Mass composition interpretation of ultra-high-energy cosmic rays with the Pierre Auger Observatory

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PIERRE AUGER OBSERVATORY

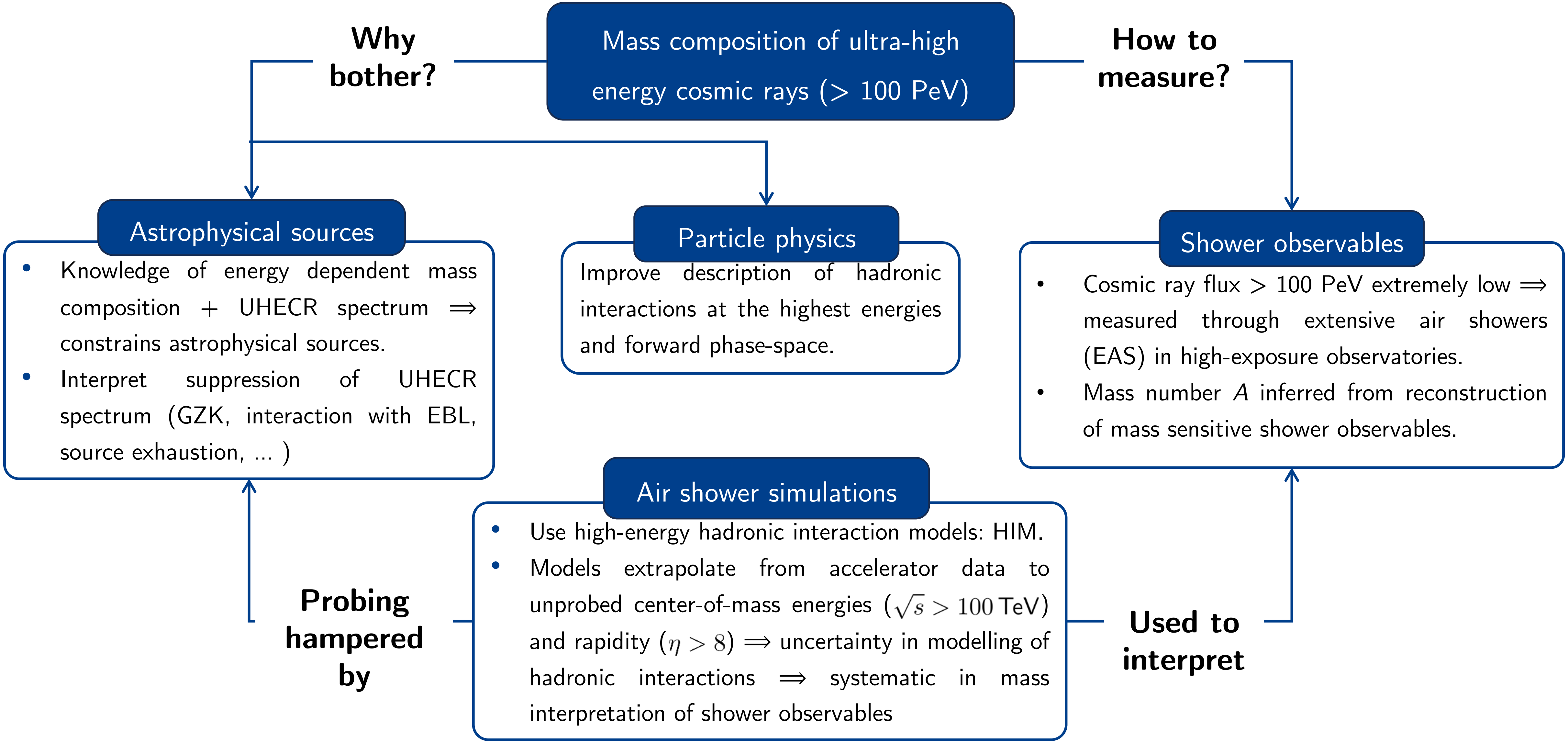
USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

IGFAE INSTITUTO GALEGO DE FÍSICA DE ALTAS ENERXÍAS

25 1999 2024

Fundación "la Caixa"

Mass composition of UHECRs – Why know it and how to infer it



Mass composition of ultra-high energy cosmic rays (> 100 PeV)

Why bother?

How to measure?

Astrophysical sources

- Knowledge of energy dependent mass composition + UHECR spectrum $\Longrightarrow$ constrains astrophysical sources.
- Interpret suppression of UHECR spectrum (GZK, interaction with EBL, source exhaustion, ...)

Particle physics

Improve description of hadronic interactions at the highest energies and forward phase-space.

Shower observables

- Cosmic ray flux > 100 PeV extremely low $\Longrightarrow$ measured through extensive air showers (EAS) in high-exposure observatories.
- Mass number A inferred from reconstruction of mass sensitive shower observables.

Probing hampered by

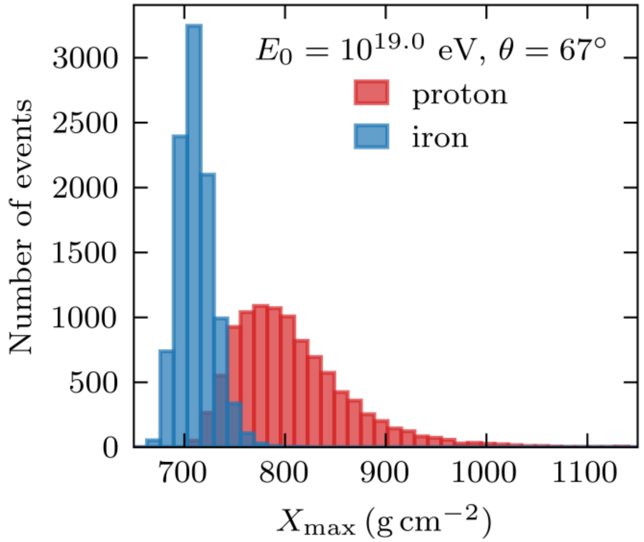
Air shower simulations

- Use high-energy hadronic interaction models: HIM.
- Models extrapolate from accelerator data to unprobed center-of-mass energies ($\sqrt{s} > 100\,\text{TeV}$) and rapidity ($\eta > 8$) $\Longrightarrow$ uncertainty in modelling of hadronic interactions $\Longrightarrow$ systematic in mass interpretation of shower observables

Used to interpret

Mass composition – shower observables

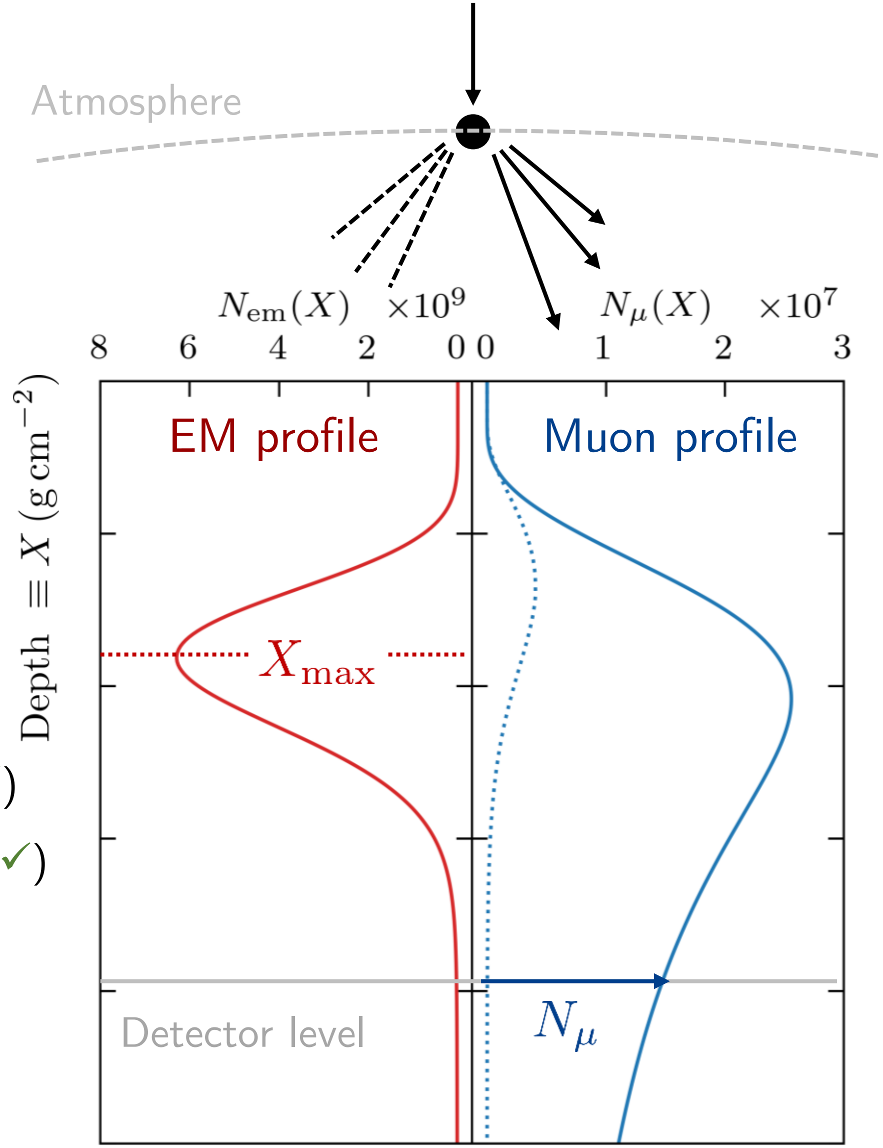
$X_{\max}$



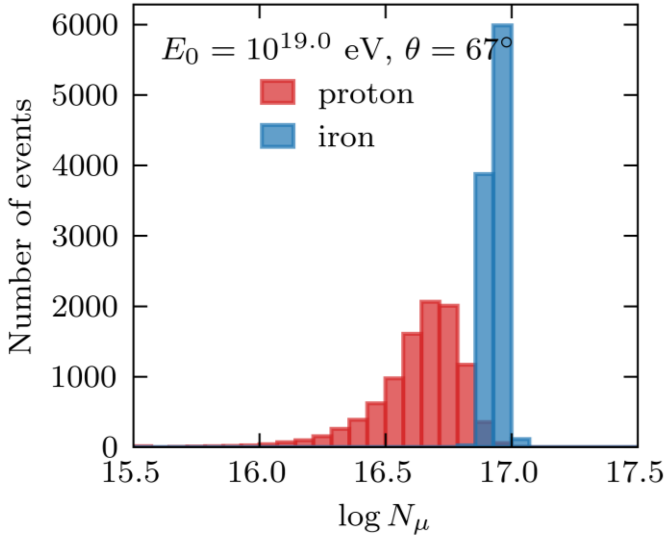
- $\langle X_{\max}(A, E_0)\rangle = \langle X^p_{\max}(E_0)\rangle - \ln A$ (✓)
- $\sigma(X_{\max})$ decrease with *A* & beam purity (✓)
- Elongation rate for fixed *A**:

$$D_{10} = \frac{\mathrm{d}\,\langle X_{\max}\rangle}{\mathrm{d}\log_{10} E_0} \simeq 60\,\mathrm{g\,cm^{-2}}/\,\text{decade}$$

*independent of *A* and Hadronic Interaction Model.



N_μ



- $\langle N_\mu(A, E_0)\rangle \simeq A^{0.07}\langle N^p_\mu(E_0)\rangle$ (✘*)
- $\sigma(N_\mu)$ decrease with *A* & beam purity (✓)

*due to muon puzzle (more ahead)

✓ Good observable ✘ In tension with HIM

The Pierre Auger Observatory - Overview

Nucl.Instrum.Meth.A 798 (2015) 172-213

Location: Pampa Amarilla, Mendoza, Argentina.

