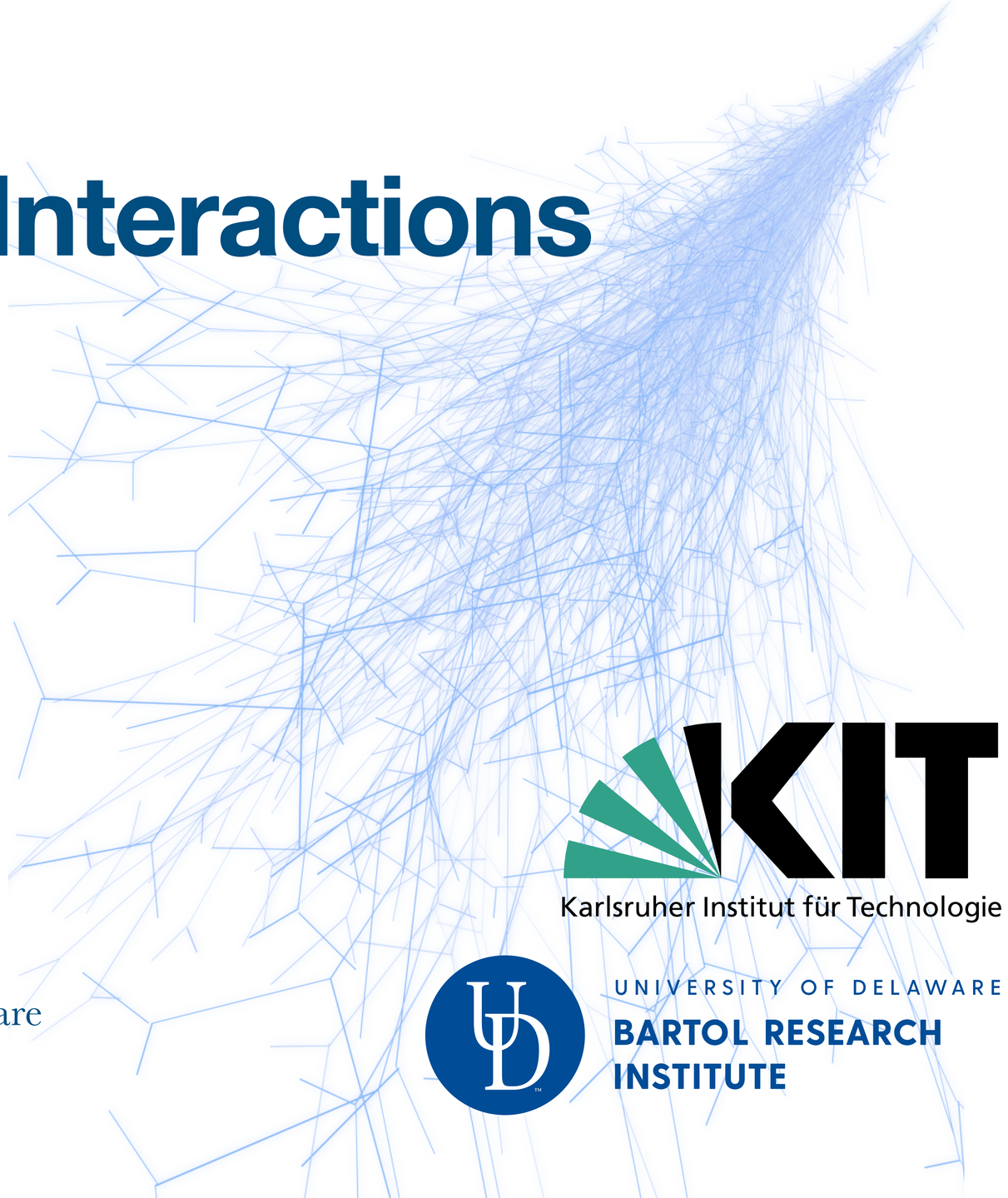
Probing Hadronic Interactions with Cosmic Rays

RICAP 2022



Dennis Soldin

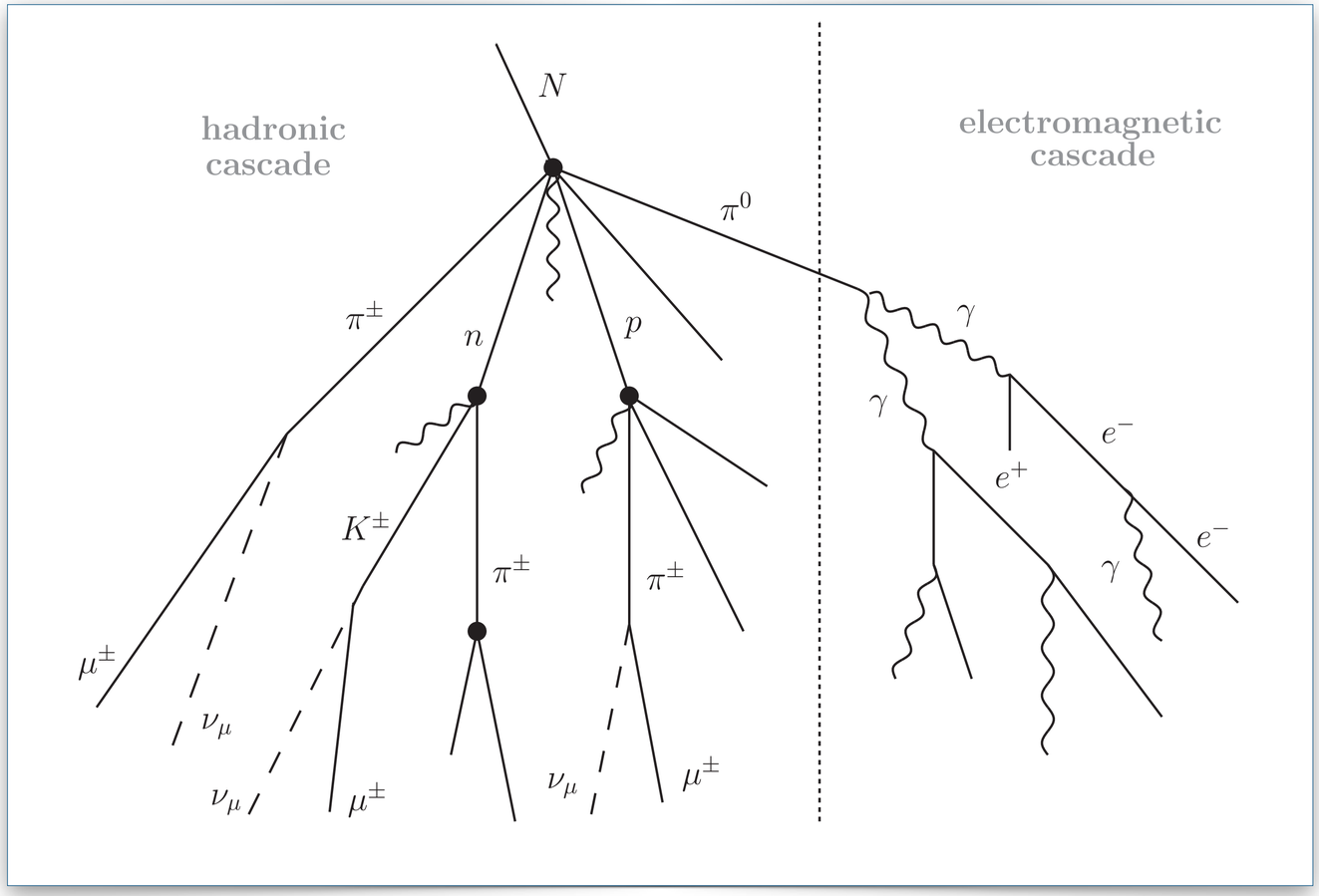
Karlsruhe Institute of Technology & University of Delaware

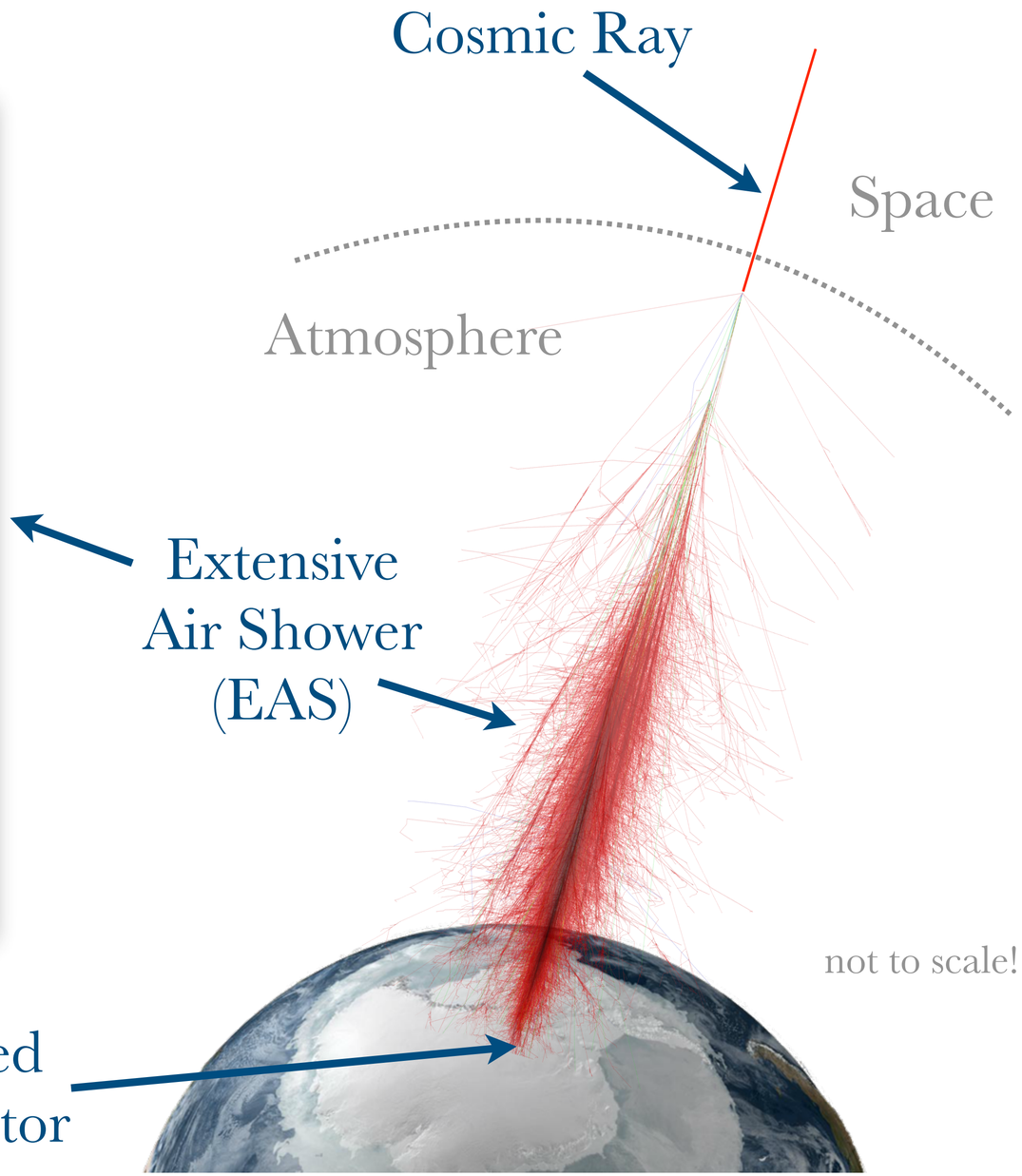
Karlsruher Institut für Technologie

UNIVERSITY OF DELAWARE

BARTOL RESEARCH INSTITUTE

Extensive Air Showers





- Hadronic interactions are crucial for the EAS development

Extensive Air Showers

- CR properties are inferred from the (secondary) particles measured at the ground

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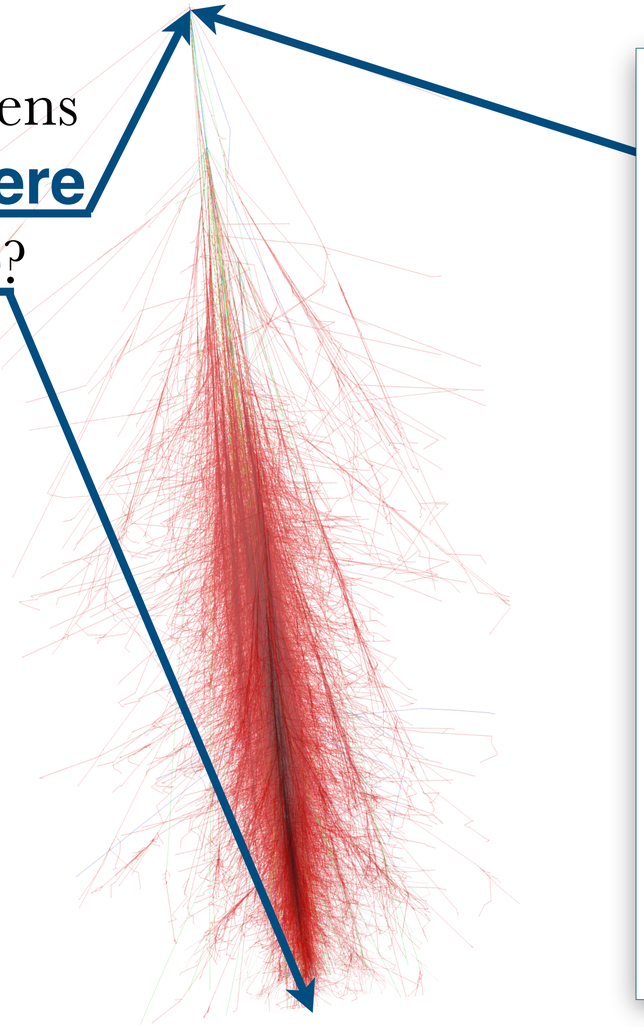

