Performance of the 433 m surface array of the Pierre Auger Observatory

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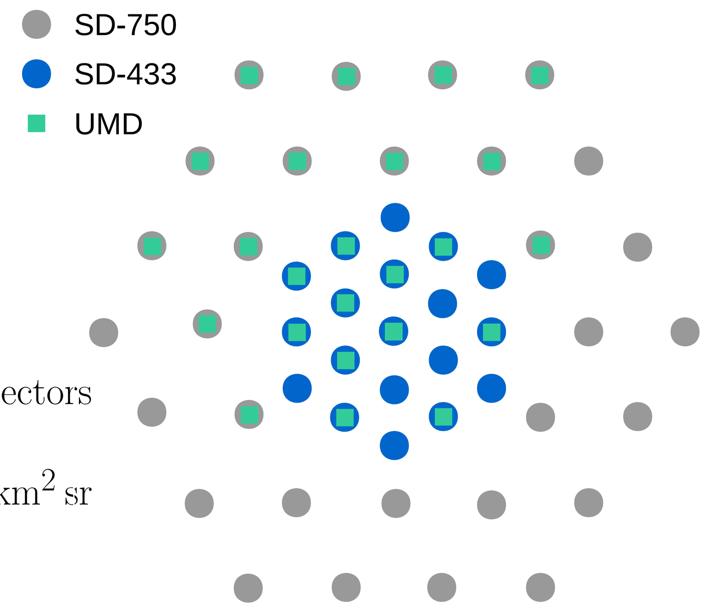
Motivation

- Photon search programme down to 10^{16} eV :
  - contribution to the multi-messenger studies in Auger
  - discovery of PeVatrons in the galactic center (Tibet AS-gamma, HAWC)
  - observations of UHE photons up to 1.4 PeV (LHAASO)
  - astrophysical neutrinos at the southern hemisphere (IceCube)
- Surface detector (SD) measurements will reach the centre of mass energy of the LHC
- Extend the energy spectrum with the surface detector measurements Cherenkov spectrum already down to 10^{16} eV [1]

Observation of the second knee with SD

Array description

- installation started in November 2011
- fully operational in May 2013
- final configuration achieved in May 2019
- 19 water-Cherenkov detectors spaced at 433 m reaching an aperture of $\sim 2\,\mathrm{km}^2\,\mathrm{sr}$ up to $\theta = 45°$



Simulations

- CORSIKA with QGSJetII-04 and FLUKA as hadronic interaction models
- 2000 proton- and 2000 iron-initiated air-showers
- continuous energy distribution as E^{-1} between 4×10^{16} eV and 10^{17} eV
- isotropic distribution up to $\theta = 55°$
- detector response simulated employing the Offline framework [2] of the Pierre Auger Collaboration

Real data and selection criteria

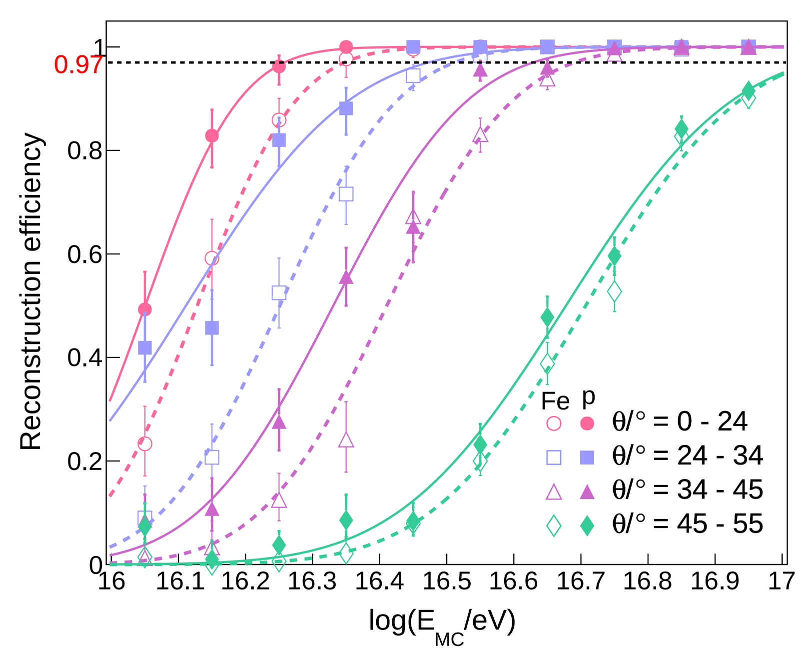
- acquired between May 2013 and May 2020
- at least three triggered WCDs in a compact triangular configuration
- six nearest WCDs around the one with the most intense signal must be operational
- events without any saturated WCDs
- final data-set was comprised by 115 thousand events

