PIERRE AUGER OBSERVATORY

Constraints on high energy particle interactions with the Pierre Auger Cosmic ray detectors

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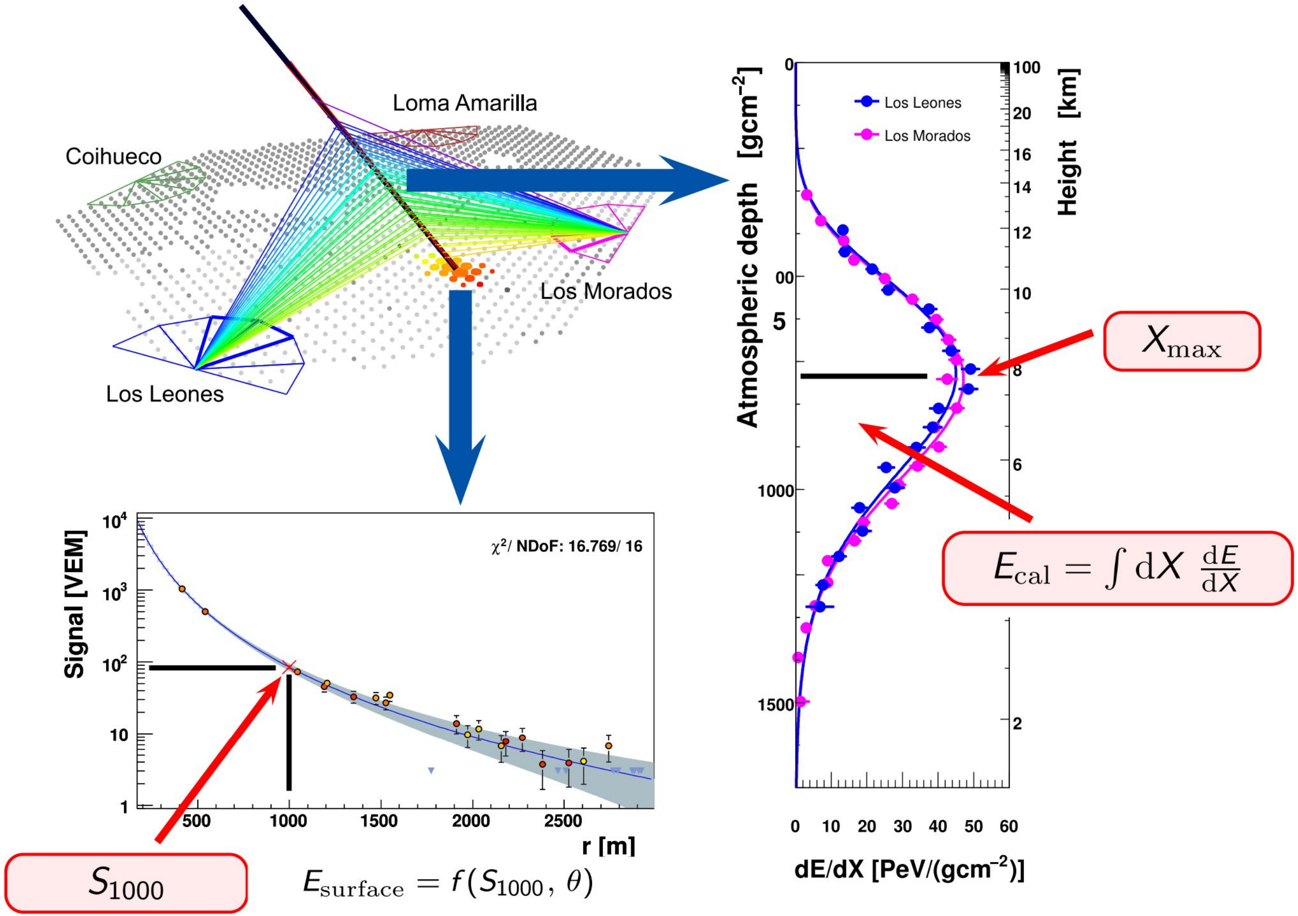
THE UNIVERSITY of ADELAIDE

