Monitoring the Aerosol Phase Function with the Coihueco Fluorescence Detector

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1: The aerosol phase function ... why Auger cares

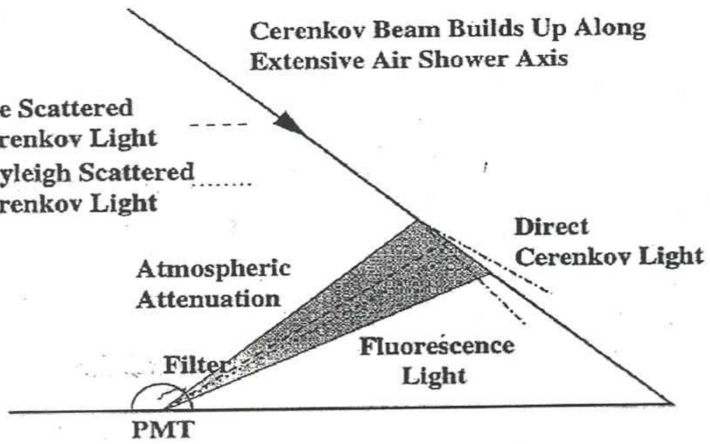
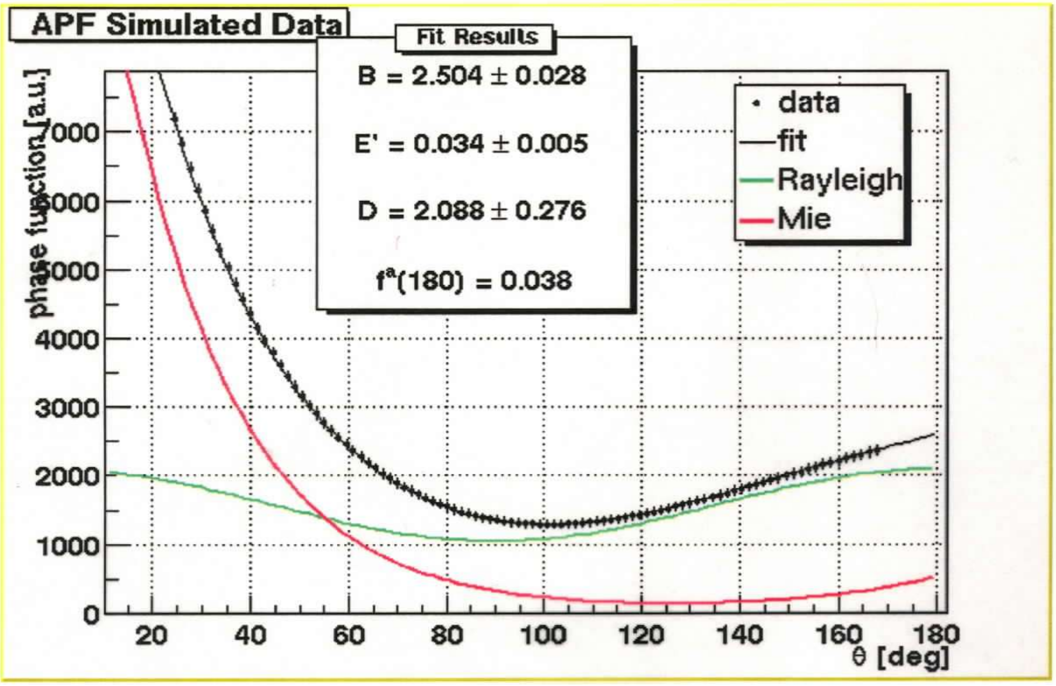


Figure 6.3: A summary of the factors that affect the light signal measured by the detector. Light is generated by the EAS and is attenuated as it travels to the detector. The actual signal measured will further depend upon detector parameters such as the transmission filter and PMT quantum efficiency. Note that most cases the light signal will be dominated by the fluorescence component.

- Through scattering in the air, some air Cherenkov light appears as a background in the fluorescence data.
- The observed light from an extensive air shower will also include a contribution of multiple-scattered light.
- To estimate the multiple-scattered and air Cherenkov light **scattered on aerosols we need the aerosol extinction length,** $\Lambda^a(z, \lambda)$**, and the aerosol phase function,** $\frac{1}{\sigma^a}(\frac{d\sigma^a}{d\Omega})$.

