technische universität dortmund

IceCube Neutrino Observatory

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Prospects of constraining hadronic interaction models with IceCube

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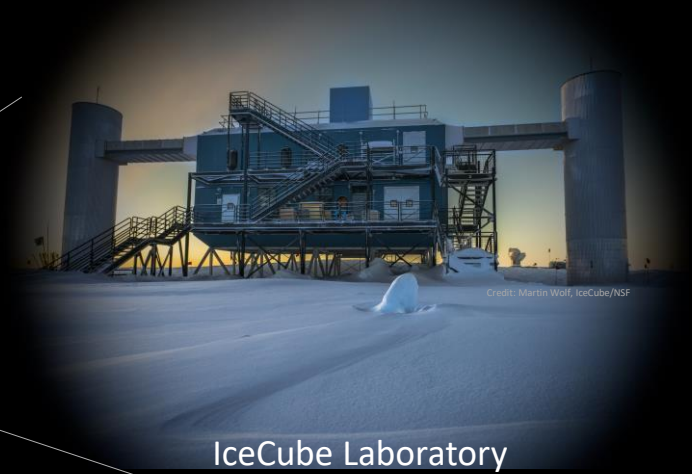
Workshop on the Tuning of Hadronic Interaction Models
Wuppertal, Germany
January 24th, 2024

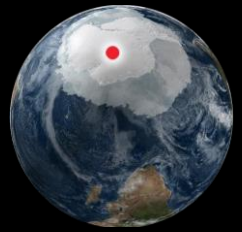
Talk Outline

- The IceCube Neutrino Detector
- Detection channels and observables in IceCube
- Analysis Methods
- Previous Analyses
- Future Analyses
- Conclusions

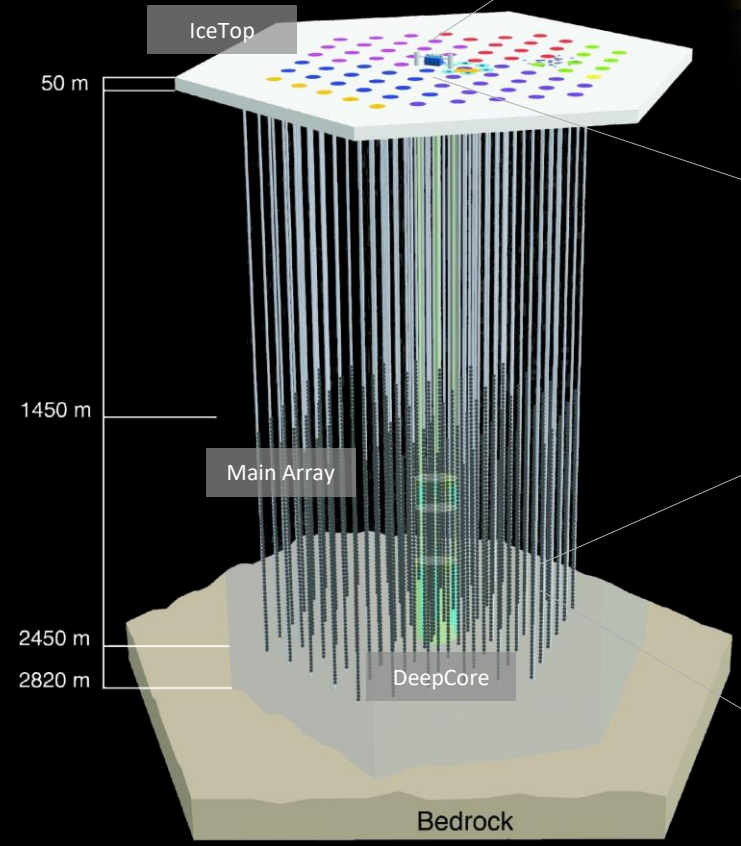
IceCube Neutrino Observatory

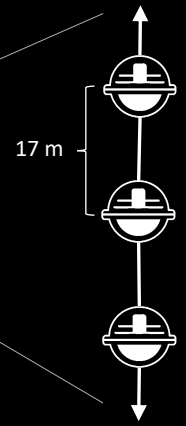


IceCube Laboratory

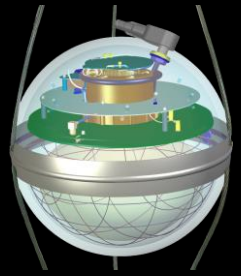


Amundsen-Scott South Pole Station, Antarctica



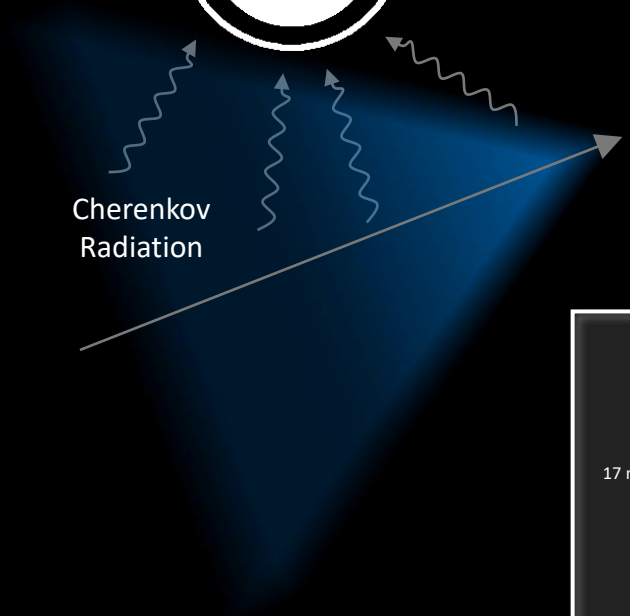


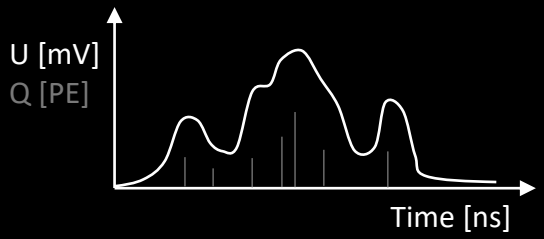
86 Strings:
78 Main Array
8 DeepCore



5160 Digital Optical Modules (DOMs)

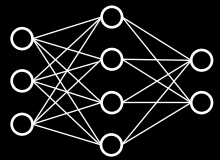
Detection Mechanism



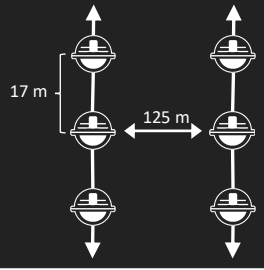


Pulse Series: (t_i, q_i)

$$\mathcal{L}\left(\vec{x}\middle|\vec{\theta}\right) = \prod_i p(x_i|\vec{\theta})$$



