Asymmetries in the lateral distributions of signals measured by surface-detector arrays

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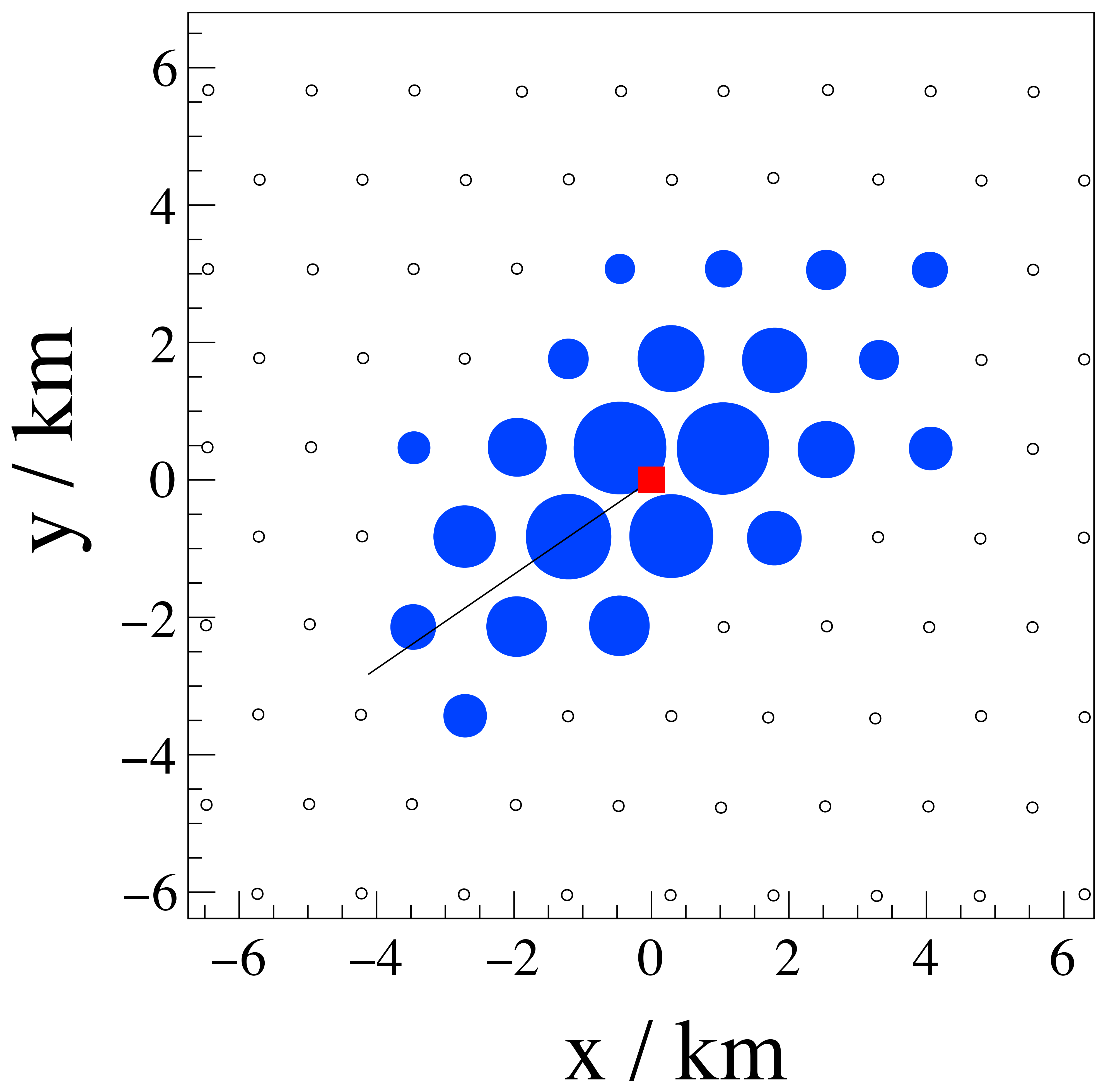
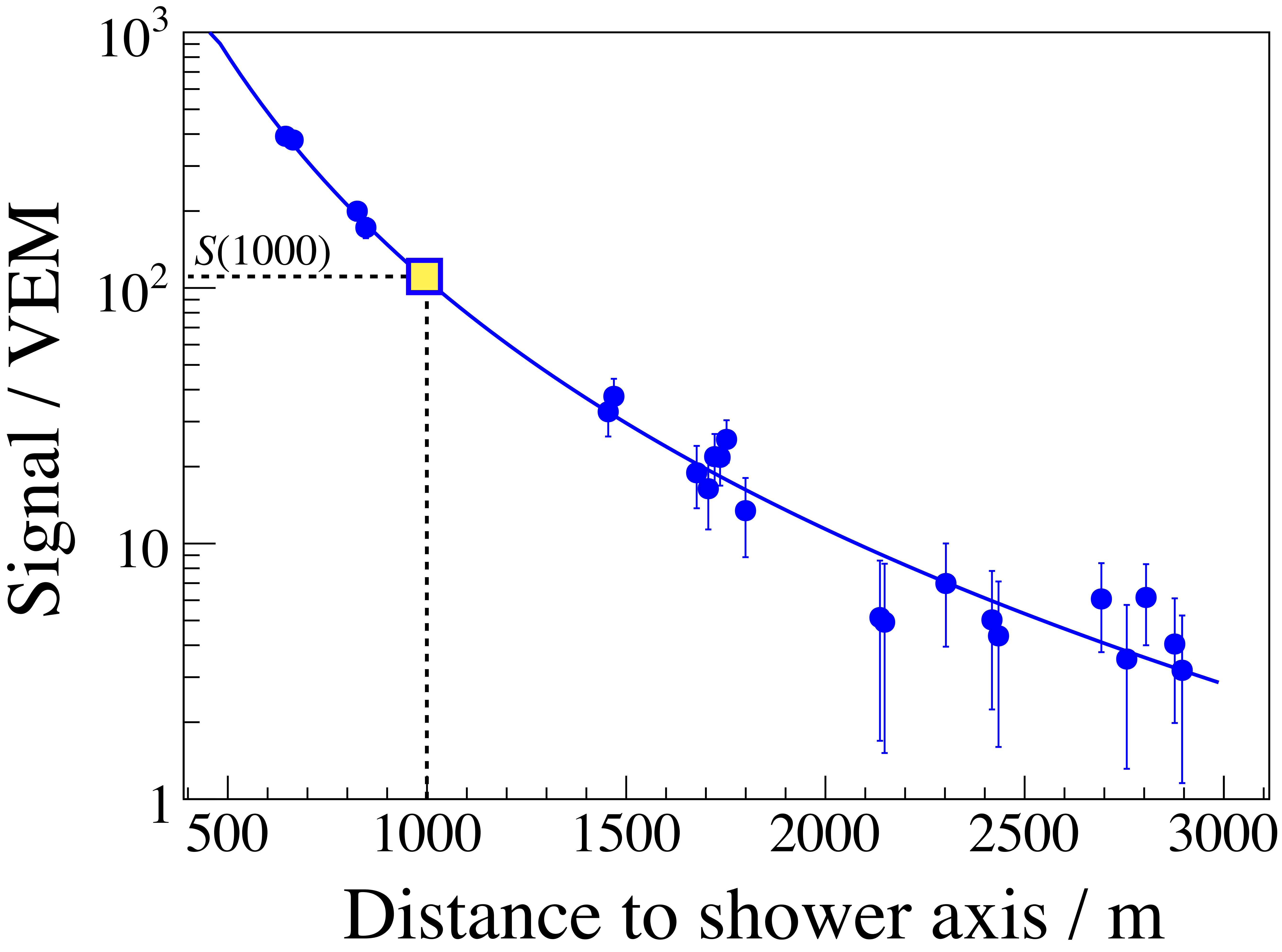
Sampling the lateral distributions of extensive air showers



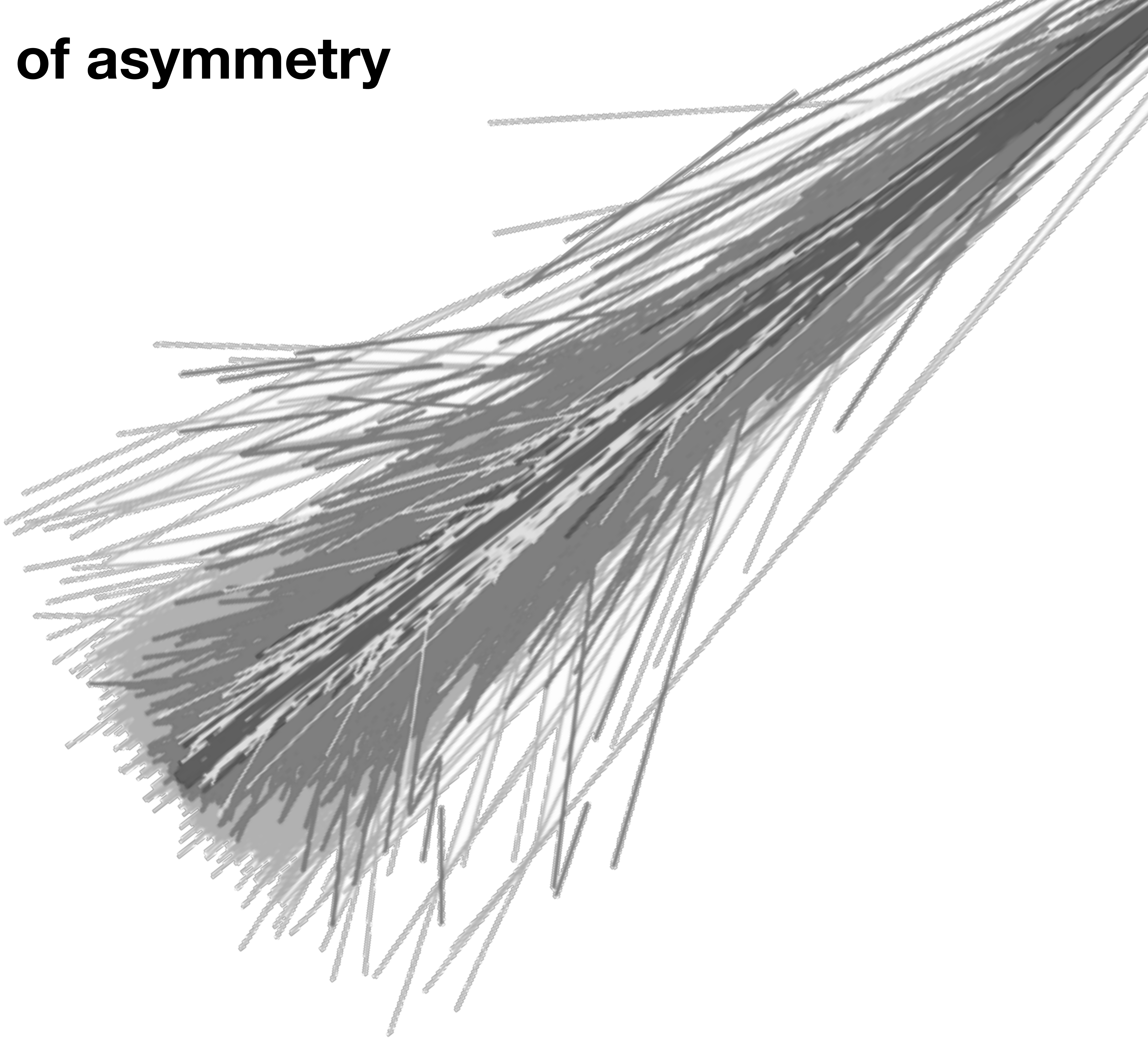


Aim: Energy and arrival direction (+mass)

