Measurement of the chemical composition of the ultra-high-energy cosmic rays with the Pierre Auger Observatory

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August 14, 2013

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Federal Ministry of Education and Research

Outline

Physics motivations

Ultra High Energy Cosmic Rays (UHECR)

- most energetic source of elementary particles available to scientists macroscopic energies $E > 1\,\mathrm{EeV}$ ($10^{18}\,\mathrm{eV}$)
- but very low flux!

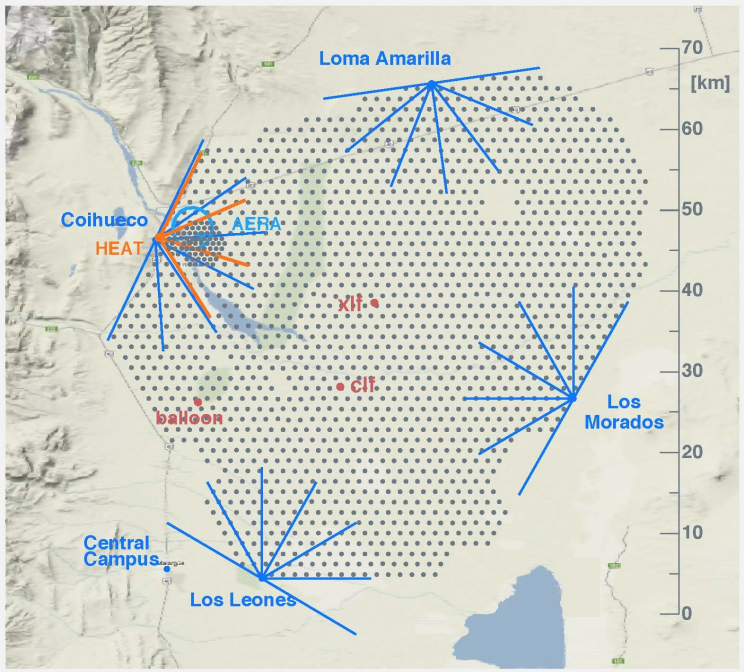
Extensive air shower (EAS)

- UHECR produce large shower of particles in Earth's atmosphere (calorimeter)
- primary cosmic ray characteristics obtained from the measured properties of extensive air showers

Pierre Auger Observatory

- hybrid cosmic ray detector for energies above 10^{17} eV located in the Pampa Amarilla near Malargüe, Argentina
- measures energy, arrival directions and properties of extensive air showers

Pierre Auger Observatory



Surface Detector (SD)

- 1660 water-Cherenkov detector stations
- 1500 m on an hexagonal grid
- 3000 km^2 aperture
- measures lateral distribution
- duty cycle 100%

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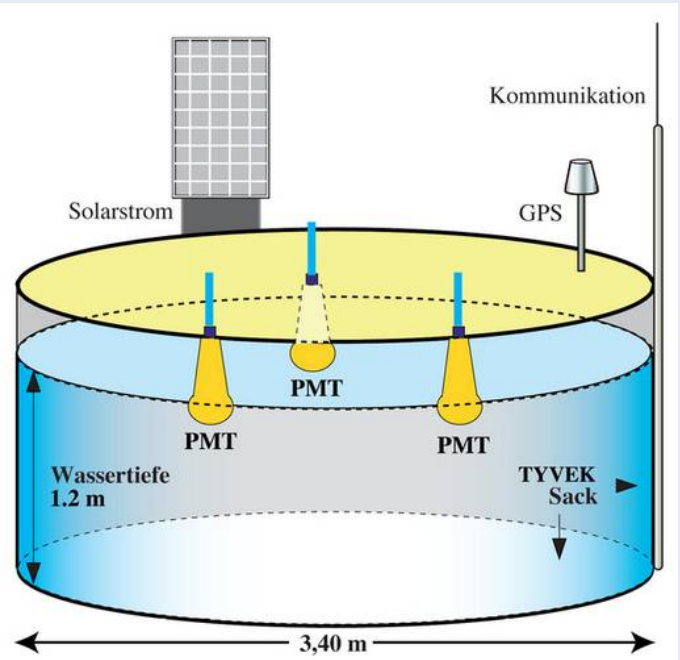

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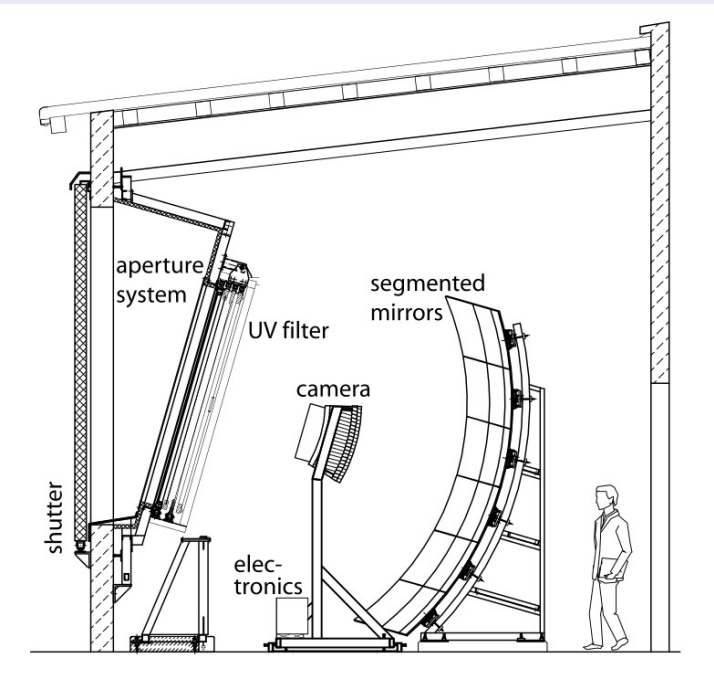
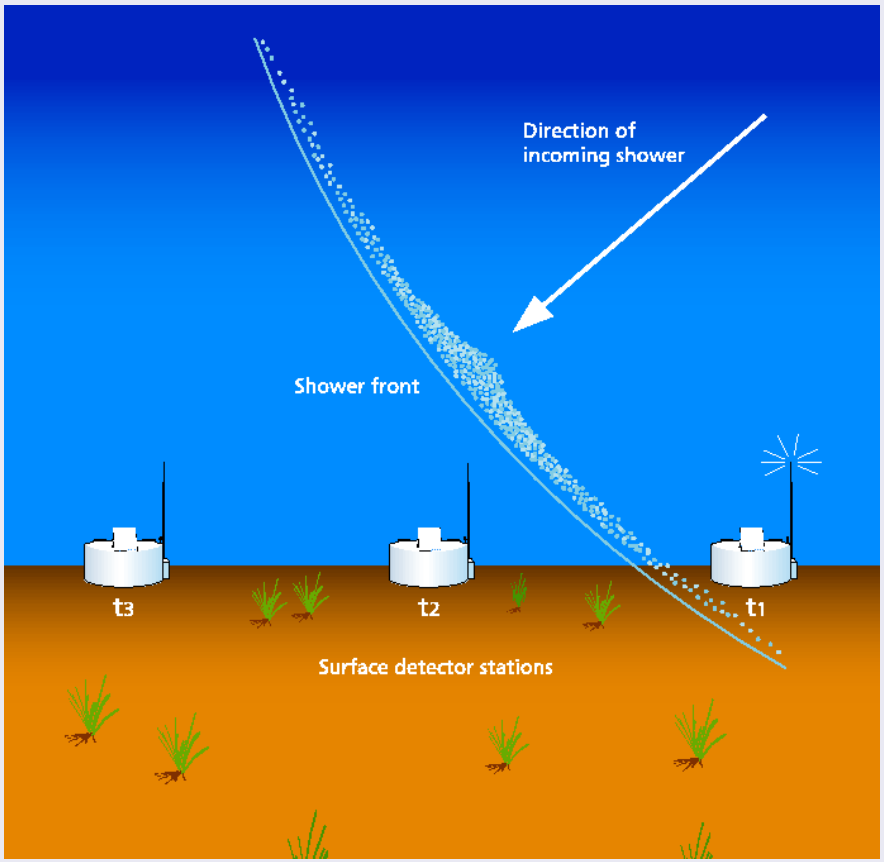


