Testing hadronic interactions with the Pierre Auger Observatory

F. Diogo on behalf of the Pierre Auger Collaboration

CRIS 2016

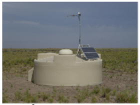
8^{th} July 2016

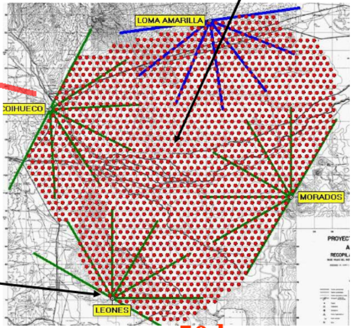
Pierre Auger Observatory

Malargue - Argentina

3000 km²

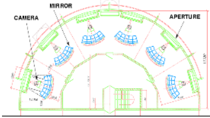
SD 1600 water Cherenkov detec. on a 1.5 km hexagonal grid



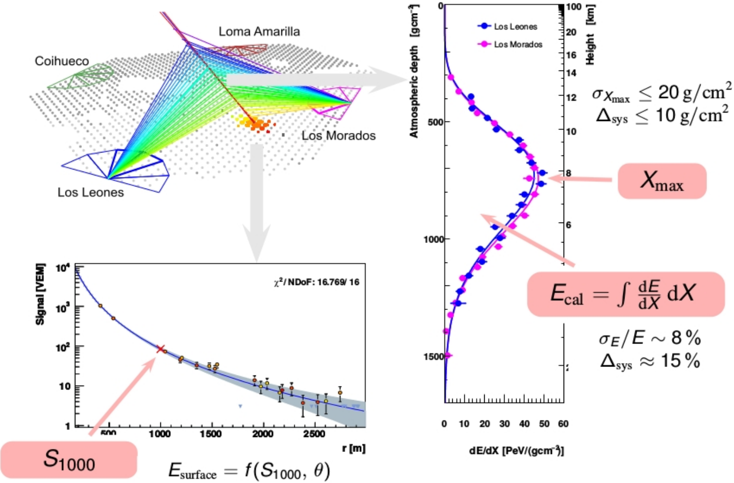


50 km

FD 4 x 6 fluorescence telescopes



Shower observables



Outline

FD images electromagnetic shower development

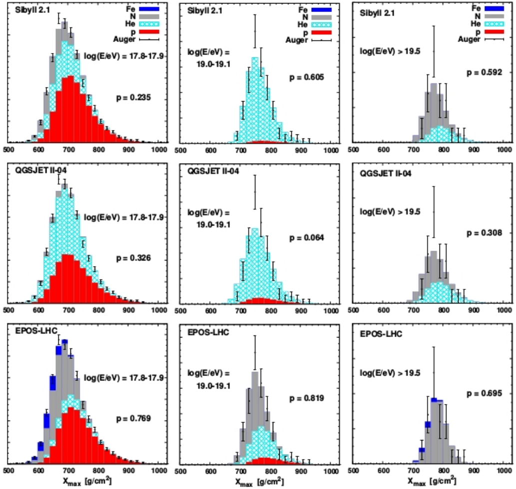
- X_{max}
  - primary composition trends
  - interaction cross-section
- shower development

