PIERRE AUGER OBSERVATORY

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PoS(ICRC2021)310

Adjustments to Model Predictions of Depth of Shower Maximum and Signals at Ground Level using Hybrid Events of the Pierre Auger Observatory

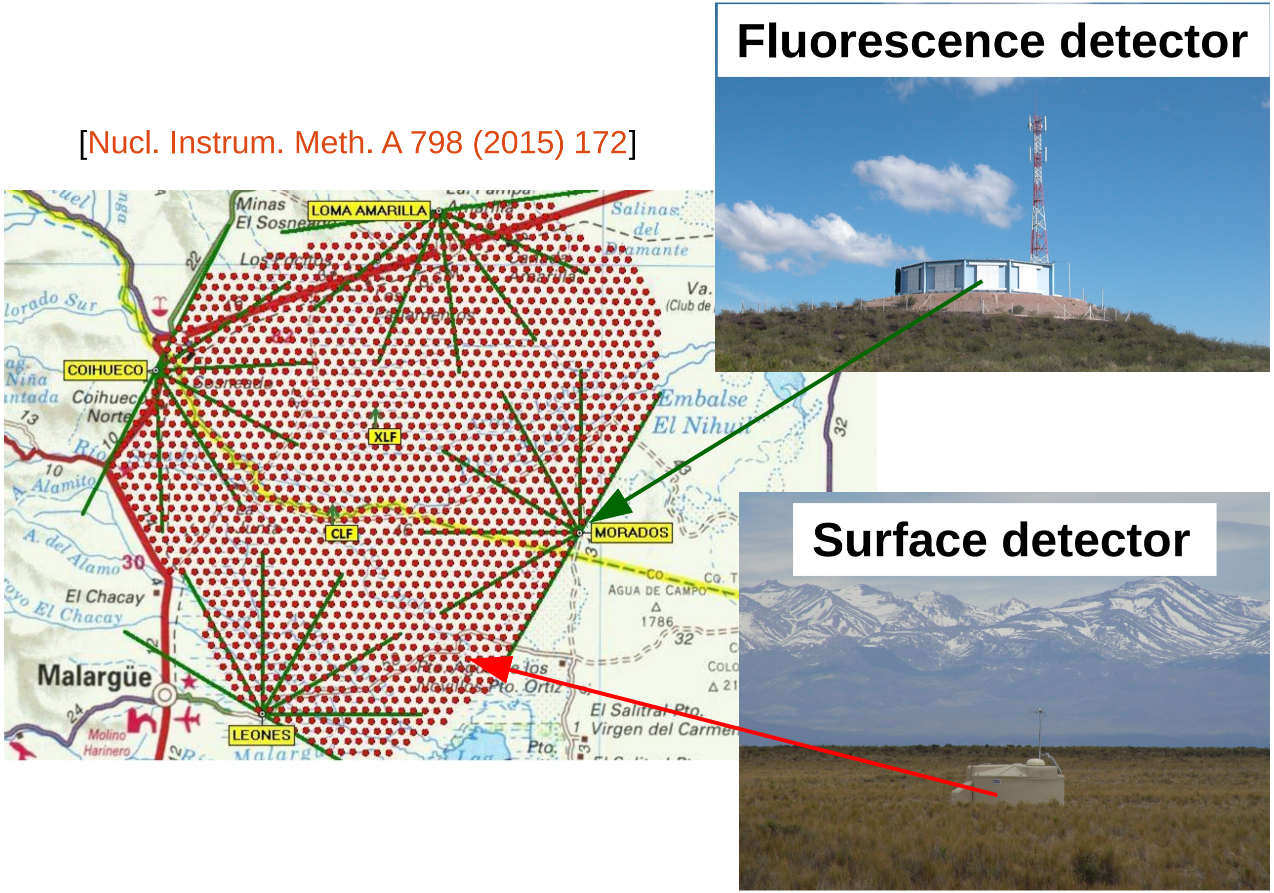
Jakub Vícha[a] for the Pierre Auger Collaboration[b]

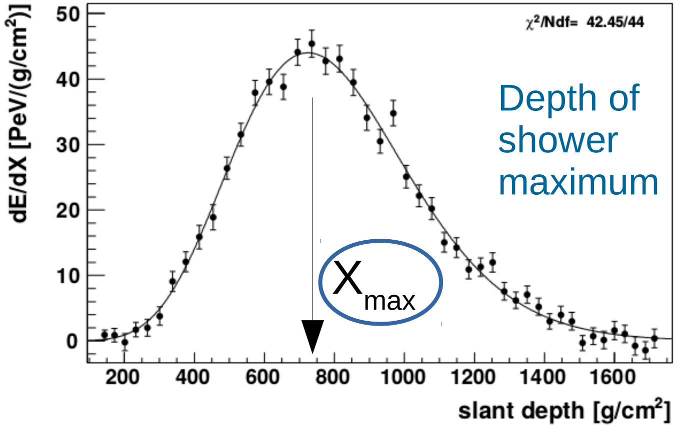
[a] Institute of Physics of the Czech Academy of Sciences, Prague
[b] Observatorio Pierre Auger, Av. San Martín Norte 304, 5613 Malargüe, Argentina

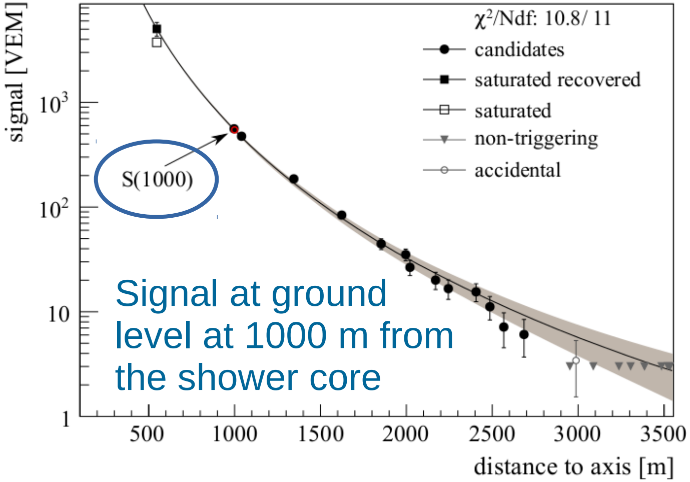
vicha@fzu.cz

Hybrid detection at the Pierre Auger Observatory

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





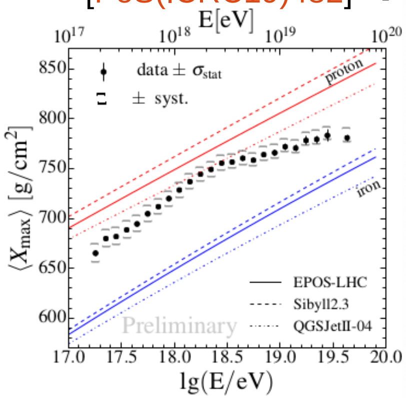


Mass composition & tests of hadronic interactions

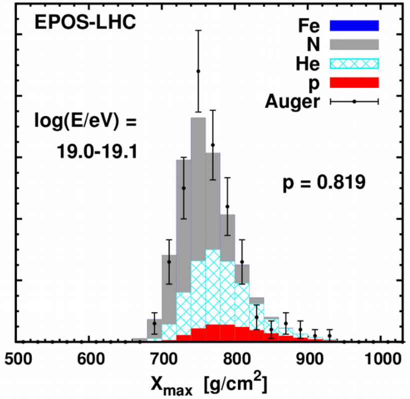
Deficit of simulated muon signal: previous analyses in Auger

