Universidad Nacional
de La Plata

CONICET

PIERRE AUGER OBSERVATORY

Tests of hadronic interactions using the Pierre Auger Observatory

Dr. Patricia Hansen for the Pierre Auger collaboration
IFLP (CCT La Plata-CONICET),
Dpto. de Física, Fac. de Cs. Exactas y
Dpto. de Cs. Básicas, Facultad de Ingeniería,
Universidad Nacional de La Plata.

ICHEP2018 SEOUL
JULY 4 - 11, 2018 COEX, SEOUL

high Energy

Comparison between data on UHECR-induced showers collected at the Pierre Auger Observatory and predictions from models of hadronic interactions based on LHC data for the following observables:

-The muon production depth.

Laura Collica for the Pierre Auger Collaboration, Eur. Phys. J. Plus (2016) 131: 301

The Pierre Auger Collaboration, Physical Review D 90, 012012 (2014)

-Mean number of muons in highly inclined air showers.

The Pierre Auger Collaboration, Physical Review D 91, 032003 (2015); ERRATA: Phys. Rev. D 91, 059901 (2015)

Other results of the Pierre Auger Observatory (that I will not present)

-The muon content of hybrid events (detected simultaneously with the fluorescence and surface detector) .

The Pierre Auger Collaboration, PRL 117, 192001 (2016)

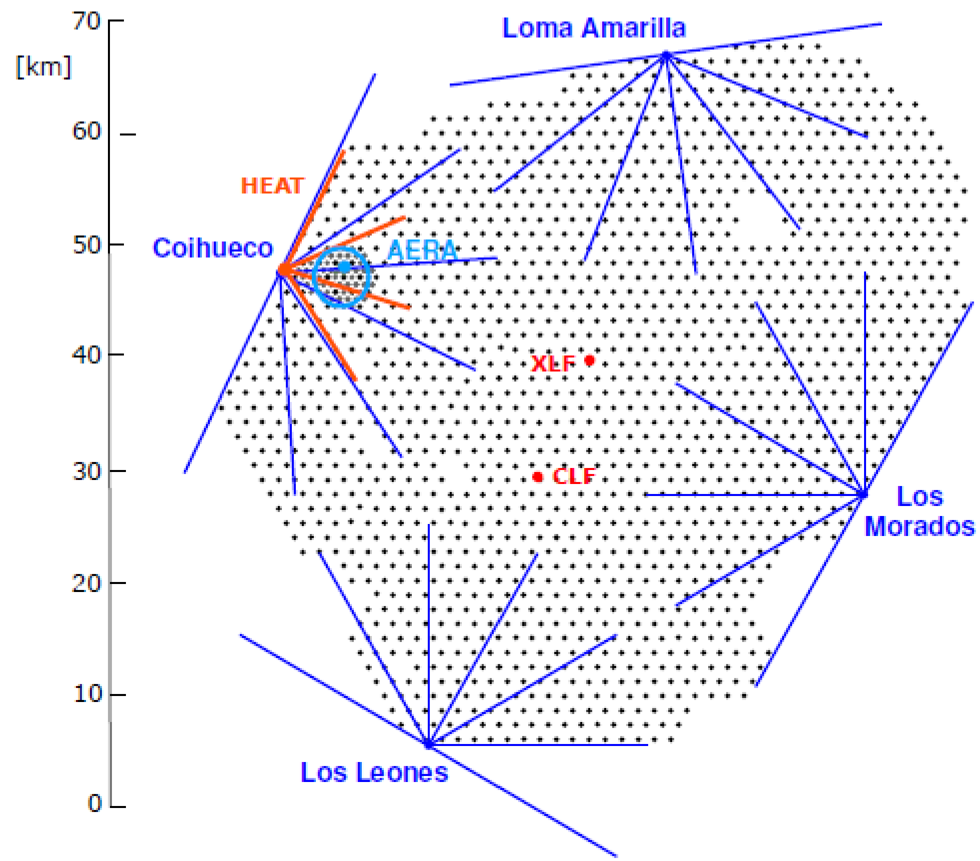
-The time profile of the signals recorded with the water cherenkov detectors.

The Pierre Auger Collaboration, Phys. Rev. D 96, 122003

-The azimutal asymetry in the rise time of signals in the Auger surface detector.

The Pierre Auger Collaboration, Phys. Rev. D 93, 072006 (2016)

The Pierre Auger Observatory: a hybrid detector of UHECR



Layout of the Pierre Auger Observatory.
Water-Cherenkov detectors are shown as black dots and the azimuthal field of view of the 27 fluorescence Telescopes are indicated by blue and red lines.

