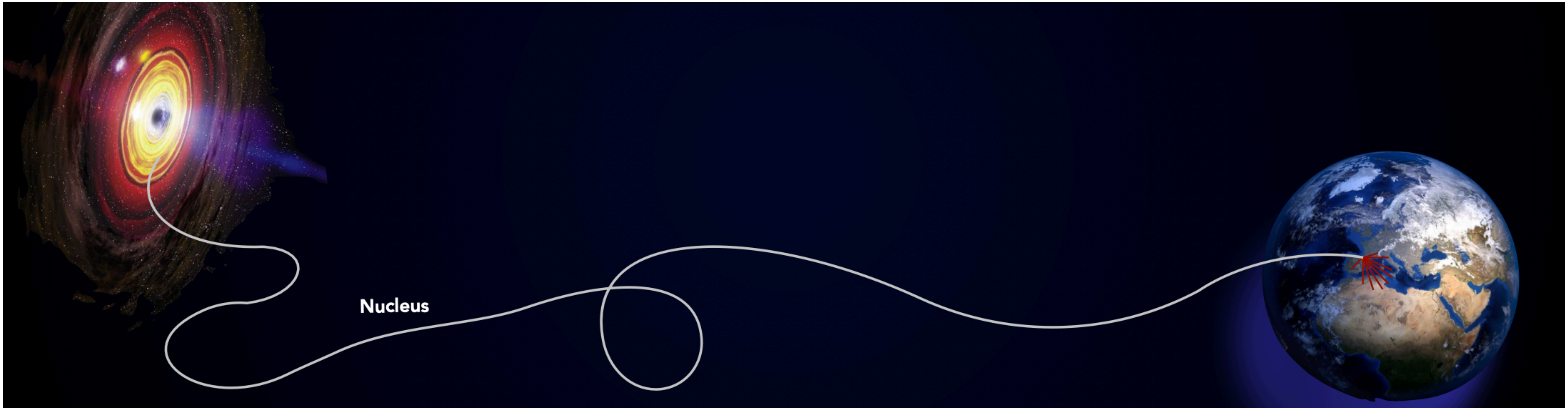
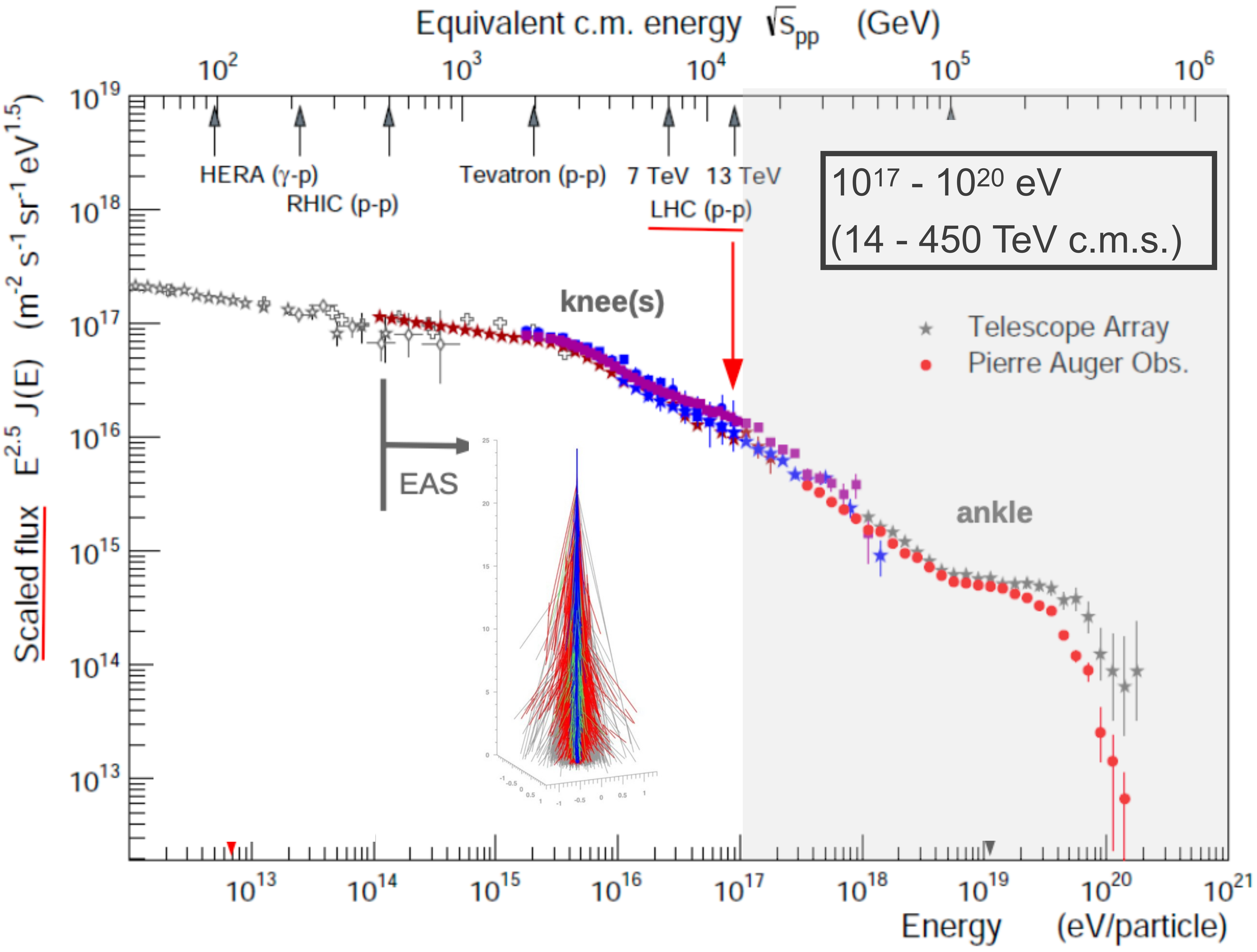
Exploring Hadronic Interactions Beyond Collider Energies: Insights from the Pierre Auger Observatory

Analisa Mariazzi on behalf of the Pierre Auger Collaboration



Physicis in Collision 2023 PIC2023

Cosmic rays: the most energetic particles in the Universe



High energy cosmic rays are very difficult to measure because the flux is too small and one need huge detectors. They cannot be measured directly .

Energy of CRs far above the ones achievable by present accelerators :

Possibility to study hadronic interactions at the most extreme energies

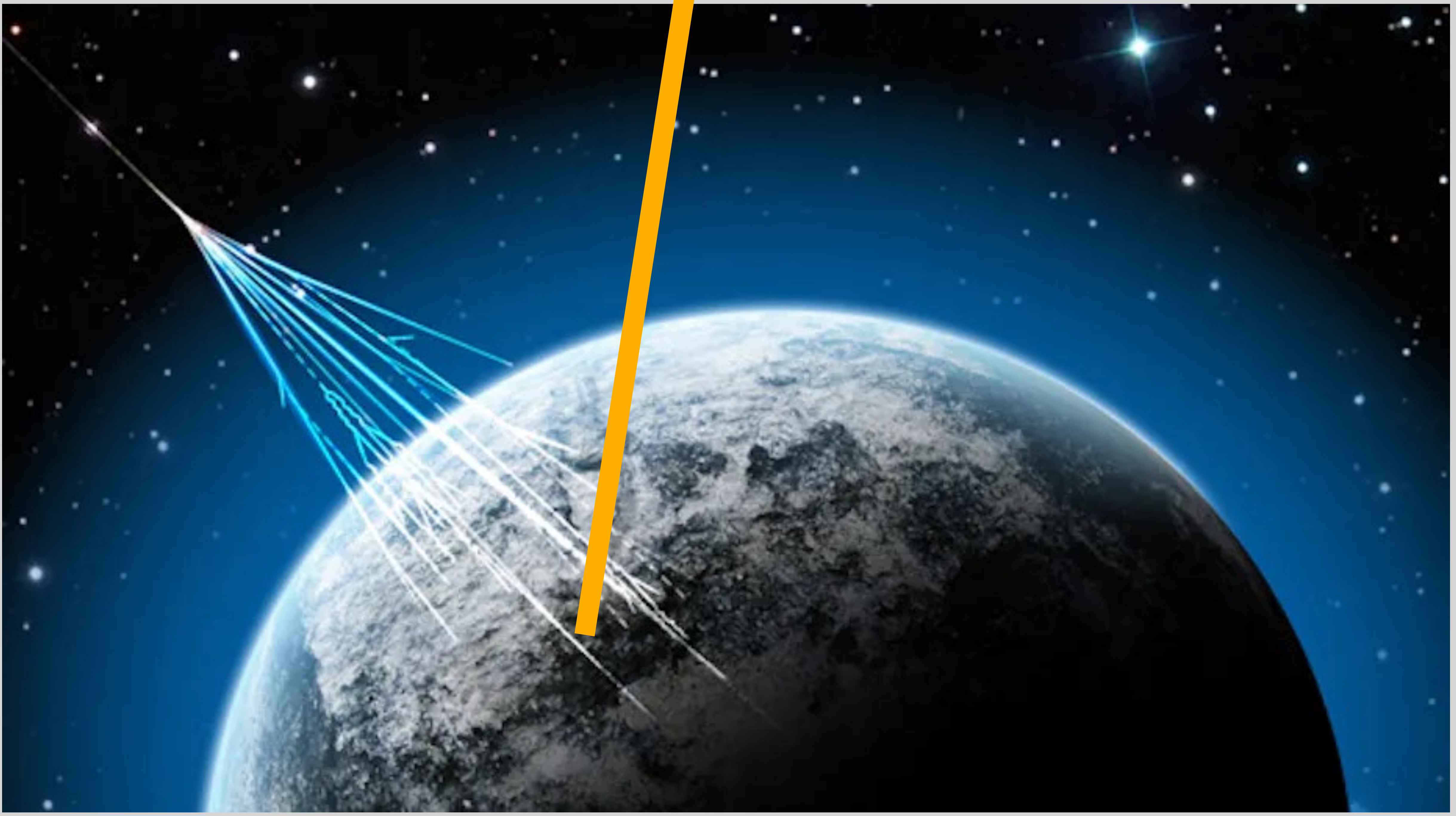
Sources/acceleration

Extensive air shower

Detector

Cosmic ray particle

Earth’s atmosphere as a calorimeter



Challenges in cosmic ray science :

➔ Uncertainty on primary energy, mass composition

➔ Extrapolation from LHC energy

➔ Extreme forward regions critical :

Pseudo-rapidity $|\eta| \lesssim 5$ at LHC.

$\eta \approx 7 - 11$ covers the majority of the energy flow of the first interactions.

➔ Hadron-Air interactions are critical:

Collision systems include p-p, p-Pb, Pb-p, Pb-Pb at LHC.

p-Air ... Fe-Air, π-Air interactions are of utmost importance for air shower physics.

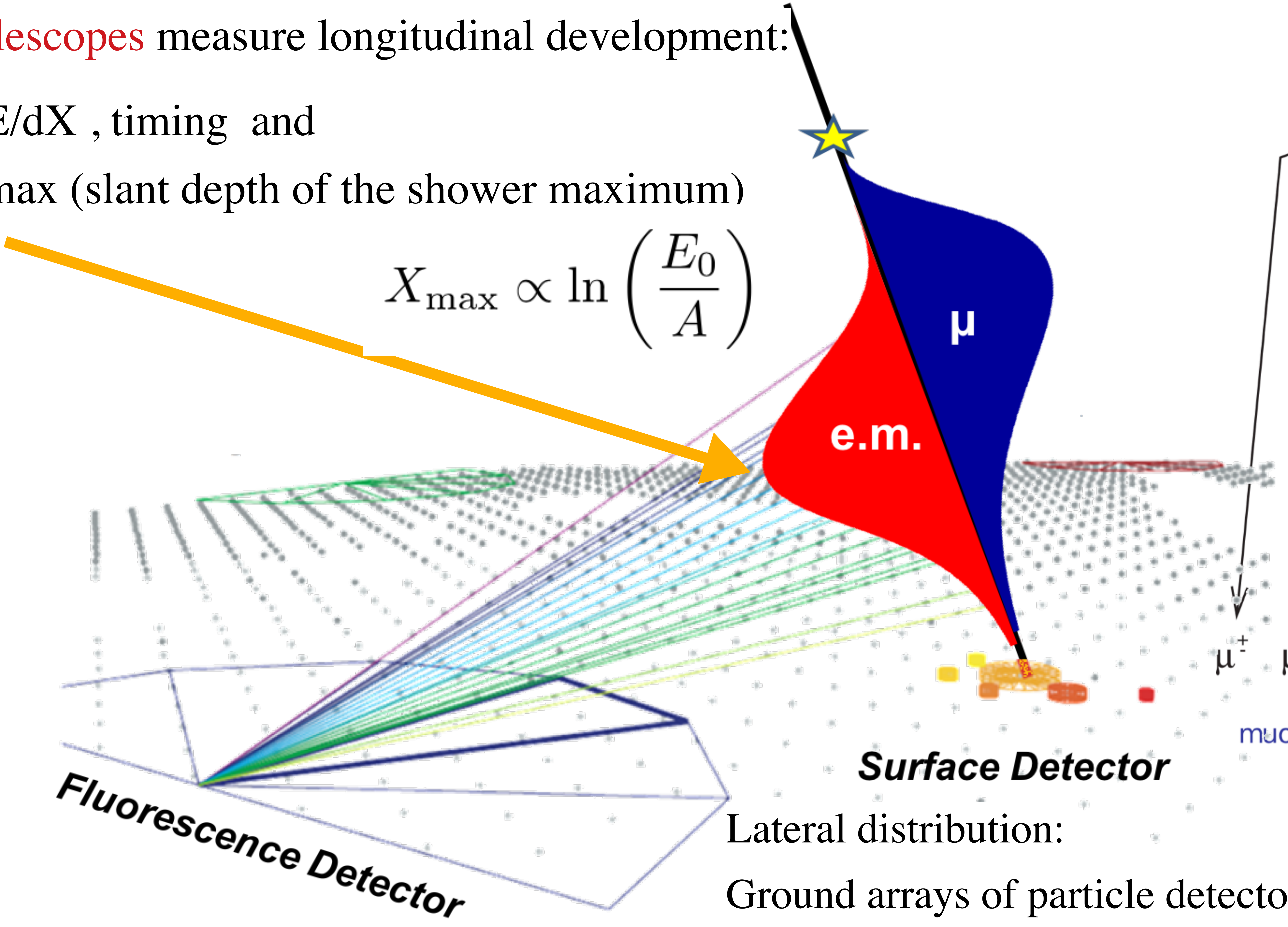
Extensive air showers

Telescopes measure longitudinal development:

dE/dX , timing and

Xmax (slant depth of the shower maximum)

