2011 MUNICH TAUP

Pierre Auger Observatory
studying the universe's highest energy particles

The nuclear mass composition of UHECR with the Pierre Auger Observatory

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The Pierre Auger Observatory

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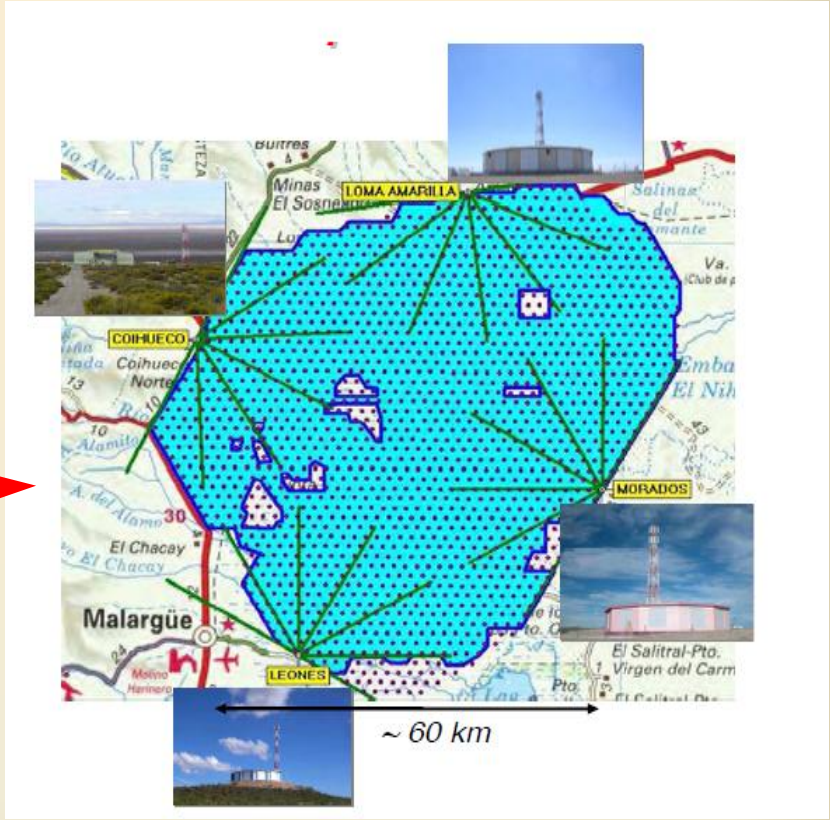
Latitude 35 S – Longitude 69 W

1400m a.s.l. X=870 g cm^2

Data taking since 2004

Installation completed in 2008



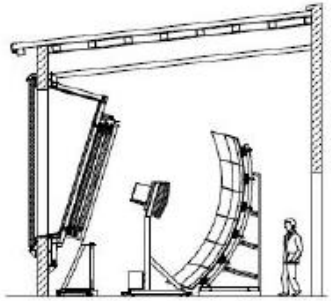
Surface Detector (SD)
1600 Cherenkov stations spaced 1.5 km
Area of 3000 km^2
100% duty cycle
Provides Large Statistics

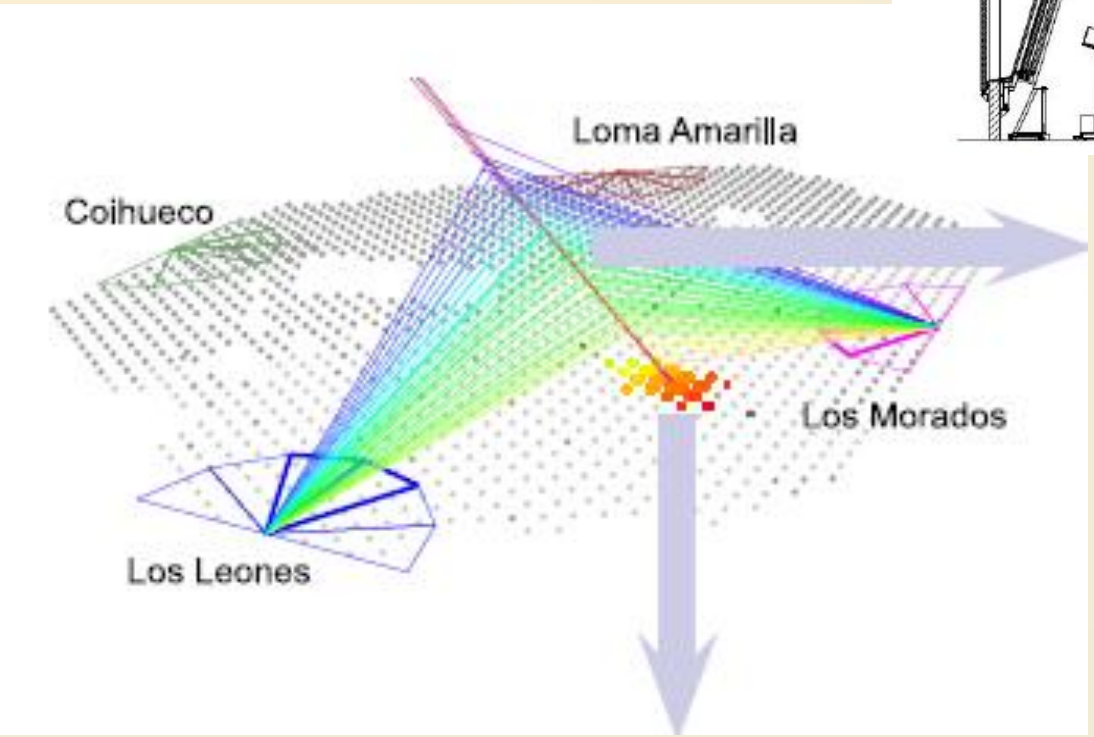
Fluorescence Detector (FD)
4 building with 6 telescopes each
Telescope f.o.v. 30 x 30 deg
~10% duty cycle
Provides High Accuracy

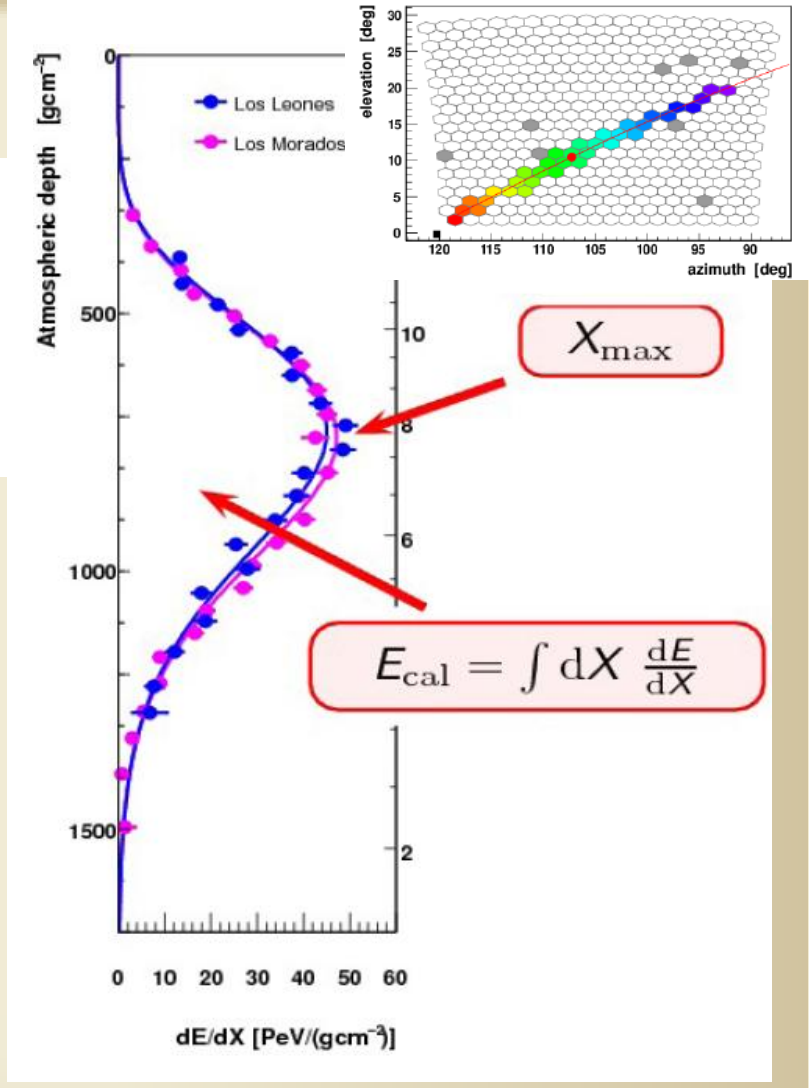
+ Enhancements: AMIGA, HEAT, Radio, etc

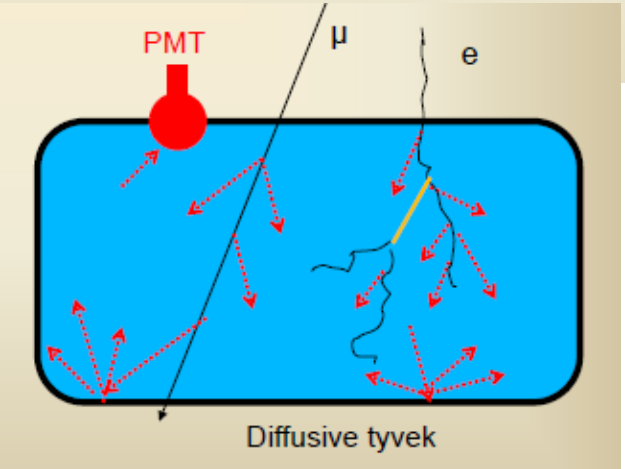
See also the other Auger contributions on: Photons, neutrinos, anisotropies, hadronic interactions, Auger Enhancements, and the review talks on Cosmic Rays