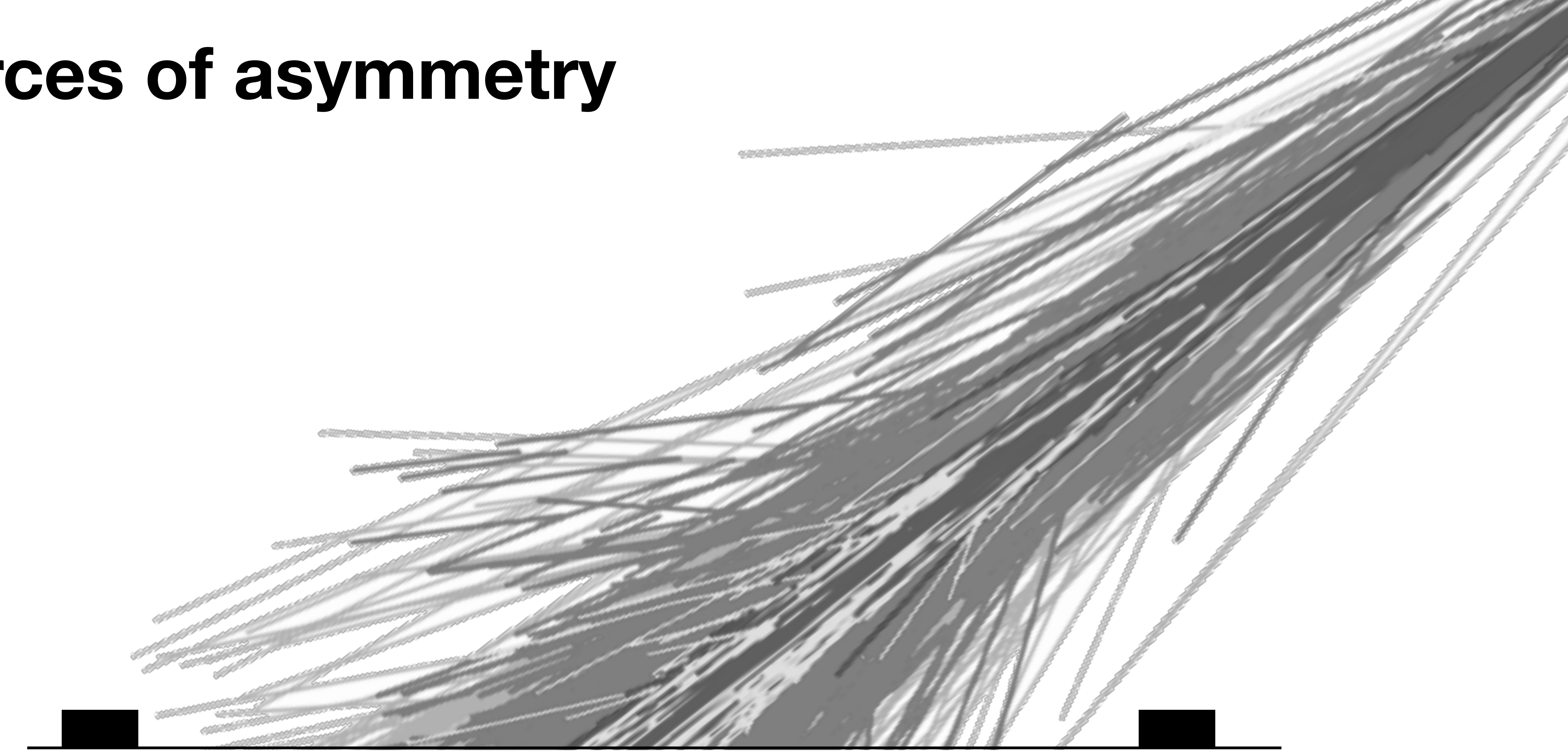
Need: Shower axis, shower size, and core (at least as a stepping stone)

Plots adapted from: Auger Collaboration, 2020 JINST 15 P10021, *Reconstruction of events recorded with the surface detector of the Pierre Auger Observatory*

Sources of asymmetry



Sources of asymmetry



Sources of asymmetry*

- Different degrees of atmospheric attenuation

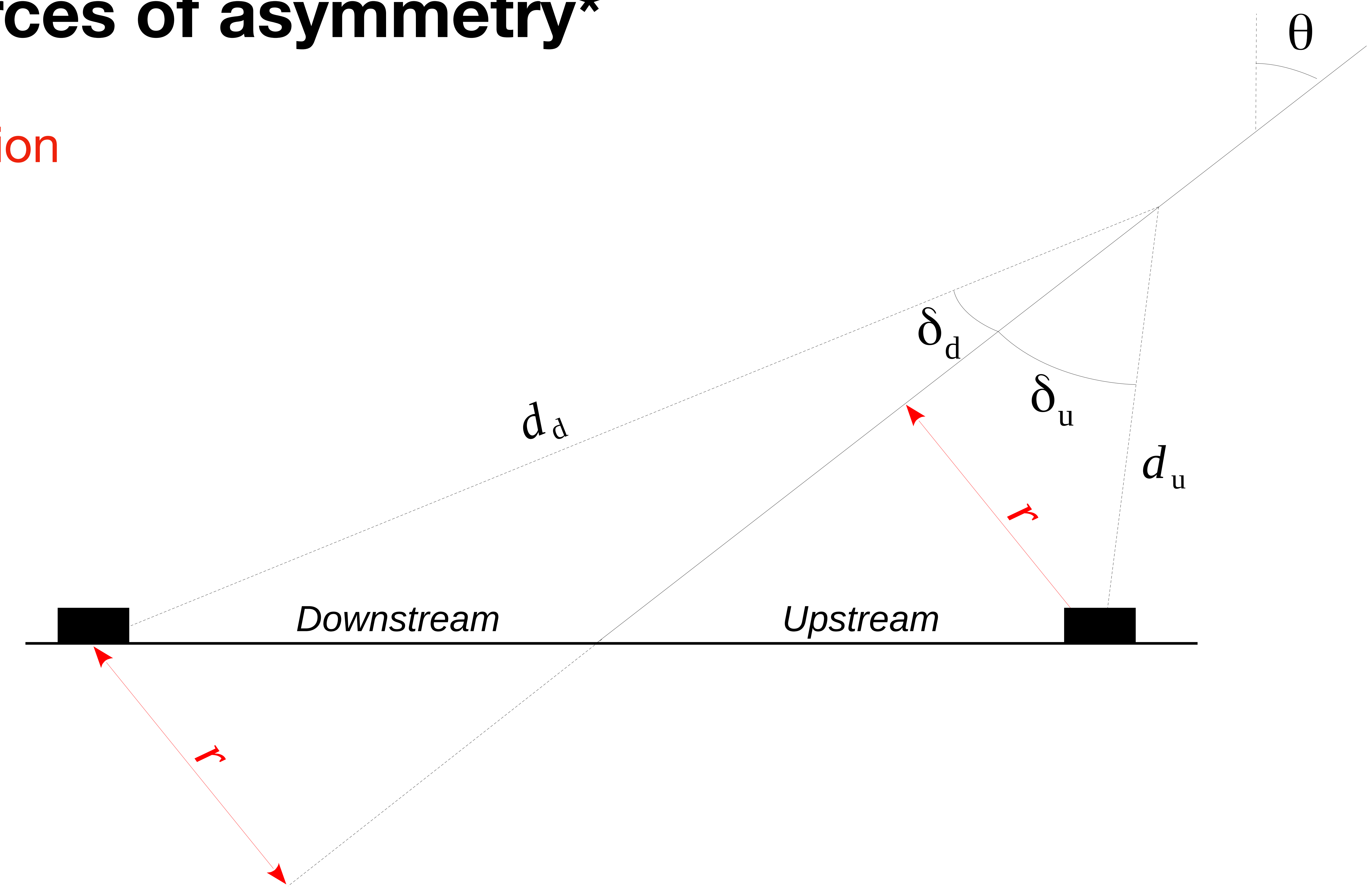
$$f_{\mathrm{att}}(d) = \exp\left(\frac{d}{\lambda}\right)$$

- Different solid angle of detectors (from perspective of apex)

$$\Omega = A/d^2$$

- Angular distribution of produced particles

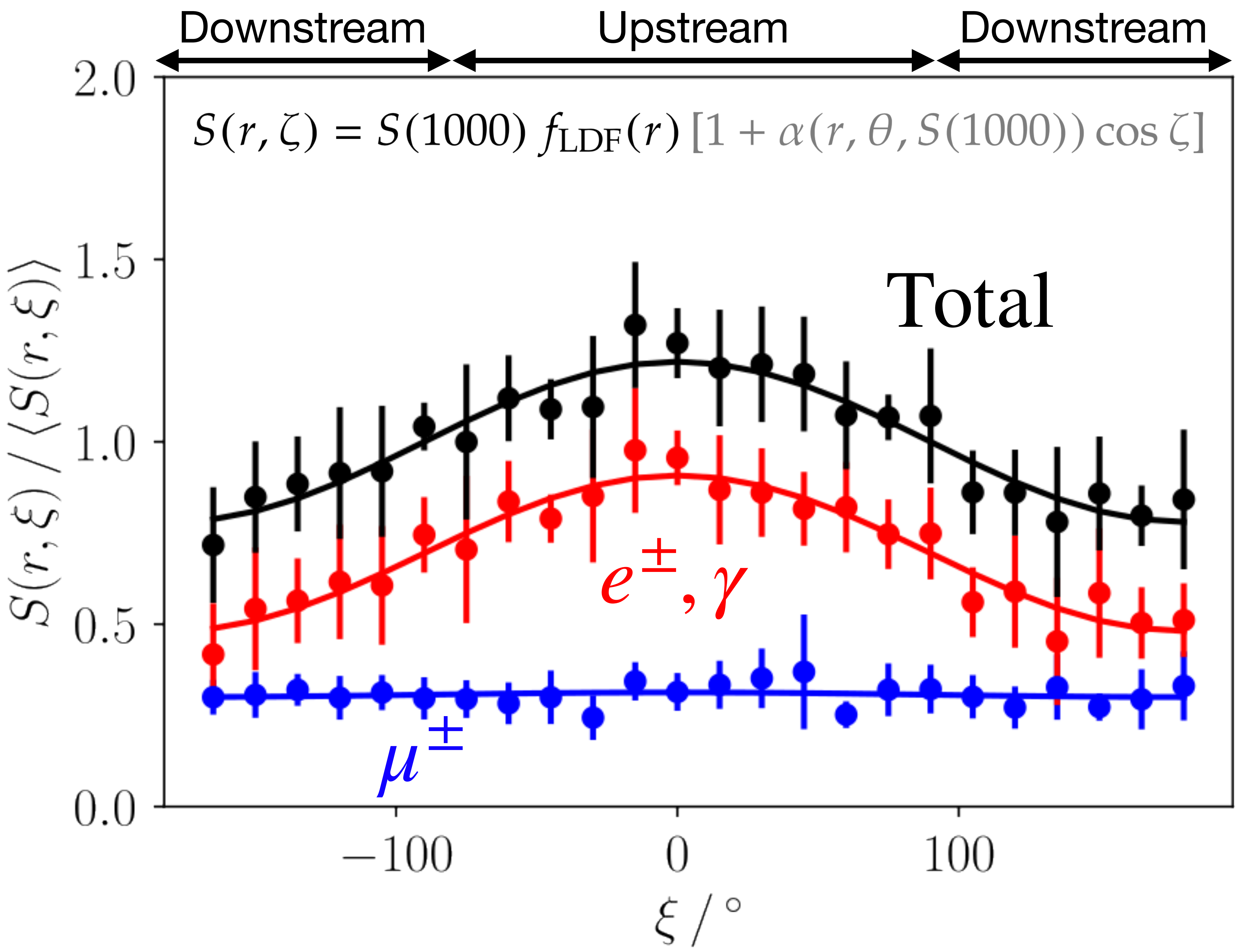
$$\mathrm{ADF}(\delta) = \left(\frac{\delta}{\delta_0}\right)^{-\gamma}$$



$$\alpha \propto 2 + \frac{d(\theta)}{\lambda} - \gamma$$

*Lukas Armbruster, Bachelor thesis, *Asymmetries of the Lateral Distribution of Particles at the Ground*