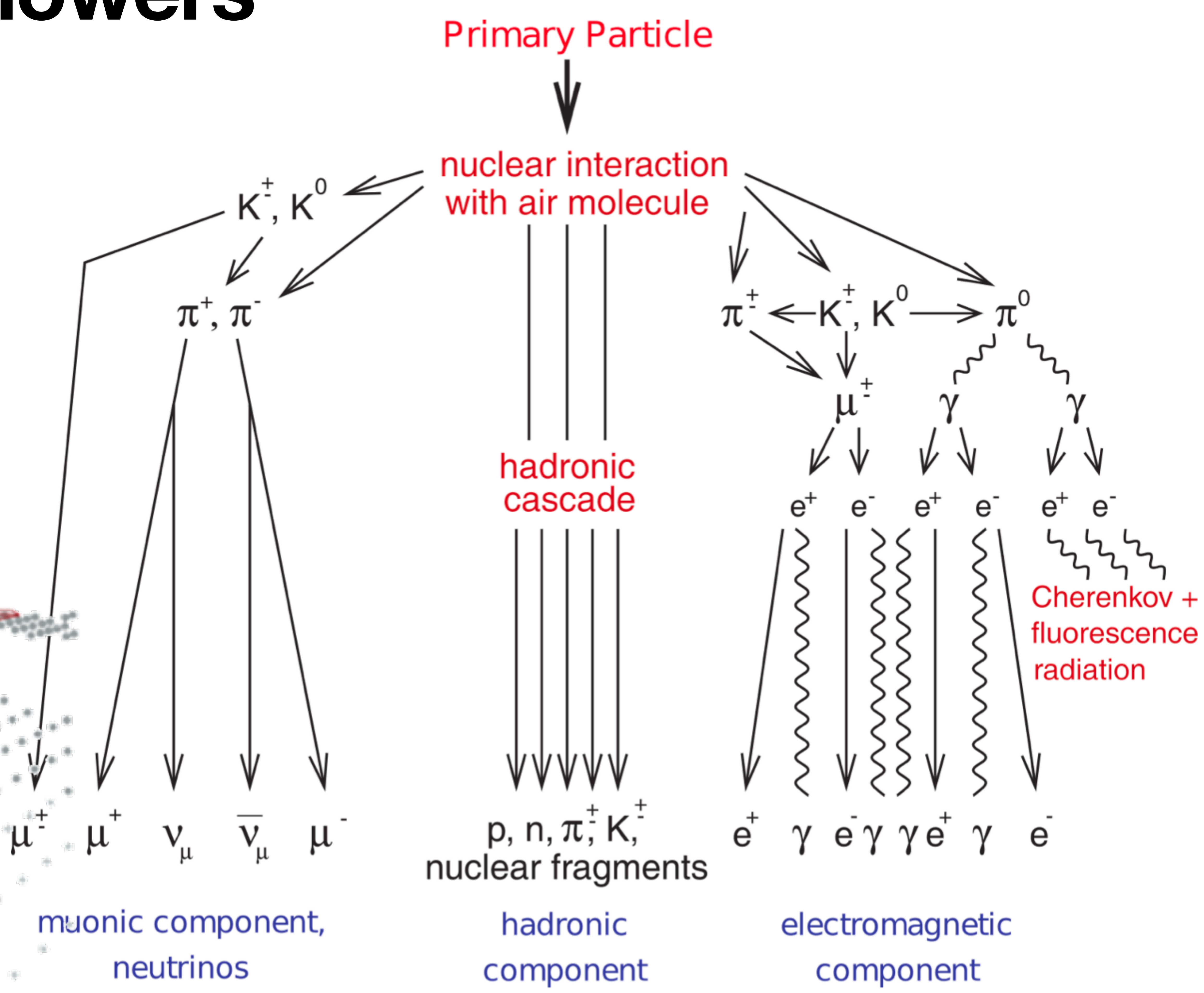
$$X_{\max} \propto \ln\left(\frac{E_0}{A}\right)$$



Lateral distribution:

Ground arrays of particle detectors

measure particle fluxes and timing



$$N_\mu = A^{1-\beta}\left(\frac{E_0}{\xi}\right)^{\beta}$$

$$\beta = \frac{\ln(N_{mult}\,\alpha)}{\ln(N_{mult})}$$

Fraction of charged pions

Multiplicity

Muon number **beta parameter** depends on multiplicity, pion charge-ratio, and elasticity

connection between air shower physics and hadronic interaction models

Extensive air showers

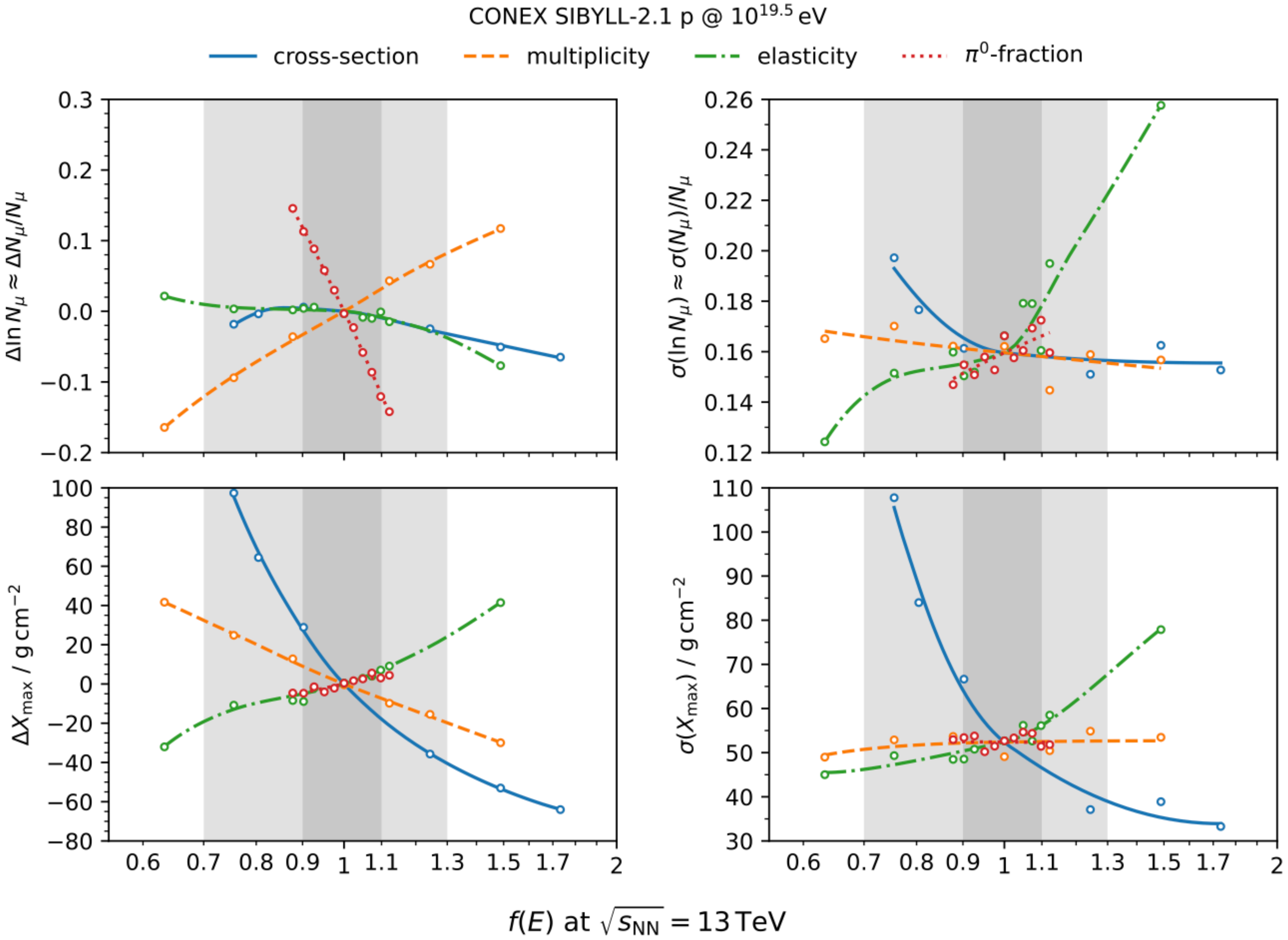
Air shower development dominated by:

-mass and energy of primary CR

-cross-sections (p-Air and (π-K)-Air)

-elasticity: ($E_{leading}$/E_{total}(lab frame))
-multiplicity (total number of secondary hadrons)

-Fraction of π0 (charge ratio)



Fraction of π^0:

Impact on the mean number of muons

Multiplicity:

Impact on the mean number of muons and also on ⟨Xmax⟩

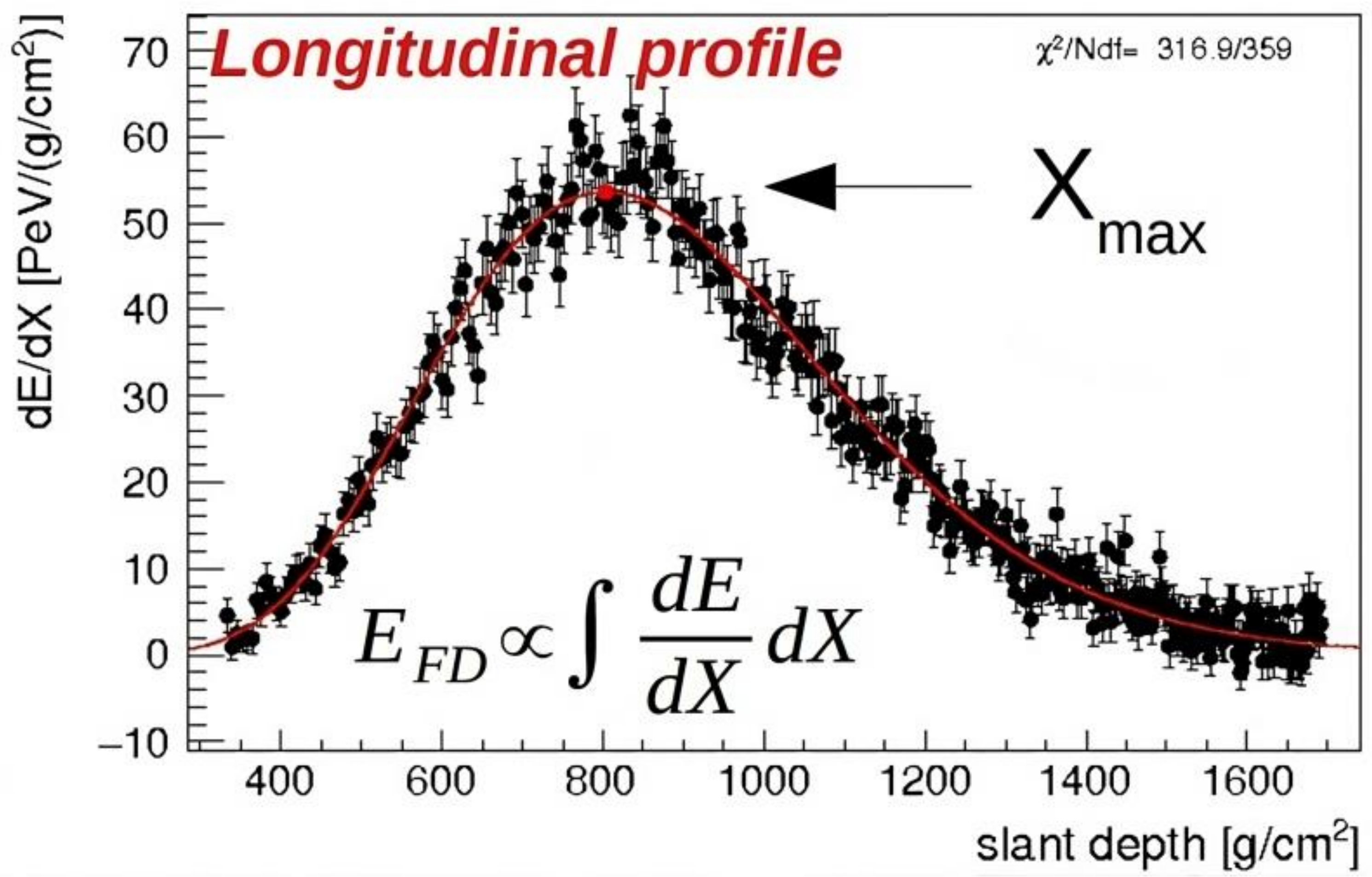
Elasticity:

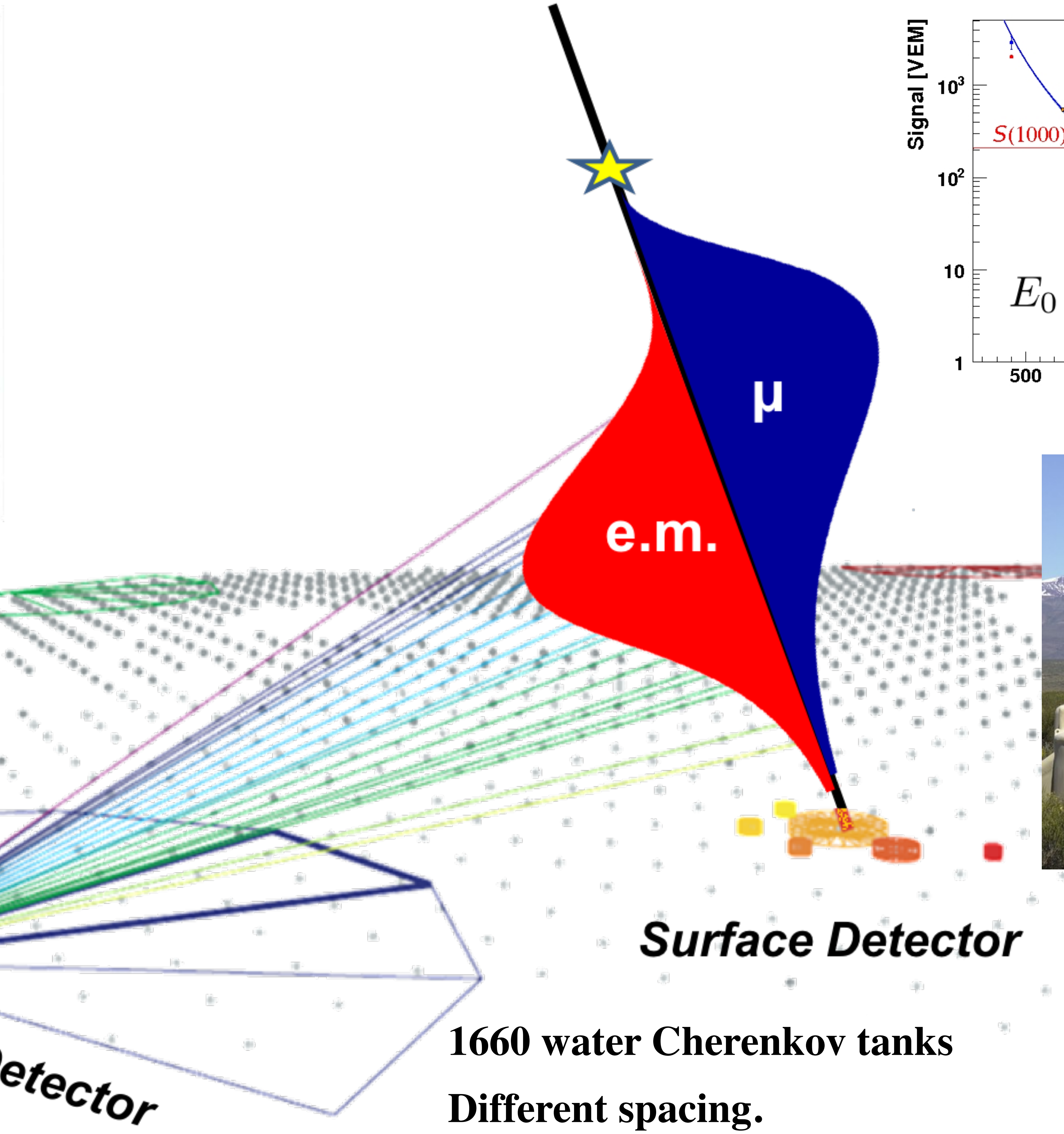
Impact on the fluctuation of the number of muons and also on ⟨Xmax⟩.

Cross section:

The Xmax distribution is most sensitive to the inelastic cross section.

