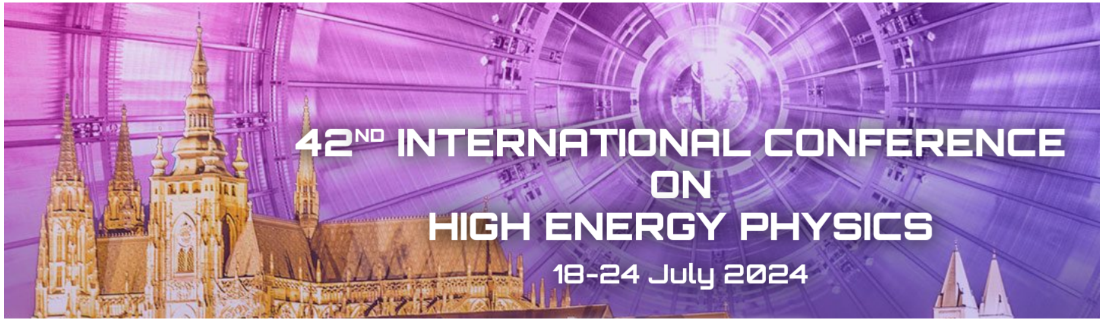

Probing hadronic interactions using the latest data from the Pierre Auger Observatory

Jakub Vícha

for the Pierre Auger Collaboration

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Observables relevant to hadronic interaction models

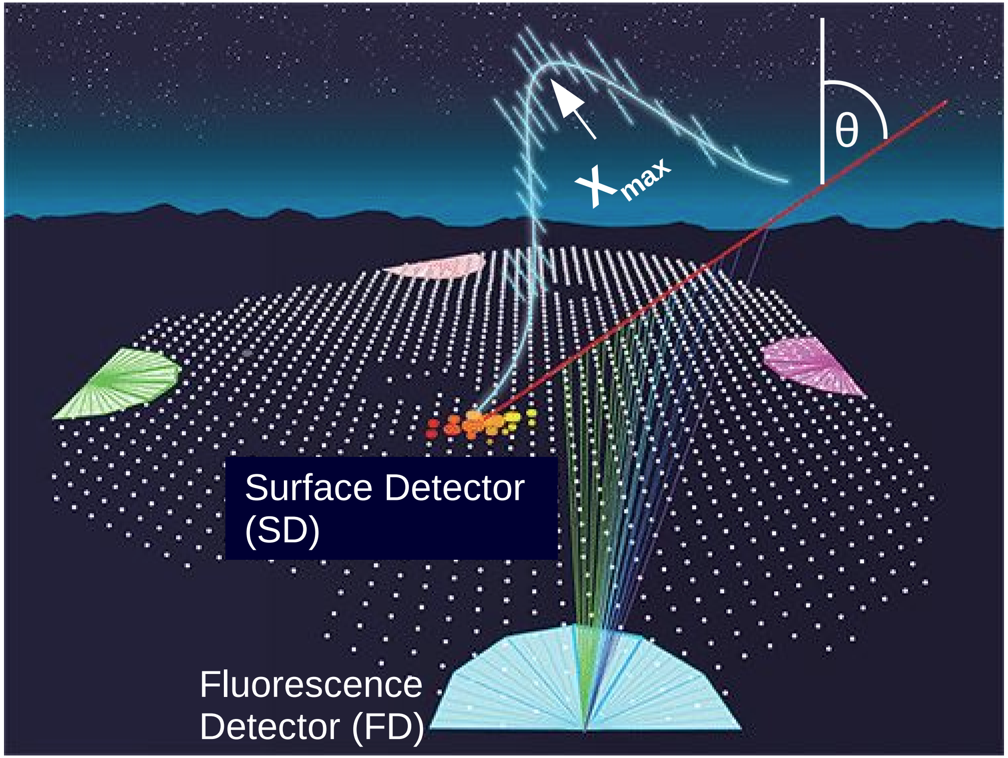
SD signal

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

  [Phys. Rev. D 91 (2015), 032003]
- muon production depth
  - for core distance r > 1500m, θ>65°

  [Phys. Rev. D 90 (2014) 012012]
- muon energy spectrum
  - from attenuation with θ and r

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



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

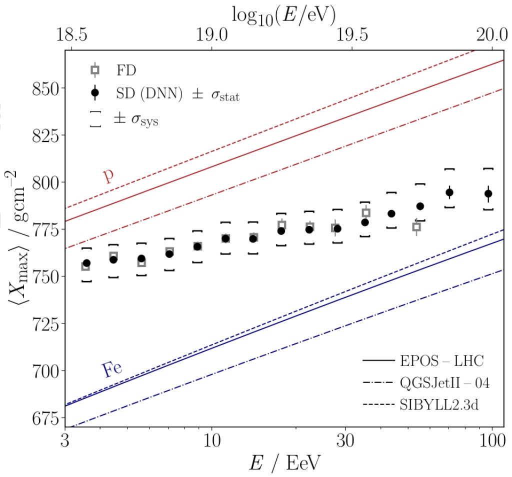
  [Phys. Rev. Lett. 109 (2012) 062002, PoS ICRC2023 (2023) 438]
- average shape of longitudinal profiles

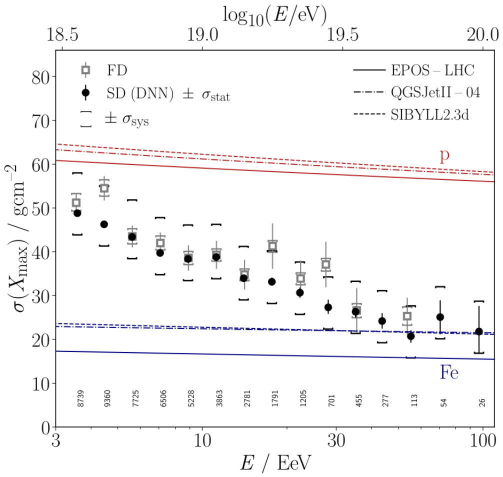
  [JCAP 03 (2019) 018]
- frequency of anomalous showers

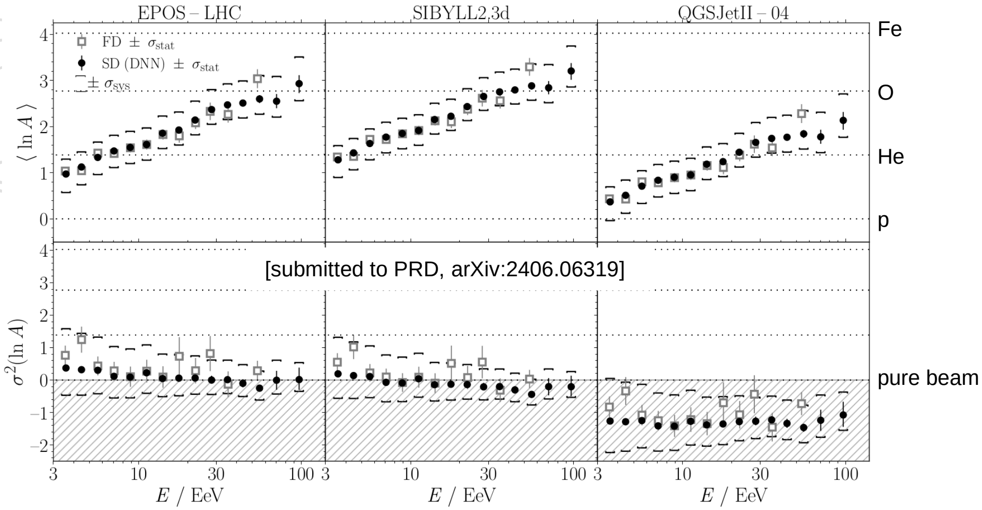
  [EPJ Web of Conferences 144 (2017) 01009]

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

Observables relevant to hadronic interaction models







[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

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

$$\sigma^2_{\ln A} = \frac{\sigma^2(X_{max}) - \sigma^2_{sh}(\langle \ln A\rangle)}{b\ \sigma_p^2 + f_E^2}$$

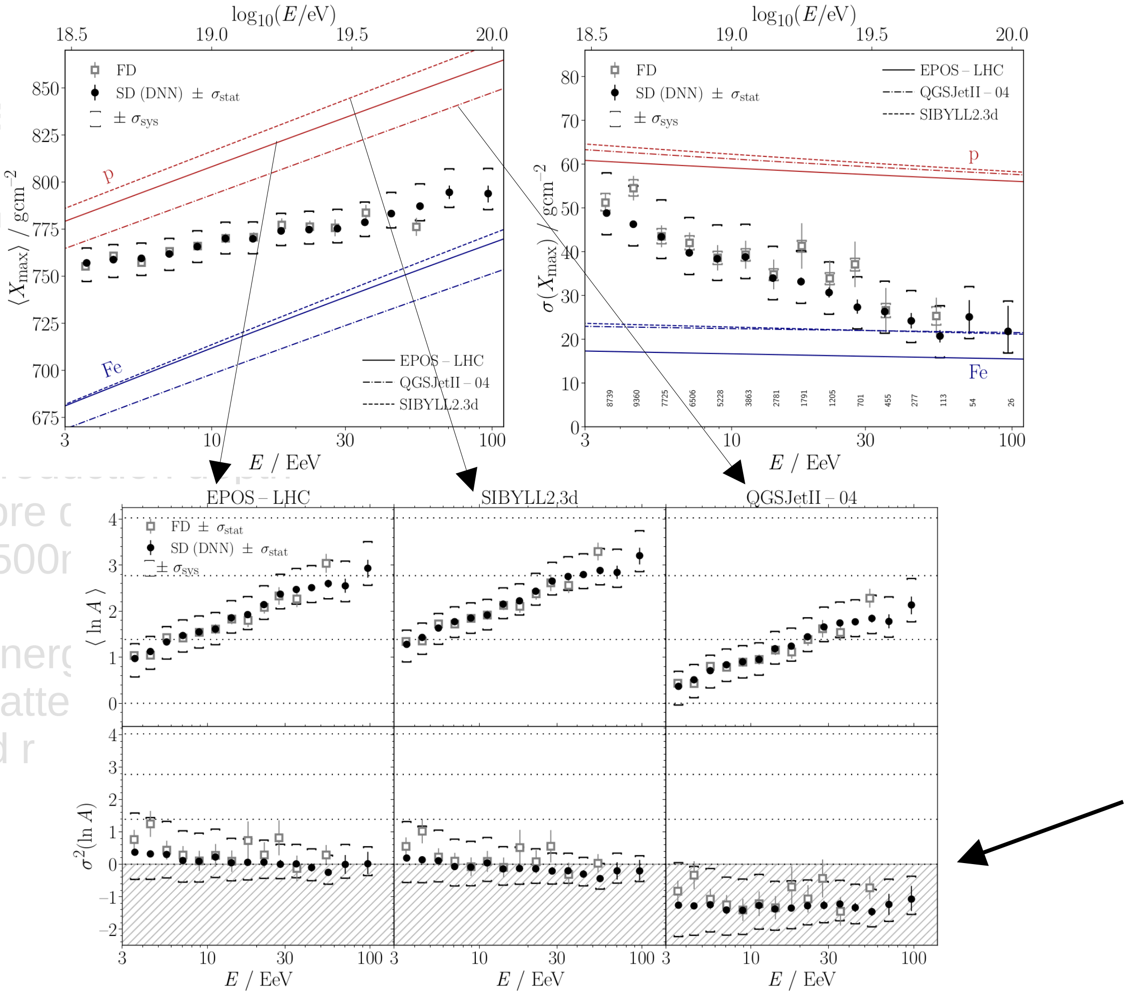
[JCAP 02 (2013) 026]