SD is also sensitive to muons

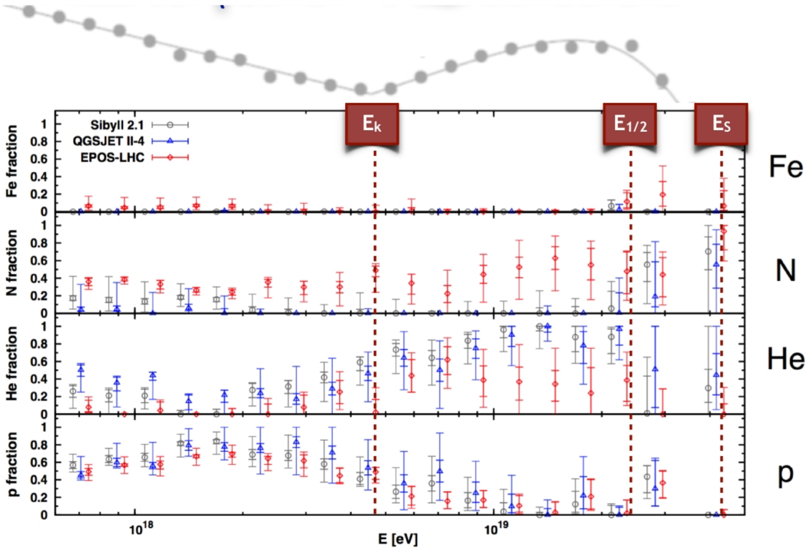
- X^{μ}_{max}
- Number of muons

Use consistency of SD and FD observables to check hadronic models

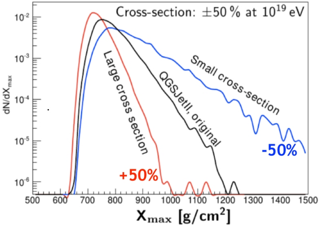
X_{max} distributions - composition fit



Mass composition from X_{max}

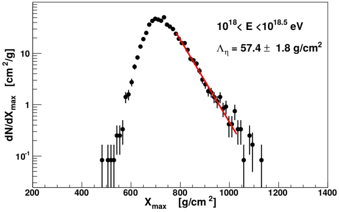


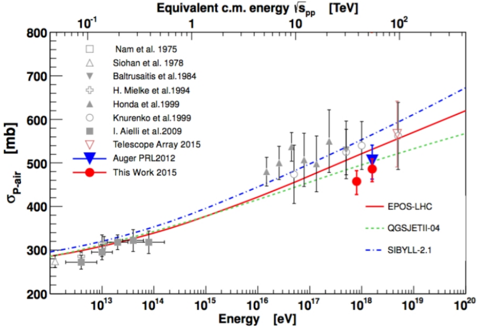
Proton-air cross section



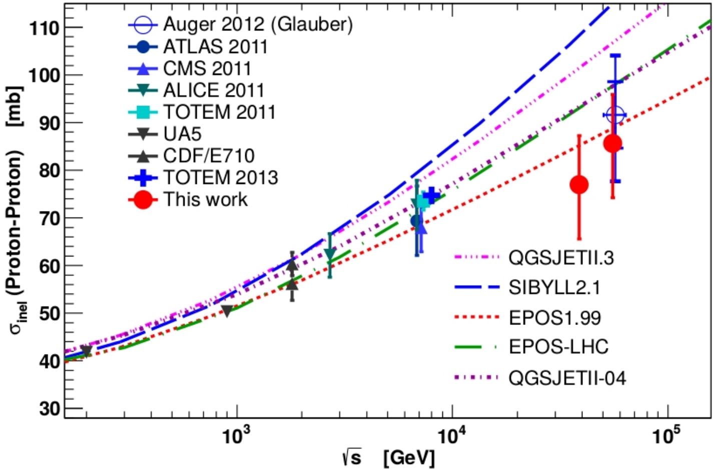
Distribution of first interaction depths dominate the tail of the X_{max} distribution

