Testing Model Predictions of Depth of Air-Shower Maximum and Signals in Surface Detectors using Hybrid Data 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

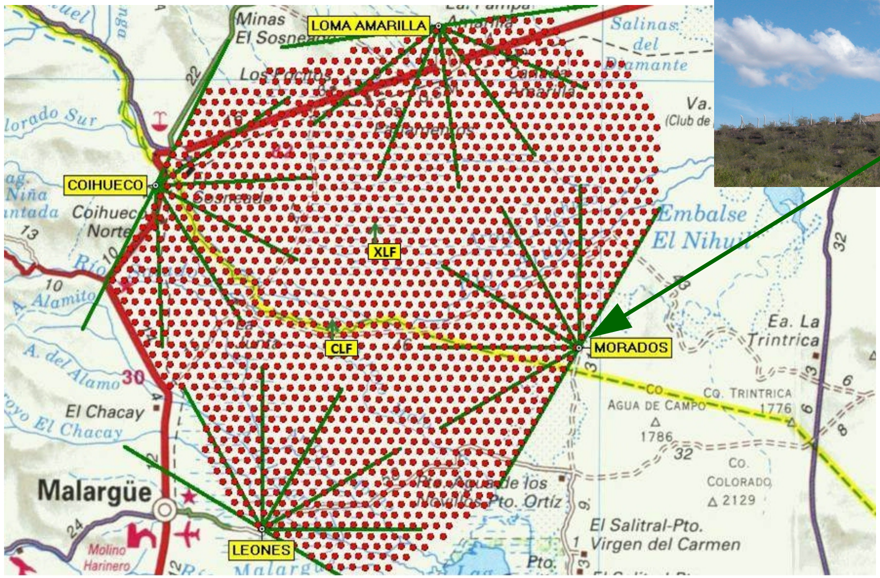
vicha@fzu.cz

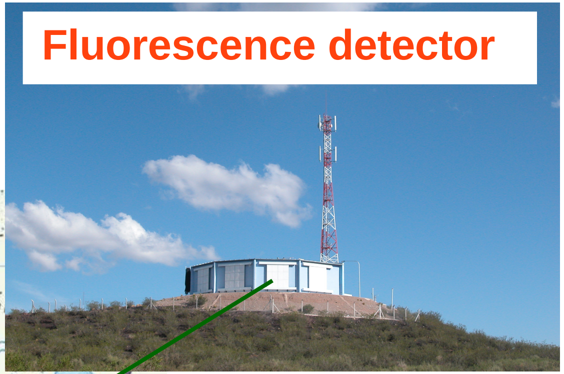
Gran Sasso Science Institute, L'Aquila, Italy

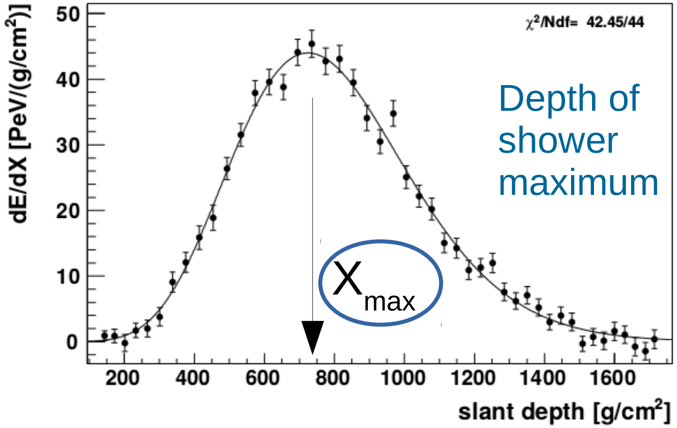
5th Oct 2022

Hybrid detection at the Pierre Auger Observatory

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

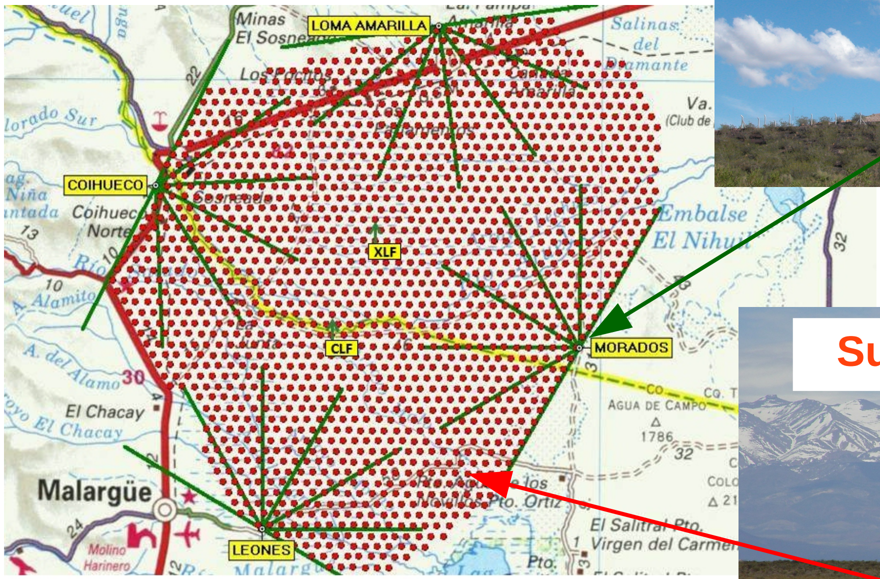


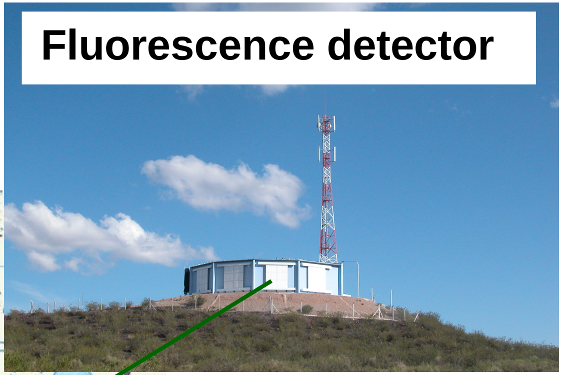


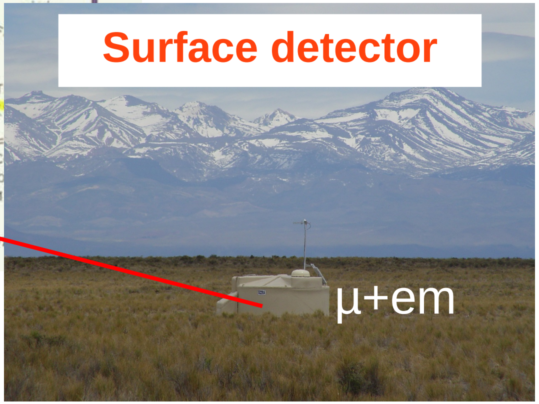


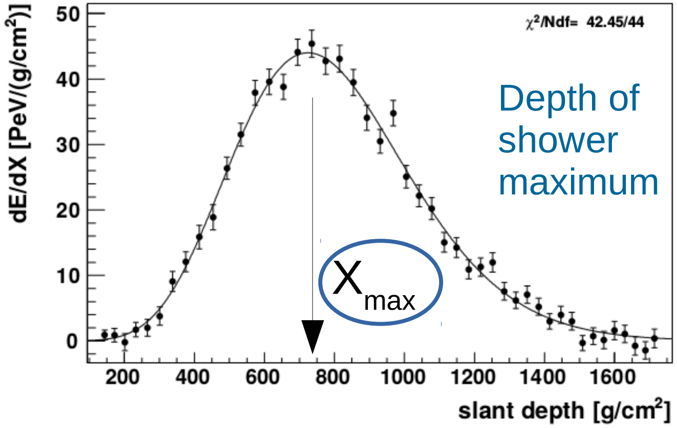
Hybrid detection at the Pierre Auger Observatory

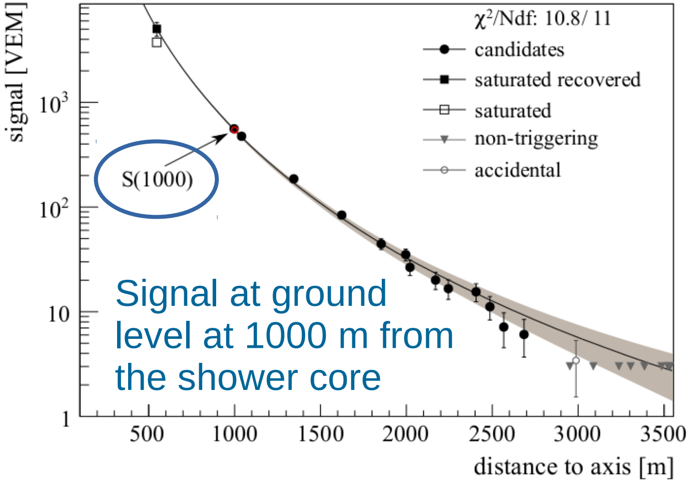
[Nucl. Instrum. Meth. A 798 (2015) 172]









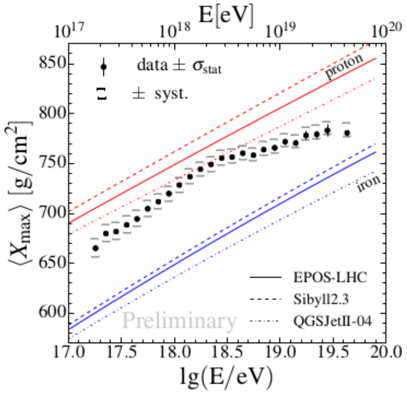


Mass composition & tests of hadronic interactions

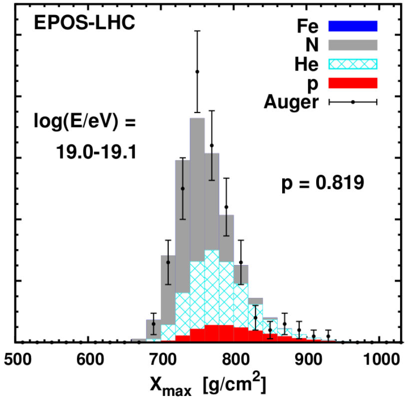
Deficit of simulated muon signal: previous analyses in Auger

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

[PoS(ICRC19)482]



