Universität Siegen

HEP Experimental High Energy Physics

CPPS Center for Particle Physics Siegen

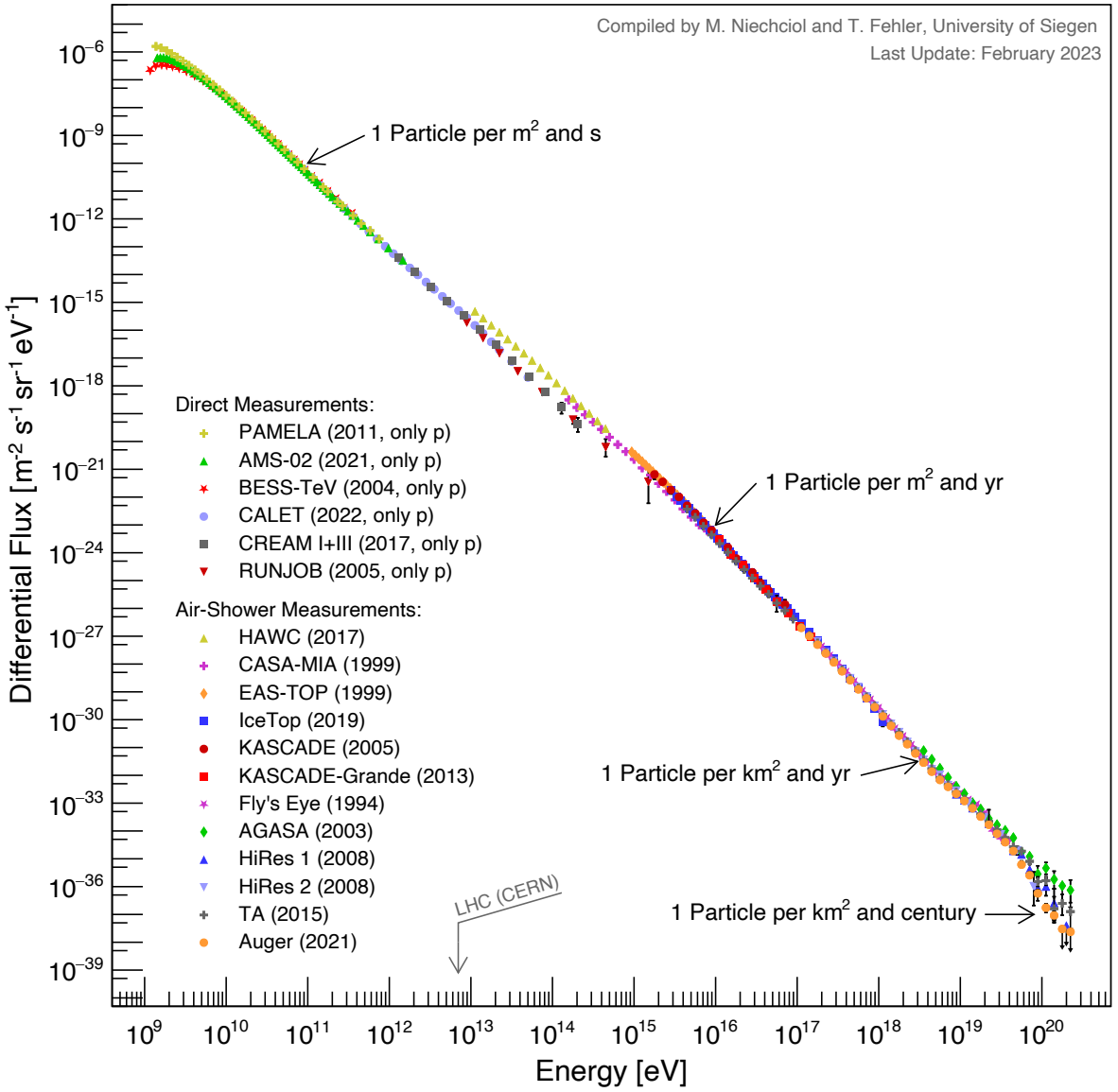
Astroparticle Physics Session Introduction

