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On the need for unbiasing azimuthal asymmetry in signals measured by surface detector arrays

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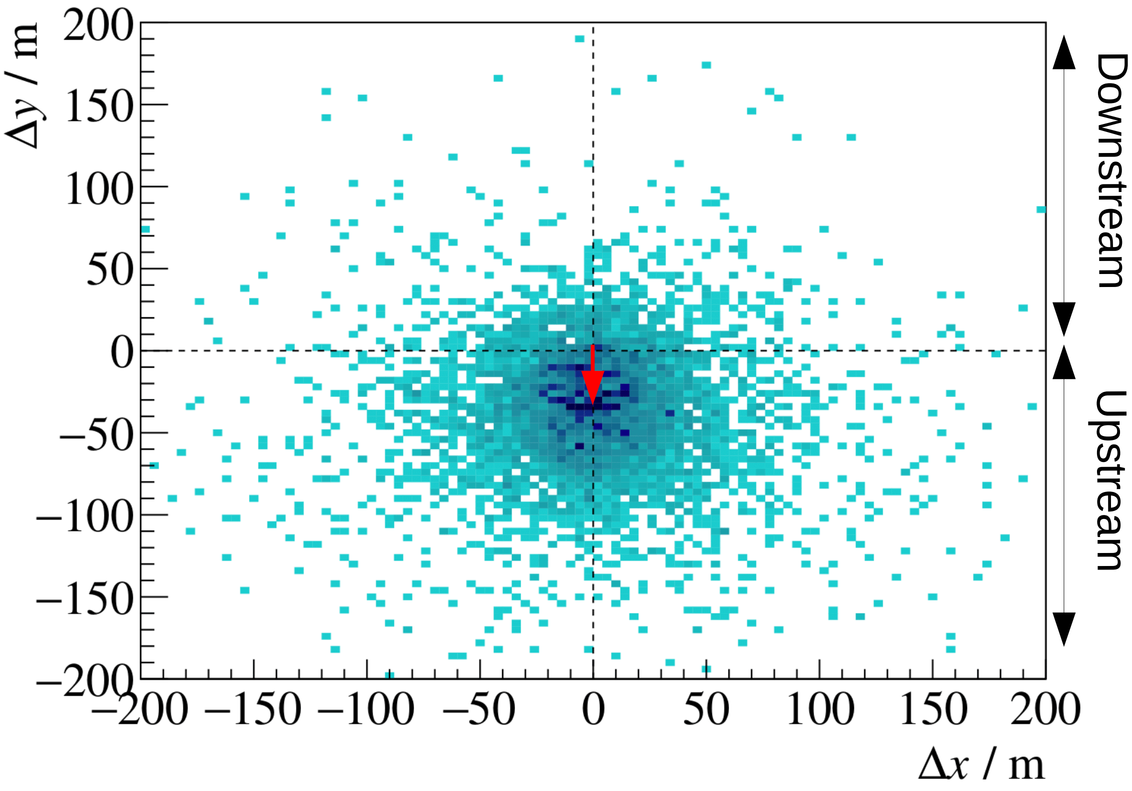
Azimuthal asymmetry in signal

Azimuthal asymmetry in signals **observed in the water-Cherenkov detector** of the surface detector is combination of:

- **geometrical effects** from the inclination of the shower
- **attenuation of the charged particles** from their point of emission to the ground

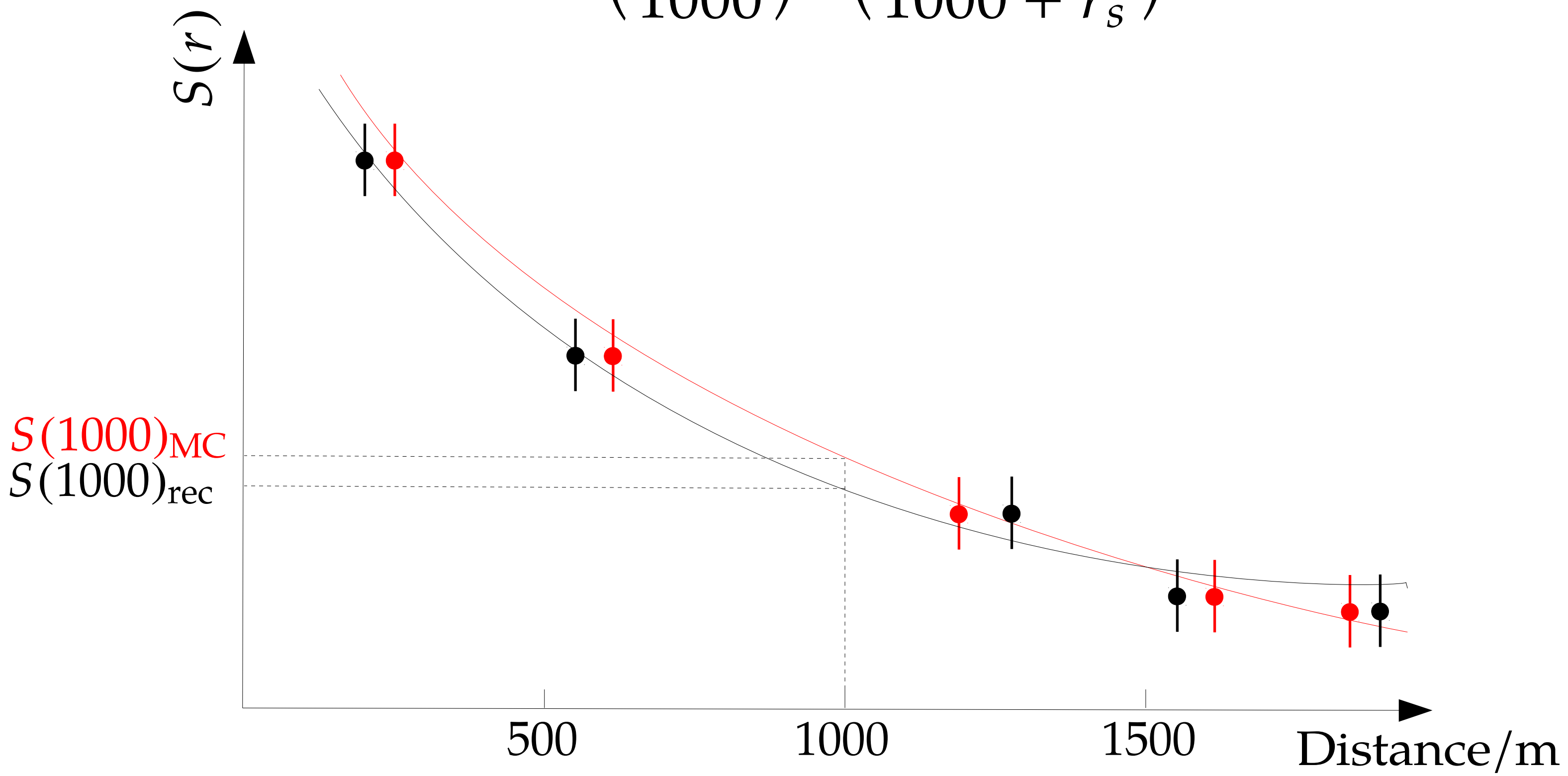
From the **surface detector of the Pierre Auger Observatory**: introduction of a **bias (~40 m) in the reconstruction of the core** of the shower when **axisymmetric LDF** is used



