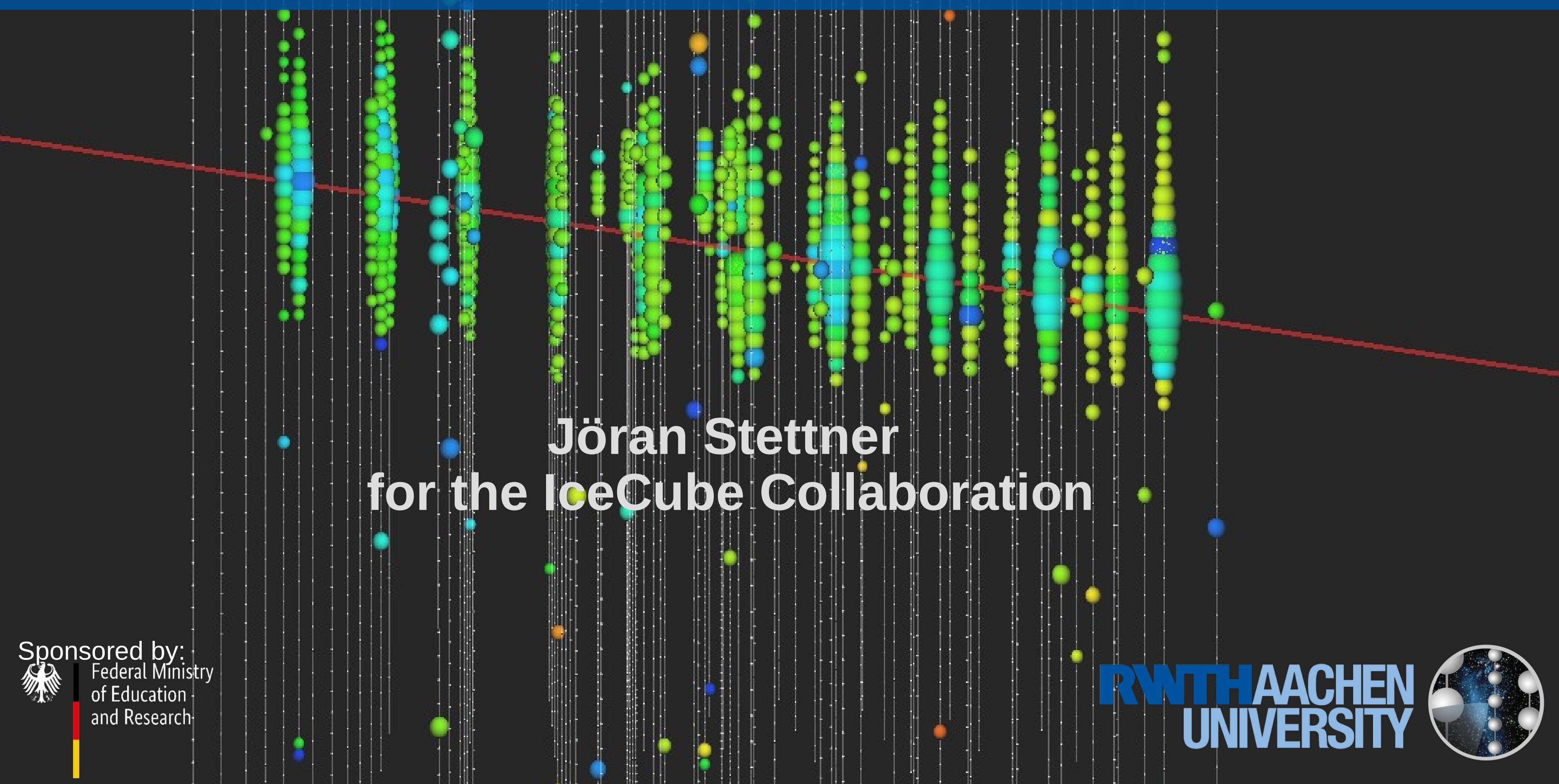
Measurement of the Diffuse Astrophysical Muon-Neutrino Spectrum with Ten Years of IceCube Data



