Testing the Pointing of IceCube Using the Moon Shadow in Cosmic-Ray-Induced Muons

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1. Introduction

Cosmic rays are blocked by the moon, so IceCube measures a deficit in cosmic-ray-induced muons with high statistics. Therefore, this moon shadow is used as a standard candle in muons, which enables several applications for the moon shadow analysis:

- Test of different analysis techniques without the need of Monte-Carlo simulations
- Testing of different directional reconstruction algorithms

Improved analysis methods[1] are used, compared to the previously performed moon shadow analysis from 2014[2], including better uncertainty estimation, background and source descriptions.

2. Analysis

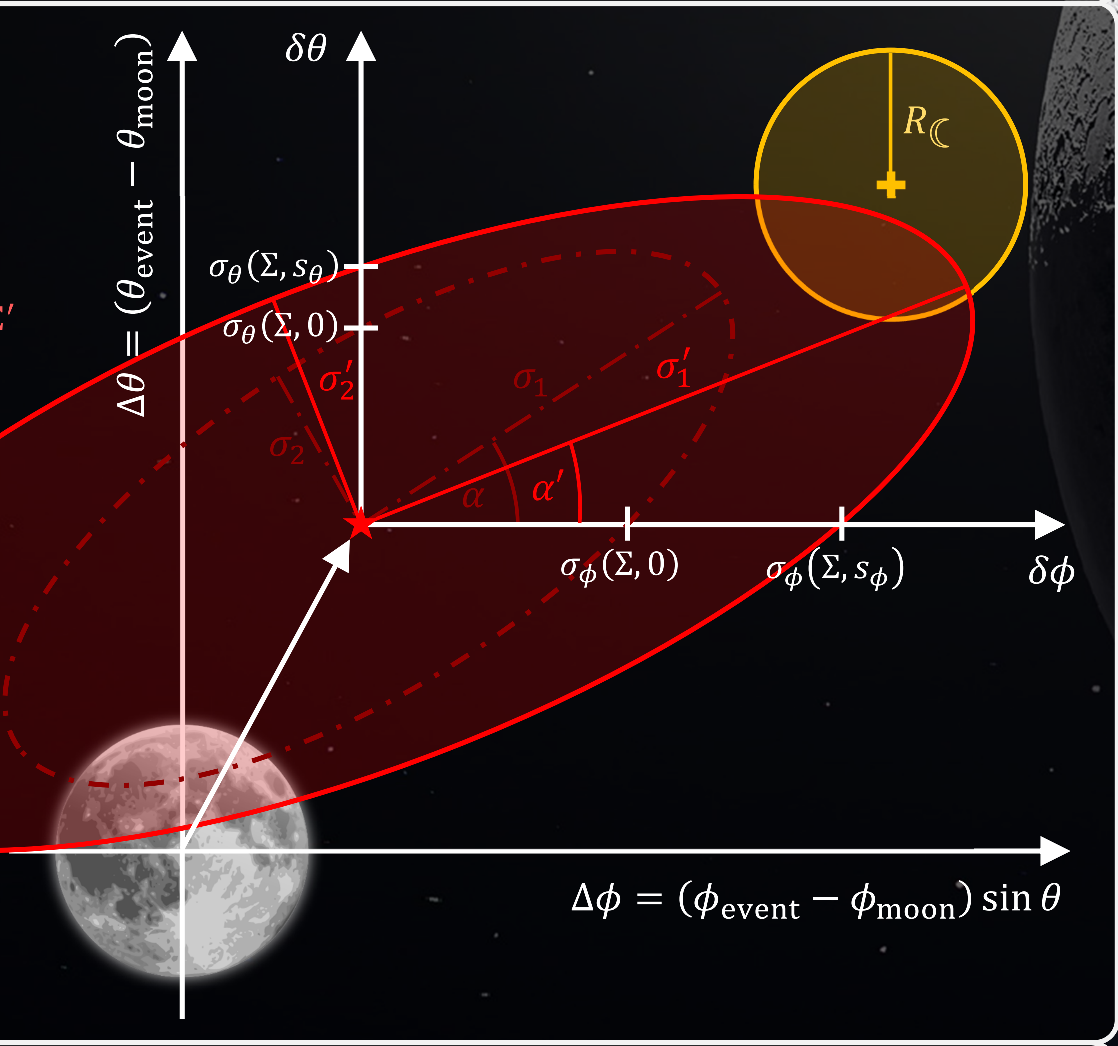
The source hypothesis $\tilde{S}$ is tested on a $\pm 3°$ grid moving with the moon by comparing events in $\pm 10°$ to the background hypothesis $\tilde{B}$, using a maximum-likelihood method, with the likelihood function

$$\log L(n_s, \Delta\phi, \Delta\theta | \vec{x}_{1..N}, \Sigma'_{1..N}) = \sum_{i=1}^{N} \frac{n_s}{N} \tilde{S}(\Delta\phi, \Delta\theta | \vec{x}_i, \Sigma'_i) + \left(1 - \frac{n_s}{N}\right) \tilde{B}(\vec{x}_i, \Sigma'_i).$$

