Tests and modifications of hadronic interactions in cosmic-ray showers

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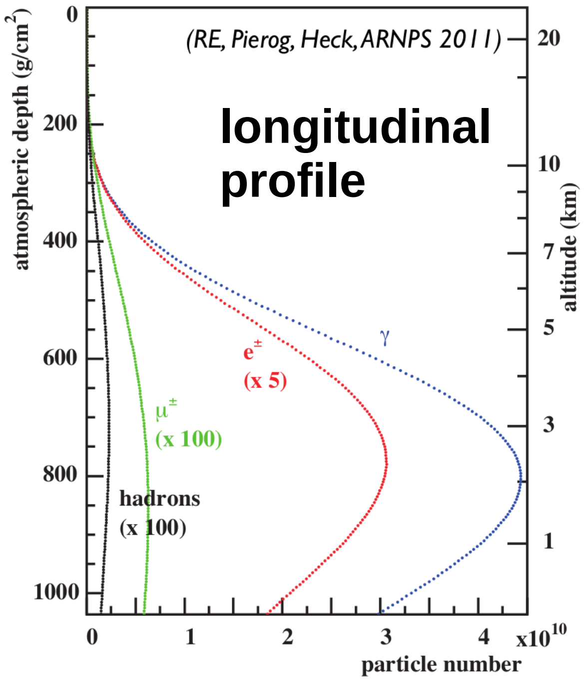
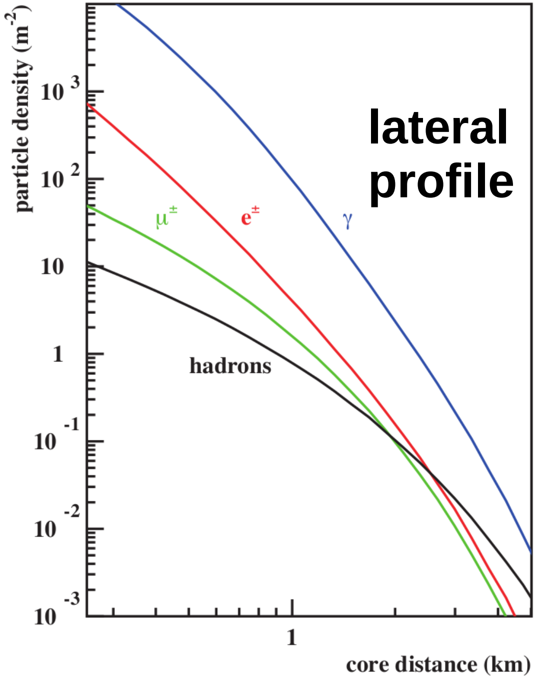
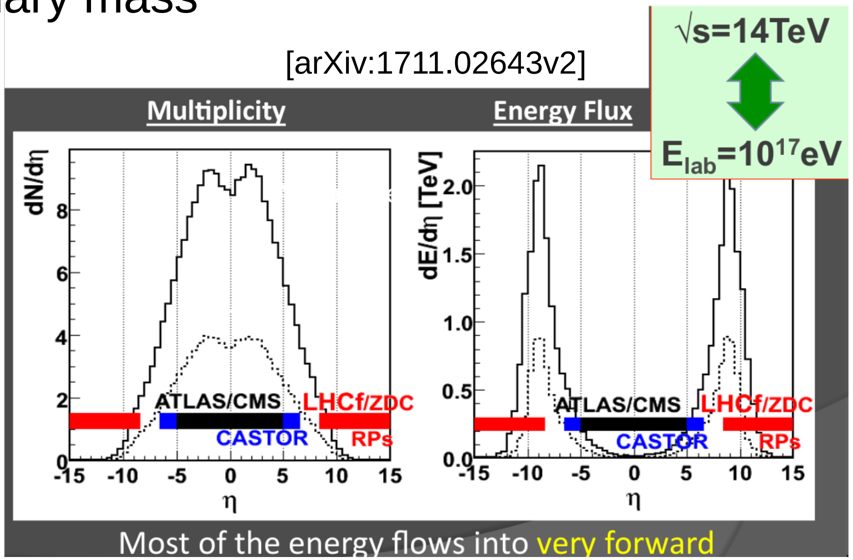
Hadronic interactions in air showers

- Extrapolated to higher energies and different kinematic regions than accessible
  - ➔ systematic uncertainty on interpreted mass composition
- Depth of shower maximum (X_{max})
- Number of muons (decays of $\pi^{\pm}$)

} sensitive to primary mass







Current models of hadronic interactions:
EPOS-LHC, QGSJet II-04, Sibyll 2.3d

Observables relevant to hadronic interaction models

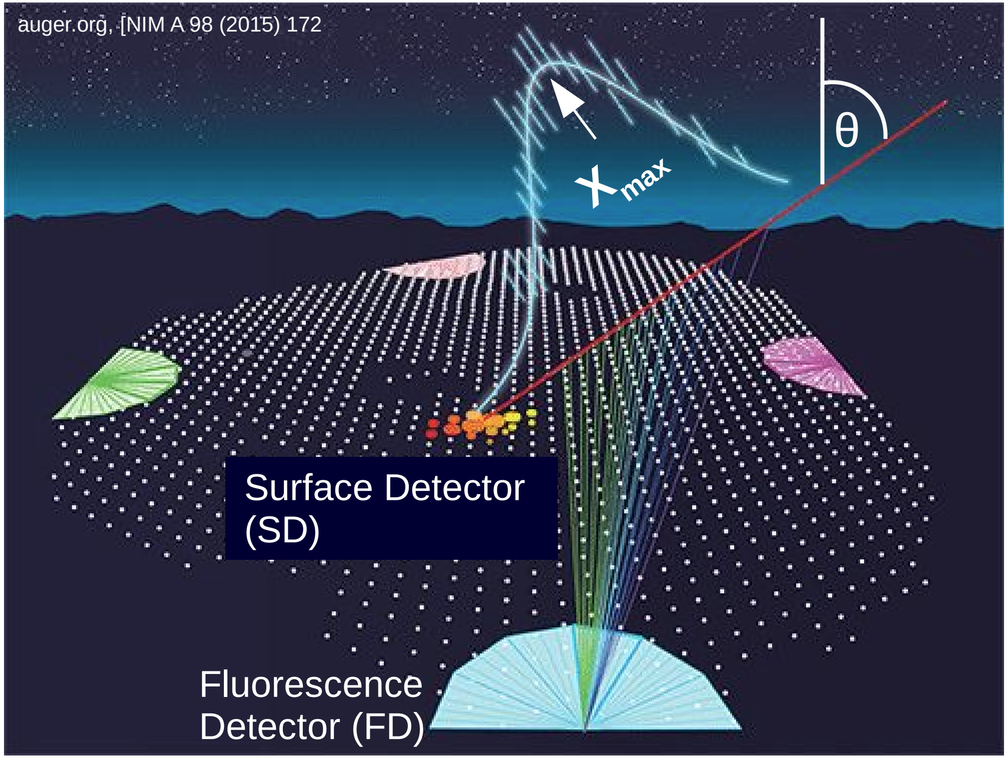
The Pierre Auger Observatory - *the best instrument to study HI in UHECR*

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



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 talks of Tobias Schulz and Vitor de Souza for more detail

Observables relevant to hadronic interaction models

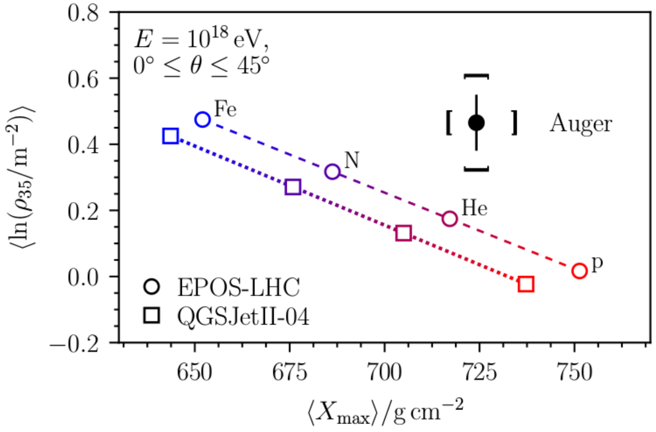
SD signal

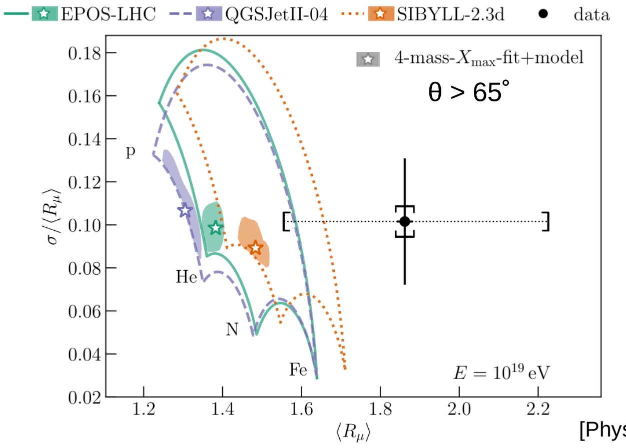
- muon content
  - ➔ from buried scintillators, θ<60°
  - ➔ from N_{19}, θ>65°

- 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]

FD Longitudinal profile

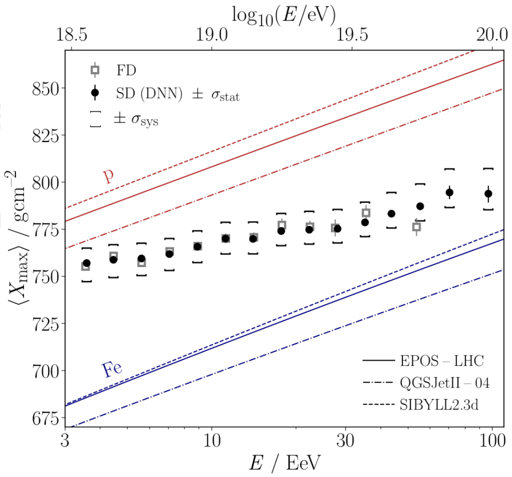
- estimation of primary masses from X_{max} fits
- longitudinal profiles
- frequency of anomalous showers

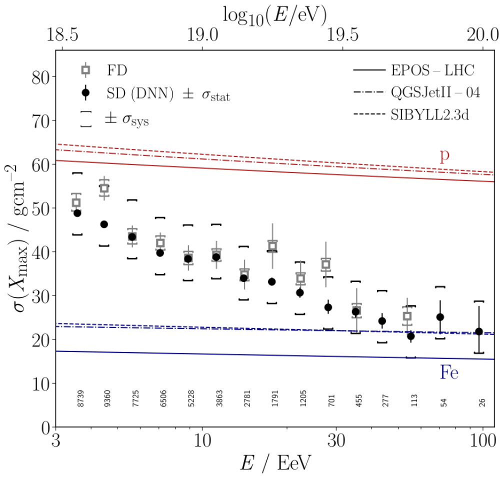
> - Problem to describe the size of the muon content - **factor ~1.3-1.6** !
> - Muon fluctuations consistent with data
>
>   (no obvious problem in the first interaction)

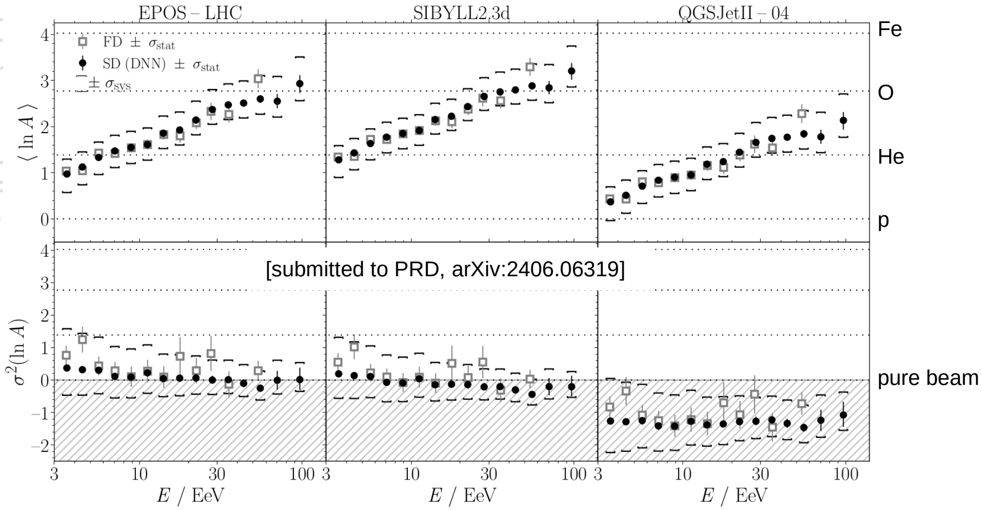
Observables relevant to hadronic interaction models

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
- p-air cross-section from
- frequency of anomalous showers

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

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

[JCAP 02 (2013) 026]