Jöran Stettner
for the IceCube Collaboration

Sponsored by:
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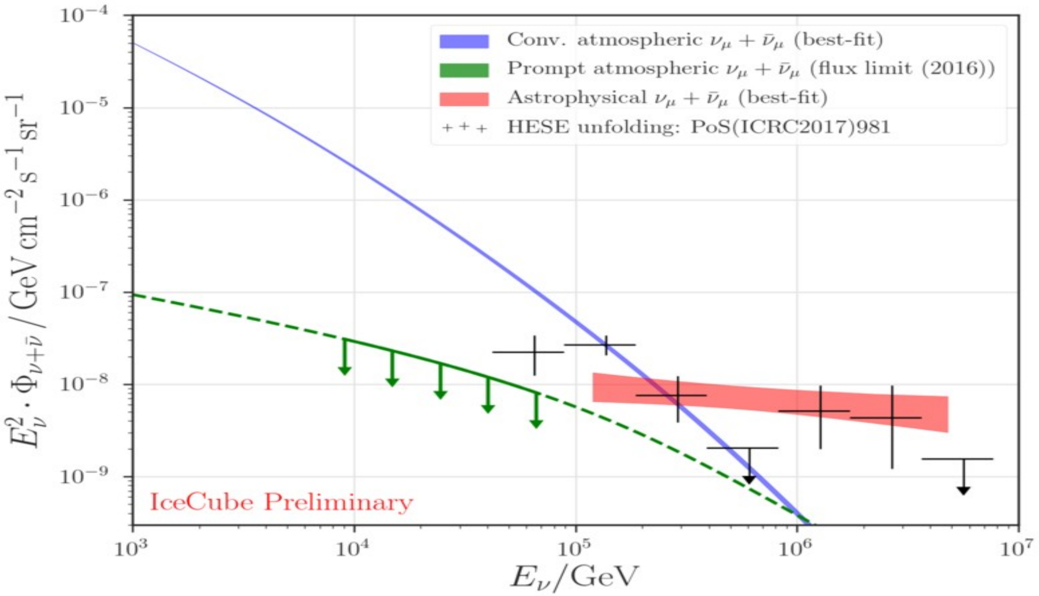
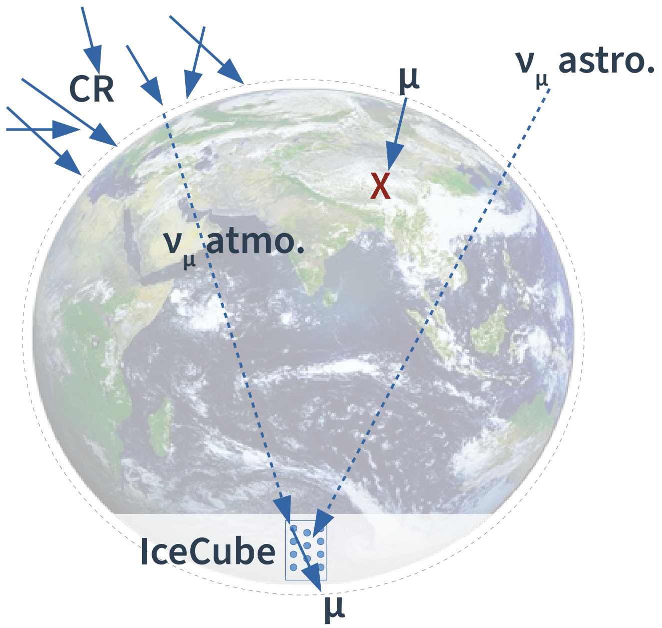


Outline

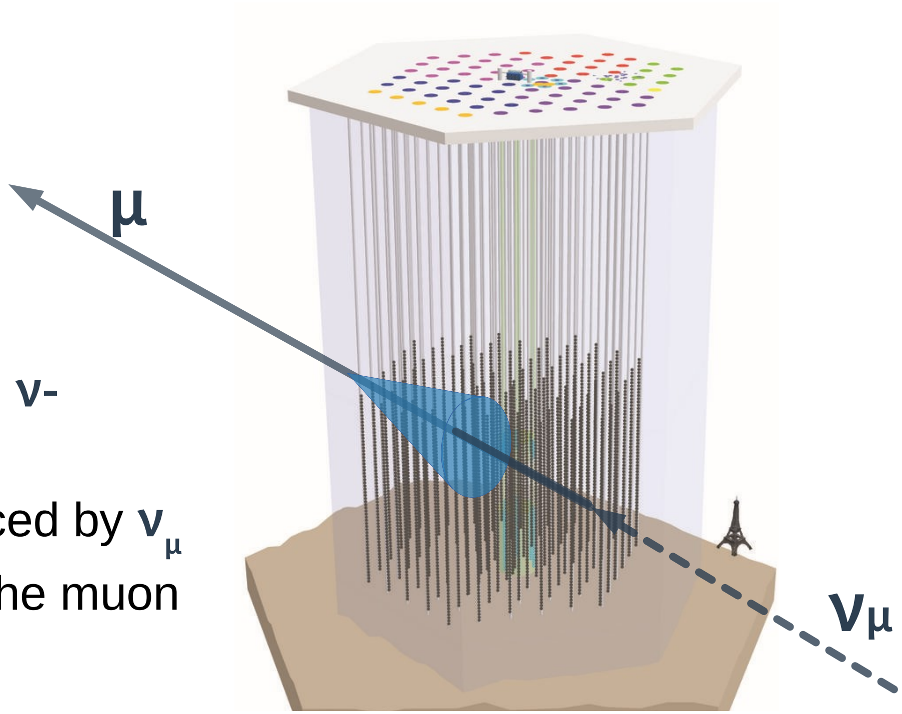
- IceCube and the ‘Northern Sky NuMu‘ Event Selection
- Updated Dataset (Pass-2)
- Analysis Method
- Improved Treatment of Systematic Uncertainties
- Updated Results
- Systematics and Impact on Fit-Results

IceCube and the ‘Northern Sky NuMu‘ Event Selection

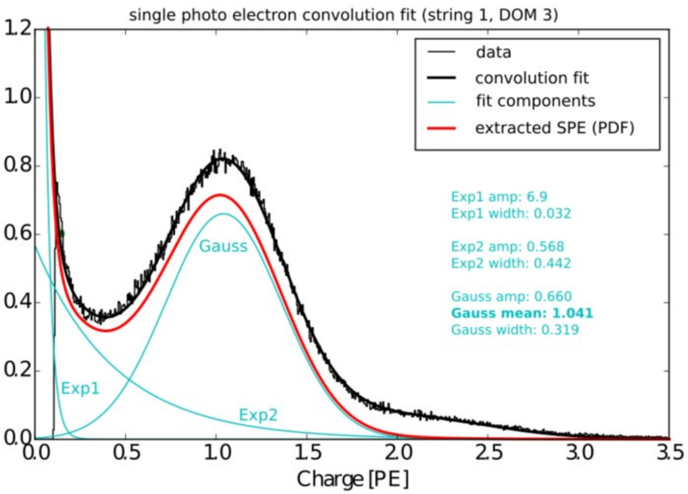


- Restrict field of view to Northern Celestial Hemisphere (Zenith θ>85°)
  - Earth shields atmospheric muons efficiently (99.7 % purity)
  - Neutrinos (atmospheric and astrophysical) reach the detector

