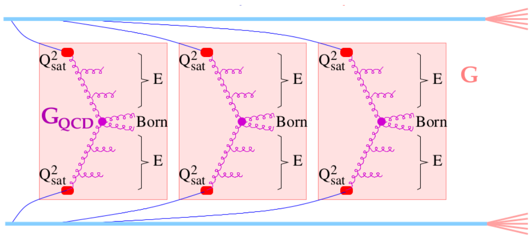

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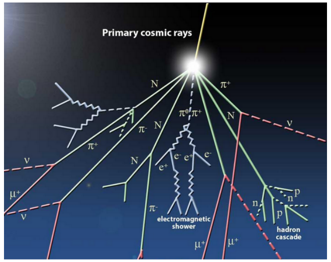

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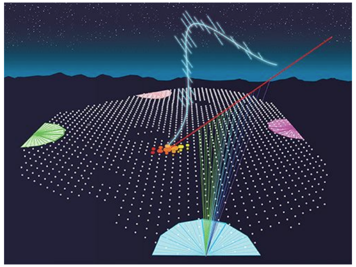

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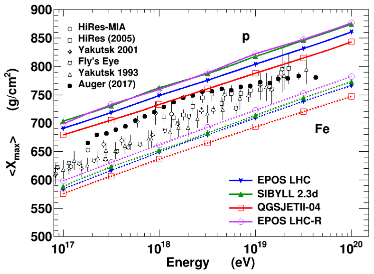


Overview of hadronic interaction studies at the Pierre Auger Observatory

Jakub Vícha* for the Pierre Auger Collaboration

*FZU - Institute of Physics of the Czech Academy of Sciences, Prague

vicha@fzu.cz

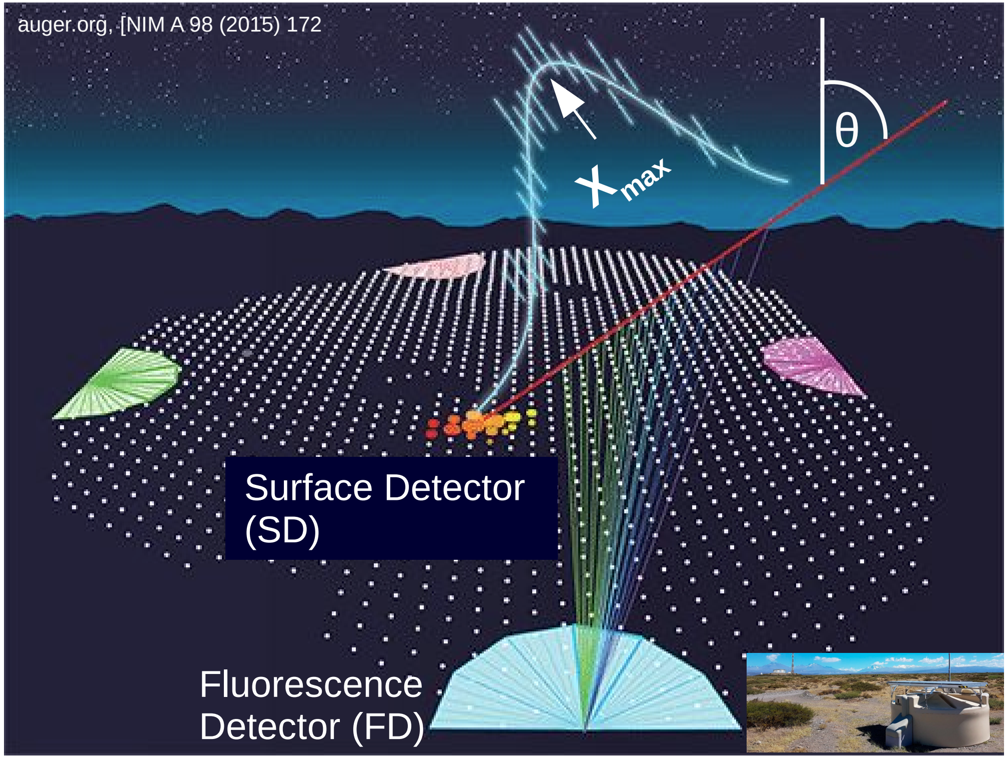
PIERRE AUGER OBSERVATORY

FZU Institute of Physics of the Czech Academy of Sciences

The Pierre Auger Observatory - *the best instrument to study hadronic interactions above √s ≈ 50 TeV*

SD signal

- muon content
  - from buried scintillators, θ<45°
  - from N_{19}, θ>65°
- muon production depth
  - for core distance r > 1500m, θ>65°
- muon energy spectrum
  - from attenuation with θ and r
- rise time of signal vs. r



see details about hadronic interactions in the R. Conceicao's invited review

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
- average shape of longitudinal profiles
- frequency of anomalous showers

The Pierre Auger Observatory - *the best instrument to study hadronic interactions above √s ≈ 50 TeV*

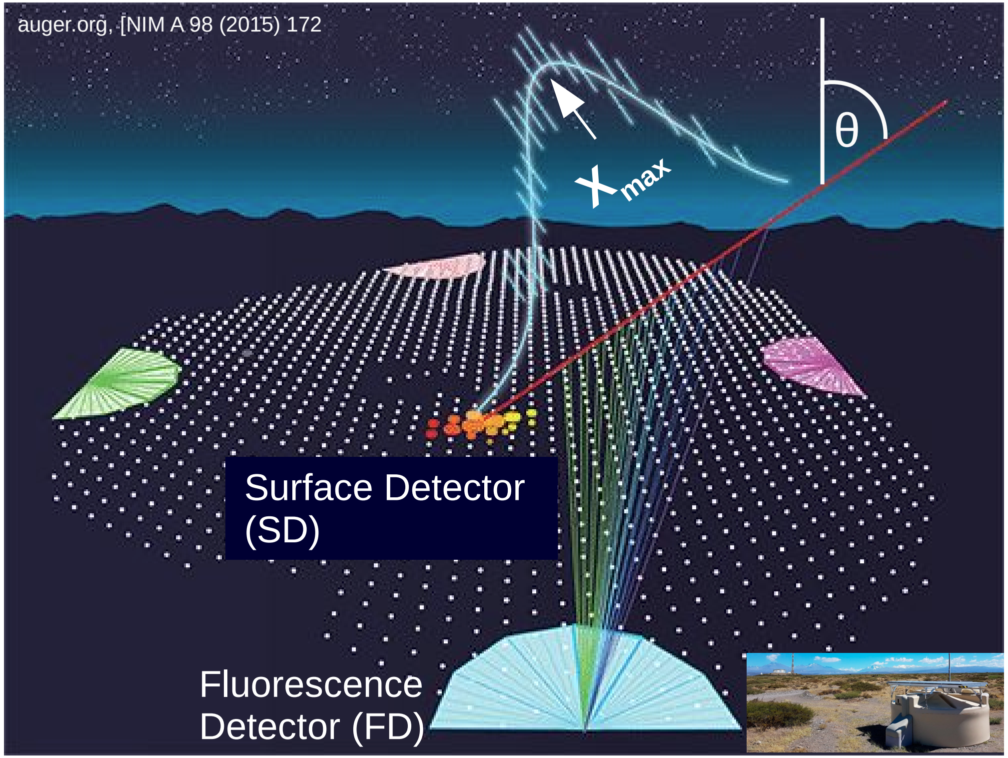
SD signal

- muon content
  - from buried scintillators, θ<45°
  - from N_{19}, θ>65°
- 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
- rise time of signal vs. r

  [Phys. Rev. D 96 (2017) 122003]

+ neutrons in SSDs, see talk of T. Schulz



not covered here, see references

FD longitudinal profile

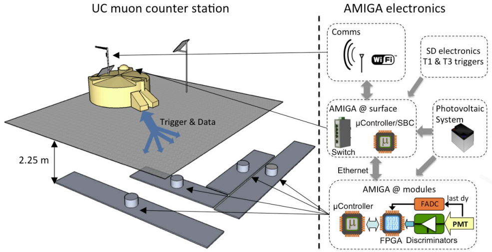
- estimation of primary masses from X_{max} fits
- interpretation of X_{max} moments using ln A
- p-air cross-section from tail of X_{max} distribution
- average shape of longitudinal profiles

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

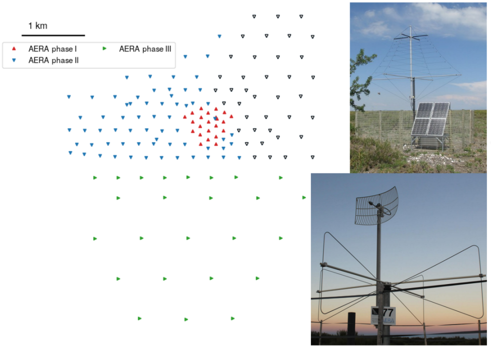
  [EPJ Web of Conferences 144 (2017) 01009]

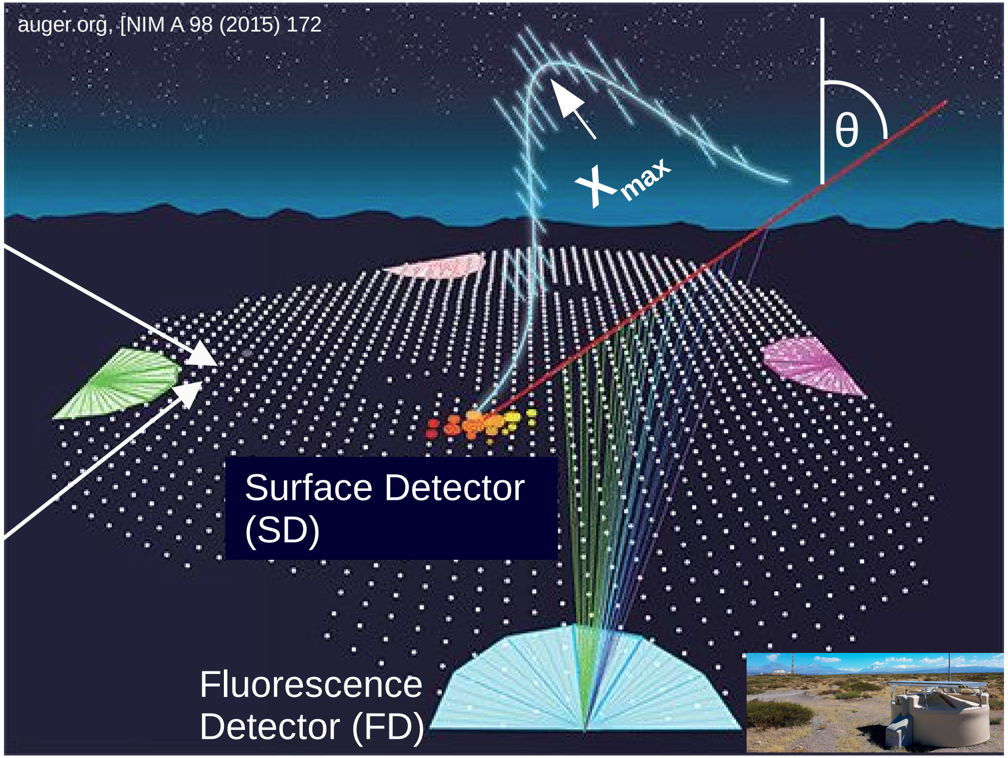
The Pierre Auger Observatory - *the best instrument to study hadronic interactions above √s ≈ 50 TeV*

+ UMD

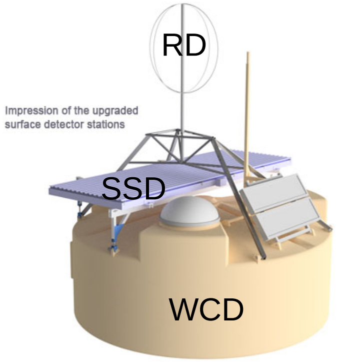


+ AERA





+ AugerPrime



Especially for combination of SD and FD observables !

Observables relevant to hadronic interaction models

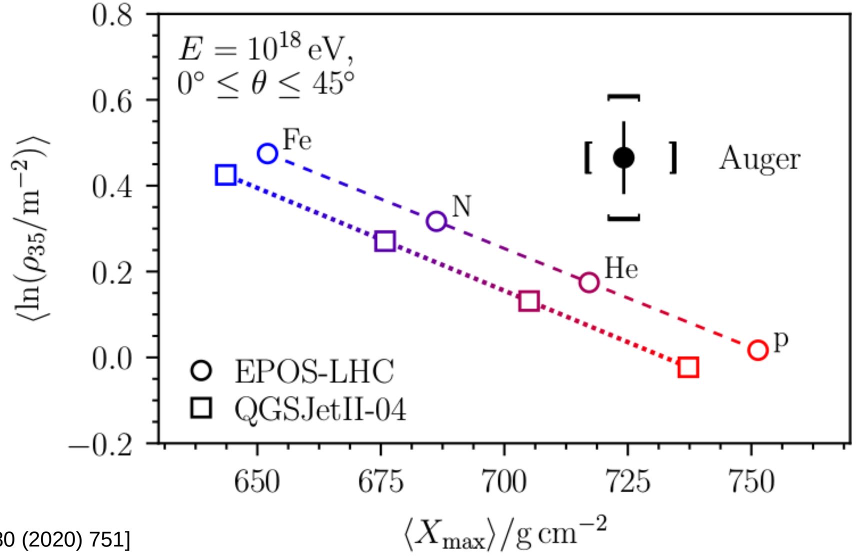
PIERRE AUGER OBSERVATORY

SD signal

- muon content
  - from buried scintillators, θ<45°
  - from N_{19}, θ>65°
- muon production depth
  - for core distance r > 1500m, θ>65°

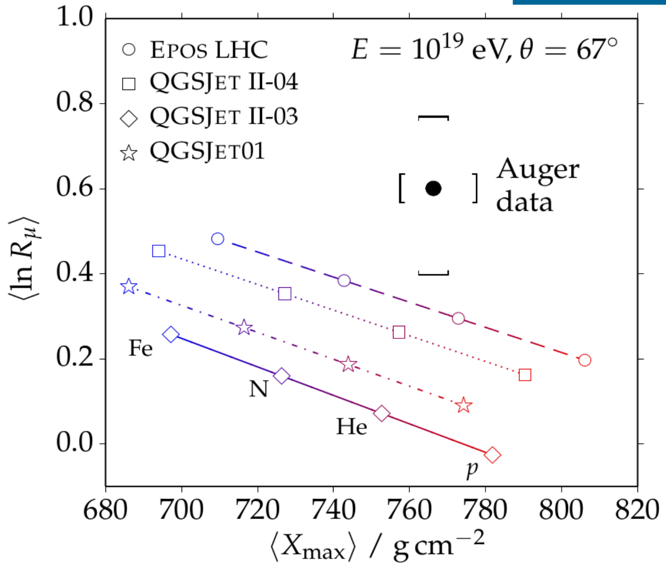
10^{18} eV

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

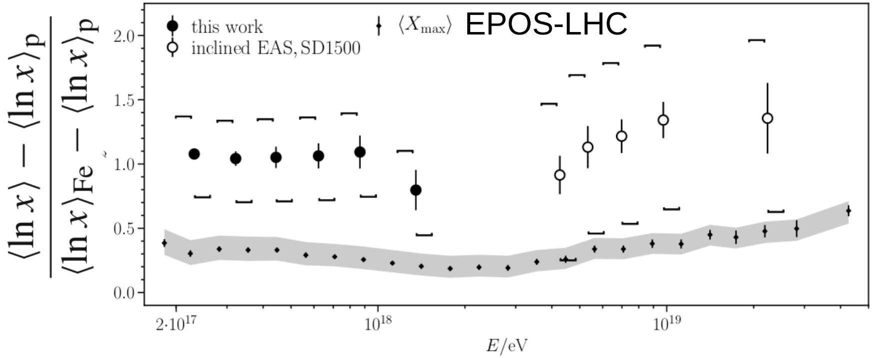


[Phys. Rev. D 91 (2015) 032003]

10^{19} eV



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



- ~2-3σ problem to describe the size of the muon content: **factor ~1.3-1.6** !
- problem seen at various energies and zenith angles

rage shape of
gitudinal profiles

uency of anomalous
wers

Observables relevant to hadronic interaction models

SD signal

- muon content
  - ➔ from buried scintillators, θ<45°
  - ➔ from N_{19}, θ>65°
- muon production depth
  - ➔ for core distance r > 1500m, θ>65°
- muon energy spectrum
  - ➔ from attenuation with θ and r
- rise time of signal vs. r

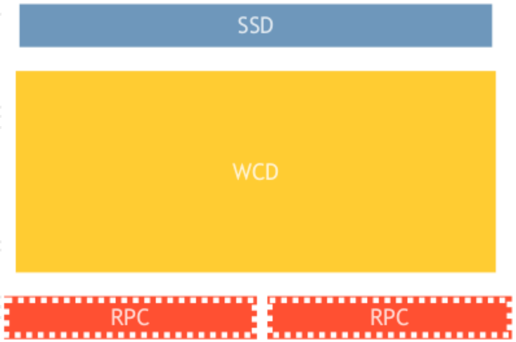
- very hard in general with SD only
- large systematics from energy scale
- multi-detector approach necessary:
  - ➔ SD+FD at different zenith angles
  - ➔ WCD+RPC+SSD+UMD+RD @ AugerPrime

see R. Conceicao's invited review

FD longitudinal profile

- estimation of primary masses from X_{max} fits
- interpretation of X_{max} moments using ln A

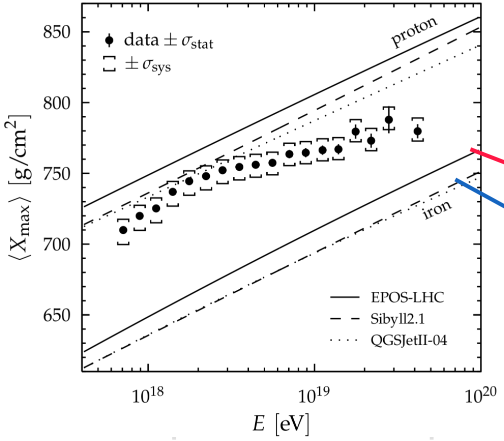
+ Radio Detector



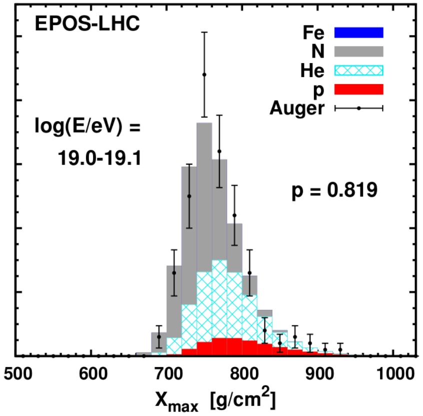
+ Underground Muon Detector

Observables relevant to hadronic interaction models

[Phys. Rev. D 90 (2014) 122005]