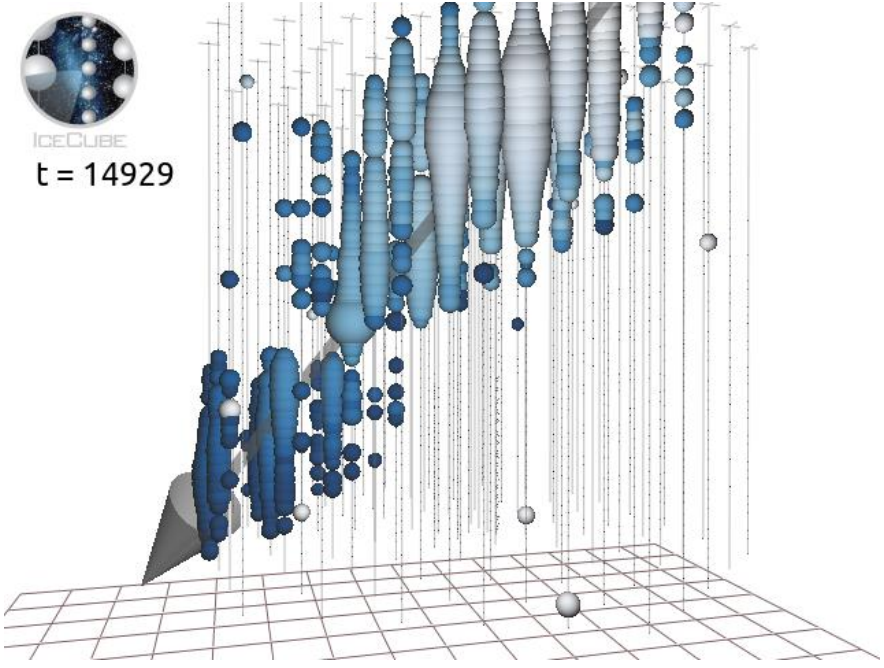
Sparse Instrumentation:



- Limited resolution for distinction of laterally separated muons
- Limited resolution for distinction of neutrino flavors

