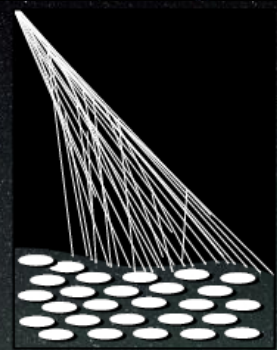


Do we hear heavy-metal of cosmic rays at the highest energies ?



PIERRE
AUGER
OBSERVATORY

Jakub Vícha

Department of Astroparticle Physics



Institute of Physics of the
Czech Academy of Sciences

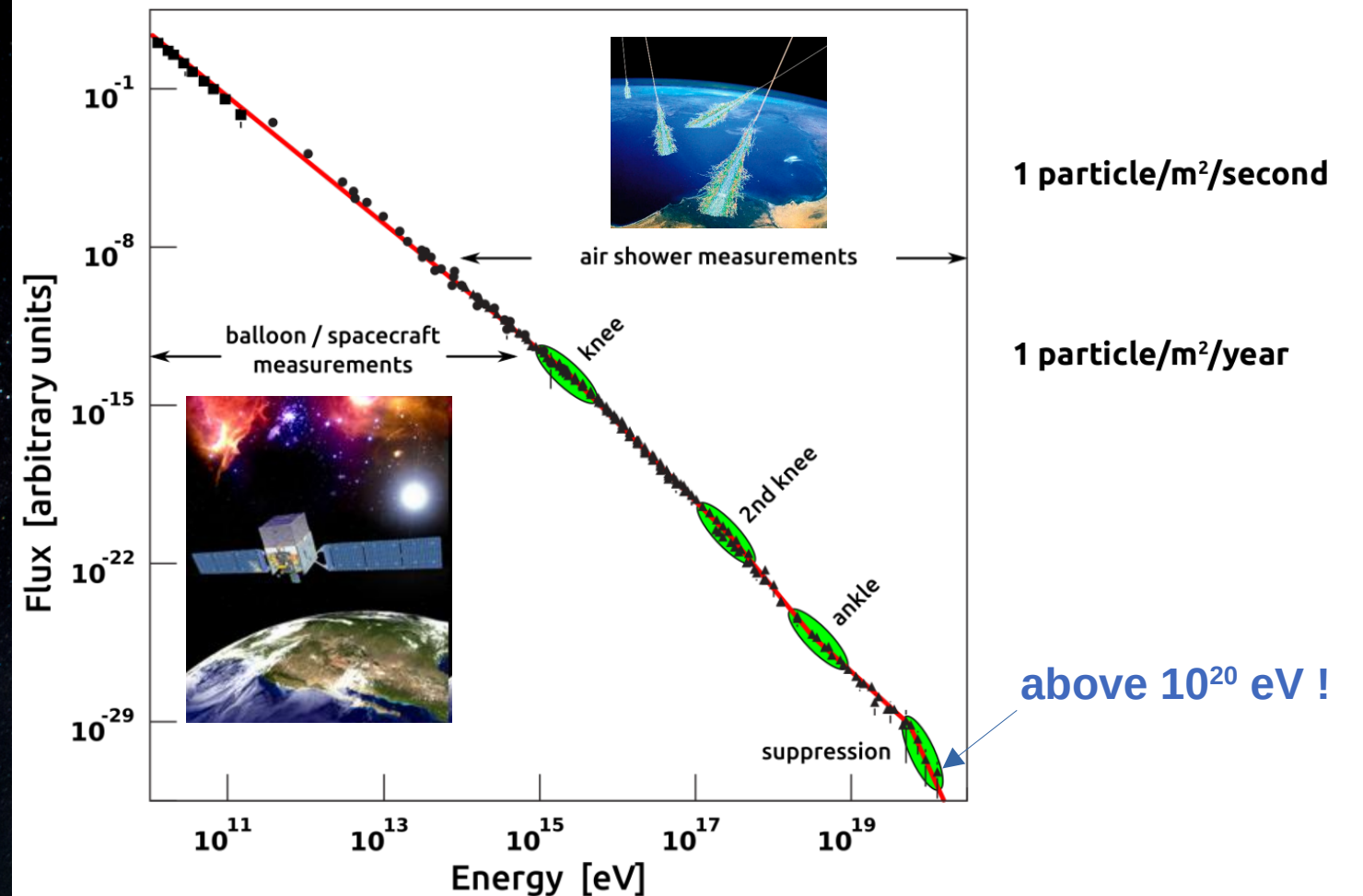
Outline of the talk

- Brief introduction to cosmic rays
- State of the art: Ultra-high energy cosmic rays (UHECR)
- Muon puzzle and how we got beyond
- Heavy-metal scenario of UHECR and its consequences

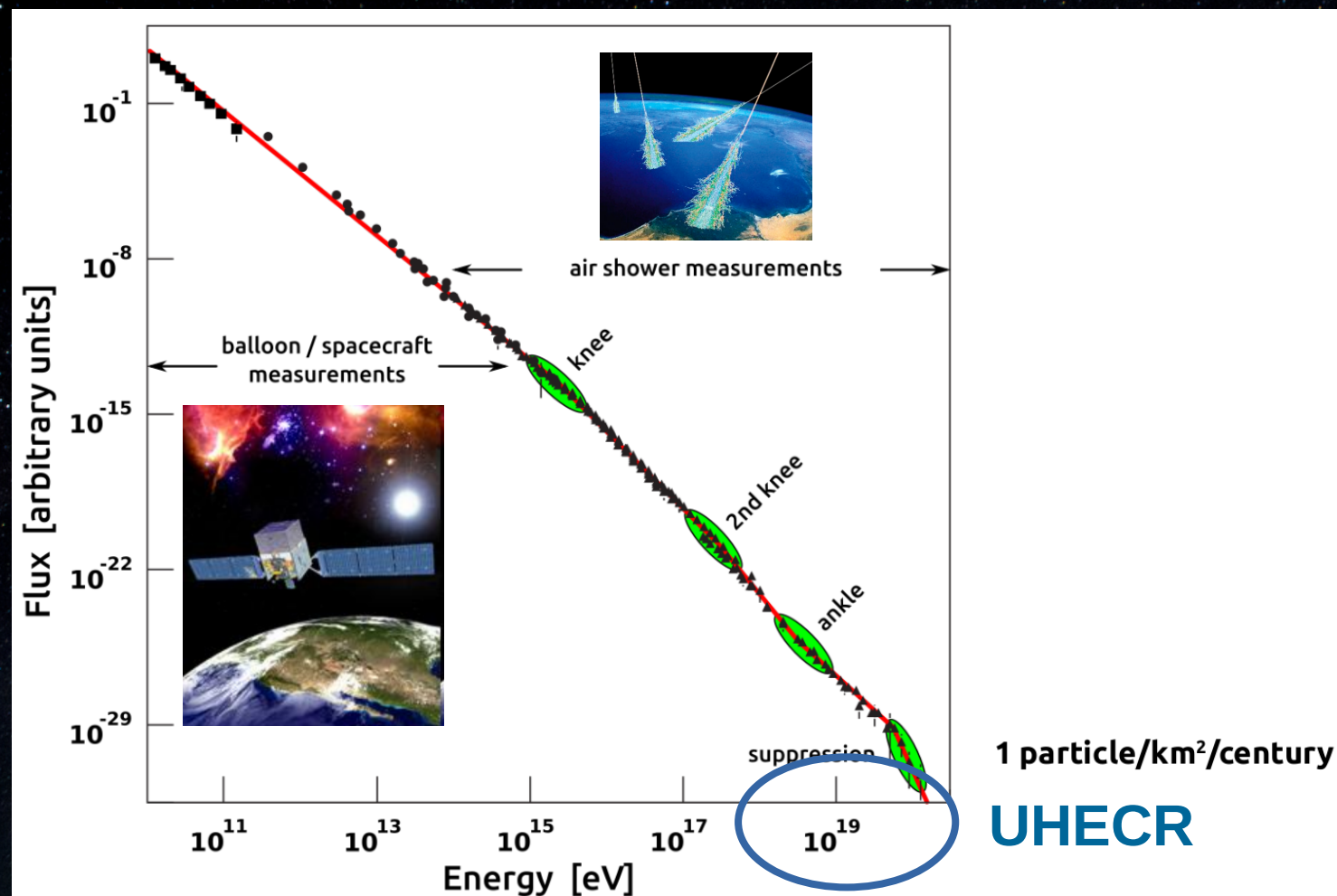
Cosmic rays: steeply falling flux

$$J(E) = 1.8 \frac{E^{-\gamma}}{\text{cm}^2 \cdot \text{s} \cdot \text{sr} \cdot \text{GeV}}$$

$$\gamma \approx 3$$

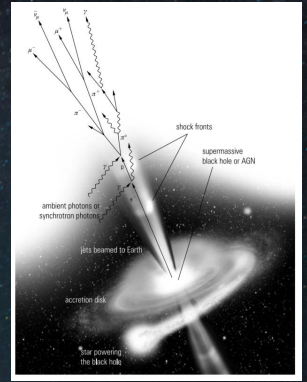
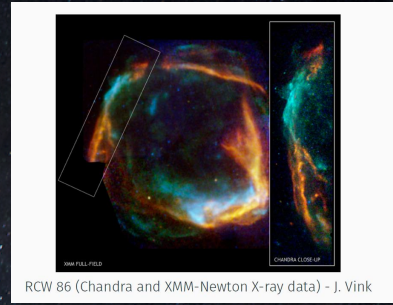
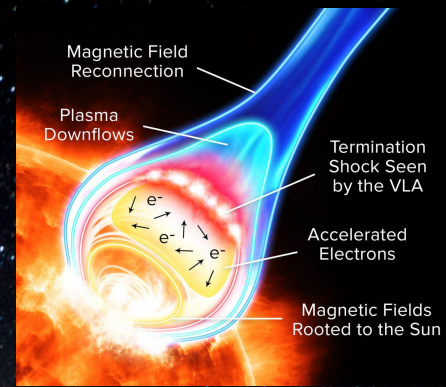
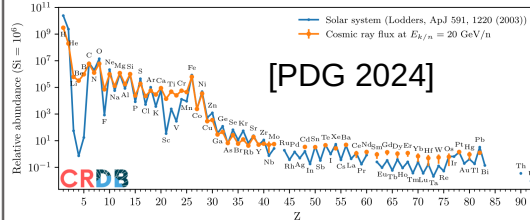
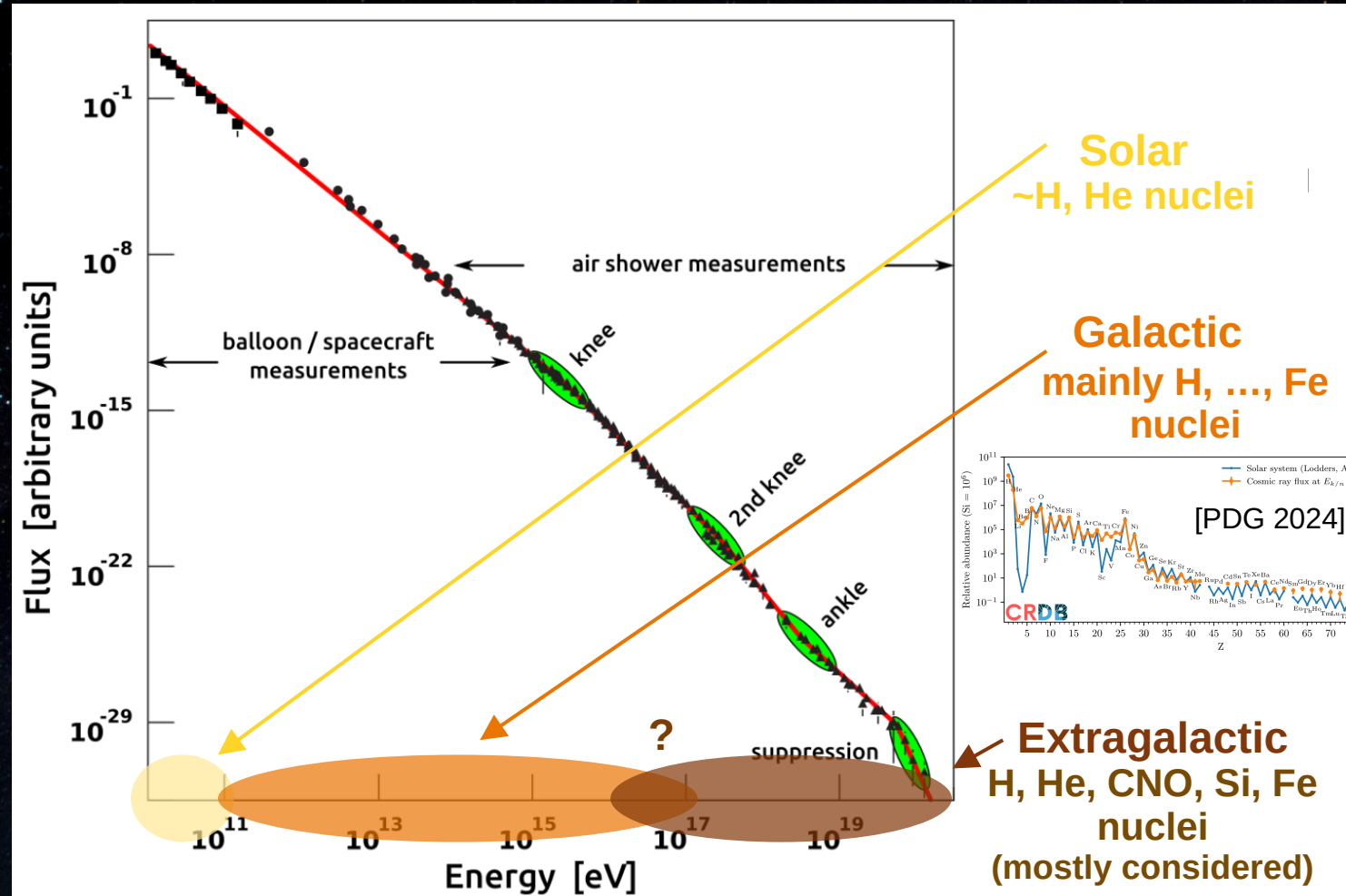


Cosmic rays: steeply falling flux



Need of huge observatories to collect a reasonable statistics of events

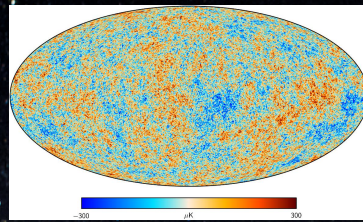
Cosmic rays: general origin



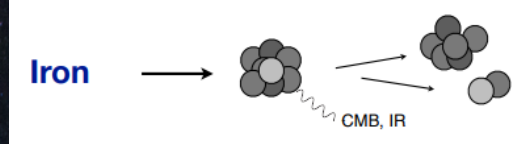
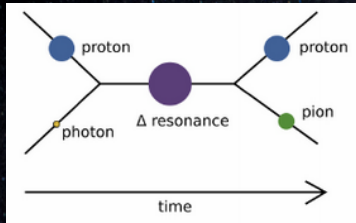
Cosmic-ray propagation

$$1 \text{ G} = 10^{-4} \text{ T}$$

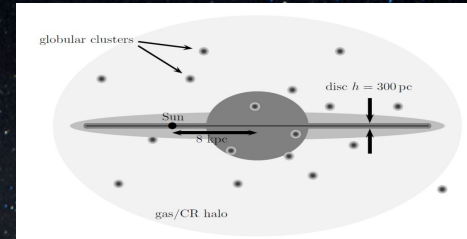
Interactions with cosmic microwave background



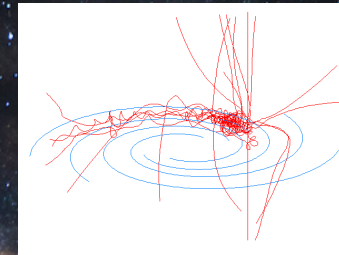
"GZK limit" theoretically predicted in 1966



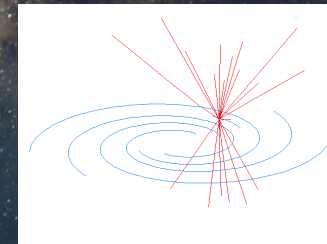
Bending in Galactic magnetic field $\sim \mu\text{G}$



$$r_l [\text{kpc}] = \frac{E [10^{18} \text{ eV}]}{Z \cdot B [\mu\text{G}]}$$

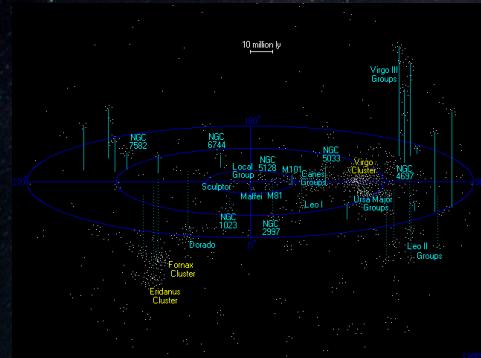
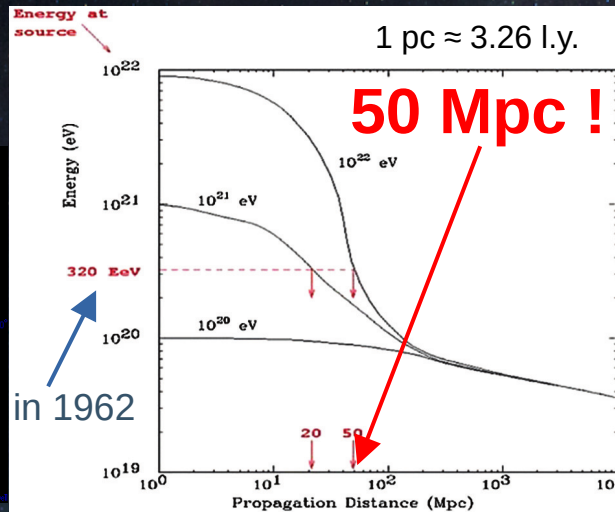


p 10^{18} eV
Fe $26 \cdot 10^{18}$ eV



p 10^{20} eV
Fe $26 \cdot 10^{20}$ eV

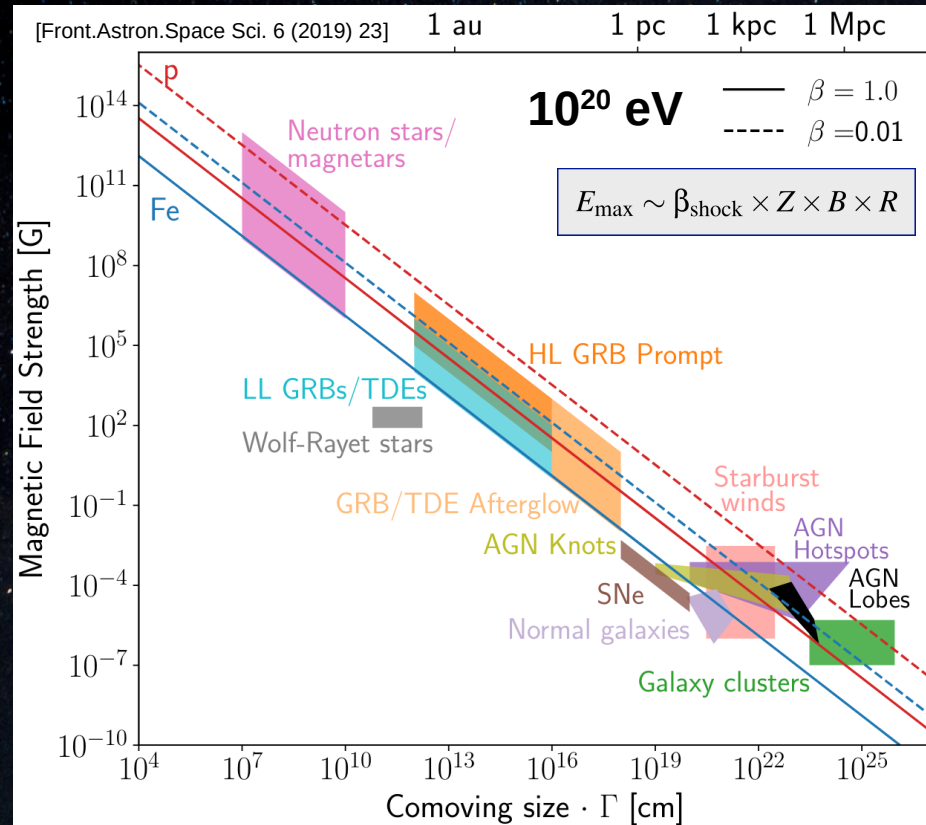
Extragalactic magnetic field is usually considered weaker $\sim \text{nG}$, but it might interact at larger distances ...



Long-lasting mystery at the highest energies

Hillas 1984

Candidates need to be well above the lines



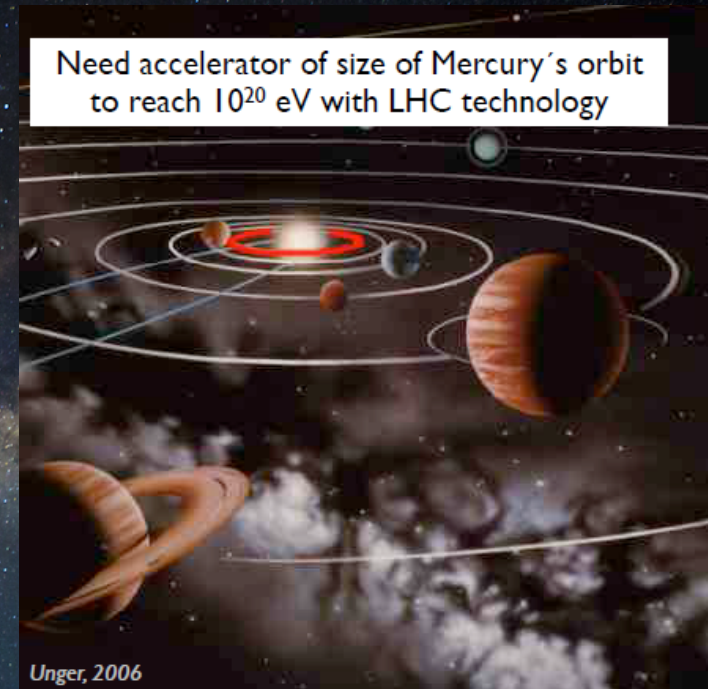
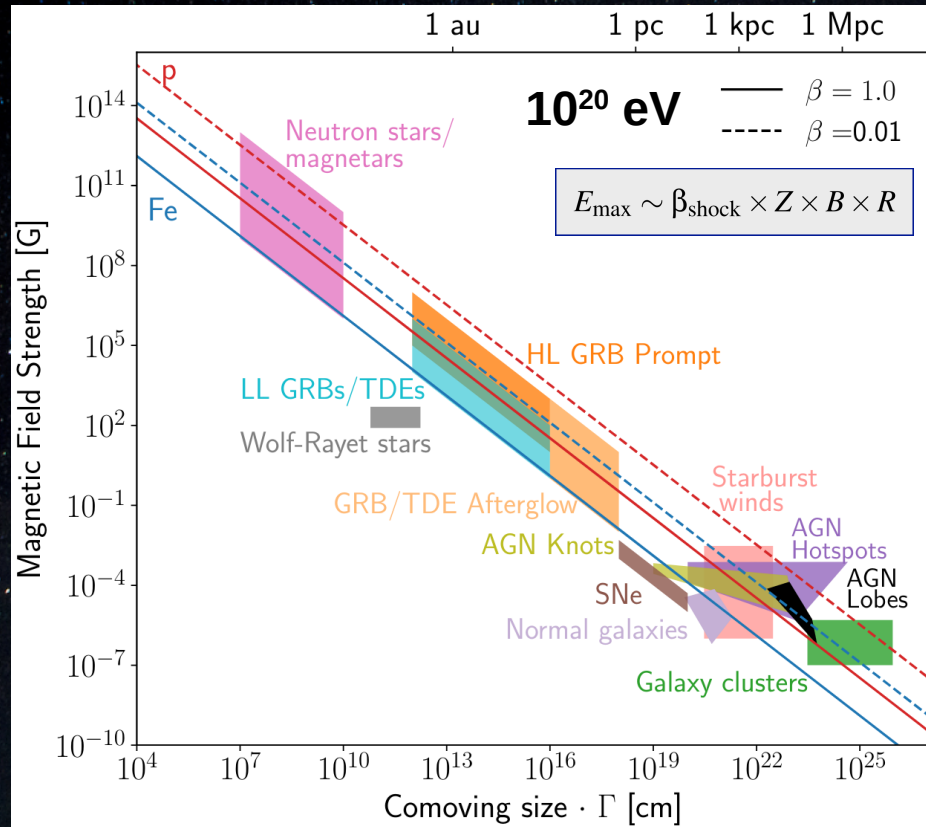
Relation between the size of acceleration region and its magnetic field strength
→ constraints on candidate sources

Ideal case, still need to account for:

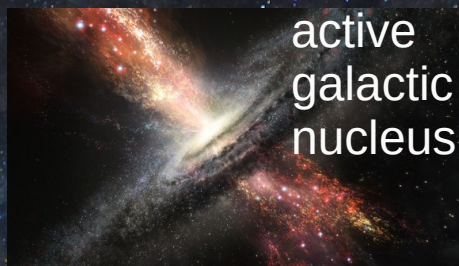
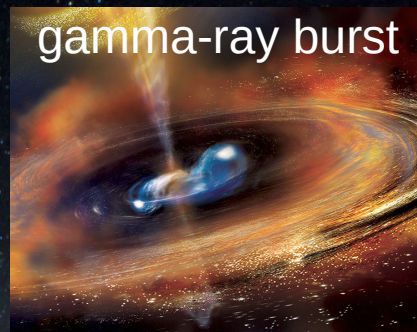
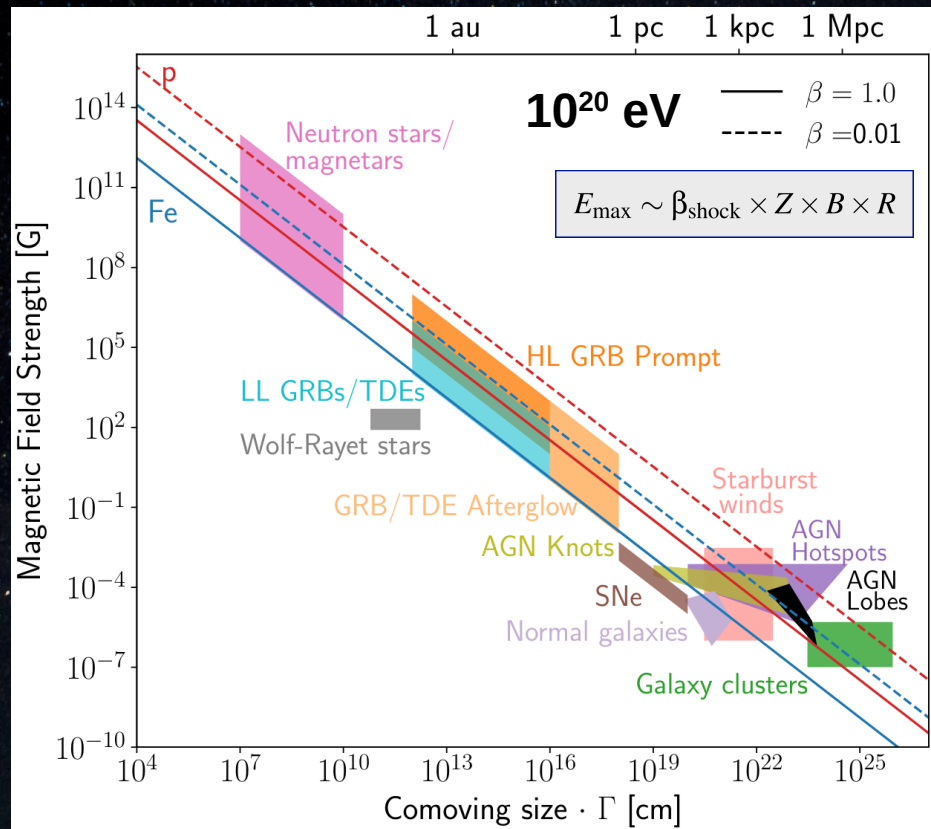
- energy losses
- efficiency of acceleration
- luminosity of source
- ...