Fluorescence Telescopes

Surface detector array

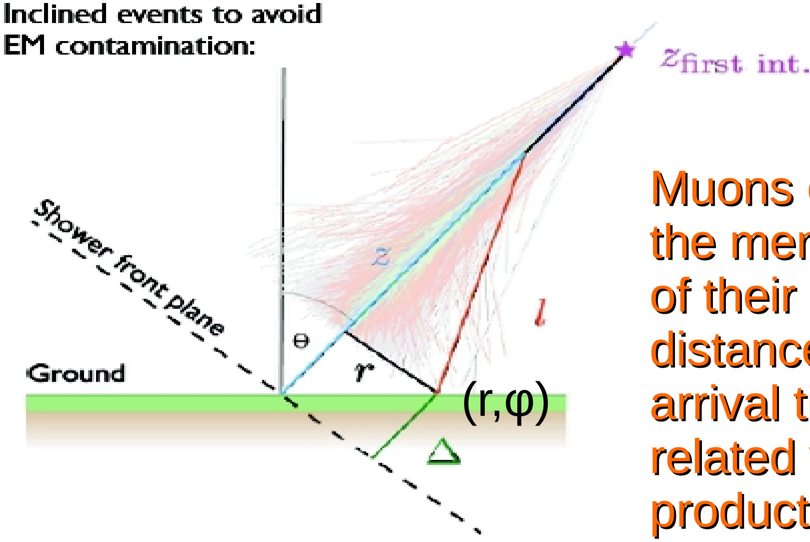
Muon production depths (MPD)

We present a method to estimate the muon production depth distribution by measuring the muon arrival times at the ground recorded with the Surface detector array of Auger.

The maximum of the MPD is called: $X^{*\mu}_{max}$

This parameter corresponds to the depth of maximum production of muons as the shower develops through the atmosphere.
It is an important observable for hadronic Interaction studies.

Inclined events to avoid EM contamination:



Muons can retain the memory of their production distance. Their arrival time can be related with their production distance.

Equation for the production height, z:

$$z = \frac{1}{2}\left(\frac{r^2}{ct_g} - ct_g\right) + \Delta$$

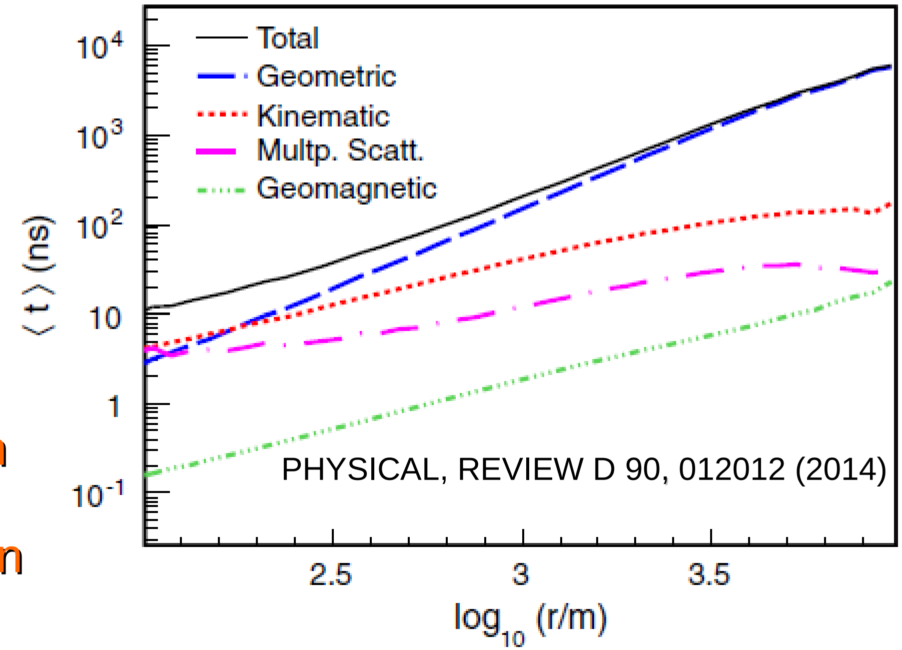


Figure. Average muons arrival time delays as a function of distance from the shower core for 10^{19} eV proton showers at 60^0 -

The total delay and its contributions are shown.