Observables relevant to hadronic interaction models

SD signa

- muon c
  - from
    scinti
  - from
- muon p
  - for core d
    r > 1500r
- muon energ
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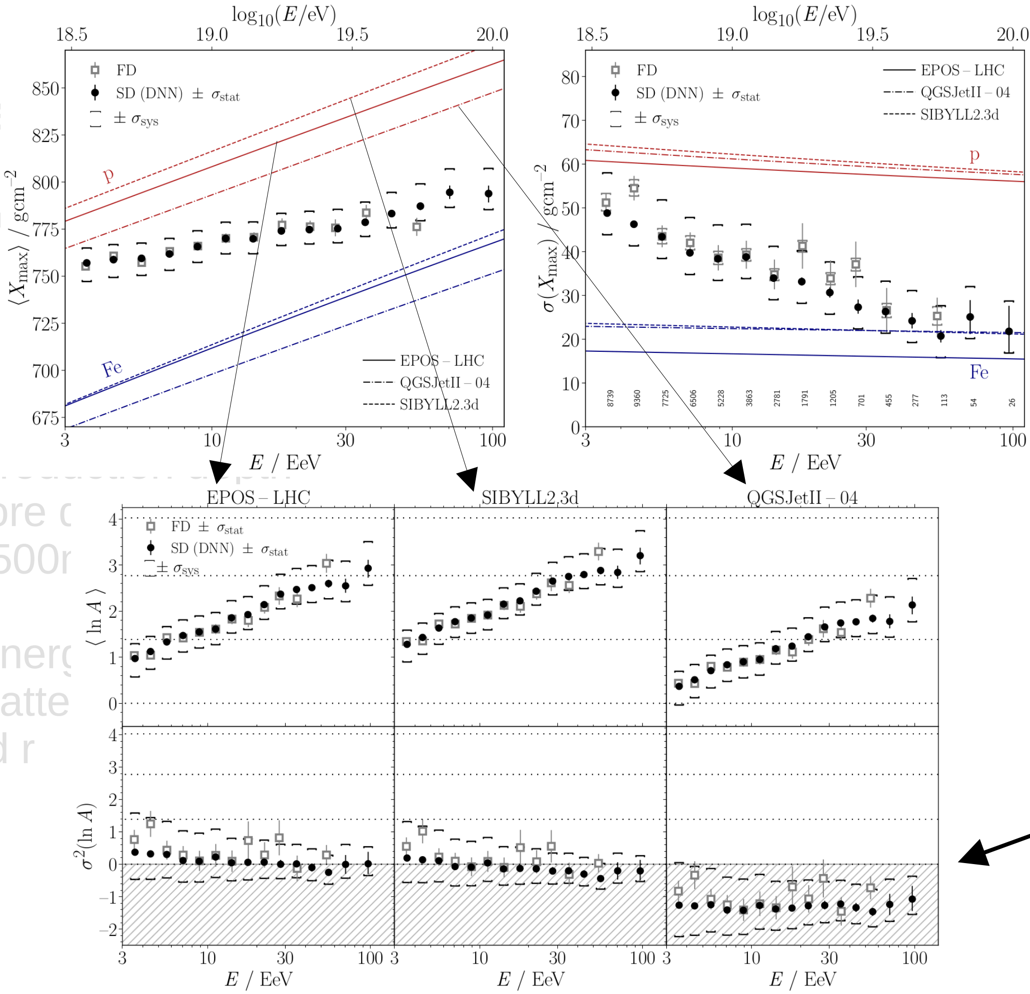
    θ and r

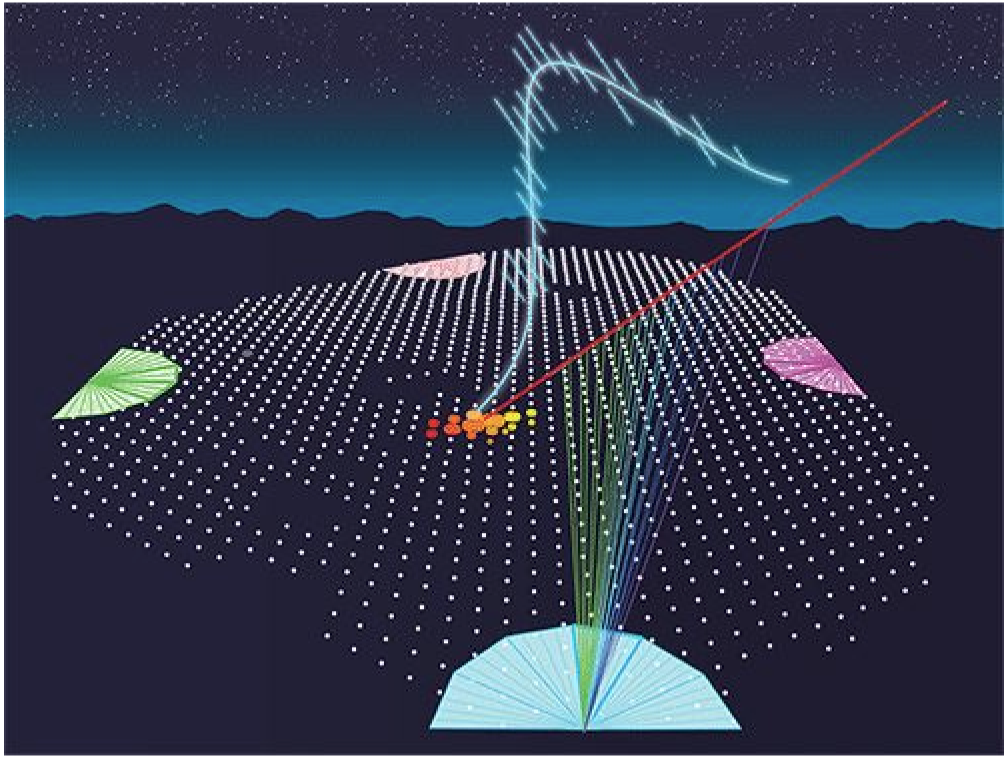


FD longitudinal profile

- 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 !**

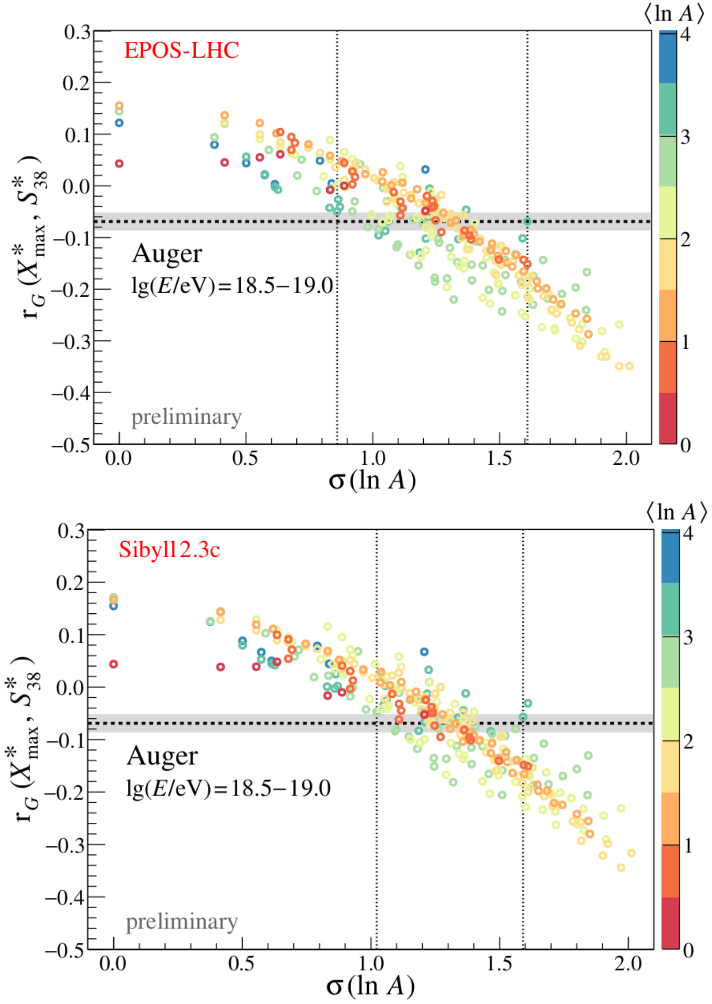
Combining SD and FD observables



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}

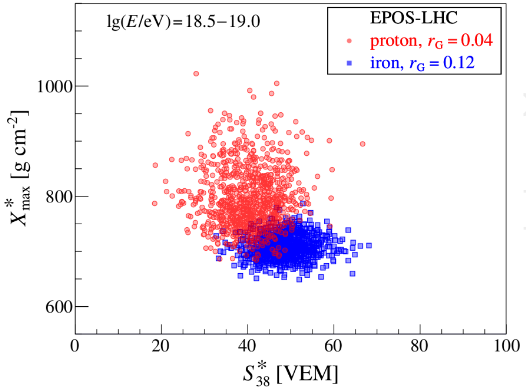
Combining SD and FD observables



Ground signal + Longitudinal profile

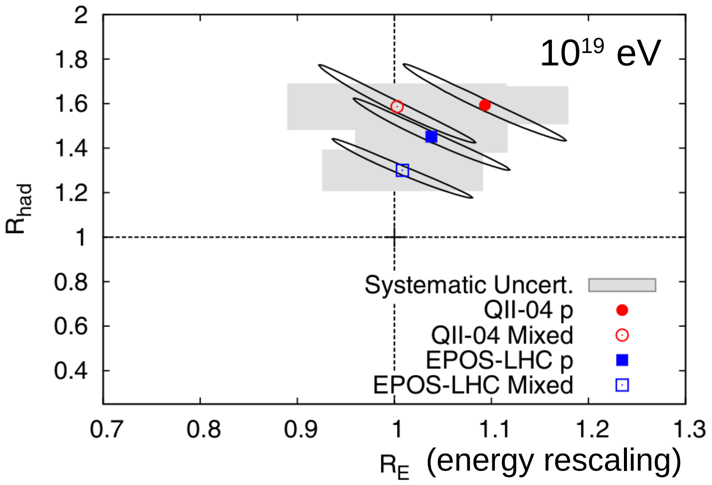
- correlation between X_{max} and S(1000)

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

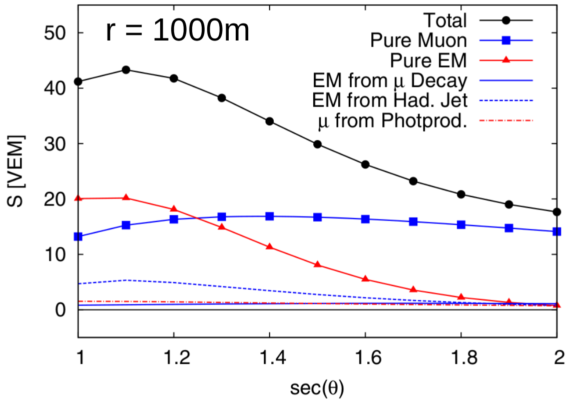


- ~Model-independent estimator of spread of beam masses
- Tension with light masses from X_{max} fits for QGSJet II-04 (**too shallow X_{max} scale**)

Combining SD and FD observables



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

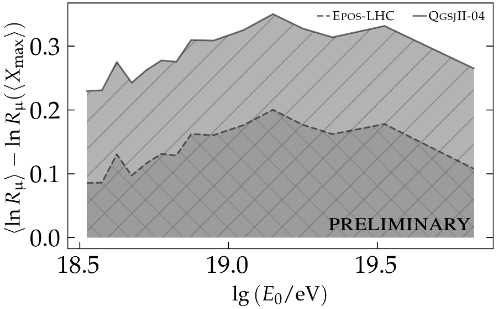


Ground signal + Longitudinal profile

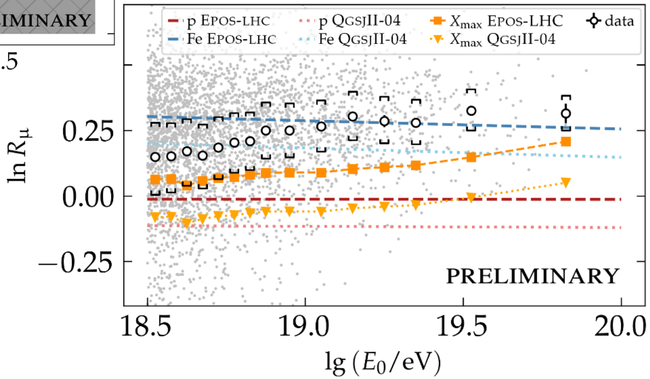
- correlation between X_{max} and S(1000)
- top-down approach -> R_{had} **~ 1.3 - 1.6 !**
  [Phys. Rev. Lett. 117 (2016) 192001]
- applying shower-universality approach -> R_{had}
- 2-dim distributions [S(1000),X_{max}] -> $R_{had}(\theta)$, ΔX_{max}

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

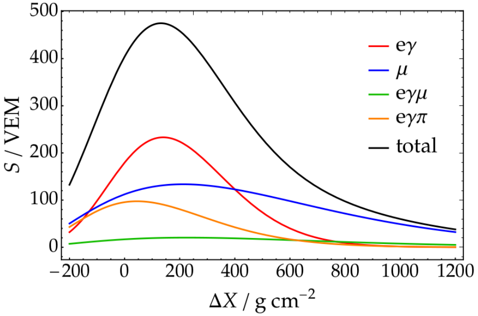
Combining SD and FD observables

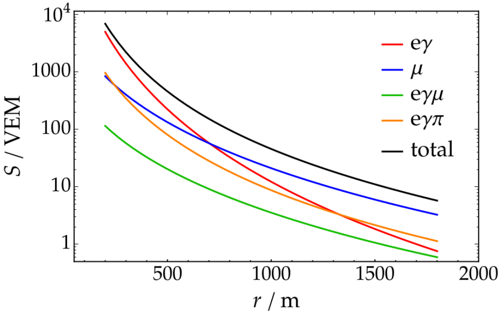


energy and X_{max} from FD



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





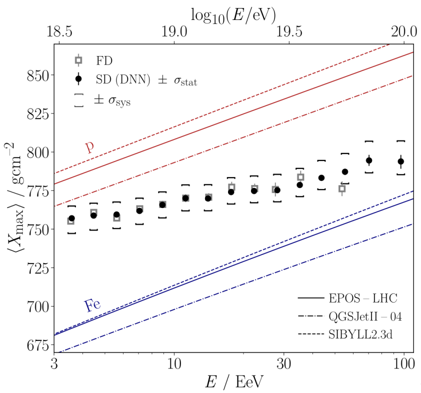
Ground signal + Longitudinal profile

- correlation between X_{max} and S(1000)
-
- top-down approach -> R_{had}
- applying shower-universality approach -> R_{had} ~ **1.1 - 1.3** [PoS(ICRC2023)339, arXiv:2405.03494]
- 2-dim distributions [S(1000),X_{max}] -> $R_{had}(\theta)$, ΔX_{max}

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

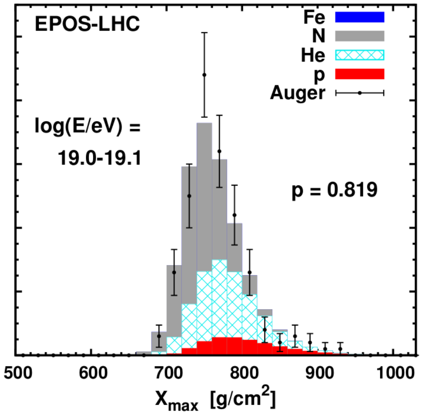
Mass composition & tests of hadronic interactions

[submitted to PRD, arXiv:2406.06319]



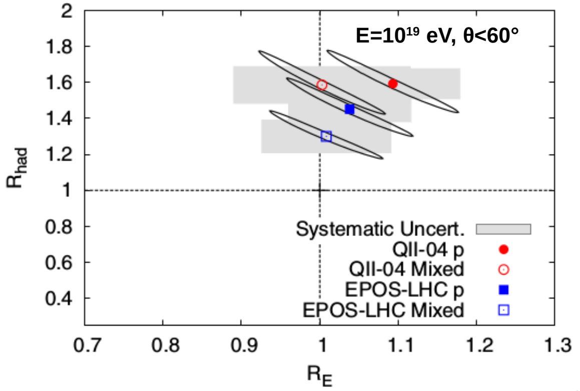
MC X_{max} scale ?

