Probing hadronic interactions at the 100 TeV scale with the Pierre Auger Observatory

Eva dos Santos[1], for the Pierre Auger Collaboration[2]

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The XIX International Conference on Topics in Astroparticle and Underground Physics
Xichang, Sichuan, China, 24-30 August 2025

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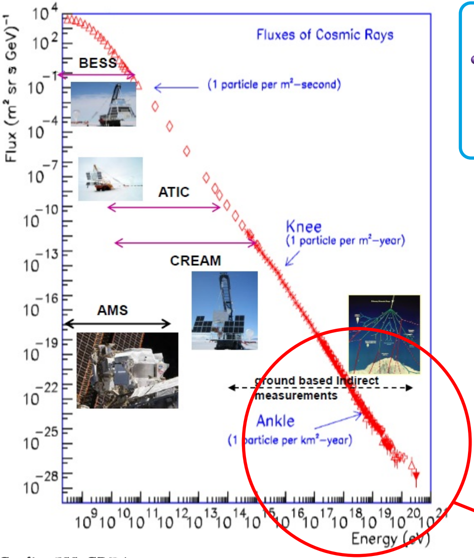
MINISTRY OF EDUCATION, YOUTH AND SPORTS

FZU

Cosmic Ray Spectrum



Credits: ISS-CREAM

Direct measurements

Cosmic rays are mostly fully ionized atomic nuclei

- Mostly protons, although most stable elements can also be found
  - About 1% are electrons
  - Vestigial traces of anti-matter, such as positrons and anti-protons

“Almost” featureless power law spectrum:

$$\frac{dN}{dE} \propto E^{-\gamma}$$

- $>$ 10 decades in energy
- $>$ 30 orders of magnitude in flux
- 3 main spectral features

Don't miss T. Bister's talk this afternoon about the combined fit results using Auger data!

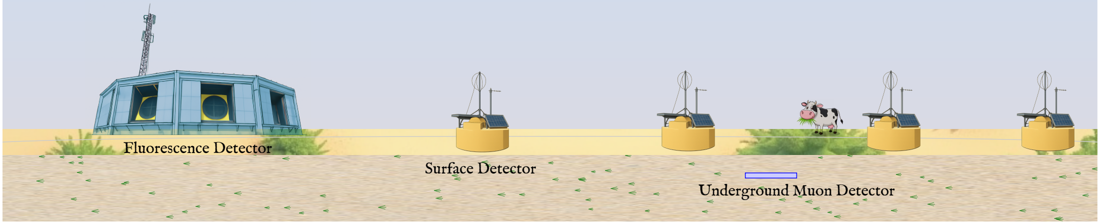
Pierre Auger Observatory

Extensive air showers

- Hadronic cascade
  - Ruled by QCD processes
    - Multi-particle production cannot be calculated from first principles
- Electromagnetic cascade
  - EM interactions well described by perturbative QED
    - Agreement between theory and experimental data within less than 10^{-9}
  - After ≈ 6 generations, about $\sim 90\%$ of the cosmic-ray energy is transferred to the e.m. cascade

Cosmic Ray

- Muon component
  - Muons and neutrinos propagate deep in the atmosphere, and underground
  - Carry about 10% of the shower energy, called the "missing energy"
  - Conserve information about the hadronic cascade
  - Decayed muons feed the electromagnetic cascade



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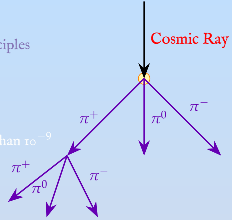

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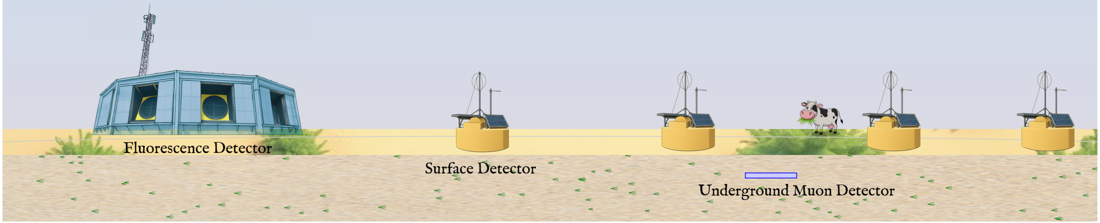