Very difficult to find a consistent theory ...
(Somewhat easier for heavier nuclei)

Long-lasting mystery at the highest energies



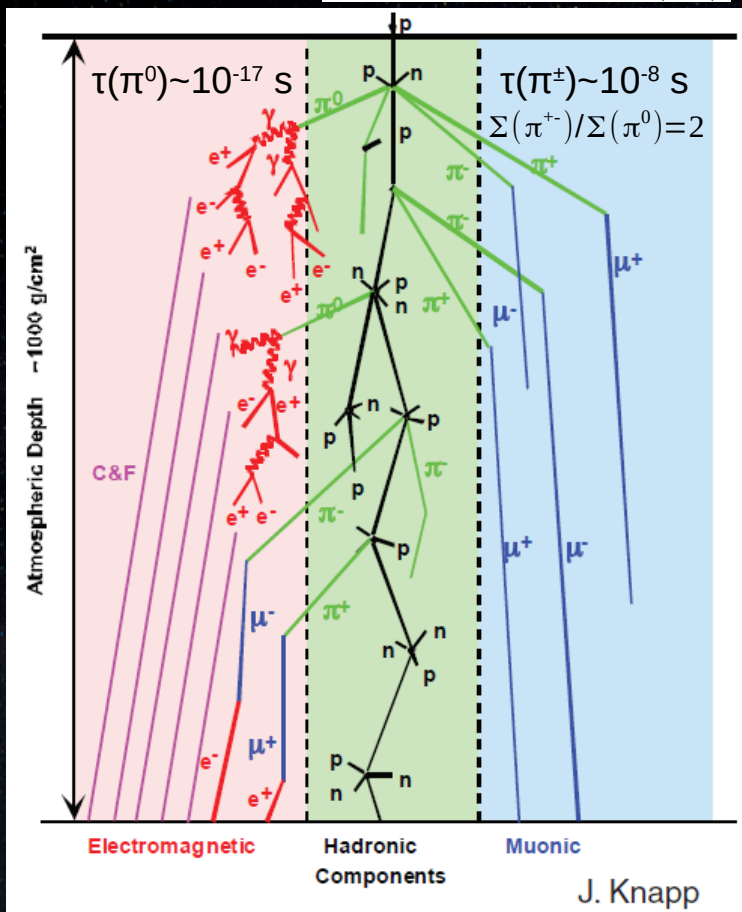
Long-lasting mystery at the highest energies



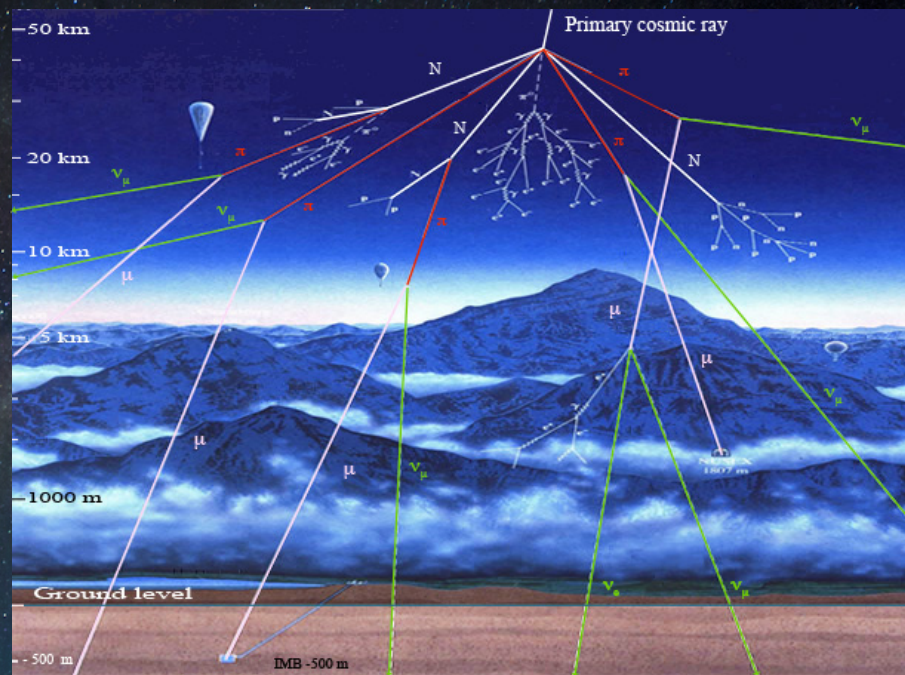
Extensive air showers

$$\pi^0 \rightarrow \gamma + \gamma$$

$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu (\bar{\nu}_\mu)$$



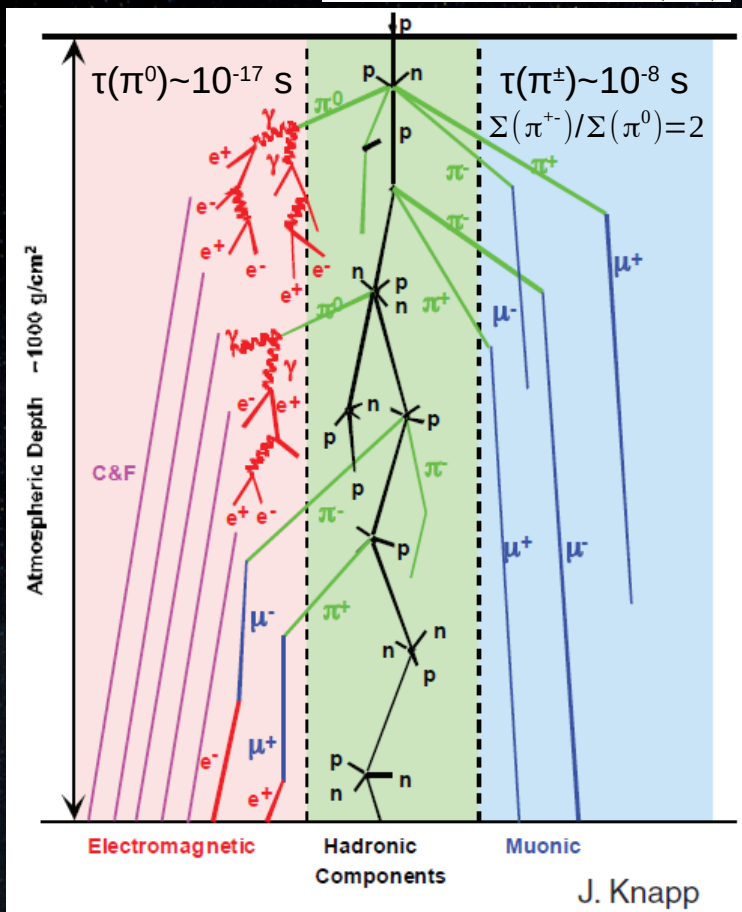
- For UHECR: billions of particles
- Secondary hadrons (mostly pions)
- Electromagnetic cascade (from π^0 decay)
- Muons (from π^\pm , K ... decay)



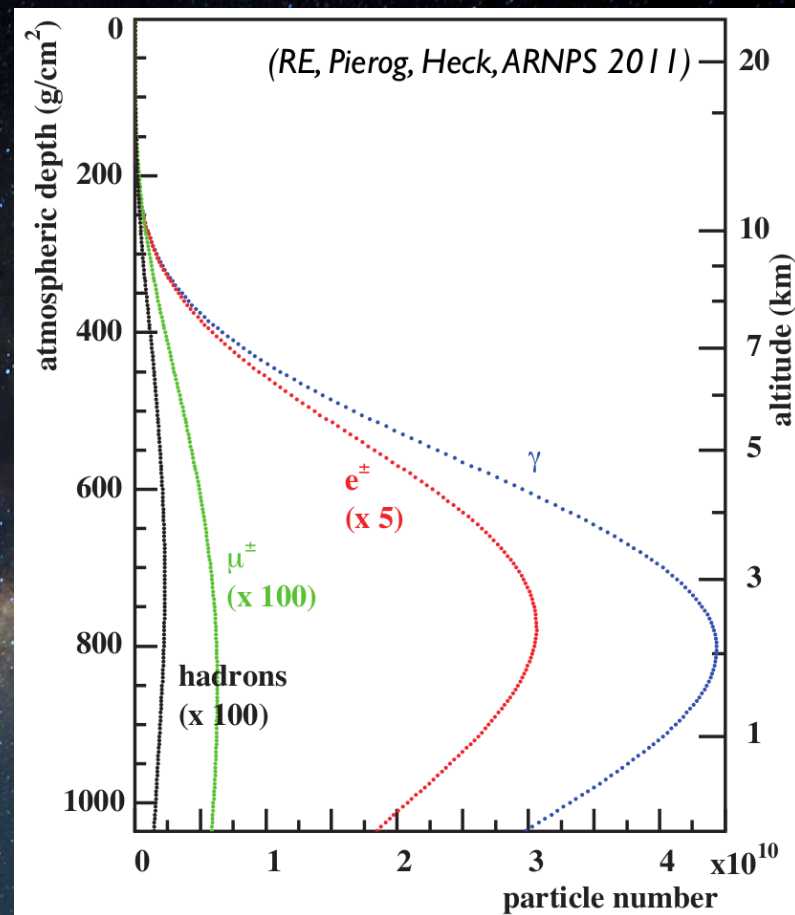
Extensive air showers

$$\pi^0 \rightarrow \gamma + \gamma$$

$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu (\bar{\nu}_\mu)$$



Longitudinal profile



Extensive air showers: X_{\max}

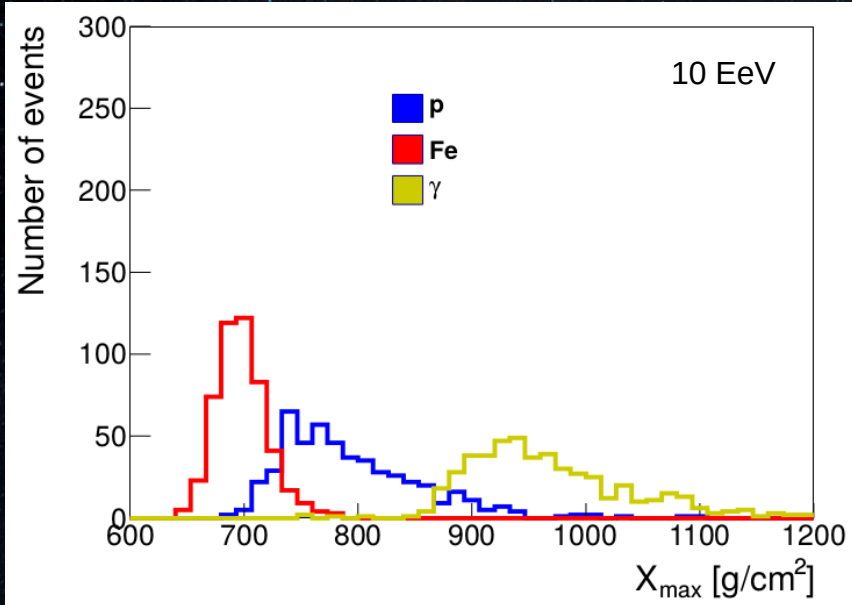
Longitudinal profile

[Astropart. Phys. 22 (2005) 387, Astropart. Phys. 35 (2012) 660]

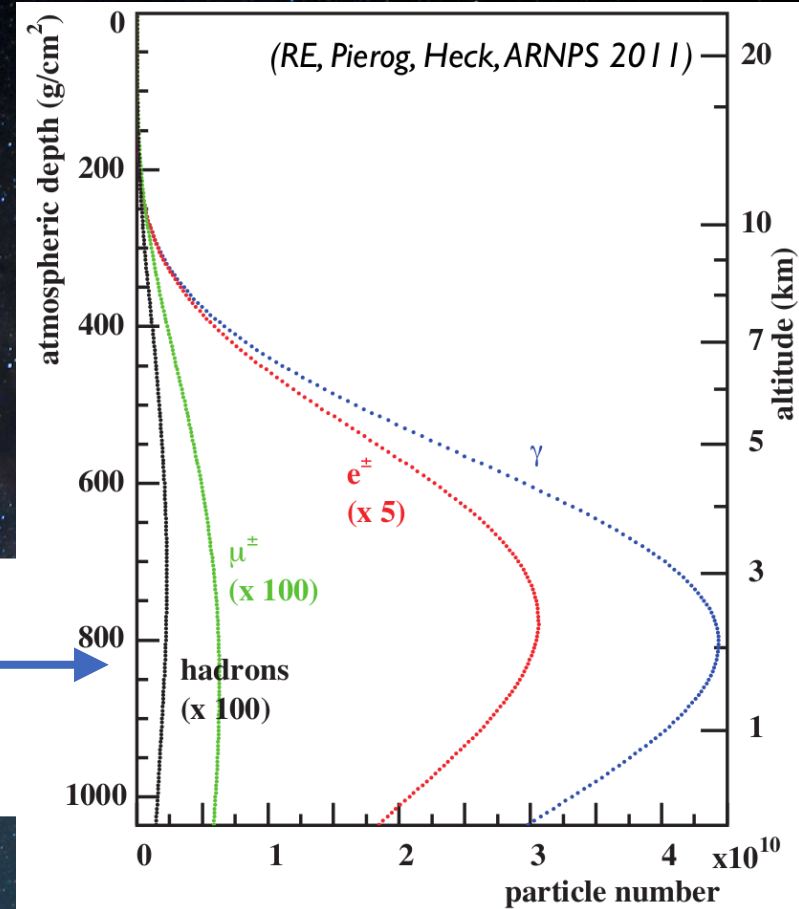
$$X_{\max}(A) \approx X_0(E_0/A) + \lambda_r \ln[\zeta_c^e \kappa E_0/A] - \lambda_r \ln[3 N_{ch}(E_0/A)]$$

$$X = \int_{\infty}^h \rho \cdot dl / \cos(\theta)$$

Sensitivity to primary mass A



X_{\max} :
slant depth of
maximal number
of particles

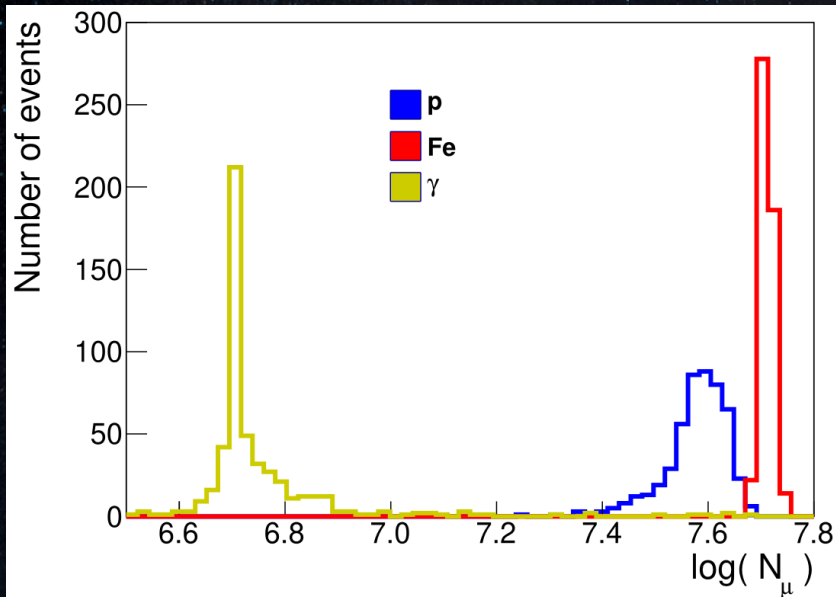


Extensive air showers: muons

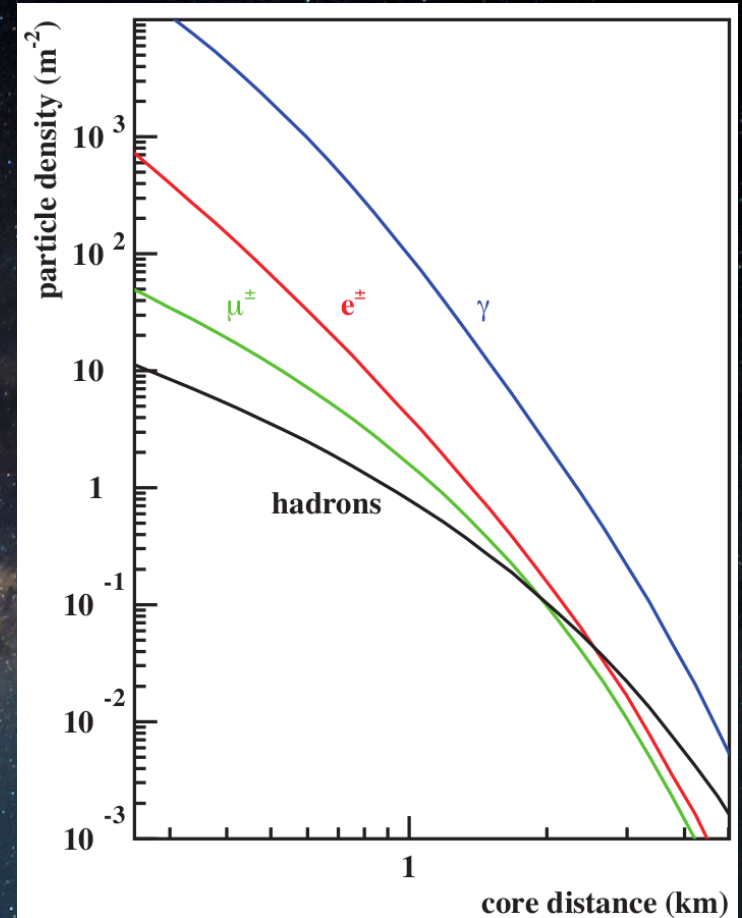
[Astropart. Phys. 22 (2005) 387, Astropart. Phys. 35 (2012) 660]

$$N_{\mu}(A) \approx [\zeta_c^n E_0 / A]^{\beta}, \quad \beta \approx 1 - \frac{1 - \kappa}{3 \ln[N_{ch}]} \approx 0.9$$

Sensitivity to primary mass A

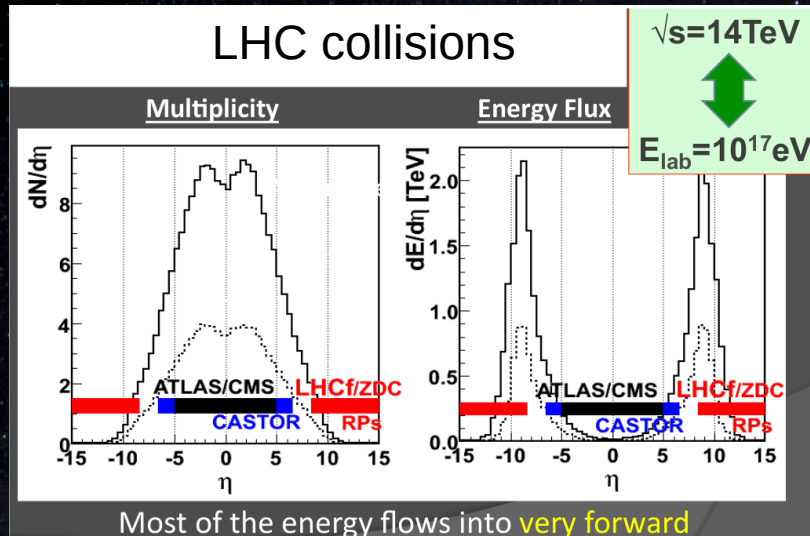


Lateral profile

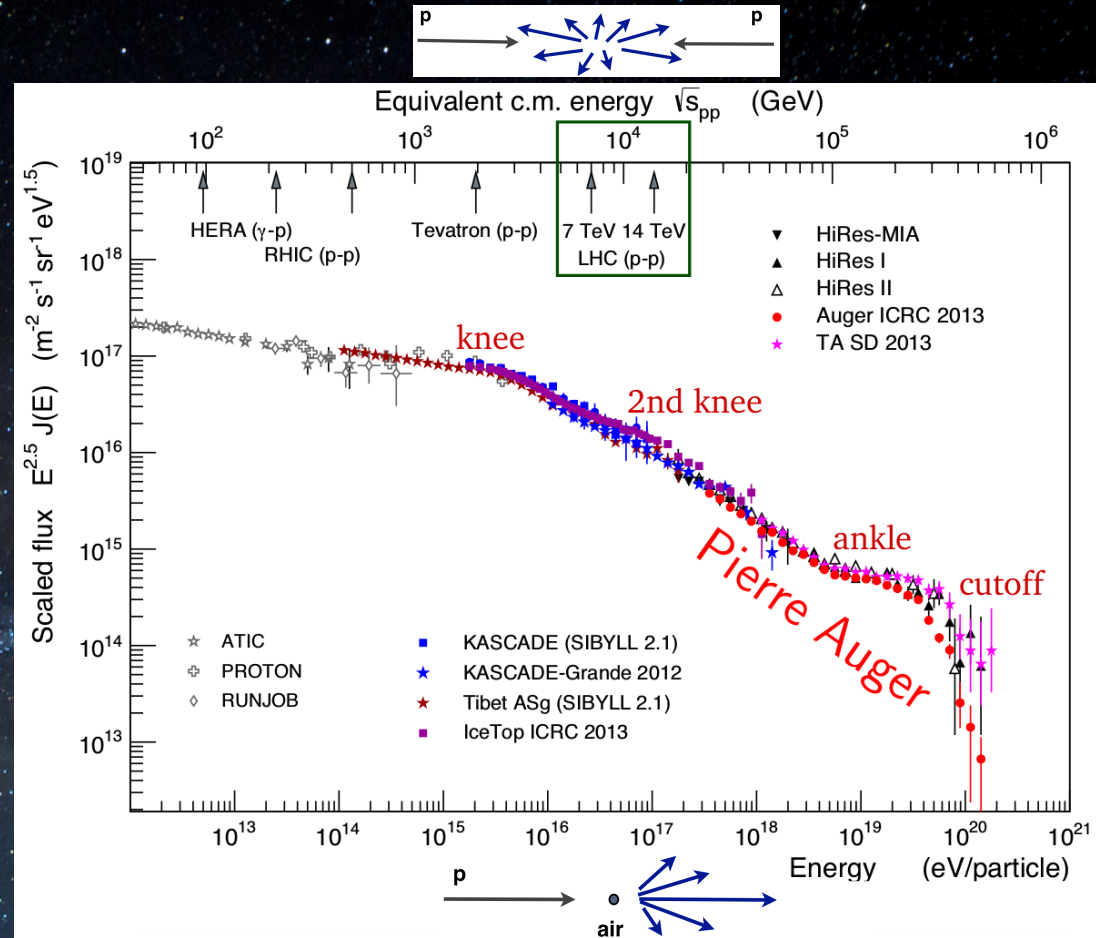


Extrapolation of hadronic interactions

Main source of systematic uncertainties on interpreted mass composition

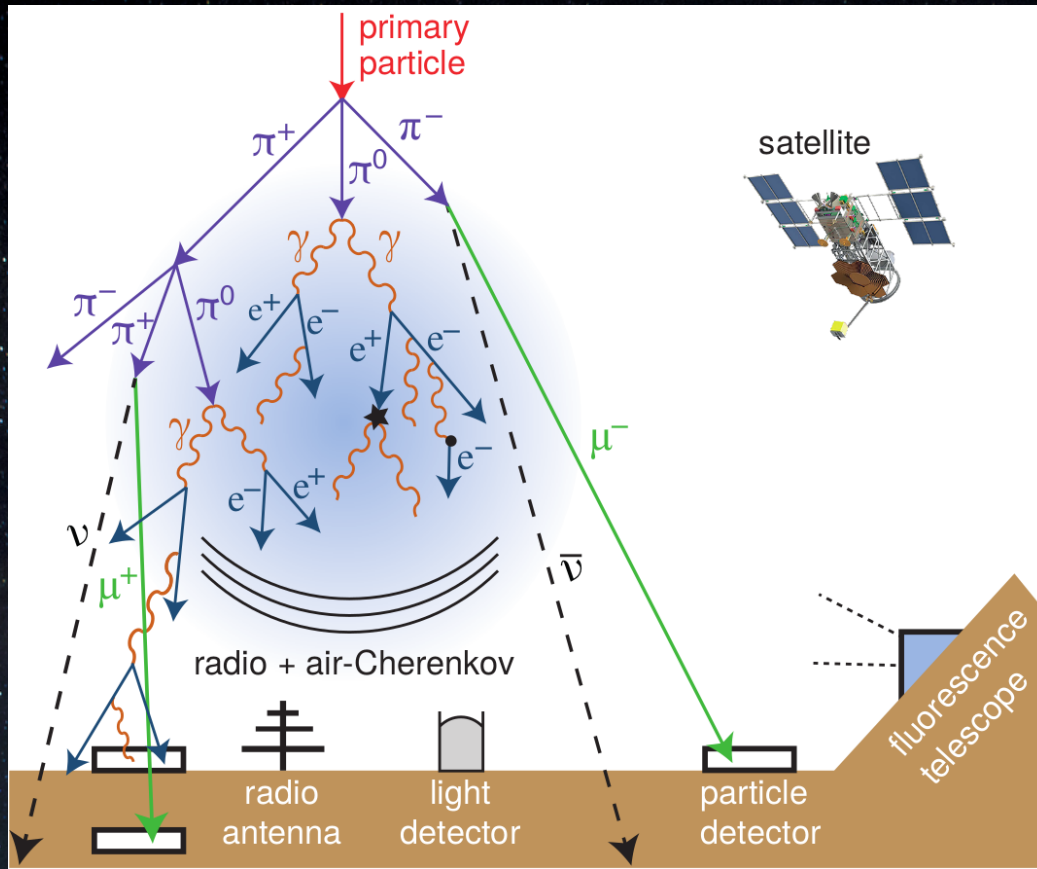


Different kinematic regions and several orders in magnitude of energy



Currently used models of high-energy hadronic interactions: EPOS, QGSJet, Sibyll

Detection of extensive air showers



Collimated Cherenkov radiation in air or in water

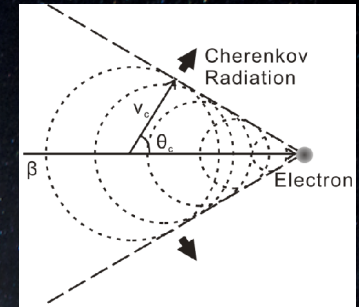
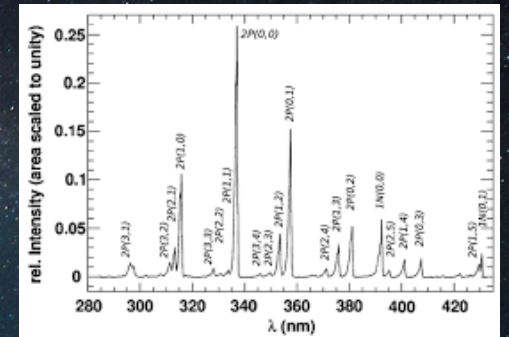
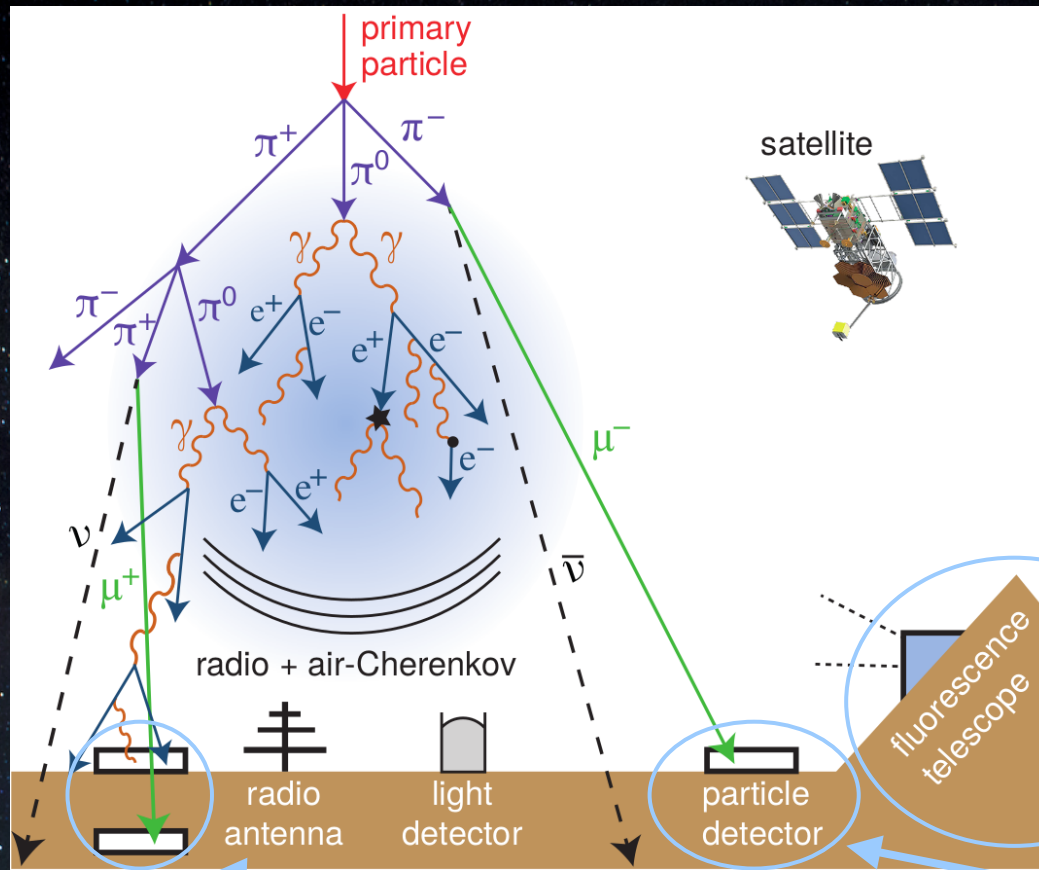