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

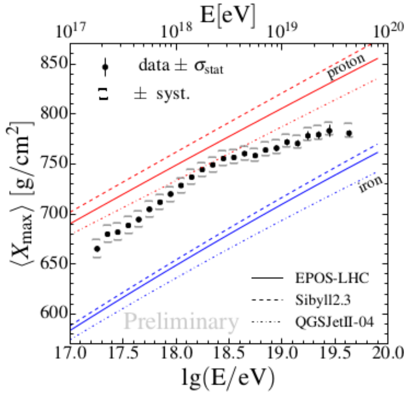


Mass composition & tests of hadronic interactions

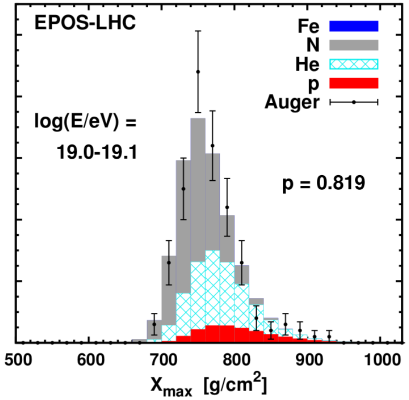
Deficit of simulated muon signal: previous analyses in Auger

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

[PoS(ICRC19)482]

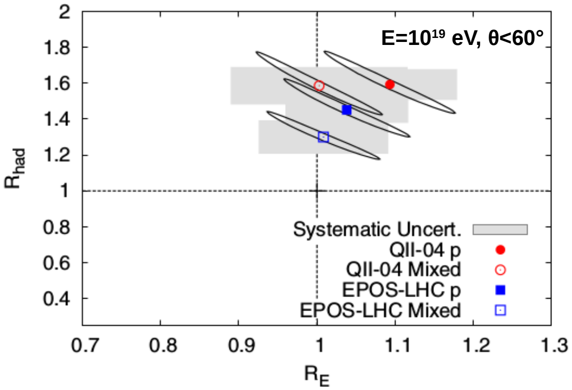


[Phys. Rev. D 90 (2014) 122006]

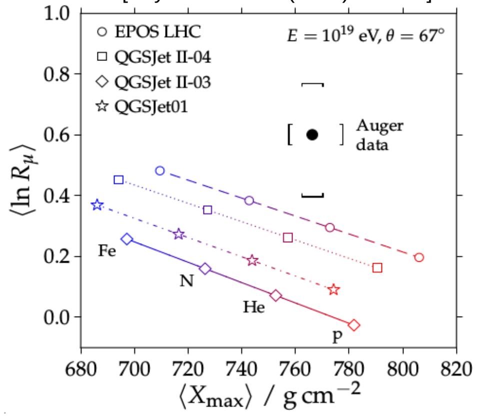


2) **Discrepancy in predicted and measured ground signal** is usually evaluated using the inferences on the mass composition from the X_{max} analysis

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



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

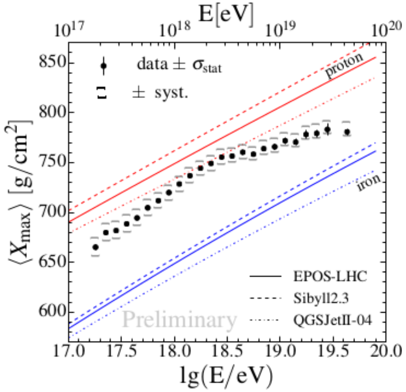


Mass composition & tests of hadronic interactions

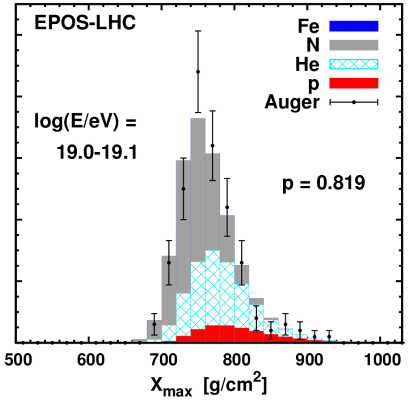
Deficit of simulated muon signal: previous analyses in Auger

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

[PoS(ICRC19)482]

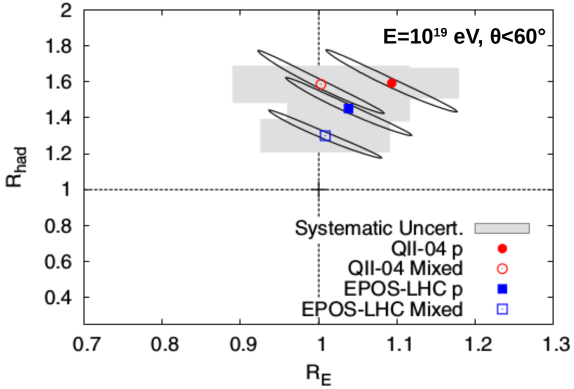


[Phys. Rev. D 90 (2014) 122006]

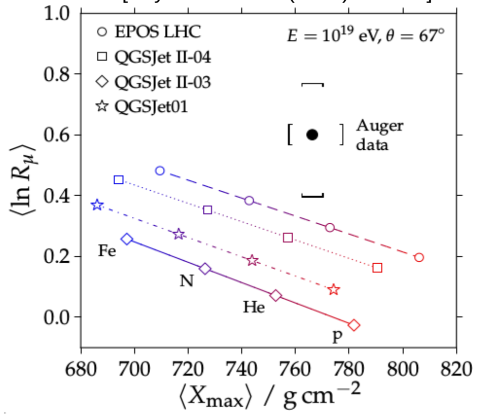


2) **Discrepancy in predicted and measured ground signal** is usually evaluated using the inferences on the mass composition from the X_{max} analysis

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



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

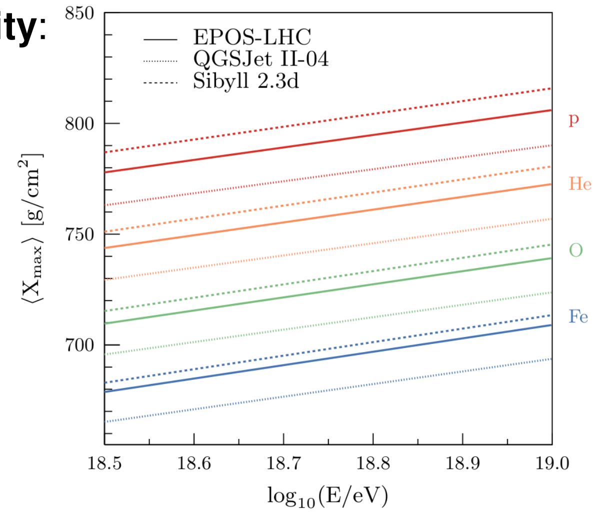


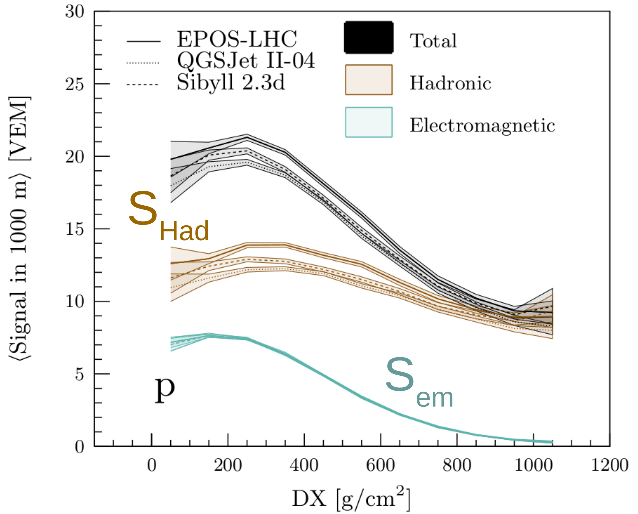
This work

Mass composition fit of observed [X_{max},S(1000)](θ) distributions with free 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
- **Main differences** between model predictions:
  - Scale of $\langle X_{max} \rangle$ and $\langle S_{Had} \rangle$ are approx. primary and energy independent





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

ad-hoc adjustments

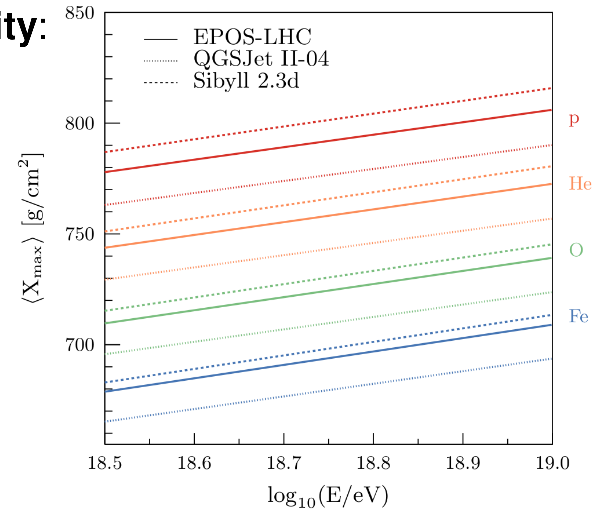
$$X_{max} \rightarrow X_{max} + \Delta X_{max}$$

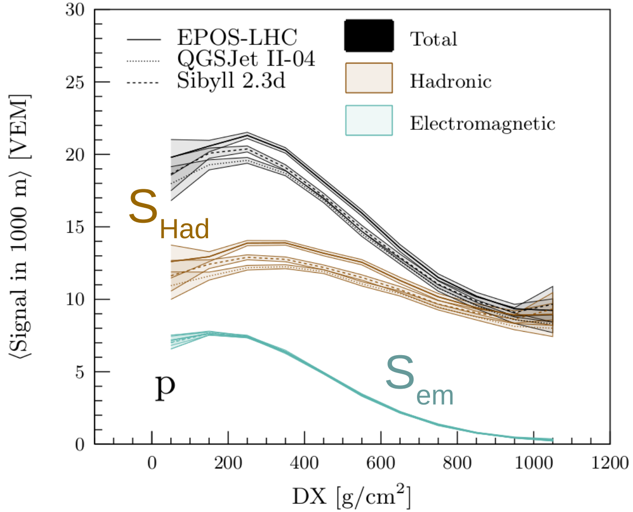
$$S_{Had}(\theta) \rightarrow S_{Had}(\theta) \cdot R_{Had}$$

New !

Motivations for adjustments of MC predictions

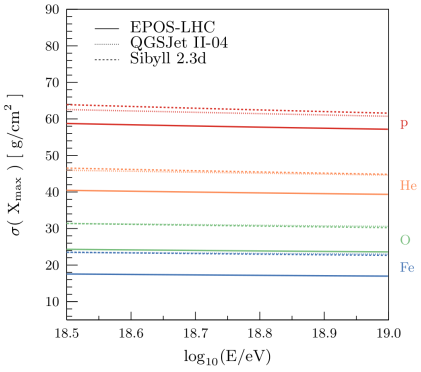
- Properties of **4-component shower universality**:
  [Astropart. Phys. 87 (2017) 23, Astropart. Phys. 88 (2017) 46]
  - $S(1000) = S_{Had} + S_{em}$
  - S_{em} very universal
- **Main differences** between model predictions:
  - Scale of $\langle X_{max} \rangle$ and $\langle S_{Had} \rangle$ are approx. primary and energy independent





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

- Ignored **model differences**:
  - $R_{Had}(\theta)$ - see backup, PoS(ICRC2021)310
  - fluctuations of X_{max} and S(1000)
  - mass dependence of R_{Had}, ΔX_{max}
  - etc.