Goals:

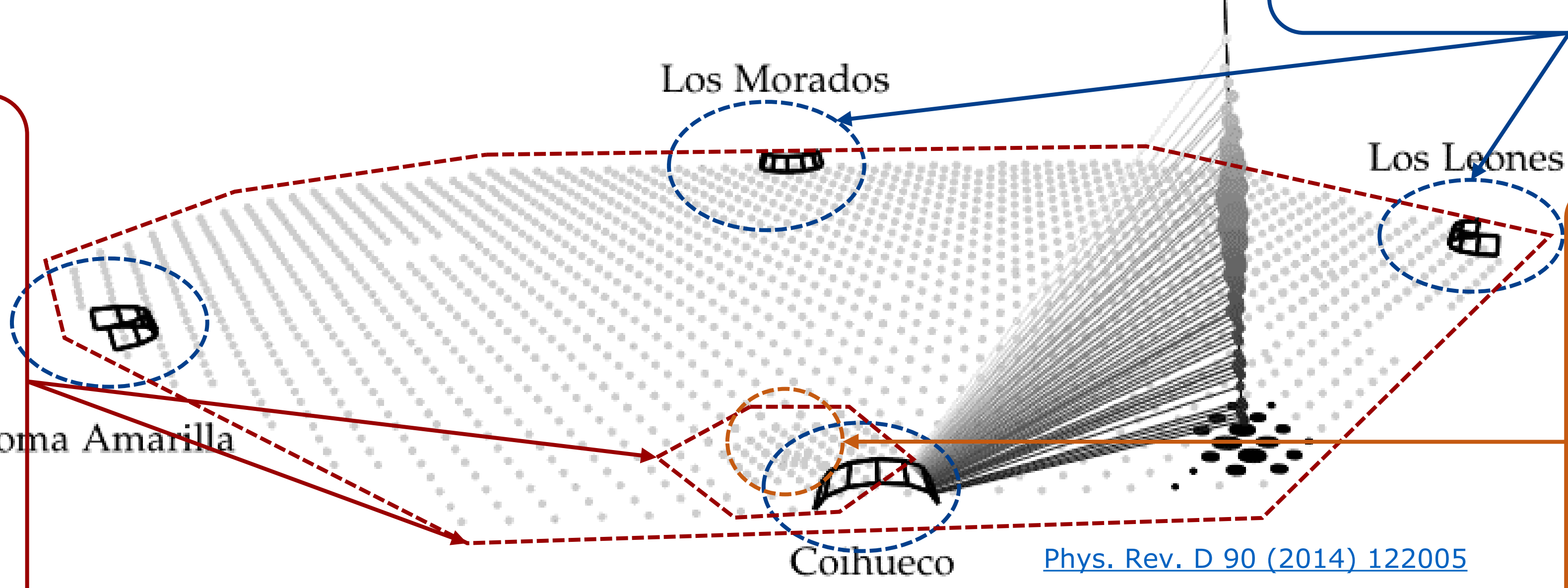
- measure arrival direction[1] and energy spectrum[2] of cosmic rays above $10^{16.5}$ eV;
- interpret UHECRs mass composition.

Data taking period: since 2004.

Height / atmospheric depth: 1400 m a.s.l. / 880 g $\mathrm{cm^{-2}}$;

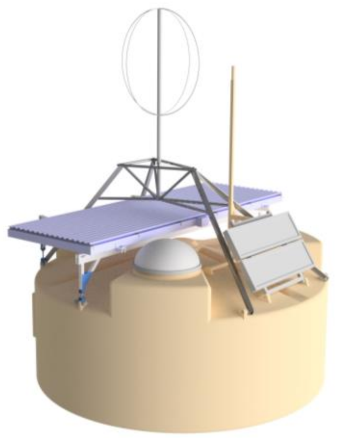
Fluorescence detector (FD)

Hybrid event

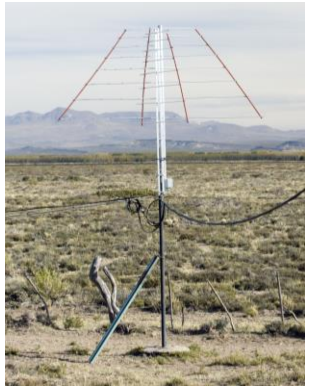


Phys. Rev. D 90 (2014) 122005

Surface detector (SD)



AERA



[1] Dr. João de Mello Neto talk on 26/08 at 4:15 PM

[2] Fiona Ellwanger talk on 26/08 at 3:15 PM

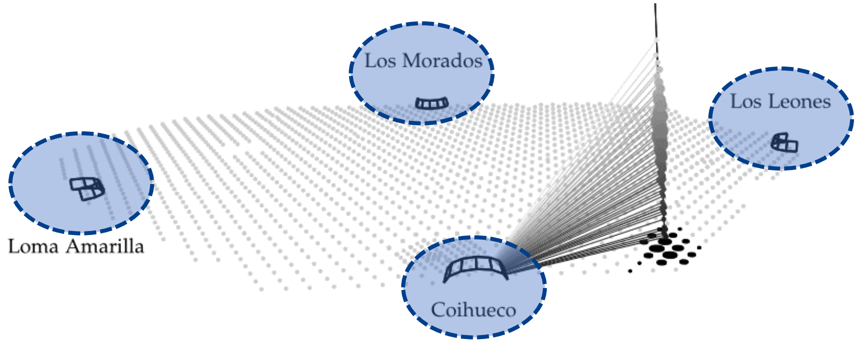
FLUORESCENT DETECTOR MEASUREMENTS

Fluorescence detector: working principles

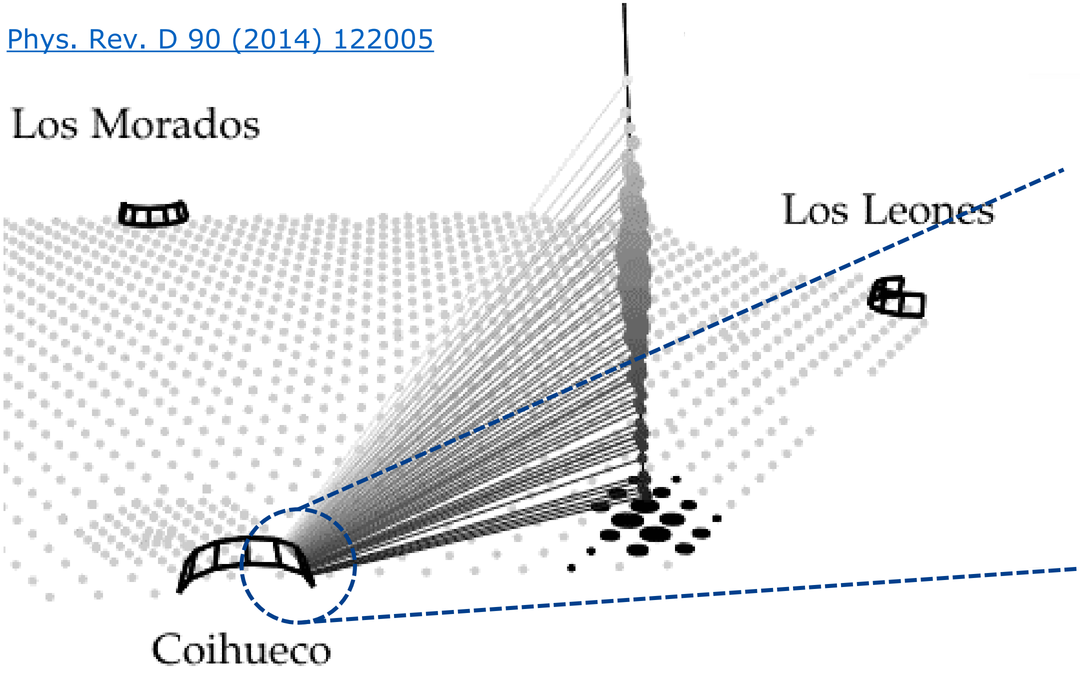
Nucl. Instrum. Meth. A 620 (2010) 227-251

Fluorescence detector (FD)

- 27 fluorescence telescopes (24 regular + 3 HEAT);
- 4 sites overlooking SD with aperture 180° (in azimuth) x 30° (in elevation);
- Measures fluorescence emission from EAS:
- Duty cycle of ∼15 % ⟹ limits statistics ⟹ worse precision.

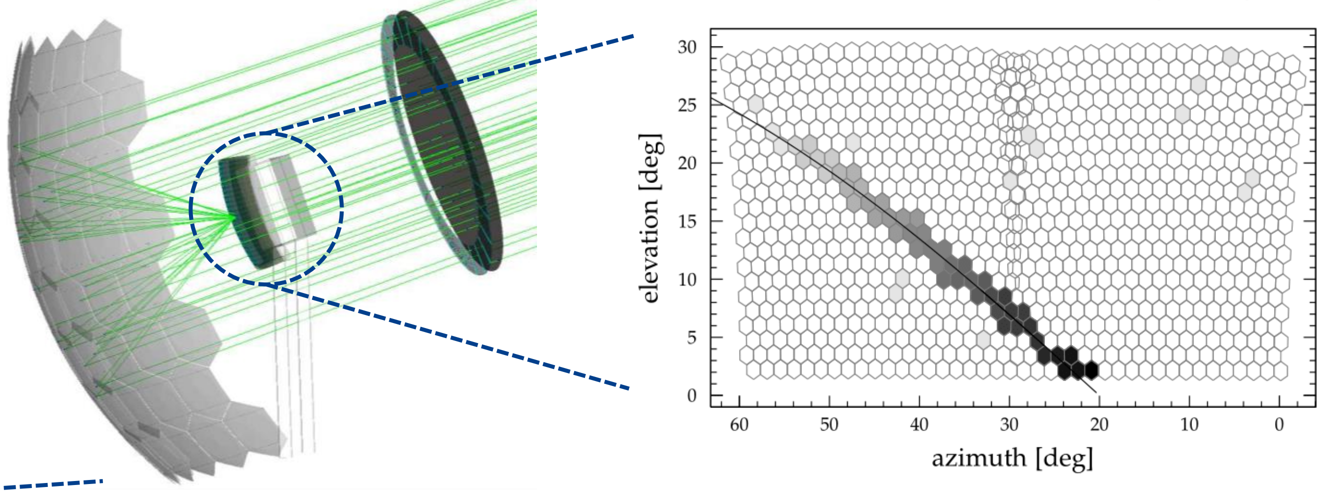


Phys. Rev. D 90 (2014) 122005



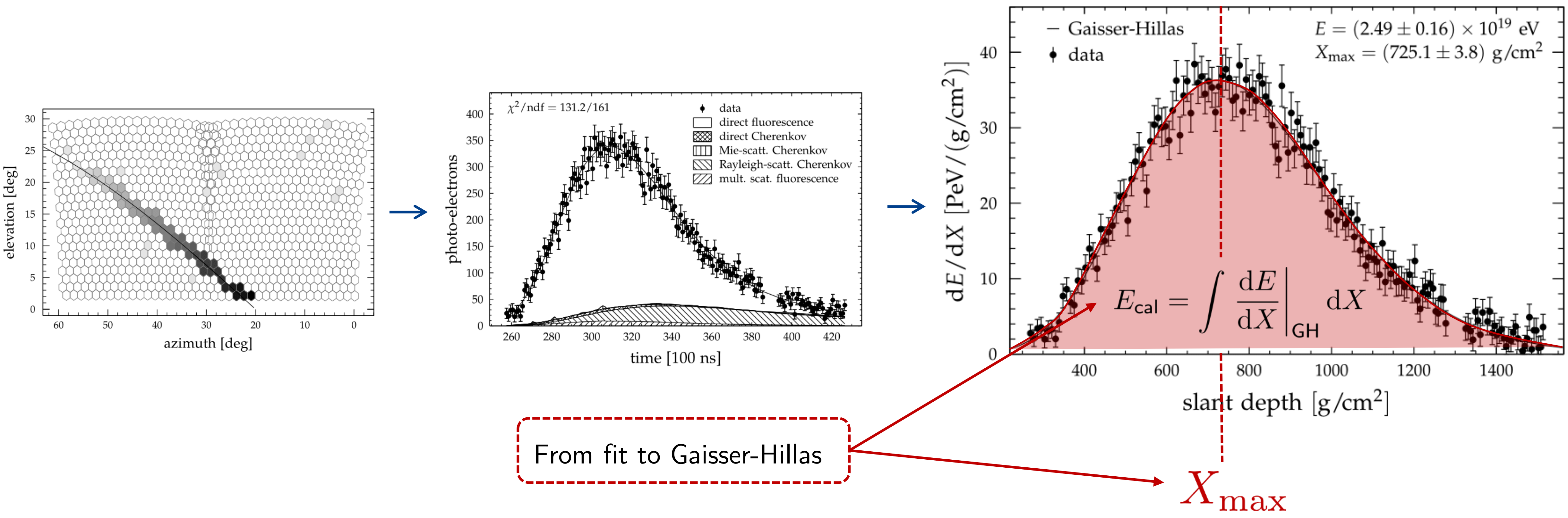
Fluorescence light collection

Signal and time information for each photo-multiplier (pixel)



Direct observation of the shower longitudinal profile!