Asymmetry

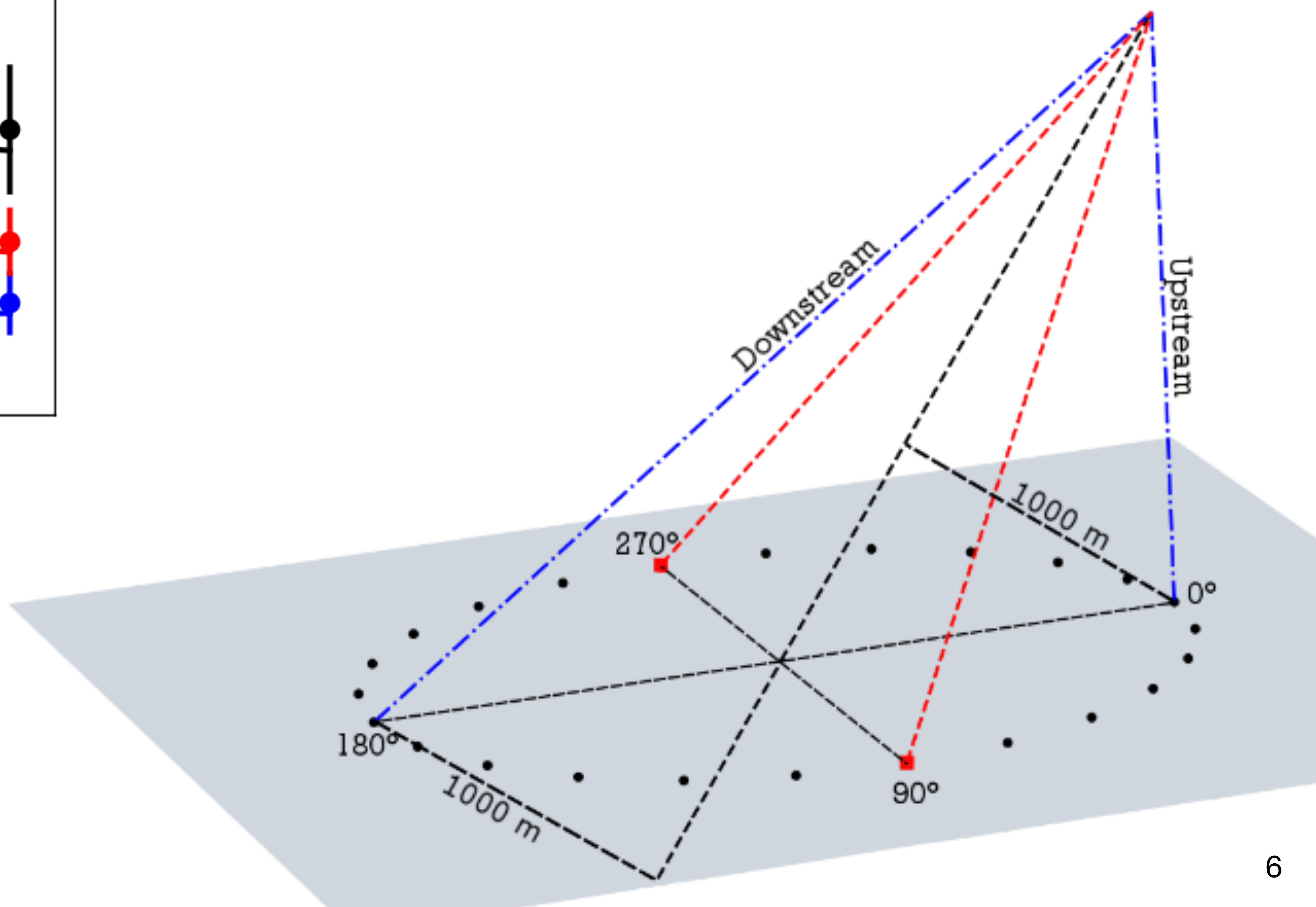


$$\alpha \propto 2 + \frac{d(\theta)}{\lambda} - \gamma$$

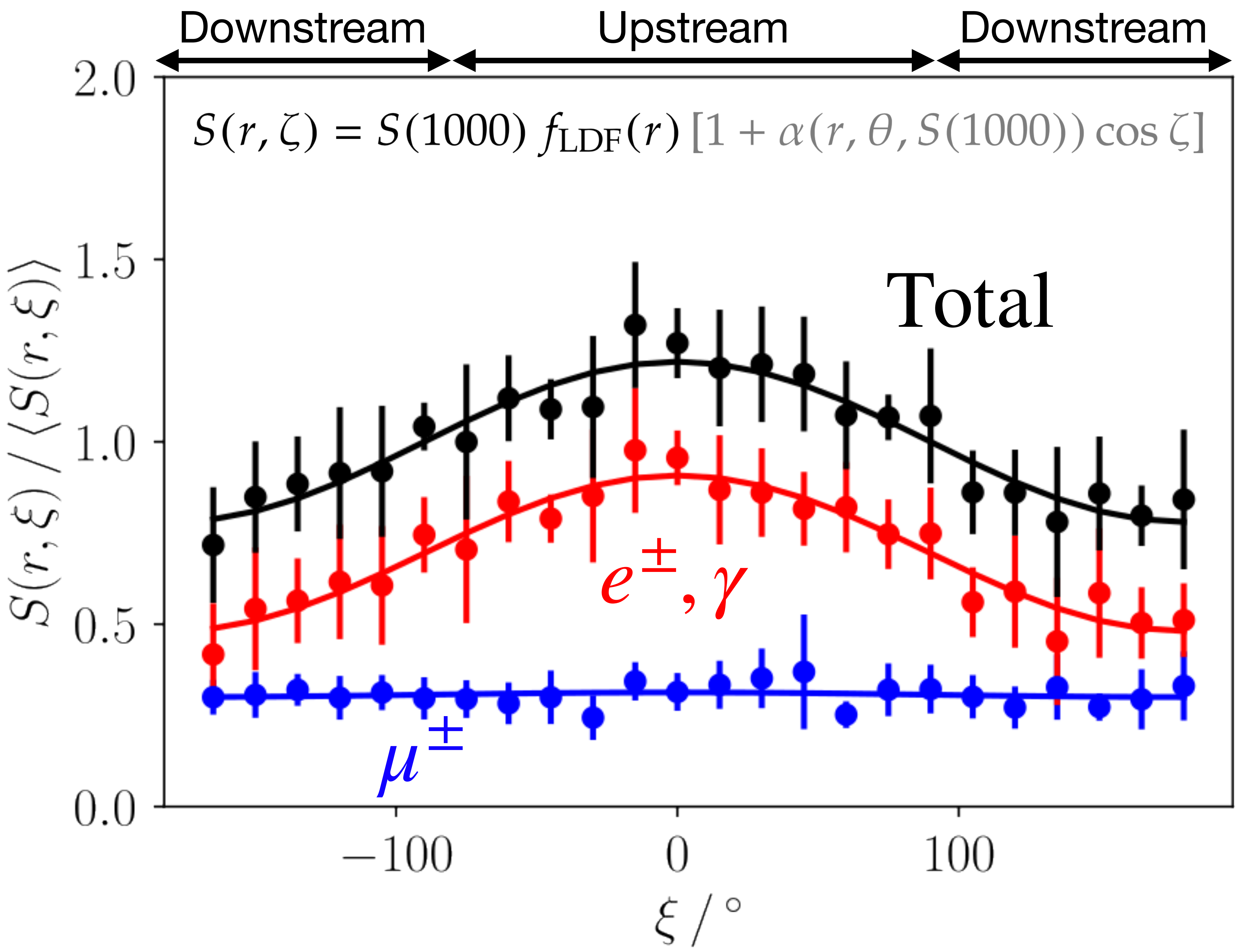
Solid angle

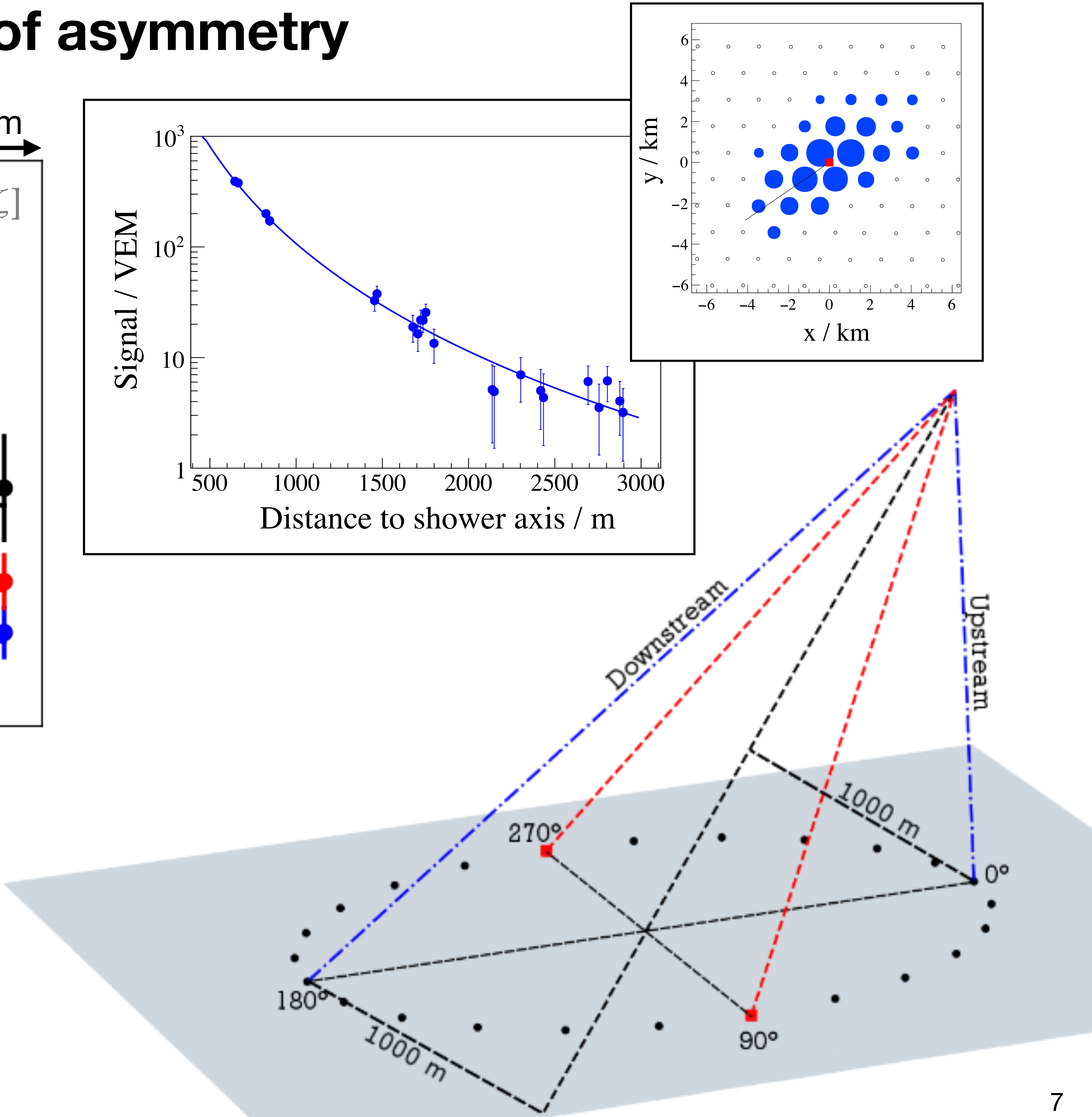
Attenuation

ADF



Impact of asymmetry

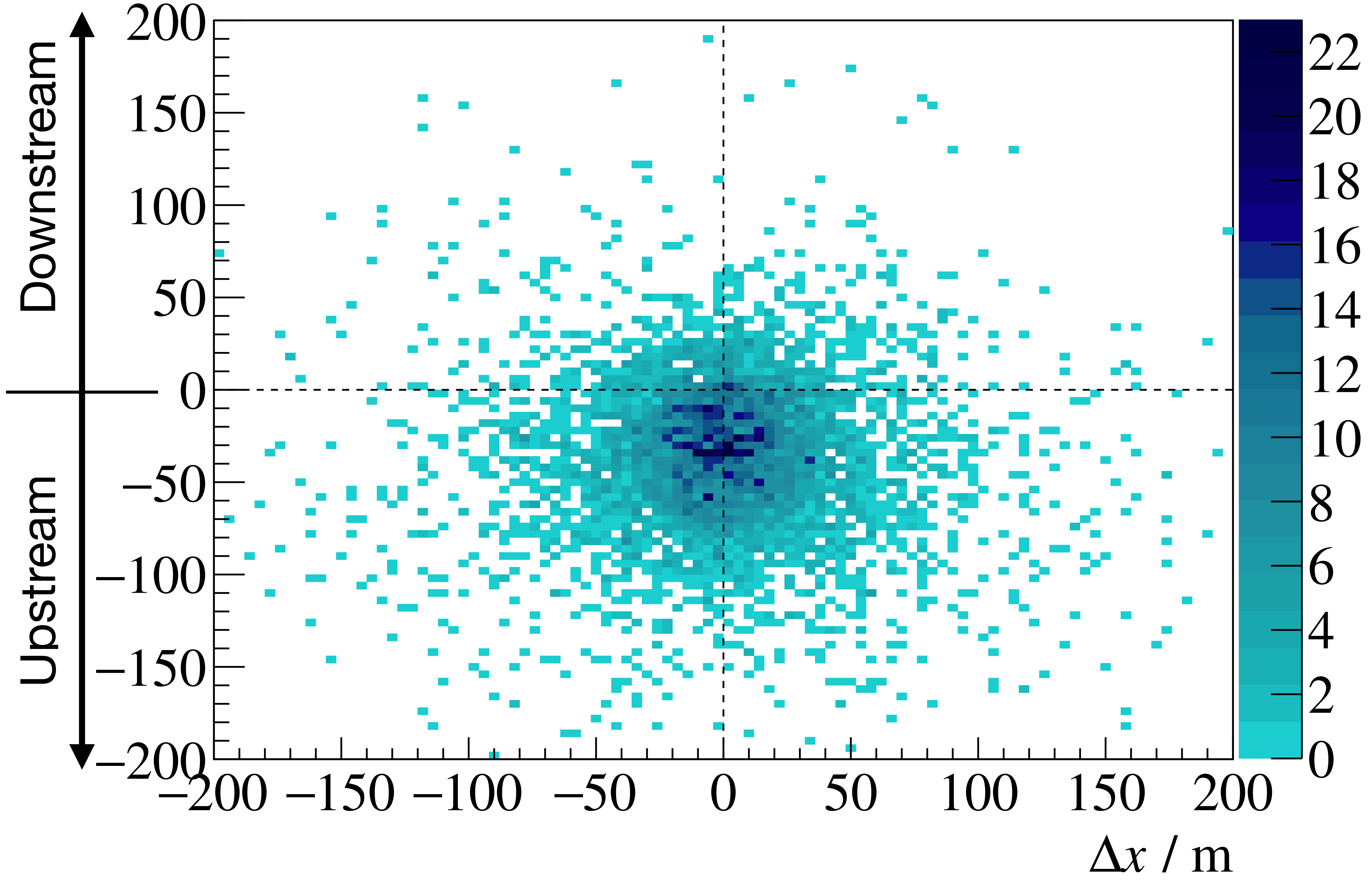


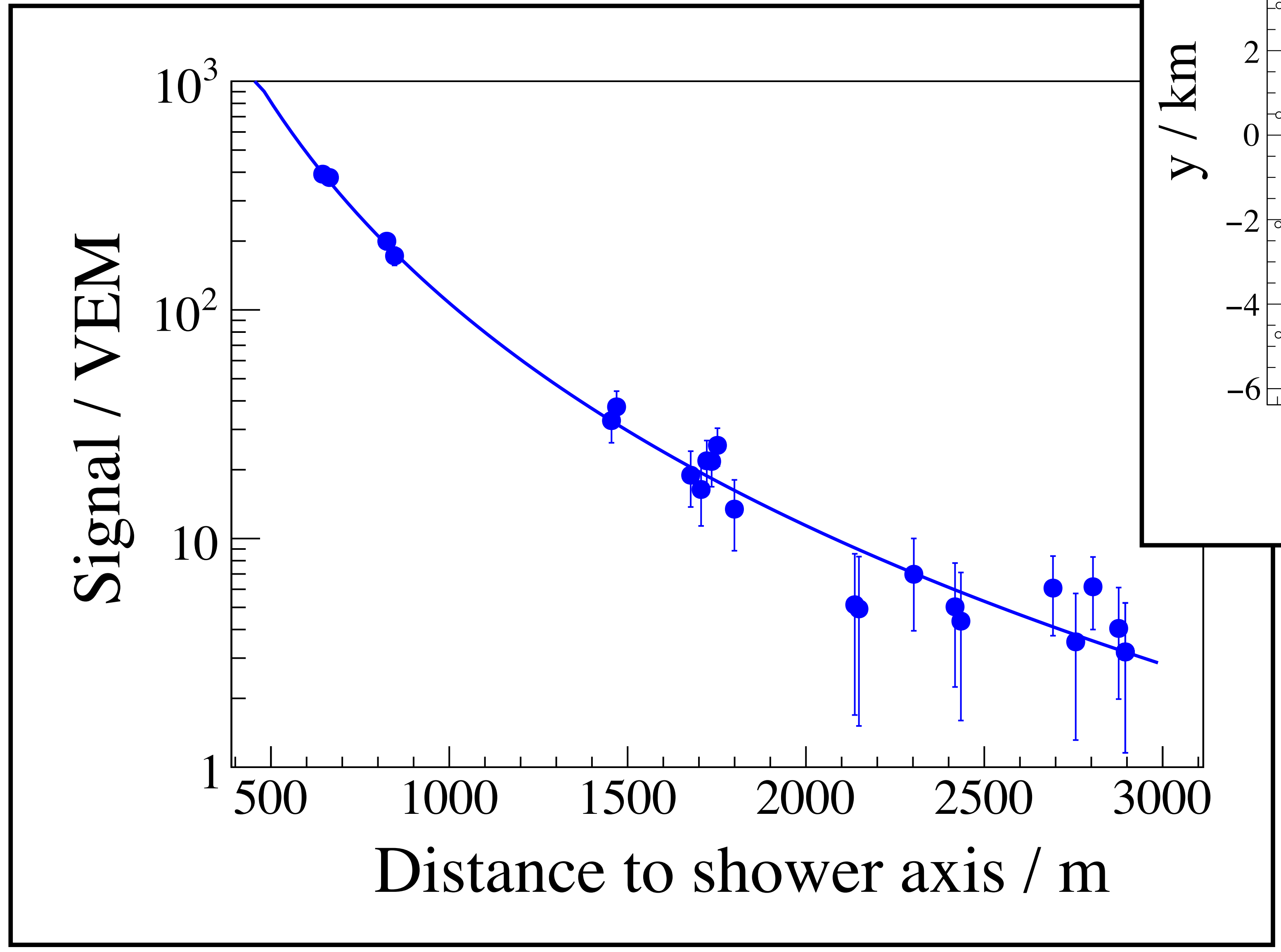


