Air Shower Physics with IceCube

Academia Sinica High-Energy Physics Seminar
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ICECUBE
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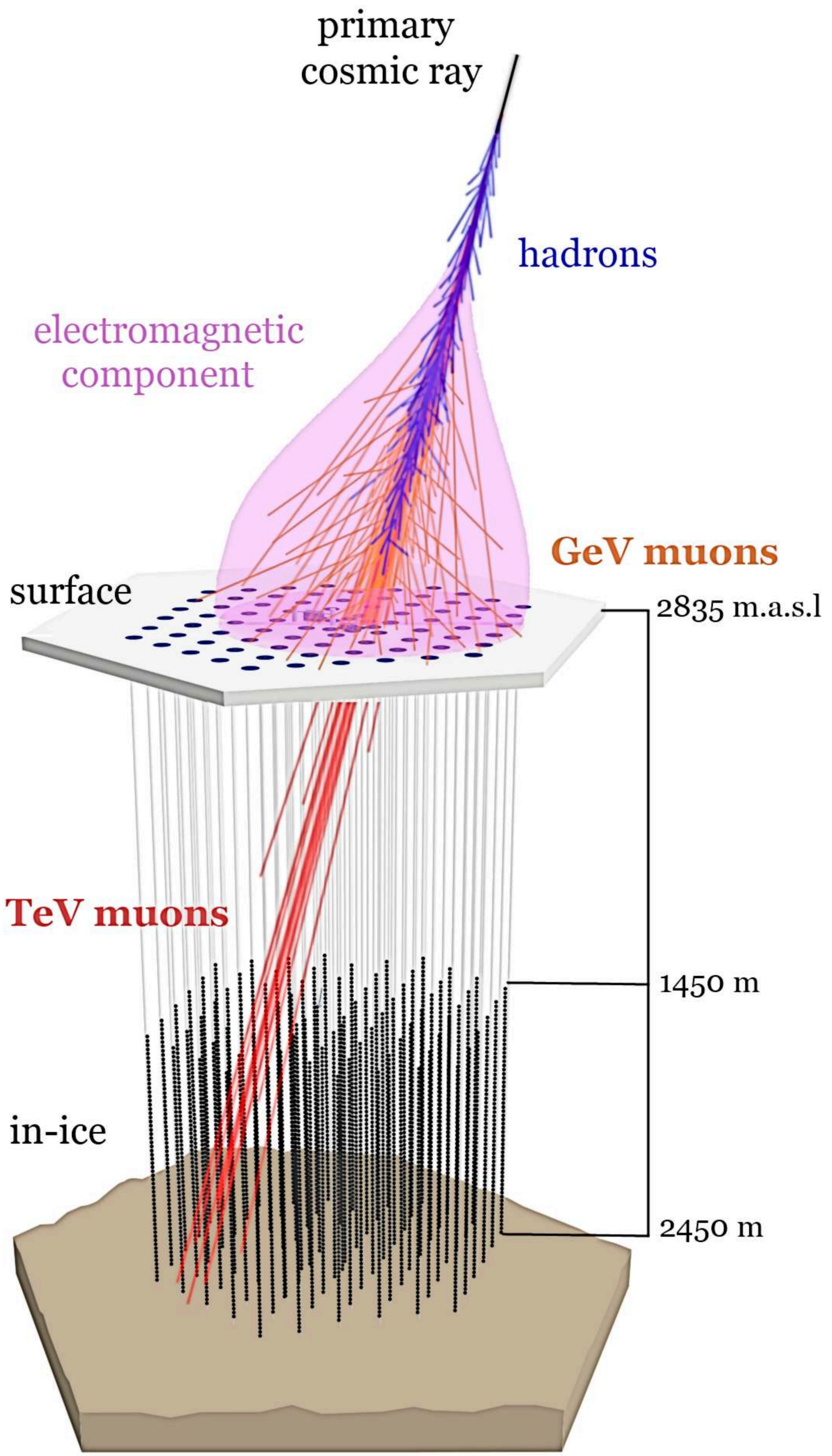
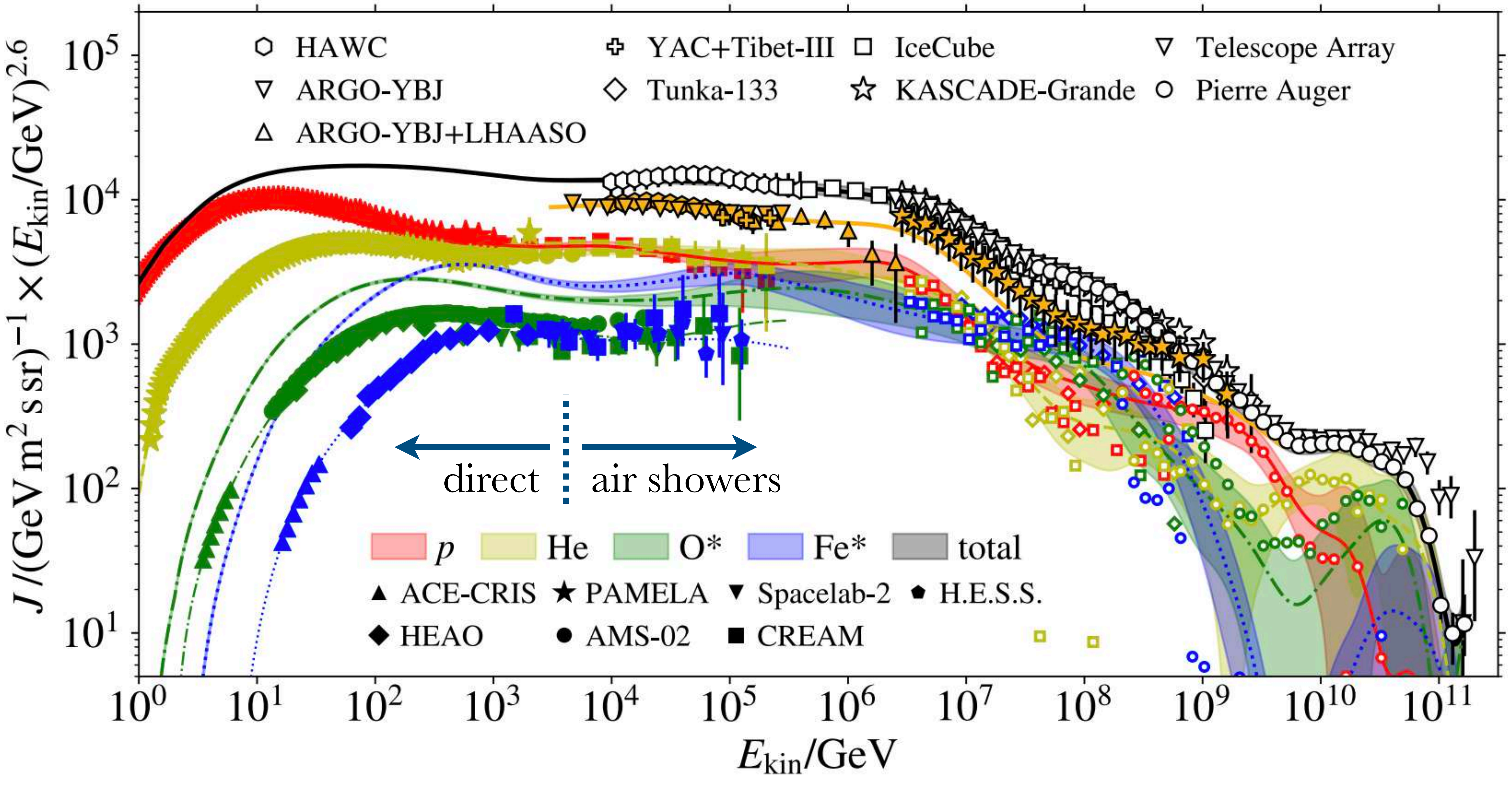
Outline

- Introduction
- The IceCube Neutrino Observatory
- The Muon Puzzle:
  - Measurement of GeV Muons in IceTop
  - Global Muon Measurements
  - Outlook & Perspectives
- Beyond the Muon Puzzle:
  - High-energy muon measurements in IceCube

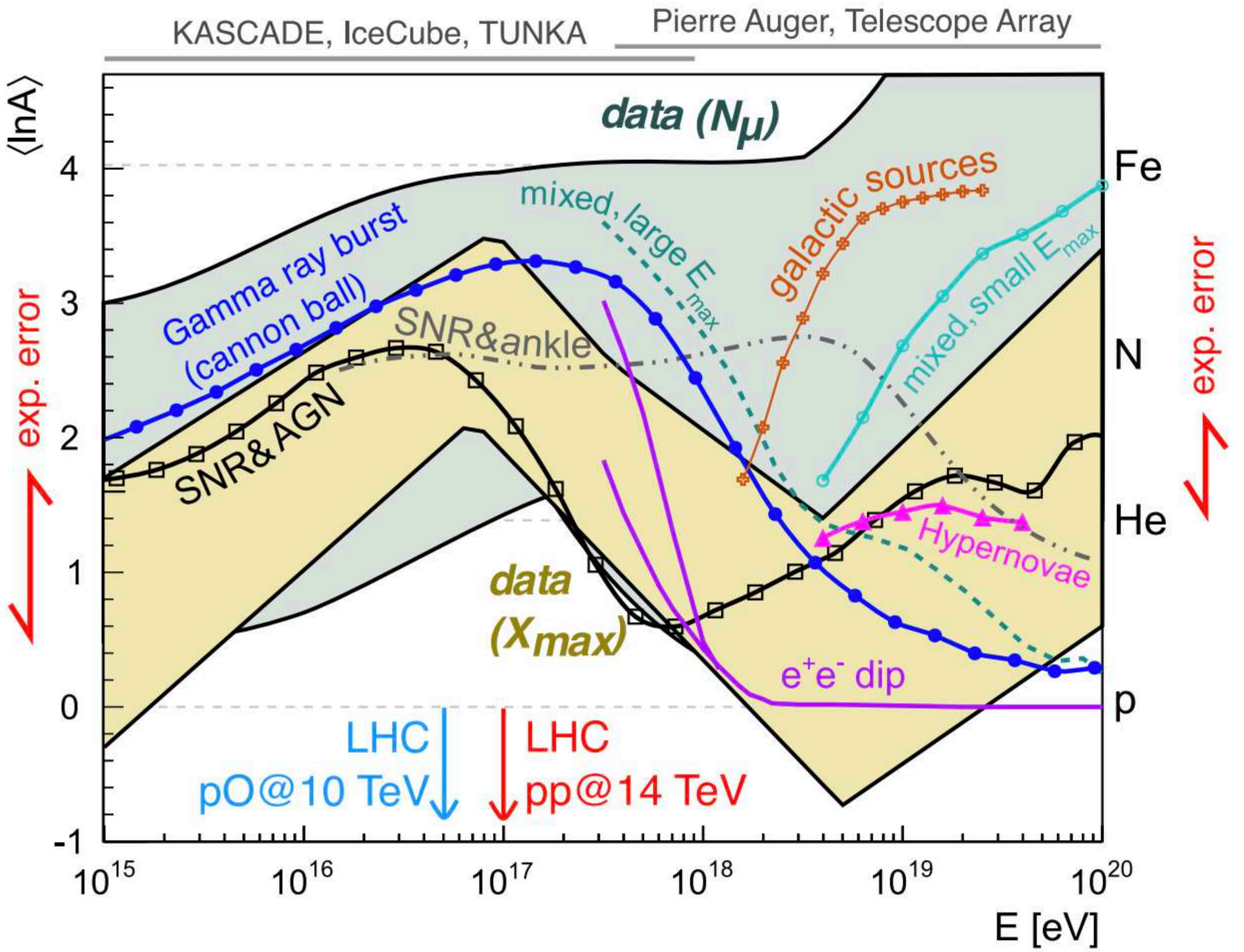


Cosmic Rays

- Cosmic rays (CRs) are charged particles that reach Earth with energies up to $\gtrsim 100\,\mathrm{EeV}$
- Large systematic uncertainties in CR mass composition measurements!
- Because initial CR properties are inferred indirectly from air shower measurements
- Example: Global-Spline-Fit (GSF) model

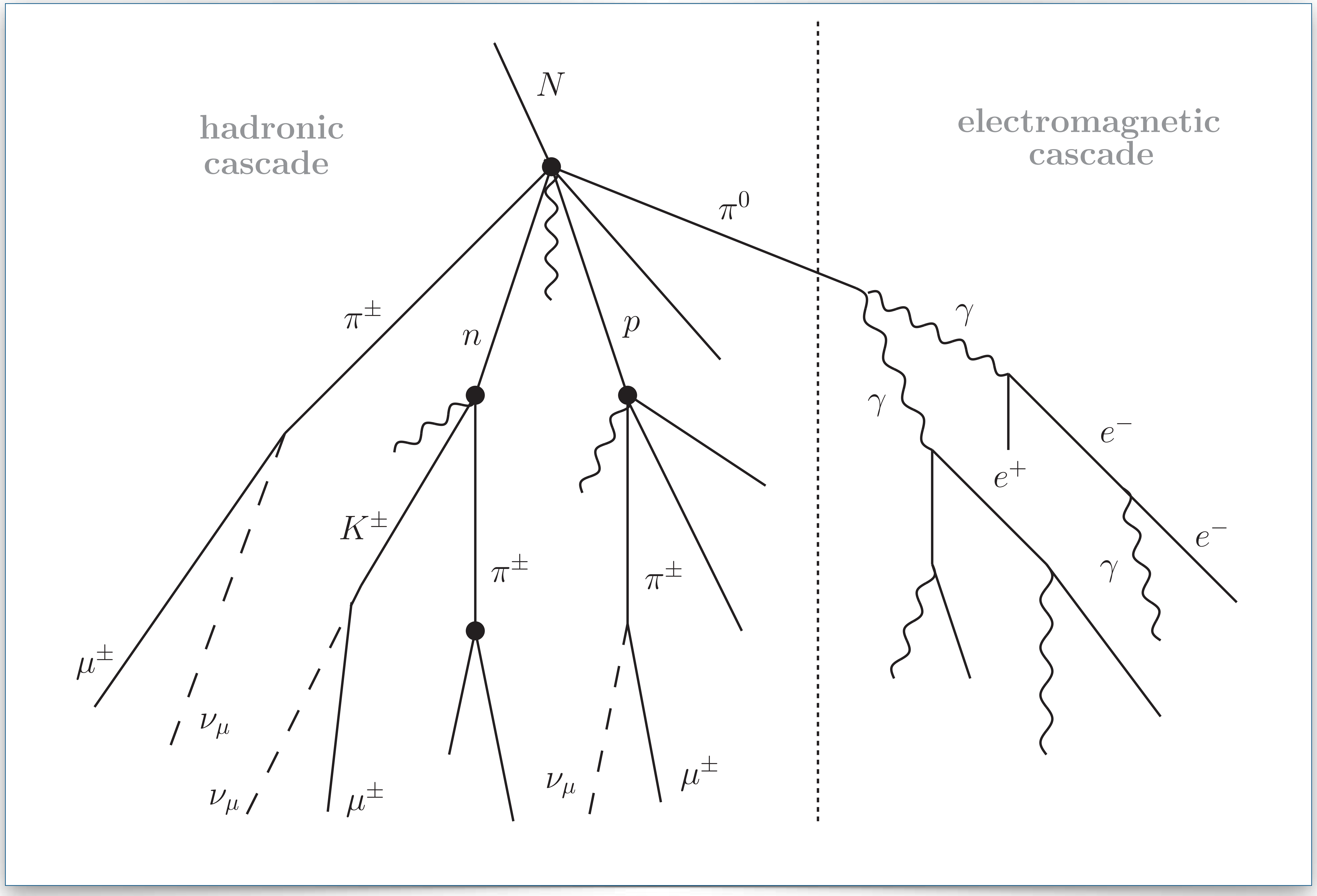


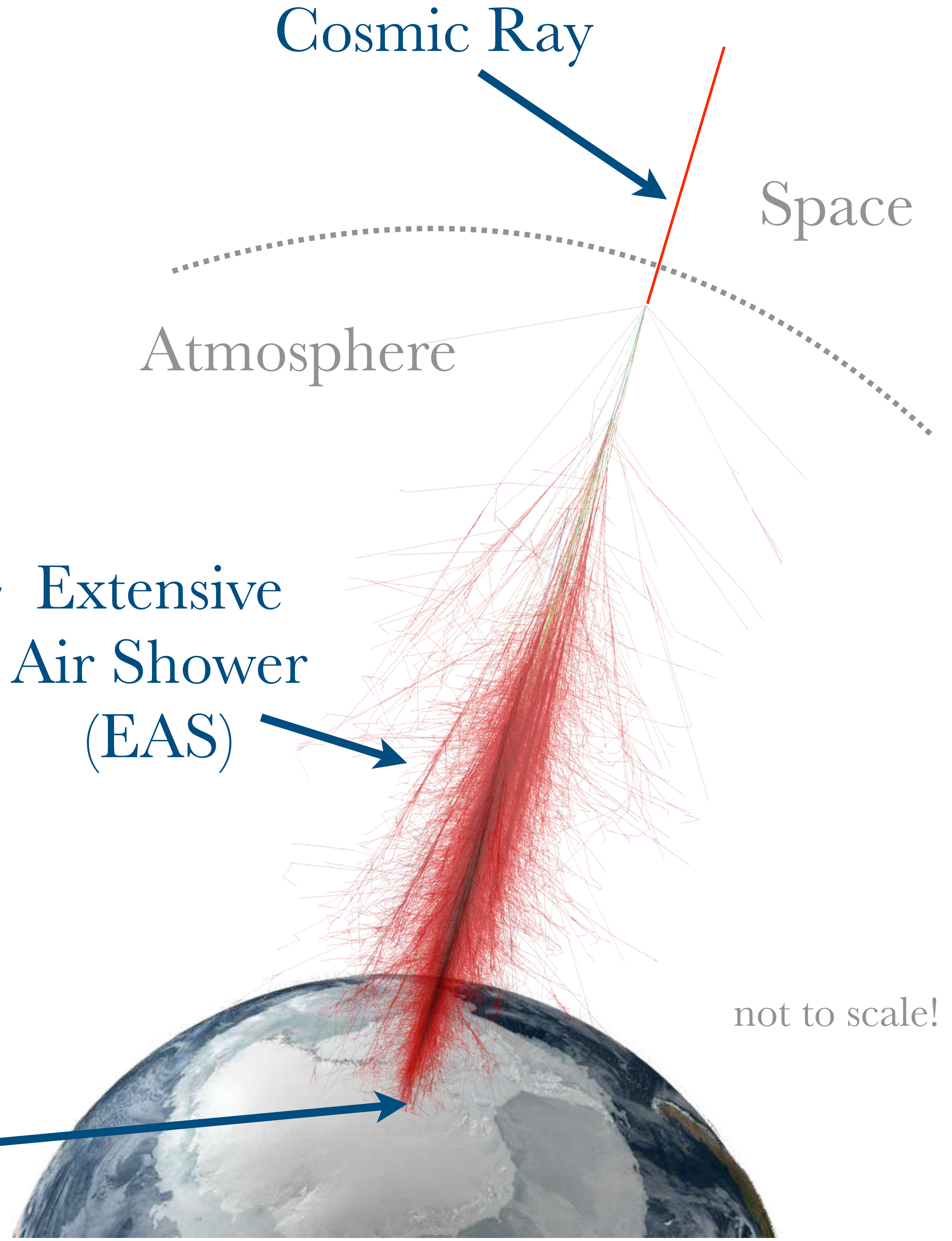
[H.P. Dembinski, R. Engel, A. Fedynitch, T. K. Gaisser, F. Riehn, T. Stanev, PoS ICRC2017 (2017) 533]



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

Extensive Air Showers





Cosmic Ray

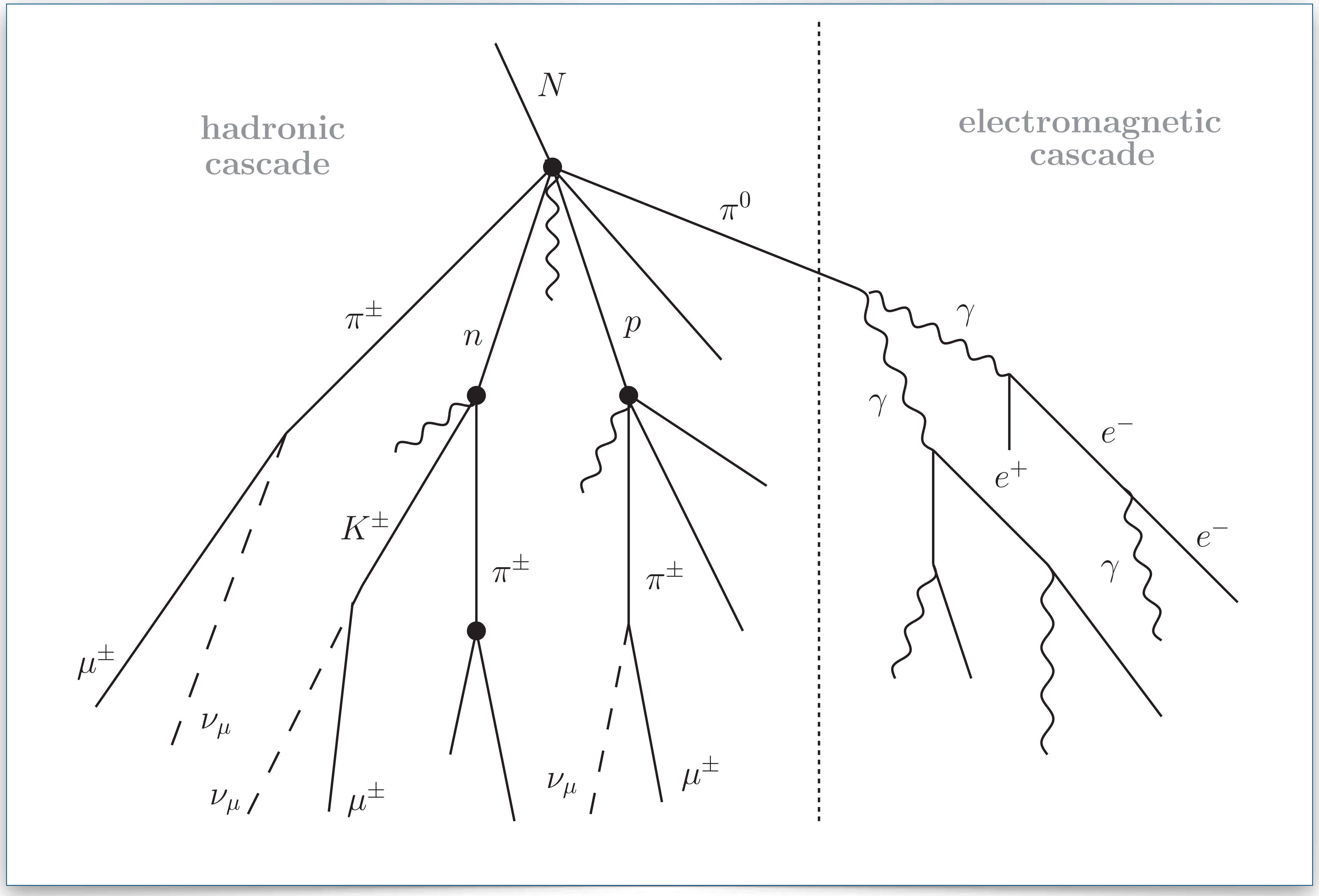
Extensive Air Shower (EAS)

Ground-Based Particle Detector

Atmospheric Muons

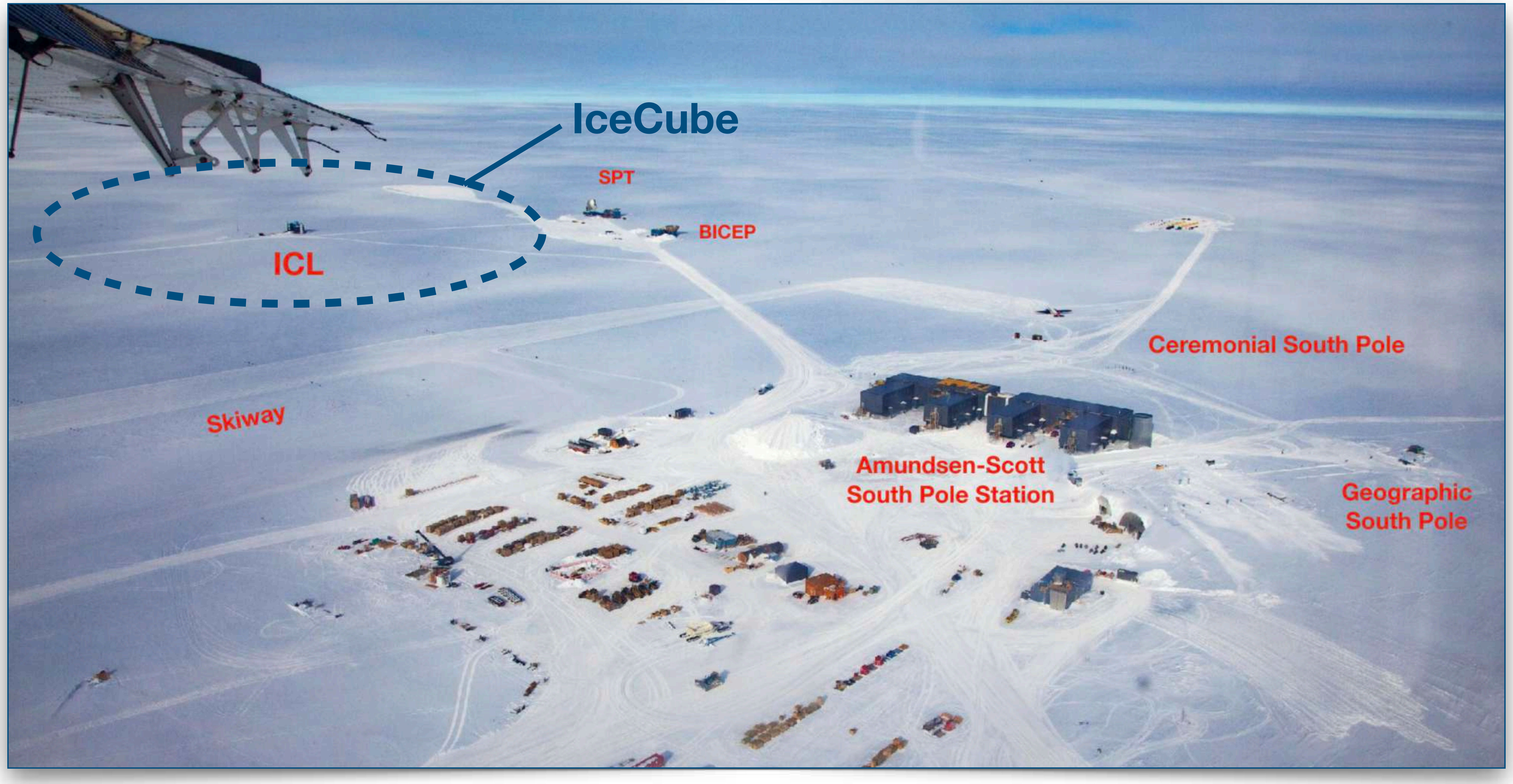
- Muons are the messengers of the hadronic cascades in air showers
- <u>Many challenges in the description of muon production in EAS:</u>
  - Projectile/target masses, hadron composition
  - Nuclear effects
  - Energies beyond current colliders
  - Forward region
  - Can not be described in pQCD!
  - Very limited collider data!

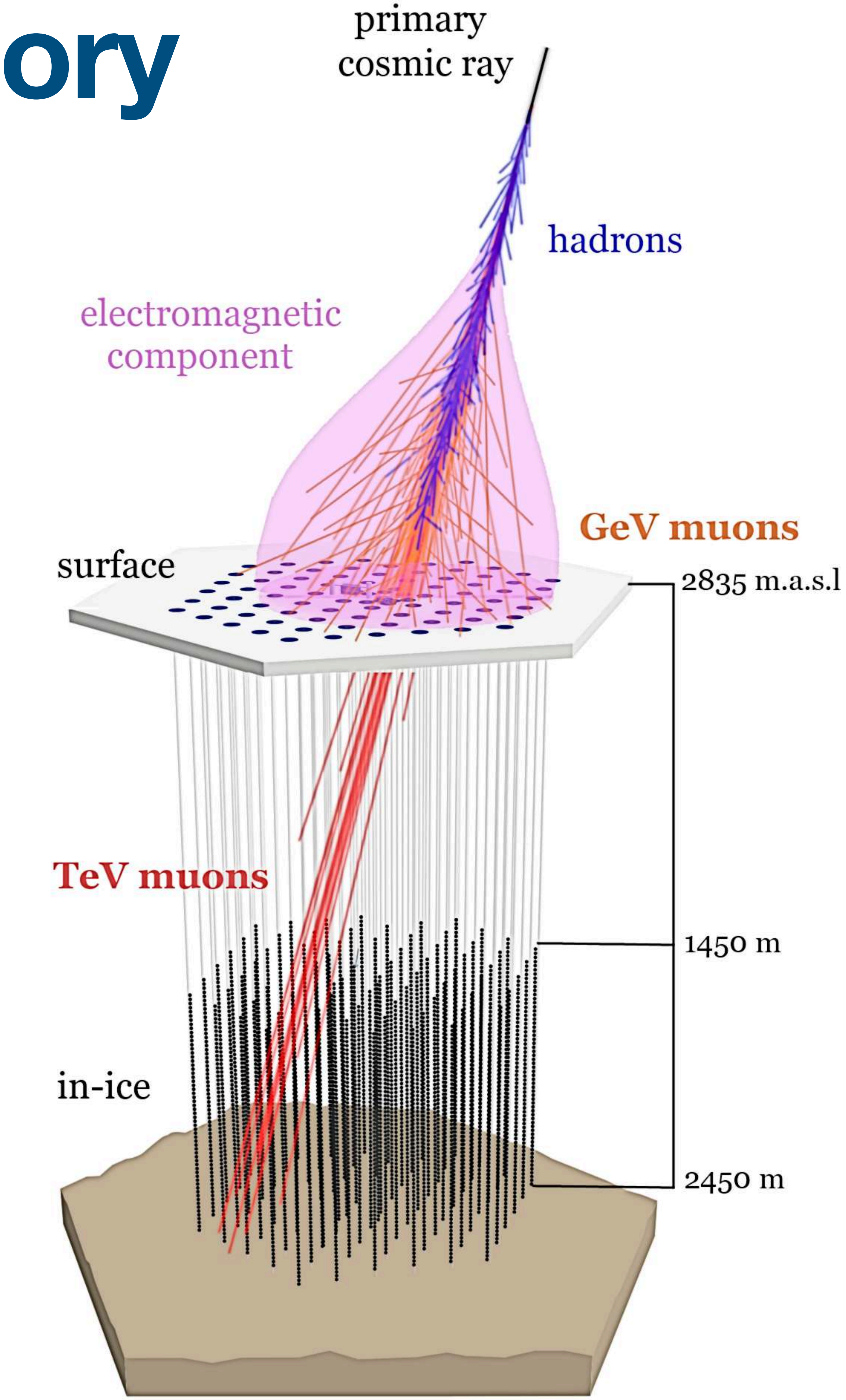
→ <u>Phenomenological models required!</u>



The IceCube Neutrino Observatory

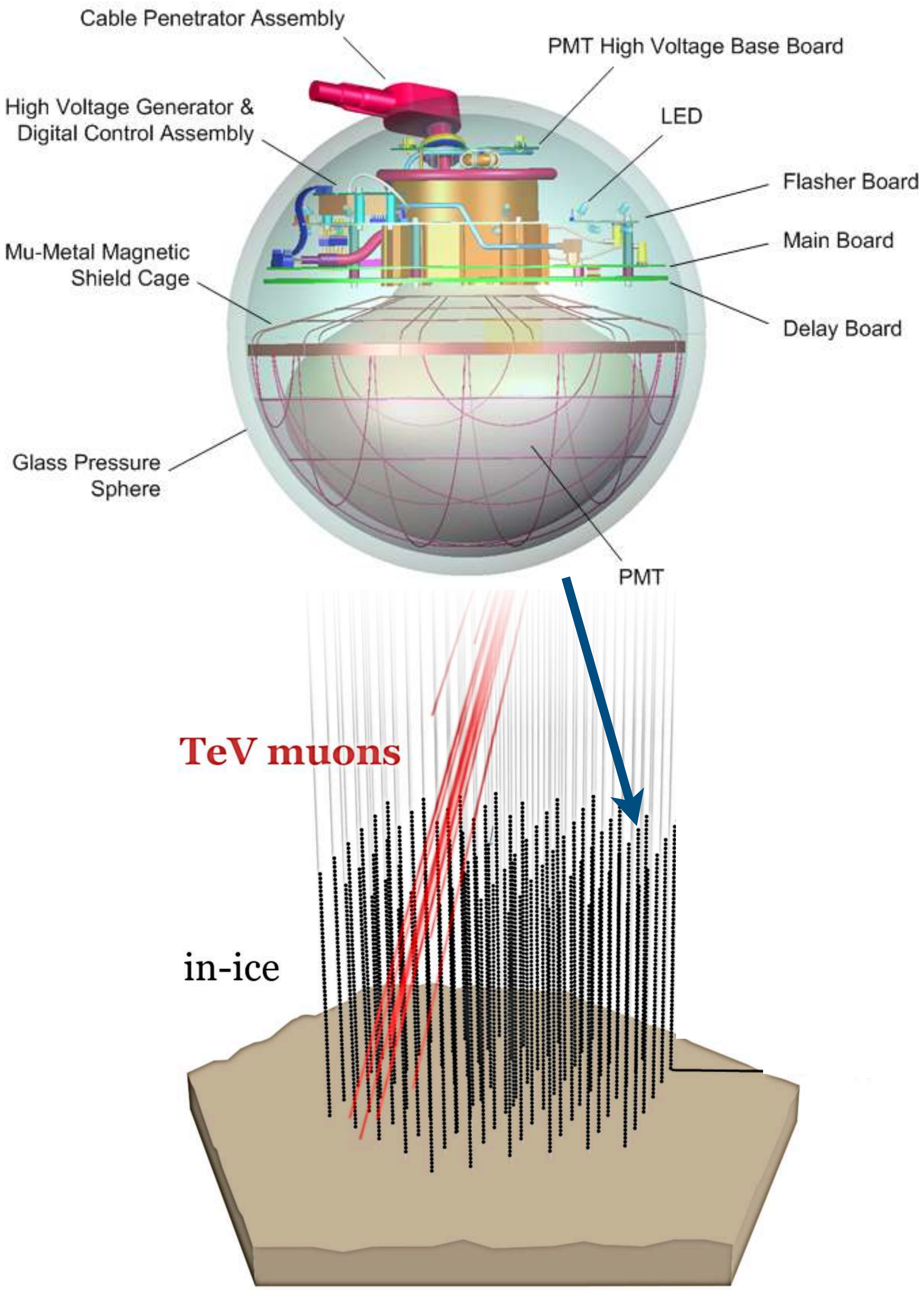
- Hybrid cubic-kilometer Cherenkov detector at South Pole
  - Surface detector at 2835 m.a.s.l
  - In-ice detector at depths between 1450 m and 2450 m



