Assessing aerosol induced errors in Monte Carlo based air-shower reconstruction for atmospheric Cherenkov detectors

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AtmoHEAD workshop
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Outline

This is a project that evolved within the H.E.S.S. collaboration
as part of a verification of our Monte Carlo simulations.

$\rightarrow$ Also check out our contribution at the 'γ-2022'!

In this talk:

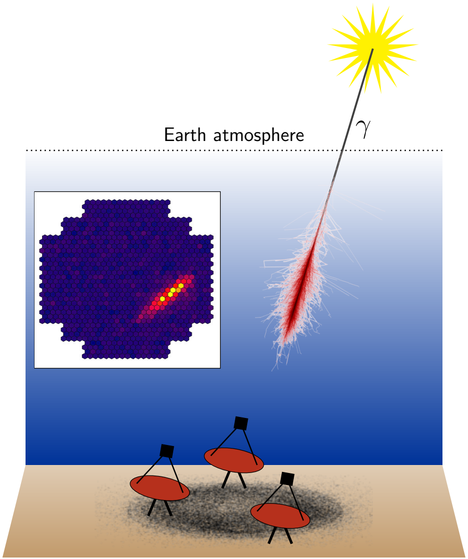
1. The H.E.S.S. experiment and imaging atmospheric Cherenkov telescopes (IACTs)
2. The atmosphere in Monte Carlo (MC) simulations for IACTs
3. An approach to assess aerosol induced air-shower reconstruction errors

The H.E.S.S. experiment

- Array of five IACTs to detect γ rays in the very high energy (VHE) domain
- Khomas Highland of Namibia 1835 m asl
- 107 m^2 (CT1–4) and 614 m^2 (CT5) mirror area
- 5° and 3.2° field of view
- Energy range: $\sim$ 30 GeV to $\sim$ 100 TeV

Very brief IACT basics

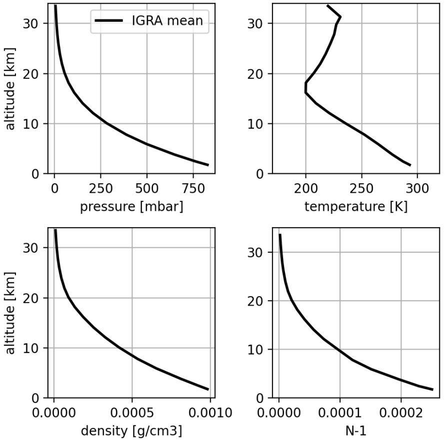
- Atmosphere as calorimeter
- Physics basis:
  1. Air shower cascades via pair-production
  2. Cherenkov emission from charged particles
- IACTs capture Cherenkov photons and image air shower events
- Direction via stereoscopy
- Energy via brightness/size
- Shower reconstruction based on extensive Monte Carlo simulations, i.e. from shower evolution to optical propagation and electronic response ("*simulated images vs. measurements*")



Atmosphere description in MC simulations

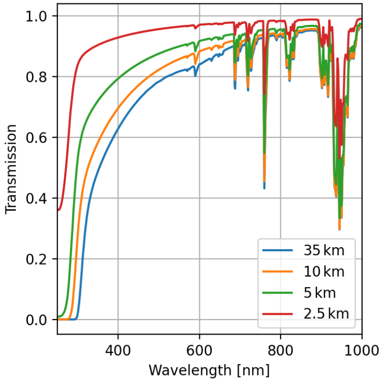
1. Density profile

- Shower evolution and Cherenkov photon production (Frank-Tamm formula)
- Temperature, density, refractive index



2. Transmission profile

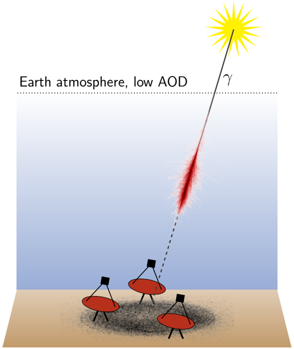
- *What fraction of emitted photons reaches the ground?*
- Temperature, water, ozone, other trace gases and molecules, **aerosols**, wind, . . .

