Discussion:
Particle Physics in the Context of GCOS

GCOS Workshop 2022

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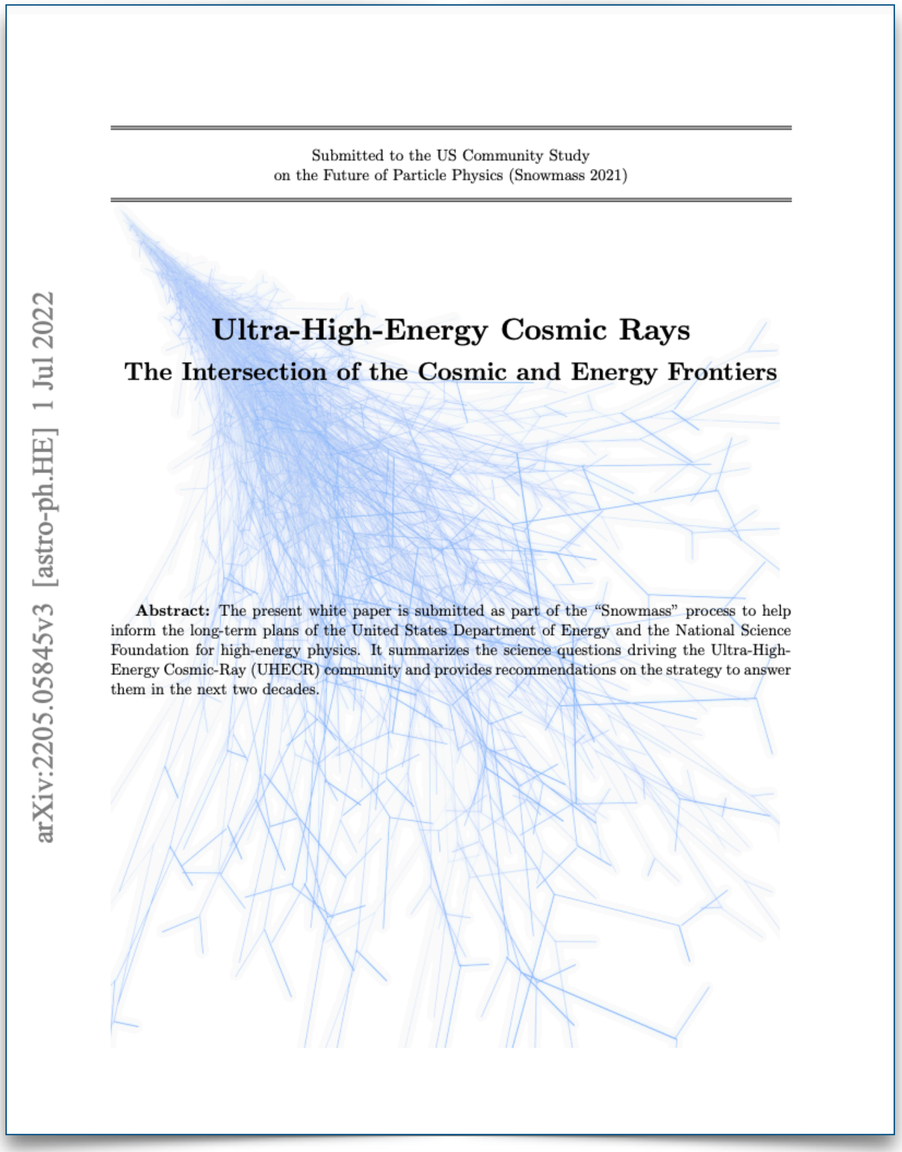
Outline

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



[arXiv:2205.05845]

Snowmass 2022 White Paper

- This talk: summary & discussion of the Snowmass White Paper's particle physics sections

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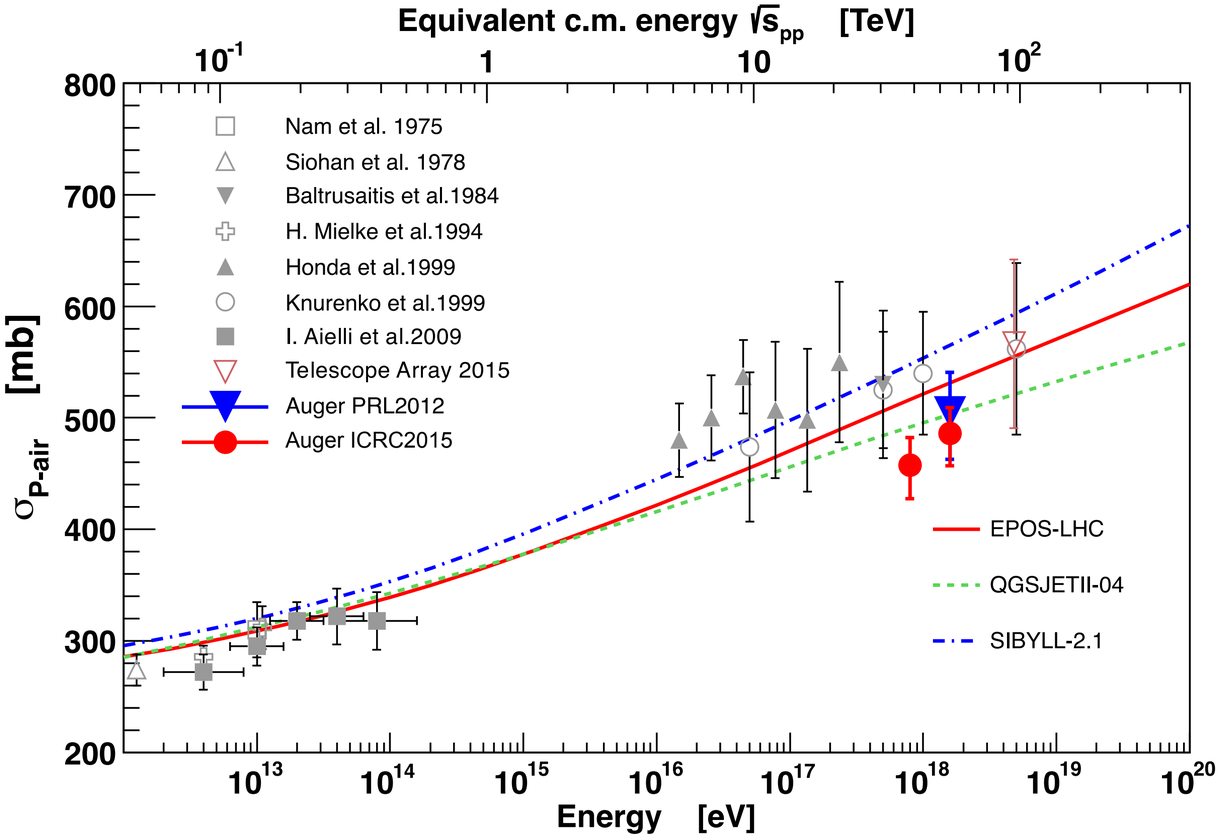
Contents

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)]

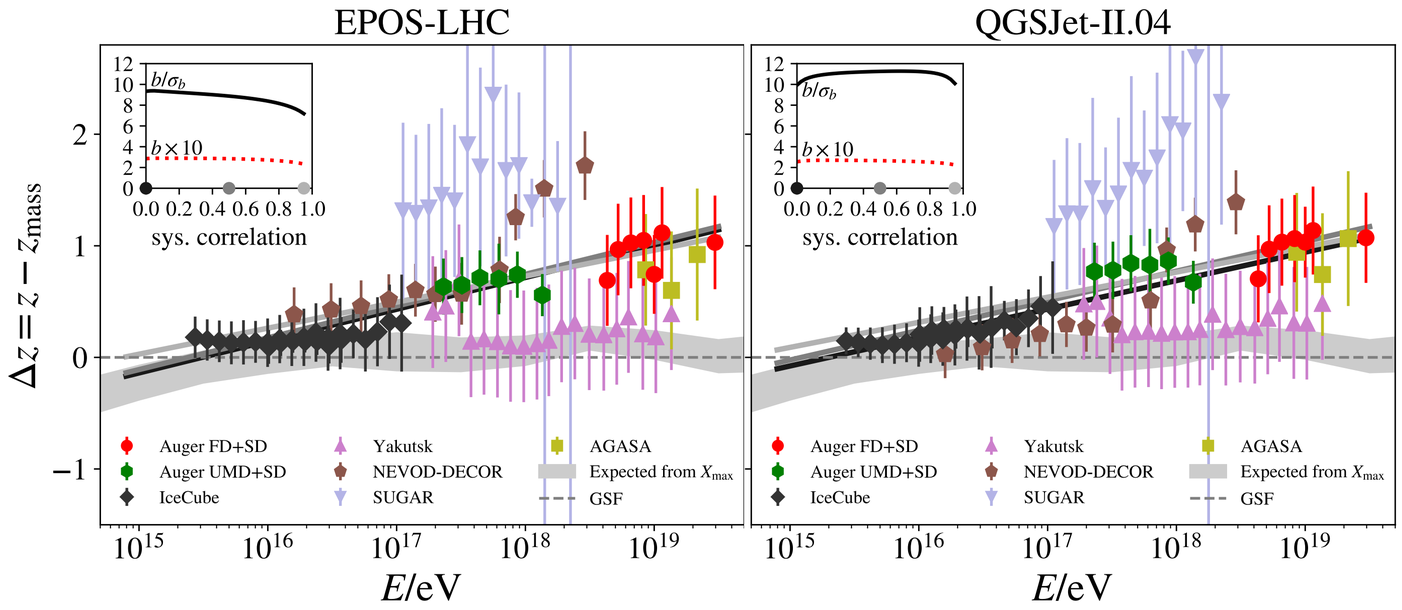
What is the current status of the field?