The efficiency ϵ

- Array efficiency ϵ defined as the probability of reconstructing an event.
- Array efficiency fitted with:

$$\epsilon(E) = \frac{\mathrm{erf}\left(a \times \log_{10}\frac{E_{\mathrm{MC}}}{10^{16}\,\mathrm{eV}} + b\right) + 1}{2}$$

1. 97% efficiency above 50 PeV for $\theta < 45°$
   a lower energy threshold of 30 PeV can be reached when restricting the zenith angle up to $\theta = 35°$
2. lower energy threshold for p than for Fe
3. maximum zenith angle of 45°

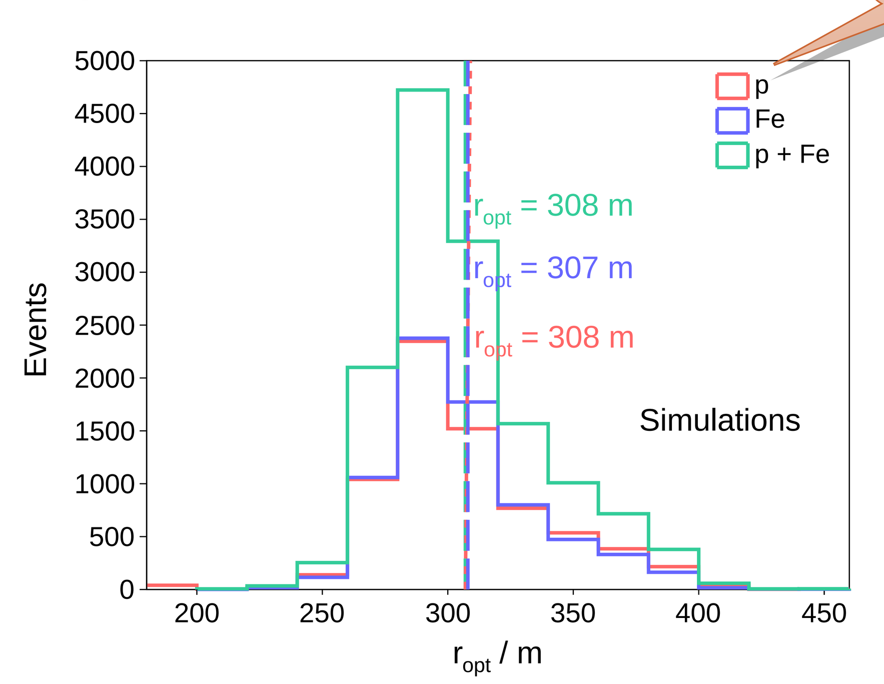


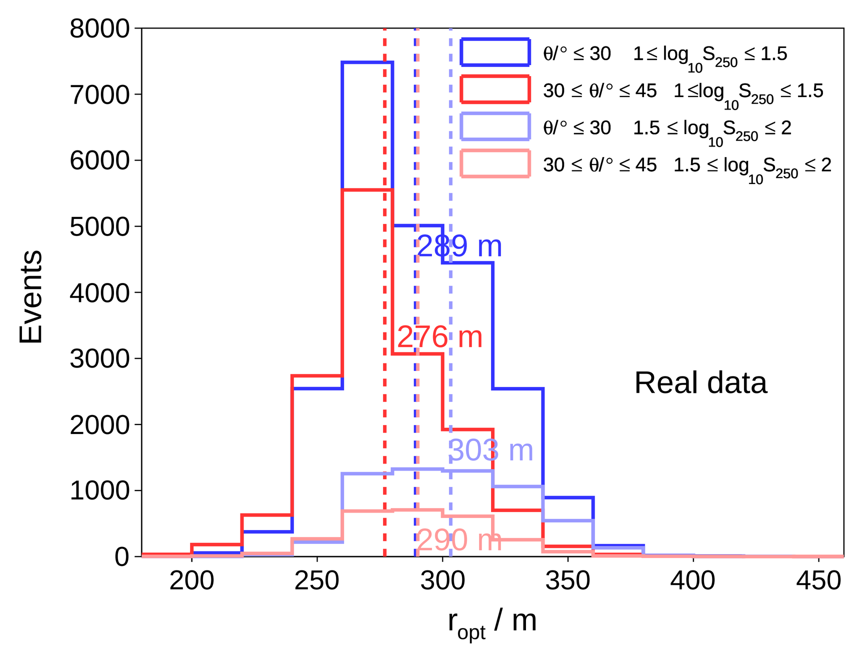
Optimal distance r_{opt}

- estimated during the event reconstruction
- minimal systematic uncertainty in the fitted LDF
- depends on the spacing and geometry [3]
- r_{opt} is estimated to be about 300 m

r_{opt} independent of primary

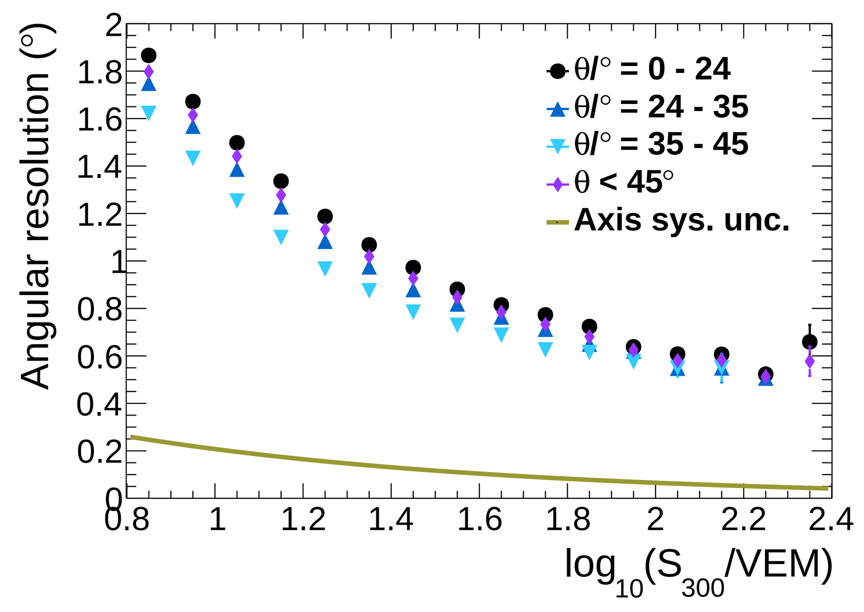
Compatible results obtained from data and simulations