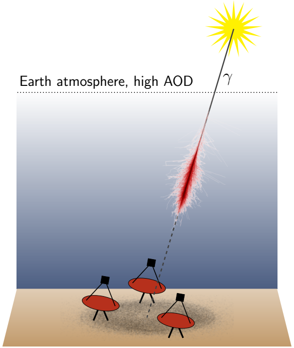


Atmospheric variations

Variations in the **transmission profile**

- change the Cherenkov light yield and thus energy threshold affecting energy reconstruction
  (*"1 TeV shower in bad conditions can yield Cherenkov signal similar to a 0.5 TeV shower in good conditions"*)
- can be accounted for by adapting atmospheric model in MC simulations ...
  This may become unpractical with huge parameter space to cover!
- are often not fully taken into account; MC productions with few standard atmospheres, "bad weather" data discarded/excluded from analyses





This raises questions:

- How to define 'good conditions'?
- What are the remaining variations?
- What is the impact on different levels of the analysis?
  ⇒ Also important for MC validataion(!!),
  i.e., what deviations to expect/accept between MC and data?

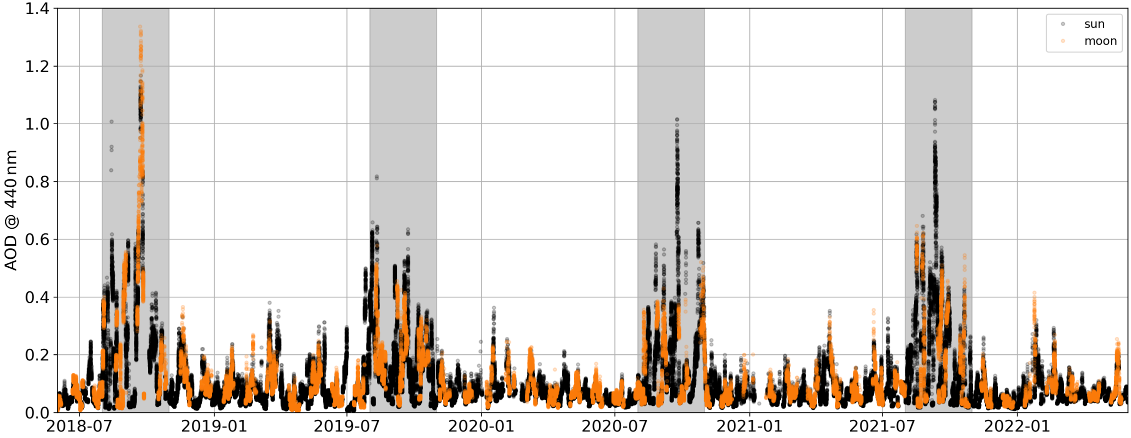
How large are these variations at the H.E.S.S. site?

Data sources:

- The AErosol RObotic NETwork AERONET, which provides **multispectral aerosol data** from just 250 m next to our telescopes **since Feb. 2016**, **pre-calibrated** and in **almost real-time**.
- Integrated Global Radiosonde Archive IGRA, with data from **∼20k weather-balloon flights** performed **around WHK since 1970 until today** with **daily updates** of raw data and derived data products.
- In-service Aircraft for a Global Observing System IAGOS, providing data gathered with **meteorological sensors carried on commercial flights** with **2398 take-offs and landings in WHK**.