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



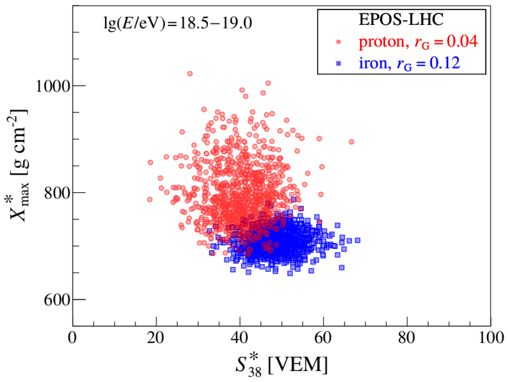
Prim. fraction fit

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



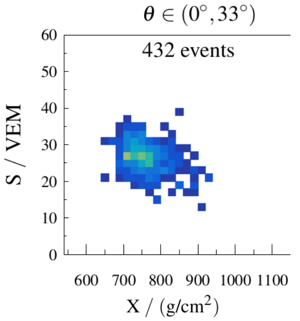
Deficit in MC hadronic signal

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



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

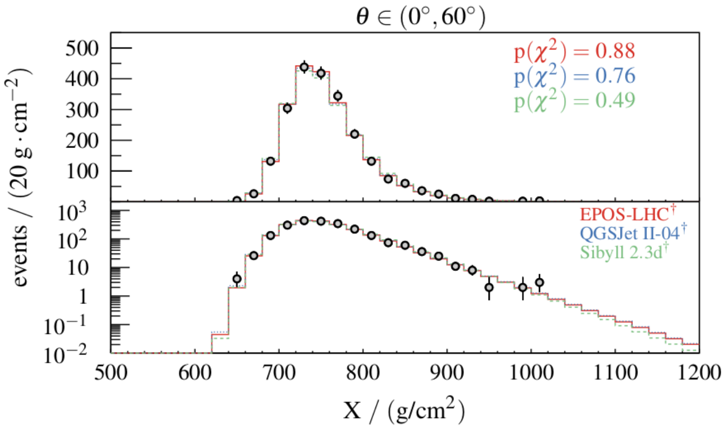
[Phys. Rev. D 109 (2024) 102001]

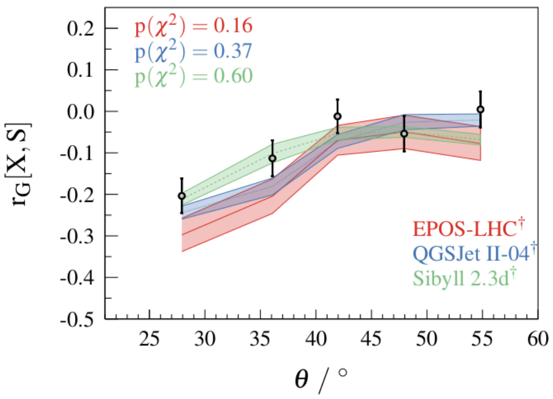


Mass composition fit of observed [X_{max},S(1000)](θ) distributions with free modification of MC predictions **not only of hadronic signal but also of X_{max}**

Improvement in data description

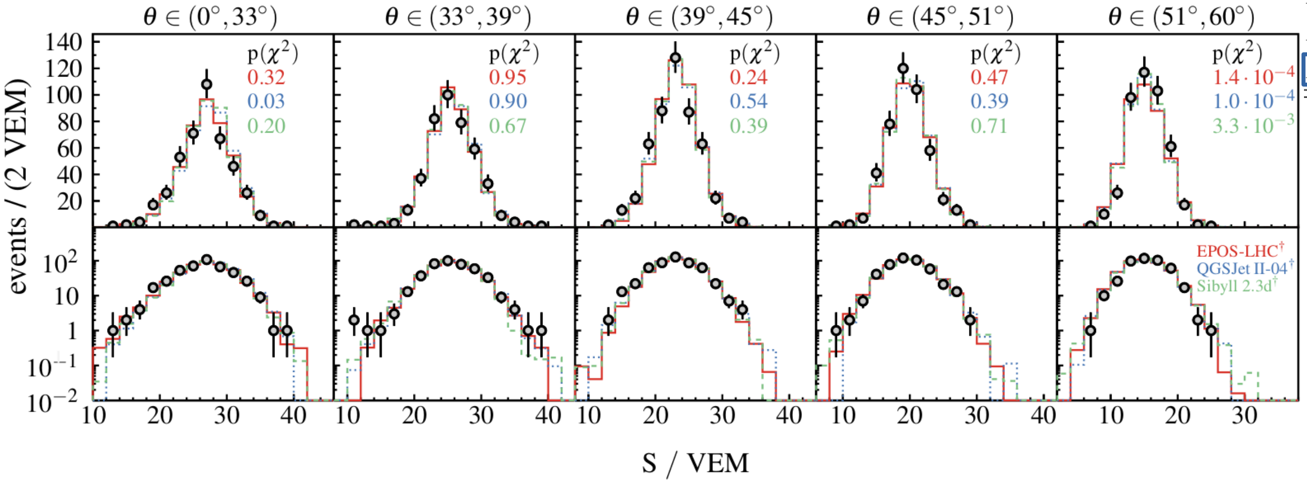
[Phys. Rev. D 109 (2024) 102001]





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
$R_{had}(\theta)$	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

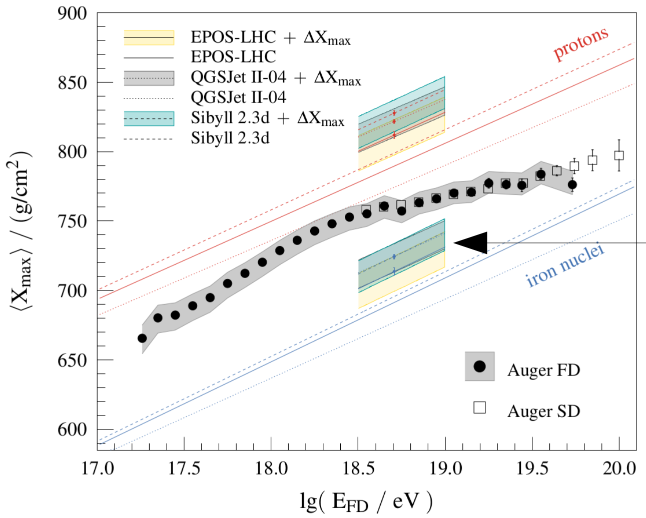


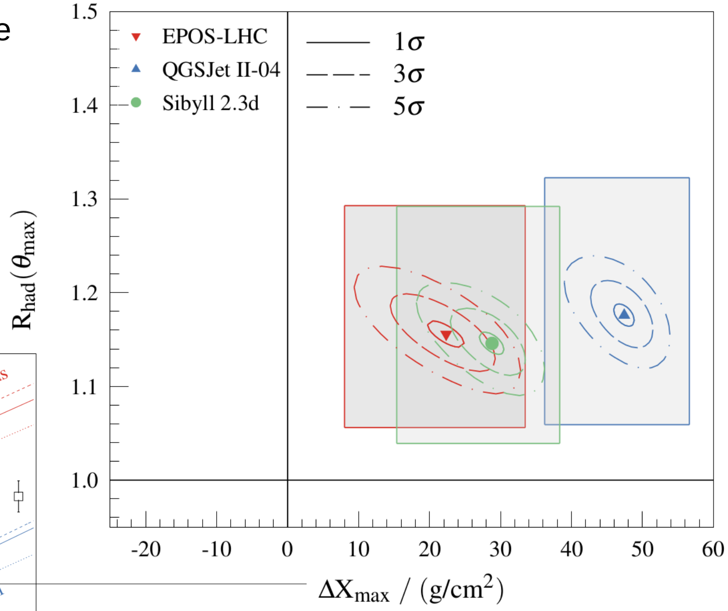
Significant improvement >5σ using R_{had} and ΔX_{max}
(Likelihood ratio tests for nested model using Wilks‘ theorem)

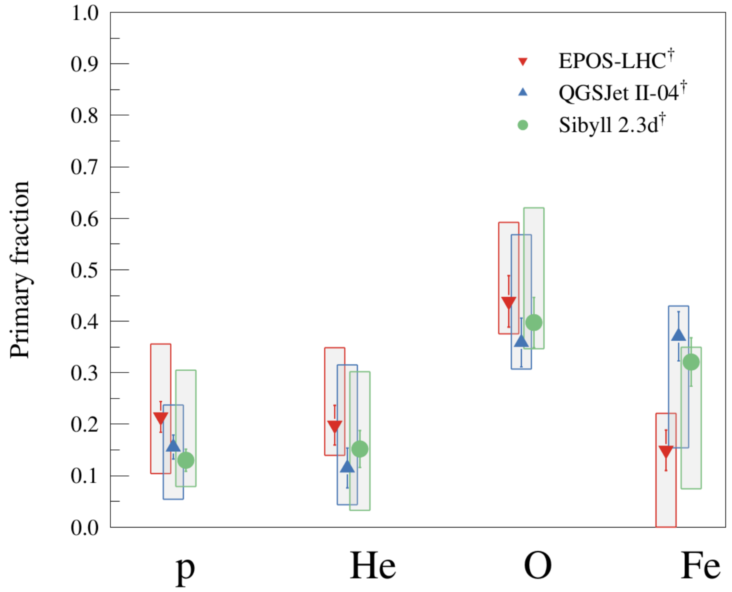
Fitted parameters

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

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



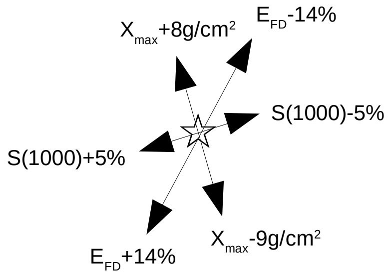




- **Deeper X_{max} predictions for all models !**
- Alleviated “muon problem“ to ~15-25%
- Smaller model differences in mass composition

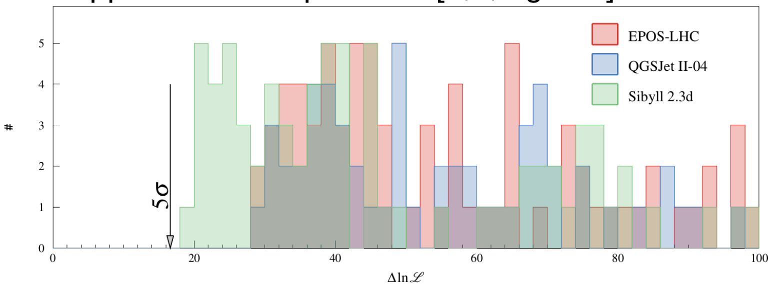
Scanning in combinations of experimental systematics

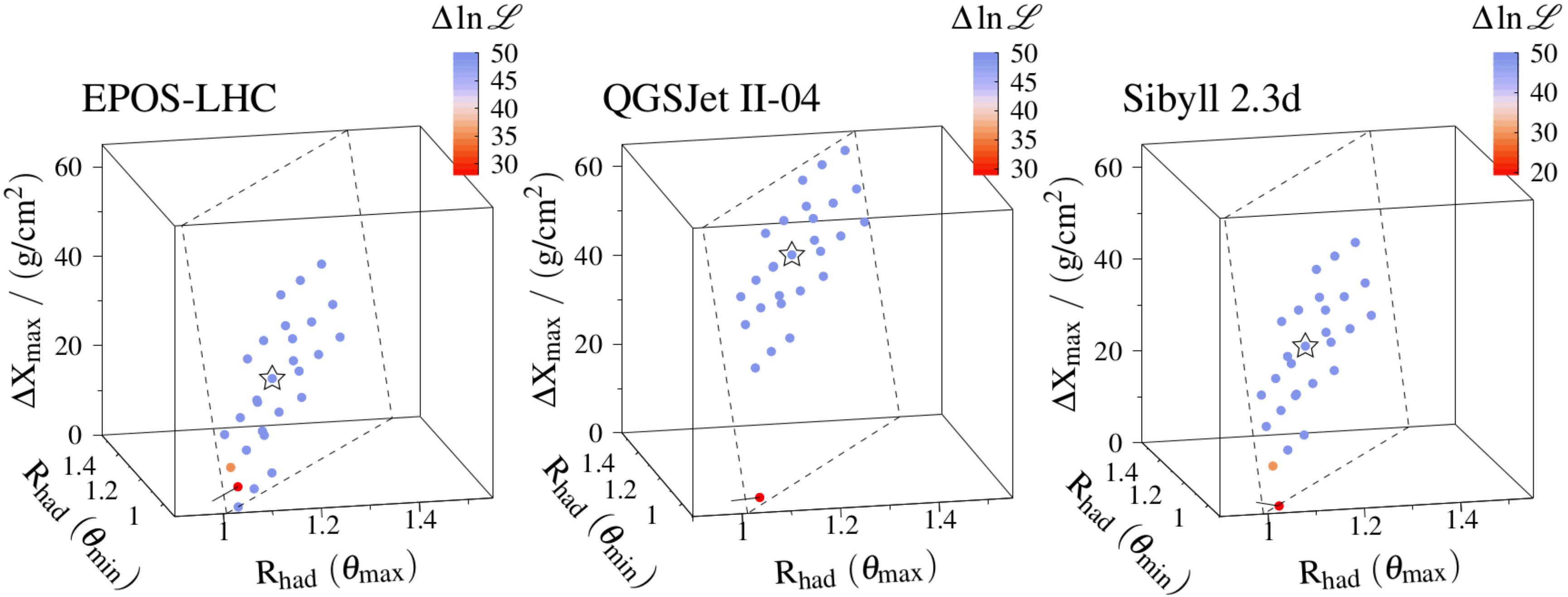
[Phys. Rev. D 109 (2024) 102001]