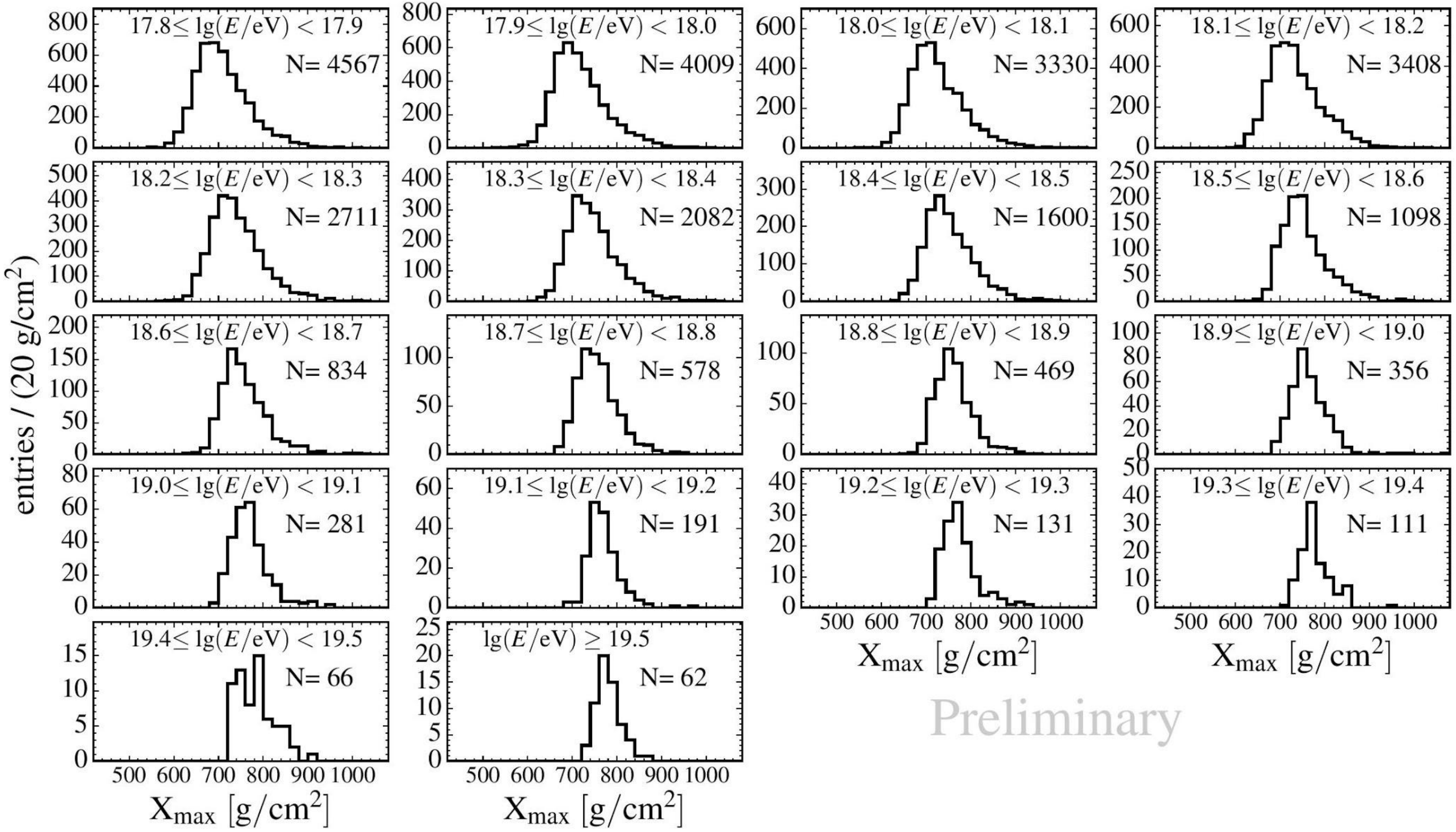
TeVPA meeting
2- 6 Dec, 2019, Sydney

The Pierre Auger Observatory



