Measurement of the inelasticity distribution of neutrino-nucleon interactions for 100 GeV < E_ν < 1 TeV with IceCube DeepCore

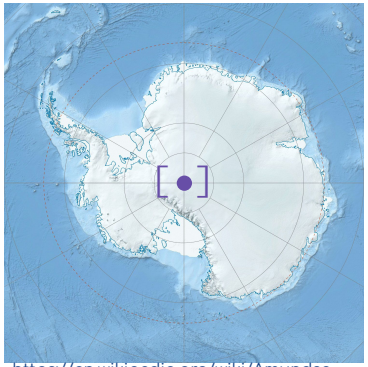
Maria Liubarska

for the IceCube Collaboration

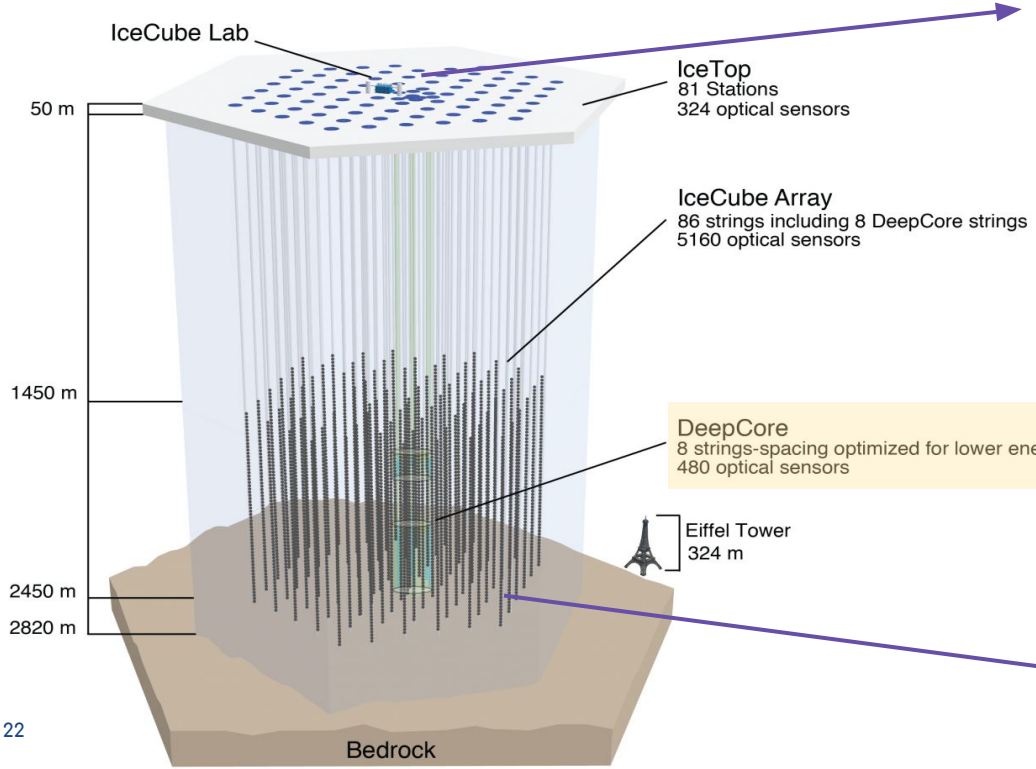
August 25

NuFACT 2023

IceCube Neutrino Observatory



https://en.wikipedia.org/wiki/Amundsen%E2%80%93Scott_South_Pole_Station



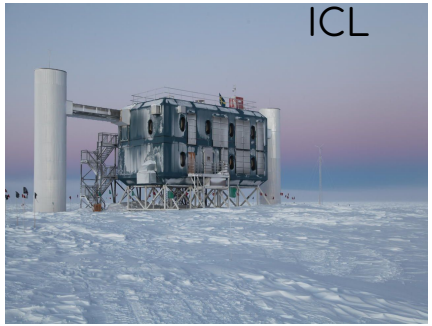


photo credit: Sven Lidstrom

IceCube DOM

NuFACT23 IceCube talks and posters:

1. Maria Prado Rodriguez, Aug. 22
2. Alfonso Garcia, Aug. 23
3. Minjin Jeong, Aug. 23 (poster session)
4. Seowon Choi, Aug. 25

Inelasticity

★ Inelasticity is a fraction of neutrino energy transferred to the hadronic system in an inelastic neutrino-nucleon interaction

$$y = \frac{E_{hadr}}{E_\nu}$$

★ Inelastic scattering cross sections depend on inelasticity

✧ DIS cross section:

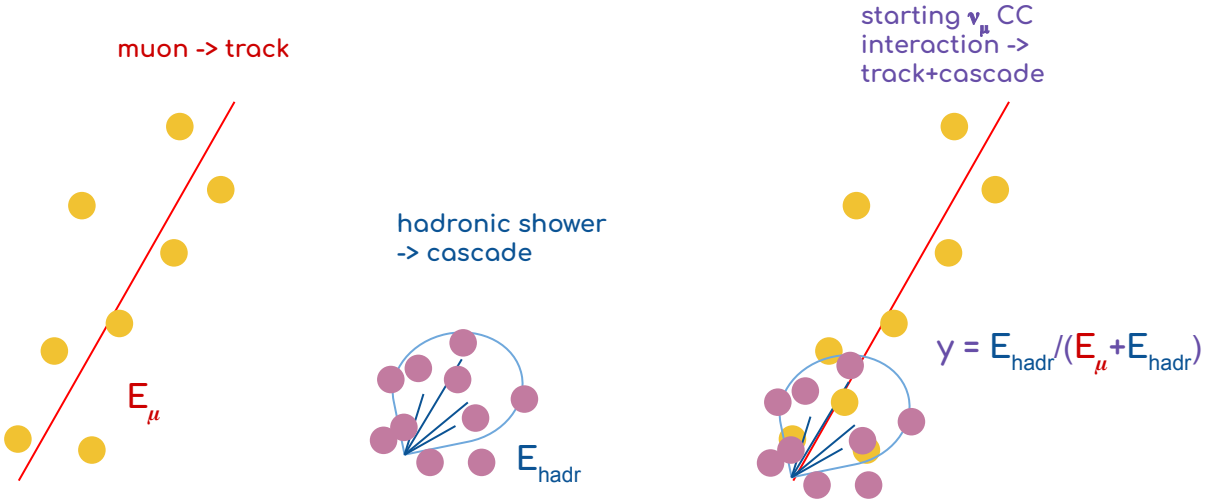
$$\frac{d^2\sigma_{CC}^{\nu N}}{dx\,dy} = 2x\sigma_0 \left(\sum_{d,s} f_q^N(x) + (1-y)^2 \sum_{\bar{u},\bar{c}} f_{\bar{q}}^N(x) \right)$$

