UNIVERSITÄT SIEGEN

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

Investigating signal fluctuations of the surface detector array of the Pierre Auger Observatory using pair tanks

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Lateral Distribution Function (LDF)

- Lateral particle density of EAS described by LDF:

$$S(r) = S_{1000} \cdot \left(\frac{r}{1000\,\mathrm{m}}\right)^{\beta} \cdot \left(\frac{r+700\,\mathrm{m}}{1700\,\mathrm{m}}\right)^{\beta}$$

with $\beta = 0.9 \sec\theta - 3.3$

- Primary energy estimation via S_{1000}

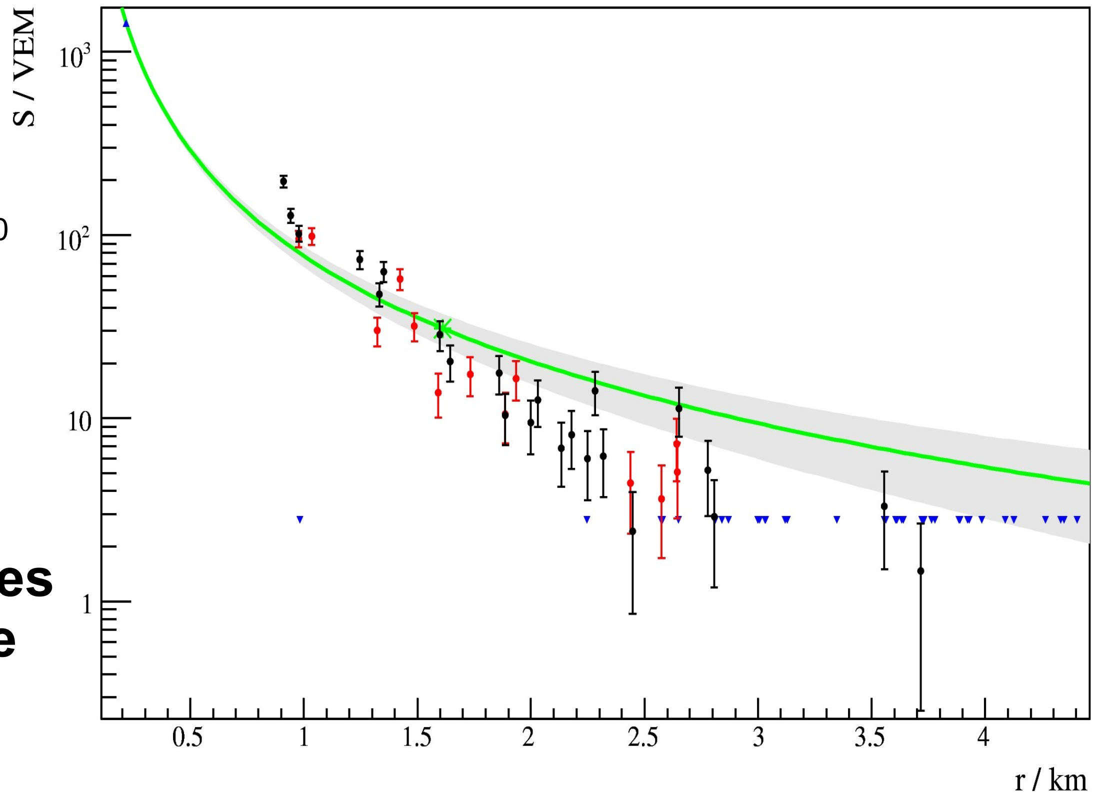
- Fit of LDF to station signals
  → weighted by signal fluctuations

- **Knowledge of signal uncertainties of central importance for reliable energy estimation!**

- Official uncertainty parameterization:

$$\sigma = \left[(0.32 \pm 0.09) + (0.42 \pm 0.07)\sec\theta\right] \cdot \sqrt{S}$$

(Auger Offline v2r4p1, Nucl. Inst. Meth. A 2006)



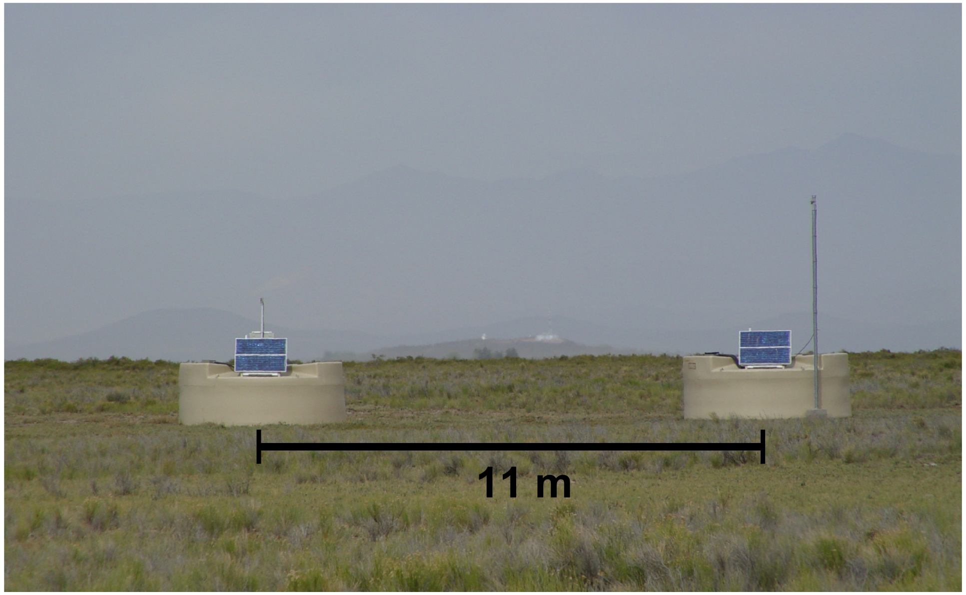
LDF fit for SD event with event ID 4801049 (E=30 EeV)