- IceCube at the South Pole:
  - ~ 1 km^3 clear ice instrumented
  - Detection of secondary particles from **ν**-interactions via Cherenkov light
  - Select high-quality muon-tracks induced by **ν_μ**
  - Reconstruct direction and energy of the muon



Updated Dataset and Pass-2



- The Single-Photo-Electron (SPE) peak was ~4% shifted
- Pass-2:
  - Re-Calibration program for the whole detector
  - Applied our best knowledge (calibration, event-selection etc.) backwards to the historical data

- The updated dataset from 9.5 years of data-taking:

IC59 (Pass1)	IC79 + IC86 (Pass2)

May 2009 → December 2018

- In total, ~650.000 observed muon-neutrino events

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Analysis Method

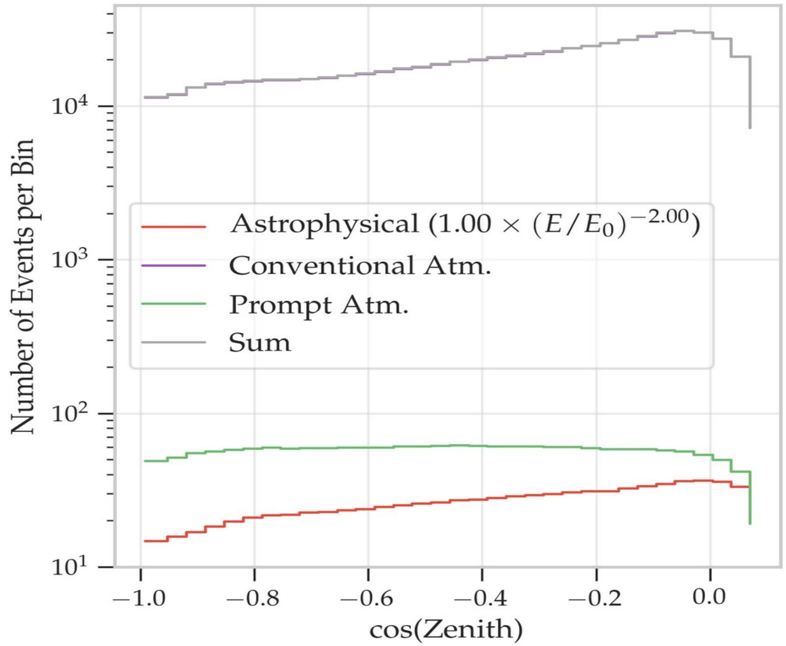
Expected Neutrino Fluxes

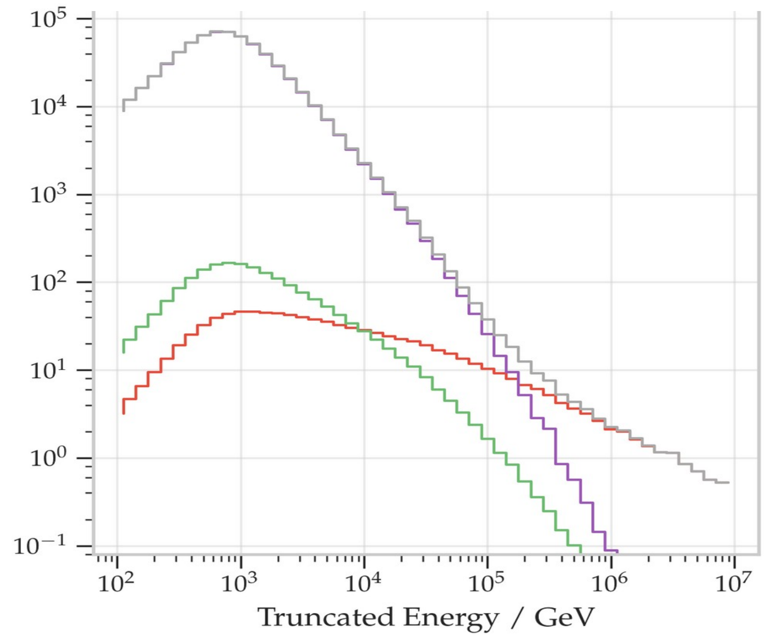
- Model neutrino flux with three components:
  - 'Conventional' atmospheric neutrinos from K/Pi decays in air-showers
  - 'Prompt' atmospheric neutrinos from decays of charmed hadrons in air-showers

  Atm. flux predictions computed with MCEq [1] (Sibyll2.3c and H4a as CR-model)

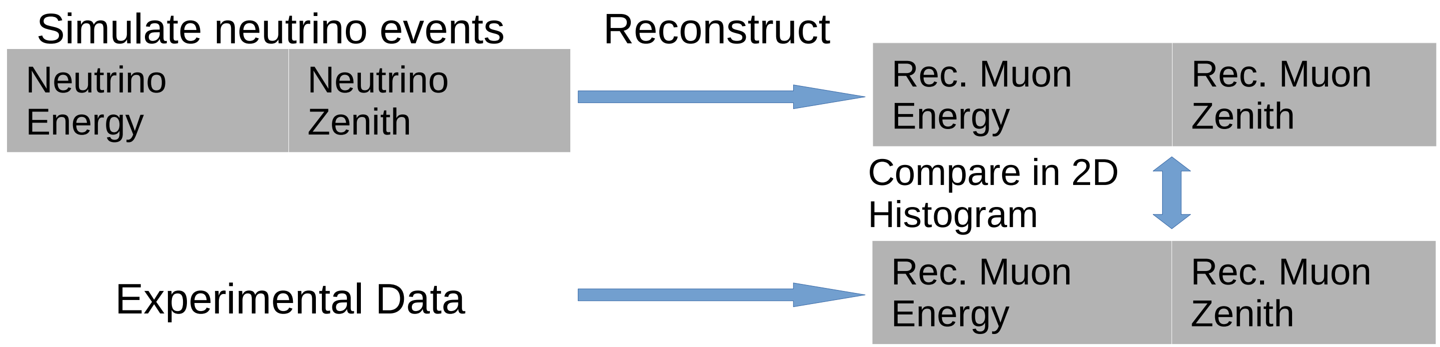
  - Isotropic flux of astrophyiscal neutrinos, power-law energy spectrum

$$\frac{d\phi}{dE} = \Phi_{astro} \times \left(\frac{E_\nu}{100\,\mathrm{TeV}} \right)^{-\gamma_{astro}}$$