1) **Mass composition is inferred from X_{max}** measurements using the nominal X_{max} predictions of hadronic interaction models

[PoS(ICRC19)482]

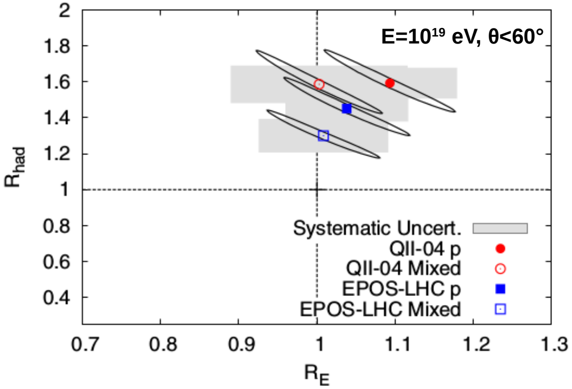


[Phys. Rev. D 90 (2014) 122006]

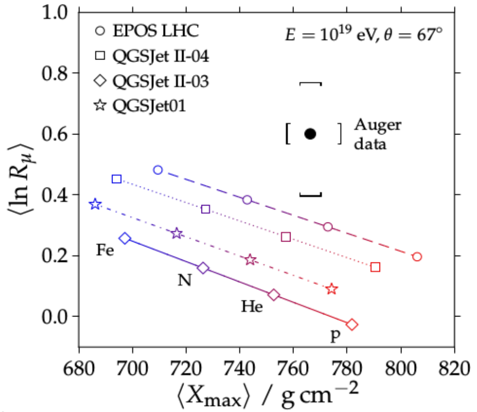


2) **Discrepancy in muon content at ground** between simulations and data is evaluated using the inferences on the mass composition from the X_{max} analysis

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



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

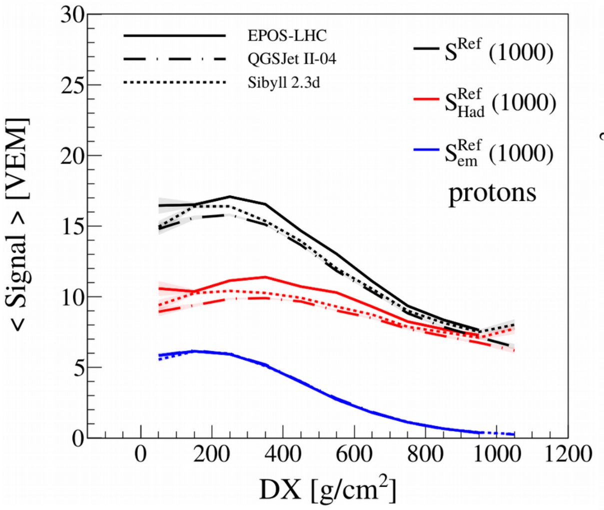


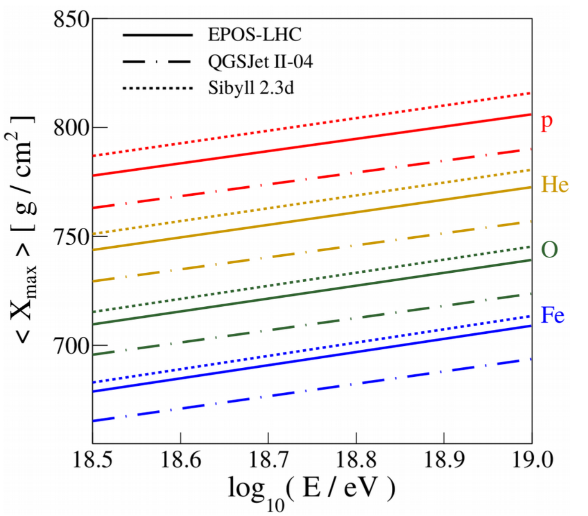
This work

Global fit of observed [X_{max},S(1000)] distributions with free mass composition and adjustments of MC predictions **not only to hadronic signal but also to X_{max}**

Motivations for adjustments 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
  - Scale of $\langle X_{max} \rangle$ and $S_{Had}(\theta)$ (normalization and attenuation of S_{Had}) are the **main differences** between model predictions that are roughly primary and energy independent





$$DX = 880\, g/cm^2/\cos(\theta) - X_{max}$$

- Not-accounted **higher-order model differences**:
  - fluctuations of X_{max} and $S(1000)$
  - mass dependence of $R_{Had}(\theta)$, ΔX_{max}
  - etc.

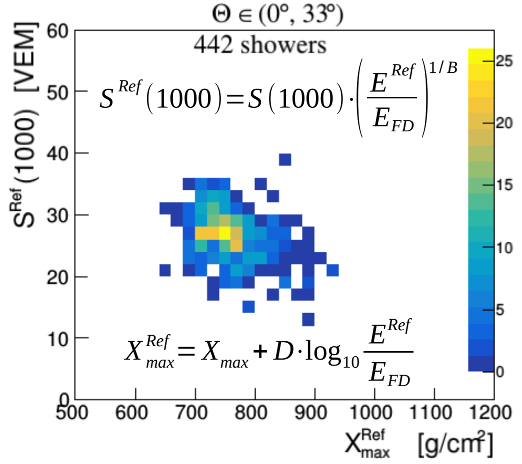
ad-hoc adjustments

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

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

Global fit method

Auger data

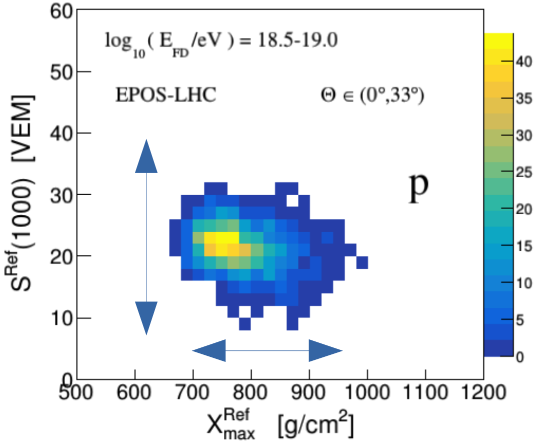


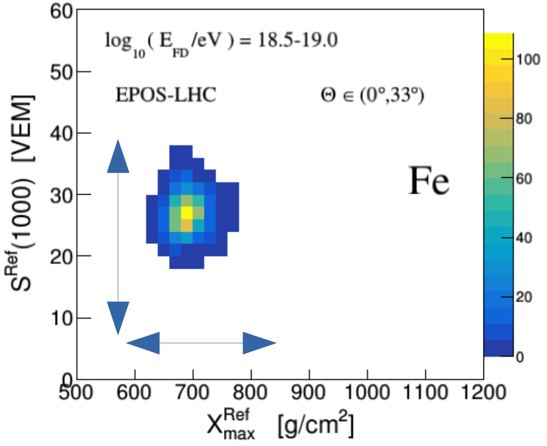
Simultaneous likelihood ratio fit of **two-dimensional distributions** of X_{max} and S(1000) in 5 zenith-angle bins with **MC templates** for combinations of four primary nuclei (p,He,O,Fe)