Fluorescence Detector (FD)

- 5 fluorescence telescope sites
- 27 telescopes
- located at array borders
- field of view $30° \times 30°$
- measures longitudinal shower profile
- duty cycle 12%

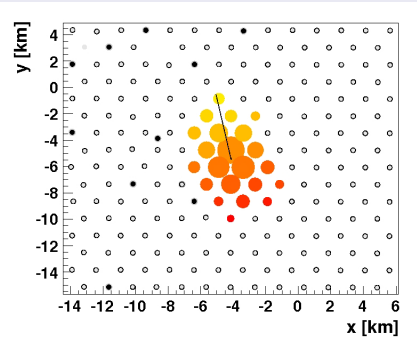
FD and SD

SD-Reconstruction

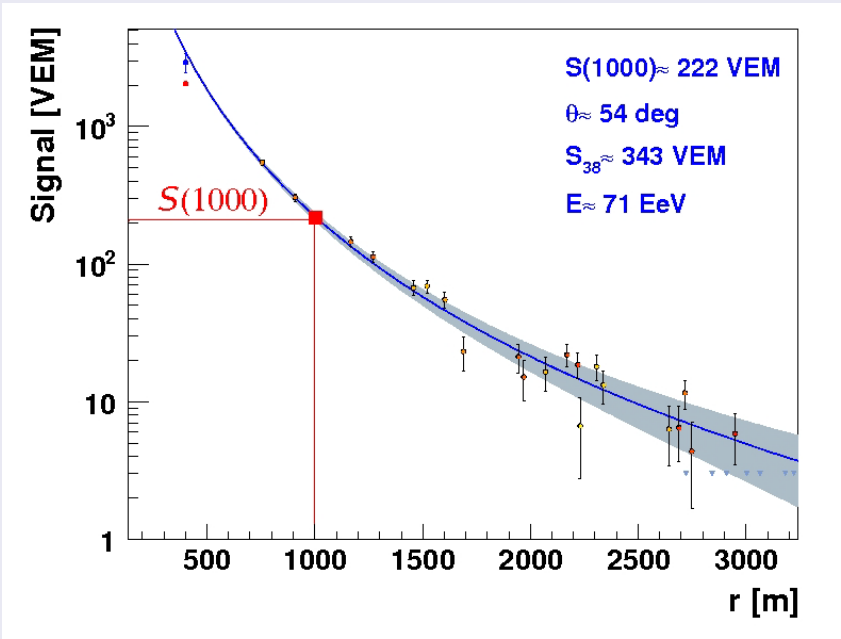


- Energy and arrival direction
- Primary properties:
  - Risetime asymmetry
  - Muon production depth