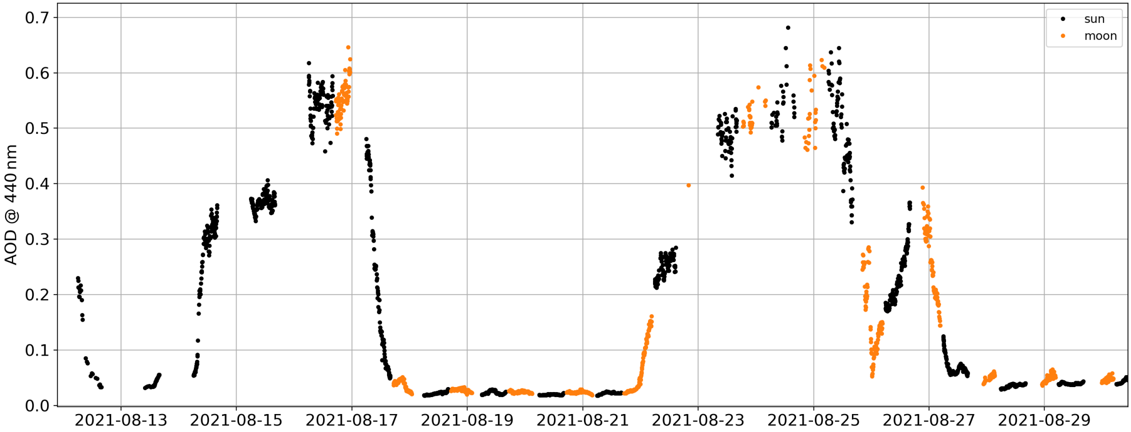
The AERONET station at the H.E.S.S. site.

AERONET HESS site - aerosol data



- Annual biomass-burning in southern Africa from August to October → *clearly visible!*
- Strong fluctuations! Also during non-biomass burning season.

AERONET HESS site - aerosol data



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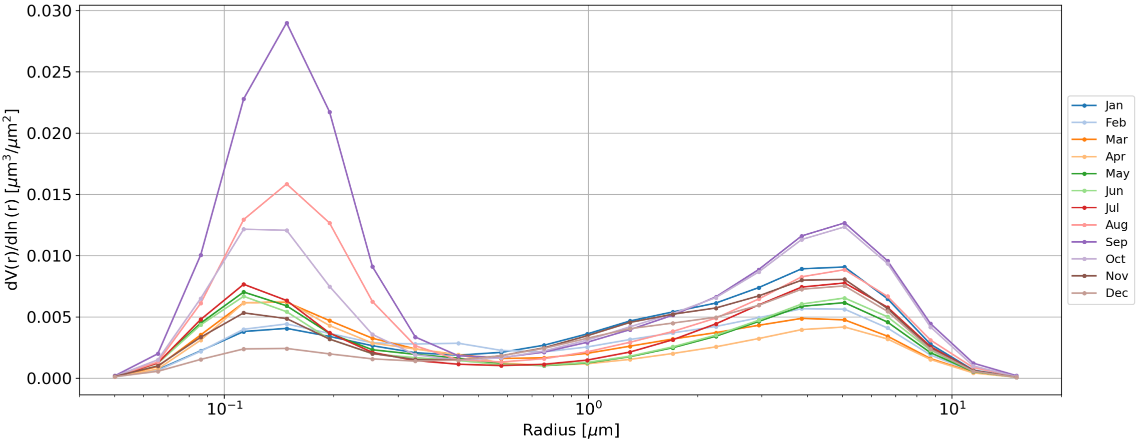
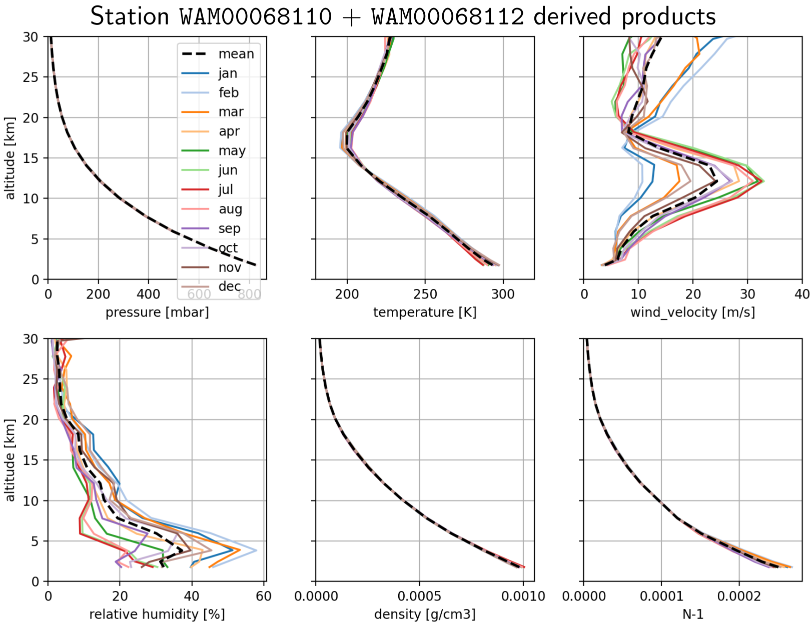