Azimuthal asymmetry in signal

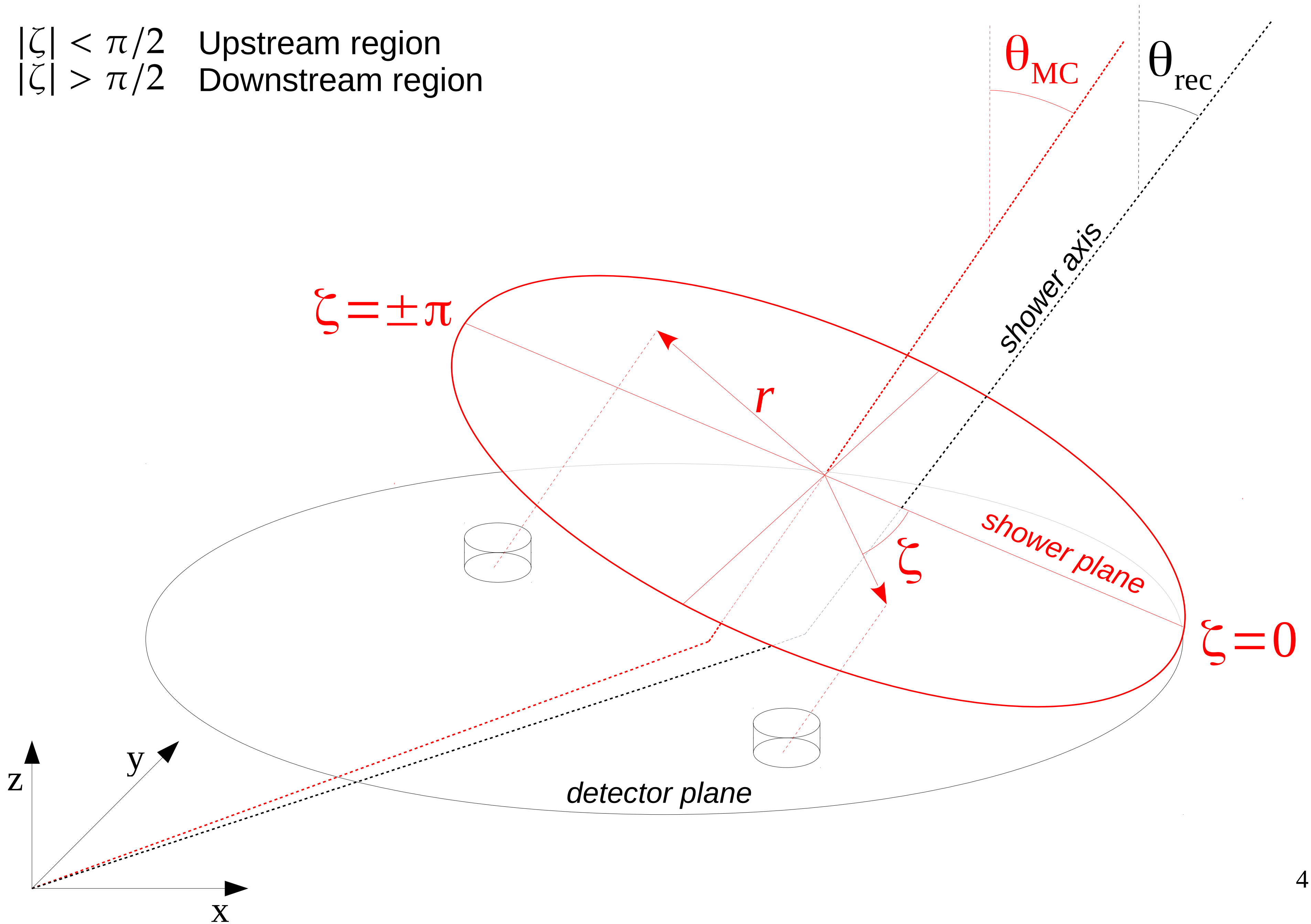
$$S(r) = S(1000)\, f_{\text{LDF}}(r)$$

$$f_{\text{LDF}}(r) = \left(\frac{r}{1000}\right)^{\beta} \left(\frac{r + r_s}{1000 + r_s}\right)^{\beta+\gamma}$$



Azimuthal asymmetry in signal

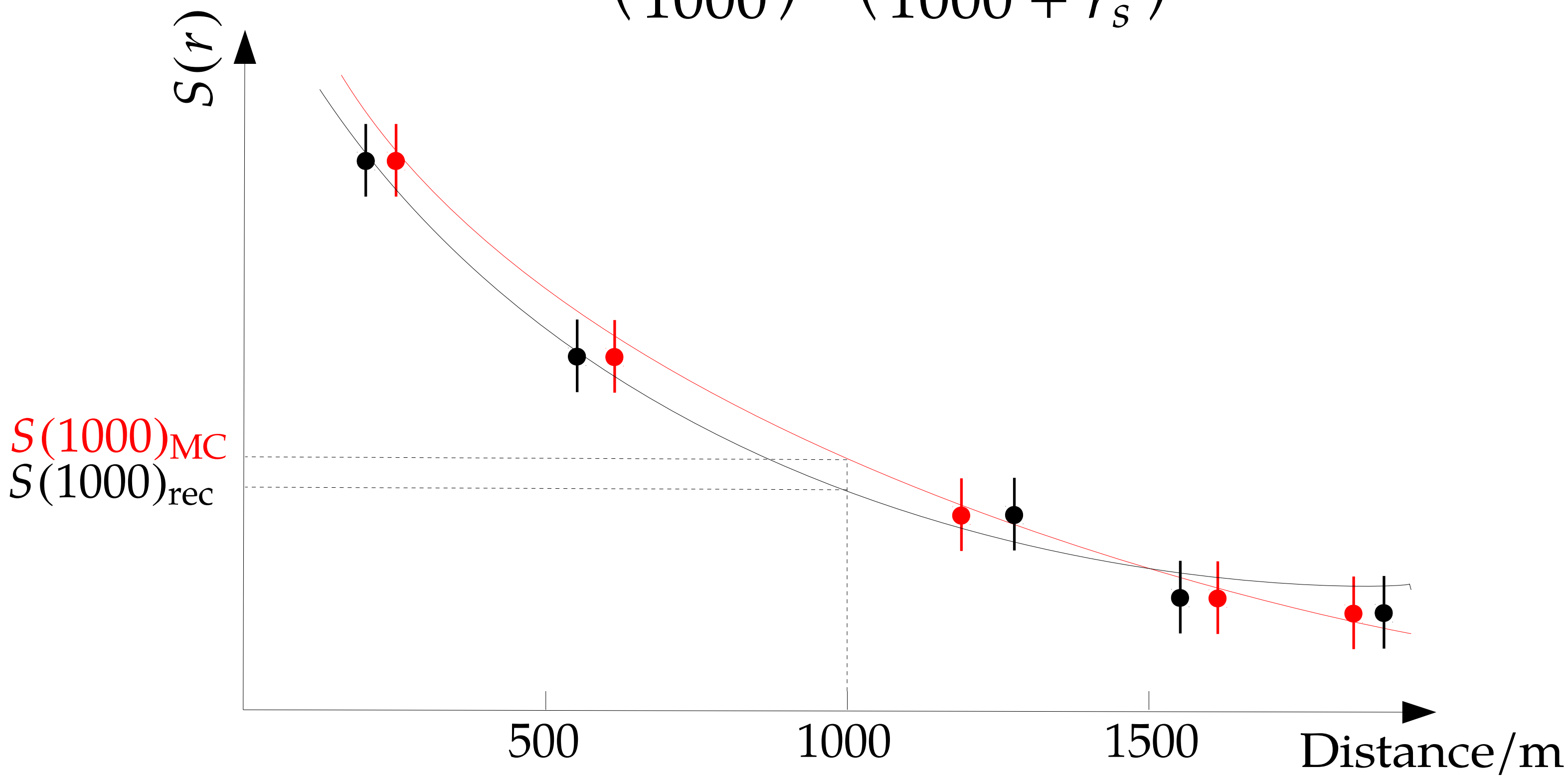
$|\zeta| < \pi/2$ Upstream region
$|\zeta| > \pi/2$ Downstream region



Azimuthal asymmetry in signal

$$S(r,\zeta) = S(1000)\, f_{\mathrm{LDF}}(r)\, [1 + \alpha(r,\theta,S(1000))\cos\zeta]$$

$$f_{LDF}(r) = \left(\frac{r}{1000}\right)^{\beta} \left(\frac{r + r_s}{1000 + r_s}\right)^{\beta+\gamma}$$



Parametrisation of $\alpha(r,\theta,S(1000))$ **using simulations**

Simulated data-sets

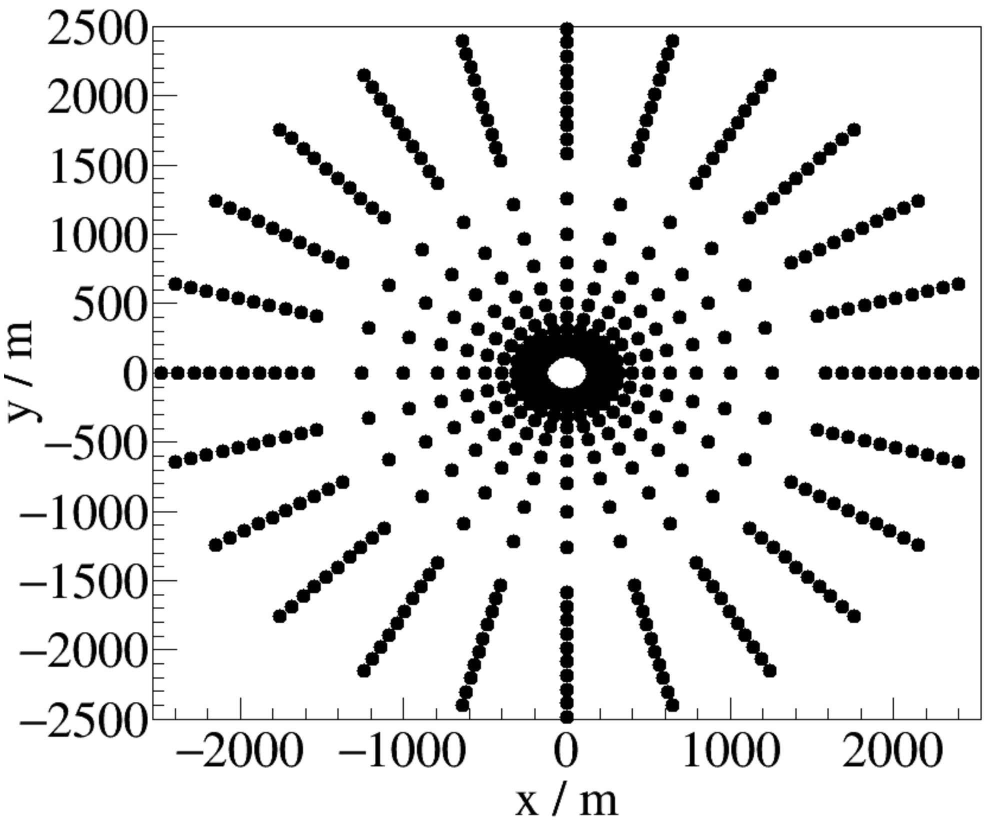
- hadronic model :
  QGSJet-II.04, **EPOS-LHC**
- primary : **Proton**, **Iron**

- Continuous library
  lg(*E* / eV) = 18.5 – 20.0
  θ / ° = 0 – 60 (flat distribution in $\sin^2\theta$)