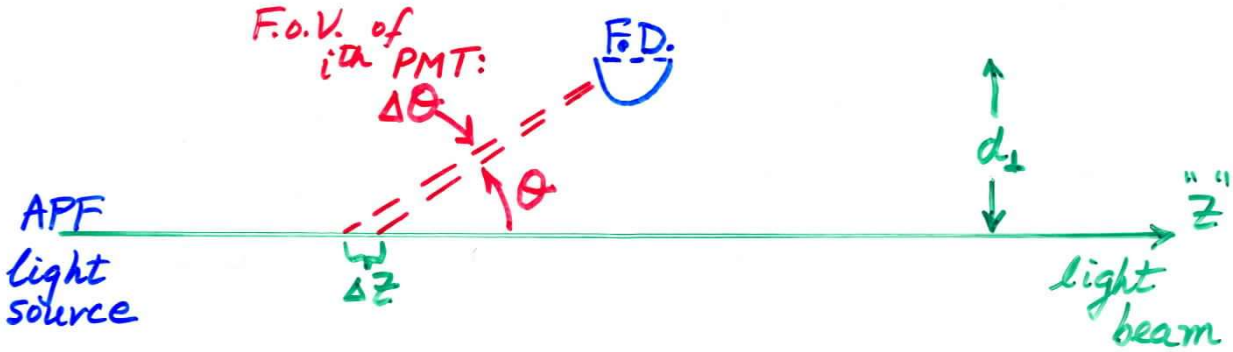
2: Use Auger FD to view side-scattered light



Simulated $\frac{1}{\sigma^a}(\frac{d\sigma^a}{d\Omega})$ measurement using one of the nearby *aerosol phase function* light sources.

- As the Auger fluorescence detectors view $\sim 180°$ in azimuth, even a fixed direction light beam crossing the fluorescence field of view allows $\frac{1}{\sigma^a}(\frac{d\sigma^a}{d\Omega})$ to be determined.
- Dedicated APF, *aerosol phase function*, light sources will be located near 2 fluorescence sites.

APF light source geometry



$$\text{Signal}_i = I_{APF} \times T \times \left(\frac{1}{\Lambda^m}\left(\frac{1}{\sigma}\frac{d\sigma}{d\Omega}\right)^m + \frac{1}{\Lambda^a}\left(\frac{1}{\sigma}\frac{d\sigma}{d\Omega}\right)^a \right) \Delta z_i \, \Delta\Omega_i \, \varepsilon_i$$

where: $T \doteq e^{-\text{light path}/\Lambda_{TOT}}$ ≈ 1 for short paths

$$\Delta z_i \doteq \frac{d^2 \Delta\theta_i}{d_\perp}$$ ["cylinder approx." $\sin\theta \, \Delta z_i = d\Delta\theta_i$]

$$\Delta\Omega_i \doteq \frac{\text{Area (Telescope Aperture)}}{d^2}$$

thus: $\Delta z_i \Delta\Omega_i \doteq \dfrac{\text{Area} \times \Delta\theta_{PMT}}{d_\perp}$ ie constant!!