Pierre Auger measures X_{max} Distributions ...

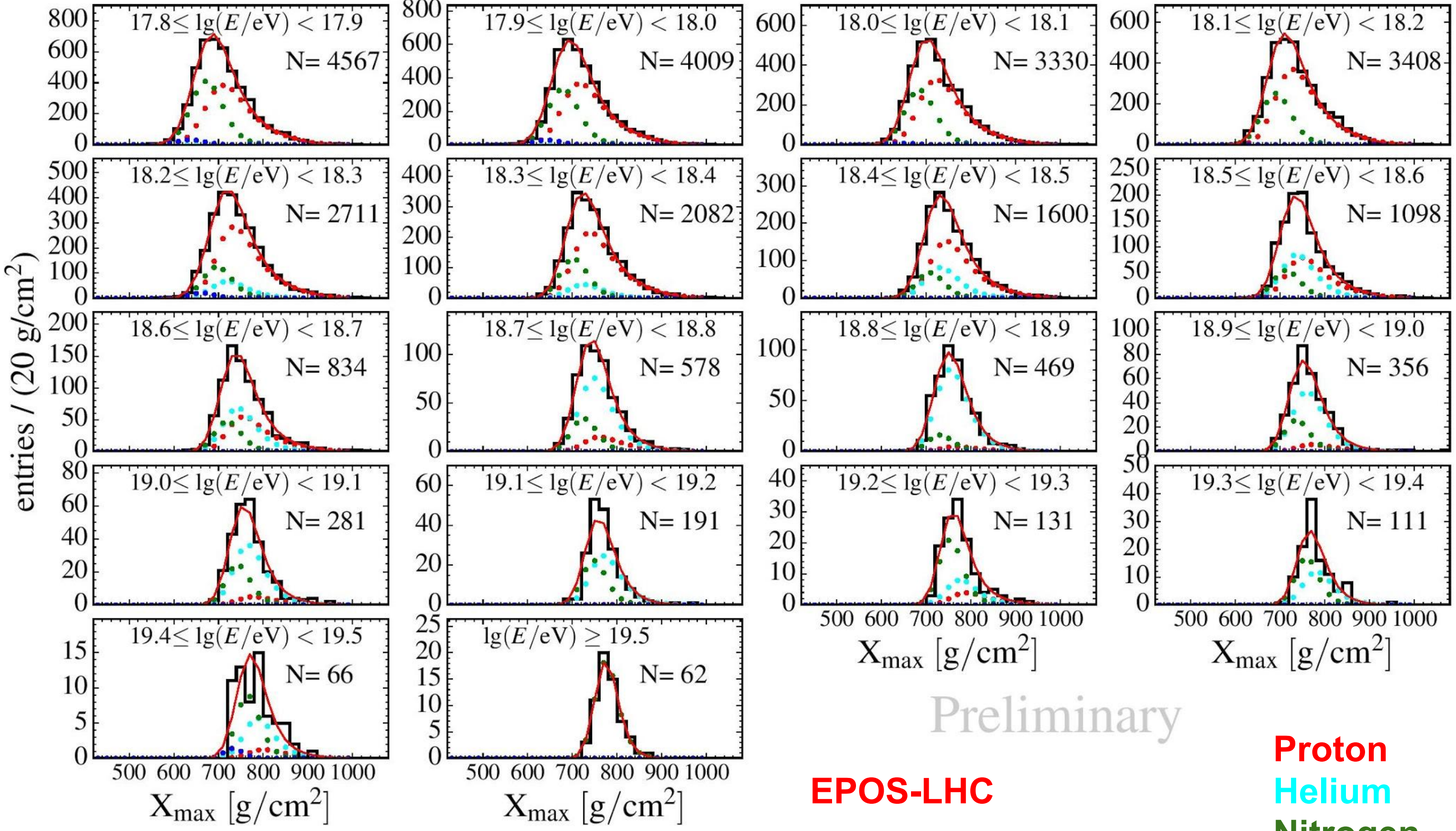
(i.e. it does not measure the cosmic rays composition)