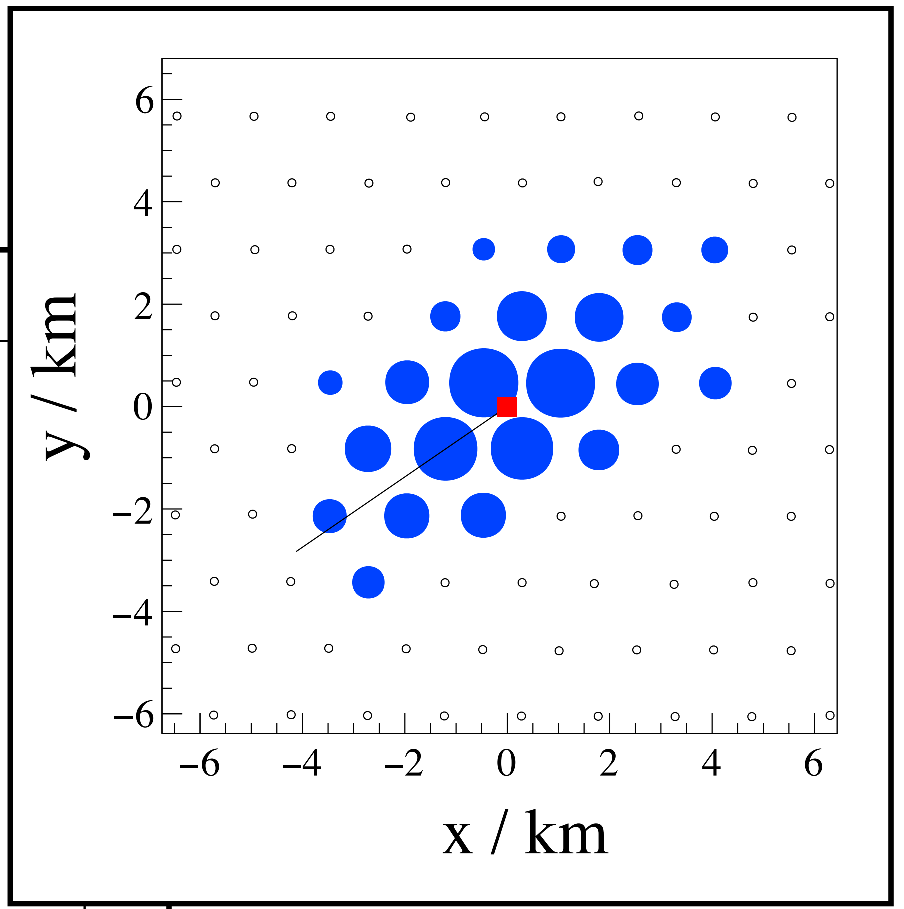
$$\alpha \propto \underbrace{2}_{\text{Solid angle}} + \underbrace{\frac{d(\theta)}{\lambda}}_{\text{Attenuation}} - \underbrace{\gamma}_{\text{ADF}}$$

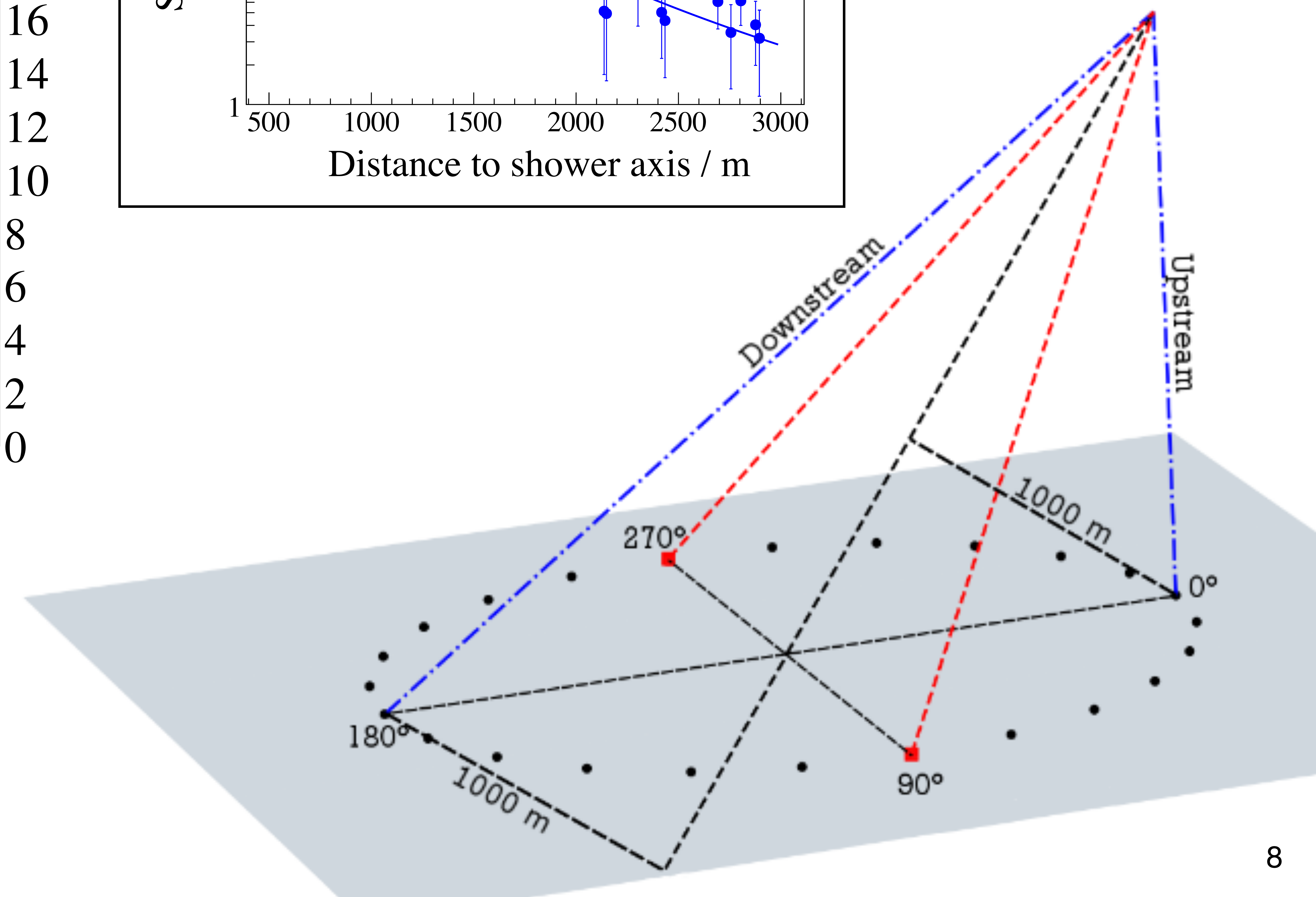
Impact of asymmetry

For 1500 m isometric triangular grid of water-Cherenkov detectors (Auger-like)

