Probing hadronic interactions with measurements at ultra-high energies with the Pierre Auger Observatory

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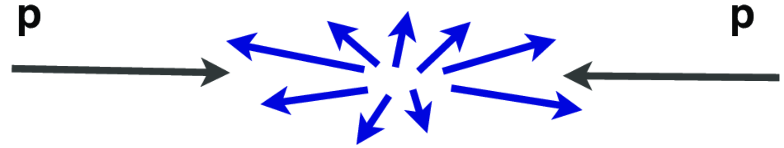
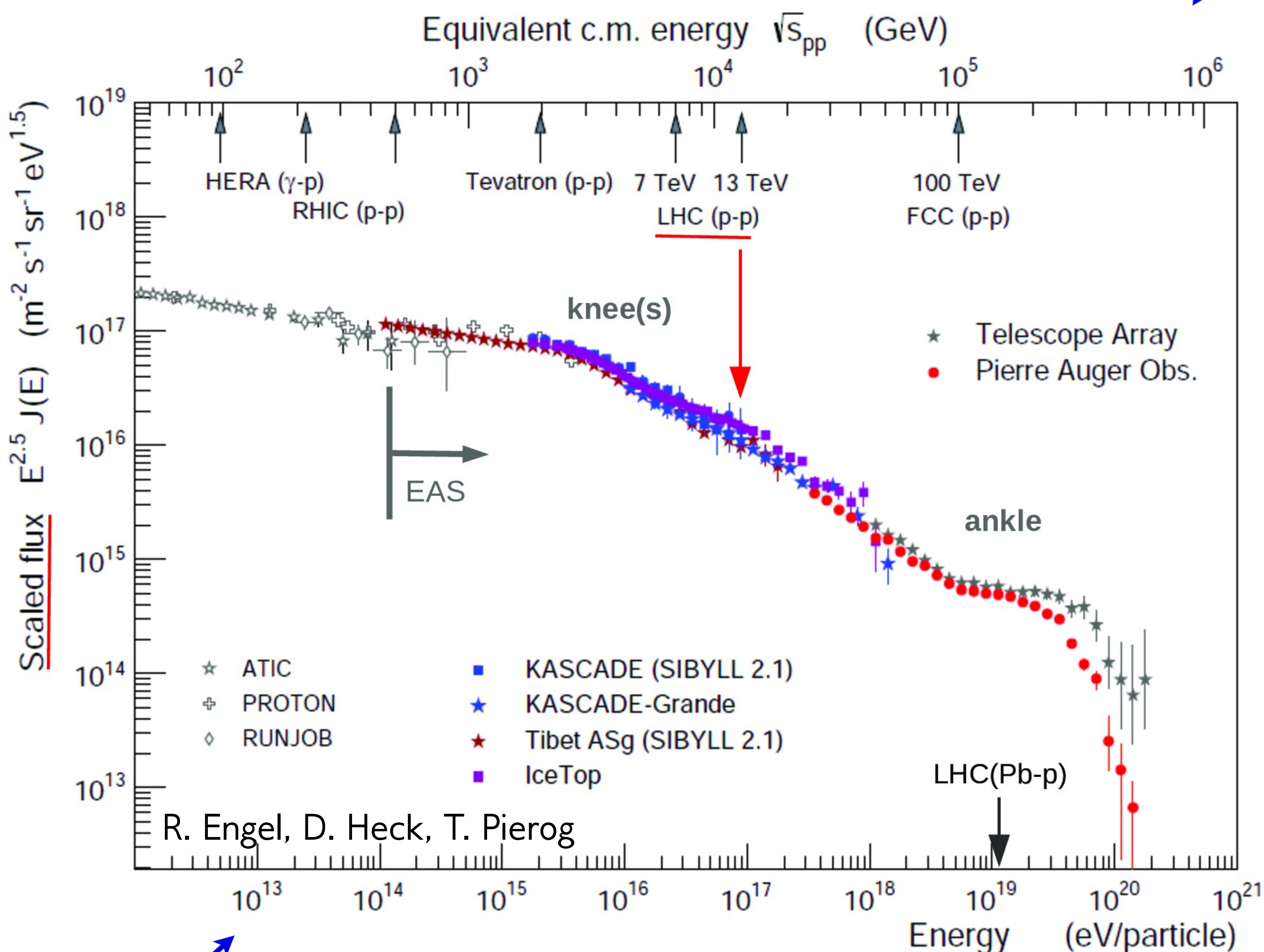
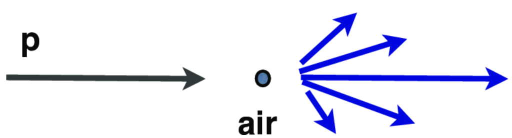
PIERRE AUGER OBSERVATORY

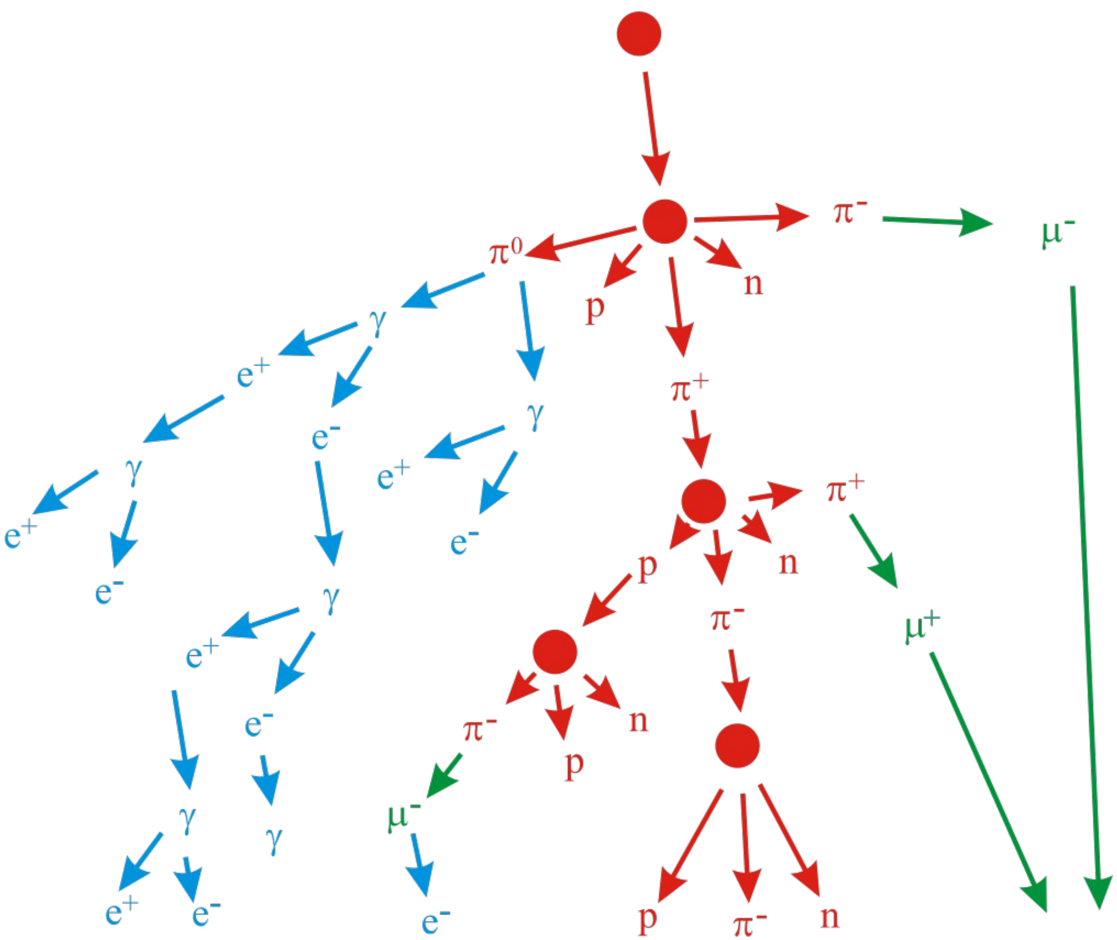
Ultra-high-energy cosmic rays







Air showers and the complexity of composition



Hadronic interactions

Mass composition

Shower components

Muonic from decay of charged pions

+ from photo-production

Electromagnetic (EM) from decay of neutral pions

+ from muon decay

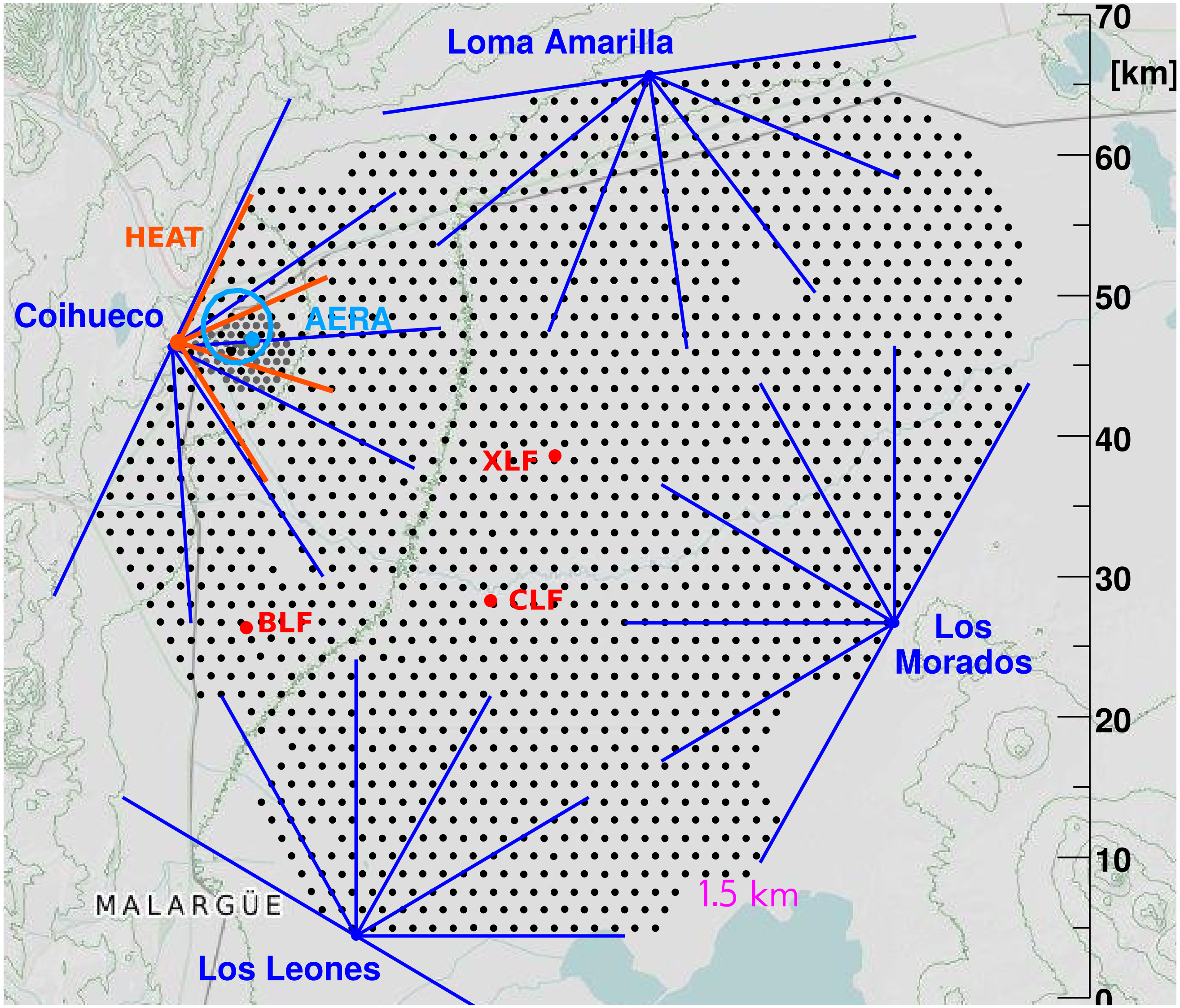
+ from low energy pion decay

Composition complexity

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

Electromagnetic component remains more-or-less the same

Pierre Auger Observatory



Fluorescence Detector (FD)

27 telescopes, 15% duty cycle

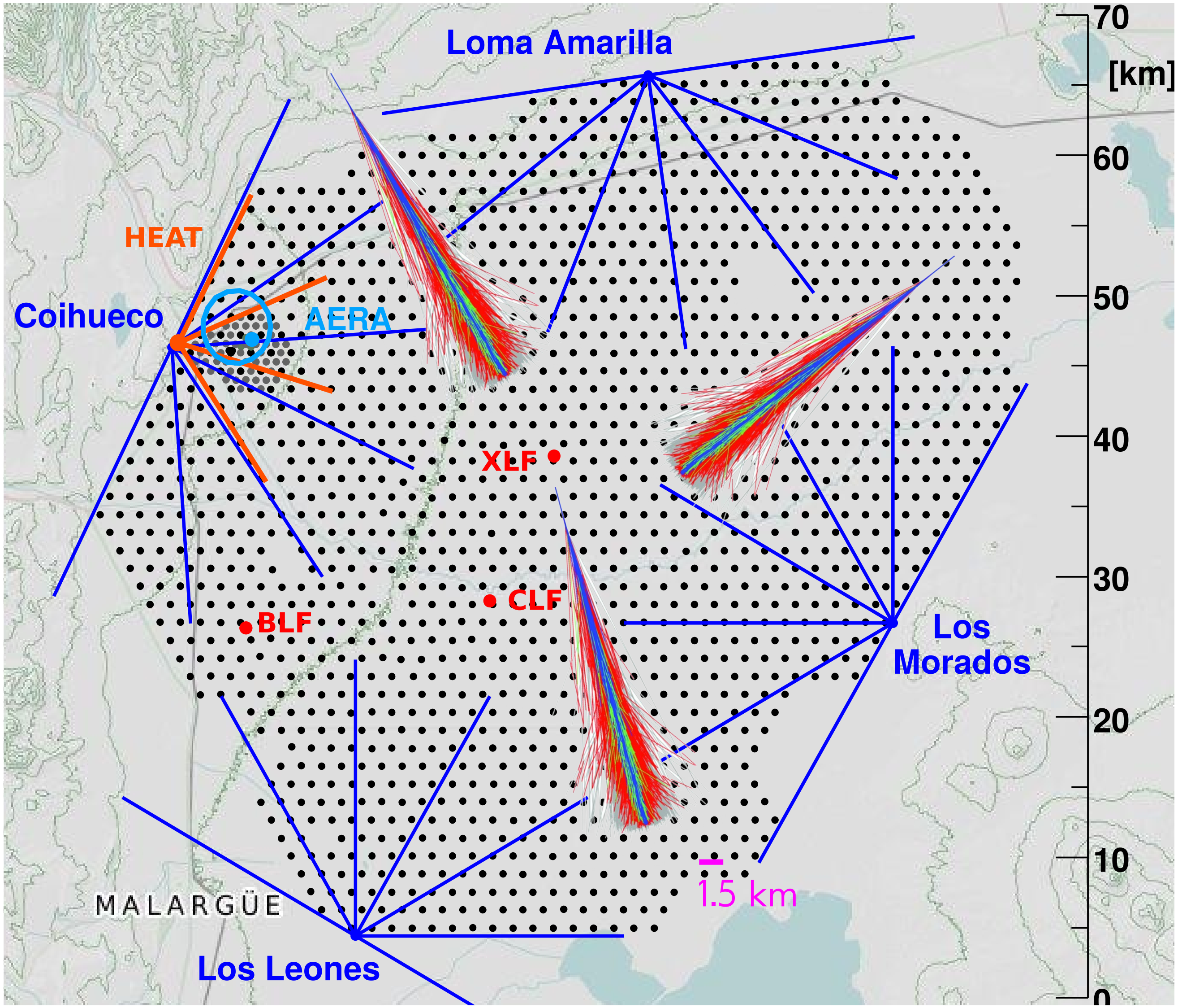
Surface Detector (SD)

