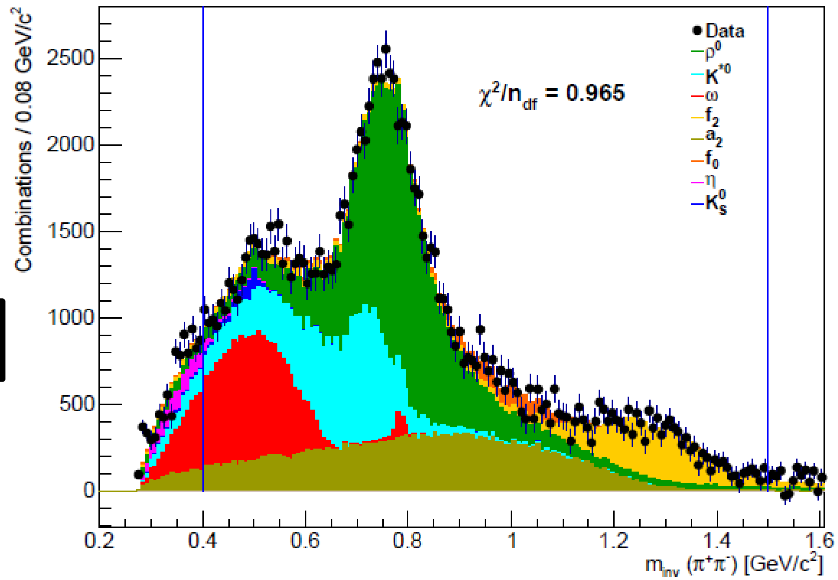


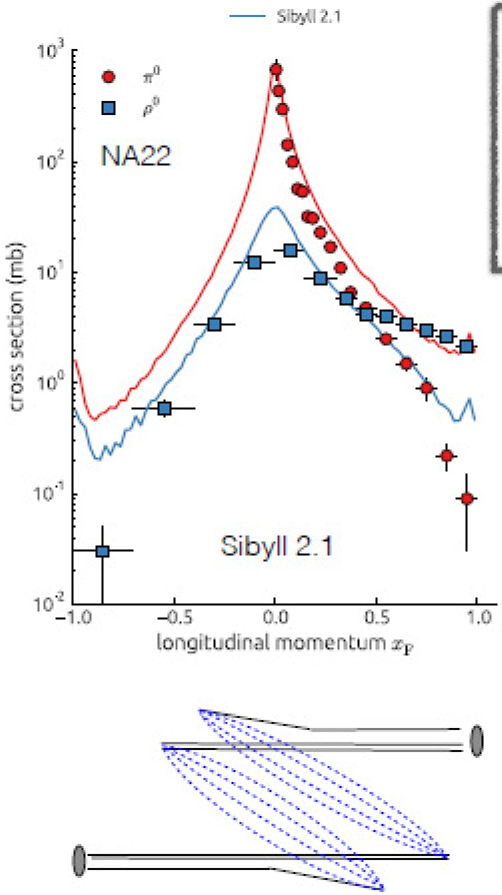
Figure 4: $\pi^+\pi^-$ mass distribution in π^-+C interactions at 158 GeV/c in the range $0.4 < x_F < 0.5$. Do error bars denote the data and the fitted resonance templates are shown as filled histograms. The lines indicate the range of the fit.

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

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 (i)

