Tests of Hadronic Interaction Models with TeV-PeV Muons in IceCube

GCOS Workshop 2021

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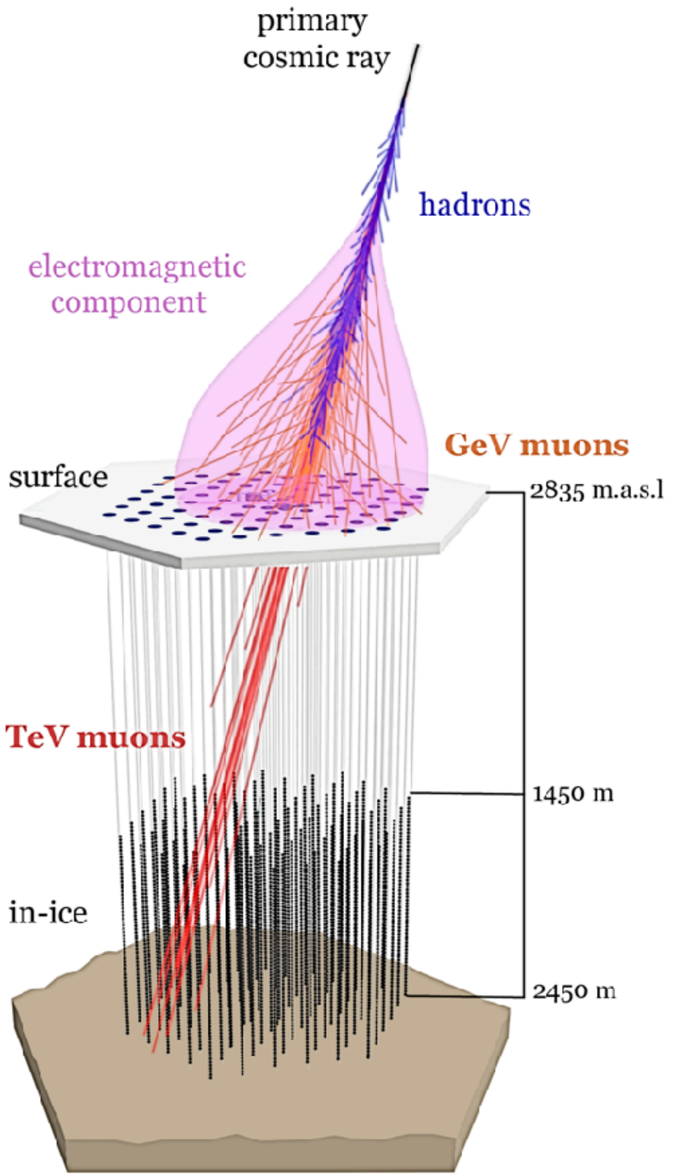
Outline

- The Muon Puzzle (GeV Muons)
- TeV Muons in IceCube
- PeV Muons in IceCube
- Summary & Conclusions



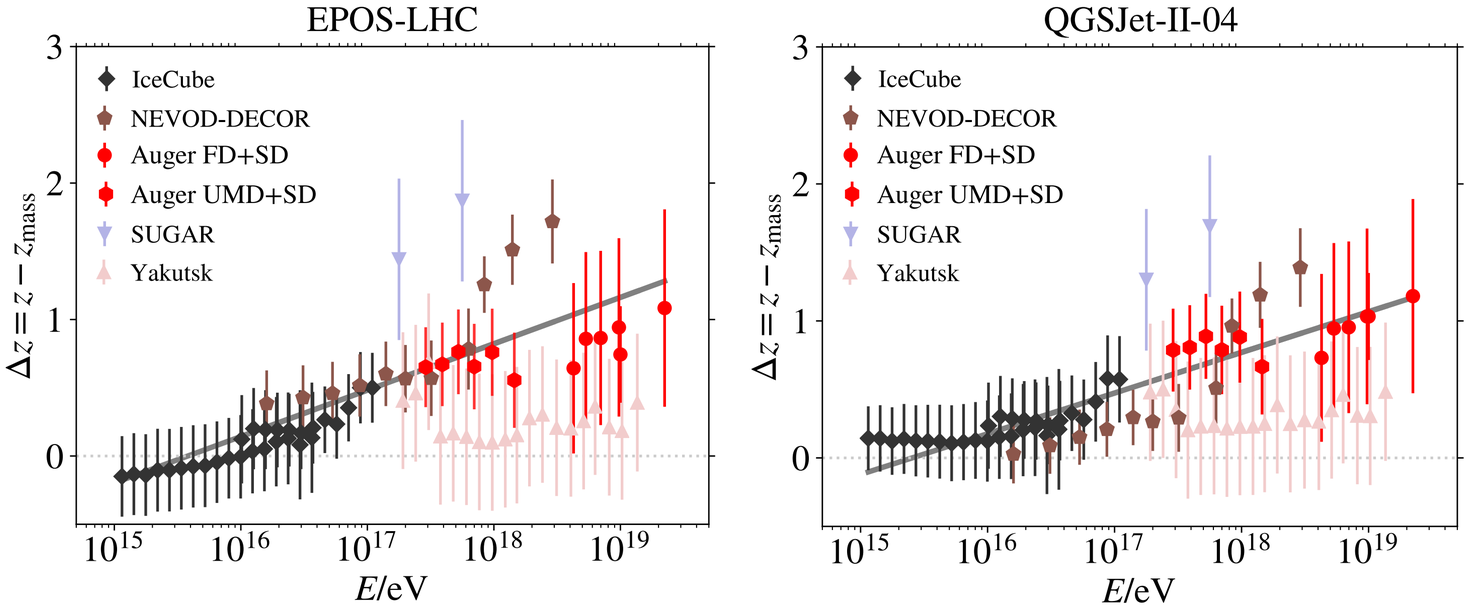
The Muon Puzzle (GeV Muons)

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

- z-value:

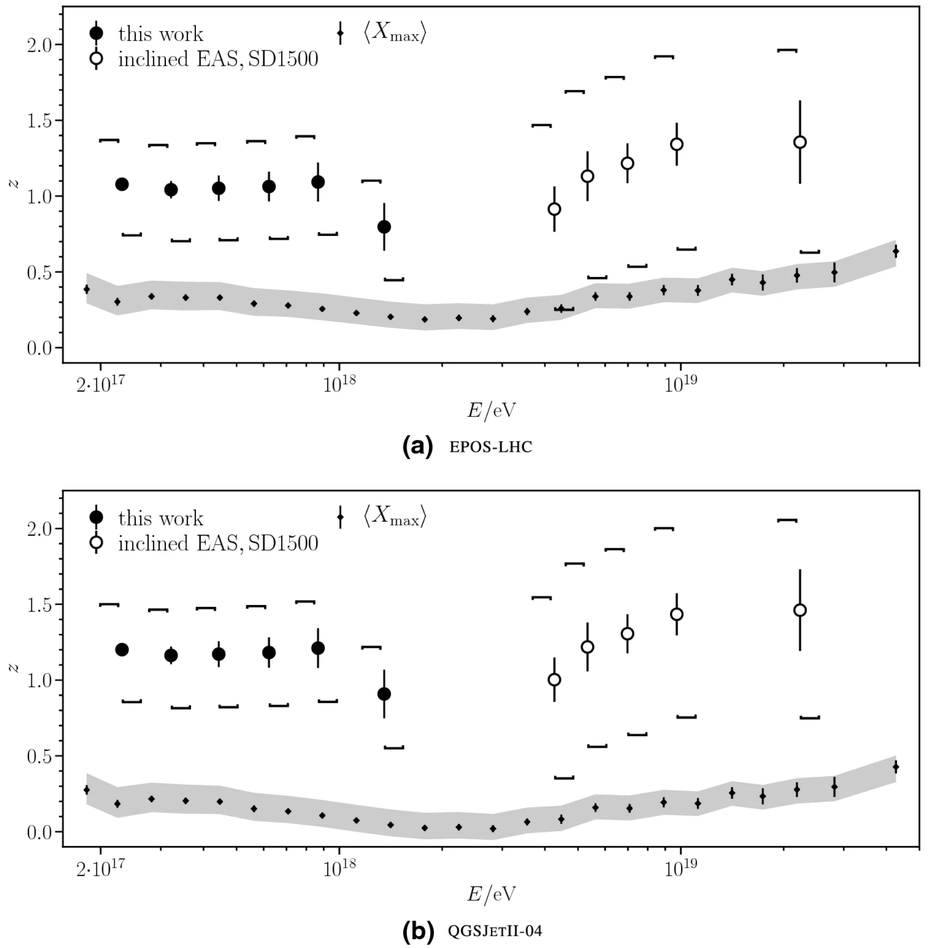
$$z = \frac{\ln(\rho_\mu) - \ln(\rho_{\mu,\mathrm{p}})}{\ln(\rho_{\mu,\mathrm{Fe}}) - \ln(\rho_{\mu,\mathrm{p}})}$$