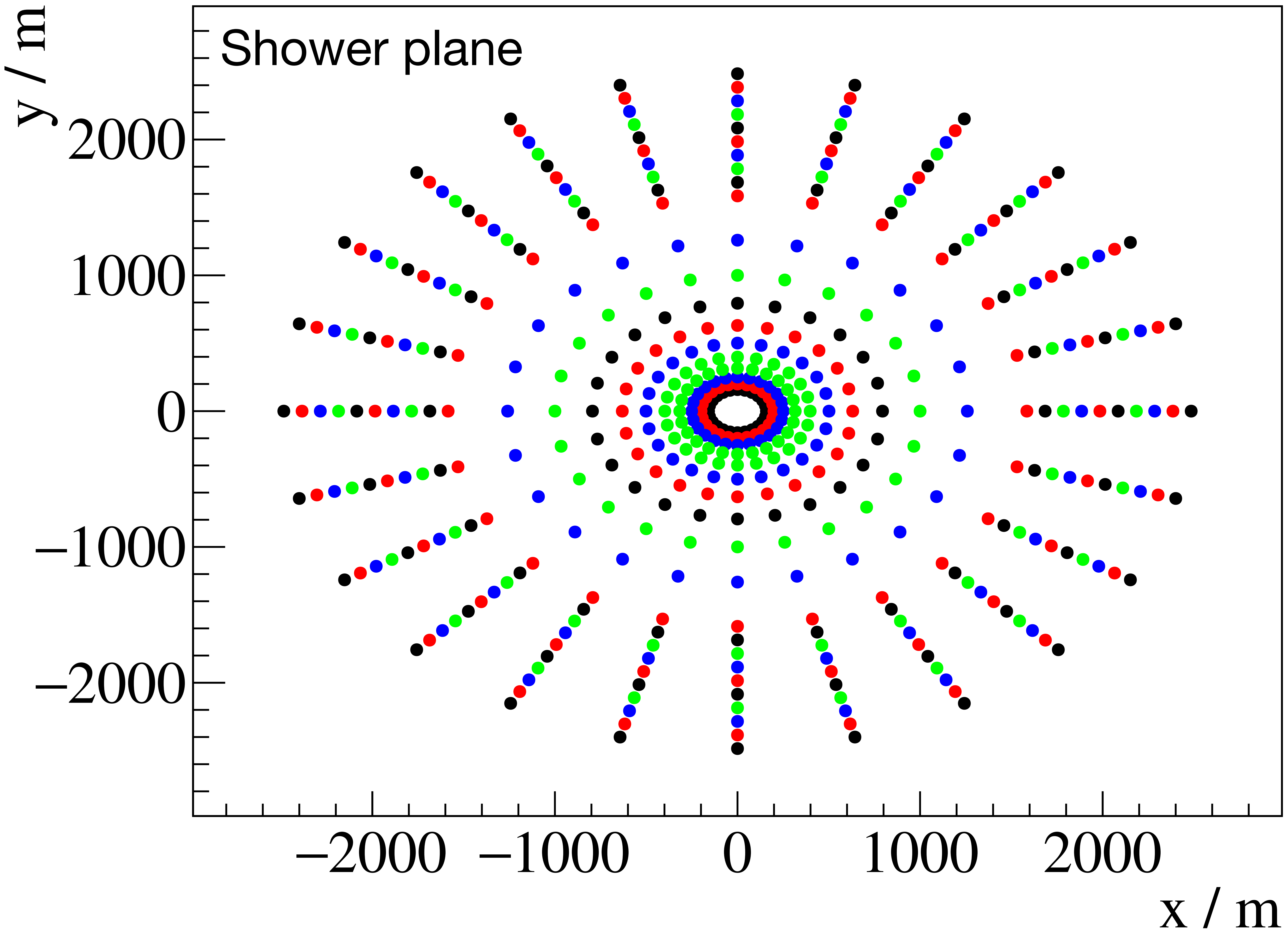








Simulations



Primaries: p, Fe

Hadronic interaction models: EPOS-LHC, QGSJet II-04

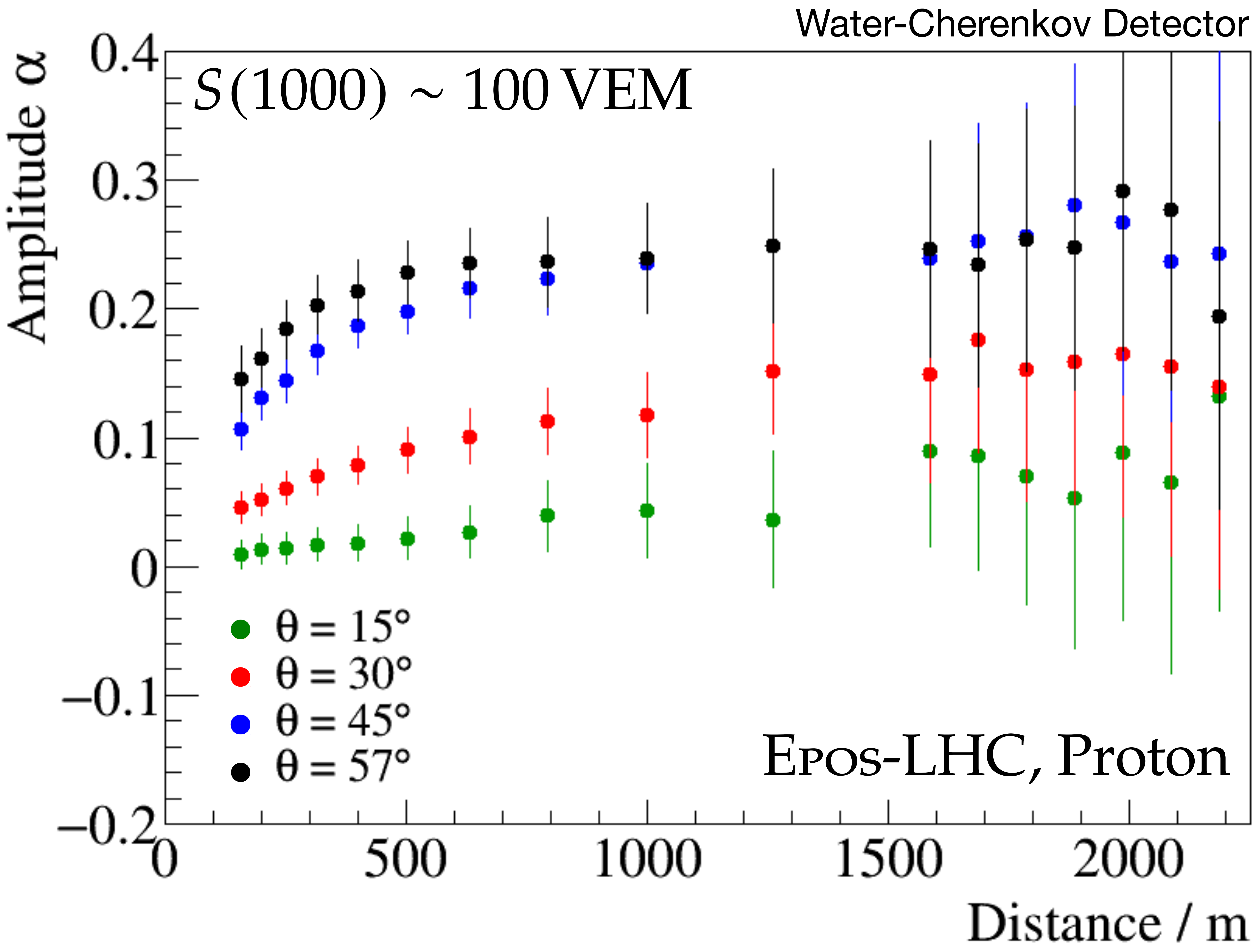
lg(E/eV): [18.5, 20.0]

θ/°: [0, 60]