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

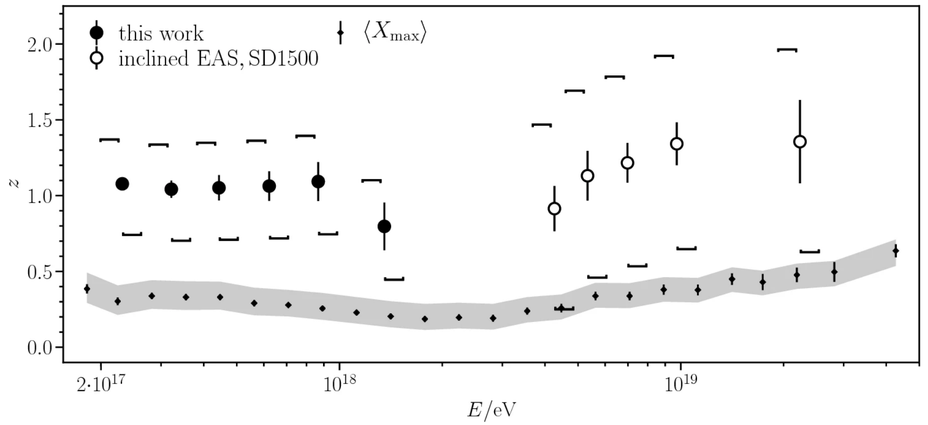
- z-value:

$$z = \frac{\ln(\rho_\mu) - \ln(\rho_{\mu,\mathrm{p}})}{\ln(\rho_{\mu,\mathrm{Fe}}) - \ln(\rho_{\mu,\mathrm{p}})}$$

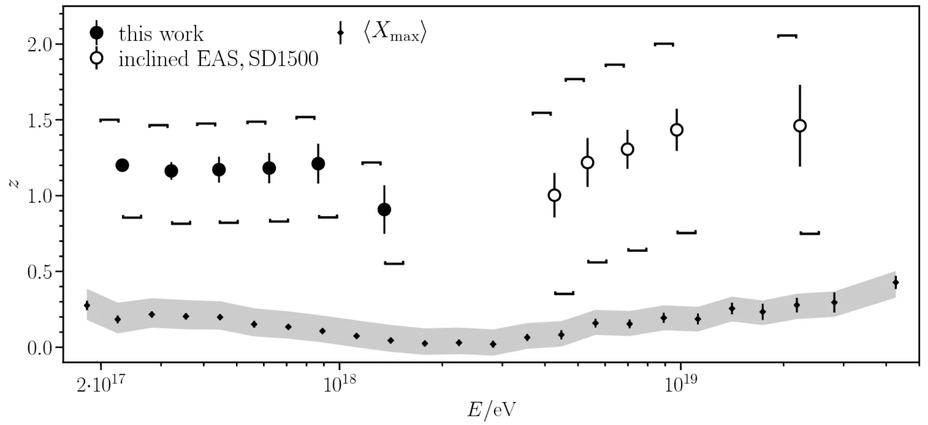
$z = 0$: proton , $z = 1$: iron



[D. Soldin et al. (WHISP), PoS(ICRC2021)349 (2021)]



(a) EPOS-LHC



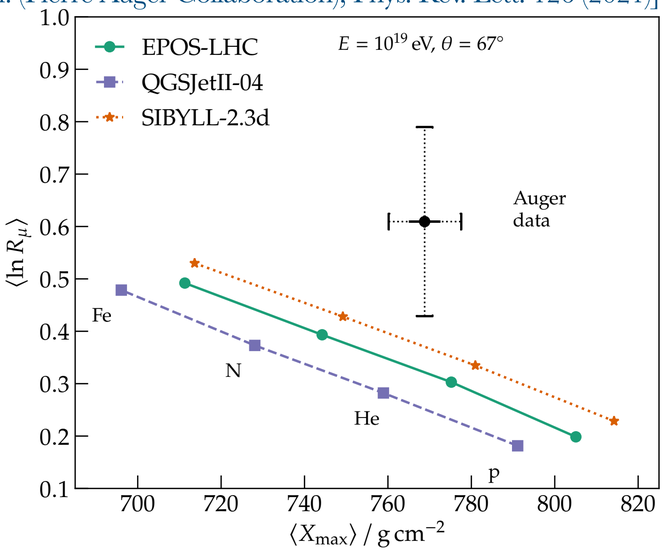
(b) QGSJetII-04

[A. Aab et al. (Pierre Auger Collaboration), Phys. Rev. D91 (2015)]
[A. Aab et al. (Pierre Auger Collaboration), Eur. Phys. J. C 80 (2020)]

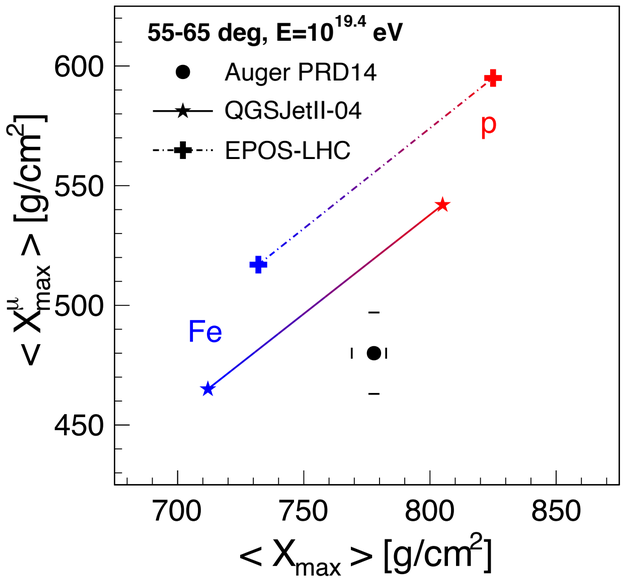
What is the current status of the field?

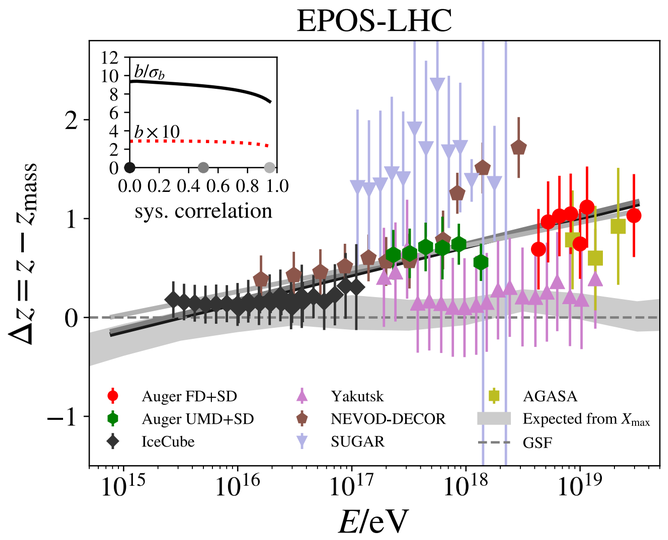
- Muon Puzzle:
  - Up to ~30% discrepancies in N_μ
  - N_μ vs. $X_{\max}$ and $X_{\mu,\max}$ vs. $X_{\max}$
  - WHISP: excess towards high energies
    - slope in $z - z_{\text{mass}}$ significant at ~8σ
  - Origin remains unknown!
- Challenge for accelerators:
  - Interactions of EAS particles
  - CM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