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



[H.P. Dembinski et al. (WHISP), EPJ Web Conf. 210 (2019)]

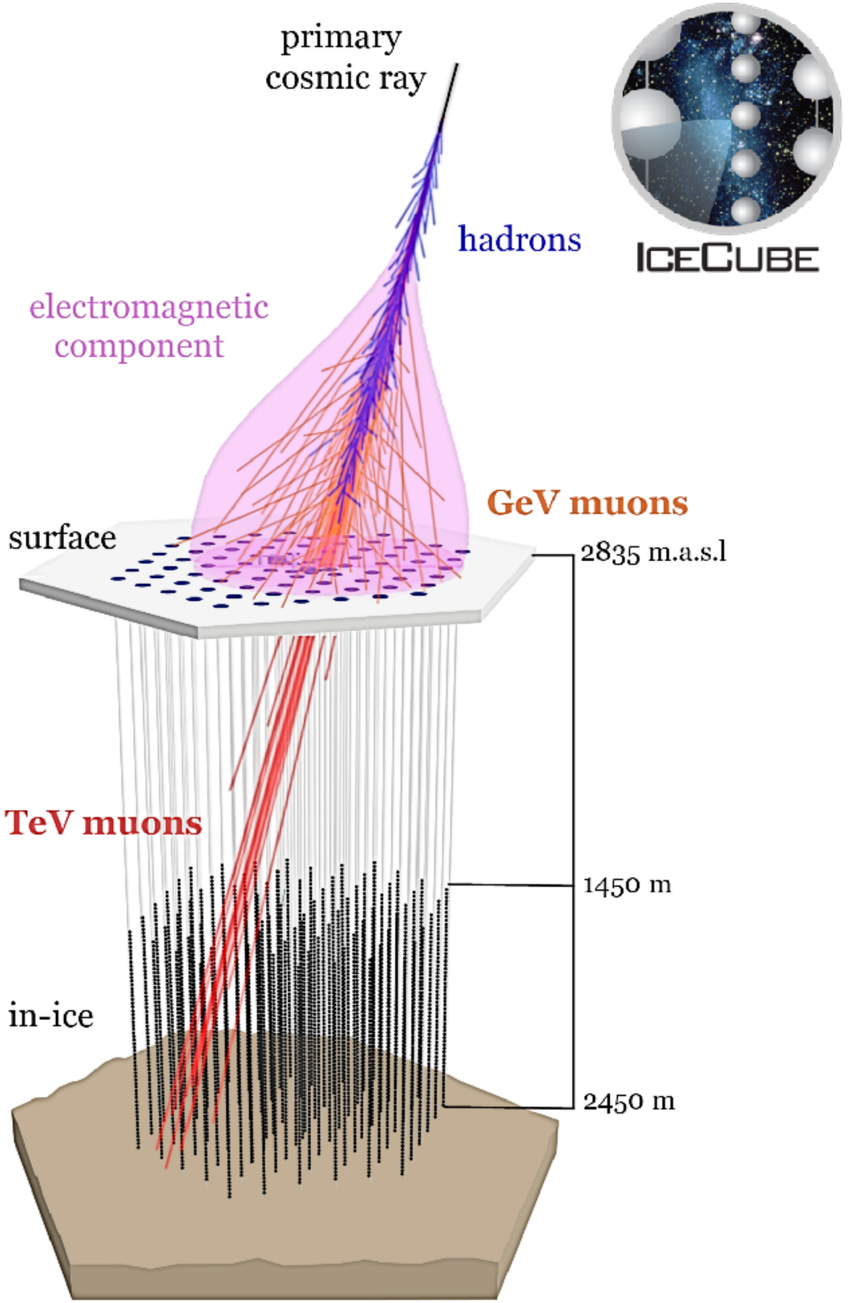
[A. Aab et al. (Pierre Auger Collaboration), Phys. Rev. D91 (2015)]



Muons in IceCube

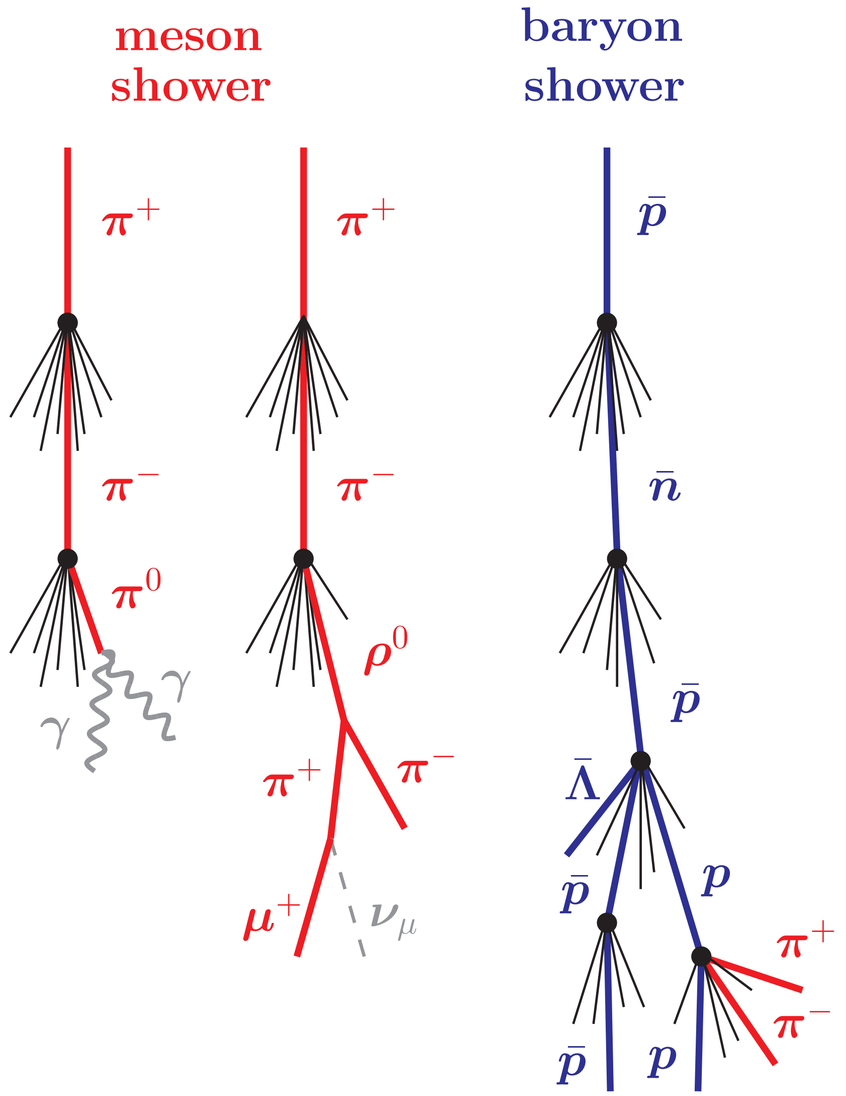
- Hybrid cubic-kilometer particle detector at South Pole
- Surface detector, IceTop, measures:
  - Electromagnetic EAS component (EAS energy)
  - GeV muon content
- In-ice detector measures:
  - TeV (up to several PeV) muon content
- Ideal facility to study lepton production in the forward region in EAS!
- Muon Puzzle: GeV muons!!
  - Why TeV muons?!?
  - Why PeV muons?!?

} this talk!



Why TeV Muons?

