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

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for IceCube Collaboration
Stony Brook University
DIS2018

Outline

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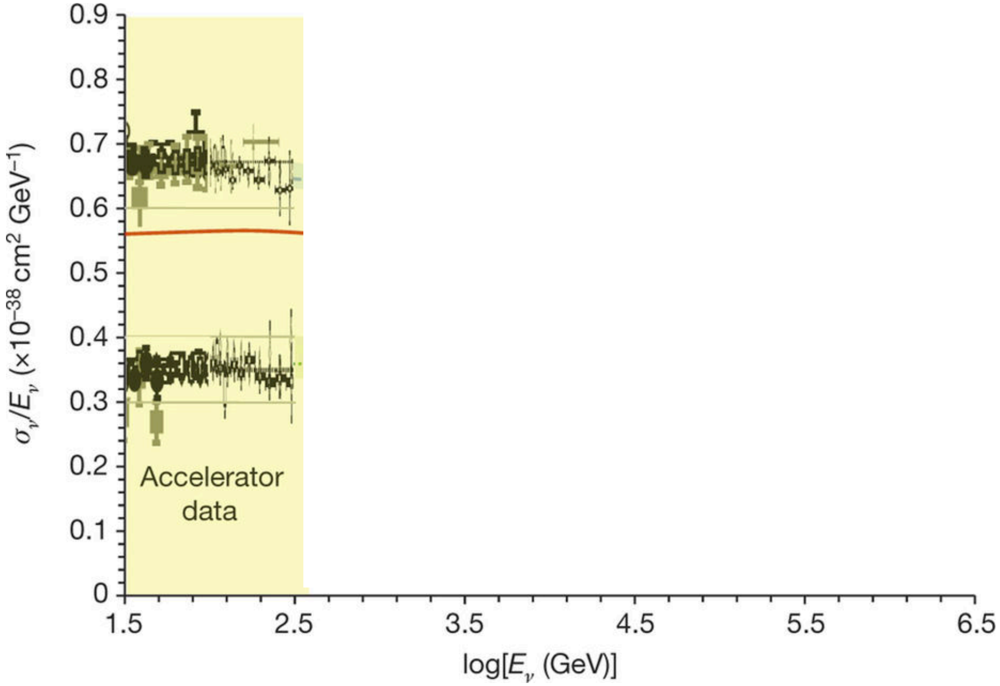
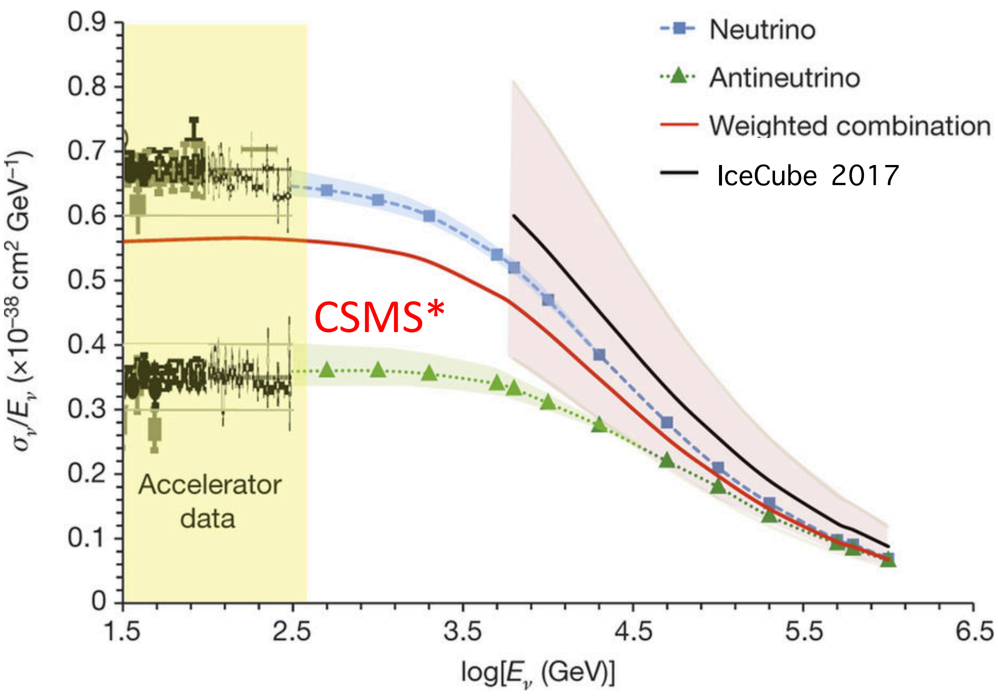
- Introduction
- IceCube Detector
- Analysis Method
- Data Sample
- Cross Section Measurement
  - statistical uncertainty
  - systematic uncertainty
- Summary

Introduction



- Accelerator data contributes up to~100GeV in **ν−N** cross section measurement. **Exciting (new) physics awaits at much higher energy range**.

Introduction



IceCube, Nature (2017), 10.1038

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

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

Introduction

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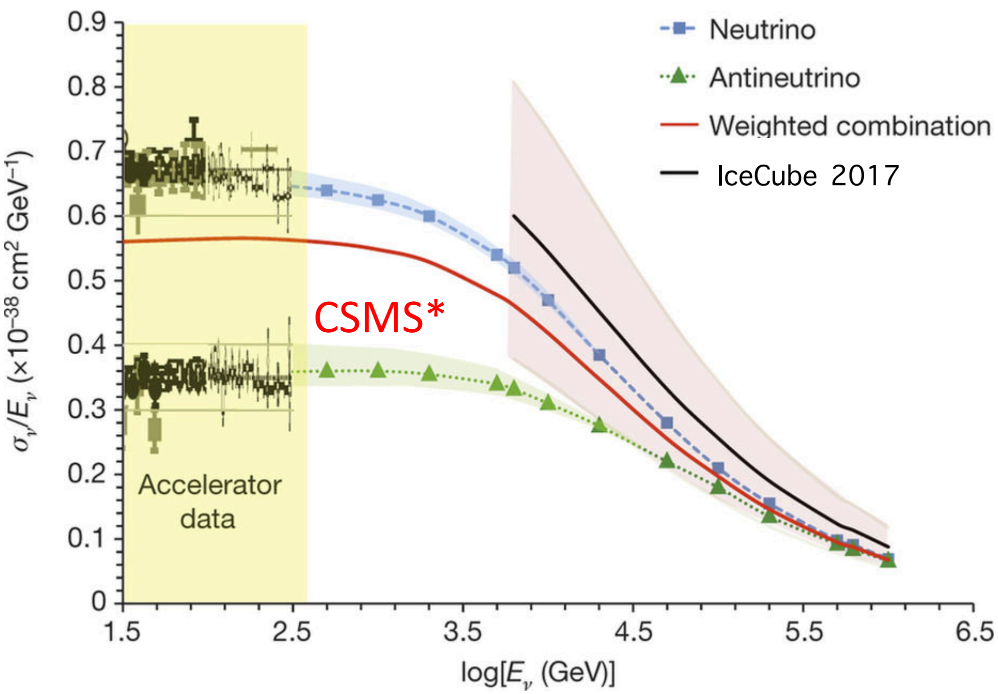

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- Accelerator data contributes up to~100GeV in ν–N cross section measurement. **Exciting (new) physics awaits at much higher energy range.**
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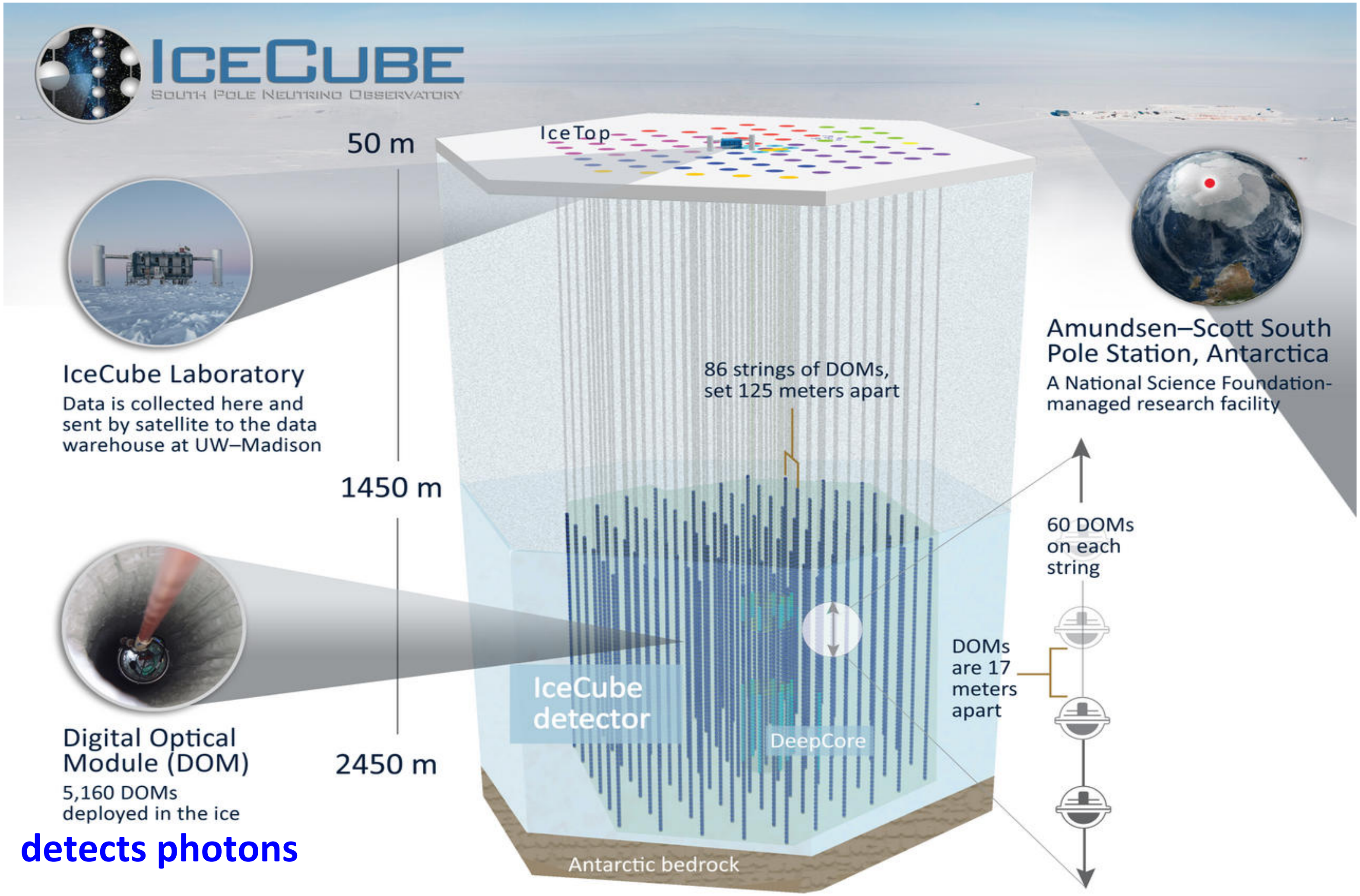
- This analysis will present a **novel method** to measure the **energy dependence** of ν–N cross section using 5yr IceCube $\nu_\tau+\nu_e$ sample.

CSMS: JHEP 08, 042 (2011)

IceCube Detector



detects photons

IceCube Detector

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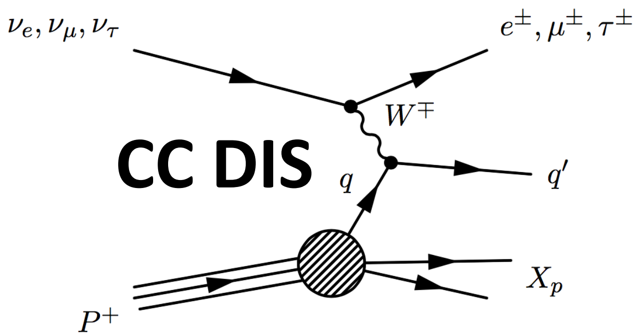
Neutrinos

