Highest energy astro-particle physics with the Pierre Auger Observatory

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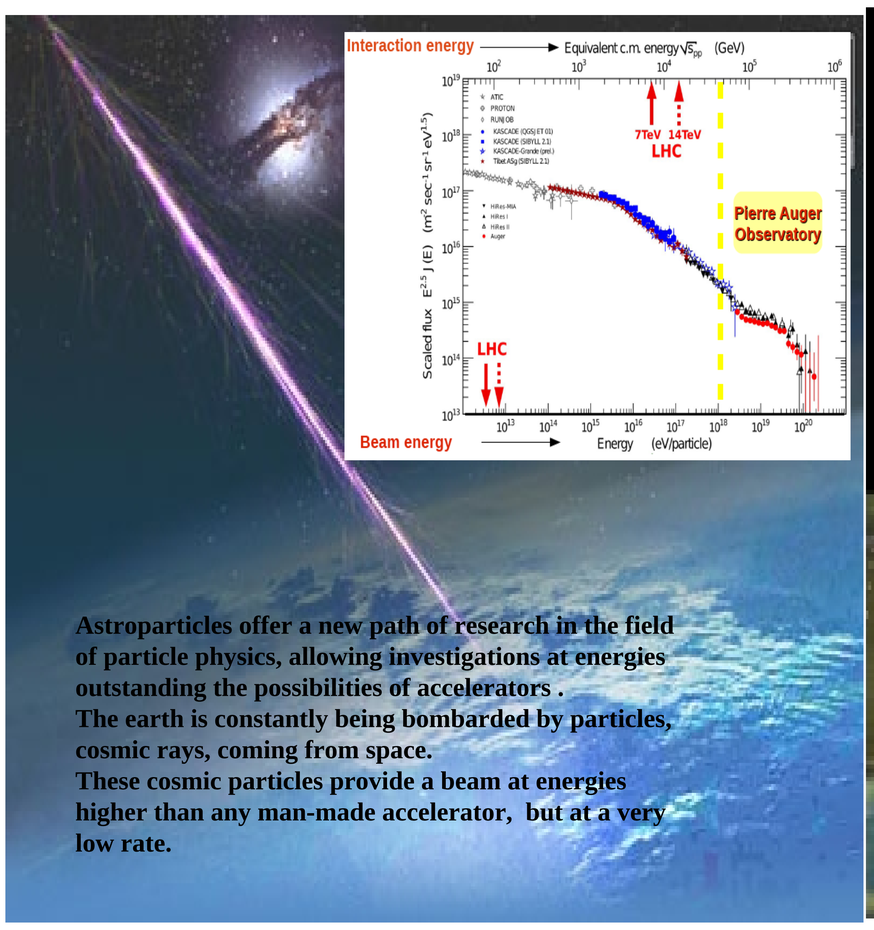
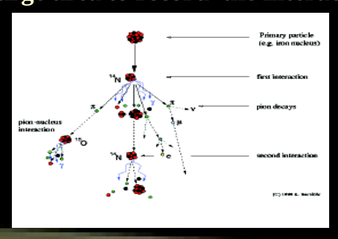
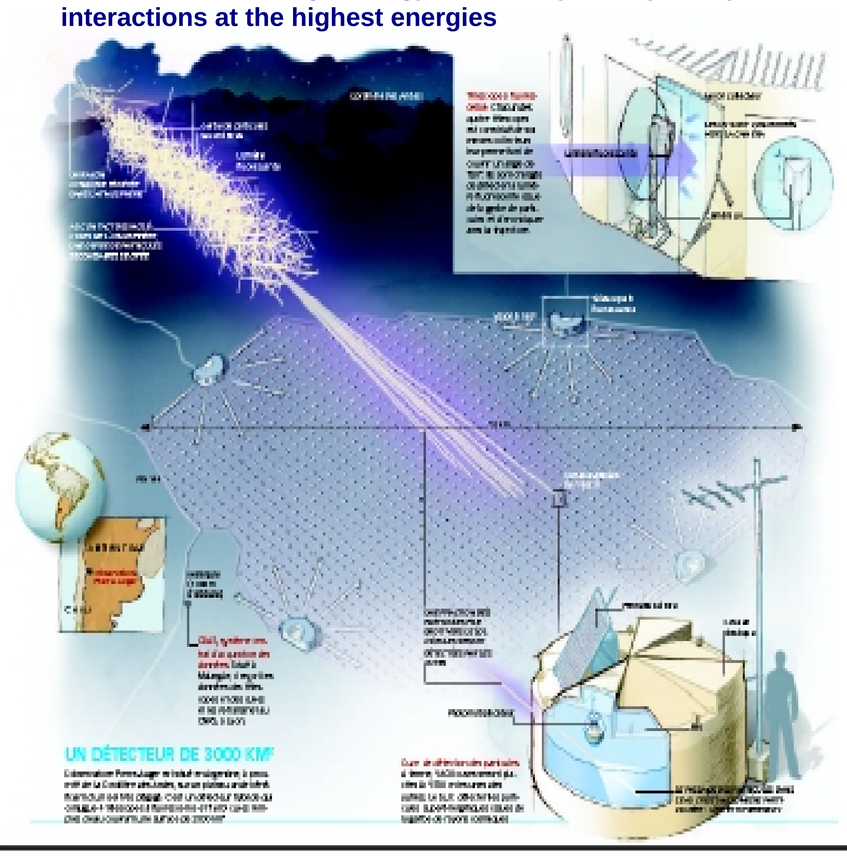