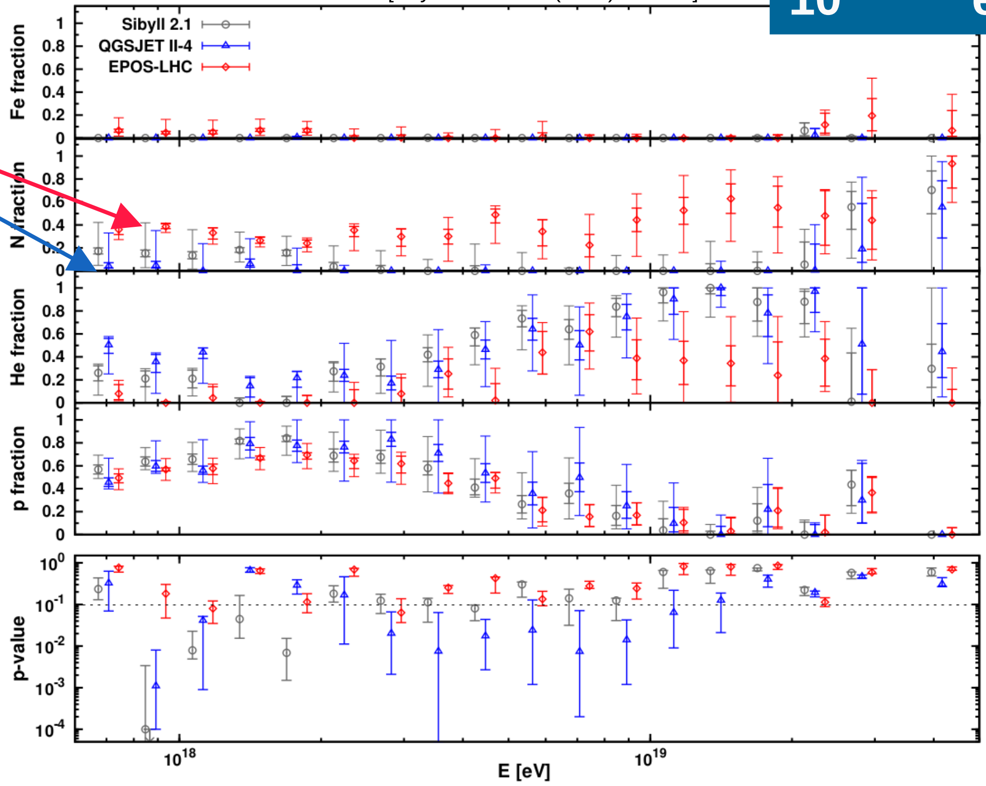


→ for core distance



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

$10^{17.8\text{-}19.6}$ eV



FD longitudinal profile

- estimation of primary masses from X_{max} fits

dependent on MC X_{max} scale
- input into many hadronic interaction studies

- average shape of longitudinal profiles
- frequency of anomalous showers

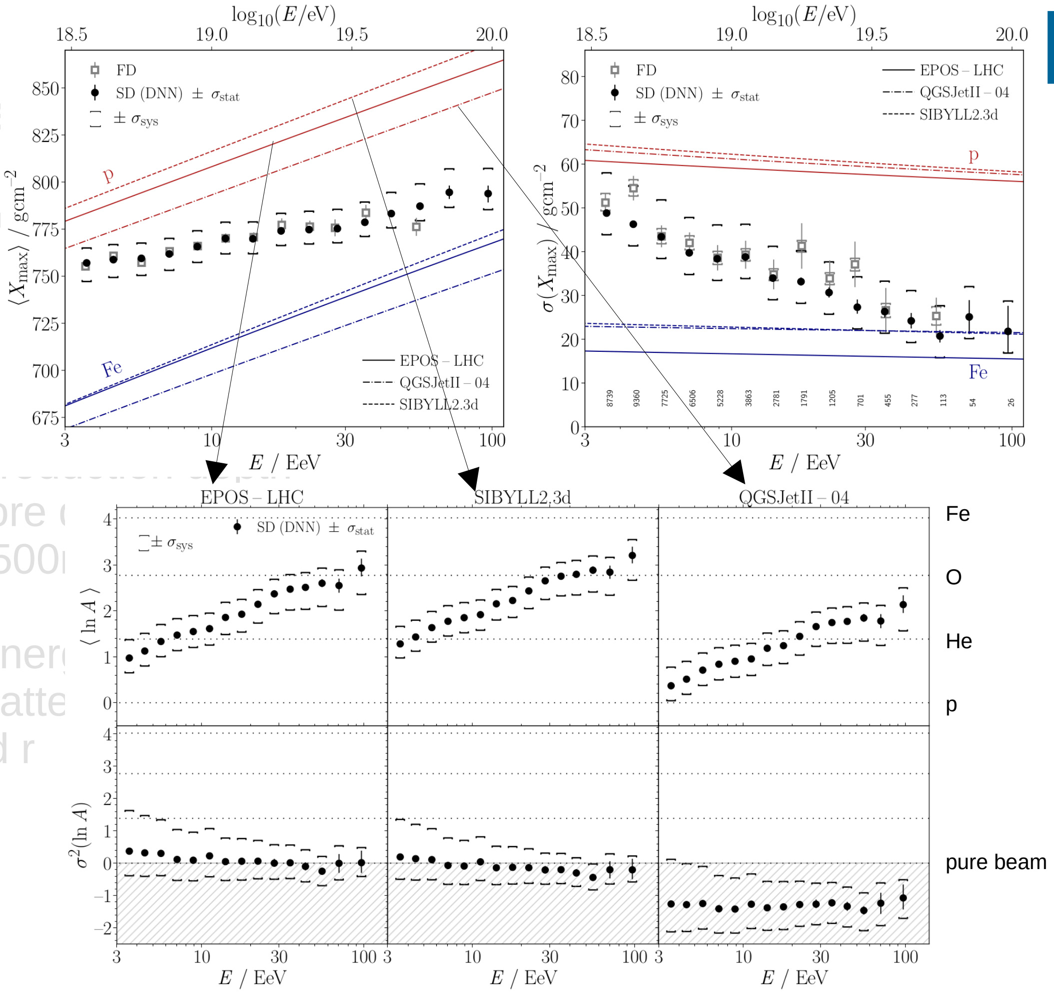
see talk of T. Fitoussi for update

Observables relevant to hadronic interaction models

[accepted in PRD, arXiv:2406.06319]

SD signa

- muon c
  - from
    scinti
  - from
- muon p...
  - for core
    r > 1500
- muon ener
  - from atte
    θ and r



$10^{18.5\text{-}20.0}$ eV

FD longitudinal profile

- estimation of primary masses from X_{max} fits
- interpretation of X_{max} moments using ln A

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

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

[JCAP 02 (2013) 026]

Strong dependance on the MC X_{max} scale

Observables relevant to hadronic interaction models

[accepted in PRD, arXiv:2406.06319]

$10^{18.5\text{-}20.0}$ eV

SD signa

- muon c
  - from
    scinti
  - from
- muon p
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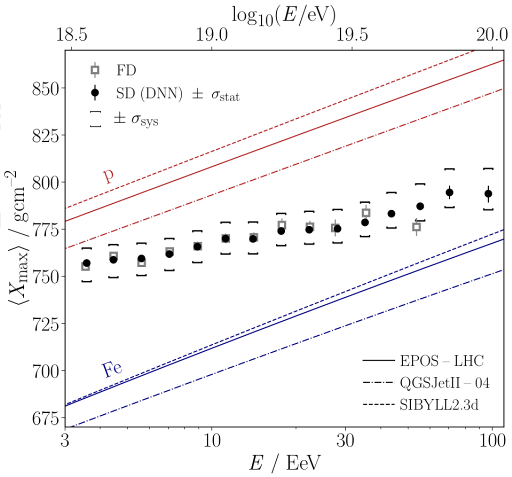
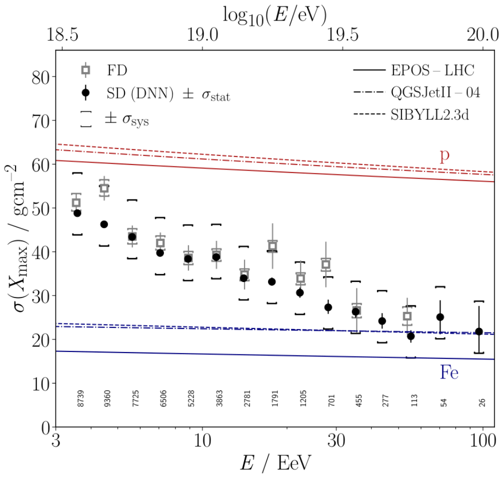
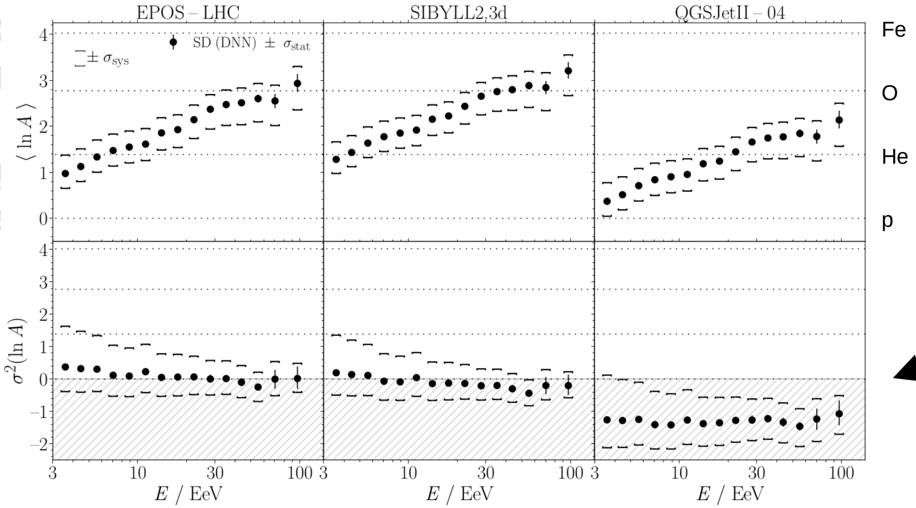
    r > 1500
- muon ener
  - from atte
    θ and r







FD longitudinal profile

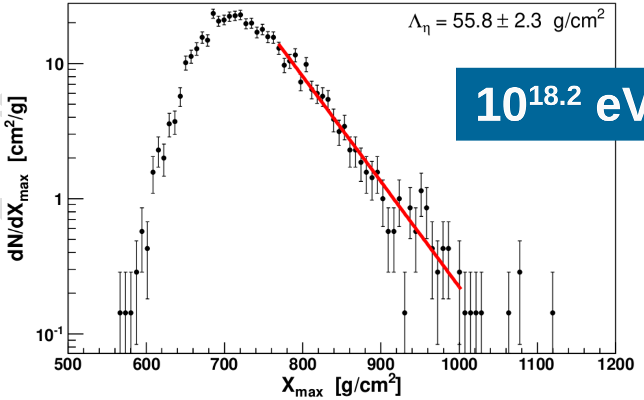
- estimation of primary masses from X_{max} fits
- interpretation of X_{max} moments using ln A
- p-air cross-section from tail of X_{max} distribution

showers

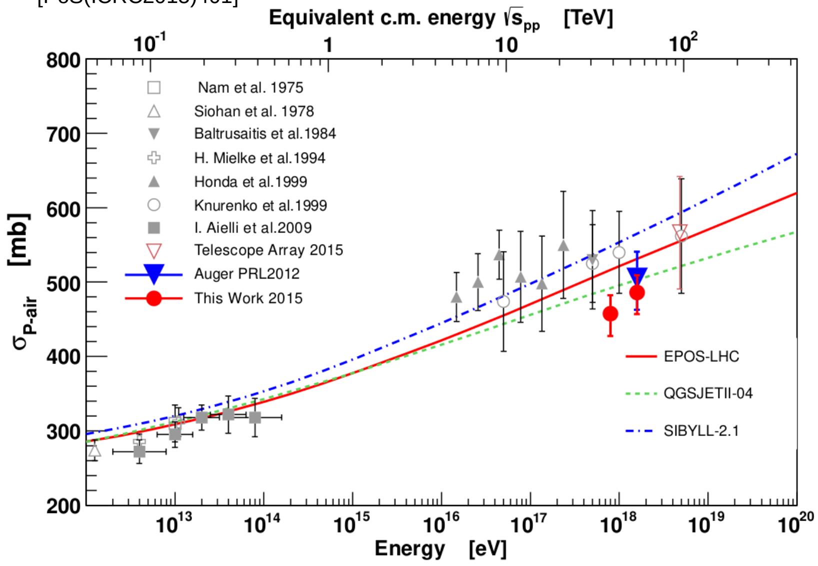
Indication of too shallow predictions of <X_{max}> for all three models !

Observables relevant to hadronic interaction models

[Phys. Rev. Lett. 109 (2012) 062002]

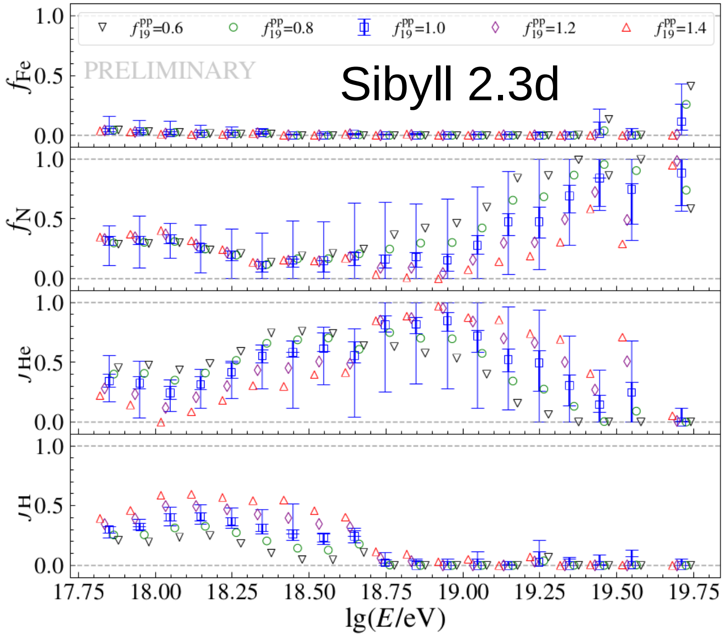


[PoS(ICRC2015)401]

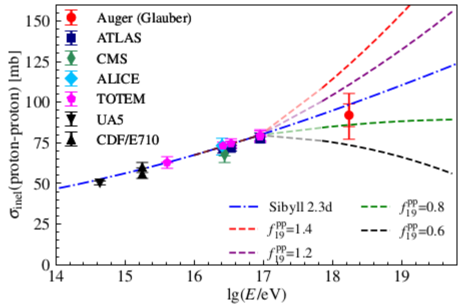


$10^{17.7-19.8}$ eV ?

[PoS(ICRC2023)438]



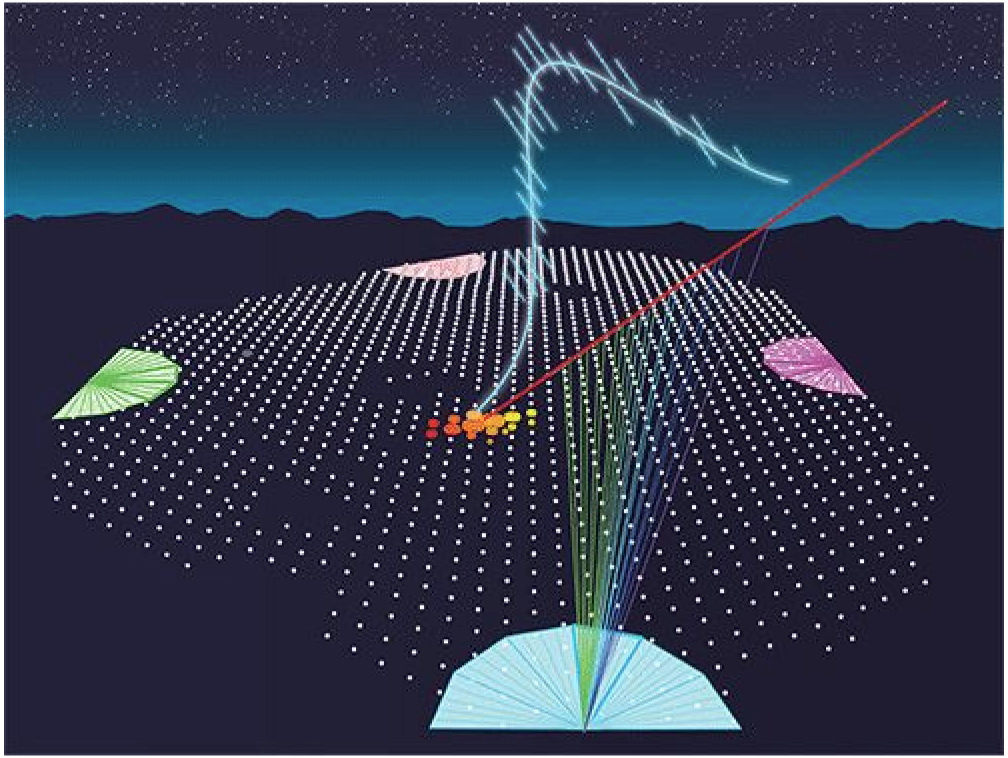
FD longitudinal profile



- p-air cross-section from tail of X_{max} distribution

- p-air cross-section consistent with current models
- new approach: composition+cross-section fit (decrease of systematics from He and X_{max} scale)
  see O. Tkachenko's talk

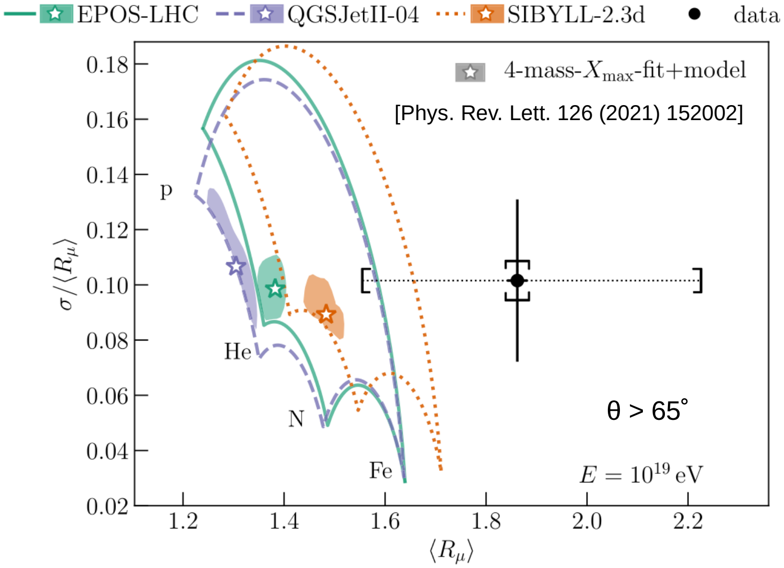
Combining SD and FD observables

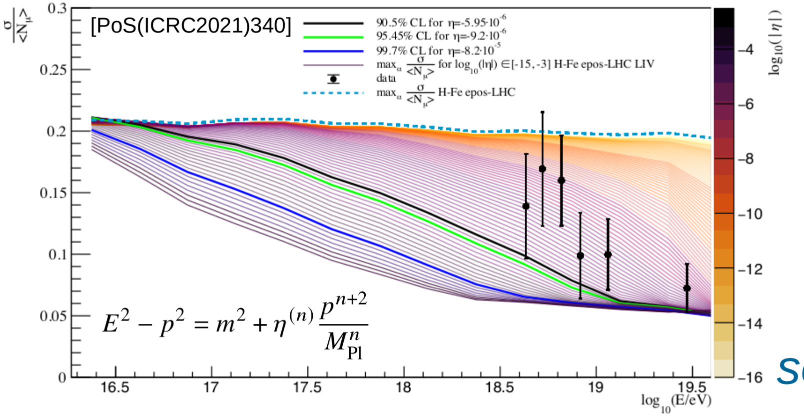


Ground signal + Longitudinal profile

- inclined showers + FD -> $\sigma(N_\mu)$
- 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

- inclined showers + FD -> σ(N_μ)

~$10^{18.6\text{-}19.5}$ eV

- correlation between X_{max} and S(1000)
- top-down approach -> R_{had}

- confirmation of a problem to describe the size of the muon content: **factor ~1.3-1.6**
- muon fluctuations are consistent with data (no obvious problem in the first interaction)

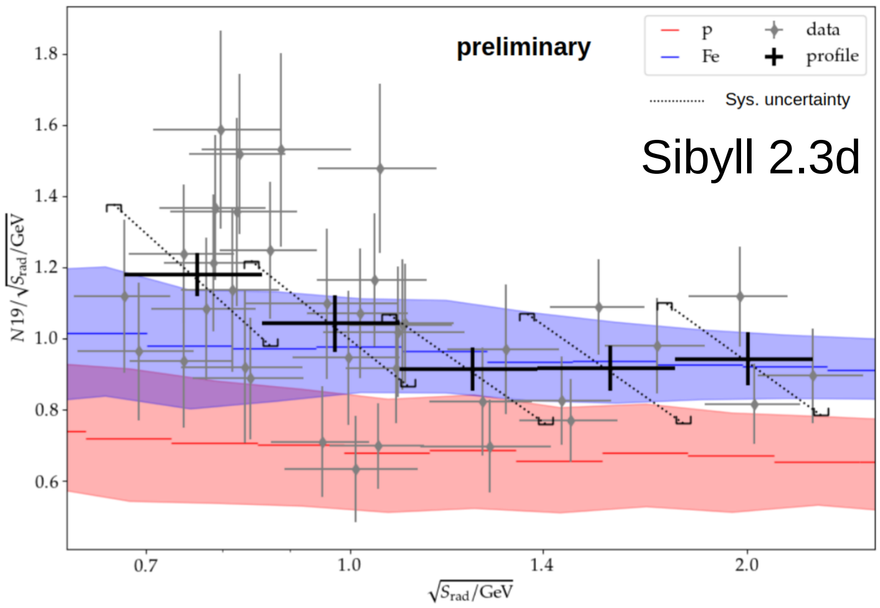
  ➔ Strong constraints on the Lorentz invariance violation