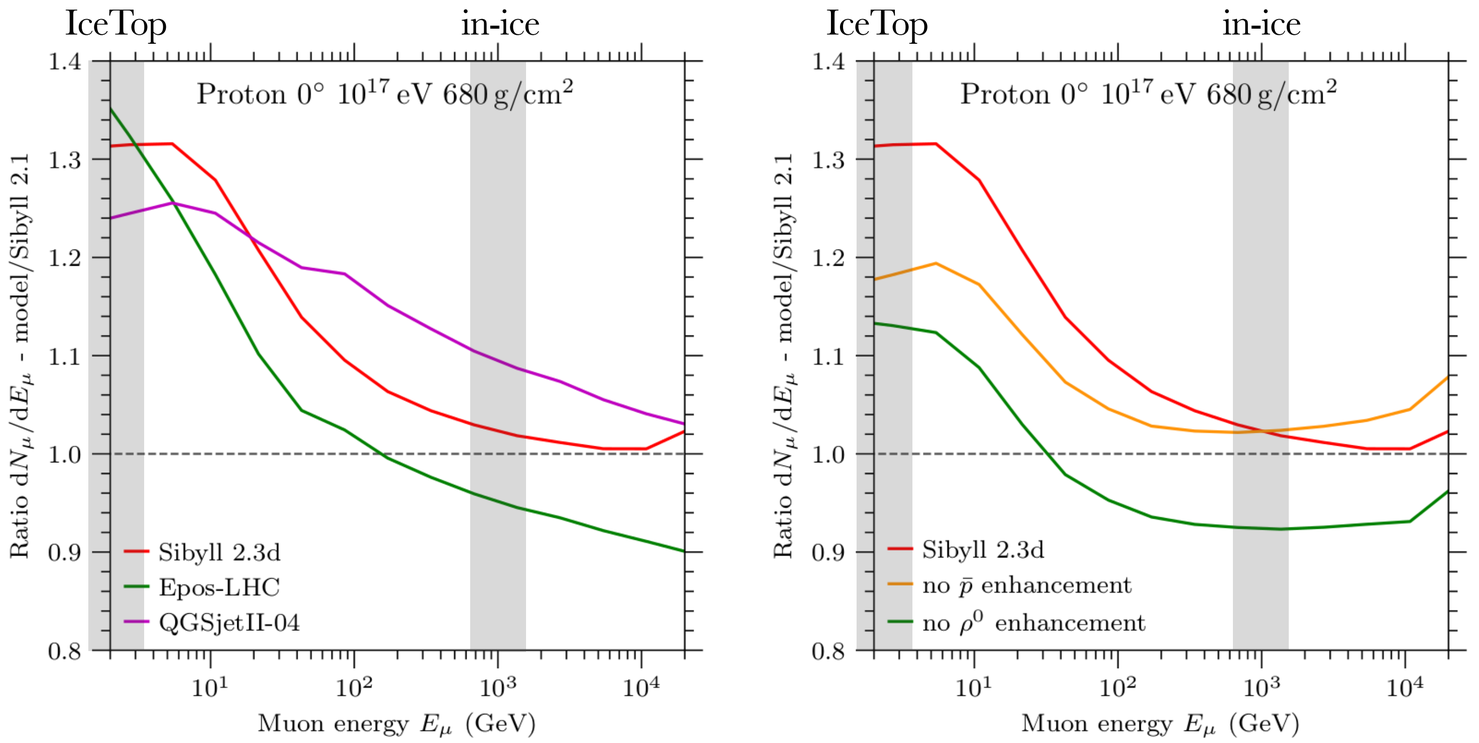
- Possible explanations for the Muon Puzzle:
  - Neutral rho meson enhancement, e.g. [1]
    - Leading particle in meson shower could be ρ_0
    - Decay of ρ_0 via charged pions into muons
    - Muon production at all energies
  - Baryon enhancement, e.g. [2]
    - Baryon anti-baryon production
    - Many re-interactions, low-energy particles
    - Mainly low-energy muons
  - New physics, e.g. [3]
    - Hadronic physics at high energies
- Different predicted muon spectra!



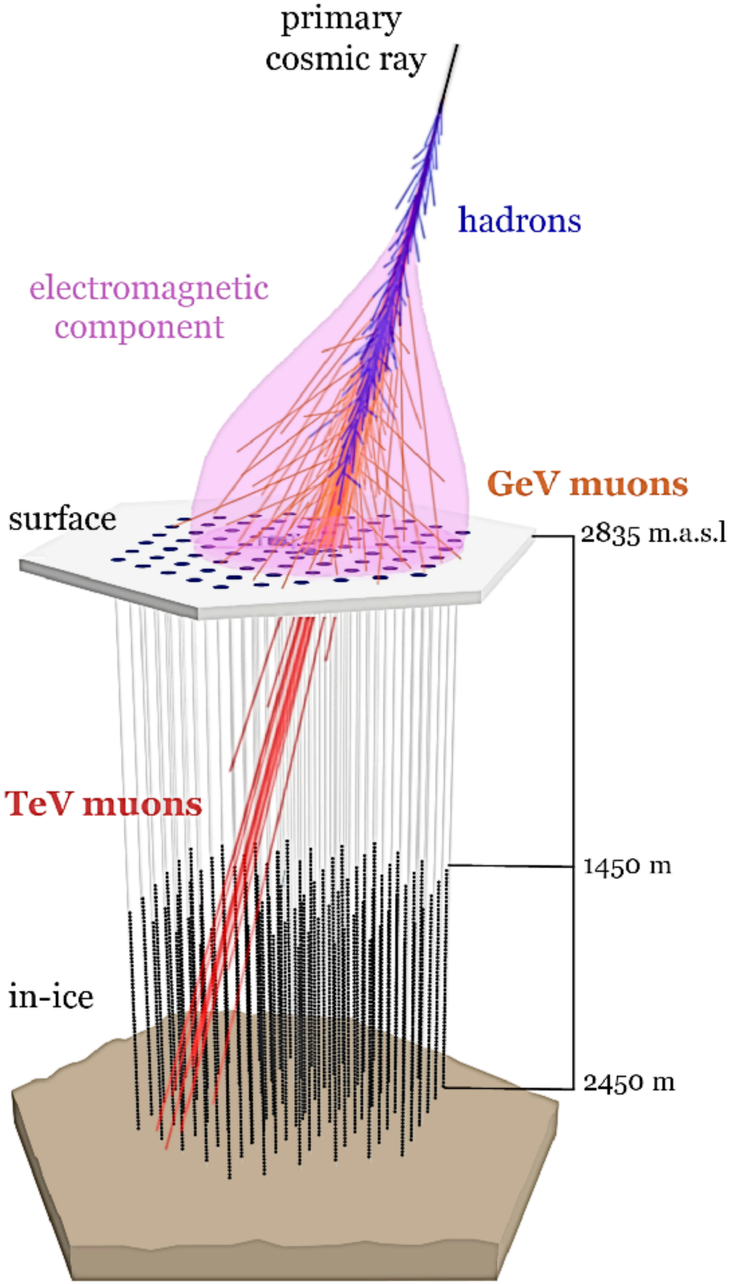
[1]: See e.g. [F. Riehn et al., Phys. Rev. D102 (2020)]
[2]: See e.g. [T. Pierog, K. Werner, Phys. Rev. Lett., 101 (2008)]
[3]: See e.g. [G. R. Farrar, J. D. Allen, EPJ Web Conf., 53 (2013)]

Why TeV Muons?

- Multiple (two+) muon energy regimes in IceCube!
- Coincident measurements provide spectral muon information
- Unique tests of multi-particle production (forward region)
- EAS energy from EM component