- **Freedom** in X_{max} (ΔX_{max}) and S(1000) ($R_{Had}(\theta)$) and primary fractions
- Change of S_{Had} and S_{em} due to ΔX_{max} incorporated
- **Degeneracy between mass composition and ΔX_{max} reduced due to the correlation between S(1000) and X_{max}**

[Phys.Lett. B762 (2016) 288]

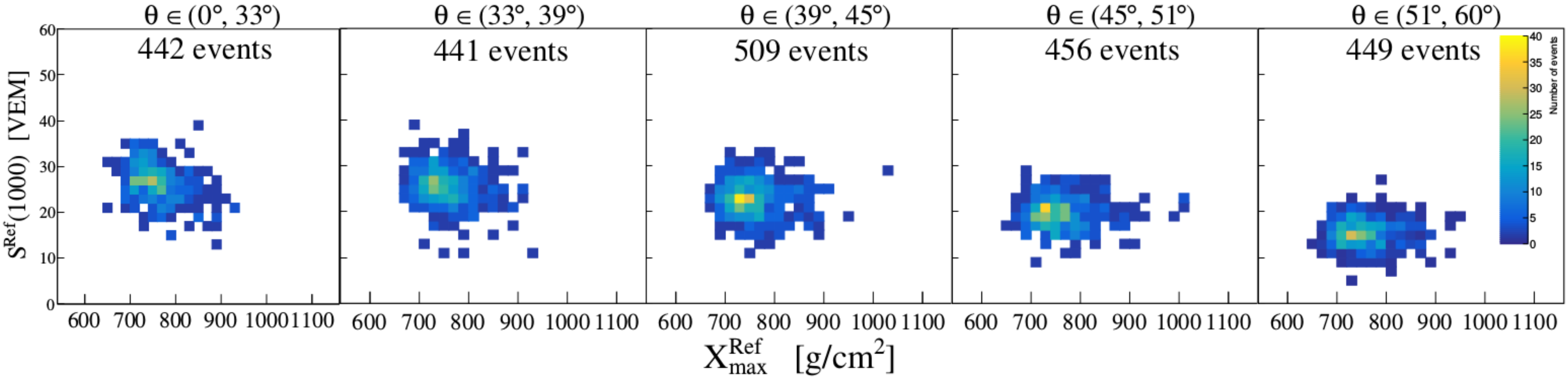
MC templates: from ~15k showers per primary and model (EPOS-LHC, QGSJet II-04, Sibyll 2.3d)





Measured data

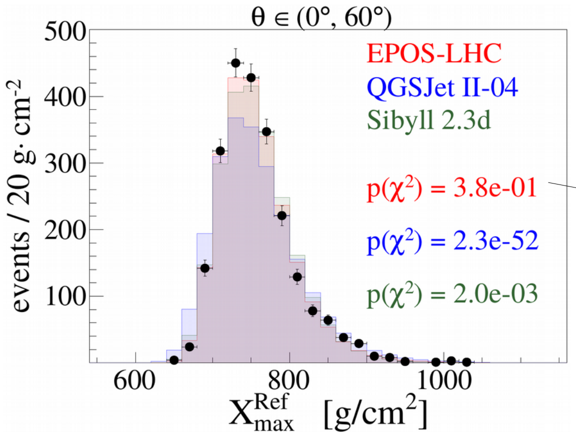
2297 high-quality showers for $\log_{10}(E_{FD}\ [\mathrm{eV}]) = \mathbf{18.5\text{-}19.0}$, $\theta < 60°$

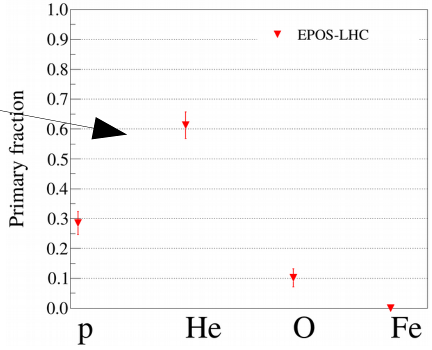


Event selection according to [Phys. Rev. D 90 (2014) 122005, PoS(ICRC19)482] and [Phys. Rev. D 102 (2020) 062005]

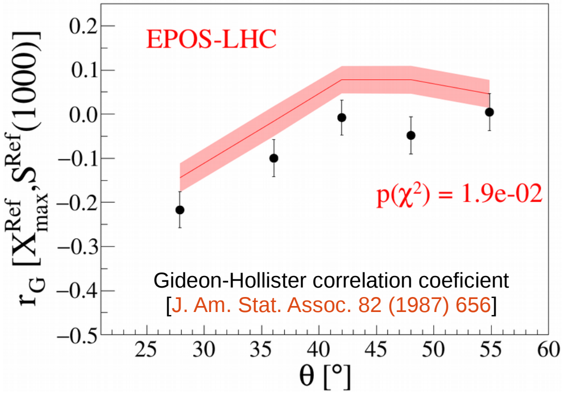
EPOS-LHC without any adjustment to MC predictions

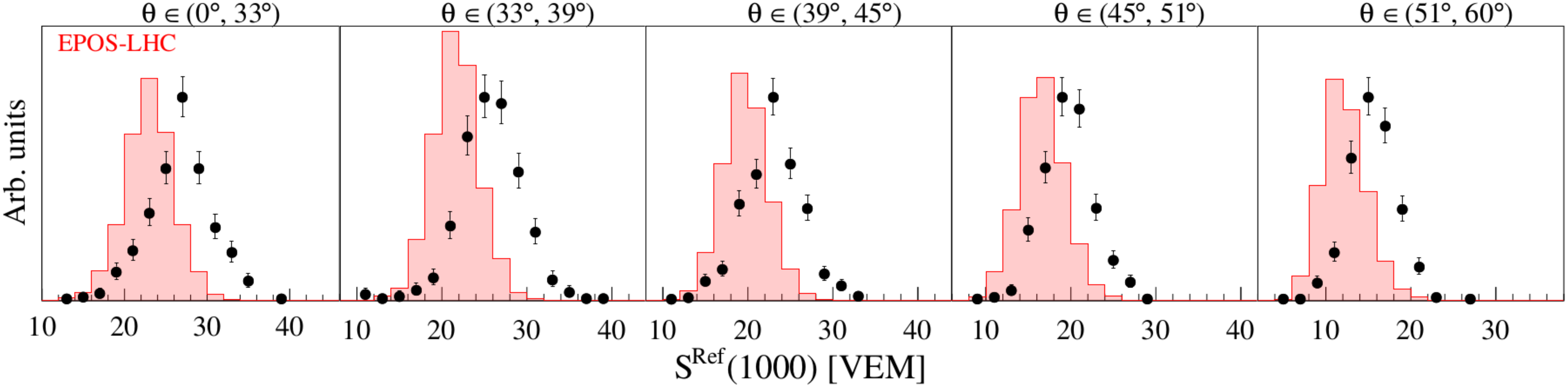
Fit X_{max} distribution to obtain **primary fractions**





