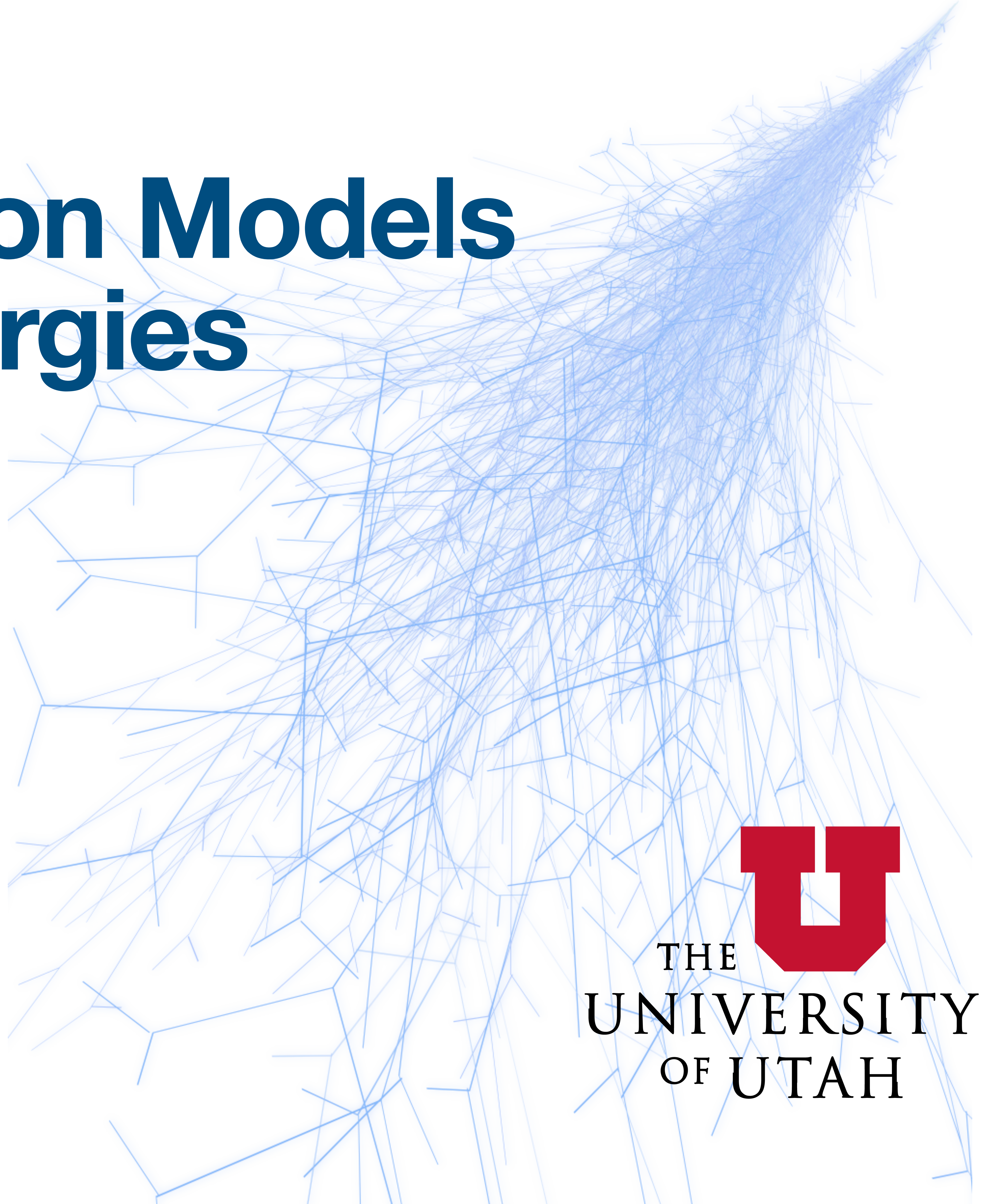
Hadronic Interaction Models at the Highest Energies

CIPANP 2025

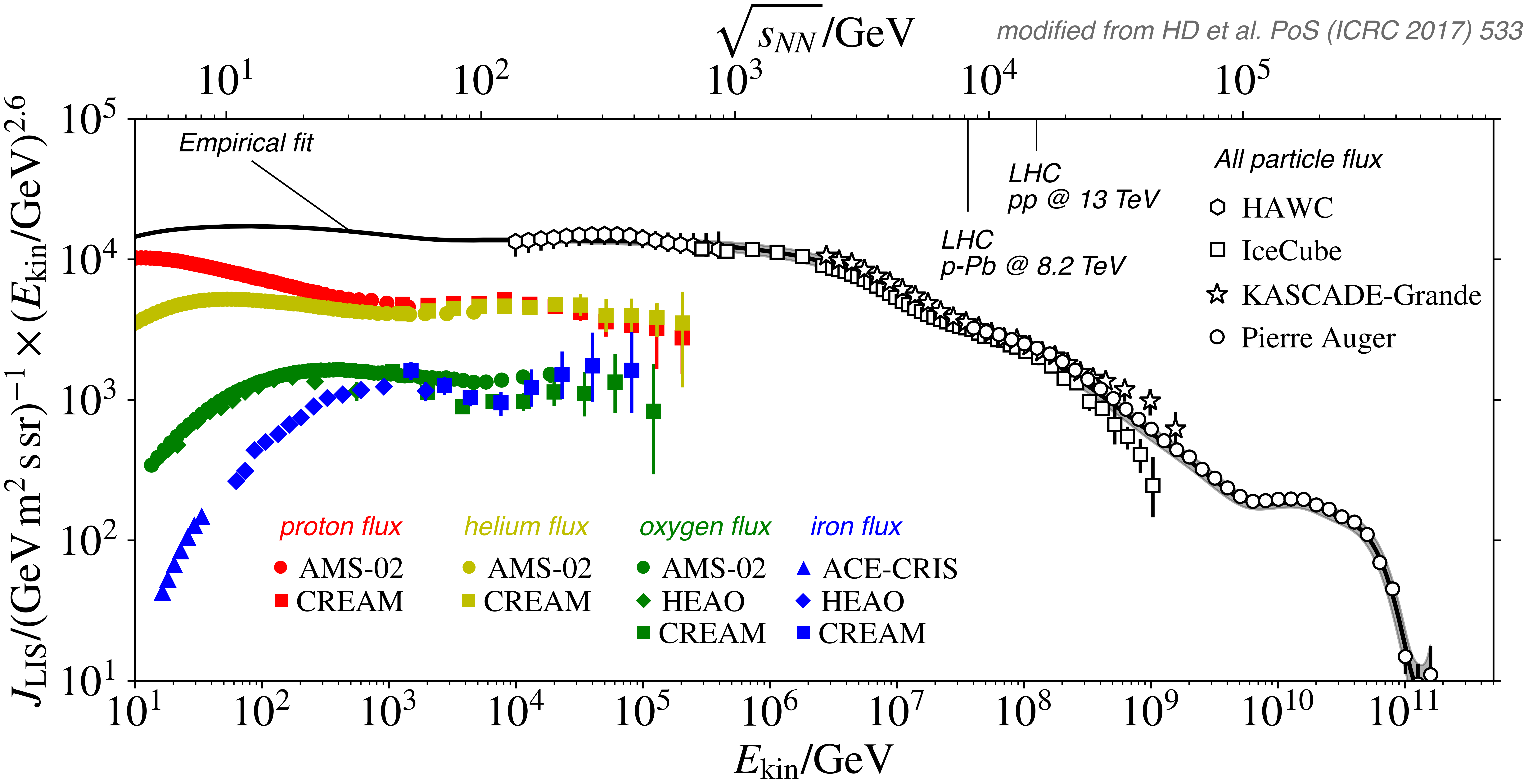


Dennis Soldin
University of Utah

THE UNIVERSITY OF UTAH

The Highest Energies

- This talk: Cosmic-ray measurements at energies above 1 PeV



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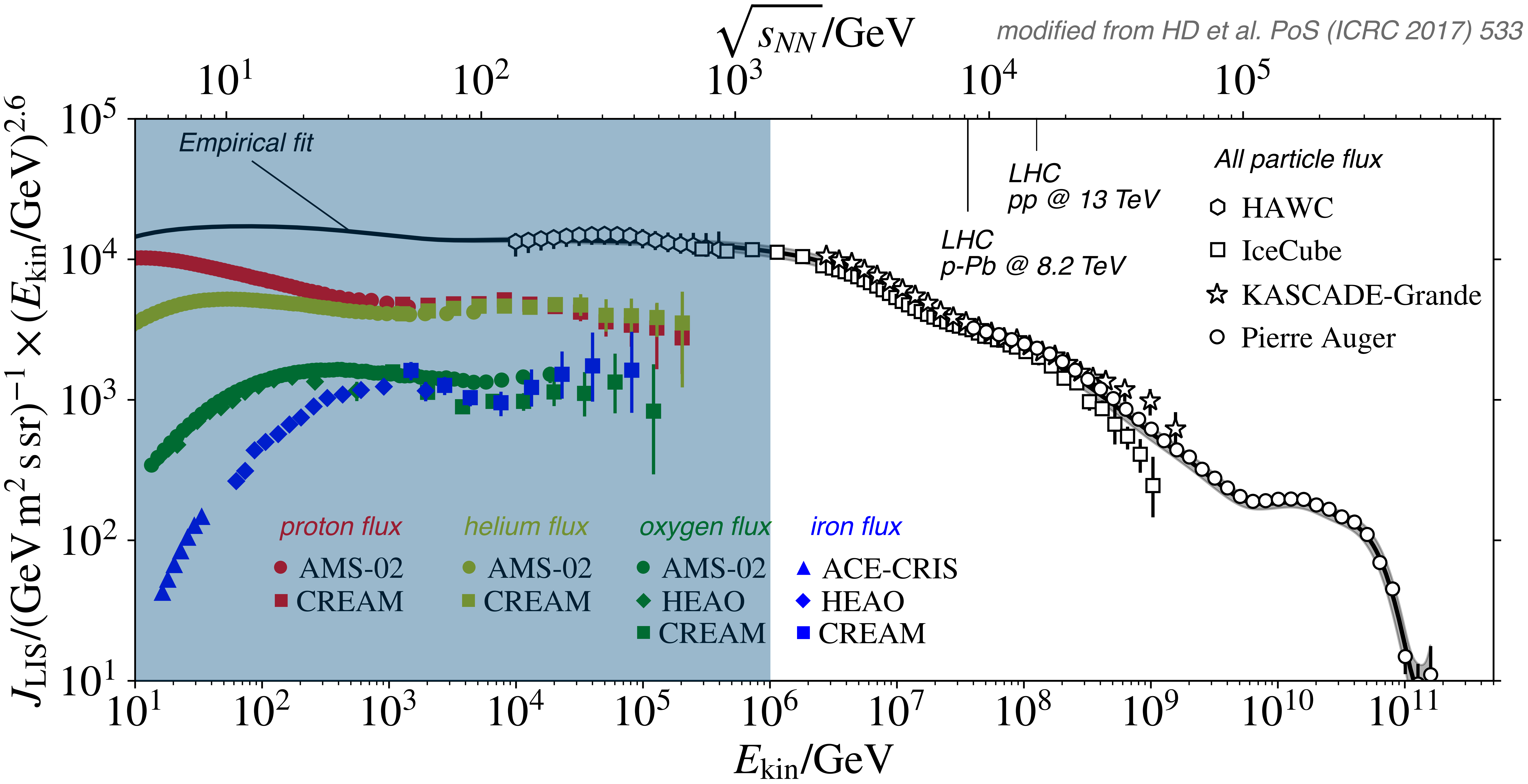
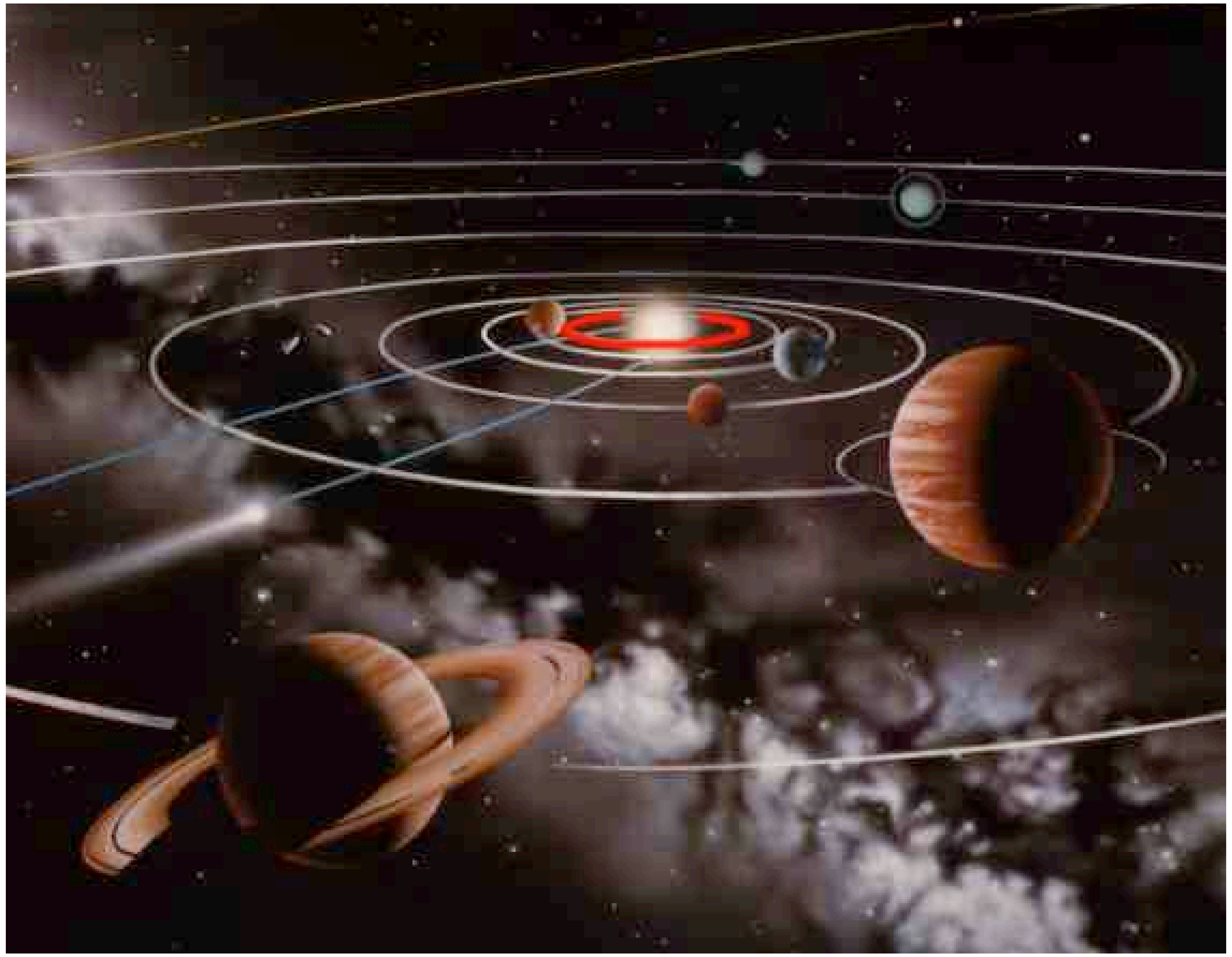


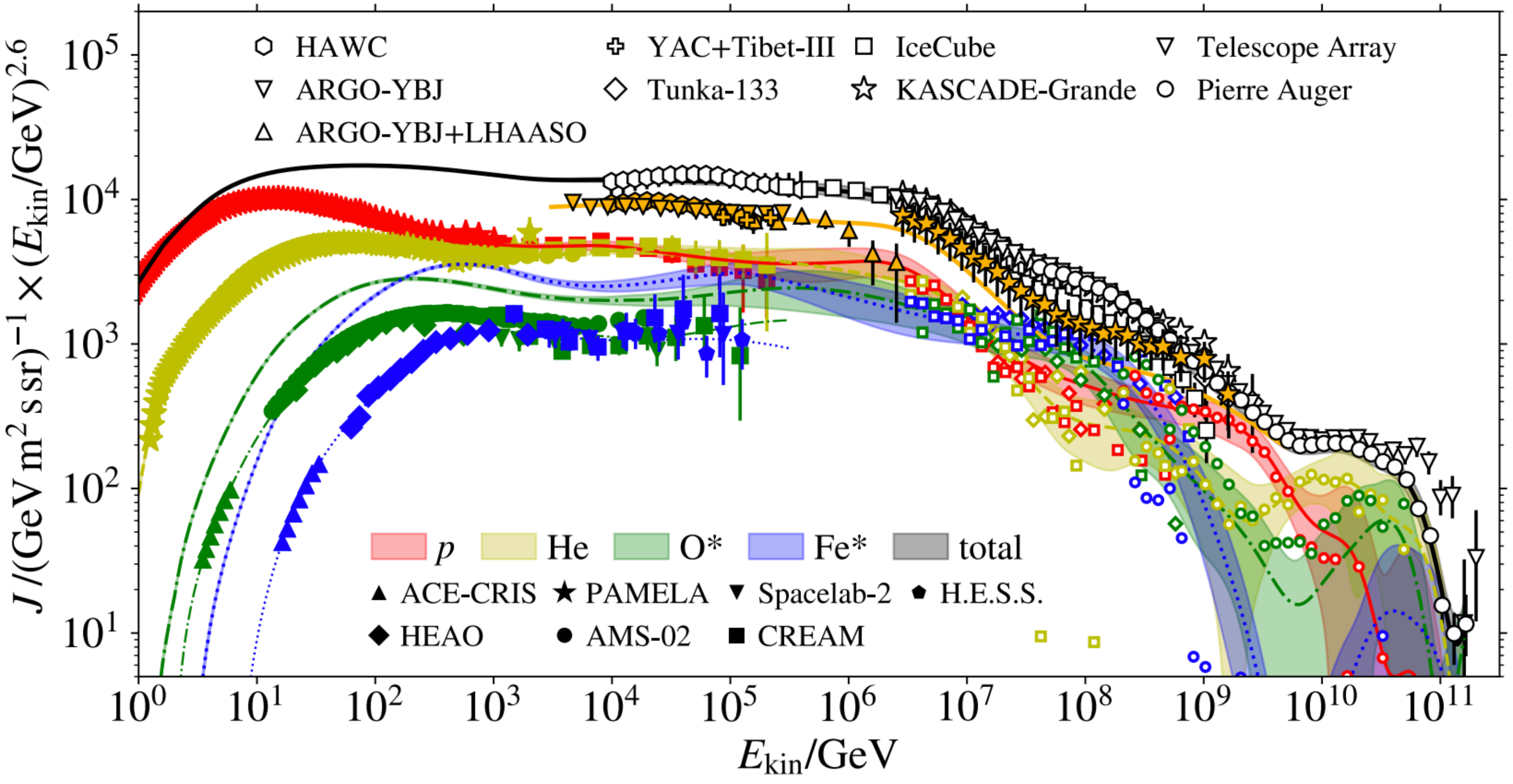
Ultra-High Energy

- Large Hadron Collider (LHC), 27 km circumference, superconducting magnets
- Need accelerator of size of Mercury's orbit to reach 10^{20} eV with current technology!

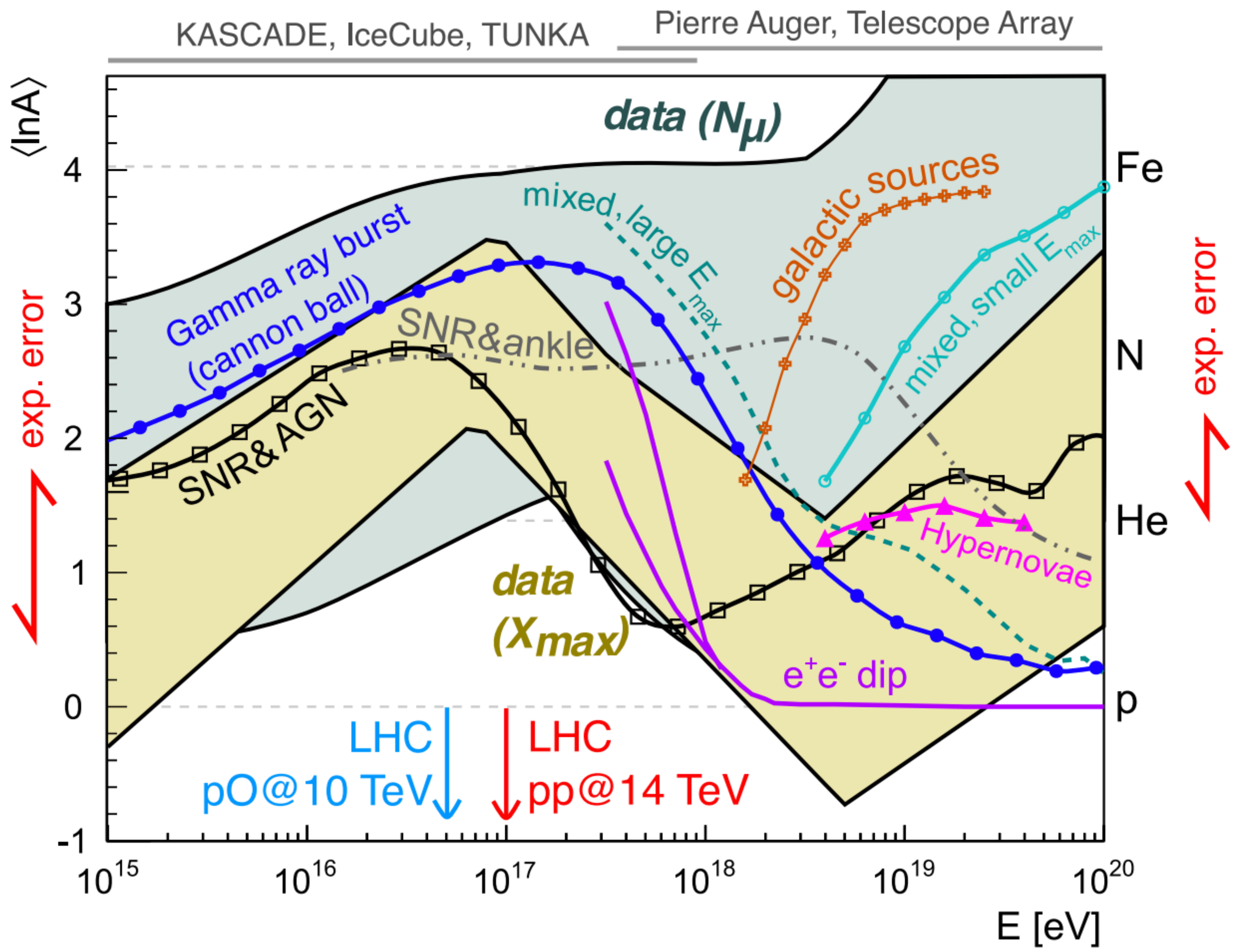


Cosmic Rays

- Energy spectrum very well-known up to above $\sim 100\,\mathrm{EeV}$ ($10^{20}\,\mathrm{eV}$)
- However, large uncertainties in CR mass composition measurements remain!
- CR properties are inferred indirectly from measurements of Extensive Air Showers (EAS)!