Fluorescence detector: $X_{\max}$ and primary energy estimation



Phys. Rev. D 90 (2014) 122005

From fit to Gaisser-Hillas

- Determination of primary energy: $E_0 = E_{\text{cal}} + E_{\text{inv}}$;
- Data driven correction for invisible energy (10 – 15 %); https://arxiv.org/abs/1307.5059
- Resolution in E_0 of $\sim 8\%$ and systematic uncertainty of 14 %. Phys. Rev. D 102 (2020) 062005 (Editor's Suggestion)

FD measurements of mean and variance of $X_{\max}$

Data (PoS(ICRC2023)249):

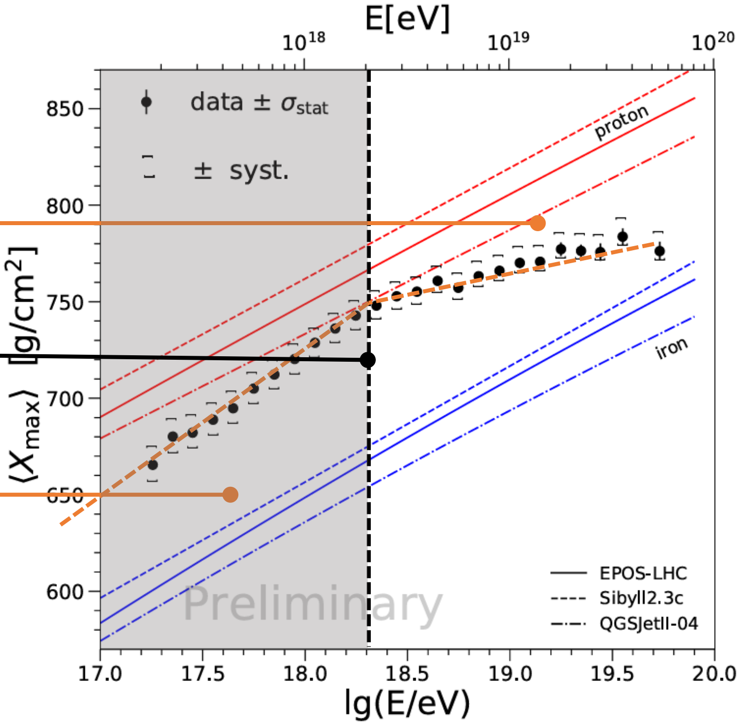
- From 12/2004 to 12/2017;
- $E_0 = [10^{17.2}, 10^{18.1}]$ eV for HEAT and $E_0 > 10^{17.8}$ eV for regular FD;
- 47 863 events (after quality cuts).

Precision / Accuracy:

Resolution in $X_{\max}$: 25 to 15 gcm^{-2}

Systematics below 10 g cm^{-2}

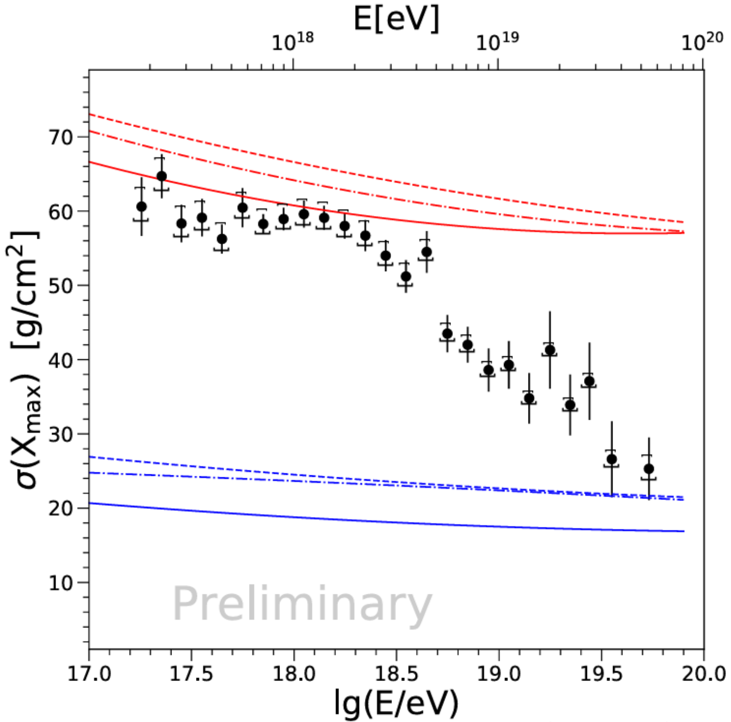
Phys. Rev. D 90 (2014) 122005



$D_{10} = 26 \pm 2\,\mathrm{g\,cm}^{-2}/\,\mathrm{decade}$

break at $E_1 = 10^{18.3}$ eV

$D_{10} = 77 \pm 2\,\mathrm{g\,cm}^{-2}/\,\mathrm{decade}$



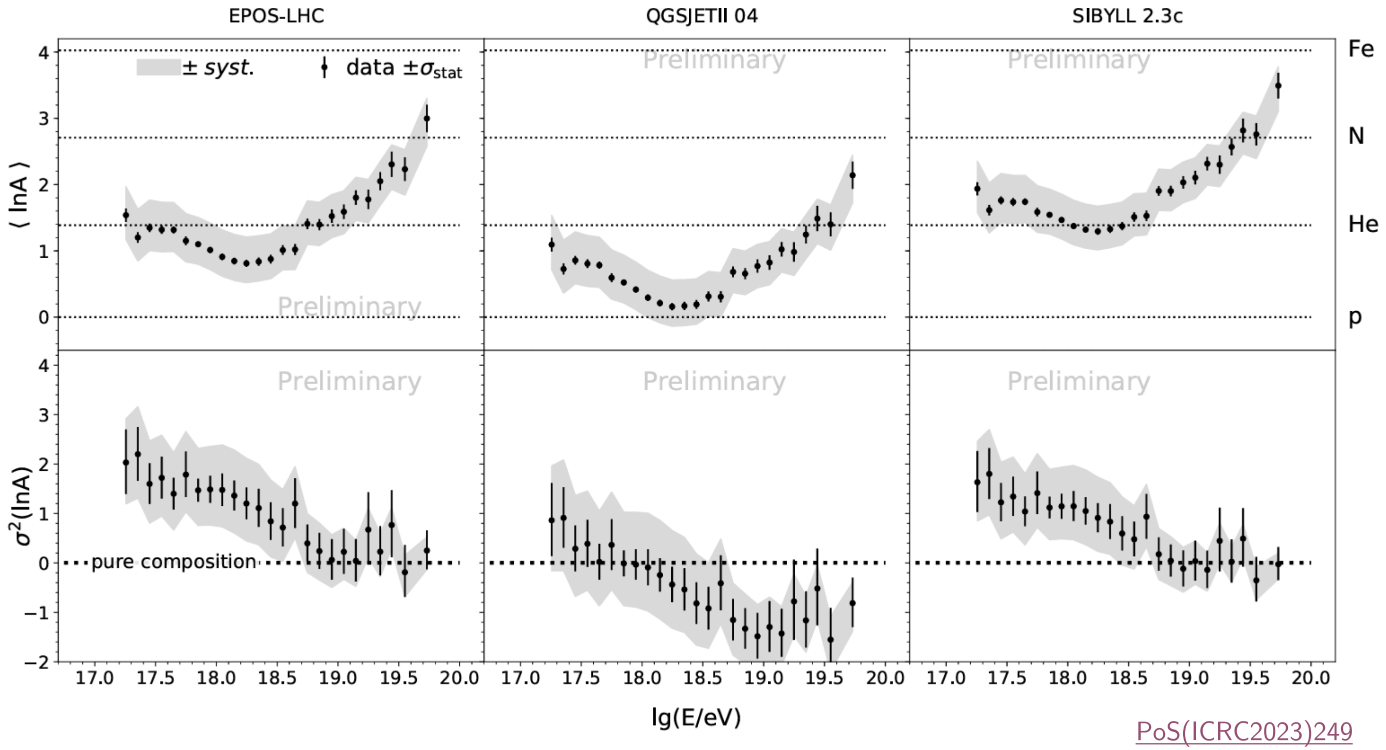
PoS(ICRC2023)249

- Composition gets lighter up to $10^{18.3}$ eV and then heavier up to the highest energies;
- $\sigma(X_{\max})$ decrease with energy $\Longrightarrow$ increasingly heavier and purer composition above $10^{18.3}$ eV $\Longrightarrow$ strong constraints on sources.

Inference of mean and variance of ln A from FD measurements

Using EAS simulations with different hadronic interaction models convert: $\langle X_{\max} \rangle \rightarrow \langle \ln A \rangle$ and $\sigma^2(X_{\max}) \rightarrow \sigma^2(\ln A)$

JCAP 02 (2013) 026



PoS(ICRC2023)249

- Models employ different physics ⟹ different absolute values of ln A;
- Primary mass becomes lighter (proton / He) up $10^{18.3}$ eV and heavier up-to the highest energies (N / Fe);
- Negative $X_{\max}$ fluctuations for QGSJetII-04 ⟹ model description of $X_{\max}$ disfavored by data.

4-mass fit to FD data

Method:

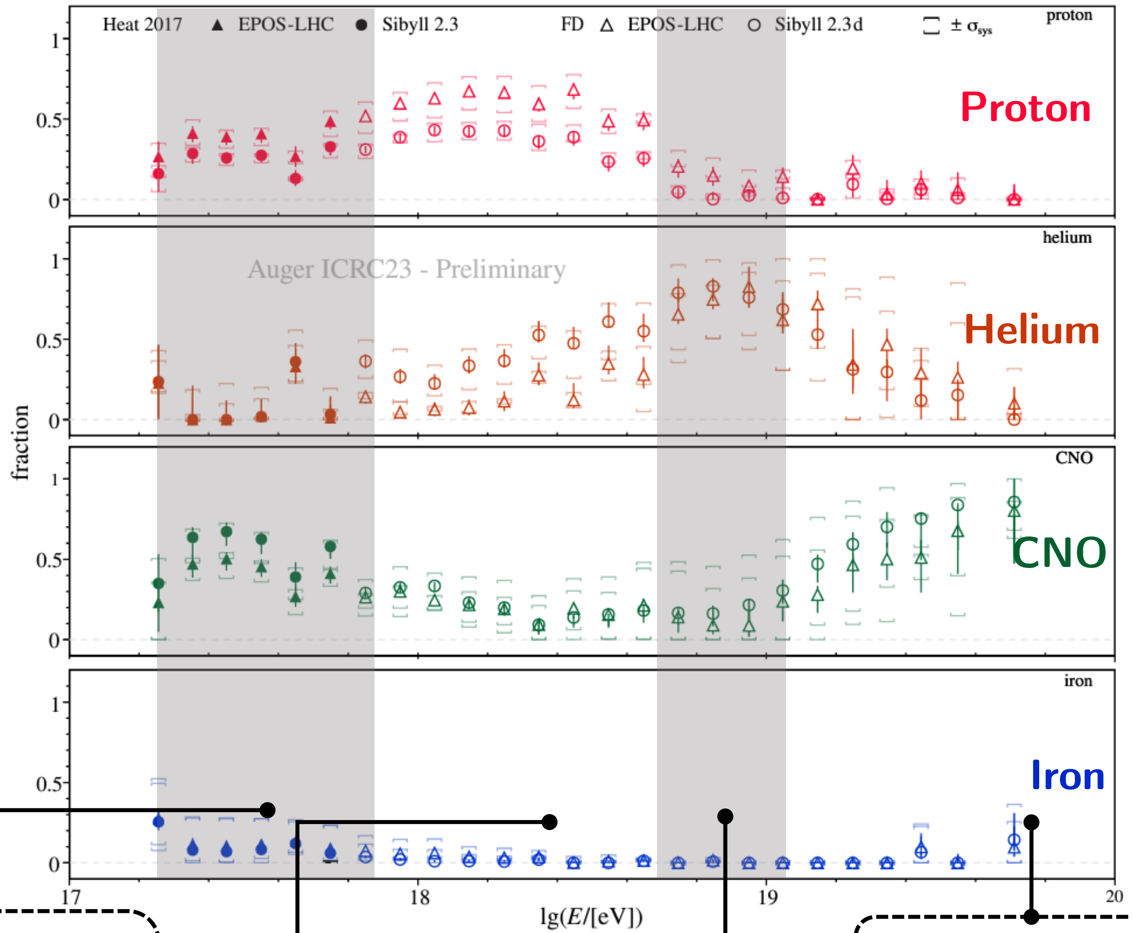
- Generate templates of $X_{\max}$ distributions for different fractions of primaries proton : Helium : CNO : Iron;
- Fit generated distributions to data to extract fractions of each primary as a function of energy.

