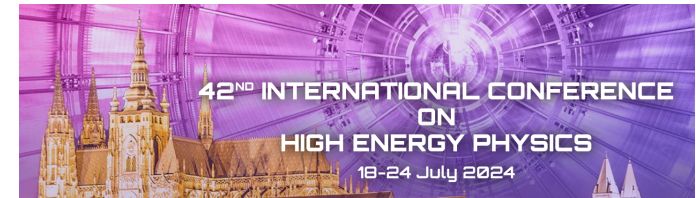# Probing hadronic interactions using the latest data from the Pierre Auger Observatory

Jakub Vícha

for the Pierre Auger Collaboration
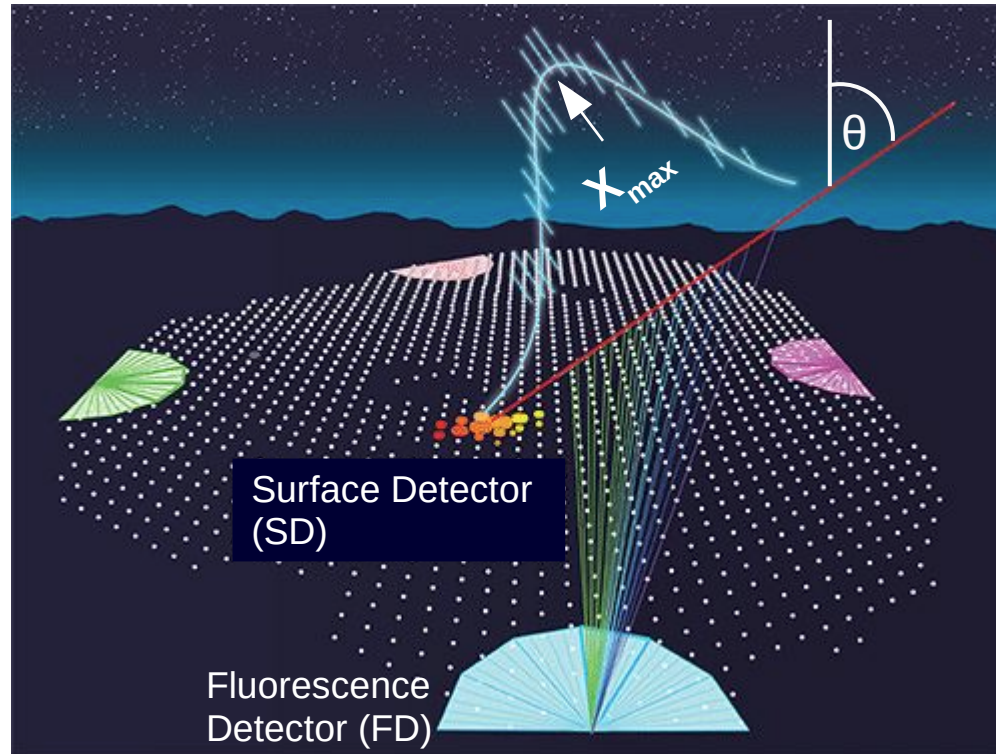
vicha@fzu.cz

FORTE

42ND INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS
18-24 July 2024

Observables relevant to hadronic interaction models

SD signal

- muon content
  - from buried scintillators, $\theta < 60°$
  - from N_{19}, $\theta > 65°$
    [Phys. Rev. D 91 (2015), 032003]

- muon production depth
  - for core distance $r > 1500m$, $\theta > 65°$
    [Phys. Rev. D 90 (2014) 012012]

- muon energy spectrum
  - from attenuation with θ and r

See linked references and talks of A. Yushkov and T. Fitoussi for details about measurements

The Pierre Auger Observatory (auger.org, [NIM A 98 (2015) 172])

θ

X_{max}

Surface Detector (SD)

Fluorescence Detector (FD)

FD longitudinal profile

- estimation of primary masses from X_{max} fits
  [PRD 90 (2014) 122006, PoS ICRC2023 (2023) 438]

- interpretation of X_{max} moments using ln A
  [JCAP 02 (2013) 026, PoS (ICRC2023) 365]

- p-air cross-section from tail of X_{max} distribution
  [Phys. Rev. Lett. 109 (2012) 062002, PoS ICRC2023 (2023) 438]

- average shape of longitudinal profiles
  [JCAP 03 (2019) 018]

- frequency of anomalous showers
  [EPJ Web of Conferences 144 (2017) 01009]

Observables relevant to hadronic interaction models

SD signa

- muon c
  - ➔ from
    scinti
  - ➔ from

- muon p
  - ➔ for core c
    r > 1500r
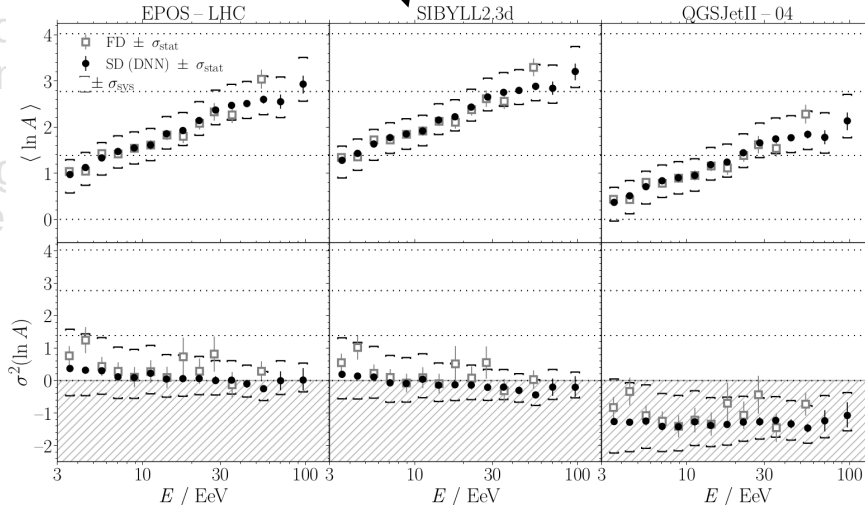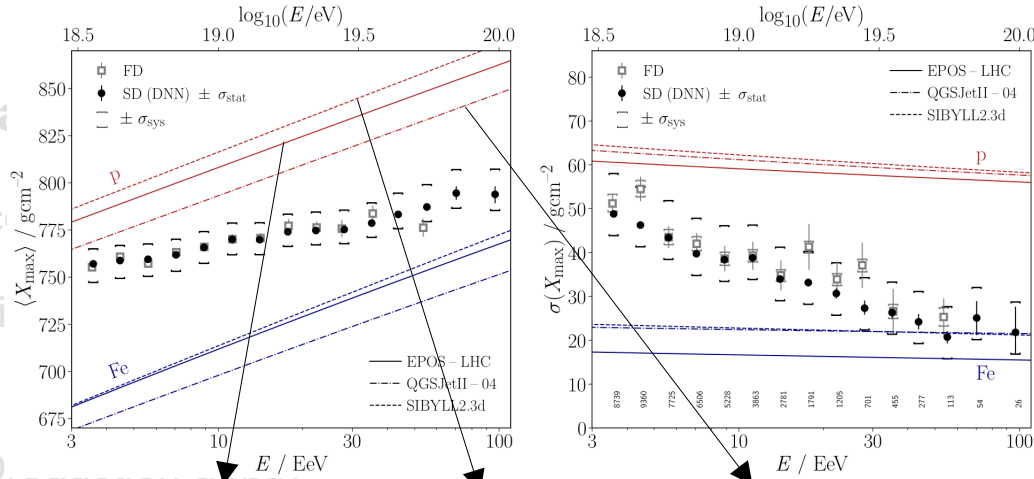
- muon energ
  - ➔ from atte
    θ and r
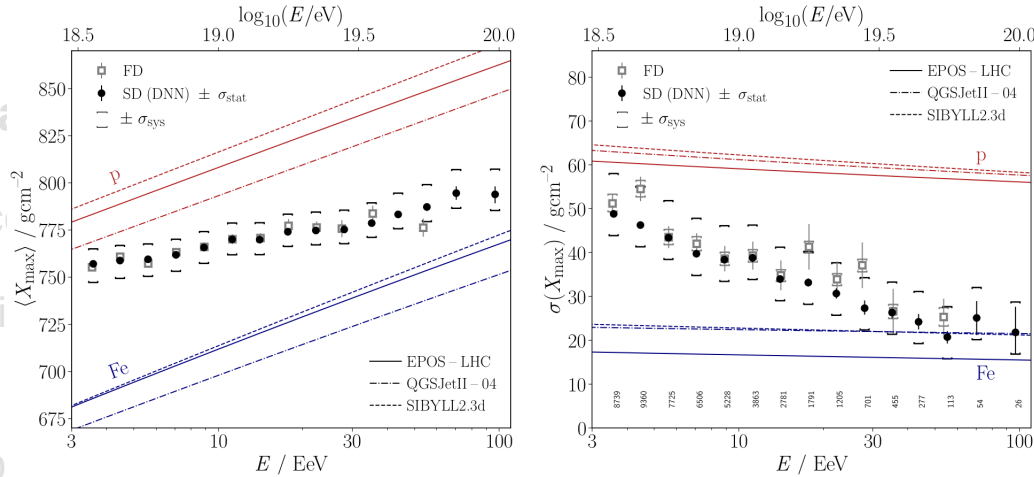
[submitted to PRD, arXiv:2406.06319]

FD longitudinal profile

- estimation of primary
  masses from X_{max} fits

- interpretation of X_{max}
  moments using ln A

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

$$\sigma^2_{\ln A} = \frac{\sigma^2(X_{max}) - \sigma^2_{sh}(\langle \ln A \rangle)}{b \, \sigma^2_p + f^2_E}$$

[JCAP 02 (2013) 026]

- air cross section from

- frequency of anomalous
  showers

Observables relevant to hadronic interaction models

SD signal

- muon content
  - from scinti...
  - from

- muon production depth
  - for core distances r > 1500m

- muon energy
  - from attenuation θ and r

FD longitudinal profile

- estimation of primary masses from X_{max} fits
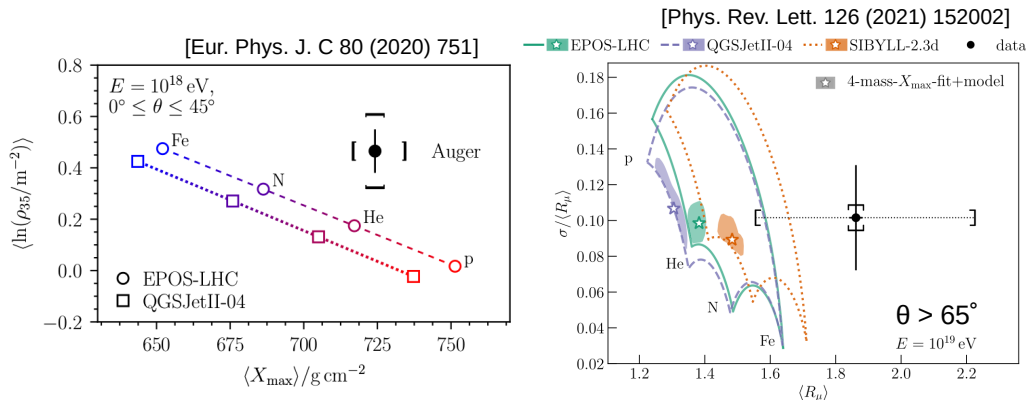
- interpretation of X_{max} moments using ln A

- p-air cross-section from tail of X_{max} distribution

- Strong dependance on the MC X_{max} scale
- **Indication of too shallow predictions of <X_{max}> for all three models !**

Observables relevant to hadronic interaction models

SD signal

- **muon content**
 - ➜ from buried scintillators, θ<60°
  - ➜ from N_{19}, θ>65°

- **muon production depth**
  - ➜ for core distance r > 1500m, θ>65°

- muon energy spectrum
  - ➜ from attenuation with θ and r

[Eur. Phys. J. C 80 (2020) 751]

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

[Phys. Rev. D 90 (2014) 012012]

- Problem to describe the size of the muon content - **factor ~1.3-1.6** !

