Observation of the Shadows of the Moon and Sun Using the Pierre Auger Observatory at an Average Energy of 7×10^{17} eV

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CosPa Meeting October 2025

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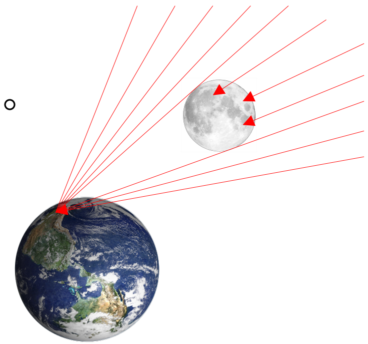
Can we see the lunar and solar shadows above 10^{16} eV?

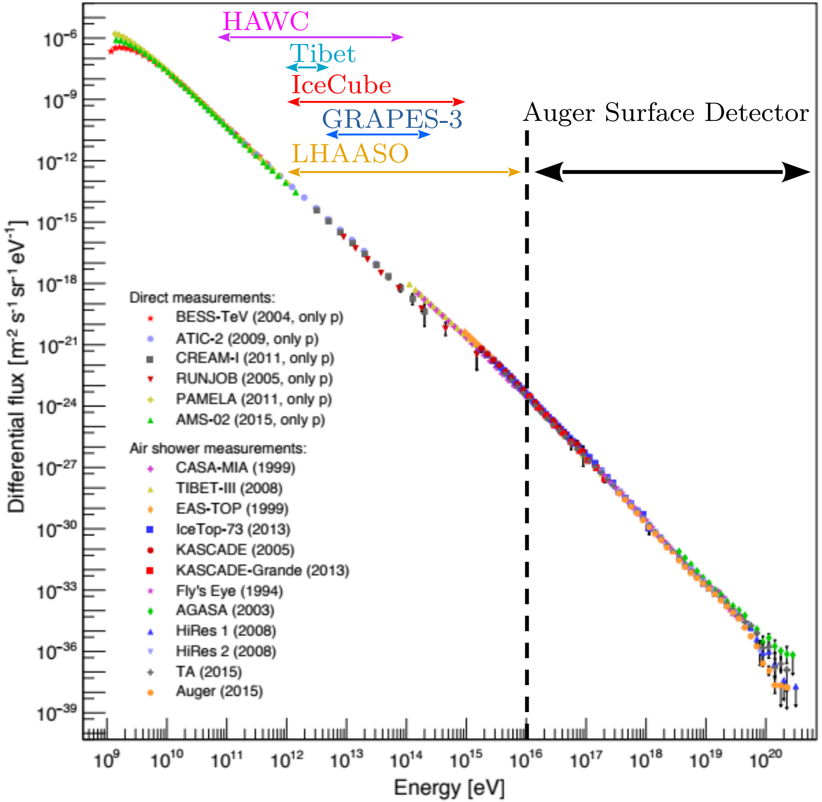
Cosmic rays are blocked by the Moon and the Sun

Similar angular radius of ~0.26°



Observations of the shadows of the Moon and of the Sun exist up to 10^{16} eV to verify pointing and resolution of astroparticle observatories