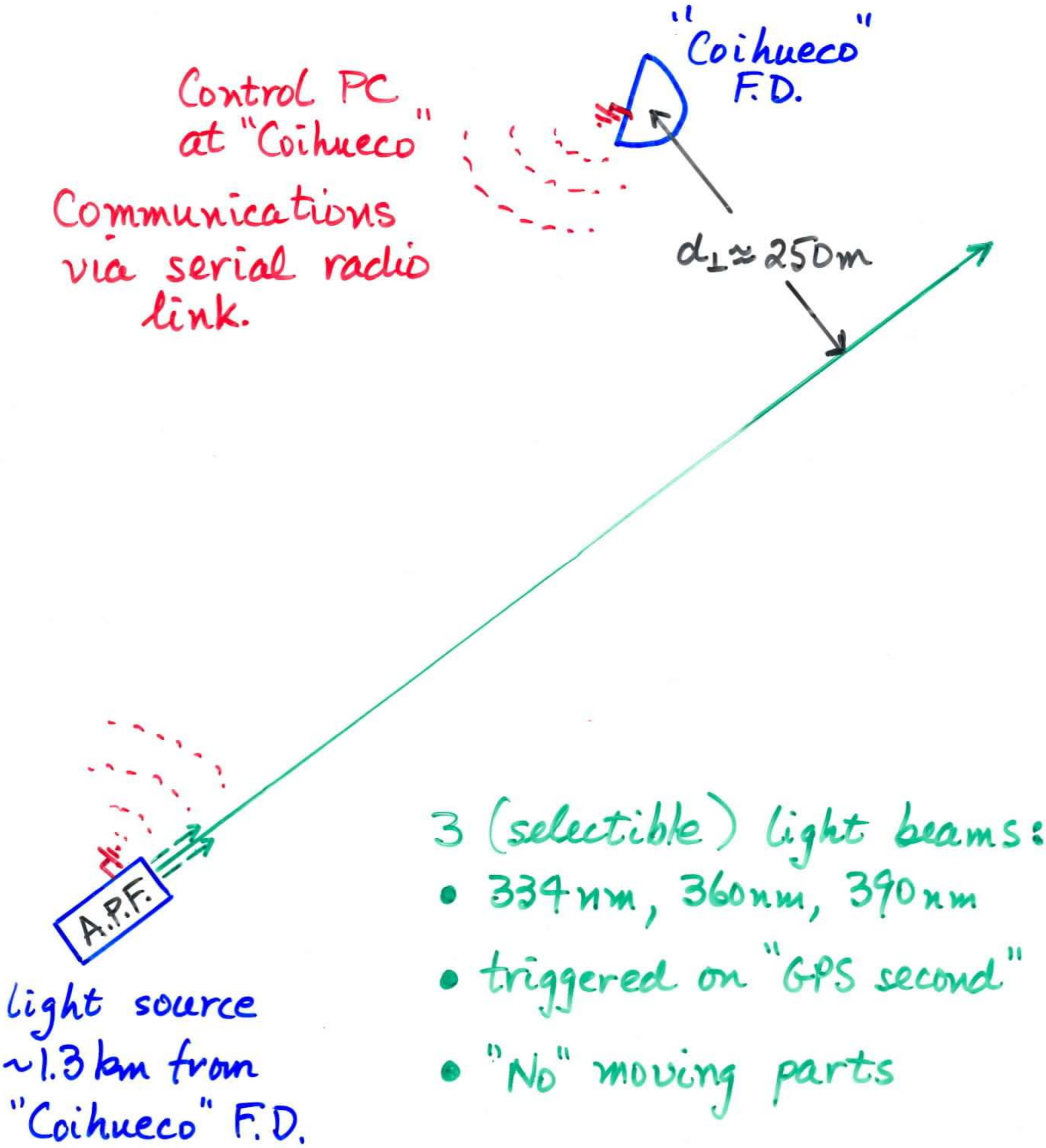
ε_i are the known (flat fielded) efficiencies

3: The first Auger APF light source

The APF light source includes three separate light sources at ∼330nm, 360nm and 390nm.

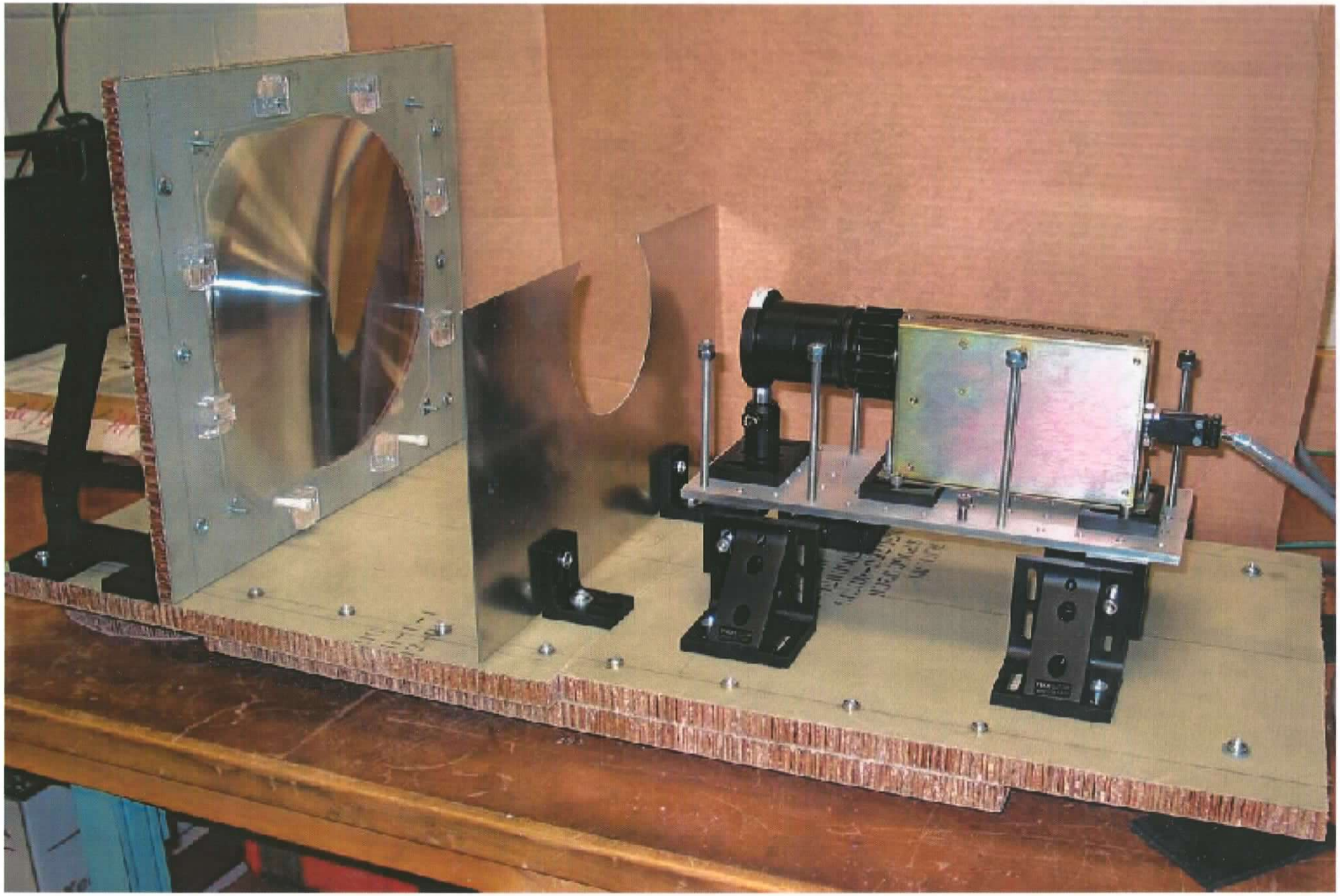
- The APF light sources provide a near-horizontal, pulsed light beam directed across the field of view of a near-by fluorescence detector.
- Three sources provide experimental cross checks as well as the potential to measure wavelength variations in the aerosol phase function.

