Hadronic Interactions & Synergies between UHECRs and Particle Physics

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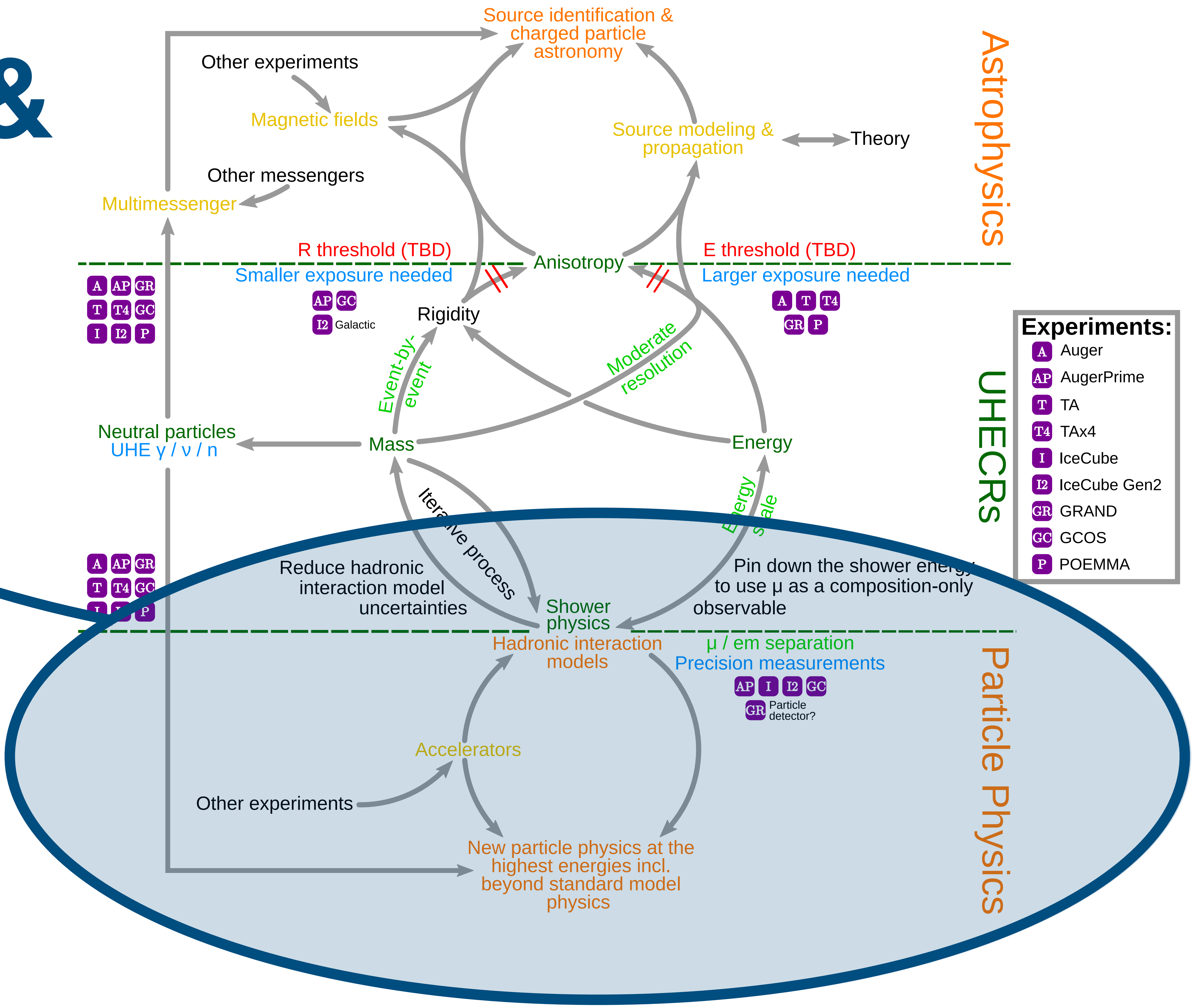