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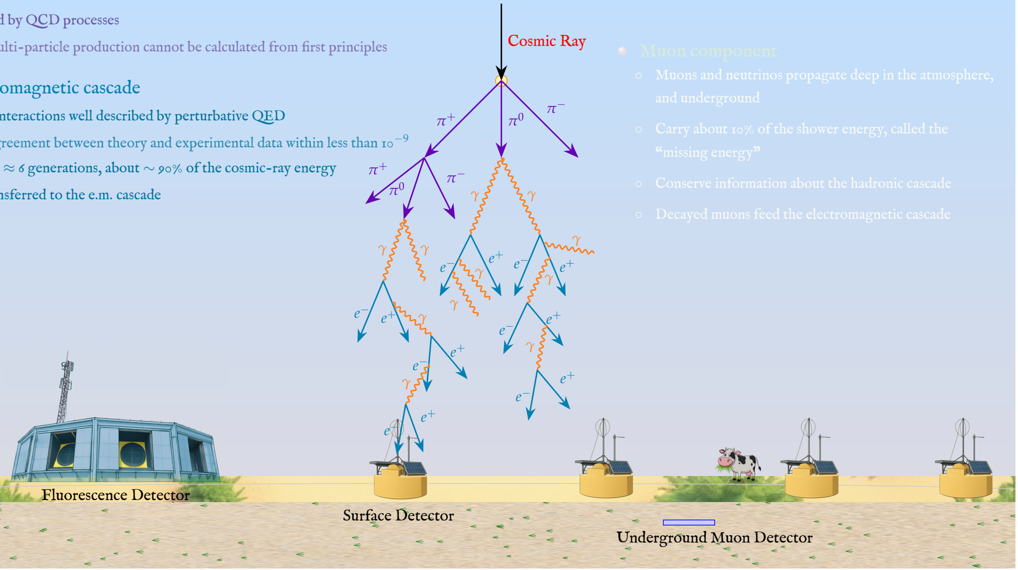

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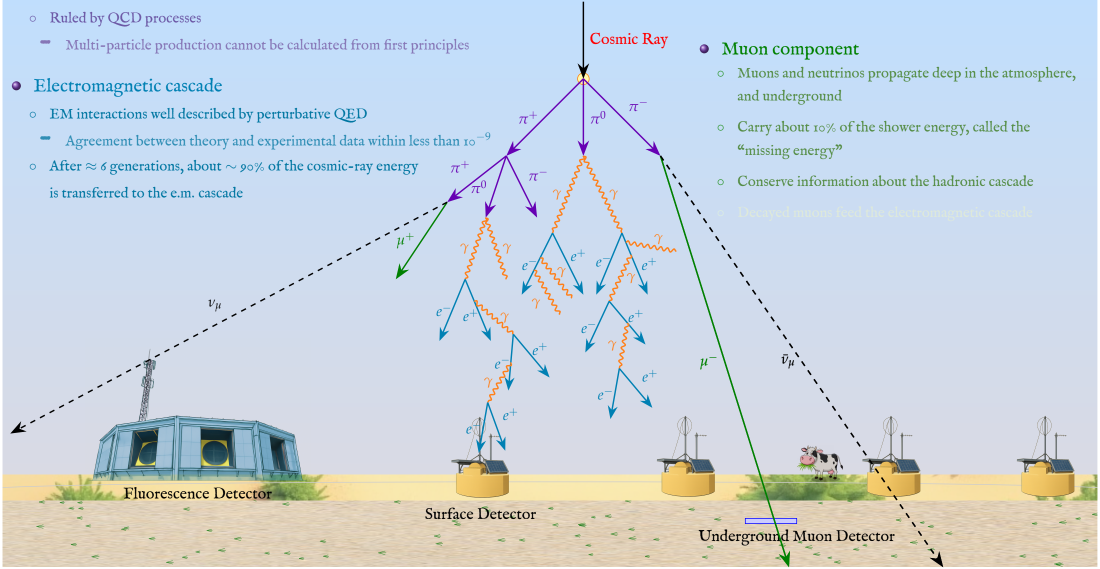