Lateral profile

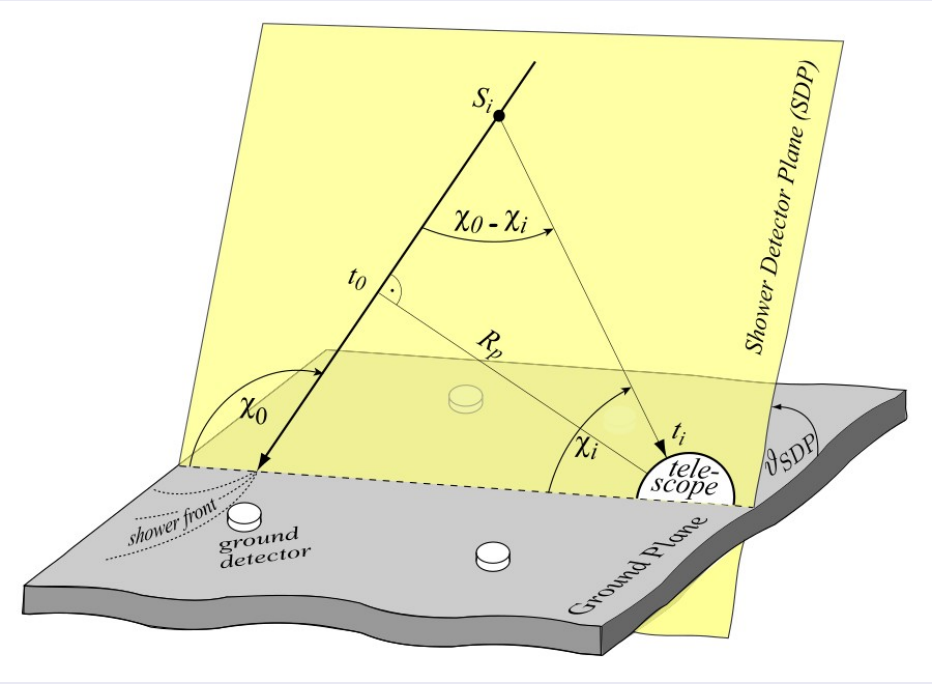


SD energy estimator



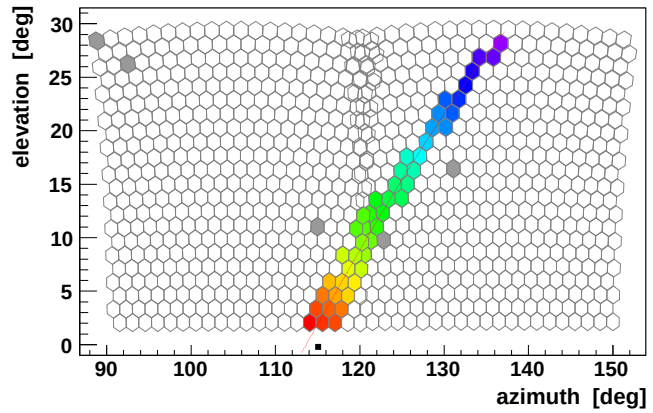
FD-Reconstruction for hybrid events

Shower-Detector-Plane

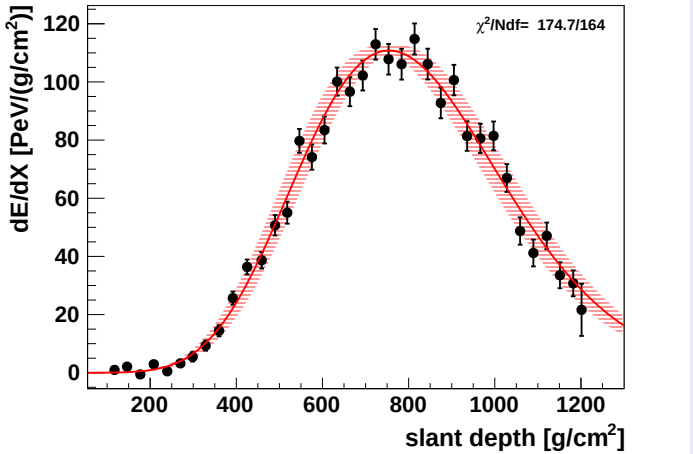


- accurate energy measurement
- arrival direction reconstruction
- composition sensitive observable shower maximum X_{max}