- surface detector of the **Pierre Auger Observatory**

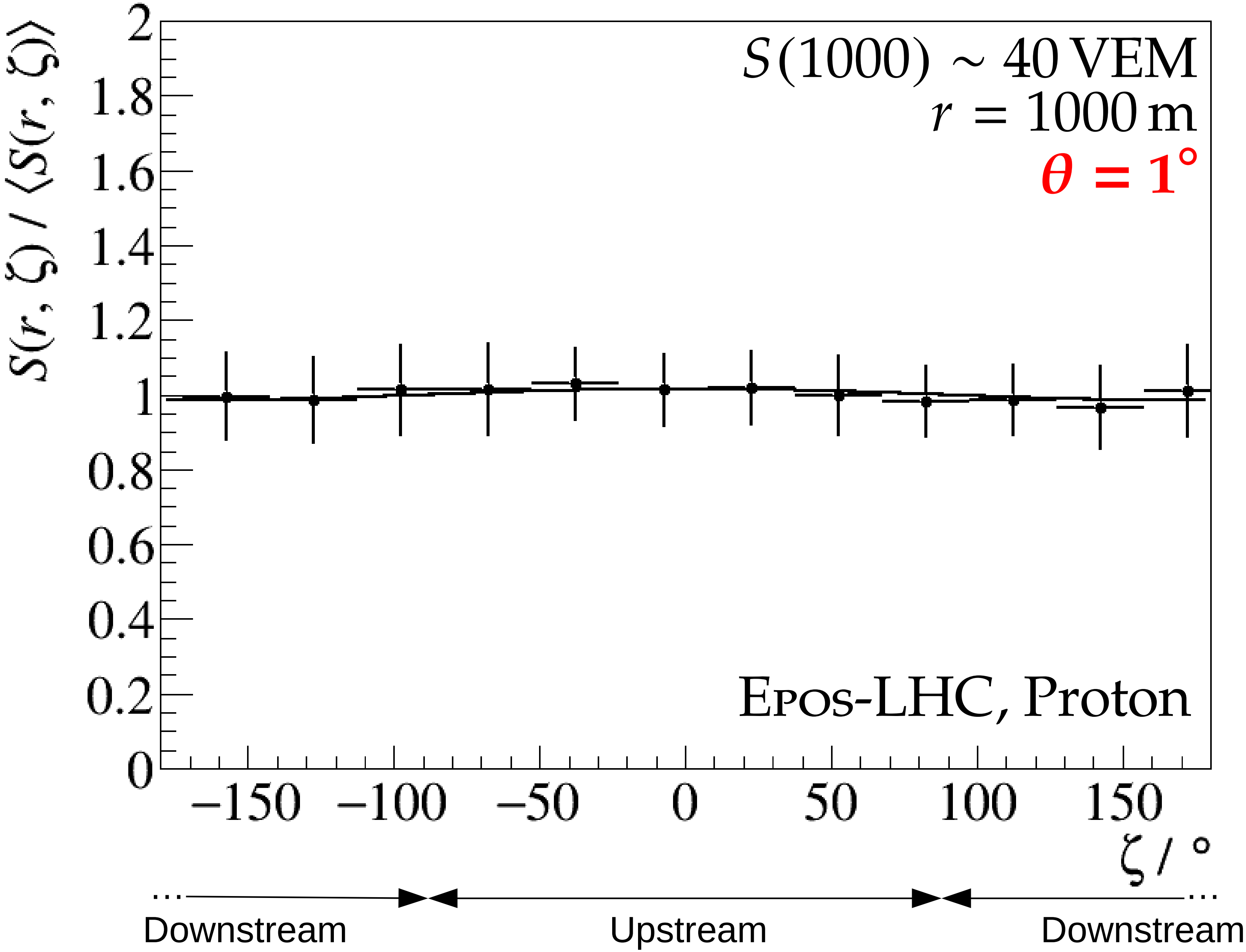
- **20 dense rings** = 24 detectors at a fixed distance from the shower axis

- Offline simulation and reconstruction frameworks[1,2]

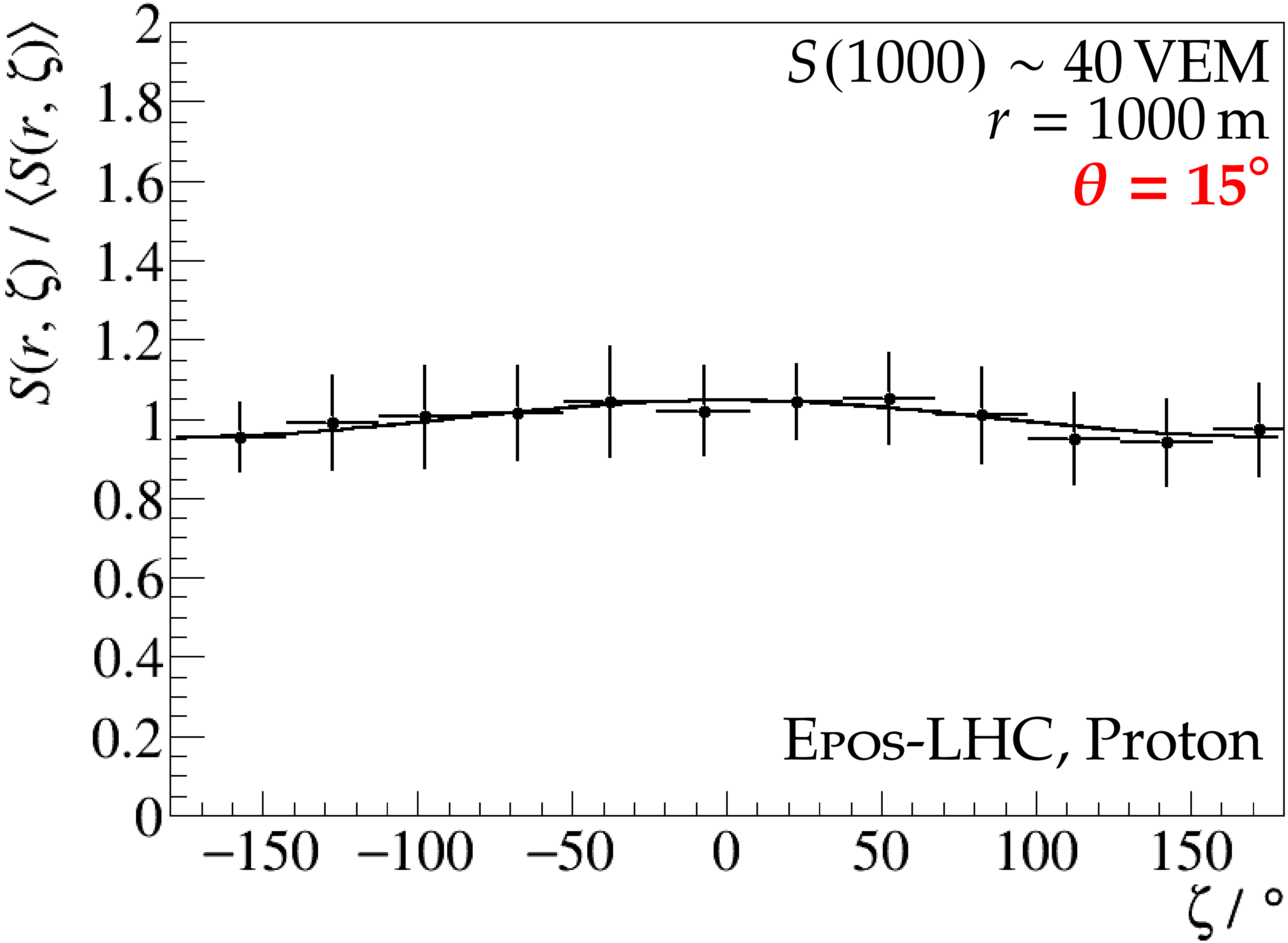


[1] S. Argirò et al., *Nucl. Instrum. Meth. A* **580** (2007) 1485-1496, [0707.1652]
[2] A. Aab et al. [Pierre Auger Coll.], *JINST* **15** (2020) P10021, [2007.09035]

