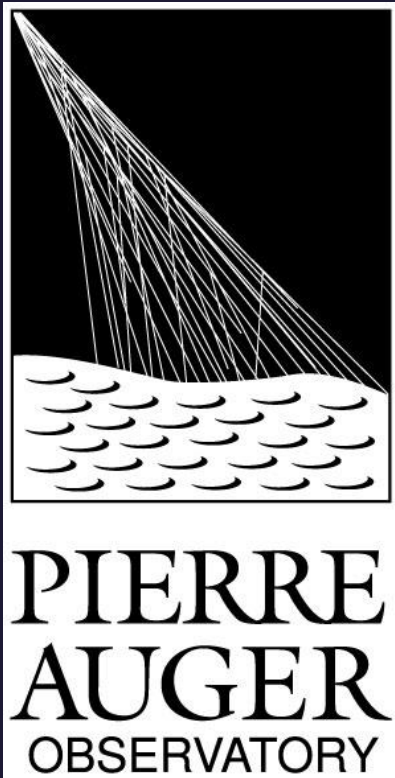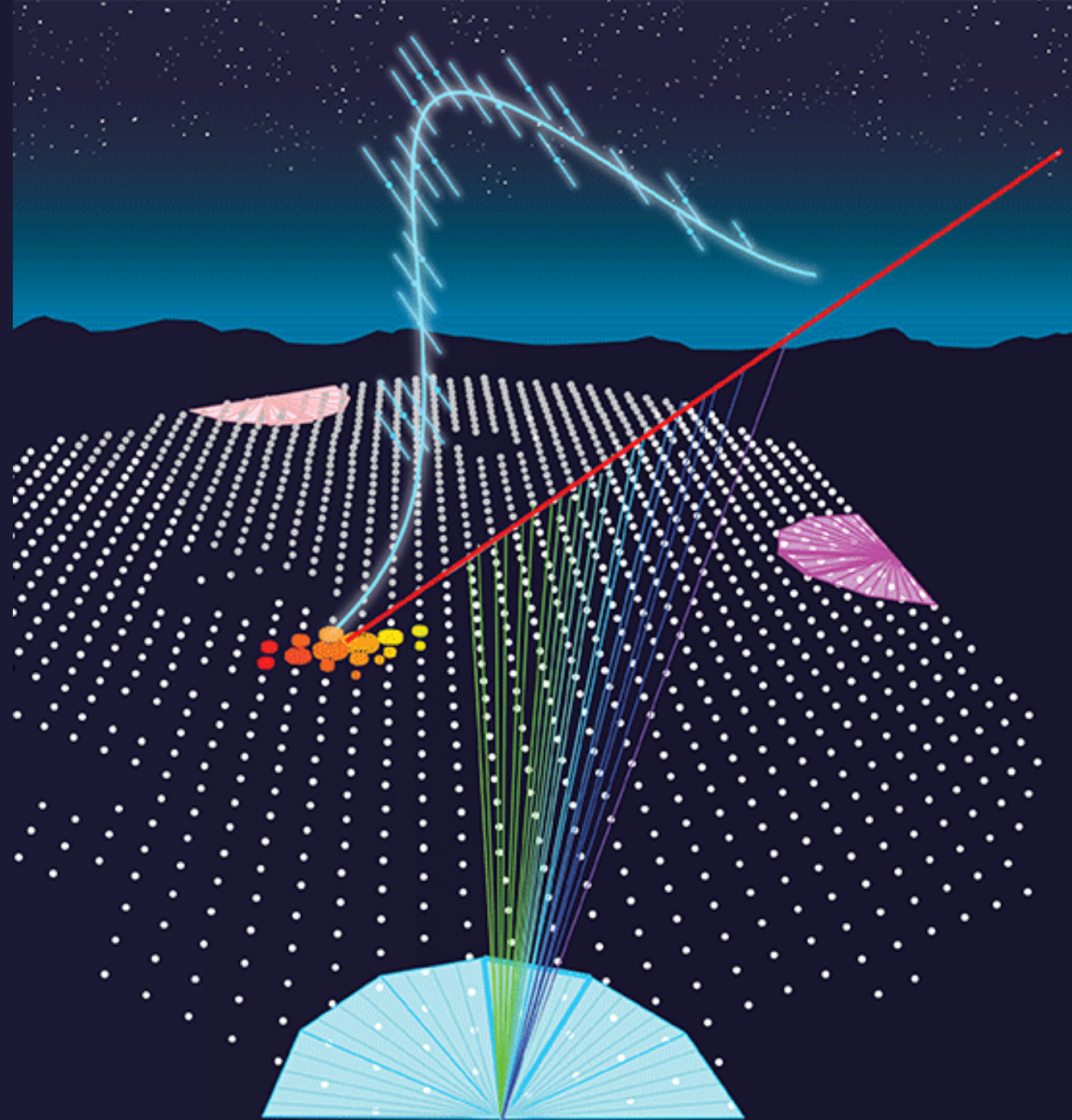# Overview of Data Analyses

Alena Bakalová

Joint Olomouc + Prague astroparticle meeting, Olomouc 14.10.2024

Overview of Data Analyses of Ultra-high-energy Cosmic Rays

1. Mass Composition Task
2. Air Shower Physics Task
3. CR Phenomenology
4. Energy spectrum
5. Data and Simulations
6. Other analyses

MASS COMPOSITION PHYSICS TASK

- **Alexey Yushkov** task leader of the mass composition physics tasks

- Selected topics
  - FD Xmax measurements, Xmax S38 correlation (Alexey Yushkov)
  - Joined Auger TA task (Alexey Yushkov, Olena Tkachenko)
  - Extraction of muon traces from WCD signals, Risetime and Delta method studies (Margita Kubátová, Alexey Yushkov)
  - Xmax from Stereo and SD2FD reconstructions (Nikolas Denner, Jakub Vícha, Vladimír Novotný)
  - Cherenkov Xmax using HeCo (Shayoni Panja, Alexey Yushkov)
  - p/He from tail of Xmax distributions (Jhansi Bhavani Vuta , Alexey Yushkov)
 - MPD from AMIGA using Machine Learning (Leo Östman, Alexey Yushkov)
  - …
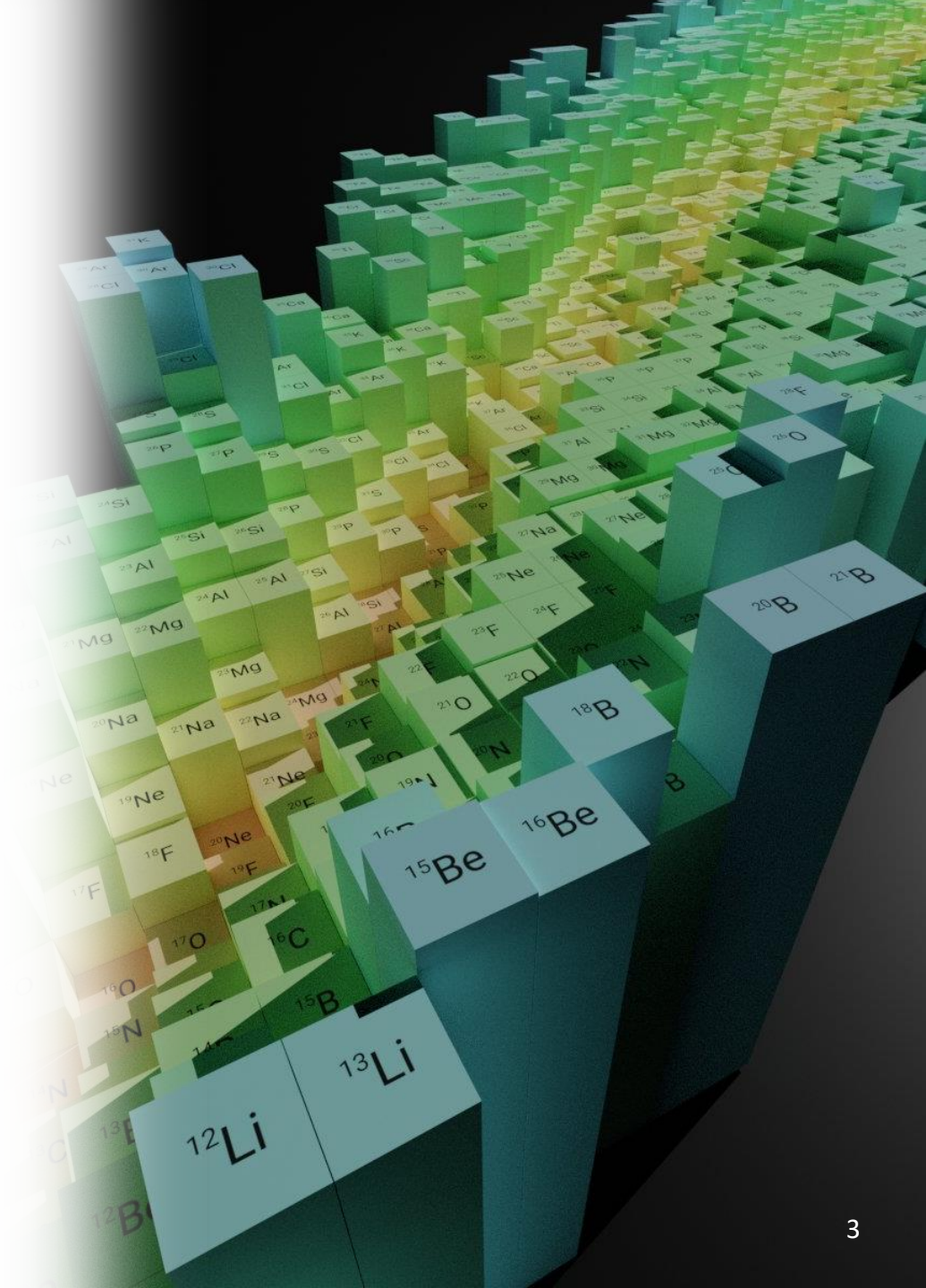
MASS COMPOSITION OF UHECRS