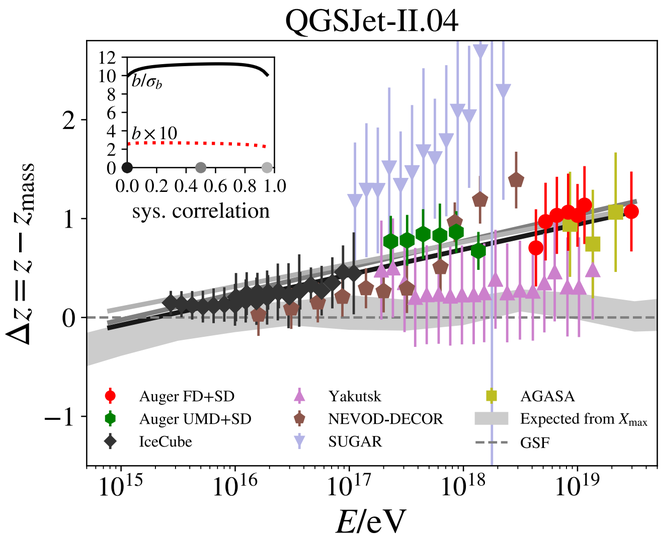
[A. Aab et al. (Pierre Auger Collaboration), Phys. Rev. Lett. 126 (2021)]



[L. Cazon, PoS(ICRC2019)005 (2020)]





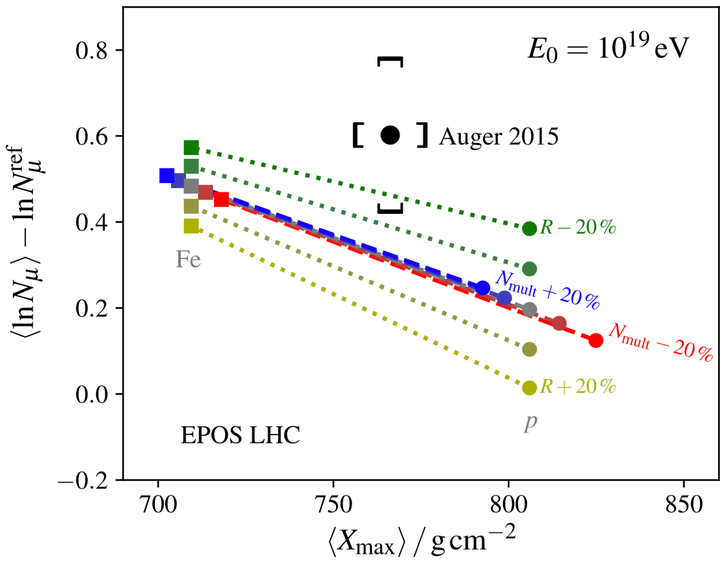


[D. Soldin et al. (WHISP), PoS(ICRC2021)349 (2021)]

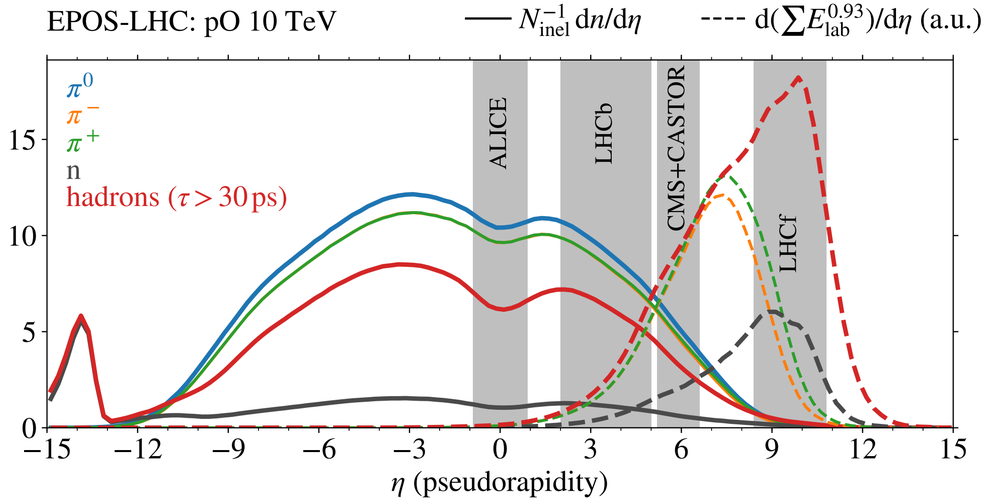
What is the current status of the field?

- 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!

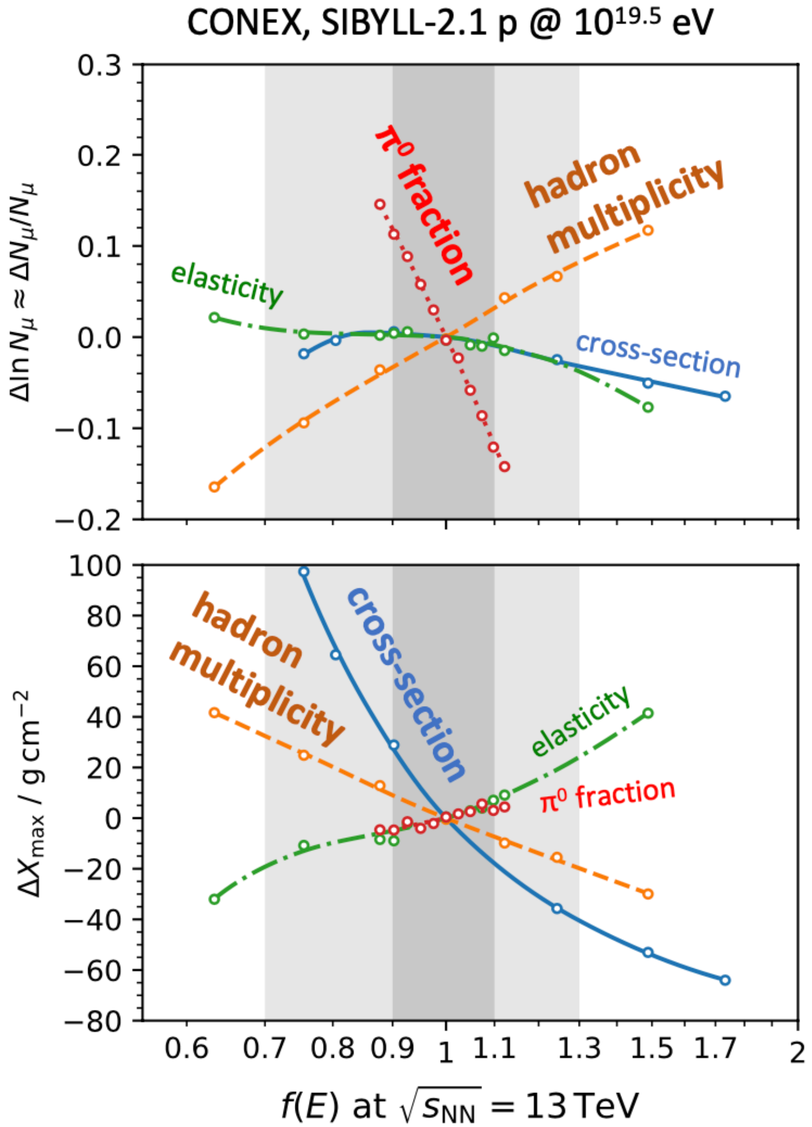
[S. Baur et al., arXiv:1902.09265 (2019)]



[J. Albrecht et al., Astrophys.Space Sci. 367 (2022)]