Marcus Niechciol
Center for Particle Physics Siegen, University of Siegen

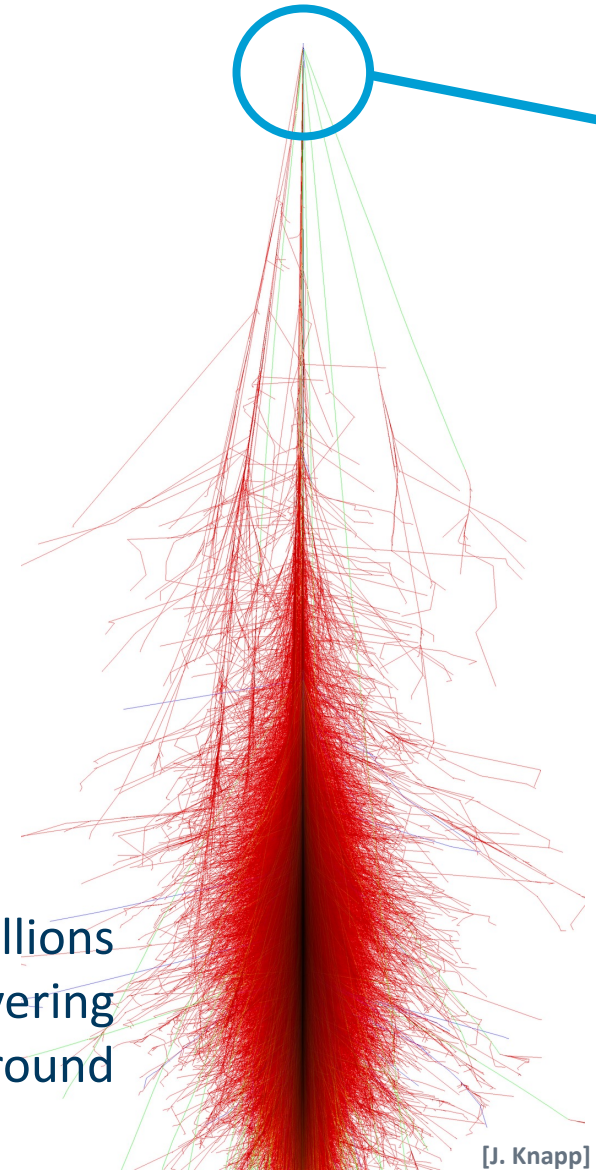
CPPS Retreat
15 February 2024

Photo by S. Saffi (Univ. of Adelaide)