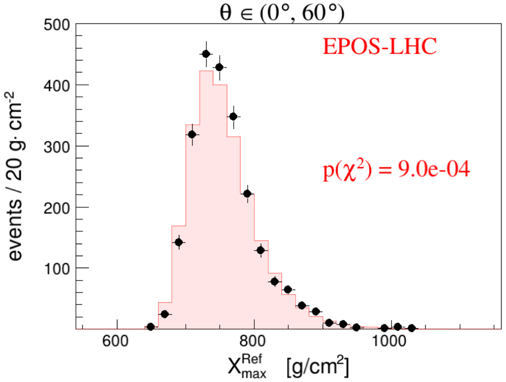
Reasonable fit to X_{max} using EPOS-LHC, but poor description of S(1000) and correlation of [S(1000), X_{max}]

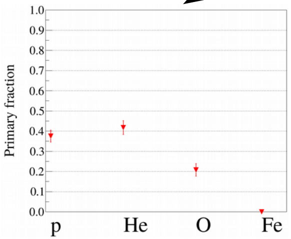


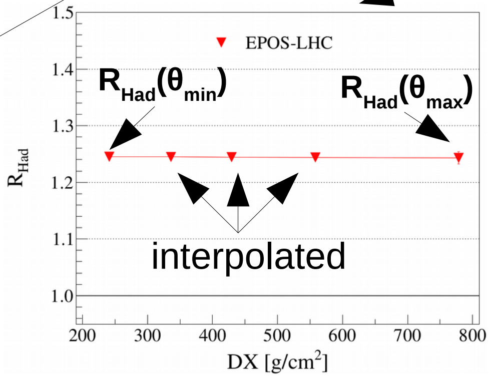


EPOS-LHC predictions adjusted for $R_{Had}(\theta)$

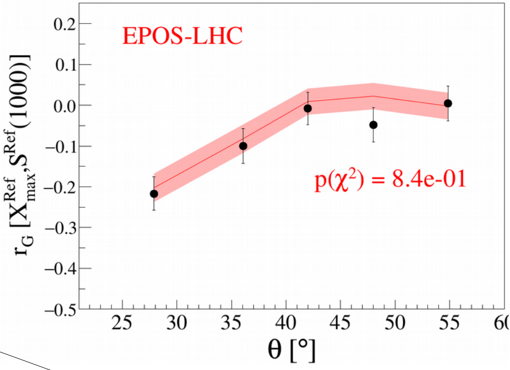
One global fit of [S(1000),X_{max}] distributions with free **primary fractions** and **$R_{Had}(\theta)$** (ΔX_{max} is fixed to zero)

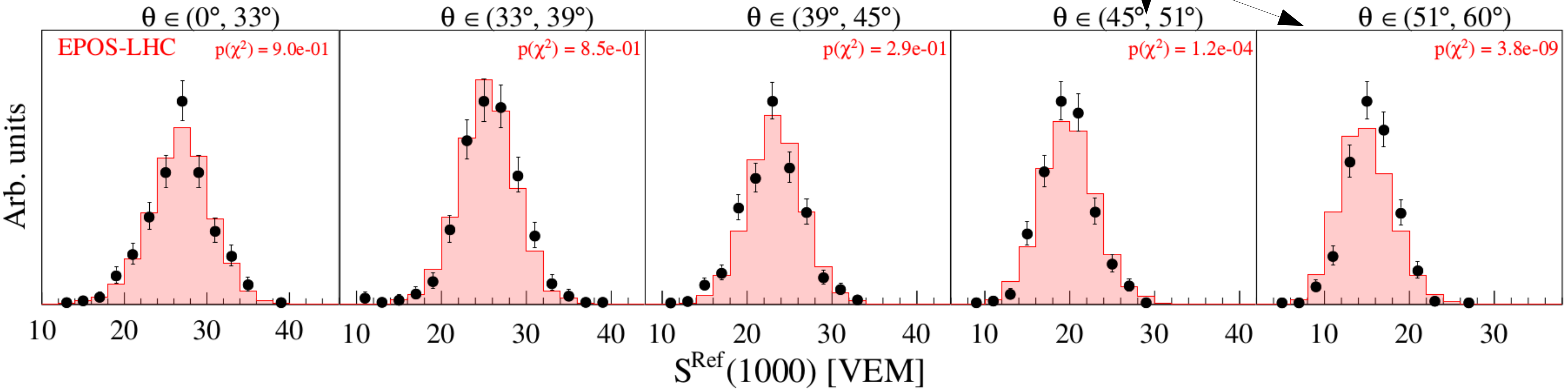






S(1000) at higher zeniths still poorly described

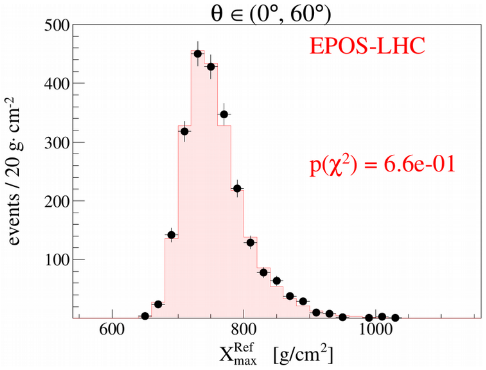


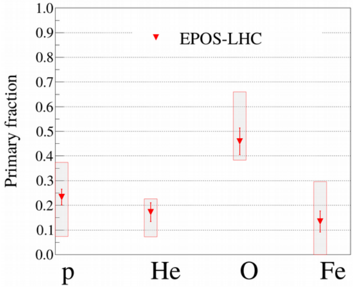


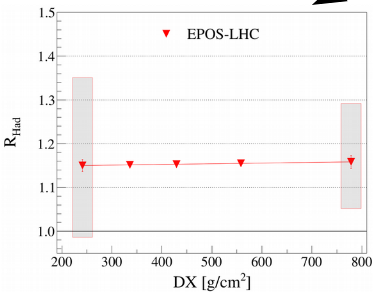
EPOS-LHC predictions adjusted for $R_{Had}(\theta)$ and ΔX_{max}

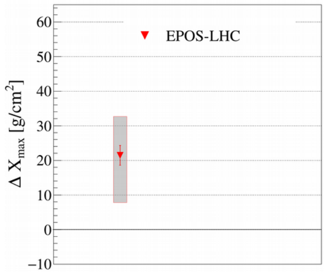
One global fit of [S(1000),X_{max}] distributions with free **primary fractions**, **$R_{Had}(\theta)$, ΔX_{max}**