- Measurements of the depth of the shower maximum X_{max} and correlation between X_{max} and the signal in the SD stations (**A. Yushkov**)

- **FAL paper** X_{max} from phase I data in preparation
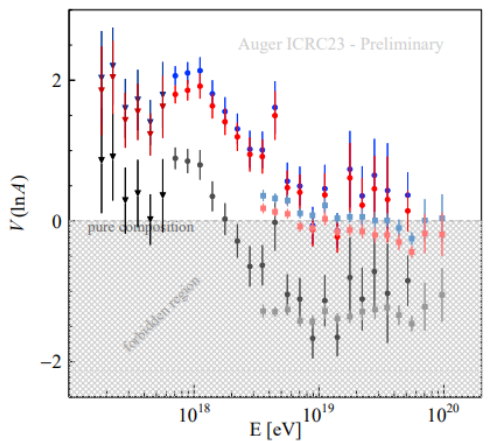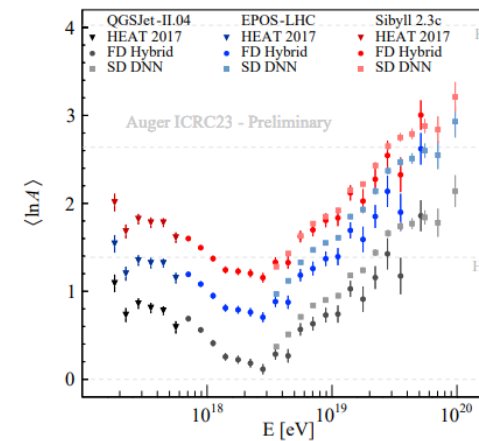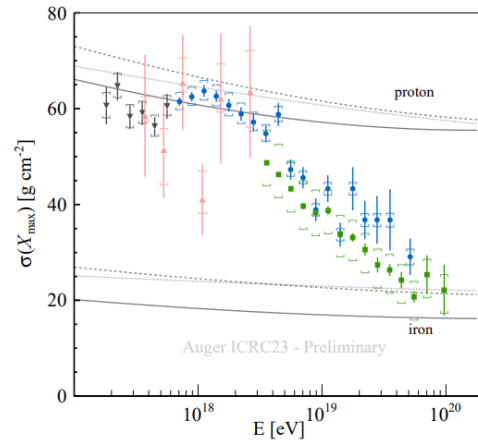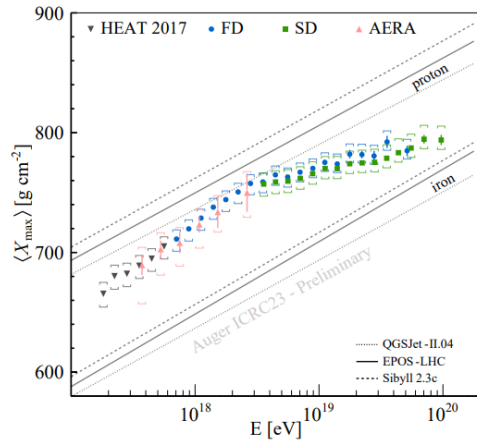

- Correlation factor remains significantly negative (6.4σ from zero) **below the ankle** → mixed mass composition
- Correlation factor becoming compatible with zero **at higher energies** → less mixed compositions
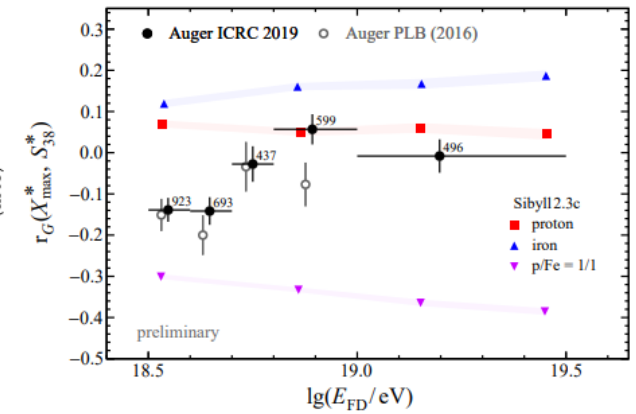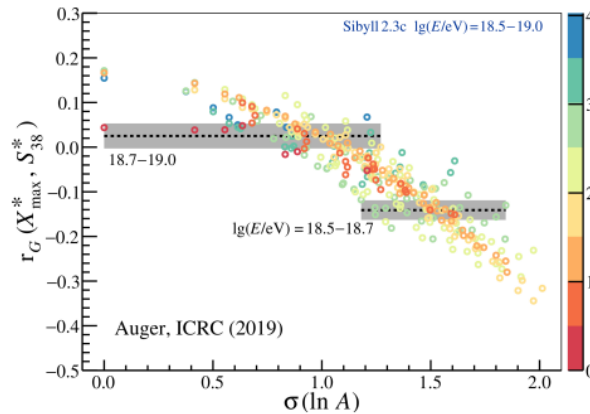
AUGER-TA MASS COMPOSITION

- Comparison of the first two moments and the shapes of Xmax distributions for energies above $10^{18.2}$ eV (**A. Yushkov, O. Tkachenko**)
  - **Auger** - 12/2004 – 12/2017, the data set contains 12773 events
  - **TA** - 05/2008 – 11/2016, the data set contains 3330 events