Detectors: Water Cherenkov Detector
1.2 m depth, 1.8 m radius

Scintillator
1 cm thickness, 4 m^2 area

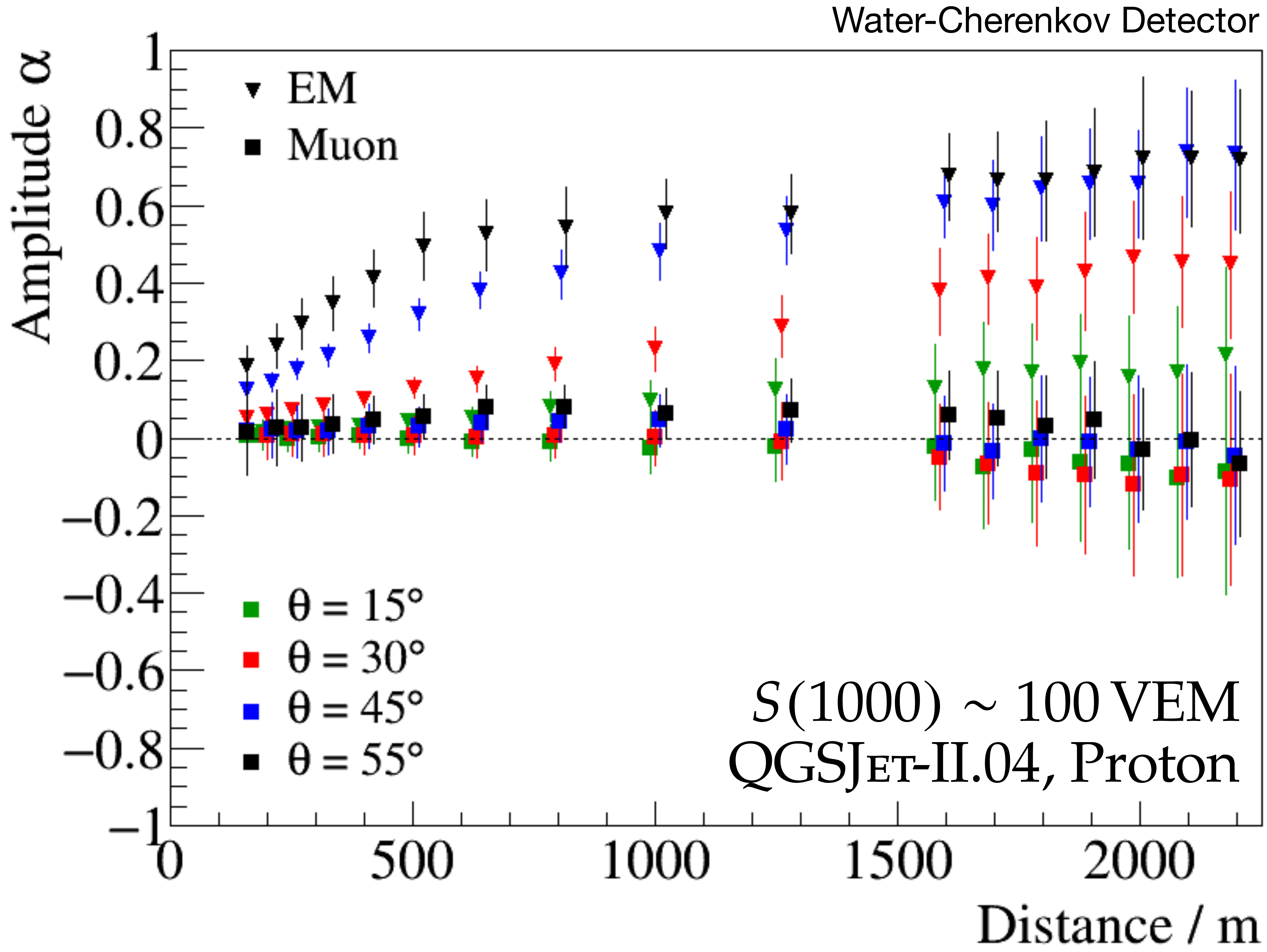
Amplitude of asymmetry



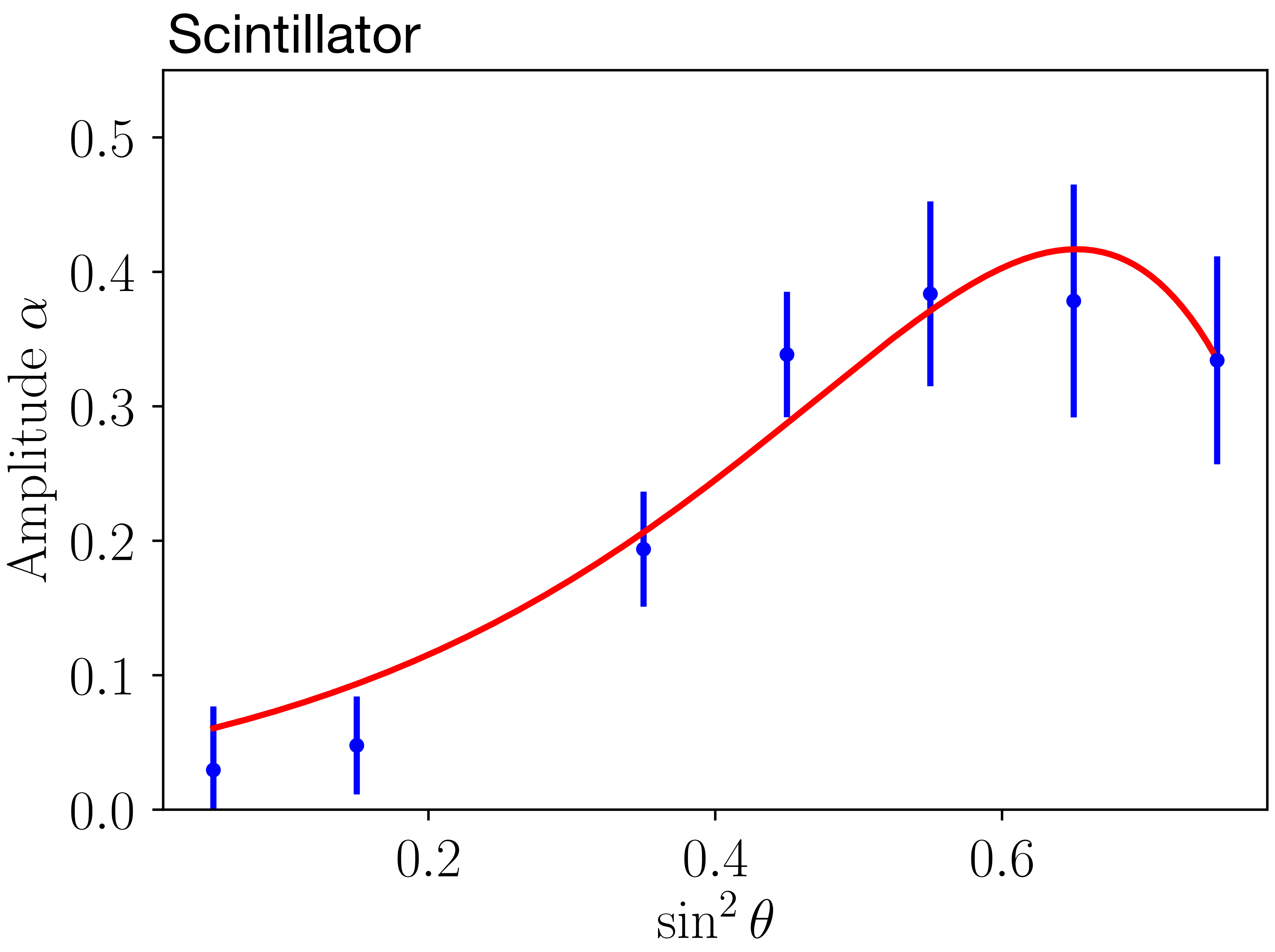
Increasing amplitude with distance from shower axis at distances ≲ 500 m

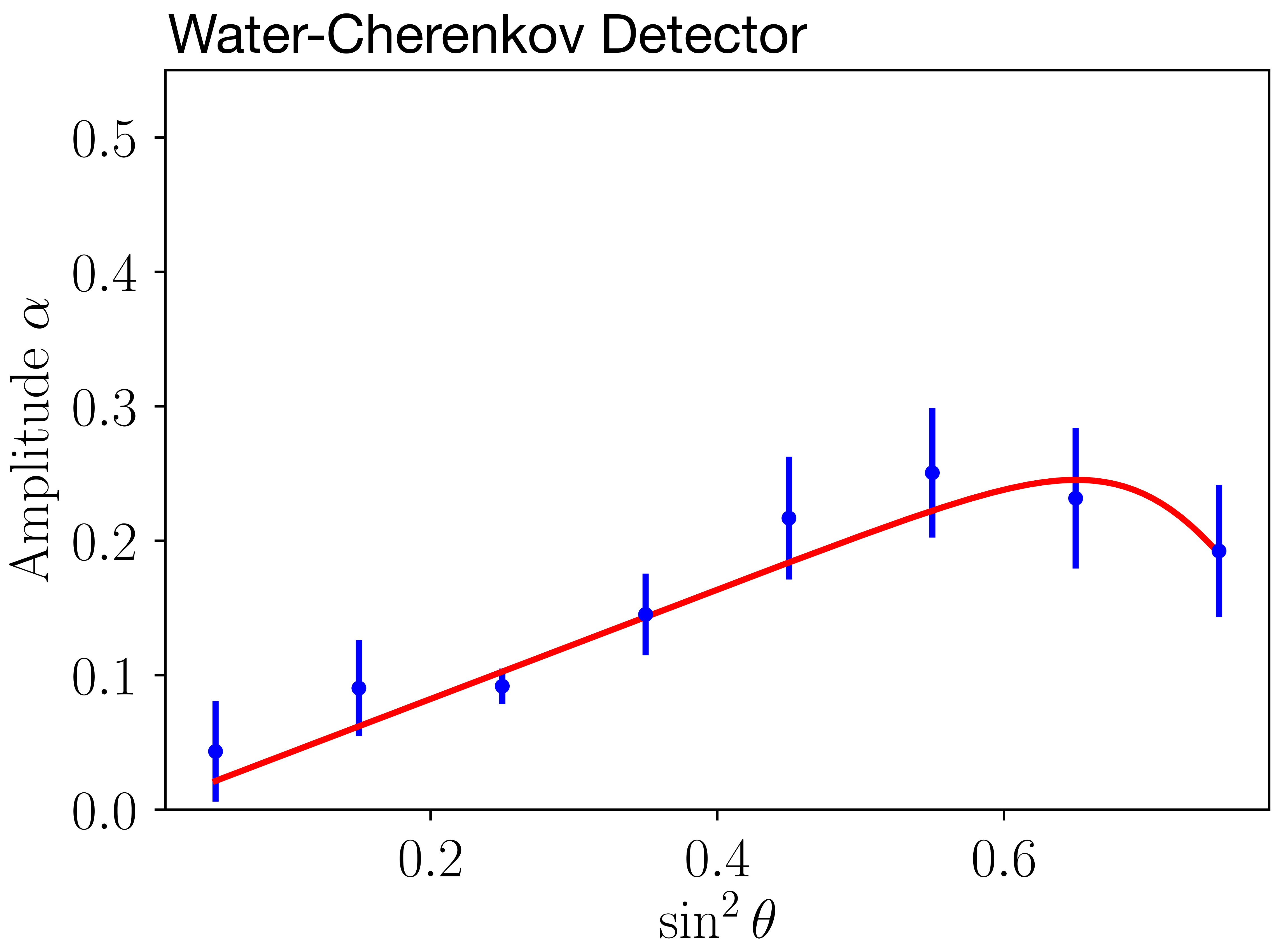
Beyond ~500 m, relatively distance-independent amplitude

Amplitude of asymmetry



Amplitude of asymmetry

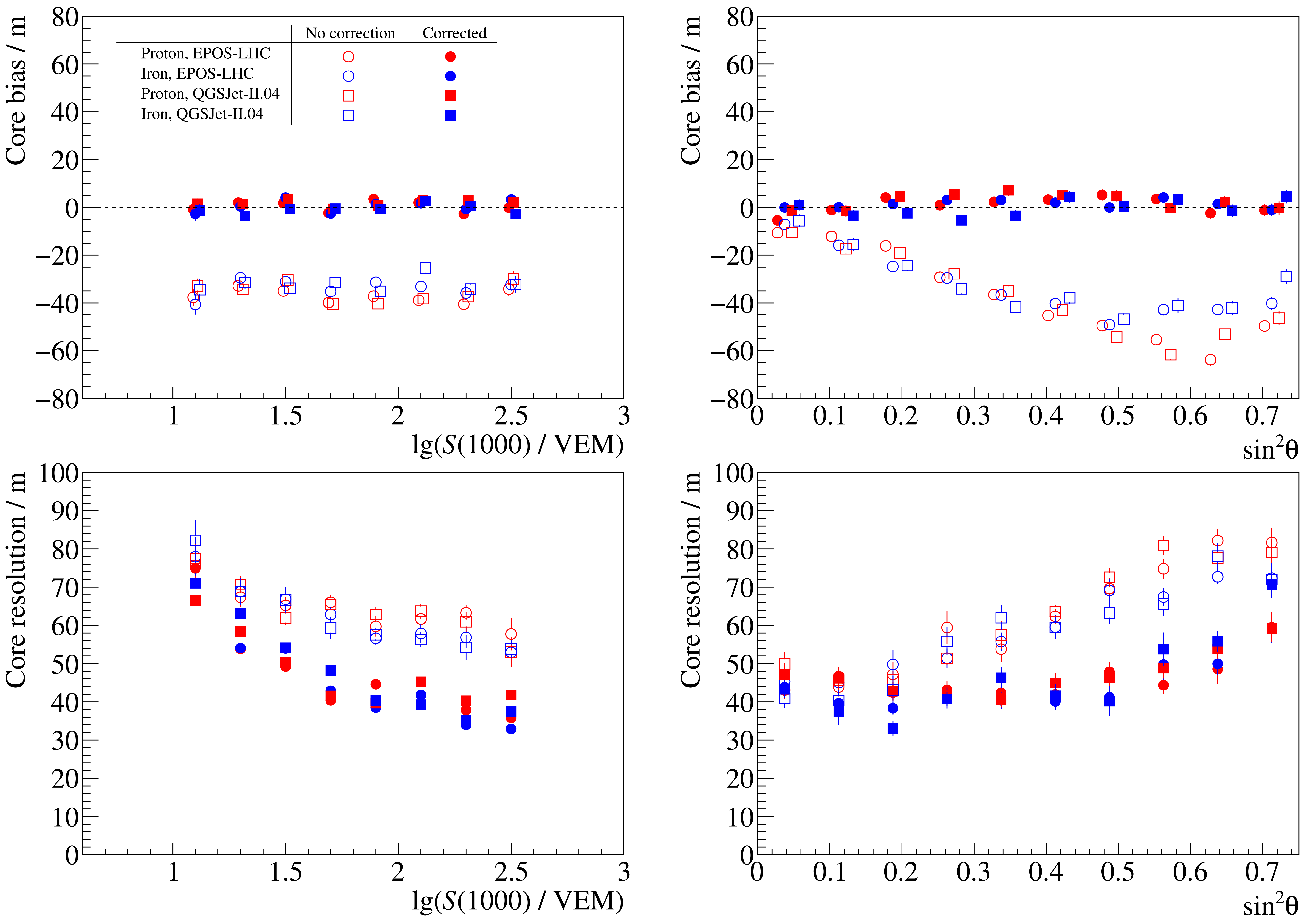




lg(E/eV): [19.5, 19.6]