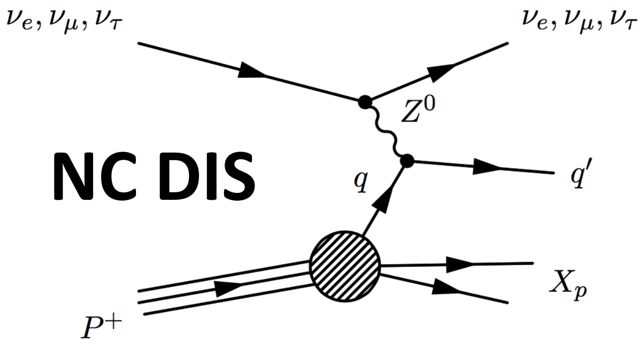
ν_e, ν_μ, ν_τ

ν_e, ν_μ, ν_τ

IceCube Detector

Neutrinos -> DIS

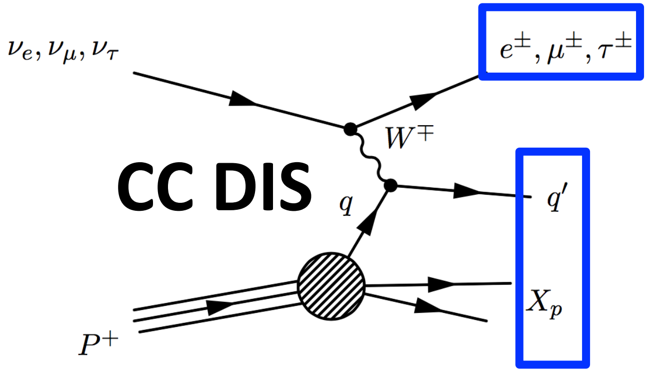




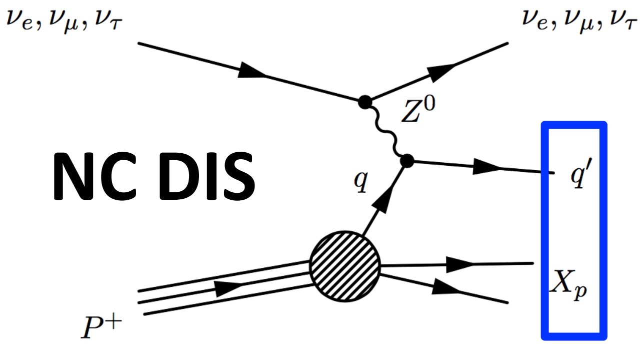
IceCube Detector

Neutrinos -> DIS -> charged secondaries

CC DIS

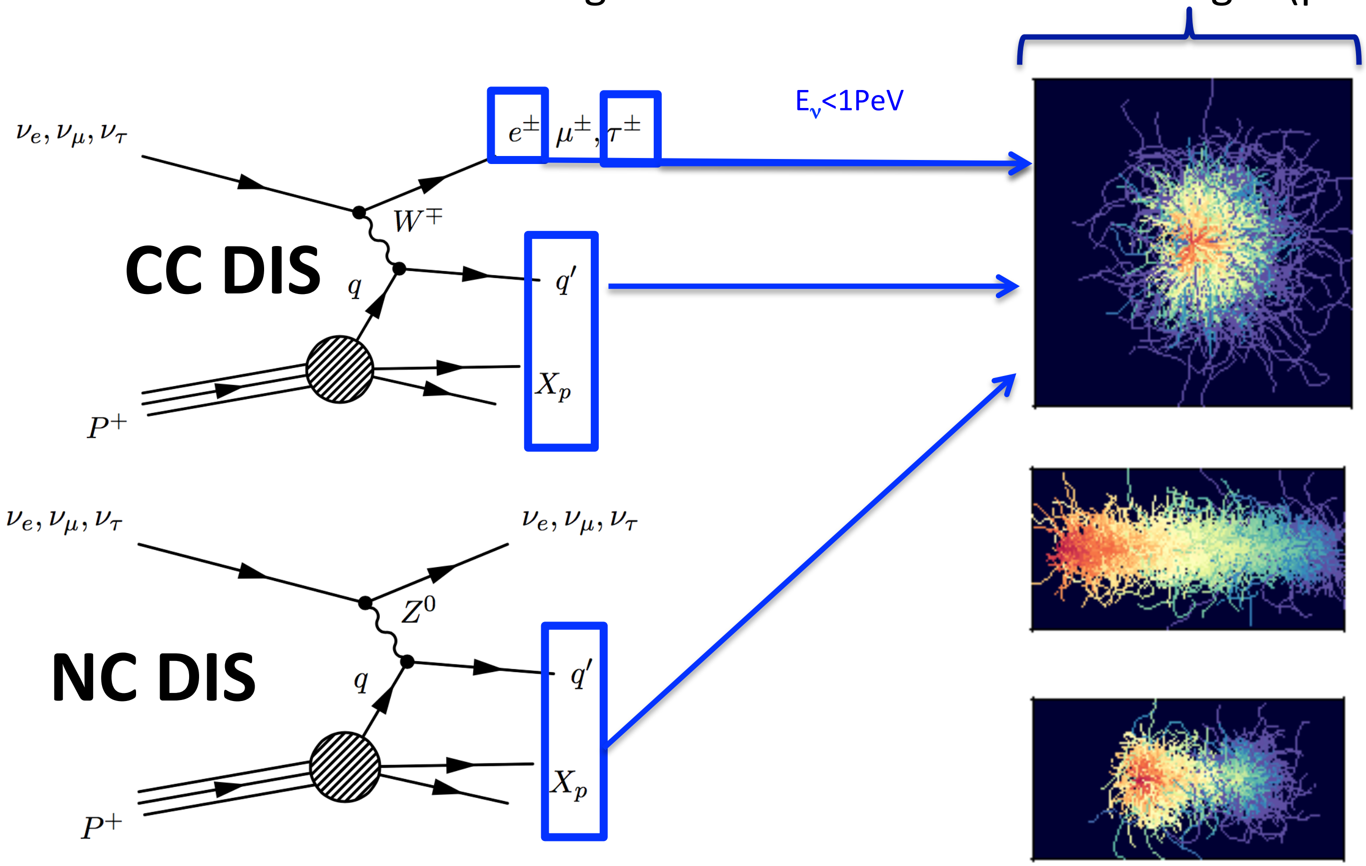


NC DIS



IceCube Detector

Neutrinos -> DIS -> charged secondaries -> Cherenkov Light (photons)



Cascade

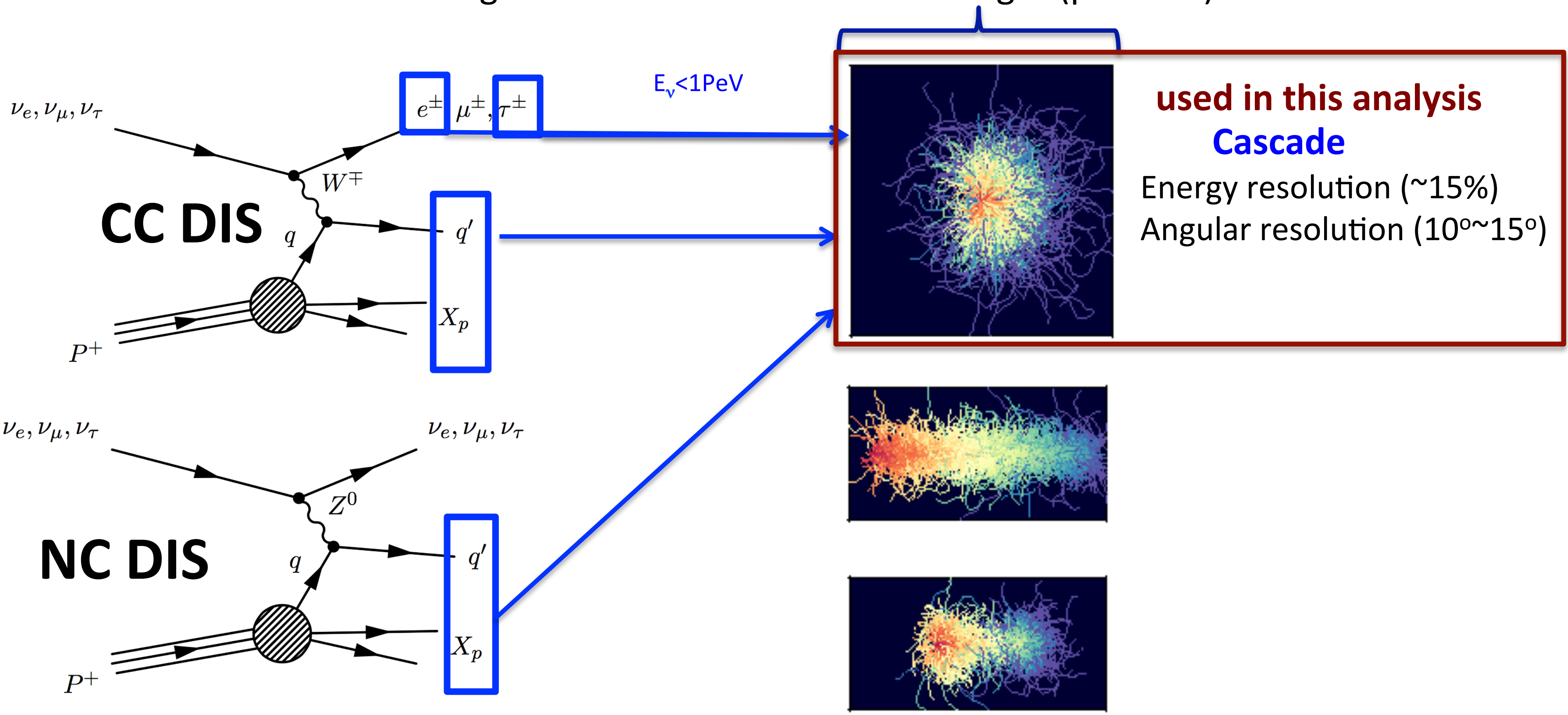
Energy resolution (~15%)

Angular resolution (10°~15°)

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

IceCube Detector

Neutrinos -> DIS -> charged secondaries -> Cherenkov Light (photons)



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IceCube Detector

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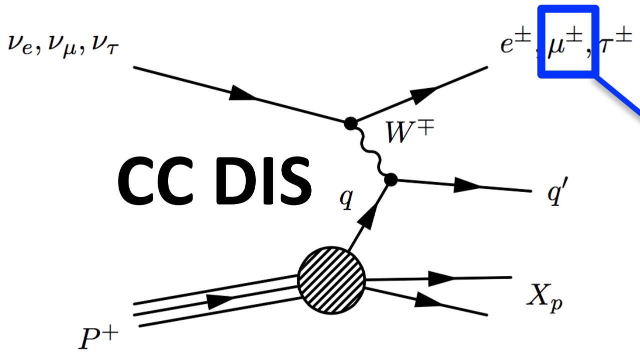
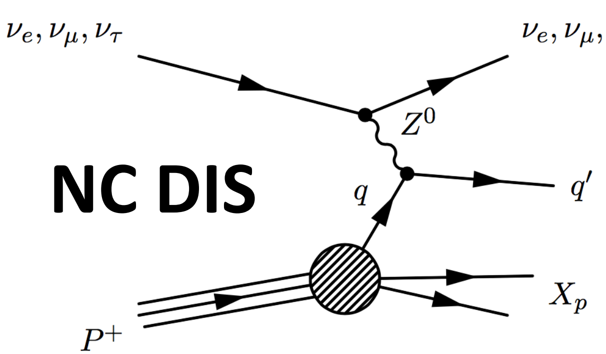
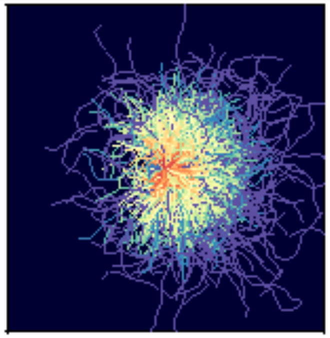


CC DIS



NC DIS

used in IceCube 2017 cross section measurement



used in this analysis

Cascade

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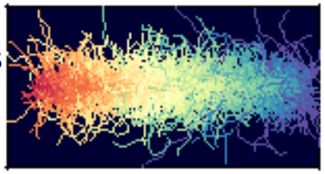
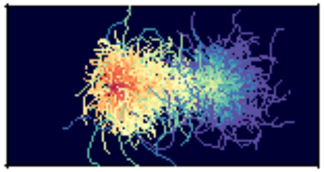


Track

Only lower bound on E_ν

Angular resolution (0.2°~1°)

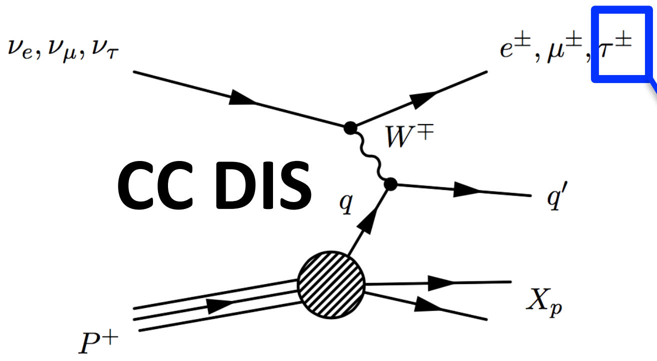


Artificial color: red (early in time), blue (late in time)

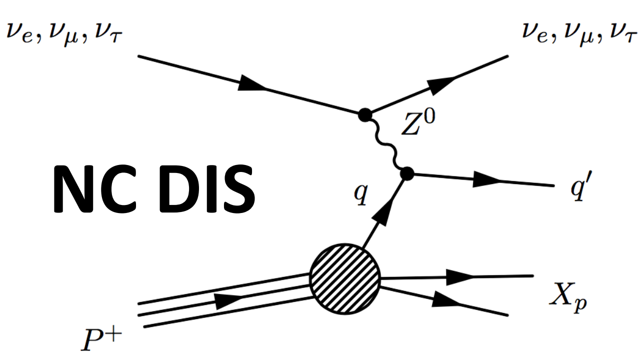
IceCube Detector

Neutrinos -> DIS -> charged secondaries -> Cherenkov Light (photons)

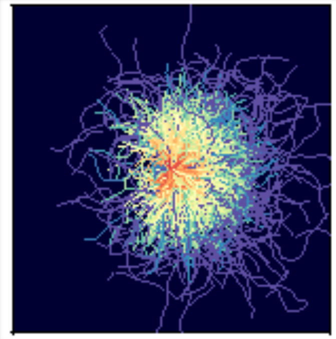
CC DIS



NC DIS



E_ν>1PeV



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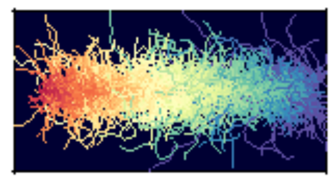

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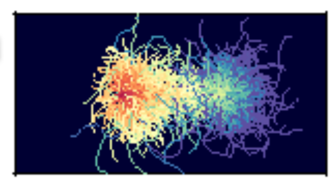


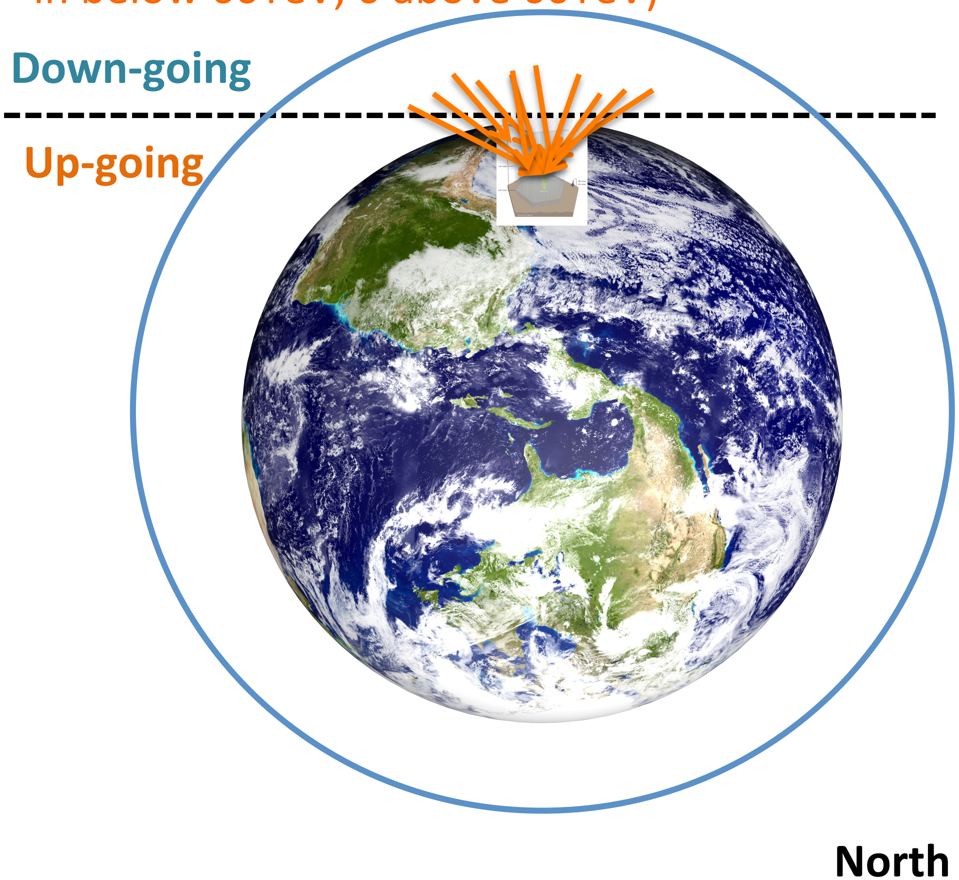
"Double-Bang"