- showers

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



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

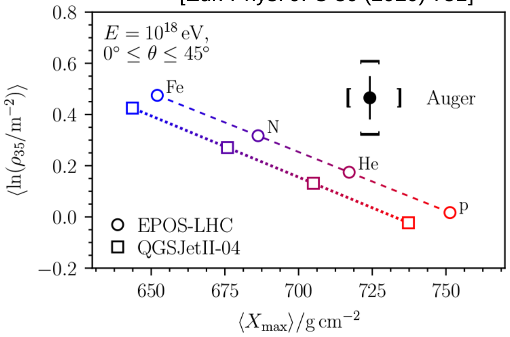
- Strong dependance on the MC X_{max} scale
- **Indication of too shallow predictions of <X_{max}> for all three models !**

Observables relevant to hadronic interaction models

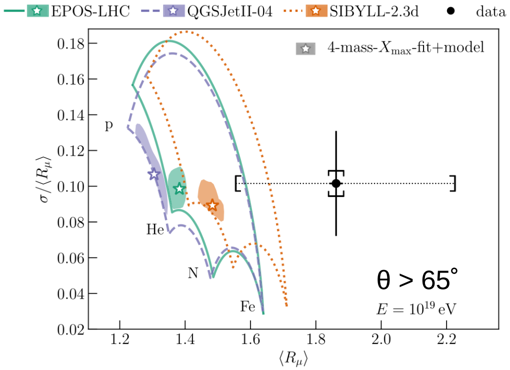
SD signal

- 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]

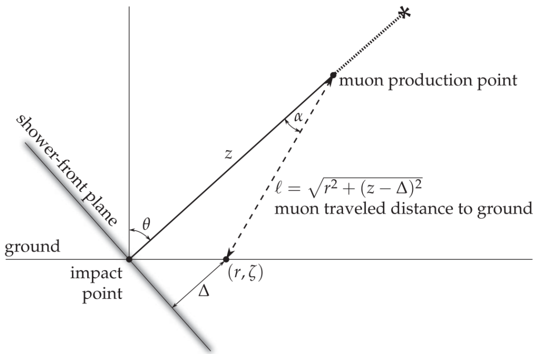


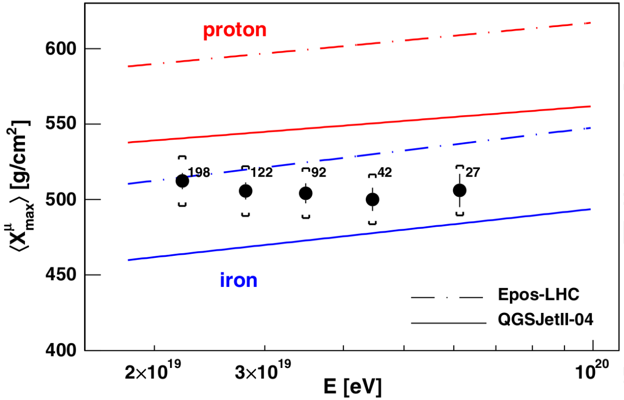
[Phys. Rev. Lett. 126 (2021) 152002]



- 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)

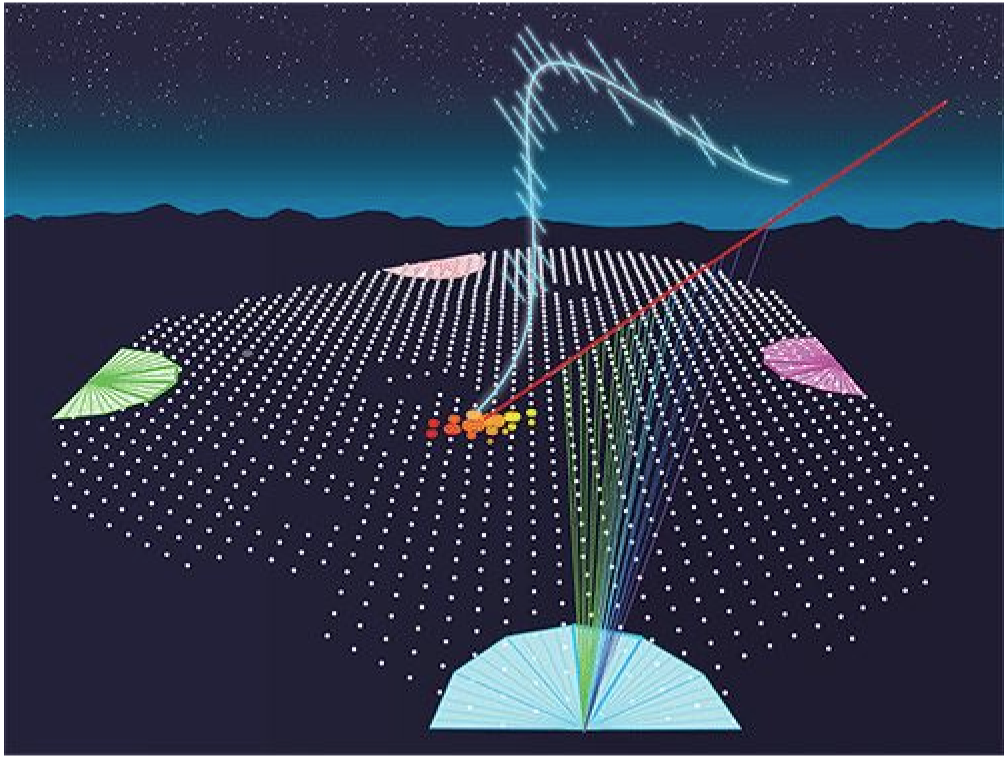




[Phys. Rev. D 90 (2014) 012012]

- MPD tunable by pion diffraction (loosely constrained)

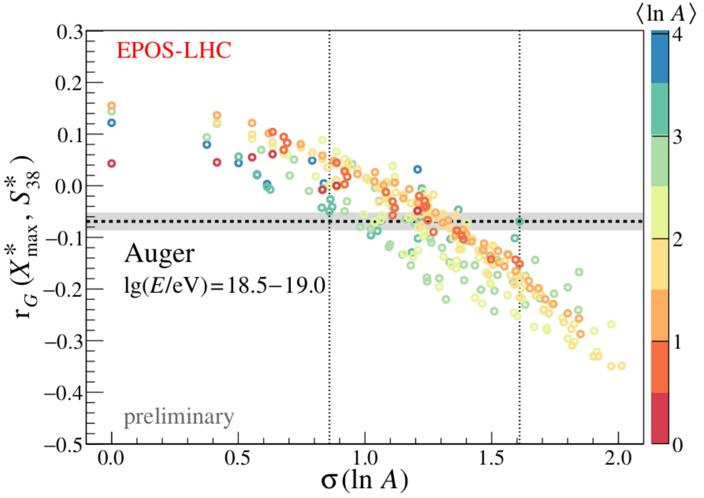
Combining SD and FD observables

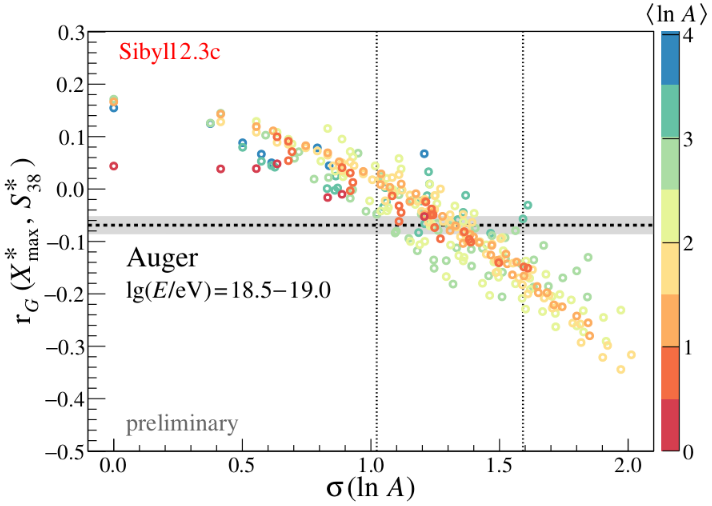


Ground signal + Longitudinal profile

- 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

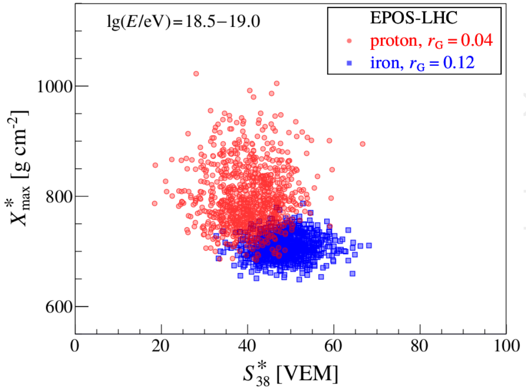




Ground signal + Longitudinal profile

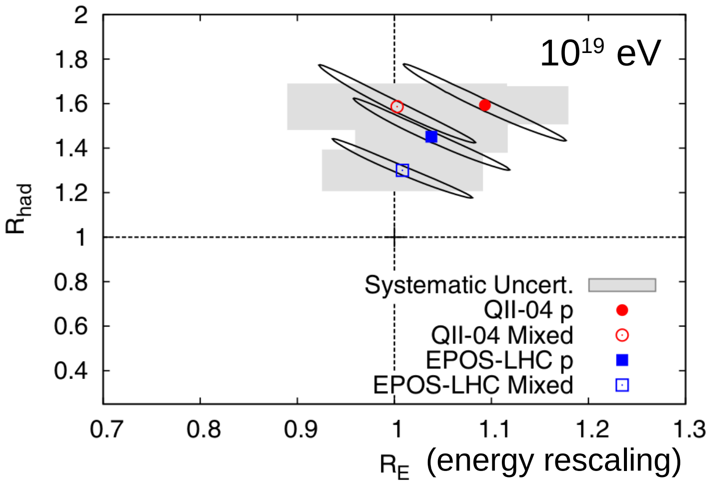
- correlation between X_{max} and S(1000)

