Relevance of hybrid data to the tuning of hadronic interaction models

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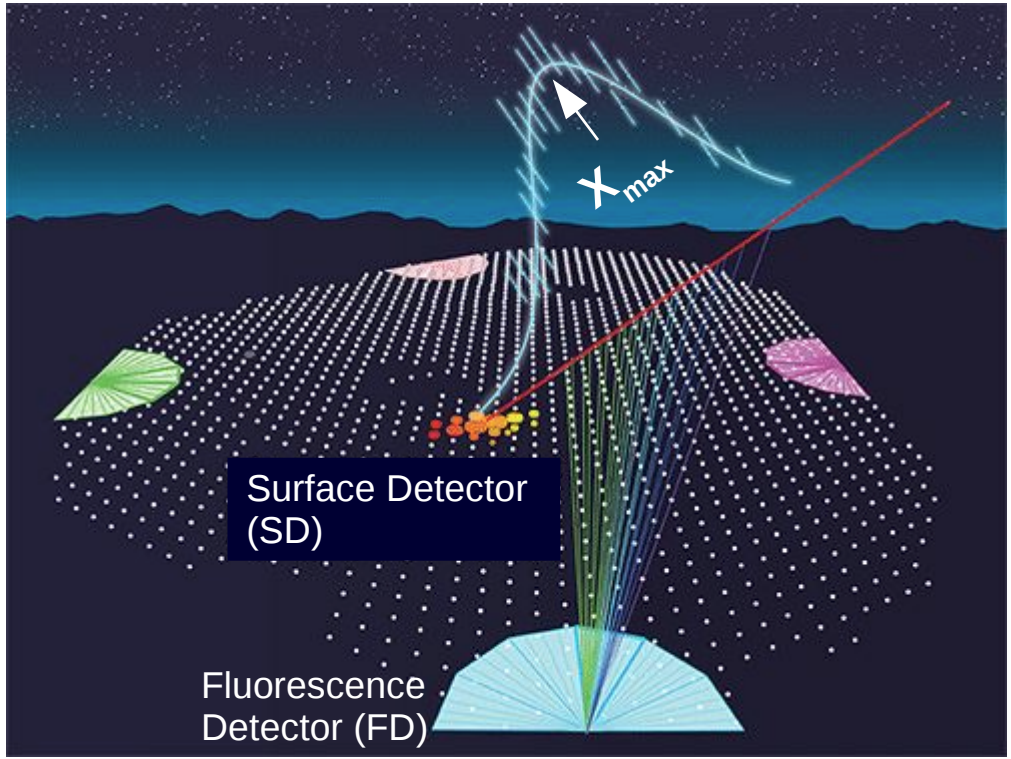
Observables relevant to hadronic interaction models

SD signal

- muon content
  - ➔ from S(1000), θ<60°
  - ➔ from N_{19}, θ>65°
    [Phys. Rev. D 91 (2015), 032003]
- muon production depth
  - ➔ for r > 1500m, θ>65°
    [Phys. Rev. D 90 (2014) 012012]
- muon attenuation
  - ➔ from θ and core dependance



FD Longitudinal profile

- estimation of primary masses from X_{max} fits
  [PRD 90 (2014) 122006]
- interpretation of X_{max} moments
  [JCAP 02 (2013) 026]
- p-air cross-section from tail of X_{max} distribution
  [Phys. Rev. Lett. 109 (2012) 062002]
- average shape of longitudinal profiles
  [JCAP 03 (2019) 018]
- frequency of anomalous showers

See references and talks of Markus (muons) and Tim (radio)

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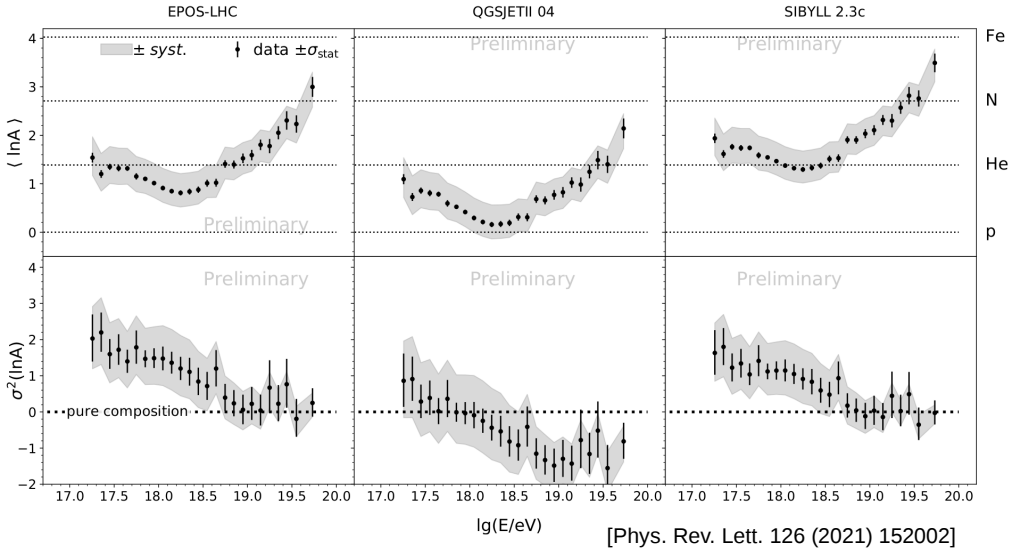
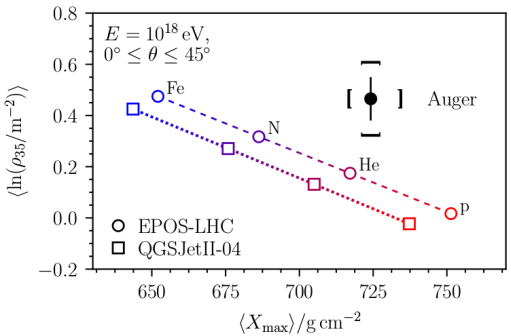
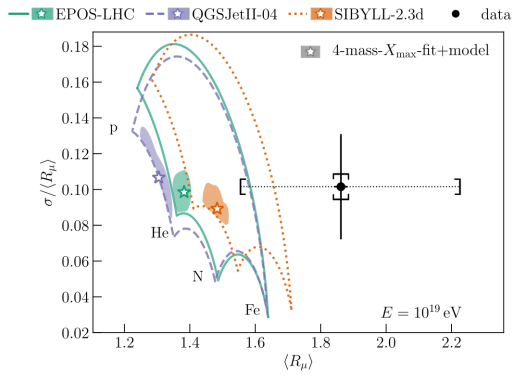
[PoS(ICRC2019)482]



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



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



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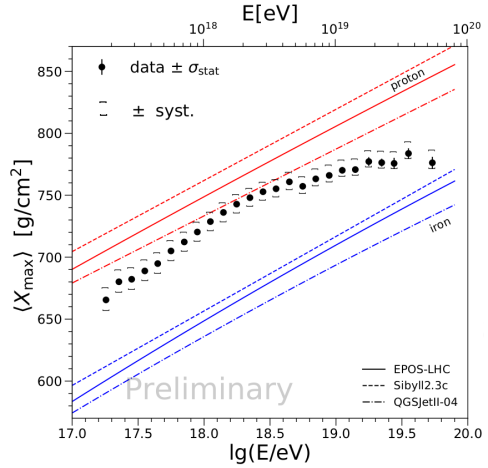
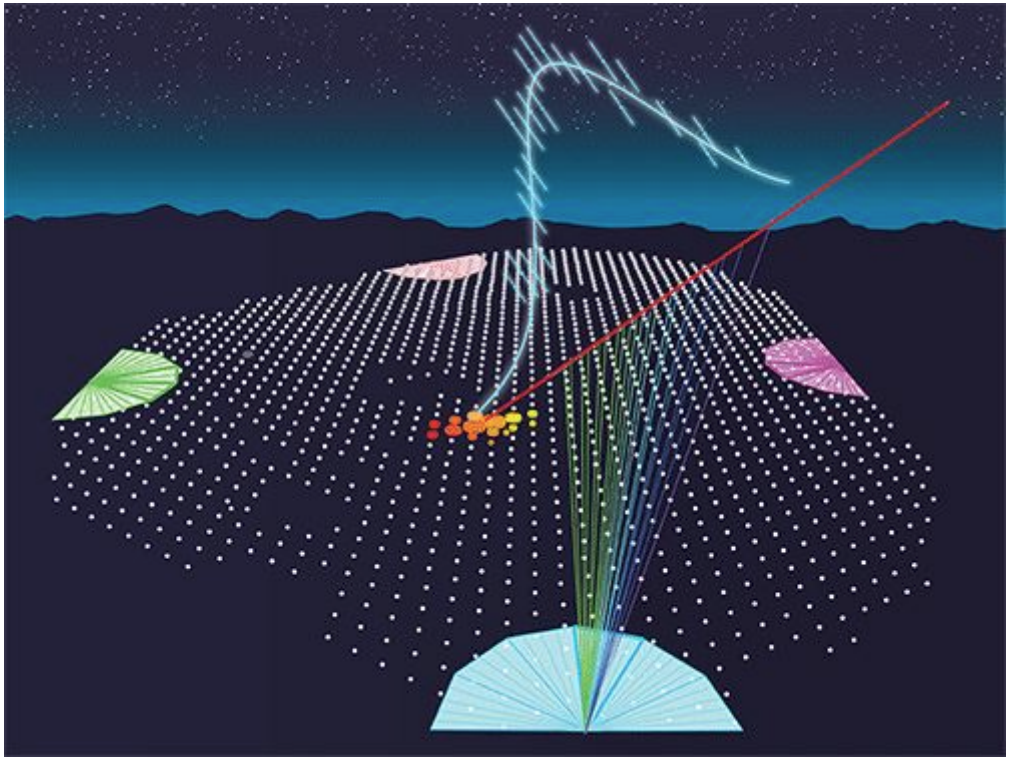


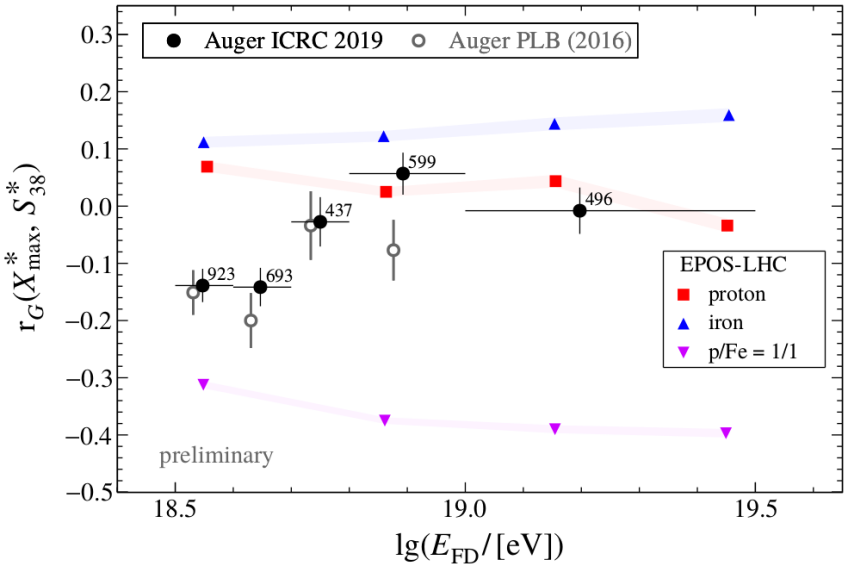
Hybrid observables relevant to hadronic interaction models