Analysis Method: Forward Folding Fit



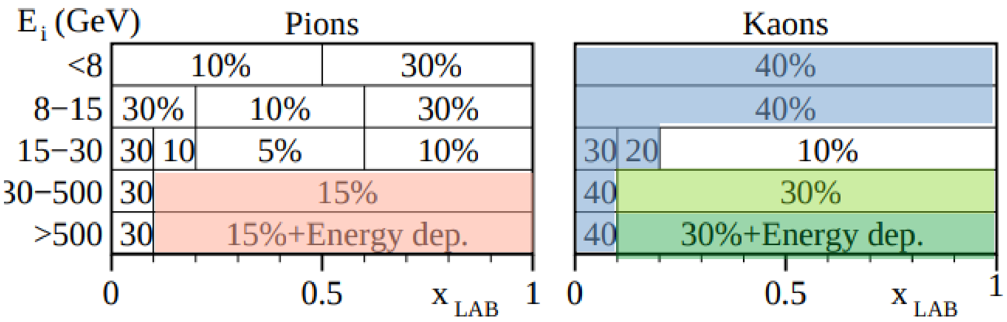
- Two-dimensional histogram:
  - 50 bins in truncated energy, 33 bins in cos(Zenith)

- Poisson Likelihood per bin

$$\mathcal{L} = \prod_{i=1}^{n_{\mathrm{bins}}} \mathcal{L}_i(\mathrm{Data}|\mu) \cdot \prod_{m}^{\mathrm{Param.}} \mathcal{L}_m(\xi|\xi_0)$$

- Expectation μ given as sum of all components
- Nuisance parameters ξ in the fit to cover systematic uncertainties
  - Detector effects: DOM-efficiency (light yield) and ice-properties (scat+abs)
  - Atmospheric fluxes: Primary CR-flux model (H4 and GST4) and Barr-parameters

Improved Treatment of Systematic Uncertainties



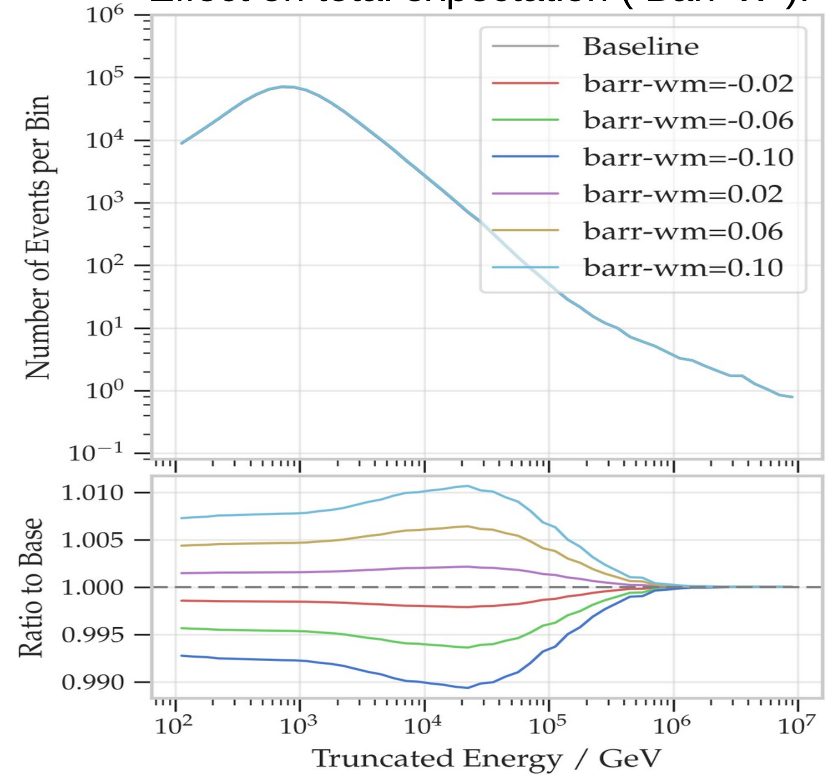
H^+, H^-, W^+, W^-

Y^+, Y^-, Z^+, Z^-

- New approach to cover uncertainties from hadronic interaction models:
  - Variation of eight Barr-parameters [2] which independently scale production rates for pions and kaons
  - Implemented in the fit as nuisance parameters
    - Priors according to uncertainty-scale in [2]

    → More freedom to cover shape differences

Effect on total expectation (Barr-W^-):