- AugerMixes are processed using the TA detector simulation, event reconstruction and analysis chain
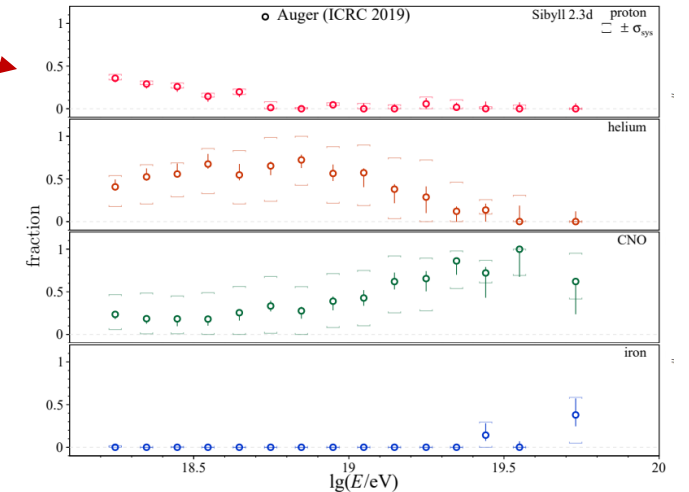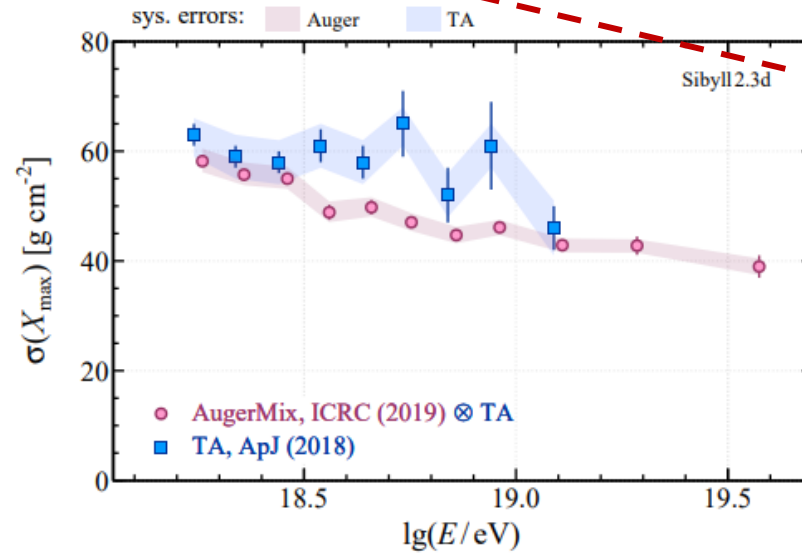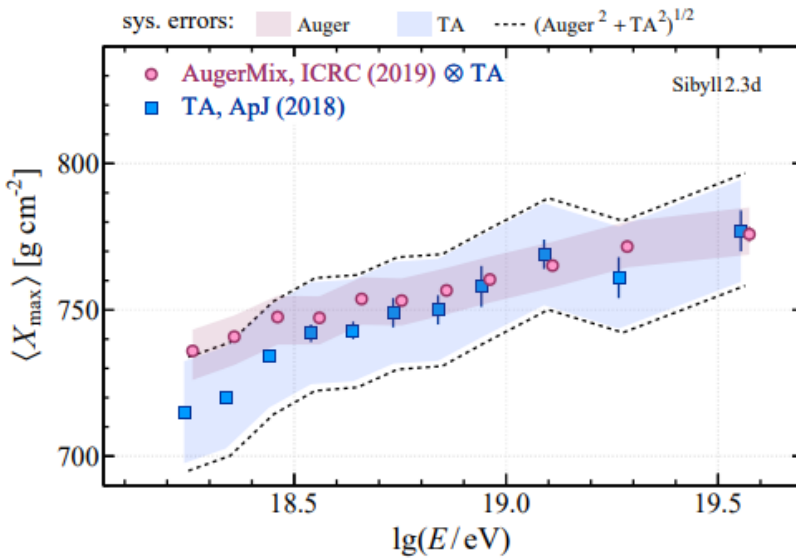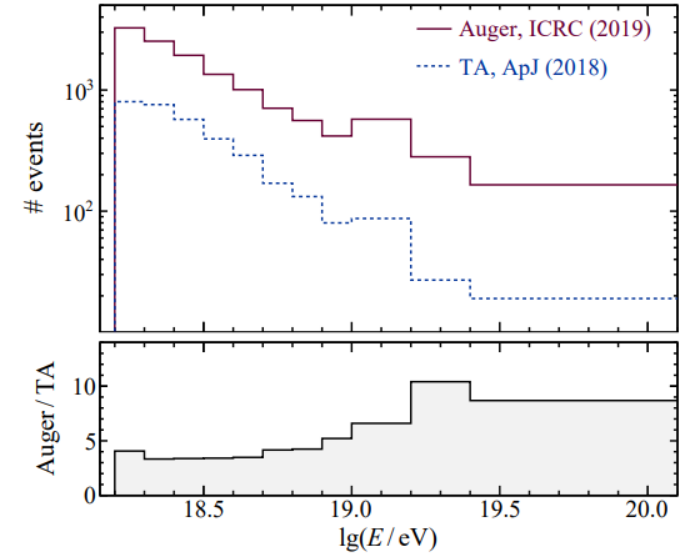
For more details see POS(ICRC2023)249

5

EXTRACTION OF MUON TRACES FROM WCD SIGNALS

- Predictions of the muon traces using deep neural network (DNN) and recurrent neural network (RNN)
  - Extraction of S_μ in first 200 bins of time traces in water
    Cherenkov detectors (WCDs)