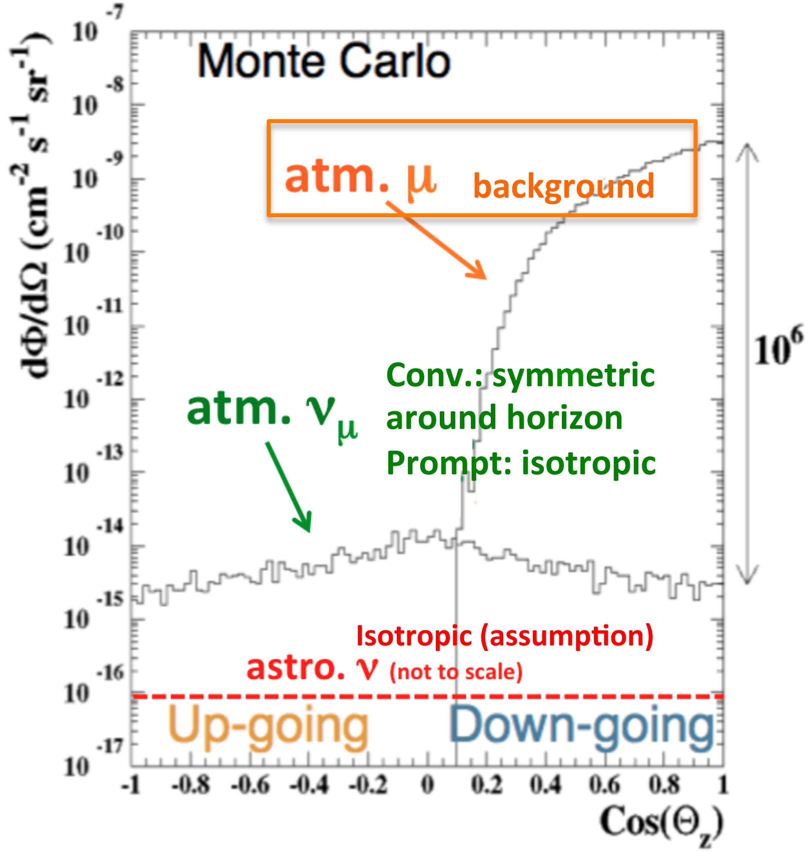
Has not been observed yet

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

IceCube Detector

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





IceCube Detector

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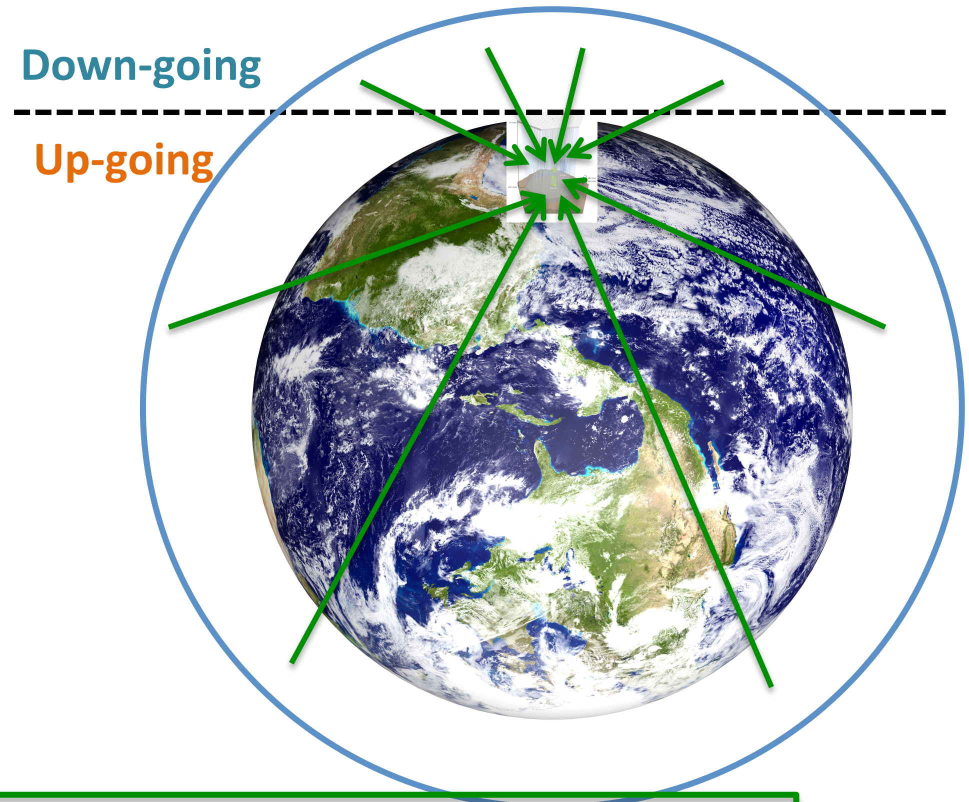
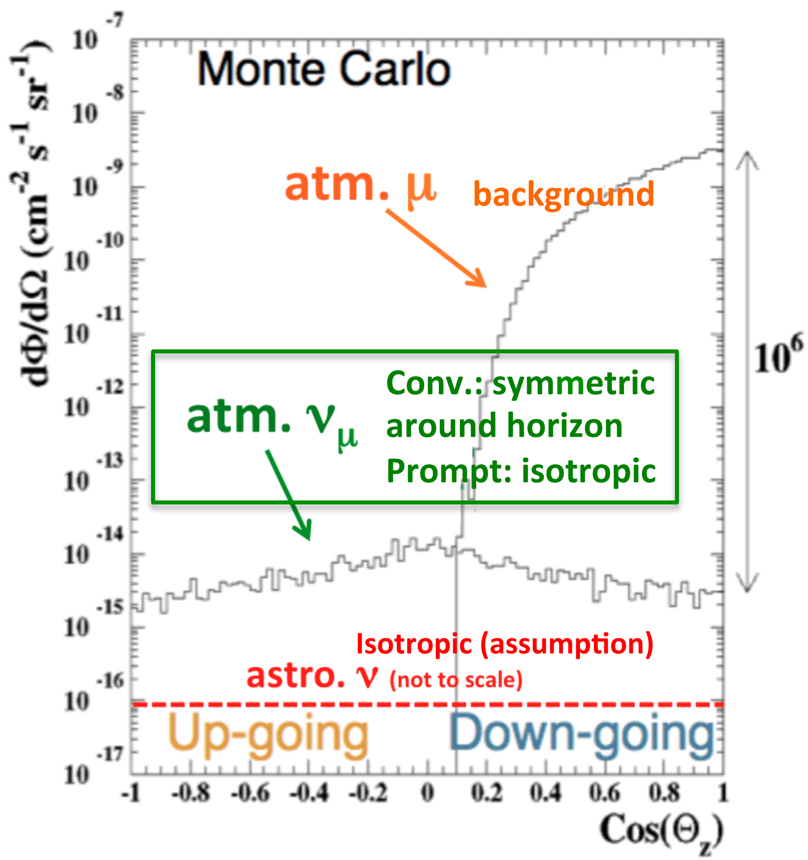
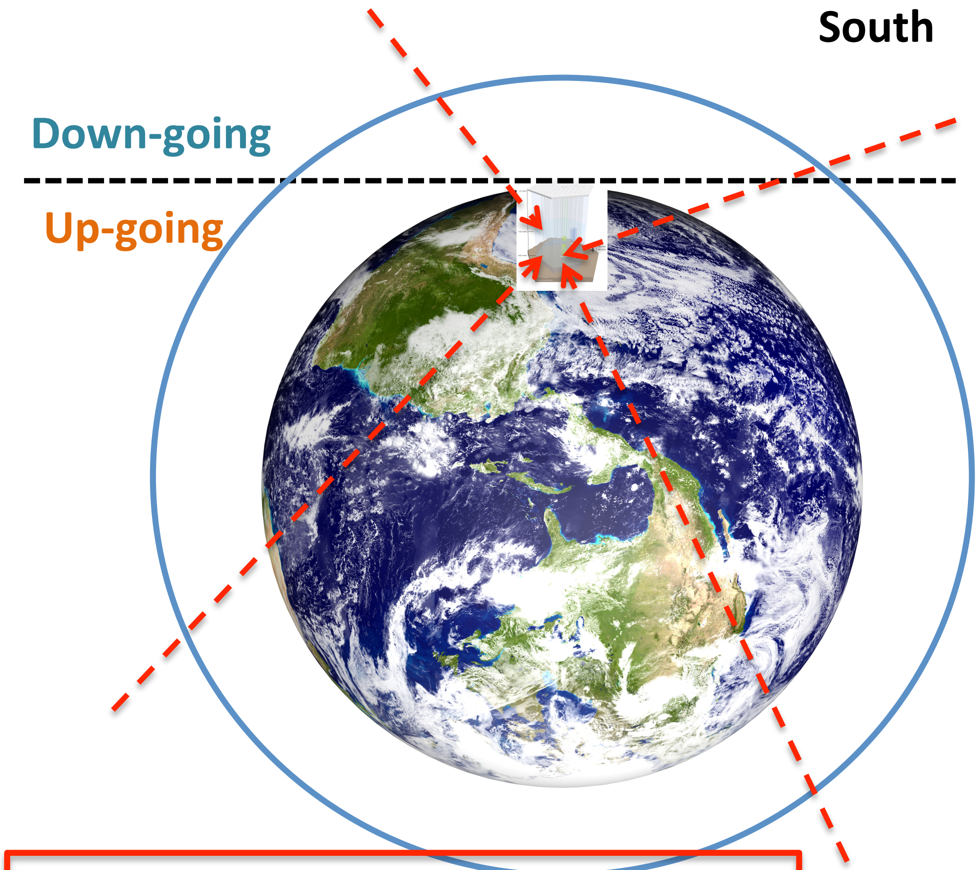
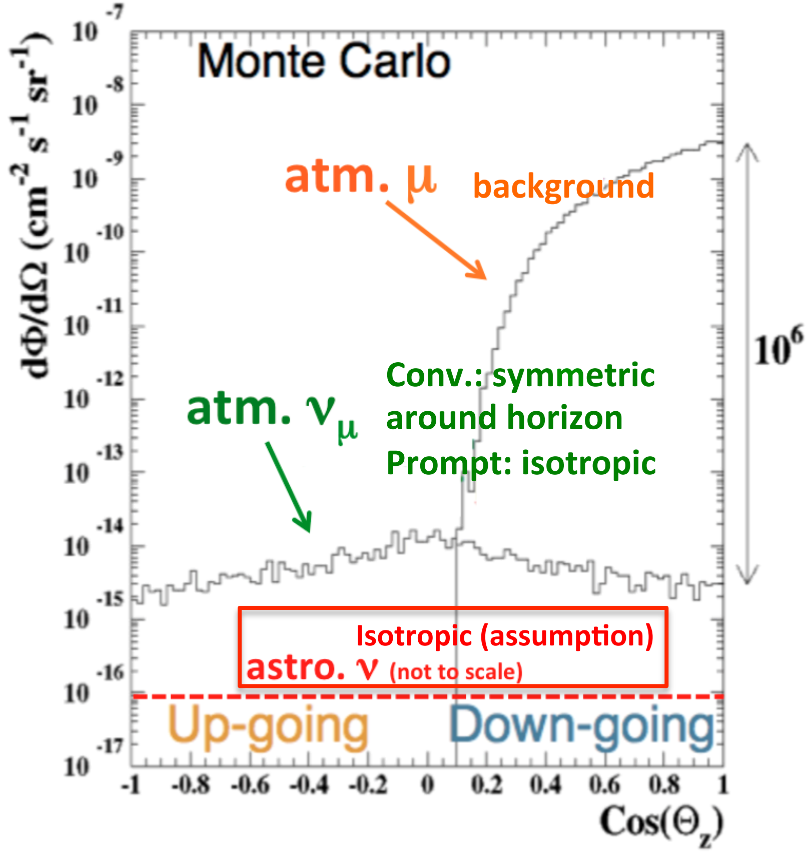




Equal amount of atm. neutrinos are **produced** in down-going region and up-going region.

IceCube Detector



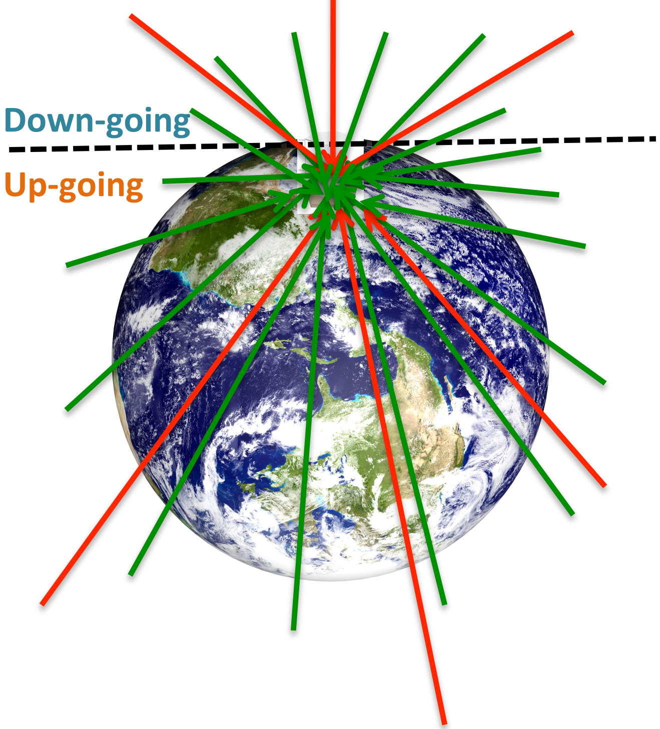


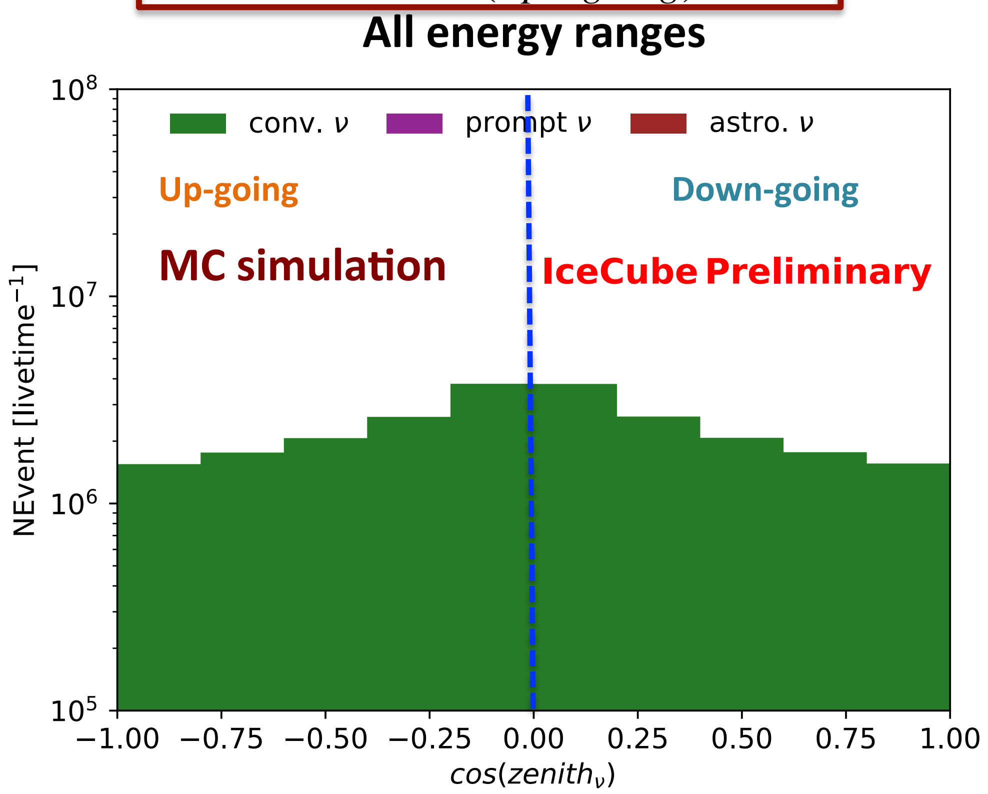
Equal amount of astro. neutrinos are **produced** in down-going region and up-going region.