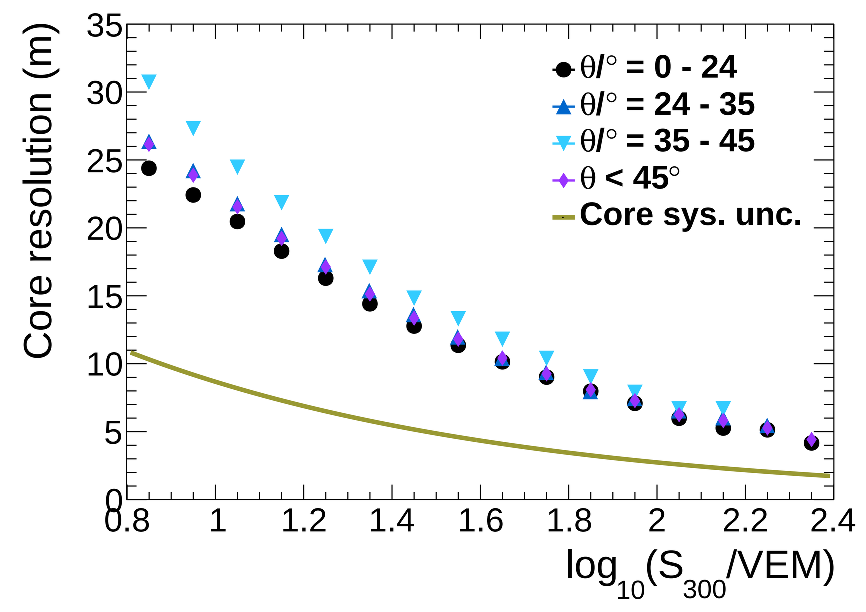


Geometry resolution

The angular resolution better than $\sim 1.8°$



The core position resolution better than 30 m



Lateral distribution function

Lateral Distribution Function (LDF): Signal distribution measured at the ground as function of the distance to the shower core

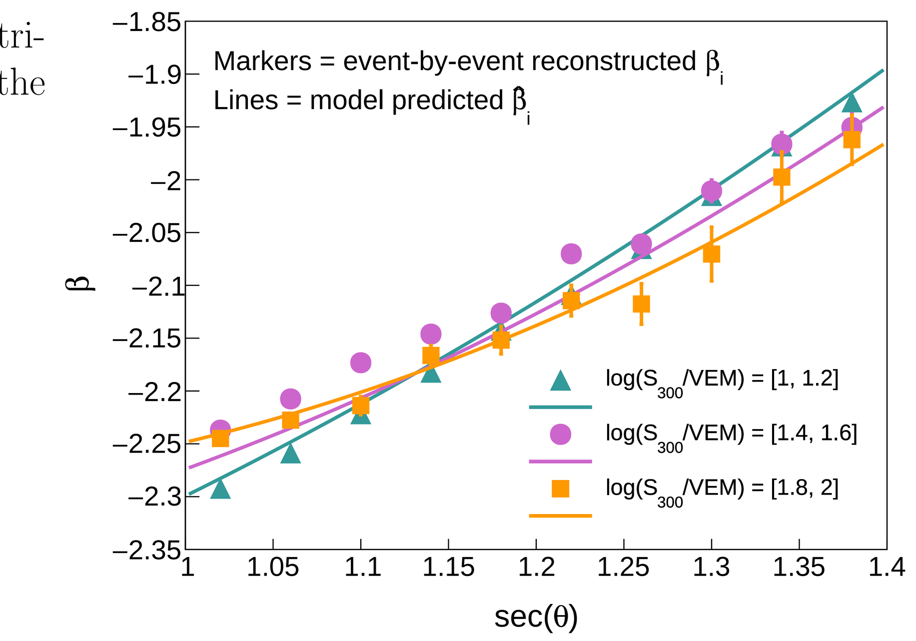
$$S(r) = S(r_{\mathrm{opt}}) \cdot \left(\frac{r}{r_{\mathrm{opt}}}\right)^{\beta} \left(\frac{r + r_{\mathrm{opt}}}{r_{\mathrm{scale}} + r_{\mathrm{opt}}}\right)^{\beta}$$

- The event-by-event β described by

$$\beta(\log S_{300}, \theta) = a(\theta) + b(\theta) \times \log_{10} S_{300}$$

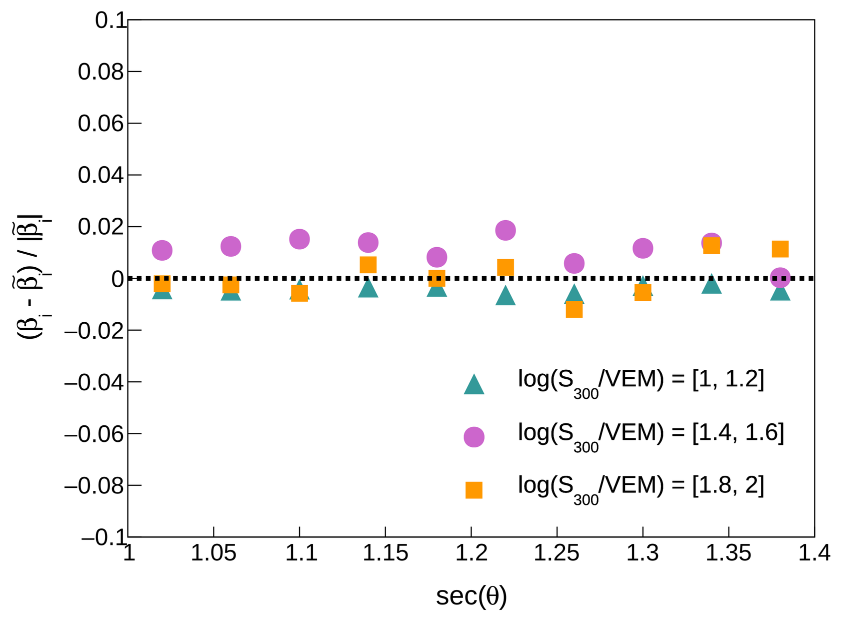
$$\begin{pmatrix} a \\ b \end{pmatrix} = \begin{pmatrix} -3.72 & 1.30 & 0.055 \\ 0.98 & -1.30 & 0.385 \end{pmatrix} \times \begin{pmatrix} 1 \\ \sec\theta \\ \sec^2\theta \end{pmatrix}$$