- Small biases on integrated S_μ and muon rise time

- Rise time and delta method

PhD topic of **M. Kubátová**, supervised by **A. Yushkov**
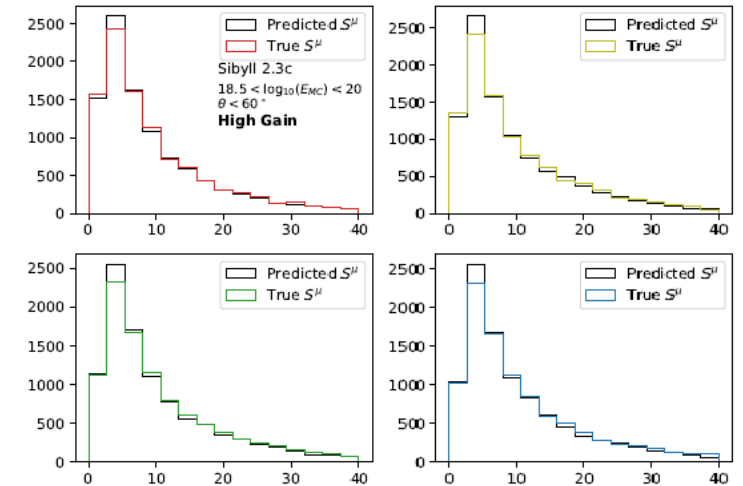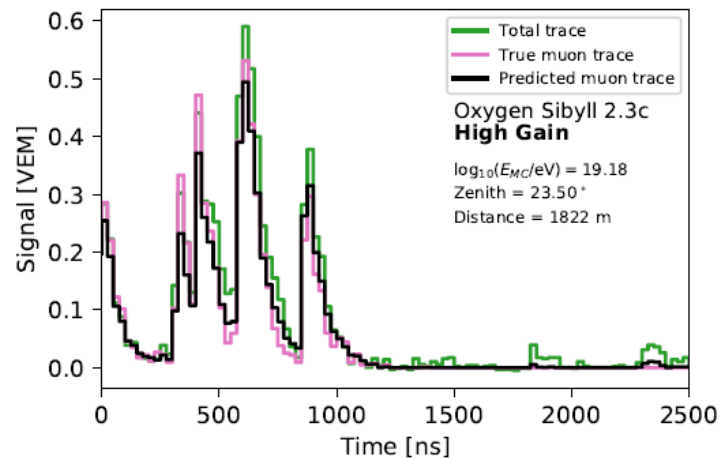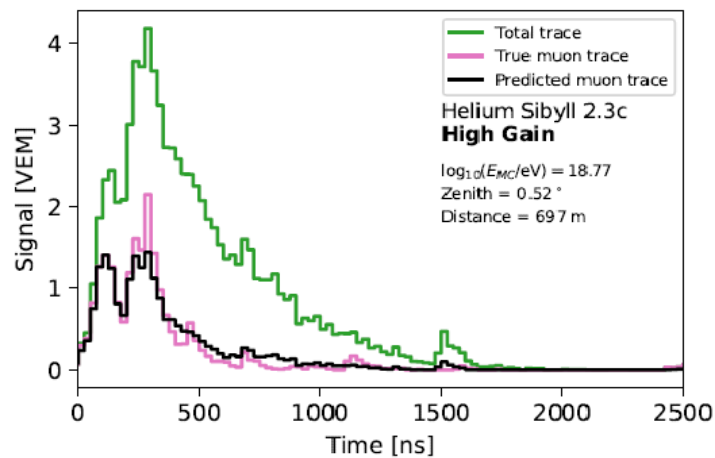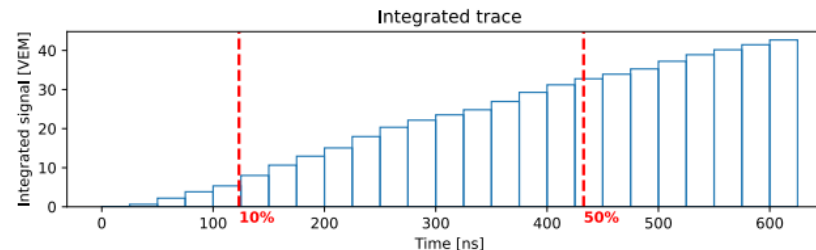
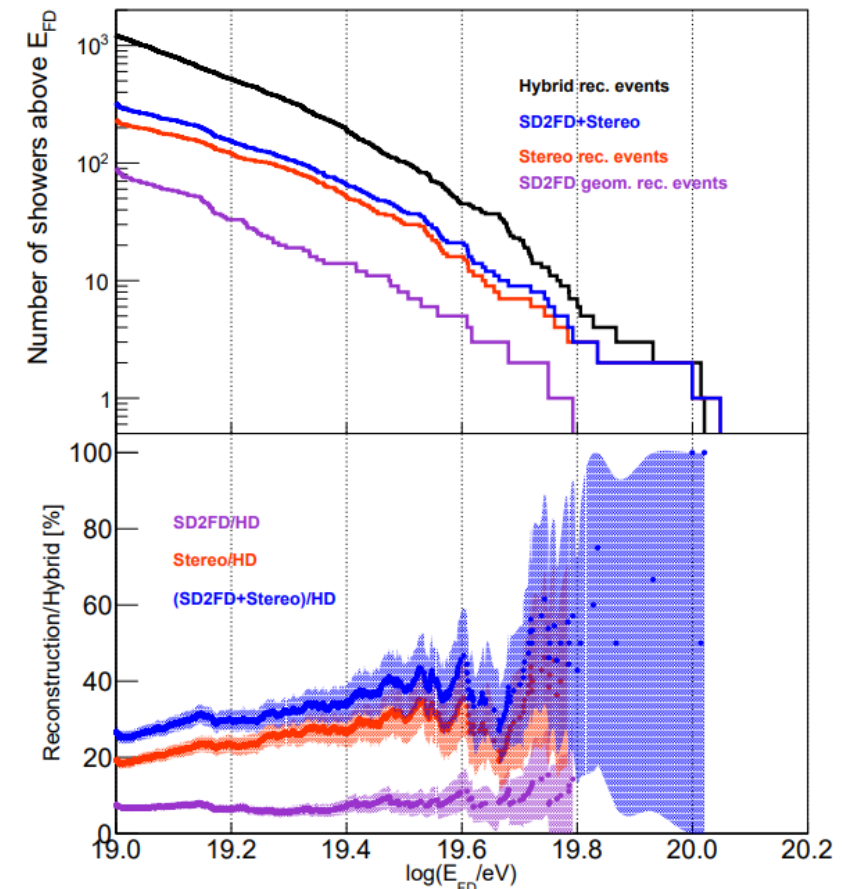# XMAX FROM STEREO AND SD2FD RECONSTRUCTIONS

- Potential to increase the Xmax analysis data set with Stereo and SD2FD Reconstructions (**N. Denner, J. Vícha, V. Novotný**)

  1. **Stereo:** Two or more eyes used for geometry reconstruction (no SD information needed)

  2. **SD2FD:** Axis estimated from SD geometry

- Around 40% of new events could be added by the Stereo and SD2FD methods above $10^{19.5}$ eV!

Highest-energy Stereo event - Coihueco

Number of unique events after standard hybrid Xmax selection
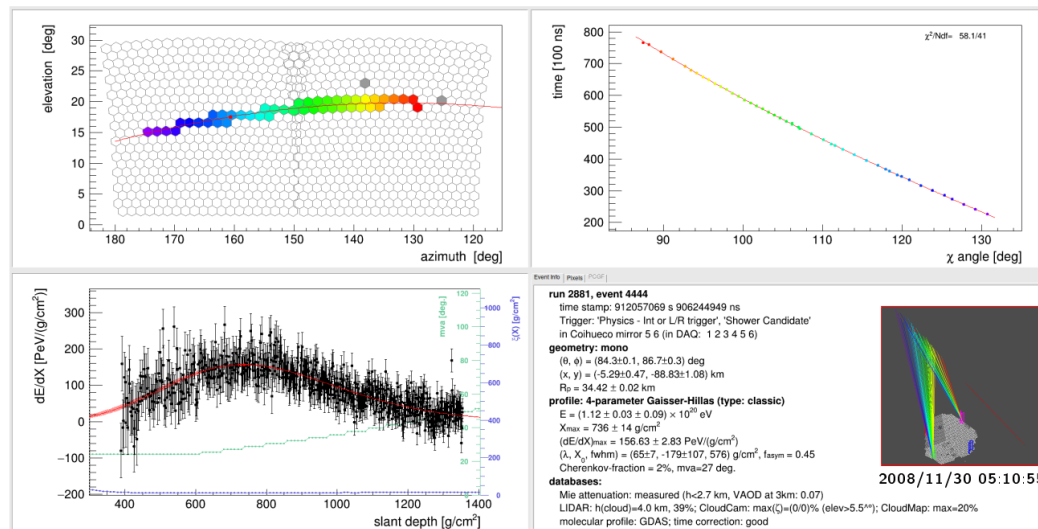
AIR SHOWER PHYSICS TASK

