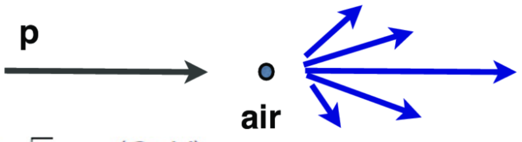
Probing hadronic interactions at the highest energies
with the Pierre Auger Observatory

T. Schulz KIT Karlsruhe Institute of Technology, on behalf of the Pierre Auger Collaboration | 29.08.2024

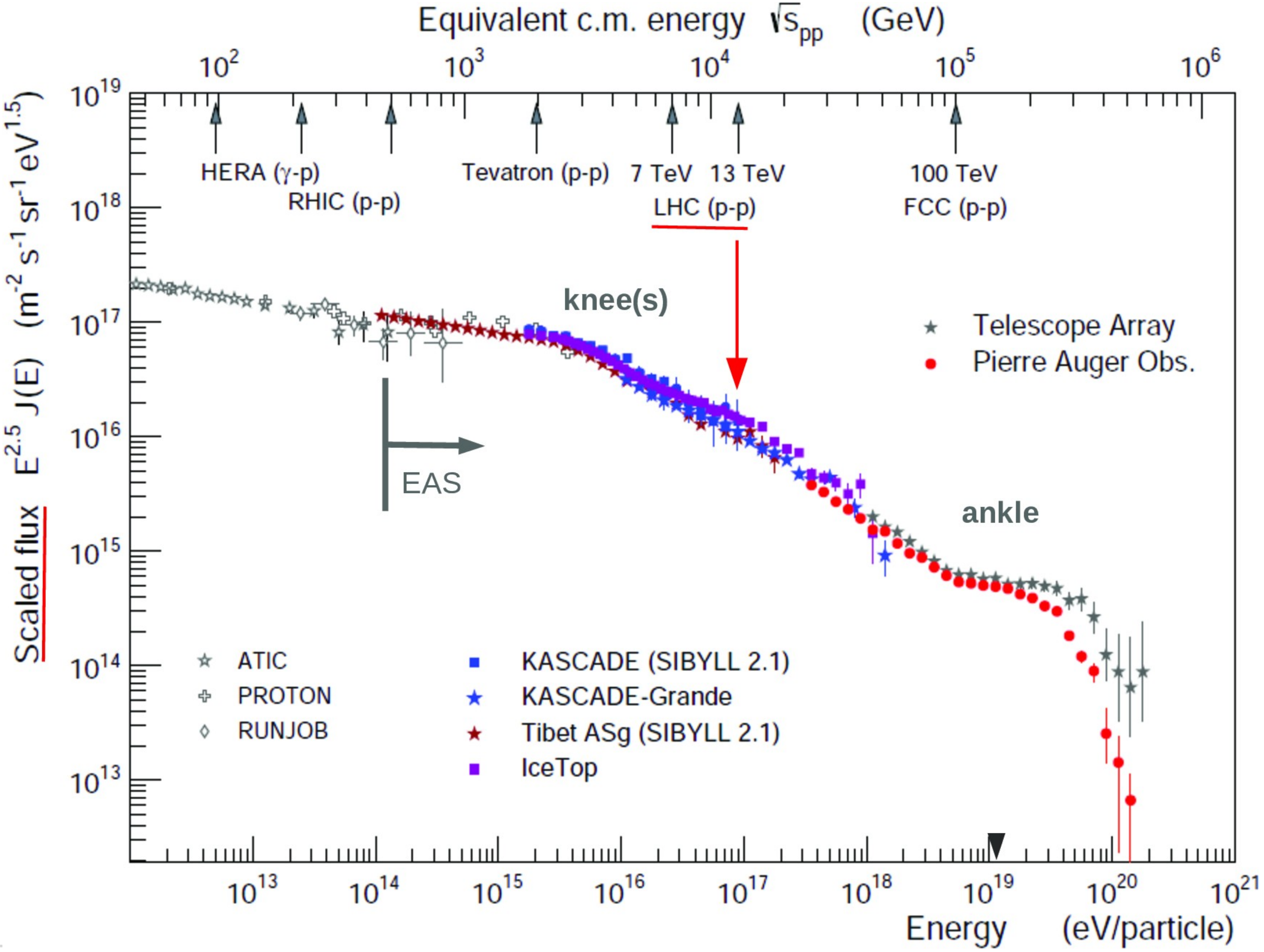
XIII International Conference on New Frontiers in Physics

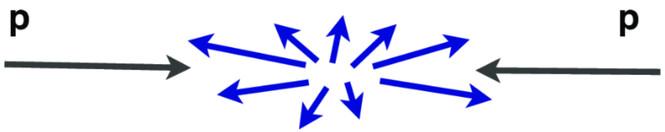
Ultra-high-energy cosmic rays



- **UHECRs** give access to hadronic interactions at **energies far above** the ones achievable by human-made accelerators

- Extrapolation of hadronic models needed when describing **extensive air showers**