Challenge at the highest energies: Low statistics

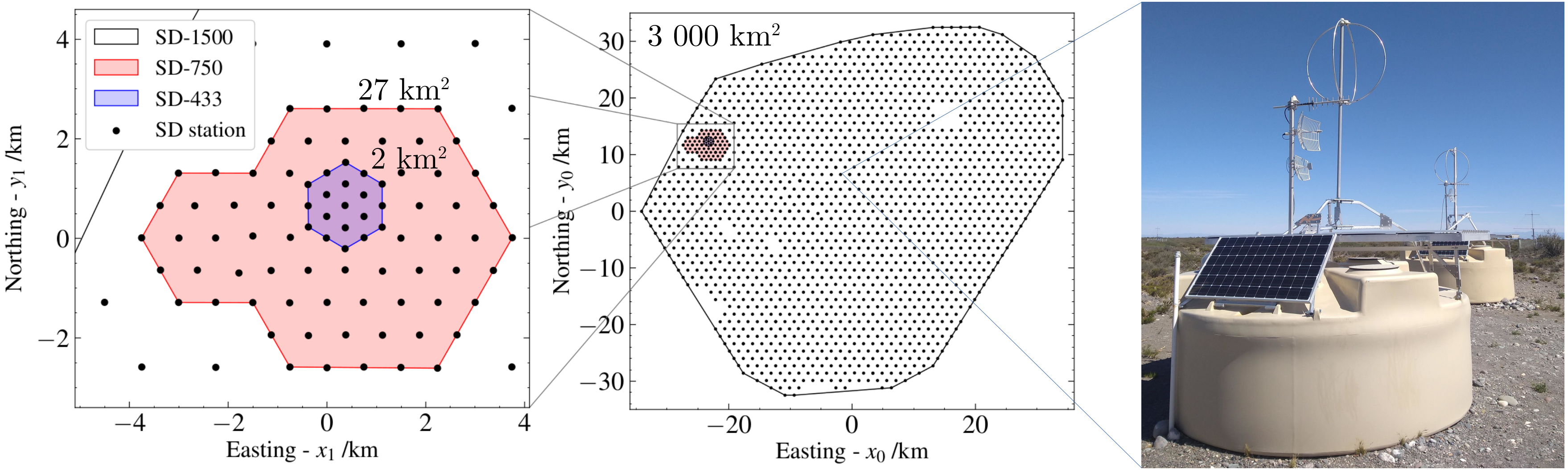


T. L. Fehler. Hybrid Search for Photons with the Low-Energy Extensions of the Pierre Auger Observatory.
https://www.hep.physik.uni-siegen.de/pubs/master/fehler-master.pdf

The Surface Detector arrays of the Pierre Auger Observatory

3 Arrays placed on interlaced triangular grids in Malargüe, Argentina

Start of data taking in 2004, AugerPrime upgrade installation in 2022 - 2024



A. Aab et al. (Pierre Auger Collaboration) NIM A 798 (2015)

>18 000 events within 5° of both the Moon and the Sun

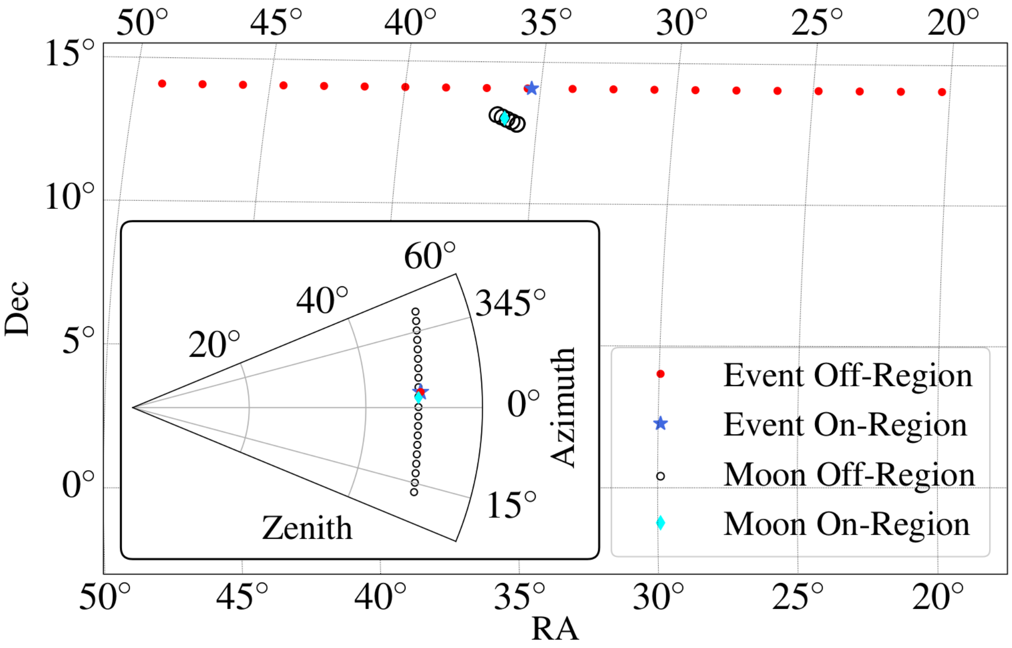
Expected isotropic events (no Moon/Sun)