FD event view

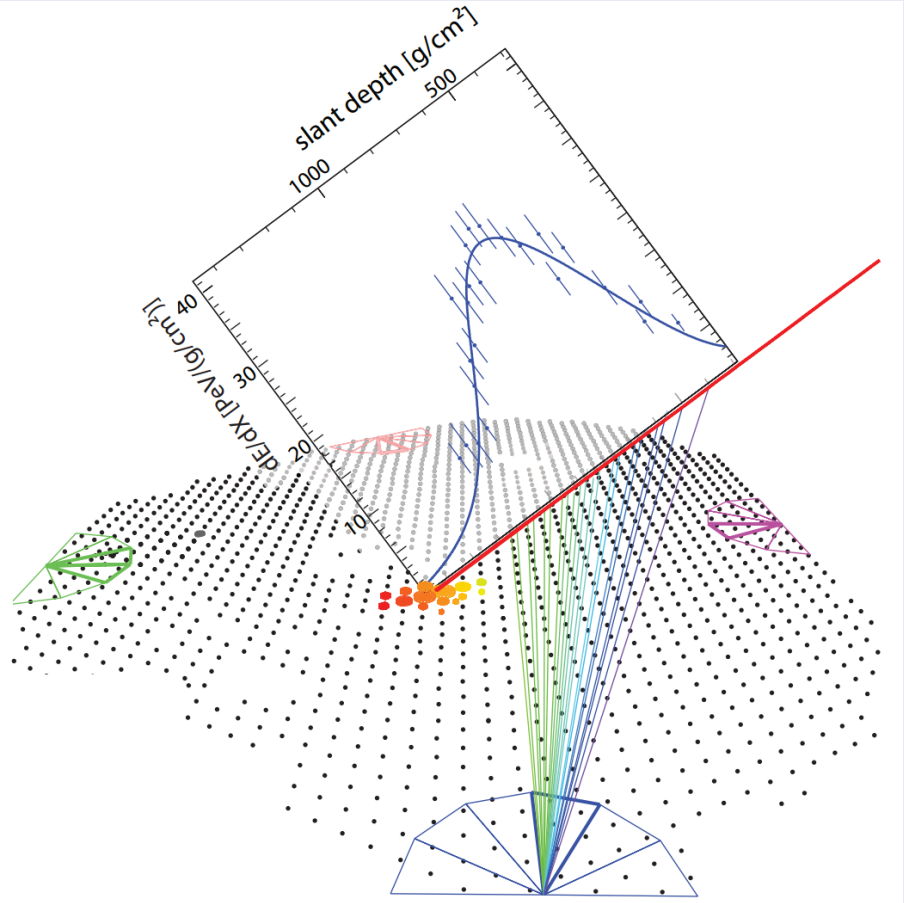


Energy deposit profile

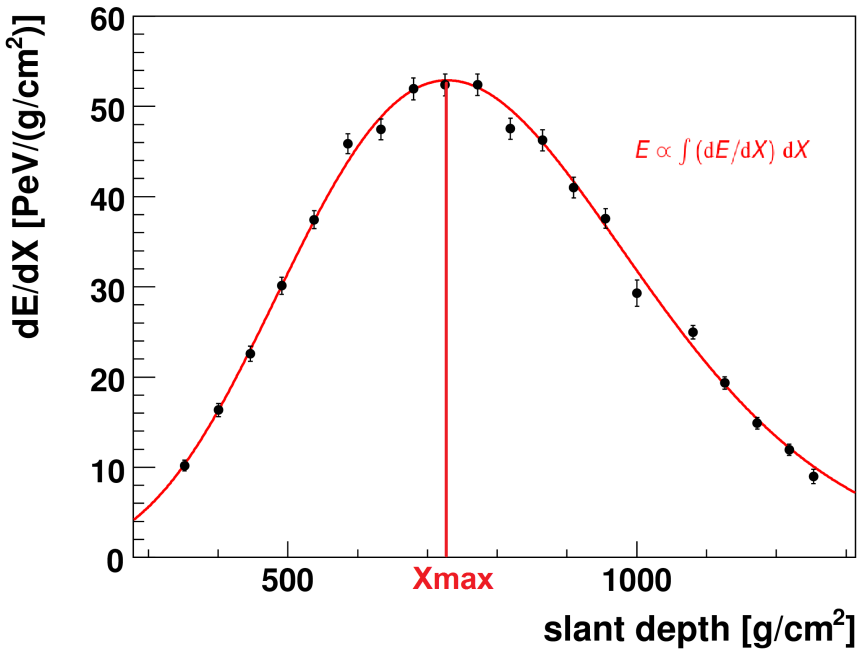


Measurement of the air shower parameter X_{max}

Energy deposition profile



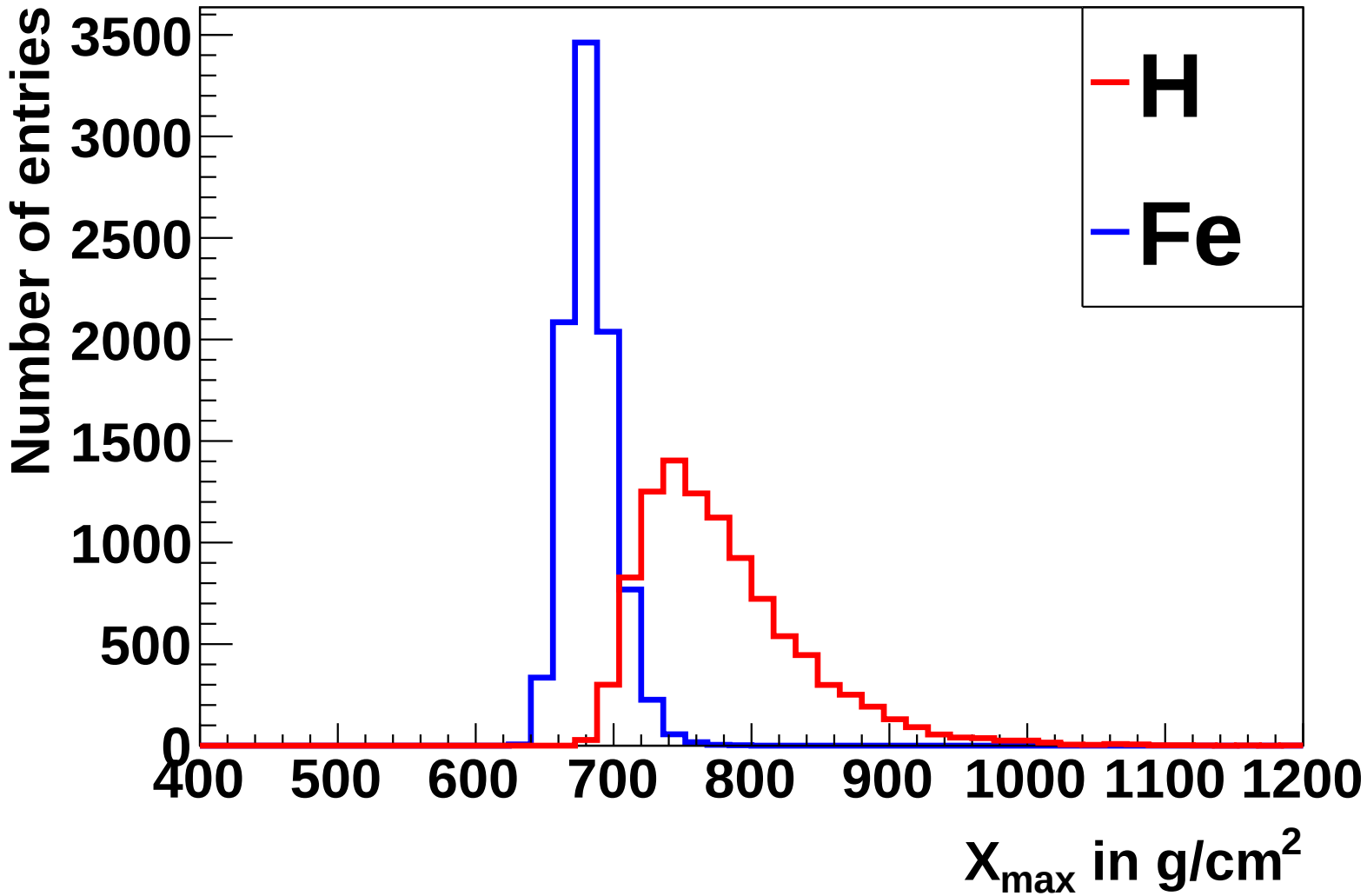
