Muon content of air showers – methods of studying the problem and recent results

Jan Pękala, *Institute of Nuclear Physics PAS, Kraków*

Accelerator measurements and ultra-high energy cosmic rays

Analysis of cosmic ray observations at ultra-high energies requires air shower simulations

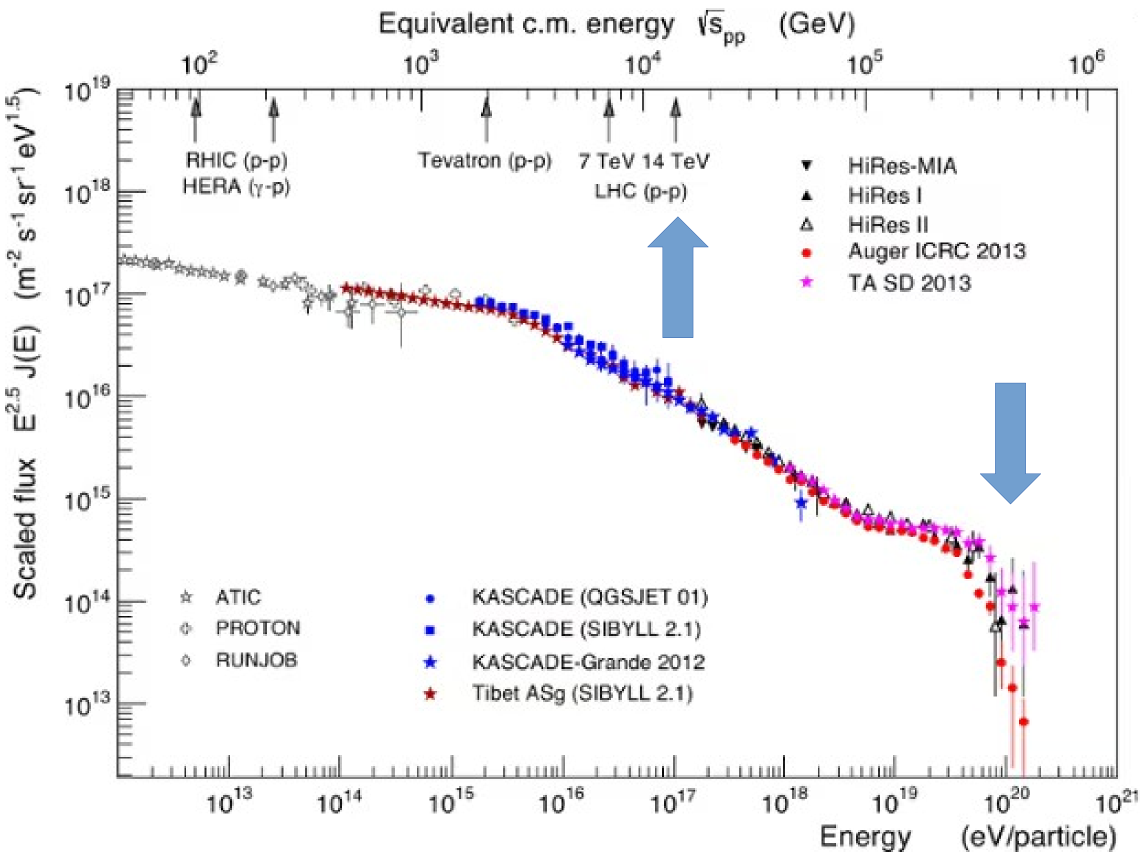
Simulations are based on nuclear interaction models

Accelerator measurements used to construct models:

⇨ available at energies orders of magnitude lower

⇨ important pseudorapidity range not covered in measurements

⇨ different projectile/target compositions

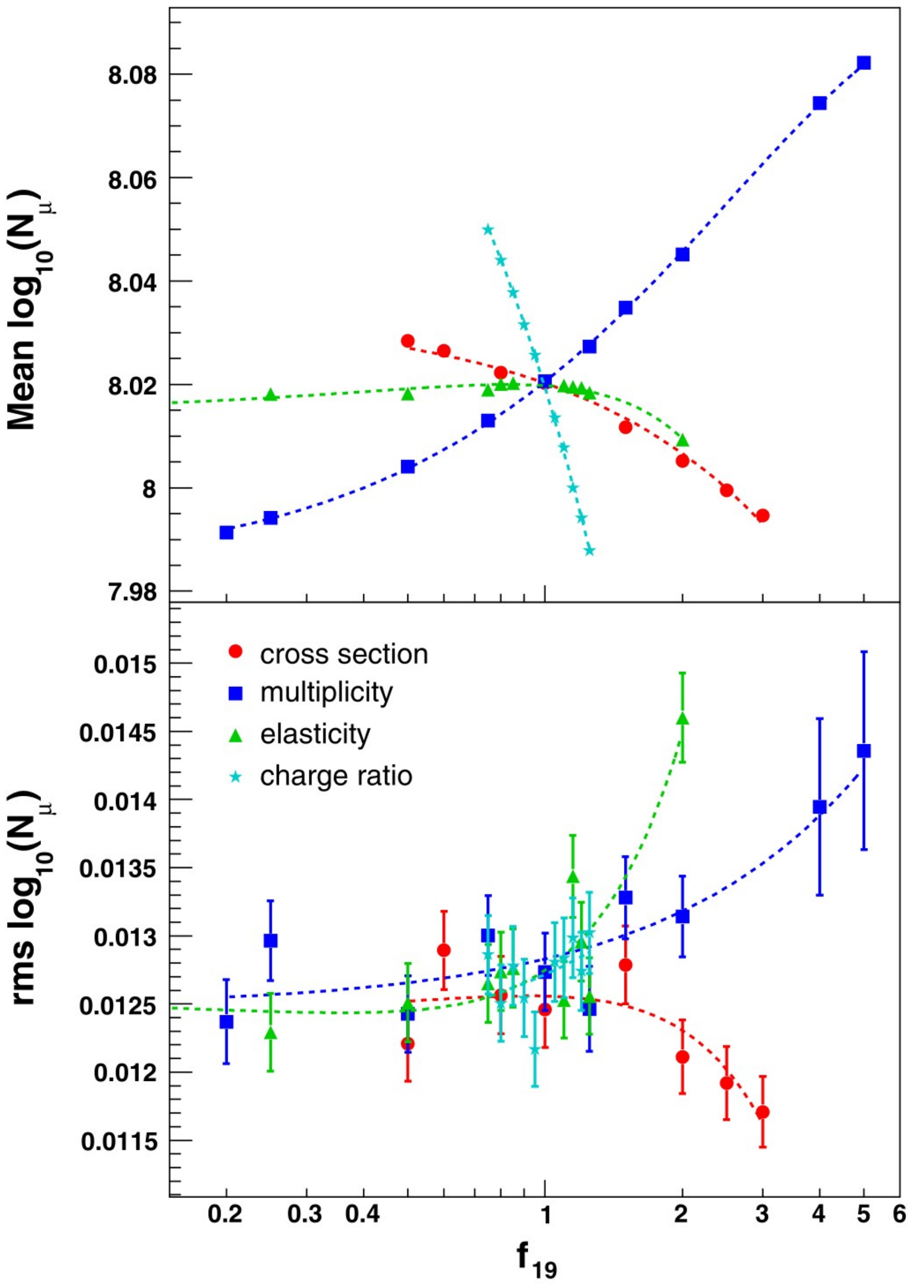


Hadronic models versus muon signal

Extrapolation up to ultra-high energies necessary

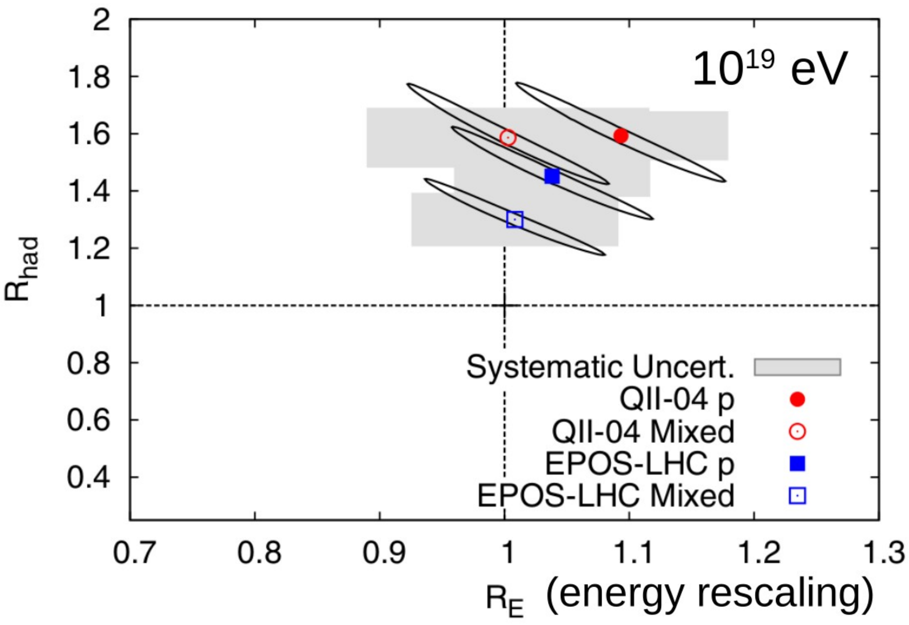
Air shower development dominated by few parameters:
- *primary mass and energy*
- *cross-sections*
- *elasticity*
- *multiplicity*
- *charge ratio*

Cosmic ray observations can constrain the models



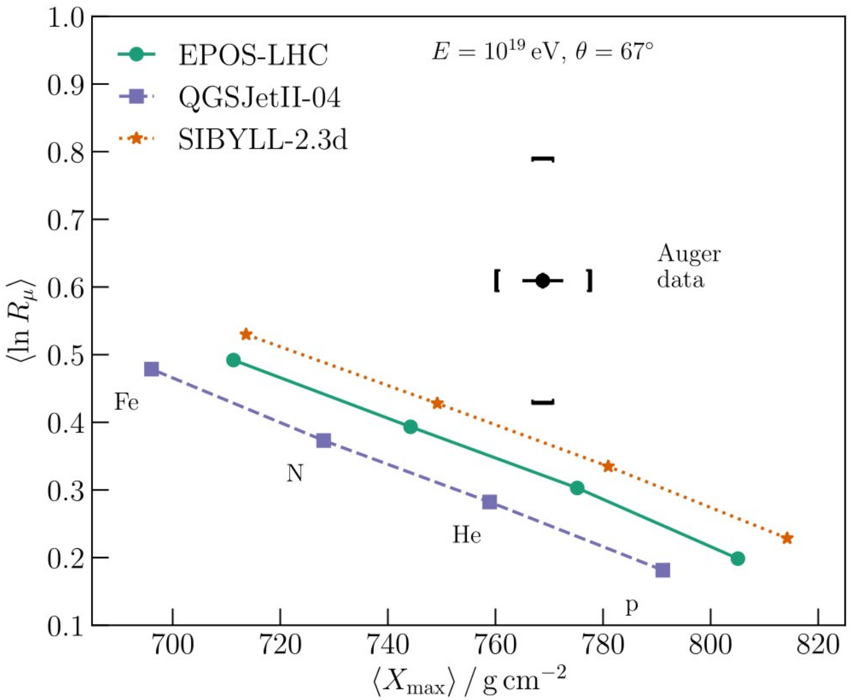
Deficit of muons in simulations

Muon content of air showers determined in various observations: using buried detectors, from measurements of inclined showers