J. Bellido for the Pierre Auger Collaboration, PoS(ICRC2017)506.

… then, we use predictions from hadronic models to estimate the composition

(different models have different X_{max} predictions)

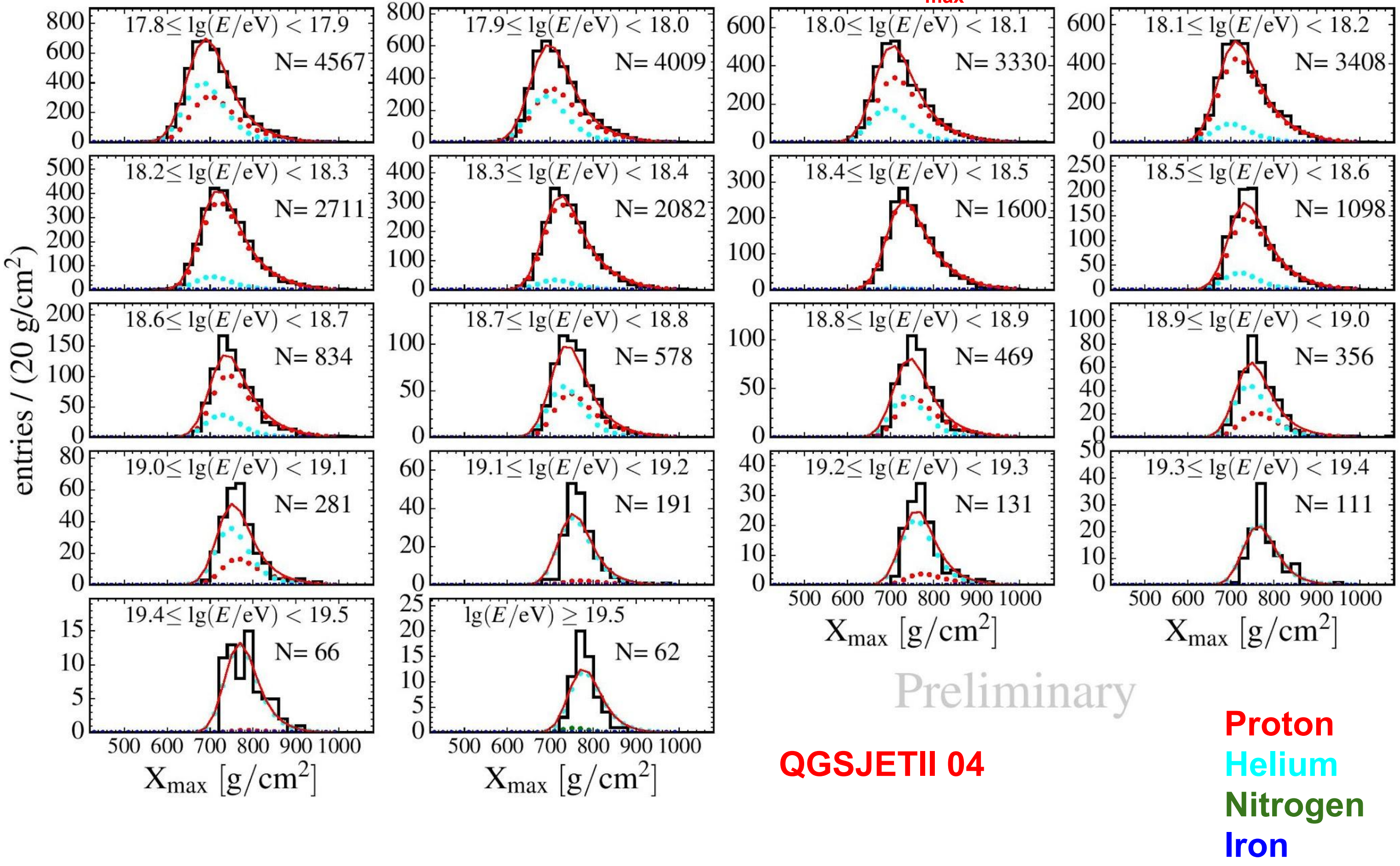


EPOS-LHC

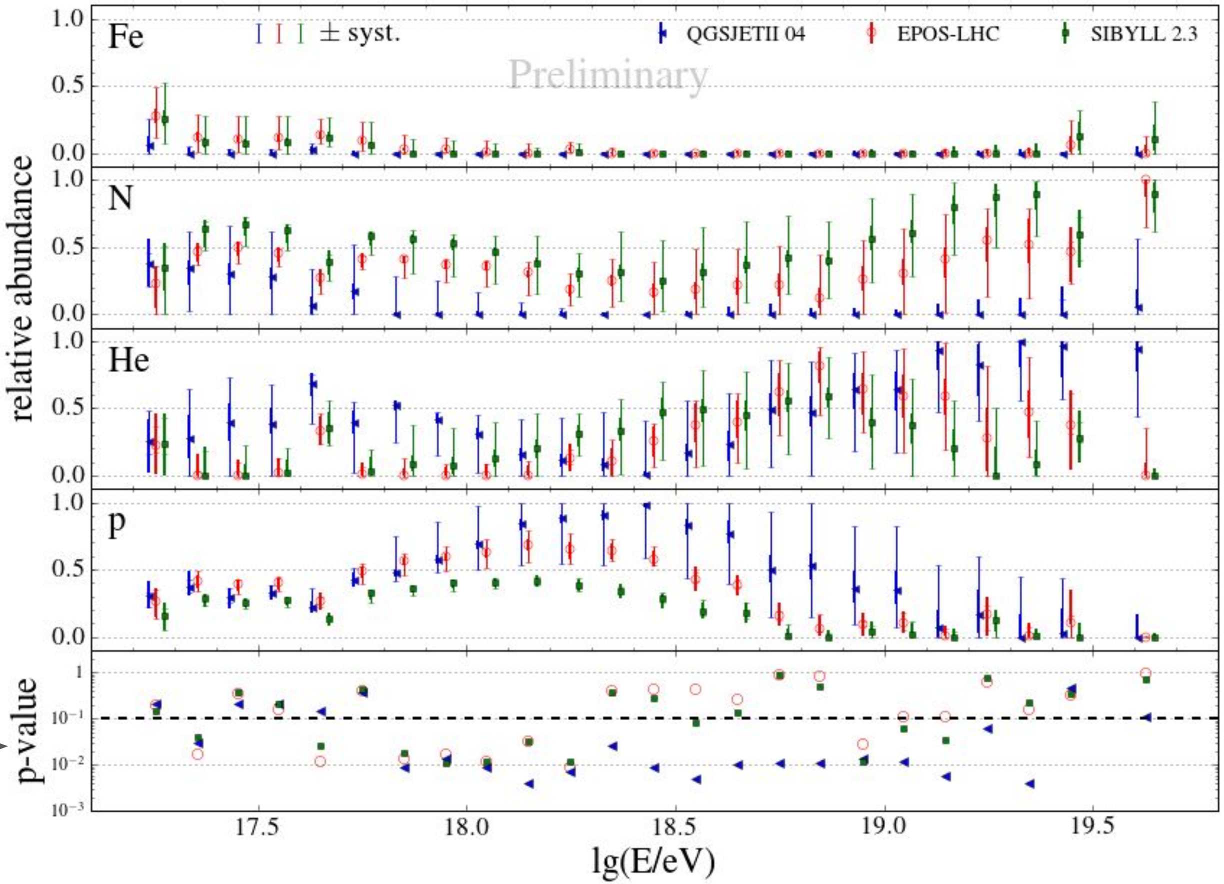
Proton
Helium
Nitrogen
Iron

… then, we use predictions from hadronic models to estimate the composition

(different models have different X_{max} predictions)



Therefore, the estimated composition is model dependent and the systematics from the models are not possible to estimate