Astroparticles offer a new path of research in the field of particle physics, allowing investigations at energies outstanding the possibilities of accelerators .
The earth is constantly being bombarded by particles, cosmic rays, coming from space.
These cosmic particles provide a beam at energies higher than any man-made accelerator, but at a very low rate.

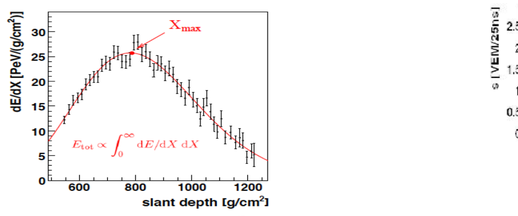
Ultra high energy cosmic rays can be studied via the observation of the showers they generate in the atmosphere.
When entering the Earth's atmosphere, these particles interact with air nuclei and produce gigantic cascades of secondary particles, called extensive air showers.
Extensive air showers can be detected spreading detectors over a large area to record the interactions of secondary particles.



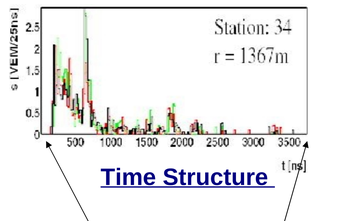
A unique and powerful design to observe, understand , characterize ultra high energy cosmic rays and probe particle interactions at the highest energies



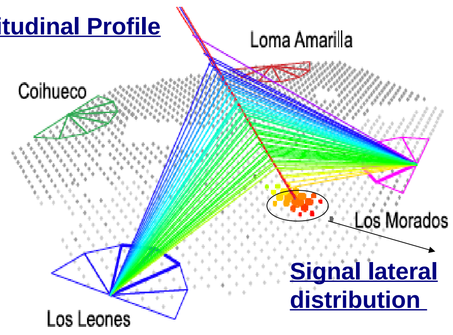
Extensive air shower observables



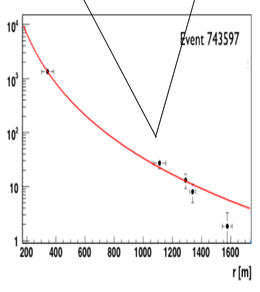
Longitudinal Profile



Time Structure



Signal lateral distribution



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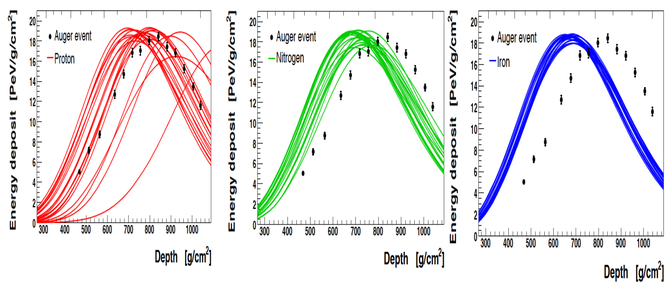
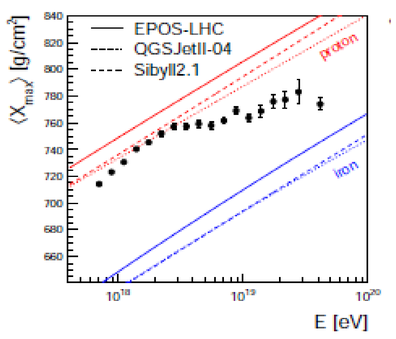
Longitudinal profile: mass composition





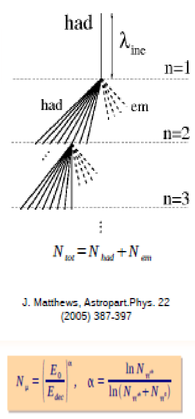
Energy: energy deposit profile integral (E_{cal})

Mass composition : mean and fluctuations of depth of maximun development of the shower (X_{max})

Extensive air showers simplified model

$$X_{max} \sim \lambda_e \ln\left[(1-k).E_0/(2.N_{tot}.A)\right] + \lambda_{ine}$$