1660 water-cherenkov detectors

100% duty cycle

Location: Malargüe, Mendoza, Argentina
Height: 1450 meters
Atm. Depth: 860 g/cm^2
Energy Threshold: $10^{17.5}$ eV

Pierre Auger Observatory

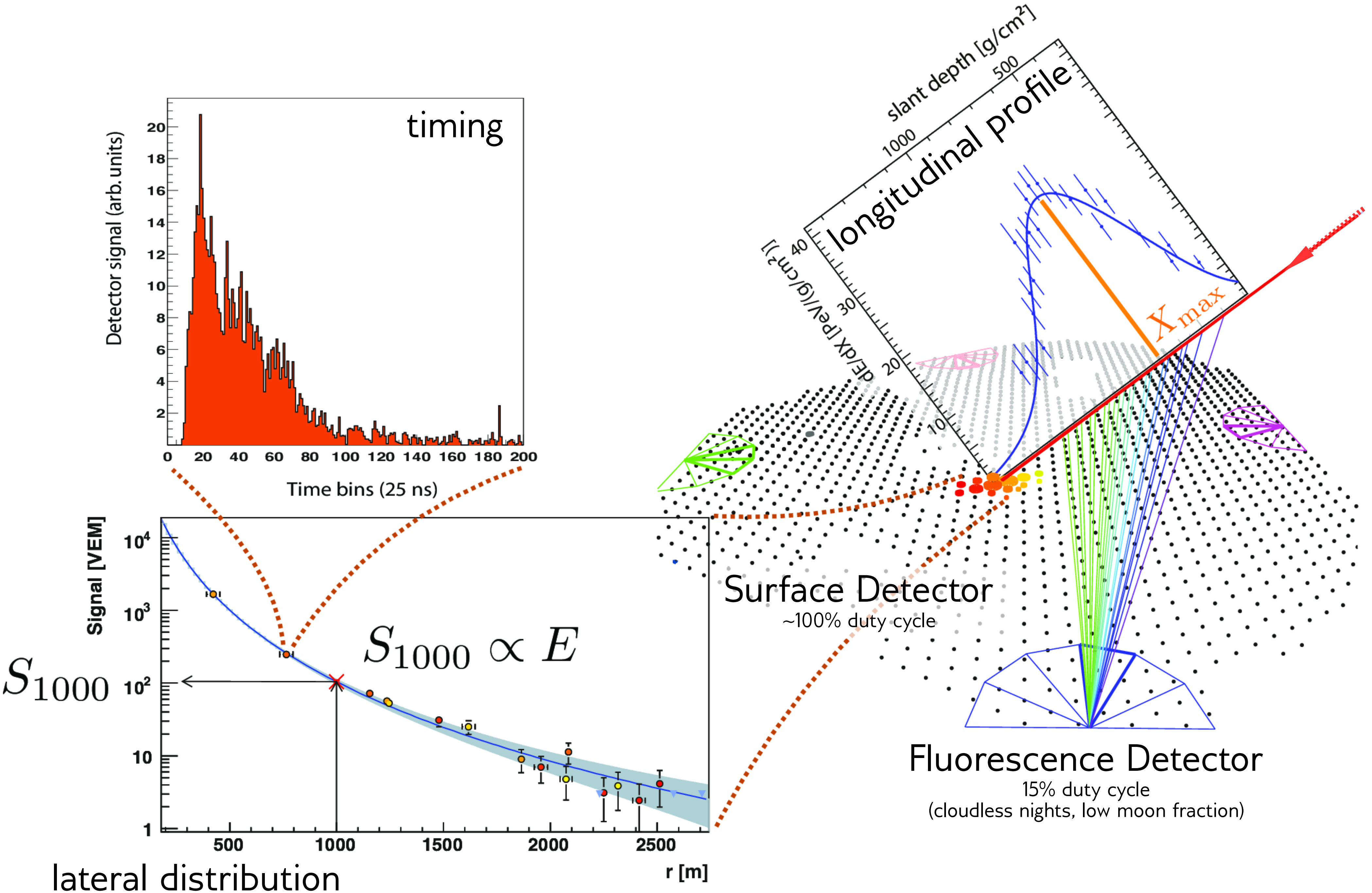


Fluorescence Detector (FD)
27 telescopes, 15% duty cycle

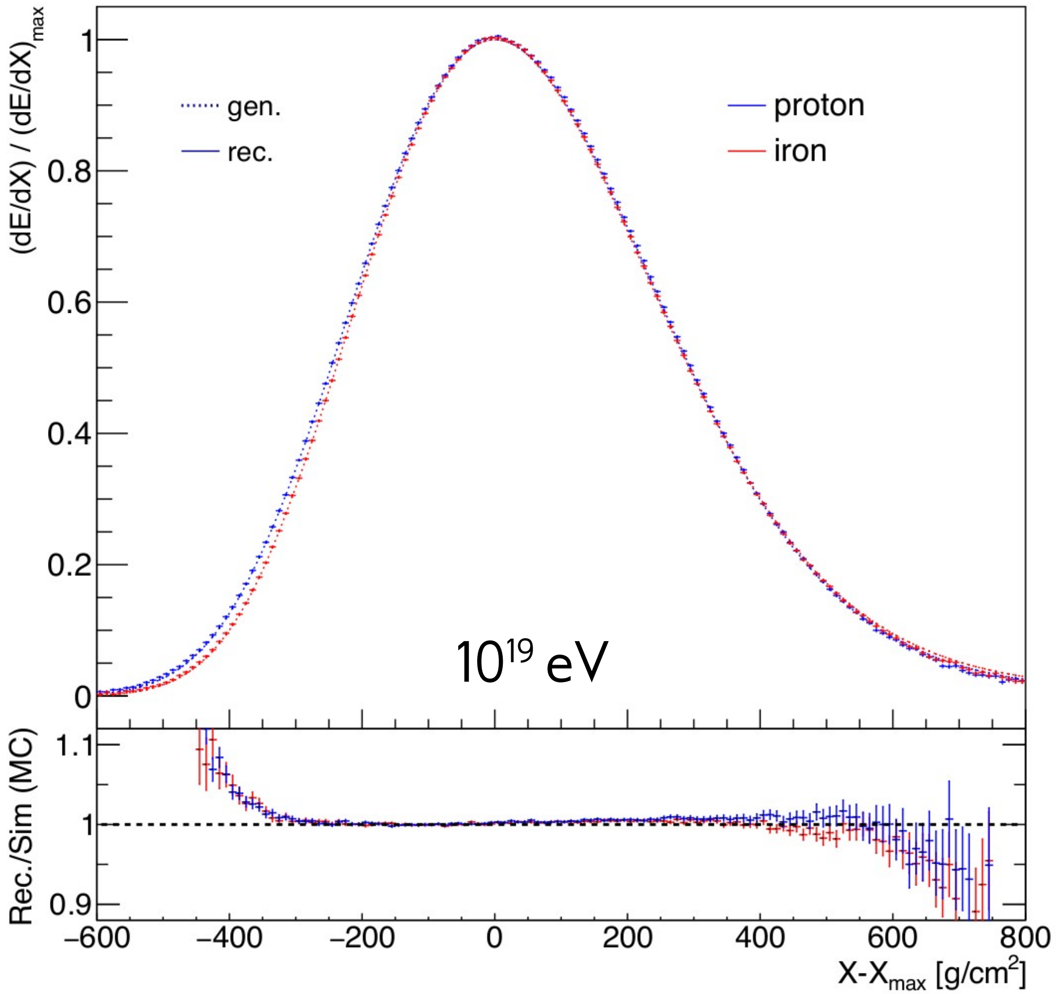
Surface Detector (SD)
1660 water-cherenkov detectors
100% duty cycle

Location:	Malargüe, Mendoza, Argentina
Height:	1450 meters
Atm. Depth:	860 g/cm^2
Energy Threshold:	$10^{17.5}$ eV

Hybrid detector



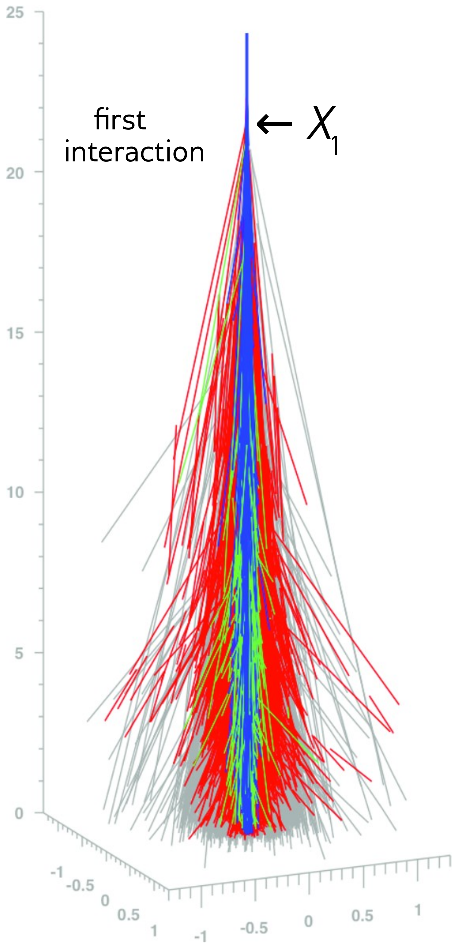
Longitudinal shower development

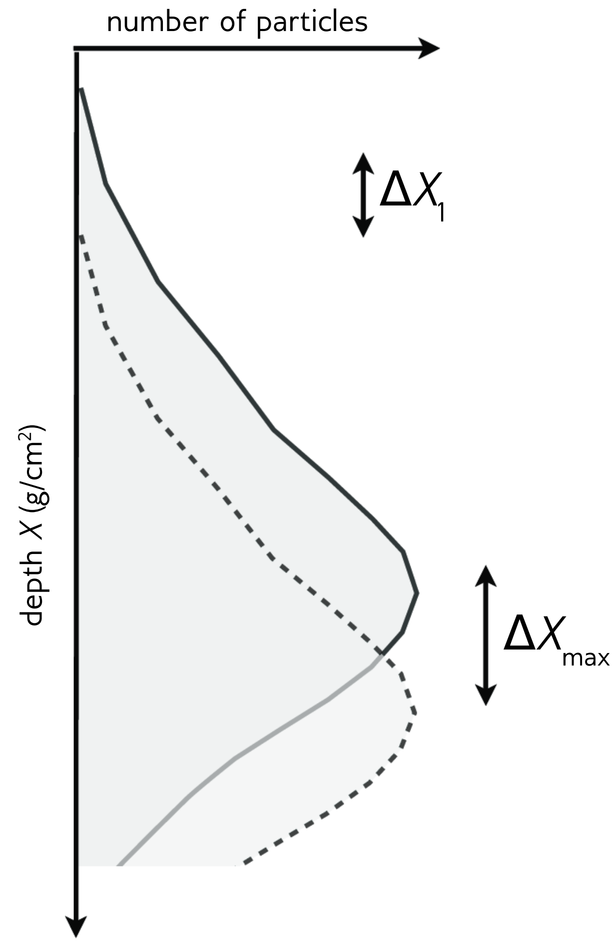


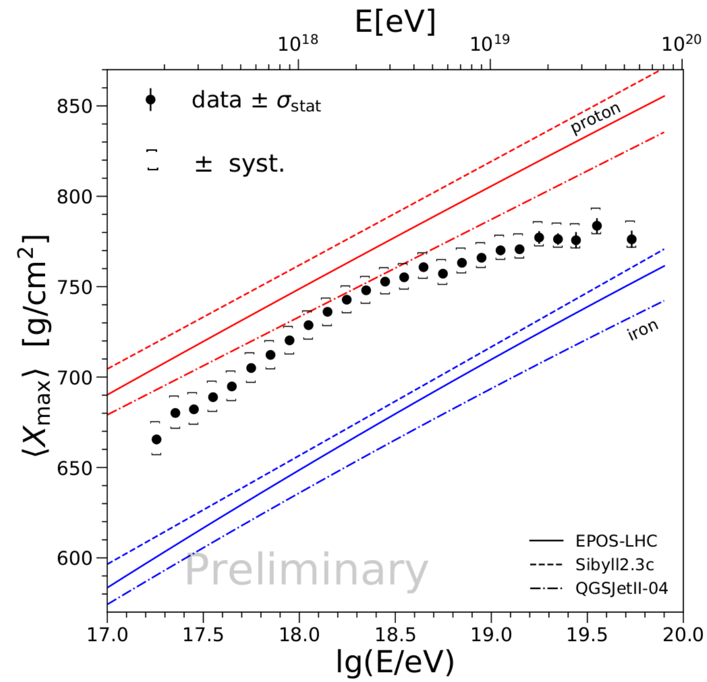
Gaisser Hillas function describes shape of longitudinal profile well
(within measurement uncertainties)

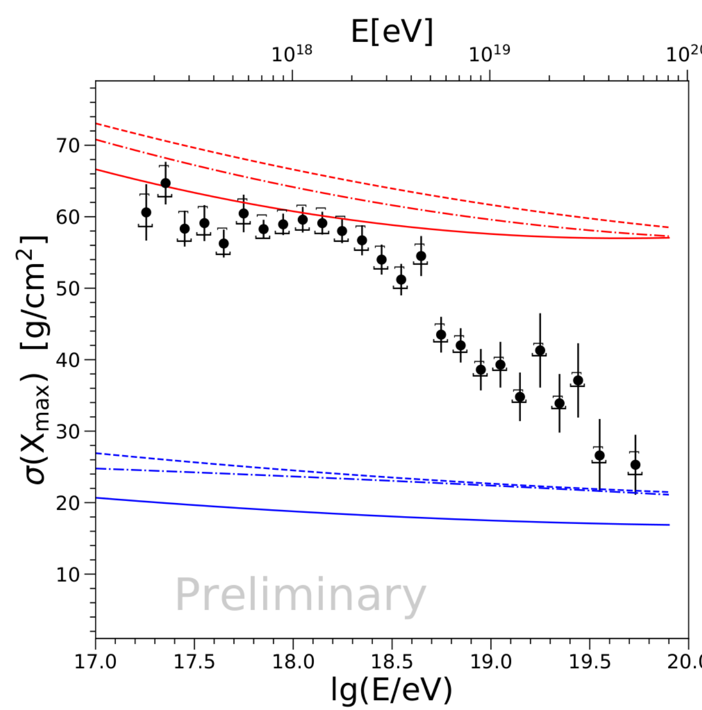
Universal for primaries of different mass