APF light source at "Coihueco"



3 (selectible) light beams:

- 334 nm, 360 nm, 390 nm
- triggered on "GPS second"
- "No" moving parts



4: A simple APF simulation

- Studies have been done with a simplified model

- Model does match measured quantities:

  1. source intensities (2.5μJ/pulse at 334nm, 4μJ/pulse at 360nm and 390nm)
  2. FD efficiencies (0.125 PEs/γ at 360nm, 0.080 PEs/γ at 334nm and 390nm) and 2.2m diameter Schmidt corrected telescope aperture
  3. night sky backgrounds (170 360nm-equivalent $\gamma/m^2/\mu$sec) ... and each datum was assumed to include 3 adjacent channels (transverse to the track) $\times$ 4μsec (pulse duration)
  4. typical molecular and aerosol horizontal attenuation lengths
  5. actual locations of APF source and Coihueco FD with a 2° angle of APF beam to the horizontal

- But telescope details, PMT signal and readout details, multiple scattered light, ... were **not** included

5: Some *fine print* details

- Cylindrical geometry is almost correct ... in practice the simulated signals were corrected by actual "$\Delta z \cdot \Delta\Omega$" *versus* approximate "Area$\cdot\Delta\theta/d_\perp$"

- No correction for light attenuation is almost correct ... in practice the simulated signals were corrected by $e^{light-path(\theta)/\Lambda_{tot}}$ where: $light-path(\theta)$ is the total light travel distance (for a given scattering angle) and Λ_{tot} is the horizontal attenuation length **at the height of the fluorescence detector**

- The aerosol signal is almost correct ... but it is actually proportional to ALBEDO/Λ^a where ALBEDO $<$ 1 means that some of the aerosol light is absorbed (*versus* all scattered). [The simulation used ALBEDO $=$ 0.9]

6: 2-parameter and 3-parameter fits

- Two **Mie** scattering *phase function* parameterizations were compared (fitted) to the data:
  1. **2-parameter** form:

$$f^a(\mu) = \frac{1-g^2}{4\pi}\left(\frac{1}{(1+g^2-2g\mu)^{3/2}} + f\frac{3\mu^2-1}{2(1+g^2)^{3/2}}\right)$$

  2. **3-parameter** form:

$$f^a(\theta) = \frac{1}{2\pi}\left(\frac{e^{-B\theta} + E'e^{-D(\pi-\theta)}}{(\frac{1+e^{-B\pi}}{1+B^2}) + \frac{E'(1+e^{-D\pi})}{1+D^2}}\right)$$

- **Rayleigh** scattering phase function from theory
- The relative fractions of Rayleigh (molecular) and MIE (aerosol) are set by $1/\Lambda^m$ and $ALBEDO/\Lambda^a$ respectively.
- The horizontal attenuation lengths (Λ^m and Λ^a) are known from local T,P and horizontal backscattered LIDAR shots.
- For 2-parameter fits there is some sensitivity to ALBEDO ... else it must be an input (*e.g.* ALBEDO = 0.9)
- The overall intensity (normalization) is an additional parameter. For stable light sources and known/stable detector efficiencies this is essentially constant ... and thus can be averaged over many hours/nights of APF light source operation!