Geometric delay of arriving muons:

t_g: **is the time delay of muons with respect to the shower** ***front plane traveling at speed of light*.**

$$c \cdot t_g = l - (z - \Delta)$$
$$= \sqrt{r^2 + (z-\Delta)^2} - (z - \Delta)$$

$$t_g = t - \langle t_\epsilon \rangle$$

$$z = \frac{1}{2}\left[\frac{r^2}{c(t - \langle t_\epsilon \rangle)} - c(t - \langle t_\epsilon \rangle)\right] + \Delta - \langle z_\pi \rangle$$

The production distance for each muon in a shower can be related to the production depth X^{μ} (total amount of traversed matter)

using $X^{\mu}(z) = \int_{z}^{\infty} \rho(z')\,dz'$

where ρ is the atmospheric density.

PHYSICAL, REVIEW D 90, 012012 (2014)

Eur. Phys. J. Plus (2016) , 131: 301

The set of production depths forms the MPD distribution that describe the longitudinal development of the muons generated in an air shower.

For each event, the reconstructed MPD profile Is fitted to a Universal Shower Profile(USP) function.

$$\frac{1}{N}\frac{dN}{dX} = \left[1 + \frac{R}{L}\left(X - X^{\mu}_{max}\right)\right]^{R^{-2}} e^{\left(-\frac{X - X^{\mu}_{max}}{LR}\right)}$$

***X*:** slant depth.

There are four parameters:

***N*:** number of muons.

X^{μ}_{max}: point along the shower axis where the muon production reaches its maximum.

***L*:** represents the profile width.

***R*:** quantifies the deformation of the profile with respect to a Gaussian distribution.

The muon production depth reconstruction in a wide energy and angular range.

-Perform the analysis closer to the shower core such that enough muons are sampled
-Refine the tecnique to take into account the electromagnetic componet.

Distances from the core [1200 m, 4000 m]
Zenith angle [45^0, 65^0]
E > $10^{19.2}$ eV

Recontructed MPD distribution

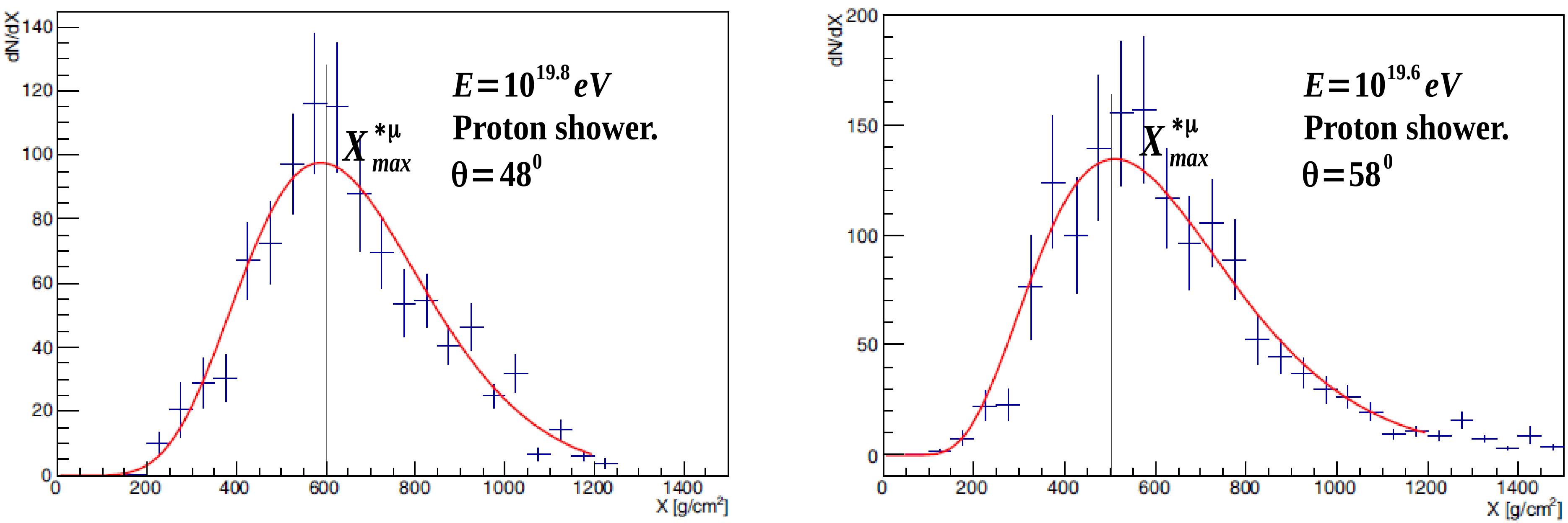


Figure. The reconstructed MPD distribution simulated using QGSjetII-04 model. The USP function fits are also shown.