- Model independent parameters :
  - E_0 = primary energy
  - A = primary mass
  - λ_e = electromagnetic mean free path
- Model dependent parameters :
  - k = elasticity
  - N_{tot} = total multiplicity
  - λ_{ine} = hadronic mean free path (cross section)



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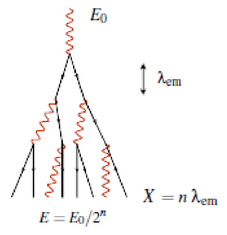


Shower maximum: $E = E_c$

From Heitler $N_e = \left|\frac{E_0}{E_{dec}}\right|^\alpha$, $\alpha = \frac{\ln N_{e^\pm}}{\ln(N_{e^\pm}+N_{\gamma^0})}$

$$N_{max} = E_0/E_c$$
$$X_{max} \sim \lambda_{em} \ln(E_0/E_c)$$

Electromagnetic showers cascade theory

Energy loss of electron: $\frac{dE}{dX} = -\alpha - \frac{E}{X_0}$

Critical energy: $E_c = \alpha X_0 \sim 85\,MeV$

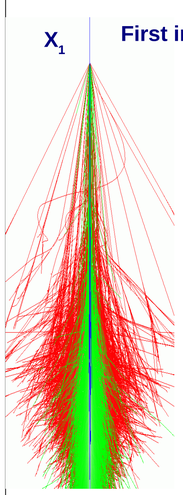
Radiation length: $X_0 \sim 36\,g/cm^2$

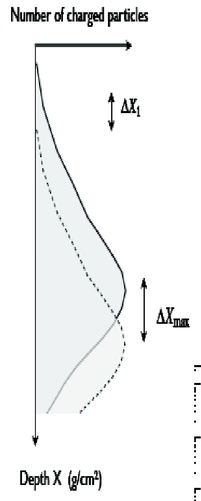
$$\frac{d\Phi_e(E)}{dX} = -\frac{\sigma_e}{\langle m_{air}\rangle}\Phi_e(E) + \int_E^\infty \frac{\sigma_e}{\langle m_{air}\rangle}\Phi_e(\tilde{E})P_{e\to e}(\tilde{E},E)d\tilde{E} + \int_E^\infty \frac{\sigma_\gamma}{\langle m_{air}\rangle}\Phi_\gamma(\tilde{E})P_{\gamma\to e}(\tilde{E},E)d\tilde{E} + \alpha\frac{\partial\Phi_e(E)}{\partial E}$$

$$X_{max} \approx X_0 \ln\left(\frac{E_0}{E_c}\right) \qquad N_{max} \approx \frac{0.31}{\sqrt{\ln(E_0/E_c) - 0.33}}\frac{E_0}{E_c}$$

Proton-air cross section from air showers

X_1 **First interaction depth**



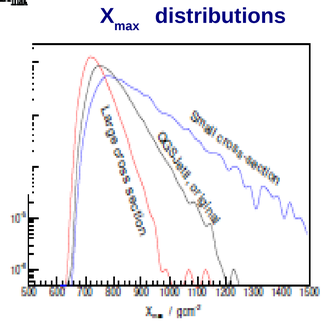


$$\frac{dP}{dX_1} = \frac{1}{\lambda_{int}} e^{-X_1/\lambda_{int}}$$

$$RMS(X_1) = \lambda_{int}$$

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

X_{max} **distributions**



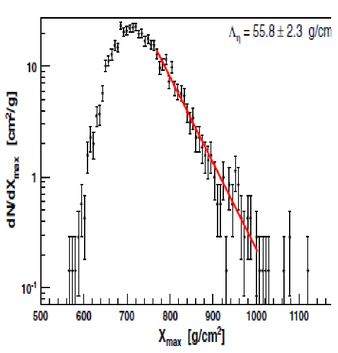
X_1 is not measured directly.

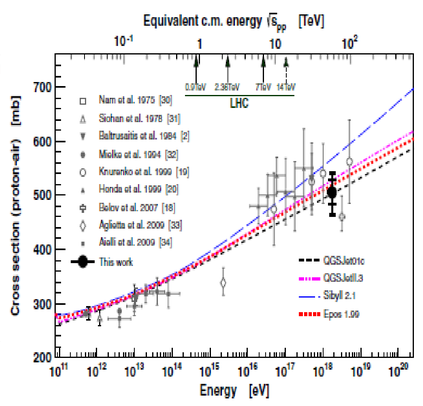
Use fluctuations in shower development

X_{max} distribution tail sensitive to cross section

Proton-air cross section of particle production

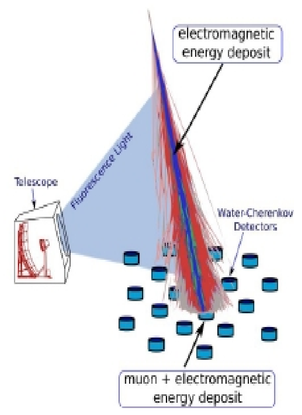
Selection of proton by selecting very deep showers

