PIERRE AUGER OBSERVATORY

Experimental Constraints to high energy hadronic interaction models using the Pierre Auger Observatory part-I

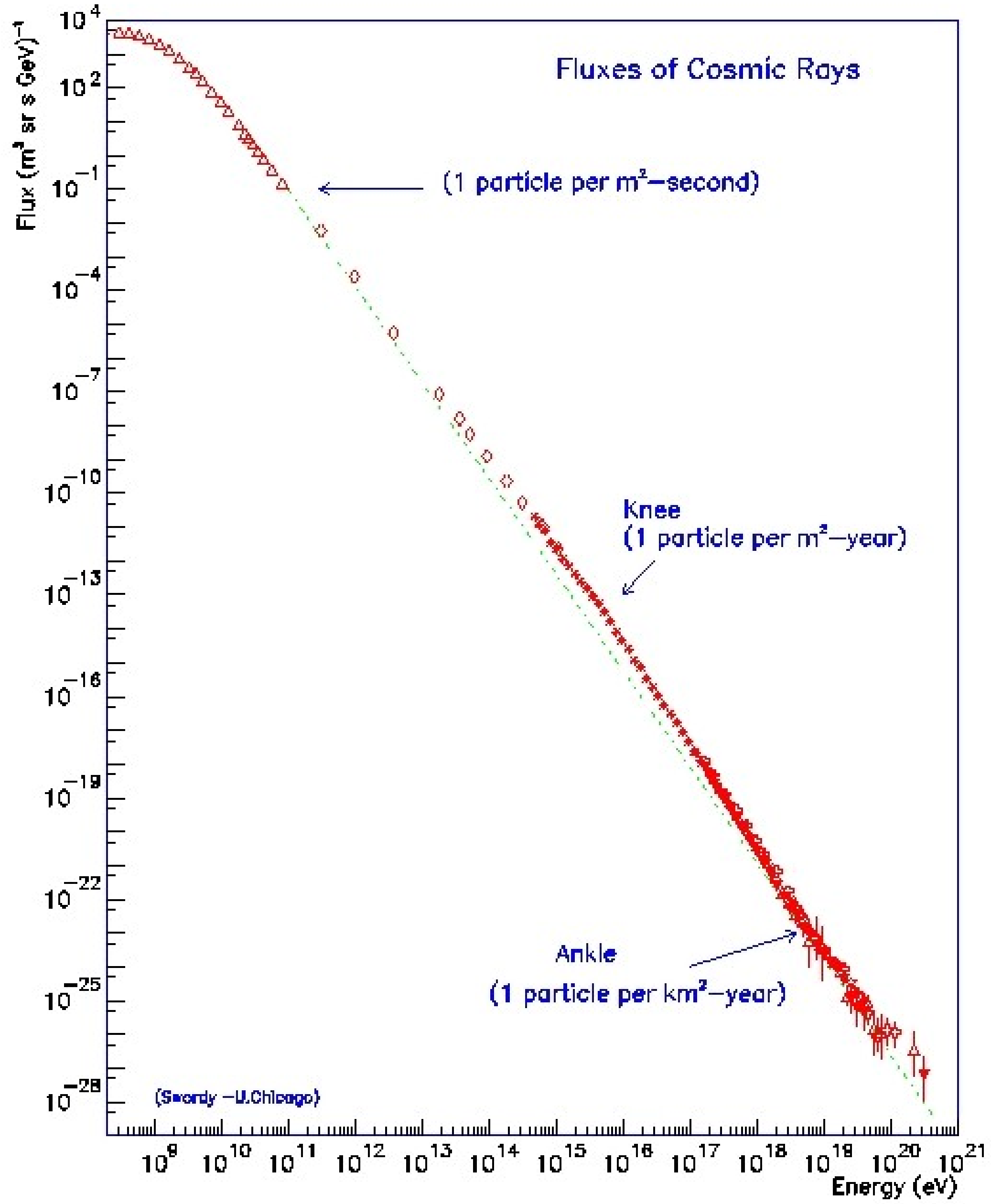
(cosmic rays, the Auger detectors, event reconstruction, observations)

Jose Bellido

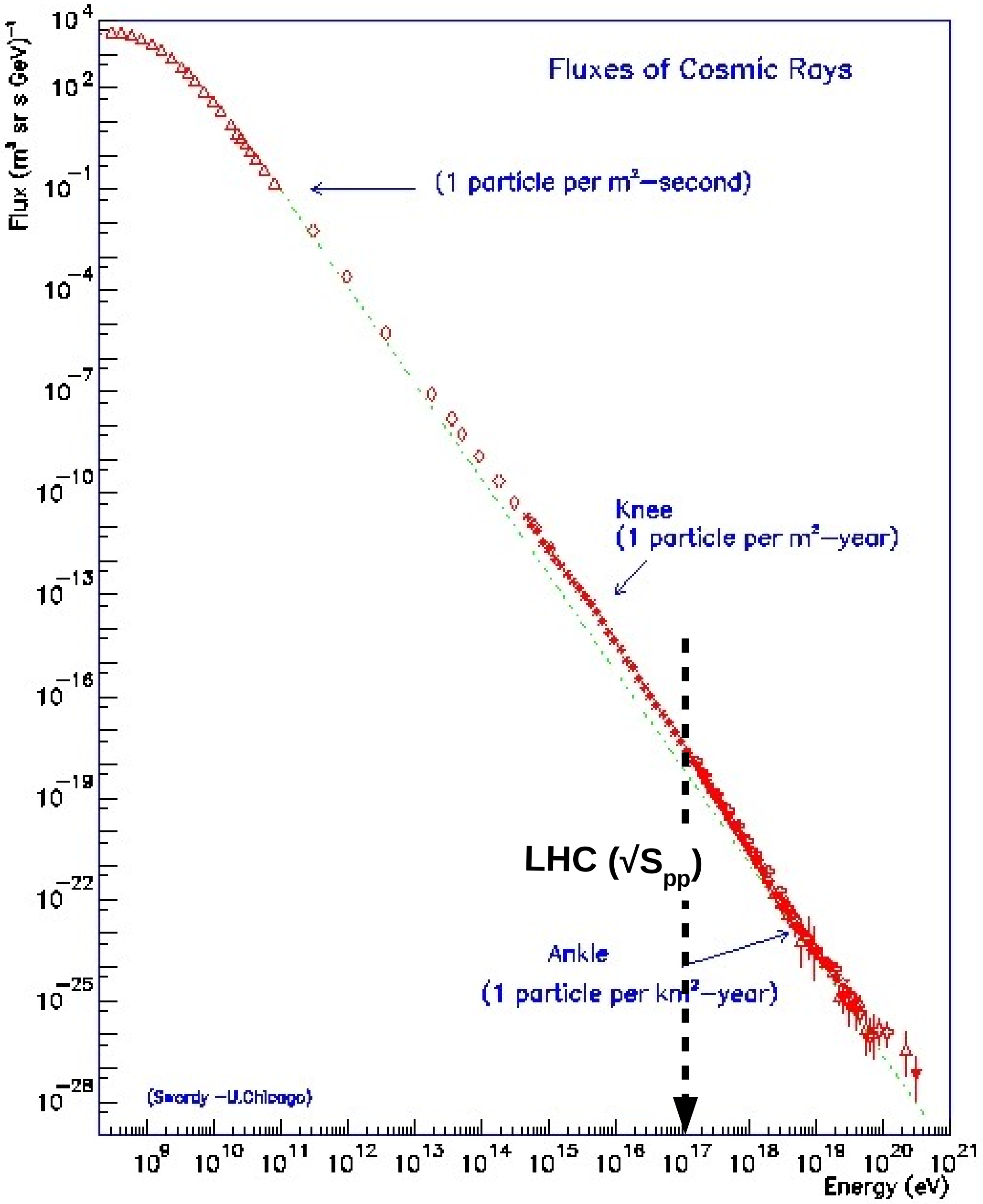
THE UNIVERSITY of ADELAIDE

QCD @ Cosmic Energies, 16 – 20 of May, 2016, Chalkida, Greece

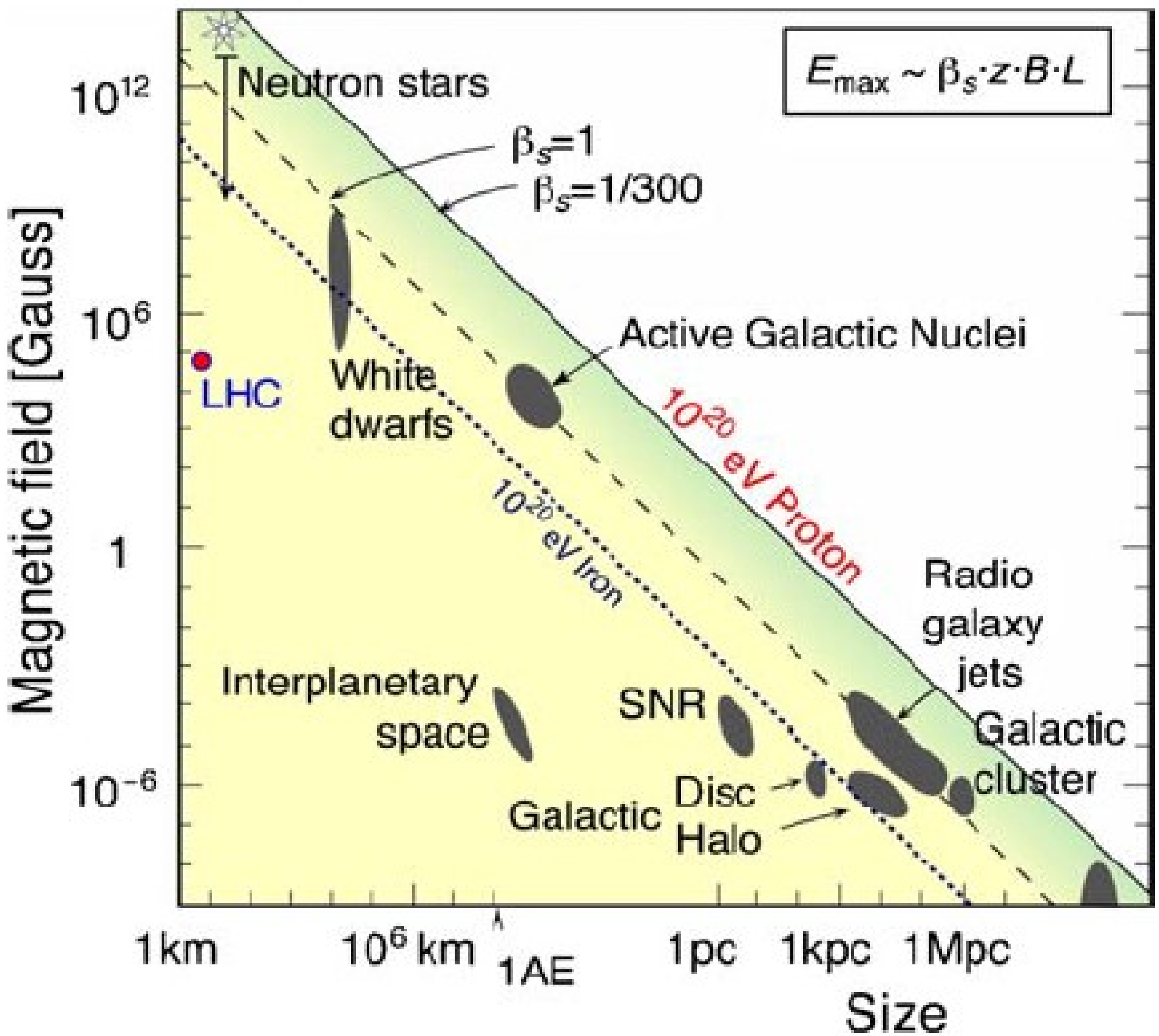
Cosmic Rays flux as a function of energy



Cosmic Rays flux as a function of energy



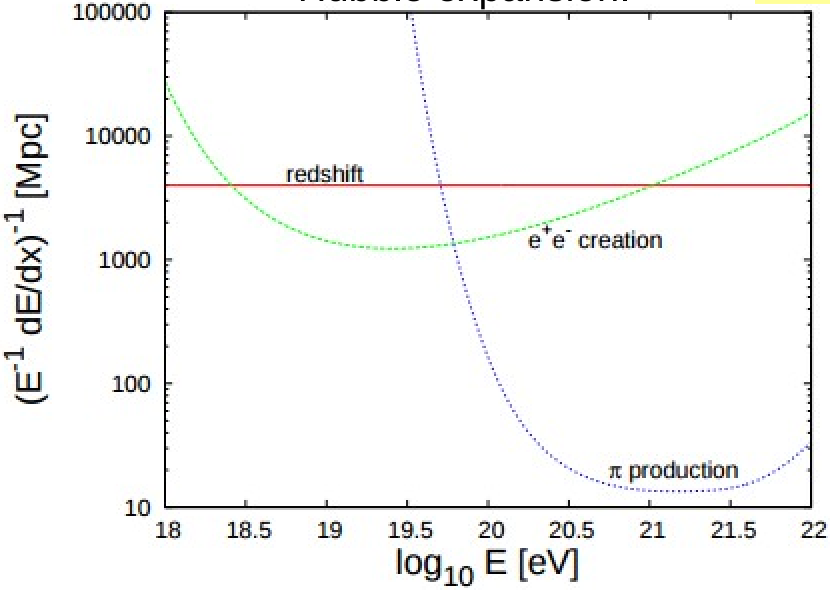
There is not clear explanation for cosmic rays with energies above 10^{20} eV



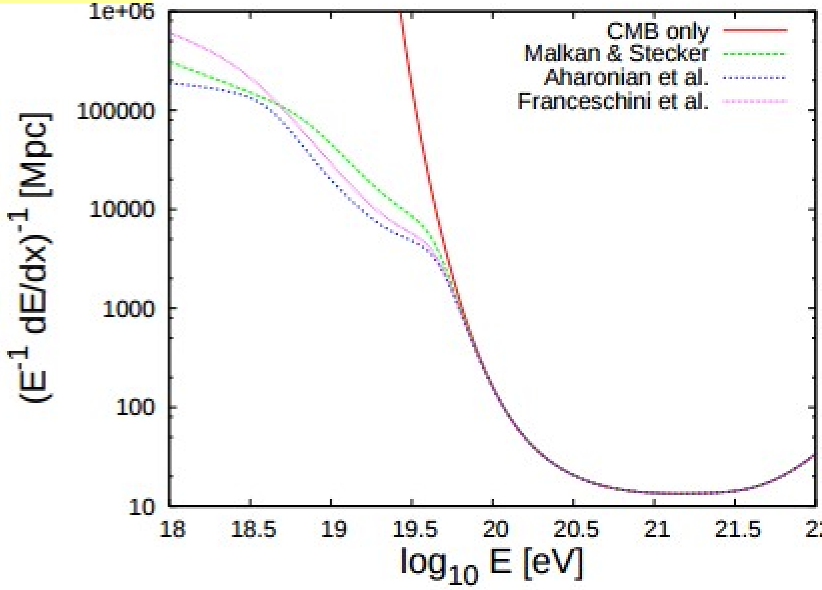
Energy loss lengths for UHE cosmic rays propagating through the universe

protons

Interaction with CMB and Hubble expansion.

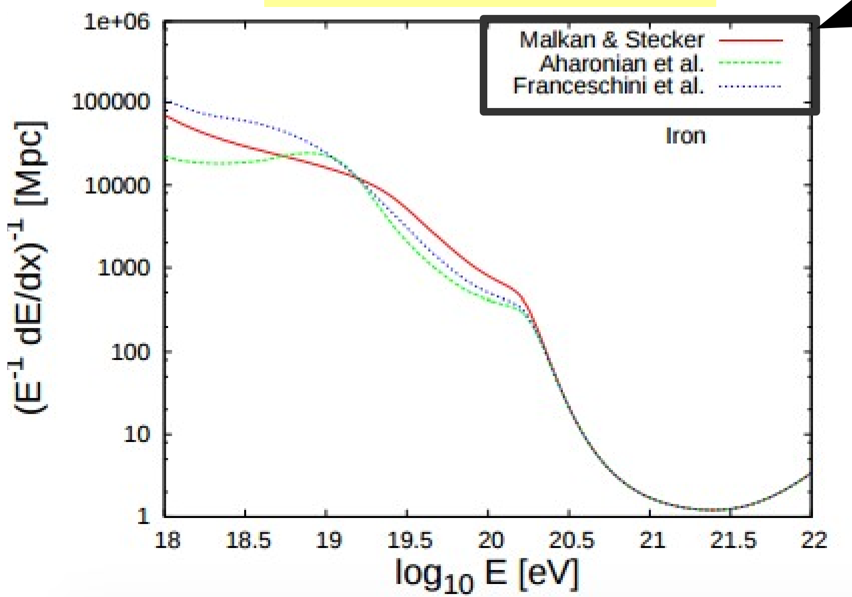


Interaction with CMB and CIB



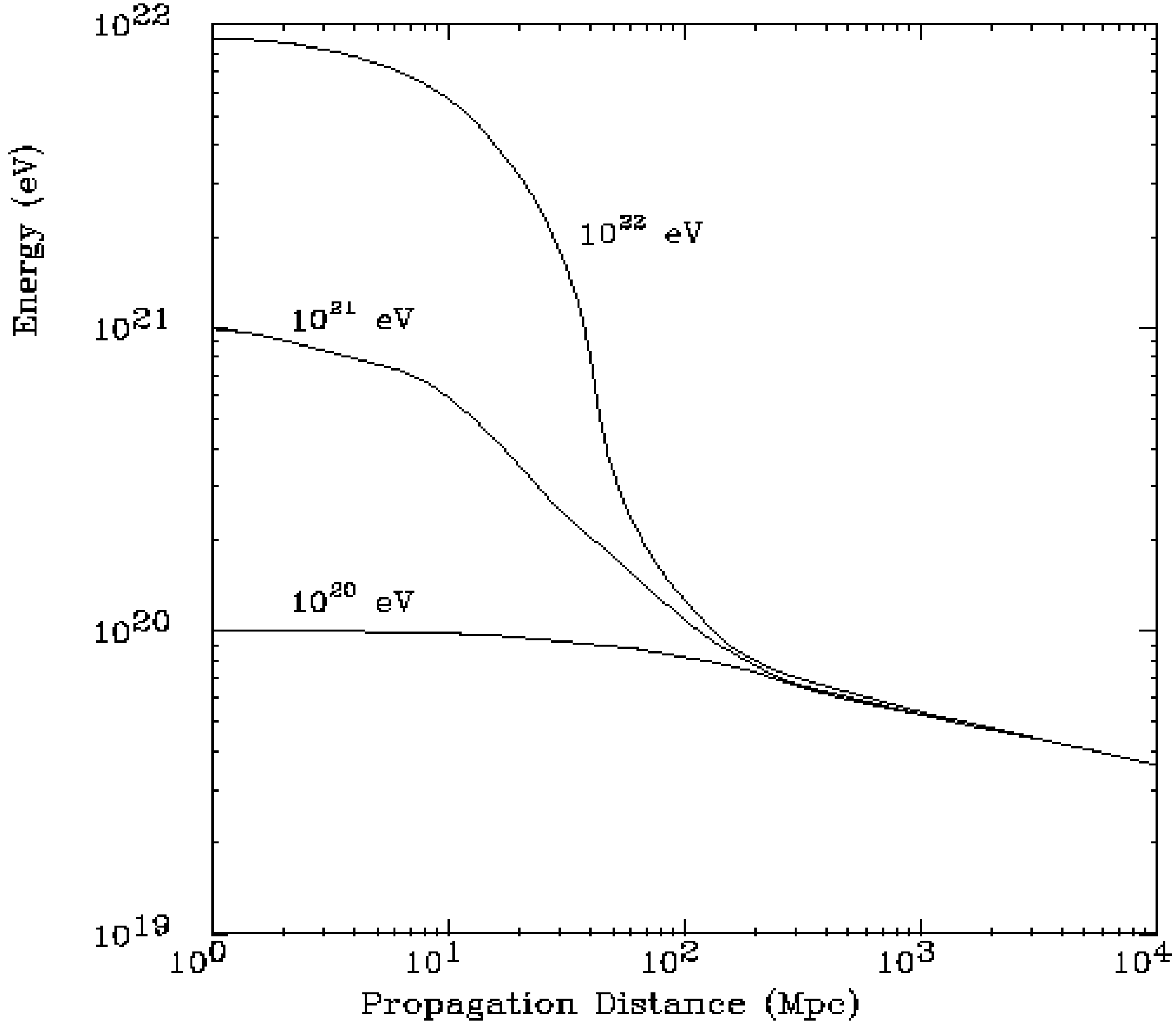
Iron
(photodesintegration)

Cosmic infrared background models (CIB)

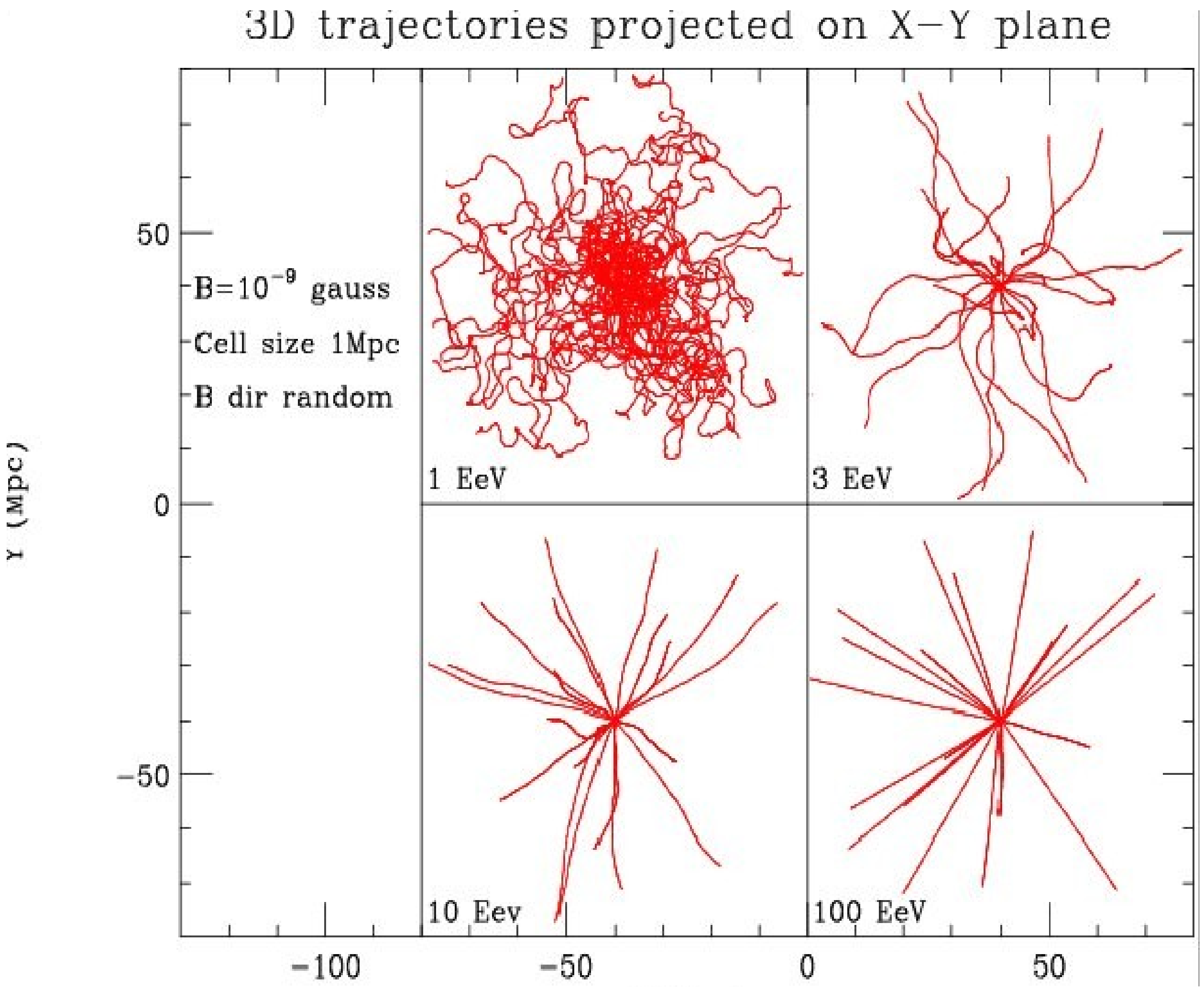


D. Hooper et.al.
Astropart.Phys. 27 (2007), 199

Protons with energies above $6 * 10^{19}$ eV interact with the microwave background radiation and they rapidly lose energy (GZK cutoff)



Cosmic rays with energies above 10^{20} eV point back to their sources



Auger science case

Based on the first Auger ICRC proceedings
M. Boratav et al, ICRC 1997, Durban

"The Pierre Auger Observatory...employing a giant array of **particle counters and an optical fluorescence detector**...aims at studying, with high statistics, cosmic rays with energies around and above the so-called Greisen-Zatsepin-Kuzmin spectral cutoff...Its main aims are:...

- a precise reconstruction of the **energy spectrum**…
- the **identification of primaries**, even if only statistical...Are they protons, nuclei, or perhaps something exotic? (e.g., the detection of a large amount of gammas and neutrinos would be an indication in favor of "exotic" theories...)...Inferences on mass composition will be drawn from the study of shower properties that might constrain hadronic interaction models at energies well beyond the reach of accelerator-based experiments…
- a **systematic study of the arrival directions**, that will indicate if there is anisotropy in the distribution and/or clusters which would indicate the existence of point sources..."