Cosmic Rays

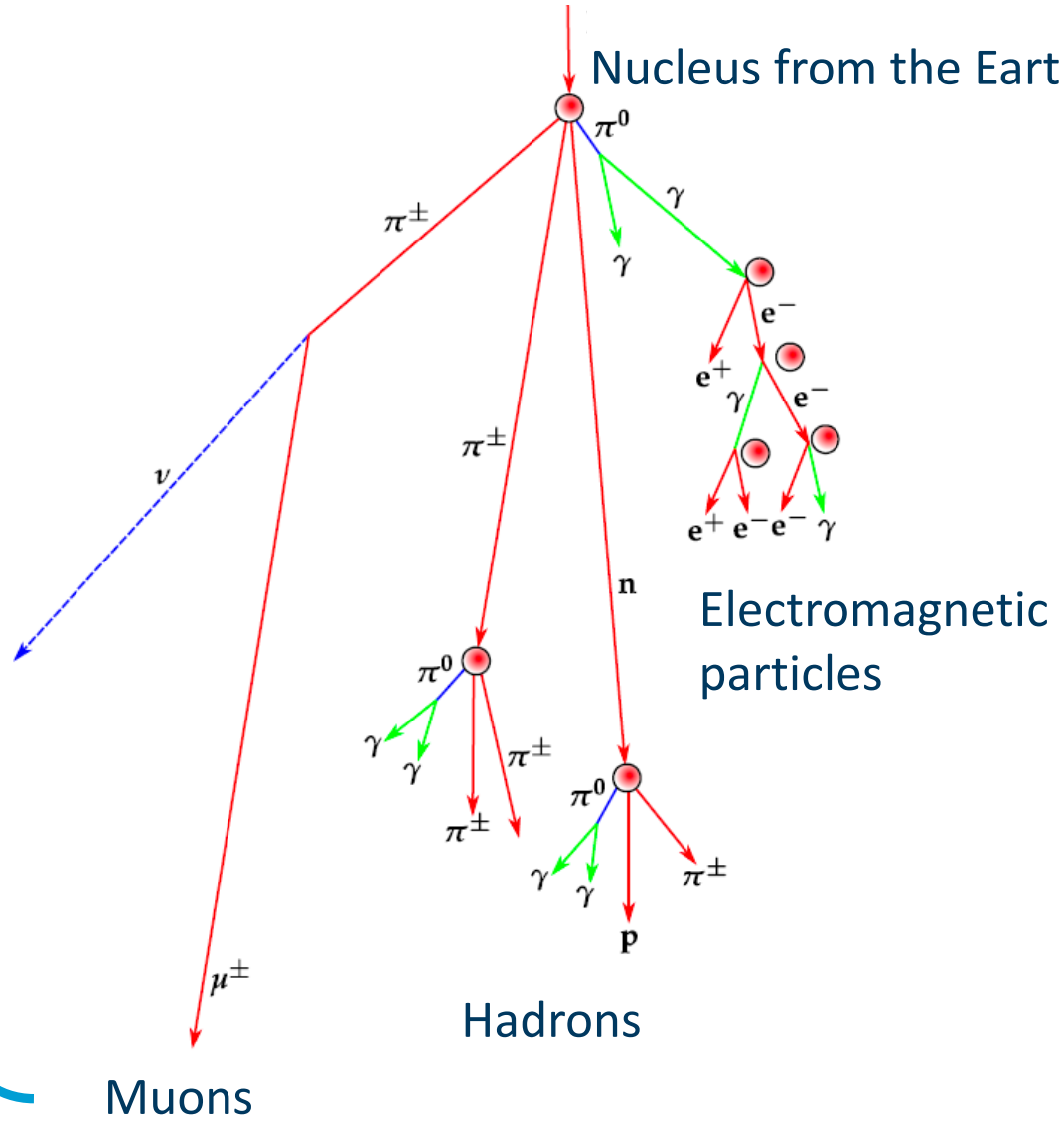

Compiled by M. Niechciol and T. Fehler, University of Siegen
Last Update: February 2023
1 Particle per m^2 and s
1 Particle per m^2 and yr
1 Particle per km^2 and yr
1 Particle per km^2 and century
LHC (CERN)
Direct Measurements:
PAMELA (2011, only p)
AMS-02 (2021, only p)
BESS-TeV (2004, only p)
CALET (2022, only p)
CREAM I+III (2017, only p)
RUNJOB (2005, only p)
Air-Shower Measurements:
HAWC (2017)
CASA-MIA (1999)
EAS-TOP (1999)
IceTop (2019)
KASCADE (2005)
KASCADE-Grande (2013)
Fly's Eye (1994)
AGASA (2003)
HiRes 1 (2008)
HiRes 2 (2008)
TA (2015)
Auger (2021)
Differential Flux [m^{-2} s^{-1} sr^{-1} eV^{-1}]
Energy [eV]

Extensive Air Showers



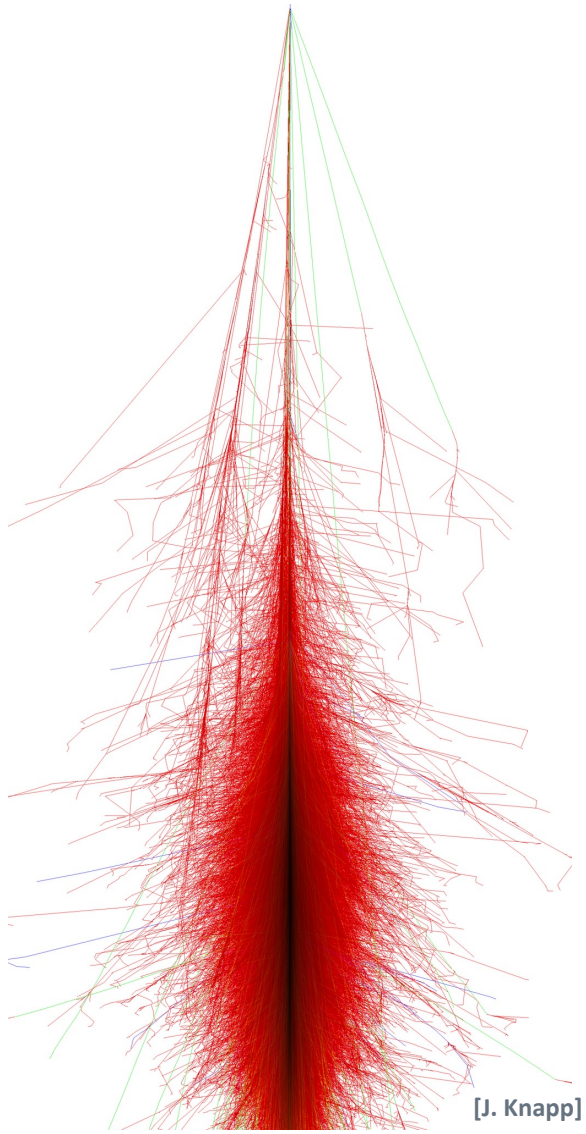
[J. Knapp]