$$\frac{dp}{dX_1} = \frac{1}{\lambda_{p-Air}} e^{-X_1/\lambda_{p-Air}}$$

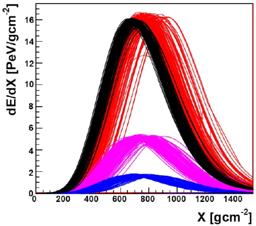


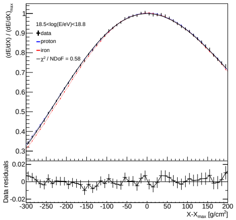


Proton-Proton cross section



Average electromagnetic profile shape

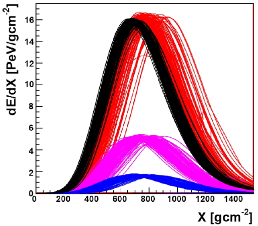


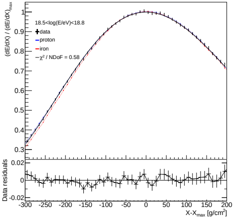


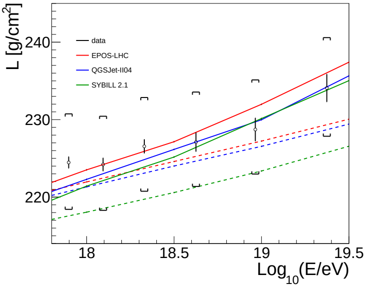
Profile shape is described by 2 parameters

- L (width) and R (asymmetry)
- Indication of Δ: $X_{max} = X_1 + \Delta$

Average electromagnetic profile shape







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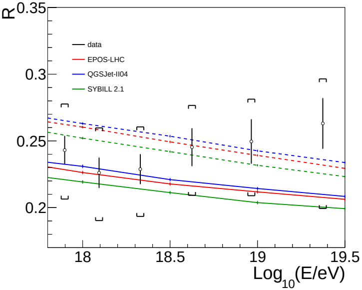
New independent test on models

- good agreement, compatible with X_{max}
- h.e. models can consistently explain electromagnetic profile variables



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X_{max}

primary composition trends

interaction cross-section

shower development

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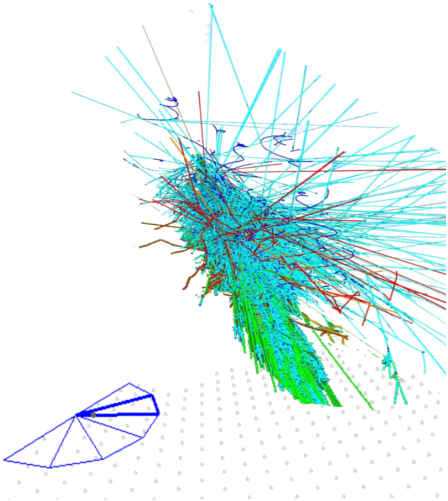
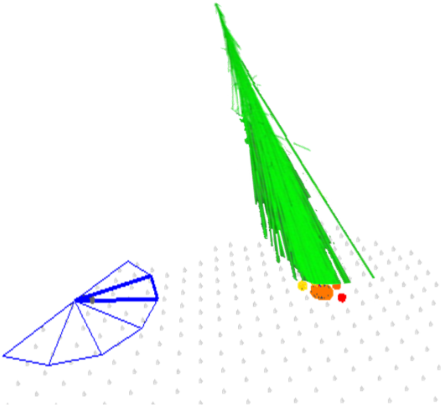
Use consistency of SD and FD observables to check hadronic models

Imaging the muon production profile



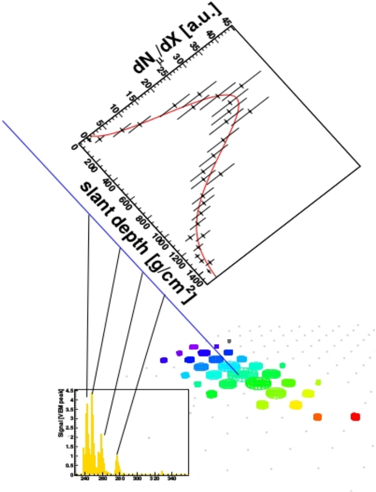
Imaging the muon production profile



Muons interact scarcely with the atmosphere

- preserve information from their production point

Imaging the muon production profile



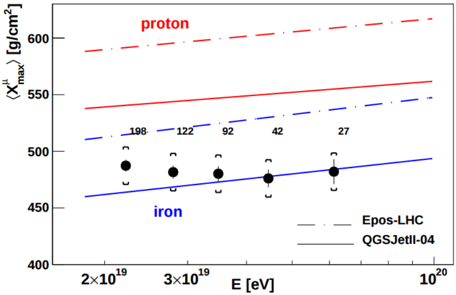
Muons interact scarcely with the atmosphere