X_{max}-Parameter



- X_{max} is fitted with Gaisser-Hillas-Function
- $X_{max} \propto ln(A)$

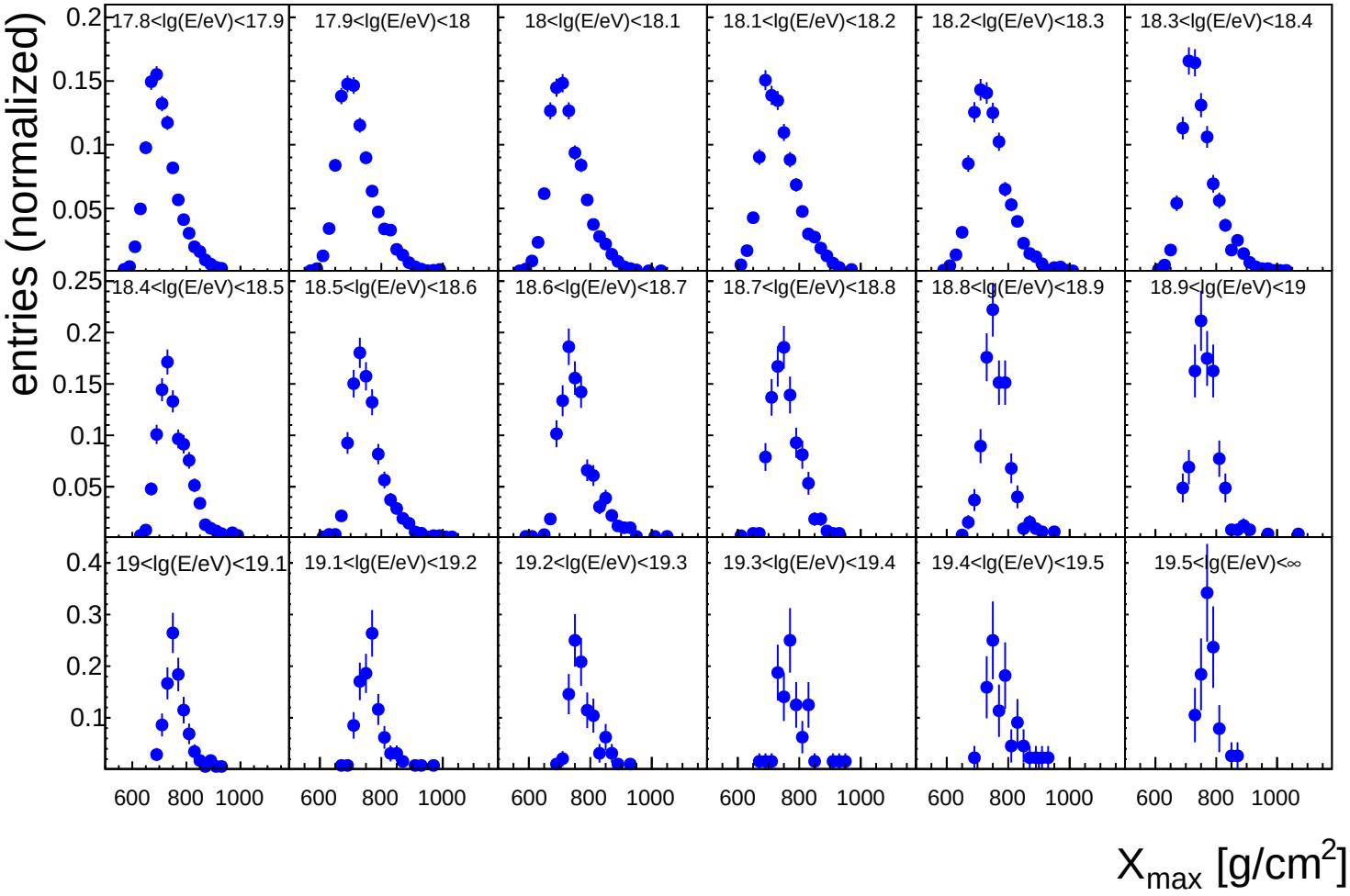
X_{max}-distributions from Monte-Carlo

- $< X_{max} >$ and $\sigma_{X_{max}}$ sensitive to composition of primary UHECRs