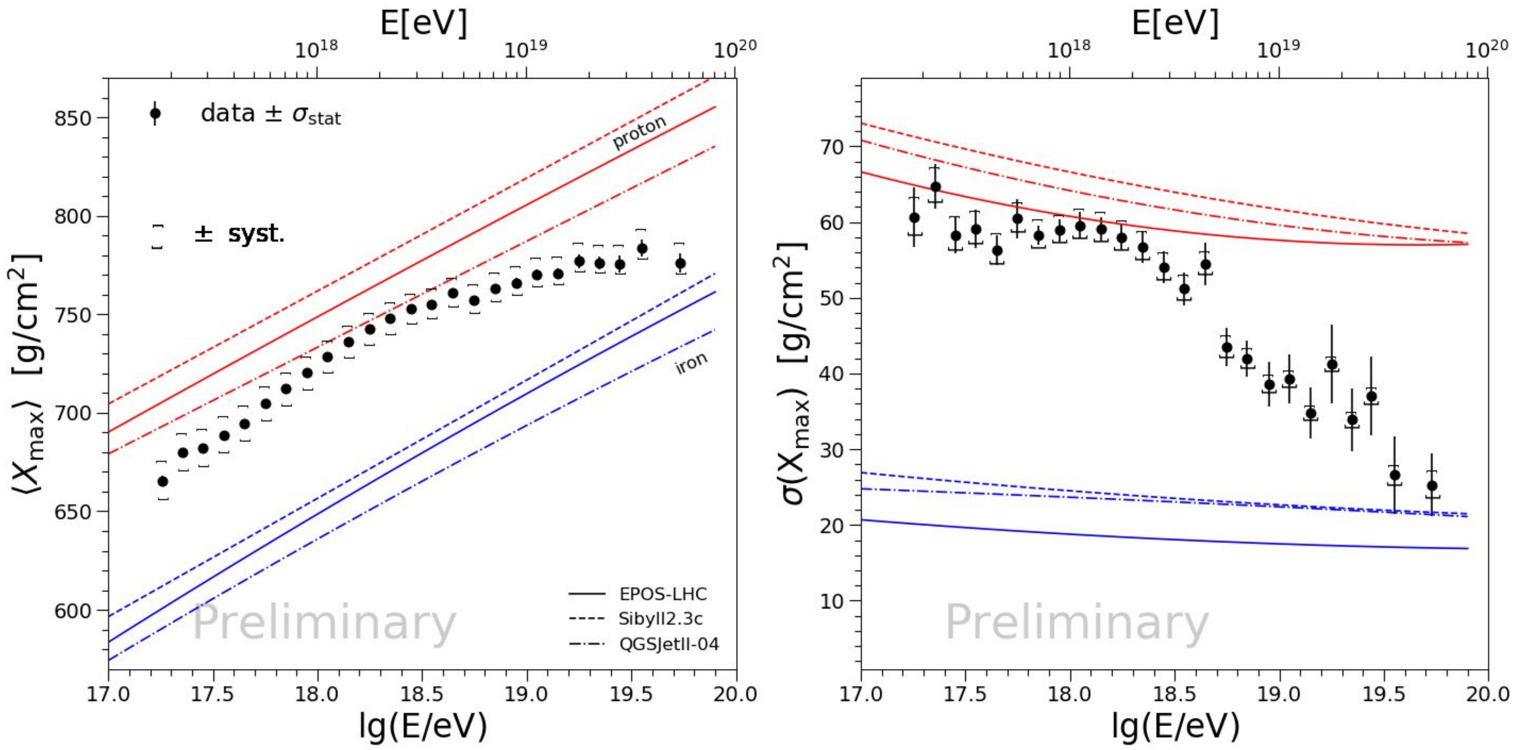


The small p-values indicate that none of the models are able to find a composition mix that is able to reproduce the observed X_{max} distributions.

J. Bellido for the Pierre Auger Collaboration, PoS(ICRC2017)506.

But, is there anything that we can say about the composition that is independent of the models?

Yes, there is!



- The composition is not constant above $10^{17.2}$ eV
- It is the lightest at $10^{18.3}$ eV and gets heavier above and below $10^{18.3}$ eV

A. Yushkov for the Pierre Auger Collaboration, PoS(ICRC2019)482.

But, is there anything that we can say about the composition that is independent of the models?

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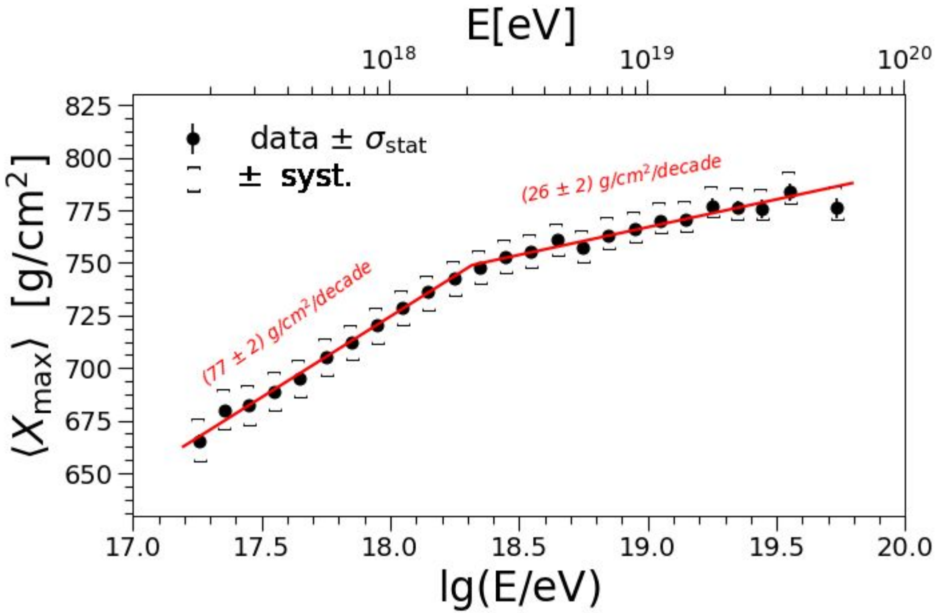
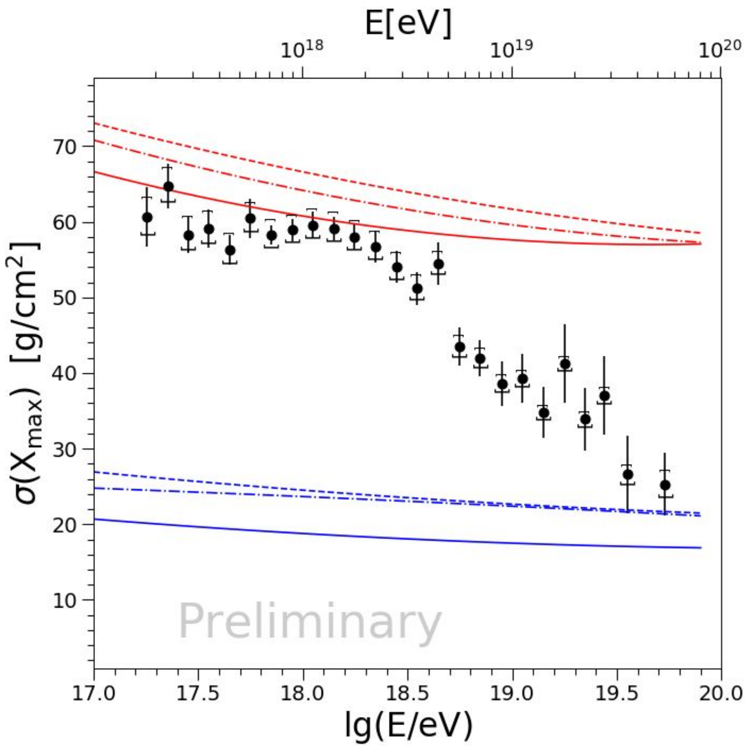