SD signal fluctuations

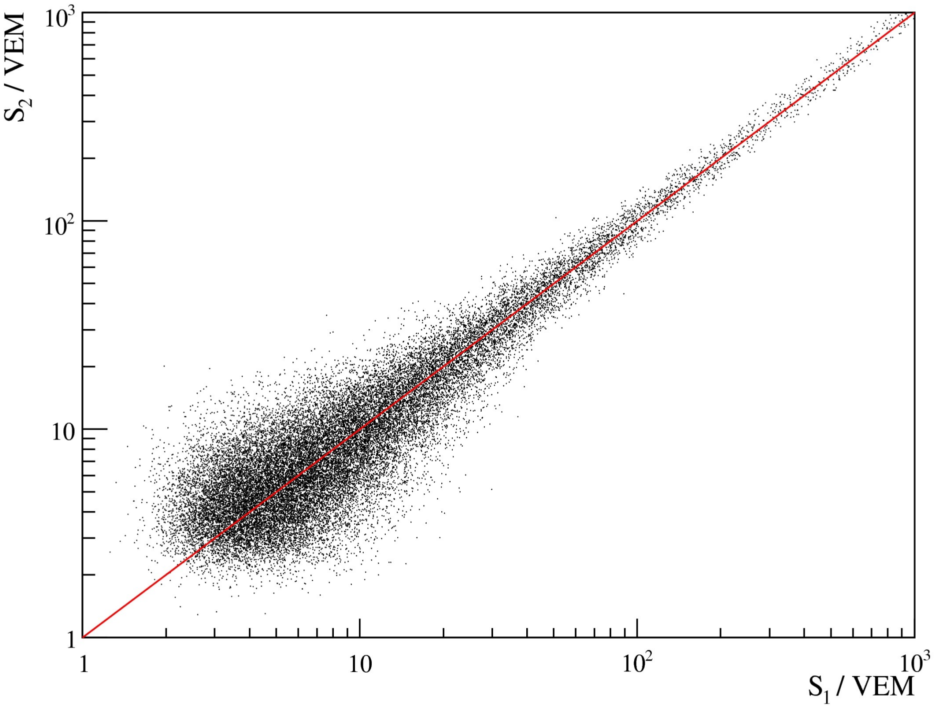
- Measured by pair tanks (distance: 11 m)
  - signal measured in units of VEM
  (**V**ertical **E**quivalent **M**uon)
- 28 pairs (7 triplets)
- Number of particles in SD tank:
  → Poissonian statistics
  (sampling fluctuations)
- Relative signal deviation:

$$\frac{\Delta S}{\bar{S}} := \sqrt{2} \cdot \frac{S_1 - S_2}{S_1 + S_2}$$

- Other sources of signal fluctuations:
  - fluctuations inside tank
  - muon track length (zenith angle)
  - LDF effect
  - azimuthal effect

