A measurement of the diffuse astrophysical muon neutrino flux using six years of IceCube data

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What is a diffuse astrophysical muon neutrino flux?

Looking in all directions at the same time

- A cosmic neutrino flux can be detected even if the individual source flux is below the detection threshold
- IceCube starting event measurement: \( \nu \) flux per flavor \( \sim 1 \times 10^{-8} \) GeV cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\)
- 2 Questions:
  1) Is the flux from the Northern Sky for the muon neutrino channel the same?
  2) What are the properties of this flux?

Promising candidate \( \rightarrow \) abundant extragalactic sources (e.g. AGN)
IceCube detector

Detection principle:
- \( \nu_\mu \) interaction near or inside the detector
- Detection of Cherenkov light produced by secondary relativistic, charged particles

Search strategy:
- Select high-energy up-going muon track
  - Northern sky neutrino sample: high purity and high efficiency

Previous IceCube analysis:
- IC59: from 2009 – 2010
  (~20,000 neutrinos, excess 1.8\( \sigma \))
- IC79 + IC86: from 2010-2012
  (~35,000 neutrinos, excess 3.7\( \sigma \))

Aartsen et al., PRD 89 (Mar. 2014)
Aartsen et al., PRL 115 (Aug. 2015)
Multi-PeV track event
June 11th 2014

Observables:
- Position → DOM position
- Time of pulse → color
- Charge of pulse → size

track-like neutrino event
\[ E_{\text{dep}} = 2.6 \pm 0.3 \text{ PeV} \]

- Muon and neutrino energy are at least 2.6 PeV
- angular uncertainty (stat. + sys.): \(~0.27^\circ\)
- p-value < 0.01% to be of atmospheric origin
- No closeby source candidate in TeVCat, Fermi’s 2FGL & 3FGL
  - ATEL #7856

→ Through-going neutrino induced muon

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Signal signature

- Atmospheric neutrino background

  Conventional atmospheric neutrinos
  - From pion and kaon decays produced by cosmic ray interactions with the atmosphere
  - Energy spectrum: \( \frac{d\phi}{dE} \propto E^{-3.7} \)

  Prompt atmospheric neutrinos
  - From heavy meson decays produced by cosmic ray interactions with the atmosphere (not measured yet)
  - Energy spectrum: \( \frac{d\phi}{dE} \propto E^{-2.7} \)

- Astrophysical neutrino signal
  - Energy spectrum: \( \frac{d\phi}{dE} \propto E^{-2} \)

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Analysis strategy

- Combined likelihood fit using multiple years
  - Analyze 6 years of IceCube data (2009 – 2015)
  - All systematic uncertainties are parameterized continuously

- Neutrino sample properties:
  - High-purity: > 99.9%

- Large statistics used to constrain the systematic uncertainties from non-signal region
The analysis method

- Analyze 2-dimensional energy vs. zenith angle distribution
- Likelihood function: binned Poisson likelihood
  → Include systematic uncertainties as free continuous nuisance parameters

\[
L(n|\mu(\theta, \xi)) = \prod_{i=1}^{N} \frac{(\mu_i(\theta, \xi))^{n_i}}{n_i!} \exp(-\mu(\theta, \xi))
\]

- Expectation:
  \[
  \mu_i(\theta, \xi) = \mu_i^{conv} + \mu_i^{prompt} + \mu_i^{astro}
  \]
The challenge: Systematic uncertainties

- **Detection uncertainties:**
  - e.g. optical sensor efficiency, optical ice properties at South Pole, neutrino interaction cross section, muon energy loss cross section

- **Atmospheric $\nu_\mu$ prediction uncertainties:**
  - e.g. rate, shape and composition of the primary cosmic ray spectrum, ratio of pion to kaon decay in air showers

- Systematic effects on observables are continuously parameterized and included in the likelihood fit

- **Advantage of high statistics** of conventional atmospheric $\nu_\mu$:
  - Strong constraints on systematic uncertainties from non-signal region

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Excellent data/mc agreement for all six years

Clear excess @ high reconstructed muon energies
Unfolded astrophysical muon neutrino spectrum

Assuming best-fit power law:

+++ Unfolding
Conv. atmospheric $\nu_\mu + \bar{\nu}_\mu$

Astrophysical $\nu_\mu + \bar{\nu}_\mu$

IceCube Preliminary

Multi-PeV track neutrino energy pdf

Multi-PeV track p-value < 0.01%
to be of atmospheric origin

Atmospheric-only hypothesis excluded by $5.9\sigma$
Measurement of the astrophysical flux

- Best-fit astrophysical normalization @ 100TeV:
  
  \[(0.82^{+0.30}_{-0.26}) \times 10^{-18} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}\]