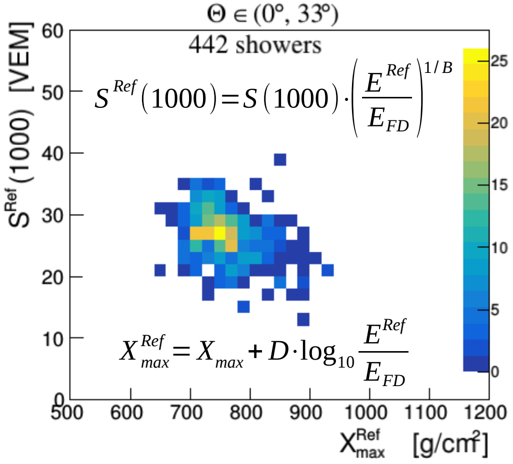
ad-hoc adjustments

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

New !

Global fit method

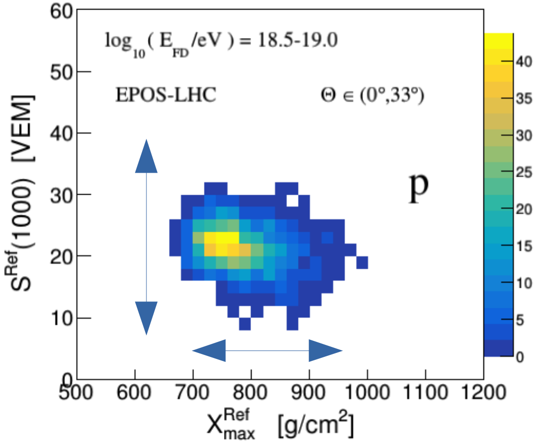
Auger data

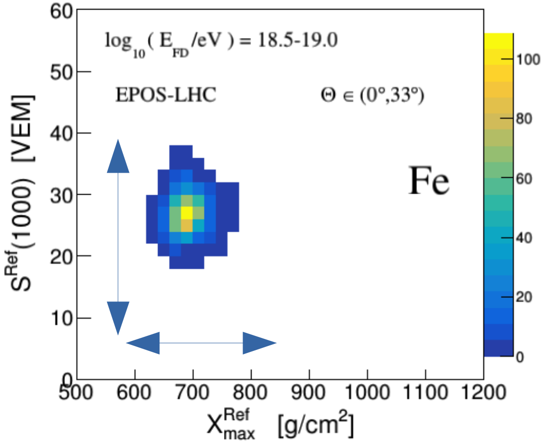


Simultaneous likelihood ratio fit of **two-dimensional distributions** of X_{max} and S(1000) in 5 zenith-angle bins with **MC templates** for combinations of four primary nuclei (p,He,O,Fe)

New !

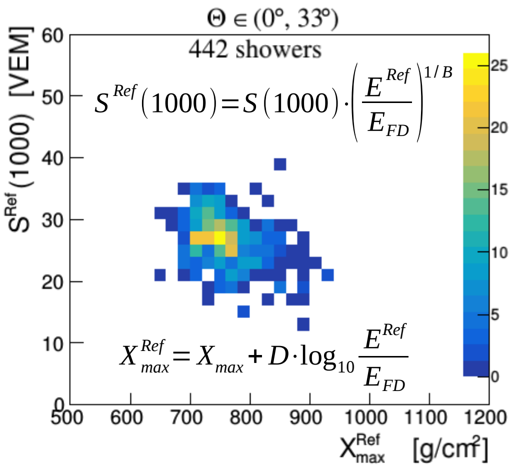
MC templates: from ~15k showers per primary and model (EPOS-LHC, QGSJet II-04, Sibyll 2.3d)





Global fit method

Auger data

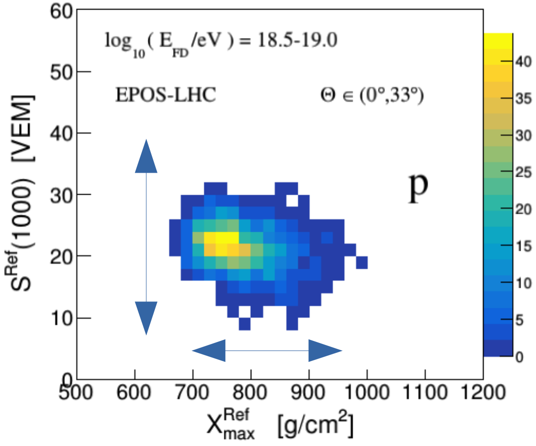


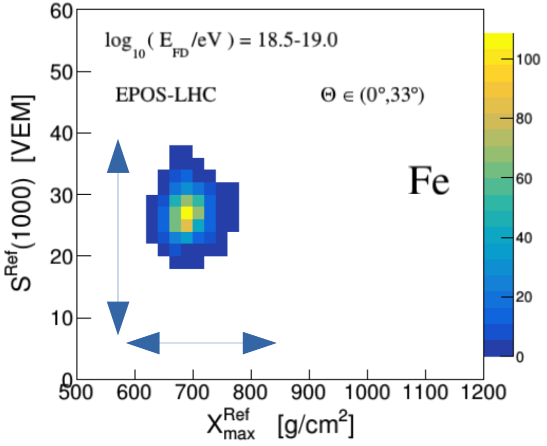
Simultaneous likelihood ratio fit of **two-dimensional distributions** of X_{max} and S(1000) in 5 zenith-angle bins with **MC templates** for combinations of four primary nuclei (p,He,O,Fe)

New !

- **Freedom** in X_{max} (ΔX_{max}) and S(1000) (R_{Had}) 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 nearly model-independent correlation between S(1000) and X_{max}** [Phys. Lett. B 762 (2016) 288]

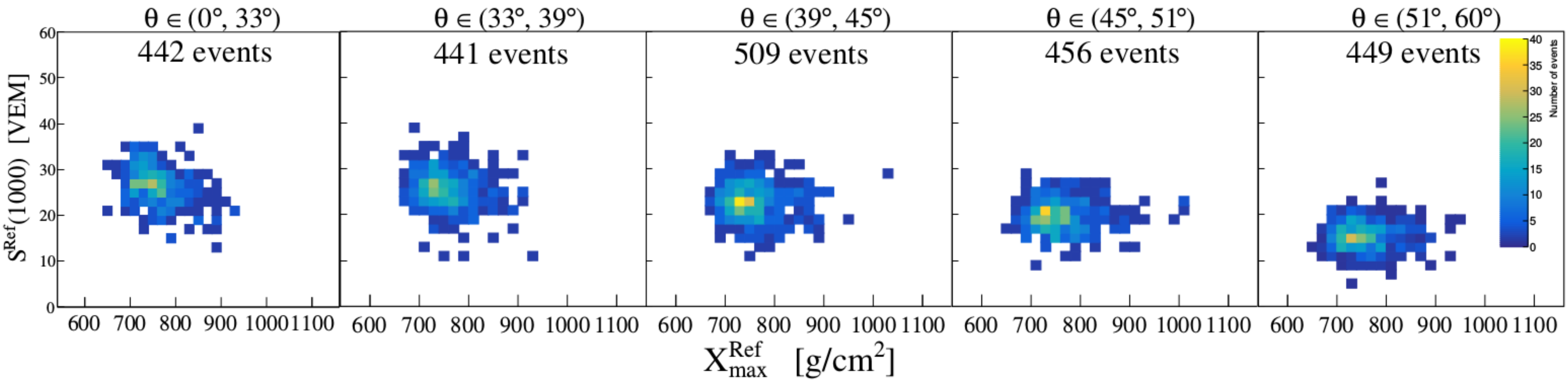
MC templates: from ~15k showers per primary and model (EPOS-LHC, QGSJet II-04, Sibyll 2.3d)