Extensive air showers

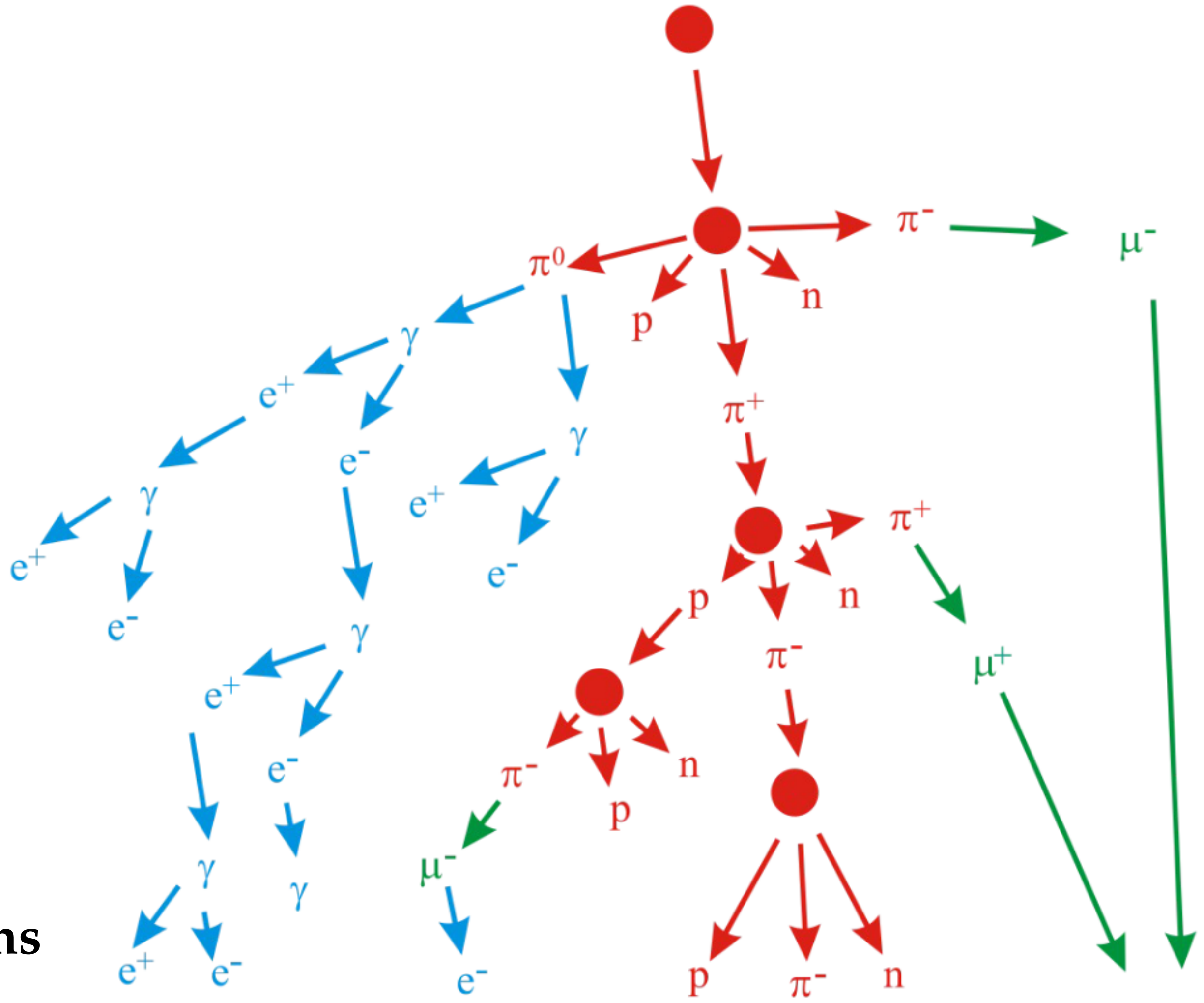
Electromagnetic

- from **neutral pion decay**
- **90%** of total energy

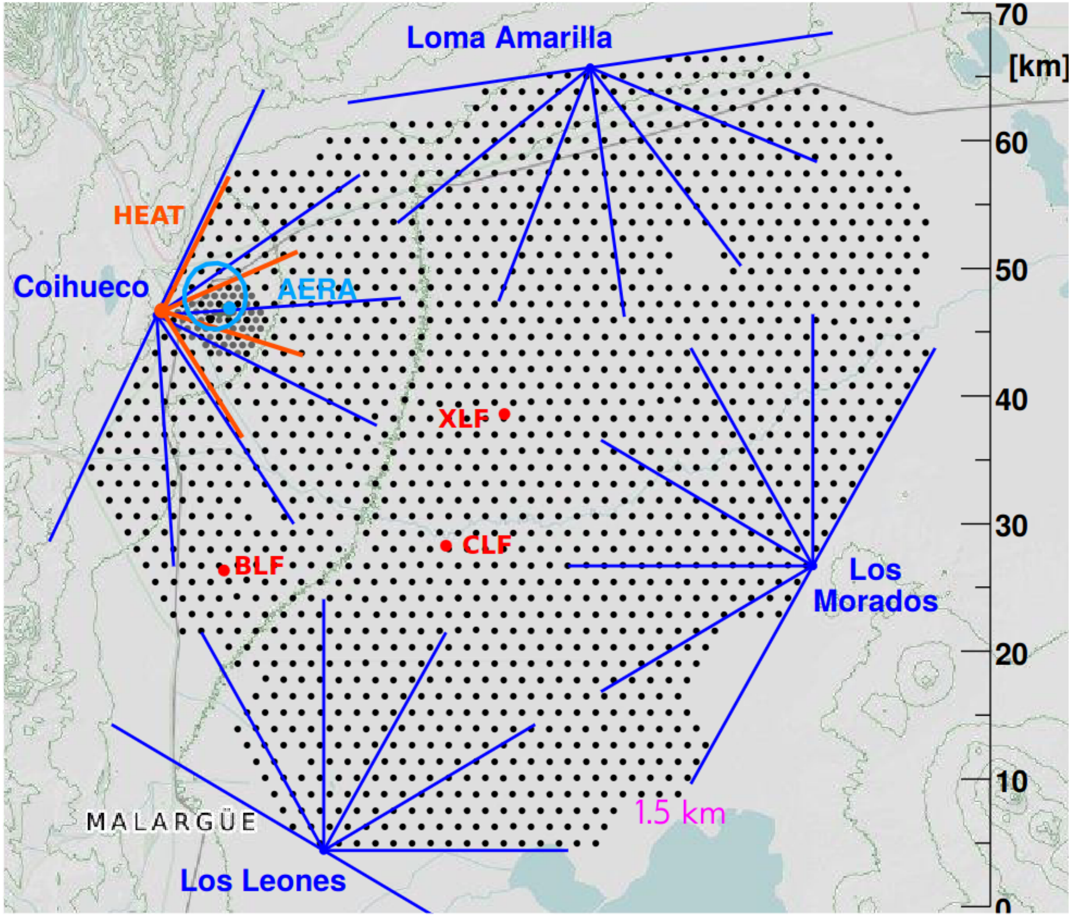
Hadronic

- **muons** from charged pion decay
- tracer of **hadronic component**

- **Higher mass primaries** induce showers with **larger hadronic** component and thus **more muons**



The Pierre Auger Observatory



Location: Malargüe, Mendoza, Argentina

Surface Detector **(SD)**

- 1660 water Cherenkov detectors (100% duty cycle)
- $E > 10^{18.5}$ eV ($10^{17.5}$ eV, $10^{16.5}$ eV)

Fluorescence Detector **(FD)**

- 27 telescopes @ 4 sites (15% duty cycle)
- $E > 10^{18}$ eV (10^{17} eV)

Hybrid detector

FD

- Calorimetric estimation of $\boldsymbol{E}$

- Depth of shower maximum $\boldsymbol{X}_{\mathbf{max}}$ (also SD)

  - p-air **cross section**

SD

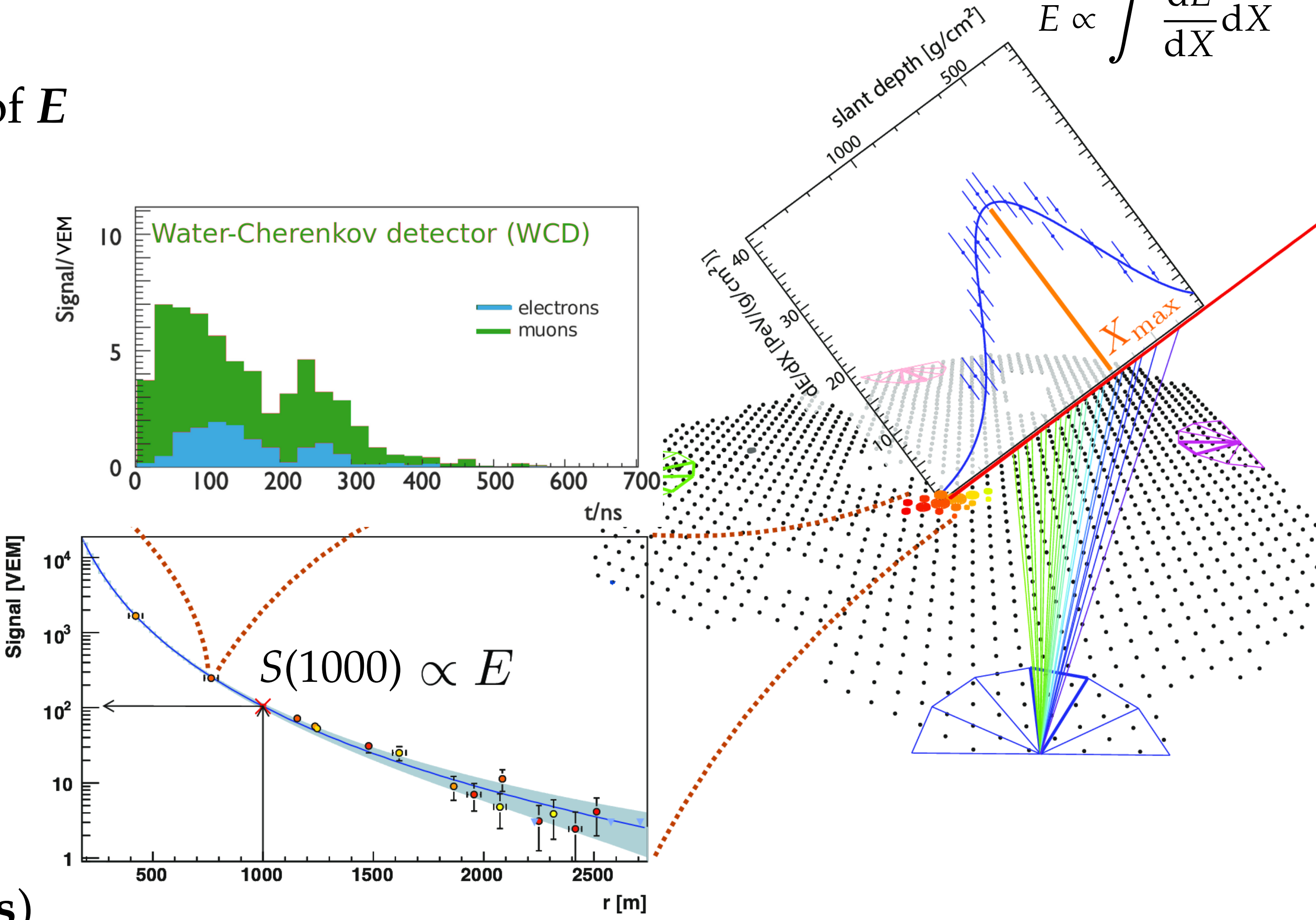
- Energy estimator via $\boldsymbol{S}$**(1000)**