Combined information from surface and fluorescence detectors

Problem to reproduce the muon signal in simulations – significant deficit



Rescaling factor needed: ~1.3 – 1.6

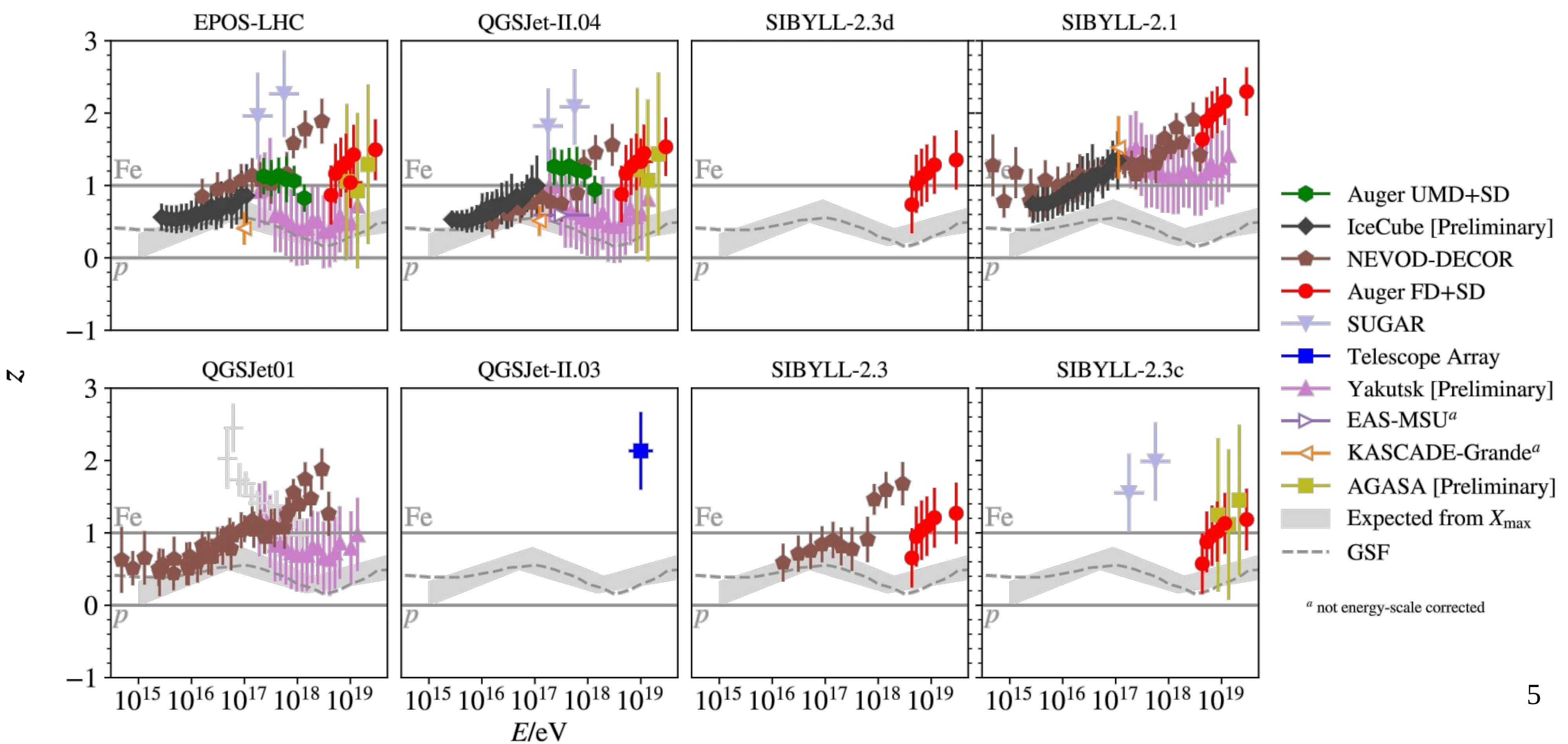
Discrepancy seen at various energies, zenith angles