- **Jakub Vícha** task leader of the Air Shower Physics Task

- Selected analysis
  - MOCHI - Modified Characteristics of Hadronic Interactions (J. Ebr, J.Blažek, J. Vícha, P. Trávníček, E. Santos, N. Denner)
  - Mass composition and cross-section from Xmax fits (O. Tkachenko)
  - MC modifications using [Xmax,S1000] fits (J.Vícha)
  - A Heavy-Metal Scenario of UHECR (J. Vícha and others)
  - Anomalous shower profiles (J. Blažek, P. Trávníček)
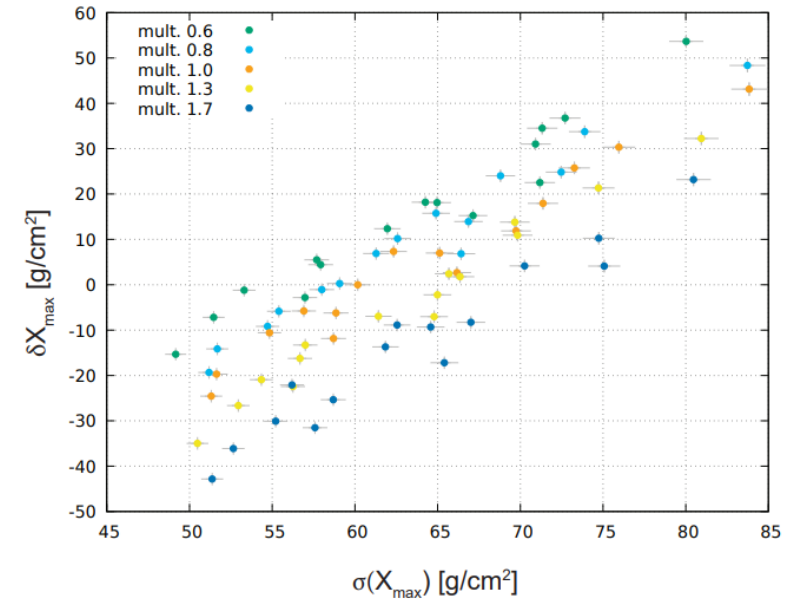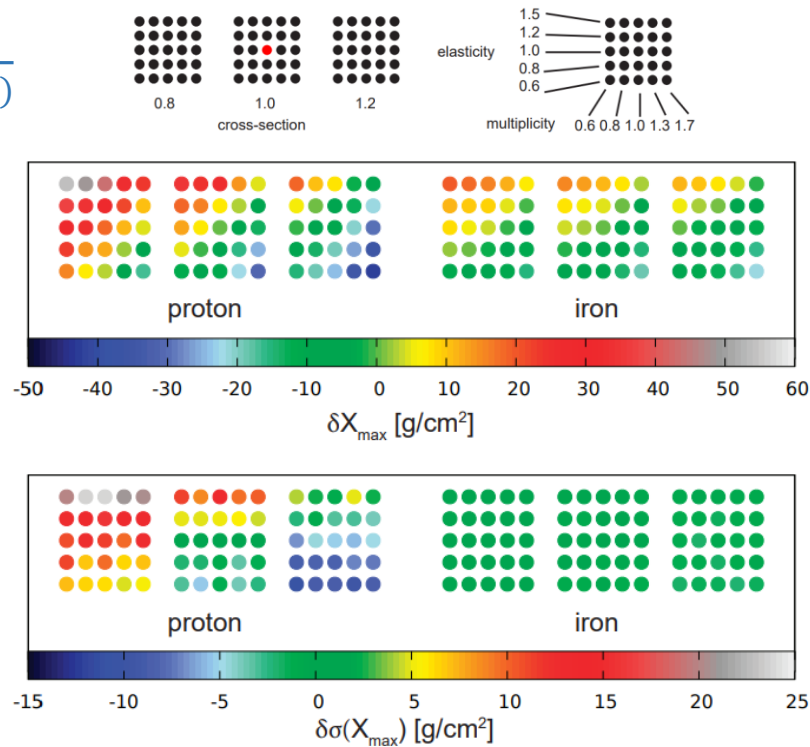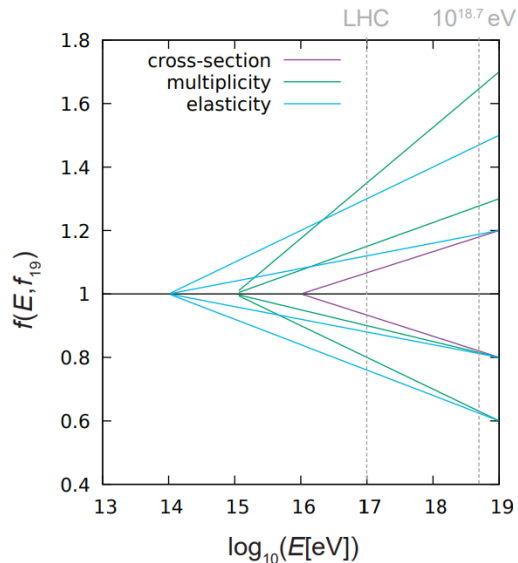 - Rmu from universality on hybrid data (J. Vícha)
  - …

MODIFED CHARACTERISTICS OF HADRONIC INTERACTIONS

- Modification of macroscopic parameters of hadronic interaction models to better describe measurements (**J. Ebr, J. Blažek, J. Vícha, P. Trávníček, N. Denner, E. Santos**)

- Changes of multiplicity, elasticity and cross-section with CORSIKA 7.741 with CONEX option, Sibyll 2.3d

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

*For more details see POS(ICRC2023)245, POS(ICRC2021)441 and EPJ WoC 283:05005*

# MASS COMPOSITION AND CROSS-SECTION FROM XMAX FITS

- Simultaneous mass composition and cross section measurement (**O. Tkachenko**)

- Vary the proton-proton cross section + perform a standard composition fit → self-consistent estimation of the interaction cross sections and cosmic-ray primary composition

$$\sigma_{\text{mod}}^{pp} = \sigma_{\text{orig}}^{pp} f^{pp}(E_0, E)$$

- Shift in the Xmax scale as another fit parameter
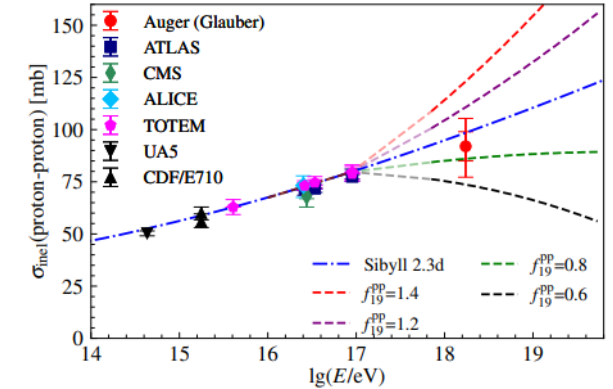
PoS (ICRC2023) 438
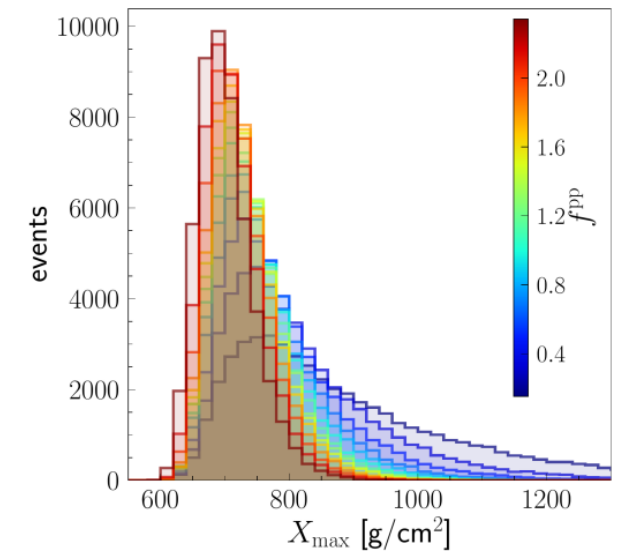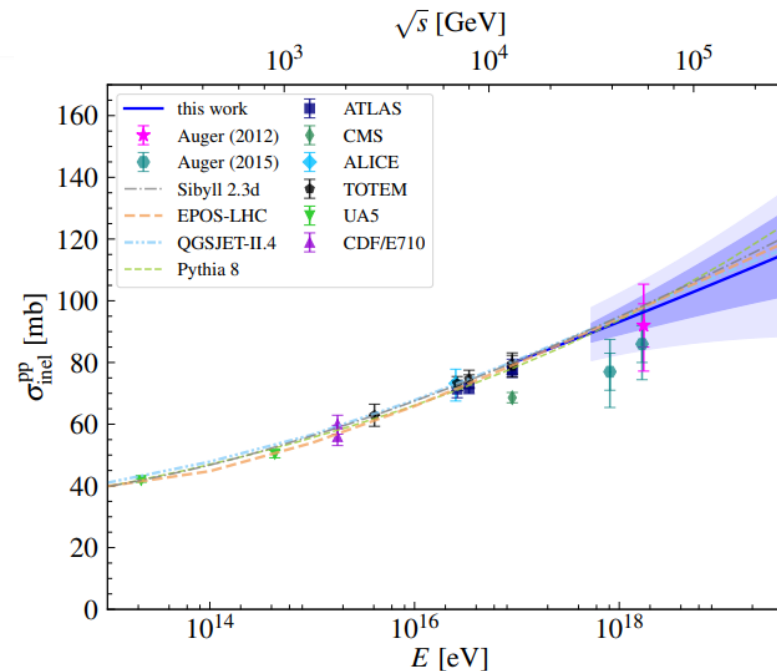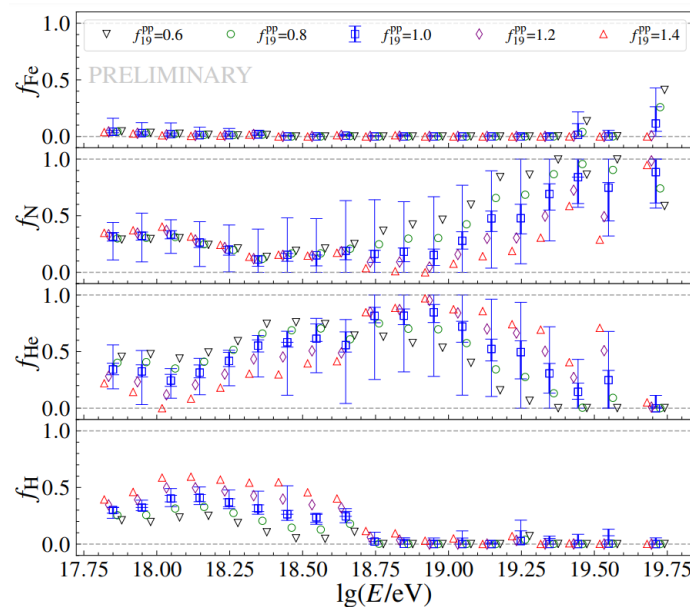
O. Tkachenko Ph.D. thesis

