The atmospheric-dependent calculation of air fluorescence and its implementation in the reconstruction of air showers

María Monasor for the Pierre Auger Collaboration
University of Chicago & Universidad Complutense de Madrid

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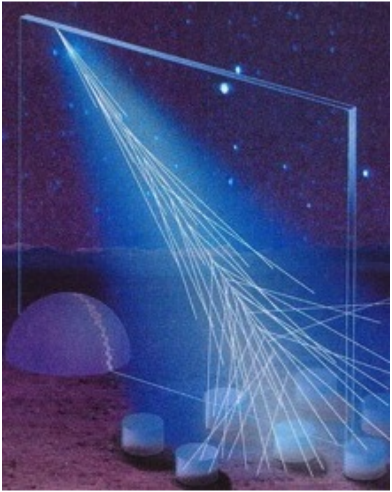
Outline

UV light production in EAS



- A CR with enough energy develops an EAS of particles, mainly e^{+} and e^{-}.
- They deposit energy ionizing and exciting N_2 that later will fluoresce isotropically and mainly in the near UV band.
- The emmited fluorescence light is directly proportional to the energy of the primary particle.
- Cosmic ray experiments such as Fly's Eye and HiRes, and at present the Pierre Auger Observatory and the Telescope Array, have successfully used this radiation to study UHECRs.

Fluorescence yield

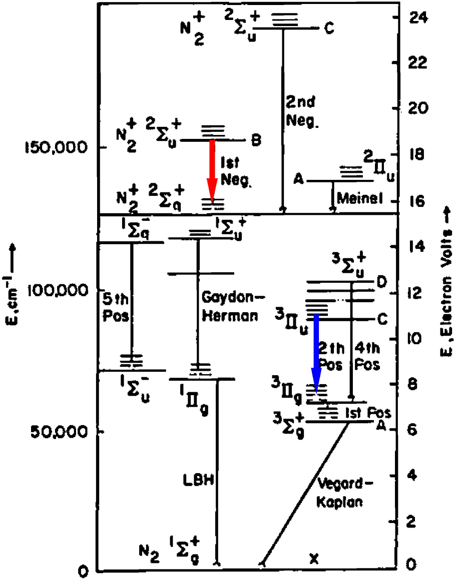
The **fluorescence yield** (FY) is defined as the number of UV photons emmited per unit of deposited energy.

In the range of interest for cosmic ray experiments, **300-400 nm**, the emission comes basically from two systems of the N_2 and N_2^+ molecules.

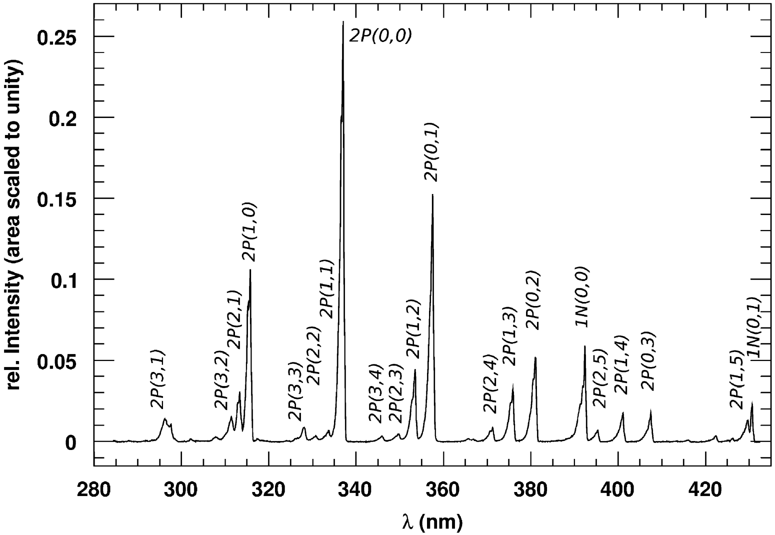
The electronic transitions between different vibrational levels give rise to molecular bands in the above spectral range.

