Work in Progress

Atmospheric-Neutrino Flux-Integrated Differential Cross-Section Measurement in IceCube

IceCube Lab (ICL)
Sven Lidstrom, NSF

Shivesh Mandalia • 22.03.2016

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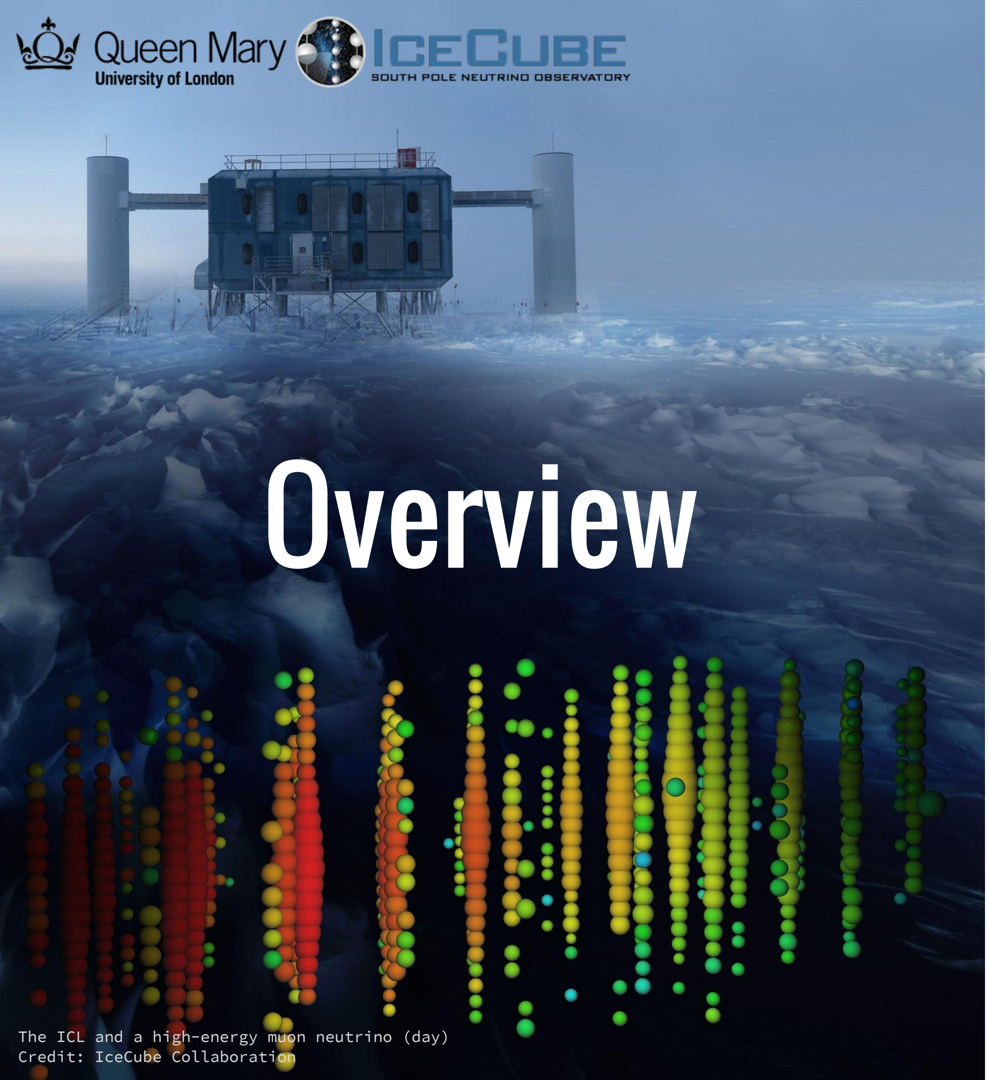
ICECUBE SOUTH POLE NEUTRINO OBSERVATORY



The ICL and a high-energy muon neutrino (day)
Credit: IceCube Collaboration

Overview

- Introduction
- The IceCube Experiment
- MC Sample
- Analysis
- Conclusion

Introduction

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Introduction

Standard Cross-section Measurements

- Modern neutrino experiments rely heavily on neutrino flux predictions, which have been historically difficult to define precisely

$$\text{rate} \sim \int \Phi \times \sigma \times \epsilon$$

- Hampers our ability to determine the cross-section from a measurement
- Common to model the neutrino flux, assuming a neutrino interaction cross-section model which leads to biases in the measurement

Many distributions

Divide by integrated flux

Flux-integrated
Differential
Cross-section

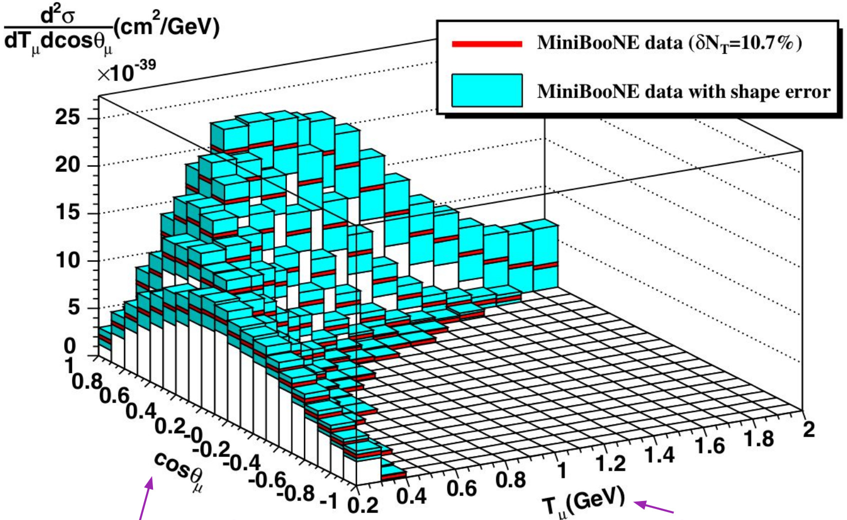
Introduction

No atmospheric based neutrino experiment has yet performed a differential cross-section measurement

Flux-integrated Differential Cross-section Measurement

- The cross-section has been normalised with an absolute predicted flux and has not been adjusted based on measured processes
- Multitude of cross-section distributions allow for the most stringent tests for a given physics mode
- Most model-independent measurement