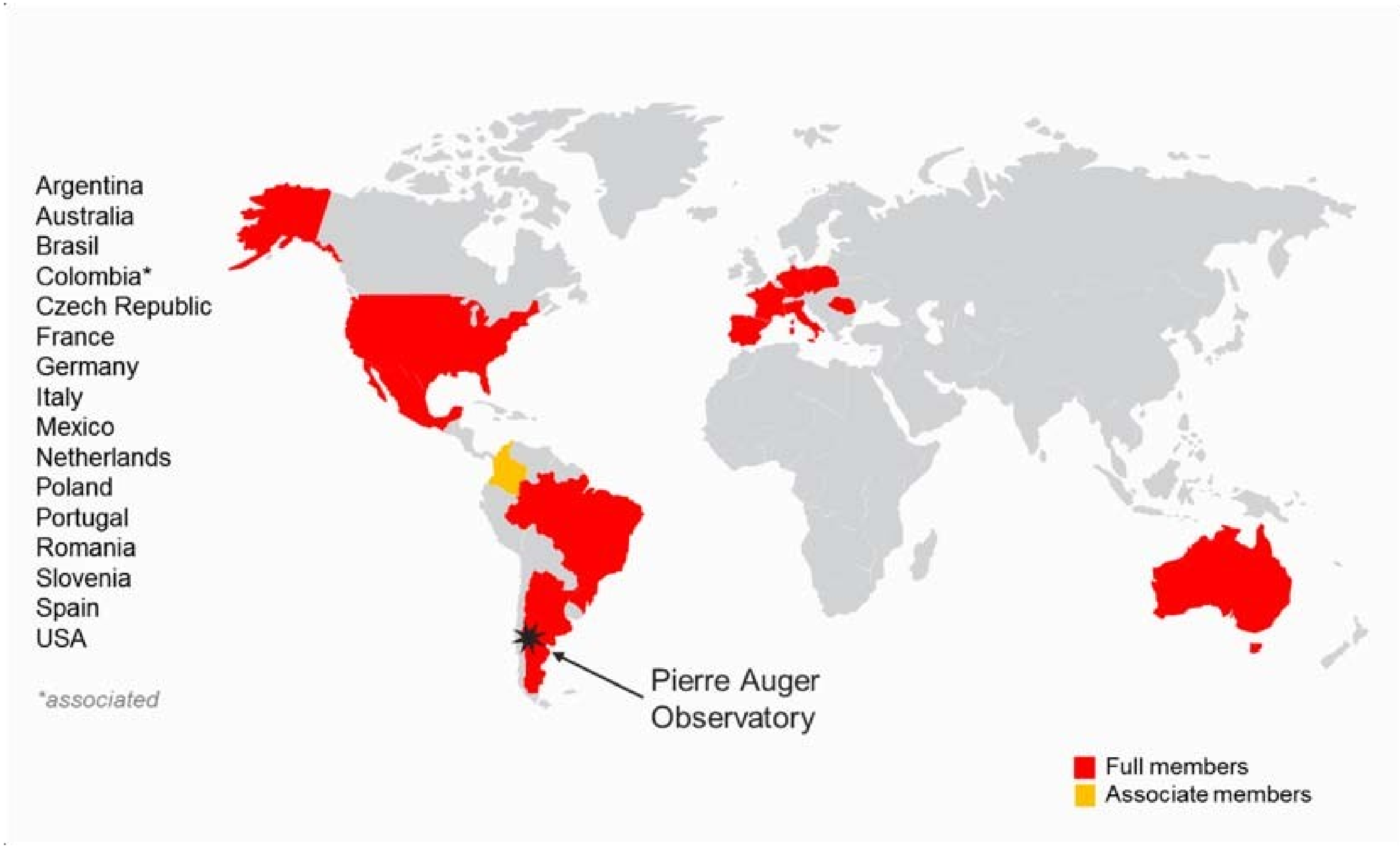
Auger science case

Based on the first Auger ICRC proceedings
M. Boratav et al, ICRC 1997, Durban

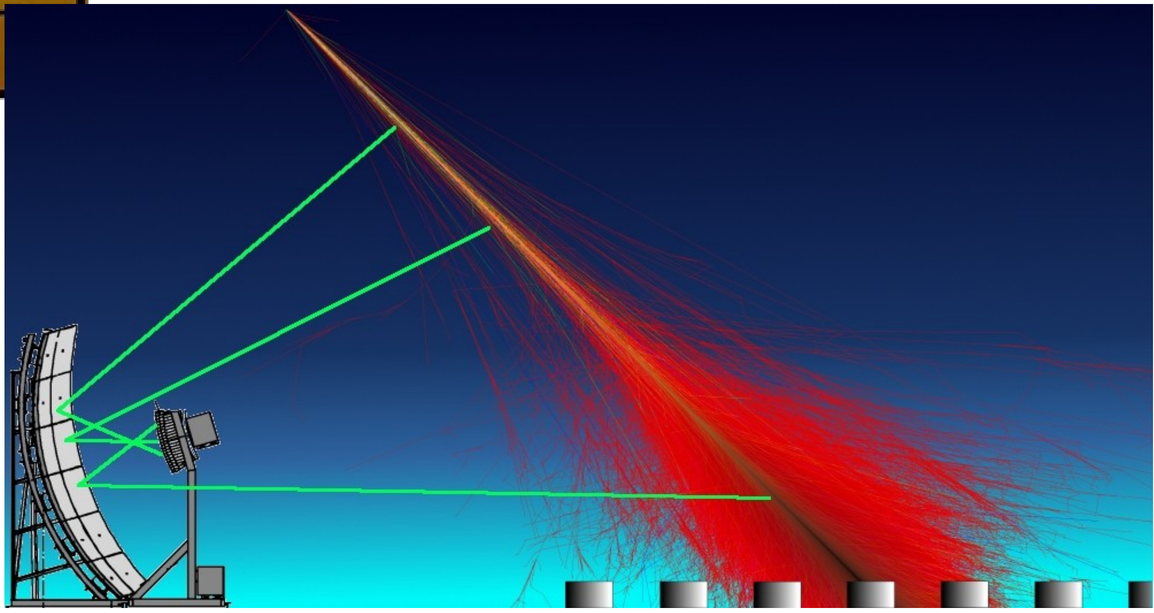
“The Pierre Auger Observatory...employing a giant array of **particle counters and an optical fluorescence detector**...aims at studying, with high statistics, cosmic rays with energies around and above the so-called Greisen-Zatsepin-Kuzmin spectral cutoff...Its main aims are:...

- a precise reconstruction of the **energy spectrum**…
- the **identification of primaries**, even if only statistical...Are they protons, nuclei, or perhaps something exotic? (e.g., the detection of a large amount of gammas and neutrinos would be an indication in favor of “exotic” theories...)...Inferences on mass composition will be drawn from the study of shower properties that **might constrain hadronic interaction models at energies well beyond the reach of accelerator-based experiments**…
- a **systematic study of the arrival directions**, that will indicate if there is anisotropy in the distribution and/or clusters which would indicate the existence of point sources...”

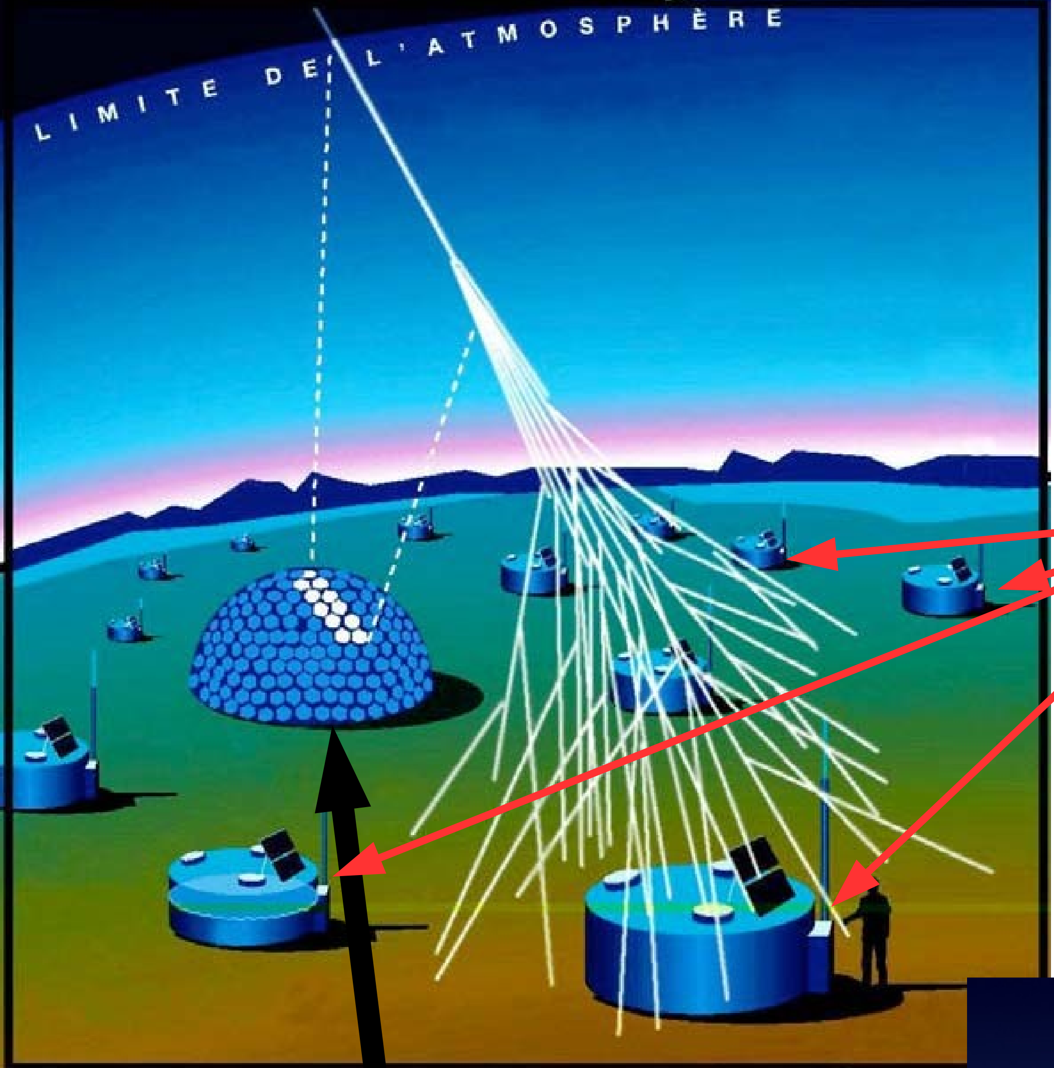
The Pierre Auger Collaboration



"The Pierre Auger Observatory...employing a giant array of particle counters and an optical fluorescence detector...is a "hybrid" ground detector..."

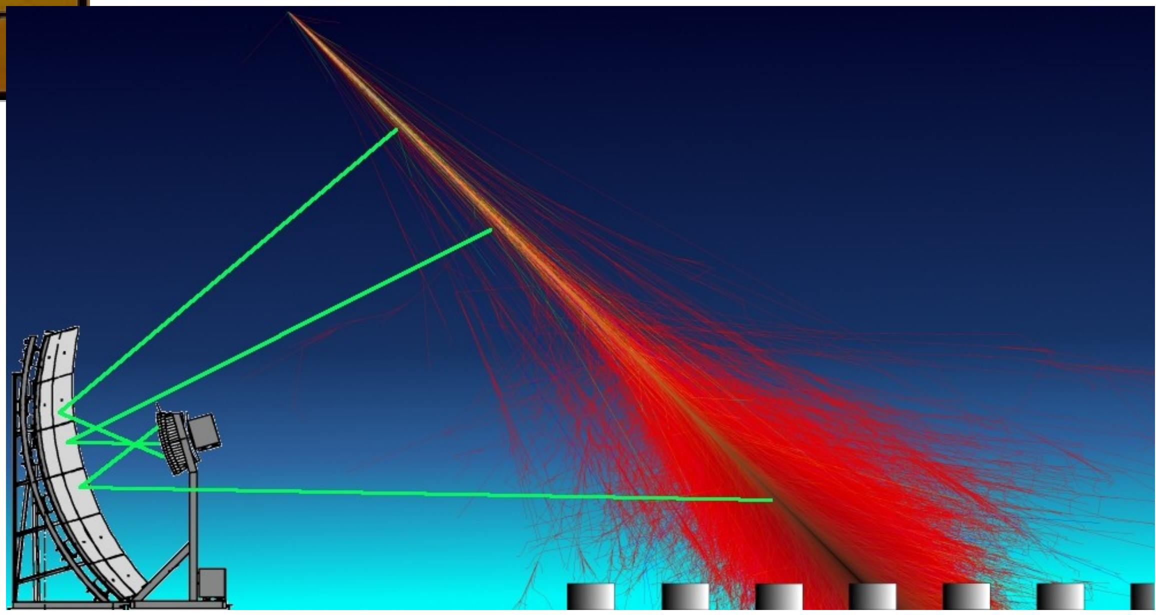


“The Pierre Auger Observatory...employing a giant array of particle counters and an optical fluorescence detector...is a “hybrid” ground detector...”

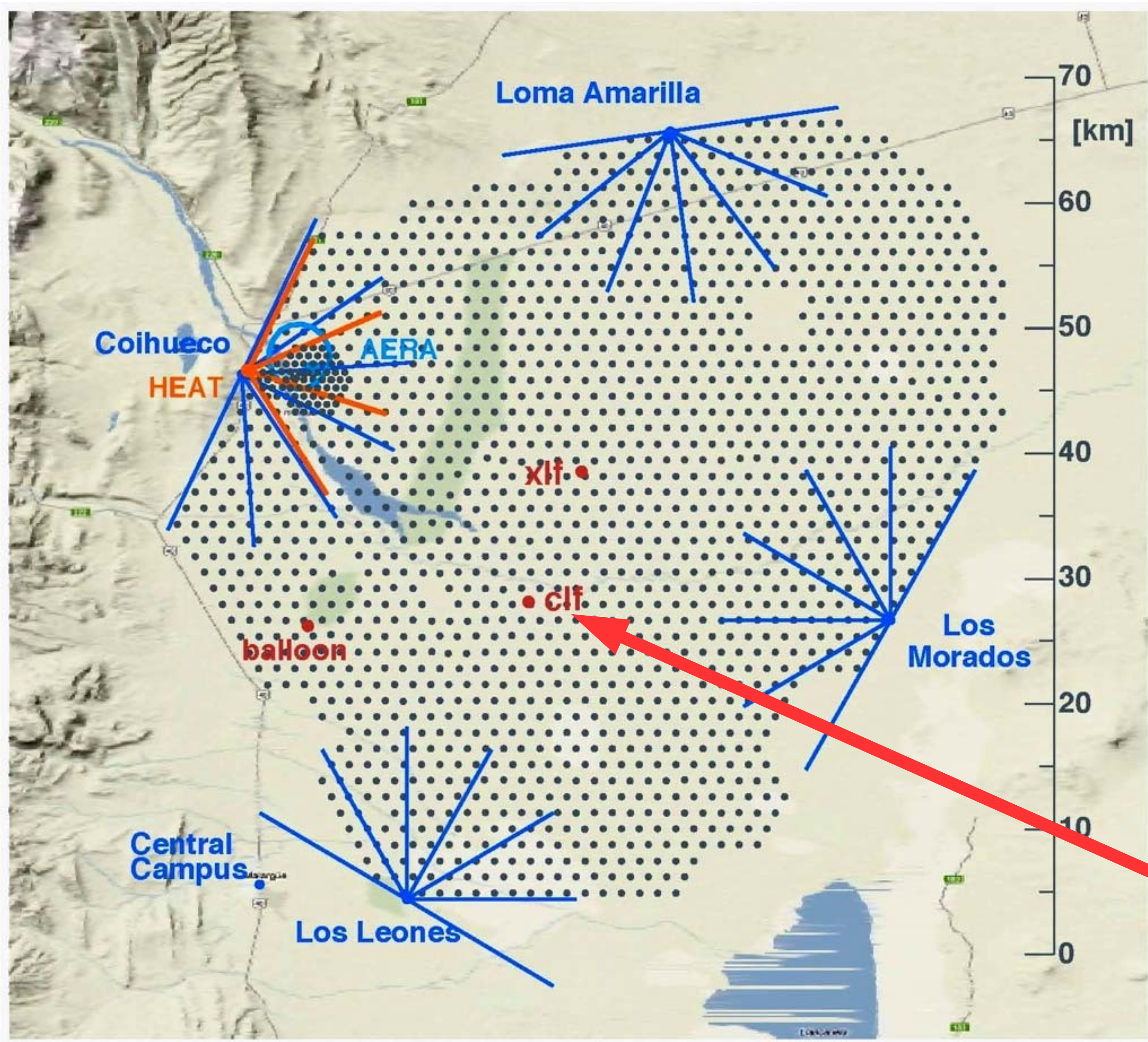


Surface Detector (SD)

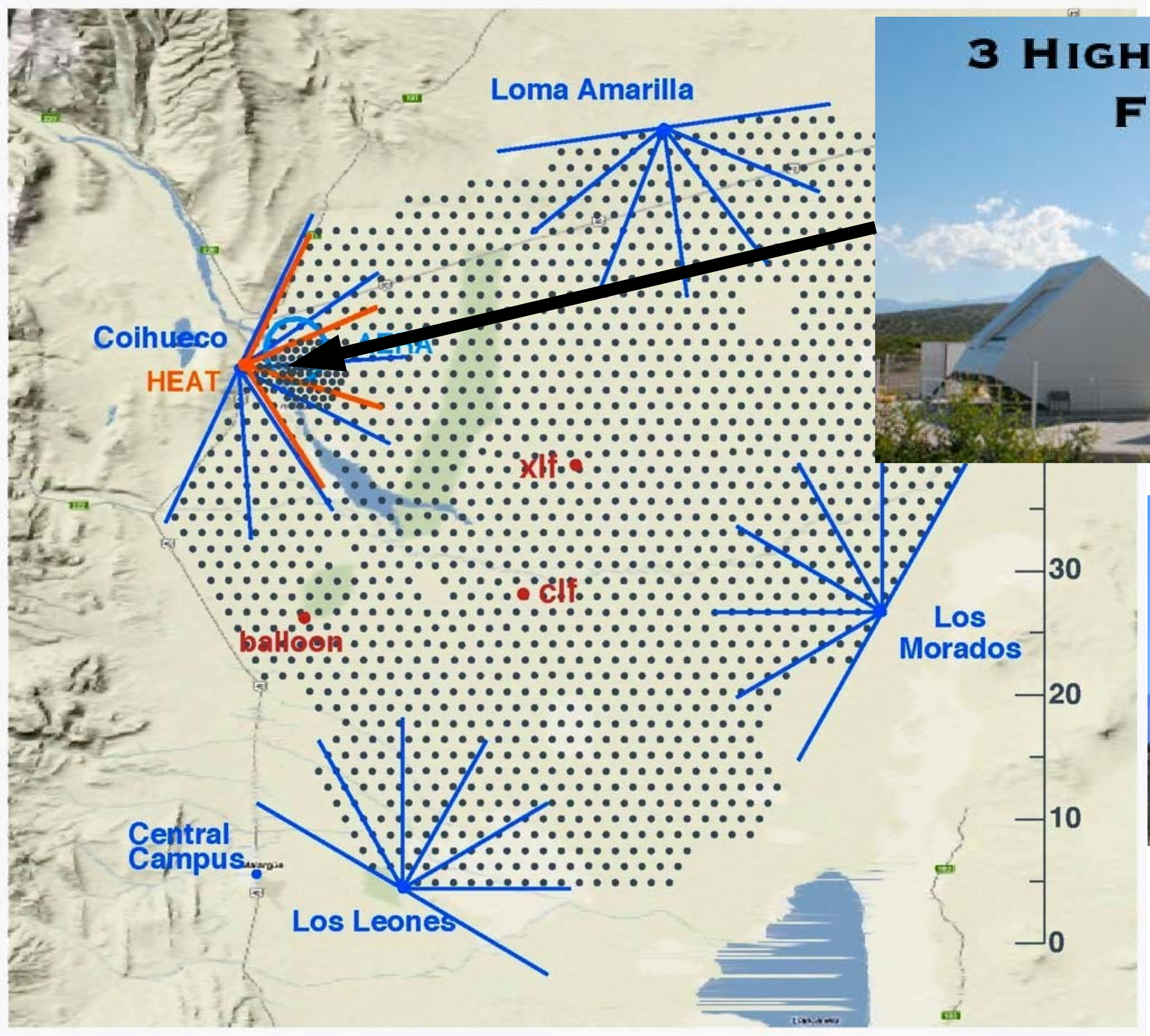
Fluorescence Detector (FD)