Therefore, the number of source events n_s is fit with regards to the total number of events N for each grid point, where $\vec{x}_i = (\delta\phi_i, \delta\theta_i)^T$ is the positional vector from the reconstructed direction to the grid point.

Coordinate System

- Grid point with source hypothesis
- Reconstructed event direction with scaled uncertainty estimation Σ'
- Unscaled uncertainty estimation Σ



Background Term

The off-source region, defined by different azimuth values in the same zenith band as the source region, is used to determine the true background distribution B in zenith dependency. For this purpose, the sum of the scaled Gaussian uncertainty distributions of all events, evaluated on grid points relative to the center position of the off-source region, is taken.

The probability to be a background event for events in the source region is calculated as the expected value of the background distribution under the event's Gaussian distribution:

$$\tilde{B}(\vec{x}_i, \Sigma') = E[B(x)]_{f_{2D}(x|\vec{x}_i, \Sigma'_i)}$$

Event Uncertainty Estimation

The uncertainties of the directional reconstructions of the muons are often approximated by two-dimensional asymmetric Gaussian distributions in the likelihood landscape, described by the covariance matrix Σ defined by semi-major and -minor axes σ_1, σ_2 and the rotational angle α. The uncertainties are typically underestimated; therefore, a scaling is done in azimuth and zenith directions:

$$\Sigma' = S\Sigma S = SR\Lambda R^T S \quad \text{with} \quad \Lambda = \begin{pmatrix} \sigma_1^2 & 0 \\ 0 & \sigma_2^2 \end{pmatrix}, \; R = \begin{pmatrix} \cos(\alpha) & -\sin(\alpha) \\ \sin(\alpha) & \cos(\alpha) \end{pmatrix}, \; S = \begin{pmatrix} s_\phi & 0 \\ 0 & s_\theta \end{pmatrix}$$

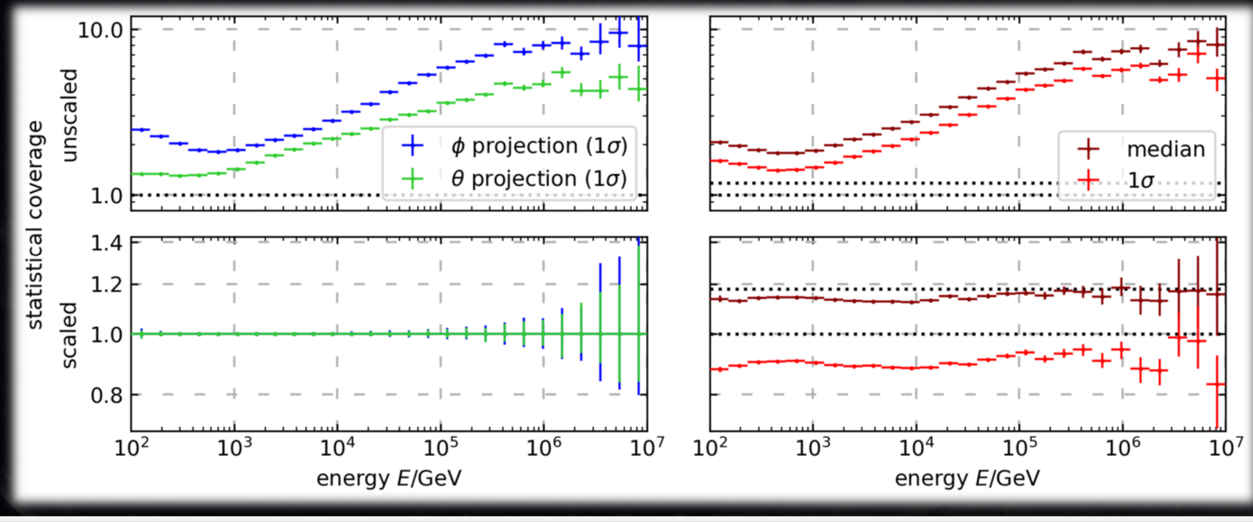
$$f_{2D}(\vec{x}, \Sigma') = \frac{1}{2\pi s_\theta s_\phi \sigma_1 \sigma_2} e^{-\frac{a\delta\phi^2 + b\delta\theta^2 + c\delta\phi\delta\theta}{2(s_\phi s_\theta \sigma_1 \sigma_2)^2}} \quad \text{with} \quad \begin{aligned} a &= s_\theta^2(\sigma_1^2 \sin(\alpha)^2 + \sigma_2^2 \cos(\alpha)^2) \\ b &= s_\phi^2(\sigma_1^2 \cos(\alpha)^2 + \sigma_2^2 \sin(\alpha)^2) \\ c &= s_\phi s_\theta \sin(2\alpha)(\sigma_2^2 - \sigma_1^2) \end{aligned}$$