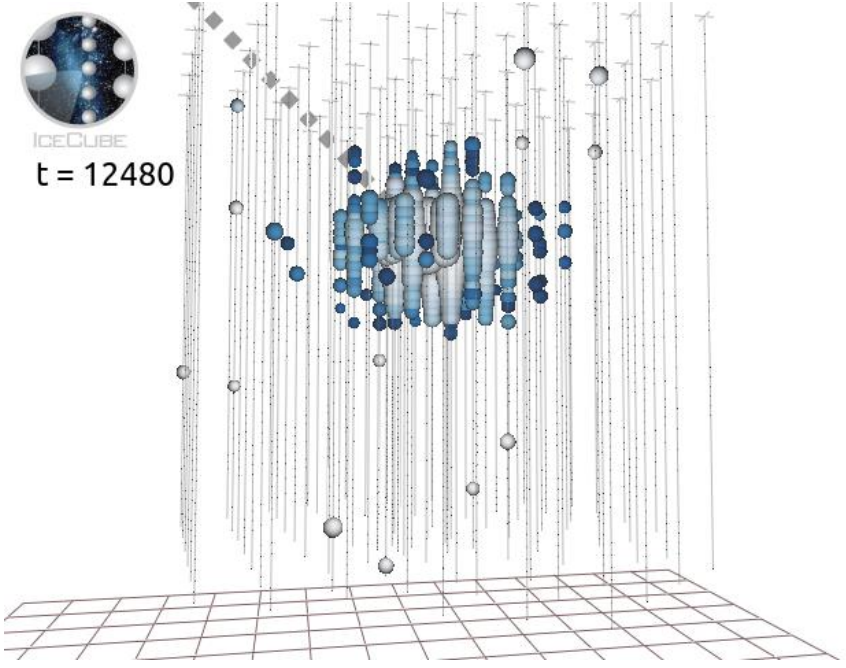
Event Topologies

Entering Tracks



Atmospheric muons
Neutrino-induced muons

Starting Tracks and Cascades



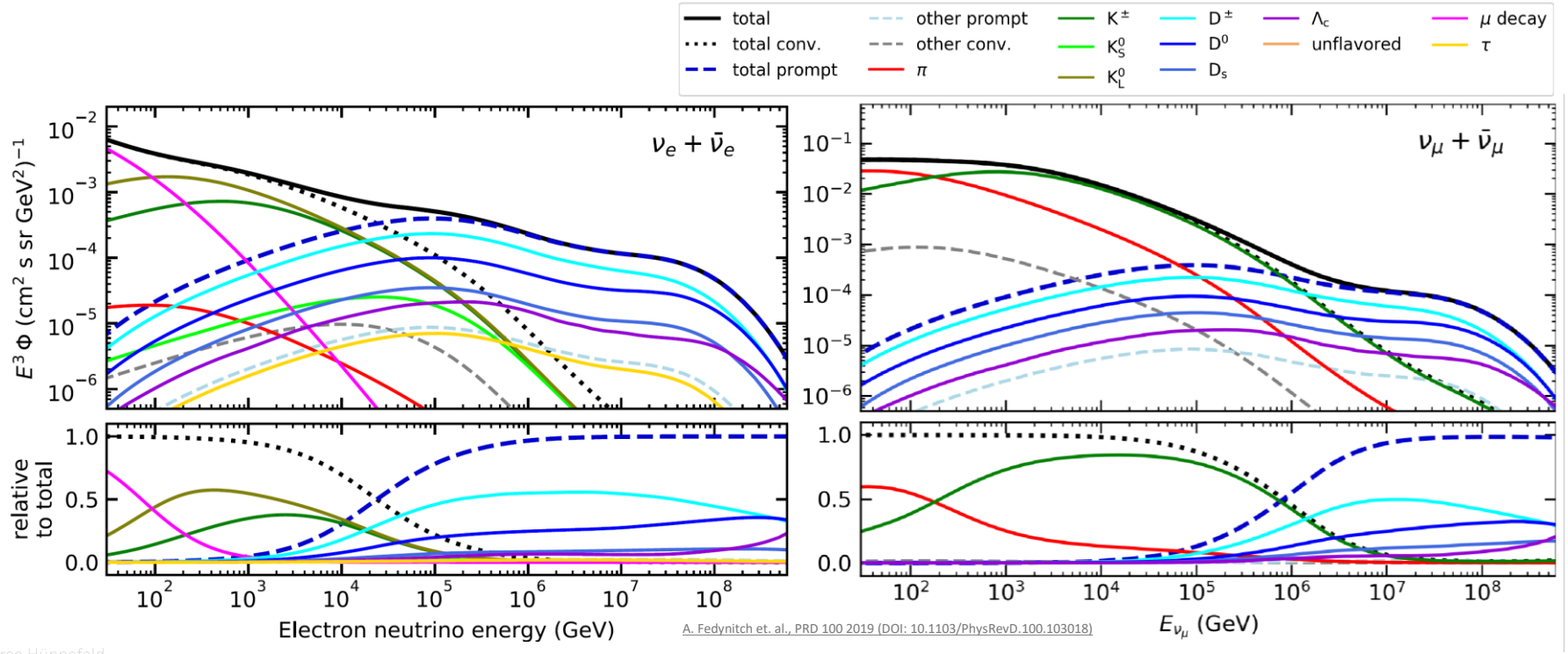
Neutrino-induced showers and muons

Observables in IceCube

Detection channels

- Entering tracks: atmospheric muons/bundles
- Starting/up-going tracks: ν_μ charged-current interactions
- Starting showers (cascades): all-flavor neutrino ν_*

Can probe different quantities of air showers



A. Fedynitch et. al., PRD 100 2019 (DOI: 10.1103/PhysRevD.100.103018)

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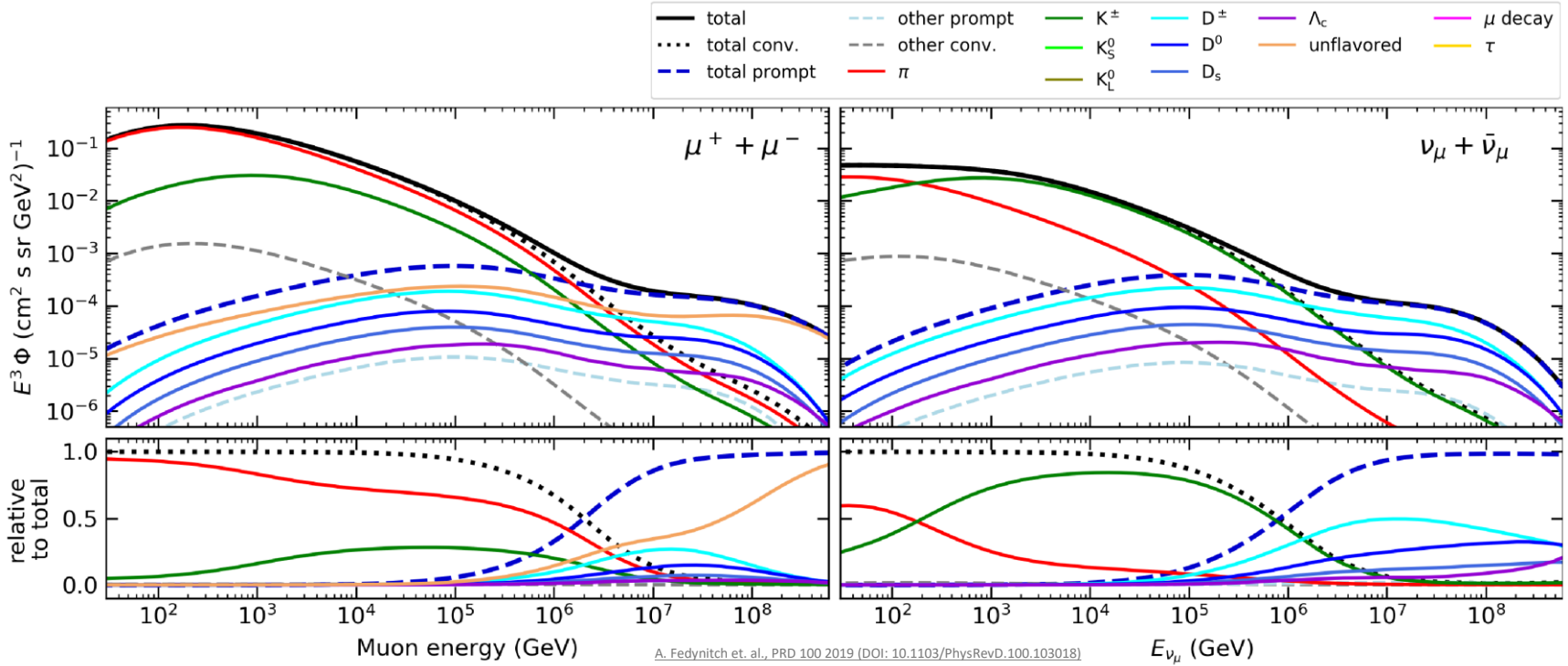

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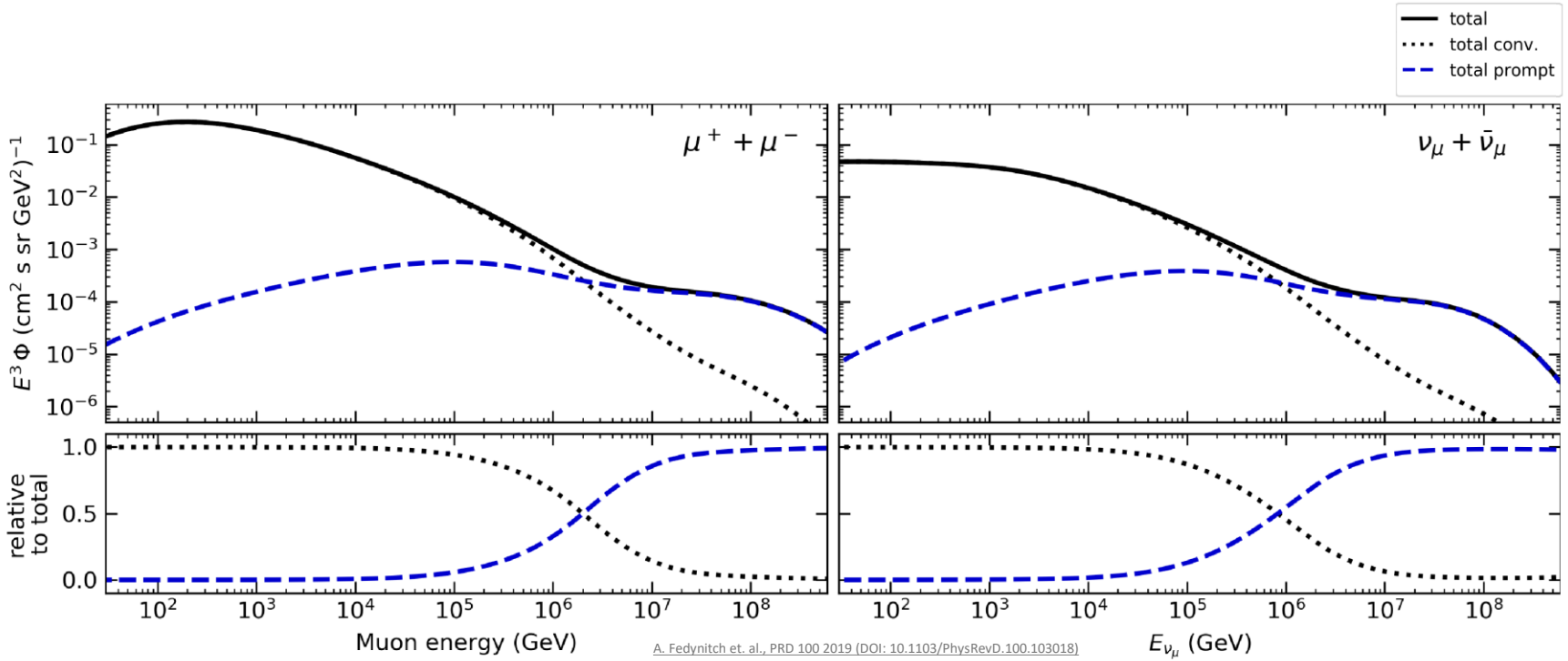