Measured data

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



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

Progressive adjustments to MC templates

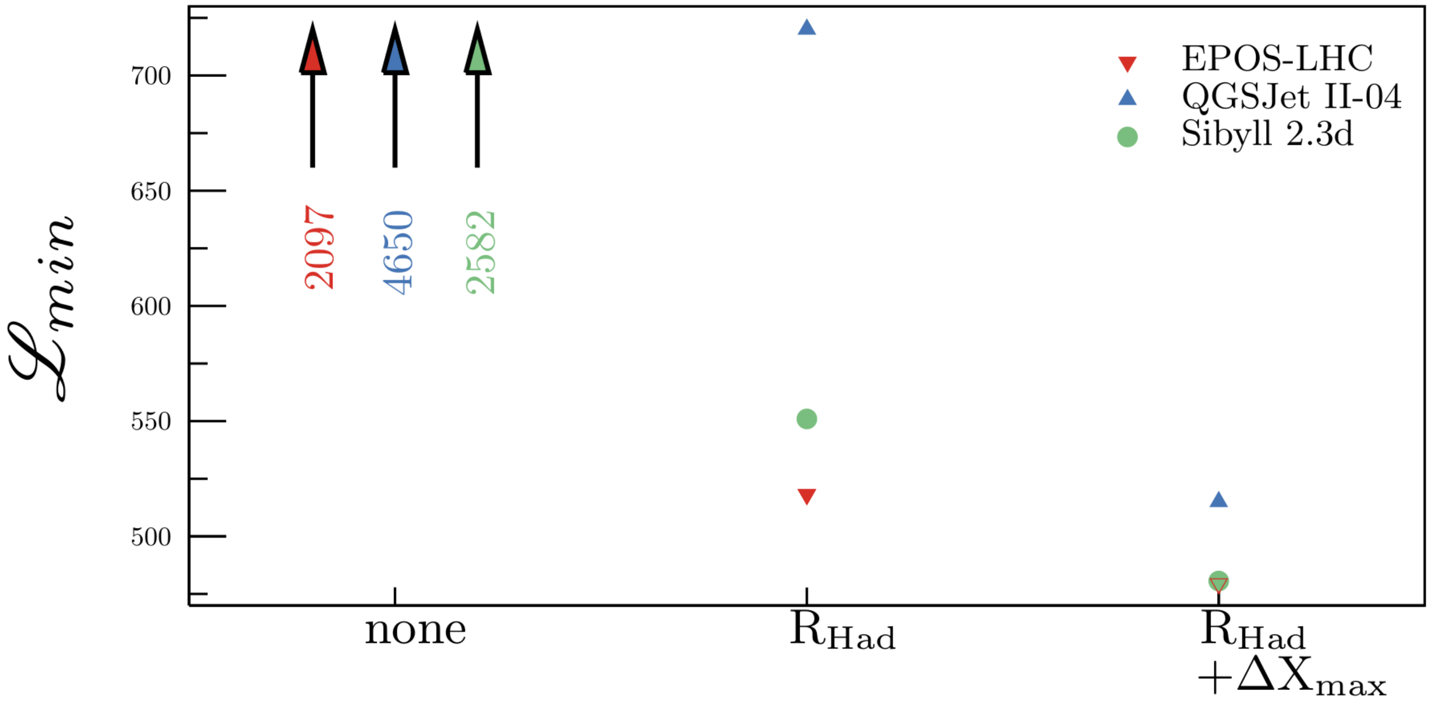
1) NO adjustment at all

↓

2) R_{Had}

↓

3) $R_{Had} + \Delta X_{max}$



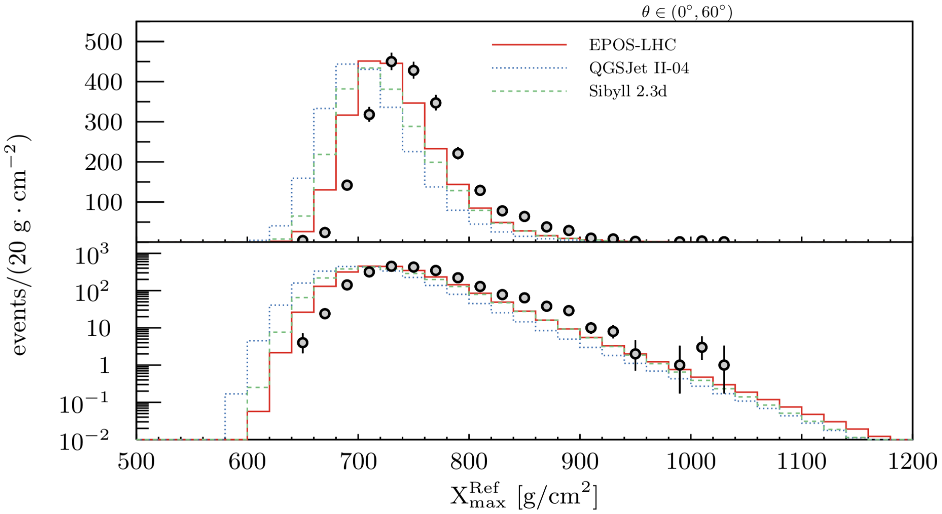
θ bins, 2D bins

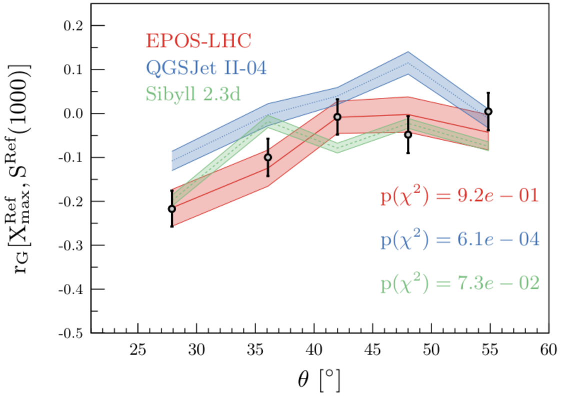
$$\forall n_{jz} > 0: \quad \mathscr{L} = \sum_z \sum_j \left(C_{jz} - n_{jz} + n_{jz} \cdot \ln \frac{n_{jz}}{C_{jz}} \right)$$

$$\forall n_{jz} = 0: \quad \mathscr{L} = \sum_z \sum_j C_{jz},$$

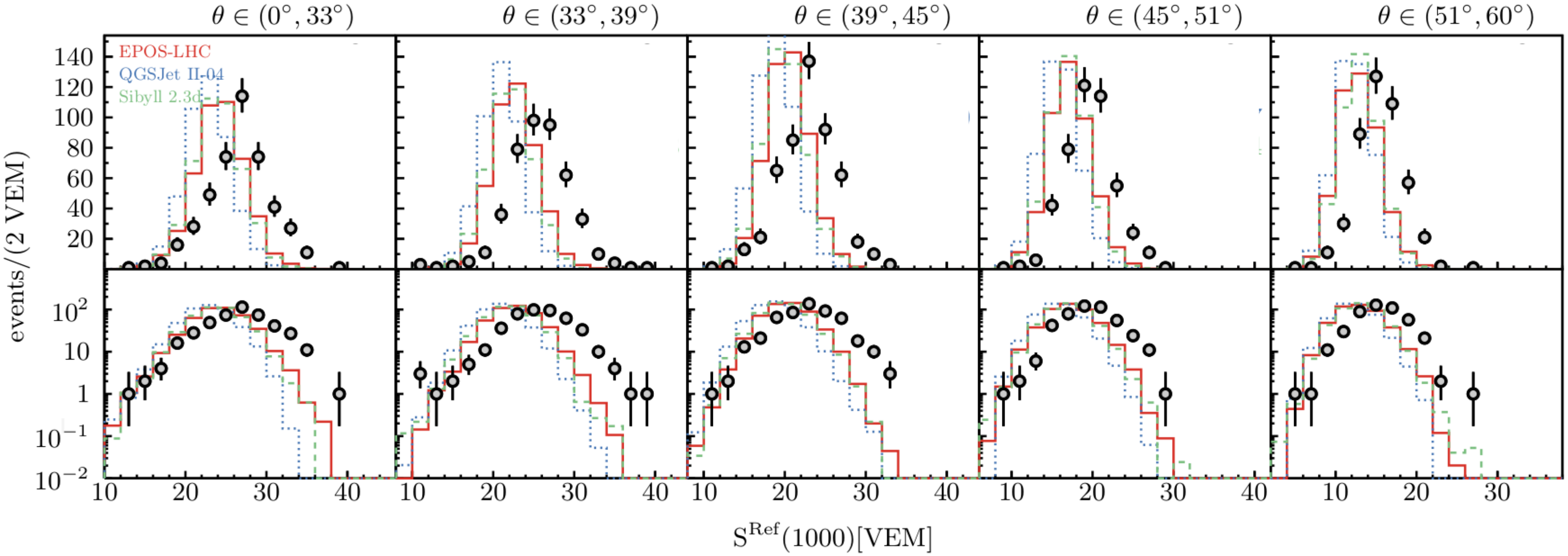
n_{jz} - measured number of events
C_{jz} - predicted number of events

1) NO adjustments

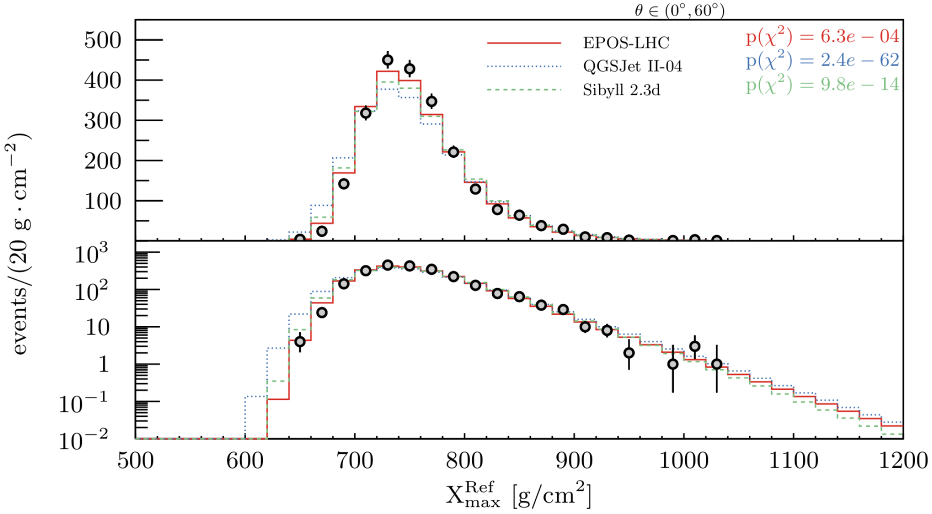




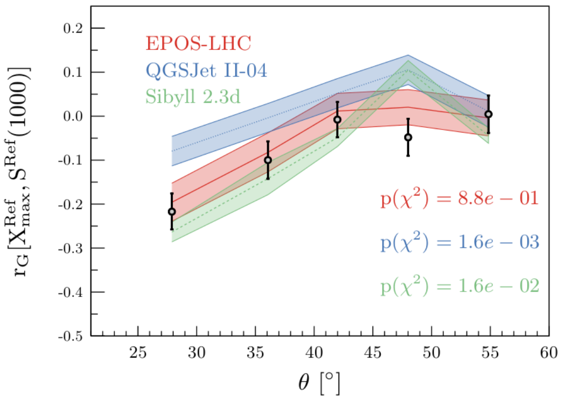
Gideon-Hollister correlation coeficient
[J. Am. Stat. Assoc. 82 (1987) 656]