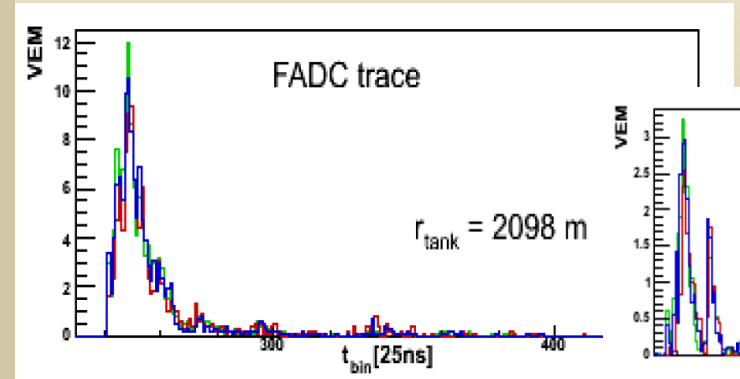
Hybrid detector
FD & SD

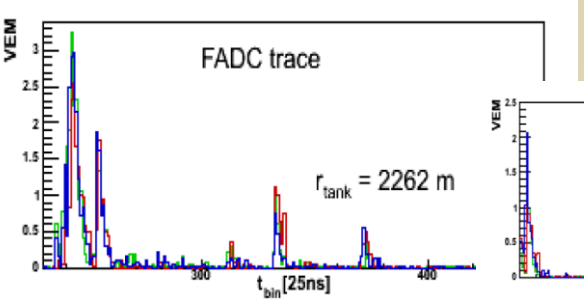


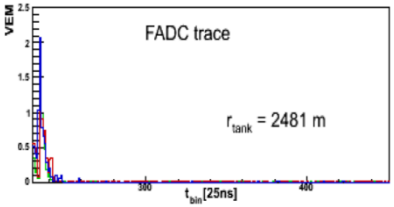




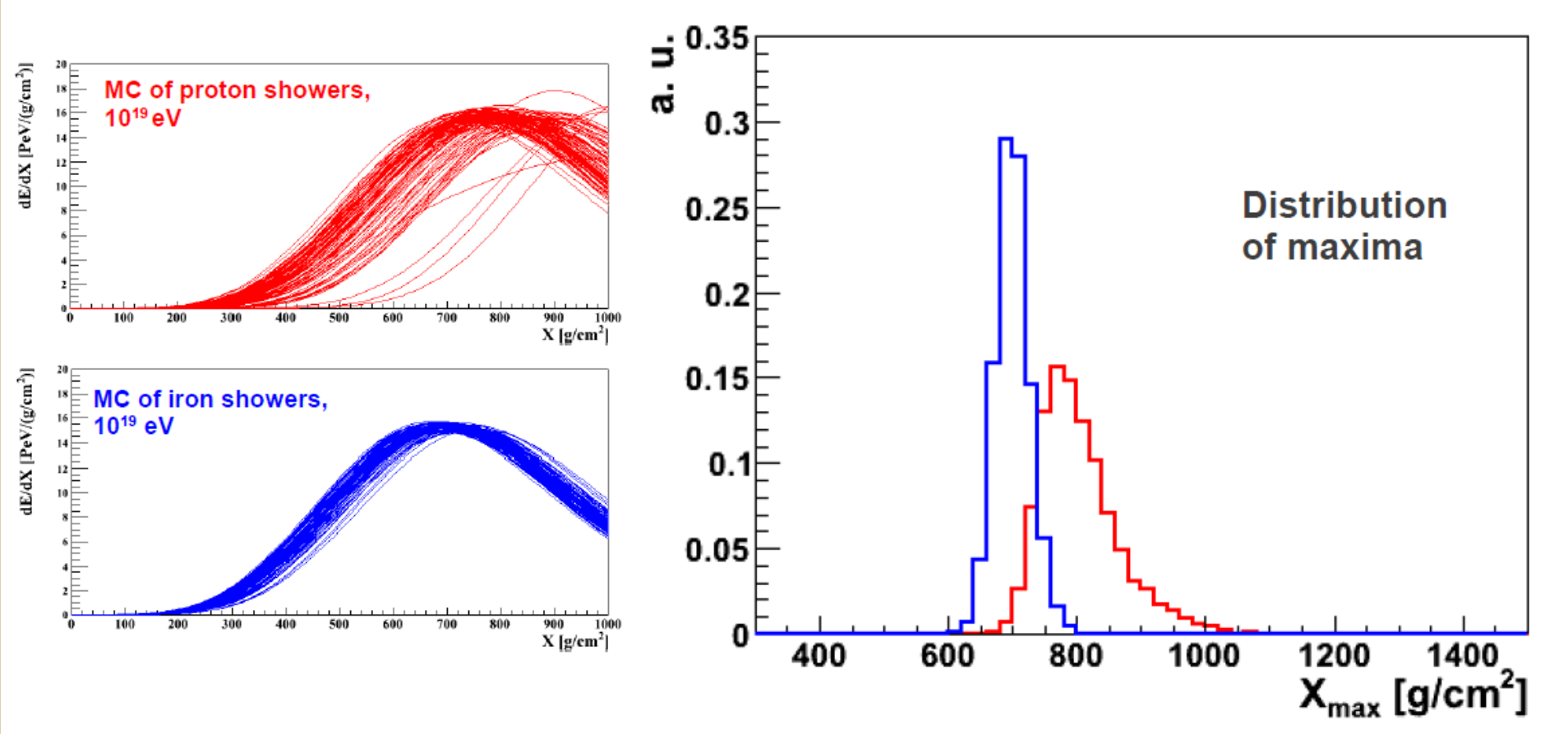








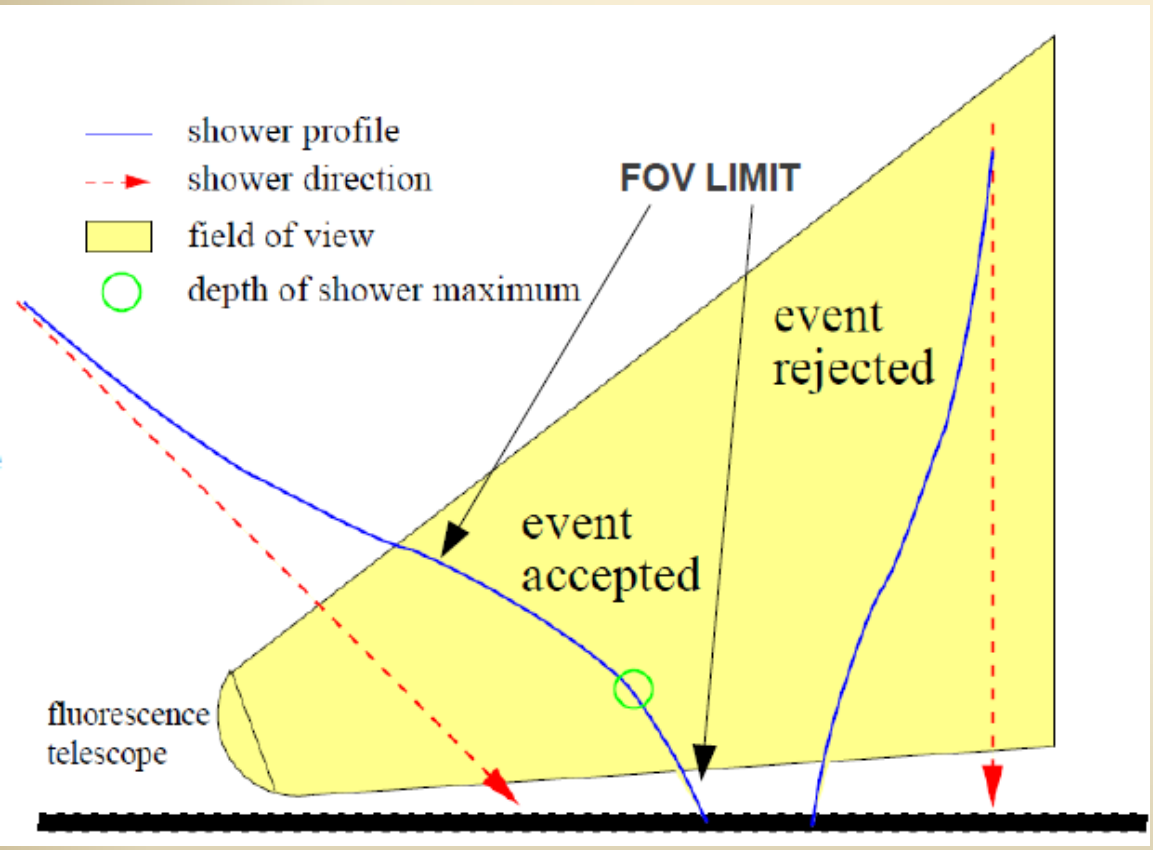
X_{max} and primary composition



- X_{max} reflects properties of the first interaction through X_1
- Distributions for heavy primaries, as iron, are narrower and shallower. Lighter primaries, like protons, have a characteristic tail towards deep X_{max}
- Hadronic interaction models predict different $\Delta X = X_1 - X_{max}$. .

Selection cuts

Data Sample: FD events with signal in at least 1 SD station from December 2004 to September 2010



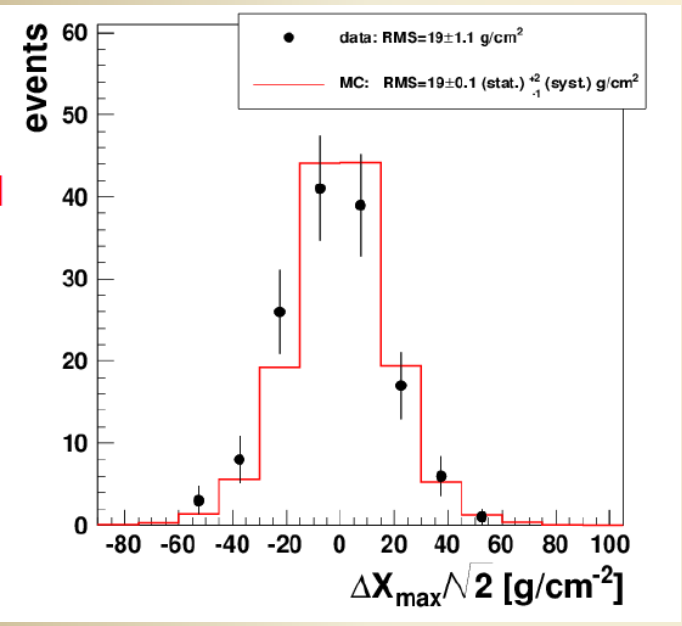
Selection of high quality events:
- Low aerosol content (vert. opt. depth > 0.1) & cloud coverage (<25%).
- χ^2/Ndf < 2.5 for profile fit
- Statistical uncertainty X_{max} < 40 g/cm^2
-Angle between shower and telescope > 20° (avoid high Cherenkov fractions)
- X_{max} observed

15979 events pass this quality selection [E > 10^{18} eV].