Pierre Auger Observatory: Multi hybrid detection of extensive air showers





$$E_0 = E_{\text{cal}} + E_{\text{invisible}}$$

A Quasi-calorimetric energy measurement

~ 15% duty cycle

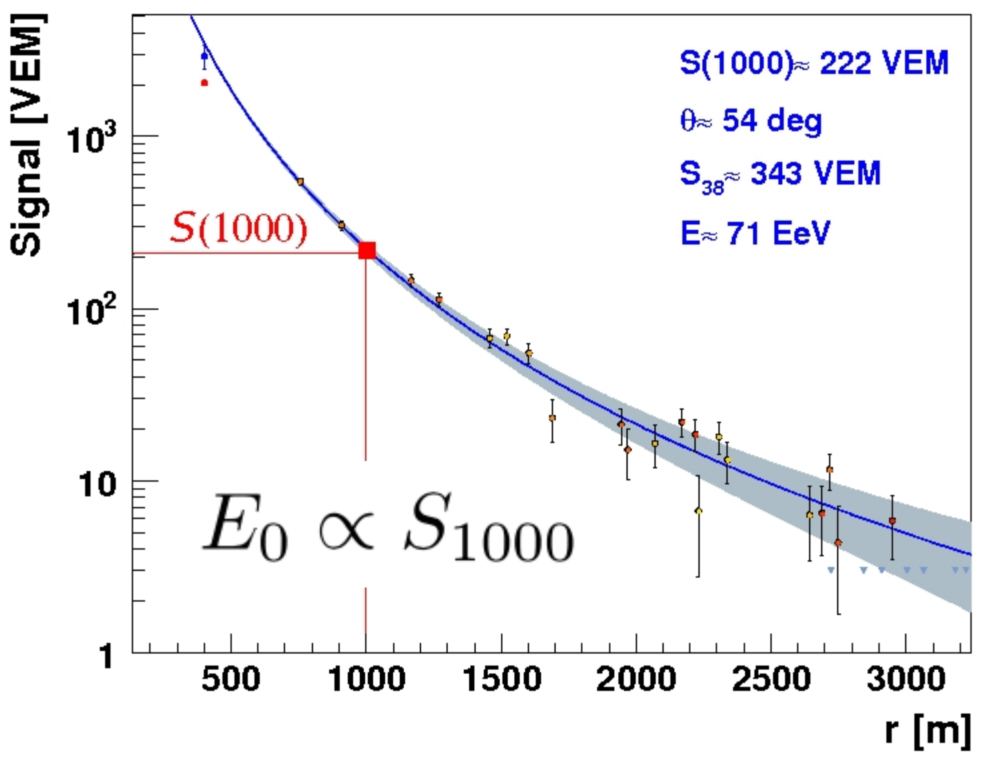
4 building with 6 telescopes each + 3 high elevation telescopes

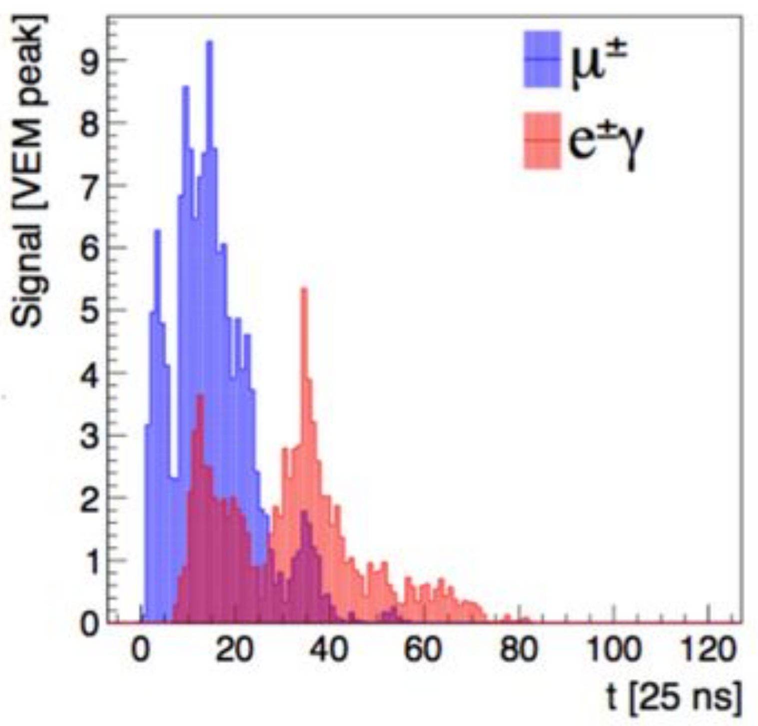
1660 water Cherenkov tanks

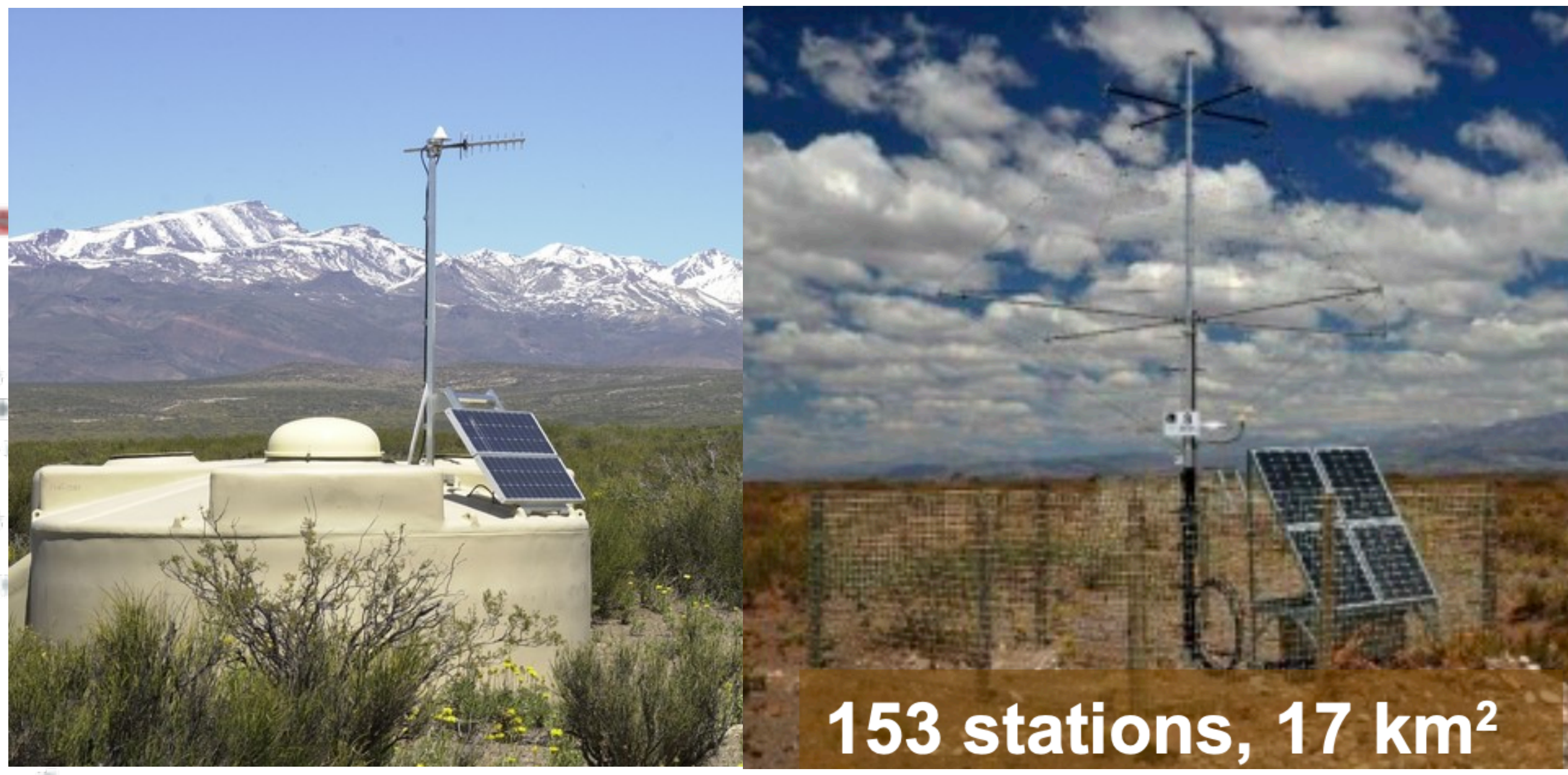
Different spacing.

Area of 3000 km²

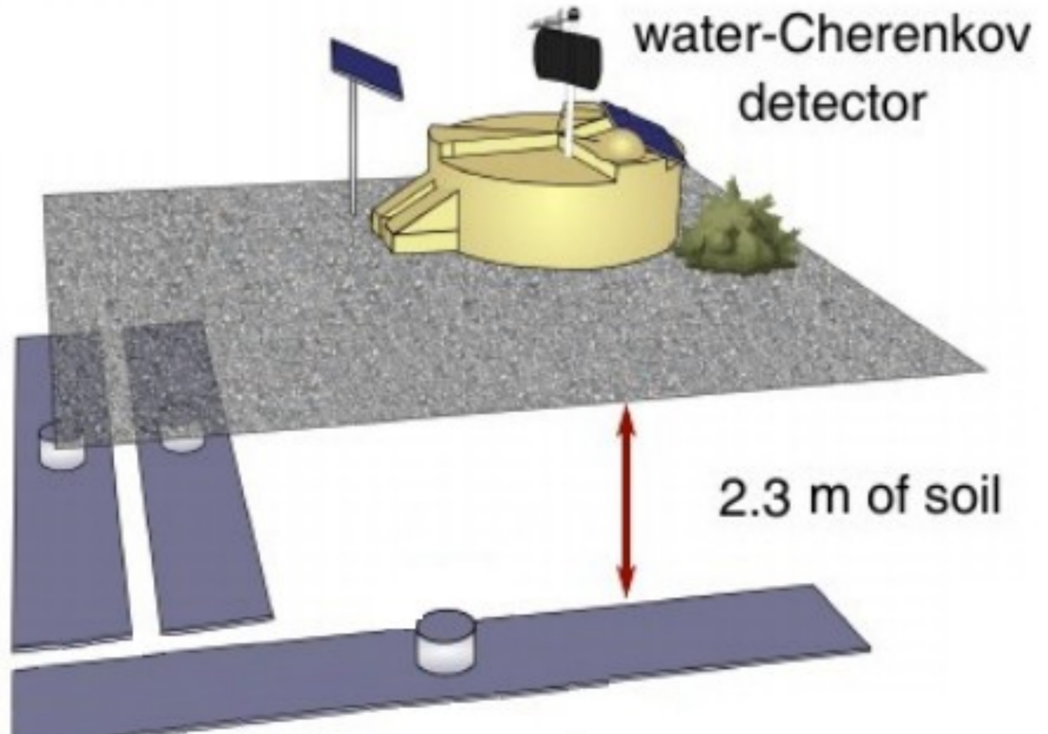
Sensitive to both e.m. and muonic shower components



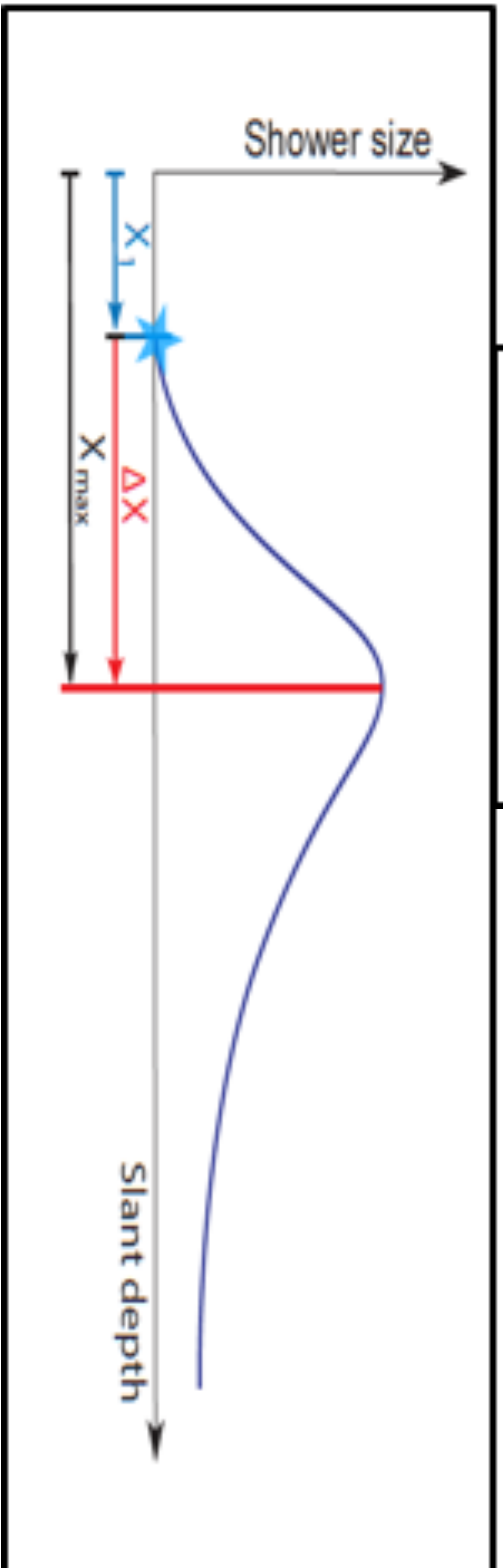




AugerPrime will add new detectors, becoming a multi-hybrid instrument.