The Pierre Auger Observatory, Argentina



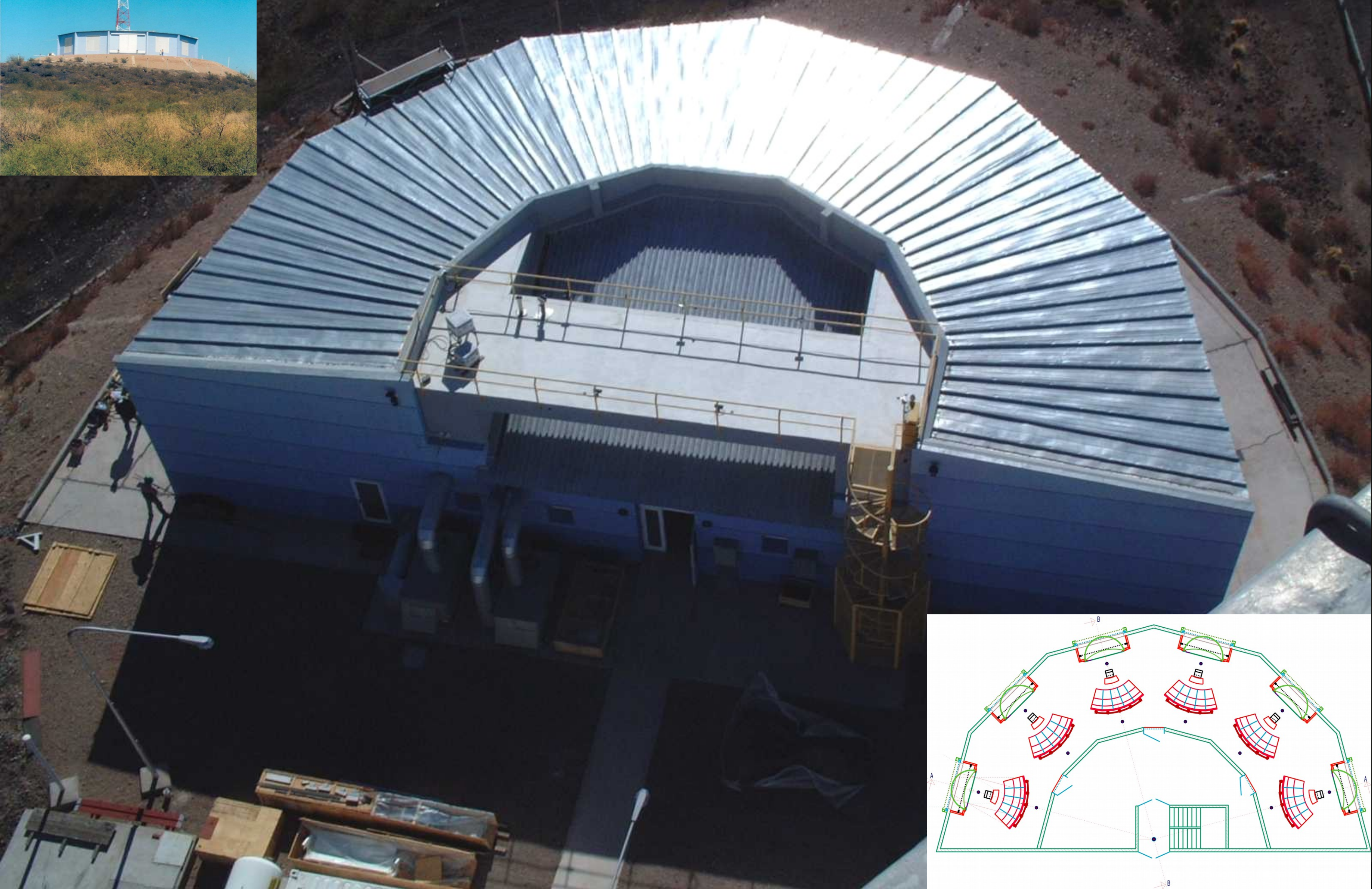
The Pierre Auger Observatory, Argentina



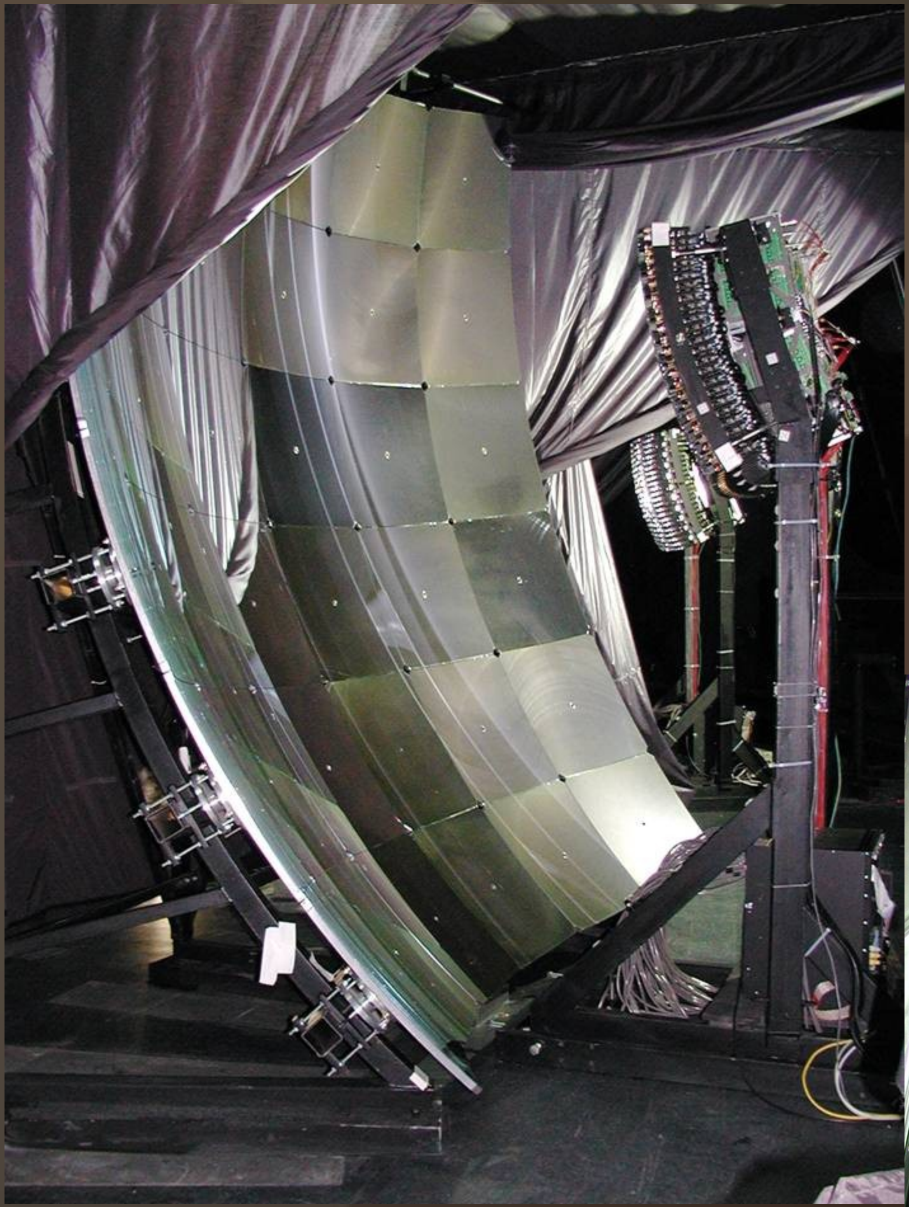
HEAT

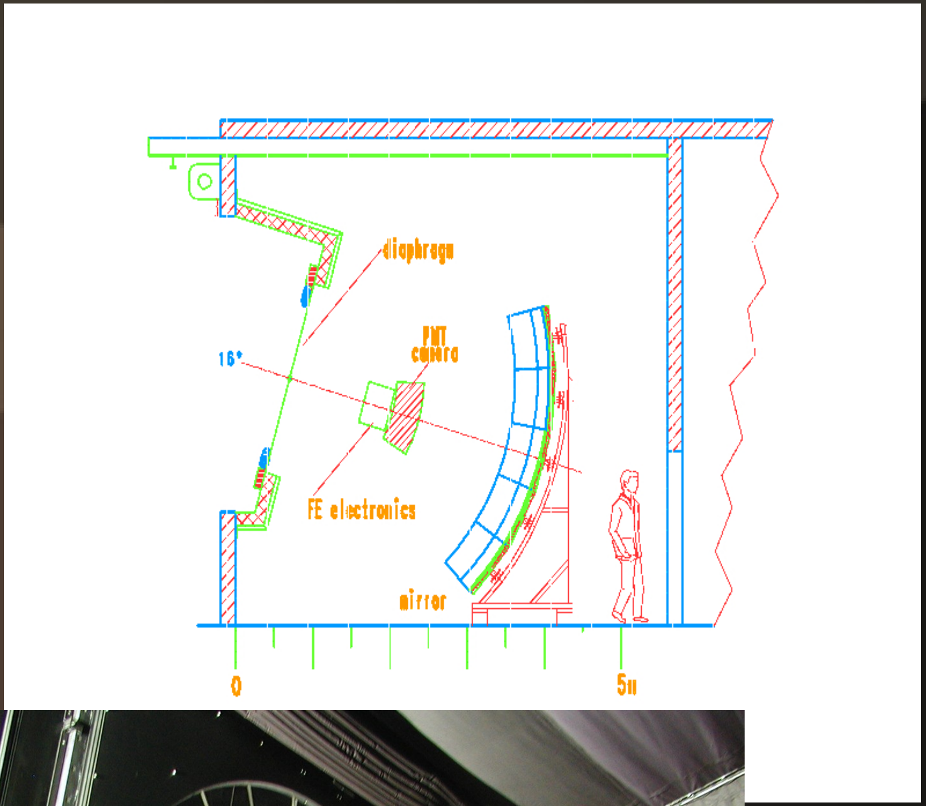
The Fluorescence Detector

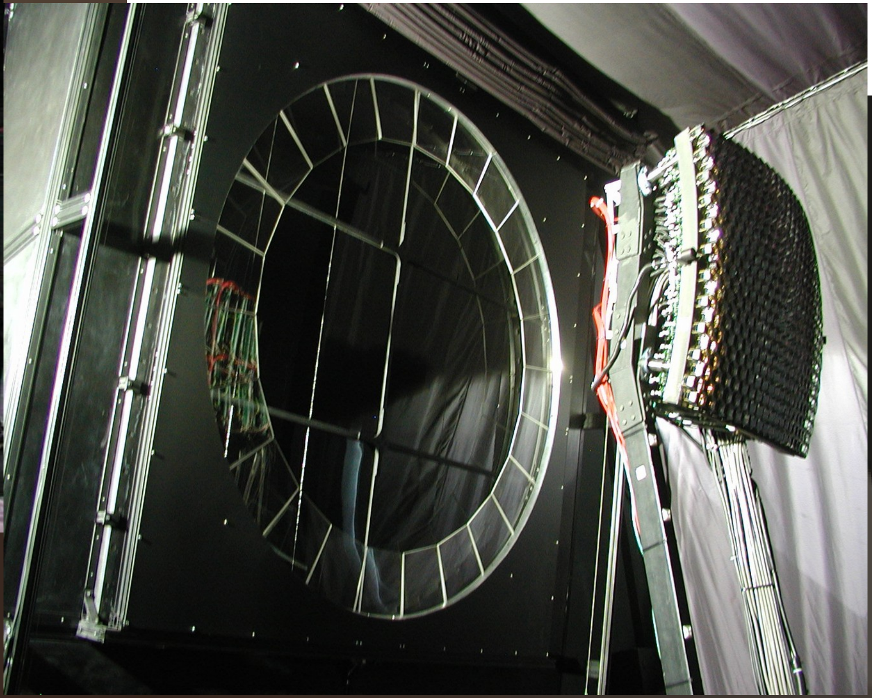
Los Leones

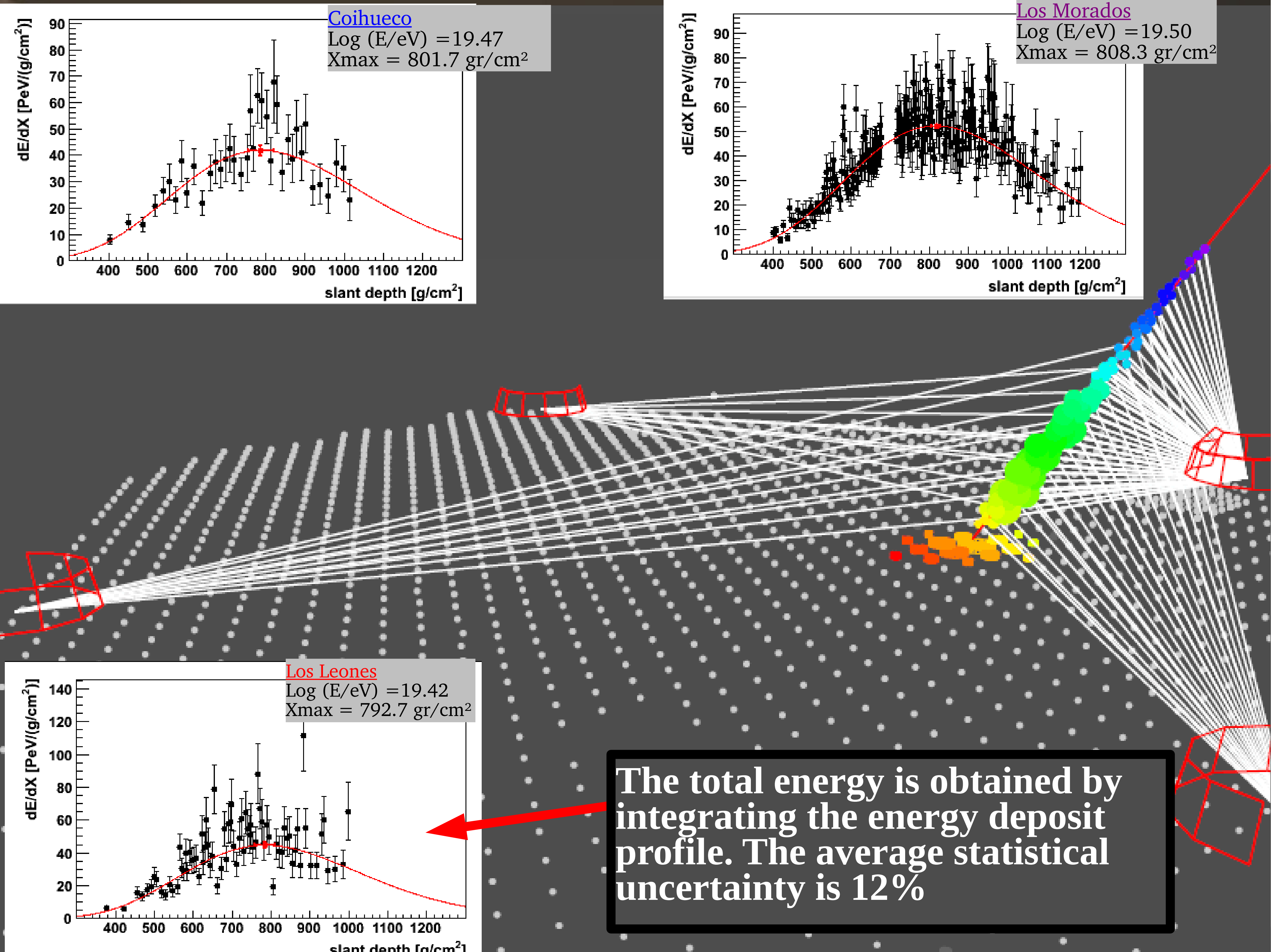


The Fluorescence Detector







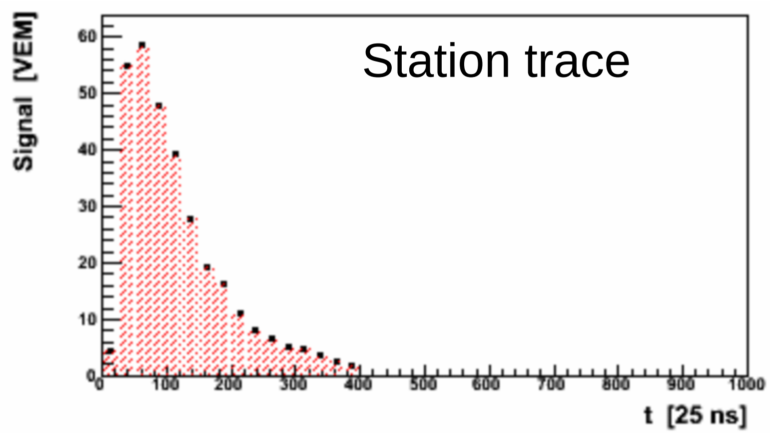

Coihueco
Log (E/eV) =19.47
Xmax = 801.7 gr/cm²
dE/dX [PeV/(g/cm²)]
slant depth [g/cm²]
Los Morados
Log (E/eV) =19.50
Xmax = 808.3 gr/cm²
dE/dX [PeV/(g/cm²)]
slant depth [g/cm²]
Los Leones
Log (E/eV) =19.42
Xmax = 792.7 gr/cm²
dE/dX [PeV/(g/cm²)]
slant depth [g/cm²]
The total energy is obtained by integrating the energy deposit profile. The average statistical uncertainty is 12%

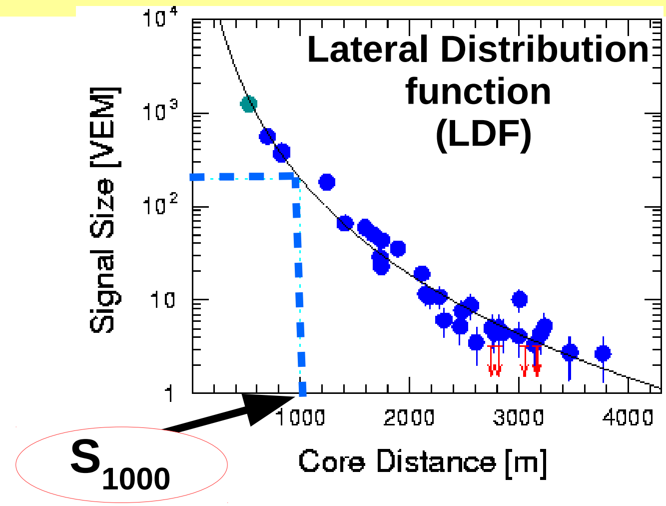
Event Reconstruction
Arrival direction, energy and mass

Geometry (arrival direction)

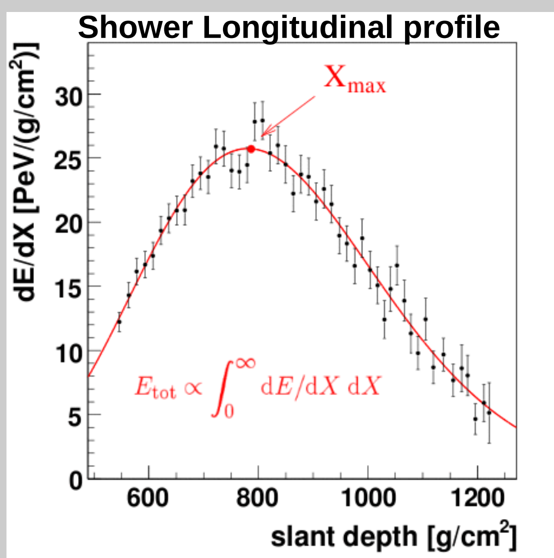
- **from timing and position information of the triggered SD stations.**
- **For the subset of events that also triggered the FD (hybrid events): from pixel timing, pixel FOV direction and position and timing of only the brightest SD station.**

With SD





With FD



The X_{max} resolution is in average 20 g/cm²

Calorimetric metric measurement of the energy

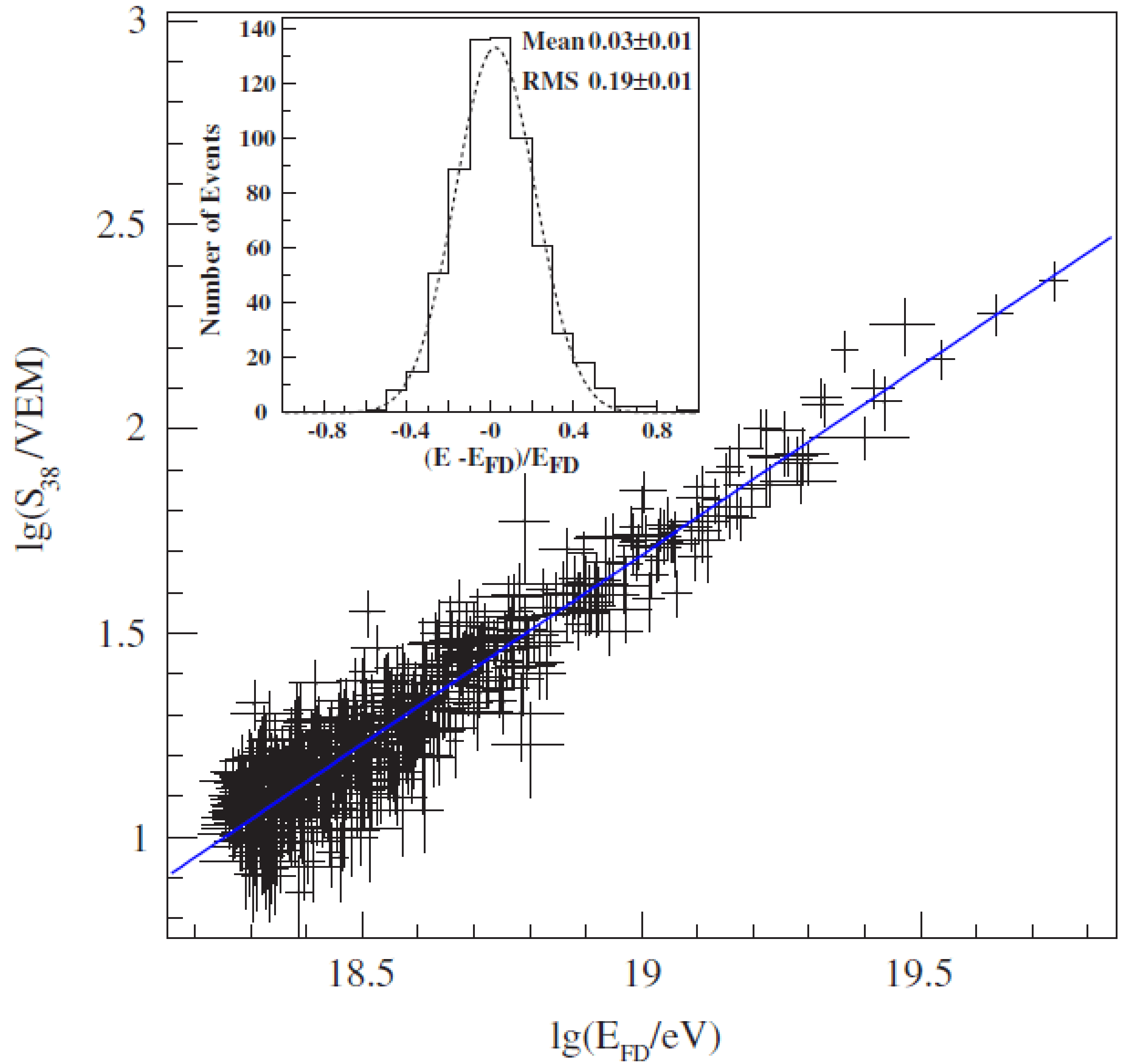
The Energy scale from the FD is transferred to the SD

The energy converter:

Compare ground parameter S(1000) with the fluorescence detector energy.

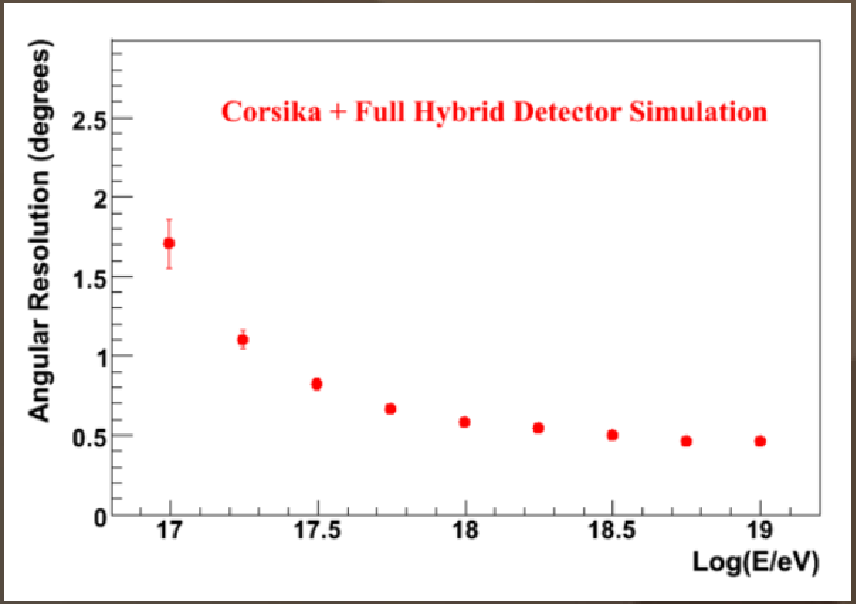
The systematic uncertainties of the fluorescence detector (14%) are transferred to the surface detector.

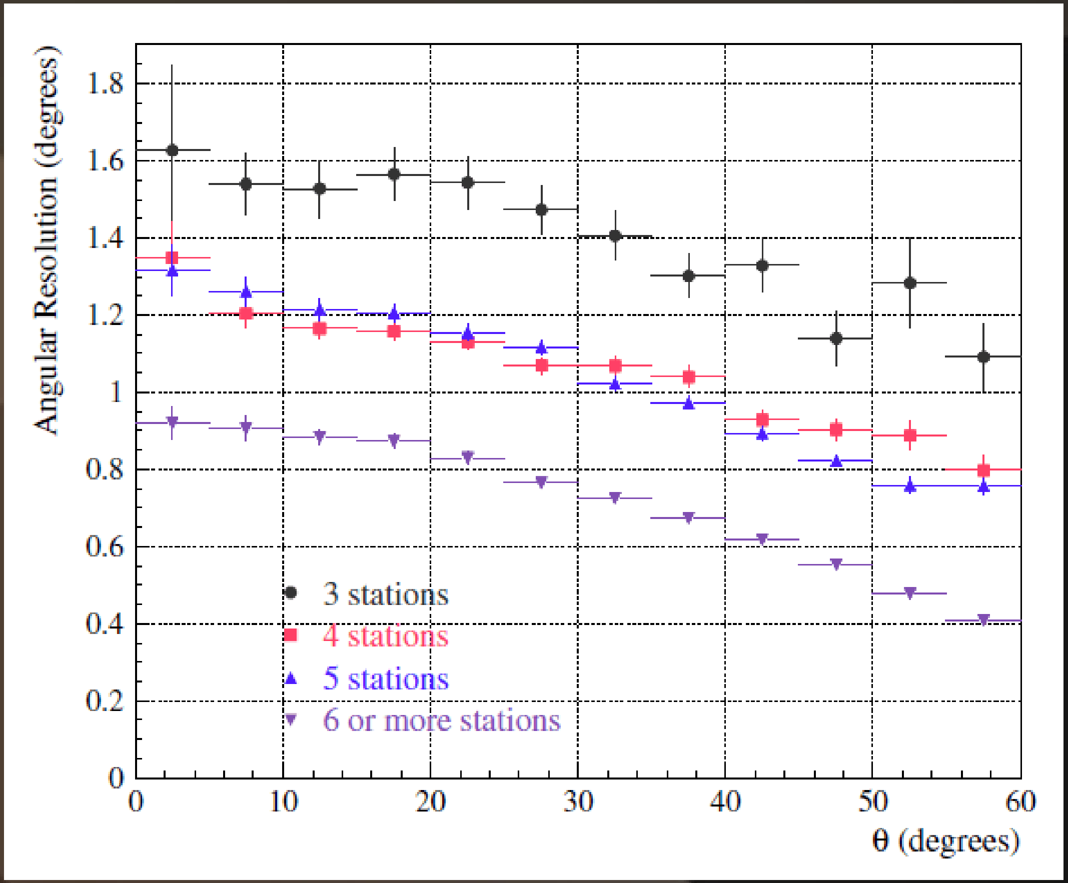
The surface detector energy resolution is about 20% at the lowest energies and 10% at the highest energies.



Note: S_{1000} for a given shower energy varies depending on the zenith angle. So, S_{38} is the corresdepending expectation for a 38˚ shower, given the S_{1000} measurement.

