Introduction to projects

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Data Analysis

- These slides are on indico!
- The Pierre Auger Collaboration has released 10% of its data for the general public.
- If this was an independent detector, it would be the 3rd largest cosmic ray observatory ever built (almost as much data as the telescope array has taken)
- https://opendata.auger.org

What you will do in groups of 4-5

- Use Jupyter notebooks to perform analyses on:
  - The energy calibration
  - The energy spectrum
  - The depth of maximum of shower development
  - The proton air cross section
  - The ultra high energy cosmic-ray sky

- Naturally we expect you to read and understand the corresponding papers and go beyond the standard analyses in the prepared notebooks!

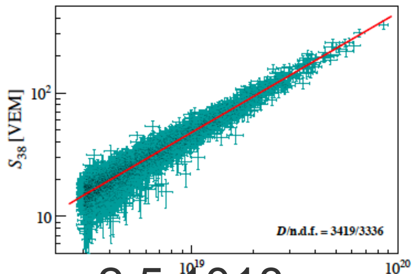
- You will have 2 hours today, 2.5 hours tomorrow and 1 hour on Wednesday to work on the project

- Finally, each group will discuss its results in 5 minute presentations on Wednesday
  - The discussions will be evaluated and eternal fame and small prizes will be available to the winning group!

Groups and Projects

Angevaare, Joran	Hoeve, Jaco ter	Ó Fearraigh, Brían	Ammerman, Juan	Bolognani, Carolina
Bianchi, Antonella	Maggiore, Ricardo	Rosas Torres, Francisco	Arneman, Dylan van	Brookes, Emily
Boer, Bob	Meijer, Quirijn	Tapia, Enzo	Barel, Marten	Degens, Jordy
Gupta, Vikas	Missio, Marion	Hofman, Bas	Biolchini, Alice	Dongen, Jesse van
	Moskvitina, Polina	Seneca, Jordan	Boer, Jan de	Eeden, Thijs Juan van
Feng, Zhuoran	Gupta, Pawan	Kortmann, Bryan	Muller, Rasa	Qiu, Shi
Flierman, Maricke	Janquart, Justin	Leinonen, Walter	Narola, Harsh	Rehult, Anders
Galati, Maria Domenica	Jung, Bouke	Lukashenko, Valeriia	Pang, Peter	Saharan, Mohit
Gatius, Clara	Karkout, Osama	Magni, Giacomo	Perry, Jon	Weelden, Gijs van
Greeven, Lex	Kip, Jochem	Mitchell, Alexandra	Puecher, Anna	Wollfs, Zef
The energy calibration	The energy spectrum	The depth of maximum of shower development	The proton air cross section	The ultra high energy cosmic-ray sky

Energy Calibration:



1. <u>Read the paper (up to section IV)</u>

Pierre Auger Collaboration [A. Aab et al.], "A measurement of the cosmic ray energy spectrum above 2.5·1018 eV using the Pierre Auger Observatory", Phys. Rev. D. 102 (2020) 062005. DOI: https://doi.org/10.1103/PhysRevD.102.062005
arXiv: https://arxiv.org/abs/2008.06486

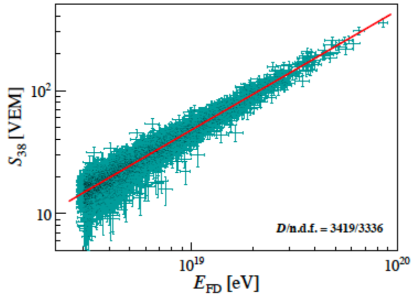
2. <u>Explore the notebook:</u>

Q1: What are the S(1000) and S38 parameters? Which one is a better energy estimator and why? Why 1000 and 38 and not some other numbers?

Q2: What energy is “missed” in the FD calorimetric energy (*fd_calEnergy*), on which shower observables does it depend? Make a plot of the missed energy as a function of these variables. What particles are missed in FD energy but not (so much) in SD?

Q3: A parametrization of the shower-to-shower fluctuations in SD is given as a function of FD energy. Make a plot of this variable and comment on the shape. Where do these fluctuations come from?