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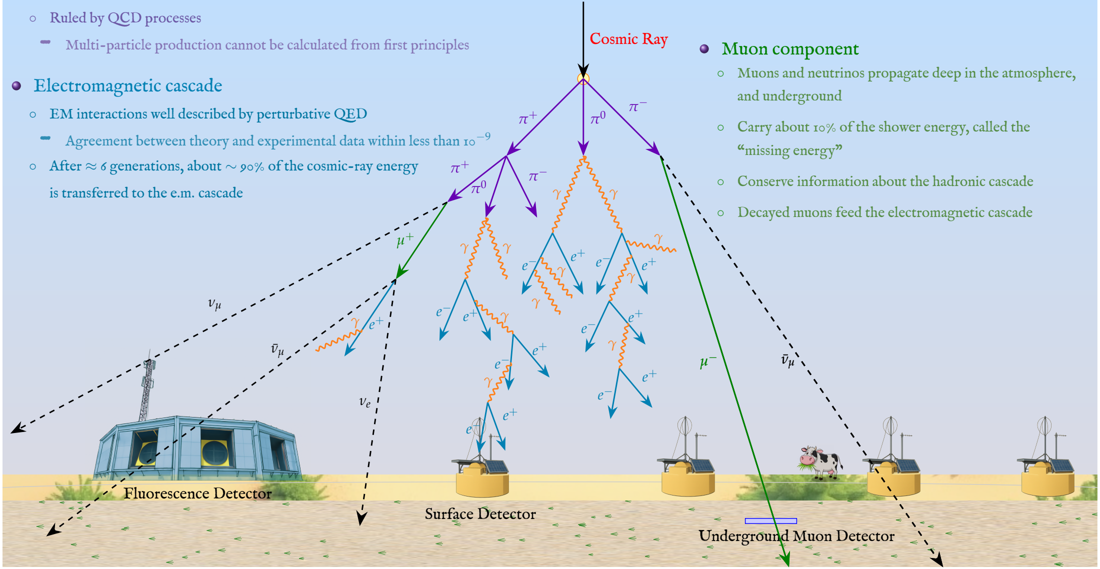

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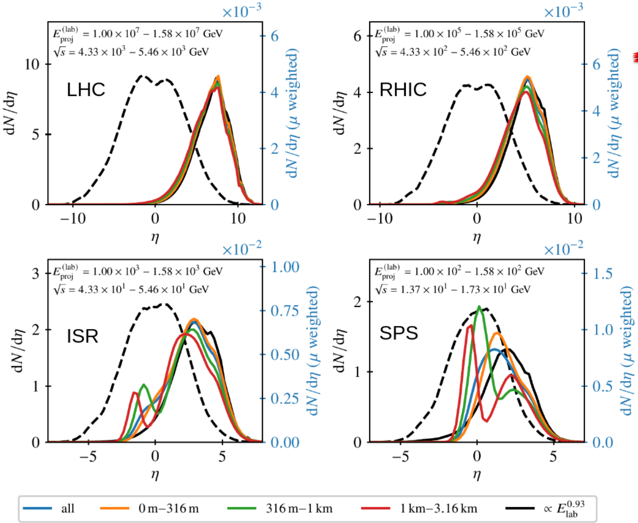
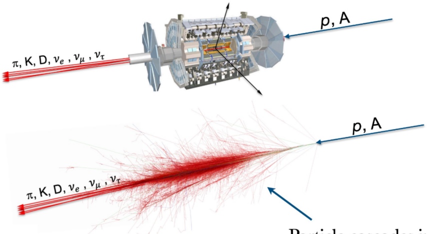
Particle production phase-space in extensive air showers





Particle cascades in the atmosphere initiated by high-energy cosmic rays

- High-energy muons:
  - Production peaks at $\eta \sim 10$
  - Dominant close to the shower core ($r \lesssim 1000$ m)
- Low-energy muons:
  - Produced at the last hadronic generations
    - Mid-rapidity range $\eta \lesssim 5$
  - Dominant far from the shower core ($r \gtrsim 1000$ m)
- Both populations are equally important!!!

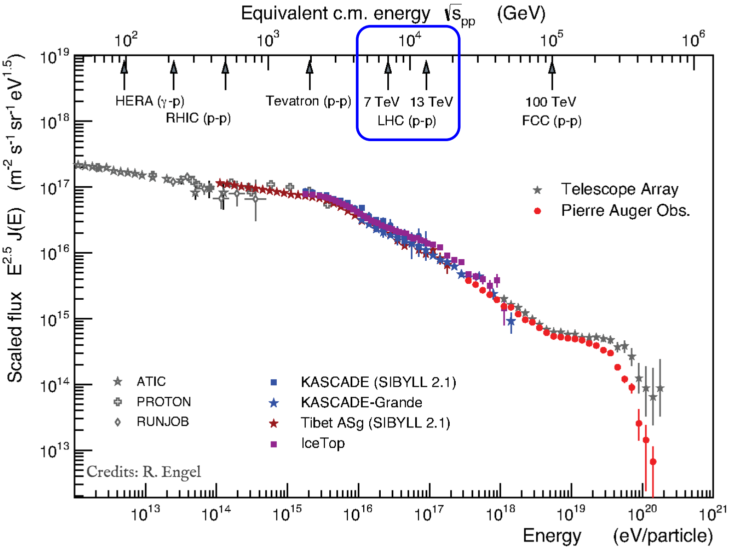
Pseudo-rapidity: $\eta = -\ln(\tan(\theta/2))$, θ - particle emission angle