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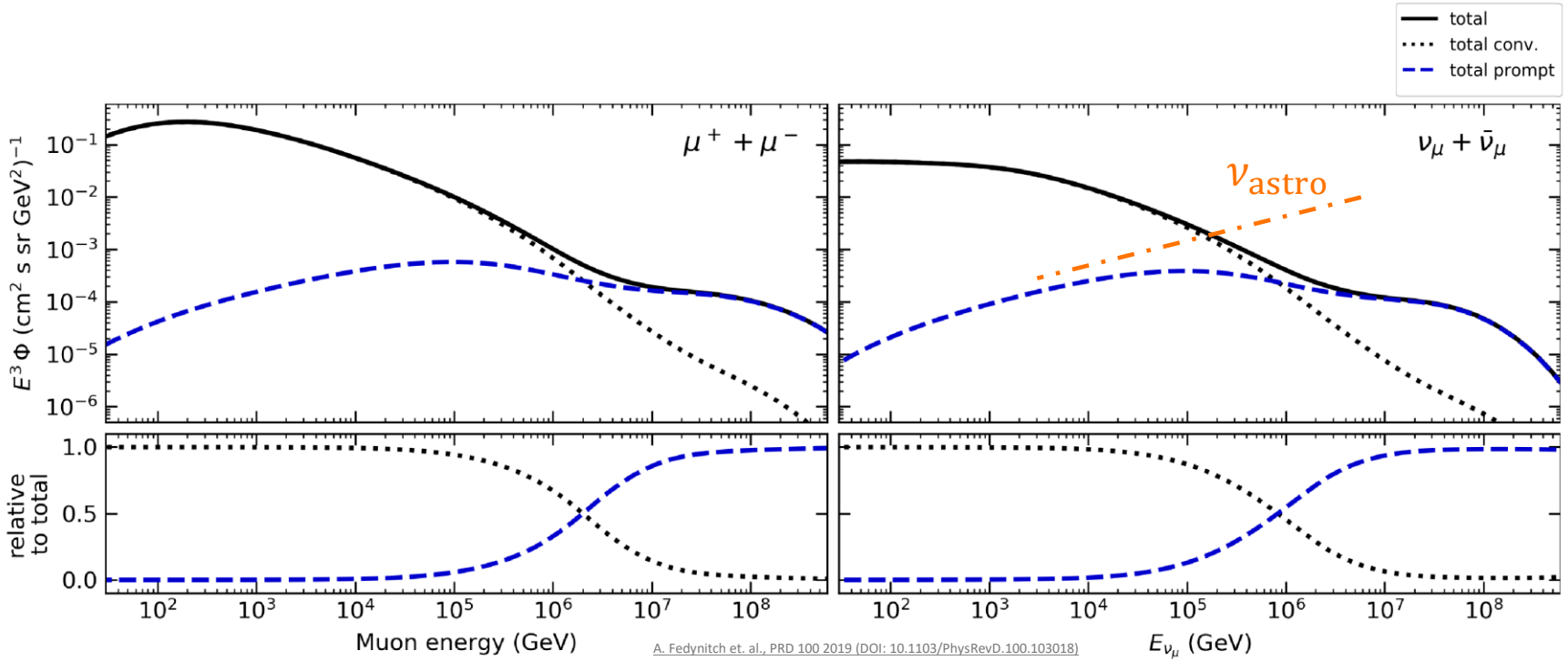
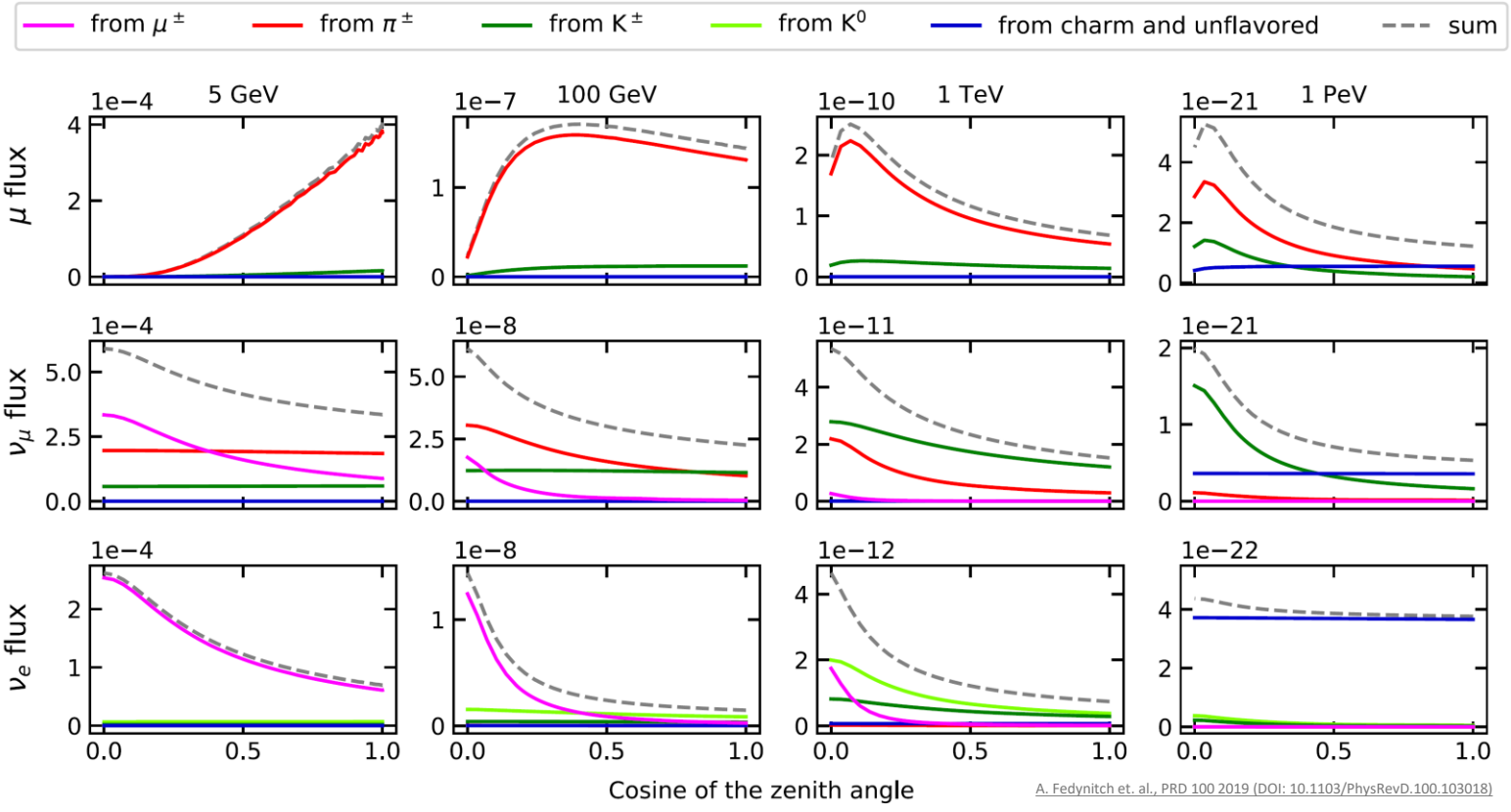