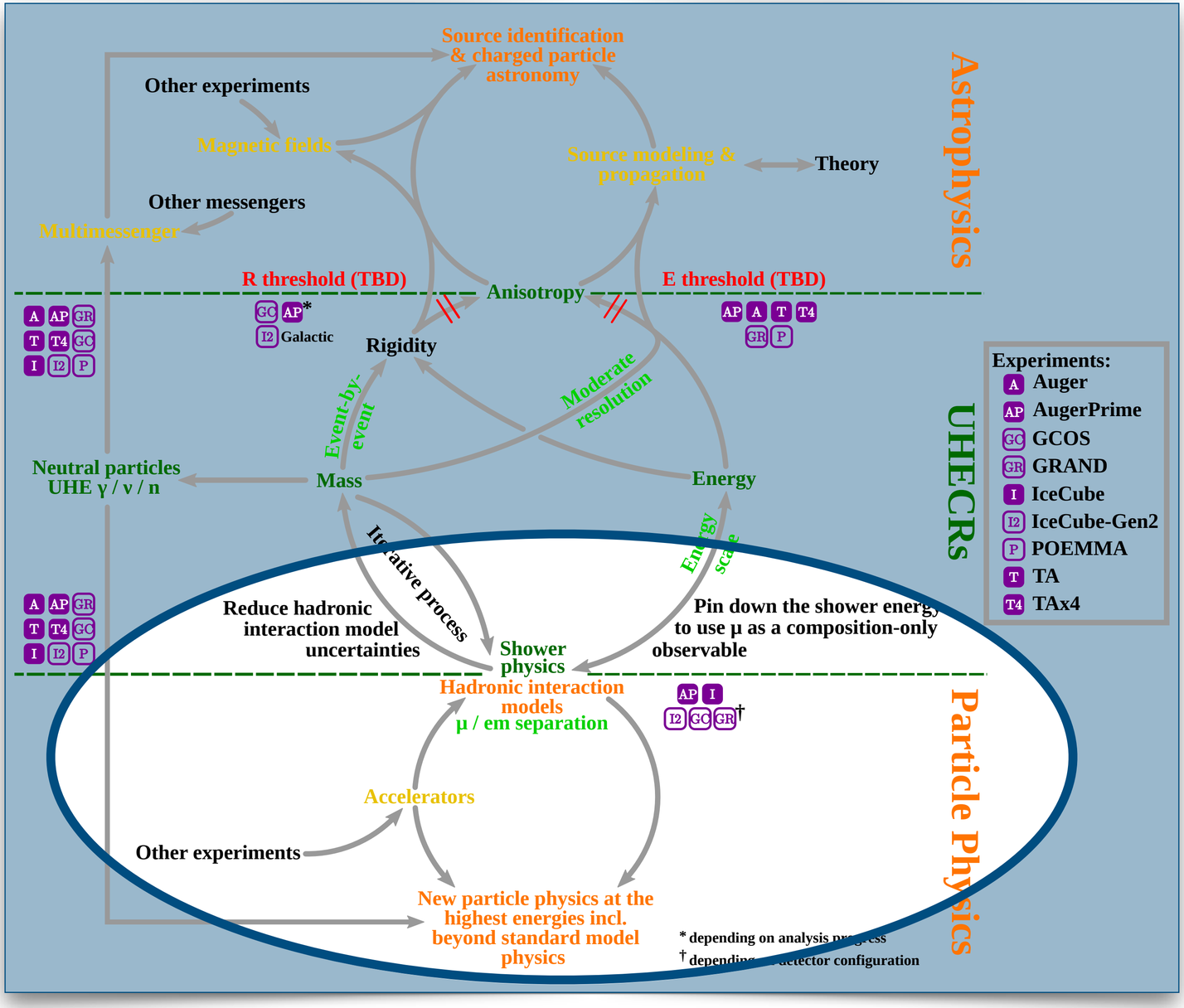


[R. Ulrich, R. Engel, M. Unger, Phys. Rev. D 83 (2011)]



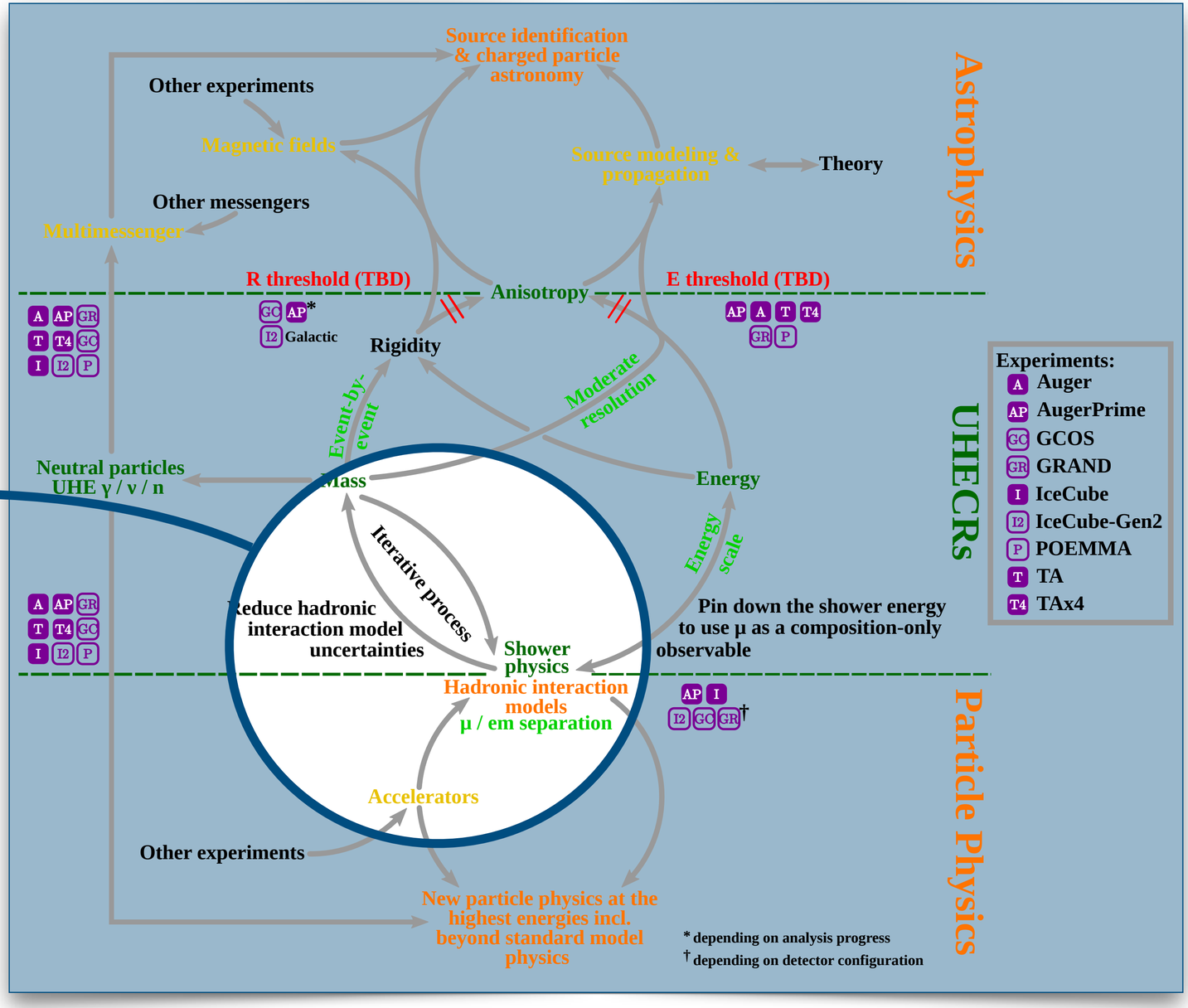
Where are we going to be 10 years from now?

- Current uncertainties of muon measurements: ~15-20 %
- Proton EAS: fluctuations of same order
- Iron EAS: ~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 (~10-15%)



Where are we going to be 10 years from now?

- 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: $X_{\max}$, $X_{\mu,\max}$
- Zenith angle evolution: muon spectrum!
- Machine learning techniques