Figure 1. Schematic of Cherenkov radiation

Isotropic emission of fluorescence light



Detection of extensive air showers



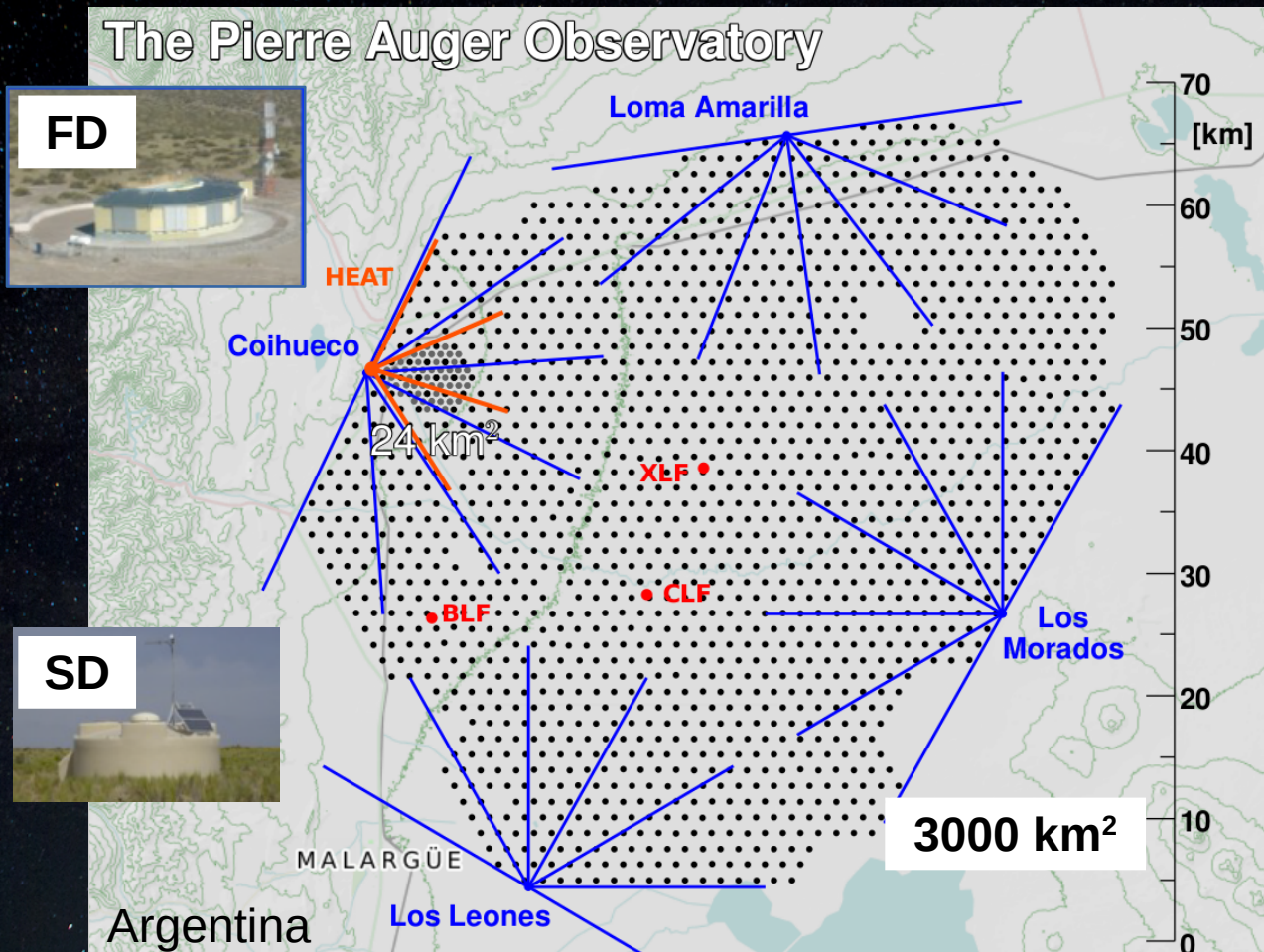
Most common techniques

Fluorescence detector (FD):
precise measurement with
~13% duty cycle

Surface detector (SD):
shower sampling at
large area with
~100% duty cycle

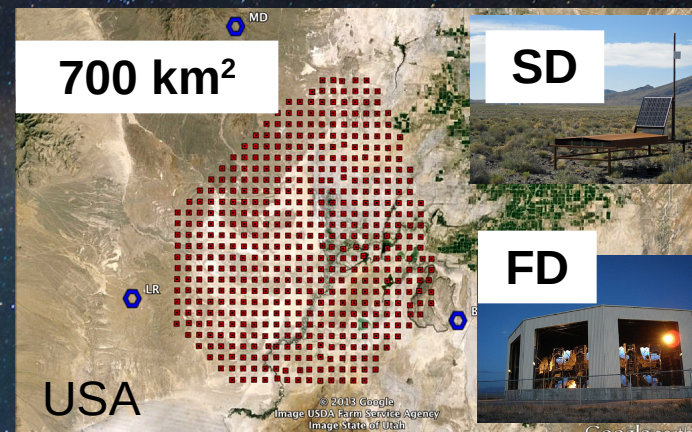
Observatories of ultra-high energy cosmic rays

The Pierre Auger Observatory



Pierre Auger Observatory:
1660 water-Cherenkov stations
in the Southern hemisphere

Telescope Array:
507 scintillators in the
Northern hemisphere

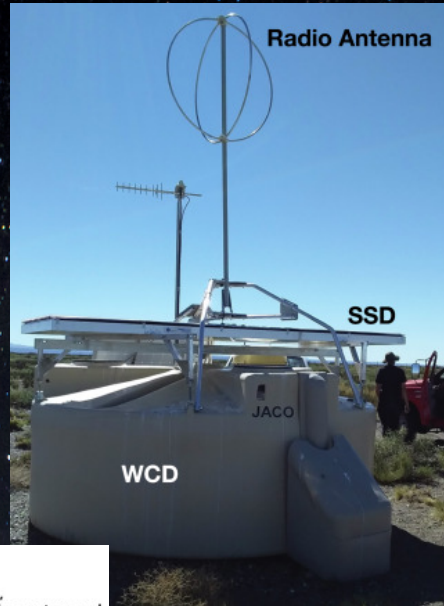


Upgraded observatories

AugerPrime

Better mass discrimination using:

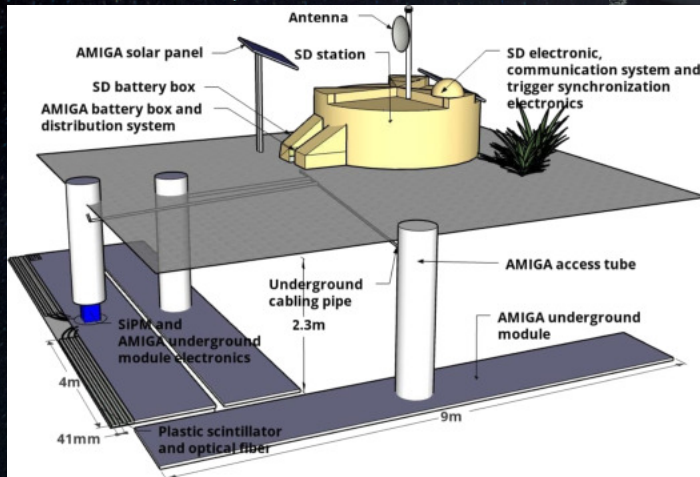
- SSDs
- Radio
- Faster electronics
- Small PMT
- AMIGA



$\sim em$

$\mu + em$

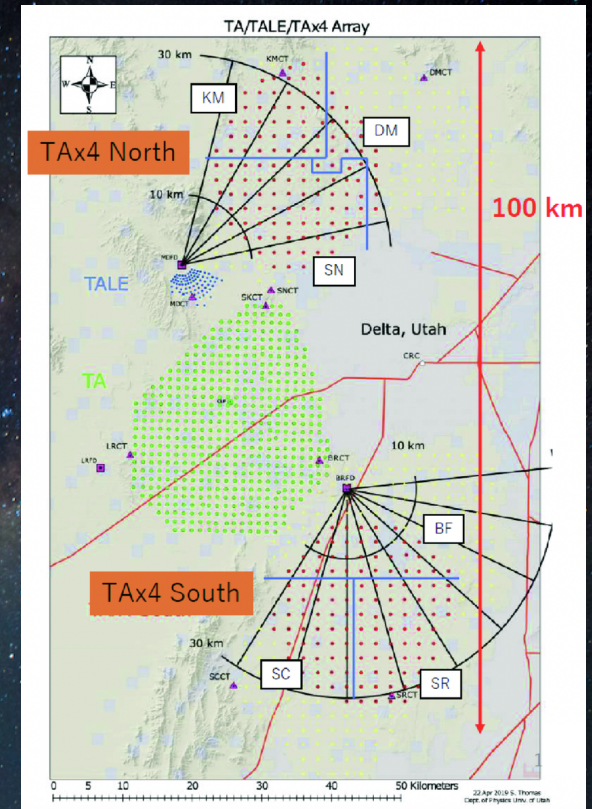
μ



TA x 4

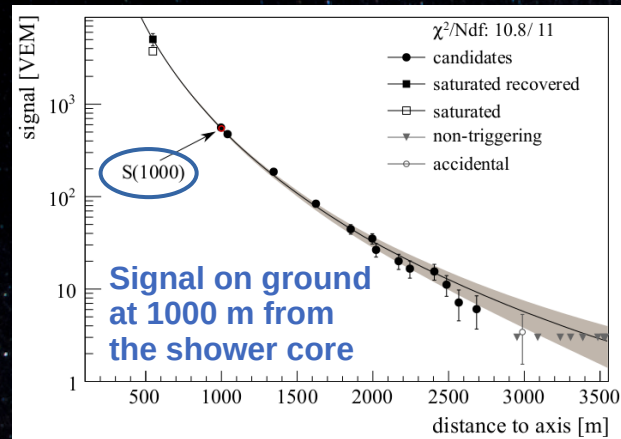
Increase exposure $> 10^{19}$ eV:

- more surface stations
- more fluorescence telescopes

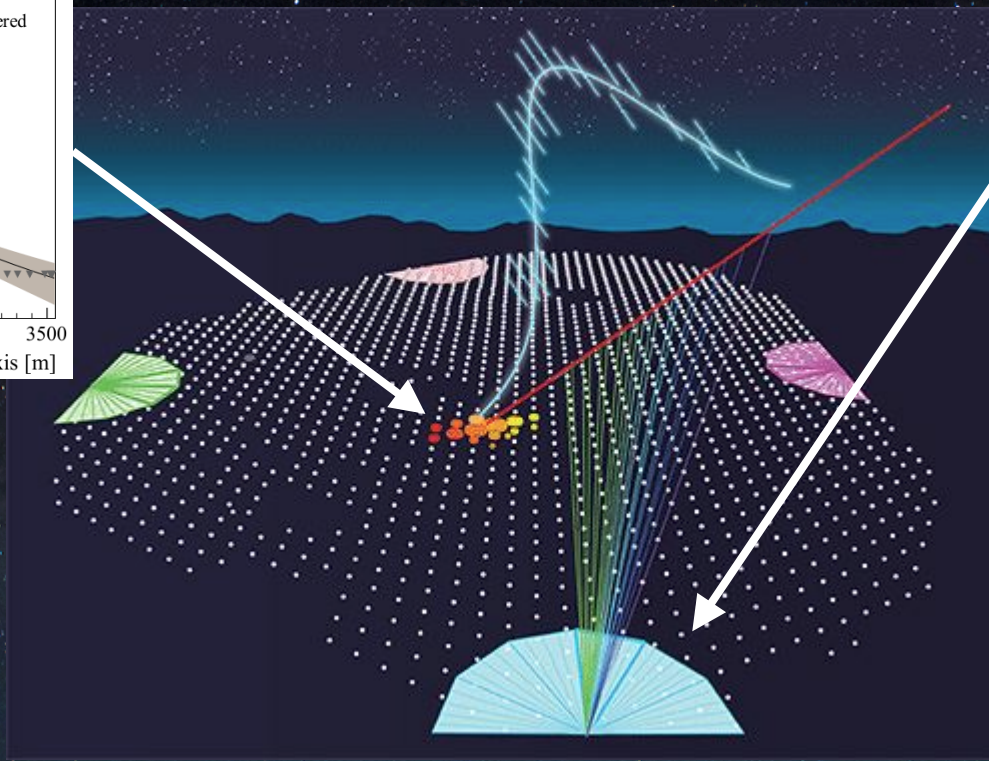


Reconstruction of air showers at Auger

Surface detector reconstruction

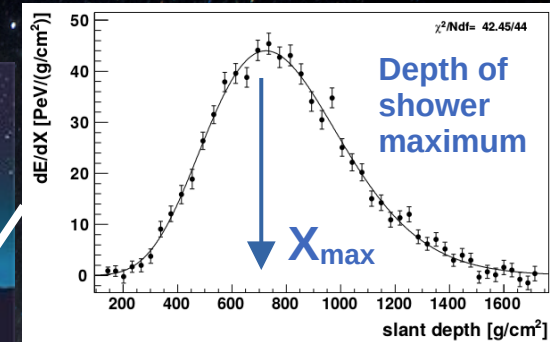


- calibrated by precise FD energy
- sensitive to em and muon particles



→ Energy, direction, mass

Hybrid reconstruction



- timing information from SD station closest to the shower core
- measurement of X_{max} of em component

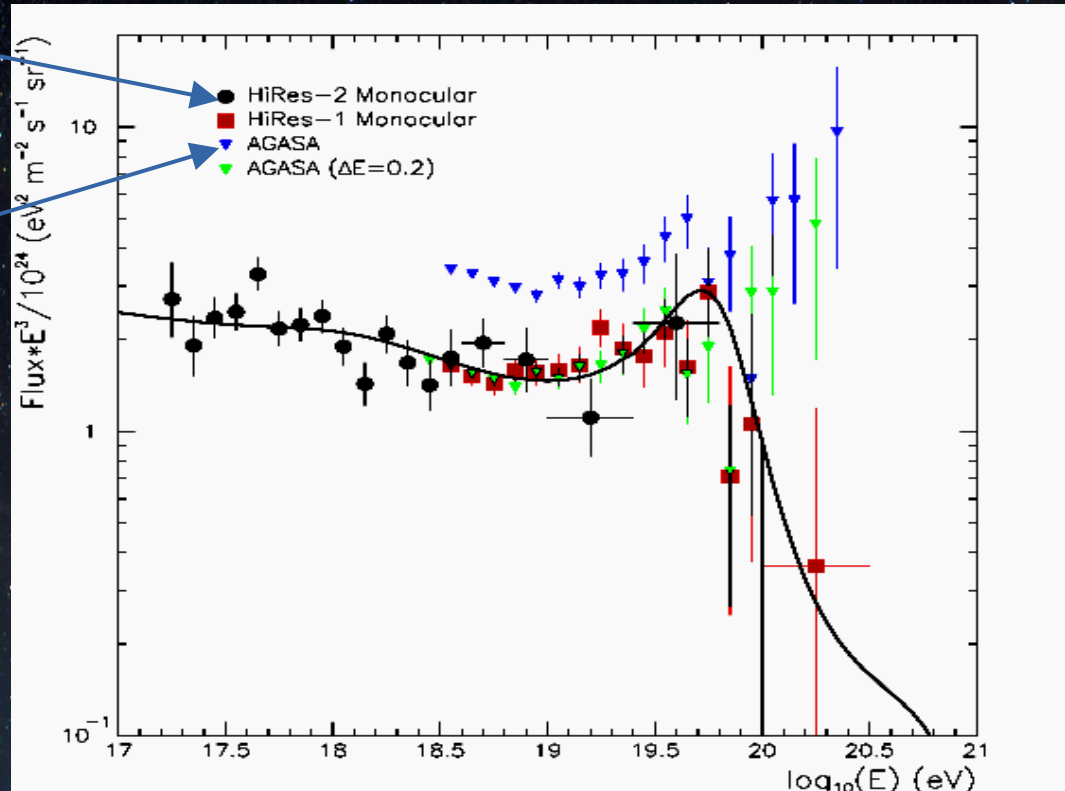
Energy spectrum at ultra-high energies

Around year 2000

[Phys. Rev. Lett. 100 (2008) 101101]

FD

SD

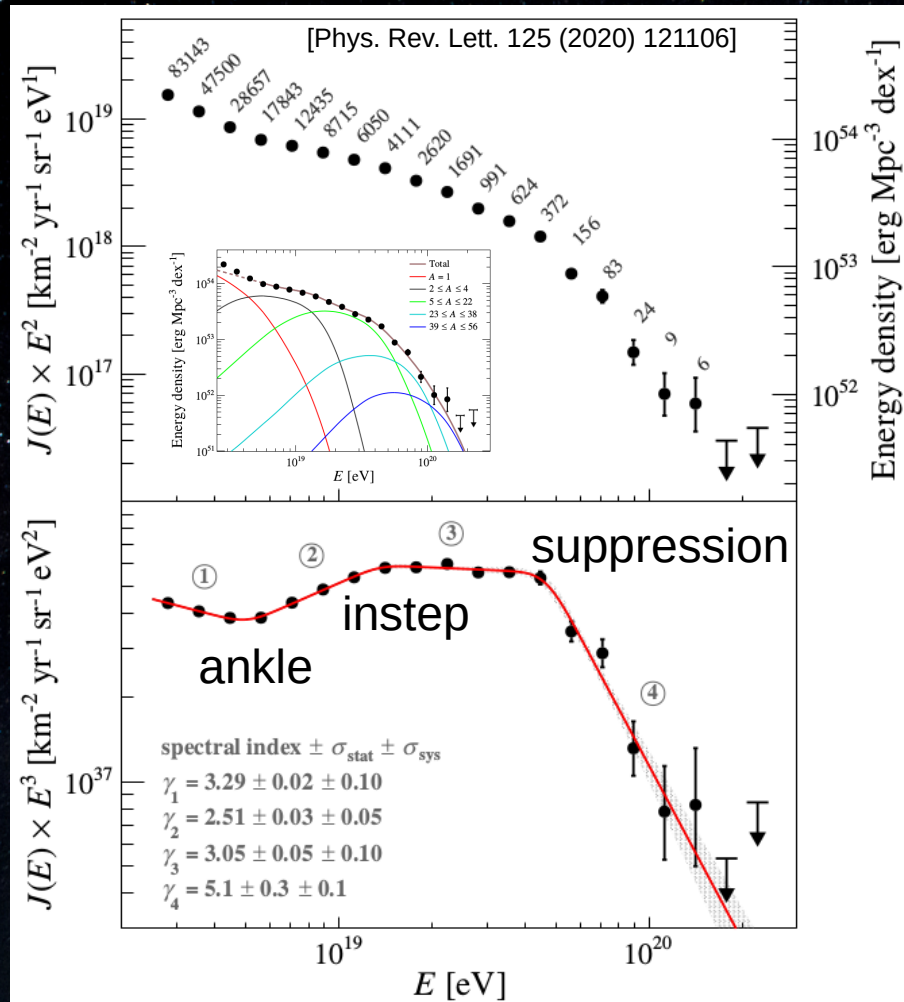


Exotic sources
like decays of
superheavy
particles?

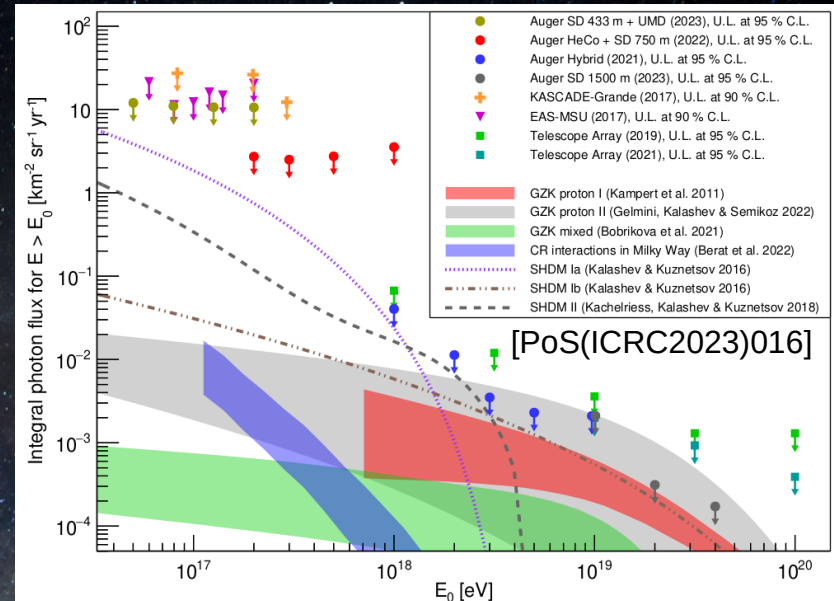
Or GZK effect of
protons?

Actually the first
strong indication
of a problem to
describe
secondary muons
by simulation...

Energy spectrum at ultra-high energies

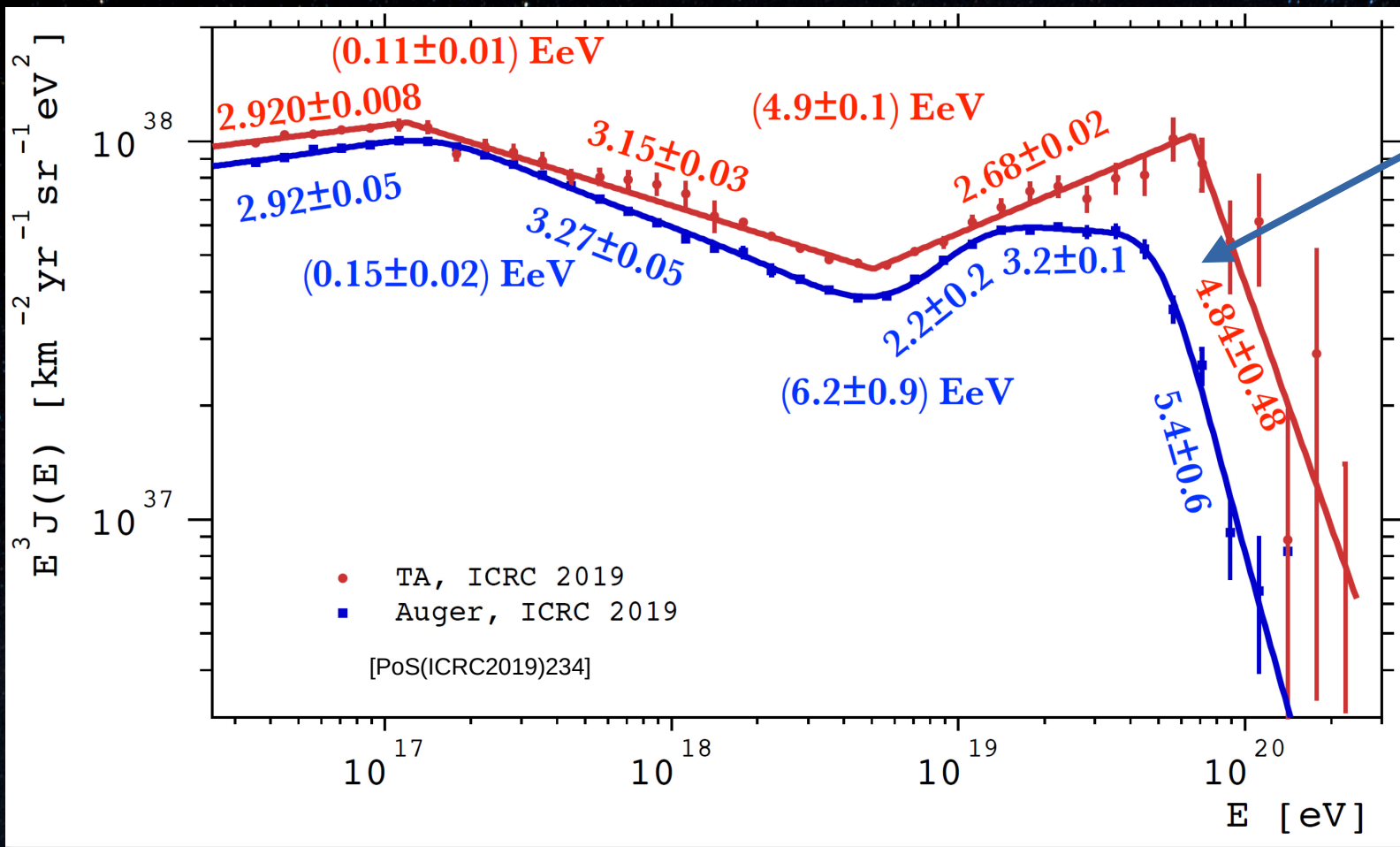


No exotic scenario



Origin of spectral features is unclear
 → need to know mass composition and origin
 (propagation effects vs. different spectral
 indices of different types of sources)

Auger vs. TA: energy spectrum



factor of ~ 3 :
Systematics or
different max.
energy of sources
in the Northern
and Southern
hemispheres?