Depth of shower maximum



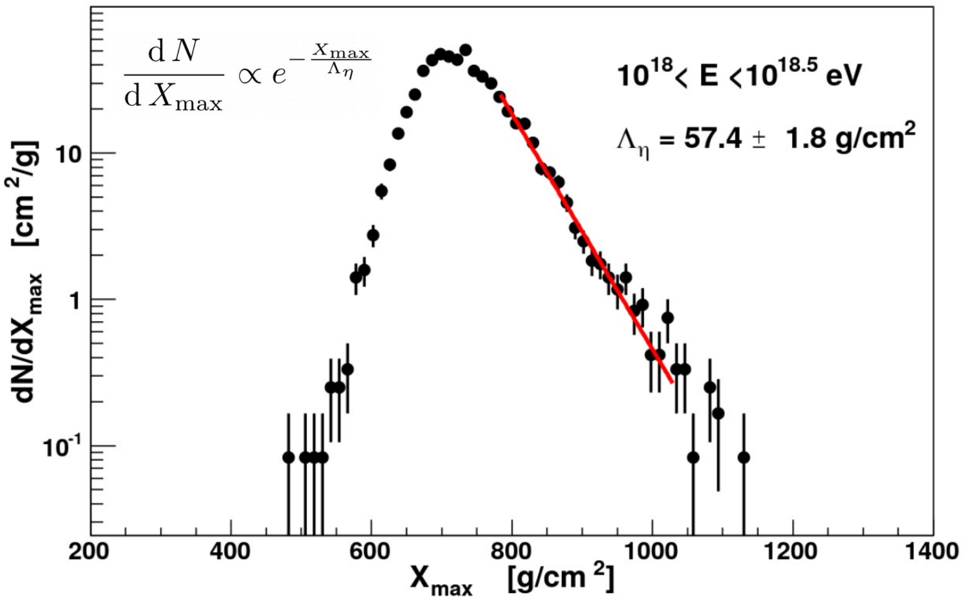


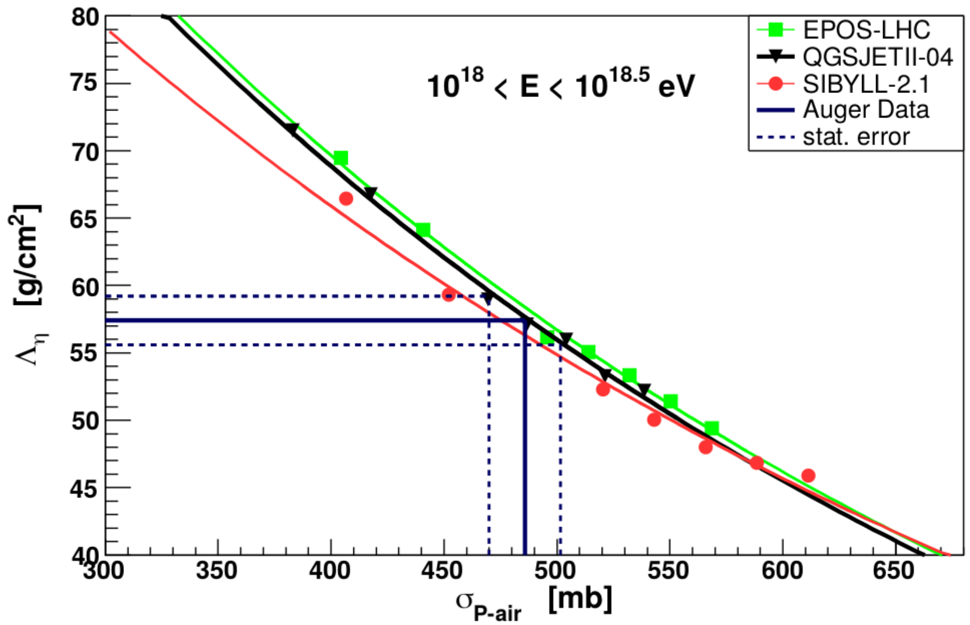




Depth of shower maximum
and fluctuations therein

Cross section measurement



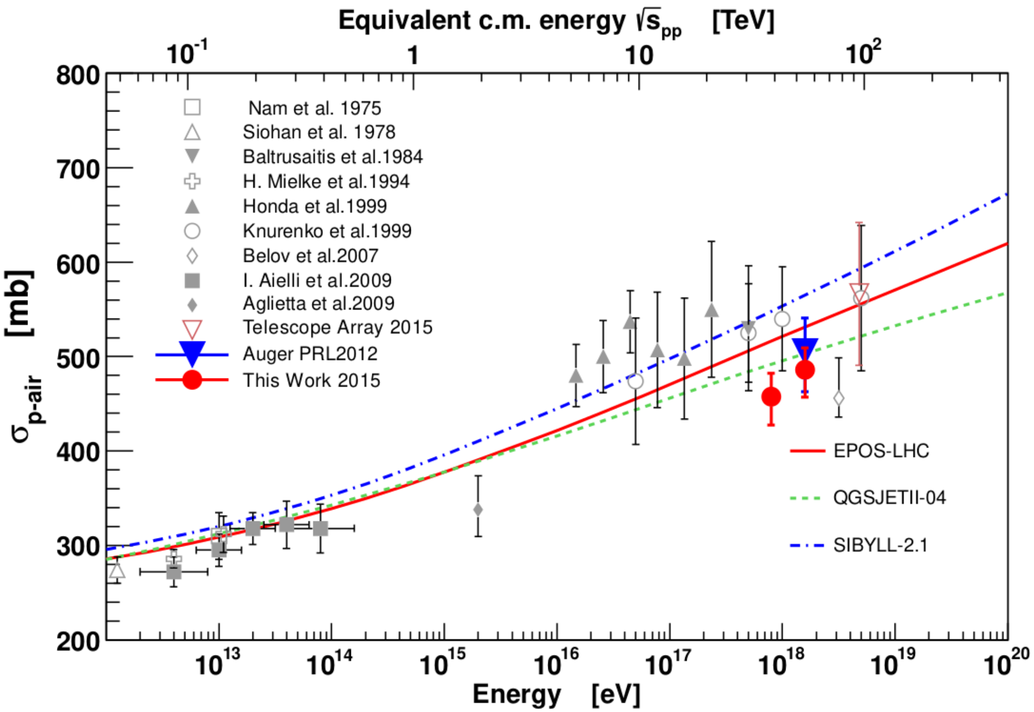


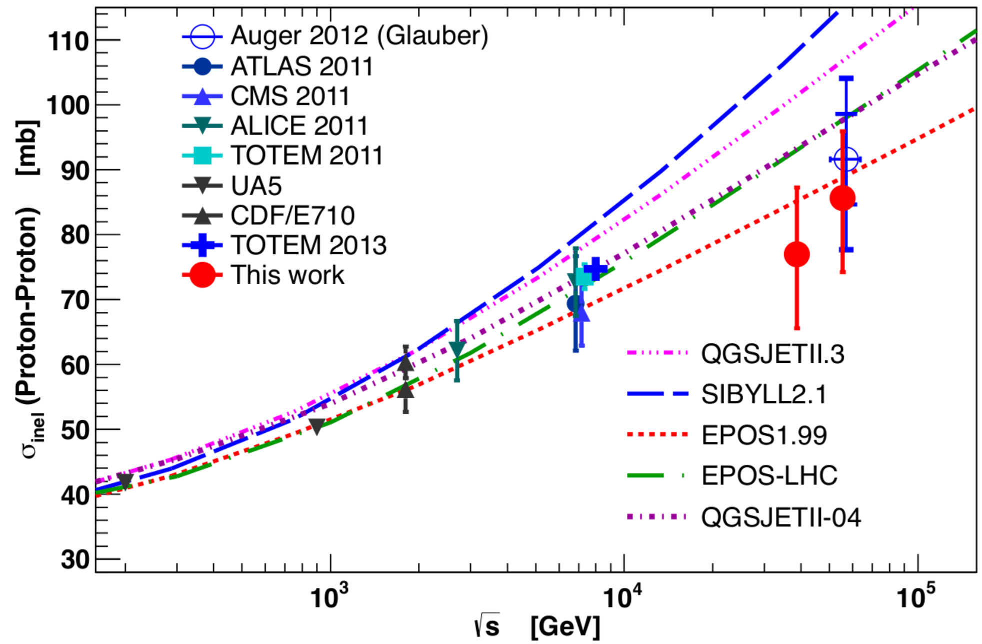
Intervals of energy used:

LAB	COM pp
$10^{17.8}$-10^{18} eV	38.7 TeV
10^{18}-$10^{18.5}$ eV	55.5 TeV

20% most deeply penetrating showers used as most likely to be proton

Cross section measurement



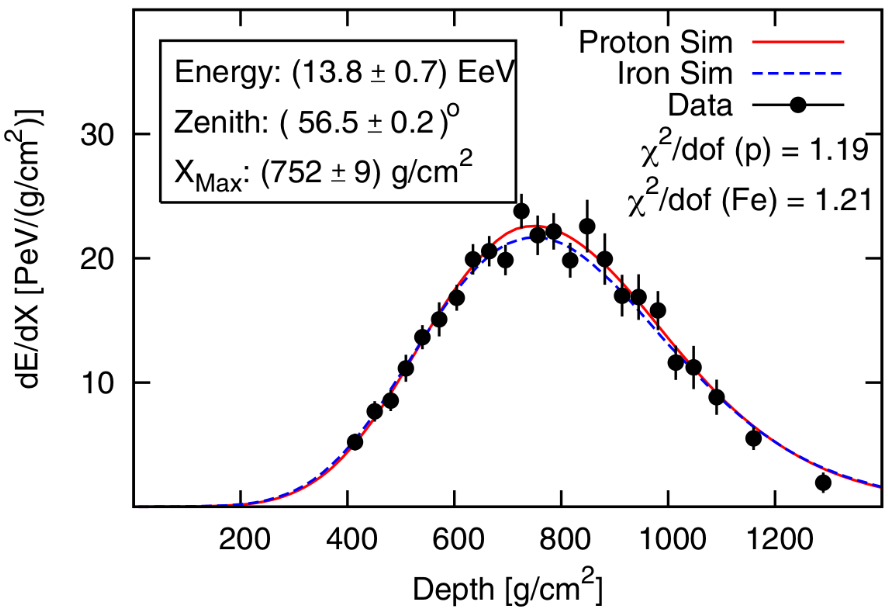


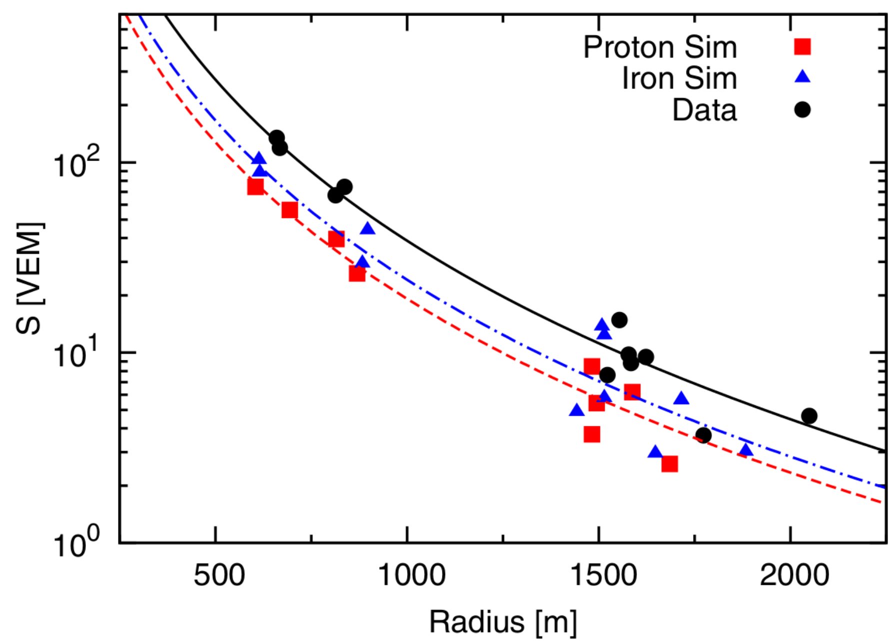
Glauber theory used to convert p-air to inelastic pp cross section