- Best-fit spectral index:
  
  \[\gamma_{\text{astro}} = 2.08 \pm 0.13\]

- Best-fit prompt normalization:
  
  \[0 \times \text{ ERS}\]

- Astrophysical flux cannot be explained by only a prompt flux
- Spectral index nearly independent of a prompt flux

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The measured astrophysical flux

- Atmospheric-only hypothesis excluded by 5.9σ
- Best-fit astrophys. norm. @ 100 TeV:
  
  \[
  (0.82^{+0.30}_{-0.26}) \times 10^{-18} \frac{1}{\text{GeV cm}^2 \text{ s sr}}
  \]
- Best-fit spectral index:
  
  \[\gamma_{\text{astro}} = 2.08 \pm 0.13\]
- Energy ranges:
  
  220 TeV – 8.3 PeV

- Best fit astrophysical neutrino flux and conventional atmospheric neutrino flux predicted by Honda
- ERS prediction for a prompt atmospheric neutrino flux (best-fit prompt norm. is zero)
Summary of the diffuse IceCube results

- 90% C.L. contours of the different IceCube analyses
- Results of IC tracks (6yr) and IC combined analysis (3 yr tracks slightly correlated) not compatible within > 3.6σ (two sided significance)
Comparison to HESE 4 year

HESE 4 year unfolding
(\rightarrow dominted by shower-like events)

- Energy threshold @ about 60 TeV
- Softer spectral index currently driven by low energy bin

6 year up-going numu analysis

- Energy threshold @ about 200 TeV
- @ high energies ($\gtrsim 200$ TeV)

HESE 4 year analysis (left) compatible with $E^{-2}$

PoS(ICRC2015)1081

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Results of a simple galactic plane analysis

- **Question**: Could a dominant galactic component be the reason for the tension?
  - Split data into two right ascension regions with similar amount of statistics

- Fits compatible: p-value = 49%
  - No evidence for a dominant flux from the galactic plane

- Fit of region with galactic plane has slightly higher norm. and softer spectral index
  - Hint for a galactic component?

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Presented the currently most precise measurement of a diffuse flux of astrophysical muon neutrinos

→ Astrophysical flux @ 5.9σ level:
  \[ 0.82 \cdot (E/100\text{TeV})^{-2.08} \times [10^{-18}\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}] \]

→ No evidence for a dominant flux from the galactic plane

Tension of 3.6σ between up-going track and all-sky cascade analysis

→ Indication of a spectral break
Thank you for your attention!
Backup slides
Discussion

- The diffuse muon analysis is ...
  - sensitive only at high energies (above ~200 TeV)
  - sensitive only in the Northern Hemisphere

- We should keep in mind that ...
  - the energy spectrum need not be a single power law
  - there could be more than one component (e.g. one galactic and one extragalactic)
IceCube data @ trigger level
Downgoing muon rejection

- Rejection of muon events from cosmic ray air showers by restriction to Northern hemisphere
- Mis-reconstructed muon events in the upgoing region
  - Can be removed by quality criteria on track reconstruction

Use a Boosted Decision Tree (BDT → machine learning algorithm)
  - High-purity neutrino sample (> 99.9%) with high neutrino efficiency
    (~ 70,000 neutrino events per year)

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Parameterization of systematic uncertainties

Example: Optical sensor efficiency

- Simulation of datasets with different optical sensor efficiencies (e.g. ±10%, ±20%)
  → BUT datasets have low statistics especially at higher energies (signal region)
- Use Kernel Density Estimation (KDE) to approximate pdfs in regions of low statistics (arXiv:0709.1616)

Reweight the high-statistics baseline dataset to a dataset with different optical efficiencies by reweighting each event

\[ w_i = w_i^{\text{baseline}} \cdot f_i^{\text{DOM}} \]
Parameterization of systematic uncertainties
Example: Optical sensor efficiency

- Comparison between systematic dataset (here: opt. eff. 80%) and reweighted baseline dataset (here: opt. eff. 100% → 80%) by using the KDE method

- No differences within statistical uncertainties between systematic dataset and reweighted baseline dataset
Simple galactic plane analysis

IceCube Preliminary

- 2009/10: \( p_{\text{chi}2} = 0.84, \ p_{\text{ks}} = 0.29 \)
- 2010/11: \( p_{\text{chi}2} = 0.91, \ p_{\text{ks}} = 0.76 \)
- 2011/12: \( p_{\text{chi}2} = 0.84, \ p_{\text{ks}} = 0.56 \)
- 2012/15: \( p_{\text{chi}2} = 0.36, \ p_{\text{ks}} = 0.48 \)