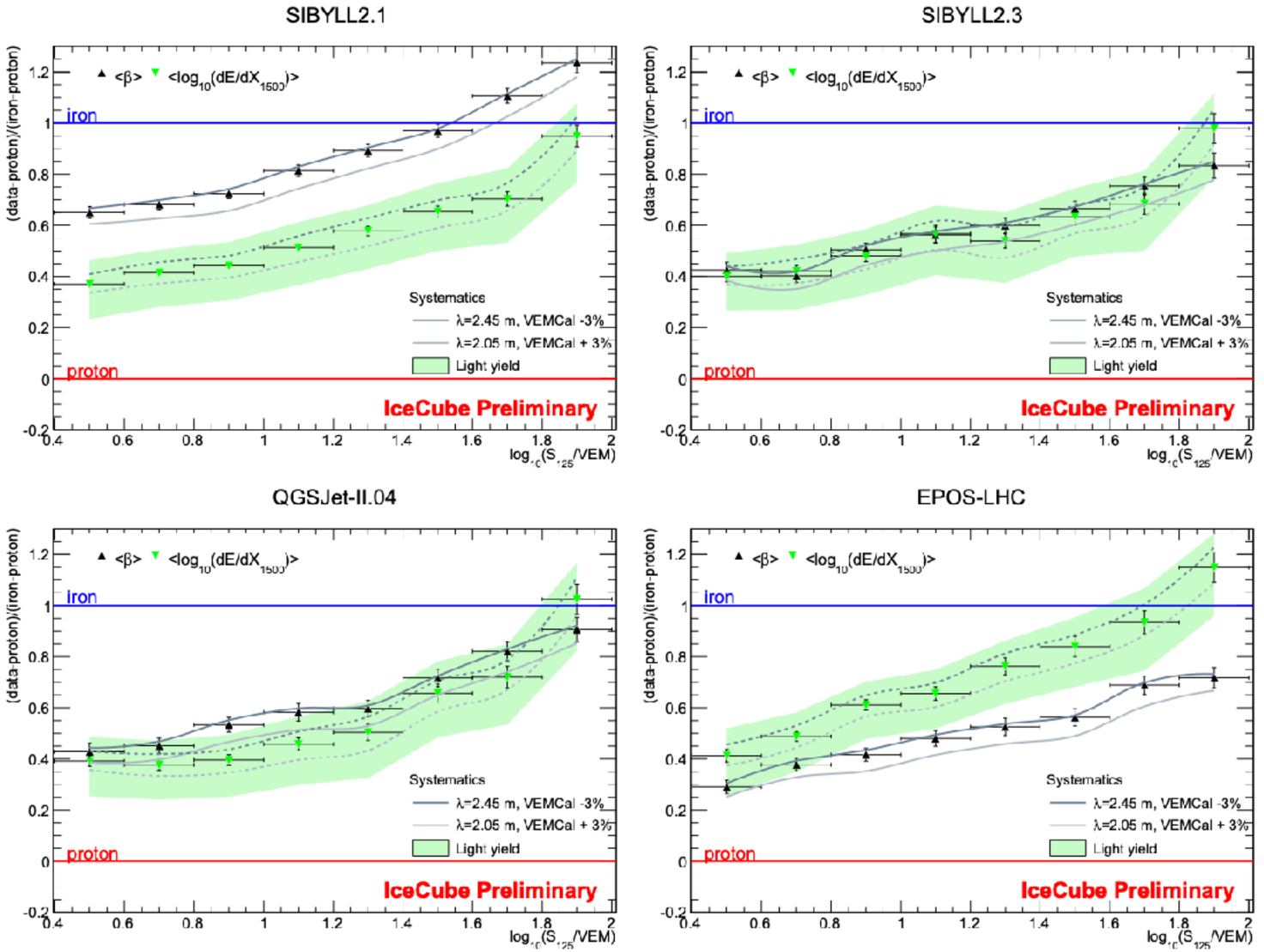


[F. Riehn et al., Phys. Rev. D102 (2020)]



Preliminary Studies with IceCube

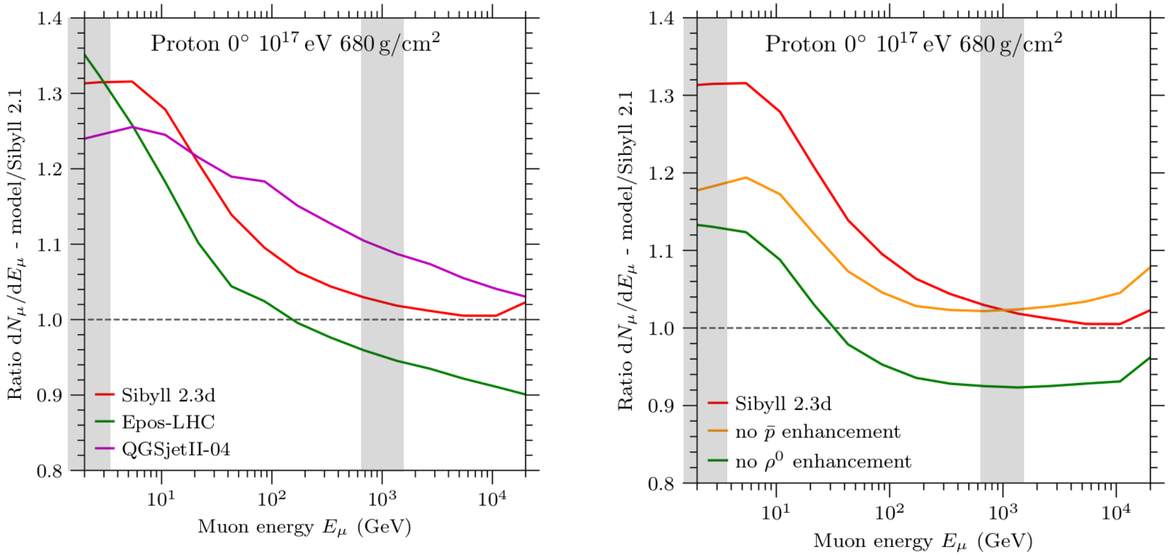
- Coincident EAS measurement
- β: "LDF slope parameter"
  (GeV muons + EM part)
- dE/dX: "in-ice muon estimator"
  (TeV muons)
- These proxies should yield the same result
- Assuming realistic CR flux, TeV muons in data/MC agree fairly well
  (Best agreement: Sibyll models)
- In contrast to GeV muons…
- Further studies in preparation…
  (see upcoming ICRC 2021!)



[S. De Ridder et al. (IceCube Collaboration), PoS(ICRC2017)319]

IceCube Surface Enhancement

- Upcoming IceCube surface radio/scintillator enhancements:
  - Energy scale cross-calibration
  - Better GeV muon separation
  - Larger solid angles (i.e. inclined EAS)
  - Higher EAS energies, closing gap to Auger
- Better understanding of muon production in EAS
- Improved muon-based composition analyses!



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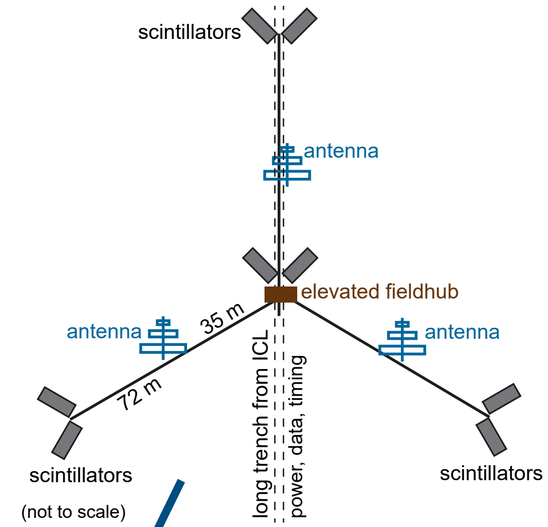
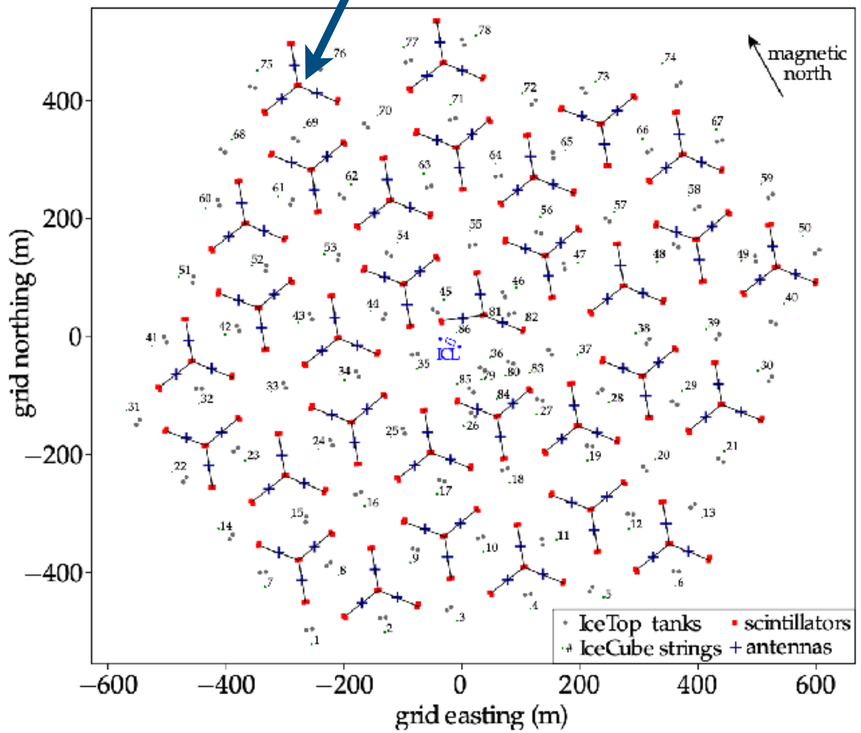