- **muon** production depth

- Risetime

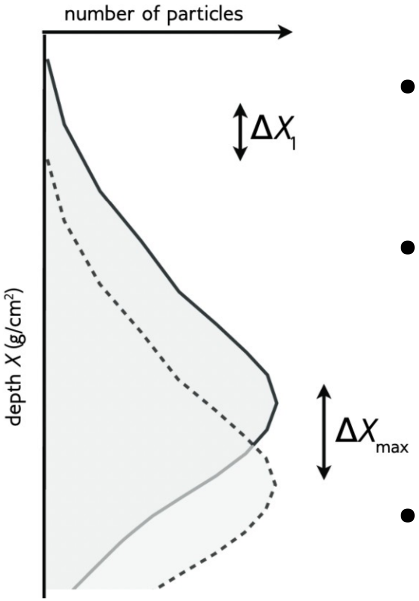
- muon content (from **buried scintillators**)

$$E \propto \int \frac{\mathrm{d}E}{\mathrm{d}X} \mathrm{d}X$$



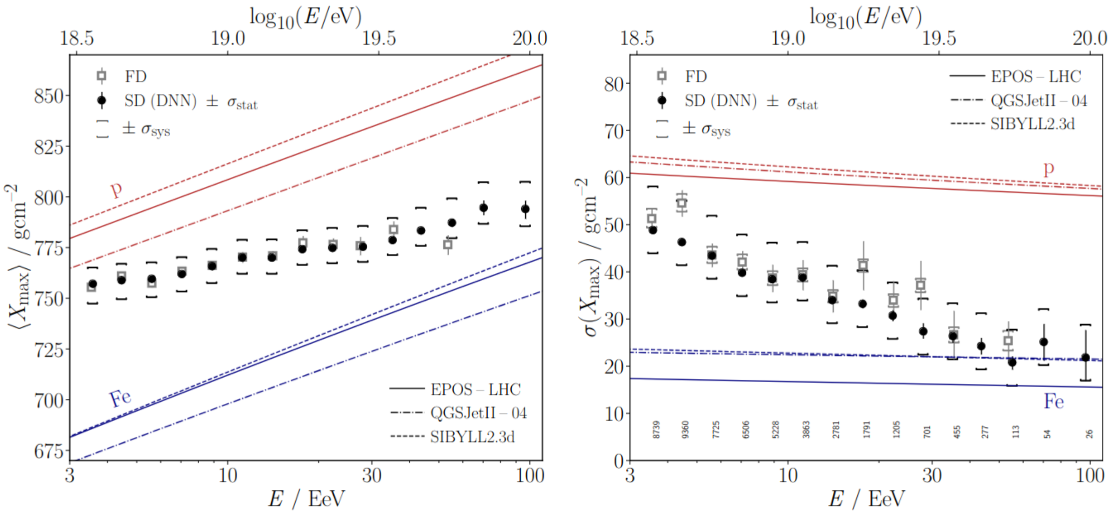
Depth of shower maximum

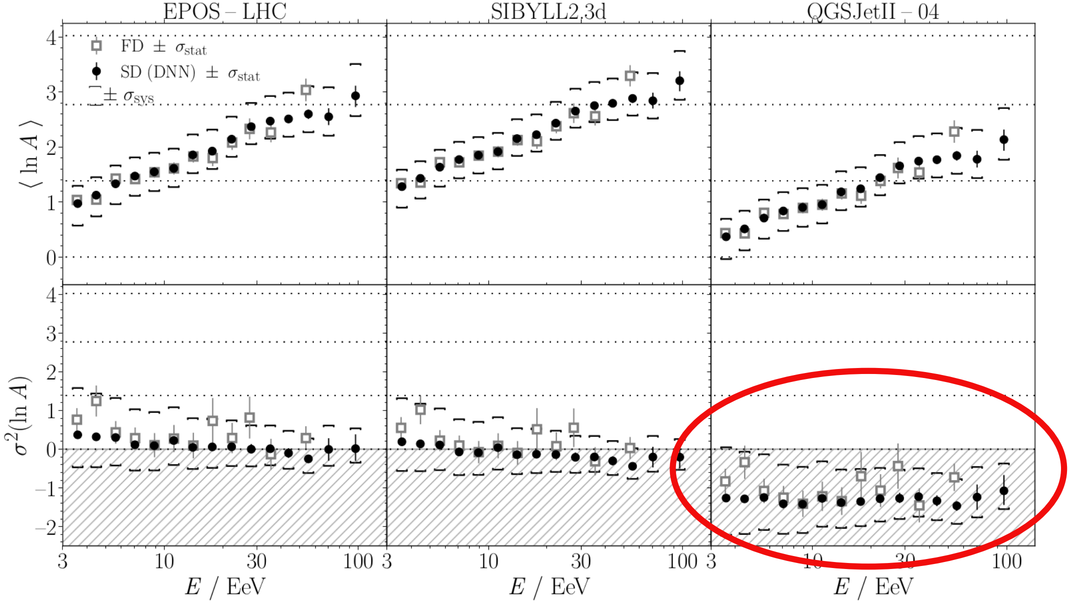
- **Direct** measurement of first and second X_{max} moments with **FD**
- **Extension** to higher energies with **DNNs & SD measurements**



- Interpretation of X_{max} moments using ln A
- **Systematic uncertainties** from hadronic interaction models
- **Tensions** for some models

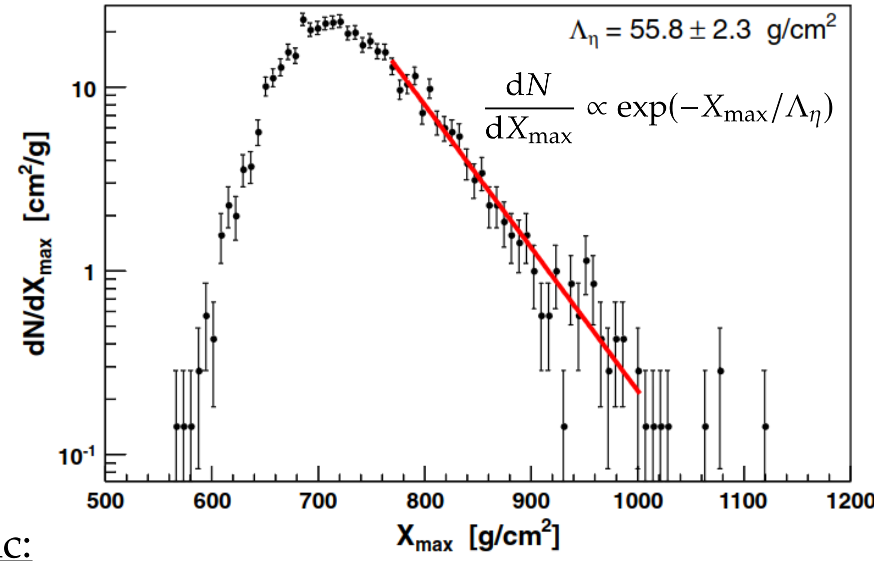
JCAP 02 (2013) 026
Phys. Rev. D 90 122005 (2014)
arXiv:2406.06319

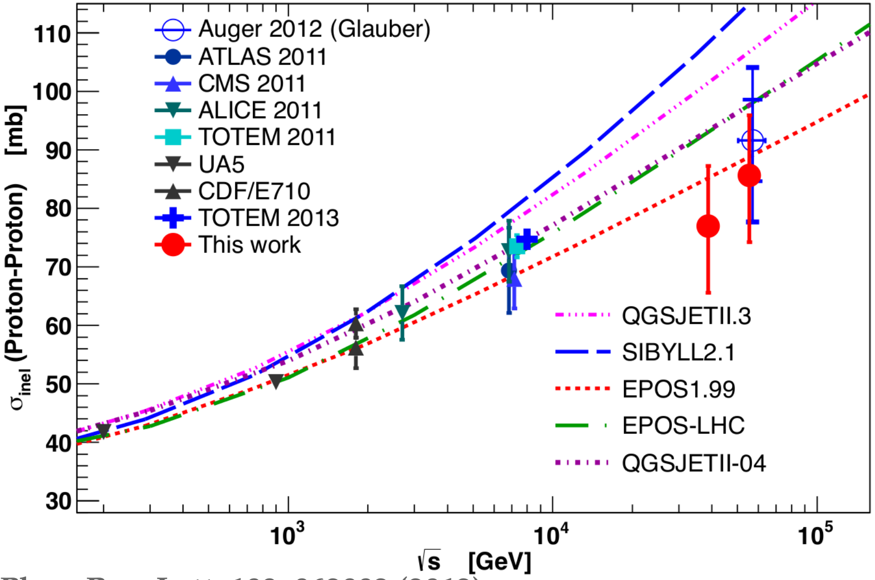




Measurement of the p-air cross section

- **Cross section** dependent observable $\boldsymbol{\Lambda_\eta}$
- **Tail of** $\boldsymbol{X_{max}}$ distribution dominated by **protons**
- **Glauber theory** used to convert p-air to inelastic **pp cross section**