- Muon fluctuations consistent with data (no obvious problem in the first interaction)
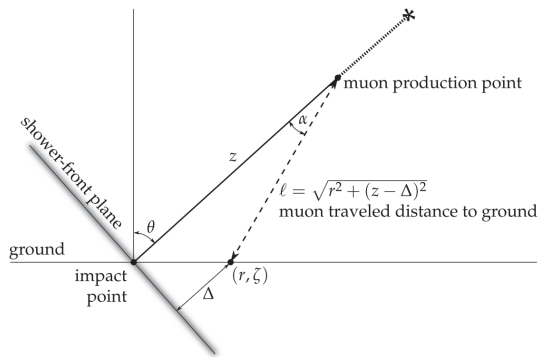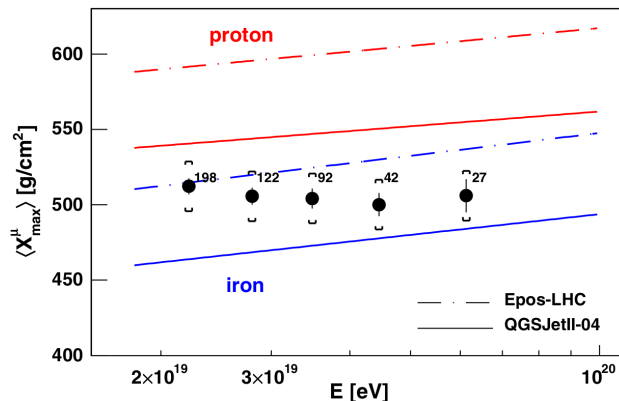
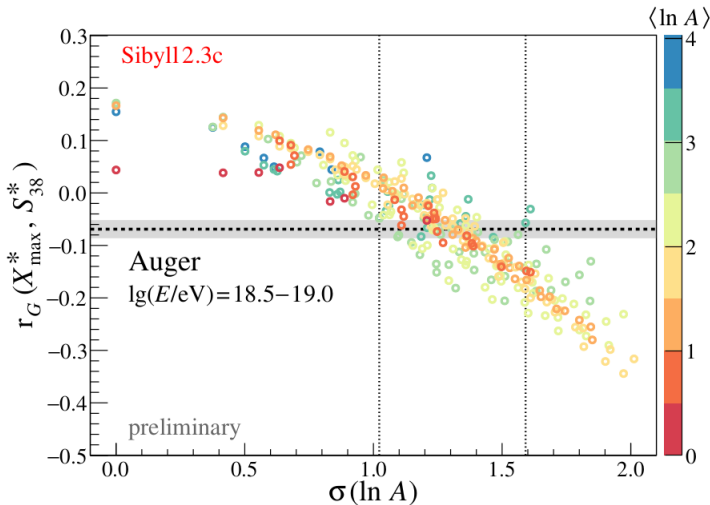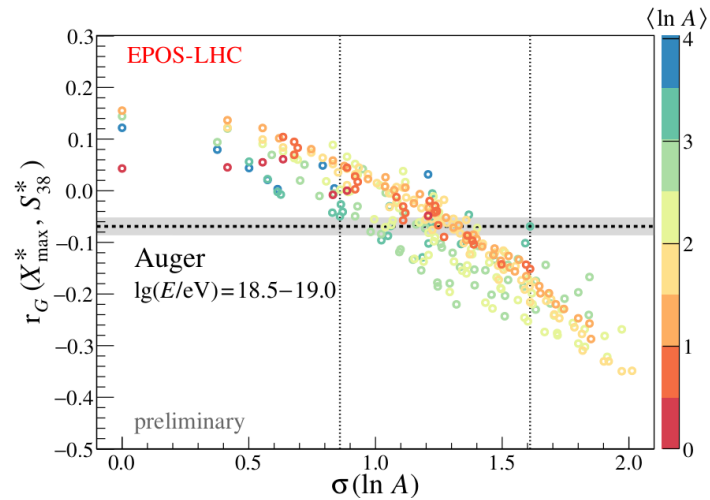- MPD tunable by pion diffraction (loosely constrained)

Combining SD and FD observables
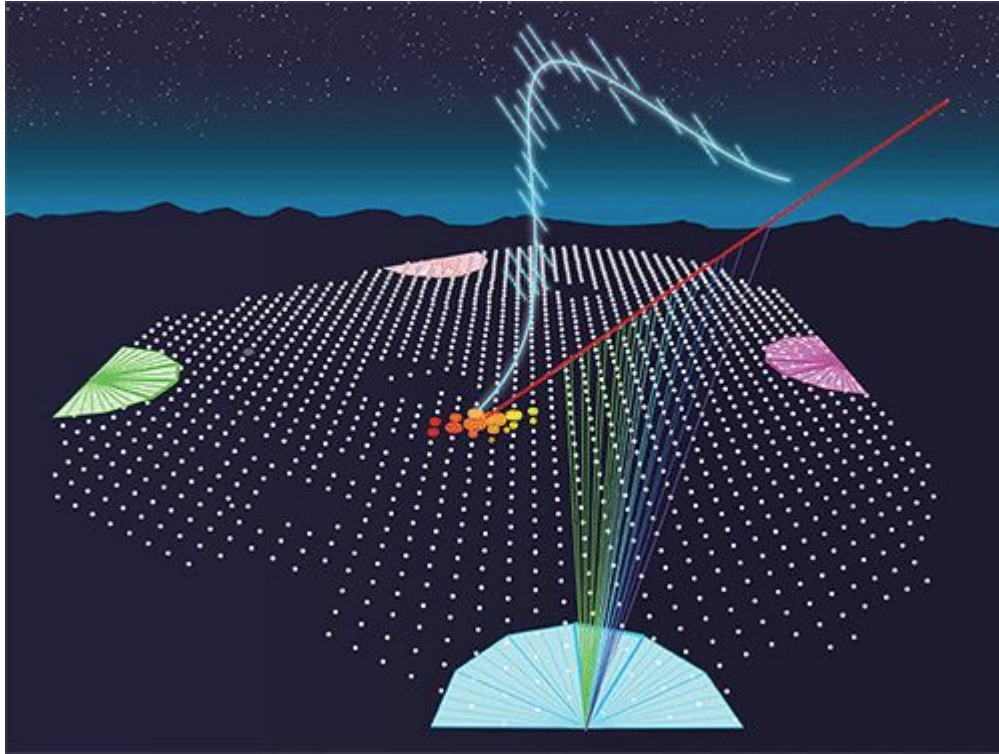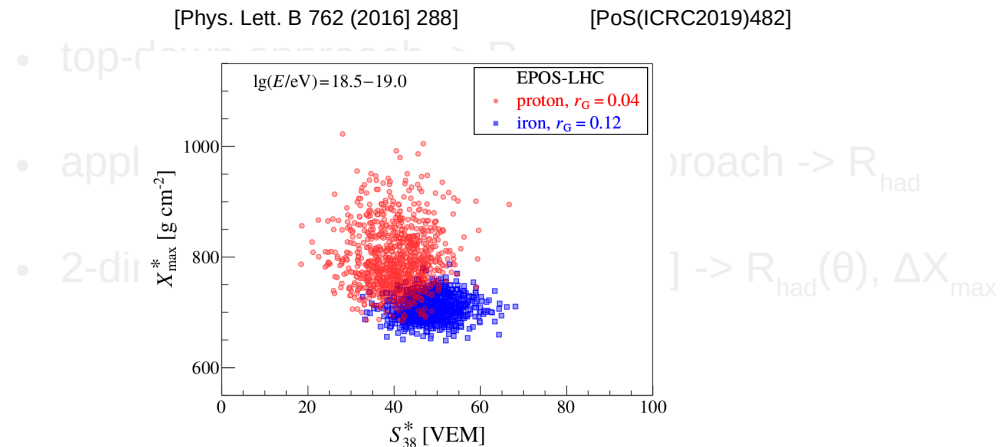

Ground signal + Longitudinal profile

- correlation between X_{max} and $S(1000)$

- top-down approach -> R_{had}

- applying shower-universality approach -> R_{had}

- 2-dim distributions $[S(1000), X_{max}]$ -> $R_{had}(\theta)$, ΔX_{max}
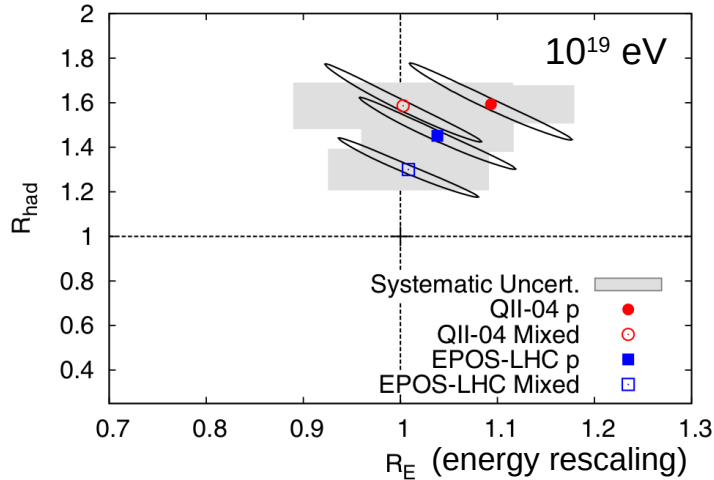
Combining SD and FD observables

Ground signal + Longitudinal profile

- correlation between X_{max} and $S(1000)$

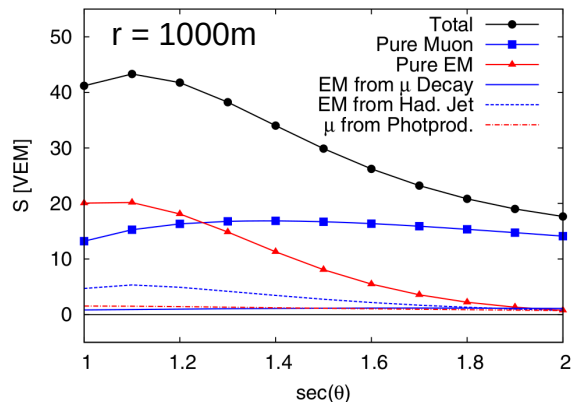[Phys. Lett. B 762 (2016) 288]   [PoS(ICRC2019)482]

- ~Model-independent estimator of spread of beam masses
- Tension with light masses from X_{max} fits for QGSJet II-04 (**too shallow X_{max} scale**)