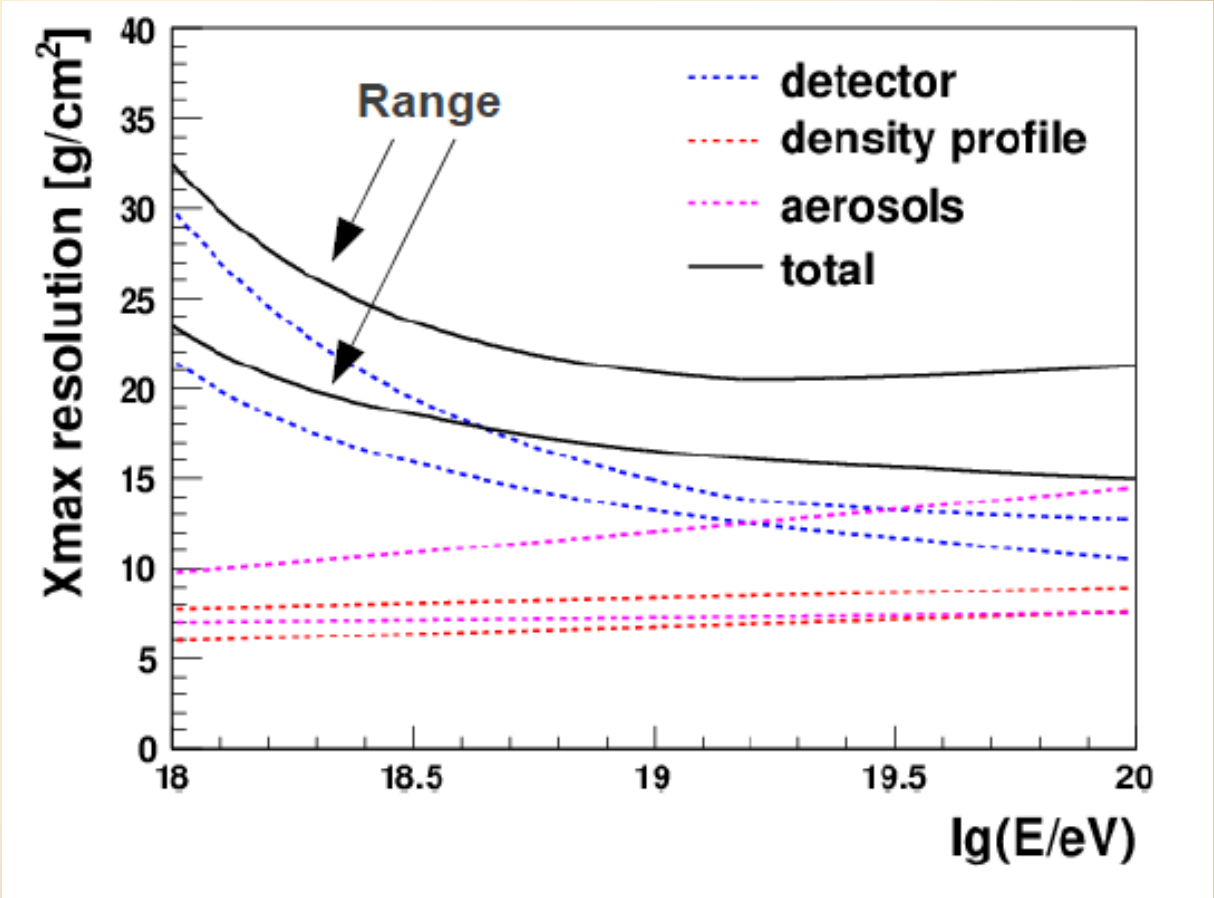
Unbiased selection:
- Select the distance to the SD station, and zenith angle so that the tank trigger probability does not depend on the mass of primary
- Select event geometries that allow to sample the whole X_{max} distribution (from measurement).

6744 events selected

X_{max} resolution



Validated with events with more than 1 FD station

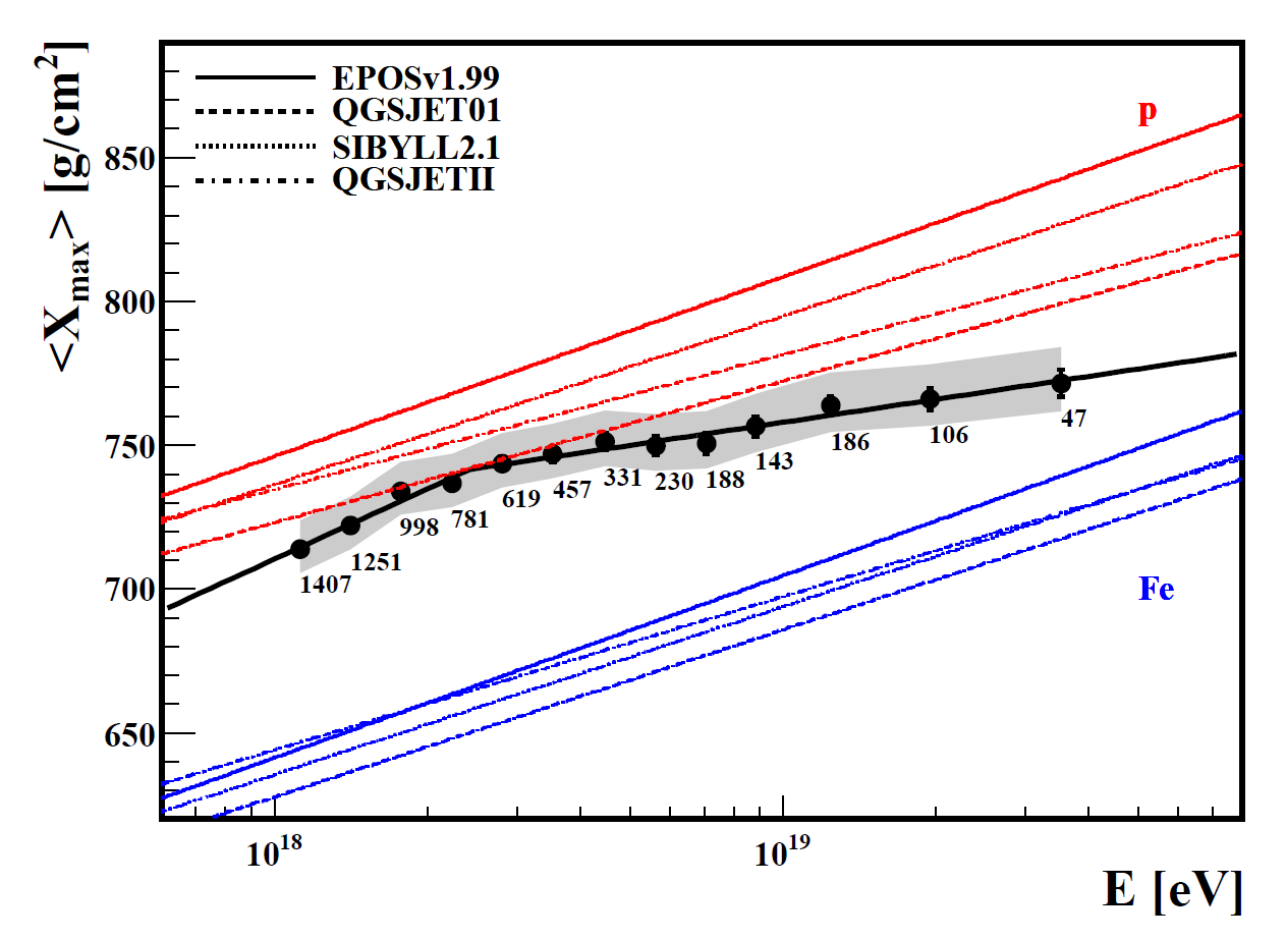


Energy dependent: low energy events have less signal and smaller tracks. At high energy, events are farther away and aerosol content uncertainty dominates.

Systematic Uncertainties
Xmax → from 10 to 13 g/cm^2
RMS(Xmax) → 5 g/cm^2

$<X_{max}>$ vs Energy

$$D_{10} = \frac{d<X_{max}>}{d\lg E} \sim \alpha\left(1 - \frac{d<\ln A>}{d\ln E}\right)\ln(10)$$



