Longitudinal profiles of the highest energy cosmic-ray air showers measured at the Pierre Auger Observatory

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Workshop JČF 2022

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June 12, 2022

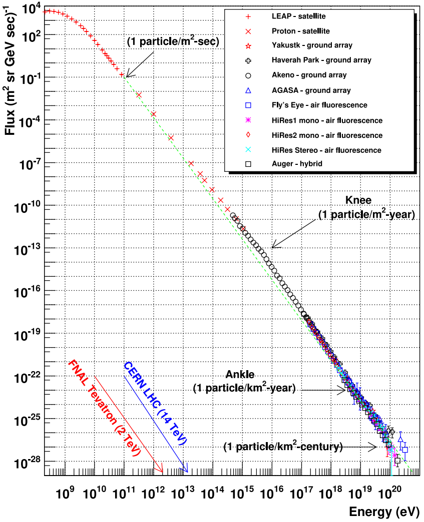
Contents

Overview

- Reconstruction of cosmic-ray air showers observed by fluorescence telescopes at the Pierre Auger Observatory using three different methods.
- Analysis of the differences between standard reconstruction method and two alternative methods.
- Combination of the results obtained from the three different methods.

Motivation I

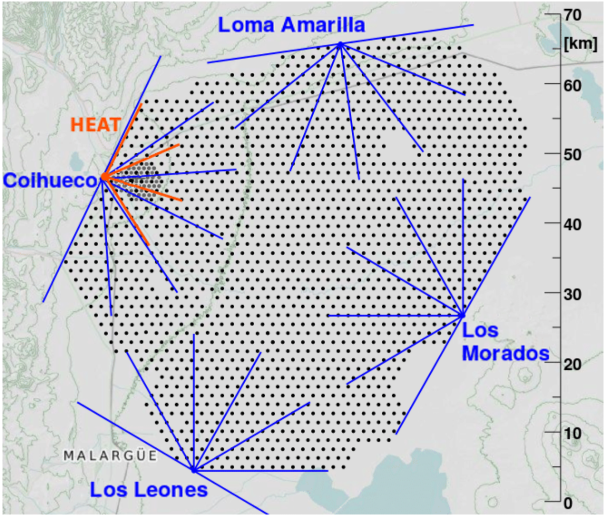
- Very small flux of cosmic rays at the end of the spectrum.
- Even smaller number of observed events selected for mass-composition analysis.



[1]

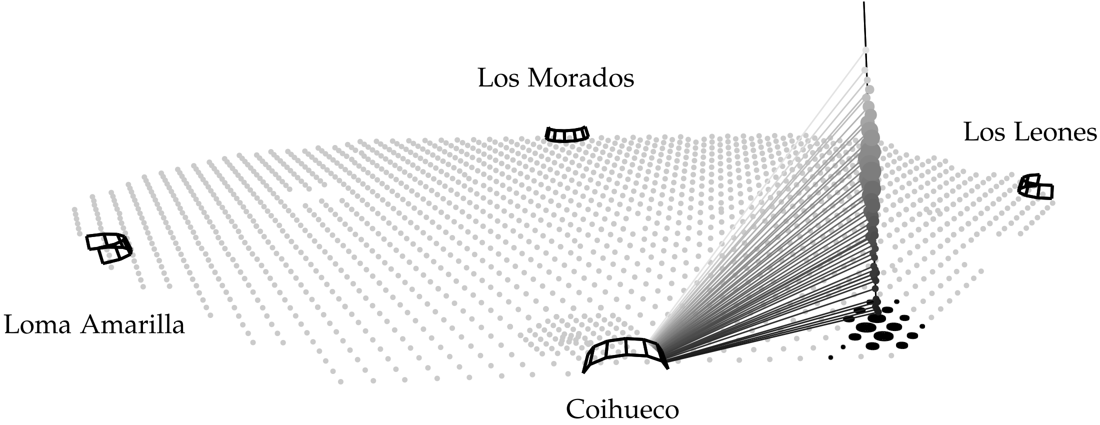
The Pierre Auger Observatory

- Hybrid detection of cosmic-ray showers: combination of two different detection methods: surface detector (SD) and fluorescence detector (FD) .
- SD: 1660 water-Cherenkov stations spread over an area of ~ 3000 km^2.
- FD: 27 fluorescence telescopes located at 4 sites.



[2]

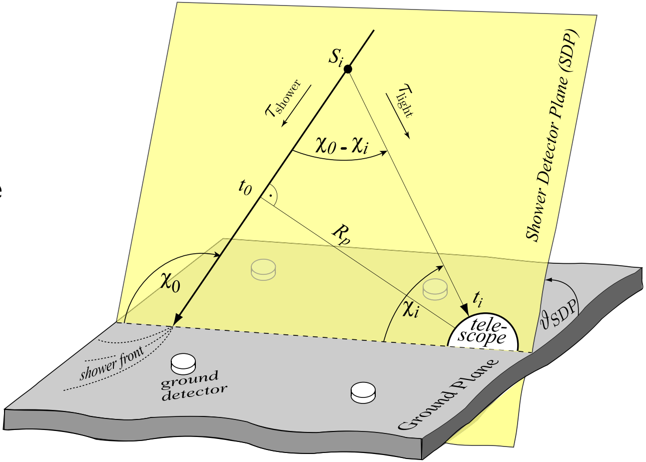
Reconstruction of shower geometry I



[3]

Reconstruction of shower geometry II

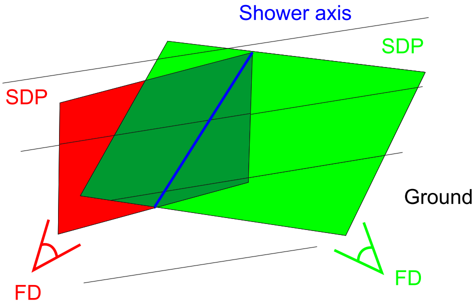
- **Standard hybrid reconstruction**: Shower geometry reconstructed using FD signal and signal from at least one SD station closest to the shower core .
- **Reconstruction using the SD geometry**: Full SD-reconstructed signal used for shower geometry estimation.