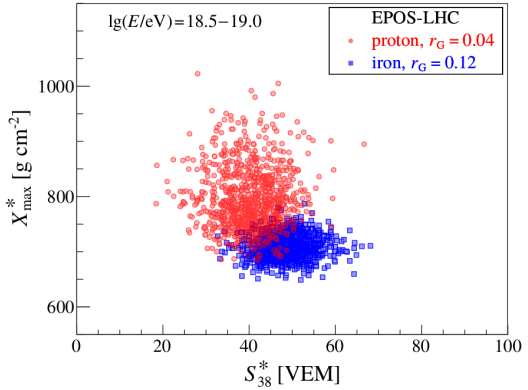


Ground signal + Longitudinal profile

- 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}

Hybrid observables relevant to hadronic interaction models





Ground signal + Longitudinal profile

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

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

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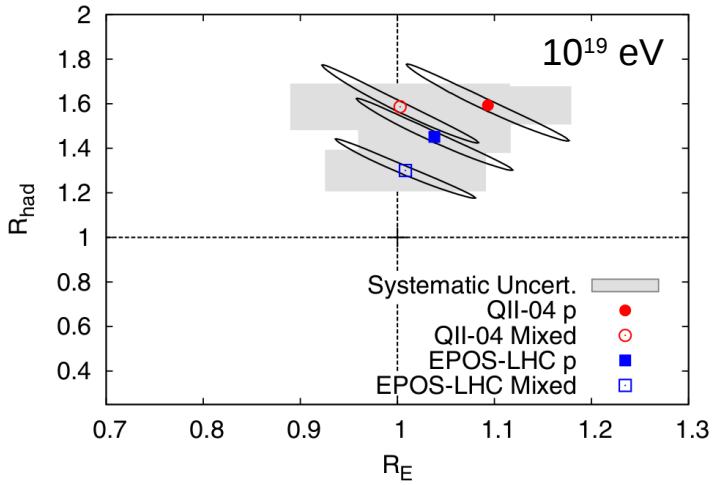
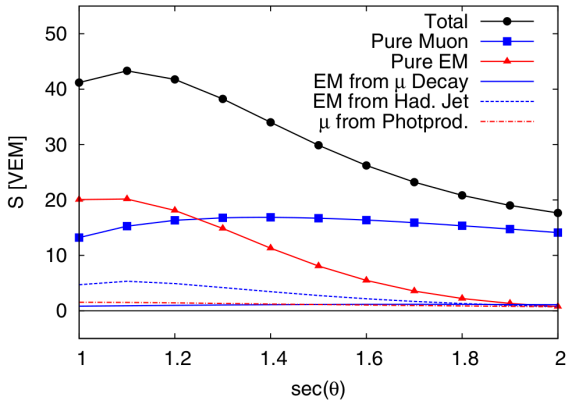
- applying shower-universality approach -> R_{had}
- 2-dim distributions S(1000),X_{max} -> $R_{had}(\theta)$, ΔX_{max}

- **~Model-independent estimator of spread of beam masses**
- **Tension with X_{max} fits for QGSJet II-04**

Hybrid observables relevant to hadronic interaction models



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



Ground signal + Longitudinal profile

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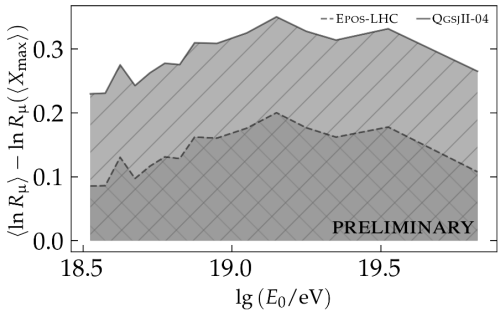
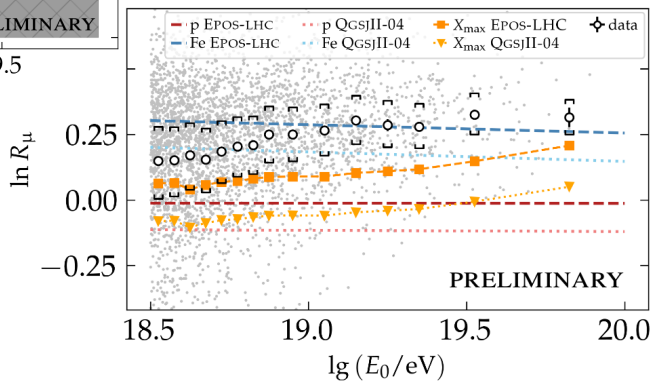
- top-down approach -> R_{had}
  [Phys. Rev. Lett. 117 (2016) 192001]
- applying shower-universality approach -> R_{had}
- 2-dim distributions S(1000),X_{max} -> $R_{had}(\theta)$, ΔX_{max}

- **Mass from measured X_{max} - depends on MC X_{max} scale**
- **Strong dependence on energy scale**

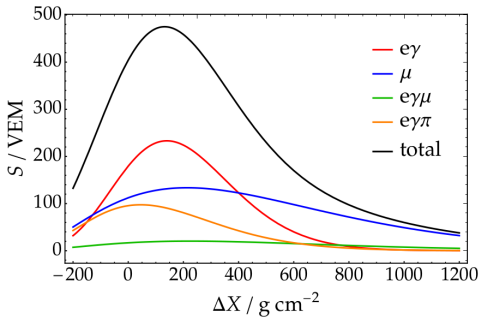
Hybrid observables relevant to hadronic interaction models

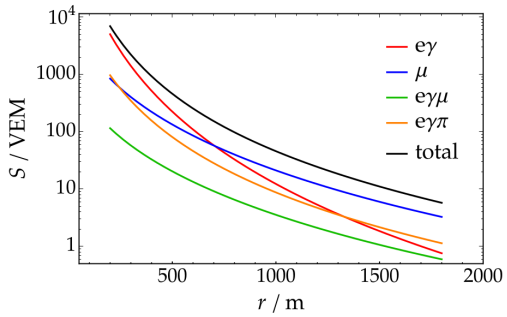


energy and X_{max} from FD



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





Ground signal + Longitudinal profile

- correlation between X_{max} and S(1000)
-
- top-down approach -> R_{had}
- applying shower-universality approach -> R_{had} [PoS(ICRC2023)339]
- 2-dim distributions S(1000),X_{max} -> $R_{had}(\theta)$, ΔX_{max}

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

Summary of tests of models using Auger data

test	energy / EeV	θ / °	EPOS-LHC	QGSJET-II-04	SIBYLL 2.3d
$X_{\max}$ moments	∼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	∼10	∼67	tension	tension	tension
mean muon number	0.2 to 2	0 to 45	tension	tension	—
fluctuation of muon number	4 to 40	∼67	no tension	no tension	no tension
muon production depth	20 to 70	∼60	tension	no tension	—
$S(1000)$	∼10	0 to 60	tension	tension	—

- **All models have problems ...**
- **Caveats: mass (MC X_{max} scale) & energy scale**
- **Can we test the models better?**

Hybrid observables relevant to hadronic interaction models

Ground signal + Longitudinal profile

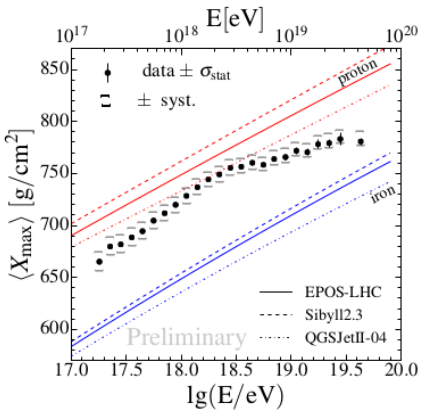
- correlation between X_{max} and S(1000)
-
- top-down approach -> R_{had}
- applying universality approach -> R_{had}
- 2-dim distributions S(1000),X_{max} -> $R_{had}(\theta)$, ΔX_{max}

- **Rest of the talk** (submitted to PRD)

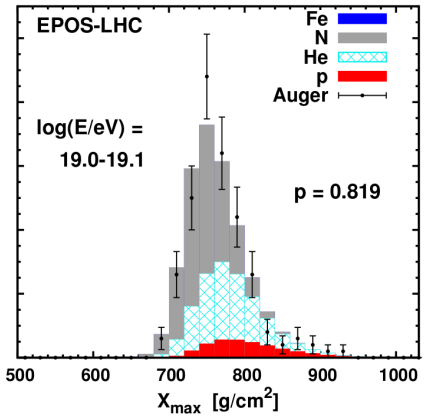
  arXiv:2401.10740 [astro-ph.HE]

Mass composition & tests of hadronic interactions

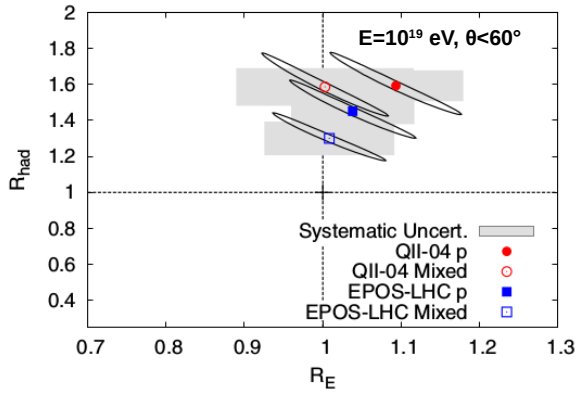
[PoS(ICRC19)482]



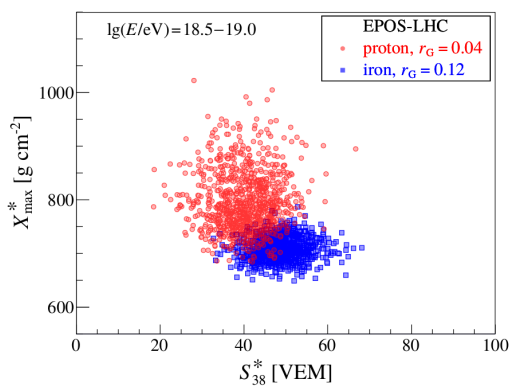
[Phys. Rev. D 90 (2014) 122006]