7: Initial (simulation based) observations

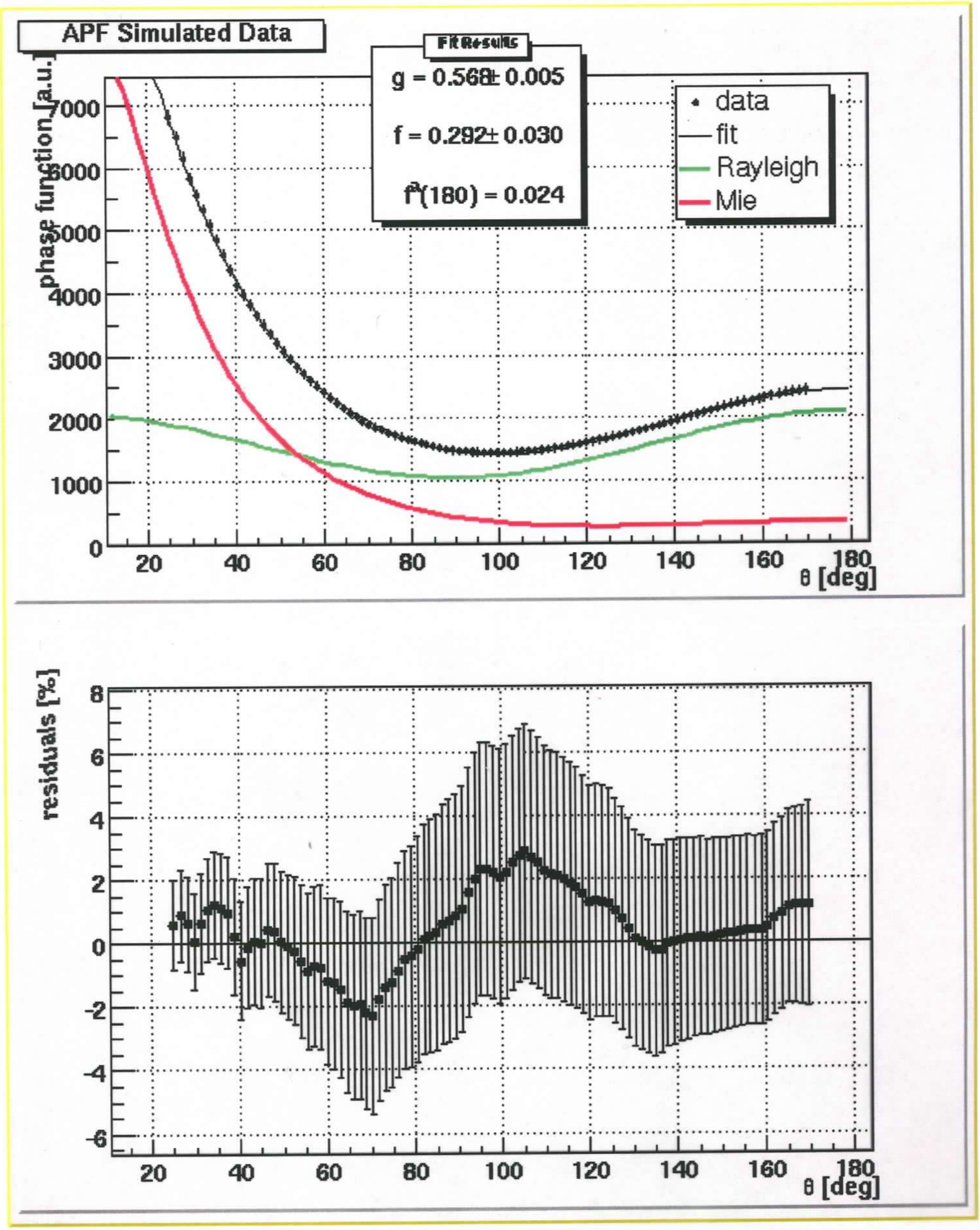
- **Cross check:** When 2-parm (or 3-parm) Mie phase functions were used as input in the simulation, the fits to the simulated data resulted in essentially the same parameters