MiniBooNE double-differential cross-section



cosine muon zenith

muon kinetic energy

PRD81(2010)092005
MiniBooNE collaboration

The IceCube Detector

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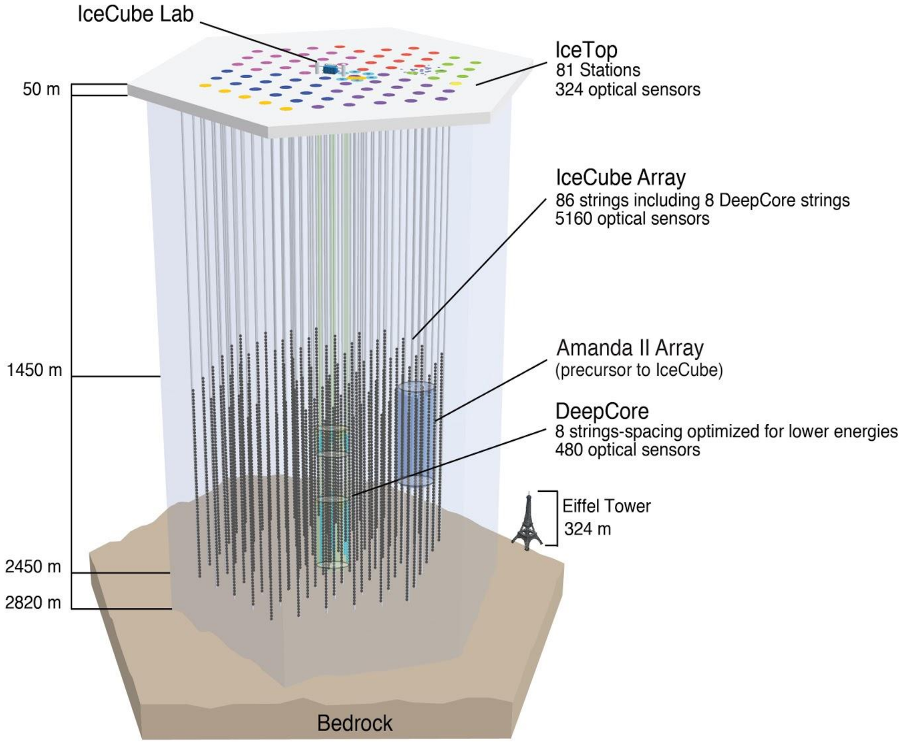
The IceCube Detector

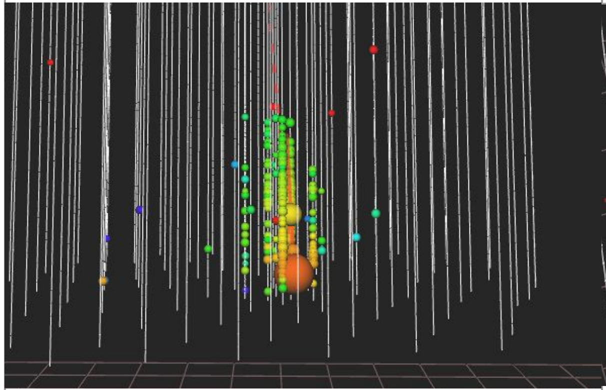
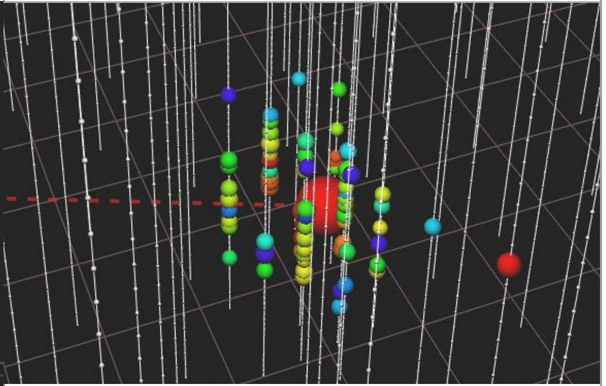
- Located at the South Pole
- 5160 Digital Optical Modules (DOMs) embedded in a cubic km of clear Antarctic ice
- DOMs contain PMTs which detect Cherenkov light
- Main Physics Goals
  - Detection of astrophysical neutrinos
  - Measure atmospheric neutrino oscillations (DeepCore)



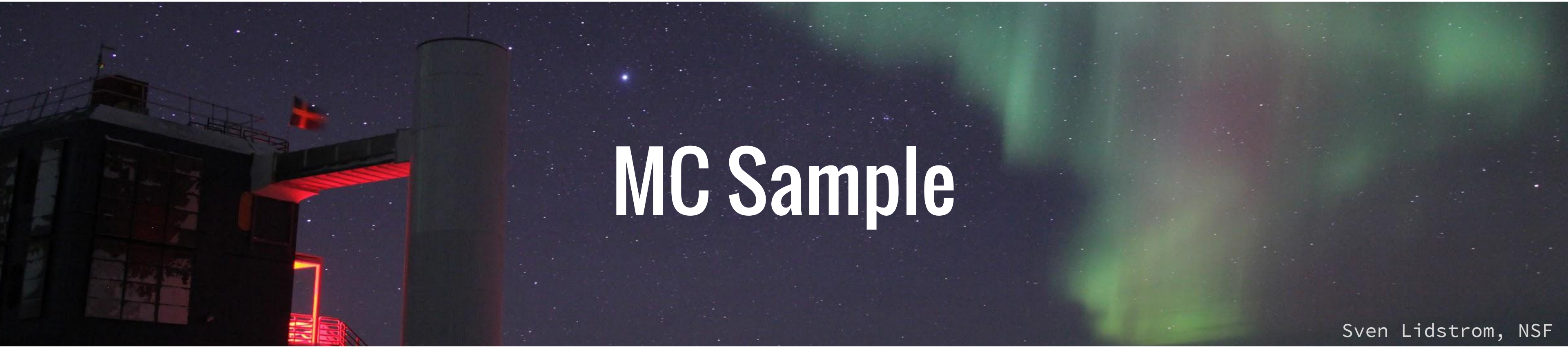
Atmospheric Neutrino Signal

IceCube triggers over 100,000 atmos. neutrino event per year - high statistics is ideal for a full 4π differential cross-section measurement

Event Signatures

CC Muon Neutrino	NC / CC Electron/Tau Neutrino
	
Track	Cascade

MC Sample



MC Sample

Using data sample optimised for a search for $\nu_\mu \rightarrow \nu_\tau$ appearance using the DeepCore inner detector

- Exposure = 3 years
- Multiple BDTs provide significant background rejection of muons
- Straight cuts focus on rejecting noise dominated triggers and muon backgrounds

Reconstruction used is based on the MultiNest algorithm

Atmospheric one-year-averaged neutrino flux at the South Pole (HAKKM, 2014)

Analysis

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Triple Differential Cross-section Formula

i,j,k = true index
α,β,γ = reconstructed index

$$\left(\frac{\mathrm{d}^3\sigma}{\mathrm{d}E\,\mathrm{d}\cos\theta\,\mathrm{d}\phi}\right)_{ijk} = \frac{\sum_{\alpha\beta\gamma} \mathrm{U}_{ijk\alpha\beta\gamma}\left(d_{\alpha\beta\gamma} - b_{\alpha\beta\gamma}\right)}{\epsilon_{ijk}\,(\Phi\ \mathrm{T})\,\Delta E_i \Delta\cos\theta_j \Delta\phi_k}$$