  (journal publication in preparation)

see talk of O. Deligny

Combining SD and FD observables

Ground signal + Longitudinal profile

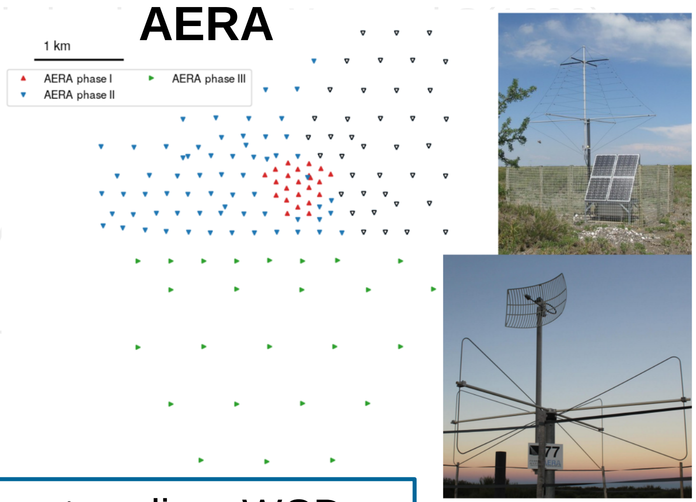


see M. Gottowik's poster

- inclined showers + **RD** ➔ $\langle N_\mu \rangle$

$\sim 10^{18.6\text{-}19.5}$ eV

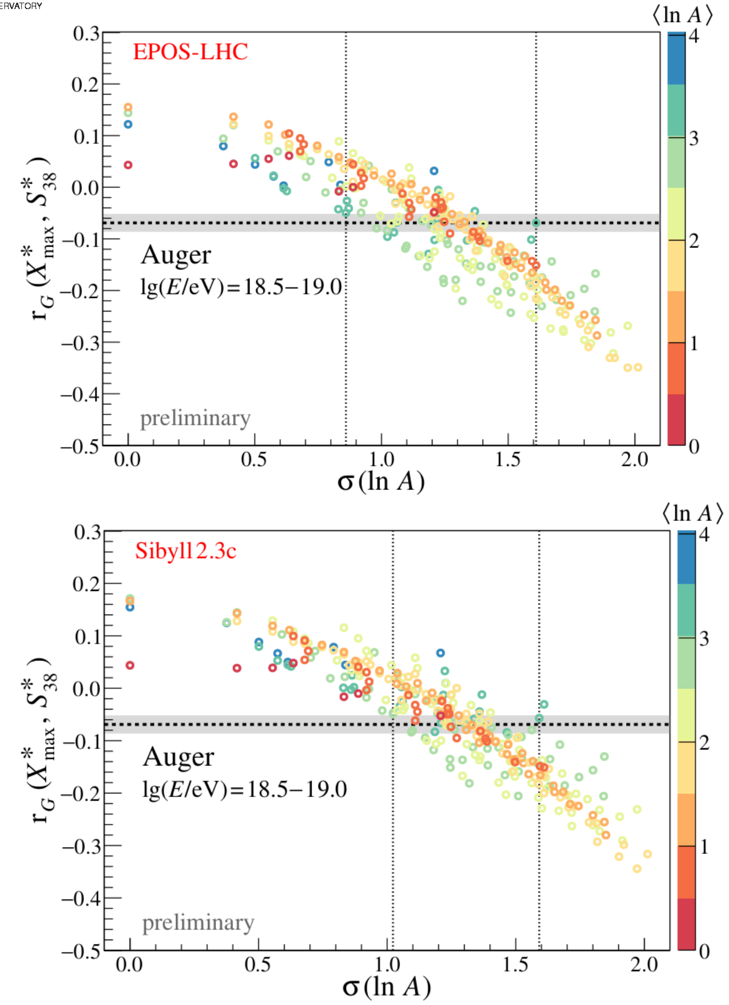
[PoS(ICRC2023)345]



- proof of concept: radio + WCD
- muon scale compatible with previous results
- journal publication in preparation

Combining SD and FD observables

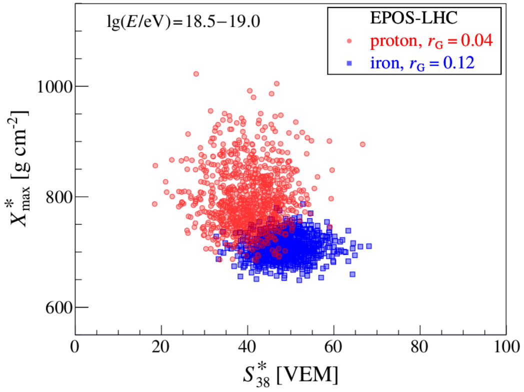
$10^{18.5\text{-}19.0}$ eV



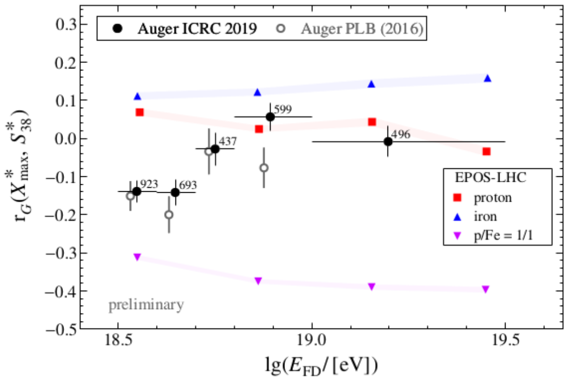
Ground signal + Longitudinal profile

- inclined showers + FD -> $\sigma(N_\mu)$
- correlation between X_{max} and S(1000)

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



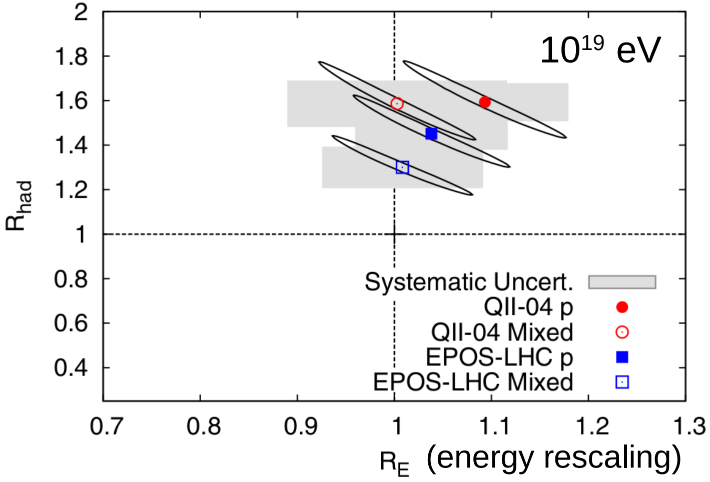
[PoS(ICRC2019)482]



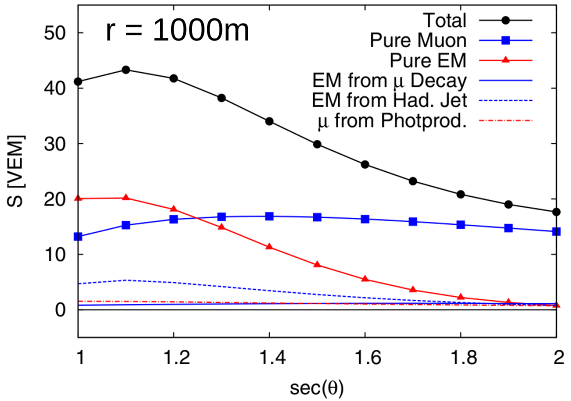
- ~model-independent estimator of spread of beam masses
- >5σ tension with light masses from X_{max} fits for QGSJet II-04 (**too shallow X_{max} scale**)

10^{19} eV

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

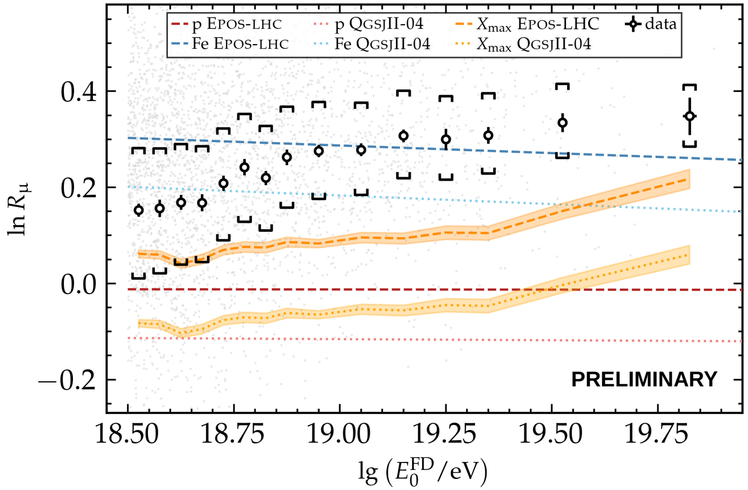
- inclined showers + FD -> $\sigma(N_\mu)$
- correlation between X_{max} and S(1000)
- top-down approach -> R_{had} **~ 1.3 - 1.6 !**

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

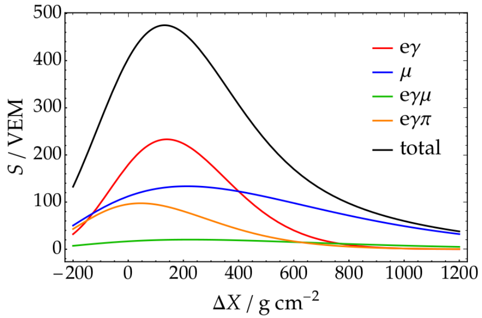
- mass from measured X_{max} - depends on MC X_{max} scale
- ~2-3σ tension with strong dependence on energy scale

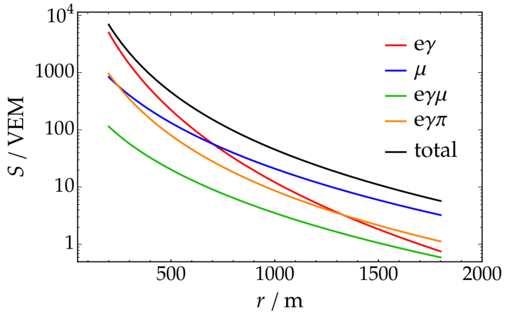
Combining SD and FD observables

shower geometry, energy and X_{max} from FD

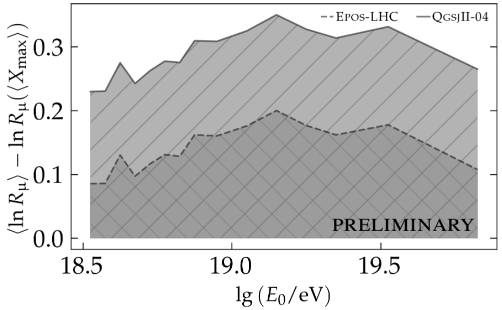


$$S_{tot} \simeq S_{e\gamma} + R_{\mu}\left(S_{\mu} + S_{e\gamma(\mu)} + S_{e\gamma(\pi)}\right)$$





Ground signal + Longitudinal profile



$10^{18.5\text{-}19.8}$ eV

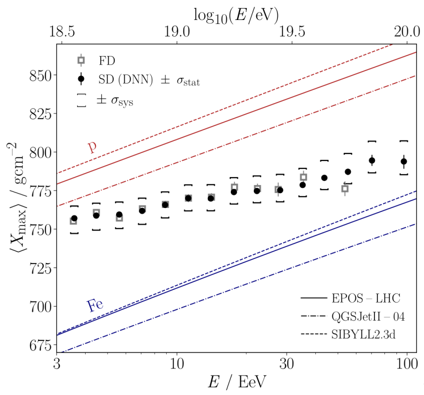
- applying shower-universality approach -> R_{had} **~ 1.1 - 1.3** [PoS(ICRC2023)339, arXiv:2405.03494]

see poster of M. Stadelmaier

- ~2σ tension
- R_{had} smaller than in top-down approach
- ~insensitive to the MC X_{max} scale
- journal publication in preparation

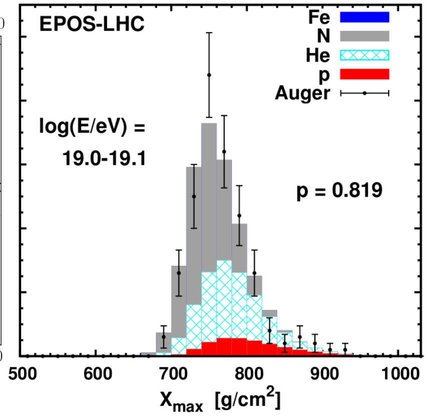
Mass composition & tests of hadronic interactions

[accepted in PRD, arXiv:2406.06319]



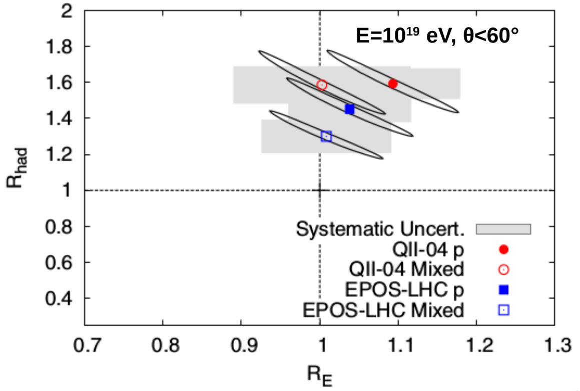
MC X_{max} scale ?

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



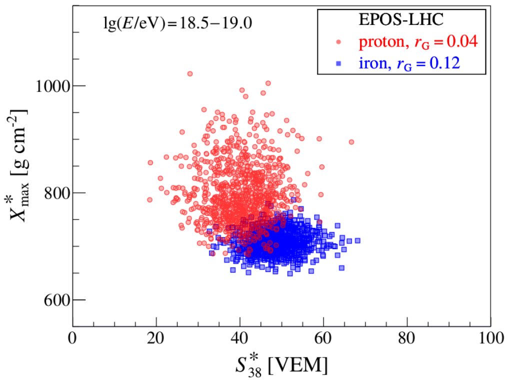
Primary fraction fit

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



Deficit in MC hadronic signal

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



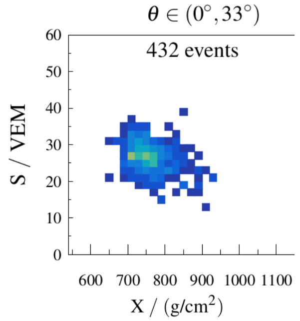
~ model-independent estimation of beam mixing from [X_{max},S(1000)] correlation

MC:

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

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

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

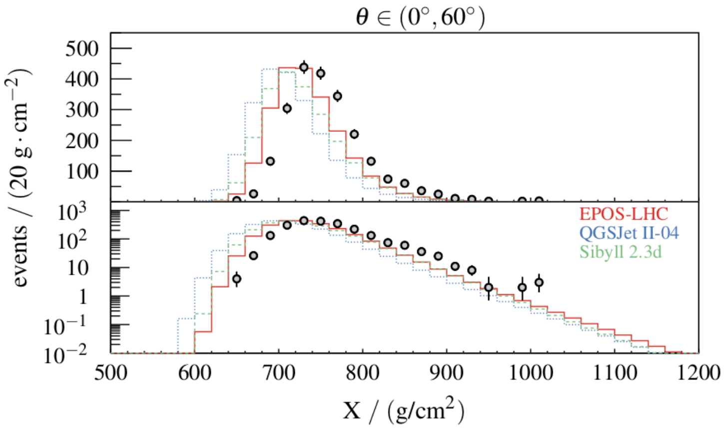


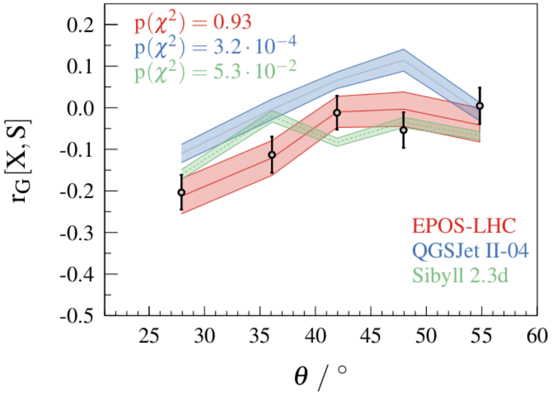
Mass composition fit of observed [X_{max},S(1000)](θ) distributions with free modification of MC predictions **not only of hadronic signal but also of X_{max}**

Improvement in data description

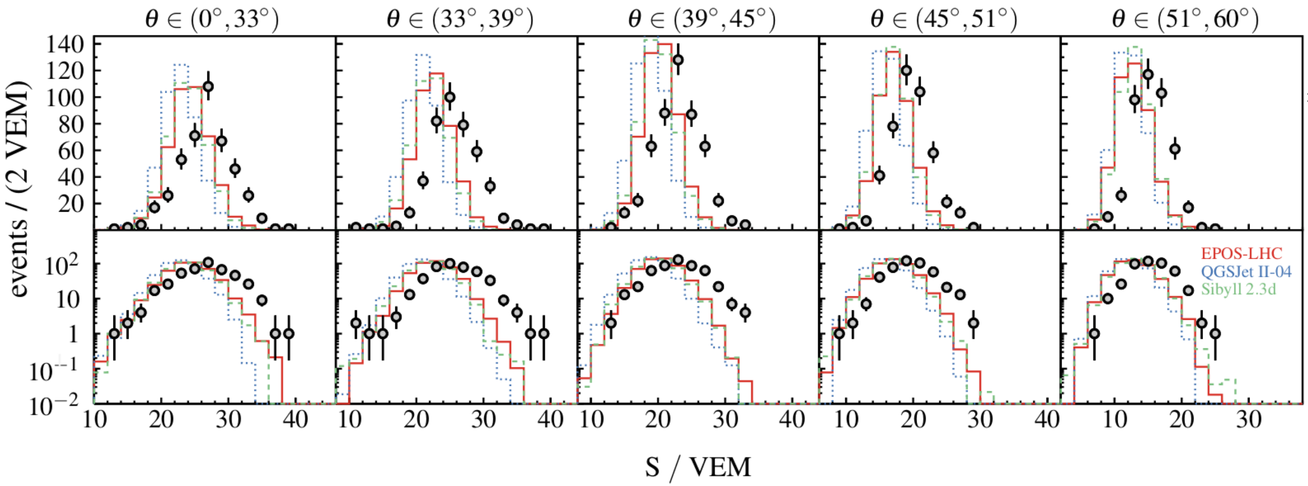
$10^{18.5\text{-}19.0}$ eV

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





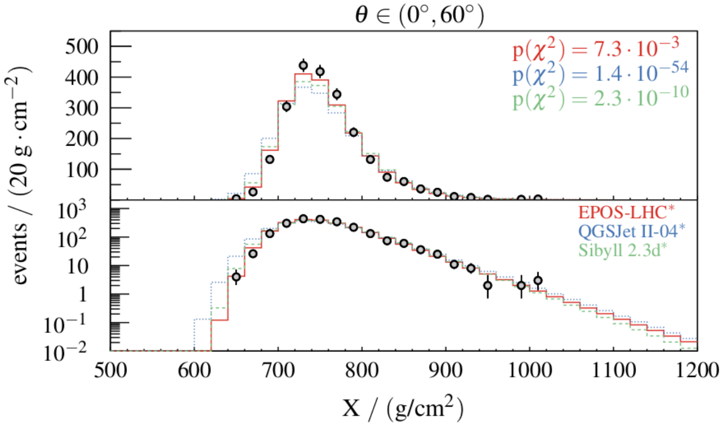
$\ln \mathscr{L}_{min}$	EPOS-LHC	QGSJET-II-04	SIBYLL 2.3d
none	2022.9	4508.0	2496.5
ΔX_{max}	738.6	1674.8	1015.7
R_{had} = const.	489.2	684.4	521.6
$R_{had}(\theta)$	489.2	673.9	517.6
R_{had} = const. and ΔX_{max}	452.2	486.7	454.2
$R_{had}(\theta)$ and ΔX_{max}	451.9	476.3	451.6