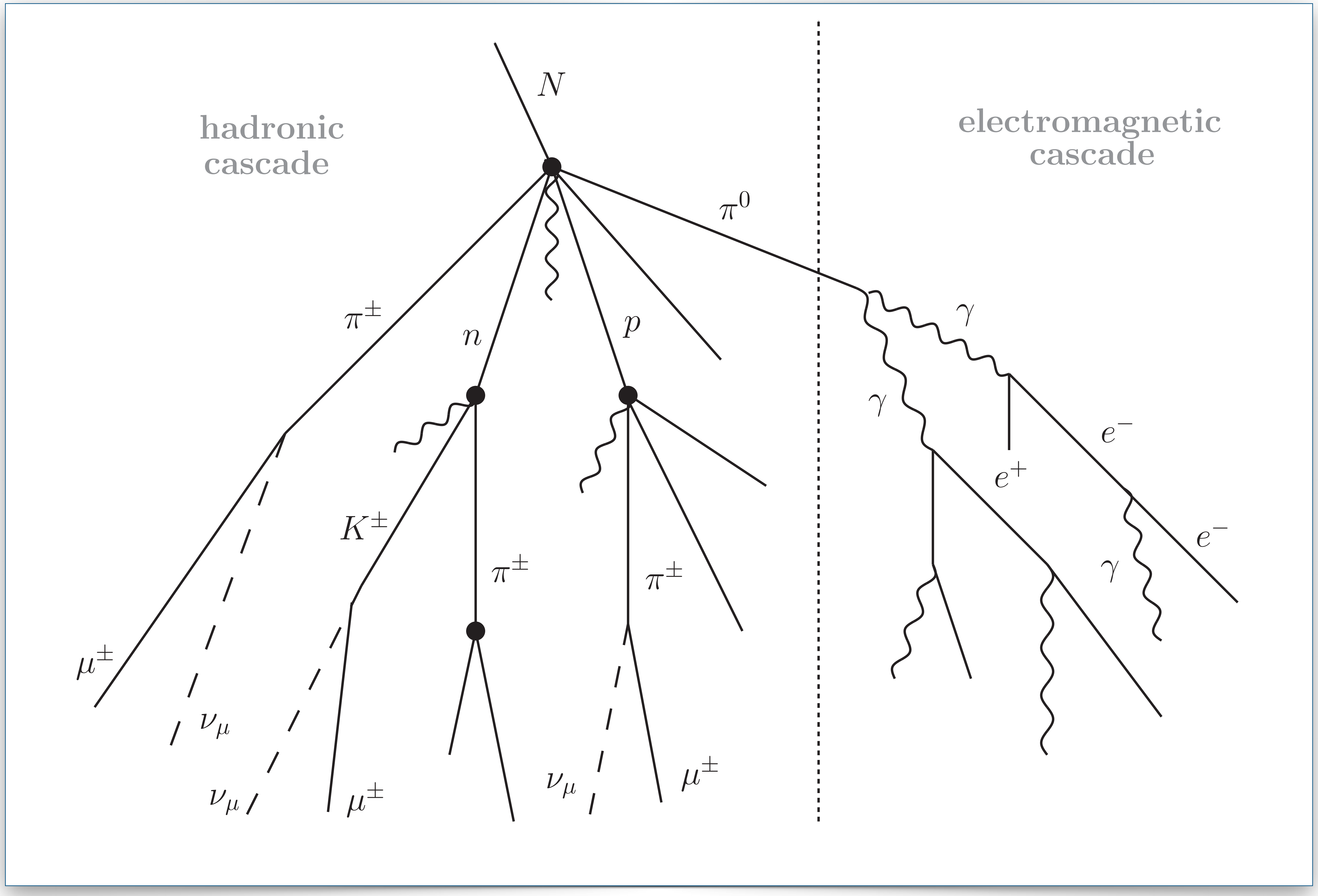


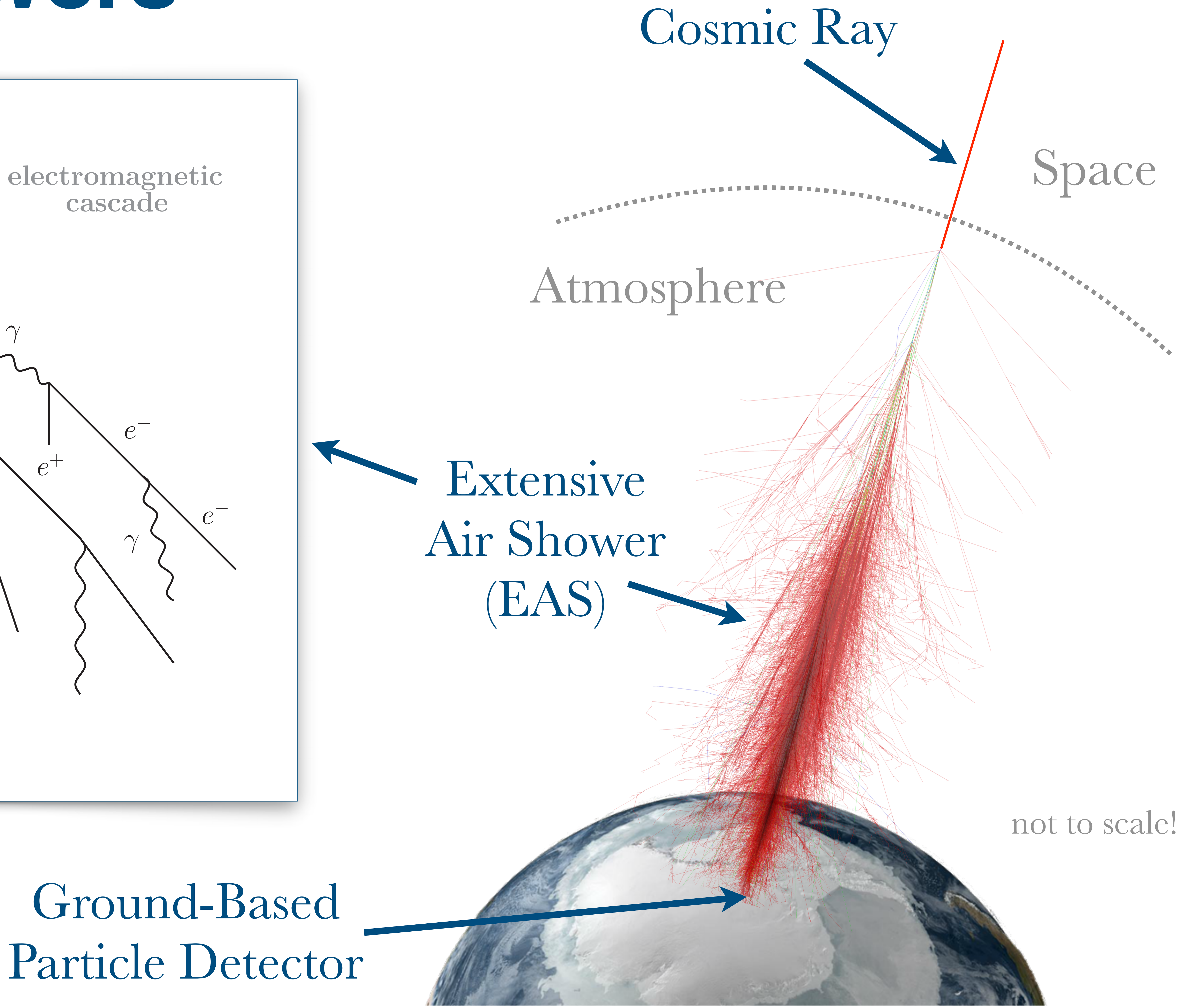
[H.P. Dembinski et al., PoS ICRC2017 (2017) 533]



[K.-H. Kampert, M. Unger, Astropart. Phys. 35 (2012) 660–678]

Extensive Air Showers





- Hadronic interactions are crucial for the EAS development

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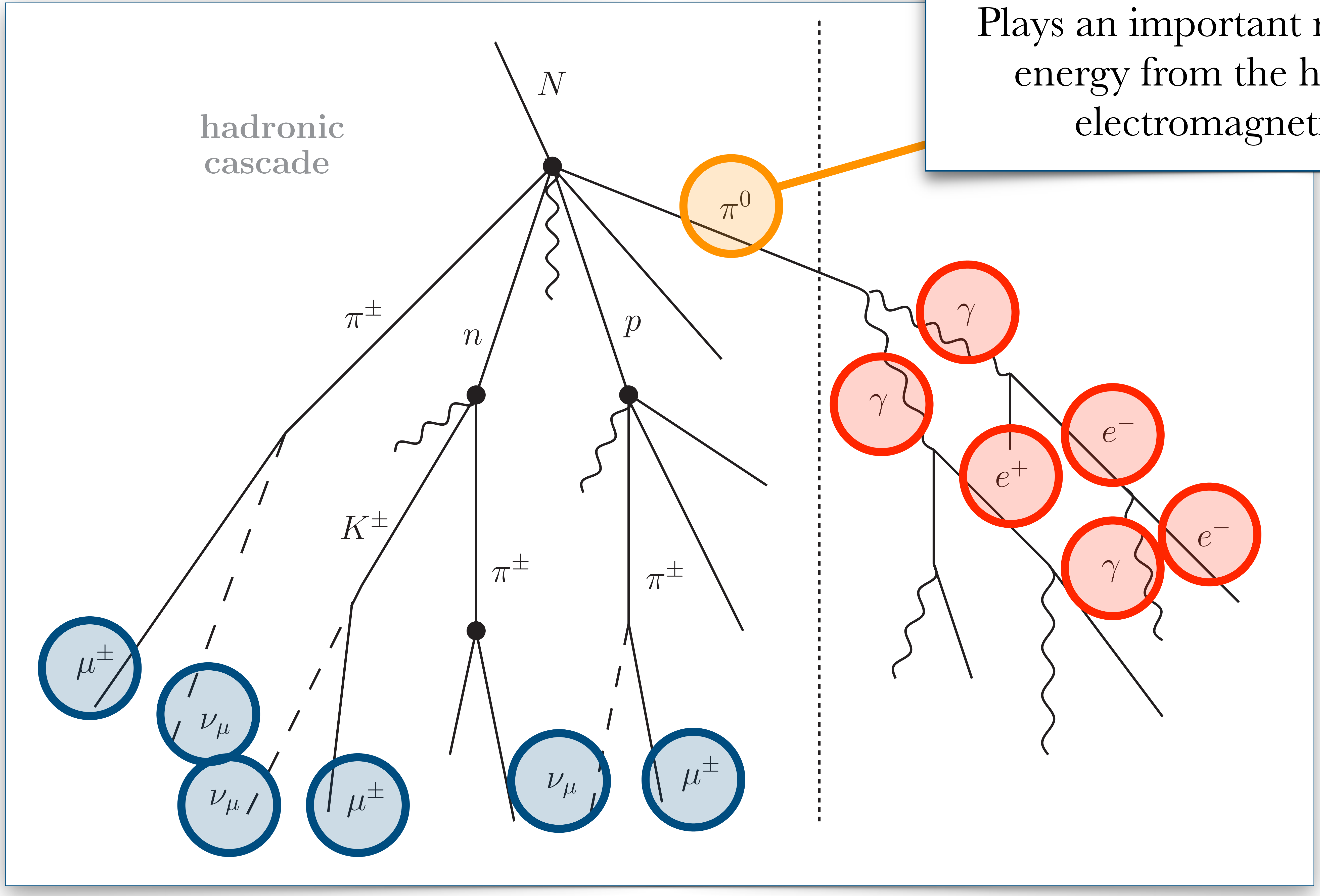
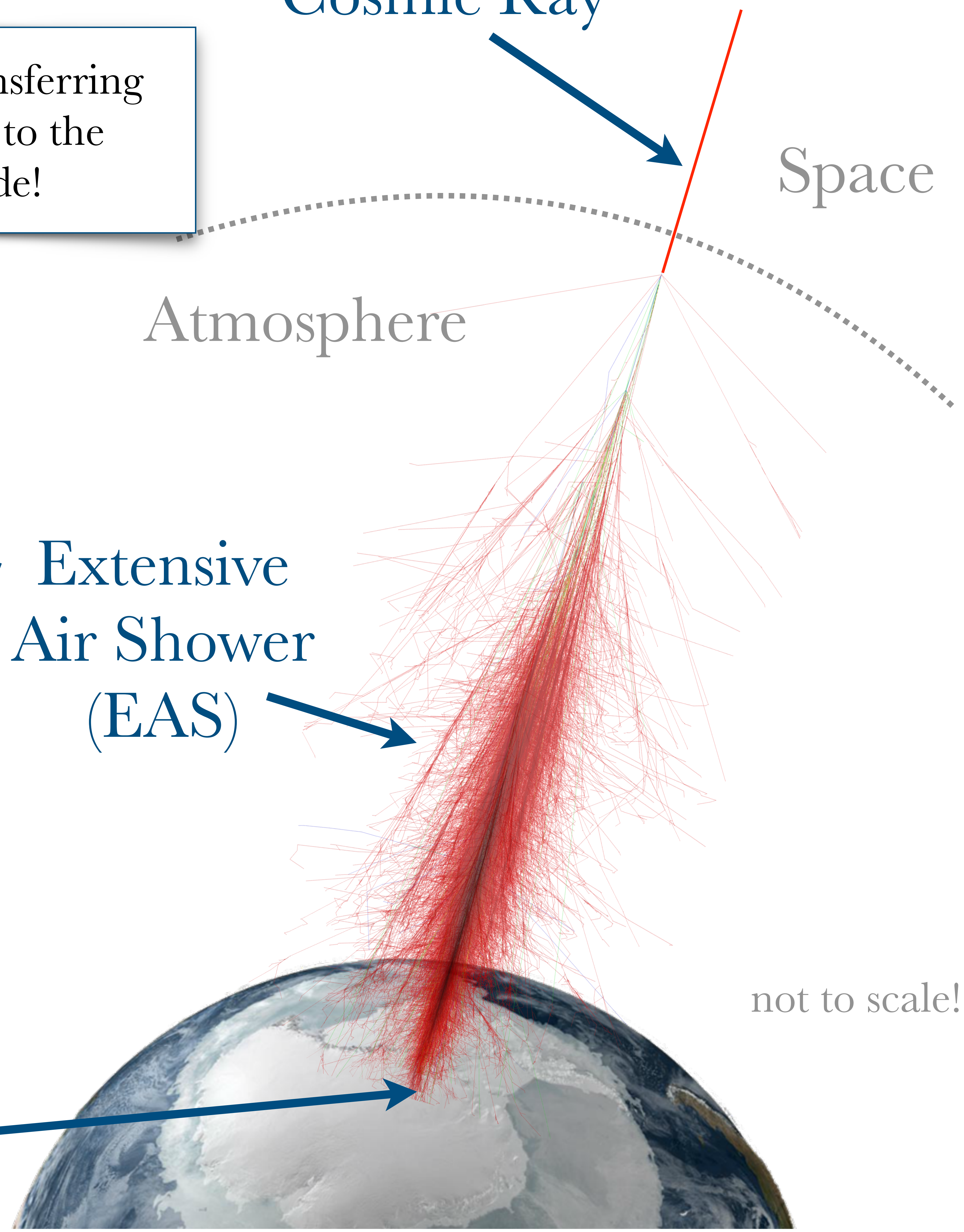


Plays an important role, transferring energy from the hadronic to the electromagnetic cascade!



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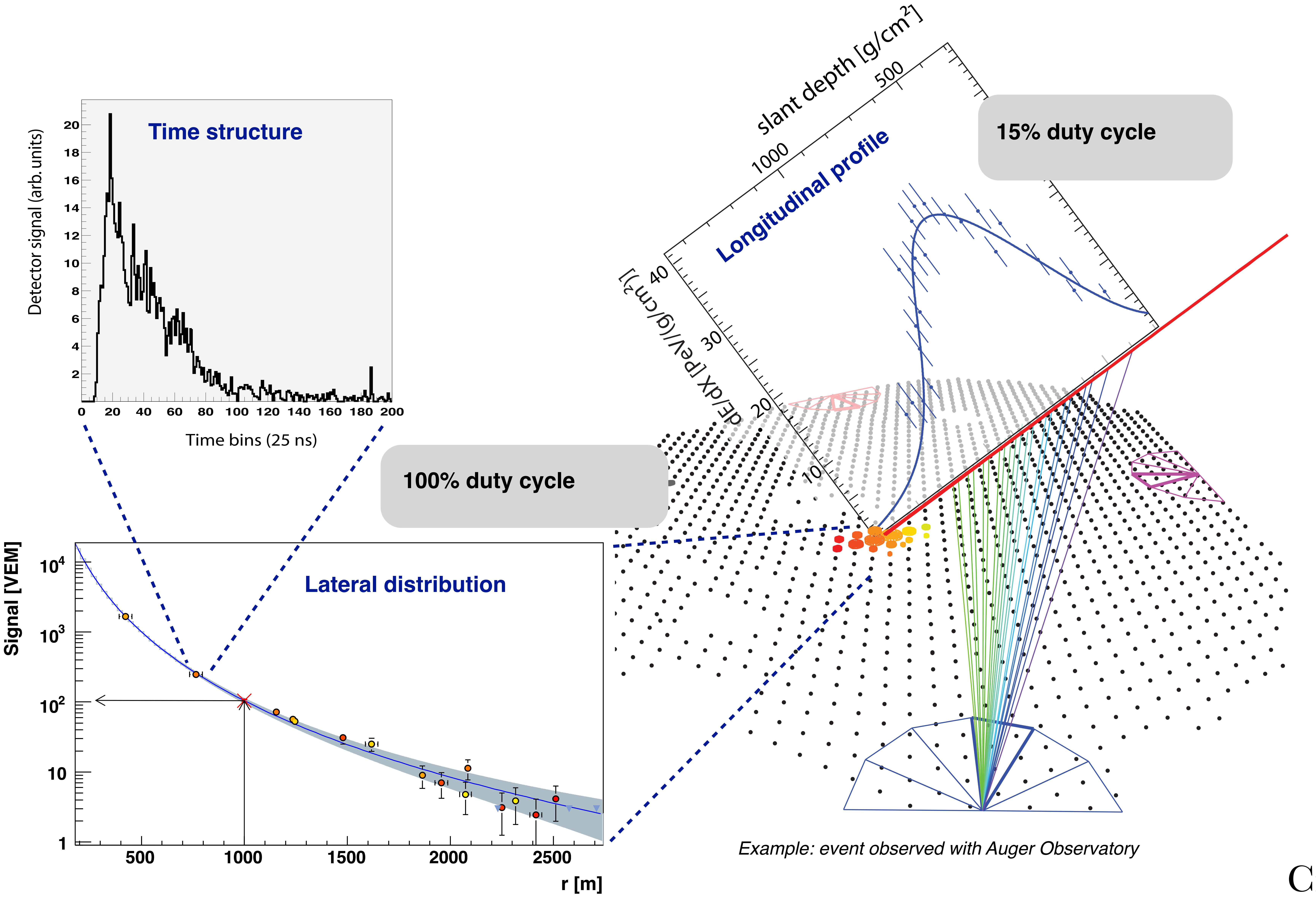
Cosmic-Ray Measurements