Results

All events recorded by the SD of Pierre Auger between January 2004 and December 2016 have been used in this analysis.
Number of UHECR analyzed 2227
Data have been studied as a function of the primary energy with $\log_{10}(E/eV)$ between 19.2 and 20

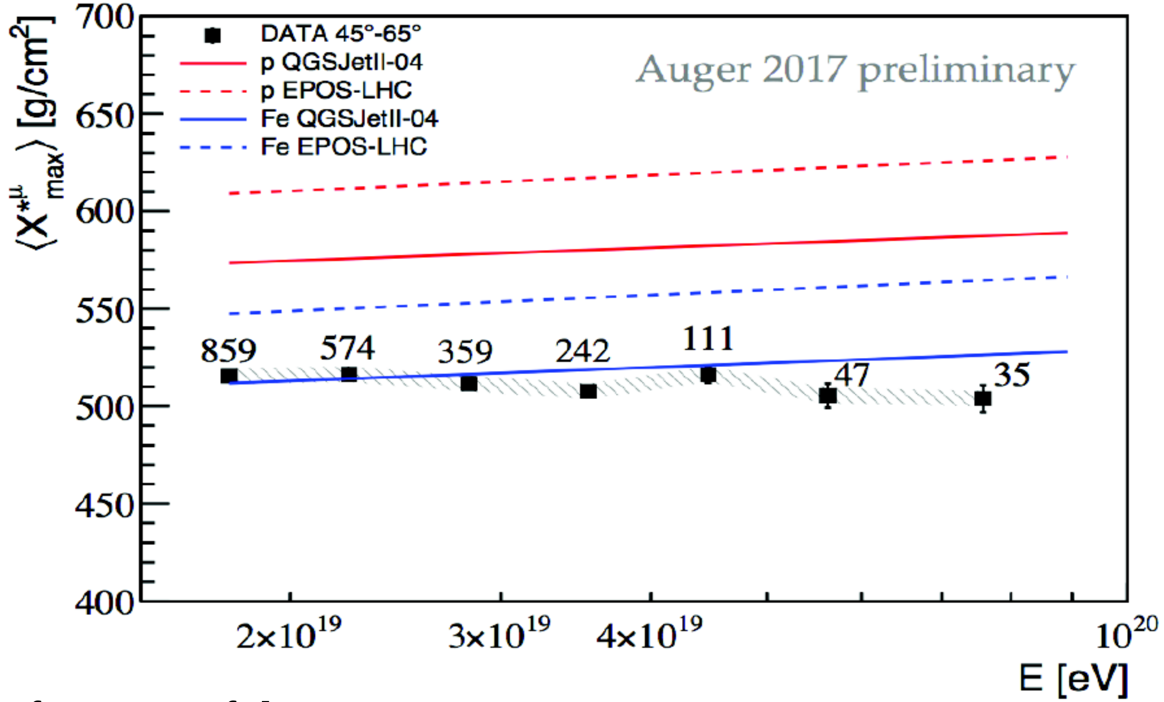


Figure. $<X^{*\mu}_{max}>$ as a function of the primary energy.
Data (black squares) are shown with statistical (black line) and sistematic uncertainties (gray band) and compared to simulations.