[4]

Reconstruction of shower geometry III

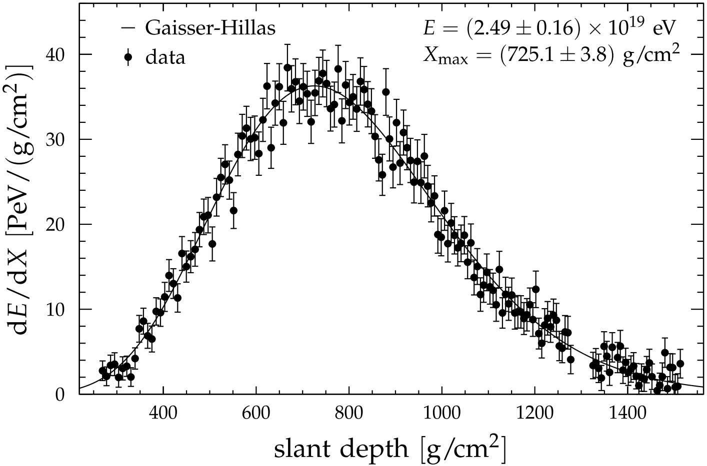
- **Stereo reconstruction**: Shower axis reconstructed by finding the best fitting axis from combination of SDP-fit from all triggered telescopes.



[5]

Shower longitudinal profile

- X_{max}: Shower depth corresponding to the maximum energy deposit (maximum number of shower particles).
- E_{cal}: Calorimetric energy of the air shower.
- Total shower energy is reconstructed using measured E_{cal} and estimated invisible energy.

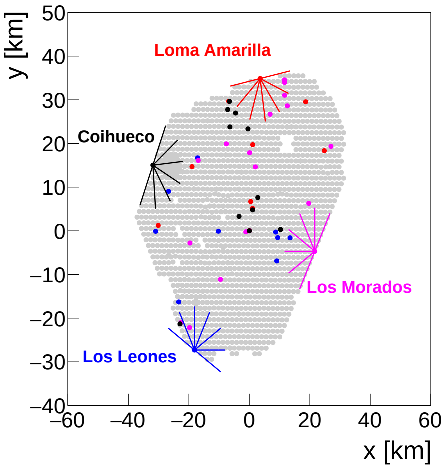


[3]

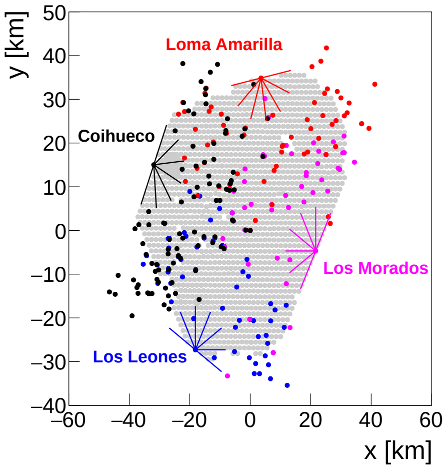
Motivation II

- Reconstruction of hybrid events using the SD geometry increases the data set mostly by showers that are further from the FD sites.
- Stereo method is able to reconstruct showers that hit the ground outside of the SD array.
- Usage of the two alternative reconstruction methods has the potential to considedrably increase the number of analysed highest energy cosmic-ray showers.

SD geometry



Stereo



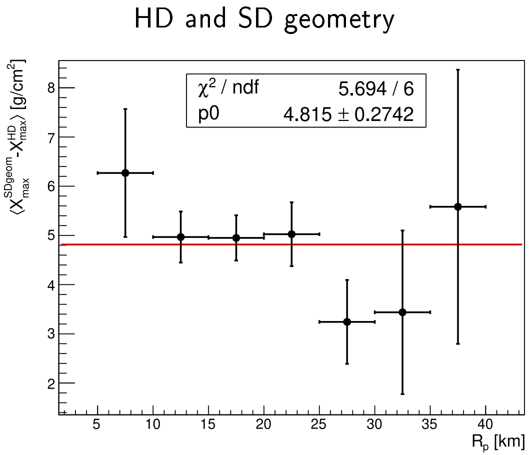
Analysis of simulated showers I

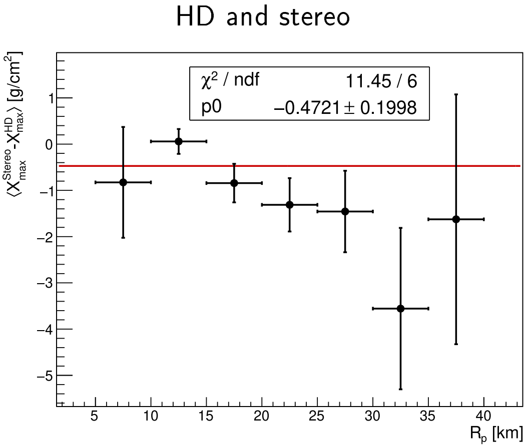
- Cosmic-ray showers initiated by protons with energies between $10^{19.5}$ eV and 10^{20} eV and with zenith angles within 60° simulated using CORSIKA 7.5700 with hadronic interaction model EPOS LHC.
- X_{max} and SD cuts applied on HD reconstructed events (2636 events selected) and events reconstructed using the SD geometry (2643 events selected).
- X_{max} applied on stereo reconstructed events (2208 events selected).