- For some (Elbert) input phase functions both 2-parm and 3-parm fits were stable and reproduced the simulated data. **In this instance a fit for the ALBEDO** *[2-parm phase function model]* **reproduced the input value** ... with an uncertainty < 0.05

- For some (Longtin) input phase functions only the 3-parm fit provides a description of the data ... but with little sensitivity to the ALBEDO

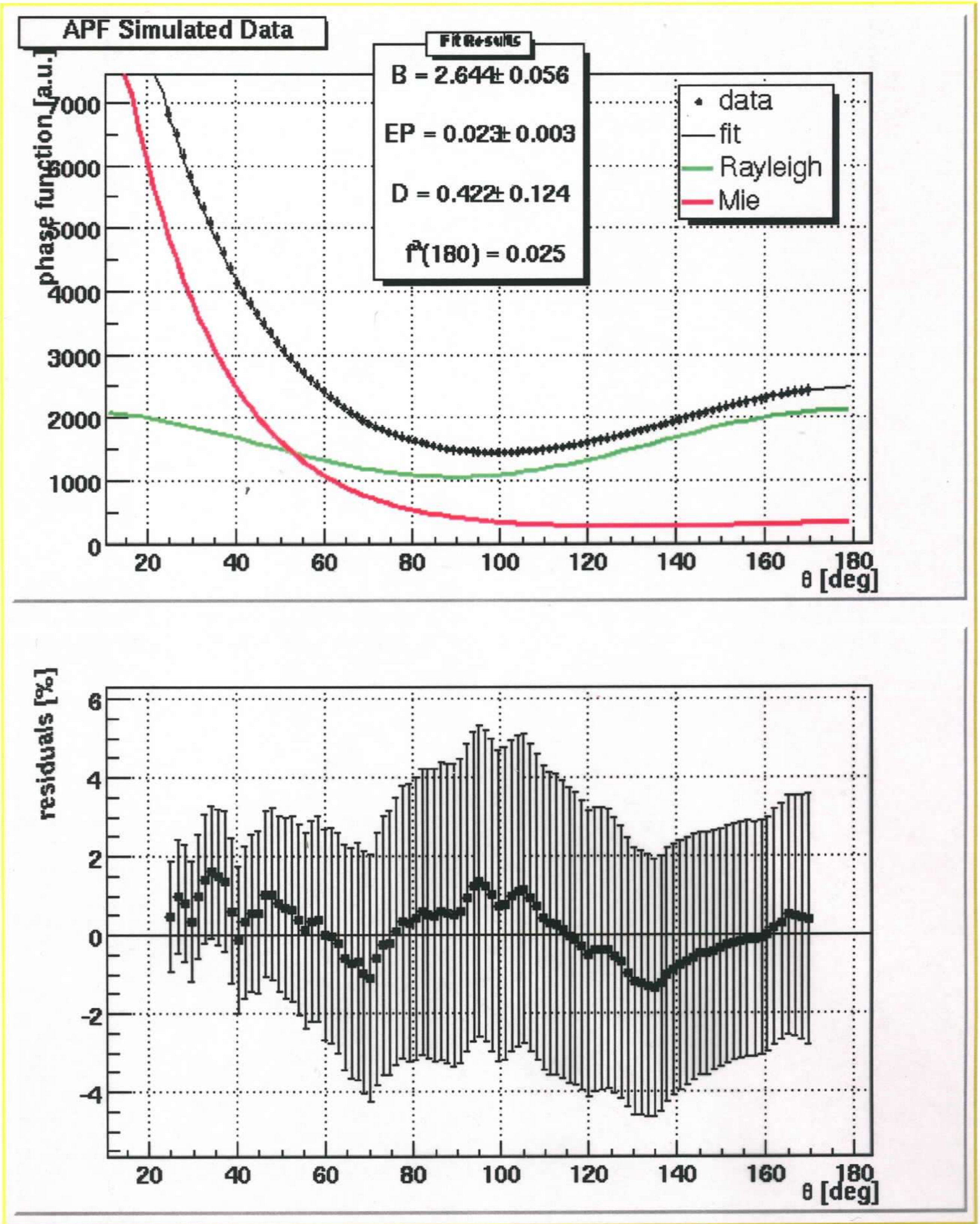
- Clearly the APF analysis is insensitive to radical (upward) variations (from smooth extrapolations) for $\theta < 20°$ and for $\theta > 170°$ ... *e.g.* from large aerosol particulates. **One indication (of radical upward variations) is a reduced value for the** ***fitted*** **ALBEDO**!