Largest source of systematic uncertainty is helium fraction

Amounts to 6% bias in calculated values if fraction at 25%

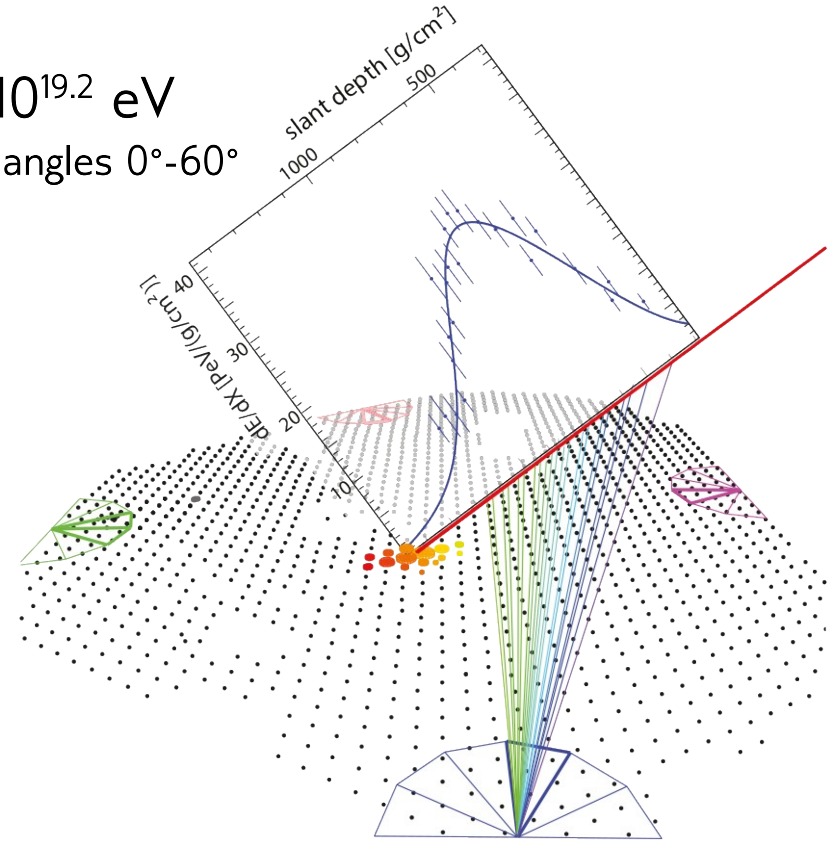
Hybrid muon measurement





$10^{18.8}$-$10^{19.2}$ eV

Zenith angles 0°-60°



411 quality hybrid events

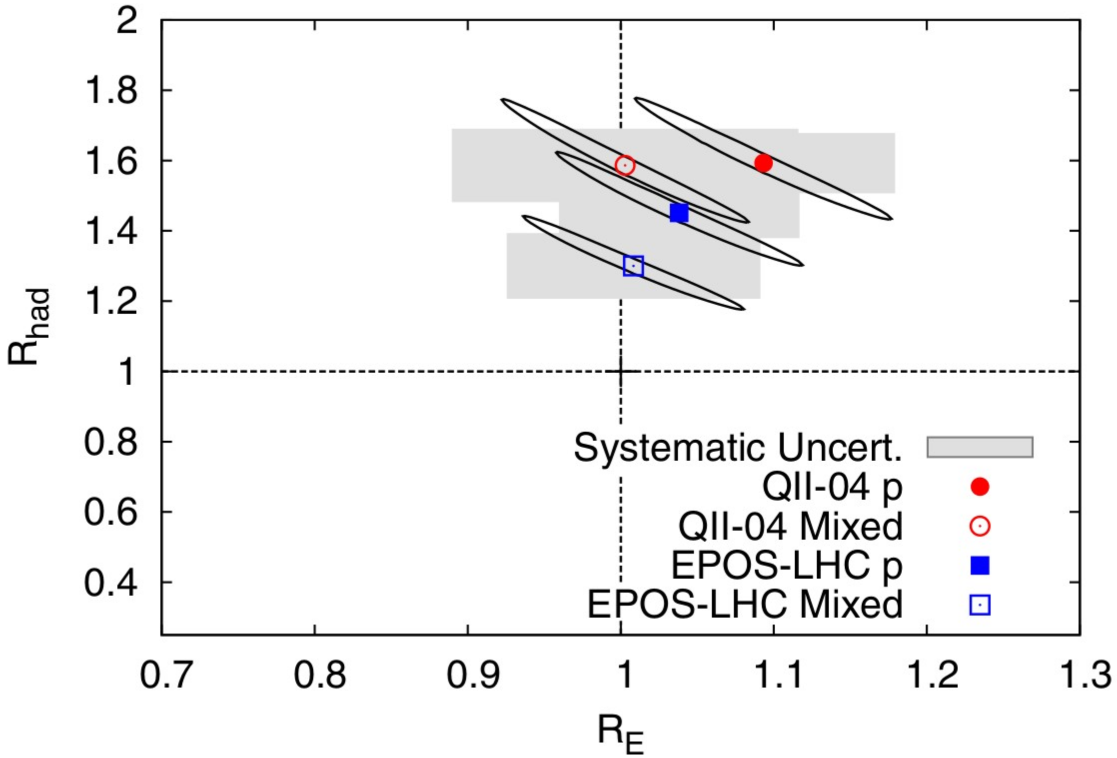
$$S_{\mathrm{resc}} = R_E \, S_{\mathrm{EM}} + R_{\mathrm{had}} \, R_E^{\alpha} \, S_{\mathrm{had}}$$

$$\alpha \simeq 0.9$$

$$R_\mu \approx 0.93 \, R_E^{0.9} \, R_{\mathrm{had}} + 0.07 \, R_E$$

Phys. Rev. Lett. 117, 192001 (2016)

Hybrid muon measurement



No energy re-scaling necessary

Hadronic re-scaling factor 1.3-1.6

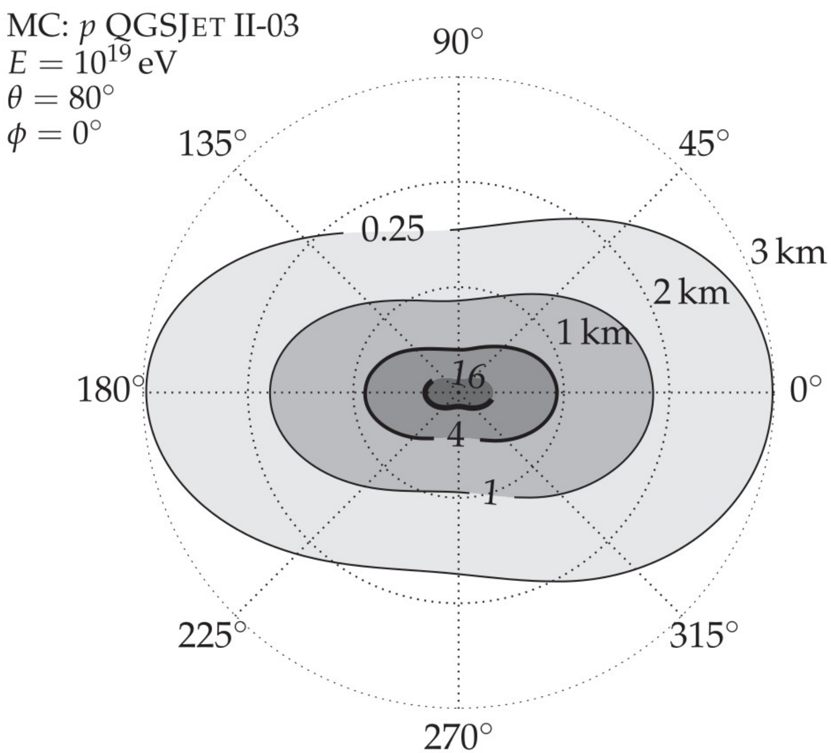
TABLE I. R_E and R_{had} with statistical and systematic uncertainties, for QGSJet-II-04 and EPOS-LHC.

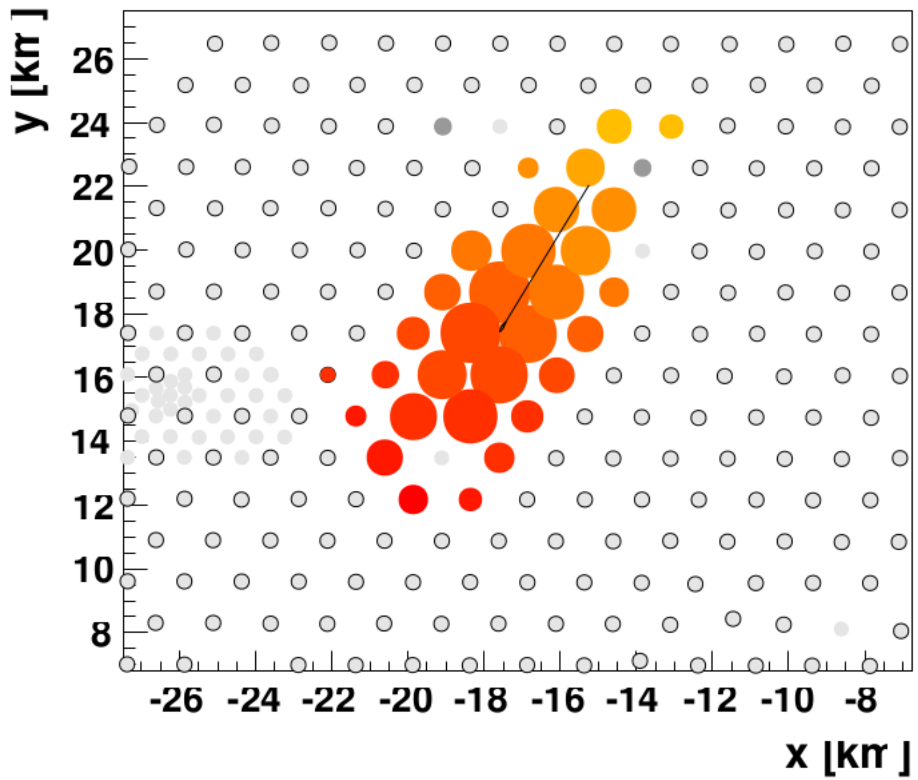
Model	R_E	R_{had}
QII-04 p	$1.09 \pm 0.08 \pm 0.09$	$1.59 \pm 0.17 \pm 0.09$
QII-04 mixed	$1.00 \pm 0.08 \pm 0.11$	$1.61 \pm 0.18 \pm 0.11$
EPOS p	$1.04 \pm 0.08 \pm 0.08$	$1.45 \pm 0.16 \pm 0.08$
EPOS mixed	$1.00 \pm 0.07 \pm 0.08$	$1.33 \pm 0.13 \pm 0.09$

EPOS-LHC with mixed composition exhibits smallest discrepancy (1.9 σ)

Phys. Rev. Lett. 117, 192001 (2016)

Muon measurement with highly inclined showers
(zenith angles 62°-80°)



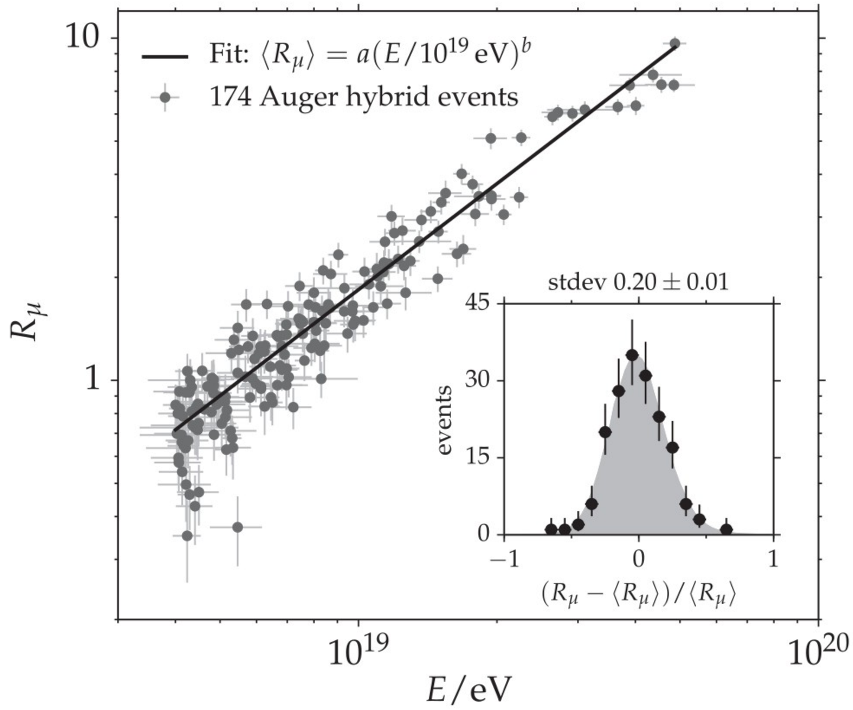


$$\rho_\mu(\mathrm{data}) = N_{19} \cdot \rho_\mu(\mathrm{QGSJETII03},\ p, E = 10^{19}\ eV,\ \theta)$$

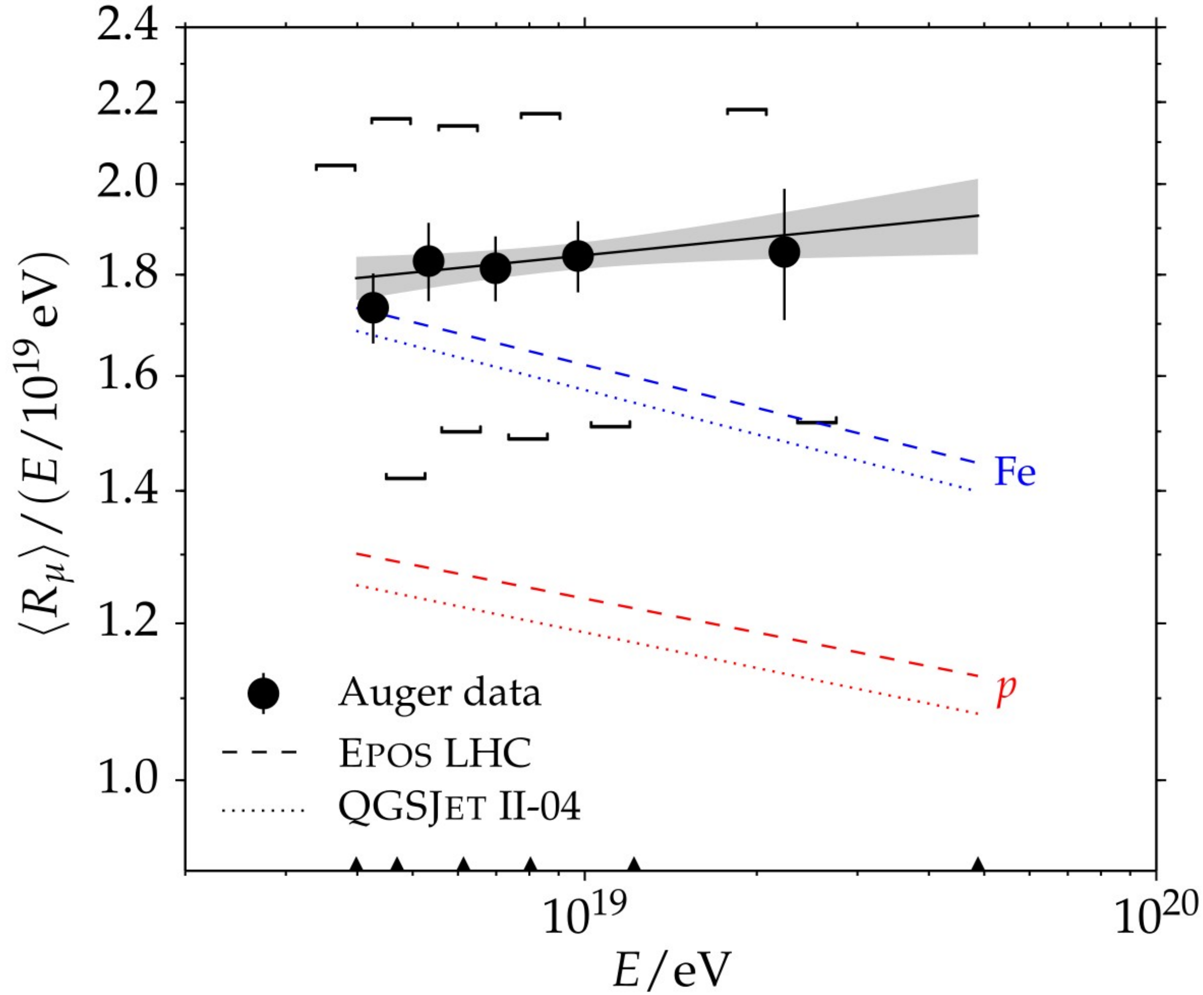
$$R_\mu = \frac{N_\mu^{data}}{N_{\mu,19}^{MC}}$$

Phys. Rev. D 91, 032003 (2015)