Example: event observed with Auger Observatory

Credit: R. Engel

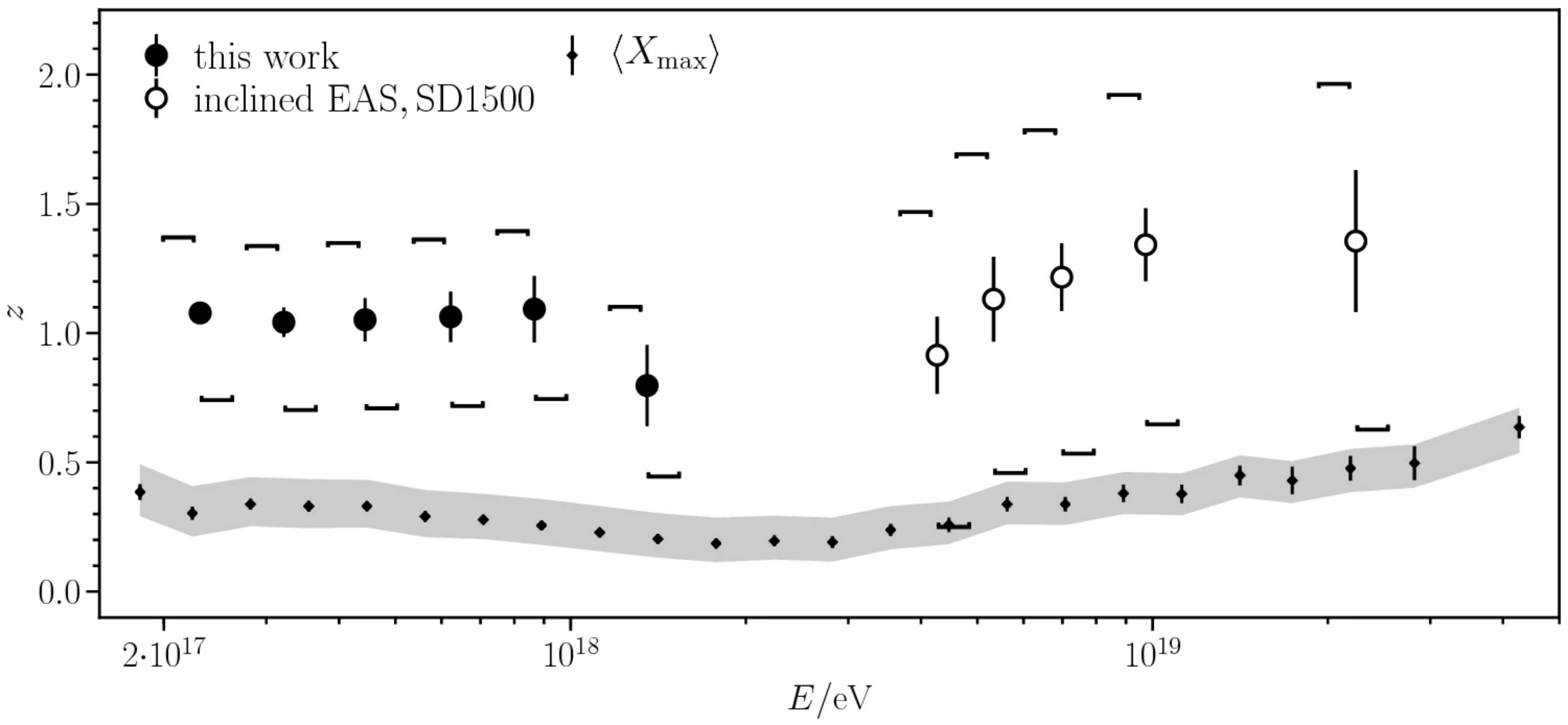
Muon Measurements in EAS

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

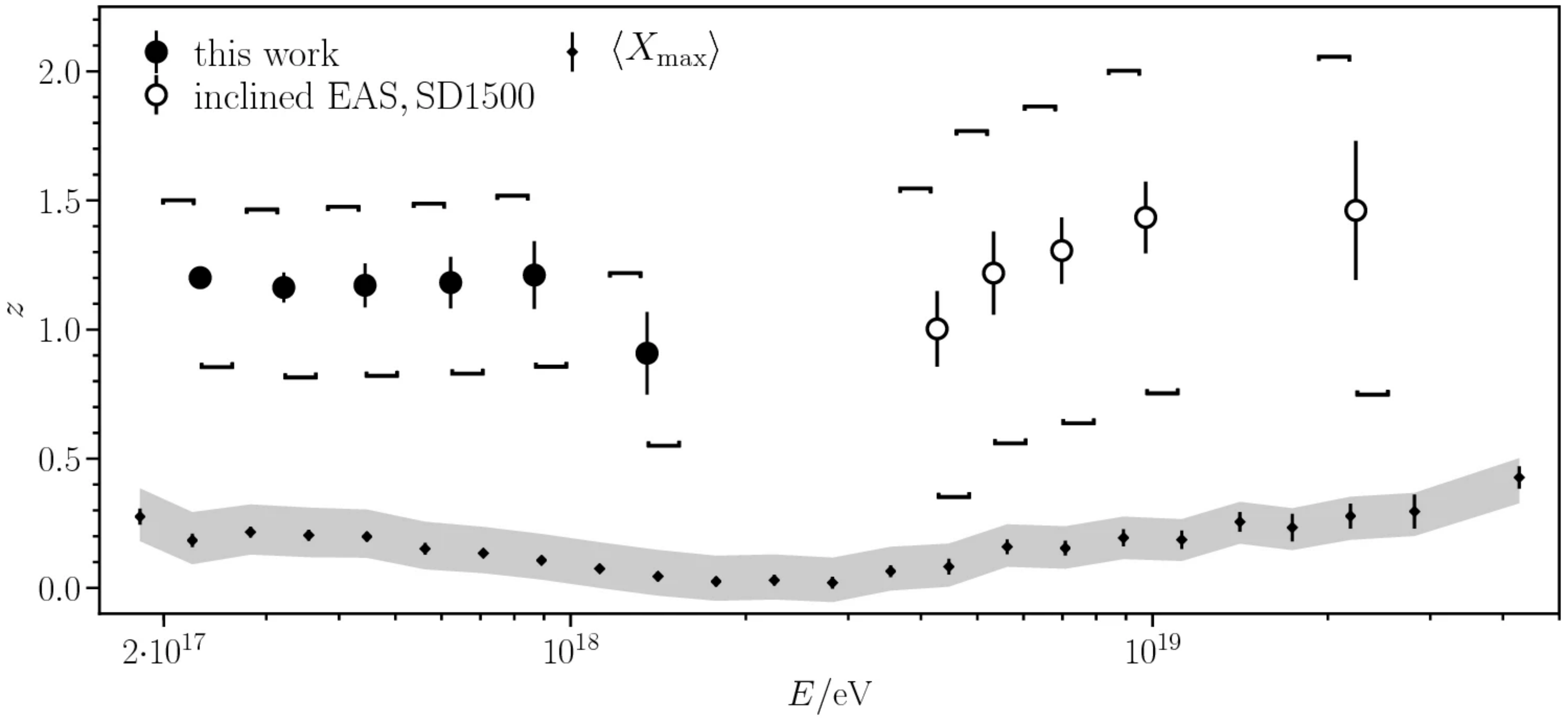
- Muons are messengers of the hadronic interactions in EAS
- Significant discrepancies in the number of muons in EAS observed between MC and data!
- Comparison to model predictions using z-values:

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

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



(a) EPOS-LHC



(b) QGSJetII-04

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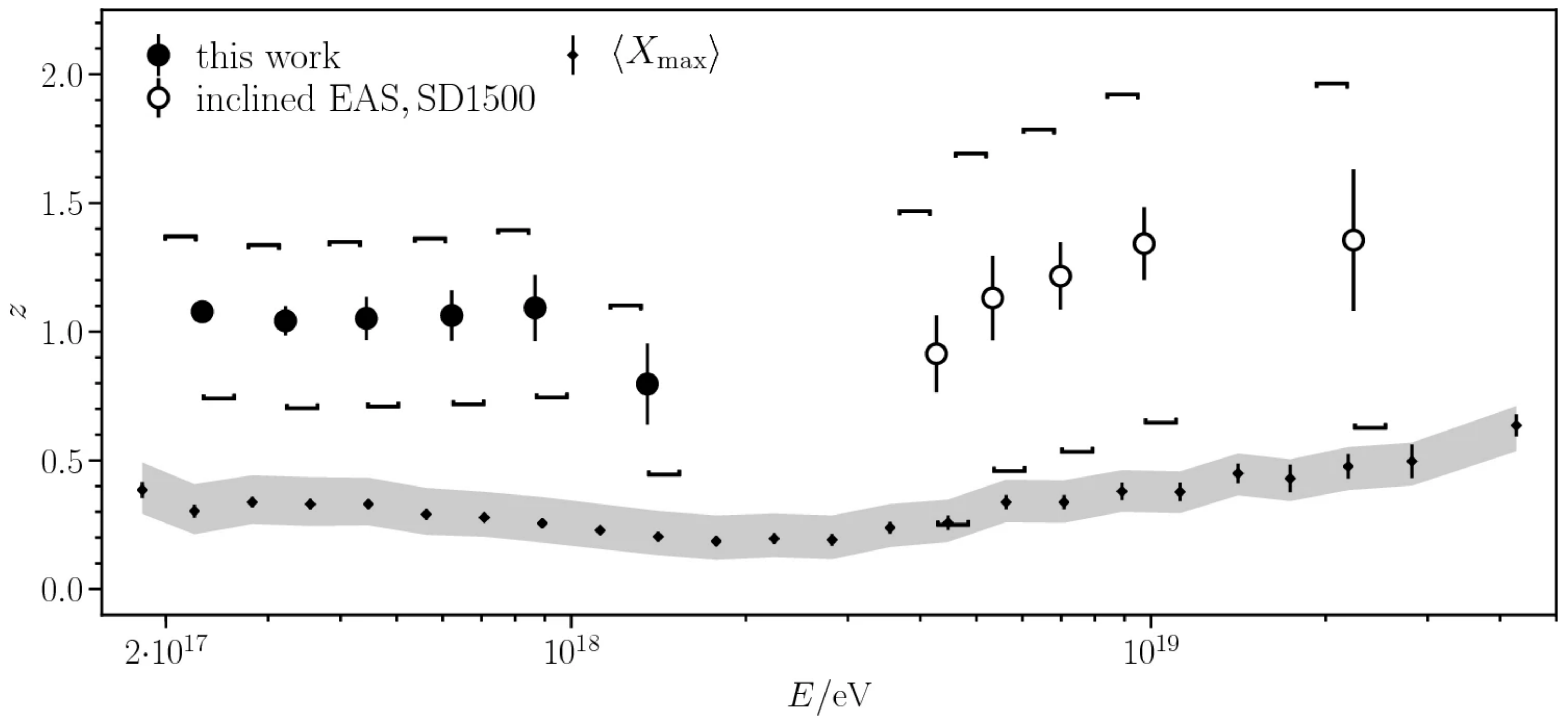

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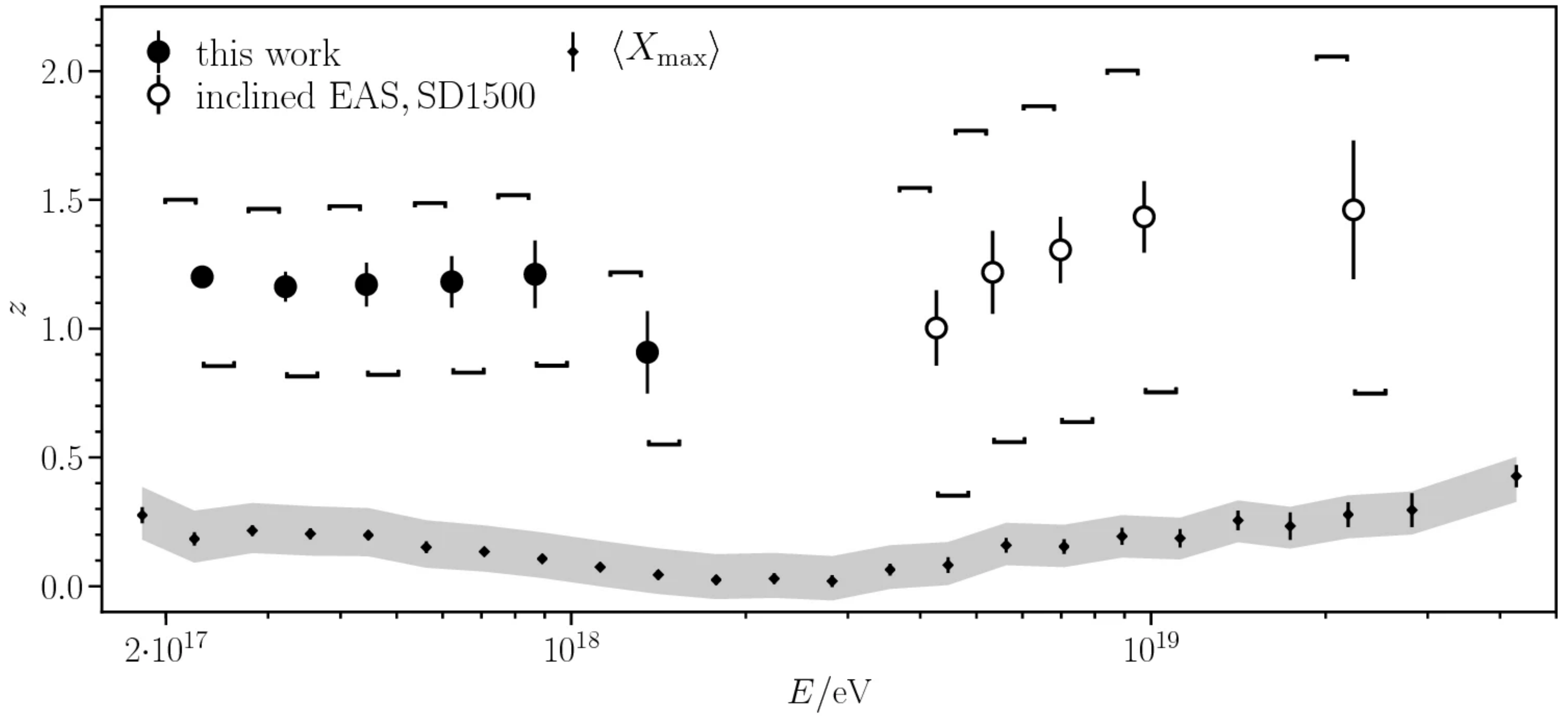

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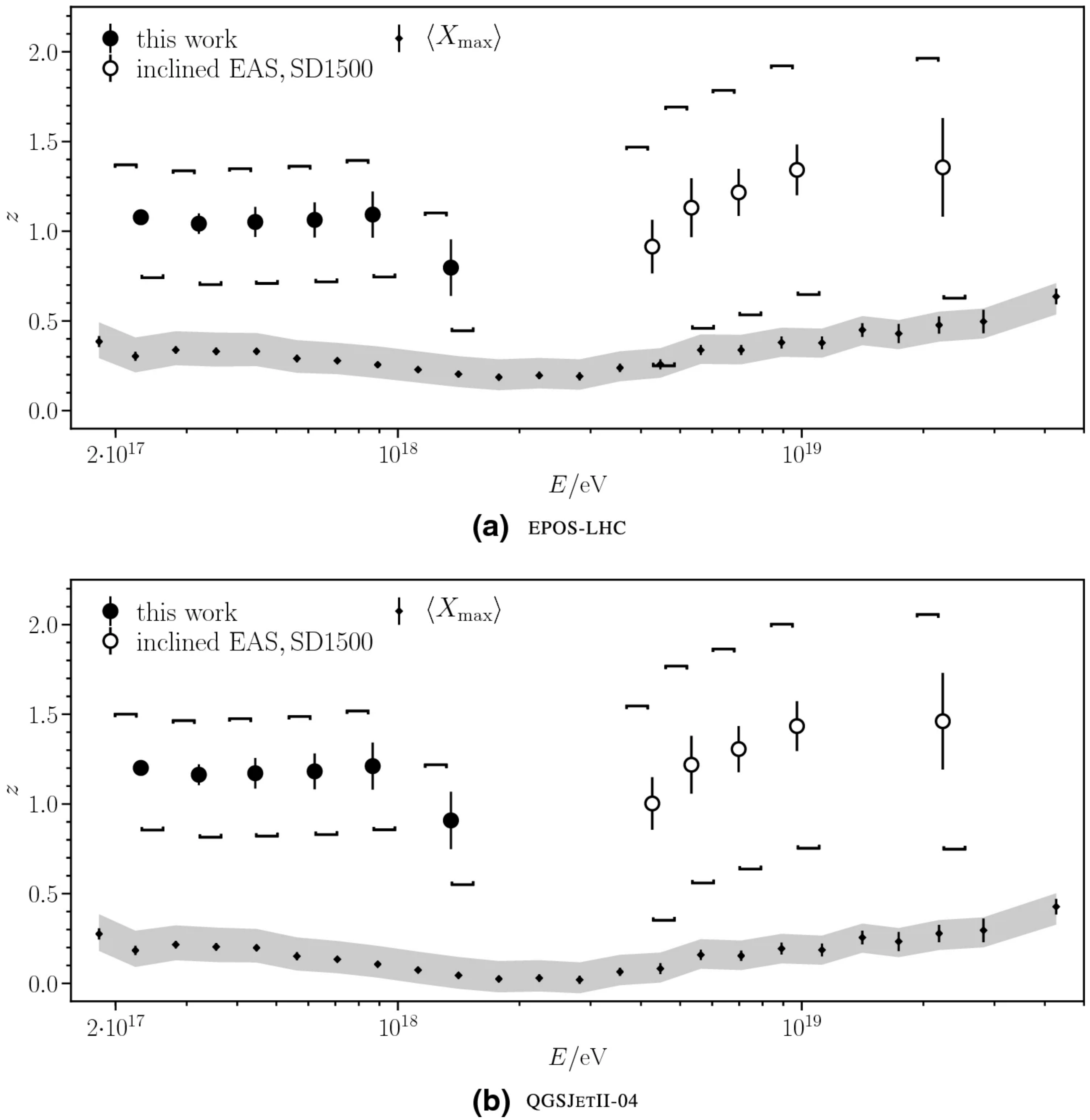
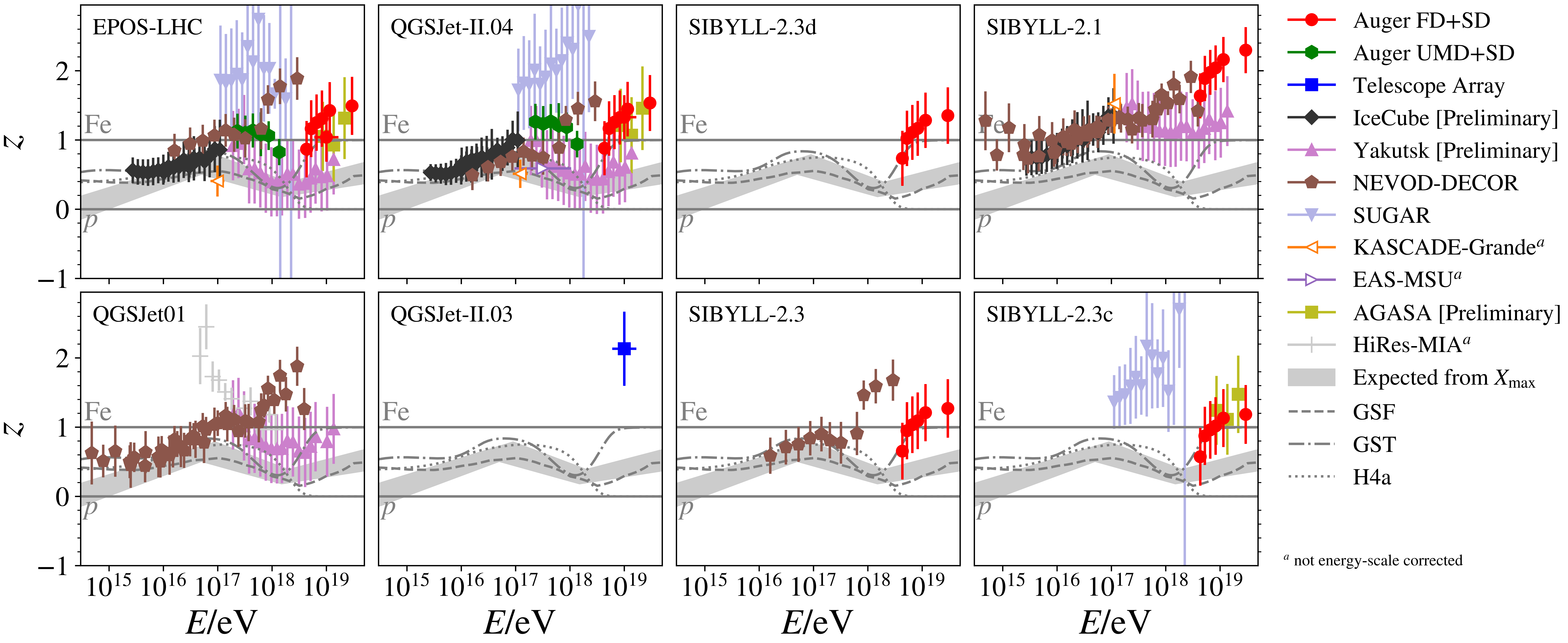