Low Energy

$$D_{10} = 82^{+48}_{-8}\ \mathrm{g/cm^2/decade}$$

High Energy

$$D_{10} = 27^{+3}_{-8}\ \mathrm{g/cm^2/decade}$$

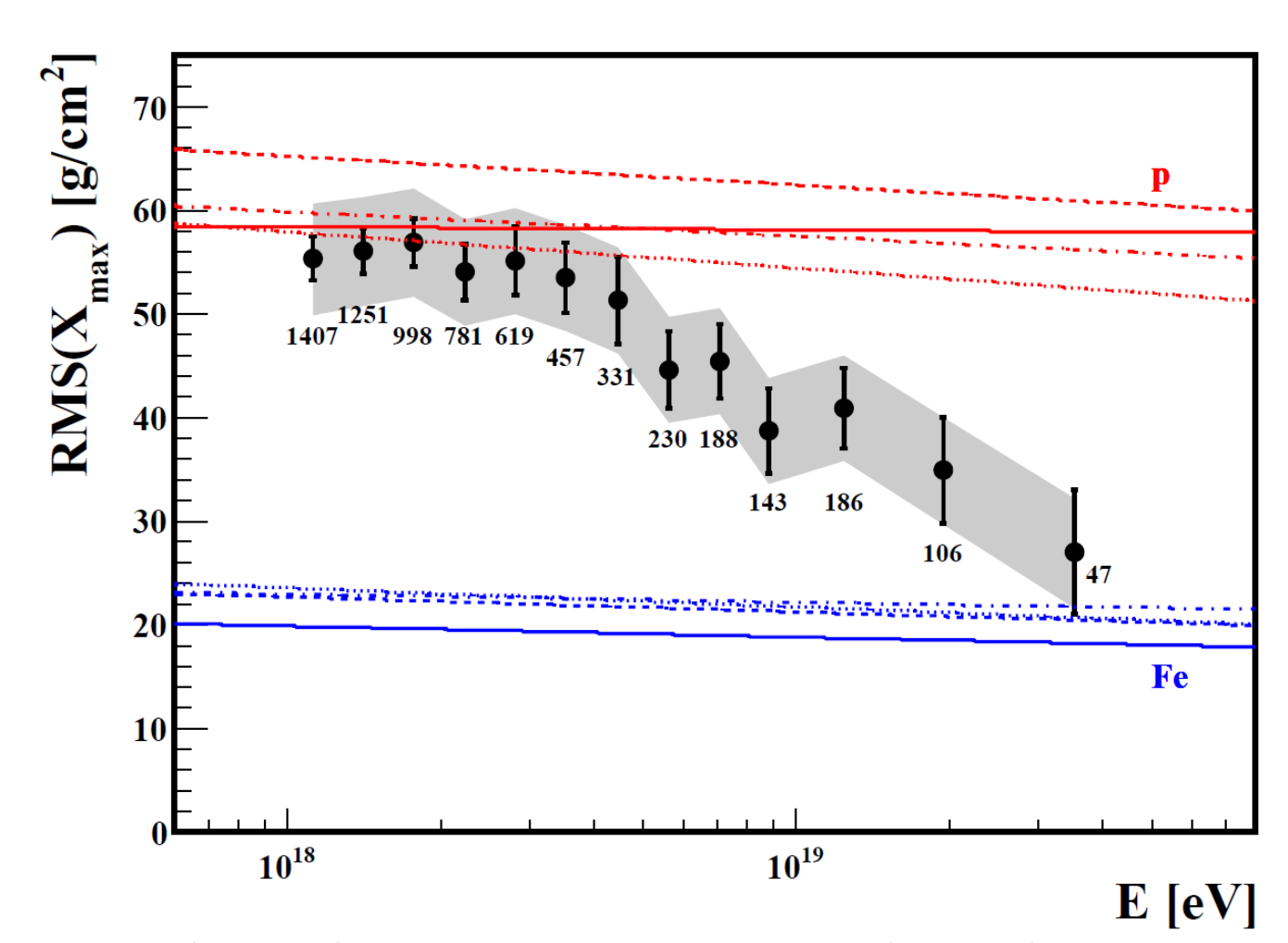
Energy break

$$\log(E_{break}/\mathrm{eV}) = 18.38^{+0.07}_{-0.17}$$

If hadronic interactions do no change much over less than 2 decades, this change on D_{10} would imply a **change on the energy dependence of the composition around the ankle**.

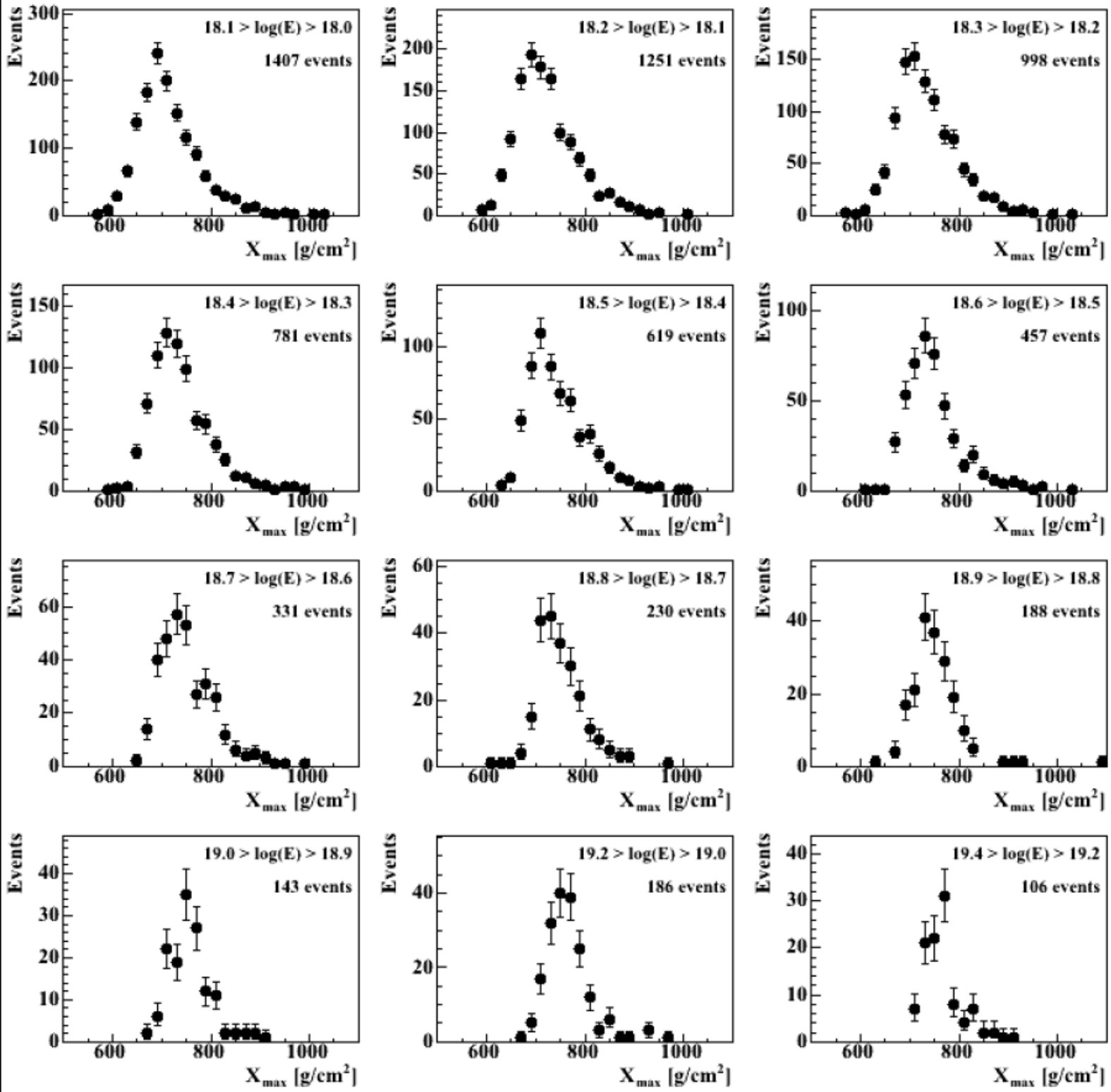
- Data are best described with two slopes; break is near the same energy as the ankle feature of the spectrum
- When compared to the models at high energy, data suggests a gradual increase of the average mass

RMS vs Energy



Resolution is subtracted from data:
27 g/cm2 → low energy
18 g/cm2 → high energy

There is a change in behavior around the same energy as <X_{max}>: above 2.5 10^{18} eV there is a fast decrease of RMS(X_{max}) towards the values expected for heavy primaries.



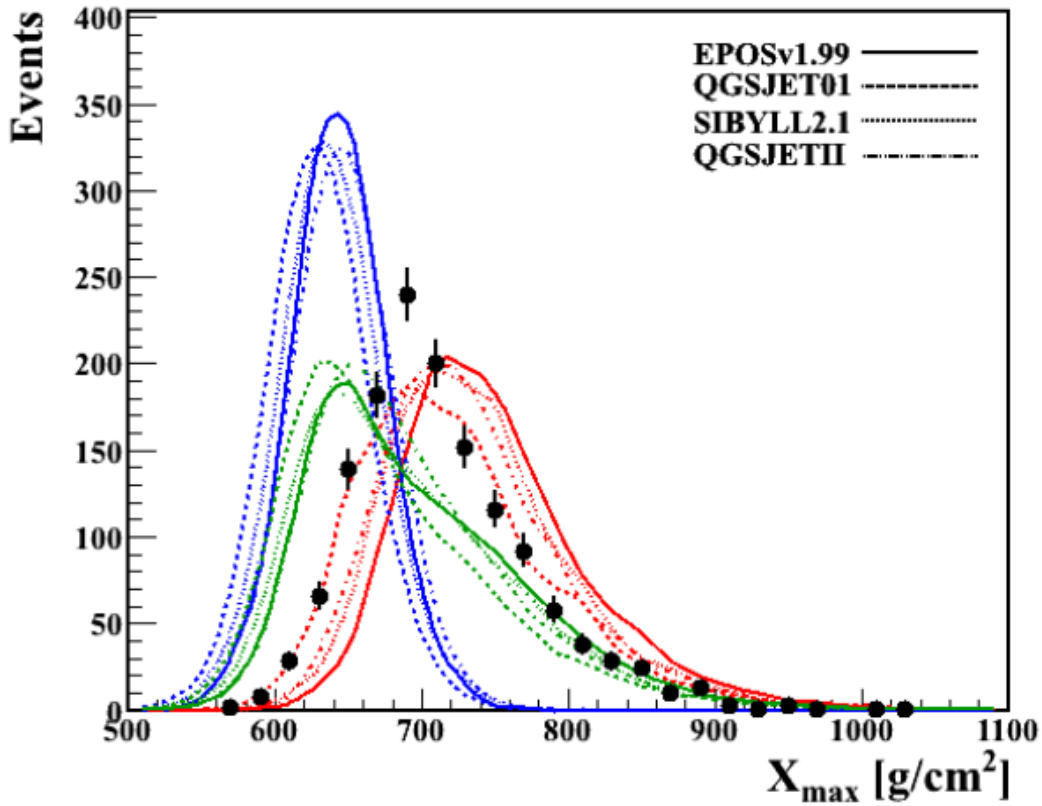
Full Distributions

As the energy increases:
- narrower distributions
- deep X_{max} tail less evident