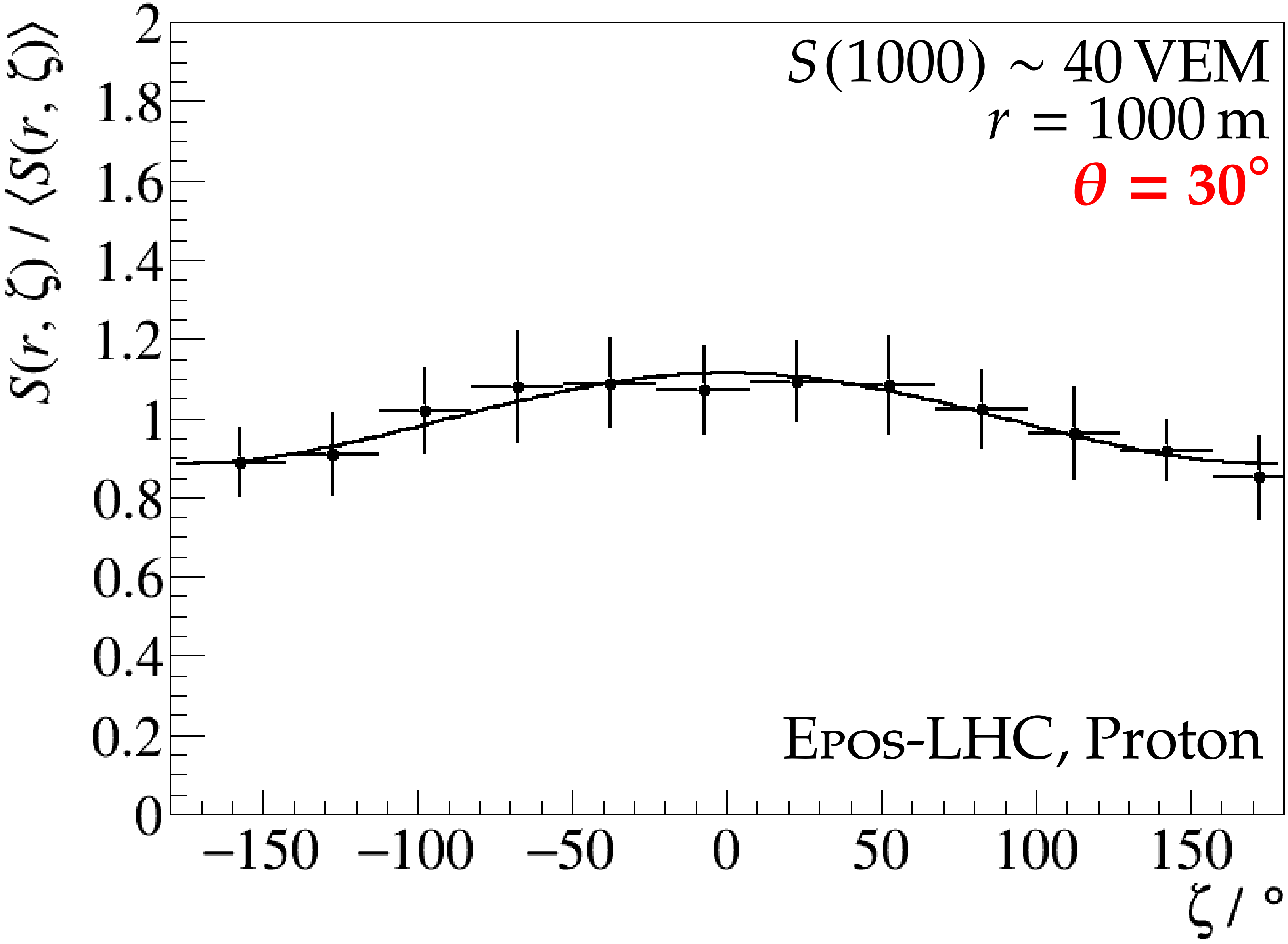
Amplitude of the asymmetry



Amplitude of the asymmetry



Amplitude of the asymmetry



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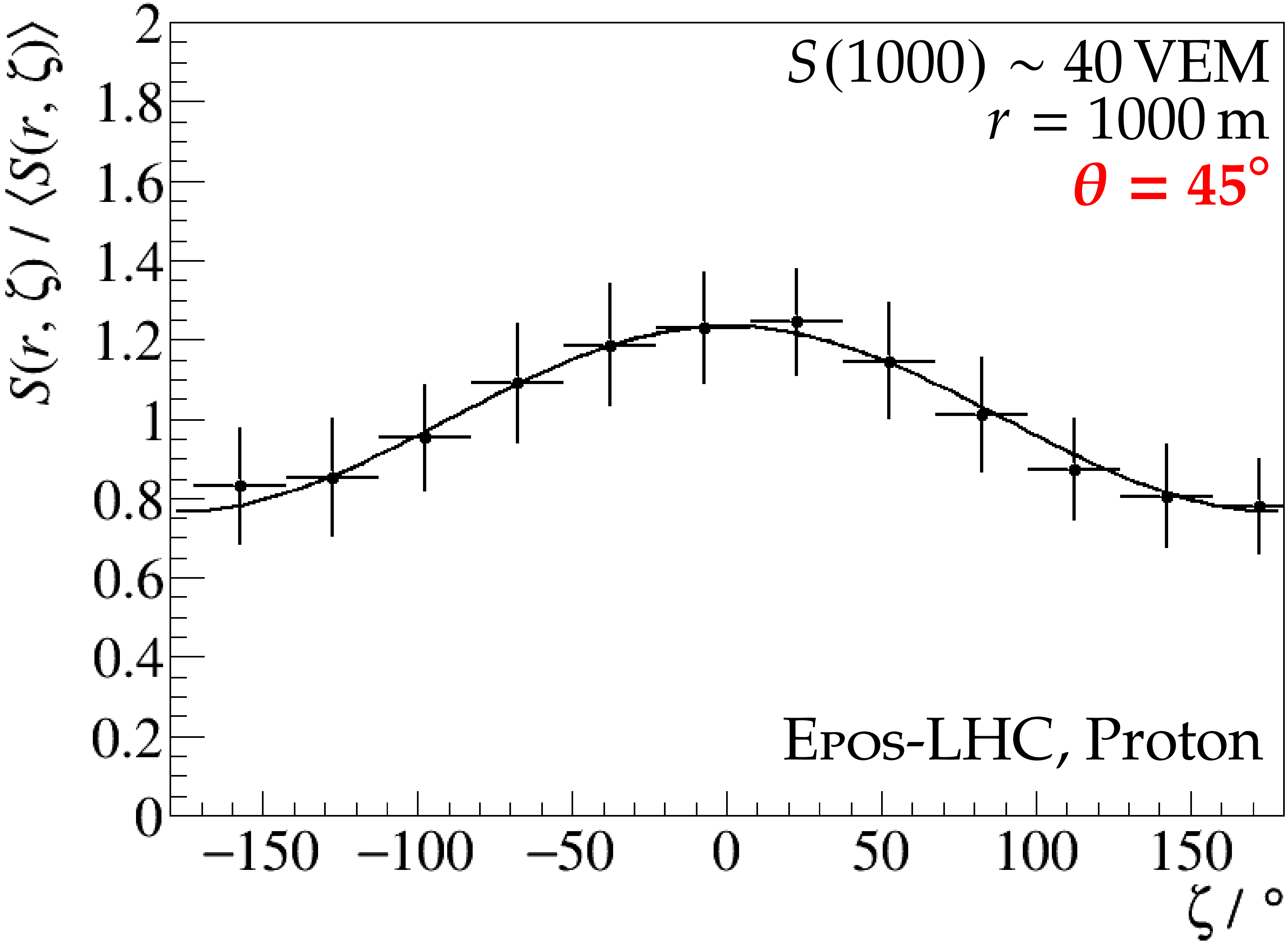
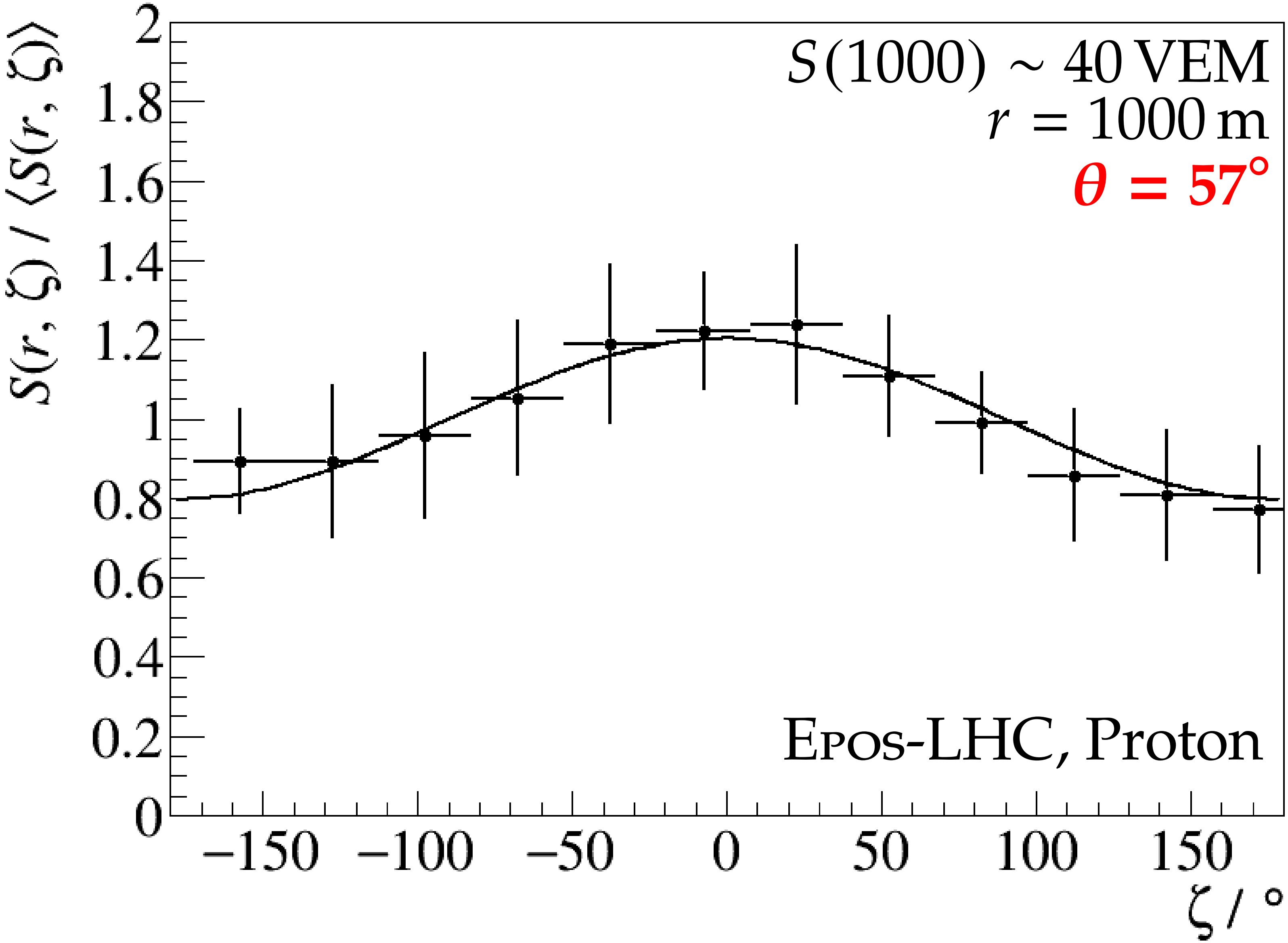
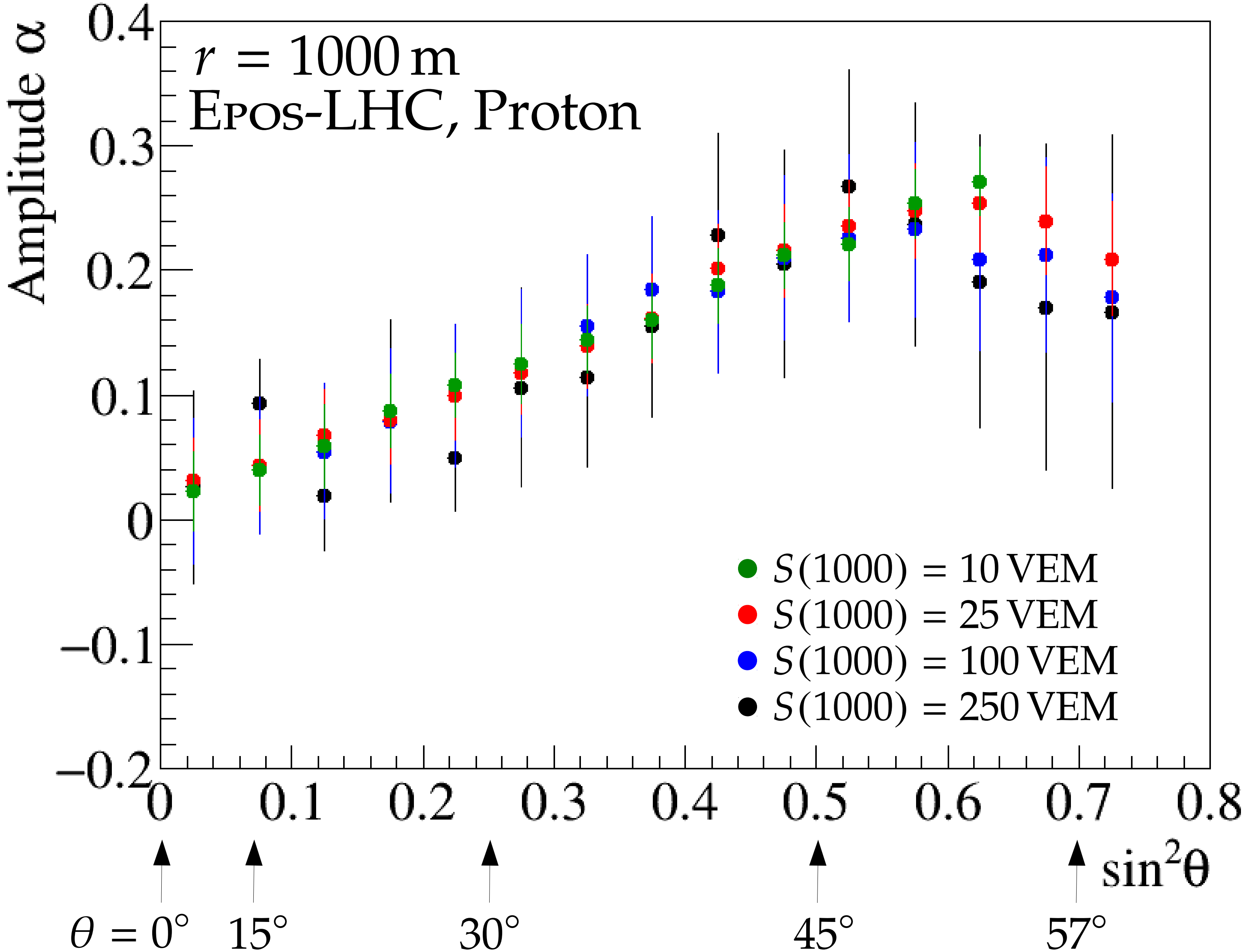