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



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



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}**

Motivations for modifications of MC predictions

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

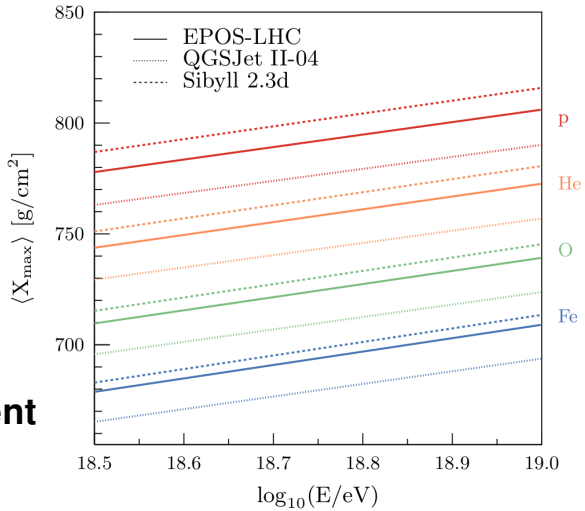
  [Astropart. Phys. 87 (2017) 23, Astropart. Phys. 88 (2017) 46]

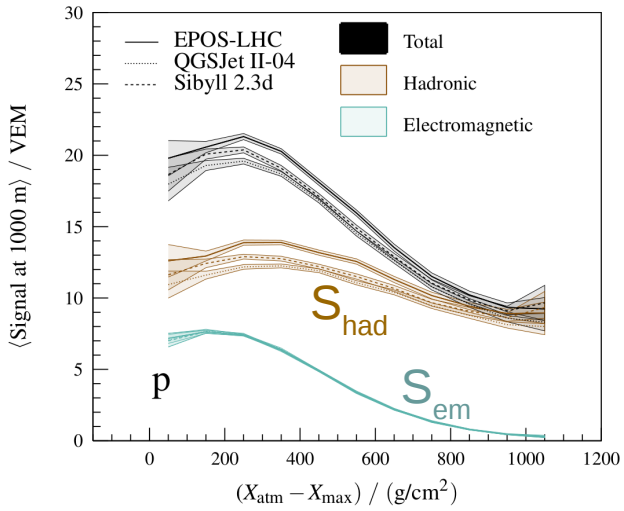
  - $S(1000) = S_{had} + S_{em}$
  - S_{em} very universal

- **Main differences** between model predictions:

  - Scale of $\langle X_{max} \rangle$ and $\langle S_{had} \rangle(\theta)$

    are **approx. primary and energy independent**





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

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

ad-hoc modifications

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

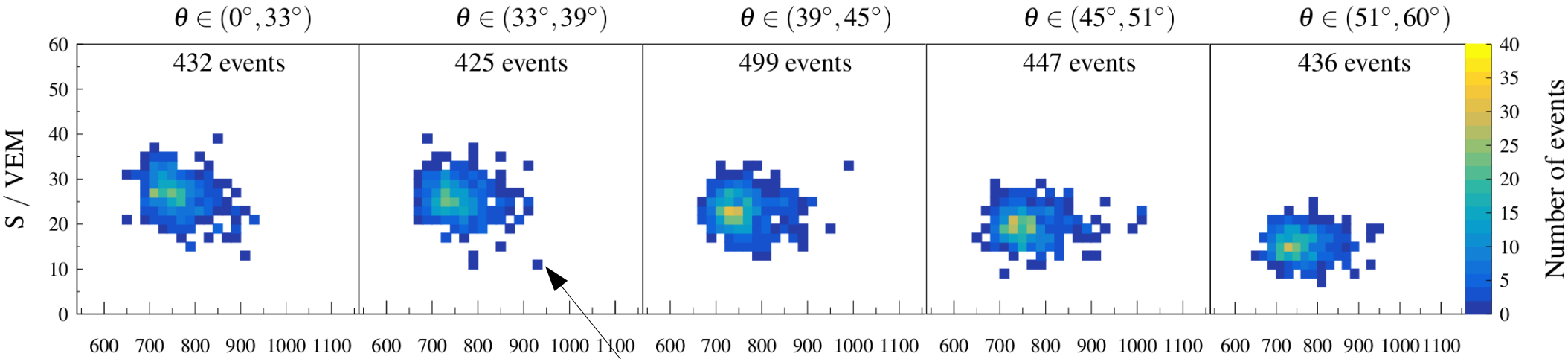
$$S_{had}(\theta) \rightarrow S_{had}(\theta) \cdot R_{had}(\theta)$$

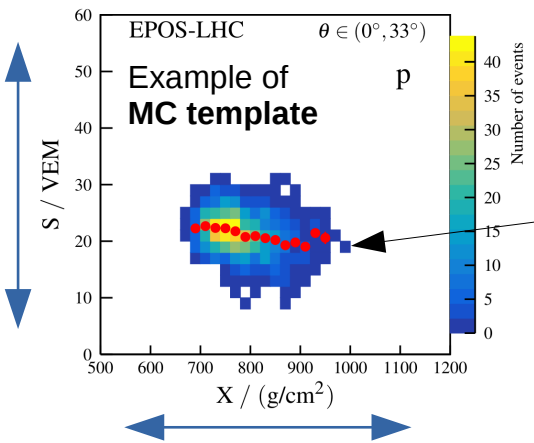
Auger data: 2239 events for $10^{18.5\text{-}19.0}$ eV

Method

$$S = S(1000)\left(\frac{E^{\mathrm{ref}}}{E_{\mathrm{FD}}}\right)^{1/B} \qquad X = X_{\max} + D\lg\left(\frac{E^{\mathrm{ref}}}{E_{\mathrm{FD}}}\right)$$

$E^{ref} = 10^{18.7}$ eV





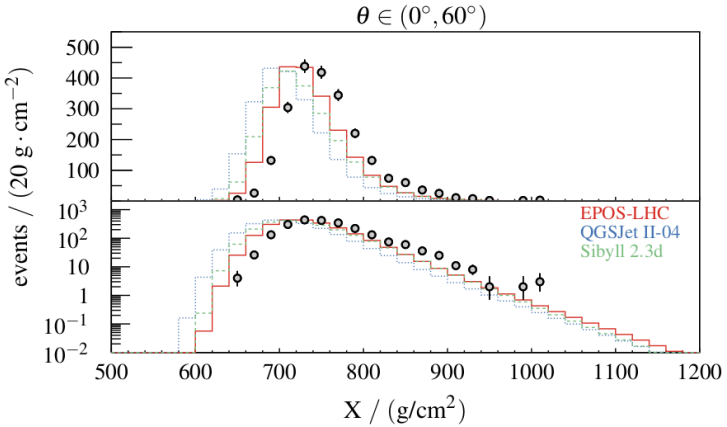
θ bins
2D bins

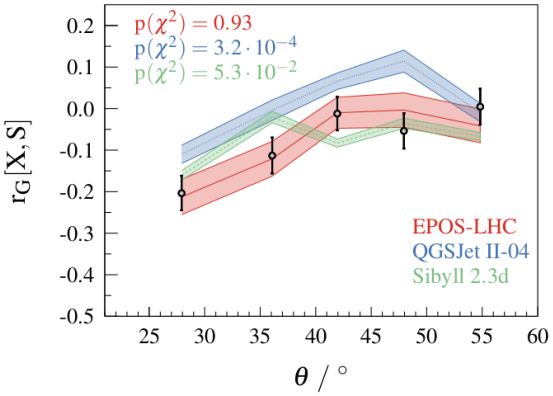
$$\ln\mathscr{L} = \begin{cases} \sum_k \sum_j (C_{jk} - n_{jk} + n_{jk}\ln\frac{n_{jk}}{C_{jk}}), & n_{jk} > 0 \\ \sum_k \sum_j C_{jk}, & n_{jk} = 0 \end{cases}$$

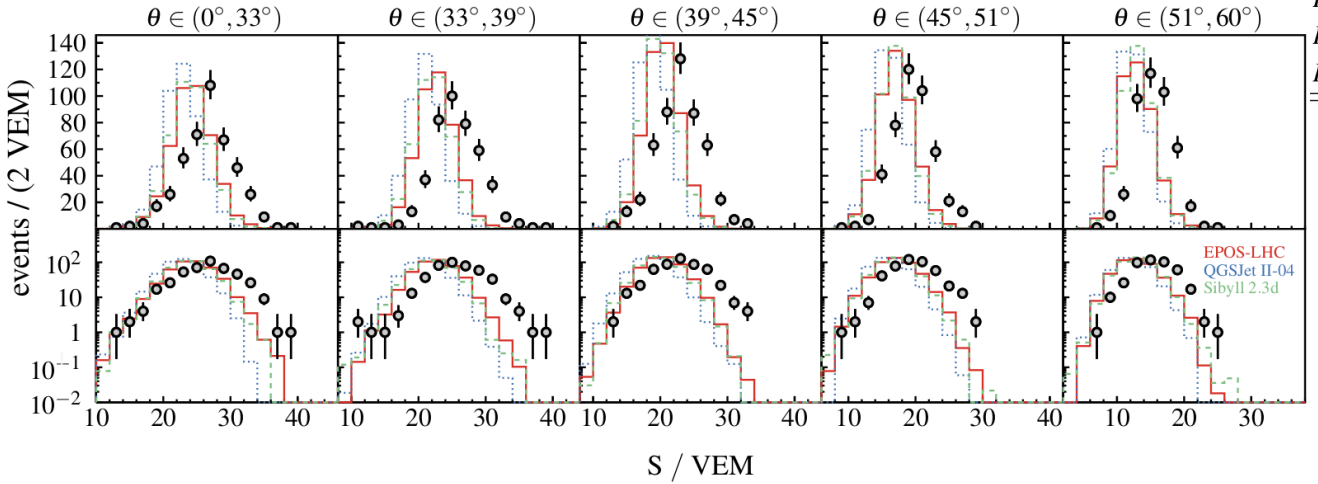
- **Freedom** in X_{max} (ΔX_{max}) and S(1000) ($R_{had}(\theta)$) and primary fractions
- Change of S_{had} and S_{em} due to ΔX_{max} incorporated

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
$R_{\text{had}} = \text{const.}$	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
$R_{\text{had}}(\theta)$ and $\Delta X_{\max}$	451.9	476.3	451.6