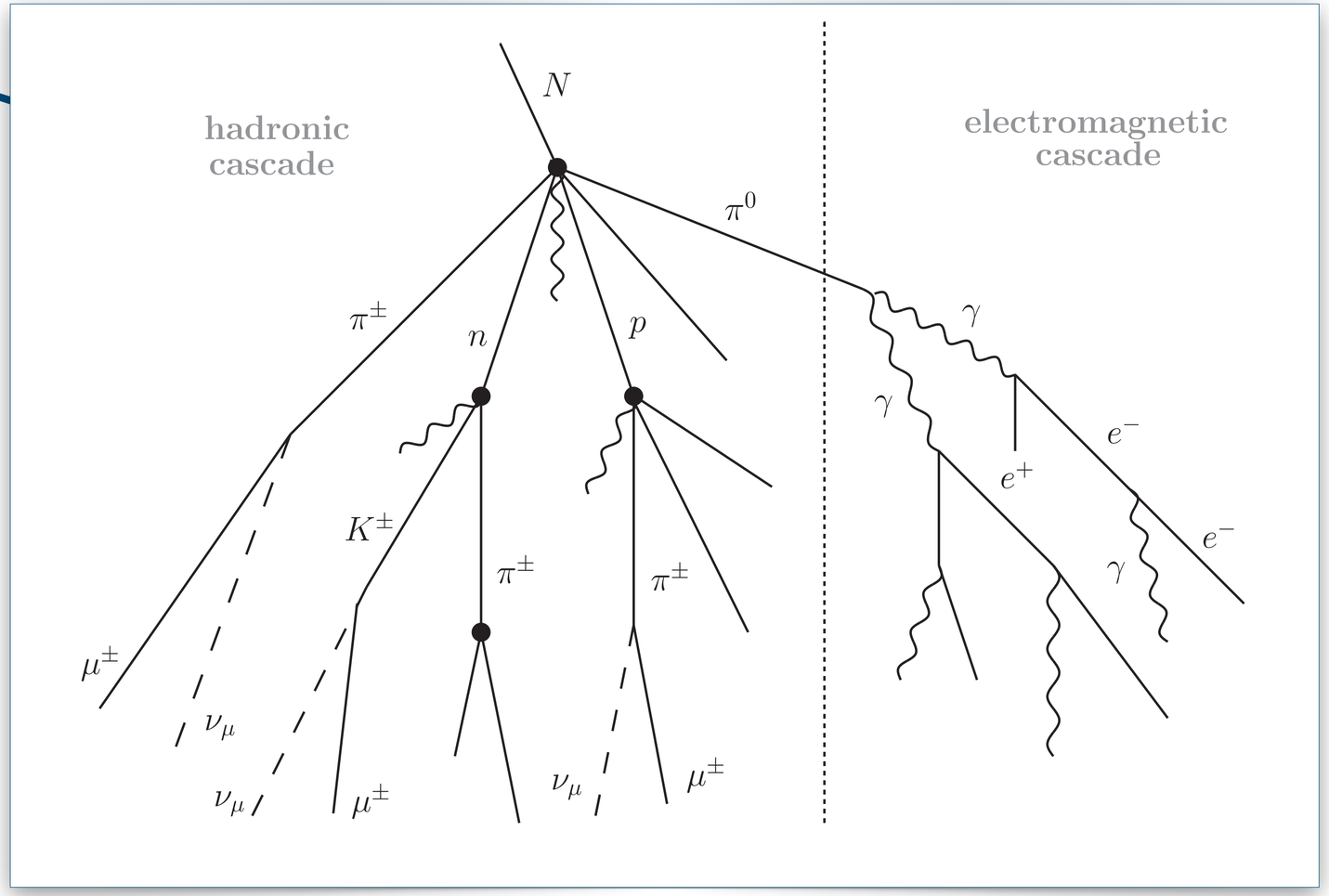

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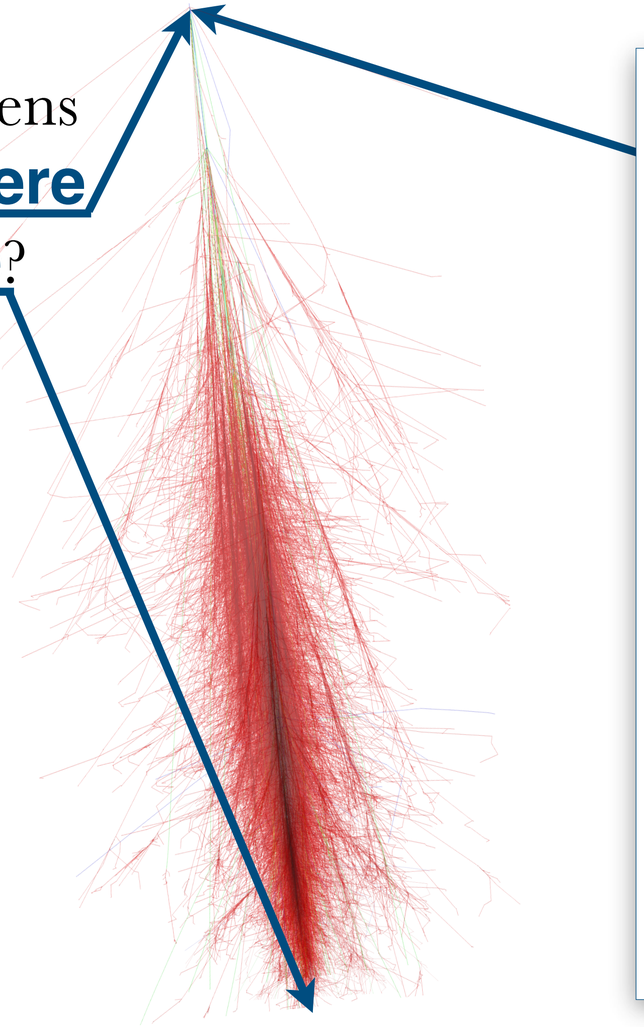

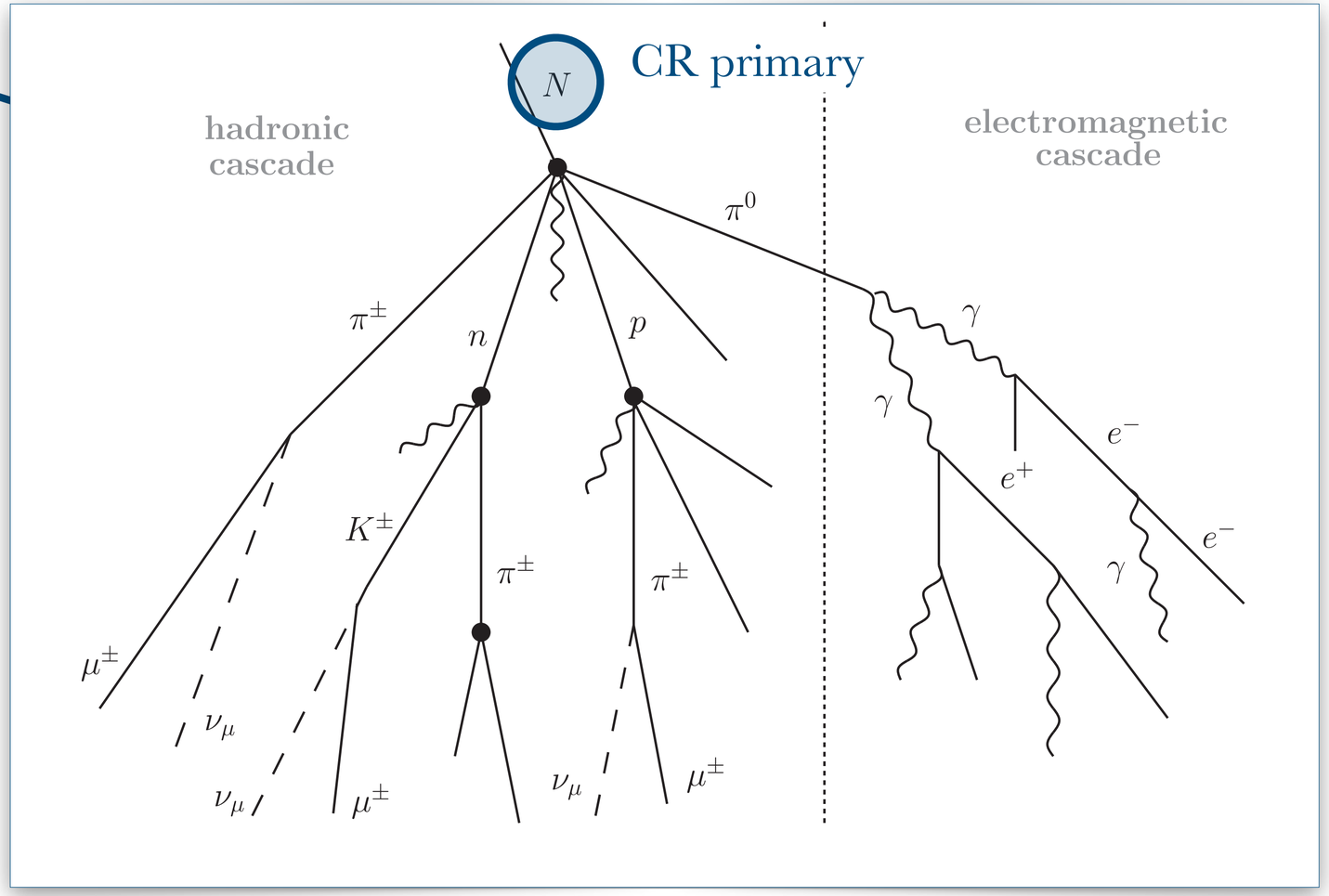

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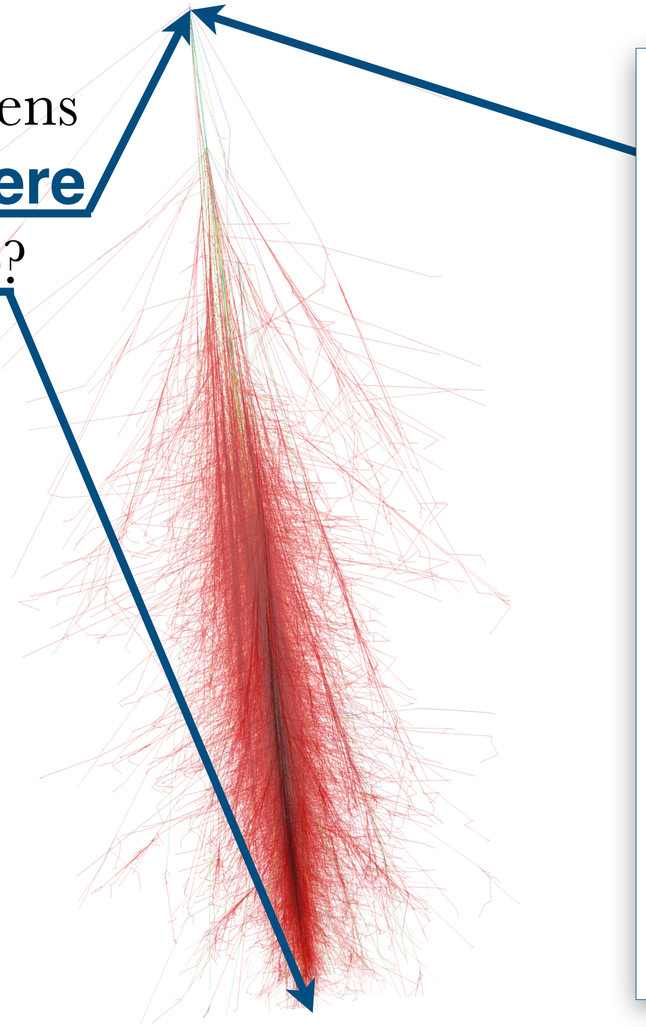

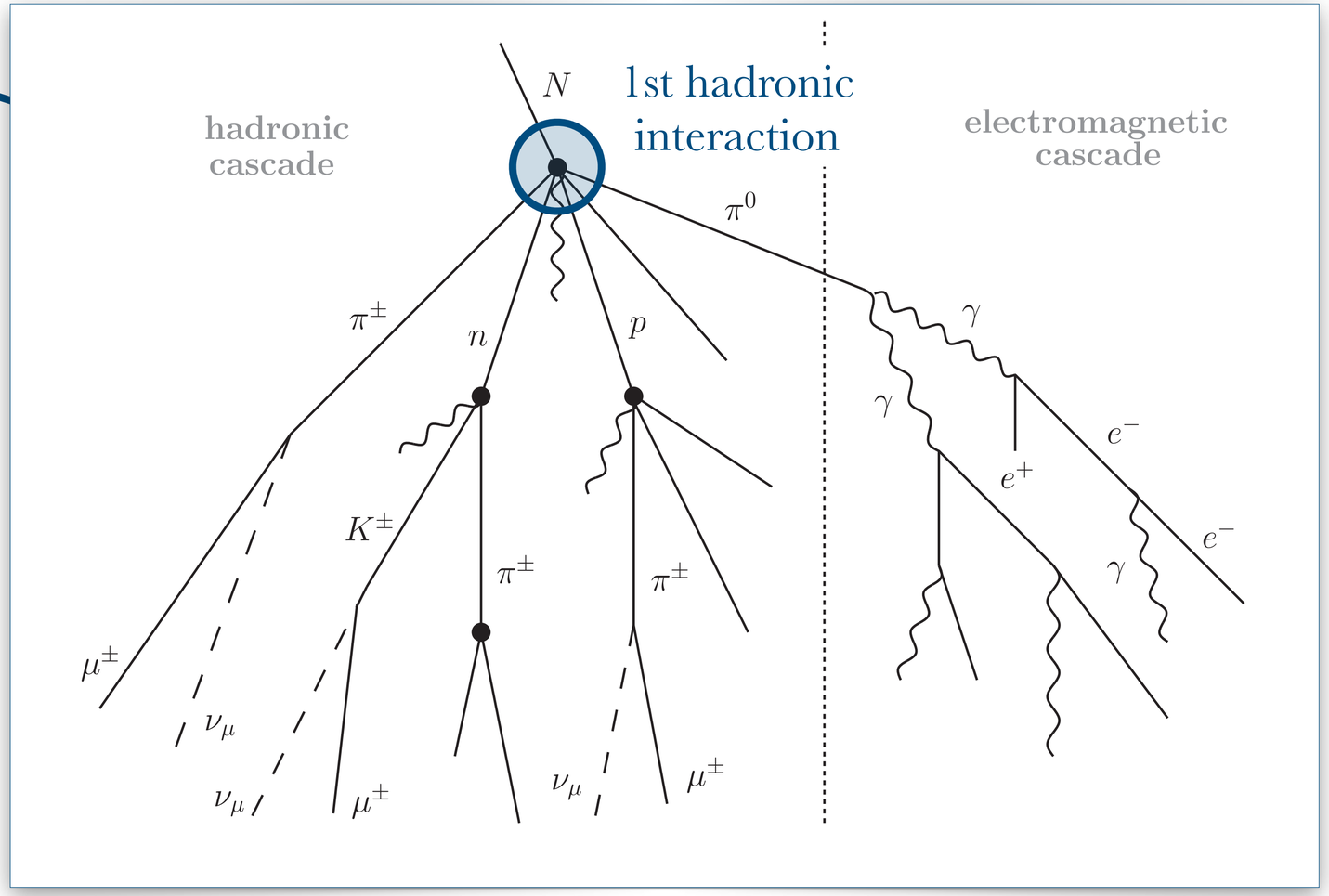

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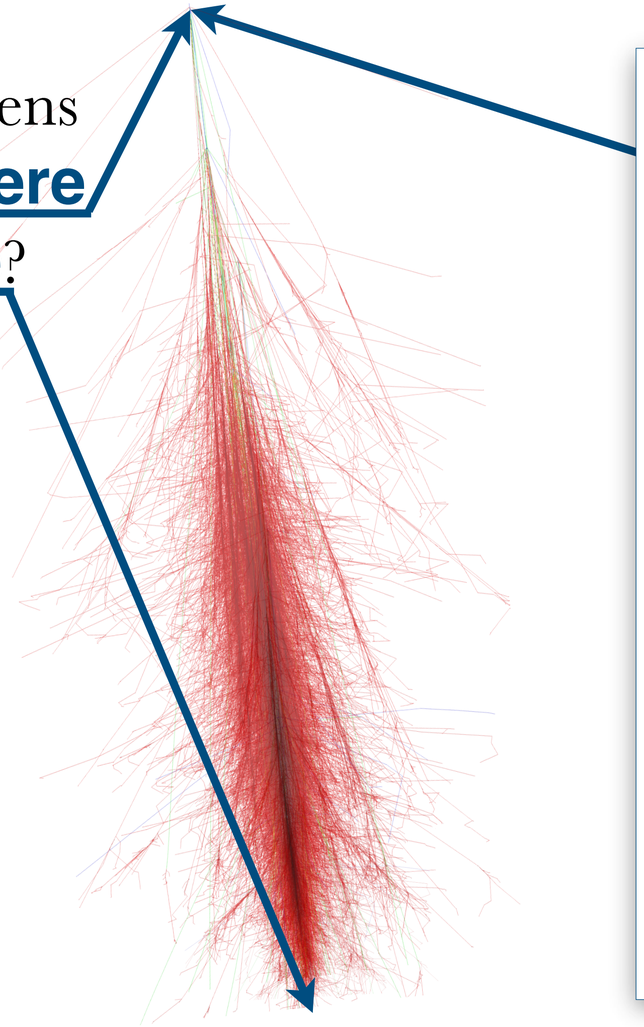