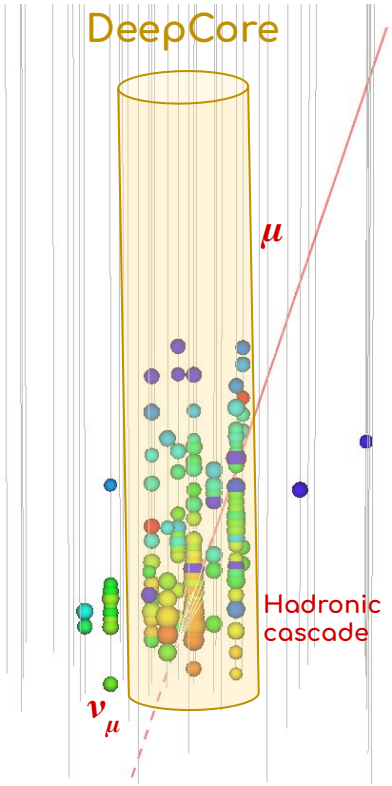
★ In IceCube, inelasticity can be reliably reconstructed for ν_μ CC events

Inelasticity reco in IceCube

[1] *IceCube Collaboration*, R. Abbasi et al., "Low energy event reconstruction in IceCube DeepCore"

- ★ ν_μ CC interactions starting inside DeepCore result in track+cascade signature
- ★ Using likelihood reconstruction algorithm [1] to recover muon and hadronic shower energies



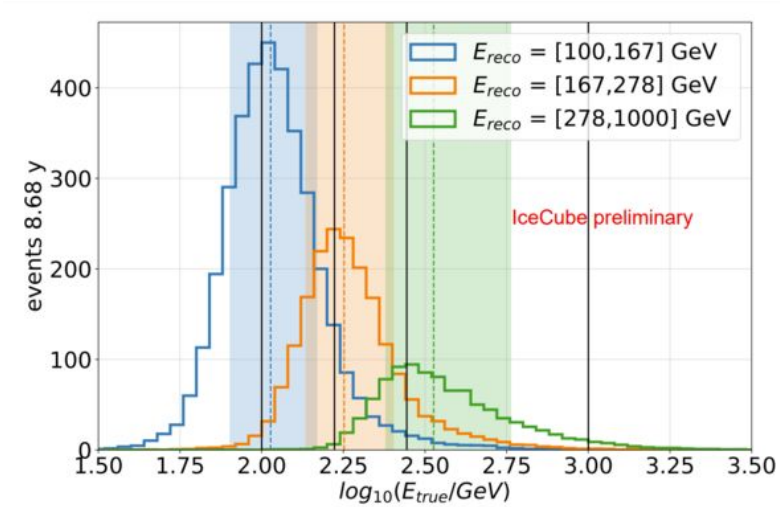


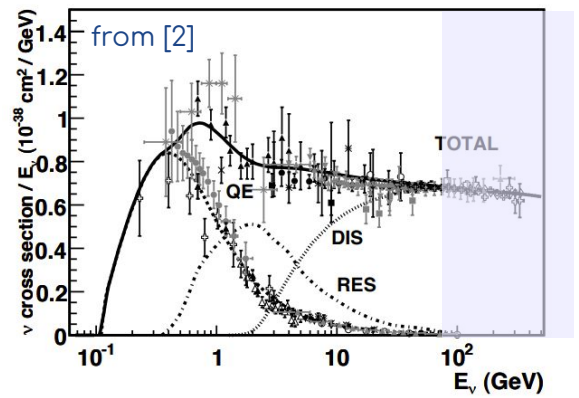
* colors show relative DOM hit time

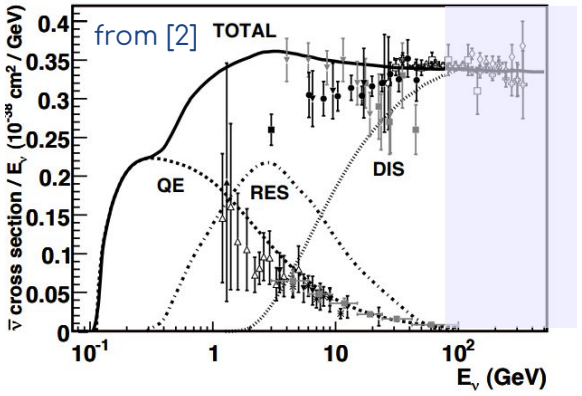
Energy range of interest

[2] J.A. Formaggio, G.P. Zeller, "From eV to EeV: Neutrino Cross Sections Across Energy Scales"

- ★ Using DeepCore data with reconstructed neutrino energy from 100 GeV to 1 TeV energy range
- ★ Measurement in 3 energy bins



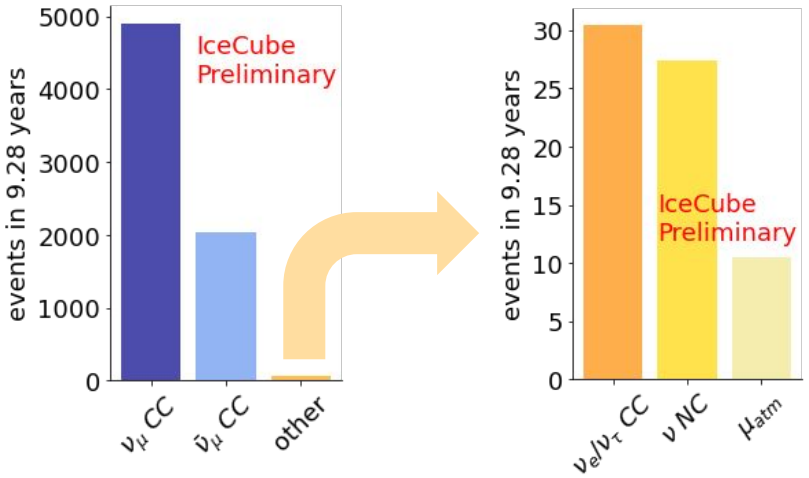


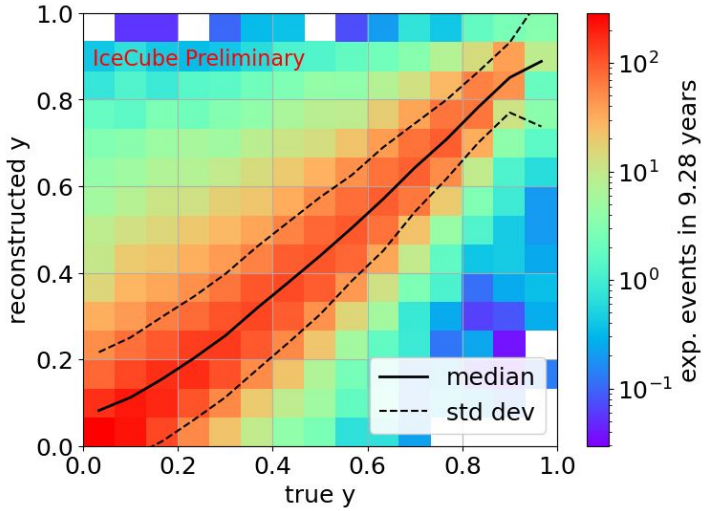


Event sample

★ 7268 events from 9.28 years of IceCube data

- ✧ Well reconstructed ν_μ CC events starting inside DeepCore
- ✧ 99% pure ν_μ CC sample
- ✧ ~10% resolution for inelasticity reconstruction in our sample