Combining SD and FD observables

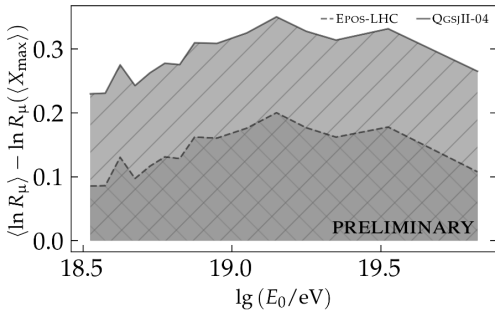$$S_{resc}(R_E, R_{had})_{i,j} \equiv R_E S_{EM,i,j} + R_{had} R_E^{\alpha} S_{had,i,j}$$

Ground signal + Longitudinal profile

- correlation between X_{max} and S(1000)

- top-down approach -> R_{had} **~ 1.3 - 1.6 !**
  [Phys. Rev. Lett. 117 (2016) 192001]

- applying shower-universality approach -> R_{had}

- 2-dim distributions [S(1000),X_{max}] -> $R_{had}(\theta)$, ΔX_{max}
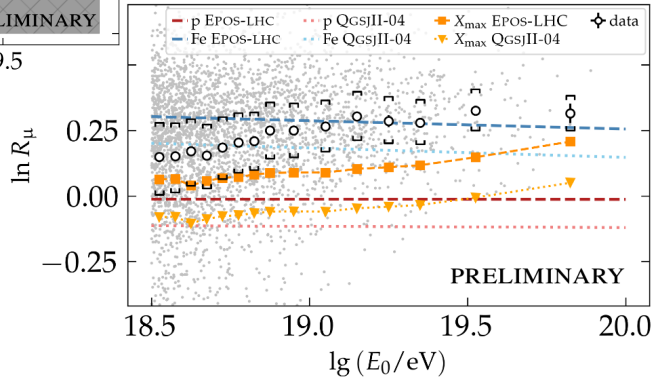
- Mass from measured X_{max} - depends on MC X_{max} scale
- Strong dependence on energy scale

Combining SD and FD observables
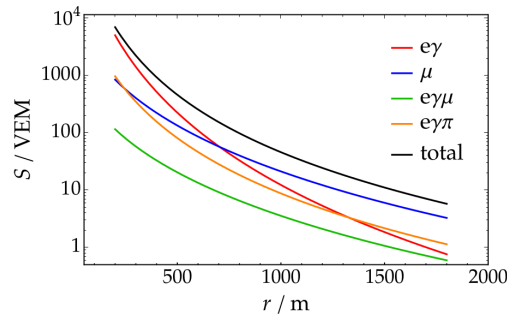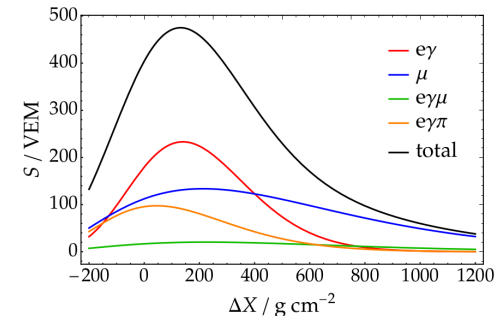

PRELIMINARY

energy
and X_{max}
from FD

PRELIMINARY

Ground signal + Longitudinal profile

- correlation between X_{max} and S(1000)
-
- top-down approach -> R_{had}

- applying shower-universality approach
  -> R_{had} ~ **1.1 - 1.3**   [PoS(ICRC2023)339, arXiv:2405.03494]

- 2-dim distributions [S(1000),X_{max}] -> $R_{had}(\theta)$, ΔX_{max}

$$S_{tot} \simeq S_{e\gamma} + R_\mu \left(S_\mu + S_{e\gamma(\mu)} + S_{e\gamma(\pi)} \right)$$

- R_{had} smaller than in top-down approach
- ~Insensitive to the MC X_{max} scale

Summary of tests of models using Auger data

test	energy / EeV	θ / $^\circ$	Epos-LHC	QGSJet-II-04	Sibyll 2.3d
X_max moments	$\sim$3 to 50	0 to 80	no tension 🟩	tension 🟥	no tension (2.3c) 🟩
X_max:$S(1000)$ correlation	3 to 10	0 to 60	no tension 🟩	tension 🟥	no tension (2.3c) 🟩
mean muon number	$\sim$10	$\sim$67	tension 🟥	tension 🟥	tension 🟥
mean muon number	0.2 to 2	0 to 45	tension 🟥	tension 🟥	—
fluctuation of muon number	4 to 40	$\sim$67	no tension 🟩	no tension 🟩	no tension 🟩
muon production depth	20 to 70	$\sim$60	tension 🟥	no tension 🟩	—
$S(1000)$	$\sim$10	0 to 60	tension 🟥	tension 🟥	—

- All models have problems ...
- Caveat: mass (MC X_max scale) & energy scale
- Can we test the models better?

Combining SD and FD observables

Ground signal + Longitudinal profile

- correlation between X_{max} and S(1000)

-

- top-down approach -> R_{had}

- applying universality approach -> R_{had}

- 2-dim distributions [S(1000),X_{max}] -> $R_{had}(\theta)$, ΔX_{max}

> - **Rest of the talk**
>   [Phys. Rev. D 109 (2024) 102001]

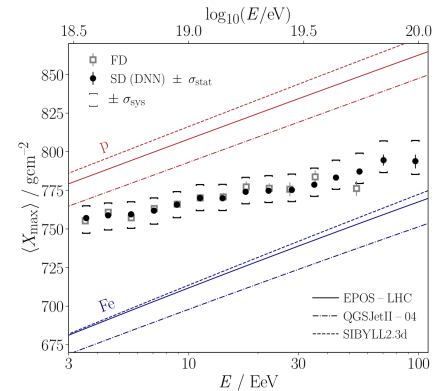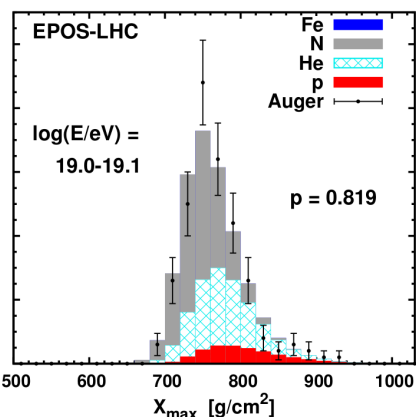# Mass composition & tests of hadronic interactions

MC X_{max} scale ?   Prim. fraction fit   Deficit in MC hadronic signal   ~ model-independent estimation of beam mixing from [X_{max},S(1000)] correlation
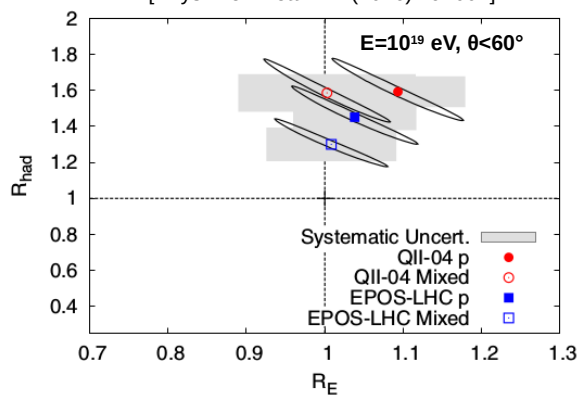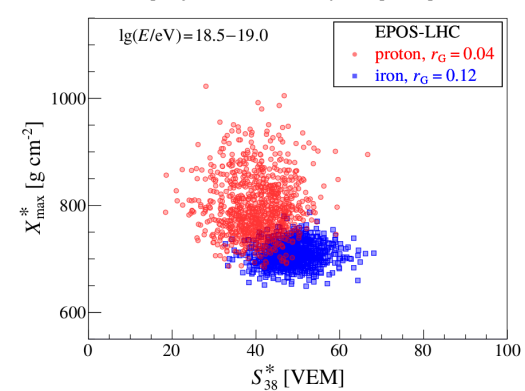
Following work: **Mass composition fit** of observed [X_{max},S(1000)](θ) distributions with free modification of MC predictions **not only of hadronic signal but also of X_{max}**
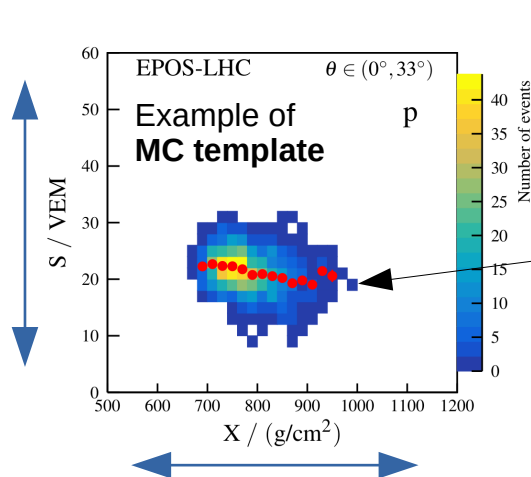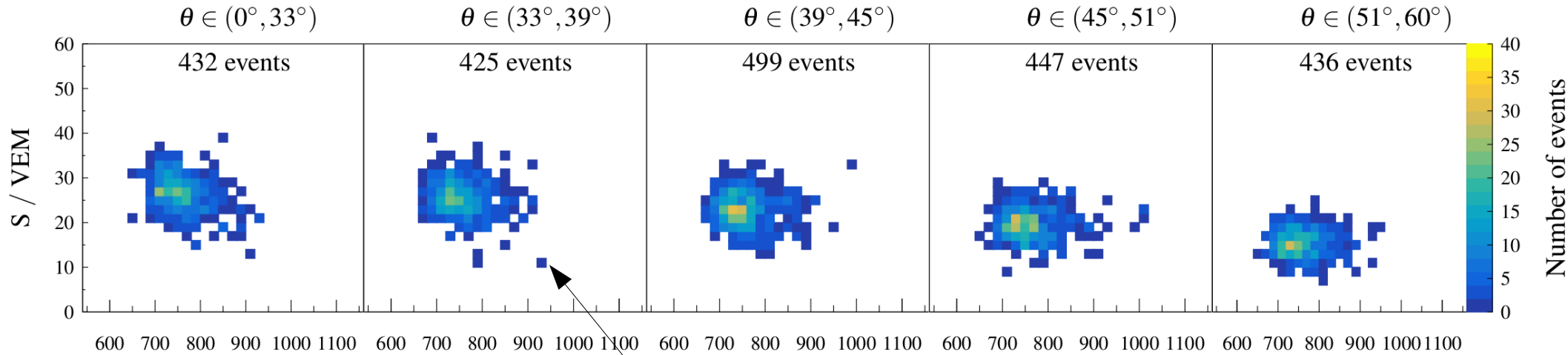
Auger data:
2239 HQ events for $10^{18.5-19.0}$ eV