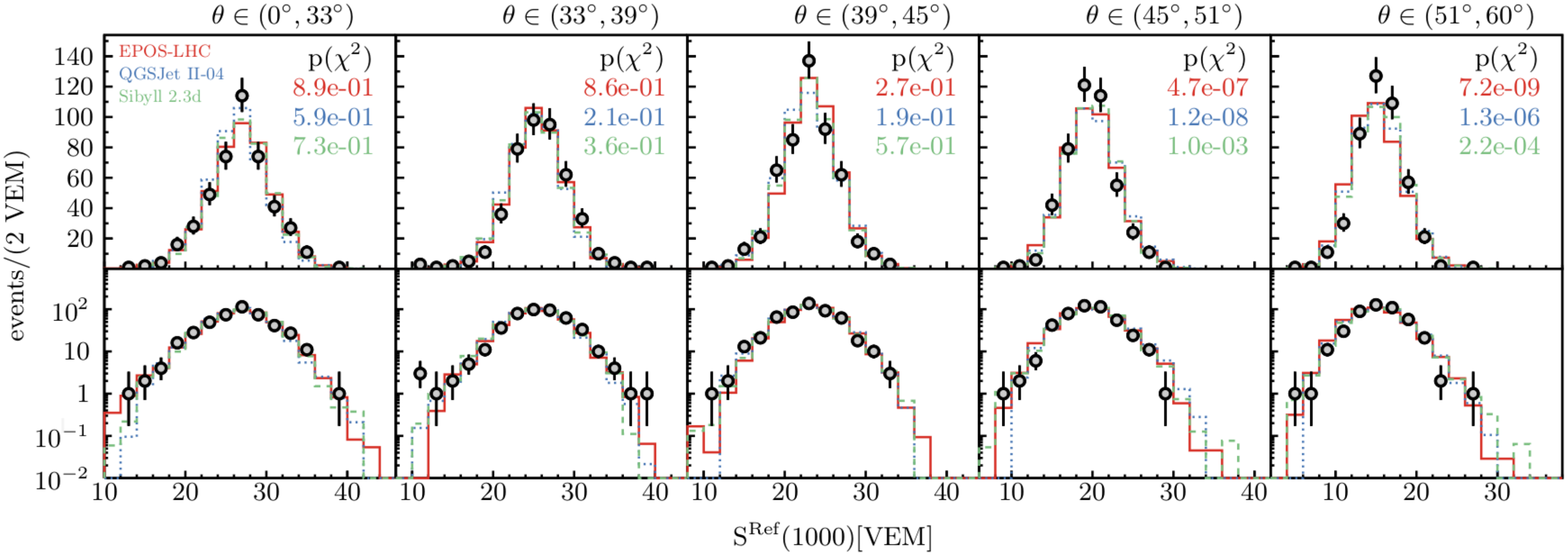
2) R_{Had}



$\theta \in (0°, 60°)$
EPOS-LHC
QGSJet II-04
Sibyll 2.3d
$p(\chi^2) = 6.3e-04$
$p(\chi^2) = 2.4e-62$
$p(\chi^2) = 9.8e-14$
events/(20 g · cm^{-2})
X_{max}^{Ref} [g/cm^2]

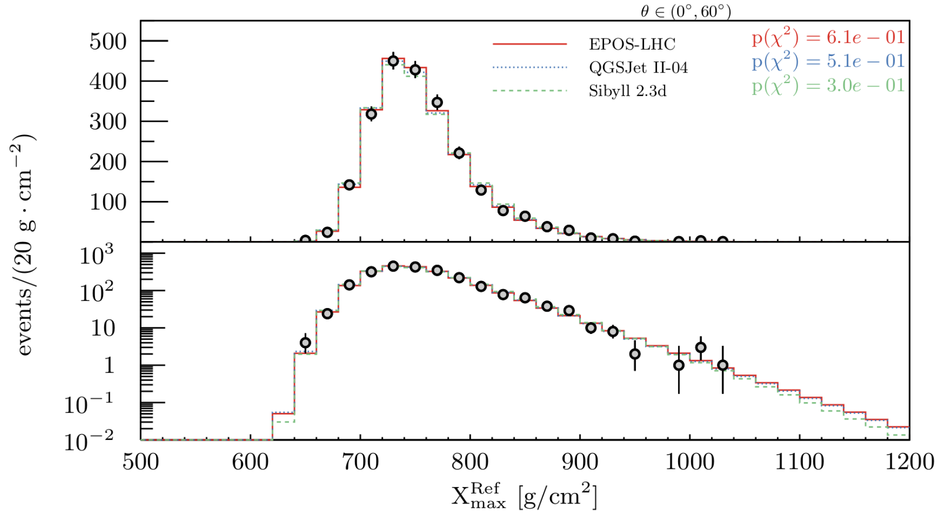


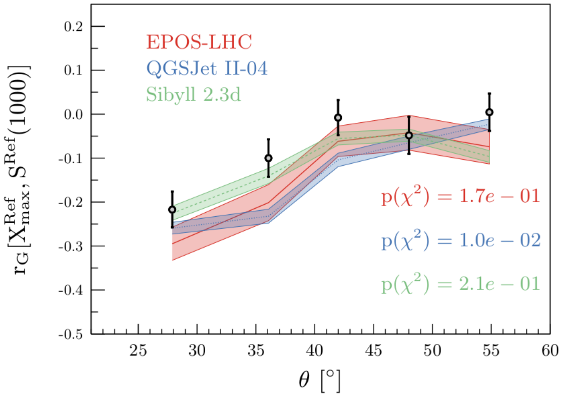
EPOS-LHC
QGSJet II-04
Sibyll 2.3d
$p(\chi^2) = 8.8e-01$
$p(\chi^2) = 1.6e-03$
$p(\chi^2) = 1.6e-02$
$r_G[X_{max}^{Ref}, S^{Ref}(1000)]$
θ [°]

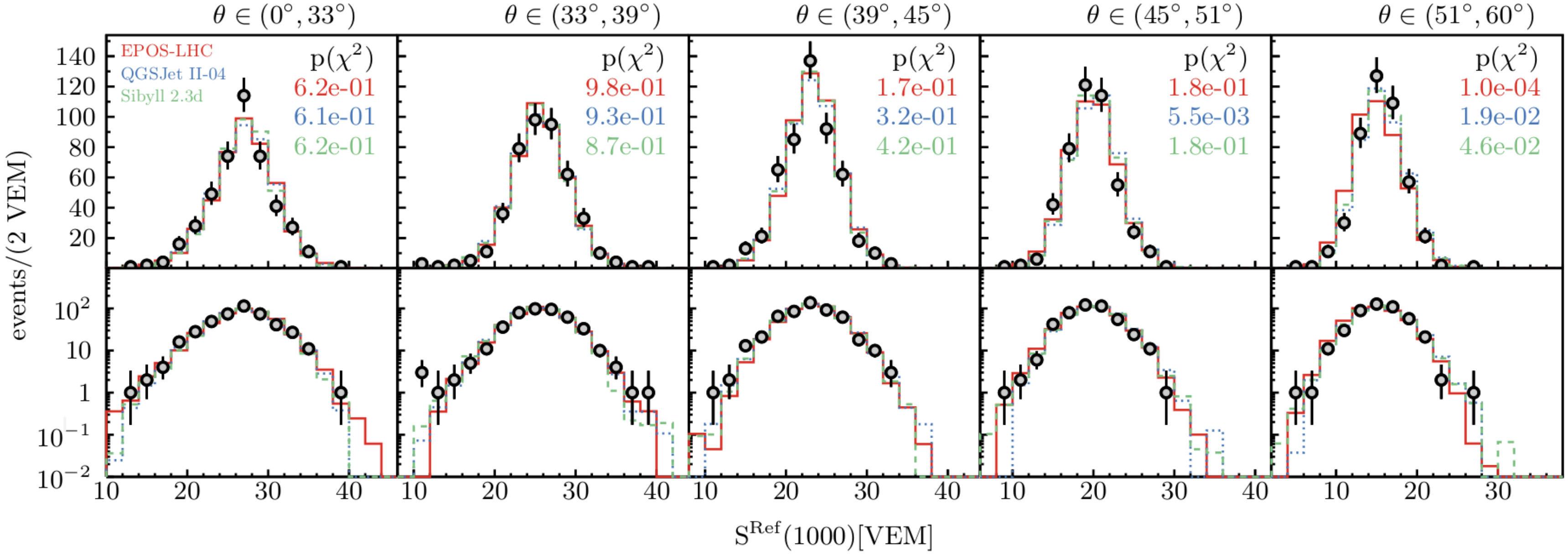


$\theta \in (0°, 33°)$
$\theta \in (33°, 39°)$
$\theta \in (39°, 45°)$
$\theta \in (45°, 51°)$
$\theta \in (51°, 60°)$
EPOS-LHC
QGSJet II-04
Sibyll 2.3d
$p(\chi^2)$
8.9e-01
5.9e-01
7.3e-01
8.6e-01
2.1e-01
3.6e-01
2.7e-01
1.9e-01
5.7e-01
4.7e-07
1.2e-08
1.0e-03
7.2e-09
1.3e-06
2.2e-04
events/(2 VEM)
$S^{Ref}(1000)$[VEM]

3) $R_{Had} + \Delta X_{max}$







Systematic Uncertainties

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

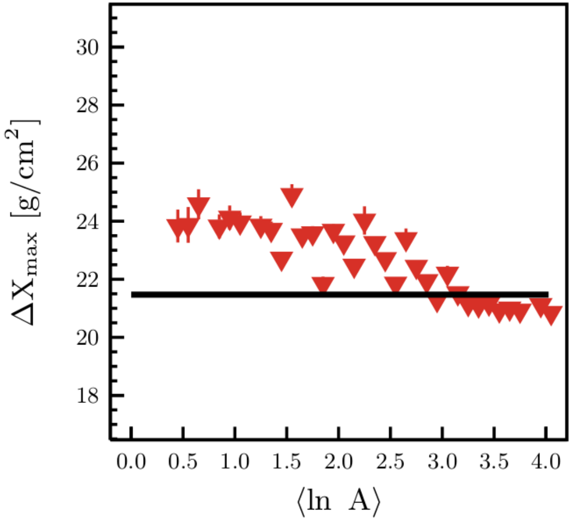
All four contributions summed in quadrature

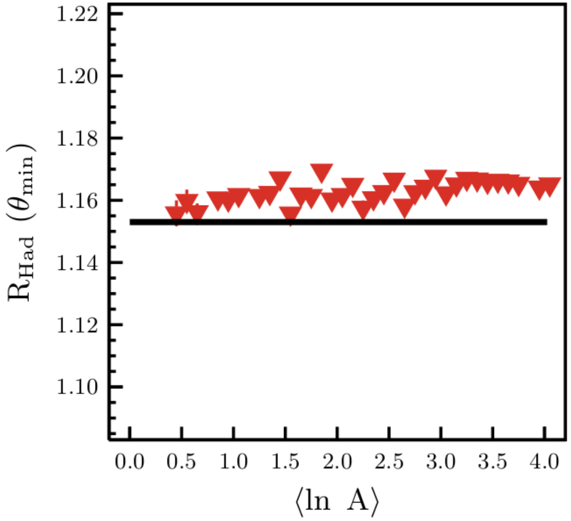
Systematic Uncertainties

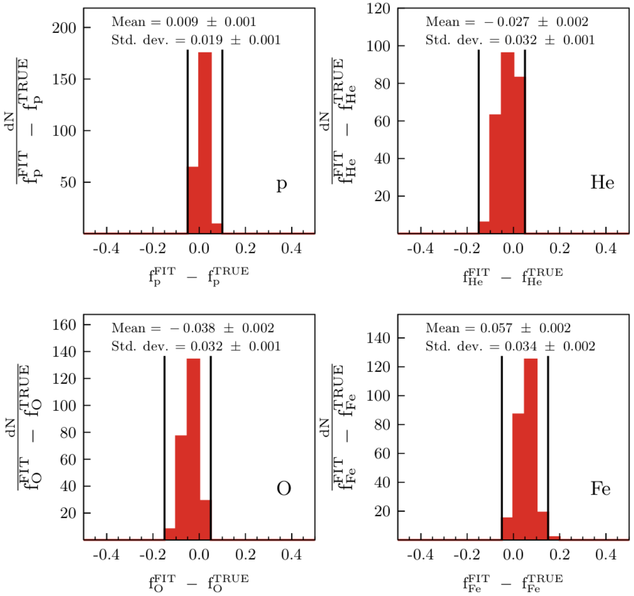
- Experimental
  1) Energy scale ± 14%
  2) X_{max} measurement +8, -9 g/cm^2
  3) S(1000) measurement ± 5%
- Method
  4) Biases from MC-MC tests for each model