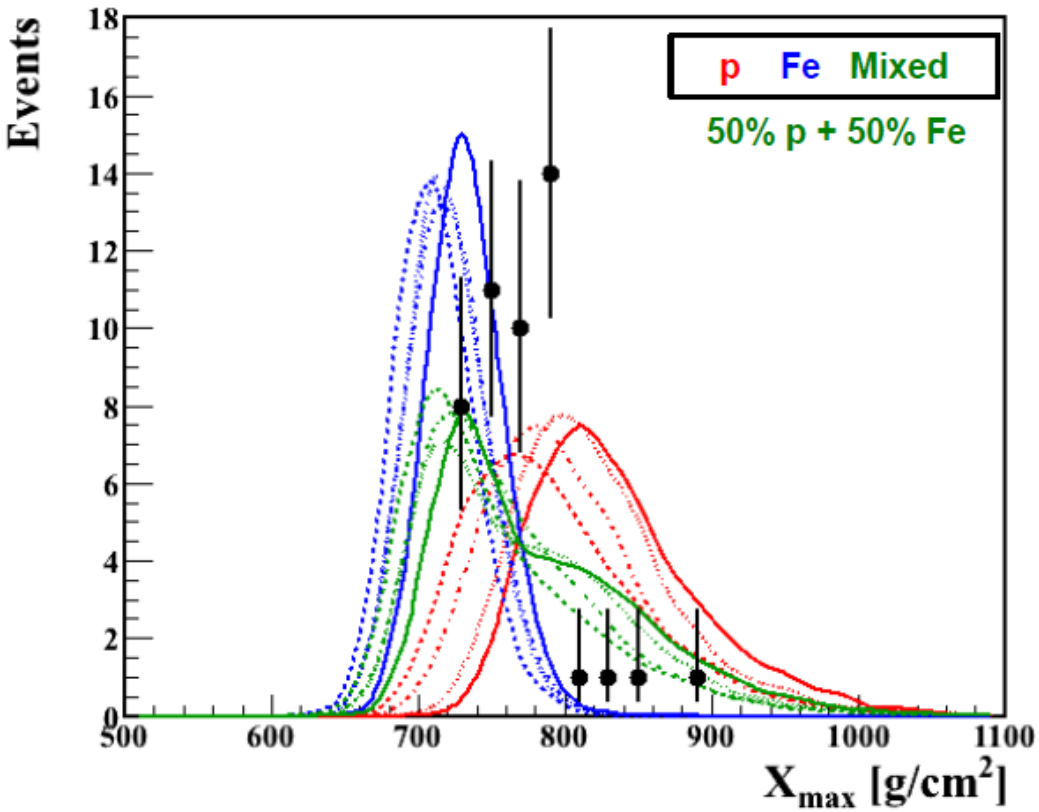
Interpretation rely on the extrapolation provided by the different models

Comparison to models

(lowest E bin) 18.1 > log(E/eV) > 18.0



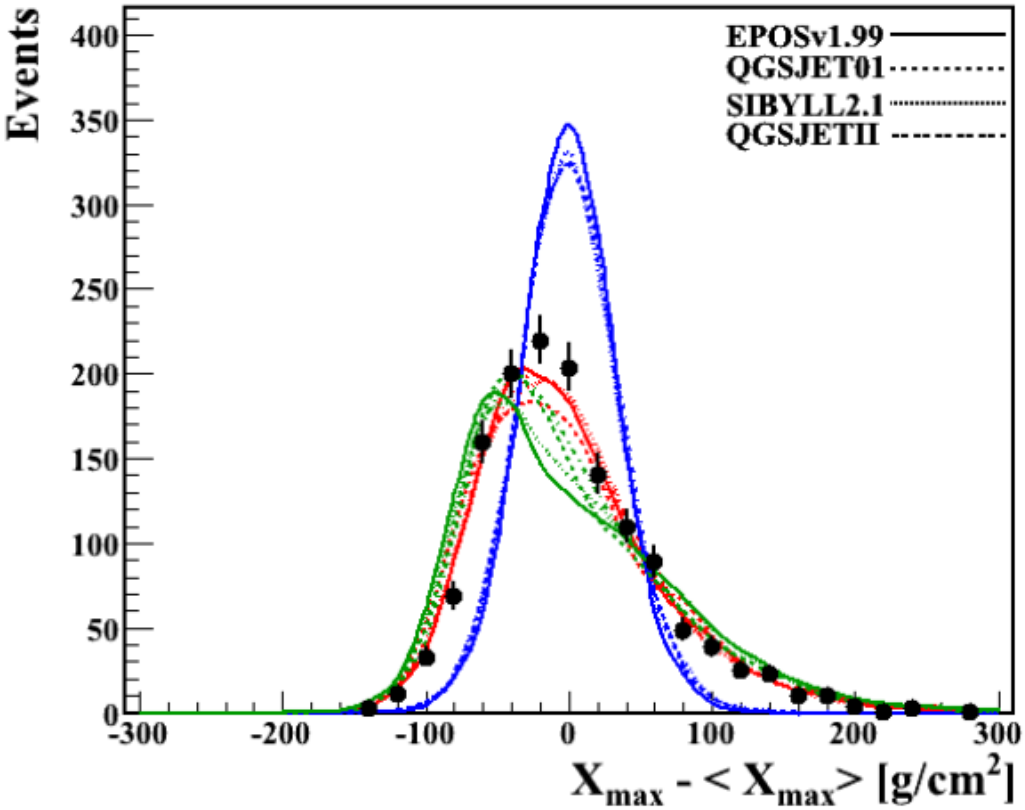
(highest E bin) log(E/eV) > 19.4



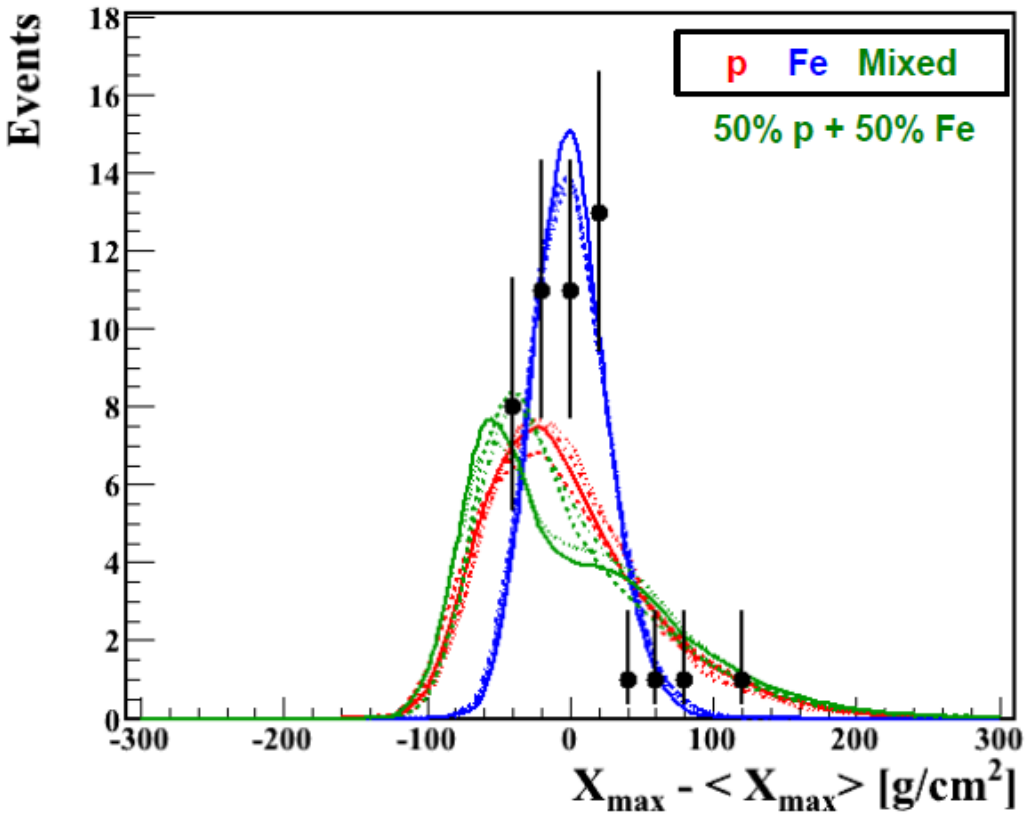
The model predictions have similar shapes but different <X_{max}>