Method

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

$$X = X_{\text{max}} + D \lg \left(\frac{E^{\text{ref}}}{E_{\text{FD}}} \right)$$
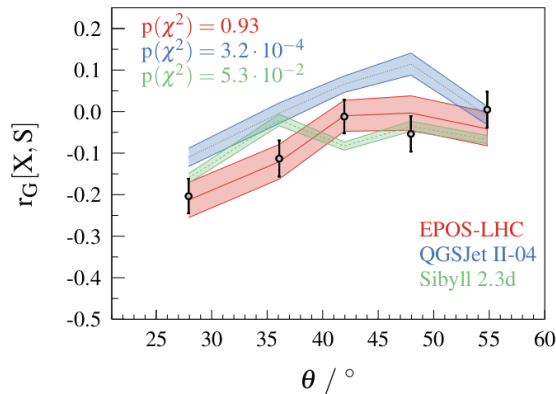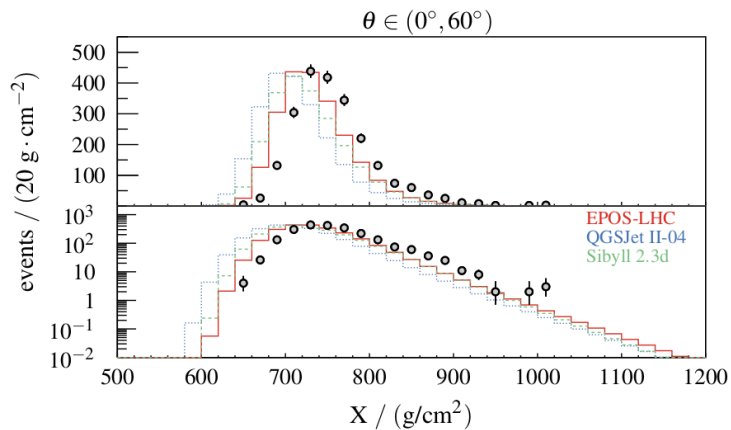
$E^{\text{ref}} = 10^{18.7}$ eV

$\theta \in (0°, 33°)$ $\theta \in (33°, 39°)$ $\theta \in (39°, 45°)$ $\theta \in (45°, 51°)$ $\theta \in (51°, 60°)$

432 events   425 events   499 events   447 events   436 events

$X / (\text{g/cm}^2)$

Example of **MC template**

EPOS-LHC $\theta \in (0°, 33°)$ p

$$\ln \mathscr{L} = \begin{cases} \sum_{k} \sum_{j} \left(C_{jk} - n_{jk} + n_{jk} \ln \frac{n_{jk}}{C_{jk}} \right), & n_{jk} > 0 \\ \sum_{k} \sum_{j} C_{jk}, & n_{jk} = 0 \end{cases}$$
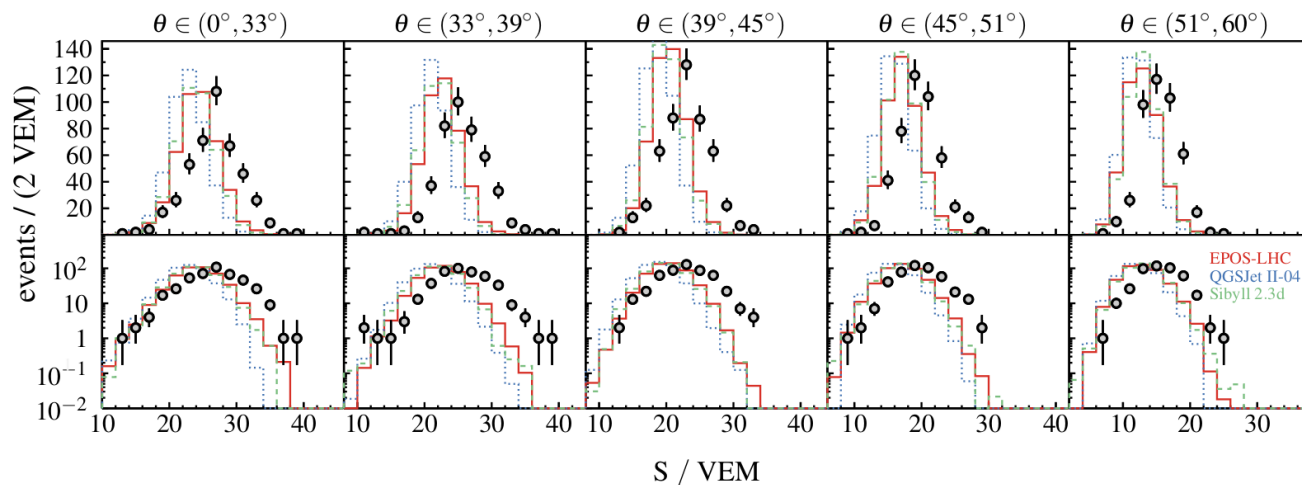
- **Freedom** in X_{max} (ΔX_{max}) and S(1000) ($R_{\text{had}}(\theta)$) and primary fractions

- 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)
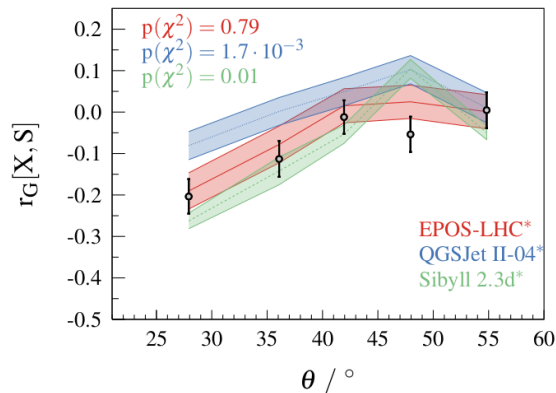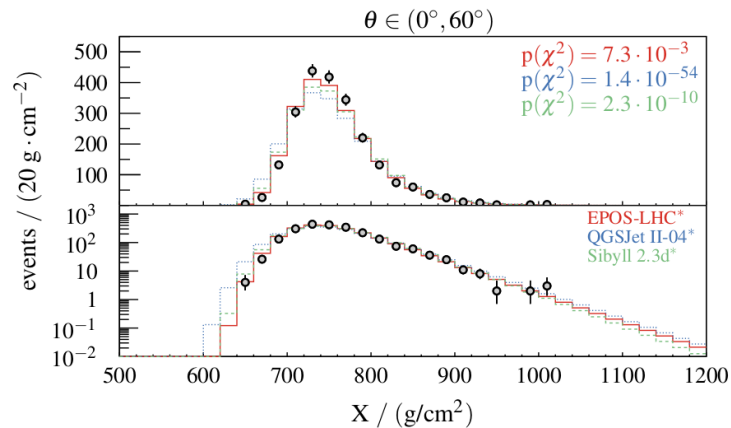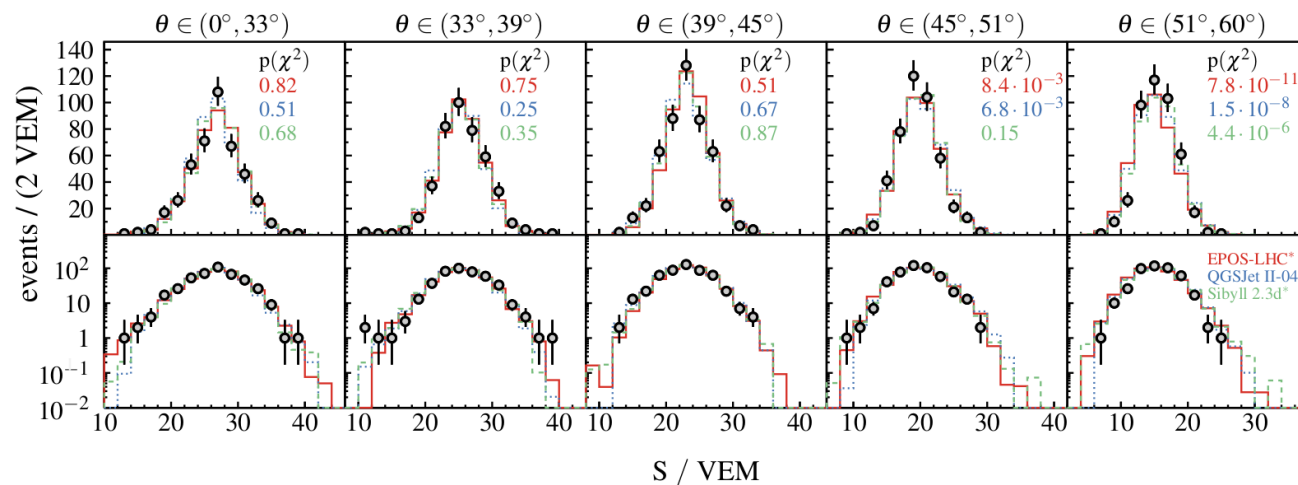
Improvement in data description

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

Improvement in data description
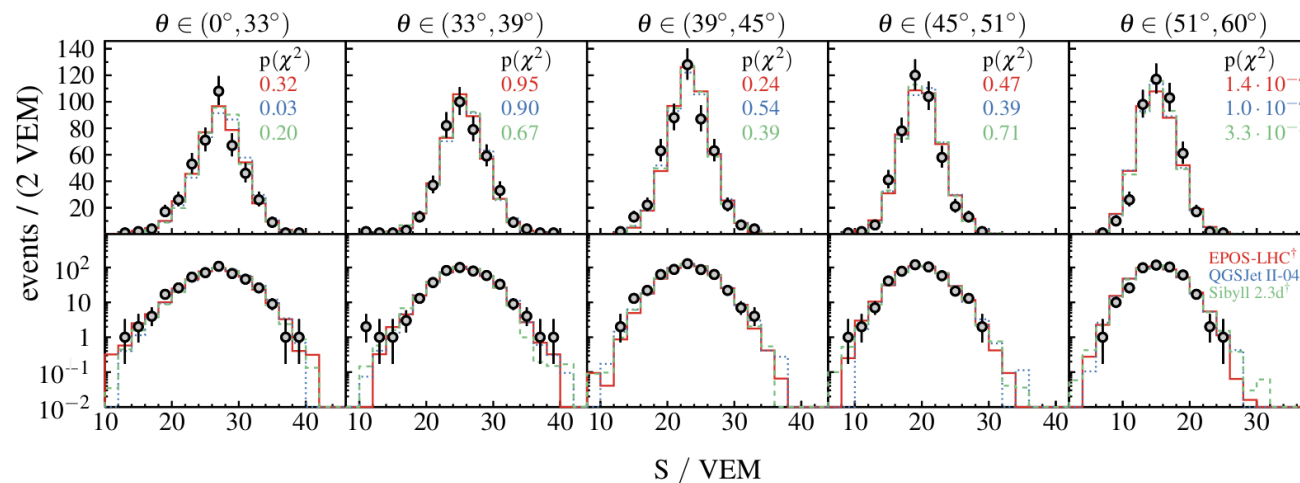
Improvement in data description
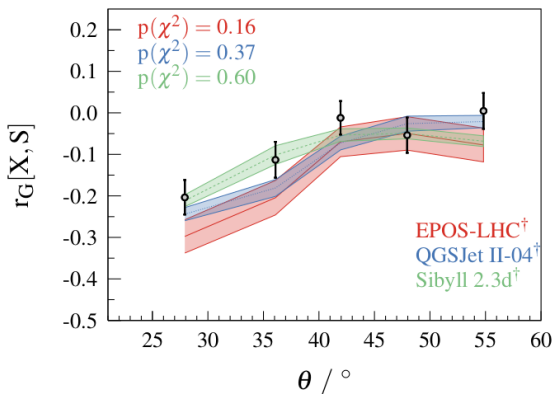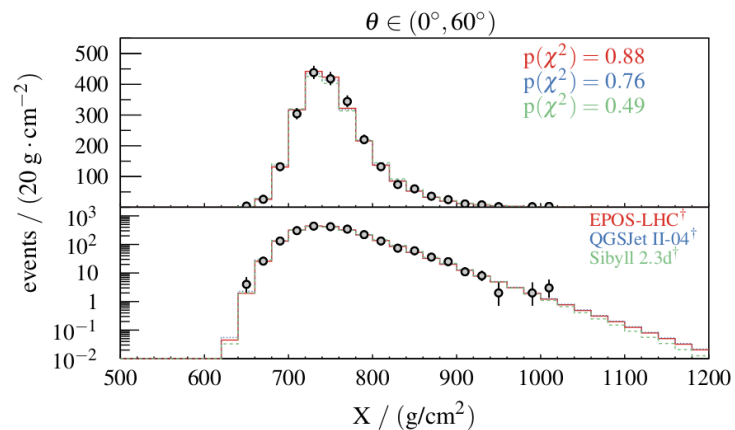
p-values of fits from MC-MC tests > 10% for all three models