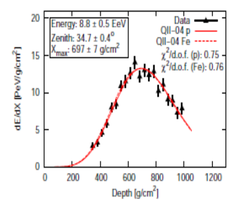




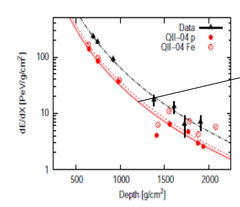
$$\sigma^{prod}_{p\text{-air}} = [505 \pm 22(stat)^{+28}_{-36}(syst)]\ mb$$

Longitudinal profile and ground signal missmatch?

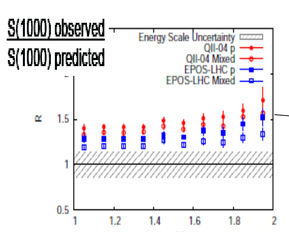




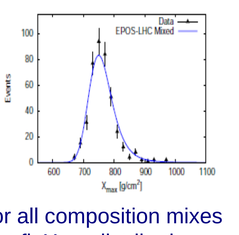
Find simulations that match the measured longitudinal profile for each event, and compare ground signals.



Model ground signal is too low



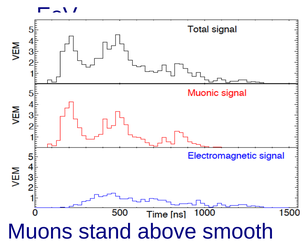
Discrepancy grows with zenith angle



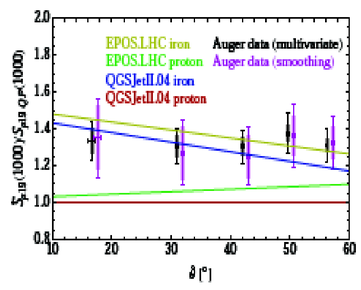
For all composition mixes that fit X_{max} distribution

Muon content from signal time structure

From FADC traces at 10 EeV



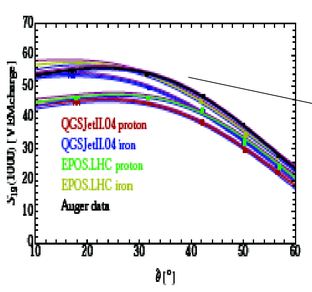
Muons stand above smooth electromagnetic component in FADC traces



Magnitud of muon fraction is comparable with predictions for iron showers.

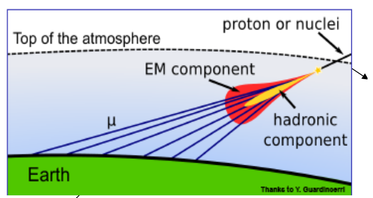
Angular dependence similar to proton showers.

Xmax distribution at 10 EeV is not compatible with iron composition.Signal is not well described by simulations

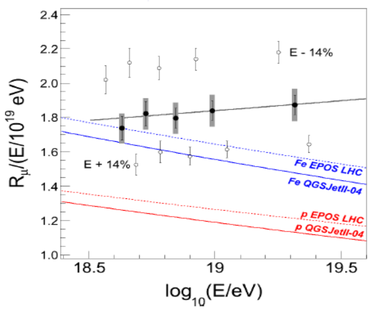


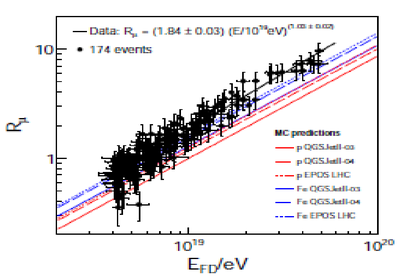
Inclined showers measurement of muon content

Above 62 deg muons dominate the recorded signals



Muons are dominant particles at ground as electromagnetic component is absorbed in the atmosphere.





Summary

- Energy reach of cosmic rays exceeds by far that of colliders.
- Proton-air cross-section measured with the Pierre Auger Observatory hybrid data at centre of mass energy per nucleon 57 TeV.
- Deviations found if longitudinal profile and surface detector signals are compared. Significant muon deficit in predictions.
- Realistic treatment of the mass composition do not remove the muon discrepancy. Hadronic shower at least 1.3 to low.
- Multiple methods reach the same conclusion : models do not accurately described muon signal (FADC traces, inclined showers, hybrid events)
- Measurements of extensive air showers at ultra-high energies can have an impact on understanding hadronic interactions at energies beyond what is accessible at accelerators.