Conveners: H. P. Dembinski, T. Pierog, D. Soldin

Contributors: M. Albrow, L. Cazon, R. Conceição, A. Fedynitch

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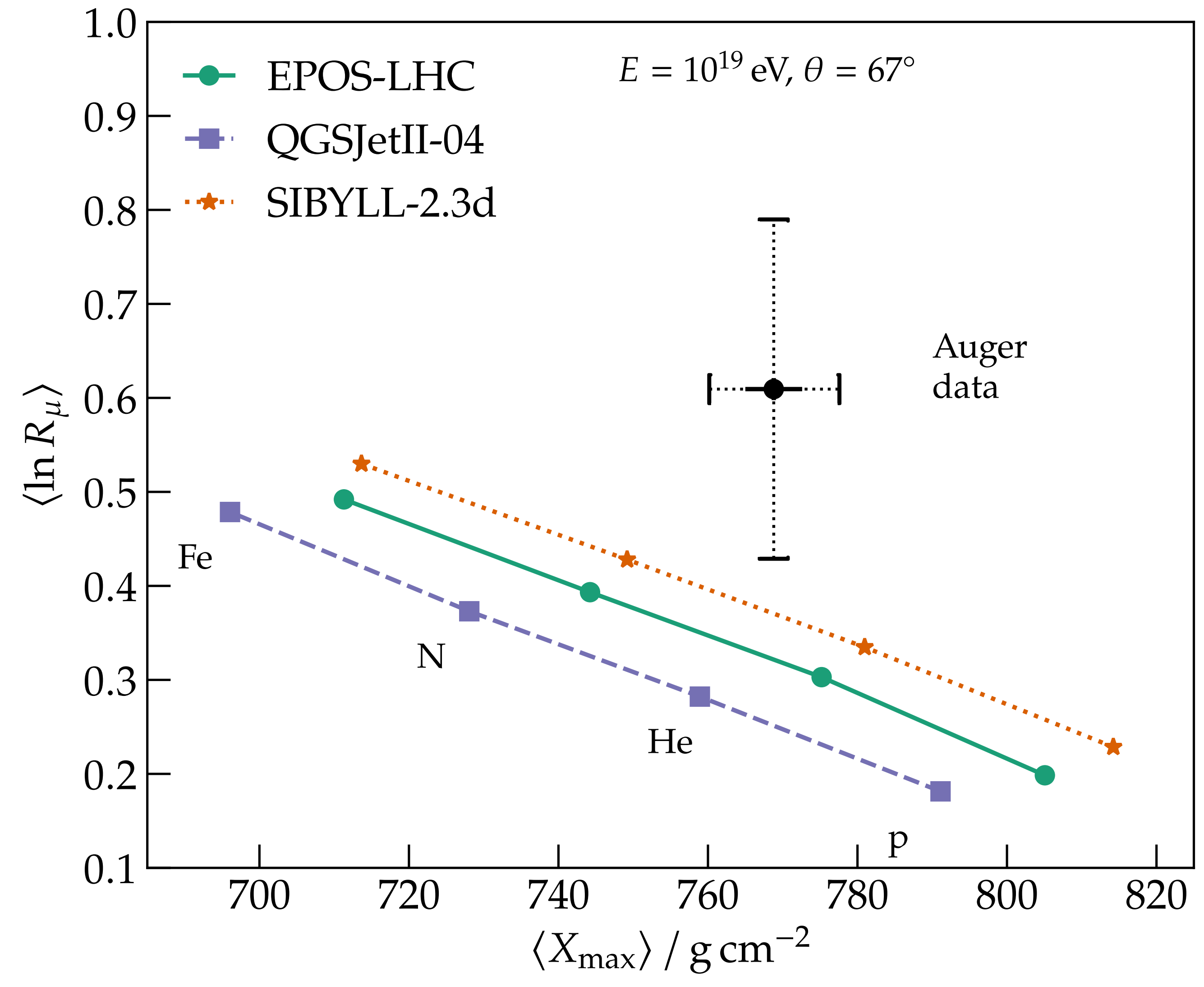