Proton air cross section

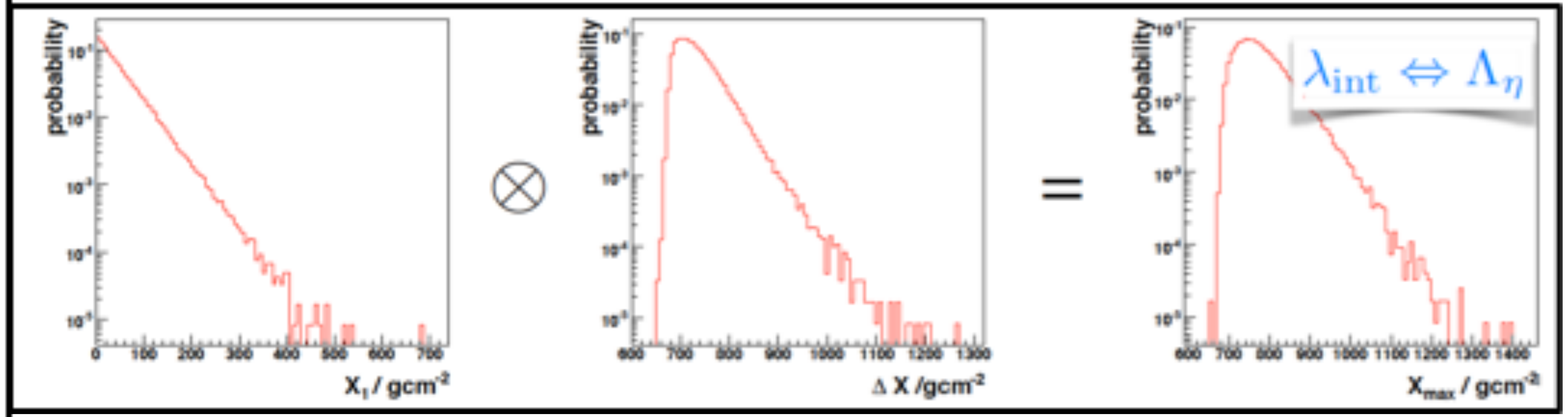


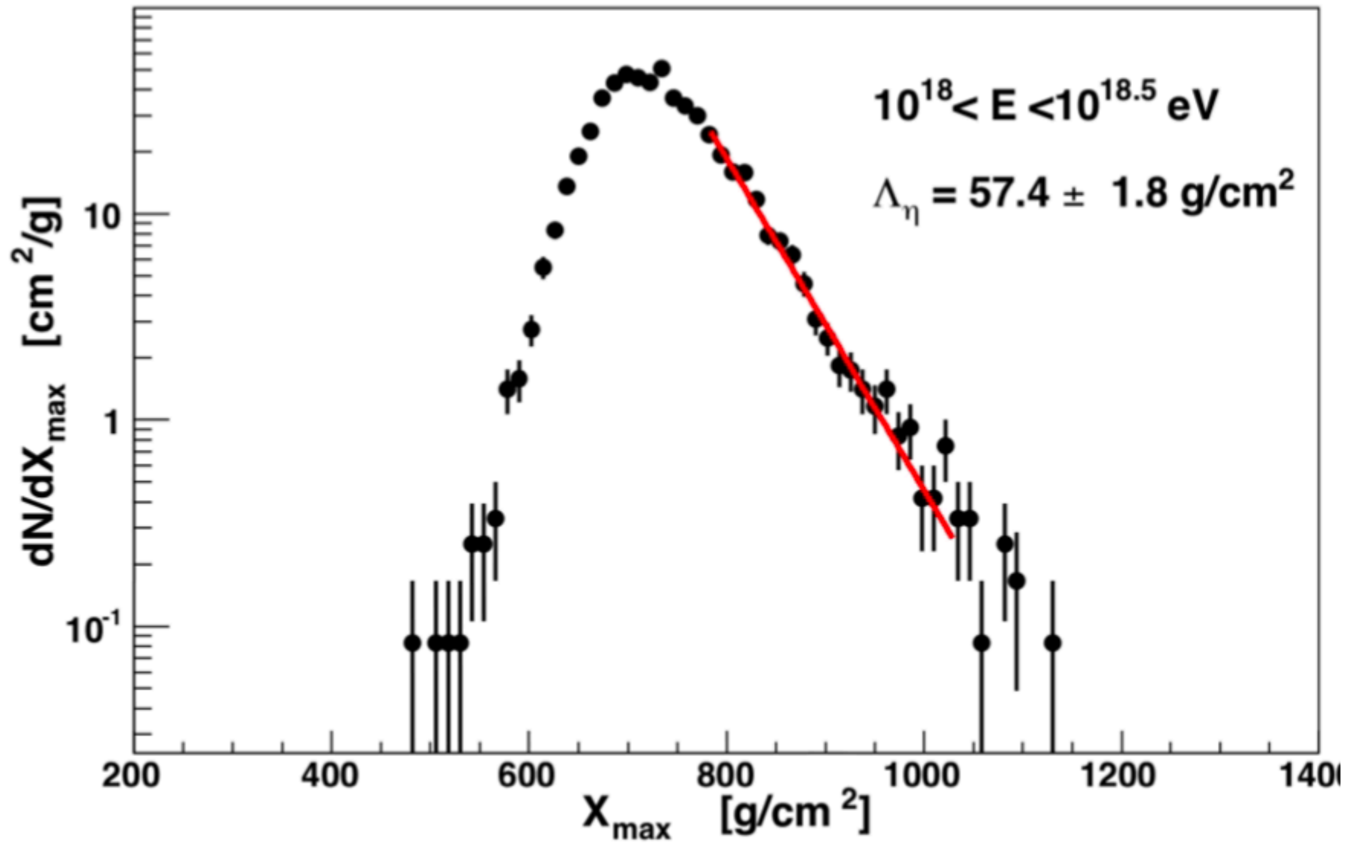
$$\sigma_{\rm int} = \frac{\langle m_{\rm air}\rangle}{\lambda_{\rm int}}$$

Cross section has a strong impact on the distribution of X_{max}

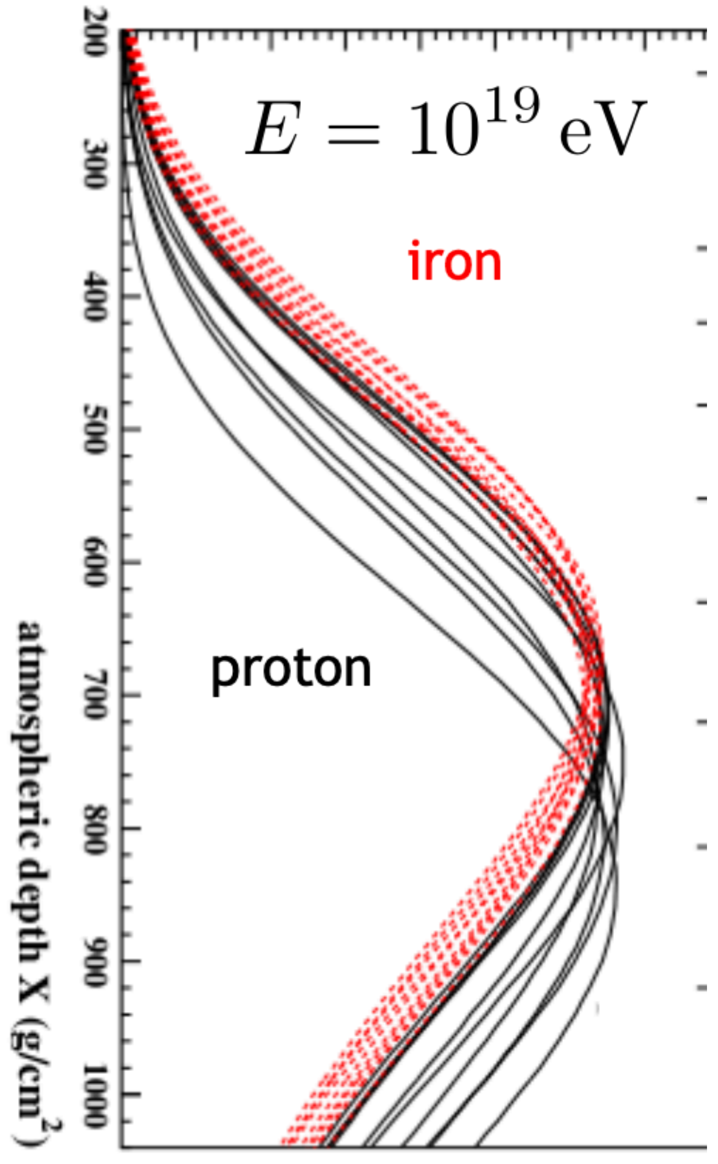
$$\frac{\mathrm{d}\,p}{\mathrm{d}\,X_1} = \frac{1}{\lambda_{\rm int}} e^{-\frac{X_1}{\lambda_{\rm int}}}$$

$$\frac{\mathrm{d}\,N}{\mathrm{d}\,X_{\rm max}} \propto e^{-\frac{X_{\rm max}}{\Lambda_\eta}}$$

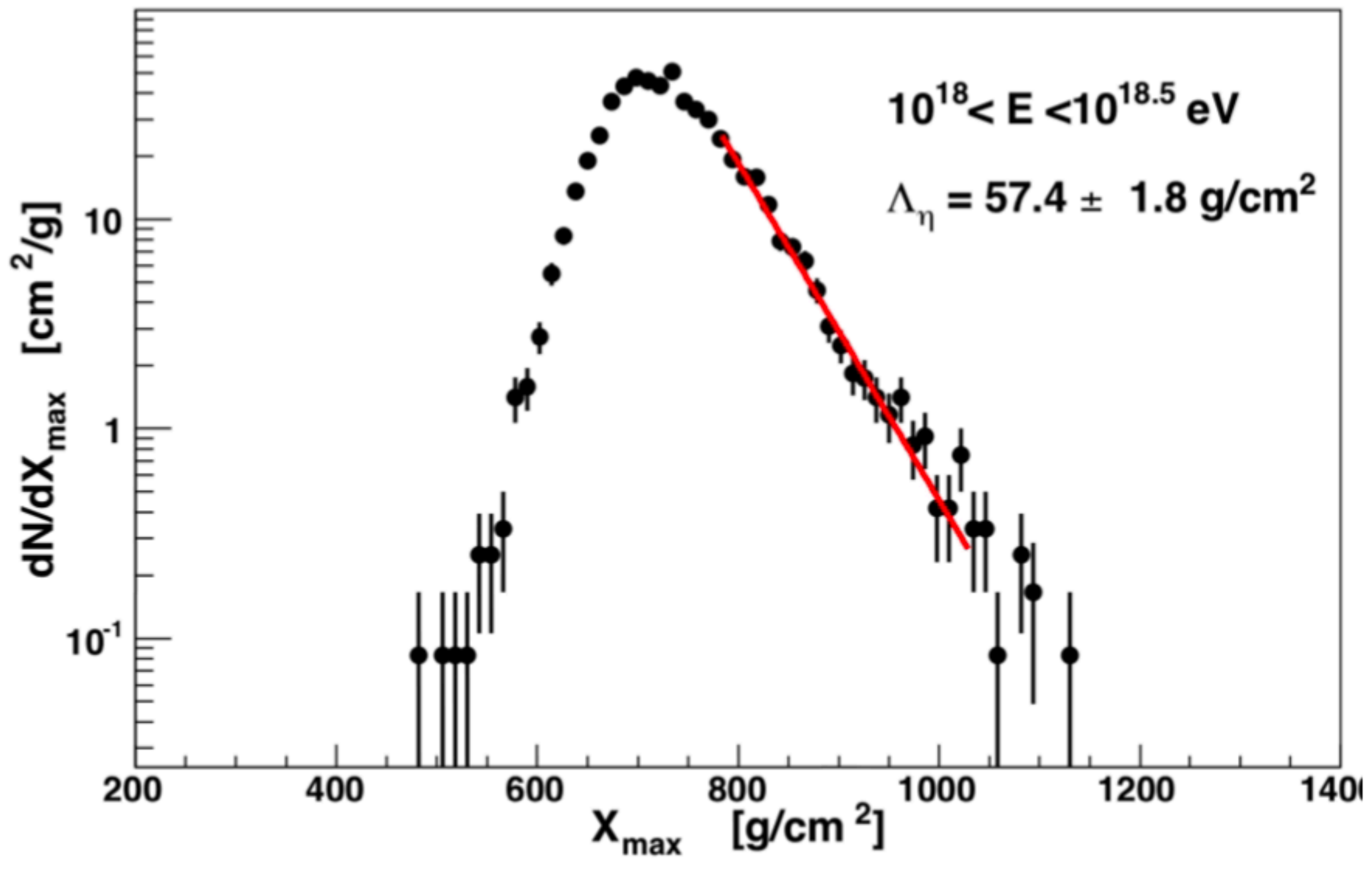


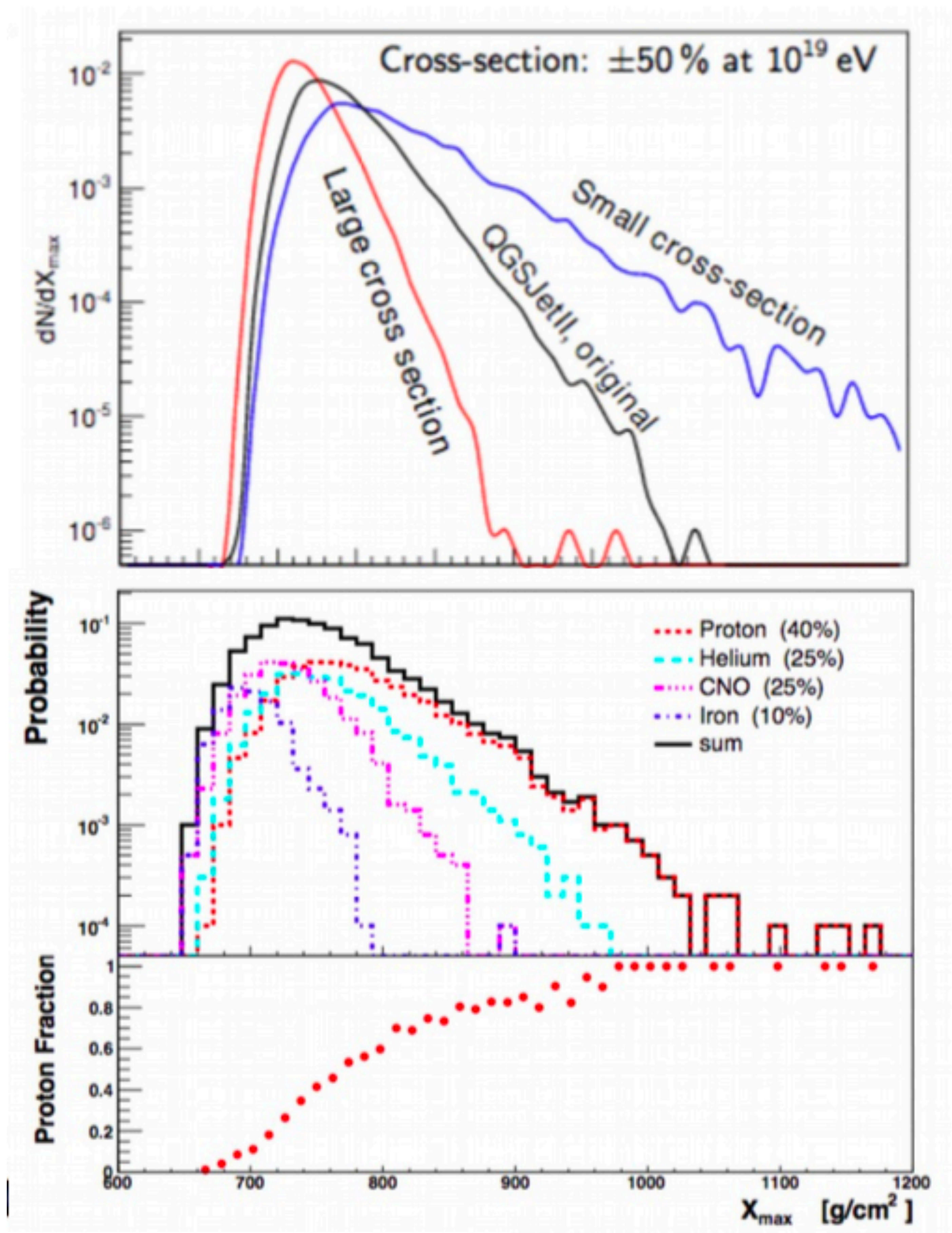


- Xmax strongly correlated with X1
- X1 distribution given by p-Air cross section at a given energy.
- Higher values of Xmax correspond to lighter primaries -> tail of Xmax distribution proton dominated
- Most important systematic: He contamination.
- Xmax distribution tail at a given energy interval
- The Xmax distribution observable related to p-Air cross section is Λη, which describes the exponential shape of the tail of the Xmax distribution via dN/dXmax ∝ exp(−Xmax/Λη).
- A conversion function between Λη and the proton- air cross-section is done by changing cross-sections in the simulations empirically.