Angular Resolution





Hybrid Angular resolution
(68% CL)

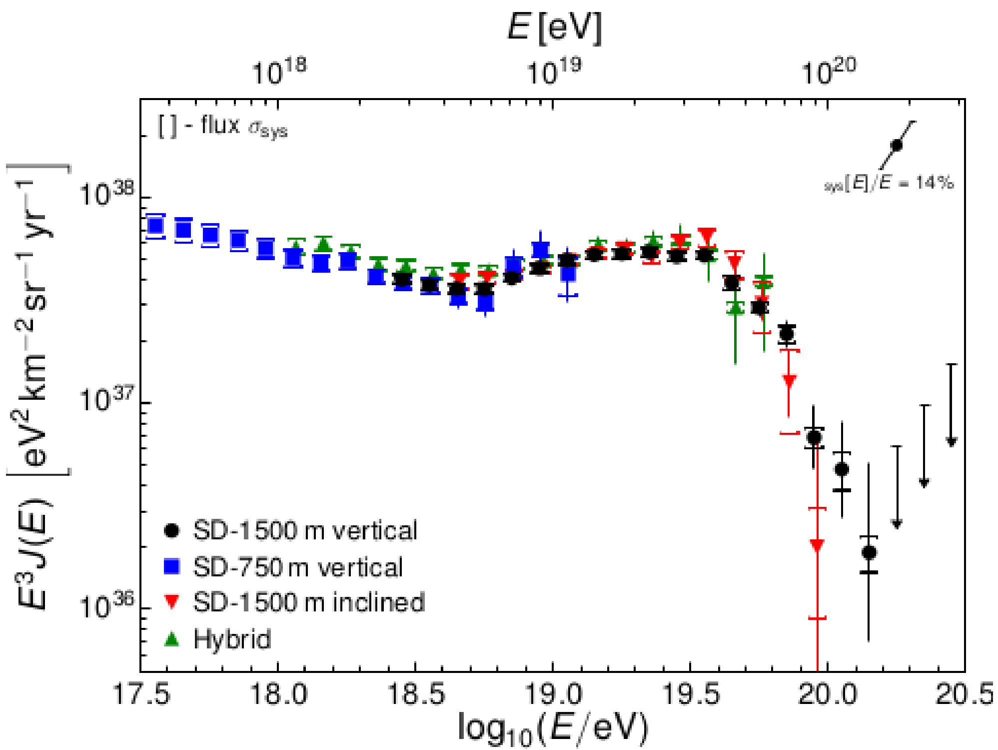
0.5 degrees above 1EeV

Surface array Angular resolution (68% CL)

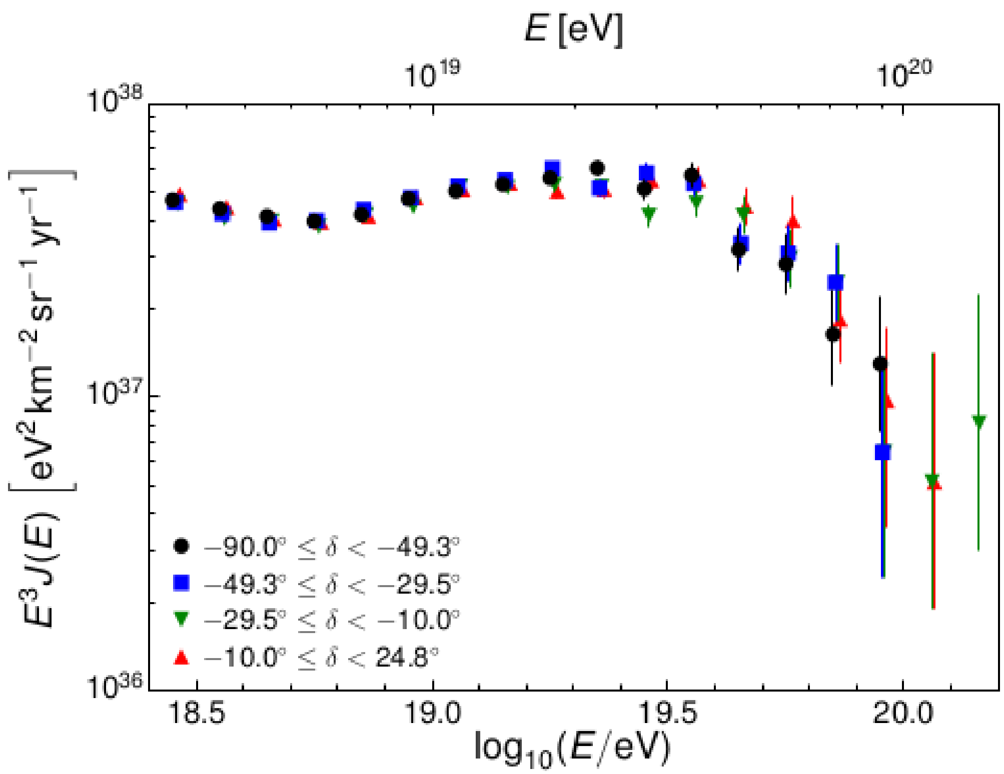
< 1.6º for 3 station events (E> 3EeV, θ < 60º)
< 1.2º for 4 station events
< 0.9º for 6 or more station events

The Cosmic Ray Energy Spectrum

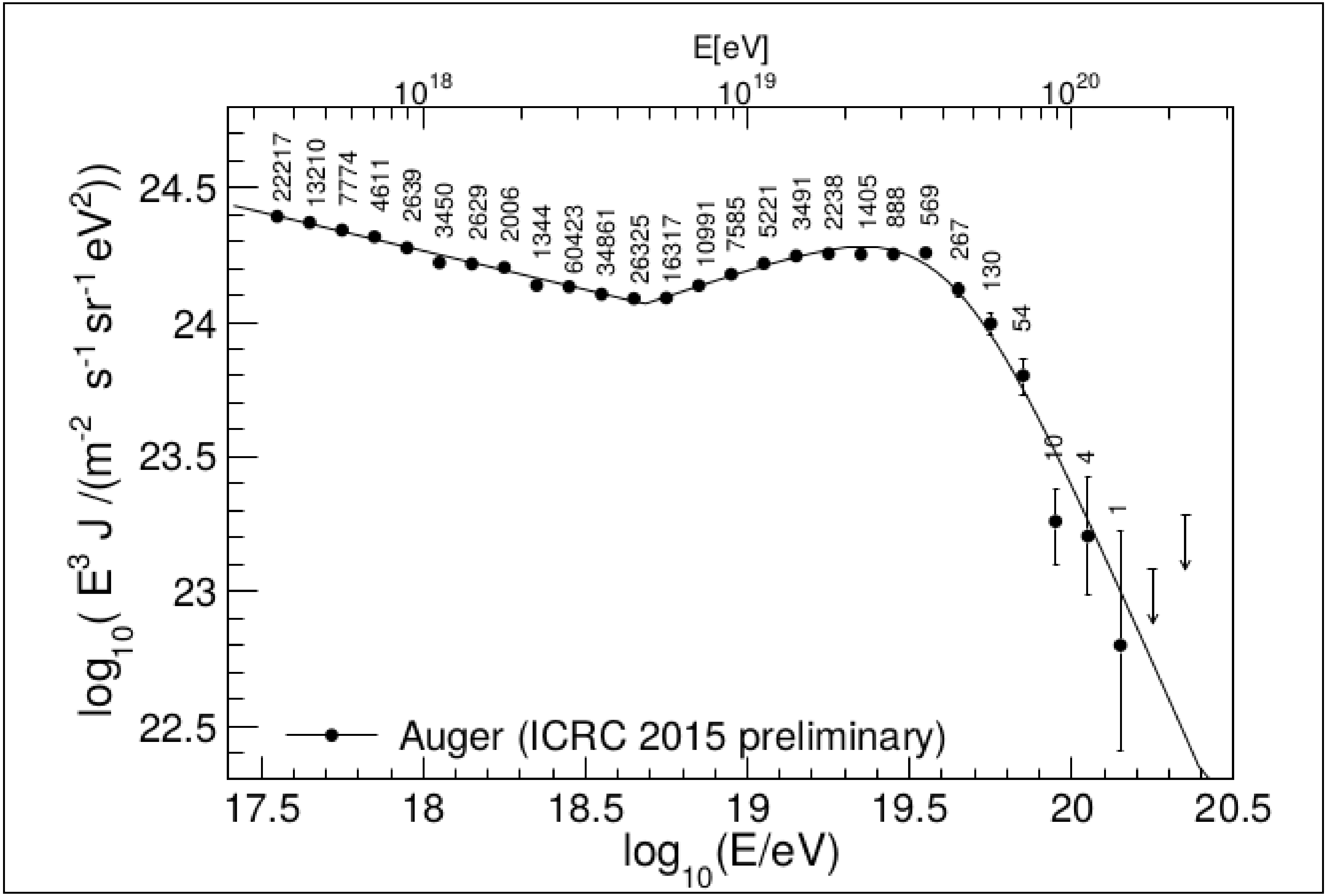
Four independent measurements



Declination dependence



The Cosmic Ray Energy Spectrum
(combining all measurements)



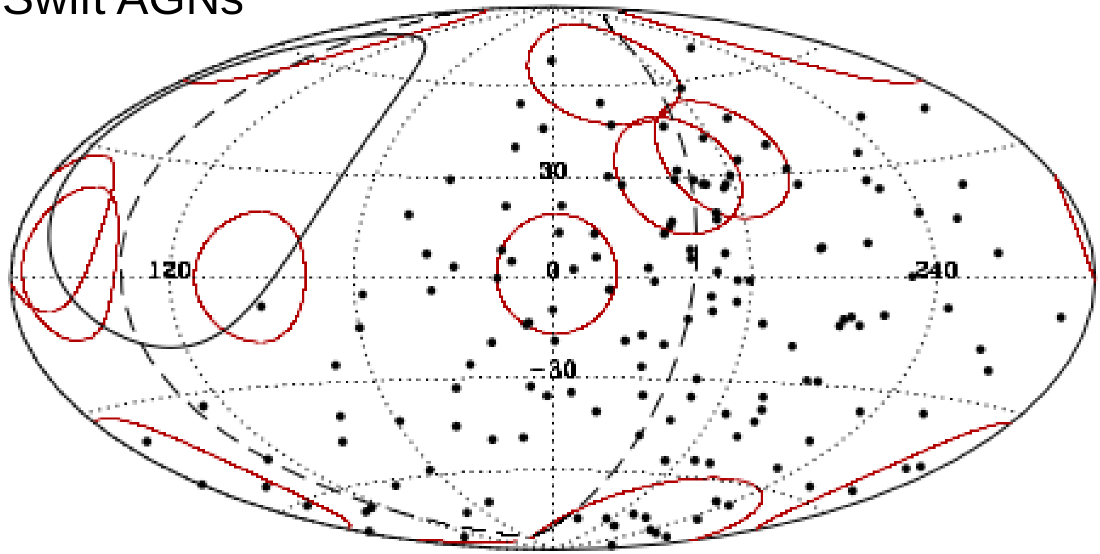
Arrival Directions

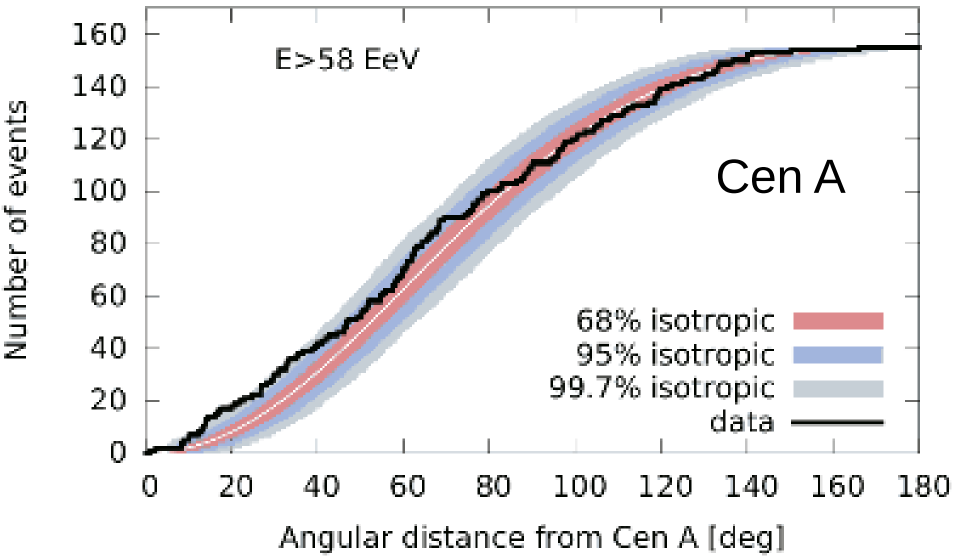
Cross correlation studies

Objects	E_{th} [EeV]	Ψ [°]	D [Mpc]	$\mathscr{L}_{min}$ [erg/s]	f_{min}	$\mathscr{P}$
2MRS Galaxies	52	9	90	-	1.5×10^{-3}	24%
Swift AGNs	58	1	80	-	6×10^{-5}	6%
Radio galaxies	72	4.75	90	-	2×10^{-4}	8%
Swift AGNs	58	18	130	10^{44}	2×10^{-6}	1.3%
Radio galaxies	72	4.75	90	$10^{39.33}$	5.1×10^{-5}	11%
Centaurus A	58	15	-	-	2×10^{-4}	1.4%

Table 1: Summary of the parameters of the minima found in the cross-correlation analyses.

Swift AGNs





Map in galactic coordinates

Auger measurements related to mass composition

FD | SD

X_{max}	$Sec(\theta_{max})$	X^{μ}_{max}	N_{mu}

Correlation factor between:

X_{max} and S_{1000}

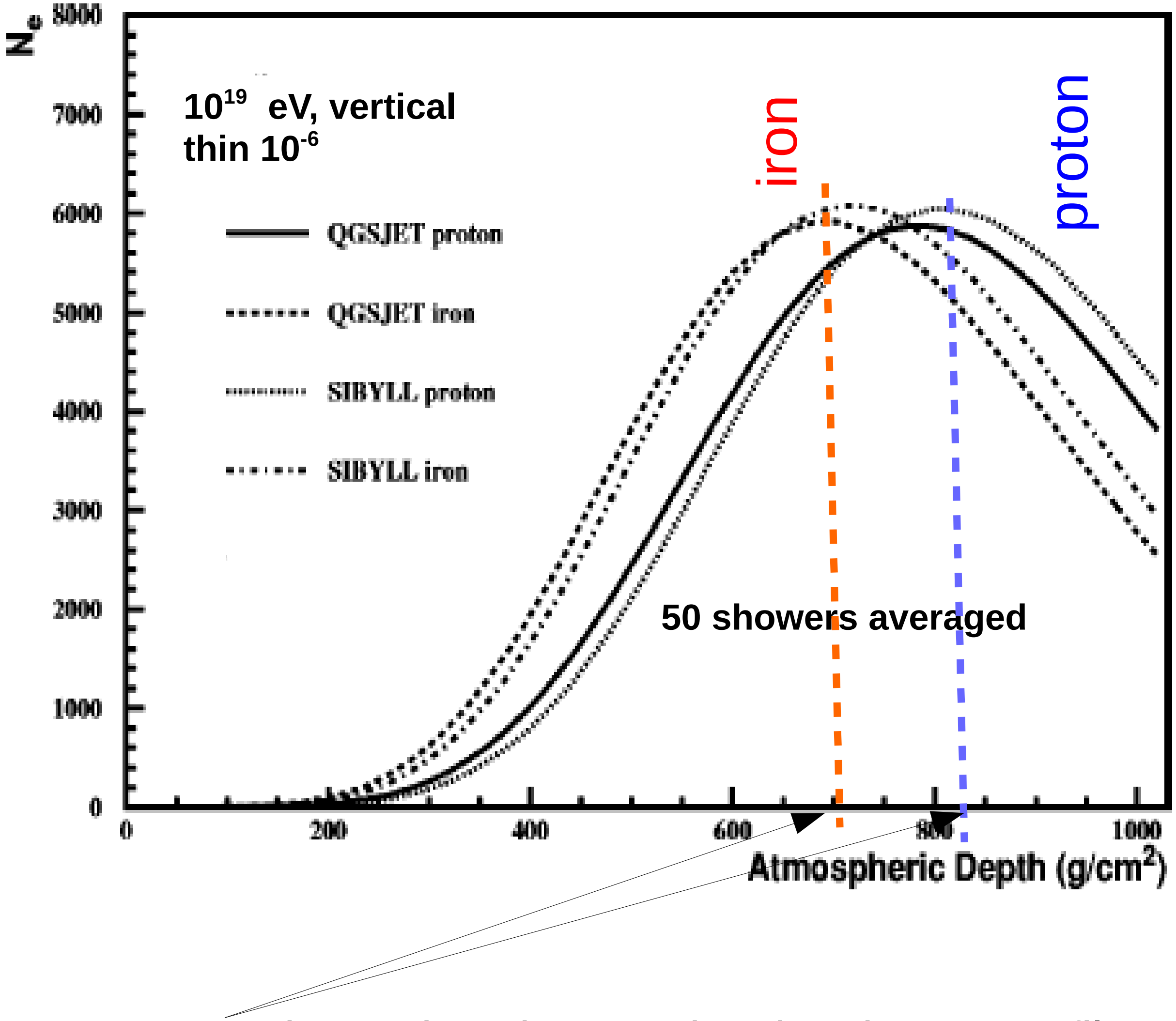
(Hybrid events)

Latest journal publications

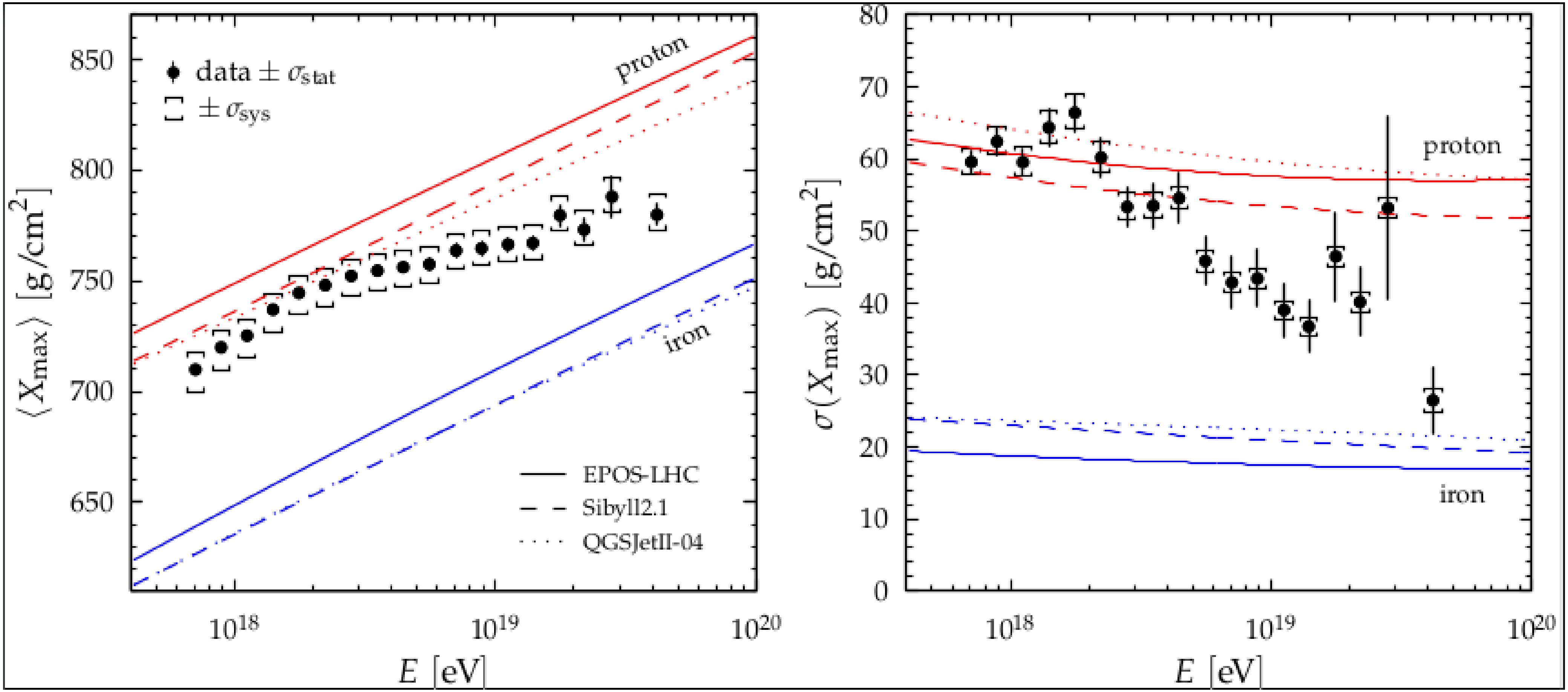
X_{max}	PHYSICAL REVIEW D **90**, 122005 (2014) **Depth of maximum of air-shower profiles at the Pierre Auger Observatory. I. Measurements at energies above $10^{17.8}$ eV** PHYSICAL REVIEW D **90**, 122006 (2014)
$Sec(\theta_{max})$	PHYSICAL REVIEW D **93**, 072006 (2016) **Azimuthal asymmetry in the risetime of the surface detector signals of the Pierre Auger Observatory**
X^{μ}_{max}	PHYSICAL REVIEW D **90**, 012012 (2014) **Muons in air showers at the Pierre Auger Observatory: Measurement of atmospheric production depth**
N_{mu}	PHYSICAL REVIEW D **91**, 032003 (2015) **Muons in air showers at the Pierre Auger Observatory: Mean number in highly inclined events**

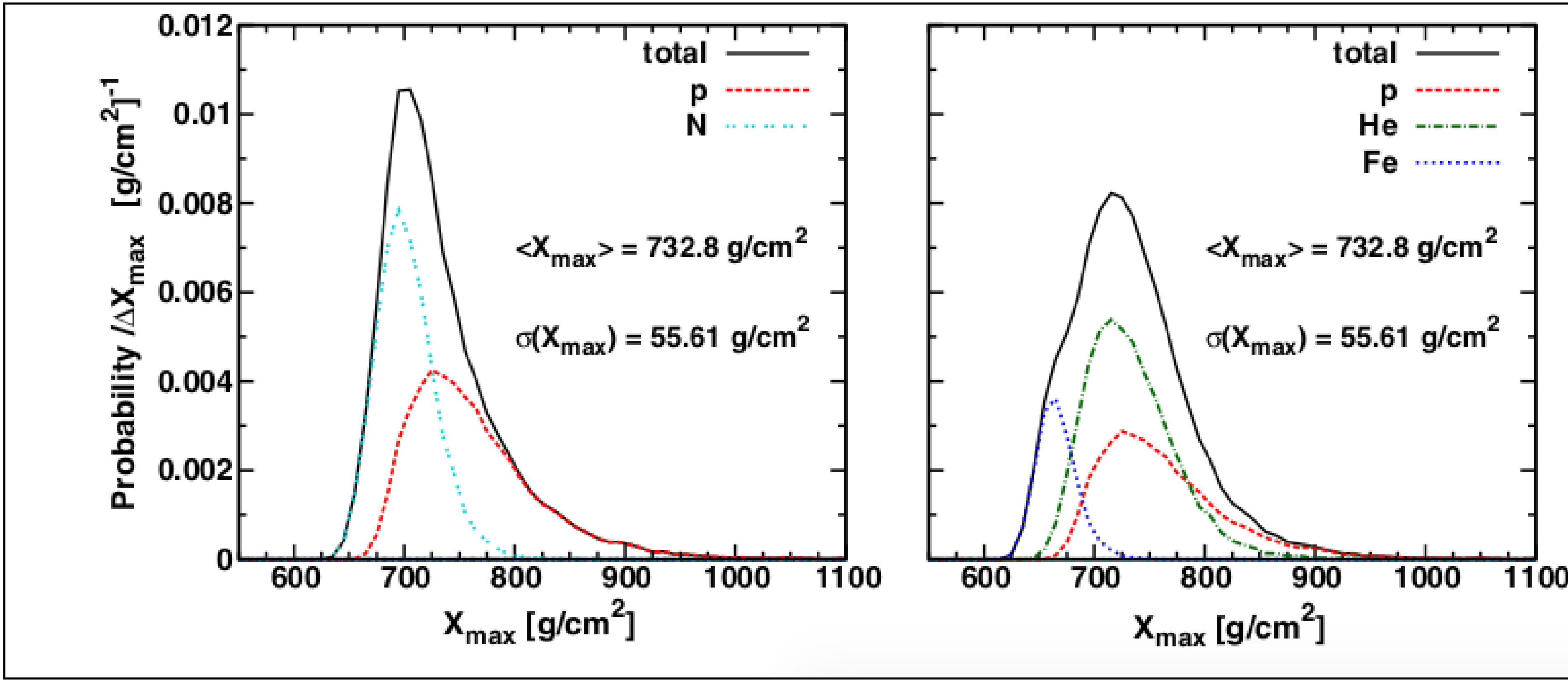
FD Observables

The expected shower profile (measured by the FD) for proton and Iron are different



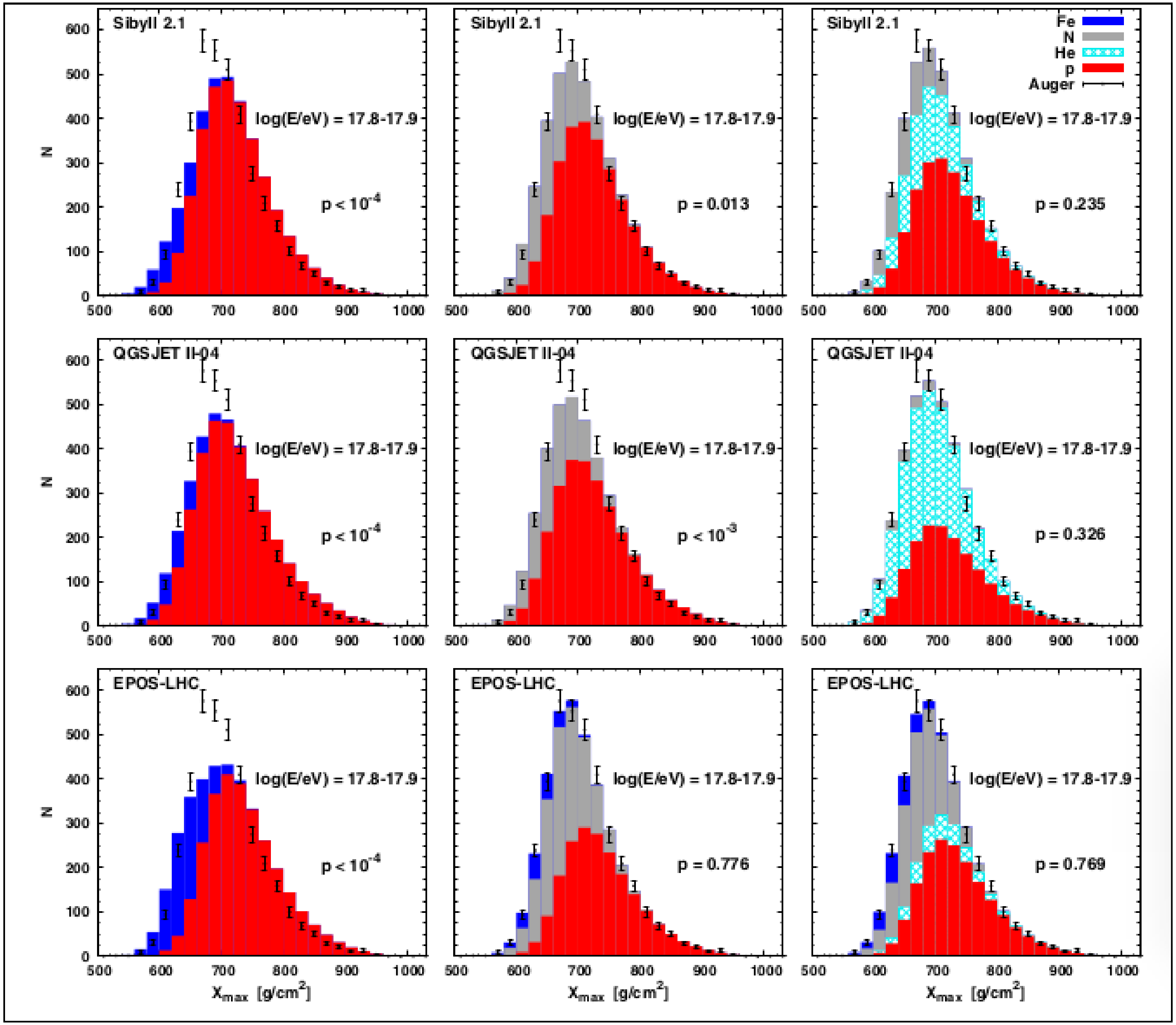
Note: X_{max} is used to characterize the shower profile.