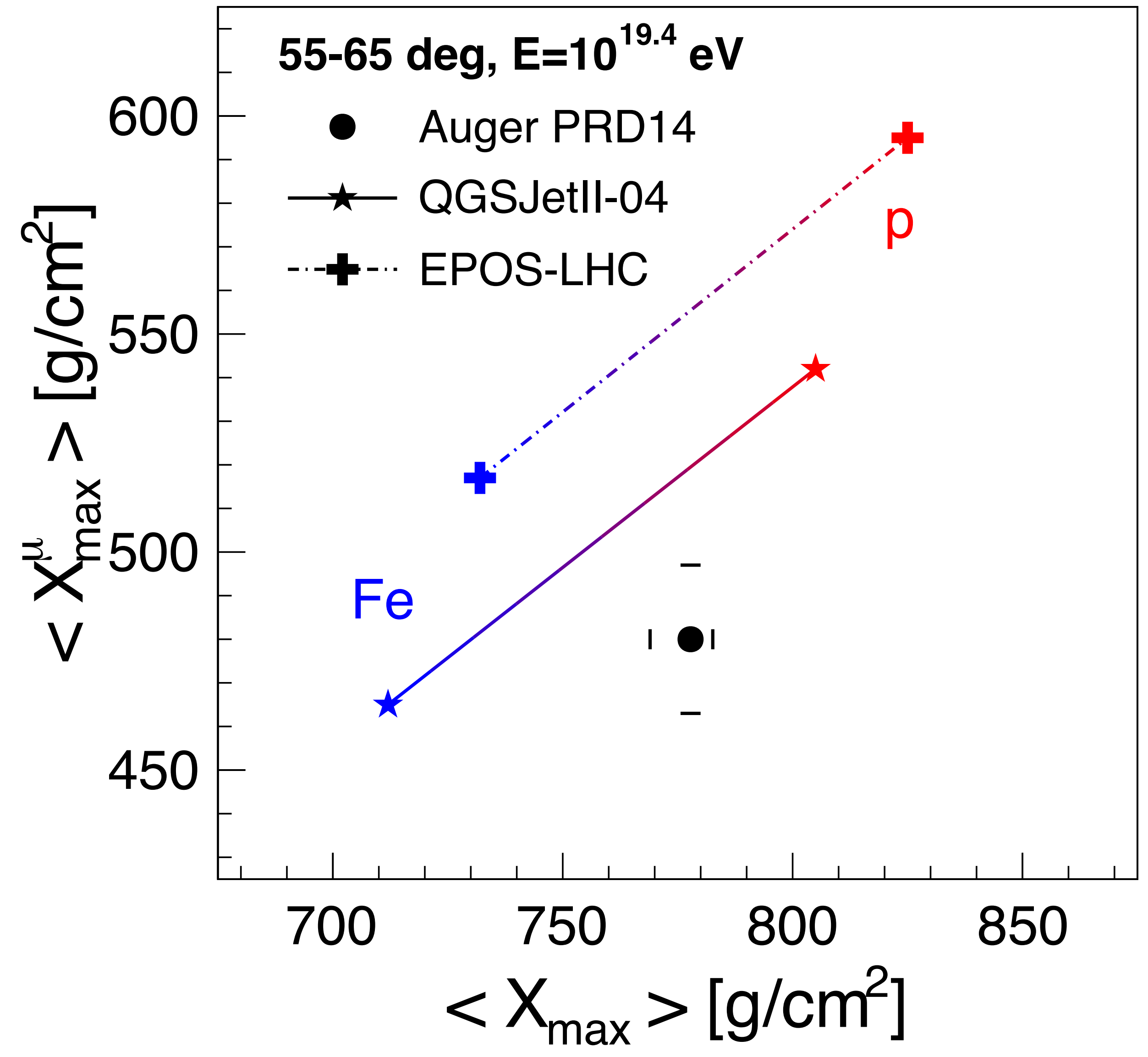
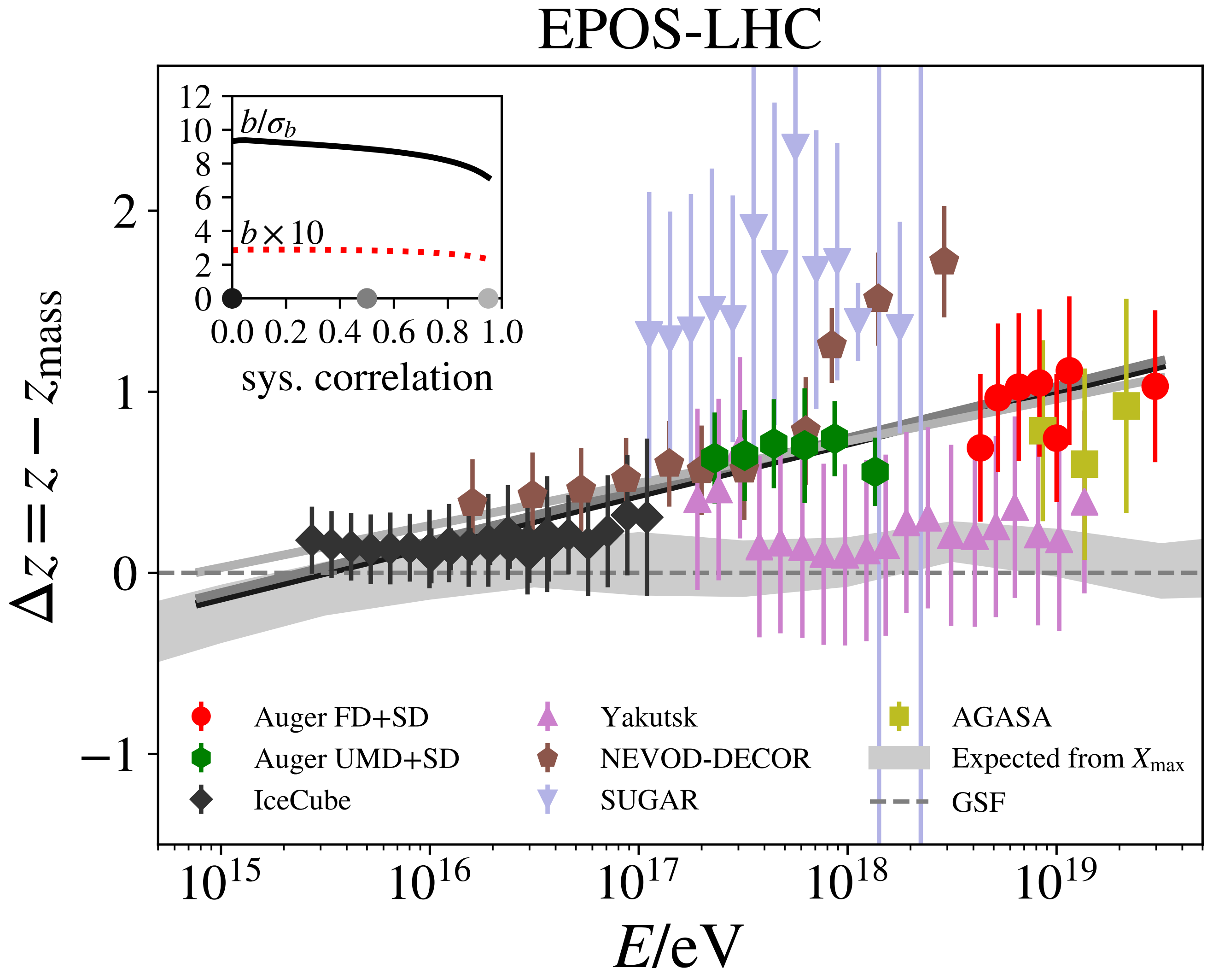
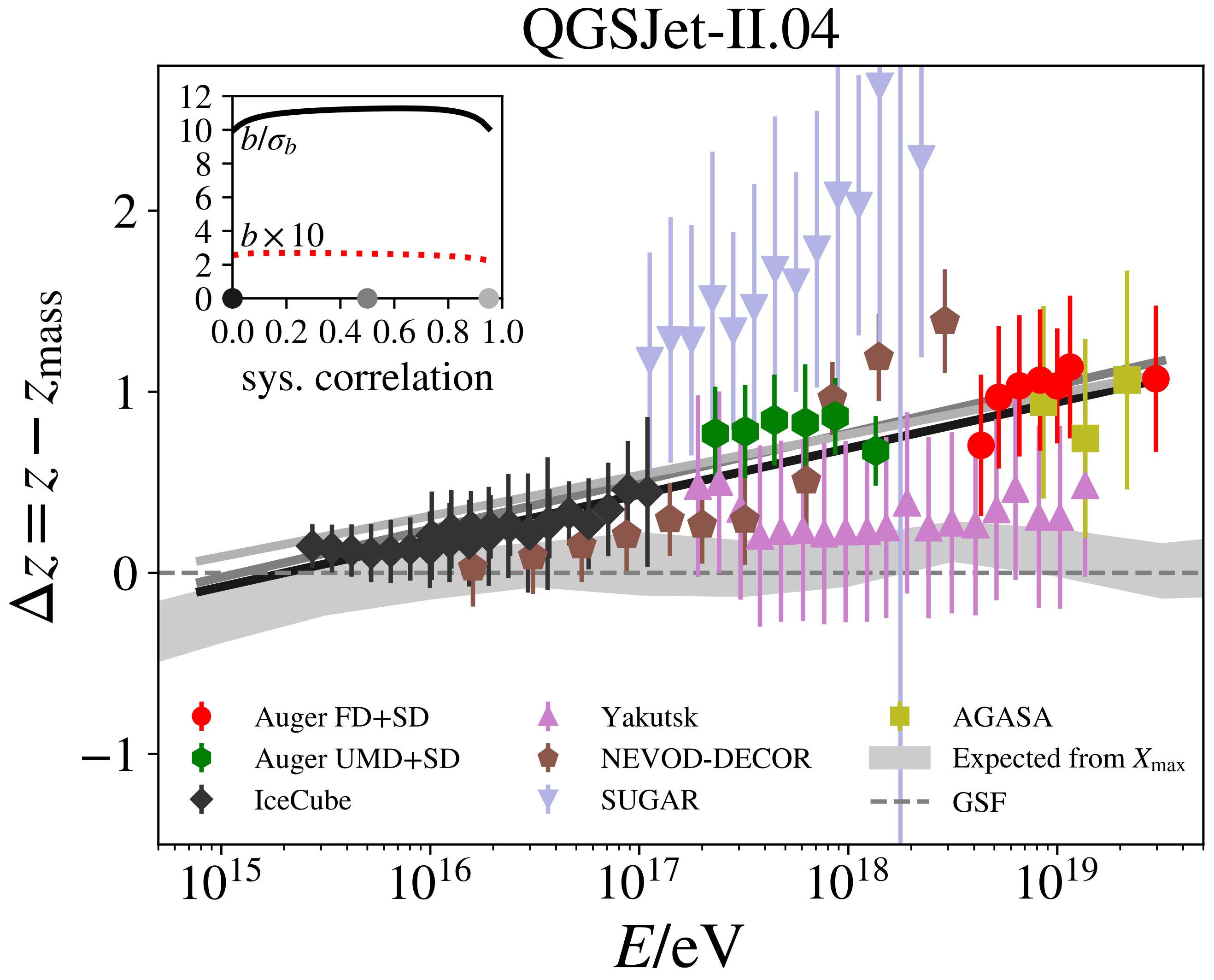
What is the current status of the field?