F. Arqueros *et al.*, New. J. Phys. **11** (2009) 065011,

http://iopscience.iop.org/1367-2630/11/6/065011

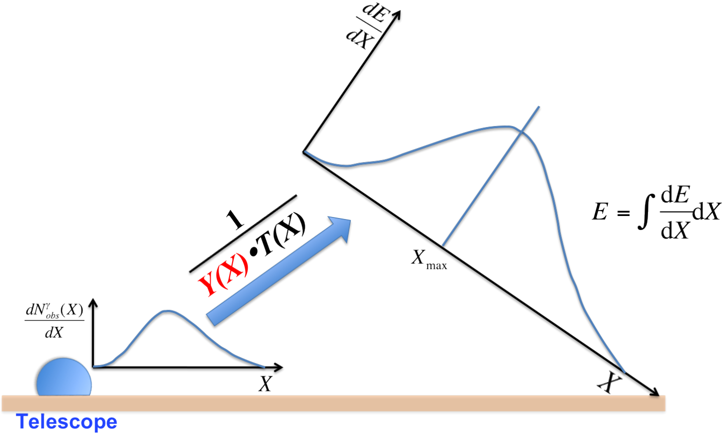


Fluorescence yield between 300-400 nm



M. Ave *et al.* [Airfly Collaboration], Nucl. Instr. Meth. A **597** (2008) 41

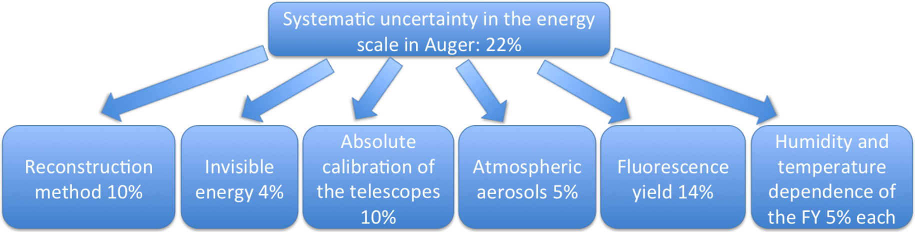
Effect on the reconstruction of air showers



- The integral of the profile $\mathrm{d}E/\mathrm{d}X$ provides a measure of the EM energy of the shower.
- A fit of the profile to a Gaisser-Hillas function will provide X_{max}, up to know the most reliable estimator for mass composition studies.

Effect on the reconstruction of air showers

Due to the proportionality between fluorescence intensity and primary energy, **the systematic uncertainty in the FY translates directly into a systematic in the primary energy** of the cosmic ray, being at present the major source of uncertainty in the reconstruction of this parameter.



Systematics in X_{max} are at the level of **16 g/cm^2** and the contribution from the dependence of the FY on atmospheric parameters is **$\sim$4 g/cm^2**.

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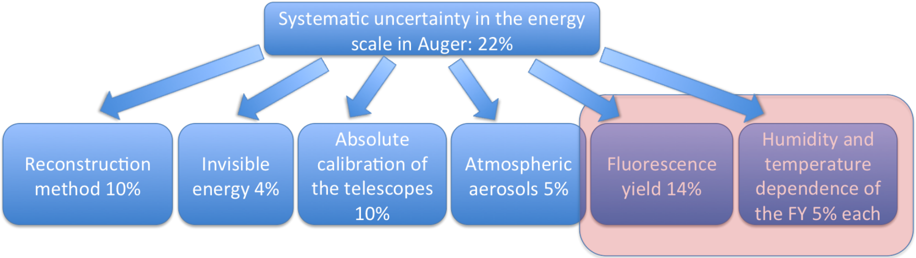

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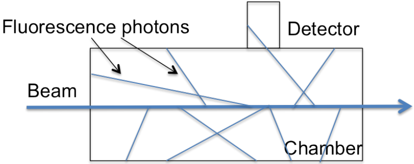
The good news are ...

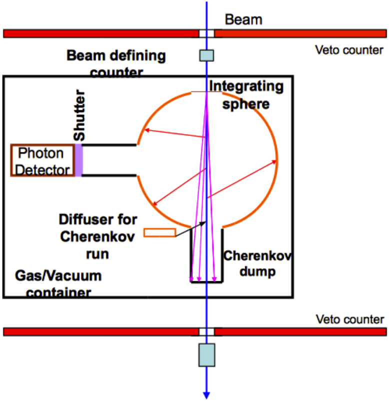
The FY can be measured in laboratory experiments injecting particles, mainly electrons, into air targets in collision chambers and under controlled enviromental conditions.