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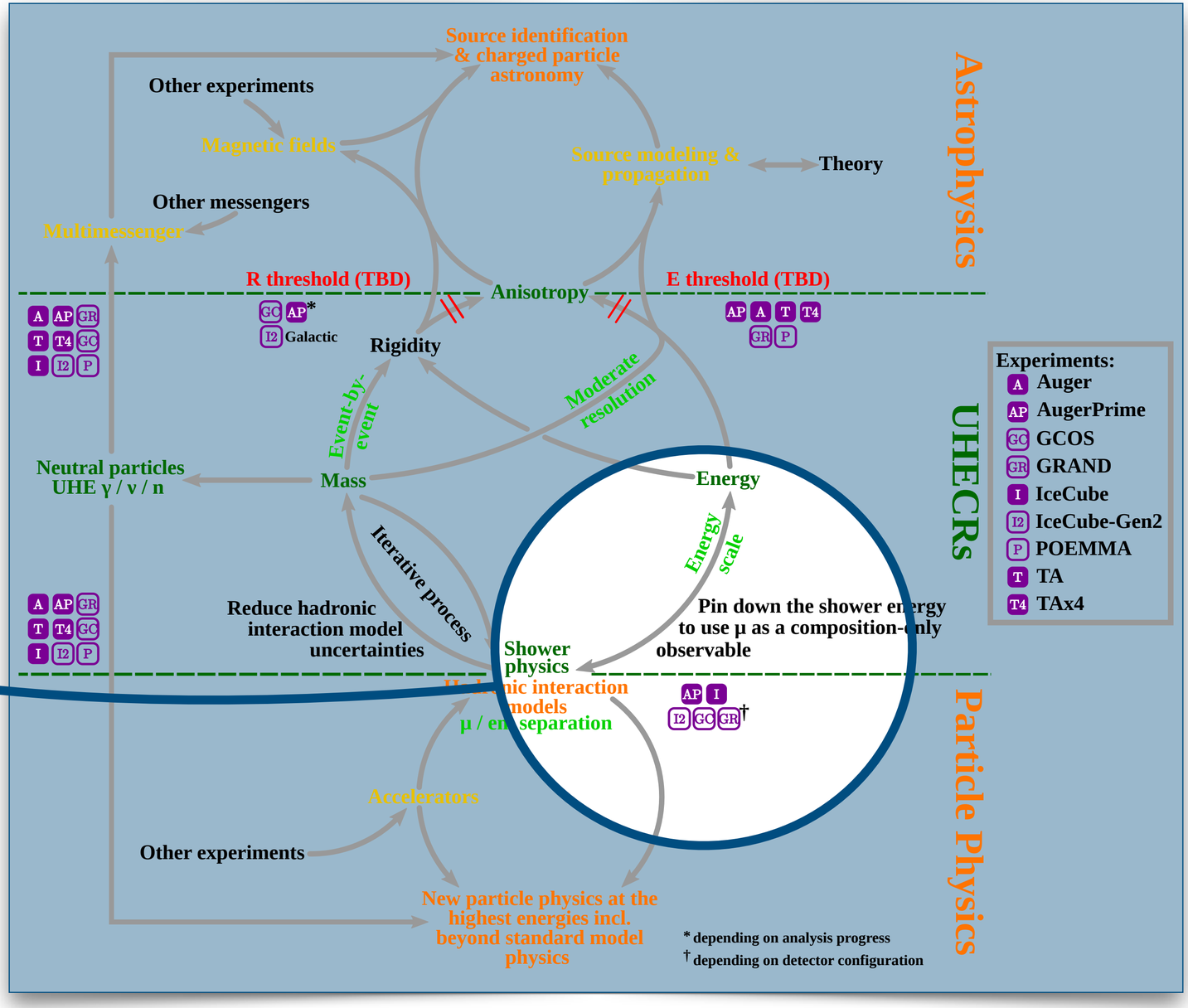

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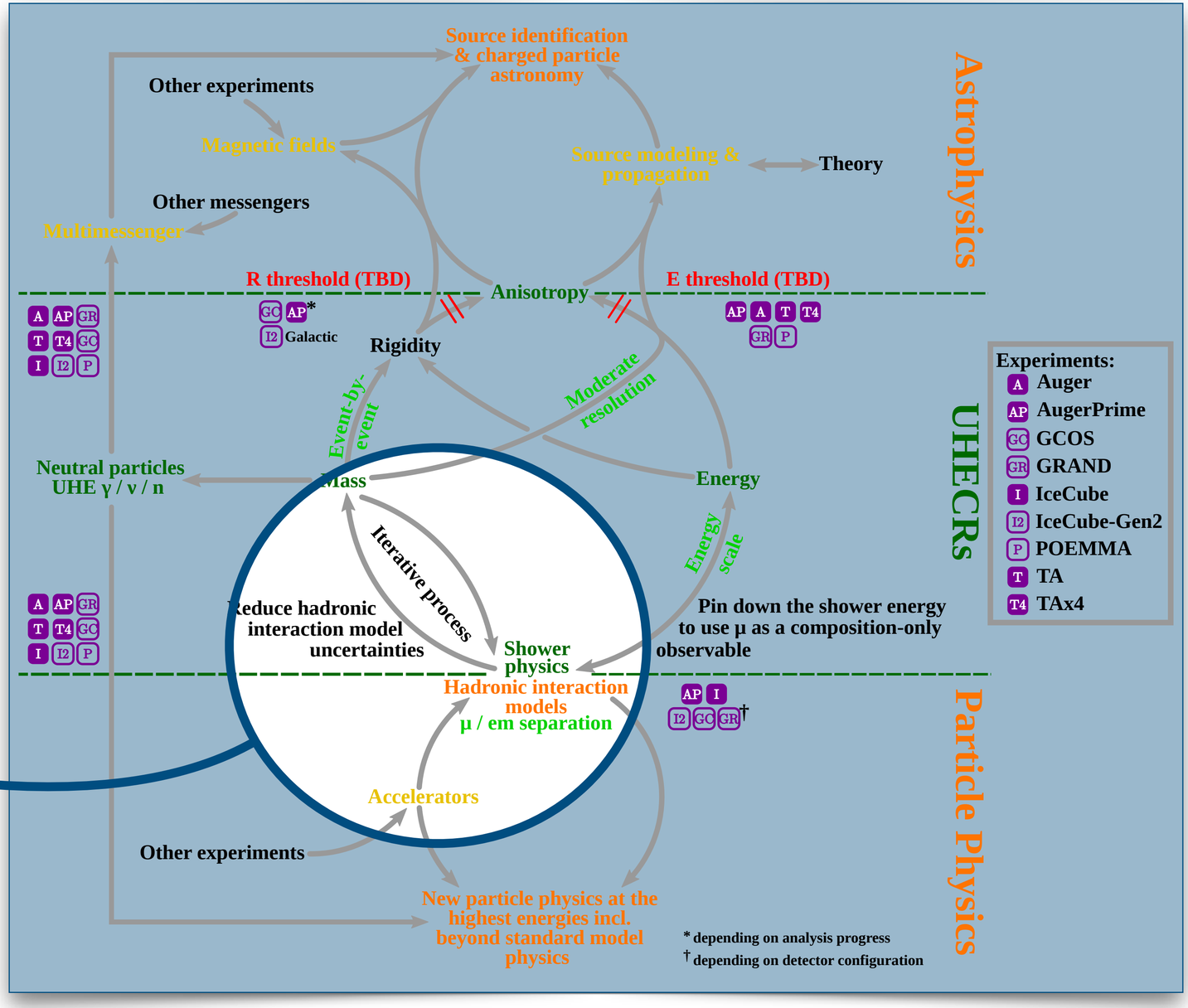