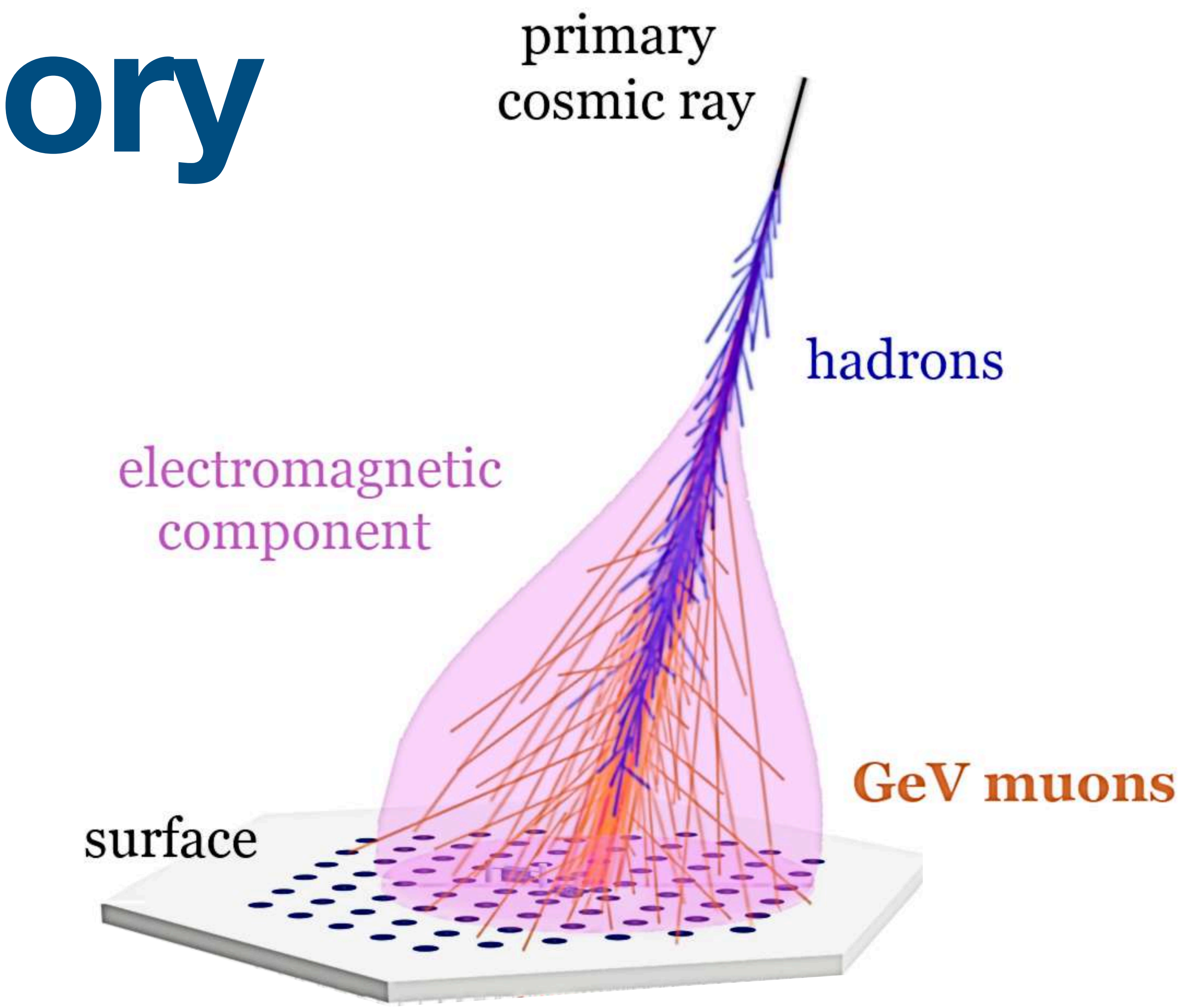


The IceCube Neutrino Observatory

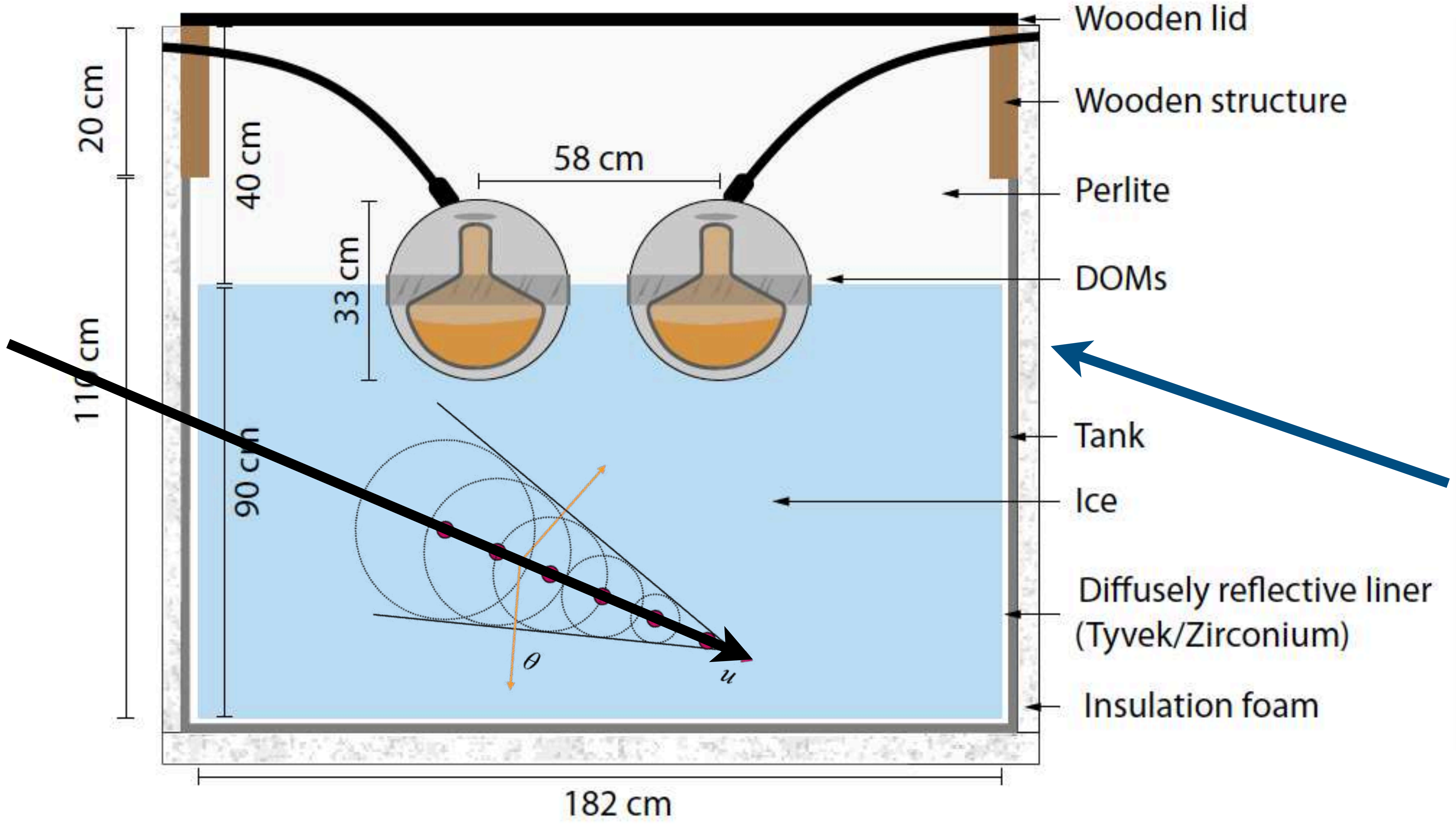
- In-ice Cherenkov detector:
  - 86 strings with grid spacing of ~125 m
  - 5600+ Digital Optical Modules (DOMs)
  - Few 100 GeV (up to several PeV) muons

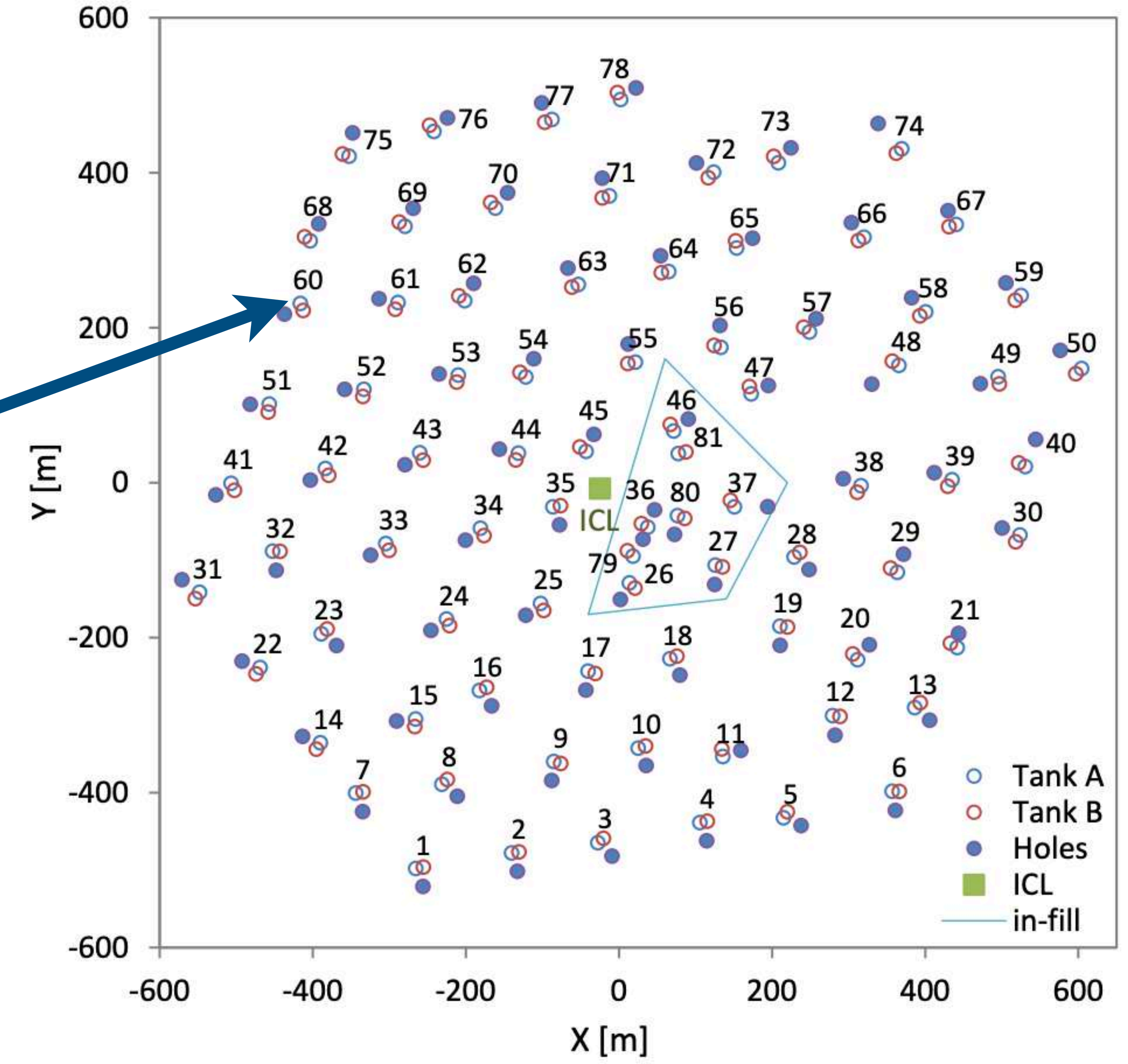


The IceCube Neutrino Observatory



- <u>Surface detector, IceTop:</u>
  - 81 stations with grid spacing of ~125 m
  - Each station: 2 tanks (each tank: 2 DOMs)
  - Electromagnetic EAS component (EAS energy)
  - GeV muon content in EAS

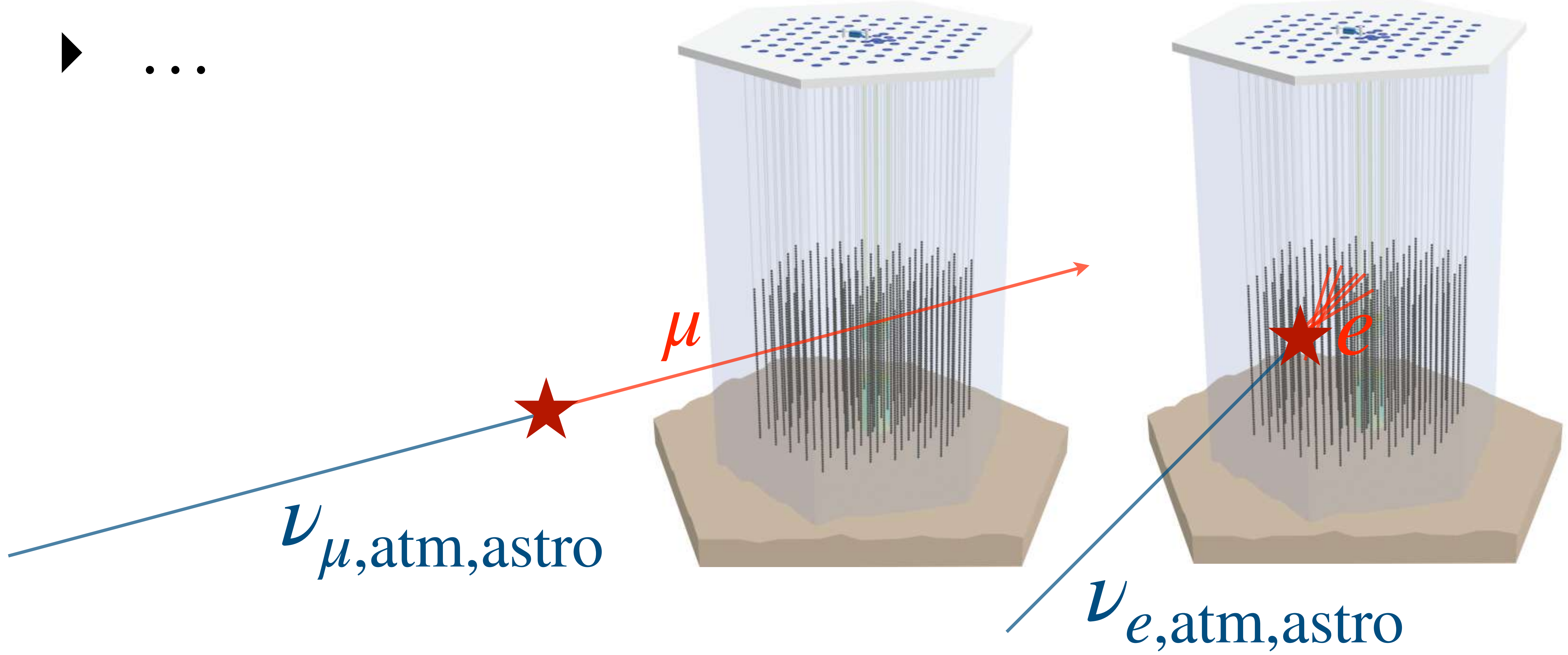


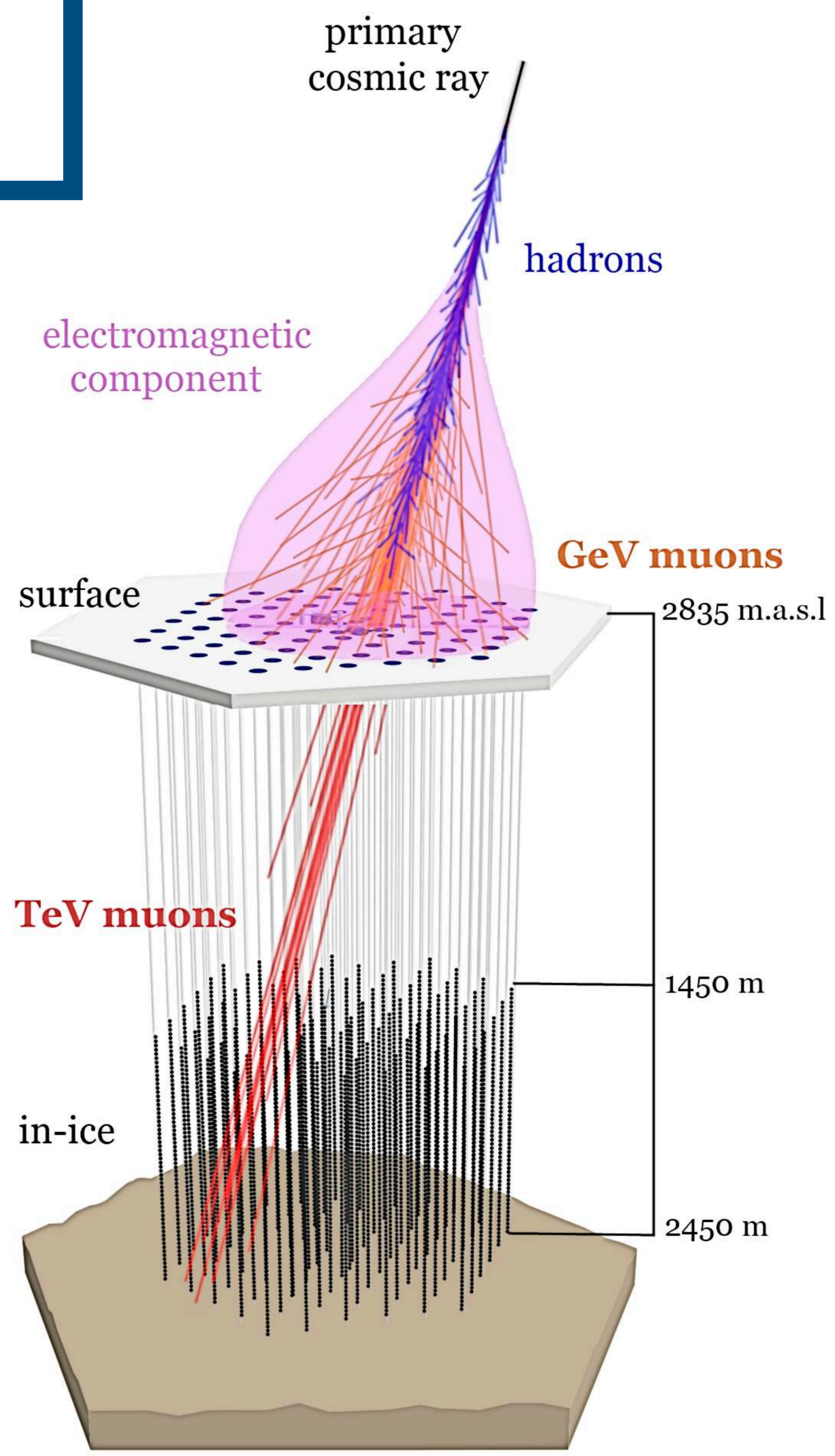


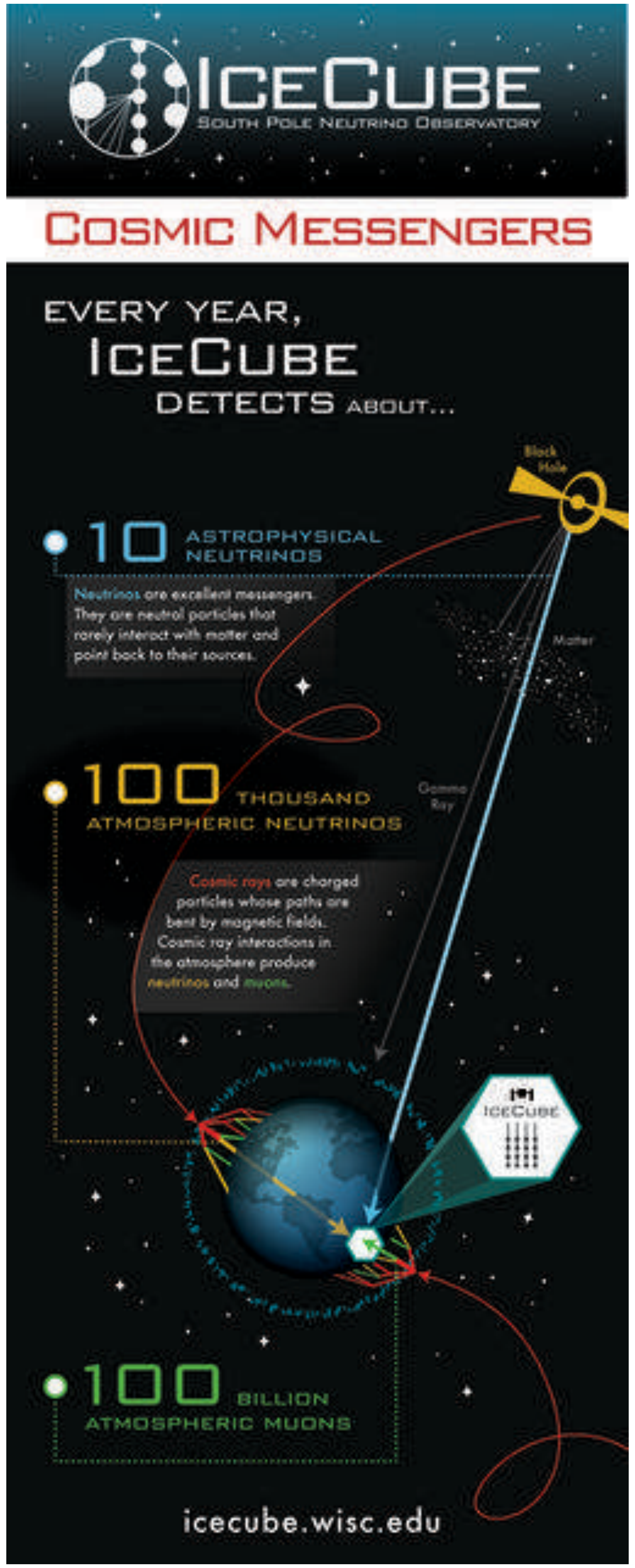
The IceCube Neutrino Observatory

- Measurements of various particles:
  - EAS particles
    - Atmospheric muons / neutrinos
    - Electromagnetic EAS component (IceTop only)
  - Astrophysical neutrinos
  - BSM particles
  - …

This talk





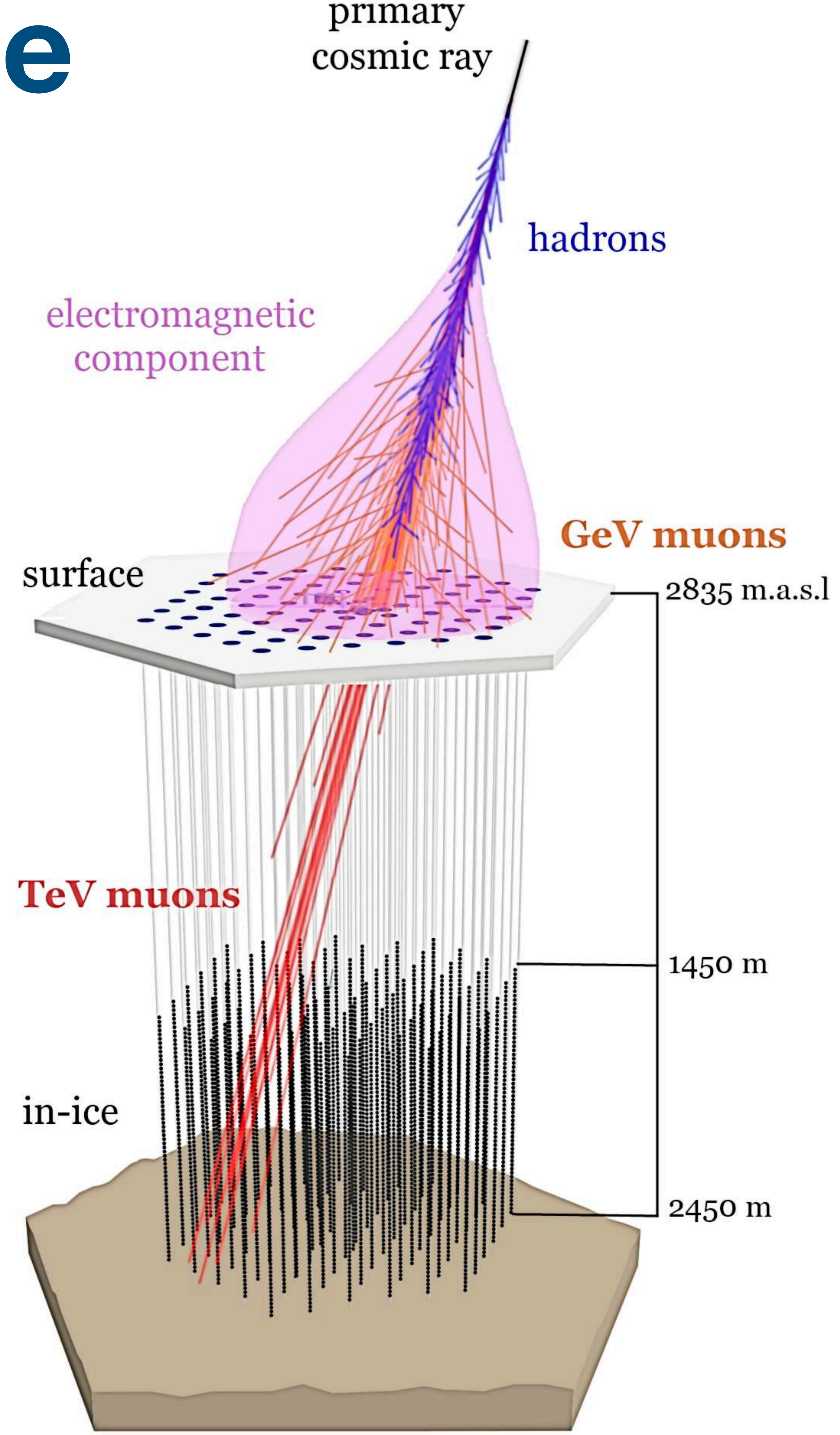


Neutrinos are excellent messengers. They are neutral particles that rarely interact with matter and point back to their sources.

Cosmic rays are charged particles whose paths are bent by magnetic fields. Cosmic ray interactions in the atmosphere produce neutrinos and muons.

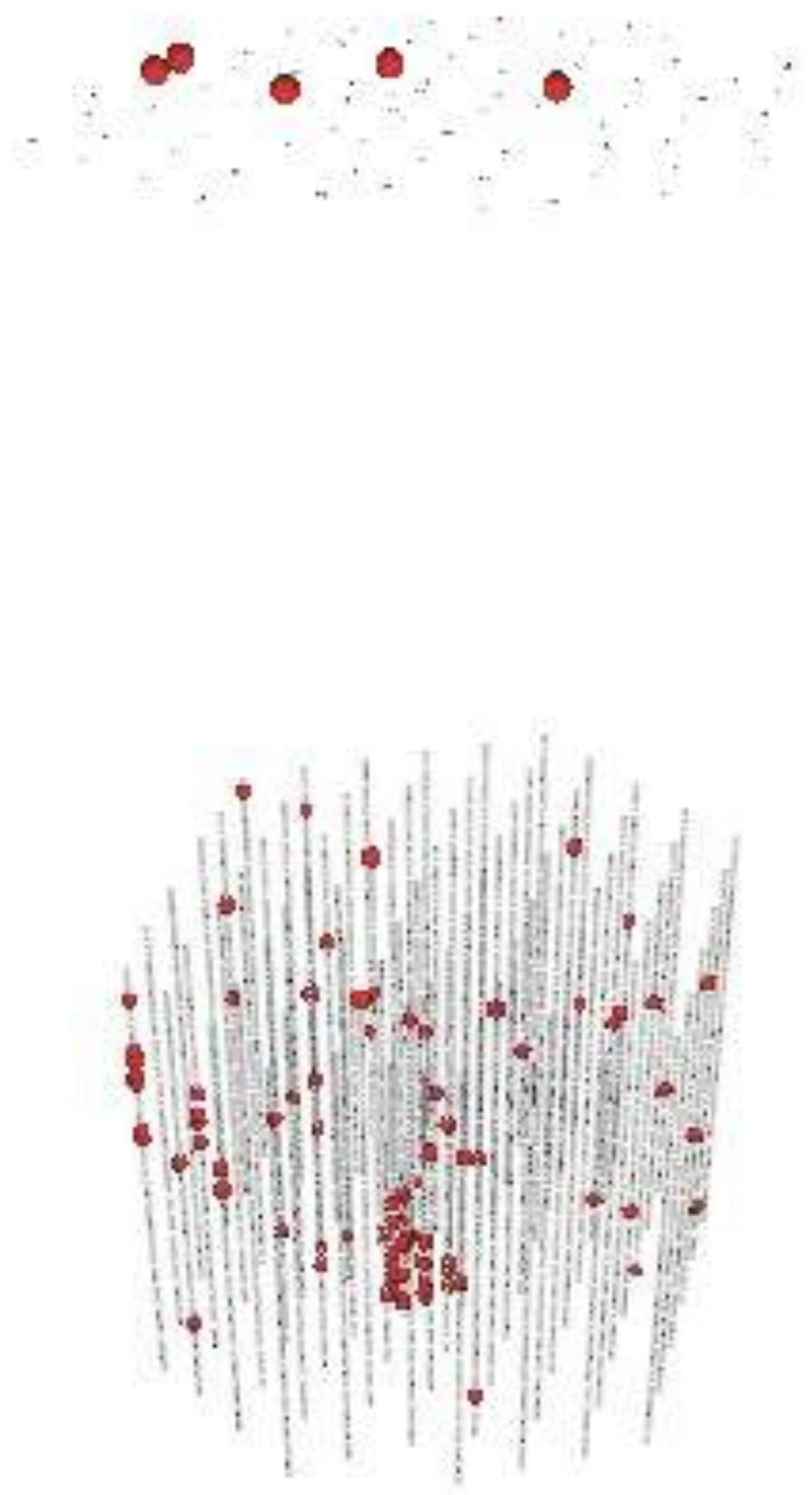
EAS Measurements with IceCube

- Surface detector, IceTop, measures:
  - Electromagnetic EAS component (EAS energy)
  - GeV muon content in EAS
- In-ice detector measures:
  - TeV (up to several PeV) muon content in EAS
- Coincident measurements possible!
- Ideal facility to study muon (hadron) production in the forward region in EAS!



EAS Measurements with IceCube

- Example: experimental data event (2012)
- Color-coding of time:
  - From red (early) to blue (late)
- Sizes of "blobs":
  - Amount of detected light by each DOM
- The red line indicates the reconstructed event trajectory

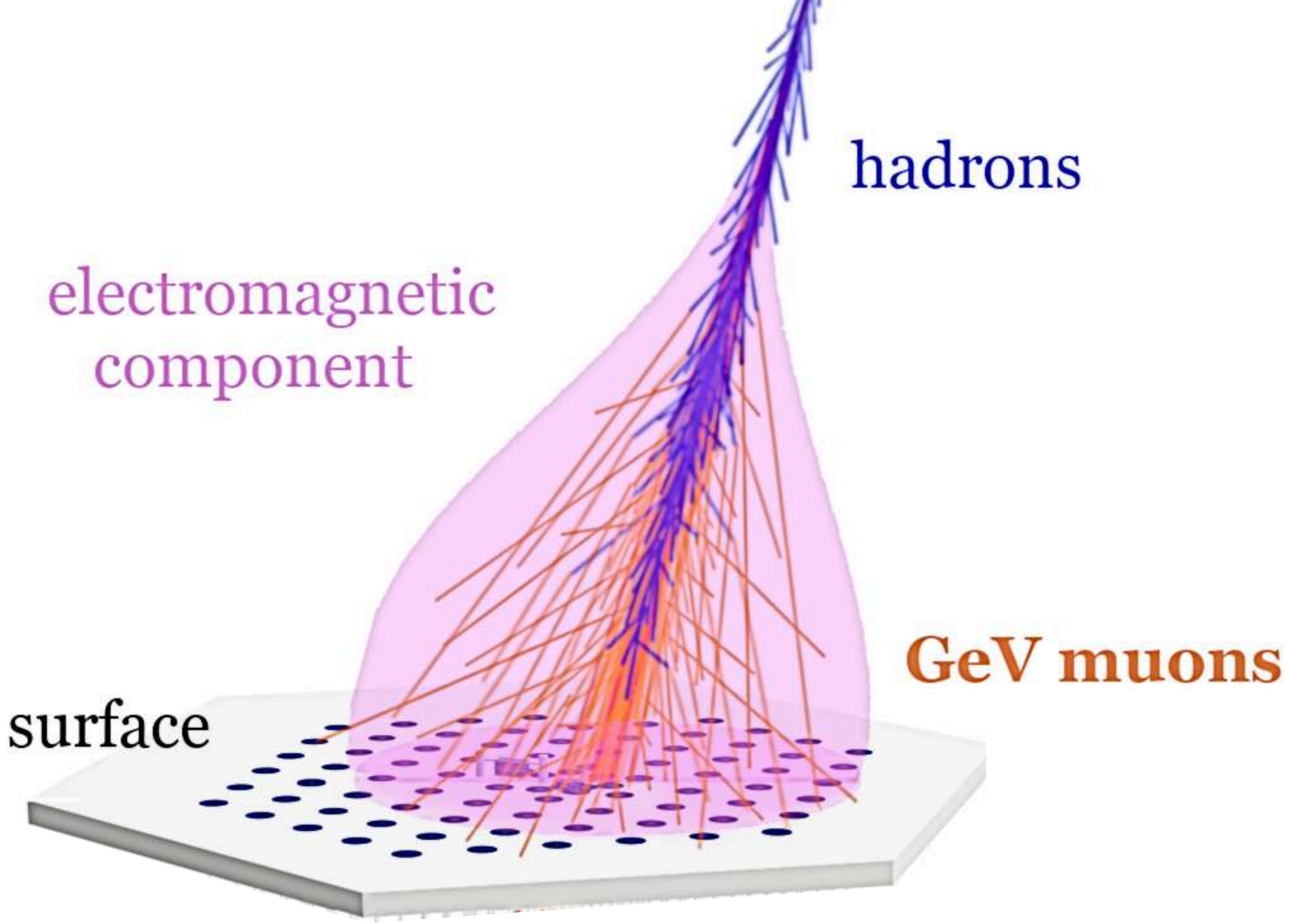


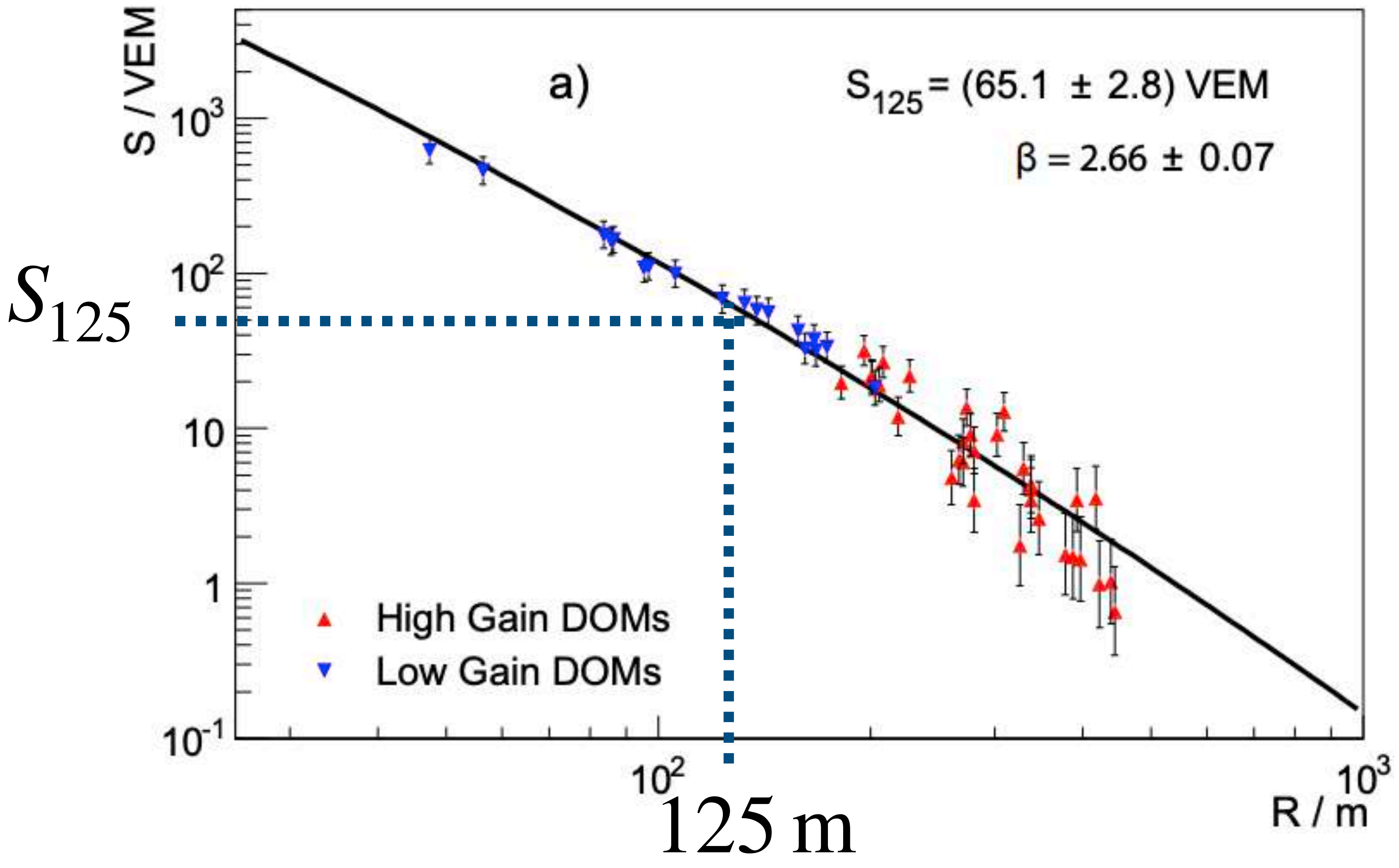
EAS Energy in IceTop

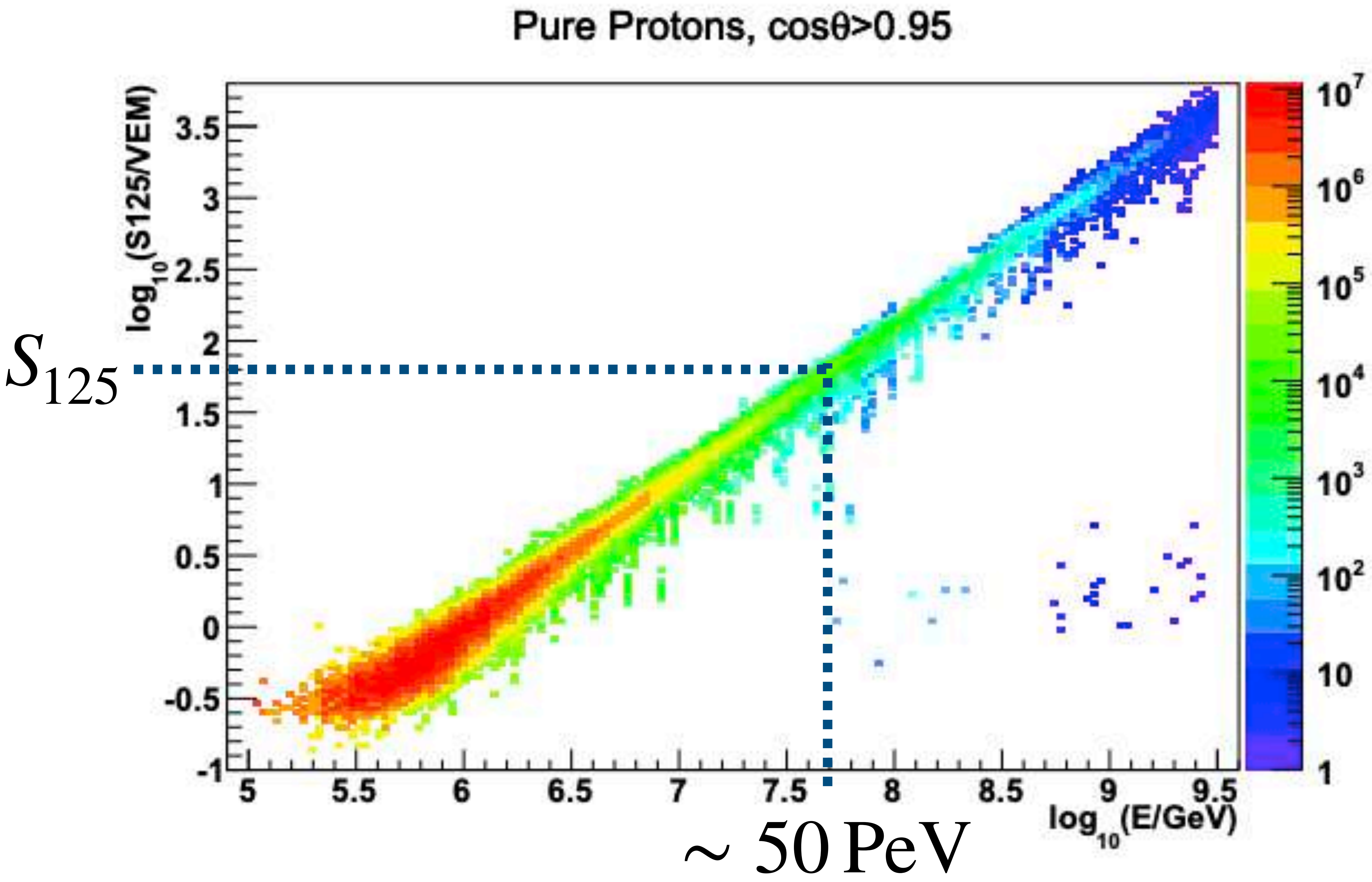
- EAS energy determined from surface signals
- Lateral Distribution Function (LDF)

$$S(r) = S_{125} \cdot \left(\frac{r}{125\,\mathrm{m}}\right)^{-\beta-\kappa\cdot\log_{10}(1/125\,\mathrm{m})}$$