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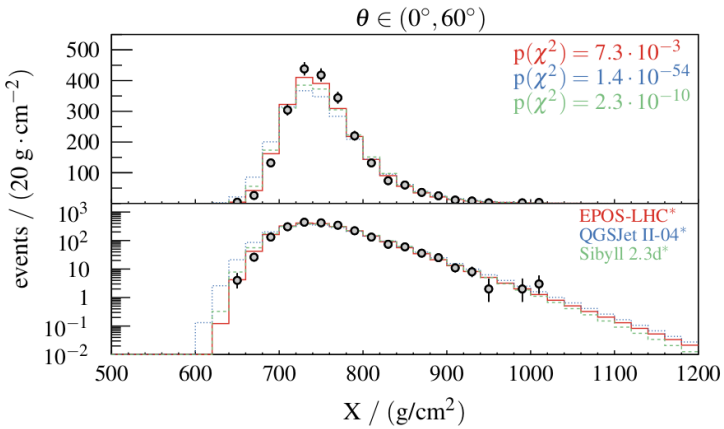

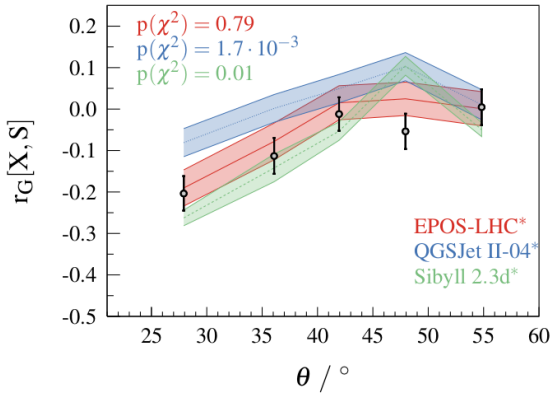

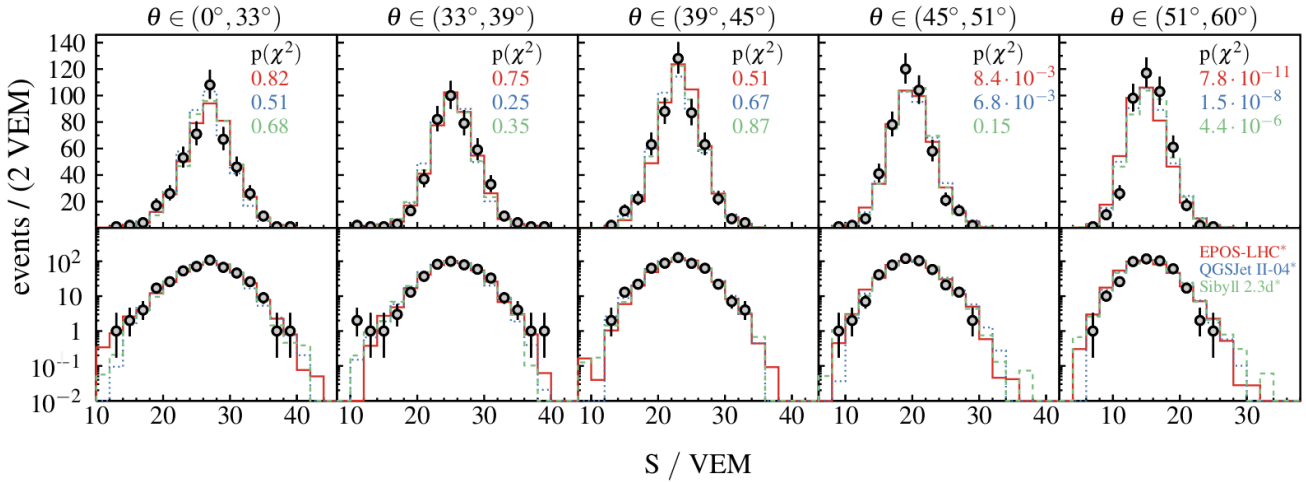

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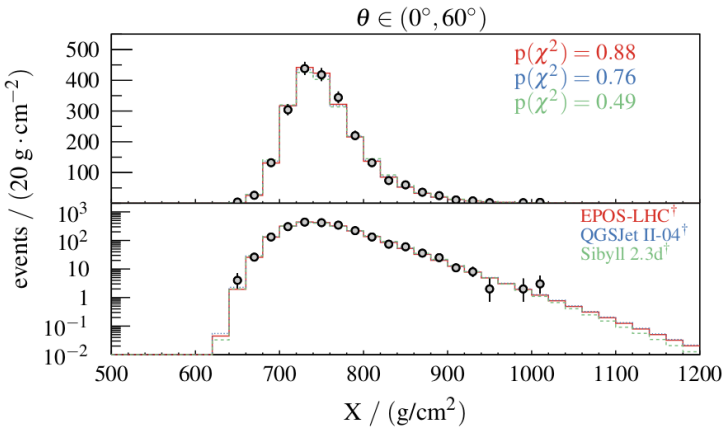

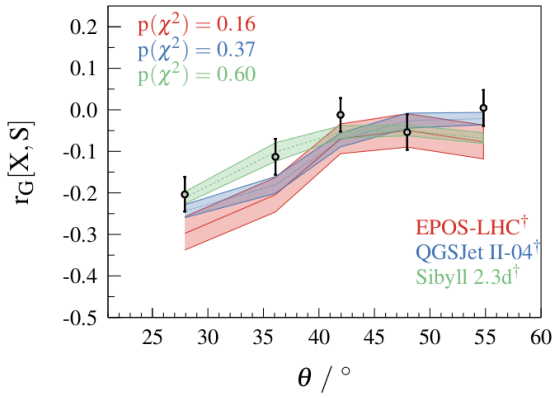

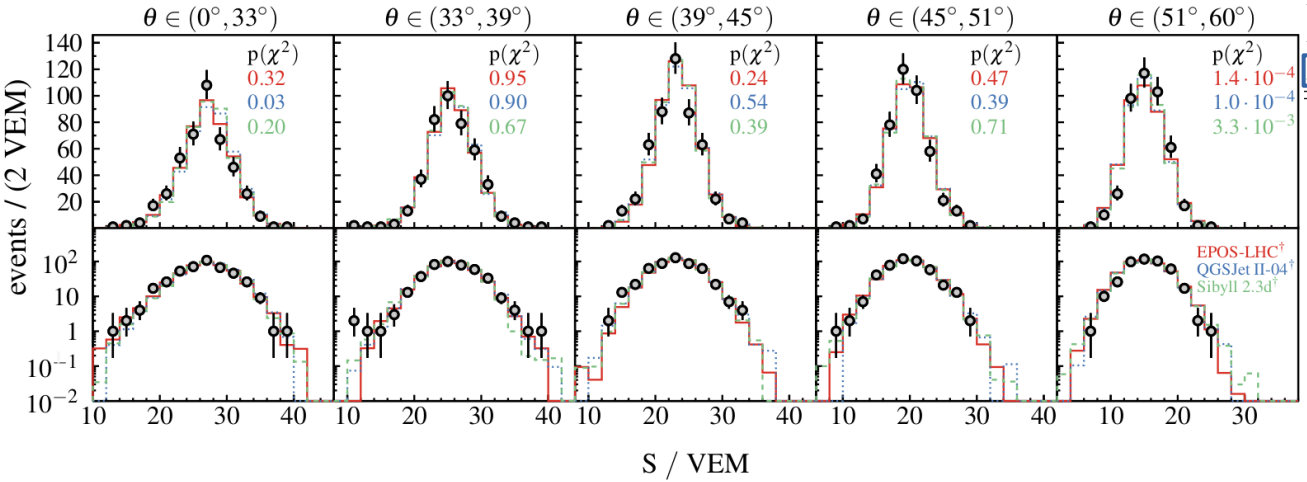

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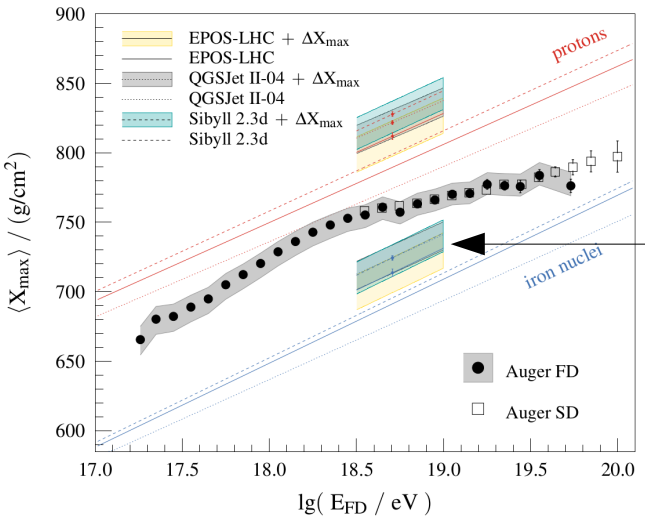
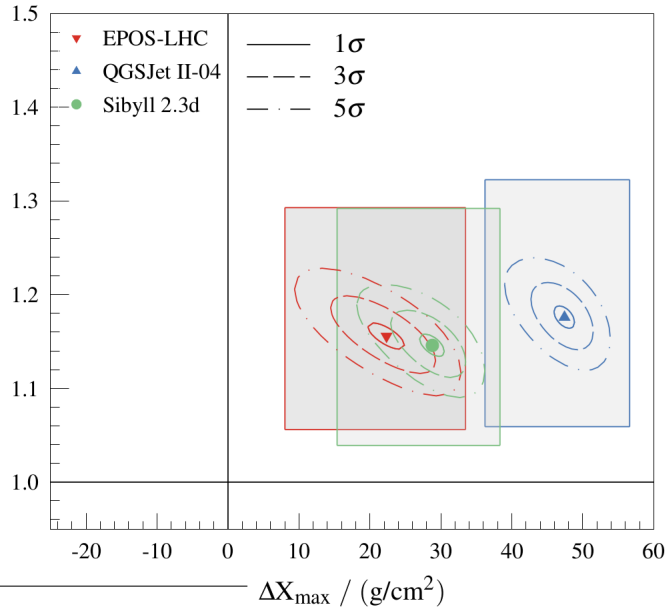
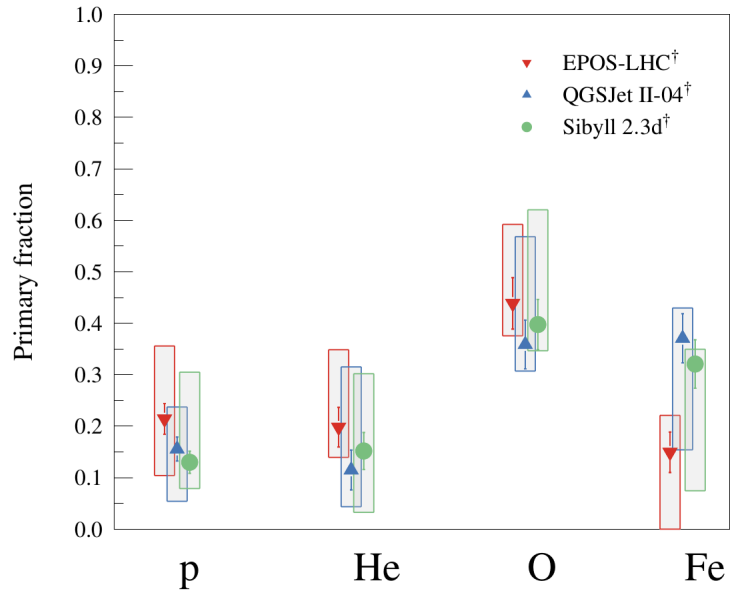
Significant improvement >5σ using R_{had} and ΔX_{max} (Likelihood ratio tests for nested model using Wilks' theorem)