35th International Cosmic Ray Conference-ICRC2017

Muonic elongation rate

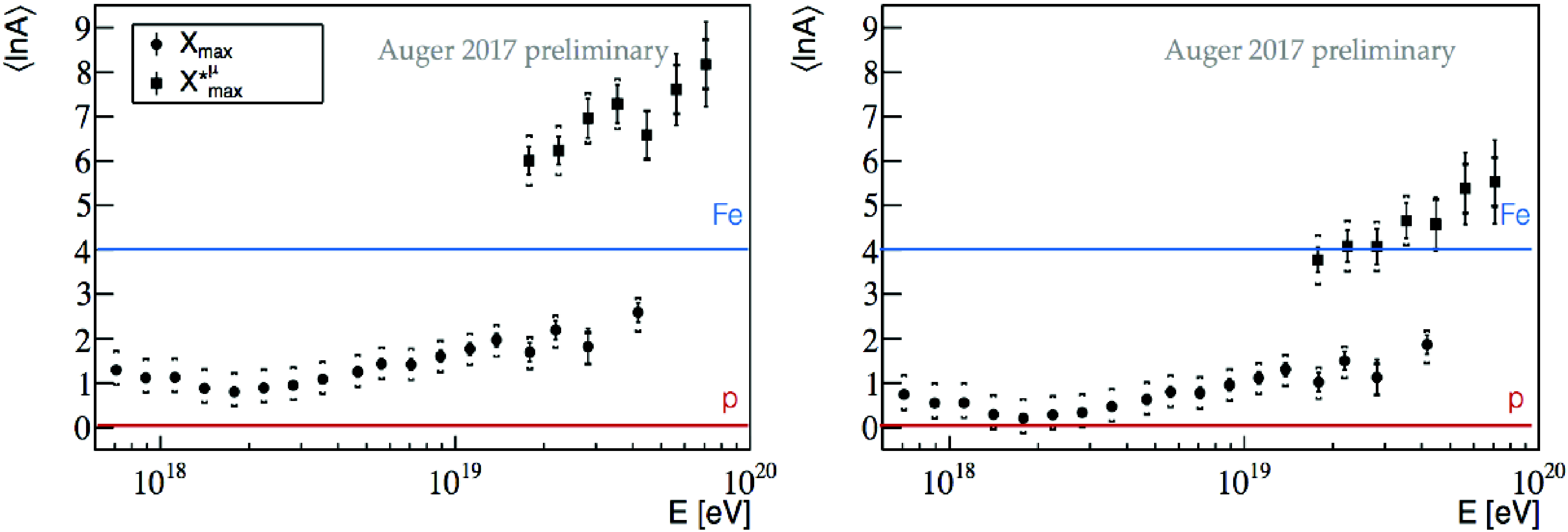
$$\frac{dX^{\mu}_{max}}{d\log_{10}E} \sim (25\, g/cm^2/decade) \quad \text{all models.}$$

$$\frac{dX^{\mu}_{max}}{d\log_{10}E} \sim (-16.9 \pm 7.2\, g/cm^2/decade)$$

No combination of hadronic interaction models and primaries (p-Fe) can explain the observed $<X^{*\mu}_{max}>$ obtained with Auger data.

$$\langle \ln A \rangle = \ln 56 \frac{\langle X^{*\mu}_{\max} \rangle_p - \langle X^{*\mu}_{\max} \rangle}{\langle X^{*\mu}_{\max} \rangle_p - \langle X^{*\mu}_{\max} \rangle_{Fe}}$$

$< X^{*\mu}_{max} >$ can be converted to a mean value of lnA with A the mass number of the primary UHECR.



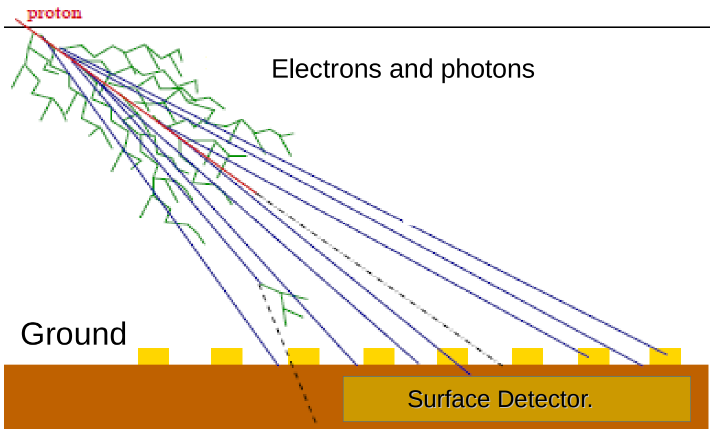
35th International Cosmic Ray Conference-ICRC2017

QGSJetII-04: Incompatibility at a level of at least 3.3 σ .
EPOS-LHC: Incompatibility at a level of at least 6 σ .