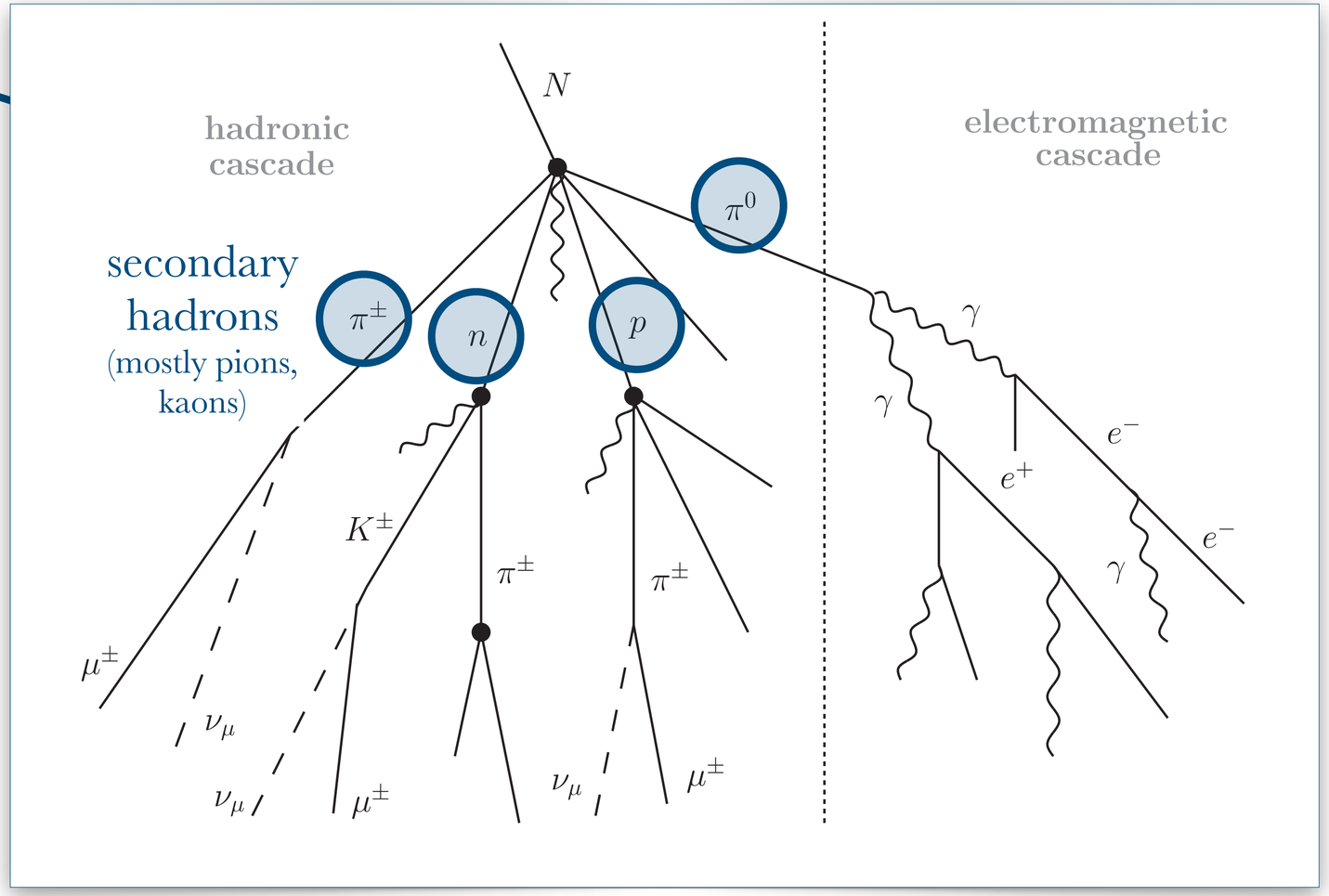

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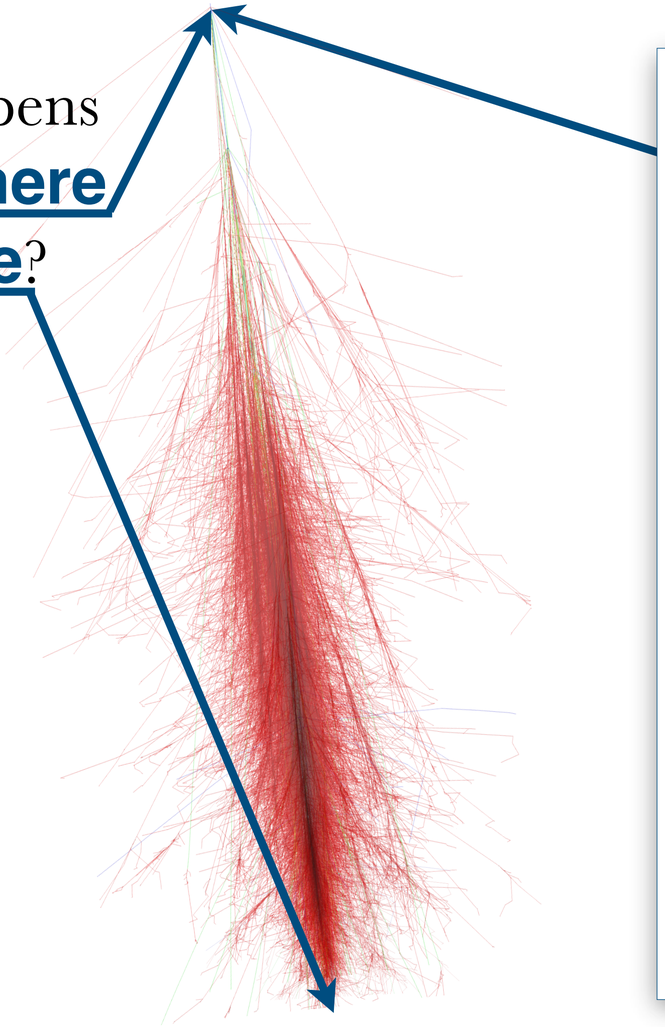

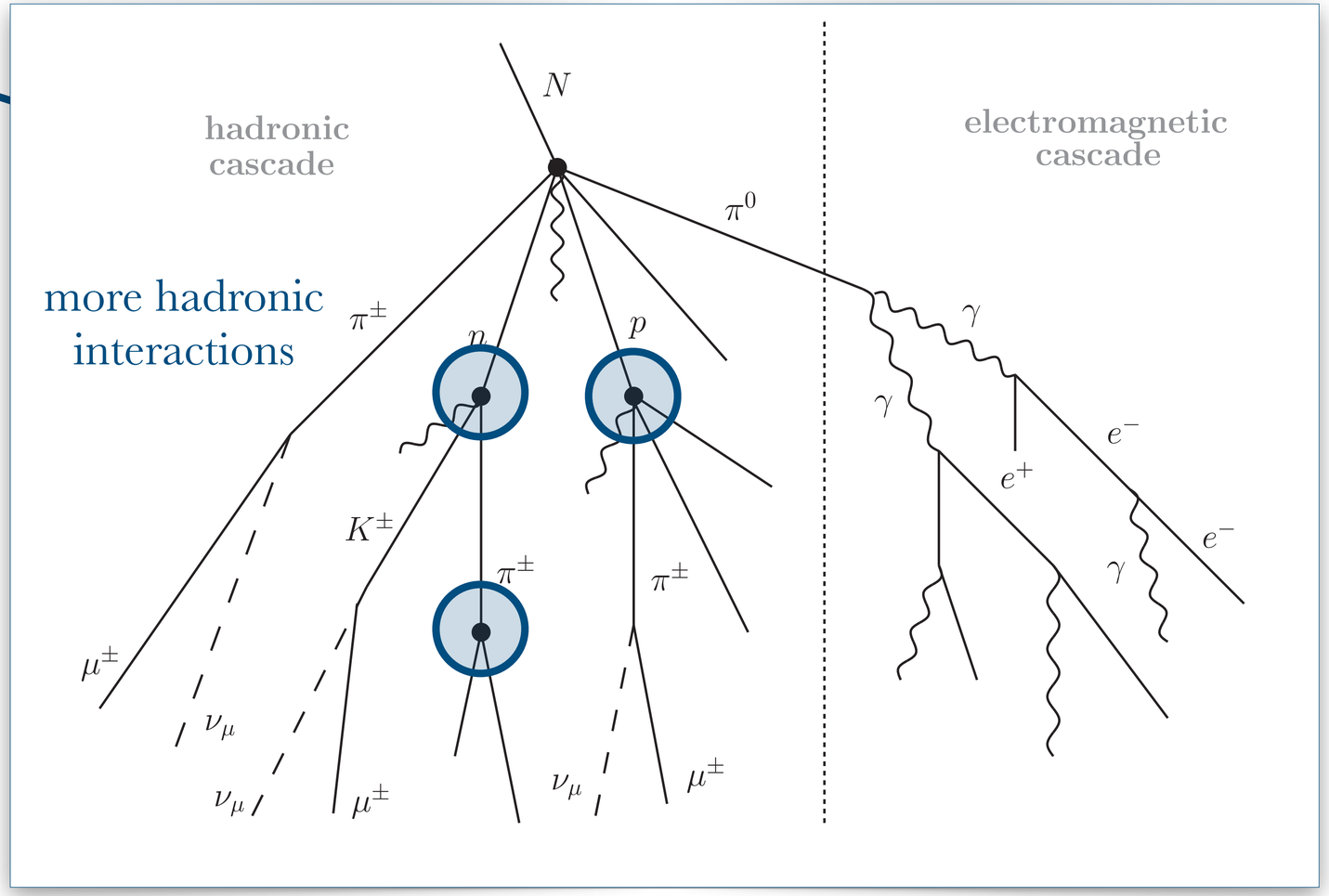

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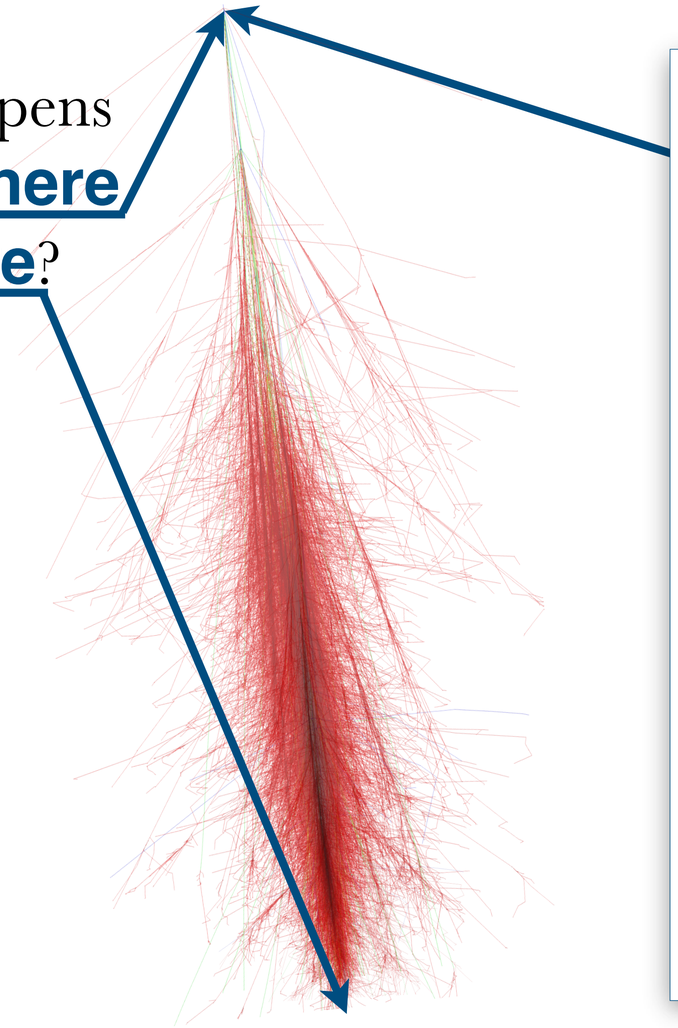