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

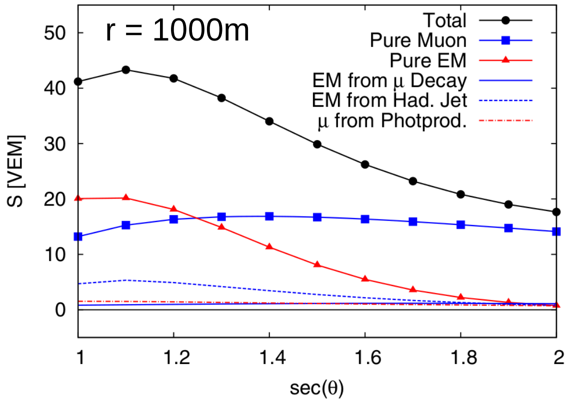


- ~Model-independent estimator of spread of beam masses
- Tension with light masses from X_{max} fits for QGSJet II-04 (**too shallow X_{max} scale**)

Combining SD and FD observables



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

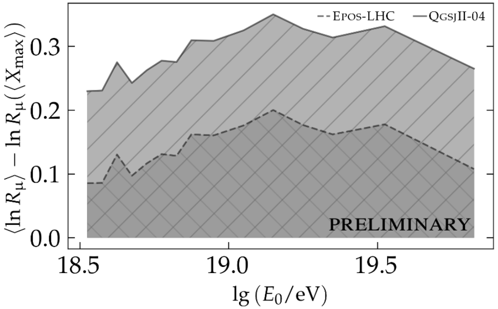


Ground signal + Longitudinal profile

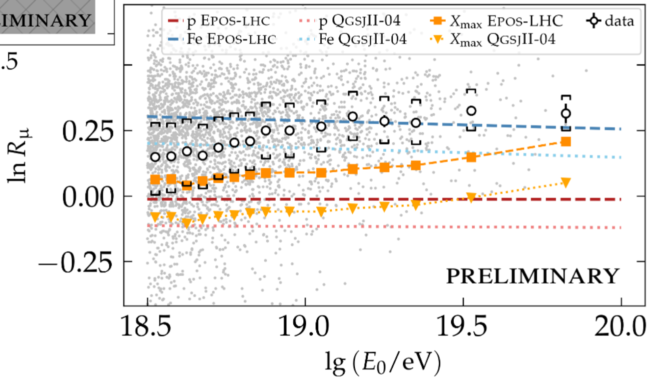
- correlation between X_{max} and S(1000)
- top-down approach -> R_{had} **~ 1.3 - 1.6 !**
  [Phys. Rev. Lett. 117 (2016) 192001]
- applying shower-universality approach -> R_{had}
- 2-dim distributions [S(1000),X_{max}] -> $R_{had}(\theta)$, ΔX_{max}

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

Combining SD and FD observables



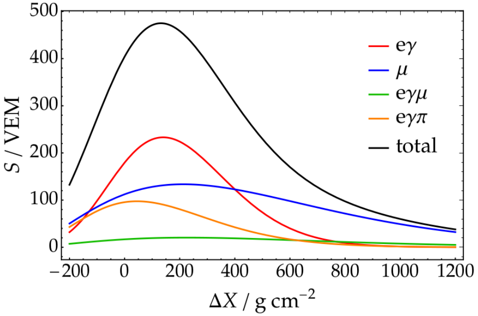
energy
and X_{max}
from FD

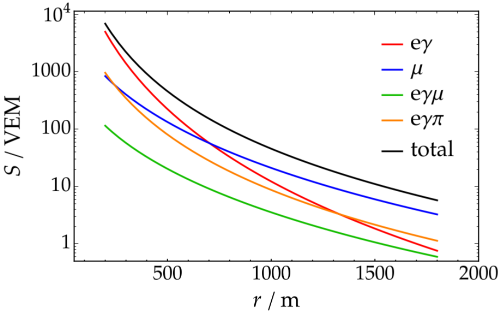


Ground signal + Longitudinal profile

- 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 / °	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 ...
- Caveat: mass (MC X_{max} scale) & energy scale
- Can we test the models better?

Combining SD and FD observables

Ground signal + Longitudinal profile

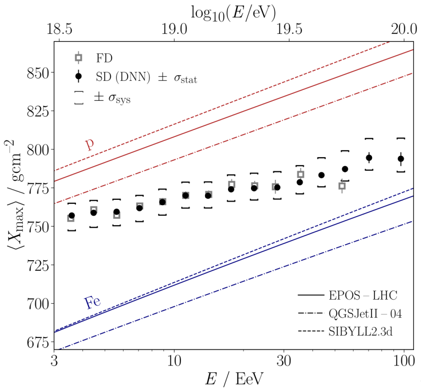
- correlation between X_{max} and S(1000)
-
- top-down approach -> R_{had}
- applying universality approach -> R_{had}
- 2-dim distributions [S(1000),X_{max}] -> $R_{had}(\theta)$, ΔX_{max}

- **Rest of the talk**

  [Phys. Rev. D 109 (2024) 102001]

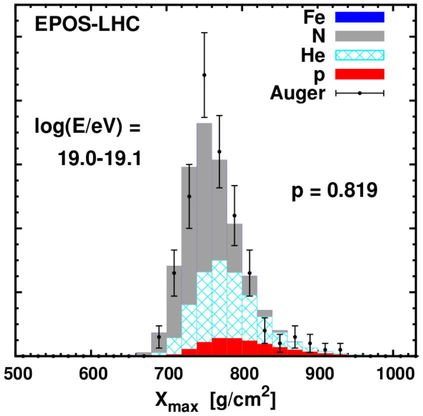
Mass composition & tests of hadronic interactions

[submitted to PRD, arXiv:2406.06319]



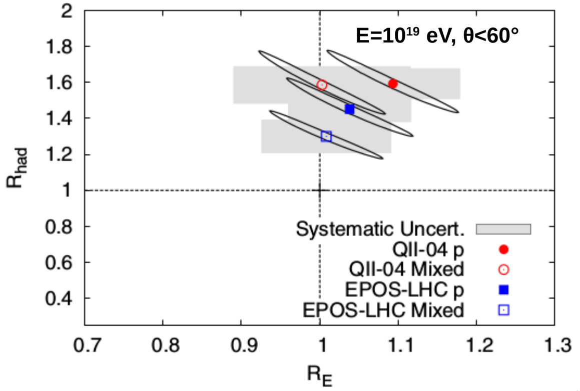
MC X_{max} scale ?

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



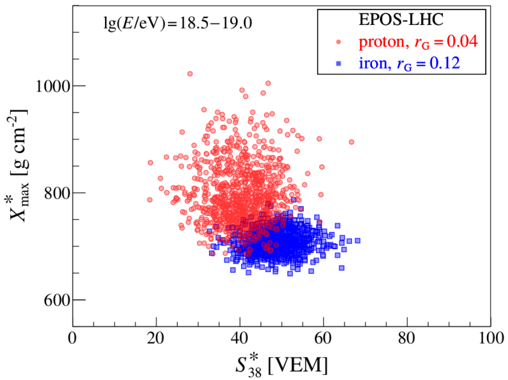
Prim. fraction fit

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



Deficit in MC hadronic signal

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



~ model-independent estimation of beam mixing from [X_{max},S(1000)] correlation

Following work:

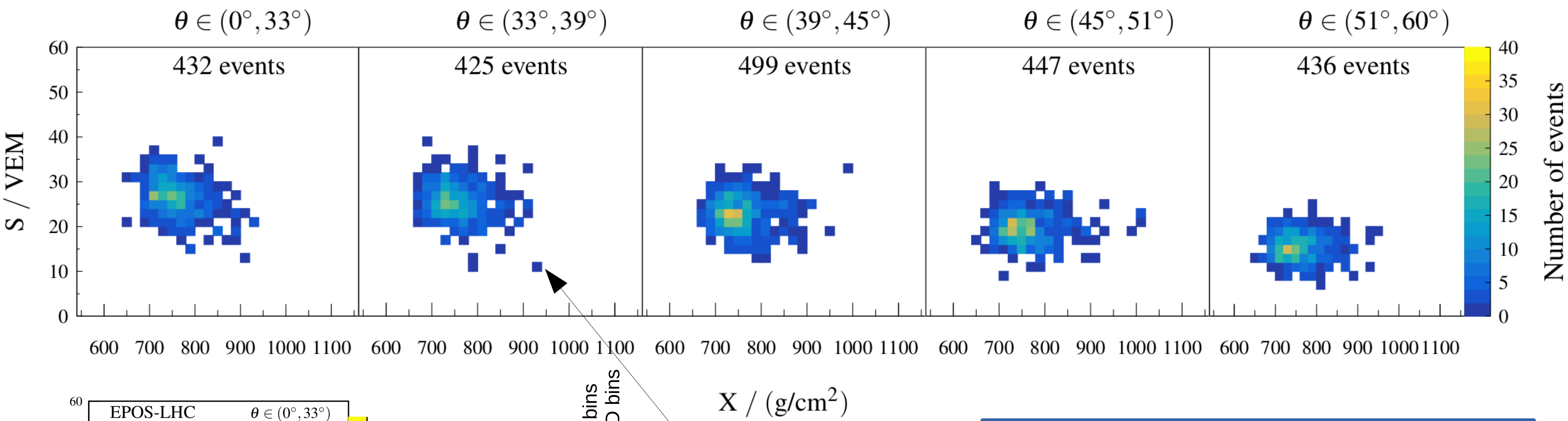
Mass composition fit of observed [X_{max},S(1000)](θ) distributions with free modification of MC predictions **not only of hadronic signal but also of X_{max}**

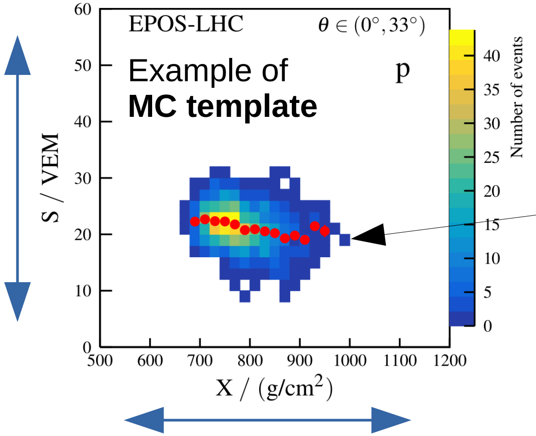
Auger data:
2239 HQ events for $10^{18.5\text{-}19.0}$ eV