The scaling factors are determined using the standard deviations of the marginalized Gaussians $\sigma_\phi(\Sigma, s_\phi) = \sqrt{b}$ and $\sigma_\theta(\Sigma, s_\theta) = \sqrt{a}$, such that they have the correct statistical coverage. As a check, the 2D standard deviations are tested for correct coverage.

The resulting equation of the scaled uncertainty ellipsis, using $\Sigma' = \mathcal{R}\Lambda' \mathcal{R}^T$, is:

$$\sigma_{2D}(\Delta\phi, \Delta\theta) = \frac{(\Delta\phi \cos(\alpha') + \Delta\theta \sin(\alpha'))^2}{\sigma_1'^2} + \frac{(-\Delta\phi \sin(\alpha') + \Delta\theta \cos(\alpha'))^2}{\sigma_2'^2}$$

$$\text{with} \quad \sigma'_{1/2} = \frac{a + b \pm d}{2} \qquad \alpha' = \begin{cases} \beta + \frac{\pi}{2} & \alpha < \pi \\ \beta + \frac{3\pi}{2} & \alpha > \pi \end{cases} \quad \text{with} \quad \begin{aligned} d &= \sqrt{(a+b)^2 - 4(\sigma_1\sigma_2 s_\phi s_\theta)^2} \\ \beta &= -\frac{1}{\sqrt{1 + \frac{(a-b-d)^2}{c^2}}} \end{aligned}$$



Source Term

For a point-like source, the Gaussian distribution of the event is evaluated on a grid point → integration with delta distribution. With the same ansatz, an extended disc-like source is integrated with a Heaviside step function over a disc around the grid point with radius $R_☾$, scaled with $\sin(\theta)$ in azimuth direction to correct the circle in the used Cartesian coordinate system:

$$\tilde{S}(\vec{x}, \Sigma') = \frac{1}{\pi \frac{R_☾^2}{\sin(\theta)}} \int_{-\infty}^{\infty} d\widehat{\delta\phi} \int_{-\infty}^{\infty} d\widehat{\delta\theta} \; \Theta\left(\begin{pmatrix} |\delta\phi - \widehat{\delta\phi}| \\ |\delta\theta - \widehat{\delta\theta}| \end{pmatrix} \leq \begin{pmatrix} R_☾ \sin(\theta)^{-1} \\ \left(R_☾^2 - (\delta\phi - \widehat{\delta\phi})^2 \sin(\theta)^2\right)^{\frac{1}{2}} \end{pmatrix} \right) f_{2D}(\hat{\vec{x}}, \Sigma')$$

Using these improved methods compared to the previous, the significance improves from 12.2σ to 13.5σ.

Evaluation

Source significance: ΔLLH to $n_s = 0$ with 1 d.o.f., significance with which a source can be identified

Pointing significance: ΔLLH to $\min(\{n_s\})$ with 2 d.o.f. (position of the minimum), provides the precision of the positional reconstruction, given by the size of the significance contours

3. Test of Directional Reconstruction Algorithms

Reconstructions are compared by using the maximum of the source significance (5 separate months of data and combined data set) and the contours of the pointing significance (only on combined data set). For a direct comparison, the exact same data must be used. The analysis requires a cut on the uncertainties, which causes a difference in the number of events depending on whether uncertainties are asymmetric or symmetric. → compare only reconstructions with the same uncertainty type

Two new directional reconstruction methods are compared to the current default **SplineReco**[3]:

CRNN-Reco[4] ↔ SplineReco
(only symmetric uncertainties with 1-dimensional scaling)

Machine-learning-based reconstruction (convolutional & recurrent neural network)

The pointing is less precise for CRNN-Reco, and source significances are smaller for all single months and the combined data set.