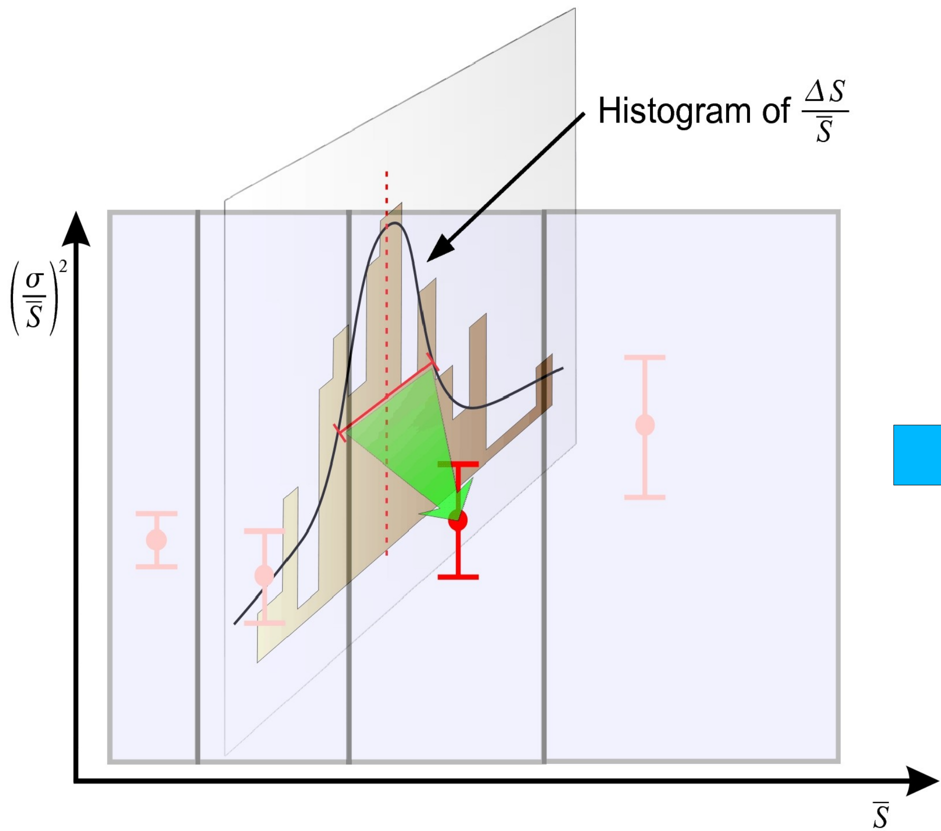


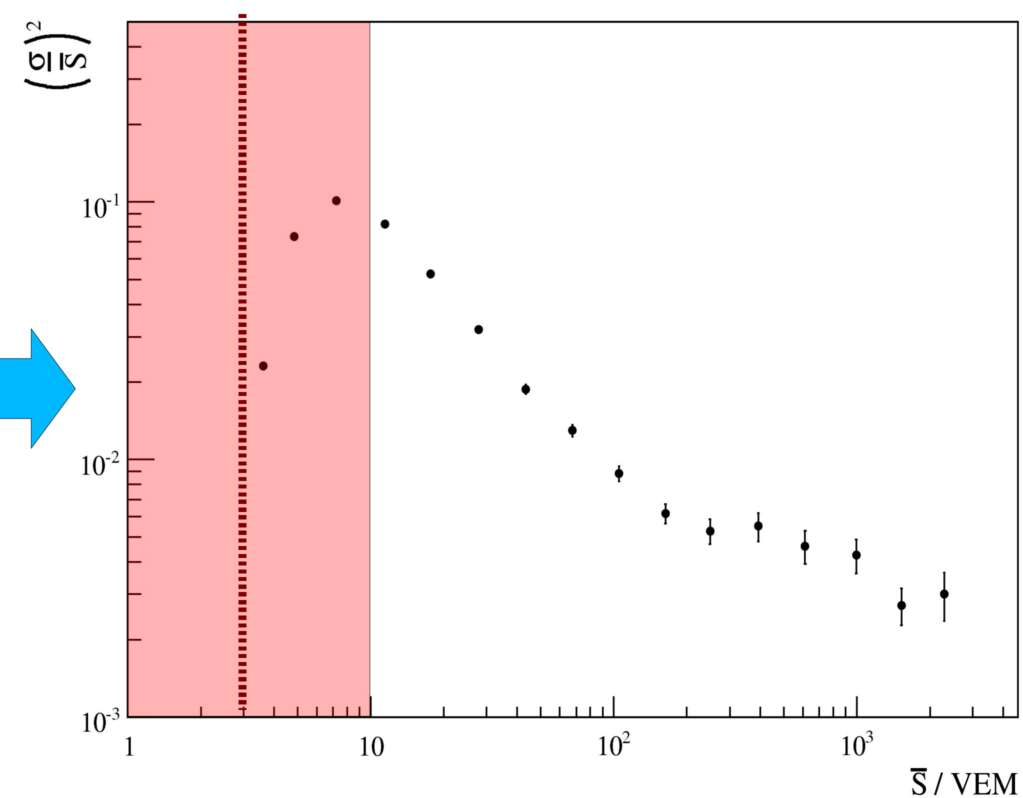
Reference: www.auger.org



Relative signal fluctuations

- Relative signal fluctuation: RMS of $\frac{\Delta S}{\bar{S}}$ distribution
- Dividing signal range of pair samples into logarithmic bins
- 3 VEM threshold cut: avoid bias due to different trigger thresholds
- For low signals: apparent decrease of signal fluctuations





Poissonian-like fluctuation model

- Poissonian-like behavior:

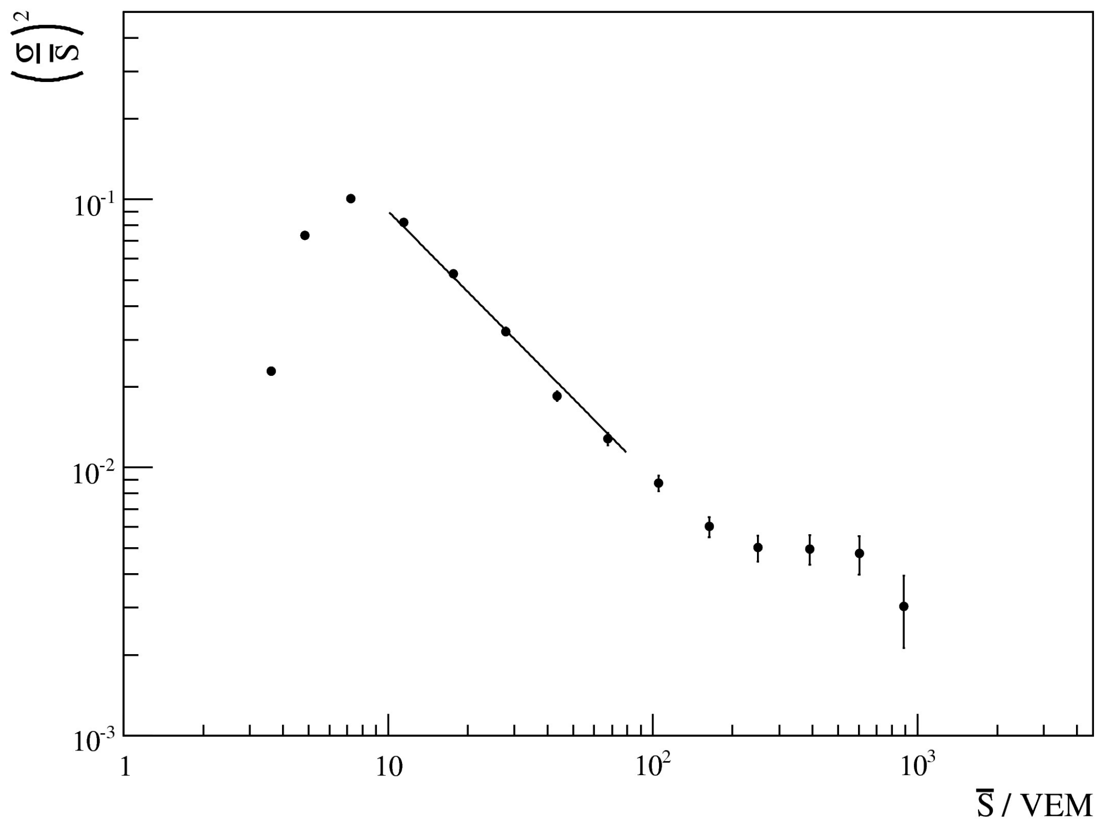
$$\sigma = p_\sigma \cdot \sqrt{\bar{S}}$$

Conversion factor particles ⟷ signal

$$\Rightarrow \left(\frac{\sigma}{\bar{S}}\right)^2 = \frac{p_\sigma^{\,2}}{\bar{S}}$$

- High signals: constant signal fluctuations

$$\left(\frac{\sigma}{\bar{S}}\right)^2 = \frac{p_\sigma^{\,2}}{\bar{S}} + p_N^{\,2}$$



- Fit results:

$p_\sigma = 0.903 \pm 0.013$ (no noise constant)

$p_\sigma = 0.934 \pm 0.008$ $p_N = 0.034 \pm 0.004$ (with noise constant)

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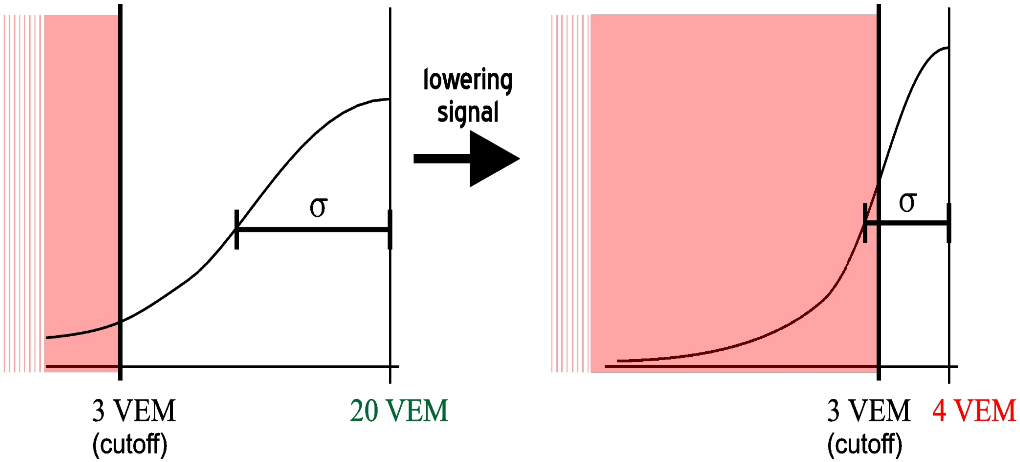
Threshold effect