- $\eta = 0$ - mid-rapidity
- $\eta \gg 1$ - forward region (beam direction); $\eta \ll 1$ - backward region

M. Reininghaus, PoS(ICRC2021)463

Center-of-mass energy

Most accelerator data taken at a different phase-space region than the one relevant for cosmic-ray showers



Extrapolations needed to go from:

- $\eta = 0$ to $\eta \gg 1$
- $\sqrt{s} \sim 10$ TeV to $\sqrt{s} \sim 100$ TeV

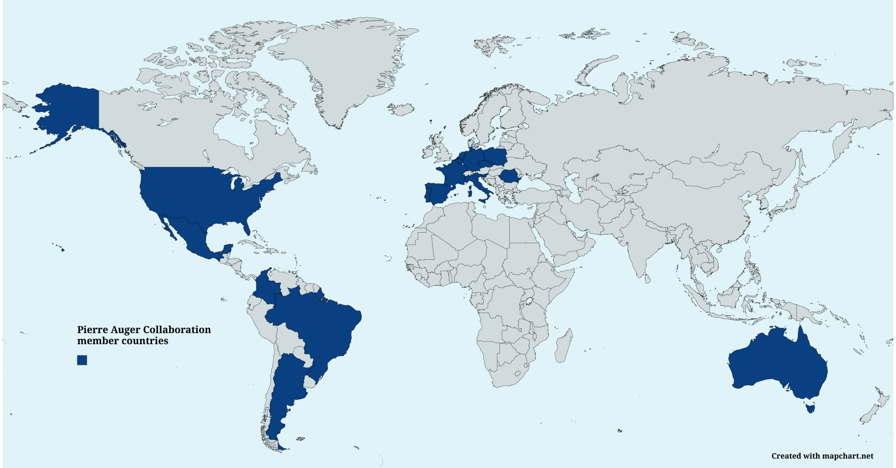
Large systematic uncertainties

Pierre Auger Collaboration

Don't miss P. Ghia's talk this afternoon for a collection of our finest results!

About 400 authors from nearly 100 institutes from 17 countries

- Argentina
- Australia
- Belgium
- Brazil
- Colombia
- Czech Republic
- France
- Germany
- Italy
- Mexico
- Poland
- Portugal
- Romania
- Slovenia
- Spain
- The Netherlands
- United States of America



Pierre Auger Observatory

Malargüe, Province of Mendoza, Argentina

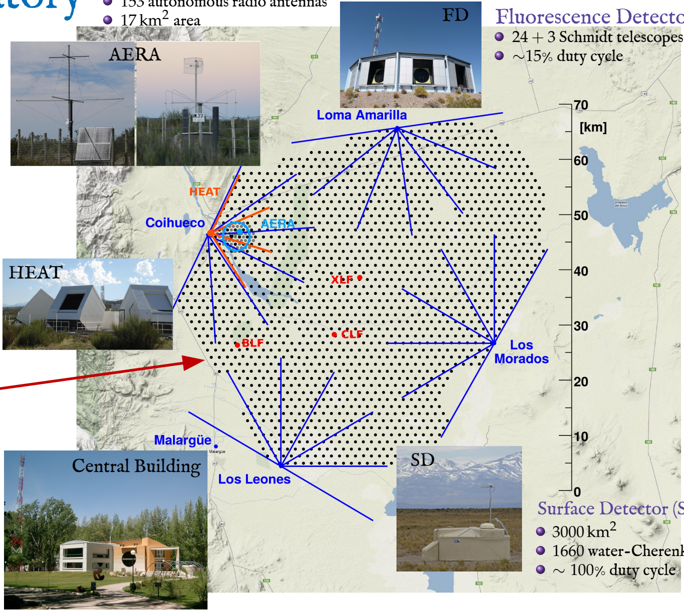
35.2° S, 69.5° W, ~ 1400 m a.s.l.