Shape comparison

(lowest E bin) 18.1 > log(E/eV) > 18.0



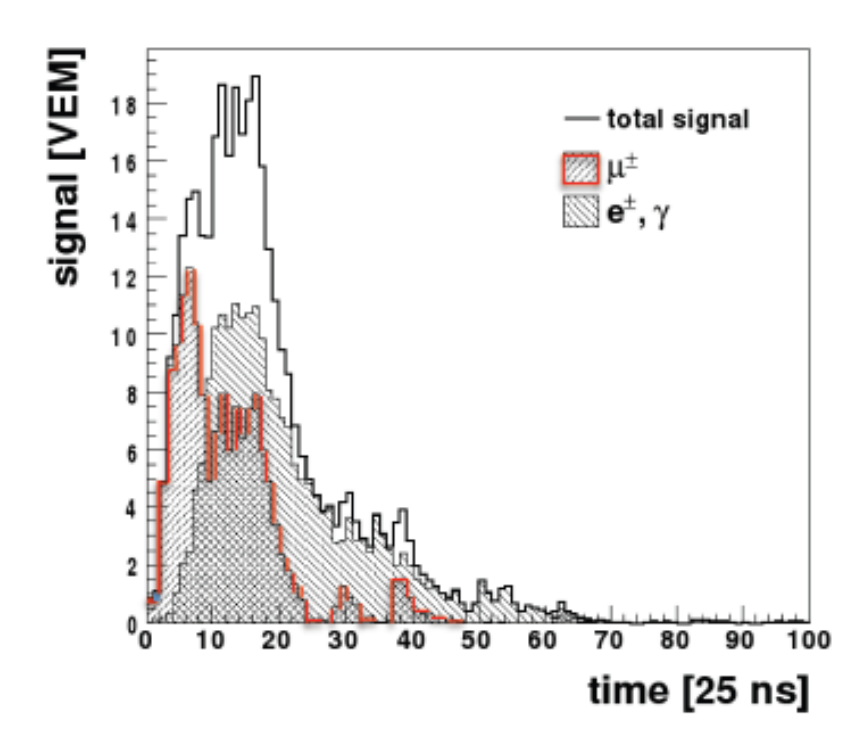
(highest E bin) log(E/eV) > 19.4



Shape at low energy fits lighter composition. Shape at high energy fits heavier

Time structure of SD signals

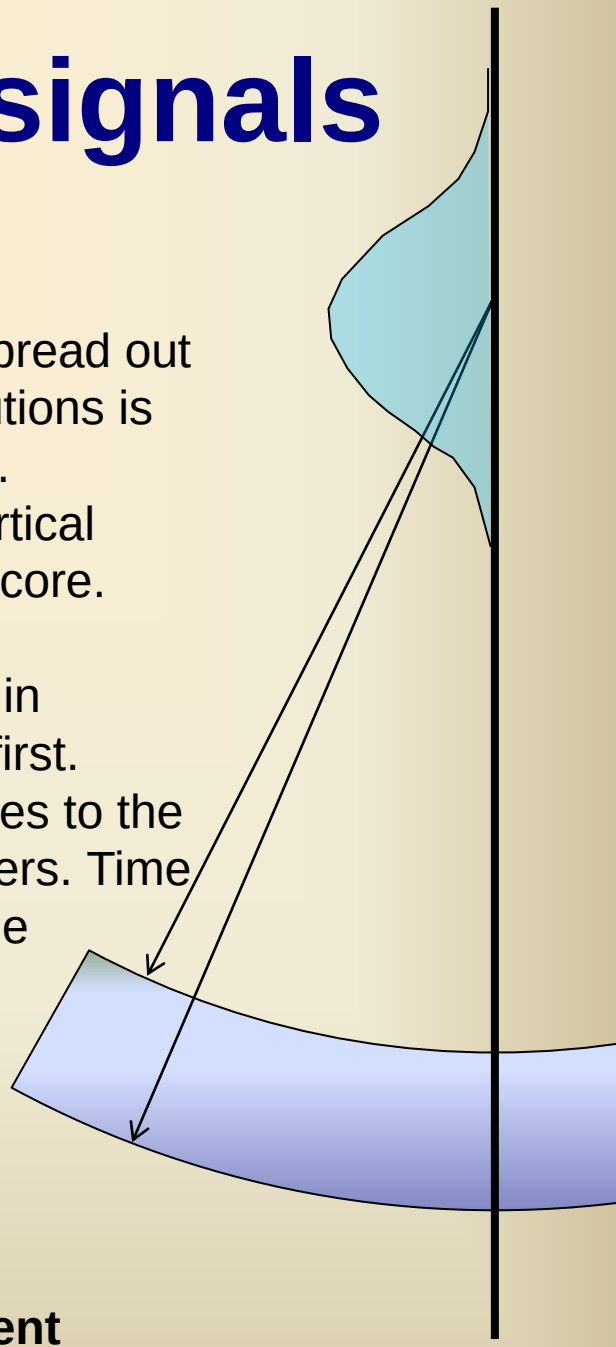
Particle signals are merged in the Cerenkov tank. (Untangling is difficult).



Risetime ($t_{1/2}$): time required to go from 10% to 50% of the total signal.

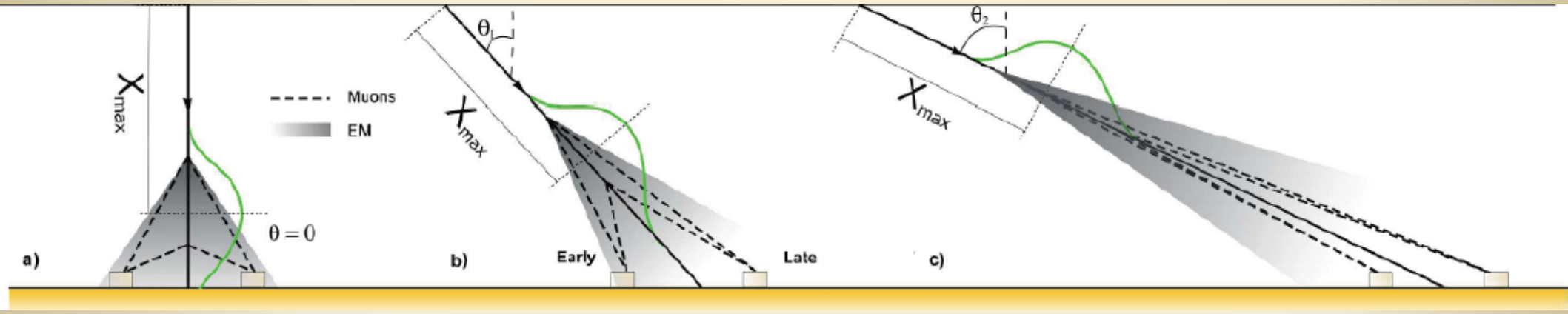
EM: muliple scattering. Spread out in time. Their time distributions is related to the shower age. Dominate the signal in vertical showers and close to the core.

μ: less interacting. Travel in straight lines, they arrive first. Dominate at large distances to the core and in inclined showers. Time distribution is related to the distance of production.



The time structure of SD signals has information about shower development

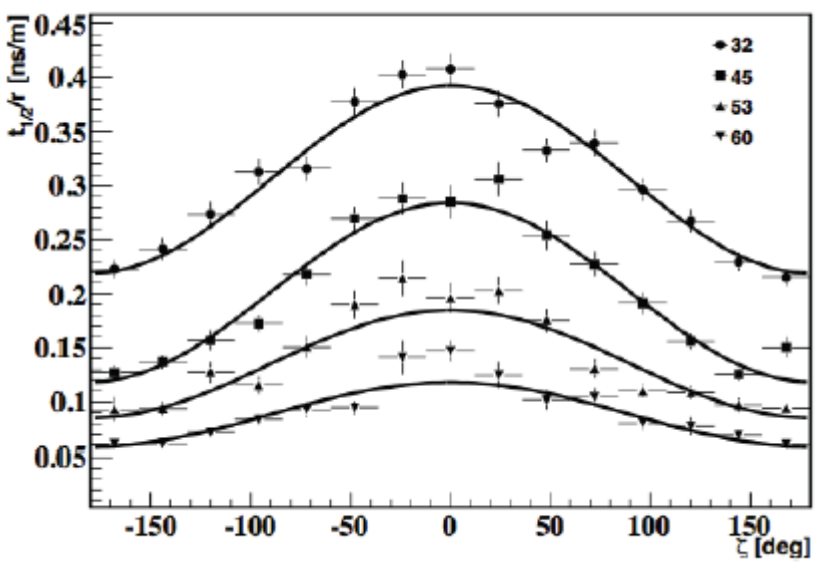
Assymetry of signal risetime



Weak assymetry | **Strong assymetry** | Weak assymetry

$$< t_{1/2} / r > = a + b \cos \varsigma$$

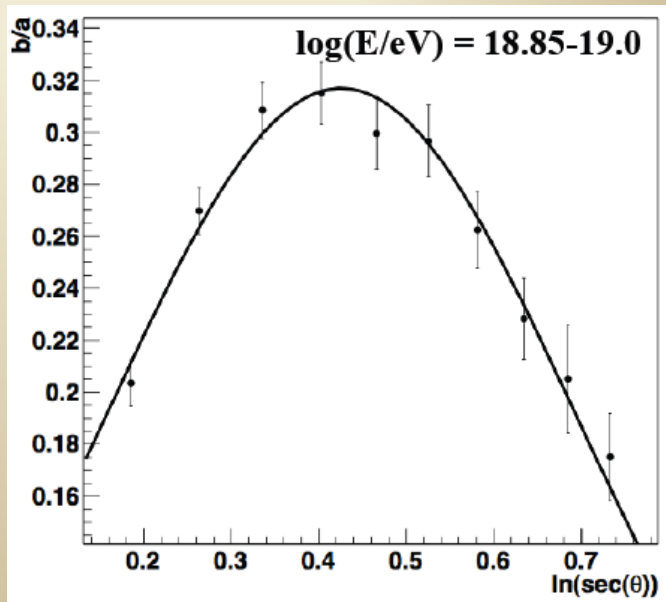
The early-late assymmetry **(b/a)** as function of the zenith angle has a maximum (Θ_{max}) which is correlated with X_{max}



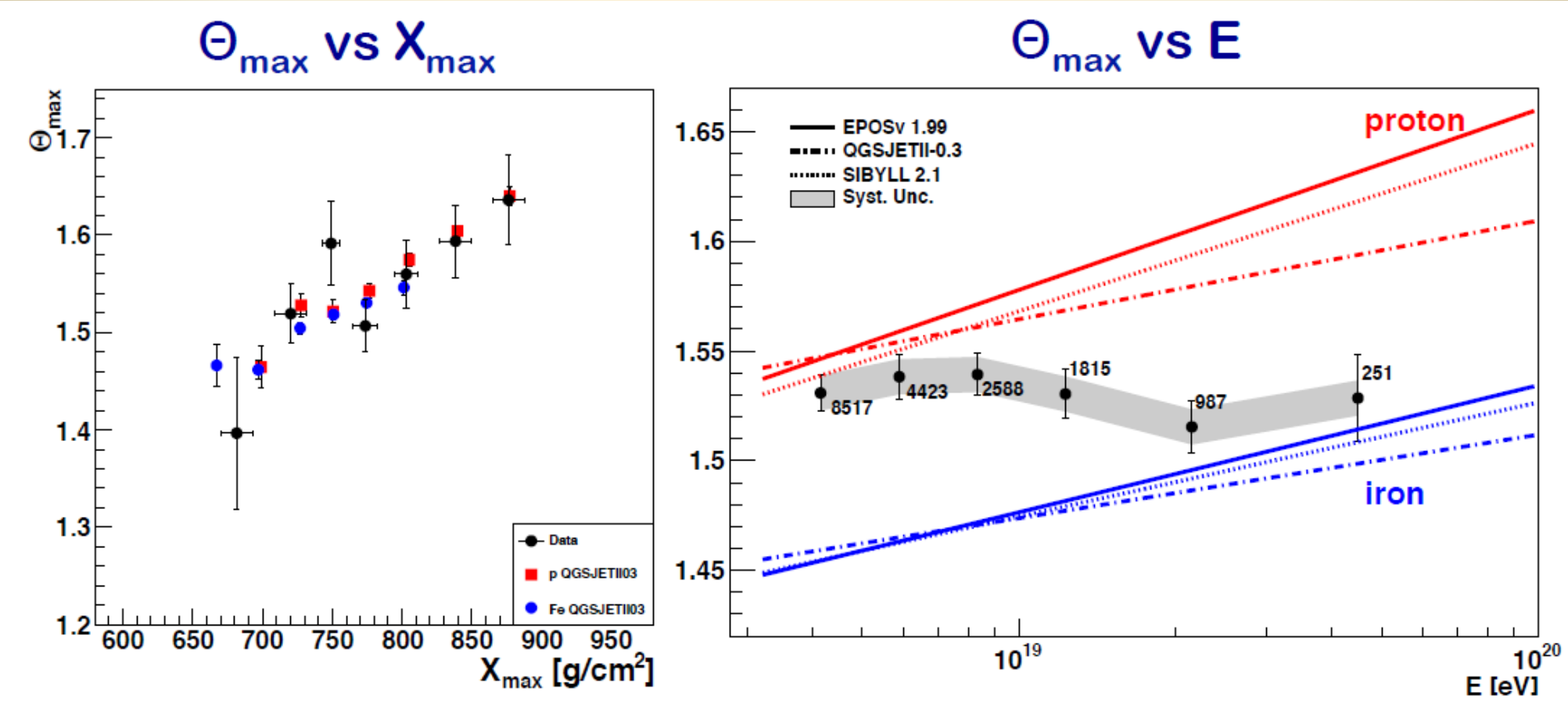
Event selection:

- $30^o < \theta < 60^o$
- 500 m < r < 2000 m
- E > 3.16 10^{18} eV

Systematic uncertainty ≤ ~10% proton-iron separation



Θ_{max} results



Using Hybrids events
Θ_{max} and X_{max} are correlated.
This correlation is independent of the primary.