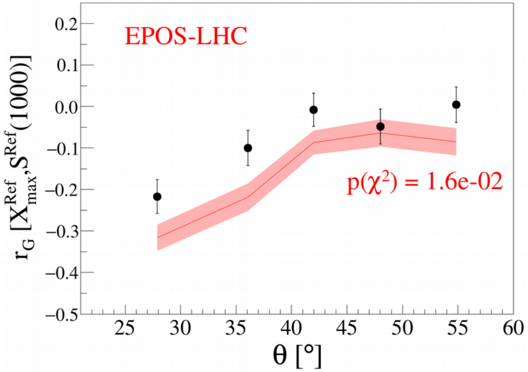
p-value of global fit: ~2.6%

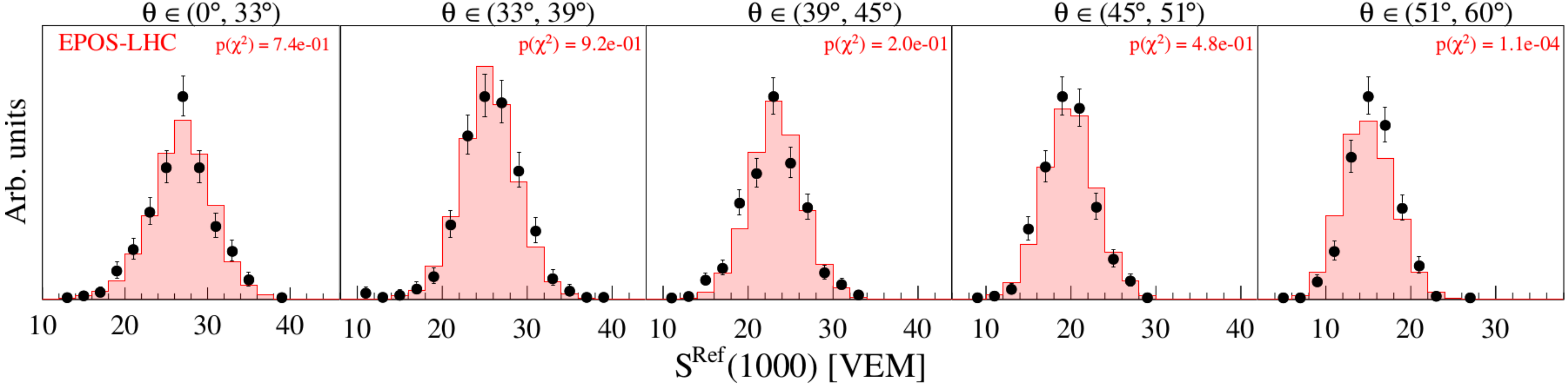








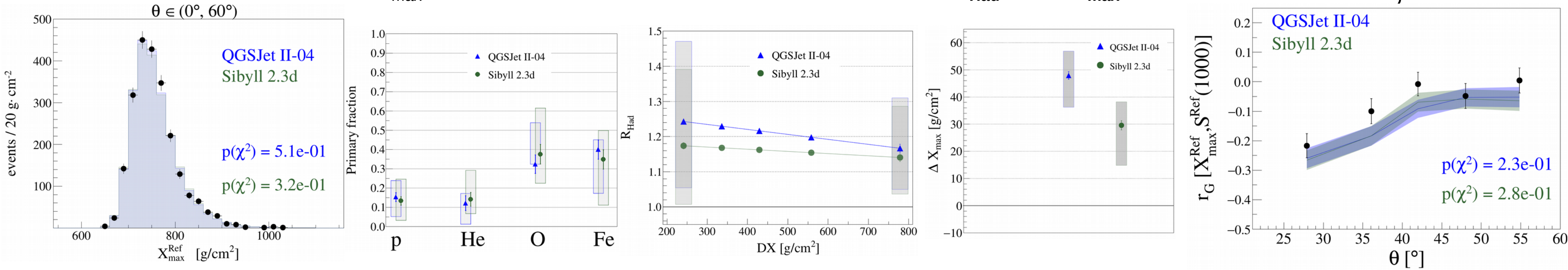


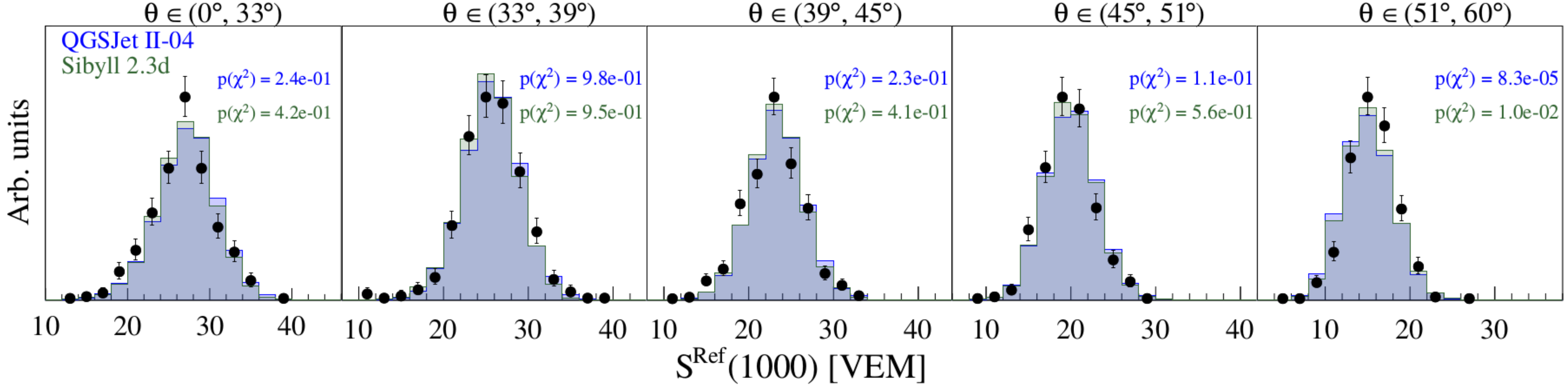


QGSJet II-04 and Sibyll 2.3d predictions adjusted for $R_{Had}(\theta)$ and ΔX_{max}

p-values of global fit:
~3.6%, ~18%

One global fit of [S(1000),X_{max}] distributions with free **primary fractions**, **$R_{Had}(\theta)$, ΔX_{max}**