Analysis Method

Proposed by D.Hooper, Phys.Rev.D 65.097303

$$R(E_\nu) = \frac{NEvents(Down-going)}{NEvents(Up-going)} = 1.0$$





When the **cross section** of neutrino-nucleon interaction is **small**, the Earth is **transparent** to neutrinos.

Analysis Method

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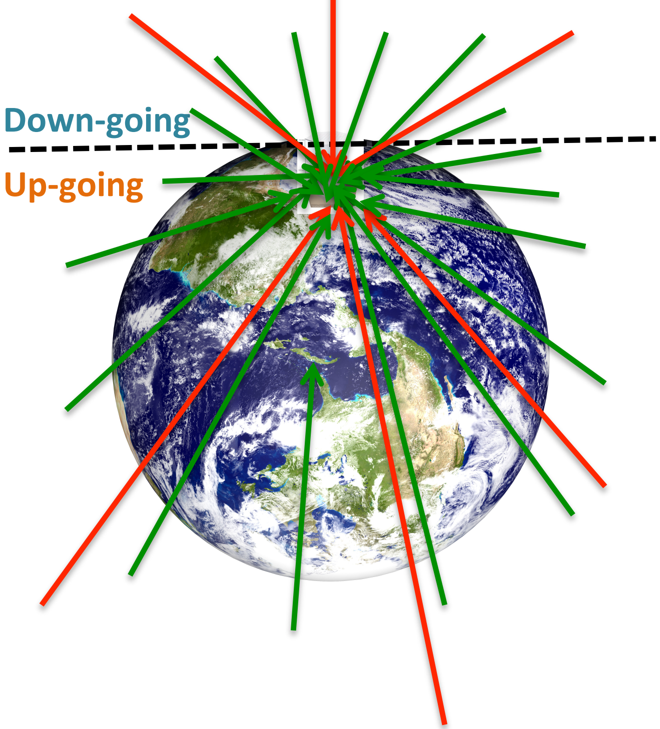
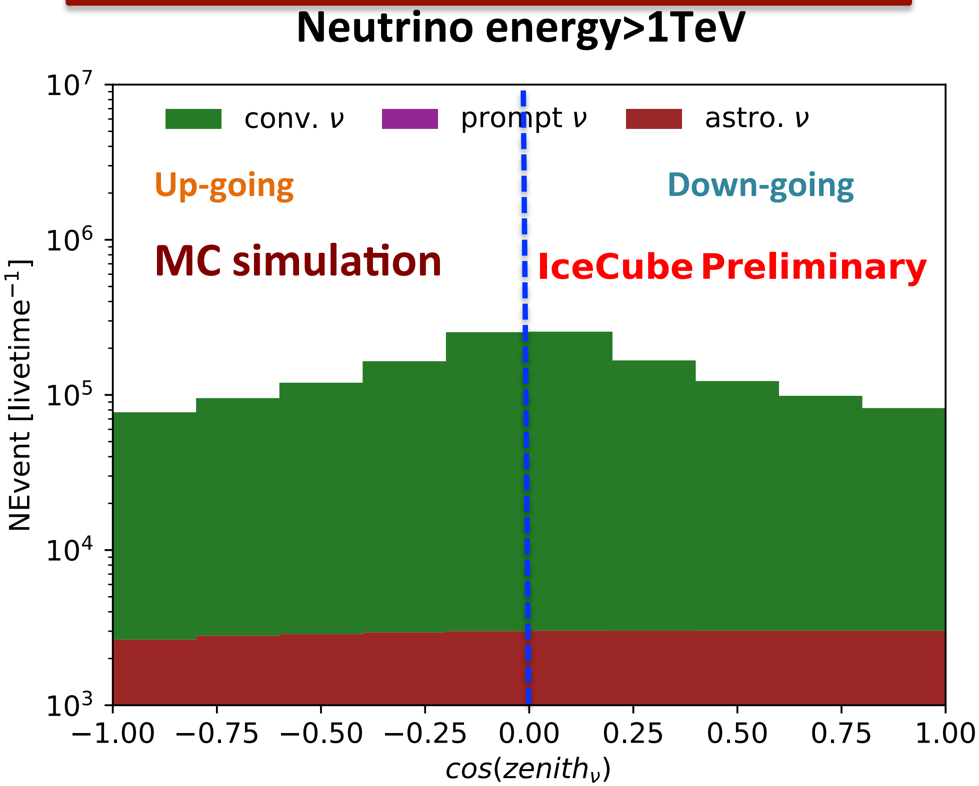


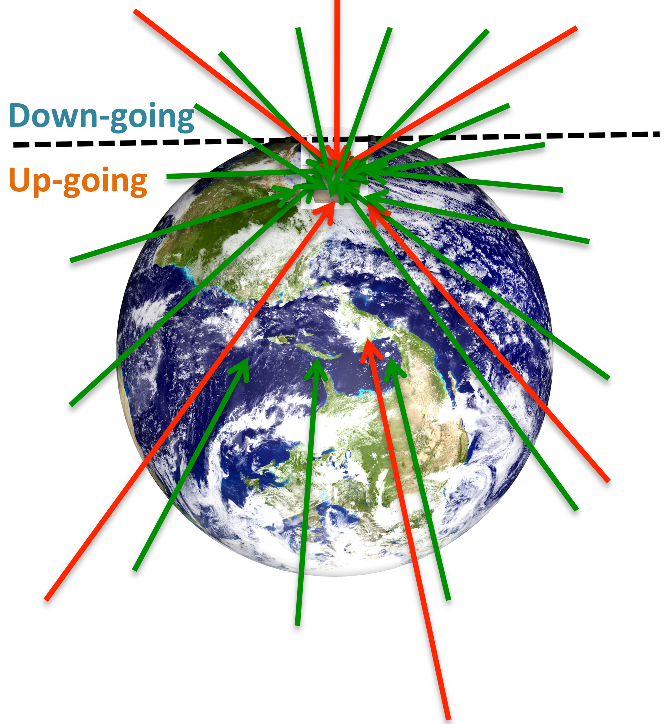
$$R(E_\nu > 1TeV) = \frac{NEvents(Down-going)}{NEvents(Up-going)} = 1.02$$



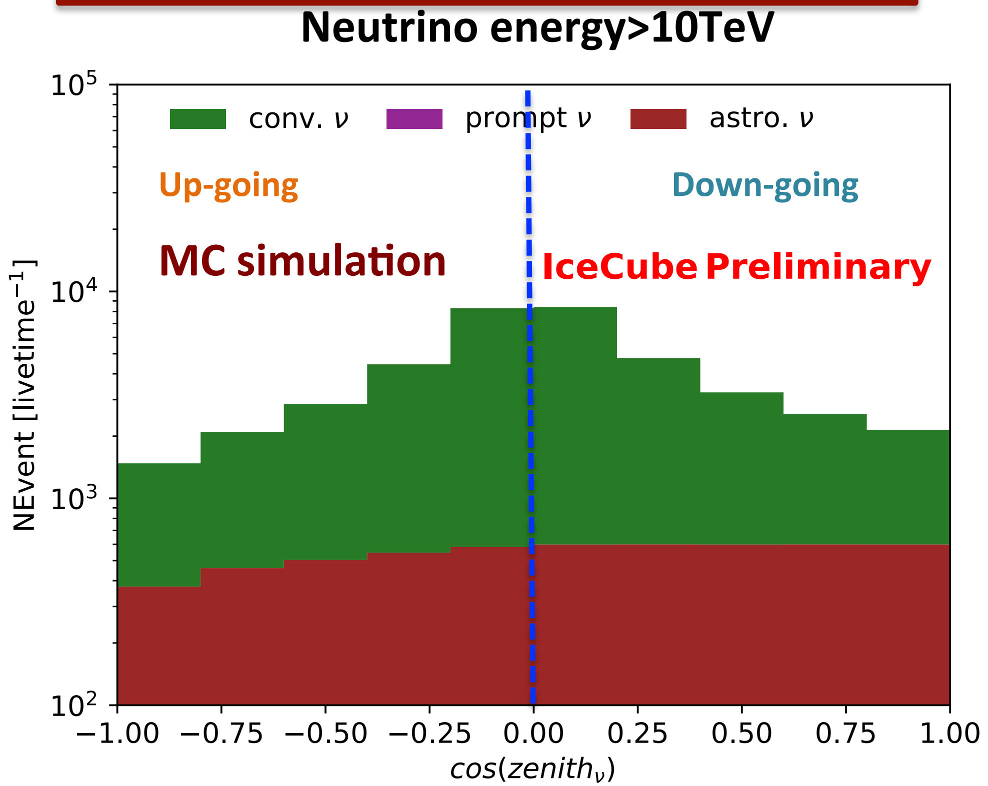
With the increase of neutrino energy, the cross section increases. The **up-going** events get absorbed by the Earth.

Analysis Method

Proposed by D.Hooper, Phys.Rev.D 65.097303



$$R(E_\nu > 10TeV) = \frac{NEvents(Down-going)}{NEvents(Up-going)} = 1.10$$



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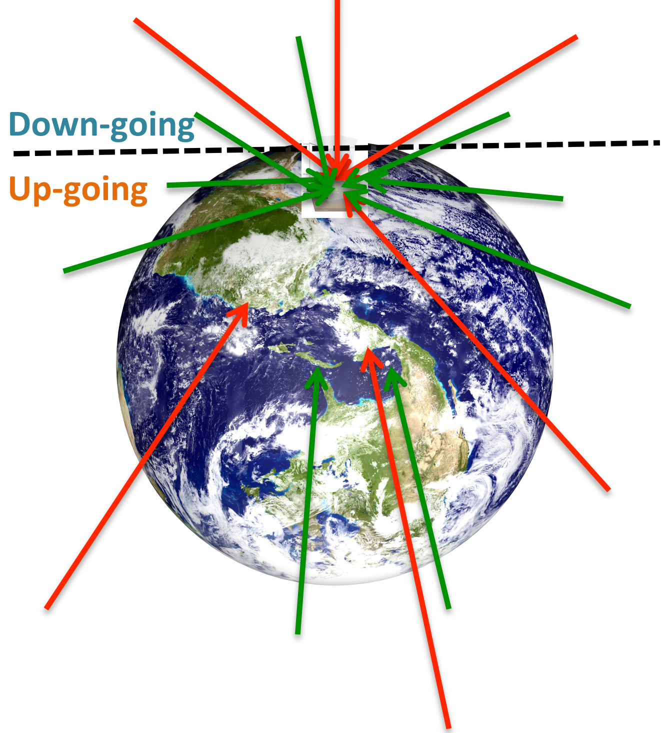
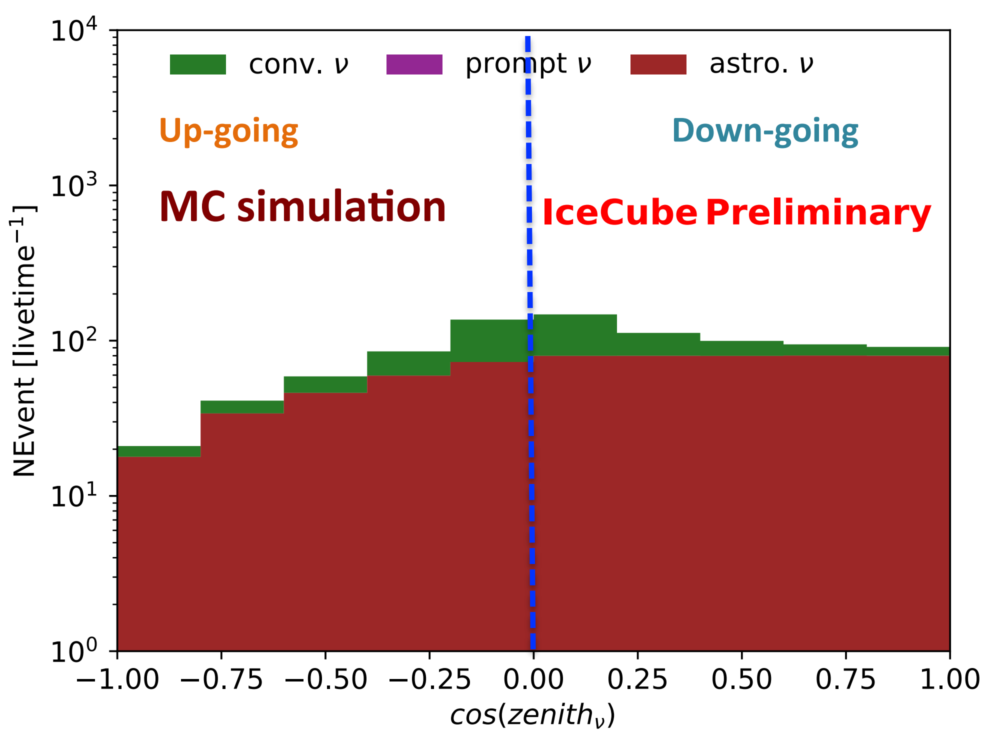


$$R(E_\nu > 100TeV) = \frac{NEvents(Down-going)}{NEvents(Up-going)} = 1.59$$

Neutrino energy>100TeV



With the increase of neutrino energy, the cross section increases. The **up-going** events get absorbed by the Earth.