Auger Engineering Radio Array (AERA)

- 153 autonomous radio antennas
- 17 km^2 area

Fluorescence Detector (FD)

- 24 + 3 Schmidt telescopes
- $\sim$15% duty cycle



Surface Detector (SD)

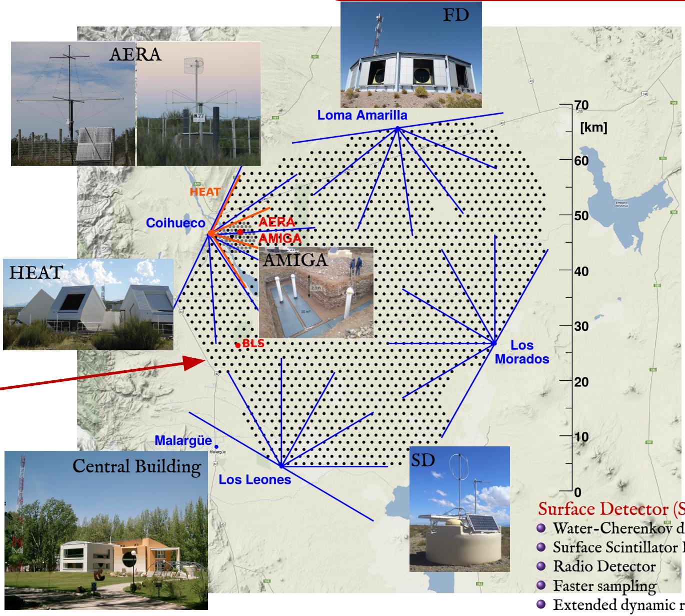
- 3000 km^2
- 1660 water-Cherenkov detectors
- $\sim$ 100% duty cycle

AugerPrime

Don't miss R. Caruso's talk on Wednesday!

Malargüe, Province of Mendoza, Argentina

35.2° S, 69.5° W, $\sim$ 1400 m a.s.l.



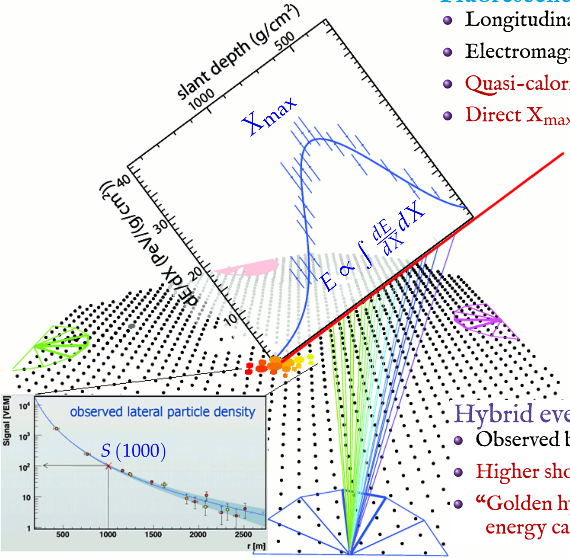
Surface Detector (SD)

- Water-Cherenkov detectors
- Surface Scintillator Detector
- Radio Detector
- Faster sampling
- Extended dynamic range

A hybrid detector

Fluorescence Detector

- Longitudinal shower profile
- Electromagnetic component
- Quasi-calorimetric energy estimation
- Direct X_{max} measurement



Surface Detector array

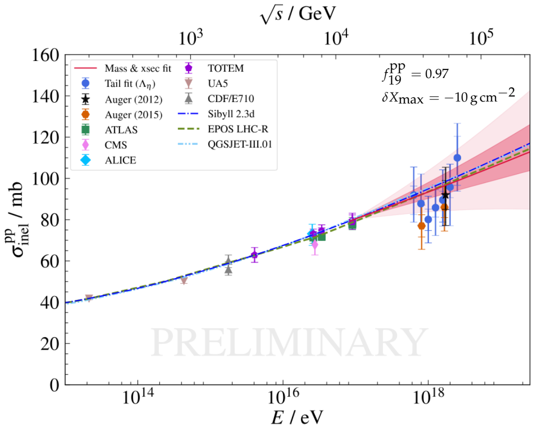
- Lateral particle distribution
- Electrons, muons,
  high-energy photons
- High statistics

Hybrid events

- Observed by both detectors
- Higher shower reconstruction accuracy
- “Golden hybrid” events provide the energy calibration of the SD array

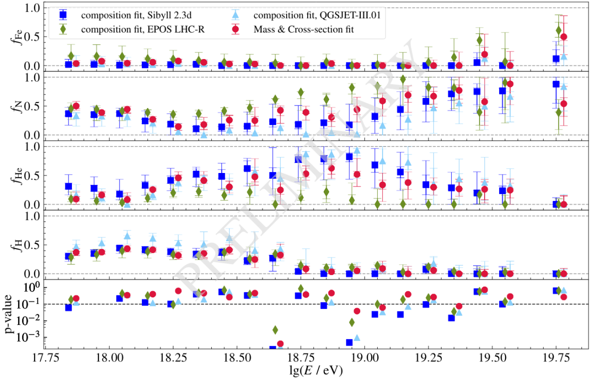
Inelastic proton-proton cross-section at $\sqrt{s} \geq 40$ TeV