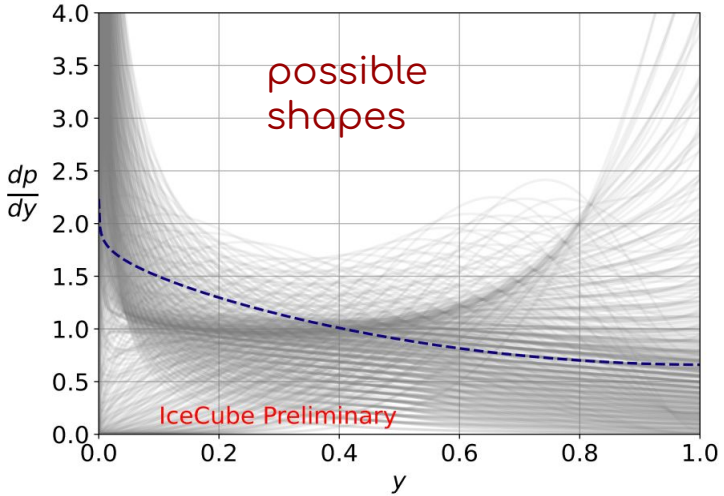
Analysis method

[3] *IceCube Collaboration*, M.G. Aartsen et al., "Measurements using the inelasticity distribution of multi-TeV neutrino interactions in IceCube"

★ Using approximate parametrization [3] for Inclusive inelasticity distribution with two independent parameters, **<y>** and **$\log_{10}\lambda$**

$$\frac{dp}{dy}(\langle y\rangle, \lambda) \equiv \frac{1}{\sigma}\frac{d\sigma}{dy}(\langle y\rangle, \lambda) =$$

$$= N(\langle y\rangle, \lambda) \cdot (1 + \epsilon(\langle y\rangle, \lambda) \cdot (1-y)^2) \cdot y^{\lambda-1}$$



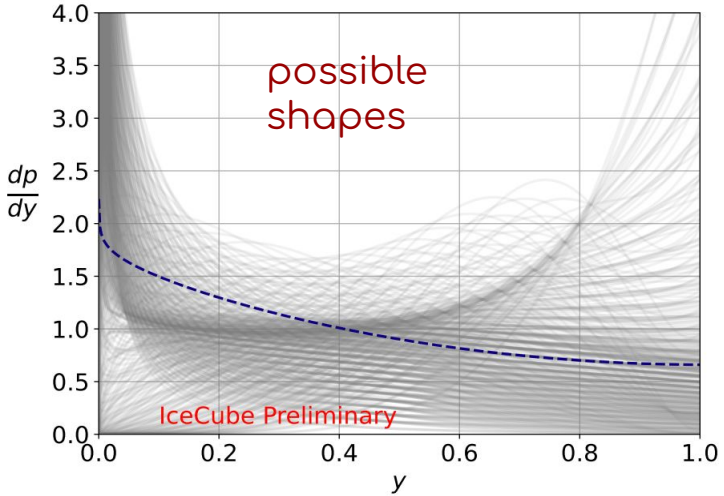
Analysis method

[3] *IceCube Collaboration*, M.G. Aartsen et al., "Measurements using the inelasticity distribution of multi-TeV neutrino interactions in IceCube"

★ Using approximate parametrization [3] for Inclusive inelasticity distribution with two independent parameters, **<y>** and **$\log_{10}\lambda$**

$$\frac{dp}{dy}(\langle y\rangle, \lambda) \equiv \frac{1}{\sigma}\frac{d\sigma}{dy}(\langle y\rangle, \lambda) =$$

$$= N(\langle y\rangle, \lambda) \cdot (1 + \epsilon(\langle y\rangle, \lambda) \cdot (1-y)^2) \cdot y^{\lambda-1}$$



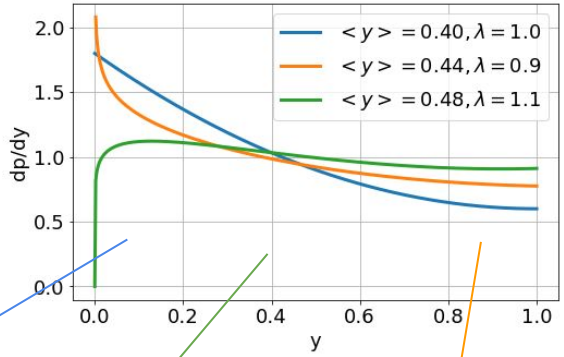
★ Measuring shape of **flux-averaged inelasticity distribution**

$$\frac{dp}{dy}_{fl.\,av.}(E) = \tilde{\Phi}_{\nu}(\Phi, \sigma, sel.; E) \cdot \frac{dp}{dy}_{\nu}(E) + \tilde{\Phi}_{\bar{\nu}}(\Phi, \sigma, sel.; E) \cdot \frac{dp}{dy}_{\bar{\nu}}(E)$$

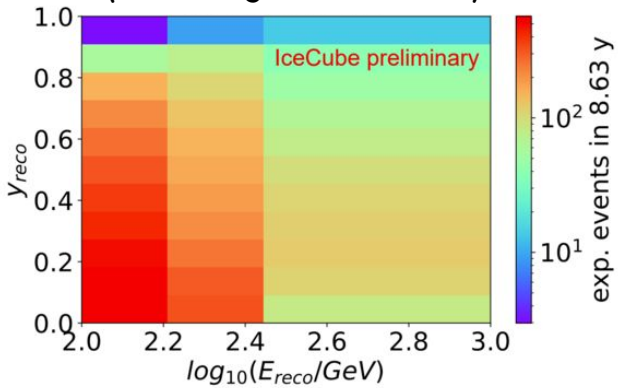
detected flux

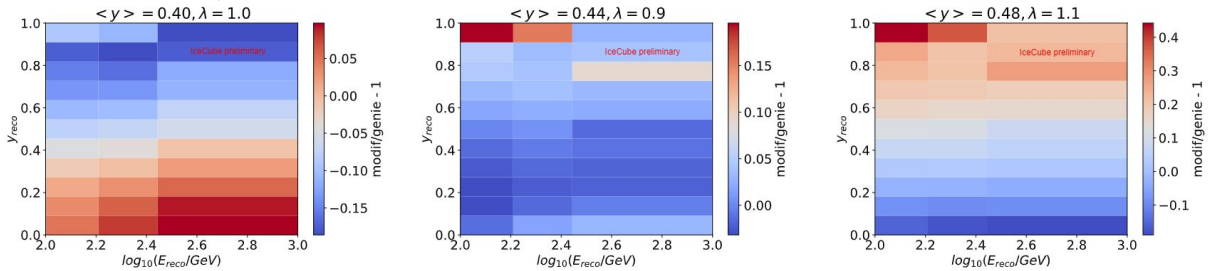
Analysis method

- ★ Forward folding method
- ★ Fitting shape of inelasticity distribution in 3 energy bins simultaneously
- ★ Systematic parameters are shared for all 3 bins and are fitted at the same time