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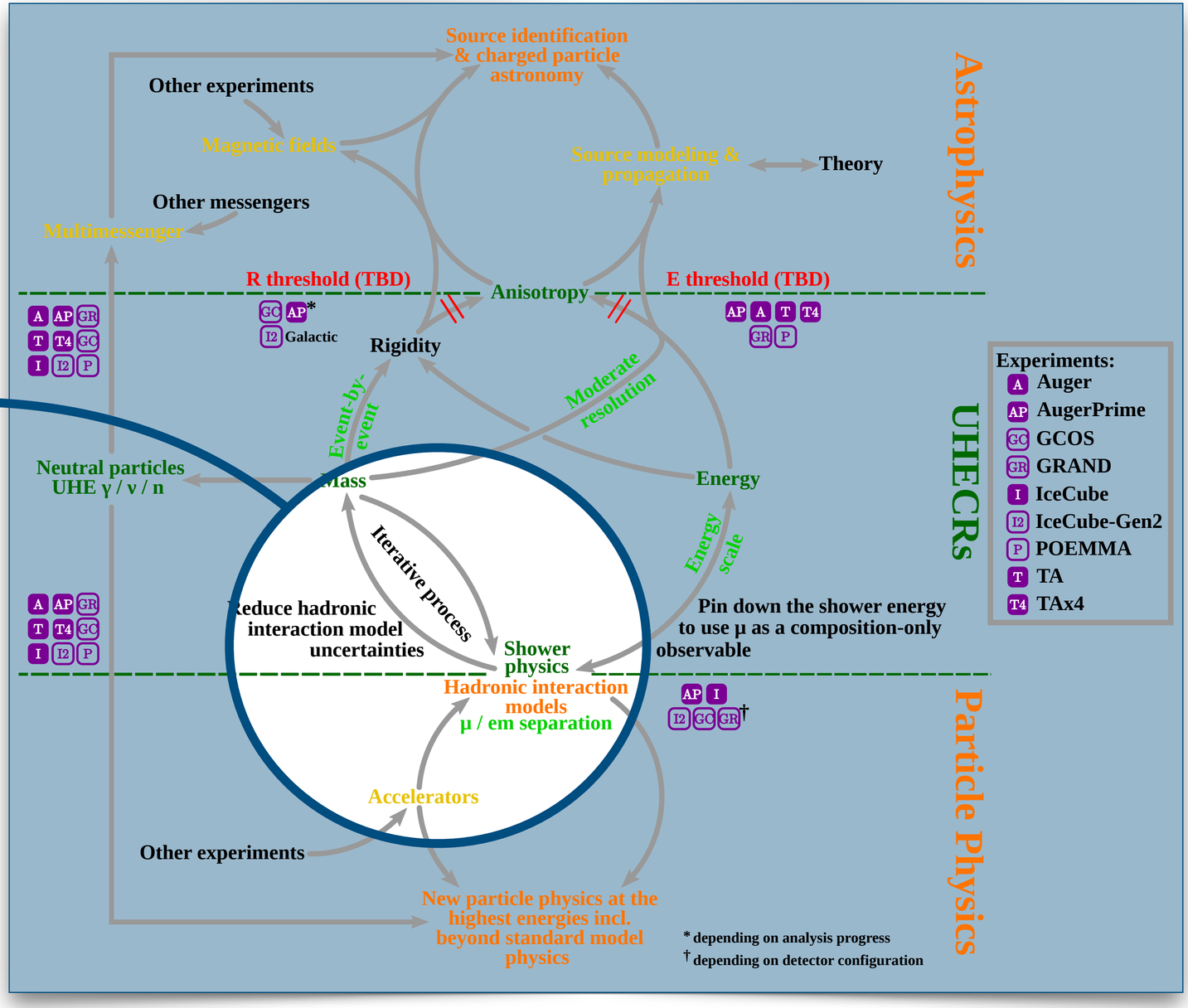
- Multi-hybrid measurements (IceCube)!
  - EAS energy:
    Surface detectors (IceTop+upgrade)
  - Muon number:
    IceTop (GeV muons)
    + in-ice array (TeV muons)
  - Two vastly different energy regimes
  - Spectral information!
- Radio extension (RD): mass & energy, resolves bias from single technology
- 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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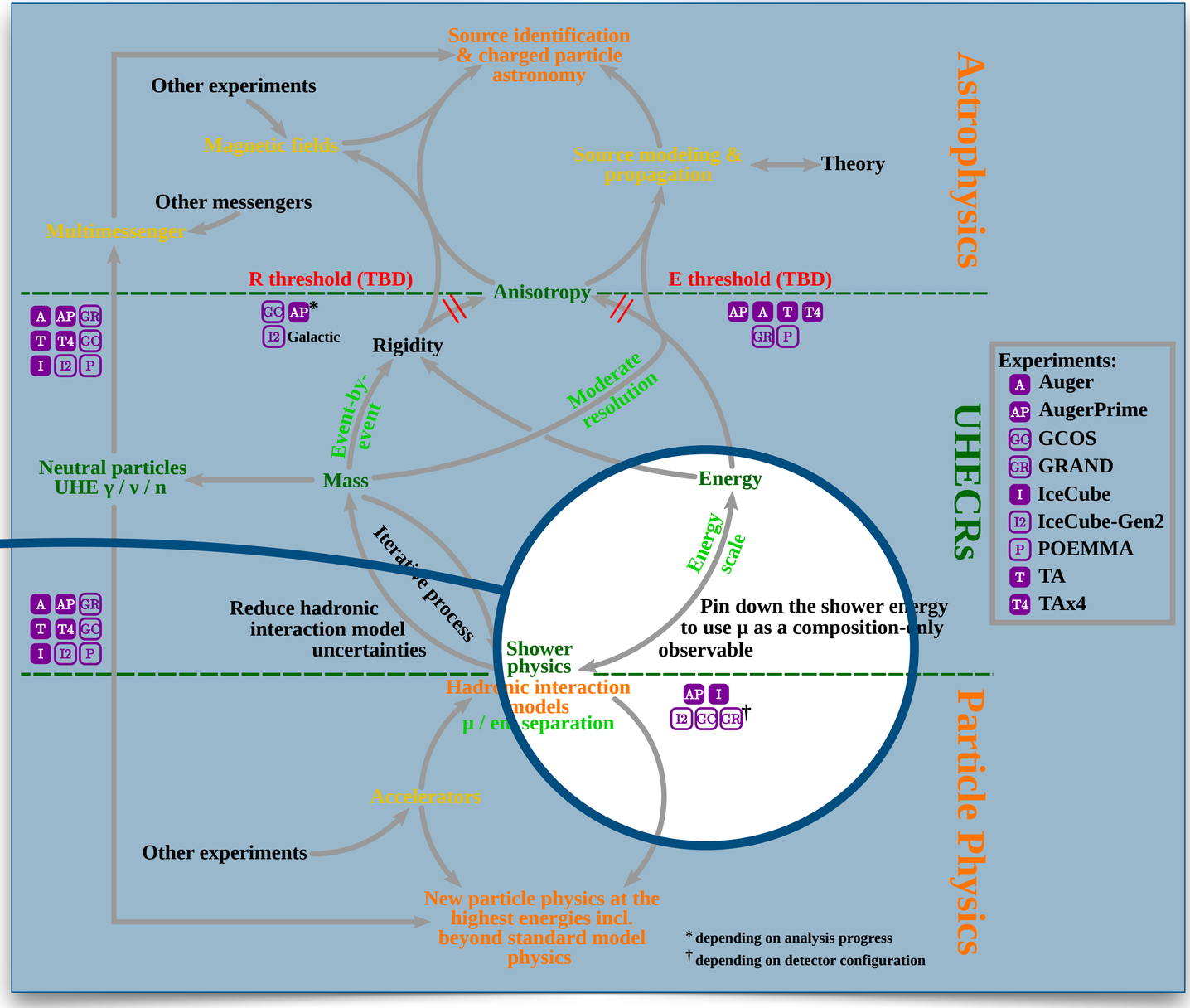

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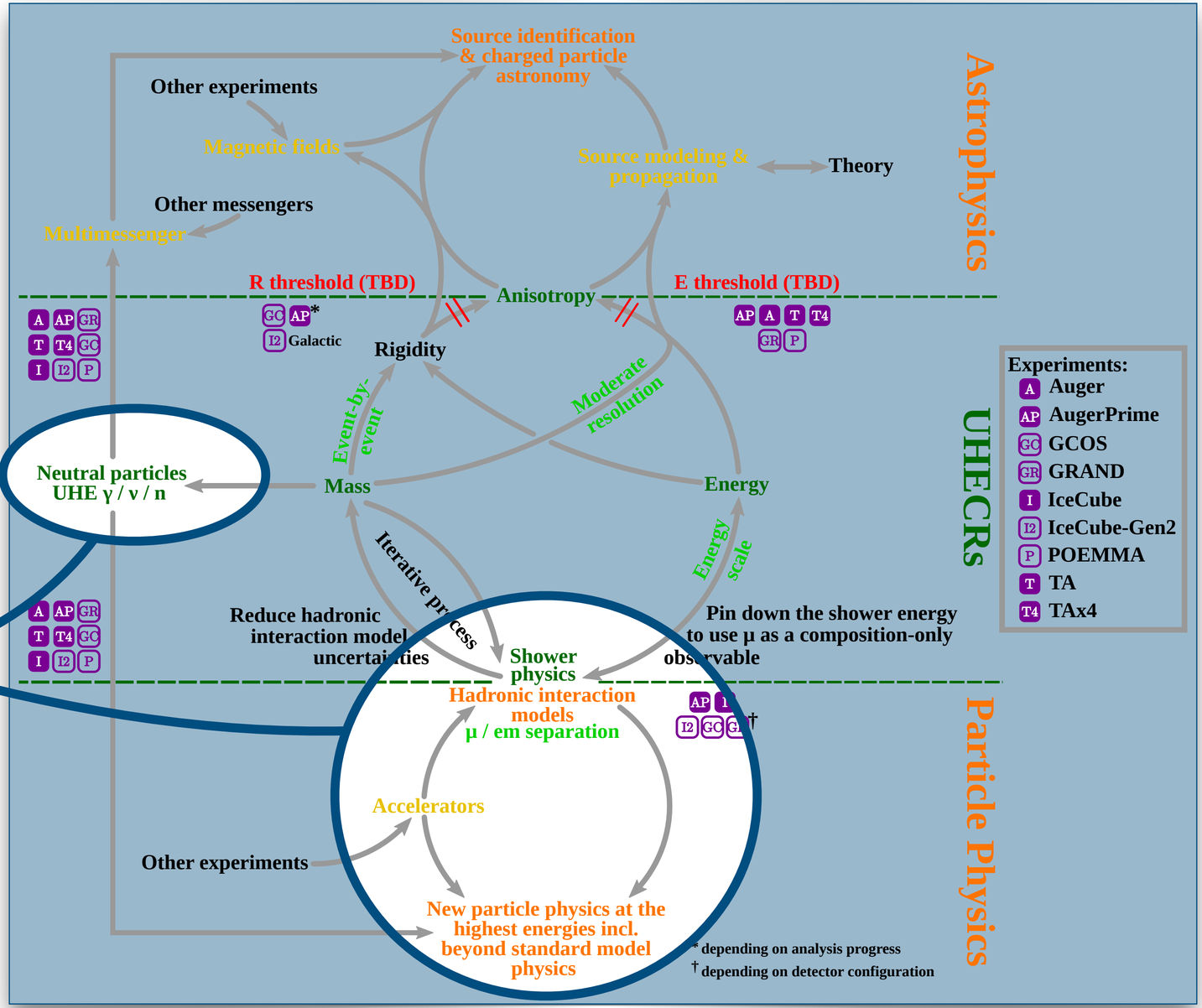