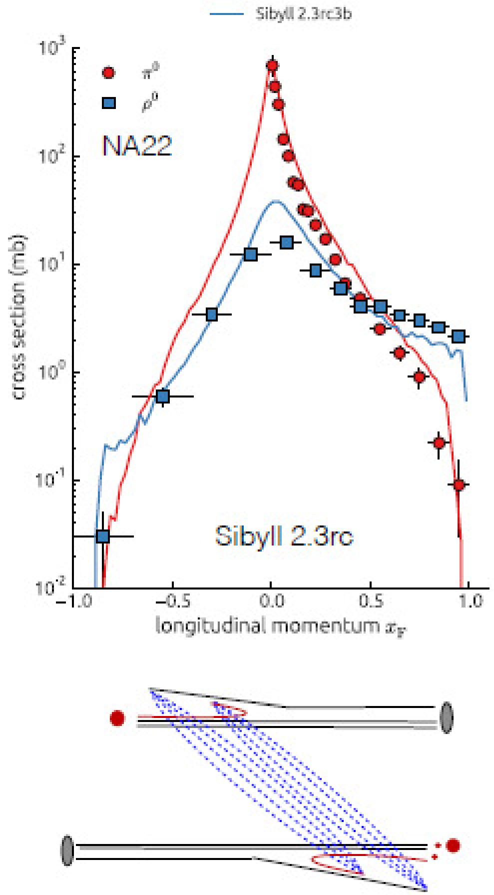


$$\pi^+ p \to \pi^0 \to 2\gamma$$

$$\pi^+ p \to \rho^0 \to \pi^+ \pi^-$$

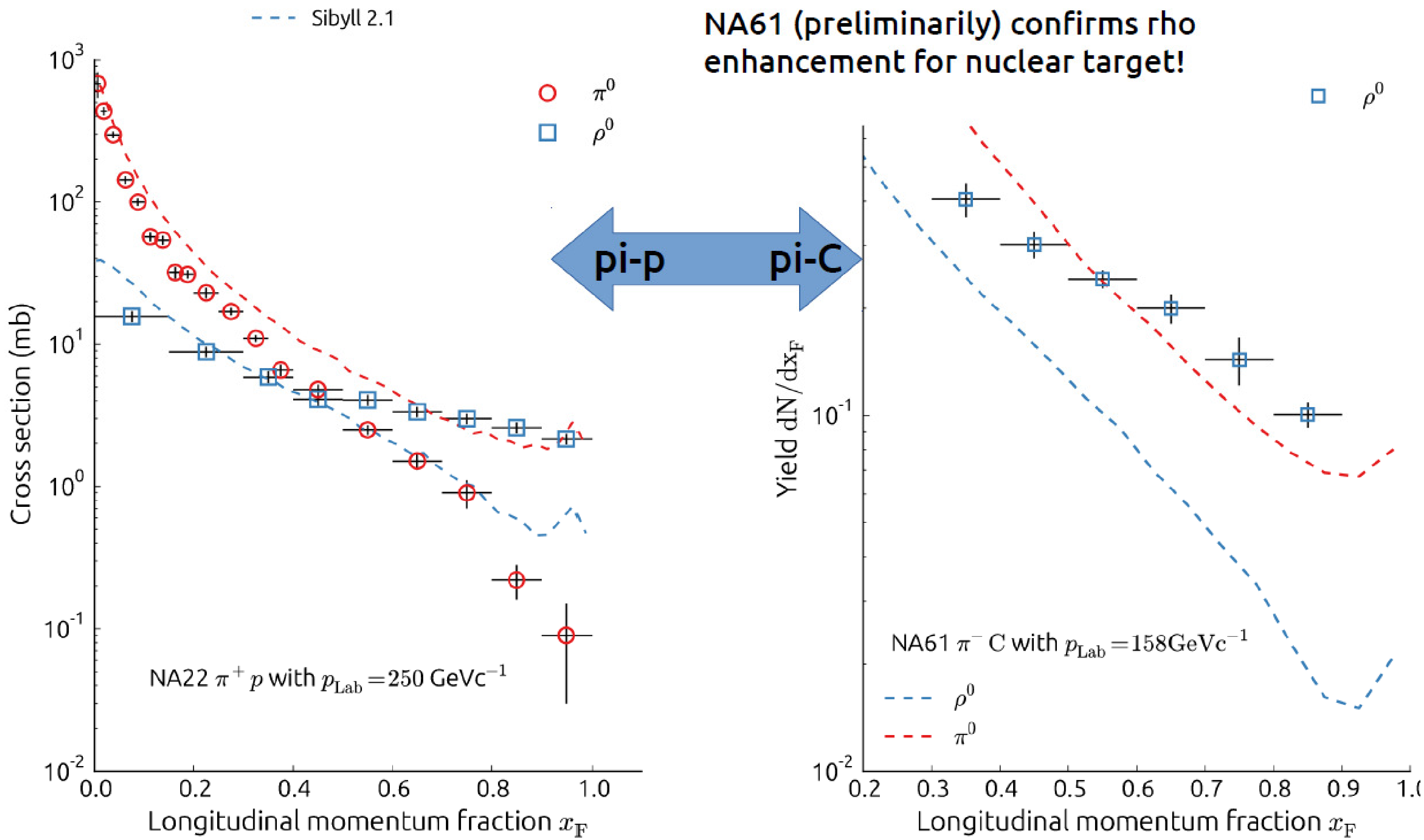
$$E_{\mathrm{lab}} = 250\,\mathrm{GeV}$$

$$x_F = p_{||} / p_{\max}$$



Riehn et al., ICRC 2015)

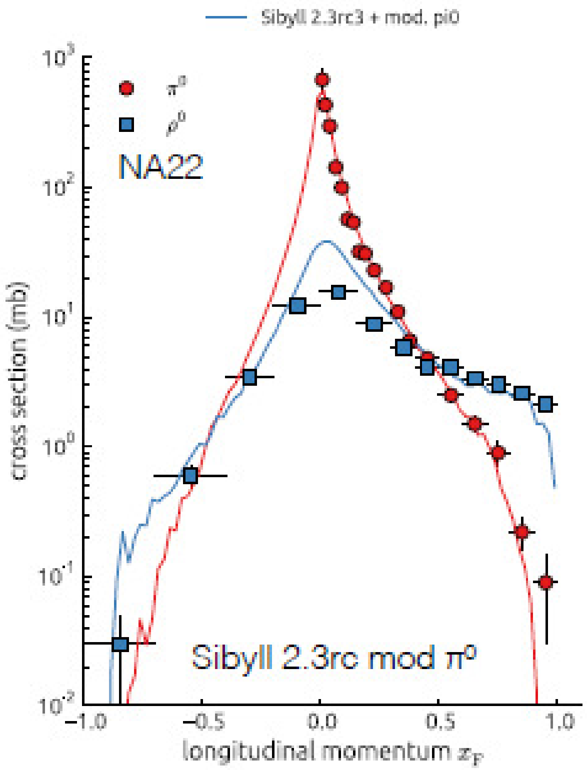
NA61 (preliminarily) confirms rho enhancement for nuclear target!