Unsmearing Matrix — $\mathrm{U}_{ijk\alpha\beta\gamma}$

Data vector — $d_{\alpha\beta\gamma}$

Background vector — $b_{\alpha\beta\gamma}$

Efficiency — ϵ_{ijk}

Flux integrated over time and E,$\cos\theta$,φ — Φ

Target number — T

Bin widths — $\Delta E_i \Delta\cos\theta_j \Delta\phi_k$

i,j,k = true index
α,β,γ = reconstructed index

$$\left(\frac{\mathrm{d}^3\sigma}{\mathrm{d}E\ \mathrm{d}\cos\theta\mathrm{d}\phi}\right)_{ijk} = \frac{\sum_{\alpha\beta\gamma} \mathrm{U}_{ijk\alpha\beta\gamma}\left(d_{\alpha\beta\gamma} - b_{\alpha\beta\gamma}\right)}{\epsilon_{ijk}\left(\Phi\ \mathrm{T}\right)\Delta E_i \Delta\cos\theta_j \Delta\phi_k}$$

Unsmearing Matrix

Efficiency

Flux integrated over time and E,cosθ,φ

Target number

Bin widths

Data vector

Background vector

Data

- **Reconstructed signal**
- **Signal Definition**
  - Muon ν, $\bar{\nu}$-H_2O CC induced muons
- **Predicted Background are cosmic rays**
  - Data consists of 20%−30% cosmic rays
  - For now just using MC sample, so only considering pure signal

Binning:

- Energy
  - 10 bins
  - log [1, $10^{2.5}$] GeV
- Cos(zenith)
  - 10 bins
  - linear [−1, 1]
- Azimuth
  - 4 bins
  - linear [0, 360]°

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Reconstructed muon energy spectrum for cosθ - [0.00 - 0.20]

i,j,k = true index
α,β,γ = reconstructe

Data

➔ Reco

➔ Signa

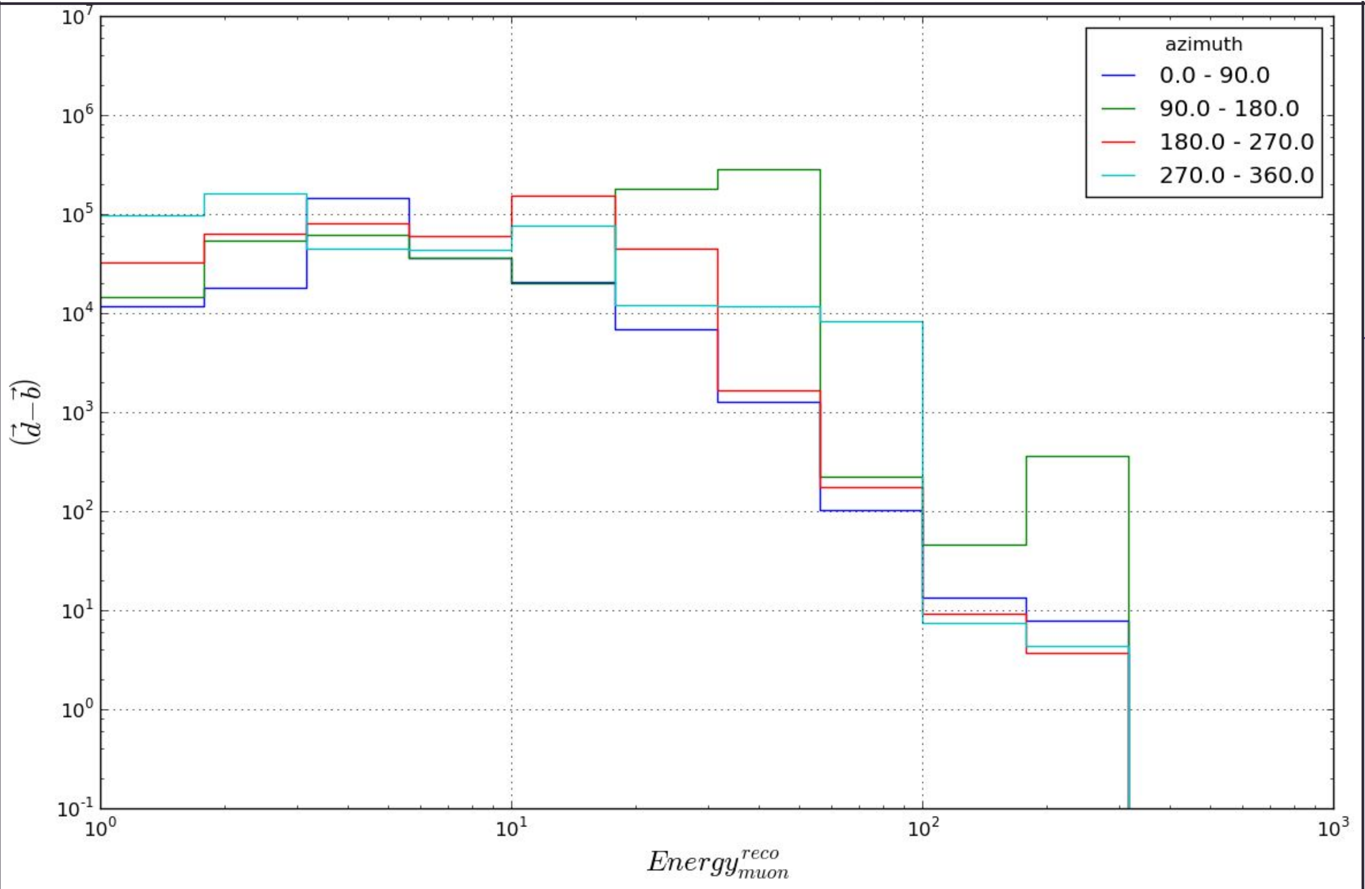
◆

➔ Predi

◆

◆

GeV



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i,j,k = true index
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$$\left(\frac{\mathrm{d}^3\sigma}{\mathrm{d}E\,\mathrm{d}\cos\theta\mathrm{d}\phi}\right)_{ijk} = \frac{\sum_{\alpha\beta\gamma} \mathrm{U}_{ijk\alpha\beta\gamma}\left(d_{\alpha\beta\gamma} - b_{\alpha\beta\gamma}\right)}{\epsilon_{ijk}\,(\Phi\;\mathrm{T})\,\Delta E_i \Delta\cos\theta_j \Delta\phi_k}$$

Data vector

Background vector

Unsmearing matrix

Efficiency

Bin widths

Target number

Flux integrated over time and E,cosθ,φ

Unfolding

➔ **Unsmearing matrix**

- Corrects for the ‘smearing’ of the data due to detection related effects and biases from event selection
- Quantifies the probability for an event in truth bin *ijk* to be reconstructed to bin *α,ß,γ*

➔ **Efficiency**

- Accounts for events lost due to selection cuts

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Unsmearing Matrix

400 bins

Bayesian Unsmearing allows for unfolding in all three dimensions with full correlations

$$\mathrm{P}\left(t_i \mid r_j\right) = \frac{\mathrm{P}\left(r_j \mid t_i\right)\ \mathrm{P}\left(t_i\right)}{\sum_k \mathrm{P}\left(r_j \mid t_k\right) \mathrm{P}\left(t_k\right)}$$