- The composition is not constant above $10^{17.2}$ eV
- It is the lightest at $10^{18.3}$ eV and gets heavier above and below $10^{18.3}$ eV
  (it gets heavier faster above)

Detailed comparison between observation and model's prediction is helping to show the deficiencies in hadronic models

Phys. Rev. Lett. **117**, 192001 (2016)

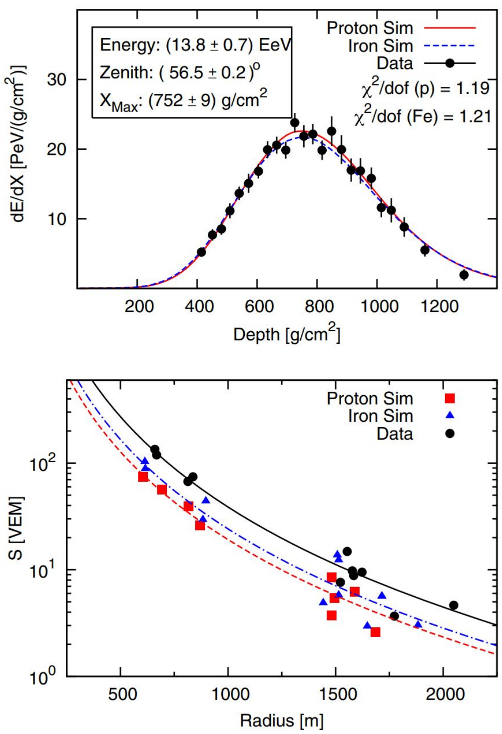


FIG. 1. Top: The measured longitudinal profile of an illustrative air shower with its matching simulated showers, using QGSJet-II-04 for proton (red solid) and iron (blue dashed) primaries. Bottom: The observed and simulated ground signals for the same event (p: red squares, dashed-line, Fe: blue triangles, dot-dash line) in units of vertical equivalent muons; curves are the lateral distribution function (LDF) fit to the signal.

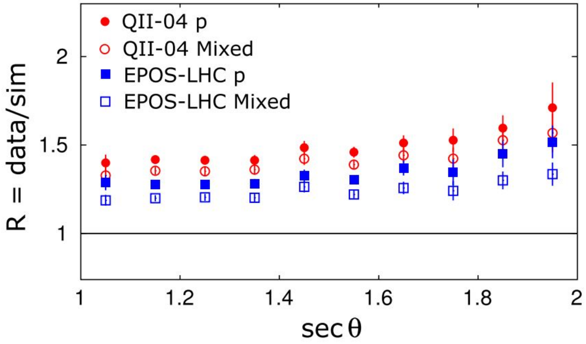


FIG. 2. The average ratio of $S(1000)$ for observed and simulated events as a function of zenith angle, for mixed or pure proton compositions.

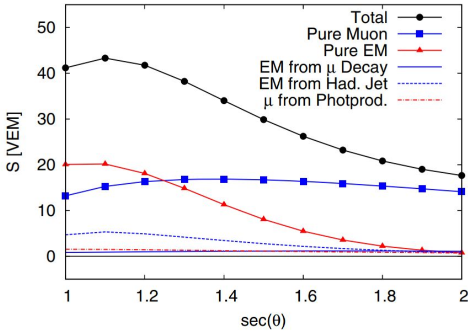


FIG. 3. The contributions of different components to the average signal as a function of zenith angle, for stations at 1 km from the shower core, in simulated 10 EeV proton air showers illustrated for QGSJet-II-04.

Detailed comparison between observation and model's prediction is helping to show the deficiencies in hadronic models

Phys. Rev. Lett. **117**, 192001 (2016)

$$S_{\mathrm{resc}}(R_E, R_{\mathrm{had}})_{i,j} \equiv R_E S_{\mathrm{EM},i,j} + R_{\mathrm{had}} R_E^{\alpha} S_{\mathrm{had},i,j}.$$

TABLE I. R_E and R_{had} with statistical and systematic uncertainties, for QGSJet-II-04 and EPOS-LHC.

Model	R_E	R_{had}
QII-04 p	$1.09 \pm 0.08 \pm 0.09$	$1.59 \pm 0.17 \pm 0.09$
QII-04 mixed	$1.00 \pm 0.08 \pm 0.11$	$1.61 \pm 0.18 \pm 0.11$
EPOS p	$1.04 \pm 0.08 \pm 0.08$	$1.45 \pm 0.16 \pm 0.08$
EPOS mixed	$1.00 \pm 0.07 \pm 0.08$	$1.33 \pm 0.13 \pm 0.09$

Depending on the model and the assumed composition. The signal from muons (muons with hadronic origins) needs to increase between 30 to 60%.