18581 SD events (Jan 2004 – Dec 2010)
$E > 3.16\ 10^{18}$ eV, and $30° < \theta < 60°$

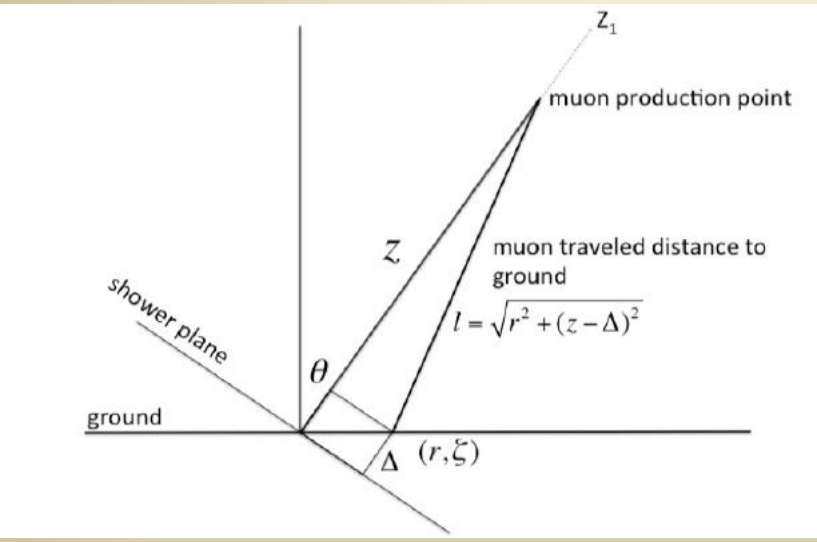
Depth Profile of Muon Production Points

Muons are produced within a narrow cylinder centered on the shower axis. They travel along straight lines, practically unaffected by multiple scattering, pair production and bremsstrahlung.

This implies a direct relation between arrival time delay and the muon production distance

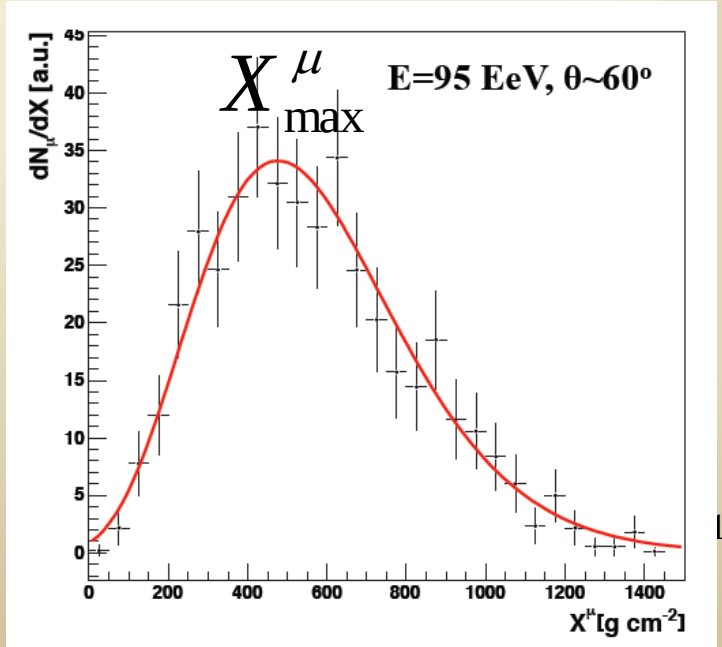
$$z \cong \frac{1}{2}\frac{r^2}{ct} + \Delta$$

Muon Production Depth : the depth, measured parallel to the shower axis, at which a given muon is produced. It can be obtained from the SD signals far from the core, for single events.



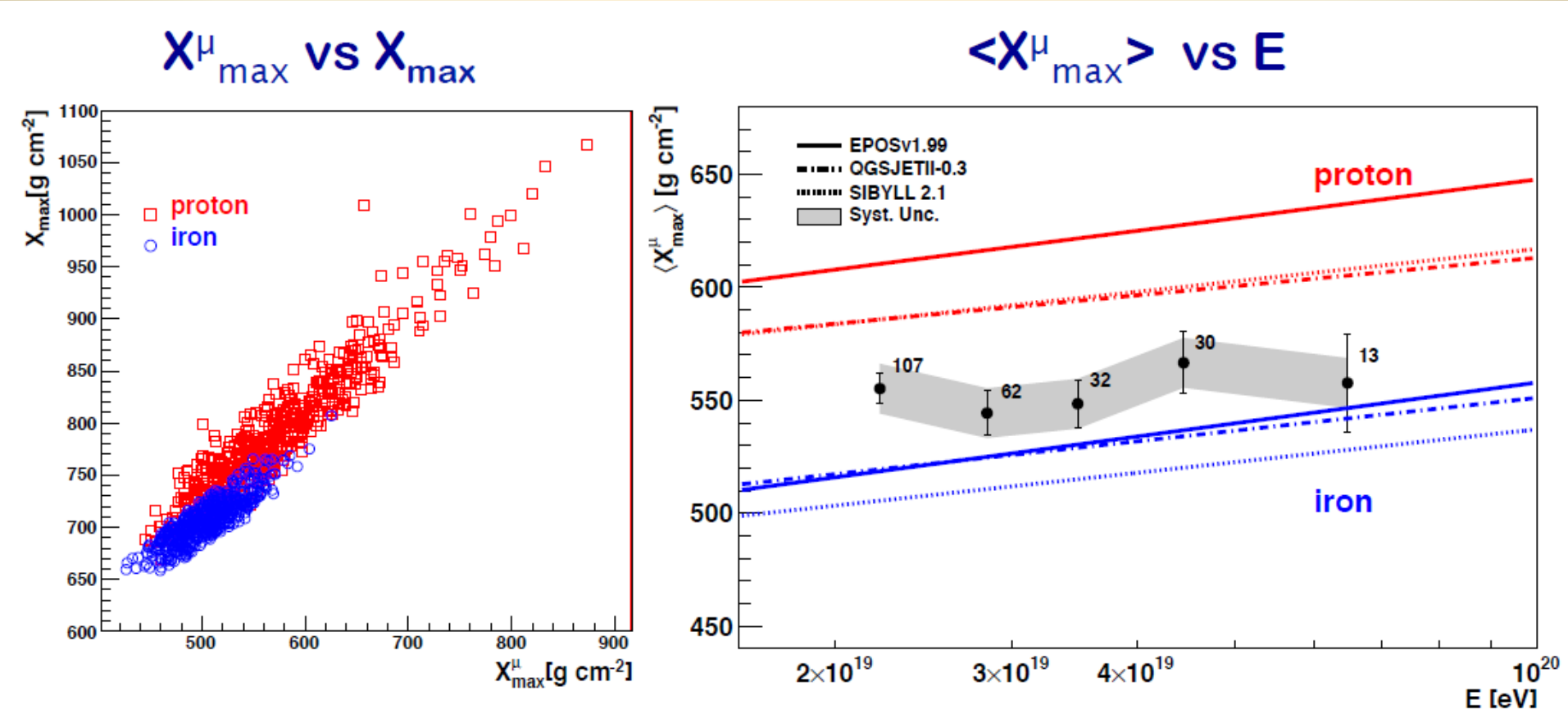
Event selection:

- 55° <θ <65°
- r > 1800 m
- E > 20 EeV



Systematic uncertainty ≤ ~11 g/cm²
(≤ 14% proton-iron separation)

X^{μ}_{max} results



MC events

244 SD events (Jan 2004 – Dec 2010)
E > 20 EeV 55° < θ < 65°

Conclusions

- $<X_{max}>$ and RMS(X_{max}) recently updated with 80% more statistics, compatible with previous publication.
- X_{max} distributions become narrower as the energy increases. The deep X_{max} tail becomes shorter.