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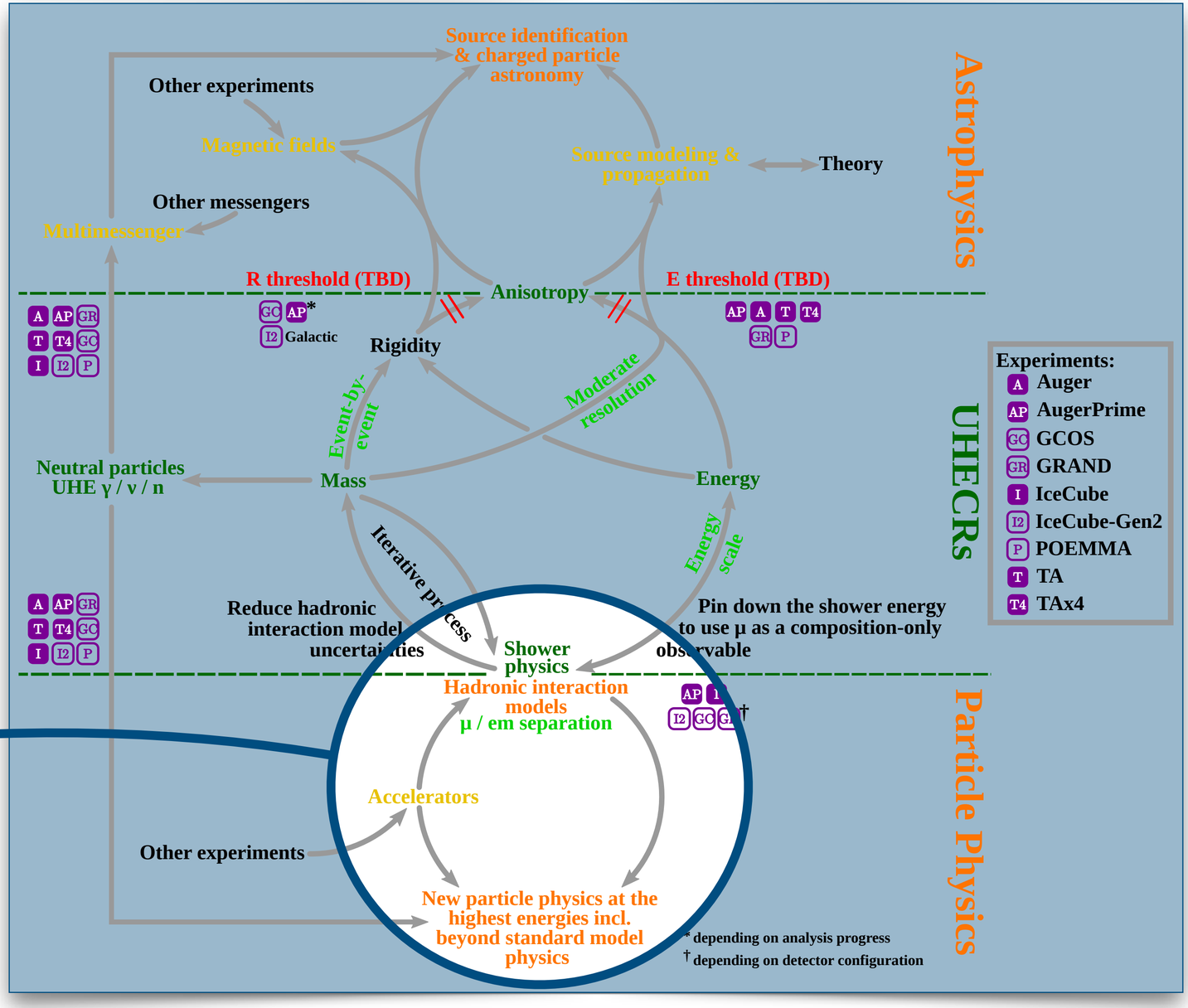
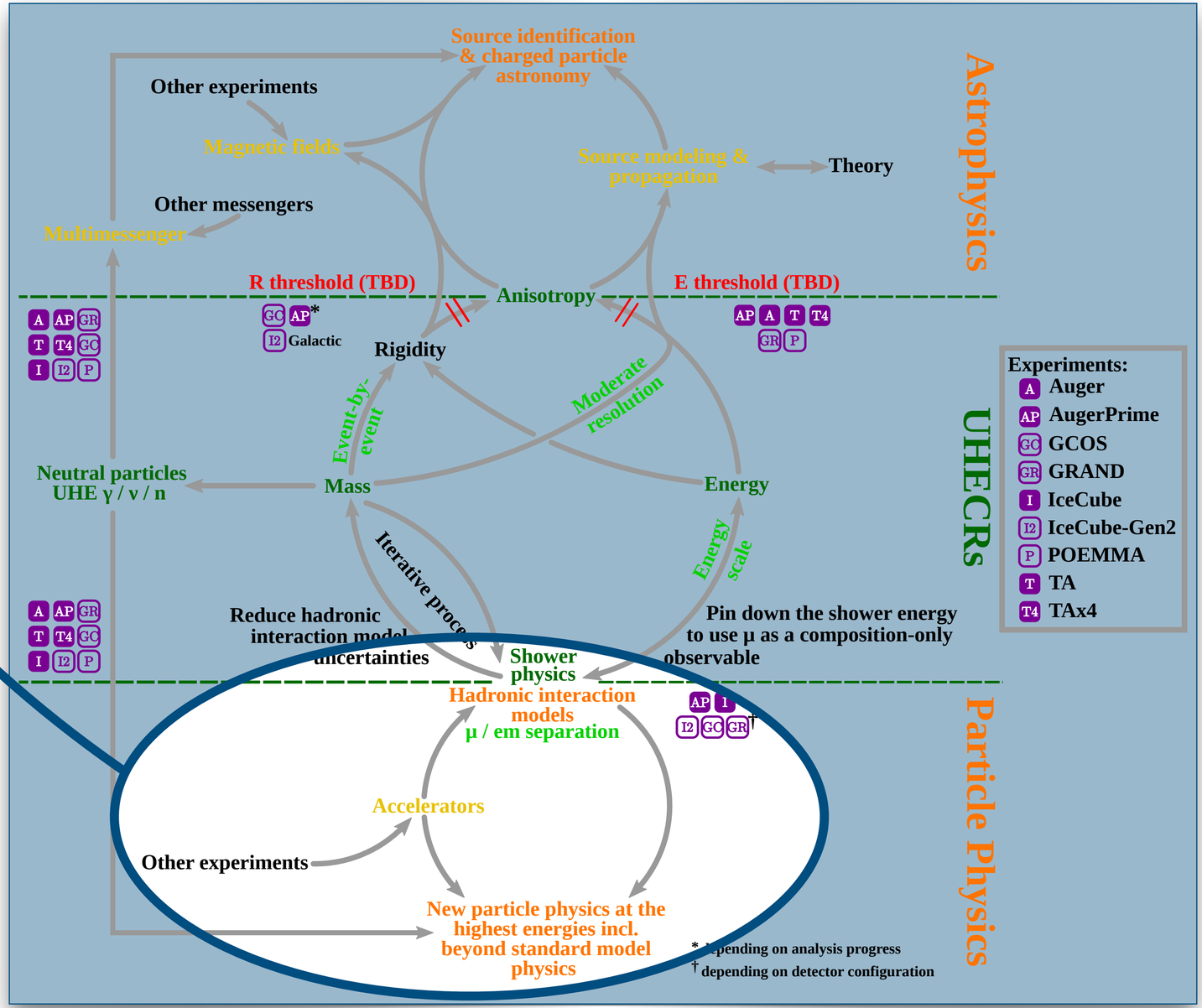


Where are we going to be 10 years from now?