The relative deficit of events:

$$\Delta = \frac{N_{\mathrm{on}} - \langle N_{\mathrm{off}} \rangle}{\langle N_{\mathrm{off}} \rangle}$$

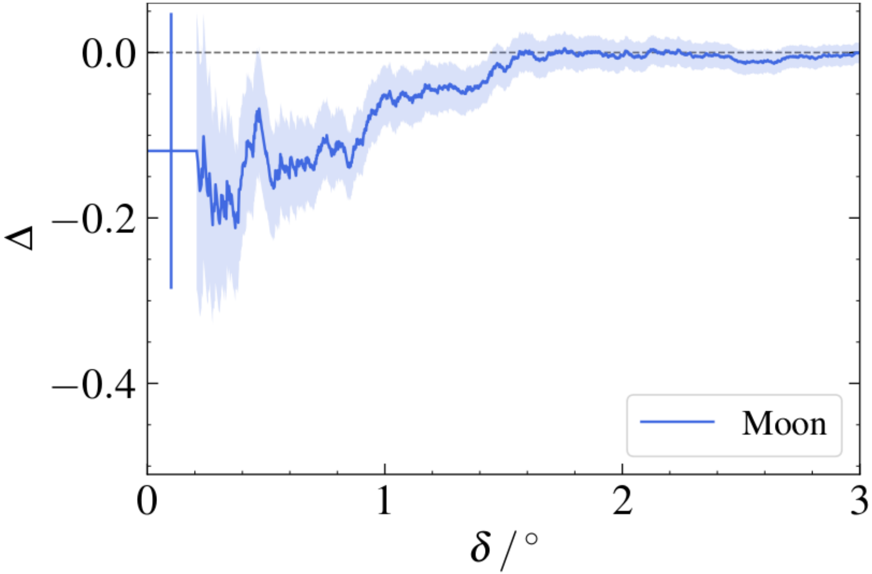
On-region centered on the Moon/Sun

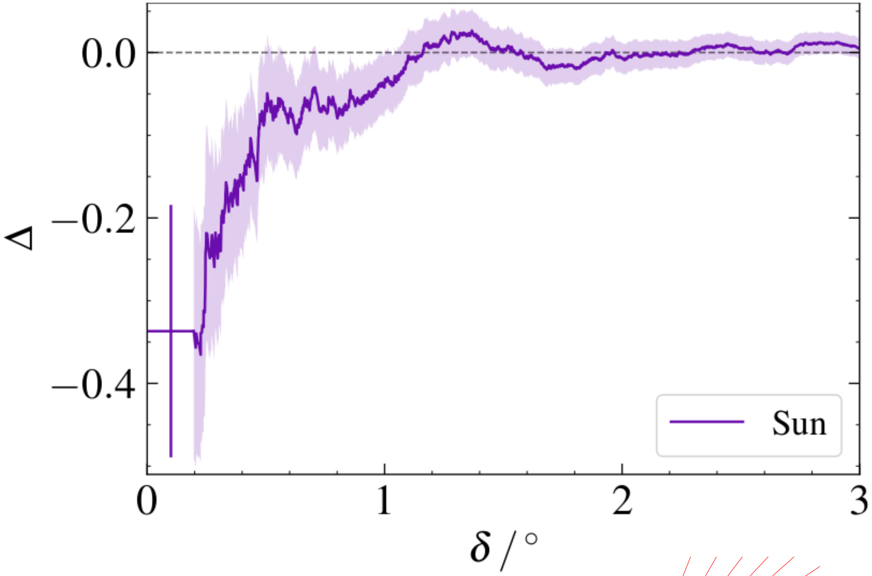
Off-region (isotropic expectation without Moon/Sun)