Energy Calibration:



3. <u>Extend the notebook:</u>

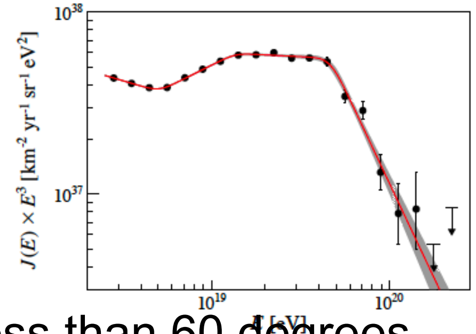
Q4: Can you observe any bias of the SD energy with respect to Xmax as measured by the FD? If so, what would be the explanation?

4. <u>Reflect on results:</u>

Q5: Can you do a better energy calibration? What would you need for that?

Q6: How could the AugerPrime upgrade (with a scintillator detector and a radio detector on top of the water Cherenkov detectors) help with the energy calibration?

The Energy Spectrum
Read the paper: Phys. Rev. D 102, 062005 (2020)
https://journals.aps.org/prd/pdf/10.1103/PhysRevD.102.062005



Preliminaries:

Q1: Calculate the aperture of a single hexagon in Auger, given that the zenith angle is less than 60 degrees

Q2: Calculate the full exposure of 1 year of Auger, assuming no holes in the detector

Explore the notebook:

Q3: Familiarize yourself with S1000 and S38; Show that S1000 is not a good energy estimator for the surface detector and S38 is

Q4: Verify that S38 does not change over time. Why is this important?

Q5: Create the energy spectrum; see if you can fit this according to the 6-parameter fit described in the article (eqn 8) What is the significance of the dropoff at the highest energies?

Beyond the notebook:

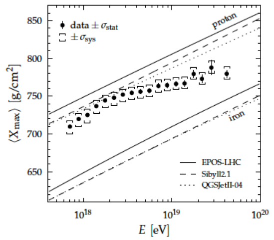
Q6: Create the spectrum for different zenith angles, similar to Fig 11 of the spectrum article. Is there a dependence of the spectrum wrt the zenith angle?

Q7: Create a spectrum for the Galactic plane, and compare this off-plane. Discuss the results and why this could be interesting

The Future

Q8: How can this measurement be improved using the upgraded Pierre Auger Observatory (with a scintillator detector and a radio detector on top of the water Cherenkov detectors)?

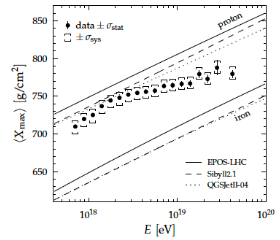
Depth of the Shower Maximum:



Read the paper:
[Physical Review D 90 (2014) 122005](https://journals.aps.org/prd/abstract/10.1103/PhysRevD.90.122005) ([arxiv]())
https://journals.aps.org/prd/abstract/10.1103/PhysRevD.90.122005

Explore the notebook:
Systematic checks:
Q1: Does the Xmax measurement depend on the zenith angle In the lowest energy bin?
Q2: Apply the correction for the FD acceptance as a function of Xmax and energy to the Xmax distributions and show the Xmax and sigma(Xmax) distributions including this correction.

Depth of the Shower Maximum:



<u>Extend the notebook:</u>

Interpretation:

Q3: The Xmax and sigma(Xmax) data points above $E>10^{19}$ eV are neither on the proton, nor on the Fe curves. What are the possible scenarios for the composition in that case? Are the scenarios compatible between the Xmax and sigma(Xmax) measurements?

Q3: Assume a pure composition in terms of one nucleus type. Determine the nucleus type as a function of energy and as a function of EPOS-LHC, Sybill2.3c and QGSJetII-04 hadronic interaction models, for both Xmax and sigma(Xmax). Are the Xmax and sigma(Xmax) results compatible?