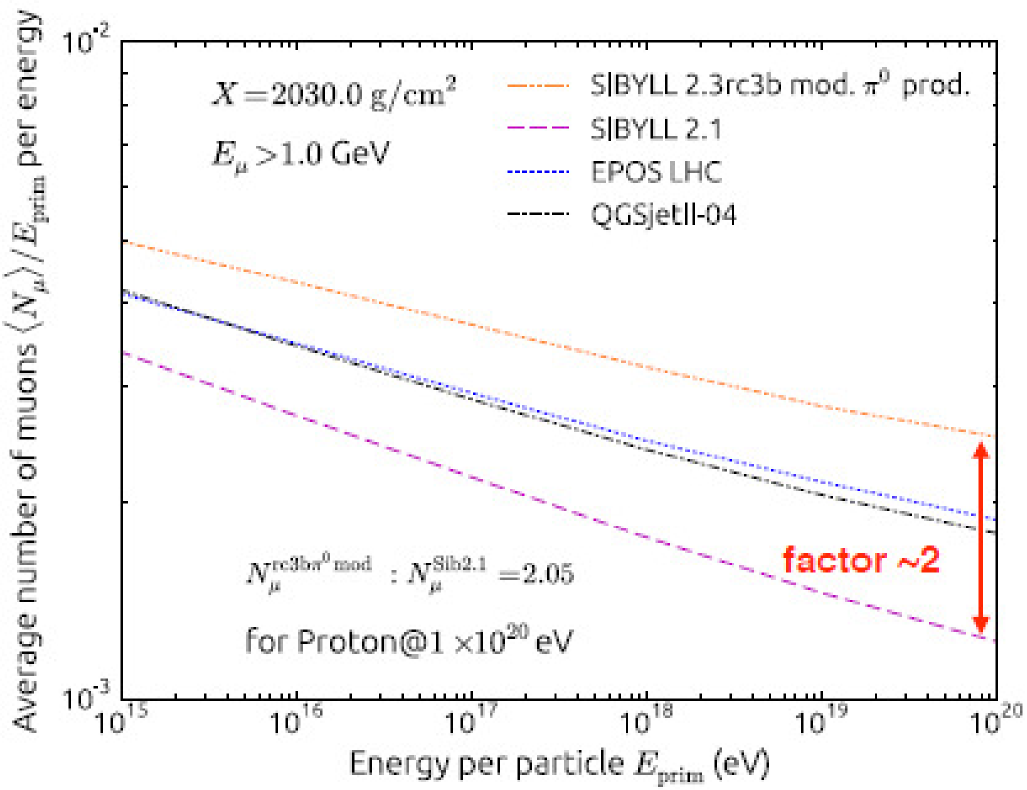


Presumably pi0 suppressed as in pi-p

(NA61 data: Herve, ICRC 2015)

Rho production in pion-proton interactions (iii)



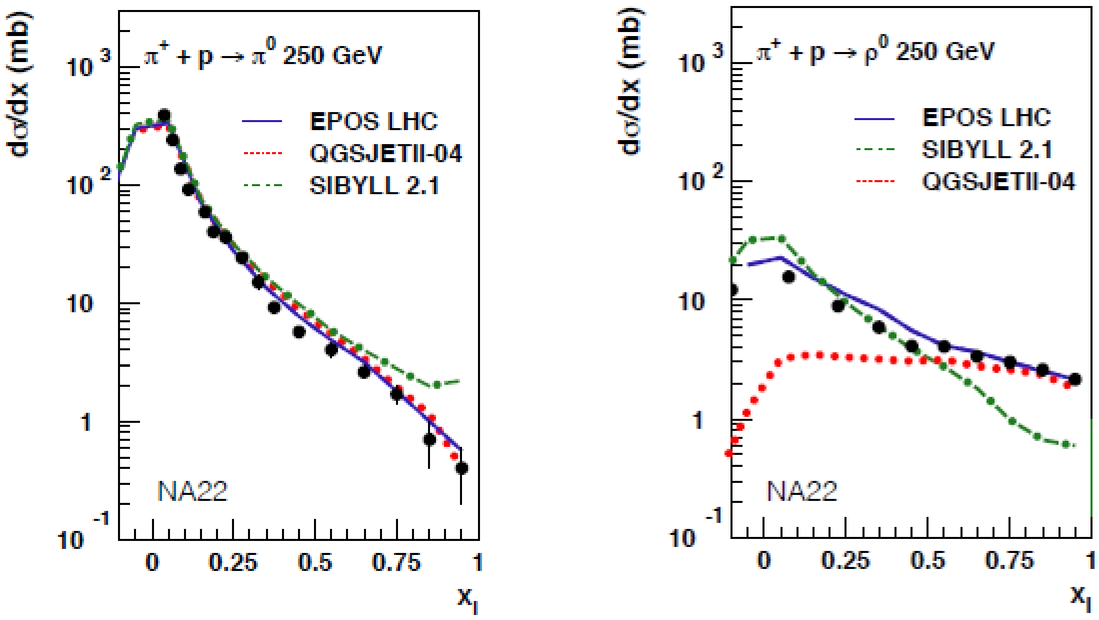


Ad hoc modified ρ^0 and π^0 production

Sibyll 2.3rc mod π^0

(Riehn et al., ICRC 2015)