Impact of taking asymmetries into account

For 1500 m isometric triangular grid of water-Cherenkov detectors (Auger-like)



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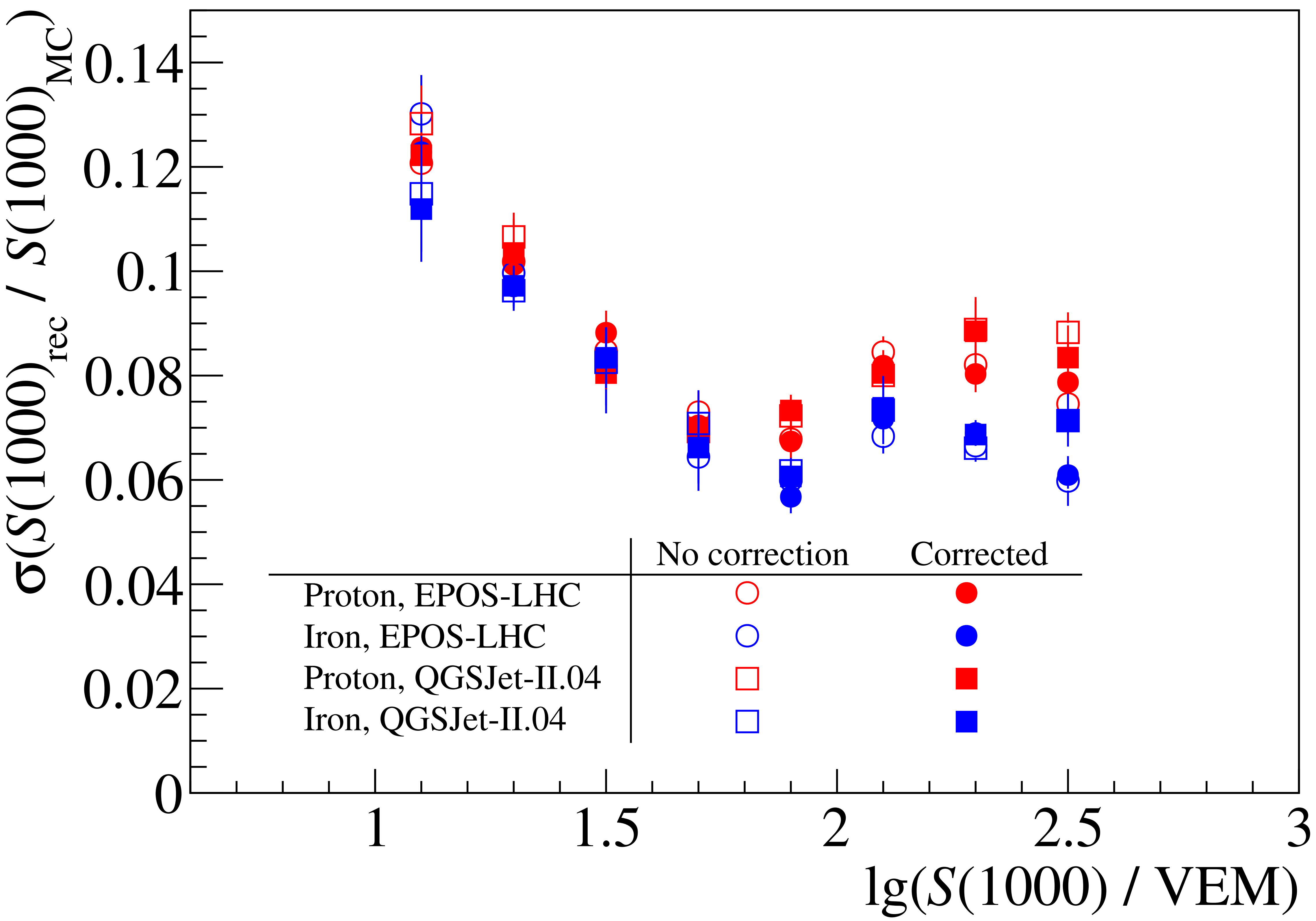