→ CRNN-Reco performs worse than SplineReco on cosmic-ray-induced muons (muon bundles)

but: CRNN-Reco intended to reconstruct single muons
→ likely to perform better if trained on muon bundles

Most importantly: machine-learning-based reconstruction trained on Monte Carlo data performs well on real data

SegmentedSpline[5] ↔ SplineReco
(asymmetric uncertainties)

Advancement over SplineReco by using a better energy-loss estimation

Both pointing contours are nearly the same, and there are only small differences in the source significances.

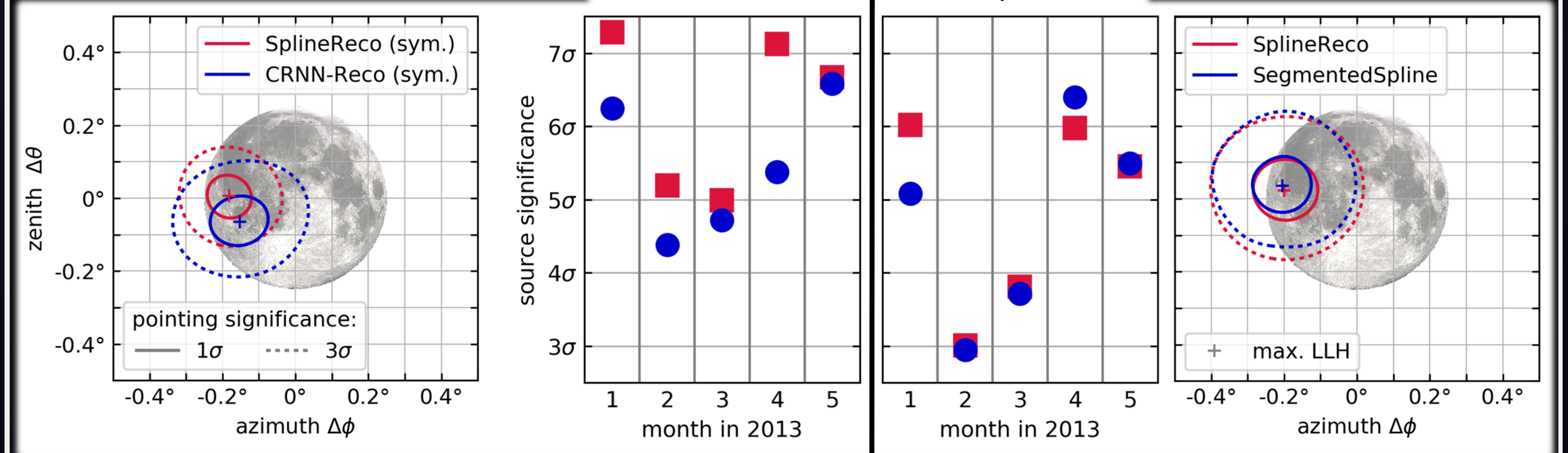
→ similar performance for SegmentedSpline and SplineReco

but: SegmentedSpline is an improvement for $\gtrsim 50$ TeV muons, while the energy of the data sample is only $1 - 10$ TeV

→ no large improvements expected

combined data set: 14.3σ / 12.7σ

combined data set: 10.0σ / 10.2σ



All reconstructions are compatible within 1σ in their pointing and show a systematic shift to the true moon position, which might be attributed to the geomagnetic field or systematic effects.

4. Outlook

- Moon analysis will be implemented as a monthly test of the detector
- Will be used to test a new detector calibration, based on real data
- Tool to test new analysis methods and direction reconstruction algorithms
- Allows new studies like investigations of the geomagnetic field

References:
[1] S. Philippen, "Observations of the Moon Shadow in Cosmic-Ray-Induced Muons with the IceCube Neutrino Observatory", Master Thesis, RWTH, 2019
[2] IceCube Collaboration, M. G. Aartsen et al., Phys. Rev. D89(2014) 102004.
[3] K. Schatto, "Stacked searches for high-energy neutrinos from blazars with IceCube", PhD thesis, Johannes Gutenberg-Universität Mainz, 2014.
[4] G. Wrede, "Recurrent Neural Networks for Reconstructing Muons.", to be published
[5] IceCube Collaboration, F. Bradascio and T. Glüsenkamp, PoSICRC2019(2019) 846.

Foto:Reddit /u/ajamesmccarthy