TeV-PeV Neutrino-Nucleon Cross Section Measurement with 5 Years’ IceCube Data

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Outline

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• Cross Section Measurement
  - statistical uncertainty
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• Accelerator data contributes up to ~100GeV in $\nu - N$ cross section measurement. **Exciting (new) physics awaits at much higher energy range.**
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• IceCube has recently published the first cross section measurement result using 1yr of up-going $\nu_\mu$ sample in energy range 6.3TeV to 980 TeV: $1.30^{+0.21}_{-0.19}\text{(stat)}^{+0.39}_{-0.43}\text{(sys)} \times \text{CSMS}^*$

*CSMS: JHEP 08, 042 (2011)*
Introduc.on

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  $1.30^{+0.21}_{-0.19} \text{(stat)} ^{+0.39}_{-0.43} \text{(sys)} \times \text{CSMS}^*$

• This analysis will present a **novel method** to measure the **energy dependence** of $\nu - N$ cross section using 5yr IceCube $\nu_\tau + \nu_e$ sample.

*CSMS: JHEP 08, 042 (2011)
IceCube Detector

IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison

50 m

1450 m

Digital Optical Module (DOM)
5,160 DOMs deployed in the ice

detects photons

2450 m

50 m

86 strings of DOMs, set 125 meters apart

60 DOMs on each string

DOMs are 17 meters apart

DeepCore

IceCube detector

Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility

Antarctic bedrock

Yiqian Xu, Stony Brook University
Neutrinos

$\nu_e, \nu_\mu, \nu_\tau$

$\nu_e, \nu_\mu, \nu_\tau$
Neutrinos -> DIS

**CC DIS**

\[ \nu_e, \nu_\mu, \nu_\tau \rightarrow e^\pm, \mu^\pm, \tau^\pm, W^\pm, q, q', X_p \]

**NC DIS**

\[ \nu_e, \nu_\mu, \nu_\tau \rightarrow Z^0, q, q', X_p \]
Neutrinos $\rightarrow$ DIS $\rightarrow$ charged secondaries

CC DIS

\[ \nu_e, \nu_\mu, \nu_\tau \rightarrow W^\pm \rightarrow q, q' \rightarrow X_p \]

NC DIS

\[ \nu_e, \nu_\mu, \nu_\tau \rightarrow Z^0 \rightarrow q, q' \rightarrow X_p \]
Neutrinos -> DIS -> charged secondaries -> Cherenkov Light (photons)

CC DIS
\[ \nu_e, \nu_\mu, \nu_\tau \rightarrow W^{\pm} \rightarrow e^{\pm}, \mu^{\pm}, \tau^{\pm} \rightarrow q', q \rightarrow X_p \]

Energy resolution (~15%) Angular resolution (10°~15°)

NC DIS

Artificial color: red (early in time), blue (late in time)
Neutrinos $\rightarrow$ DIS $\rightarrow$ charged secondaries $\rightarrow$ Cherenkov Light (photons)

CC DIS

$\nu_e, \nu_\mu, \nu_\tau$

$W^\pm$

$q$

$q'$

$X_p$

$E_\nu < 1\text{PeV}$

used in this analysis

Cascade

Energy resolution ($\sim 15\%$)
Angular resolution ($10^\circ \sim 15^\circ$)

NC DIS

$\nu_e, \nu_\mu, \nu_\tau$

$Z^0$

$q$

$q'$

$X_p$

Artificial color: red (early in time), blue (late in time)
Neutrinos \(\rightarrow\) DIS \(\rightarrow\) charged secondaries \(\rightarrow\) Cherenkov Light (photons)

**CC DIS**
- Initial state: \(\nu_e, \nu_\mu, \nu_\tau\)
- Final state: \(e^\pm, \mu^\pm, \tau^\pm\)
- \(W^\pm\) decay
- \(q, q'\)
- \(X_p\)

**NC DIS**
- Initial state: \(\nu_e, \nu_\mu, \nu_\tau\)
- Final state: \(\nu_e, \nu_\mu, \nu_\tau\)
- \(Z^0\) decay
- \(q, q'\)
- \(X_p\)

**Cascade**
- Energy resolution: \(\sim 15\%\)
- Angular resolution: \(10^\circ \sim 15^\circ\)

**Track**
- Only lower bound on \(E_\nu\)
- Angular resolution: \(0.2^\circ \sim 1^\circ\)

Artificial color: red (early in time), blue (late in time)
Neutrinos -> DIS -> charged secondaries -> Cherenkov Light (photons)