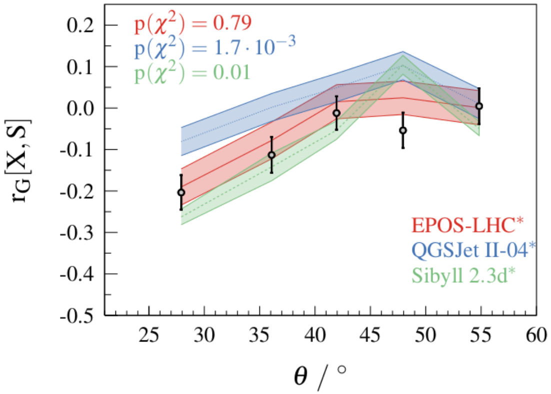


Improvement in data description

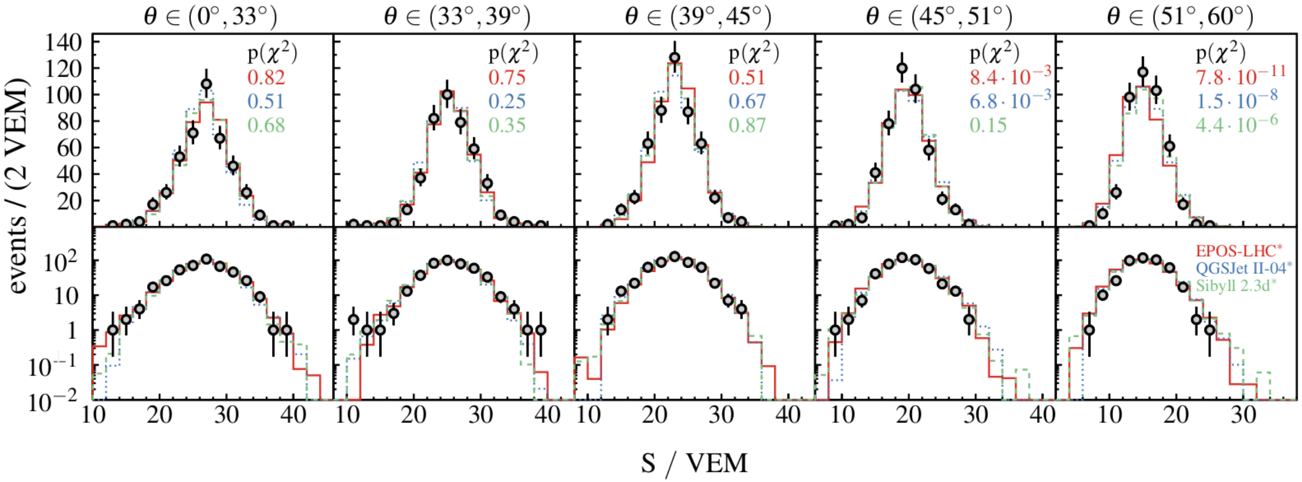
$10^{18.5\text{-}19.0}$ eV

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





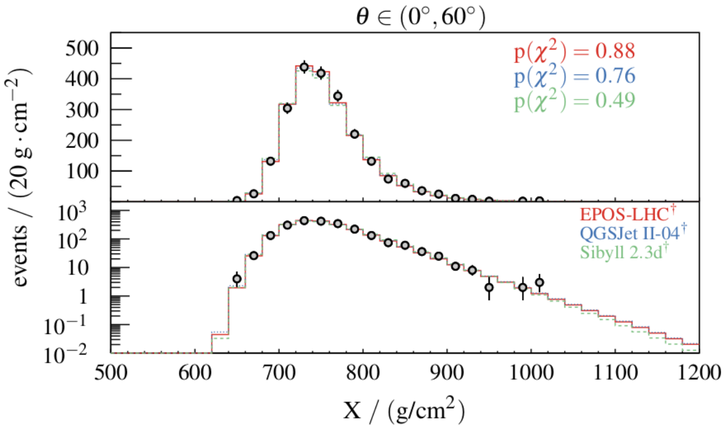
$\ln \mathscr{L}_{min}$	EPOS-LHC	QGSJET-II-04	SIBYLL 2.3d
none	2022.9	4508.0	2496.5
ΔX_{max}	738.6	1674.8	1015.7
$R_{had} = $ const.	489.2	684.4	521.6
$R_{had}(\theta)$	489.2	673.9	517.6
$R_{had} = $ const. and ΔX_{max}	452.2	486.7	454.2
$R_{had}(\theta)$ and ΔX_{max}	451.9	476.3	451.6

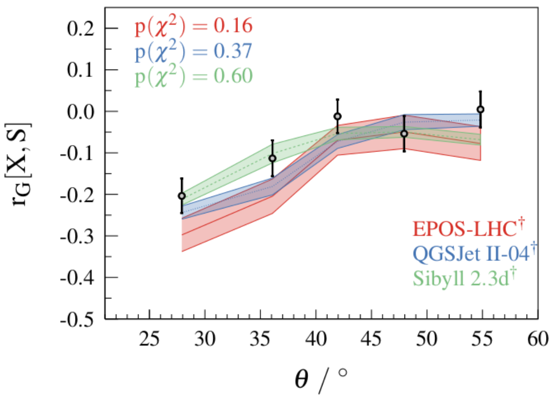


Improvement in data description

$10^{18.5\text{-}19.0}$ eV

[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
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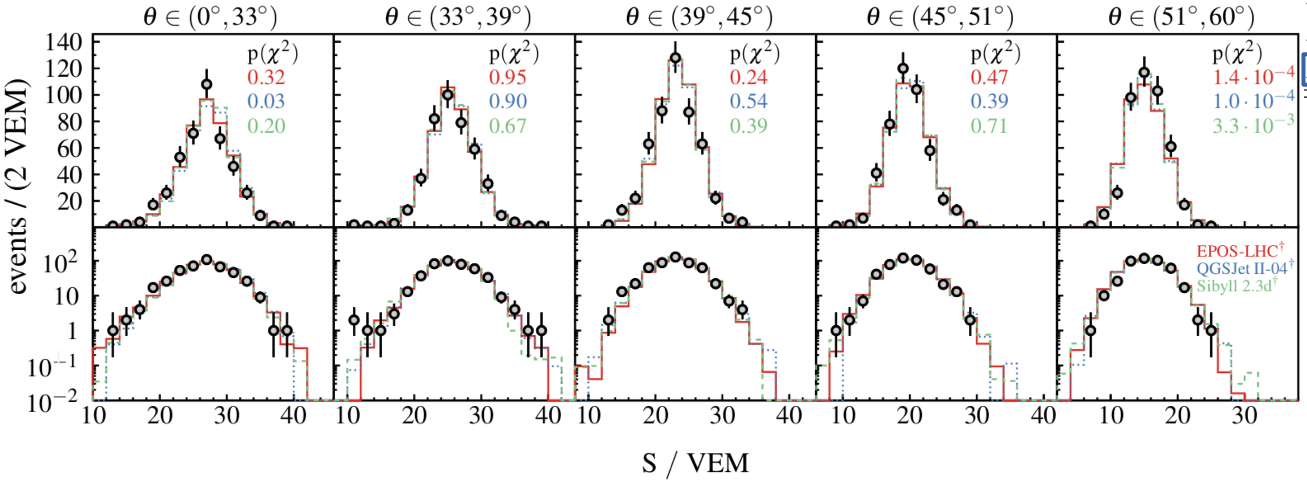


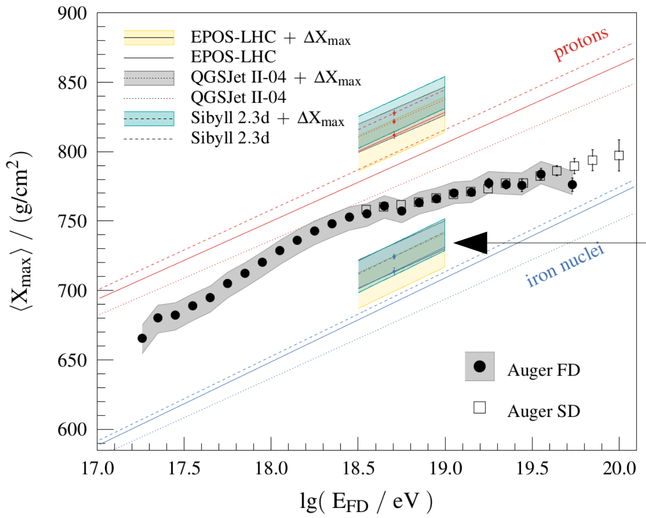
Significant improvement >5σ using R_{had} and ΔX_{max} (Likelihood ratio tests for nested model using Wilks‘ theorem)

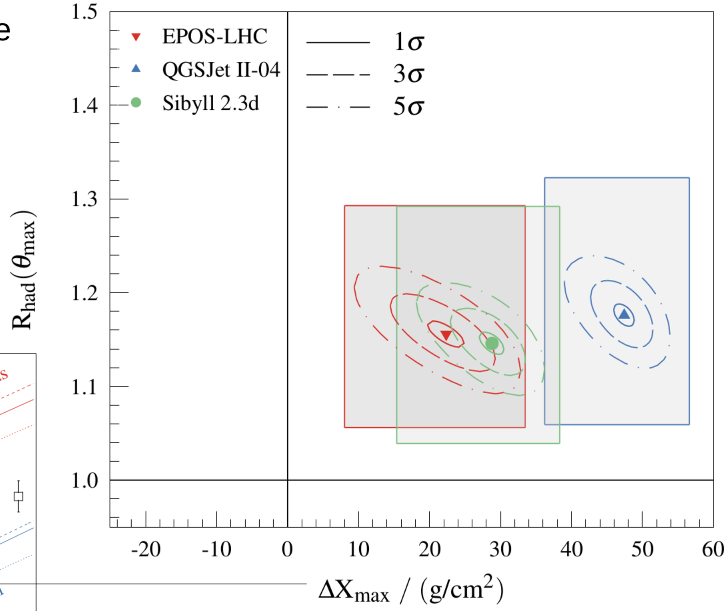
10^18.5-19.0 eV

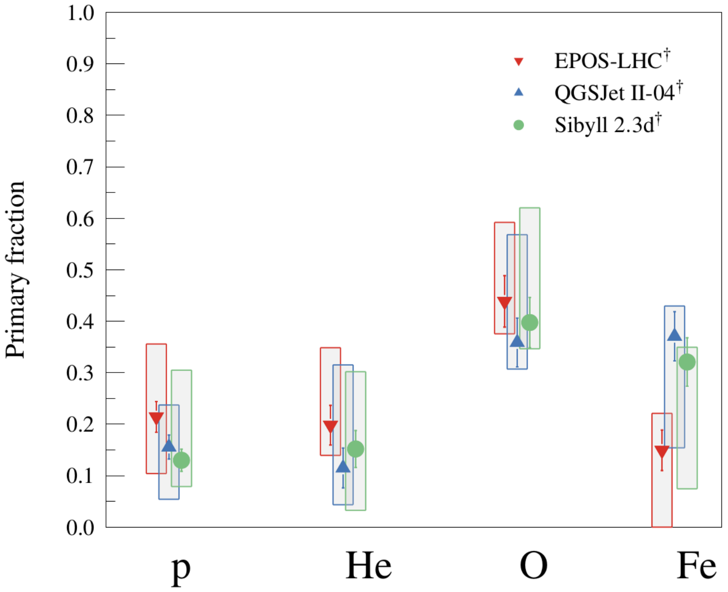
Fitted parameters

[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°)





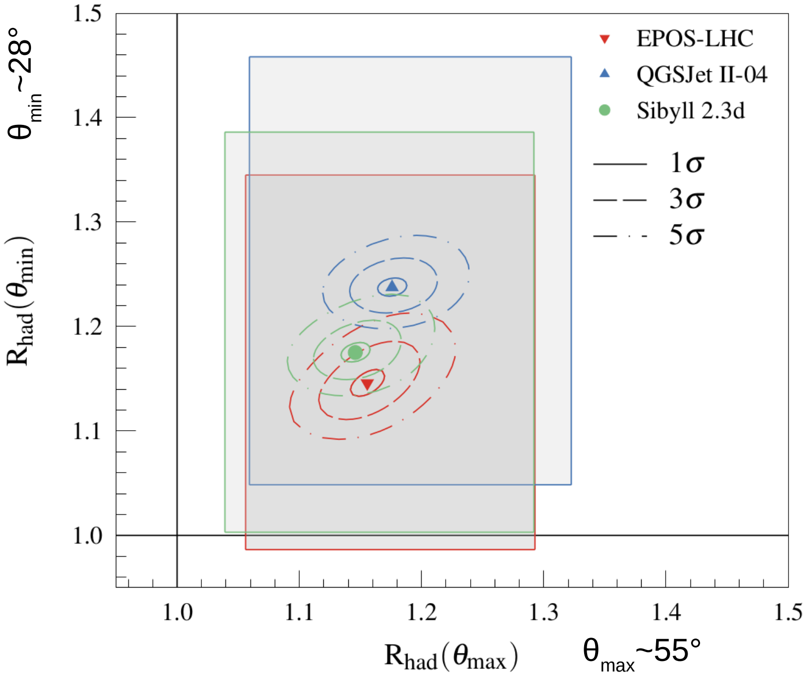


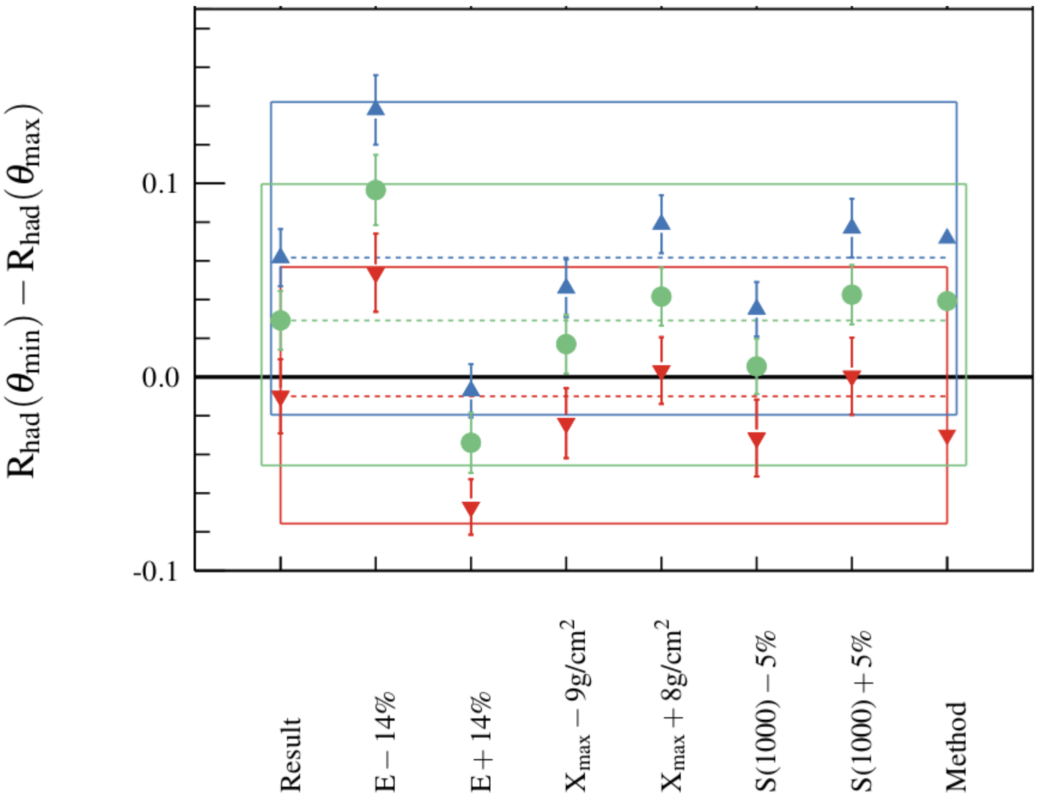
- **deeper X_{max} predictions for all models !**
- alleviated “muon problem“ to ~15-25%
- smaller model differences in mass composition

Attenuation of hadronic signal with zenith angle

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

$10^{18.5\text{-}19.0}$ eV



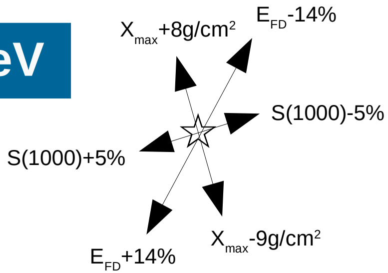


indication of harder muon spectra in QGSJet II-04 than in data

Scanning in combinations of experimental systematics

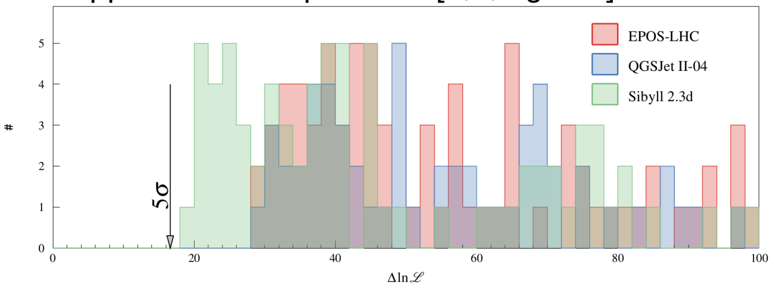
[Phys. Rev. D 109 (2024) 102001]

$10^{18.5\text{-}19.0}$ eV

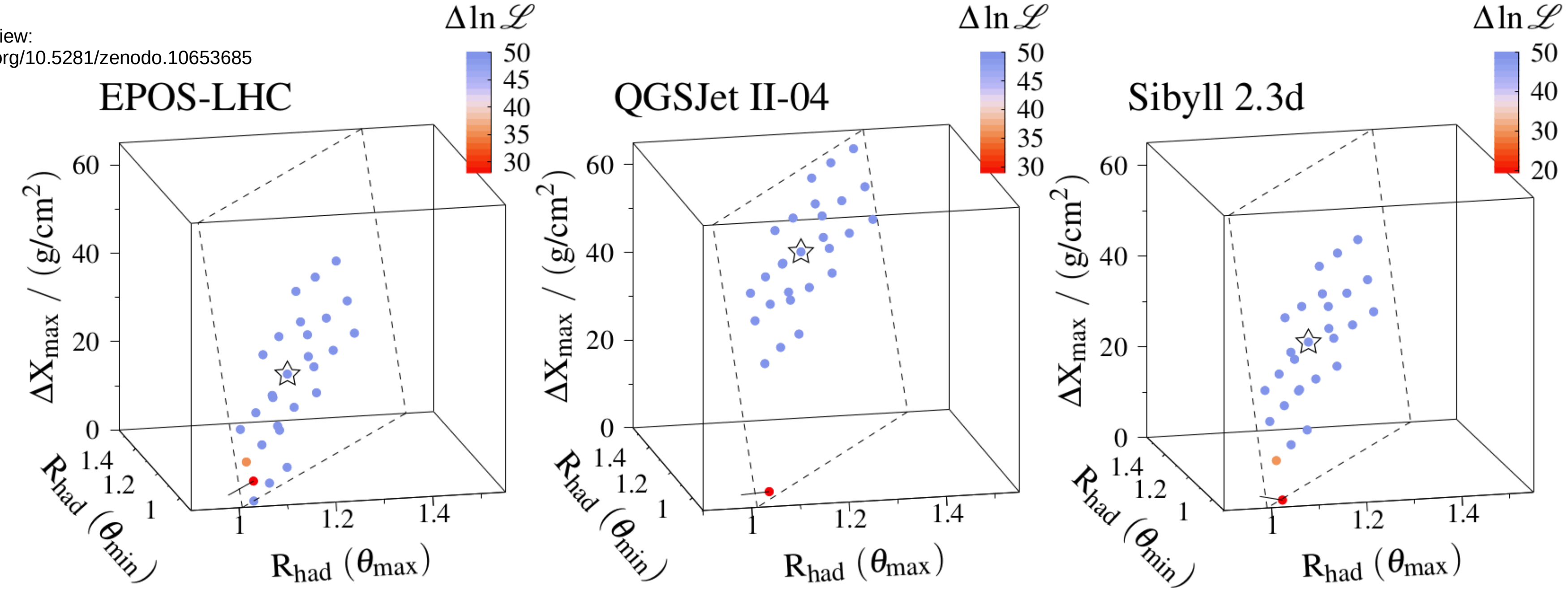


Significance of improvement of data description always above 5σ

Denser scan in the region of the closest approach of the plane to [1,1,0 g/cm^2]



Animated view:
https://doi.org/10.5281/zenodo.10653685



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)] fits	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 !

Summary on tests of models of hadronic interactions

- Indications of a problem to describe Auger data by models in many analyses

  ➔ combinations of measurements of different shower components are powerful tests of models

- Current models of hadronic interactions are proven to fail to describe combined FD+SD data at 3-10 EeV with **more than 5σ** !
  - possible underestimation of experimental systematics ruled out
  - possibility of a heavier mass composition should be considered

  ➔ alleviation of the “muon problem“ but start of the “X_{max} problem“

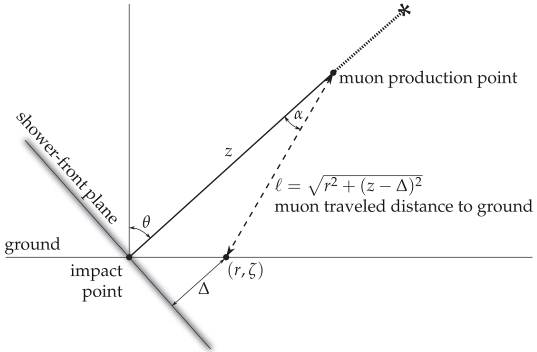
- **New models** of hadronic interactions (EPOS 4(LHCR), QGSJet III, Sibyll*, Pythia 8, ...) and **new air-shower generator** (CORSIKA 8) are approaching
- **AugerPrime** (2024-2035) will be the best cosmic-ray testing facility for hadronic interactions at √s ~ 10-200 TeV
- And new methods (Machine Learning) and more data ... Stay tuned !