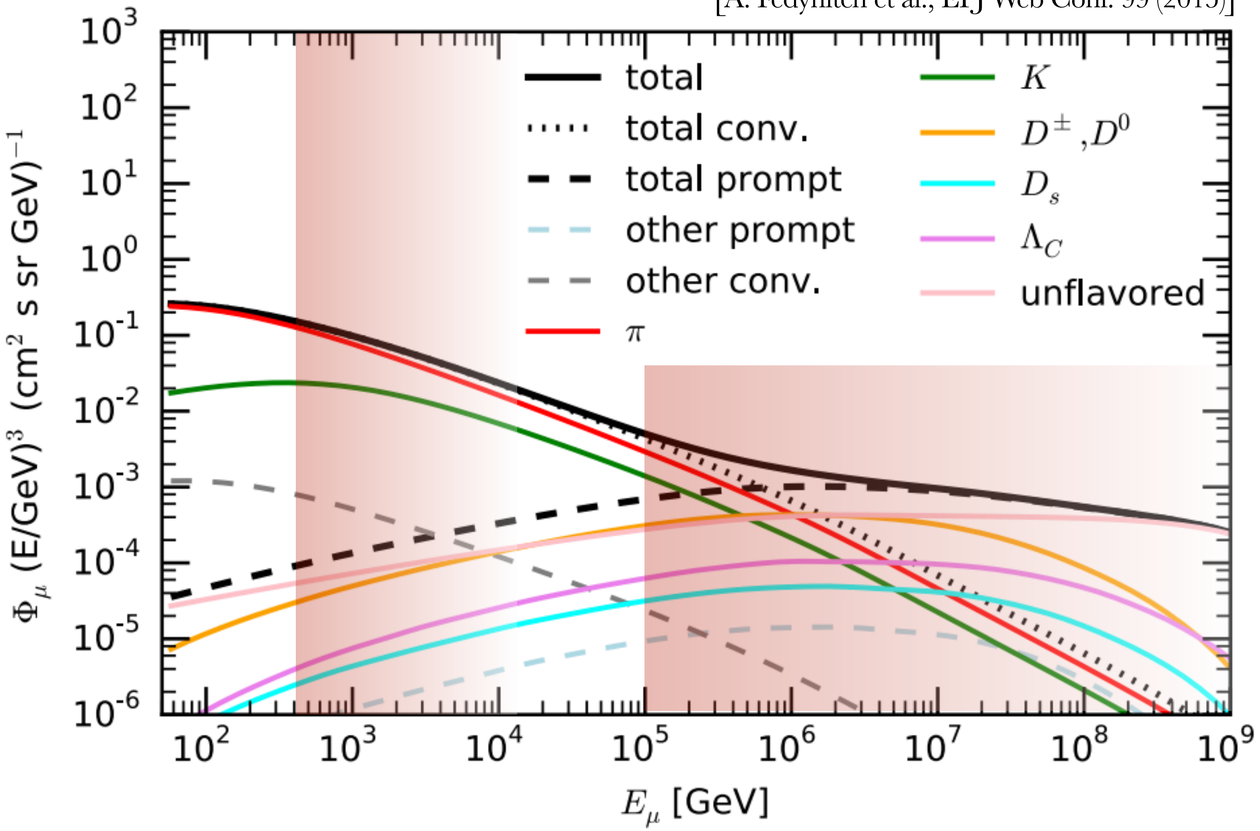


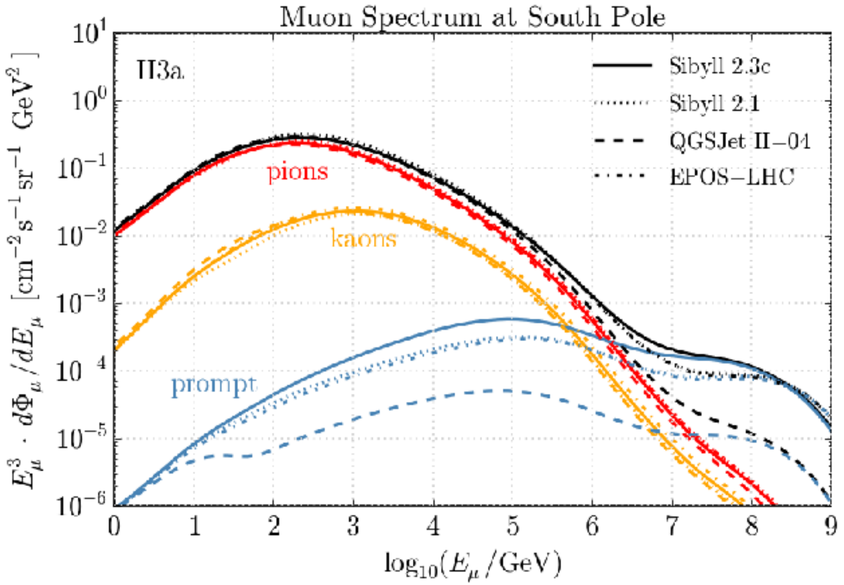
[F.G. Schröder et al. (IceCube Collaboration) PoS(ICRC2019)418]

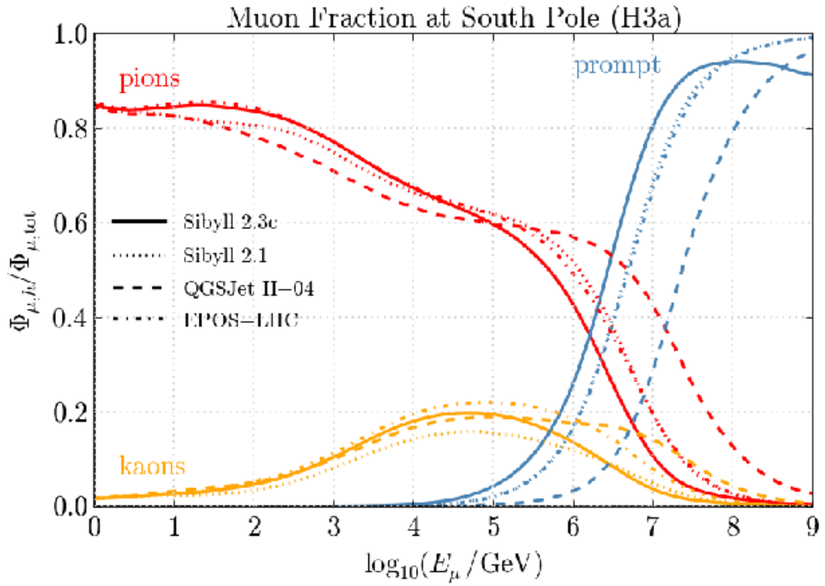
Why PeV Muons?

- Muon Puzzle expected to be unrelated to PeV muons…
- However, tests of prompt muon production in EAS!
- Background for neutrino measurements…?

[A. Fedynitch et al., EPJ Web Conf. 99 (2015)]







Obtained from MCEq [A. Fedynitch et al., EPJ Web Conf. 99 (2015)]

TeV-PeV Muon flux

- Atmospheric muon spectrum above about $E_\mu \simeq 10\,\mathrm{TeV}$
- No EAS energy (small coincidence angle)
- Best simple power law fit:

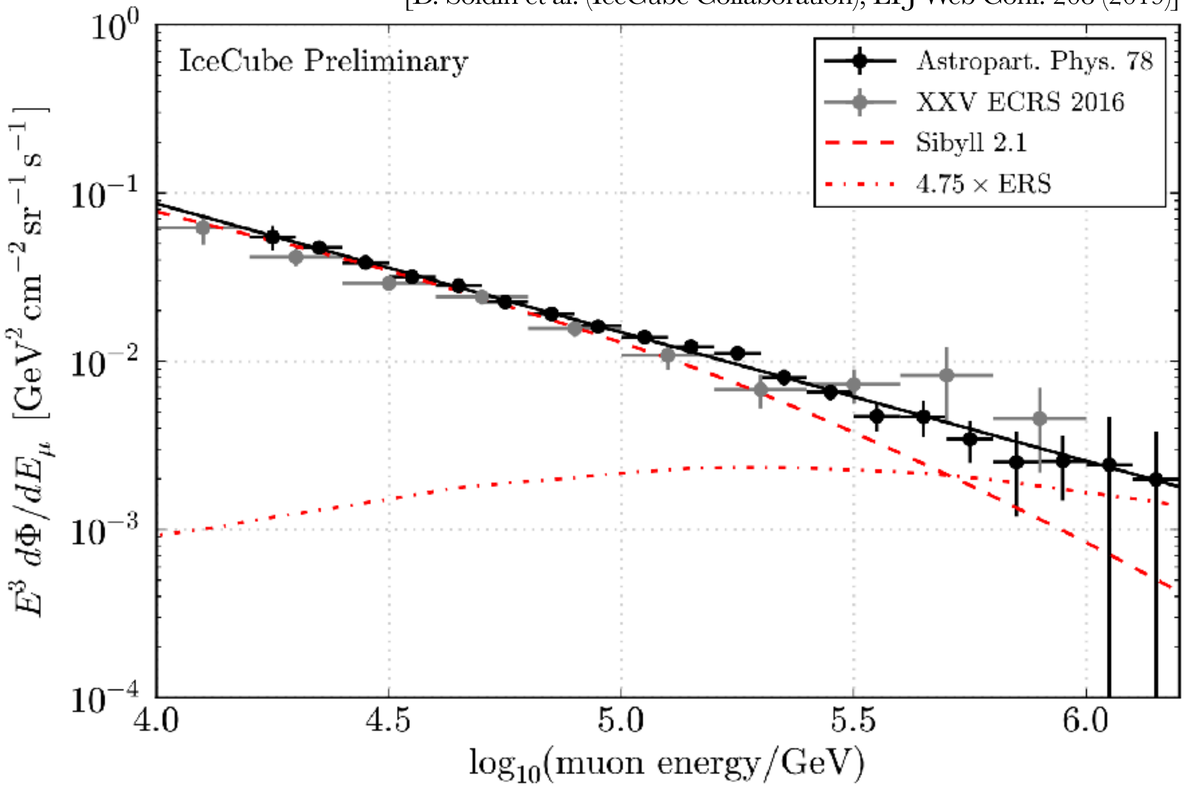
$$\frac{d\Phi}{dE_\mu} = \frac{(0.86 \pm 0.03) \cdot 10^{-10}}{\mathrm{TeV\,cm^2\,sr\,s}} \cdot \left(\frac{E_\mu}{10\,\mathrm{TeV}}\right)^{-3.76\pm0.02}$$

- Prompt best fit (H3a):

$$\Phi_{\mathrm{prompt}} = 4.75 \times \Phi_{\mathrm{ERS}}$$

- Large uncertainties due to CR flux model!
- Large prompt flux estimate…
- Muon contribution from unflavored vector mesons?

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

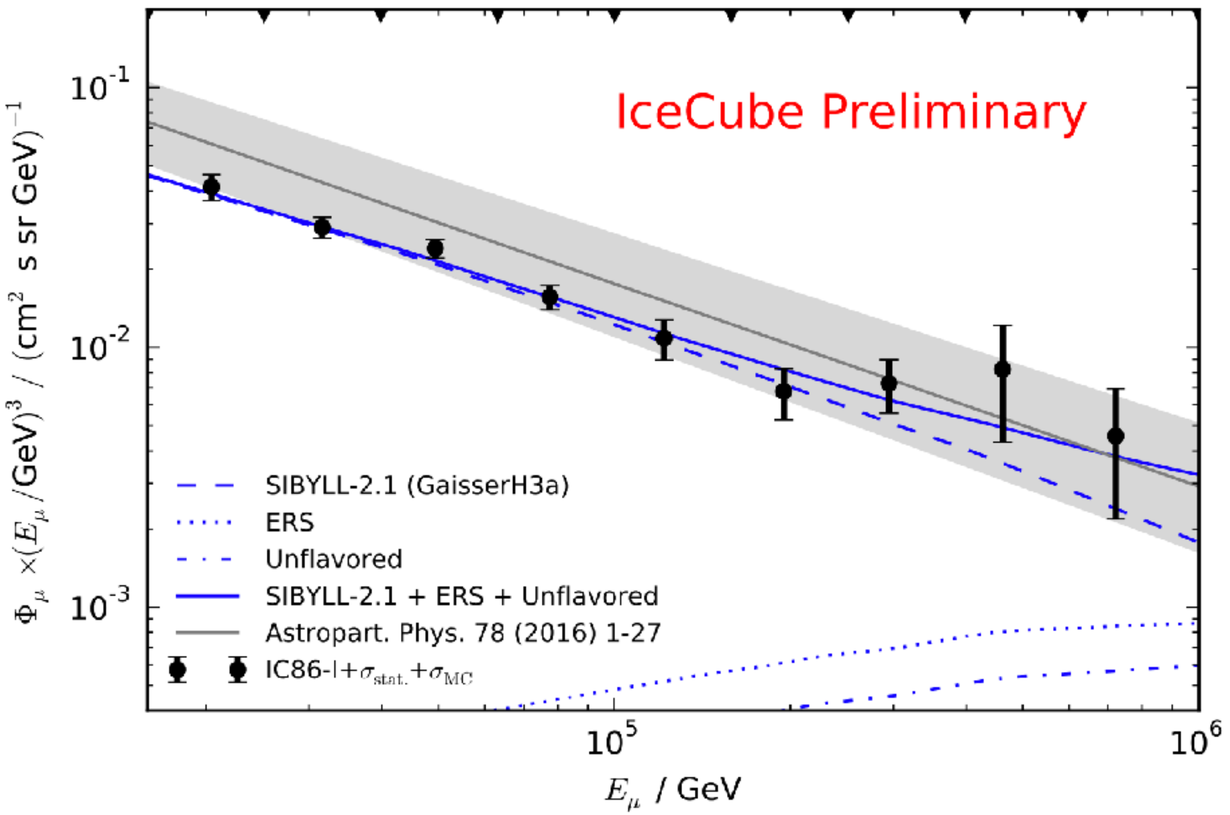


CR Model	Best Fit (ERS)	χ^2/dof	1σ Interval	Pull ($\Delta\gamma$)	$\sigma(\Phi_{\mathrm{Prompt}} > 0)$
GST-Global Fit [13]	2.14	7.96/9	1.27 - 3.35 (0.77 - 4.30)	0.01	2.64
H3a [13]	4.75	9.09/9	3.17 - 7.16 (2.33 - 9.34)	-0.03	3.97
Zats.-Sok. [35]	6.23	13.98/9	4.55 - 8.70 (3.59 - 10.68)	-0.23	5.24
PG Constant $\Delta\gamma$ [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

[M.G. Aartsen et al. (IceCube Collaboration), Astropart.Phys. 78 (2016)]

TeV-PeV Muon flux

[T. Fuchs et al. (IceCube Collaboration), XXV ECRS (2016)]



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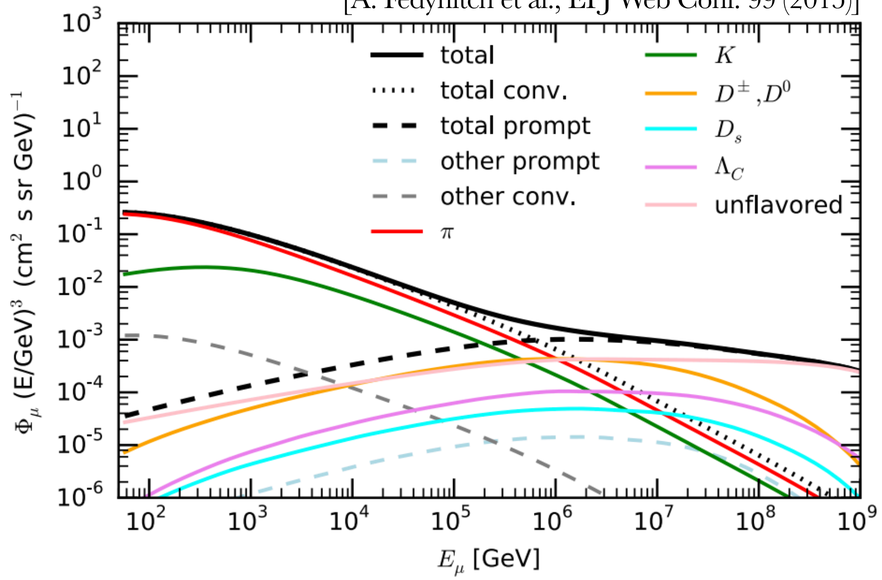
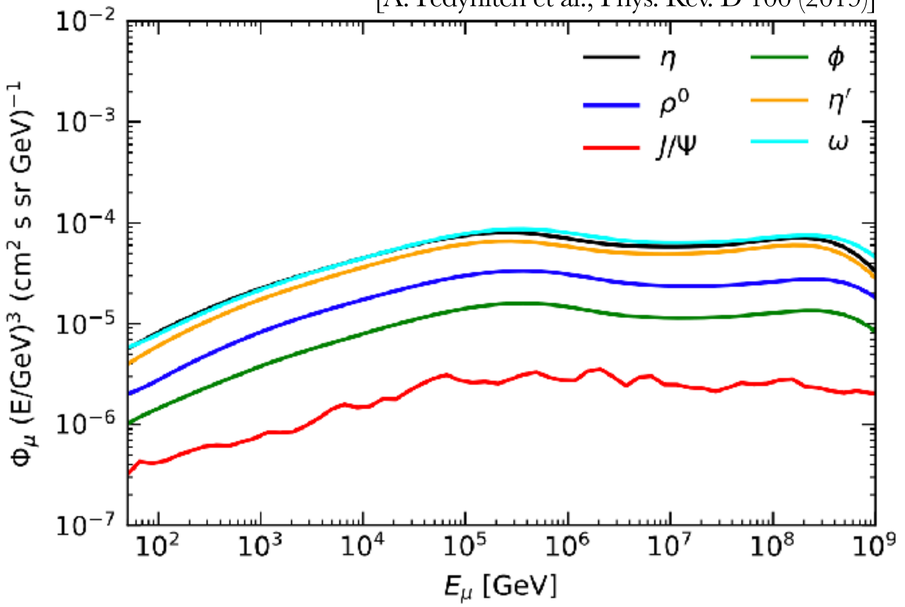