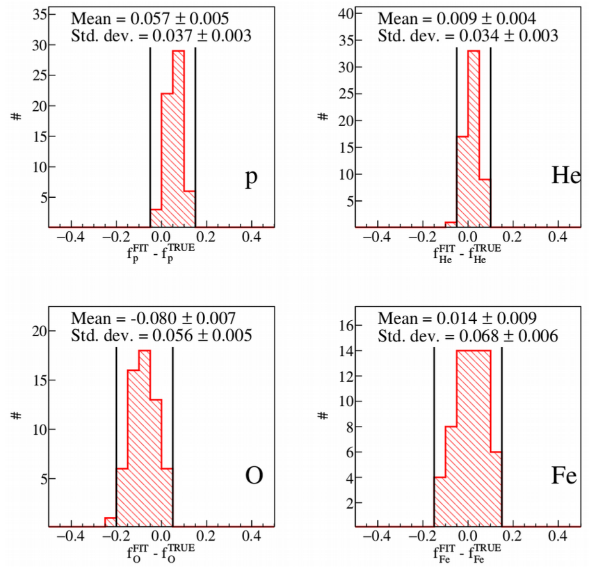


Systematic uncertainties

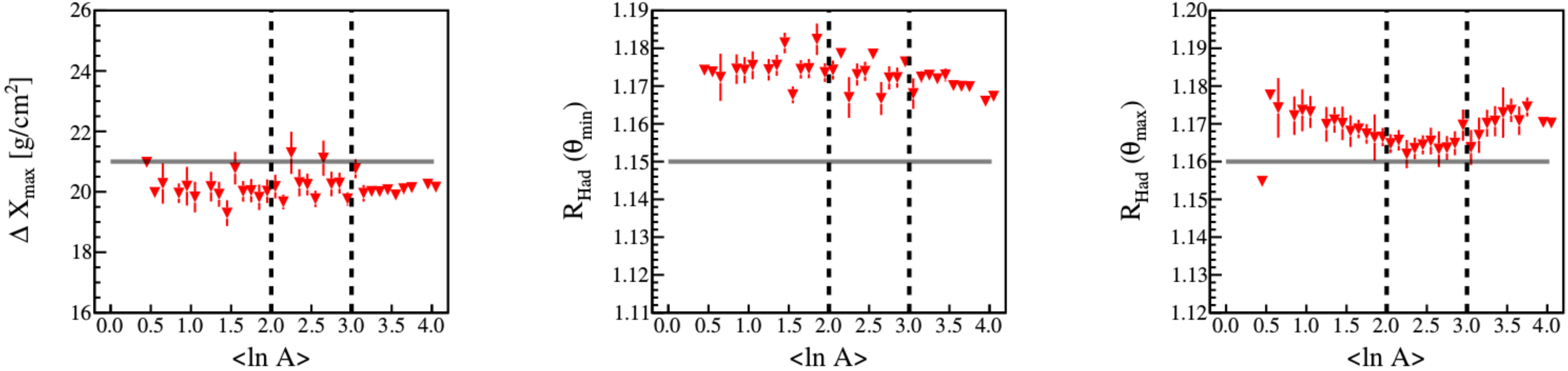
- Experimental
  1) Energy scale ± 14%
  2) X_{max} measurement +8, -9 g/cm²
  3) S(1000) measurement ± 5%
- Method
  4) Biases from MC-MC tests for each model

All four contributions summed in quadrature

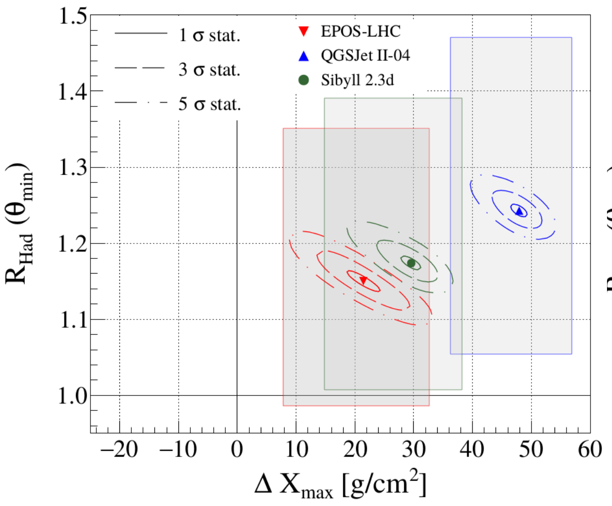
Method works within ~5 g/cm² for ΔX_{max} and few percent for R_{Had}

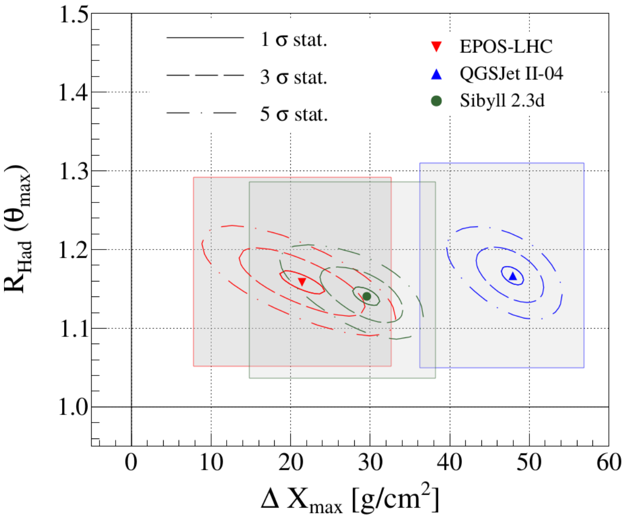


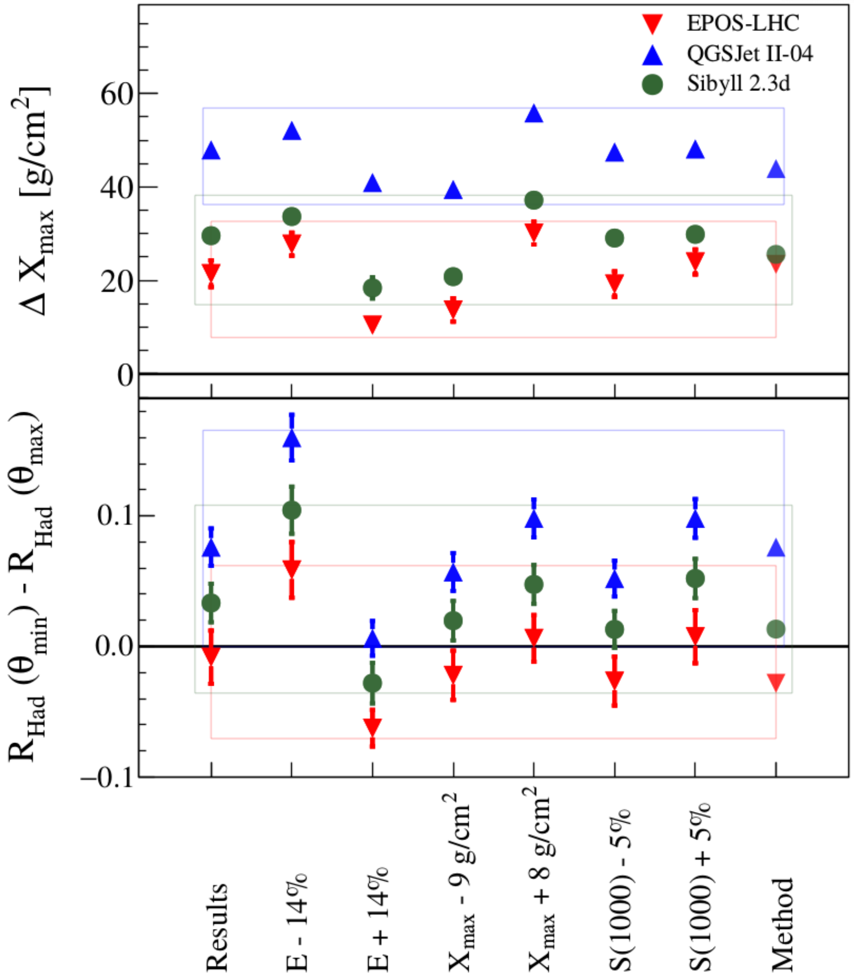
MC-MC test using EPOS-LHC with artificial changes in ΔX_{max}=21 g/cm², $R_{Had}(\theta_{min})$=1.15, $R_{Had}(\theta_{max})$=1.16