(a) EPOS-LHC

(b) QGSJETII-04

Global Muon Measurements

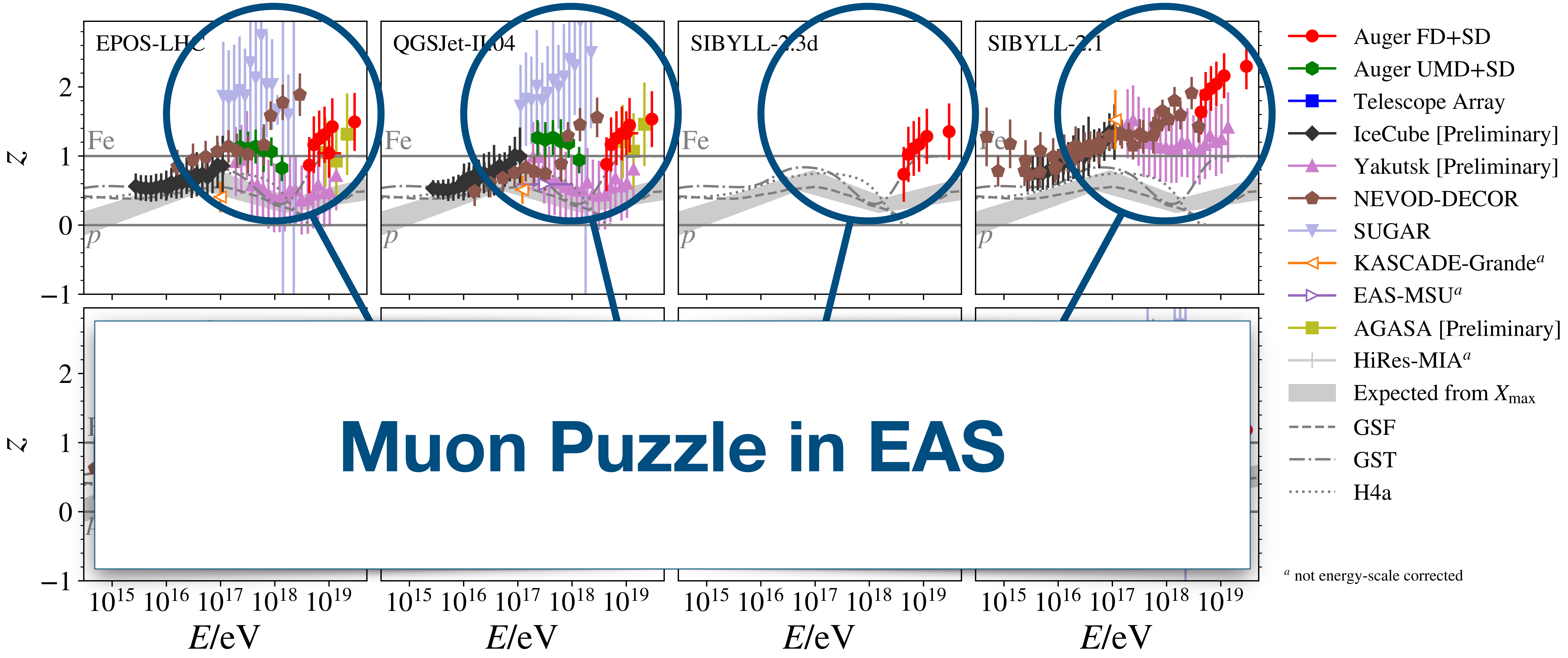
- Muon lateral density in EAS after cross-calibration of the energy-scales



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

Combined Muon Measurements

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



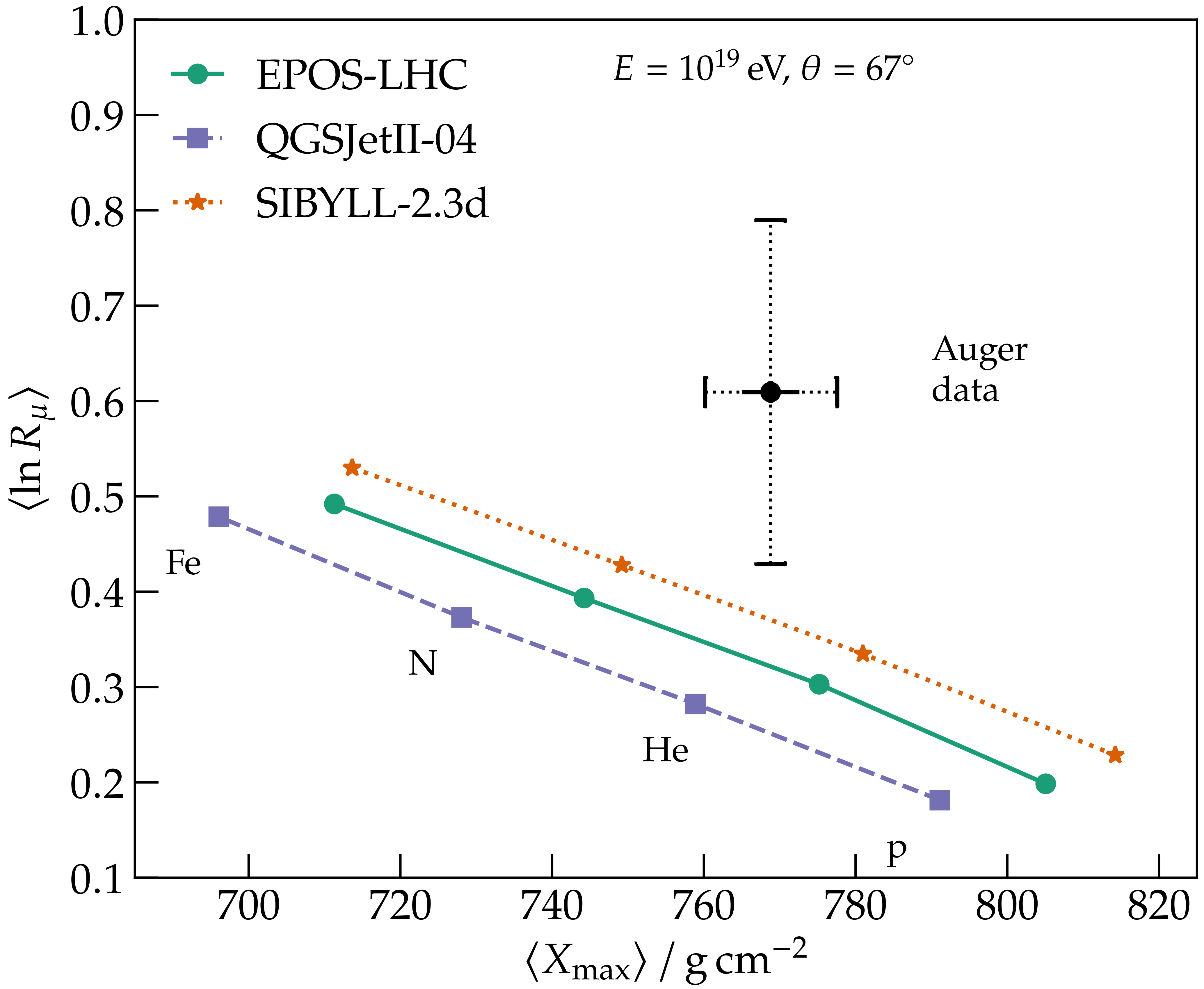
Muon Puzzle in EAS

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

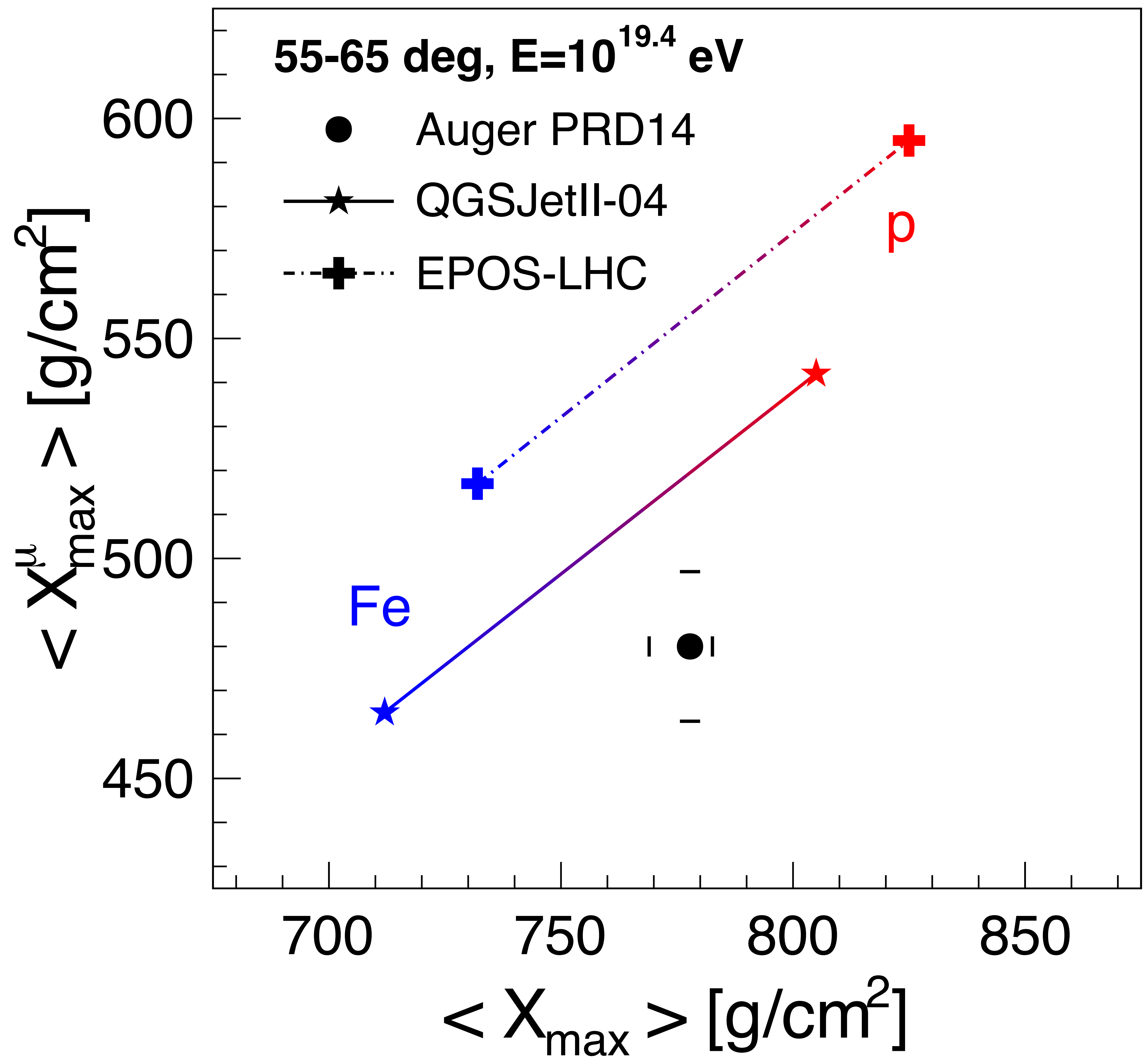
The Muon Puzzle

- Muon number (R_μ) and mean production depth as function of mean $X_{\max}$

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



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



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

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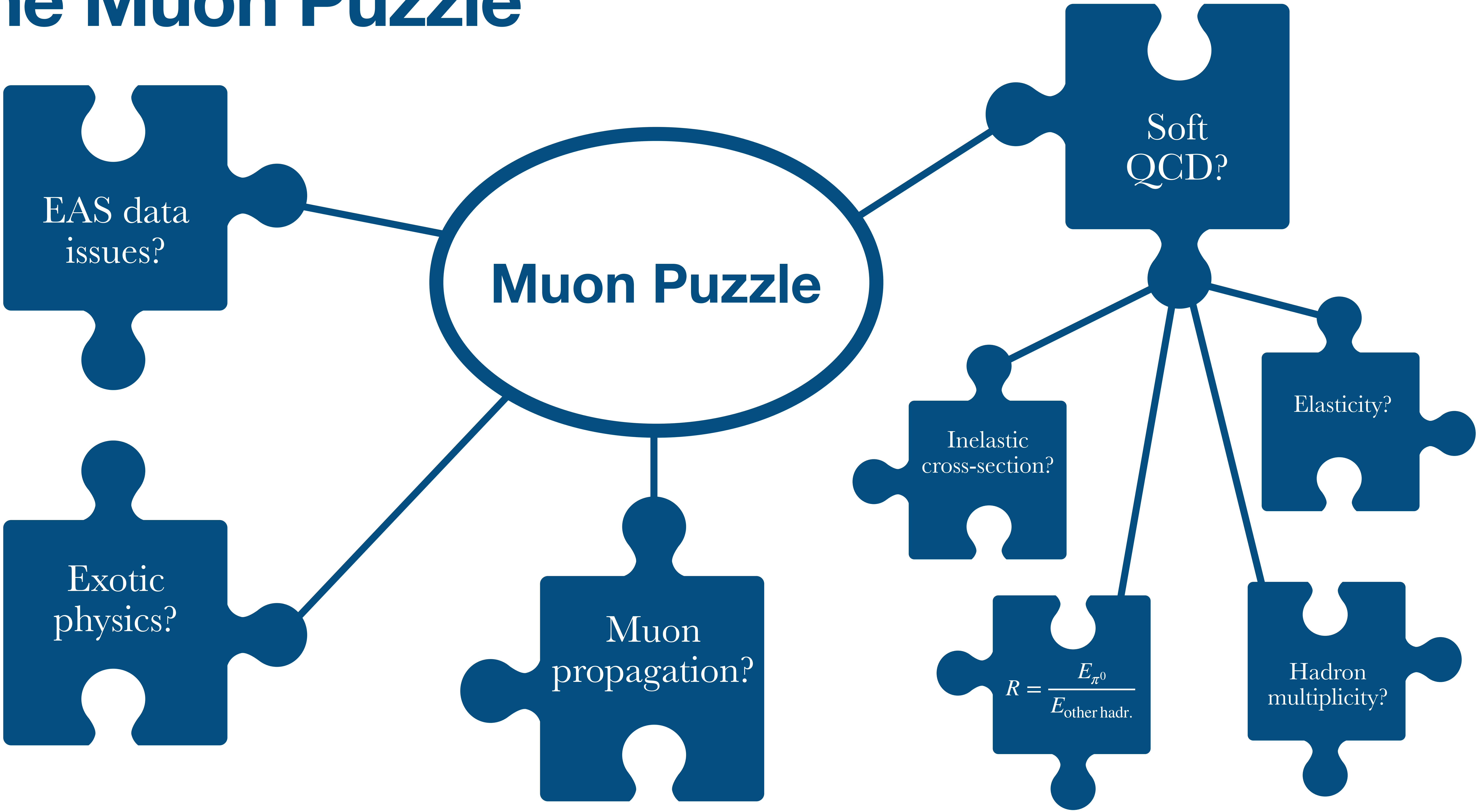

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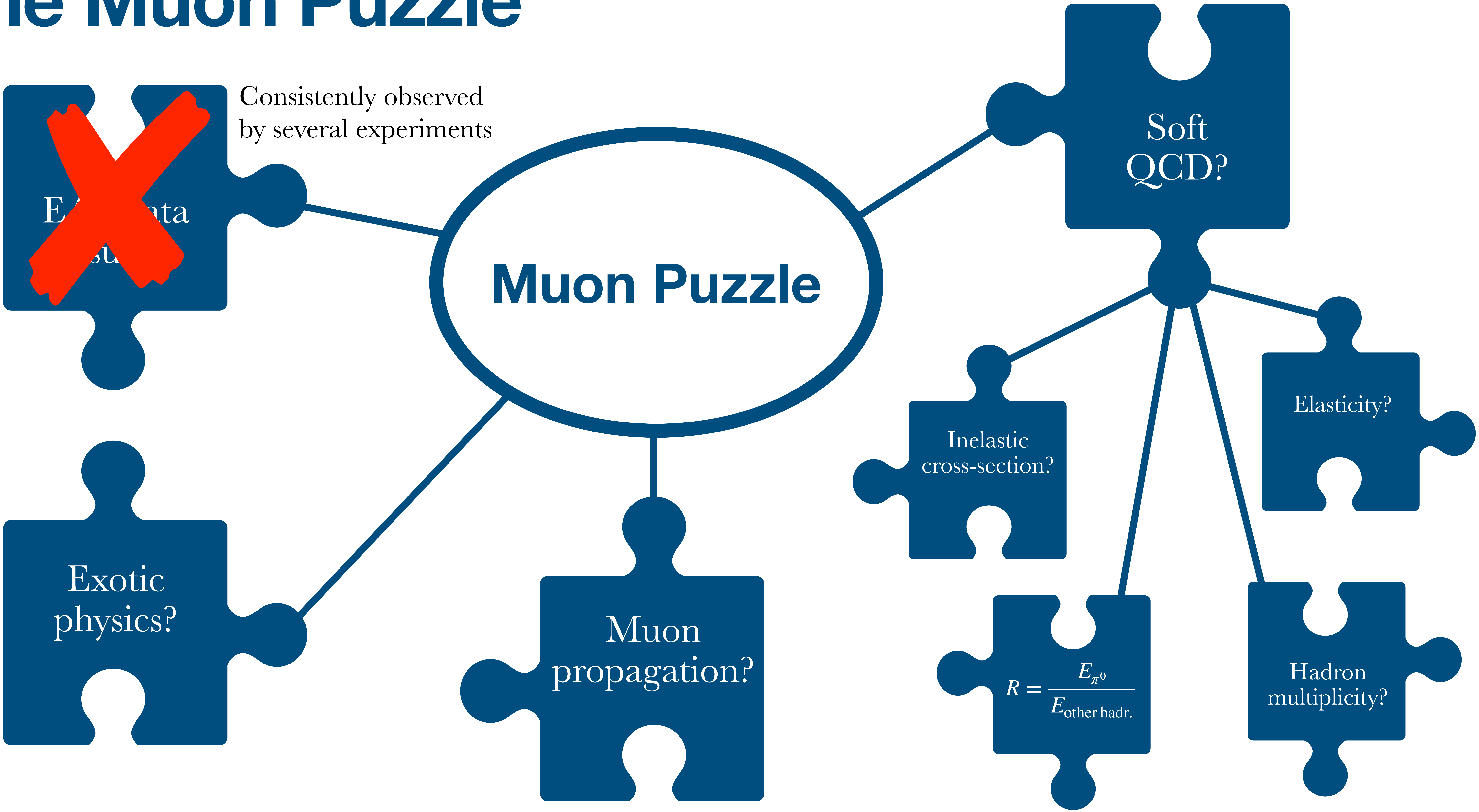

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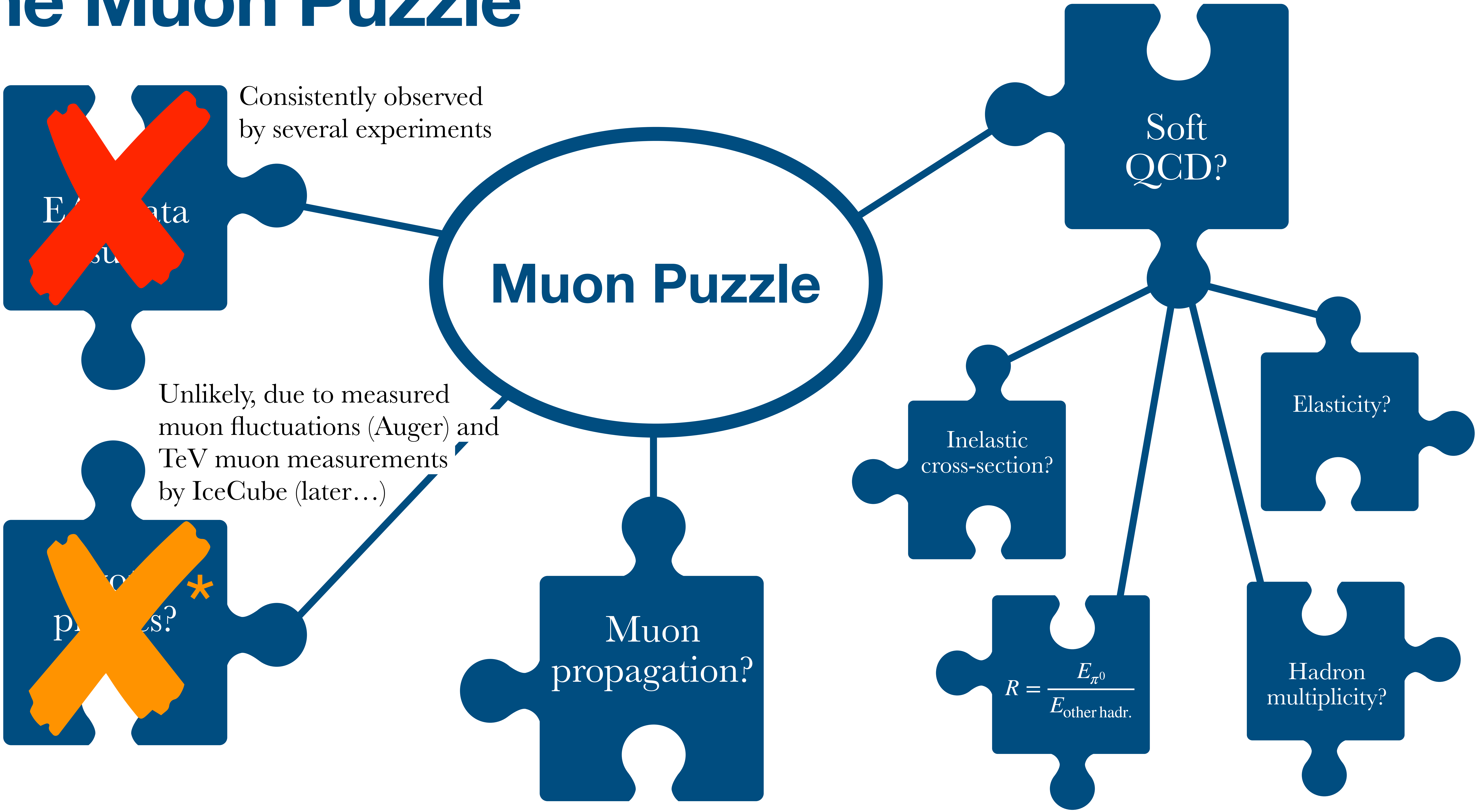