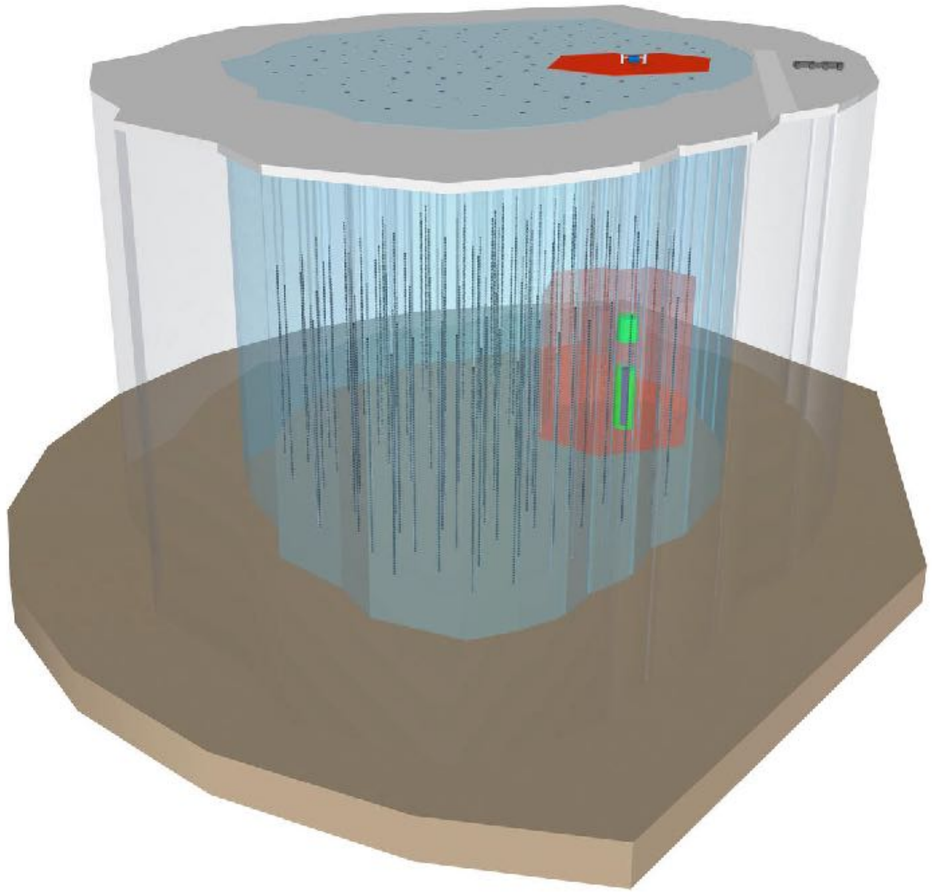
[A. Fedynitch et al., Phys. Rev. D 100 (2019)]



- Potentially large contribution from unflavored mesons?
- Measurements in IceCube-Gen2 will measure prompt muon production…

Why PeV Muons?

- Expected PeV muon flux in IceCube-Gen2:
  - $\mathcal{O}(100/\mathrm{yr}) - \mathcal{O}(1000/\mathrm{yr})$ (>1 PeV)
  - Relevant background for neutrino measurements in IceCube-Gen2!
  - First high-statistics measurement of prompt muon flux!
  - Large-scale surface detectors allow simultaneous determination of EAS energy
  - Muon flux at 1 EeV: $\sim \mathcal{O}(10^{-4}/\mathrm{yr})$
  - No significant background for cosmogenic neutrino searches in IceCube-Gen2 at EeV energies



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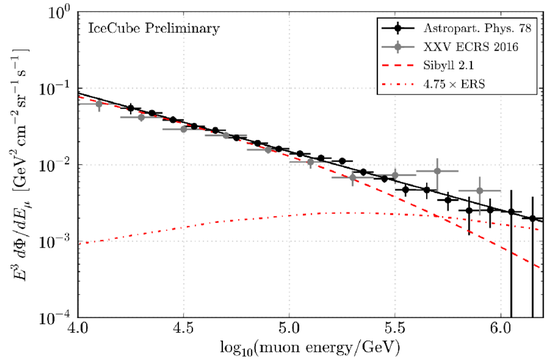