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

Significant improvement >5σ using R_{had} and $\Delta X_{\max}$
(Likelihood ratio tests for nested model using Wilks' theorem)

Fitted parameters
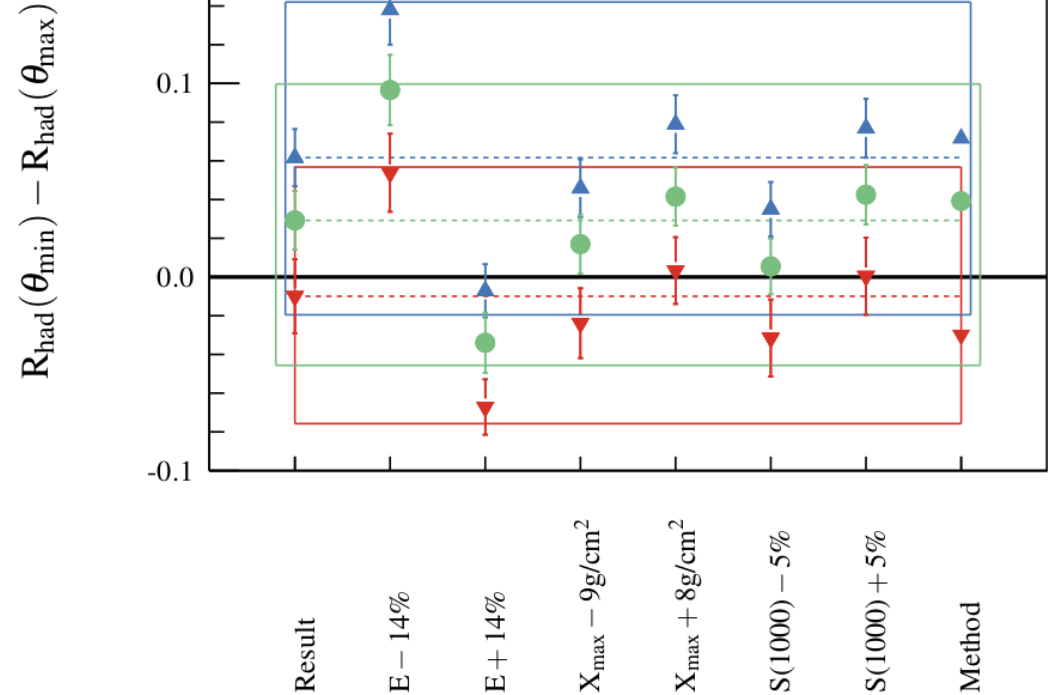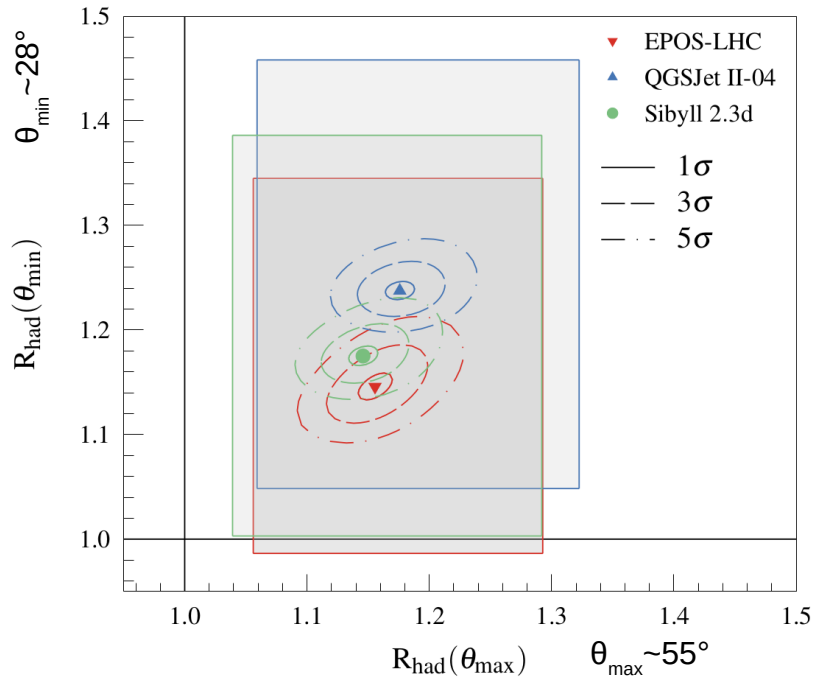
Zenith dependence of R_{had} assumed to be linear in $X_{ground}-X_{max}$
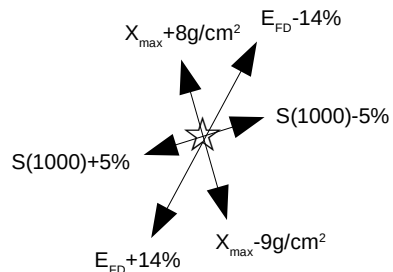$\rightarrow R_{had}(\theta_{min}\sim 28°)$, $R_{had}(\theta_{max}\sim 55°)$
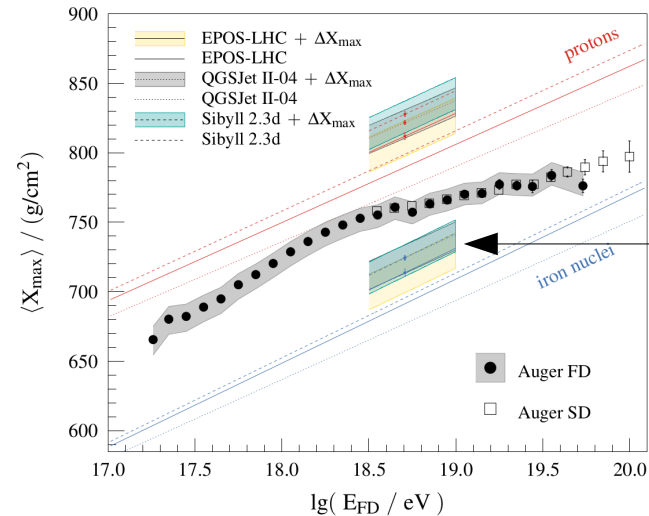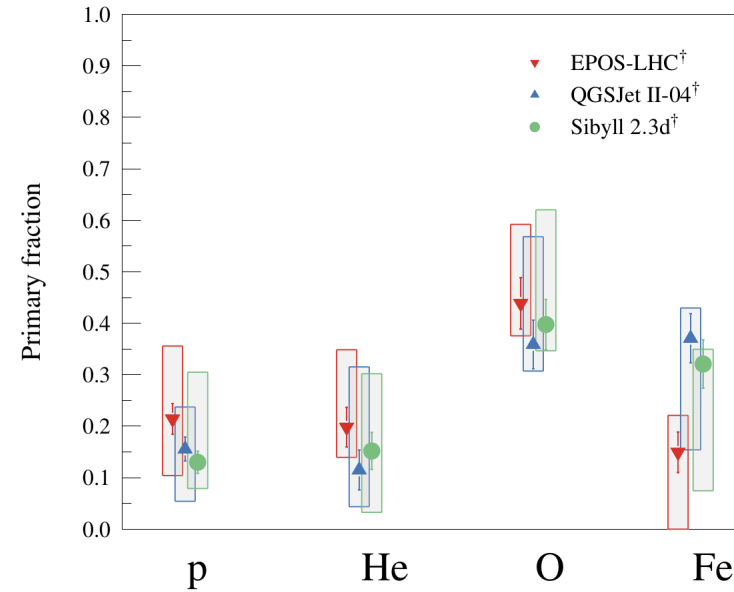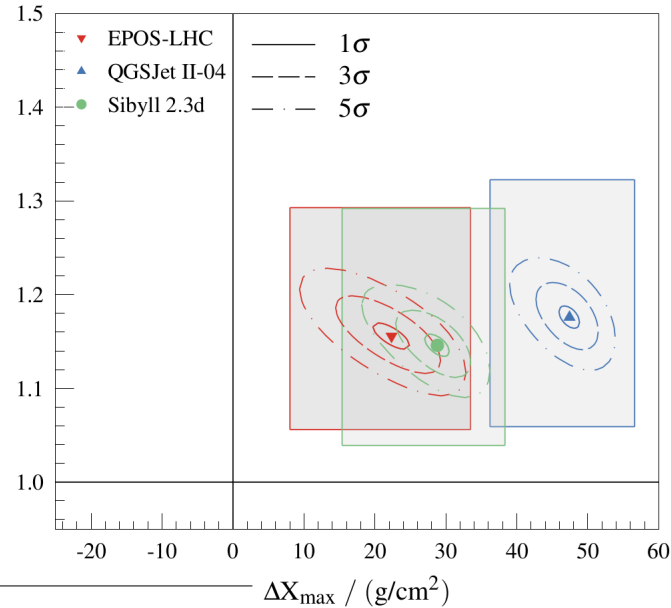
- **Deeper X_{max} predictions for all models !**
- Alleviated "muon problem"
- Smaller model differences in mass composition
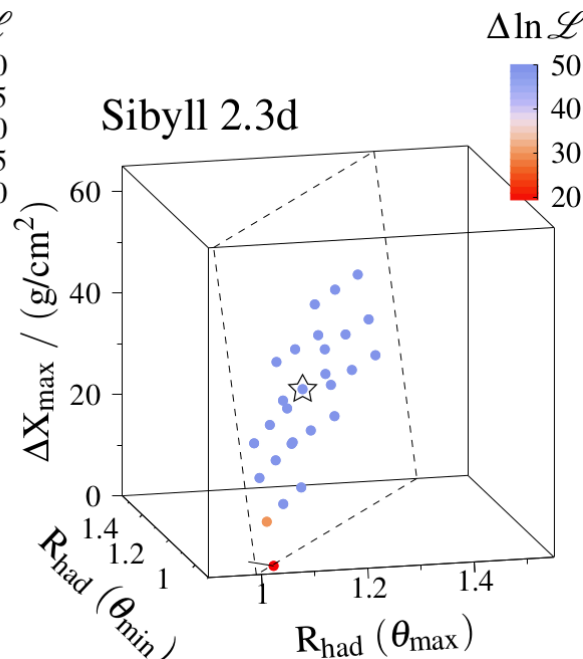
Attenuation of hadronic signal with θ