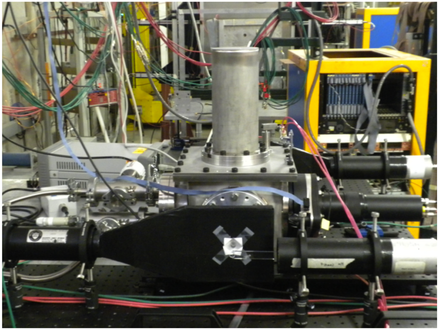


But ...

The fluorescence production is an extremely inefficient process, only a tiny fraction of the deposited energy is converted into UV fluorescence light. Many experiments have been carried out in the last 10 years to study the fluorescence emission and its dependence on atmospheric parameters.

For example Airfly ...





Principle: Compare fluorescence yield to a well known process to eliminate photo-detector systematics:

$$\underbrace{N_{337}(fluo)}_{measured} = \underbrace{Y_{fl}}_{known} \times \underbrace{Geom_{fluo}}_{MC} \times \underbrace{T_{filter} \times QE_{337}}_{\sim cancel} \times \underbrace{N_p}_{relative}$$

$$\overbrace{N_{337}(cere)} = \overbrace{Y_{cere}} \times \overbrace{Geom_{cere}} \times \overbrace{T_{filter} \times QE_{337}} \times \overbrace{N_p}$$

Description of the fluorescence yield

Apart from the radiative de-excitation, excited molecules can also decay by **collisions with enviromental molecules** (collisional quenching). The FY in ph/MeV at a certain P and T can be calculated as:

$$Y_\lambda(P, T) = \frac{Y_\lambda^0}{1 + P/P'(\lambda, T)}$$

- $\mathbf{Y_\lambda^0}$: FY in the absence of quenching.
- $\mathbf{P'}(\lambda, \mathbf{T})$: characteristic pressure at which the probability of collisional quenching equals that of radiative de-excitation.

The total FY in a certain wavelength interval $\Delta\lambda$ is:

$$Y(X) = \sum_{\Delta\lambda} Y_\lambda(X)$$

Since a typical cosmic ray shower extends up to about 20 km, the FY must be known over a wide range of air pressure and temperature.

Description of the fluorescence yield

The **characteristic pressure** $P'(\lambda, T)$ describes the dependence of the FY on atmospheric conditions and contains contributions from all possible quenchers:

$$\frac{1}{P'(\lambda, T)} = \sum_i \frac{f_i}{P'_i(\lambda, T)}\ , \quad P'_i(\lambda, T) = \frac{\sqrt{\pi m_i k T}}{4\tau_0 \sigma_{Ni}} \propto \sqrt{T}$$

For dry air:

$$\frac{1}{P'_{air}(\lambda, T)} = \frac{f_{O_2}}{P'_{O_2}(\lambda, T)} + \frac{f_{N_2}}{P'_{N_2}(\lambda, T)}$$

Humidity dependence

Water molecules are also effective quenchers so in humid air the fluorescence emission is partly suppressed. The characteristic pressure will be:

$$\frac{1}{P'_{hum}(\lambda, T)} = \frac{1}{P'_{dry}(\lambda, T)}\left(1 - \frac{P_w}{P}\right) + \frac{P_w}{P}\frac{1}{P'_w(\lambda, T)}$$

Temperature dependence

In the simplest case, the collisional cross-sections are considered constant and P' is usually assumed to be proportional to $\sqrt{T}$. Under this assumption, given a measurement of the characteristic pressure at a reference temperature T_0:

$$P'_i(\lambda, T) = P'_i(\lambda, T_0)\sqrt{\frac{T}{T_0}}$$

But **the collisional cross section** is not constant with T but **follows a power law ($\propto T^\alpha$)**. So the real dependence of P' with T is:

$$P'_i(\lambda, T) = P'_i(\lambda, T_0)\sqrt{\frac{T}{T_0}} \cdot \frac{T_0^{\alpha^i_\lambda}}{T^{\alpha^i_\lambda}} = P'_i(\lambda, T_0)\left(\frac{T}{T_0}\right)^{\alpha^i_\lambda - 1/2}$$

Many data sets available in literature ...