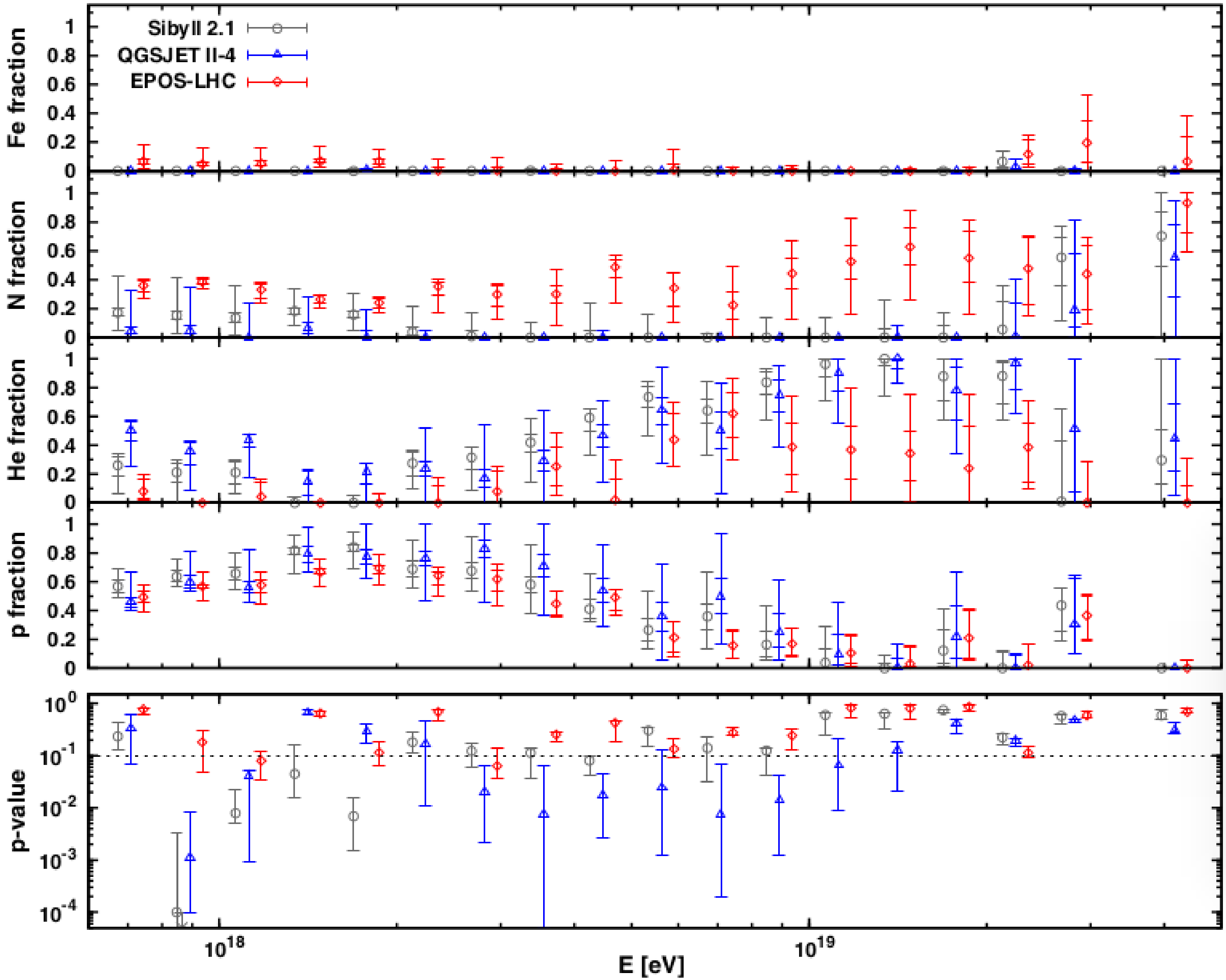

data ± σ_{stat}
± σ_{sys}
proton
iron
EPOS-LHC
Sibyll2.1
QGSJetII-04
$\langle X_{max} \rangle$ [g/cm^2]
E [eV]
$\sigma(X_{max})$ [g/cm^2]
proton
iron
E [eV]



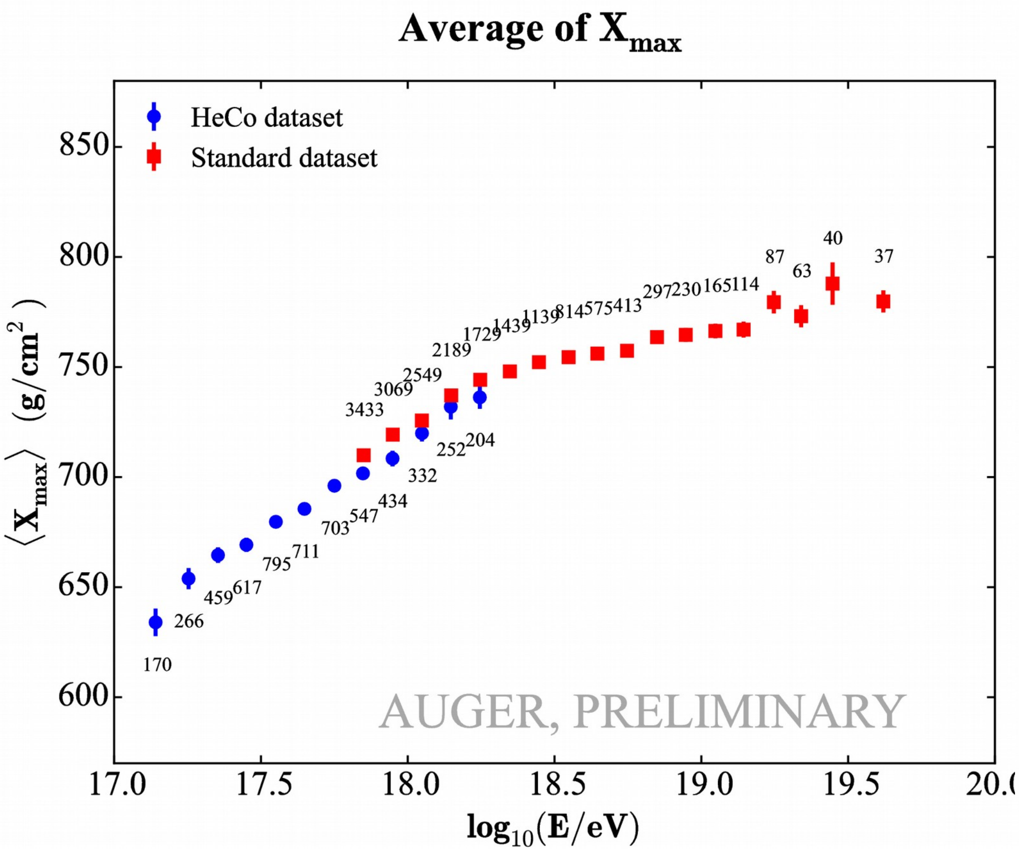
total
p
N
$<X_{max}> = 732.8\ g/cm^2$
$\sigma(X_{max}) = 55.61\ g/cm^2$
Probability $/\Delta X_{max}$ $[g/cm^2]^{-1}$
X_{max} $[g/cm^2]$
total
p
He
Fe
$<X_{max}> = 732.8\ g/cm^2$
$\sigma(X_{max}) = 55.61\ g/cm^2$
X_{max} $[g/cm^2]$

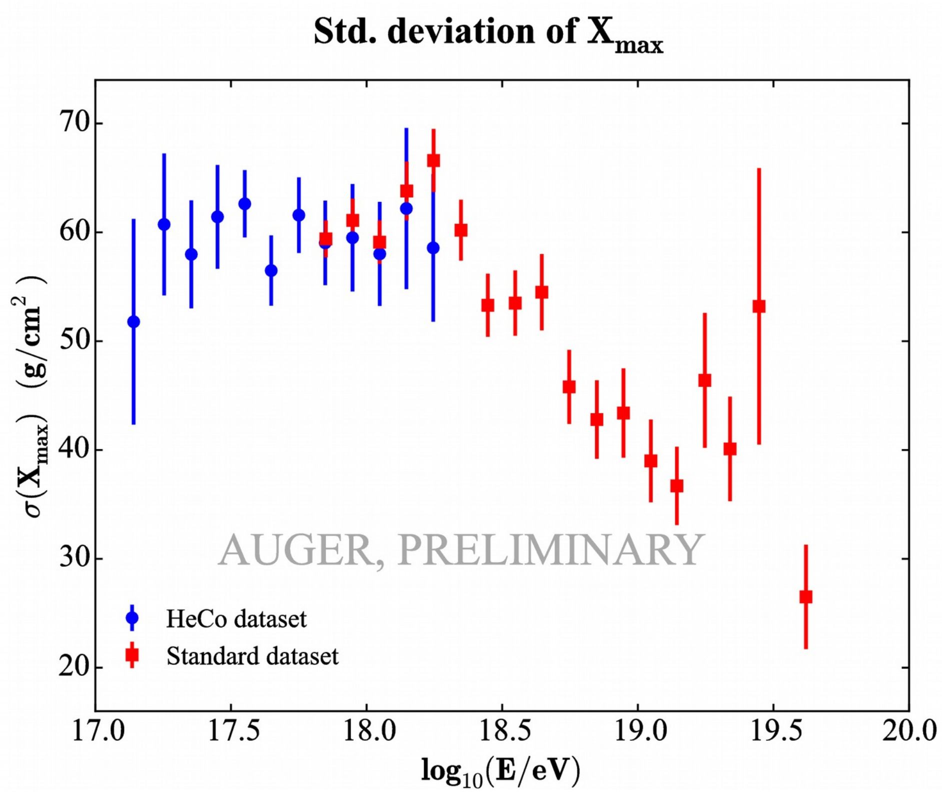
PHYSICAL REVIEW D **90**, 122006 (2014)




Fe fraction
N fraction
He fraction
p fraction
p-value
Sibyll 2.1
QGSJET II-4
EPOS-LHC
E [eV]

X_{max} moments from HEAT and from standard FD measurements

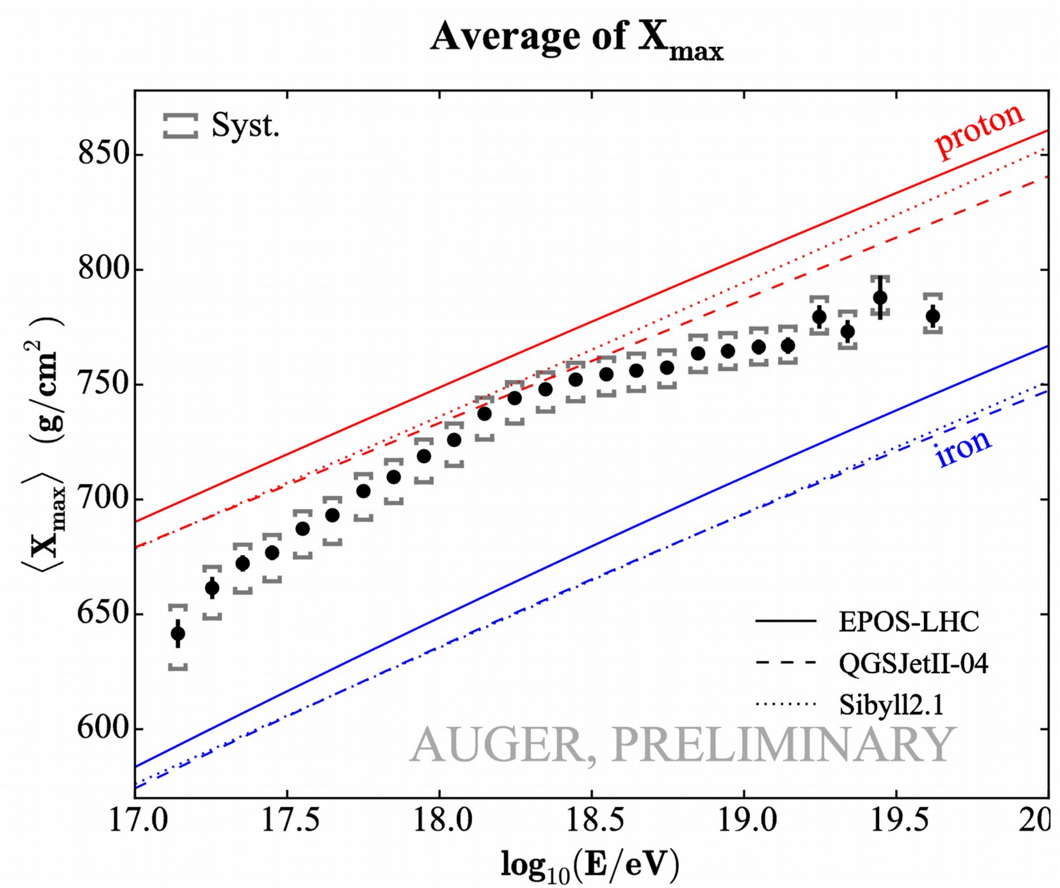


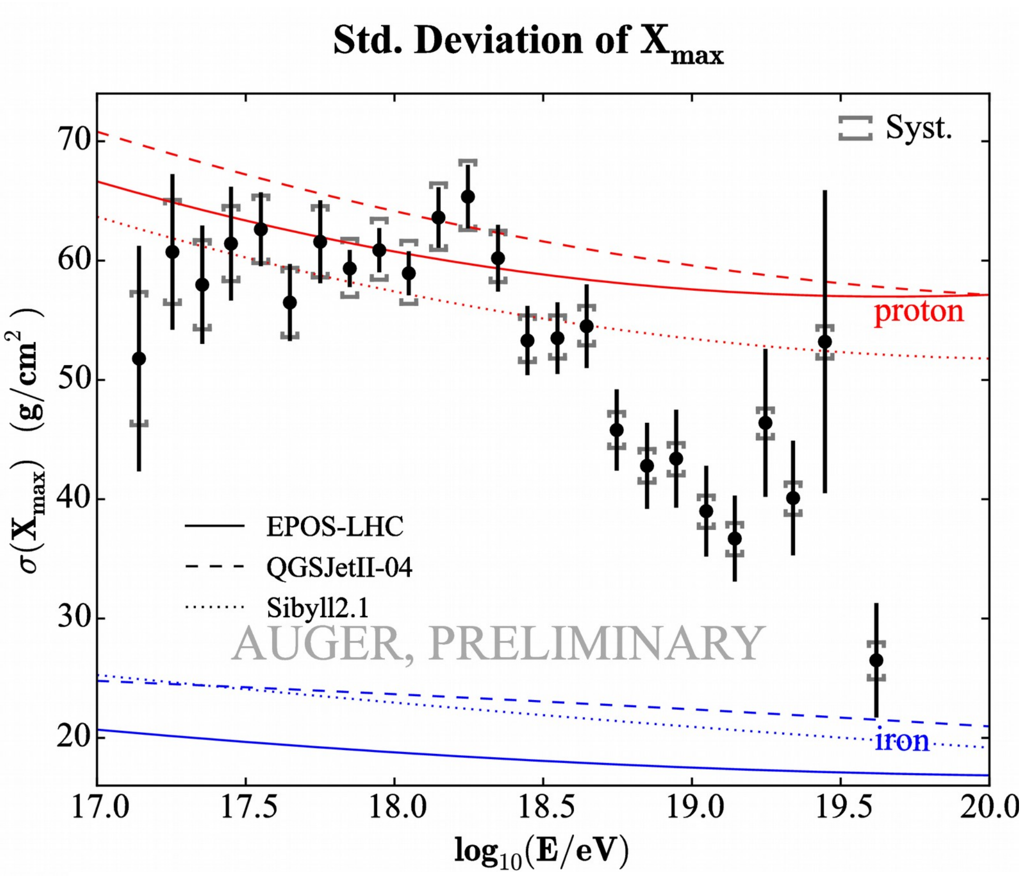


Standard FD → PHYSICAL REVIEW D **90**, 122005 (2014)

X_{max} moments combining HEAT and standard FD measurements

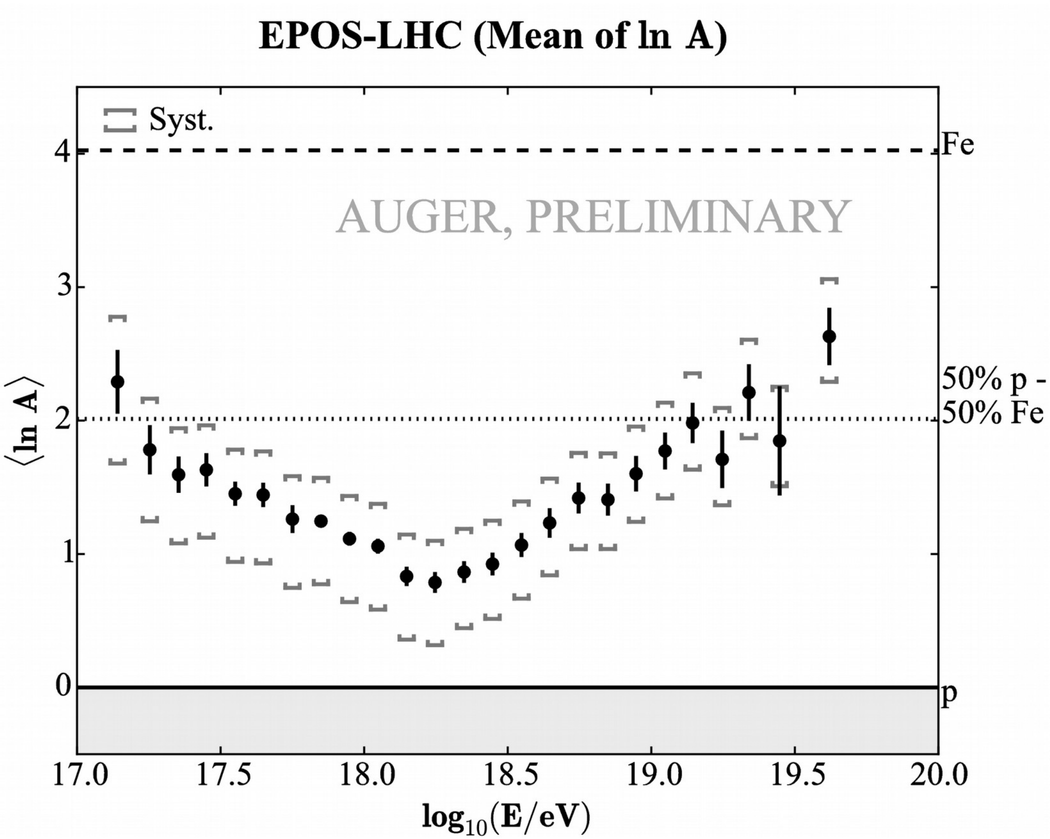
ICRC15

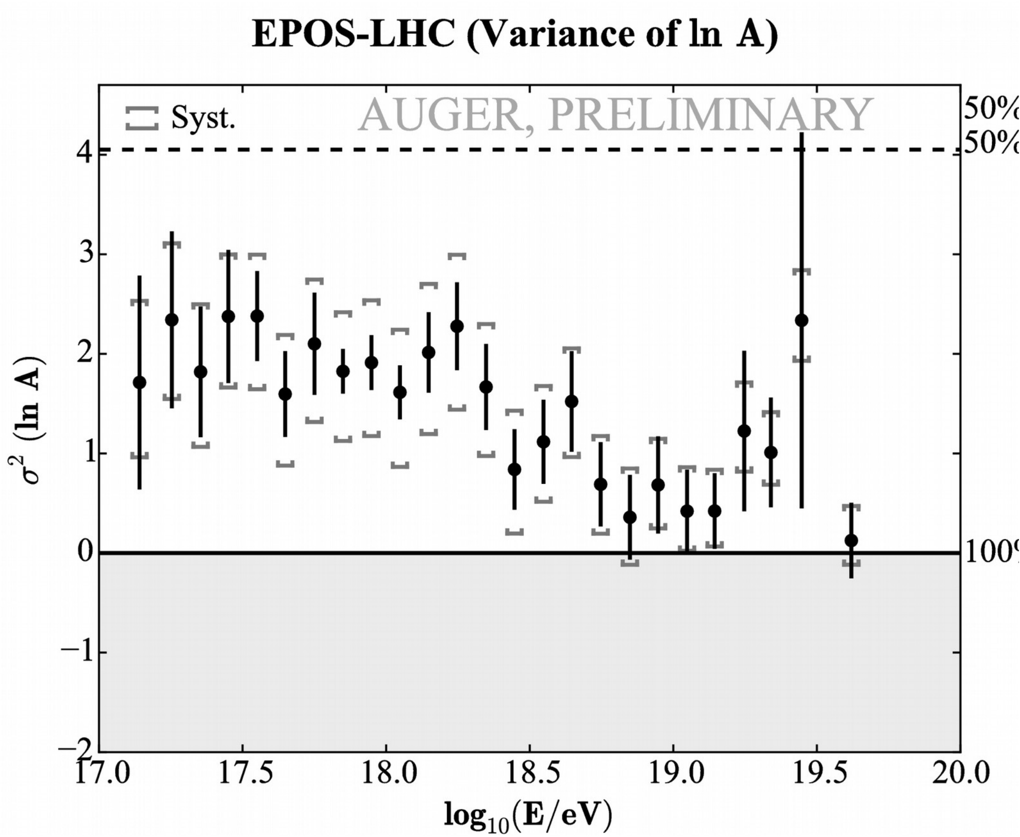




Standard FD → PHYSICAL REVIEW D **90**, 122005 (2014)

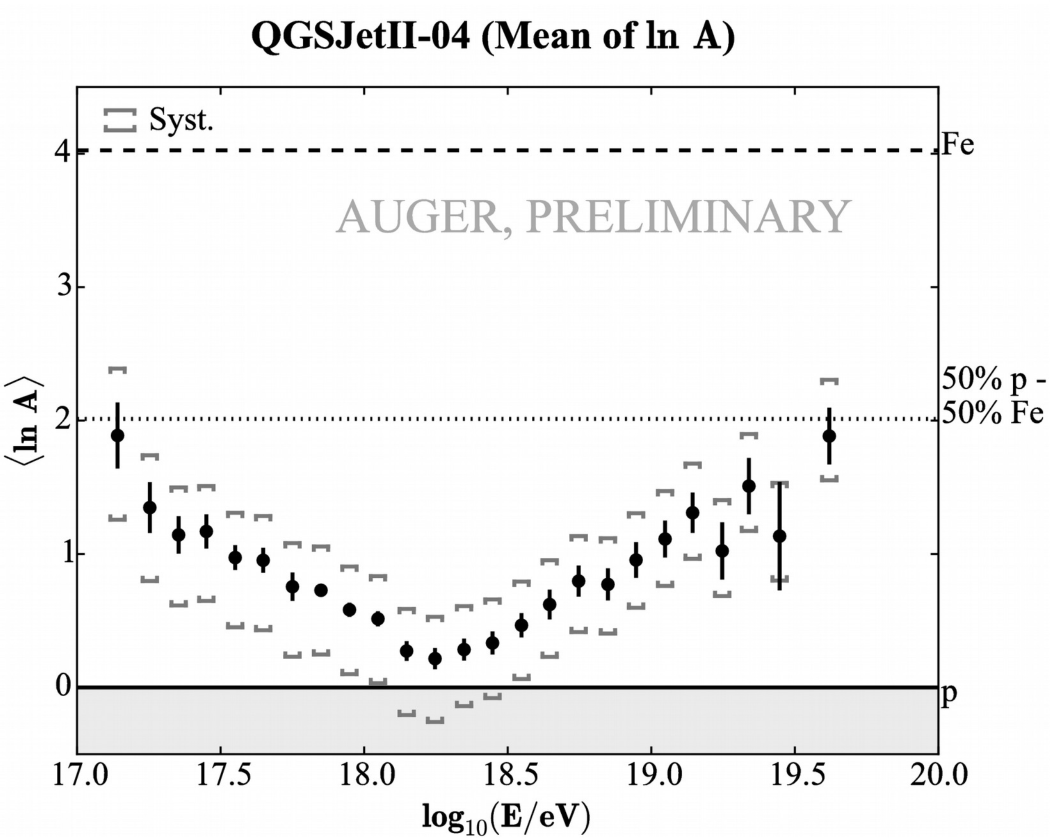
<lnA> and dispersion of lnA estimated from the X_{max} moments

