Discussion: Particle Physics in the Context of GCOS GCOS Workshop 2022

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- Particle Physics with Cosmic Rays
- Overview: Current Status
- The Next 10 Years
- Particle Physics with GCOS
- <u>Discussion</u>

Submitted to the US Community Study on the Future of Particle Physics (Snowmass 2021) 2022 Ultra-High-Energy Cosmic Rays Jul The Intersection of the Cosmic and Energy Frontiers _ [astro-ph.HE] 3 Abstract: The present white paper is submitted as part of the "Snowmass" process to help arXiv:2205.05845v inform the long-term plans of the United States Department of Energy and the National Science Foundation for high-energy physics. It summarizes the science questions driving the Ultra-High-Energy Cosmic-Ray (UHECR) community and provides recommendations on the strategy to answer them in the next two decades. Y

[arXiv:2205.05845]





Snowmass 2022 White Paper

• <u>This talk:</u> summary & discussion of the Snowmass White Paper's particle physics sections

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Particle Physics with Cosmic Rays

- EAS measurements probe particle physics at the highest energies
- Example: proton-air cross-section
- Complementary to collider measurements:
 - EAS particles: Nuclei, mesons, ...
 - CM energies: GeV to hundreds of TeV
 - Forward direction
 - Non-perturbative regime
- Crisis for high-energy physics?
 - No new particles found at LHC
 - Nature of Dark Matter is still unknown
- **Opportunity for cosmic ray physics?**



[R. Ulrich (Pierre Auger Collaboration), PoS(ICRC2015)401 (2016)]







What is the current status of the field?

- Significant discrepancies in the number of muons in EAS observed between MC and data for all recent hadronic interaction models!
- z-value:





What is the current status of the field?

- Muon Puzzle:
 - Up to ~30% discrepancies in N_{μ}
 - \blacktriangleright N_{μ} vs. X_{max} and $X_{\mu,\text{max}}$ vs. X_{max}
 - WHISP: excess towards high energies • slope in $z - z_{mass}$ significant at $\sim 8\sigma$
 - Origin remains unknown!
- <u>Challenge for accelerators:</u>
 - Interactions of EAS particles
 - CM energies: GeV to hundreds of TeV
 - Forward direction





What is the current status of the field?

- Accelerator measurements:
 - ALICE, CMS/CASTOR, LHCf, LHCb/SMOG, NA61/SHINE
 - Inelastic cross-sections
 - Hadron multiplicity
 - Elasticity
 - Hadron composition (ratio e.m. to hadr. energy flow)
 - Different
 - energies
 - rapidity ranges
 - particle types
- EAS data needed!





- Current uncertainties of muon measurements: $\sim 15-20 \%$
- Proton EAS: fluctuations of same order
- Iron EAS: $\sim 5\%$ fluctuations
- Uncertainties of muon measurements will be reduced in the next decade:
 - New detectors
 - Measurements close to shower axis
 - Larger statistics
 - Improved calibration
 - New analysis techniques (ML)
- Smaller uncertainties, better resolution $(\sim 10 - 15^{\circ}/_{\circ})$





12 IceCube-Gen2

- Multi-hybrid measurements (Auger)!
 - EAS energy: Fluorescence Detectors (FD)
 - Muon number: Surface Detectors (SD) + Scintillators (SSD) + Muon Detectors (MD)
- Event-to-event muon distributions
- Studies of the observed discrepancies in a non-degenerated way
- Radio extension (RD): mass & energy, resolves bias from single technology
- Simultaneous measurement: X_{max} , $X_{\mu,\text{max}}$
- Zenith angle evolution: muon spectrum!
- Machine learning techniques

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- Multi-hybrid measurements (IceCube)!
 - EAS energy: Surface détectors (IceTop+upgrade)
 - Muon number: IceTop (GeV muons) + in-ice array (TeV muons)
 - Two vastly different energy regimes
 - Spectral information!
- Radio extension (RD): mass & energy, resolves bias from single technology
- Measurement of prompt (PeV) muons?
- Seasonal muon flux as a probe for pion/kaon ratio (lower EAS energies)
- Machine learning techniques

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- Accelerator measurements (LHC)!
- Proton-Oxygen collisions in Run 3 (2023)
 - Importance for EAS physics
- High-Luminosity LHC!
- Forward experiments
- See later slides...

Expectation for the next decade

- Large variety of new high-precision data:
 - EAS detector upgrades will become fully operational, e.g. AugerPrime, IceCube upgrade
 - Precise muon measurements of multiple observables by multiple EAS experiments
 - New accelerator data, e.g. Run 3 at LHC (Oxygen data)
- Strong constraints on hadronic interaction models (muon enhancement models)
 - Precise characterization (solution?) of the Muon Puzzle within the next decade expected!

Open questions for the new generation of **UHECR** observatories

- New large-scale EAS observatories with particle detectors (GCOS, IceCube-Gen2, GRAND?) will provide large aperture and thus unprecedented event statistics
- Possibly new EAS observables and analysis techniques to test hadronic interaction models
 - New era of high-precision measurements with EAS!

Open questions for the new generation of **UHECR** observatories

- Precise measurements in the forward region at the High-Luminosity LHC (including new proposed experiments, e.g. Forward Physics Facility, Very Forward Hadron Spectrometer) will further constrain hadronic models
- Hadronic models have to describe both EAS and LHC measurements
 - Tests of SM predictions at energies much higher than the LHC (far-forward region)!
- Once the hadronic interaction models can successfully describe all details they will become reliable tools for the development of the proposed Future Circular Collider (FCC)
 - Validation of EAS models at the (HL-)LHC / FPF / FCC

Open questions for the new generation of UHECR observatories

- If LHC data is reproduced but Muon Puzzle remains:
 - Tests of beyond SM physics / exotic scenarios, e.g.
 - Lorentz-invariance violation
 - Super-heavy Dark Matter
 - Macroscopic Dark Matter
 - Nuclearites

Summary & Discussion

- Expectation:
 - Muon Puzzle precisely characterized (solved?)
 - High-precision particle measurements with EAS!
 - Tests of SM predictions at energies much higher than the LHC
 - Provides event generators for future collider experiments, e.g. FPF / FCC
 - If the Muon Puzzle remains unsolved
 - Tests of beyond SM physics / exotic scenarios!
- Main focus / needs of the GCOS community?
- Requirements for GCOS design?
- Probably many further questions / comments / additions...