Backup slides

Observables relevant to hadronic interaction models

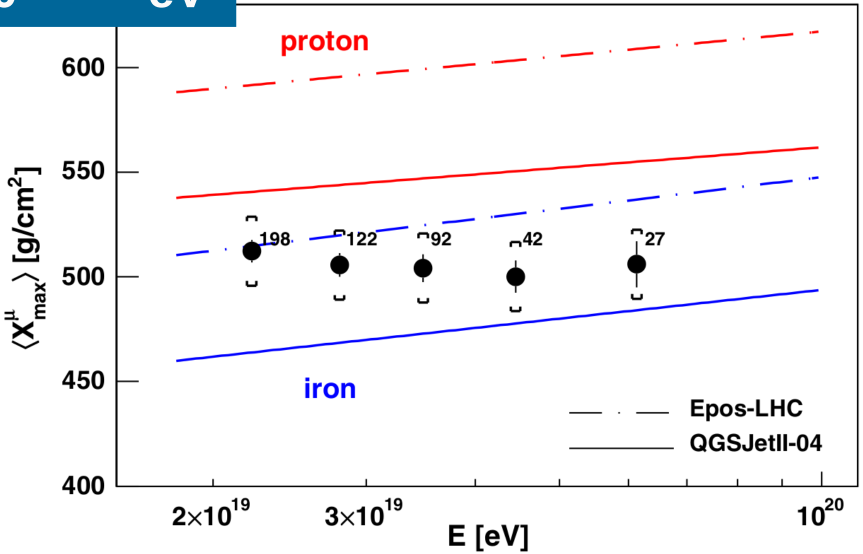
SD signal

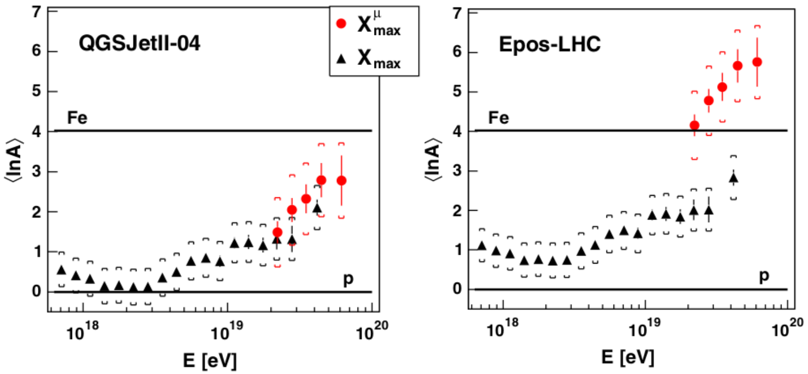
- muon content
  - from buried scintillators, θ<60°
  - from N_{19}, θ>65°
- muon production depth
  - for core distance r > 1500m, θ>65°



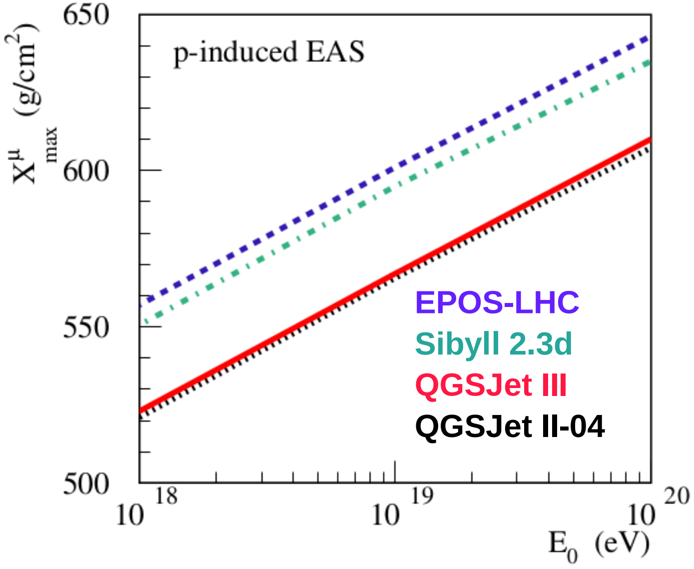
$10^{19.3\text{-}19.8}$ eV

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





[Phys. Rev. D 109 (2024) 094019]



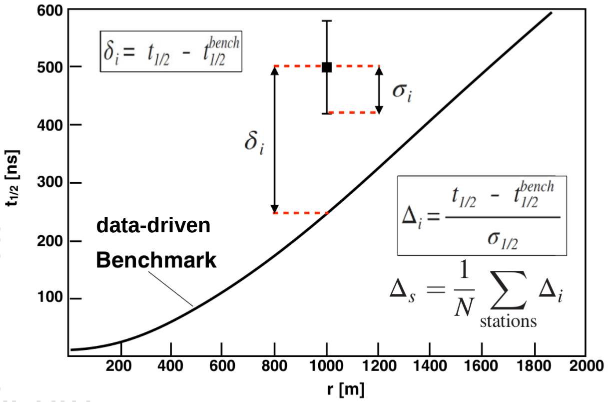
- EPOS-LHC and (likely also) Sibyll 2.3d too deep ~2σ
- MPD tunable by pion diffraction (loosely constrained by current accelerators data)

Observables relevant to hadronic interaction models

[Phys. Rev. D 96 (2017) 122003]

SD signal

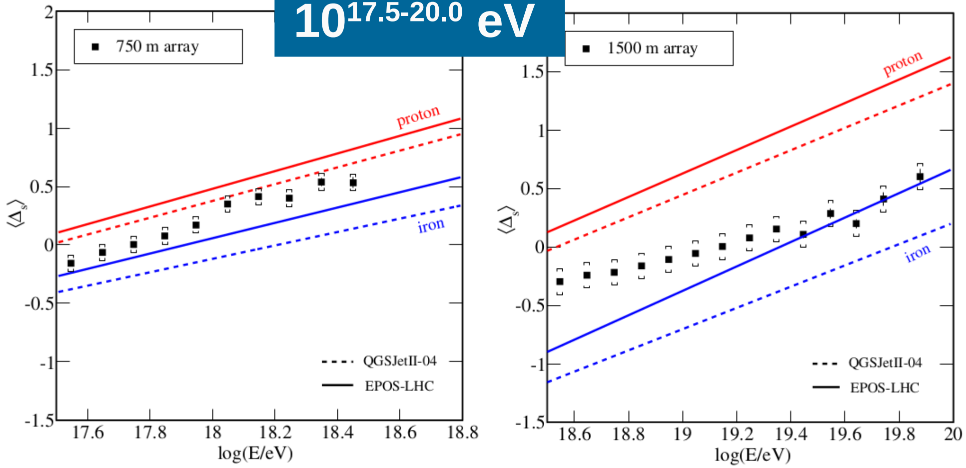
- muon content
  - from buried scintillators, θ<6
  - from N_{19}, θ>65°
- muon production depth
  - for core distance r > 1500m, θ>65°
- muon energy spectru
  - from attenuation w θ and r
- rise time of signal vs. r

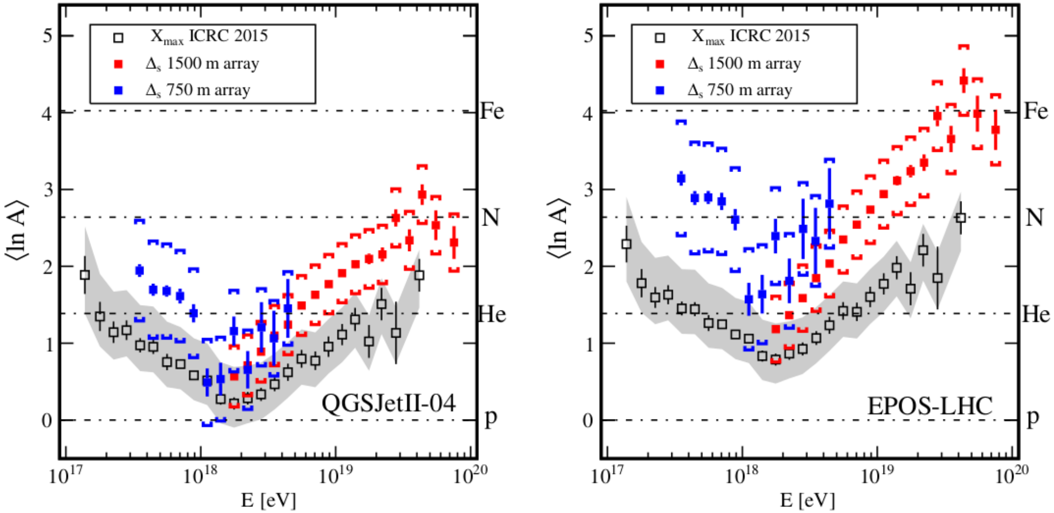


$$\langle \ln A \rangle = \ln 56 \frac{\langle \Delta_s \rangle_p - \langle \Delta_s \rangle_{data}}{\langle \Delta_s \rangle_p - \langle \Delta_s \rangle_{Fe}}$$

~1-2σ inconsistent interpretation of <ln A> between Δ_s and X_{max}

$10^{17.5\text{-}20.0}$ eV





Observables relevant to hadronic interaction models

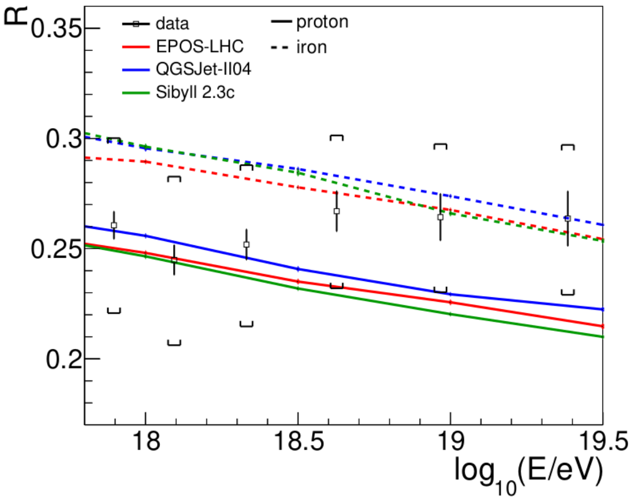
[JCAP 03 (2019) 018]

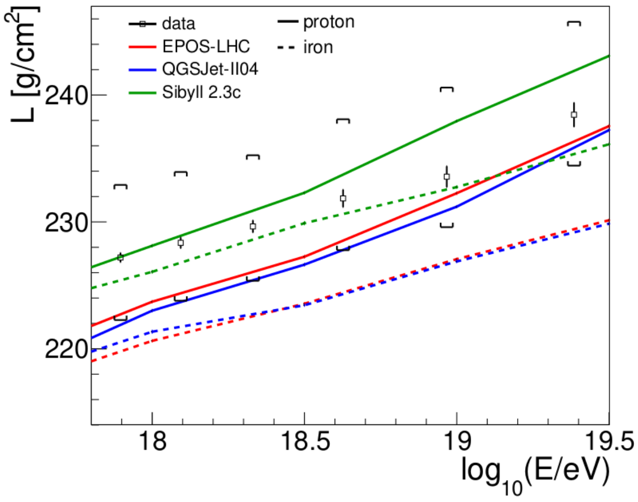
$10^{17.8\text{-}19.5}$ eV

FD longitudinal profile

$$f_{\mathrm{GH}}(X) = (\mathrm{d}E/\mathrm{d}X)_{\max} \left(\frac{X - X_0}{X_{\max} - X_0}\right)^{\frac{X_{\max}-X_0}{\lambda}} \exp\left(\frac{X_{\max} - X}{\lambda}\right)$$

$$(\mathrm{d}E/\mathrm{d}X)' = \left(1 + R\,\frac{X'}{L}\right)^{R^{-2}} \exp\left(-\frac{X'}{R\,L}\right)$$





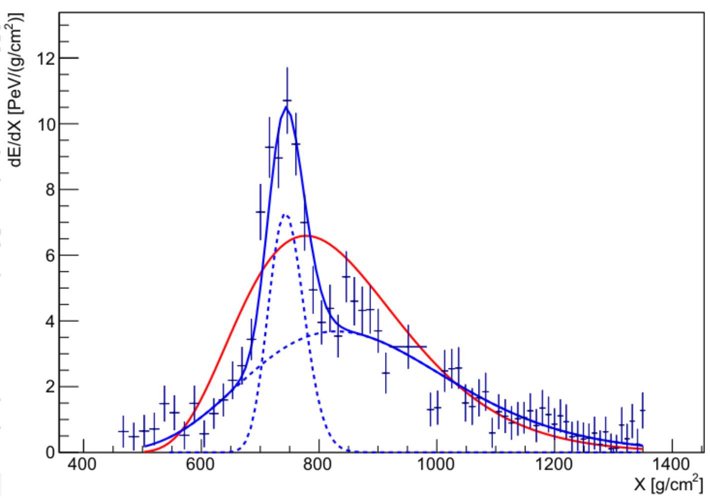
- so far consistent within ~2σ with models
- smaller systematics on aerosol measurement could improve constraints

- average shape of longitudinal profiles

Observables relevant to hadronic interaction models

[EPJ Web Conf. 144 (2017) 01009]

FD profile

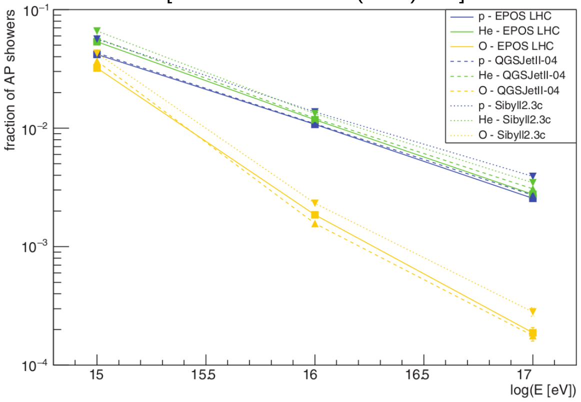


$10^{17.2\text{-}18.5}$ eV ?

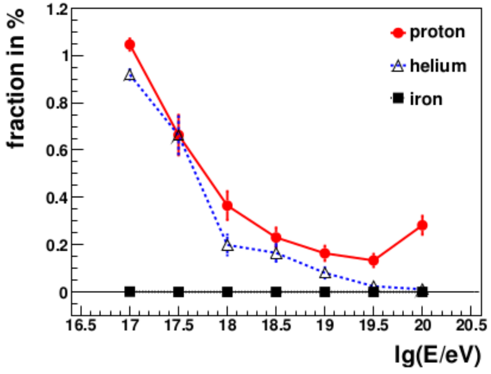
FD longitudinal profile

- ‰ effect at 10^{18} eV, % effect at 10^{16} eV
- hard to reject presence of clouds
  ➔ additional cloud measurement is needed
- possible constraints on presence of lightest primaries (and cross-section/elasticity)
- no application to the data yet

[Astron. Nachr. 340 (2019) 234]



[arXiv:1111.0504]

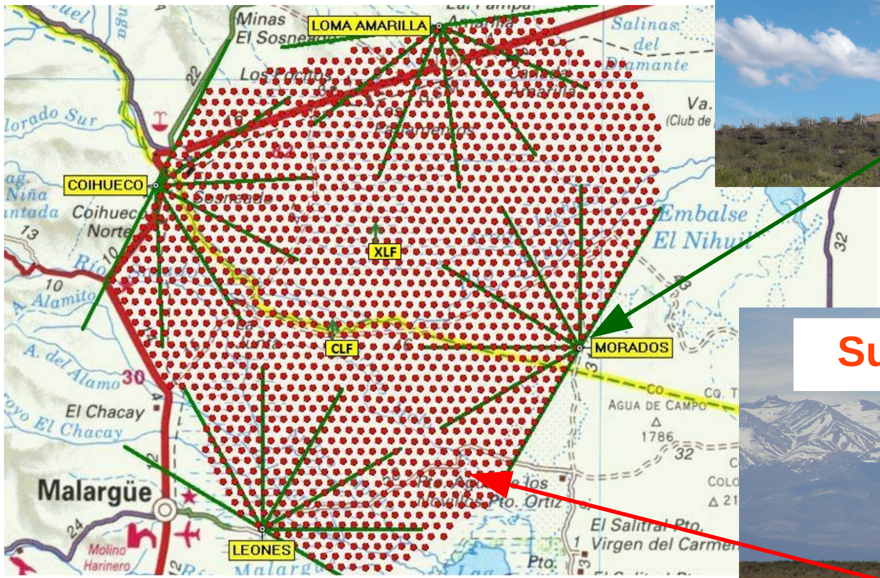


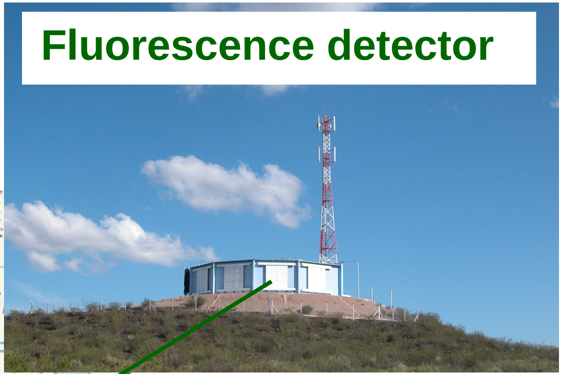
- frequency of anomalous showers

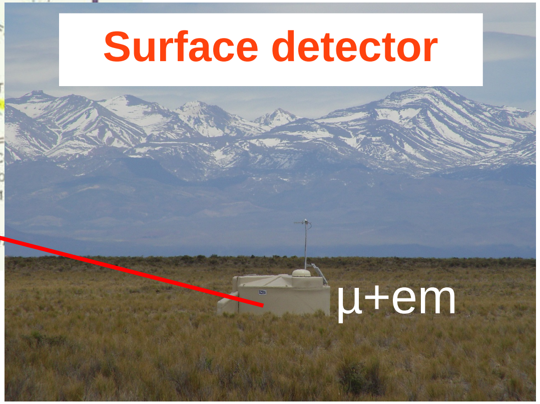
[EPJ Web of Conferences 144 (2017) 01009]

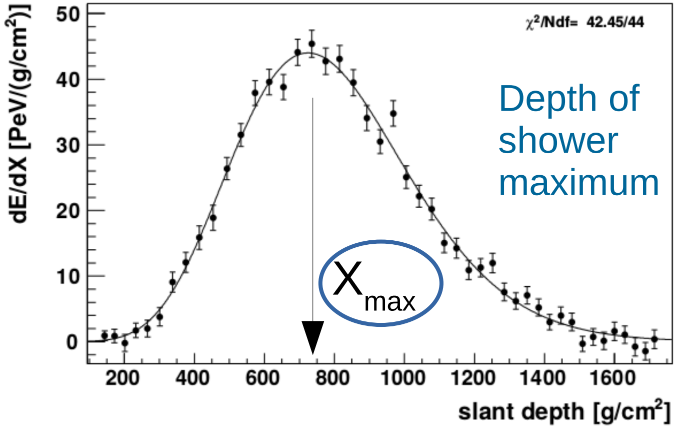
Hybrid detection at the Pierre Auger Observatory

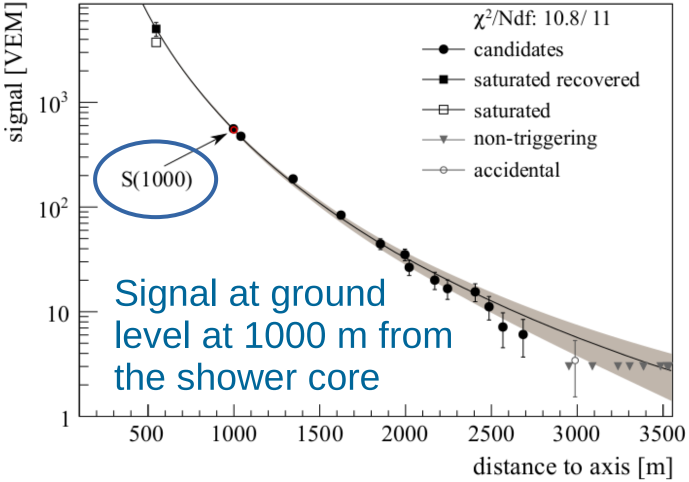
[Nucl. Instrum. Meth. A 798 (2015) 172]