**Cascade**
Energy resolution (~15%)
Angular resolution (10°~15°)

**Track**
Only lower bound on $E_\nu$
Angular resolution (0.2°~1°)

"Double-Bang"
Has not been observed yet

Artificial color: red (early in time), blue (late in time)
IceCube Detector

Mostly removed by this analysis (<10% in below 60TeV, 0 above 60TeV)

- Down-going
- Up-going

Monte Carlo

- atm. $\mu$
- atm. $\nu\mu$
- Conv.: symmetric around horizon
- Prompt: isotropic
- Isotropic (assumption)
- astro. $\nu$ (not to scale)

Yiqian Xu, Stony Brook University
Equal amount of atm. neutrinos are **produced** in down-going region and up-going region.
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When the cross section of neutrino-nucleon interaction is small, the Earth is transparent to neutrinos.
With the increase of neutrino energy, the cross section increases. The up-going events get absorbed by the Earth.
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Proposed by D. Hooper, Phys. Rev. D 65.097303

\[ R(E_\nu > 100\text{TeV}) = \frac{N\text{Events}(\text{Down-going})}{N\text{Events}(\text{Up-going})} = 1.59 \]

**Neutrino energy > 100TeV**

**MC simulation**

**IceCube Preliminary**

Yiqian Xu, Stony Brook University
With the increase of neutrino energy, the cross section increases. The up-going events get absorbed by the Earth.
Analysis Method

A simplified illustration

—assuming perfect detector, energy and direction are in true space \((E_\nu, \text{Zenith}_\nu)\).

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Down-going: not affected by the Earth

Up-going: the probability to be absorbed by the Earth scales with cross section.
Analysis Method

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1. Calculate \(R(E_\nu) = \frac{N_{\text{Event}}(\text{down}_\nu)}{N_{\text{Event}}(\text{up}_\nu)}\) in each neutrino energy bin from exp. data.

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2. With the knowledge of Earth density, we get \( R(\sigma) = \frac{\text{N}_{\text{event}(\text{down}_\nu)}}{\text{N}_{\text{event}(\text{up}_\nu)}} \) in different cross section bins.
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3. Take the ratio for each neutrino energy bin and find the corresponding cross section.

Down-going: not affected by the Earth

Up-going: the probability to be absorbed by the Earth scales with cross section.
• The data sample: collected by IceCube from May 2011 to May 2016.
• An event selection* is developed using straight cut and machine learning to select cascades and remove track-like events.
• This event selection features **high background rejection** (<10% background contamination below 60TeV, background free above 60TeV) and **high signal efficiency** (~80%).
• Below are the reconstructed (observed) **energy** and **zenith** distribution for data and MC after the event selection.

Very good Data/MC agreement!

Yiqian Xu, Stony Brook University
How do we get NEvents in neutrino energy and zenith bins from reconstructed (observed) distribution?

*NC events have much bigger difference between reconstructed energy and neutrino energy compared to CC events.
Unfolding

How do we get NEvents in neutrino energy and zenith bins from reconstructed (observed) distribution?

- An Unfolding method (Iterative Unfolding) is used to unfold zenith distribution (2bins) and energy distribution at the same time.
- An assumption of 1:1:1 flavor ratio is made.
- The probability $P(T_i | R_j)$ of an event end up in Reco bin $j$ given True bin $i$ is known.
- The probability $P(R_j | T_i)$ of an event from True bin $i$ given it’s found in Reco bin $j$ is of interest.

\[
P(T_i | R_j)^{(k)} = \frac{P(R_j | T_i)N(T_i)^{(k)}}{\sum_i P(R_j | T_i)N(T_i)^{(k)}}
\]

\[
N(T_i)^{(k+1)} = \sum_j P(T_i | R_j)^{(k)}N(R_j) / \alpha_i
\]

$\alpha_i = \sum_j P(R_j | T_i)$ corrects for acceptance losses.

Distribution in **true** space of the $k+1$ th iteration

Distribution in **reconstructed** space, aka measurement

R: reconstructed (observed) energy, zenith

T: true (neutrino) energy, zenith
Unfolding

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Take-away message: Unfolding enables the mapping from reconstructed (observed) space to true (neutrino) space.

Distribution in true space of the $k+1$ th iteration

Distribution in reconstructed space, aka measurement

R: reconstructed (observed) energy, zenith
T: true (neutrino) energy, zenith
How to estimate statistical uncertainty in iterative unfolding?

- Use MCMC to sample in reconstructed (observed) space with log uniform prior.
- MCMC sampling distribution is shown as below.