Q4: Assume a composition of only proton and iron nuclei. Determine the fractions of p and Fe nuclei as a function of energy and as a function of EPOS-LHC, Sybill2.3c and QGSJetII-04 hadronic interaction models, for both Xmax and sigma(Xmax). Are the Xmax and sigma(Xmax) results compatible?

<u>Reflect on the results:</u>

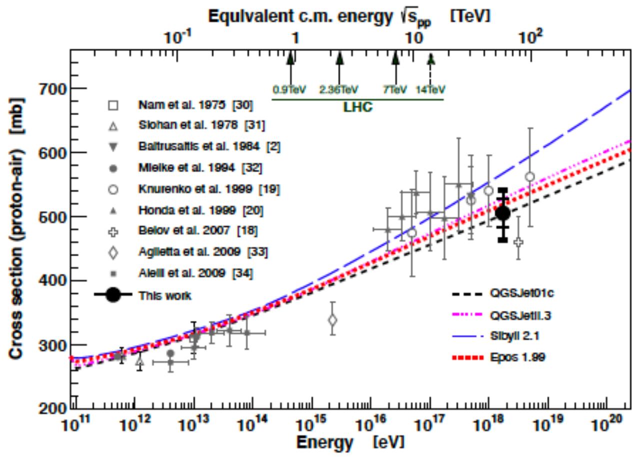
Q5: Devise a composition scenario that is compatible with both Xmax and sigma(Xmax) measurements.

<u>The future:</u>

Q6: What is needed to extend the Xmax measurement to higher energies?

Q7: What is needed to extend the composition measurement to higher energies?

p-Air cross section:
Read the paper: Phys.Rev.Lett. 109 (2012), 062002
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.109.062002



Explore the data:

Q1: Show the acceptance of the fluorescence telescopes as a function of atmospheric depth for several energy ranges and explain what you see.
Q2: Show the mean of the distribution of Xmax as a function of energy and compare it to the publications of the Pierre Auger Observatory on this topic.

Systematic checks:

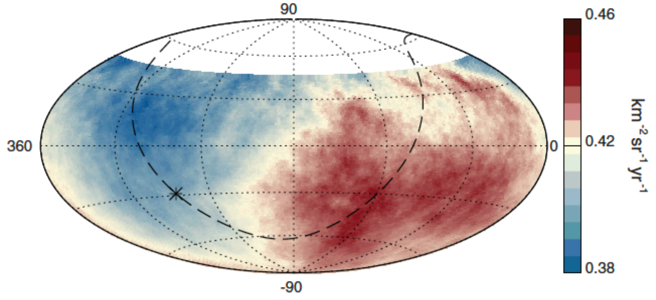
Q3: Repeat the analysis, but divide the zenith angle (theta) range in two sets theta < 35 degrees and theta > 35 degrees
Q4: In the notebook a fixed energy range is chosen, you could repeat the analysis for different energies. Scan with a fix-sliding window of log10(E/eV) = 0.2 through the full energy range and repeat the analysis. What do you observe & why?

The future:

Q5: What is needed to improve upon this measurement? Both consider experimental and theoretical arguments …

The ultra-high energy cosmic ray sky

Read the paper: [The Pierre Auger Collaboration (2017), Science 357, 6357, 1266](https://www.science.org/doi/10.1126/science.aan4338)
https://www.science.org/doi/10.1126/science.aan4338



Preliminaries

Q1: The relative exposure of Auger only depends on declination, why?

Explore the data:

Q2: Try to see what happens with the significance of the Rayleigh analysis as function of the energy cut

Q3: What happens in the 2D-plot when you change the top-hat smearing?

Beyond the notebook:

Q4: Create an analysis based upon the distance to CEN-A; modify opening angles and energy cuts within reason. Take exposure into account

Q5: Using the optimal cuts of the previous analysis what significance do you get in the 2D plot in Galactic coordinates.

Q6: Try to estimate the maximum significance, taking the “look elsewhere” effect into account

The Future:

Q7: How can this measurement be improved using the Auger upgrade (with a scintillator detector and a radio detector on top of the water Cherenkov detectors)?