Analysis of simulated showers II

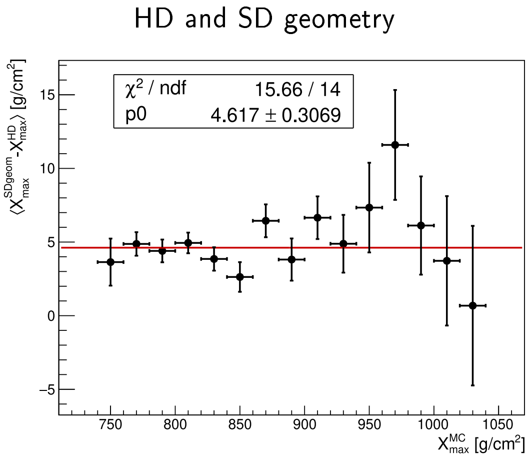
- Analysis of the difference in reconstructed X_{max} and E_{cal} between standard method and each of the alternative methods on identical MC-generated events reconstructed by identical FD sites.
- Analysis of biases and resolutions on all MC-generated events.
- HD reconstruction and reconstruction using the SD geometry: 3672 identical events reconstructed by identical FD sites.
- HD reconstruction and stereo reconstruction: 3609 identical events reconstructed by identical FD sites.

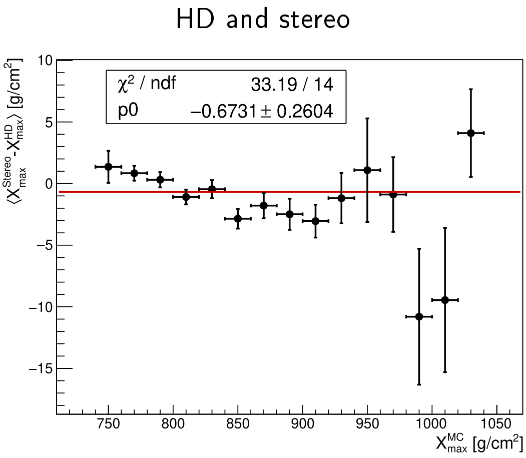
Analysis of simulated showers - difference in X_{max} vs. shower distance





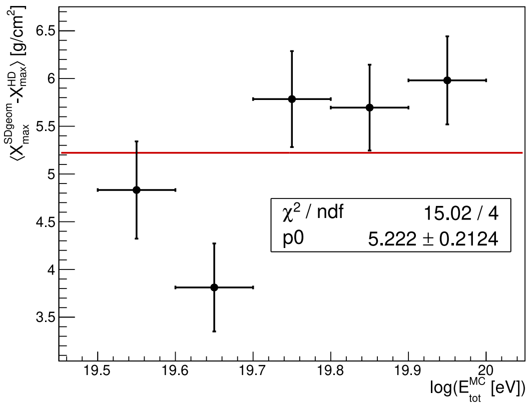
Analysis of simulated showers - difference in X_{max} vs. MC X_{max}



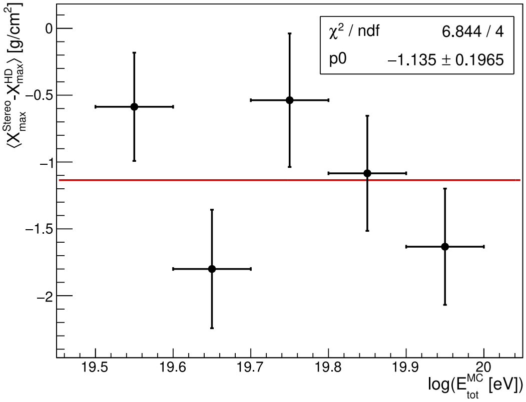


Analysis of simulated showers - difference in X_{max} vs. MC shower energy

HD and SD geometry



HD and stereo



Analysis of simulated showers - X_{max} correction factors

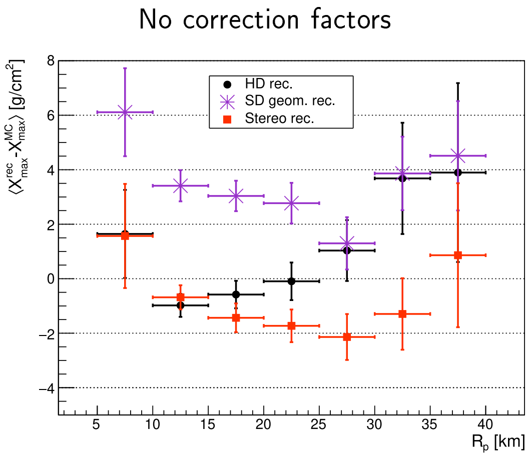
- Correction of X_{max} reconstructed using the SD geometry against the HD reconstruction was estimated as

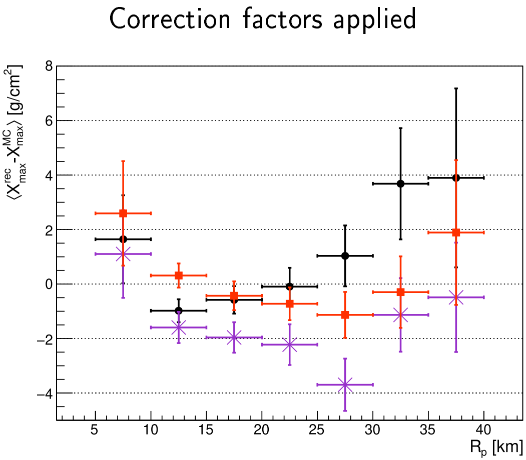
$$X_{\mathrm{max}}^{\mathrm{SDgeom}} = X_{\mathrm{max}}^{\mathrm{HD}} + 5\ \mathrm{g/cm}^2. \tag{1}$$

- Correction of X_{max} reconstructed using the stereo method against the HD reconstruction was estimated as