- Introduction air shower physics
- Cross-section measurements using EAS: synergies UHECRs and particle physics
- <u>Review Muon Puzzle:</u>
  - Auger: ~30% discrepancies in N_μ
  - N_μ vs. X_{max} and $X_{\mu,max}$ vs. X_{max}
  - WHISP: excess towards high energies
    - slope in $z - z_{mass}$ significant at ~8σ
  - <u>Origin remains unknown!</u>
- <u>Challenge for accelerators:</u>
  - Interactions of EAS particles
  - CM energies: GeV to hundreds of TeV
  - Forward direction



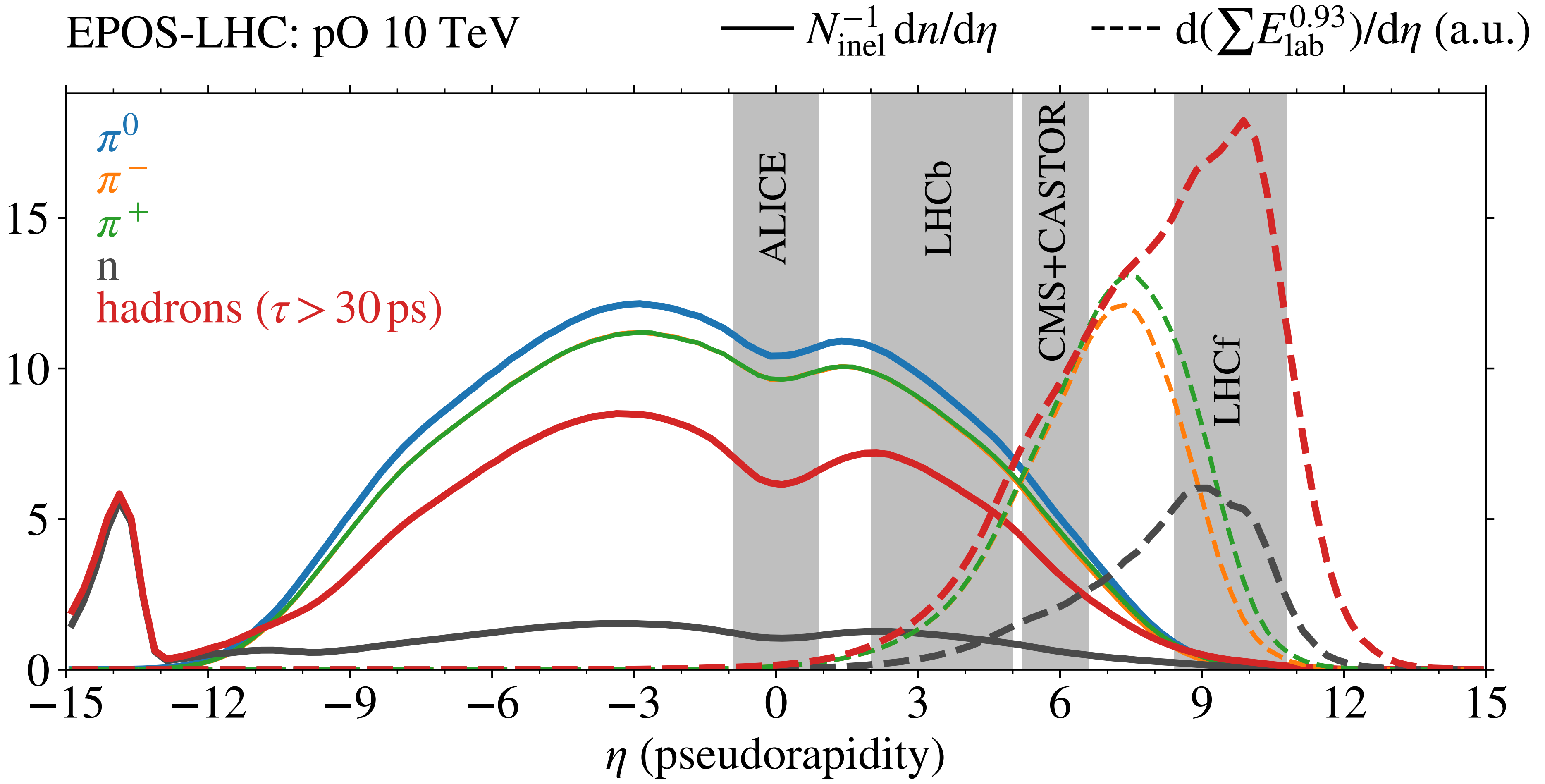


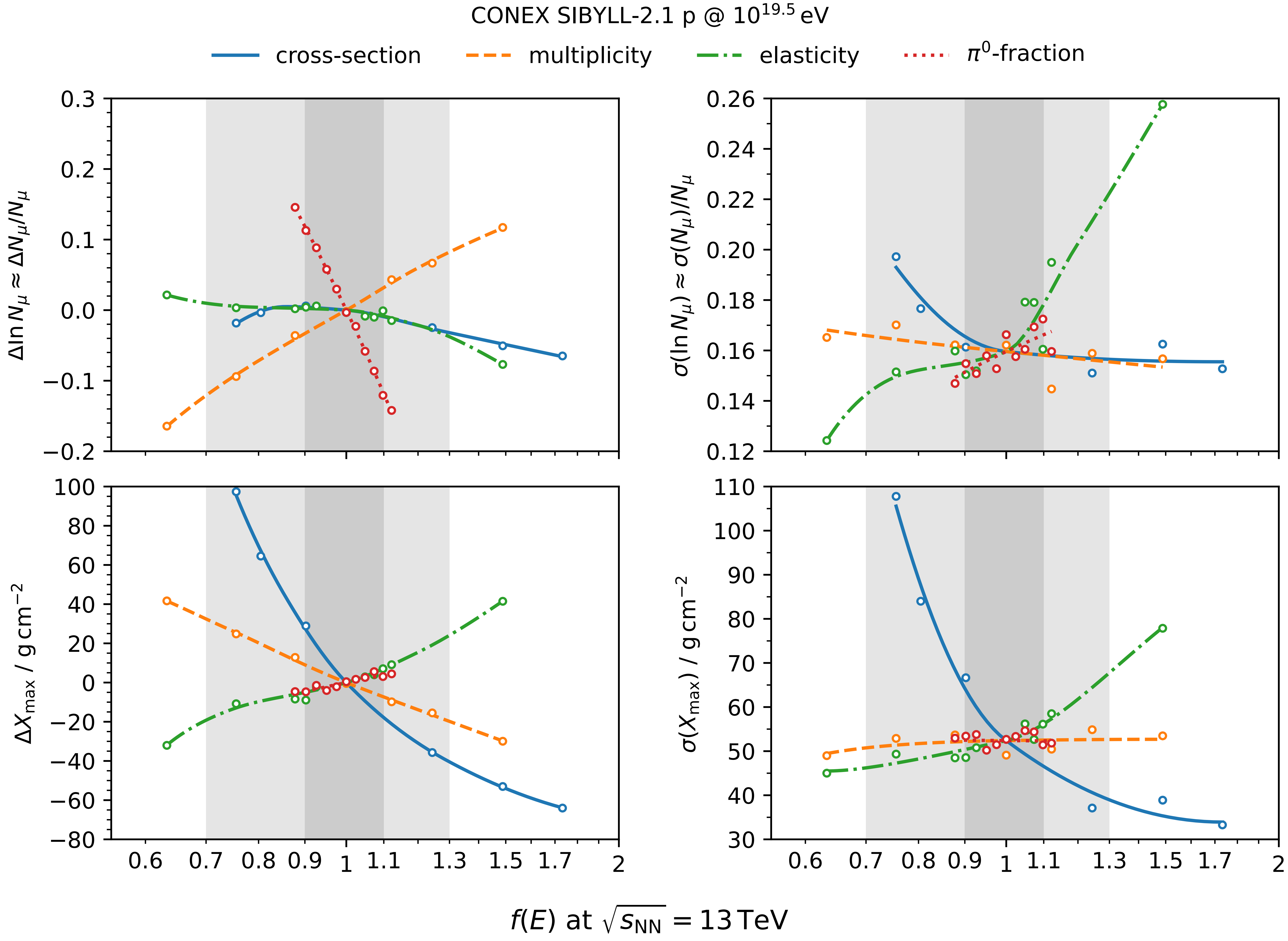




What is the current status of the field?

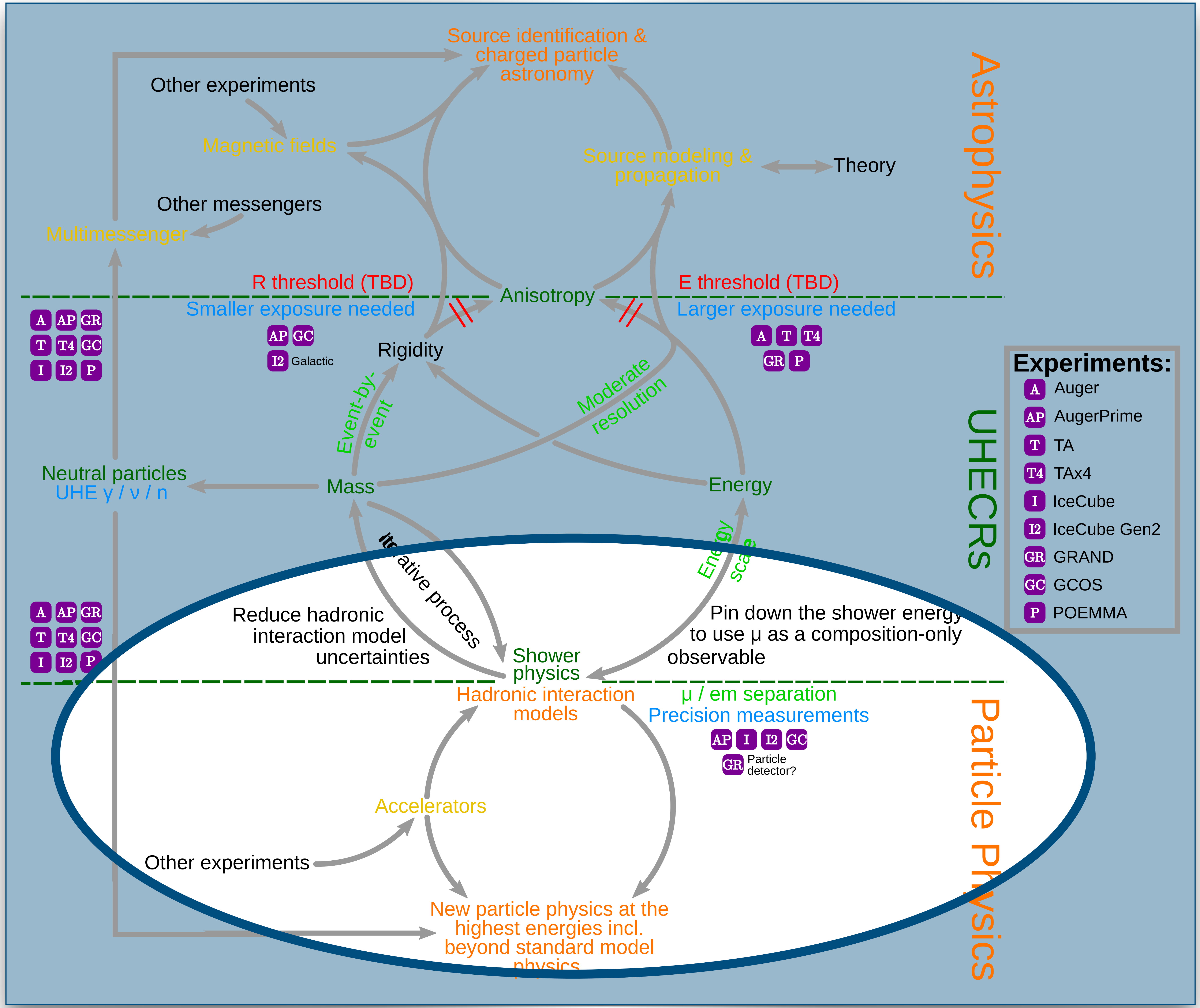
- <u>Review accelerator measurements:</u>
  - ALICE, CMS/CASTOR, LHCf, LHCb/SMOG, NA61/SHINE
    - Inelastic cross-sections
    - Hadron multiplicity
    - Elasticity
    - Hadron composition (ratio e.m. to hadr. energy flow)
  - Pseudorapidity ranges