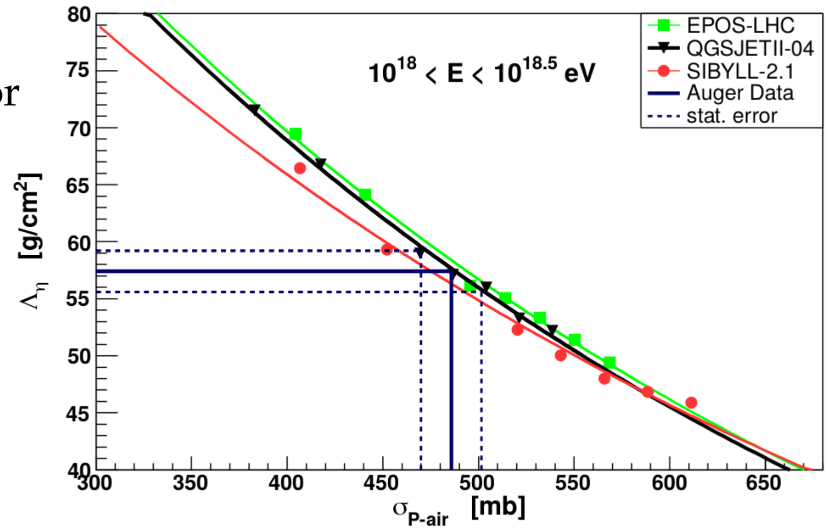


Phys. Rev. Lett. 109, 062002 (2012)
PoS (ICRC2015) 401

Largest systematic:

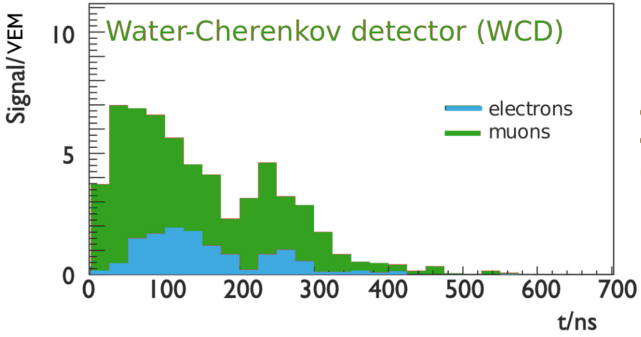
He Contamination (6% **uncertainty** for 25% He fraction)

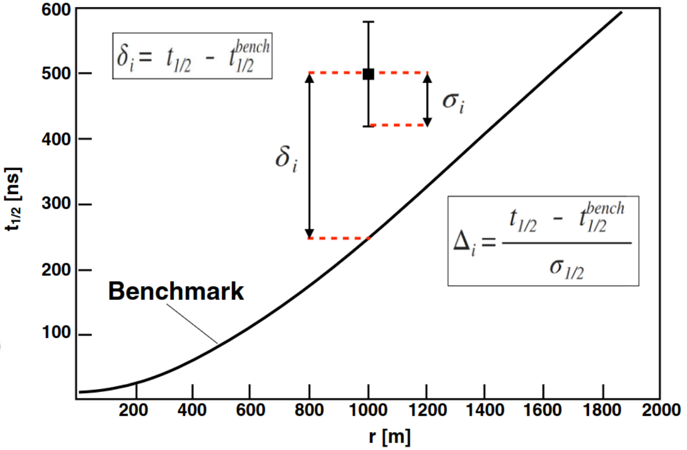
Current works on **modifying** pp interaction cross section in PoS (ICRC2023) 438



Risetime

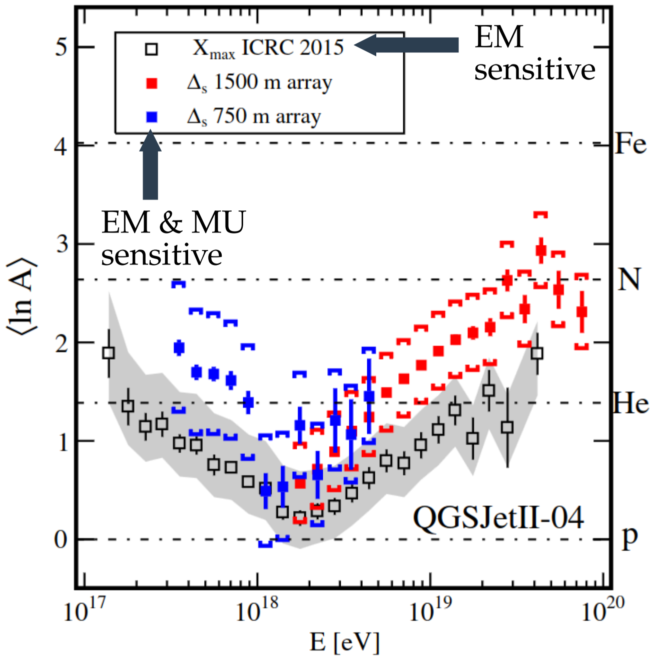
- **Risetime $t_{1/2}$** as time between 10% and 50% of total signal reached

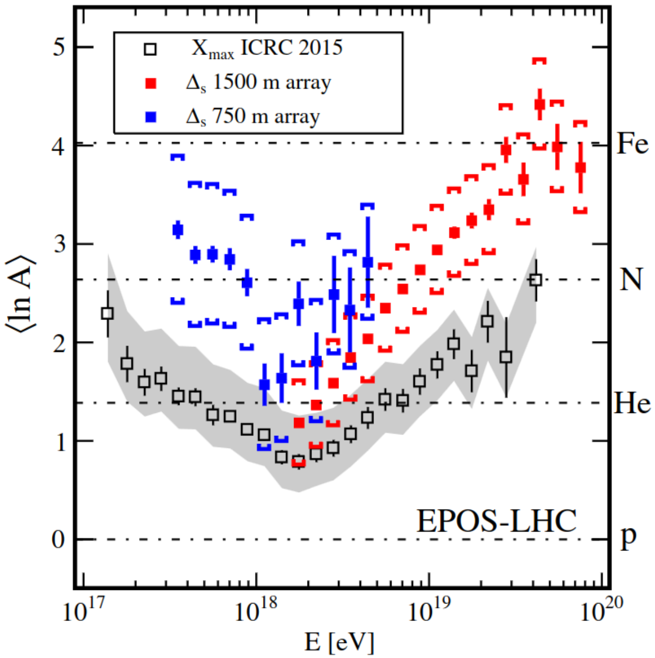




- Sensitivity to **EM and muon component**

- **Similar trends** of estimated ln A, as for X_{max} measurements, but **absolute estimate differs**





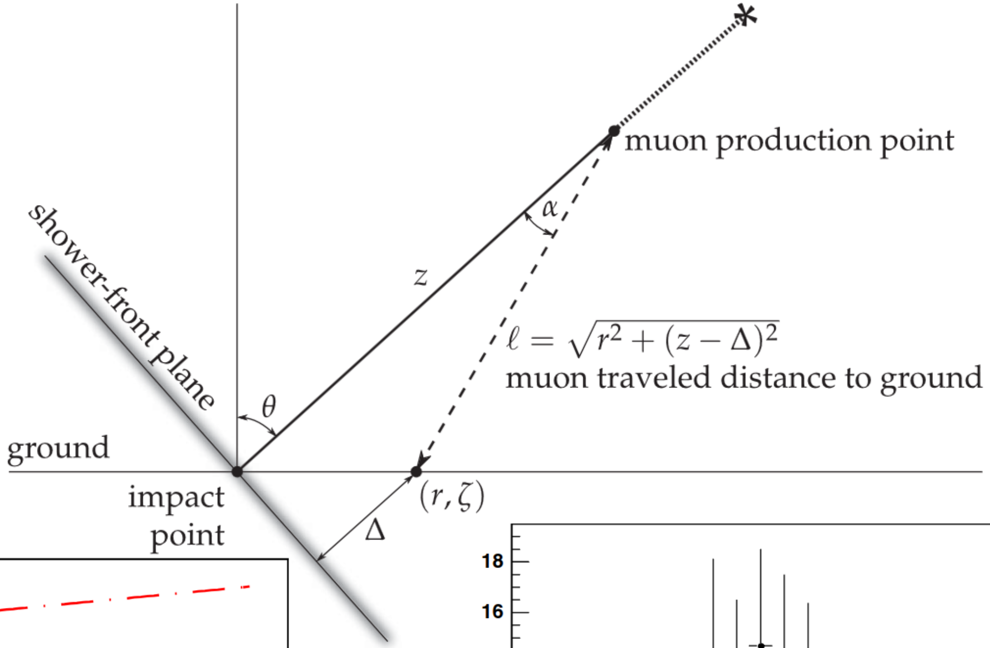
Phys. Rev. D 96, 122003 (2017)