we obtain the $\hat{\beta}_i$ from the model prediction



Residuals:

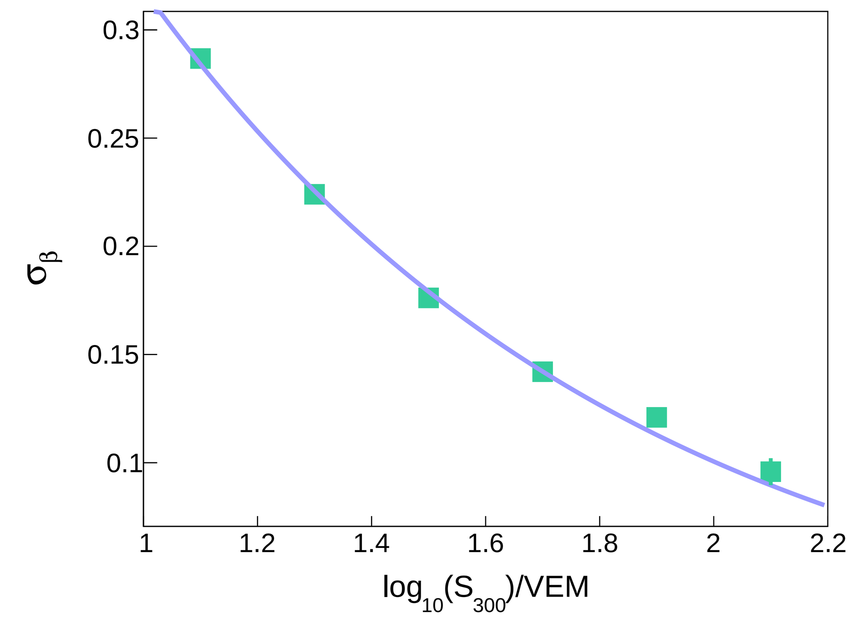
$$Res(\beta_i) := \frac{\beta_i - \hat{\beta}_i}{\hat{\beta}_i} \sim 2\%$$



The slope uncertainty model defined by:

$$\sigma_\beta = \exp\left[p_0 + p_1 \cdot \log_{10}(S_{300}/\mathrm{VEM})\right]$$

with $p_0 = (0.01 \pm 0.02)$ and $p_1 = (1.2 \pm 0.02)$



Conclusions

Reported results:

- a full-efficiency threshold of 50 PeV up to $\theta = 45°$
- the optimal distance is 300 m
- accurate description of LDF slope within 2%
- angular resolution better than $\sim 1.8°$

The SD-433 provides

- the opportunity to extend the sensitivity of the Auger surface detector down to 10^{16} eV and
- to observe second-knee feature in the CR spectrum with a full reconstruction efficiency

We have opened a new low-energy window on SD-oriented research at the Pierre Auger Observatory

References

[1] V. Novotný [for the Pierre Auger Coll.] "PoS(ICRC2021)324". In: (2021).
[2] L. Nellen [for the Pierre Auger Coll.] "PoS(ICRC2021)250". In: (2021).
[3] J. Knapp D. Newton and A. Watson. In: *Astropart. Phys. 26 414-419* (2007).