# MODIFICATIONS OF HADRONIC INTERACTION MODELS USING [XMAX,S1000] FITS

- Analysis of **J. Vícha FAL paper (Phys. Rev. D 109 (2024) 102001)**

- Existing tension between models and observations

  - poor description of data by current models

- Global fit of observed $[X_{max},S(1000)]$ distributions with free mass composition and adjustments of MC predictions to hadronic signal and X_{max}
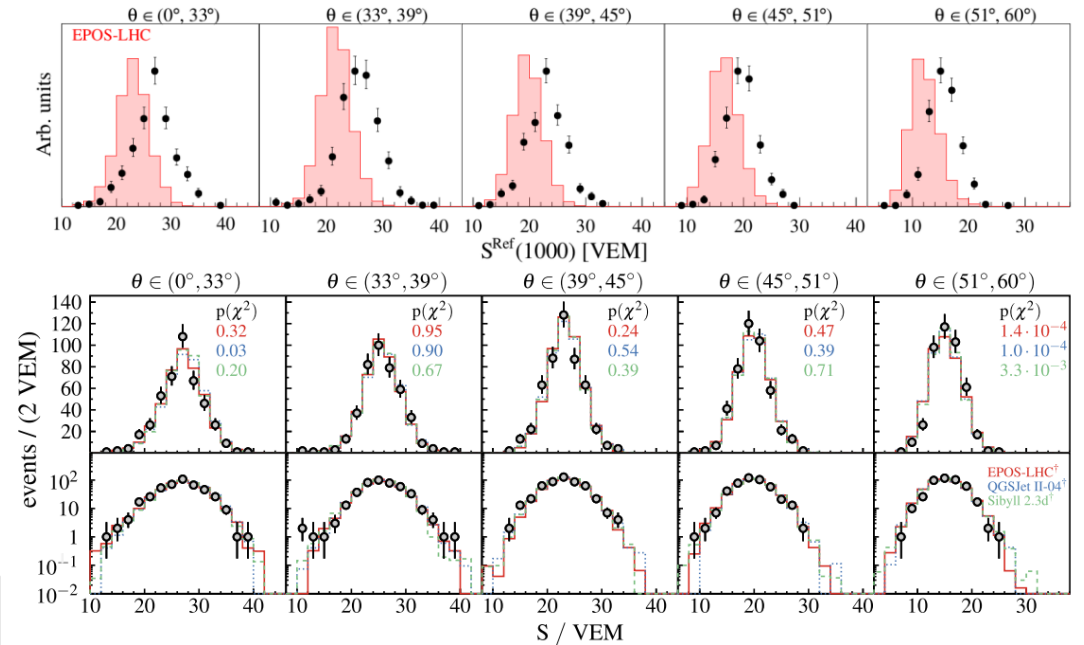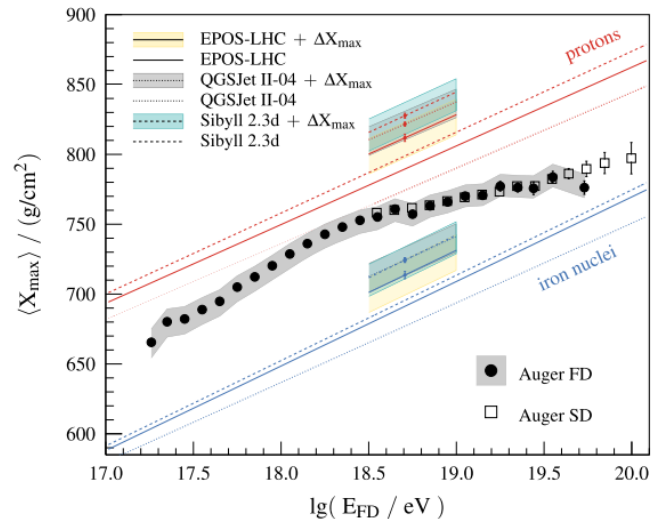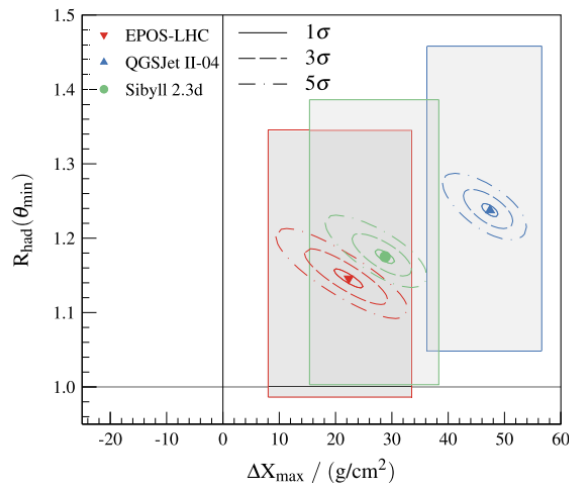
|	$R_{had}(\theta_{min})$	$R_{had}(\theta_{max})$	$\Delta X_{max}/(g/cm^2)$
Epos-LHC	$1.15 \pm 0.01^{+0.20}_{-0.16}$	$1.16 \pm 0.01^{+0.14}_{-0.10}$	$22 \pm 3^{+11}_{-14}$
QGSJet-II-04	$1.24 \pm 0.01^{+0.22}_{-0.19}$	$1.18 \pm 0.01^{+0.15}_{-0.12}$	$47^{+2}_{-1}{}^{+9}_{-11}$
SIBYLL 2.3d	$1.18 \pm 0.01^{+0.21}_{-0.17}$	$1.15 \pm 0.01^{+0.15}_{-0.11}$	$29 \pm 2^{+10}_{-13}$