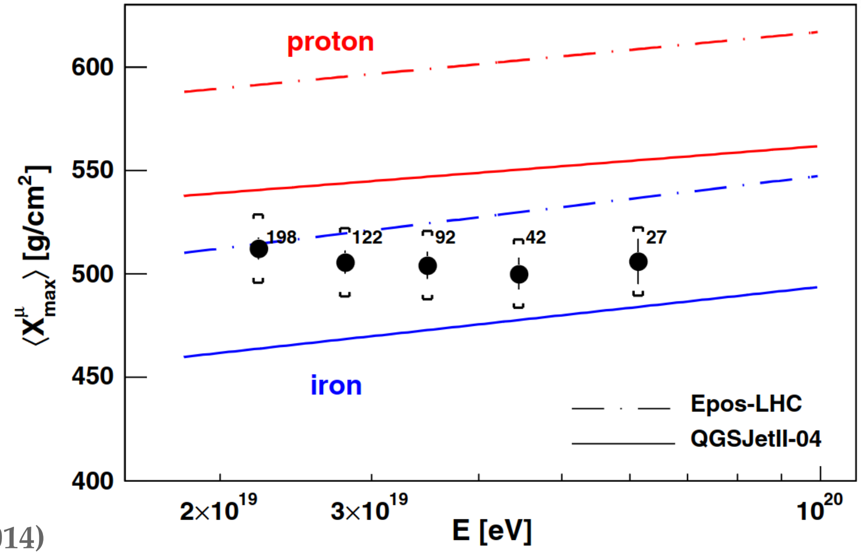
Muon production depth

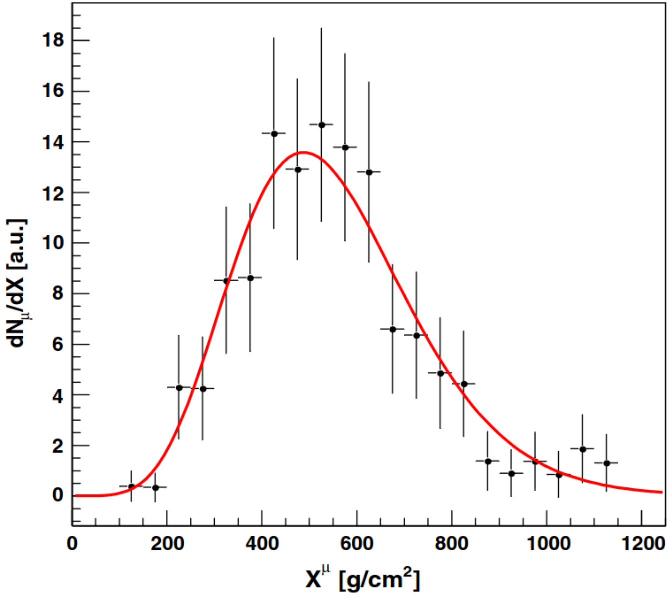
Assumptions that muons …

- are produced along shower axis
- have straight trajectories

- Given shower geometry and arrival times, muons can be **mapped** to their **production depth**





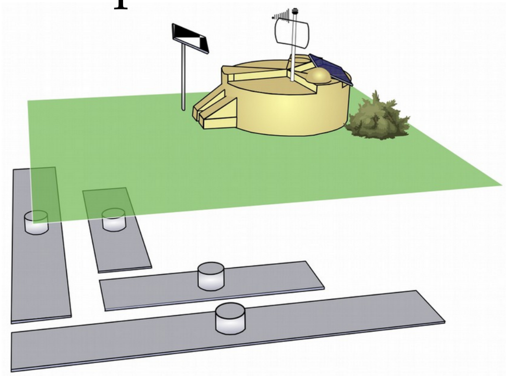


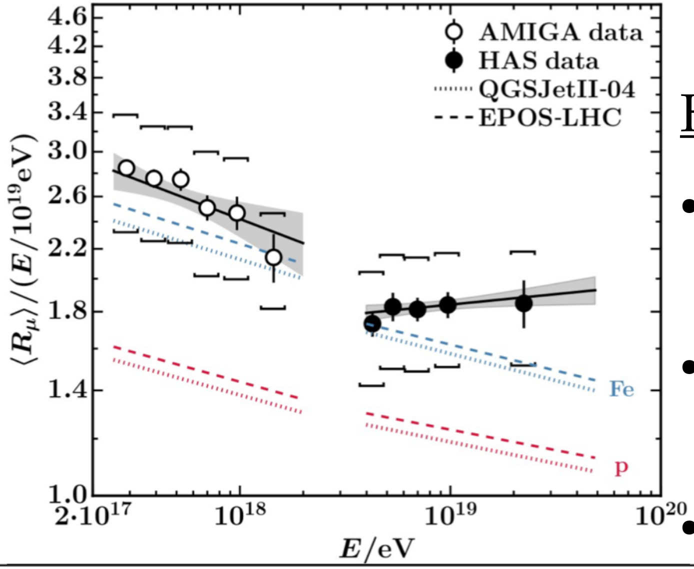
Phys. Rev. D 90, 012012 (2014)

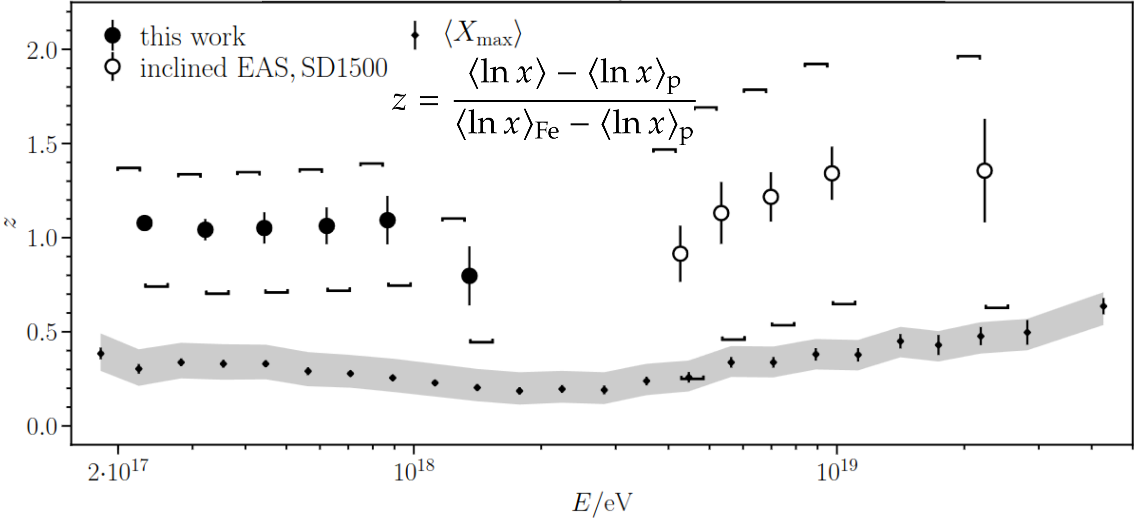
Muon number

Underground muon detector

- 30 m² scintillators, 2.3 m **underground** @ 7 SD locations
- **Direct** muon measurement
- **Larger muon content** in data, than in predictions

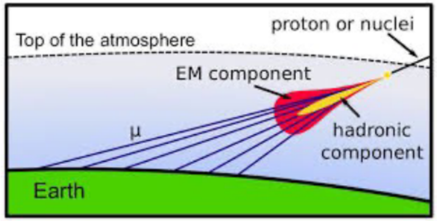






Highly Inclined Events

- **EM component** mostly **absorbed** in atmosphere
- Muon **number** R_μ obtained from SD
- **Larger muon content** in data, than in predictions