Muon measurement with highly inclined showers

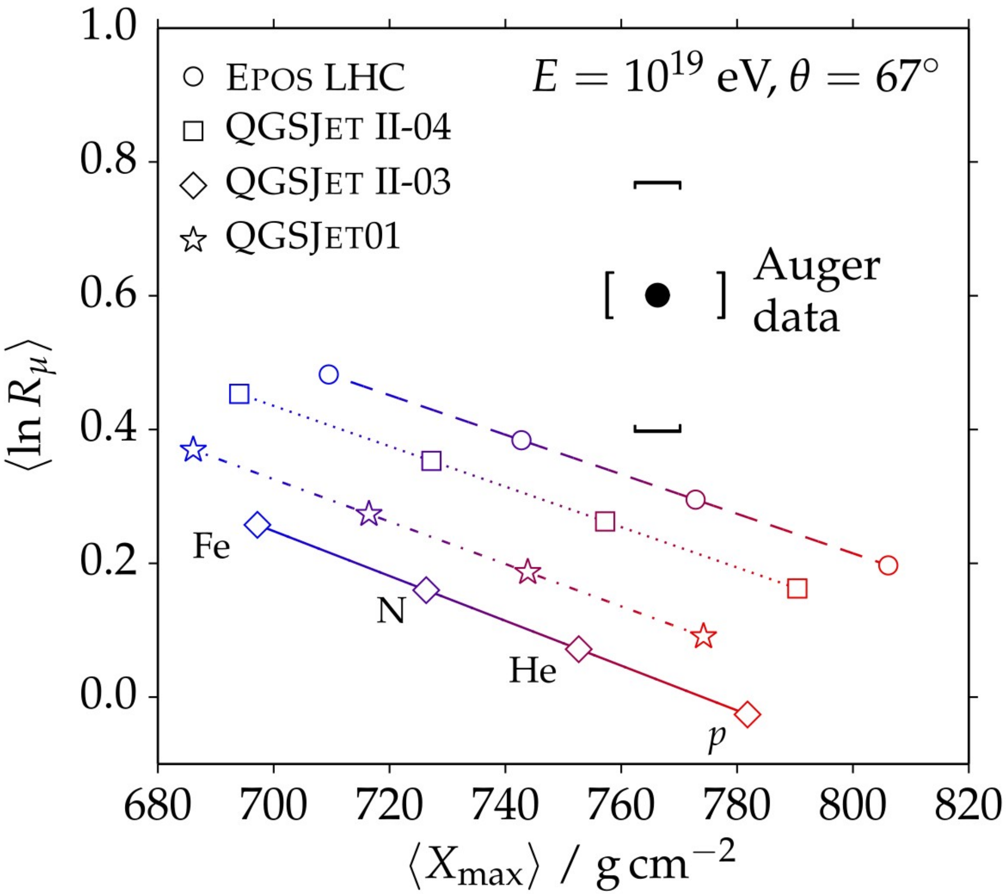


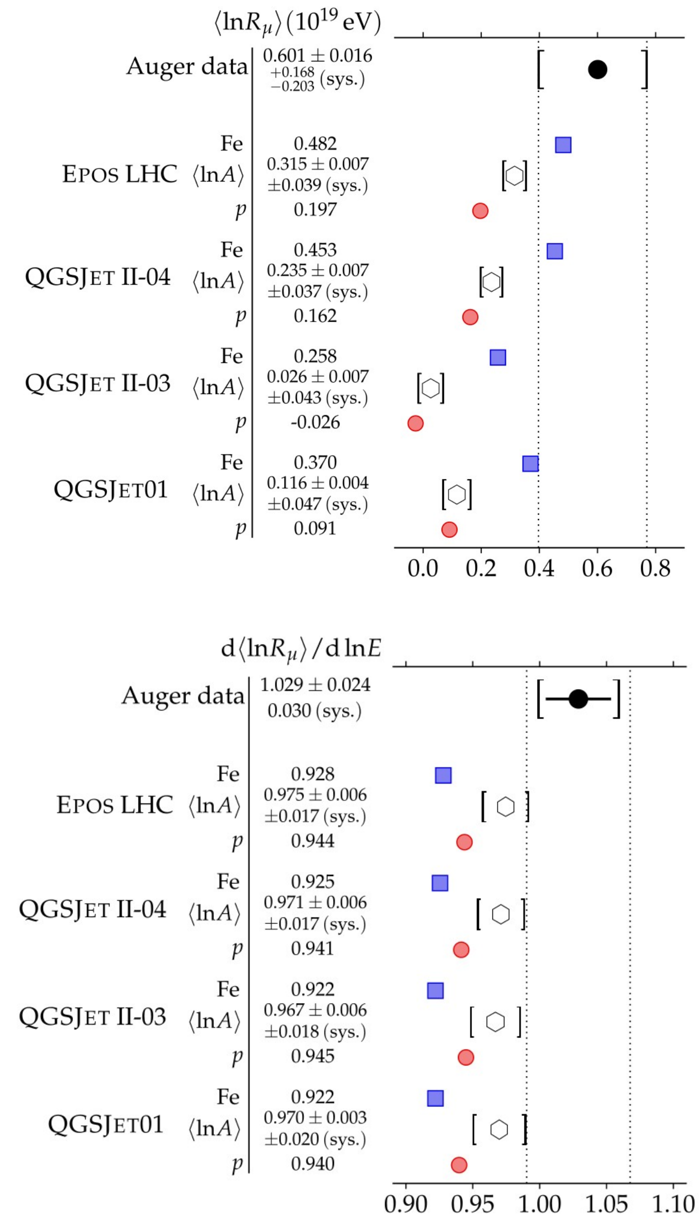
$$\langle R_\mu \rangle = a(E/10^{19}\ \text{eV})^b$$



Phys. Rev. D 91, 032003 (2015)

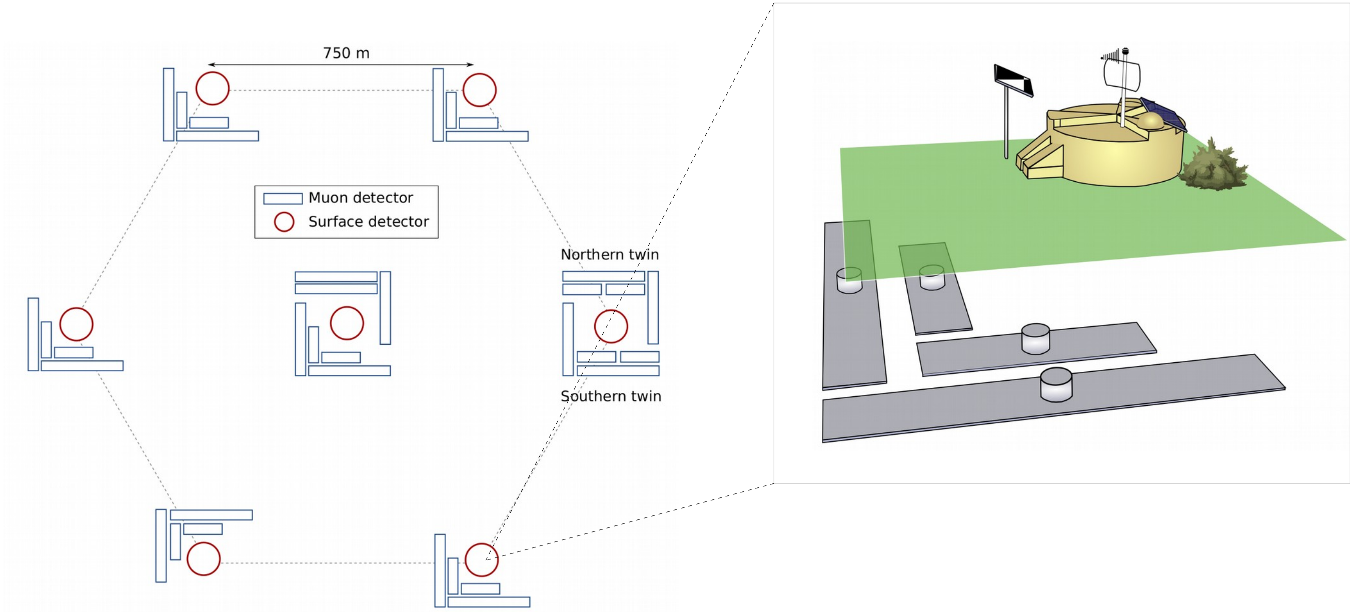
Muon measurement with highly inclined showers



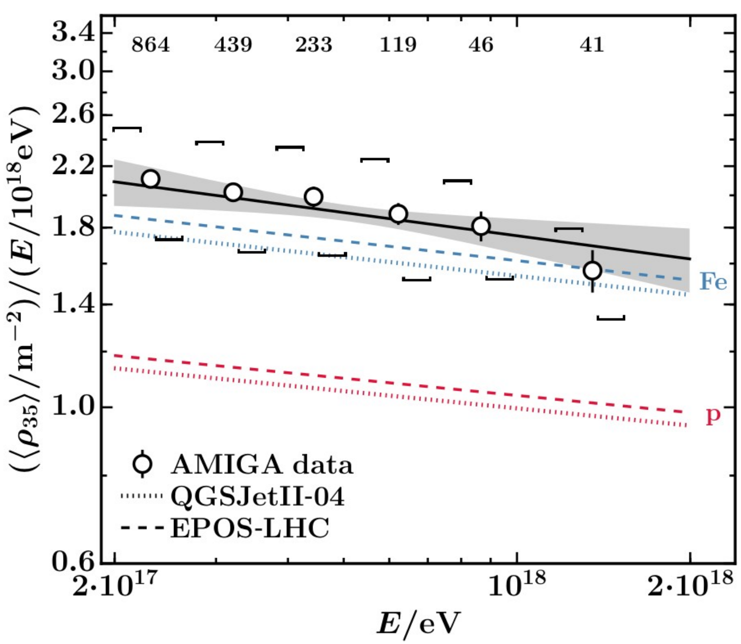


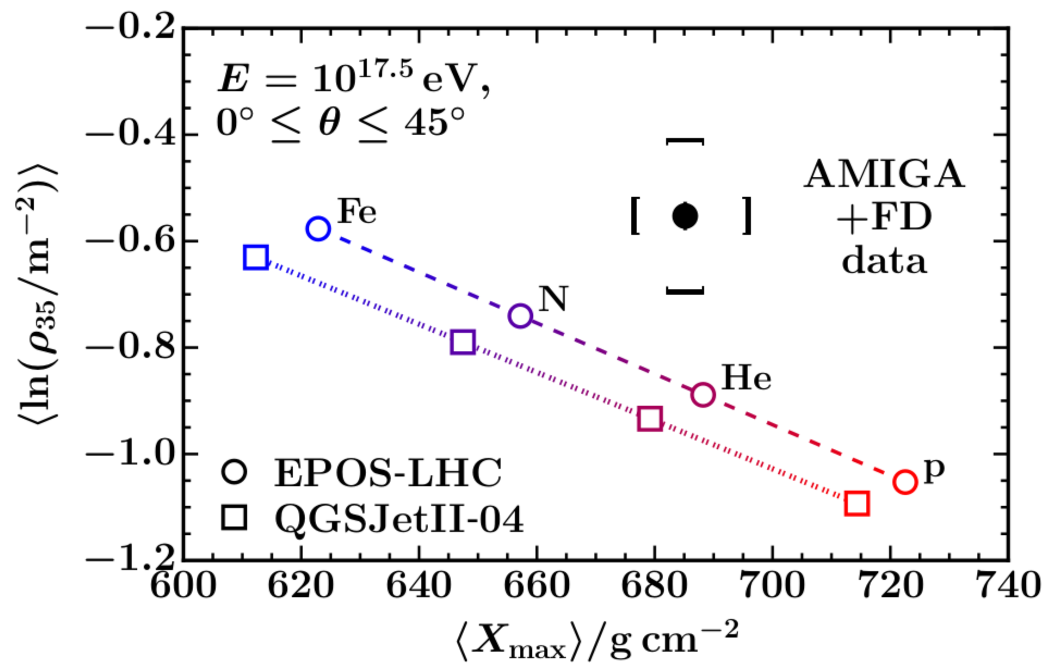
Phys. Rev. D 91, 032003 (2015)