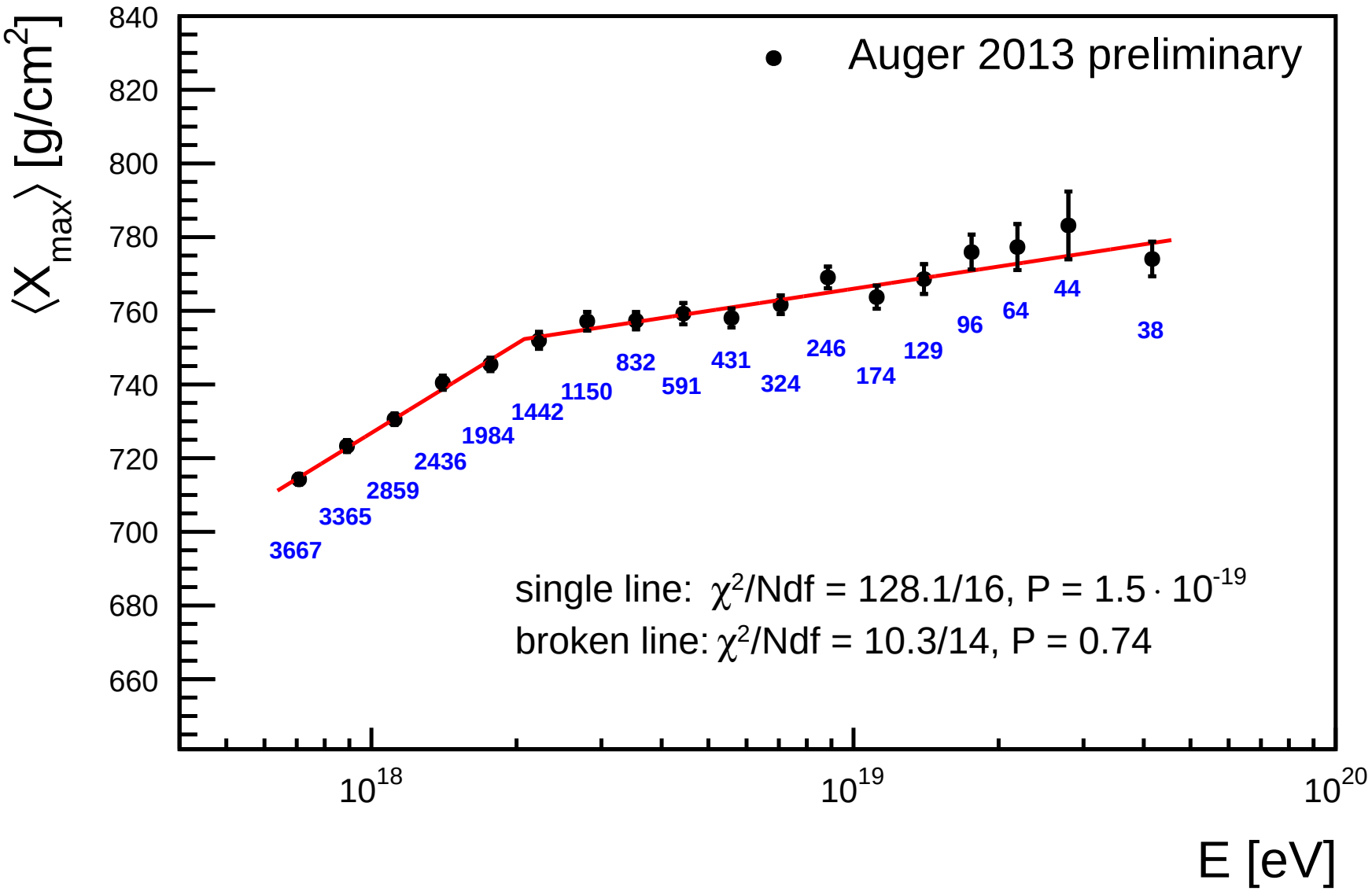


X_{max}-distribution

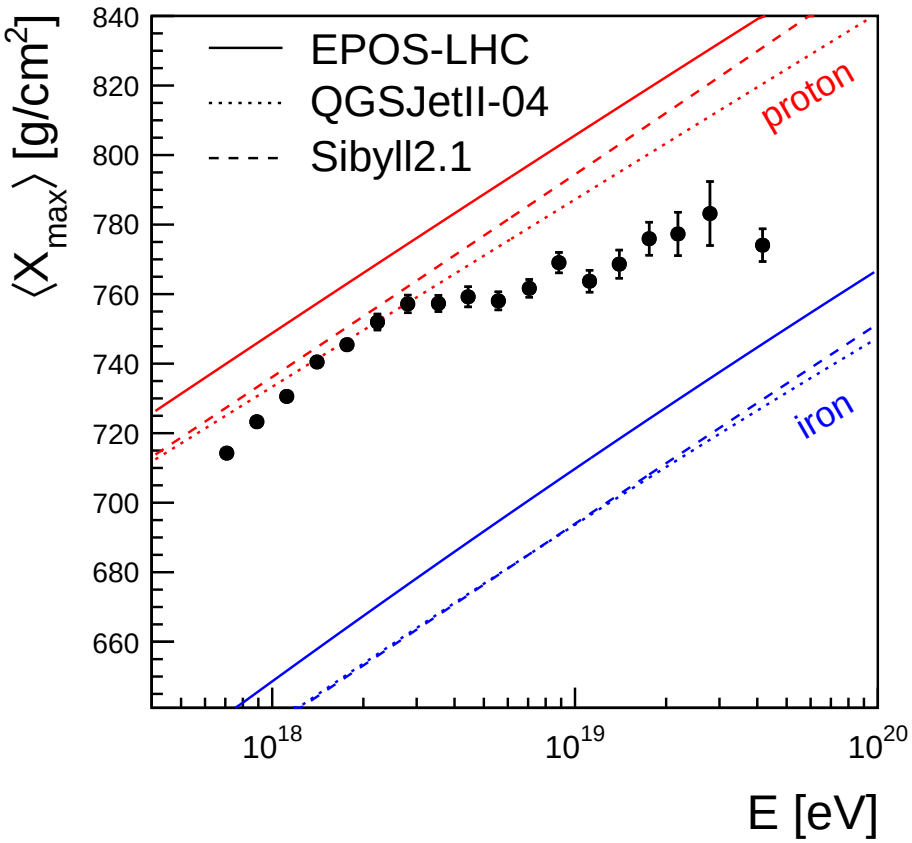
- Hybrid dataset from 01/12/2004 - 31/12/2012
- Energy threshold $10^{17.8}$ eV
- 19872 events selected

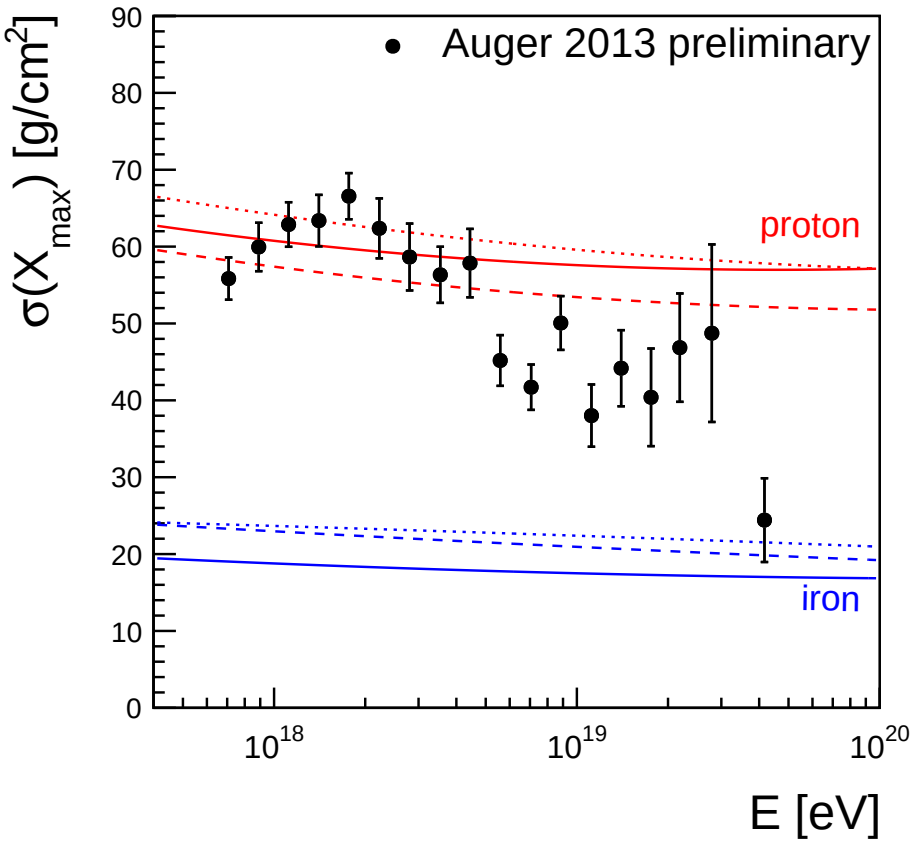


$< X_{max} >$ dependency on the energy



Comparison of $< X_{max} >$ and $\sigma(X_{max})$ with interaction models





ln(A) and σ(ln(A))

Parametrization[1] of X_{max}:

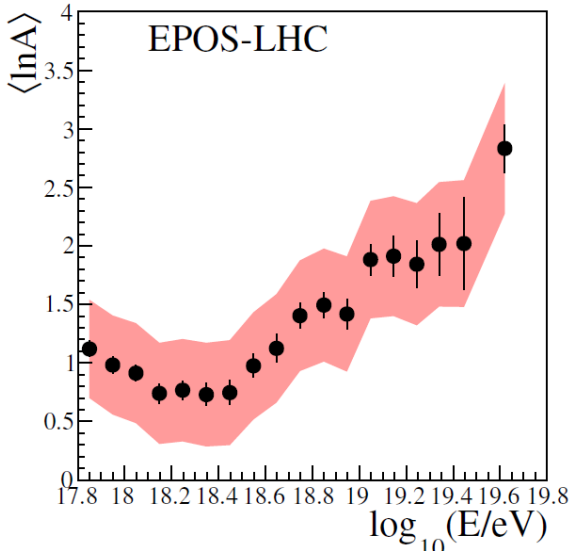
$$< X_{max} > \approx < X^{p}_{max} > + f_E < ln\, A > \quad (1)$$