- Shower size S_{125} (EAS energy), slope parameter β

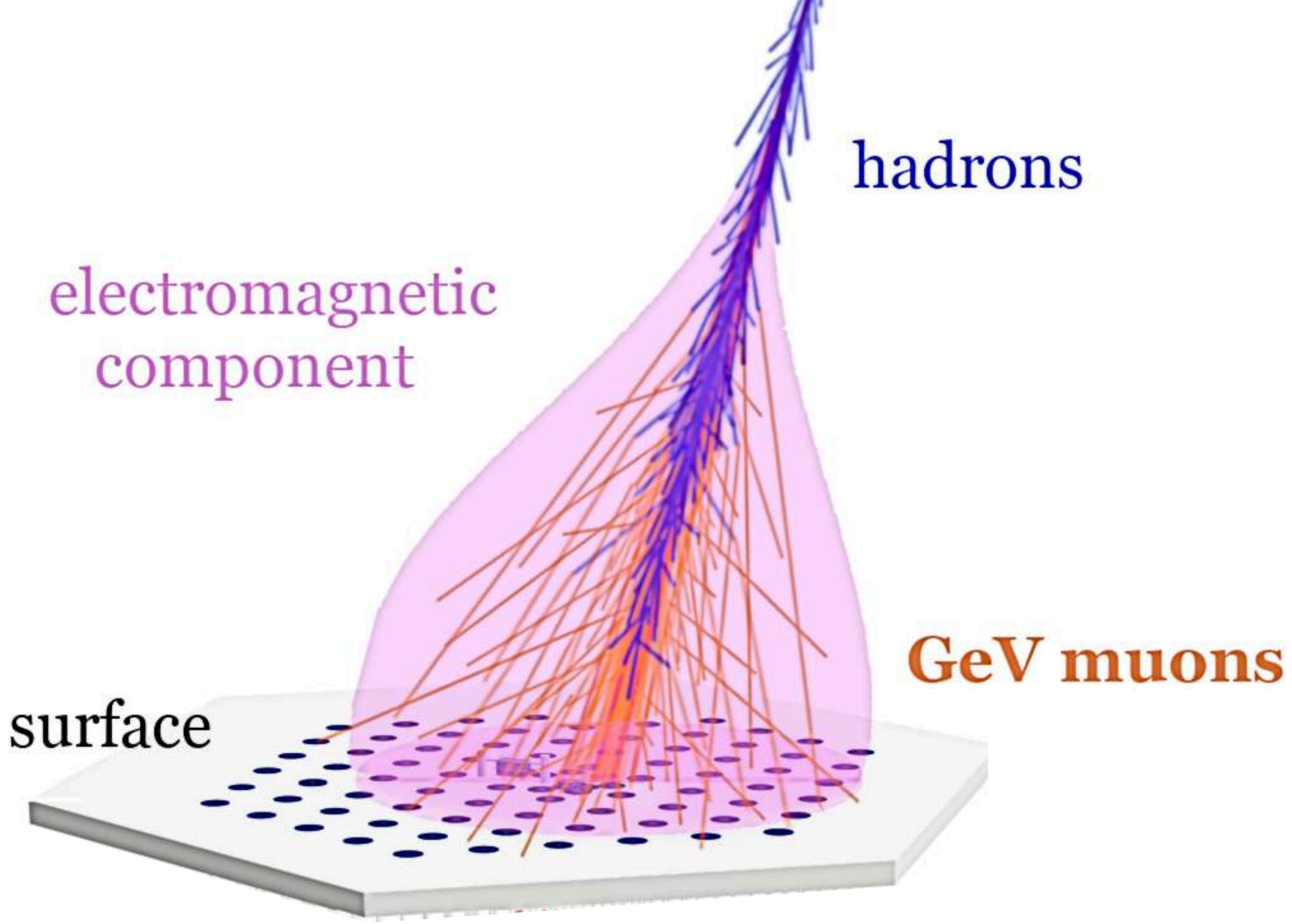


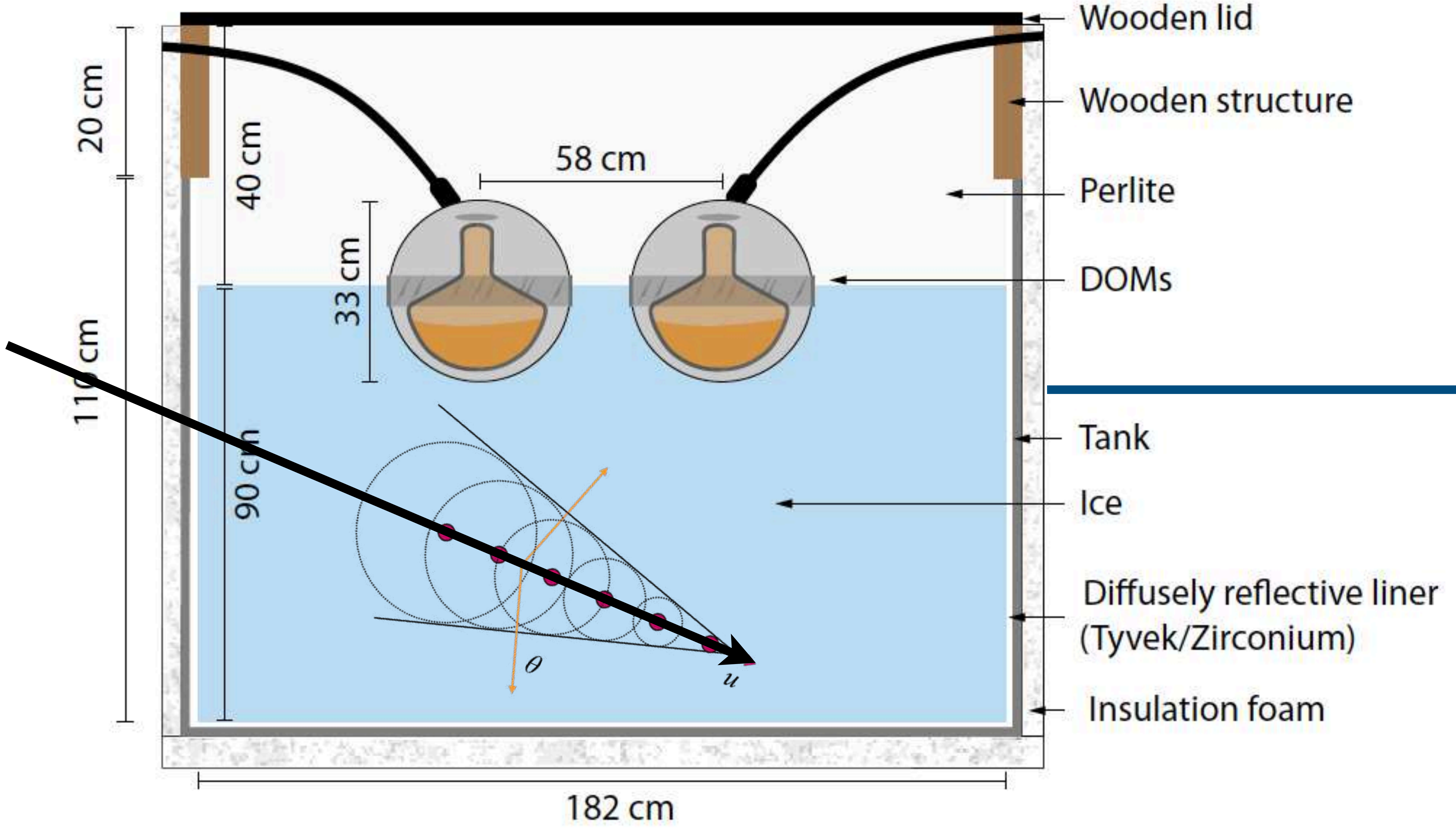


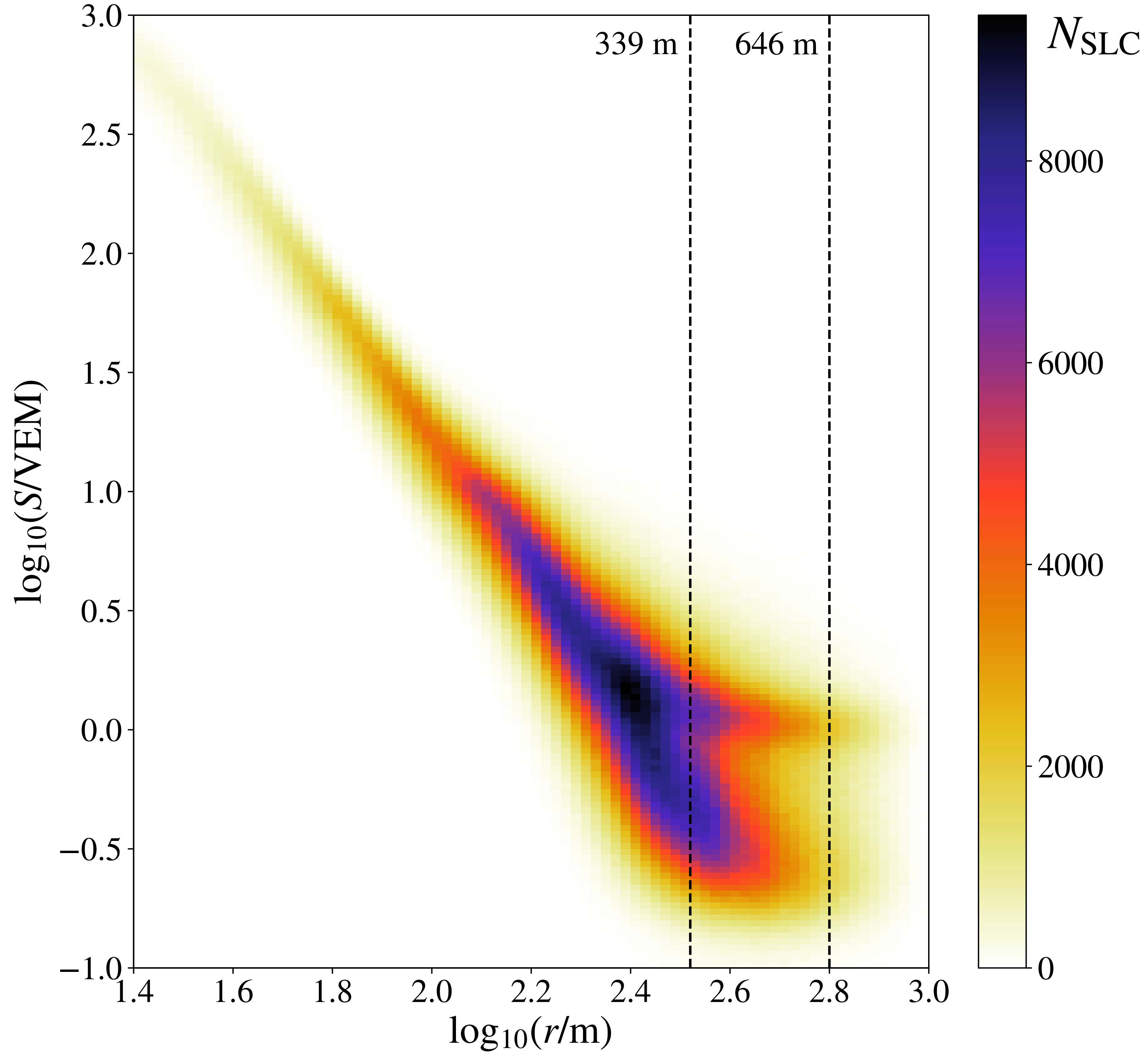


GeV Muons in IceTop

- Individual tank signals (vertical-equivalent-muon, VEM)
- Characteristic signal distributions for em part and muons
- Separation of <u>GeV muons</u> from other particles in EAS







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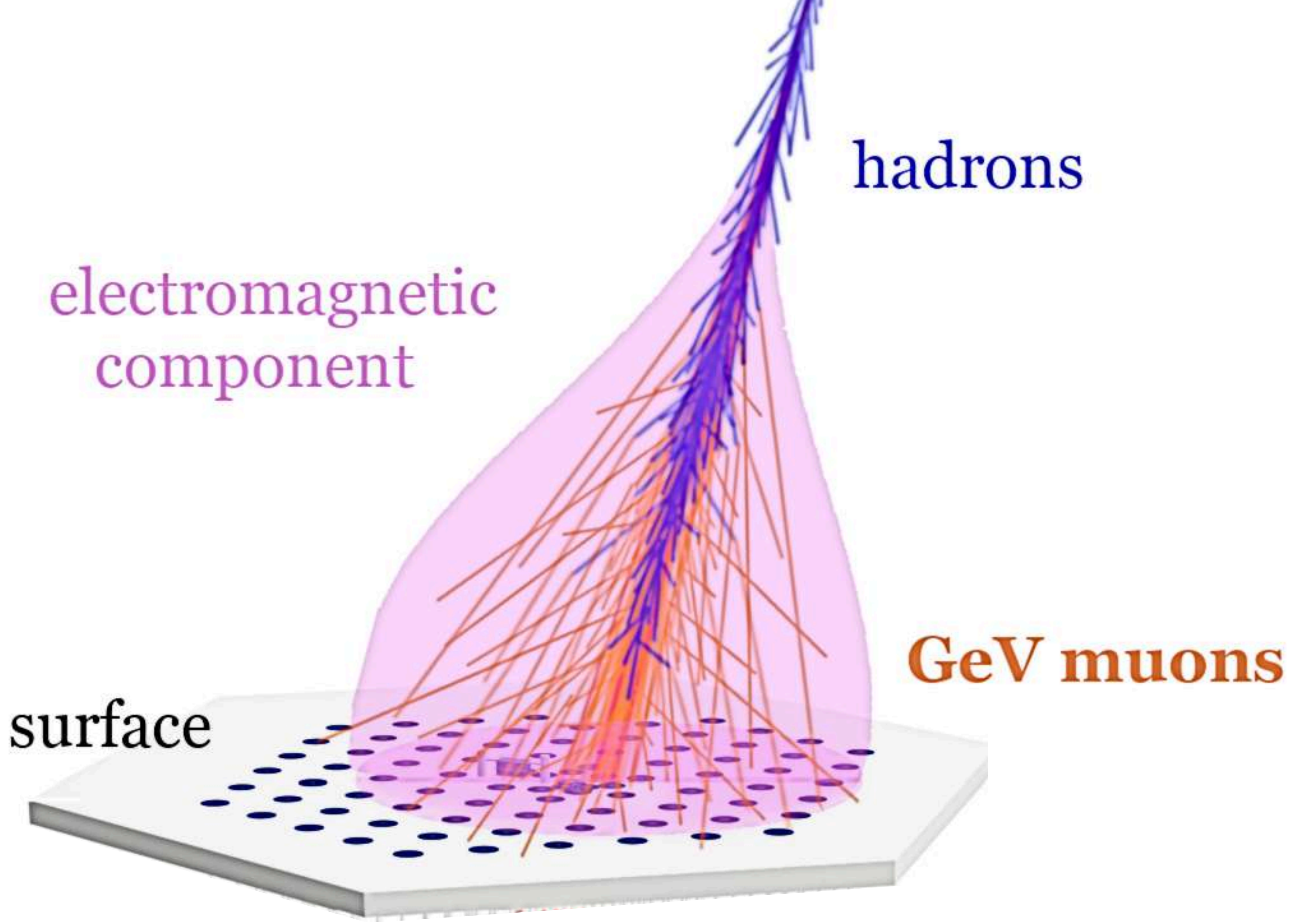

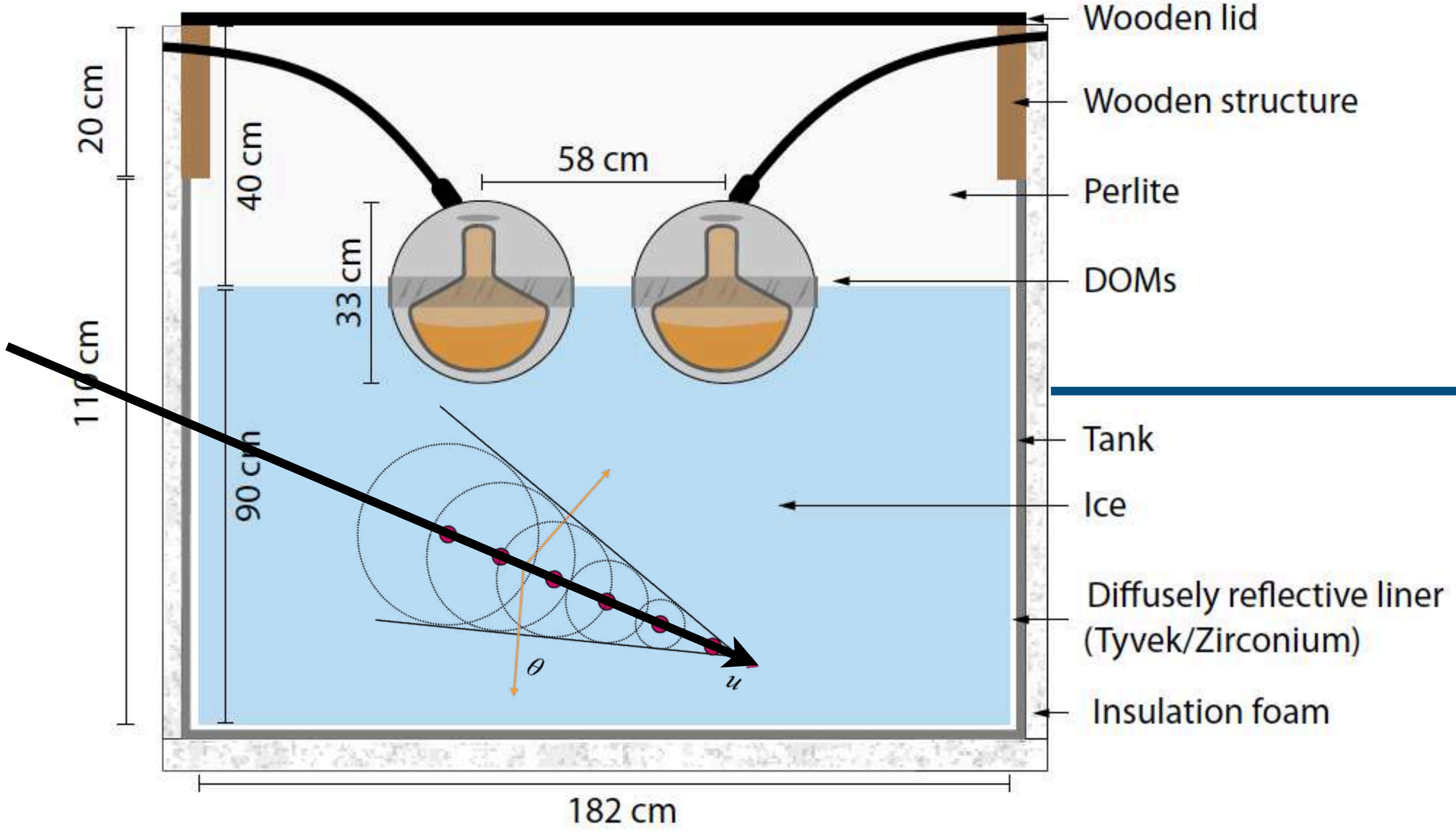

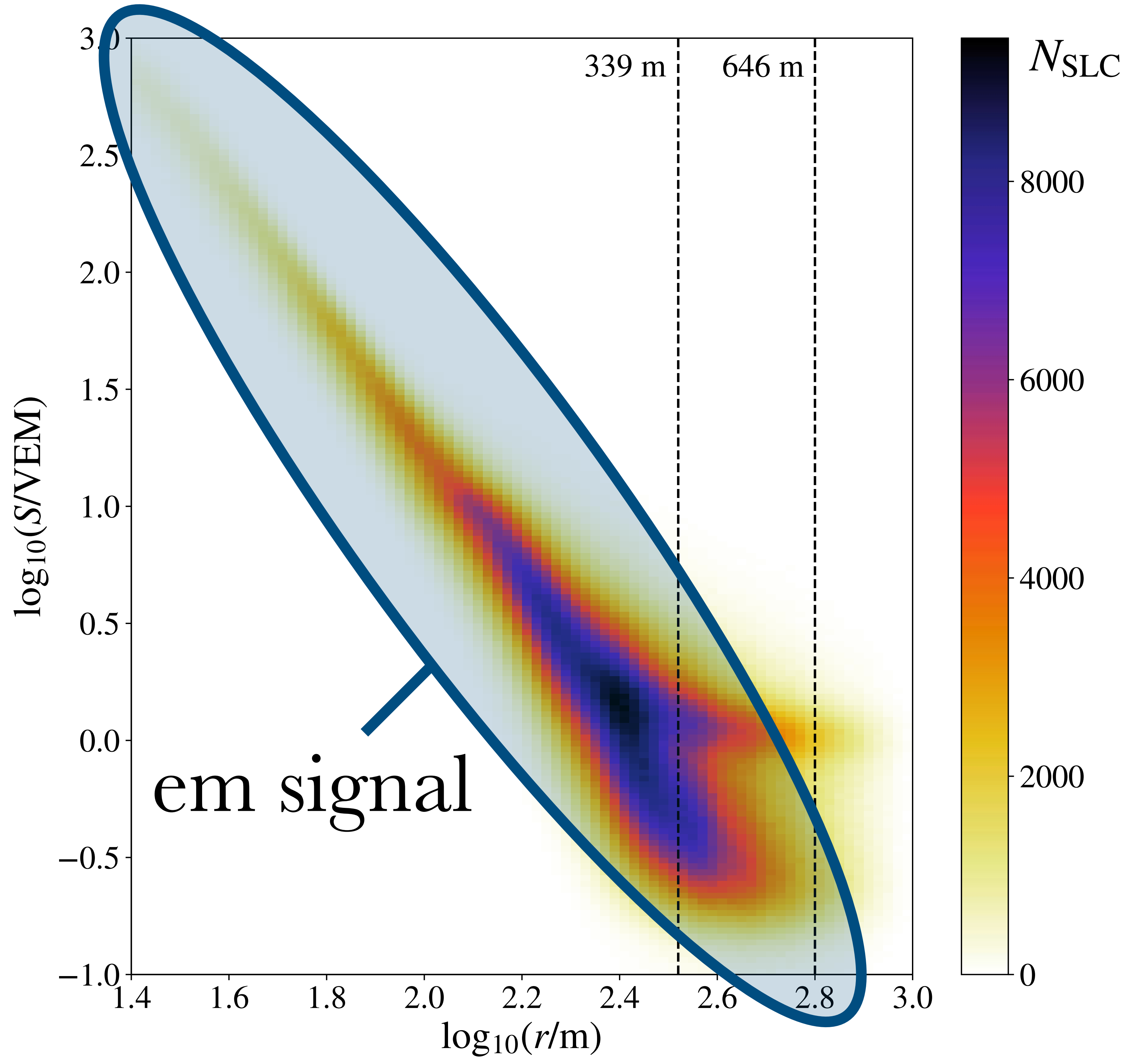

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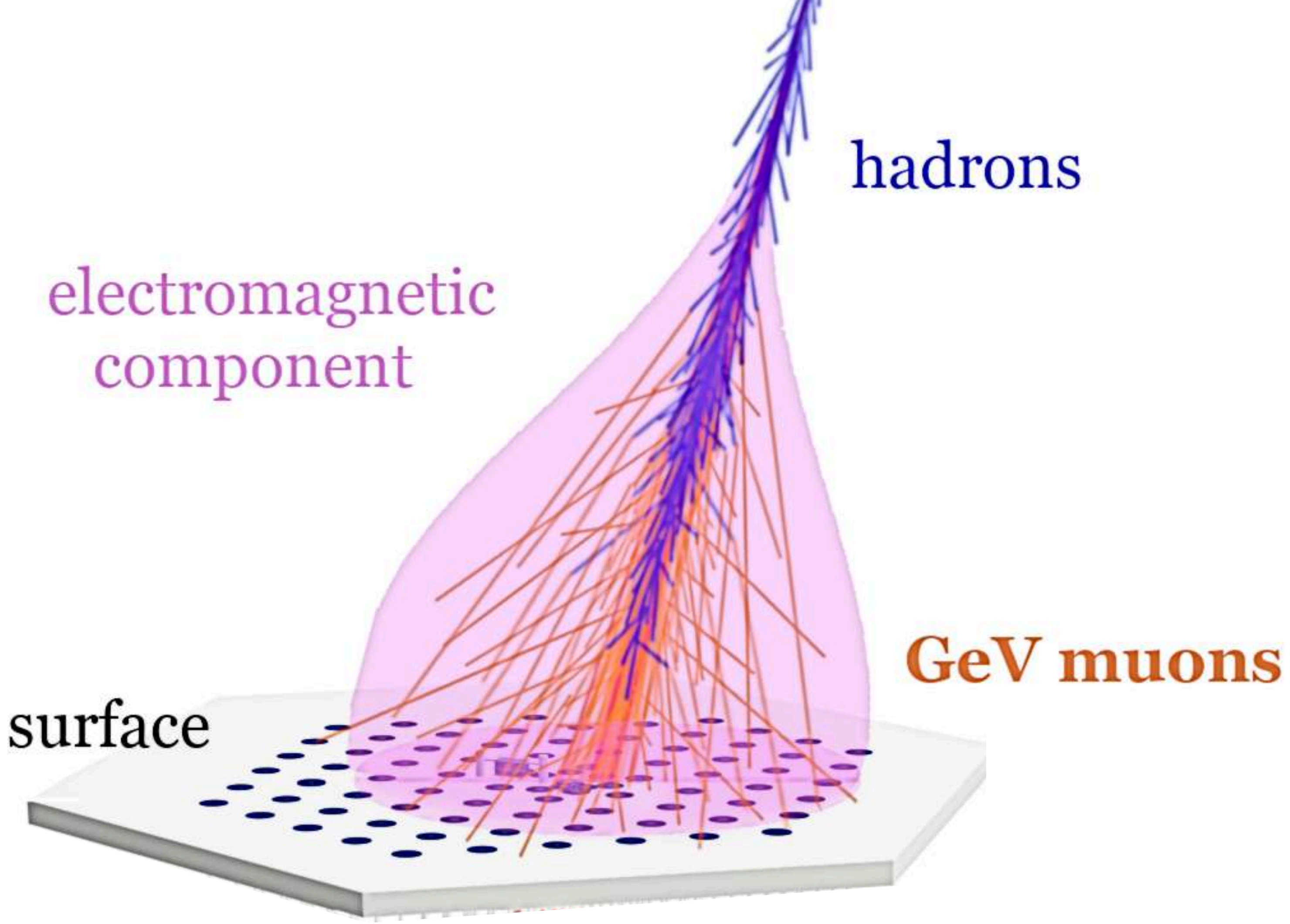