Data (PoS(ICRC2023)365):

- From 12/2004 to 12/2021;
- $E_0 > 10^{17.8}$ eV;
- 75 210 events (after quality cuts)

Results:

PoS(ICRC2023)365



CNO and proton rich composition

Light nuclei dominate ⟹ highly mixed

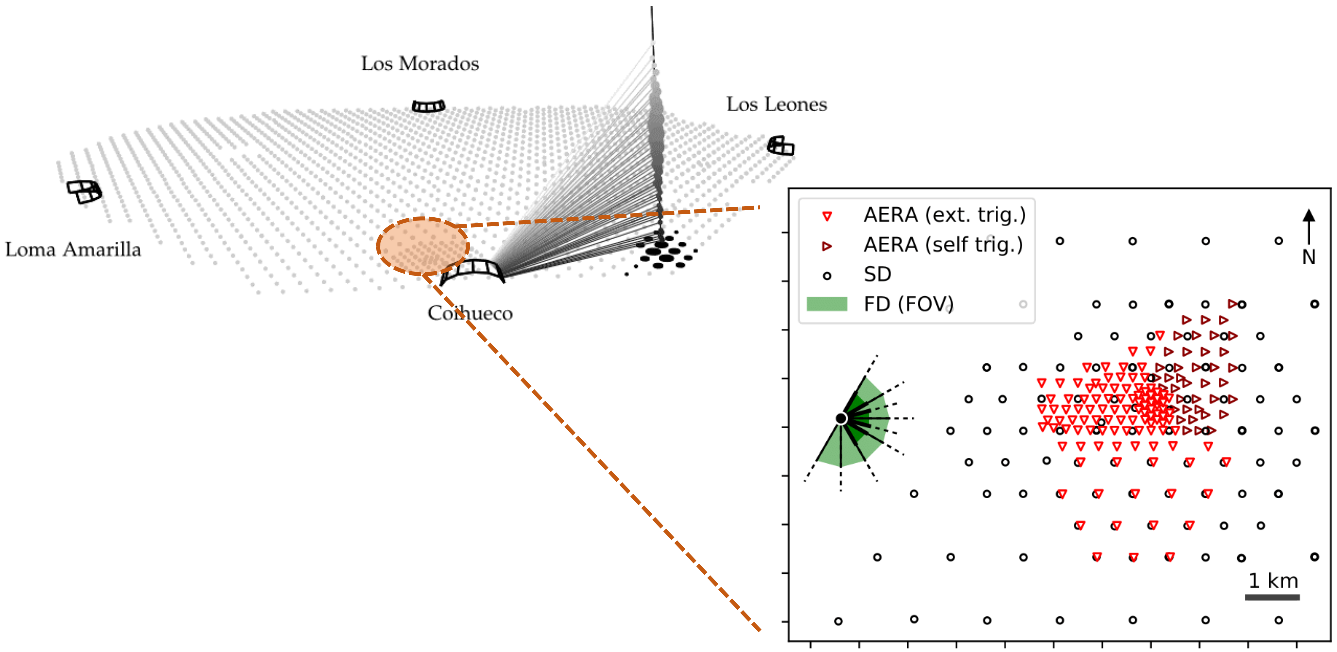
Mostly He ⟹ very pure

Mostly CNO ⟹ increasingly pure

AUGER ENGINEERING RADIO ARRAY

MEASUREMENTS

AERA: working principles

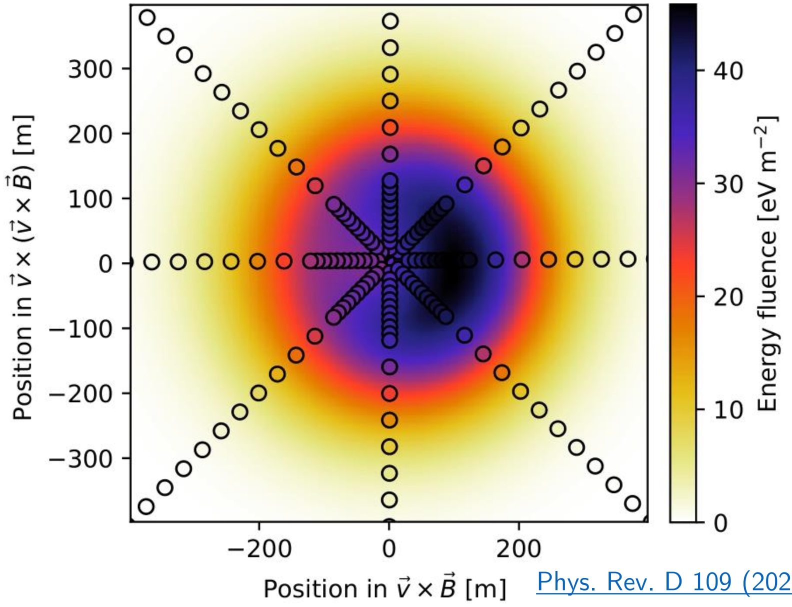


Phys. Rev. D 109 (2024) 022002

Auger Engineering Radio Array (AERA)

- Collection of 153 irregularly spaced antennas;
- Covers a total area of 17 km^2 ;
- Duty cycle of ~ 100 %;
- Measures radio emission from EAS from 30 to 80 MHz.

- Each antenna measures time dependent voltage $\Longrightarrow$ energy fluence u from the shower (after noise subtraction);
- Value of u at different radii $\Longrightarrow$ shower radio footprint.



Phys. Rev. D 109 (2024) 022002

AERA: method for $X_{\max}$ determination

Why:

- Validate radio emission in simulations;
- Validate radio-based method $\Longrightarrow$ increase in statistics due 100 % duty cycle

Main idea: Width and shape of energy fluence footprint depend on $X_{\max}$.

Method:

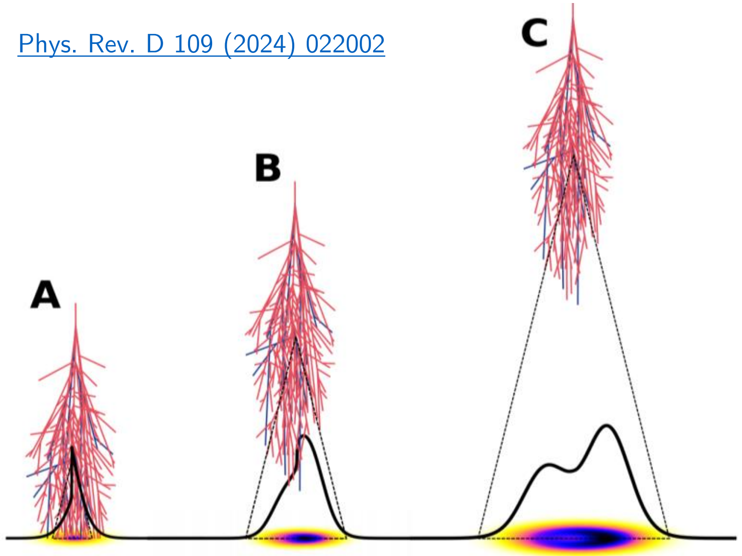
For each measured shower:

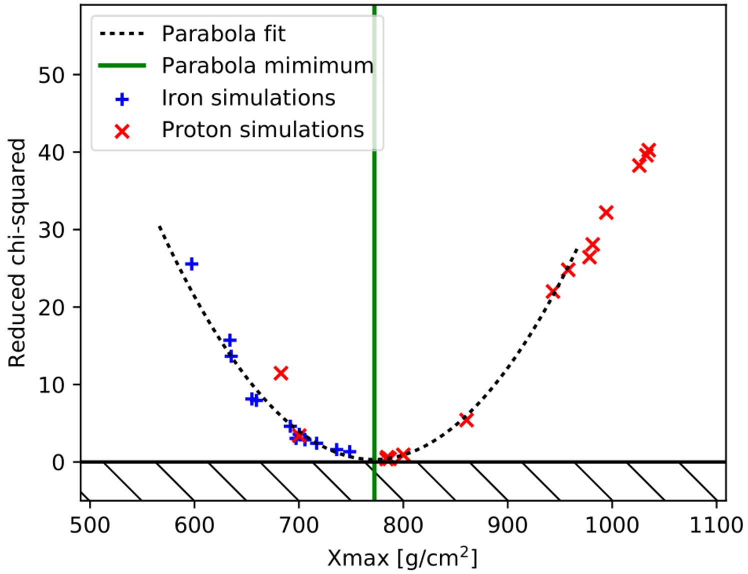
- Estimate energy (SD) and geometry (SD + AERA) $\Longrightarrow (E_{\text{SD}},\, \theta,\, \phi)$;
- Simulate 27 (15 proton + 12 iron) EAS with CORSIKA/CoREAS with different $X_{\max}$ values, for $(E_{\text{SD}},\, \theta,\, \phi)$;
- For each simulation, fit measured energy fluencies, u_{meas}, to simulated values, u_{sim}, by minimizing

$$\chi^2 = \sum_{\text{antennas}} \frac{u_{\text{meas}} - S \cdot u_{\text{sim}}(\mathbf{r}_{\text{shift}})}{\sigma_u^2}.$$

- Do parabolic fit to χ^2 to find $X_{\max}$ that minimizes it.

Phys. Rev. D 109 (2024) 022002





Phys. Rev. D 109 (2024) 022002

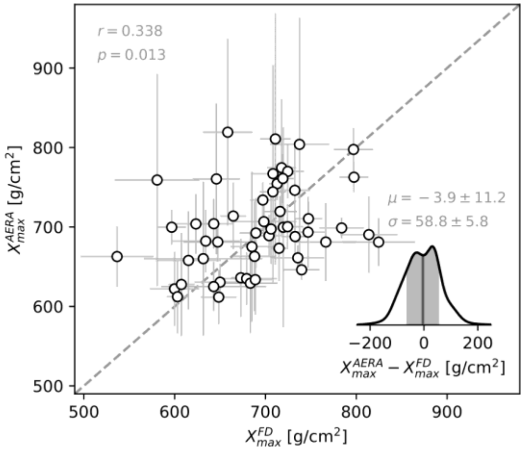
Confirmation of $X_{\max}$ scale with AERA

Data:

- From 04/2013 to 11/2019;
- $E_0 > 10^{17.5}$ and $\theta < 55°$;
- 594 events (after quality cuts).