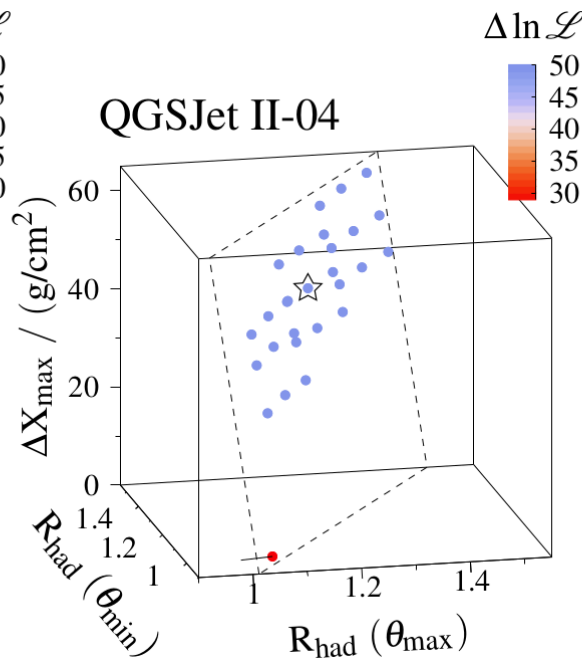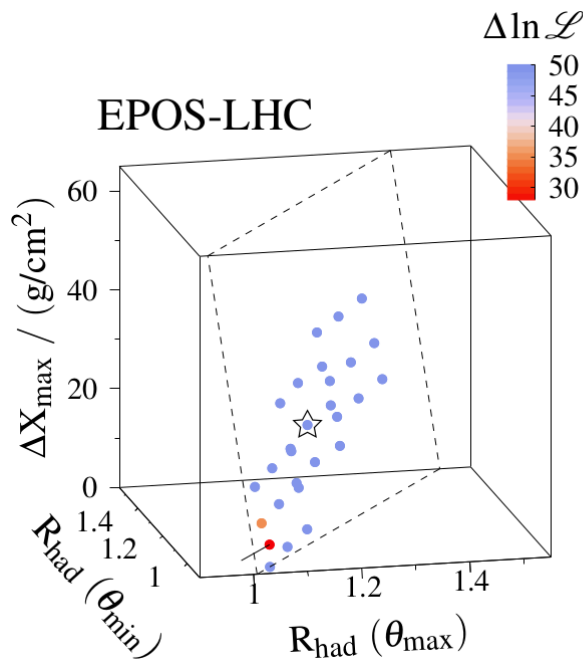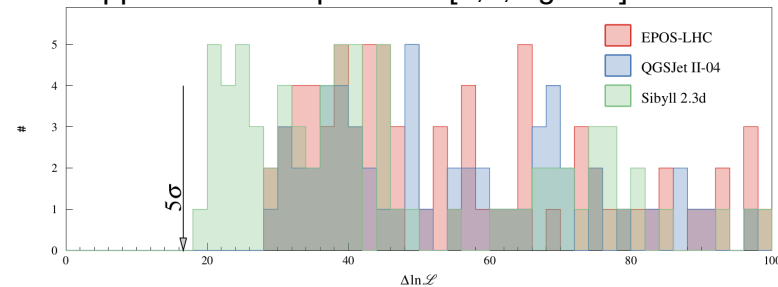Indication of harder muon spectra in QGSJet II-04 than in data

Scanning in combinations of experimental systematics

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

X$_{max}$+8g/cm^2 E$_{FD}$-14%

S(1000)-5%

S(1000)+5%

E$_{FD}$+14% X$_{max}$-9g/cm^2

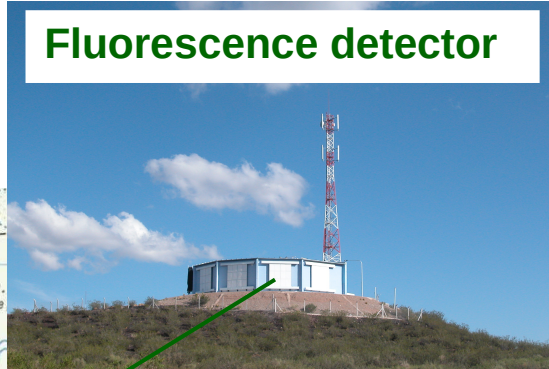Significance of improvement of data description always above 5σ

Conclusions

- Models of hadronic interactions fail to describe data of the Pierre Auger Observatory

- To improve description of combined SD and FD data at $10^{18.5\text{-}19.0}$ eV, $\theta < 60°$, we need from all current models:
  - more generated muons by about **(15 to 25)%** - alleviated "muon problem"
  - deeper generated X_{max} by about **(20 to 50) g/cm²** - consequence of possibly heavier mass composition

- This improvement in data description using R_{had} and ΔX_{max} **> 5σ** for any linear combination of experimental systematic uncertainties
  - Check [Phys. Rev. D 109 (2024) 102001] for more details

- Outlook:
  - *Auger Phase I data* (+~30%): extend energy range, adopt possible mass-dependence of modifications and study effects of fluctuations, test new models (*p+O run @ LHC*)
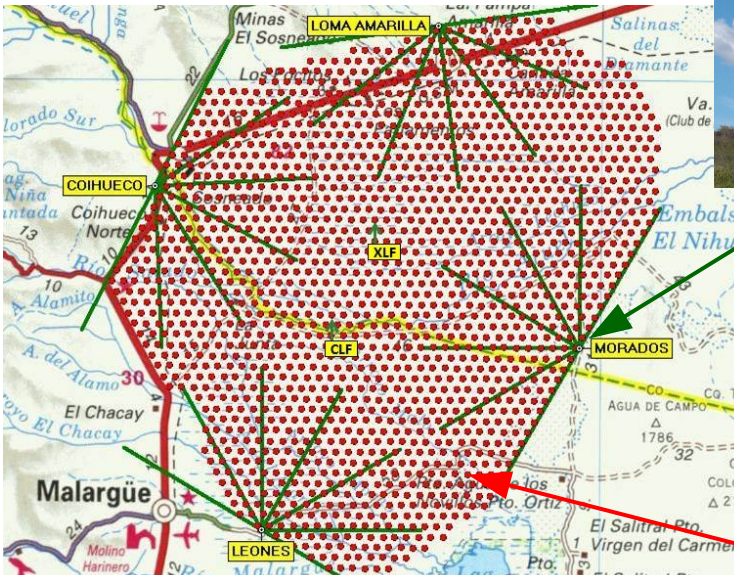 - *AugerPrime data*: better discrimination of hadronic signal, core distance dependance

Backup slides

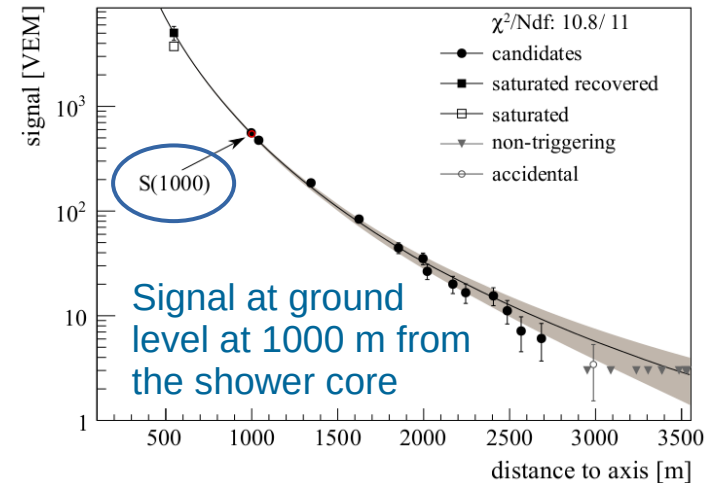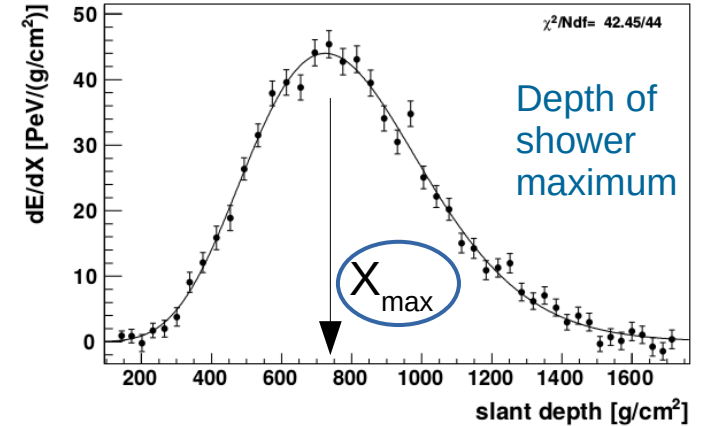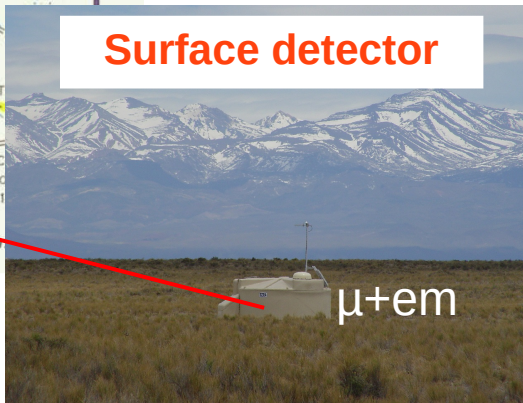# Hybrid detection at the Pierre Auger Observatory

Fluorescence detector

Surface detector

μ+em

[Nucl. Instrum. Meth. A 798 (2015) 172]

Depth of shower maximum

X_{max}

$S(1000)$

Signal at ground level at 1000 m from the shower core

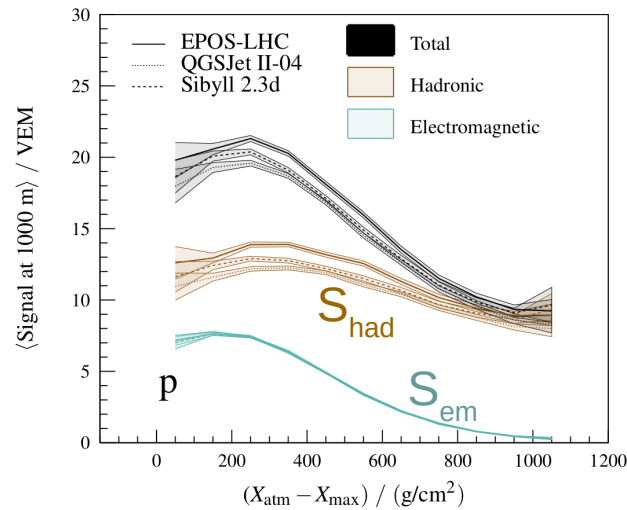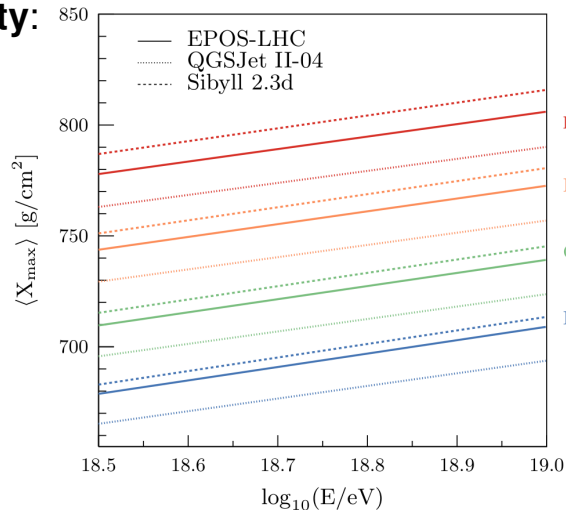# Motivations for modifications of MC predictions