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Updated Results

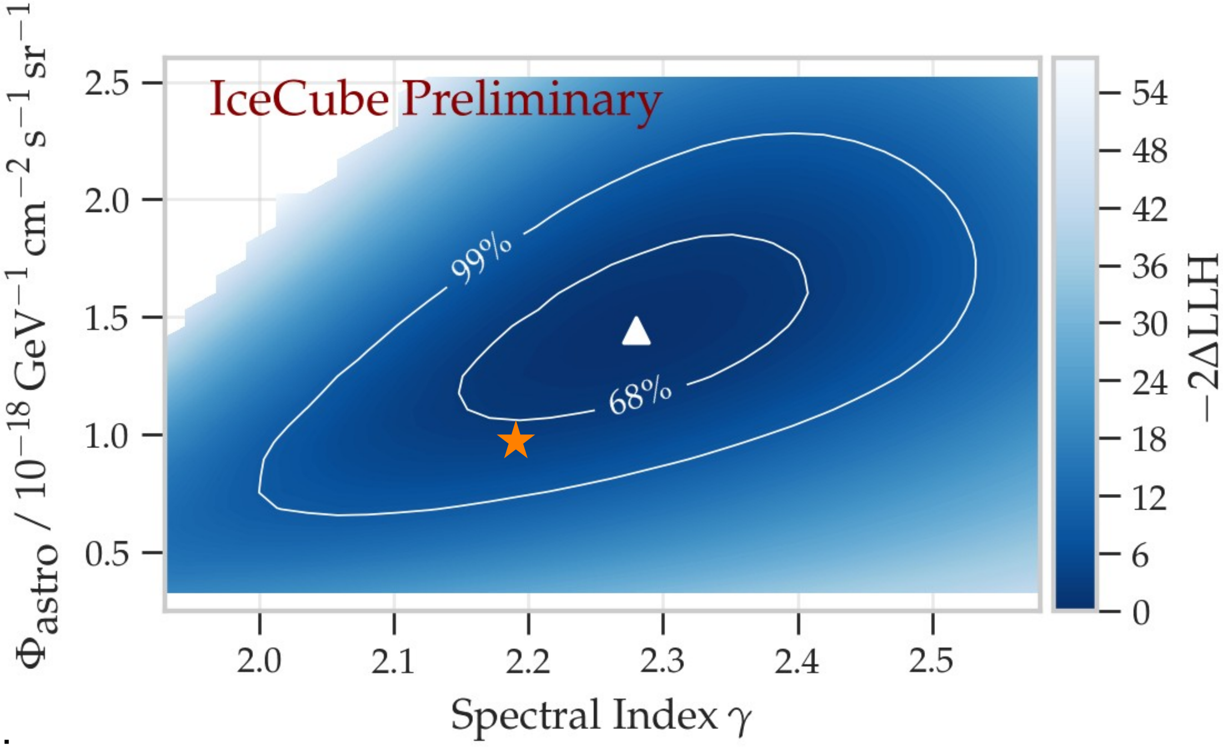
Updated Results

- Astroph. flux: $$\frac{d\phi_{\nu+\bar{\nu}}}{dE} = (1.44^{+0.25}_{-0.24}) \left(\frac{E}{100\,\mathrm{TeV}}\right)^{-2.28^{+0.08}_{-0.09}} \cdot 10^{-18}\,\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

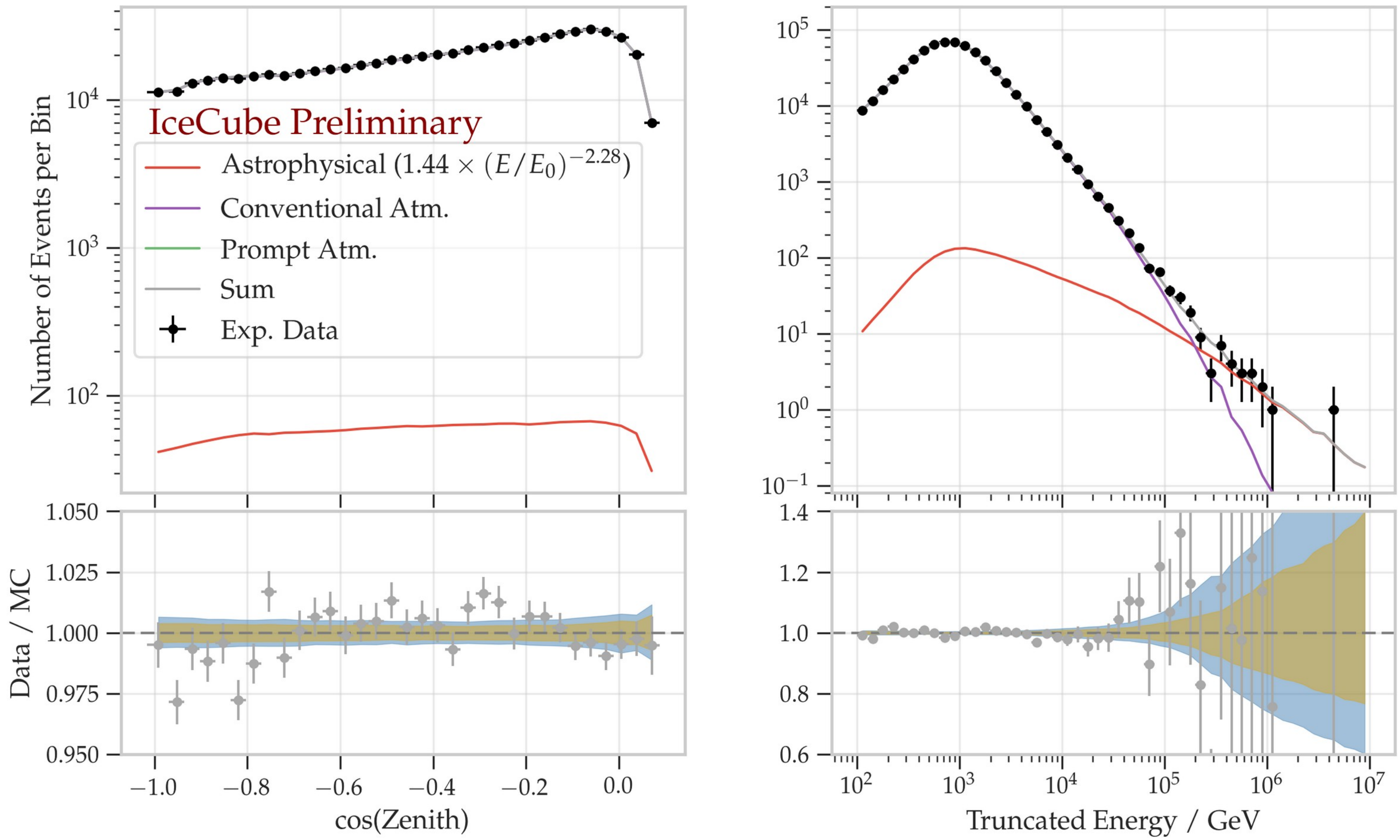
  Prompt normalization = 0

  Slightly softer spectrum compared to last iteration (γ_{astro} = 2.19)[5]