Off-Regions: Shuffling the time of the event within ±1h for the Moon (±30 min for the Sun)

Measured deficit due to the Moon and the Sun

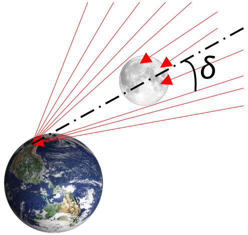




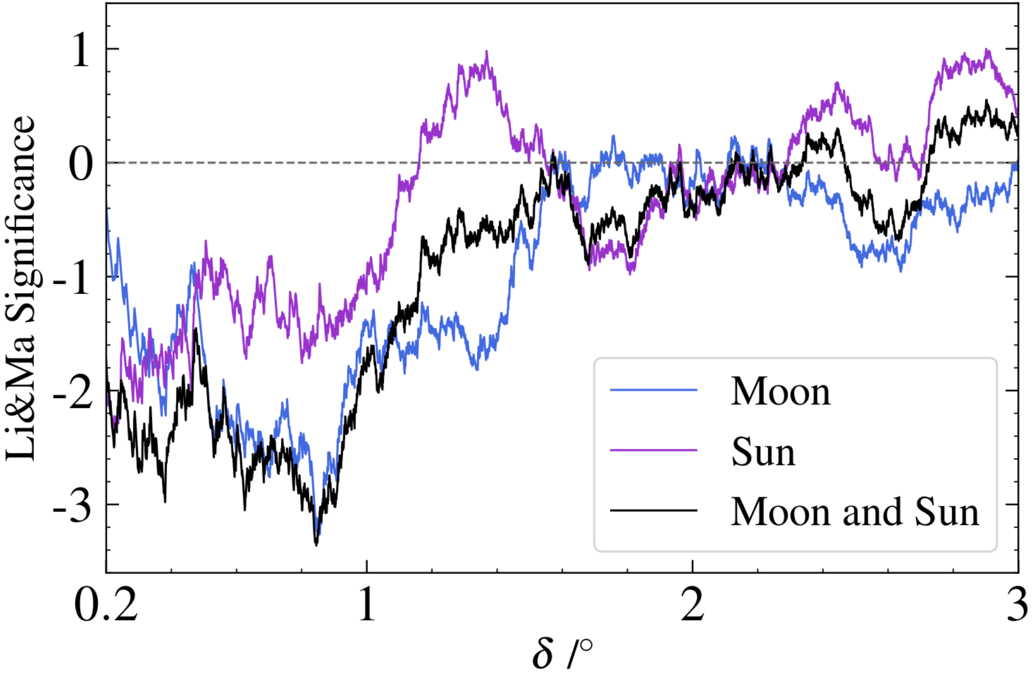
δ - Angular distance between the event and the celestial body in local coordinates

Isotropic background consistent with on-region at large δ

Correct pointing of the Observatory confirmed



Li&Ma significance of the deficits



Maximum significance:

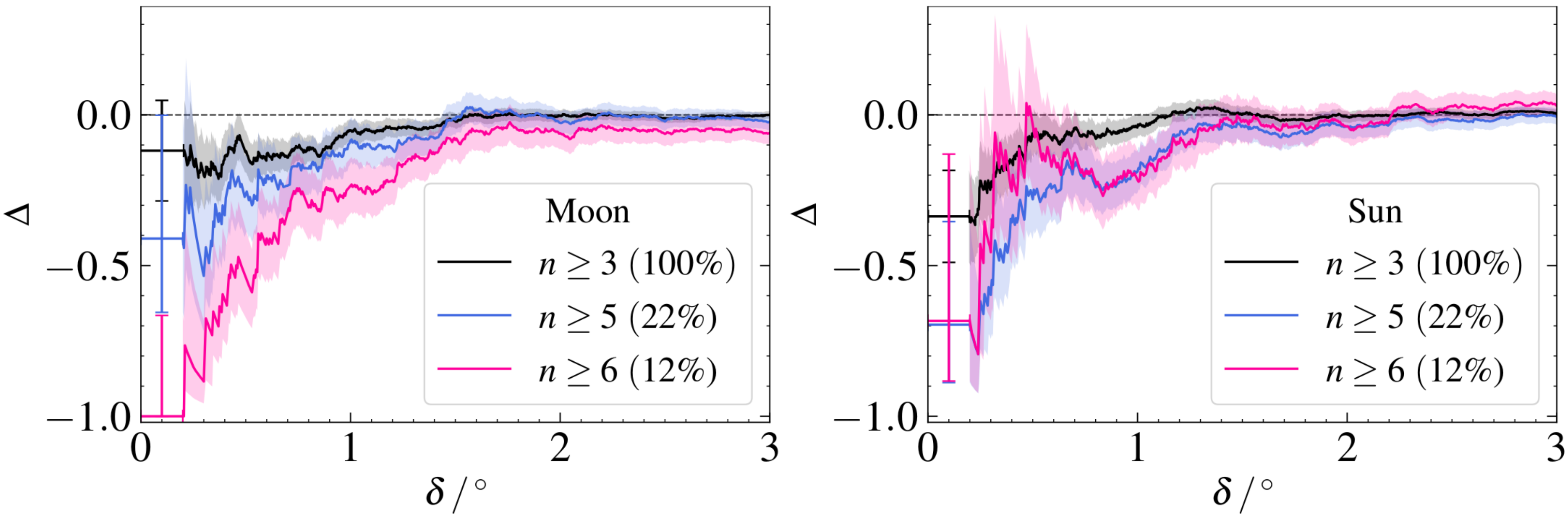
Moon: 3.3σ at 0.85°

Sun: 2.4σ at 0.23°

Combined: 3.4σ at 0.85°

T. P. Li and Y. Q. Ma Astrophys. J. 272 (1983)

Dependence on the multiplicity of events



Decrease of Δ with increasing multiplicity (n) → resolution is better for higher multiplicity

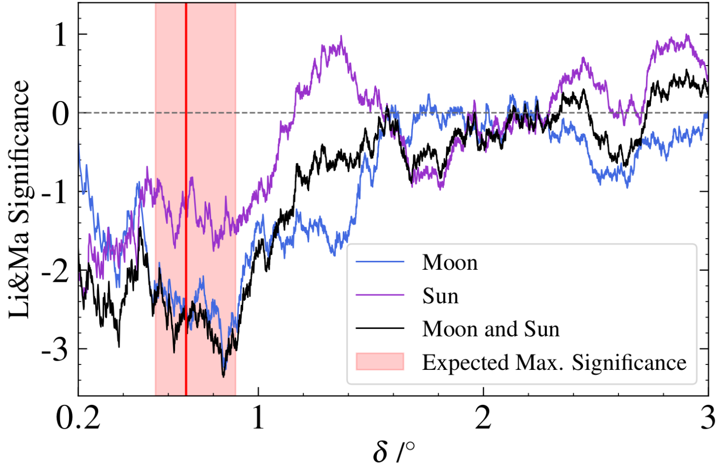
From deficit to the effective angular resolution

Likelihood: Shadowed events (disk) smeared by a 2-D symmetric Gaussian with its resolution a multiple of the effective angular resolution of the Observatory σ_{68}

σ_{68} is a combination of different event resolutions

Unbinned maximum likelihood fit of the combined shadows: $\sigma_{68} = (0.6^{+0.2}_{-0.1})^\circ$

Significance using Gaussian approximation: 3σ $\left(N_\sigma = \sqrt{2\left[\log \mathcal{L}(\sigma_{68,\mathrm{best}}) - \log \mathcal{L}(\sigma_{68} = 15^\circ)\right]}\right)$



Based on σ_{68} from the fit, the maximum significance is expected at: $\delta_0 = (0.7^{+0.2}_{-0.1})^\circ$

The number of shadowed events at δ_0:

Moon: 43±17

Sun: 21±18

Conclusions

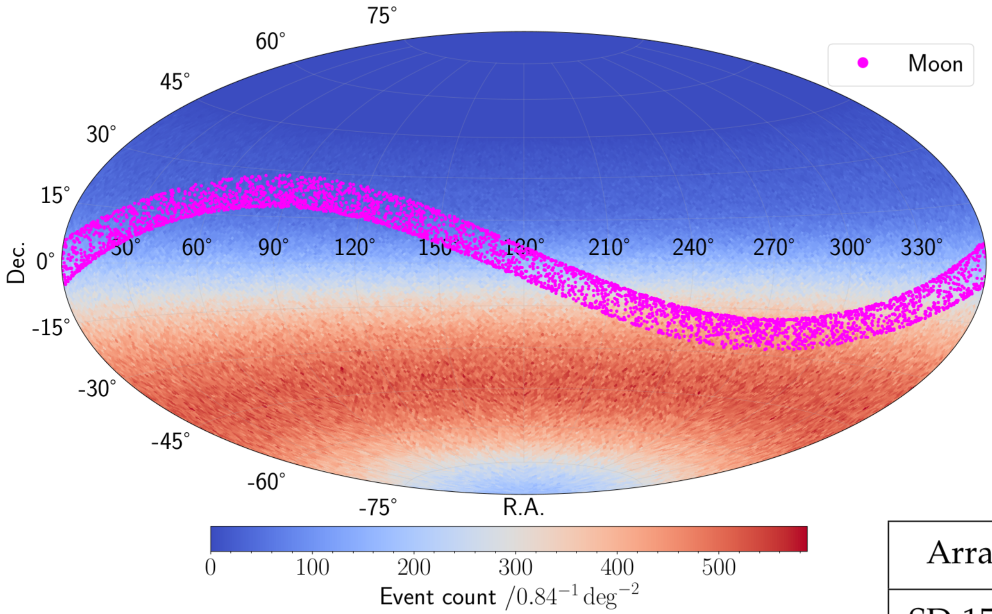
In 20 years of continuous operation, we recorded more than 10 million high-quality events above 10^{16} eV.

We observe the shadows of the Moon and the Sun with a significance of 3σ based on the likelihood and a maximum Li&Ma significance of 3.4σ.

The absolute pointing of the Observatory is confirmed and the measured effective angular resolution is $\sigma_{68} = (0.6^{+0.2}_{-0.1})^\circ$.