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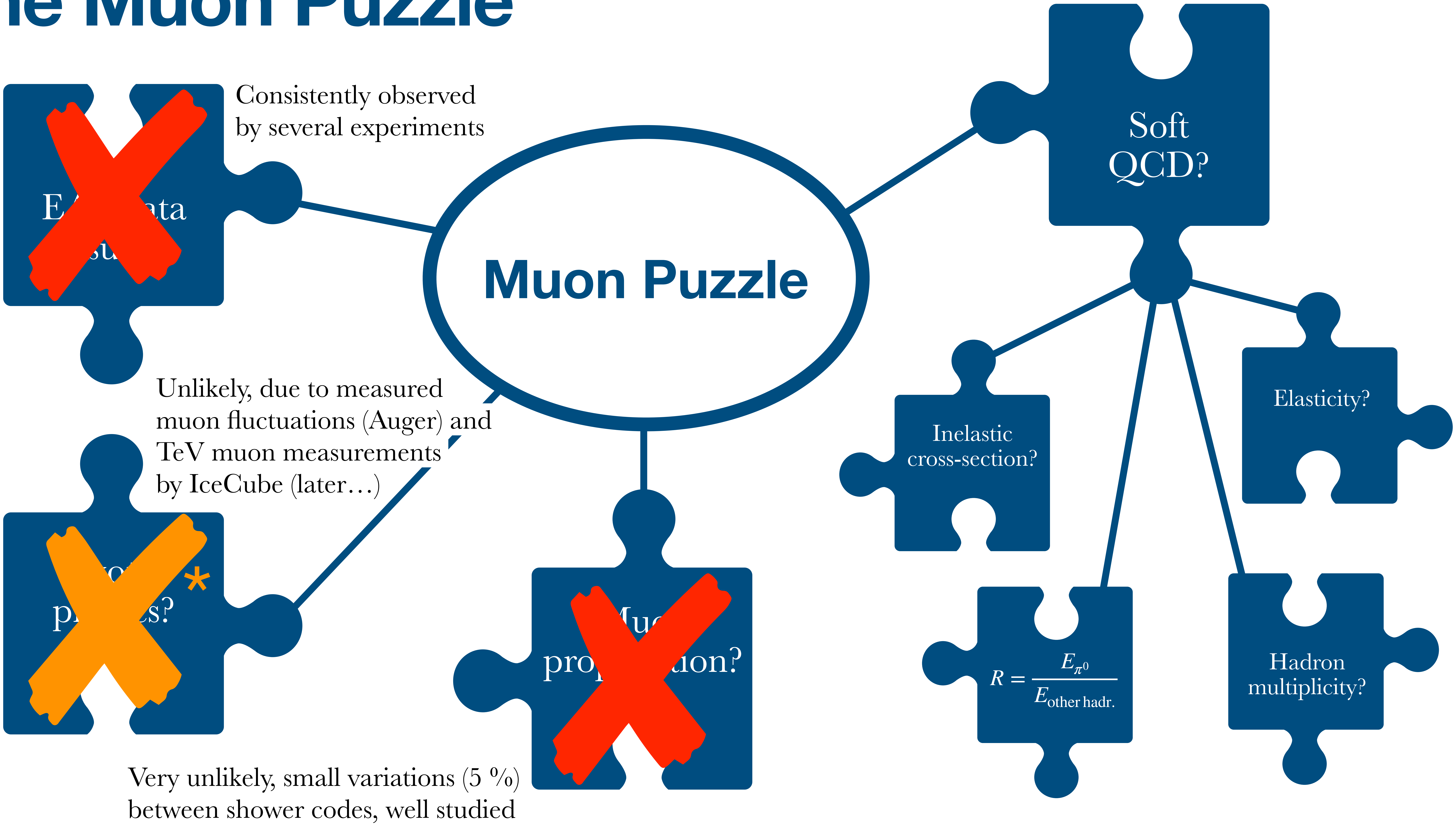
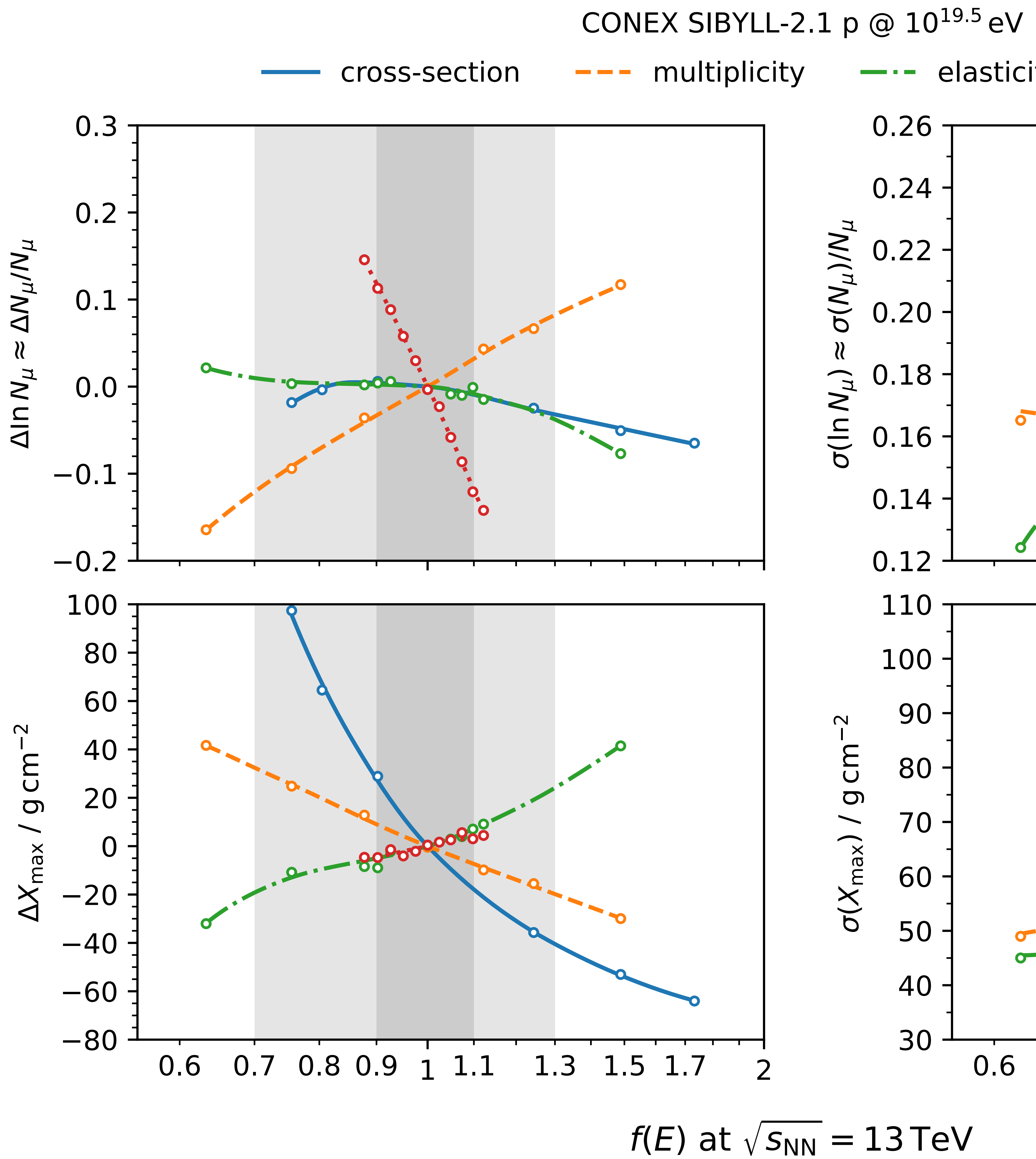
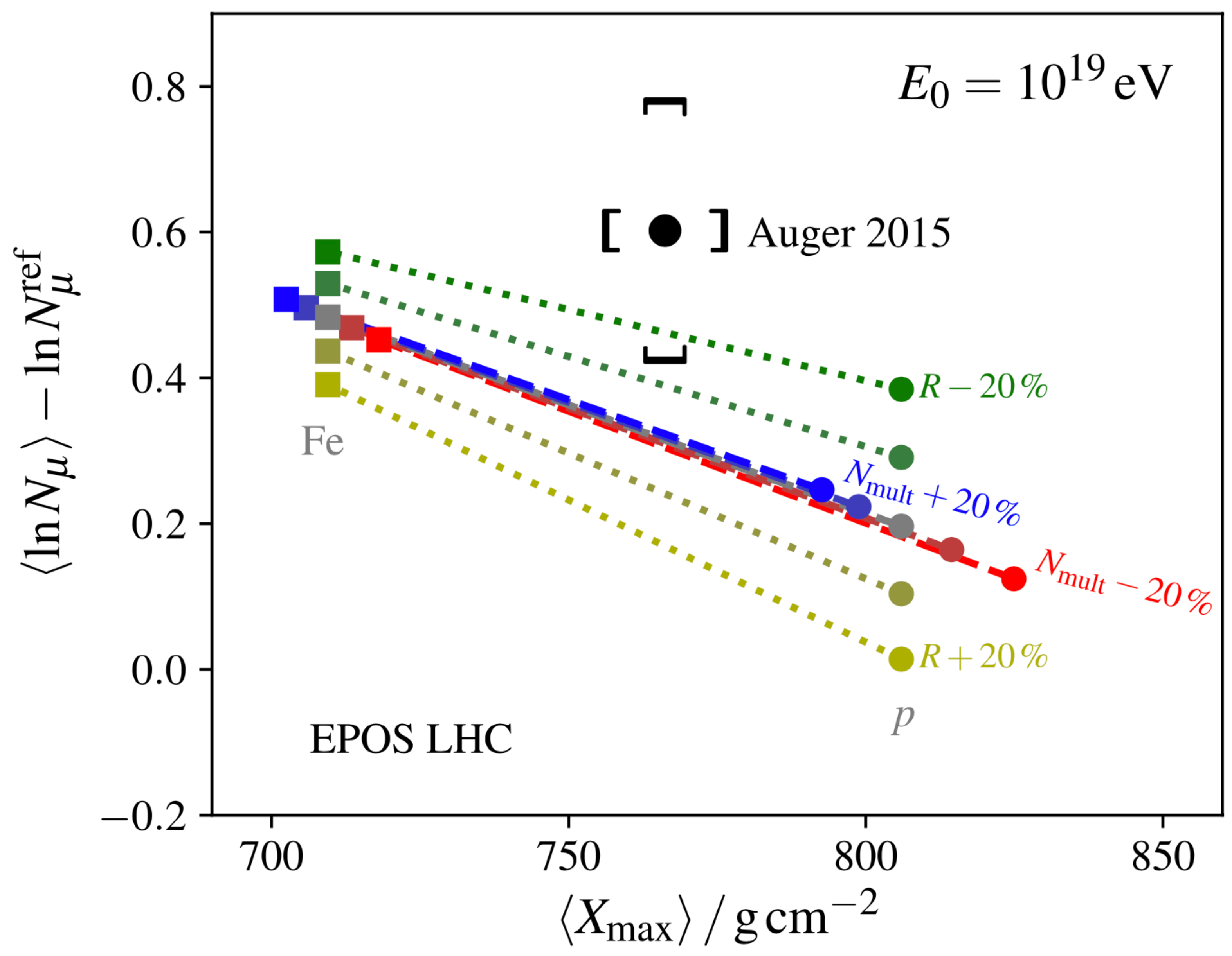


Study of Shower Impact Parameters



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



$\pm 10\,\%$ and $\pm 30\,\%$ modification

[R. Ulrich, R. Engel, M. Unger, PRD 83 (2011) 054026]
see also [J. Albrecht, ..., D. Soldin et al., Astrophys. Space Sci. 367 (2022)]

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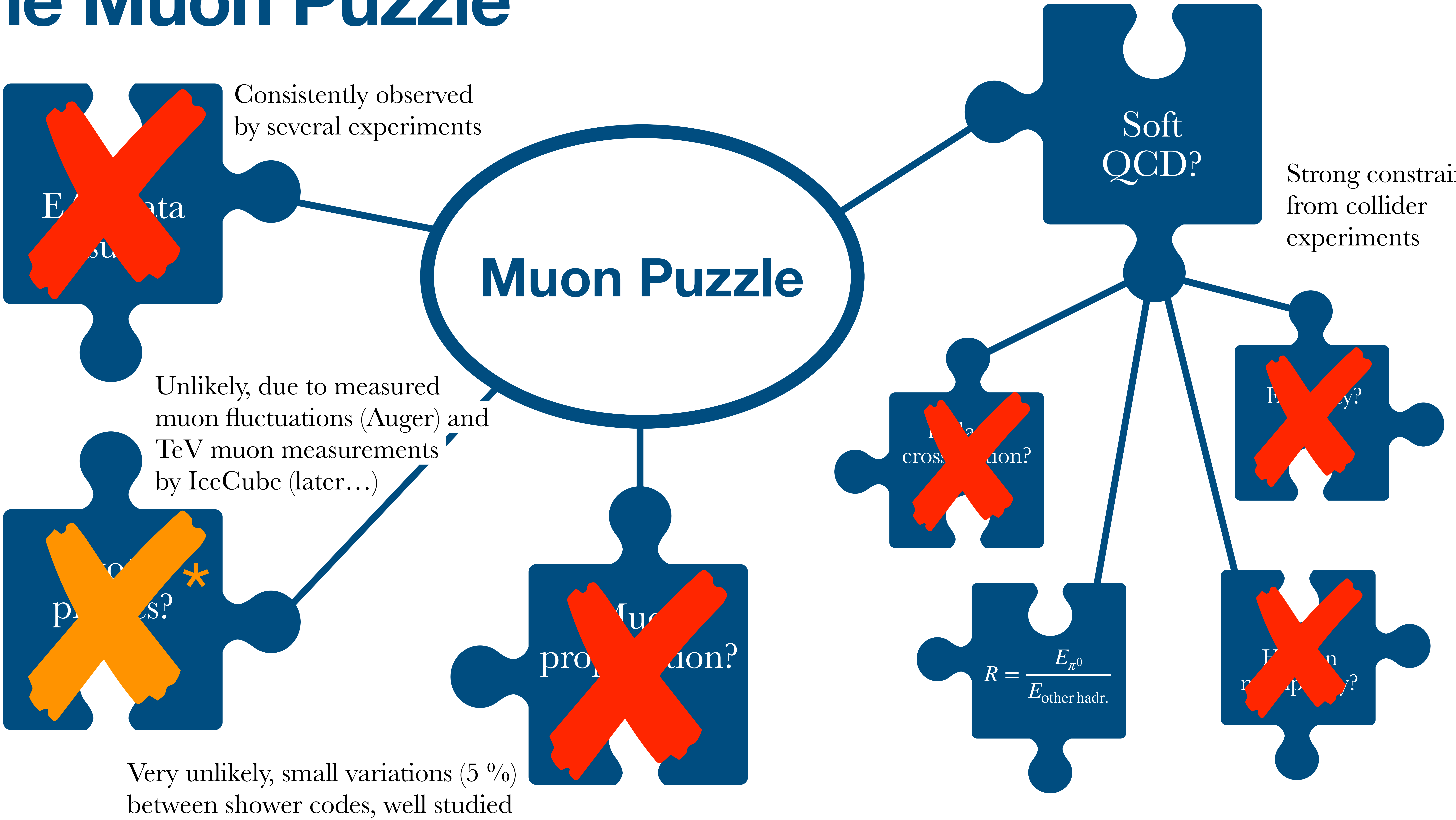
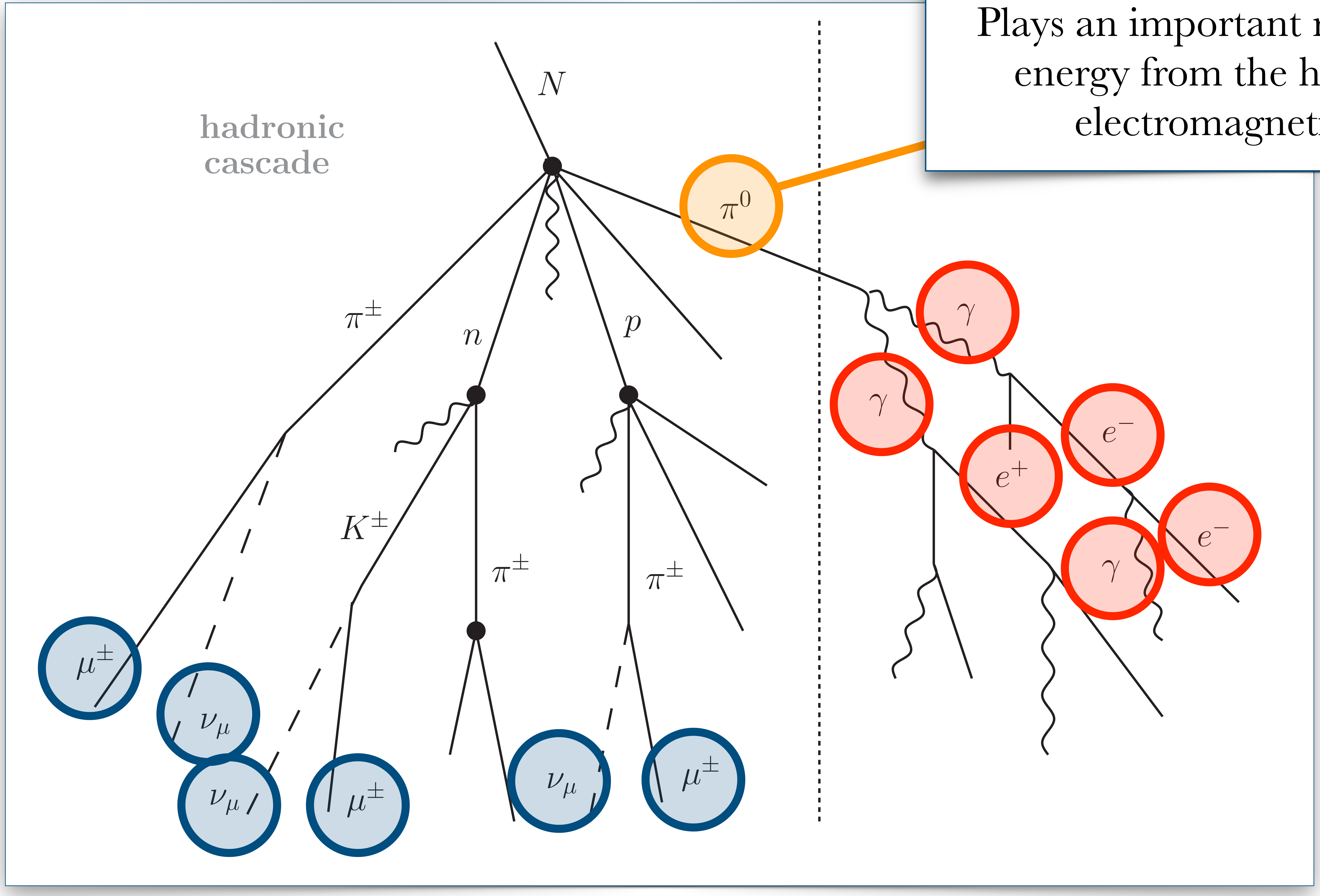