  Changes driven by medium energies:
  - Proper handling of primary CR-flux for atmospheric flux prediction
  - Improved treatment of systematics



Energy and Zenith Distributions

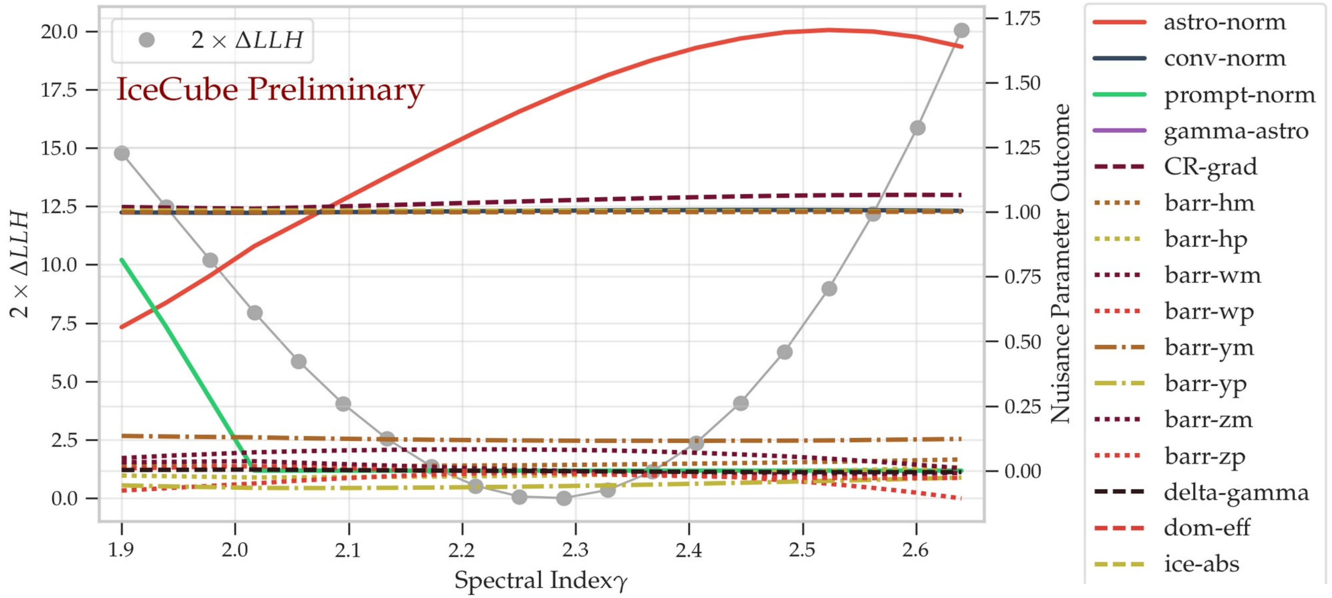


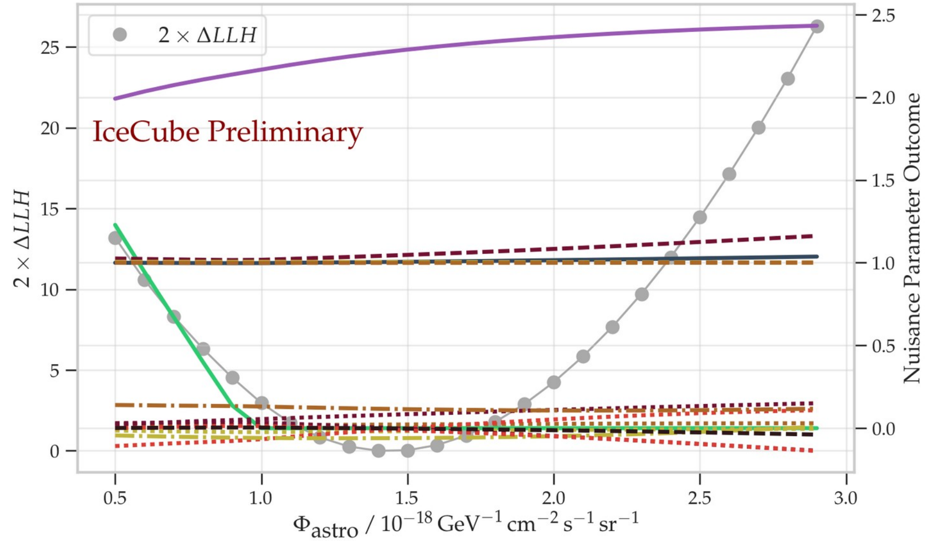
Best-fit distributions and experimental data (2010-2018)

- Excess of a high-energy component clearly visible
- More complex models for the astrophysical component are currently being tested

Systematics and Impact on Fit-Results

Astrophysical Parameters and Systematics





One-dimensional profile likelihood scans

→ The two astrophysical parameters are correlated (as expected)