Backup

10.6 Million events during 20 years of continuous operation



Uniform exposure in right ascension

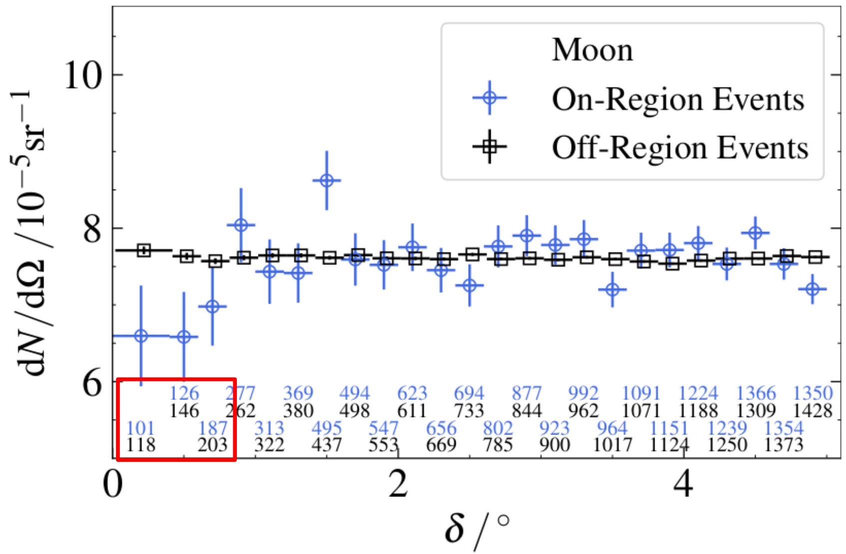
18 215 Events within 5° of the Moon

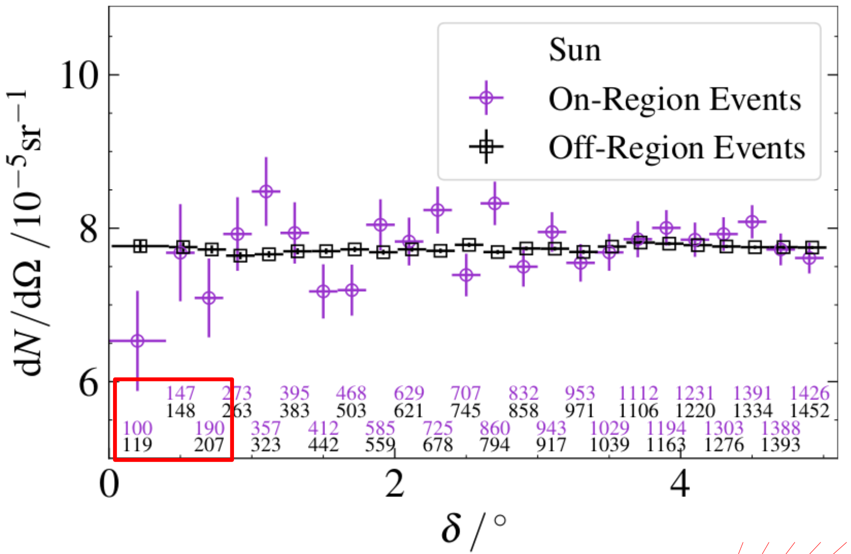
18 650 Events within 5° of the Sun

Angular resolution of ~1°

Array	Million Events	Fraction /%	Time Period
SD-1500	3.1	30	Jan 04 - Dec 22
SD-750	6.8	64	Jan 08 - Feb 23
SD-433	0.7	6	Jan 18 - Dec 21
Total	10.6		

Measured deficit due to the Moon and the Sun





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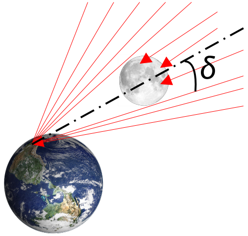


Isotropic background flat and consistent with on-region at large δ

From deficit to the effective angular resolution

Number of events in annulus at distance δ from the Moon center [CASA PhysRevD.49.1171 (1994)]

$$\frac{\mathrm{d}N}{\mathrm{d}\cos\delta} = 1 - \int_0^{\delta_c} r\,\mathrm{d}r \int_0^{2\pi} \mathrm{d}\phi\, \mathcal{G}(\sigma_{68}, \delta, r, \phi)$$

→ 2-D symmetric Gaussian point spread function

→ σ_{68} the resolution (scaled by 1.51)

Isotropic background flat in dcos(δ) (or dΩ)

Events shadowed by a disc with angular radius δ_c (integrating in polar coordinates r, ϕ)

The effective angular resolution σ_{68} is a combination of different resolutions

Unbinned maximum likelihood fit of the combined shadows: $\sigma_{68} = (0.6^{+0.2}_{-0.1})^\circ$

Significance using Gaussian approximation: 3σ $\left(N_\sigma = \sqrt{2\left[\log\mathcal{L}(\sigma_{68,\mathrm{best}}) - \log\mathcal{L}(\sigma_{68} = 15^\circ)\right]}\right)$

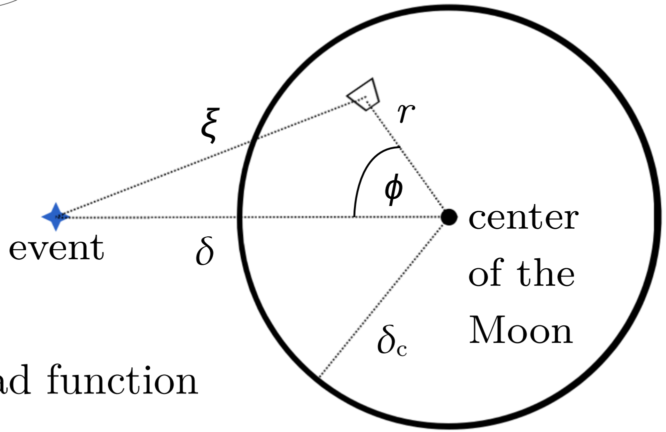
From deficit to the effective angular resolution