Deficit of muons in simulations

Observed muon content lager than predicted by simulations

⇨ Seen by different experiments

⇨ Discrepancy in analyses based on different hadronic interaction models

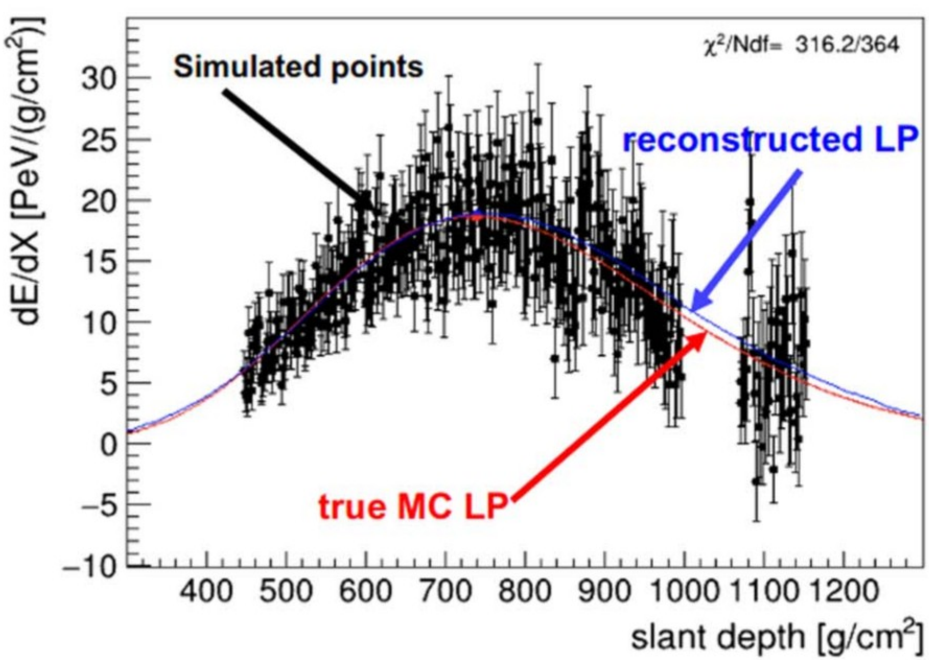


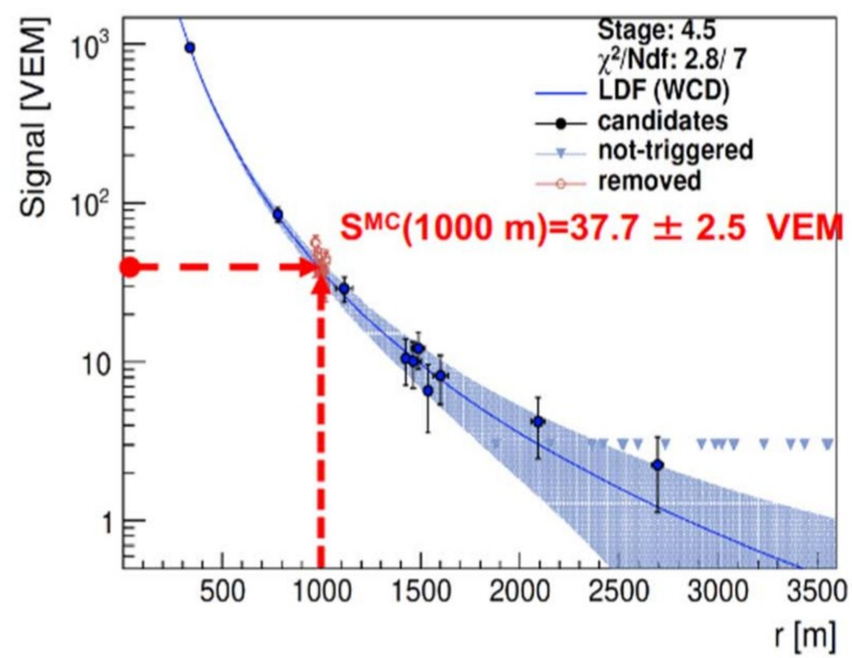
Analysis of the discrepancy: Top-Down

Using combined information from surface and fluorescence detectors to determine muonic component of air showers

Longitudinal profile measured by FD used as a reference to reproduce the observed air shower in simulations – accurate estimation of EM part

Comparing measured and simulated signal on ground – eliminating EM component enables calculating muon discrepancy





Analysis of the discrepancy: Top-Down

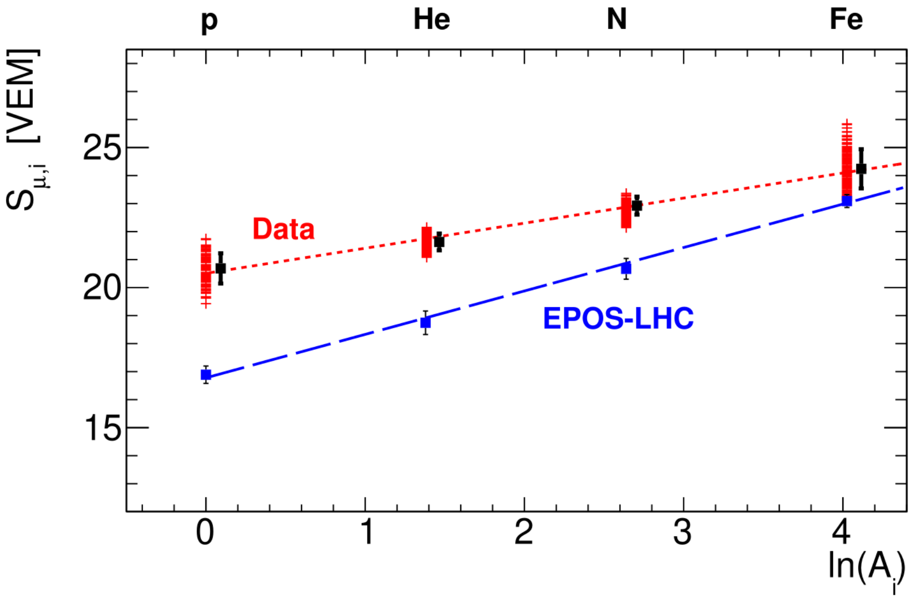
Method tested by analyzing mock sets of simulations – good recovery of the average muon signal