	$R_{\rm had}(\theta_{\rm min})$	$R_{\rm had}(\theta_{\rm max})$	$\Delta X_{\rm max}$/(g/cm^2)	$f_{\rm p}$ (%)	$f_{\rm He}$ (%)	$f_{\rm O}$ (%)	$f_{\rm Fe}$ (%)	p-value (%)
EPOS-LHC	$1.15 \pm 0.01\,^{+0.20}_{-0.16}$	$1.16 \pm 0.01\,^{+0.14}_{-0.10}$	$22 \pm 3\,^{+11}_{-14}$	$21 \pm 3\,^{+14}_{-11}$	$20 \pm 4\,^{+15}_{-6}$	$44 \pm 5\,^{+15}_{-6}$	$15 \pm 4\,^{+7}_{-15}$	10.6
QGSJET-II-04	$1.24 \pm 0.01\,^{+0.22}_{-0.19}$	$1.18 \pm 0.01\,^{+0.15}_{-0.12}$	$47^{+2}_{-1}\,^{+9}_{-11}$	$16 \pm 2\,^{+8}_{-10}$	$11 \pm 4\,^{+20}_{-7}$	$36 \pm 5\,^{+21}_{-5}$	$37 \pm 5\,^{+6}_{-22}$	19.8
SIBYLL 2.3d	$1.18 \pm 0.01\,^{+0.21}_{-0.17}$	$1.15 \pm 0.01\,^{+0.15}_{-0.11}$	$29 \pm 2\,^{+10}_{-13}$	$13 \pm 2\,^{+18}_{-5}$	$15 \pm 4\,^{+15}_{-12}$	$40 \pm 5\,^{+22}_{-5}$	$32 \pm 5\,^{+3}_{-25}$	32.6

Zenith dependence of R_{had} assumed to be linear in X_{ground}-X_{max}
→ $R_{had}(\theta_{min}\sim28°)$, $R_{had}(\theta_{max}\sim55°)$

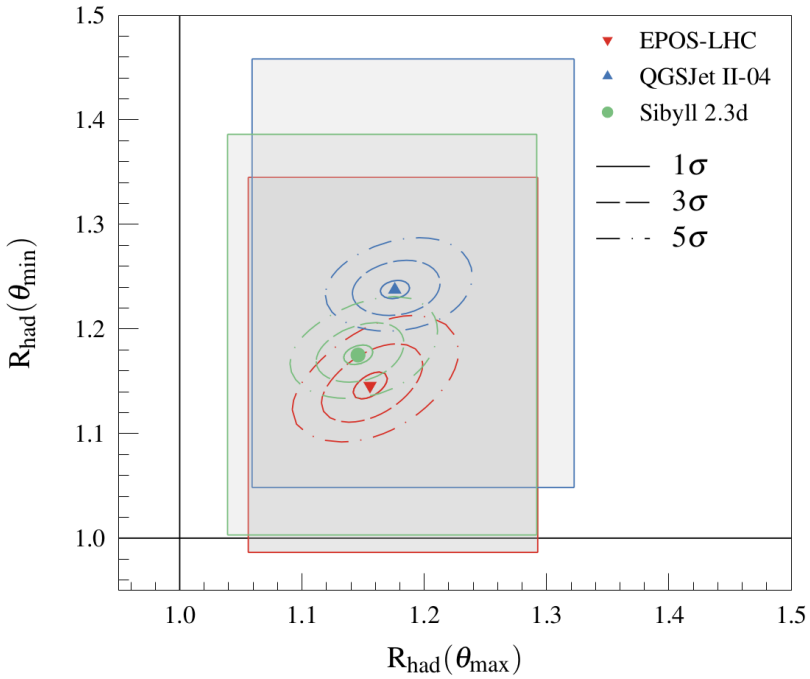


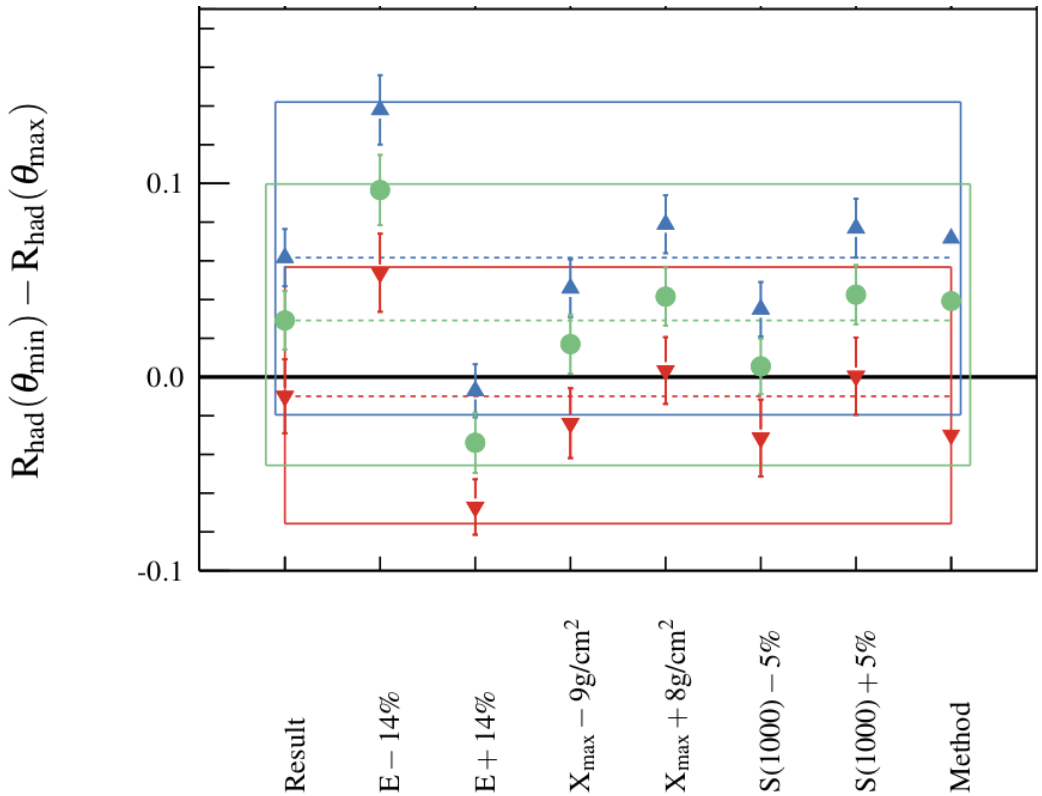




- Deeper X_{max} predictions
- Smaller model differences in mass composition
- Alleviated “muon problem“

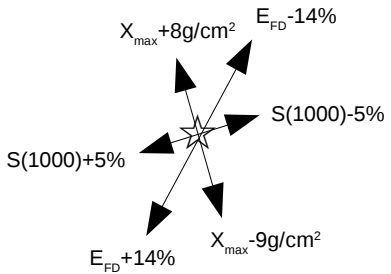
Attenuation of hadronic signal





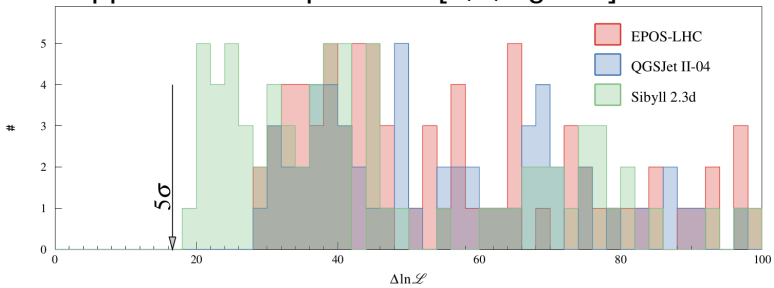
Indication of harder muon spectra in QGSJet II-04 than in data

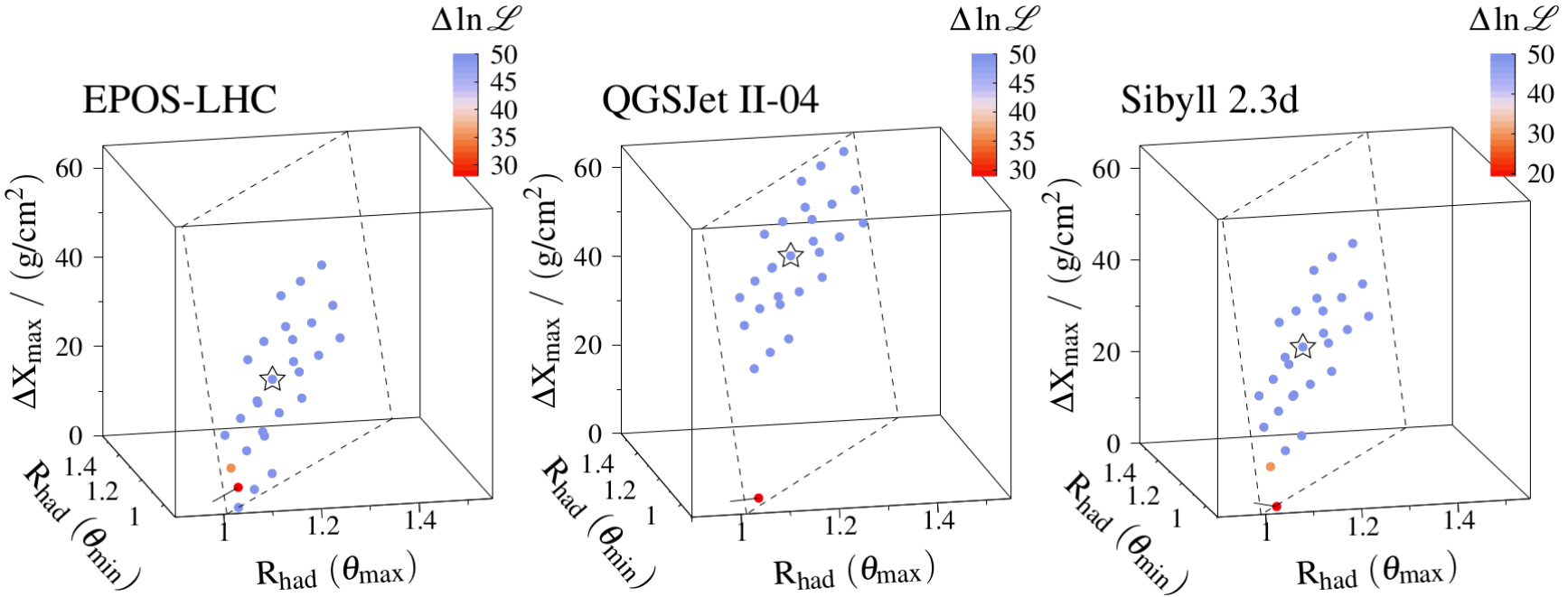
Scanning in combinations of experimental systematics