Simultaneous fit to the X_{max} distributions and cross-section



Data set:

- Hybrid events
- $E/\text{eV} = [10^{17.8}, 10^{20}]$
- Full Phase I data



Scale of X_{max} is included as a free parameter

- Allows to address uncertainties in:
  - detector response
  - hadronic interaction models

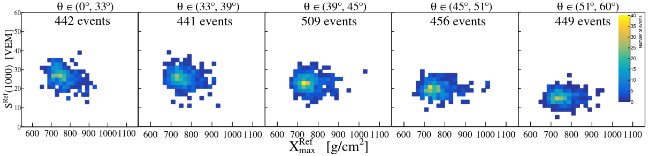
Don't miss F. Ellwanger's talk this afternoon about our searches for photon and neutrinos!

O. Tkachenko, PoS(ICRC2025)416

Data-driven consistency tests to hadronic model predictions

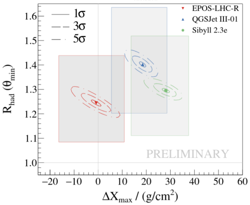
Simultaneous fit of the X_{max} distributions and the ground signal

Data set:
- "Golden hybrid" hybrid events
- $E/\mathrm{eV} = \left[10^{18.5}, 10^{19}\right]$
- $\theta < 60^\circ$
- Full Phase I data

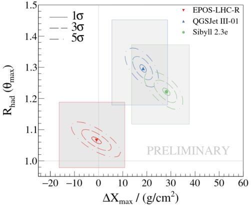


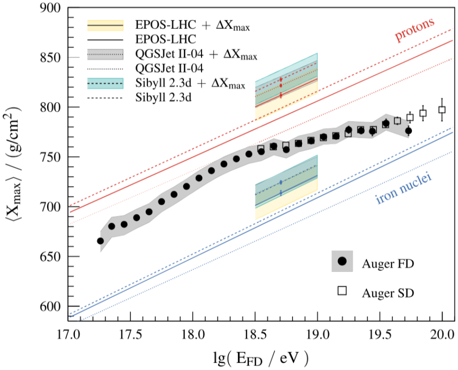
Two dimensional distributions of $S(1000)$ and X_{max} for different zenith angle bins

$\theta_{min} \approx 28^\circ$



$\theta_{max} \approx 55^\circ$



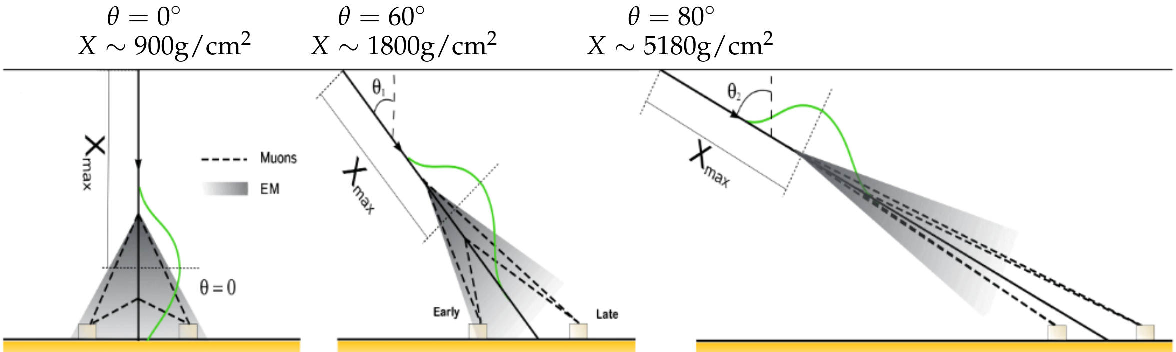


- Auger data best described if models predict deeper X_{max} ($\sim 20\,\mathrm{g\,cm^{-2}}$) values
  - Leading to a smaller muon deficit in simulations (and heavier mass composition)
  - Predicted X_{max} shift is compatible with the cross-section analysis in the same energy range
- Currently, EPOS LHC-R predictions match Auger X_{max} measurements, but QGSJETIII.01, and Sibyll 2.3e are still off
  - For EPOS LHC-R, R_{had}, is zenith-angle dependent: the predicted muon spectra are too hard

Phys. Rev. D 109, 102001 (2024)
J. Vícha, PoS(ICRC2025)431

Horizontal Air Showers

Indirect muon measurements using the SD array



- Interaction lengths rapidly increase for horizontal air showers
  - electromagnetic component heavily suppressed by the amount of atmospheric density traversed