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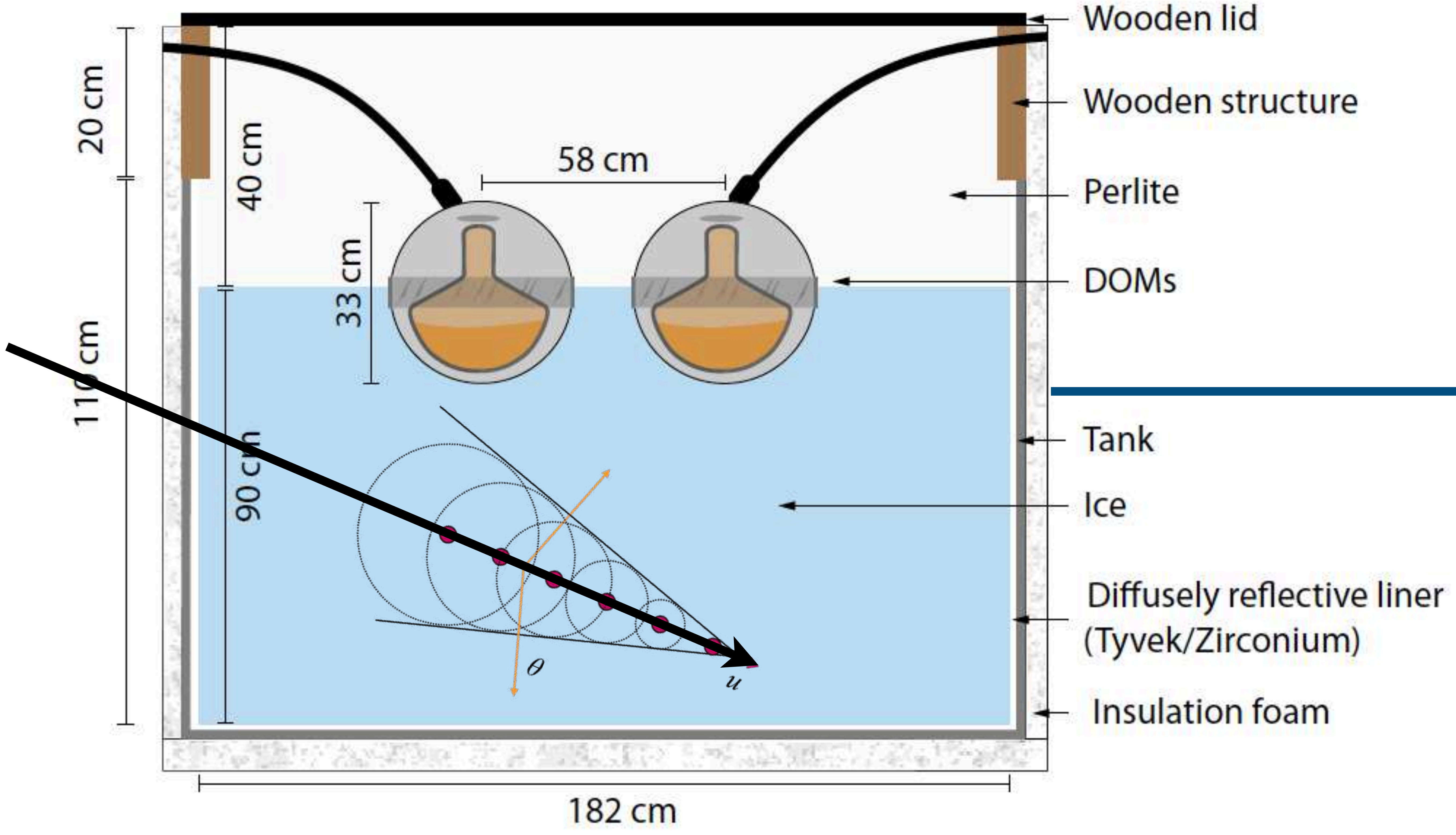
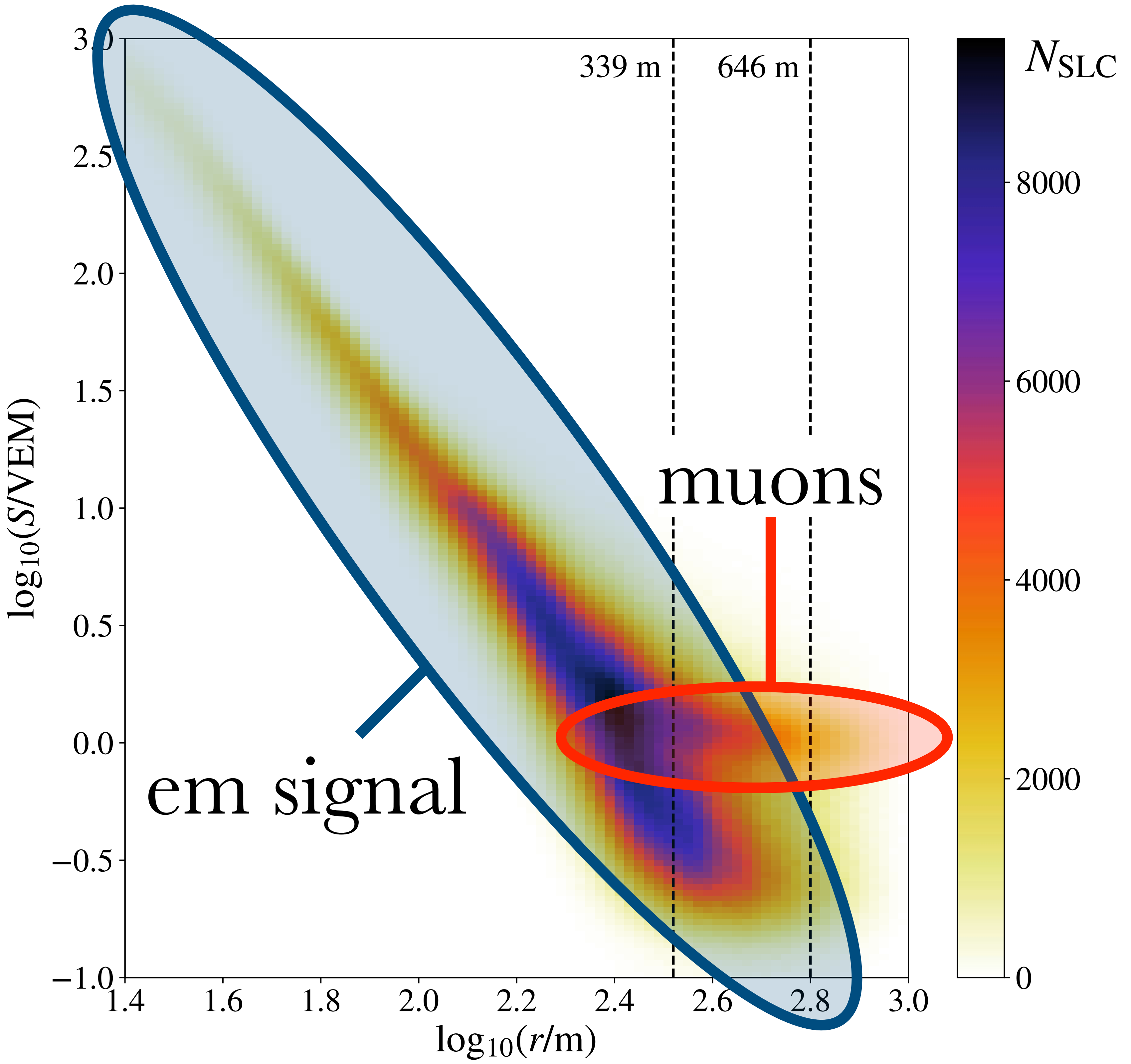
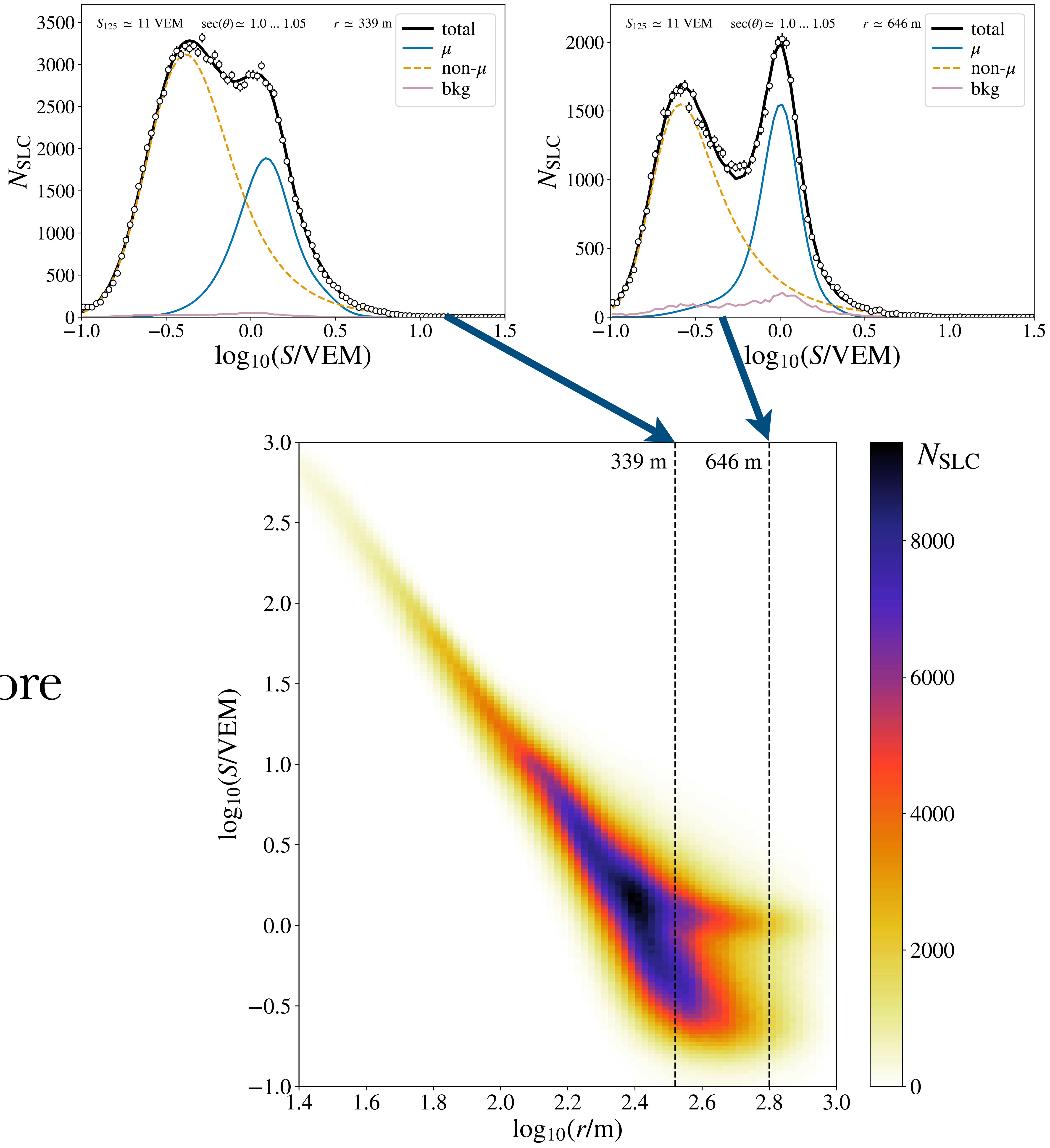




GeV Muons in IceTop

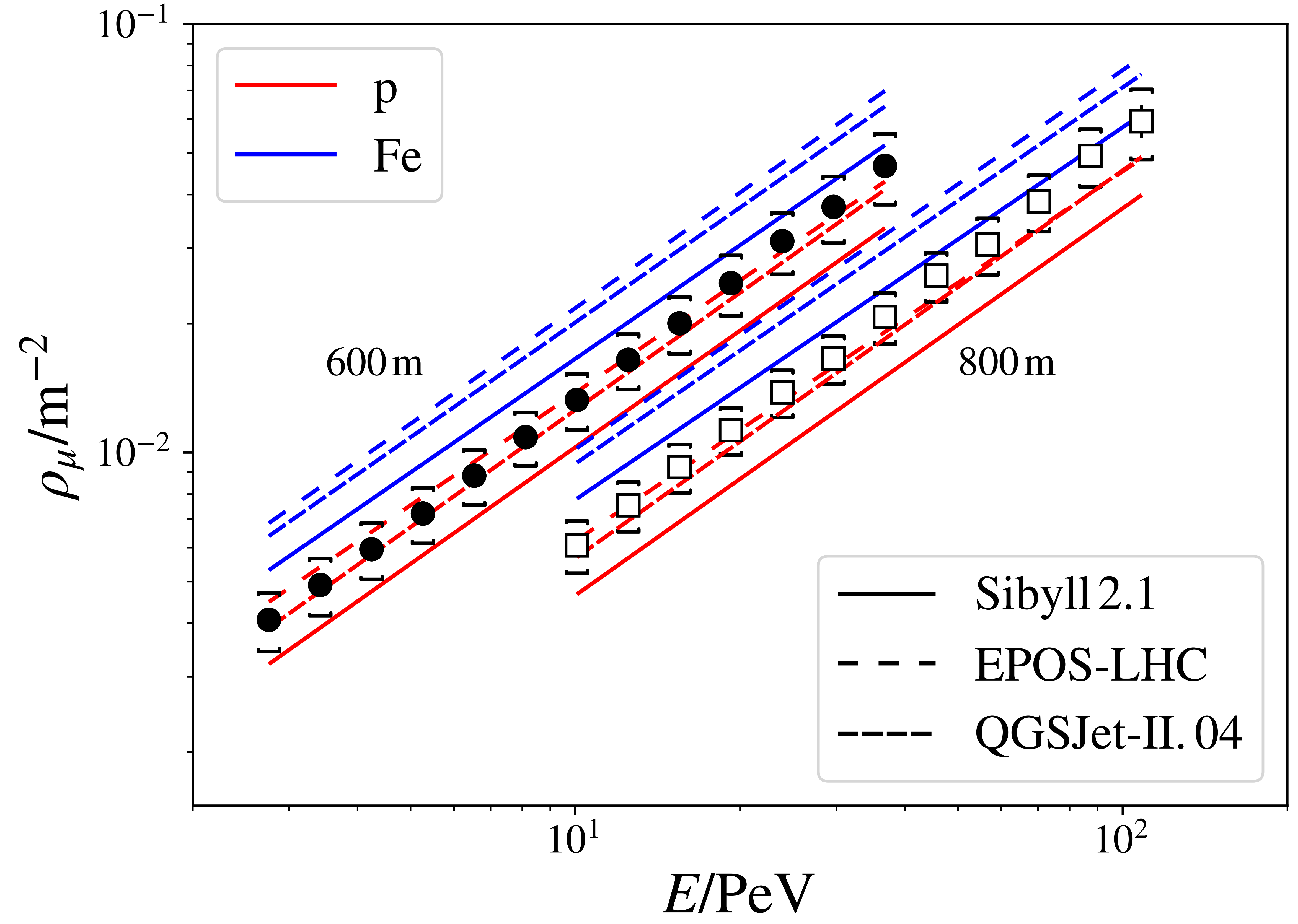
- Complex signal model, includes:
  - electromagnetic response model
  - muon response model
  - uncorrelated background
- Larger muon fraction at large distances from the shower central region
- Likelihood fits at 600 m and 800 m from the core in bins of the energy of inclined EAS ($\theta < 18°$)
- Muon density as a function of CR energy!

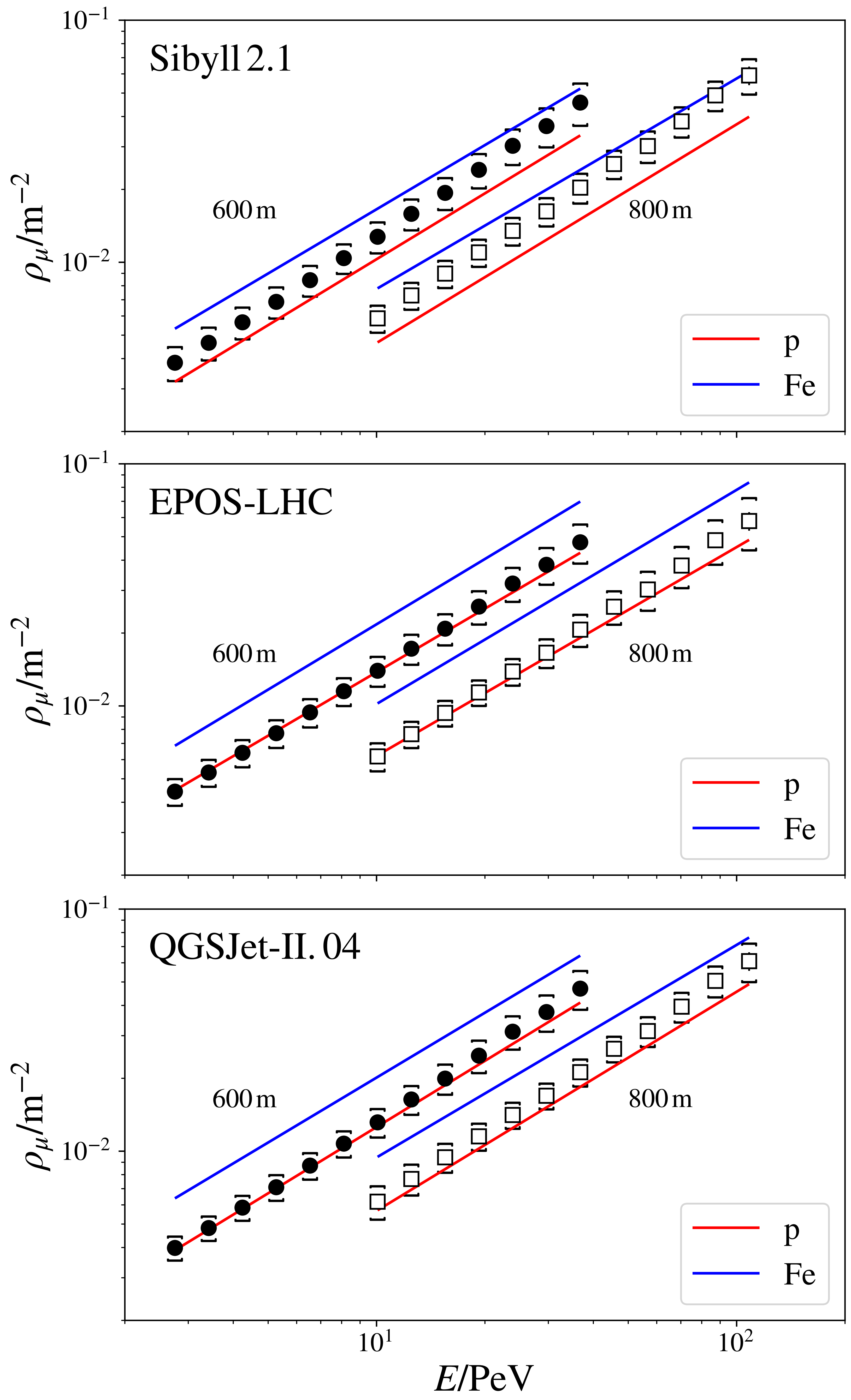
[D. Soldin et al., PoS ICRC2021 (2021) 342, IceCube Collaboration, submitted to PRD (2022)]



GeV Muons in IceTop

- Muon densities compared to model predictions





- How does the data compare to CR flux models?

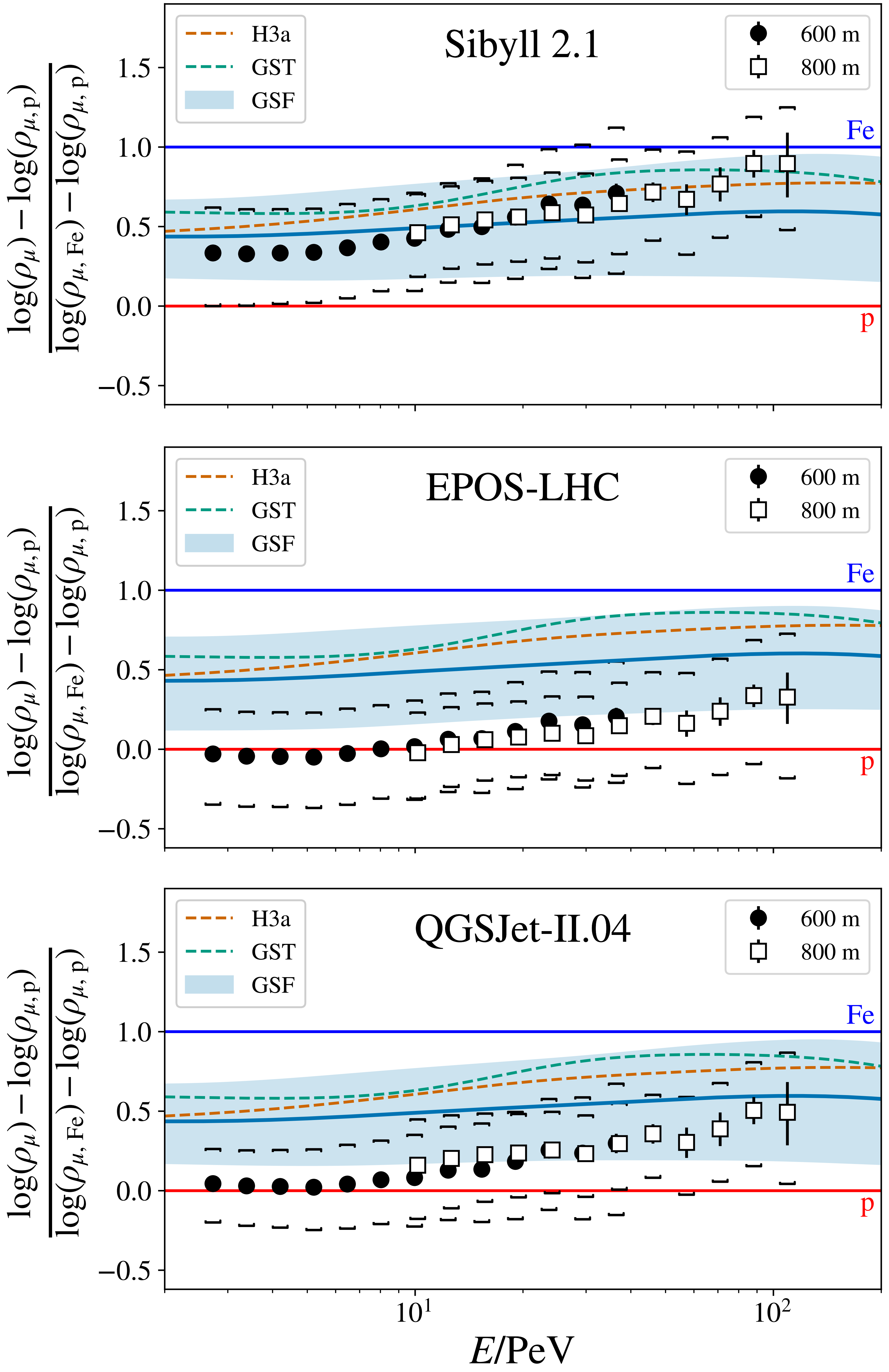
[D. Soldin et al., PoS ICRC2021 (2021) 342, IceCube Collaboration, submitted to PRD (2022)]

GeV Muons in IceTop

- The z-scale:

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

    - Proton: $z = 0$, iron: $z = 1$
- Comparison for different flux model predictions
- Best data/MC agreement for Sibyll 2.1
- EPOS and QGSJet yield very light masses (they predict more muons)
- Comparison with other experiments?



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GeV Muons in IceTop

- The z-scale:

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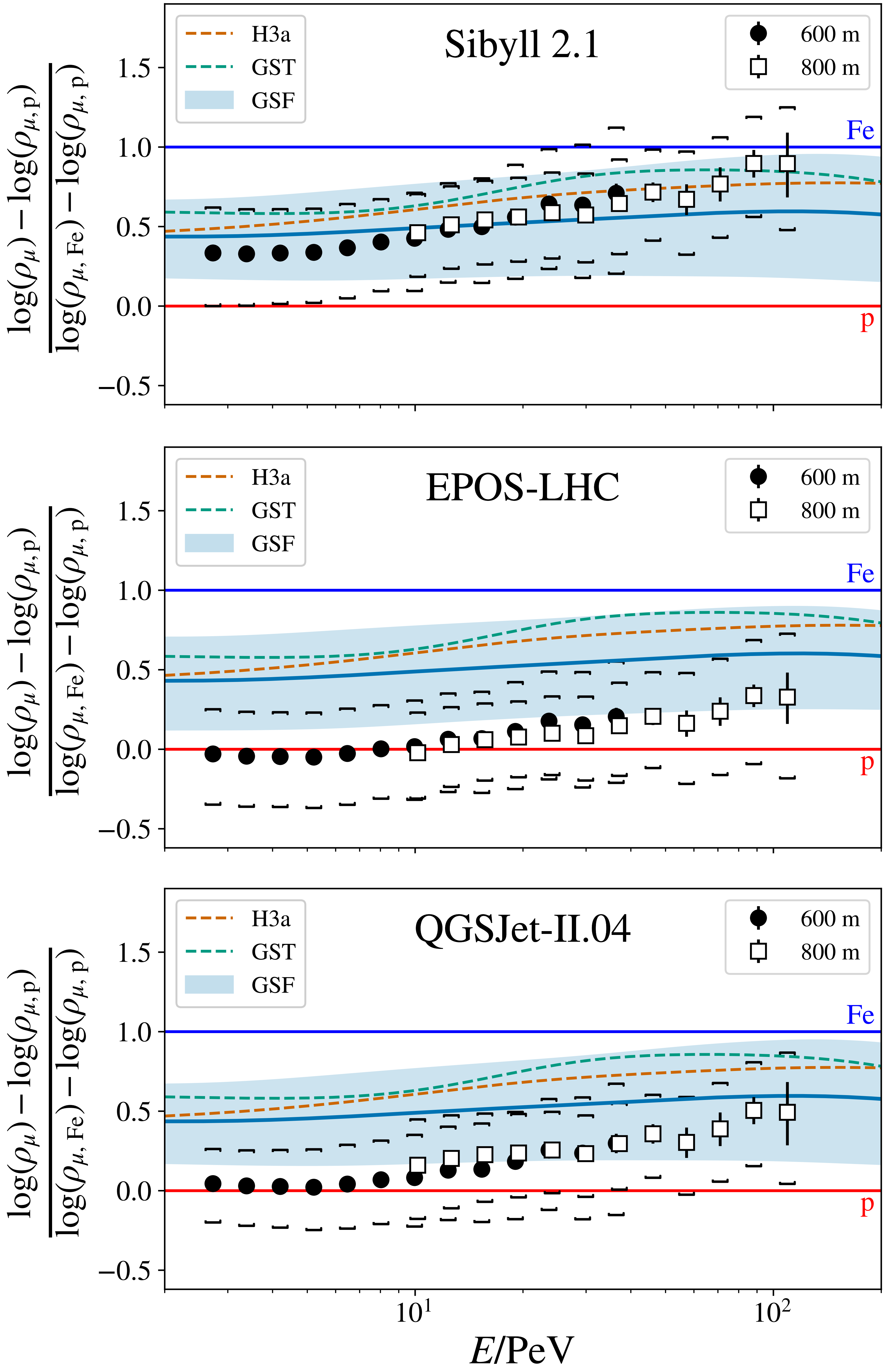

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GeV Muons in IceTop

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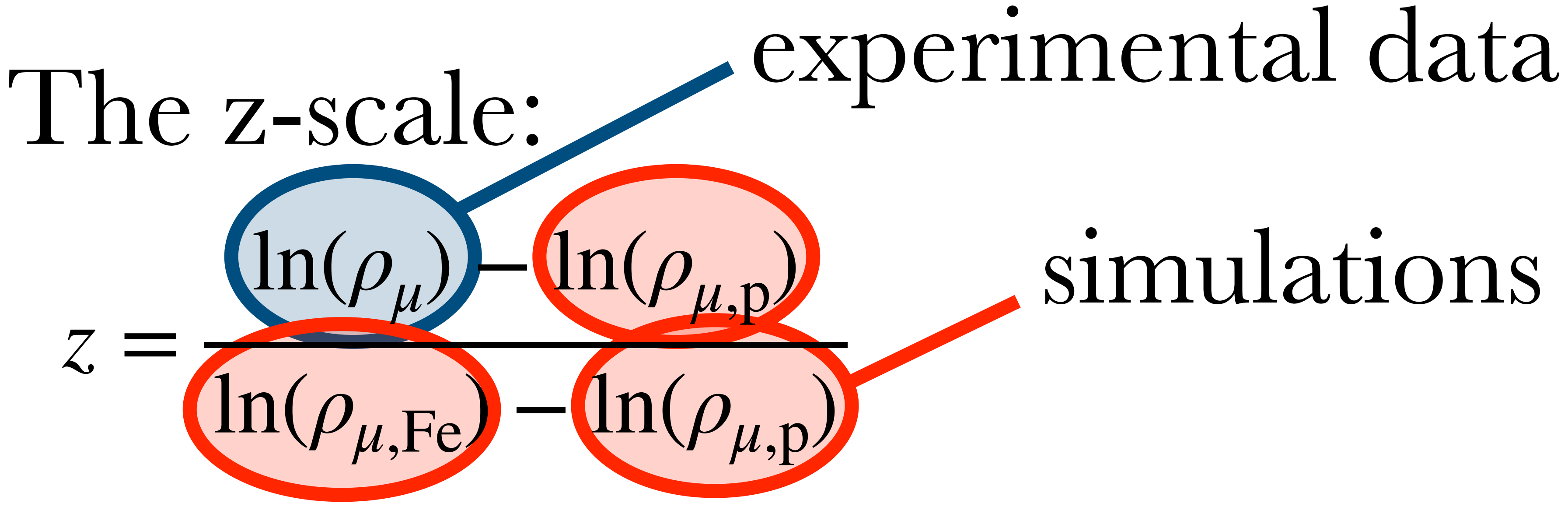

$$z = \frac{\ln(\rho_\mu) - \ln(\rho_{\mu,\mathrm{p}})}{\ln(\rho_{\mu,\mathrm{Fe}}) - \ln(\rho_{\mu,\mathrm{p}})}$$

experimental data

simulations

  - Proton: $z = 0$, iron: $z = 1$

- Comparison for different flux model predictions
- Best data/MC agreement for Sibyll 2.1
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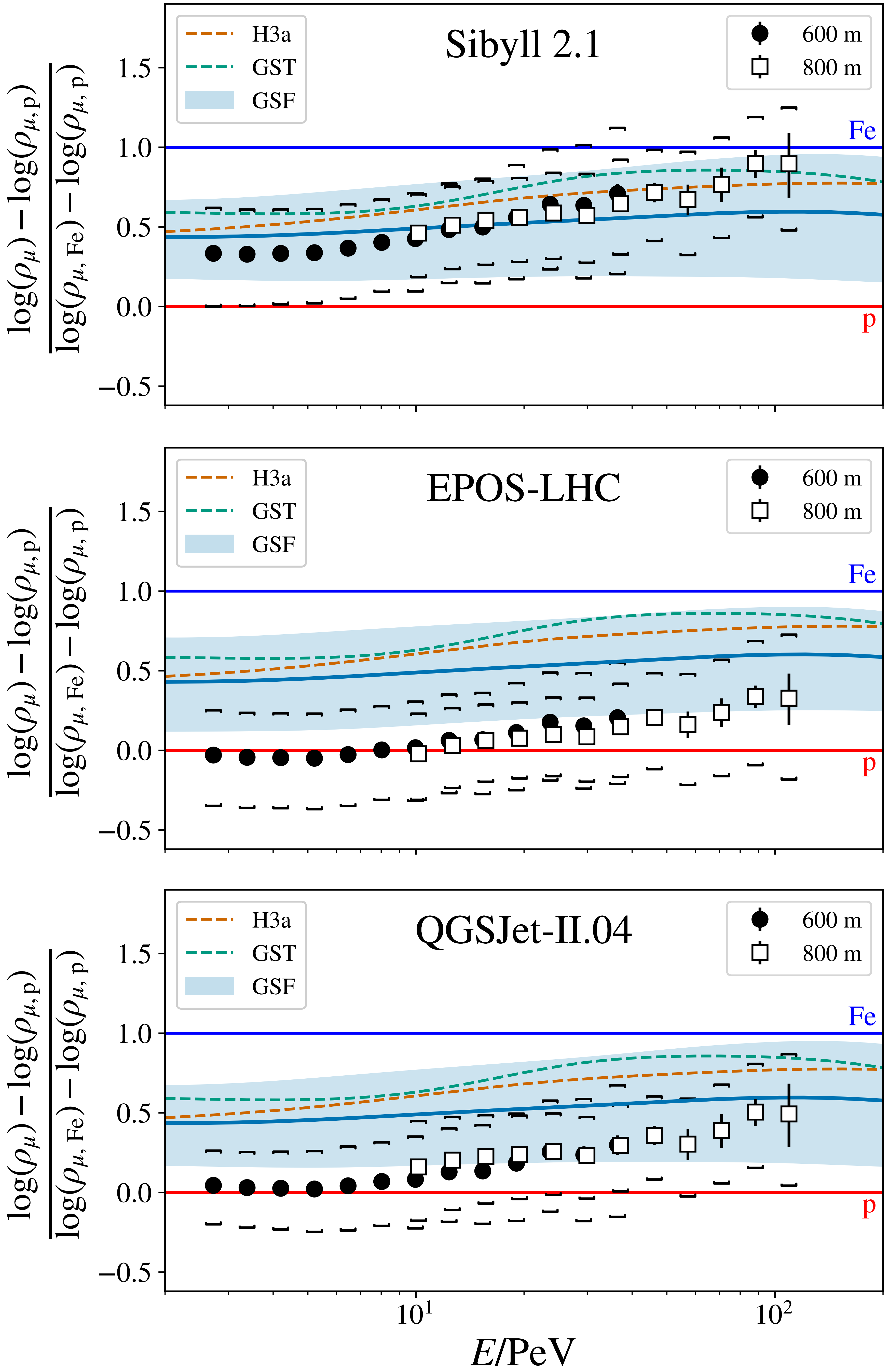
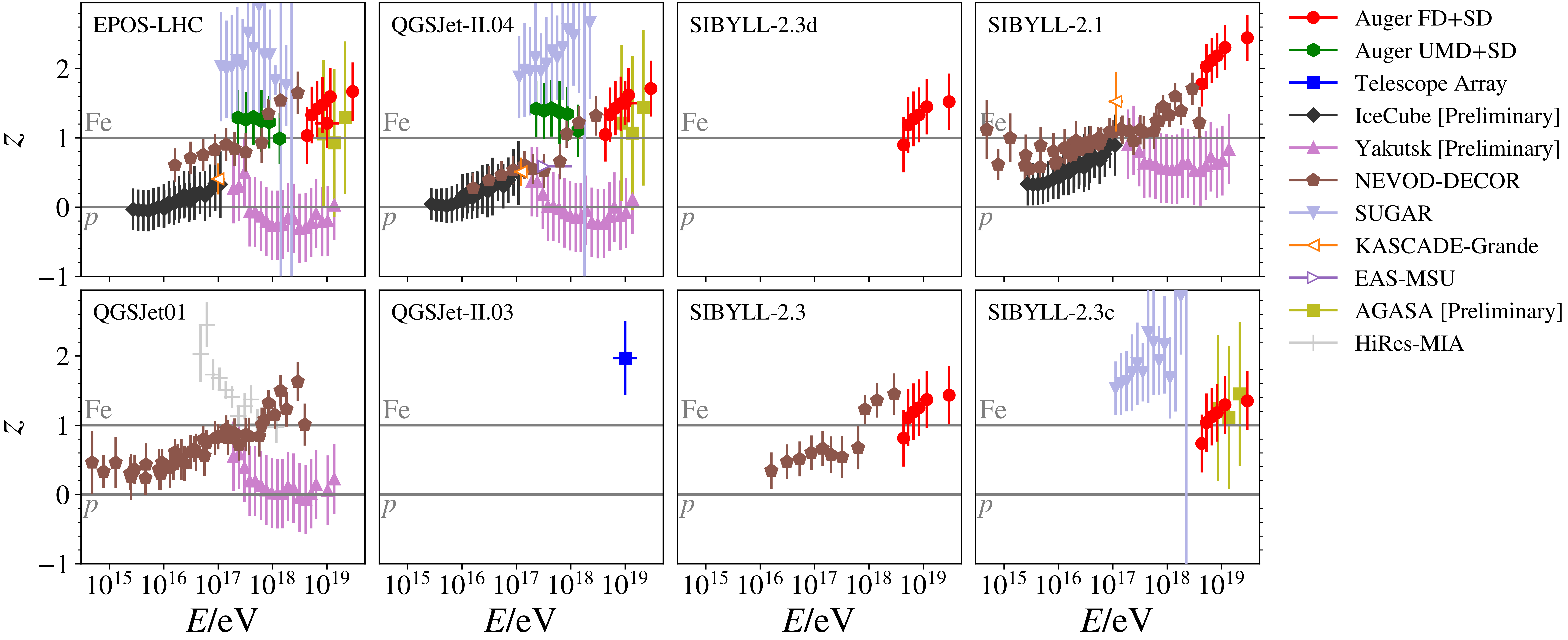


[D. Soldin et al., PoS ICRC2021 (2021) 342, IceCube Collaboration, submitted to PRD (2022)]

Data Comparison

- Muon numbers measured by 9 EAS experiments

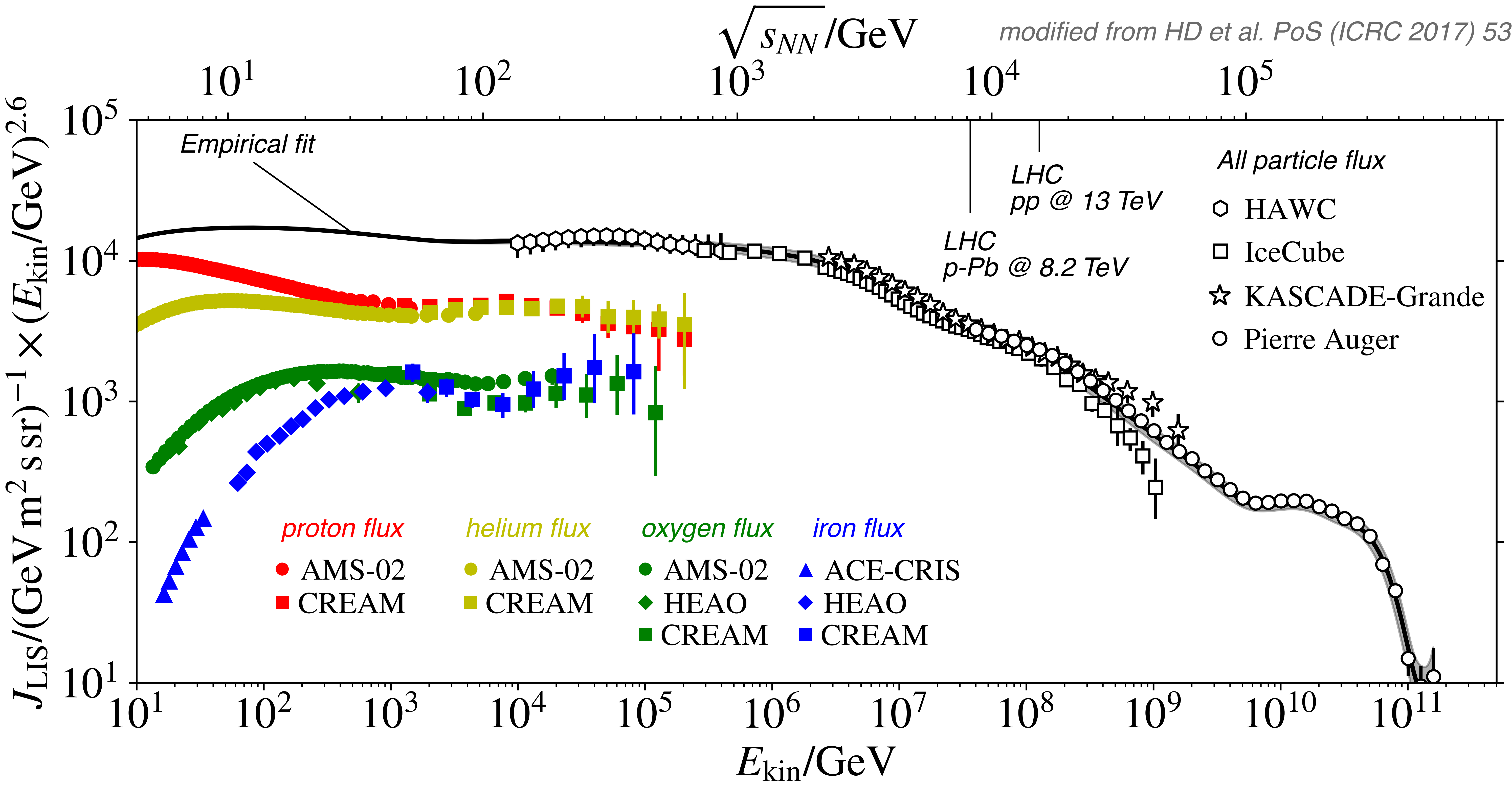
[D. Soldin et al., PoS ICRC2021 (2021) 349]