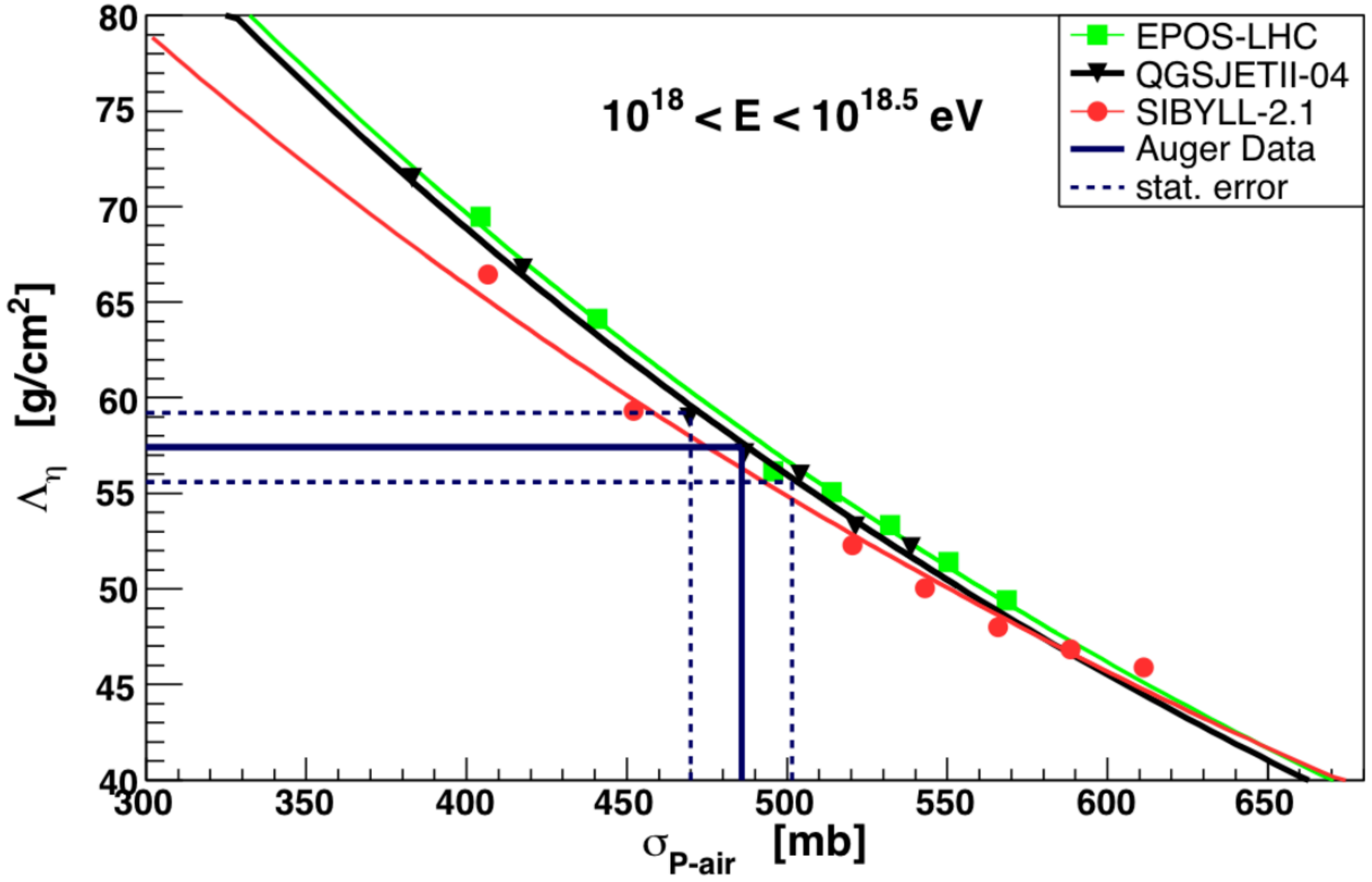


Tuning the cross section to reproduce Λη





Cross-section is changed empirically in the simulations

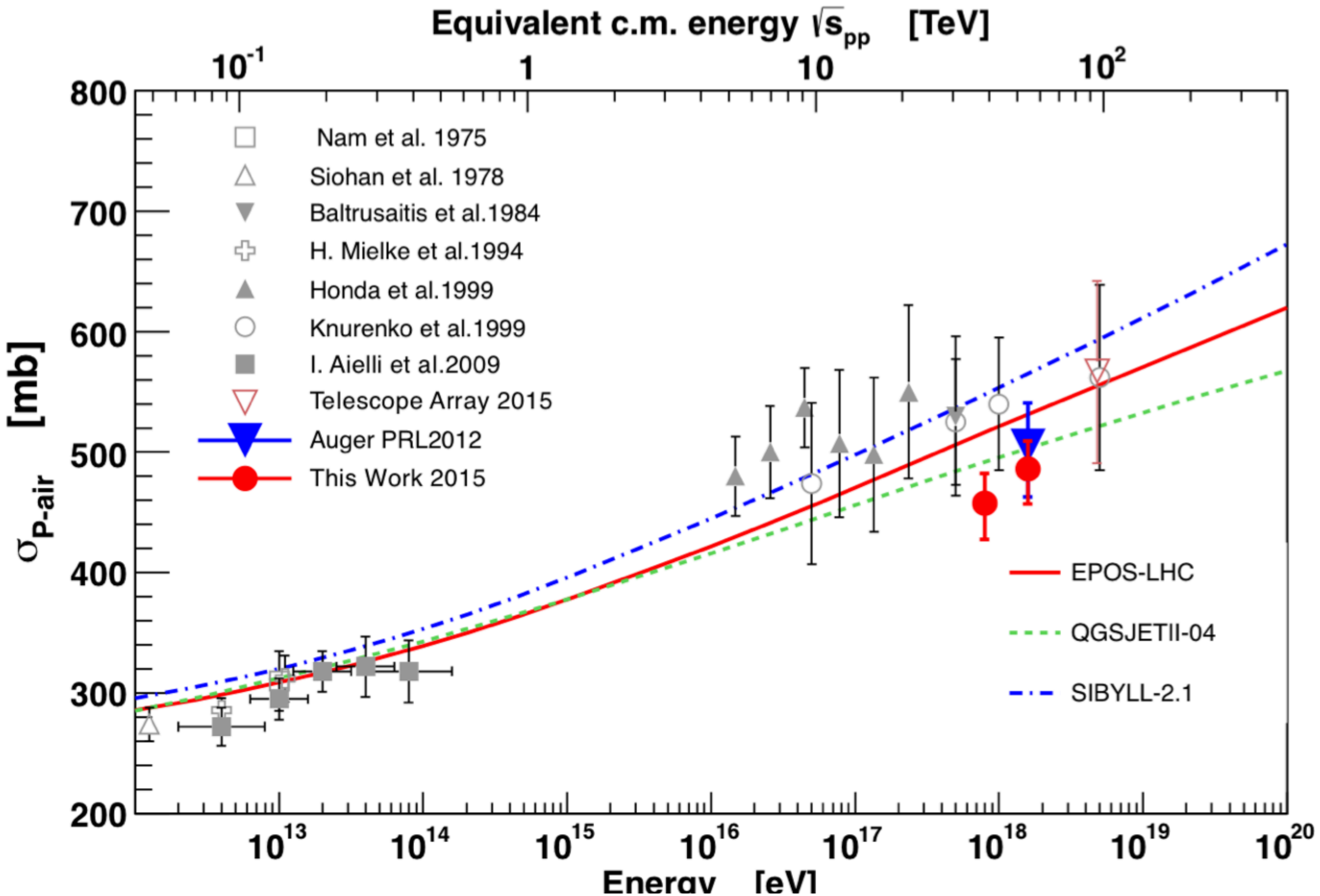


Energy dependent rescaling of the cross section
(F=1 at accelerator energies E_{thr})

$$F(E, f_{19}) = 1 + (f_{19} - 1)\ \frac{\log(E/E_{thr})}{\log(10^{19}\,\mathrm{eV}/E_{thr})}$$

For different values of f_{19}, σ_{p-air} and Λ_η are calculated.

Proton Air cross section



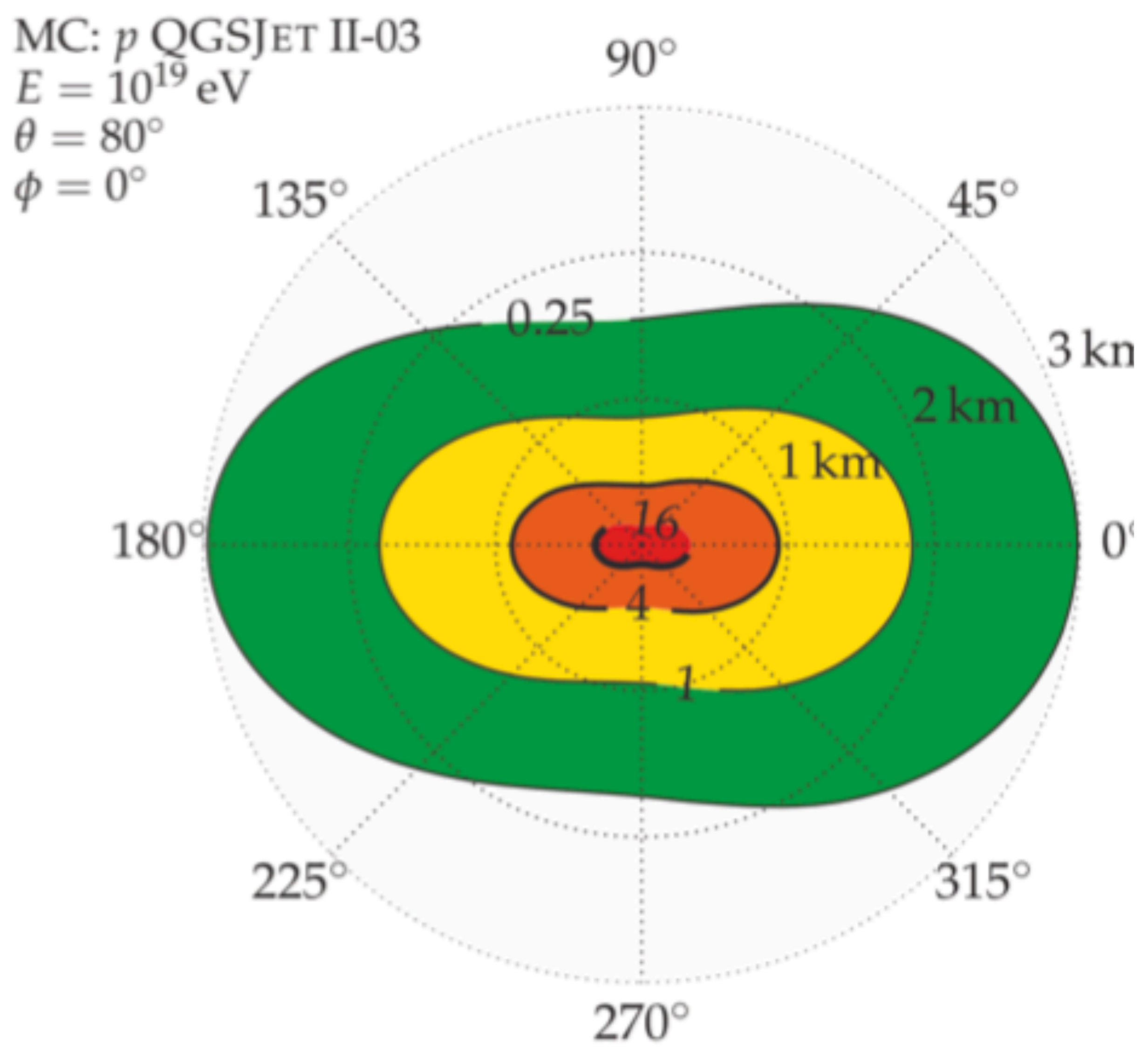
$\sigma_{p\text{-air}}$ = 457.5 mb ($10^{17.8}$ eV < E < 10^{18} eV)

$\sigma_{p\text{-air}}$ = 485.8 mb (10^{18} eV < E < $10^{18.5}$ eV)

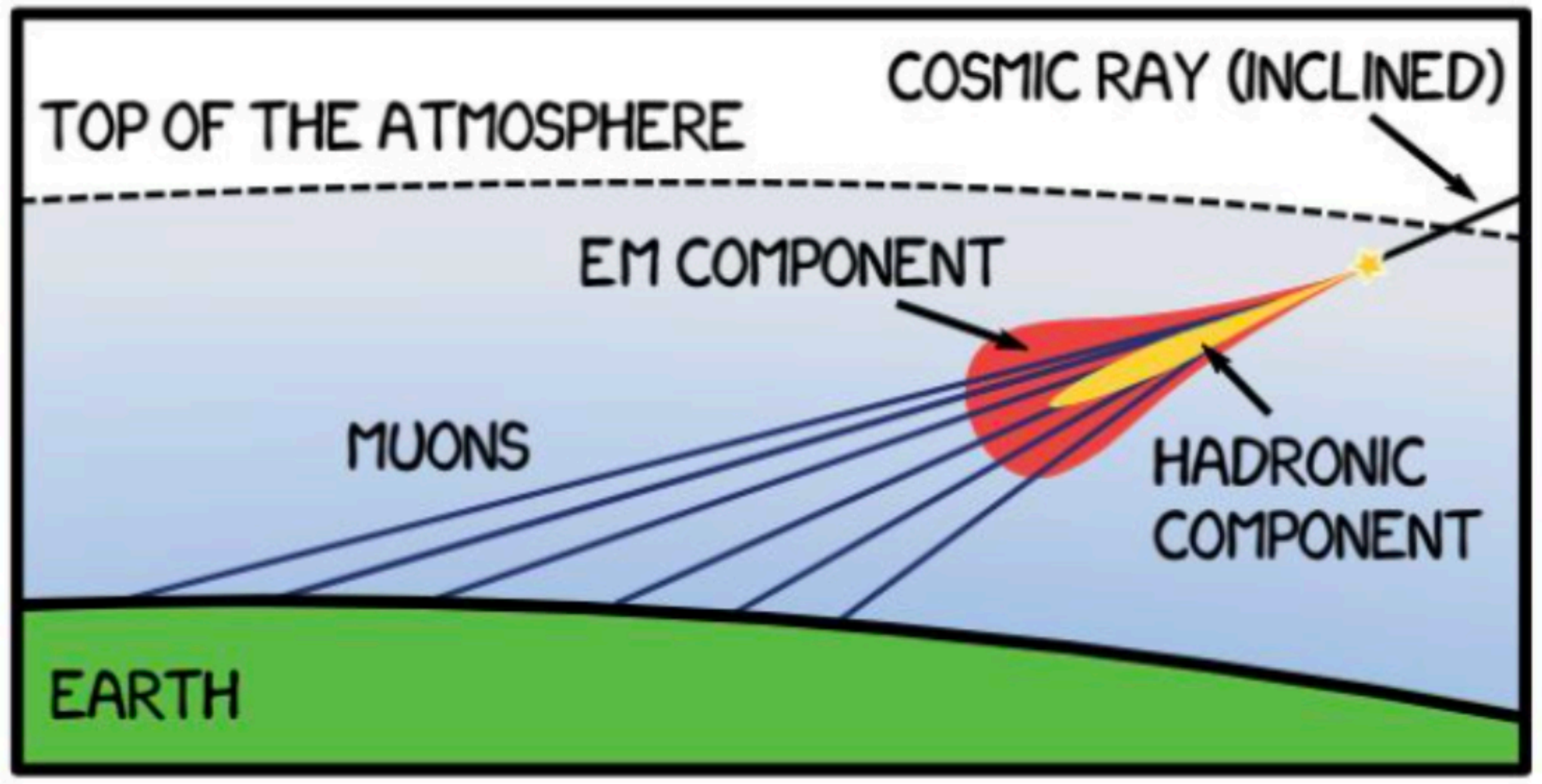
The proton-air cross section measurement measured in two energy bins centered at $10^{17.9}$ eV (38.7 TeV c.m.s.) and $10^{18.25}$ eV (55.5 TeV c.m.s.)