- Poissonian model cannot follow threshold clipping
  → correction via Toy MC
  Better: Analytical model



- Probability that one tank is below threshold:

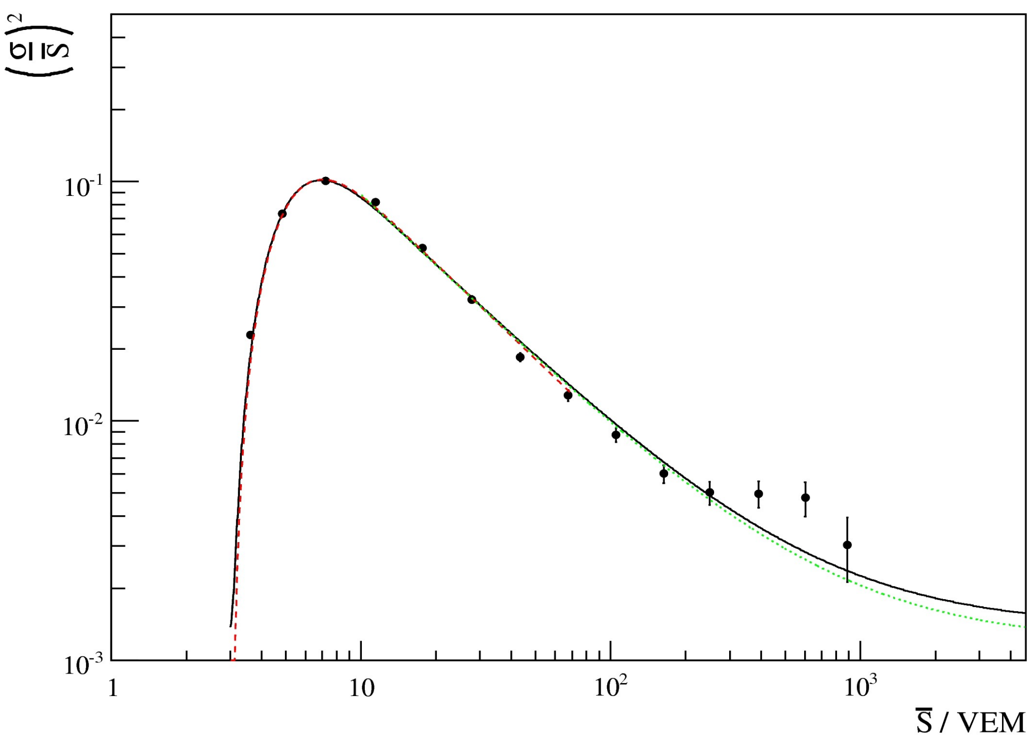
$$P(\bar{S} < S_{th}) = \frac{1}{\sqrt{2\pi p_\sigma^2 \bar{S}}} \int_{-\infty}^{S_{th}} \exp\left(-\frac{(x-\bar{S})^2}{2 p_\sigma^2 \bar{S}}\right) dx$$

- Probability that the sample remains:

$$\bar{P}(\bar{S}, p_\sigma) = 1 - 2P(\bar{S} < S_{th})$$

- Improved Poissonian model:

$$\left(\frac{\sigma}{\bar{S}}\right)^2 = \bar{P}(\bar{S}, p_\sigma) \frac{p_\sigma^2}{\bar{S}} (+ p_N^2)$$



- Fit results:

$p_\sigma = 0.952 \pm 0.007$ (no noise constant)

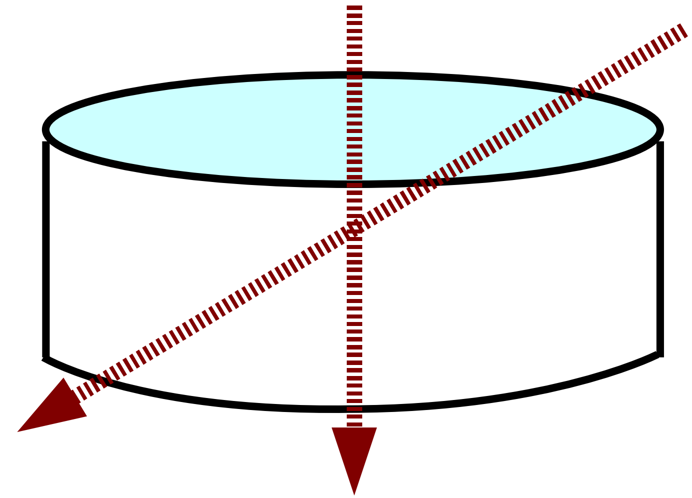
$p_\sigma = 0.933 \pm 0.007$
$p_N = 0.037 \pm 0.004$ (with noise constant)

Zenith angle dependency

- Muons traverse whole SD tank
  → track length zenith angle dependent

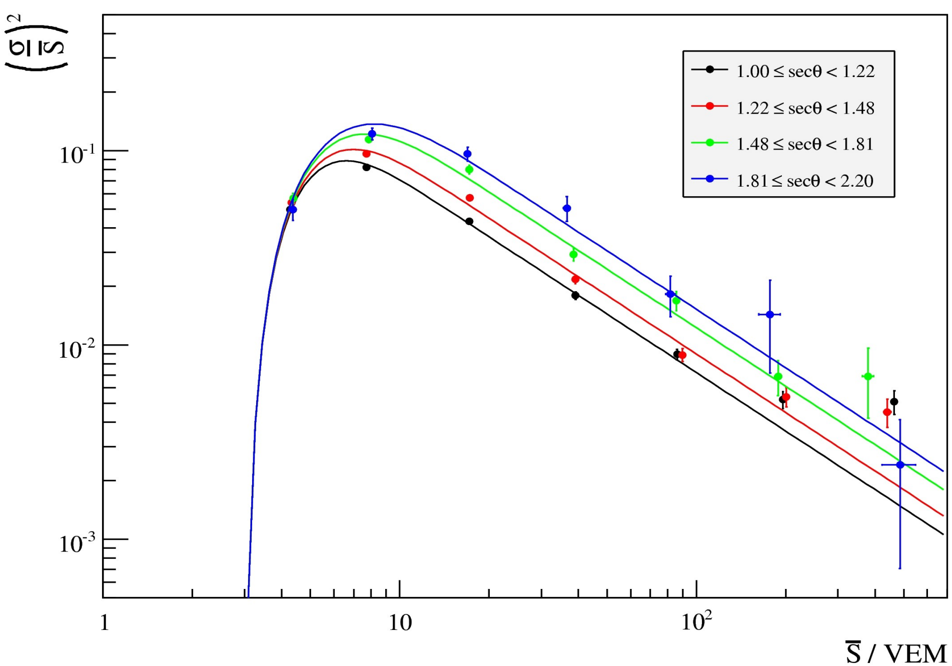
$$l_\mu = h_0 \cdot \sec\theta \quad \Rightarrow \quad p_\sigma = a + b \cdot \sec\theta$$