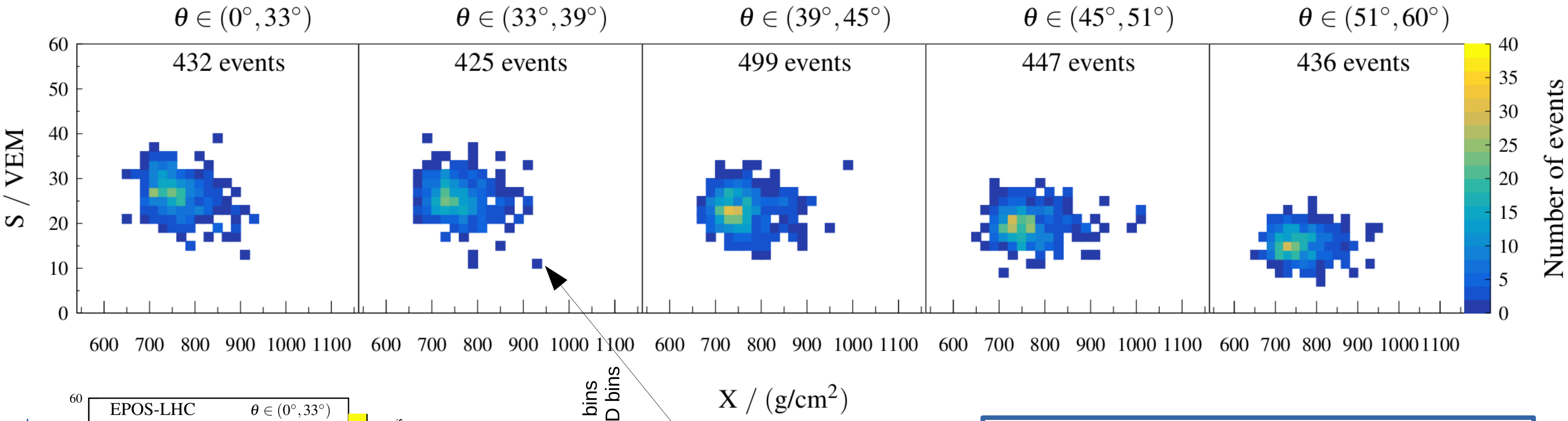


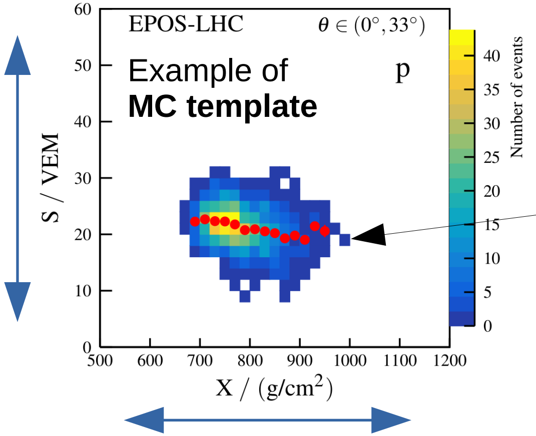
Auger data:
2239 HQ events for $10^{18.5\text{-}19.0}$ eV

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)

Motivations for modifications of MC predictions

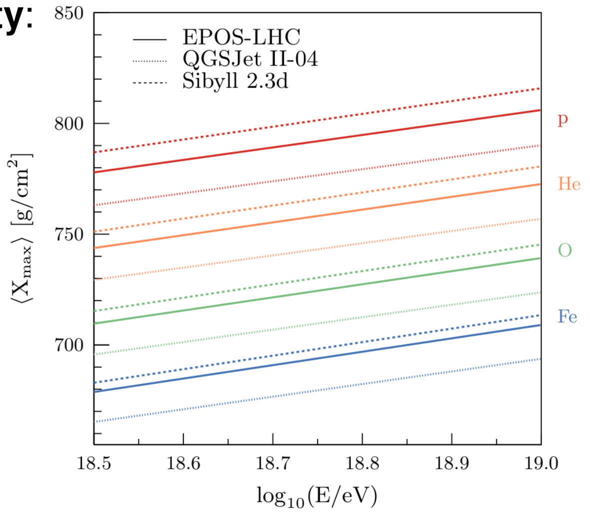
- Properties of **4-component shower universality**:

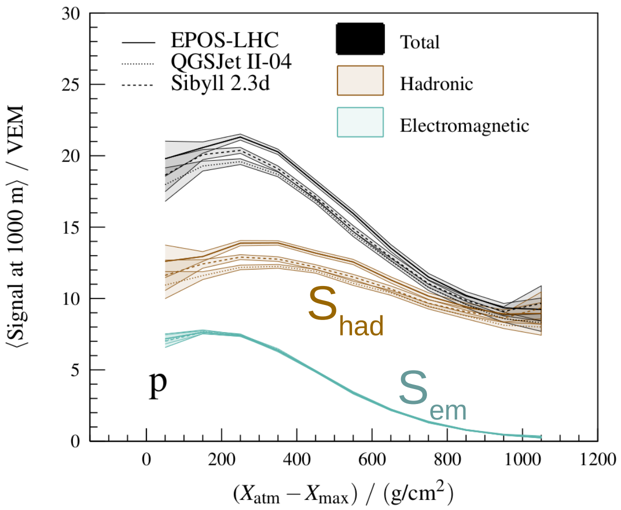
  [Astropart. Phys. 87 (2017) 23, Astropart. Phys. 88 (2017) 46]

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





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

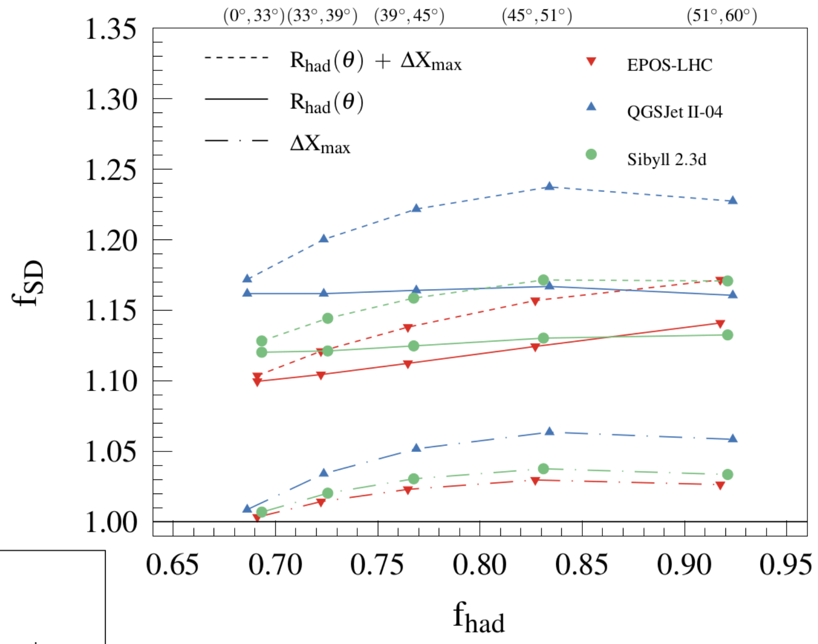
Caveat: no modifications in fluctuations or mass-depencies etc. considered

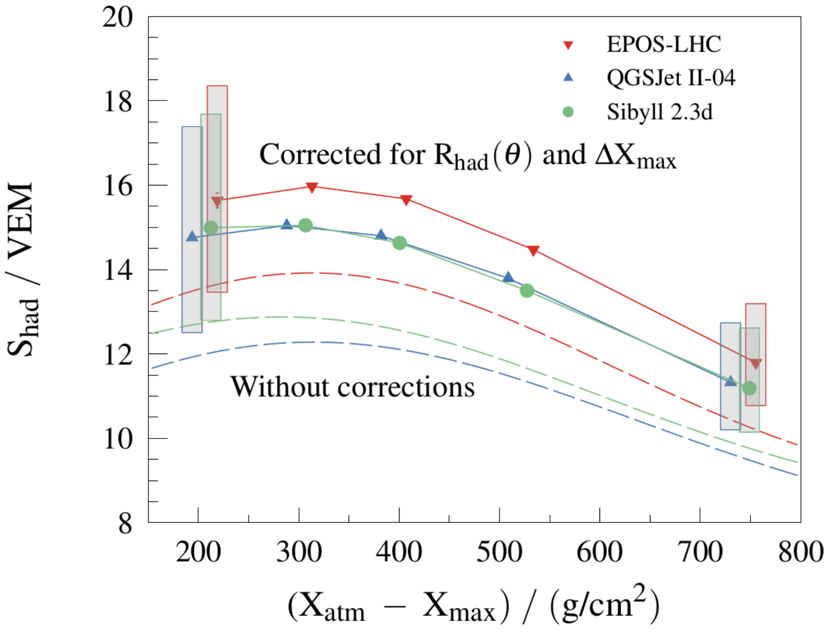
ad-hoc modifications

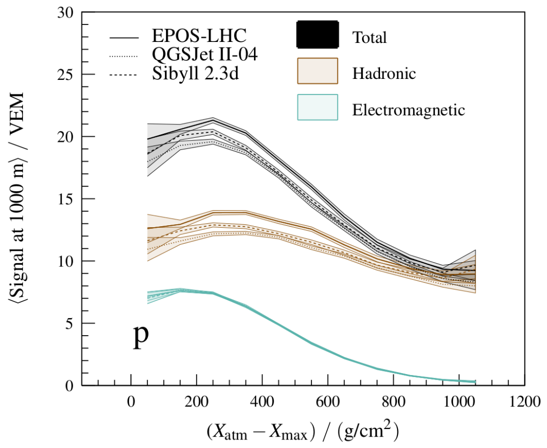
$$X_{max} \rightarrow X_{max} + \Delta X_{max}$$

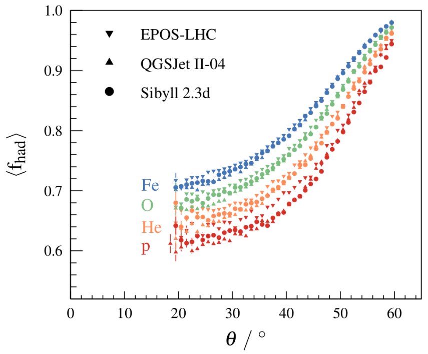
$$S_{had}(\theta) \rightarrow S_{had}(\theta) \cdot R_{had}(\theta)$$

Effect of modified X_{max} on the ground signal









Assumption on primary species

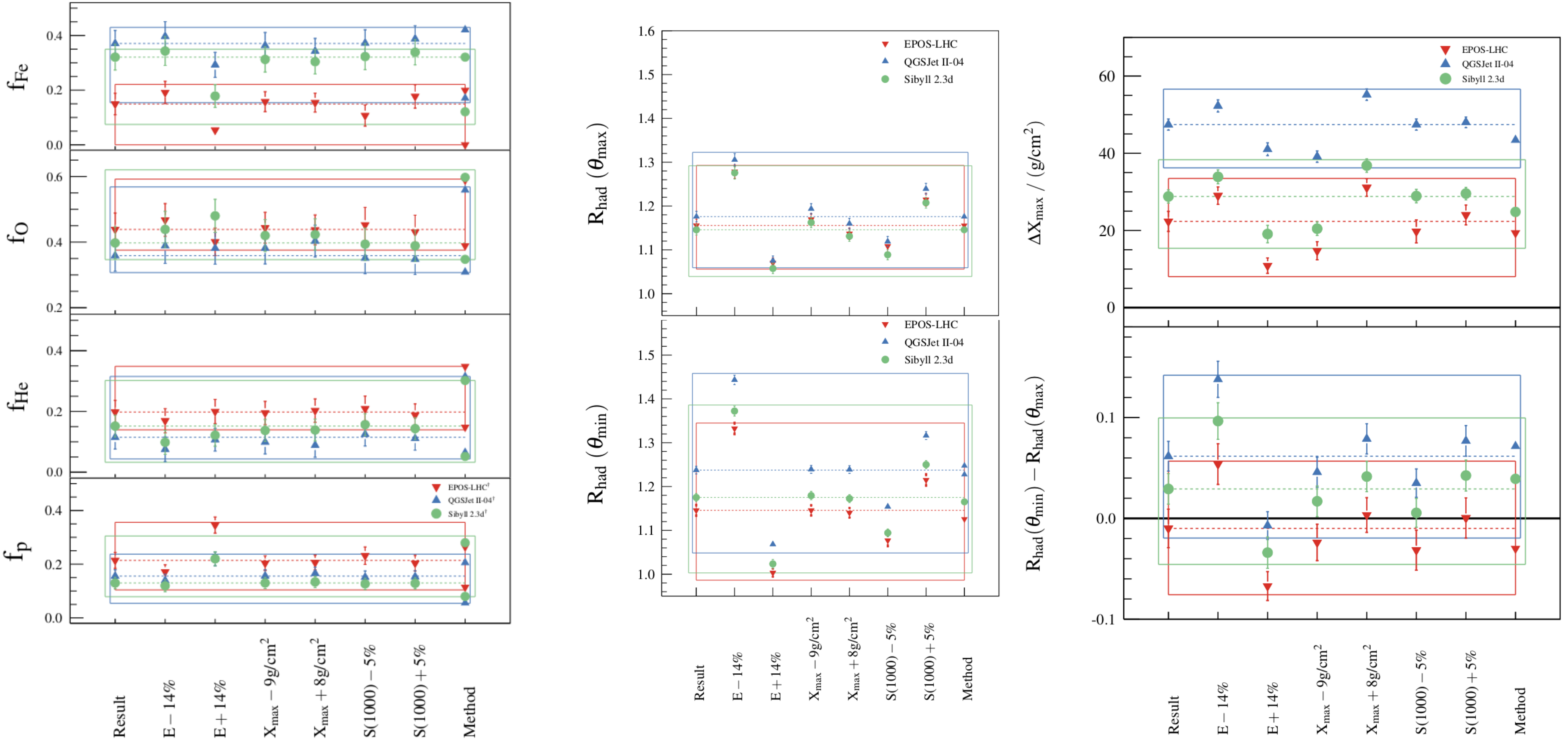
- ΔX_{max} decreases by about 5-7, 10-17 and 30-40 g/cm^2 and $R_{had}(\theta)$ increases by about 2-5%, 4-9% and 15-20% when the heaviest primary Fe is replaced by Si, O and He, respectively

$\ln \mathscr{L}_{min}$	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

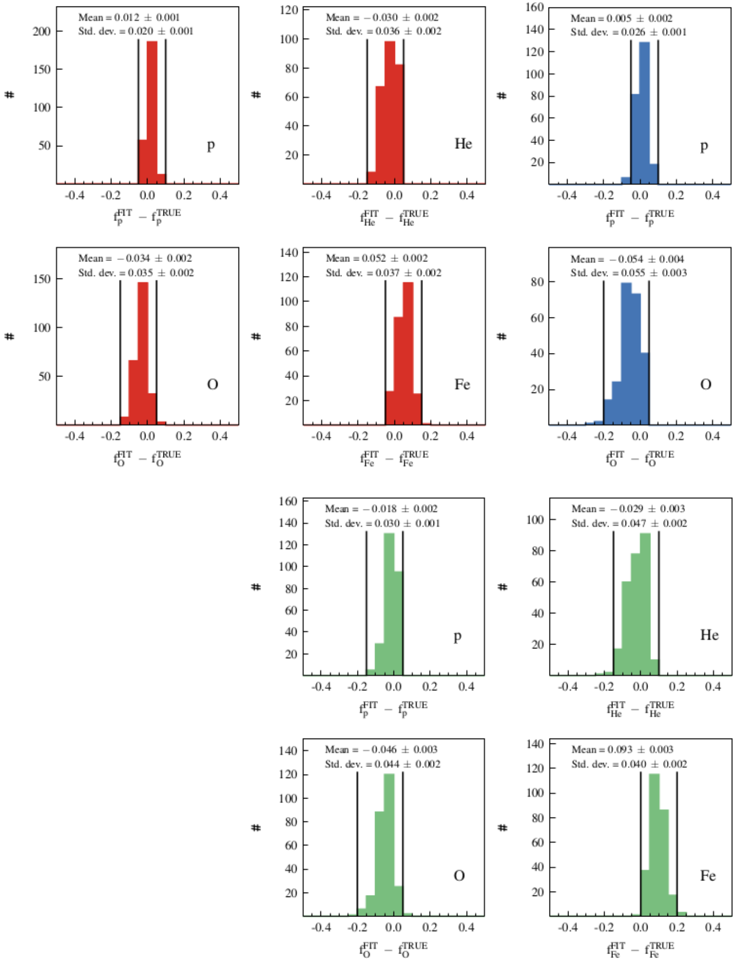
↓

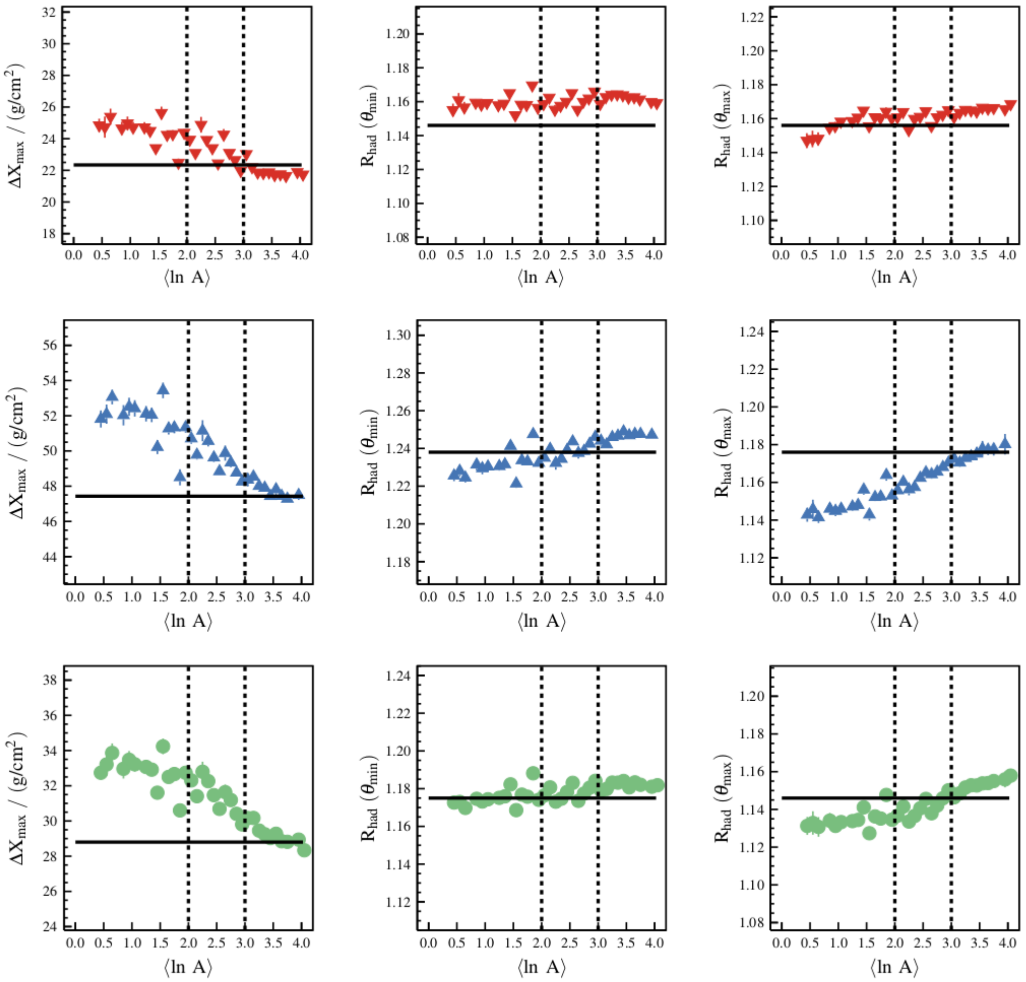
Significance of improvement of data description above 5σ