Iterative Unfolding

- Get posterior distribution in true (neutrino) space.
- Take the 68% range (from 16% to 84% in cdf) as the uncertainty.
• Assign data in **reconstructed energy** bins according to their **reconstructed direction**.
Unfolding

- Assign data in **reconstructed energy** bins according to their **reconstructed direction**.
- Apply unfolding to data distribution in reconstructed space subtract the background estimation.
Unfolding

• Assign data in reconstructed energy bins according to their reconstructed direction.
• Apply unfolding to data distribution in reconstructed space subtract the background estimation.
• We acquire NEvents in neutrino energy bins according to their true direction.

Reconstructed Space

True Space
What exactly is the ratio we are calculating?

\[ R_{\text{exp}}(E_\nu) = \frac{N(E_\nu, \text{down}_\nu)}{N(E_\nu, \text{up}_\nu)} = \frac{\Phi(E_\nu) \cdot \text{Acpt}(E_\nu, \text{down}_\nu) \cdot \sigma(E_\nu)}{\Phi(E_\nu) \cdot \text{Acpt}(E_\nu, \text{up}_\nu) \cdot \text{Absp}(\sigma(E_\nu)) \cdot \sigma(E_\nu)} \]

\[ \equiv R(E_\nu) \cdot CF(E_\nu) \]

- Ratio of \( N(E_\nu, \text{down}) \) and \( N(E_\nu, \text{up}) \) contains information of detector acceptance effects, i.e. the detector accepts down-going neutrinos and up-going neutrinos with different efficiency (DOMs pointing down-wards, self-veto, event selection effect).
- After a correction factor (calculated from simulation) is applied, the new ratio reflects information of Earth absorption only. This new ratio is what we use to measure cross section.

\[ CF(E_\nu) \equiv \frac{\text{Acpt}(E_\nu, \text{up})}{\text{Acpt}(E_\nu, \text{down})} \]

\[ \text{Acpt}(E_\nu, \text{up/down}) = \frac{N\text{Events}(E_\nu, \text{up/down, final})}{N\text{Events}(E_\nu, \text{up/down, gen})} \]
What exactly is the ratio we are calculating?

Assuming isotropic astro flux

\[
R_{\text{exp}}(E_\nu) = \frac{N(E_\nu, \text{down}_\nu)}{N(E_\nu, \text{up}_\nu)} = \frac{\Phi(E_\nu) \cdot \text{Acpt}(E_\nu, \text{down}_\nu) \cdot \sigma(E_\nu)}{\Phi(E_\nu) \cdot \text{Acpt}(E_\nu, \text{up}_\nu) \cdot \text{Absp}(\sigma(E_\nu)) \cdot \sigma(E_\nu)}
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- Ratio of \(N(E_\nu, \text{down})\) and \(N(E_\nu, \text{up})\) contains information of detector acceptance effects, i.e. the detector accepts down-going neutrinos and up-going neutrinos with different efficiencies (DOMs pointing down wards, self-veto, event selection effect).
- After a geometric factorization, the ratio reflects Earth absorption only. This new ratio is what we use to measure cross section.

**Take-away message:** detector effect is factorized, we use \(R(E_\nu)\) as the ratio to measure cross section.
How to measure the cross section with the ratio in each neutrino energy bin?

- Take the ratio in each neutrino energy bin.

\[ R(E_{\nu}) \]
How to measure the cross section with the ratio in each neutrino energy bin?

- Take the ratio in each neutrino energy bin.
- Find the corresponding cross section for that ratio in ratio vs cross section curve.
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- Take the ratio in each neutrino energy bin.
- Find the corresponding cross section for that ratio in ratio vs cross section curve.
- The cross section measured for that each neutrino energy bins is the total cross section (CC+NC), average over neutrino and anti-neutrino with the ratio 1:1.

\[
\begin{align*}
R(E_{\nu}) & \quad \rightarrow \quad \sigma(E_{\nu}) \\
R(\sigma) & \quad \rightarrow \quad \sigma(\sigma)
\end{align*}
\]

Result!
Systematic Study

- The systematic effects that change the mapping between reconstructed (observed) space and true (neutrino) space, i.e. the unfolding procedure will affect the result, thus contribute to the systematic uncertainty of this measurement.
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- The systematic effects considered in this analysis are:
  1. Photon scattering in the South Pole ice -> **Most significant systematic effect**
Systematic Study