Method

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

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





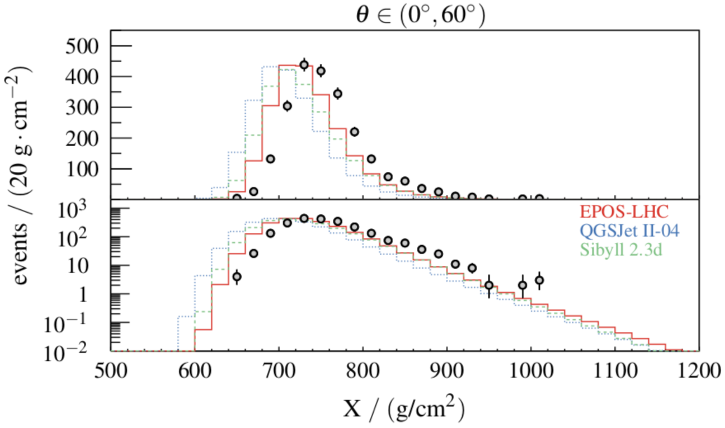
θ bins
2D bins

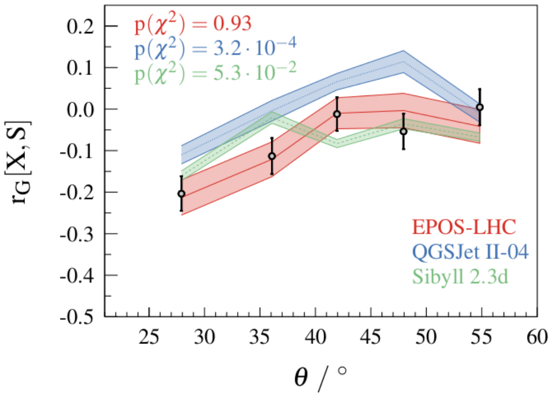
$$\ln\mathscr{L} = \begin{cases} \sum_k \sum_j \left(C_{jk} - n_{jk} + n_{jk}\ln\frac{n_{jk}}{C_{jk}}\right), & n_{jk} > 0 \\ \sum_k \sum_j C_{jk}, & n_{jk} = 0 \end{cases}$$

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

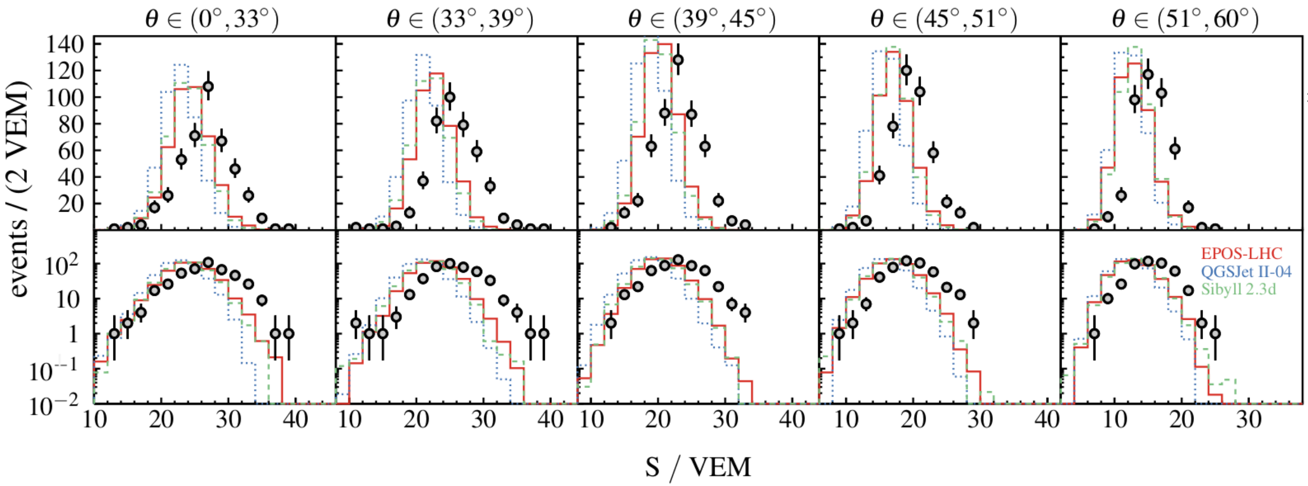
Simultaneous log-likelihood ratio fit of **two-dimensional distributions** of X_{max} and S(1000) in 5 zenith-angle bins with **MC templates** for combinations of four primary nuclei (p,He,O,Fe)

Improvement in data description





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



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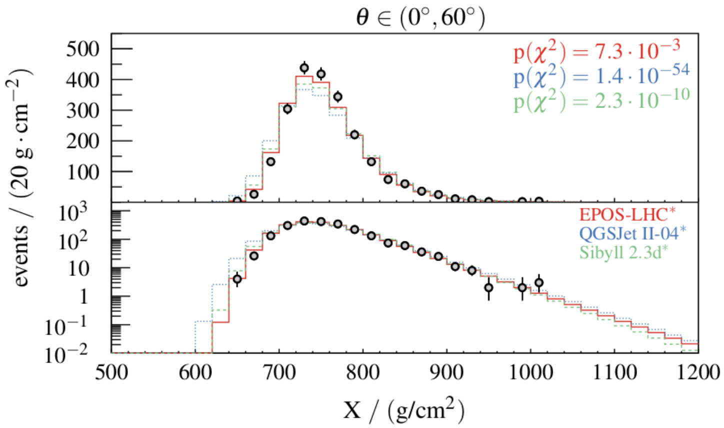

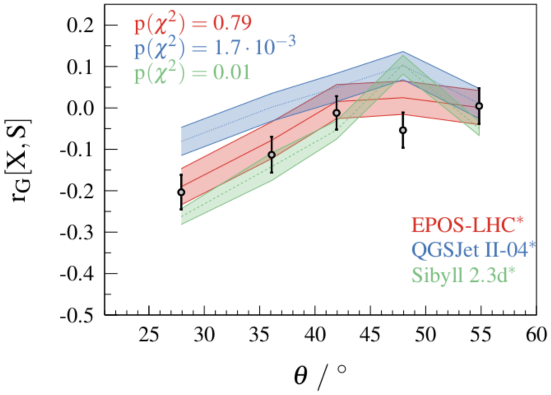

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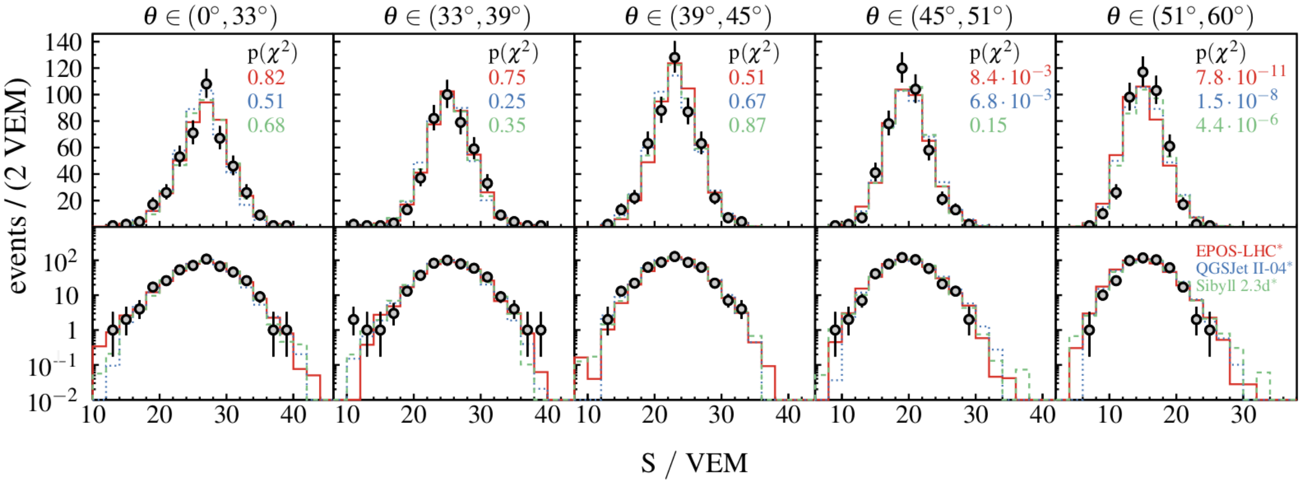
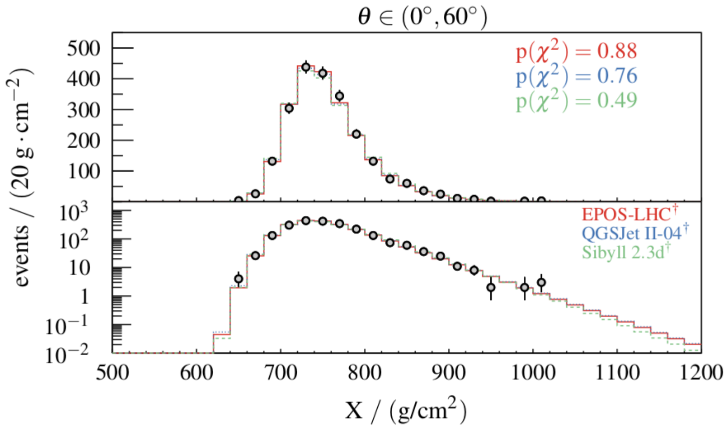
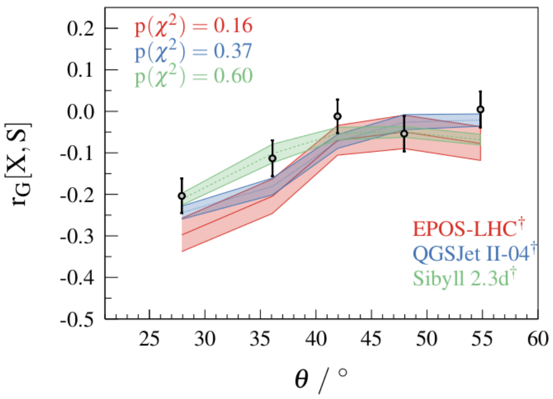