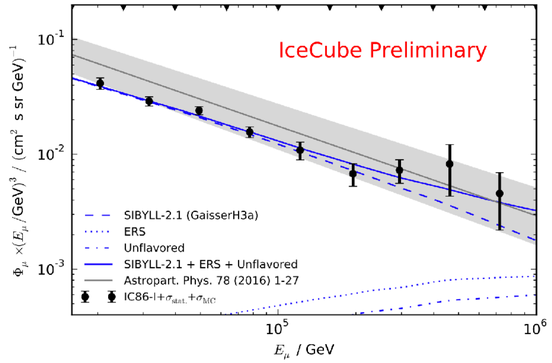

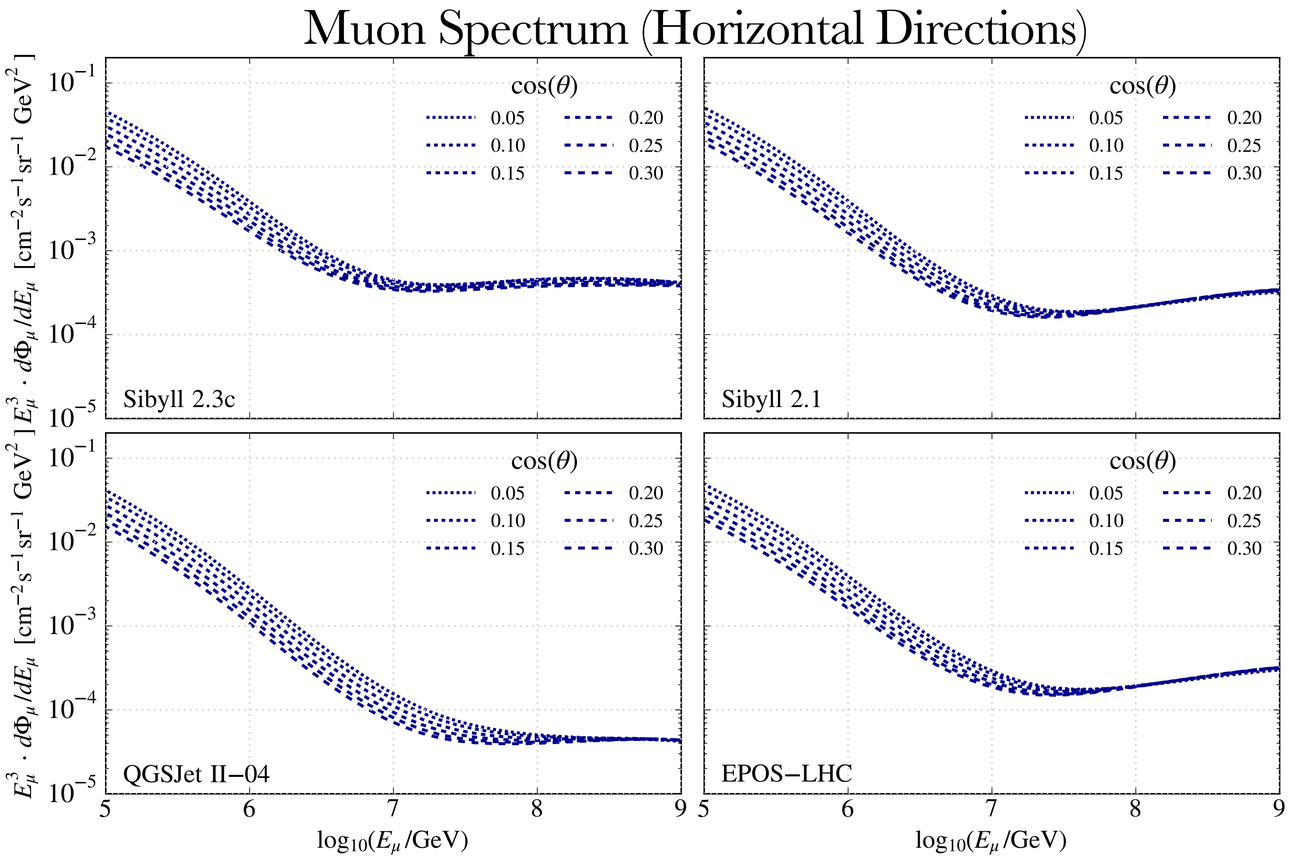

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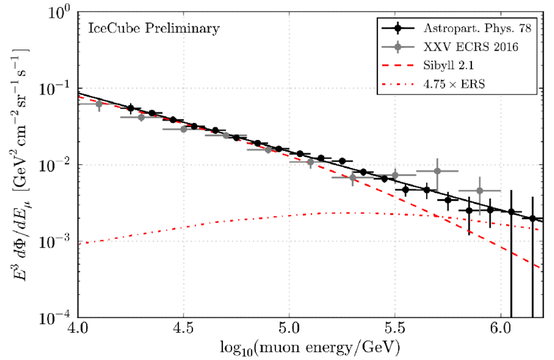
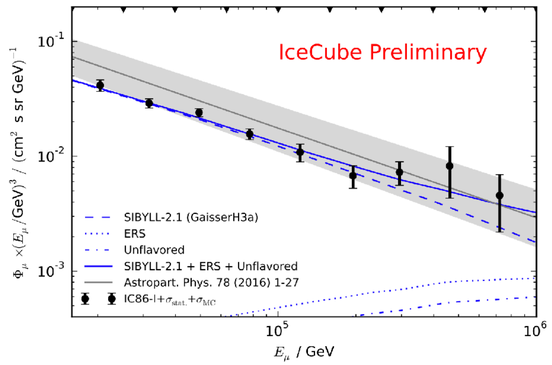
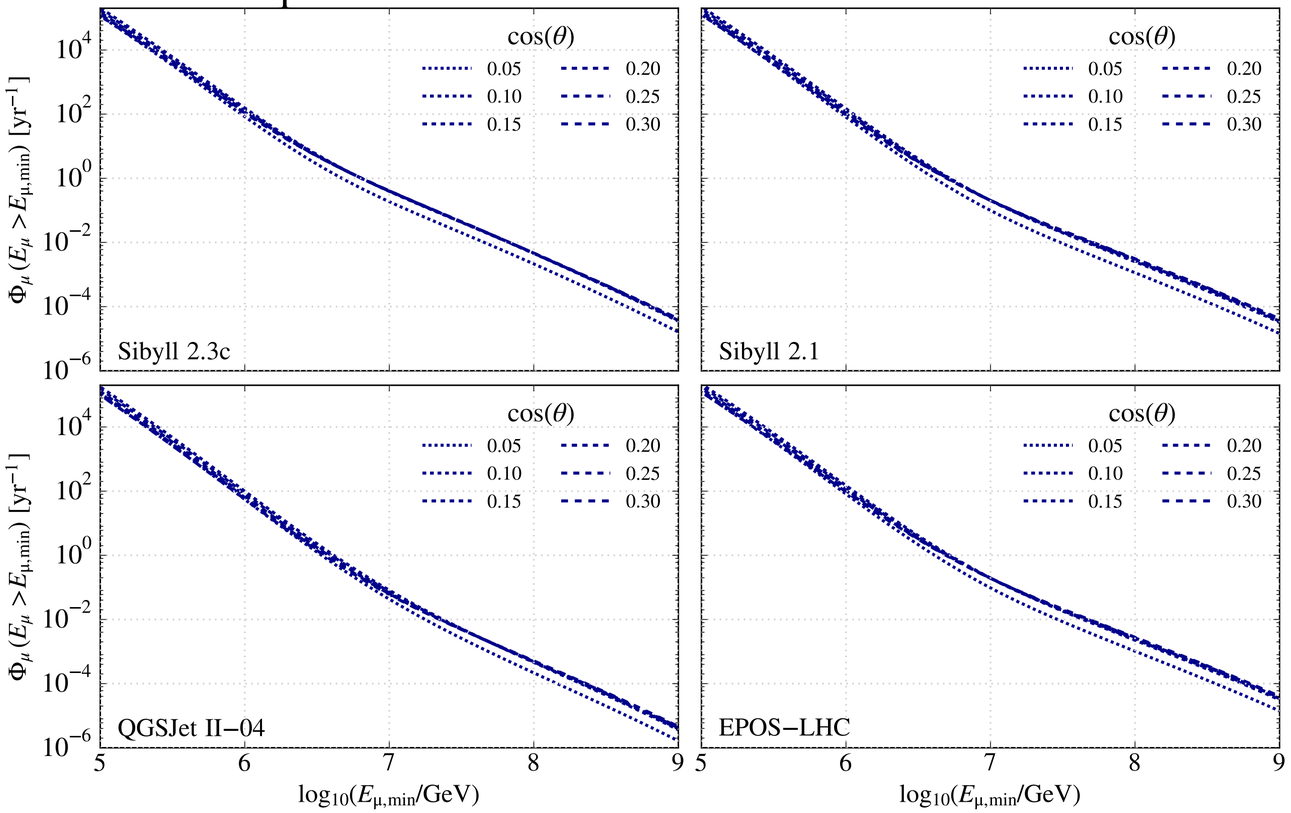




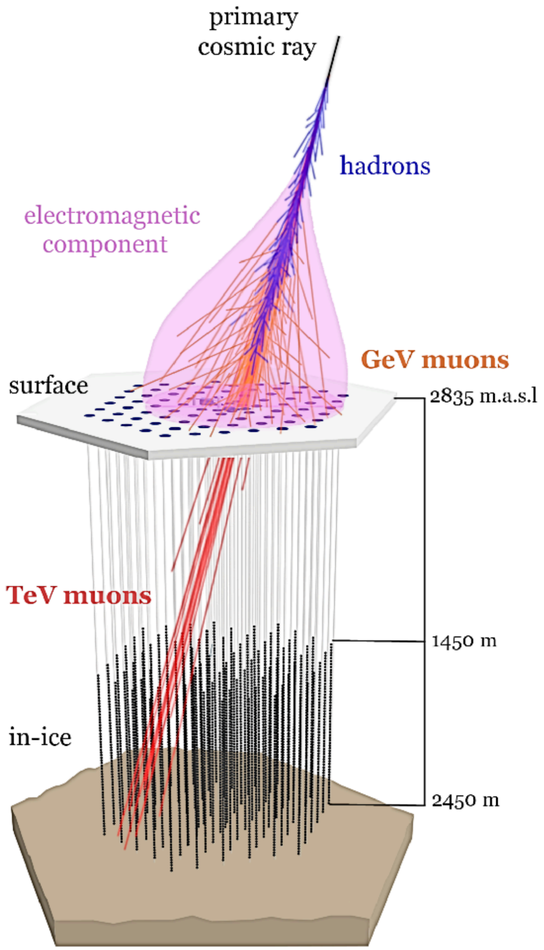
Expected number of muons in IceCube-Gen2



See also talk by A. Coleman on Thursday…

Summary & Conclusions

- Measurements of GeV-TeV muons:
  - Hybrid measurements of muons at multiple energy regimes will improve understanding of hadronic interactions in EAS!
  - Unique tests of multi-particle production in the forward region of hadronic interactions including heavy nuclei
  - Together with measurements by Auger Prime: Discovery of the origin of the Muon Puzzle within next decade..?
  - Reduced uncertainties for CR mass composition measurements
- Measurements of several TeV-PeV muons:
  - Lepton energies relevant for large-scale neutrino telescopes
  - Transition region of conventional, prompt, astrophysical fluxes
  - Reduced uncertainties in conventional/prompt lepton fluxes
  - Better understanding of the transition region conv./prompt/astro.



Thank You!