Number of events in annulus at distance δ from the Moon center:

$$\frac{\mathrm{d}N}{\mathrm{d}\cos\delta} = 1 - \int_0^{\delta_c} r\,\mathrm{d}r \int_0^{2\pi} \mathrm{d}\phi\, \frac{1}{2\pi\sigma_r^2} \exp\left[-\frac{\xi(\cos\delta; r, \phi)^2}{2\sigma_r^2}\right]$$

Isotropic background flat in $\mathrm{d}\cos(\delta)$ (or $\mathrm{d}\Omega$)

Events shadowed by the disc of the Moon/Sun

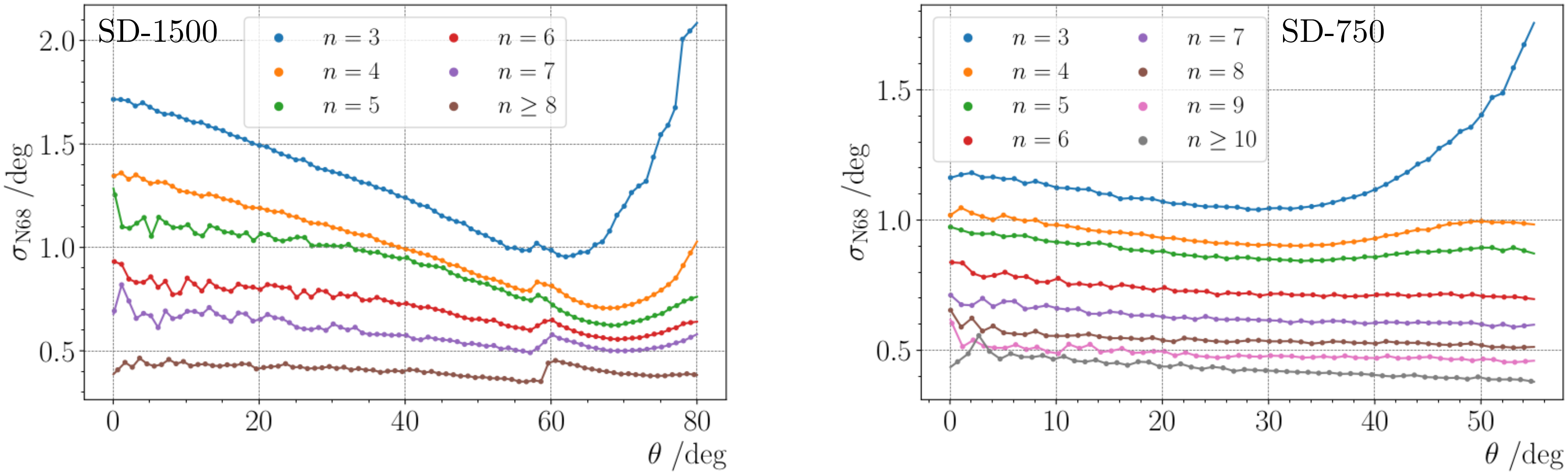


σ_r is the resolution of a symmetric 2-D Gaussian point spread function

Resolution containing 68% events: $\sigma_{68} = \sqrt{2.278}\,\sigma_r$

CASA PhysRevD.49.1171 (1994)

Angular resolution based on the event reconstruction



Medians of the angular resolution of individual events binned in multiplicity n and zenith angle θ (the resolution is scaled to 68% probability of a 2-D Gaussian)

D. de Oliveira Franco for the Pierre Auger Collaboration, PoS ICRC2023, 246 (2023)