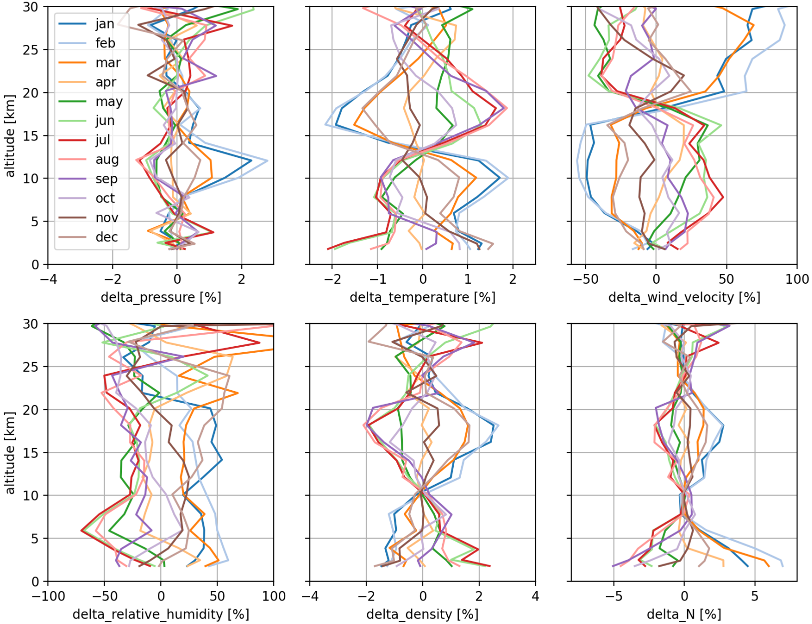
- Annual biomass-burning in southern Africa from August to October → *clearly visible!*
- Strong fluctuations! Also during non-biomass burning season.
- Extreme changes within $\mathcal{O}$(hours)!
- Derived aerosol size distribution shows varying composition

IGRA - radiosonde data

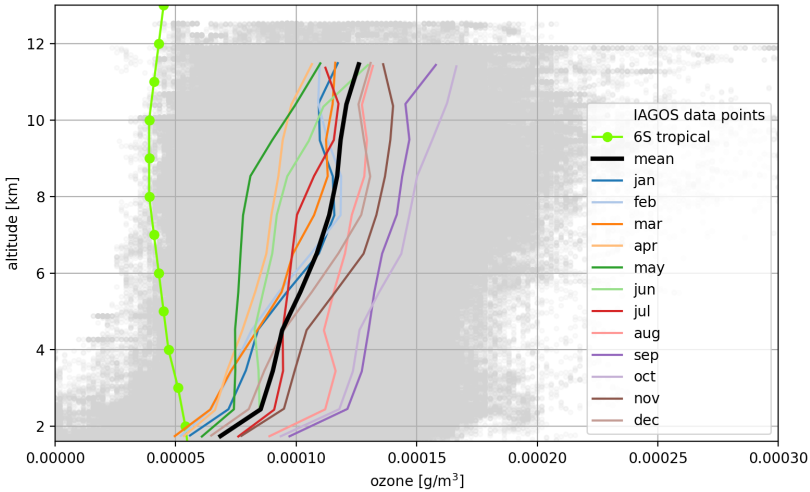


IGRA - radiosonde data

Station WAM00068110 + WAM00068112 derived products, relative dev. to mean



IAGOS - ozone data



- Deviates from tropical reference model
- Highest concentrations from August to November
  ⇒ Tropospheric ozone correlates with biomass burning season!

Assessing the influence of aerosol variations

Idea:
Compare MC transmission profile with profiles of various conditions and calculate a correction factor.