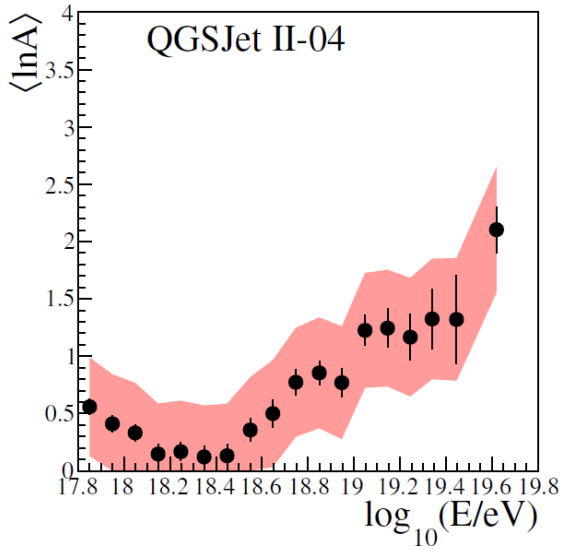
$$\sigma(X_{max})^2 \approx < \sigma^2_{sh} > + f_E^2\, \sigma(ln\, A)^2 \quad (2)$$

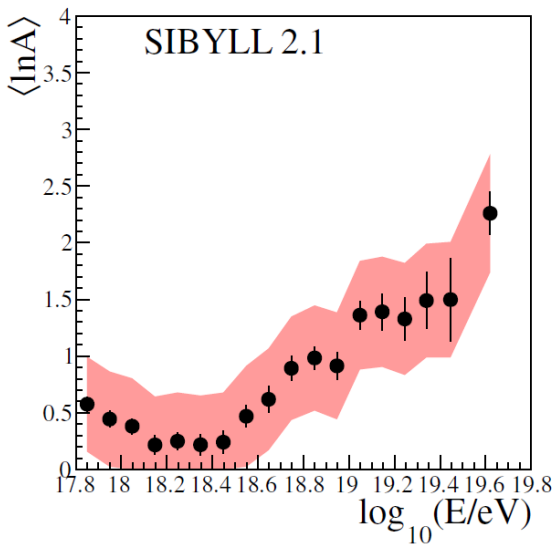
f_E	energy and model dependent parameter
$< X^{p}_{max} >$	average shower depth of protons
$< \sigma^2_{sh} >$	mass-averaged shower fluctuations
$< ln\, A >$	mean log. mass distribution
$\sigma(ln\, A)$	variance log. mass distribution

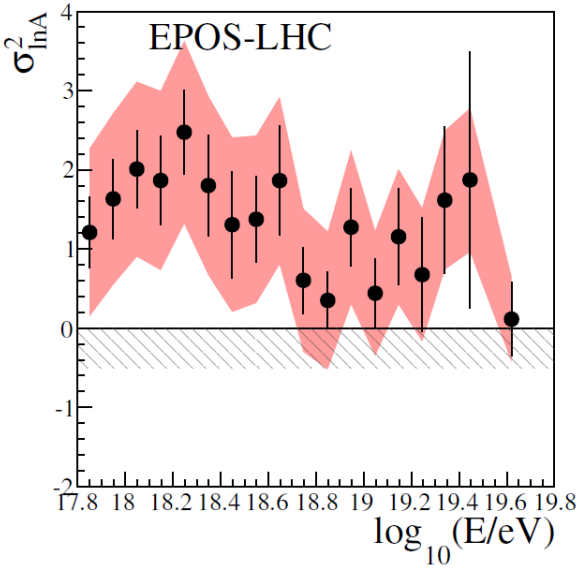
[1] J. Linsley, Proc. 18th ICRC 1983 and Proc. 19th ICRC 1985 and also K.H. Kampert& M.Unger, APP (2012) 660 and Auger Collab., JCAP (2013) 026

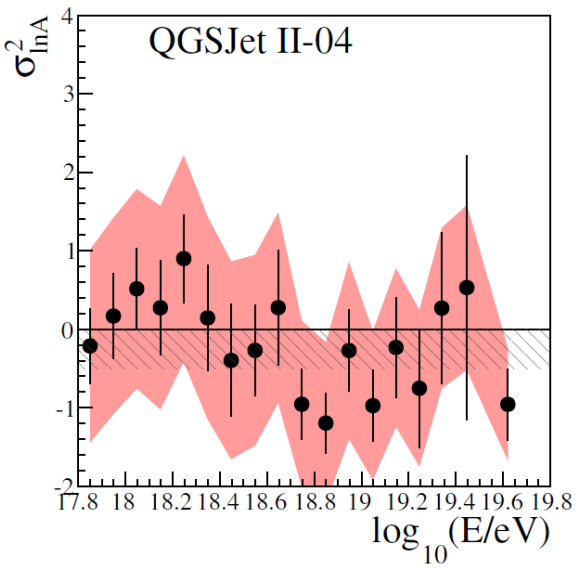
$< ln\,A >$ and σ^2_{lnA} from Auger data