Direct measurement with buried muon counters

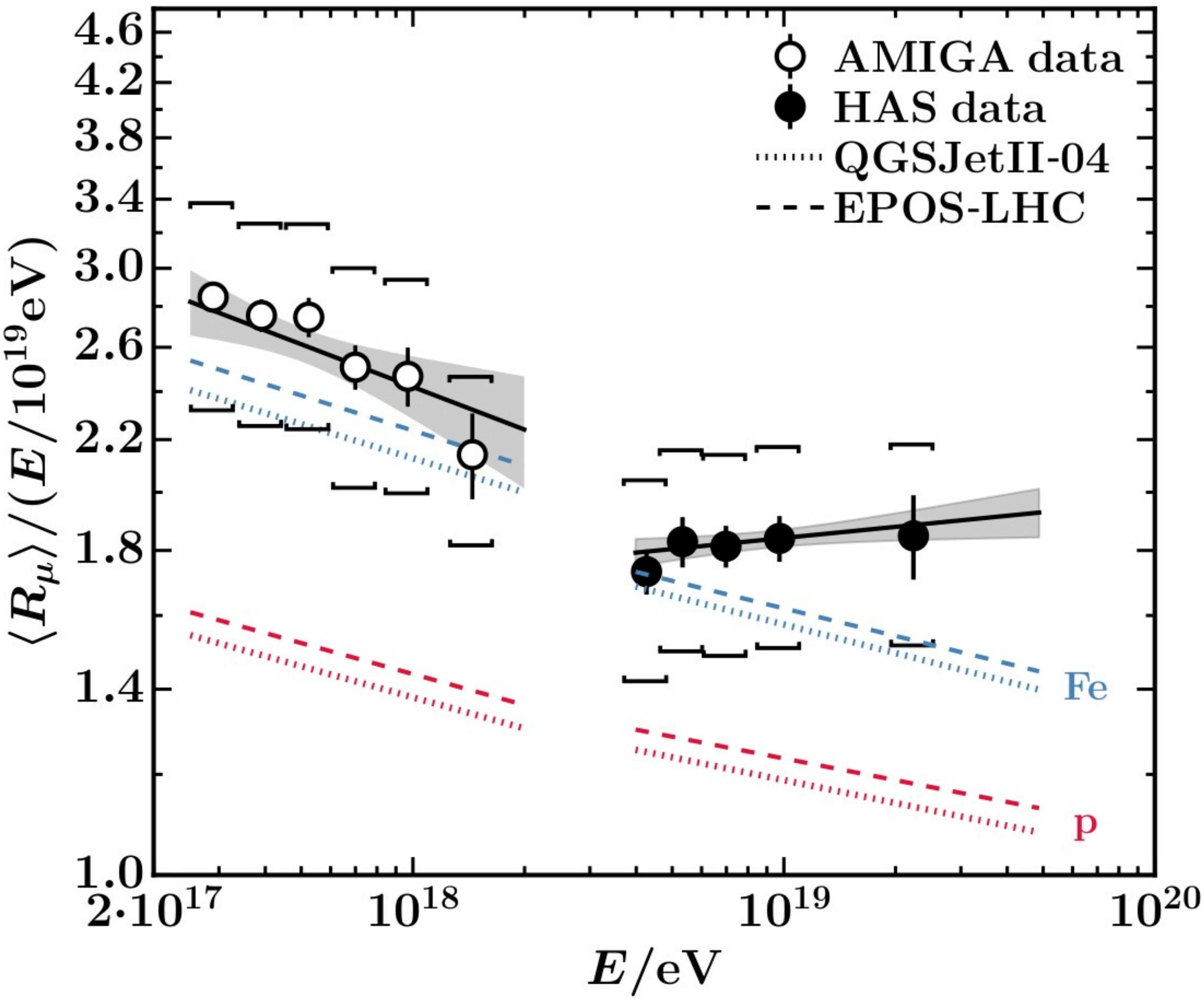


30 m² scintillators buried 2.3 m below surface at 7 WCD locations

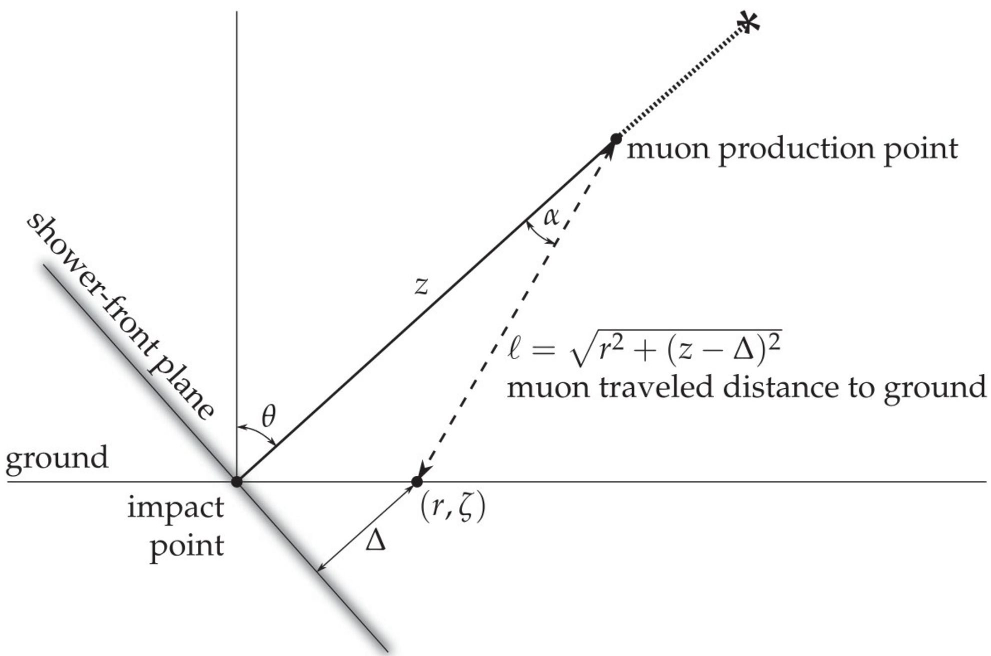




Juxtaposition

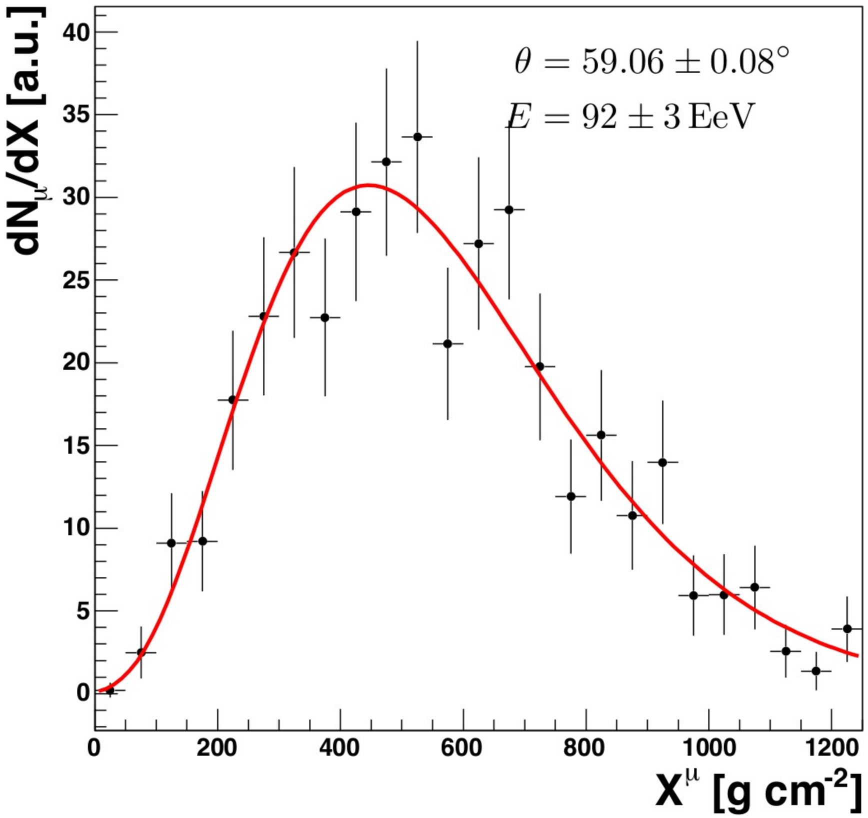


Muon production depth



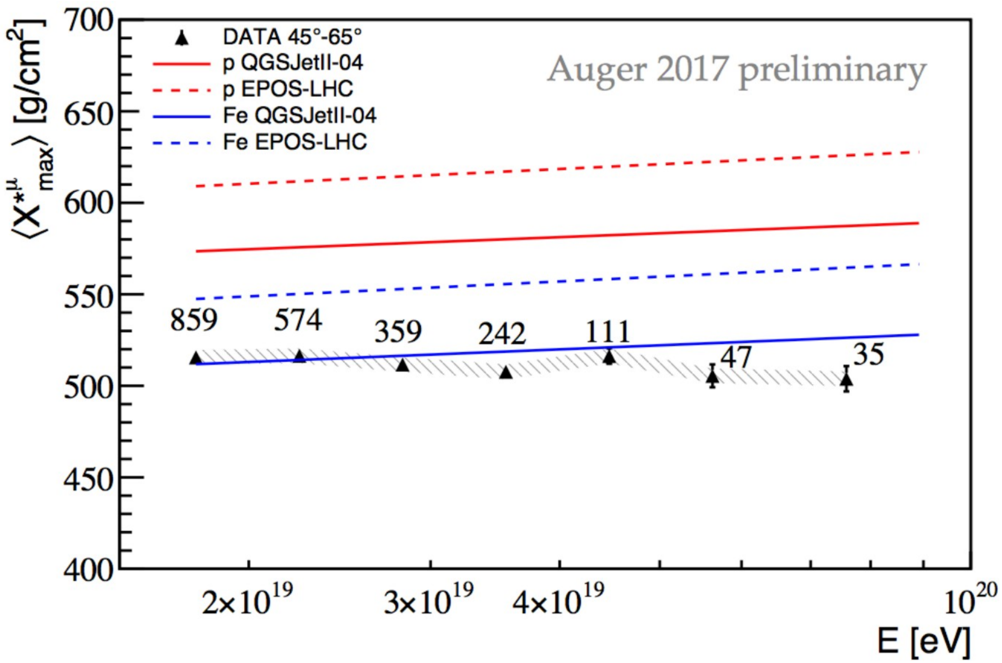
Assumption that muons...

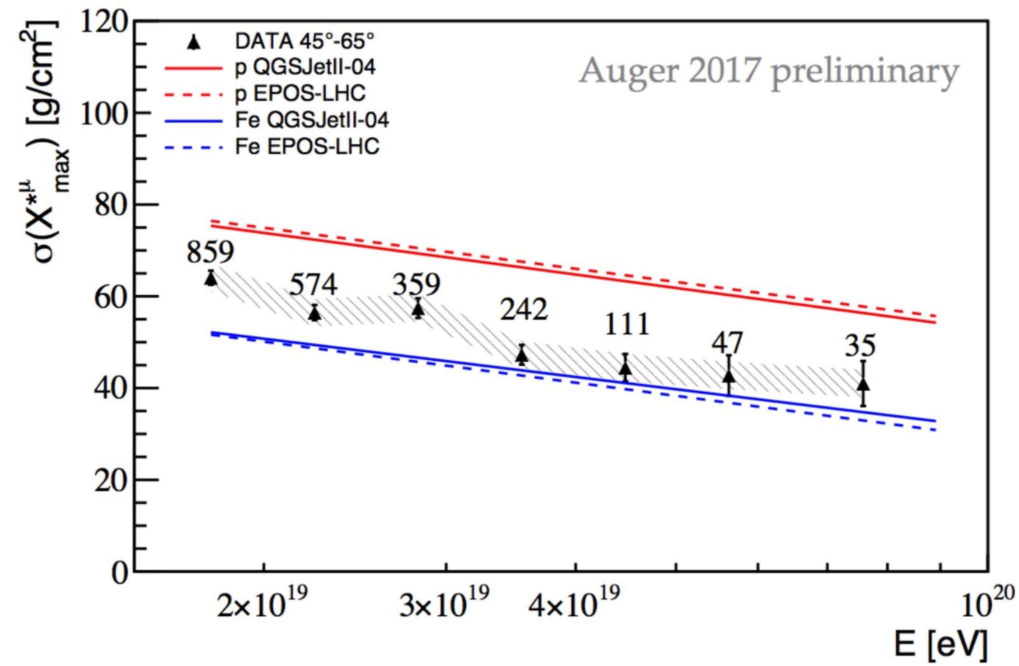
- have straight trajectories
- are produced along the shower axis

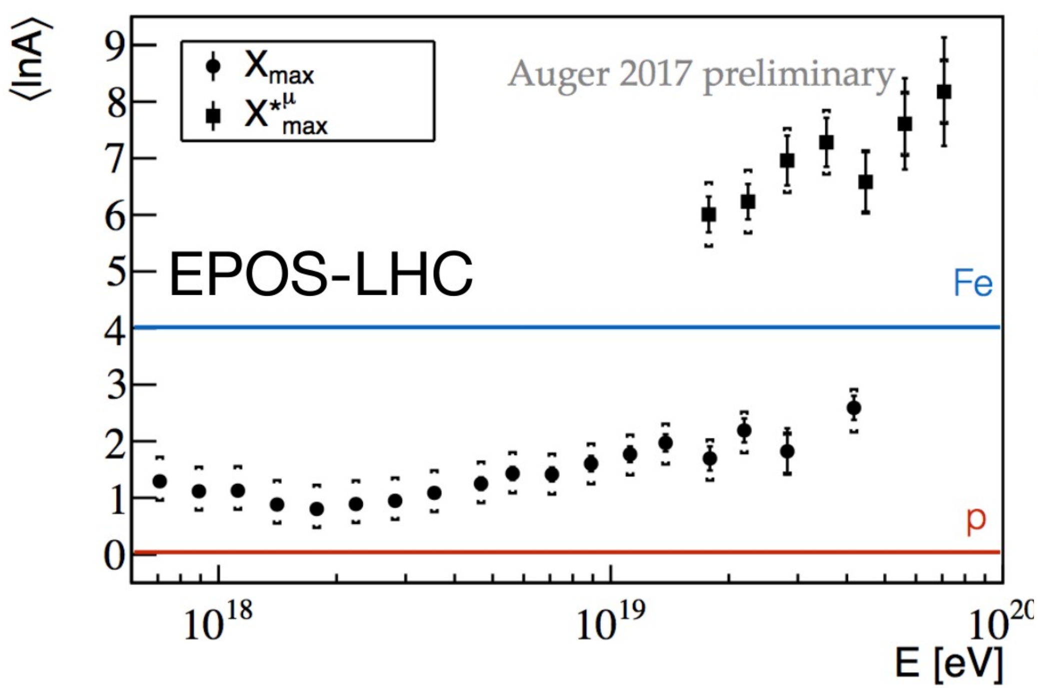


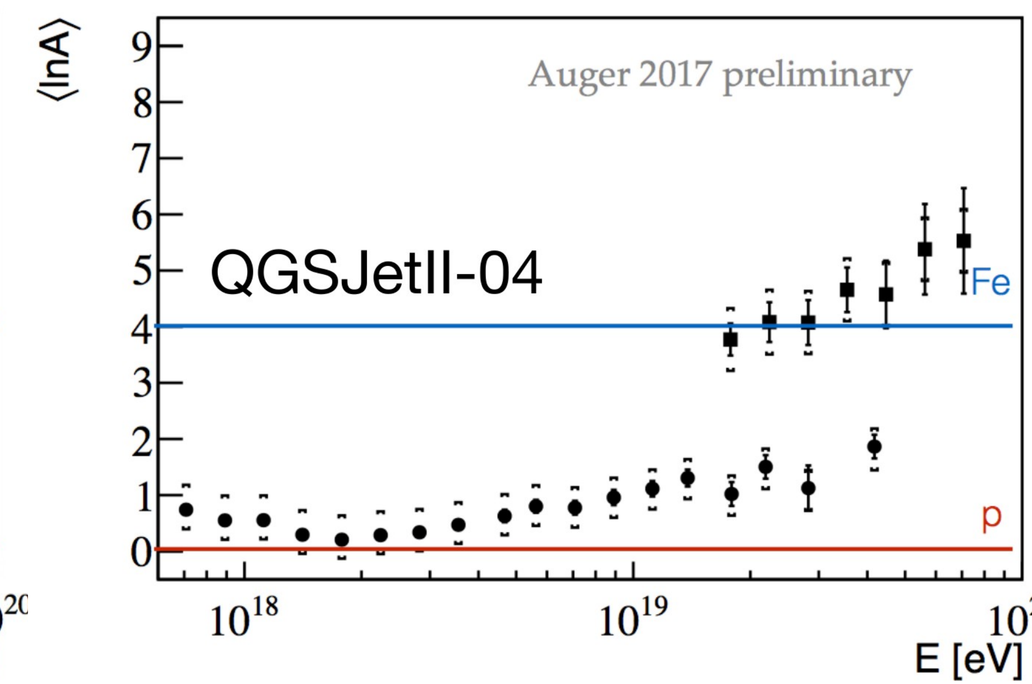
Given shower geometry and arrival time, a muon can be mapped to its production depth