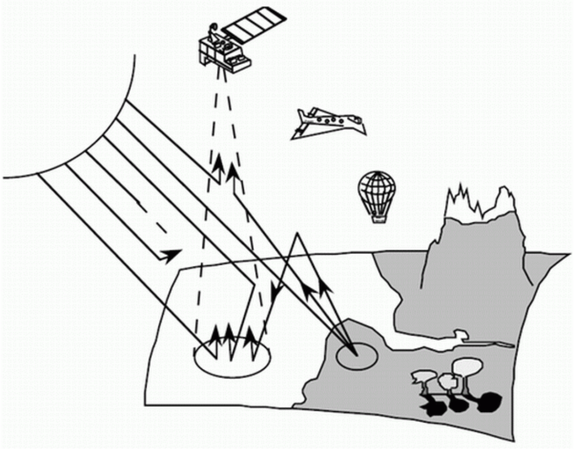
Step by step:

1. Generate transmission profiles for different atmospheric aerosol conditions
2. Fold with Cherenkov spectrum and detector quantum efficiency
3. Integrate over wavelength and divide by MC reference
4. Convert altitude to radiation lengths and incorporate zenith dependency
5. Fold with longitudinal shower profiles to account for energy dependency
6. Integrate over altitude and interpolate along axes to obtain correction factor

Disclaimer:
This approach assumes that transmission profiles only affect the total brightness of shower images, *not the brightness distribution*!
And that the total brightness scales linearly with event energy!

Step 1 - Transmission profiles

Radiative transfer simulations with Py6S - a python interface to the
Second Simulation of the Satellite Signal in the Solar Spectrum vector version
See the 6SV homepage for details and original image and description:



"It enables accurate simulations of satellite and plane observation, accounting for elevated targets, use of anisotropic and lambertian surfaces and calculation of gaseous absorption. The code is based on the method of successive orders of scatterings approximations and its first vector version (6SV1), capable of accounting for radiation polarization."

Very versatile and highly customisable!

See the Py6S documentation for details.

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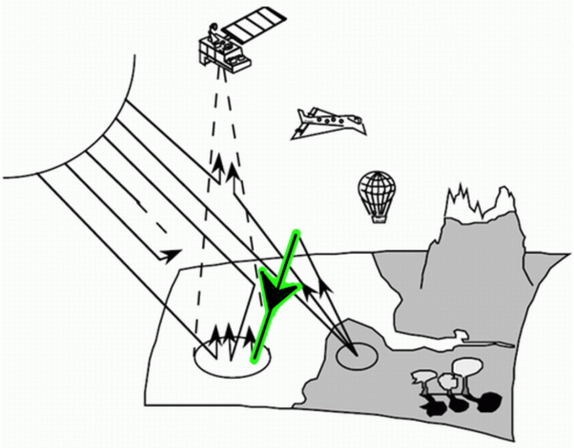

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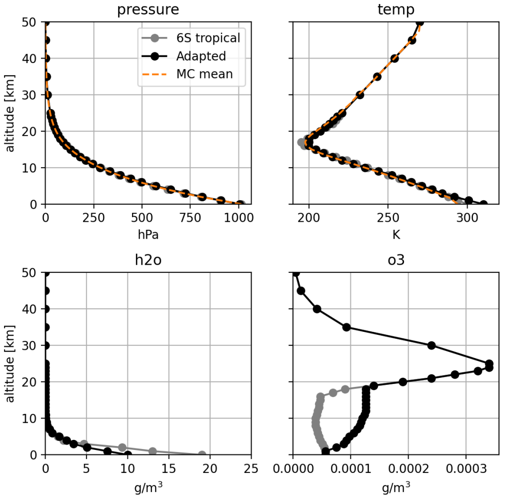
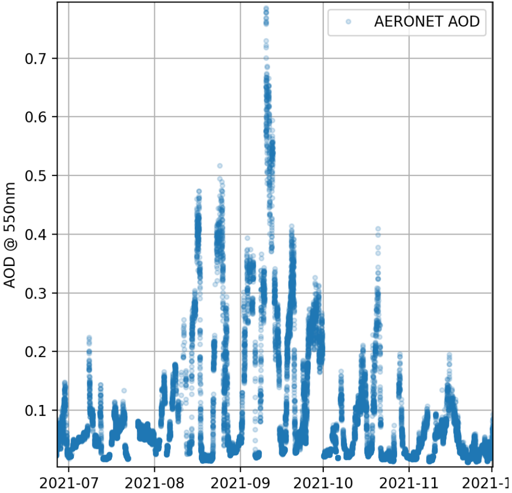
Step 1 - Transmission profiles