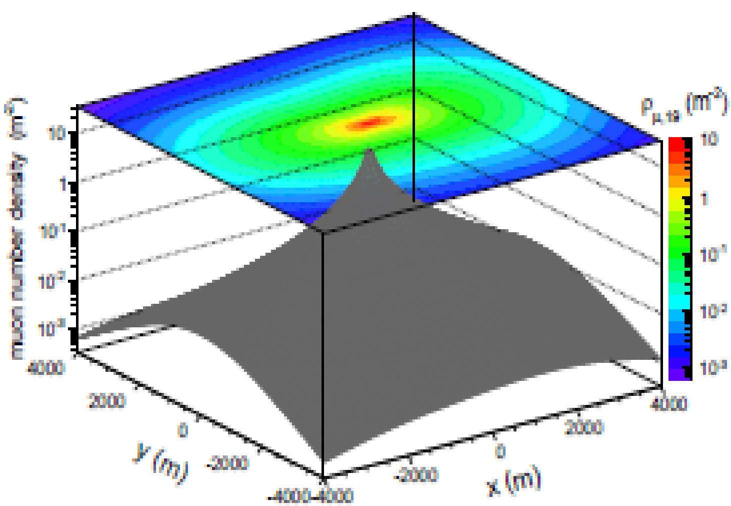
Figure. The evolution with energy of $< lnA >$ as obtained from the measured $< X^{*\mu}_{max} >$ (squares).
The results obtained for X_{max} (dots) are also shown.
(A. Aab et al. (Pierre Auger Collaboration), Phys. Rev. D 90 (2014) 122005)
EPOS-LHC (left) and QGSjetII-04 (right) are used as reference models.
Square brackets correspond to the sytematic uncertainties.

Mean number of muons in highly inclined events

PHYSICAL, REVIEW D 91, 032003 (2015)



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



-Muon number density in the coordinate plane perpendicular to the shower axis at ground level (transverse plane) for proton-induced showers of $10^{19} eV$ at $\theta = 80^0, \Phi = 0^0$ (parallel to x-axis) and core at (x,y) = (0,0).

N_{19}: scale factor which relates the observed muon densities at ground to the distribution used as a reference.

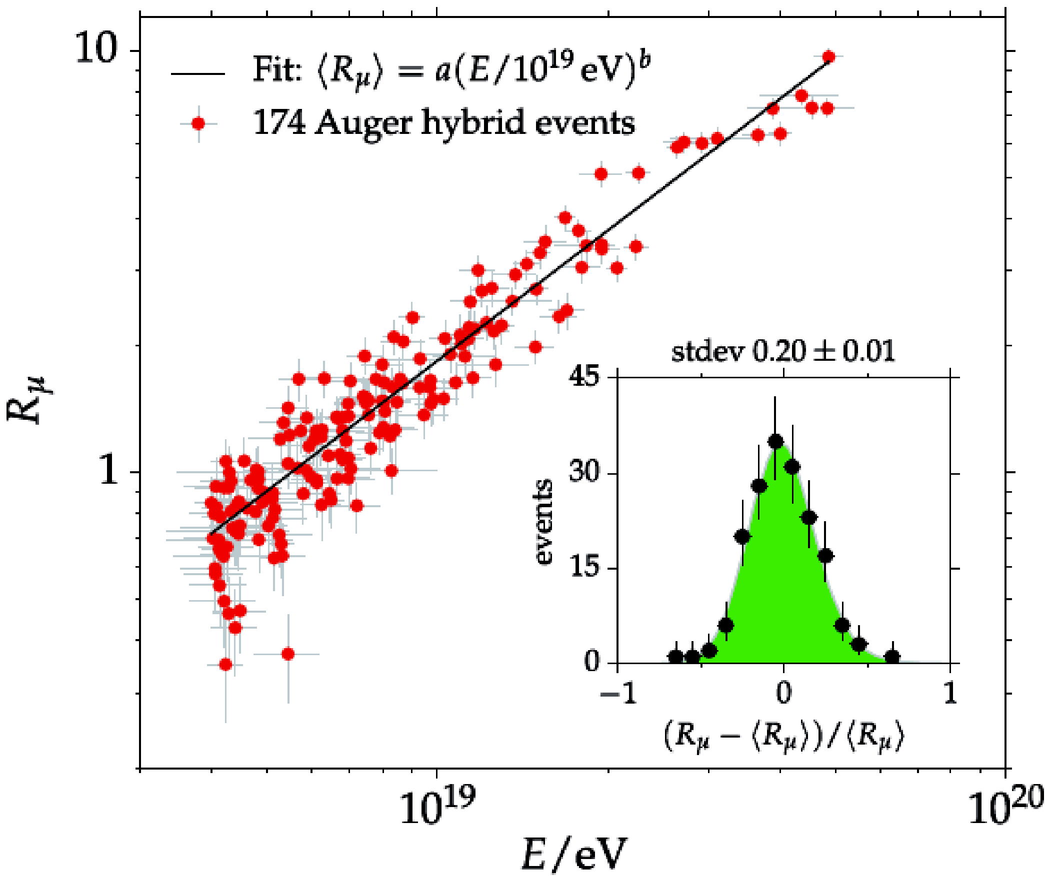
N_{19}:

-Substract the electromagnetic signal obtained by simulation (also detector response) to the measure sginal

-Fit with the reference distribution.