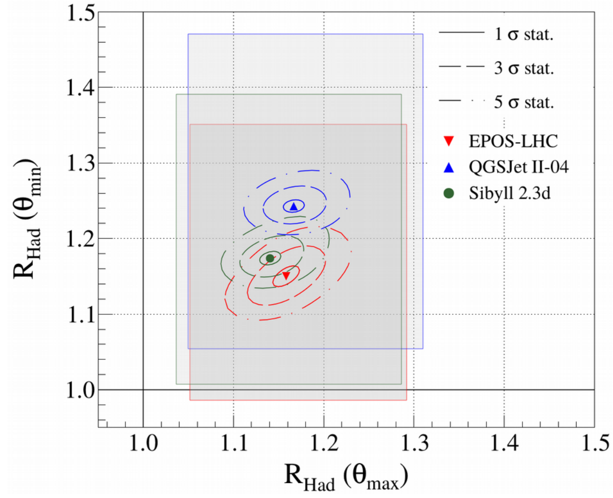


Results of the analysis





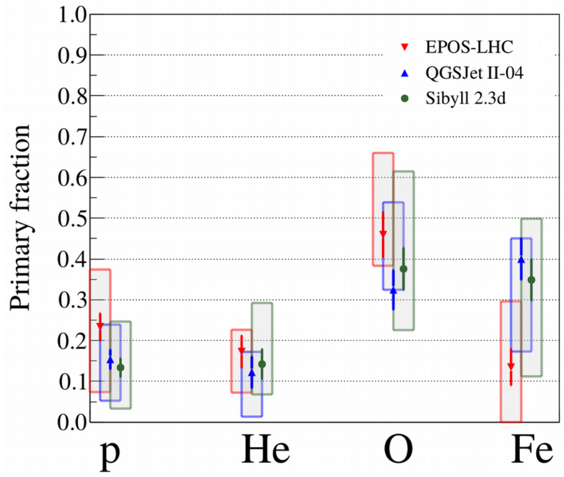


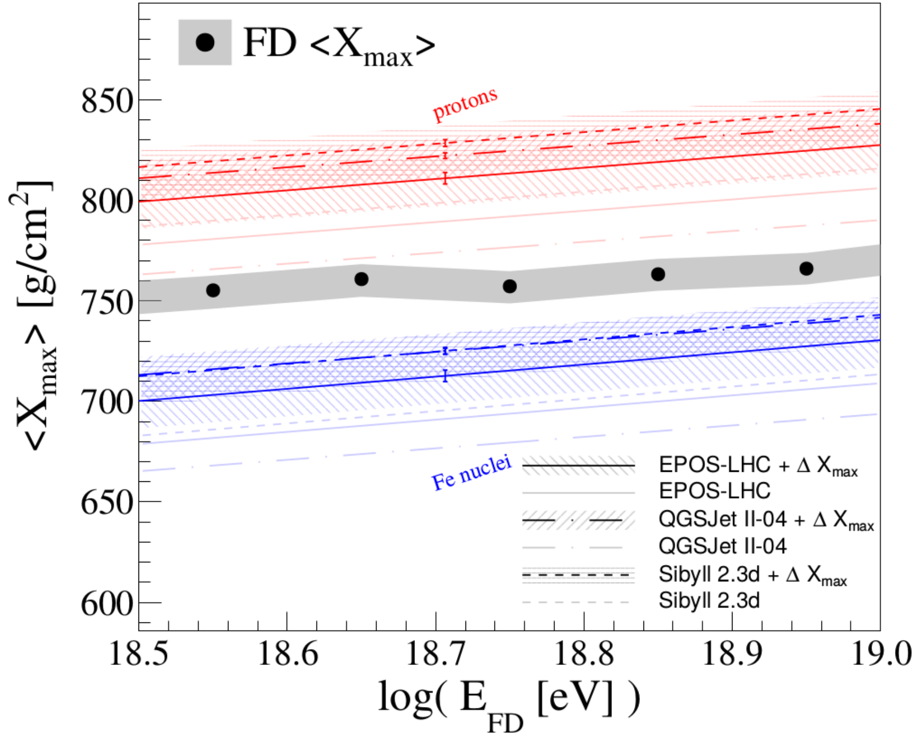


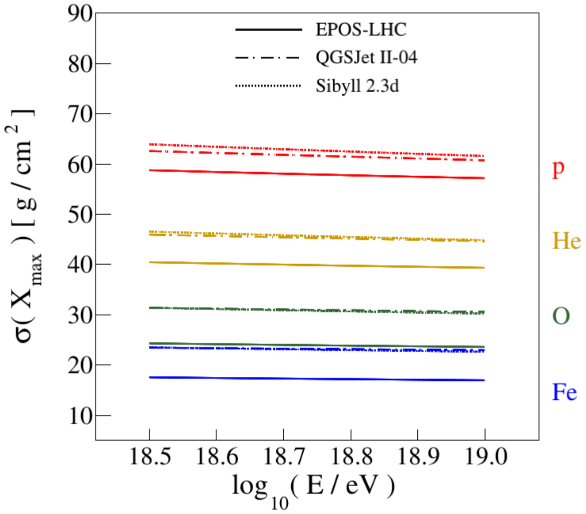
R_{Had} attenuation is correlated with the energy scale

Less model-dependent mass composition

$\langle X_{max} \rangle$ MC scale found lower by ~10 g/cm^2 for EPOS-LHC mainly due to lower $\sigma(X_{max})$, checked by artificially smeared X_{max}