All four contributions summed in quadrature

Method works within ~5 g/cm^2 for ΔX_{max} and few percent for R_{Had}

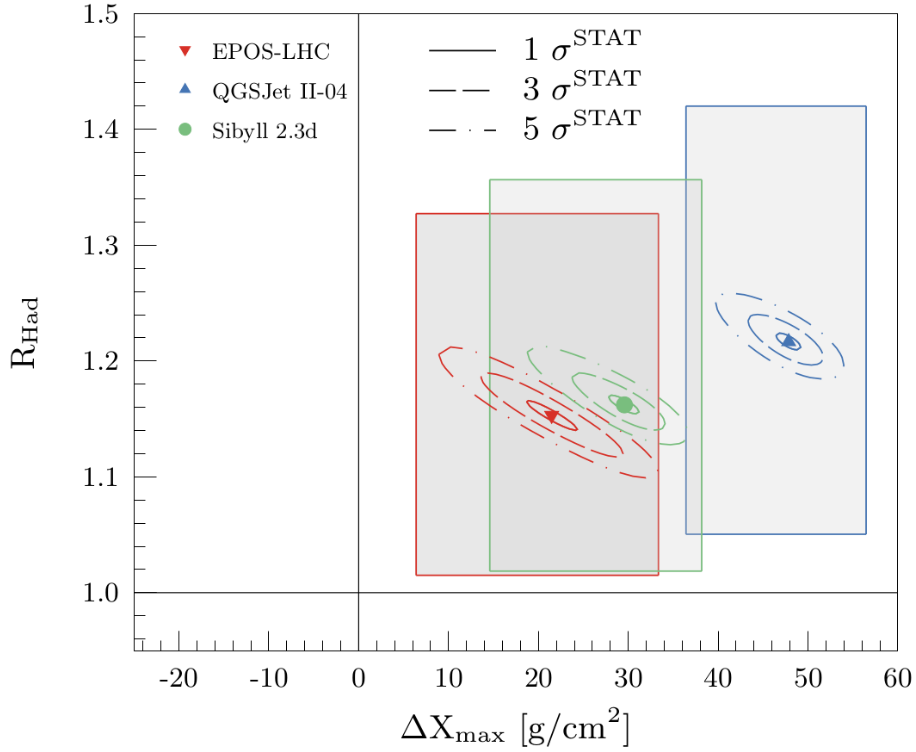


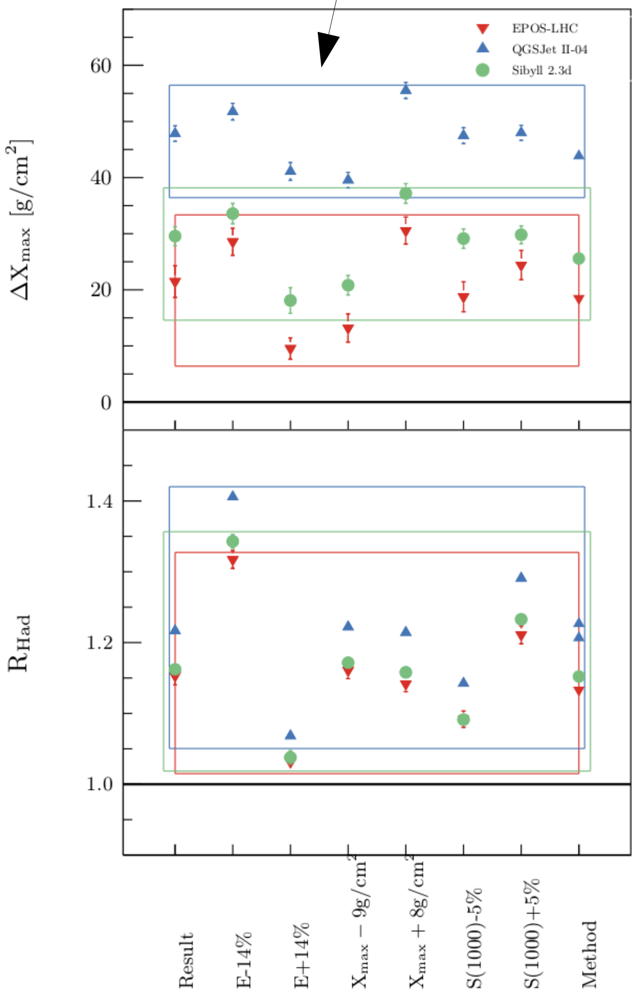




MC-MC tests using EPOS-LHC with artificial changes in ΔX_{max}≈22 g/cm^2, R_{Had}≈1.15

Fitted MC adjustments



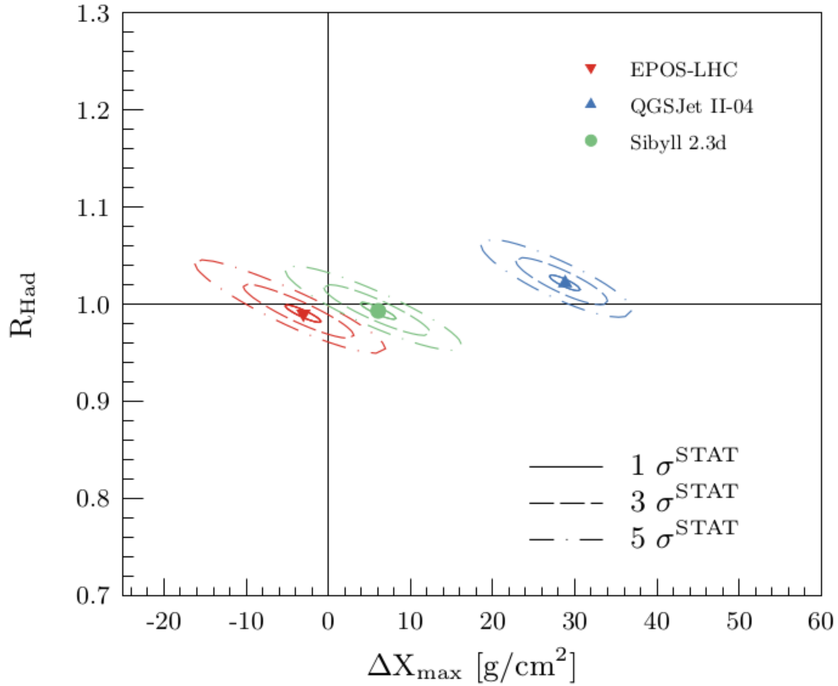


Deeper predicted $\langle X_{max} \rangle$
→ alleviated "muon puzzle"

Significance of MC adjustments

Most favorable direction for models in combinations of $1\sigma^{SYS}$ experimental systematics:

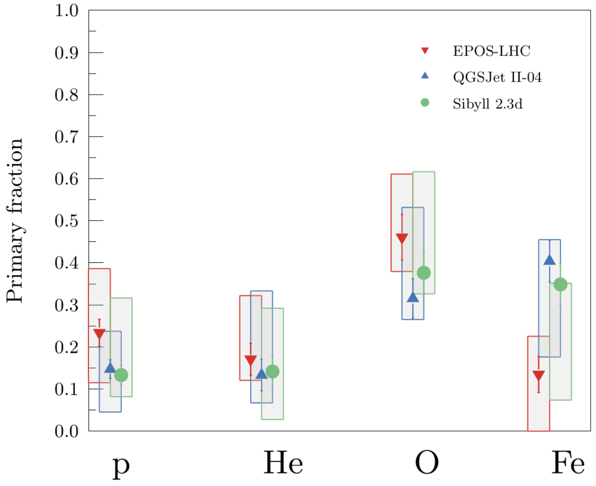
Energy + 14% & X_{max} - 9 g/cm^2 & S(1000) - 5%

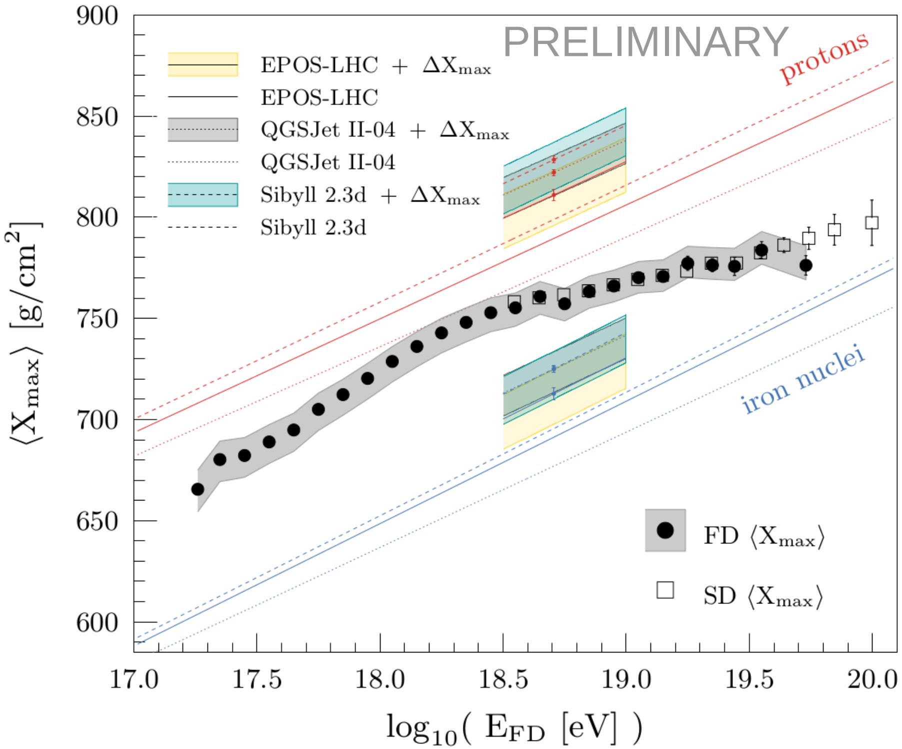


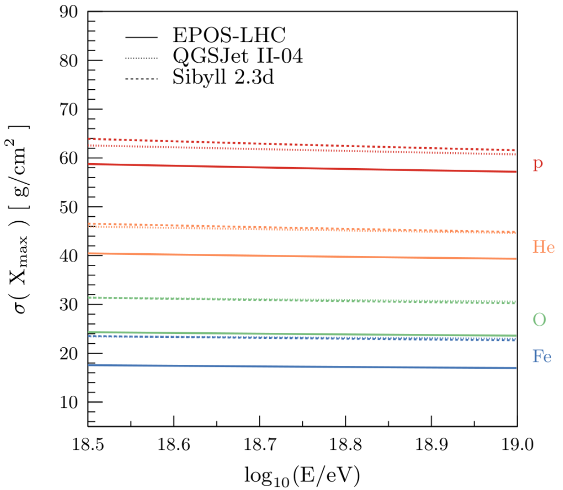
The discrepancy with the data >≈ $5\sigma^{STAT}$

Less model-dependent mass composition

⟨X_{max}⟩ MC scale found lower at **energy $10^{18.5\text{-}19}$ eV** by ~10 g/cm^2 for EPOS-LHC mainly due to lower σ(X_{max}); checked by artificially smeared X_{max}







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 signal 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** → Heavier mass composition !
  - **Hadronic signal is increased** by ~15-25% → Alleviation of the muon puzzle !