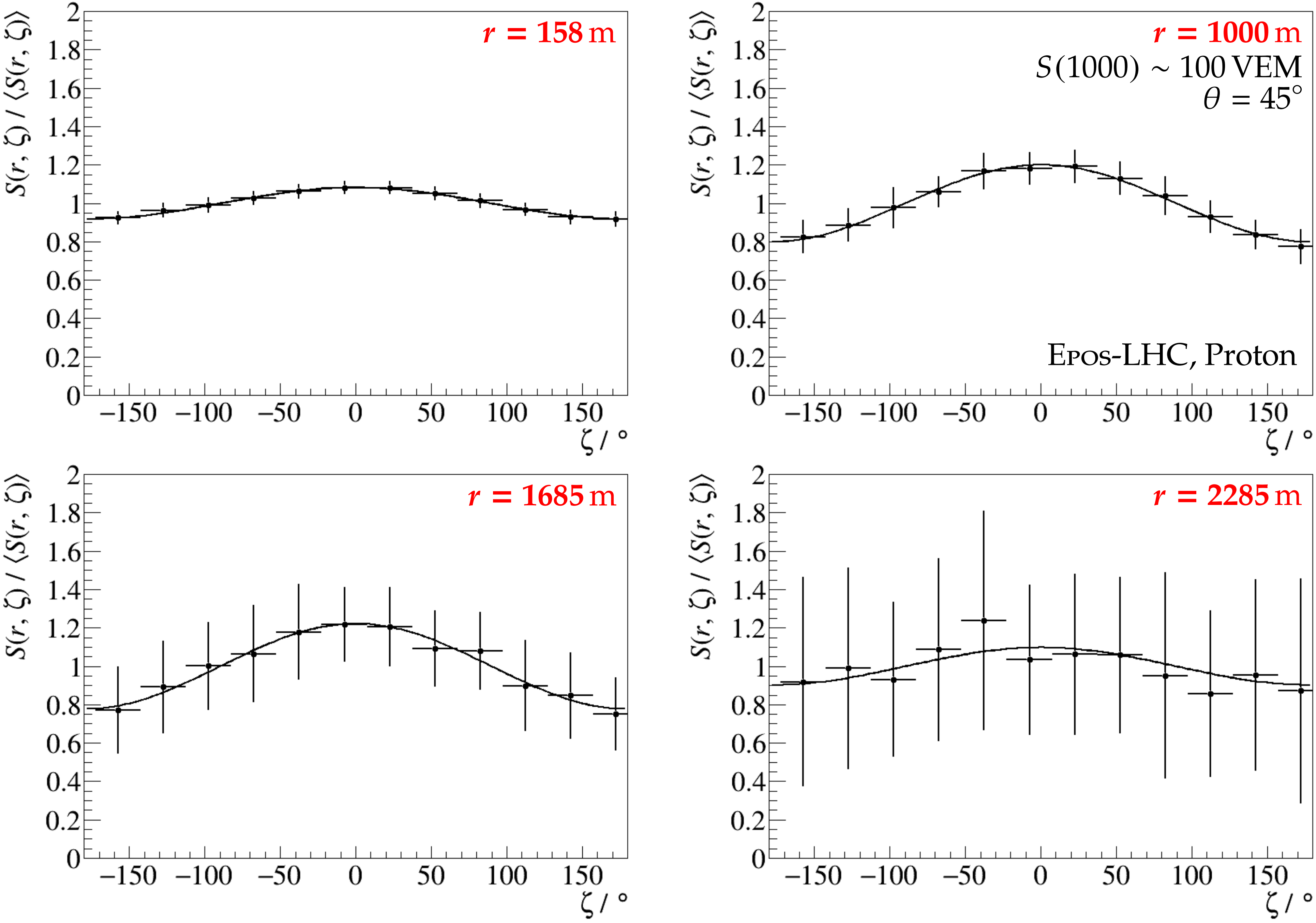
Amplitude of the asymmetry



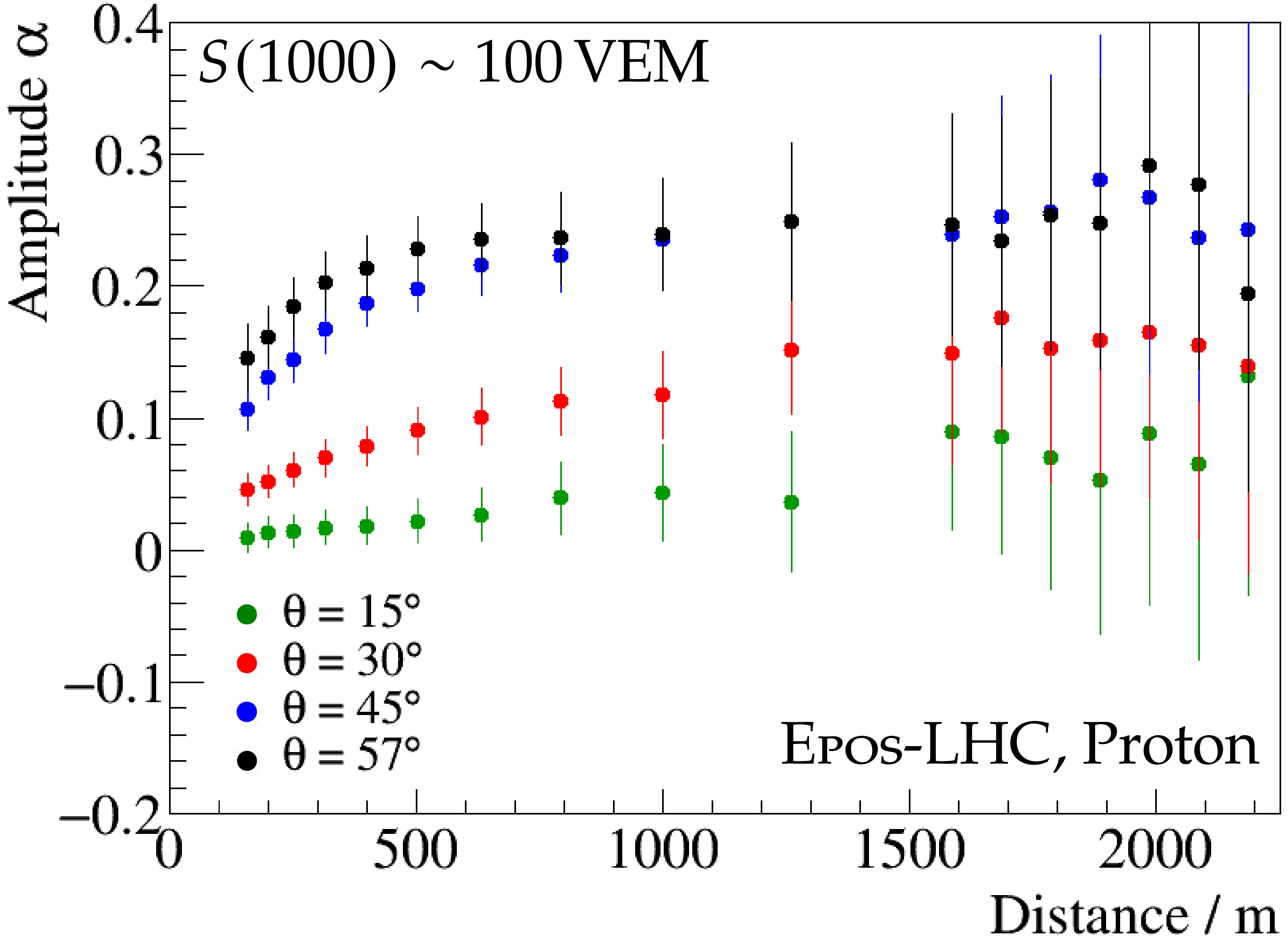
Evolution with the inclination



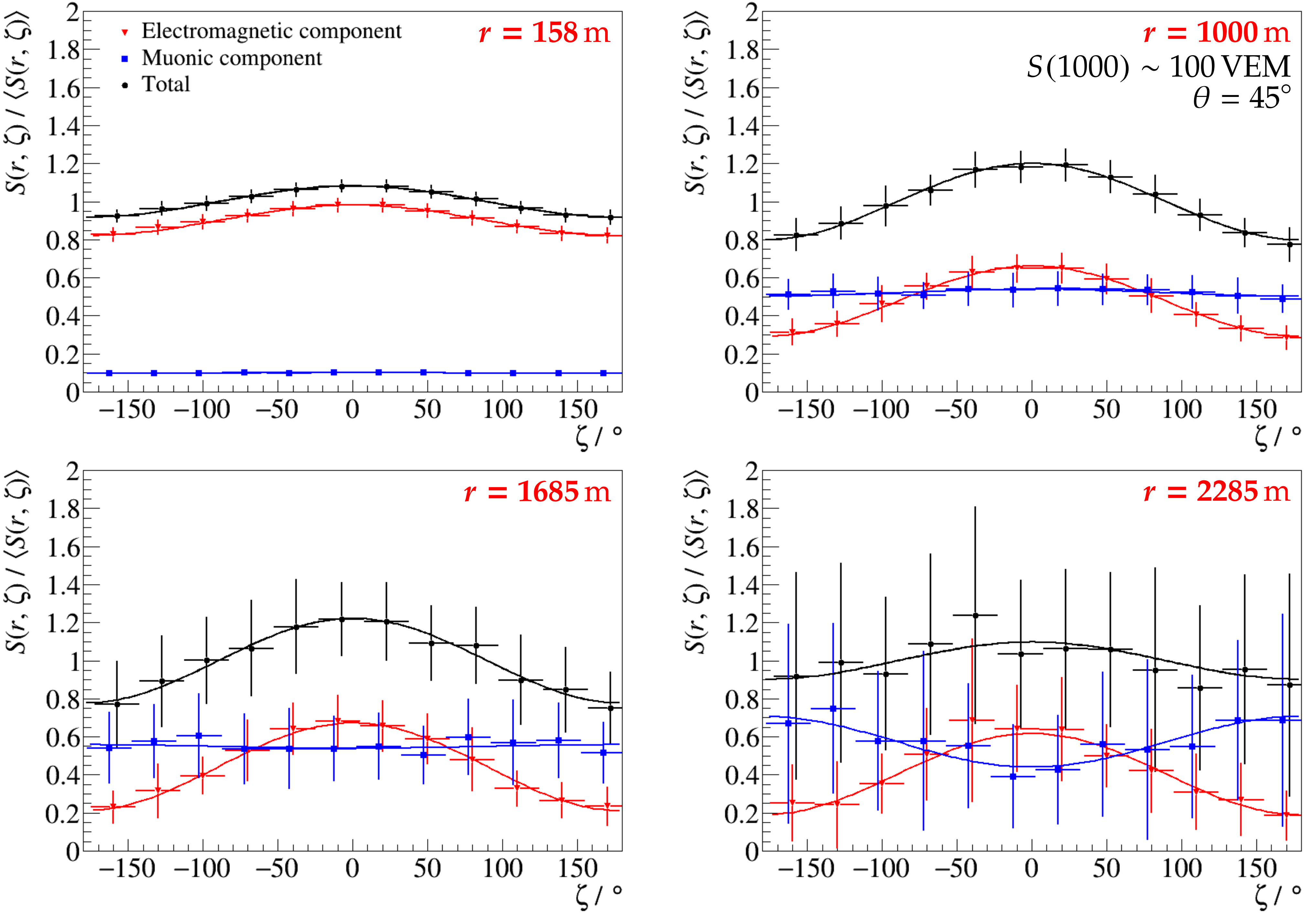
