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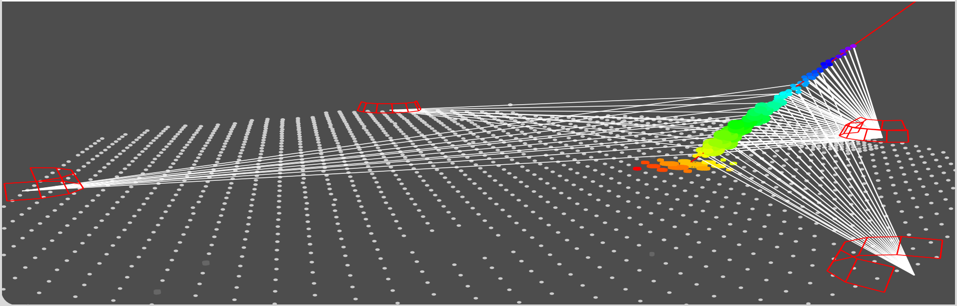
Mass composition studies with Pierre Auger Observatory

Alessio Porcelli for the Pierre Auger Collaboration | August 27th, 2013

PIERRE AUGER OBSERVATORY

INSTITUT FÜR KERNPHYSIK (IKP)



Scientific case

Experimental results:

- Energy spectrum
- Anisotropies in the distribution of their arrival directions
- Mass of the primary particles
- Hadronic interactions

ALL images and results, if not differently specified, are from ICRC13 Auger Collaboration's talks.

Scientific case

Experimental results:

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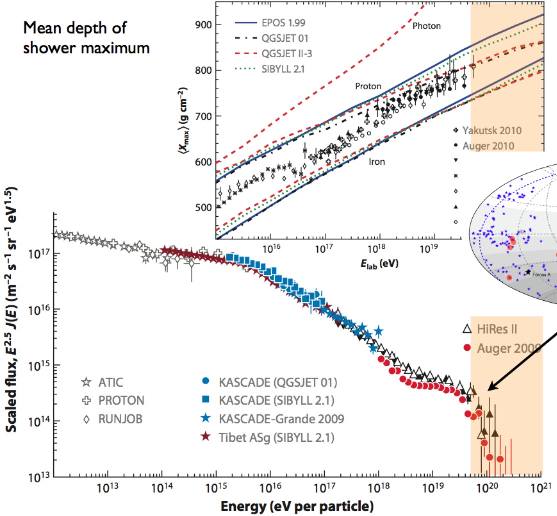
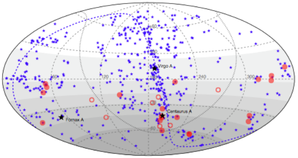
Why measure composition?

Some important features: source, flux suppression, ankle explanation, . . .



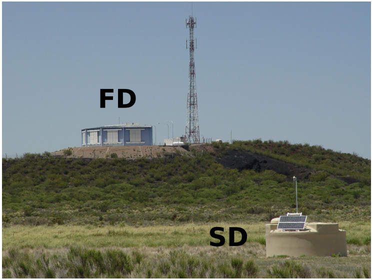


Auger: Correlation with sources / source regions?

(RE, Heck & Pierog, Ann. Rev. Nucl. Part. Sci. 61, 2011)

Measuring the mass of the primaries...

Fluorescence Detectors (FD) | Surface array Detectors (SD)

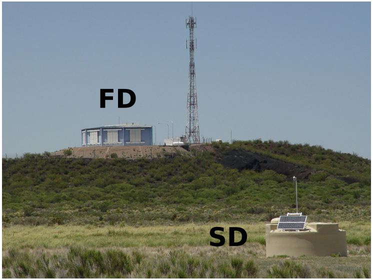


Observable used:

- X_{max}: measured through the data reconstruction using hybrid events (FD and SD data combined)
- X^{μ}_{max}: reconstructed through the Muon Production Depth method (MPD)

Measuring the mass of the primaries...

Fluorescence Detectors (FD) | Surface array Detectors (SD)



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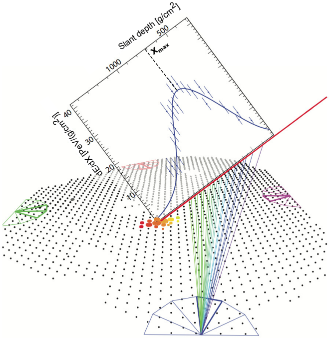
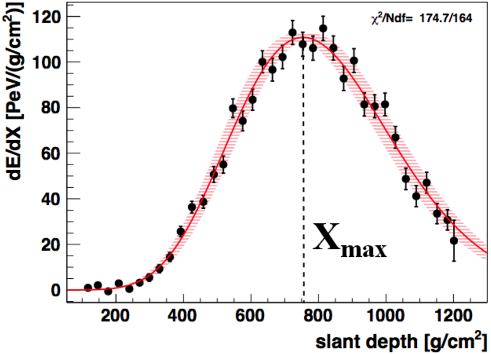
Hybrid reconstruction





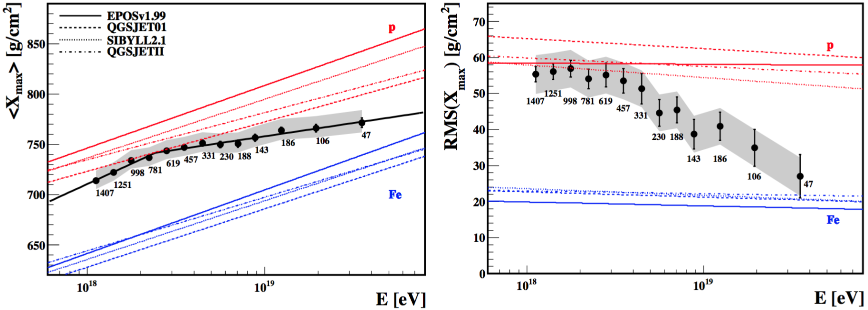
Through fluorescence light, the profile of the longitudinal shower development can measured.

Combining with the SD triggered stations, a high quality fit can be done.