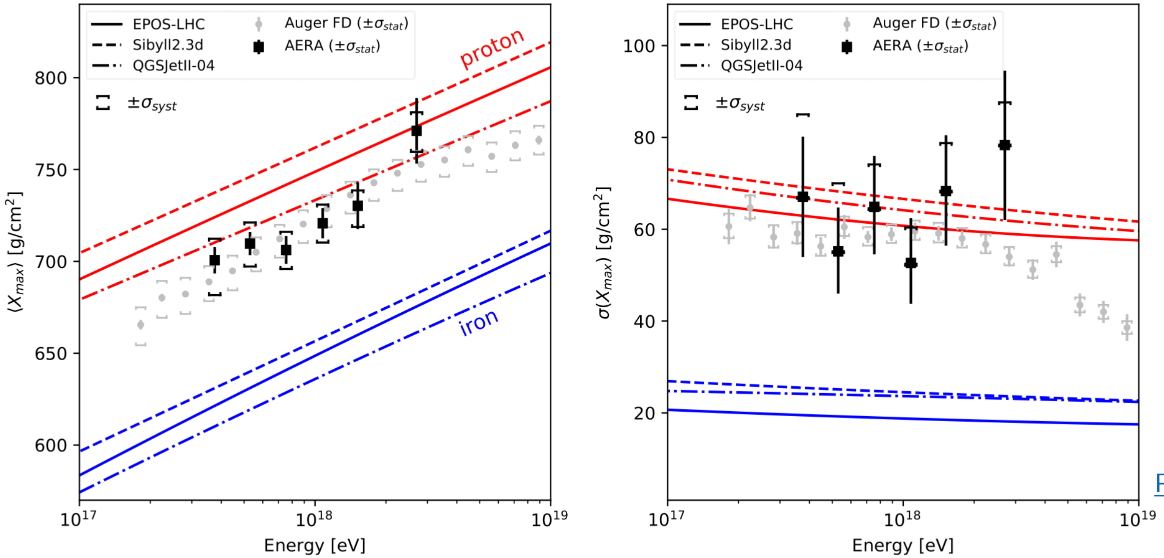
Method validation:

- Good event-by-event agreement between AERA and FD $\Longrightarrow$ no bias!;
- Resolution from 50 to 15 g cm^{-2} and systematics < 15 g cm^{-2} Phys. Rev. D 109 (2024) 022002



Phys. Rev. Lett. 132 (2024) 021001

Results:



Phys. Rev. Lett. 132 (2024) 021001

- First and second moments of $X_{\max}$ compatible with those obtained with FD measurements;
- Simulated radio emission from EAS validated!

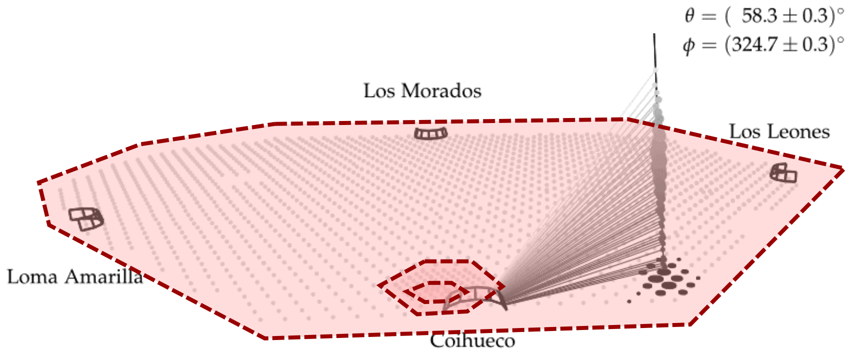
SURFACE DETECTOR ARRAY MEASUREMENTS

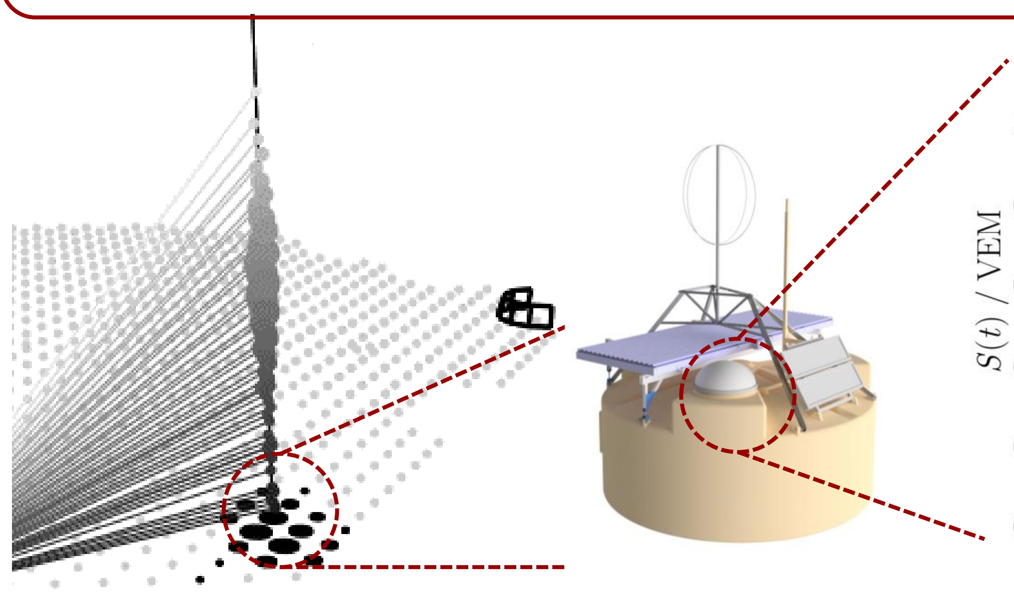
Surface detector array: working principles

Nucl. Instrum. Meth. A 613 (2010) 29-39

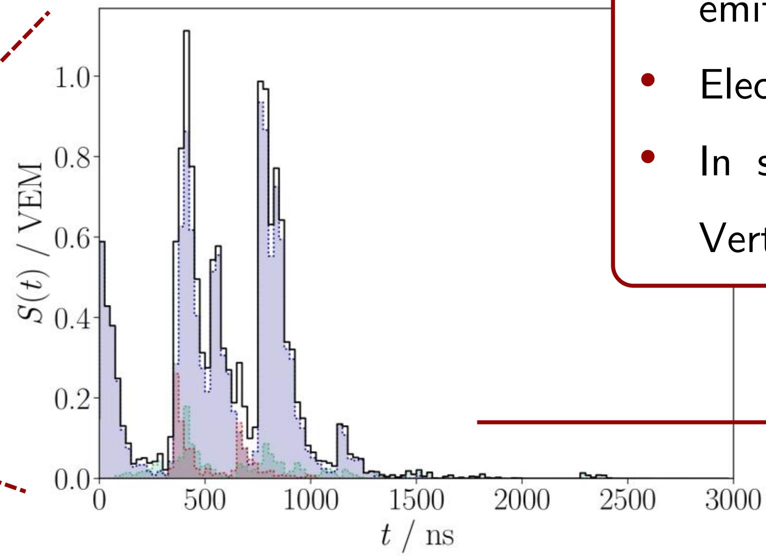
Surface detector array (SD)

- 1660 water-Cherenkov detectors (WCD) over 3000 km^{-2};
- Triangular grid with spacings:
  - 1 500 m ($E_{\text{th}} = 10^{18.5}$ eV)
  - 750 m ($E_{\text{th}} = 10^{17.5}$ eV) and 433 m ($E_{\text{th}} = 10^{16.5}$ eV);
- Samples the particle content of the shower front;
- Duty cycle of 100 %.





Trace



- 3 PMT collect Cherenkov radiation emitted by shower particles;
- Electric signal discretized in 25 ns bins;
- In situ calibration: signal converted to Vertical Equivalent Muon (VEM), $S(t)$.

Total signal:

$$S(\mathbf{r}_{\text{station}}) = \sum_{\text{time bin } i} S(t_i)$$

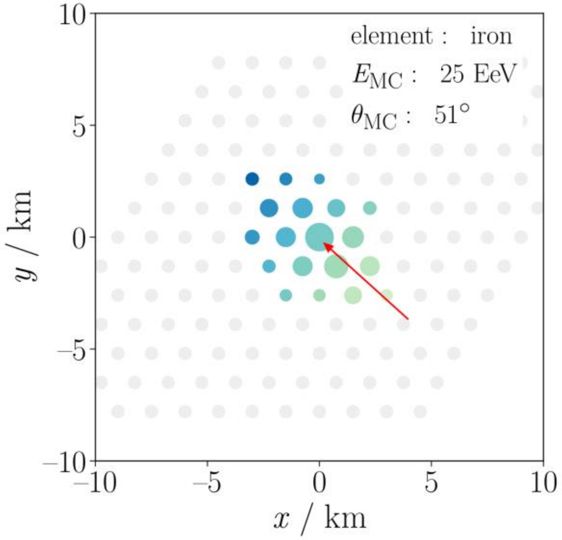
Surface detector array: primary energy estimation

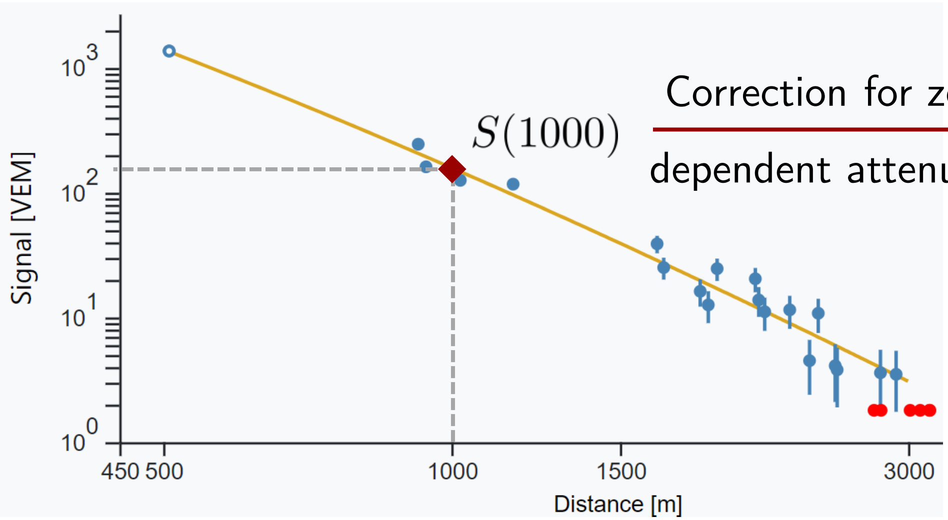
- **Energy estimation** from WCD signals:

Spatial (circle size) and time (color) of signal footprint

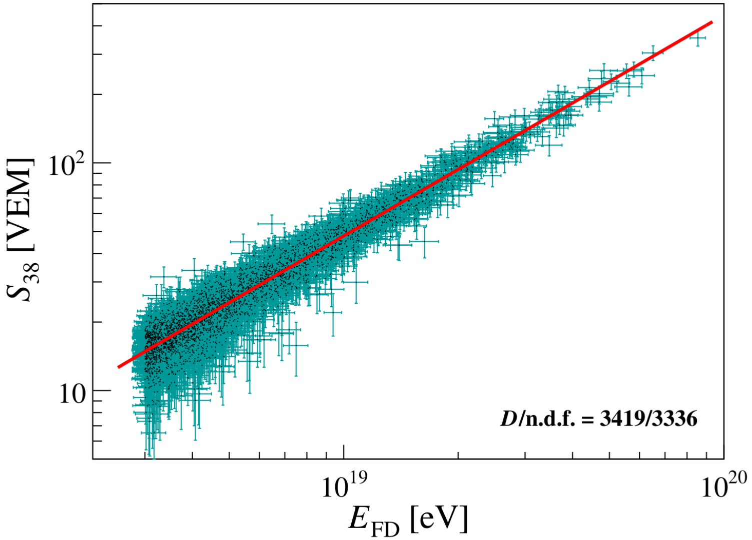
Lateral distribution function (LDF) of S: S as function of distance to shower core, **r**

Energy calibration of S_{38} from hybrid events $\Longrightarrow E_{\mathrm{SD}}$;





Correction for zenith dependent attenuation



Phys. Rev. D 102 (2020) 062005 (Editor's Suggestion)

- SD has trigger system to discern random signals from physical events: based on coordinate triggering of stations in time and spatial configurations

DNN estimation of $X_{\max}$ from WCD signals

arXiv:2406.06319 submitted to PRD

Why:

- SD has 100 % duty cycle $\Longrightarrow$ increase statistics at the highest energies w.r.t FD