Cascade of billions
of particles, covering
a large area on ground



Measuring Extensive Air Showers

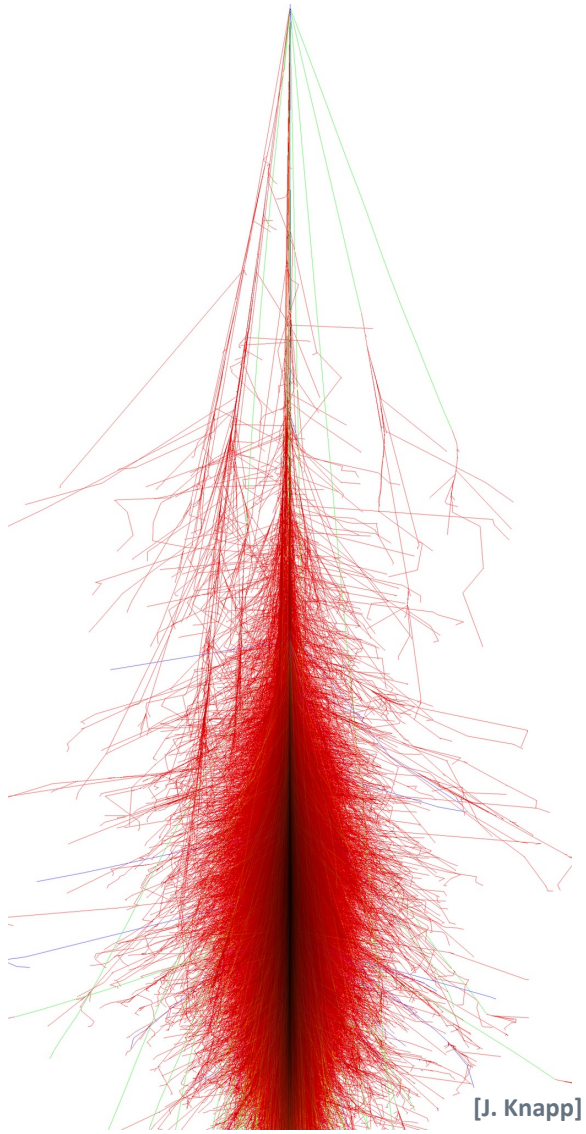
- Two main **measurement techniques** currently
  - Measuring the (lateral distribution of) **secondary particles on ground** with a sparse detector array
    - Possibility to cover large areas in a cost-effective way
    - Duty cycle close to $100\,\%$
  - Measuring the **fluorescence light** emitted in the atmosphere when the air shower passes through (proxy for the longitudinal development)
    - Good knowledge of the atmosphere needed to interpret the data
    - Measurement only possible in clear, moonless nights (duty cycle reduced to $\sim 15\,\%$)
- **Future**: radio measurements of air showers



[J. Knapp]

Simulating Extensive Air Showers

- Needed for the proper **interpretation** of measurements
- Typical approach: **full MC simulations** using CORSIKA
  - Use **thinning algorithms** to reduce computing demands
  - Can also use a **hybrid approach** with full MC for the first part of the shower plus numerical solution of cascade equations for the later parts (CONEX simulation code)
- Detailed modelling of **hadronic interactions** crucial
  - Constraint: **lack of accelerator data** at the highest energies / in the extreme forward region / for p-air (CNO) interactions
  - **Different models** available based on different theoretial *ansätze* (e.g. EPOS, QGSJET, SIBYLL), but all have some shortcomings ("**muon puzzle** in air showers")



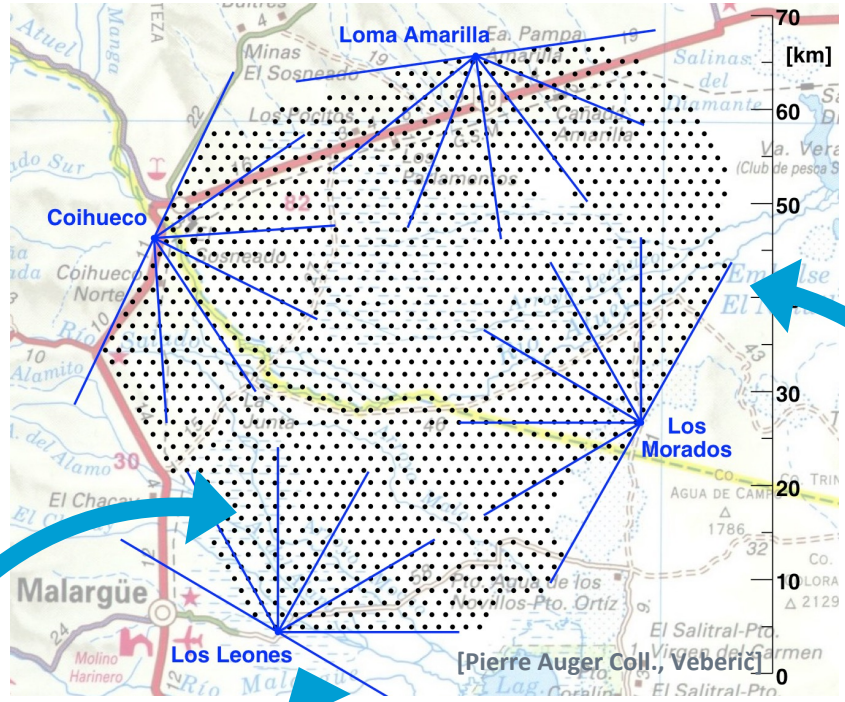
[J. Knapp]

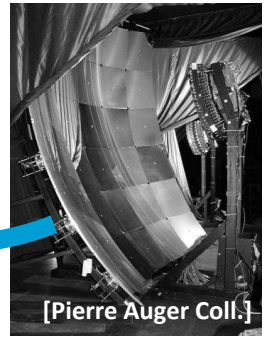
Pierre Auger Observatory

[Pierre Auger Coll., NIM A 798 (2015) 172]