Although different authors have used different parametrizations, all the measurements can be described with the set of equations presented before. There are 3 data sets that have been widely used in cosmic ray experiments to describe the FY in dry air:

1. **Kakimoto-Bunner** (formerly used by HiRes)
   - $Y(P_0, T_0)$ and $P'(T_0)$ from Kakimoto *et al.* for 337, 357 and 391 nm lines ($P_0 = 1013$ hPa, $T_0 = 288$ K) (Nuc. Instr. and Meth. A **372** (1996) 527)
   - The remaining spectrum is distributed according to Bunner (Ph.D. Thesis, Cornell University (1967))
2. **Nagano**
   - $Y(P_0, T_0)$ and $P'(T_0)$ from his own measurements ($P_0 = 1013$ hPa, $T_0 = 293$ K) (Astropart. Phys. **22** (2004) 235)
3. **Nagano-Airfly** (Presently used in Auger)
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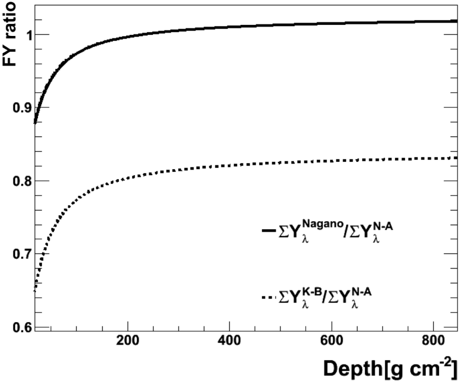
Comparison of data sets



- Differences between Nagano and Nagano-Airfly are almost negligible ($\sim$2 %).
- Discrepancies at the level of 20 % are observed between Kakimoto-Bunner and the other data sets.

But fluorescence photons are detected with telescopes that have **λ-dependent optical systems**. Relative differences between two FY data sets are **not directly translated to** E since the relative intensities of the molecular bands are modified by the detector efficiency.

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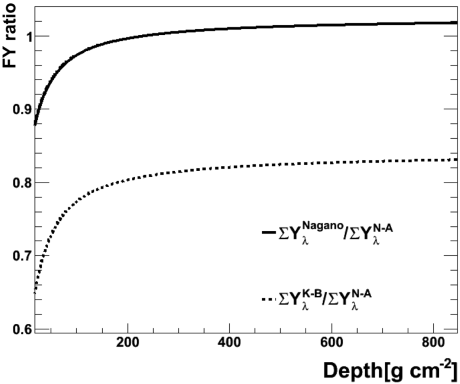

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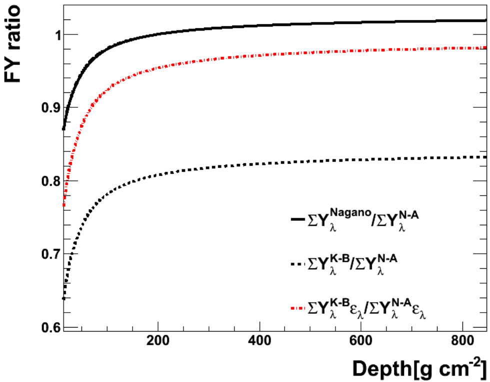

When the detector efficiency of the Auger telescopes is included:

- Differences between Nagano and N-A data sets remains constant because the FY spectra are very similar.
- But the differences between N-A and K-B are drastically reduced.

But fluorescence photons are detected with telescopes that have **λ-dependent optical systems**. Relative differences between two FY data sets are **not directly translated to** E since the relative intensities of the molecular bands are modified by the detector efficiency.

Data available for additional temperature and humidity effects

- For the temperature dependence of the cross section:
  1. Airfly coll. has measured the values of α_λ for 4 bands at 293 K in air (Nucl. Instrum. Meth. A **597** (2008) 50).
  2. Measurements of α^i_λ for each component desiarable but difficult.