The profile maximum is the X_{max}

Remind: 2011 results

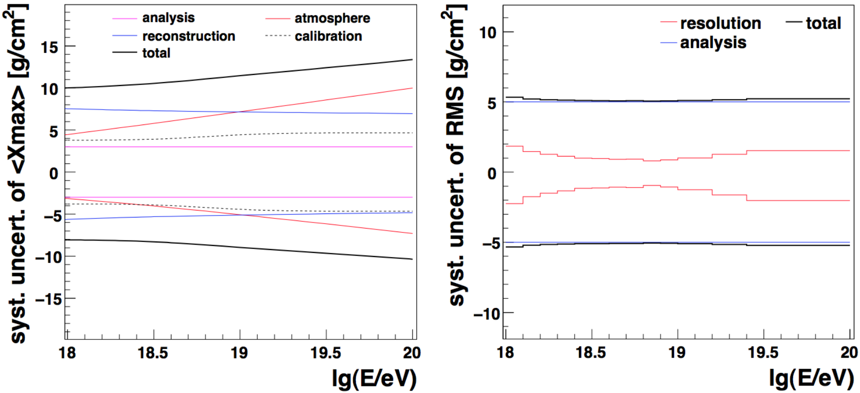
$\langle X_{\max} \rangle$ and $\sigma(X_{\max})$:
compared with hadronic interaction models



(black solid line is the **Elongation Rate**: $\mathrm{d}\langle X_{\max} \rangle / \mathrm{d}\log_{10}(E)$)

Remind: 2011 results

$\langle X_{\max} \rangle$ and $\sigma(X_{\max})$: study of their systematics



$$\text{Systs}_{\langle X_{\max} \rangle} = \text{analysis} \oplus \text{reconstruction} \oplus \text{calibration} \oplus \text{atmosphere}$$

$$\text{Systs}_{\sigma(X_{\max})} = \text{analysis} \oplus \text{resolution}$$

ICRC13 results - Update summary

Update on reconstruction:

- Extended the data period to 31/12/2012
- Lower energy threshold: $10^{17.8}$ eV
- Improved reconstruction
- Updated energy scale

Update of statistics:

- 19872 events selected
- New binning at high energy thanks to more statistics available
- 38 events above $10^{19.5}$ eV

Update of hadronic interaction models:

- LHC-retuning

$\langle X_{max} \rangle$ and $\sigma(X_{max})$

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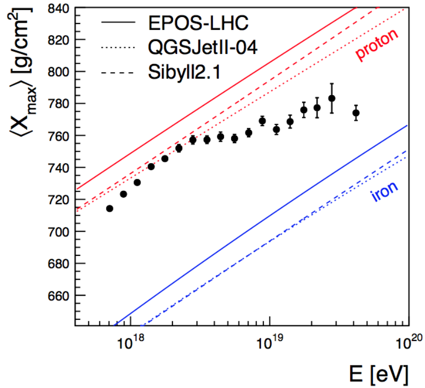
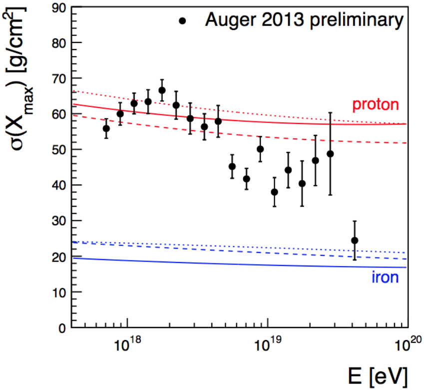
Preliminary results!





Models of hadronic interaction taken into account to interpret the results: **Epos-LHC** (solid), **QGSJETII** (dotted) and **Sibyll** (dashed)

Update in details

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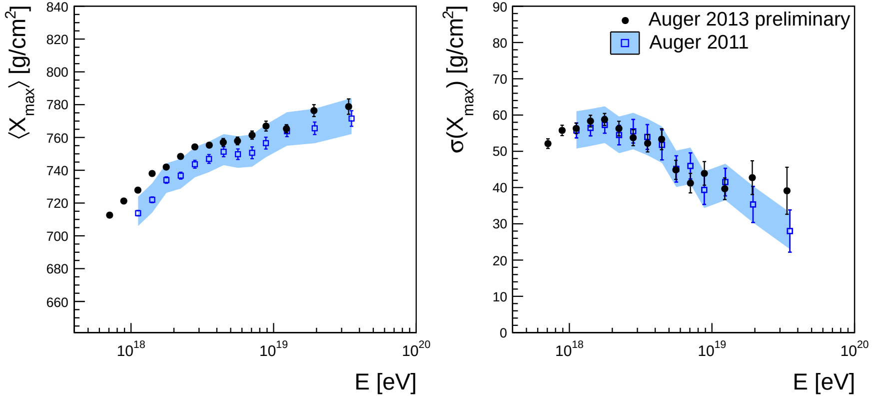
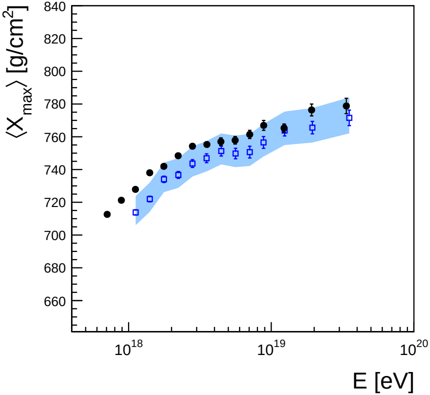
New reconstruction and calibration