- **Surface Detector (SD)**
  - ~1660 water Cherenkov detector stations, covering about 3000 km^2
- **Fluorescence Detector (FD)**
  - Four FD stations with 27 telescopes
- Data taking started in **2004**
- Detector upgrade (**AugerPrime**) ongoing

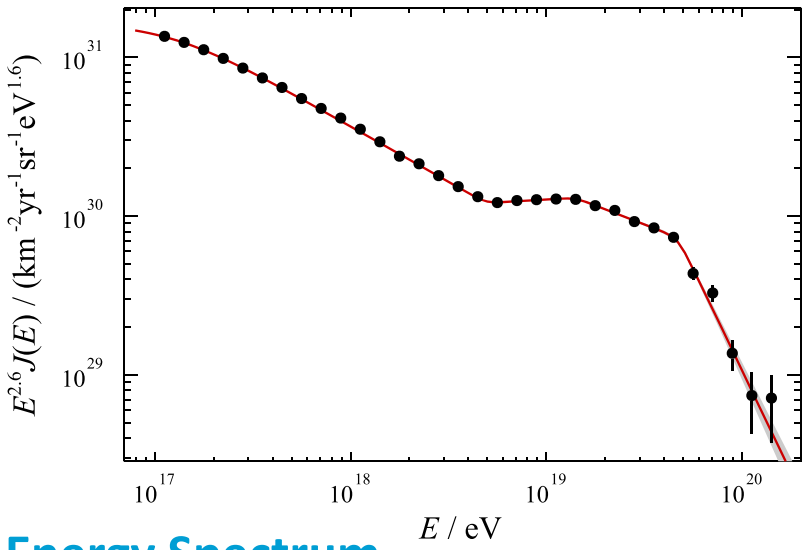
PIERRE AUGER OBSERVATORY





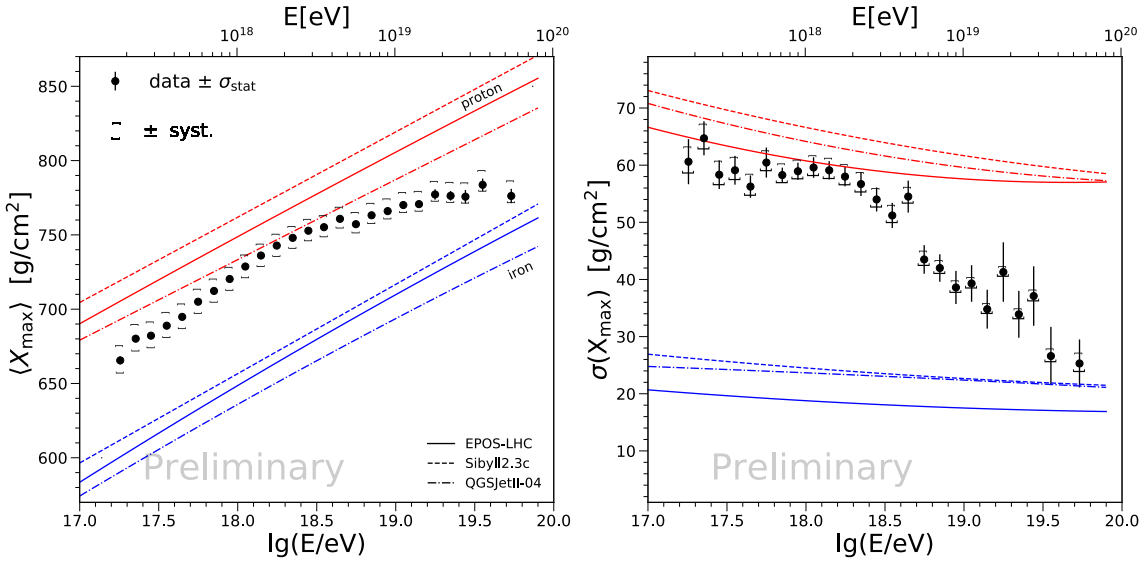
Pierre Auger Observatory – Key Results

[Pierre Auger Coll., Eur. Phys. J. C 81 (2021) 966]