Sky map above 100 EeV

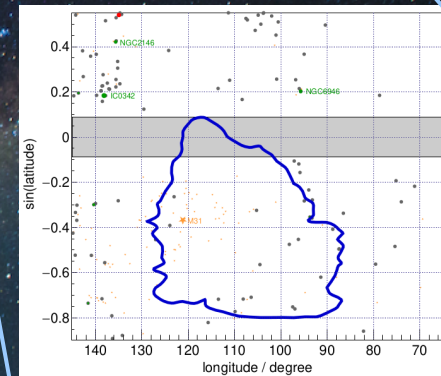
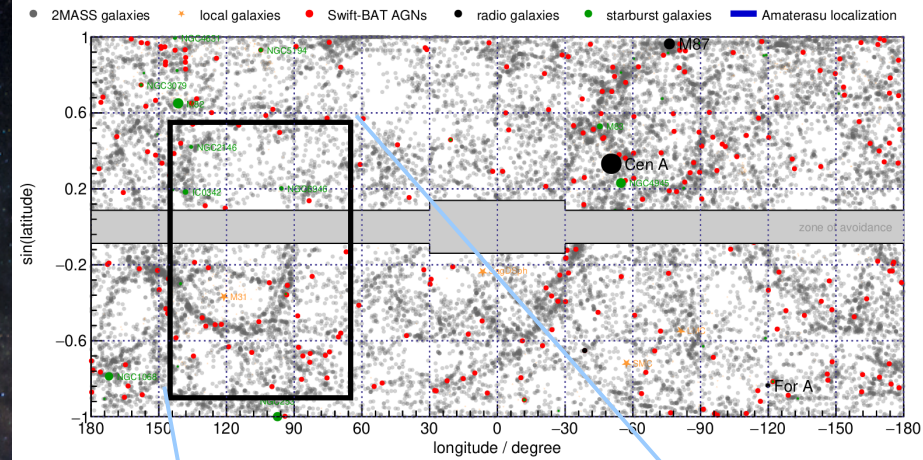
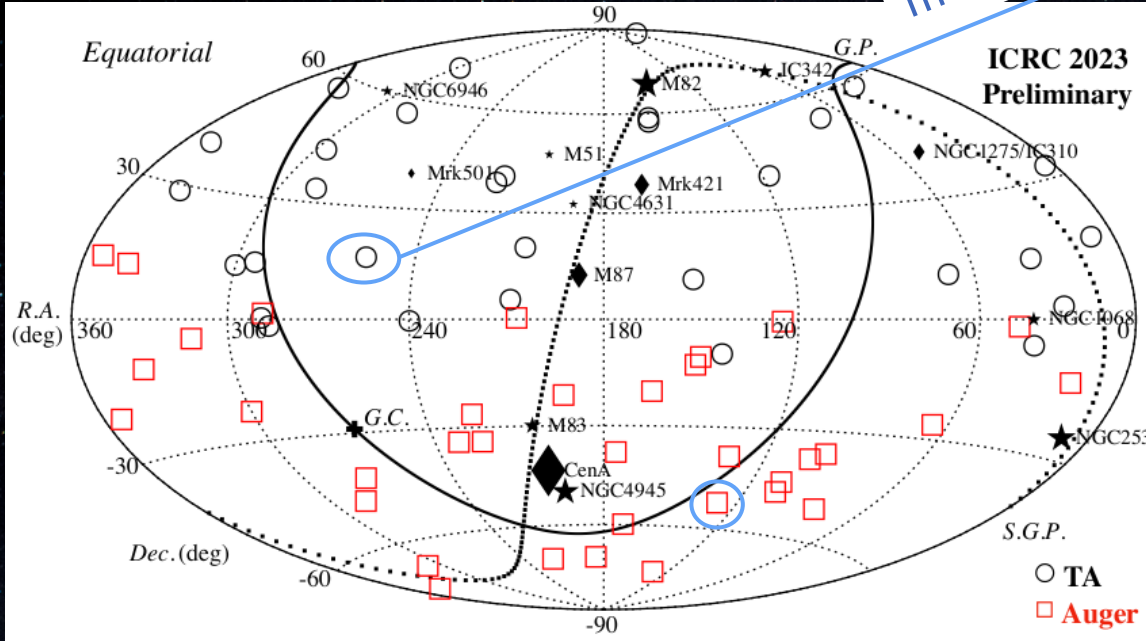
Backtracking of Fe nucleus

[ApJL 962 (2024) L5]

most energetic

equatorial coord.

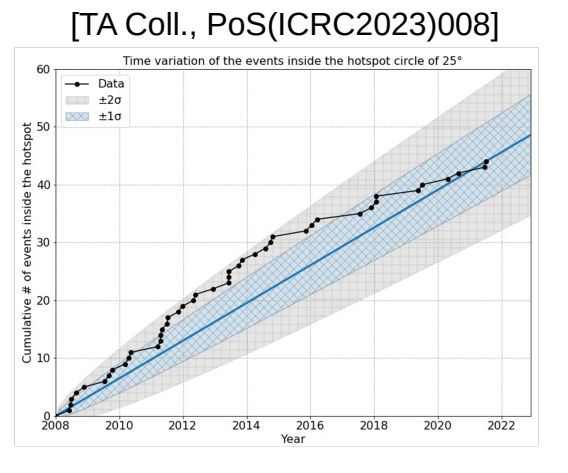
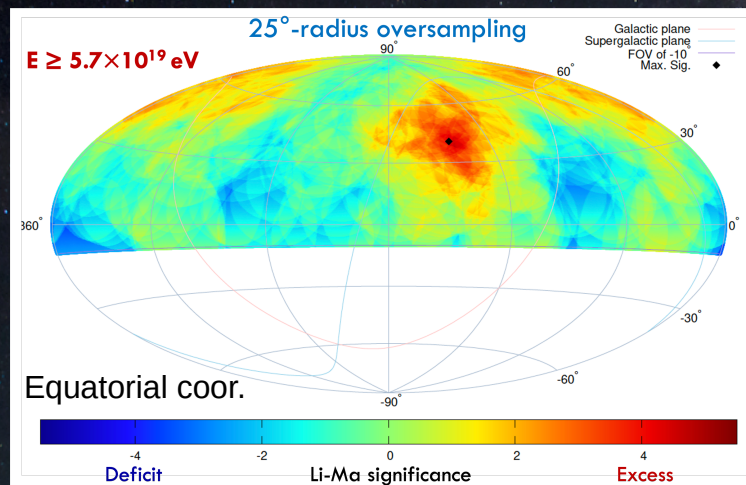
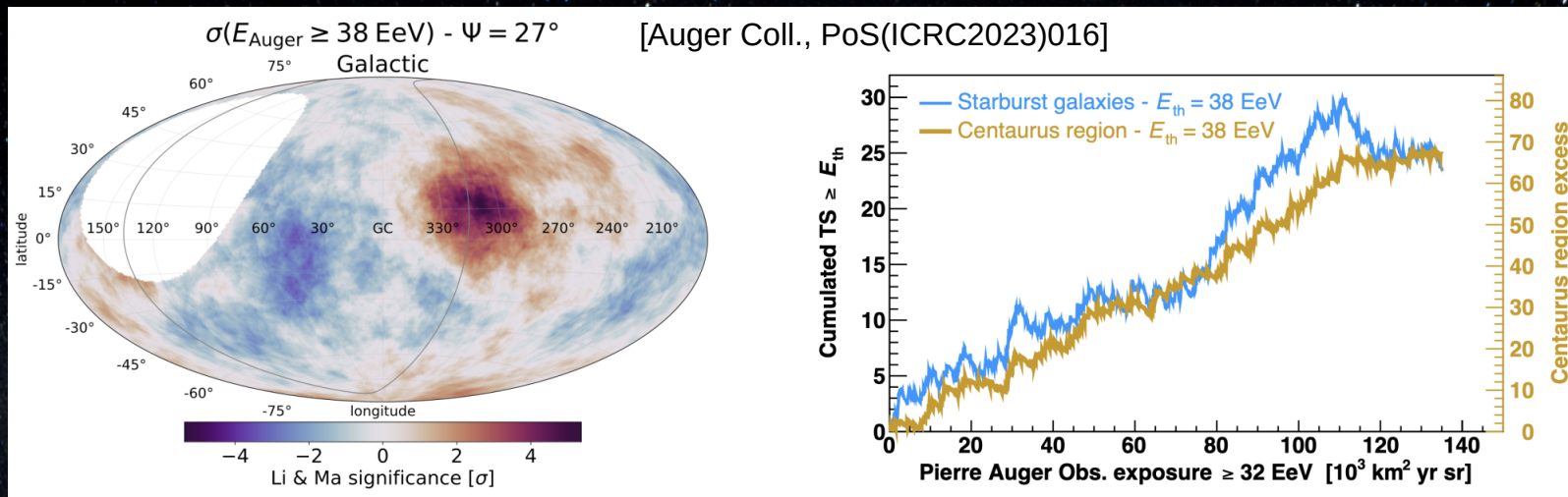
[PoS (ICRC2023) 031]



(d) $E_{low}, D_{0.1} = 25$ Mpc

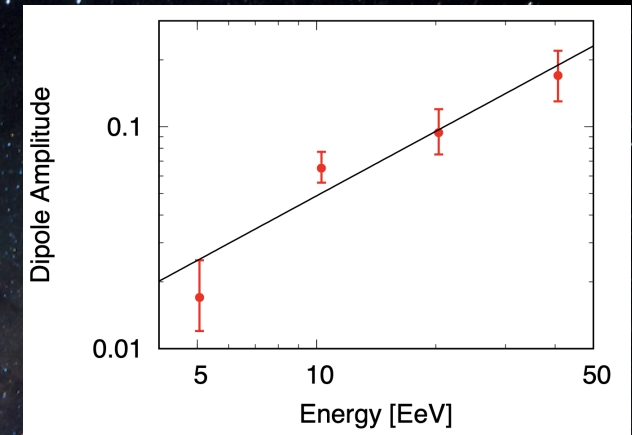
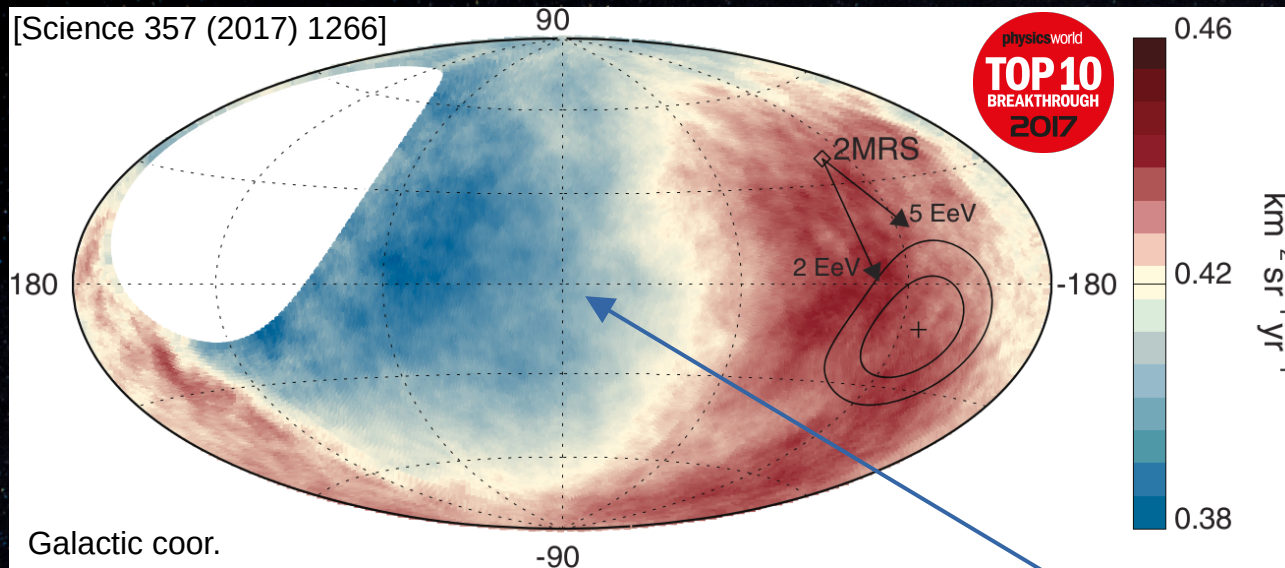
- No obvious clustering of events
- Accounting for Galactic magnetic field does not help
 - stronger Galactic or extragalactic magnetic fields ?
 - new type of sources ? exotic origin ?

Anisotropy searches at intermediate scales



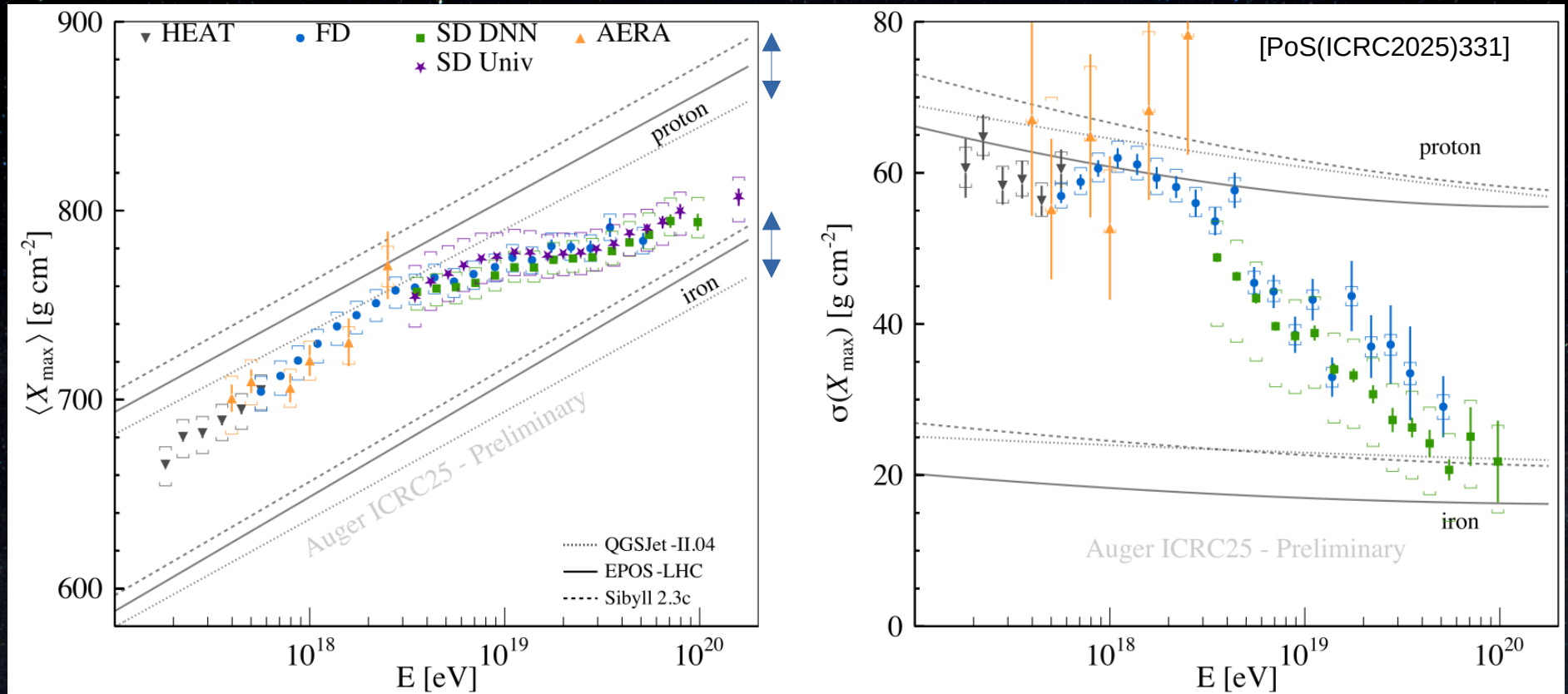
~3 σ global significance

Anisotropy searches at large scales



- **More than 5σ wrt. isotropy above 8 EeV**
- Direction of the dipole $> 120^\circ$ away from the Galactic center
→ **Extragalactic origin!**

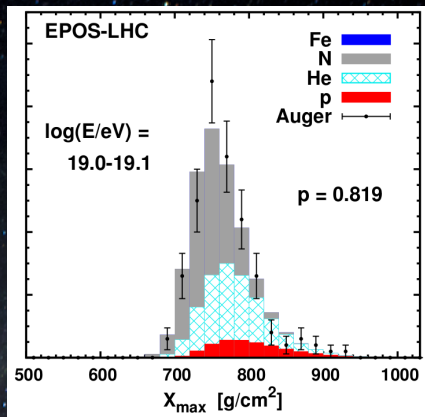
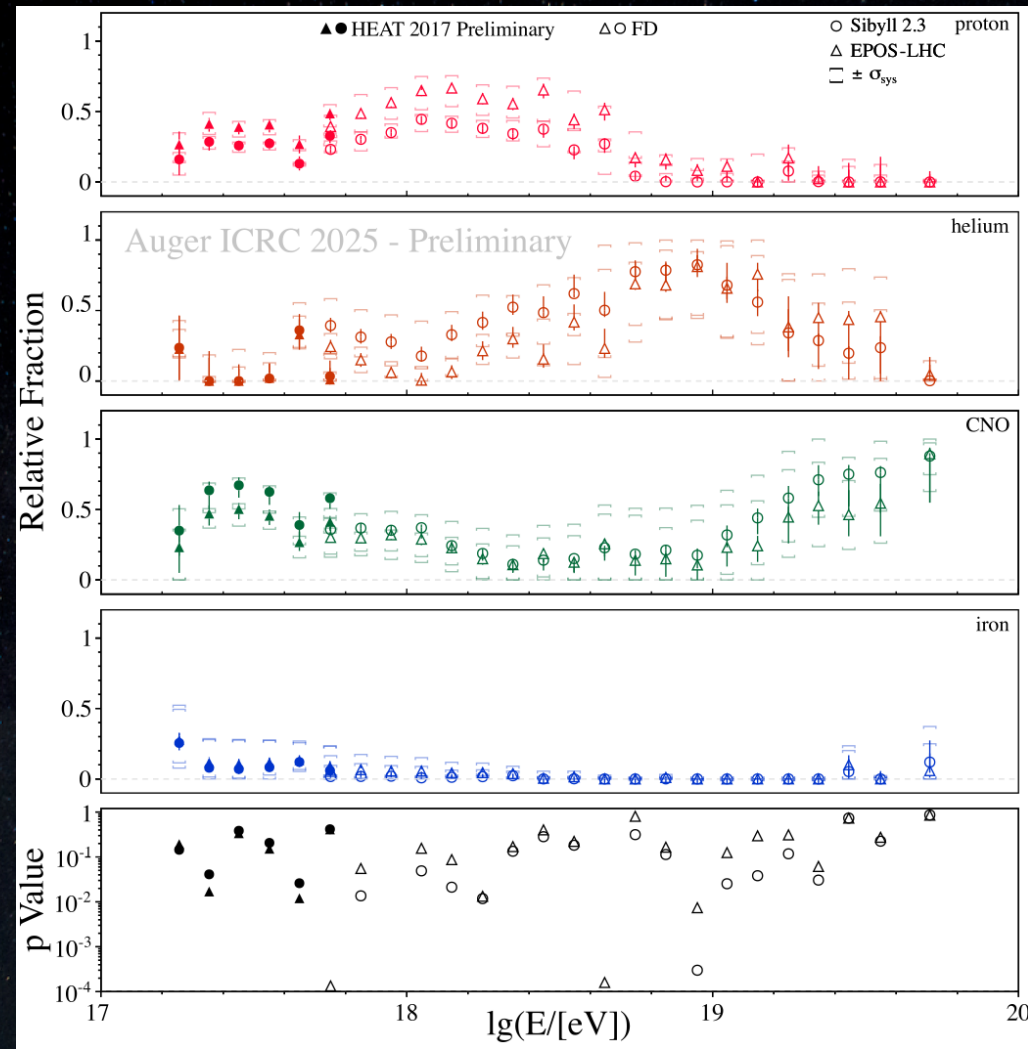
Mass composition of cosmic rays: X_{\max} moments



- Mass composition is getting heavier towards highest energies
- Interpretation based on X_{\max} scale predicted by a HI model

Mass composition of cosmic rays: fitting X_{\max} distributions

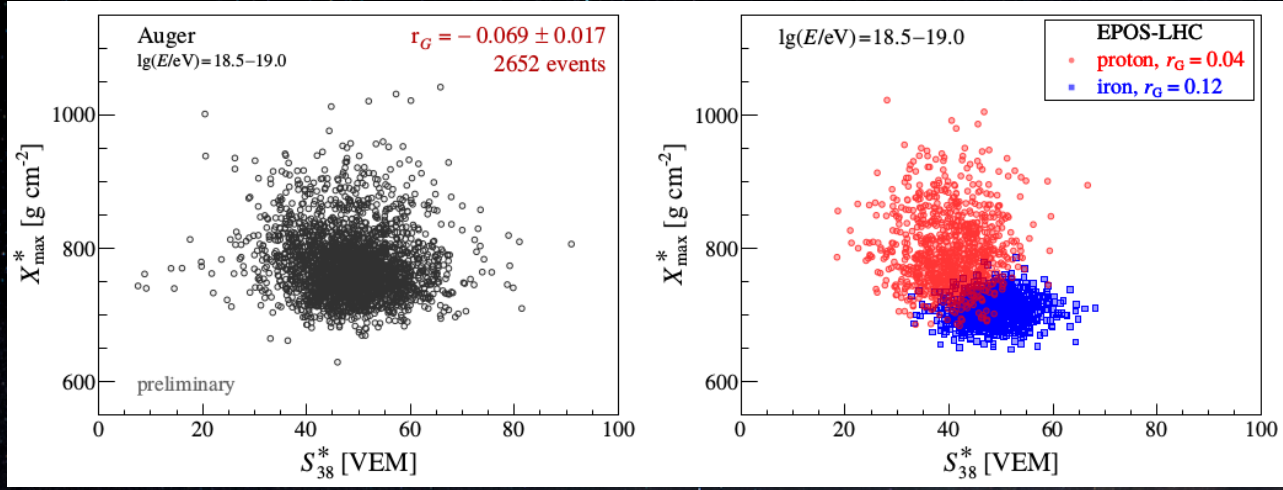
[PoS(ICRC2025)331]



- Fitted Fe fraction very low
- Seemingly low spread between the two selected models

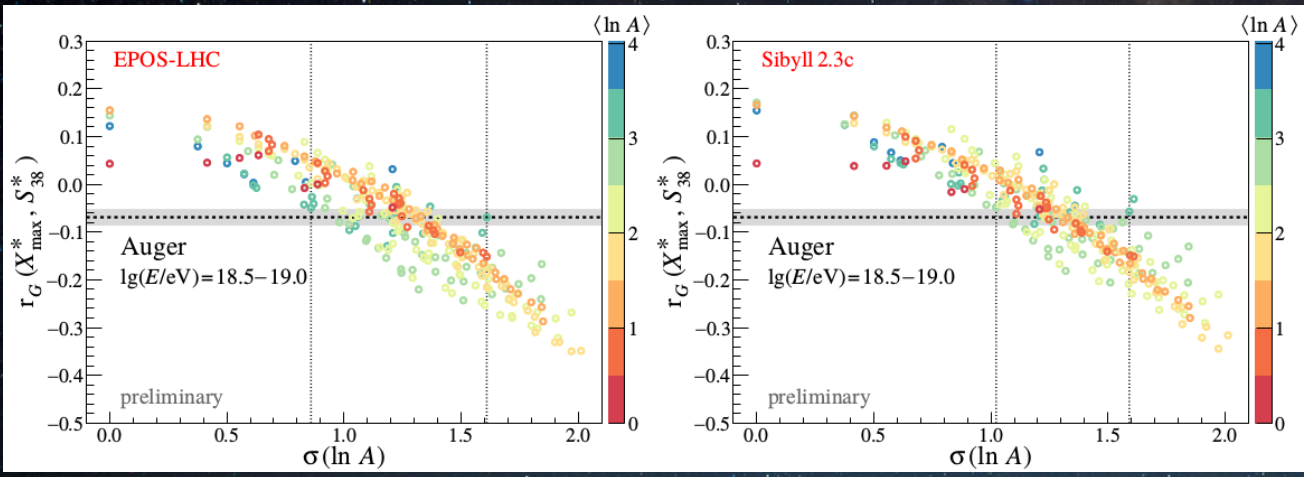
Correlation between ground signal and X_{\max}^*

[Phys. Lett. B 762 (2016) 288]



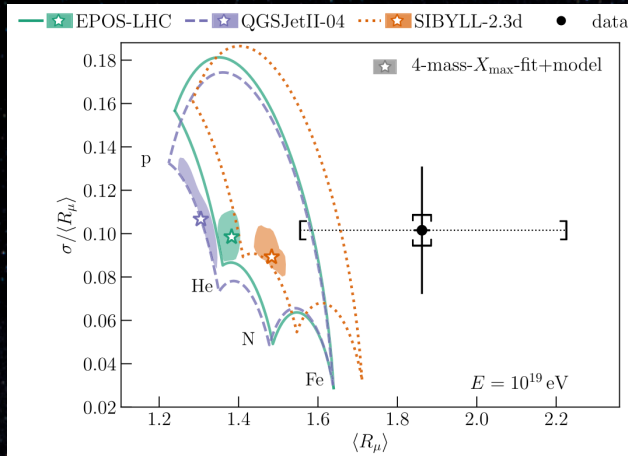
Model-independent estimation of mass mixing
 → evidence of presence of nuclei heavier than He

Tension with QGSJet II-04 mass fractions (p+He only)
 → QGSJet II-04 predicts too shallow X_{\max} !