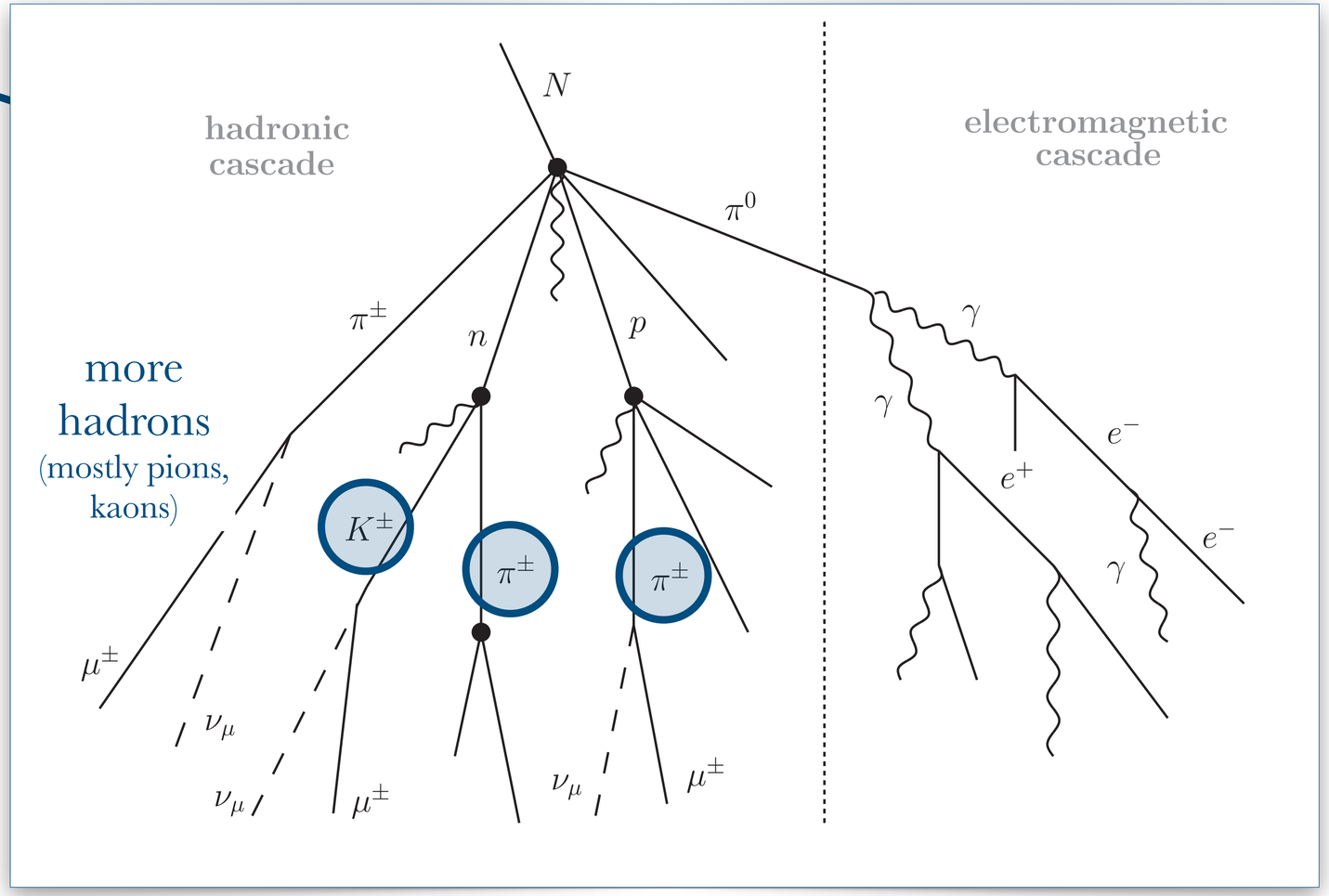

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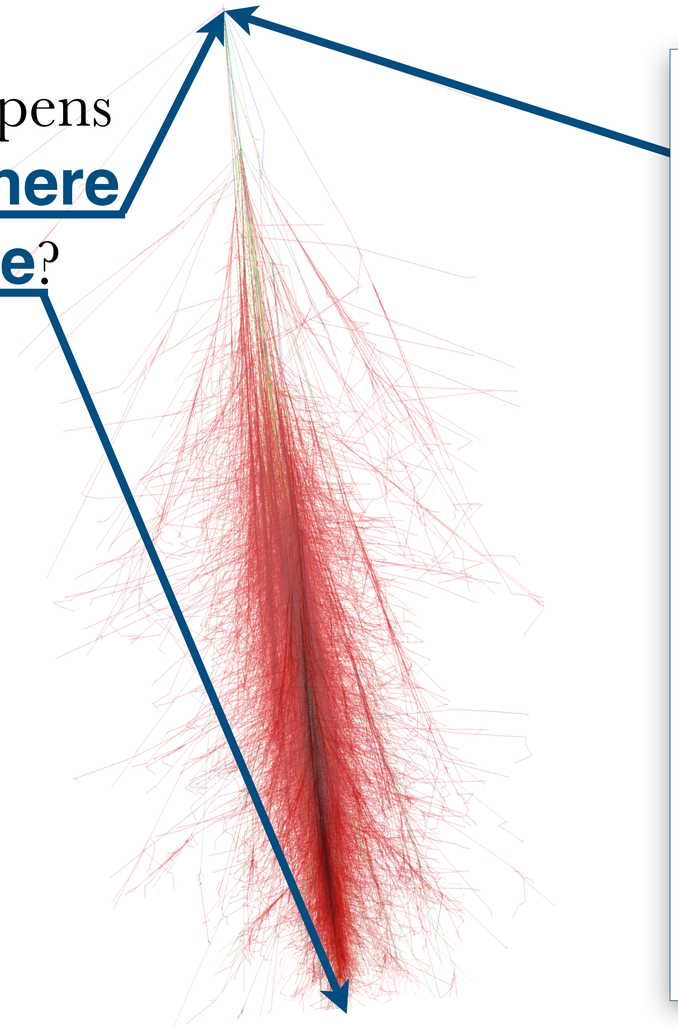

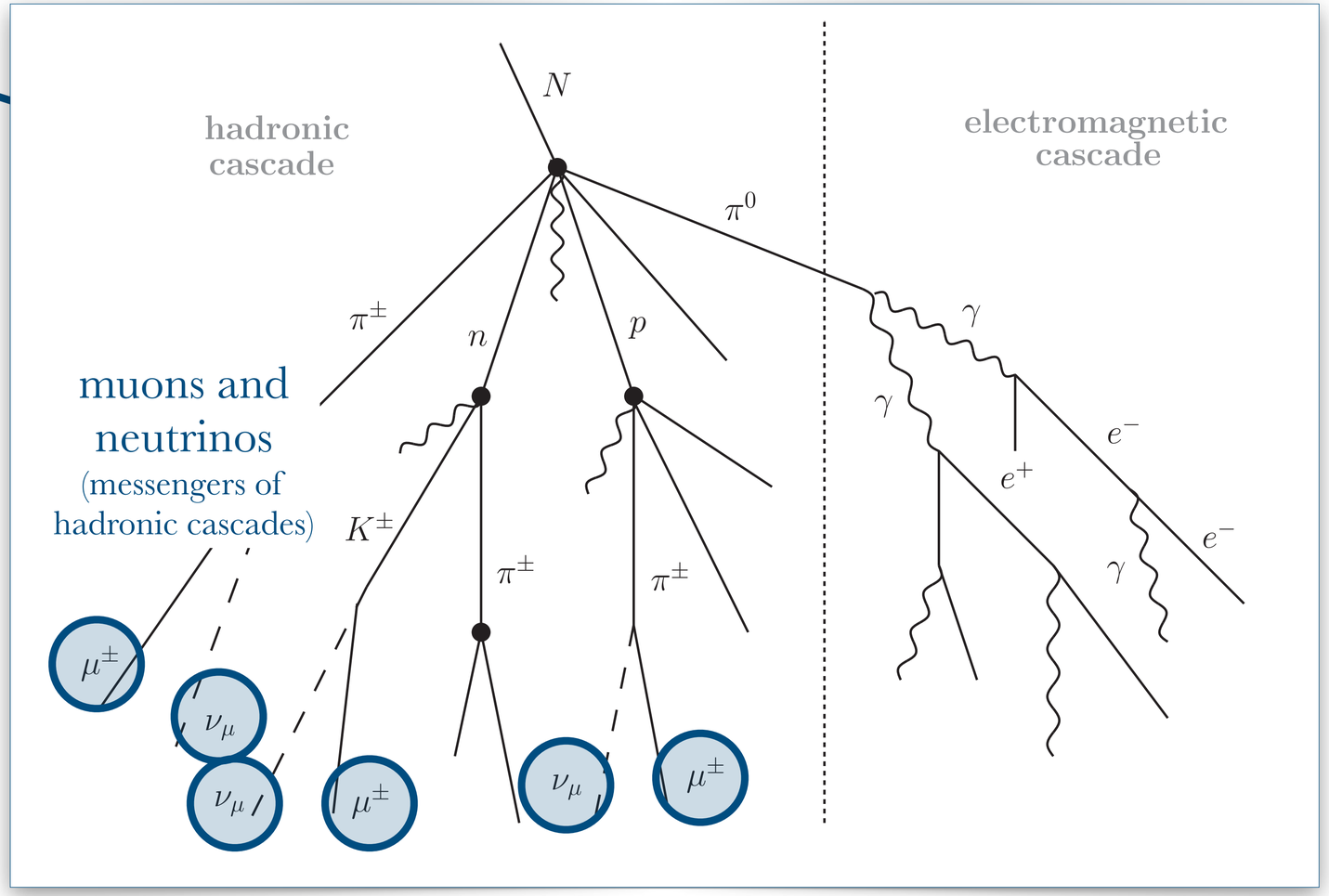

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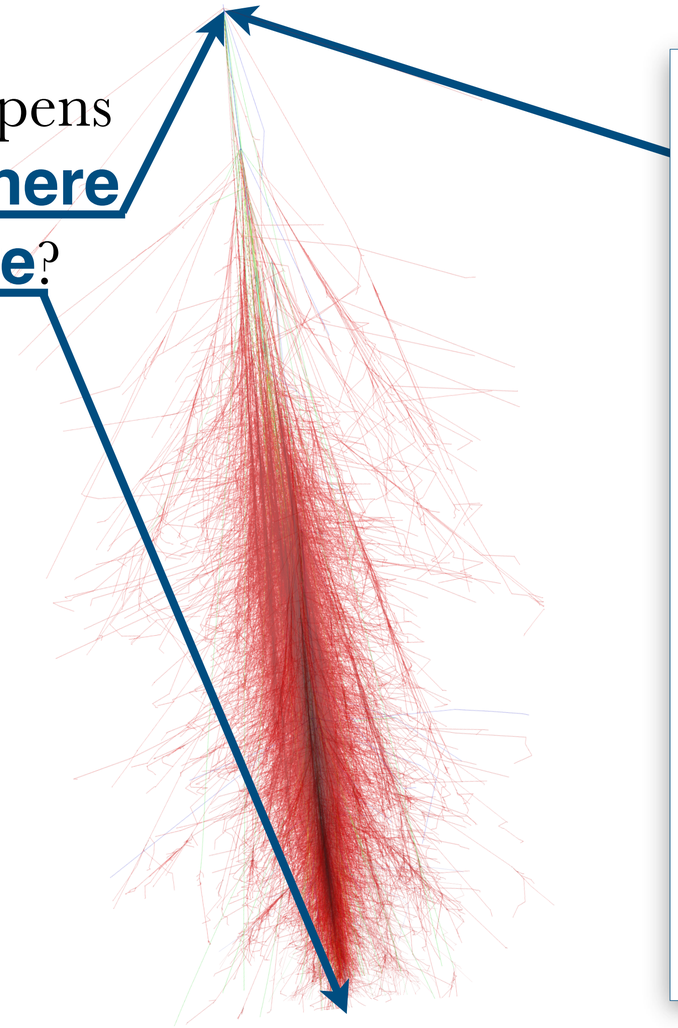

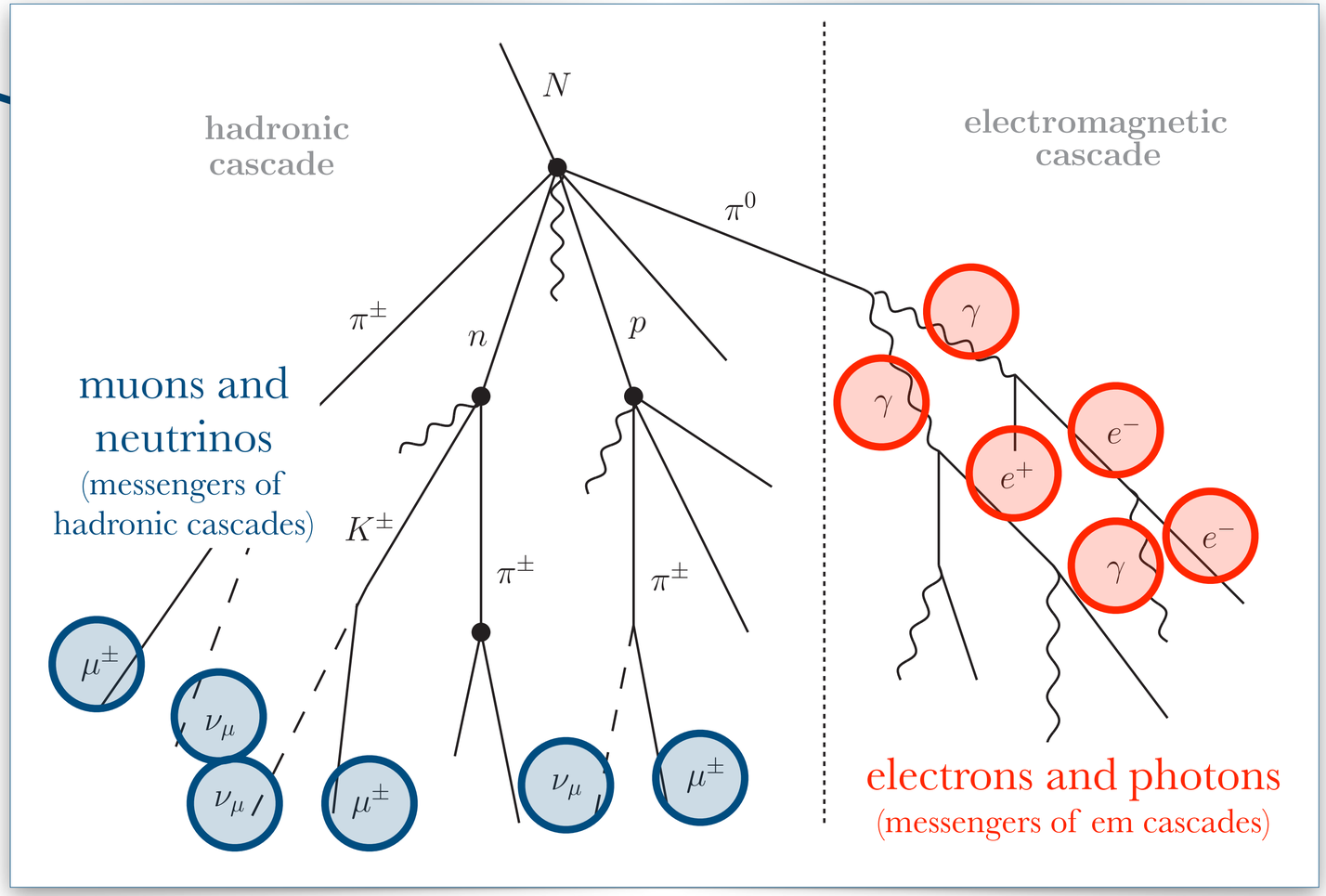

Extensive Air Showers

Plays an important role, transferring energy from the hadronic to the electromagnetic cascade!