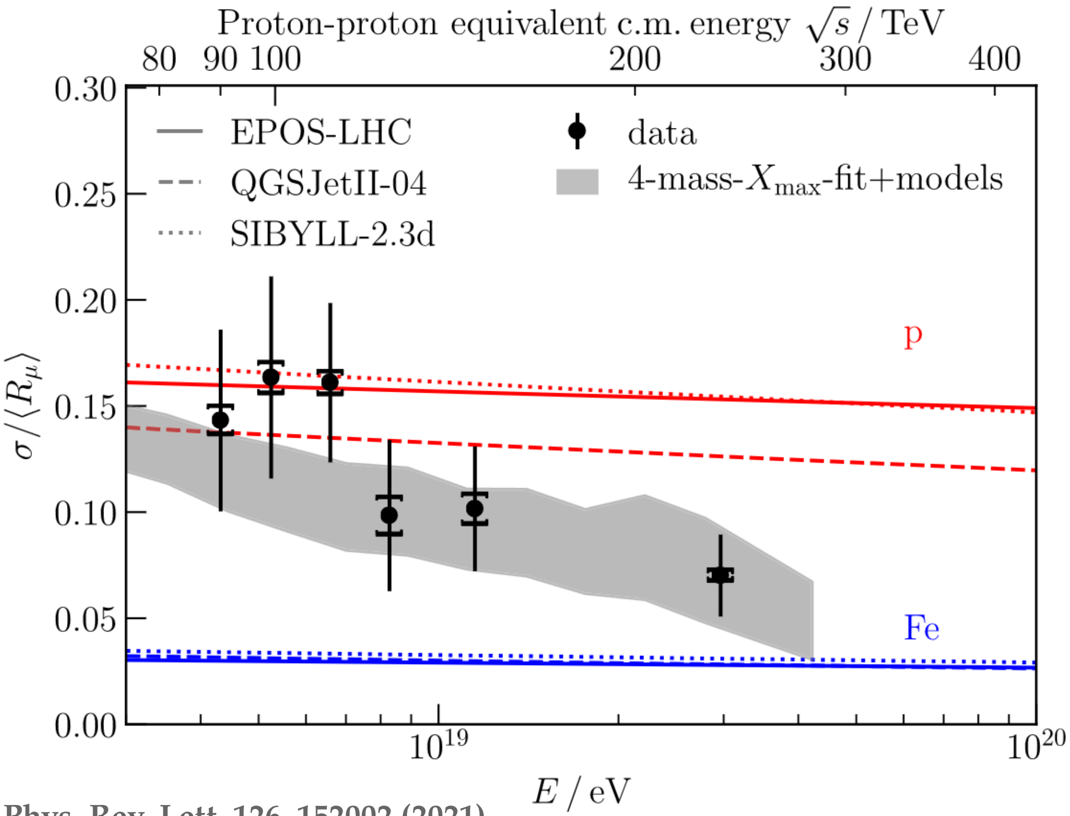


Eur. Phys. J. C 2020 80:751

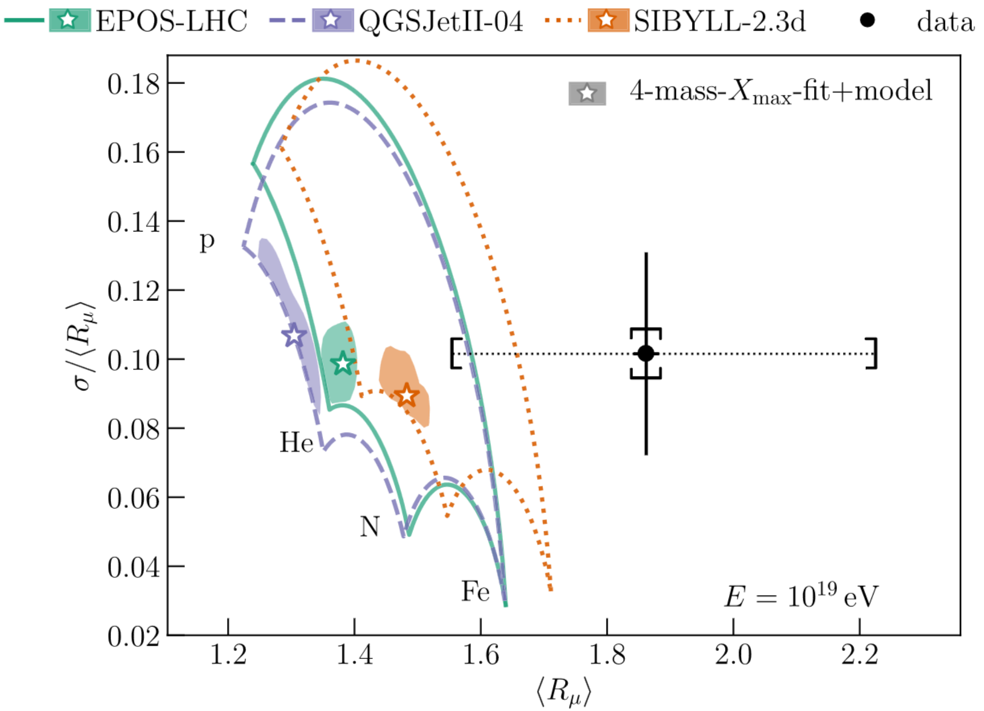
Phys. Rev. D 91, 032003 (2015)

Fluctuations of muon number

- **Fluctuations** in number of muons R_μ



Phys. Rev. Lett. 126, 152002 (2021)



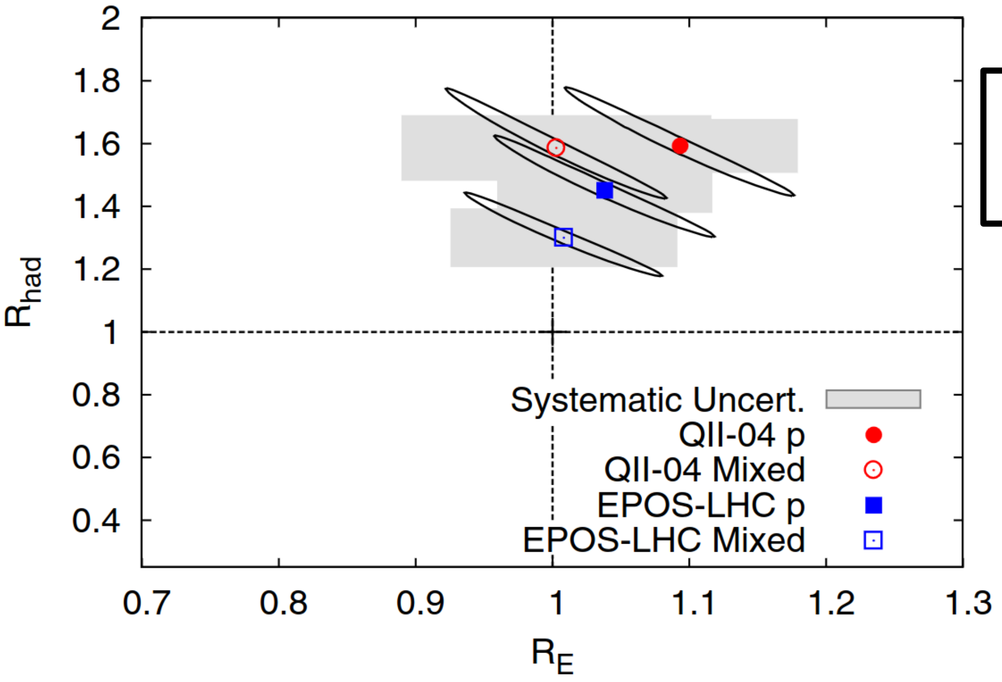
- Muon density fluctuations **consistent with expectations**