Truth bin

Reco bin

P (event has migrated **from** true bin t_i **to** recon bin r_j)

P (true bin t_i)

P (event has migrated **to** true bin t_i **from** recon bin r_j)

Normalisation

D'Agostini
Nucl.Instrum.Meth. A362 (1995) 487-498

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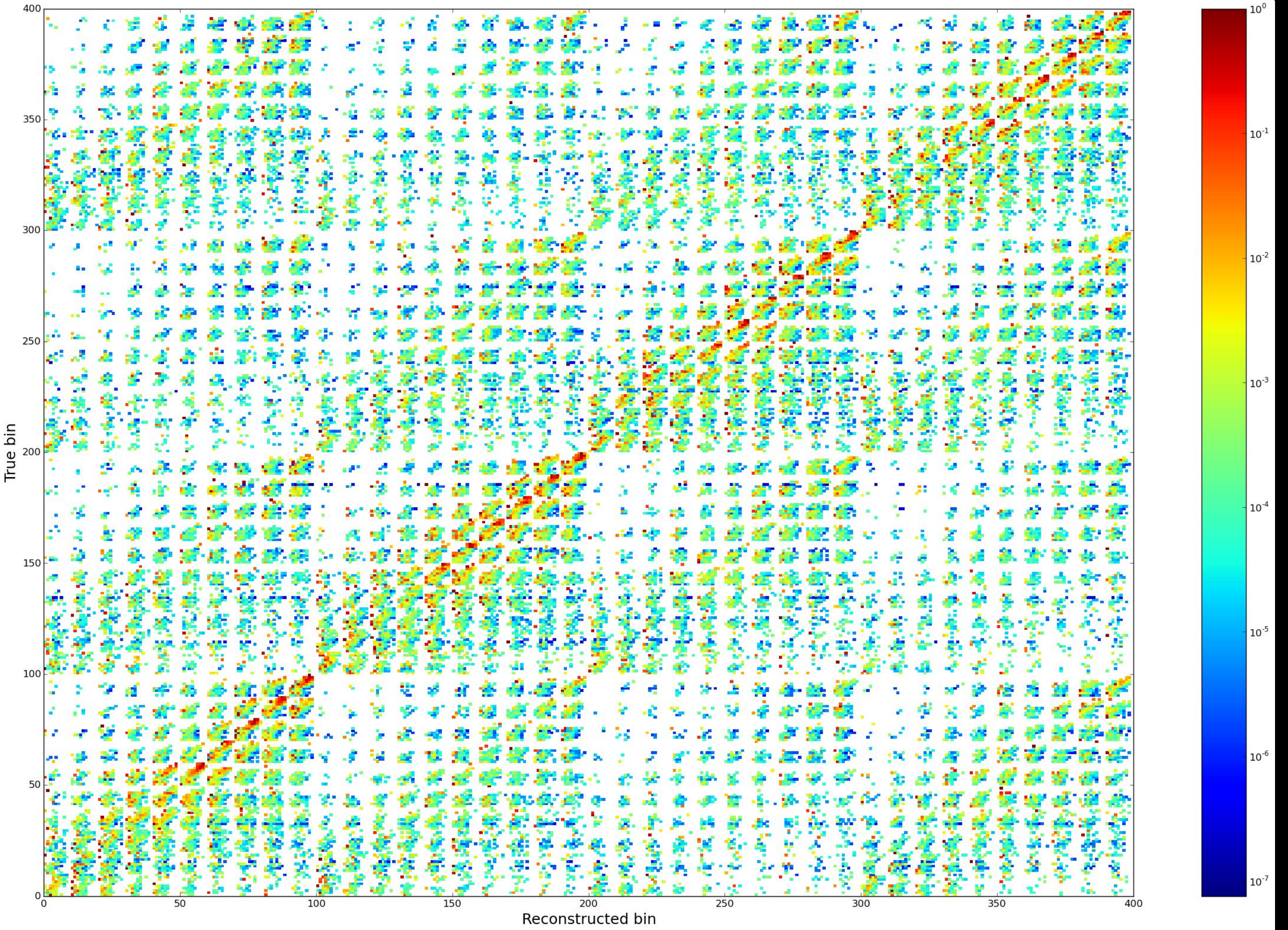
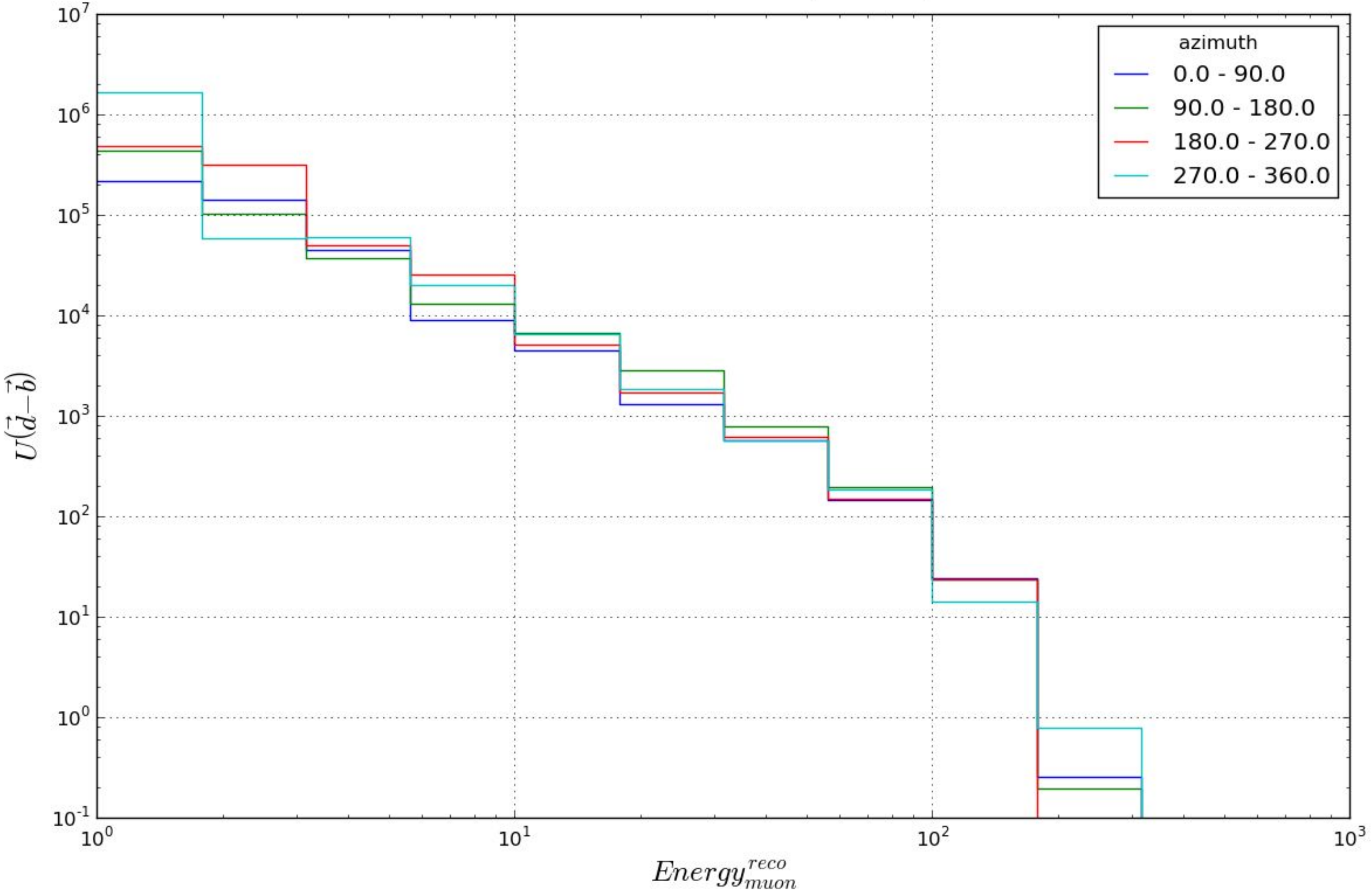
Unsmearing Matrix