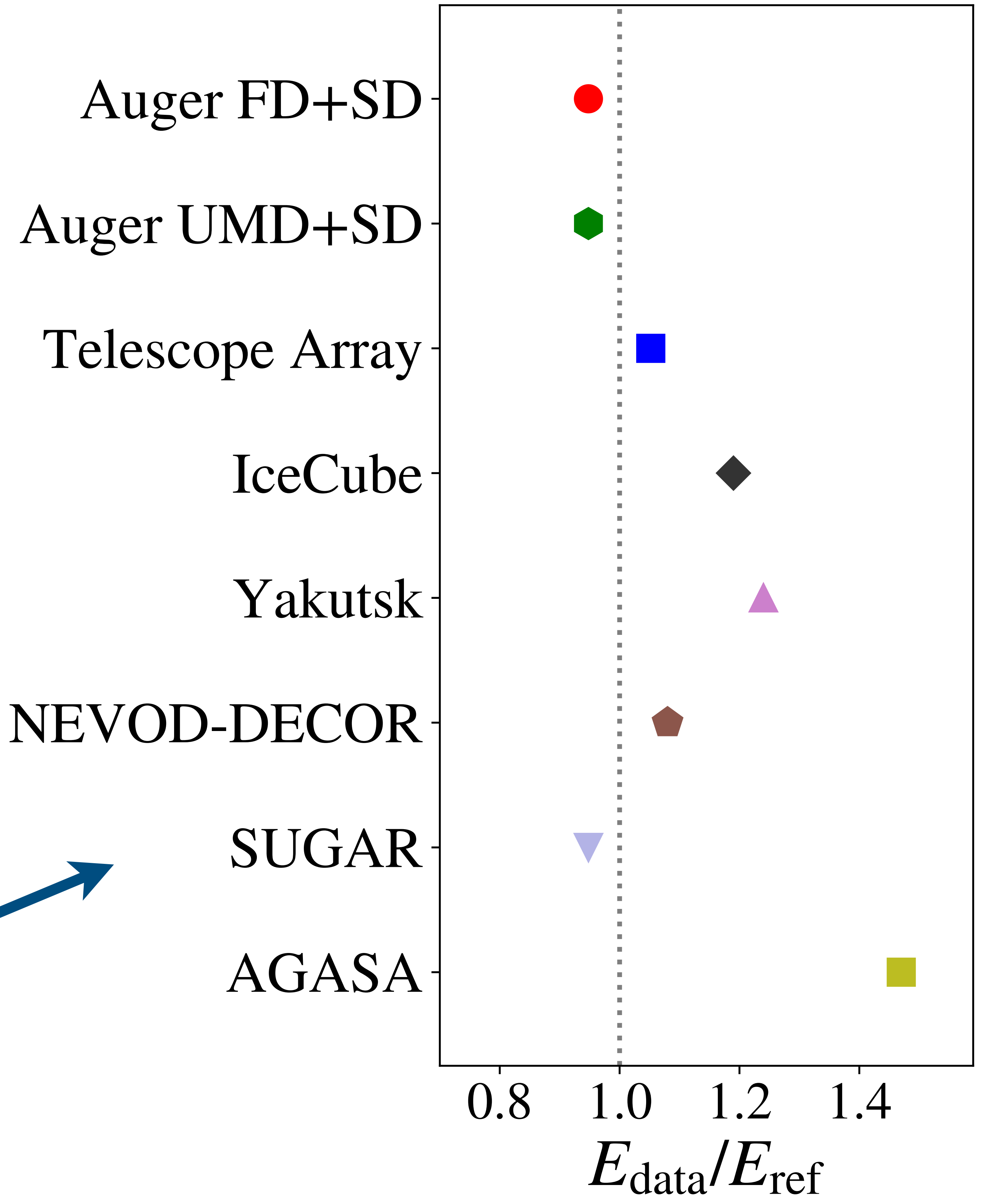
- Working Group for Hadronic Interactions and Shower Physics (WHISP)

Energy-Scale Cross-Calibration

- Known energy-scale offsets between EAS experiments!
- 20% offset in energy causes 18% shift in muons!
  - Energy rescaling required! ("line up all features")
- Reference model: Global-Spline Fit (GSF)



modified from HD et al. PoS (ICRC 2017) 533

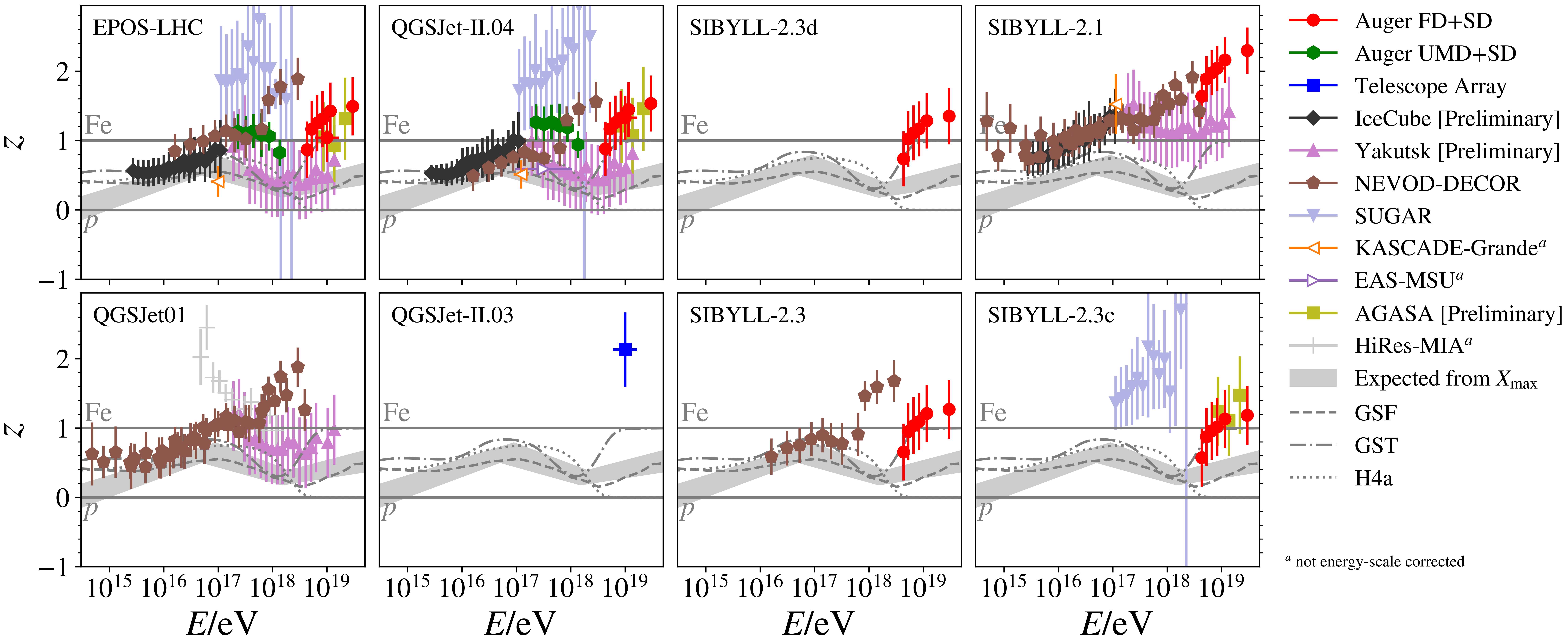


[H. P. Dembinski et al., PoS(ICRC2017)533]

The Muon Puzzle

- Muon numbers in EAS after energy-scale cross-calibration

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



- (Most) muon measurements indicate mass composition heavier than iron at high E_0!

The Muon Puzzle

Muon Puzzle

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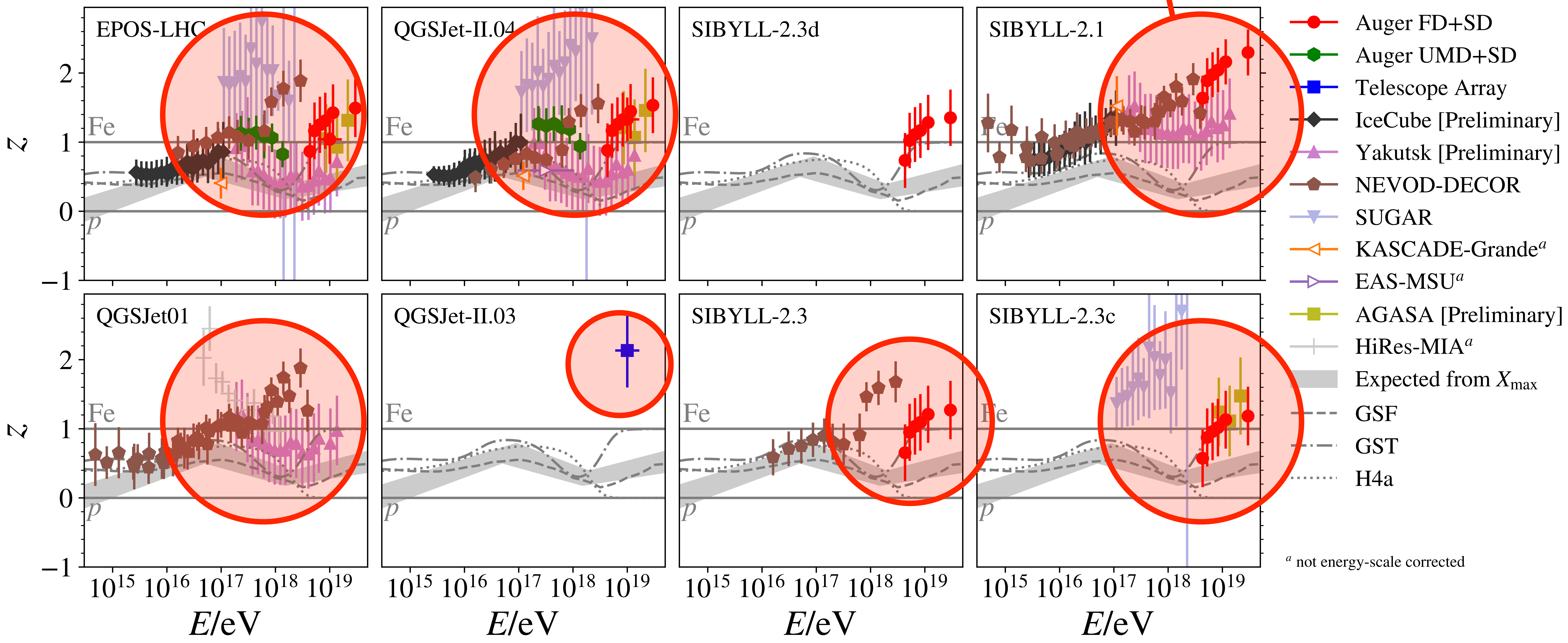
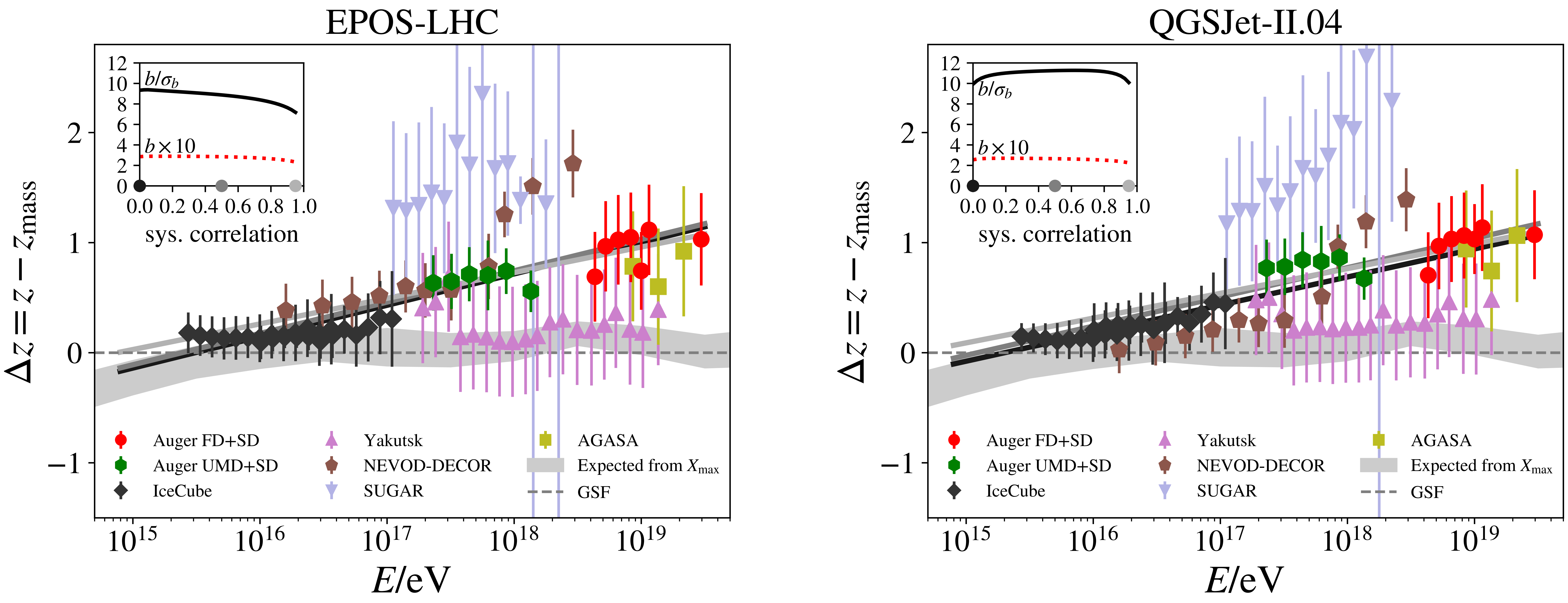
[D. Soldin et al., PoS ICRC2021 (2021) 349]



- (Most) muon measurements indicate mass composition heavier than iron at high E_0!

The Muon Puzzle

- Subtract mass-dependence through $\Delta z = z - z_{\text{mass}}$, i.e. data/model agreement at $\Delta z = 0$
- The expected z_{mass} is obtained from the Global Spline Fit (GSF) flux model which is (mostly) consistent with measurements of the maximum of shower depth, X_{max}



EPOS-LHC

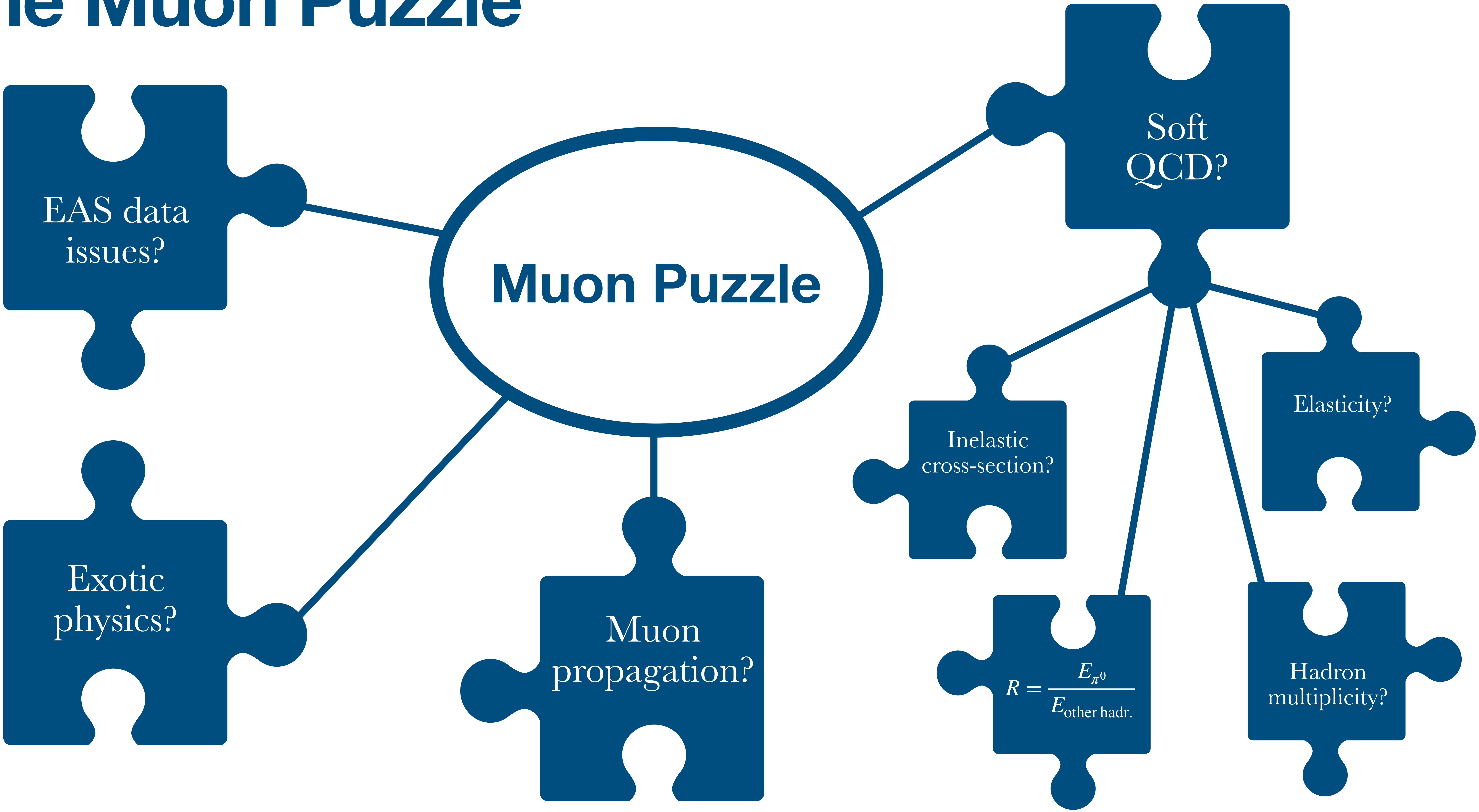
QGSJet-II.04

- <u>Slope of a linear fit is non-zero with a significance at $\gtrsim 8\sigma$ level</u>

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

For details, please see [J. Albrecht et al., Astrophys. Space Sci. 367 (2022) 3, 27]

The Muon Puzzle



Muon Puzzle

EAS data issues?

Exotic physics?

Muon propagation?

Soft QCD?

Inelastic cross-section?

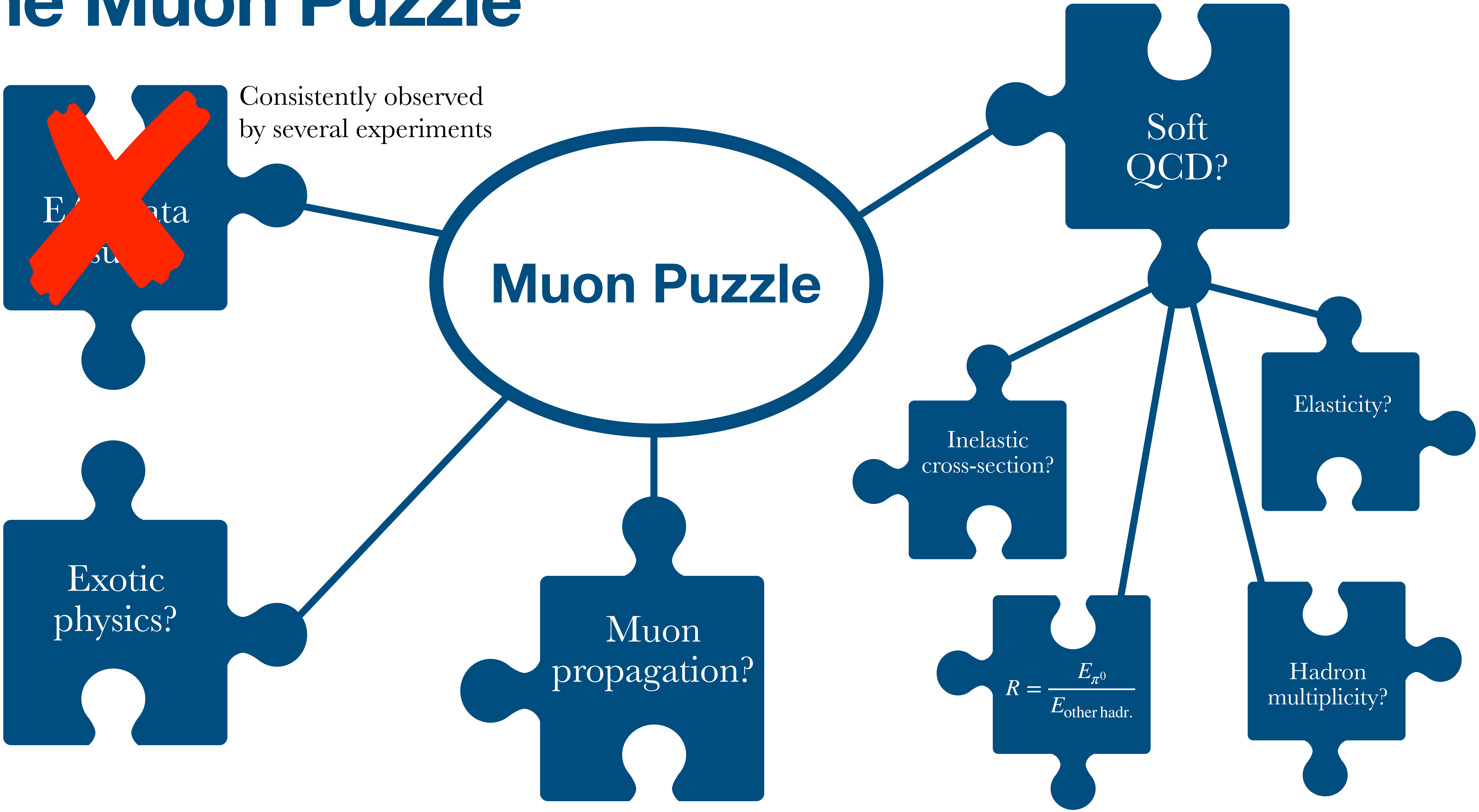
Elasticity?

$R = \frac{E_{\pi^0}}{E_{\text{other hadr.}}}$

Hadron multiplicity?

For details, please see [J. Albrecht et al., Astrophys. Space Sci. 367 (2022) 3, 27]

The Muon Puzzle



Muon Puzzle

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Consistently observed
by several experiments

Exotic
physics?

Muon
propagation?

Soft
QCD?

Inelastic
cross-section?

Elasticity?

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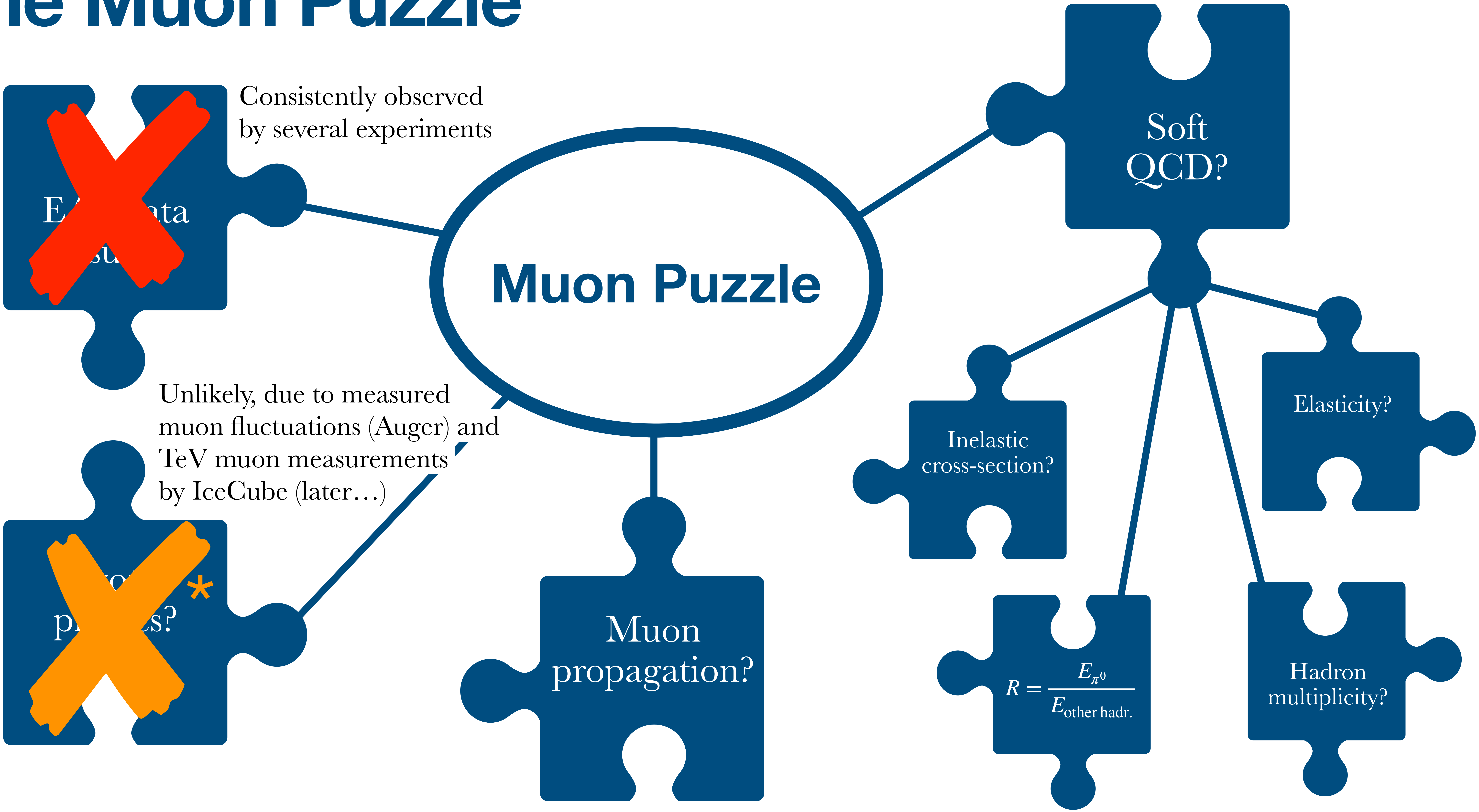

Muon Puzzle

Consistently observed by several experiments

Unlikely, due to measured muon fluctuations (Auger) and TeV muon measurements by IceCube (later…)

Muon propagation?

Soft QCD?

Inelastic cross-section?

Elasticity?

$R = \frac{E_{\pi^0}}{E_{\text{other hadr.}}}$

Hadron multiplicity?

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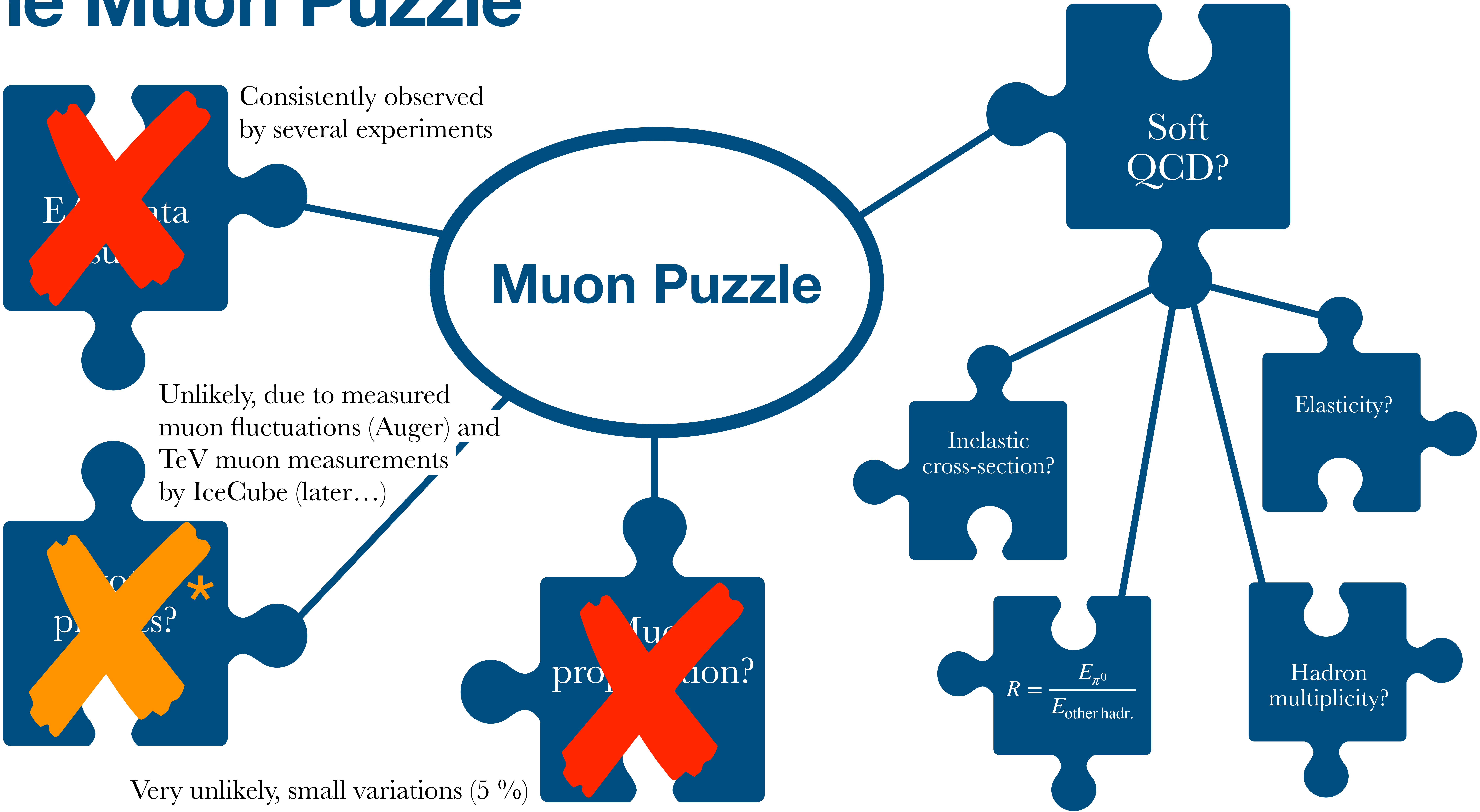


Consistently observed
by several experiments

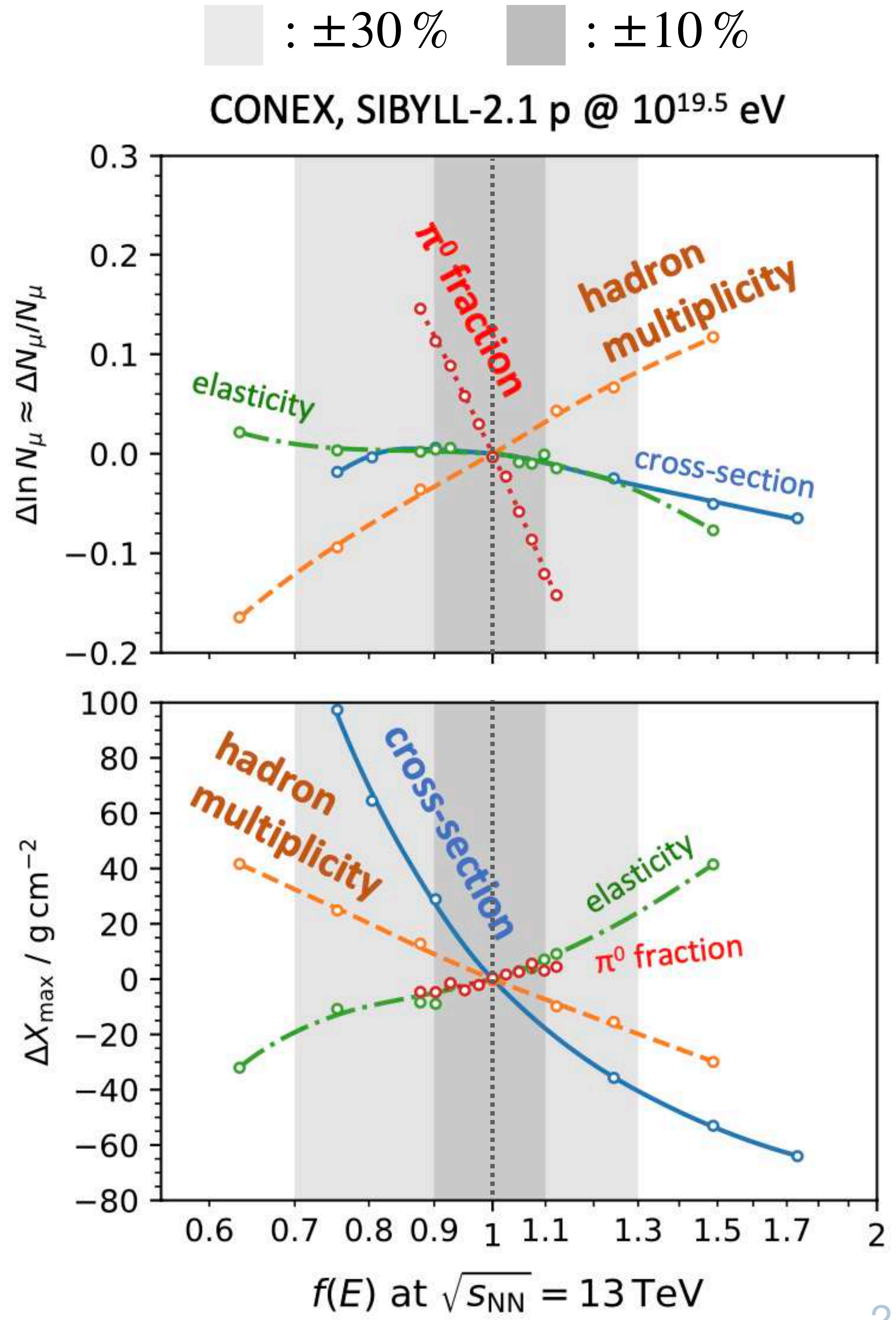
Unlikely, due to measured
muon fluctuations (Auger) and
TeV muon measurements
by IceCube (later…)

Very unlikely, small variations (5 %)
between shower codes, well studied

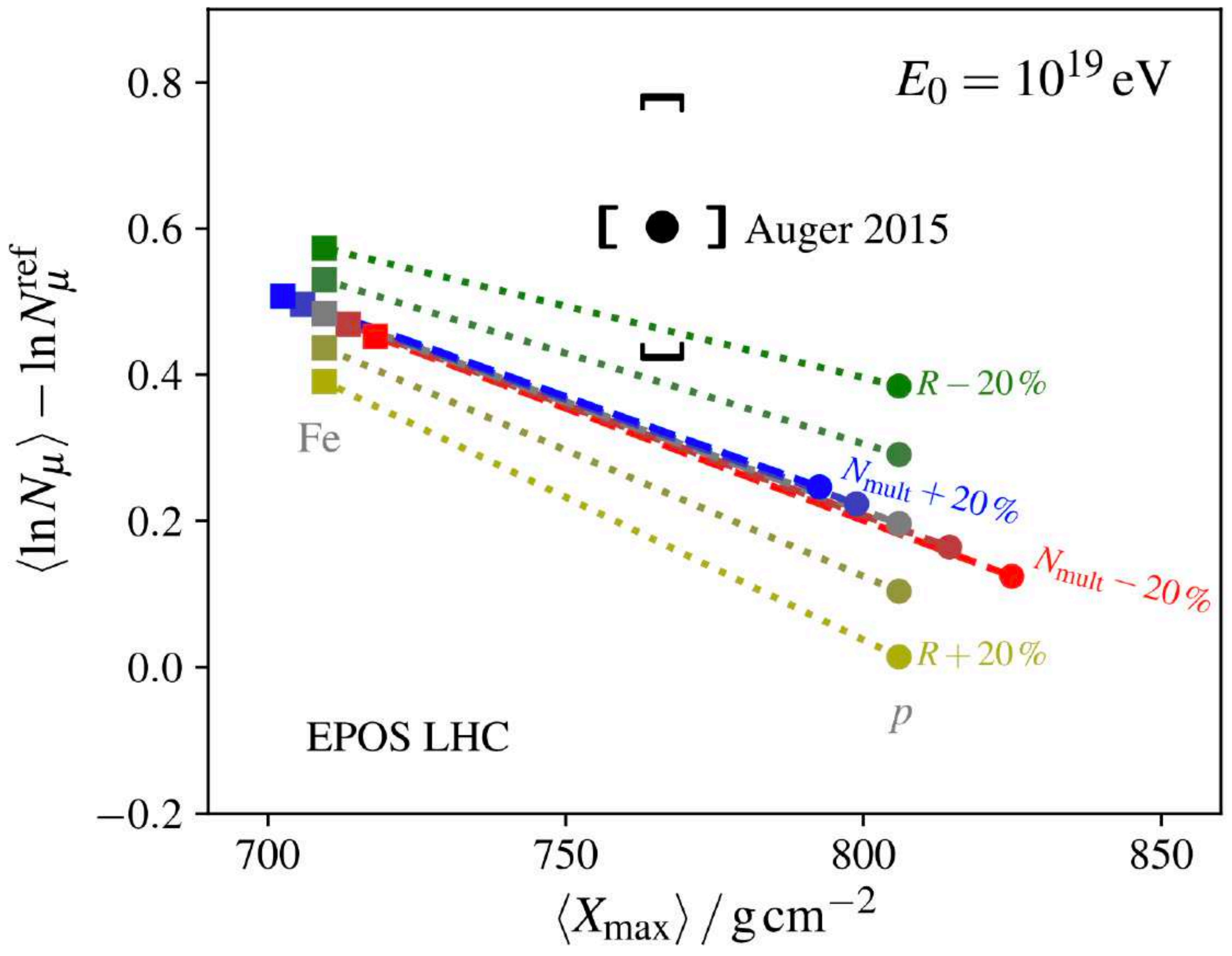
The Muon Puzzle

- Number of muons, N_μ: (needs to be increased)
  - Very sensitive to π^0 fraction
  - Sensitive to hadron multiplicity
- Shower depth, $X_{\max}$: (needs to remain unchanged)
  - Very sensitive to cross-section
  - Sensitive to hadron multiplicity
  - Not sensitive to π^0 fraction
- Only the π^0 fraction, R, can (barely) solve the muon puzzle!