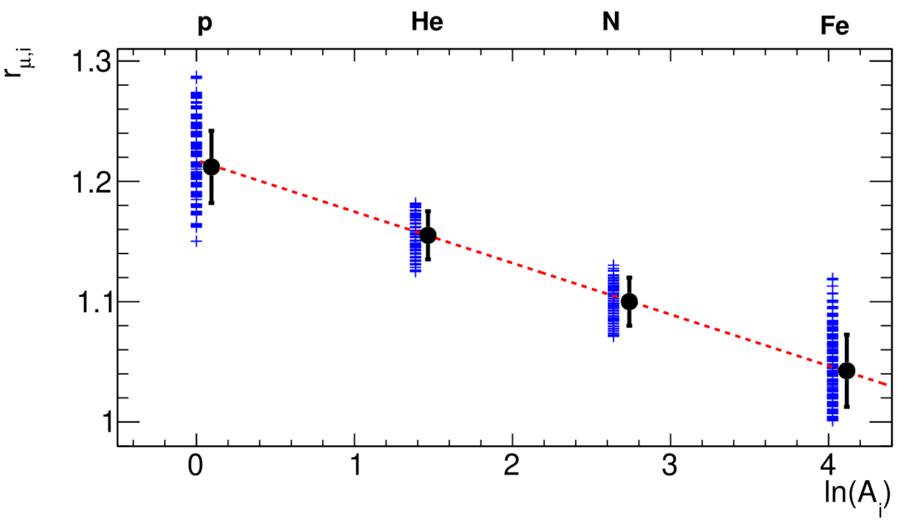
Determination of muon rescaling factors

Possibility of constraining nuclear interaction models - β exponent of Heitler-Matthews model:

$$N_\mu = N_\mu^p A^{1-\beta}$$

Analysis of a very deep event (see poster #116 by Megha Mogarkar)



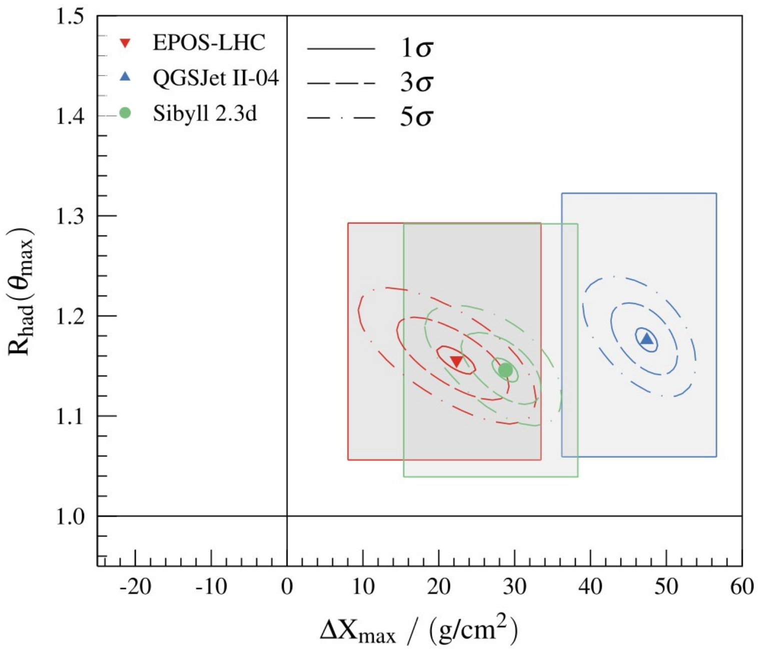


New approach: simultaneous fit of signal and X_{max}

X_{max} predicted by different models vary significantly (~25 g/cm²)

⇨ X_{max} scale uncertainty

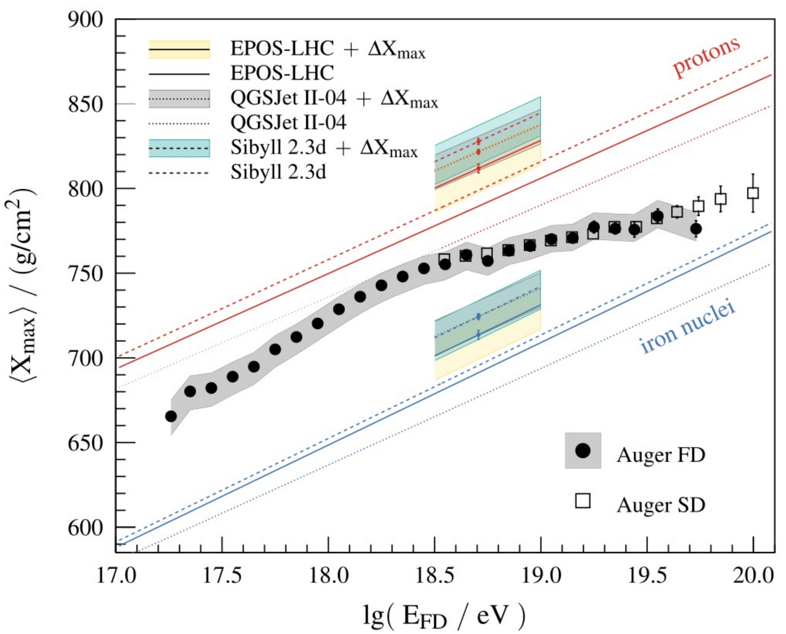
⇨ Allowing the shift of the scale by fitting X_{max} shift



Simultaneous fit of X_{max} and signal at ground S(1000):