Improvement in data description





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
ΔX_{max}	738.6	1674.8	1015.7
$R_{had} =$ const.	489.2	684.4	521.6
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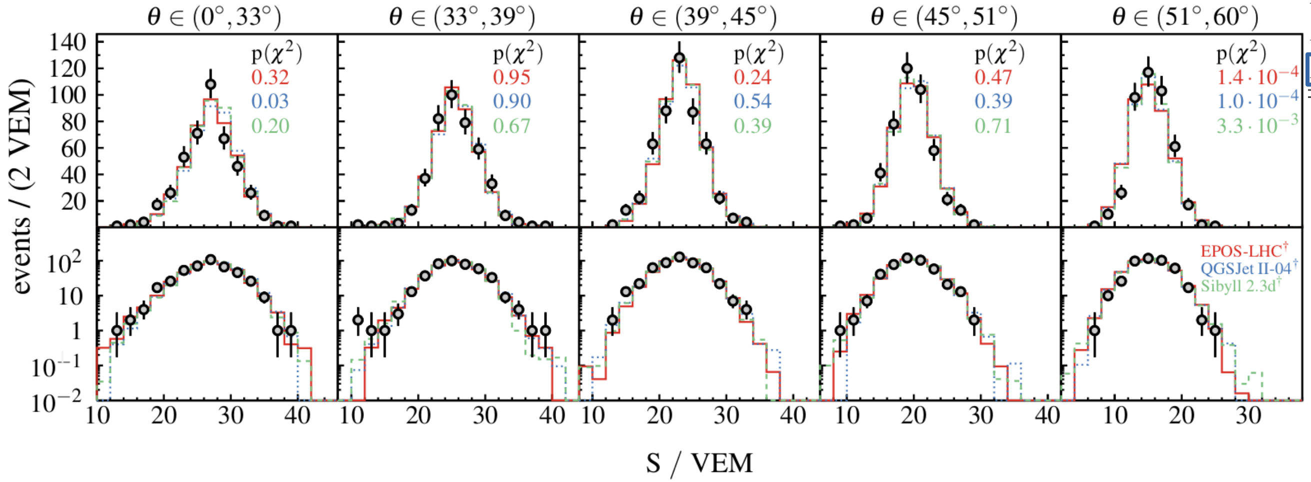
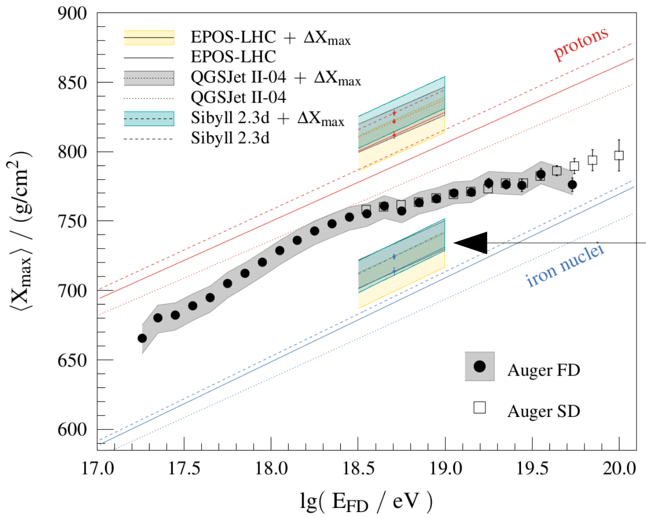
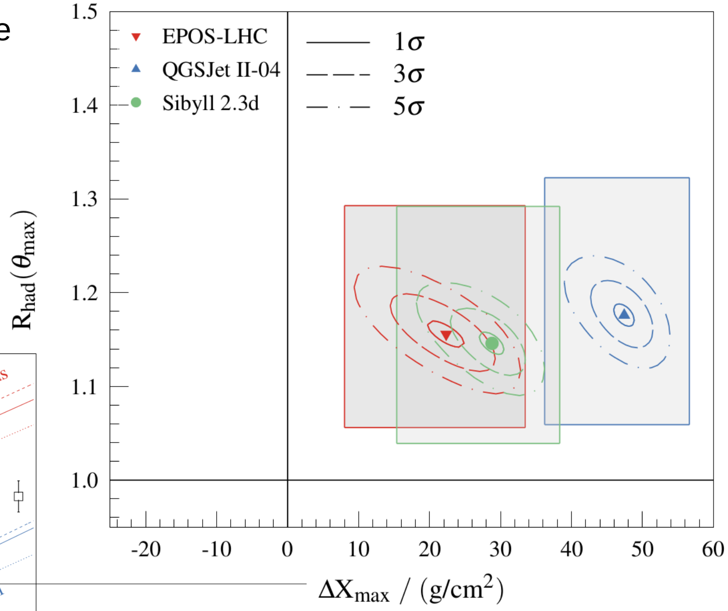


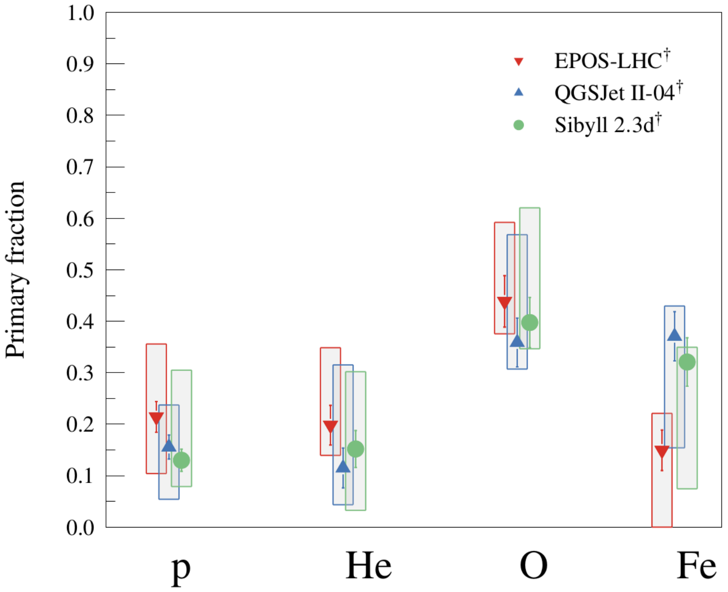
Significant improvement >5σ using R_{had} and ΔX_{max}
(Likelihood ratio tests for nested model using Wilks' theorem)

Fitted parameters

Zenith dependence of R_{had} assumed to be linear in X_{ground}-X_{max}
→ $R_{had}(\theta_{min}$~28°), $R_{had}(\theta_{max}$~55°)

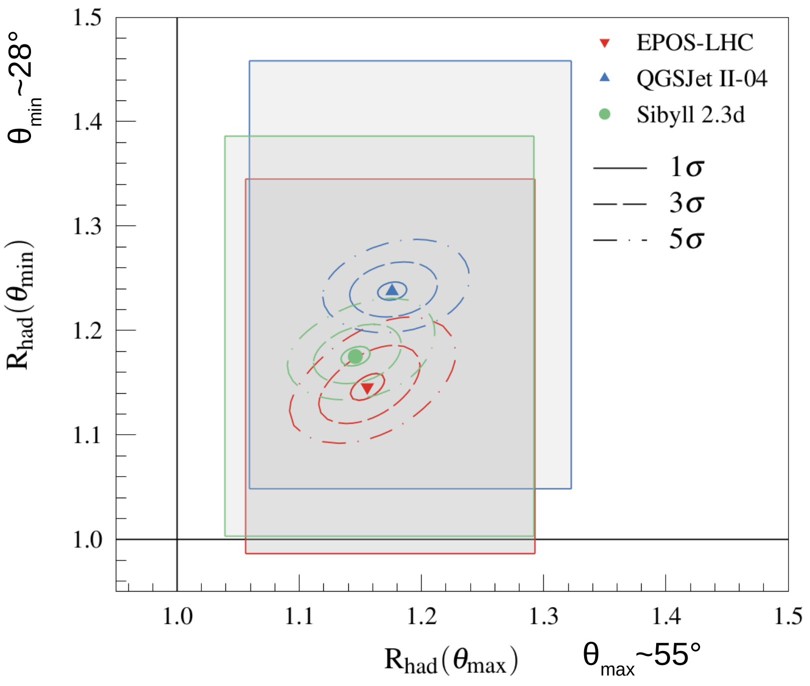


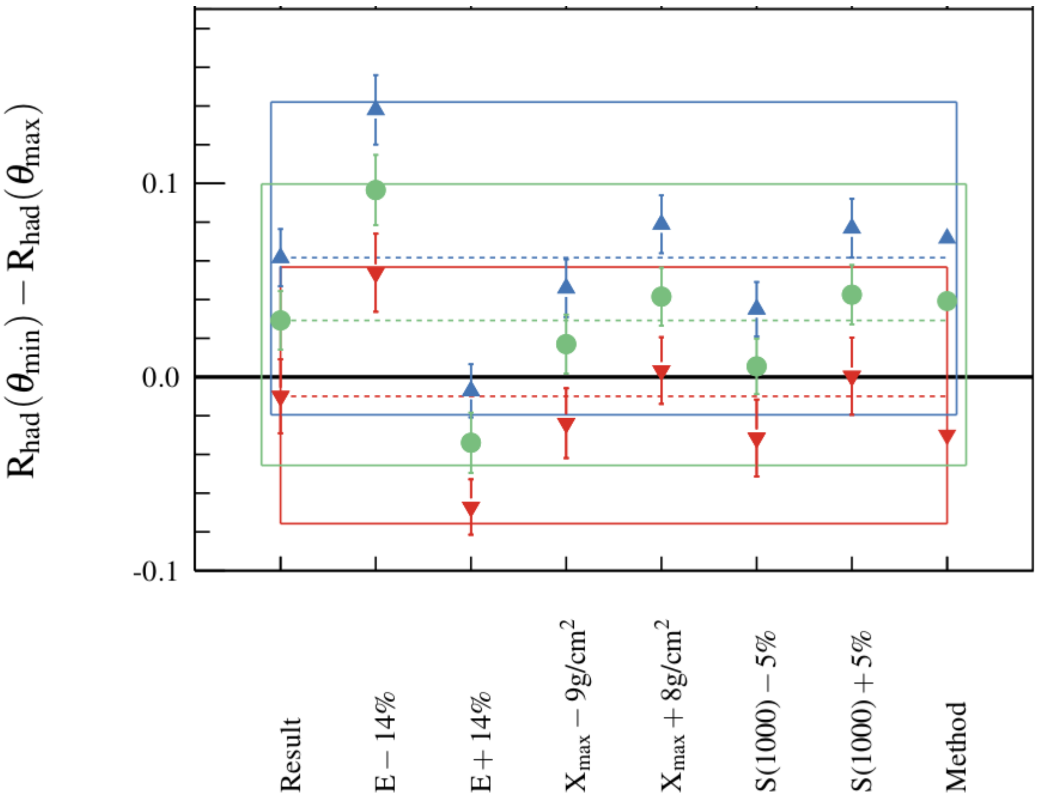




- **Deeper X_{max} predictions for all models !**
- Alleviated “muon problem“
- Smaller model differences in mass composition

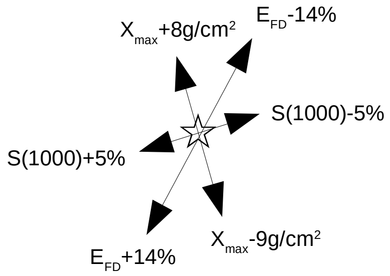
Attenuation of hadronic signal with θ





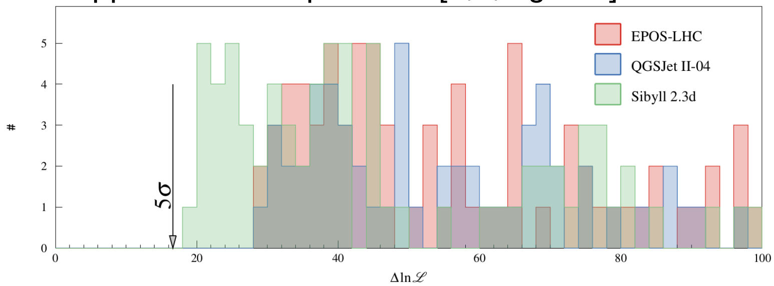
Indication of harder muon spectra in QGSJet II-04 than in data