- For the P'_w values:
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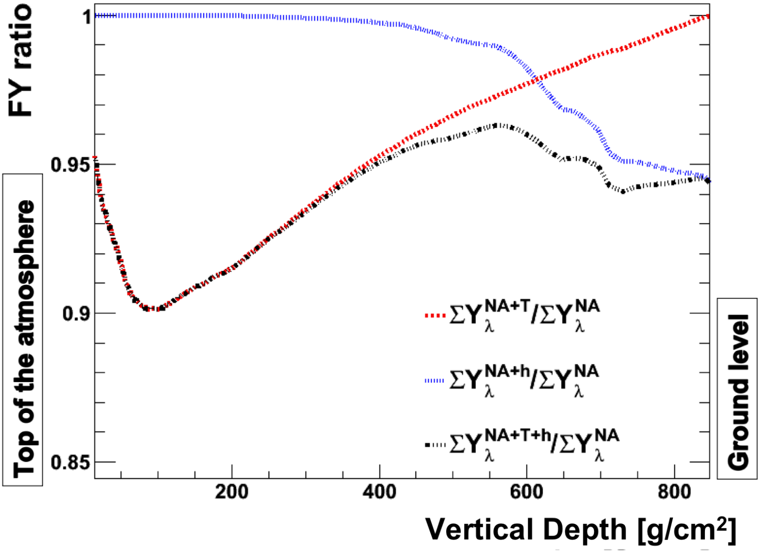
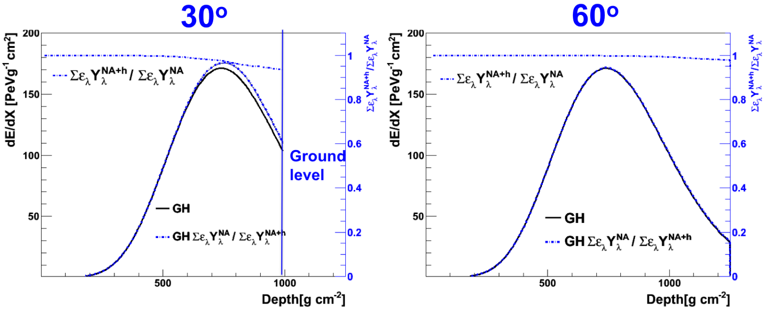
Effect on humidity and temperature



Humidity effect on shower profiles:

The impact of these contributions, both humidity and temperature, are highly **dependent on the shower geometry**

(Depth = Vertical Depth/$\cos\theta$).



The humidity effect is relevant for vertical showers ($\sim 6\,\%$) (X_{max} closer to the ground), than for inclined ones (they develop higher in the atmosphere) for which the effect is almost negligible.

Temperature effect on shower profiles:

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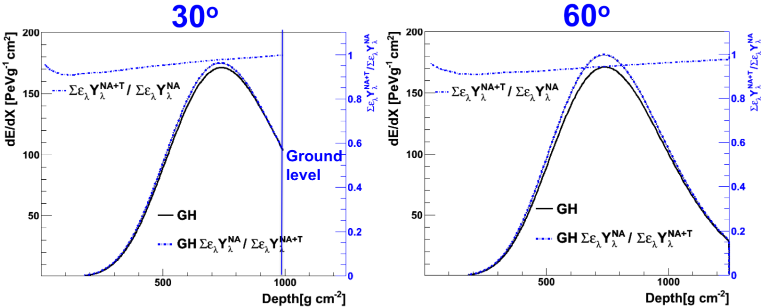
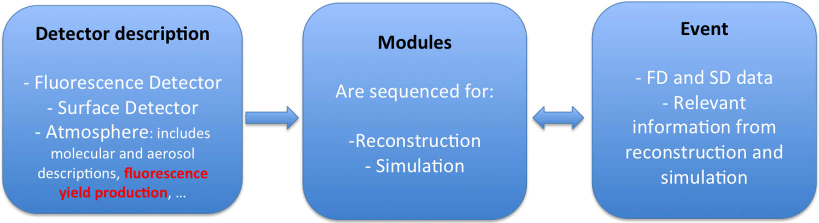


The temperature dependence of the collisional cross-section has a larger effect is relevant for inclined showers (∼5 %). For vertical showers the effect is almost negligible.