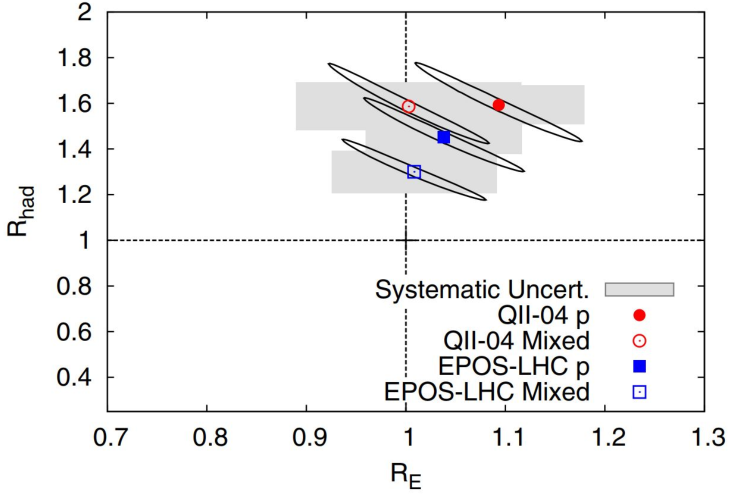


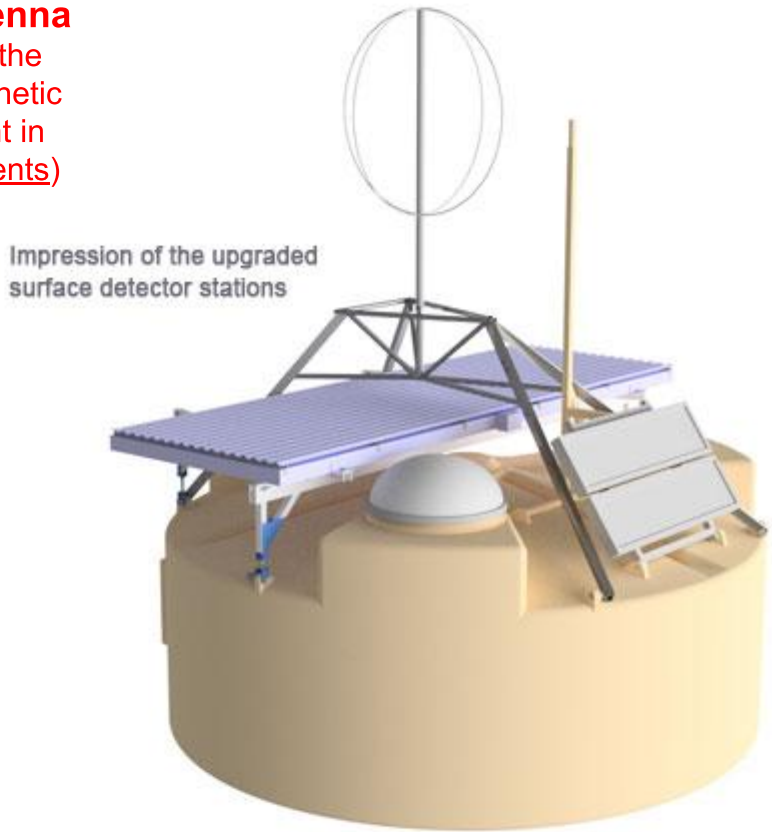
FIG. 4. Best-fit values of R_E and R_{had} for QGSJet-II-04 and EPOS-LHC, for pure proton (solid circle, square) and mixed composition (open circle, square). The ellipses and gray boxes show the 1-σ statistical and systematic uncertainties.

The Pierre Auger Observatory is going through an upgrade phase:

AugerPrime

Radio antenna
(to detect the electromagnetic component in inclined events)

New electronics
(to increase the sampling rate from 40 to 120 MHz)



Introducing a small PMT
(to increase the dynamic range)

Plastic scintillator
(to detect the electromagnetic component in vertical events)

The Pierre Auger Observatory Upgrade - Preliminary Design Report, arXiv:1604.03637

An engineering array and a PreProduction array already deployed

Engineering Array (since Sep 2016): Includes scintillator detectors, small-PMT and new electronics
PreProduction array (since Mar 2019): Includes only scintillator detectors