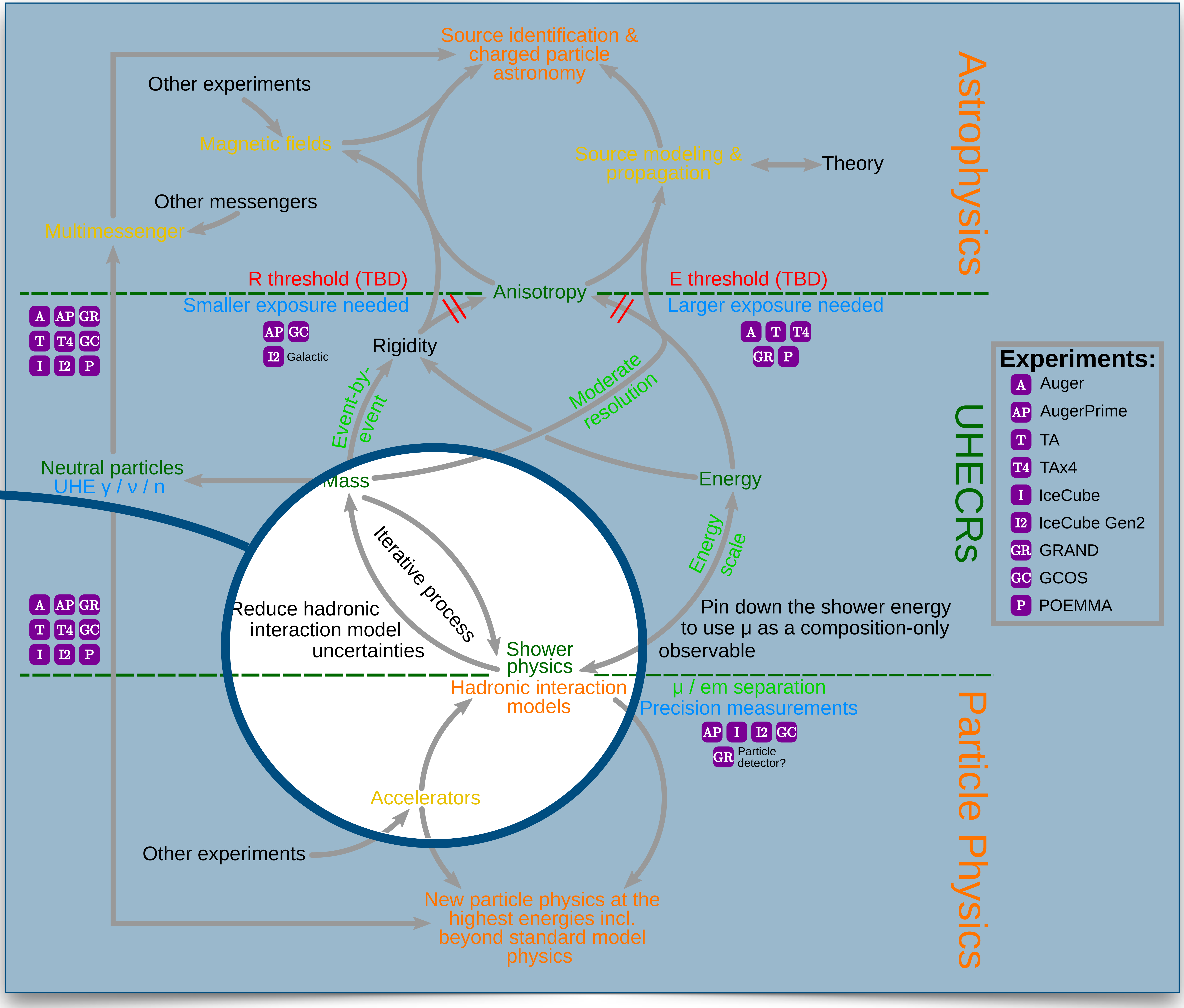
Where are we going to be 10 years from now?

- 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 next decade:
    - Larger detectors
    - Measurements close to shower axis
    - Larger statistics
    - Improved calibration
    - New analysis techniques (ML)
- <u>Smaller uncertainties, better resolution!</u>



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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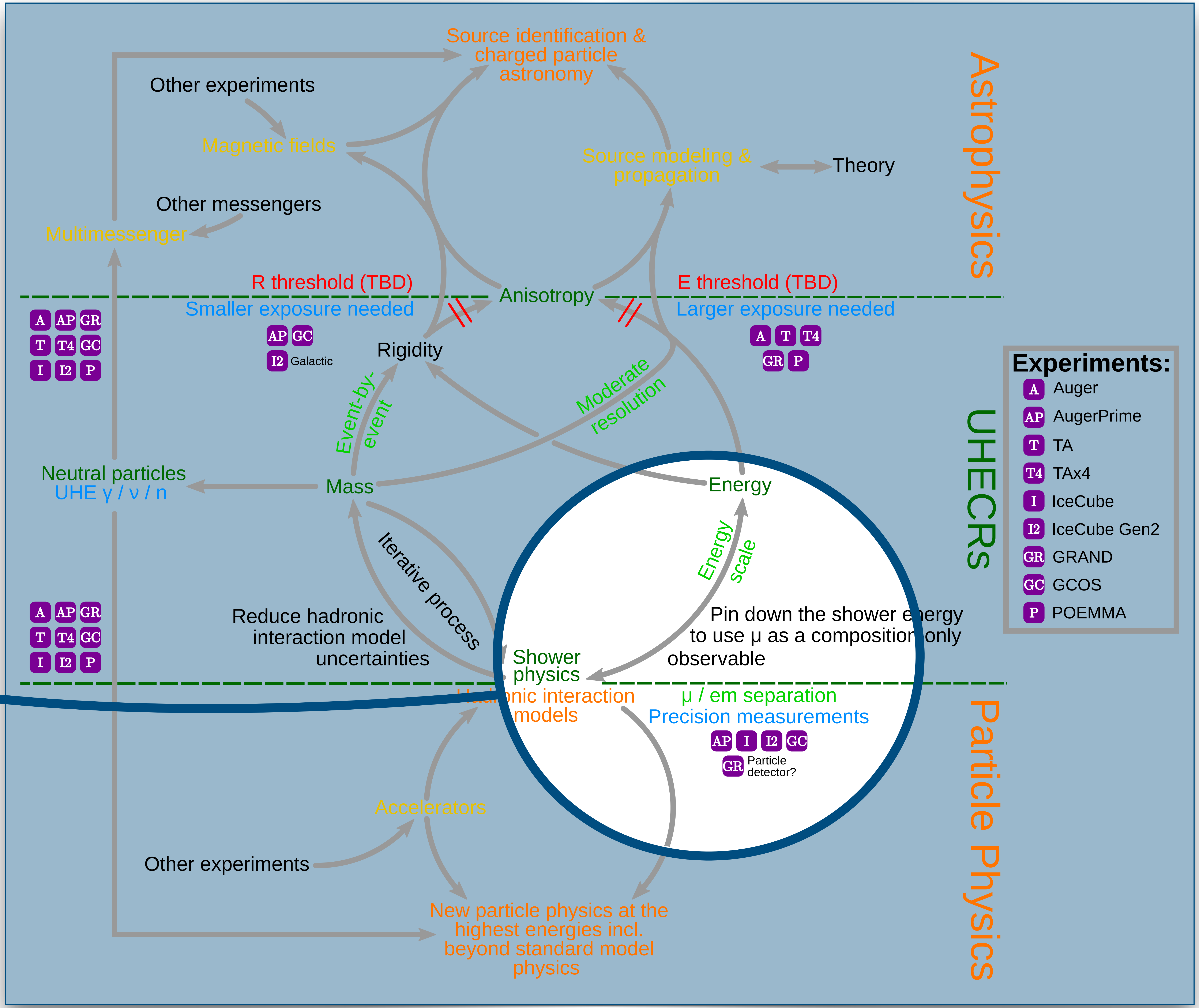