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/cm^2]





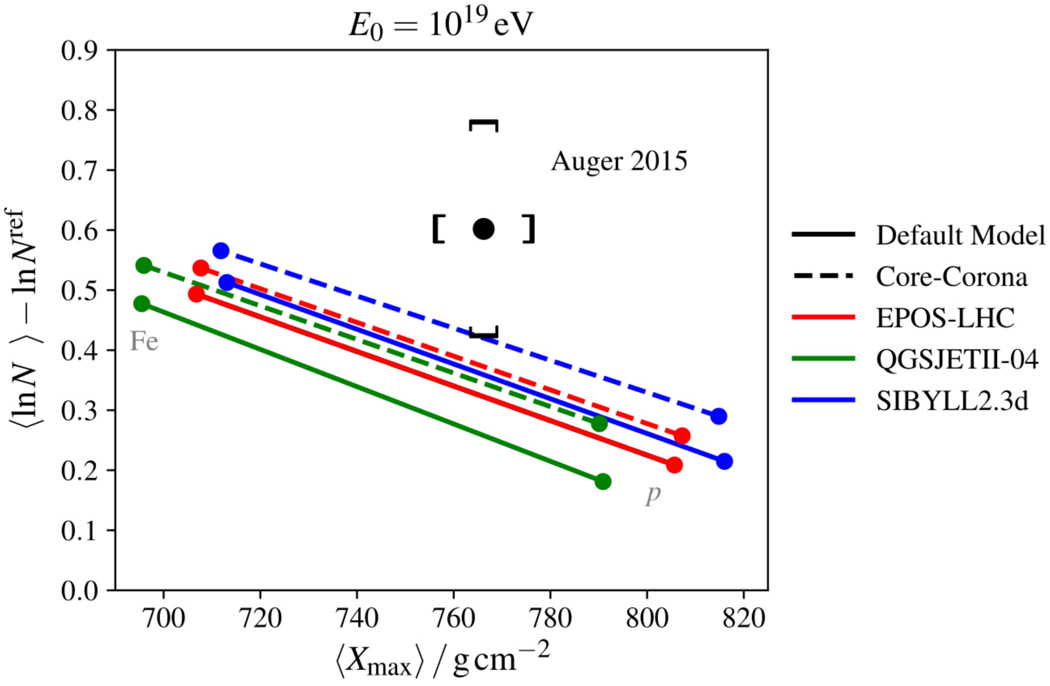
Summary of tests of models using Auger data

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	—
[X_{max}, S(1000)]	3 to 10	0 to 60	tension	tension	tension

- All models have problems ...
- A need to describe consistently both X_{max} and ground signal - issue in both observables !

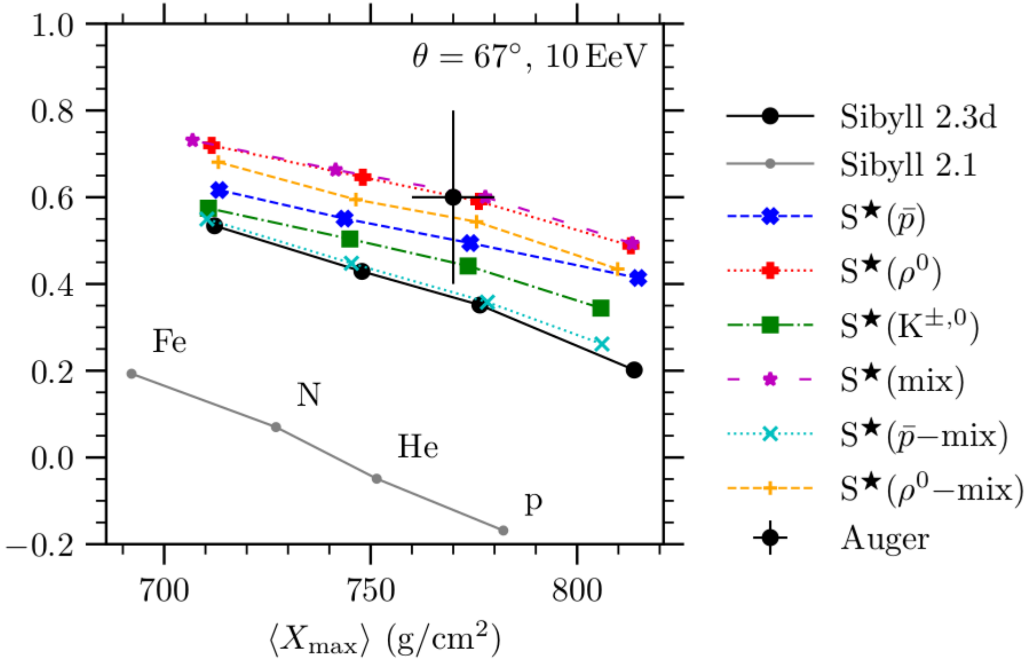
Adding muons ~ without changing X_{max}

Core-corona model - collective statistical hadronization ➔ EPOS 4



[Phys. Rev. D 107 (2023) 094031]

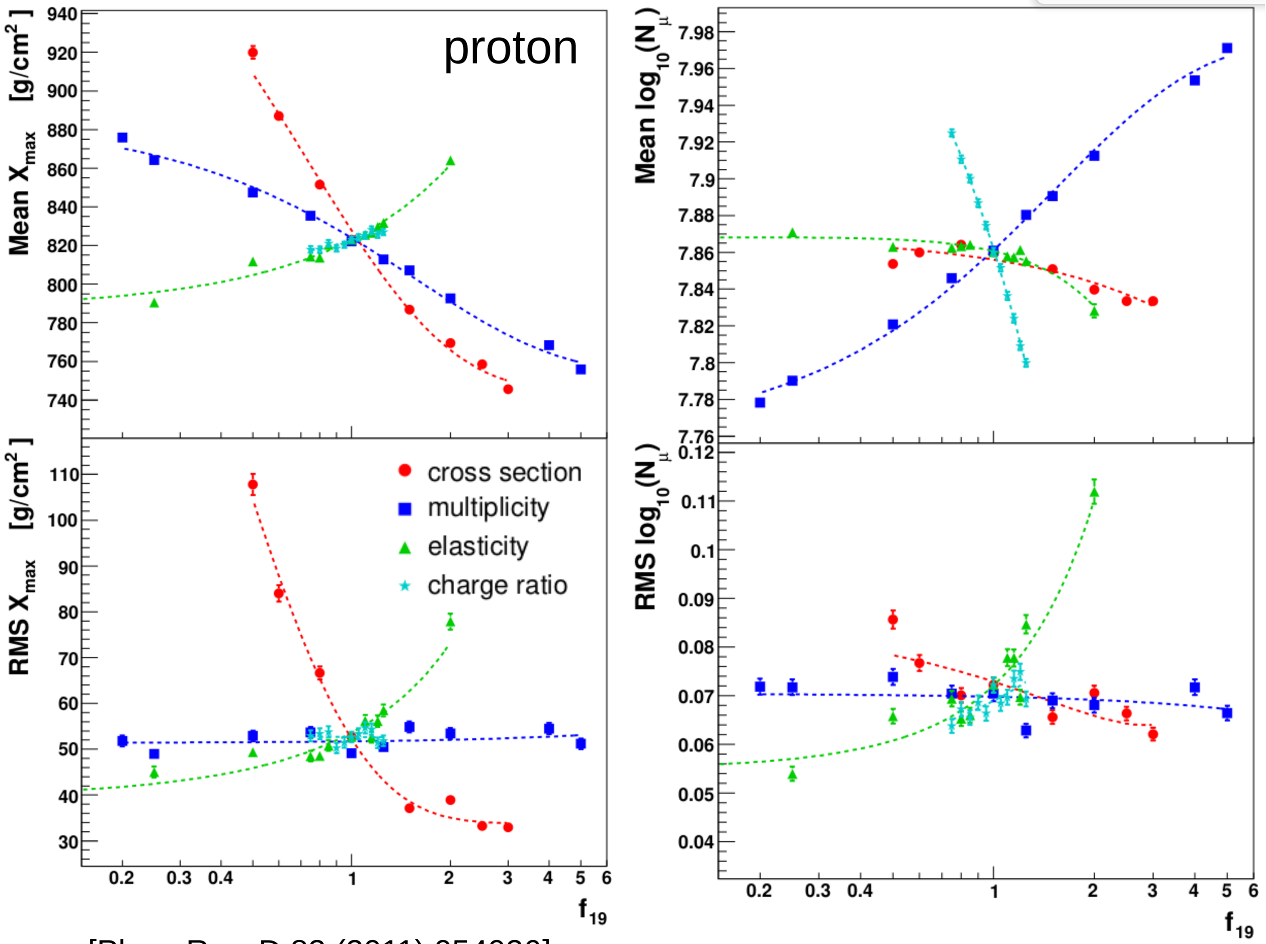
Sibyll * - artificial enhancement of muons



[PoS(ICRC2023)429]

Modifications of hadronic interactions

- 1D CONEX simulations
- Sibyll 2.1 @ $10^{19.5}$ eV
- Cross-section modification, or resampling of produced particles
- Energy threshold for modifications 10^{15} eV

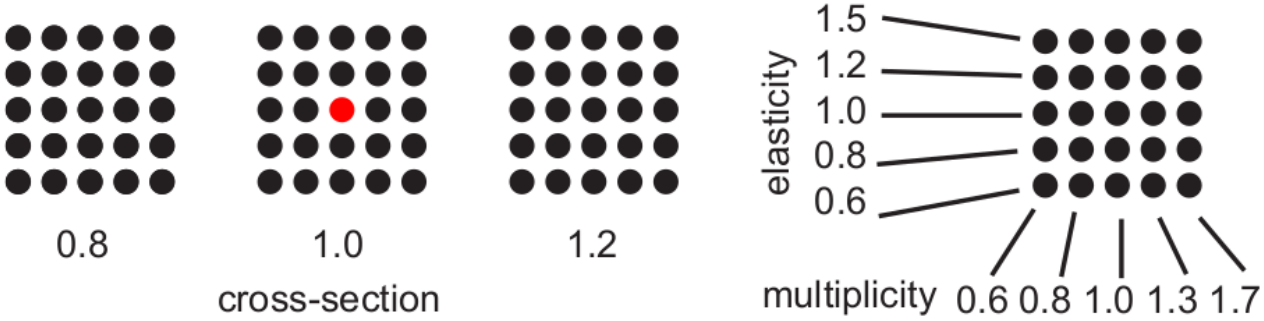


[Phys. Rev. D 83 (2011) 054026]

Towards more complex explanation: MOCHI

***MO**dified **C**haracteristics of **H**adronic **I**nteractions*

- CONEX in CORSIKA: 3D information
- Modification factors in **cross-section**, **multiplicity** and **elasticity**



- **MOCHI library**:
  - Sibyll 2.3d
  - energy $10^{18.7}$ eV
  - protons and iron nuclei
  - 5 zenith angles
  - 1000 showers per „bin“
  - 750 000 showers (~200 TB, ~250y CPU time)

See [PoS(ICRC2023)245] for more detail

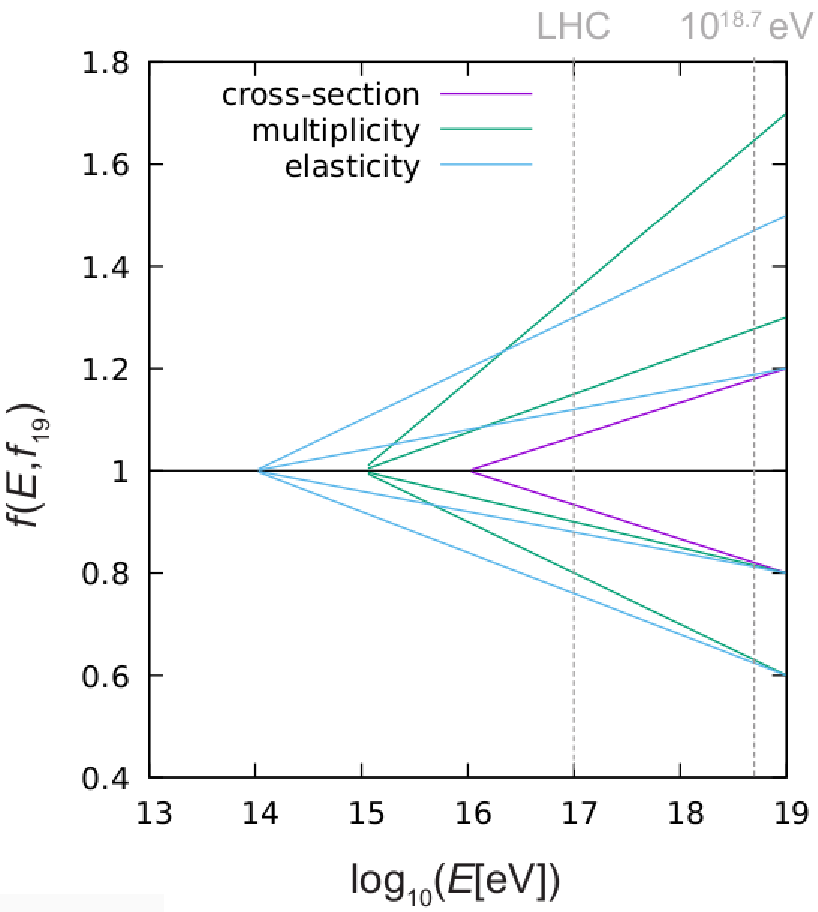
Range of modifications and thresholds

Cross-section ($E_{thr} = 10^{16}$ eV)
- well constrained for p-p at LHC to a few %
- unc. in conversion to p-A limited by CMS p-Pb measurement