Measurement of the EAS muon content with hybrid inclined showers

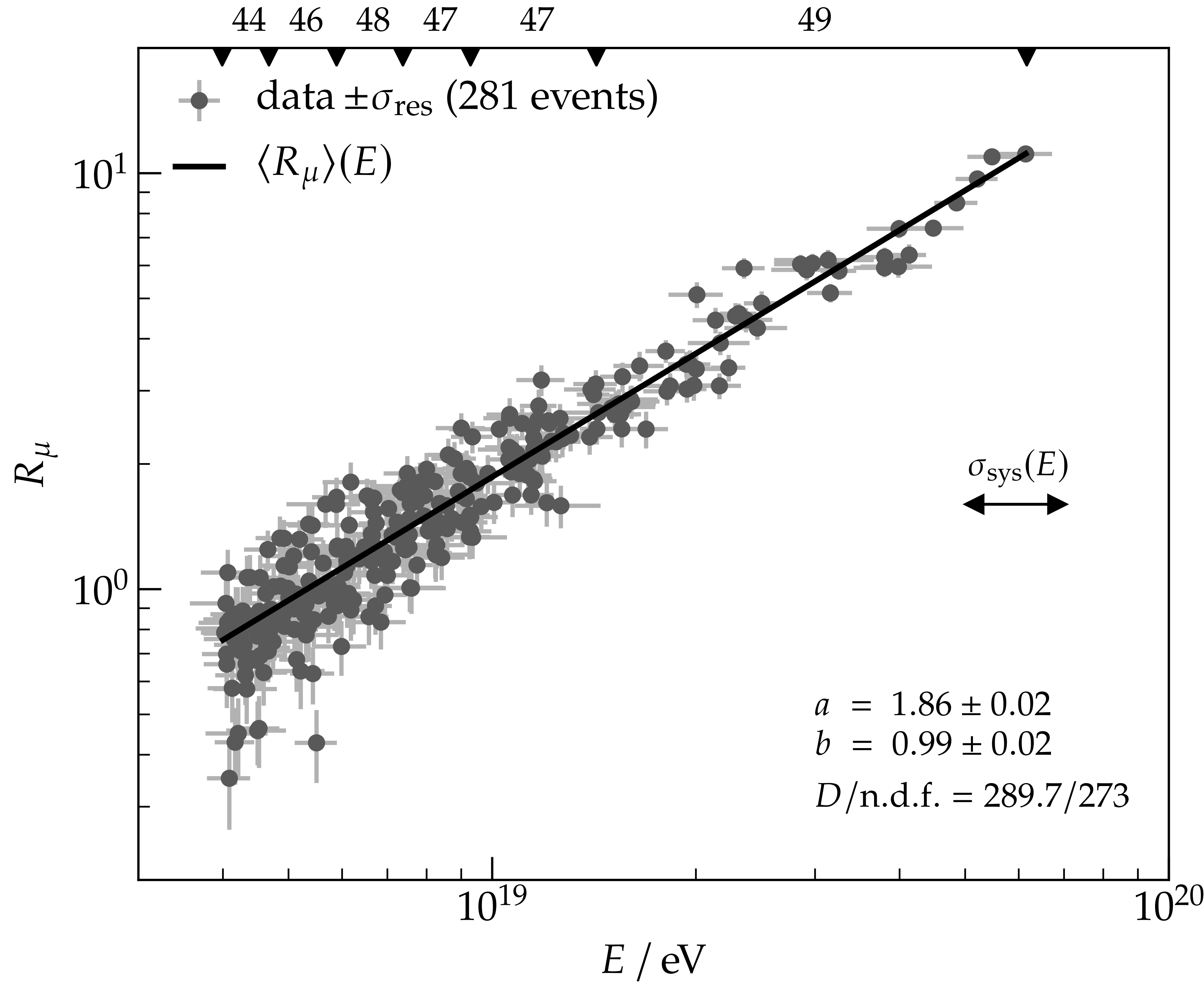
Muon reference map example



Only muons in very inclined events



Muons detected with the SD array



Fit with a reference muon map from MC ($\varrho_{\mu,19}$)

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

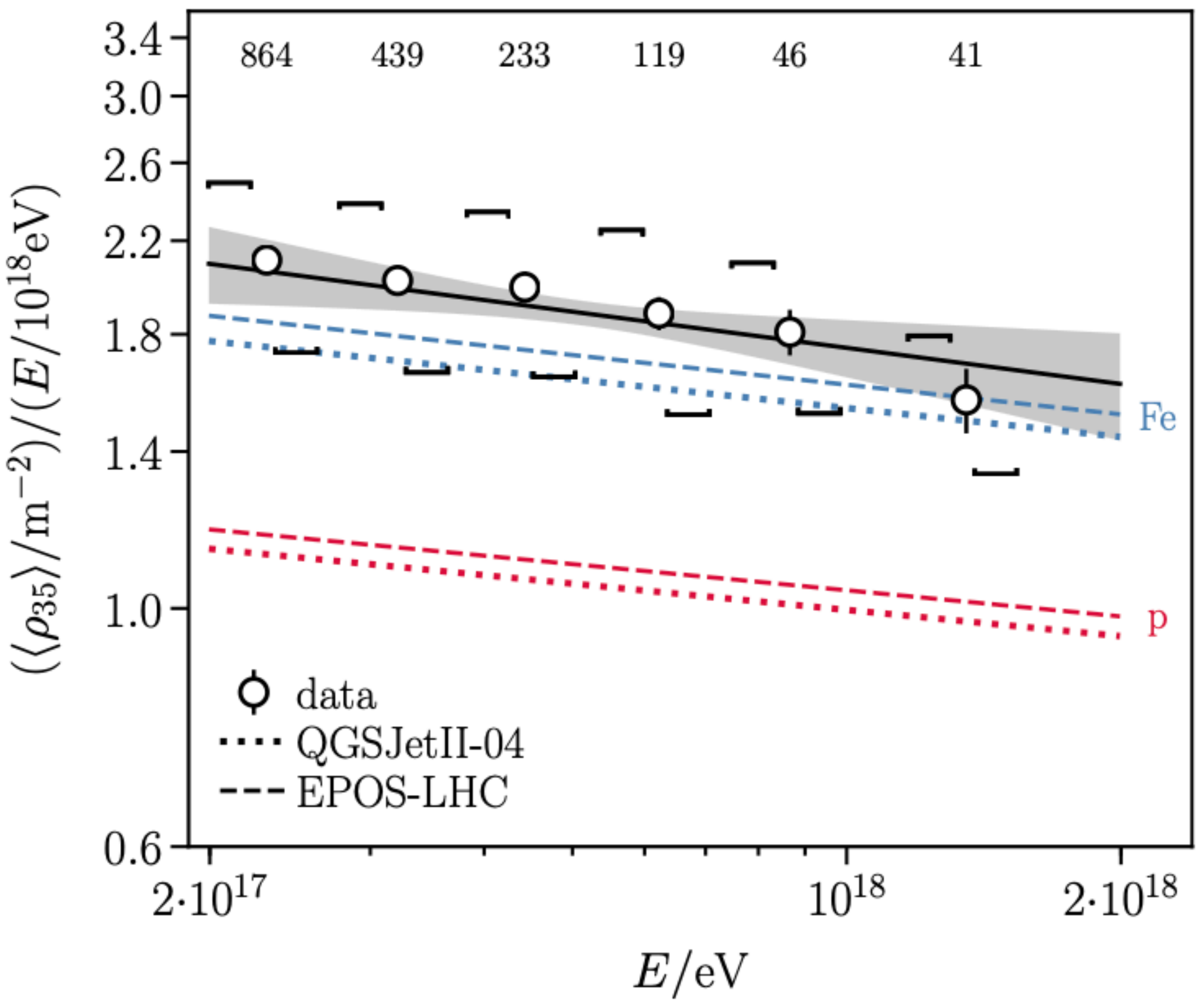
Normalization factor muon density N_{19}

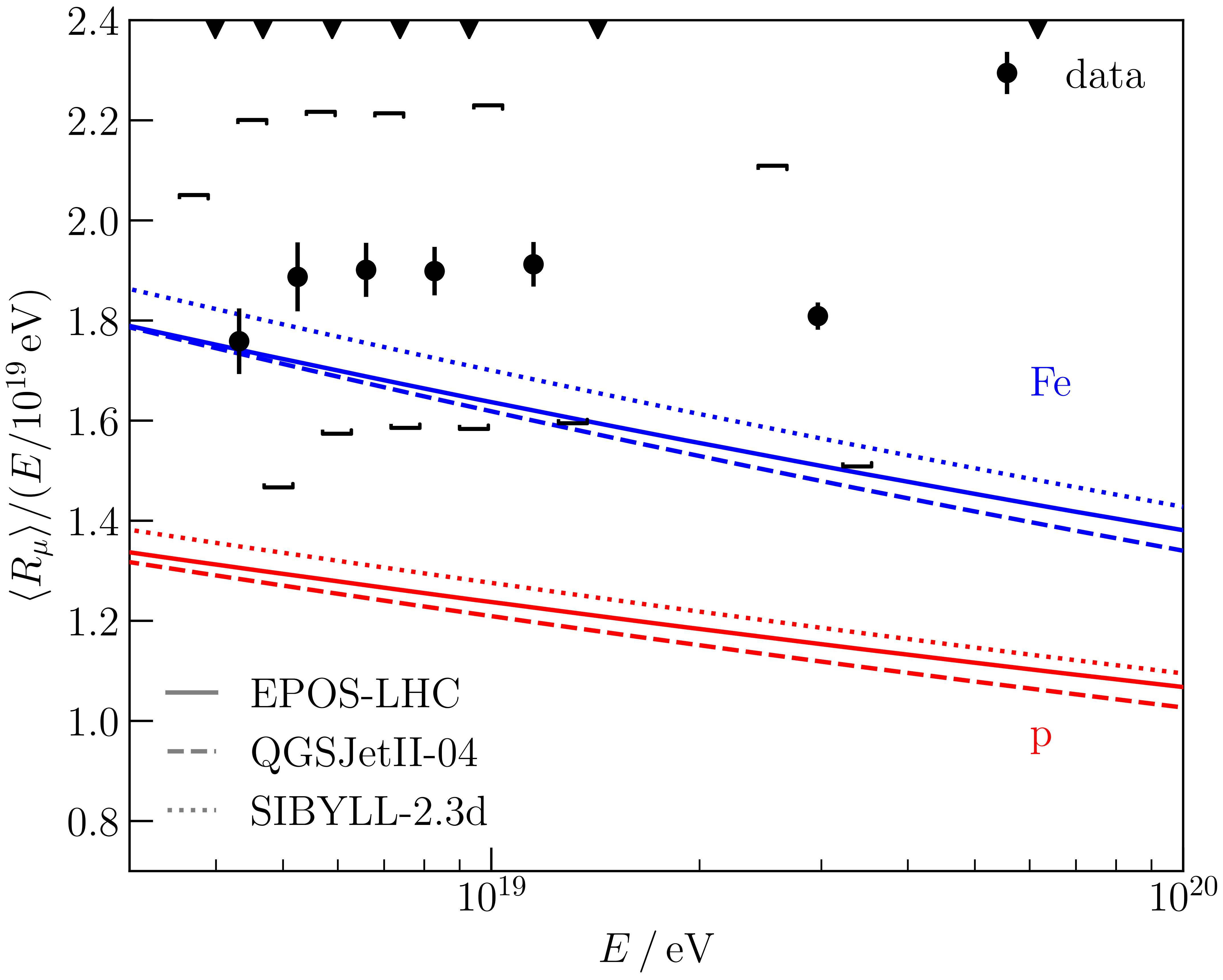
$$\boxed{R_\mu = \frac{N_\mu^{data}}{N_{\mu,19}^{MC}}}$$

Rμ is the total number of muons at ground relative to a 10^{19} eV proton shower

Data only calibration SD vs. FD hybrid events with zenith angles [62°, 80°] and E > 4.10^{18} eV .

Measurement of the EAS muon content over extended energy range

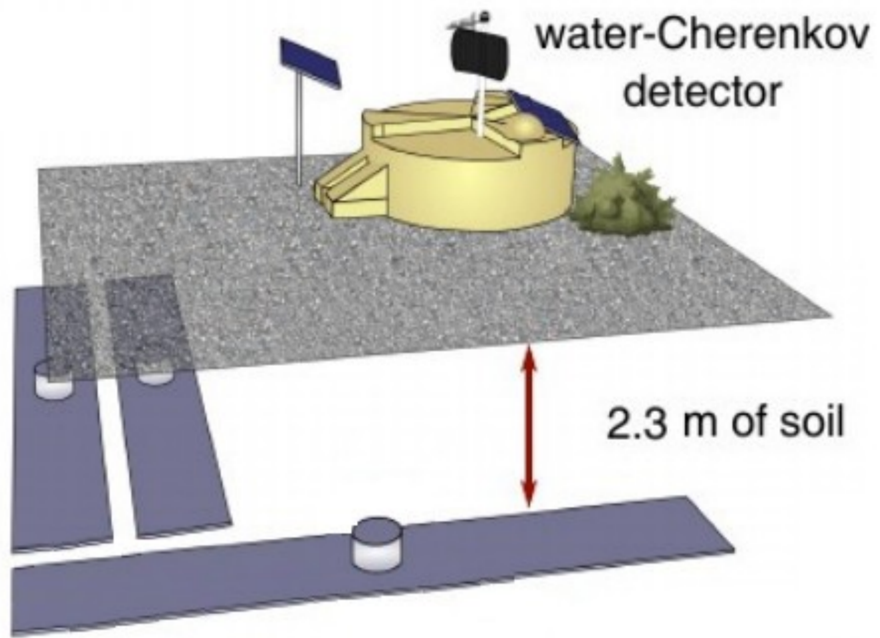




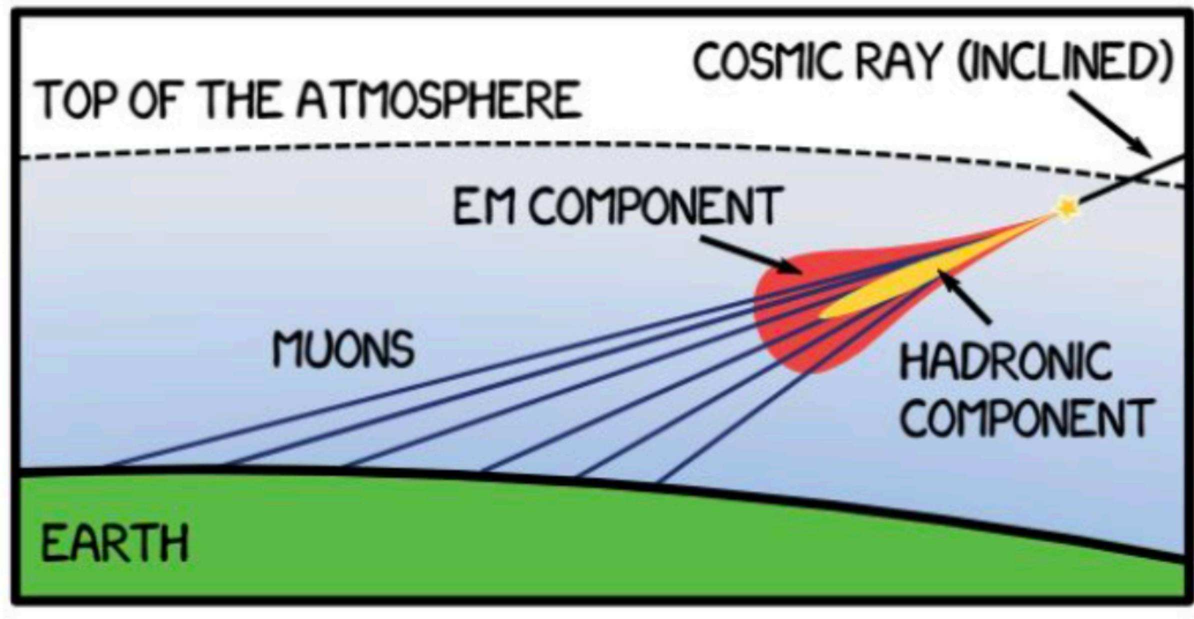
AMIGA UMD(underground muon detectors)