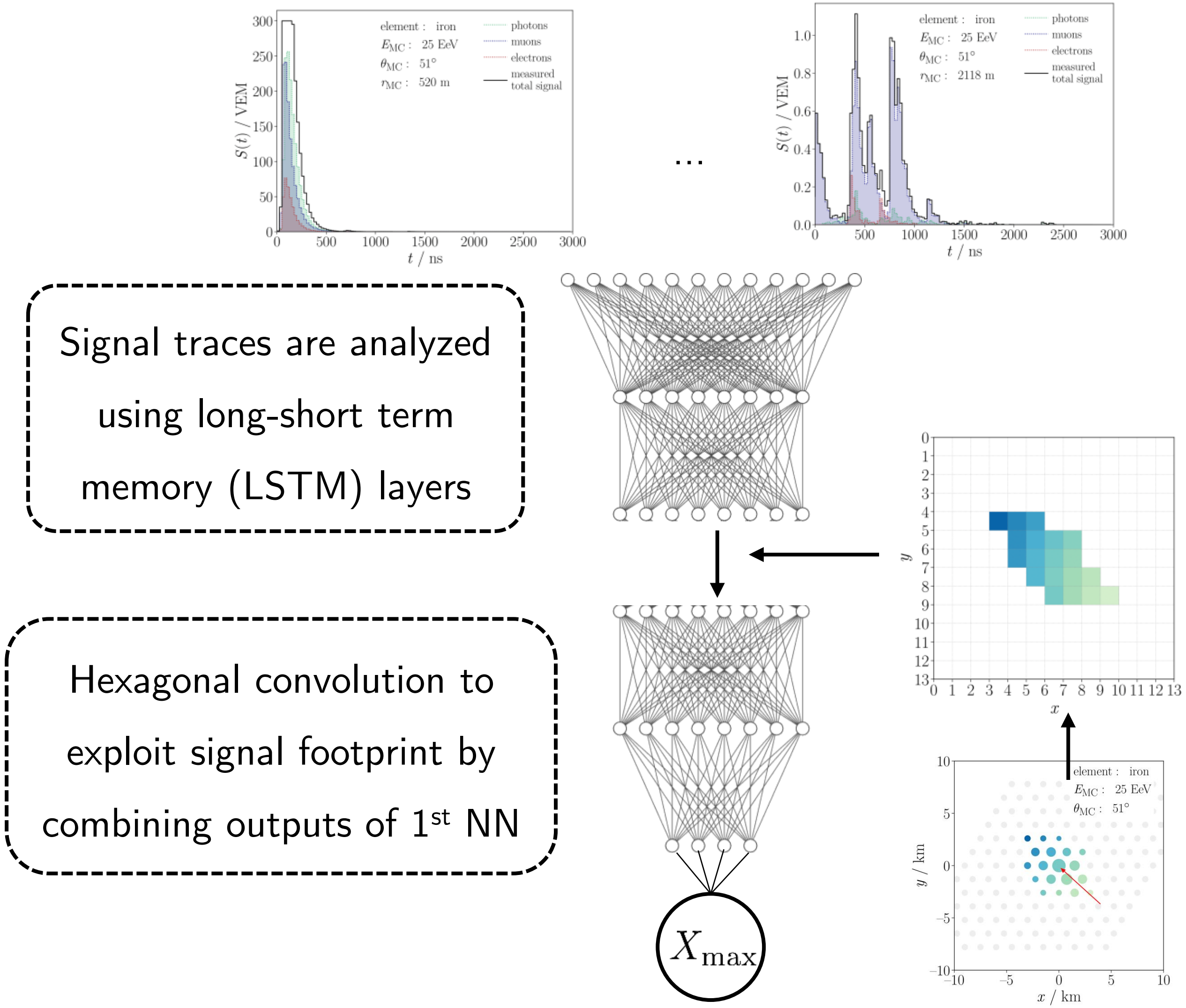
Main idea:

Information about $X_{\max}$ contained in:

- WCD traces: EM and muonic components attenuate and scatter differently $\Longrightarrow$ produce distinct traces in WCD from each other and as a function of $X_{\max}$;
- Strength and spatial distribution of WCD signals

Complex problem $\Longrightarrow$ use deep neural network trained on WCD signals for EAS simulations to estimate $X_{\max}$;

Deep neural network architecture (2 connected NN):



Signal traces are analyzed using long-short term memory (LSTM) layers

Hexagonal convolution to exploit signal footprint by combining outputs of 1st NN

DNN estimation of X_{max}: performance on hybrid data

Training data:

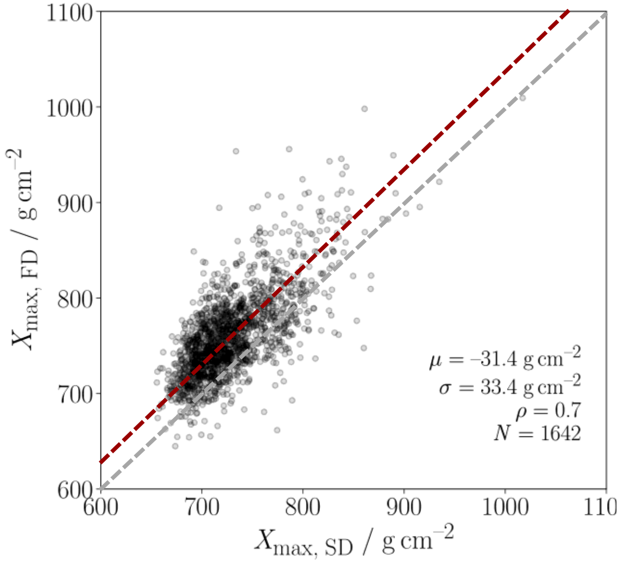
- SD response to 400 000 CORSIKA + EPOS-LHC showers;
- Primaries: p, He, O and Fe.
- $E_0 \in [1,\, 160]$ eV with E^{-1} spectrum and $\theta < 60^\circ$

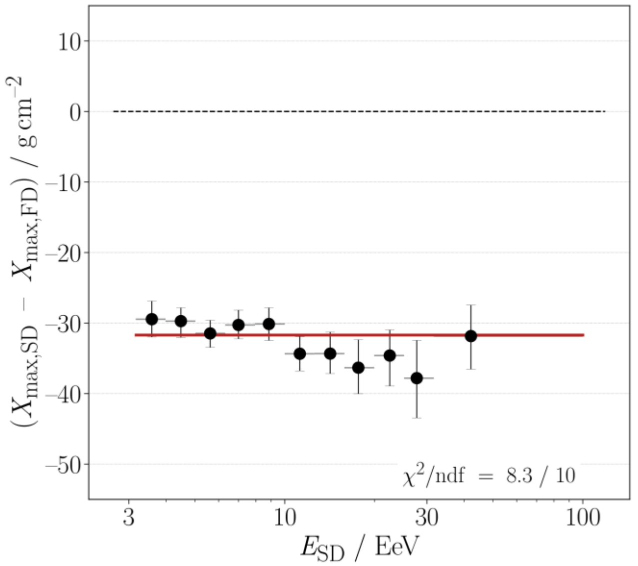
Hybrid data:

- From 01/01/2004 to 31/08/2018;
- $E_0 > 10^{18.5}$ eV and $\theta < 60^\circ$;
- 1 642 events (after quality cuts)

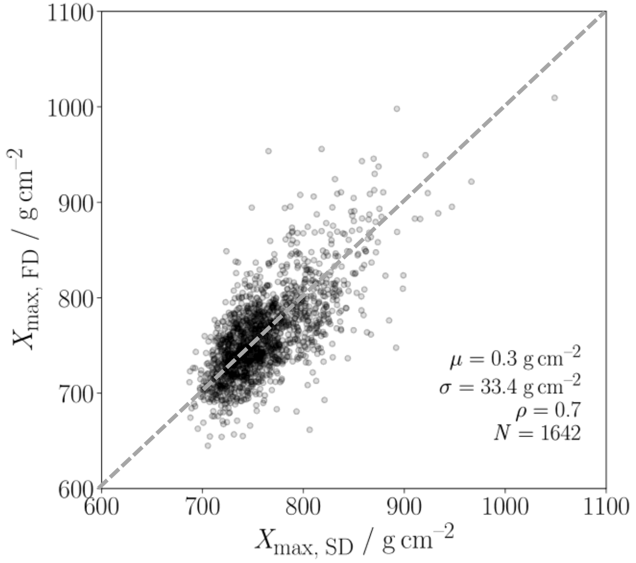
Results:

arXiv:2406.06319 submitted to PRD





Scale X_{max} to match FD data



- Precise determination of event-by-event X_{max};
- Energy independent underestimation of X_{max} by 30 g cm^{-2} $\Longrightarrow$ simulations do not describe EAS consistently.

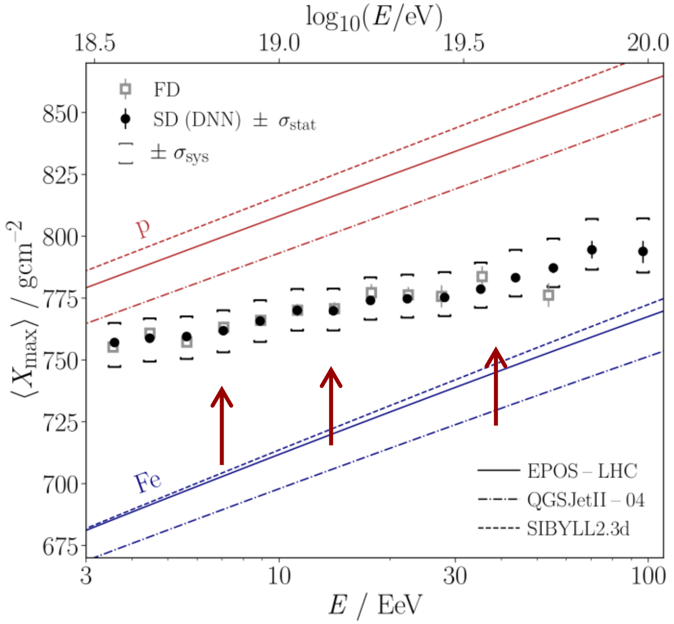
DNN estimation of moments of $X_{\max}$: full SD dataset

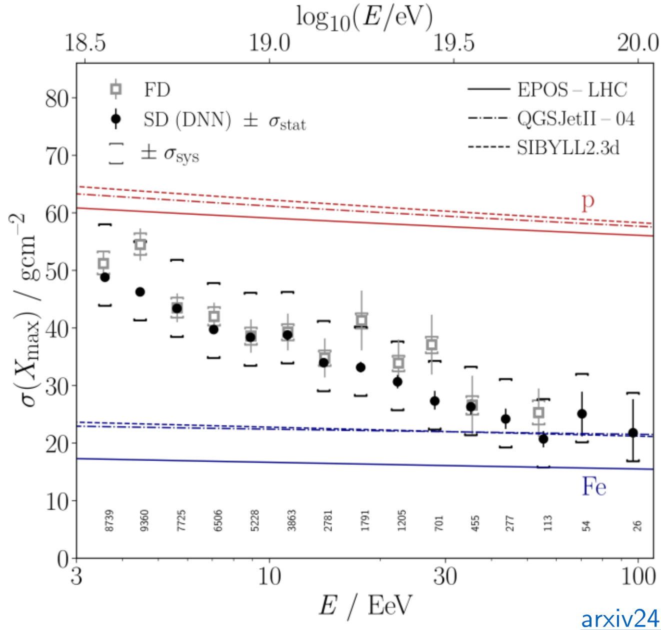
Full SD data:

- From 01/01/2004 to 31/08/2018;
- $E_0 > 10^{18.5}$ eV and $\theta < 60°$;
- 48 824 events (after quality cuts).