"Elbert"



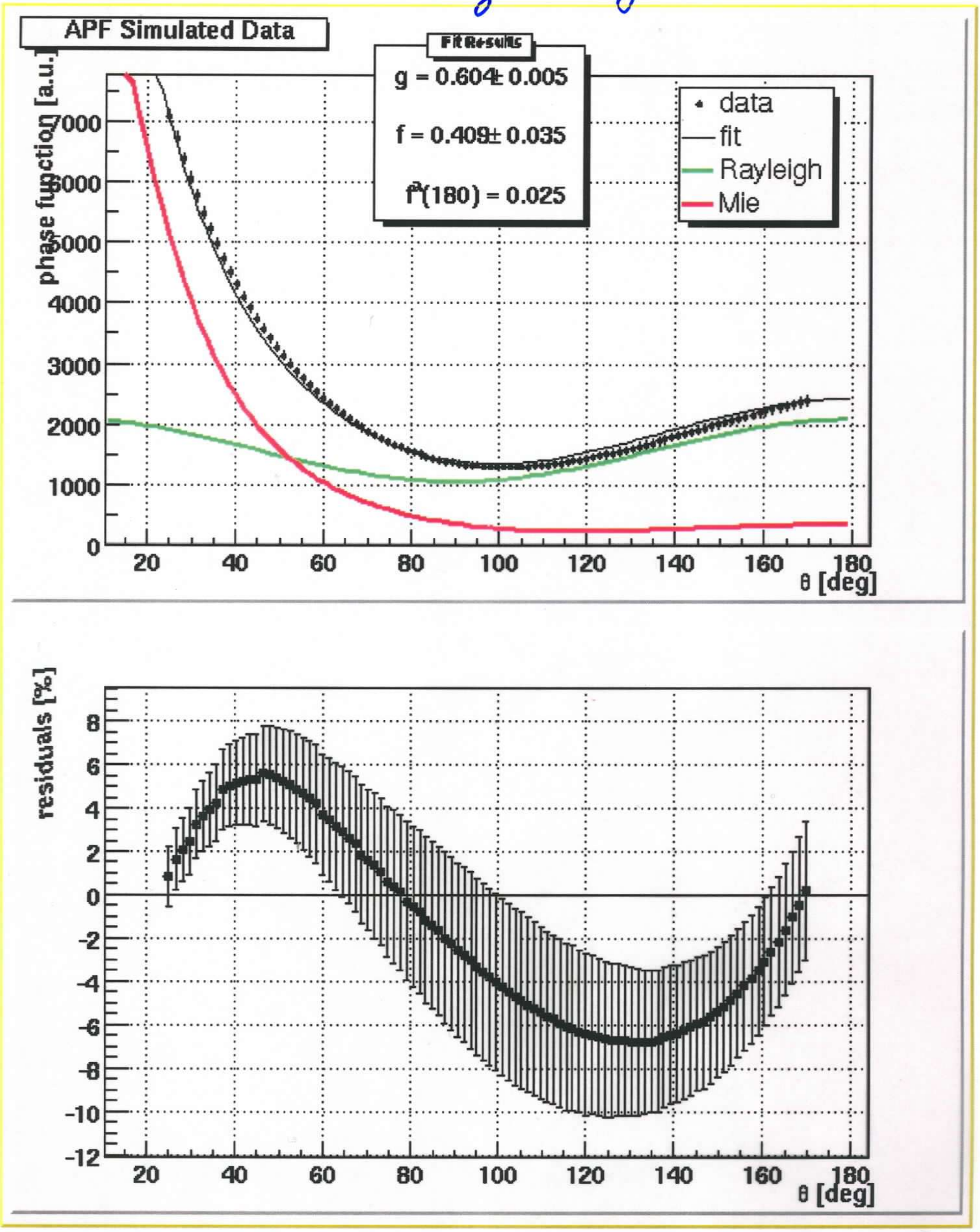
APF Simulated Data
Fit Results
g = 0.568± 0.005
f = 0.292± 0.030
f²(180) = 0.024
data
fit
Rayleigh
Mie
phase function [a.u.]
0
1000
2000
3000
4000
5000
6000
7000
20
40
60
80
100
120
140
160
180
θ [deg]
residuals [%]
-6
-4
-2
0
2
4
6
8
20
40
60
80
100
120
140
160
180
θ [deg]

"Elbert"