Muon production depth

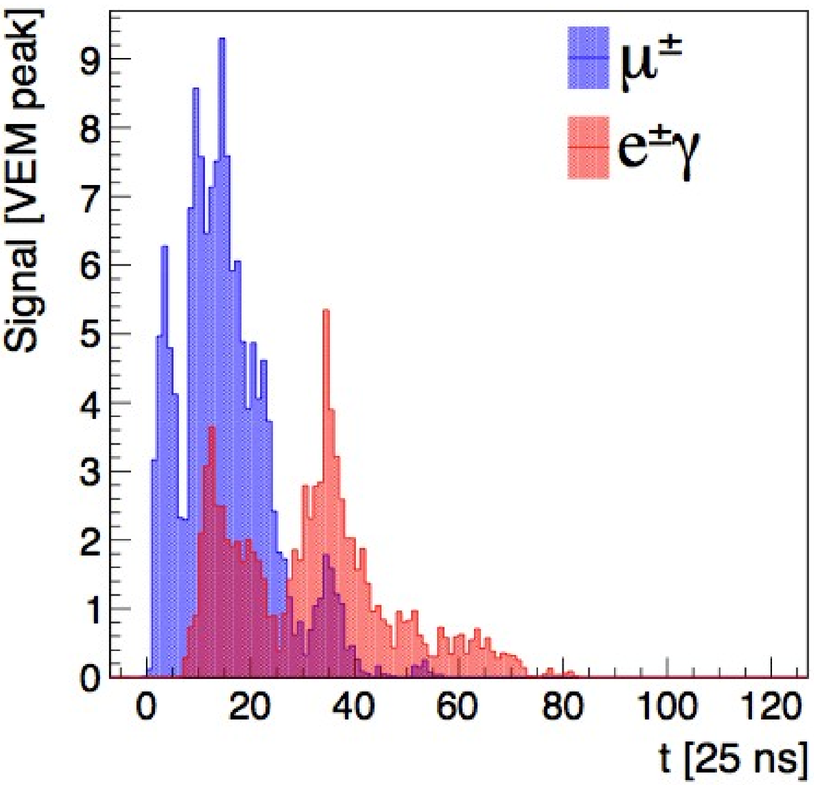


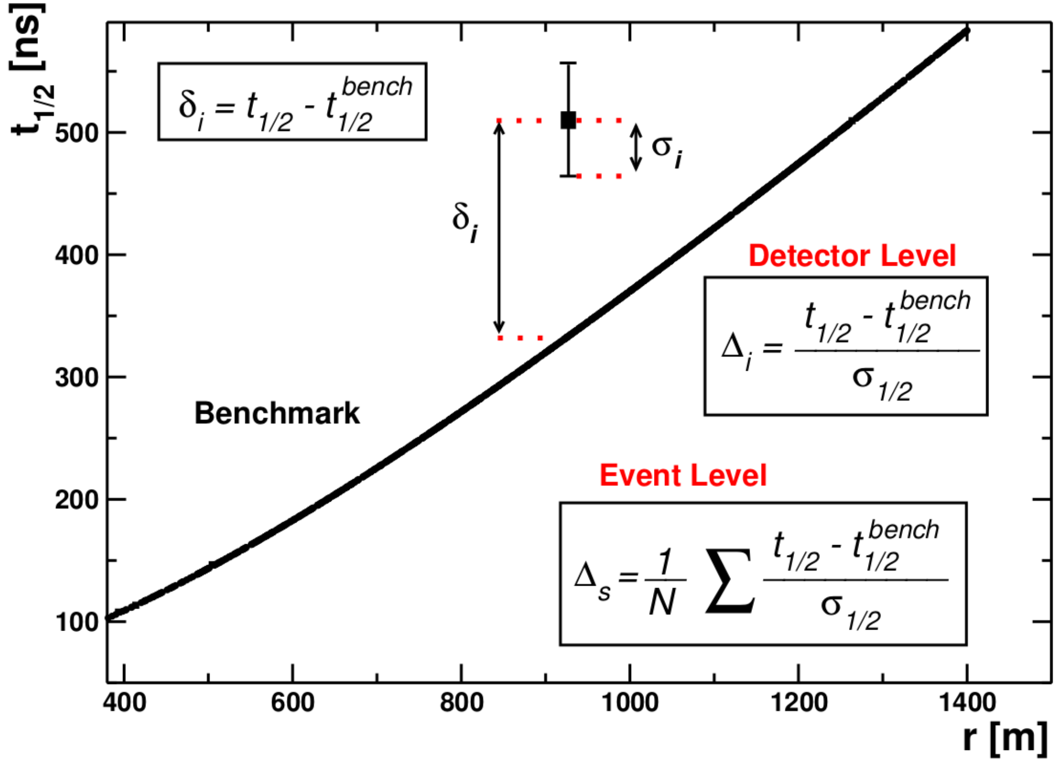






Measurement with risetime



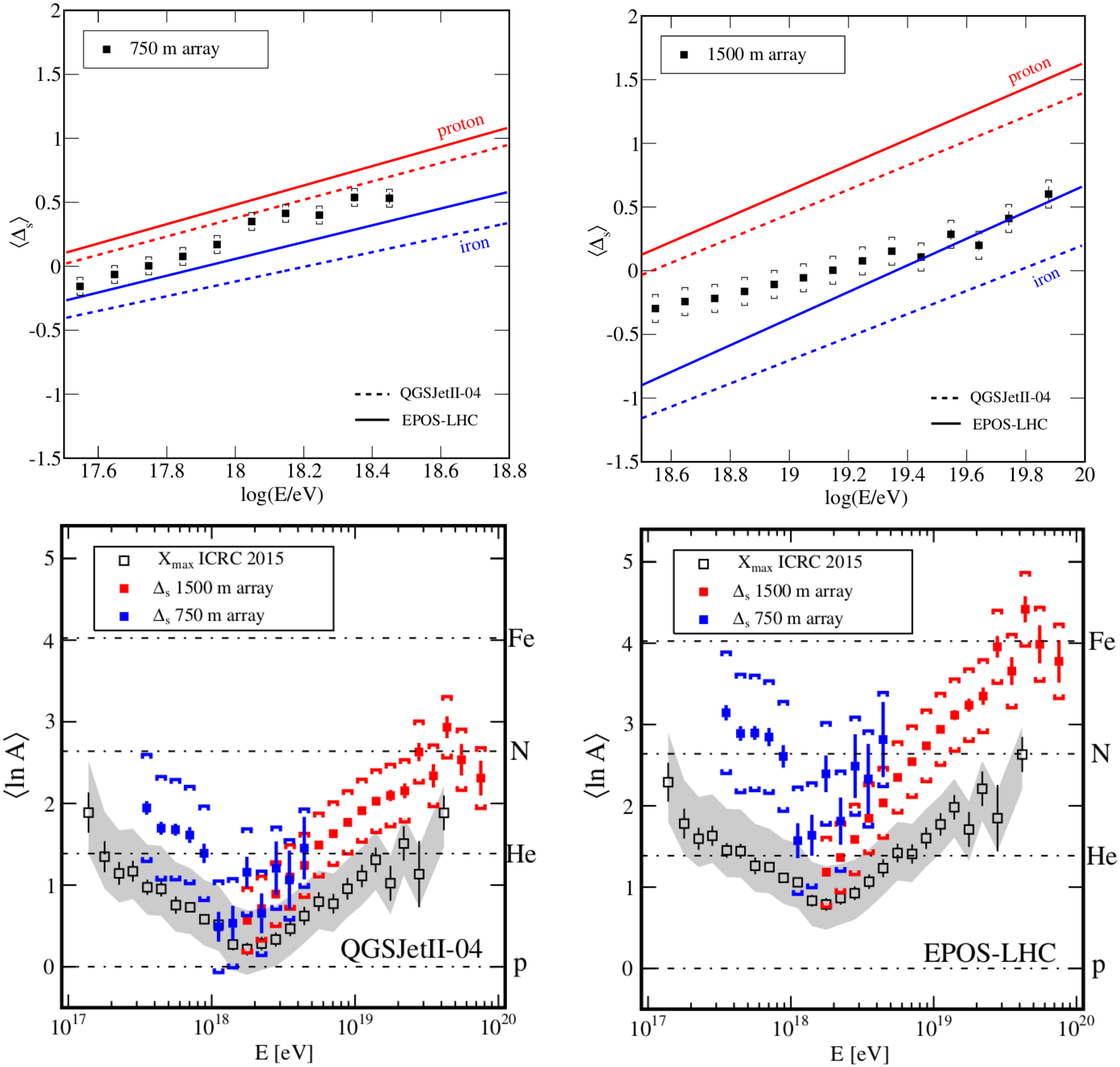


Time between integrated signal reaching 10% and 50% of the total signal used

Sensitivity to magnitudes of both shower components

Phys. Rev. D 96, 122003 (2017), ICRC2019

Measurement with risetime



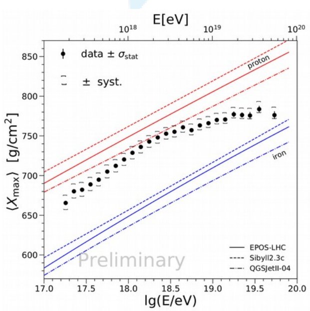
Phys. Rev. D 96, 122003 (2017), PoS ICRC2019

Summary

Auger's **hybrid design** facilitates measurements of the **electromagnetic (EM)** and **hadronic components** showers (through muons)

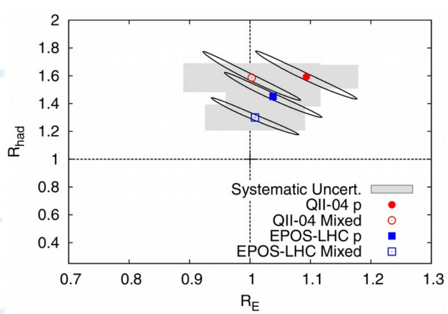
Estimates of **mass composition** from showers' **electromagnetic** component **in conflict** with measurements more sensitive to **hadronic** component

→ Muon deficit observed in simulations (tuned to most up-to-date hadronic interaction models)



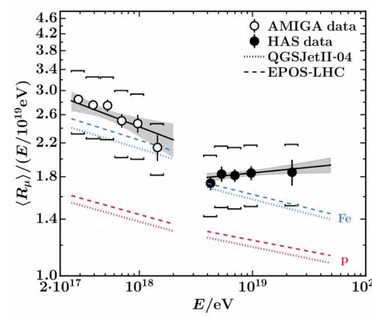
Depth of shower maximum

Hybrid

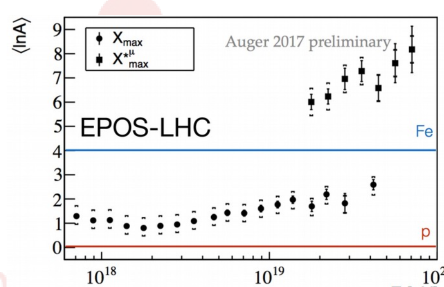


Hybrid re-scaling

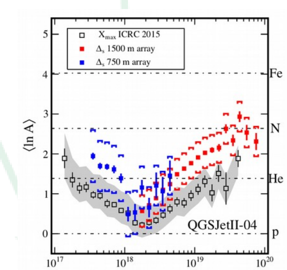
Buried muon counters



R_μ from inclined showers

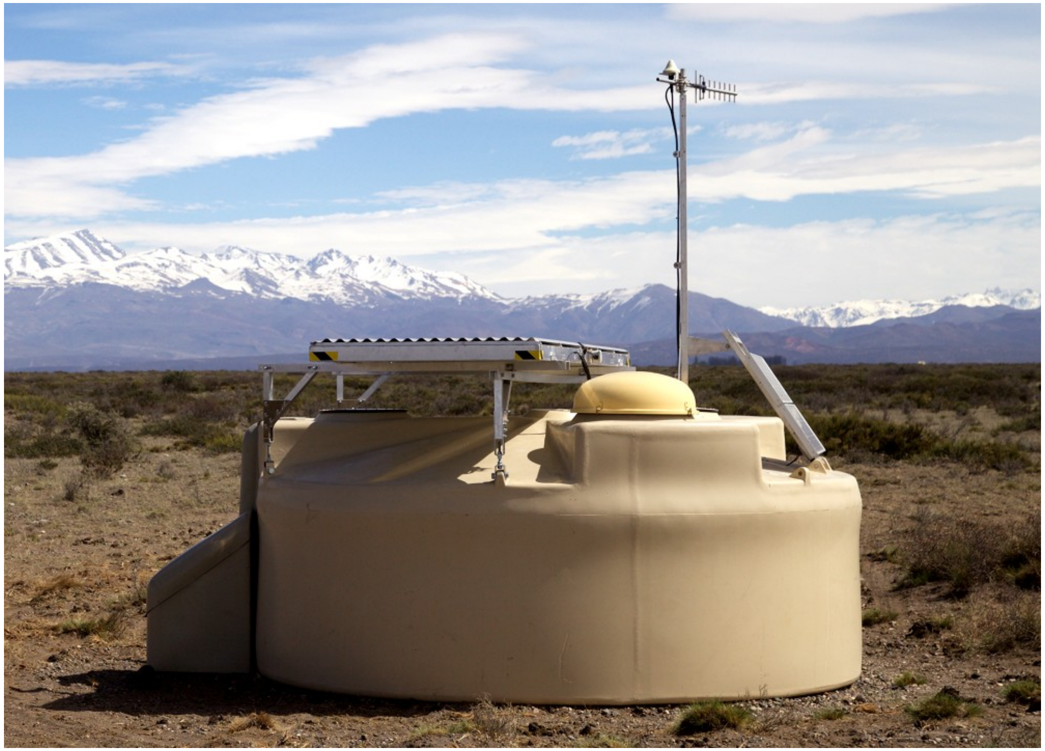


Muon production depth



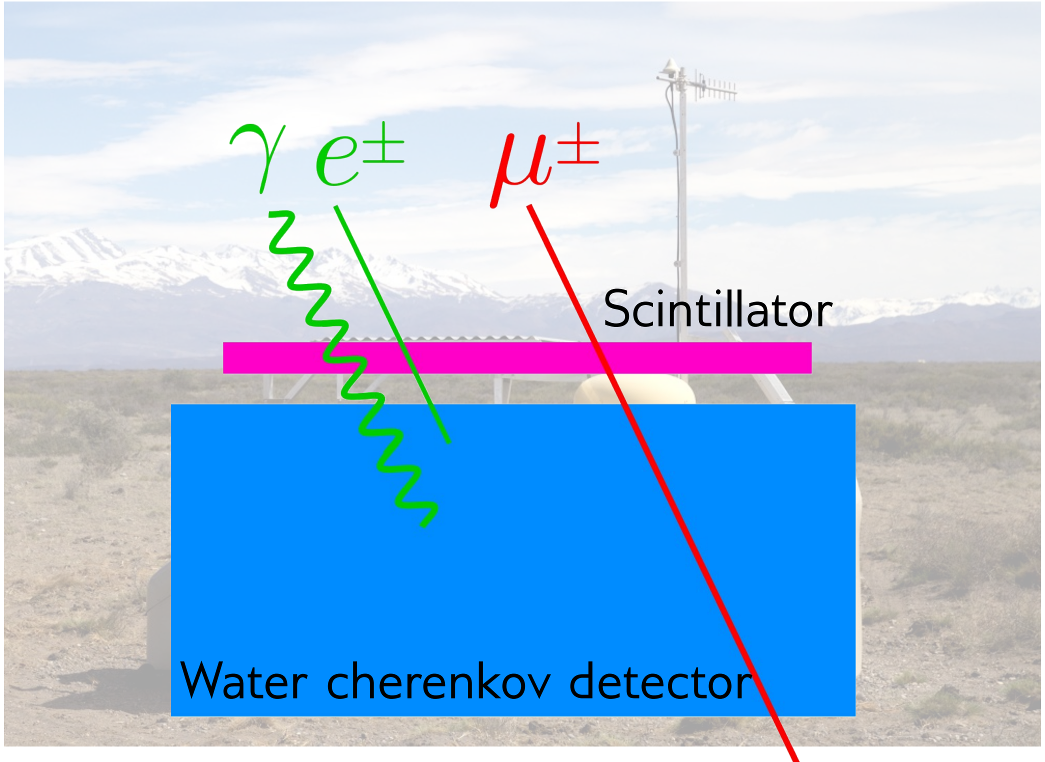
Risetime

AugerPrime



- 4 m^2 **S**cintillator **S**urface **D**etector atop each of the existing **W**ater-**C**herenkov **D**etectors