- Properties of **4-component shower universality**:

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

  – $S(1000) = S_{had} + S_{em}$

  – S_{em} 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**
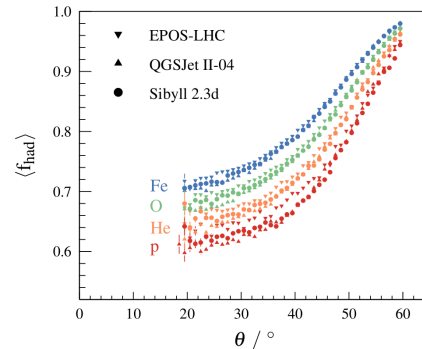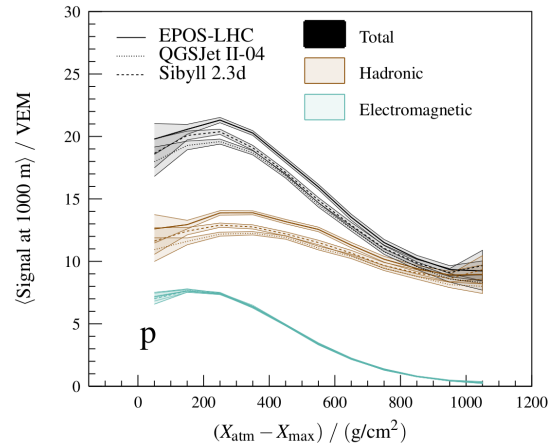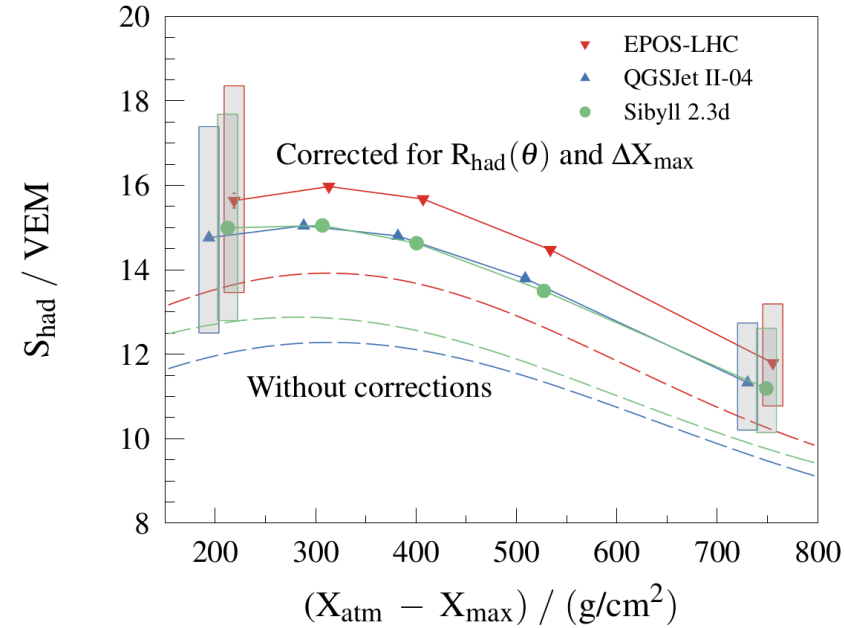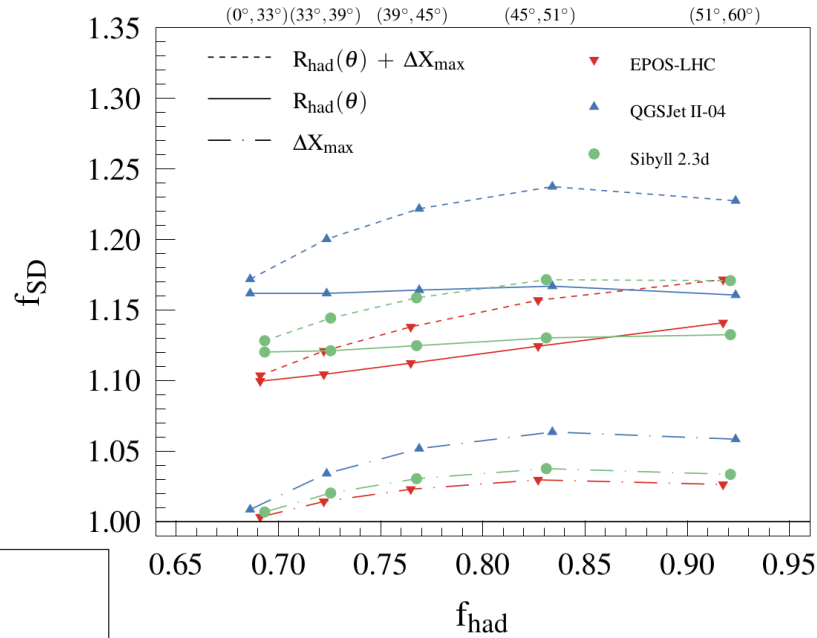

$$X_{atm} = 880/\cos\theta \quad g/cm^2$$

Caveat: no modifications in fluctuations or mass-depencies etc. considered

ad-hoc modifications

$$X_{max} \rightarrow X_{max} + \Delta X_{max}$$
$$S_{had}(\theta) \rightarrow S_{had}(\theta) \cdot R_{had}(\theta)$$

# Effect of modified X_max on the ground signal

Assumption on primary species

- ΔX_{max} decreases by about 5-7, 10-17 and 30-40 g/cm^2 and $R_{had}(\theta)$ increases by about 2-5%, 4-9% and 15-20% when the heaviest primary Fe is replaced by Si, O and He, respectively

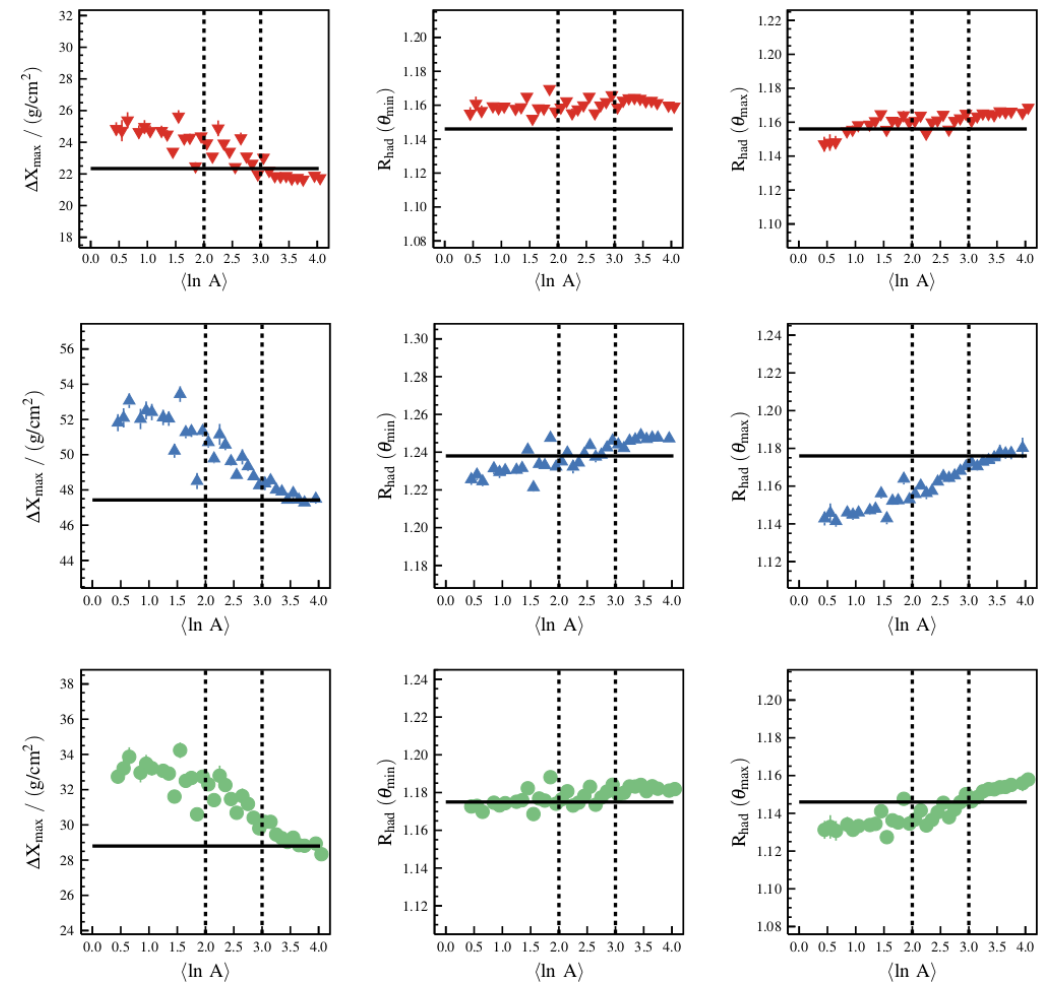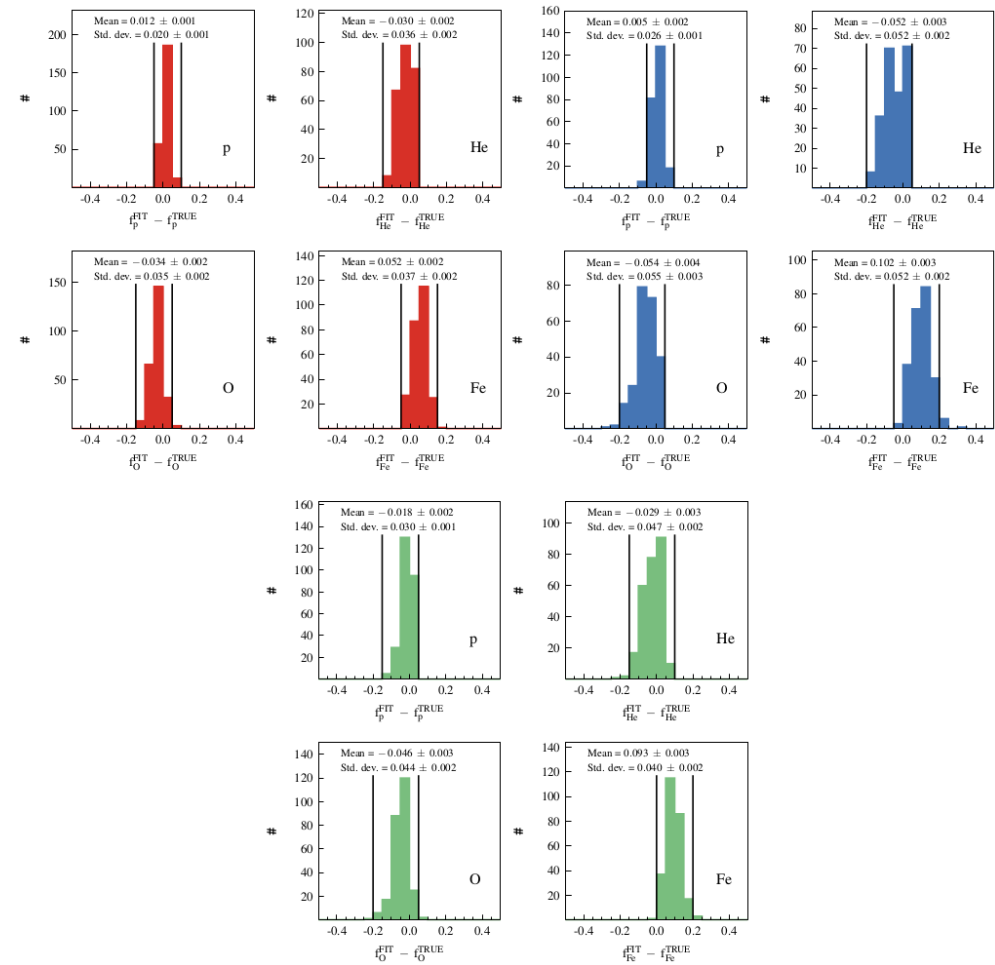| $\ln \mathscr{L}_{min}$	EPOS-LHC	QGSJET-II-04	SIBYLL 2.3d
p He	518.3	633.5	563.5
p He O	467.5	523.3	486.6
p He O Fe	451.9	476.3	451.6