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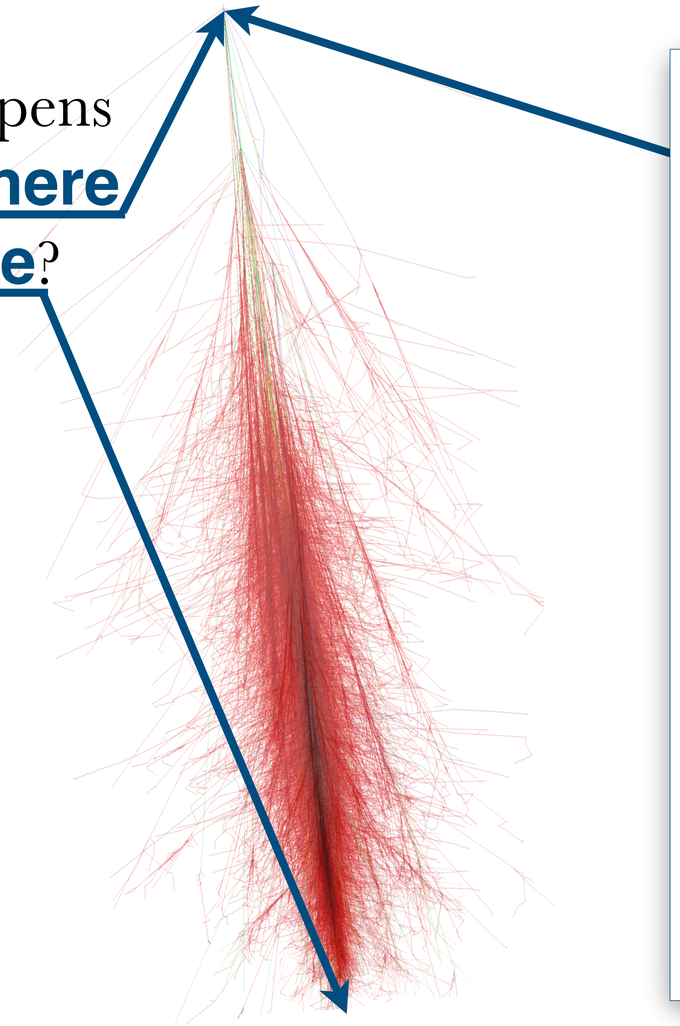

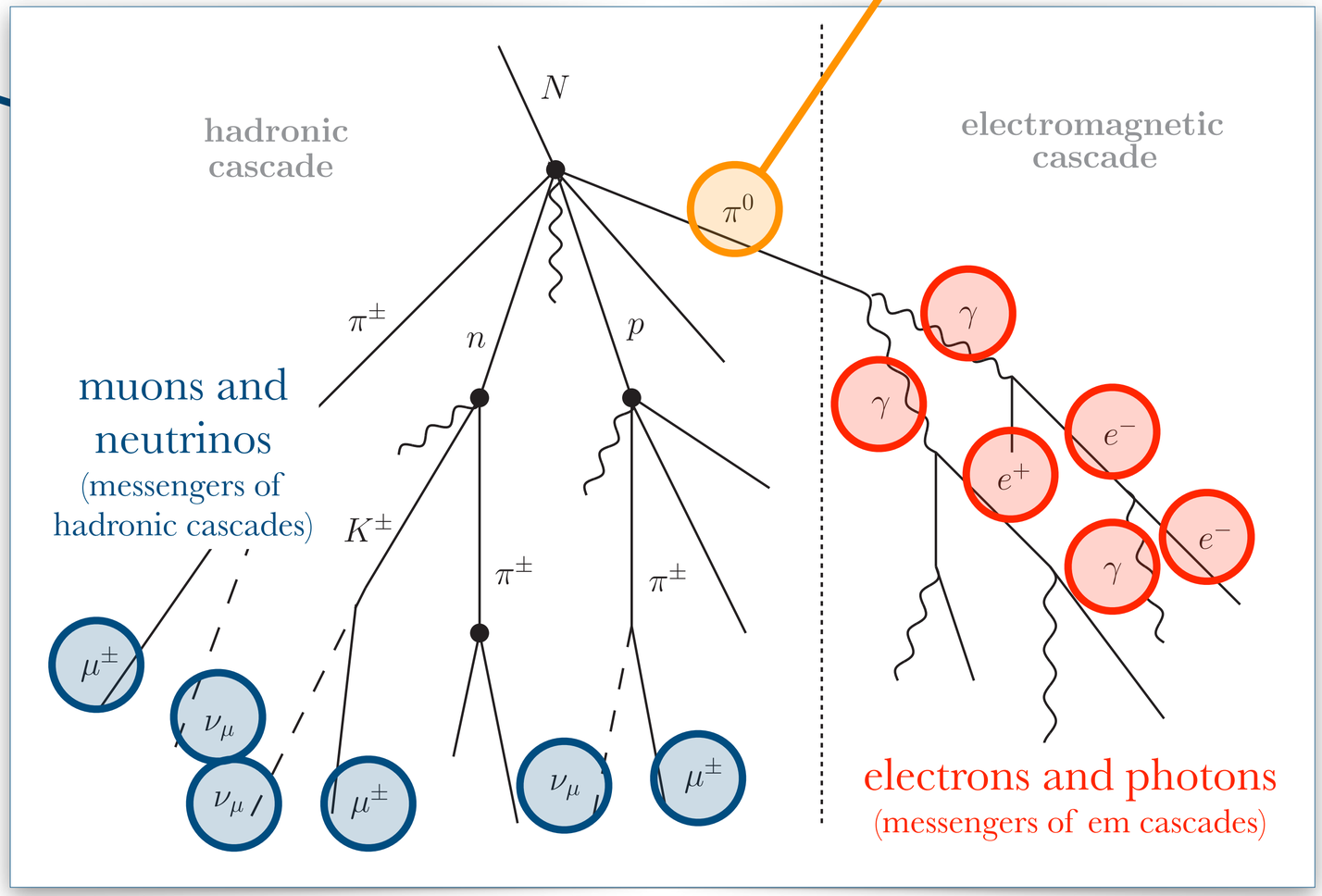

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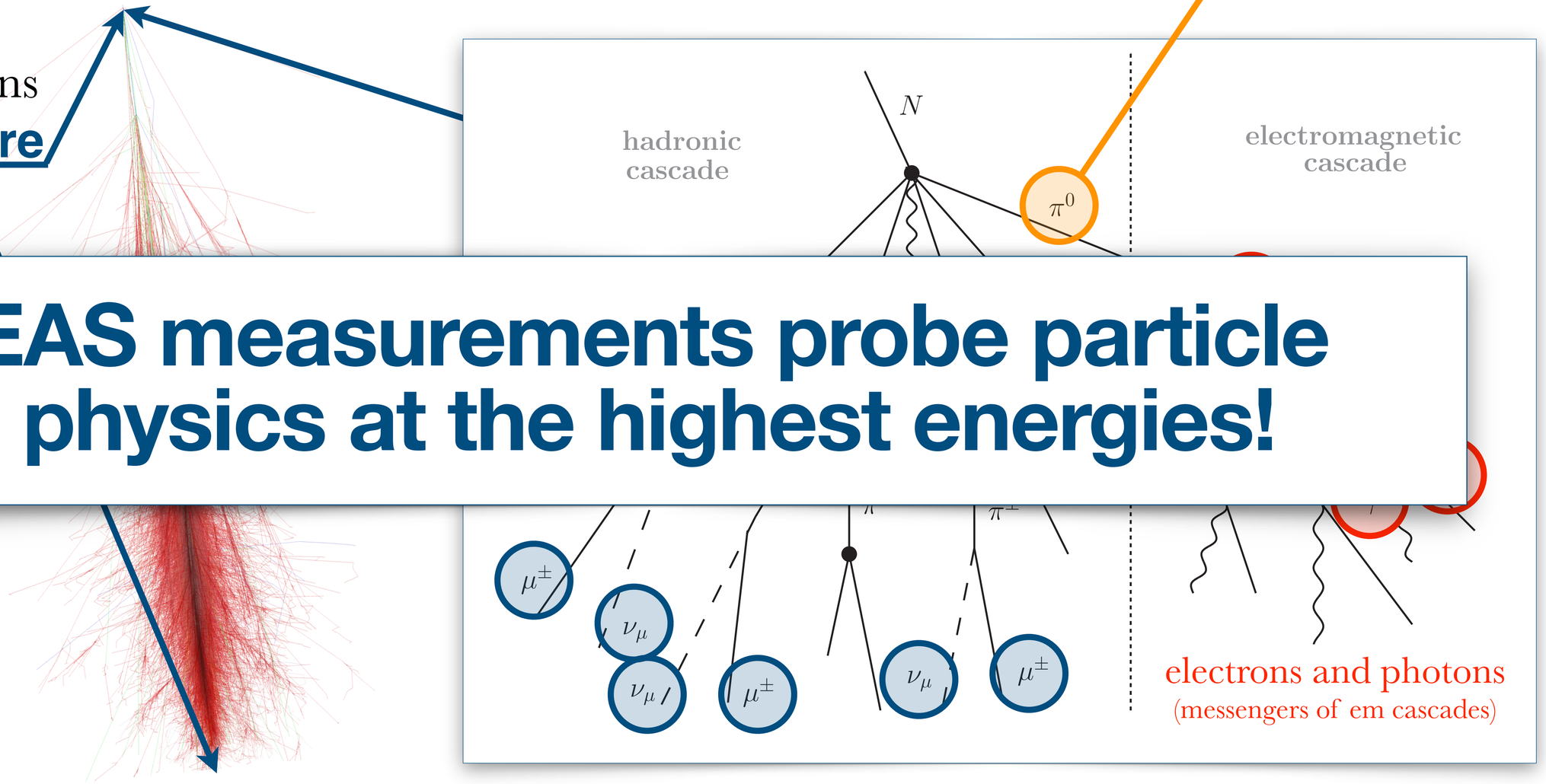
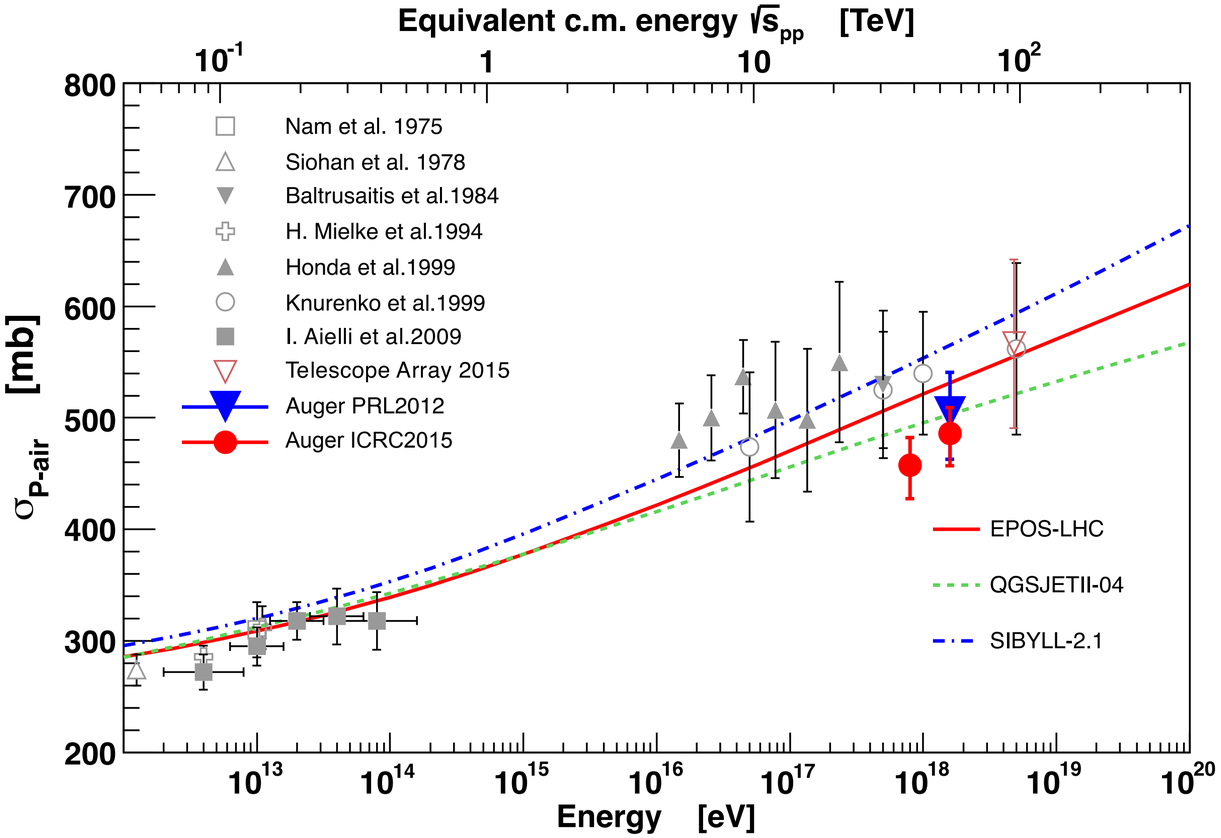


EAS measurements probe particle physics at the highest energies!