Multiplicity ($E_{thr} = 10^{15}$ eV)
- no p-A data, limited rapidity coverage

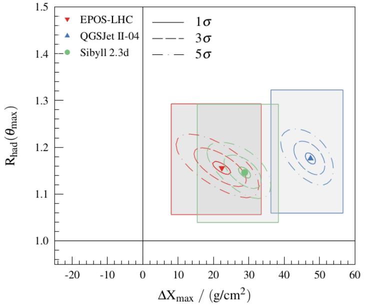
Elasticity ($E_{thr} = 10^{14}$ eV)
- difficult at accelerators, limits from nuclear emulsion chambers
- recent LHCf neutron elasticity measurement?
- range of modifications limited by internal consistency

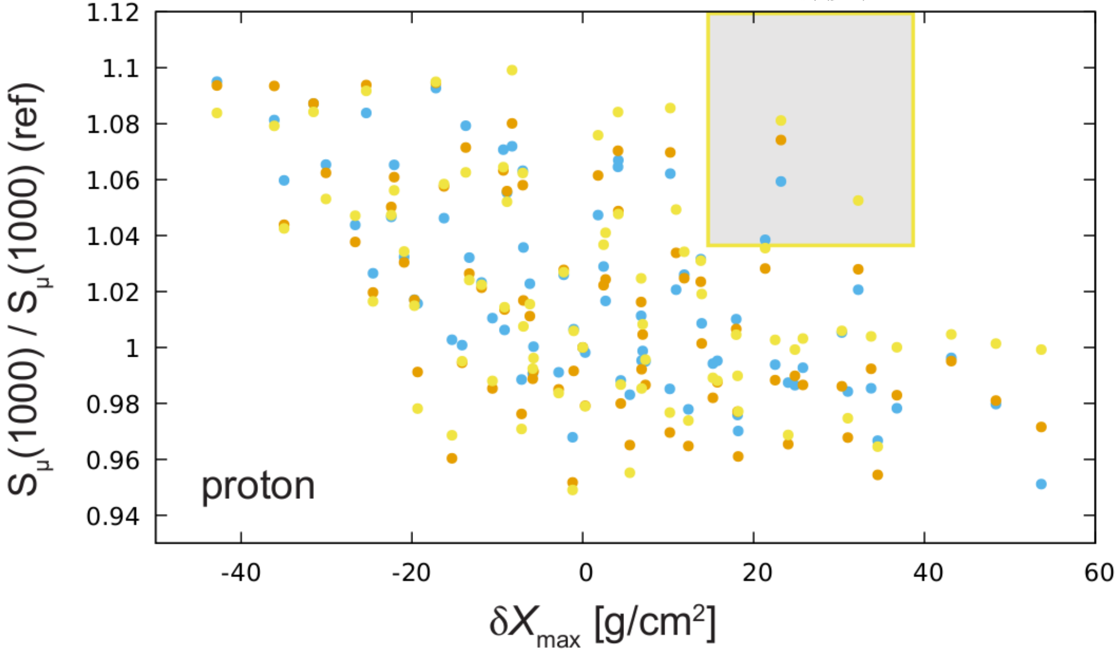
$$f(E, f_{19}) = 1 + (f_{19} - 1) \cdot \frac{\log_{10}(E/E_{thr})}{\log_{10}(10\ \mathrm{EeV}/E_{thr})}$$

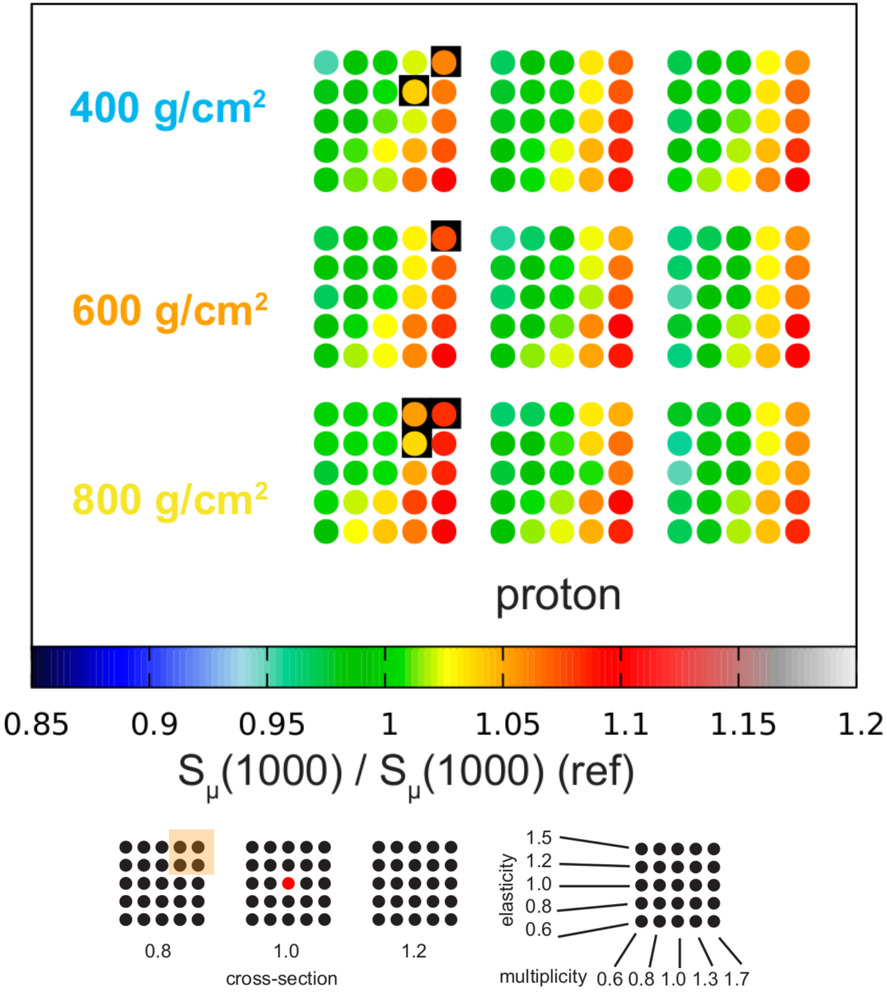


Comparison with Auger results

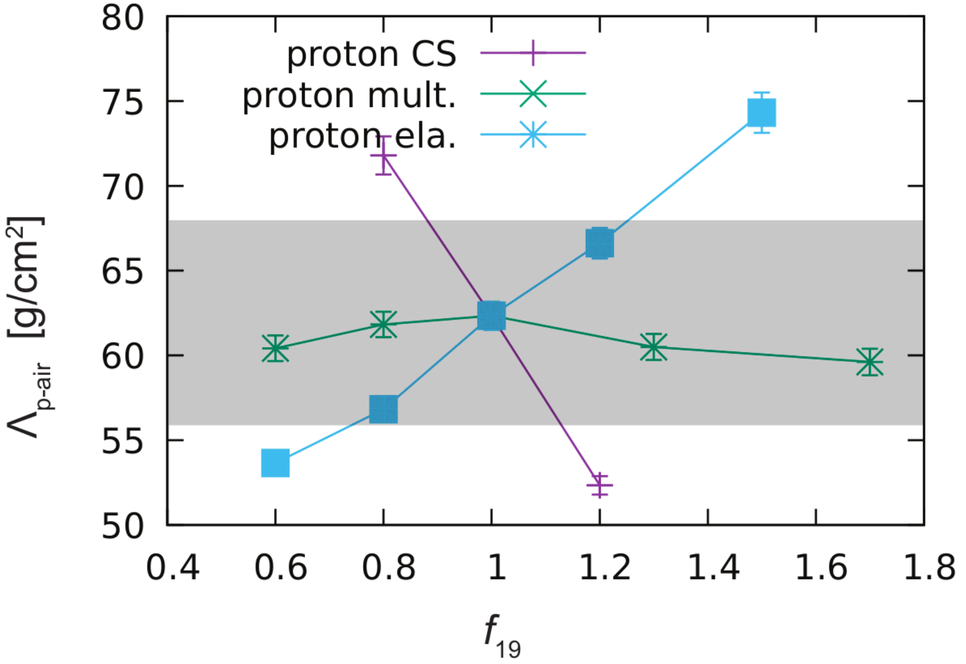
[Phys. Rev. D 109 (2024) 102001]

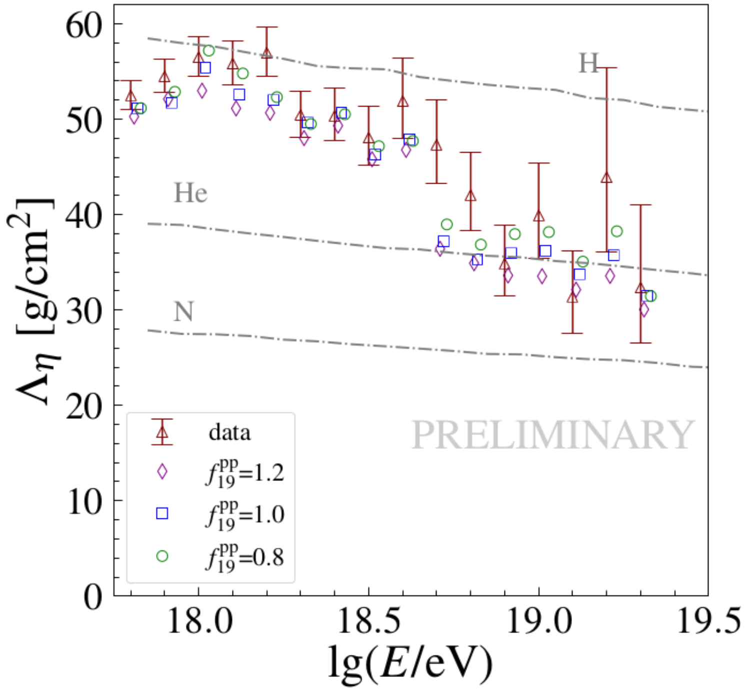


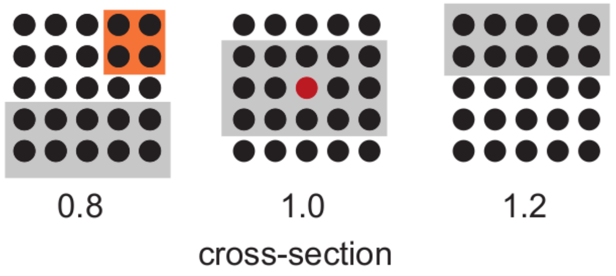


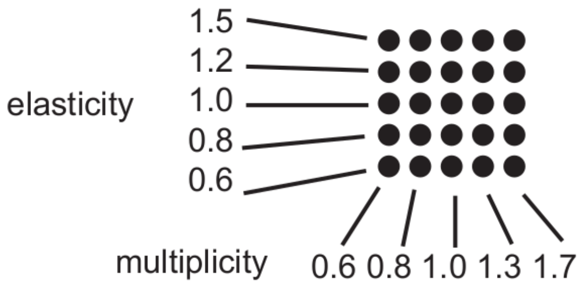


Effect on tail of X_{max} distribution



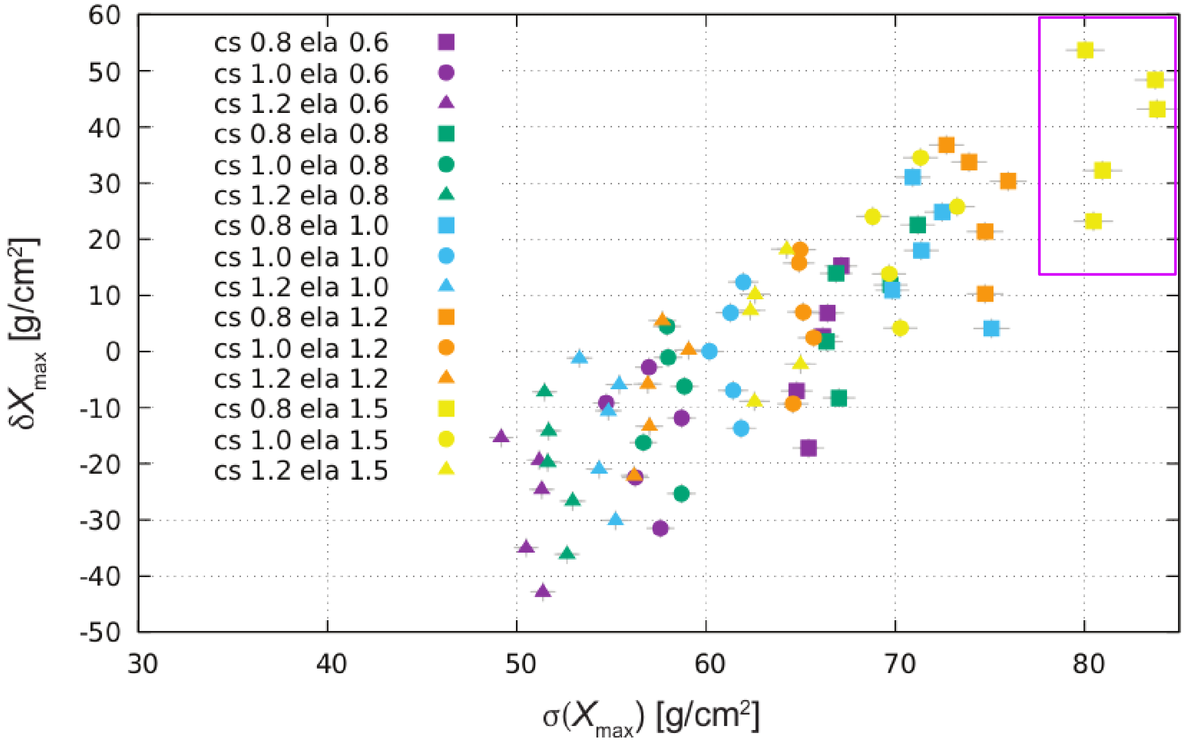




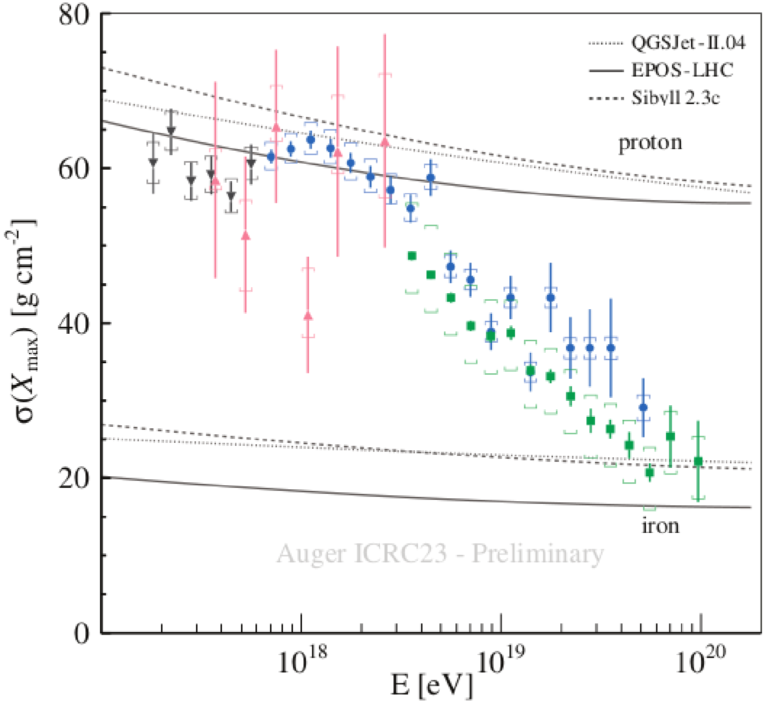


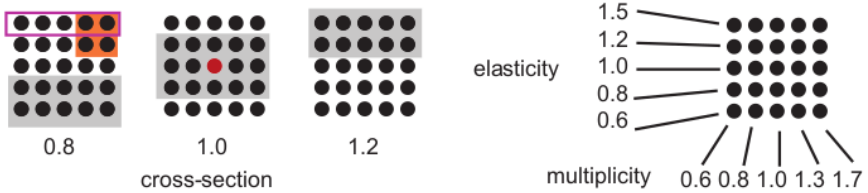
Slope of X_{max} tail distribution for protons too constrained by Auger data