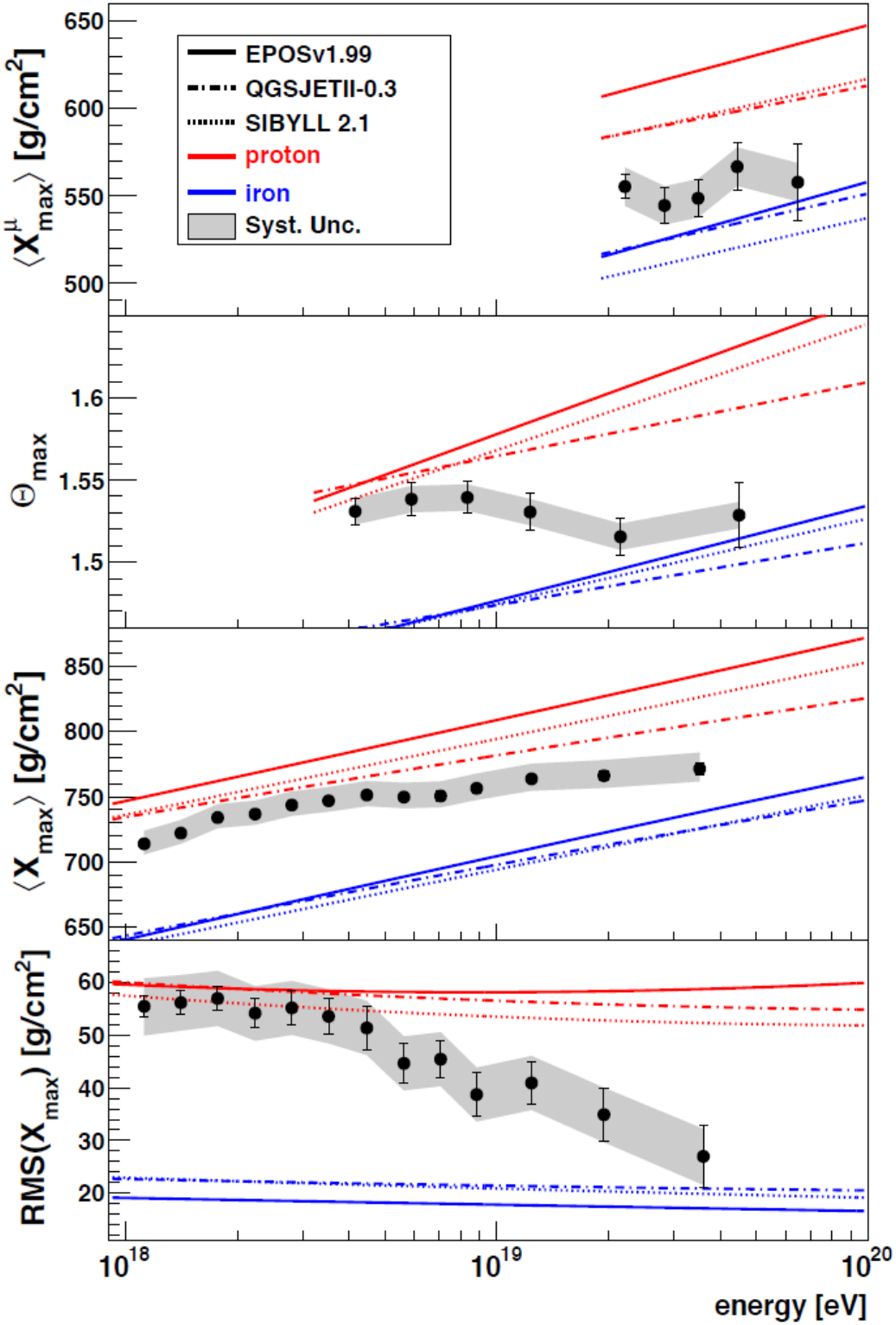
INTERPRETATION

- If hadronic interactions do no change much over less than 2 decades, this change on D_{10} would imply a change on the energy evolution of composition around the ankle towards heavier
- At low energy, the data is consistent with a significant fraction of protons
- The shape of the distributions is heavy-like at high energy, but for most of the models data would have to be adjusted to simultaneously match X_{max} and RMS(X_{max}) to a given composition mixture.
- **Change on the predictions of the available hadronic models would modify the interpretation in terms of primary mass**

Summary SD & FD

,Several SD observables related with the longitudinal development of air showers have been reconstructed: SD statistics allows us to reach higher energies.

- **Compatible results with different systematics.**
- **Assuming that the hadronic interaction models are correct**, the comparison of the data and simulation leads to the conclusion that **the mean mass rises as the energy increases.**

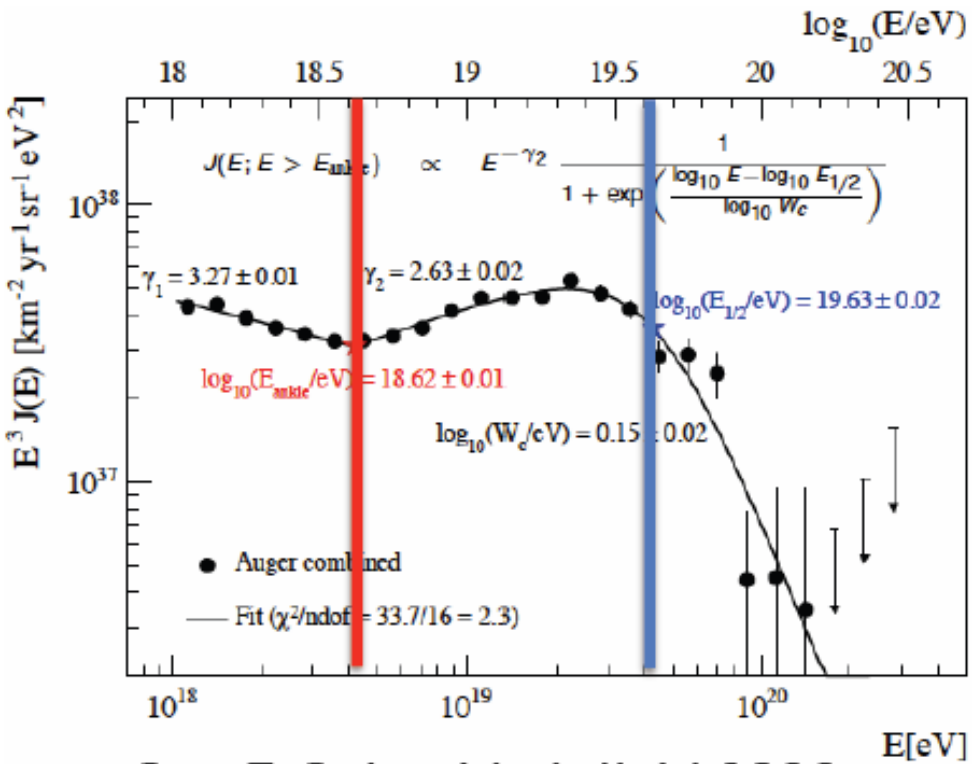


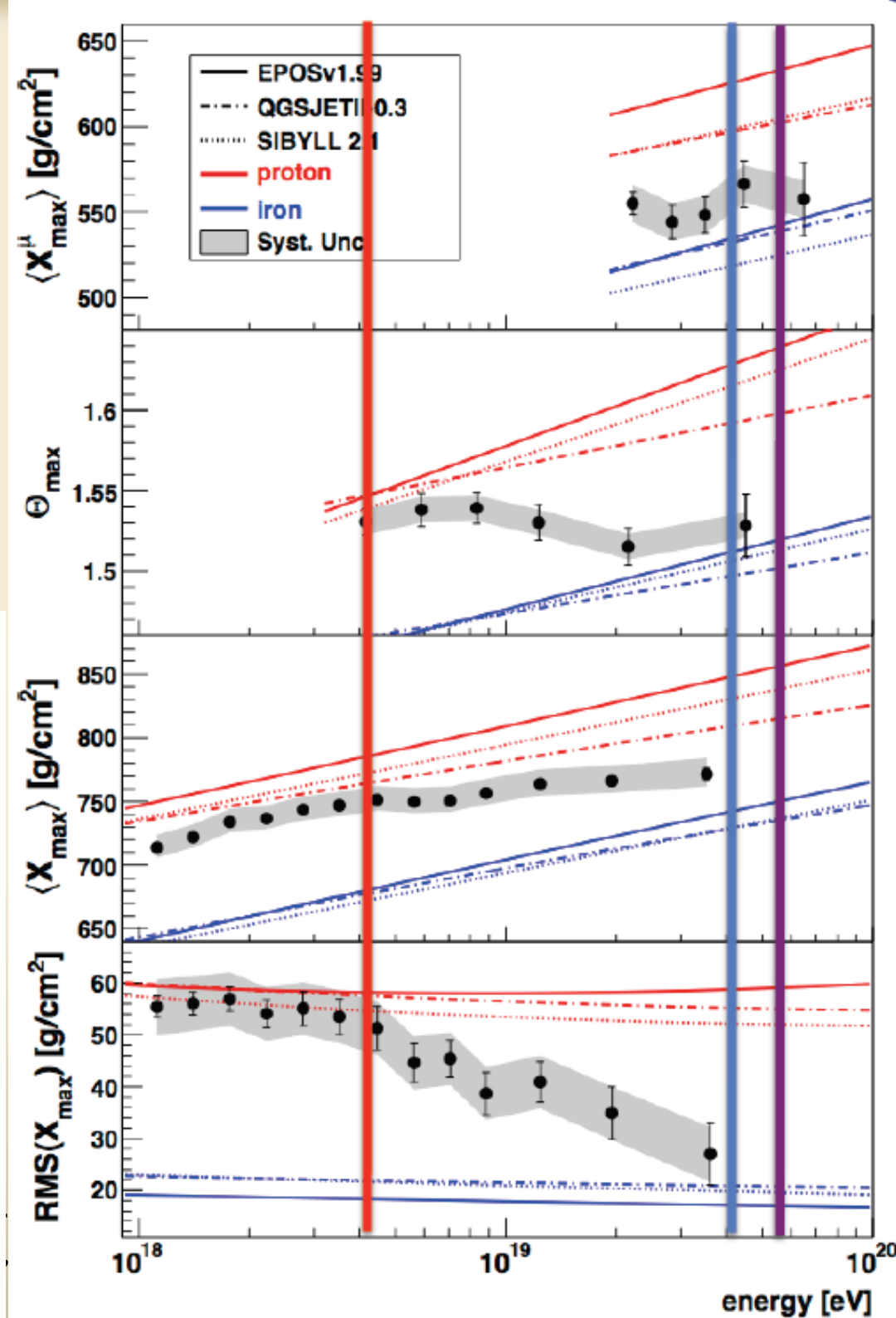
L. Cazón

The End

Back up slides

Spectrum


log10(E/eV)
18
18.5
19
19.5
20
20.5
E^3 J(E) [km^-2 yr^-1 sr^-1 eV^2]
γ1 = 3.27 ± 0.01
γ2 = 2.63 ± 0.02
log10(E1/2/eV) = 19.63 ± 0.02
log10(Eankle/eV) = 18.62 ± 0.01
log10(Wc/eV) = 0.15 ± 0.02
Auger combined
Fit (χ²/ndof = 33.7/16 = 2.3)
E[eV]


EPOSv1.99
QGSJETII 0.3
SIBYLL 2.1
proton
iron
Syst. Unc
⟨X^μ_max⟩ [g/cm²]
Θ_max
⟨X_max⟩ [g/cm²]
RMS(X_max) [g/cm²]
energy [eV]