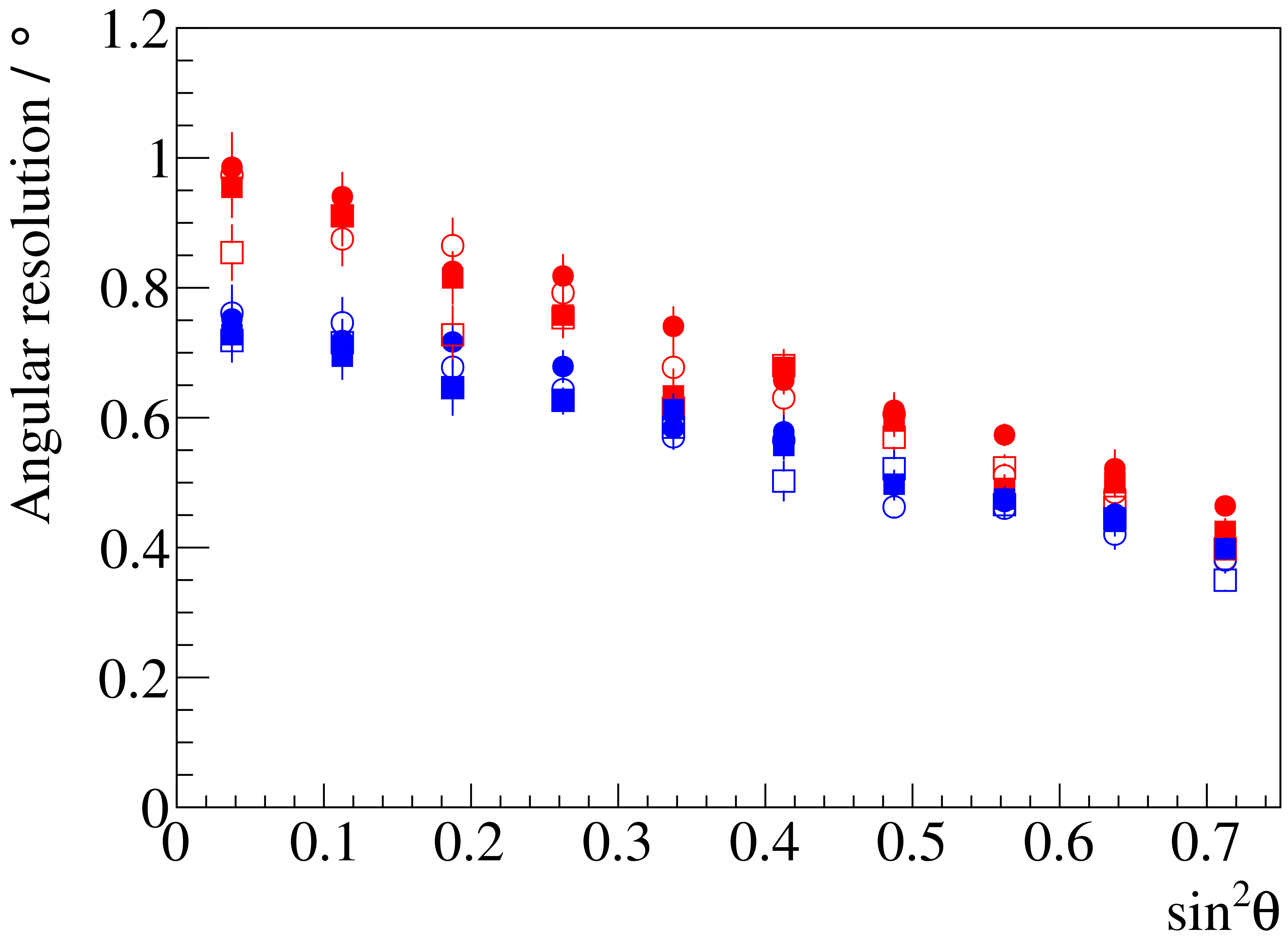

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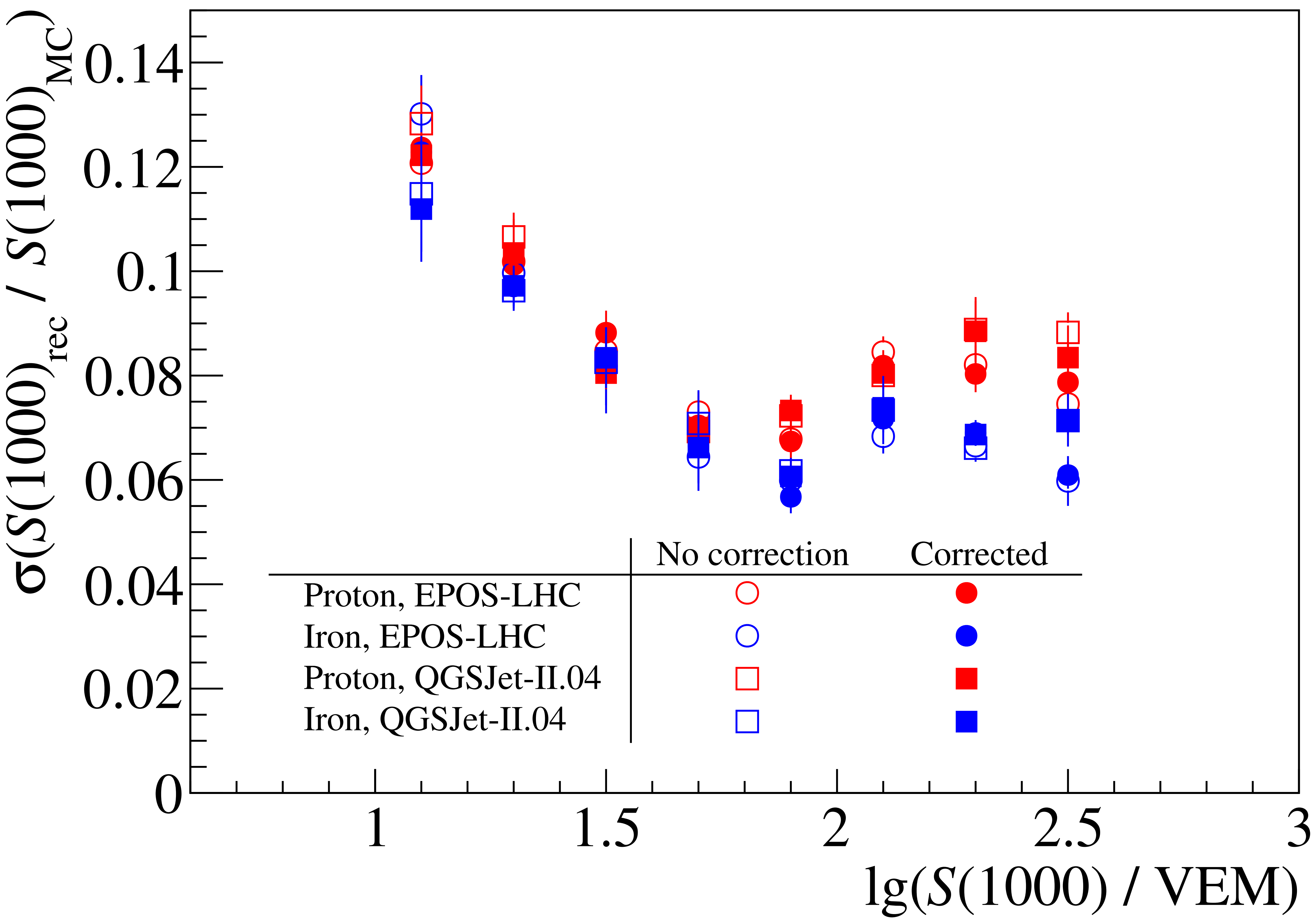
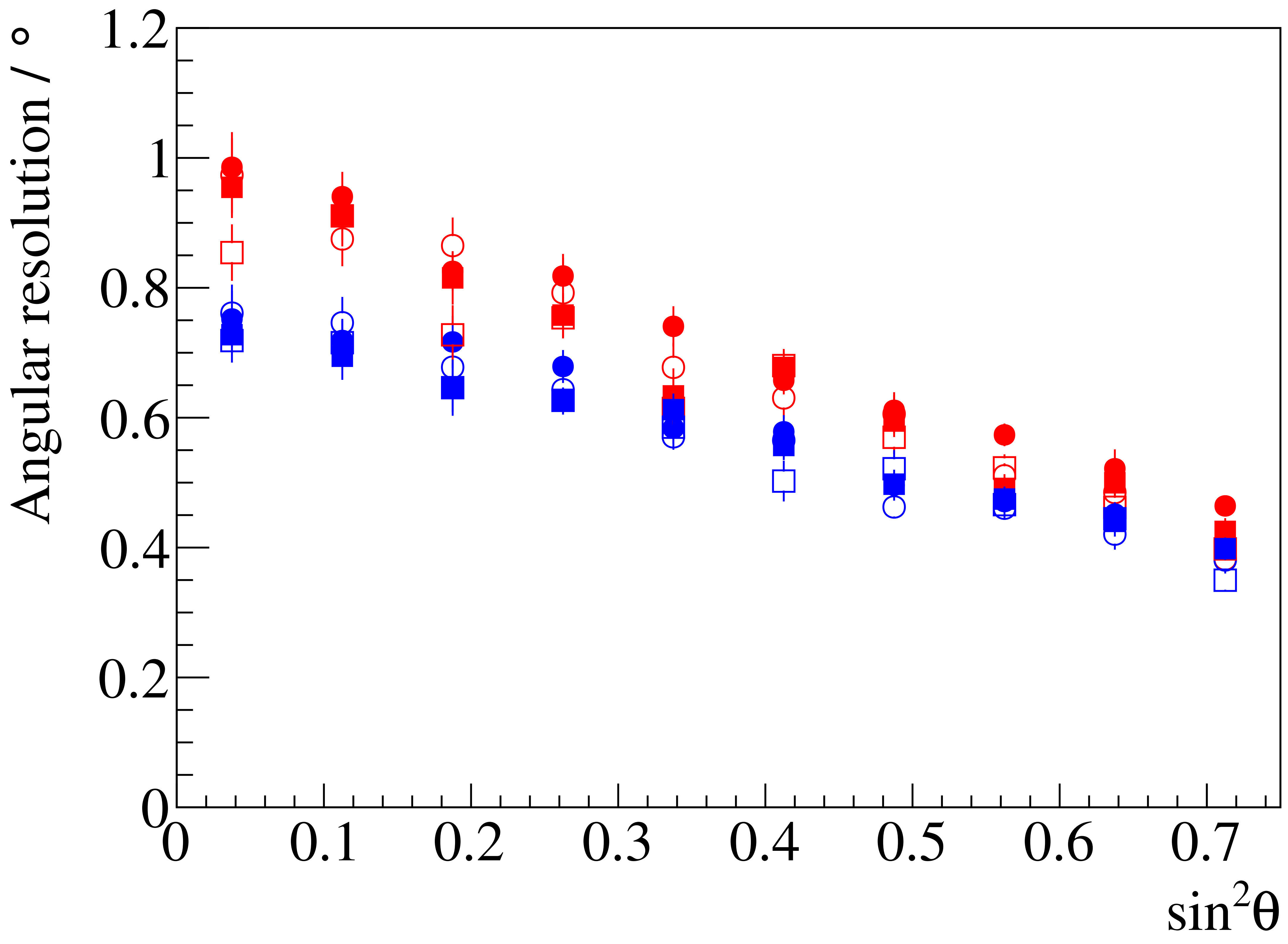
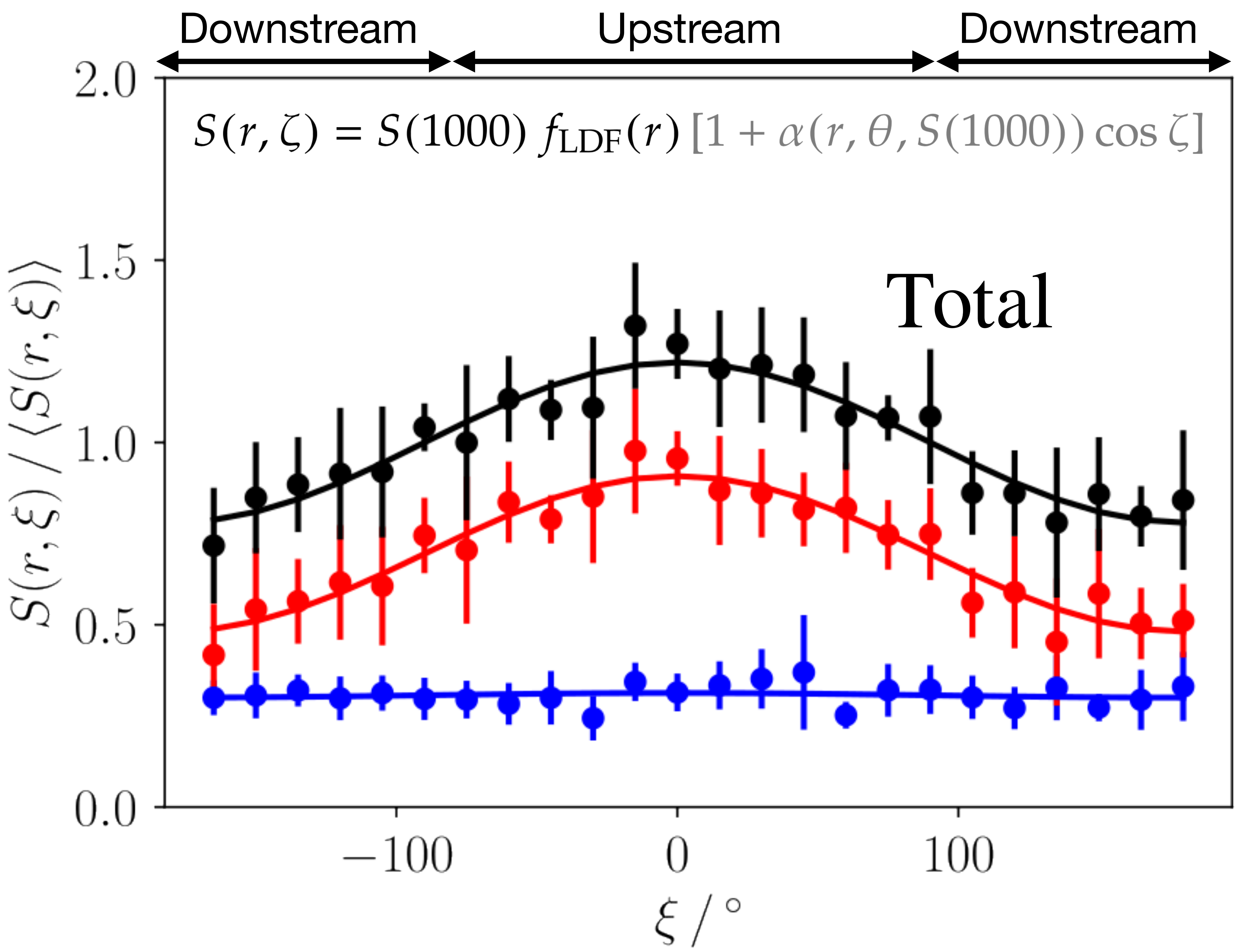




Negligible bias in arrival direction (< 0.1°) and S(1000) and change therein with correction) negligible

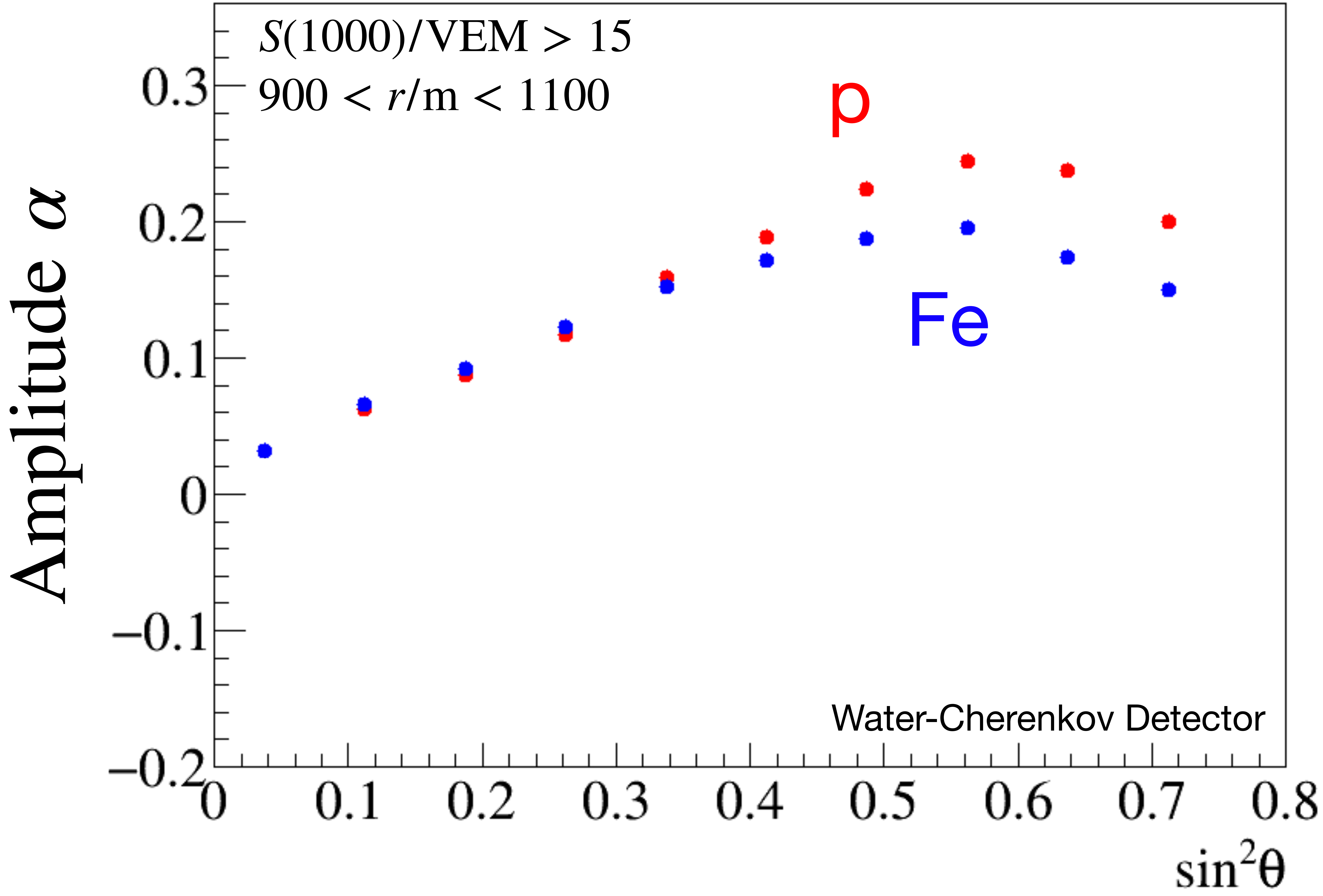
Summary

- Asymmetries in simulated signals with relative amplitudes of up to 25% (40%) for water-Cherenkov (scintillator detectors)
- Interplay between geometric and attenuative effects and signal fraction from different shower components
- Dependencies on distance to shower axis and zenith angle
- Biases of ~40 m in core position if not taken into account
- Improvement in core resolution of up to 50% if taken into account



For details (e.g. functional forms of the asymmetry parameterizations in r, θ, and S(1000)), please see upcoming proceeding

Mass dependence



Parameterization

$$S(r,\zeta) = S_{1000} f_{\rm LDF}[1 + b(r,\theta,\log(S_{1000}))\cos\zeta]$$

$$b(r,\theta,\log(S_{1000})) = k(\theta,\log(S_{1000}))\,\mathrm{erf}\left(\frac{r}{r_0(\theta,\log(S_{1000}))}\right)$$

$$k(\theta,\log(S_{1000})) = \frac{k_0 + k_1\sin^2\theta}{1+\exp\left(-\frac{\sin^2\theta - k_2(\log(S_{1000}))}{k_3(\log(S_{1000}))}\right)}$$

$$r_0(\theta,\log(S_{1000})) = r_1(\log(S_{1000})) + r_2(\log(S_{1000}))\sin^4\theta$$

Water-Cherenkov Detector