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 g/cm²]





Conclusions

- Combination of signals from surface and fluorescence detectors is a powerful tool to examine models of hadronic interactions
- Fitting 2D distributions of S(1000),X_{max} measured at Auger $10^{18.5\text{-}19.0}$ eV, $\theta < 60°$:
  - MC X_{max} should be deeper in the atmosphere by about 20 to 50 g/cm^2
  - MC hadronic signal should be increased by about 15 to 25% (alleviation of the “muon problem“)
  - heavier mass composition (reduction of differences between models)
  - improvement in data description using R_{had} and $\Delta X_{max} > 5\sigma$ for any linear combination of experimental systematic uncertainties

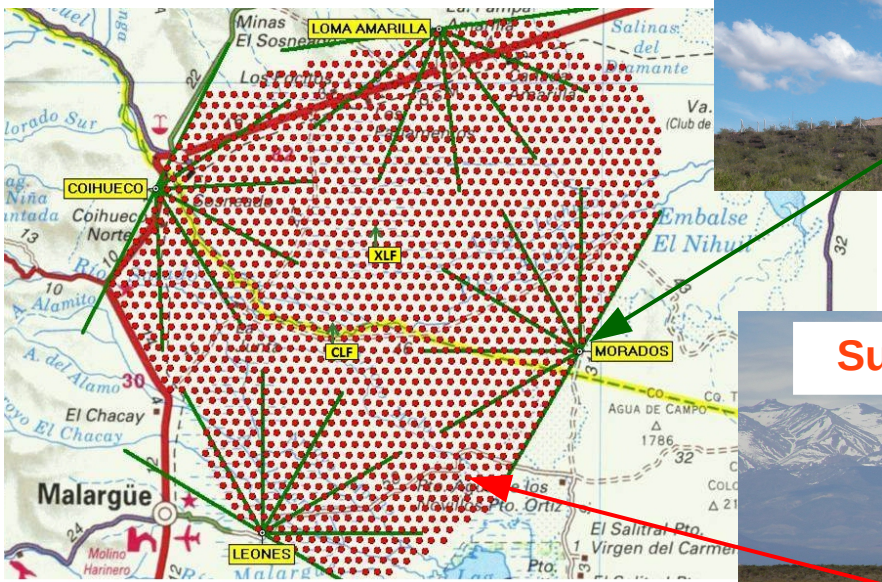
Check arXiv:2401.10740 [astro-ph.HE] for more details

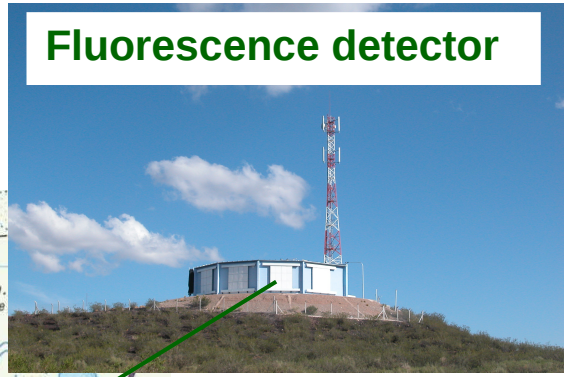
- Outlook:
  - extend energy range, adopt possible mass-dependence of modifications and study effects of fluctuations, test new models

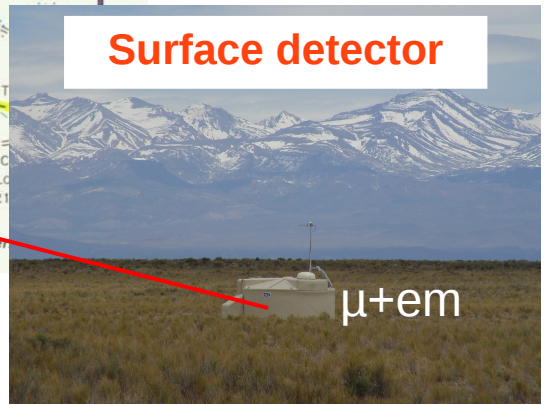
Backup slides

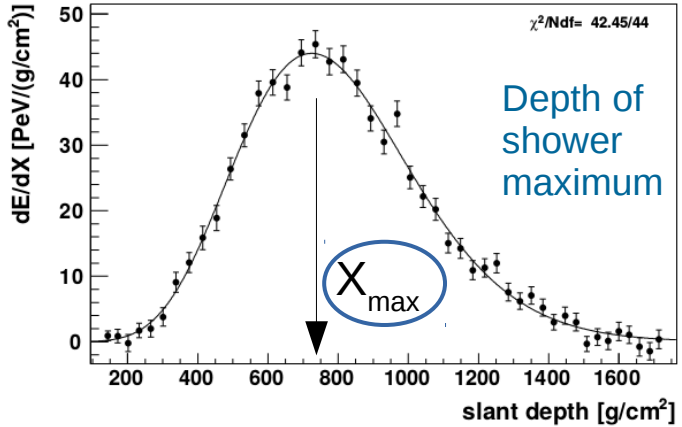
Hybrid detection at the Pierre Auger Observatory

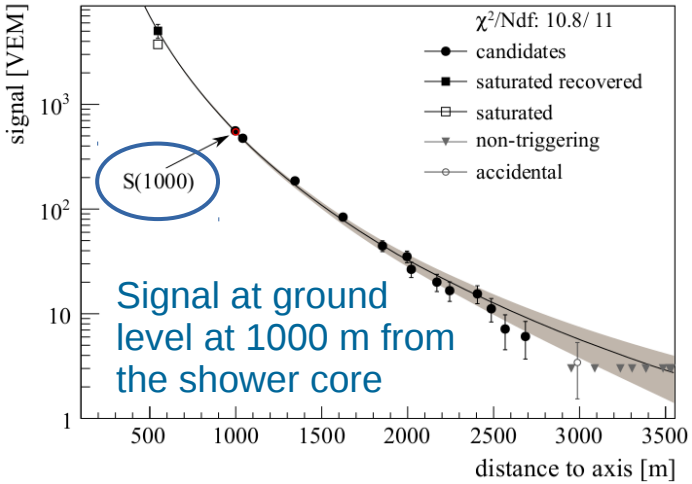
[Nucl. Instrum. Meth. A 798 (2015) 172]