Effect on X_{max} fluctuations



PoS(ICRC2023)365





Lower cross-section and high elasticity leads to very high X_{max} fluctuations that may be difficult to reconcile with data

Conclusions

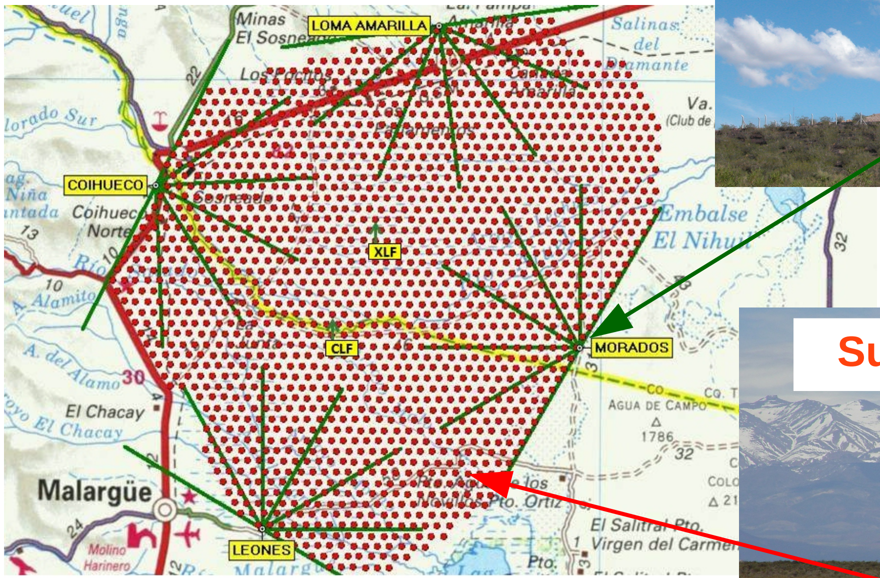
- We are facing **change of mass-composition paradigm** ➔ we should start seriously consider “disappointing“ heavy scenario of ultra-high energy cosmic rays
- Models of hadronic interactions proven to fail to describe air-shower data > 5σ
  - possible underestimation of experimental systematics ruled out
- Modifications of macro-parameters (cross-section, multiplicity, elasticity) of hadronic interactions does not seem (preliminary) to be enough

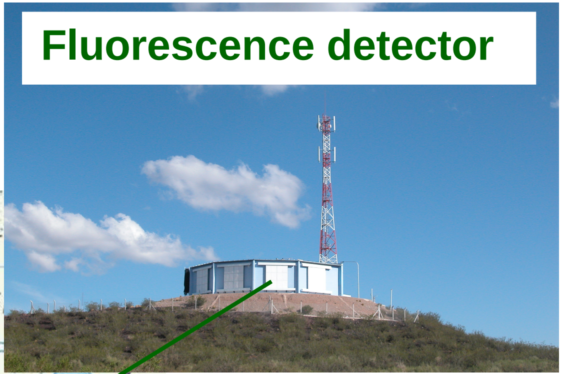
  ➔ different approach is needed: modifying micro parameters (production rates and energy spectra of secondary particles) or (not exclusively!) revisions of models of hadronic interactions (EPOS 4, QGSJet III?, ...)
- **p + O run** at LHC is extremely important for decrease of systematic uncertainties on mass composition of UHECR
- **AugerPrime** (2024-2035) will be the best test facility so far for hadronic interactions at $\sqrt{s}$ ~ 100 TeV

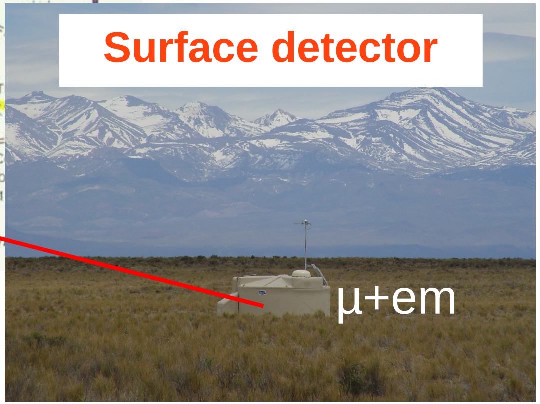
Backup slides

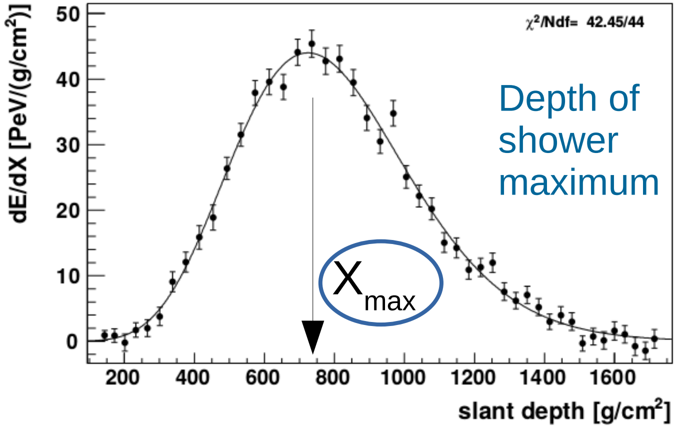
Hybrid detection at the Pierre Auger Observatory

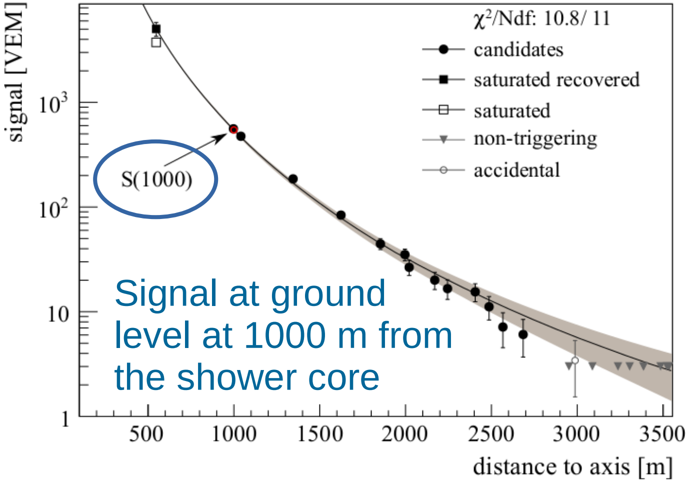
[Nucl. Instrum. Meth. A 798 (2015) 172]









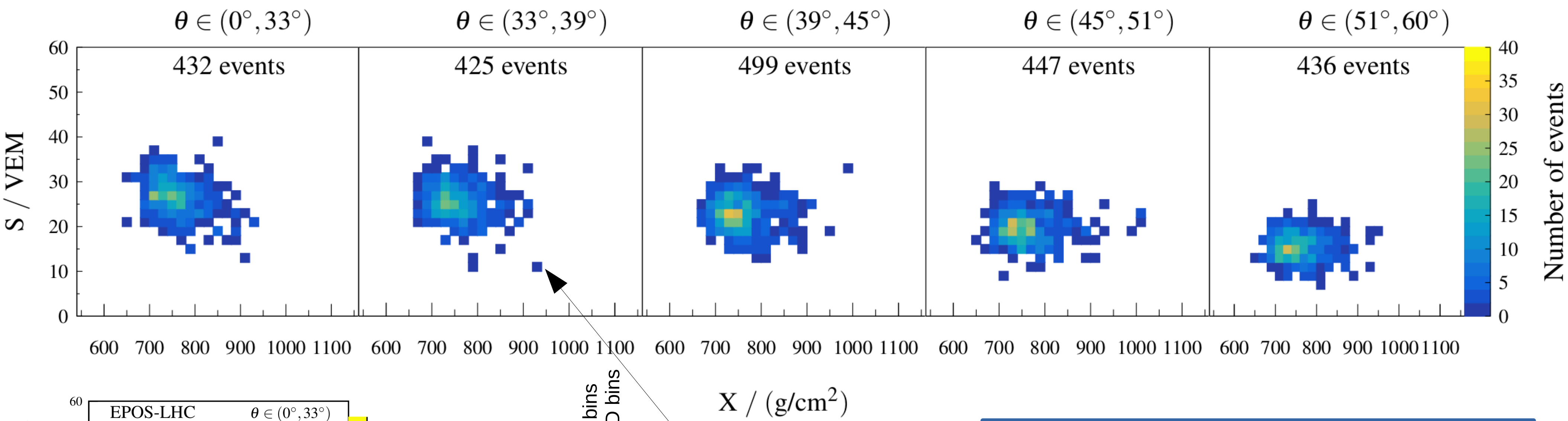


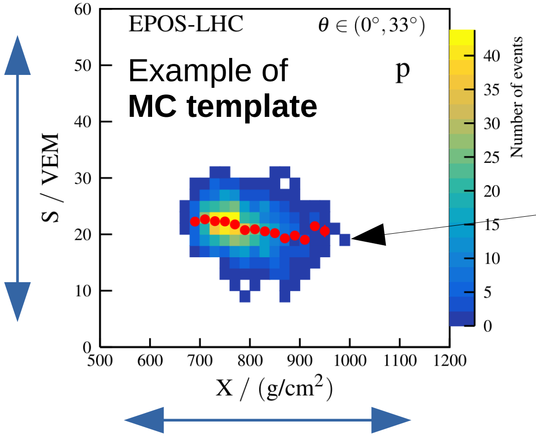
Method

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

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

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





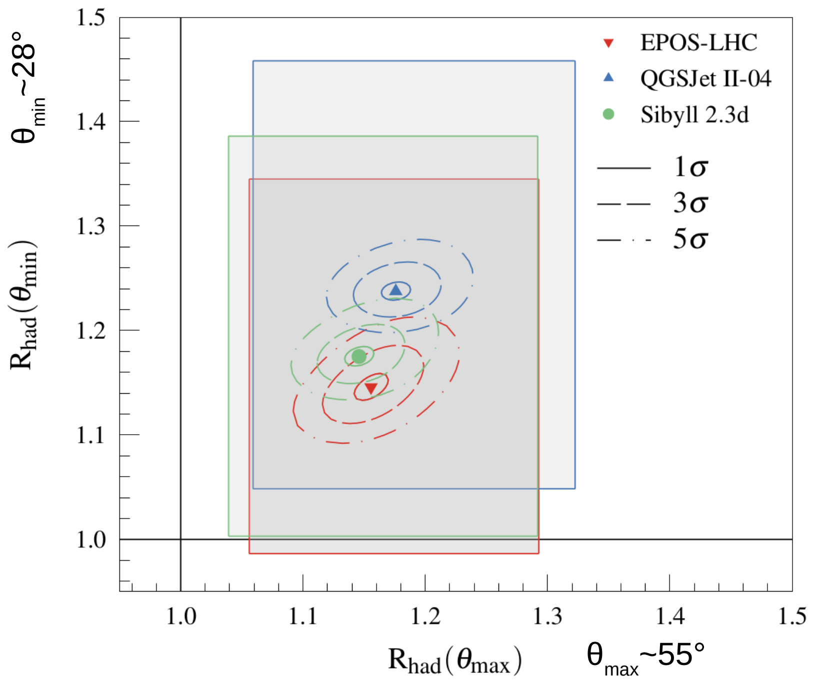
θ bins
2D bins

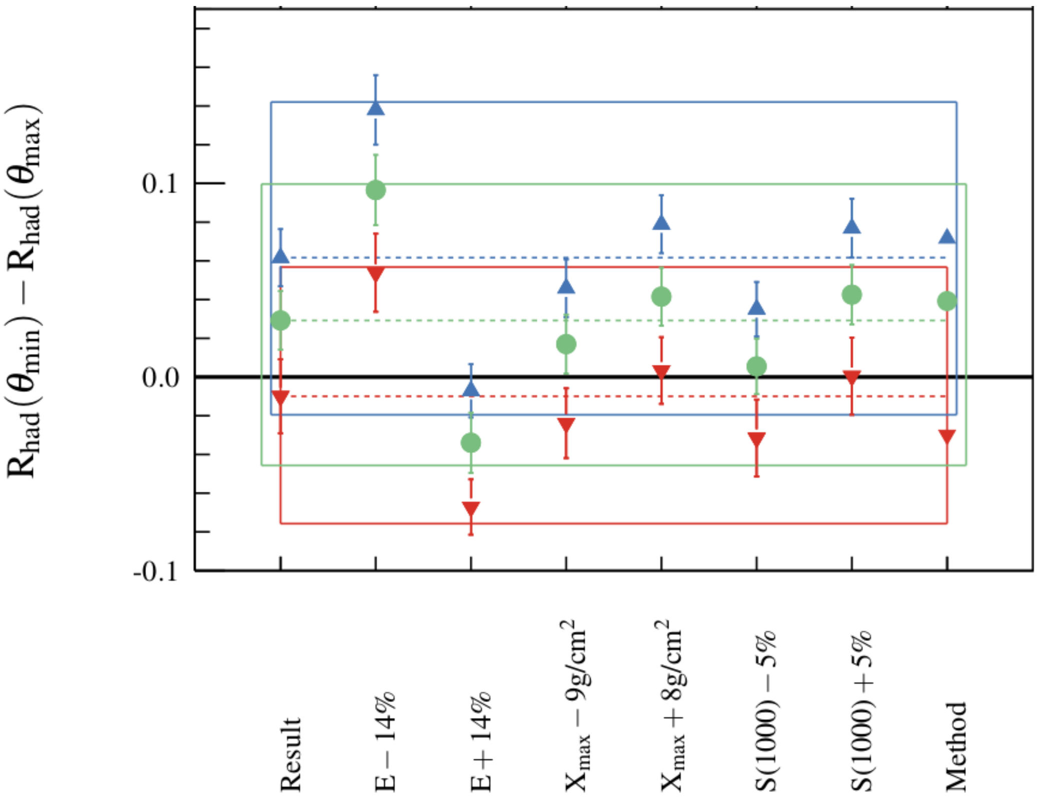
$$\ln\mathscr{L} = \begin{cases} \sum_k\sum_j \left(C_{jk} - n_{jk} + n_{jk}\ln\frac{n_{jk}}{C_{jk}}\right), & n_{jk} > 0 \\ \sum_k\sum_j C_{jk}, & n_{jk} = 0 \end{cases}$$