X_{max} shifted by 20-50 g/cm² deeper

Hadronic signal rescaling factor smaller: 1,15 – 1,25

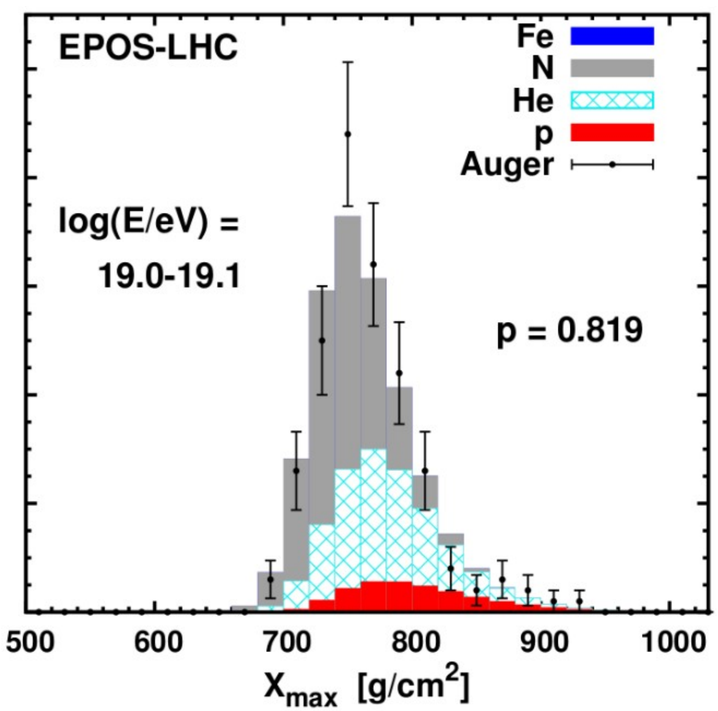


New approach: simultaneous fit of signal and X_{max}

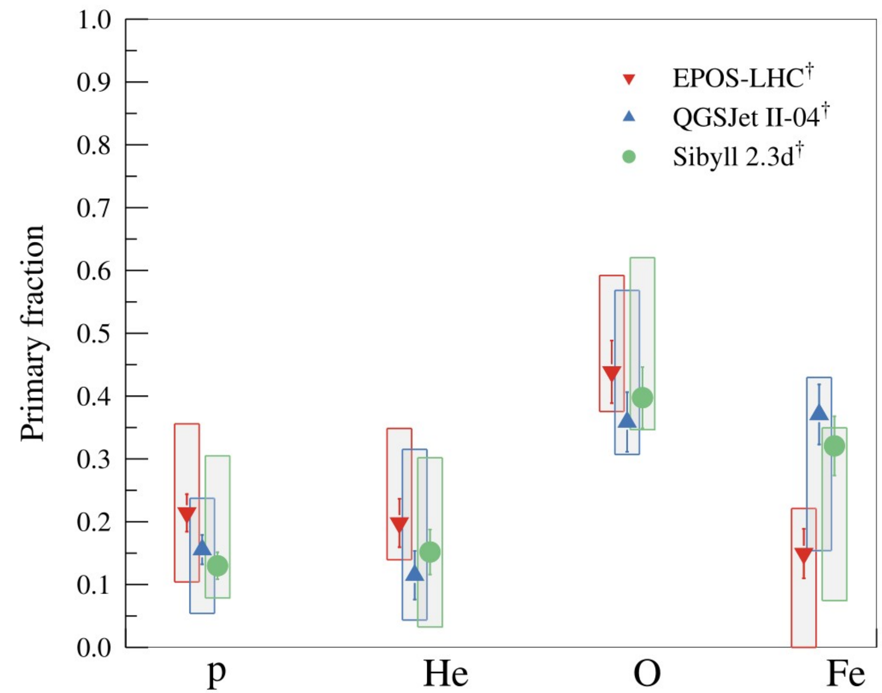
Implications for composition:

Deeper X_{max} ⇨ shift towards heavier primaries

⇨ better agreement with higher muon content



Phys. Rev. D 90 (2014) 122006



Phys. Rev. D 109 (2024) 102001

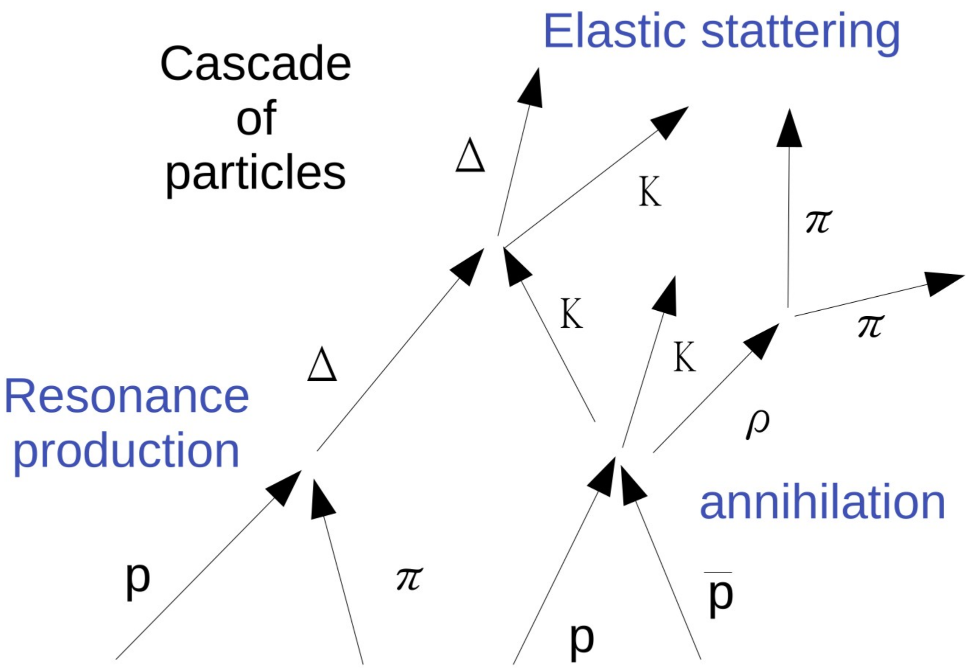
New models of hadronic interactions

Models were updated using first LHC results, but new data now available

EPOS LHC-R almost ready – including more physical processes for better tuning

Even without direct impact on the air shower development, it changes model parameters and extrapolation