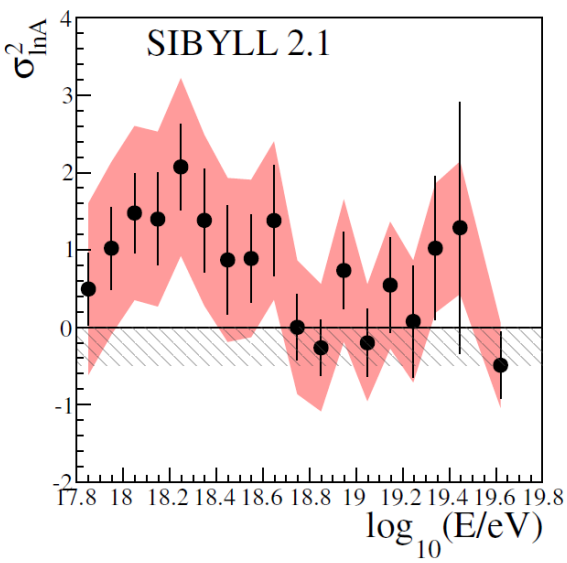




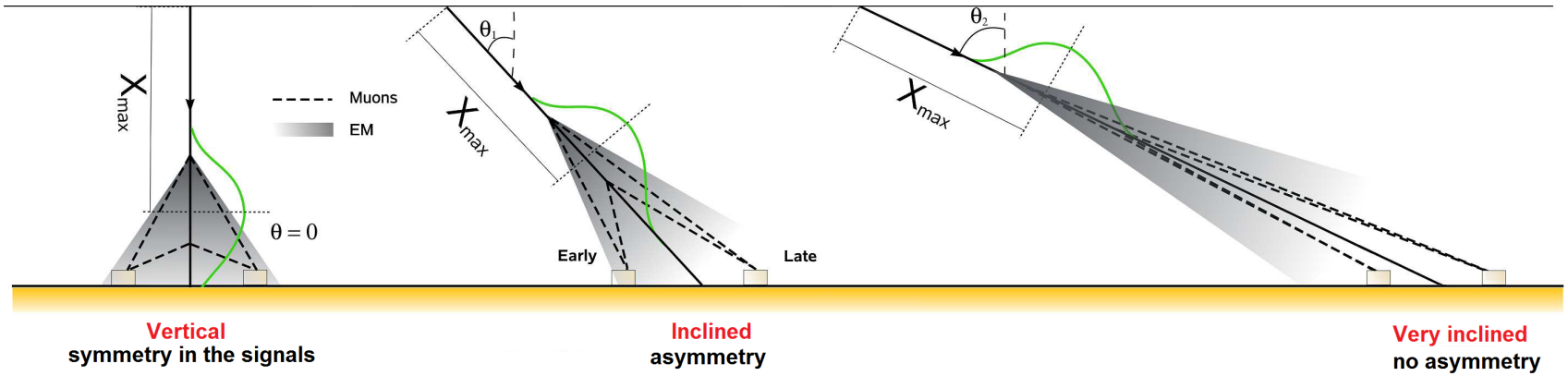


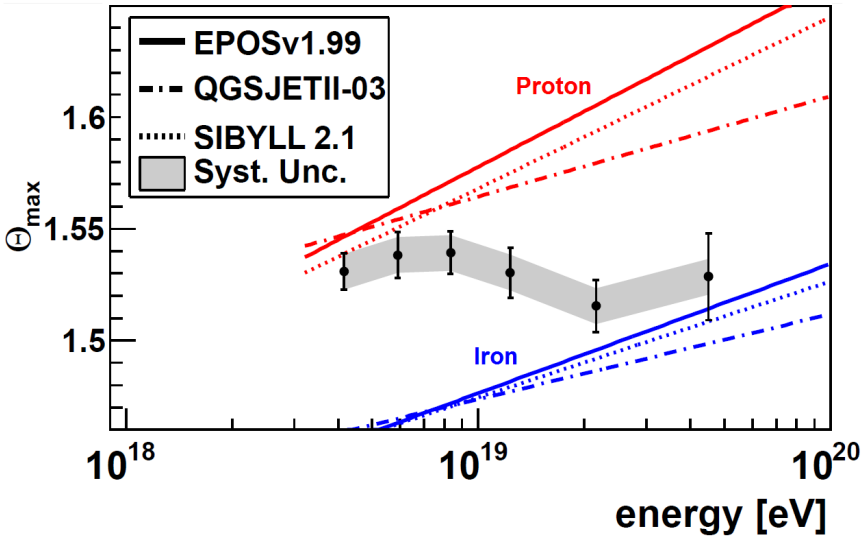






Azimuthal asymmetry in SD events



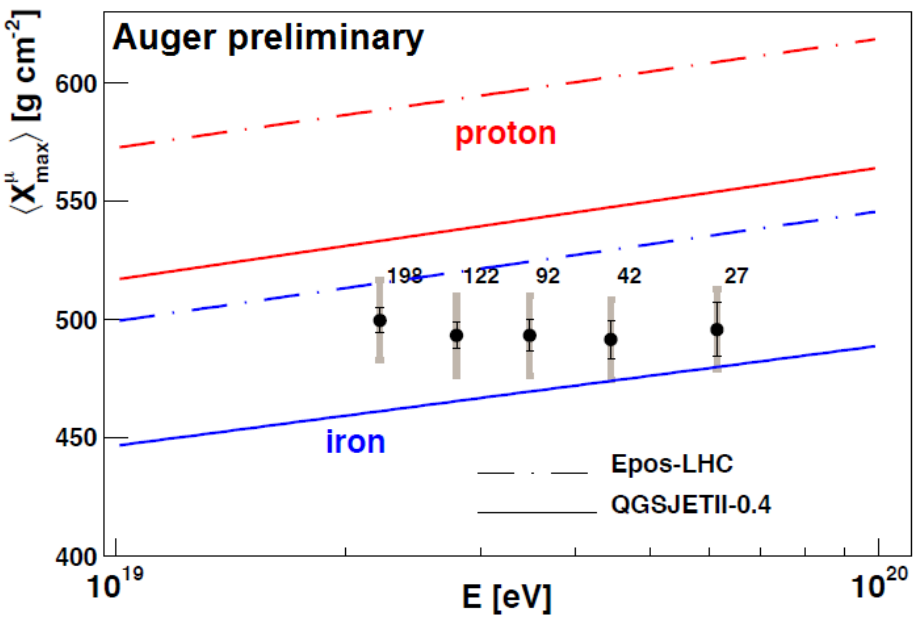


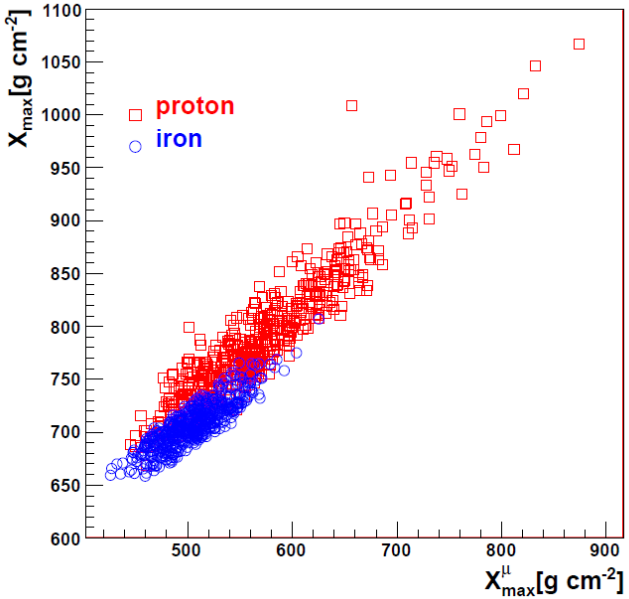
Θ_{max} is defined as the value of $sec(\Theta)$ for the zenith angle that gives maximum asymmetry

- events with $30^\circ <$zenith$< 60^\circ$
- $E > 20\,\mathrm{EeV}$
- $0.5 < r < 2\,\mathrm{km}$ from shower axis

Muon Production Depth

X^{μ}_{max} in SD events





- use muon arrival time differences
- events with 55° <zenith< 65°
- $E > 20\,\mathrm{EeV}$
- $r > 1.8\,\mathrm{km}$ from shower axis

Summary

Summary

- FD X_{max} measurement shows change of composition with increasing energy
- mixed scenario: light dominated at low energies, heavier with increasing energy (interpretation is very model dependent)
- challenging science case at the highest energy