  Caveat: other differences in model predictions under study (shower-to-shower fluctuations etc.)

- The statistical significance of the adjustments is **greater than ~5σ^{STAT}** even for the combination of experimental systematic shifts within 1σ^{SYS} that are the most favorable for the models

Stay tuned: paper in preparation [PoS(ICRC2021)310]

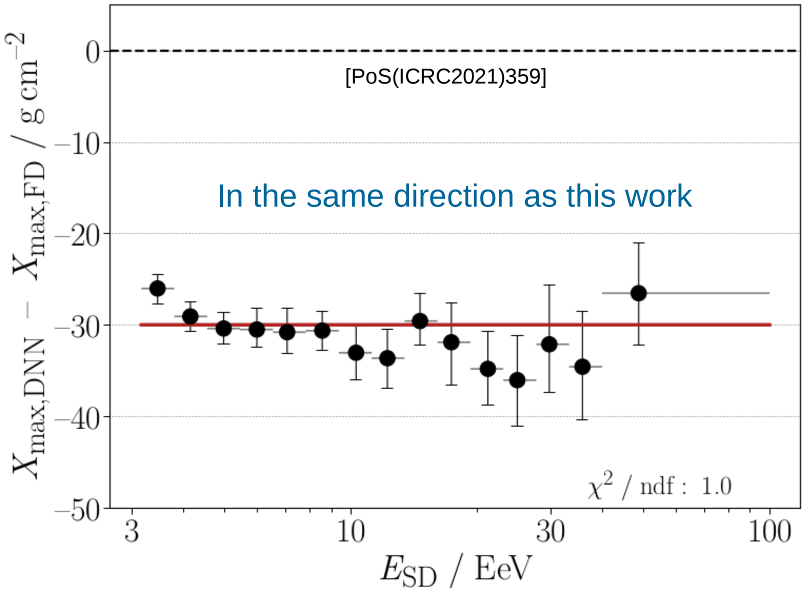
Backup slides

$$N \propto N_0 \cdot E_0^{\alpha} \qquad \kappa \propto \kappa_0 \cdot E_0^{-\omega}$$

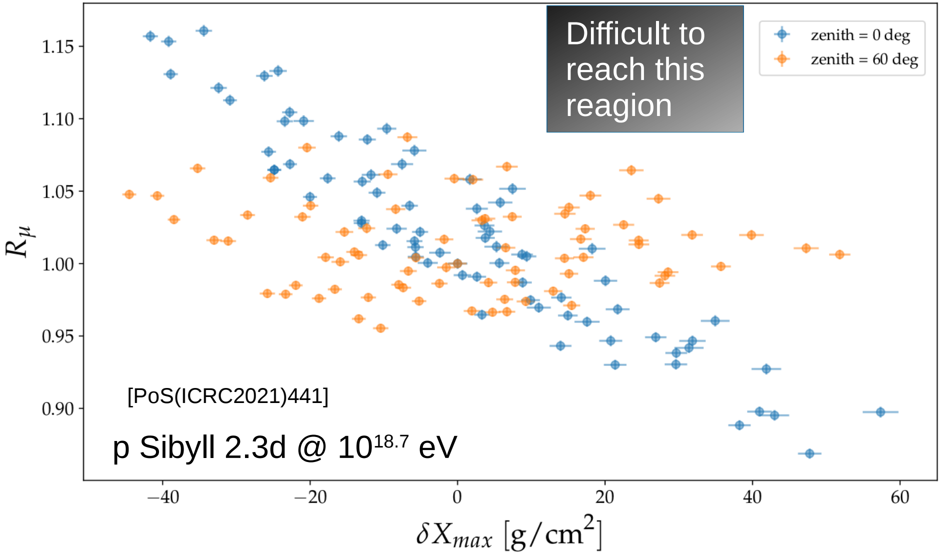
Matthews [Astropart. Phys. 22 (2005) 387] model: Ad-hoc change of multiplicity (N_0) or elasticity (κ_0) would **change X_{max} independently on primary and energy**

$$X_{\max}^{\mathrm{A}} = X_1^A + X_0 \ln \frac{\kappa E_0}{A \cdot 2N\xi_c^{\pi}} = X_1^A + (1-\alpha-\omega)\cdot\left(X_0 \ln \frac{E_0}{A\cdot \xi_c^{\pi}}\right) + X_0 \cdot (\ln \kappa_0 - \ln N_0)$$

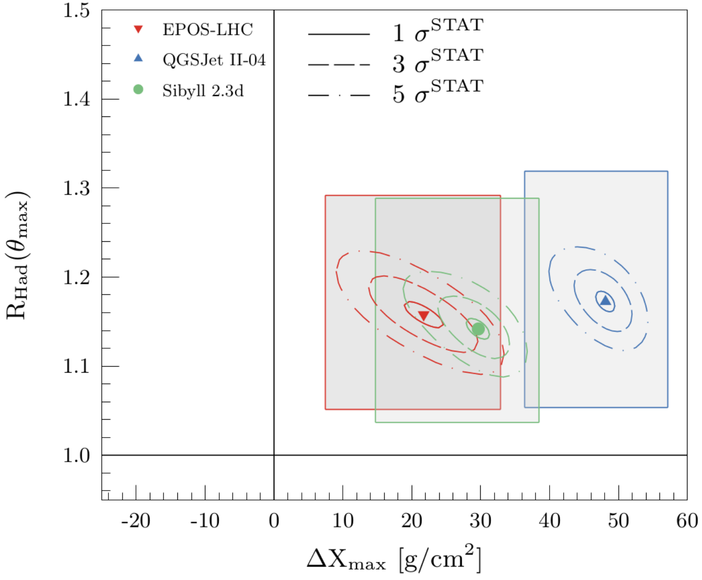
DNN method applied to Auger data from EPOS-LHC simulations

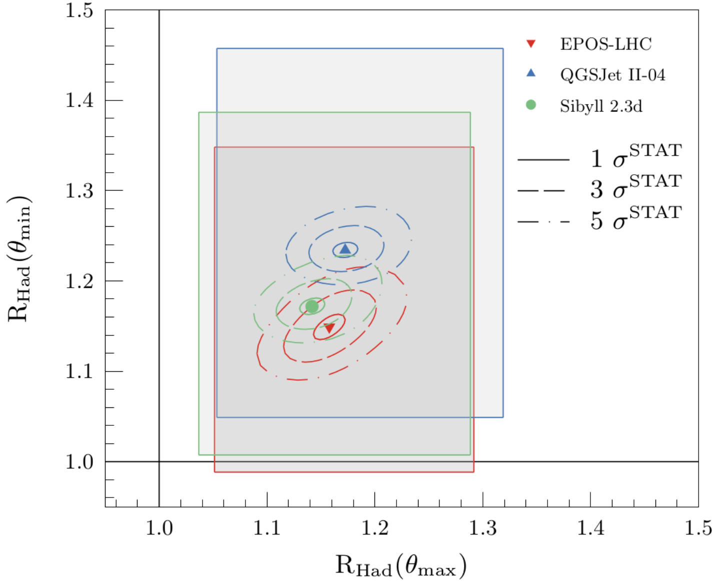


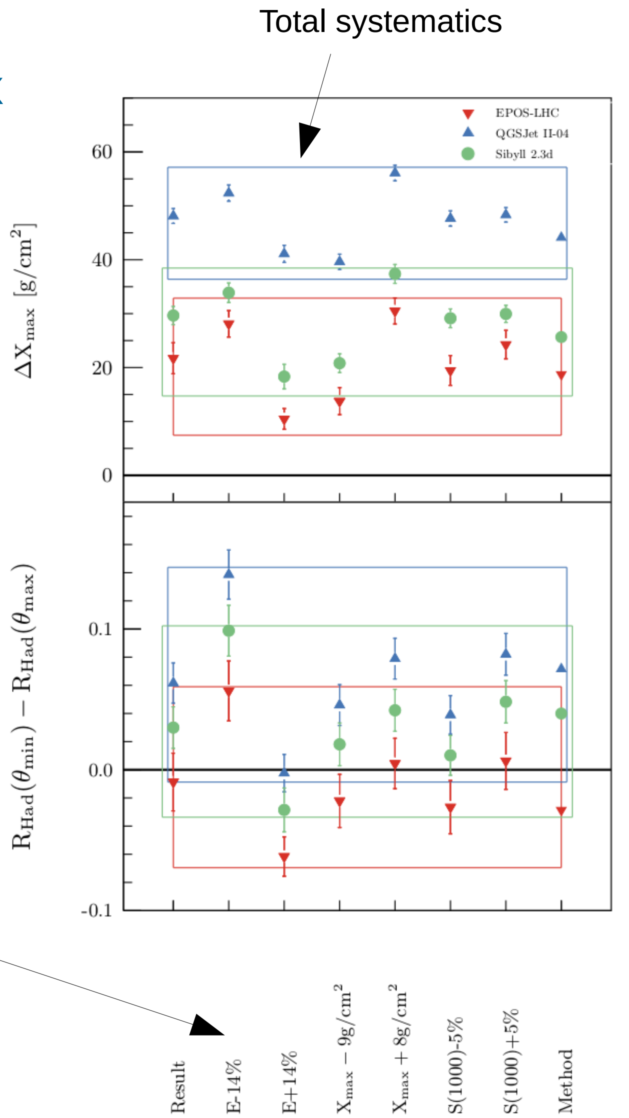
Conservative estimation of possibilities using combination of changes in cross-section, elasticity, multiplicity