Amplitude vs distance



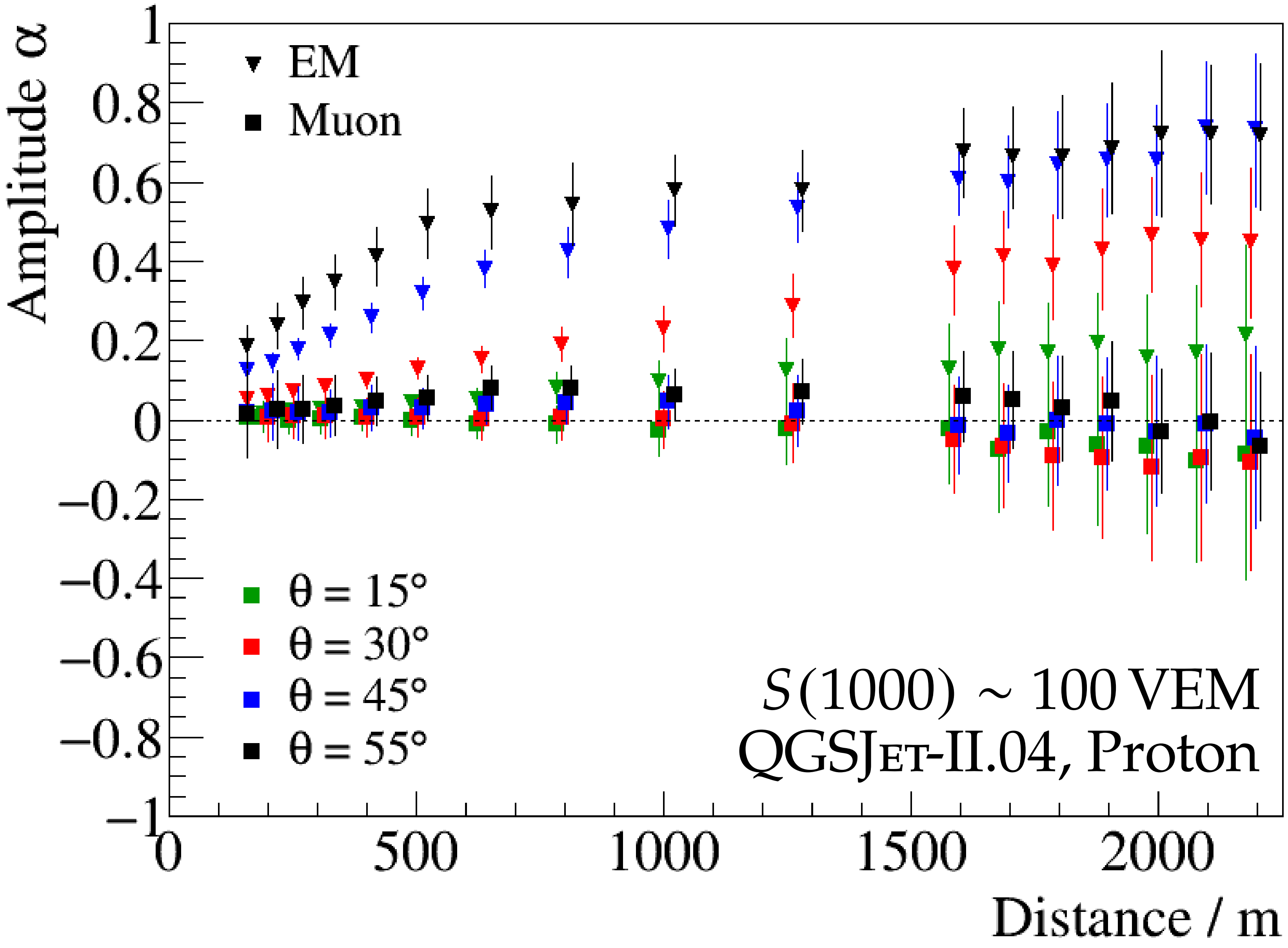
Evolution with the distance



Electromagnetic vs Muonic components



Electromagnetic vs Muonic components



Negative amplitude?