Open questions related to rho production

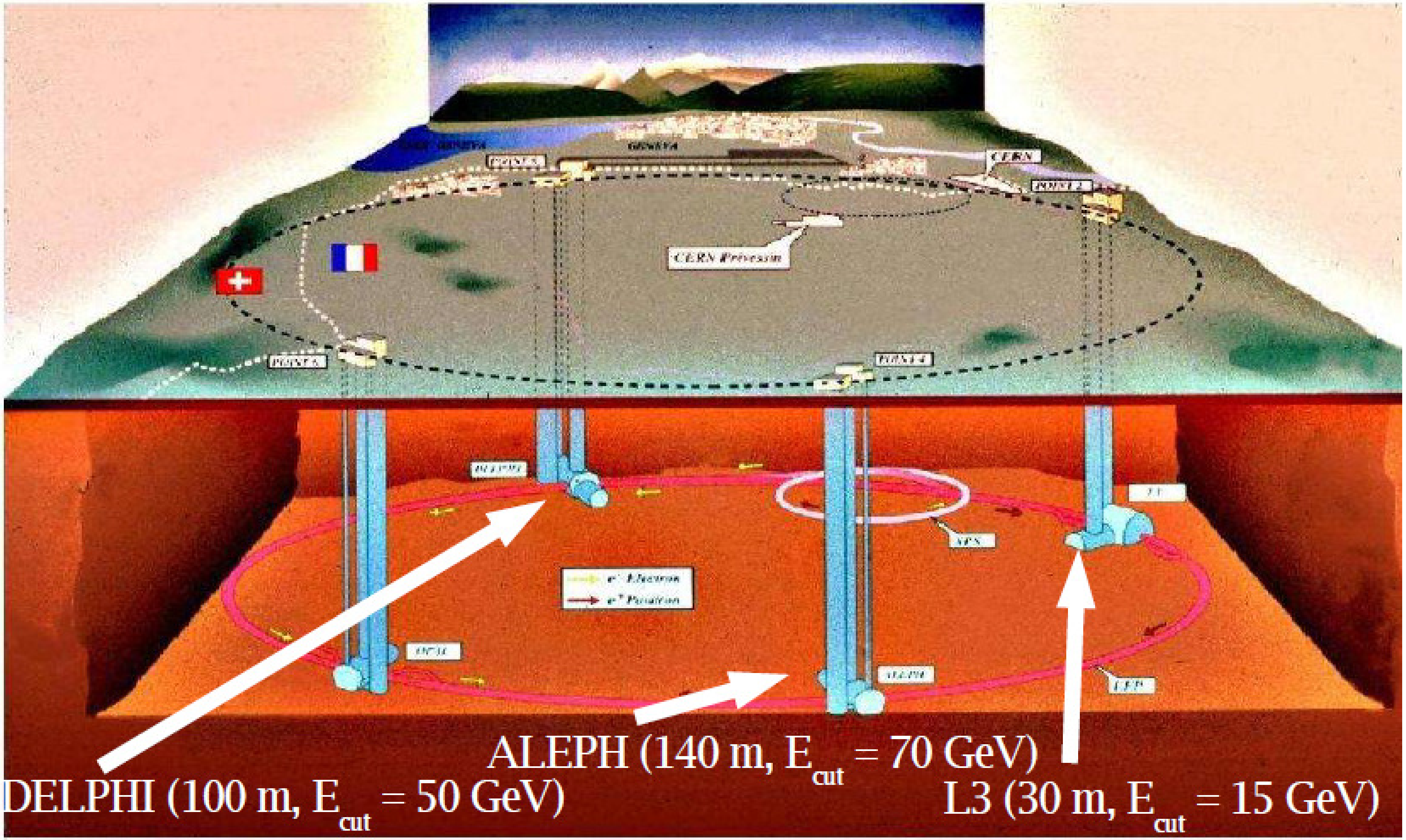


- EPOS and QGSJet tuned to reproduce π-p data
- Apparently origin of rho production not understood
- Suppression of π^0 production rather strong
- Energy dependence of these effects could be important

(Pierog 2015)

Similar muon problem to what was seen at LEP?