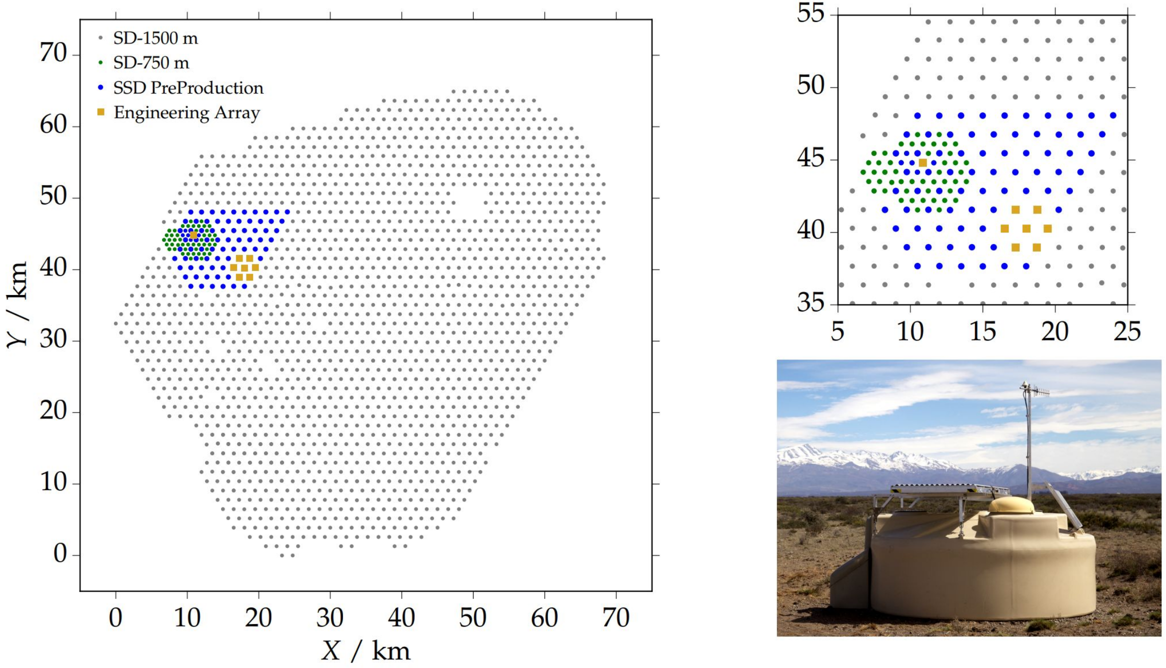


Figure 1: *Left:* Layout of the surface detector. *Top right:* Zoomed area containing the engineering array (golden squares) and SSD preproduction locations (blue dots). *Bottom right:* Photograph of an upgraded station of the surface detector.

A. Taboada for the Pierre Auger Collaboration, PoS(ICRC2019)434.

AugerPrime will add another dimension in the comparison between observation and model's prediction

AugerPrime first measurements

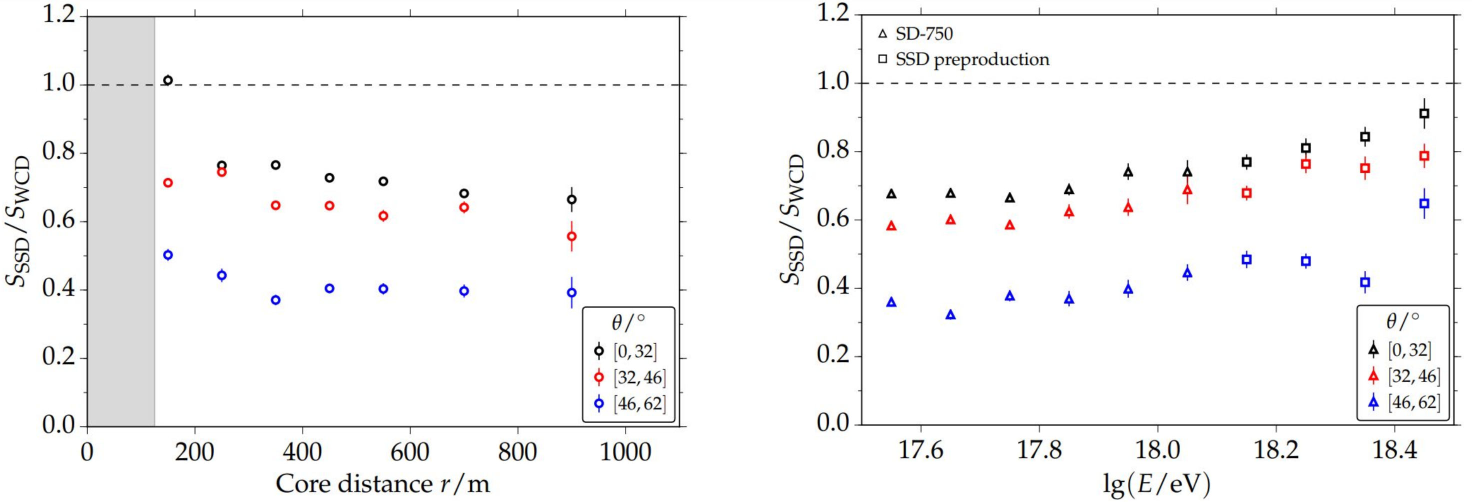
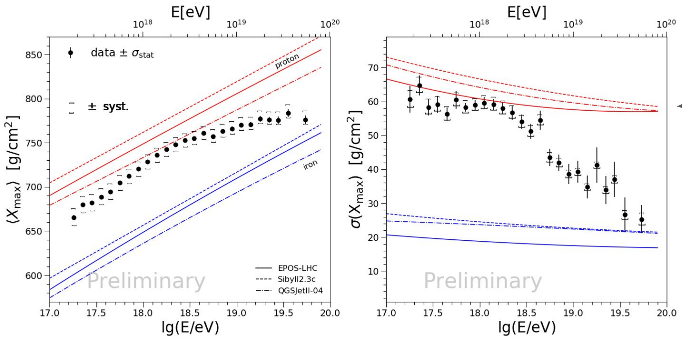


Figure 5: *Left:* Ratio of SSD and WCD signals as a function of the core distance, for different zenith angles of incidence. The gray area shows the region of saturated signals. *Right:* Ratio of signals as a function of the reconstructed energy. Data from the SD-750 m array (triangles) and SSD preproduction array (squares) are used. Ranges in zenith are chosen according to equal bins in $\sin^2\theta$.

A. Taboada for the Pierre Auger Collaboration, PoS(ICRC2019)434.

Summary

1. The interpretation of cosmic rays mass composition (from air shower measurements) is currently uncertain due to deficiencies in high energy hadronic interaction models.
2. Comparison between observation and expectations from model are helping to identify some of the deficiencies in the models.
3. **AugerPrime** will add another dimension in the comparison between observations and model expectations.
4. The Pierre Auger Collaboration is currently working on a more robust approach for estimating the mass composition. Where X_{max} distributions, together with the surface detector signals are used to constrain, at the same time, the composition and **model corrections**. A paper is in preparation.



Corrections on the normalization of the **X_{max} moment's rails, R_E and R_{had}**

$$S_{\text{resc}}(R_E, R_{\text{had}})_{i,j} \equiv R_E S_{\text{EM},i,j} + R_{\text{had}} R_E^{\alpha} S_{\text{had},i,j}.$$