Example: Proton-Air Cross-Section

- Proton-air cross-section measured by Auger and TA
- 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
- <u>Opportunity for cosmic ray physics?</u>



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

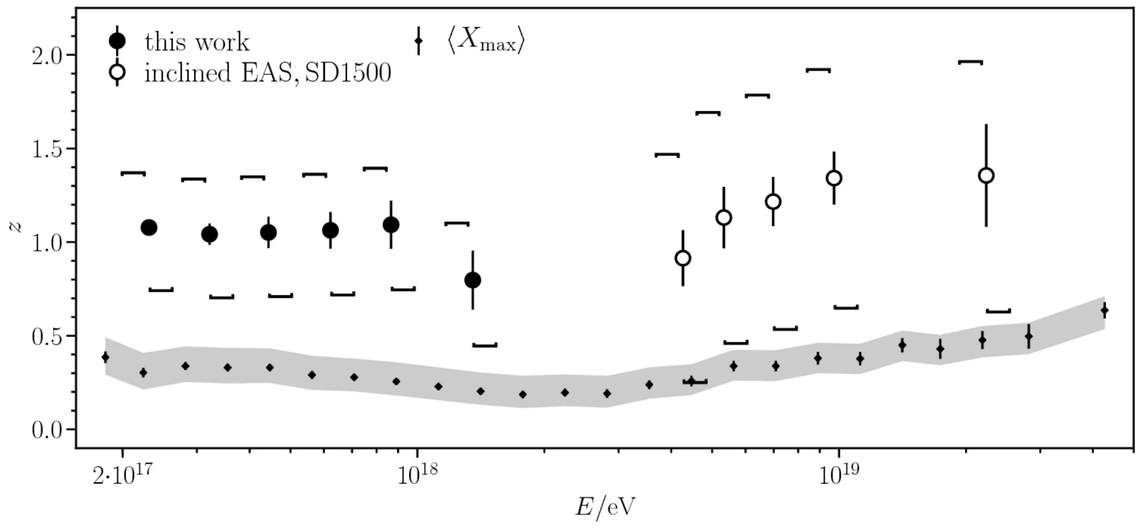
Muon Measurements in EAS

- Muons are messengers of the hadronic interactions in EAS
- Significant discrepancies in the number of muons in EAS observed between MC and data!
- Comparison to model predictions using z-values:

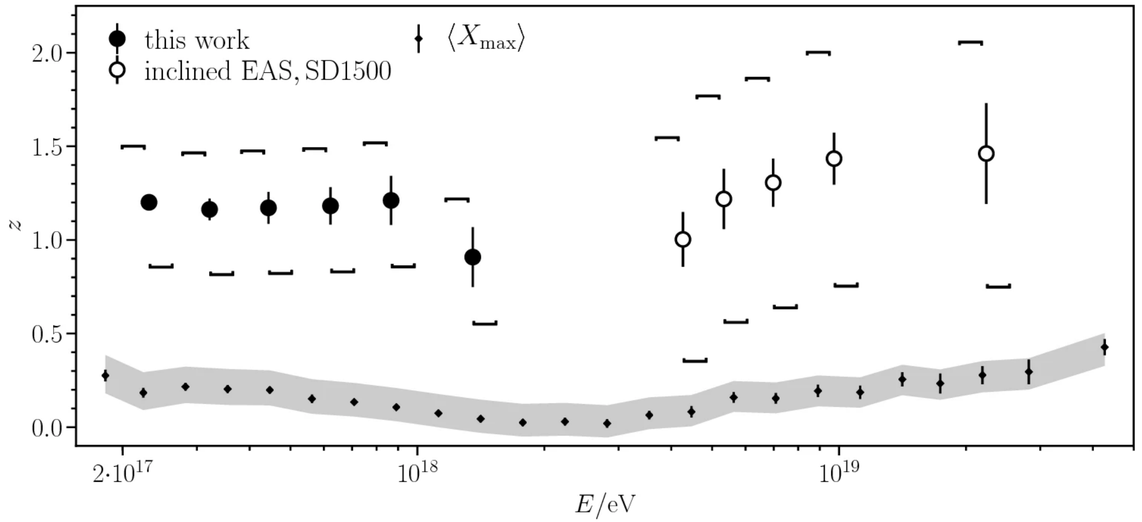
$$z = \frac{\ln(\rho_\mu) - \ln(\rho_{\mu,\mathrm{p}})}{\ln(\rho_{\mu,\mathrm{Fe}}) - \ln(\rho_{\mu,\mathrm{p}})}$$

- Data agrees with proton composition: $z = 0$
- Data agrees with iron composition: $z = 1$
- z-values depend on hadronic models

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



(a) EPOS-LHC



(b) QGSJetII-04

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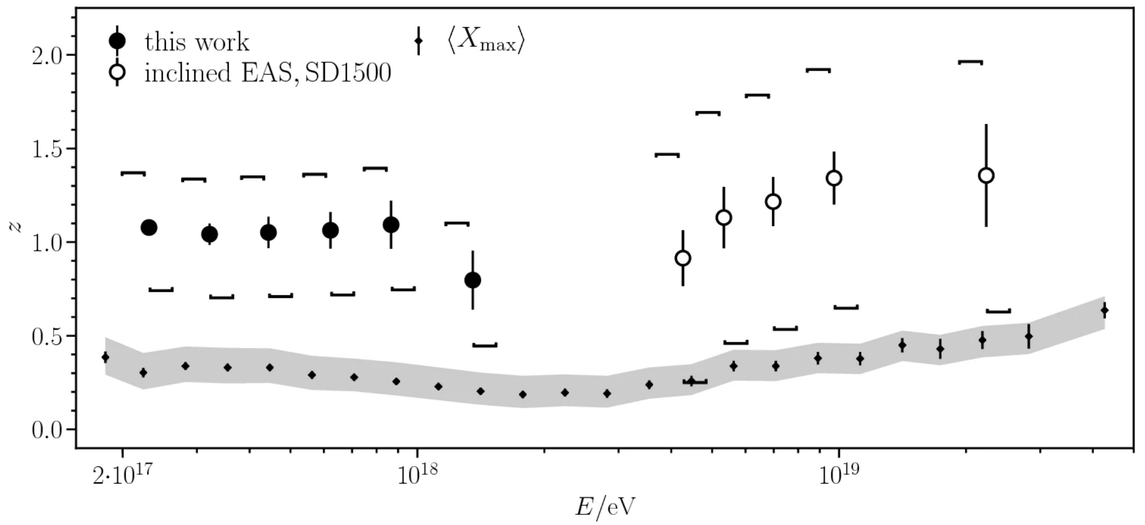

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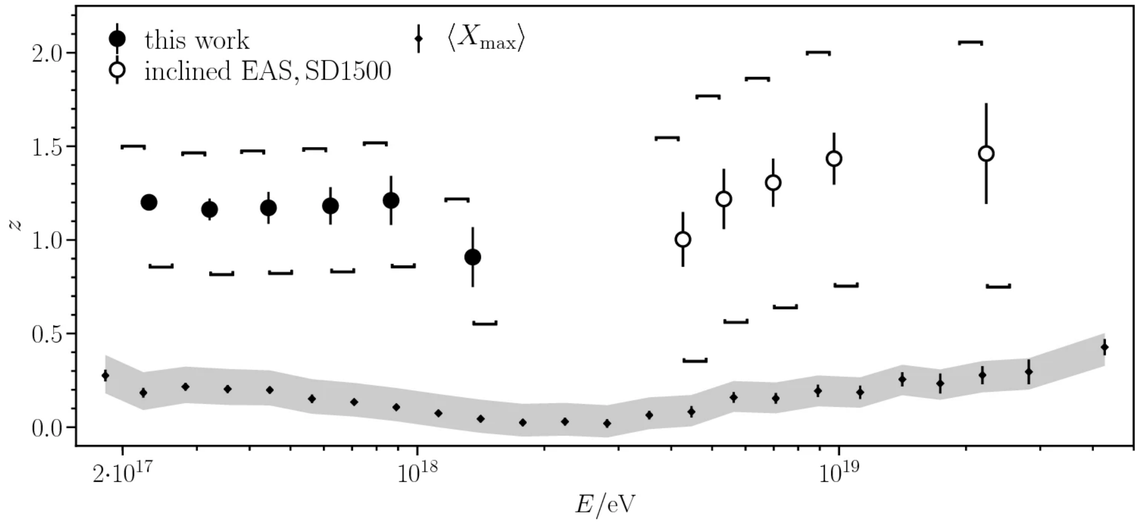

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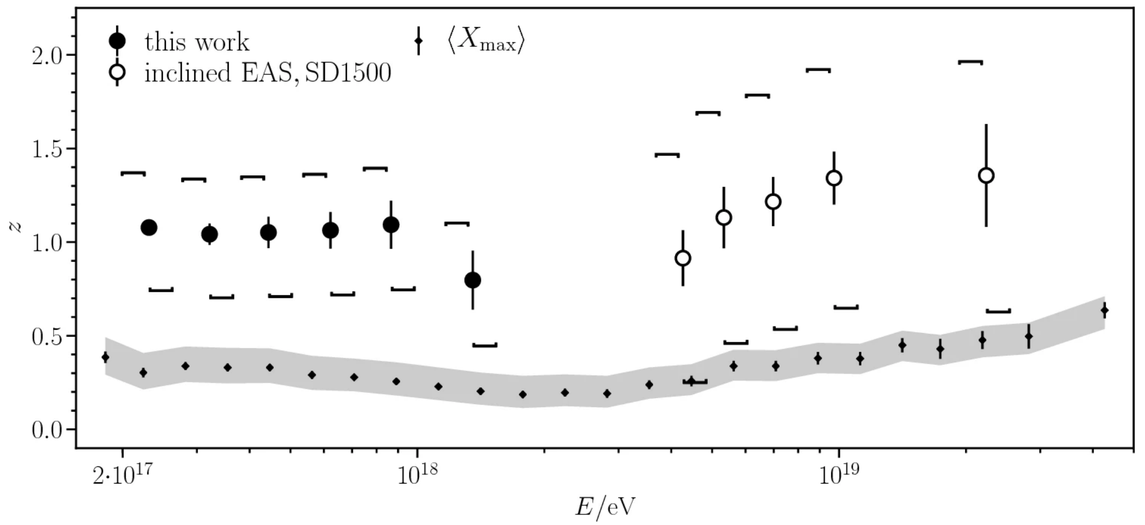

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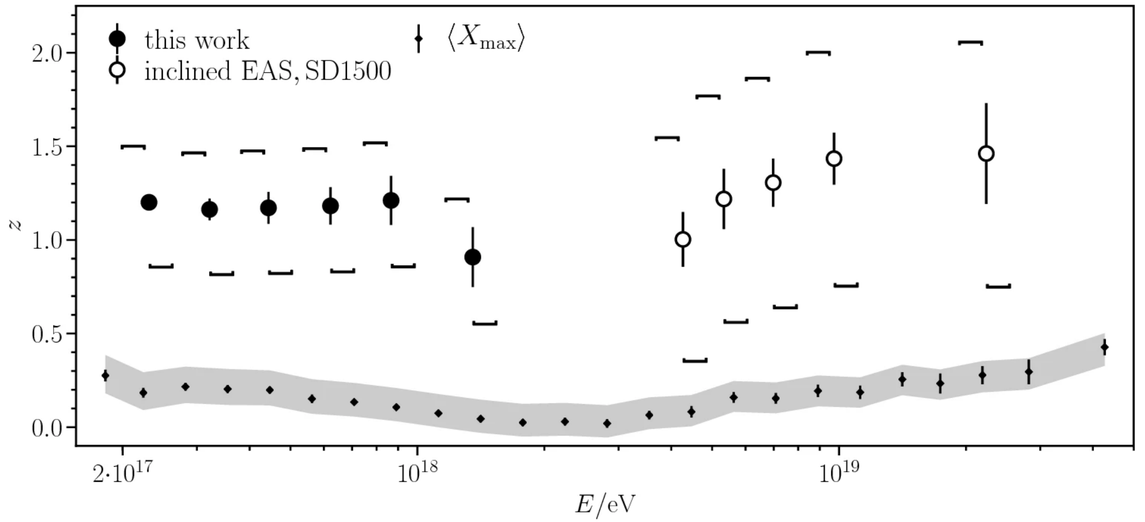
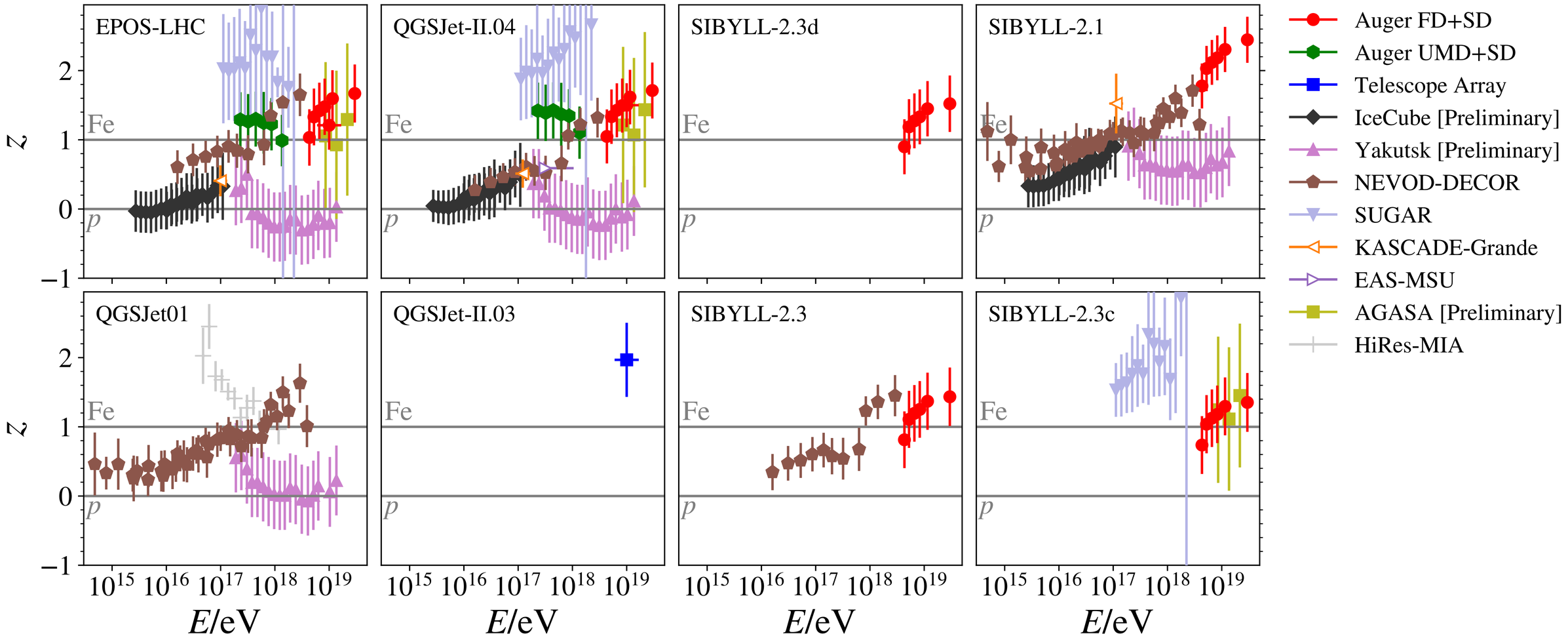