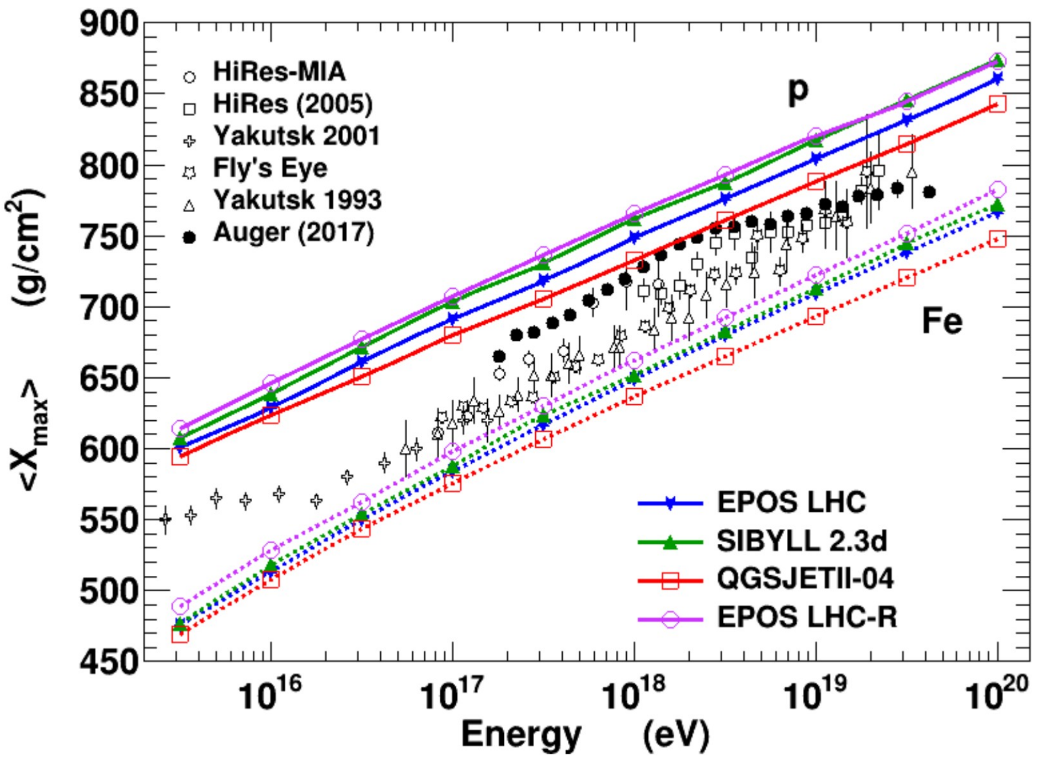
Hadronic rescattering – change string fragmentation parameters

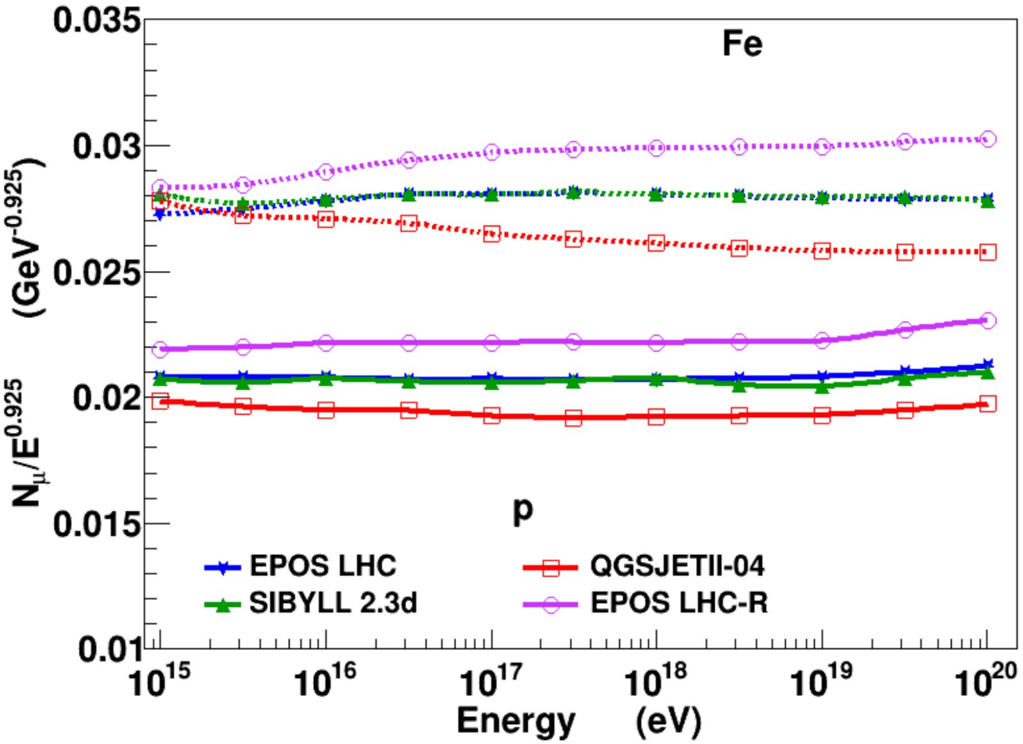


New models of hadronic interactions

Motivated by Auger data – shift of X_{max} by +15 g/cm²
- in full agreement with accelerator data