# A HEAVY-METAL SCENARIO OF UHECR

- **J. Vícha, O. Tkachenko, A. Bakalová, A. L. Müller**

- Heavy mass composition at the highest energies - **SAL paper in preparation**

- Implications of heavy metal scenario at the highest energies

  - Mass composition with shifted Xmax scale
  - Primary fractions
  - Energy spectrum of individual mass groups
 - Arrival directions with heavy primaries
  - …
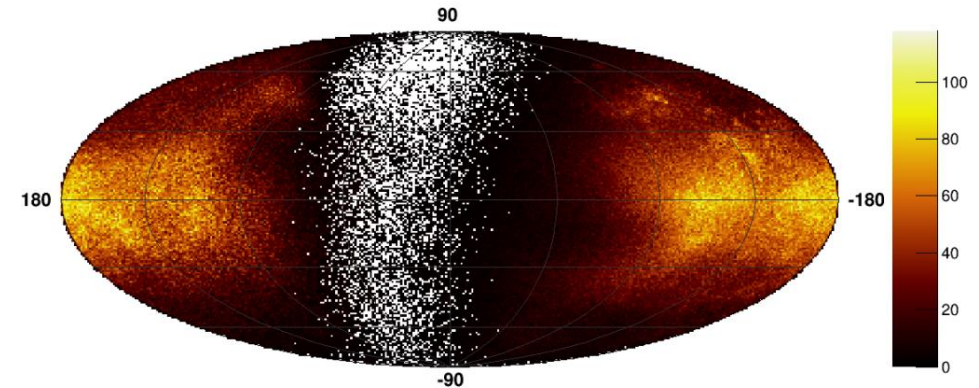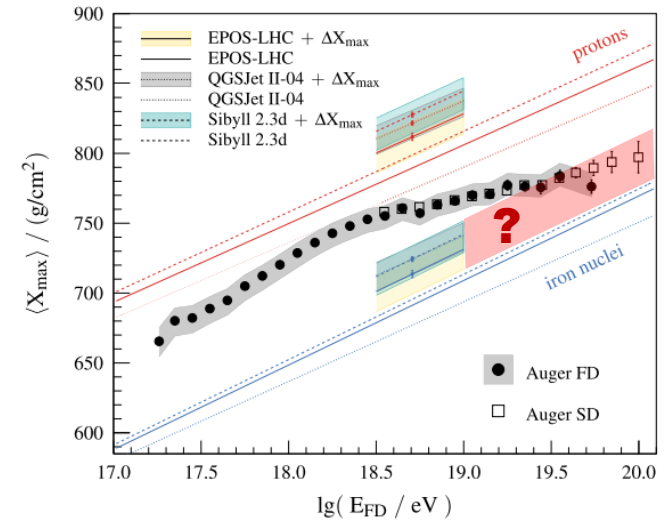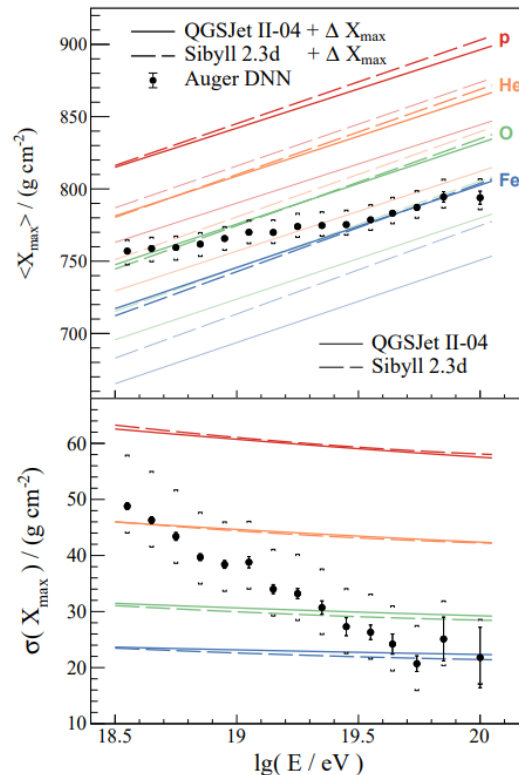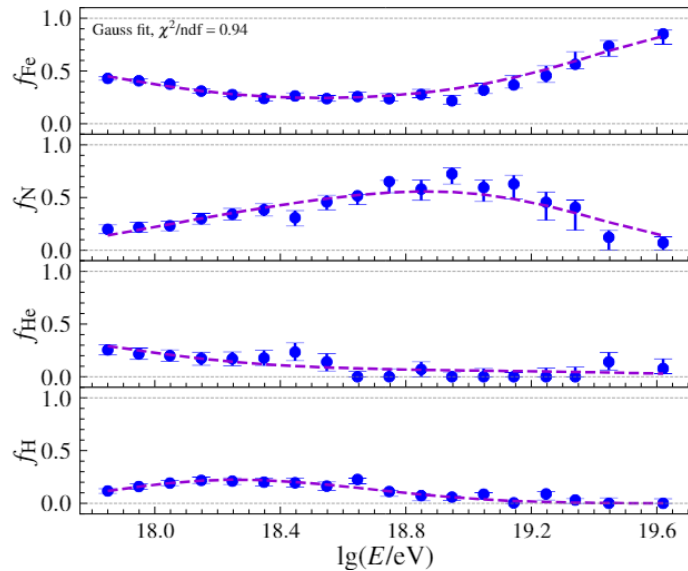
PHYSICALLY MOTIVATED CLOSEBY SOURCES

- Influence of the Galactic magnetic field (GMF) on the direction and the amplitude of the dipole **JCAP12(2023)016** (**A. Bakalová, J. Vícha, P. Trávníček**)

- Analysis repeated using fitted fractions from heavy-metal scenario and new models of GMF

- More physicaly relevant scenario using selected closeby sources (**A. Bakalová, J. Vícha, A. L. Müller**)
  - Objects of interest AGNs, Seyfert II, Starburt Galaxies …
  - New models of Galactic magnetic field
  - Dipole above 8 EeV
  - Small scale anisotropies above 40 EeV
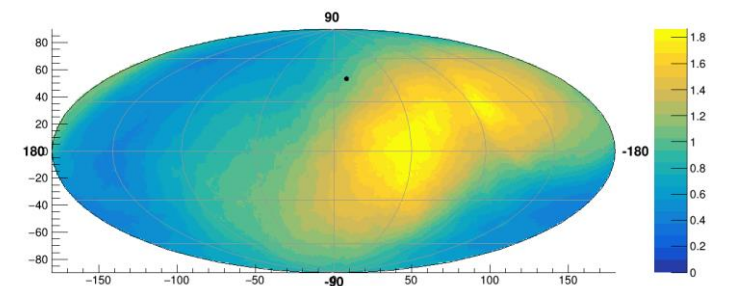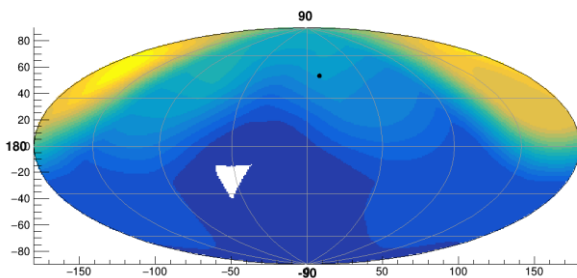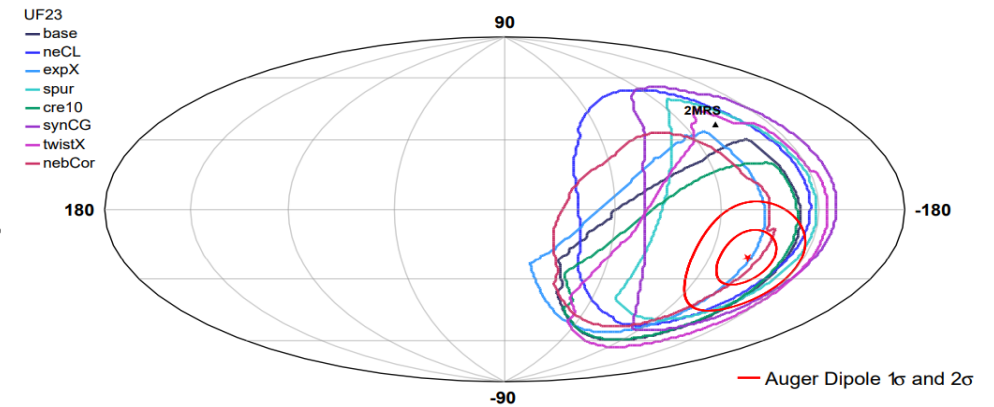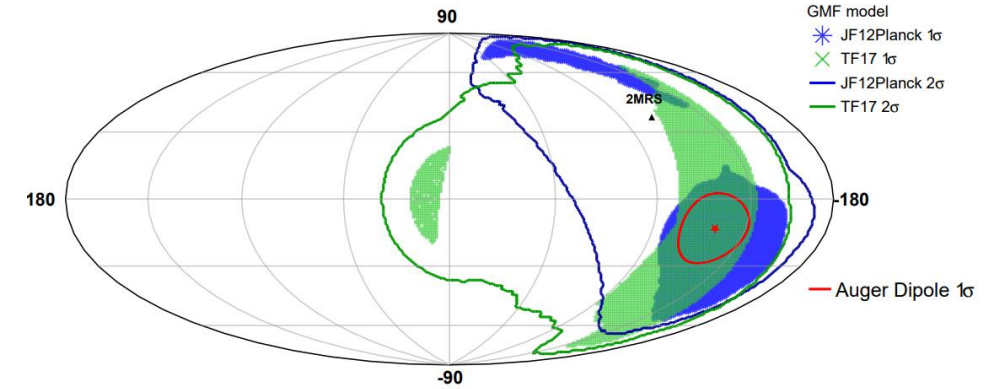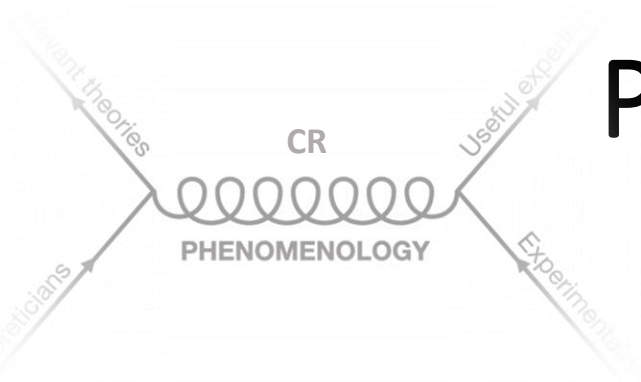
Energy Spectrum from Cherenkov Dominated Data
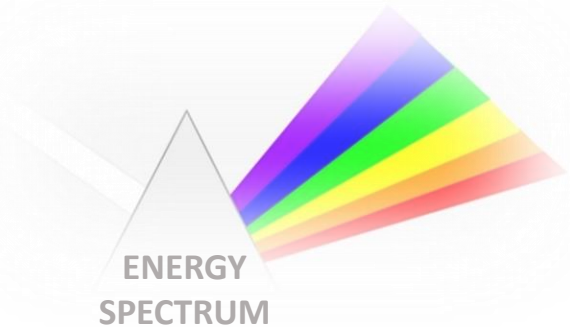
- New reconstruction method of Cherenkov–dominated events developed and implemented by **V. Novotný**