Detection of CR by LEP experiments

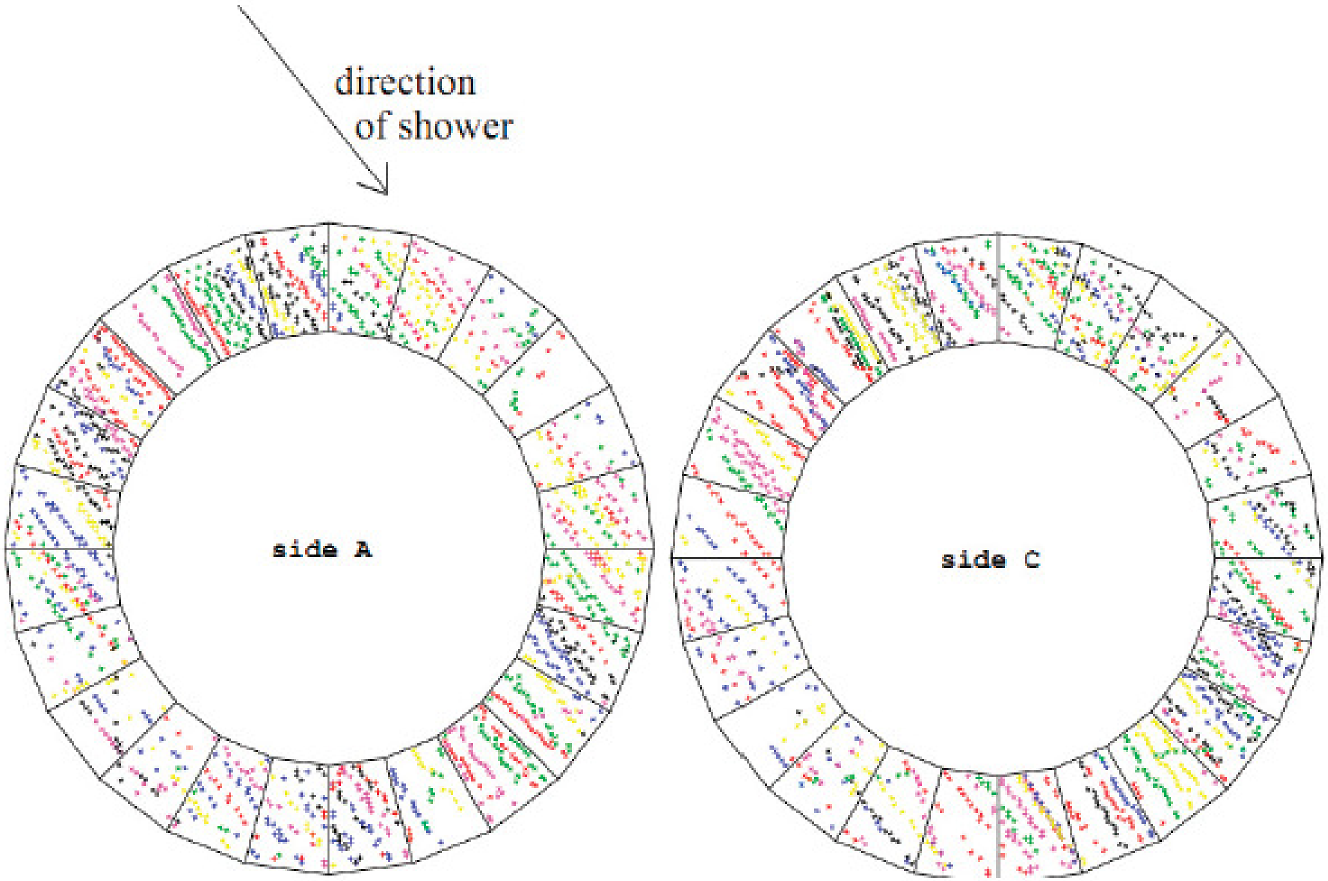


DELPHI as a cosmic ray detector

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

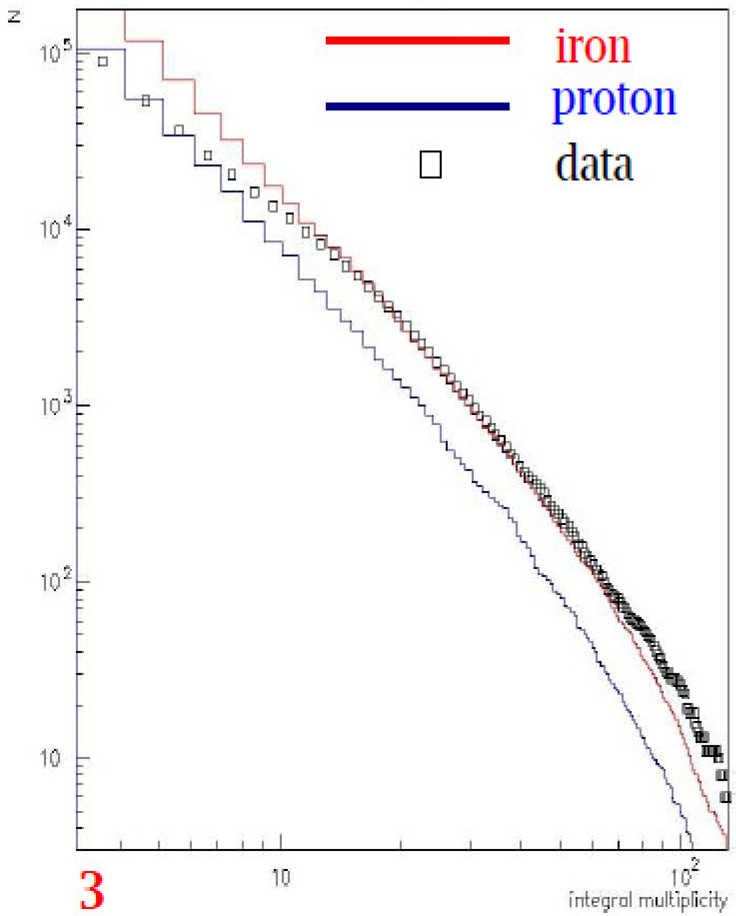
Bundles of parallel tracks in HCAL