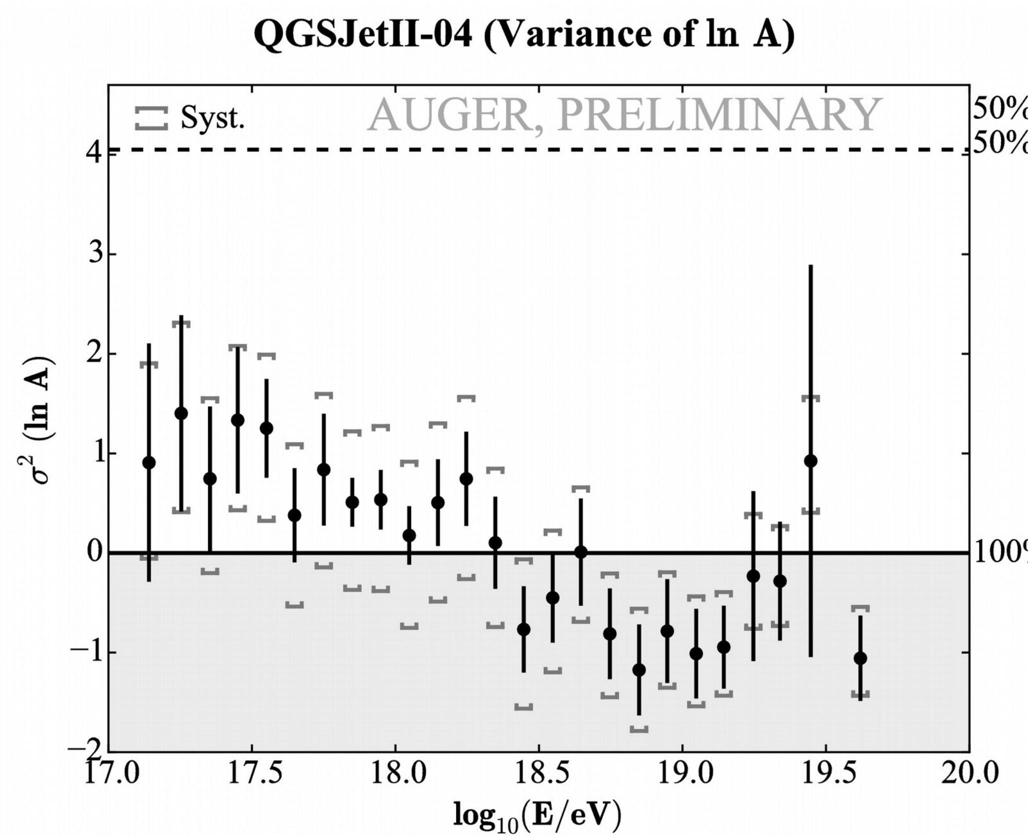


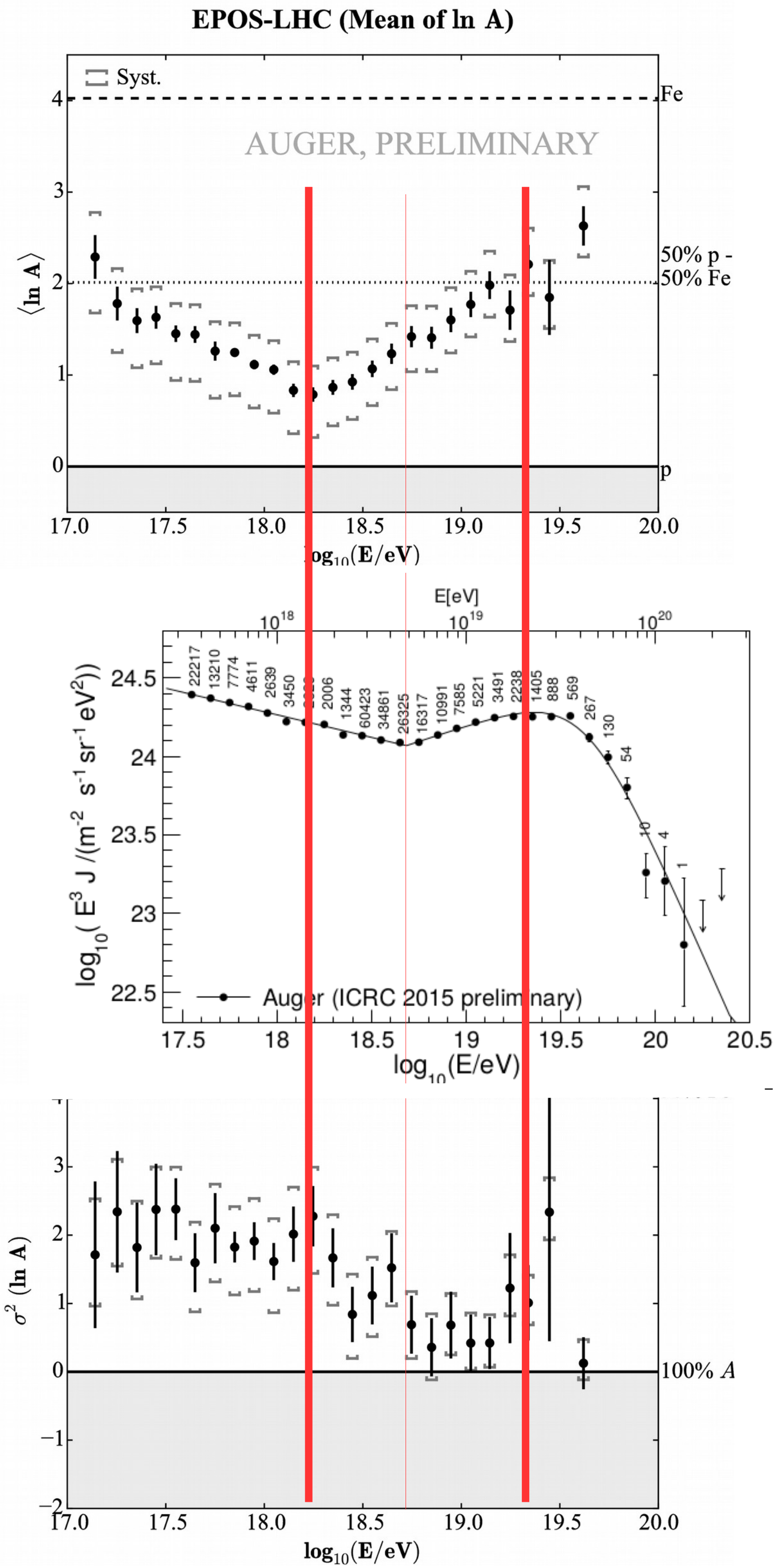


<lnA> and dispersion of lnA estimated from the X_{max} moments

ICRC15





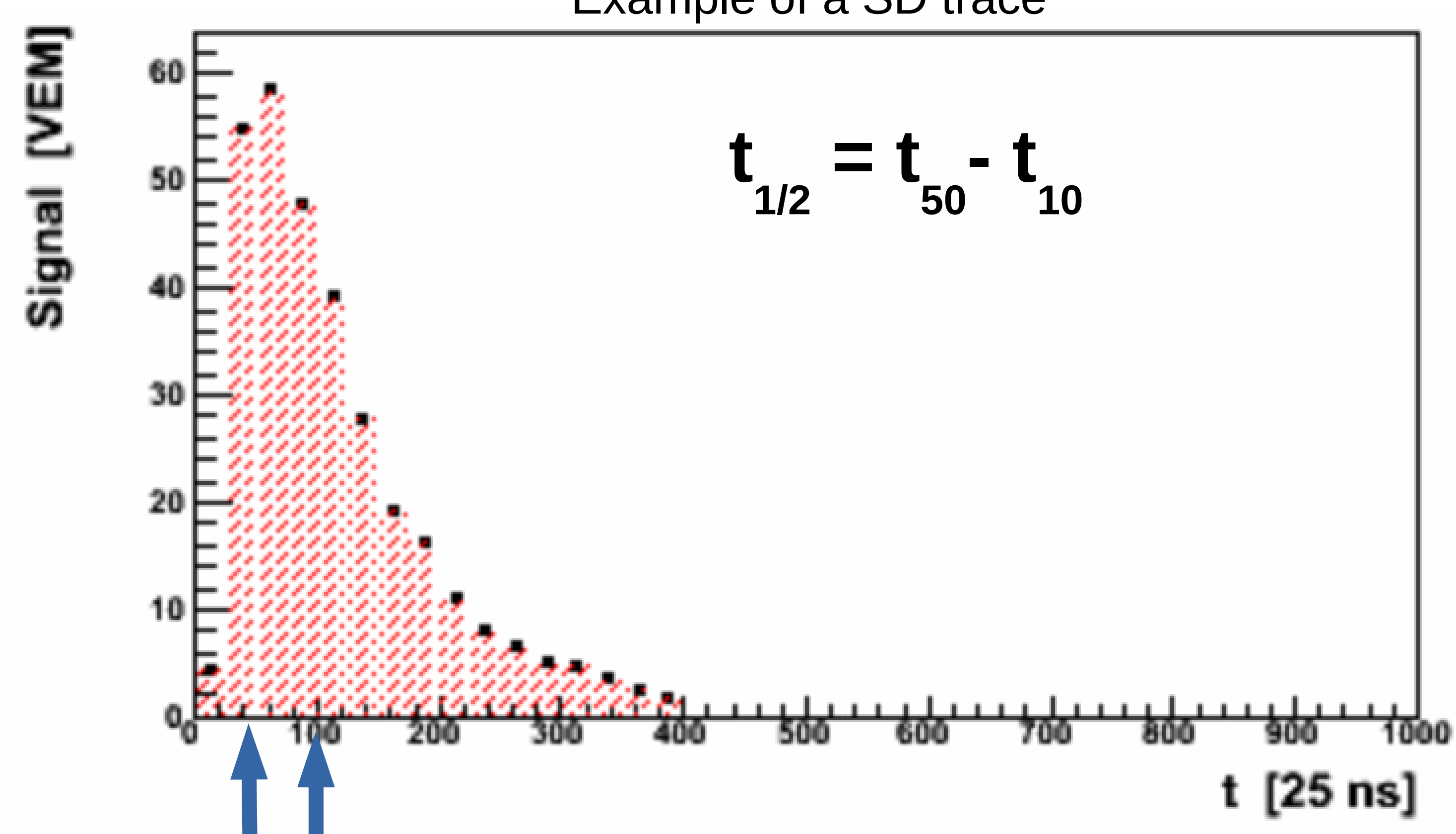

EPOS-LHC (Mean of ln A)
Syst.
Fe
AUGER, PRELIMINARY
50% p -
50% Fe
p
⟨ln A⟩
log10(E/eV)
E[eV]
Auger (ICRC 2015 preliminary)
log10(E3 J /(m-2 s-1 sr-1 eV2))
log10(E/eV)
σ2 (ln A)
100% A
log10(E/eV)

SD Observables

$Sec(\theta_{max})$

Definition of rise time, '$t_{1/2}$'

Example of a SD trace



t_{50} = time that takes to accumulate 50% of the total signal

t_{10} = time that takes to accumulate 10% of the total signal

Sec(θ_{max})

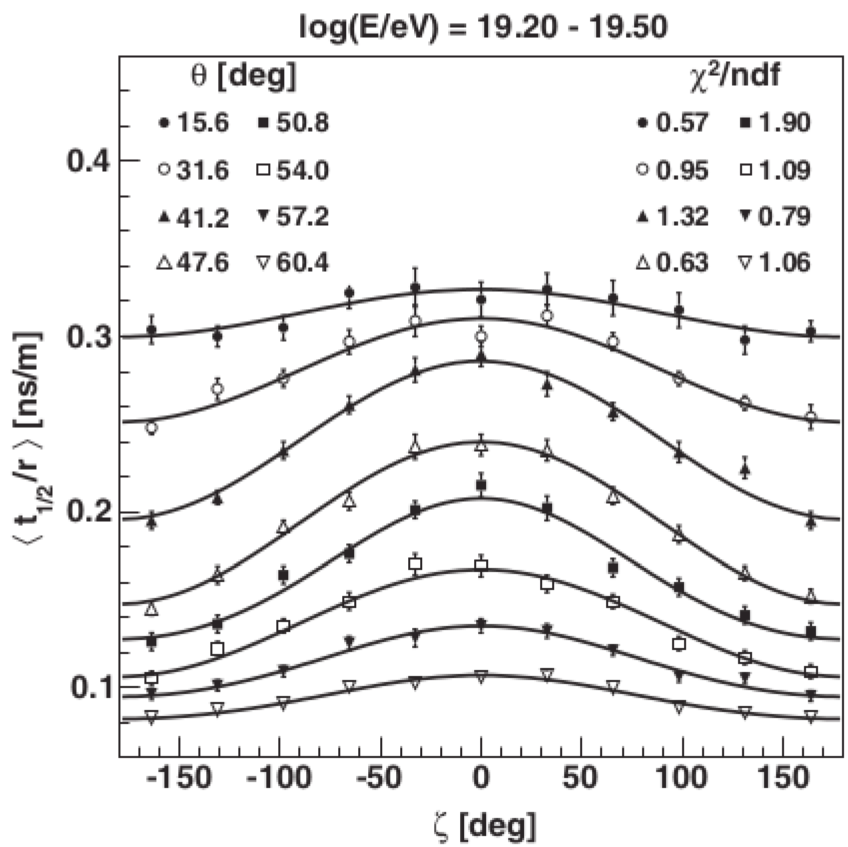
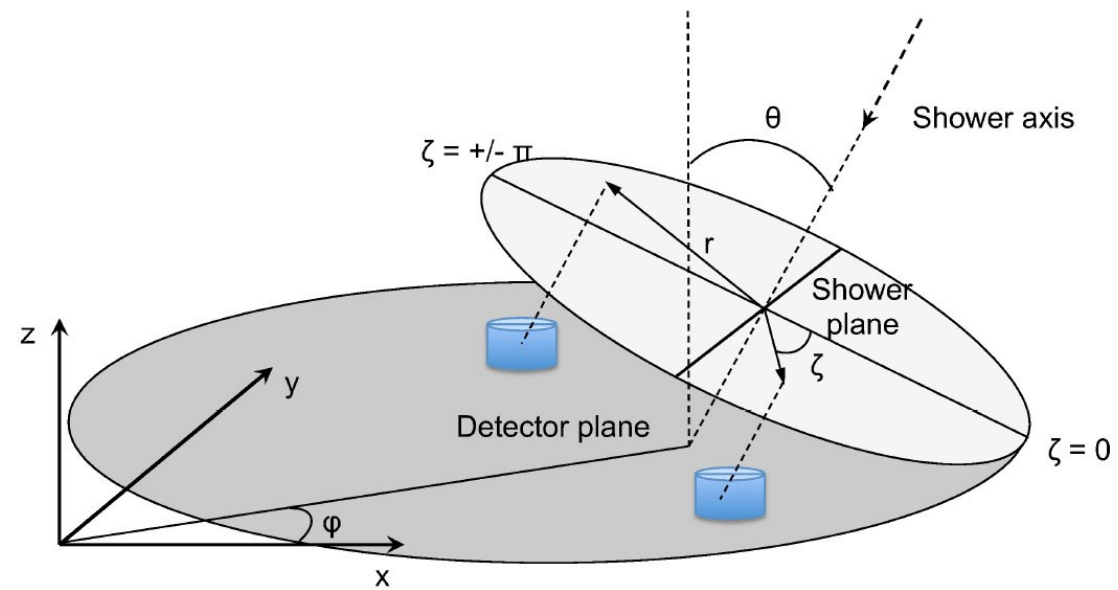


FIG. 4. Dependence of $\langle t_{1/2}/r \rangle$ on the polar angle ζ in the shower plane for primary energy $\log(E/\mathrm{eV}) = 18.55$–$18.70$ (top) and 19.20–19.50 (bottom) at different zenith angles bands. Each data point represents an average (with the corresponding uncertainty) over all stations surviving the selection criteria (see text).



$\mathrm{Sec}(\theta_{max})$

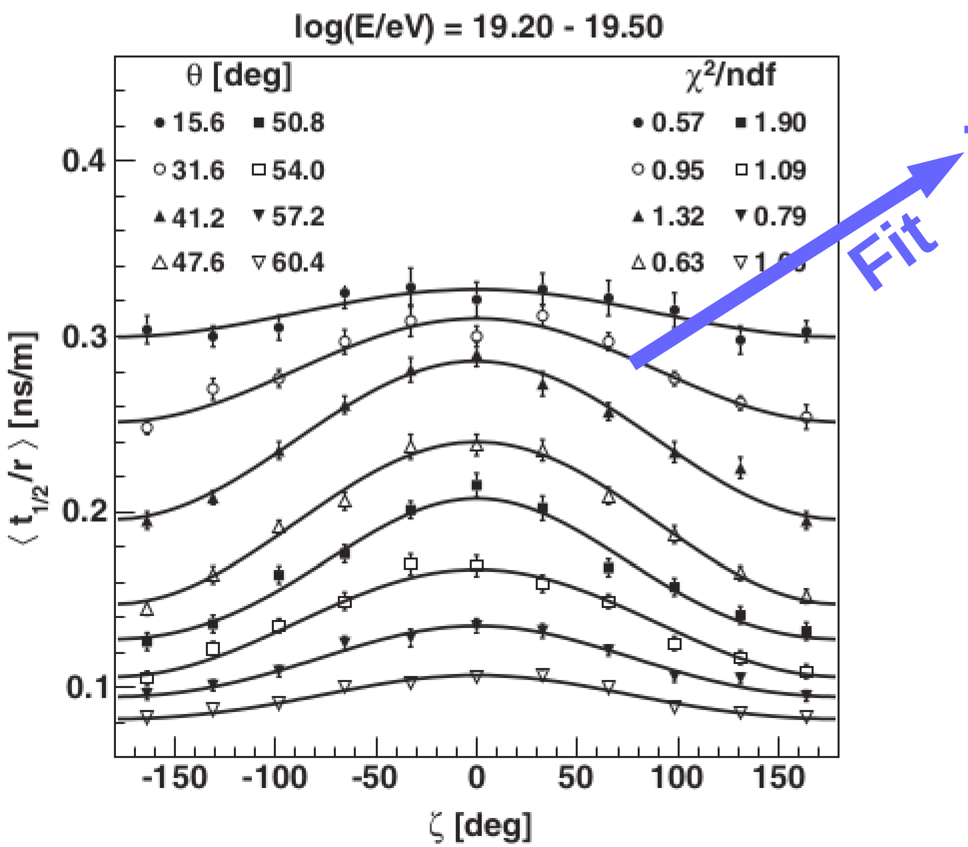
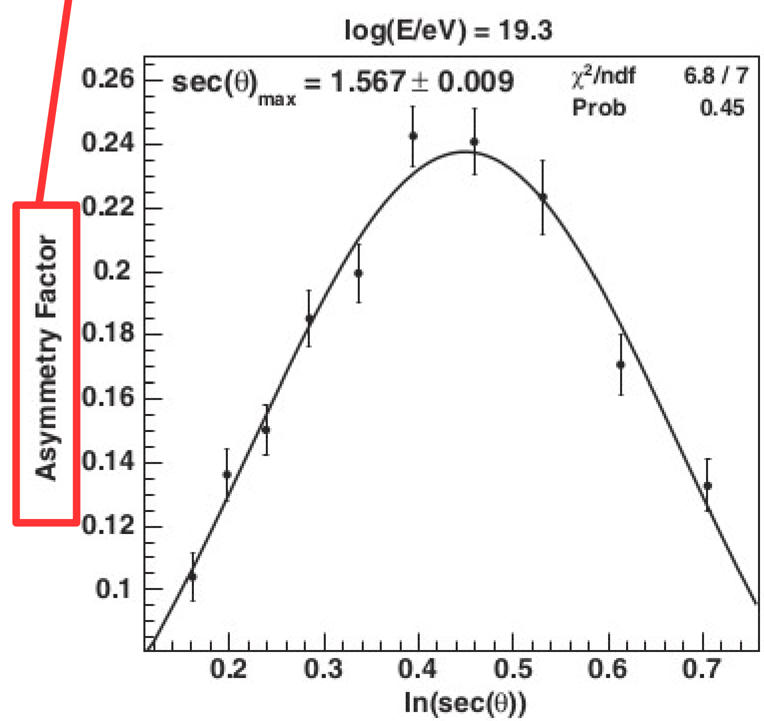


FIG. 4. Dependence of $\langle t_{1/2}/r \rangle$ on the polar angle ζ in the shower plane for primary energy $\log(E/\mathrm{eV}) = 18.55$–$18.70$ (top) and 19.20–19.50 (bottom) at different zenith angles bands. Each data point represents an average (with the corresponding uncertainty) over all stations surviving the selection criteria (see text).

10^{19} eV (bottom panel). For each zenith-angle band the data are fitted to the function $\langle t_{1/2}/r \rangle = a + b \cos \zeta + c \cos^2 \zeta$. The asymmetry with respect to ζ is evident and the ratio $b/(a+c)$, the so-called asymmetry factor, is used to give a measure of the asymmetry. In Fig. 4 results for a



$Sec(\theta_{max})$

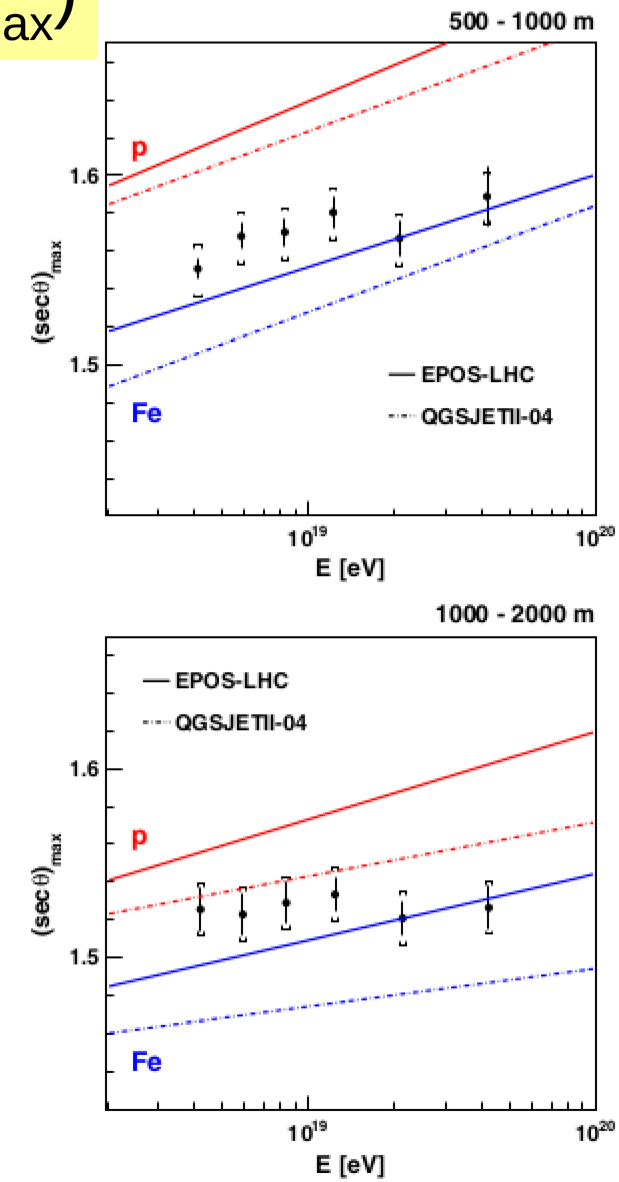


FIG. 9. Comparison between $(\sec\theta)_{max}$, for both data and Monte Carlo predictions in the 500–1000 m interval (top) and in the 1000–2000 m interval (bottom) using both hadronic models EPOS-LHC (solid lines) and QGSJETII-04 (dashed lines), for both primaries, proton (red) and iron (blue).

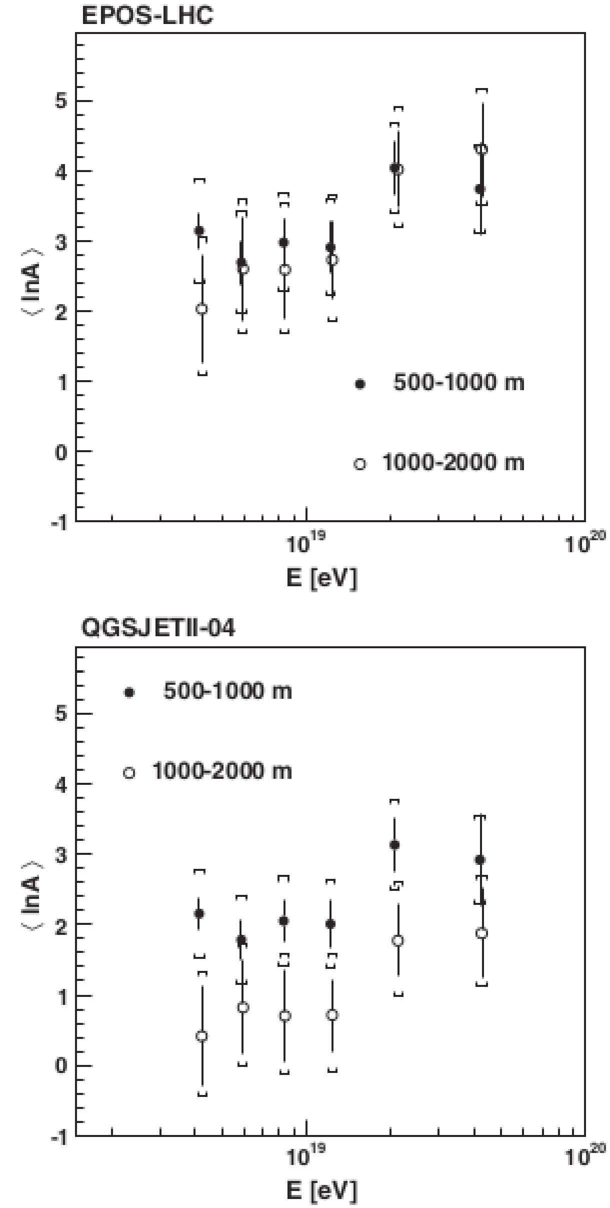


FIG. 10. Comparison of $\langle \ln A \rangle$ as a function of energy for both core distance intervals predicted by EPOS-LHC (top panel) and QGSJETII-04 (bottom panel).