Analysis template
(assuming GENIE model)





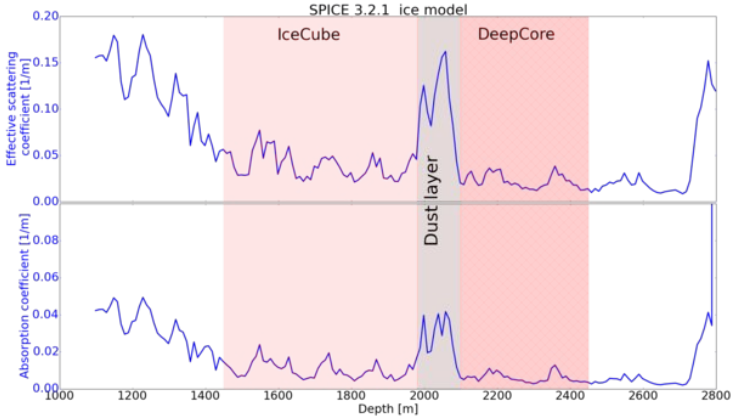
Modifications to the template from injecting different shapes

Systematic uncertainties

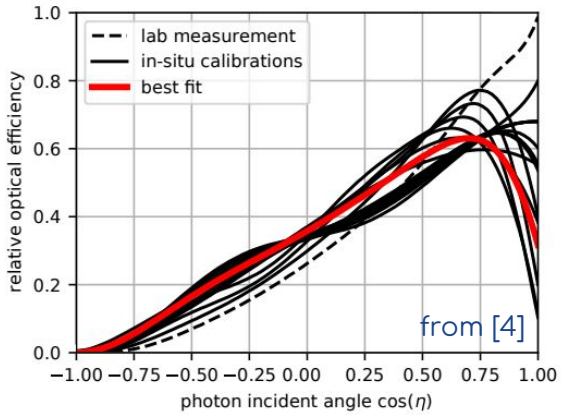
[4] *IceCube Collaboration*, R. Abbasi et al., "Measurement of atmospheric neutrino mixing with improved IceCube DeepCore calibration and data processing"

- ★ Systematic treatment as described in [4]
- ★ Most relevant systematics for this analysis related to detector & ice uncertainties

Group	Systematic	Nominal value	Prior	Range
Flux	delta_index	0.0	± 0.1	[-0.5, 0.5]
Detector	dom_eff	1.0	± 0.1	[0.8, 1.2]
	bulk_ice_abs	1.0	uniform	[0.85, 1.15]
	bulk_ice_scatter	1.0	uniform	[0.85, 1.15]
	hole_ice_p0	-0.2674	± 0.6	[-2.0, 1.0]
	hole_ice_p1	-0.04206	± 0.12	[-0.2, 0.2]
Normalization	aeff_scale	1.0	uniform	[0.0, 3.0]