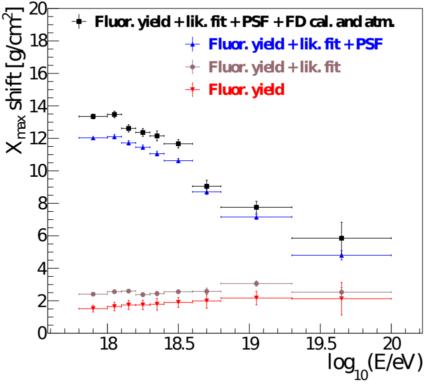


$\Delta X_{\rm max} \sim 10\ {\rm g/cm^2}$ at low energies of systematics

Update in details

New reconstruction and calibration



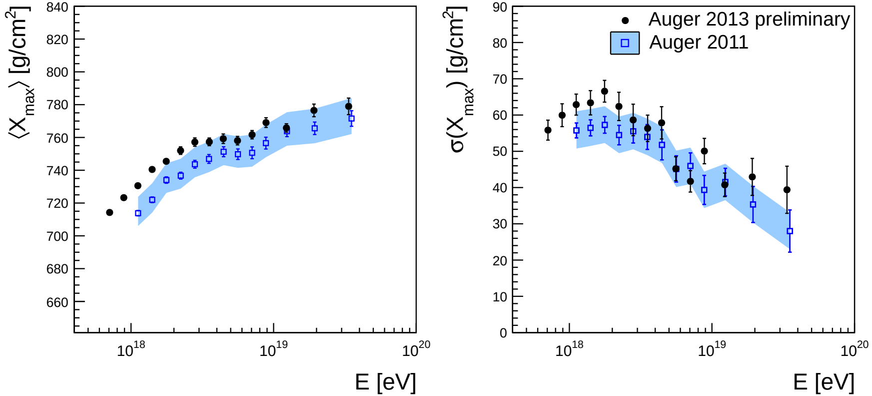


$\Delta X_{\rm max} \sim 10\ {\rm g/cm^2}$ at low energies of systematics

($\sim$ by convolution of Point Spread Function with lateral shower width)

Update in details

$X_{\rm max}$ acceptance correction (after the data selection)



Systematics correction to $X_{\rm max}$-moments, $\mathcal{O}(5\,\mathrm{g/cm^2})$

Update in details

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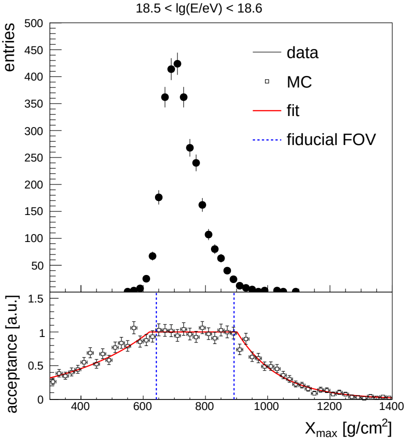
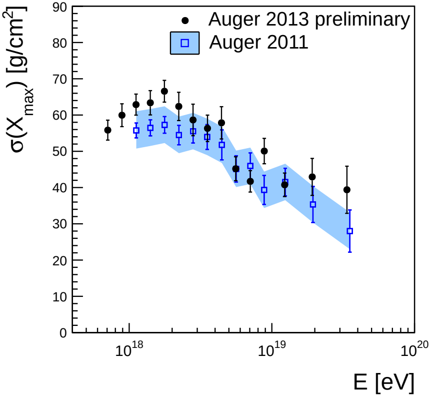
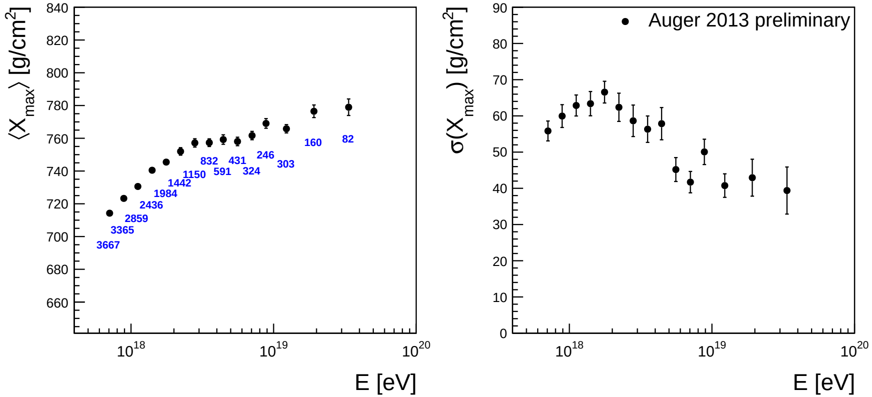




Systematics correction to $X_{\max}$-moments, $\mathcal{O}(5\,\mathrm{g/cm^2})$
(properly weighted the deep and shallow showers with lower acceptance)

Update in details

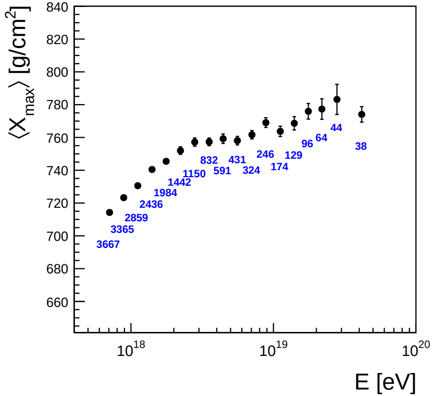
ICRC13 old binning

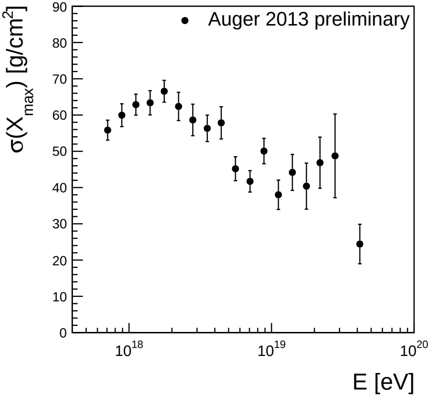


Enough statistics for new binning at high energies

Update in details

ICRC13 new binning





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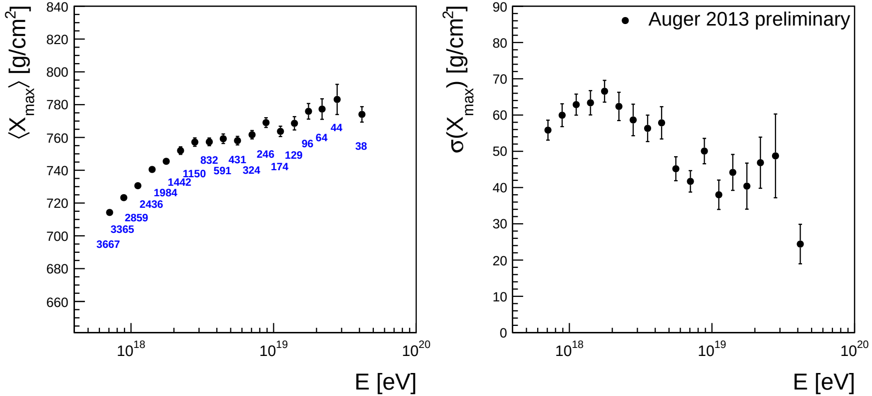