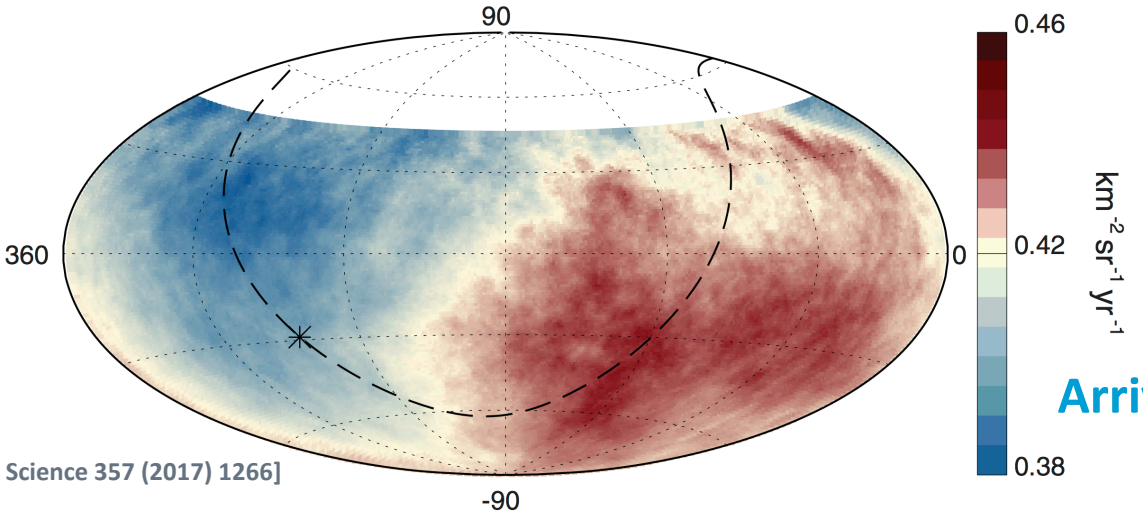


Energy Spectrum

[A. Yushkov (Pierre Auger Coll.), PoS (ICRC2019) 482]



Composition



[Pierre Auger Coll., Science 357 (2017) 1266]

Arrival Directions

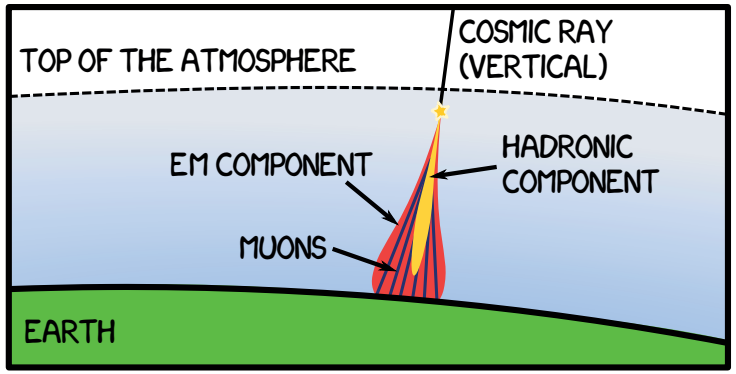
Multimessenger Astronomy

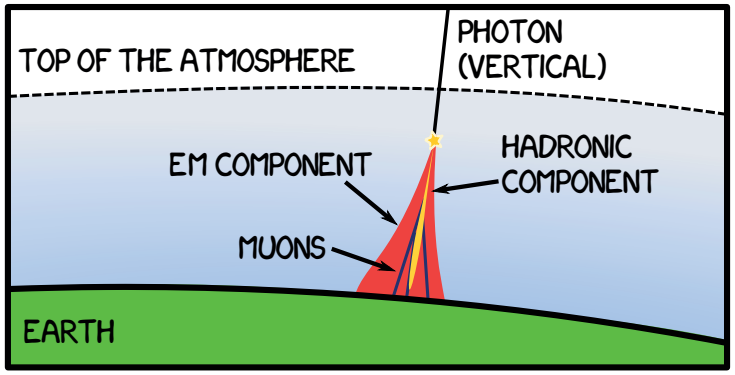
- **Combine observations with different "messenger particles"** to gain complementary information about a specific astrophysical object (or class of objects):
  - Cosmic Rays (nuclei) – Photons (electromagnetic radiation) – Neutrinos – Gravitational Waves

    Point directly back at their source
  - Some **breakthrough discoveries**:
    - 2017: first coincident observation of electromagnetic radiation and a gravitational wave (GW170817)
    - 2019: measurement of a high-energy neutrino from a flaring blazar (TXS 0506+056)

Focus of our Group: Search for UHE photons

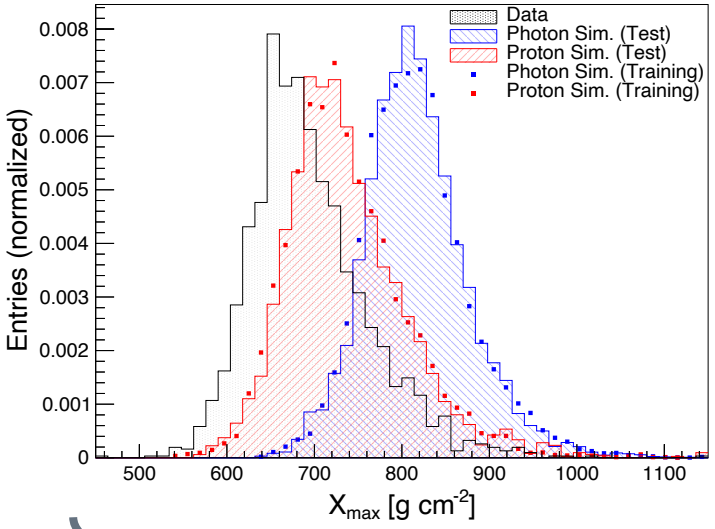
- First detection of an EeV photon would be a **breakthrough**, not only for multimessenger astronomy (search for the sources of UHE cosmic rays), but also, e.g., for fundamental physics
  - **Main challenge**: distinguishing photon-induced air showers from the **vast background** of showers initiated by cosmic protons and heavier nuclei
  - Exploit **characteristic differences** to proton/nucleus-induced showers
  - **In a nutshell:** Searching for UHE photons means looking for **deep (vertical) showers with few muons**