[R. Ulrich, R. Engel, M. Unger, PRD 83 (2011) 054026]

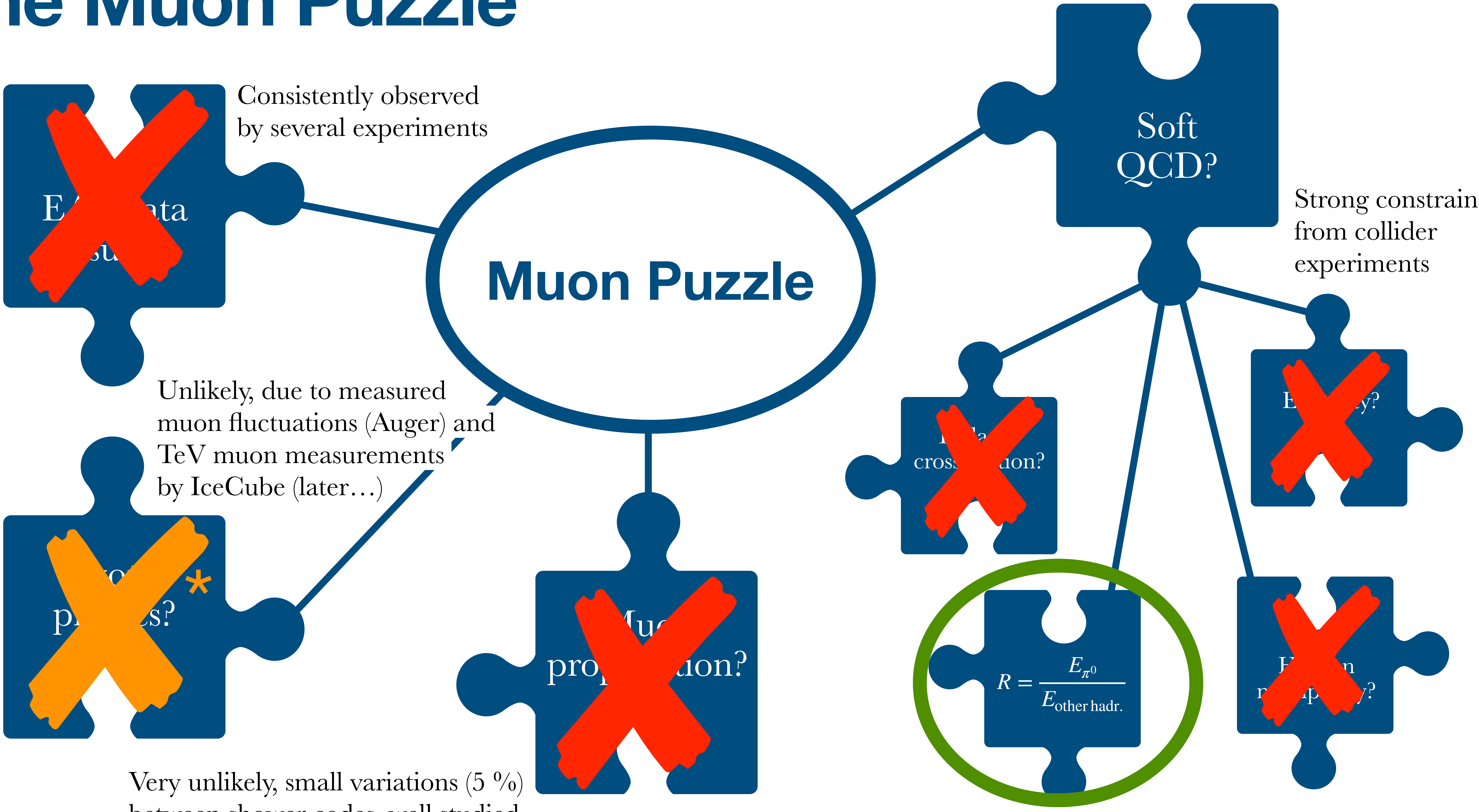


[S. Baur et al., arXiv:1902.09265 (2019)]



For details, please see [J. Albrecht et al., Astrophys. Space Sci. 367 (2022) 3, 27]

The Muon Puzzle



Consistently observed by several experiments

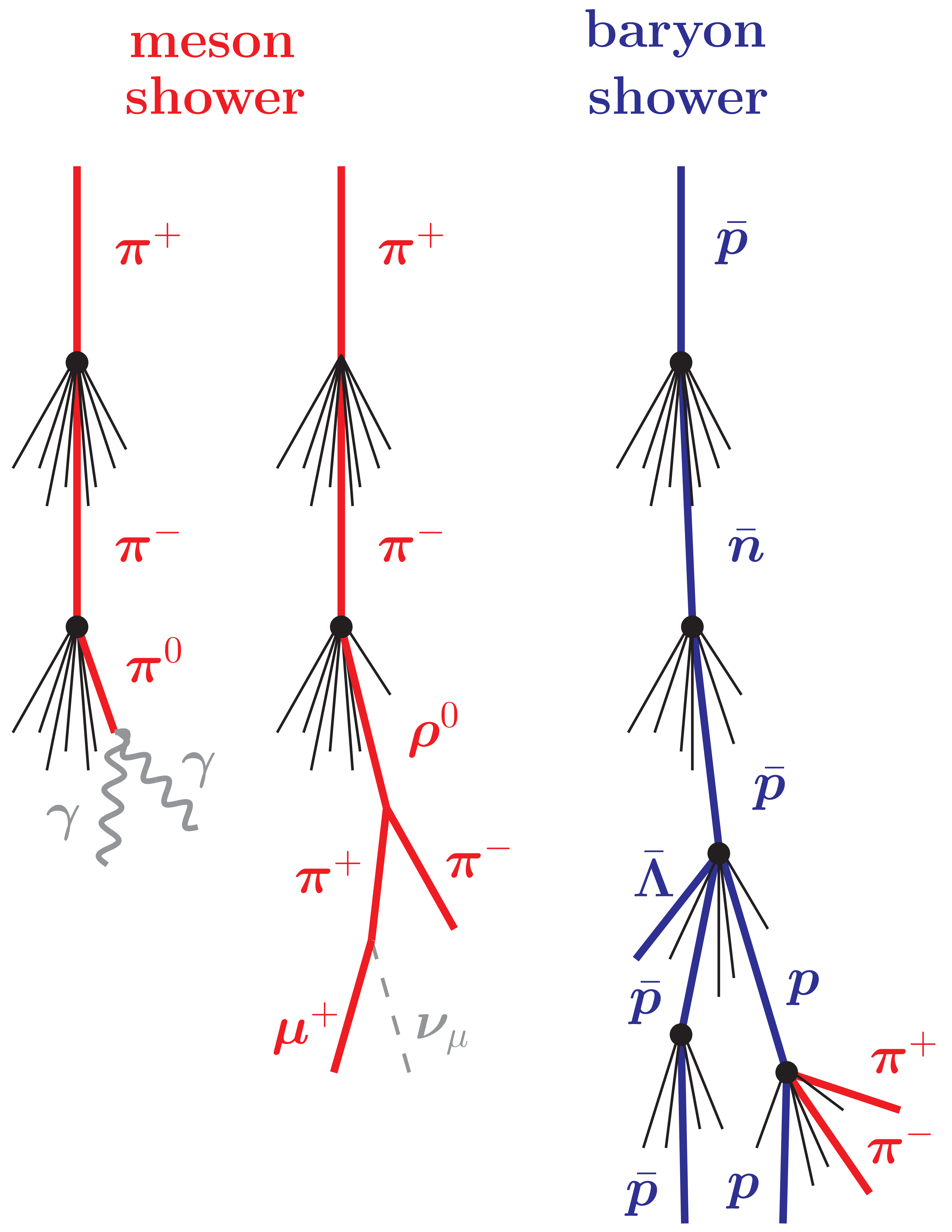
Unlikely, due to measured muon fluctuations (Auger) and TeV muon measurements by IceCube (later…)

Very unlikely, small variations (5 %) between shower codes, well studied

Strong constraints from collider experiments

The Muon Puzzle

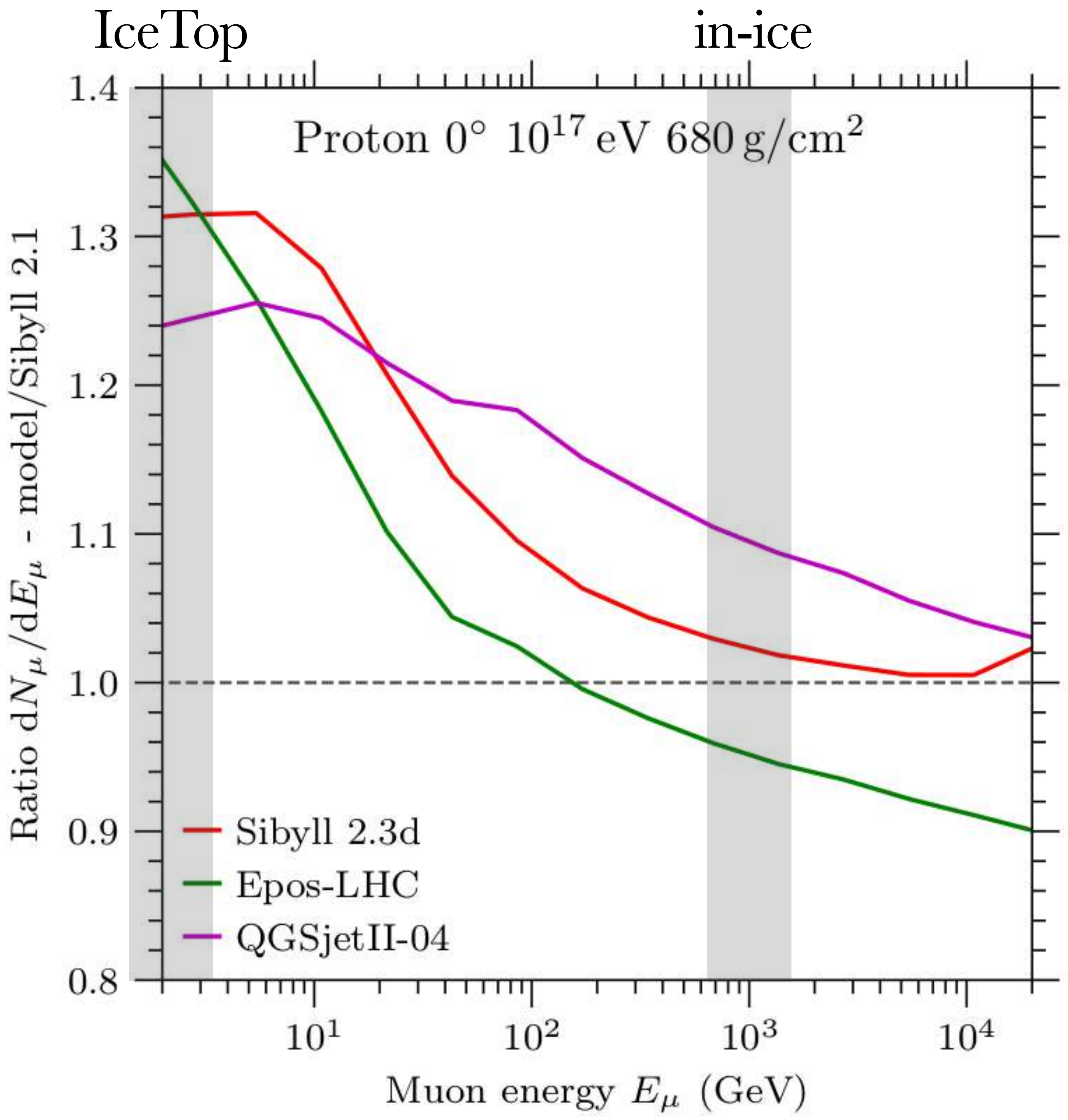
- Difficult to change R within standard QCD
- Possible explanations for the Muon Puzzle:
  - Neutral rho meson enhancement, e.g. [1]
    - Decay of ρ_0 via charged pions into muons
    - Muon production at all energies
  - Baryon enhancement, e.g. [2]
    - Many re-interactions, low-energy particles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

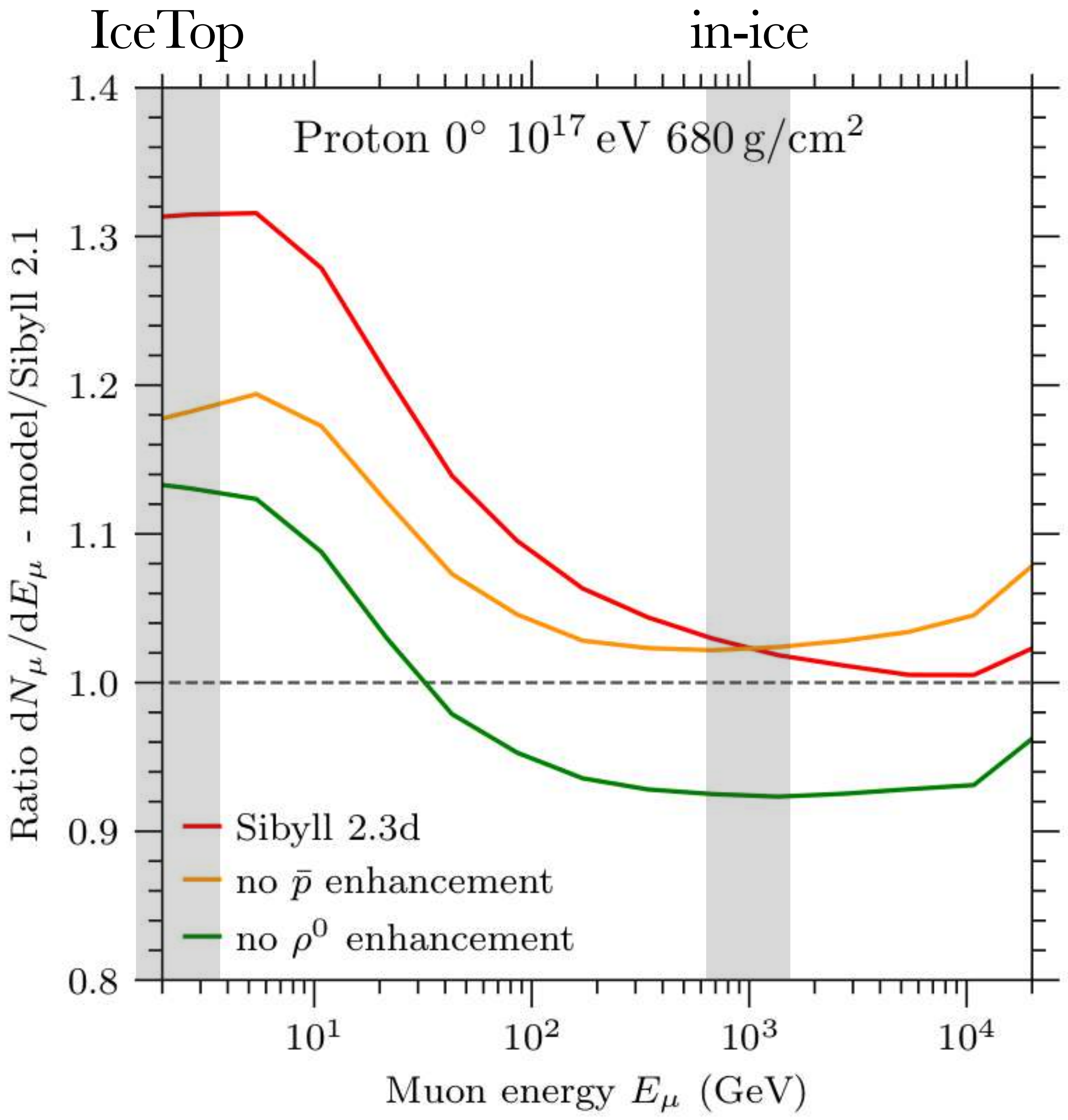


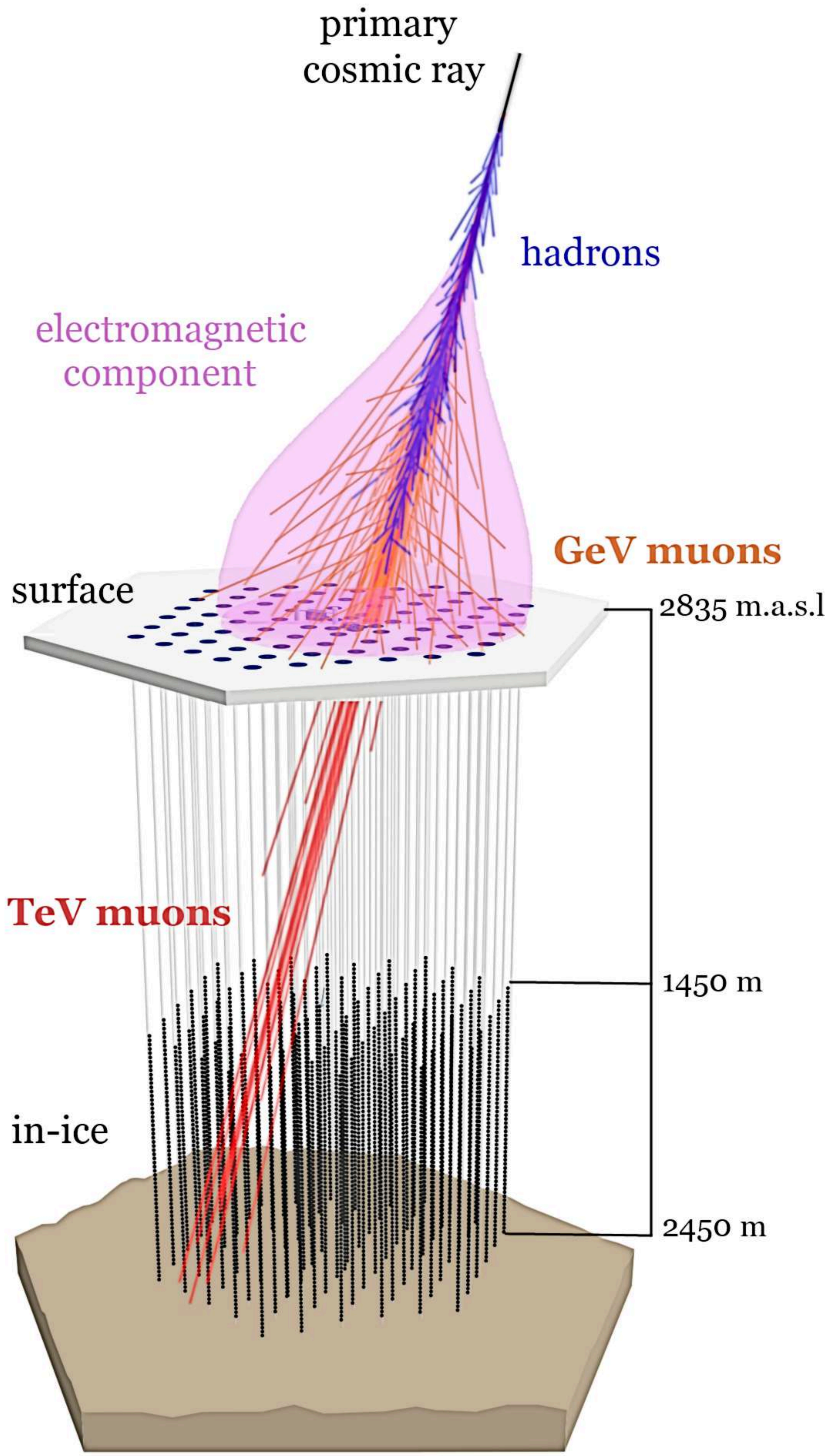
[1]: See e.g. [F. Riehn, R. Engel, A. Fedynitch, T. K. Gaisser, T. Stanev, Phys. Rev. D 102 (2020)]
[2]: See e.g. [T. Pierog, K. Werner, Phys. Rev. Lett., 101 (2008)]
[3]: See e.g. [ALICE Collaboration, Nature Phys. 13 (2017) 535]

The Muon Puzzle and IceCube

- Coincident measurements provide spectral muon information
- Unique tests of multi-particle production (forward region)!
- Will strongly constrain / exclude muon production models
- Crucial contribution to solve the Muon Puzzle



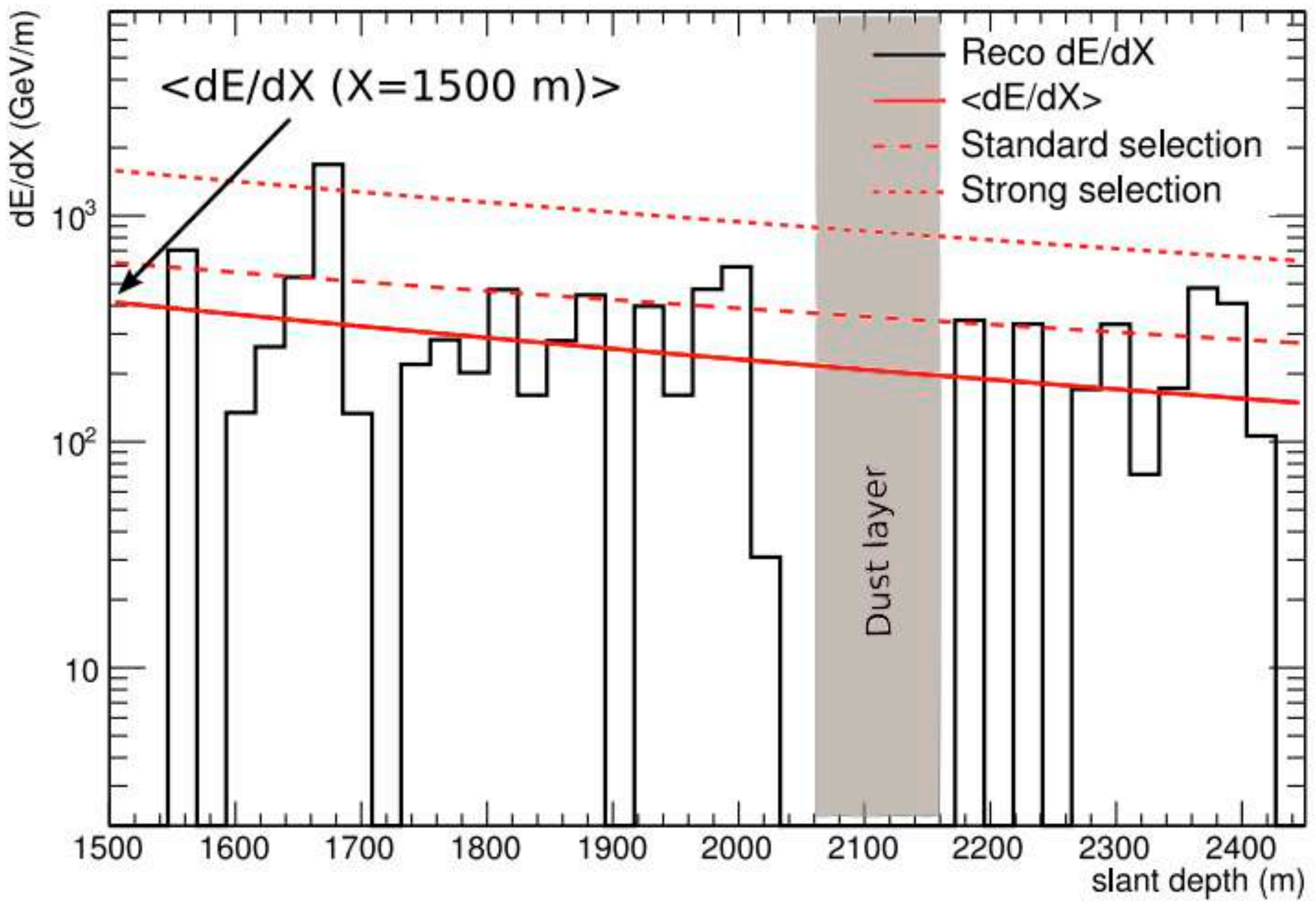


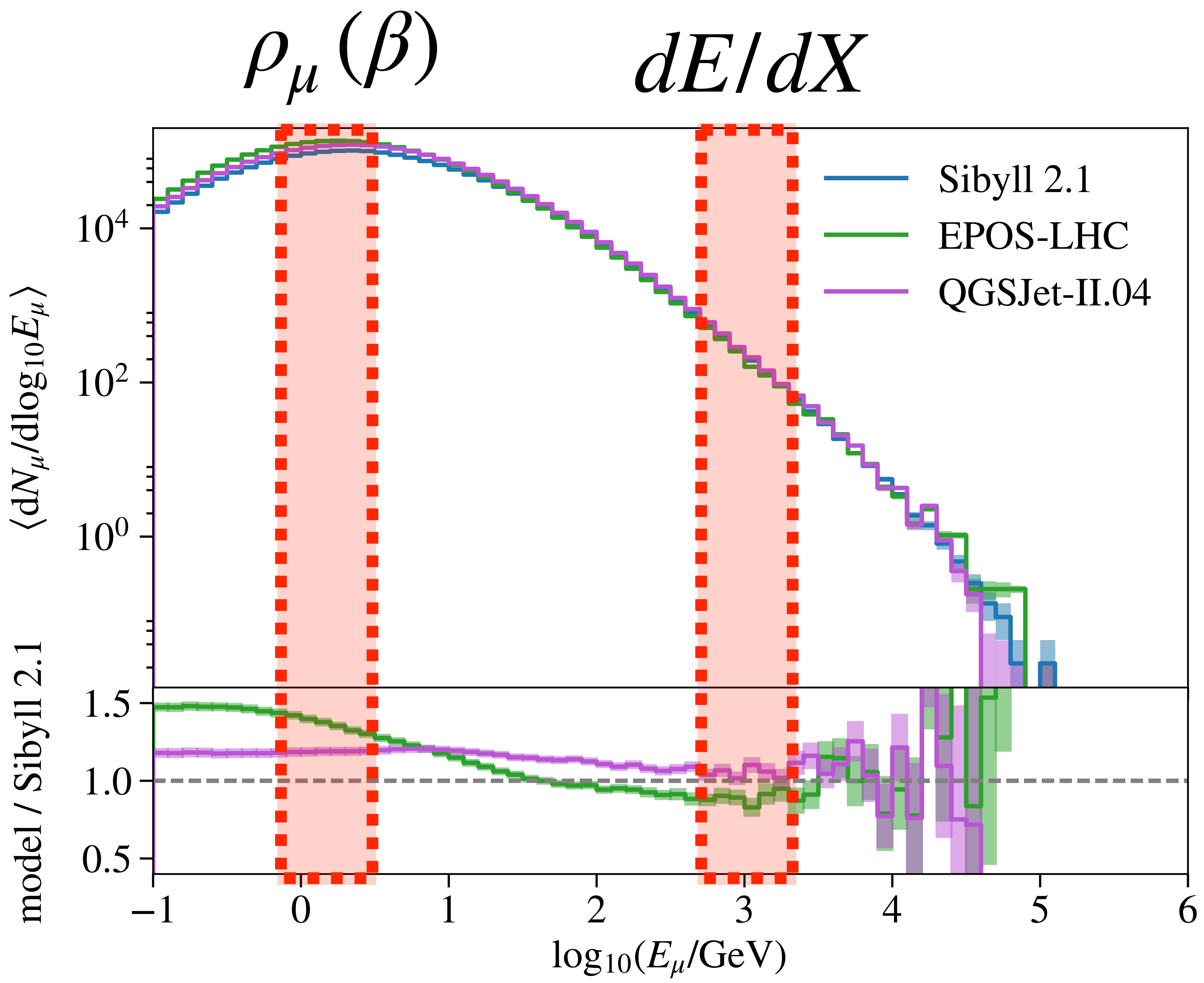


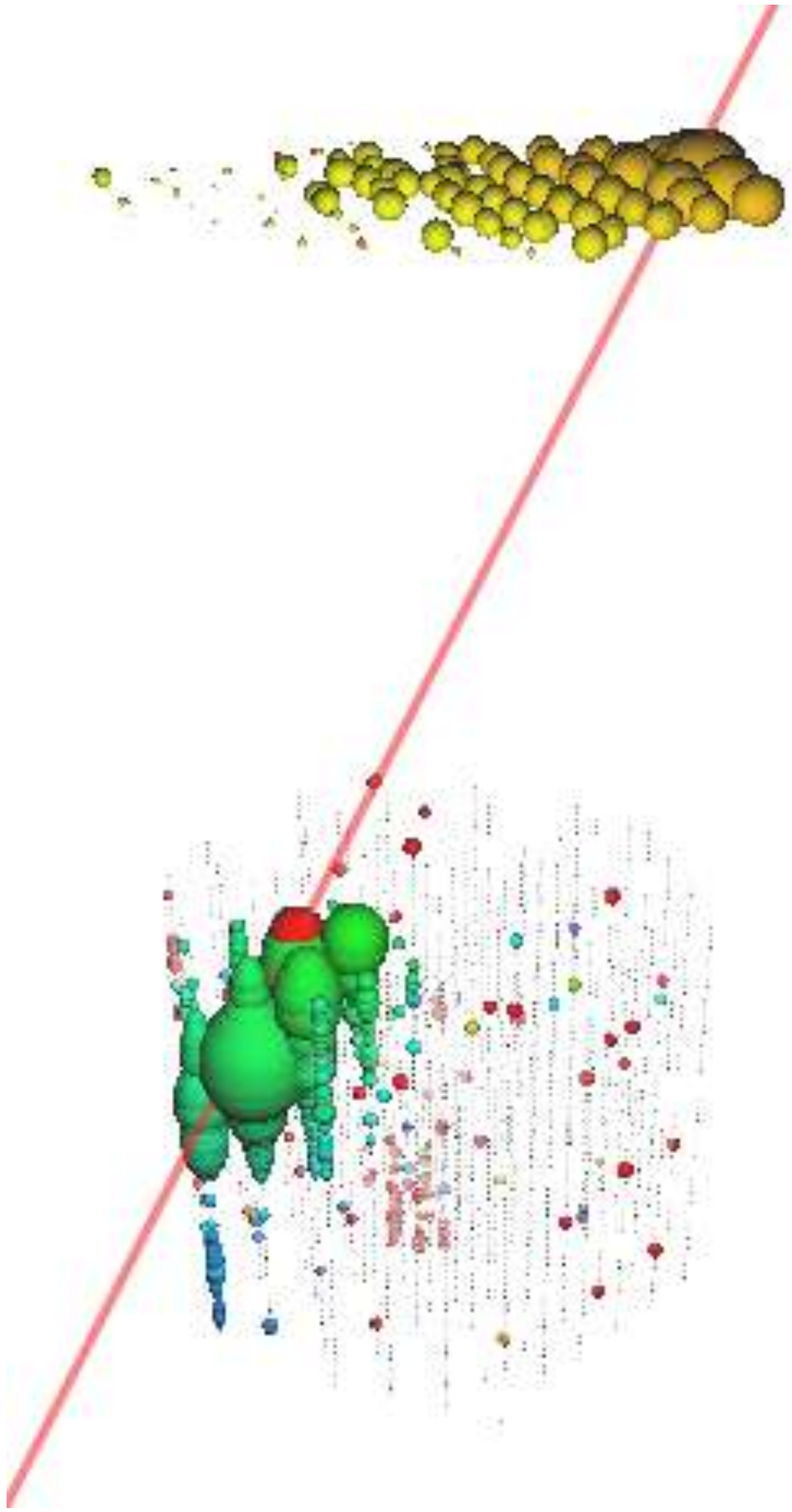
[F. Riehn, R. Engel, A. Fedynitch, T. K. Gaisser, T. Stanev, Phys. Rev. D 102 (2020)]

Hybrid Muon Measurements

- Preliminary studies of three muon estimators:
  - Muon density, ρ_μ (GeV muons)
  - Deposited in-ice energy, dE/dX (TeV muons)
  - LDF slope parameter, β (GeV muons + em)
- Analysis ongoing…

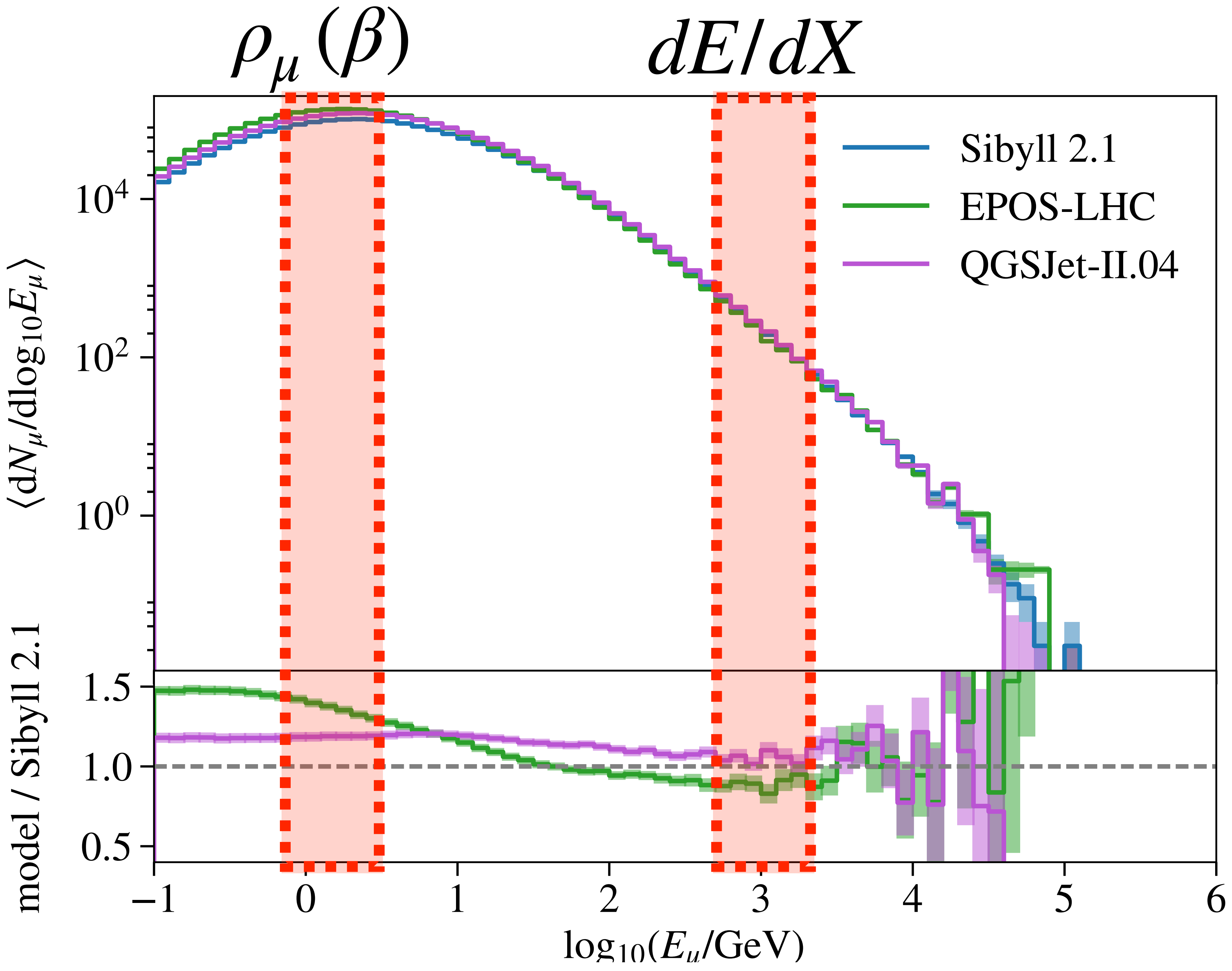


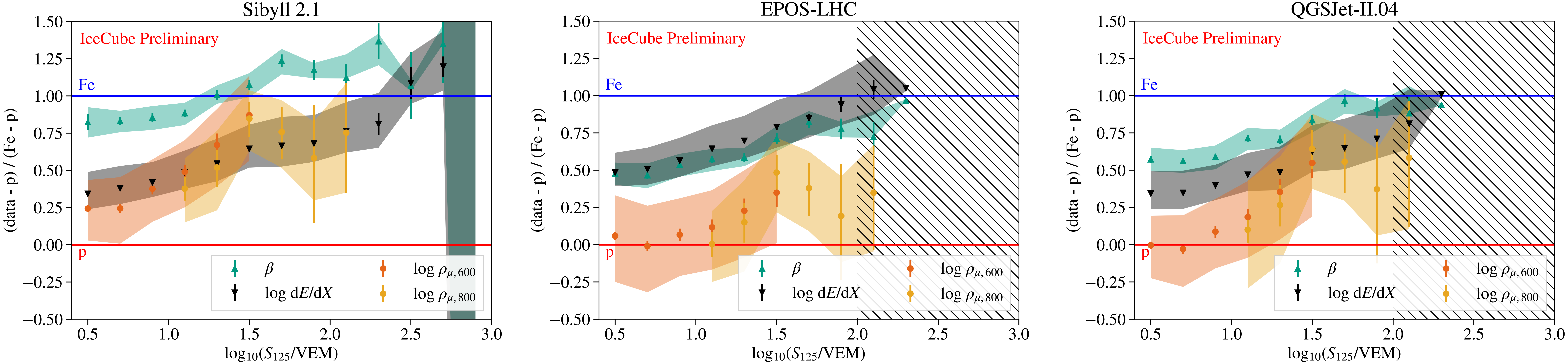




Hybrid Muon Measurements

- Very preliminary results!
- Inconsistencies within each model observed!
- However, no obvious discrepancies of TeV muons observed and exotic models (e.g. BSM) are thus disfavored
- Improved analysis ongoing…