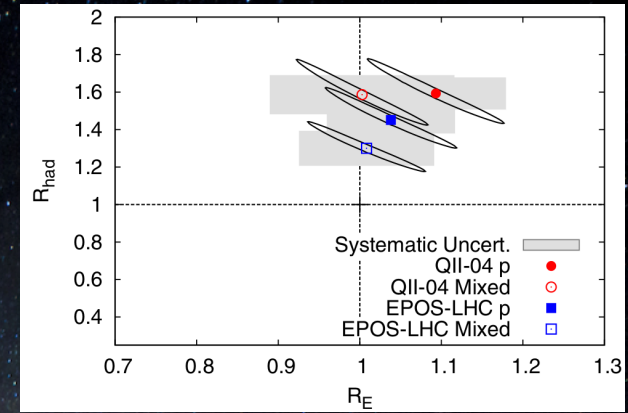
Muon puzzle in Auger data

[Phys. Rev. Lett. 126 (2021) 152002]



Inclined showers (zenith angle $\theta > 60^\circ$) with suppressed em contamination ~ direct measurement of muons

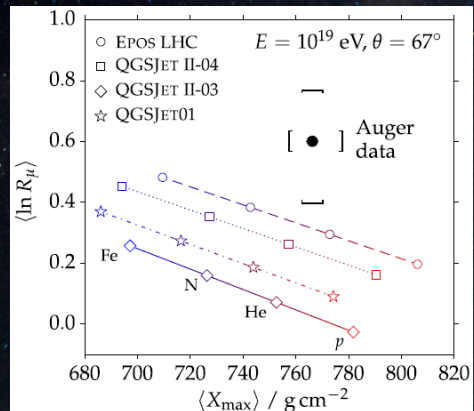
[Phys. Rev. Lett. 117 (2016) 192001]



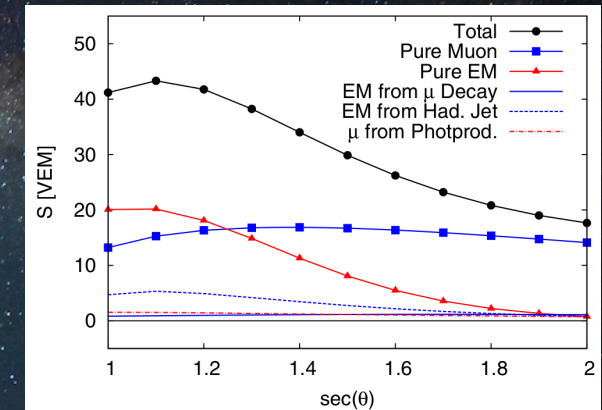
Showers within 60° - indirect estimation of hadronic component ~ muon content

Direct measurement of muons with inclined showers ($> 60^\circ$)

[Phys. Rev. D 91, 032003 (2015)]

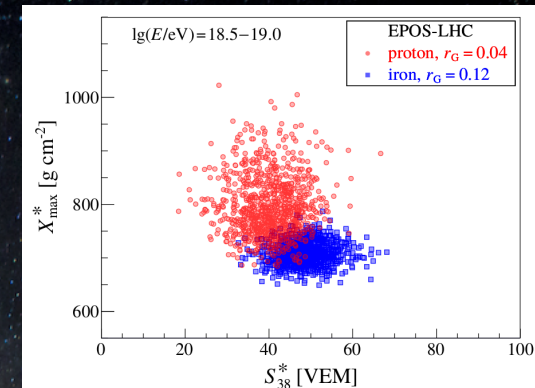
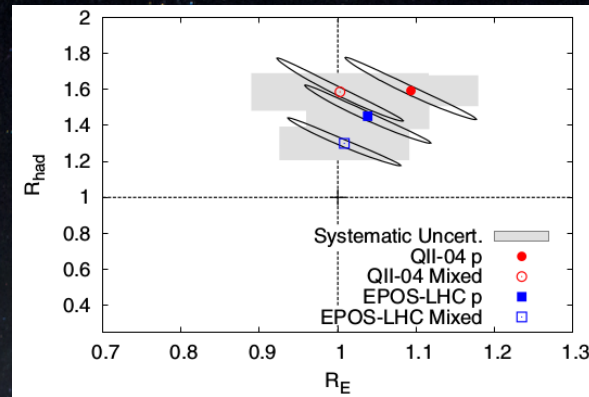
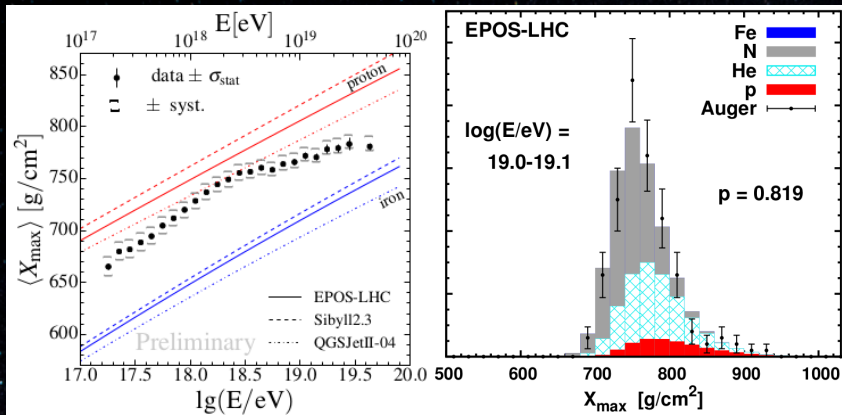


Models underestimate the amount of muons by ~30-60% wrt. predicted X_{\max} scale



Beyond the Muon puzzle

[Phys. Rev. D 109 (2024) 102001]



Mass composition fit of observed $[X_{\max}, S(1000)](\theta)$ distributions with free modification of MC predictions **not only of hadronic signal but also of X_{\max}**

Main differences in model predictions

[Astropart. Phys. 87 (2017) 23, Astropart. Phys: 88 (2017) 46]

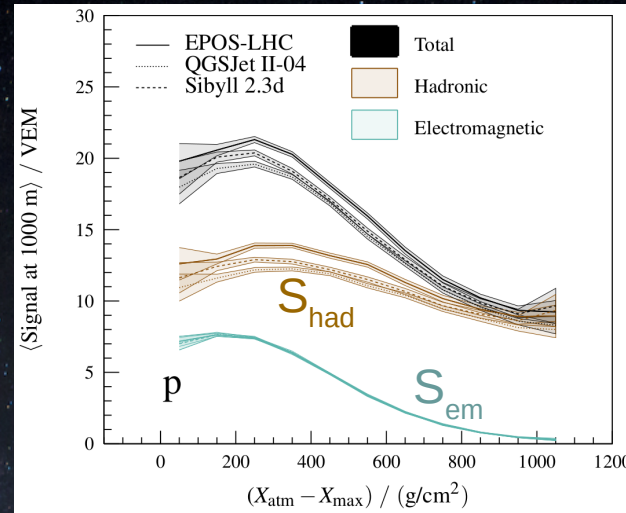
- Properties of 4-component shower universality:

$$S(1000) = S_{had} + S_{em}$$

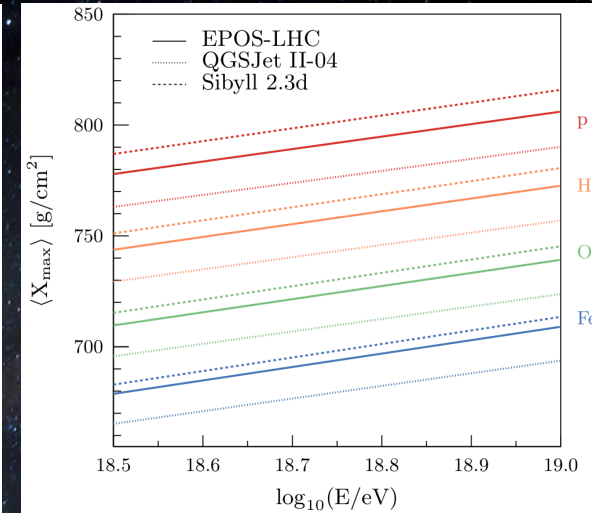
S_{em} is very universal

- Main differences between model predictions:

- scale of $\langle X_{max} \rangle$ and $\langle S_{had} \rangle(\theta)$
- are approx. primary and energy independent



$$X_{atm} = 880 / \cos\theta \text{ g/cm}^2$$



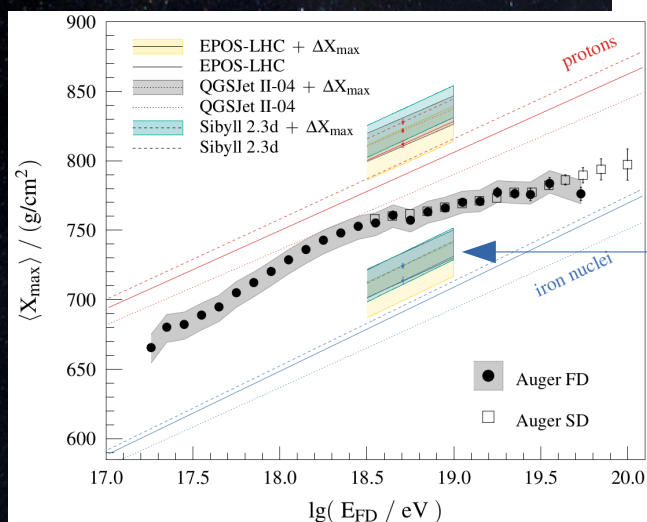
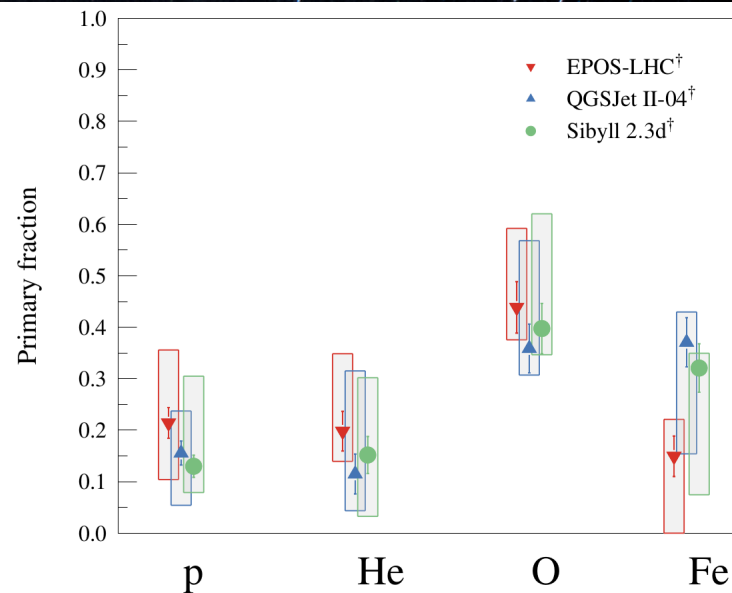
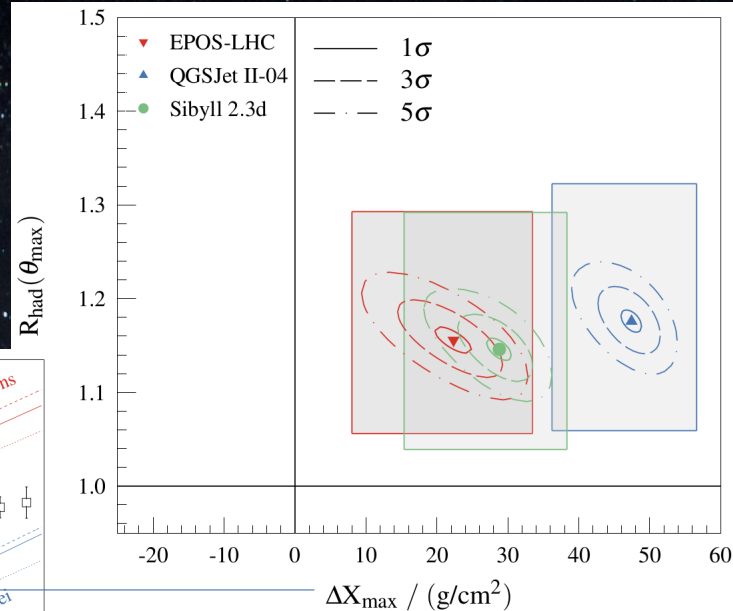
ad-hoc modifications

$$X_{max} \rightarrow X_{max} + \Delta X_{max}$$

$$S_{had}(\theta) \rightarrow S_{had}(\theta) \cdot R_{had}(\theta)$$

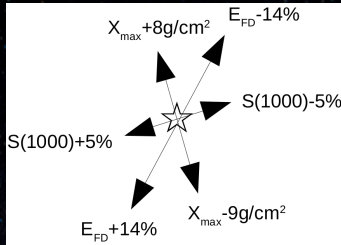
Fitted parameters

Zenith dependence of R_{had}
 assumed to be linear in $X_{\text{ground}} - X_{\text{max}}$
 $\rightarrow R_{\text{had}}(\theta_{\text{min}} \sim 28^\circ), R_{\text{had}}(\theta_{\text{max}} \sim 55^\circ)$



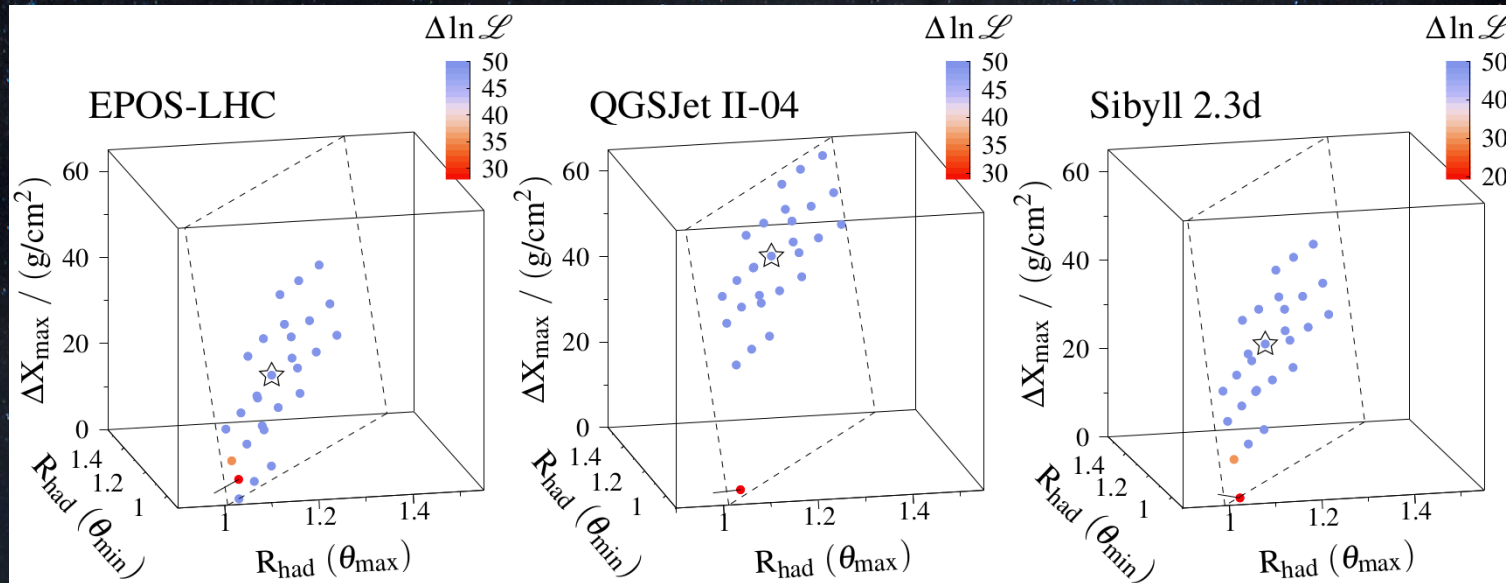
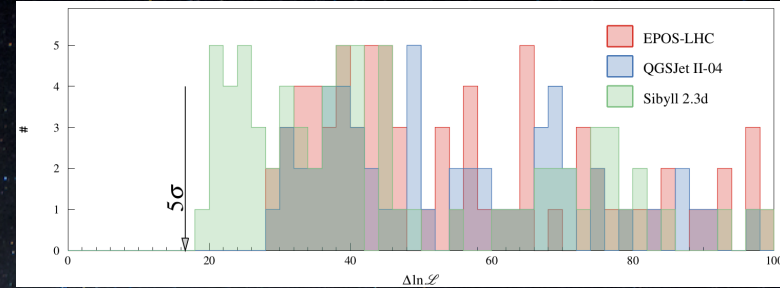
- Deeper X_{max} predictions \rightarrow heavier mass composition
- Smaller model differences in mass composition
- Alleviated “muon puzzle“: from $\sim 30\text{-}60\%$ to $\sim 15\text{-}25\%$

Scanning in combinations of experimental systematics



Significance of improvement of data description always above 5σ

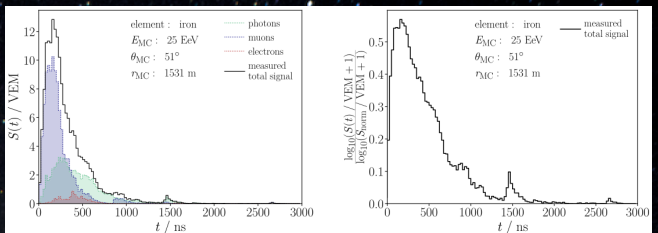
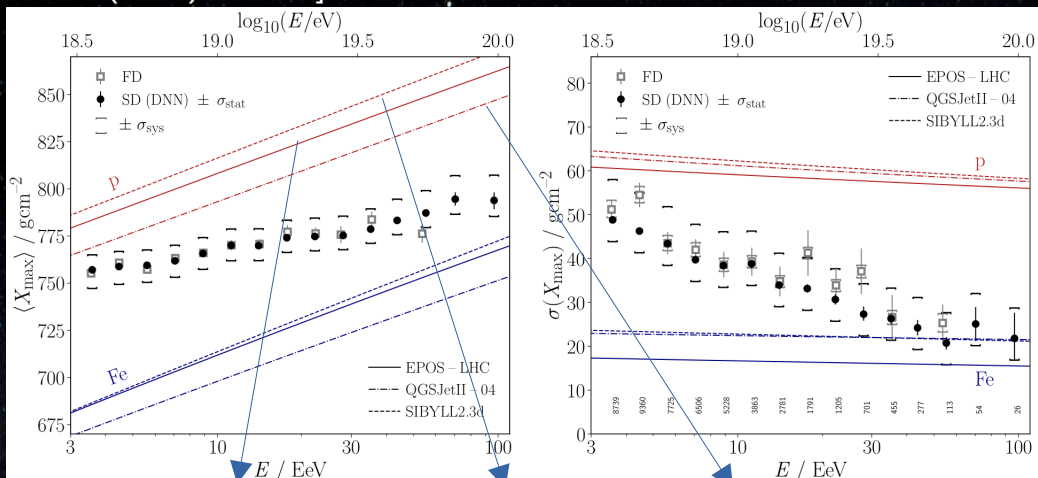
Denser scan in the region of the closest approach of the plane to $[1,1,0 \text{ g/cm}^2]$



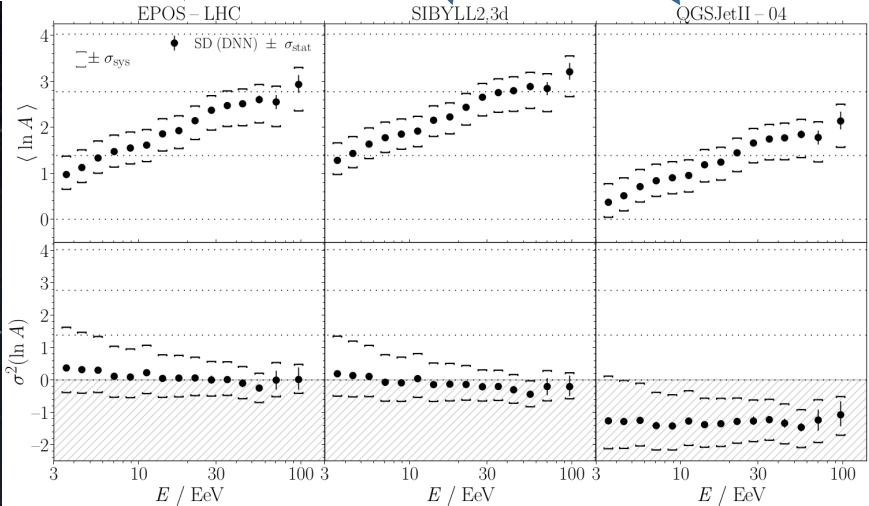
[link to the animated rotation of plots](#)

Auger DNN applied to time traces of SD signals

[Phys. Rev. D 111 (2025) 022003]



Interpretation of both X_{\max} moments depends on MC X_{\max} scale



$$\langle \ln A \rangle = \frac{\langle X_{\max} \rangle - \langle X_{\max} \rangle_p}{f_E}$$

$$\sigma_{\ln A}^2 = \frac{\sigma^2(X_{\max}) - \sigma_{\text{sh}}^2(\langle \ln A \rangle)}{b \sigma_p^2 + f_E^2}$$

[JCAP 02 (2013) 026]

Indication of too shallow MC predictions !
(Gradual increase of $\langle \ln A \rangle$ while $\sigma^2(\ln A)$ is almost constant)

Heavy-metal Scenario of UHECR

[JV, A. Bakalová, O. Tkachenko, A. L. Müller, M. Stadelmaier: *Astrophys. J. Lett.* 986 (2025) L34]

- Measured data are better described by deeper model predictions on X_{\max} (for EPOS-LHC, QGSJet II-04, Sibyll 2.3d) which implies a heavier mass composition
- How well are the cosmic-ray data at UHE described by the heaviest possible mass composition ?

Note: trans-iron nuclei not considered

Assumptions

- 1) Only freedom in model predictions is the mass- and energy-independent X_{\max} **scale**
- 2) **Pure Fe nuclei** above $10^{19.6}$ eV (beginning of flux suppression) as the heaviest nuclei

Heavy-metal Scenario: Determining the X_{\max} scale

- EPOS-LHC unphysical $\sigma^2(X_{\max})$ [PoS(ICRC2023)230] → omitted
- Use of Auger DNN data

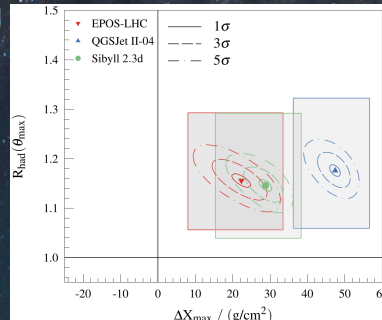
$$MC: X_{\max} \rightarrow X_{\max} + \Delta X_{\max}$$

Fitting ΔX_{\max} above $10^{19.6}$ eV to have pure Fe nuclei:

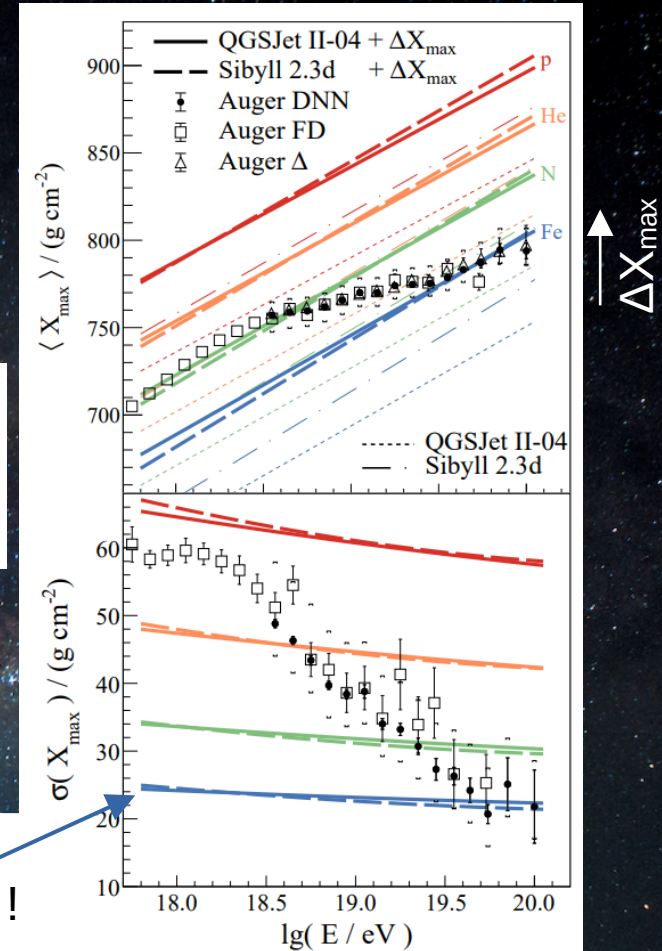
Sibyll 2.3d: $\Delta X_{\max} = 29 \pm 1_{-7}^{+12}$ g/cm²
 QGSJet II-04: $\Delta X_{\max} = 52 \pm 1_{-8}^{+11}$ g/cm²

Consistent with ΔX_{\max} from $[X_{\max}, S(1000)]$ fits at 3-10 EeV

[Phys. Rev. D 109 (2024) 102001]

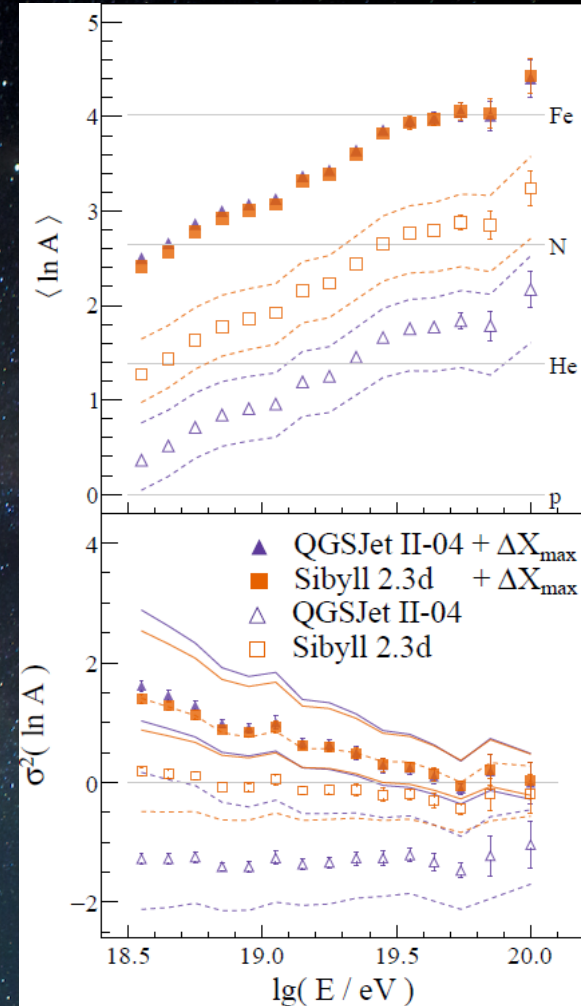
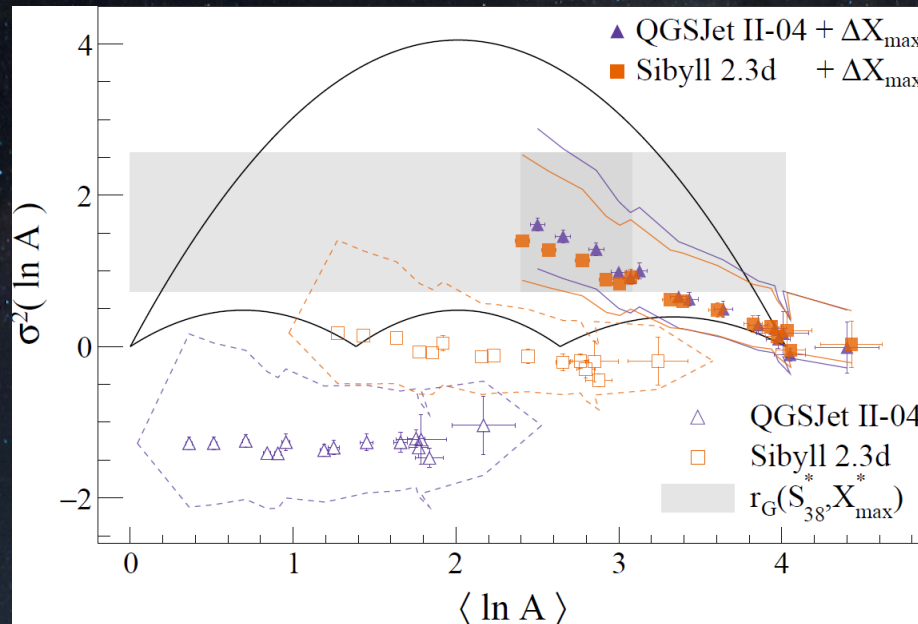


Very universal !