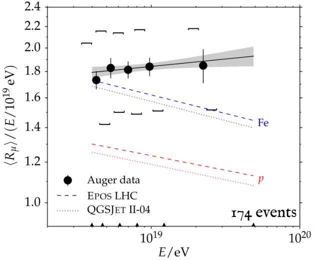
Muon measurements from Horizontal Air Showers

Indirect muon measurements

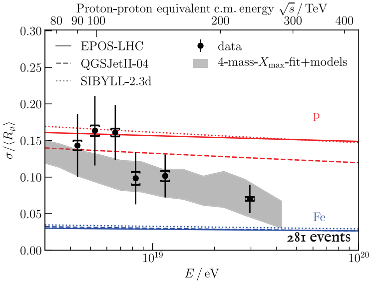
Data set:

- "Golden hybrid" hybrid events
- $E > 4 \times 10^{18}$ eV
- $62^\circ < \theta < 80^\circ$

SD



Phys. Rev. D 91 (2015) 059901



Phys. Rev. Lett. 126 (2021) 152002

- Muon content in data from SD measurements marginally compatible with model predictions for iron primaries, but fluctuations agree with FD $\sigma\left(X_{\max}\right)$ measurements

Two possible explanations:

1. Increase in the muon content may be due to small modifications in hadronic interactions accumulating over many generations
2. Very particular modification of the first interaction changing $\langle R_\mu \rangle$ without affecting $\sigma / \langle R_\mu \rangle$

Phys. Lett. B 784, (2018), 68

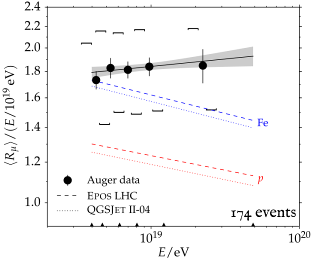
Muon measurements from Horizontal Air Showers

Indirect muon measurements

Data set:
- "Golden hybrid" hybrid events
- $E > 4 \times 10^{18}$ eV
- $62^\circ < \theta < 80^\circ$

Data set:
- Radio + SD hybrid events
- $E > 4 \times 10^{18}$ eV
- $65^\circ < \theta < 80^\circ$

SD



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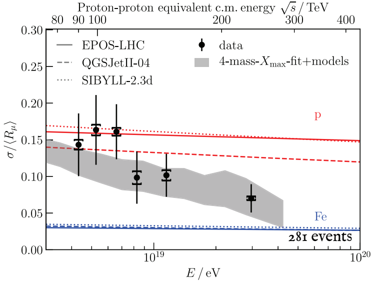
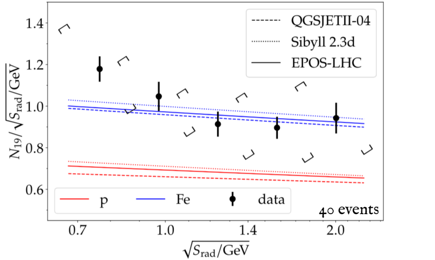


Phys. Rev. Lett. 126 (2021) 152002

AERA

Proof-of-concept



M. Gottowik, PoS(ICRC2025)275; Submitted to Phys. Rev. D

- Muon content in data from SD measurements marginally compatible with model predictions for iron primaries, but fluctuations agree with FD $\sigma\,(X_{\max})$ measurements

  Two possible explanations:
  1. Increase in the muon content may be due to small modifications in hadronic interactions accumulating over many generations
  2. Very particular modification of the first interaction changing $\langle R_\mu \rangle$ without affecting $\sigma / \langle R_\mu \rangle$
- Muon content in data from radio measurements is compatible with model predictions for iron-induced air showers

Phys. Lett. B 784, (2018), 68

Characterizing the neutron shower content with AugerPrime

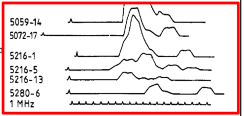
Neutrons generate subliminal pulses in scintillator detectors

Sub-luminal pulses from cosmic-ray air showers

John Linsley

Department of Physics and Astro[nomy, University of New]
Mexico 87131, USA

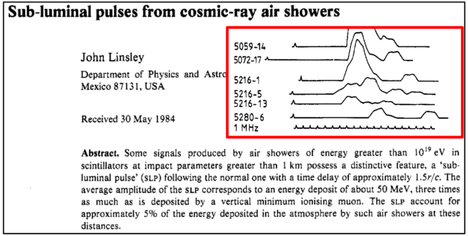
Received 30 May 1984



Abstract. Some signals produced by air showers of energy greater than 10^{19} eV in scintillators at impact parameters greater than 1 km possess a distinctive feature, a 'sub-luminal pulse' (SLP) following the normal one with a time delay of approximately $1.5r/c$. The average amplitude of the SLP corresponds to an energy deposit of about 50 MeV, three times as much as is deposited by a vertical minimum ionising muon. The SLP account for approximately 5% of the energy deposited in the atmosphere by such air showers at these distances.