- **Small effect accumulating** over several interactions

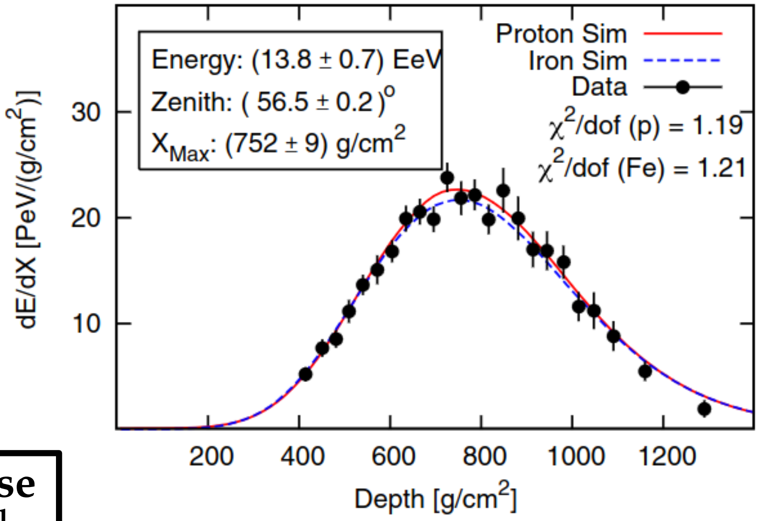
Hybrid measurement

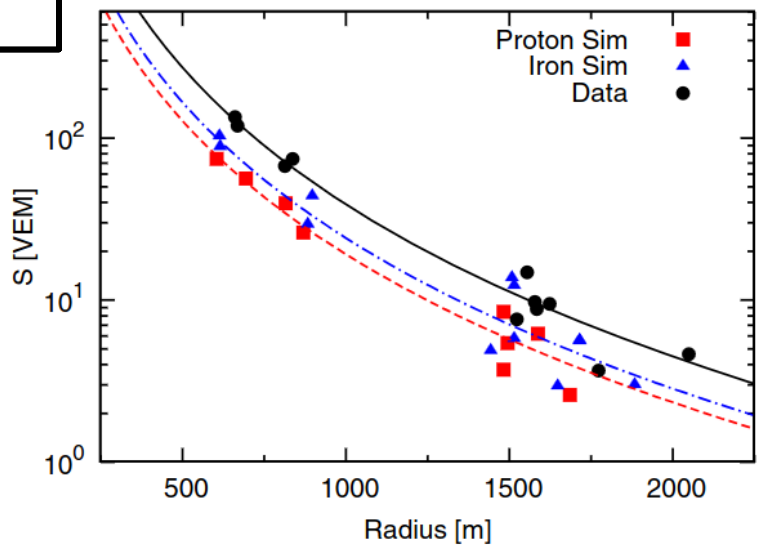
- Select **simulations with matching FD** profile and compare SD signals

- $S_{resc} = R_E\, S_{EM} + R_{had}\, R_E^{\alpha}\, S_{had}$



30% - 60% increase of muonic signal needed



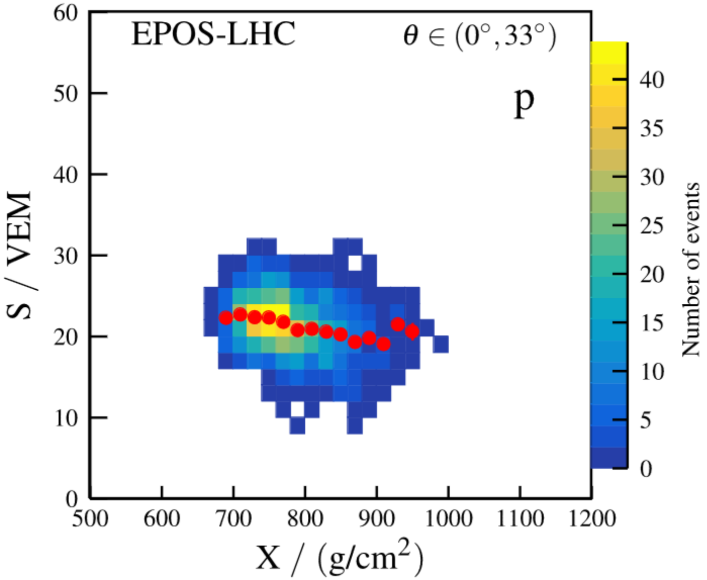


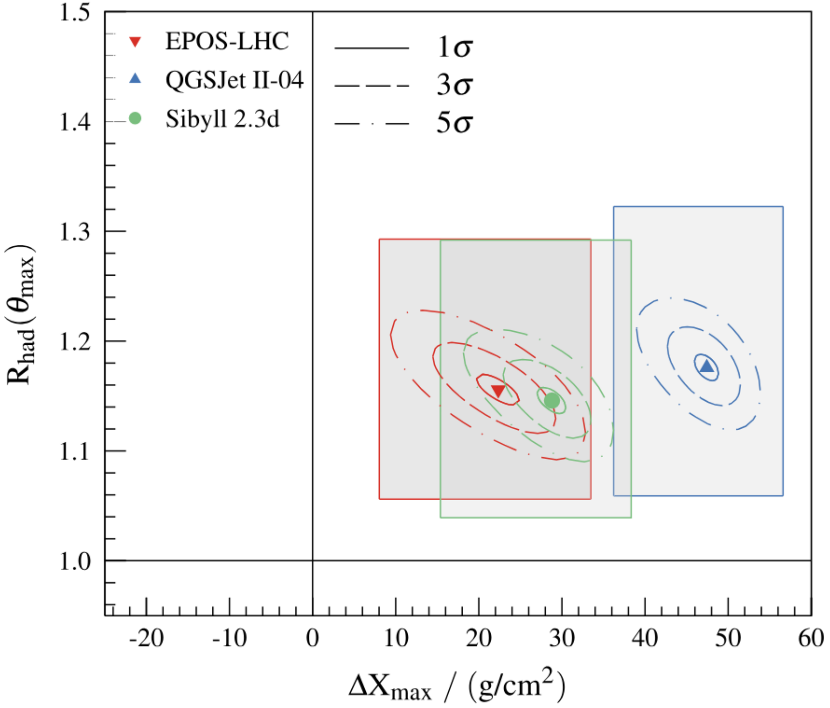
Phys. Rev. Lett. 177, 192001 (2016)

Modification of the MC X_{max} scale

- Fit of **[S(1000), X_{max}]** distributions to **MC templates**

- **Freedom** of primary fractions, $R_{had}(\theta)$ and ΔX_{max}





- **Alleviated „muon problem“** with shift of MC X_{max}

- **Smaller model differences** for mass composition

15% - 25% increase of muonic signal needed

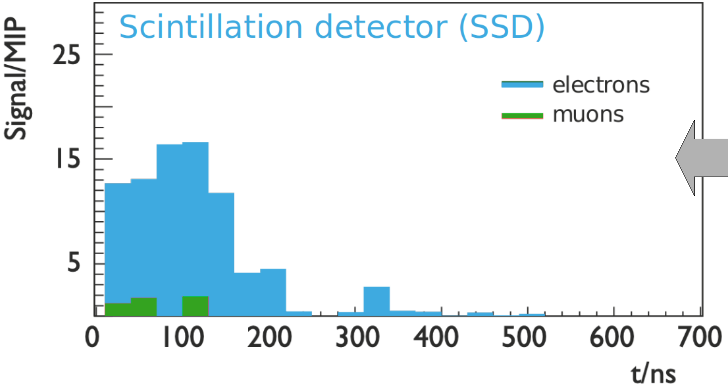
	$R_{had}(\theta_{min})$	$R_{had}(\theta_{max})$	$\Delta X_{max}/(g/cm^2)$
Epos-LHC	$1.15 \pm 0.01^{+0.20}_{-0.16}$	$1.16 \pm 0.01^{+0.14}_{-0.10}$	$22 \pm 3^{+11}_{-14}$
QGSJet-II-04	$1.24 \pm 0.01^{+0.22}_{-0.19}$	$1.18 \pm 0.01^{+0.15}_{-0.12}$	$47^{+2}_{-1}{}^{+9}_{-11}$
SIBYLL 2.3d	$1.18 \pm 0.01^{+0.21}_{-0.17}$	$1.15 \pm 0.01^{+0.15}_{-0.11}$	$29 \pm 2^{+10}_{-13}$

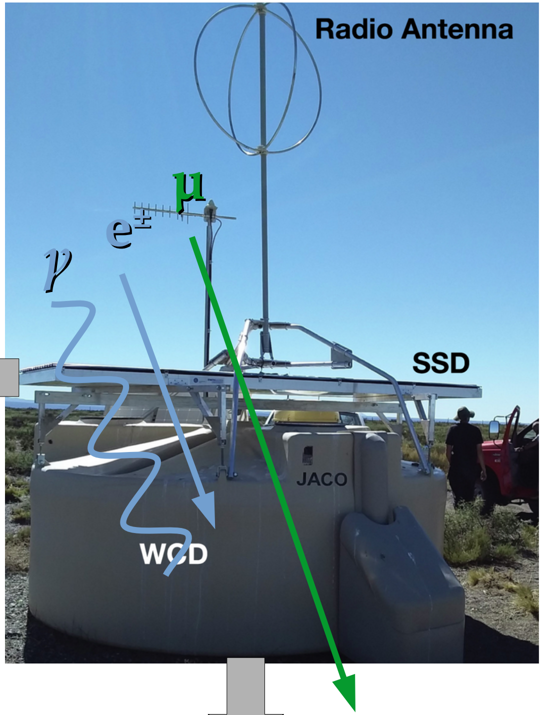
Phys. Rev. D 109, 102001 (2024)