Sec(θ_{max})

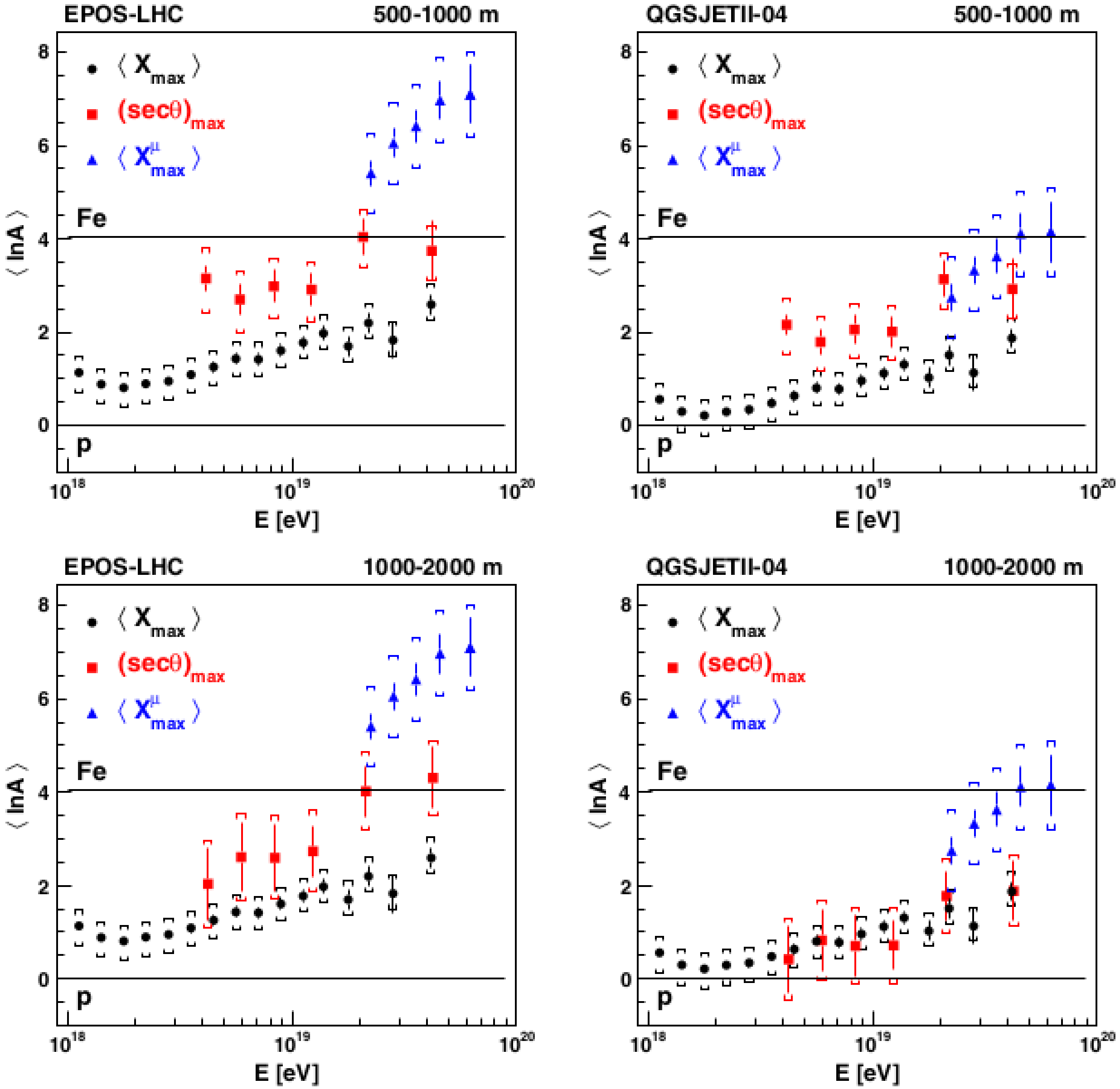
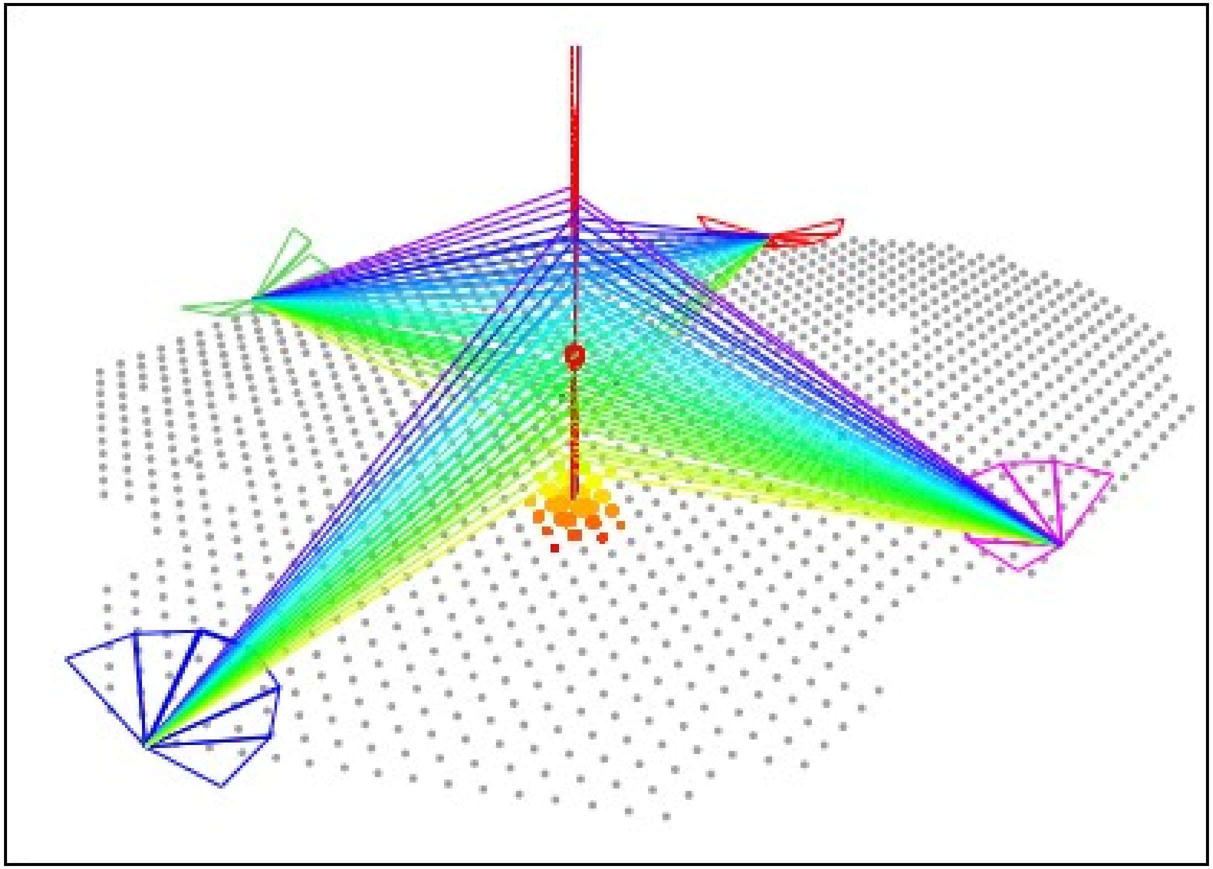


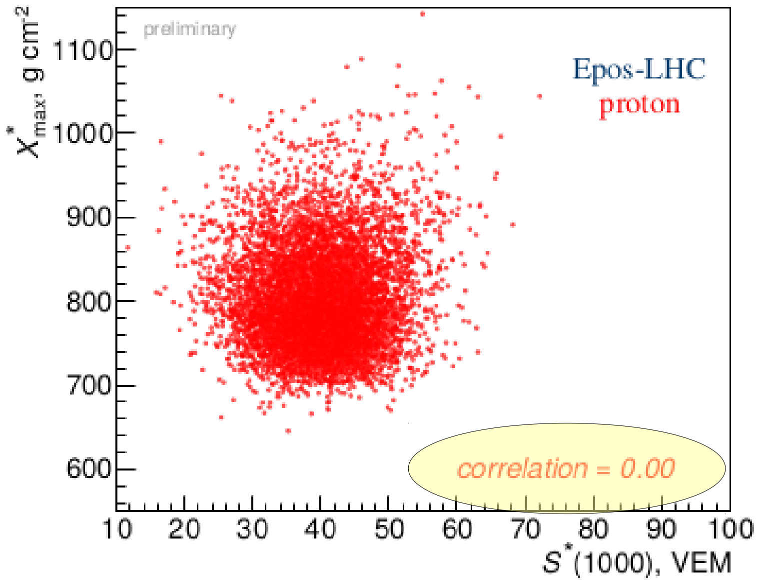
FIG. 11. ⟨ln A⟩ as a function of energy as predicted by EPOS-LHC and QGSJETII-04. Results from the asymmetry analysis in both r intervals are shown and compared with those from the elongation curve [5] and the MPD method [13].

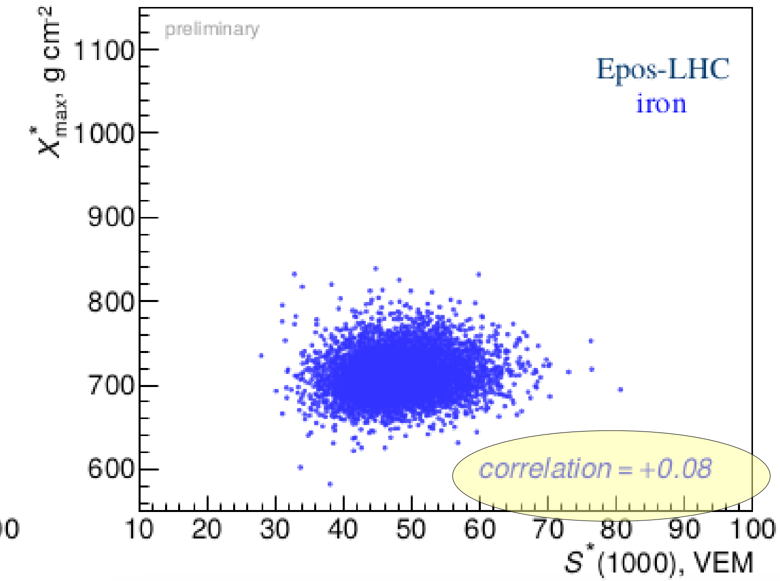
SD + FD Observables
(hybrid events)

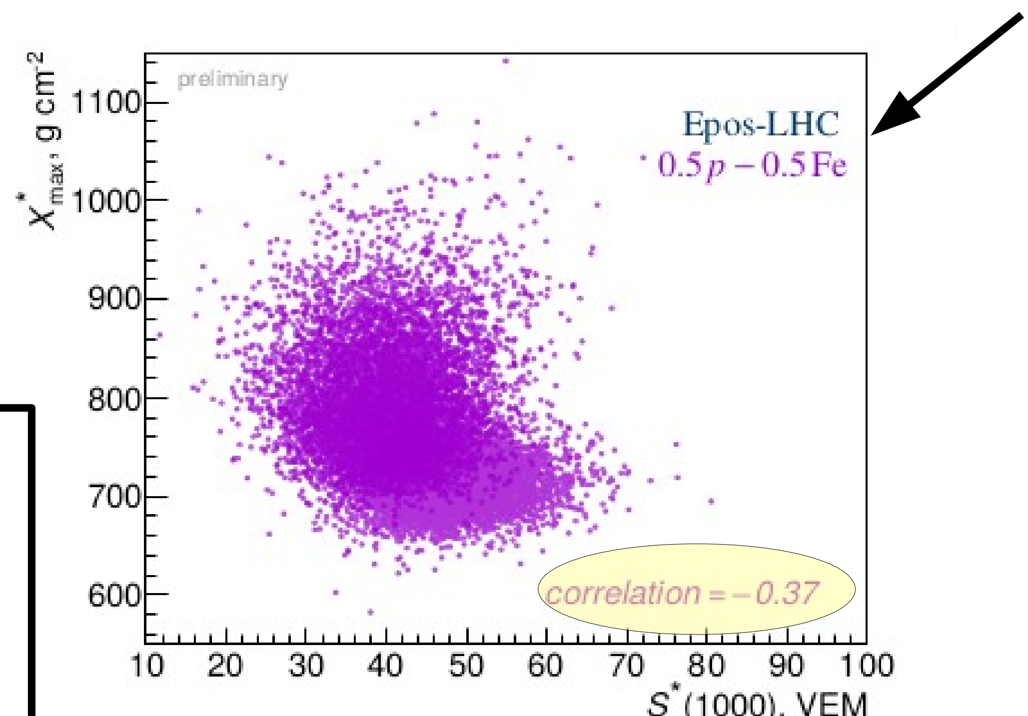


Correlation factor between:

X_{max} and S_{1000}







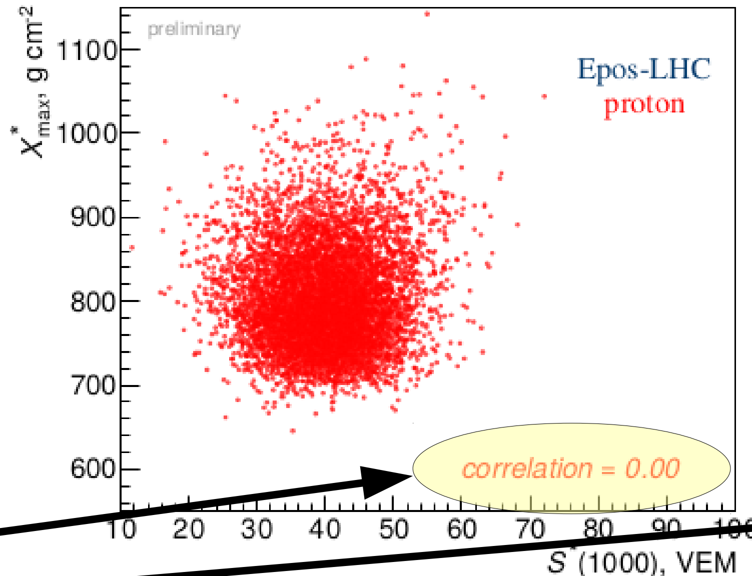
FD: depth of shower maximum, X_{max} , scaled to 10 EeV

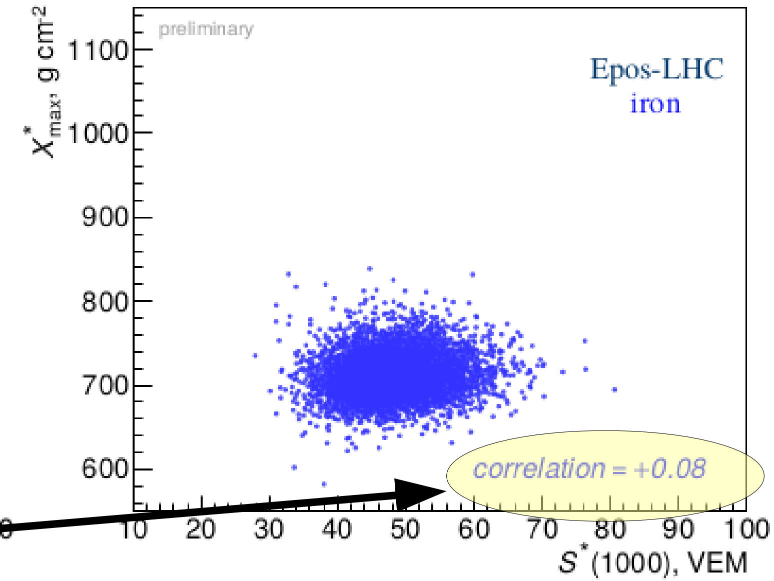
SD: signal at 1000 m from the core, $S_{(1000)}$, scaled to 10 EeV and 38°.

The scaled observables are used, they are marked with an asterisk

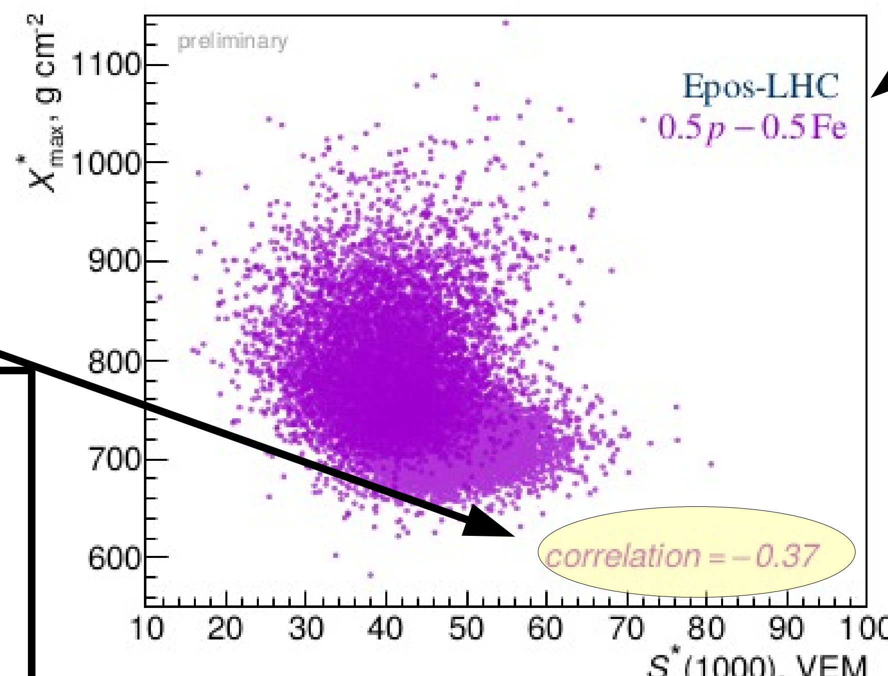
Correlation factor between:

X_{max} and S_{1000}





For pure compositions
Correlation factor ≈ 0



For mixed compositions
Correlation factor ≠ 0

FD: depth of shower maximum, X_{max} , scaled to 10 EeV

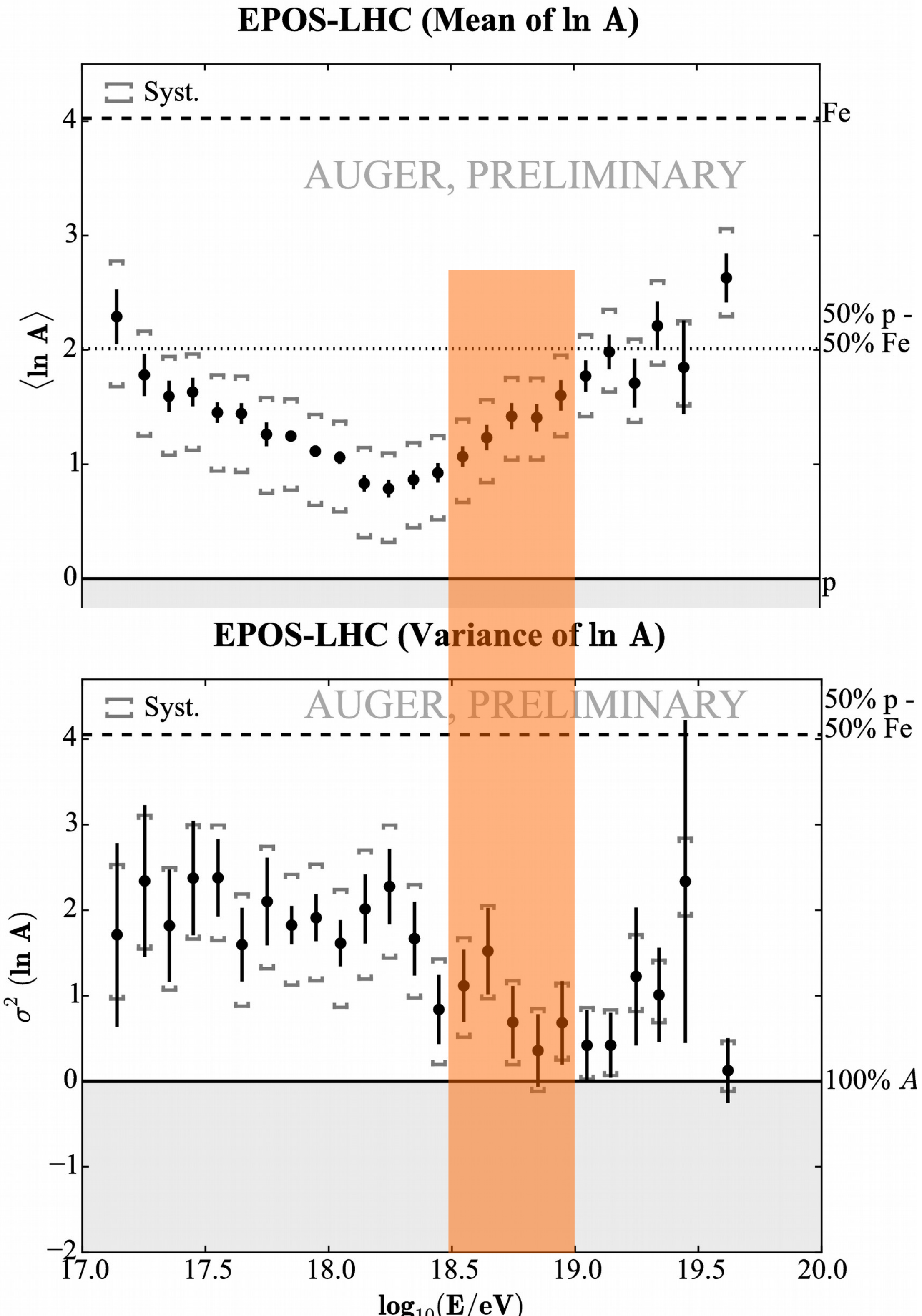
SD: signal at 1000 m from the core, $S_{(1000)}$, scaled to 10 EeV and 38˚.

The scaled observables are used, they are marked with an asterisk

Data

Hybrid (FD and SD)

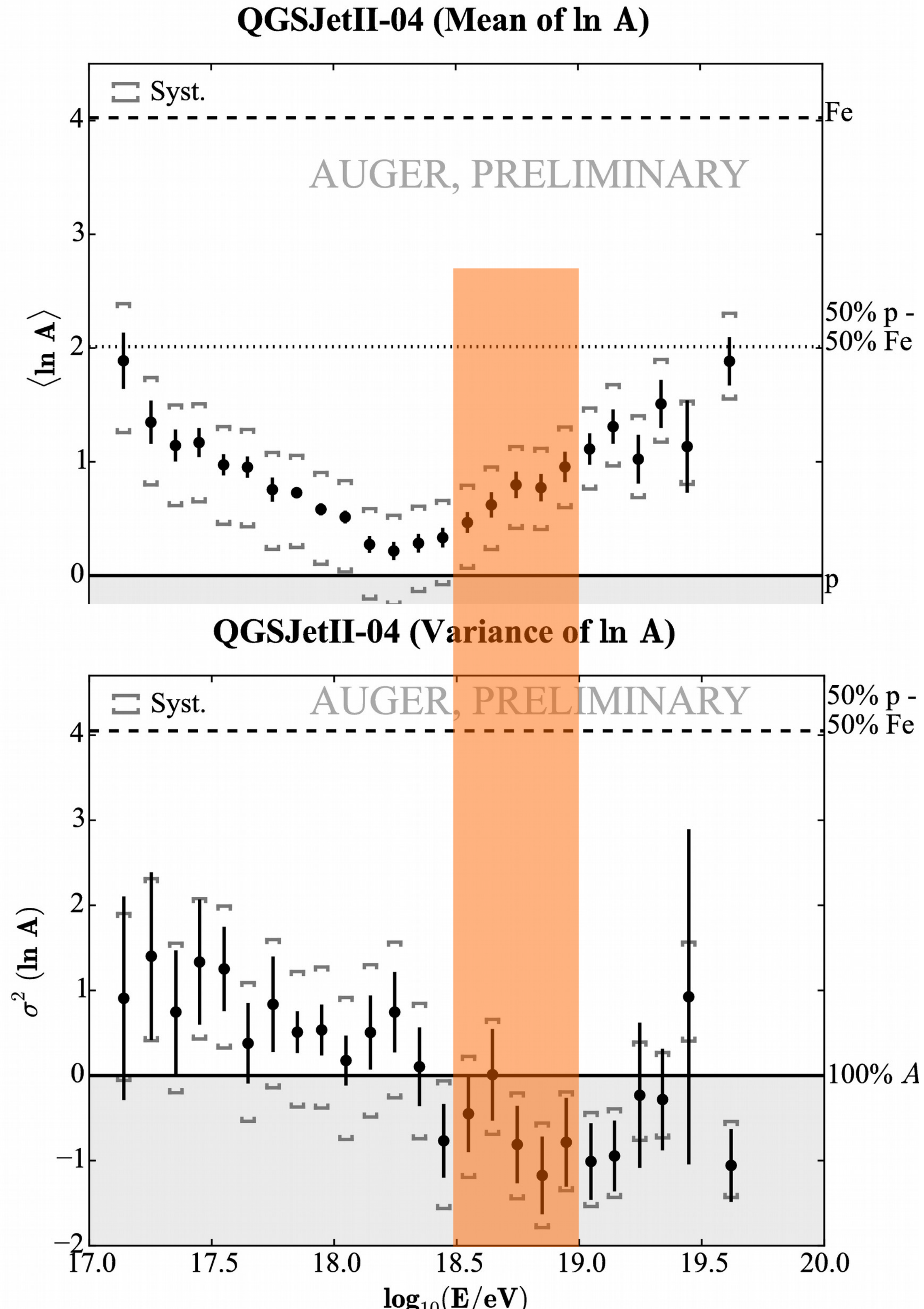
- 8 years 12/2004 − 12/2012
- lg(E/eV) = 18.5 − 19.0
- zenith angles 0 ◦ − 65 ◦
- 1376 high-quality events



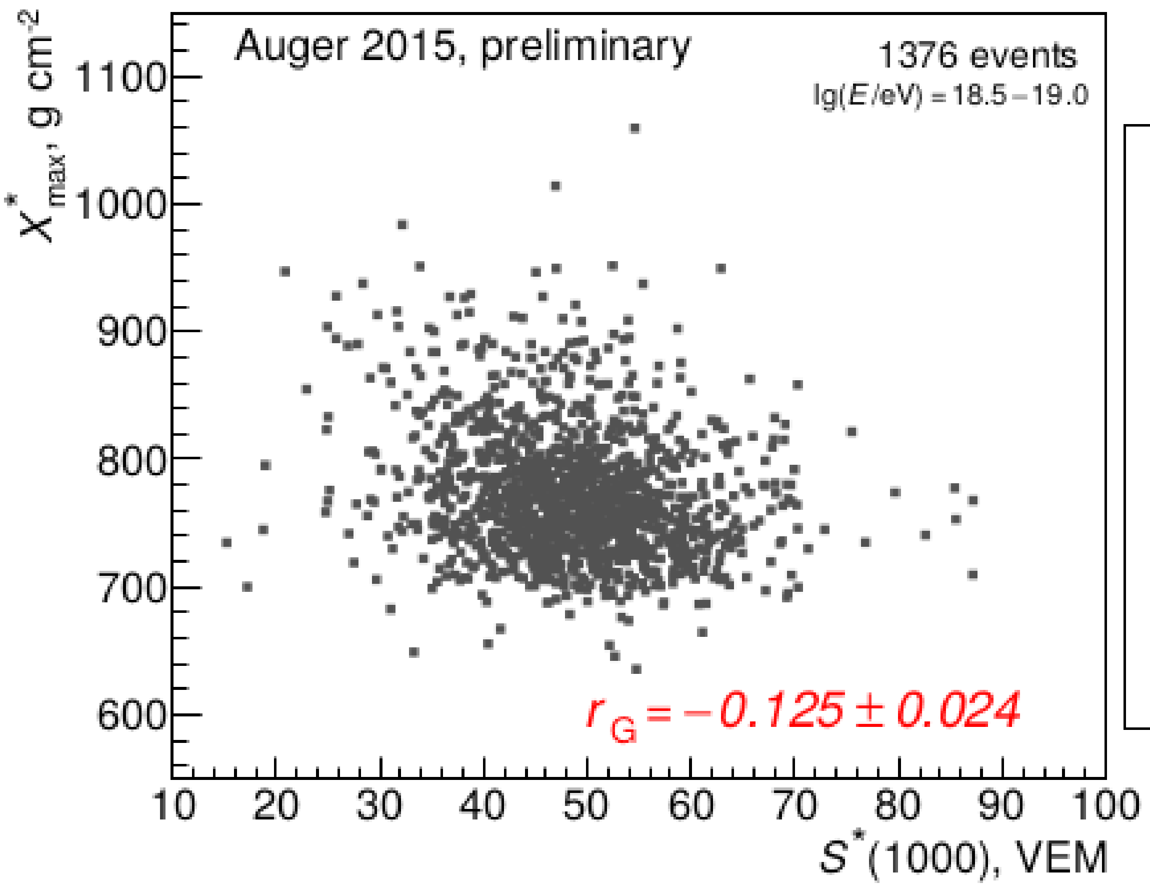
Data

Hybrid (FD and SD)