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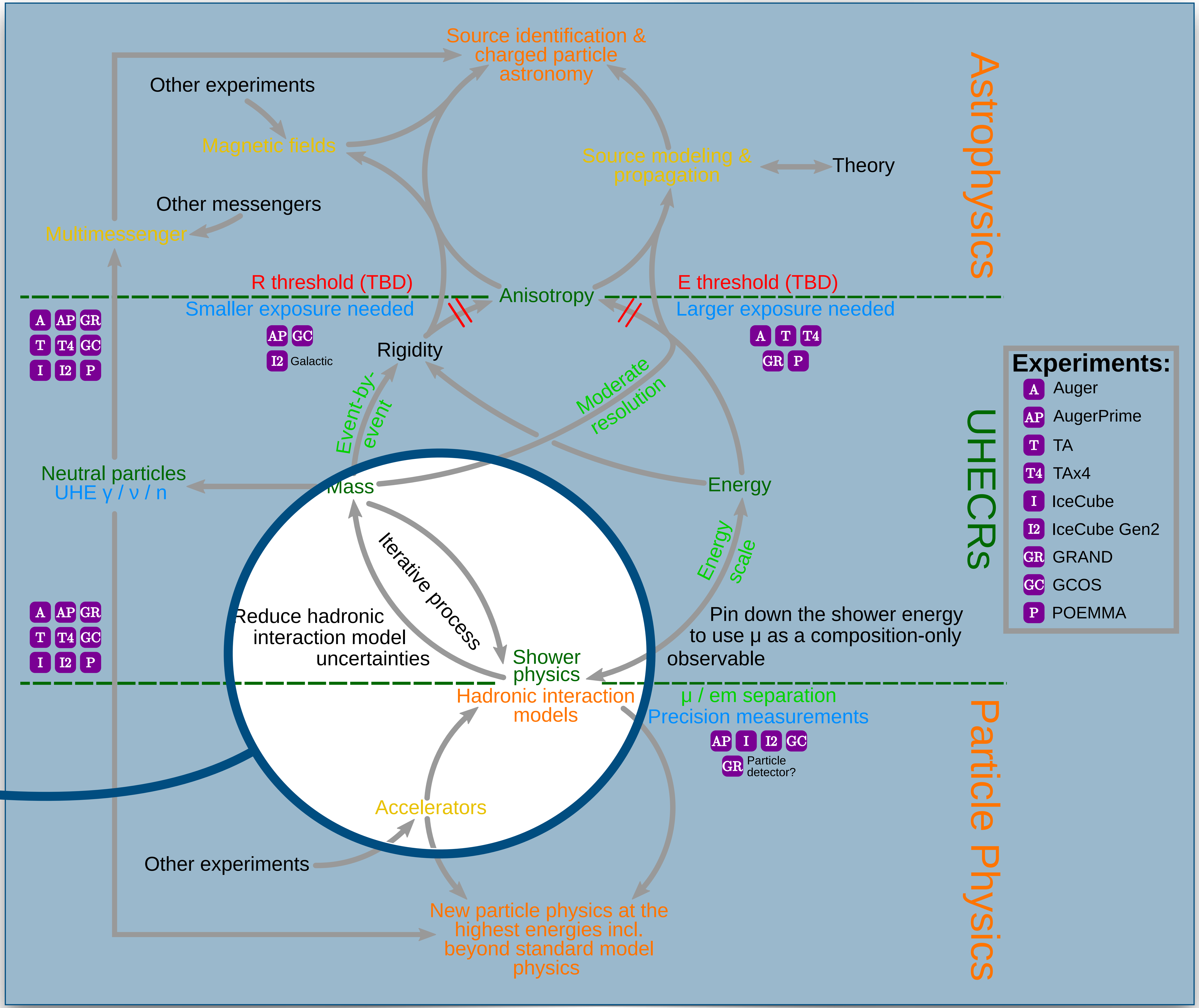

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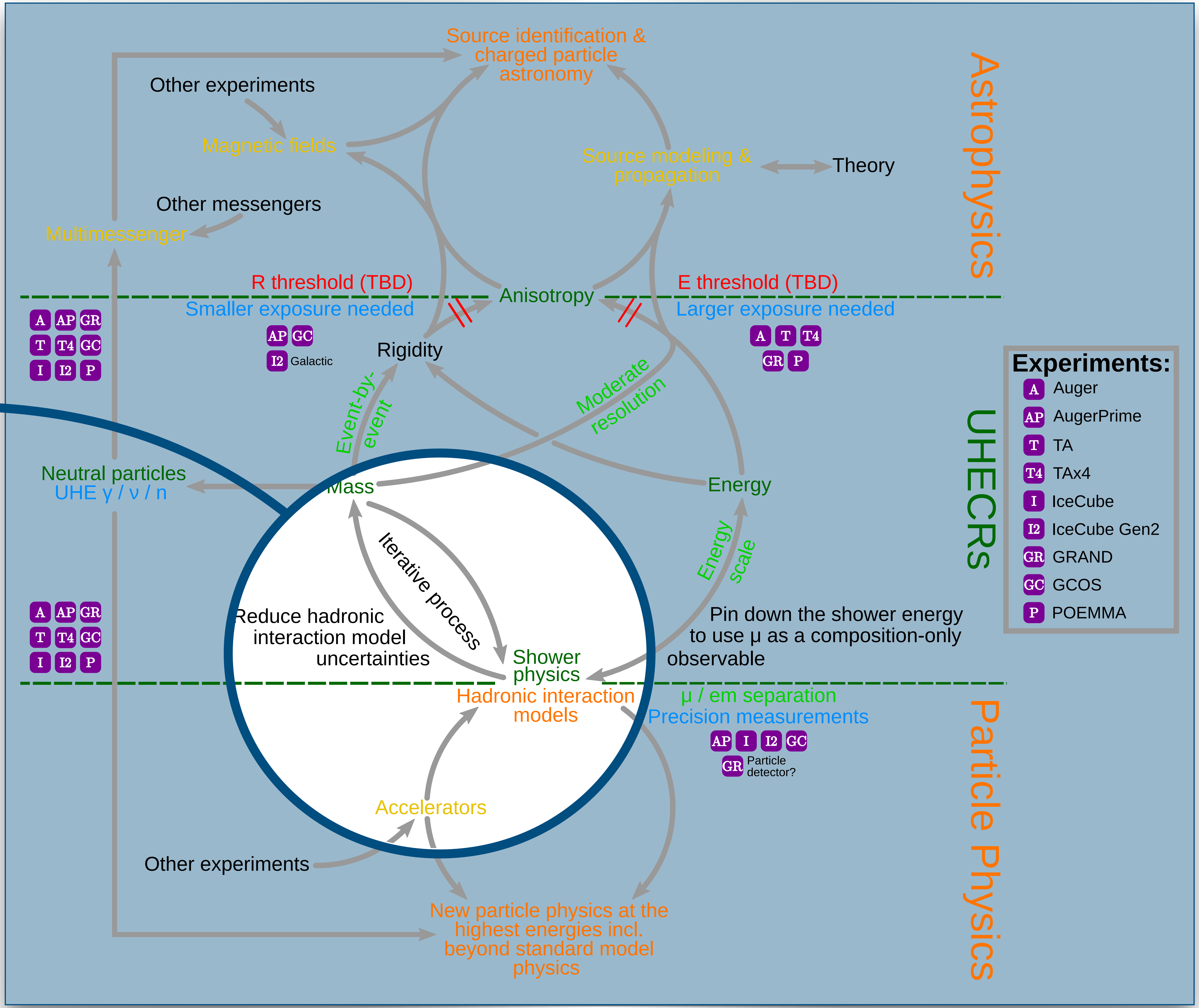
- <u>Multi-hybrid measurements (IceCube)!</u>
  - <u>EAS energy:</u>
    Surface Detectors (IceTop)
  - <u>Muon number:</u>
    IceTop (GeV muons)
    + in-ice array (TeV muons)
  - Two vastly different energy regimes
  - Spectral information!
- Radio extension (RD): mass & energy, resolves bias from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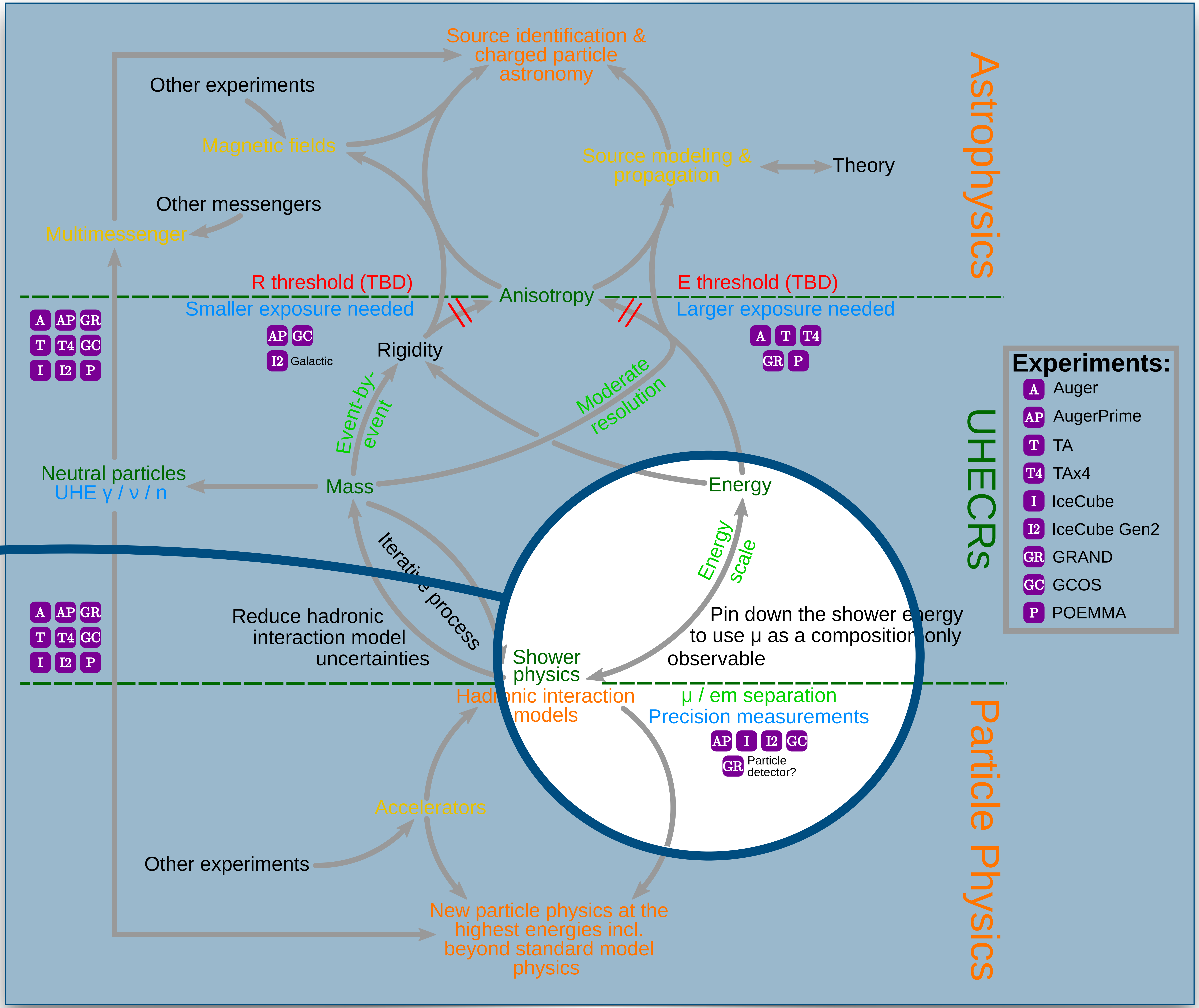