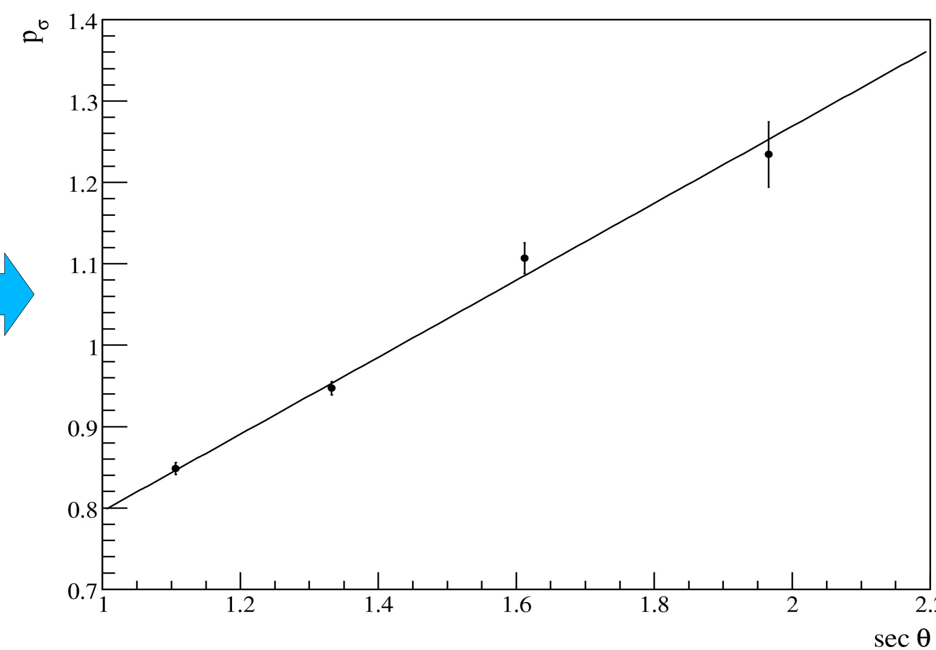
$$p_\sigma = (0.32 \pm 0.04) + (0.47 \pm 0.03) \sec\theta$$



- Official parameters (Nucl. Instr. Meth. A, 2006)

$$\sigma = \left[(0.32 \pm 0.09) + (0.42 \pm 0.07)\sec\theta\right] \cdot \sqrt{\overline{S}}$$





Impact onto energy estimation I

- LDF fit: Weighting of signals with their uncertainties

- Compare impact of official parameters

$$\sigma = \left[(0.32 \pm 0.09) + (0.42 \pm 0.07) \sec\theta \right] \cdot \sqrt{S}$$

with that of the new ones

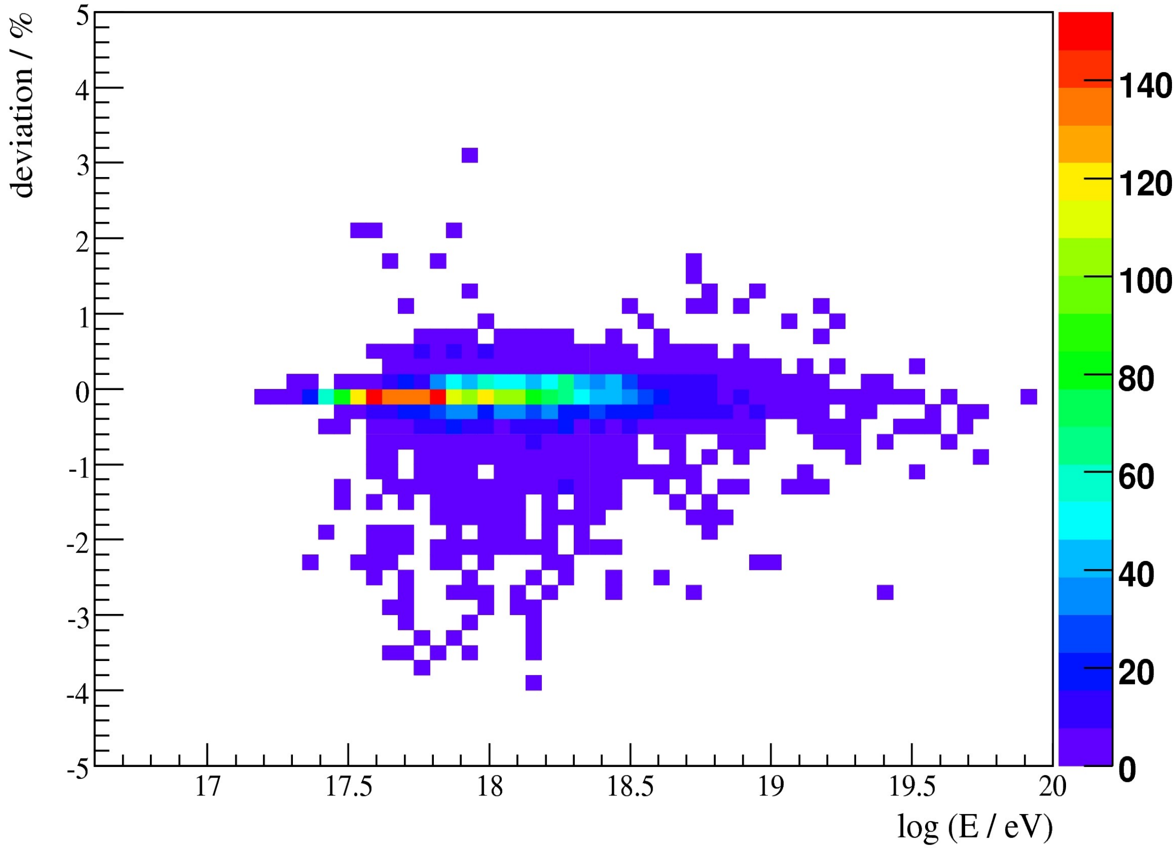
$$\sigma = \left[(0.32 \pm 0.04) + (0.47 \pm 0.03) \sec\theta \right] \cdot \sqrt{S}$$