- 8 years 12/2004 − 12/2012
- lg(E/eV) = 18.5 − 19.0
- zenith angles 0 ◦ − 65 ◦
- 1376 high-quality events



correlation is significantly negative



systematics plays only a minor role $\sigma_{syst}(r_G) \lesssim 0.01$

due to invariance of r_G to additive and multiplicative scale transformations

$r_G(X^*_{max}, S^*(1000))$ for protons

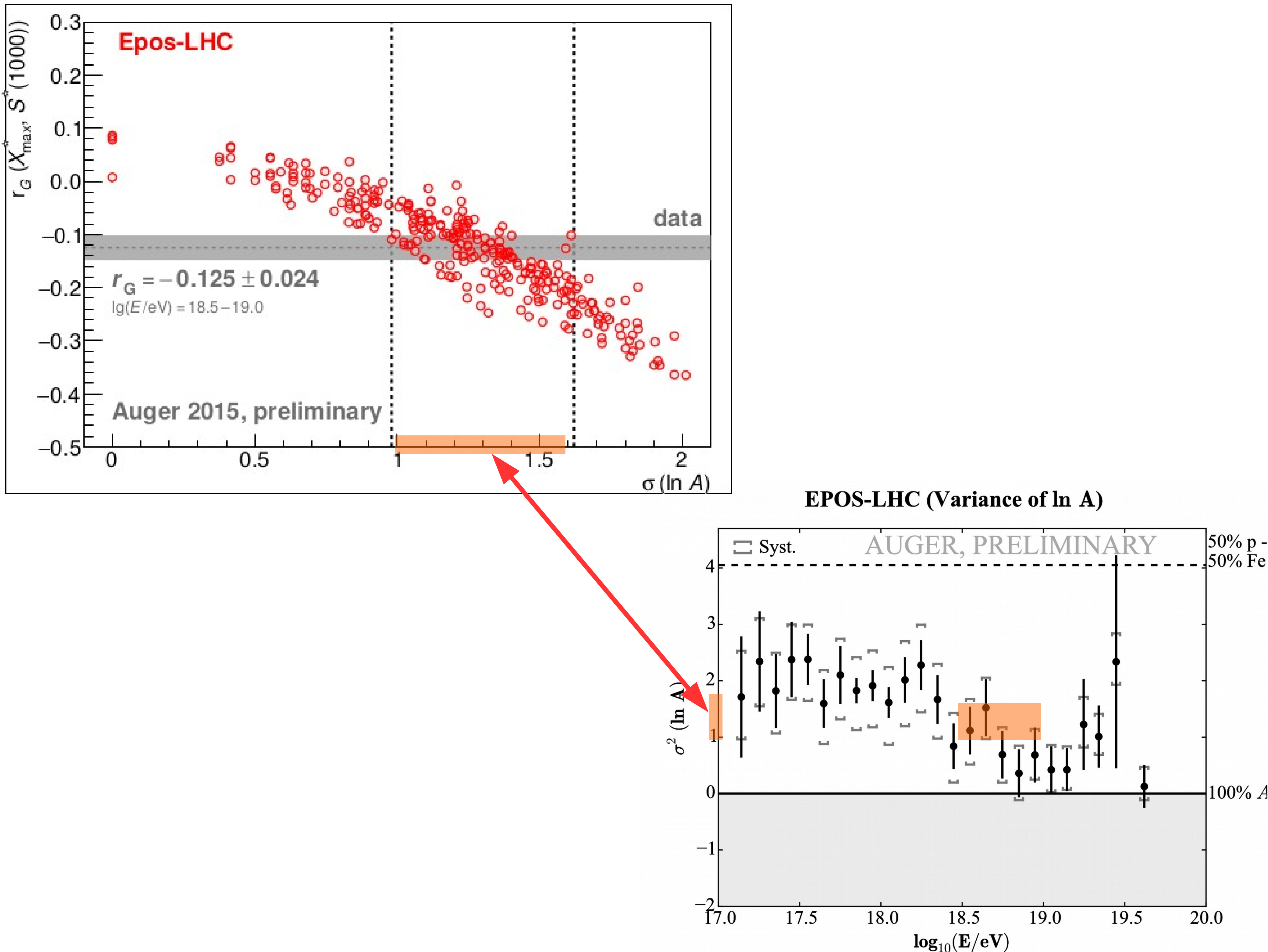
Epos-LHC	QGSJetII-04	Sibyll 2.1
0.00	+0.08	+0.07

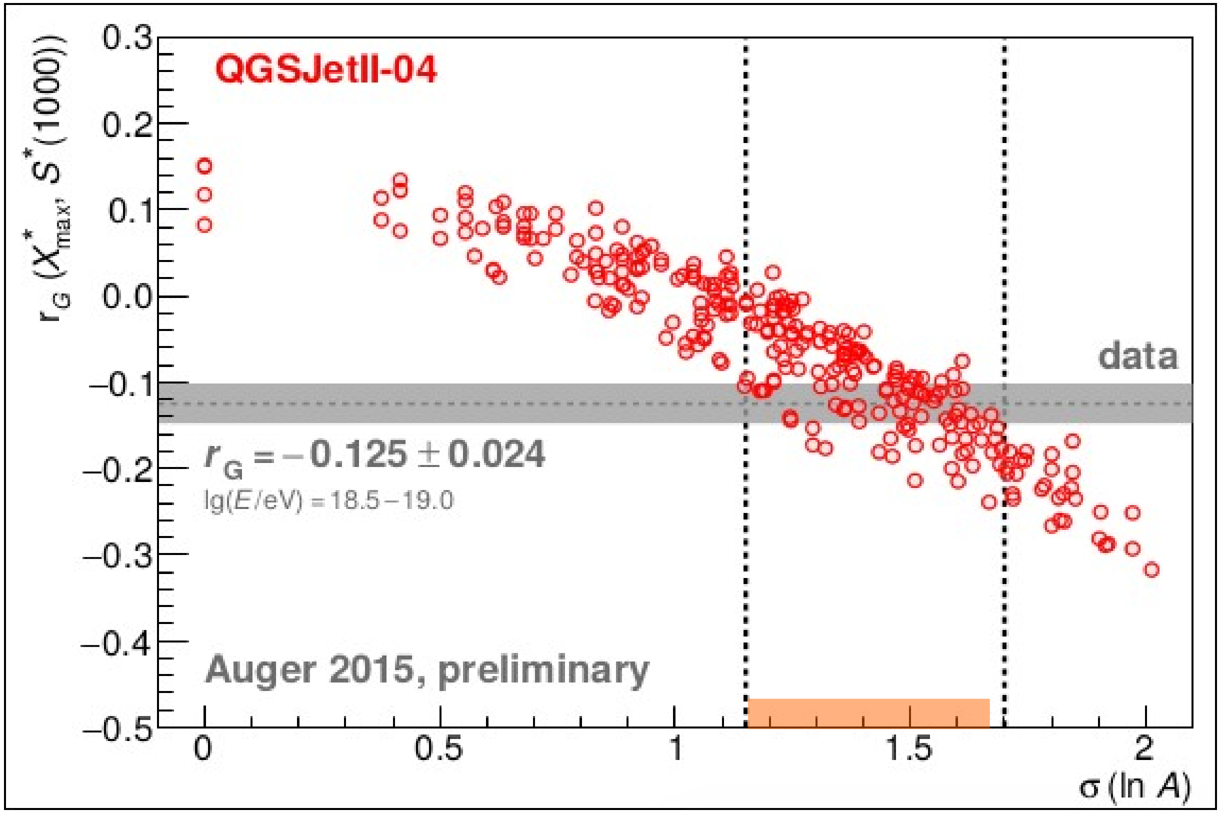
difference to data

$\approx 5\sigma$	$\approx 8\sigma$	$\approx 7.5\sigma$

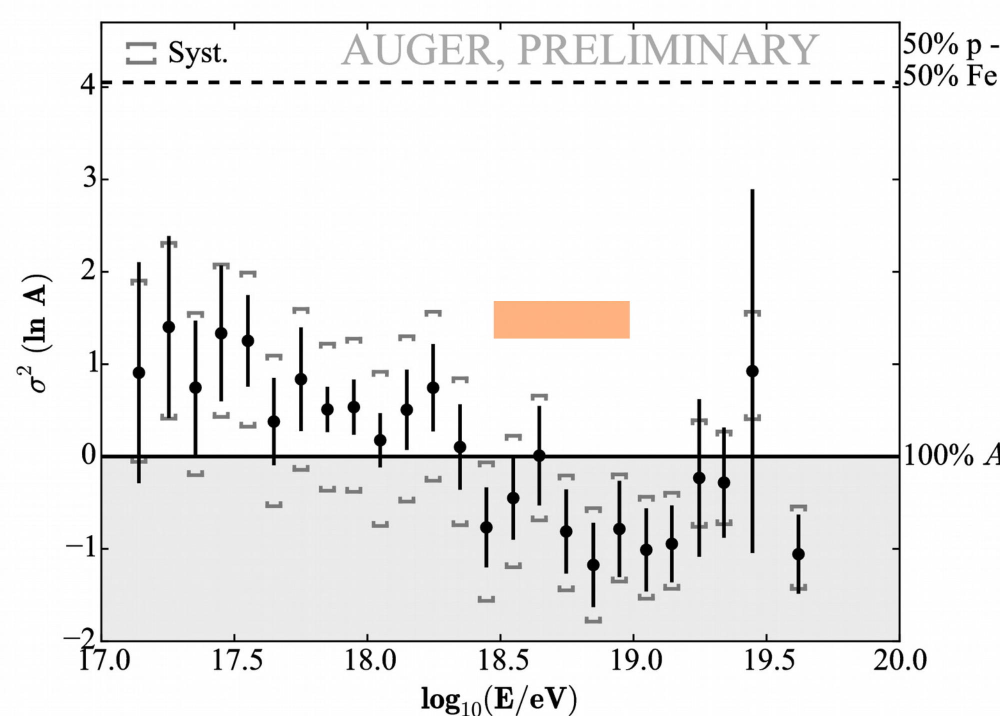
difference is larger for other pure beams

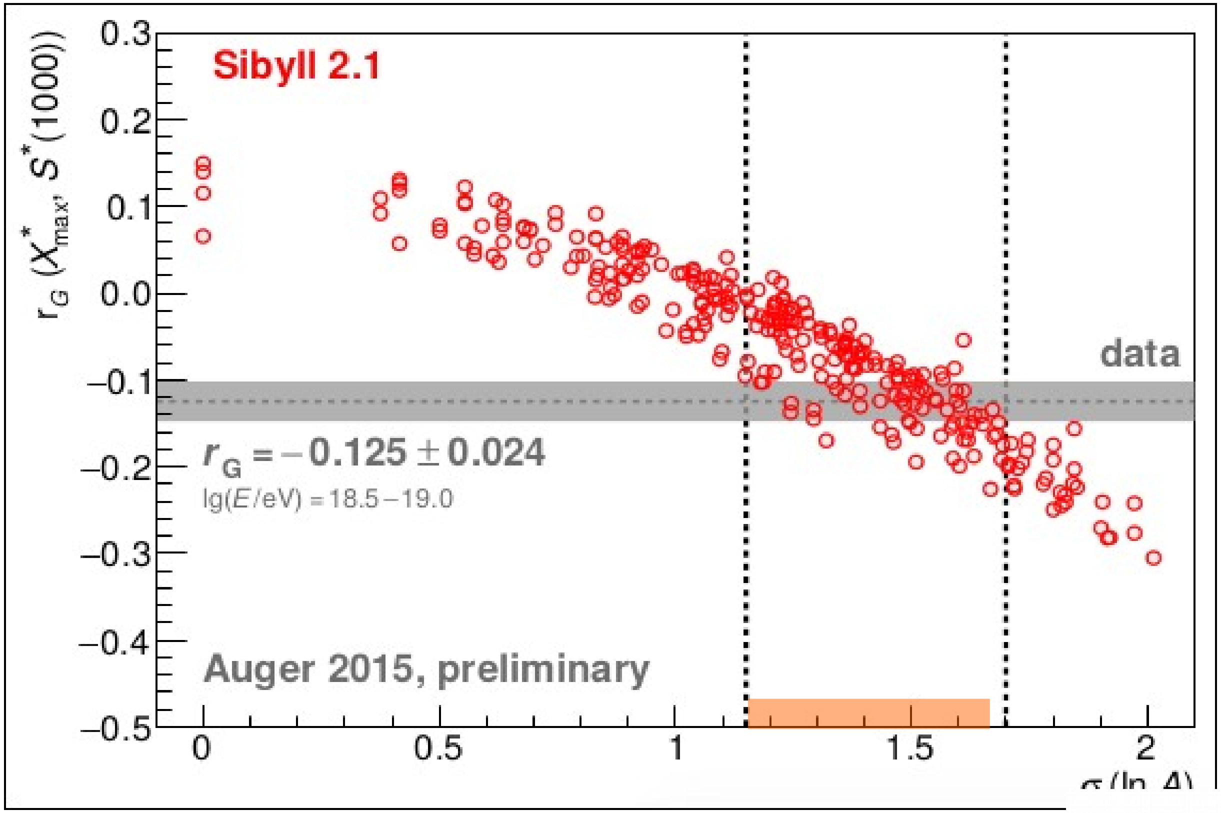
Data not consistent with pure composition

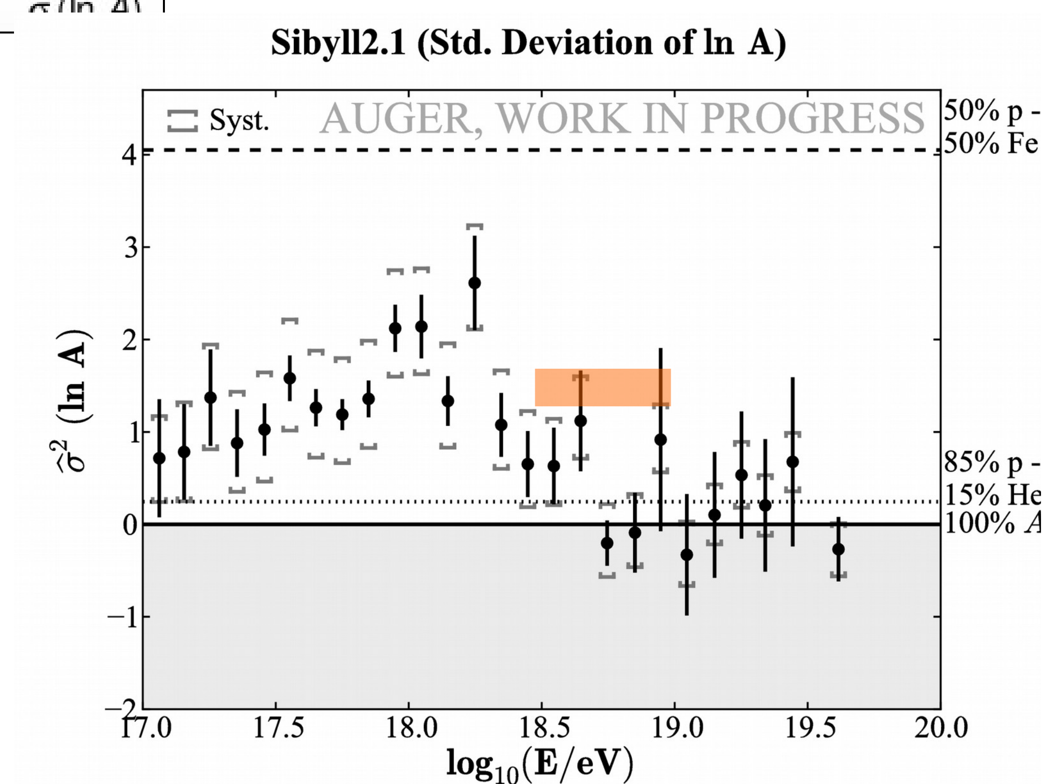

Epos-LHC
data
$r_G = -0.125 \pm 0.024$
lg(E/eV) = 18.5 – 19.0
Auger 2015, preliminary
$r_G (X_{max}, S^*(1000))$
σ (ln A)
EPOS-LHC (Variance of ln A)
Syst.
AUGER, PRELIMINARY
50% p -
50% Fe
100% A
σ^2 (ln A)
$\log_{10}(E/eV)$



QGSJetII-04 (Variance of ln A)





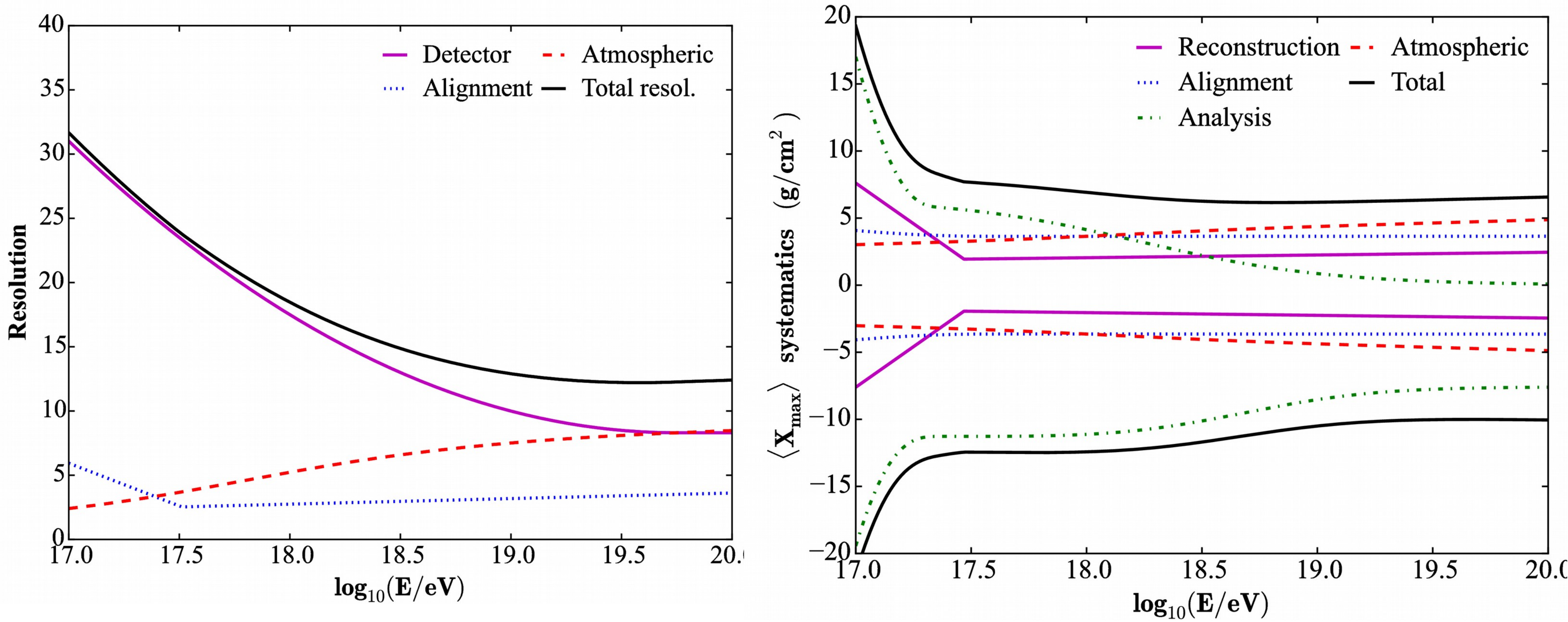


Interpretation of mass dispersion from S_{1000}, X_{max} correlation is consistent with all models.

Summary

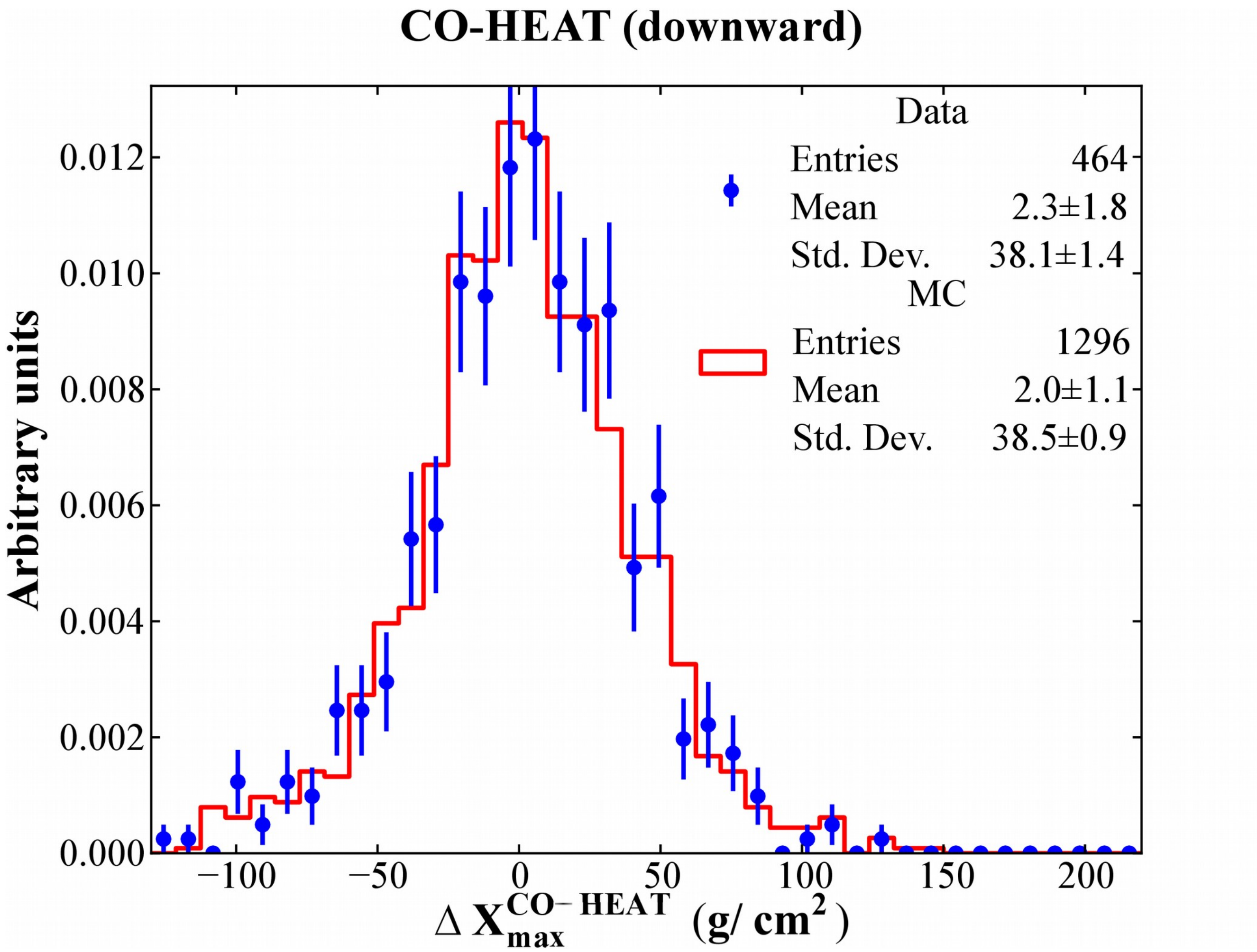
- The Pierre Auger provide a range of observables that are sensistive to different aspects (channels) of hadronic interactions in air showers.
- Observables correlated with the electromagnetic channel (X_{max}) provide a more reliable interpretation of the mass composition. While observables related to the muonic channel provide constraints to hadronic interaction models (details on following talk by Tanguy).
- Currently, none of the high hadronic intereaction models can describe coherently all the different observables.

Resolution and systematics of the reconstructed X_{max} for HEAT



Note: The detector resolution is estimated using simulations.

Validation of the HEAT detector simulation



Correlation between $X^*_{\max}$ and $S^*(1000)$

Ranking coefficient $r_{\rm G}$ [R. Gideon, R. Hollister, JASA 82 (1987) 656]

1. rank events in $X^*_{\max}$ and $S^*(1000)$
2. replace measured values by ranks:

   $X^*_{\max}(1), \ldots, X^*_{\max}(N) \Longrightarrow 1, 2, \ldots, N$

   $S^*(1000)(1), \ldots, S^*(1000)(N) \Longrightarrow 1, 2, \ldots, N$
3. count events with ranks deviating from the expectations for perfect (anti-)correlation; all events contribute 0 or 1 $\Rightarrow$ robustness against outliers

$r_{\rm G}$ is invariant to any transformations leaving ranks unchanged

e.g. to systematics in $X^*_{\max}$ and $S^*(1000)$

various coefficients applied (incl. Pearson, Spearman), conclusions unchanged