Implementation in the Auger Software

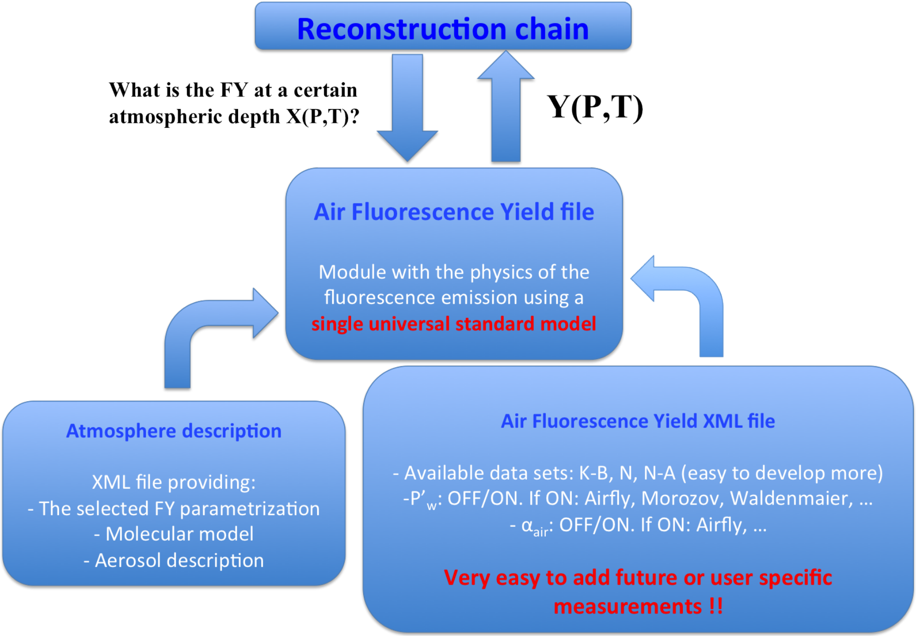
The Auger Offline Software provides the necessary tools for simulation, reconstruction and data analysis in a very flexible way that allows to merge standard and user-developed modules for all type of specific needs.



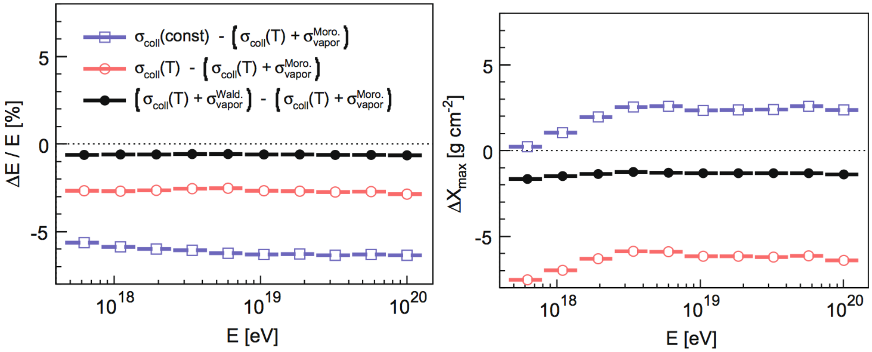
The software is driven by XML datacards that provide "switches" to study different effects: the FY data set, water vapor quenching, and the T dependence of σ_{coll} can be switched on/off in the reconstruction.

Implementation in the Auger Software

- In the Auger Software, **the calculation of the FY is done layer by layer** (it means at a certain P, T and humidity conditions) as it is being required by the reconstruction chain.
- **At present there are several algorithms**, related with the different parameterizations proposed in several works, to do it.
- With my colleagues at UCM, we are working in **a new implementation that use only one universal algorithm** based on the previous equations.
- In the corresponding XML card **the user will be able to pick the data set** to be used in the reconstruction (K-B, N, N-A, ...) **and also the additional effects**, as the humidity and/or temperature dependence, to be included.
- This algorithm will be **available soon** in the official distribution.


Reconstruction chain
What is the FY at a certain atmospheric depth X(P,T)?
Y(P,T)
Air Fluorescence Yield file
Module with the physics of the fluorescence emission using a single universal standard model
Atmosphere description
XML file providing:
- The selected FY parametrization
- Molecular model
- Aerosol description
Air Fluorescence Yield XML file
- Available data sets: K-B, N, N-A (easy to develop more)
-P'$_w$: OFF/ON. If ON: Airfly, Morozov, Waldenmaier, …
- α_{air}: OFF/ON. If ON: Airfly, …
Very easy to add future or user specific measurements !!

Effect of humidity and $\sigma_{coll}(T)$ on E and X_{max}



[Pierre Auger Collaboration], Astropart. Phys. **33** (2010) 108

- The total effect in the reconstructed E is $\sim$6 %.
- The effect in X_{max} is $\sim$3 g/cm^2.

Conclusions

1. The FY and its dependence on atmospheric parameters is up to now the major source of systematic uncertainties in the energy scale.

2. A great effort is being put on the measurement of this parameter to reduce these uncertainties.

3. Atmospheric profiles of P, T and humidity needed to estimate properly the FY and thus the energy.

4. All experimental data on FY and its dependence on both wavelength and atmospheric properties can be described a single set of equations. This "universal" parameterization is being implemented in the Auger Offline Software.

5. With this new implementation, the FY measured from different experiments and in different atmospheric conditions can be applied to the reconstruction of air showers in a very easy and intuitive way.

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