Extensive Air Showers



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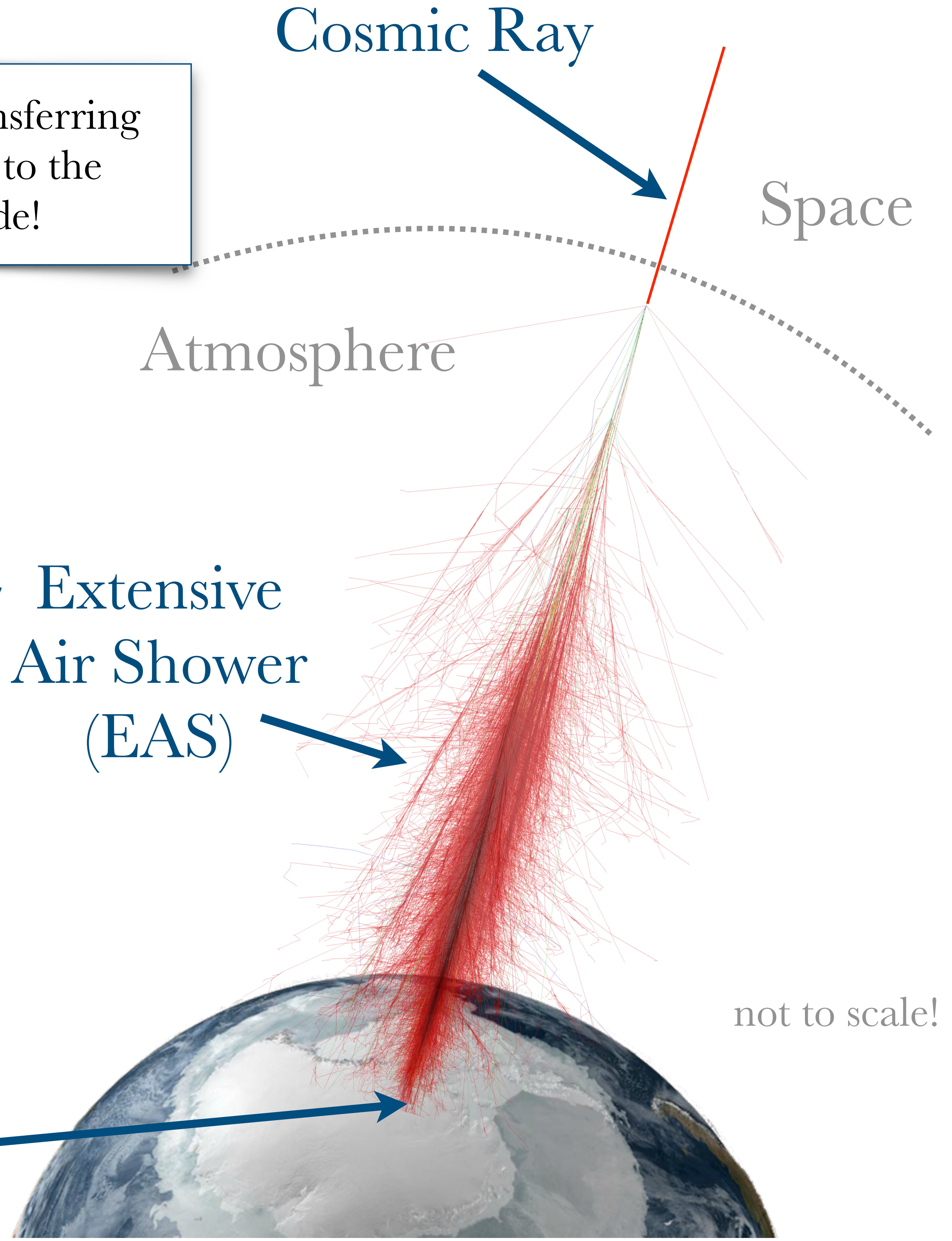
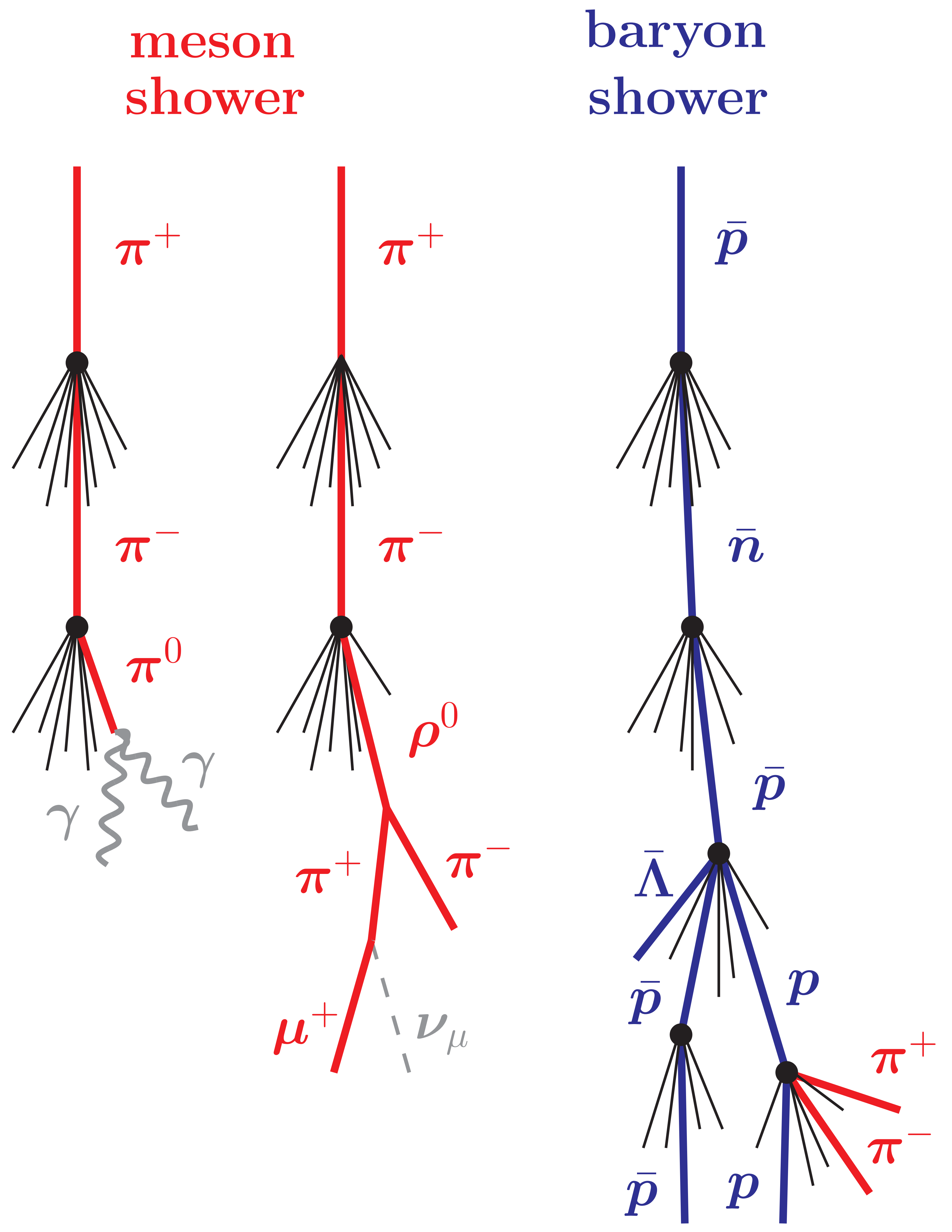


- Hadronic interactions are crucial for the EAS development

The Muon Puzzle

- Difficult to change R within standard QCD
- Possible explanations for the Muon Puzzle:
  - Neutral rho meson enhancement, e.g. [1]
    - Decay of ρ_0 via charged pions into muons
    - Muon production at all energies
  - Baryon enhancement, e.g. [2]
    - Many re-interactions, low-energy particles
    - Mainly low-energy muons
  - Stangeness enhancement, e.g. [3]
    - Evidence from ALICE at LHC
- Different predicted muon spectra!



[1]: See e.g. [F. Riehn, R. Engel, A. Fedynitch, T. K. Gaisser, T. Stanev, Phys. Rev. D 102 (2020)]
[2]: See e.g. [T. Pierog, K. Werner, Phys. Rev. Lett., 101 (2008)]
[3]: See e.g. [ALICE Collaboration, Nature Phys. 13 (2017) 535, L. Anchordoqui et al., JHEAp 34 (2022)]

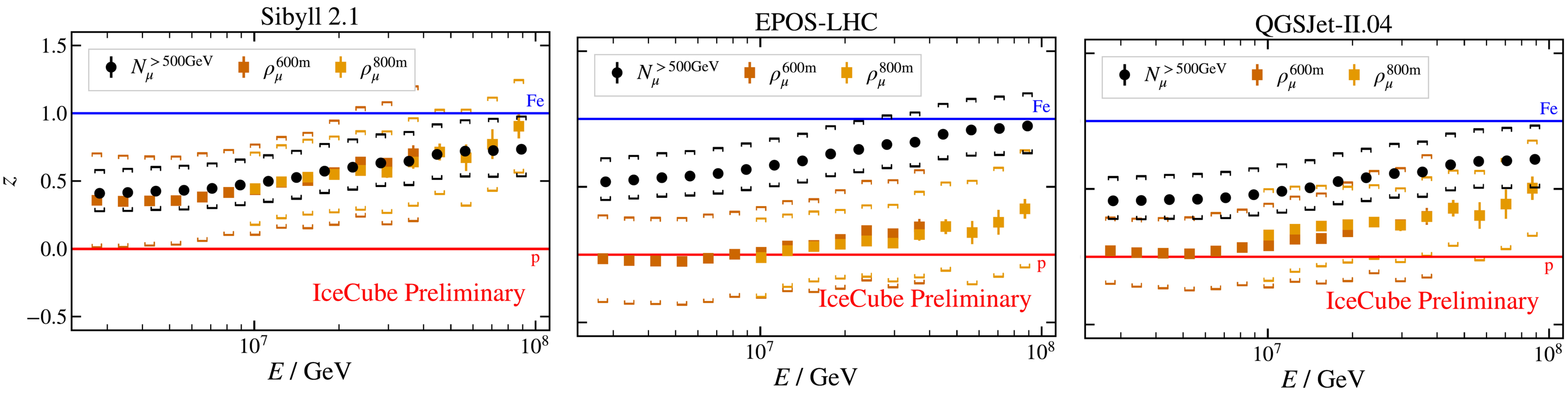
IceCube

- IceCube measures
  - GeV muons at the surface
  - TeV muons in the deep ice

→ Inconsistencies between GeV and TeV muons!

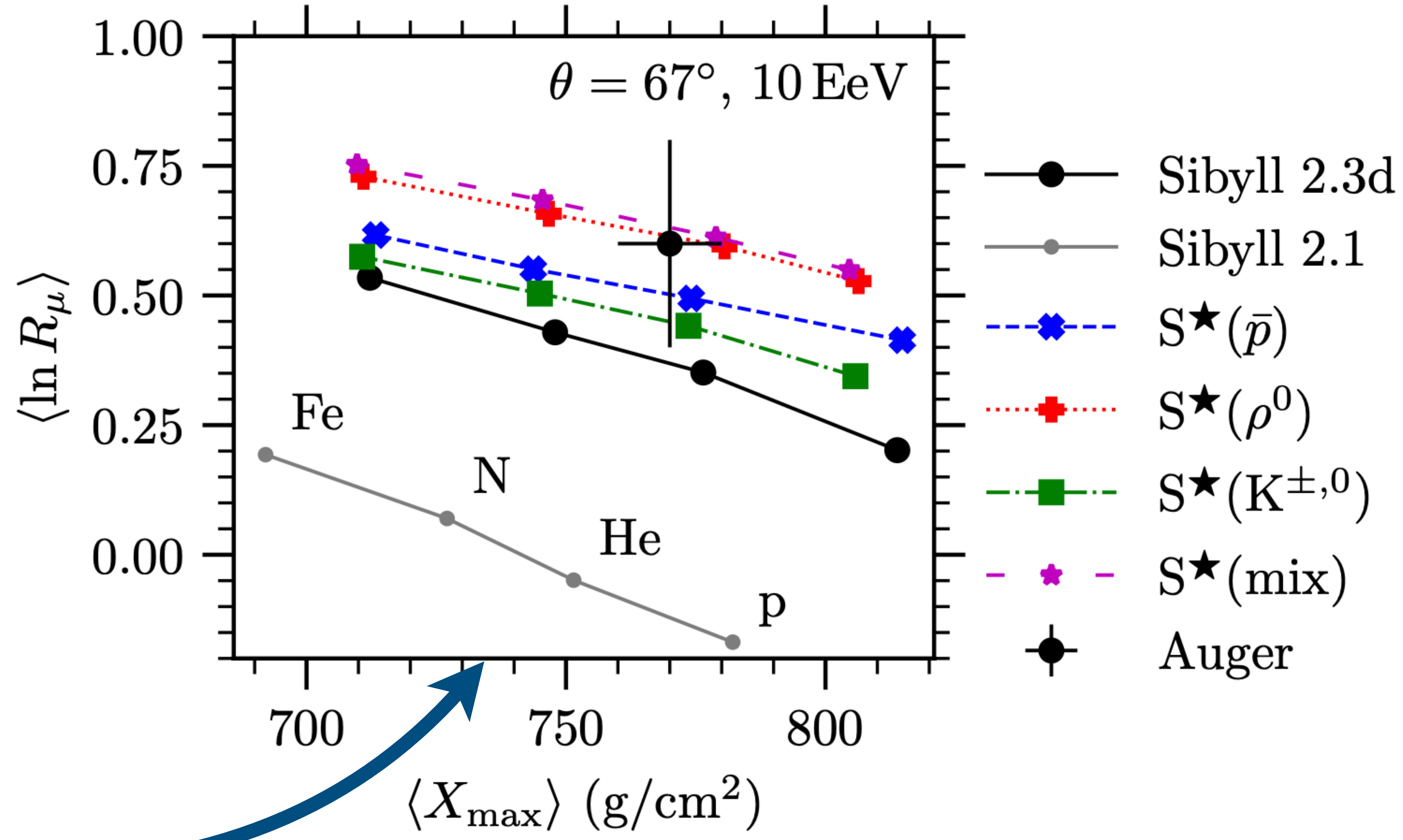
- Challenges ρ_0 enhancement, also indication from fluctuations of muons in Auger
- Sibyll 2.1 (oldest model) seems to describe data best…

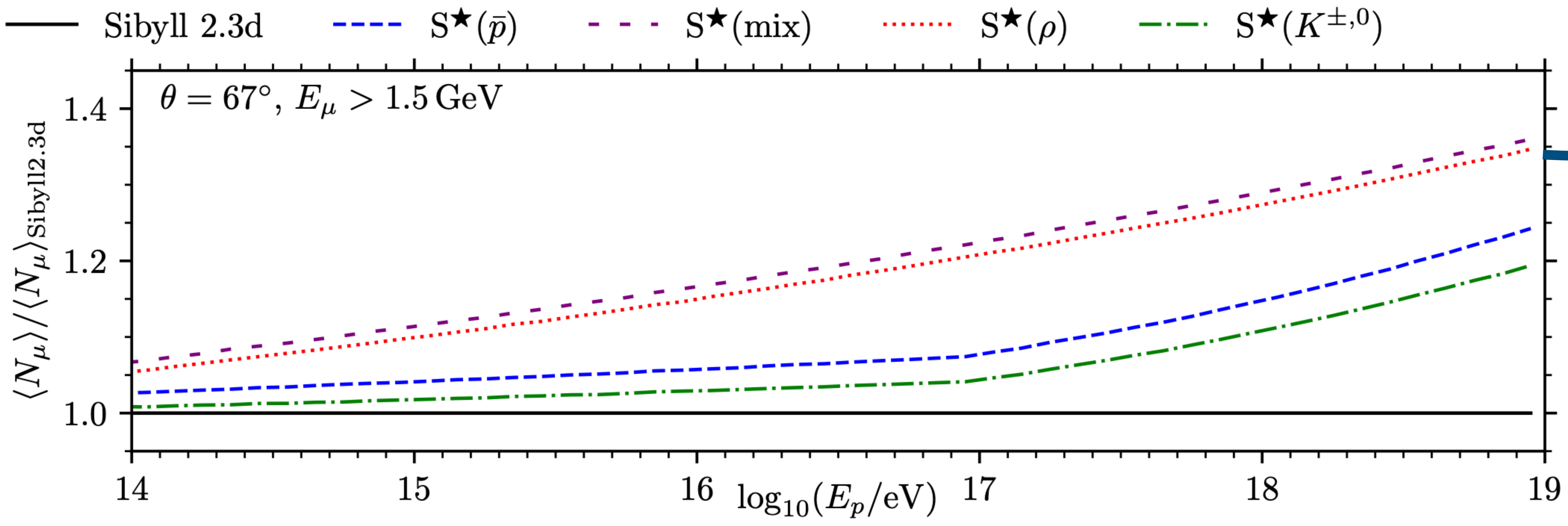
[S. Verpoest (IceCube Collaboration), PoS(ICRC2023)207 (2023)]



Sibyll *

- Series of phenomenologically modified versions of Sibyll 2.3d
- Ad-hoc event modifications:
  - ρ_0 enhancement
  - Baryon-antibaryon enhancement
  - Kaon (strangeness) enhancement



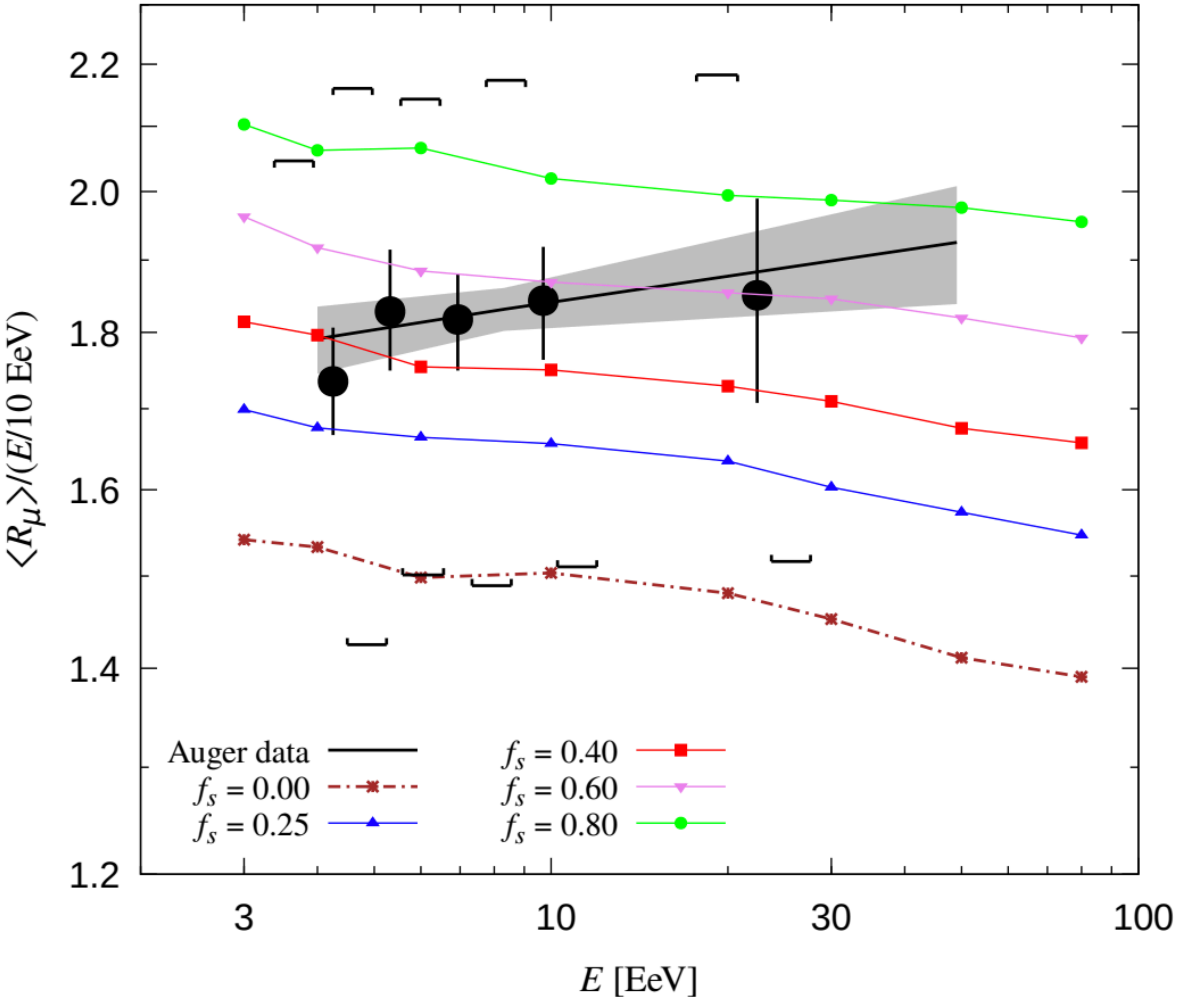


[F. Riehn, A. Fedynitch, R. Engel, Astropart. Phys. 160 (2024)]

Strangeness Enhancement

- Indications for strangeness enhancement in the mid rapidity region reported by ALICE
  [J. Adam et al. (ALICE), Nature Phys. 13, 535 (2017)]
- Can this effect also be seen in hadrons produced at forward rapidities?
- Simple toy model:
  [L. Anchordoqui et al., JHEAp 34 (2022)]
  - Strangeness enhancement realized by $\pi \leftrightarrow K$ swapping
  - Swapping fraction f_s
- Possible explanation for the Muon Puzzle in EAS!
- <u>Strong tension with latest FASER results!</u>
- See also plenary talk tomorrow…

[L. Anchordoqui et al., JHEAp 34 (2022)]