- preserve information from their production point

Muon Production Depth

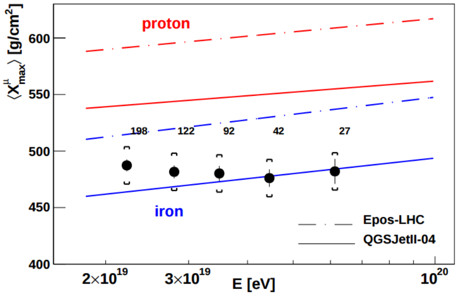
- large θ (55°-65°), r (>1.7 km)
  - dominated by muons
- time → production point
- fit profile → X^{μ}_{max}

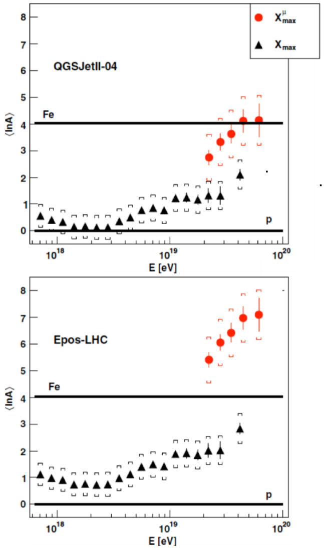
Muon Production Depth maximum



- Data bracketed only by QGSJetII04

Muon Production Depth maximum



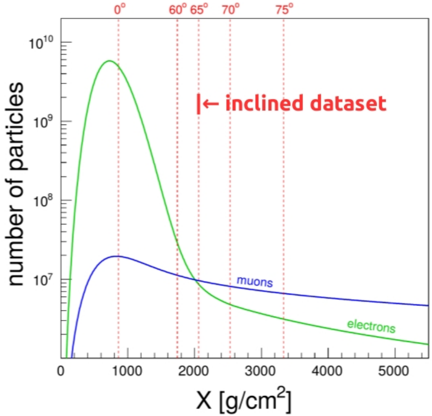


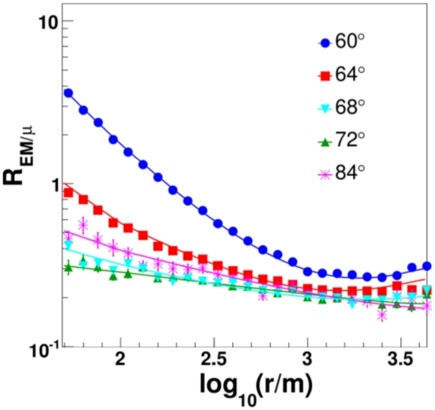
- Data bracketed only by QGSJetII04

X^{μ}_{max} (and X_{max}) can be translated into $\ln(A)$

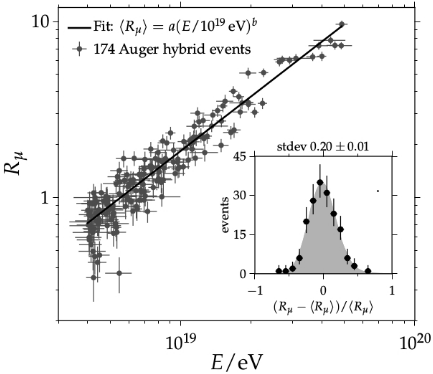
- same X_1 as X_{max}, showing differences in development length
- QGSJETII04 compatible
- EPOS-LHC incompatible at $> 6\sigma$