7 scintillator detectors

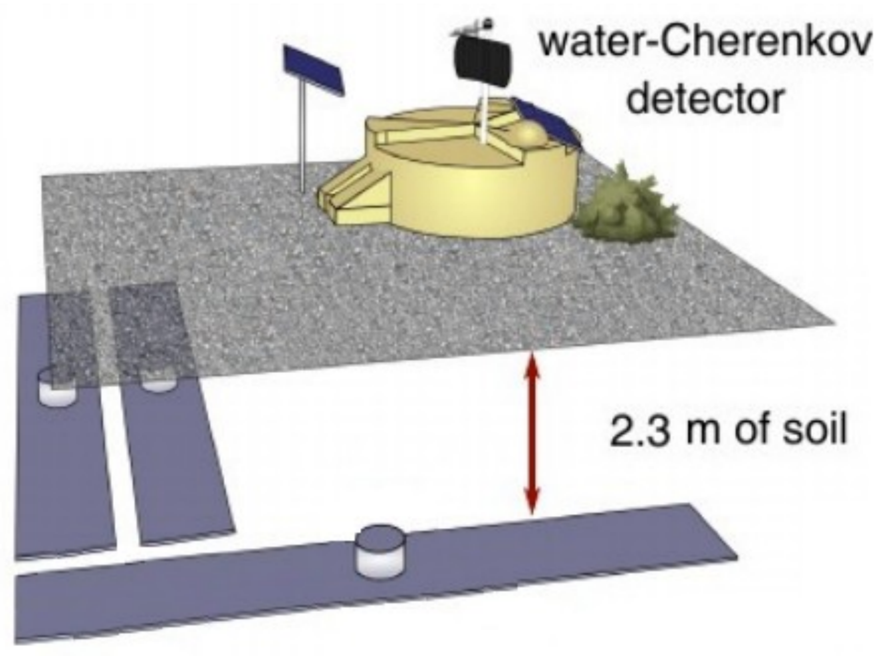
- 30 m^2 each
- 2.3 m underground



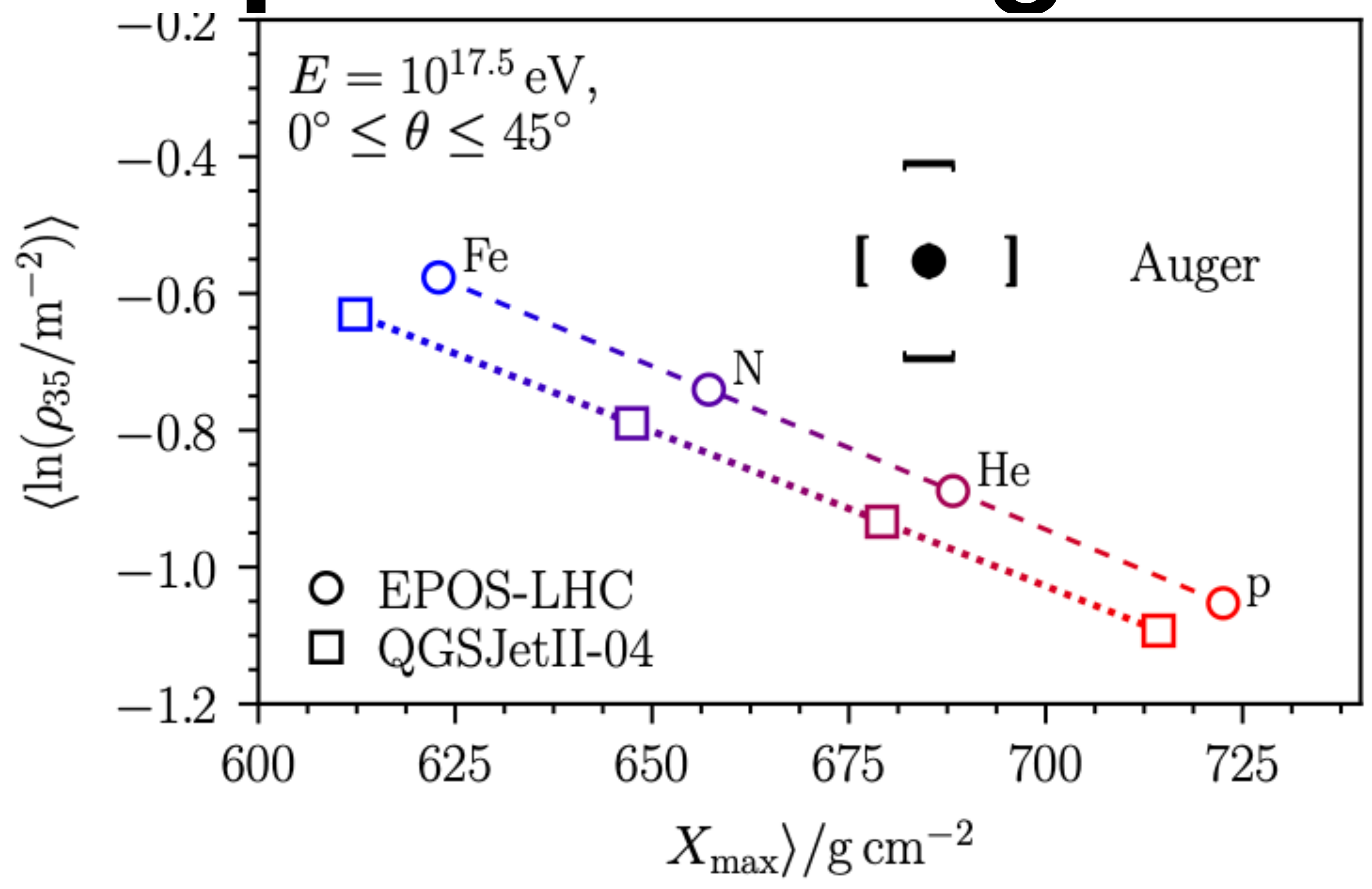
Inclined showers



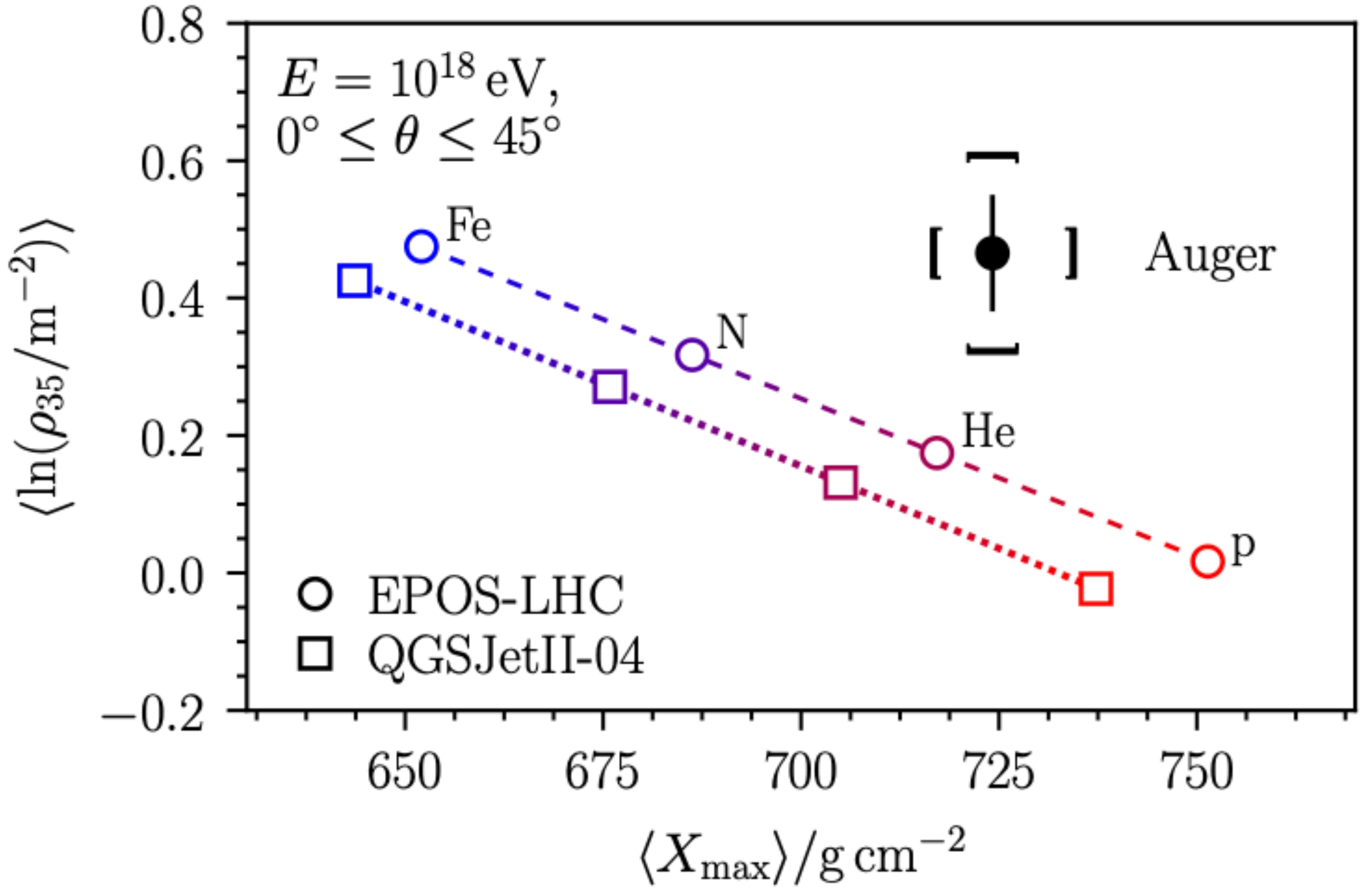
The EAS muon puzzle at Auger over extended energy range



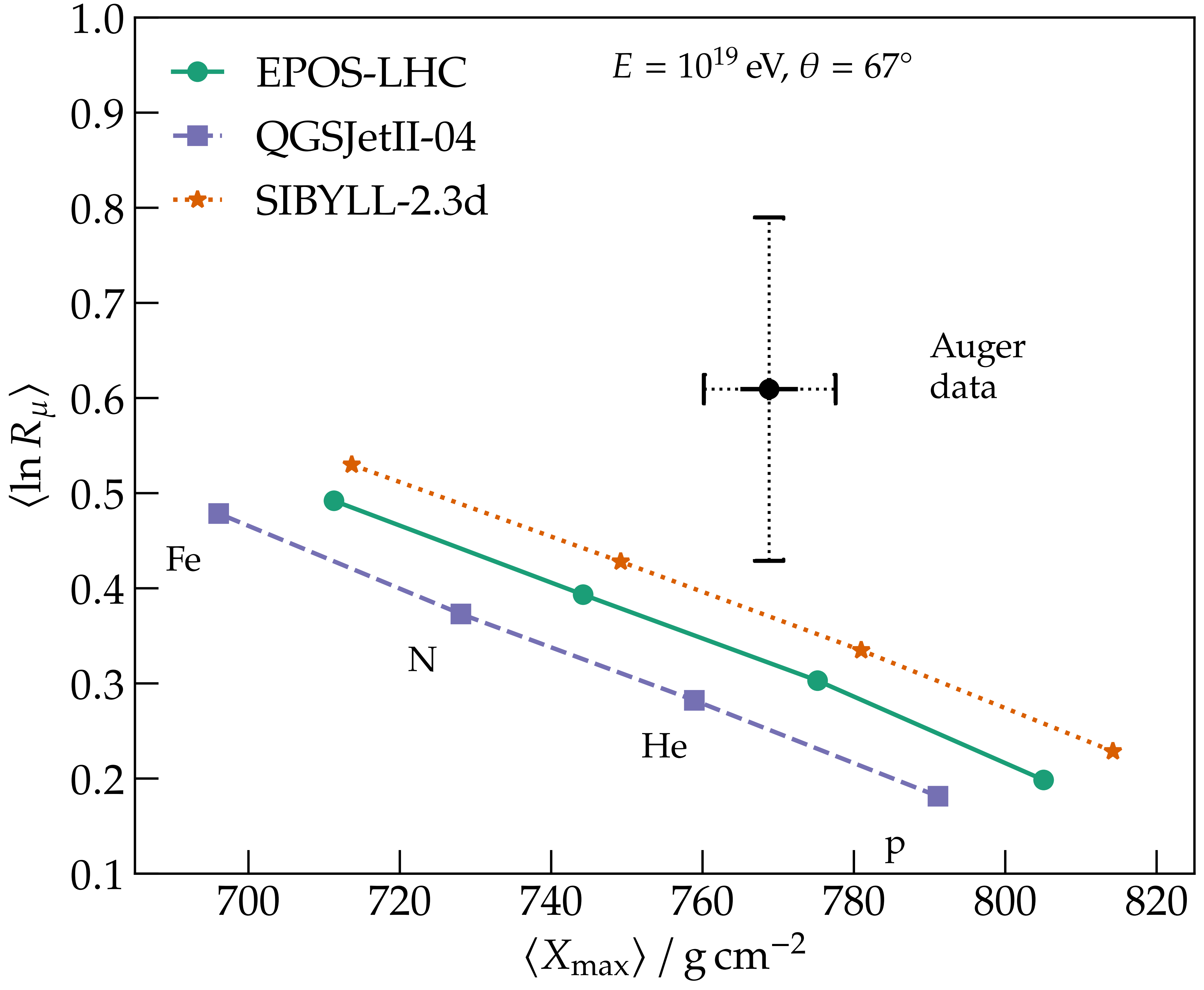
7 scintillator detectors
- → 30 m² each
- → 2.3 m underground