We define $\underline{R_\mu}$ (N_{19} with correction smaller than 5%)

Unbiased estimator of the total number of muons at ground.



Figure

The selected hybrid events above $4\,x\,10^{18}\,eV$ and a fit of the power law:

$$<R_\mu>=a\left(\frac{E}{10^{19}\,eV}\right)^b.$$

The error bars indicate statistical detection uncertainties only.
The inset shows a histogram of the residulas around the fitted curve (black dots) and for comparison the expected residual distribution computed from the fitted probablity model that describes the fluctuations.

Data sets:

Events recorded from 1 January 2004 - 1 January 2013

$E>4\,x\,10^{18}\,eV$ - Golden events. ($62^0 <$ zenith $< 80^0$).

Out of 29722 hybrid events 174 events are acepted.

$<$zenith$>=(66.9\pm0.3)^0$

$$<R_\mu>=a\left(E/10^{19}\,eV\right)^b$$

$$a=<R_\mu>\left(10^{19}\,eV\right)=\left(1.841\pm0.029\pm0.324\,(sys)\right)$$

$$b=d<\ln R_\mu>/d\ln E=\left(1.029\pm0.024\pm0.033\,(sys)\right).$$

From data:

$\theta=67^0$(average zenith angle of the data).

$E=10^{19}\,eV - R_\mu=1.84$

From simulation:

CORSIKA with QGSjetII-03 and FLUKA interaction models

$\theta=67^0$(average zenith angle of the data).