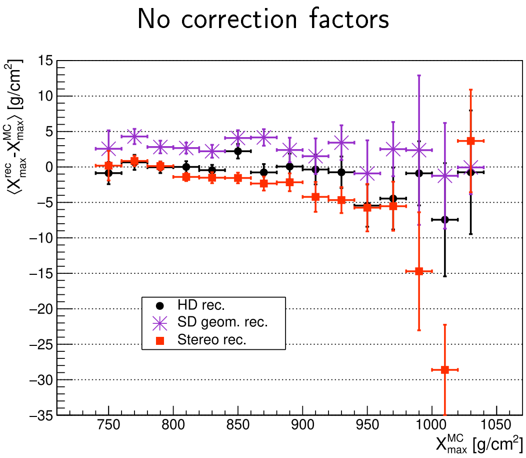
$$X_{\mathrm{max}}^{\mathrm{Stereo}} = X_{\mathrm{max}}^{\mathrm{HD}} - 1\ \mathrm{g/cm}^2. \tag{2}$$

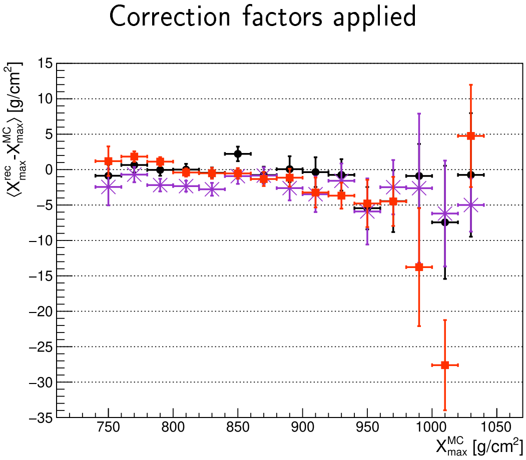
Analysis of simulated showers - X_{max} bias vs. shower distance





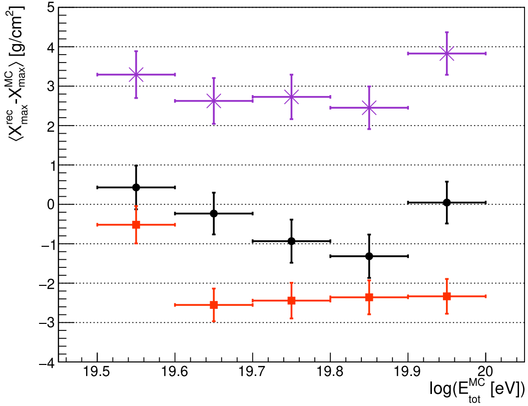
Analysis of simulated showers - X_{max} bias vs. MC X_{max}