Enough statistics for new binning at high energies
(a complete studies about the systematics will be available soon)

X_{max} and the mass composition

Proportionality between the moments of experimental observable (X_{max}) and the moments of the mass distribution ($\ln A$):

$$\langle X_{\mathrm{max}} \rangle = \langle X^p_{\mathrm{max}} \rangle - D_p \langle \ln A \rangle \qquad \sigma^2(X_{\mathrm{max}}) = \langle \sigma_i^2 \rangle + D_p^2 \sigma^2 (\ln A)$$

given:

D_p: elongation rate $(\mathrm{d}\langle X_{\mathrm{max}} \rangle / \mathrm{d} \log_{10}(E))$ - from data

$\langle X^p_{\mathrm{max}} \rangle$: average depth of protons - from proton simulation

$\langle \sigma_i^2 \rangle$: mass-averaged shower fluctuations - from simulations

X_{max} Interpretation: model of hadronic interaction are needed.

The moments of the mass distribution are:

- $\langle \ln \mathrm{A} \rangle = \sum \mathrm{f_i} \ln \mathrm{A_i}$

  e.g. pure $p \rightarrow \langle \ln A \rangle = 0$, pure $Fe \rightarrow \langle \ln A \rangle \approx 4$, $50:50\ p/Fe \rightarrow \langle \ln A \rangle \approx 2$
- $\sigma^2(\ln \mathrm{A}) = \langle \ln^2 \mathrm{A} \rangle - \langle \ln \mathrm{A} \rangle^2$

  e.g. pure $p/Fe \rightarrow \sigma^2(\ln A) = 0$, $50:50\ p/Fe \rightarrow \sigma^2(\ln A) \approx 4$

X_{max} to ln A

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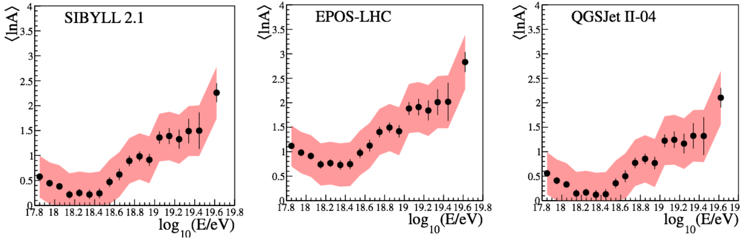
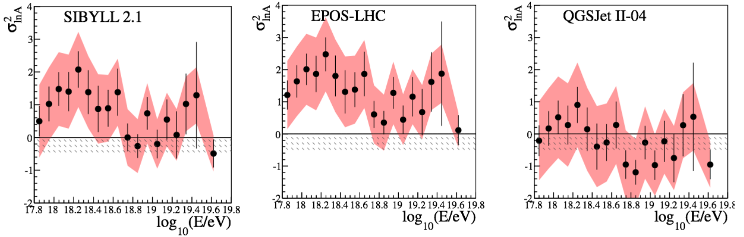
ln A



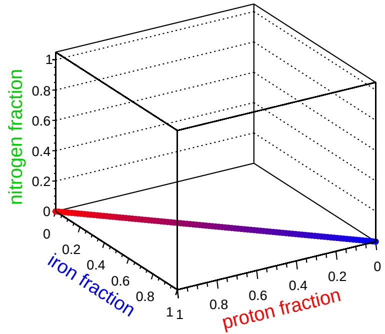
$\sigma^2(\ln A)$

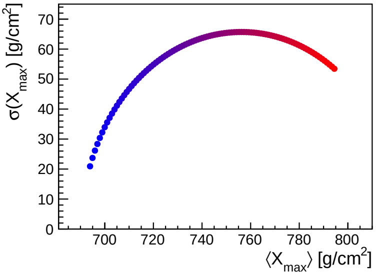


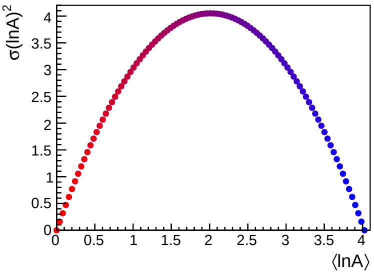
Interpret results: ln A vs σ^2(ln A) meaning

transition:

- p → Fe



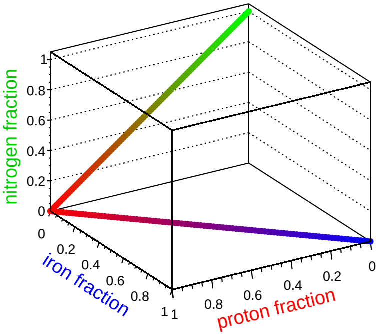


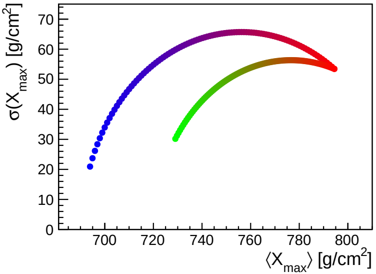


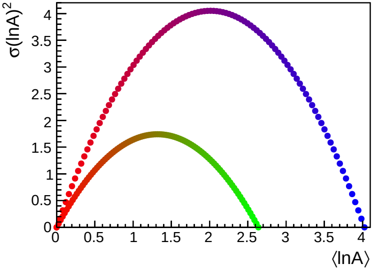
Interpret results: ln A vs $\sigma^2(\ln A)$ meaning

transition:

- p → Fe
- p → N



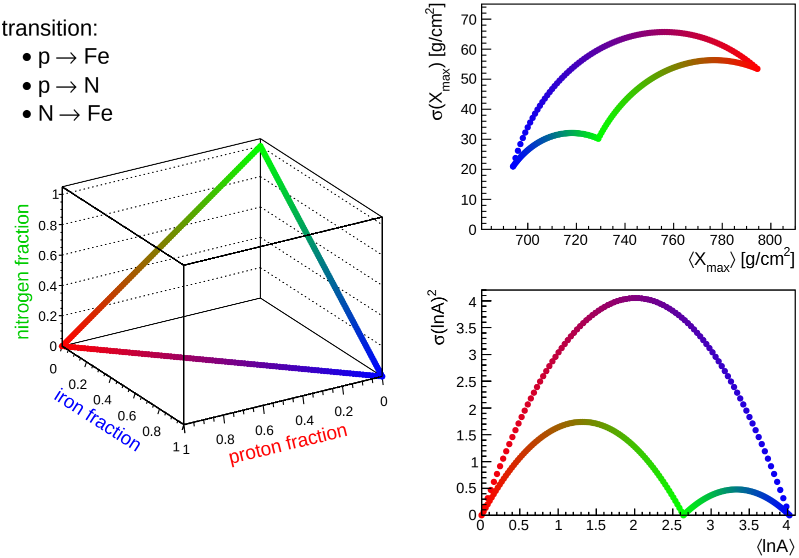




Interpret results: $\ln A$ vs $\sigma^2(\ln A)$ meaning

transition:

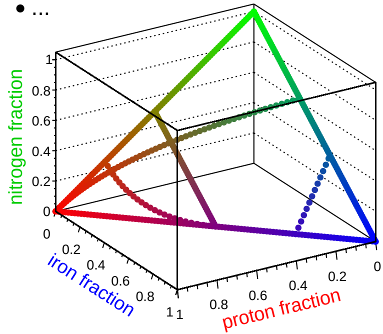
- p → Fe
- p → N
- N → Fe

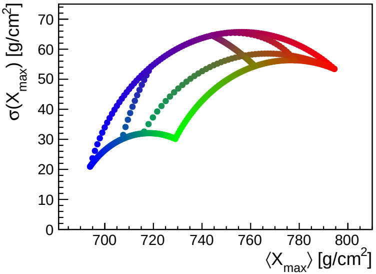


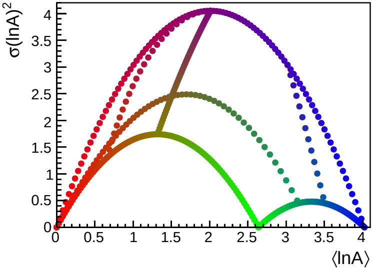
Interpret results: ln A vs $\sigma^2(\ln A)$ meaning

transition:

- p $\rightarrow$ Fe
- p $\rightarrow$ N
- N $\rightarrow$ Fe
- ...



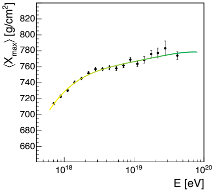


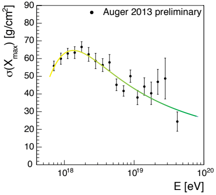


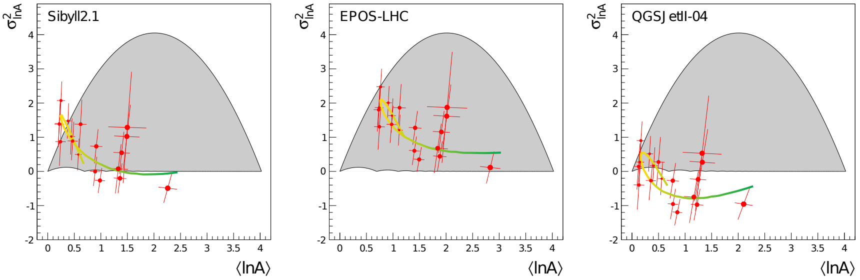
Interpret results: $\ln A$ vs $\sigma^2(\ln A)$ applied

trajectory of data in $\langle \ln A \rangle - \sigma^2(\ln A)$ plane (Dot size $\propto$ energy)

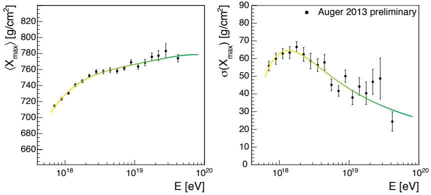
+ shifting by the systematics







Interpret results: ln A vs $\sigma^2(\ln A)$ applied



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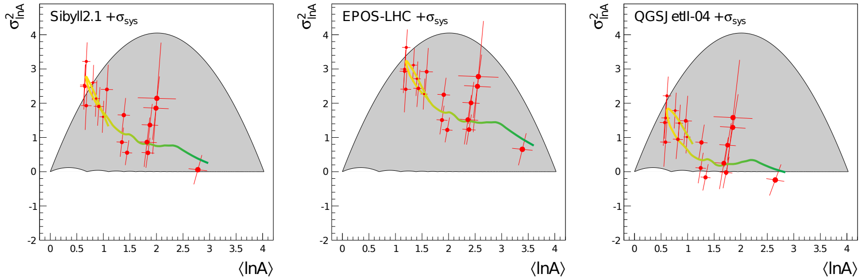
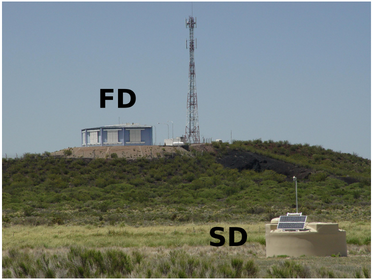


All models are compatible with a mixed composition within systematics

Measuring the mass of the primaries...

Fluorescence Detectors (FD) Surface array Detectors (SD)

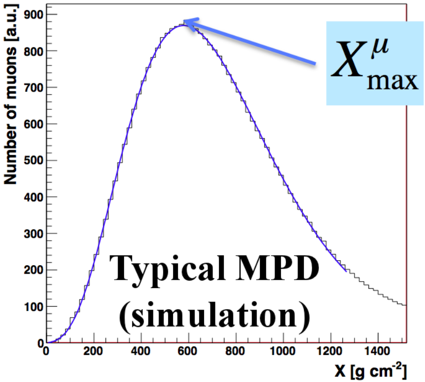


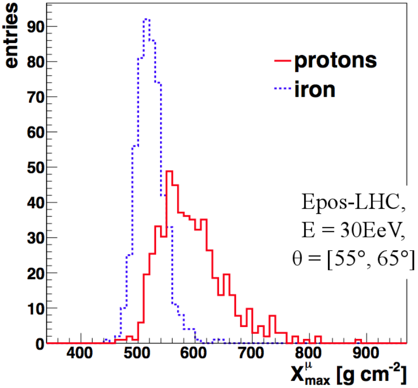
Observable used:

- $X_{\max}$: measured through the data reconstruction using hybrid events (FD and SD data combined)
- $X^{\mu}_{\max}$: reconstructed through the Muon Production Depth method (MPD)

Muon Production Depths method (MPD)

Muons at the ground carry information about their production point: reconstruct their production distribution along the shower axis



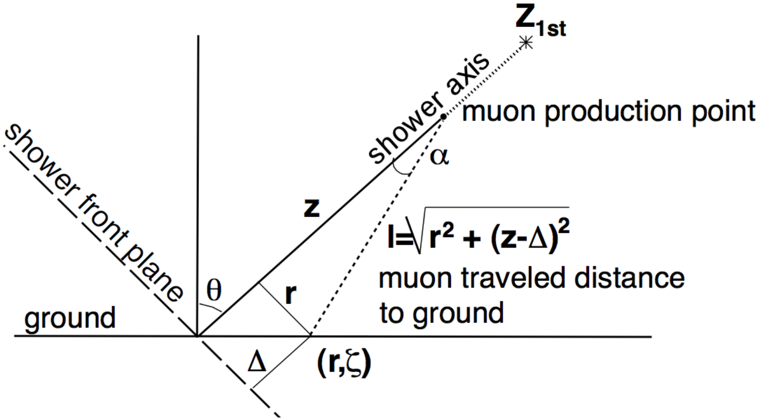


The maximum of this distribution is the observable X^{μ}_{max}

(Similar correlation to ln A as X_{max} do)

MPD estimation: geometry delay

μ are produced along the shower and follows straight lines

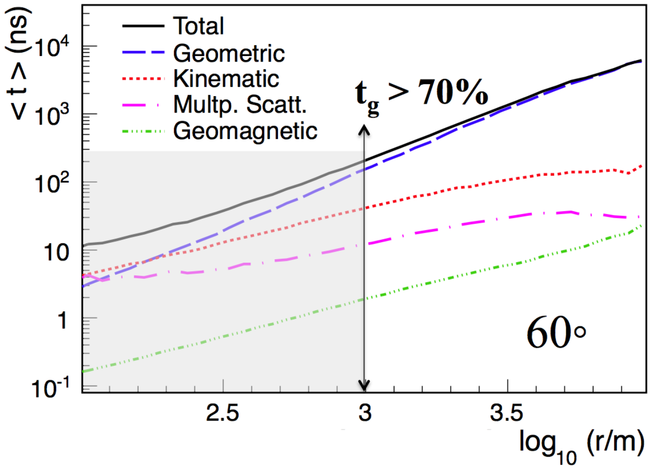


Geometrical delay:

$$ct_g = l - (z - \Delta) = \sqrt{r^2 + (x - \Delta)} - (z - \Delta)$$

MPD estimation: total delay

measured delay $t = t_g + t_\varepsilon + t_{\mathrm{multp.scatt.}} + t_{geomag}$

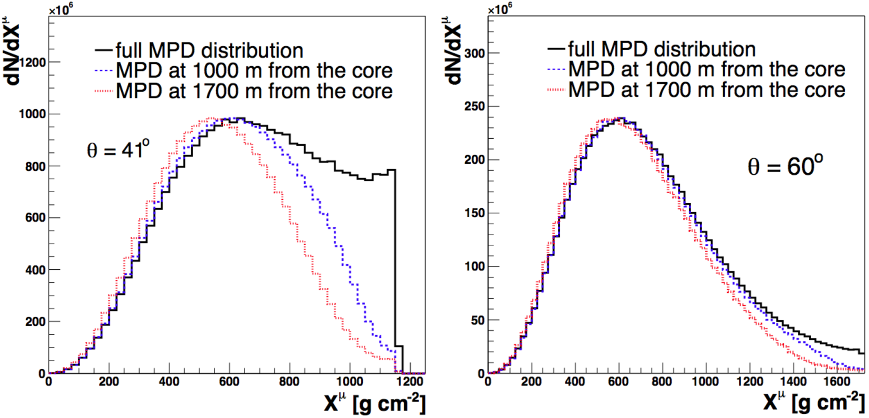


$$t_g \simeq t - \langle t_\varepsilon \rangle$$

MPD estimation: shower geometry

Decay probability shape of MPD distribution at the ground

(an electromagnetic component is also present at the ground)



There is a zenith angle and core distance dependence!

60^{o} is a good candidate!

Analysis criteria

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Selection of the data:

- Inclined event:
  - $[55^{\circ}, 65^{\circ}]$ as fixed zenith angle to avoid dependency to that
  - avoid electromagnetic contamination
- Surface detectors far from the core:
  - Optimization to reduce the systematics given by the time delay of the muon arrival to the detectors
  - Shower energies $>$ 20 EeV to have enough station far from the core

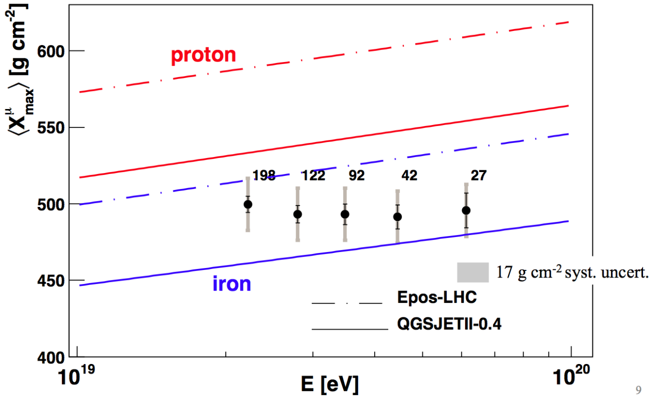
Analyzed data:

Data set: 1 January 2004 $\div$ 31 December 2012

Event left after selection: 481

MPD results: $\langle X^{\mu}_{max} \rangle$

Models of hadronic interaction taken into account to interpret the results:
Epos-LHC (dot-dashed) and **QGSJETII** (solid)