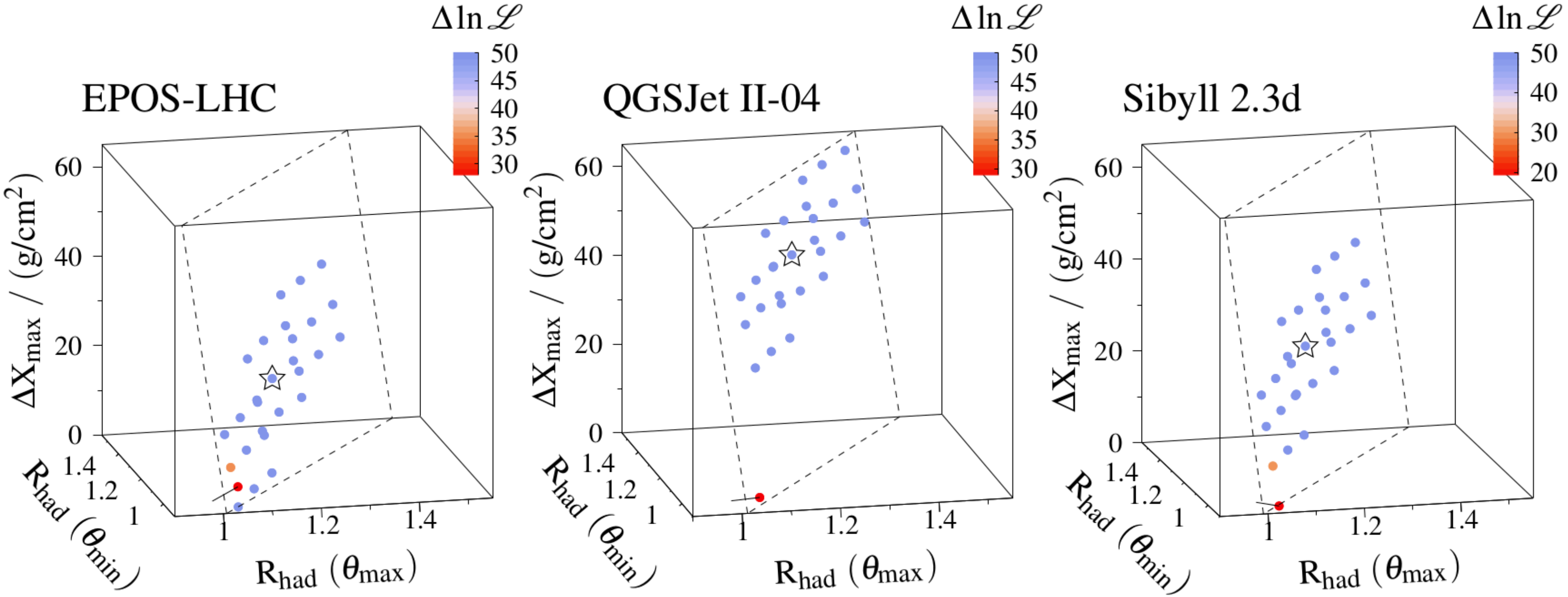
Scanning in combinations of experimental systematics



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

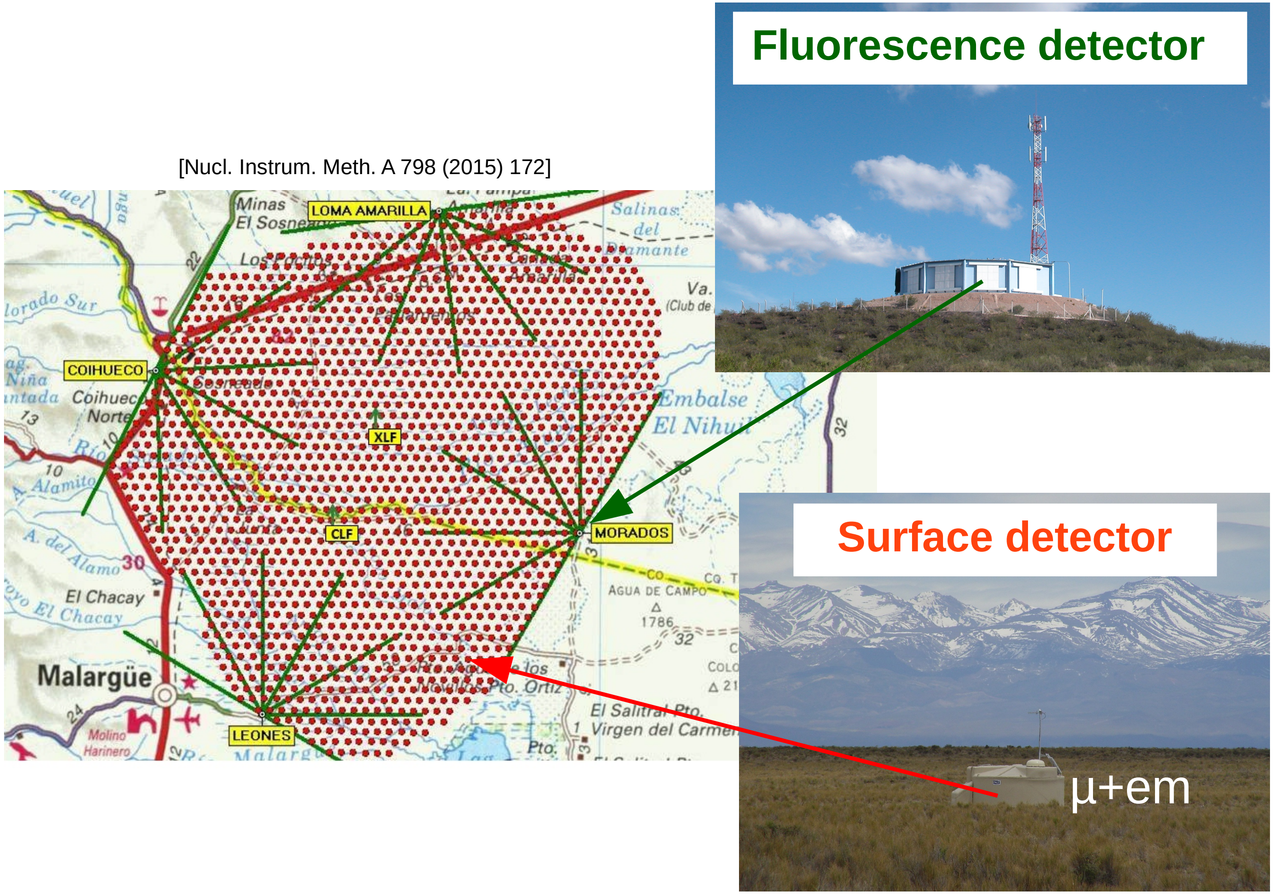
- Models of hadronic interactions fail to describe data of the Pierre Auger Observatory
- To improve description of combined SD and FD data at $10^{18.5\text{-}19.0}$ eV, $\theta < 60°$, we need from all current models:
  - more generated muons by about **(15 to 25)%** - alleviated “muon problem“
  - 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

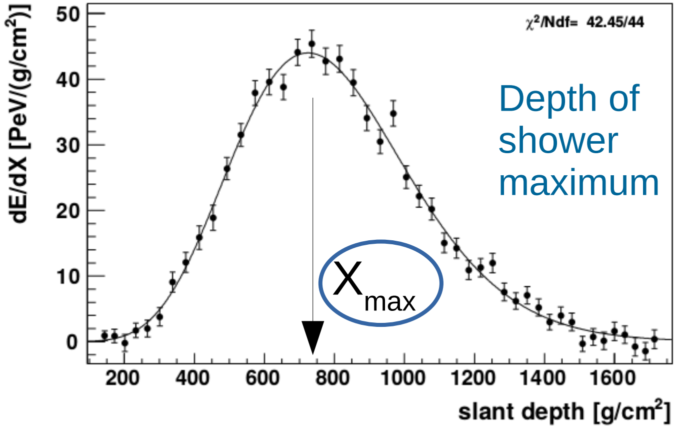
- Outlook:
  - *Auger Phase I data* (+~30%): extend energy range, adopt possible mass-dependence of modifications and study effects of fluctuations, test new models (*p+O run @ LHC*)
  - *AugerPrime data*: better discrimination of hadronic signal, core distance dependance