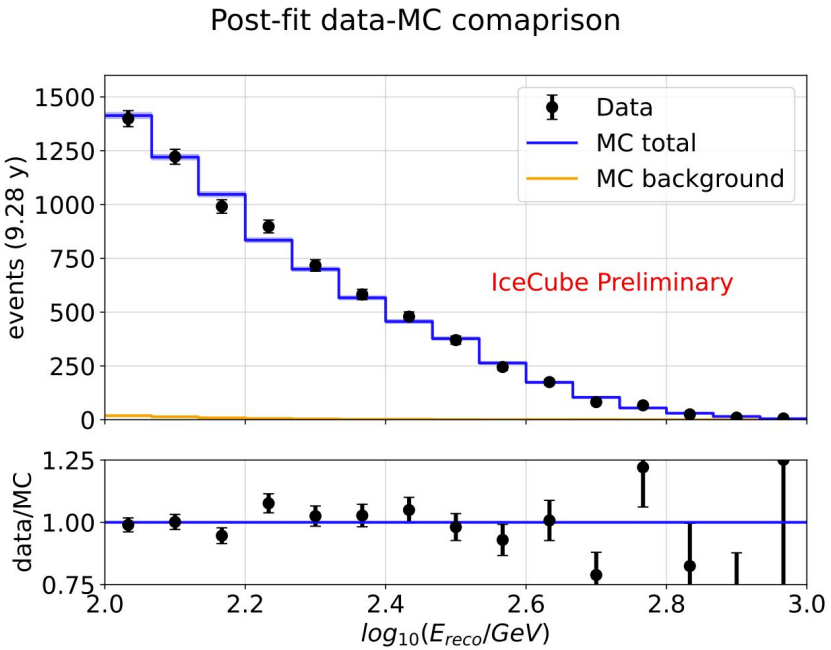
credit: Summer Blot

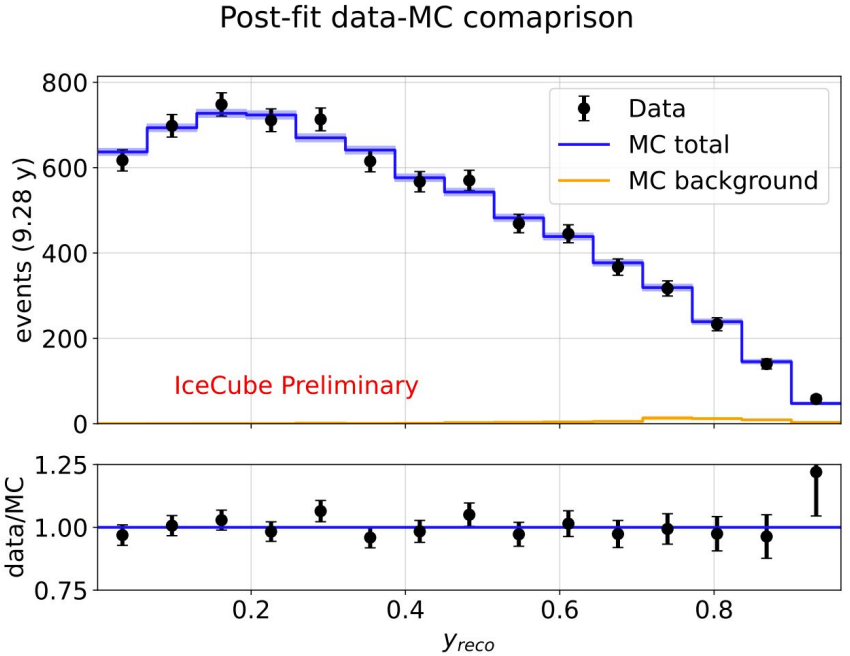


Results

Data-MC agreement

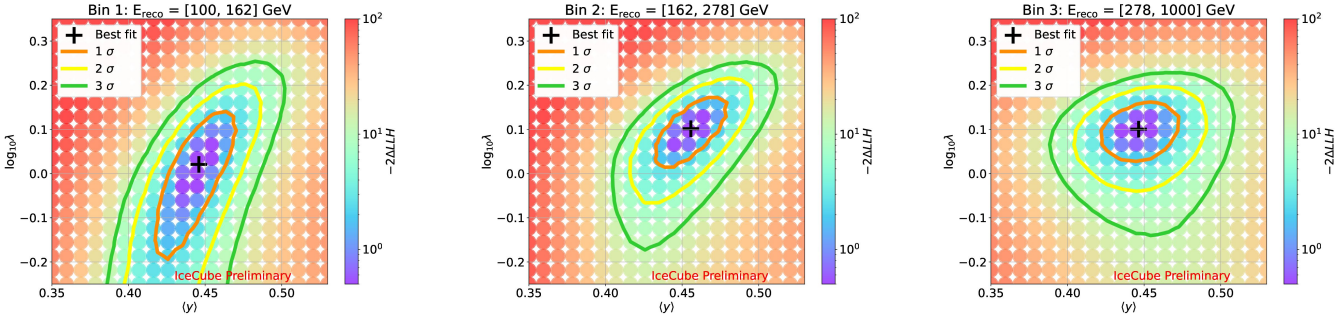
★ Fit p-value = 9.5%





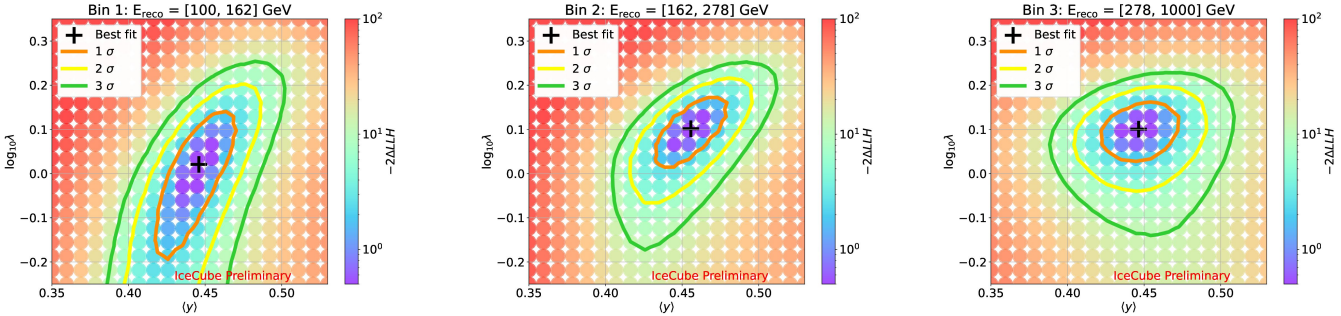
Results in (<y>, λ) space

★ Best fit points for a set of physics parameters in each of three energy bins

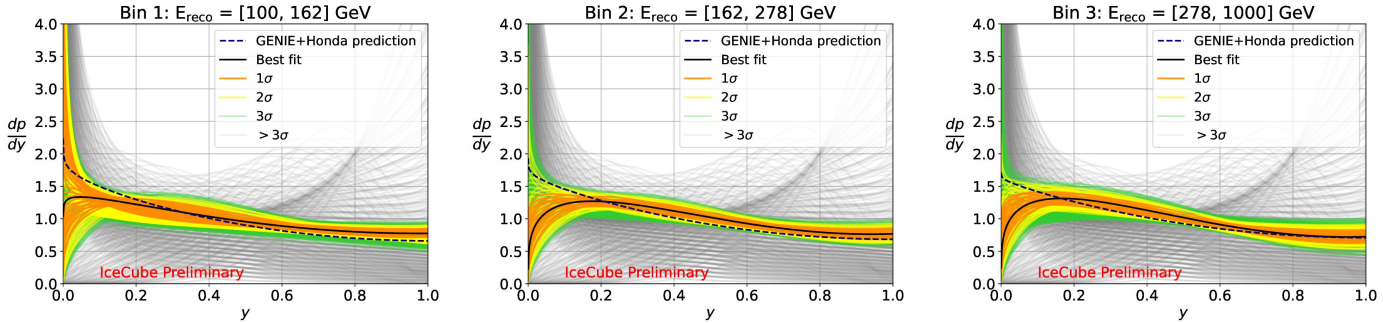


Results in (<y>, λ) space

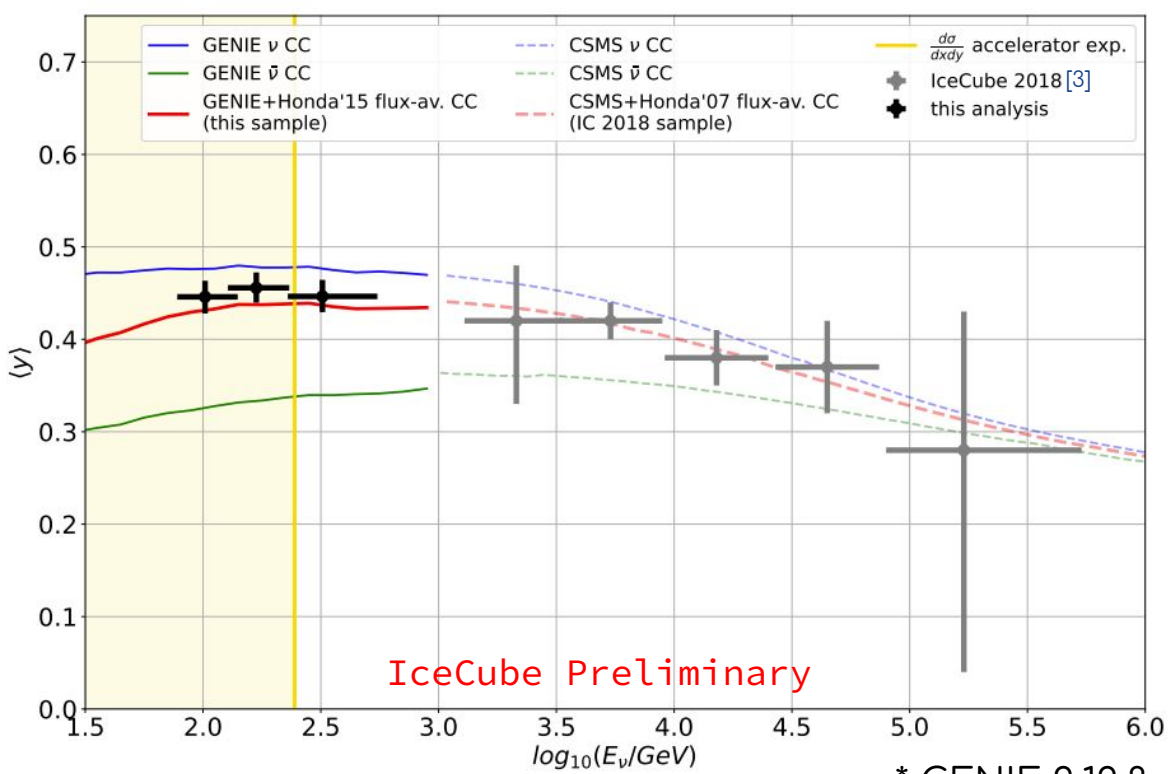
★ Best fit points for a set of physics parameters in each of three energy bins