Analysis Method

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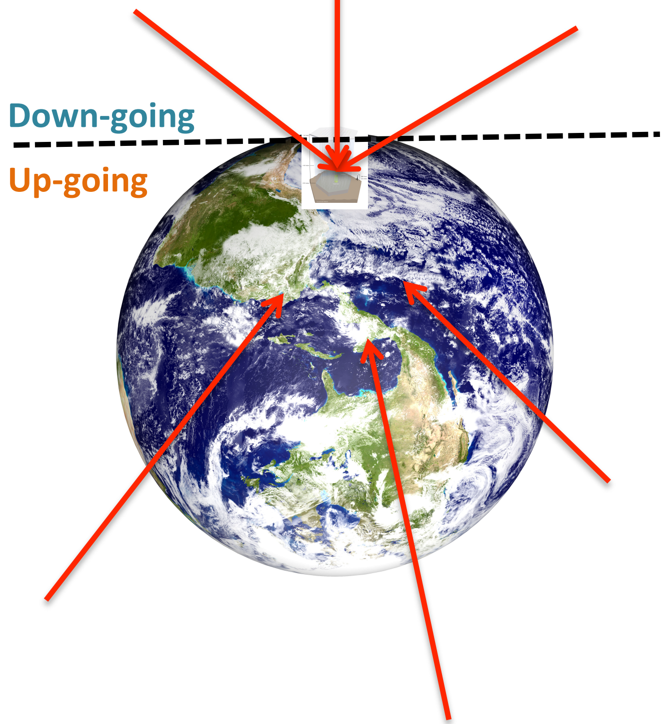
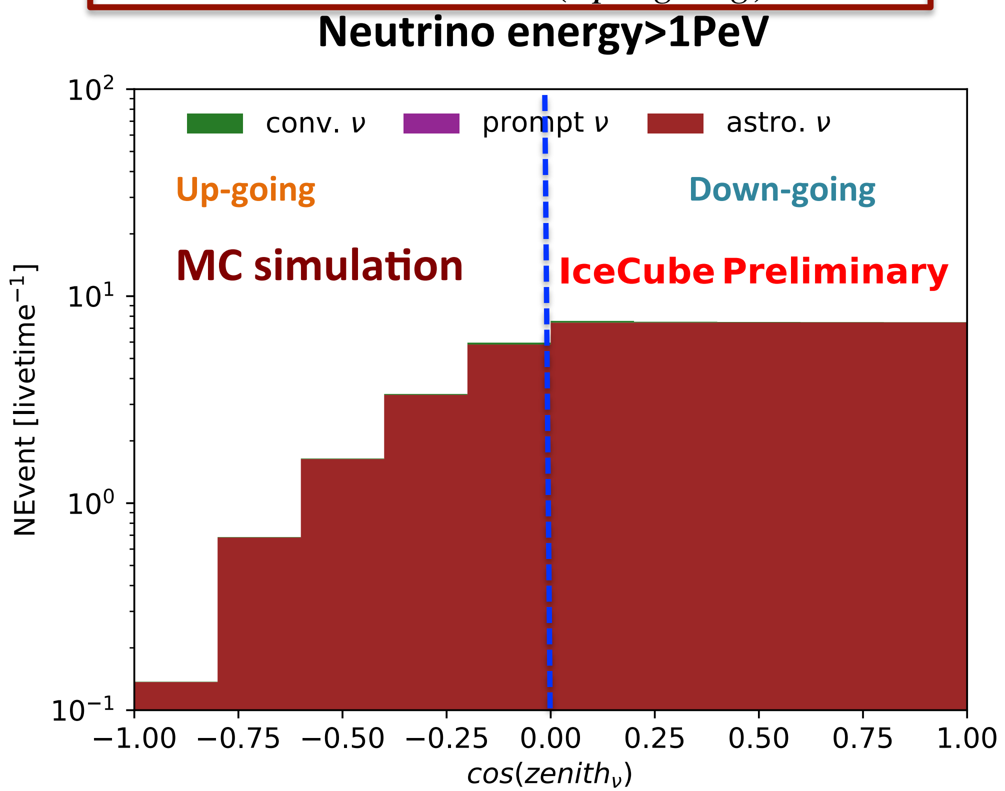
$$R(E_\nu > 1PeV) = \frac{NEvents(Down-going)}{NEvents(Up-going)} = 3.19$$





With the increase of neutrino energy, the cross section increases. The **up-going** events get absorbed by the Earth.

Analysis Method

Stony Brook University

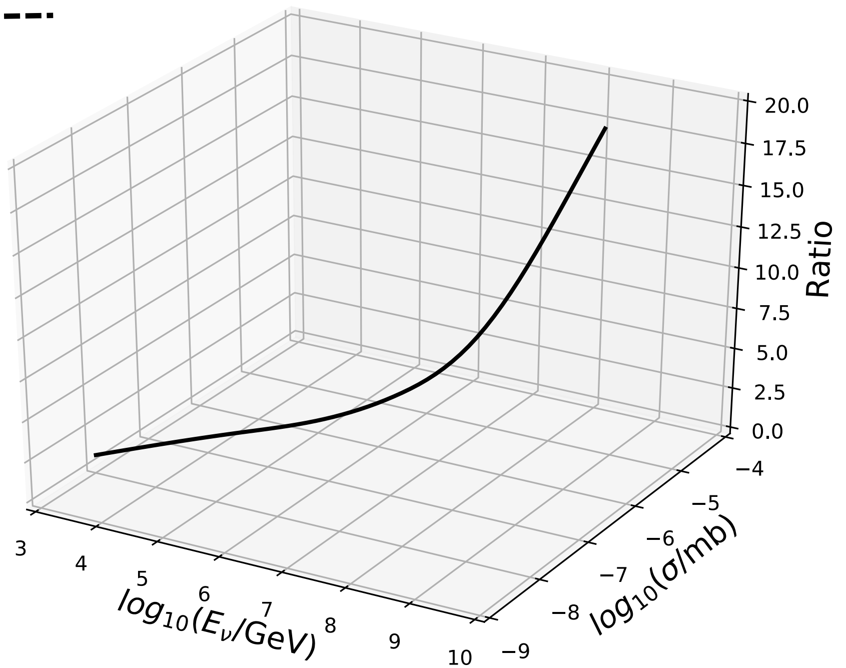
A simplified illustration

—assuming perfect detector, energy and direction are in true space (E_ν, $Zenith_\nu$).

Proposed by D.Hooper, Phys.Rev.D 65.097303

Down-going: not affected by the Earth

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



Analysis Method

Stony Brook University

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1. Calculate $R(E_\nu)$ =NEvent($down_\nu$)/ Nevent(up_ν) in each neutrino energy bin from exp. data.

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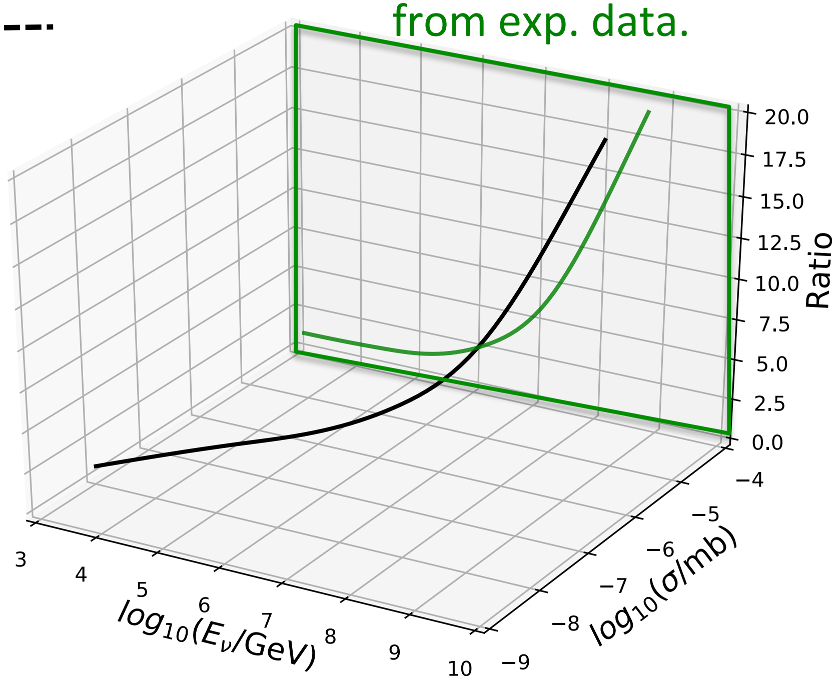

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Stony Brook University

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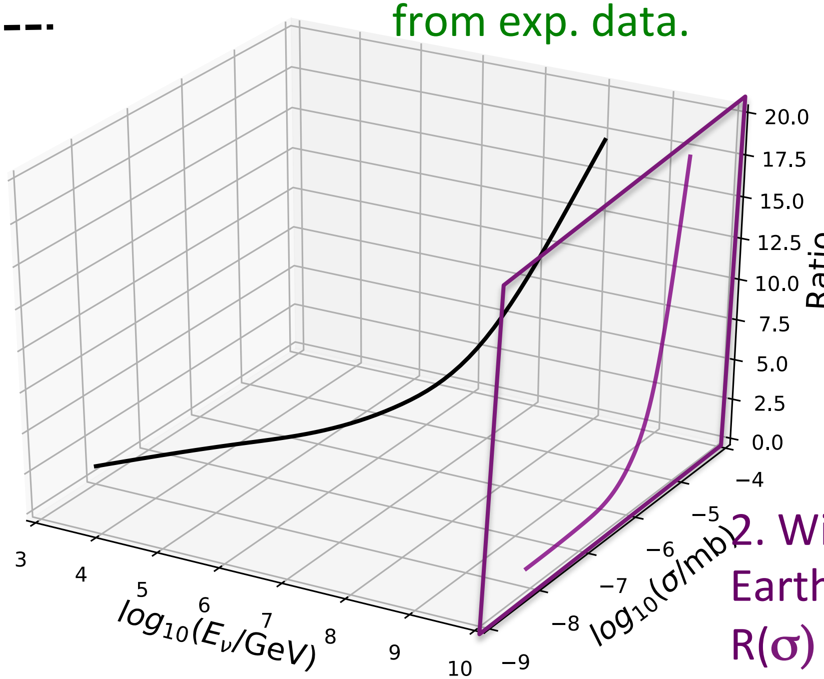

2. With the knowledge of Earth density, we get $R(\sigma)$ =Nevent($down_\nu$)/ Nevent(up_ν) in different cross section bins.

Analysis Method

A simplified illustration

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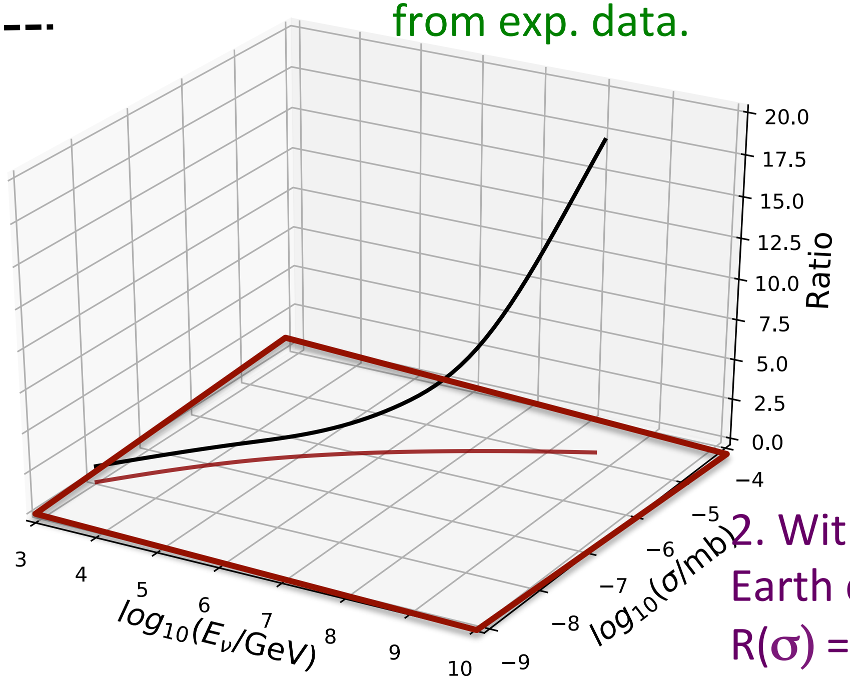


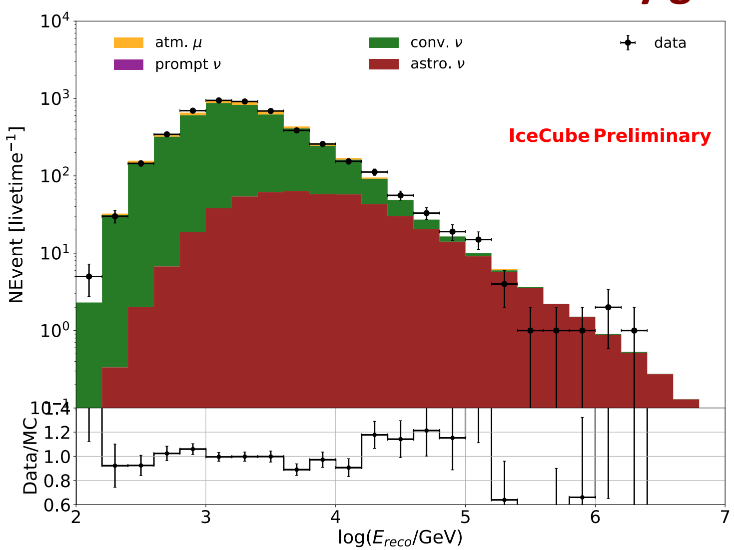
2. With the knowledge of Earth density, we get R(σ) =Nevent($down_\nu$)/ Nevent(up_ν) in different cross section bins.

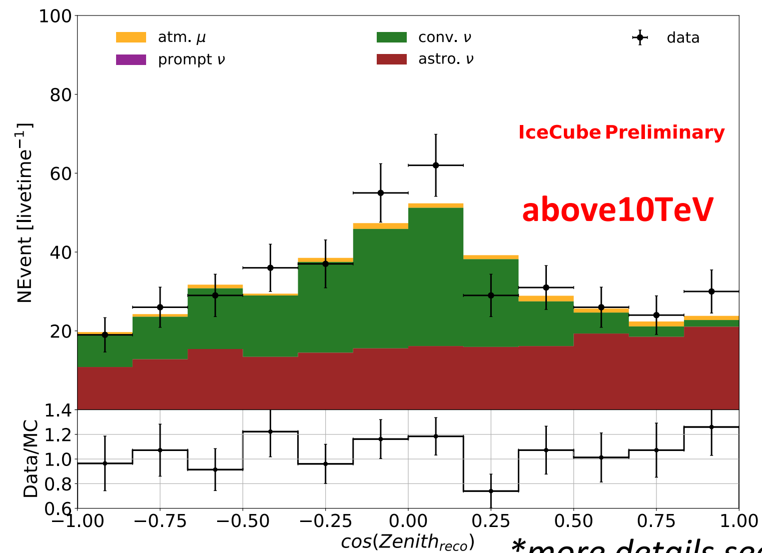
3. Take the ratio for each neutrino energy bin and find the corresponding cross section.

Data Sample

- 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!