- **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)

Attenuation of hadronic signal with θ



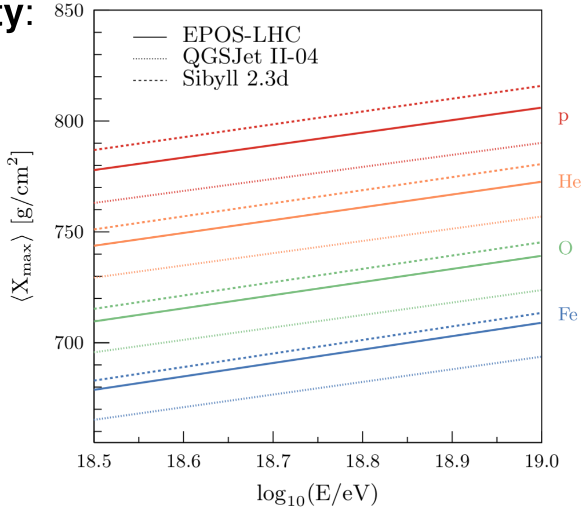


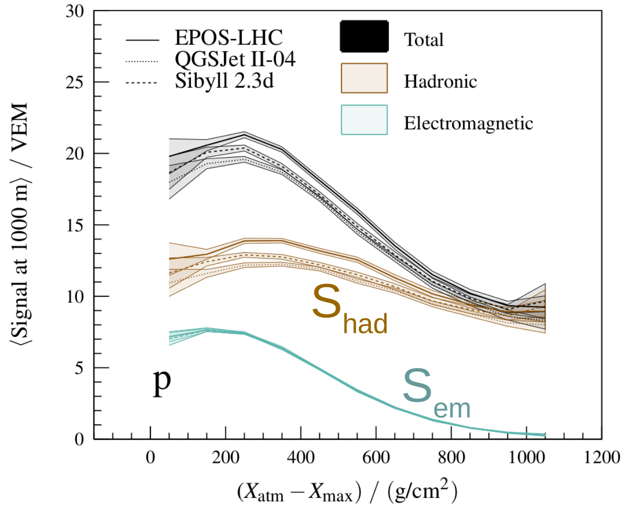
Indication of harder muon spectra in QGSJet II-04 than in data

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**





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

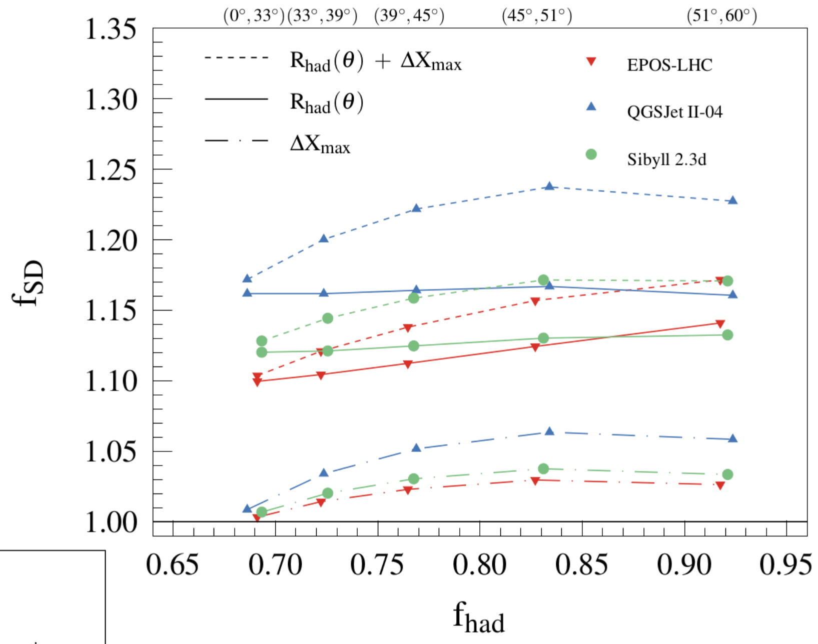
Caveat: no modifications in fluctuations or mass-depencies etc. considered

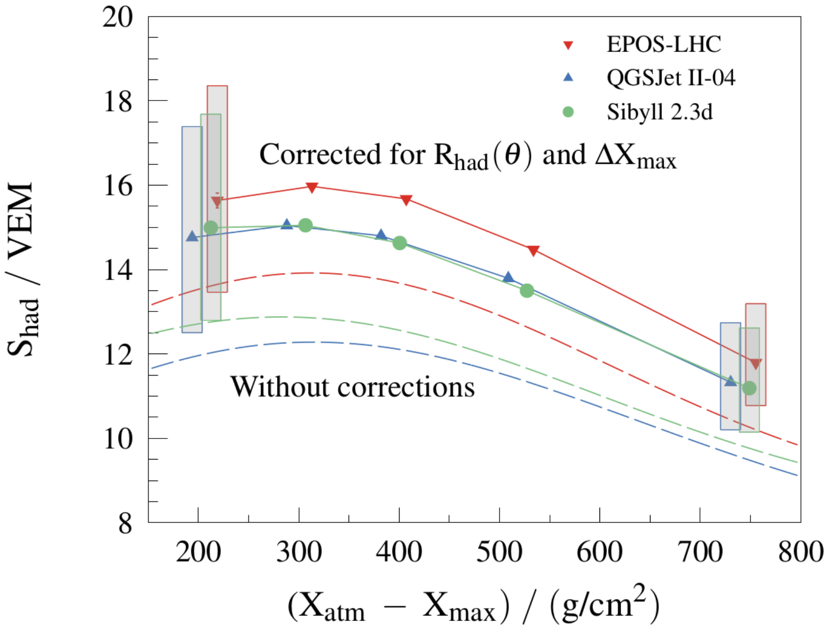
ad-hoc modifications

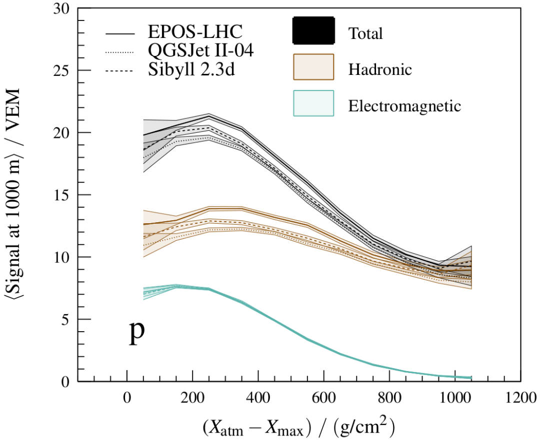
$$X_{max} \rightarrow X_{max} + \Delta X_{max}$$

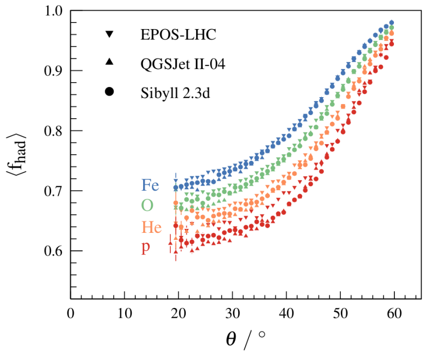
$$S_{had}(\theta) \rightarrow S_{had}(\theta) \cdot R_{had}(\theta)$$

Effect of modified X_{max} on the ground signal









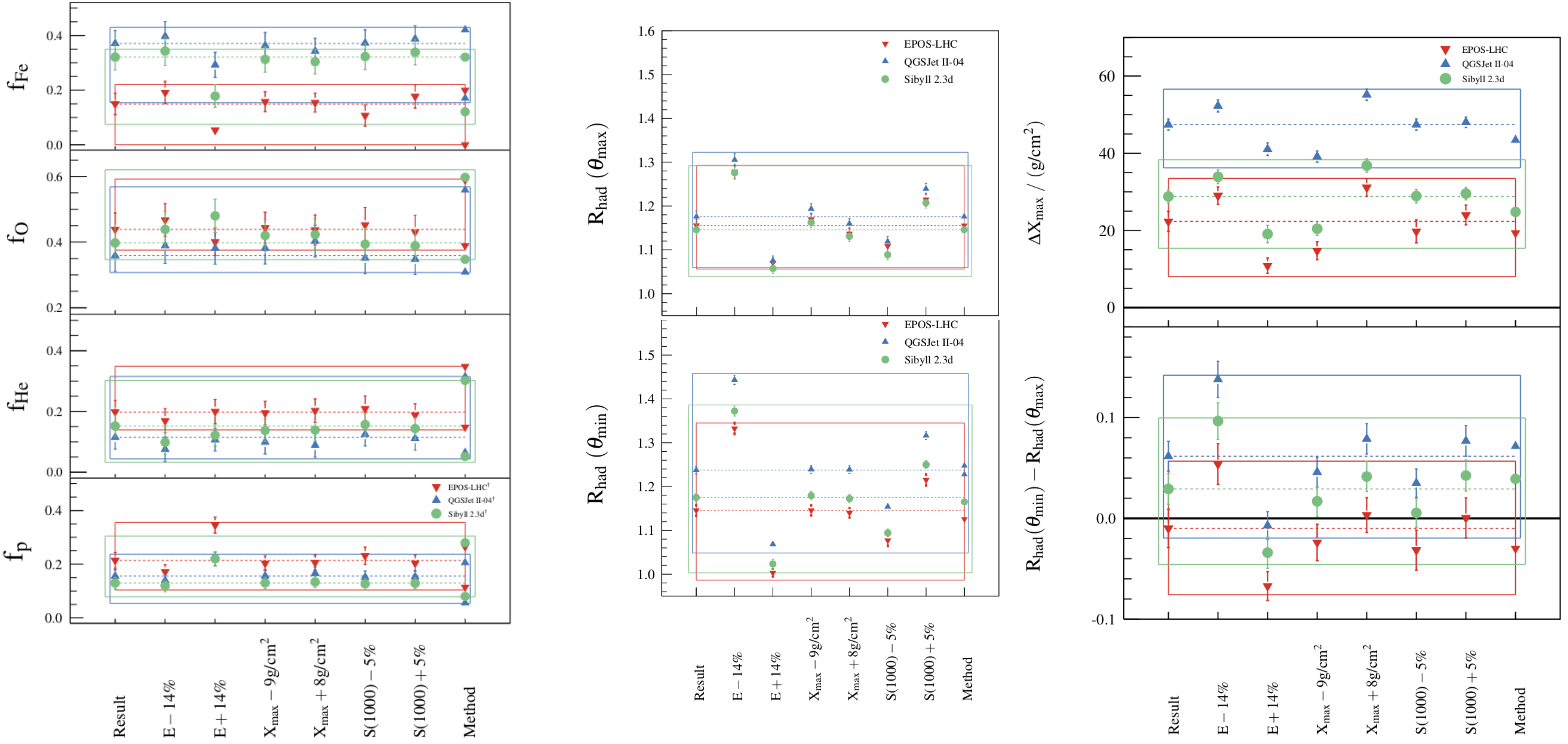
Assumption on primary species

- 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

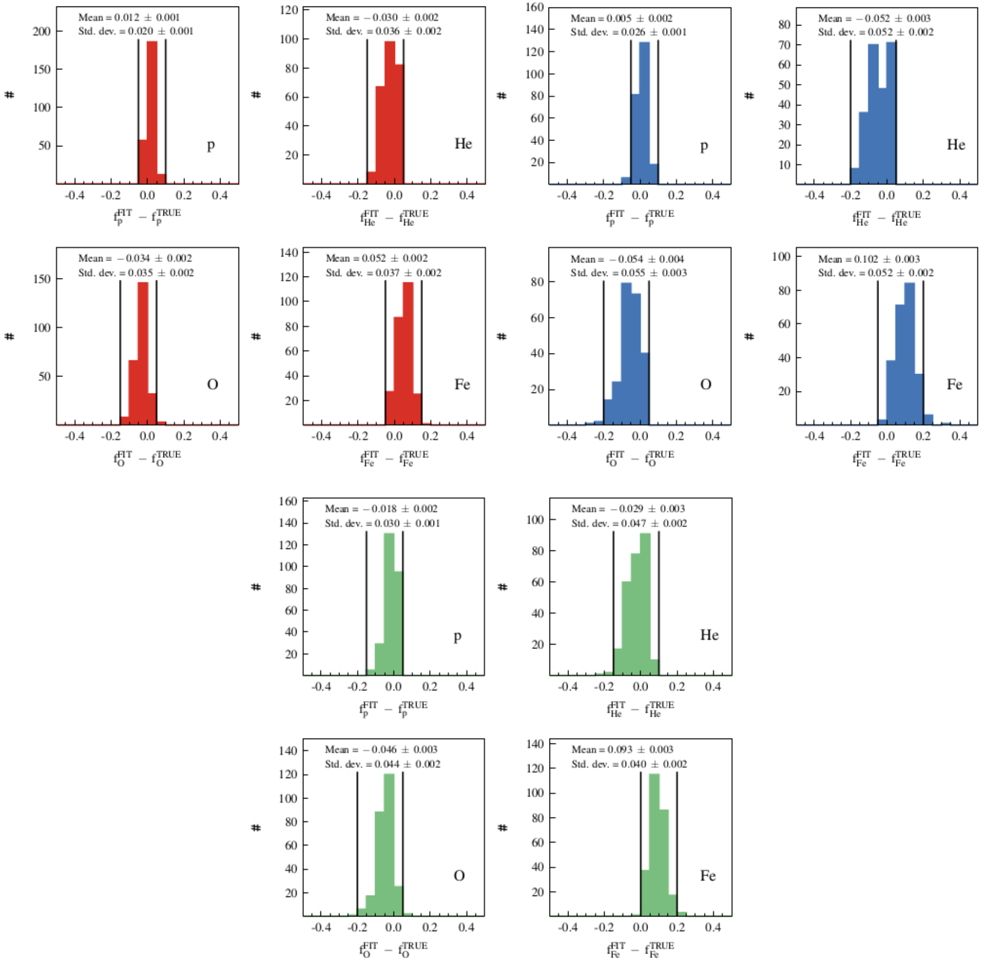
$\ln \mathscr{L}_{min}$	EPOS-LHC	QGSJET-II-04	SIBYLL 2.3d
p He	518.3	633.5	563.5
p He O	467.5	523.3	486.6
p He O Fe	451.9	476.3	451.6