- Allows to extend the reconstruction of the energy spectrum from Pierre Auger Observatory data down to **$6 \cdot 10^{15}$ eV**

- The profile constrained geometry fit method is described in detail in Ph.D. thesis of V. Novotný
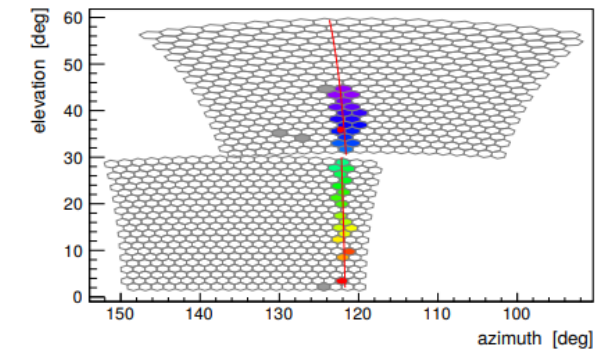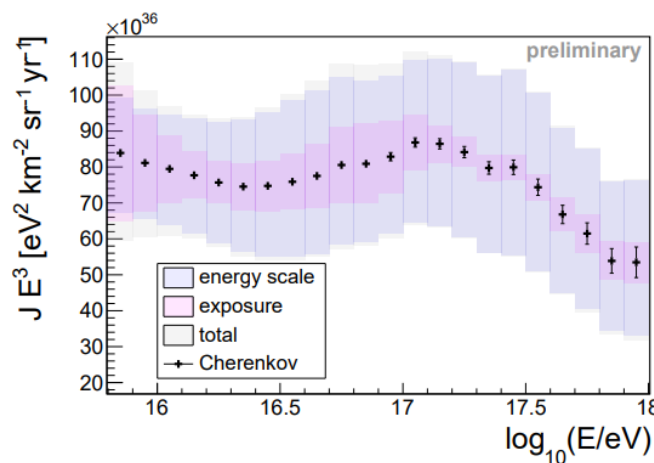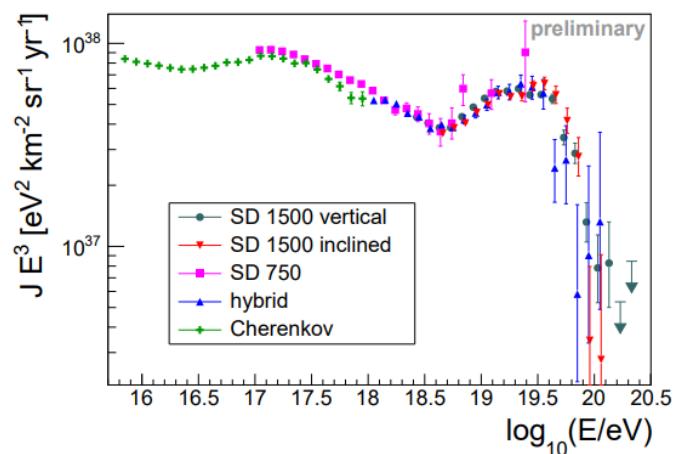
(a) Camera view
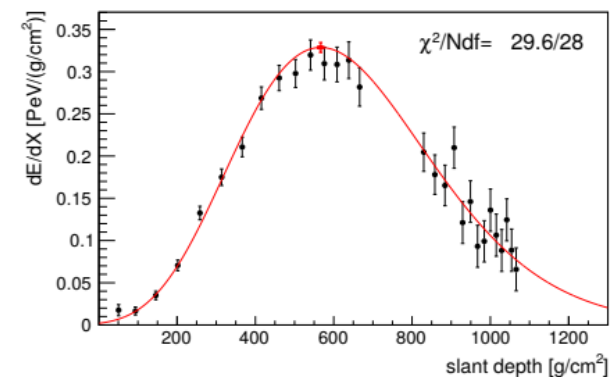
(b) Energy deposit profile

V. Novotný, Ph.D. thesis

V. Novotný, PoS(ICRC2021)324

DATA AND SIMULATIONS

- **Monte Carlo simulations**
  - **E. Santos** coordinator of the Monte Carlo simulations task
  - Production of official simulation libraries for the whole Collaboration (**E. Santos, A. Yushkov**) - used in FAL papers

- **A Catalog of the Highest-Energy Cosmic Rays**
  - Release of 100 most energetic events
  - 78 EeV to 166 EeV
  - **V. Novotný** reponsible for the FD part
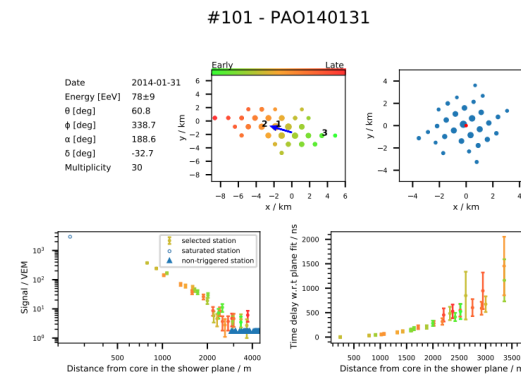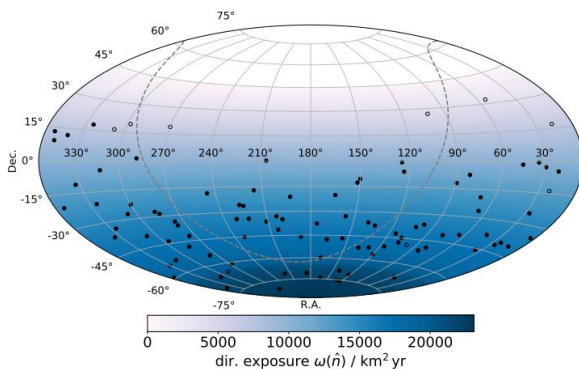
Other Topics and Non Auger Analyses

- Neutral Particles Physics Task
  - Search for upward-going showers with the Pierre Auger Observatory (**Vladimír Novotný, Jiří Blažek**) – FAL paper submitted
- Muon seasonal variations (**Jordi Tuneu, Eva Santos**)
- Invisible energy from KASCADE data (**Jakub Vícha, Vladimír Novotný**)

- Defence of **five** bachelor theses in September 2024
  - **Marie Benedová** - Influence of the Galactic magnetic field on arrival directions of ultra-high energy cosmic rays
  - **Radovan Beňo** - Modified Hadronic Interactions and their Effect on the Composition of Cosmic Rays
  - **Lucie Karczubová** - Mass composition of UHECRs using hybrid data of the Pierre Auger Observatory
  - **Martin Šmíd** - Propagation of UHECRs for the case of heavy composition of primary particles
  - **Simona Velichová** - Superposition model of cosmic-ray showers