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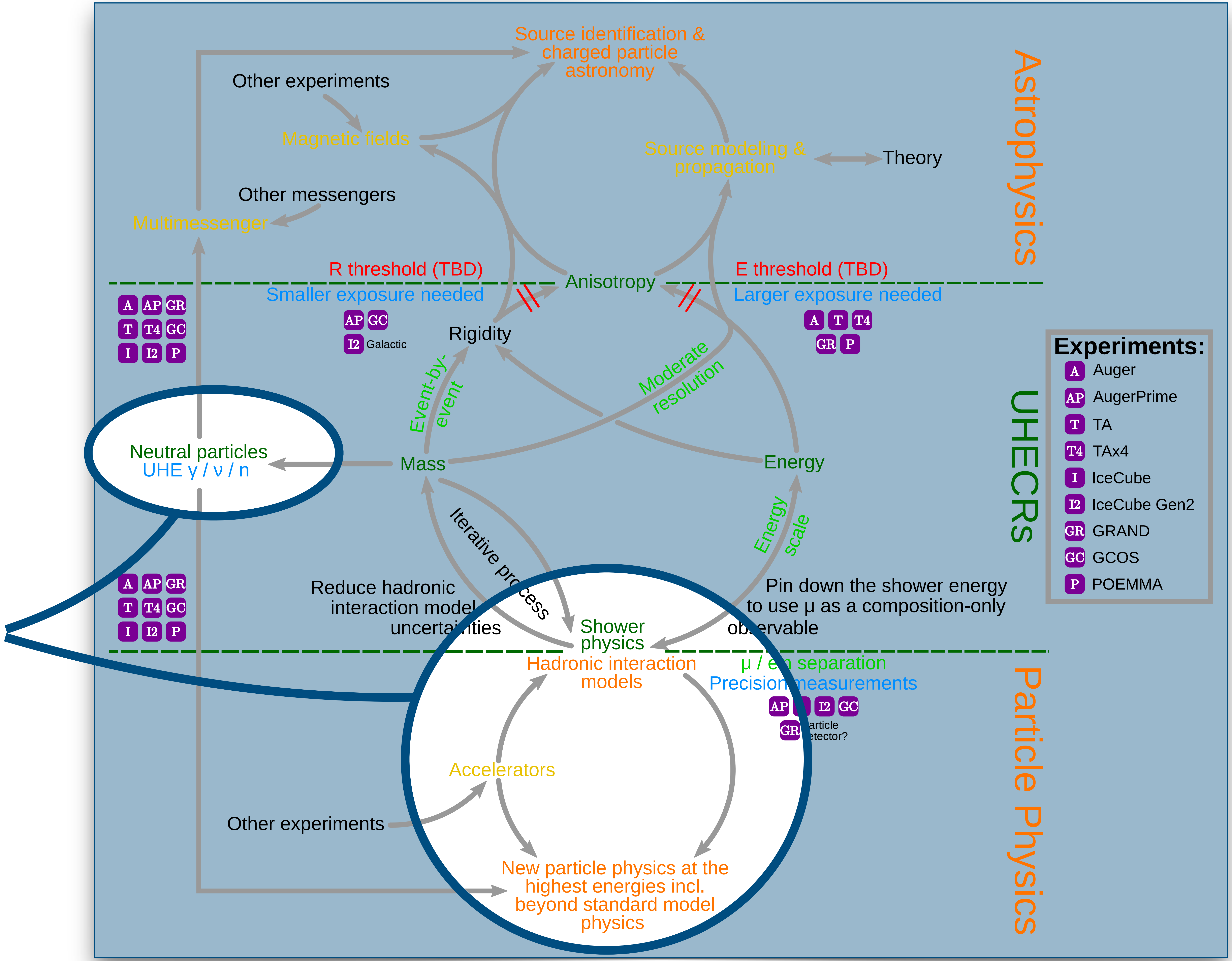