A. Fedynitch et. al., PRD 100 2019 (DOI: 10.1103/PhysRevD.100.103018)

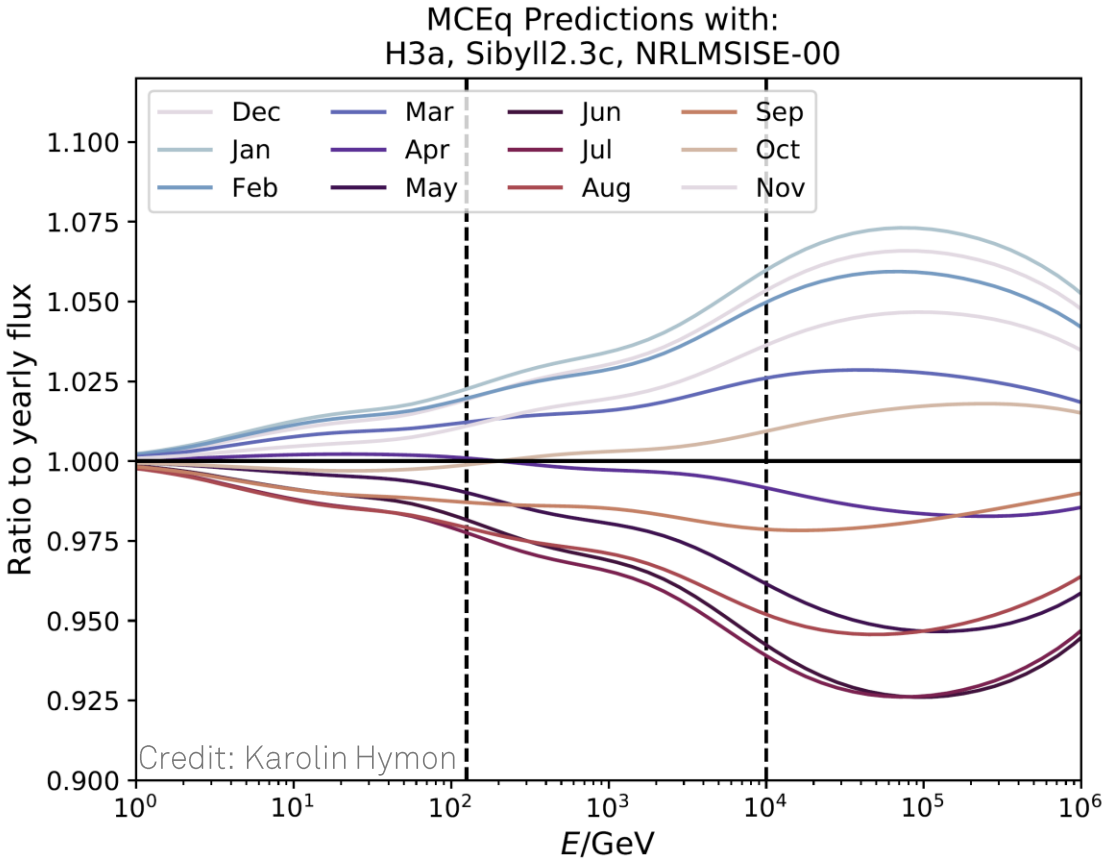
Observables in IceCube: zenith distribution