Significance of improvement of data description above 5σ

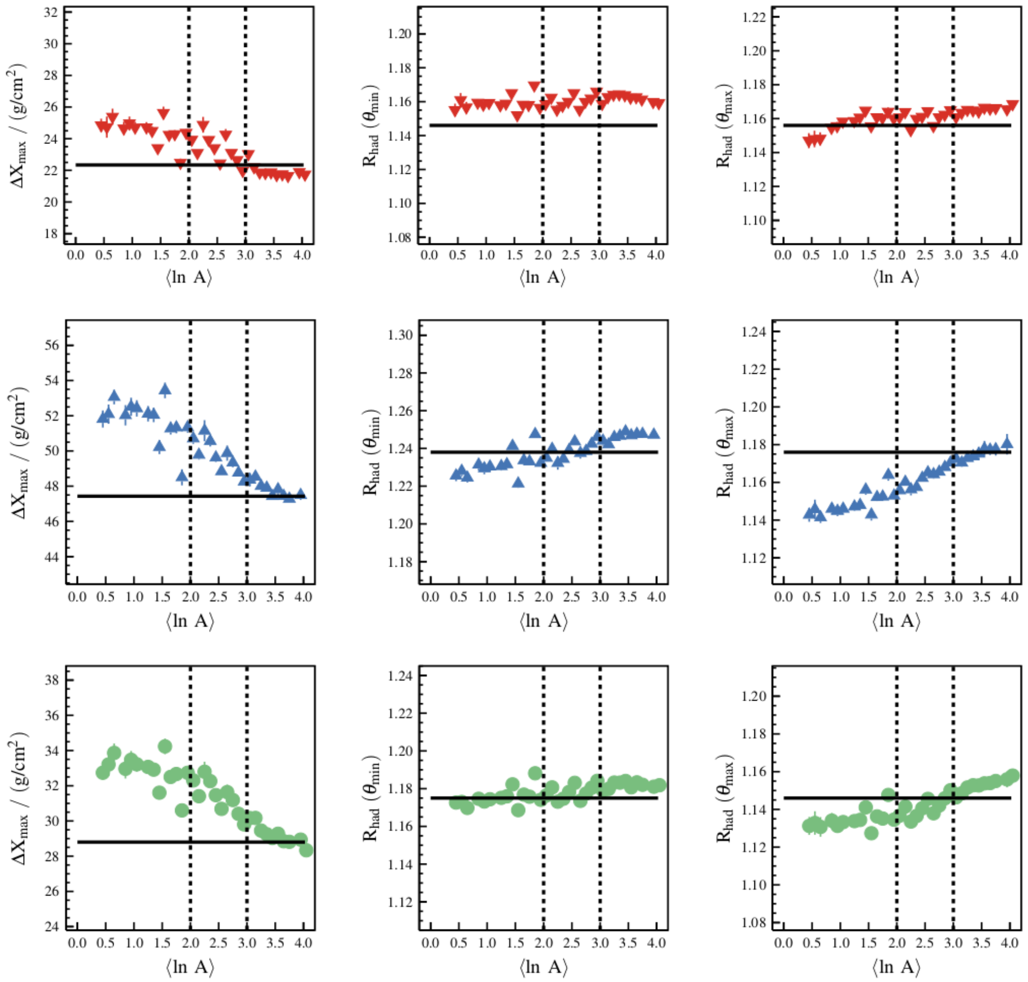
Systematic uncertainties



MC-MC tests



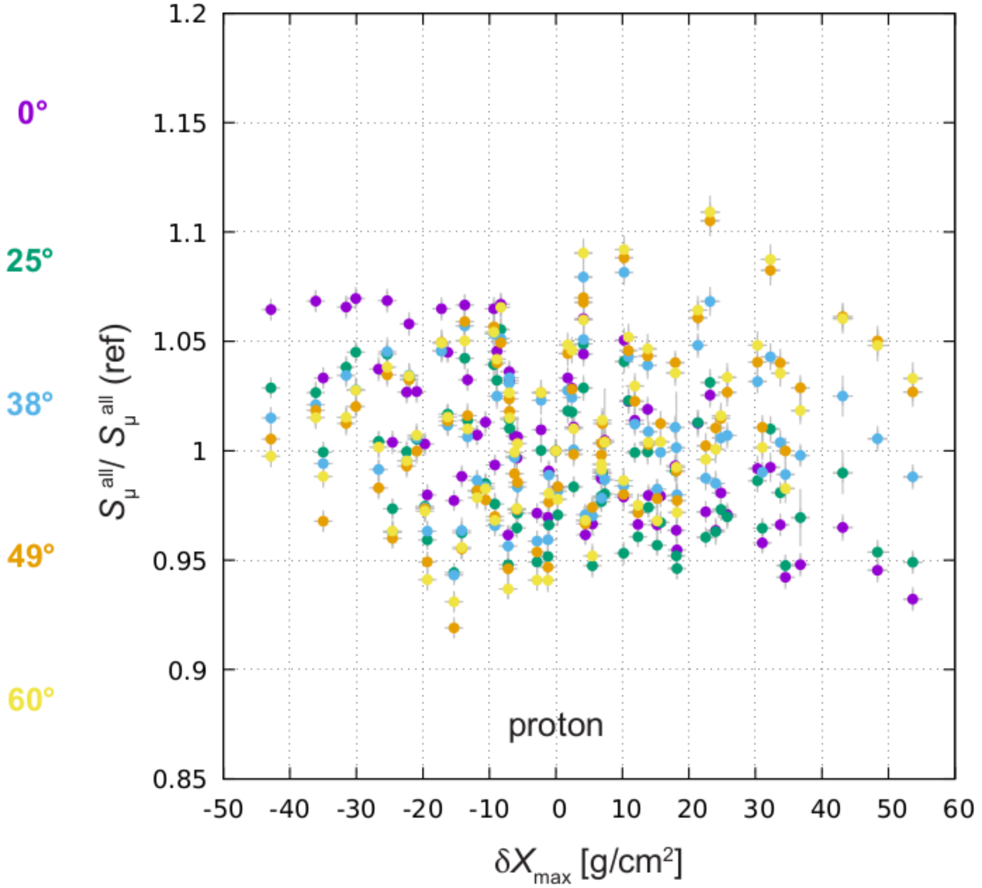
Mean = 0.012 ± 0.001
Std. dev. = 0.020 ± 0.001
p
Mean = −0.030 ± 0.002
Std. dev. = 0.036 ± 0.002
He
Mean = 0.005 ± 0.002
Std. dev. = 0.026 ± 0.001
p
Mean = −0.052 ± 0.003
Std. dev. = 0.052 ± 0.002
He
Mean = −0.034 ± 0.002
Std. dev. = 0.035 ± 0.002
O
Mean = 0.052 ± 0.002
Std. dev. = 0.037 ± 0.002
Fe
Mean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



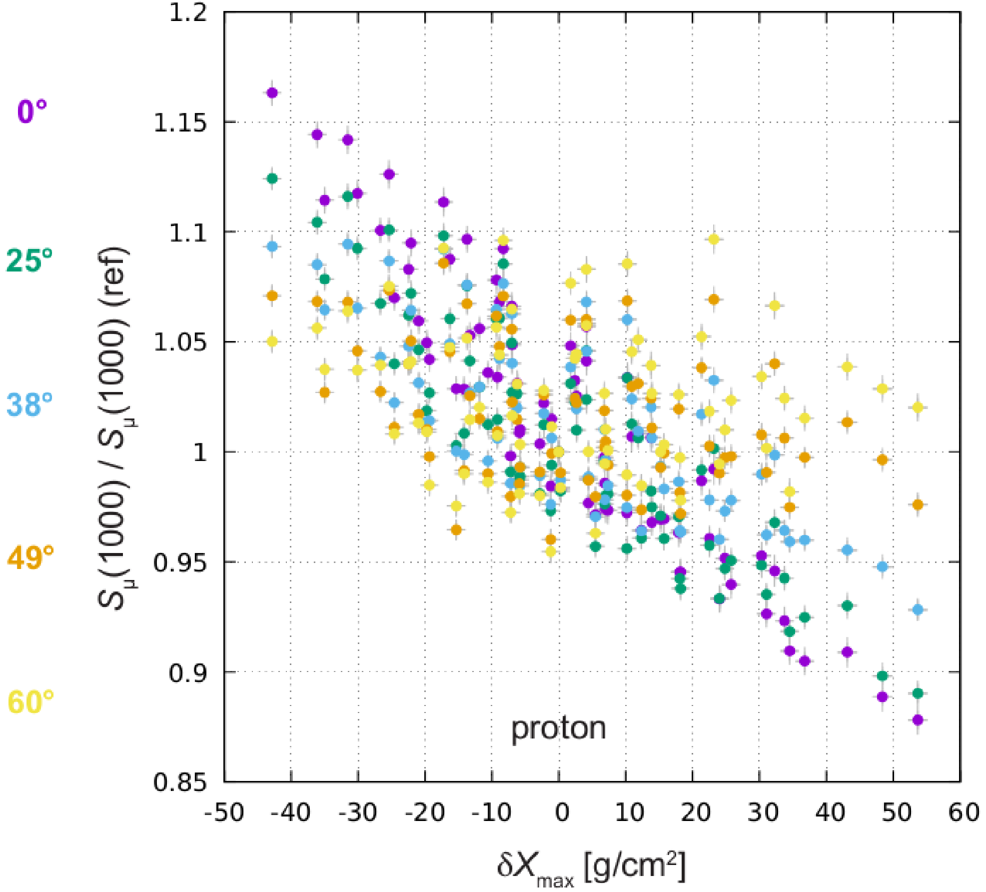
ΔX_{max} / (g/cm^2)
R_{had} (θ_{min})
R_{had} (θ_{max})
⟨ln A⟩

Importance of 3D simulation

All muons



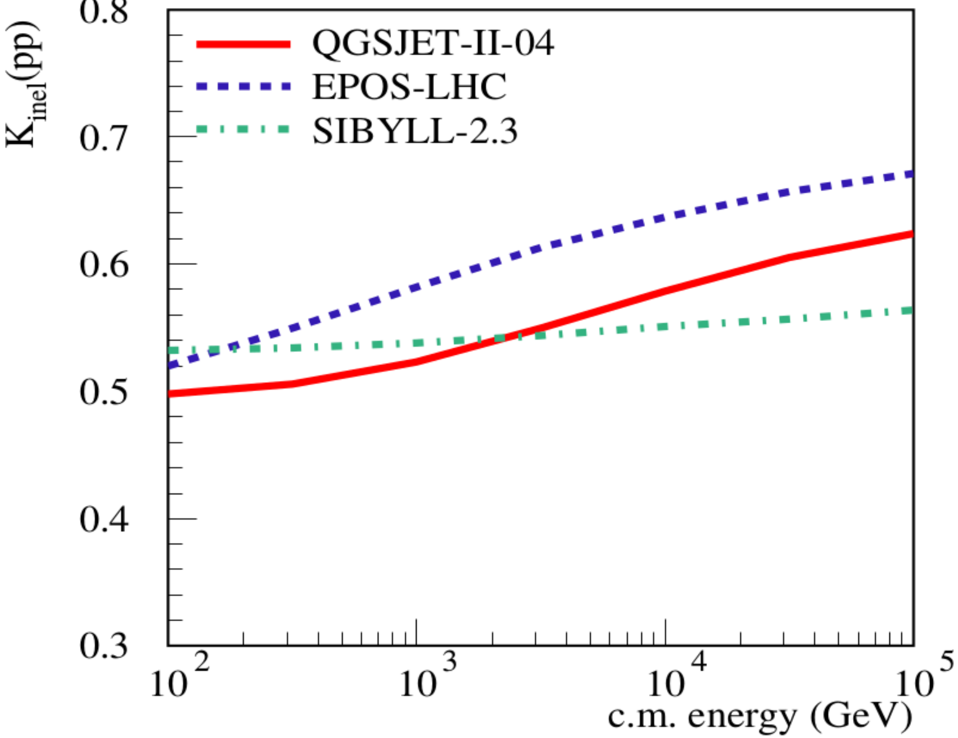
Muons around 1000m



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

$$X^{\mathrm{A}}_{\mathrm{max}} = X^{A}_{1} + X_0 \ln \frac{\kappa E}{A \cdot 2N\xi^{\pi}_{\mathrm{c}}} =$$

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

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

MOCHI (preliminary)

[PoS(ICRC2023)245]

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