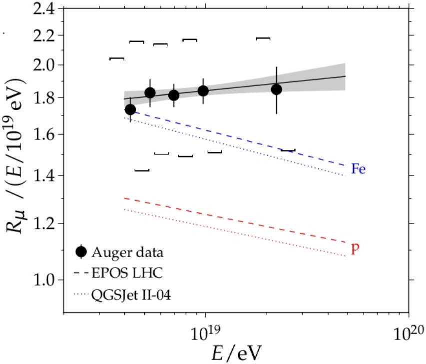
Measuring muon number - inclined events



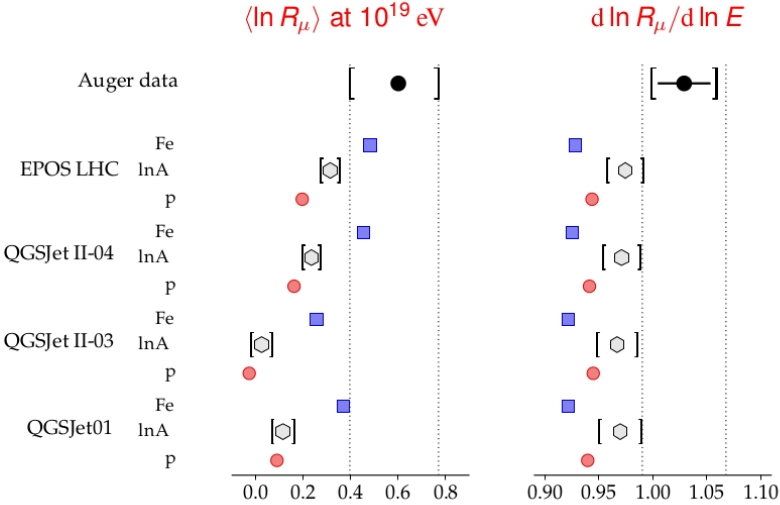


Numbers of muons: energy evolution

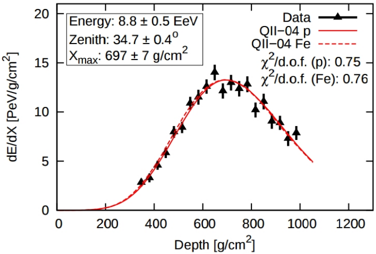


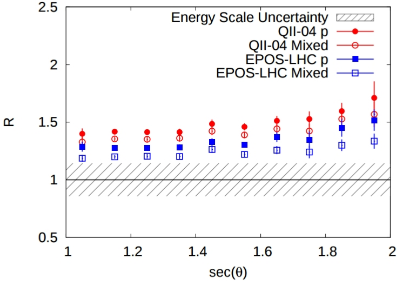


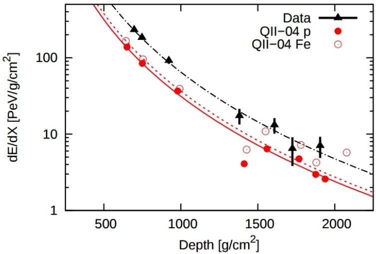
Numbers of muons: energy evolution parameters



Top-down: Matching hybrid events with simulation

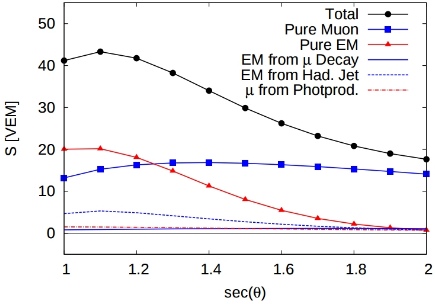


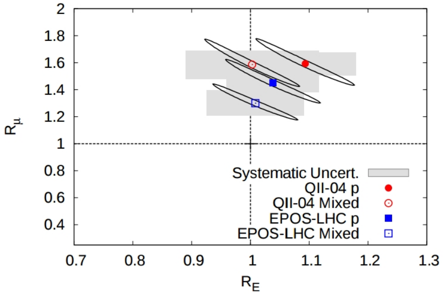




- Match simulation with measured FD profiles
- compare SD S(1000) parameter
  - clear excess in data