A. Fedynitch et. al., PRD 100 2019 (DOI: 10.1103/PhysRevD.100.103018)

Prompt component unaffected by Atmosphere

Observables in IceCube: seasonal variations



Prompt component unaffected by Atmosphere

Analysis methods

Observables

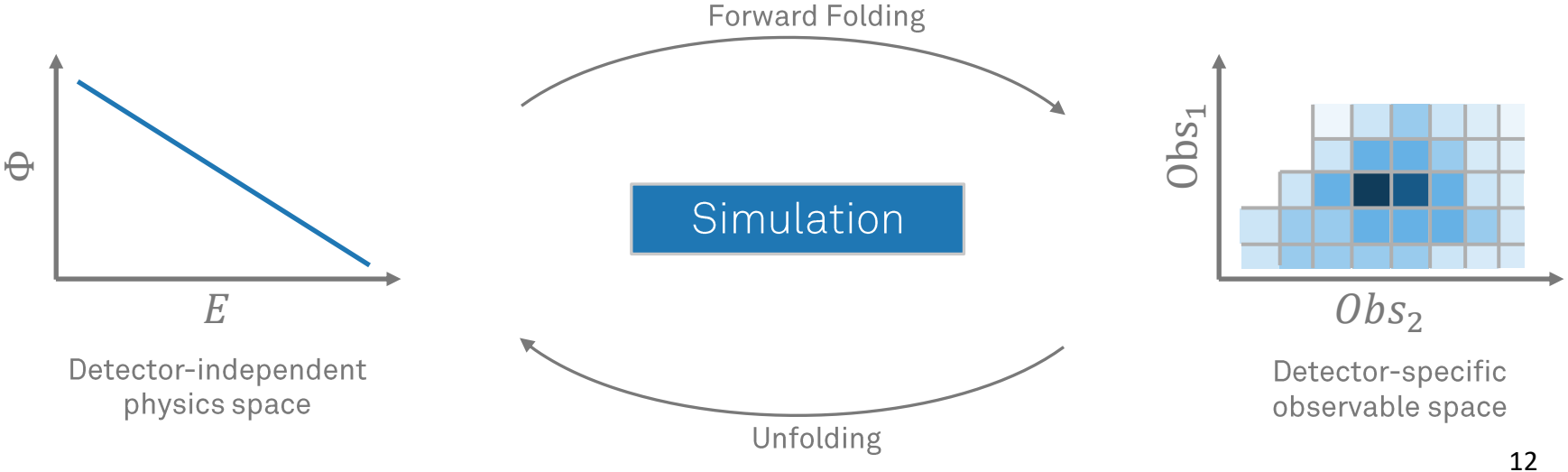
- Energy, zenith, seasonal variation (+ characteristics of muon bundles)

Analysis Methods

- Forward folding
- Unfolding of spectra

Goal: testing or constraining parameters of a specific model

Goal: model-independent measurement



Previous Analyses: Atmospheric Muons

Unfolding of high-energy muon spectrum[1]

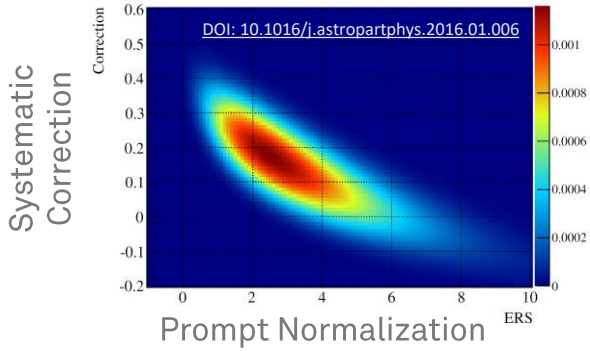
- Unfolding analysis utilizing 1 year of data (2011)
- Analysis limited by simulation statistics

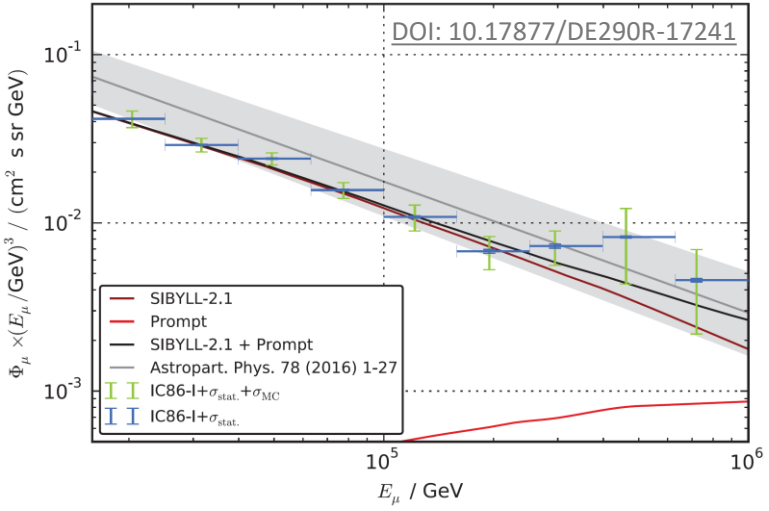
Characterization of the atmospheric muon flux[2]

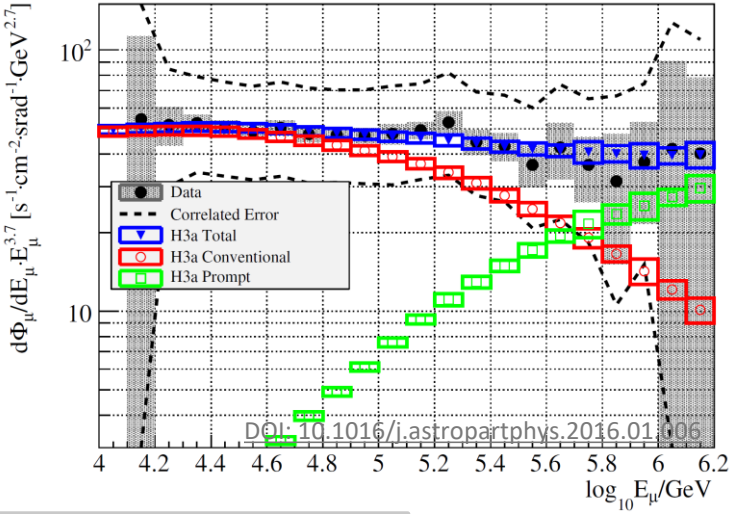
- Measurement utilizing 2 years of data (2010, 2011)
- Analysis limited by data/MC agreement

[1]DOI: 10.17877/DE290R-17241 [2]DOI: 10.1016/j.astropartphys.2016.01.006

Both analyses suffer from systematic uncertainties







Indications for the prompt component, but inconclusive due to systematics

Previous Analyses: Neutrino Measurements

Forward folding analyses

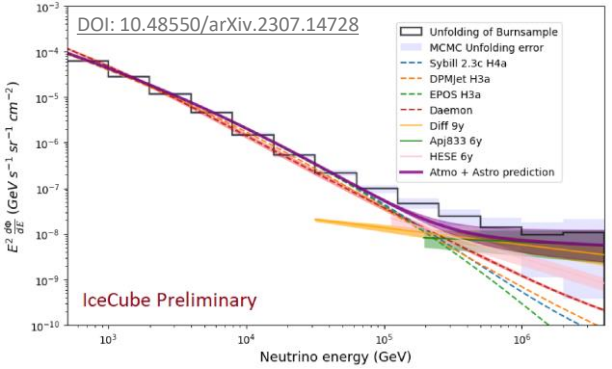
- Combined fit on tracks and cascades with over 10 years of data[1]
- Forward folding fit on 6 years of cascade data[2]