- Mean energy deviation:

$$\left\langle \frac{\Delta E}{E} \right\rangle = (-0.200 \pm 0.008)\%$$

- RMS:

$$RMS\left(\frac{\Delta E}{E}\right) = (0.497 \pm 0.005)\%$$



negligible

Impact onto energy estimation II

- How will estimated energy change when shifting all signals $\pm 1\,\sigma$?
- Minus case: intercept negative signals ➡ set signal to zero
- Mean energy deviation (**minus case**)

$$\left\langle \frac{\Delta E}{E} \right\rangle = (-16.1 \pm 0.2)\%$$

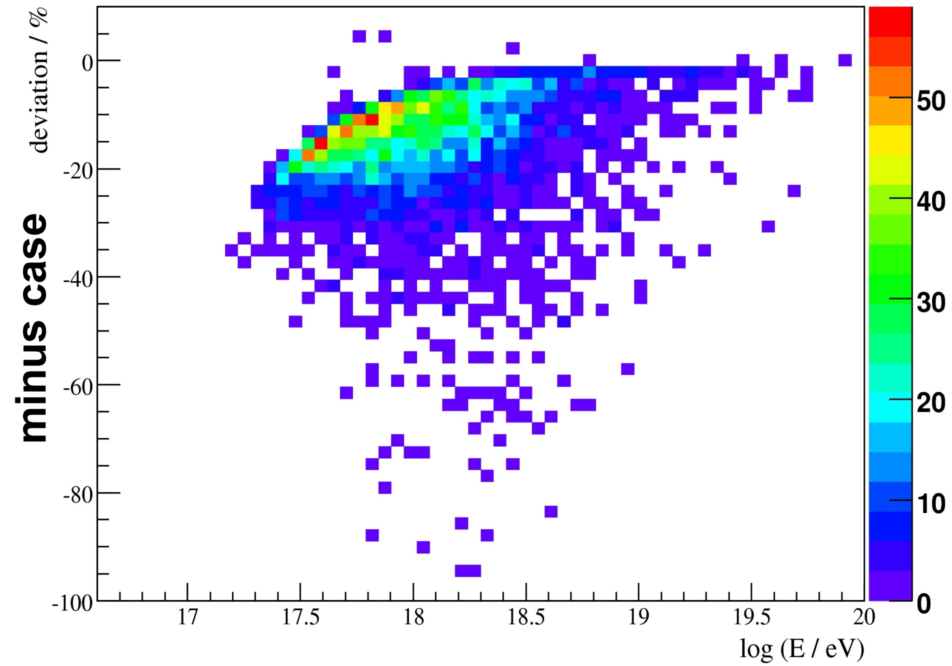
$$RMS\left(\frac{\Delta E}{E}\right) = (10.33 \pm 0.11)\%$$

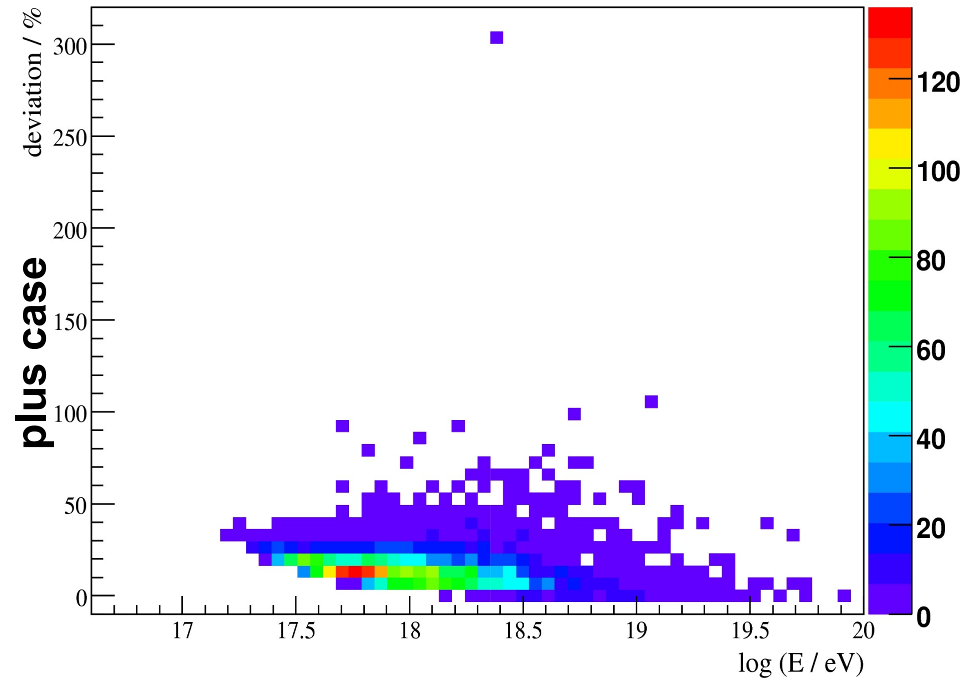
- Mean energy deviation (**plus case**)

$$\left\langle \frac{\Delta E}{E} \right\rangle = (+15.9 \pm 1.8)\%$$

$$RMS\left(\frac{\Delta E}{E}\right) = (10.80 \pm 0.12)\%$$

- Occurrence of such "worst cases" rather improbable (0.9% for 3-fold event, $p_{wc} \simeq \left(\frac{1}{6}\right)^N$ for N-fold event)





Conclusions

- Zenith angle dependency: Official parameters approved, statistical uncertainties improved by factor 2
- Energy estimation stable, deviations due to updated fluctuation parameters negligible
- Signal strength dependent signal fluctuations: All methods lead to compatible results
- Best model: Analytical model with threshold prediction (includes data points <10 VEM)