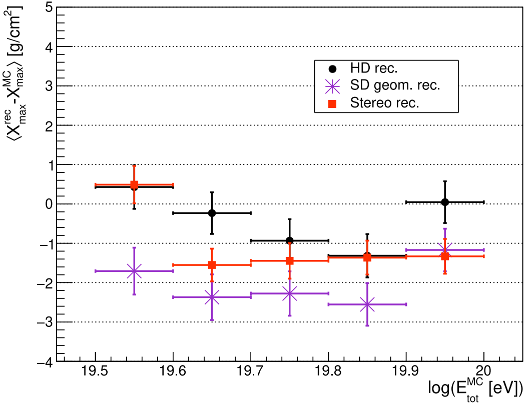


Analysis of simulated showers - X_{max} bias vs. MC shower energy

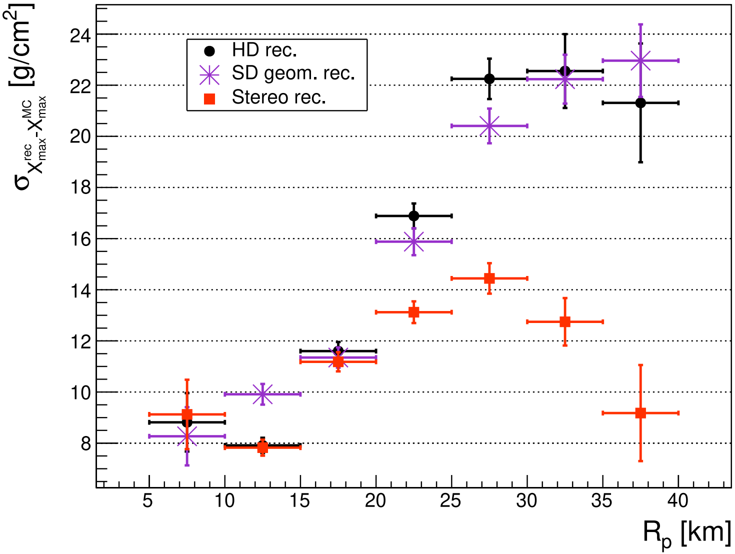
No correction factors



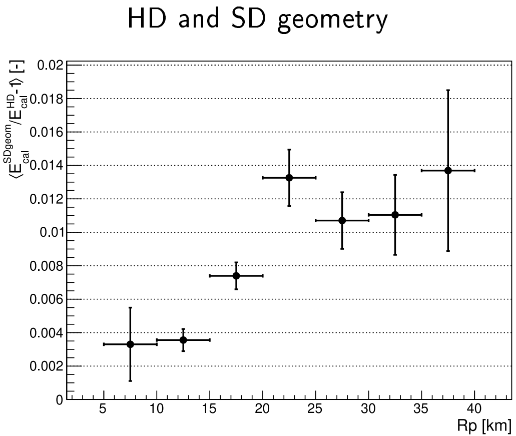
Correction factors applied

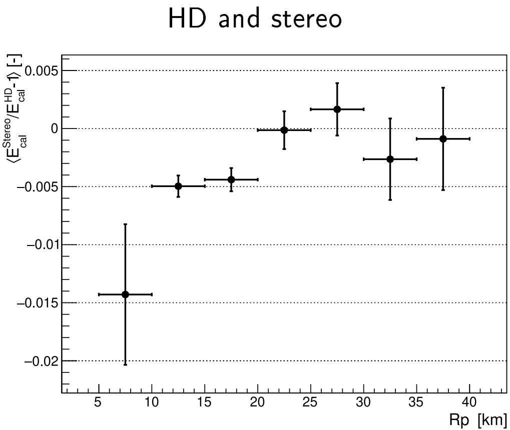


Analysis of simulated showers - X_{max} resolution vs. shower distance

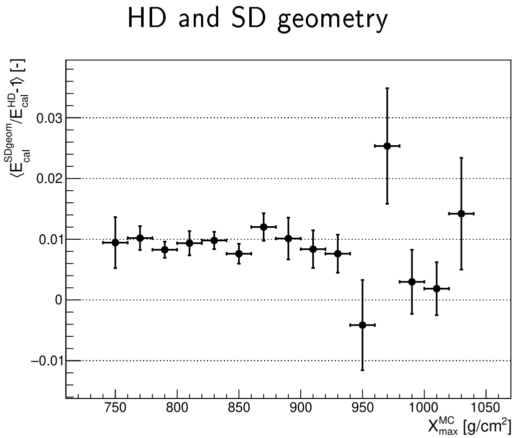


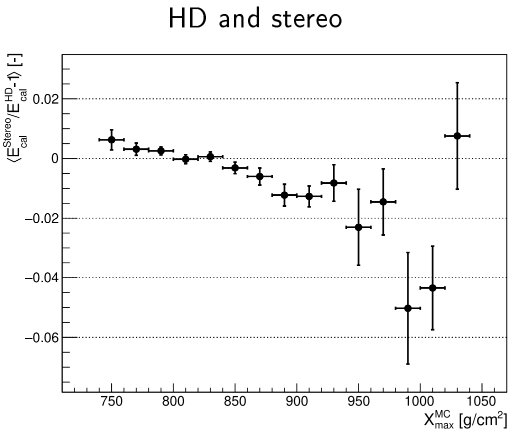
Analysis of simulated showers - difference in E_{cal} vs. shower distance





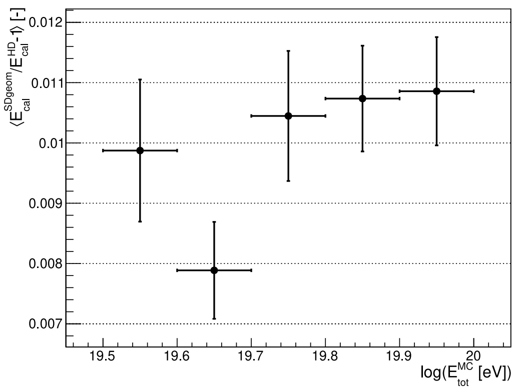
Analysis of simulated showers - difference in E_{cal} vs. MC X_{max}



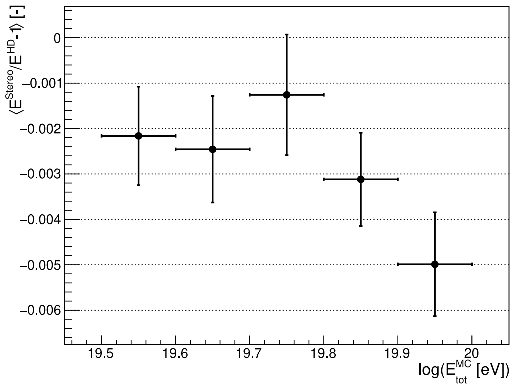


Analysis of simulated showers - difference in E_{cal} vs. MC shower energy

HD and SD geometry



HD and stereo

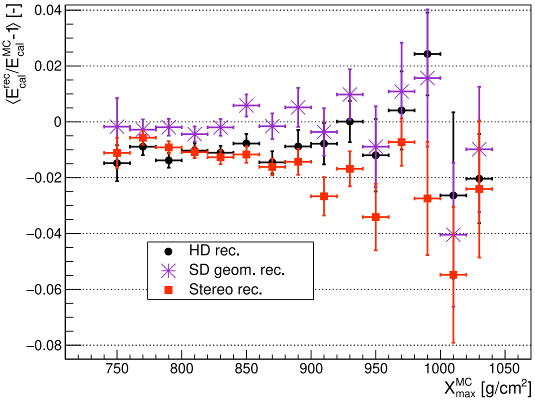


Analysis of simulated showers - E_{cal} correction factors

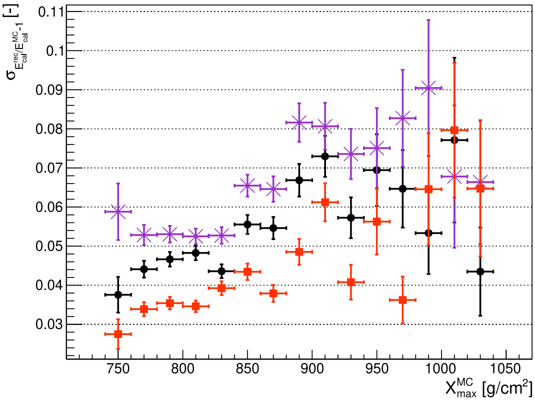
- Differences are lower than $\approx 5\% \implies$ shift in X_{max} is lower than 1.2 g/cm^2.
- No correction is needed in case of E_{cal}.

Analysis of simulated showers - E_{cal} bias and resolution vs. MC X_{max}

E_{cal} bias



E_{cal} resolution



Analysis of simulated showers - conclusions

1. Simple correction factors applied on X_{max} reconstructed using the alternative methods lower the differences in X_{max} bias.