Unsmeared reconstructed muon energy spectrum for cosθ - [0.00 - 0.20]



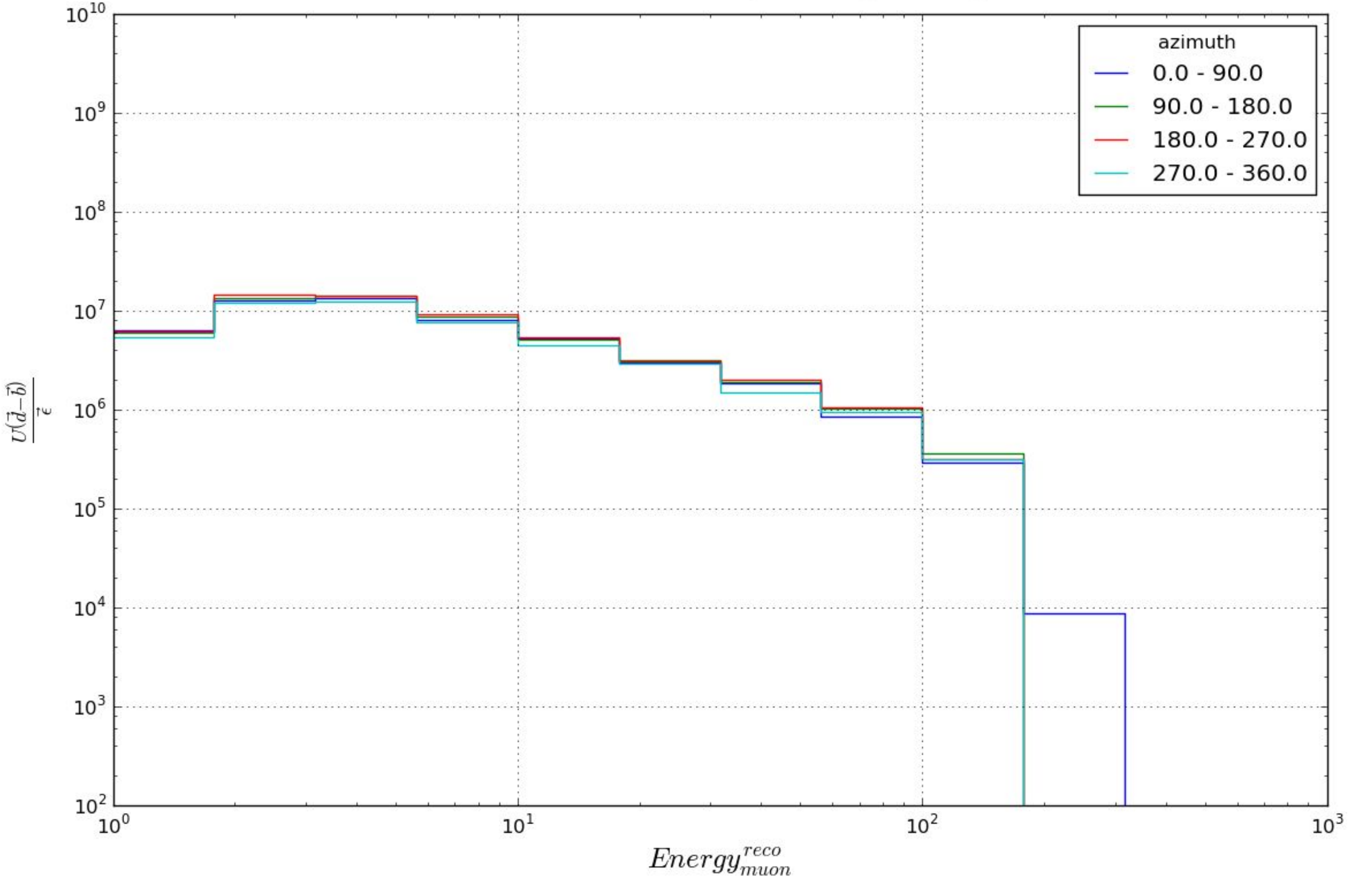
Efficiency

$$\epsilon_{ijk} = \frac{N_{ijk}^{\text{after}}}{N_{ijk}^{\text{before}}}$$

- Measure by comparing to generated GENIE MC events with correct normalisation
  - Normalisation found by comparing GENIE number of events with Honda Flux times the cross section of the spline which was input into GENIE to generate the events
- Normalised using
  - Target Number = 4.183×10^{37} water molecules
  - Exposure = 3 years

Efficie

Unsmeared reconstructed muon energy spectrum with **efficiency correction** for
cosθ - [0.00 - 0.20]



- Meas ... on
  - ... lux times ... events
- Norm
  -
  -

i,j,k = true index
α,β,γ = reconstructed index

Unsmearing Matrix | Data vector | Background vector

$$\left(\frac{\mathrm{d}^3\sigma}{\mathrm{d}E\,\mathrm{dcos}\theta\mathrm{d}\phi}\right)_{ijk} = \frac{\sum_{\alpha\beta\gamma} \mathrm{U}_{ijk\alpha\beta\gamma}\left(d_{\alpha\beta\gamma} - b_{\alpha\beta\gamma}\right)}{\epsilon_{ijk}\,(\Phi\,\mathrm{T})\,\Delta E_i \Delta\mathrm{cos}\theta_j \Delta\phi_k}$$