(b) QGSJetII-04

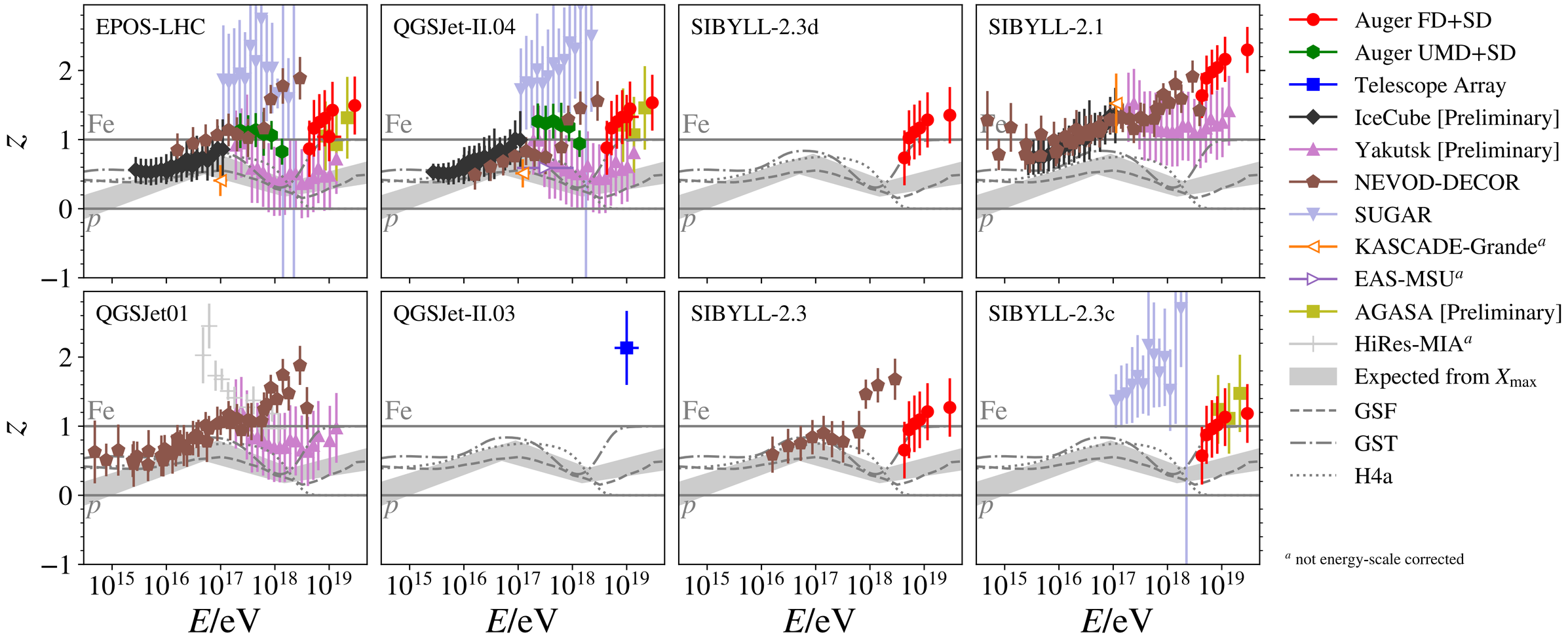
Combined Muon Measurements

- Muon lateral density in EAS as reported by 9 experiments (known energy offsets)



Combined Muon Measurements

- Muon lateral density in EAS after cross-calibration of the energy-scales



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

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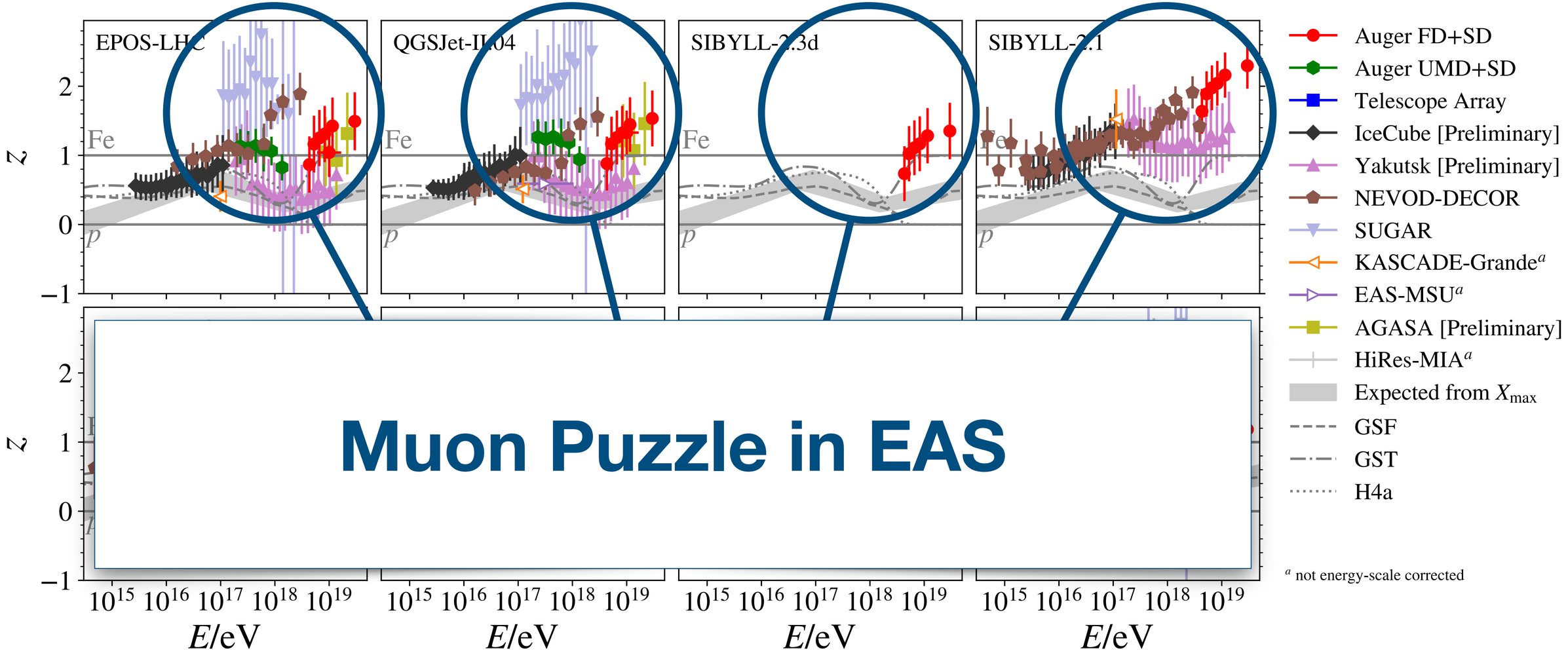


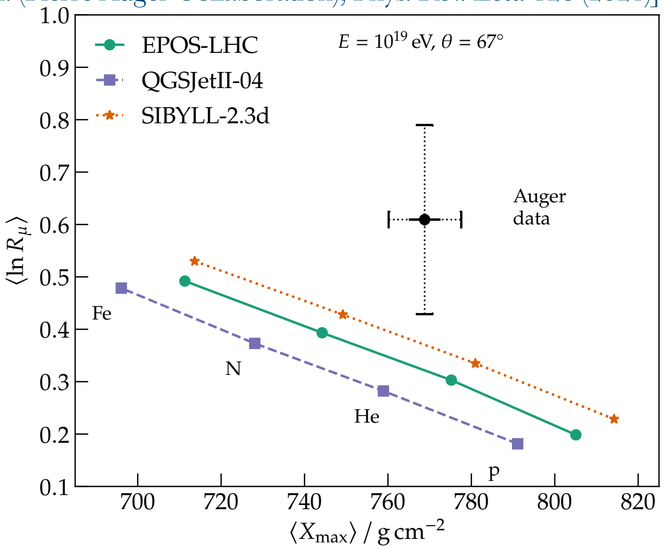
Muon Puzzle in EAS

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

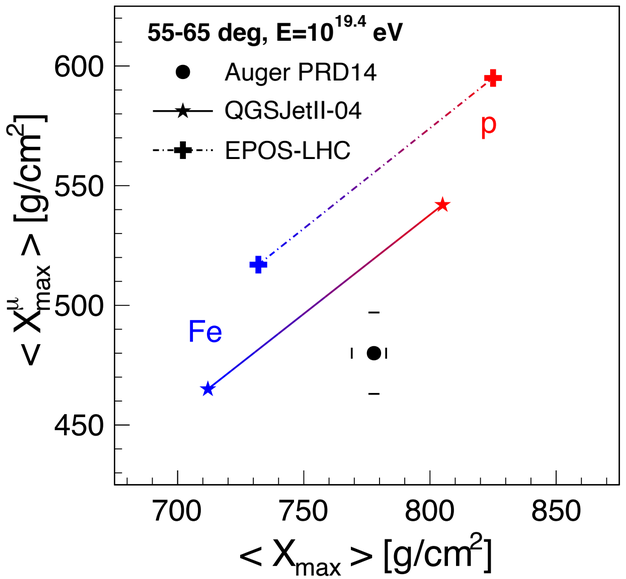
The Muon Puzzle in EAS

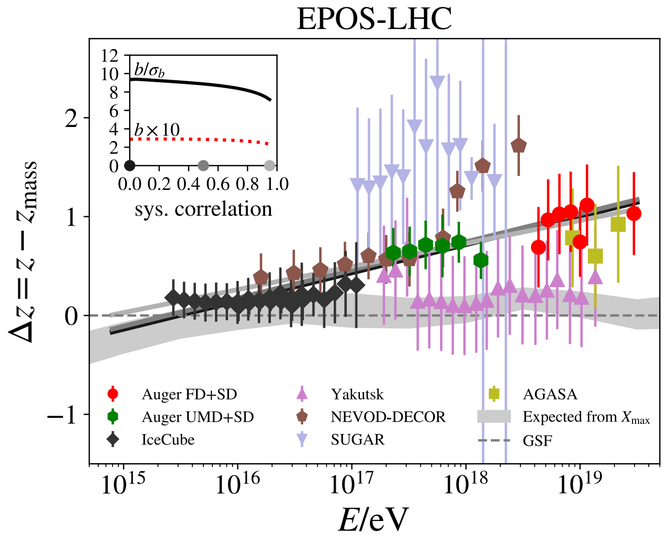
- Muon Puzzle:
  - Up to ~30% discrepancies in N_μ
  - N_μ vs. $X_{\max}$ and $X_{\mu,\max}$ vs. $X_{\max}$
  - WHISP: excess towards high energies
    - slope in $z - z_{\text{mass}}$ significant at ~8σ
  - Origin remains unknown!
  - Severe discrepancies in our understanding of hadronic interactions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

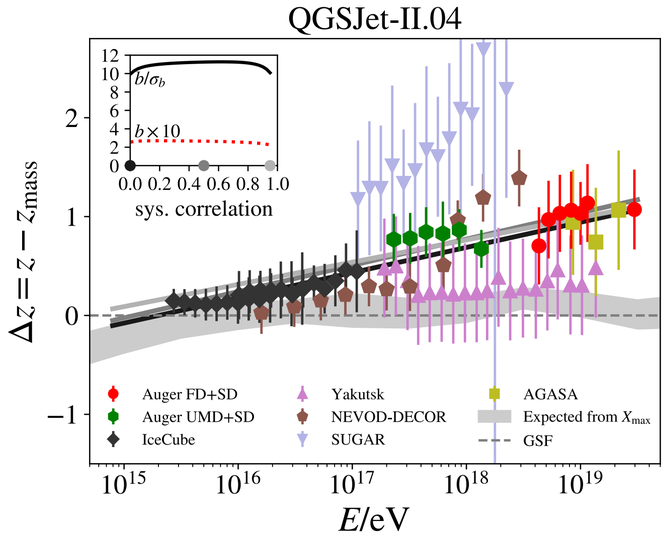
[A. Aab et al. (Pierre Auger Collaboration), Phys. Rev. Lett. 126 (2021)]



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





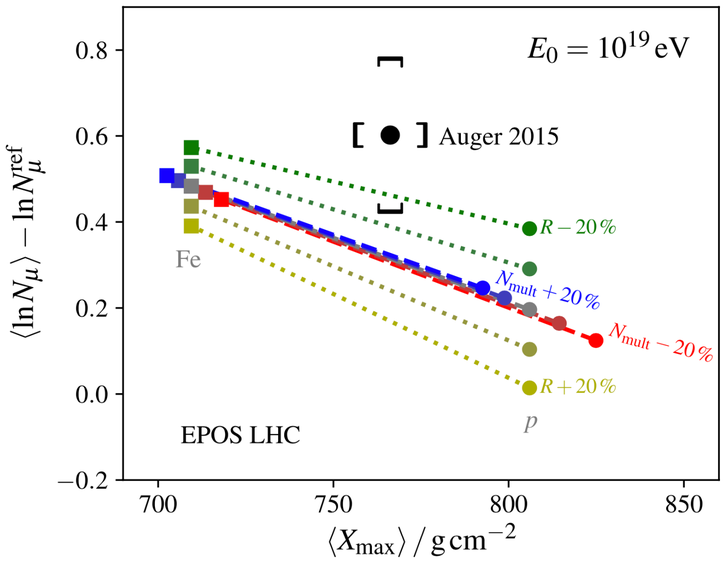


[D. Soldin et al. (WHISP), PoS(ICRC2021)349 (2021)]

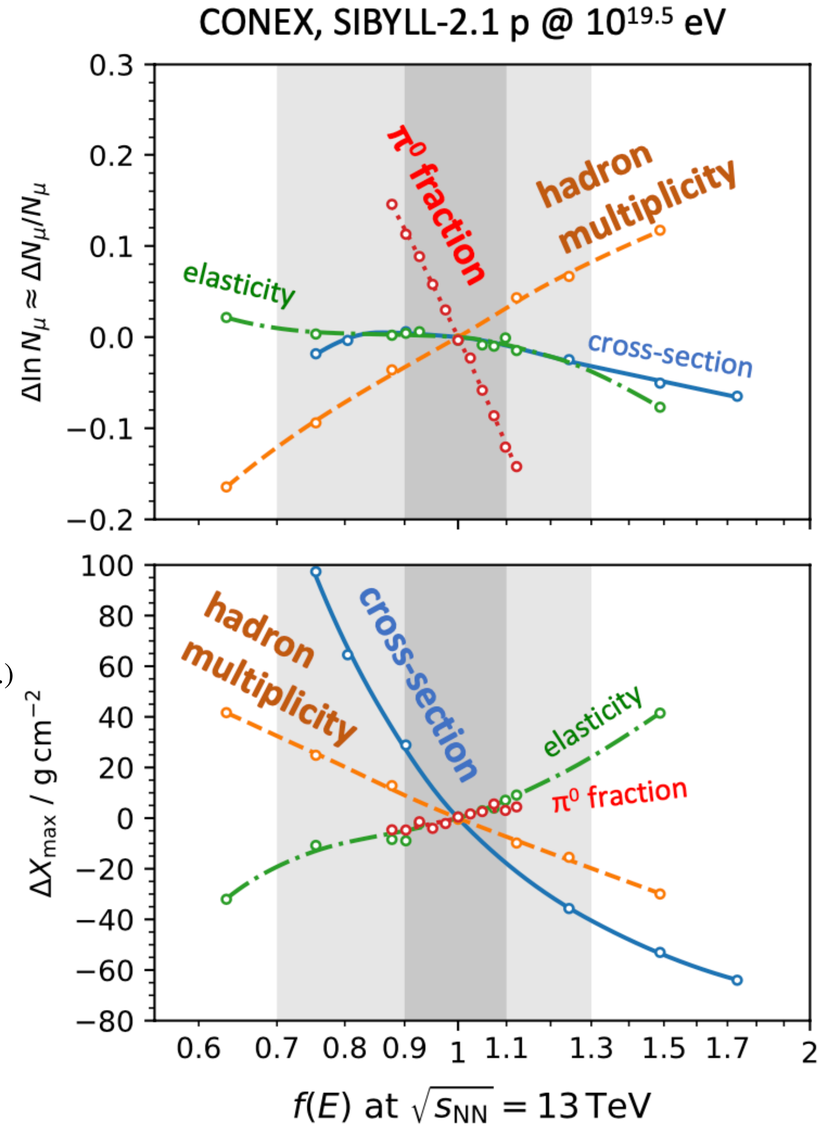
The Muon Puzzle in EAS

- 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!