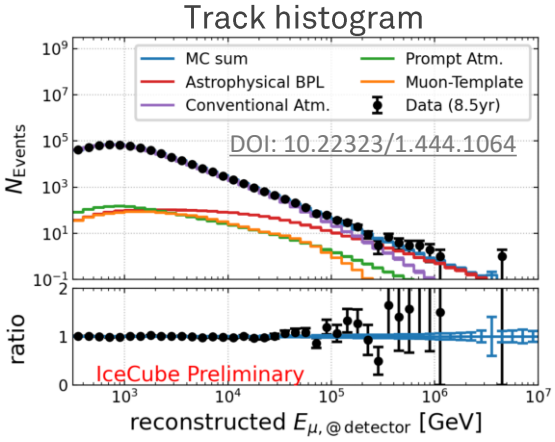
Unfolding analyses

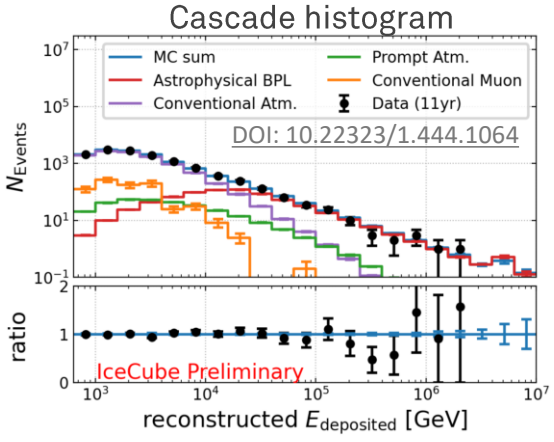
- Muon-neutrino spectrum on 11 years of northern tracks[3]

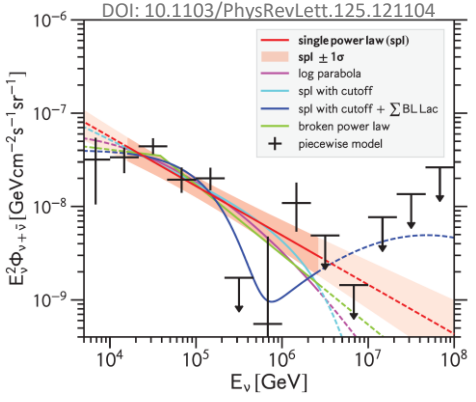
(non-exhaustive list: many more analyses exist)

[1] DOI: 10.22323/1.444.1064
[2] DOI: 10.1103/PhysRevLett.125.121104
[3] DOI: 10.48550/arXiv.2307.14728







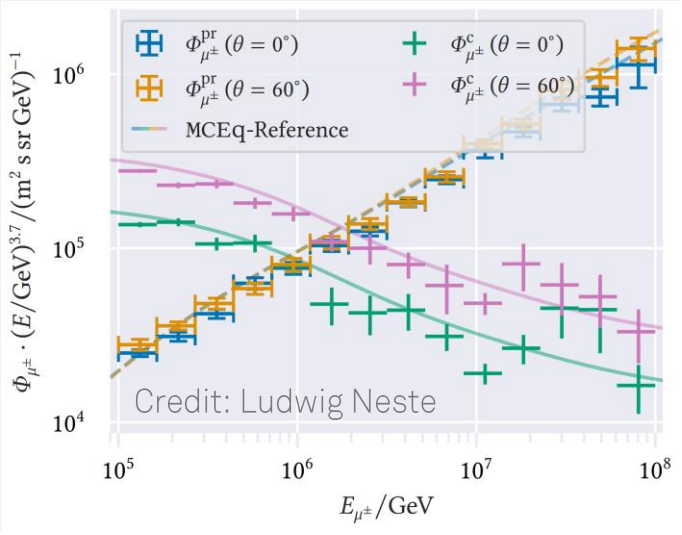


Prompt component not sufficiently constrained due to astrophysical flux

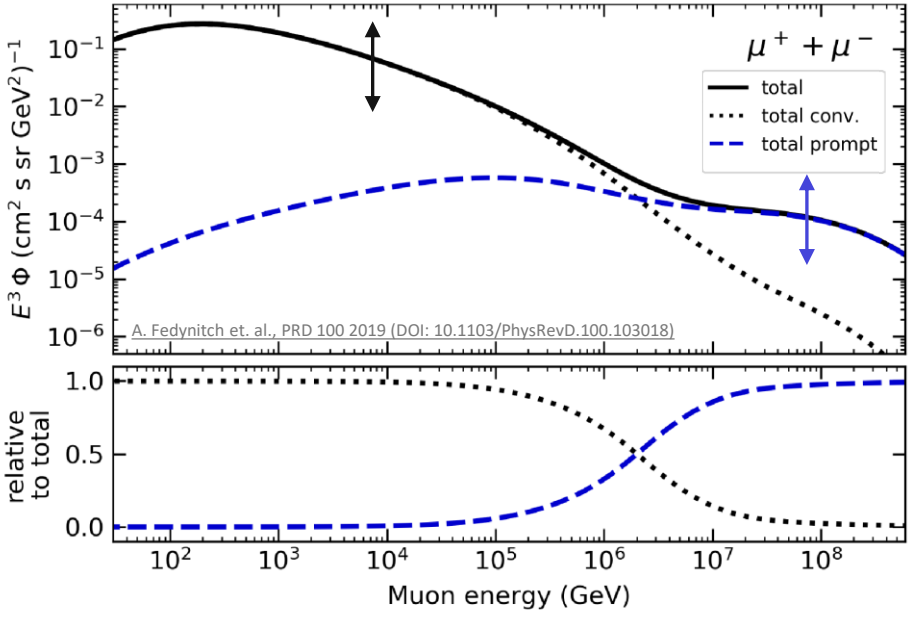
Future Analyses: Atmospheric Muons

Combined unfolding and forward folding analysis

- Updated muon analysis with increased statistics
- Unfold muon spectrum at Earth's surface
- Forward folding fit to constrain prompt contribution under certain model assumptions
- Tagging of decay channels via EHIST option in CORSIKA 7