Systematic uncertainties



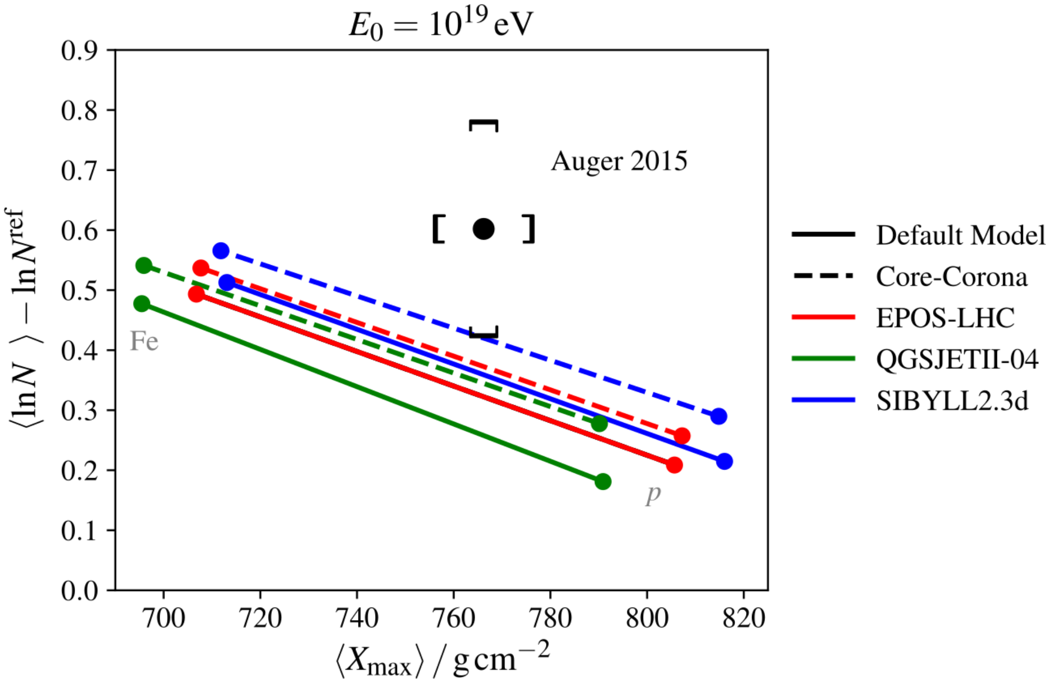
MC-MC tests


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
#


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

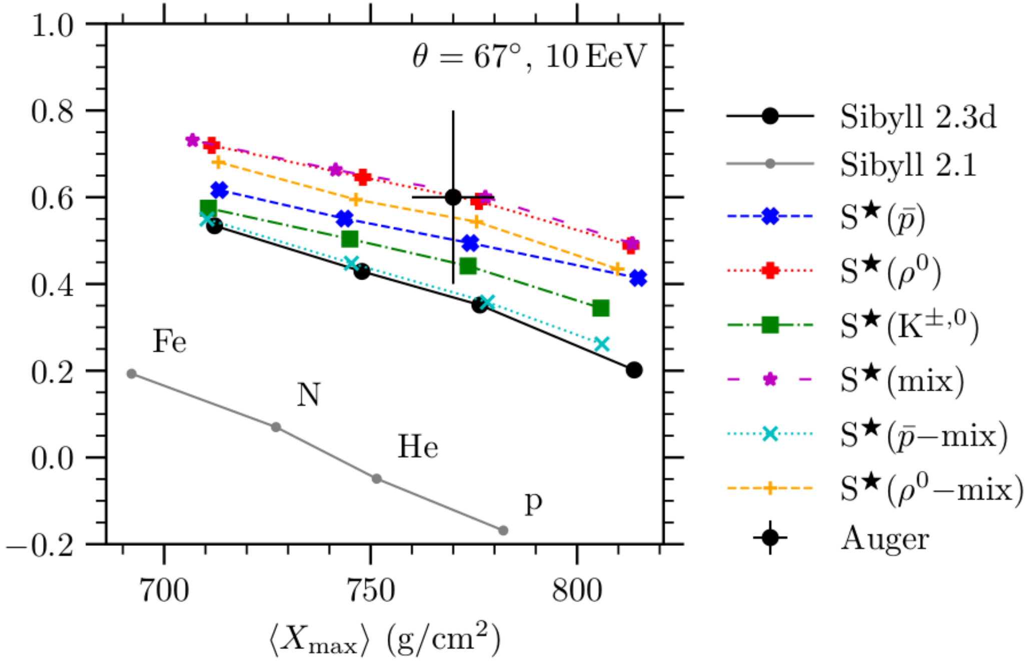
Adding muons ~ without changing X_{max}

Core-corona model - collective statistical hadronization ➔ EPOS 4



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

Sibyll * - artificial enhancement of muons

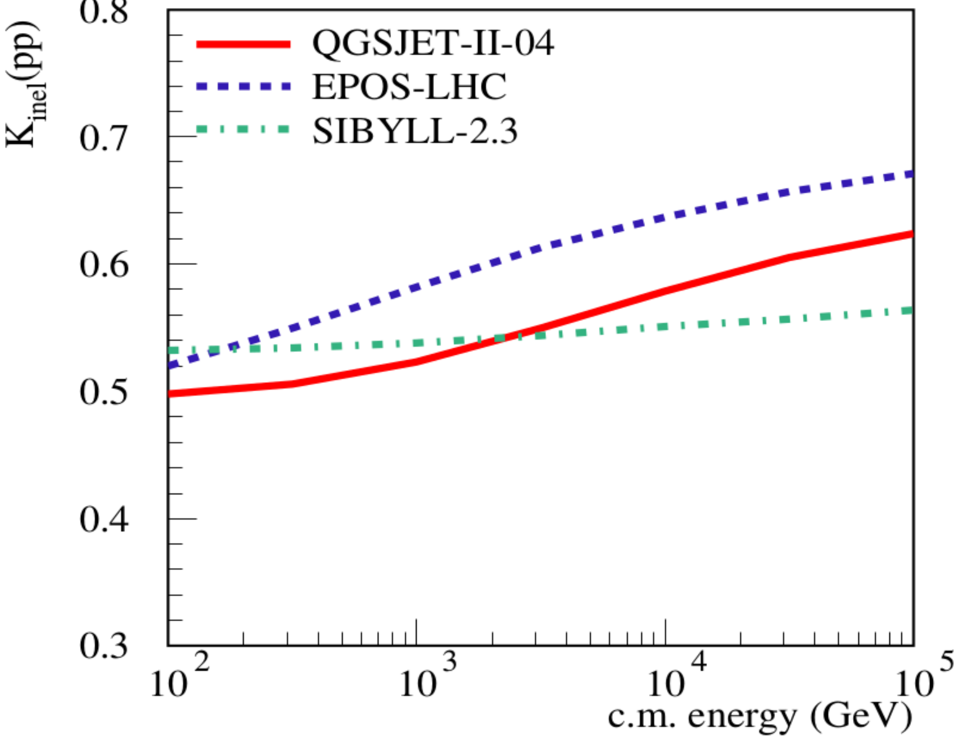


[PoS(ICRC2023)429]

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

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

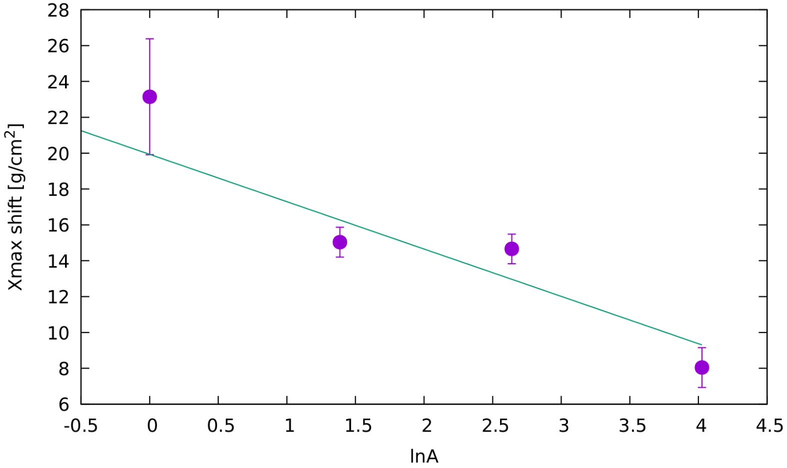
$$X^A_1 + (1-\alpha-\omega)\cdot(X_0 \ln \frac{E}{A\cdot \xi^{\pi}_{\mathrm{c}}}) + X_0 \cdot (\ln \kappa_0 - \ln N_0)$$

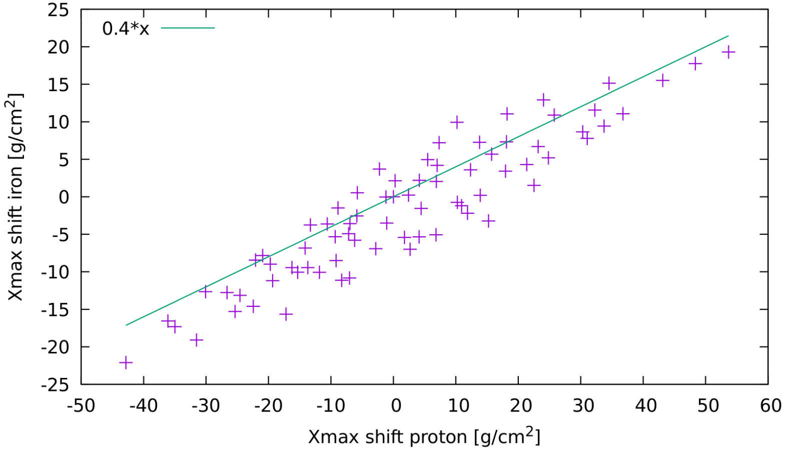
$$\begin{matrix} \kappa_0 \rightarrow f_{\kappa}\kappa_0 \\ N_0 \rightarrow f_N N_0 \end{matrix} \quad \Rightarrow \quad X^A_{max}{}' = X^A_{max} + X_0(\ln(f_{\kappa}) - \ln(f_N))$$

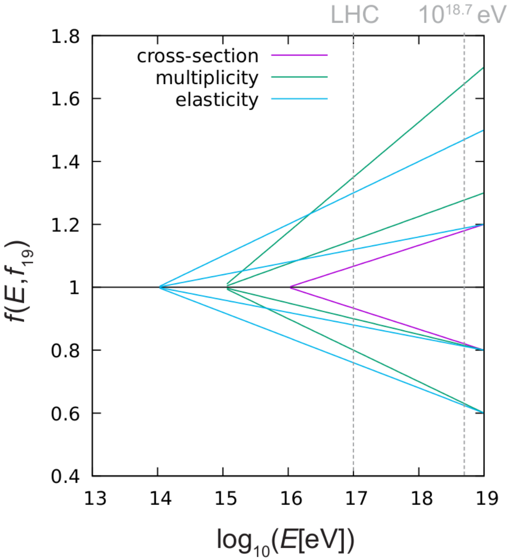
MOCHI (preliminary)

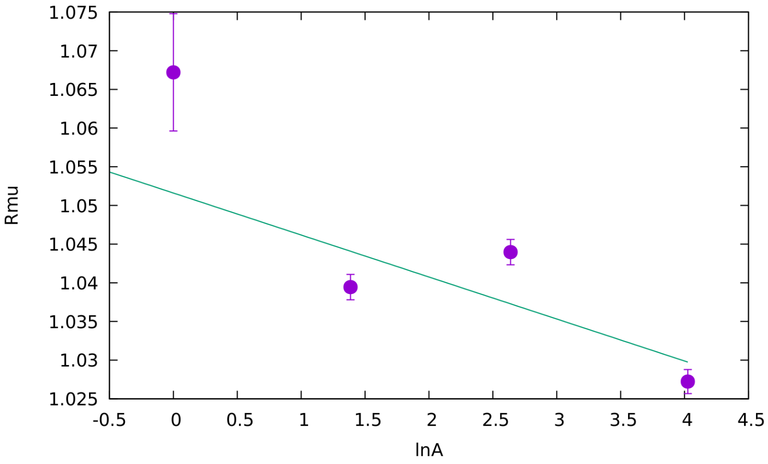
[PoS(ICRC2023)245]

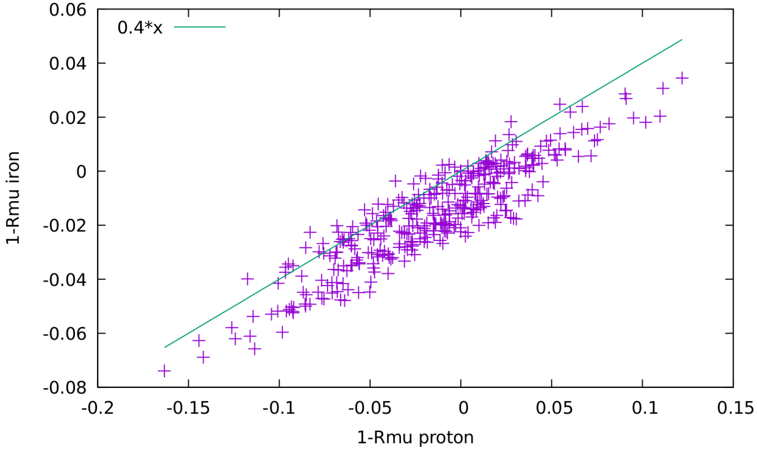
“changing the shape of energy dependence“ ➔ mass-dependent modifications





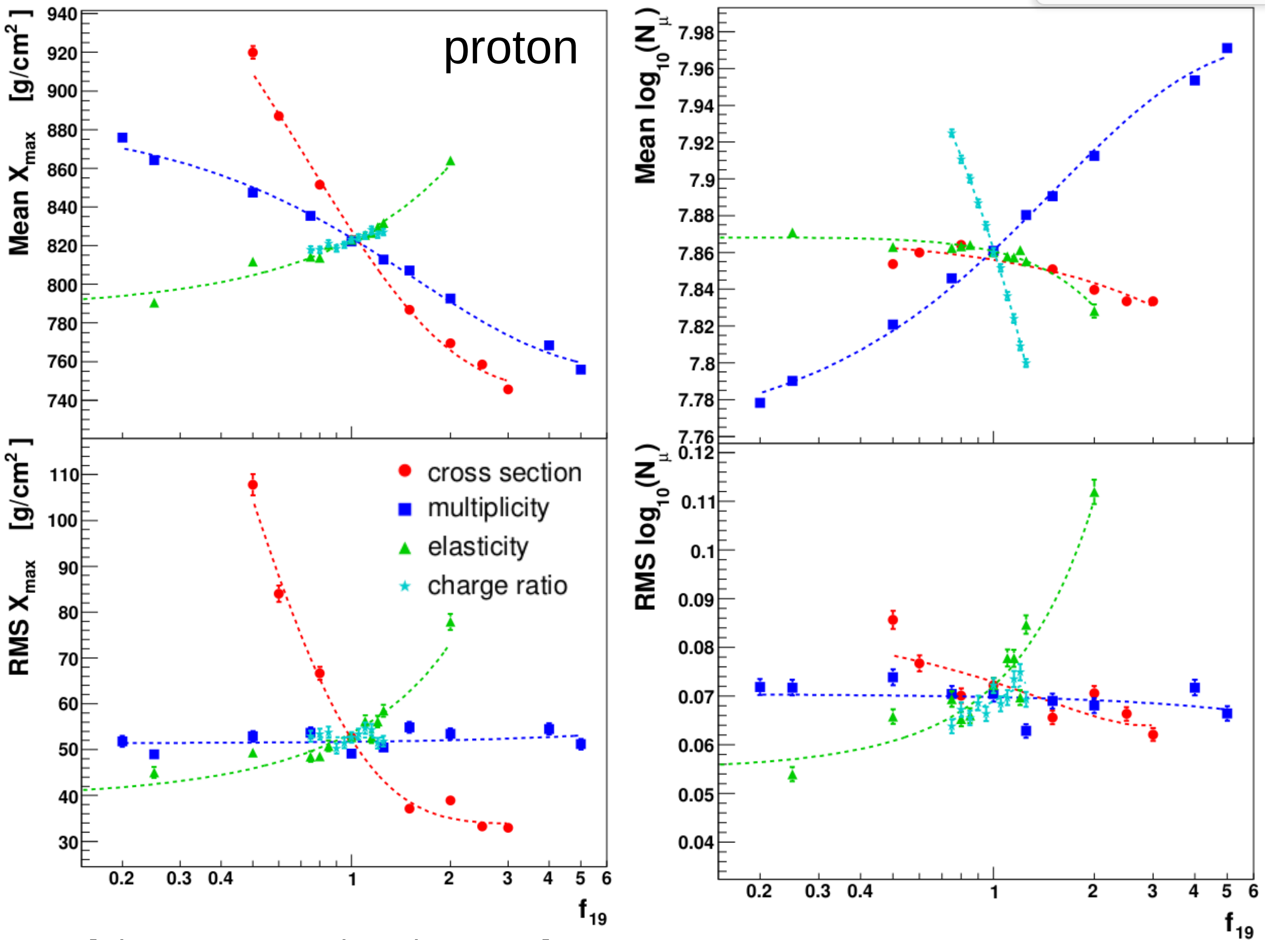






Modifications of hadronic interactions

- 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

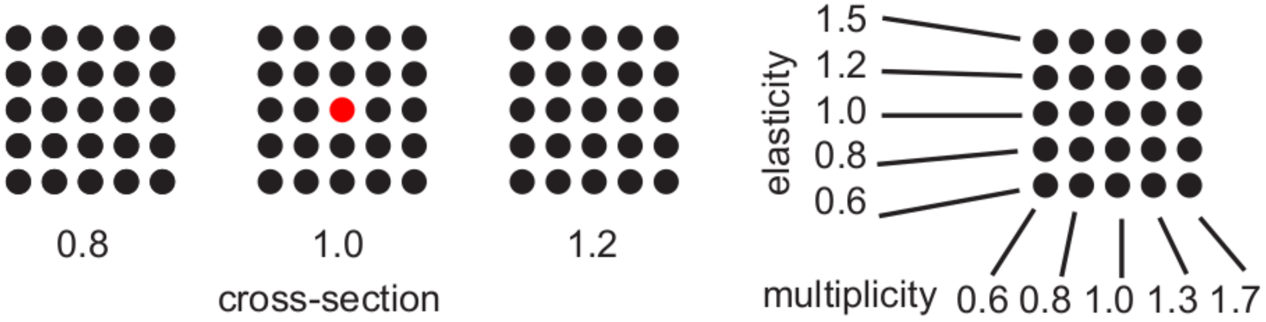


[Phys. Rev. D 83 (2011) 054026]

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

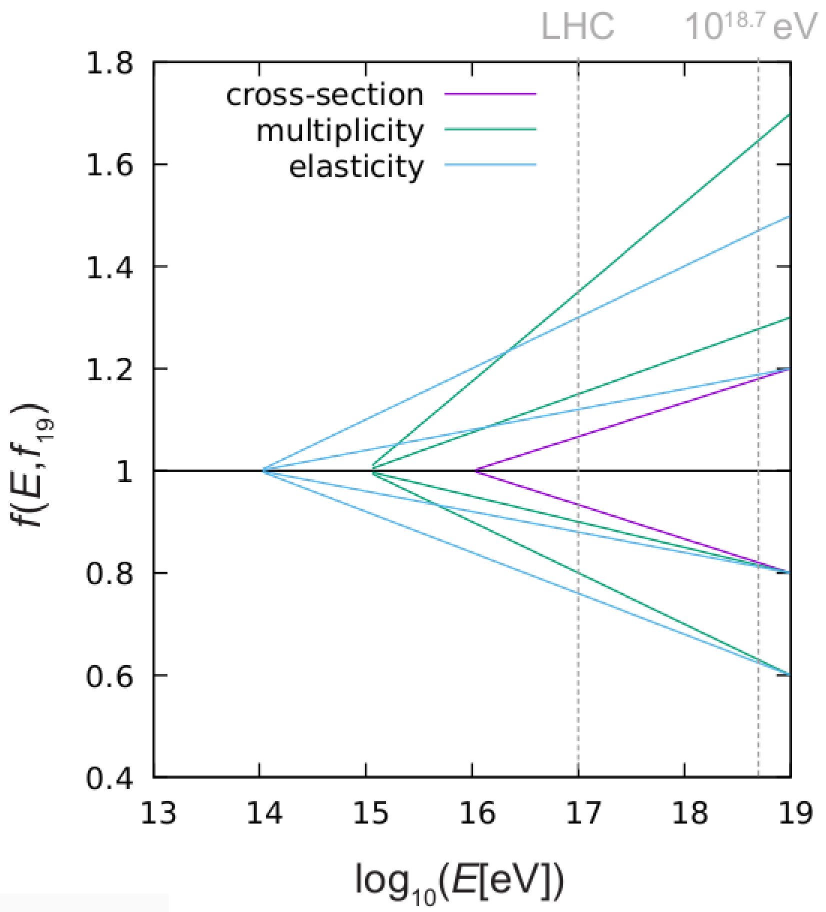
Range of modifications and thresholds

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

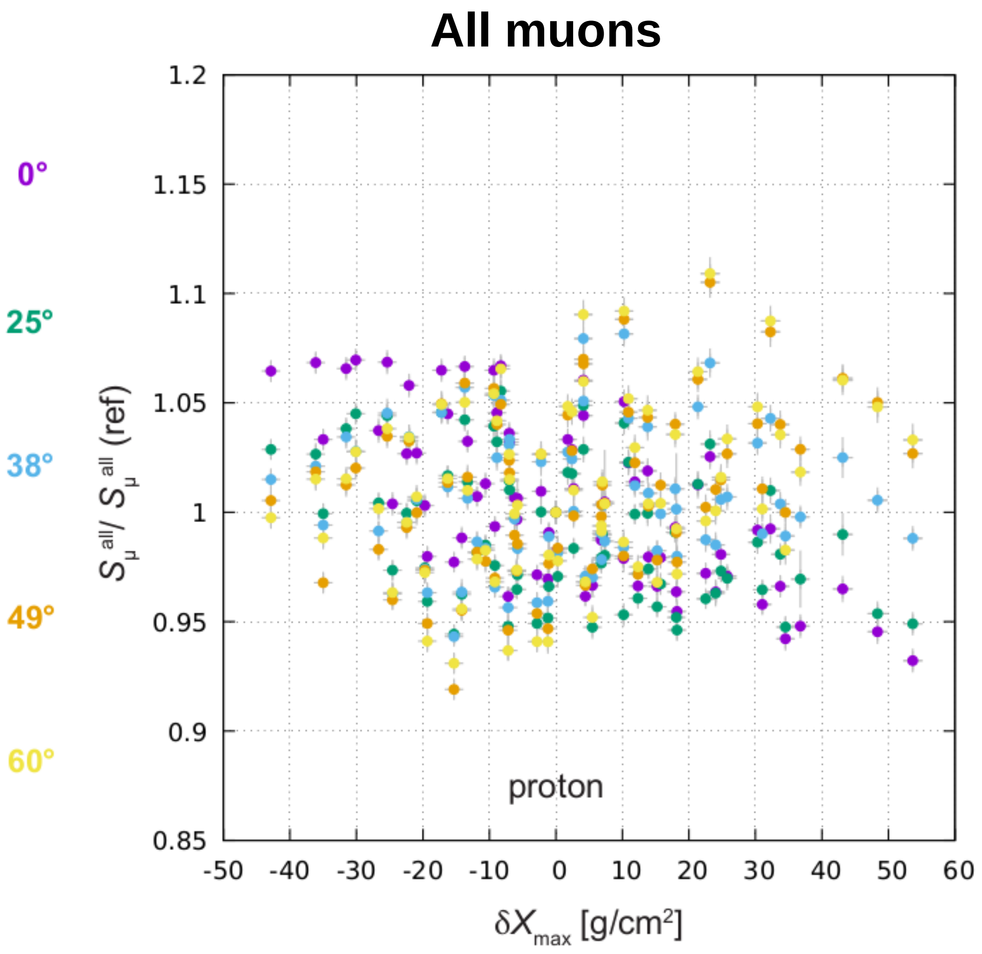
Multiplicity ($E_{thr} = 10^{15}$ eV)
- no p-A data, limited rapidity coverage