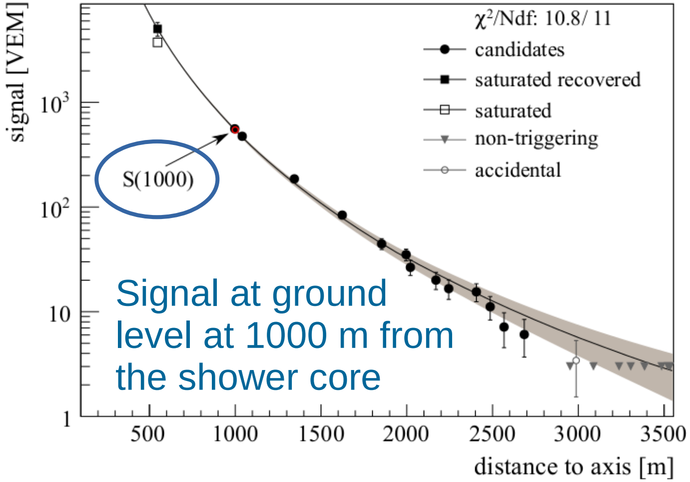
Backup slides

Hybrid detection at the Pierre Auger Observatory

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

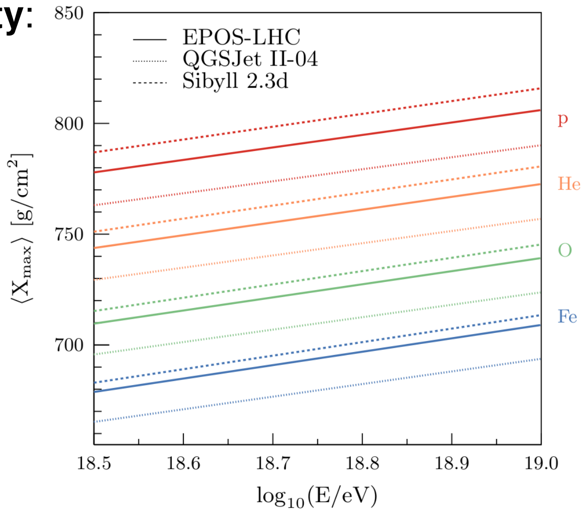


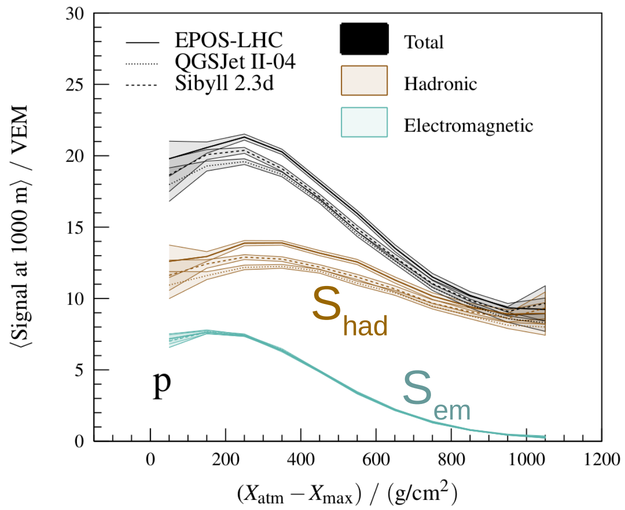




Motivations for modifications of MC predictions

- 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**





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

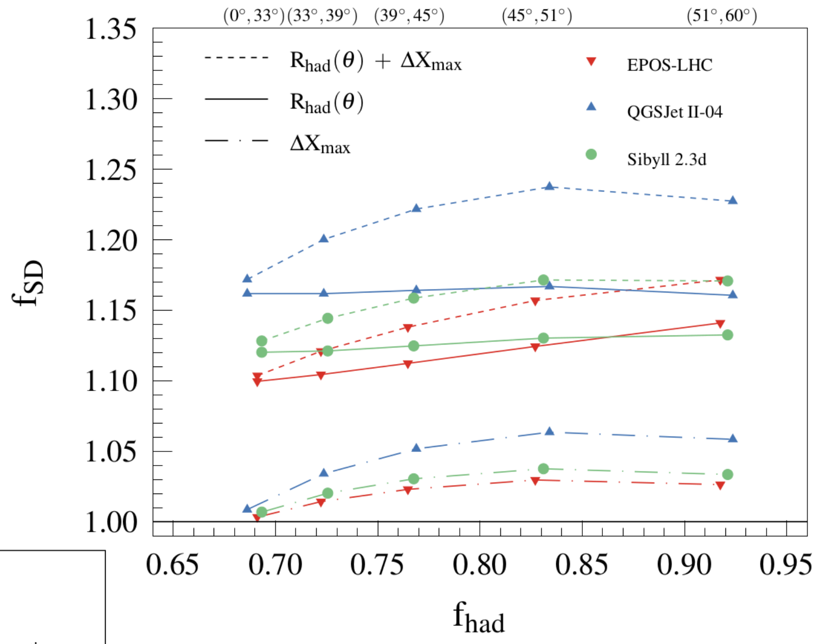
Caveat: no modifications in fluctuations or mass-depencies etc. considered

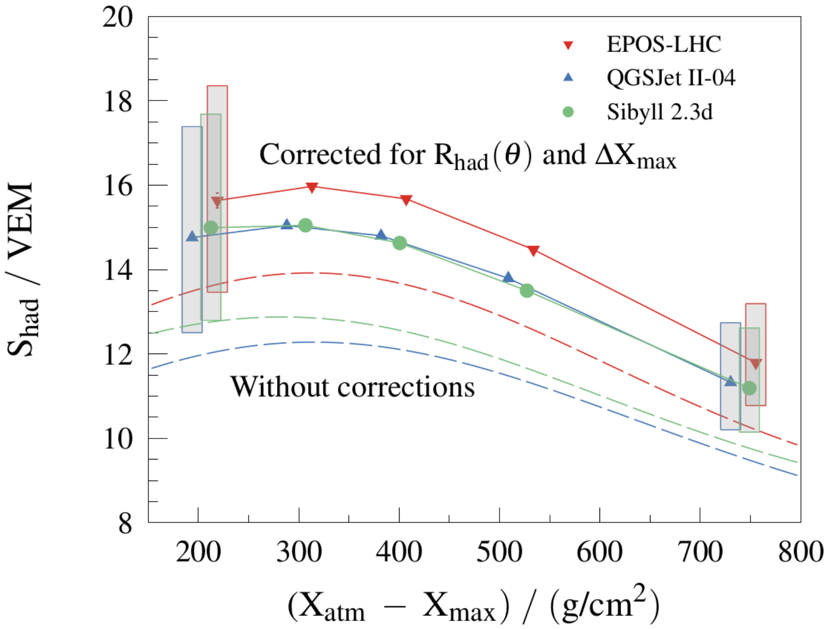
ad-hoc modifications

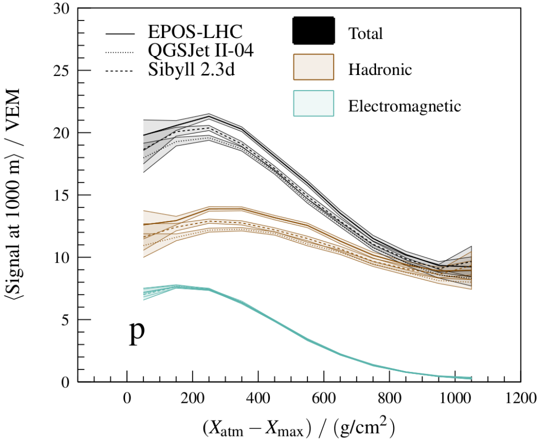
$$X_{max} \rightarrow X_{max} + \Delta X_{max}$$

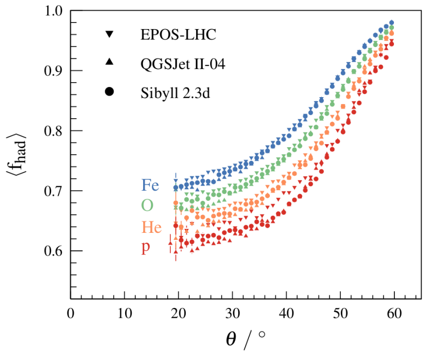
$$S_{had}(\theta) \rightarrow S_{had}(\theta) \cdot R_{had}(\theta)$$

Effect of modified X_{max} on the ground signal









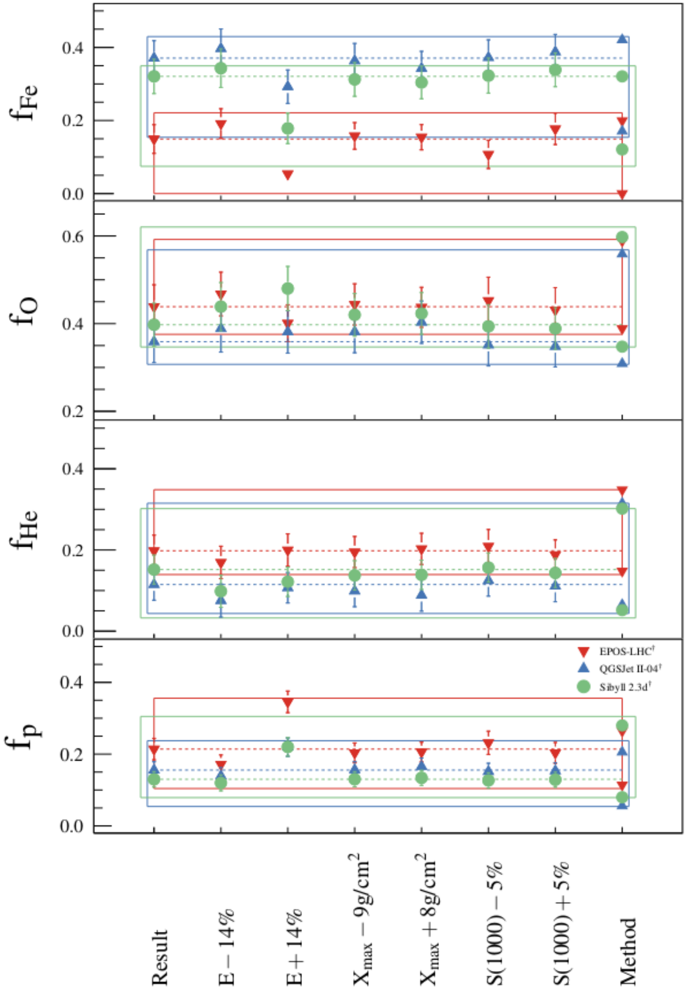
Assumption on primary species

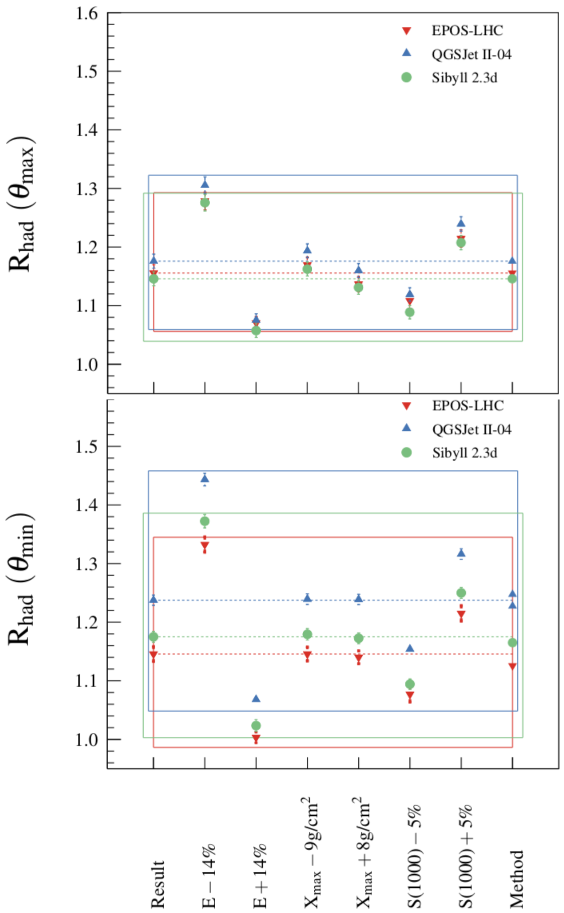
- ΔX_{max} decreases by about 5-7, 10-17 and 30-40 g/cm^2 and $R_{had}(\theta)$ increases by about 2-5%, 4-9% and 15-20% when the heaviest primary Fe is replaced by Si, O and He, respectively