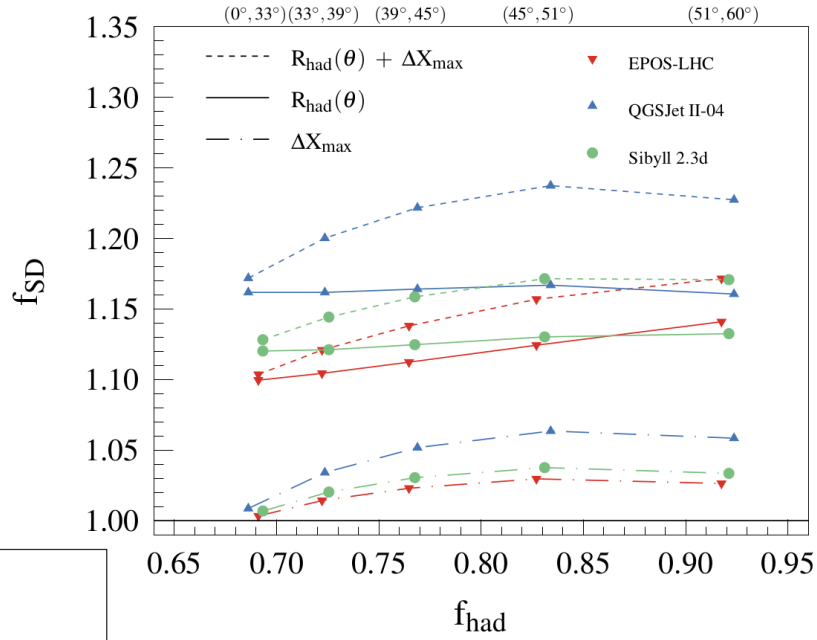


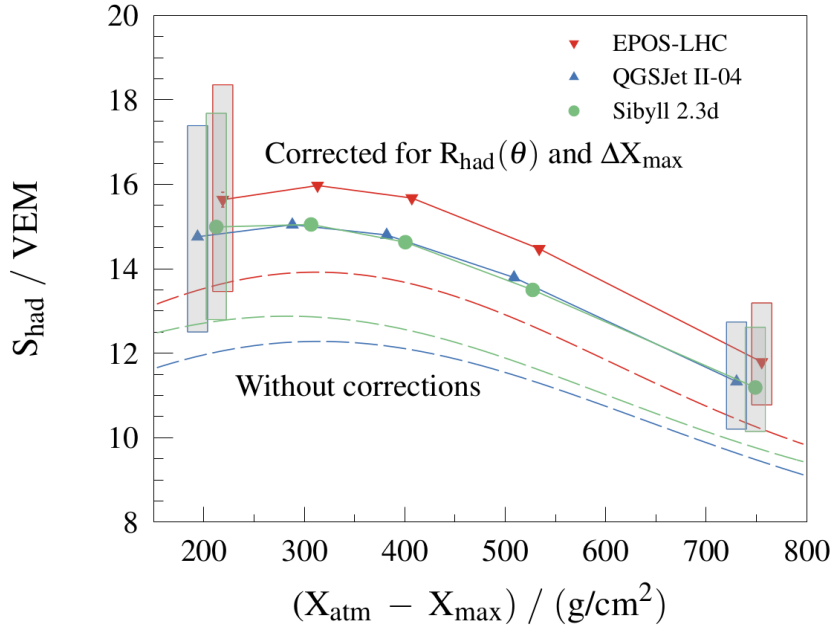


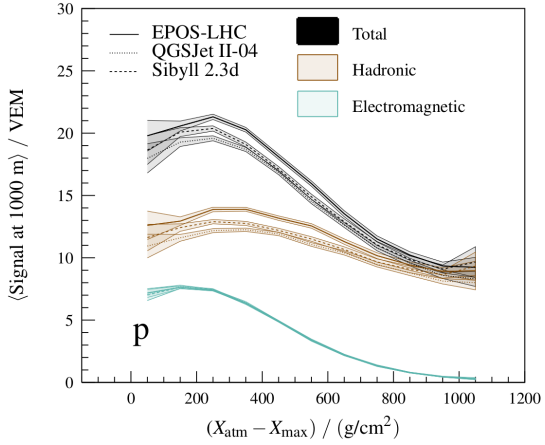


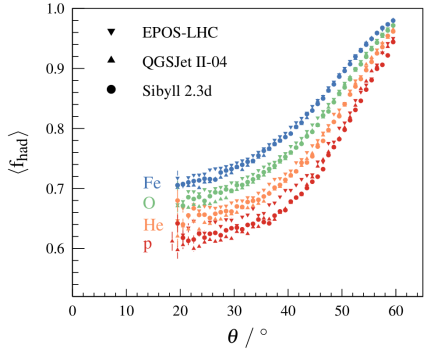


Effect of modified X_{max} on the ground signal









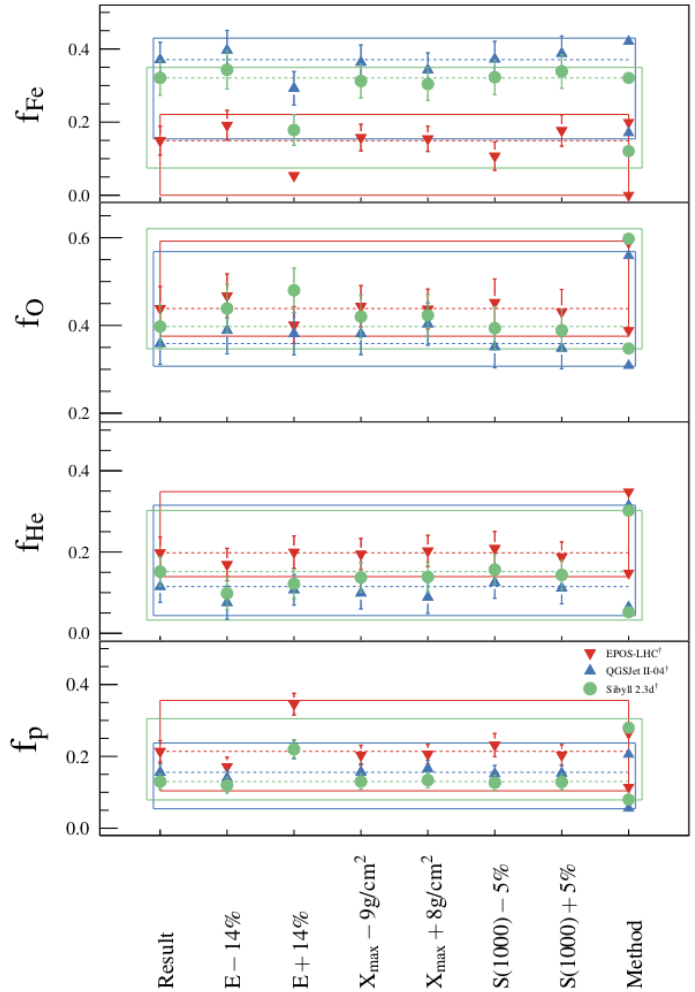
Assumption on primary species

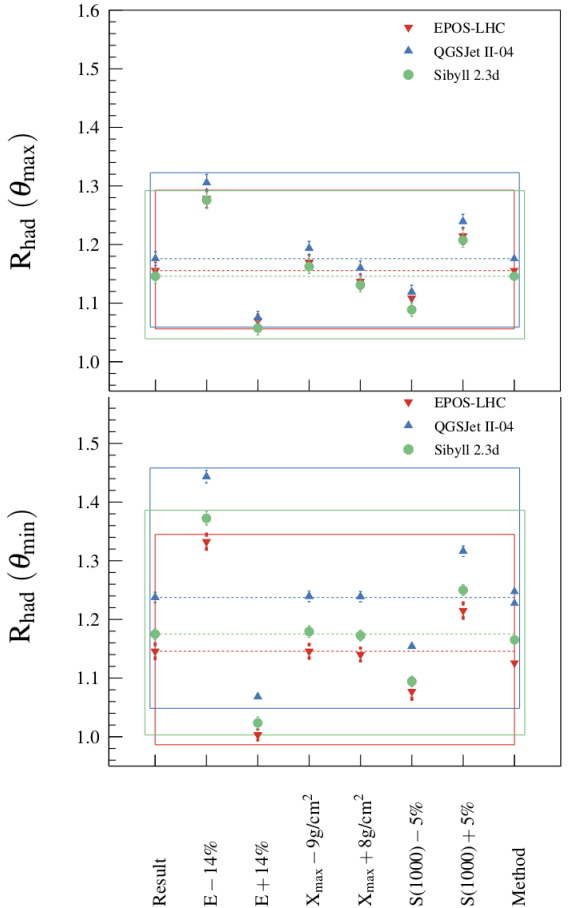
- ΔX_{max} decreases by about 5-7, 10-17 and 30-40 g/cm2 and $R_{had}(\theta)$ increases by about 2-5%, 4-9% and 15-20% when the heaviest primary Fe is replaced by Si, O and He, respectively

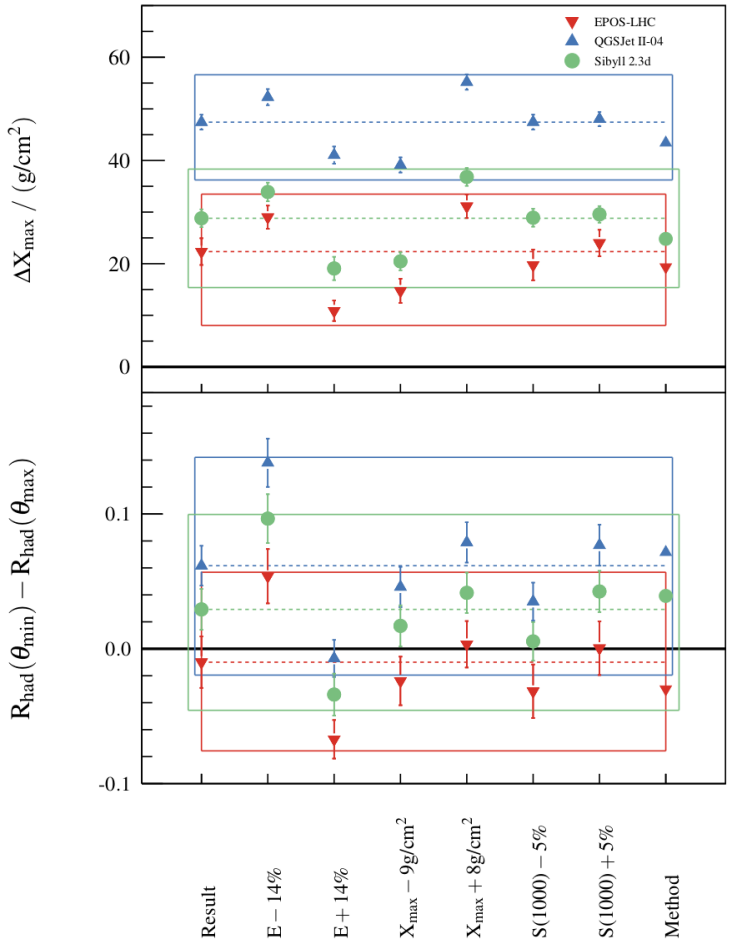
$\ln \mathscr{L}_{min}$	EPOS-LHC	QGSJET-II-04	SIBYLL 2.3d
p He	518.3	633.5	563.5
p He O	467.5	523.3	486.6
p He O Fe	451.9	476.3	451.6