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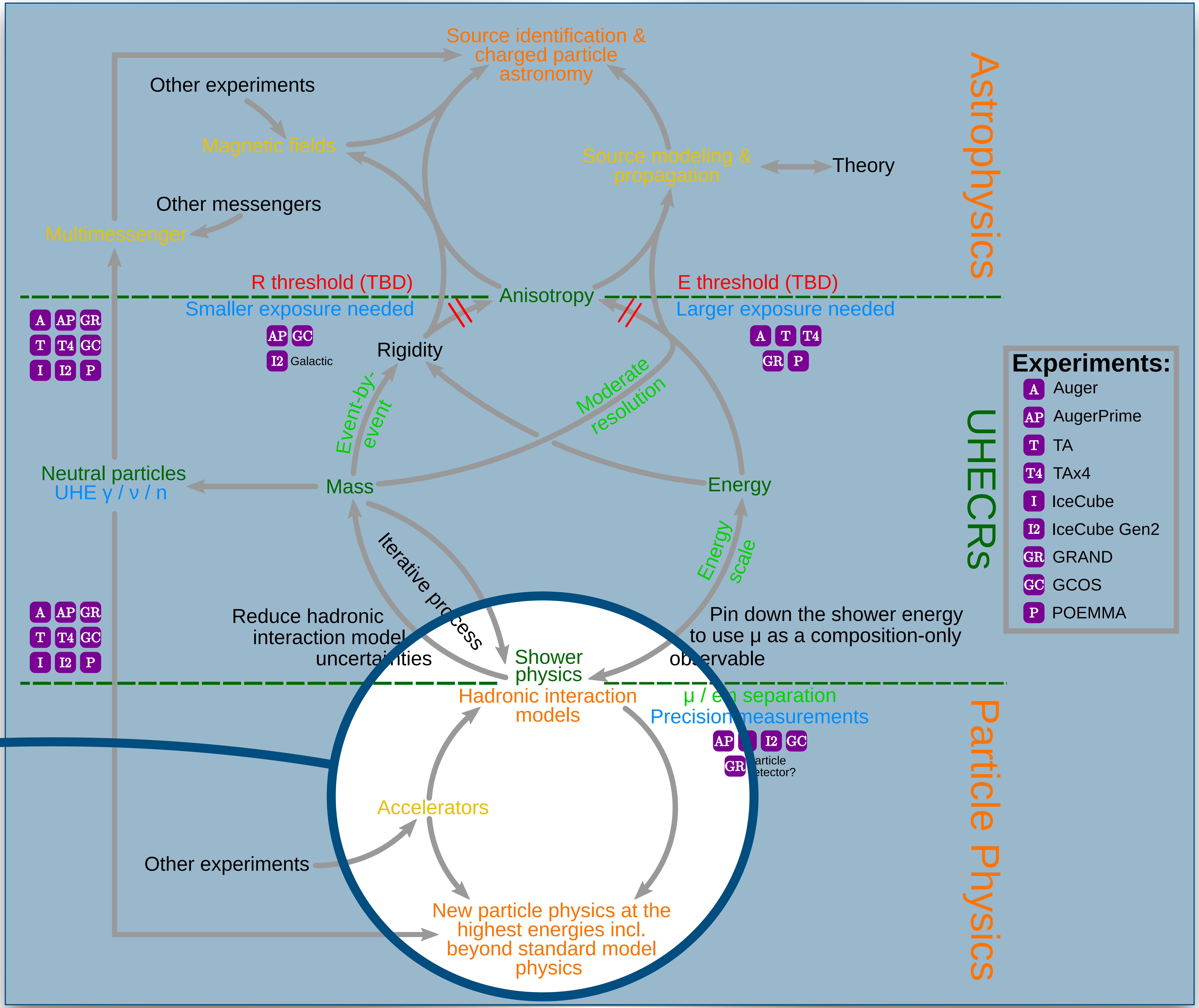
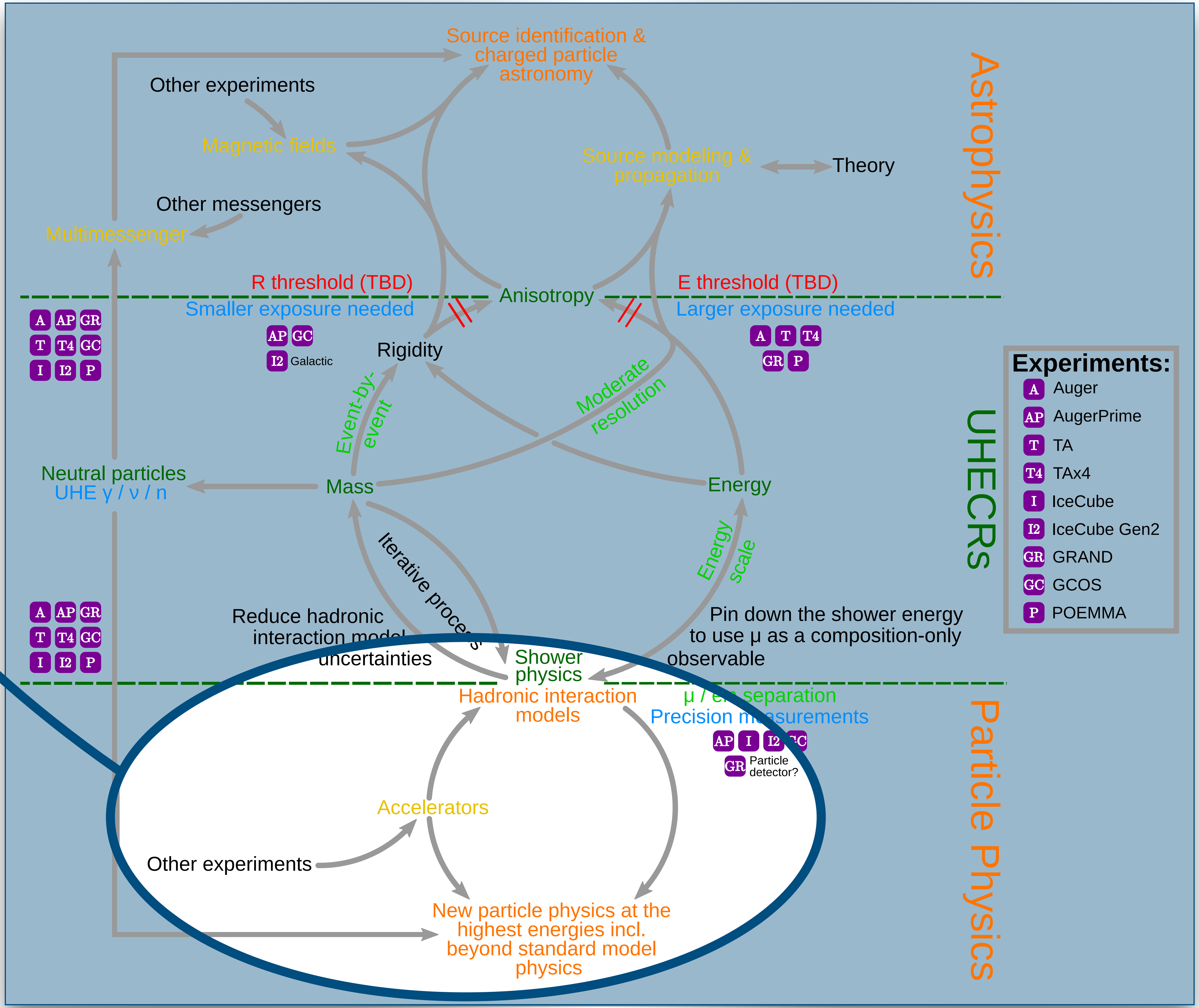


Where are we going to be 10 years from now?

- <u>Accelerator measurements (LHC)!</u>
- Proton-Oxygen collisions in Run 3 (2023)
  - Importance for EAS physics
- High-Luminosity LHC!
- Forward experiments



Open questions for the new generation of UHECR observatories

- <u>Expectation:</u> precise characterization (solution?) of the Muon Puzzle within the next decade
- New large-scale EAS observatories with particle detectors (GCOS, IceCube-Gen2, GRAND?) provide large aperture and thus unprecedented event statistics
  - <u>New era of high-precision measurements with EAS!</u>
- New EAS observables and analysis techniques to test hadronic interaction models
- Precise measurements in the forward region at LHC (including new proposed experiments, e.g. Forward Physics Facility, Very Forward Hadron Spectrometer at LHC) will strongly constrain hadronic models
- Hadronic models have to describe both EAS and LHC measurements
  - <u>Tests of SM predictions at energies much higher than the LHC (far forward region)!</u>
- If LHC data is reproduced but Muon Puzzle remains:
  - <u>Tests of BSM/exotic scenarios</u>
- First statistically significant measurement of prompt muons, probe of charm production (IceCube-Gen2)

White Paper Status

- Draft still in progress…
  - Refinements of the text
  - Adding some missing parts
  - Beyond 10 years outlook still in progress…
  - Mature draft expected next week!
    - Circulation to experimental collaborations
- Thanks to all contributors!
  - M. Albrow, L. Cazon, R. Conceição, A. Fedynitch, H. P. Dembinski, T. Pierog, D. Soldin
- Thanks to the conveners!
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- Please contact us if you have further input / comments

Thank you!