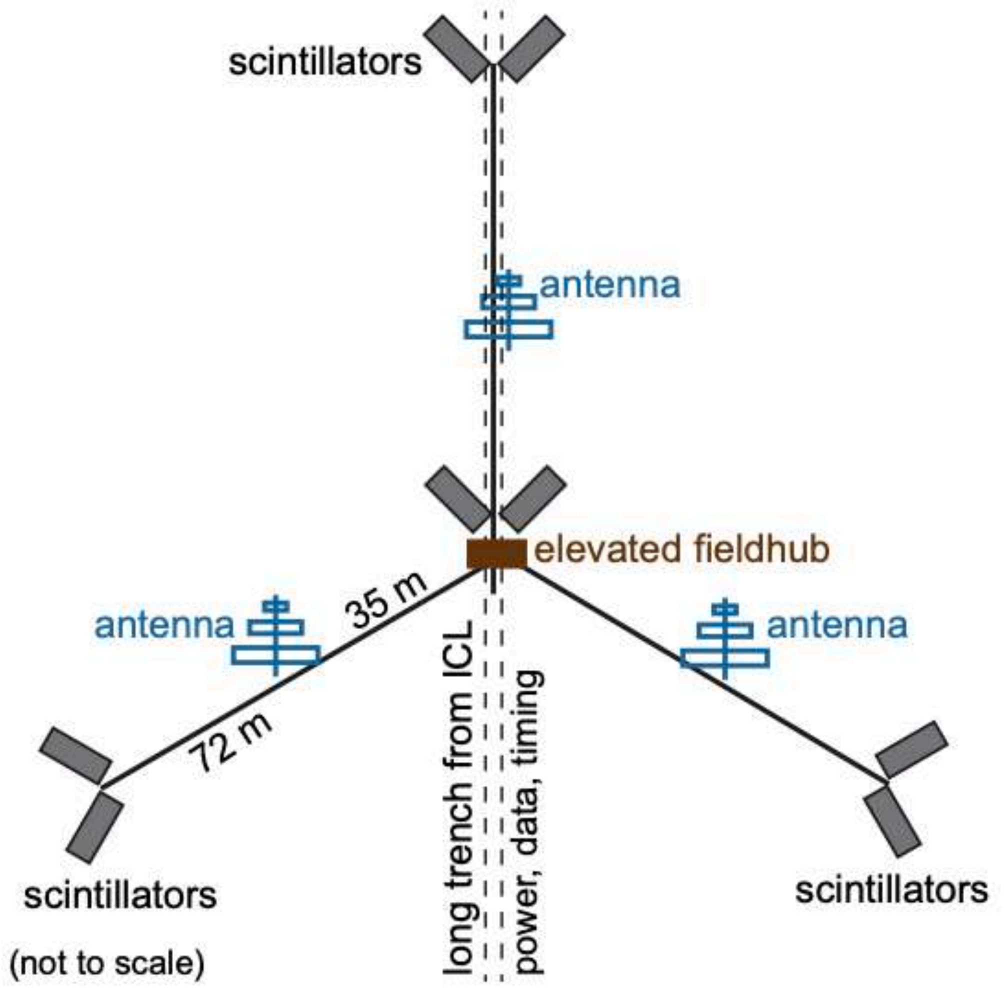


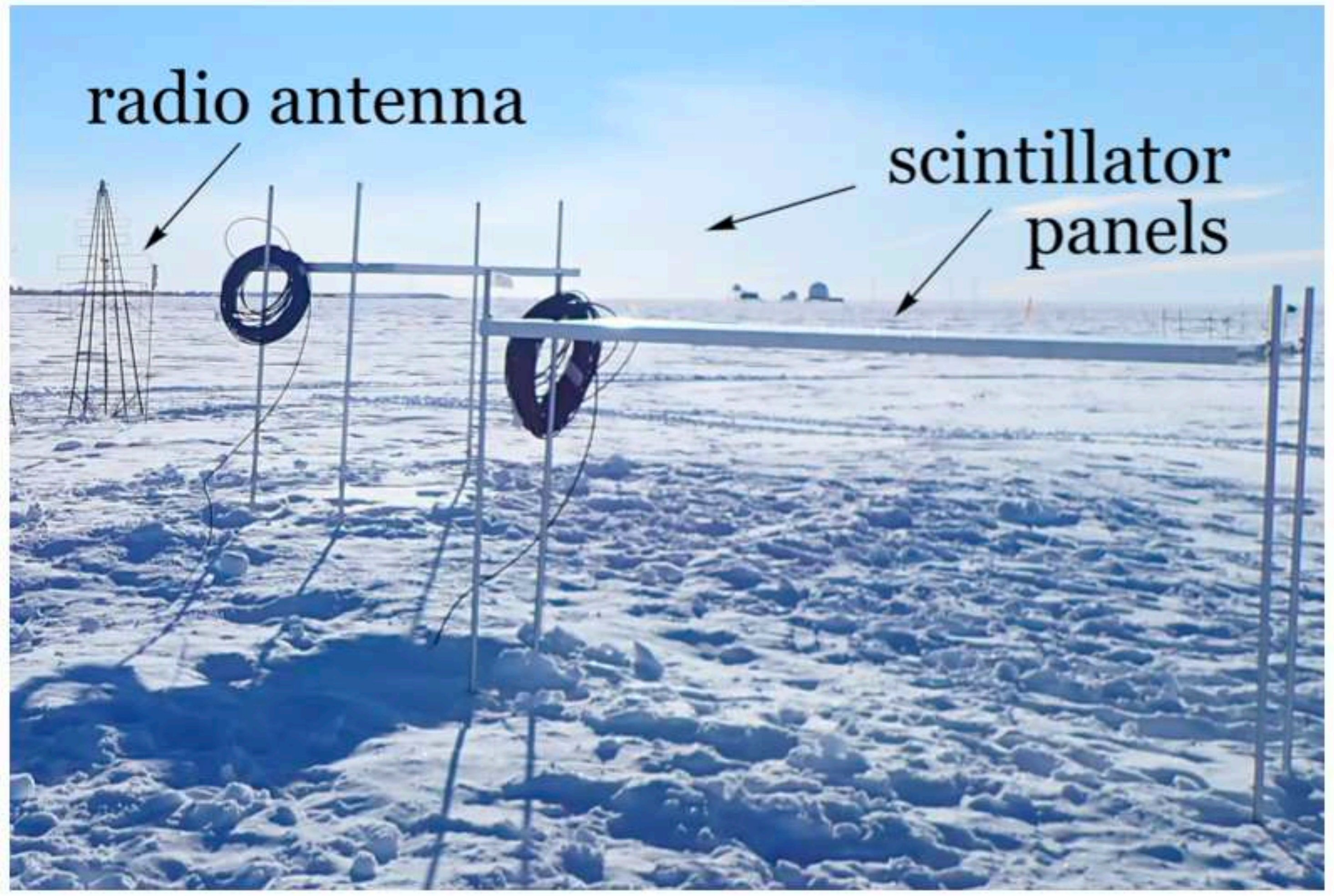


[S. Verpoest, D. Soldin, S. De Ridder et al., PoS ICRC2021 (2021) 357]

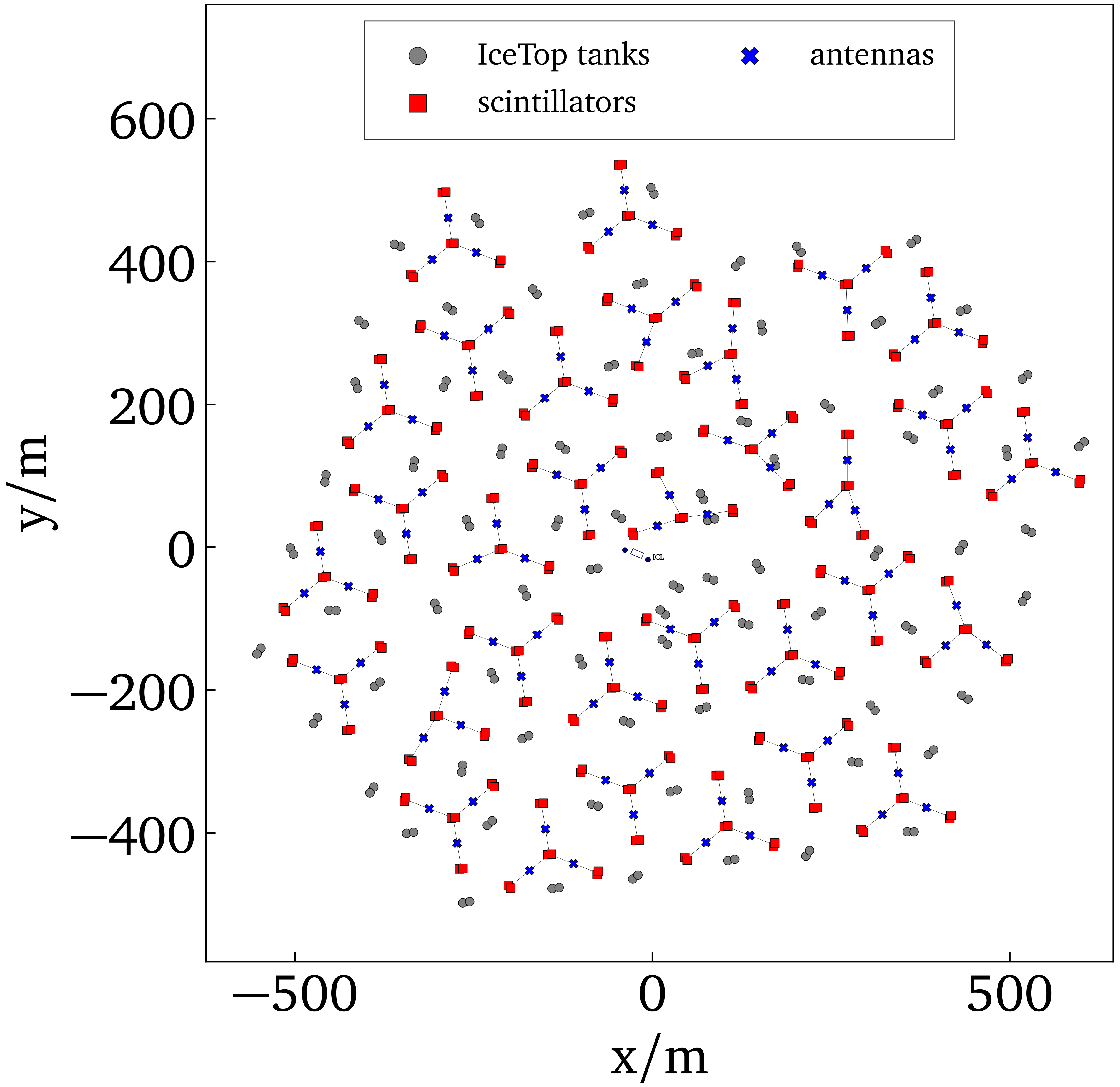
Future IceCube Detector Improvements

- Surface enhancement in progress:
    - New scintillator array
        - Better GeV muon separation in EAS
    - New radio antenna array
        - Improved EAS energy reconstruction
        - Increased angular acceptance



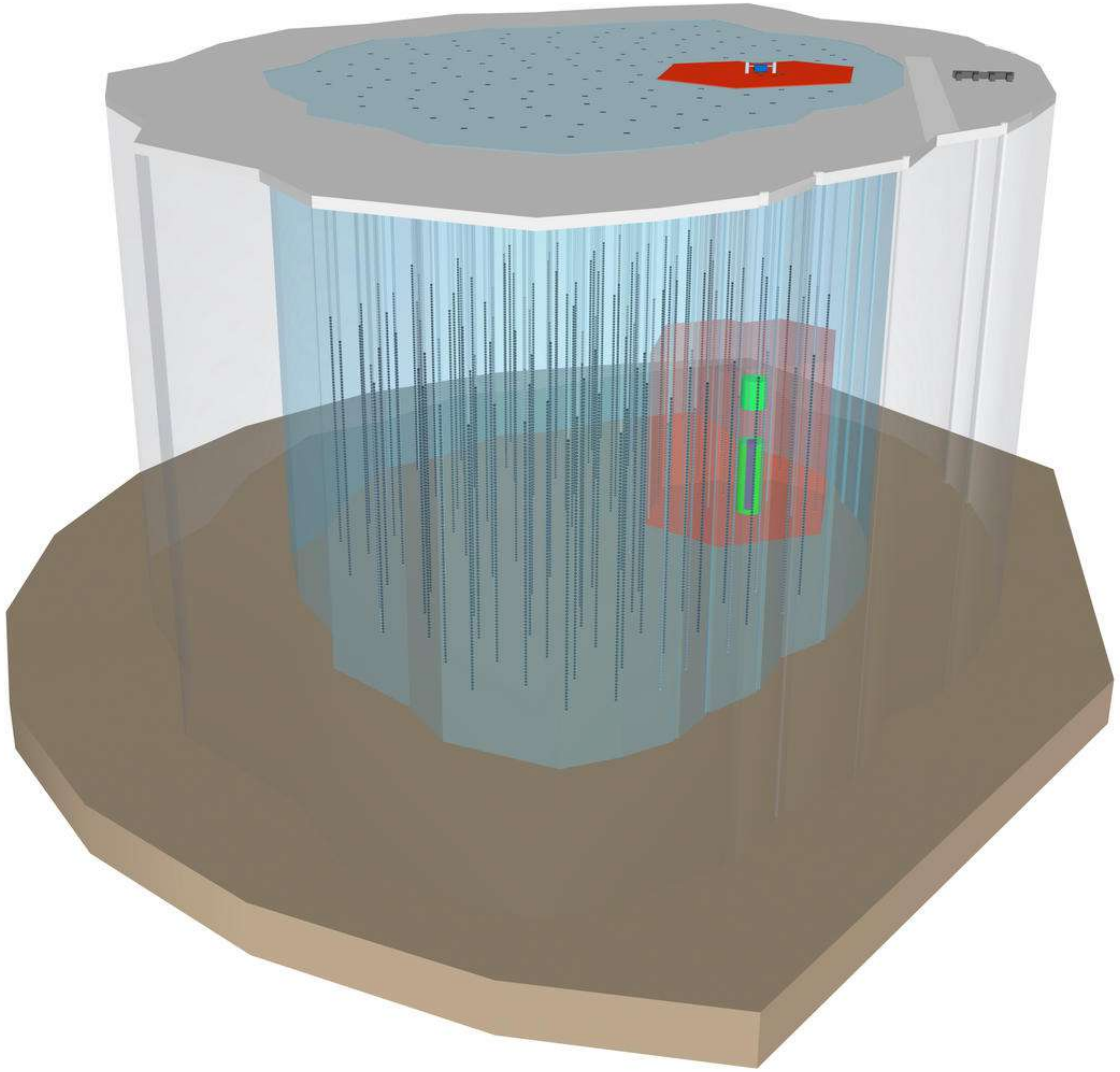


[A. Haungs et al., EPJ Web Conf. 210 (2019)]



Future Detector Improvements

- IceCube-Gen2:
  - Significant larger in-ice and surface detectors
  - Increased solid angle, larger inclinations
  - Increased statistics at the highest energies
    - Measurement of prompt muons!
    - Close the gap to Auger in muon measurements!
  - Better understanding of the absolute energy scale
  - Reduced in-ice systematics
  - …



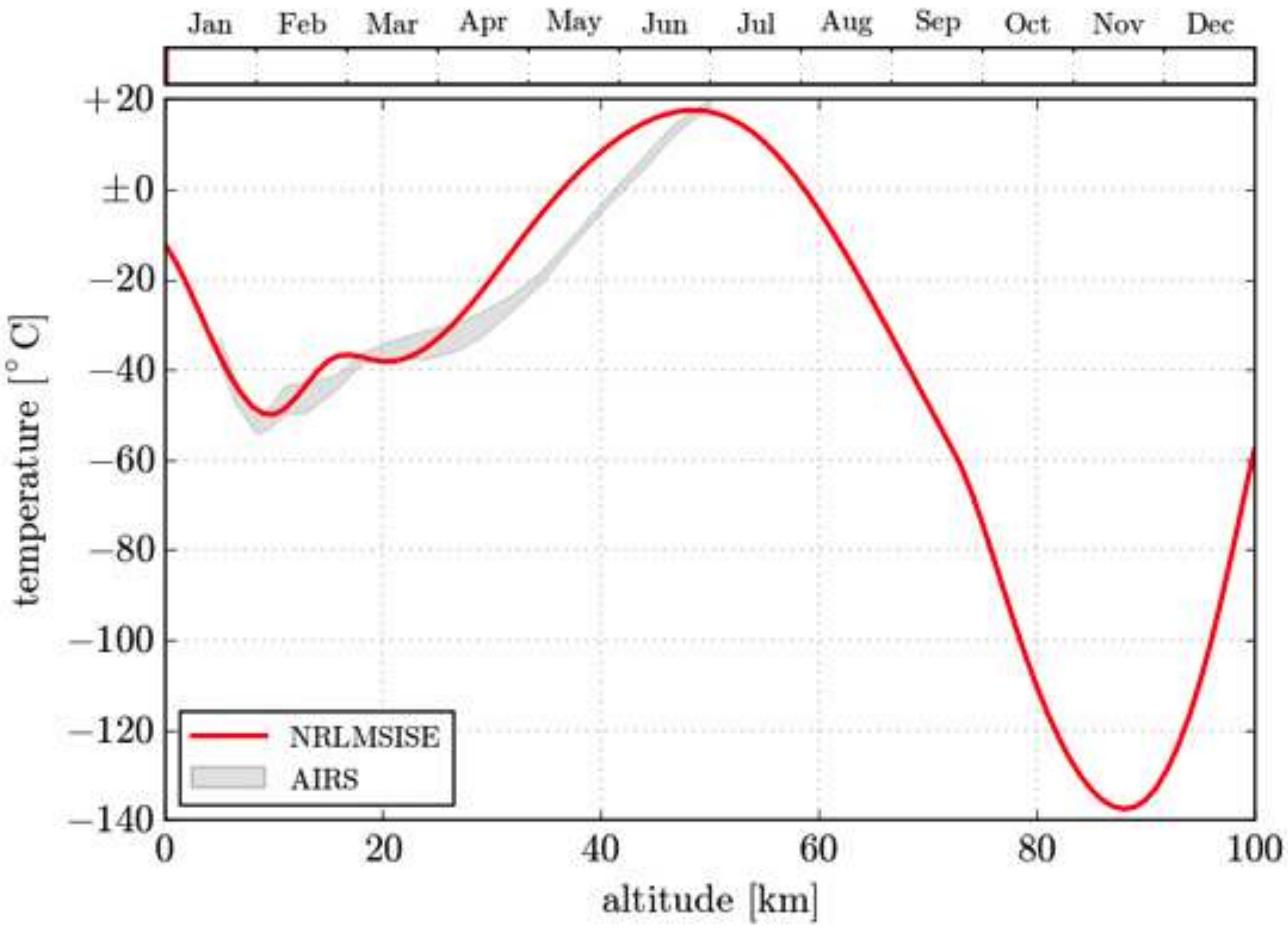
[IceCube-Gen2 Collaboration, arXiv:1412.5106]

Summary (I) - The Muon Puzzle

- Large uncertainties in cosmic ray measurements due to hadronic interaction models
- Measurements of atmospheric muons in air showers show significant excess (increasing with EAS energy) compared to current model predictions
    - Muon Puzzle in EAS
- Hybrid muon measurements with IceCube and IceTop provide unique information
- Together with other upcoming measurements (e.g. by the Pierre Auger Observatory) they will strongly constrain muon production models to solve the Muon Puzzle
- This will:
    - Improve our understanding of multi-particle production in the forward region
    - Improve hadronic interaction models in EAS simulations
    - Reduce uncertainties in the interpretation of CR measurements

Physics Beyond the Muon Puzzle…

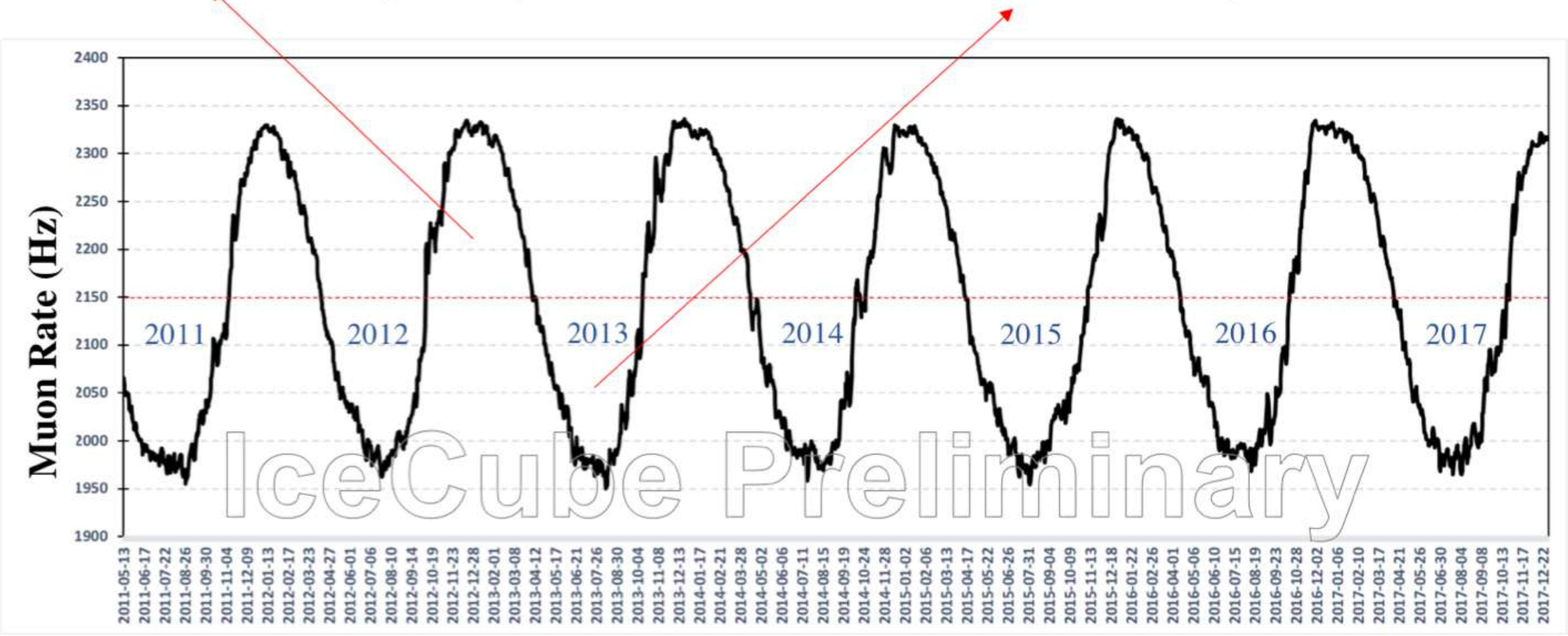
- Atmospheric muon flux depends on atmospheric density (temperature, pressure)!



Seasonal Variations of TeV Muons

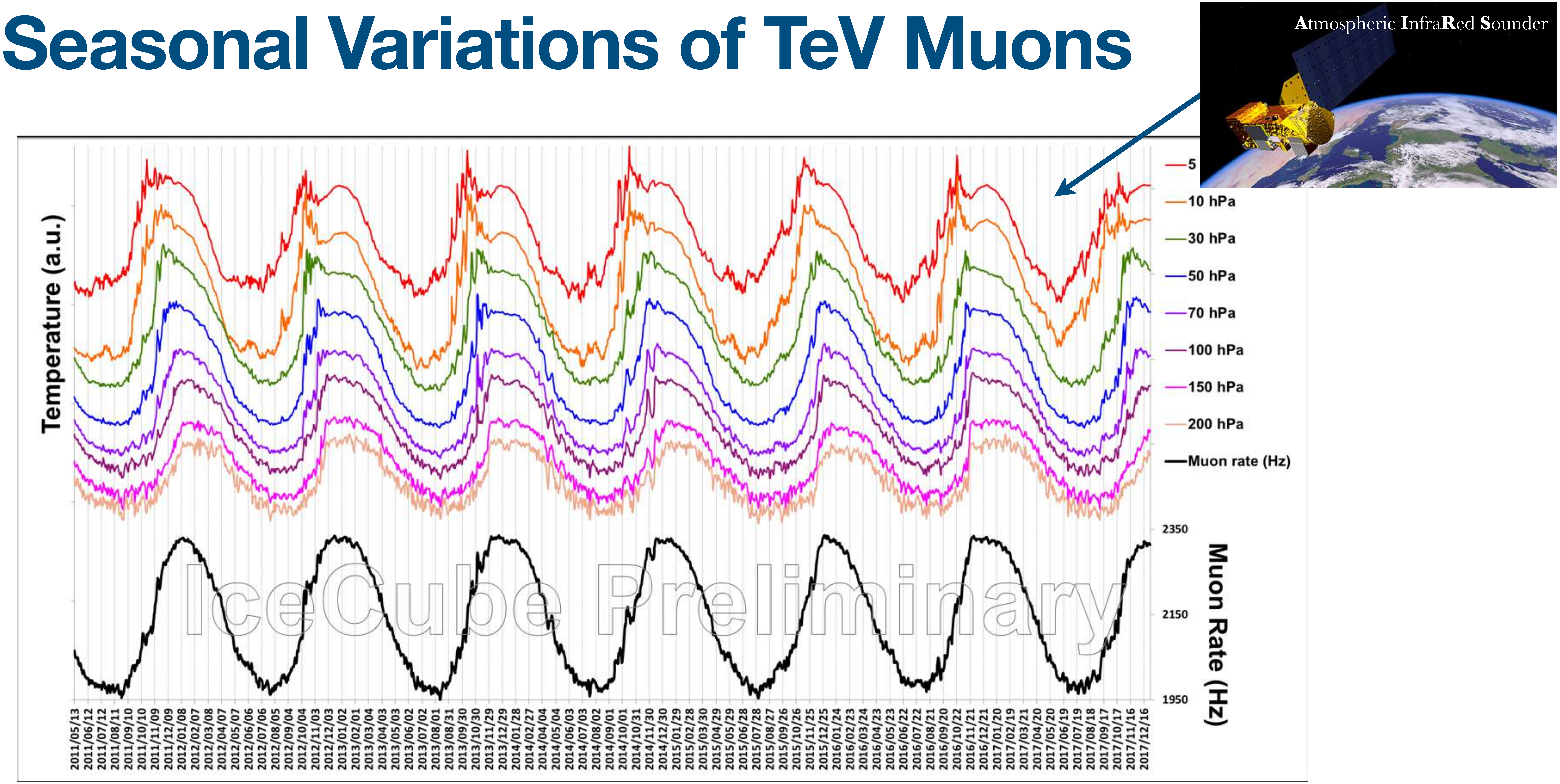
Summer atmosphere
warmer => less dense => pions decay to muons

Winter atmosphere
colder => more dense => pions interact



[S. Tilav, T. K. Gaisser, D. Soldin, P. Desiati, PoS ICRC2019 (2020) 894]

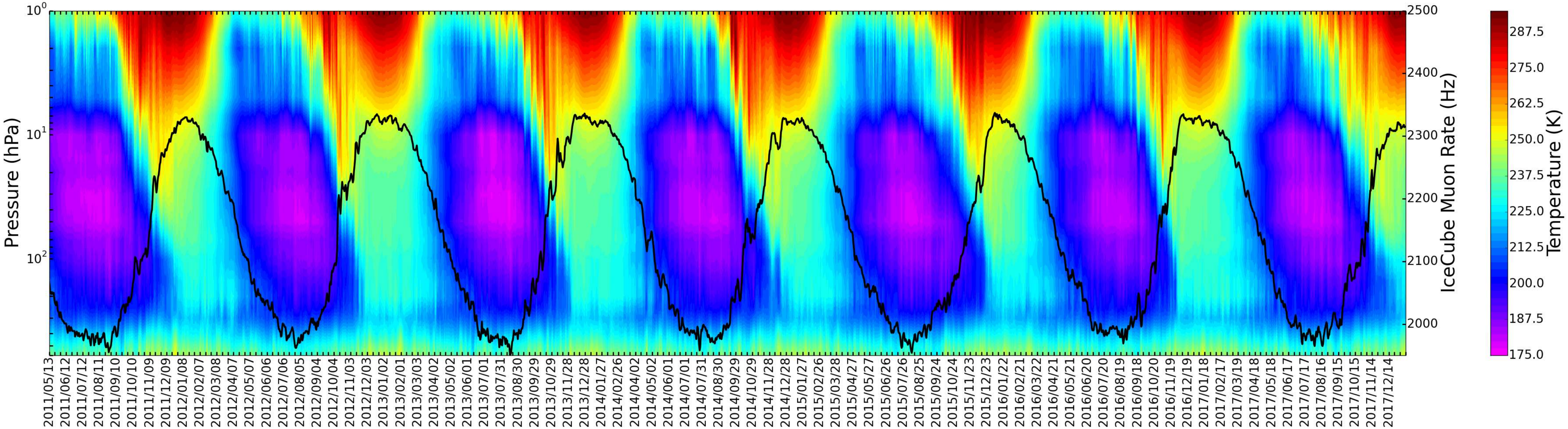
Seasonal Variations of TeV Muons

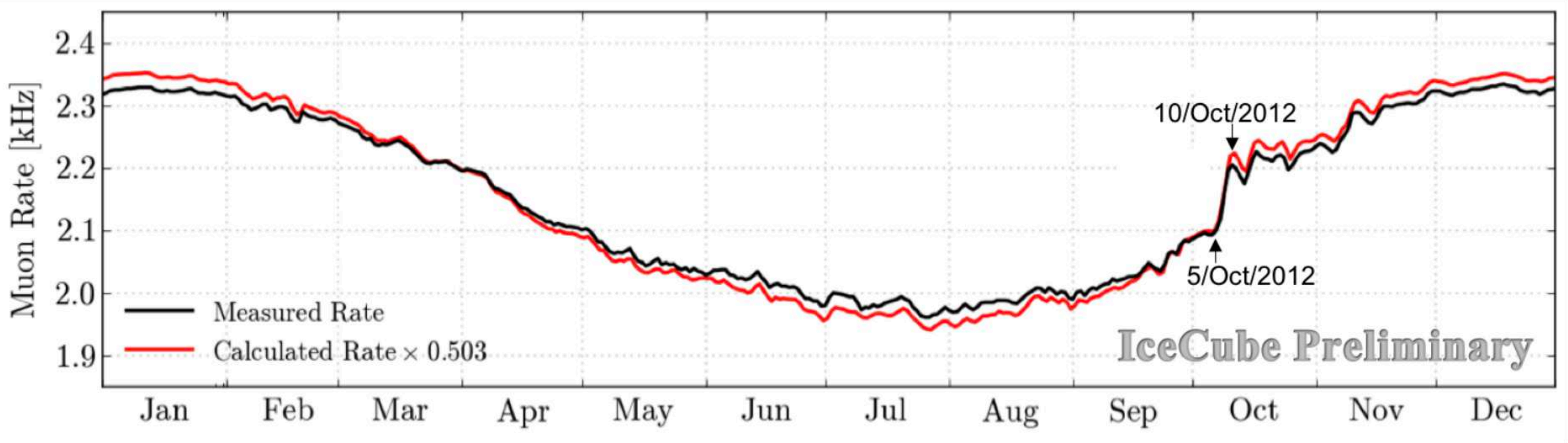


[S. Tilav, T. K. Gaisser, D. Soldin, P. Desiati, PoS ICRC2019 (2020) 894]

Seasonal Variations of TeV Muons

[S. Tilav, T. K. Gaisser, D. Soldin, P. Desiati, PoS ICRC2019 (2020) 894]