Efficiency

Bin Widths

Target Number

Flux integrated over time and E,cosθ,φ

Flux + Factors

- **Bin Width**
- **Flux integrated over time and energy, cosθ, φ**
  - Exposure = 3 years
- **Target Number = 4.183 x 10^{37} water molecules**
  - Cylinder with R = 600 m, L = 1200m
  - Ice density = 0.922 M g m^{-3}
  - Molar mass of water = 18.01528 g mol^{-1}

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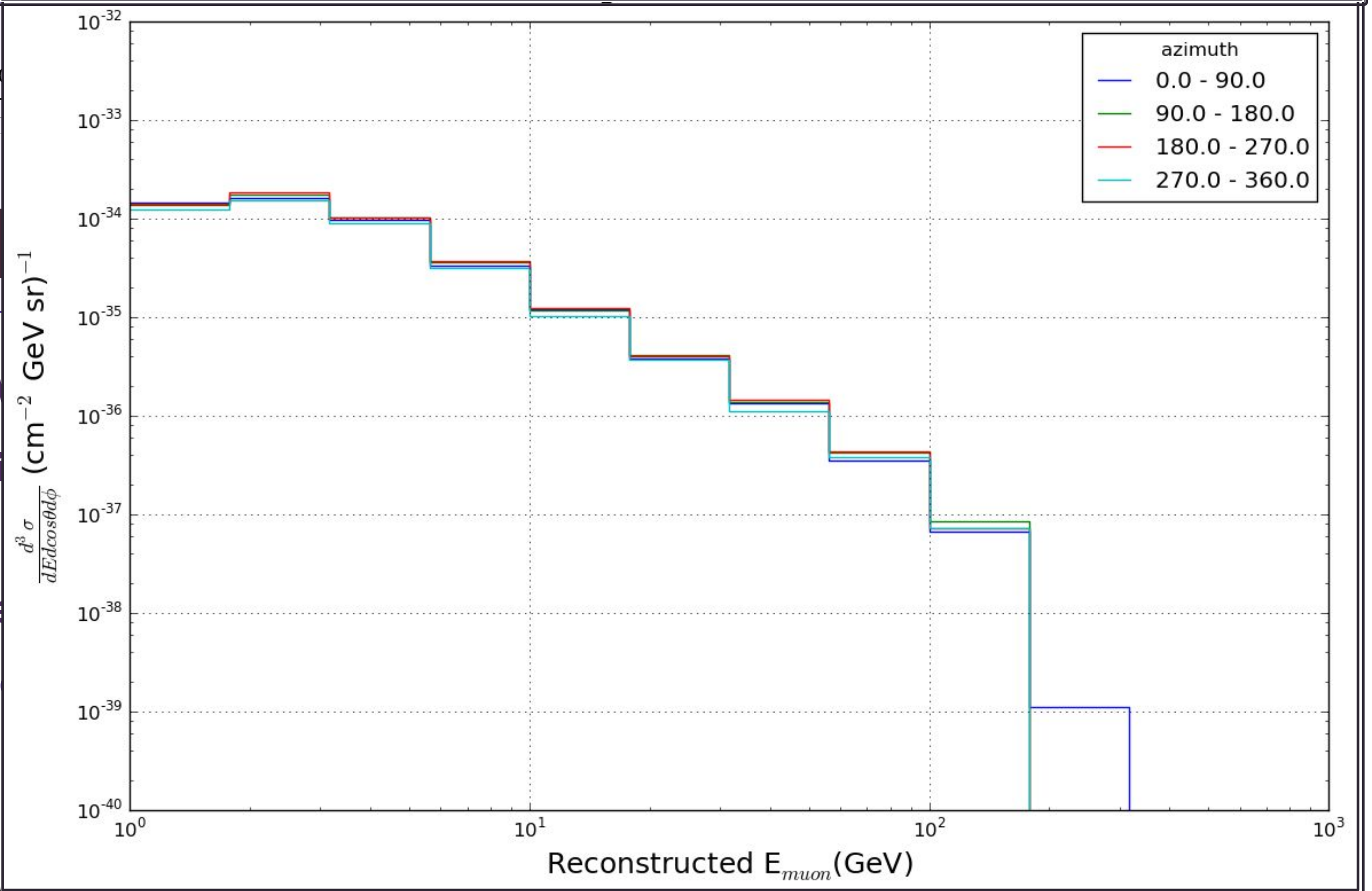
i,j,k = true index
α,β,γ = reconstruct

Flux +

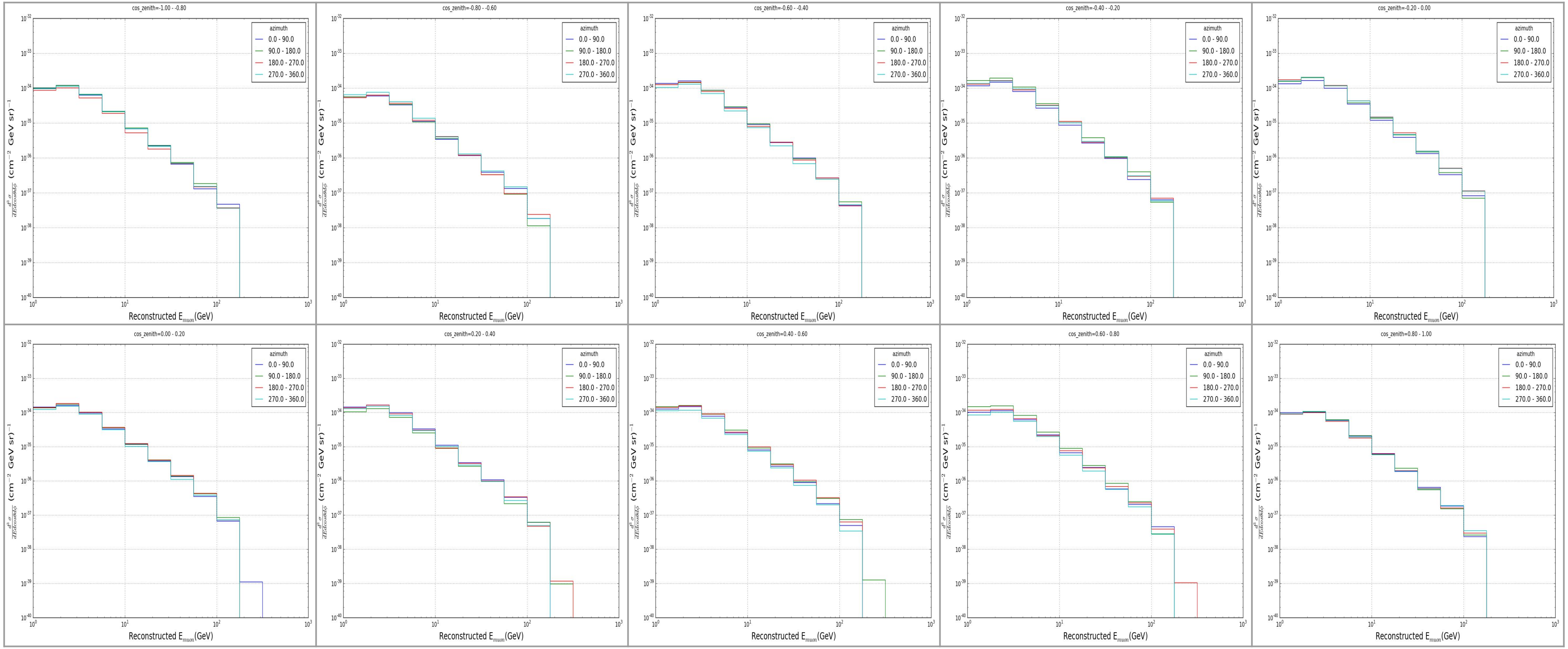
Flux-Integrated Triple-Differential Cross-section for cosθ – [0.00 – 0.20]