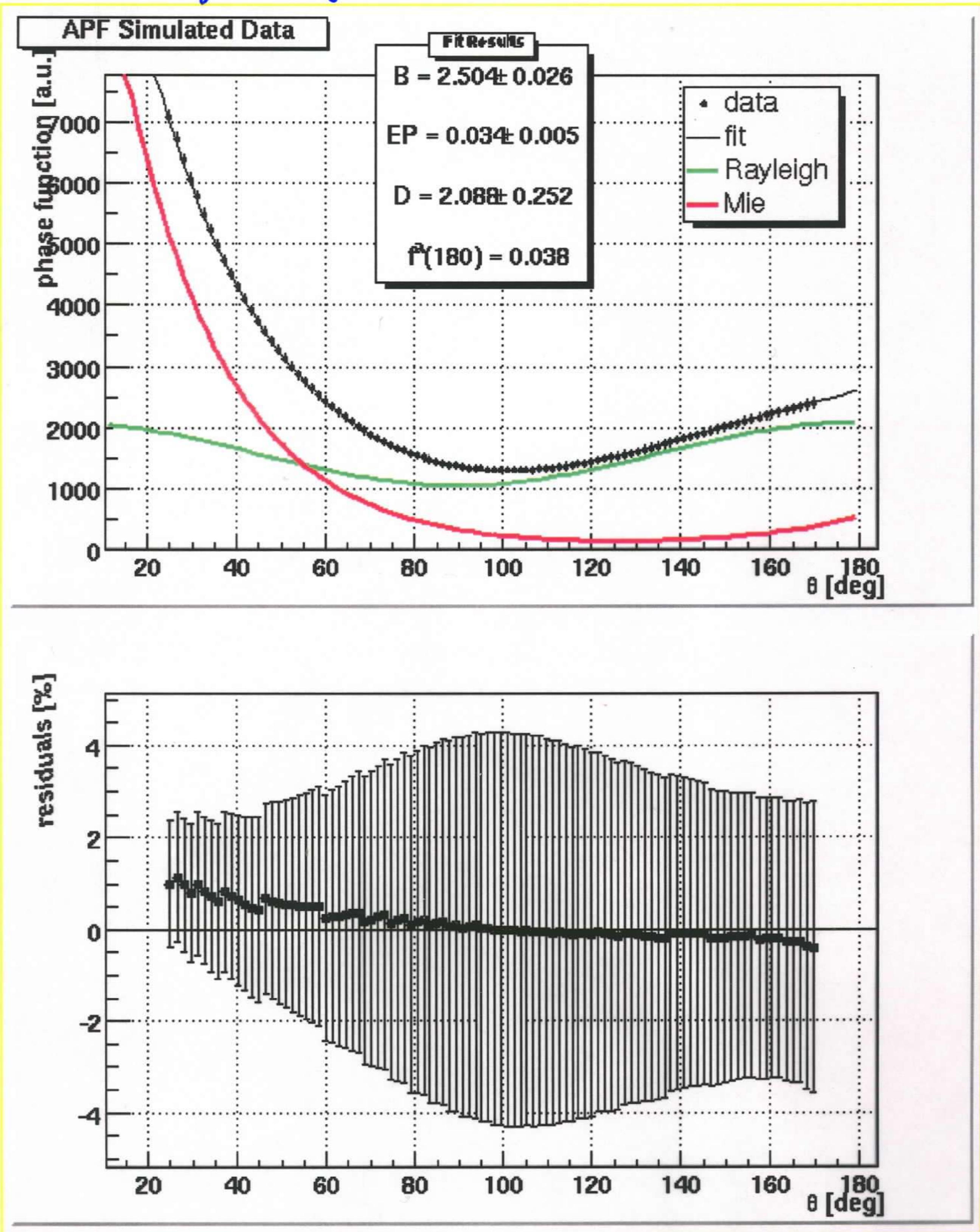


APF Simulated Data
Fit Results
B = 2.644± 0.056
EP = 0.023± 0.003
D = 0.422± 0.124
f³(180) = 0.025
data
fit
Rayleigh
Mie
phase function [a.u.]
θ [deg]
residuals [%]
θ [deg]

Parameterized Longtin



Parameterized longtin: B=2.50, EP=0.035, D=2.141



8: Possible Atmospheric Community Involvement

- Auger will measure (every hour during Auger FD data taking):
  1. the aerosol phase function (in the near UV)
  2. the aerosol horizontal extinction length (at several wavelengths)
  3. the aerosol optical depth *VS* height (at 355nm)
  4. air temperature, pressure, humidity, wind speed and direction (+ radiosonde balloons ...)
  5. cloud cover

- **Are these of interest to the atmospheric community?**

- **Can the atmospheric community provide us with guidance on how to extrapolate the aerosol phase function to heights of several kilometers above the ground level?**