Precision / accuracy: arXiv:2406.06319 submitted to PRD

- Resolution between 45 and 30 g cm^{-2}
- Systematics in mean and var < 10 g cm^{-2}

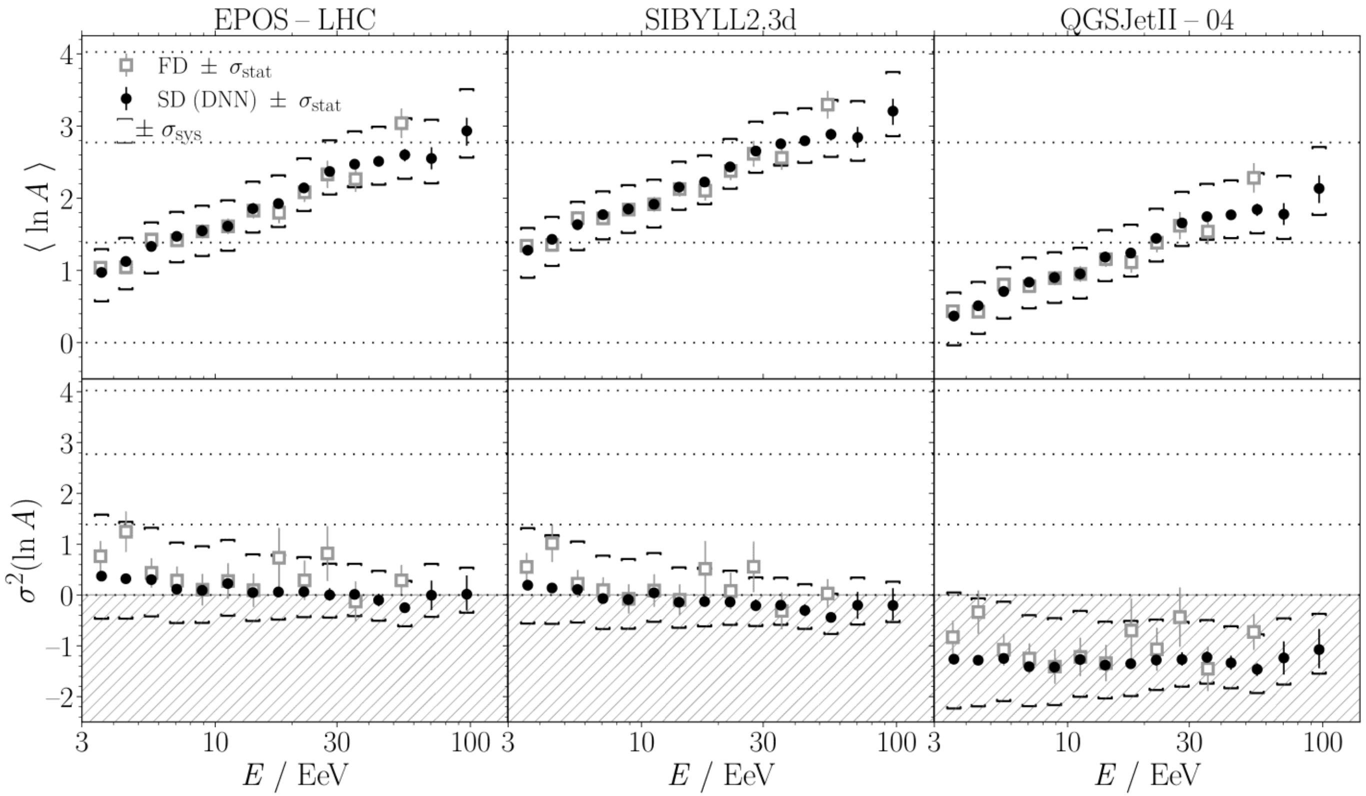




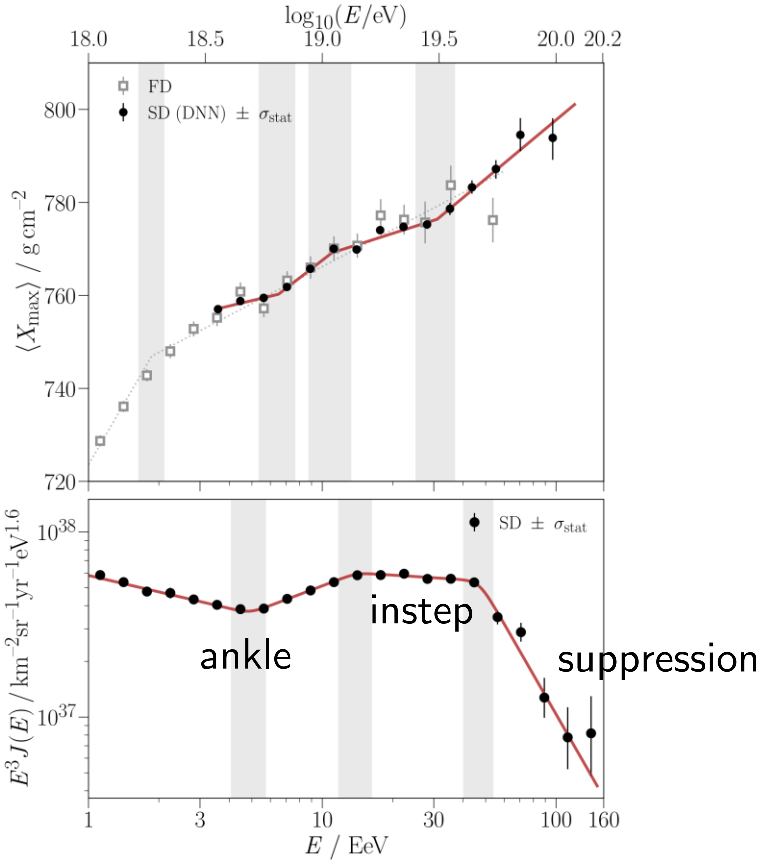
arxiv2406.06315 submitted to PRL

- Agreement with FD measurements (after bias correction);
- 10-fold increase in statistics (wrt FD) ⟹ observe 3 breaks in elongation rate: constant elongation rate excluded at 4.4σ!
- First estimation $X_{\max}$ moments above 50 EeV: strong evidence of no light component > 50 EeV ⟹ spectrum suppression not likely due to GZK.

DNN: mass inference and elongation rate breaks



arXiv:2406.06319 submitted to PRD



arxiv2406.06315 submitted to PRL

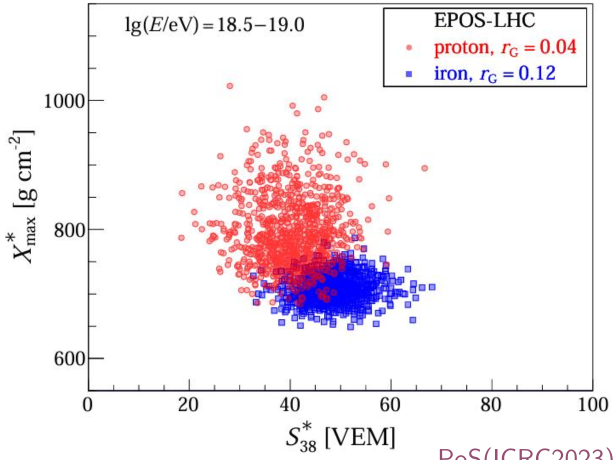
- Inferred mass composition in agreement with FD measurements;
- Highest source of uncertainty in mass composition is modelling of hadronic interactions.

- 3 breaks in elongation rate close to ankle, instep and suppression regions of UHECR energy spectrum
- Studies on going to determine astrophysical scenarios matching these 2 sets of breaks

Composition mixing in hybrid events: combining shower observables

Main idea:

- $X_{\max}$ decreases with ln A and $\ln N_\mu$ increases with ln A $\Longrightarrow$ anti-correlation for composition mixture;
- S_{38} dominated by muons $\Longrightarrow$ determine correlation coefficient between S_{38} and $X_{\max}$: r_G;

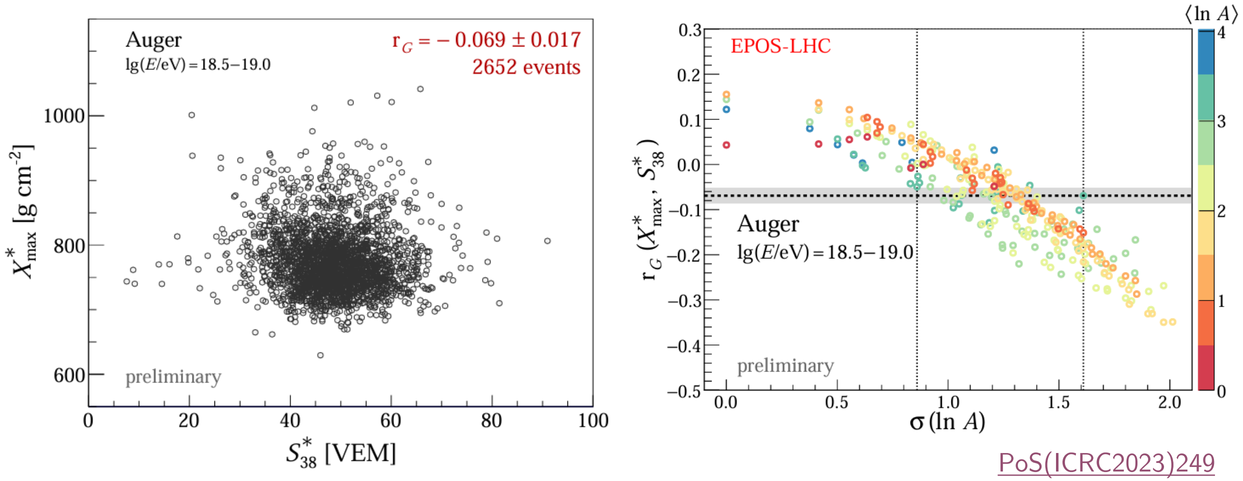


PoS(ICRC2023)249

Data:

- From 01/01/2004 to 31/12/2017;
- $E_0 > 10^{18.5}$ eV;
- 2652 events (after quality cuts).

Results:



PoS(ICRC2023)249

- Method resilient to scaling of variables and chosen hadronic interaction model;
- $\sigma(\ln A) = 1.35 \pm 0.35$ in ankle region;
- Correlation coefficient < any p-He mixture $\Longrightarrow$ evidence nuclei with A > 4 around ankle.

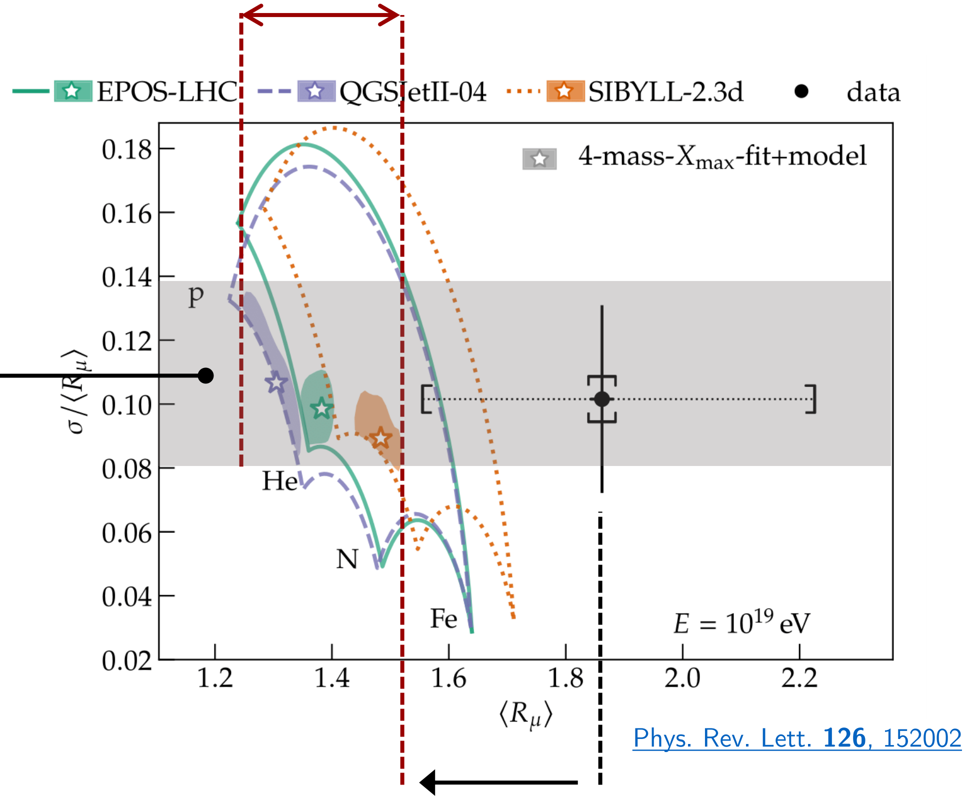
Primary mass estimation from shower-to-shower muon fluctuations

Motivation:

- Measured fluctuations of N_μ compatible with predictions by hadronic interaction models;
- Inclined showers ($\theta > 60^\circ$) $\implies$ EM component attenuated $\implies$ WCD signal directly probes number of muons

Expected muon fluctuations for X_max composition

Expected muon scale from X_max composition



Phys. Rev. Lett. **126**, 152002

Muon underestimation in simulations $\implies$ **Muon Puzzle**!