- Bin W
- Flux
- Targ

Work in Progress

Work in Progress



Results

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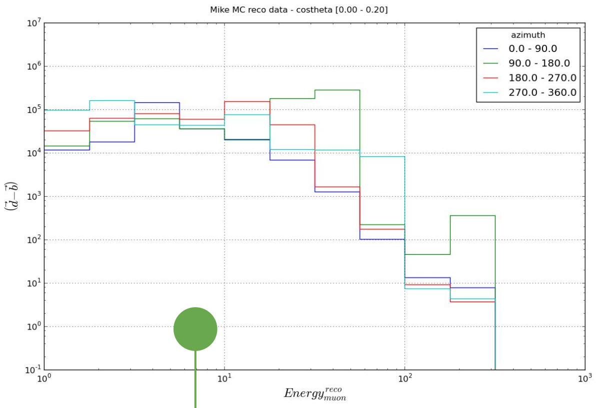
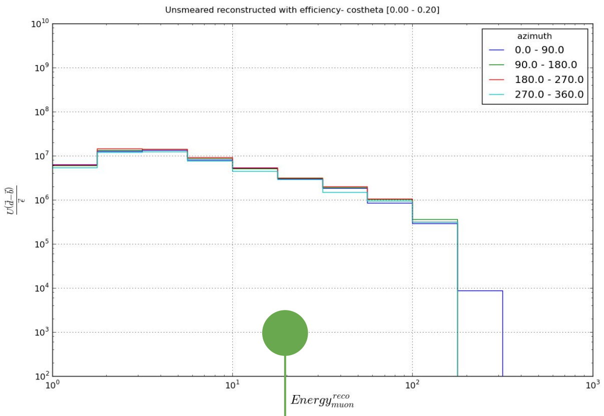
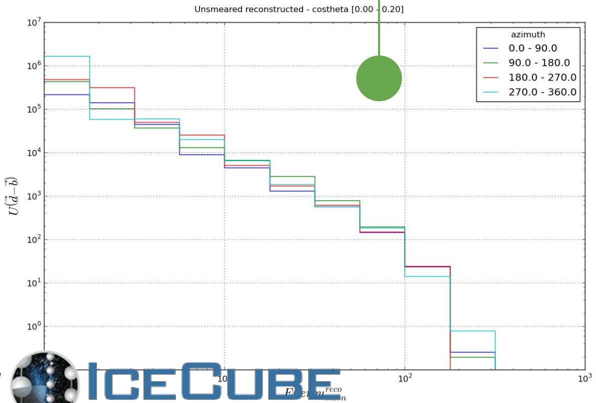
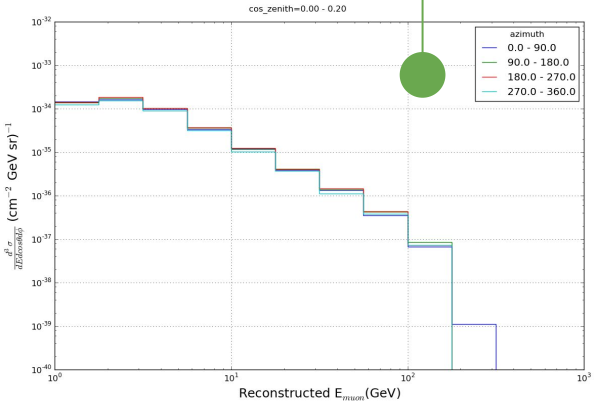




$$\vec{d}-\vec{b} \;\rightarrow\; \mathbf{U}\left(\vec{d}-\vec{b}\right) \;\rightarrow\; \frac{\mathbf{U}\left(\vec{d}-\vec{b}\right)}{\vec{\epsilon}} \;\rightarrow\; \frac{\mathrm{d}^3\sigma}{\mathrm{d}E\,\mathrm{d}\cos\theta\,\mathrm{d}\phi}$$





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Conclusion

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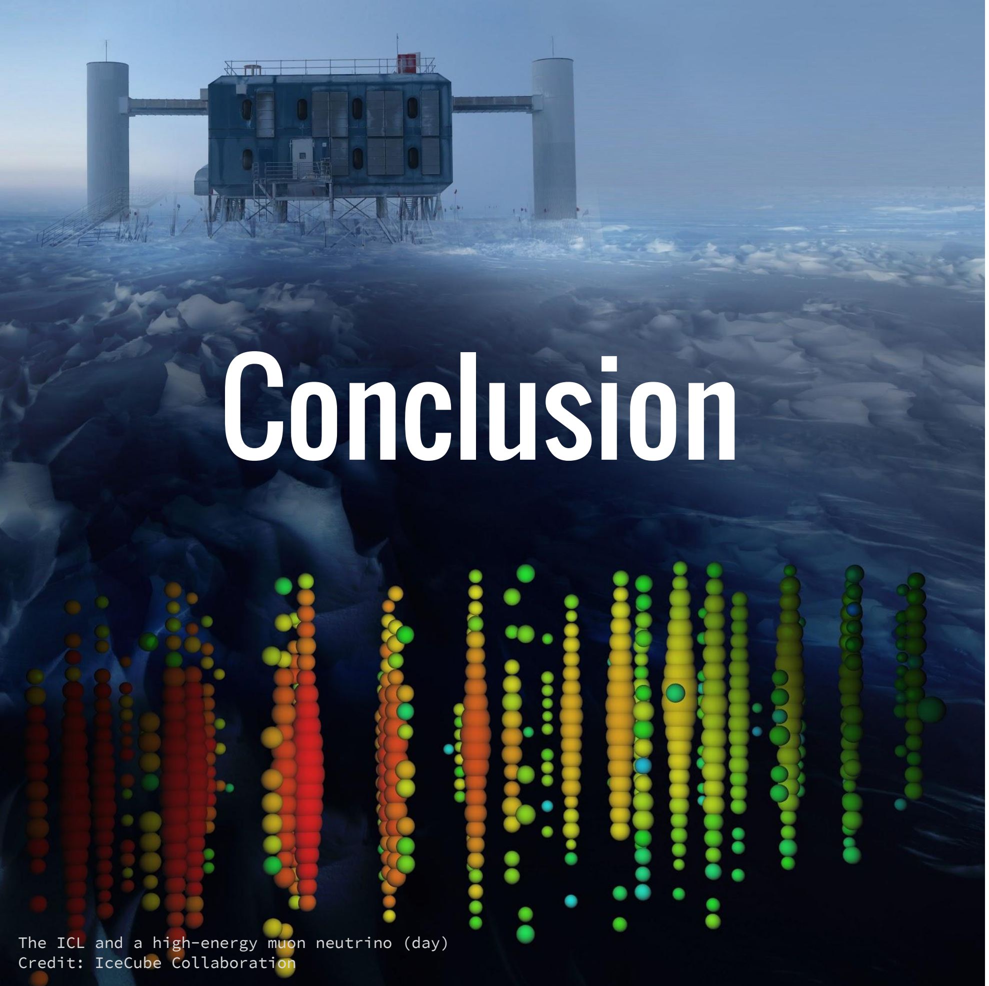
Conclusion