2. E_{cal} reconstructed using the alternative methods does not shift the X_{max} by more than $1.2\ \mathrm{g/cm^2}$.

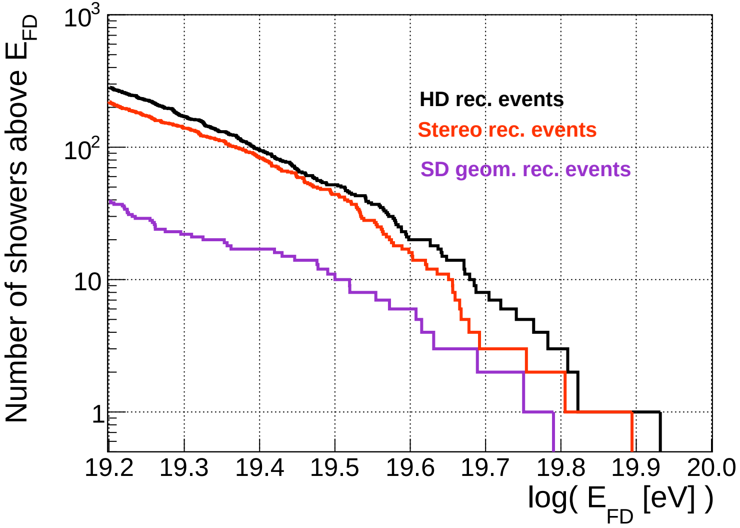
3. The differences in resolution of both X_{max} and E_{cal} between all three methods are within acceptable bounds of about $5\ \mathrm{g/cm^2}$.

$\Longrightarrow$ The properties reconstructed using the three different methods can be combined together after introducing simple correction factors for X_{max} without considerably biasing the results.

Combination of the reconstruction methods - data selection

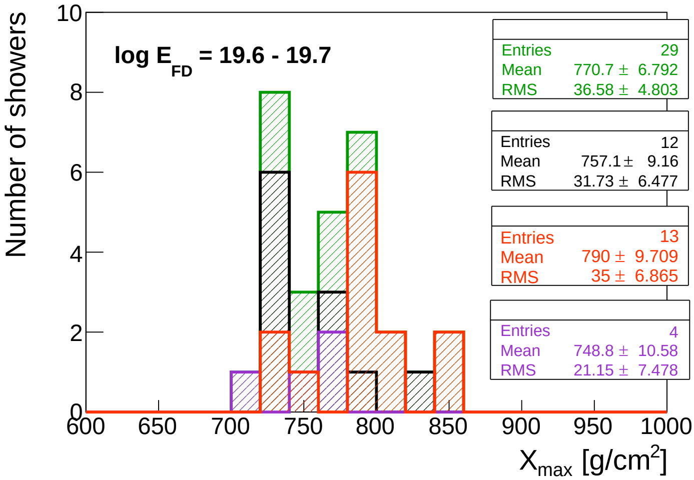
- Analysis of all selected HD events, additional events reconstructed using the SD geometry and additional stereo-reconstructed events.
- Pierre Auger Observatory data taken from January 1, 2004 up to December 31, 2018 with energies above $10^{19.2}$ eV and zenith angles below 60°.
- X_{max} and SD cuts applied on HD reconstructed events (284 events selected) and events reconstructed using the SD geometry (40 additional events).
- X_{max} applied on stereo reconstructed events (221 additional events).
- Previously estimated correction factors from MC applied on X_{max} reconstructed using the SD geometry and using the stereo method.

Number of showers above E_{FD}



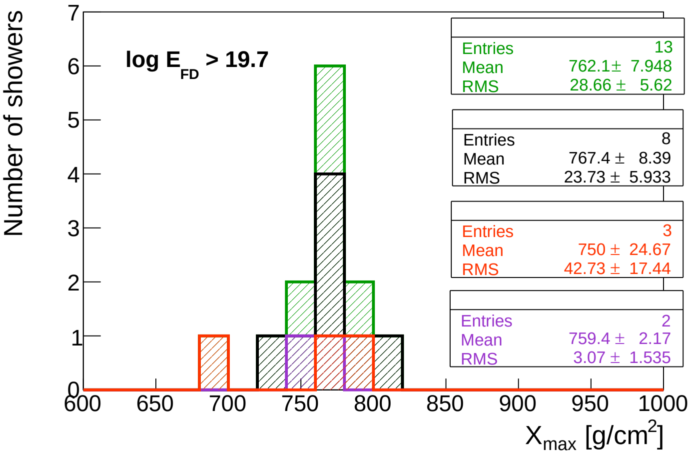
Combination of X_{max} distributions - energetic bin between $10^{19.6}$ eV and $10^{19.7}$ eV

- Green: Combined results
- Black: HD reconstruction
- Orange: Stereo reconstruction
- Violet: Reconstruction using the SD geometry



Combination of X_{max} distributions - energetic bin above $10^{19.7}$ eV

- Green: Combined results
- Black: HD reconstruction
- Orange: Stereo reconstruction
- Violet: Reconstruction using the SD geometry



Conclusions

1. Analysis of reconstruction methods based on simulated showers shows that the differences in systematics due to reconstruction of all three methods are within acceptable boundaries after introducing simple correction factors for reconstructed X_{max} $\Longrightarrow$ it is possible to combine results from all three methods.

2. Due to technical difficulties, the combined data do not draw the whole picture. We could not therefore conclude the full increase of the number of selected events for energies above $10^{19.2}$ eV. Yet, it should be more than 10% corresponding to several years of data taking of showers for standard X_{max} analysis.

Literature I

[1] S.P. Swordy.
The Energy Spectra and Anisotropies of Cosmic Rays.
Space Science Reviews, 99:85–94, Oct 2001.

[2] The Collaboration.
The Pierre Auger Cosmic Ray Observatory.
Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 798, Feb 2015.