Fit for conventional (↕) and prompt (↕) normalization

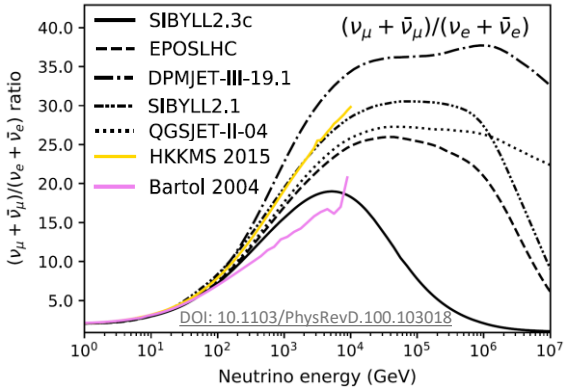


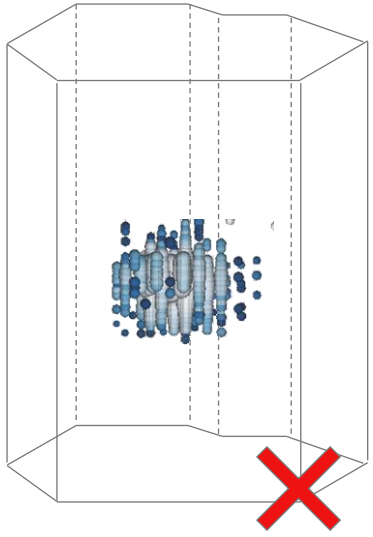
Early sensitivity estimates show promising results

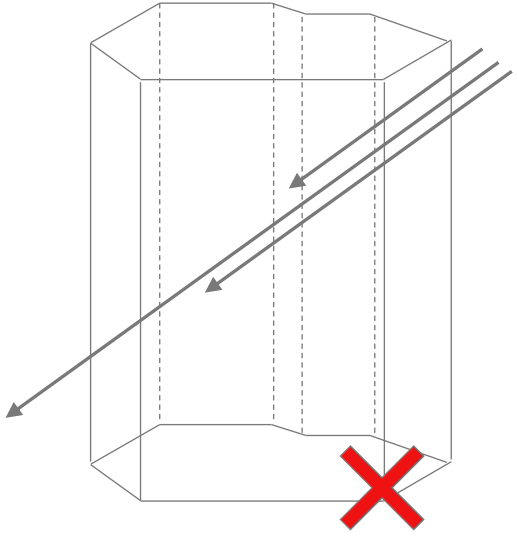
Future Analyses: Atmospheric Neutrinos

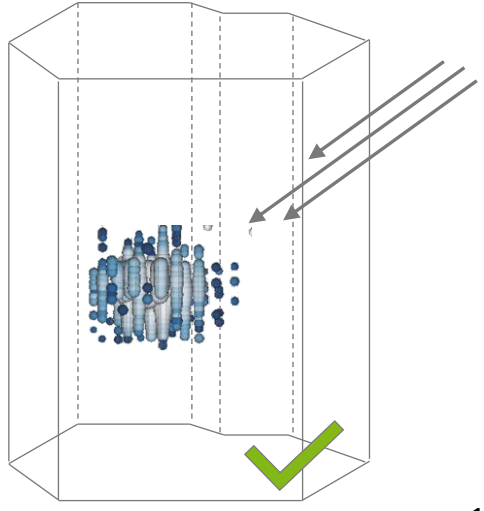
Atmospheric neutrino analysis

- Dedicated event sample to remove contribution of astrophysical neutrinos
- Unfold atmospheric neutrino flux
- Forward folding fit to constrain flux components
- Ratio and combined fits in flavors and with muons to constrain individual contributions to prompt and conventional fluxes
- Challenging analysis due to rare event signature









Conclusions

Constraining hadronic interaction models in IceCube

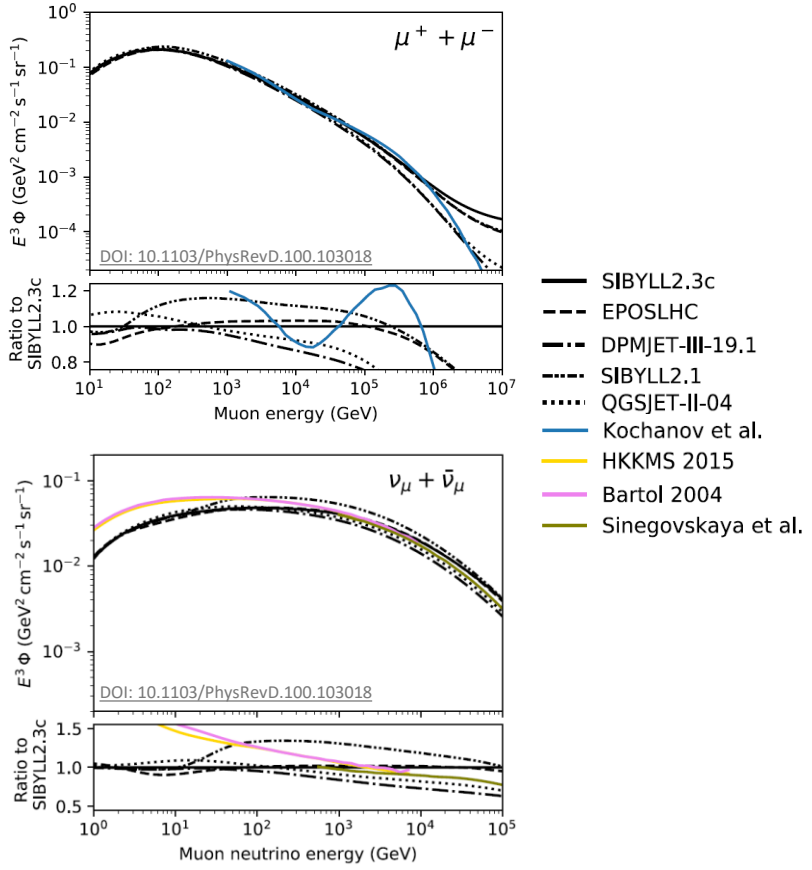
- Constrain models via measured muon and neutrino spectra
- Observables: energy, zenith, seasonal variations
- Detection channels: atmospheric muons, ν_μ-CC, ν_* (cascades)

Previous Analyses

- Many analyses for neutrino flux measurements
- Astrophysical neutrino flux complicates measurement of atmospheric conventional and prompt flux components
- Prior muon analyses almost 10 years old, limited by systematics

Future Analyses:

- Updated muon analyses on more than 10 years of data
- Dedicated atmospheric neutrino sample to obtain clean measurement of atmospheric neutrino flux
- Combination of multiple detection channels will reduce systematic uncertainties such as the primary cosmic ray flux



IceCube has a unique ability to contribute in the tuning of hadronic interaction models

THE ICECUBE COLLABORATION

AUSTRALIA
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UCLouvain
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

CANADA
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University of Alberta–Edmonton

DENMARK
University of Copenhagen

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Humboldt–Universität zu Berlin
Karlsruhe Institute of Technology
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