AugerPrime



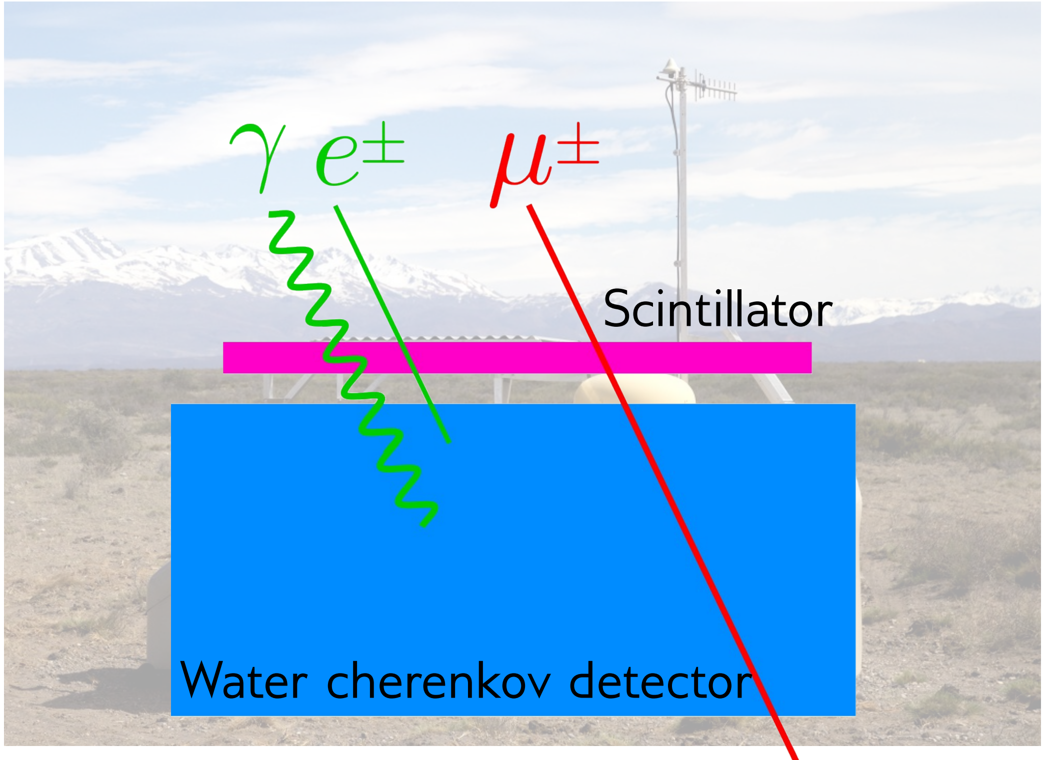
Disentangle **muonic** and **electromagnetic** shower components using differing responses

- 4 m^2 **S**cintillator **S**urface **D**etector atop each of the existing **W**ater-**C**herenkov **D**etectors

Hadronic interactions

Mass composition

AugerPrime



Disentangle **muonic** and **electromagnetic** shower components using differing responses

- 4 m² **S**cintillator **S**urface **D**etector atop each of the existing **W**ater-**C**herenkov **D**etectors
- A small PMT for extended dynamic range and improved 12-bit 120 MHz electronics for more precisely measured waveforms
- An **U**nderground **M**uon **D**etector covering 23.5 km² for direct muon measurements
- A radio antenna atop each SSD+WCD to extend mass sensitive sky coverage and exposure

Hadronic interactions

↕

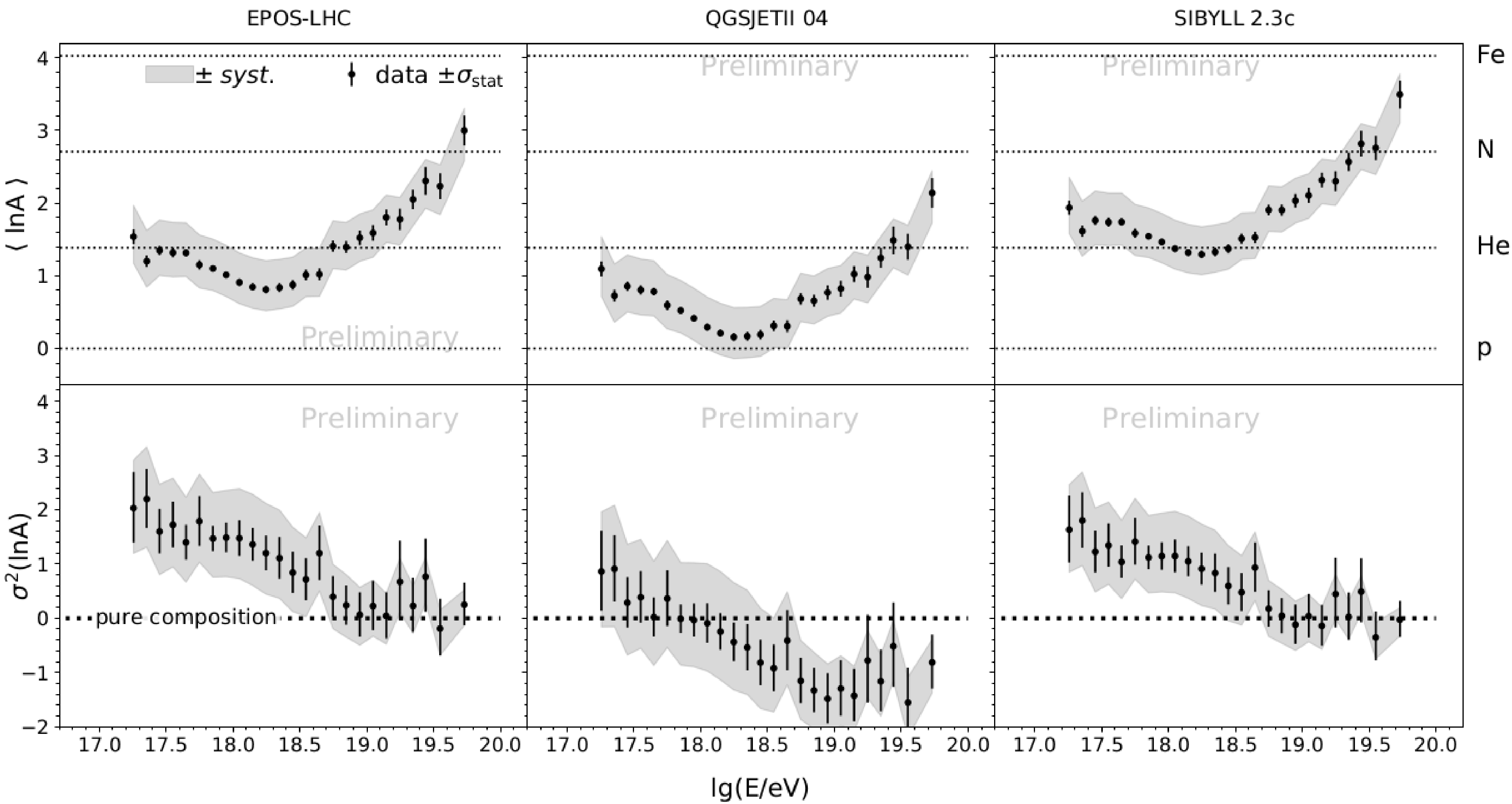
Mass composition

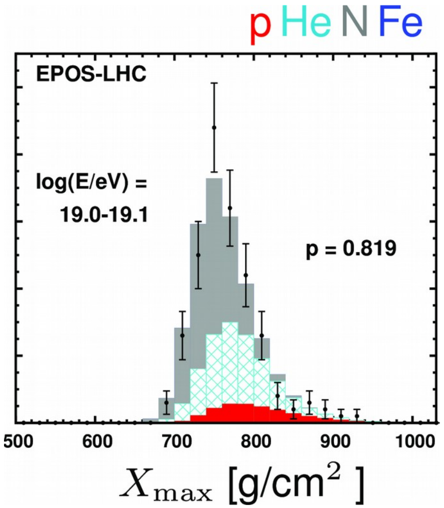
See talk by G. Cataldi from Tuesday:

The AugerPrime Upgrade of the Pierre Auger Observatory

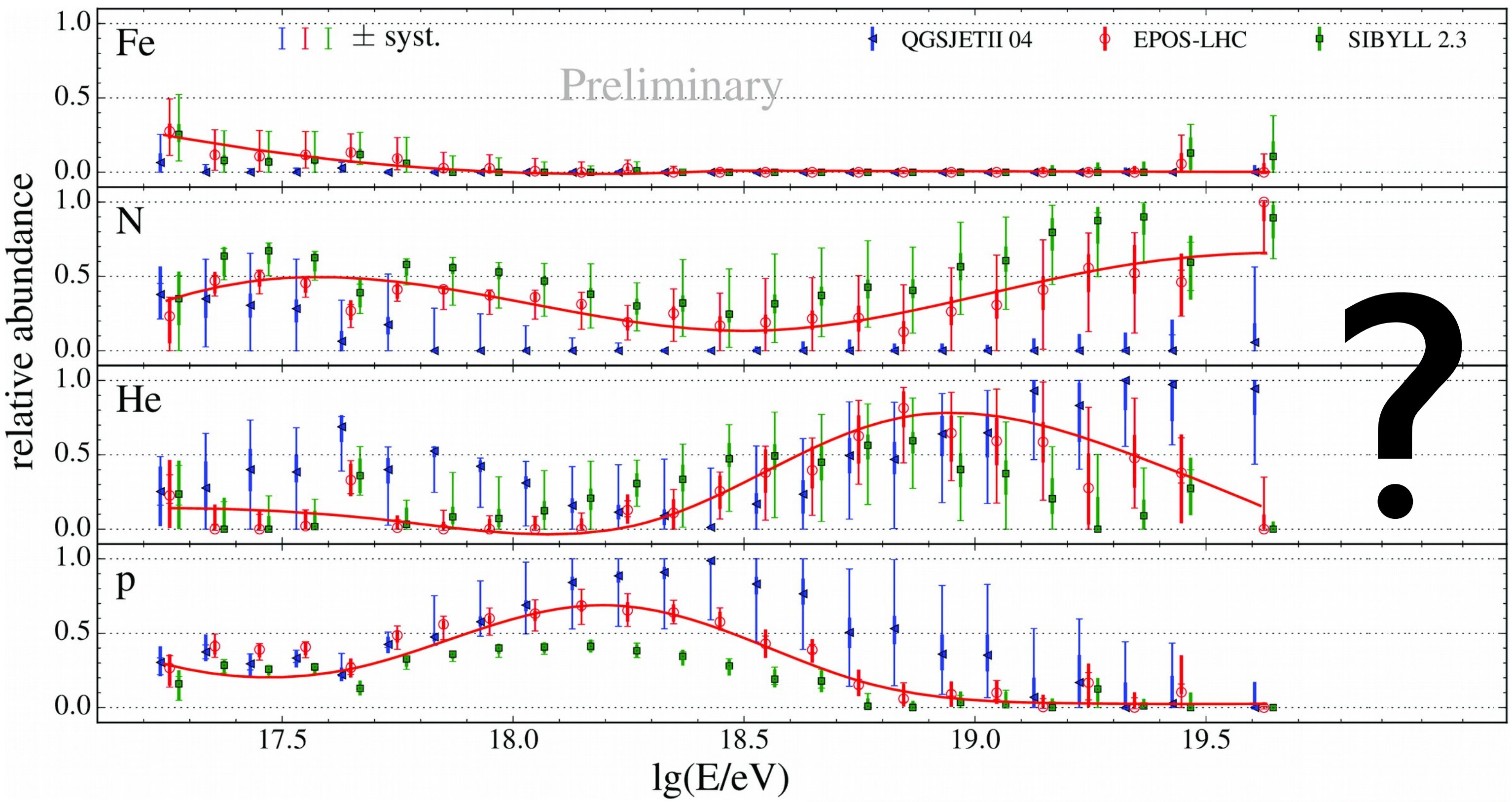
Thanks

Backup


EPOS-LHC
QGSJETII 04
SIBYLL 2.3c
± syst.
data $\pm\sigma_{\mathrm{stat}}$
Preliminary
Fe
N
He
p
$\langle \ln A \rangle$
$\sigma^2(\ln A)$
pure composition
lg(E/eV)



Monte-carlo Xmax distributions fit to data



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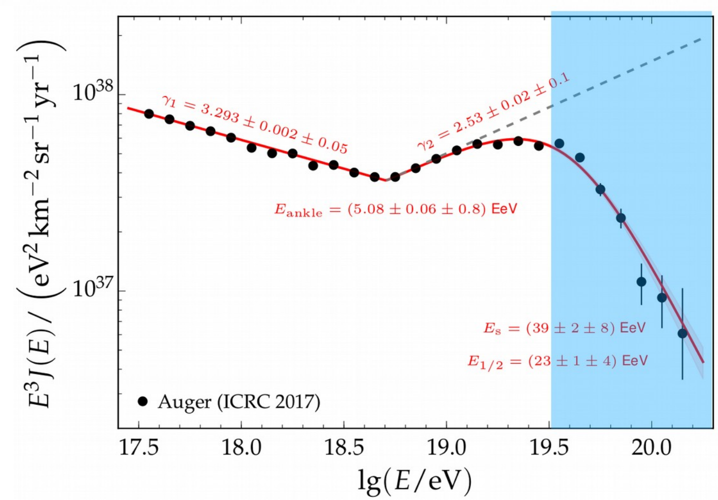

Need mass sensitive measurement with nearly 100% duty cycle

… with decent single event resolution on mass for light element selection