Amplitude of the asymmetry[3] = combination of:

- attenuation over the distance from the emission point to the ground

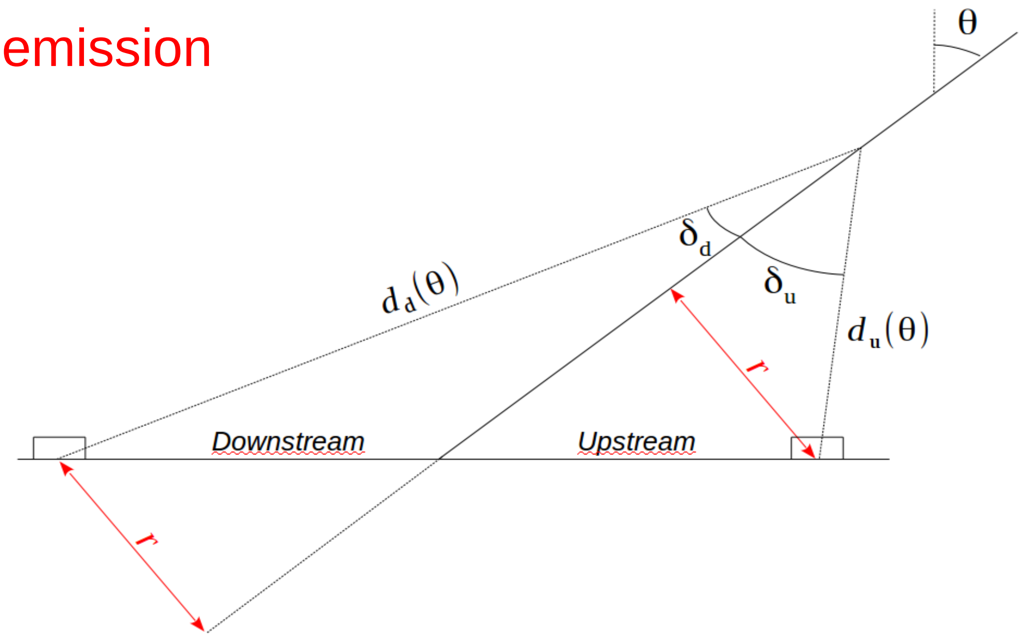
$$f_{\text{att}}(d(\theta)) = \exp(-d(\theta)/\lambda)$$

- dependence of particle density in a fixed solid angle

$$\Delta\Omega \propto 1/d^2$$

- angular distribution function of the emission of particles

$$\text{ADF}(\delta) \propto (\delta/\delta_0)^{-\gamma}$$

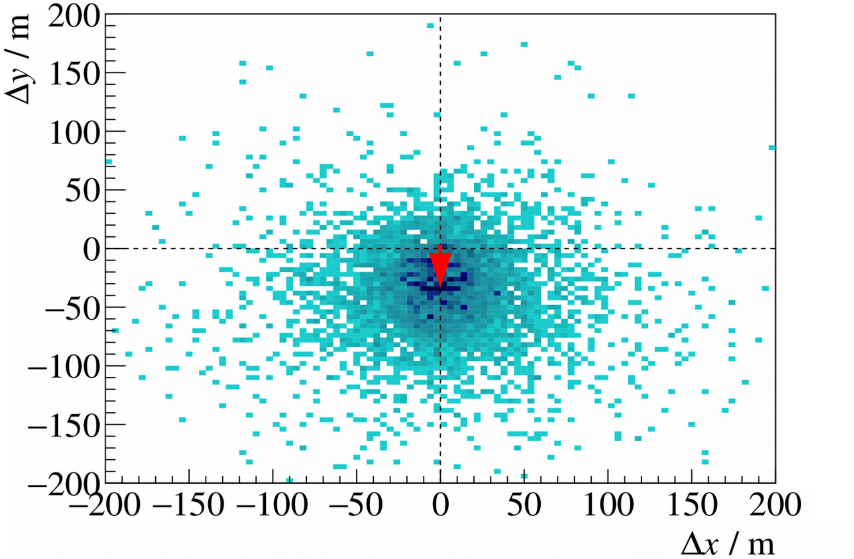


$$\alpha \propto 2 + \frac{d(\theta)}{\lambda} - \gamma$$

[3] L. Armbruster, *Master thesis*

Impact on the core reconstruction

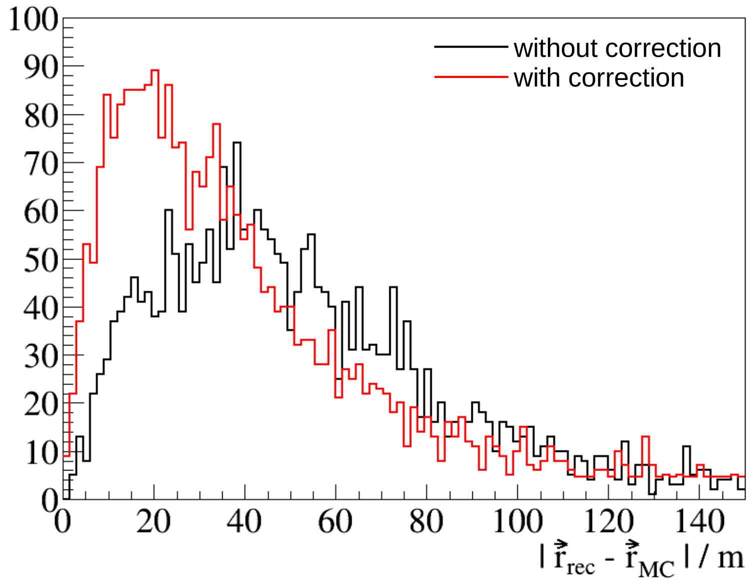
Bias in the core position:



Core bias = mean value in the upstream-downstream direction

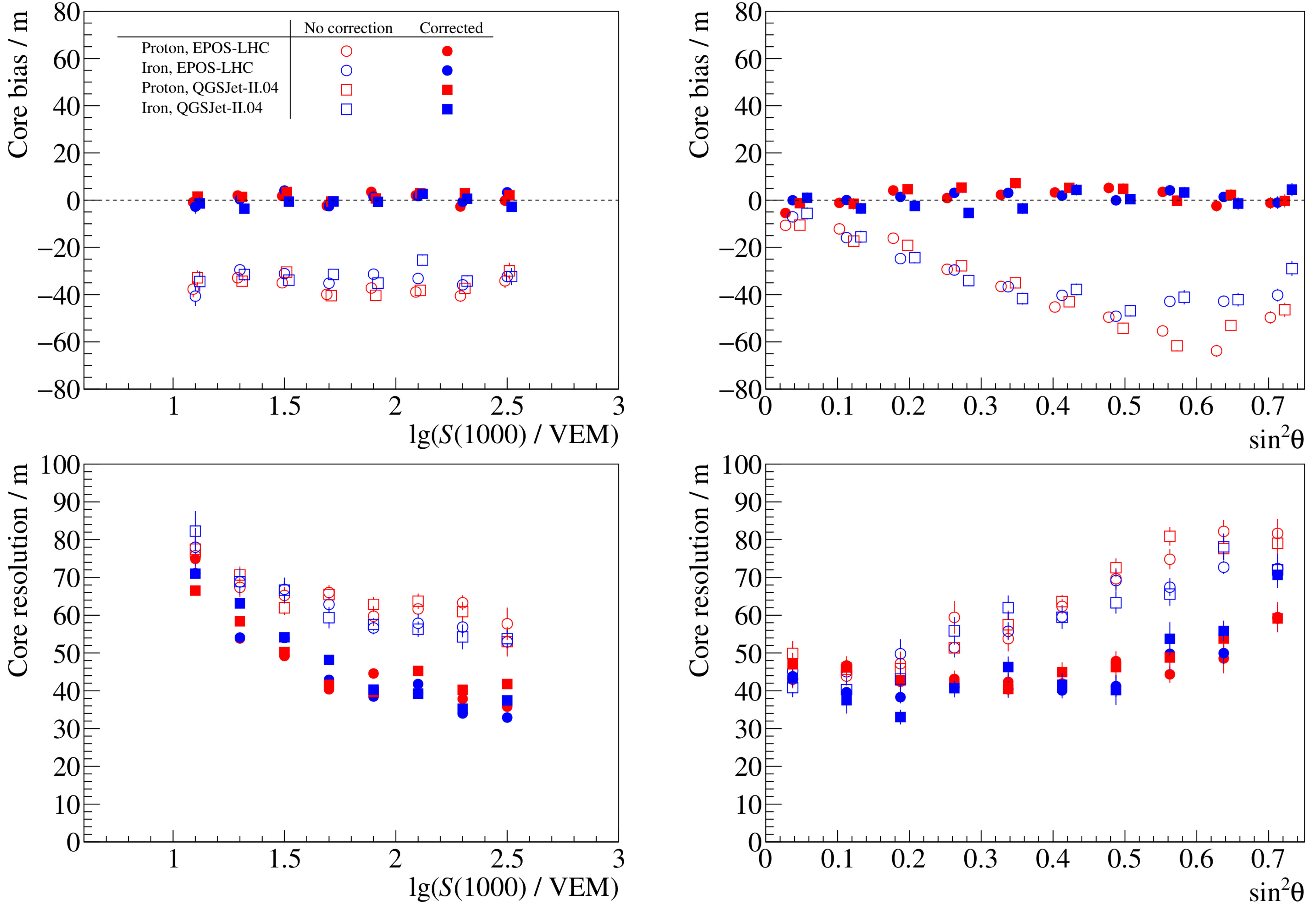
No bias in the perpendicular direction

Resolution of the core position:



Core resolution = distance at which **68.3% of the cumulative distribution of the distance** between the simulated and reconstructed positions of the core, is reached