Backup slides

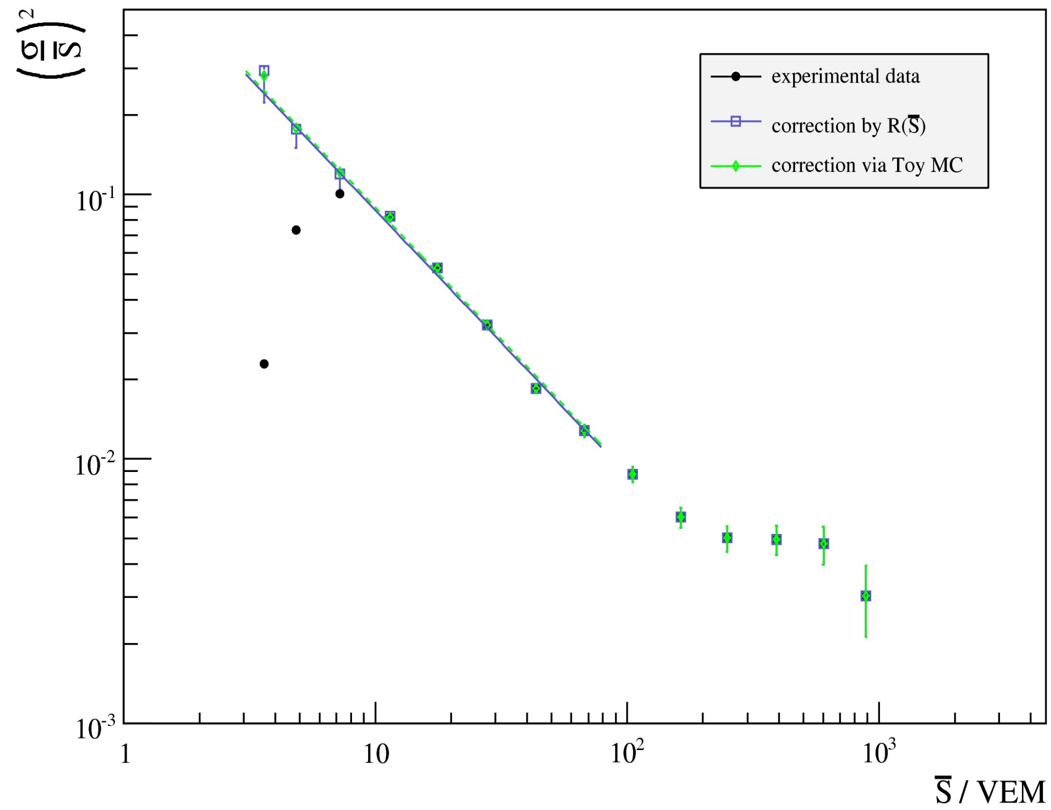
Correction of threshold effect

- Threshold clipping (S<10 VEM):
  correction either via
  - Toy MC
  - correction function

- Toy MC:
  - generate simulated signal spectrum
  - take out signal of sim spectrum
    two fluctuated signal values
  (Gaussian distribution with $\sigma = p_\sigma \sqrt{S}$)
  - create relative signal fluctuation plots **with** and **without** 3 VEM threshold cut
  - For each bin: correction factor

- Correction factor: obtained from threshold prediction

$$R(\bar{S}) = \bar{P}(\bar{S}, p_\sigma)^{-2}$$



Dependency on the distance to the shower axis

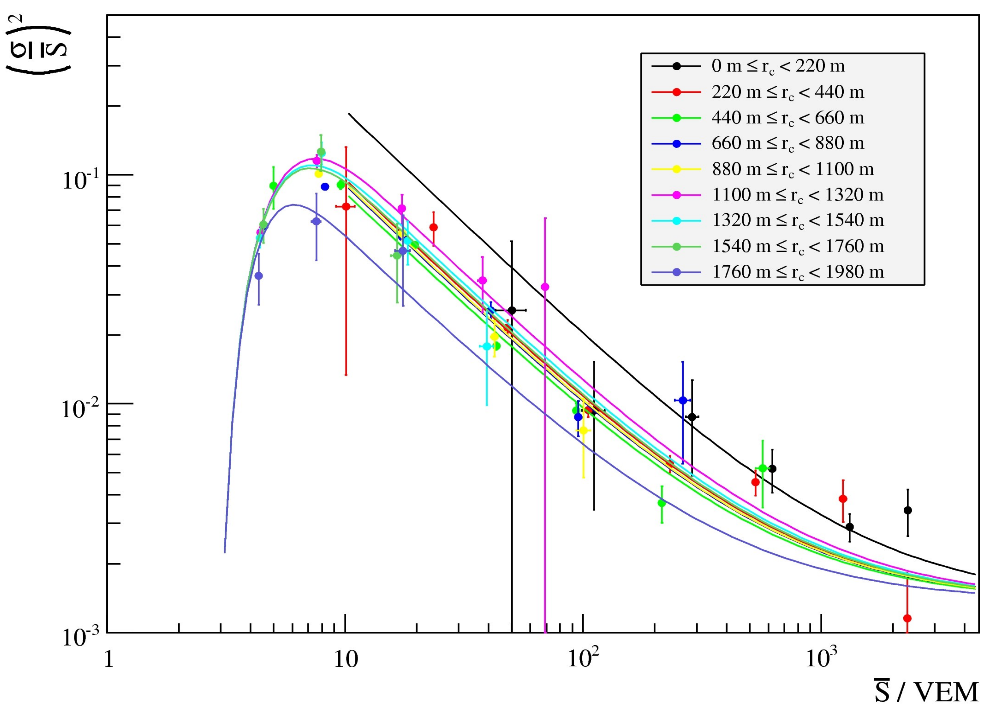
- Low distance to shower axis: additional difference of number of particles:

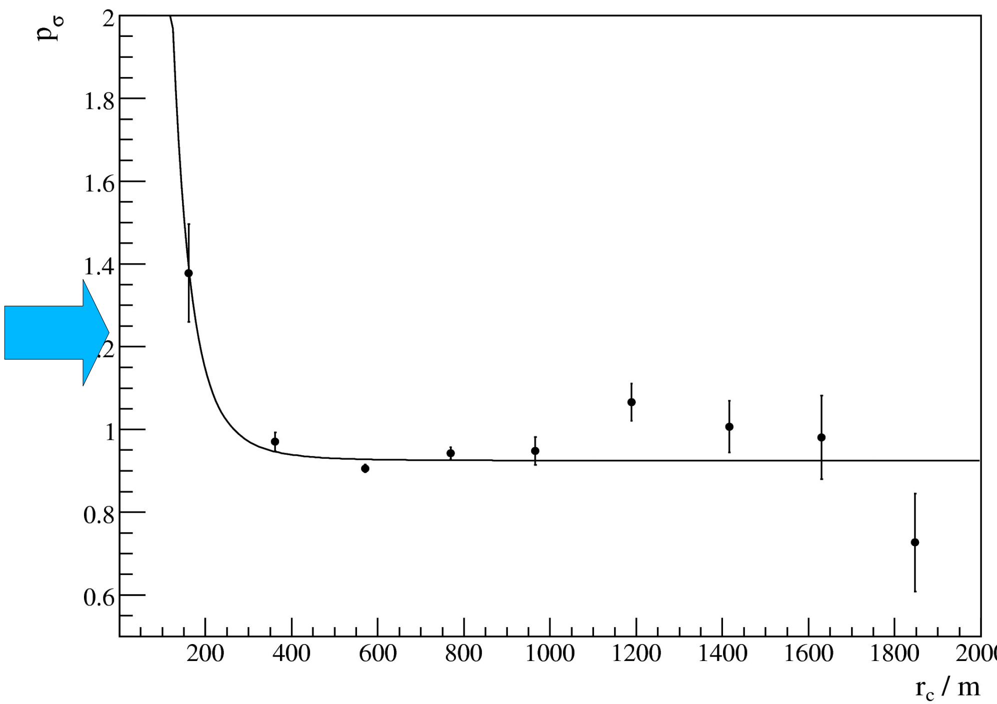
$$\sigma^2 = \left(p_\sigma \sqrt{S}\right)^2 + \left(p_\sigma \Delta S_{LDF}\right)^2$$

- ΔS_{LDF} from NKG-like LDF: $\Delta S_{LDF} = \frac{\partial S_{LDF}(r_c)}{\partial r_c} \Delta r_c$

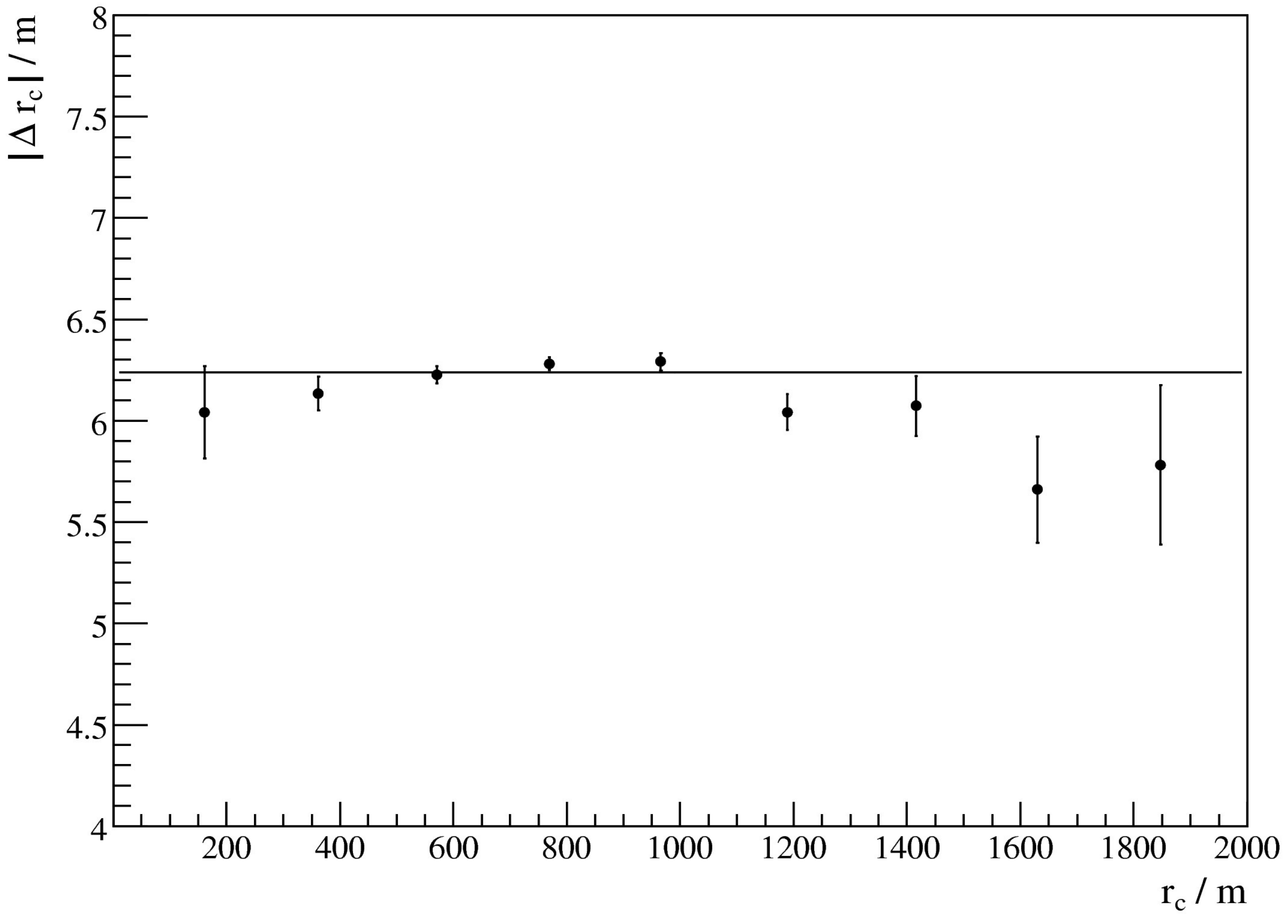
$$p_\sigma(r_c) = p_{\sigma,0} \sqrt{1 + S_0 \left(\frac{\partial f(r_c)}{\partial r_c}\right)^2 f(r_c)^{\beta-2}} \quad \text{with } f(r_c) = \frac{r_c}{1000\,\mathrm{m}} \frac{r_c + 700\,\mathrm{m}}{1700\,\mathrm{m}}$$

- Fit results: $p_{\sigma,0} = 0.925 \pm 0.009 \quad \beta = -1.9 \pm 0.9 \quad S_0 = (210 \pm 500)\,\mathrm{VEM}$





Is Δr_c isotropic?



$$\langle \Delta r_c \rangle = (6.24 \pm 0.02)\,\mathrm{m}$$