- 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

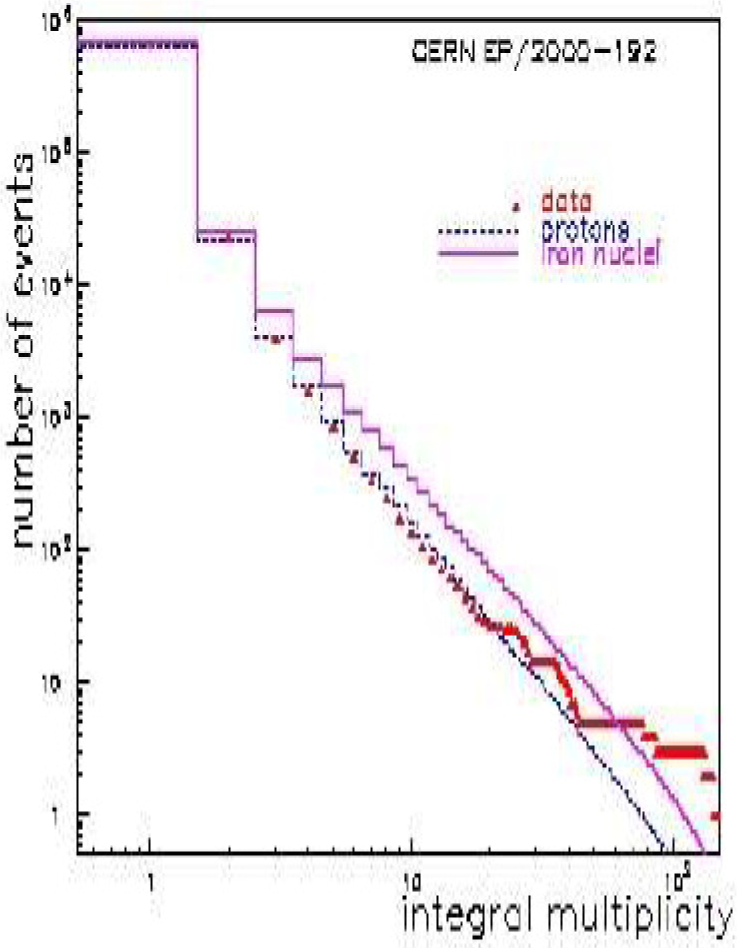


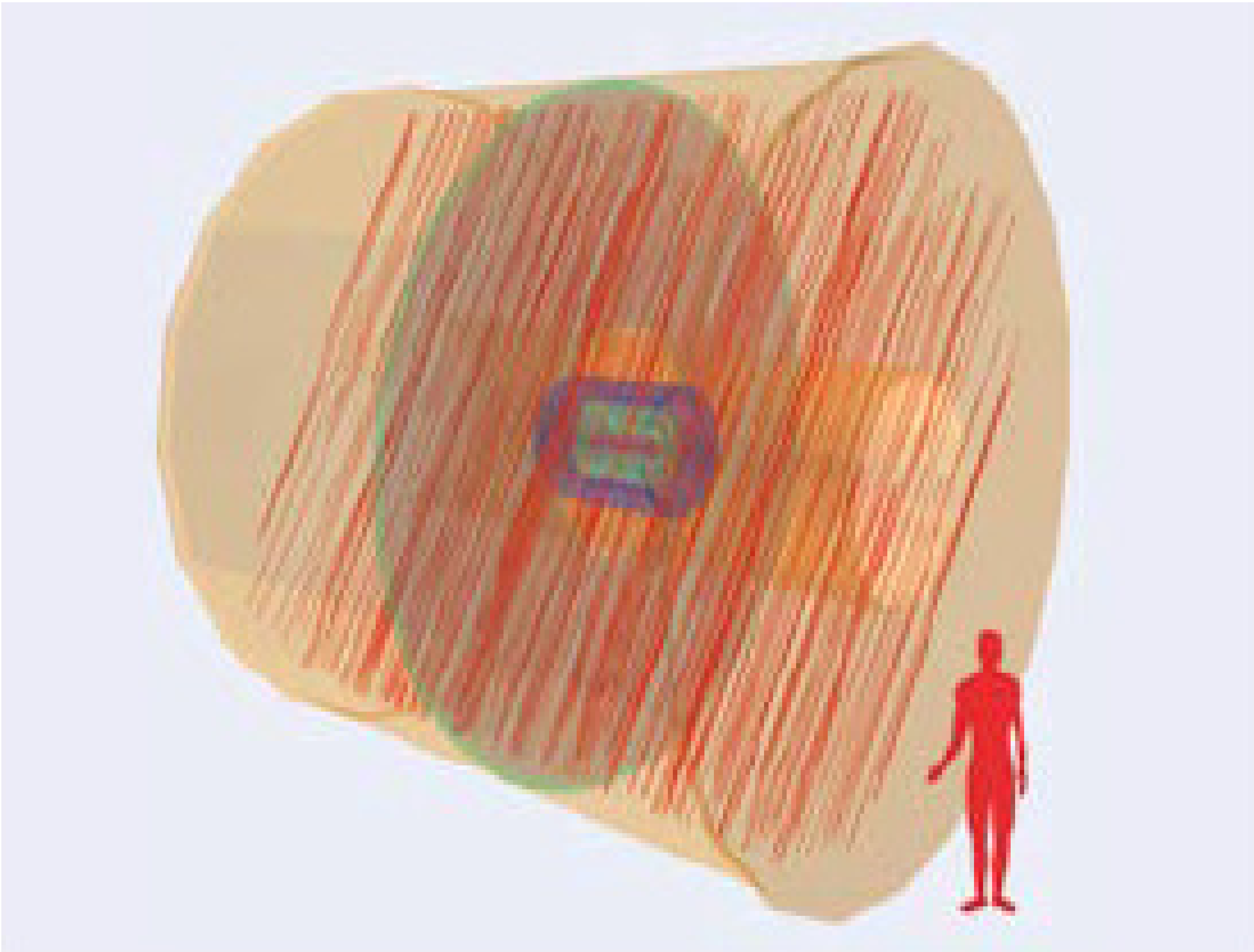
Results

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

ALICE
The ALICE collaboration