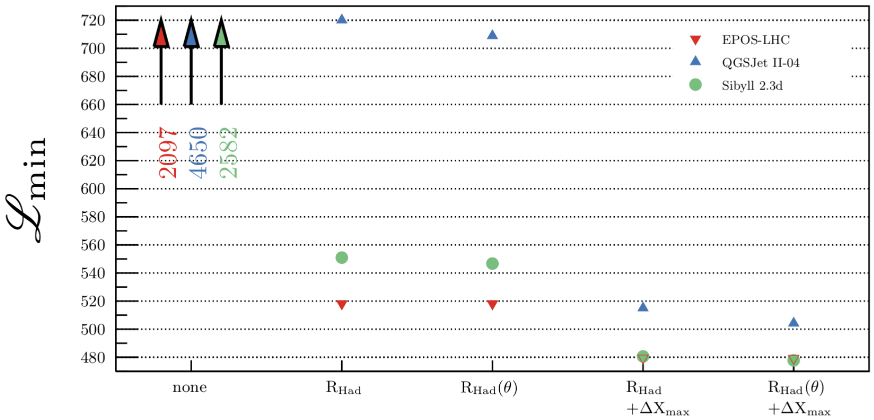


Fitting $R_{Had}(\theta) + \Delta X_{max}$



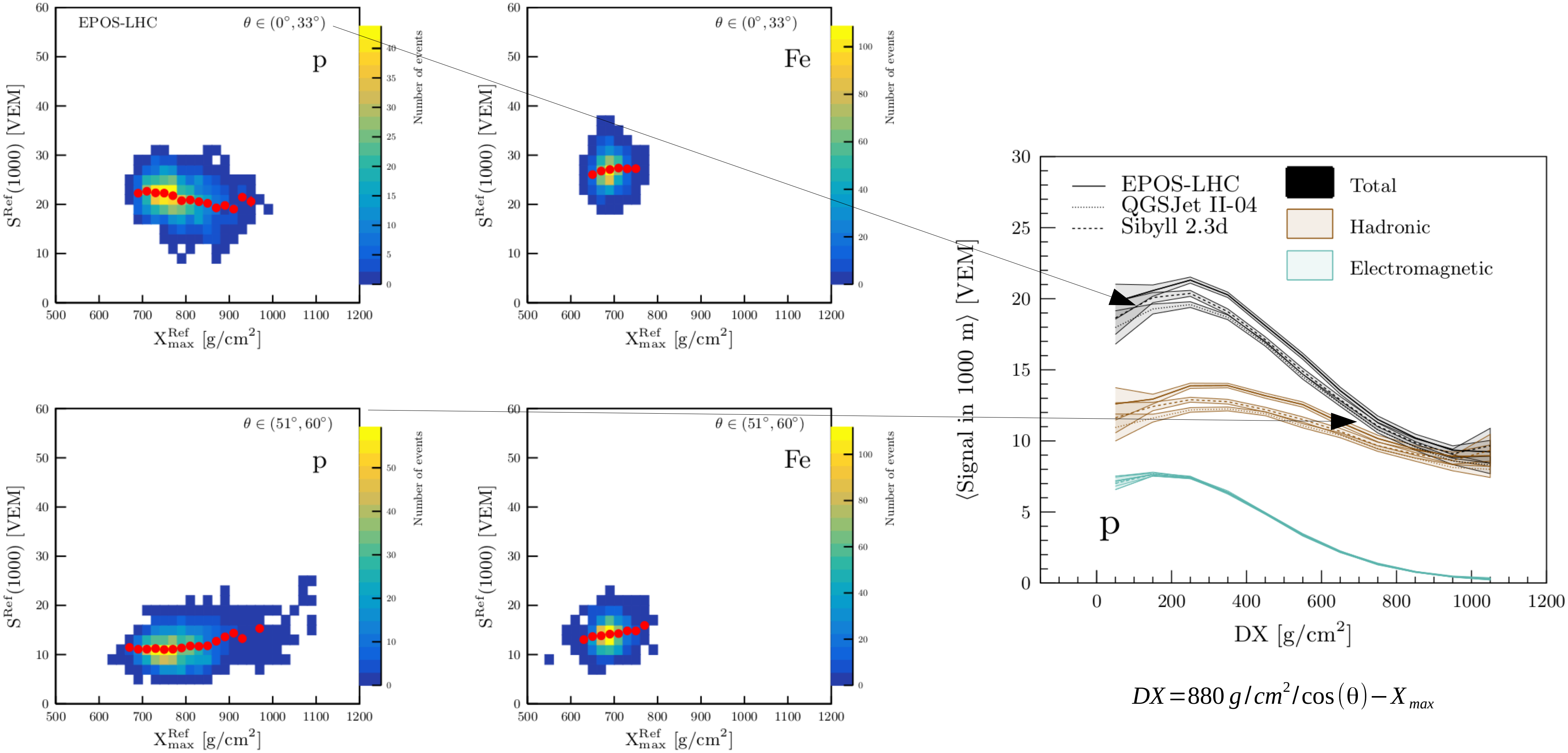






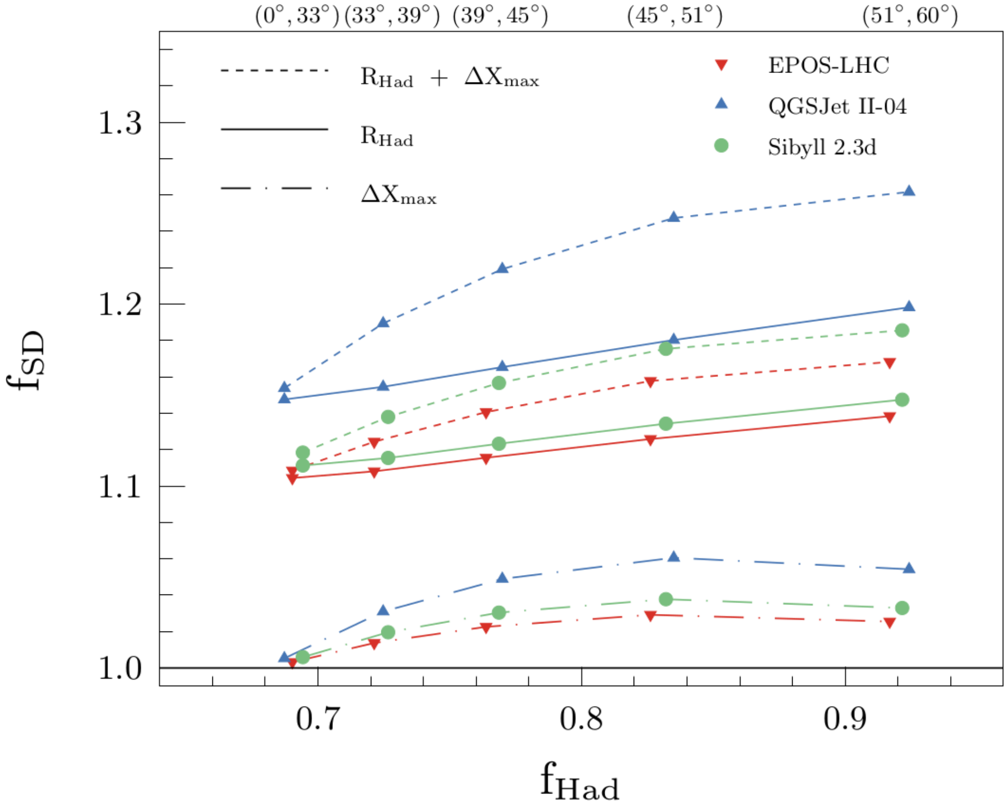
R_{Had} attenuation is correlated with the energy scale

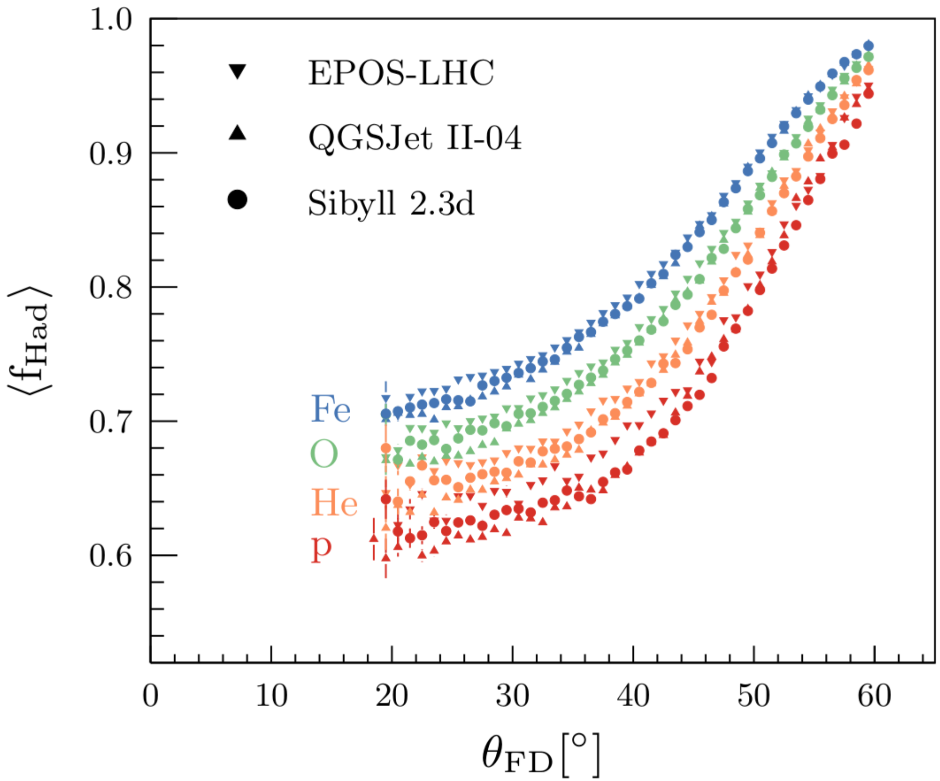
θ-dependent correlation between X_{max} and ground signal



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

Contributions to rescaling of ground signal





Fitting procedure

$$E^{Ref} = 10^{18.7}\, eV$$
$$B = 1.031$$
$$D = 58\, g/cm^2$$

zenith bins, 2D bins, MC, data

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

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

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

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

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

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

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

$$R_{Had}(\theta) = R_{Had}(\theta_{min}) + (R_{Had}(\theta_{max}) - R_{Had}(\theta_{min})) \cdot \frac{DX(\theta) - DX(\theta_{min})}{DX(\theta_{max}) - DX(\theta_{min})}$$