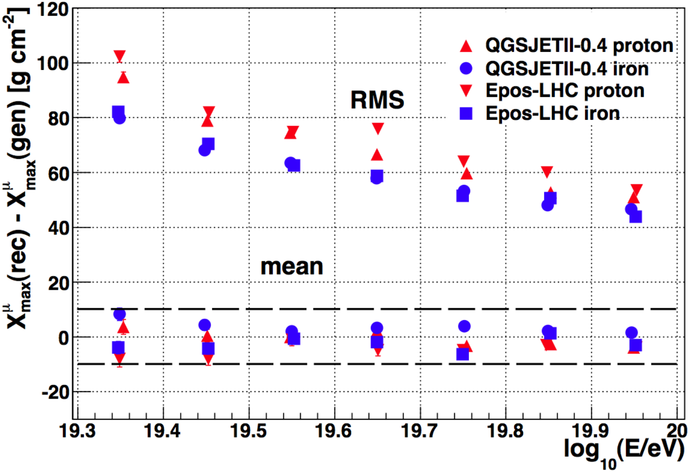
(Larger differences between hadronic models compared to the $X_{\max}$)

MPD results: systematics

source	syst. uncertainties $(\mathrm{g/cm^2})$
core time	5
atmospheric profile	8
fitting procedure	3
selection efficiency	2
energy uncertainties	3
seasonal	8
Reconstruction bias (driven by hadronic model and primary)	10
Total	**17**

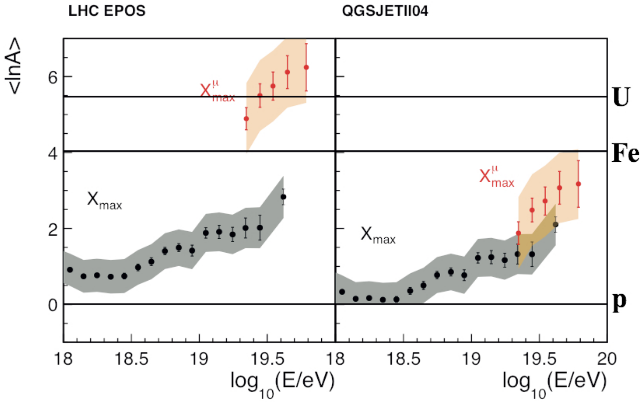
Reconstruction bias: 60% of the systematics contribution!

MPD results: reconstruction bias



X_{max} and X^{μ}_{max}

Compare results with Epos-LHC (left) and QGSJETII (right)



Model discrepancy

Further investigation needed.

Conclusion

- FD though the X_{max} measurement:
  - results compatible with previous findings
  - all interpretation, thought different hadronic model, are compatible with a CR mixed composition
  - $\langle \ln A \rangle$ decrease until $\sim 10^{18.3}$ eV and increase at high energy
  - Ultra high energy showers fluctuate less then predicted by proton simulation
- SD through X^{μ}_{max} measurement from MPD method:
  - new and promising approach to use the longitudinal development of extensive air showers to measure the mass composition
  - strong dependence to hadronic model to interpret the results
- Compare X_{max} and X^{μ}_{max} through hadronic interaction models:
  - discrepancy between models
  - Further understanding about hadronic model is needed to use the combined potential of X_{max} and X^{μ}_{max}

Outlook

- Long $X_{\max}$ journal paper is ongoing
- Studies to extend measurement to lower energies (HEAT, Infill, ...)
- Studies to improve knowledge about muons and extensive air shower (AMIGA, collaboration with NA61/SHINE and LHC, ...)
- More methods to use the longitudinal development of extensive air showers for study the mass composition (Universality, ...)
- Planed SD upgrade (increase muon detection capabilities)

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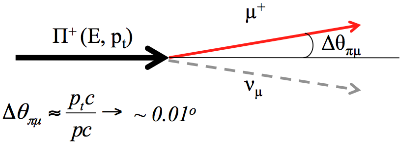
Thank you!

Backups

Muons kinematics

$$
\begin{array}{llll}
\pi^\pm & \rightarrow & \mu^\pm + \nu_\mu(\bar{\nu}_\mu) & \sim 100\% \\
K^\pm & \rightarrow & \mu^\pm + \nu_\mu(\bar{\nu}_\mu) & \sim 64\% \\
 & \rightarrow & \pi^\pm + \pi^0 & \sim 21\% \\
 & \rightarrow & \pi\text{s} + \text{fermions} & \sim 15\%
\end{array}
$$



Angle to the shower:

$$\sin\alpha \approx \frac{cp_t}{E}$$

Distance traveled before decaying:

$$l = \gamma c \tau_\pi = \frac{E}{m_\pi c^2} c\tau_p i$$

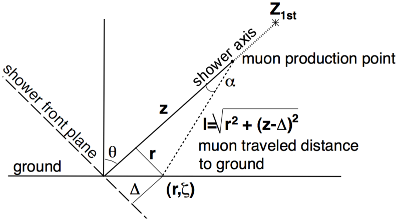
Transverse distance:

$$\Rightarrow r_\pi = l \sin\alpha = \frac{\tau_\pi p_t}{m_\pi} \sim \text{few 10 m!!!}$$

independent of pion *E*!

Why SD far from the core?

Muon product point must be measured



$$z = \frac{1}{2}\left(\frac{r^2}{ct_g} - ct_g\right) - \Delta$$
$$= \frac{1}{2}\left(\frac{r^2}{ct - c\langle t_\varepsilon\rangle} - ct - c\langle t_\varepsilon\rangle\right) - \Delta$$

$$\Rightarrow \begin{cases} X^\mu = \int_z^\infty \rho(z')\,dz' \\ \delta X^\mu \propto \dfrac{\delta t}{r^2 \cos\theta} \end{cases}$$

(ρ is the atmospheric density in function of the distance z')

Using tanks far from the core reduces δX^μ

EPOS and QGSJETII

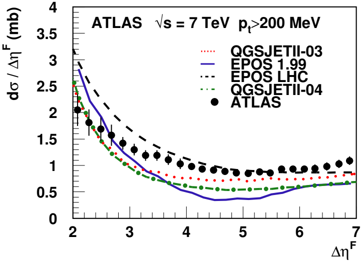
EPOS

- Constrained to reproduce LHC data
- LHC Proton-proton rapidity gap is reproduced