E-mail: ALICE-publications@cern.ch

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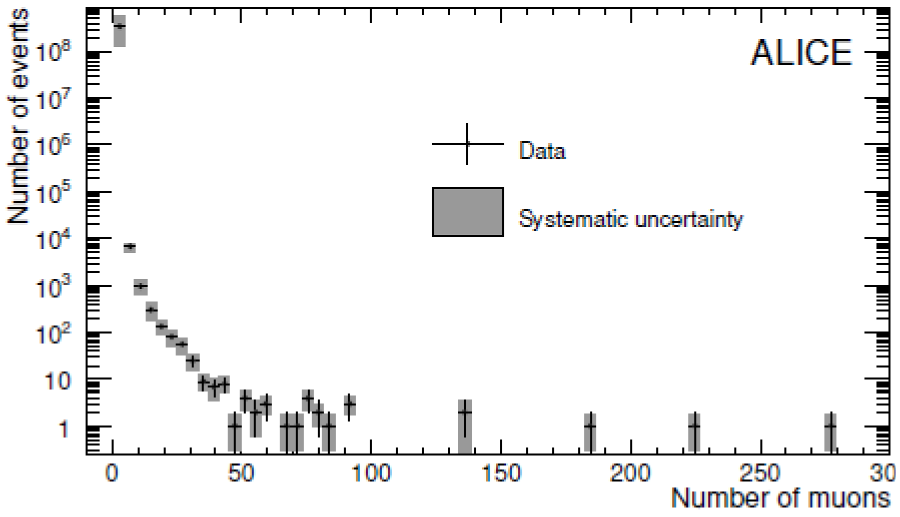
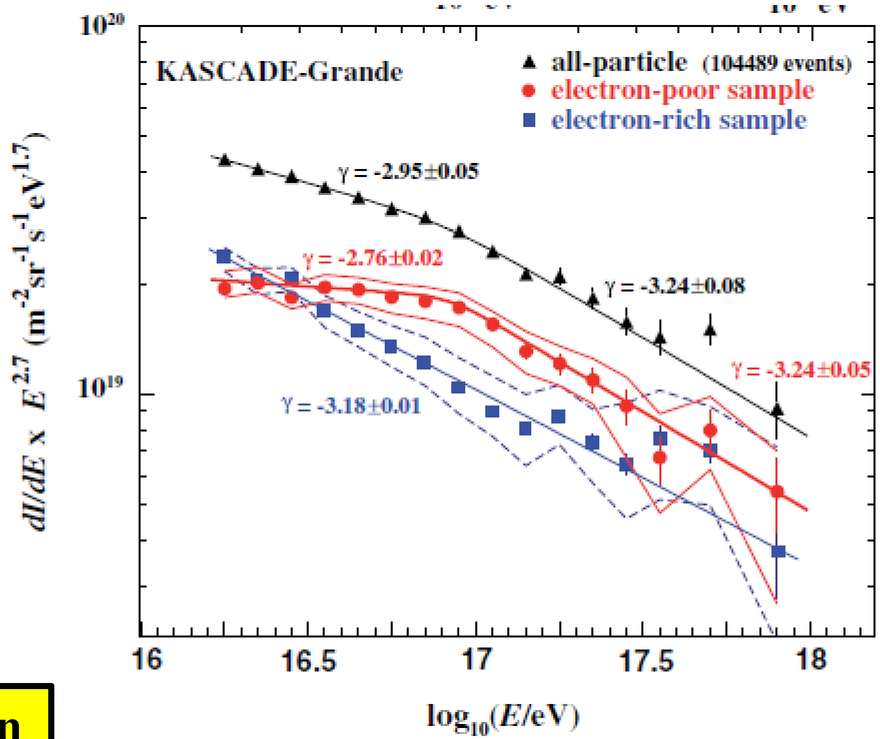
Published January 19, 2016

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)