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     - photon scattering variations in the bulk ice-> implemented

bulk ice (the ancient glacial ice)
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   - photon scattering variations in the hole ice -> lack of simulation, will be added in the near future

hole ice (the refrozen ice around the DOMs)
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  2. Photon absorption in the South Pole Ice
  3. DOM efficiency

  \[
  \text{negligible effect on the result}^* \\
  \]

*more details see backup*
Systematic Study

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  1. Photon scattering in the South Pole ice **- Most significant systematic effect**
     - photon scattering variations in the bulk ice -> implemented
     - photon scattering variations in the hole ice -> lack of simulation, will be added in the near future
  2. Photon absorption in the South Pole Ice
  3. DOM efficiency
  4. Self-Veto effect*: the uncertainty on this parameter itself is small.
  5. Astrophysical neutrino flux: **Due to the ratio method, the uncertainty associated with flux is negligible.**

*more details see backup
Using the matrices built with different systematic simulation datasets to unfold data results in different NEEvents neutrino energy & zenith bins -> different ratios in neutrino energy bins as shown in the left plot below.
Systematic Study

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- Different ratios correspond to different cross sections. The light red band in the right plot shows the partial systematic uncertainty for this analysis.
Neutrino energy dependence (in 6.3TeV-10PeV range) of neutrino-nucleon cross section measurement result with statistic uncertainty and statistic + partial systematic uncertainty
Combined Uncertainty

Neutrino energy dependence (in $6.3\text{TeV}-10\text{PeV}$ range) of neutrino-nucleon cross section measurement result with statistic uncertainty and statistic + partial systematic uncertainty in comparison with more models.

![IceCube Preliminary graph](chart.png)

- IceCube 5yr Cascade
- CSMS 2011
- $1.30^{+0.60}_{-0.62} \times \text{CSMS (IceCube 1yr } \nu_\mu \text{)}$
- CTW 2011
- BDH 2014

CSMS: JHEP 08, 042 (2011)
• A novel analysis has been developed to measure neutrino-nucleon cross section in 6.3TeV-10PeV region using 5 years’ IceCube Cascade sample.

• Iterative Unfolding is used to map from reconstructed energy and direction to neutrino energy and direction.

• The method to estimate statistical uncertainty using MCMC is presented.

• All but one (hole ice scattering variations) systematic effects have been evaluated.

• The measurement result with uncertainties has been presented. The result shows consistency with the CSMS standard model cross section.
Backup
Event Selection

- Event sample was separated into two parts: low energy (<60 TeV) and high energy (E>=60 TeV).
- The high energy part applies straight cut on variables that have separation power in event topology.

- The low energy part applies gradient boosted multi-class decision trees to classify events into three groups: cascade, starting track and track.
The unfolded ratio in neutrino energy bins for Data

The MCMC posterior distribution of unfolded ratio in neutrino energy bins for Data
To study the effect of ice property and DOM efficiency change, baseline reconstructed distribution is used to be unfolded with all the systematic datasets (abs, scat, scatabs, DOMEff, HoleIce 30)

The plot shows that the systematic parameter that affects the result the most is scattering (Bulk Ice) and holeice.

It’s shown that HoleIce 30 simulation describe the sample used for this analysis better. Therefore we define HoleIce 30 as new baseline. We will show how to treat the change of bulk ice scattering on HoleIce 30 and avoid overestimating its uncertainty.

New HoleIce Model will be checked (simulation is being processed).
Combined systematic and statistic uncertainty assuming 5 years’ life time in Asimov study

Combined systematic and statistic uncertainty for 2011-2015 data
Atmospheric neutrinos are produced when cosmic ray enters the atmosphere. In this process, atmospheric muons are produced as well.

Atmospheric neutrinos from the southern sky (down-going) are often accompanied by atmospheric muons, while Atmospheric neutrinos from the northern sky (up-going) do not have such effect.

Therefore the southern sky atmospheric neutrinos detection efficiency is lower than northern sky due to the muon rejection process.
The Single Power-Law

IceCube preliminary

PoS(ICRC2015)1109
\( \nu_e + \nu_\tau \)

E_{rec} > 10 TeV

PoS(ICRC2017)968
\( \nu_e + \nu_\tau \)

significant energy range
12 TeV – 2.1 PeV

this work

PoS(ICRC2017)1005
\( \nu_\mu \) Northern Sky

significant energy range
119 TeV – 4.8 PeV

poster NU022

\( \checkmark \) consistent with previous cascade analysis
\( \checkmark \) also still consistent with diffuse \( \nu_\mu \) (p=0.04)

Slide from H. Niederhausen presented in TeVPA 2017