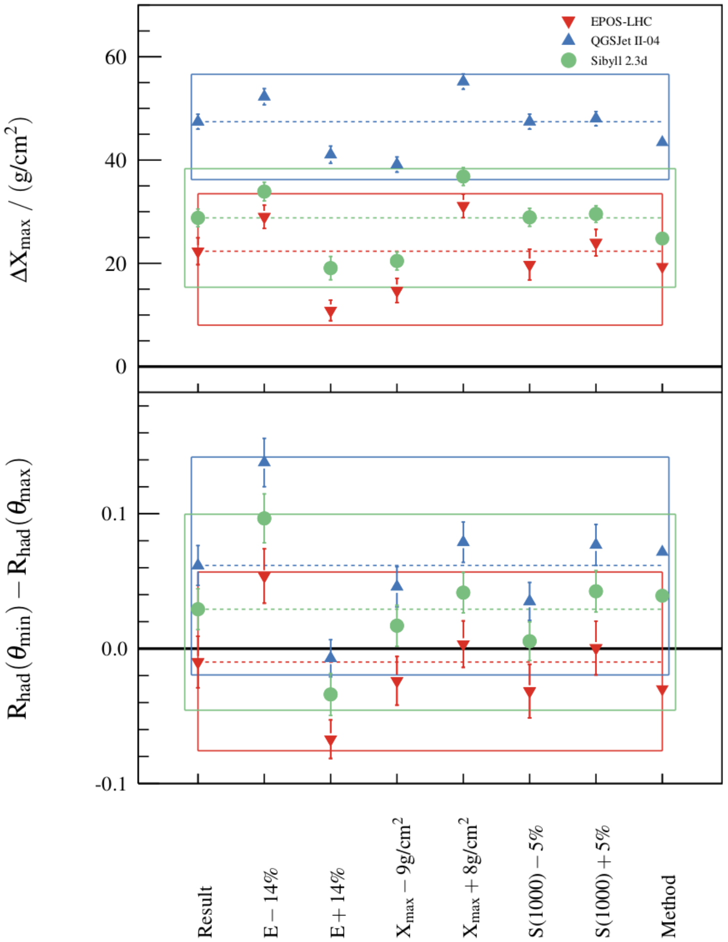
$\ln \mathscr{L}_{min}$	EPOS-LHC	QGSJET-II-04	SIBYLL 2.3d
p He	518.3	633.5	563.5
p He O	467.5	523.3	486.6
p He O Fe	451.9	476.3	451.6

Significance of improvement of data description above 5σ

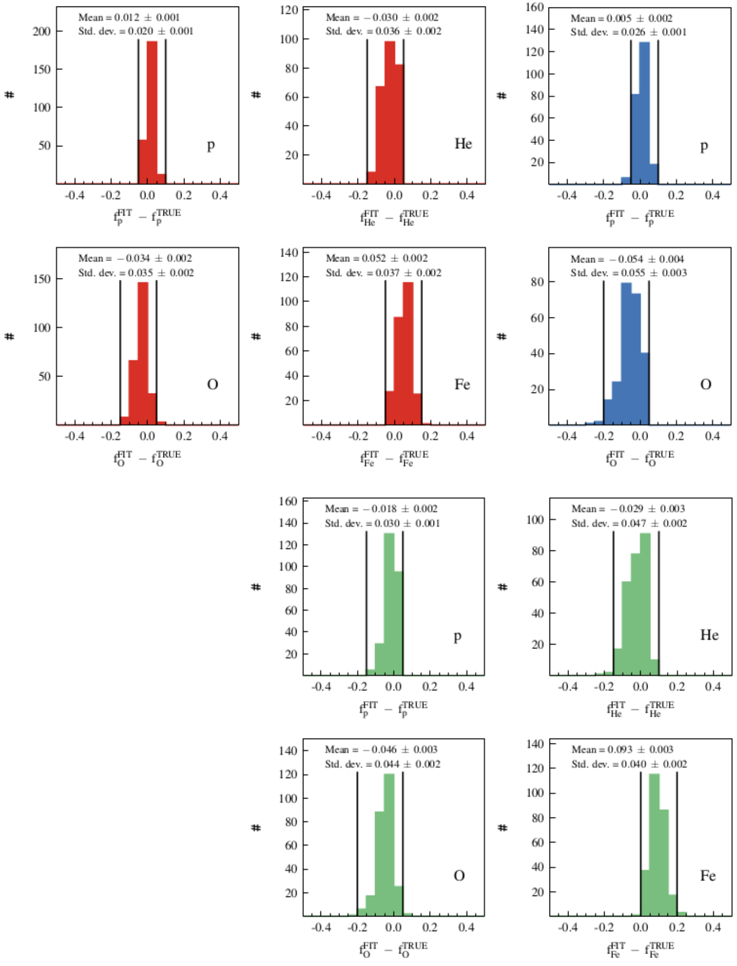
Systematic uncertainties

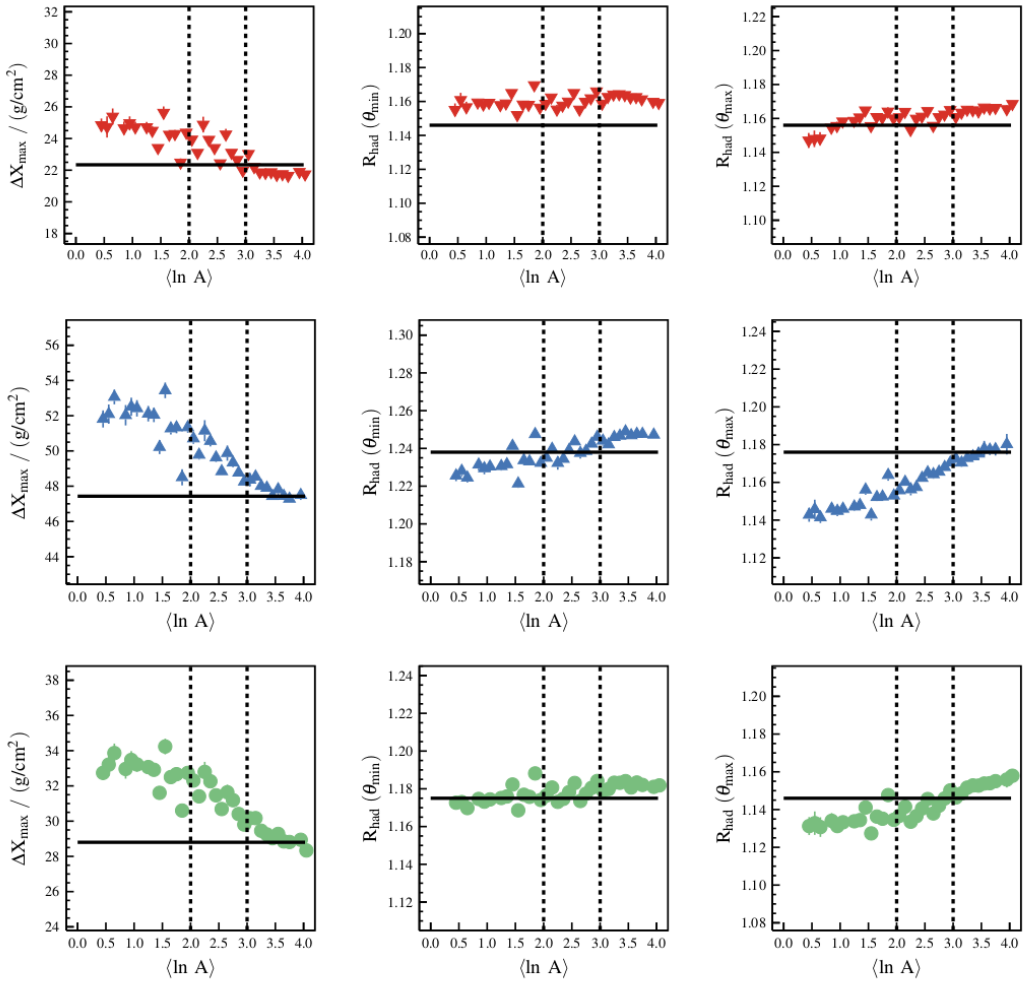






MC-MC tests

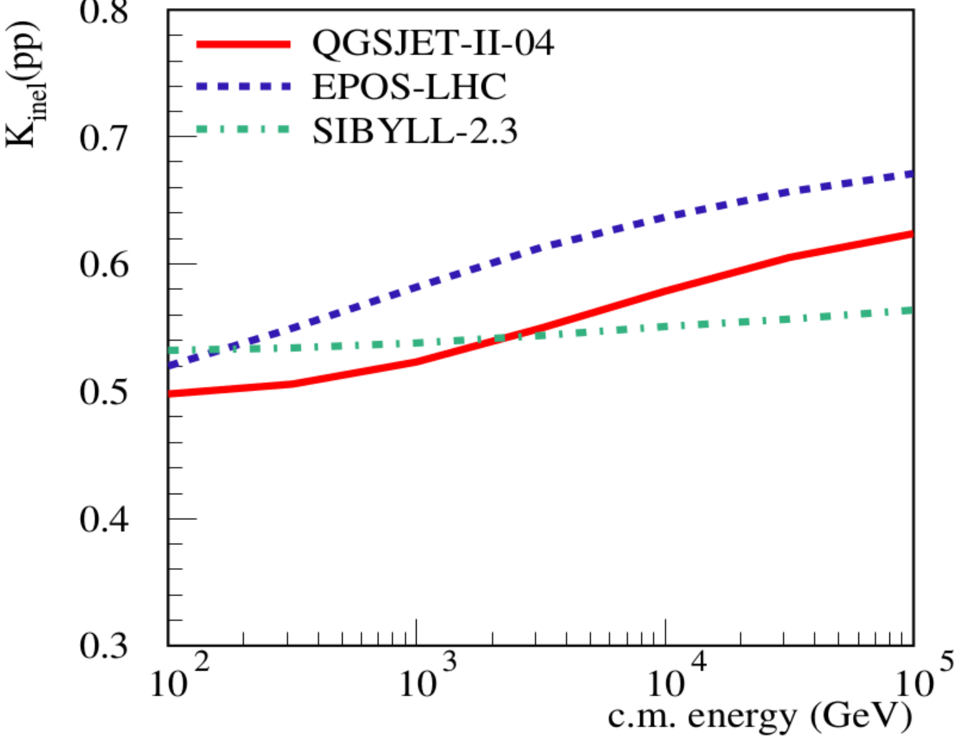

Mean = 0.012 ± 0.001
Std. dev. = 0.020 ± 0.001
p
Mean = −0.030 ± 0.002
Std. dev. = 0.036 ± 0.002
He
Mean = 0.005 ± 0.002
Std. dev. = 0.026 ± 0.001
p
Mean = −0.052 ± 0.003
Std. dev. = 0.052 ± 0.002
He
Mean = −0.034 ± 0.002
Std. dev. = 0.035 ± 0.002
O
Mean = 0.052 ± 0.002
Std. dev. = 0.037 ± 0.002
Fe
Mean = −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
#
$f_p^{FIT} - f_p^{TRUE}$
$f_{He}^{FIT} - f_{He}^{TRUE}$
$f_O^{FIT} - f_O^{TRUE}$
$f_{Fe}^{FIT} - f_{Fe}^{TRUE}$


ΔX_{max} / (g/cm^2)
R_{had} (θ_{min})
R_{had} (θ_{max})
⟨ln A⟩

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

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

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

$$\kappa_0 \rightarrow f_{\kappa}\kappa_0 \quad N_0 \rightarrow f_N N_0 \quad \Rightarrow \quad X_{max}^{A}{}' = X_{max}^{A} + X_0\left(\ln(f_{\kappa}) - \ln(f_N)\right)$$

MOCHI (preliminary)

[PoS(ICRC2023)245]

“changing the shape of energy dependence“ ➔ mass-dependent modifications