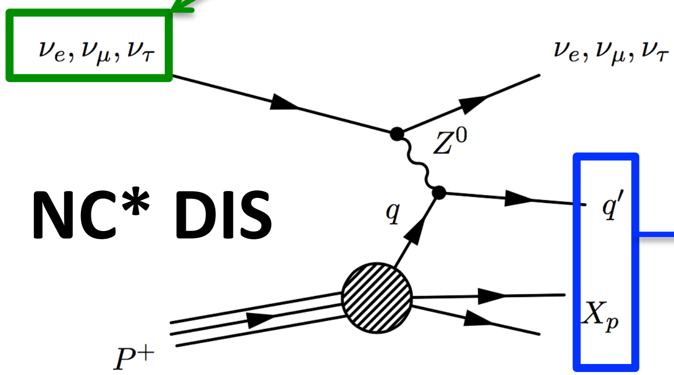


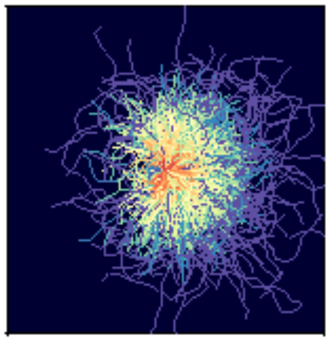


*more details see backup

Unfolding

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





Energy resolution (~15%)
Angular resolution (10^o~15^o)

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

Unfolding

Stony Brook University

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 $P(T_i \mid R_j)$ of an event end up in Reco bin j given True bin i is known.
- The probability $P(R_j \mid T_i)$ of an event from True bin i given it's found in Reco bin j is of interest.

$$P(T_i \mid R_j)^{(k)} = \frac{P(R_j \mid T_i) N(T_i)^{(k)}}{\sum_i P(R_j \mid T_i) N(T_i)^{(k)}}$$

$$N(T_i)^{(k+1)} = \sum_j P(T_i \mid R_j)^{(k)} N(R_j) / \alpha_i$$

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

$N(T_i)^{(k+1)}$: Distribution in **true** space of the k+1 th iteration

$N(R_j)$: Distribution in **reconstructed** space, aka measurement

R: reconstructed (observed) energy, zenith
T: true (neutrino) energy, zenith

Unfolding

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

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$P(R_j \mid T_i) N(T_i)^{(k)}$

$P($

$N($

j

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

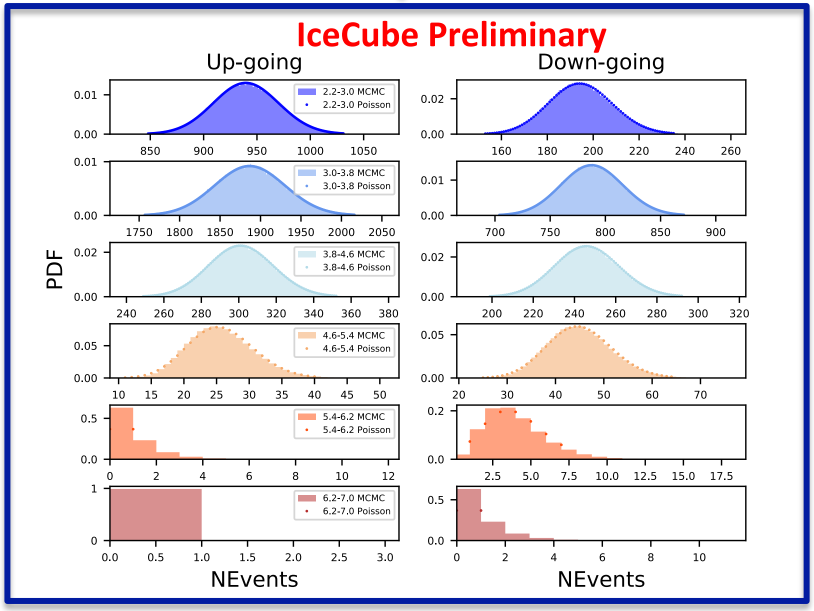
Statistical Uncertainty Estimation

How to estimate statistical uncertainty in iterative unfolding?

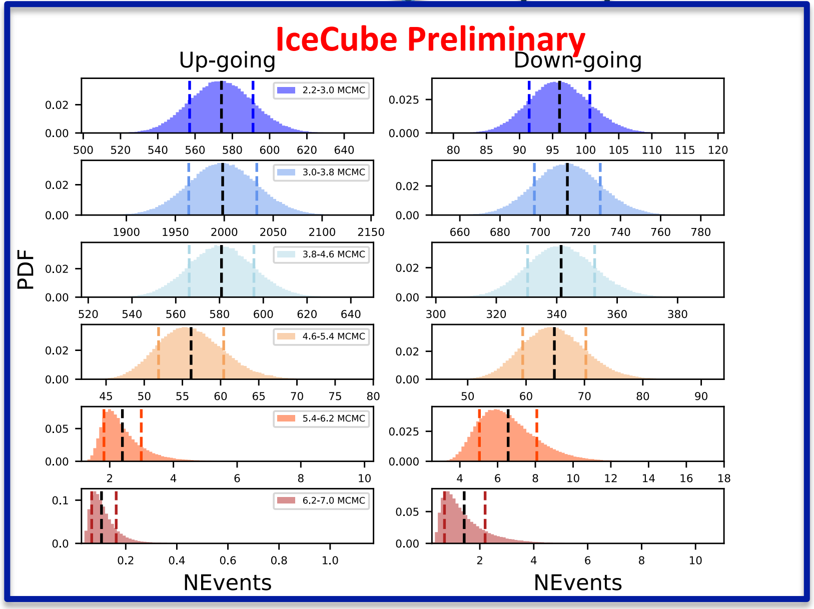
- Use MCMC to sample in **reconstructed (observed)** space with log uniform prior.
- MCMC sampling distribution is shown as below.

Iterative Unfolding →

- Get posterior distribution in **true (neutrino)** space.
- Take the 68% range (from 16% to 84% in cdf) as the uncertainty.



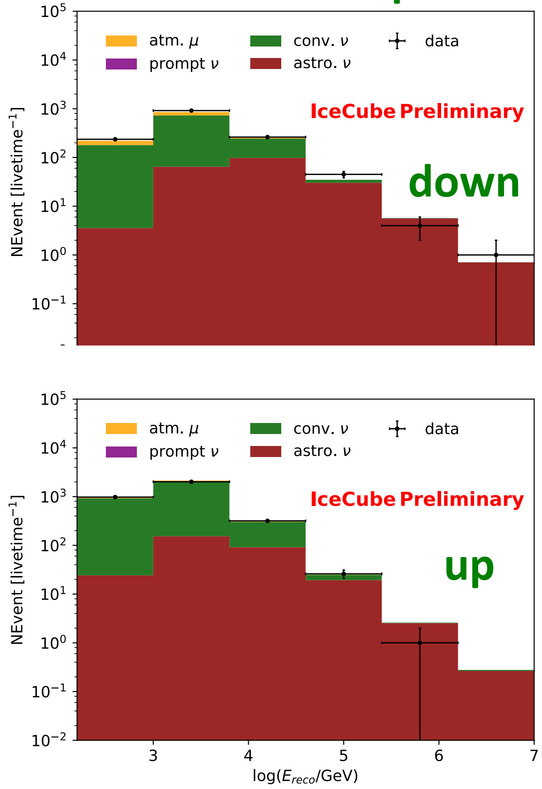
Energy Increases



Unfolding

- Assign data in **reconstructed energy** bins according to their **reconstructed direction**.

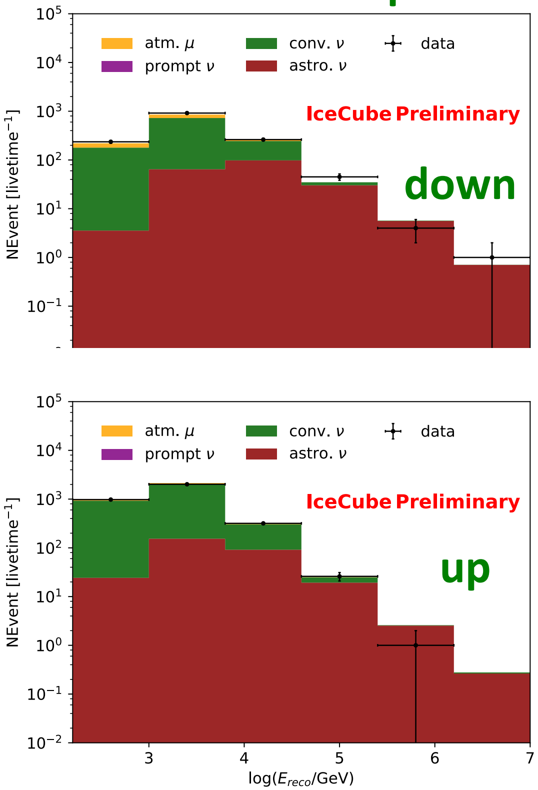
Reconstructed Space



Unfolding

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

Reconstructed Space



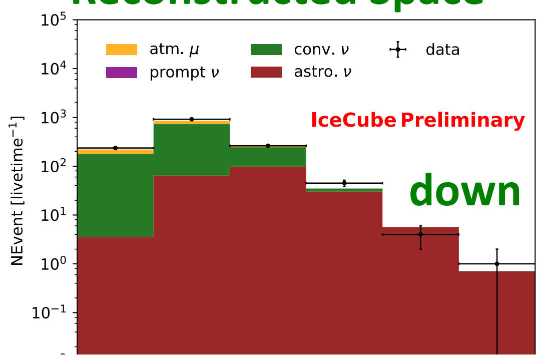
data-background

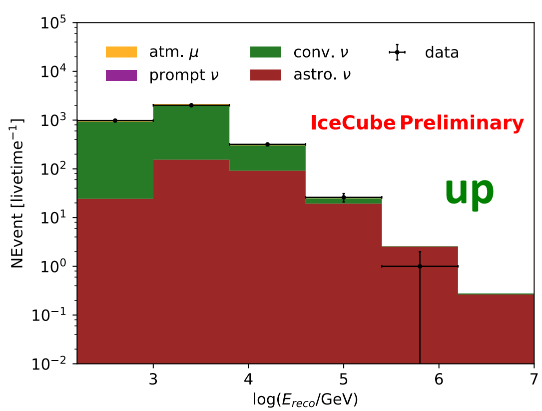
Unfolding

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

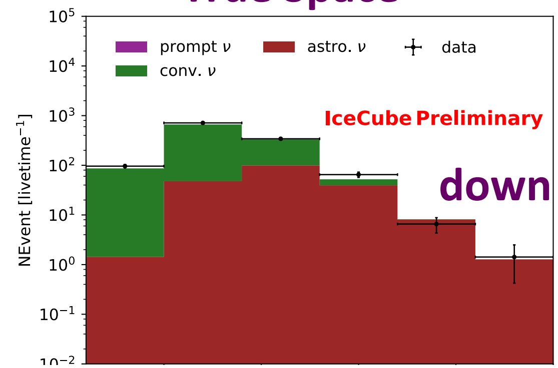


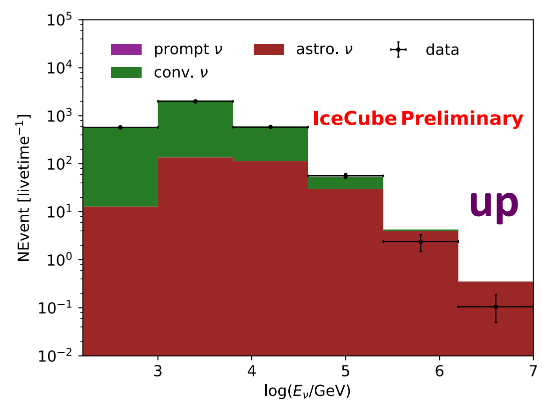


data-background

Unfolding

True Space





Ratio

Stony Brook University

What exactly is the ratio we are calculating?

Assuming isotropic astro flux

$$R_{\exp}(E_\nu) = \frac{N(E_\nu, down_\nu)}{N(E_\nu, up_\nu)} = \frac{\Phi(E_\nu)\cdot Acpt(E_\nu, down_\nu)\cdot \sigma(E_\nu)}{\Phi(E_\nu)\cdot Acpt(E_\nu, up_\nu)\cdot Absp(\sigma(E_\nu))\cdot \sigma(E_\nu)}$$

$$\equiv R(E_\nu)\cdot CF(E_\nu)$$

- Ratio of N(E_ν,down) and N(E_ν,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.

$$CF(E_\nu) \equiv \frac{Acpt(E_\nu, up)}{Acpt(E_\nu, down)}$$

$$Acpt(E_\nu, up/down) = \frac{NEvents(E_\nu, up/down, final)}{NEvents(E_\nu, up/down, gen)}$$

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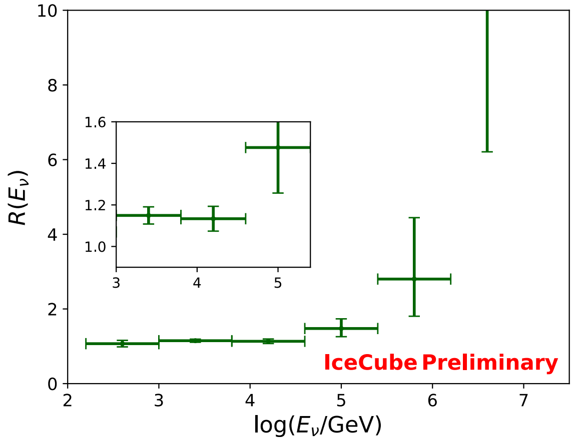
Take-away message: detector effect is factorized, we use $R(E_\nu)$ as the ratio to measure cross section.

Cross Section Measurement

Stony Brook University

How to measure the cross section with the ratio in each neutrino energy bin?

- Take the ratio in each neutrino energy bin.



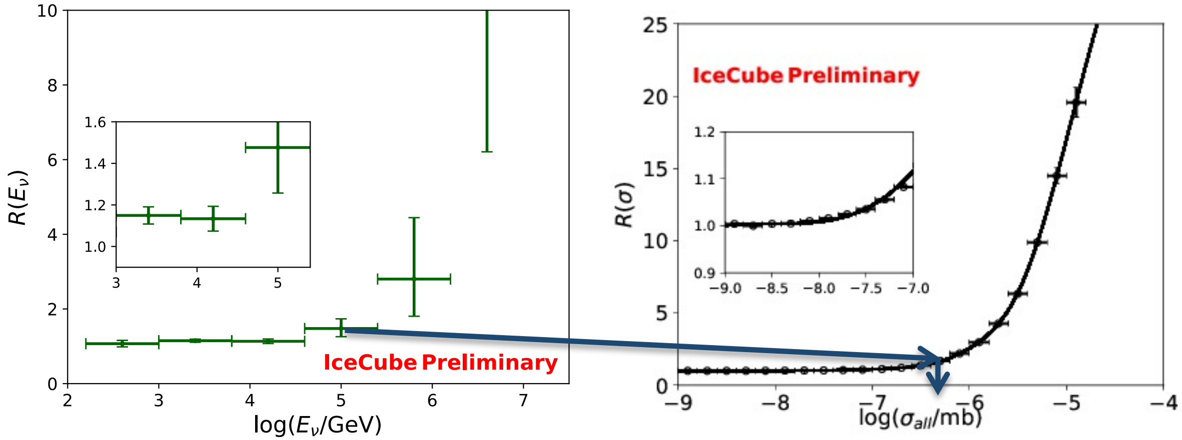
$$R(E_\nu)$$

Cross Section Measurement

Stony Brook University

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.



$$R(E_\nu)$$

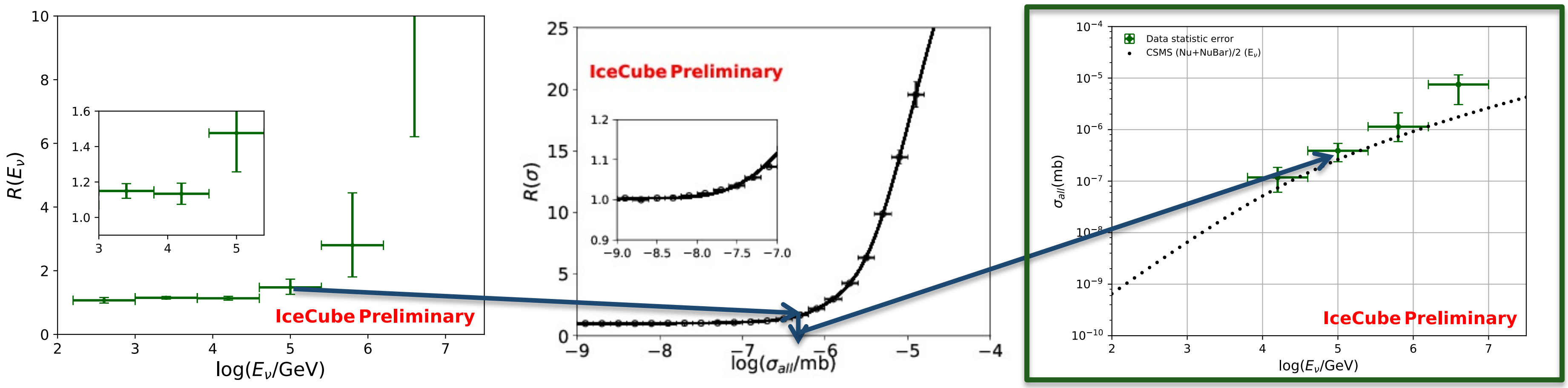
$$R(\sigma)$$

Cross Section Measurement

Stony Brook University

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.
- 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.