[3] A. Aab et al.
Depth of Maximum of Air-Shower Profiles at the Pierre Auger Observatory: Measurements at Energies above $10^{17.8}$ eV.
Phys. Rev. D, 90(12), Dec 2014.

Literature II

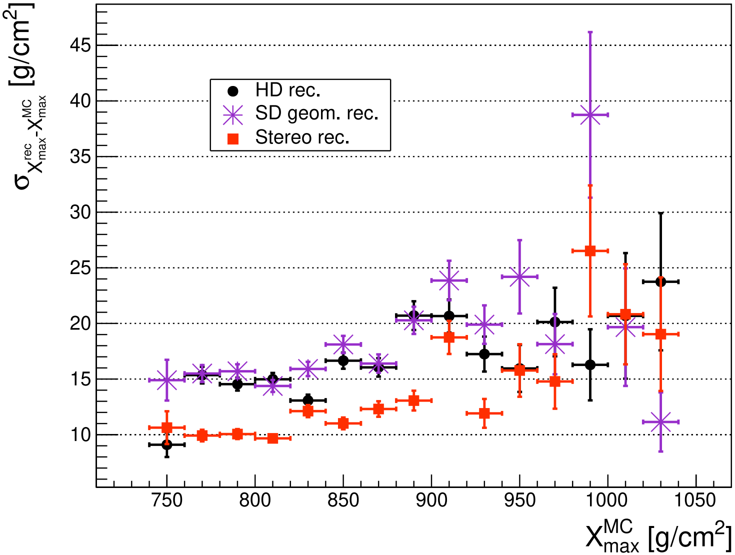
[4] D. Kuempel, K. Kampert, and M. Risse.
Geometry reconstruction of fluorescence detectors revisited.
Astropart. Phys., 30(4):167–174, Nov 2008.

[5] V. Novotný, D. Nosek, and J. Vícha.
Stereo Reconstruction at the Pierre Auger Observatory.
In *WDS 2014 – Proceedings of Contributed Papers – Physics*, pages 187–192, Prague, 2014. Matfyzpress.

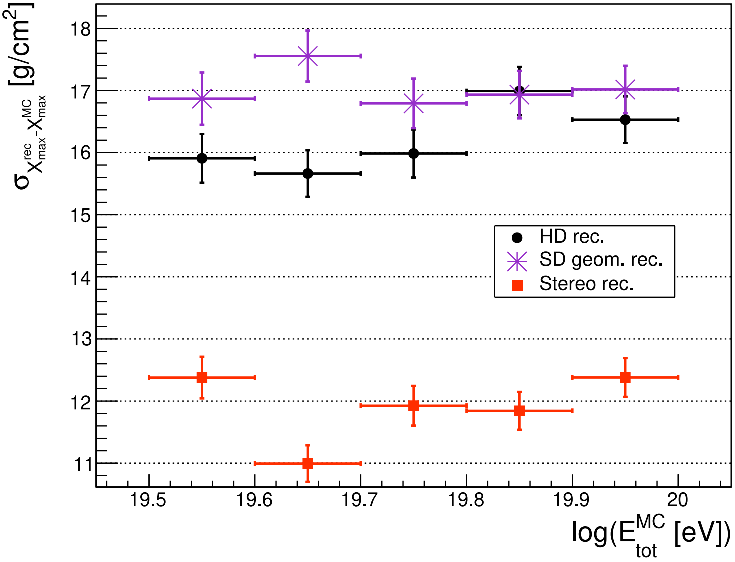
[6] The Collaboration.
Spectral Calibration of the Fluorescence Telescopes of the Pierre Auger Observatory.
Astroparticle Physics, 95, Sep 2017.

Backup

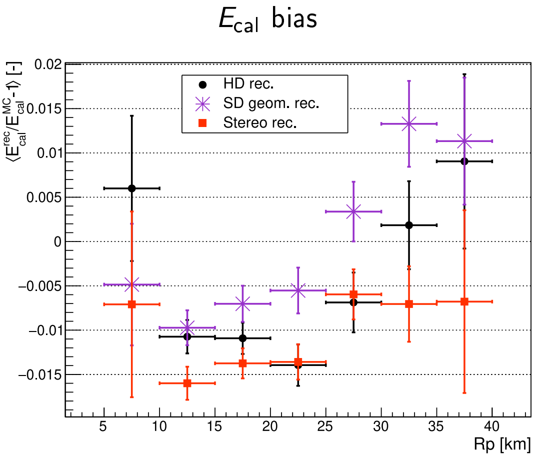
Analysis of simulated showers - X_{max} resolution vs. MC X_{max}