Outlook

- **Modification** of different characteristics of **hadronic interactions**
  (see talk by Jakub Vicha on 03.09.24)

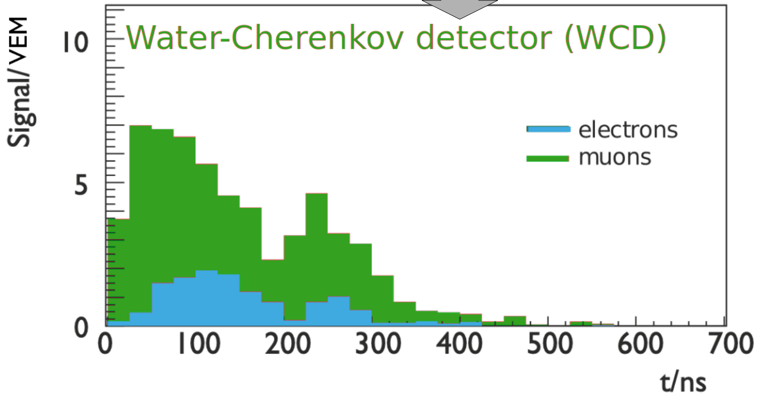
- More tests at colliders
  p-O collisions @ **LHC Run 3**





- **AugerPrime** with additional detectors
  - Scintillator surface detector
  - Underground muon detector
  - Radio antenna

→ better **discrimination of hadronic signal**
(see talk by David Schmidt on 03.09.24)



PoS (ICRC2023) 245
arXiv:1604.03637

Summary

- **UHECR** give access to interactions in high energy regions beyond those of human-made accelerators

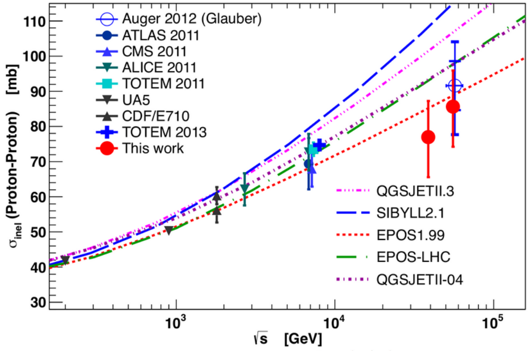
  → Auger's **hybrid detector** enables the measurement EM and muon components of EAS

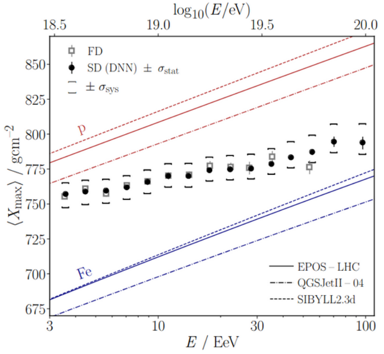
- Auger data offers complementary information on hadronic interaction models with **measurement of p-air cross section**

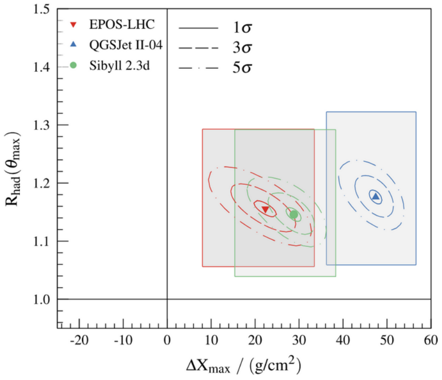
- **Testing** of hadronic interaction models via
  - measurement of X_{max}
  - measurement of **muon content**

- **Improvements** in measurement of muon discrepancy

- Further advancements with **AugerPrime** expected







BACKUP

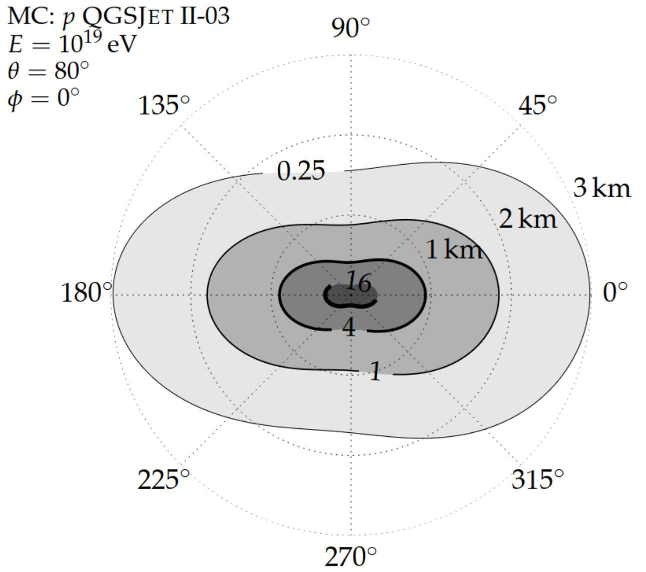
Backup: Highly inclined events

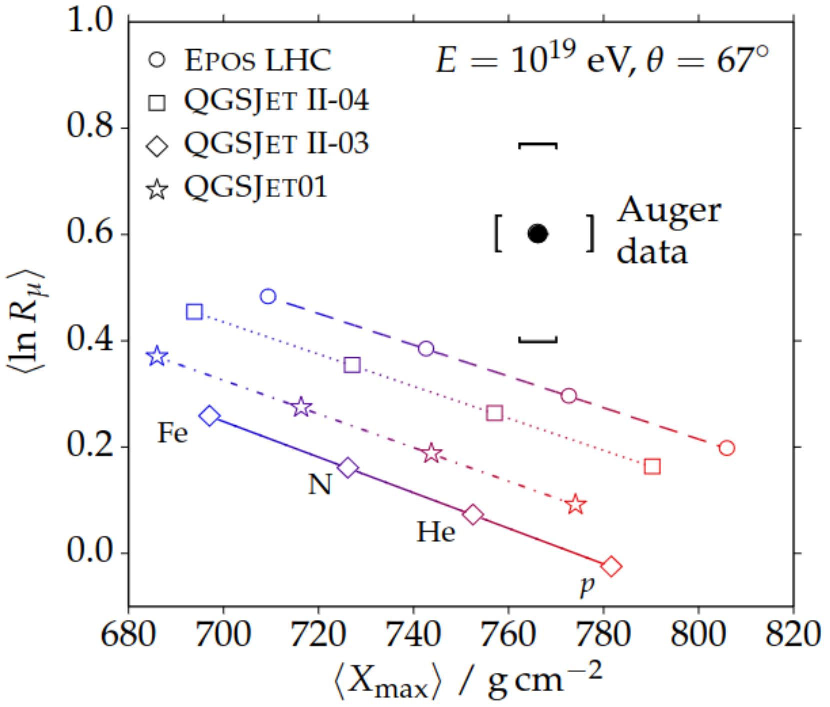
- Fit, using **reference muon map** from MC ($\rho_{\mu,19}$)

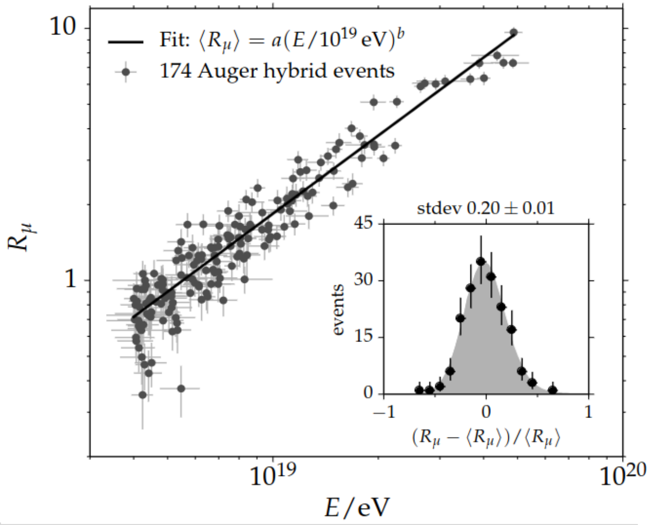
$$\rho_\mu(\vec{r}) = N_{19}\ \rho_{\mu,19}(\vec{r};\theta,\phi)$$

- Proportionality of average ***R_μ* to shower energy *E***

- **30 – 80%** deficit in muon density @ 10^{19} eV







Phys. Rev. D 91, 032003 (2015)