$R(E_\nu)$

$R(\sigma)$ → $\sigma(E_\nu)$

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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Stony Brook University

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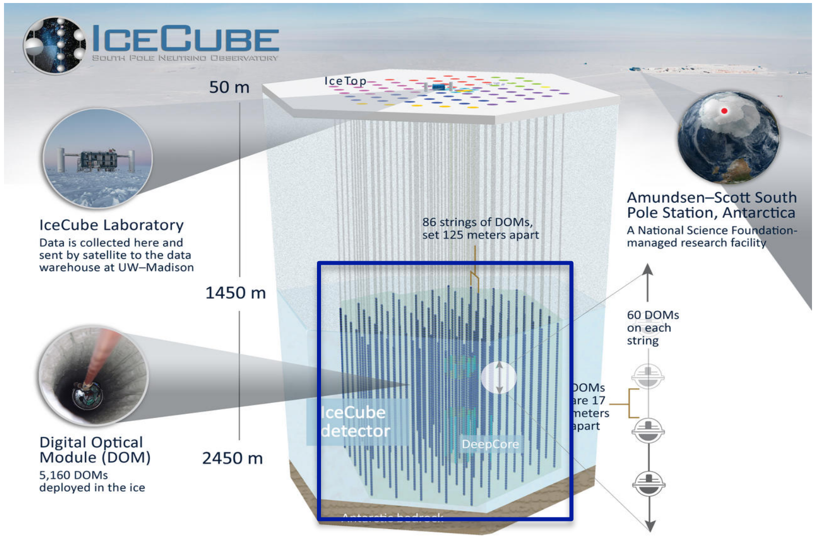
bulk ice (the ancient glacial ice)



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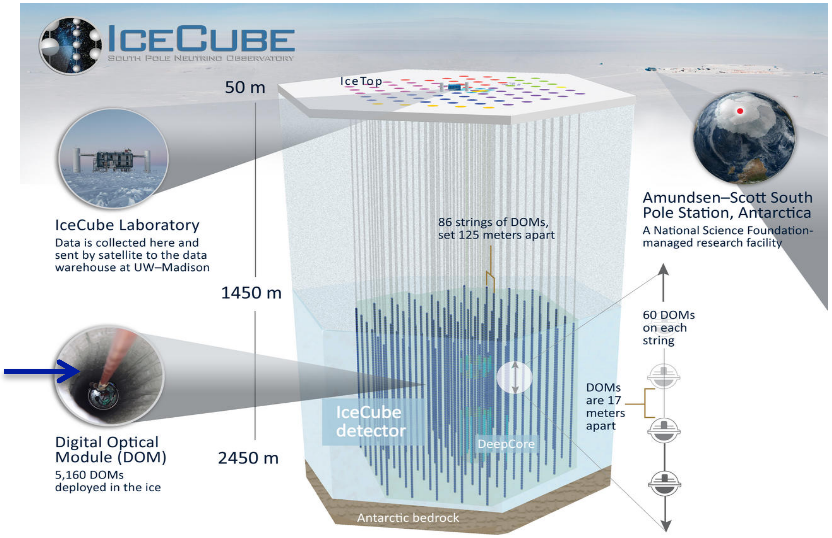
hole ice (the refrozen ice around the DOMs) →



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  3. DOM efficiency

  (2 and 3:) **negligible effect on the result***

**more details see backup*

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Stony Brook University

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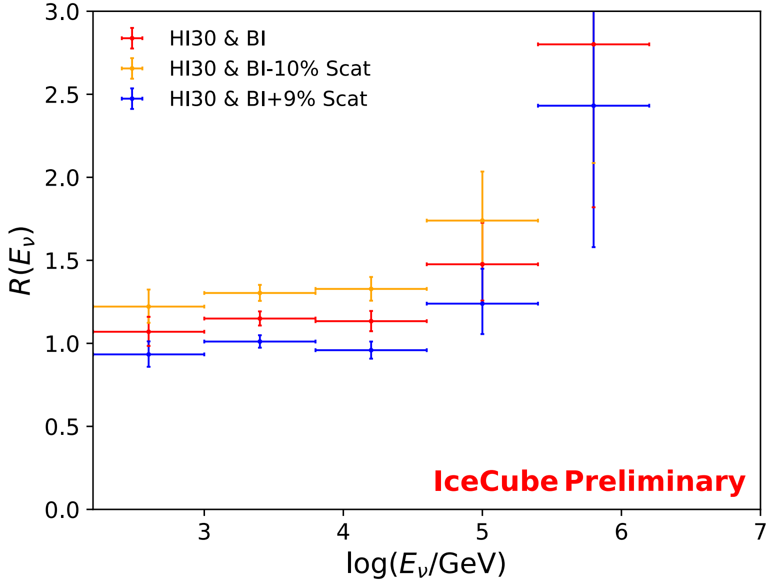
  (2 and 3:) **negligible effect on the result***

  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*

Systematic Study

- Using the matrices built with different systematic simulation datasets to unfold data results in different NEvents neutrino energy & zenith bins ->different ratios in neutrino energy bins as shown in the left plot below.



Systematic Study

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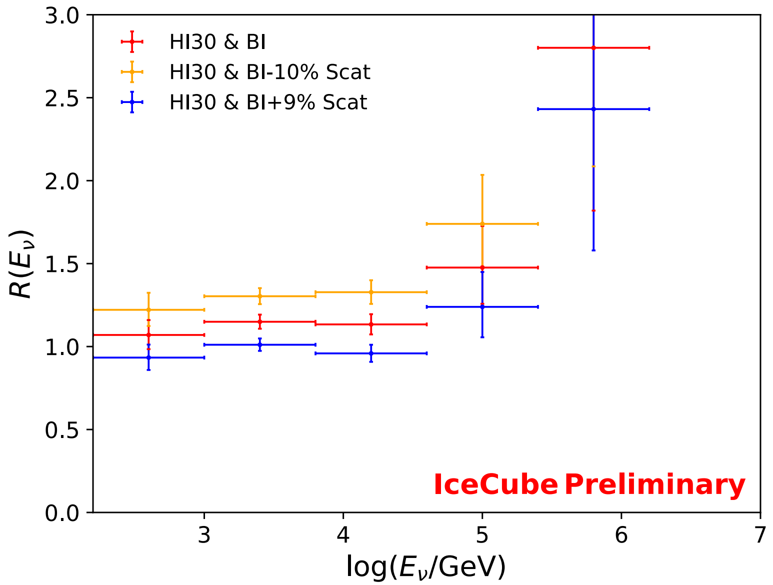
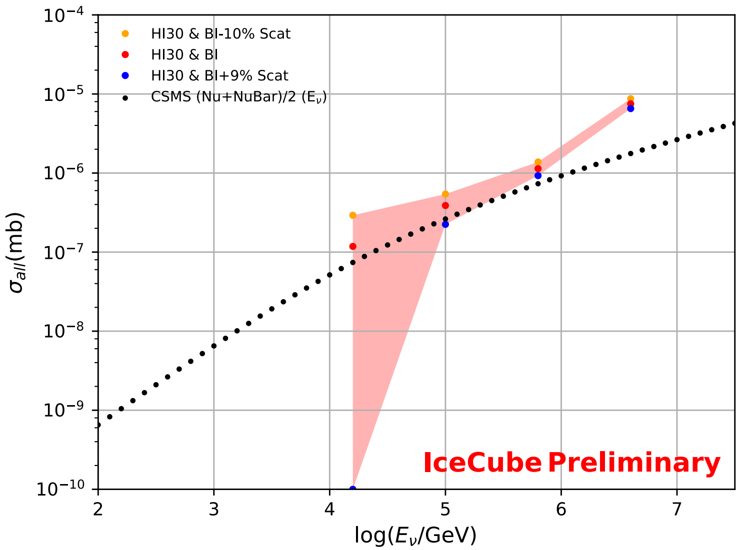
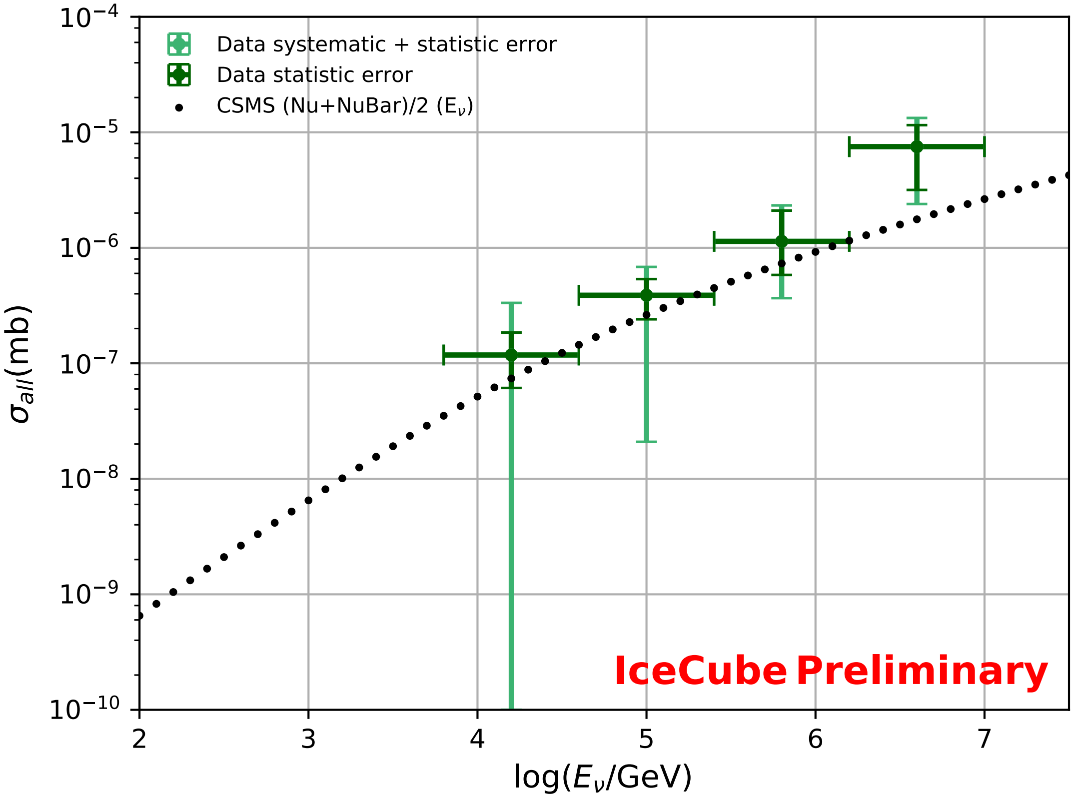
- Different ratios correspond to different cross sections. The light red band in the right plot shows the partial systematic uncertainty for this analysis.





Combined Uncertainty

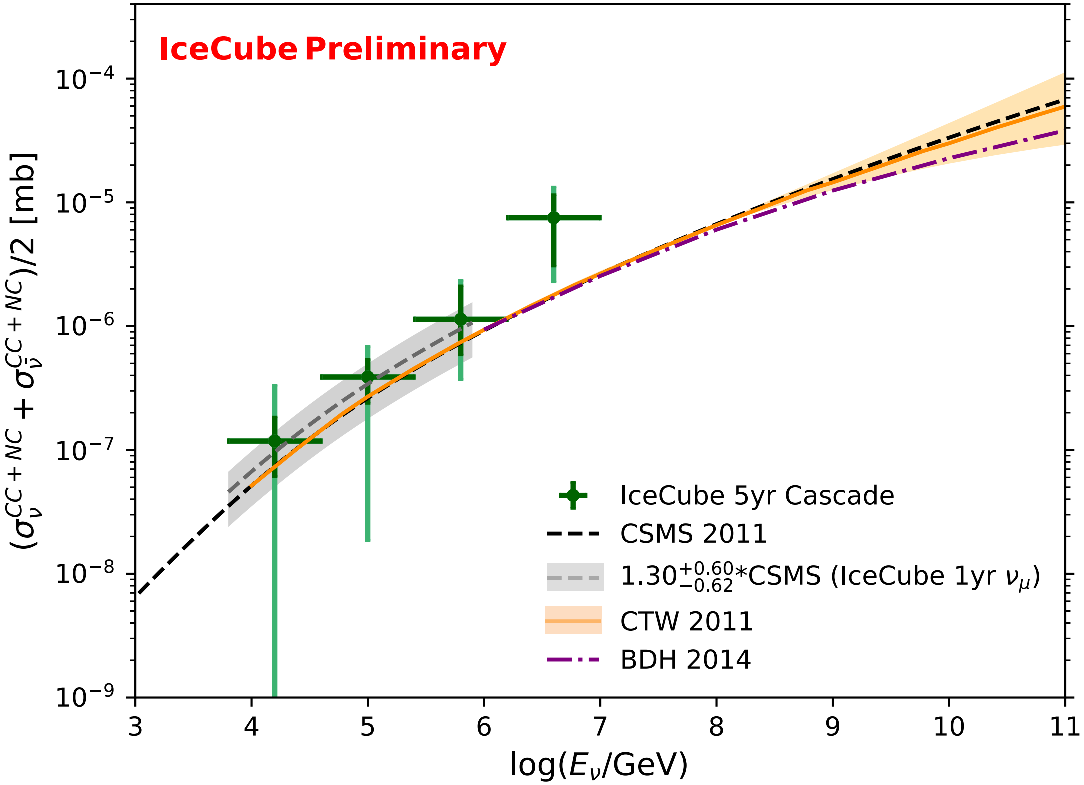
Neutrino energy dependence (in **6.3TeV-10PeV** range) of neutrino-nucleon cross section measurement result with statistic uncertainty and statistic + partial systematic uncertainty



Combined Uncertainty

Stony Brook University

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



CSMS: JHEP 08, 042 (2011)
CTW: Phys. Rev. D 83, 113009 (2011)
BDH: Phys. Rev. D 89, 094027 (2014)

Summary

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- 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