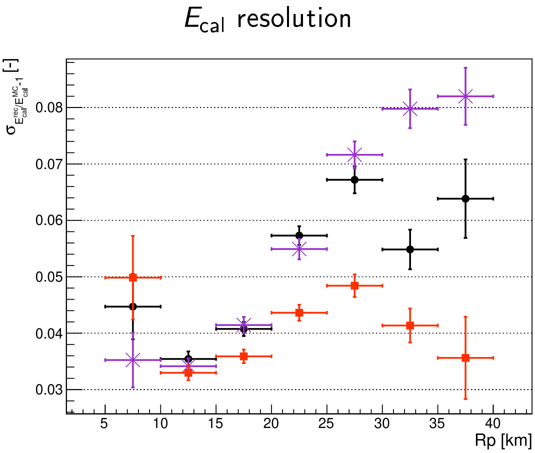


Analysis of simulated showers - X_{max} resolution vs. MC shower energy

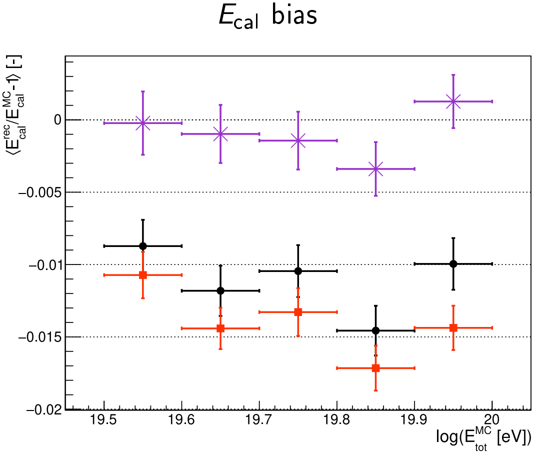


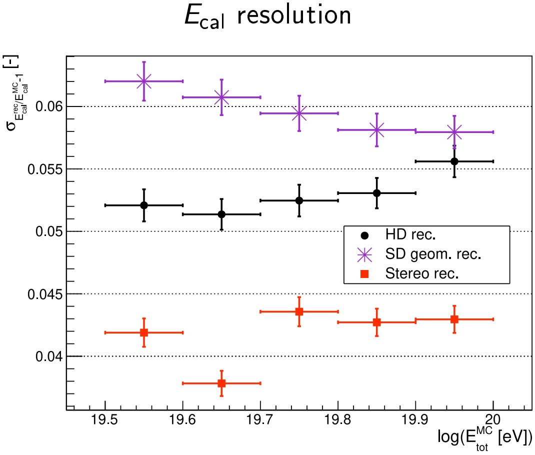
Analysis of simulated showers - E_{cal} bias and resolution vs. shower distance





Analysis of simulated showers - E_{cal} bias and resolution vs. MC shower energy





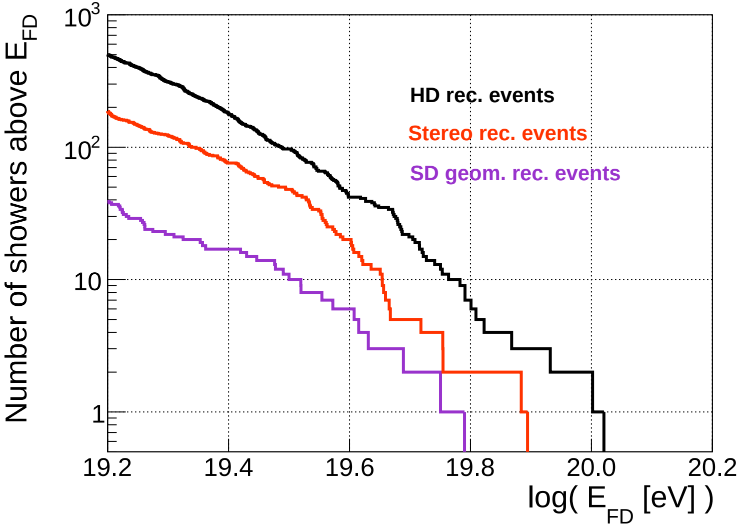
Future improvements

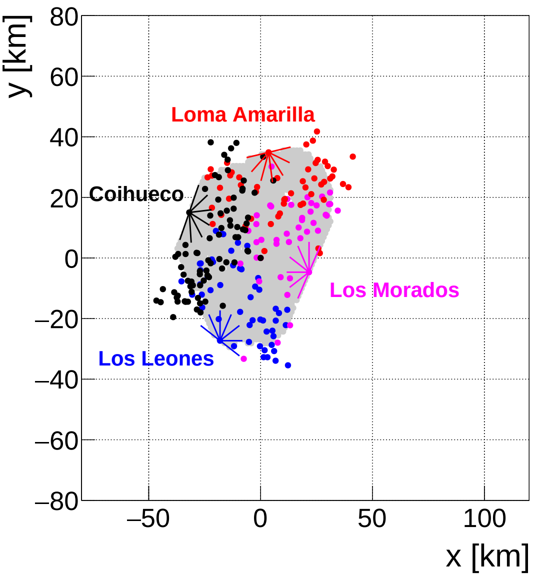
1. Adding the missing HD reconstructed showers and applying only X_{max} cuts on the HD reconstructed showers $\implies$ the number of selected HD-reconstructed data should increase, the number of selected stereo-reconstructed might decrease, the number of selected showers reconstructed using SD geometry will not differ.

2. Adding events with zenith angles above 60° $\implies$ the number of selected HD-reconstructed data should increase, the number of selected stereo-reconstructed should increase significantly, the number of selected showers reconstructed using SD geometry will not differ.

3. MC study for events with zenith angles higher than 60° and showers that do not fall directly onto the SD array.

Number of showers above E_{FD}




y [km]
80
60
40
20
0
−20
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−80
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0
50
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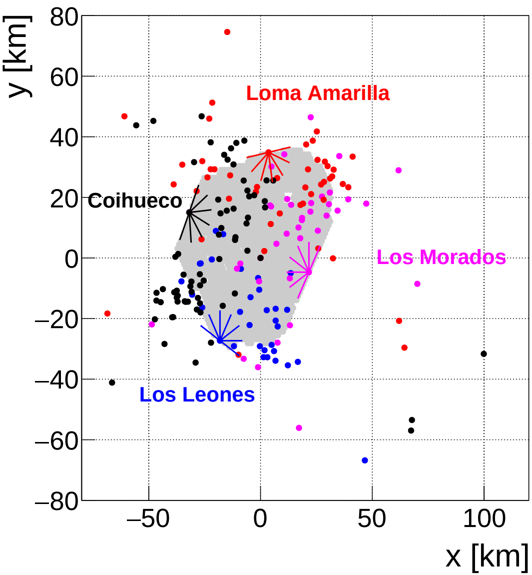
Loma Amarilla
Coihueco
Los Morados
Los Leones


y [km]
80
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x [km]
Loma Amarilla
Coihueco
Los Morados
Los Leones