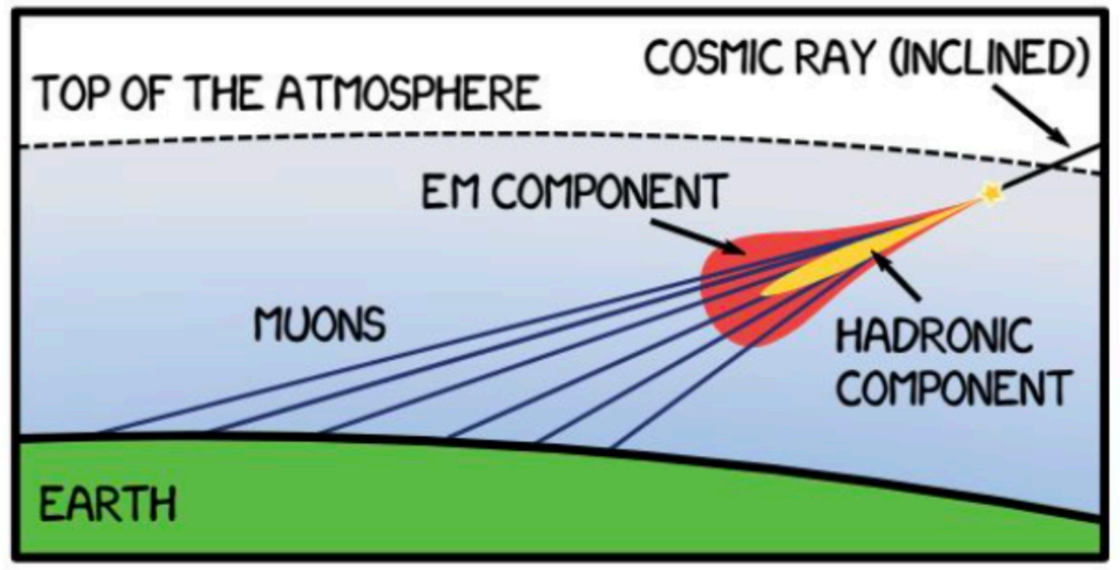


(a) $E = 10^{17.5}$ eV

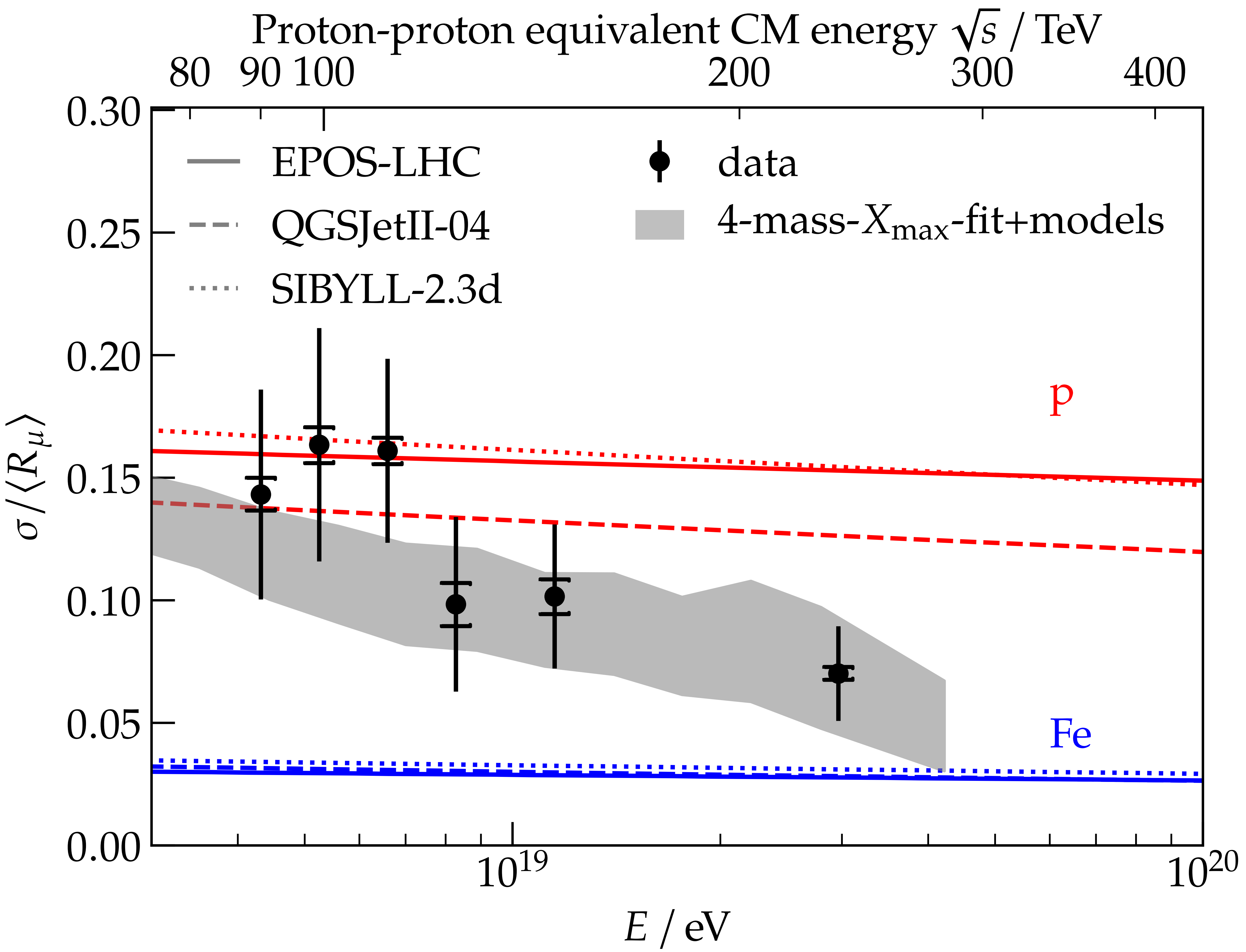


(b) $E = 10^{18}$ eV

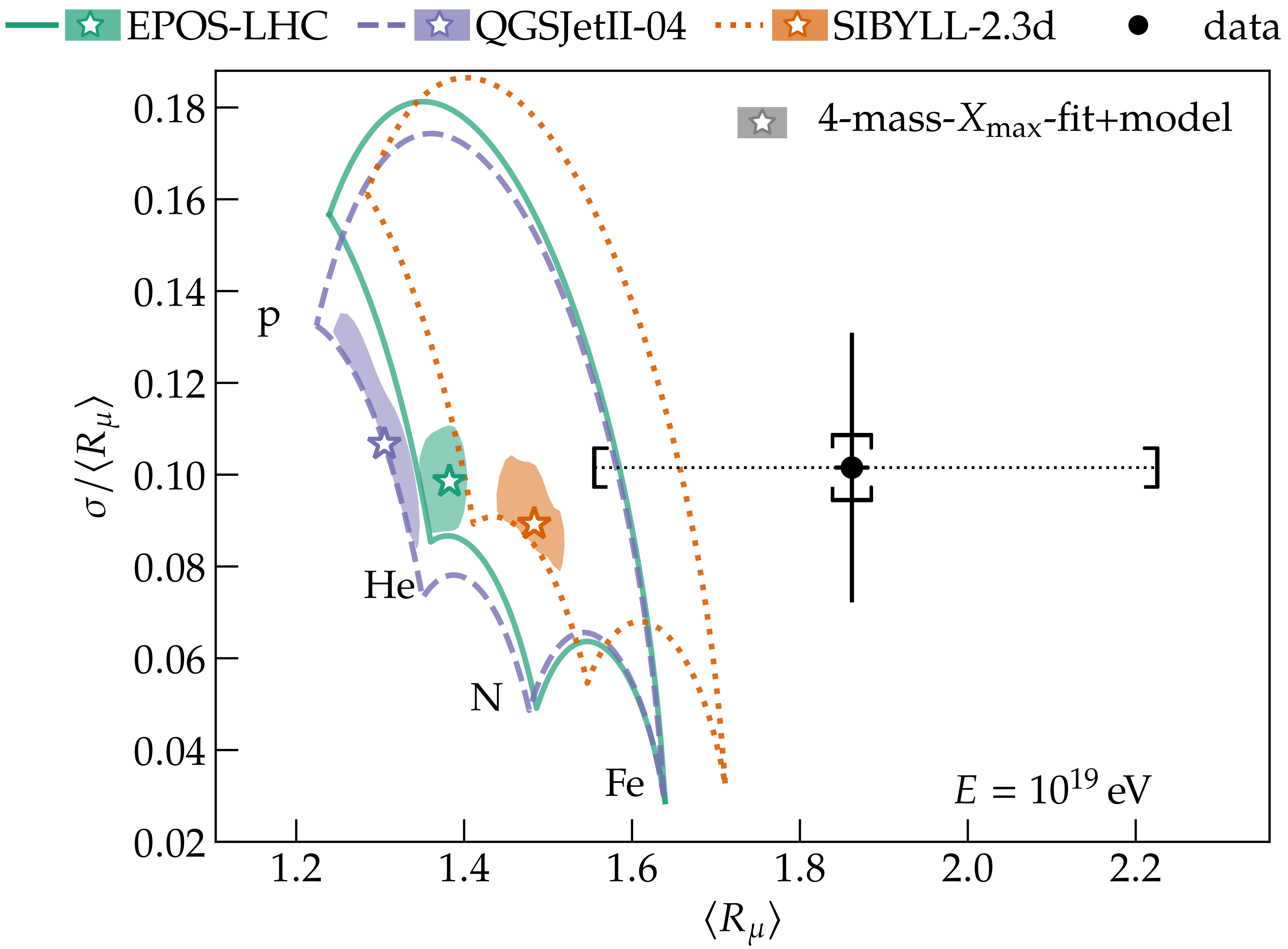




Measurement of the relative fluctuations of the number of muons



Shaded area is the expected region using mass composition obtained from Xmax studies.

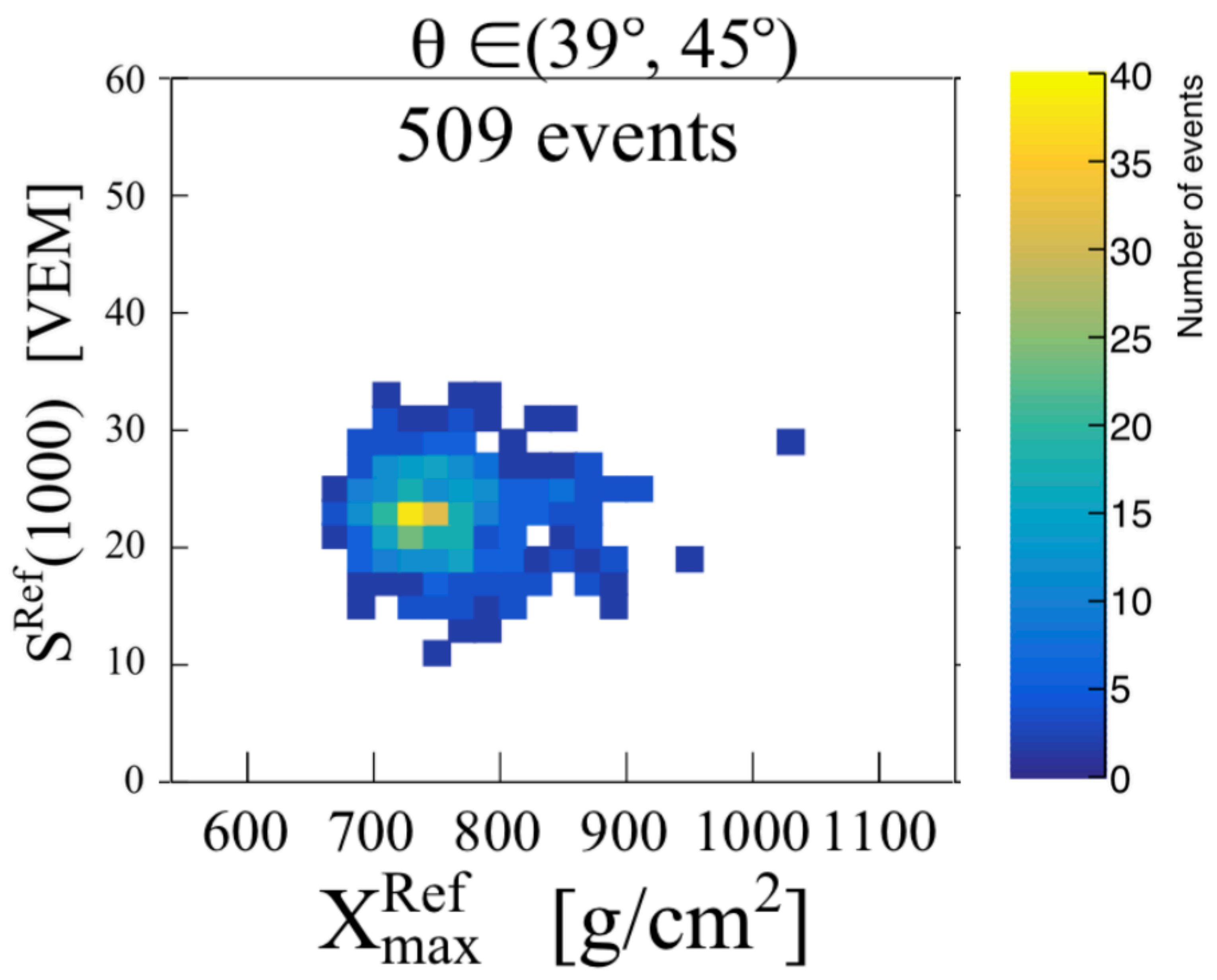


Star symbols: predictions for the corresponding mixed composition obtained from Xmax studies

Shaded regions around stars: corresponding allowed regions considering the statistical and systematic uncertainties that come from the Xmax measurements

Data: statistical uncertainties-error bars, systematic uncertainties-square brackets

Simultaneous fits to the X_{max} (FD) and the ground signal (SD)



fSD(θ) signal attenuation is model dependent is a function of RHad(θmin) and RHad(θmax) (the re-scaling parameters at the two extreme zenith angle bins).

R_{Had} rescaling hadronic component at the ground

$$X^{Ref}_{max} \equiv \widehat{X^{Ref}_{max}} + \Delta X_{max},$$
$$S^{Ref}(1000) \equiv \widehat{S^{Ref}(1000)} \cdot f_{SD}(\theta)$$

Parameters:

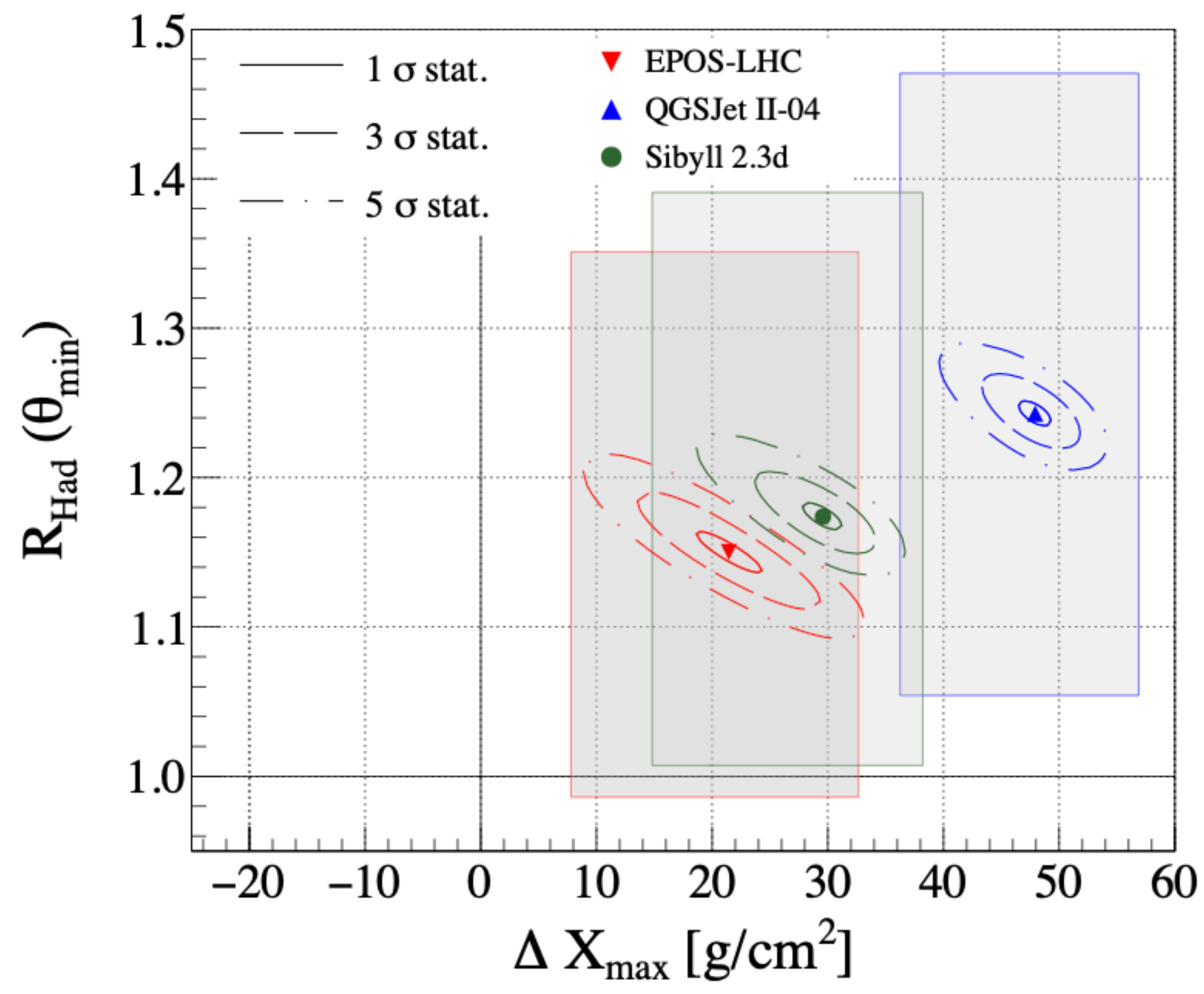
$$\Delta X_{max}, R_{Had}, R_{em}, \underbrace{\xi_1, \xi_2, \xi_3}_{}$$

Describe the 4 mass fractions

$$\phi = c \cdot f_{Gumbel}\left(X^{Ref}_{max}\right) \cdot f_{Gauss}\left(X^{Ref}_{max}, S^{Ref}(1000)\right)$$

The final MC templates are a sum of templates of the form of ϕ of individual primary species weighted by their relative fractions.

Rescaling of the hadronic signal + Xmax shift



Deeper values of Xmax are obtained (+20/30/50 g/cm2) which means a decrease in the muon deficit in simulations (15% to 25%).

Conclusions

- The Pierre Auger Observatory has measured the p-air cross section into two energy bins, both beyond the reach of LHC.
- The post-LHC hadronic interaction models are unable to provide a consistent description of the measured showers
- An intriguing discovery emerged regarding the muon content of air showers. While simulations accurately capture event-to-event muon fluctuations, the predicted mean value falls significantly short and it still lag behind our data. This discrepancy, now known as the 'muon puzzle,' remains an active area of investigation.
- Simultaneous examination of Xmax and ground signal distributions has revealed that also the simulated Xmax values deserve further investigation. All existing hadronic interaction models fail not just in their prediction for the muon flux at a specified energy, but also in the predicted depth of shower maximum: adjustments to Xmax (+20/30/50 g/cm2) may alleviate the muon deficit present in simulations (15% to 25%).
- Looking ahead, forthcoming multi-hybrid shower measurements, which include data from water-Cherenkov detectors, scintillator surface detectors, underground muon detectors, radio detectors, and FDs, will provide invaluable data for refining our understanding of hadronic interaction properties in Extensive Air Showers (EAS).