Significance of improvement of data description above 5σ

Systematic uncertainties
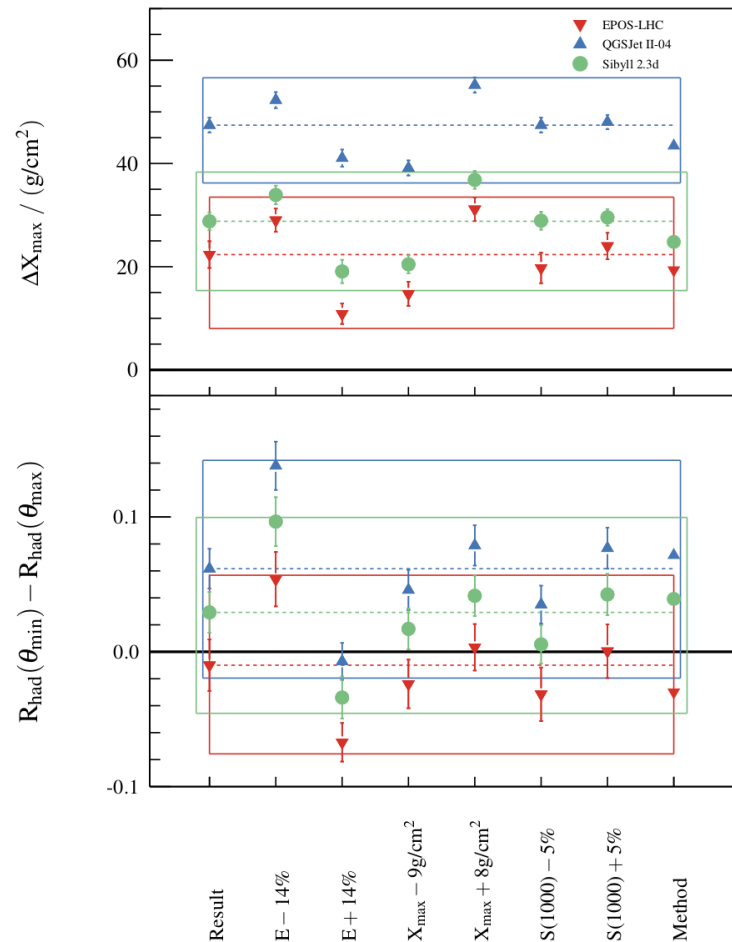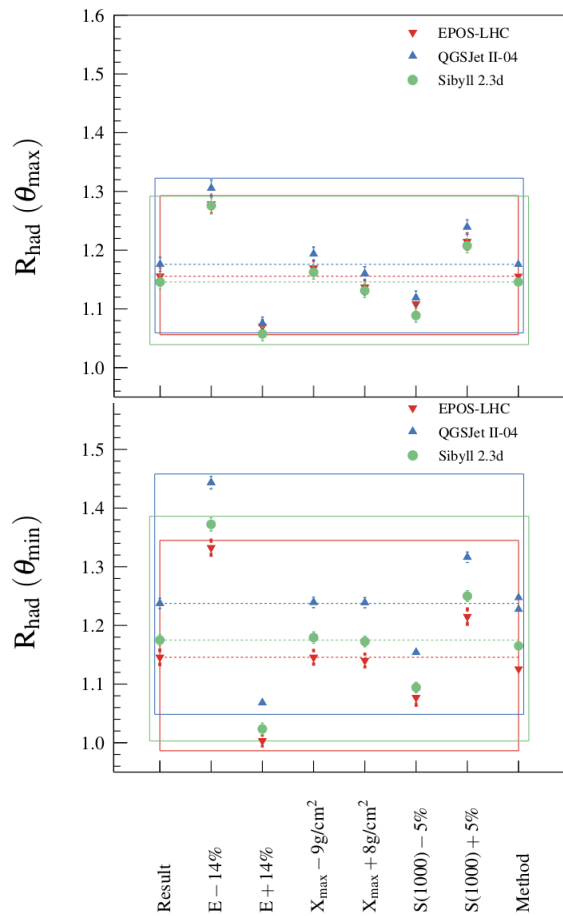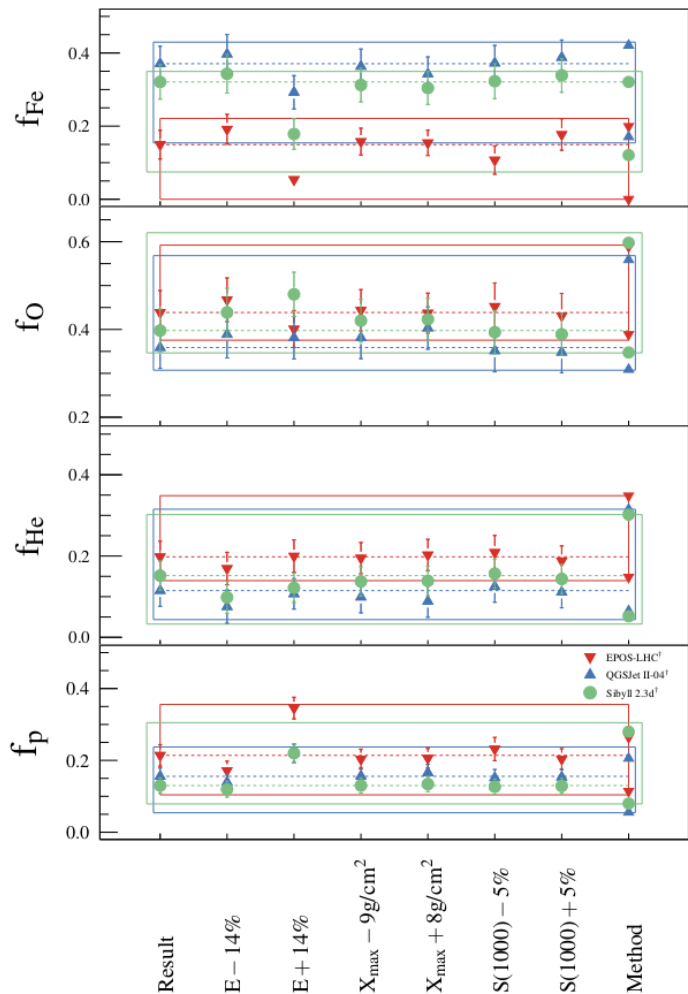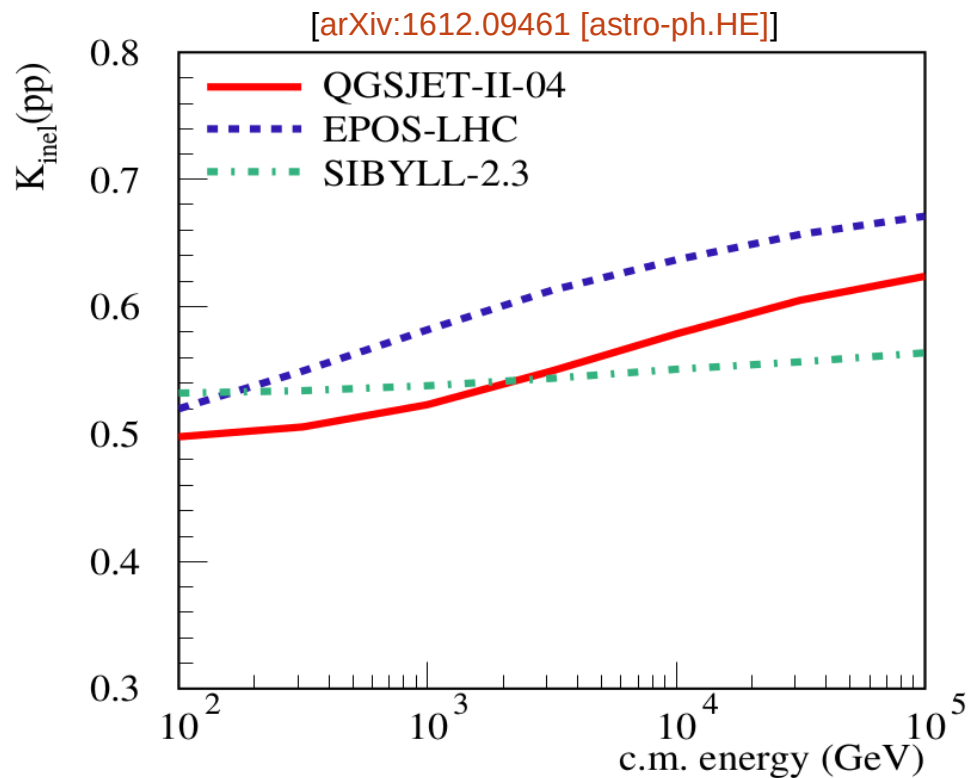
MC-MC tests

Possible mass-(in)dependence of X_{max} shift

"changing the normalization of energy dependence" ➔ mass independent modifications

[arXiv:1612.09461 [astro-ph.HE]]

multiplicity: $N \propto N_0 \cdot E^\alpha$
inelasticity: $\kappa \propto \kappa_0 \cdot E^{-\omega}$

$$X_{\mathrm{max}}^{\mathrm{A}} = X_1^A + X_0 \ln \frac{\kappa E}{A \cdot 2N \xi_c^\pi} =$$

$$X_1^A + (1 - \alpha - \omega) \cdot (X_0 \ln \frac{E}{A \cdot \xi_c^\pi}) + X_0 \cdot (\ln \kappa_0 - \ln N_0)$$

$$\begin{aligned} \kappa_0 &\to f_\kappa \kappa_0 \\ N_0 &\to f_N N_0 \end{aligned} \Rightarrow \quad X_{max}^A{}' = X_{max}^A + X_0(\ln(f_\kappa) - \ln(f_N))$$

MOCHI (preliminary) [PoS(ICRC2023)245]

"changing the shape of energy dependence" ➡ mass-dependent modifications