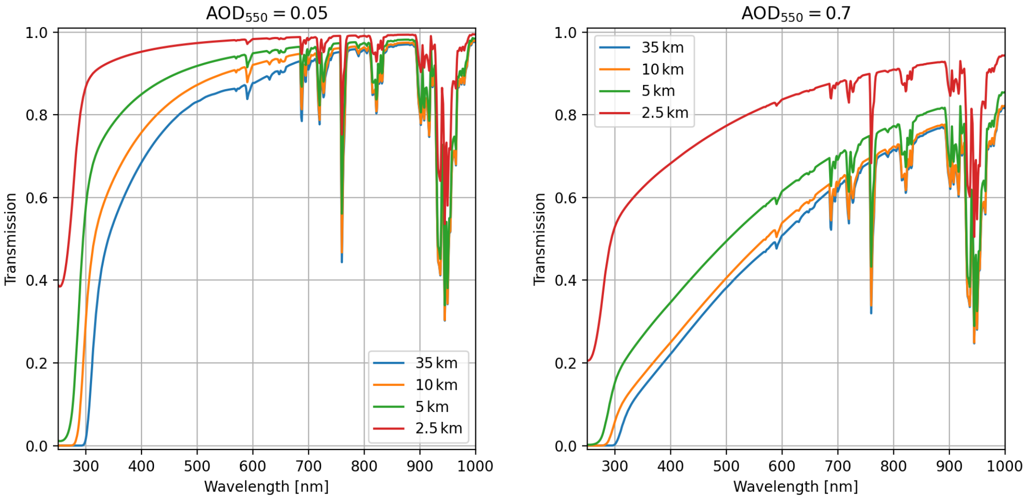
Going in to Py6S:
IGRA + IAGOS averages and AOD range scaled **biomass burning aerosol profiles**





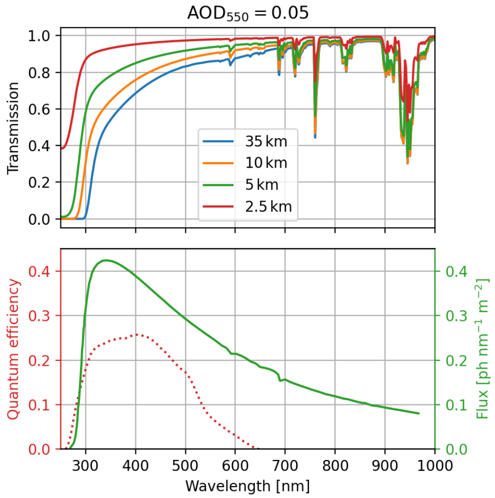
Step 1 - Transmission profiles

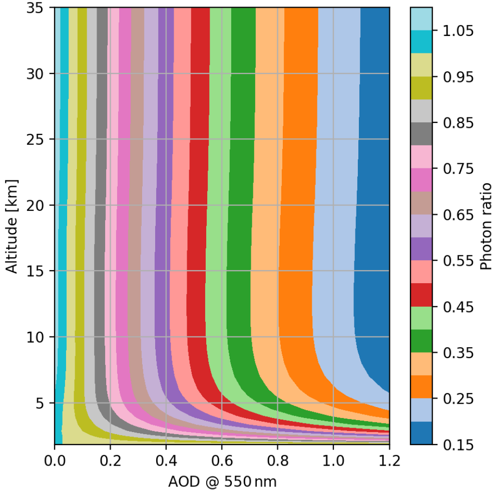
Coming out of Py6S:



Step 2 + 3

Fold profiles with Cherenkov spectrum and QE, integrate, divide by MC reference

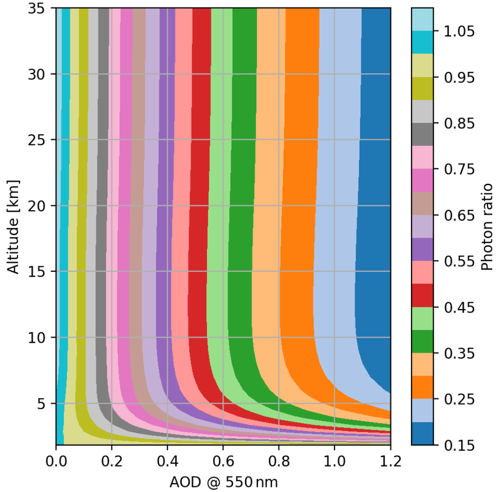


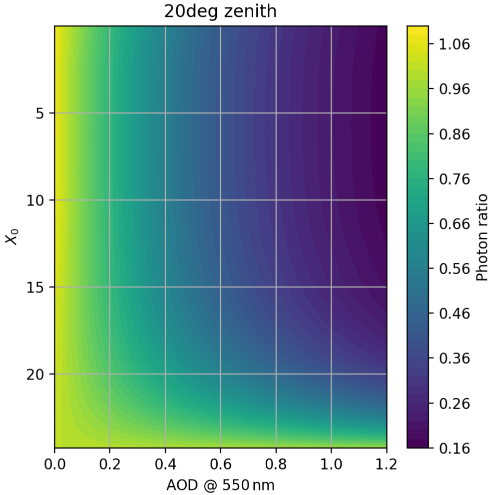


Compared to MC, what fraction of shower photons reach the ground from a given altitude for a given AOD?

Step 4

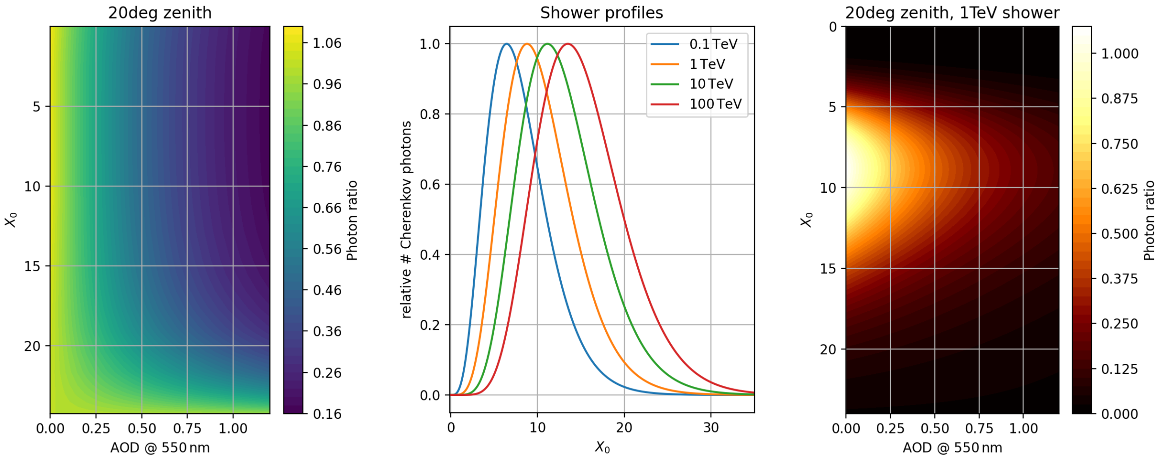
Convert altitude to radiation lengths and assume a plane parallel atmosphere