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



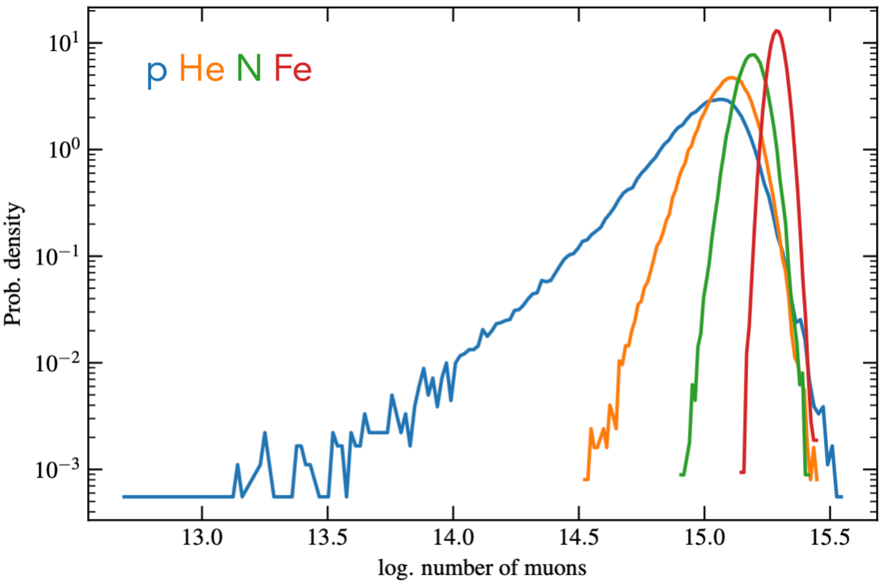
Expectation for the next decade

- 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!

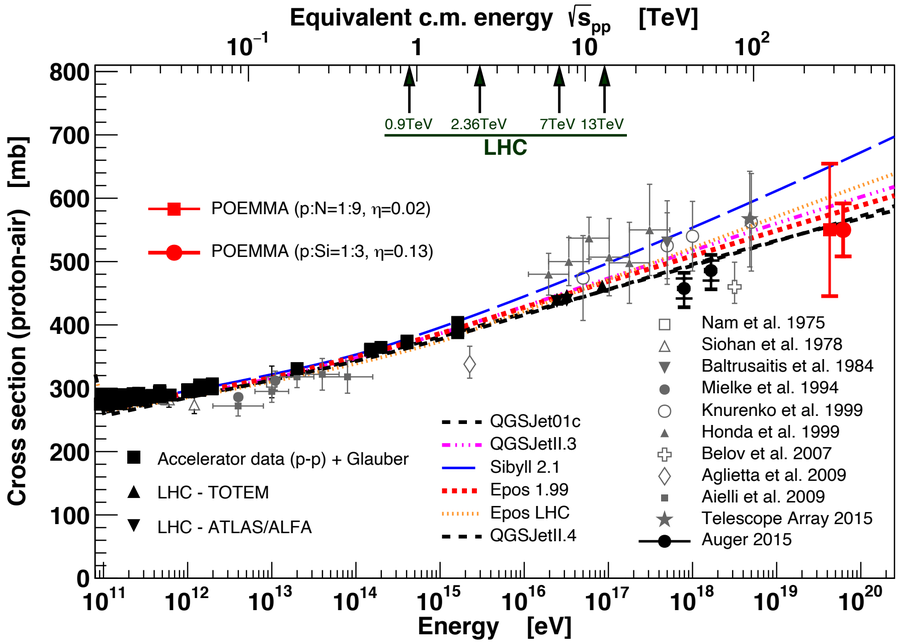
Open questions for the new generation of UHECR observatories

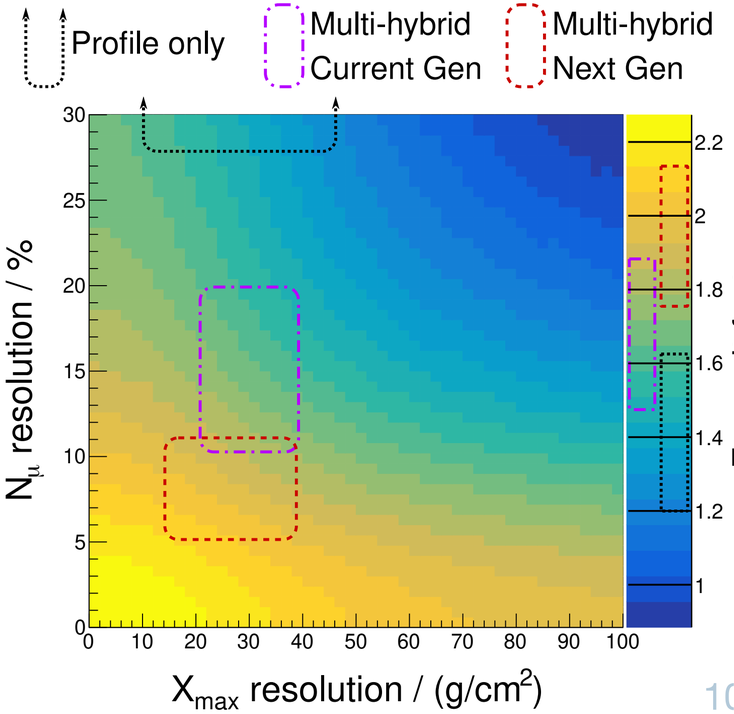
- New large-scale EAS observatories with particle detectors (GCOS, IceCube-Gen2, GRAND?) will provide large aperture and thus unprecedented event statistics
- Possibly new EAS observables and analysis techniques to test hadronic interaction models
  - <u>New era of high-precision measurements with EAS!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

[L. Cazon, R. Conceicao, F. Riehn, Phys. Lett. B 784 (2018)]



[L. A. Anchordoqui et al., Phys. Rev. D 101 (2020)]



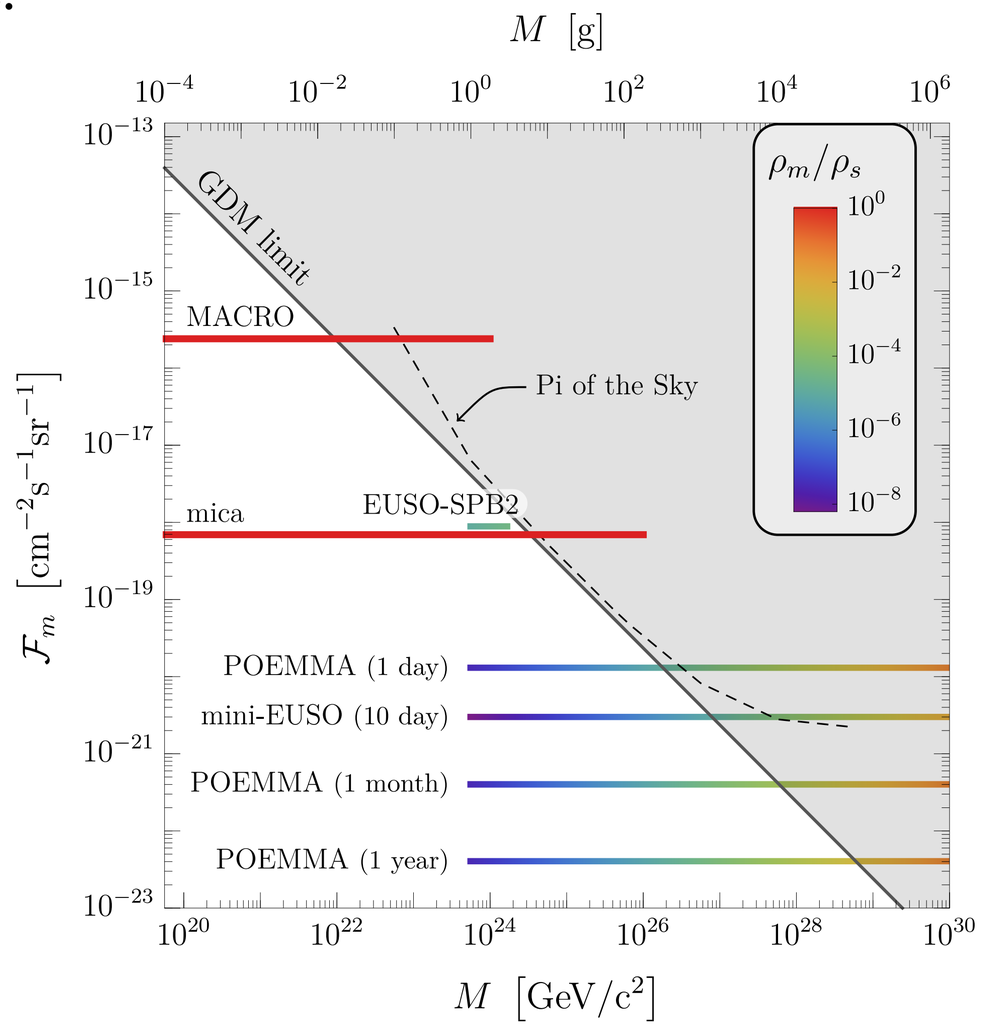


Open questions for the new generation of UHECR observatories

- 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:
  - <u>Tests of beyond SM physics /exotic scenarios, e.g.</u>
    - 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…