Top-down: Matching hybrid events with simulation

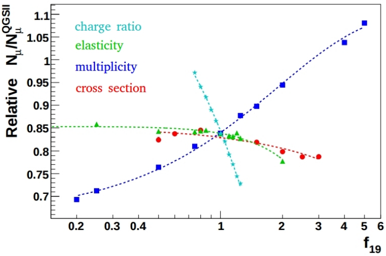


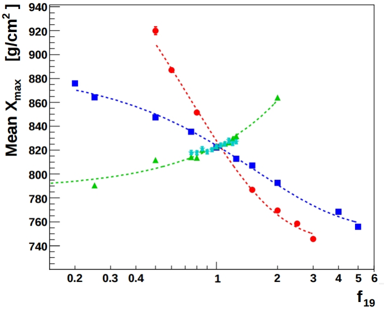


- shift the energy scale and hadronic component in simulation until we get a match in S(1000) vs $\sec(\theta)$

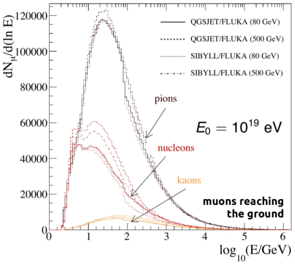
Model	R_E	R_μ
QII-04 Mixed	$1.00 \pm 0.08 \pm 0.11$	$1.59 \pm 0.18 \pm 0.11$
EPOS Mixed	$1.01 \pm 0.07 \pm 0.08$	$1.30 \pm 0.13 \pm 0.09$

What determines shower behaviour?



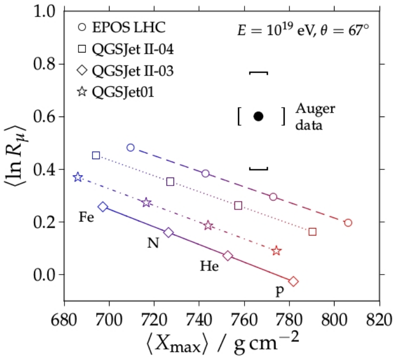


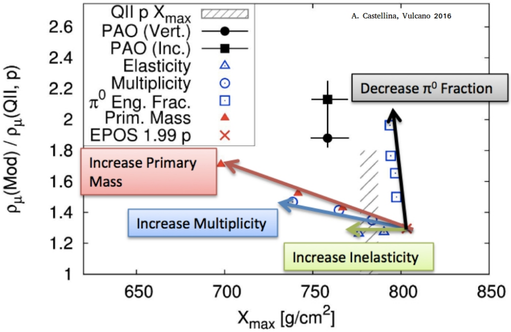
Muon parents - mostly pions



- Hadronic parameters modified in high energy models
  - cross-section (measured at $\sim 10\%$)
  - inelasticity
  - multiplicity
  - π^0 production ratio (changed with ρ^0 prod. for ex.)

X_{max} vs N_{mu} - Particle Physics





Observables have different sensitivity to parameters:

- N^{μ}: π^0 energy fraction, primary mass, multiplicity
- X_{max}: primary mass, multiplicity, inelasticity

Conclusion

Electromagnetic profile variables ($< X_{max} >$, $\sigma(X_{max})$, shape) and spectrum

- composition mixed around and above the ankle
- consistent picture within each hadronic model

In the hadronic sector there are some puzzling results

- muon number
  - at odds with predictions for mixed composition
- muon production depth vs. X_{max}
  - QGSjetII-04: marginally compatible, EPOS-LHC: incompatible
- beginning to probe which parameters control each variable
  - particle physics