Significance of improvement of data description above 5σ

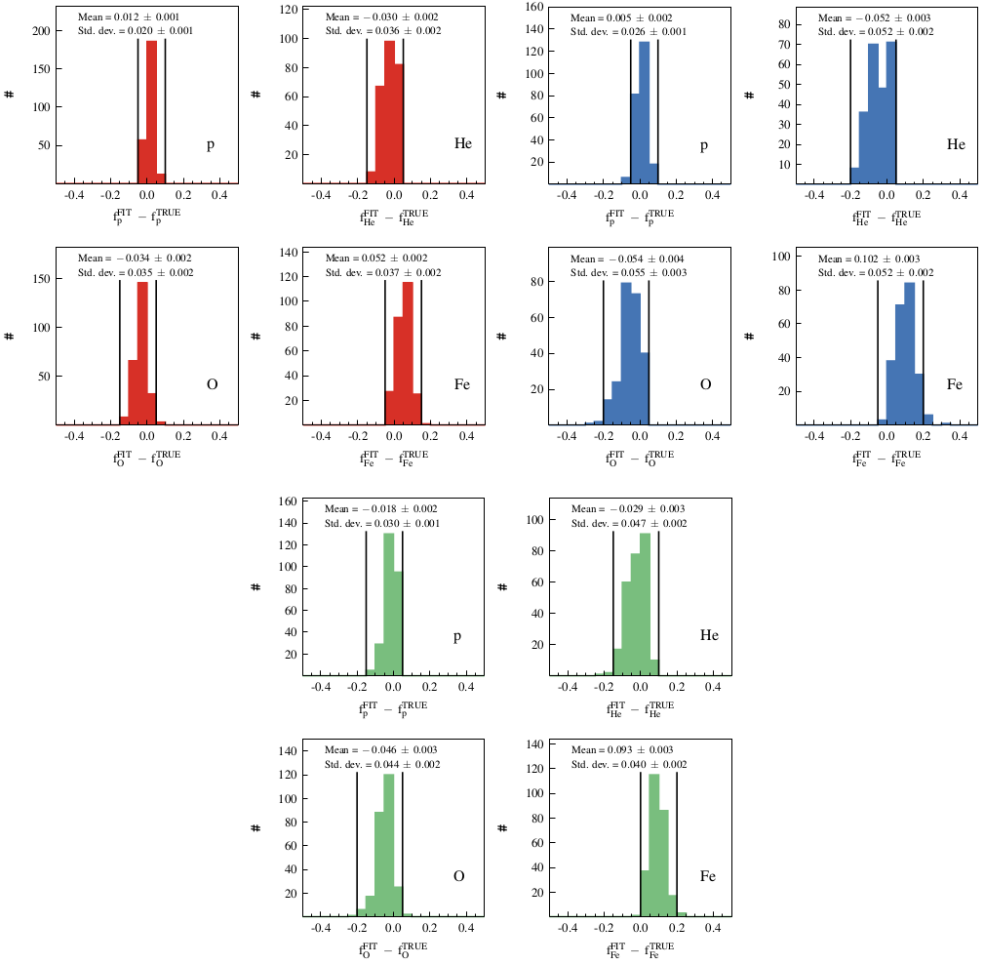
Systematic uncertainties

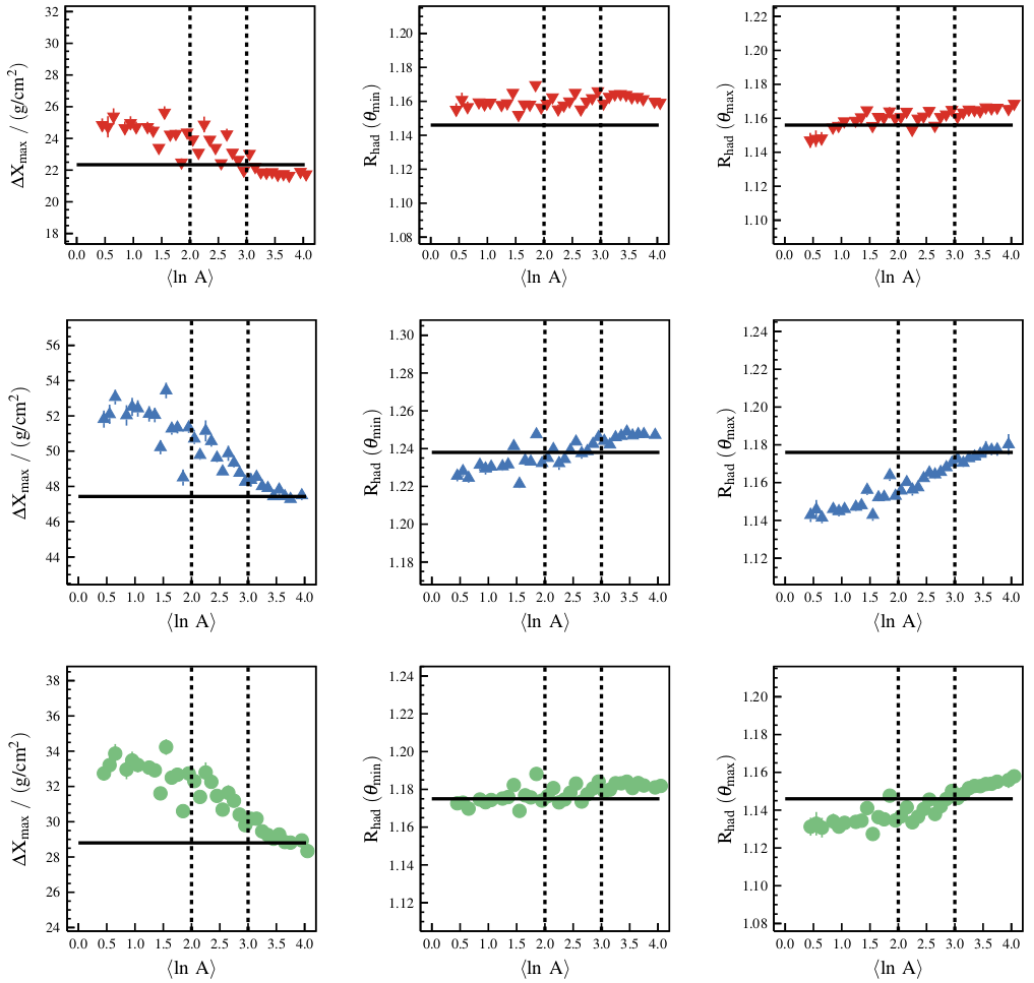






MC-MC tests

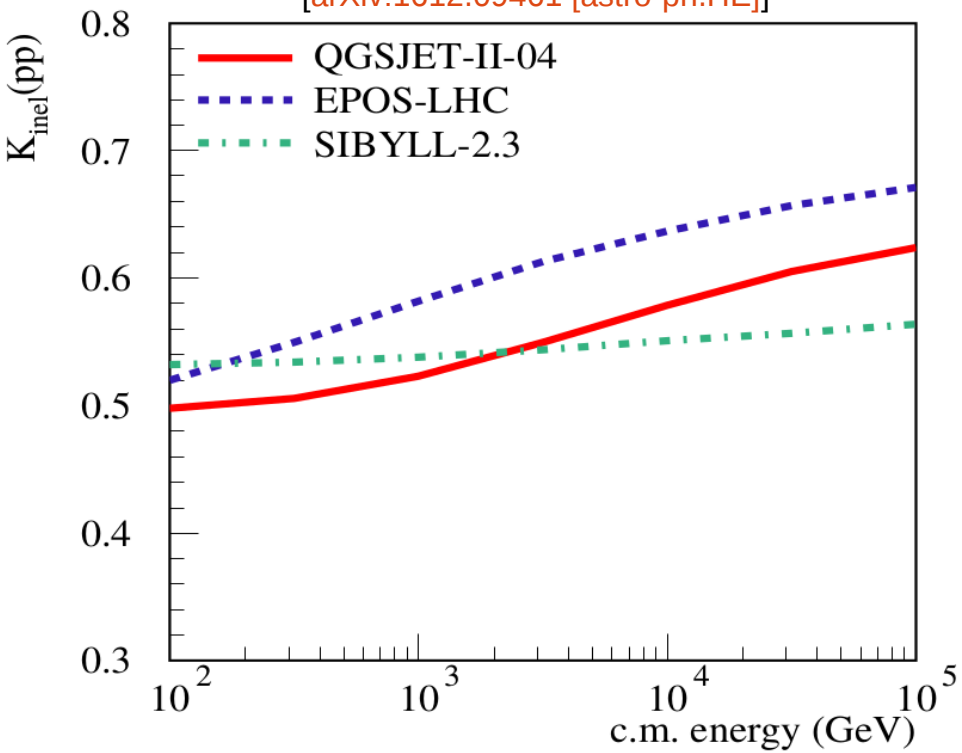

Mean = 0.012 ± 0.001
Std. dev. = 0.020 ± 0.001
p
Mean = −0.030 ± 0.002
Std. dev. = 0.036 ± 0.002
He
Mean = 0.005 ± 0.002
Std. dev. = 0.026 ± 0.001
p
Mean = −0.052 ± 0.003
Std. dev. = 0.052 ± 0.002
He
Mean = −0.034 ± 0.002
Std. dev. = 0.035 ± 0.002
O
Mean = 0.052 ± 0.002
Std. dev. = 0.037 ± 0.002
Fe
Mean = −0.054 ± 0.004
Std. dev. = 0.055 ± 0.003
O
Mean = 0.102 ± 0.003
Std. dev. = 0.052 ± 0.002
Fe
Mean = −0.018 ± 0.002
Std. dev. = 0.030 ± 0.001
p
Mean = −0.029 ± 0.003
Std. dev. = 0.047 ± 0.002
He
Mean = −0.046 ± 0.003
Std. dev. = 0.044 ± 0.002
O
Mean = 0.093 ± 0.003
Std. dev. = 0.040 ± 0.002
Fe


ΔXmax / (g/cm²)
Rhad (θmin)
Rhad (θmax)
⟨ln A⟩

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

"changing the normalization of energy dependence"

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



multiplicity: $N \propto N_0 \cdot E^{\alpha}$

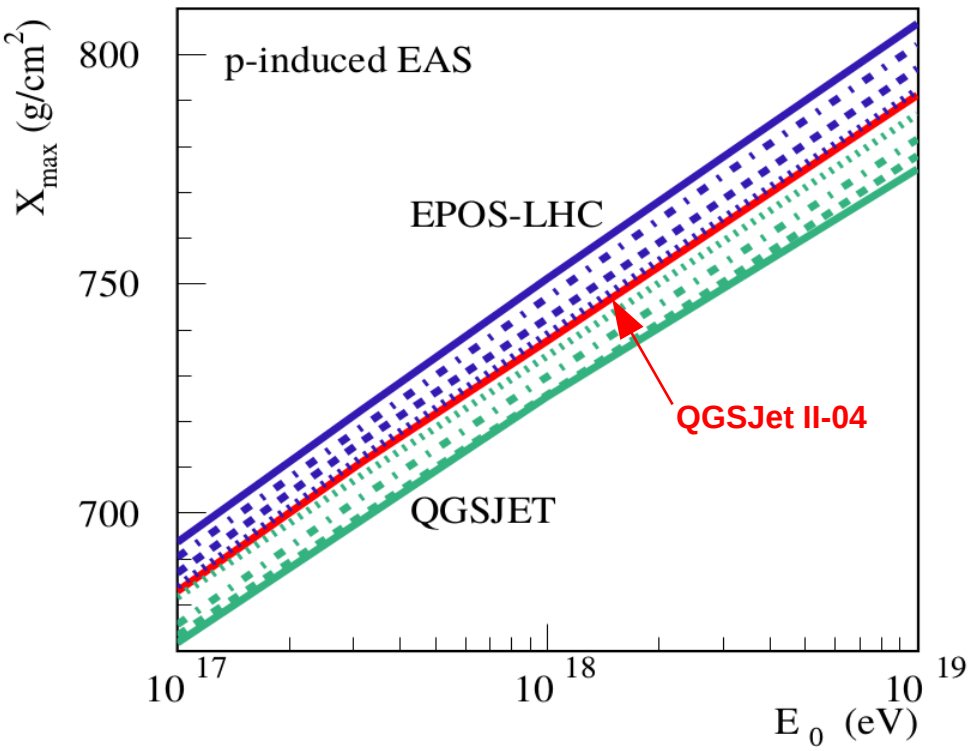
inelasticity: $\kappa \propto \kappa_0 \cdot E^{-\omega}$

$$X^{\mathrm{A}}_{\mathrm{max}} = X^A_1 + X_0 \ln \frac{\kappa E}{A \cdot 2N\xi^{\pi}_{\mathrm{c}}} =$$

$$X^A_1 + (1-\alpha-\omega)\cdot(X_0 \ln \frac{E}{A \cdot \xi^{\pi}_{\mathrm{c}}}) + X_0 \cdot (\ln \kappa_0 - \ln N_0)$$

$$\begin{matrix}\kappa_0 \rightarrow f_\kappa \kappa_0 \\ N_0 \rightarrow f_N N_0\end{matrix} \quad \Rightarrow \quad X^A_{max}{}' = X^A_{max} + X_0(\ln(f_\kappa) - \ln(f_N))$$

Cocktail of models



arXiv:1612.09461 [astro-ph.HE]: “Indeed, if we apply QGSJET-II-04 to describe both the primary interaction and the production of nucleons and antinucleons in all the secondary pion-air and kaon-air collisions, while treating the rest with EPOS-LHC, the obtained Xmax shown by the upper dotted line practically coincides with the QGSJET-II-04 results.“

What about Fe?
What about Sibyll?

MOCHI (very preliminary) [PoS(ICRC2023)245]

"changing the shape of energy dependence"