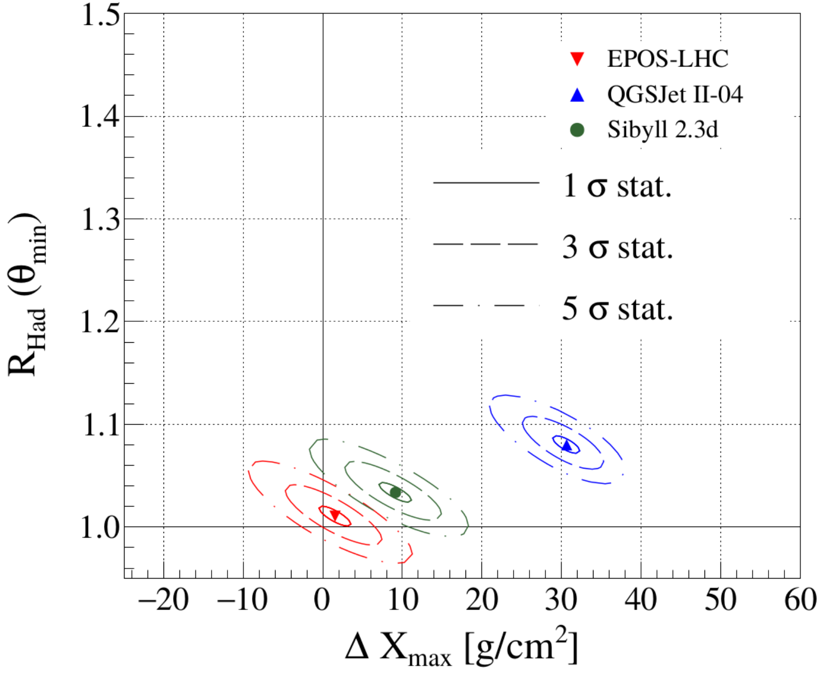


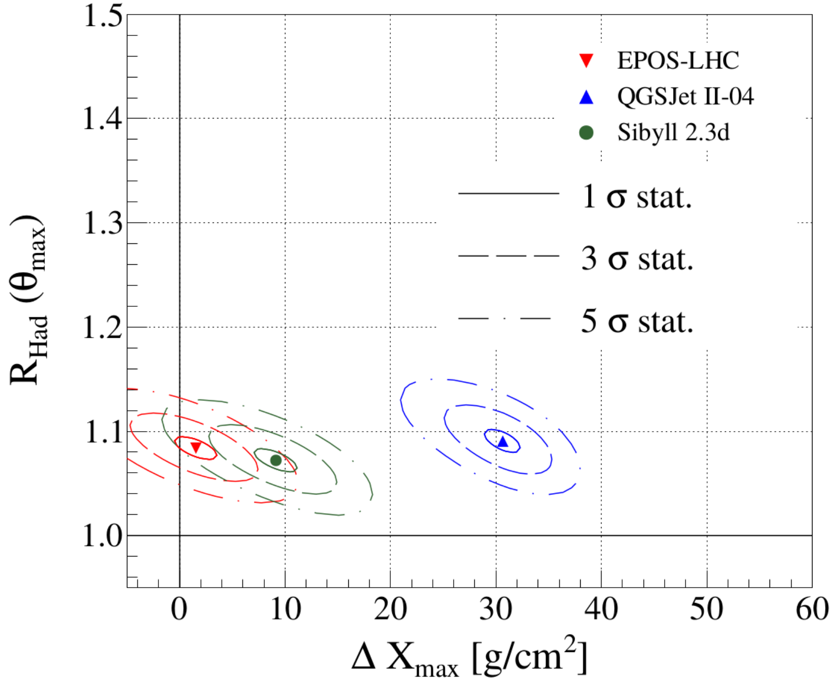


Significance of MC adjustments

Most favorable direction for models in combinations of $1\sigma_{sys}$ experimental systematics:

Energy + 14% & X_{max} - 9 g/cm²





The discrepancy with the data is larger than $5\sigma_{stat}$

Summary

- Two-dimensional distributions of [X_{max},S(1000)] for energies **$10^{18.5}$ - $10^{19.0}$ eV** and zenith angles < 60°, measured by the Pierre Auger Observatory, were fitted allowing for ad-hoc adjustments of the simulated X_{max} and hadronic signals at different zenith angles for EPOS-LHC, Sibyll 2.3d and QGSJet II-04

- For all three hadronic interaction models, the **improved description of the data** is achieved, if in the simulations:
  - **X_{max} is shifted towards deeper values**
  - **Hadronic signal is increased** by ~15-25%

- The statistical significance of the adjustments is greater than **$5\sigma_{stat}$** even for the combination of experimental systematic shifts within $1\sigma_{sys}$ that are the most favorable for the models

Backup slides

Fitting procedure

zenith bins, 2D bins, MC, data

$$\forall n_{jz} > 0: \quad \mathscr{L} = \sum_z \sum_j \left(C_{jz} - n_{jz} + n_{jz} \cdot \ln \frac{n_{jz}}{C_{jz}} \right), \qquad \forall n_{jz} = 0: \quad \mathscr{L} = \sum_z \sum_j C_{jz}$$

$$S(1000)(\theta) \cdot \left(\frac{E^{Ref}}{E_{FD}} \right)^{1/B} \cdot f_{SD}(\theta) = R_{Had}(\theta) \cdot g_{Had}(\theta, \Delta X_{max}, R_{Had}(\theta)) \cdot S_{Had}(\theta) \cdot \left(\frac{R_E \cdot E^{Ref}}{E_{FD}} \right)^{\beta} + R_{em} \cdot g_{em}(\theta, \Delta X_{max})\, S_{em}(\theta) \cdot \left(\frac{R_E \cdot E^{Ref}}{E_{FD}} \right), \quad E^{Ref} = 10^{18.7}\ eV$$

$$f_{SD}(\theta) = R_{Had}(\theta) \cdot R_E^{\beta} \cdot \left(\frac{E^{Ref}}{E_{FD}} \right)^{\beta - 1/B} \cdot g_{Had}(\theta, \Delta X_{max}, R_{Had}(\theta)) \cdot f_{Had}(\theta) + R_{em} \cdot R_E \cdot \left(\frac{E^{Ref}}{E_{FD}} \right)^{1-1/B} \cdot g_{em}(\theta, \Delta X_{max}) \cdot (1 - f_{Had}(\theta)), \quad f_{Had}(\theta) = \frac{S_{Had}(\theta)}{S(1000)(\theta)}$$

$$\Rightarrow \langle f_{SD} \rangle_z = R^z_{Had} \cdot R_E^{\beta} \cdot \left(\frac{(E^{Ref})^{\beta - 1/B}}{\langle E_{FD}^{\beta - 1/B} \rangle_z} \right) \cdot g^z_{Had}(\Delta X_{max}, R^z_{Had}) \cdot \langle f_{Had} \rangle_z + R_{em} \cdot R_E \cdot \left(\frac{(E^{Ref})^{1-1/B}}{\langle E_{FD}^{1-1/B} \rangle_z} \right) \cdot g^z_{em}(\Delta X_{max}) \cdot (1 - \langle f_{Had} \rangle_z)$$

$$R_{em} = R_E = 1$$

$$\Rightarrow \langle f_{SD} \rangle_z = R^z_{Had} \cdot \left(\frac{(E^{Ref})^{\beta - 1/B}}{\langle E_{FD}^{\beta - 1/B} \rangle_z} \right) \cdot g^z_{Had}(\Delta X_{max}, R^z_{Had}) \cdot \langle f_{Had} \rangle_z + \left(\frac{(E^{Ref})^{1-1/B}}{\langle E_{FD}^{1-1/B} \rangle_z} \right) \cdot g^z_{em}(\Delta X_{max}) \cdot (1 - \langle f_{Had} \rangle_z)$$

$$X^{Ref}_{max} + \Delta X_{max}$$