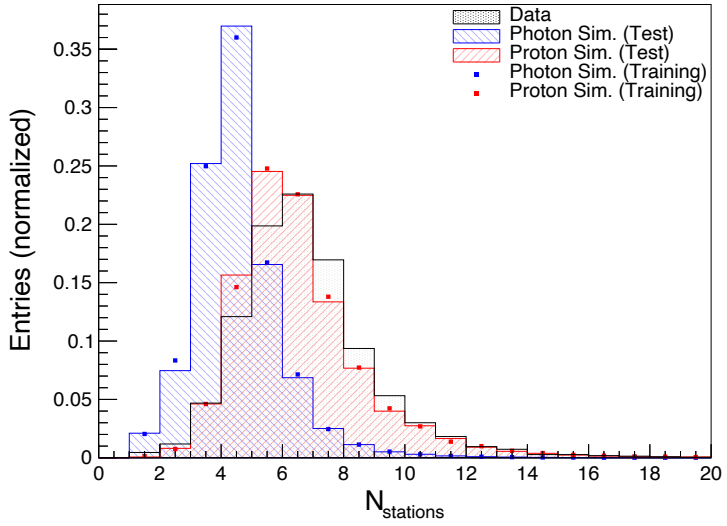


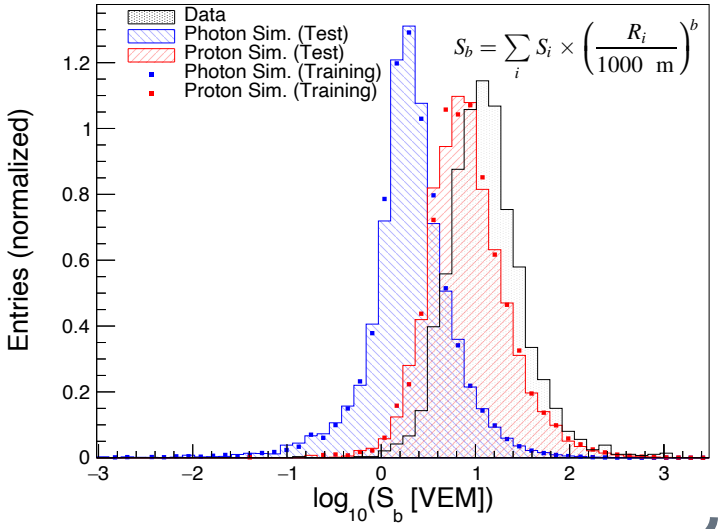


Example: Search for Photons between 2×10^{17} and 10^{18} eV

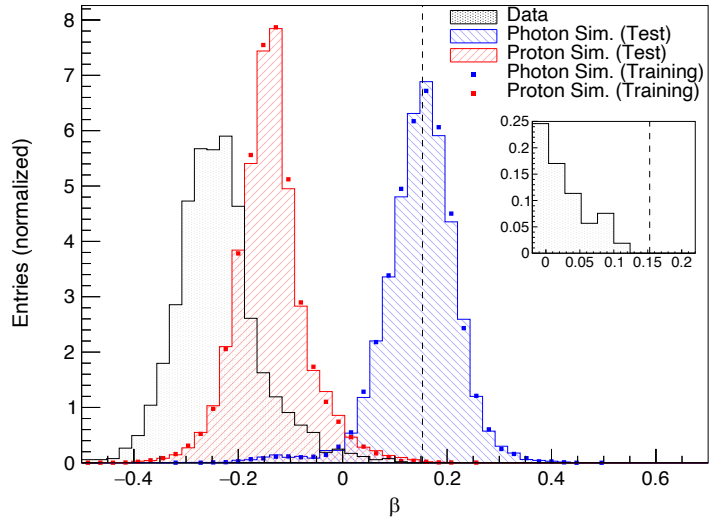
Observables







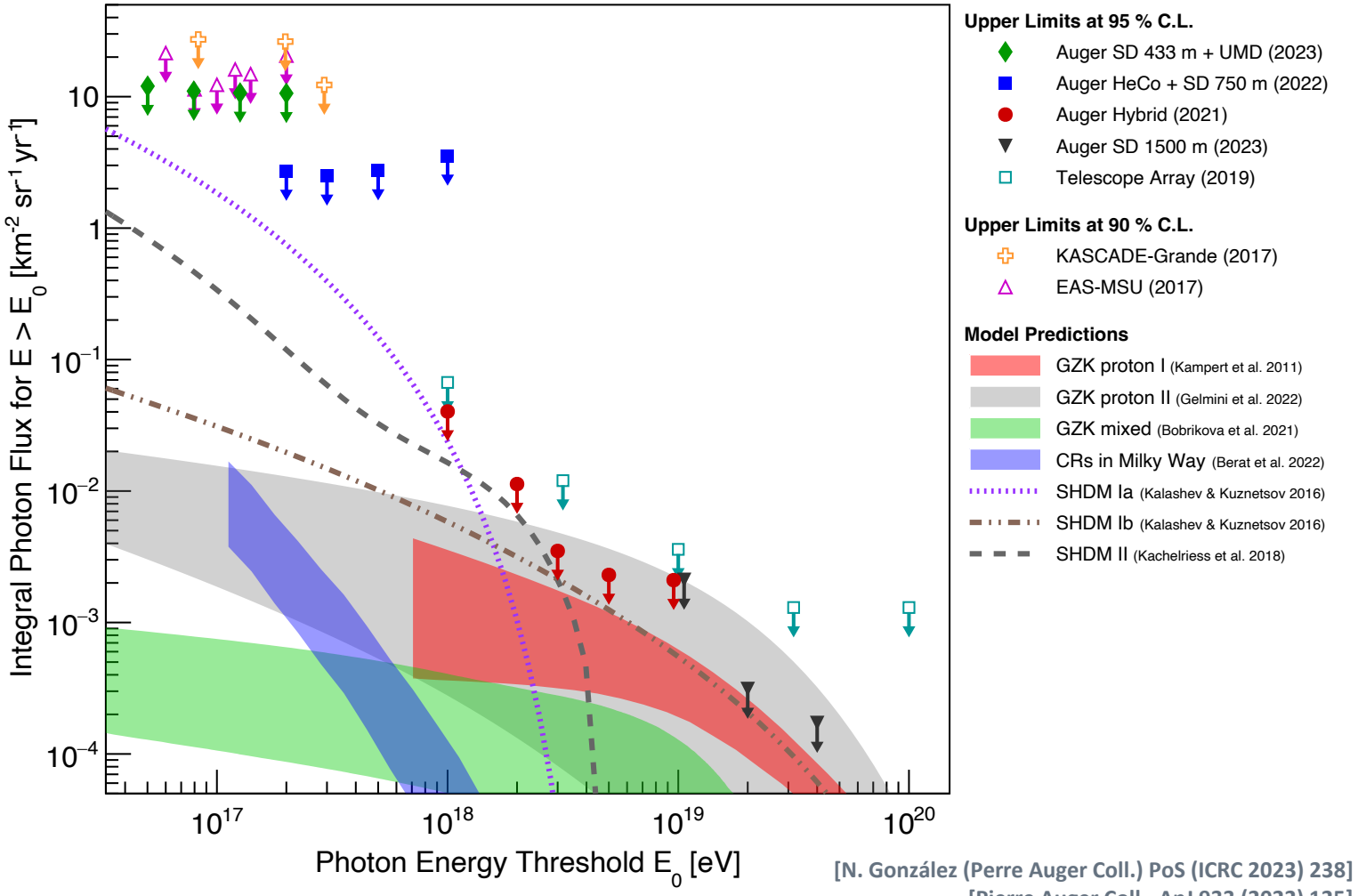
Machine Learning



- **Photon candidate cut** chosen to ensure 50 % signal efficiency, leading to ~99.9 % background rejection
- **Data period:** 1 Jun 2010 – 31 Dec 2015
- **Exposure** to photons (from simulations): ~2.5 km^2 sr yr
- **No events** pass the candidate cut

[Pierre Auger Coll., ApJ 933 (2022) 125]

Upper Limits on the Diffuse Flux of UHE Photons



[N. González (Perre Auger Coll.) PoS (ICRC 2023) 238]
[Pierre Auger Coll., ApJ 933 (2022) 125]
[P. Savina (Pierre Auger Coll.), PoS (ICRC 2021) 373]
[Pierre Auger Coll., JCAP 05 (2023) 021]
[Pierre Auger Coll., Universe 8 (2022) 579]

- **No primary UHE photon** could be unambiguously identified so far
- **Most stringent limits** on the diffuse flux of photons over a wide energy range come from Auger
- Predictions of some **cosmogenic models** (e.g., involving GZK interactions) are within reach
- Limits also useful to constrain BSM models involving **SHDM particles**
  [Pierre Auger Coll., PRL 130 (2023) 061001]
  [Pierre Auger Coll., PRD 107 (2023) 042002]
- Also done: **follow-up search for photons** for GW events from LIGO/Virgo [Pierre Auger Coll., ApJ 952 (2023) 91]