★ Can extract inelasticity distribution shapes corresponding to the best fit values of physics parameters for each of energy bins



<y> comparison to existing data



* GENIE 2.12.8

[3] *IceCube Collaboration,* M.G. Aartsen et al., "Measurements using the inelasticity distribution of multi-TeV neutrino interactions in IceCube"

[5] M. Honda et al., "Atmospheric neutrino flux calculation using the NRLMSISE-00 atmospheric model"

[6] *GENIE Collaboration,* C. Andreopoulos et al., "The GENIE Neutrino Monte Carlo Generator"

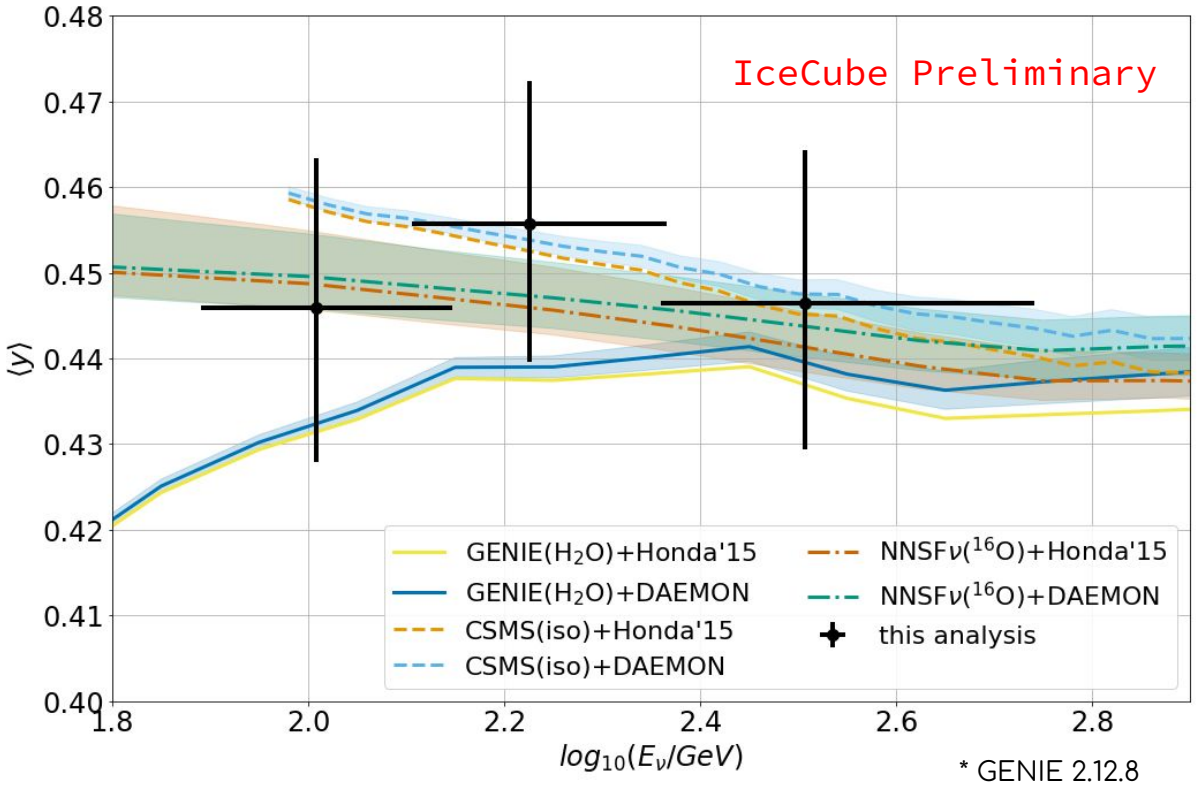
[7] A. Bodek, U.K. Yang, "Higher twist, ξw scaling, and effective LO PDFs for lepton scattering in the few GeV region"

[8] A. Cooper-Sarkar et al., "The high energy neutrino cross-section in the Standard Model and its uncertainty"

<y> comparison to model predictions

- ★ Calculated p-values for each models
  - ✧ model uncertainties not included
- ★ All tested models in agreement at 1σ level

Model combination	χ^2	p-value
GENIE + Honda'15	2.19	0.53
GENIE + DAEMON	1.91	0.59
CSMS + Honda'15	1.40	0.70
CSMS + DAEMON	1.61	0.66
NNSFν + Honda'15	0.08	0.99
NNSFν + DAEMON	0.13	0.99



* GENIE 2.12.8

[9] J. P. Yañez, A. Fedynitch, "Data-driven muon-calibrated neutrino flux"

[10] A. Candido et al., "Neutrino Structure Functions from GeV to EeV Energies"
(thanks to Alfonso Garcia for providing NNSFν cross section!)

Summary

- ★ New measurement of flux-averaged inelasticity distribution shape for neutrino energies from ~100 GeV to 1 TeV
- ★ 9.3 years of IceCube data
- ★ All tested theoretical model predictions compatible with the measurement at 1σ level
- ★ Future analyses can improve sensitivity
  - ✧ By expanding the sample with more data
  - ✧ IceCube Upgrade will offer great reduction in detector & ice uncertainties

Backup

Thank you!