QGSJETII

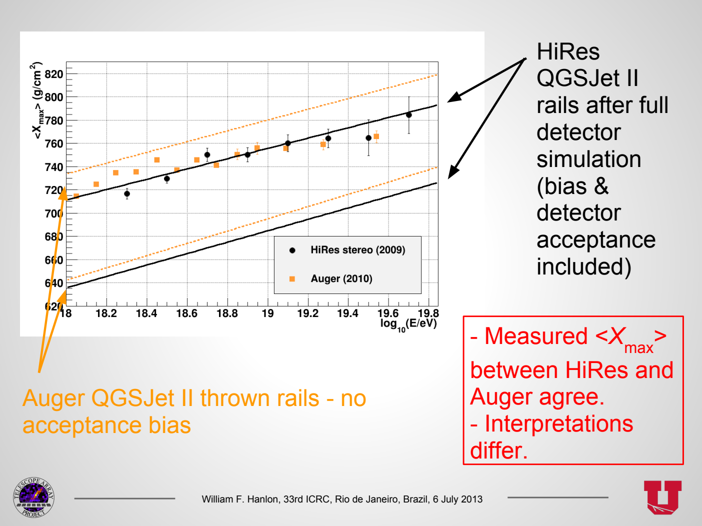
- Constrained to reproduce extensive air shower experiments
- LHC Proton-proton rapidity gap is not reproduced

Minimal assumption:
same diffraction for $p - p$, $p - \mathrm{air}$, and $\pi - \mathrm{air}$.
Probably this is the reason for the differences for X^{μ}_{max}



More studies are needed to find the best description

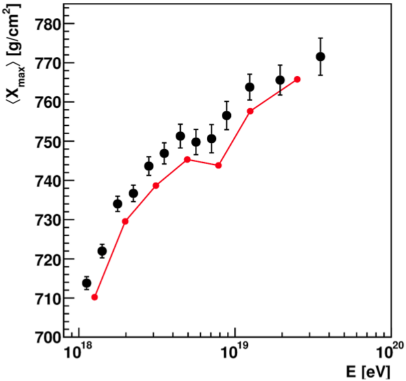
Auger-TA Difference Problem

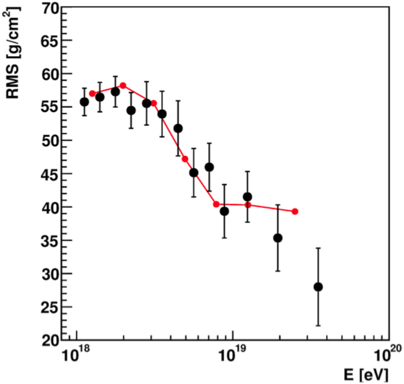


Slide taken from “Progress towards understanding the analyses of mass composition”, W. F. Hanlon, **ICRC13**

Auger fit of the data

Assumption: Auger reconstruct shower X_{max} with very little bias





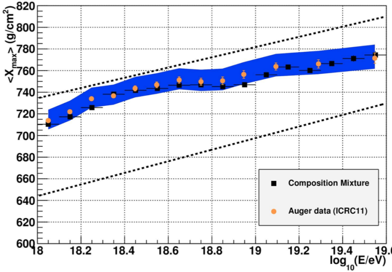
provided a 4 composition (H, He, N, Fe) sample based on fitting X_{max} from ICRC11 with χ^2 function

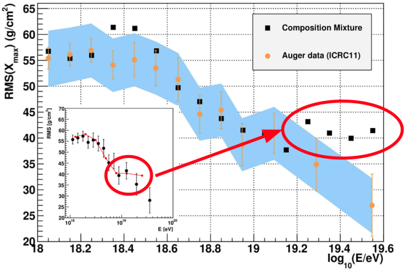
$8\,\mathrm{g/cm^2}$ of bias: poor fit on the tail (with low statistics) of X_{max} distribution

Pictures from “Progress towards understanding the analyses of mass composition”, W. F. Hanlon, **ICRC13**

TA simulation: Auger data reproduction

TA simulate using Auger composition: test it to reproduce Auger data



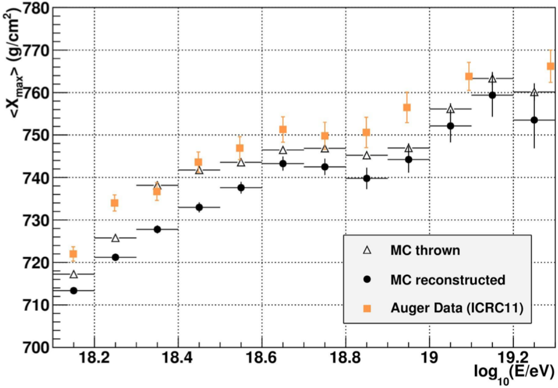


Simulations in agreement!

Pictures from “Progress towards understanding the analyses of mass composition”, W. F. Hanlon, **ICRC13**

TA simulation: reconstruction

Thrown the composition mix simulation with TA folding their telescope resolutions



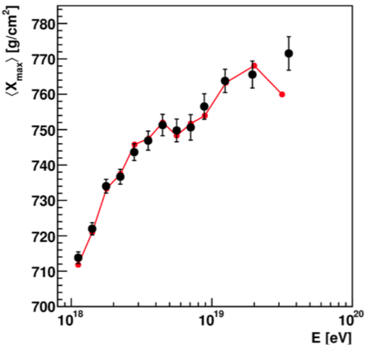
TA successfully reconstructs the Auger mix $X_{\max}$ with a small reconstruction bias ($\sim 5\,\mathrm{g/cm^2}$)

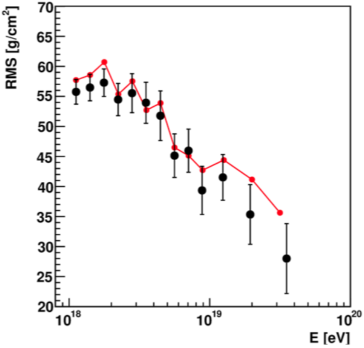
Pictures from “Progress towards understanding the analyses of mass composition”, W. F. Hanlon, **ICRC13**

Conclusion

Work still in progress!

Moreover Auger improved the fit to the data (using maximum likelihood) using the same elements:





Pictures from "Progress towards understanding the analyses of mass composition", W. F. Hanlon, **ICRC13**