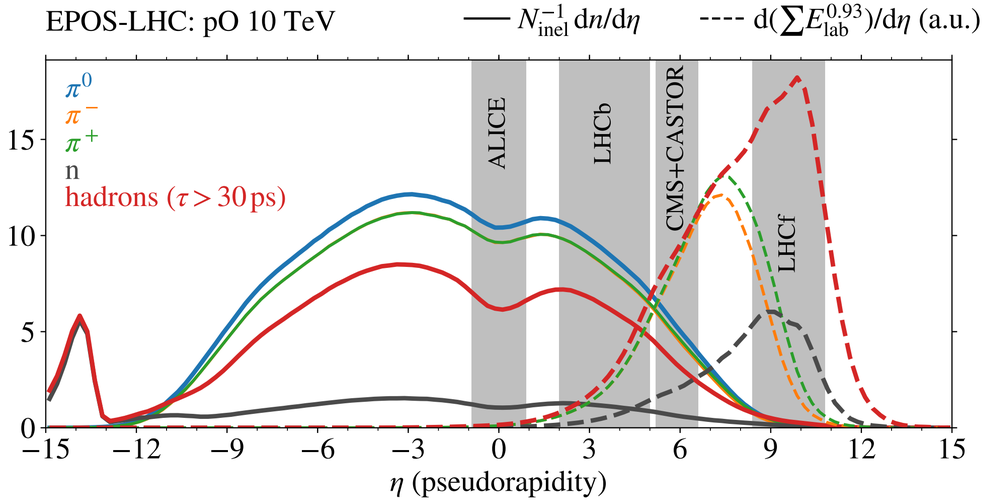
[S. Baur et al., arXiv:1902.09265 (2019)]



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

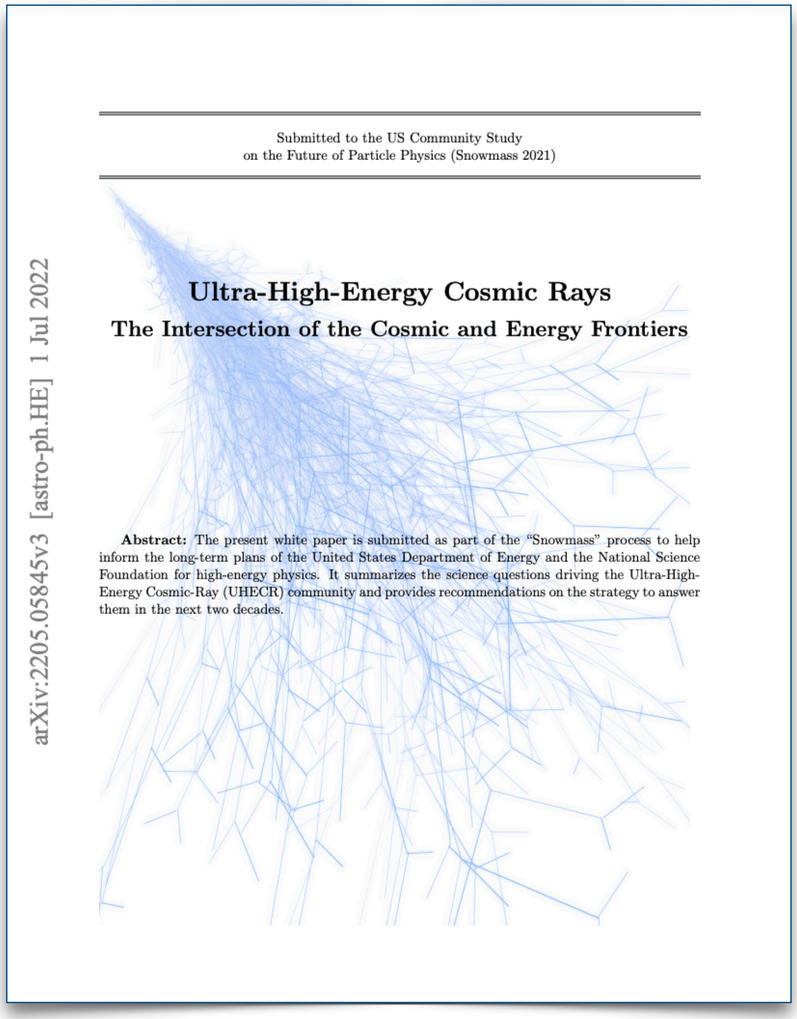


[J. Albrecht, D. Soldin et al., Astrophys.Space Sci. 367 (2022)]



Outlook into 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, e.g. N_μ, $X_{\max}$, $X_{\mu,\max}$, zenith angle evolution, spectral information (IceCube)
  - 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!

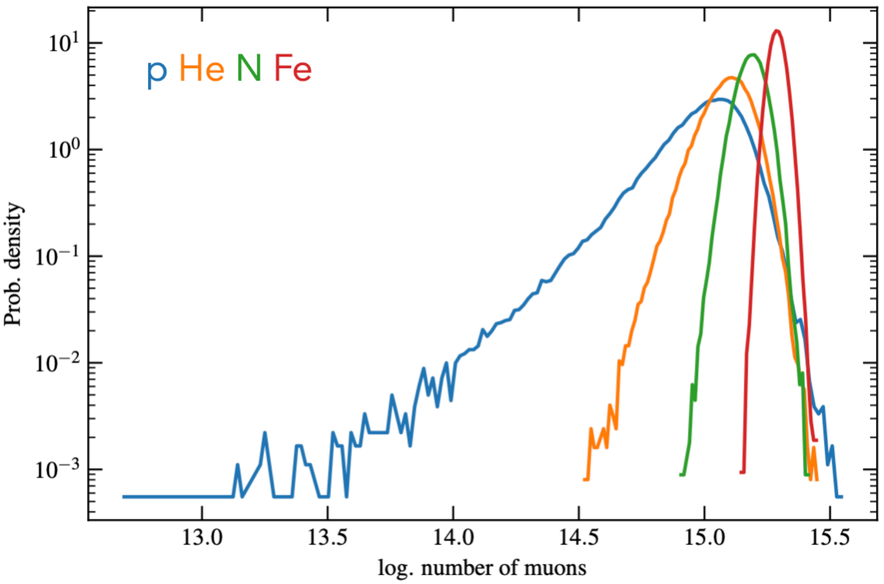


[Snowmass White Paper, arXiv:2205.05845]

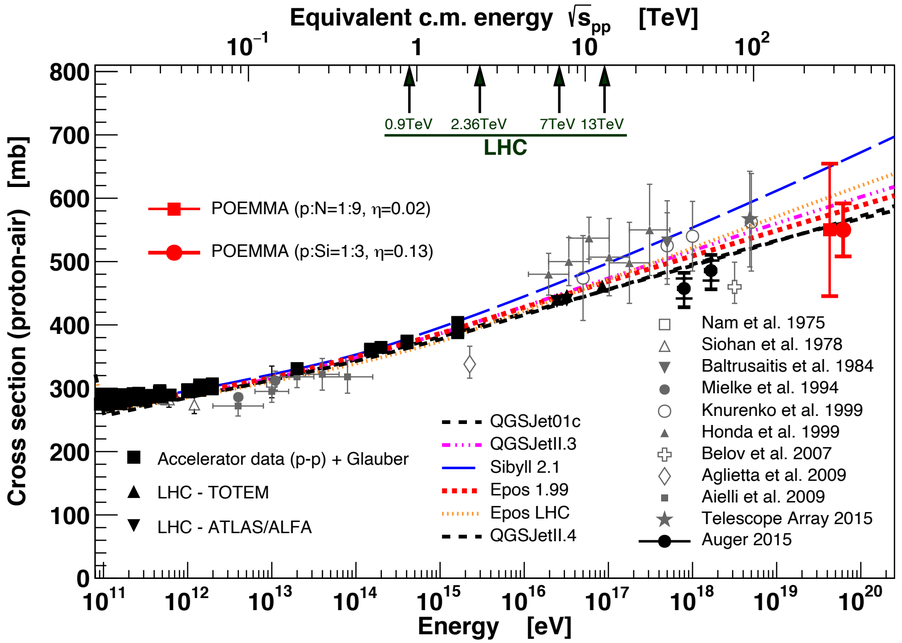
New Generation of UHECR Observatories

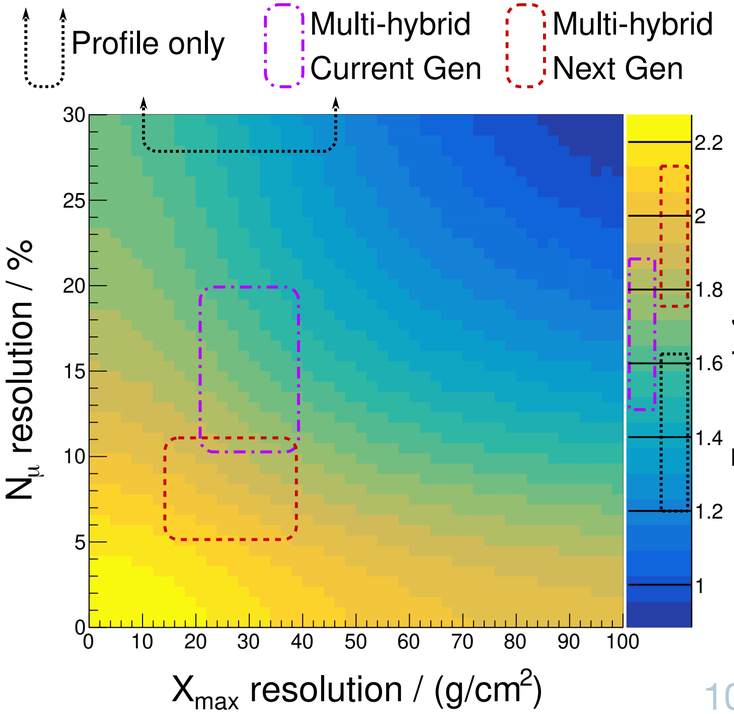
- New large-scale EAS observatories with particle detectors (GCOS, IceCube-Gen2, GRAND?) will provide large aperture and thus unprecedented event statistics
- Possibly new EAS observables and analysis techniques to test hadronic interaction models
  - <u>New era of high-precision measurements with EAS!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

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



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



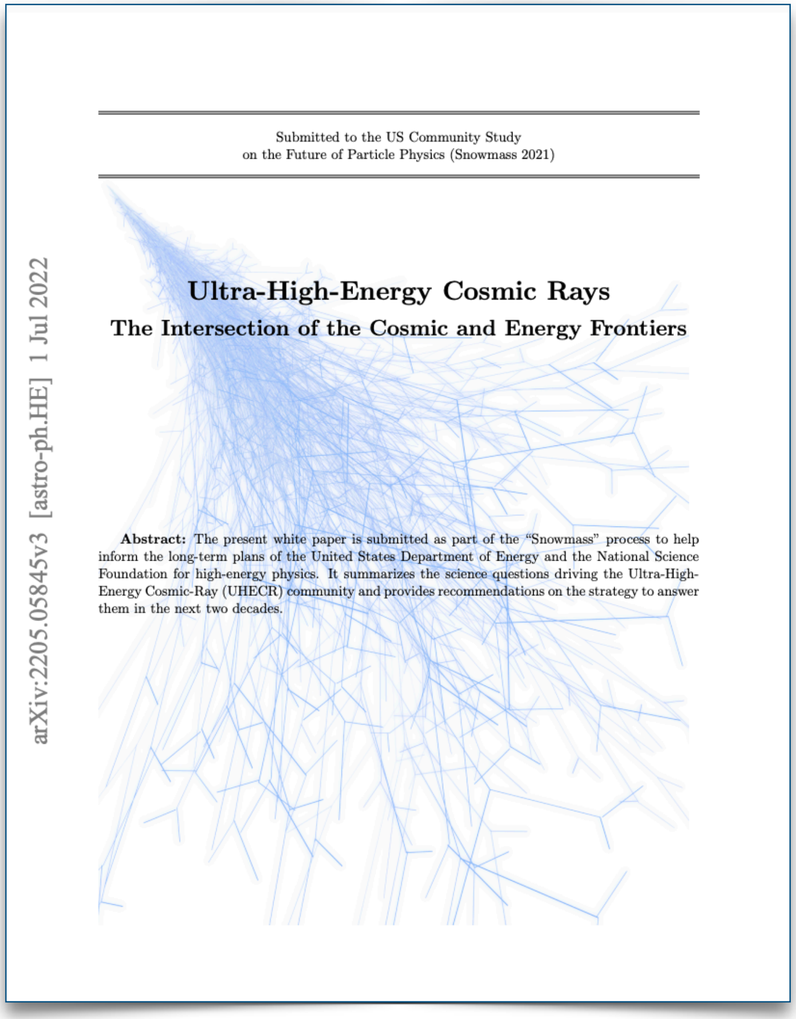


Outlook beyond the Next Decade

- 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 hadronic models 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
- 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, …

Summary & Conclusions

- EAS measurements probe hadronic interactions at the highest energies
- Large discrepancies between model predictions and data observed in multiple muon measurements
- Origin of the Muon Puzzle unknown
- Tests of SM predictions at energies beyond the LHC
- Expectation: Muon Puzzle solved by the end of decade
- High-precision particle measurements with EAS!
- Provides event generators for future collider experiments
- If the Muon Puzzle remains unsolved
  - Tests of beyond SM physics /exotic scenarios!
- Next generation experiments



[Snowmass White Paper, arXiv:2205.05845]