Method:

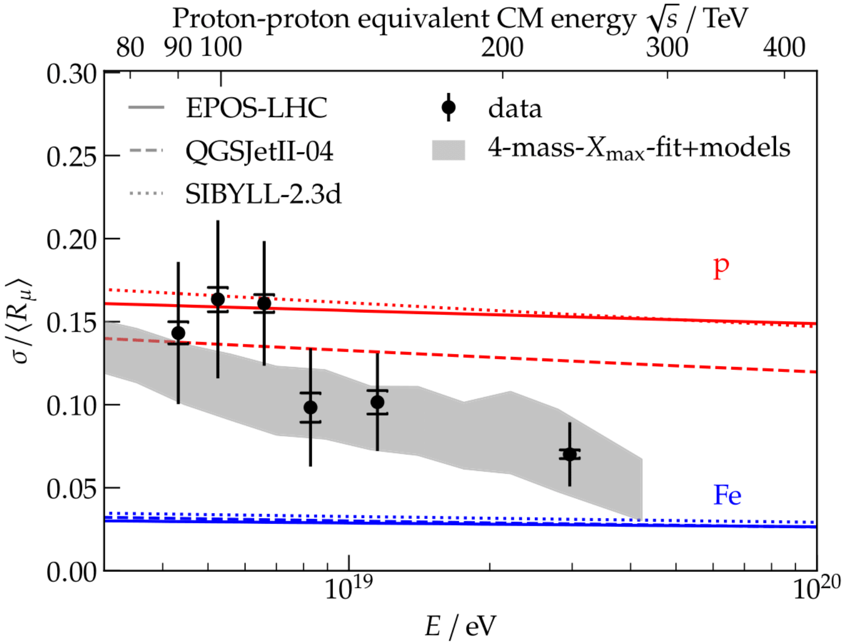
- Estimate N_μ from normalization of shower footprint $R_\mu \equiv \dfrac{N_\mu}{\langle N_\mu^\mathrm{ref} \rangle}$;
- Energy of each event provided by FD (decoupled from R_μ)

Primary mass from shower-to-shower muon fluctuations

Data:

- From 01/01/2004 to 31/12/2017 (13 years);
- $E_0 > 4$ EeV and $62^\circ < \theta < 80^\circ$;
- 281 events (after quality cuts).

Phys. Rev. Lett. **126**, 152002

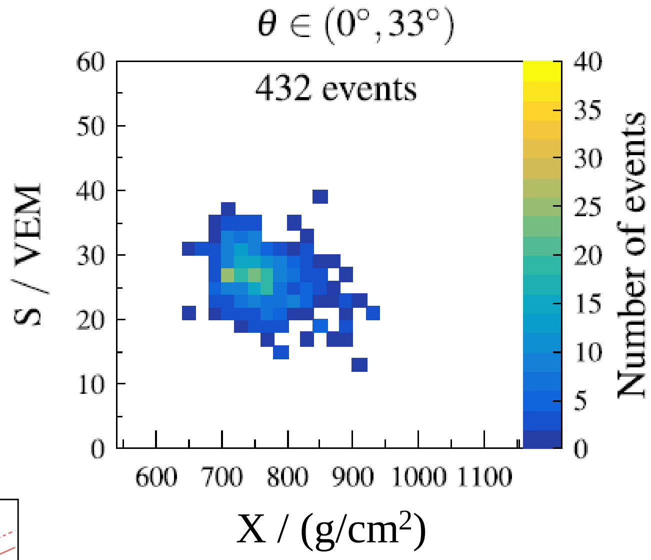


- Systematics below 7 %;
- Energy evolution of fluctuations of the number of muons compatible with composition predicted by $X_{\max}$ measurements!
- Heavier and purer composition with increasing primary energy.

Consistency of hadronic interaction models: mass inference implications

Muon puzzle + DNN results raise question: Do EAS simulations describe $X_{\max}$ (observed with FD) and S_{38} (from WCD traces) consistently?

- Use simulations to fit joint $(X_{\max}, S_{38})$ distribution allowing:
  - Shift in $X_{\max}$ scale: $\Delta X_{\max}$ (Caveat: not physically motivated).
  - Scaling of muonic component: R_{had};



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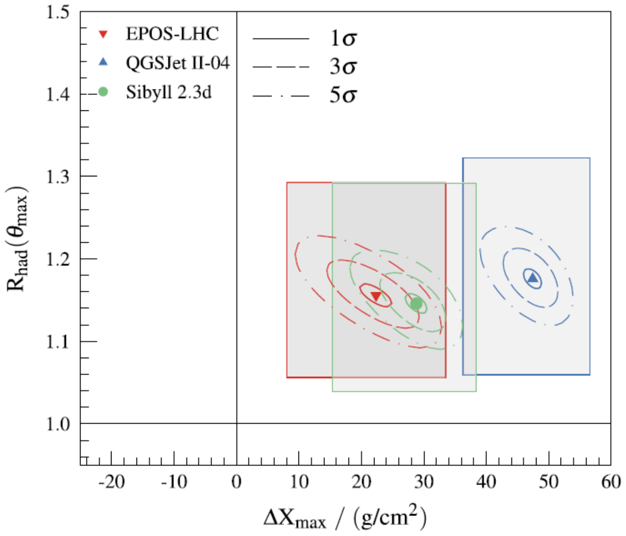

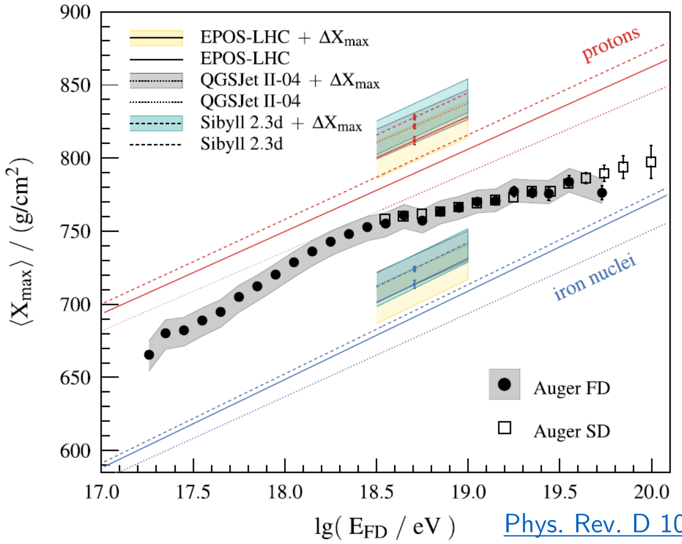

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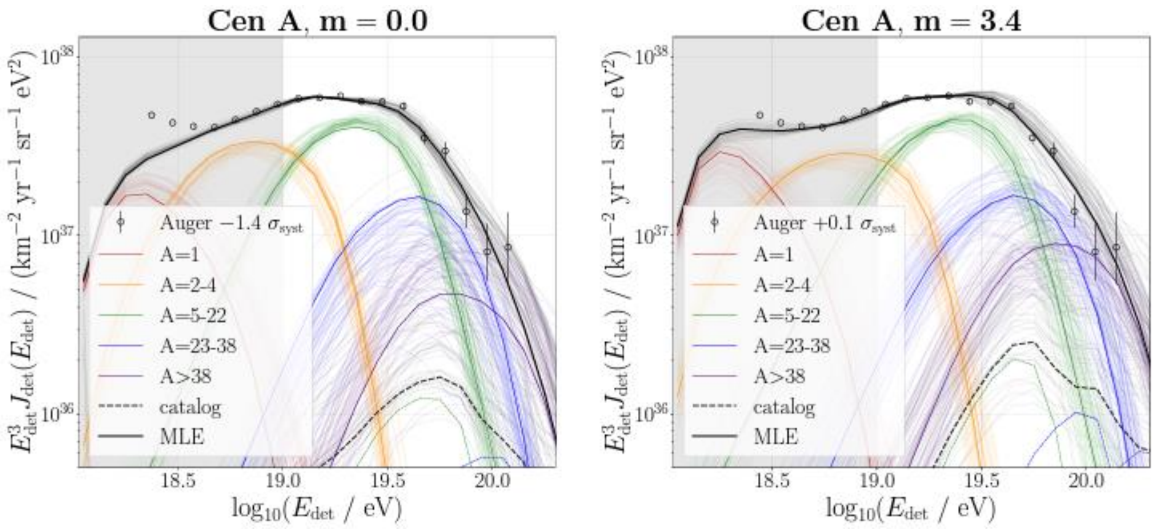
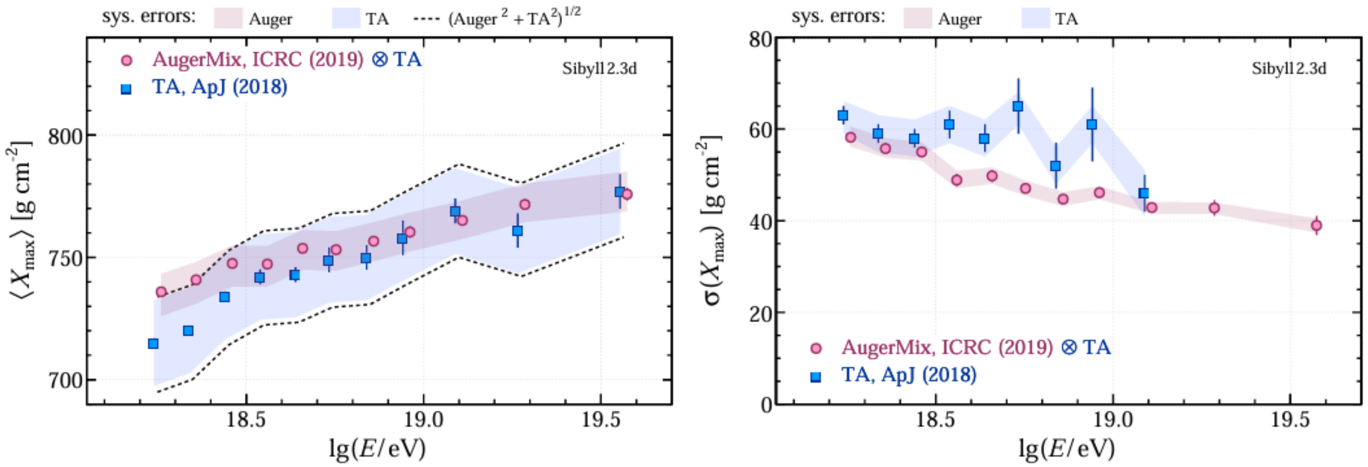
- Preferred increase in muon scale of 20 % (depends on hadronic interaction model);
- Preferred $\Delta X_{\max} \approx$ 20 – 50 g cm^{-2} $\Longrightarrow$ composition heavier than inferred from un-modified hadronic interaction models.

OTHER IMPORTANT AUGER ANALYSIS

Other important works



Combined spectrum, mass composition and arrival directions fit (JCAP 01 (2024) 022)



Agreement between Auger and TA elongation rate (PoS(ICRC2023)249)

Conclusions

- Classical FD measurements of $X_{\max}$ show composition getting lighter from 100 PeV up to ankle ($10^{18.3}$ eV) and then heavier;
- New DNN estimation of $X_{\max}$ moments reveals 3 breaks in similar energy ranges as spectrum features above 1 EeV;
- Composition of cosmic ray flux around ankle necessarily includes nuclei heavier than Helium;
- $X_{\max}$ can be measured through radio emission $\Longrightarrow$ validation of radio techniques;
- Mass interpretation highly dependent on hadronic interaction models;
- Inconsistent description of Auger data by hadronic interaction models $\Longrightarrow$ possible bias towards light nuclei.
- More data on other mass sensitive shower observables (see Dr. Nataliia Borodai talk on 26/08 at 4:50 PM)

THANK YOU!

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