$E=10^{19}\,eV - R_\mu=1$

QGSjetII-03 underpredicts the number of muons at $10^{19}\,eV$ by a factor 1.8

Comparison data vs simulation

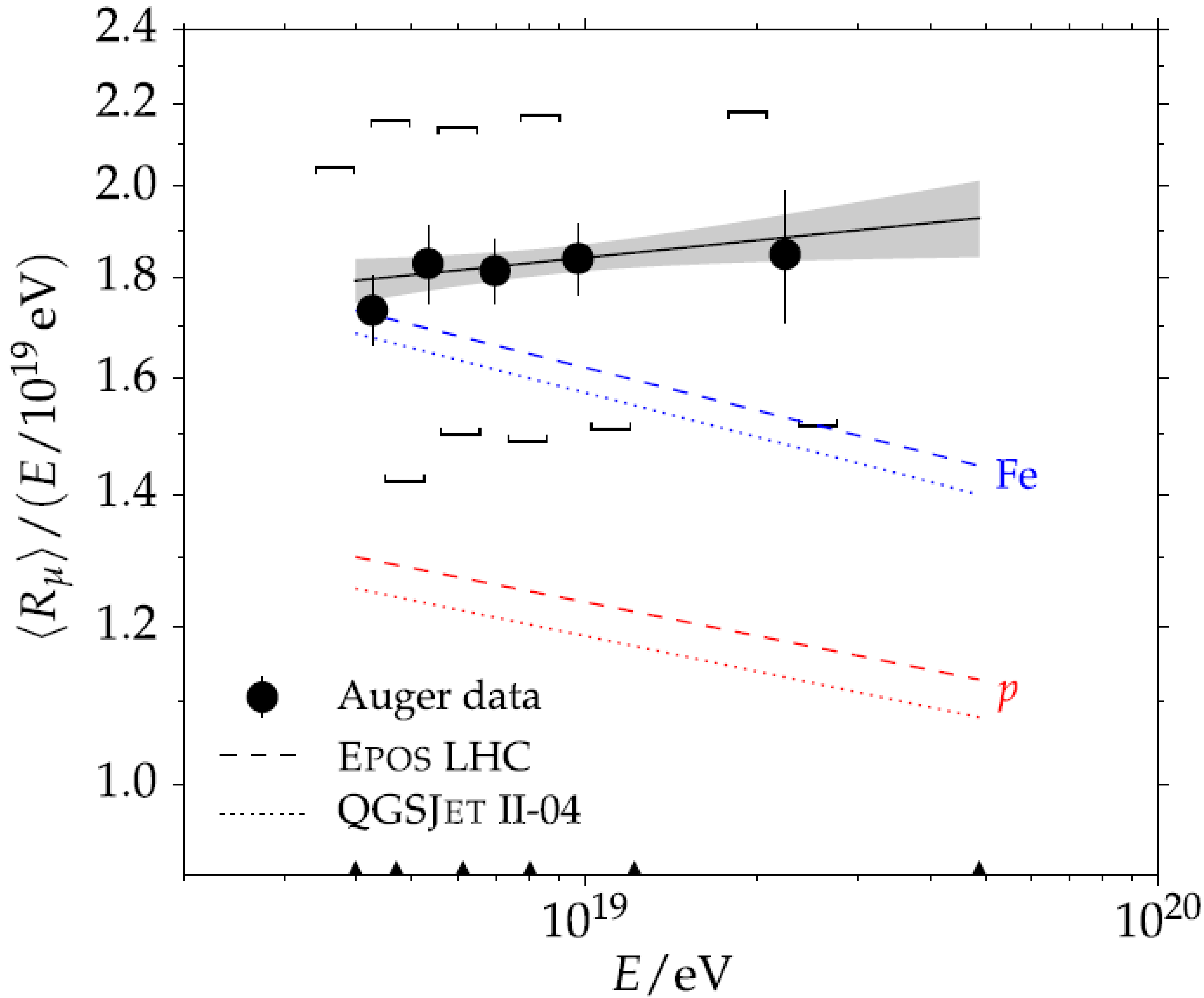


Figure. Average muon content $< R_\mu >$ per shower energy E as a function of the shower energy E in double logarithmic scale. Our data is shown bin by bin (circles) together with the fit showed in the previous slide (line). Square brackets indicate the systematic uncertainty of the measurement; the diagonal offsets represent the¿ correlated effect of systematic shifts in the energy scale.

The grey band indicates the statistical uncertainty of the fitted line.

Shown for coparison are theoretical curves for proton and iron showers simulated at $\theta = 67^0$ (dotted and dashed lines).

Conclusion

Auger is indeed contributing to hadronic physics at ultra high energy.
We compare differents observables obtained by Pierre Auger Observatory with prediction from models of hadronic interaction based on LHC data.
No current model is capable of describing the full range of data from the Pierre Auger Observatory, thus highlighting deficiencies in extrapolation beyond LHC energies.

-The muon production depth:

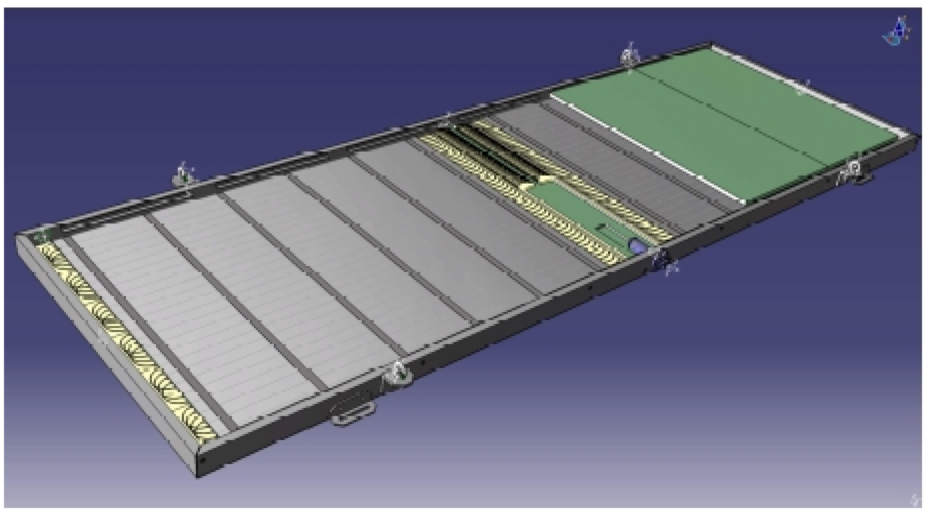
EPOS-LHC vs data: inconsistency with preditcions for all reasonable primary mass (p/Fe), in the whole energy range.
QGSjetII-04 vs data: consitency with iron expectation but not at the highest energies.
The prediction of the two hadronic models are significantly diferent in absolute value (~35g/cm^2)
The muonic elongation rate is predicted to be about ~25g/cm^2 /decade, independently of the primary mass and hadronic models, while on data we found ~16.9±7.2 g/cm^2 /decade.

-Mean number of muons in highly inclined events:

We observe a muon deficit in simulation of 30 to 80% at 10^{19} eV, depending on the model and primary particle (p/Fe).

Upgrade of the Pierre Auger Observatory: “Auger Prime”

Main goal: measure the muonic and electromagnetic components separately.
Improve determination of primary mass and further constrain hadronic Interaction models.



Layout of the Surface Scintillator Detector (SSD).

One station of the AugerPrime.