The ICL and a high-energy muon neutrino (day)
Credit: IceCube Collaboration

- **Next steps are to use fake data**
  - Background subtraction
  - Statistical + systematic uncertainties

Flux-integrated Triple-Differential Cross-section is the least model-dependent data!

Backup

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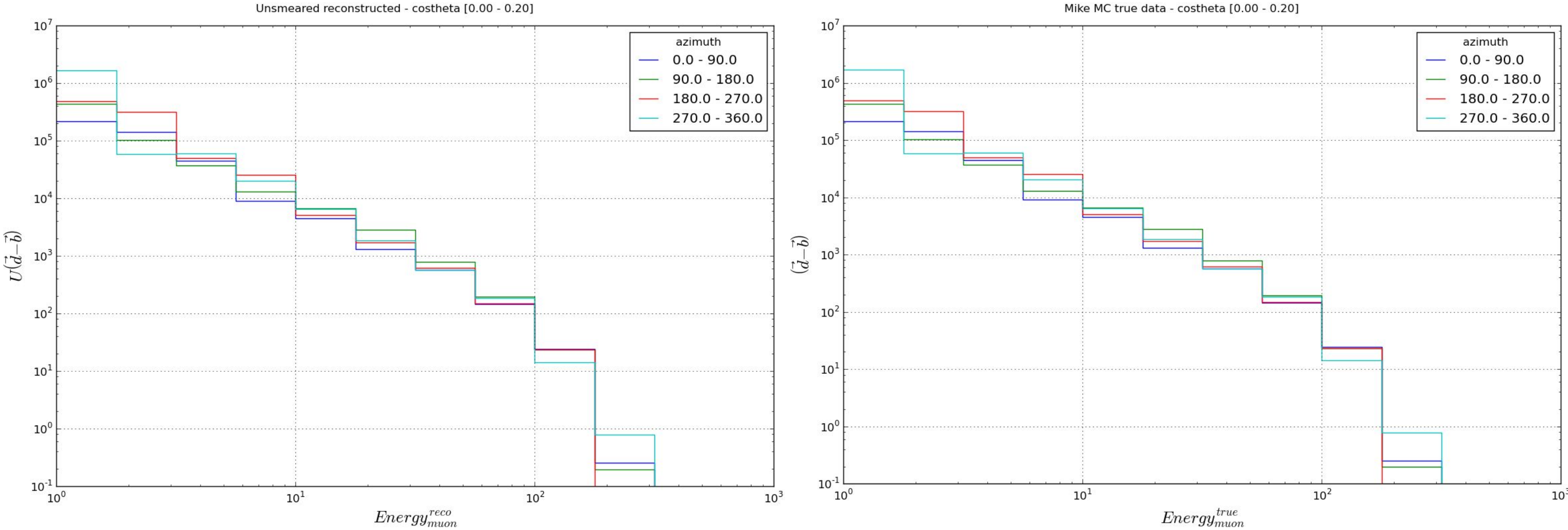
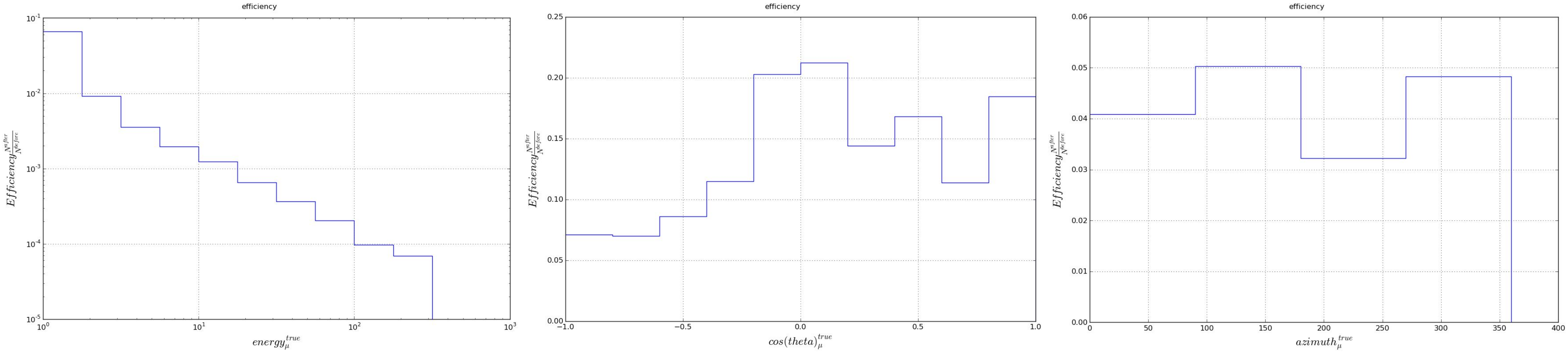
IceCube South Pole Neutrino Observatory


Unsmeared reconstructed - costheta [0.00 - 0.20]
Mike MC true data - costheta [0.00 - 0.20]
azimuth
0.0 - 90.0
90.0 - 180.0
180.0 - 270.0
270.0 - 360.0
$U(\vec{d}-\vec{b})$
$(\vec{d}-\vec{b})$
$Energy_{muon}^{reco}$
$Energy_{muon}^{true}$


efficiency
efficiency
efficiency
$Efficiency \frac{N^{after}}{N^{before}}$
$energy_{\mu}^{true}$
$cos(theta)_{\mu}^{true}$
$azimuth_{\mu}^{true}$

MC Sample

- ➔ Volume = cylinder with R=600m and H=1200m
- ➔ Data
    - Two BDTs provide significant background rejection of muons and straight cuts focus on rejecting noise-dominated triggers. At final level, the sample includes both upgoing and downgoing events with roughly 26% of the rate consisting of atmospheric muons and 1% noise triggers.
- ➔ Level 4
    - BDT trained to reduce atmospheric background
- ➔ Level 5
    - A second BDT is trained at L5 to further reduce the atmospheric muon background by a factor of 10x.
- ➔ Level 6
    - Dedicated to muon and noise trigger removal