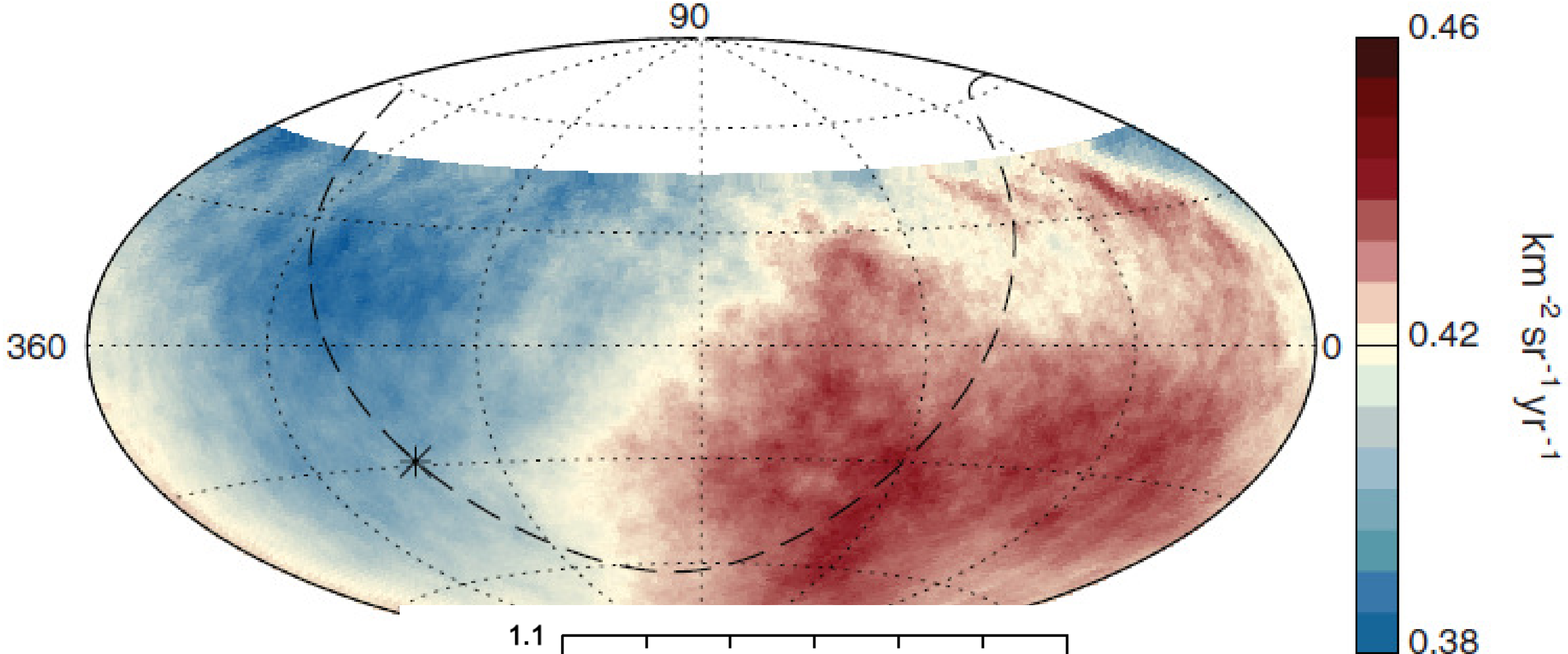
Conclusion in ALICE paper makes assumption about mass composition, in contradiction with cosmic ray data

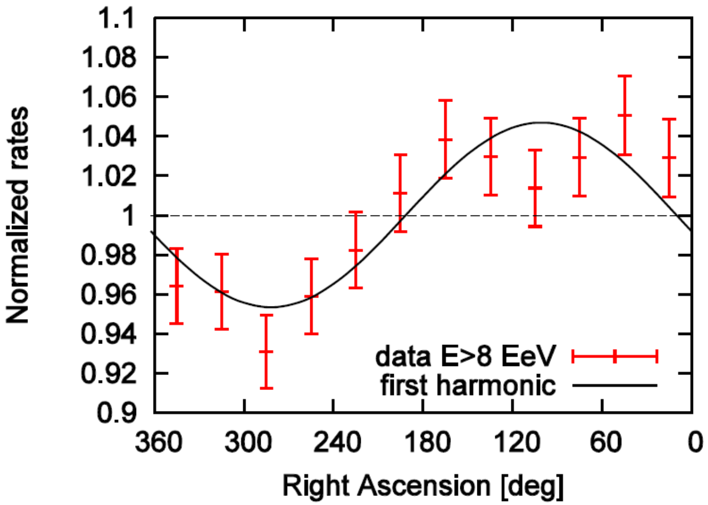
. 4 (color online). Reconstructed energy spectrum of the tron-poor and electron-rich components together with the particle spectrum for the angular range 0°–40°. The error

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.

UCAP

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





Significance ~ 5.2 sigma

Summary:

- **Energy spectrum shows two features:**

  Flattening at ~ 4 x 10^{18} eV

  Steepening at about 4 x 10^{18} eV

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

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

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

- **How does this vary with energy?**

- **Future plans to identify muons in other ways**

Back Up Slides