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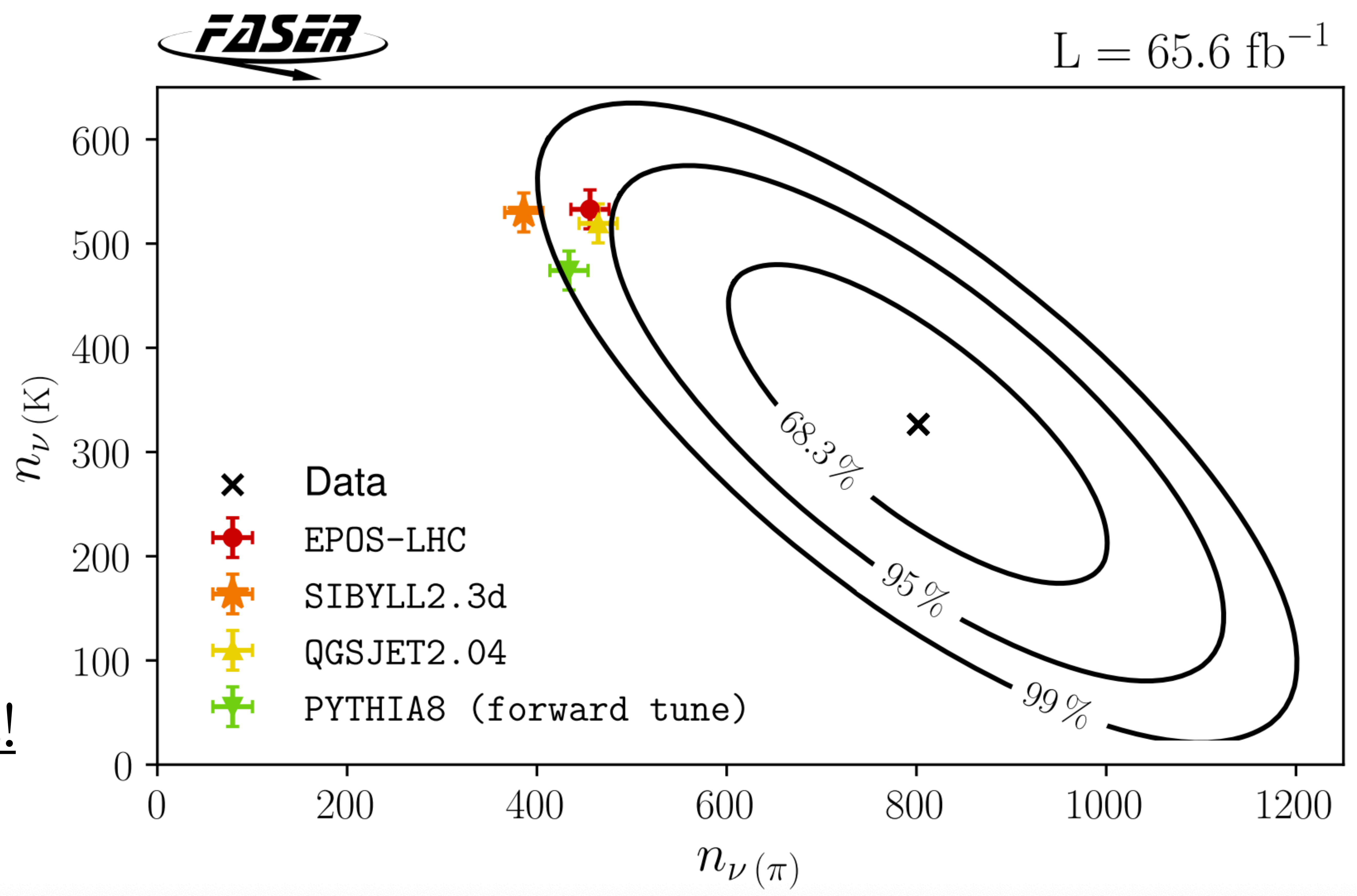
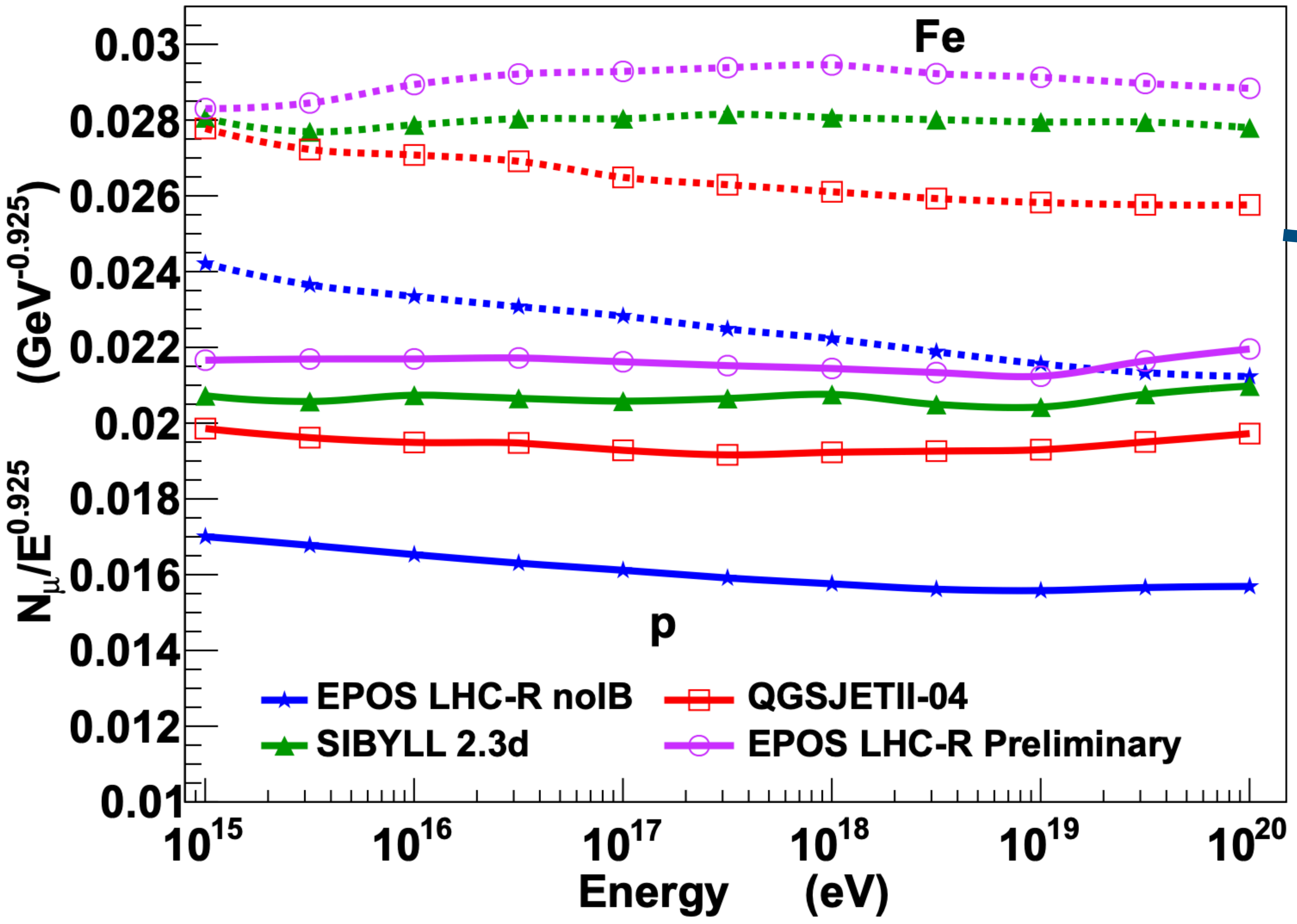
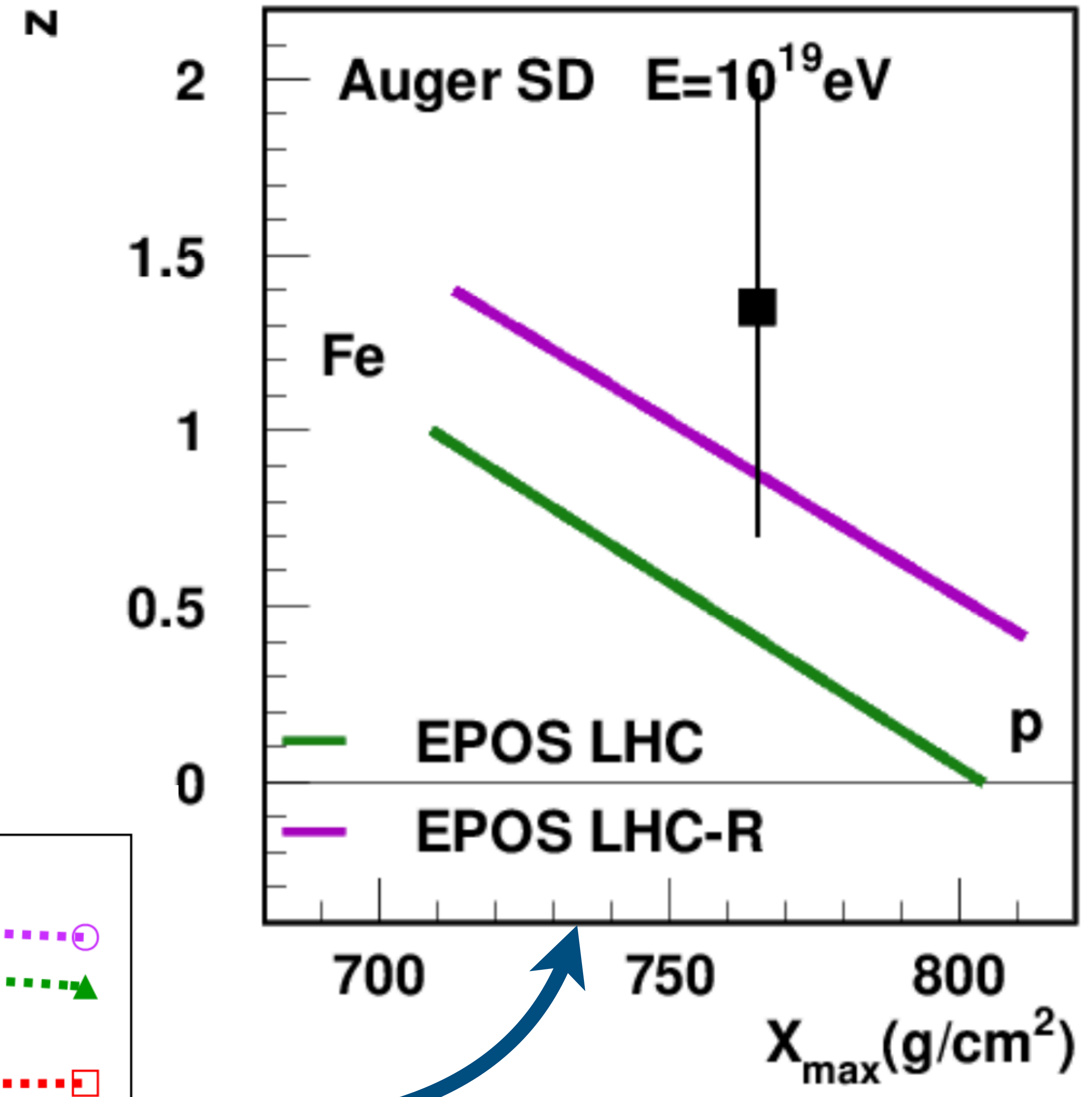
[R. M. Abraham et al. (FASER Collaboration), Phys. Lett. 134 (2025)]



EPOS-LHC-R

- Update of EPOS-LHC model
  - Enhancement of ρ_0 through modified collective hadronization
    - Core-corona effect
  - Best description of LHC / NA61 data
  - Also, change of X_{max} through 10% change in inelastic cross-section
  - Tests with EAS data required!!

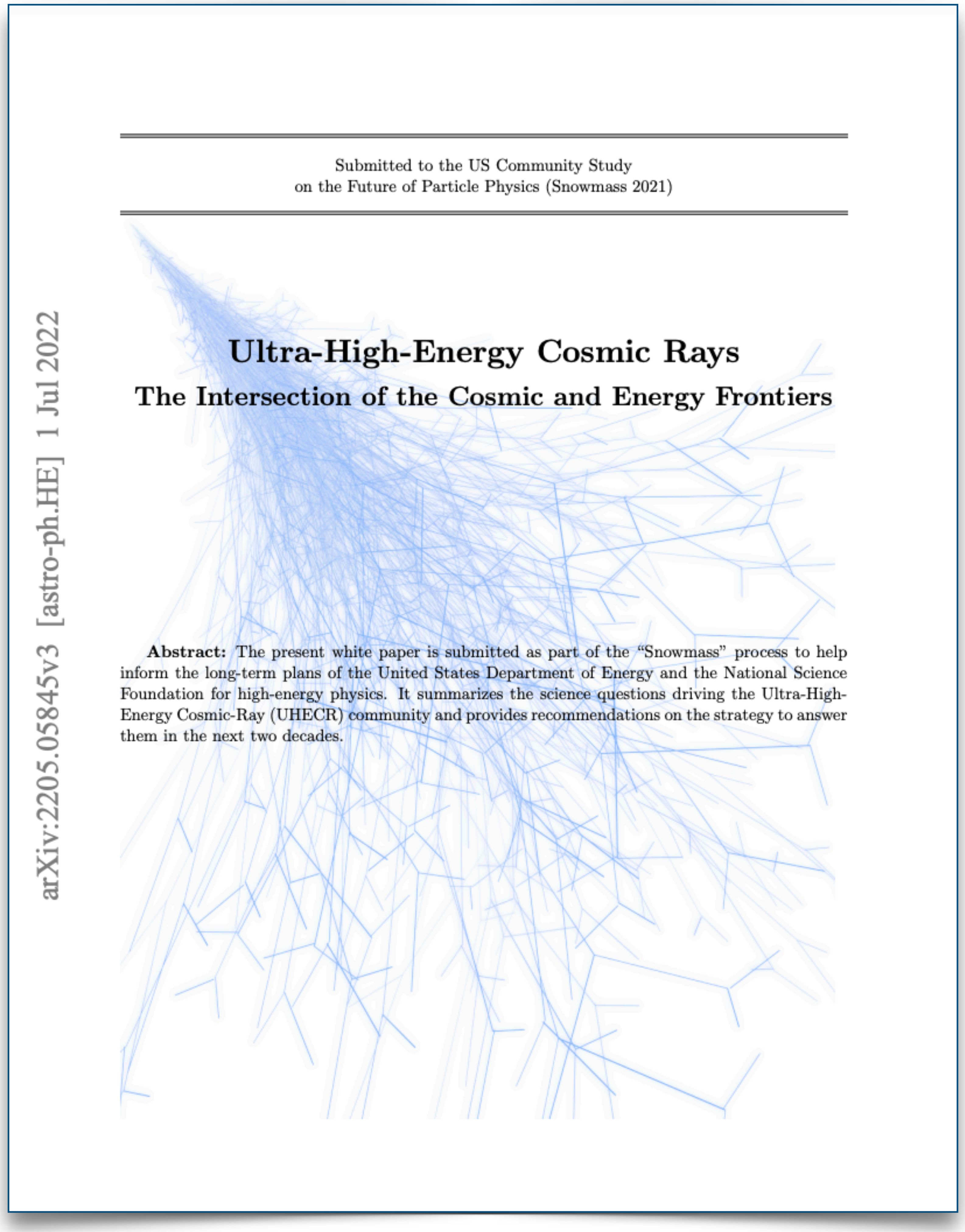




[T. Pierog, K. Werner, PoS(ICRC2013)230 (2023)]

Outlook into the Next Decade

- Large variety of new 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}, $X_{\mu,\mathrm{max}}$, zenith angle evolution, spectral information
  - 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!
- See also talk by E. Mayotte today,


Submitted to the US Community Study
on the Future of Particle Physics (Snowmass 2021)

arXiv:2205.05845v3 [astro-ph.HE] 1 Jul 2022

Ultra-High-Energy Cosmic Rays
The Intersection of the Cosmic and Energy Frontiers

Abstract: The present white paper is submitted as part of the "Snowmass" process to help 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.

[A. Coleman, ..., D. Soldin et al., Astropart. Phys. 149 (2023)]

Outlook beyond the Next Decade

- Precise measurements in the forward region at the High-Luminosity LHC will further constrain hadronic interaction 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, …
- Exciting times ahead!

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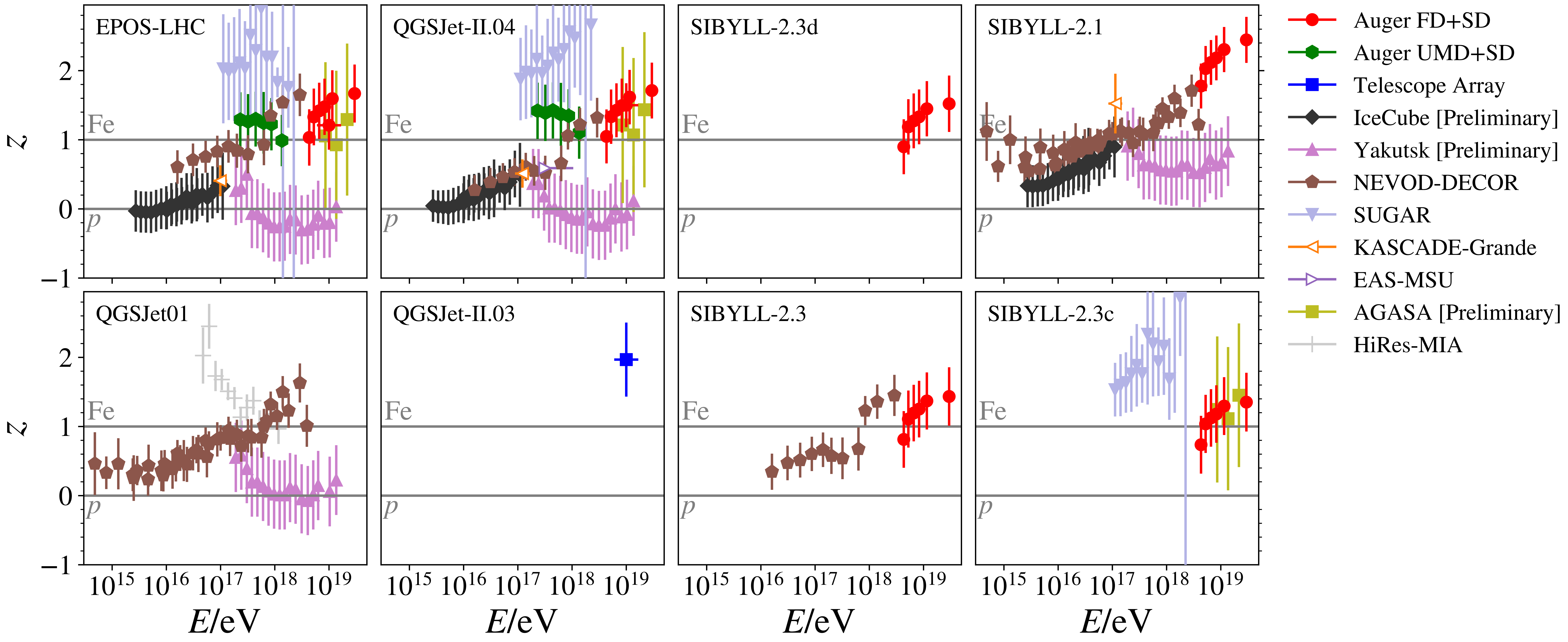
Thank you!