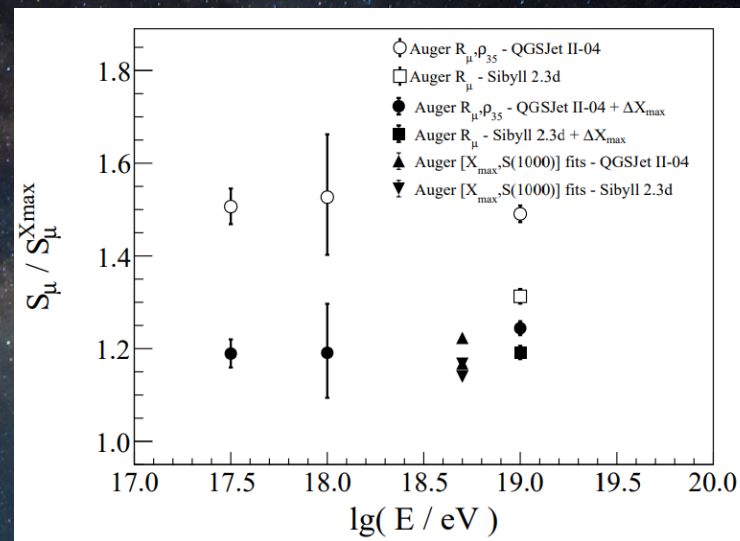
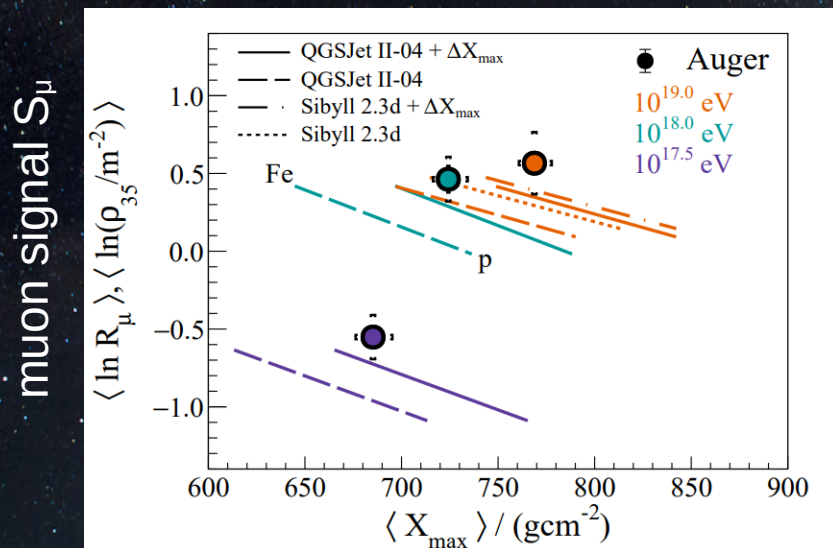
Heavy-metal Scenario: In A moments within "umbrella"

- X_{\max} moments from Auger DNN
- In A moments within the allowed region of the umbrella plot
- $\sigma^2(\ln A)$ consistent with results from correlation coefficient r_G of X_{\max} and ground signal in 3-10 EeV [Phys. Lett. B 762 (2016) 288]



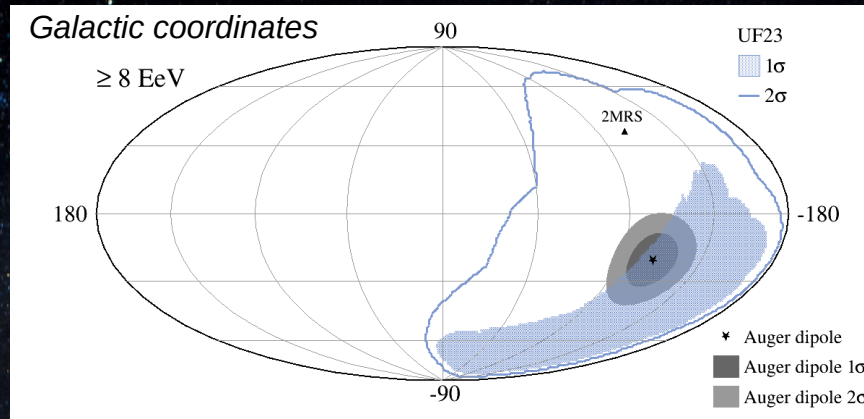
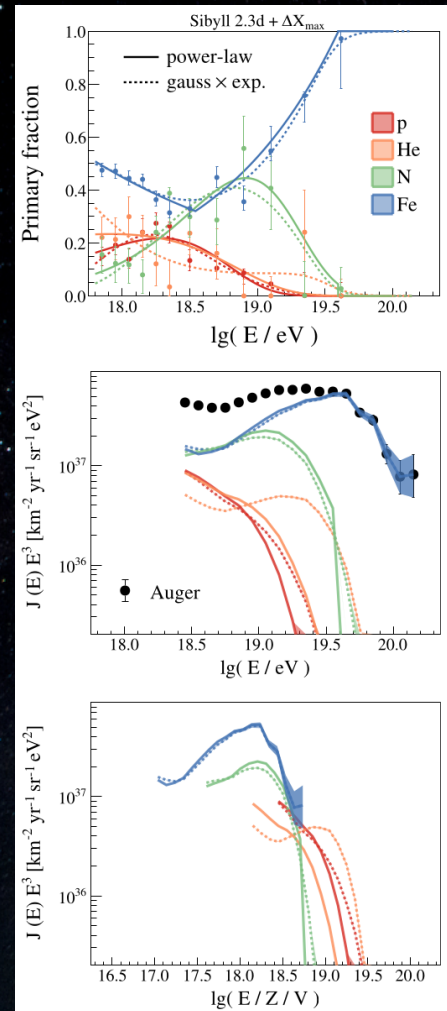
Heavy-metal Scenario: Alleviation of the muon problem

- Heavier mass composition means more predicted muons
- The muon problem is reduced by approximately half, without an indication of a zenith or an energy dependence

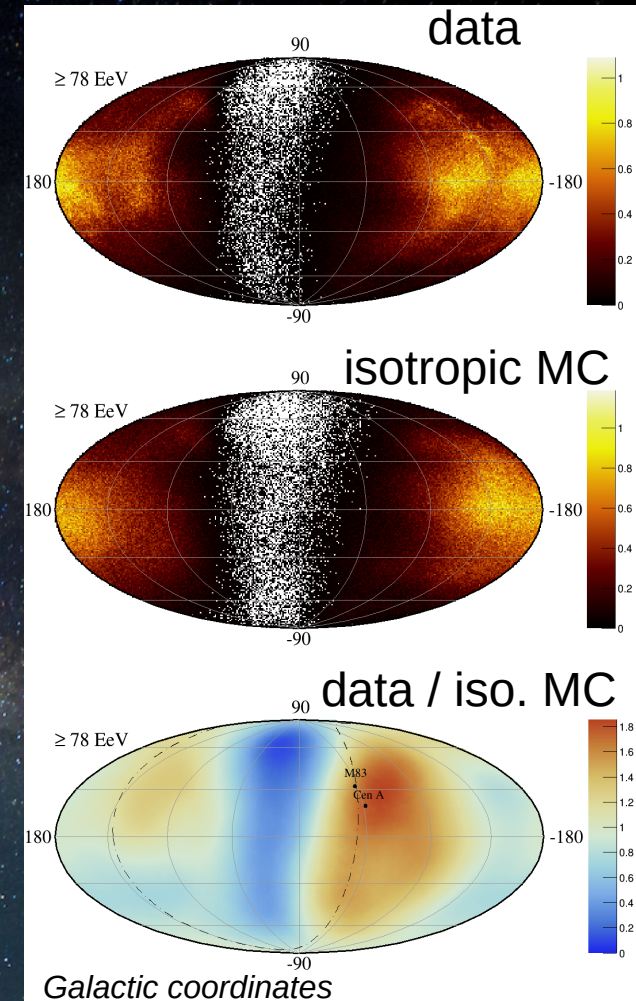


Heavy-metal Scenario: Astrophysical Consequences

Backtracking

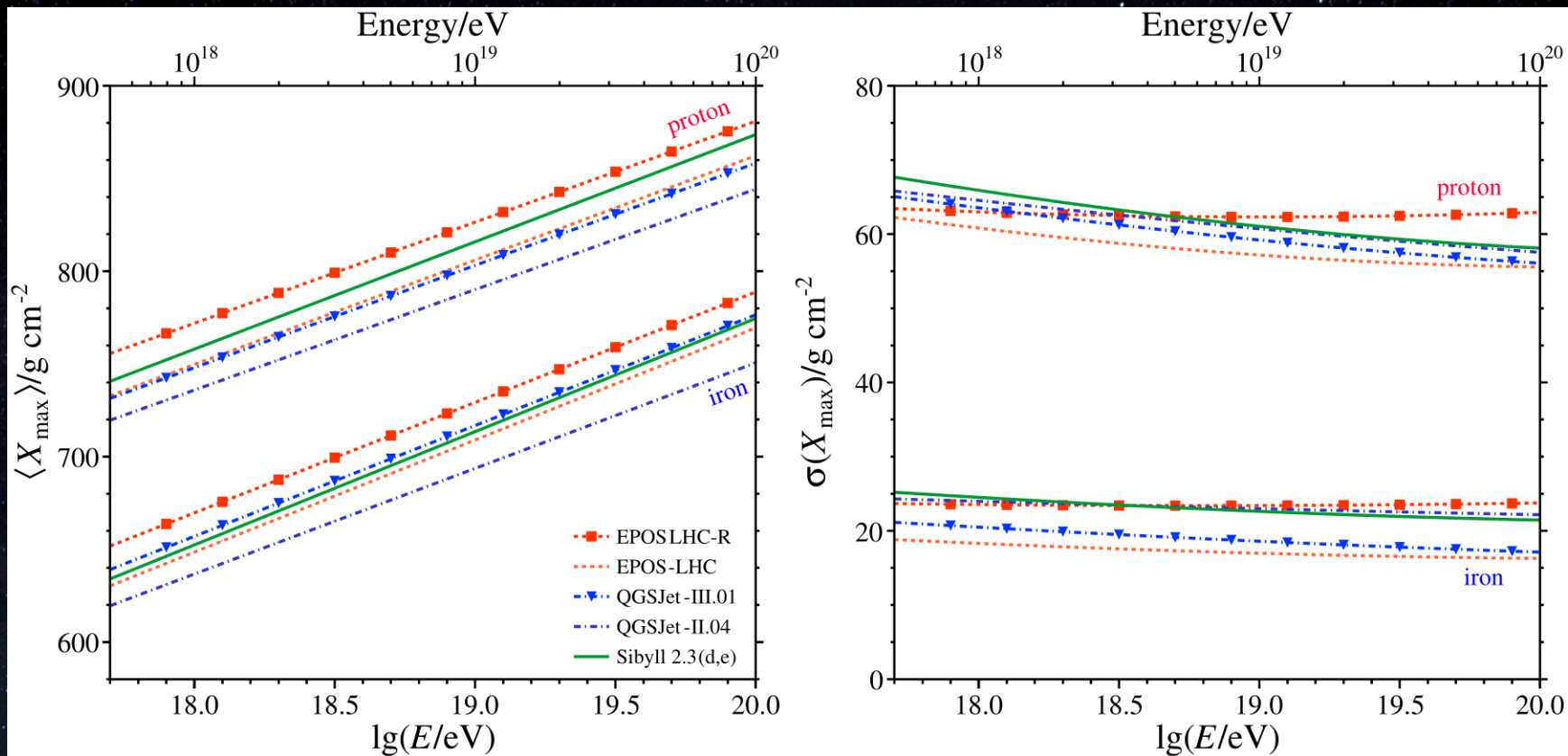


- Instep feature (~ 15 EeV) caused by fading of N nuclei
- N and Fe nuclei might originate from sources with the same rigidity cutoff (~ 2 EV)
- Dipolar distribution of arrival directions above 8 EeV and also the arrival directions of the highest-energy particles explainable



New models: Mean and std. dev. of X_{\max} distributions

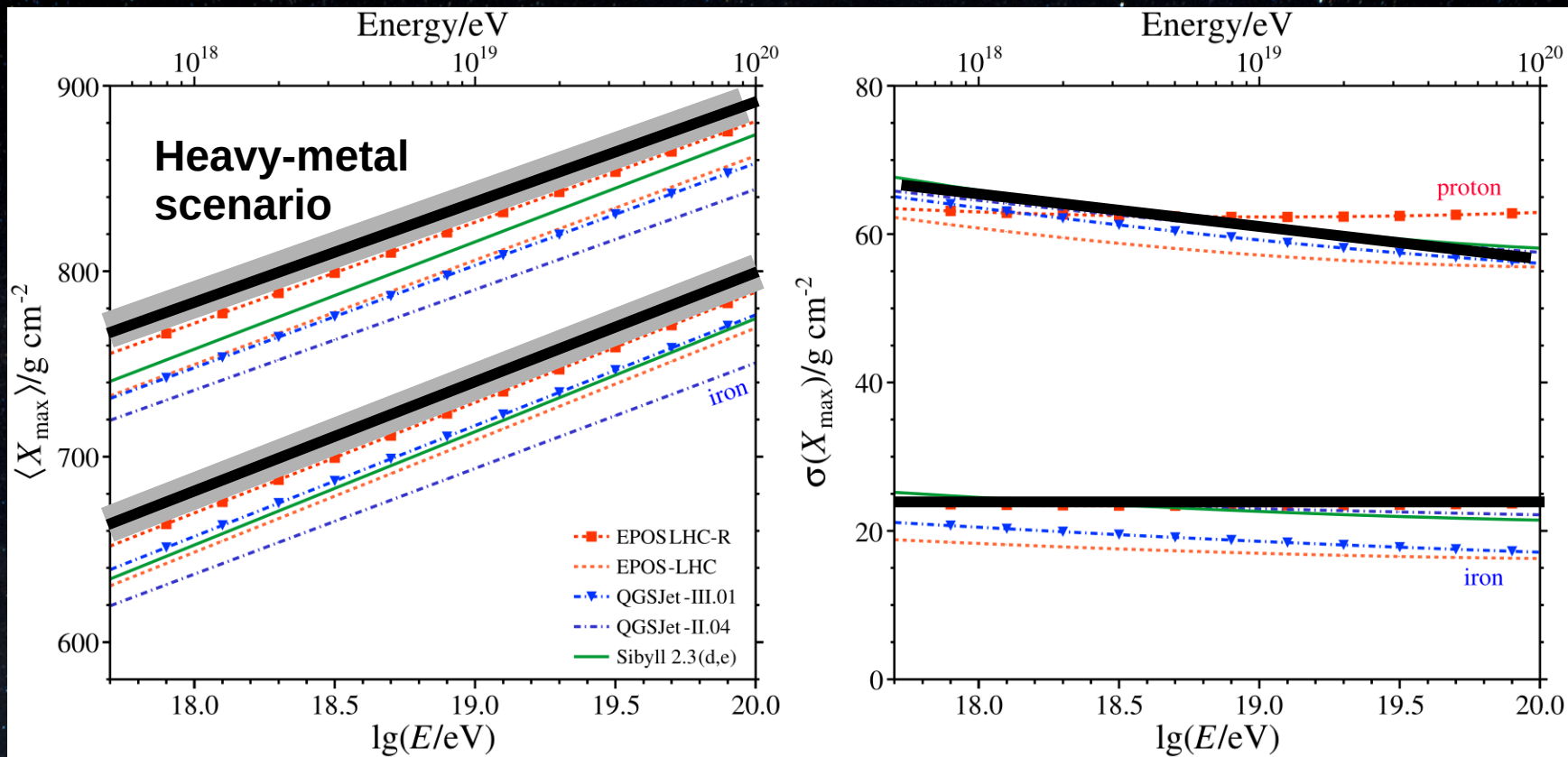
[Pos(ICRC2025)442]



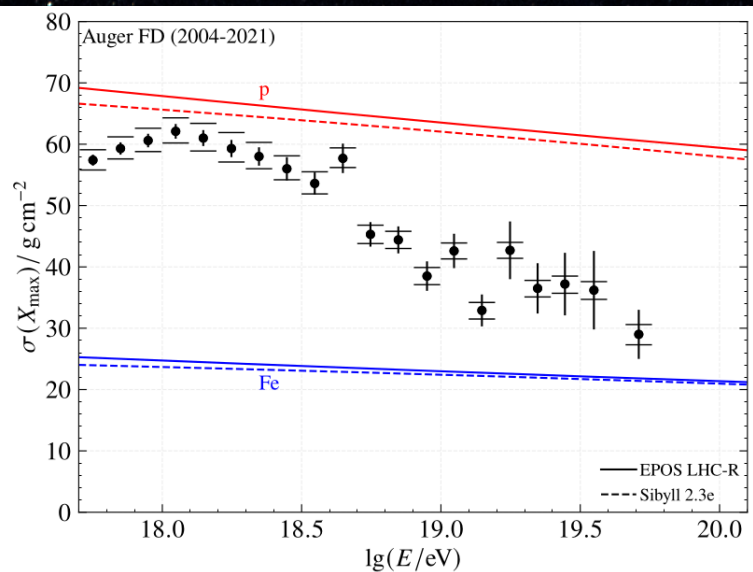
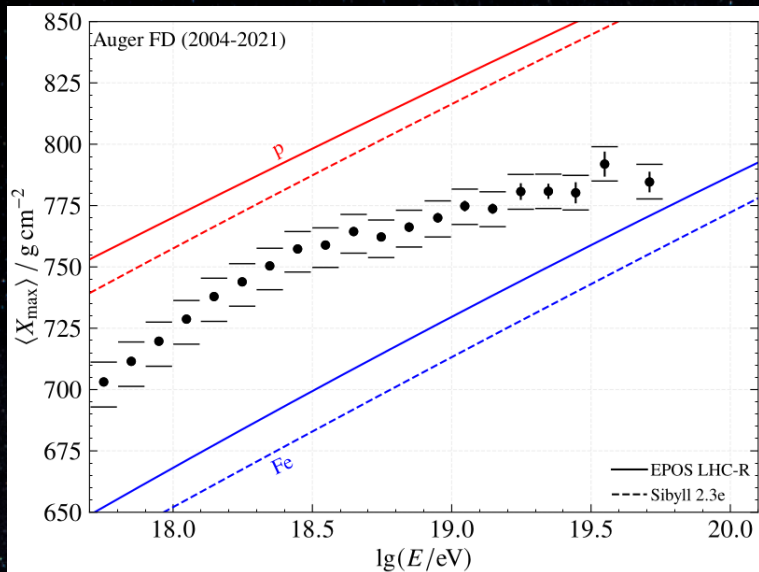
EPOS and QGSJet got deeper by $\sim 25 \text{ g/cm}^2$ in X_{\max} predictions
QGSJet predicts unphysical X_{\max} fluctuations for Fe nuclei (as old EPOS)

New models: Mean and std. dev. of X_{\max} distributions

[Pos(ICRC2025)442]

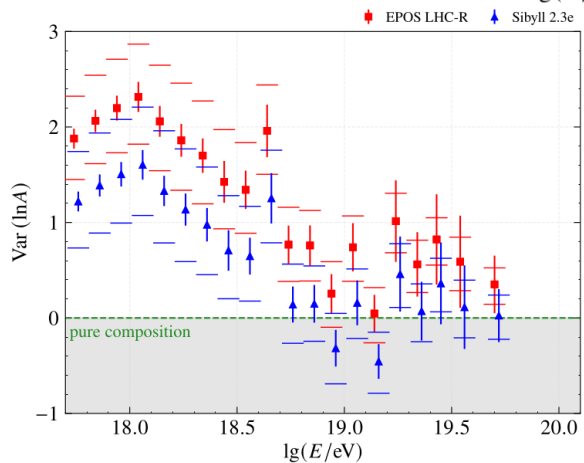
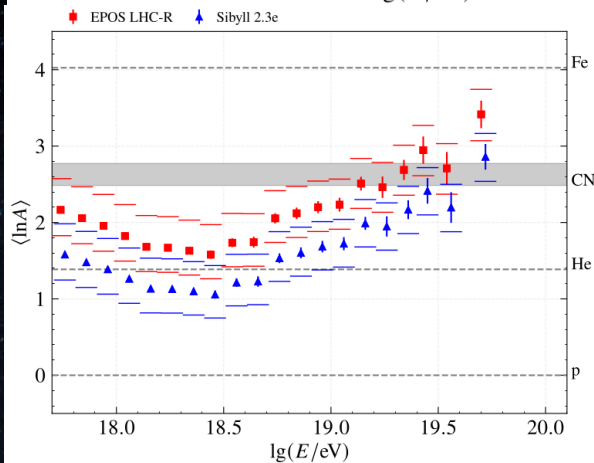


New models and new data



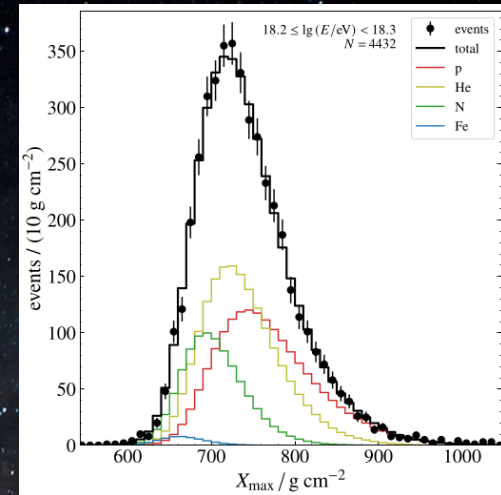
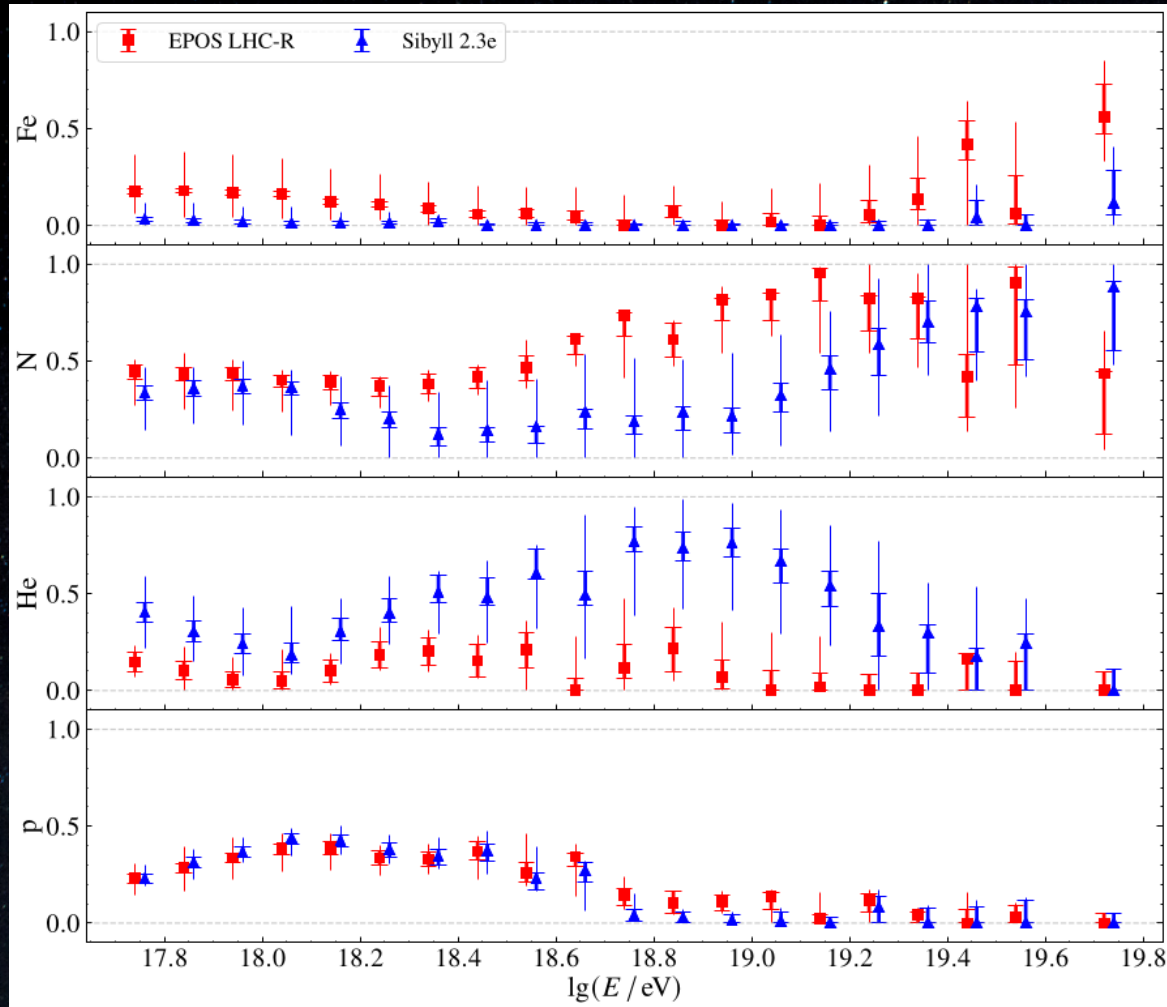
New FD data !
submitted to PRD

[arXiv:2605.12598]



Interpreted mass composition got
heavier, but larger differences
between models occurred

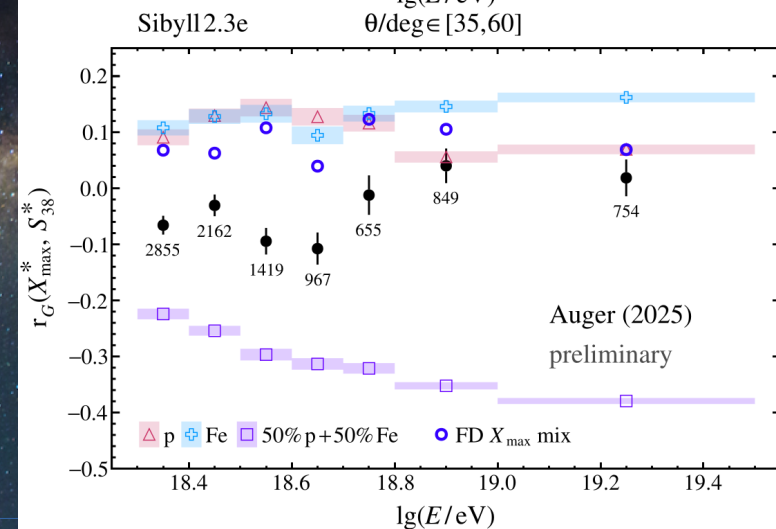
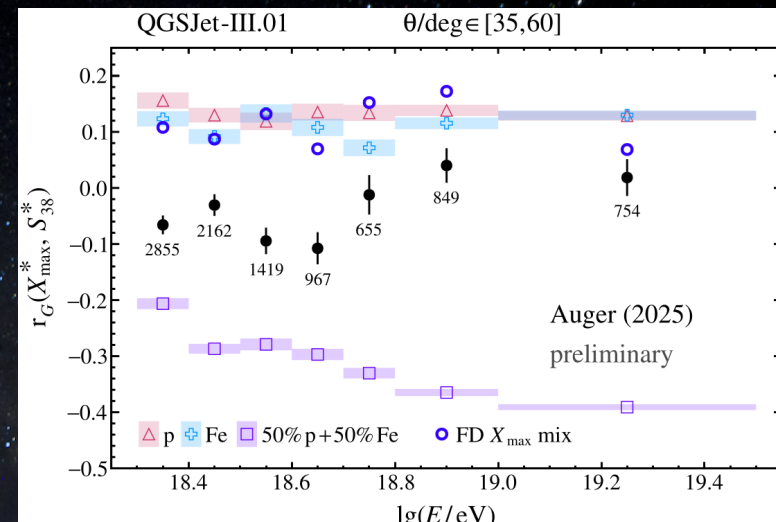
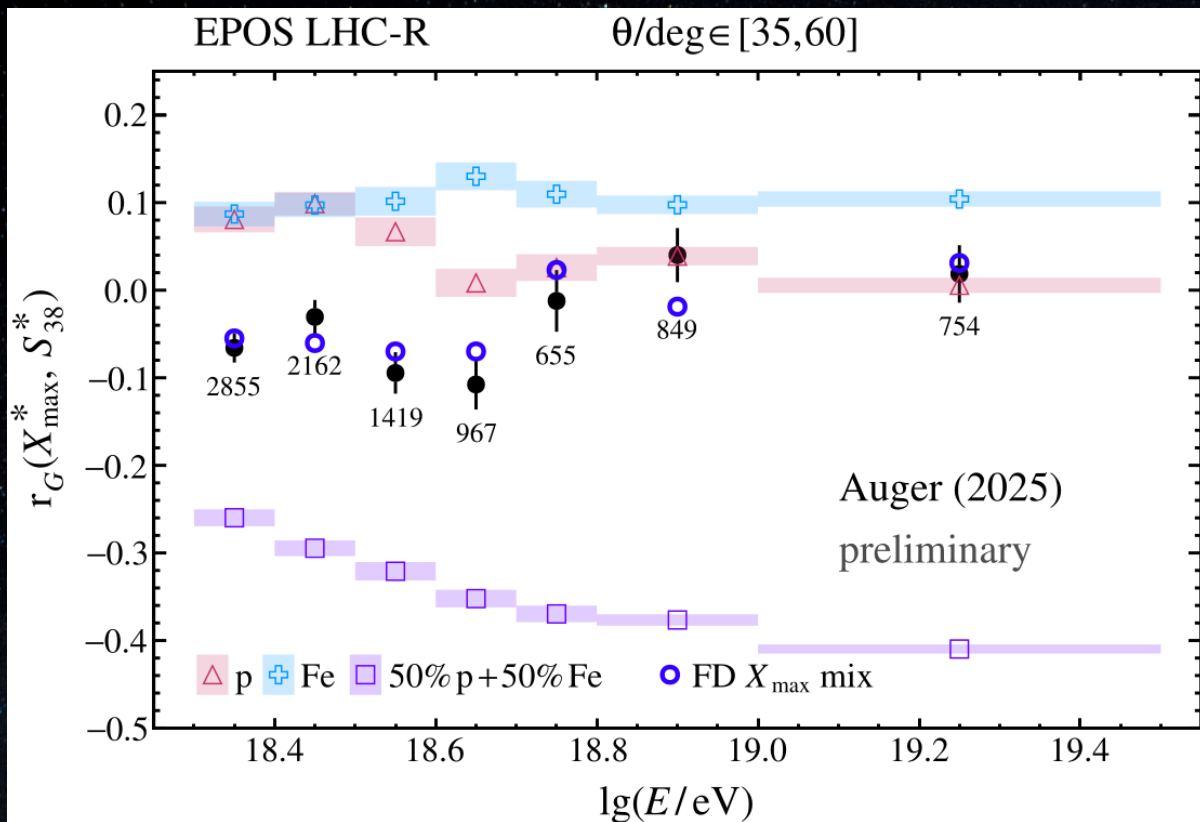
New models: primary fraction fits to X_{\max} distributions



Interpreted mass composition got heavier, but larger differences between models occurred.