Impact on the core reconstruction



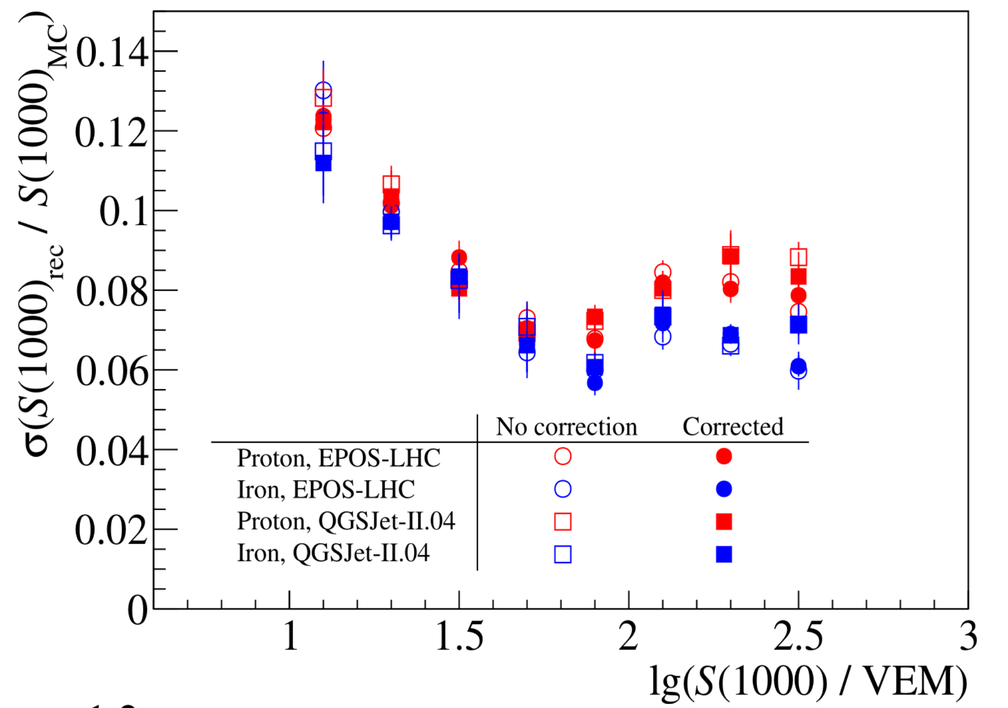
Impact on zenith and *S*(1000)

Uncertainties in *S*(1000):

Comparison of:

$S(1000)_{MC}$ *S*(1000) computed from the ring of 24 detectors at 1000 m

$S(1000)_{rec}$ reconstructed *S*(1000)

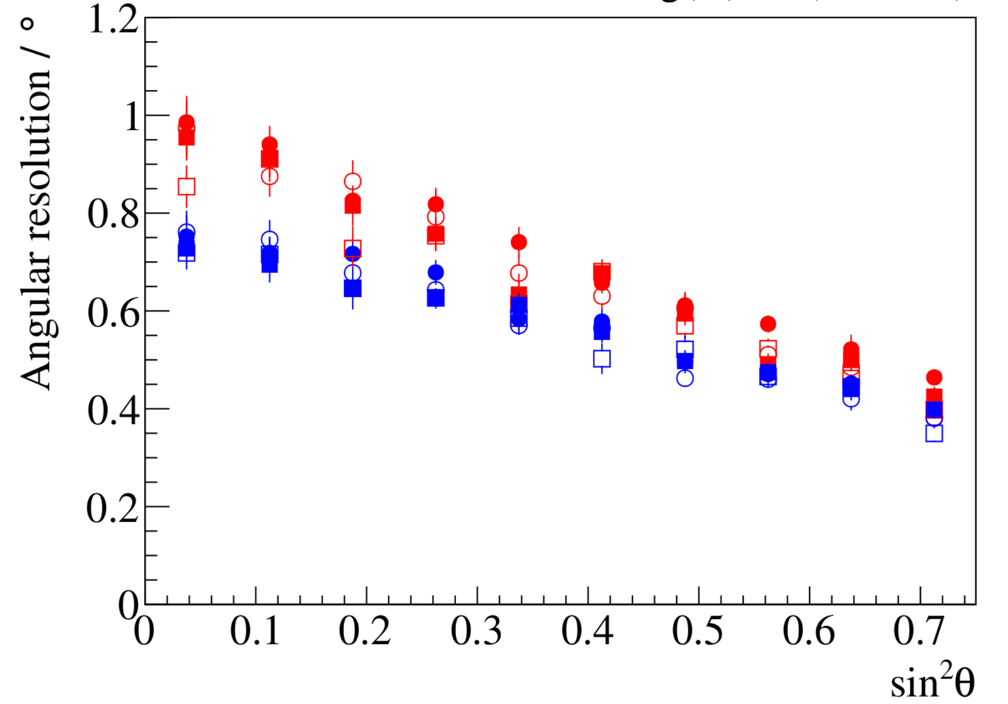


Angular resolution:

Opening-angle:

$$\sin\eta = |\hat{a}_{MC} \times \hat{a}_{rec}|$$

Angular resolution = angle at which **68.3% of the cumulative distribution of η** is reached



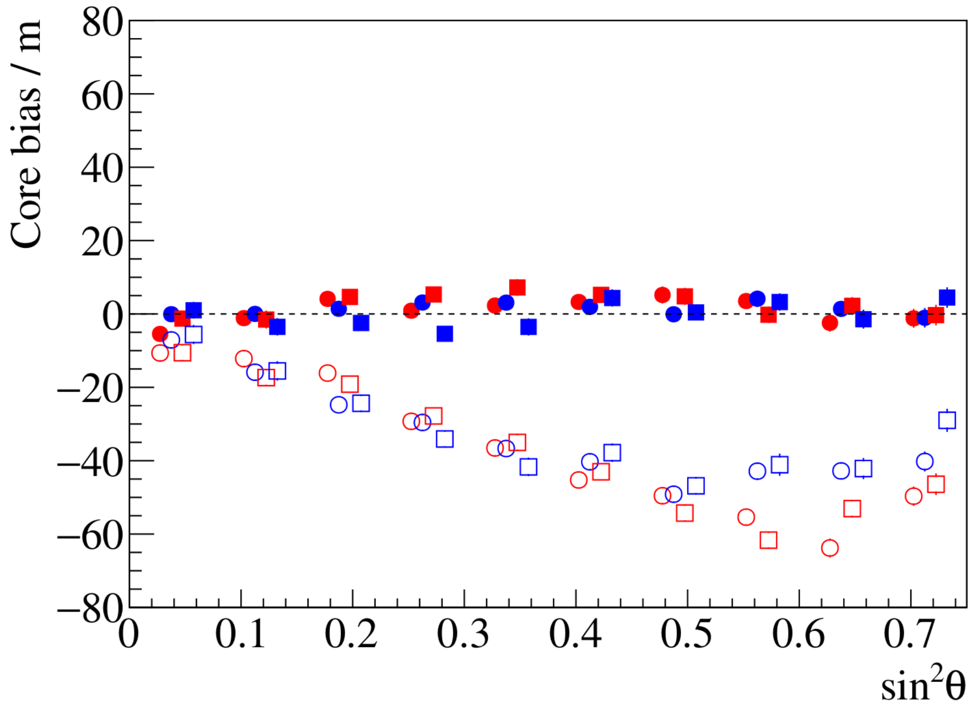
To conclude…

Azimuthal asymmetry in signals **observed in the water-Cherenkov detector** of the surface detector are combination of:

- **geometrical effects** from the inclination of the shower
- **attenuation of the charged particles** from their point of emission to the ground

From simulations, **development of a model describing the amplitude of the asymmetry**:
- suppression of the bias
- improvement of the resolution

No impact observed on the uncertainties in *S*(1000) or on the angular resolution



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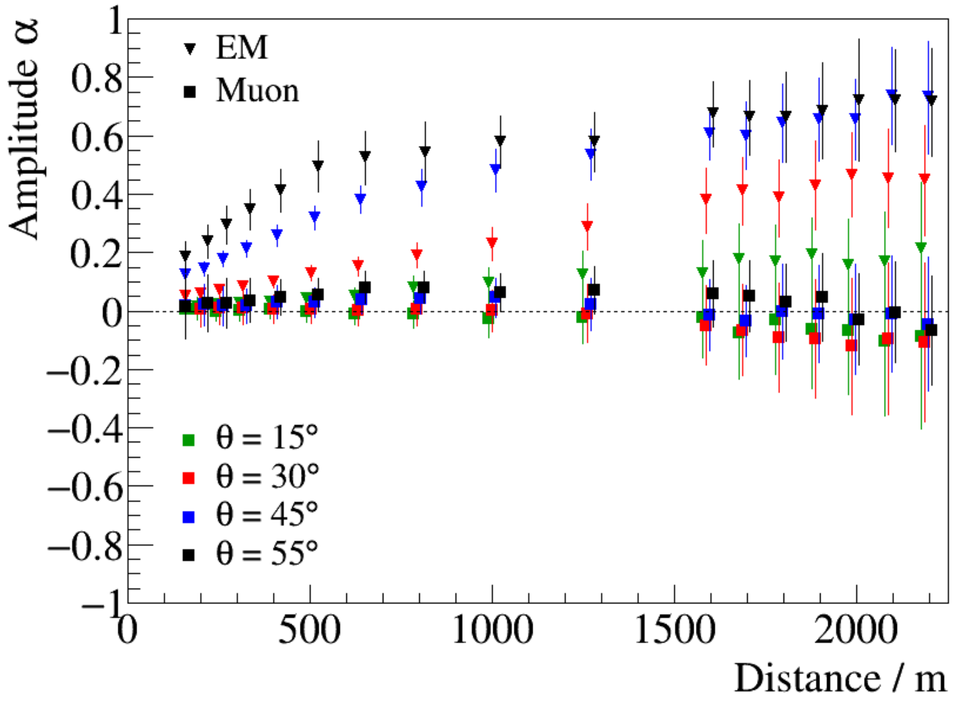

Amplitude of the asymmetry is a **balance between electromagnetic and muonic components** of the shower:
- scintillator detectors?
- muon deficit in simulations?

Trugarez !*

* Thank you!