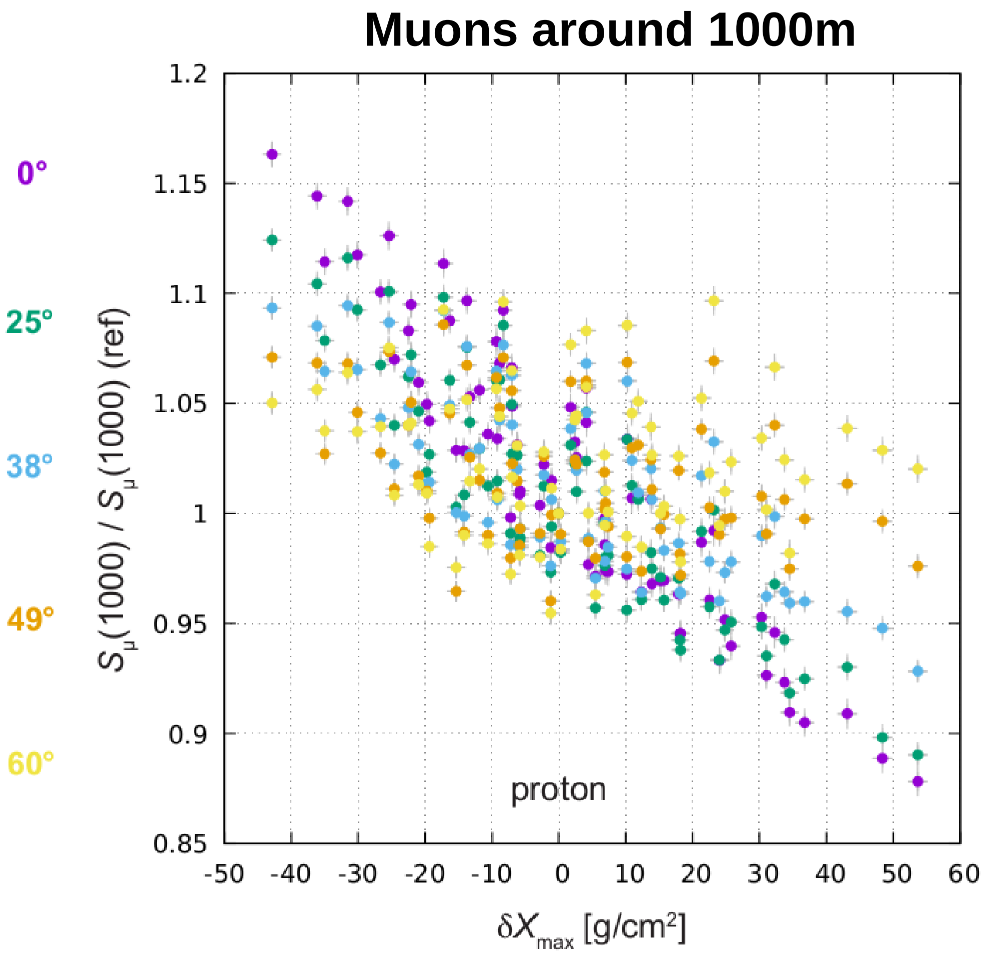
Elasticity ($E_{thr} = 10^{14}$ eV)
- difficult at accelerators, limits from nuclear emulsion chambers
- recent LHCf neutron elasticity measurement?
- range of modifications limited by internal consistency

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



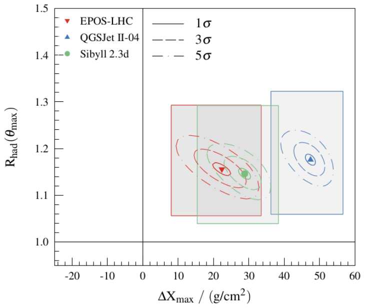
Importance of 3D simulation

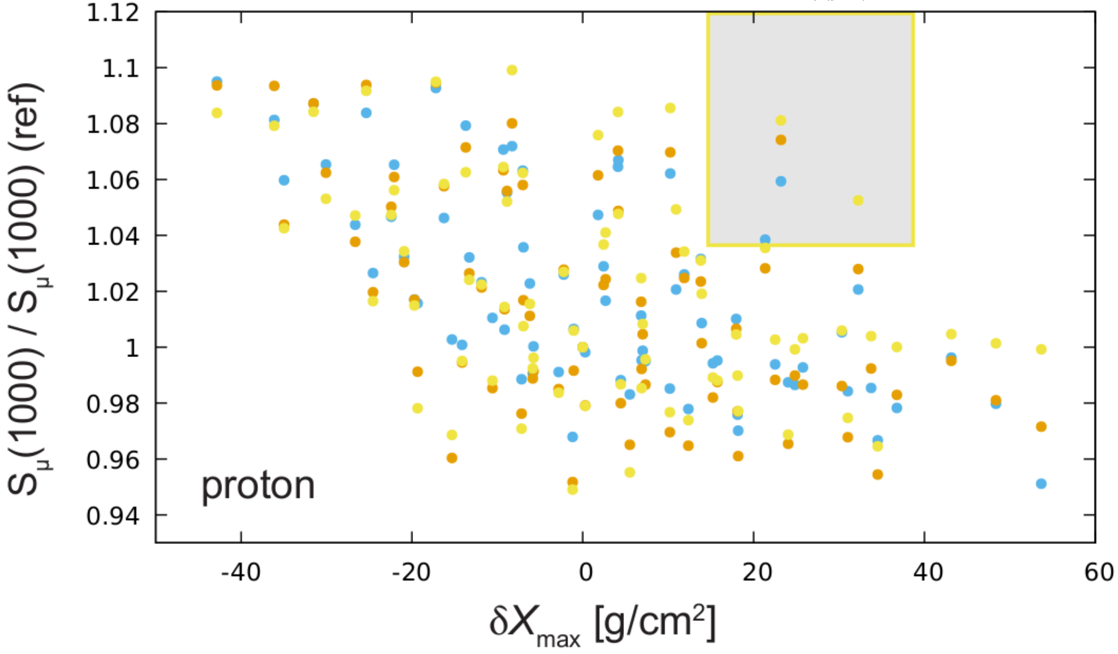


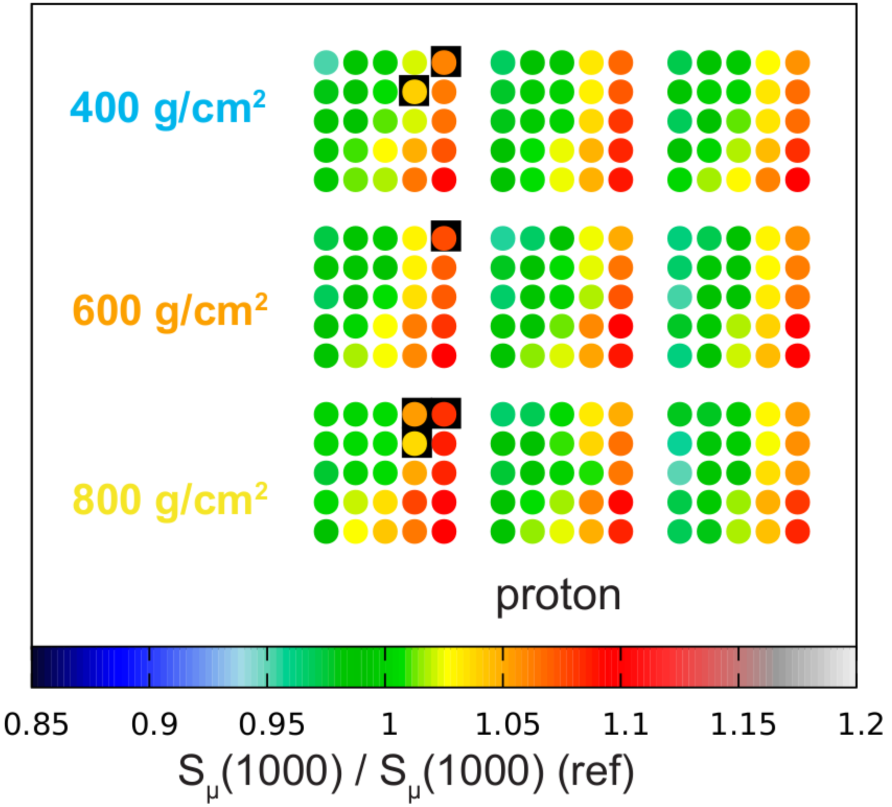


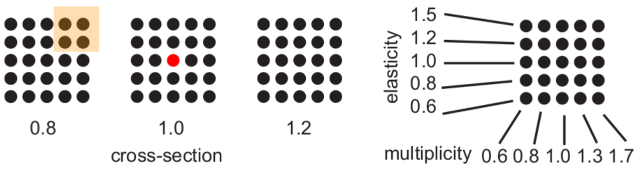
Comparison with Auger results

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

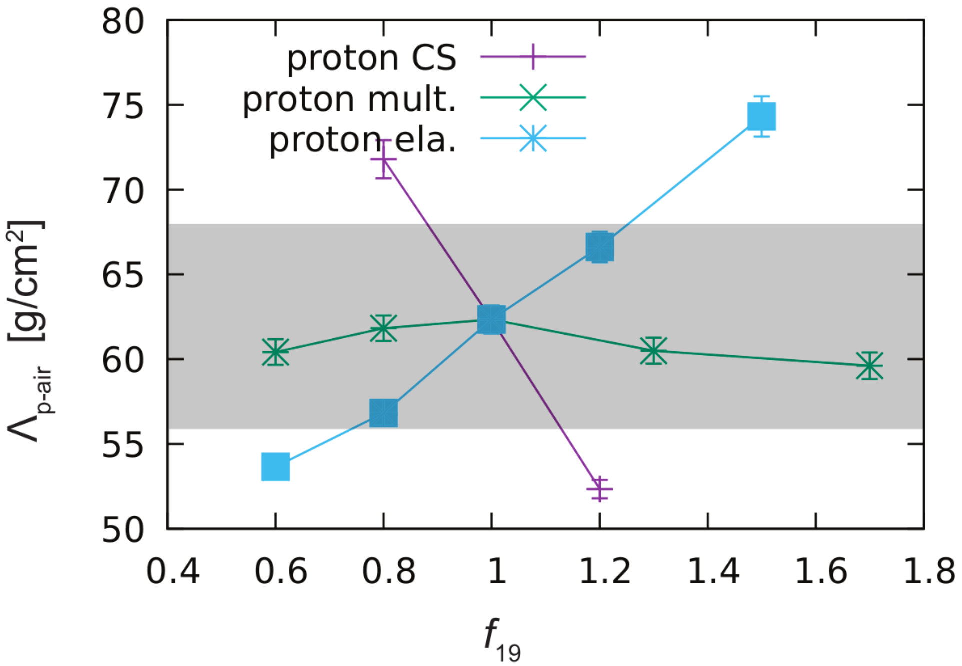


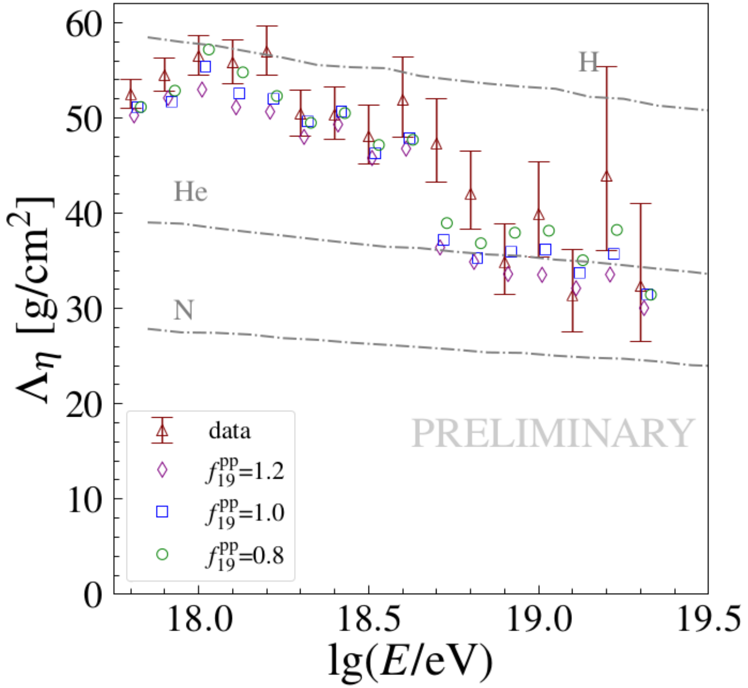


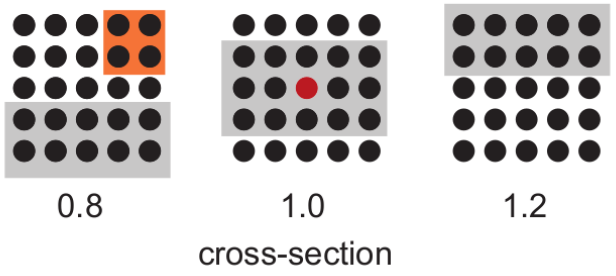


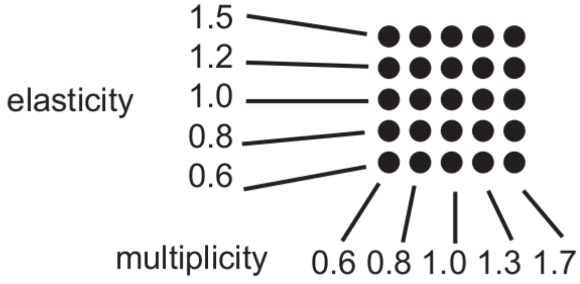


Effect on tail of X_{max} distribution



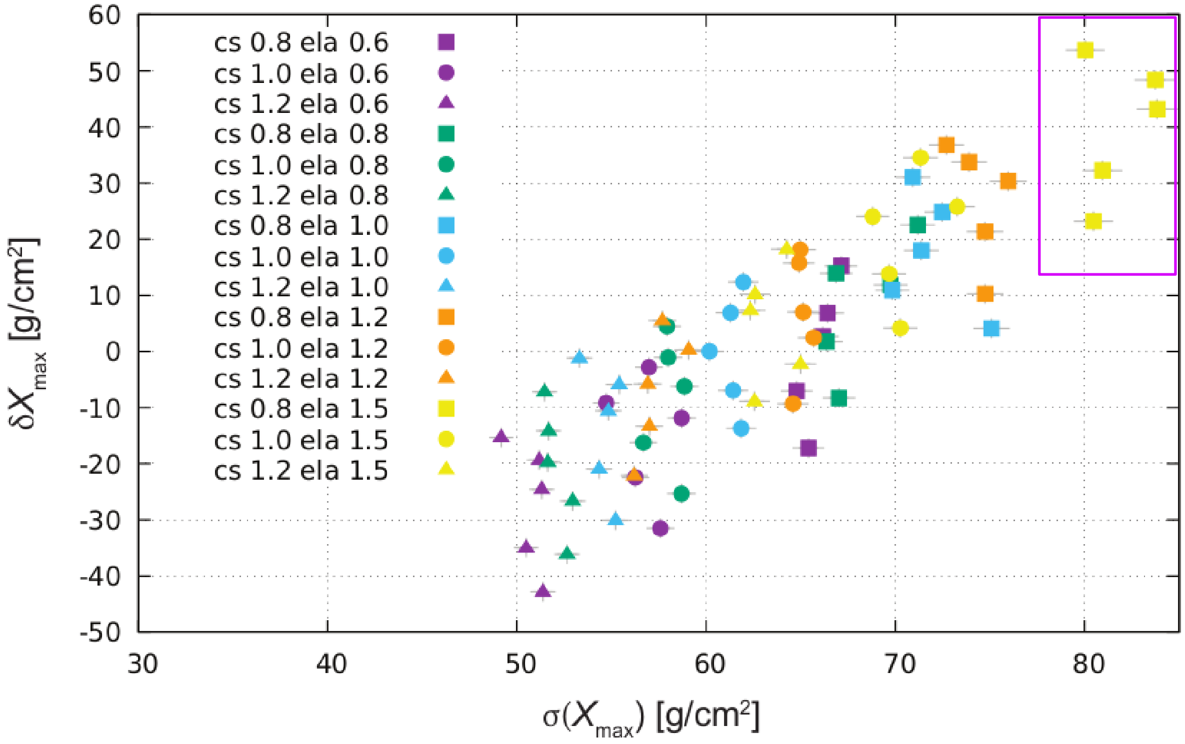




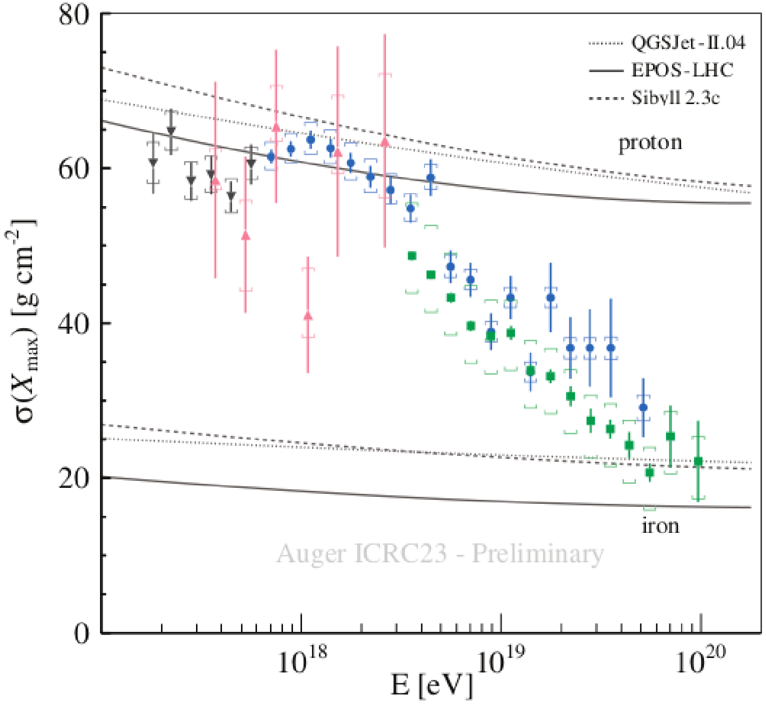


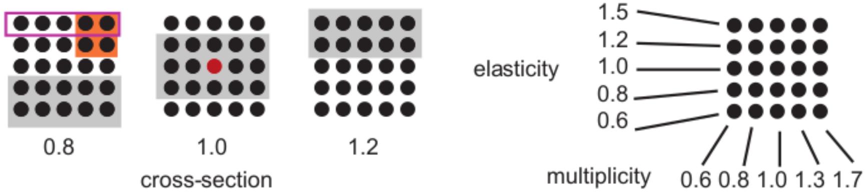
Slope of X_{max} tail distribution for protons too constrained by Auger data

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