Characterizing the neutron shower content with AugerPrime

Neutrons generate subliminal pulses in scintillator detectors



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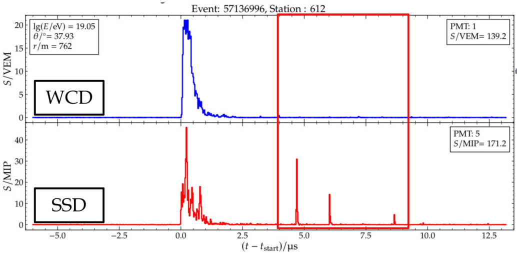
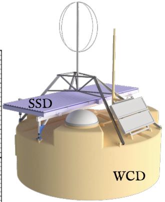
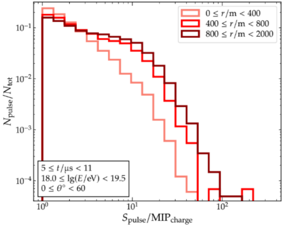
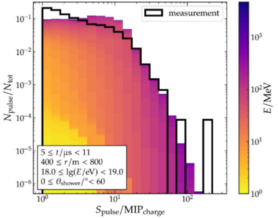








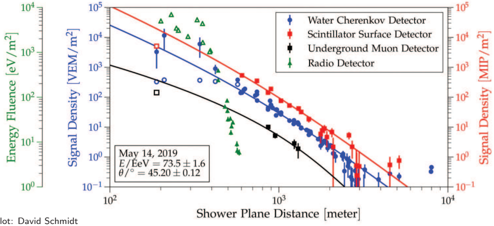
- AugerPrime SSDs have sensitivity to the shape of the neutron spectra
- Neutron component will be included in the simulations

T. Schulz, PoS(ICRC2025)388

Summary and Conclusions

- Cosmic rays are a challenging, yet unique channel to probe hadronic interactions at the $\sqrt{s} \gtrsim 100$ TeV scale:
  - Hadronic interaction models still cannot consistently describe the extensive air shower development
    - Nuclear mass composition estimations inferred from SD and FD observables are in tension
    - Data-driven studies using hybrid events show that the modeling of both the muon and electromagnetic components must be improved
  - Proton-proton cross-section measurements indicate a slightly lower cross-section rescaling factor accompanied by a slight shift in $X_{\max}$ towards heavier mass composition

- With the advent of AugerPrime:
  - Multi-hybrid events will provide enhanced mass composition estimation with reduced systematic uncertainties stemming from hadronic interaction models
    - The Surface Scintillator and Radio detectors will allow for a better separation of the electromagnetic and muonic shower components
    - The Underground Muon Detector will allow for a direct measurement of the muon content at the nominal energy at the LHC
  - The Surface Scintillator Detector is also sensitive to the neutron spectra
    - Work to incorporate neutrons in future simulations is ongoing



Plot: David Schmidt

Stay tuned!

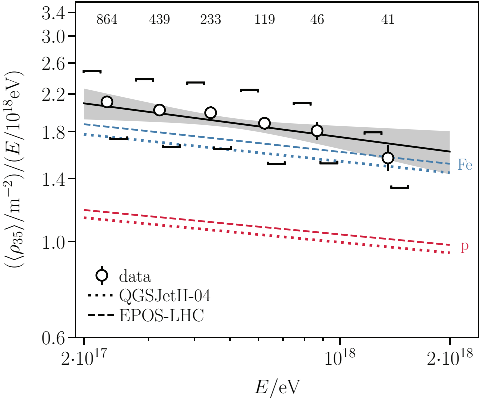

Thank you very much
for your attention!
Any questions or comments?


Backup slides

Direct measurement of the muon content

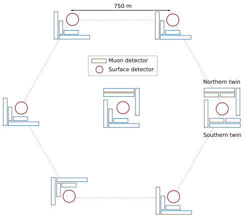
Auger Muons and Infill for the Ground Array - Engineering Array (EA)

Within LHC $\sqrt{s}$ energy!!



Data set:

- 1742 AMIGA EA events
- 2×10^{17} - 2×10^{18} eV
- October 2015 - October 2016
- $\theta < 45°$



AMIGA
Engineering Array

- Muon deficit in simulations of 8% (14%) for EPOS-LHC (QGSJetII-04) assuming pure iron composition

Eur. Phys. J. C 80 (2020) 751