→ Very little correlation with other parameters

→ Only for much harder or smaller astroph. fluxes, a prompt flux is needed to fill the gaps (light green line)

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Benchmark cases I

- Best-fit astroph. Flux: (no prompt) $$\frac{d\phi_{\nu+\bar{\nu}}}{dE} = (1.44^{+0.25}_{-0.24}) \left(\frac{E}{100\,\mathrm{TeV}} \right)^{-2.28^{+0.08}_{-0.09}} \cdot 10^{-18}\,\mathrm{GeV^{-1}cm^{-2}s^{-1}sr^{-1}}$$

- What if a prompt flux is present ?
  Repeated the fit with prompt normalization fixed to 1 x baseline prediction (MCEq)
  → Astro. normalization decreases
  → Spectral index hardens slighlty

- Best-fit astroph. parameters, if prompt=1.0:

ϕ_0 = 1.17 / std. units
γ_{astro} = 2.24

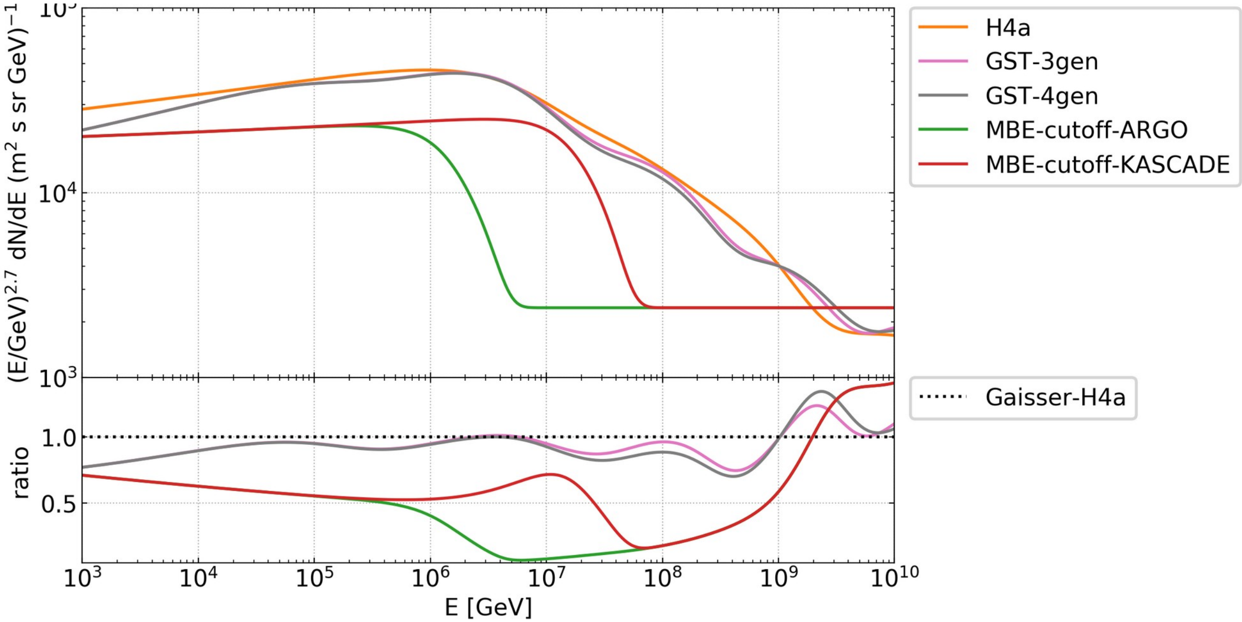
→ Astrophysical flux remains necessary to explain the experimental data

Benchmark cases II

- Best-fit: $$\frac{d\phi_{\nu+\bar{\nu}}}{dE} = (1.44^{+0.25}_{-0.24}) \left(\frac{E}{100\,\mathrm{TeV}}\right)^{-2.28^{+0.08}_{-0.09}} \cdot 10^{-18}\,\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

- Impact of different primary CR-flux models:

  (covering a wide range, tuned to different measurements below the knee)



→ Very small changes of the astrophysical parameters:

CR-Model	Change of γ_{astro}	Change of Φ_{astro}	$\Delta\gamma_{\mathrm{CR}}$	ΔLLH
Gaisser-Hillas, H4a	–	–	0.06	–
Gaisser-Stanev-Tilav, GST-4gen	-0.007	-0.115	0.01	4.4
GSF-beta	-0.007	-0.234	0.03	1.8
Mascaretti et al. (KASCADE w. cutoff)	0.015	-0.235	-0.04	-2.1
Mascaretti et al. (ARGO-YBJ w. cutoff)	-0.011	0.116	0.02	-1.9