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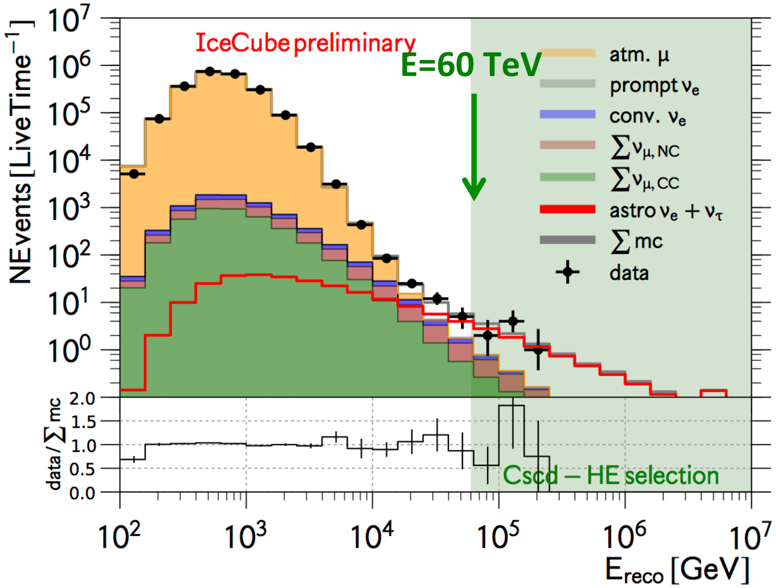
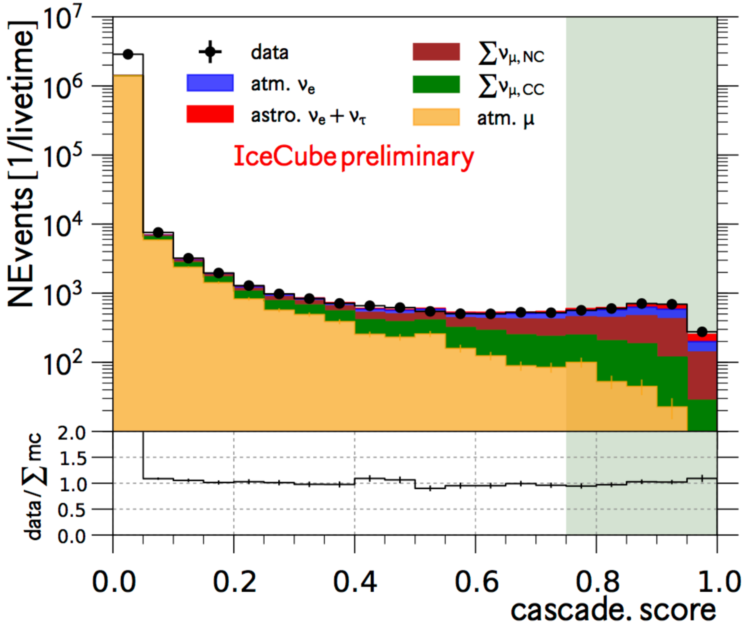


- Event sample was separated into two parts: low energy (<60TeV) and high energy (E>=60TeV)
- The high energy part applies straight cut on variables that have separation power in event topology.

- The low energy part applies gradient boosted multi-class decision trees to classify events in to three groups: cascade, starting track and track.



Statistical Uncertainty Estimation

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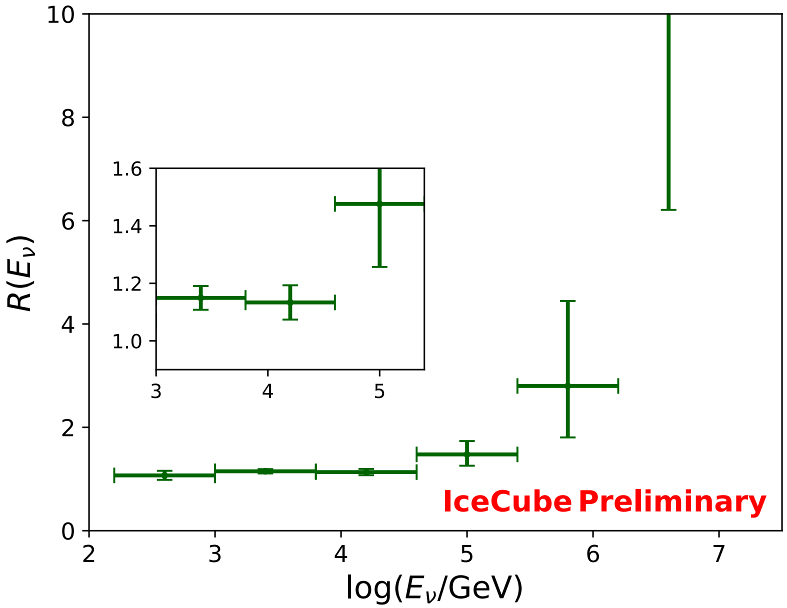
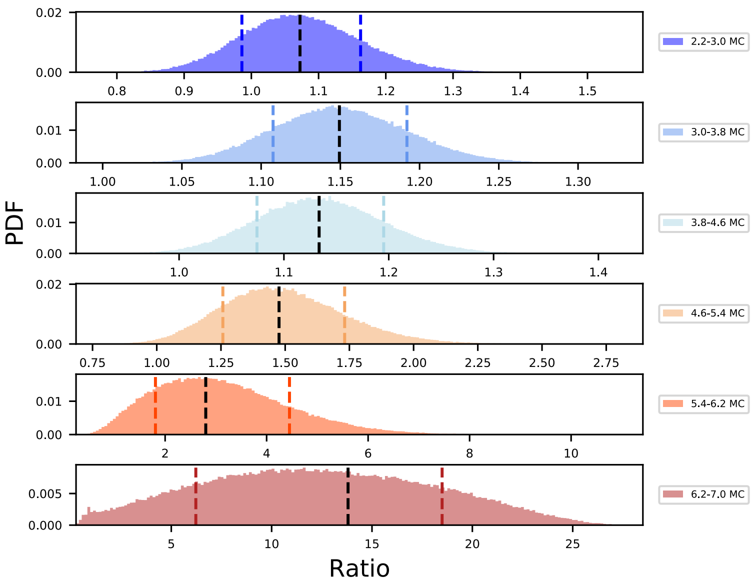
The unfolded ratio in neutrino energy bins for Data



The MCMC posterior distribution of unfolded ratio in neutrino energy bins for Data

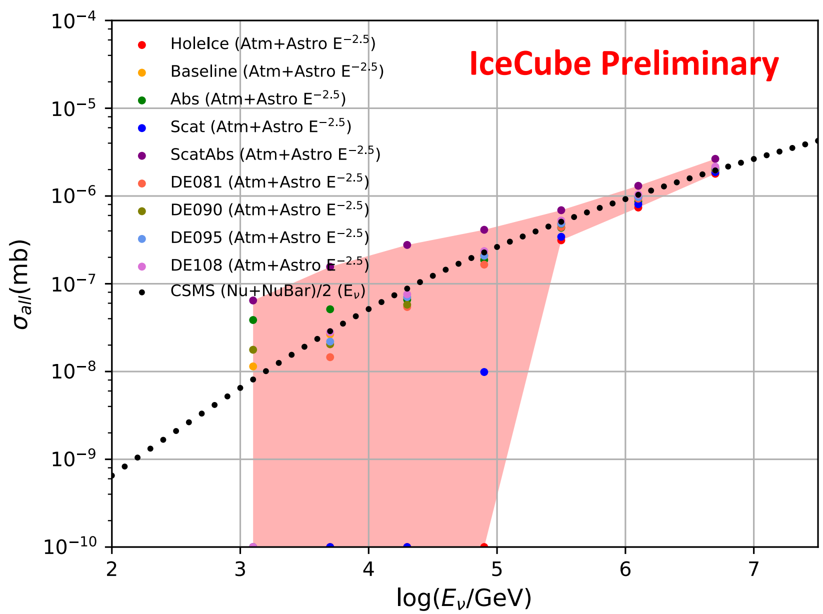
IceCube Preliminary



Systematic Study

Stony Brook University

- 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).



Expected Sensitivity

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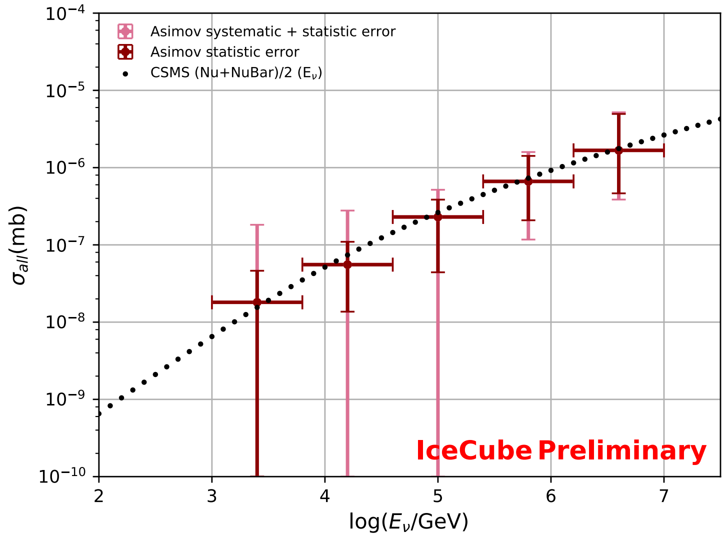
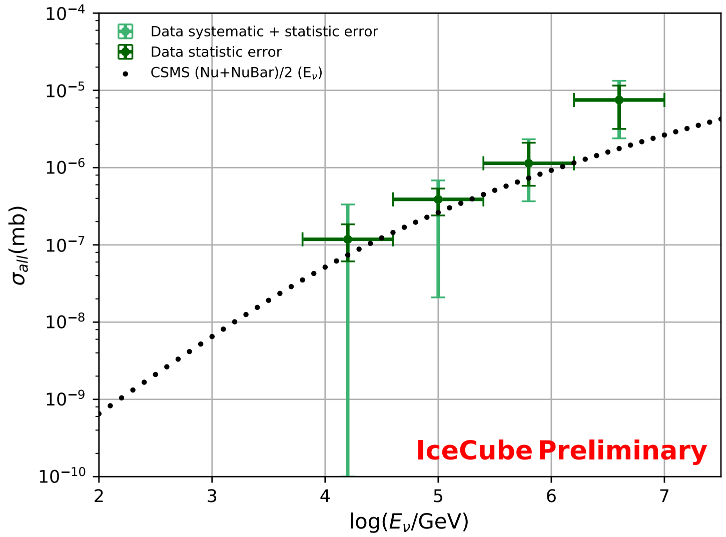
Combined systematic and statistic uncertainty assuming **5years' life time in Asimov study**



Combined systematic and statistic uncertainty for **2011-2015 data**



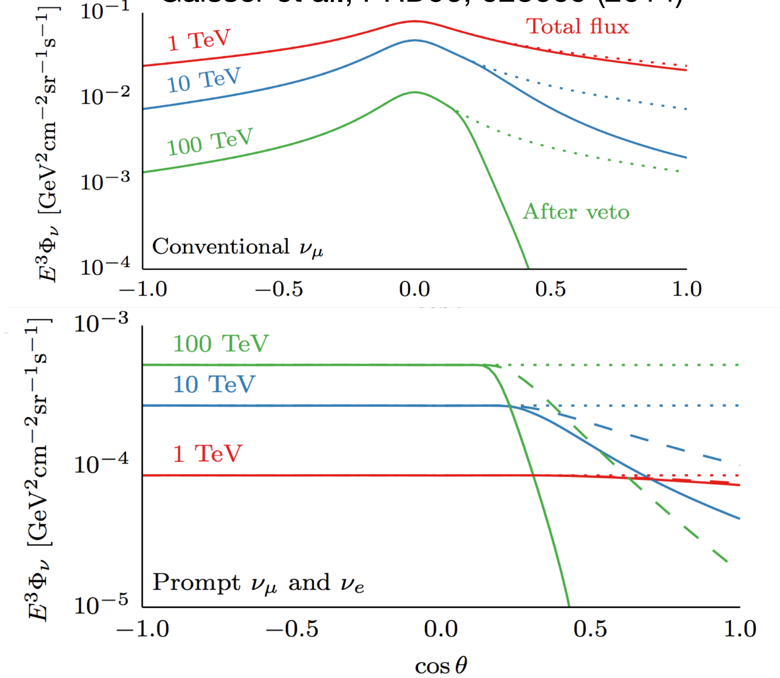
Self-Veto

- 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.

Gaisser et al., PRD90, 023009 (2014)



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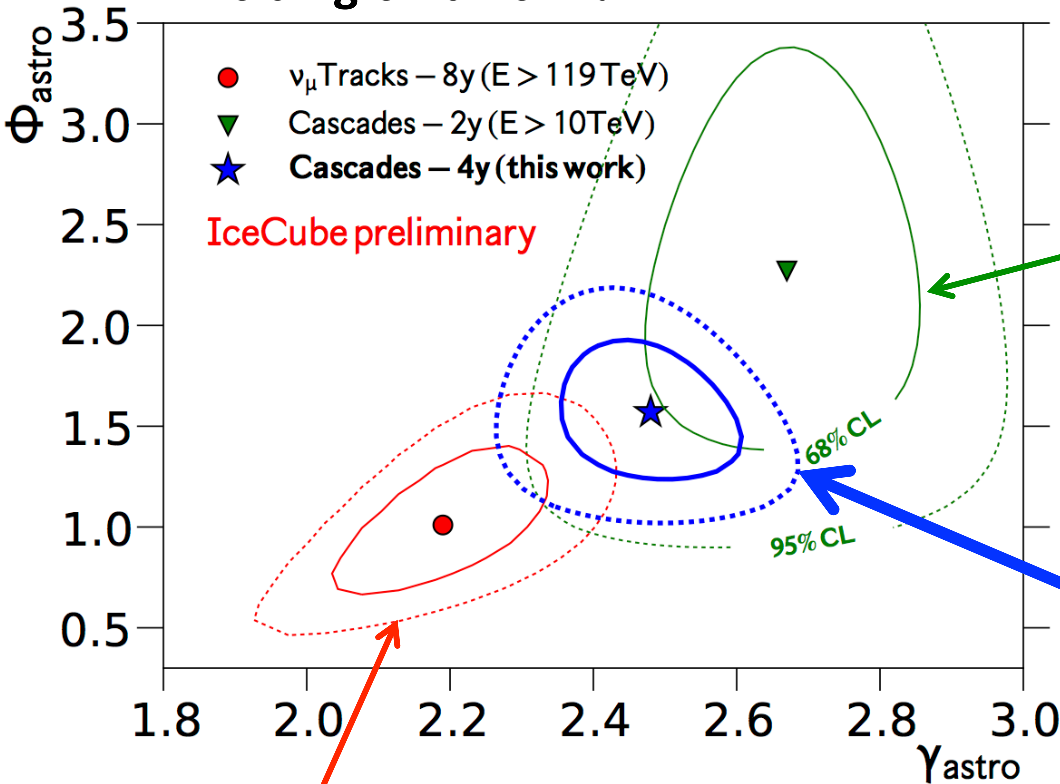
Astrophysical Neutrino Flux

ICECUBE

The Single Power-Law



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

E_{rec} > 10 TeV

this work
PoS(ICRC2017)968
$\nu_e + \nu_\tau$

significant energy range
12 TeV – 2.1 PeV

PoS(ICRC2017)1005
ν_μ Northern Sky

significant energy range
119 TeV – 4.8 PeV

poster NU022

- ✓ **consistent with previous cascade analysis**
- ✓ also still consistent with diffuse ν_μ (p=0.04)

Slide from H. Niederhausen presented in TeVPA 2017