Backup

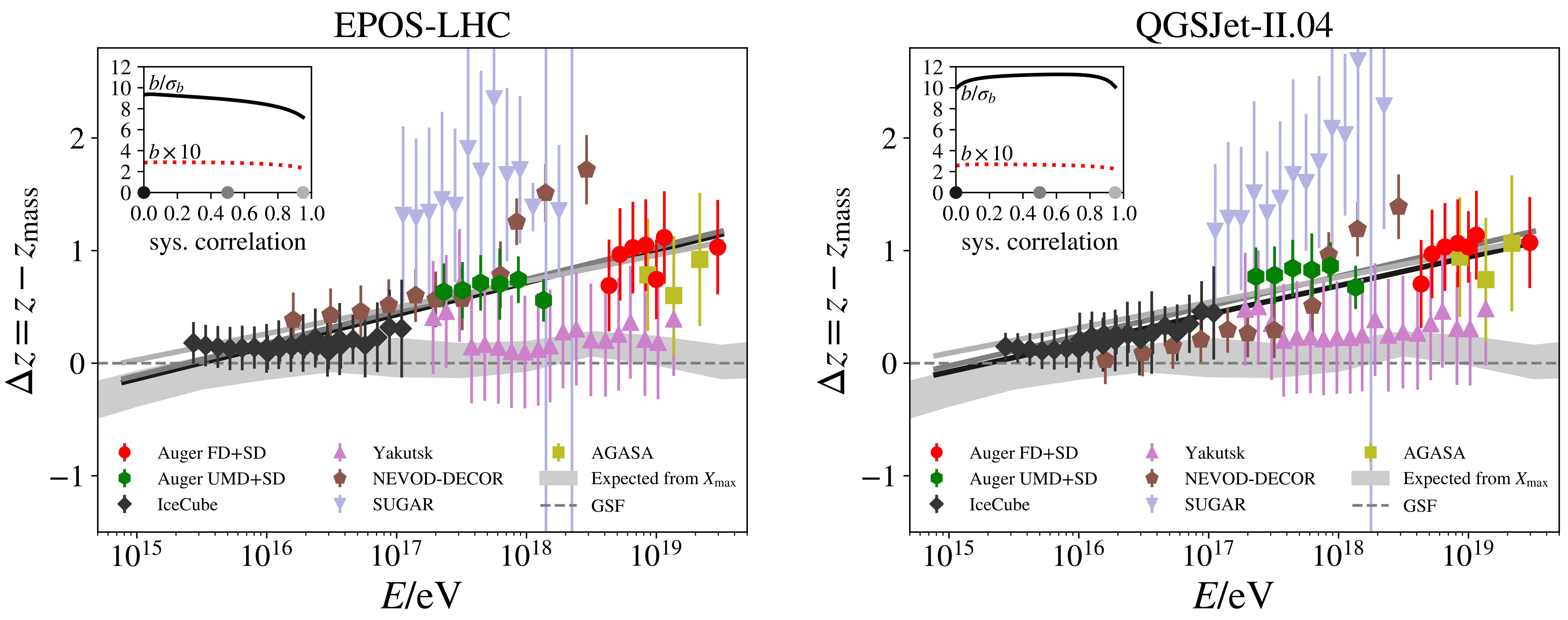
Global Muon Measurements

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



The Muon Puzzle

- Subtracting expected values z_{mass} obtained from GSF flux model (consistent with X_{max})



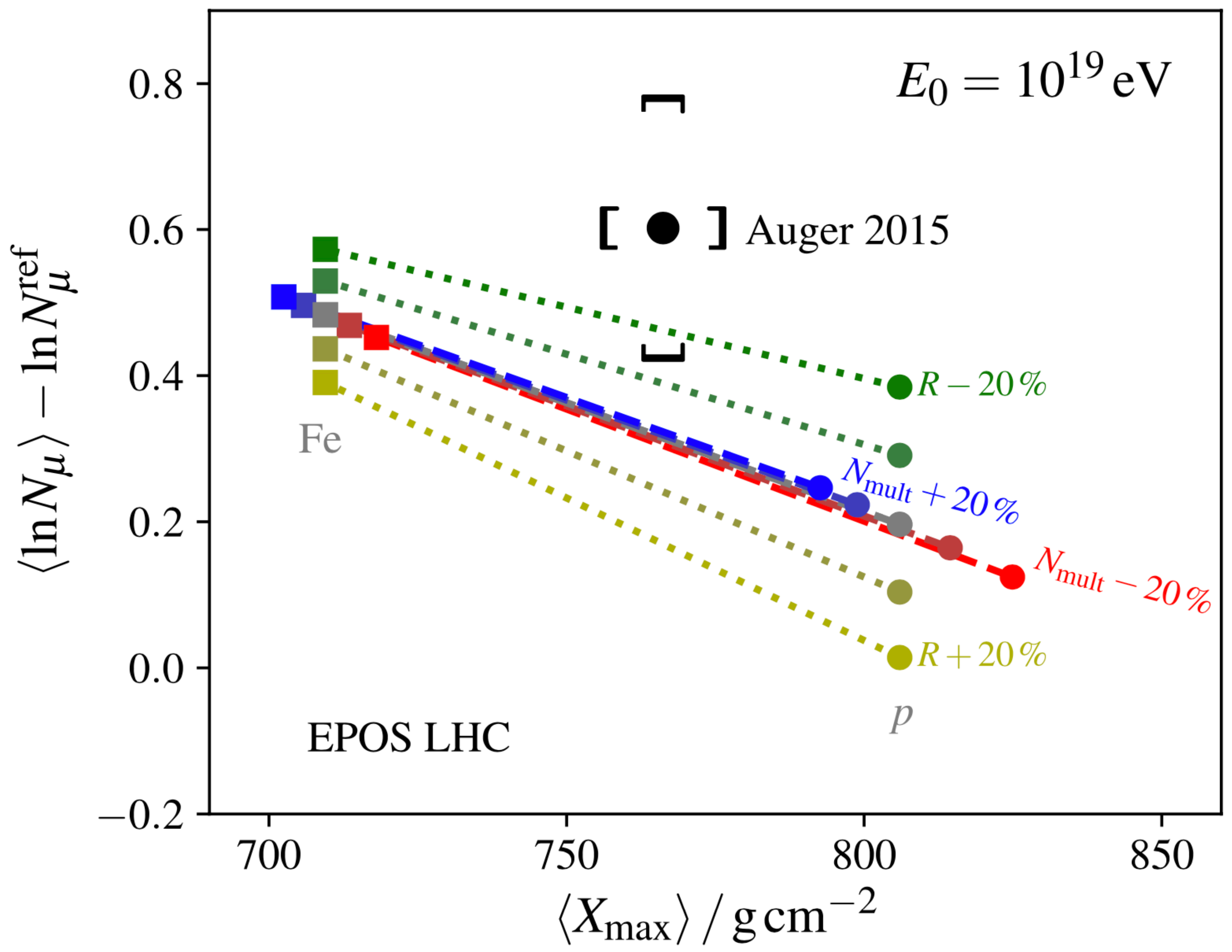
[D. Soldin et al. (WHISP), PoS ICRC2021 (2021) 349]

- Slope of the excess is significant with more than 8σ!
- Indicates severe shortcomings in the understanding of hadronic interactions

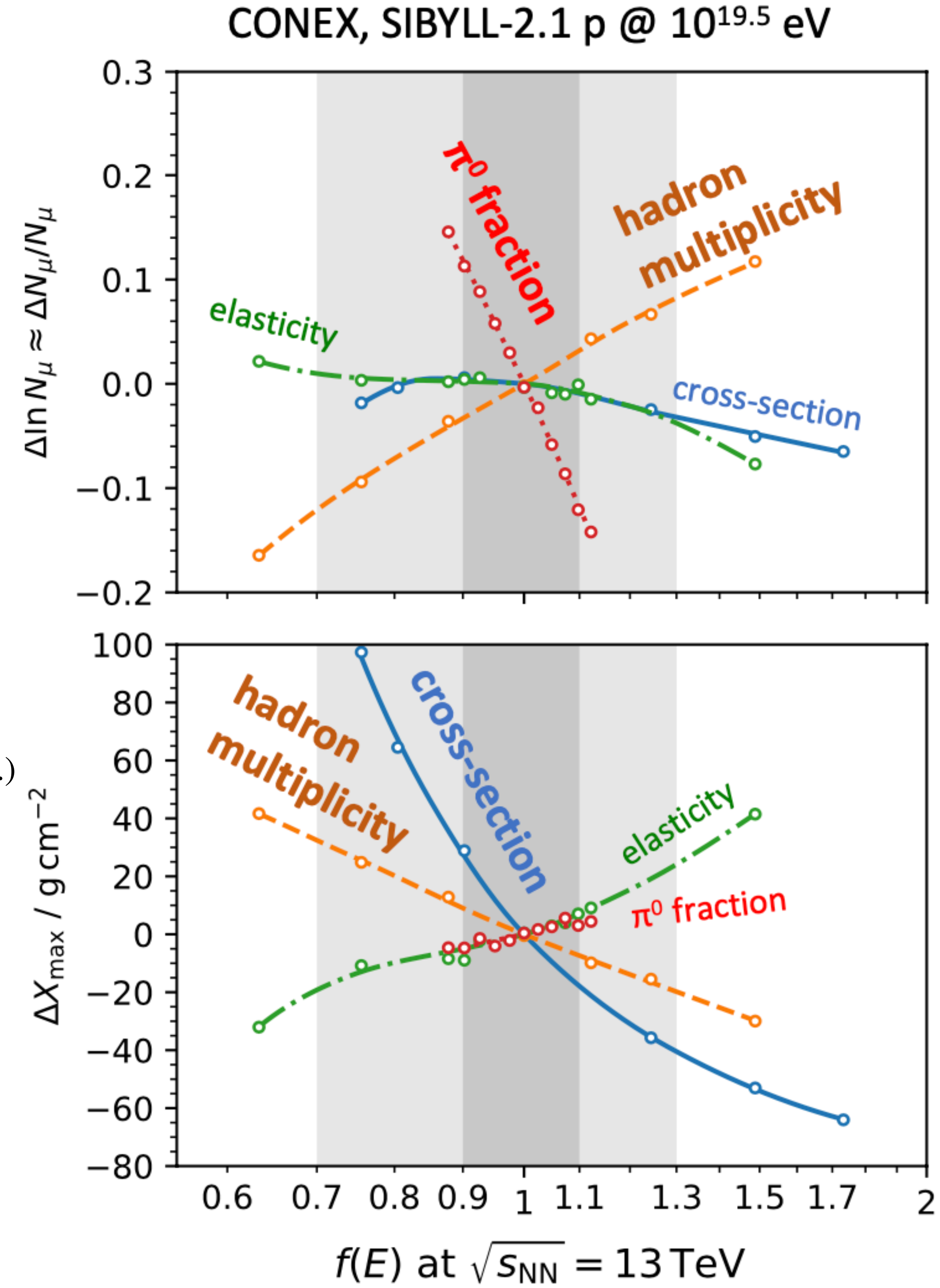
The Muon Puzzle in EAS

- 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!

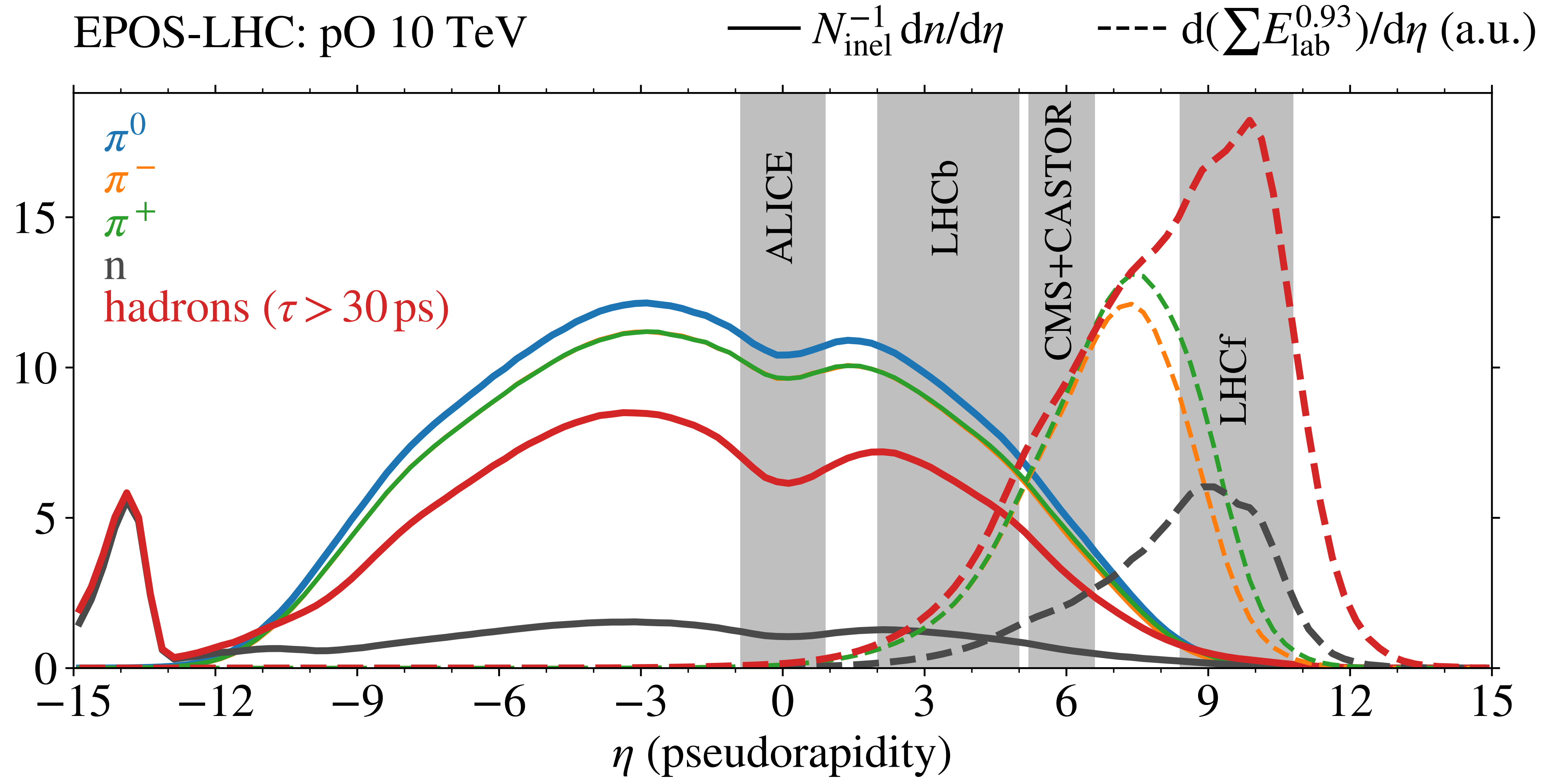
[S. Baur et al., arXiv:1902.09265 (2019)]



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

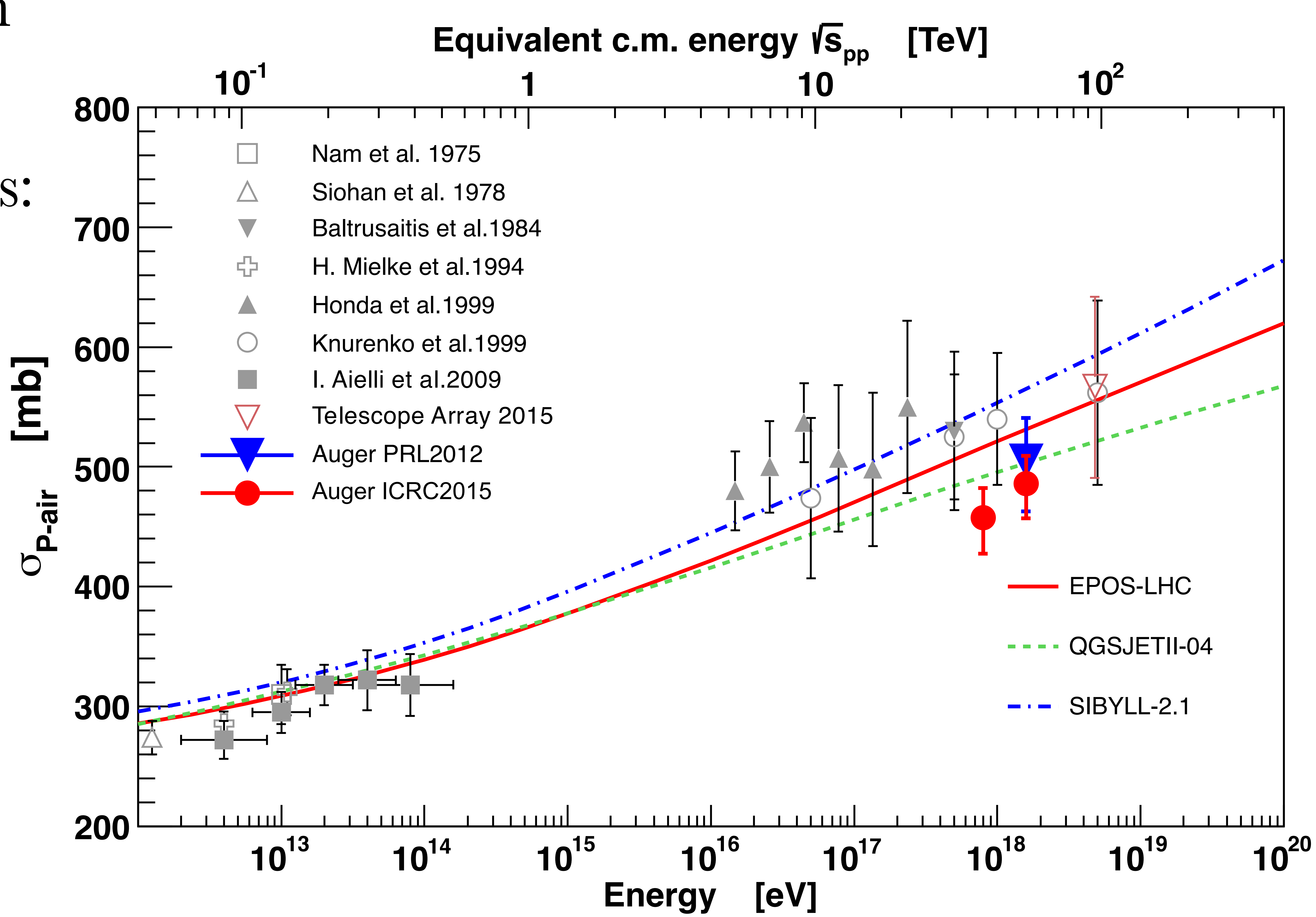


[J. Albrecht, D. Soldin et al., Astrophys.Space Sci. 367 (2022)]



Proton-Air Cross-Section

- Proton-air cross-section measured by Auger and TA
- Based on measurements of the maximum of the (EM) production depth, X_{max}
- Complementary to collider measurements:
  - EAS particles: Nuclei, mesons, …
  - CM energies: GeV to hundreds of TeV
  - Forward direction
  - Non-perturbative regime

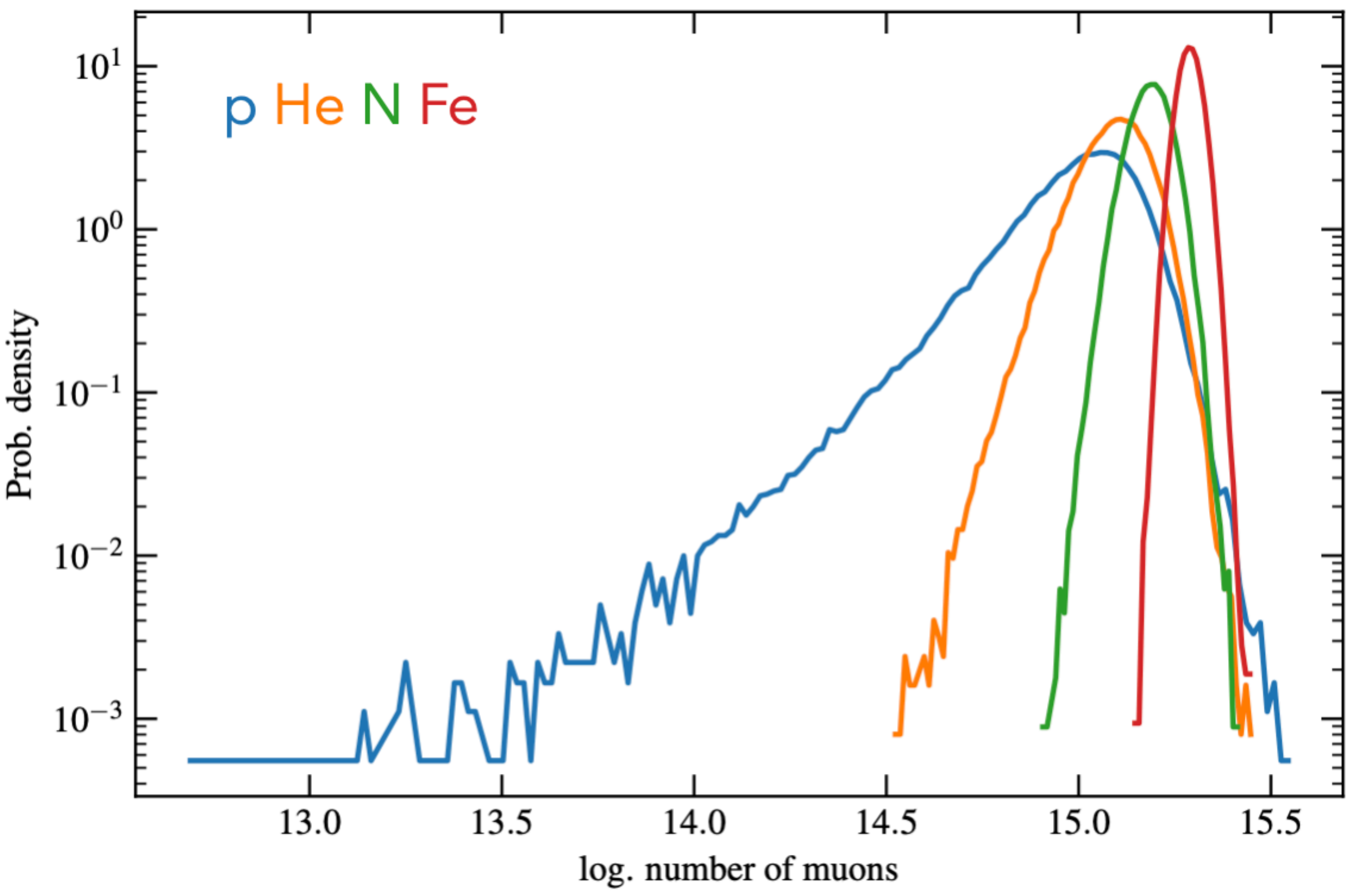


[R. Ulrich (Pierre Auger Collaboration), PoS(ICRC2015)401 (2016)]

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!

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



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