New models: correlation between ground signal and X_{\max}

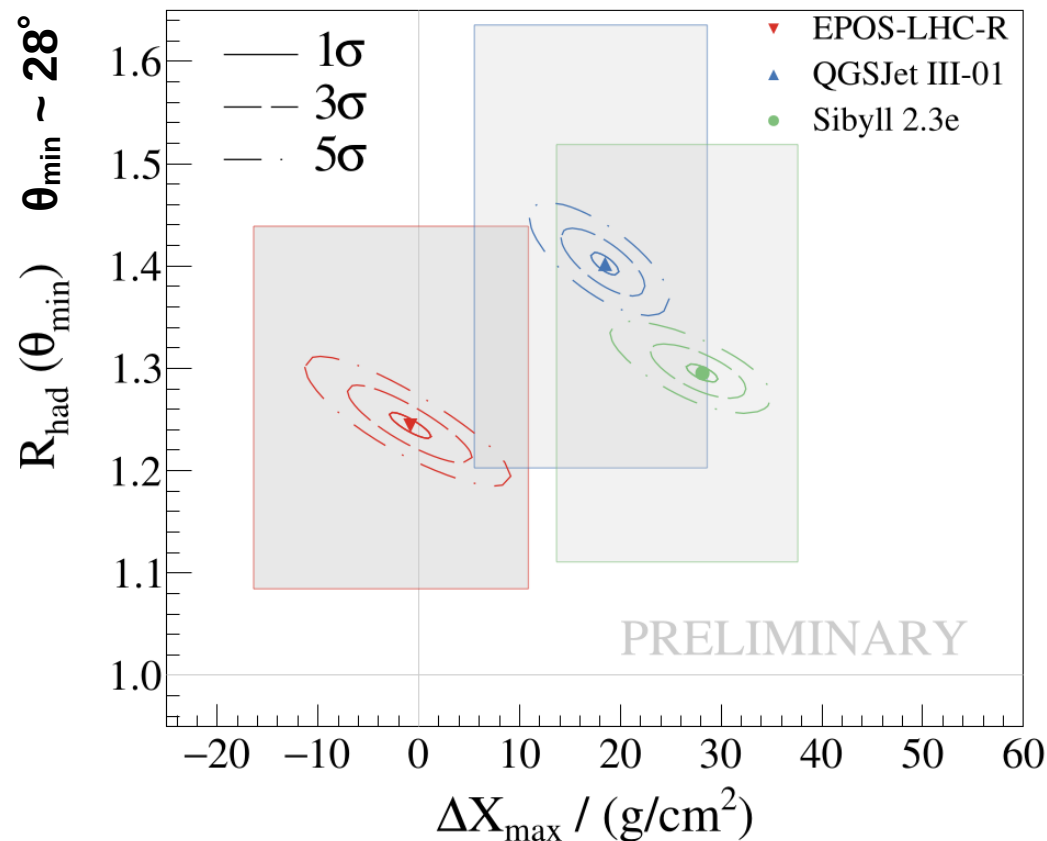
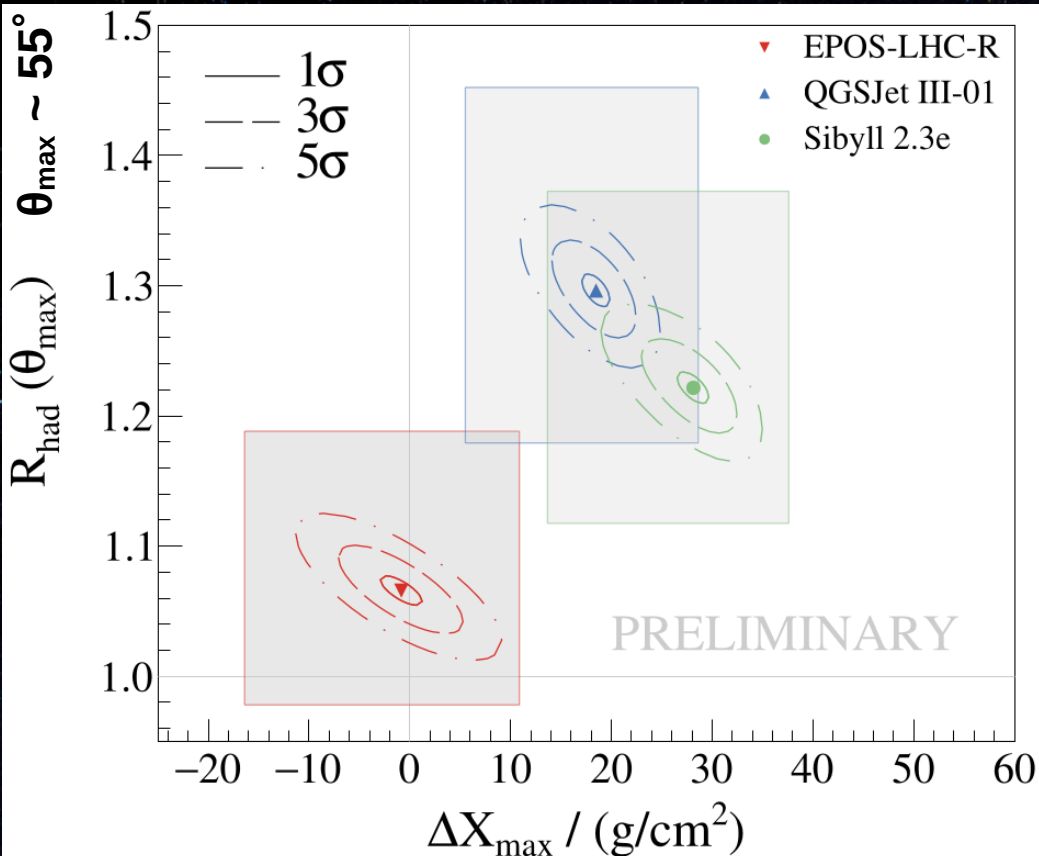
A. Yushkov for Pierre Auger Coll. [Pos(ICRC2025)442]



Mixing predicted by EPOS consistent with data

New models: $[X_{\max}, S1000](\theta)$ fits

[JV for Pierre Auger Coll., PoS(ICRC2025)431]



EPOS-LHC-R predicts consistent X_{max} scale, but there is tension in muon attenuation with θ

Summary

- Air-shower modelling is crucial to interpret the mass composition, which is the key to understand the origin of UHECR
- Tests of hadronic-interaction model predictions using air-shower data have revealed **problems both in N_μ and X_{\max}**
- The recent developments in hadronic interaction models decreased some of the tension, but discrepancies remain, yet **mass composition is interpreted heavier than before**
- Considering the freedom in X_{\max} scale and the heaviest possible mass composition, the **Heavy-metal scenario is a viable UHECR possibility** given the current Pierre Auger Observatory data, though astronomically unpleasant
- What could help in near future:
 - ▶ p-O collisions at LHC last year - first results from ATLAS [arXiv:2604.05512], LHCf this Summer ?
 - ▶ data from upgraded AugerPrime and TA x 4
- We should be open also to new theories like ultra-heavy nuclei from binary neutron star mergers (transients !) - see Division Seminar of Glennys Farrar, June 15th, 10 a.m.



PIERRE
AUGER
OBSERVATORY

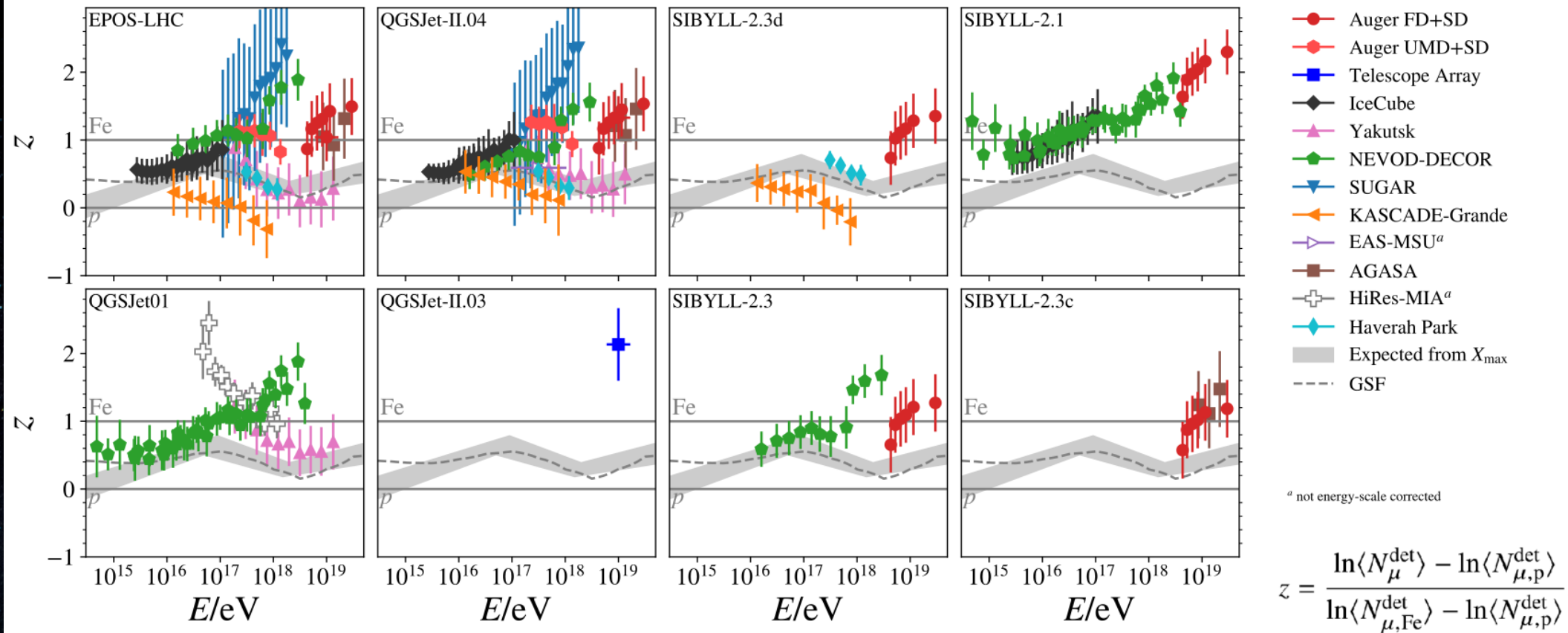
Thank you for your attention!



Backup slides

Muon content observed by multiple experiments

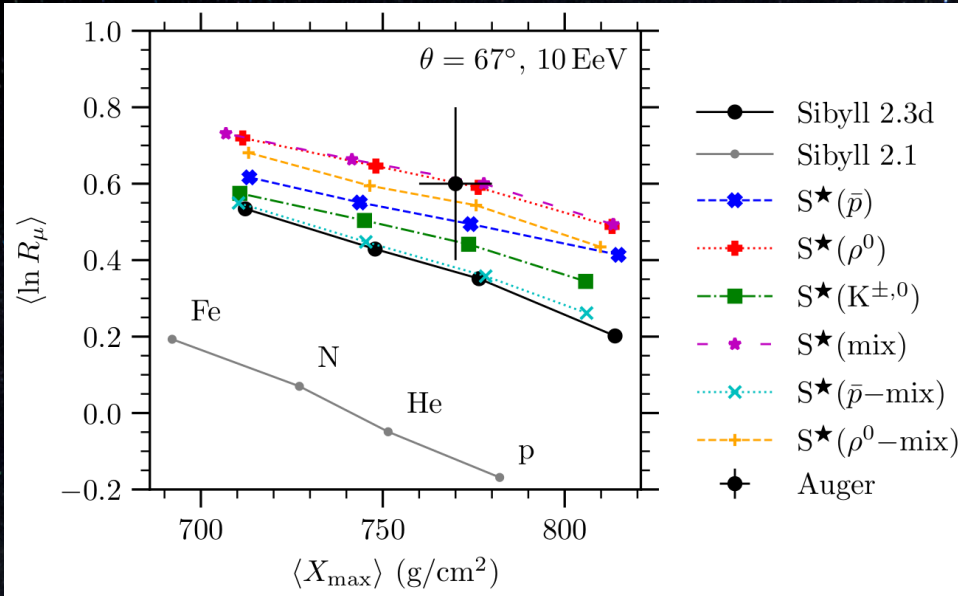
[Astrophysics and Space Science 367 (2022) 27]



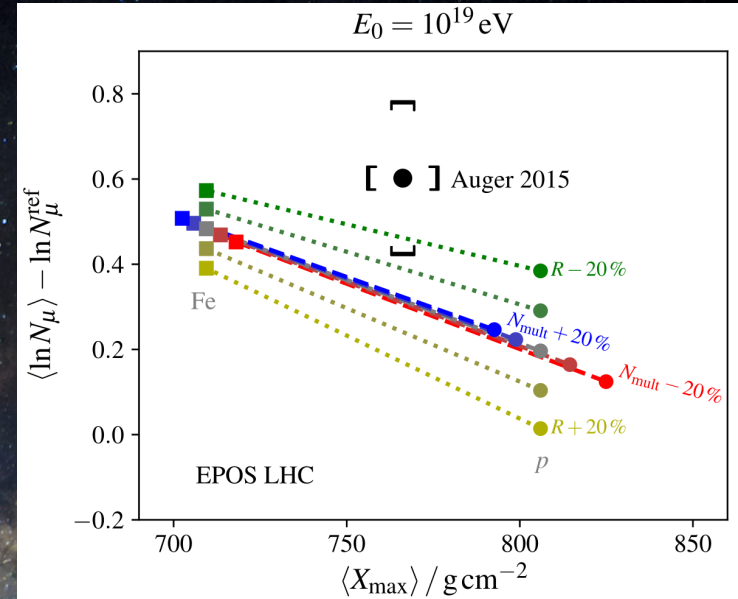
No clear observation of energy dependence of the muon deficit in simulations

Models enhancing the muons

[PoS(ICRC2023)429]



[PRD 107 (2023) 094031]



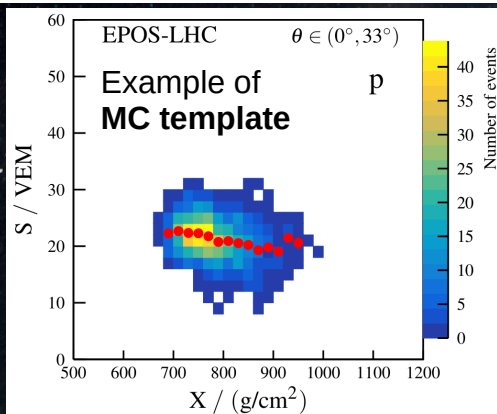
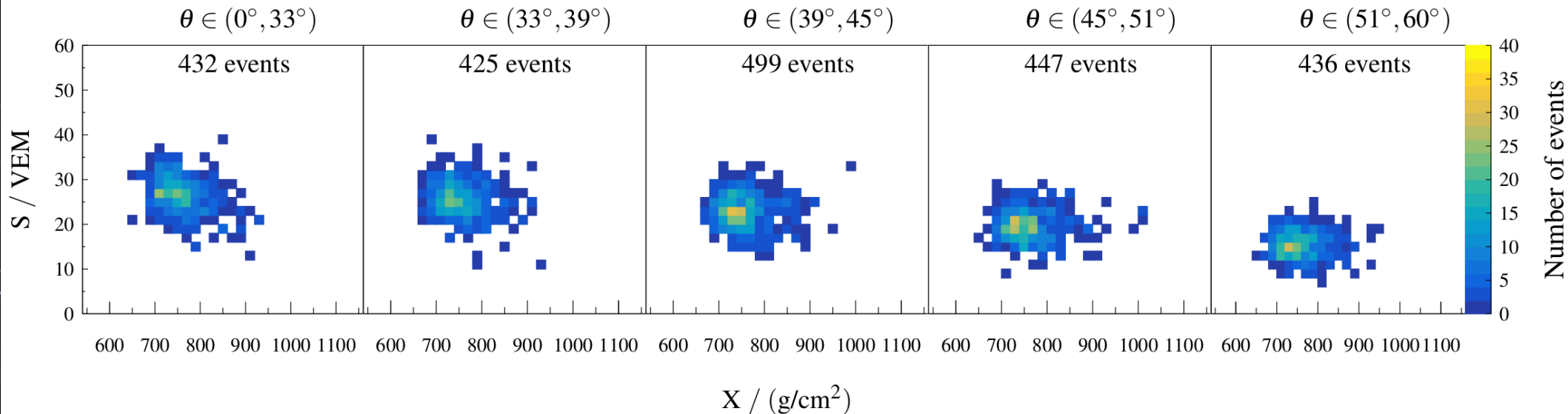
Predicted X_{\max} scale ~untouched !

Auger data: 2239 events
for $10^{18.5-19.0}$ eV

Method

$$S = S(1000) \left(\frac{E^{\text{ref}}}{E_{\text{FD}}} \right)^{1/B}$$

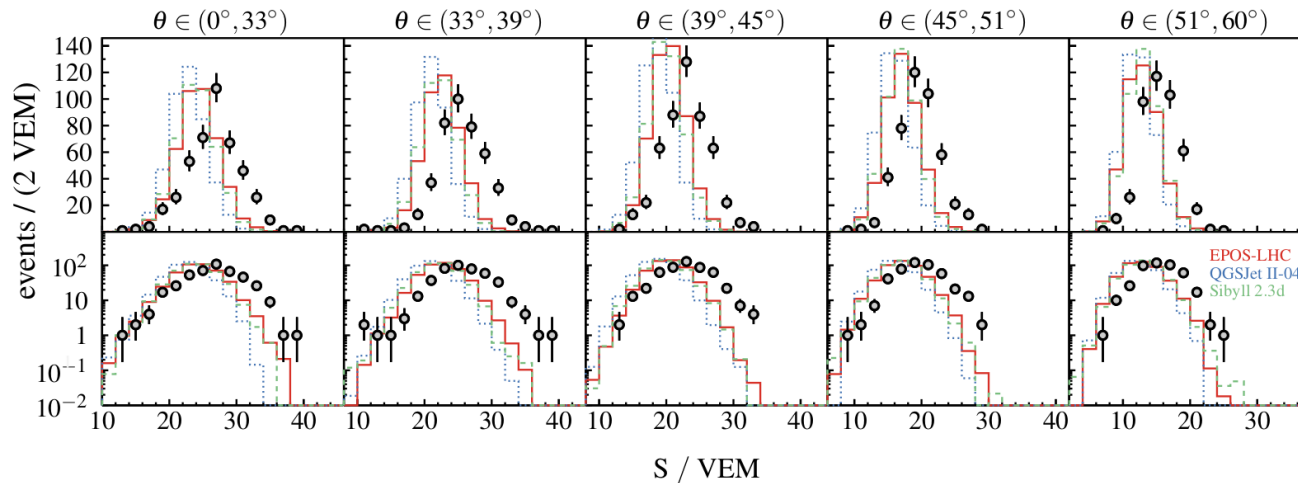
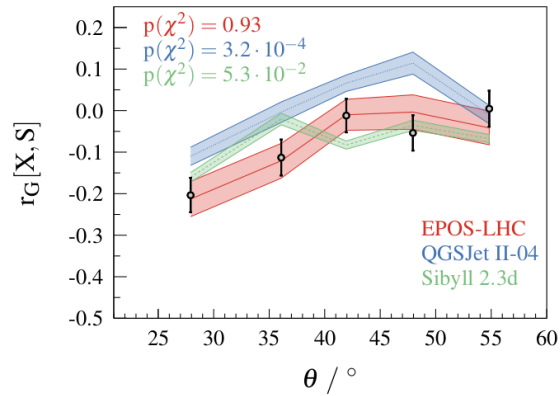
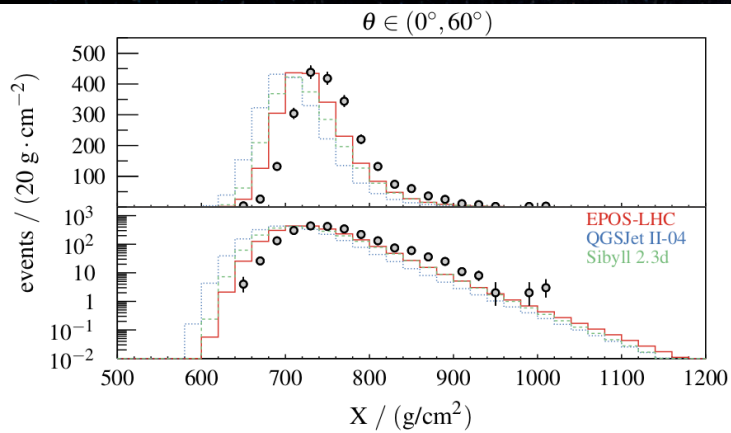
$$X = X_{\text{max}} + D \lg \left(\frac{E^{\text{ref}}}{E_{\text{FD}}} \right)$$



- **Freedom** in X_{max} (ΔX_{max}) and $S(1000)$ ($R_{\text{had}}(\theta)$) and **primary fractions**
- Change of S_{had} and S_{em} due to ΔX_{max} incorporated

Simultaneous log-likelihood ratio fit of **two-dimensional distributions** of X_{max} and $S(1000)$ in 5 zenith-angle bins with **MC templates** for combinations of four primary nuclei (p, He, O, Fe)

Improvement of data description



MC prediction

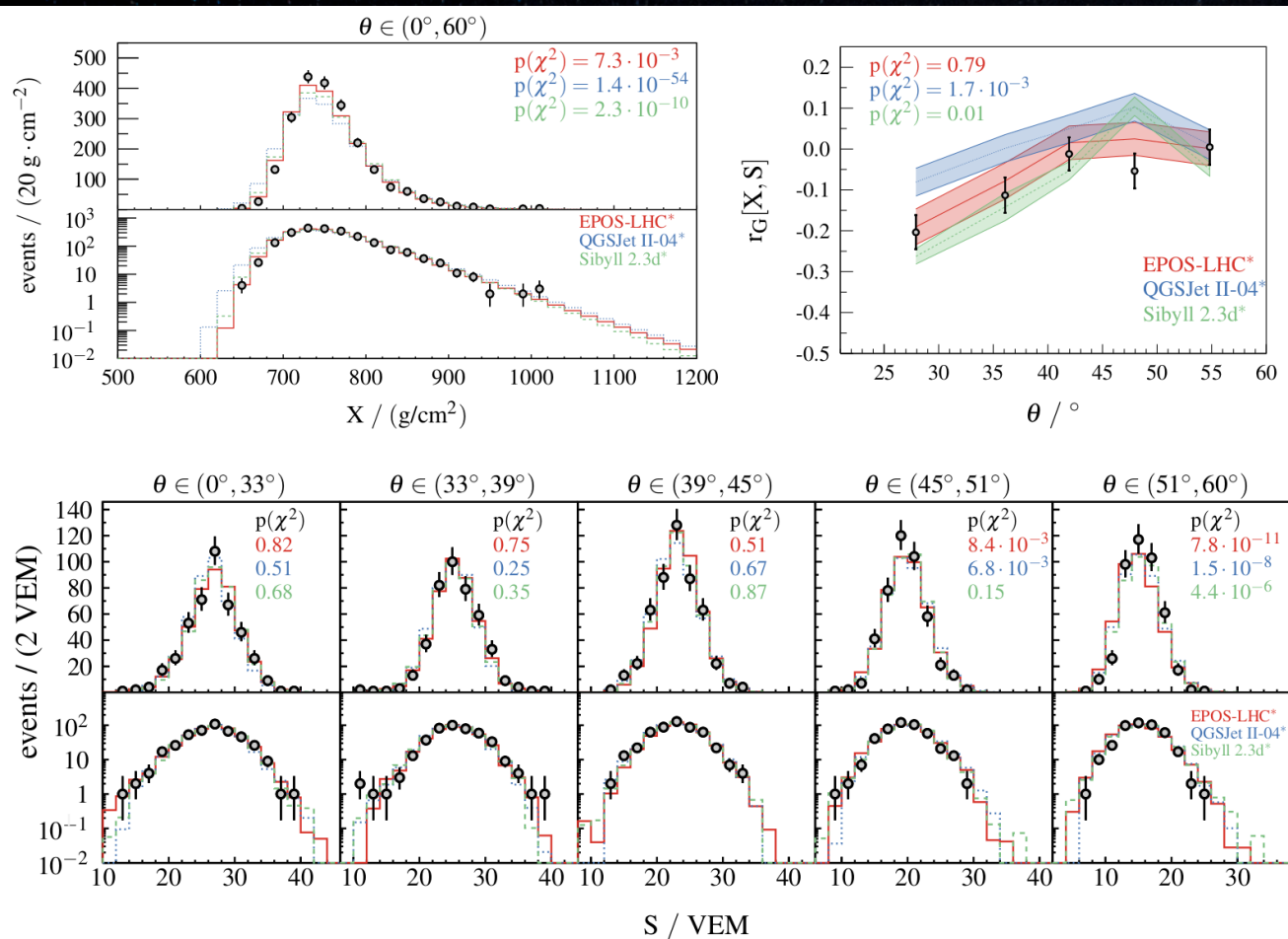
θ bins
2D bins

Measured number of showers

$$\ln \mathcal{L} = \begin{cases} \sum_k \sum_j (C_{jk} - n_{jk} + n_{jk} \ln \frac{n_{jk}}{C_{jk}}), & n_{jk} > 0 \\ \sum_k \sum_j C_{jk}, & n_{jk} = 0 \end{cases}$$