Increase of the number of muons by ~10%

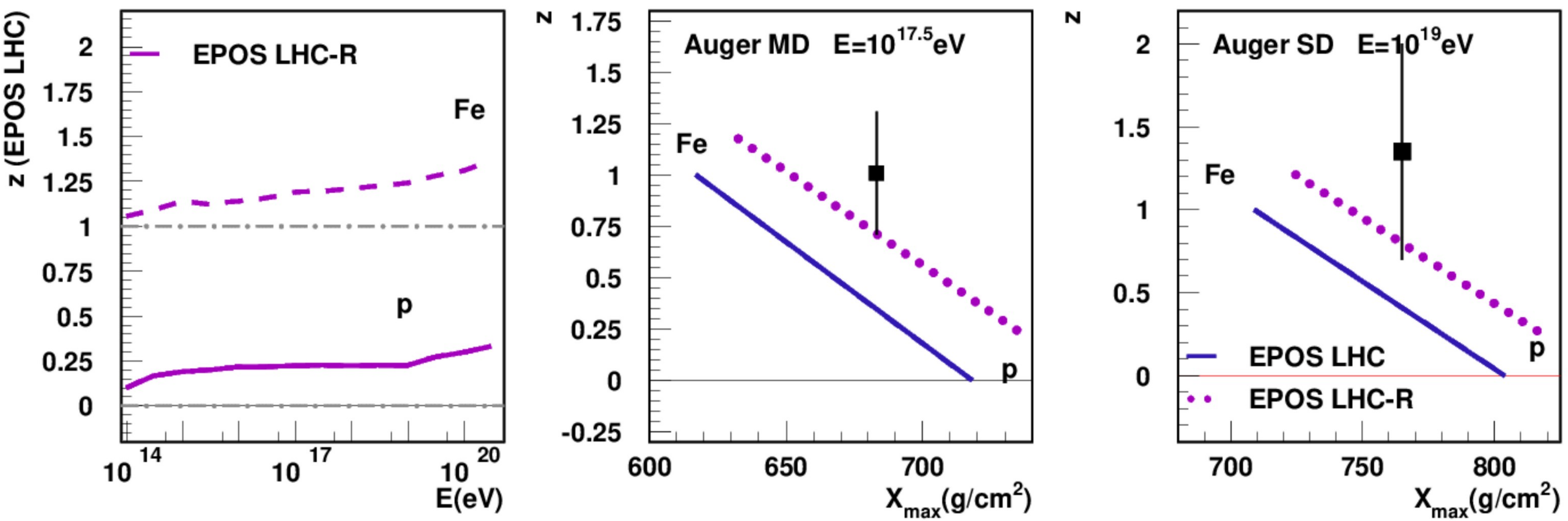




New models of hadronic interactions

Deeper X_{max} ⇨ larger <ln A> ⇨ reduction of muon discrepancy

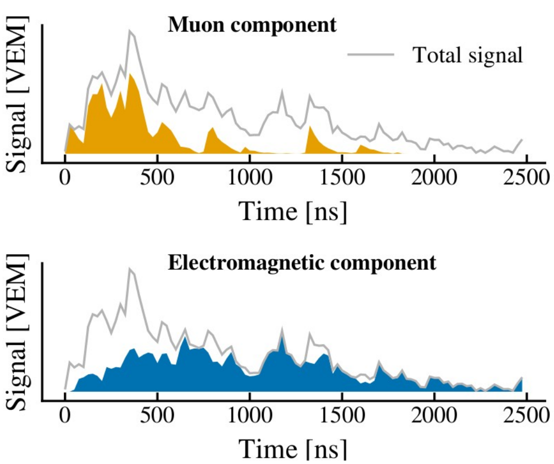
Energy and mass dependent increase of muon content due to collective effects
⇨ further decrease of the gap ⇨ agreement within systematical uncertainty

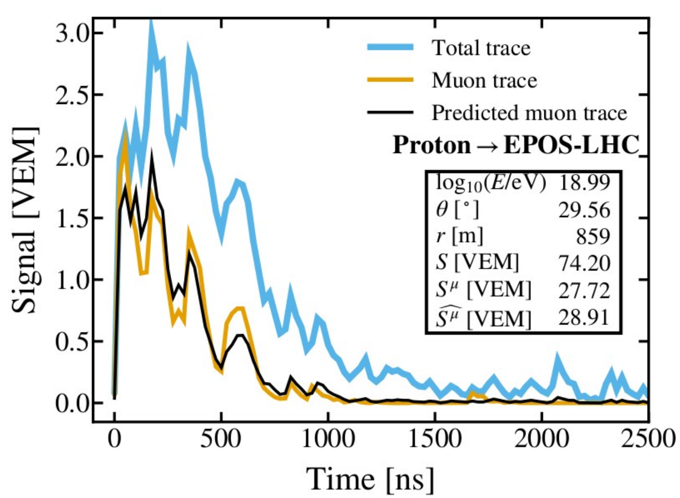


AugerPrime upgrade: better muon measurements

AugerPrime components designed specifically for precise measurements of the muonic component

New methods (machine learning) can improve analysis of older data





Summary

Multiple analyses compared observed air shower signal with simulation results

Current models of hadronic interactions fail to describe data from FD and SD

Results of new analyses indicate possibility of heavier primary composition (decreasing muon problem, but shifting X_{max} scale)

New models of hadronic interactions (EPOS LHC-R, QGSJet III, SibyII*, Pythia 8,...) and new air-shower generator (CORSIKA 8) in preparation

More high quality data – AugerPrime (2024-2035+)

New methods (Machine Learning)...