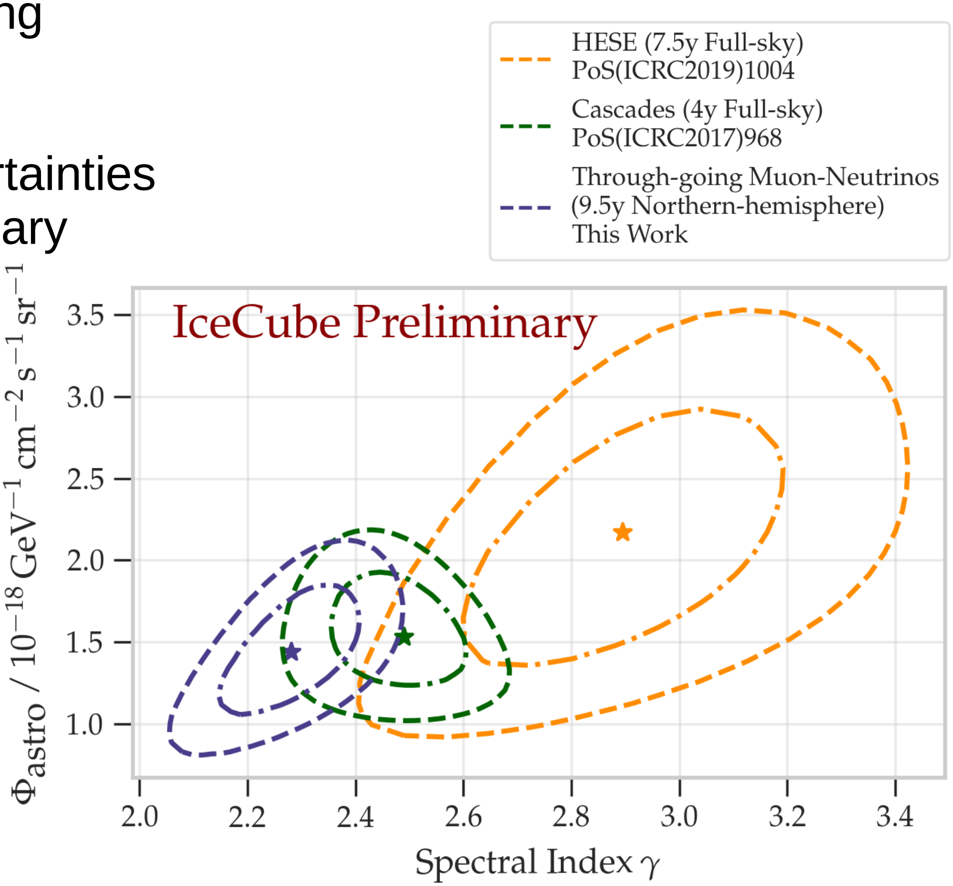
Summary and Outlook

- Updated the sample of up-going muon-neutrinos
  - Pass-2 re-calibration and re-processing
  - 9.5 years of experimental data

- Improved treatment of systematic uncertainties
  - Hadronic interaction models and primary cosmic-ray fluxes (MCEq)

- Updated best-fit astrophysical flux:

$$\frac{d\phi_{\nu+\bar{\nu}}}{dE} = (1.44^{+0.25}_{-0.24}) \left(\frac{E}{100\,\mathrm{TeV}}\right)^{-2.28^{+0.08}_{-0.09}}$$



Stay tuned:
- Working on other astrophysical models
- A global fit to all data-sets is being prepared

References

[1] A. Fedynitch, R. Engel, T. K. Gaisser, F. Riehn, and T. Stanev, EPJ Web Conf. 99 (2015) 08001.

[2] G. D. Barr, S. Robbins, T. K. Gaisser, and T. Stanev, Phys. Rev. D 74 (Nov, 2006) 094009

[3] T. K. Gaisser, Astroparticle Physics 35 (07, 2012) 801–806

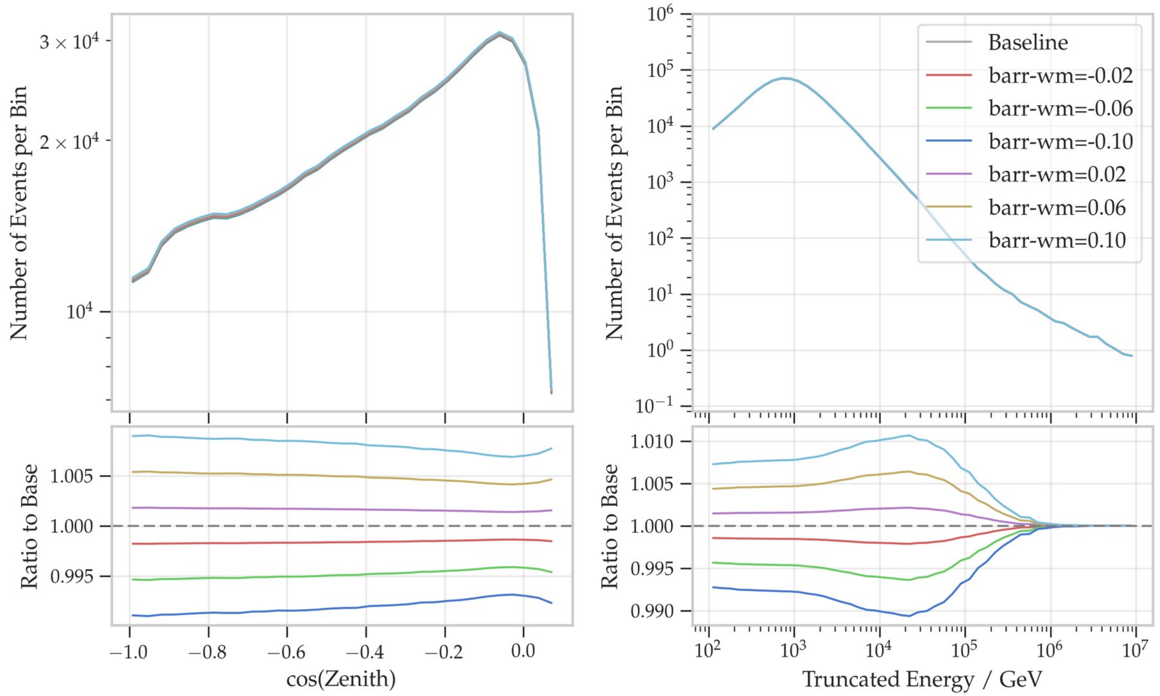
[4] T. K. Gaisser, T. Stanev, and S. Tilav, Front. Phys. 8 (2013) 748–758

[5] IceCube Collaboration, PoS(ICRC2017)1005 (2017)

Backup

Impact of Barr W-

Effect on total expectation (Barr-W$^-$):



Comparison to 8y result