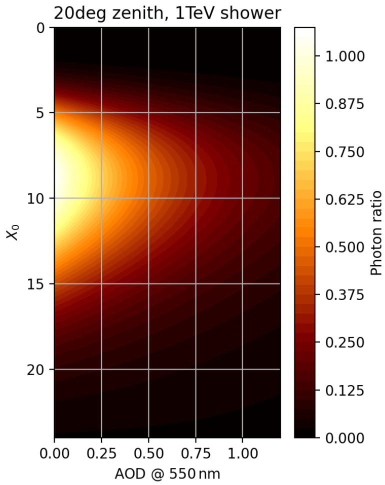
Step 5

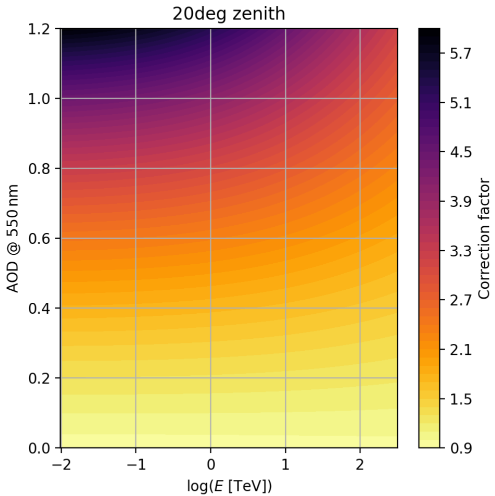
Fold with longitudinal shower profiles [arXiv:2010.13822]



Step 6.1

Integrate over X_0 and calculate ratio to reference to obtain correction factor

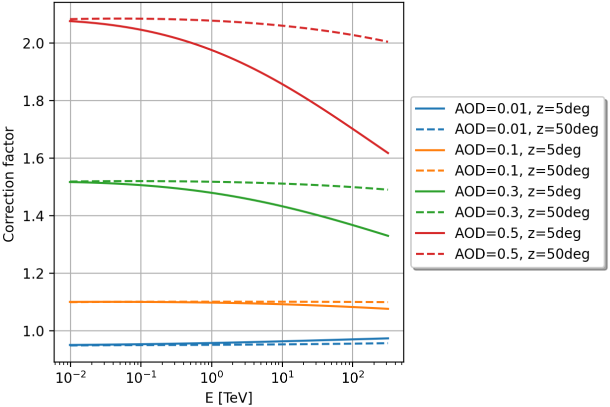


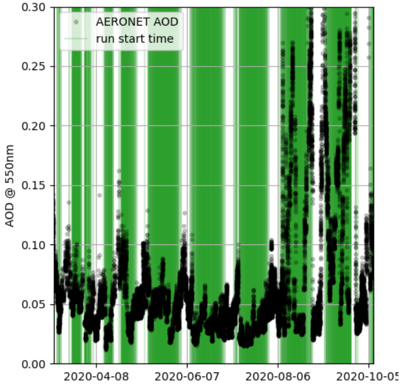


Step 6.2

Multidimensional grid interpolation to generate simple correction function $f_c(\mathrm{AOD}_{550}, E, \vartheta)$

Almost linear for moderate AODs, but strongly non-linear towards low zenith angles and high AODs:





$\Rightarrow \sim 10\%$ uncertainty even under "good" conditions!

Applications

The proposed scheme

- is not limited to IACTs but applicable for atmospheric Cherenkov detectors in general
- is in principle not limited to AOD; other parameters can be included
- can be used to estimate systematics introduced by various atmospheric variations on different levels:

  1. Assume certain condition → 2. Adapt scheme → 3. Assess impact on measurement

  In combination with `gammapy`, the effect on higher-level results can also be explored, but also adaptable for lower-level data like trigger rates or muon efficiencies!
- can be used to *correct* reconstructed air-shower energies (in combination with adapting IRFs)!
  But how to determine the AOD during darkness?
  Luckily there are several solutions — also presented here at this workshop!
  - LIDAR measurements
  - Stellar photometry
  - Estimates from detector specific parameters e.g. atmospheric Cherenkov transparency coefficients

Conclusion and outlook

In this talk we presented a scheme to

- assess the influence of aerosol and other atmosphere variations on atmospheric Cherenkov detector data
- get a better handle on systematic uncertainties and biases on different data levels
- refine/correct reconstructed air-shower energies and IRFs

Ongoing work:

- Estimating the AOD from atmospheric Cherenkov transparency coefficients
- Extending the scheme to include aerosol compositions measurable at the H.E.S.S. site
- Application as a correction scheme on H.E.S.S. data

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Thank You!