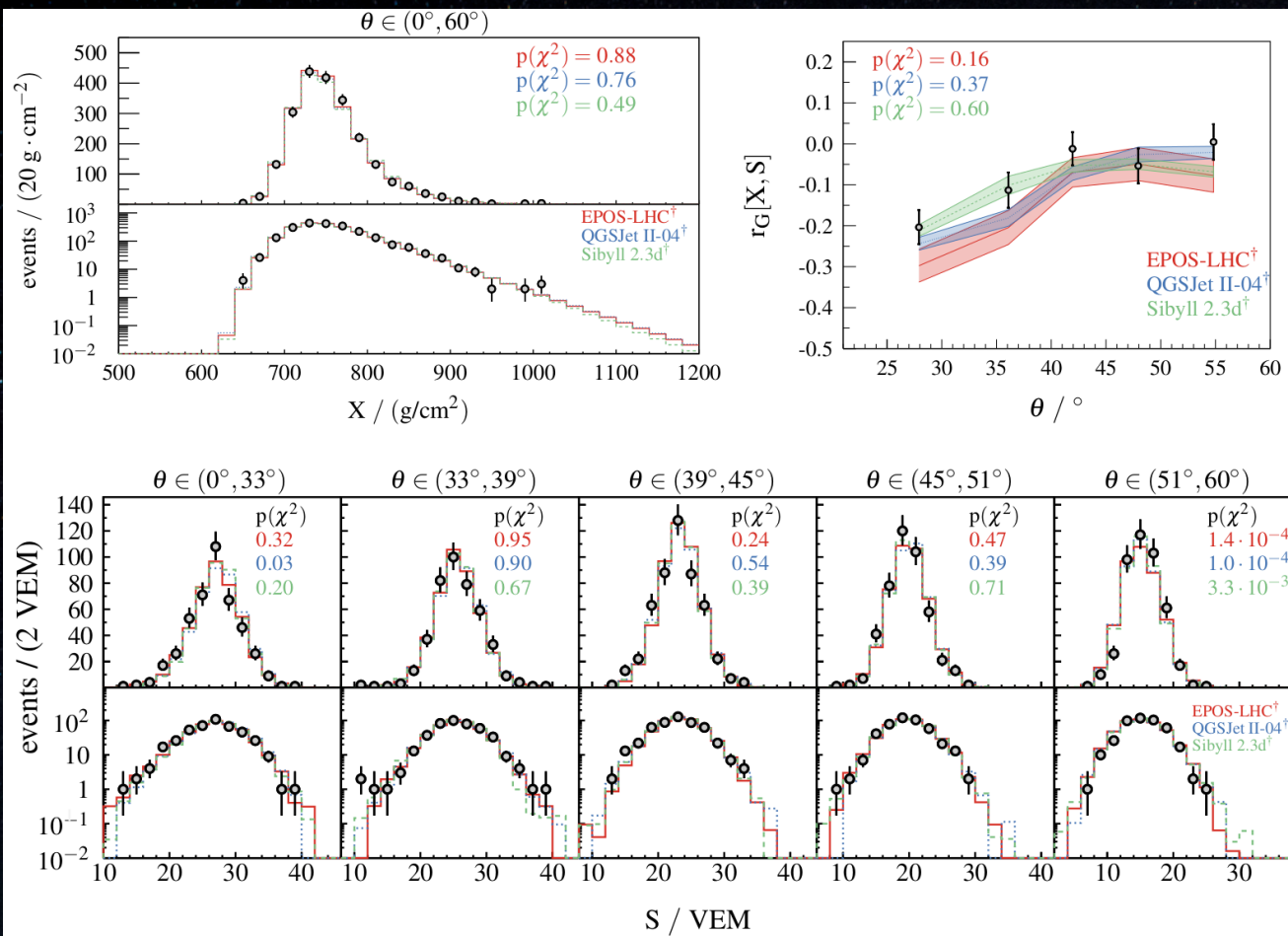
$\ln \mathcal{L}_{\min}$	EPOS-LHC	QGSJET-II-04	SIBYLL 2.3d
none	2022.9	4508.0	2496.5
ΔX_{\max}	738.6	1674.8	1015.7
$R_{\text{had}} = \text{const.}$	489.2	684.4	521.6
$R_{\text{had}}(\theta)$	489.2	673.9	517.6
$R_{\text{had}} = \text{const. and } \Delta X_{\max}$	452.2	486.7	454.2
$R_{\text{had}}(\theta) \text{ and } \Delta X_{\max}$	451.9	476.3	451.6

Improvement of data description



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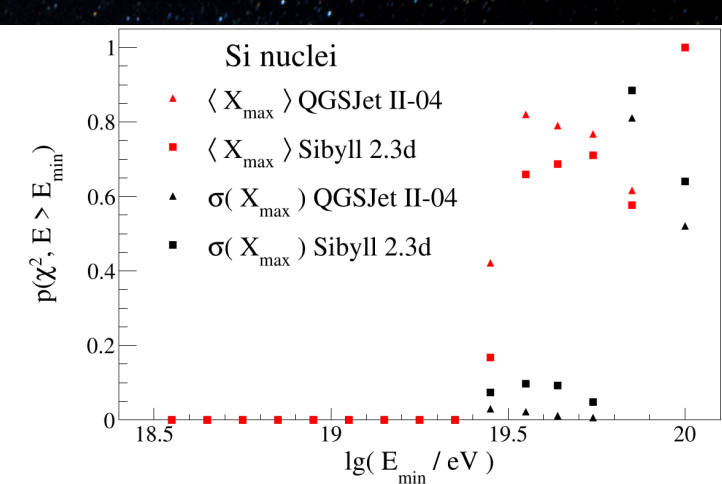
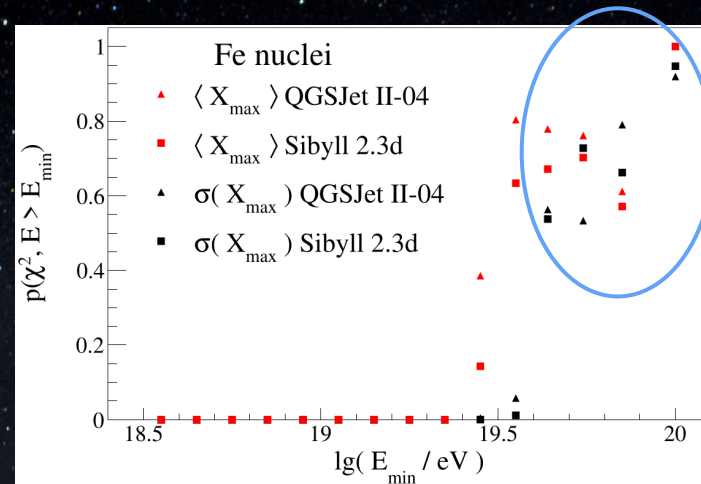
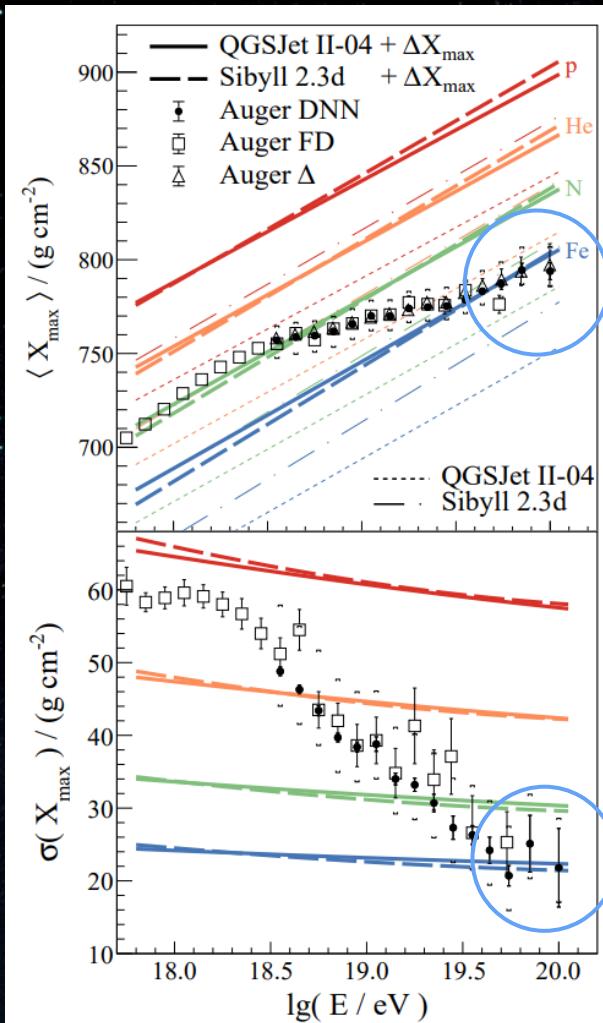
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$R_{\text{had}}(\theta)$ and ΔX_{\max}	451.9	476.3	451.6

Significant improvement $> 5\sigma$
using both (!) R_{had} and ΔX_{\max}

Heavy-metal Scenario: why pure Fe beam above $10^{19.6}$ eV ?



Caveat: sys. uncert. not considered

- $d \langle X_{\max} \rangle / d (\lg E)$ and $\sigma(X_{\max})$ of single primary species are very universal quantities
- for Fe nuclei: data above $10^{19.6}$ eV are fully consistent with a pure beam

Heavy-metal Scenario: Fairly described tail of X_{\max}

- Good description of the X_{\max} distributions from Auger FD measurement [Phys. Rev. D 90 (2014) 122005]

- Compared to slope of the X_{\max} tail

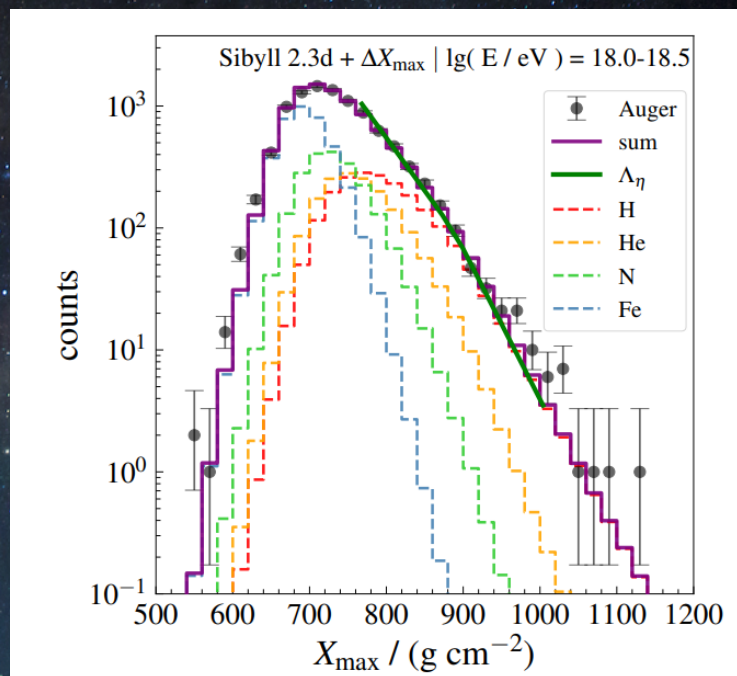
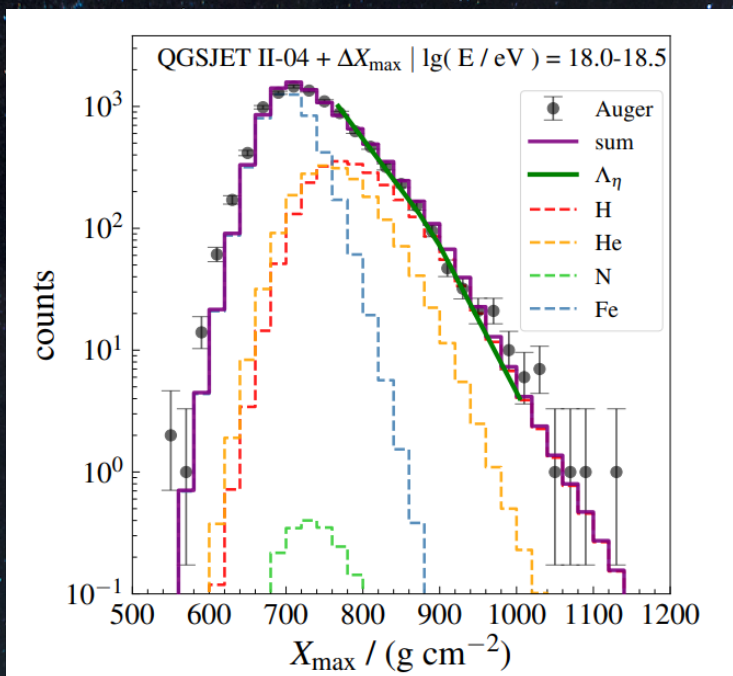
$$\Lambda_{\eta} = 55.8 \pm 2.3 \text{ (stat.)} \pm 1.6 \text{ (sys.) g cm}^{-2} \text{ from [Phys. Rev. Lett. 109 (2012) 062002]}$$

$$\text{QGSJet II-04} + \Delta X_{\max} : \Lambda_{\eta} = 51.9 \pm 0.4 \text{ g cm}^{-2}$$

$$\text{Sibyll 2.3d} + \Delta X_{\max} : \Lambda_{\eta} = 50.0 \pm 0.4 \text{ g cm}^{-2}$$

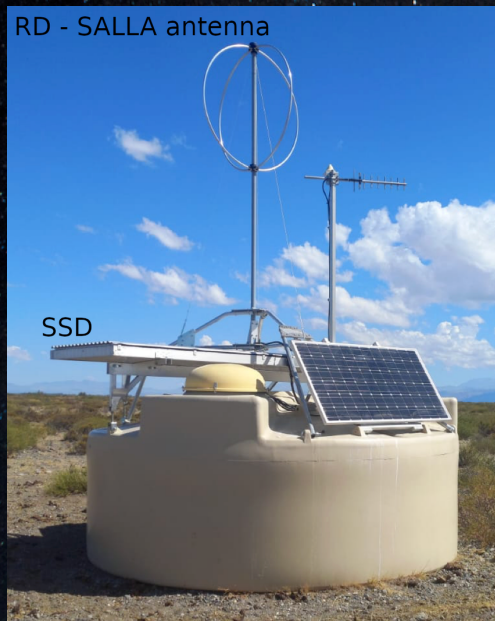
Higher Λ_{η} might be obtained by:

- Lower fraction of He nuclei
- Smaller p-p inelastic cross section in models
- Higher elasticity in models

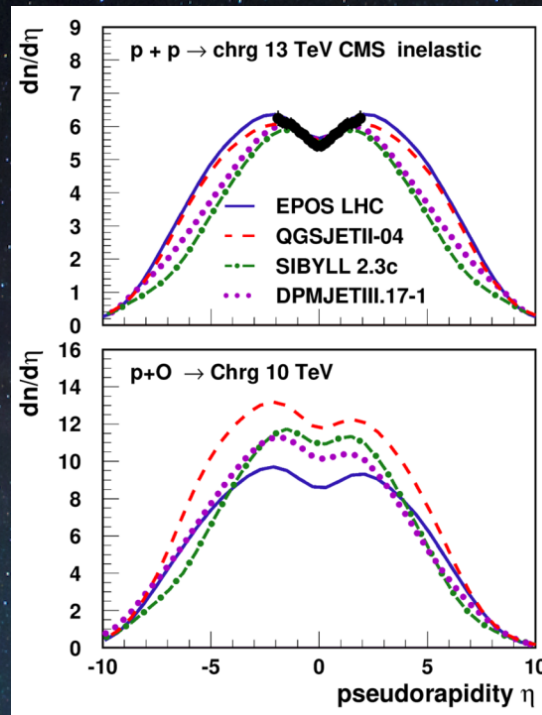


What could help

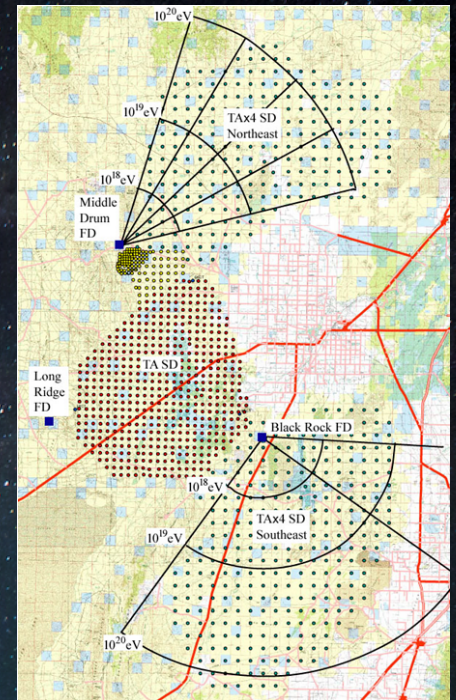
AugerPrime:
improvement of
primary mass
identification



Updates of models of hadronic interactions and their tuning to new LHC data (p+O collisions in 2025)

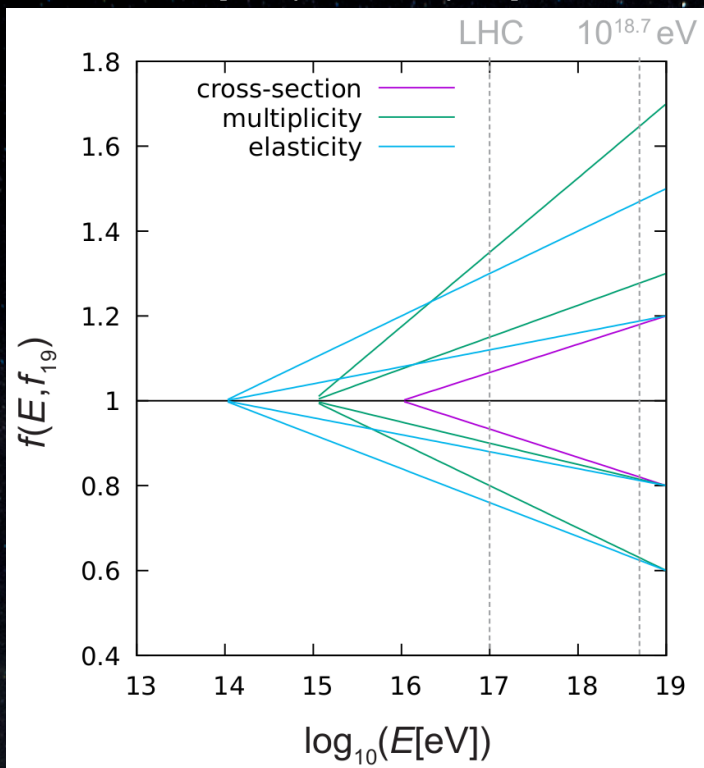


TA x 4:
increase of statistic

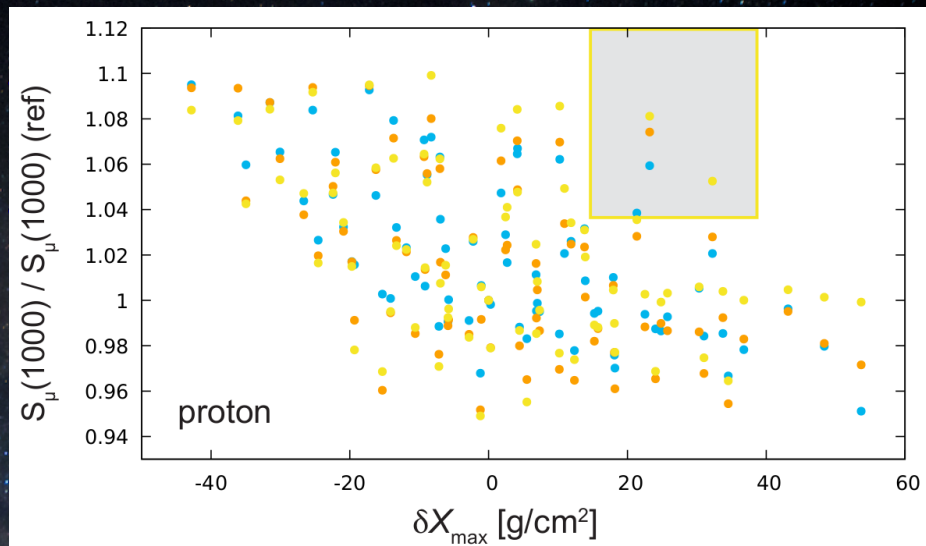


What could also help: Phenomenology studies

[PoS(ICRC2021)310]



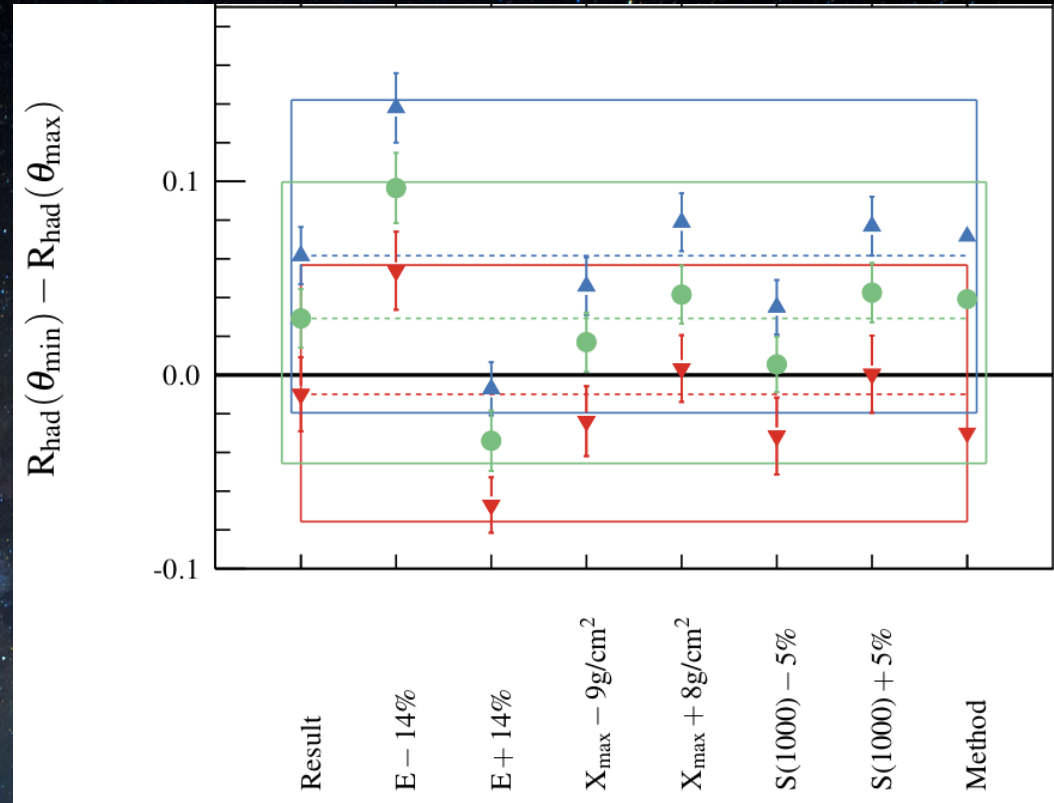
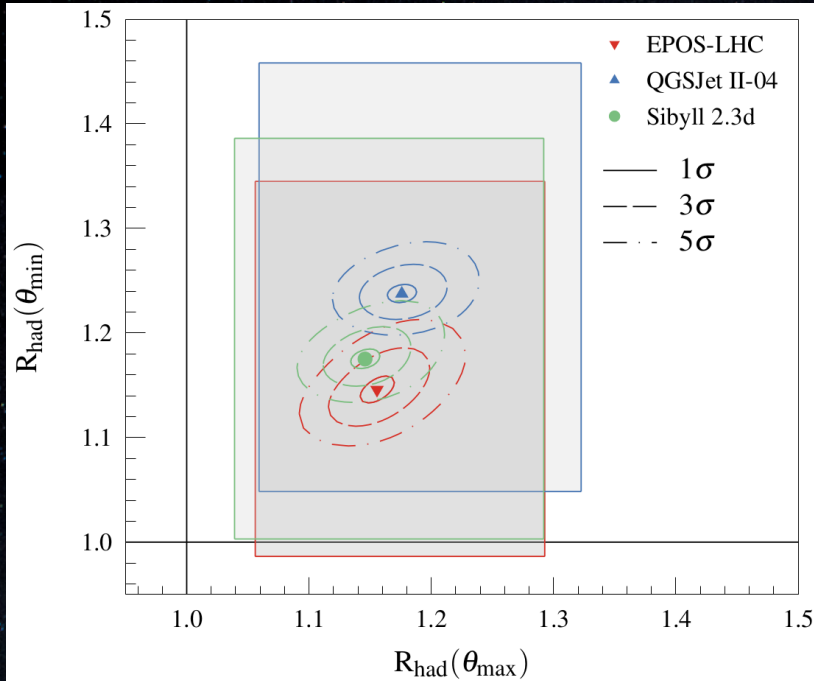
Combinations of ad-hoc modifications of cross-section, elasticity and multiplicity of interactions



$$f(E, f_{19}) = 1 + (f_{19} - 1) \cdot \frac{\log_{10}(E/E_{\text{thr}})}{\log_{10}(10 \text{ EeV}/E_{\text{thr}})}$$

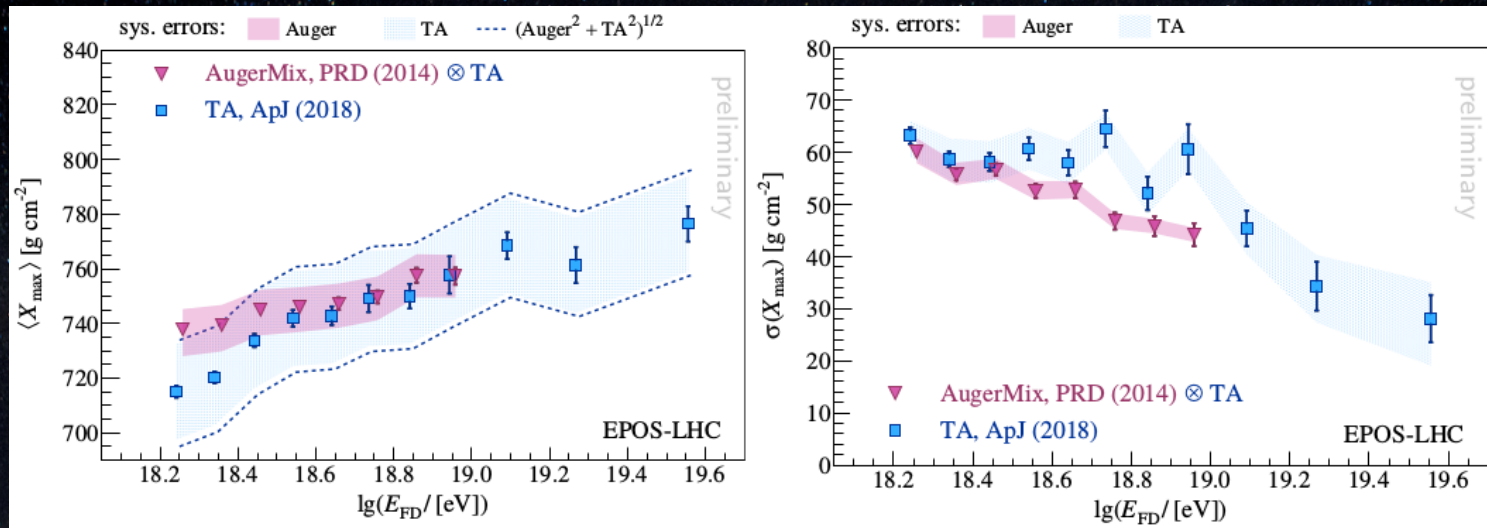
Difficult with modifications of “macro” parameters... We need to go to “micro” parameters like energy spectra and production rates of secondary particles

Attenuation of hadronic signal



Indication of harder muon spectra in QGSJet II-04 than in data

Auger vs. TA: X_{\max}



Auger and TA measurements of X_{\max} are compatible