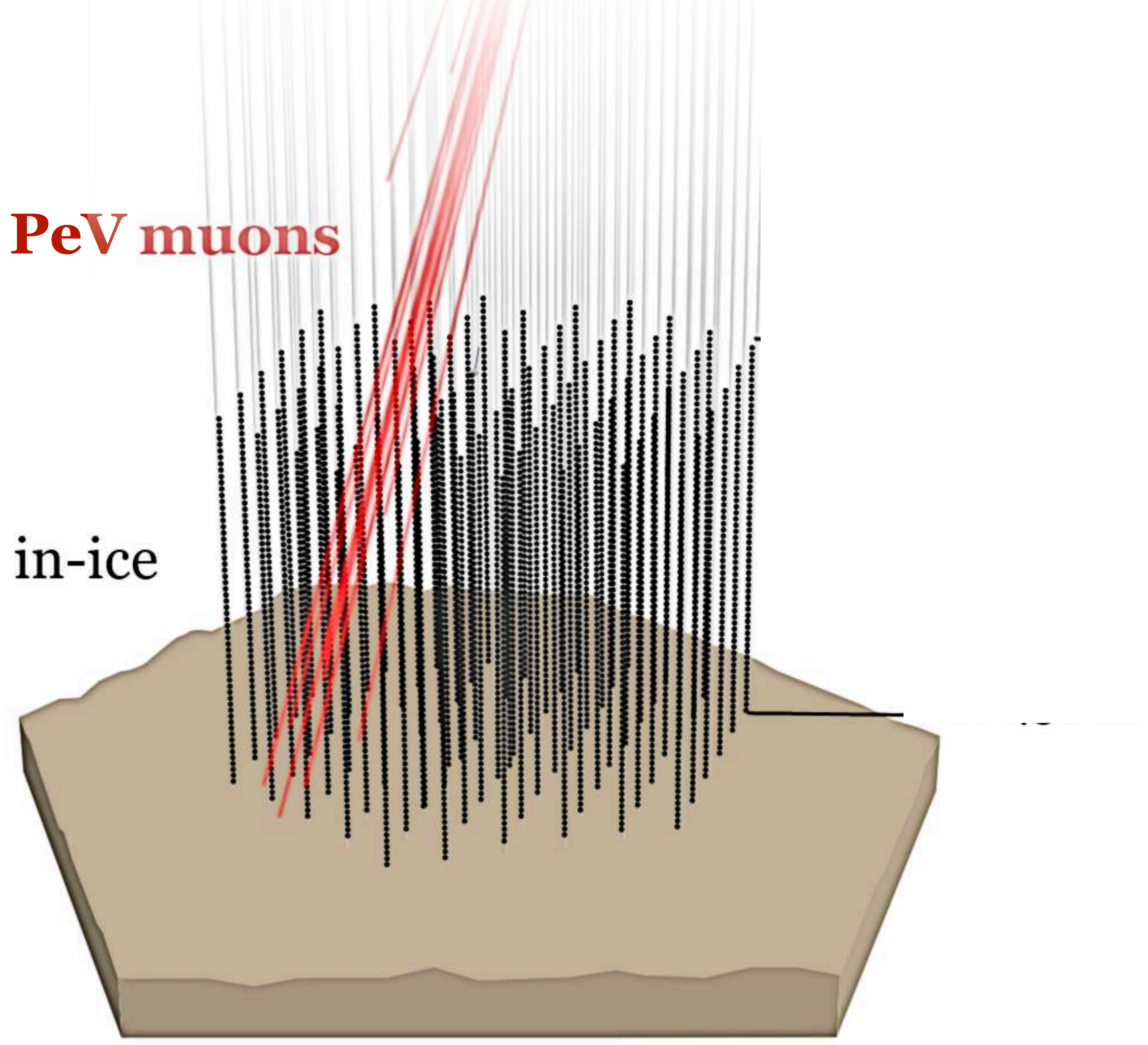


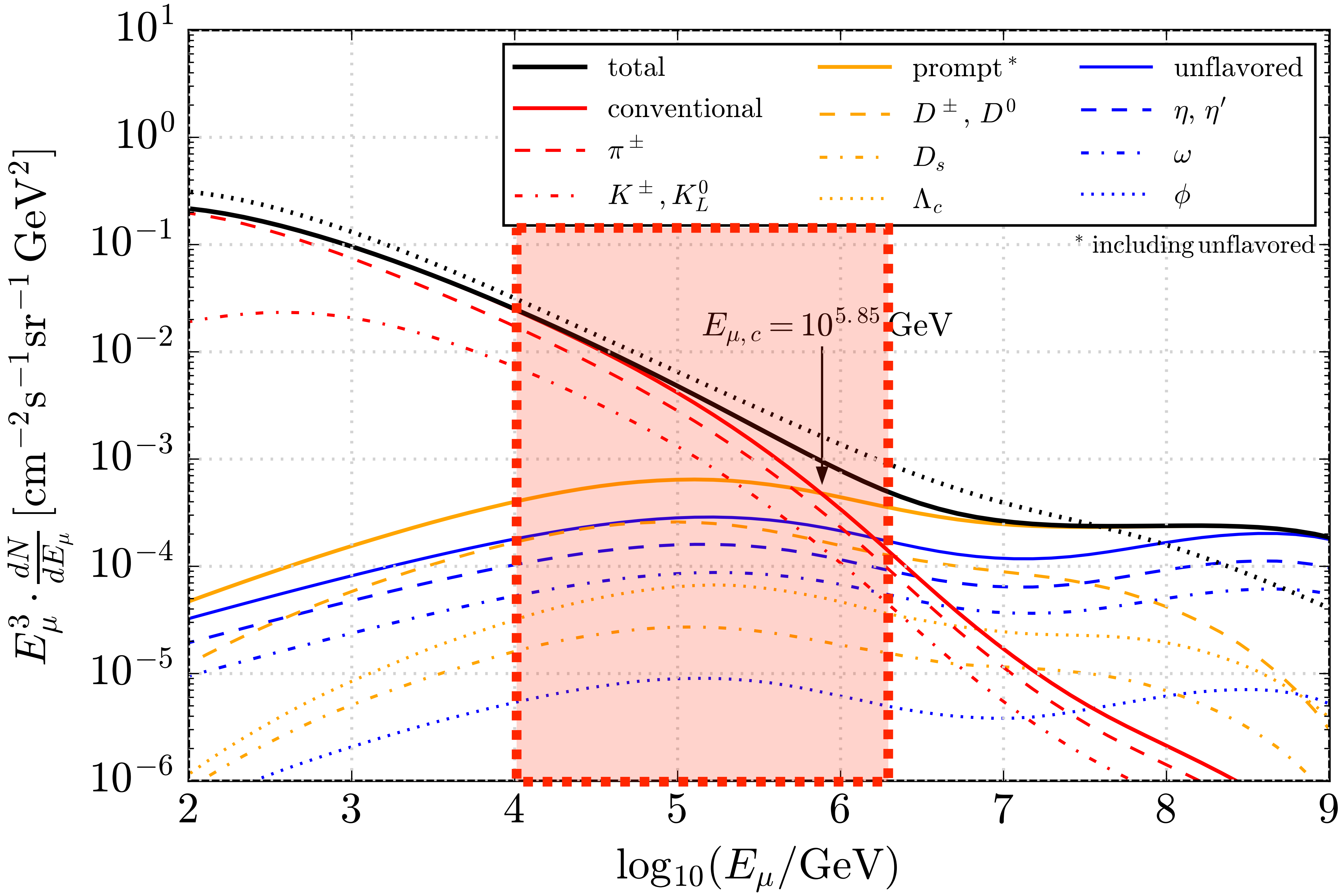


- Probe of atmospheric conditions (stratosphere)
- Sensitive to the kaon/pion ratio in EAS!
- Analysis in progress…

PeV Muons in IceCube

- For muon energies from GeV to TeV, the muon production is dominated by pion and kaon decays ("conventional flux")
- "Prompt muons" from decay of heavy hadrons (e.g. $D^{\pm}$, D^0, Λ_c) are expected to dominate at PeV energies!
- Prompt flux has yet to be experimentally confirmed…
- Also, yields information about prompt atmospheric neutrino production
- Expected to be relevant background for astrophysical neutrino searches in the PeV region
- Understanding of prompt fluxes important for neutrino astrophysics!

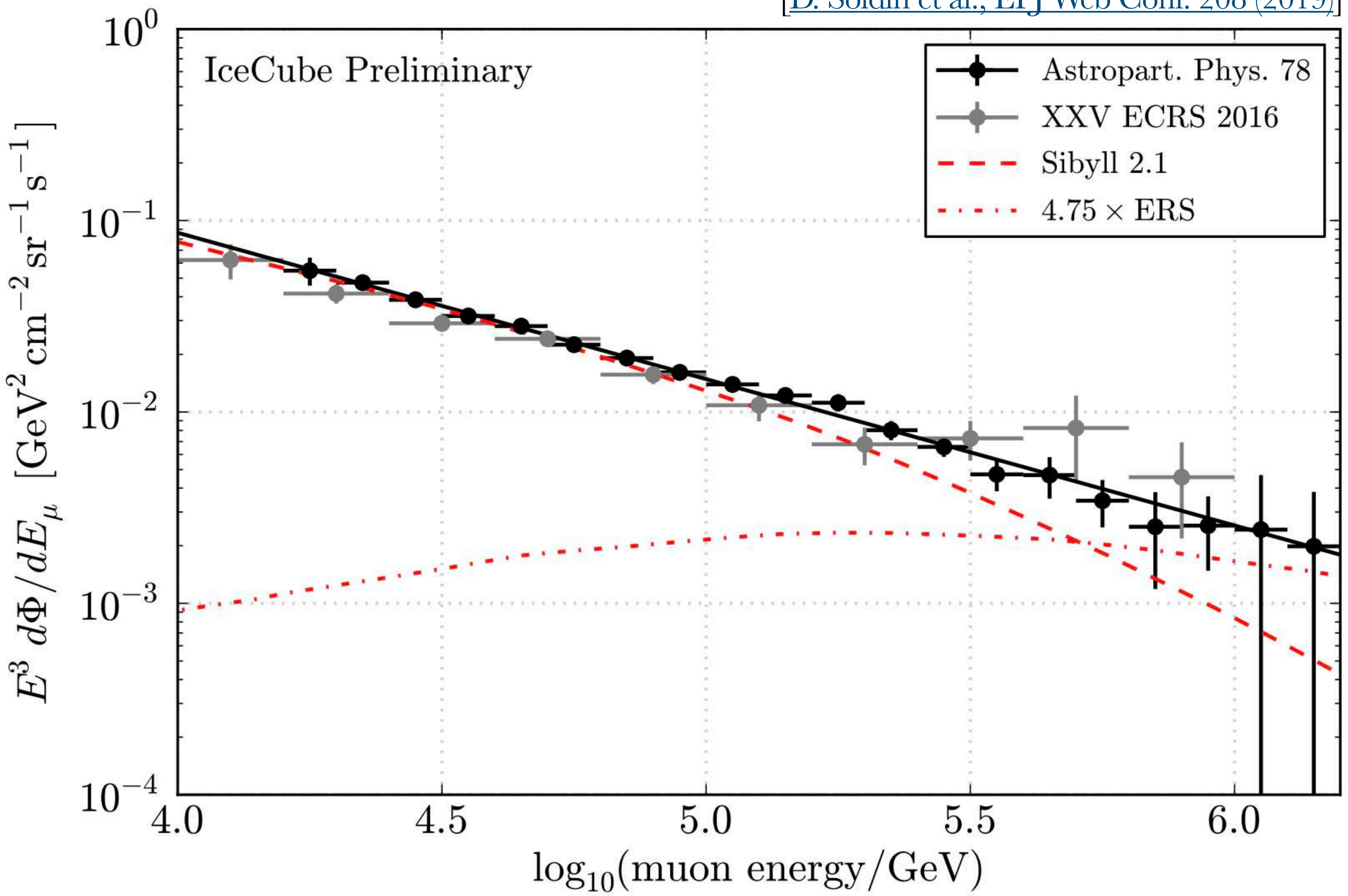


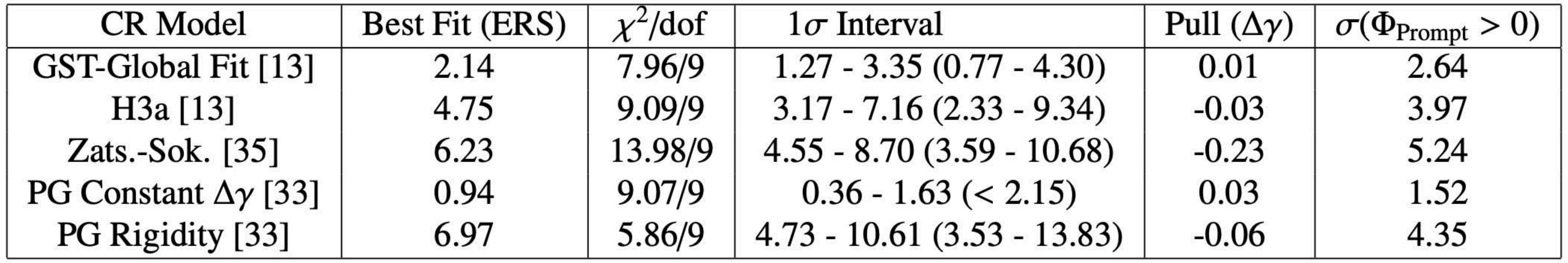


PeV Muons in IceCube

- Atmospheric muon spectrum above $E_\mu \simeq 10\,\text{TeV}$
- Reaching the transition region where the prompt muon flux becomes dominant
- Large uncertainties due to CR flux model assumption!
- Low statistics at high energies
  - Larger in-ice detector needed!
- Here: no EAS energy
  - New reconstruction methods needed (more tomorrow…)
  - Larger surface detector needed!

[D. Soldin et al., EPJ Web Conf. 208 (2019)]





CR Model	Best Fit (ERS)	χ^2/dof	1σ Interval	Pull ($\Delta\gamma$)	$\sigma(\Phi_{\text{Prompt}} > 0)$
GST-Global Fit [13]	2.14	7.96/9	1.27 - 3.35 (0.77 - 4.30)	0.01	2.64
H3a [13]	4.75	9.09/9	3.17 - 7.16 (2.33 - 9.34)	-0.03	3.97
Zats.-Sok. [35]	6.23	13.98/9	4.55 - 8.70 (3.59 - 10.68)	-0.23	5.24
PG Constant $\Delta\gamma$ [33]	0.94	9.07/9	0.36 - 1.63 (< 2.15)	0.03	1.52
PG Rigidity [33]	6.97	5.86/9	4.73 - 10.61 (3.53 - 13.83)	-0.06	4.35

[IceCube Collaboration, Astropart.Phys. 78 (2016)]

Lateral Separation of TeV Muons

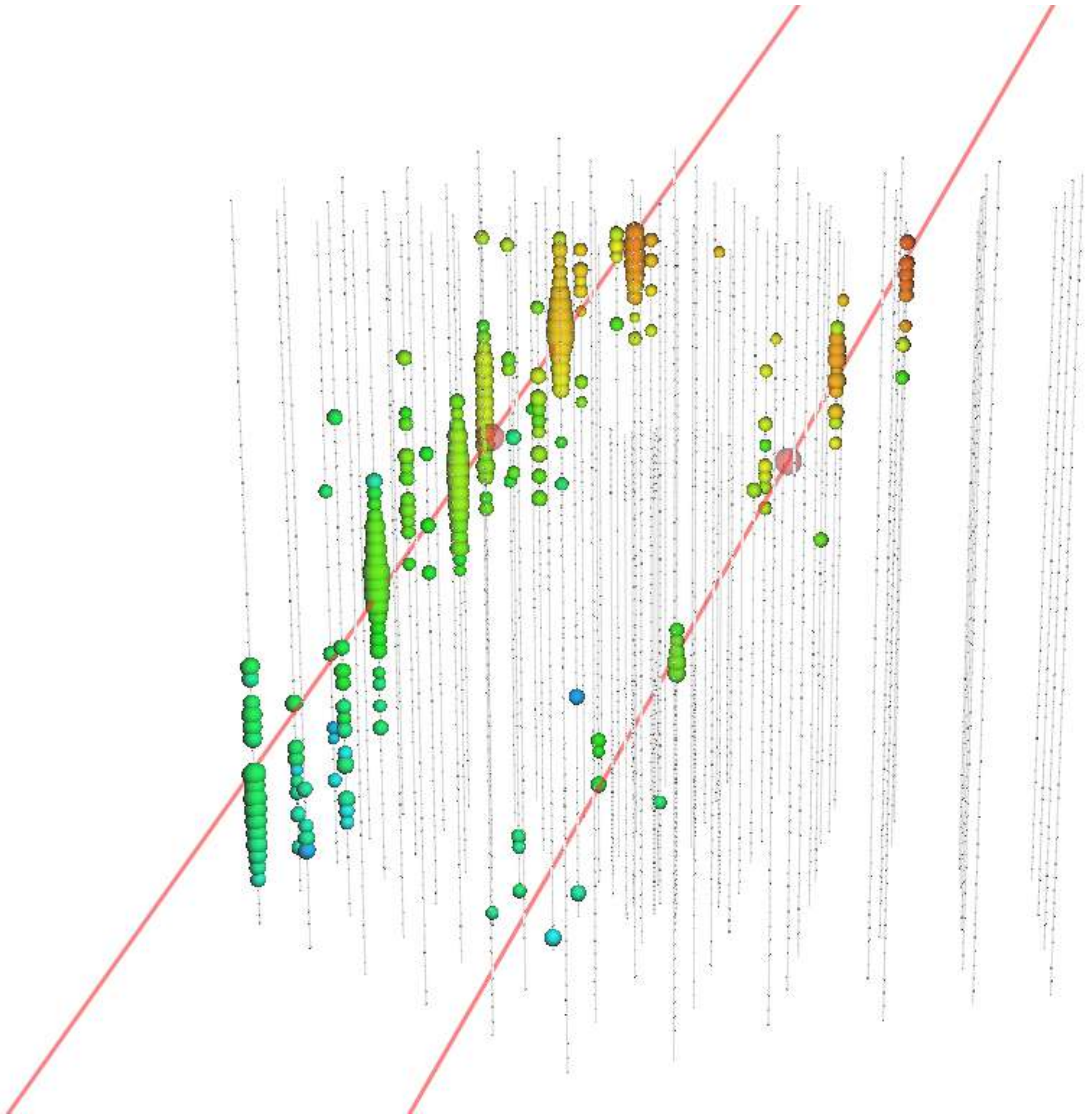
- High-energy interactions can produce secondaries with large transverse momentum, p_T, that might decay into muons

- Isolated muons separate from shower core while traveling to the detector

- Lateral separation:

$$d_\mathrm{T} \simeq \frac{p_\mathrm{T} \cdot H}{E_\mu \cdot \cos(\theta)}$$

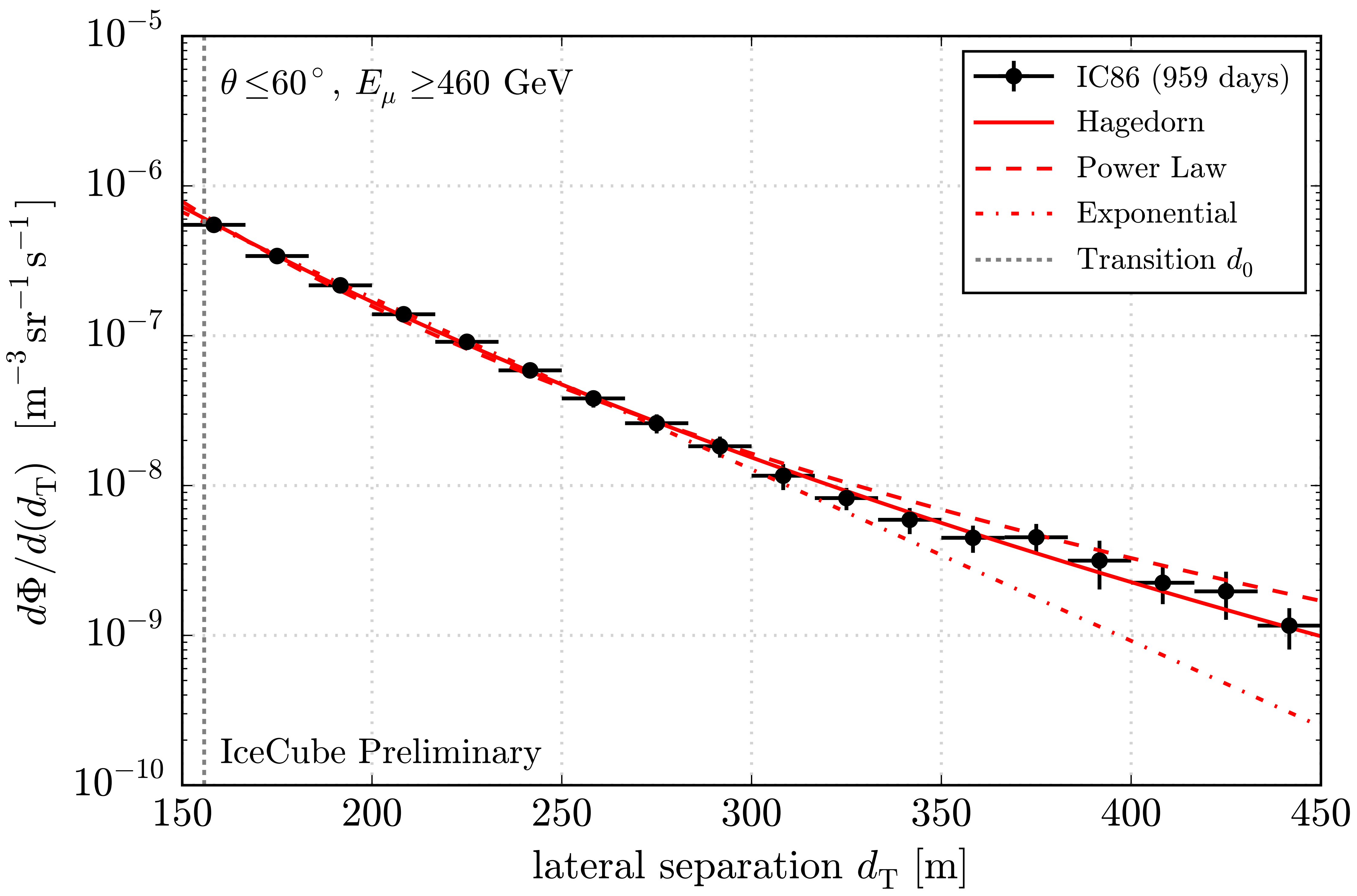
- Minimal resolvable separation ~135m
  - Typical $p_\mathrm{T} \gtrsim 2\,\mathrm{GeV/c}$
  - pQCD regime!

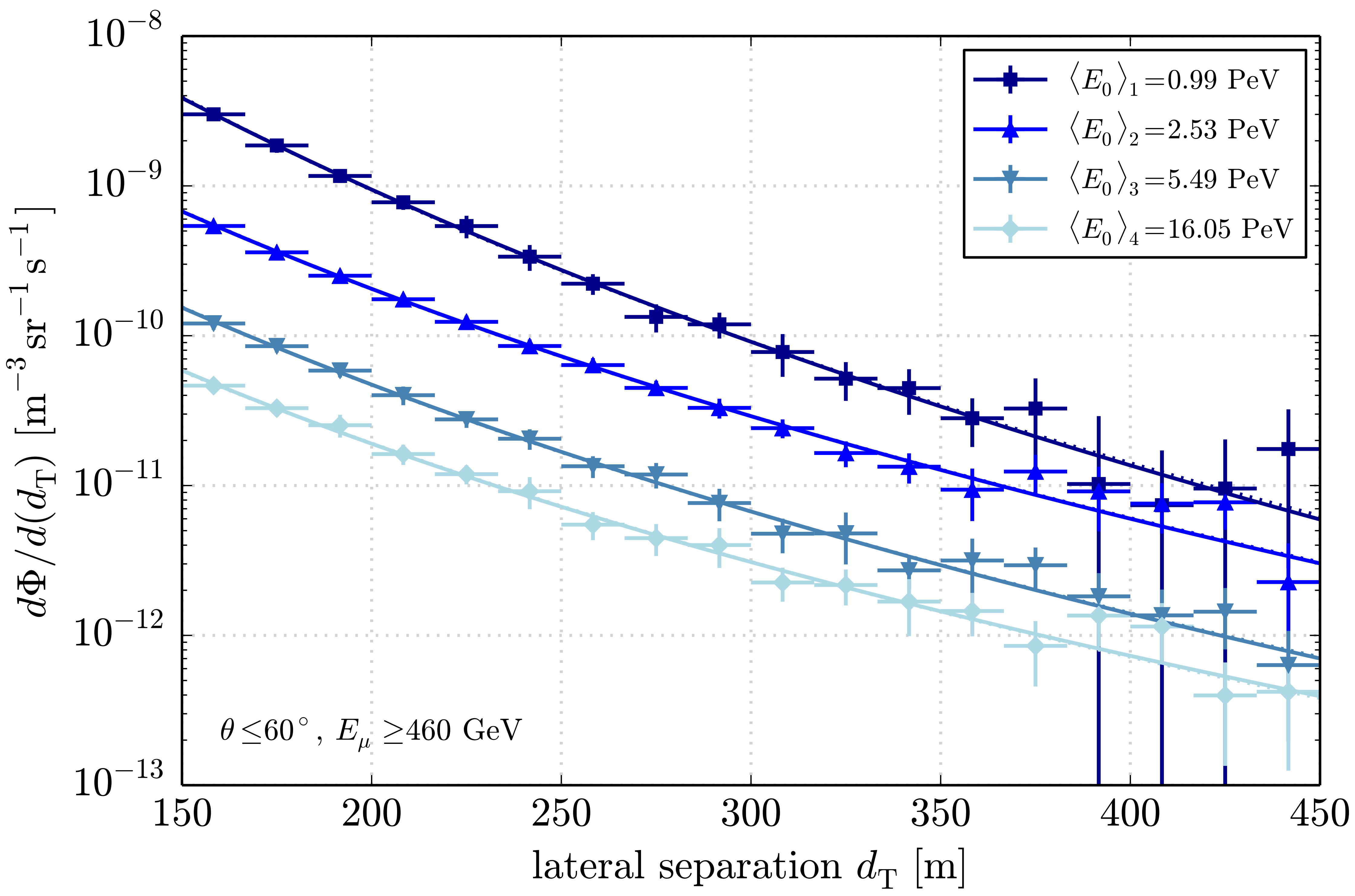


Lateral Separation of TeV Muons

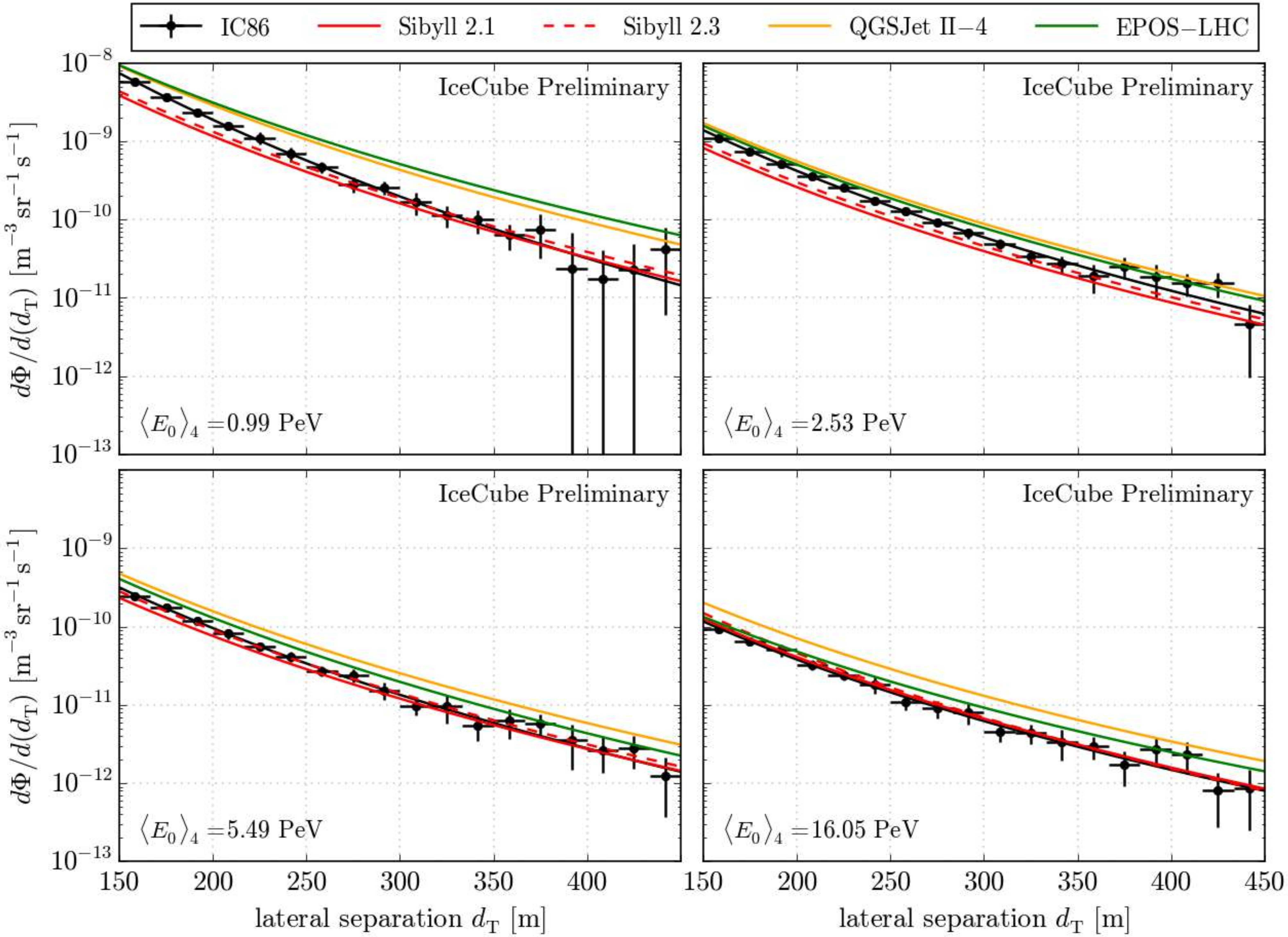
- Lateral separation distribution after background subtraction (4 primary cosmic ray energy bins)
- Accounting for trigger/filter efficiencies, using effective areas

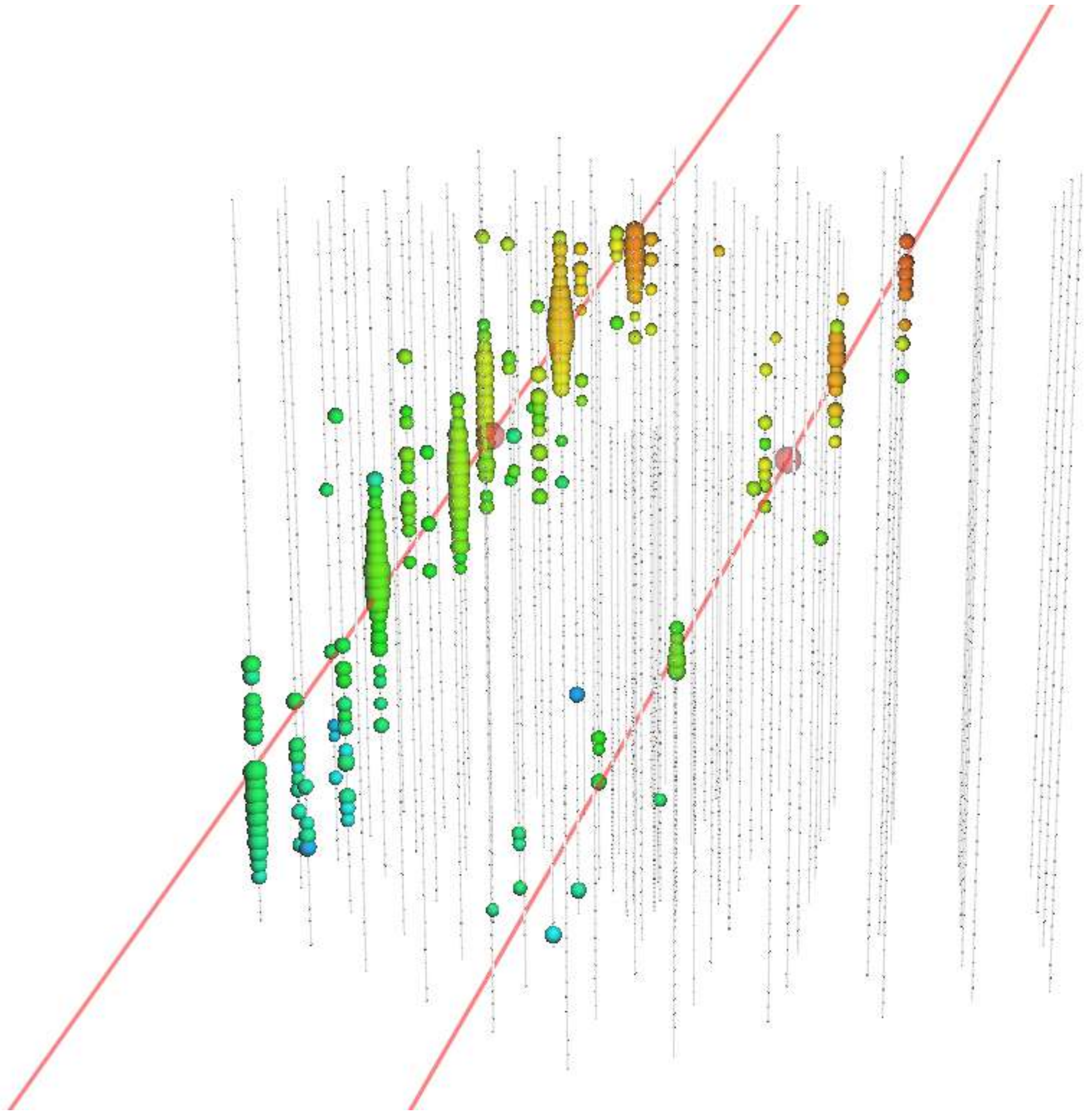
[D. Soldin et al., EPJ Web Conf. 208 (2019)]





Lateral Separation of TeV Muons

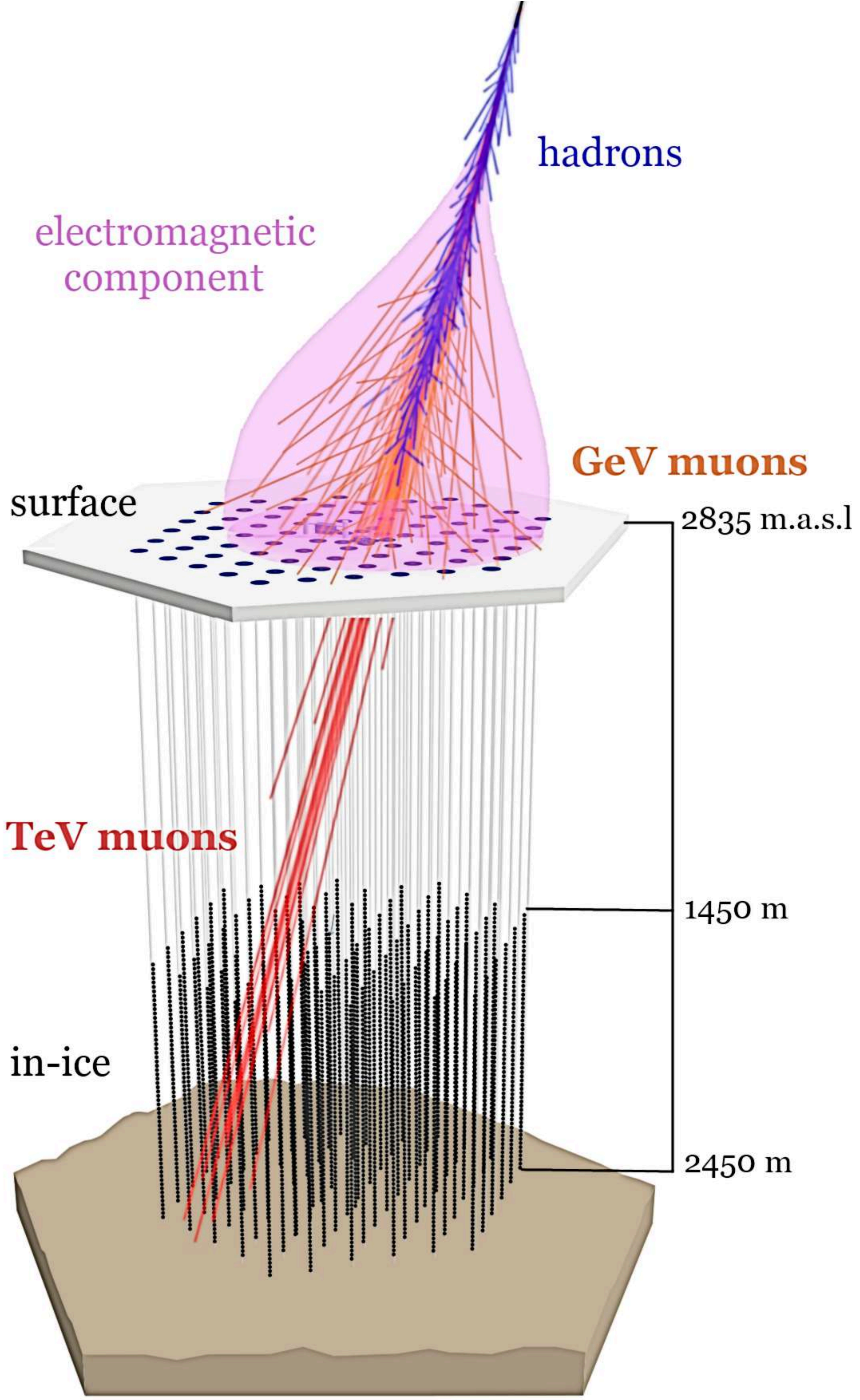




[D. Soldin et al., EPJ Web Conf. 208 (2019)]

Summary (II) - Beyond the Muon Puzzle

- IceCube provides important EAS measurements beyond the Muon Puzzle!
- Seasonal variations of the TeV muon flux
  - Probe of atmospheric conditions
  - Test of kaon-to-pion ratio in EAS
- High-energy muon spectrum
  - Muon energies up to a few PeV
  - Probe of prompt atmospheric muon flux
- Lateral separation of TeV muons
  - Tests of muon production in the pQCD regime
- Multiple other analyses in preparation…



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