Best fit parameters

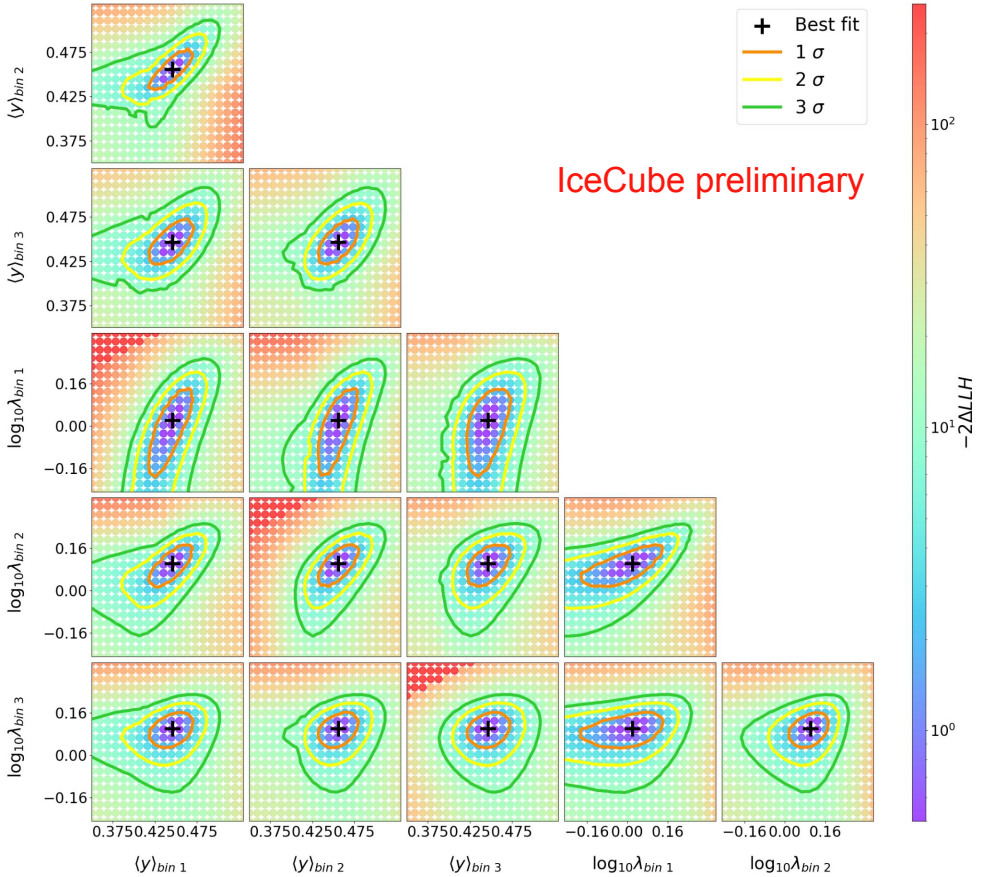
Physics parameters:

Parameter	Best fit	Allowed range
$\langle y \rangle$ bin 1	$0.45 \pm 0.02 \pm 0.005$	$[0, 1]$
$\langle y \rangle$ bin 2	$0.46 \pm 0.02 \pm 0.004$	$[0, 1]$
$\langle y \rangle$ bin 3	$0.45 \pm 0.02 \pm 0.006$	$[0, 1]$
$\log_{10} \lambda$ bin 1	$0.02^{+0.09}_{-0.12}$	$[-4, 0.8]$
$\log_{10} \lambda$ bin 2	$0.10^{+0.06}_{-0.05}$	$[-4, 0.8]$
$\log_{10} \lambda$ bin 3	$0.10^{+0.05}_{-0.04}$	$[-4, 0.8]$

Nuisance parameters:

Group	Systematic	Best fit value	Nominal value	Prior	Range
Flux	delta_index	0.11	0.00	± 0.1	[-0.5, 0.5]
Detector	dom_eff	1.07	1.00	± 0.1	[0.8, 1.2]
	bulk_ice_abs	1.00	1.00	uniform	[0.85, 1.15]
	bulk_ice_scatter	1.01	1.00	uniform	[0.85, 1.15]
	hole_ice_p0	-0.5991	-0.2674	± 0.6	[-2.0, 1.0]
	hole_ice_p1	-0.02251	-0.04206	± 0.12	[-0.2, 0.2]
Normalization	aeff_scale	0.78	1.00	uniform	[0.0, 3.0]

2d scan for all combinations



Neutrino fraction estimate

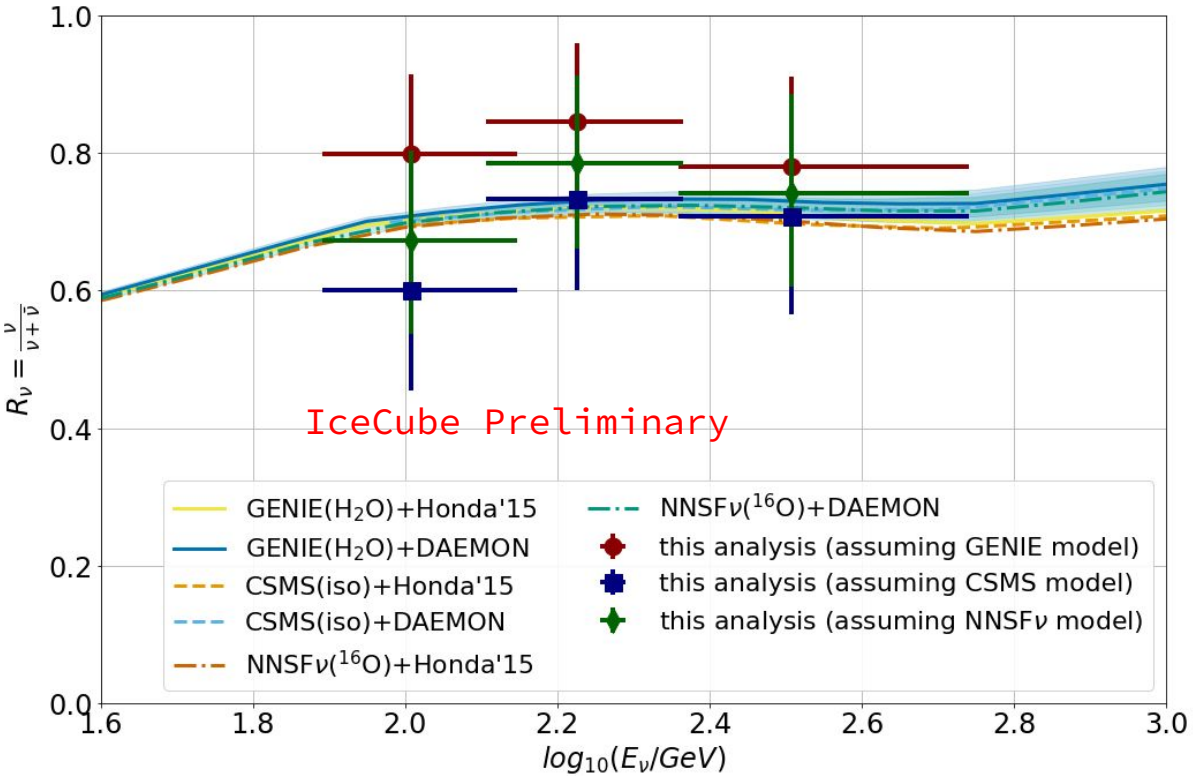
- ★ Our mean inelasticity result can be used to make an estimate of **neutrino fraction in the detected flux** assuming certain cross section model
  - ✧ **Detected flux** is convolution of atmospheric neutrino flux, neutrino cross sections and selection effects
- ★ This is **not** an independent measurement, but a simple calculation:

We measure this

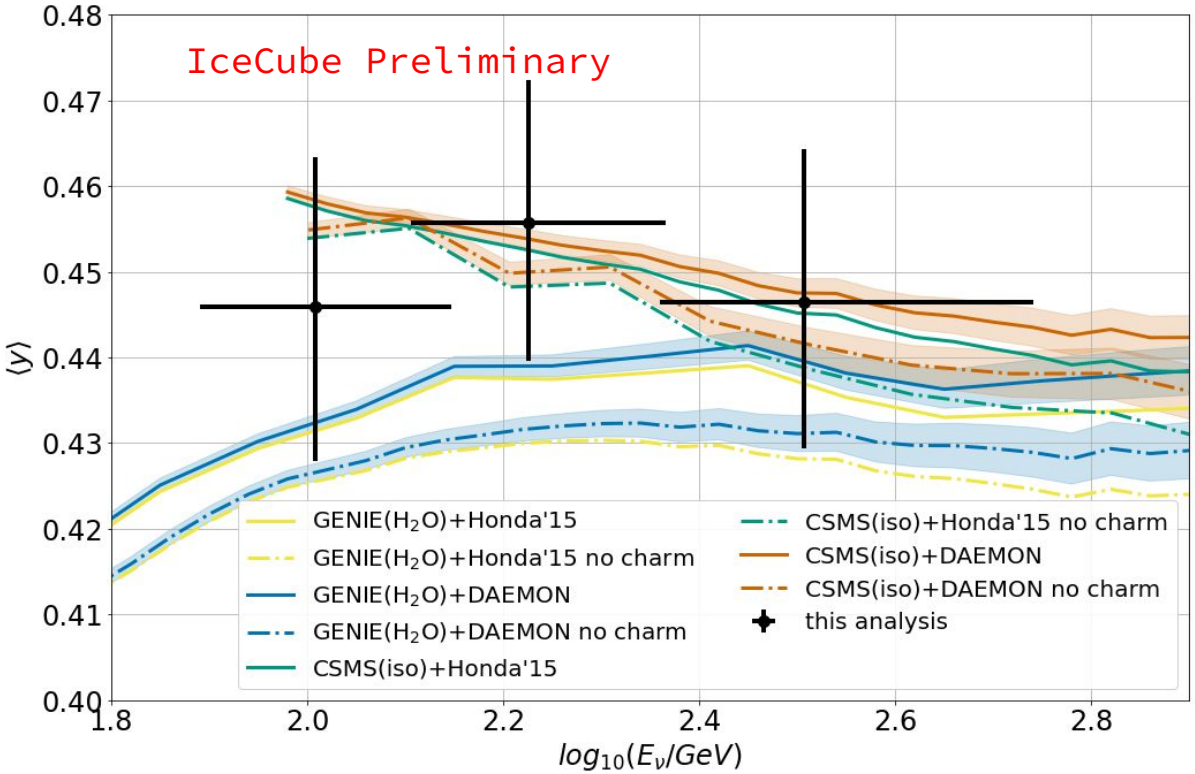
$$R_\nu = \frac{\langle y \rangle_{fl.\,av.} - \langle y \rangle_{\bar{\nu}}}{\langle y \rangle_\nu - \langle y \rangle_{\bar{\nu}}} \qquad \sigma(R_\nu) = \frac{\sigma(\langle y \rangle_{fl.\,av.})}{\langle y \rangle_\nu - \langle y \rangle_{\bar{\nu}}}$$

Get this from cross section model

Neutrino fraction in sample



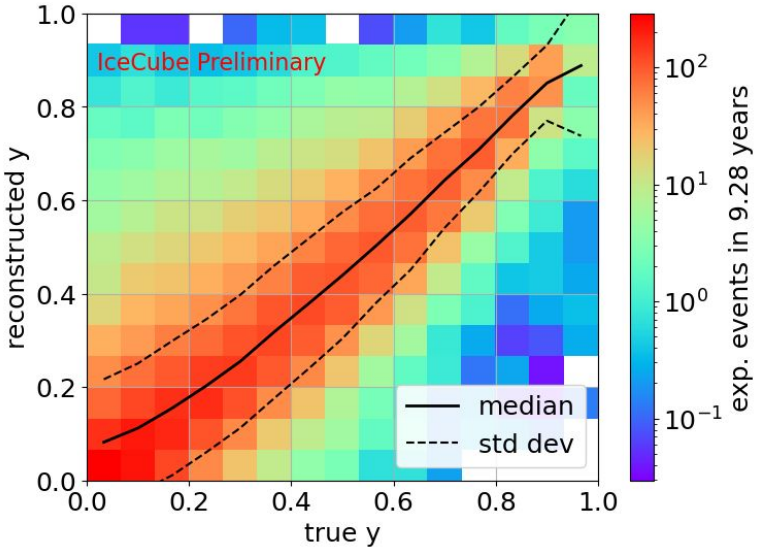
Comparison to models without charm

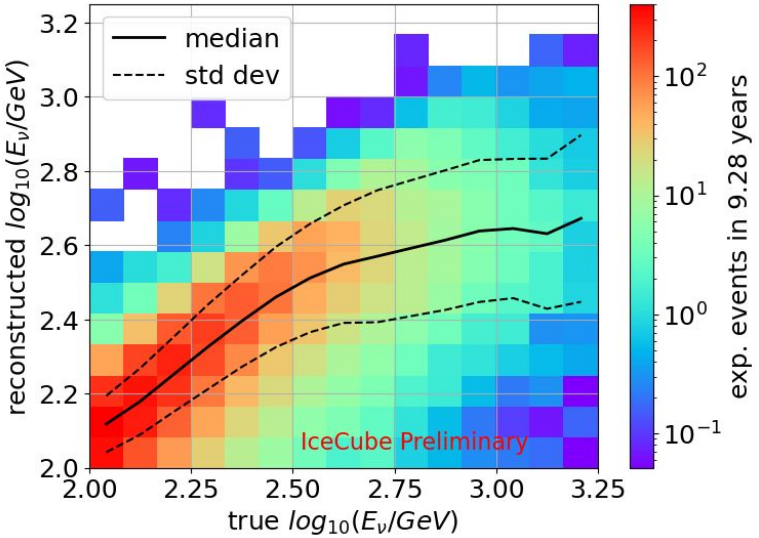


Neutrino interaction types

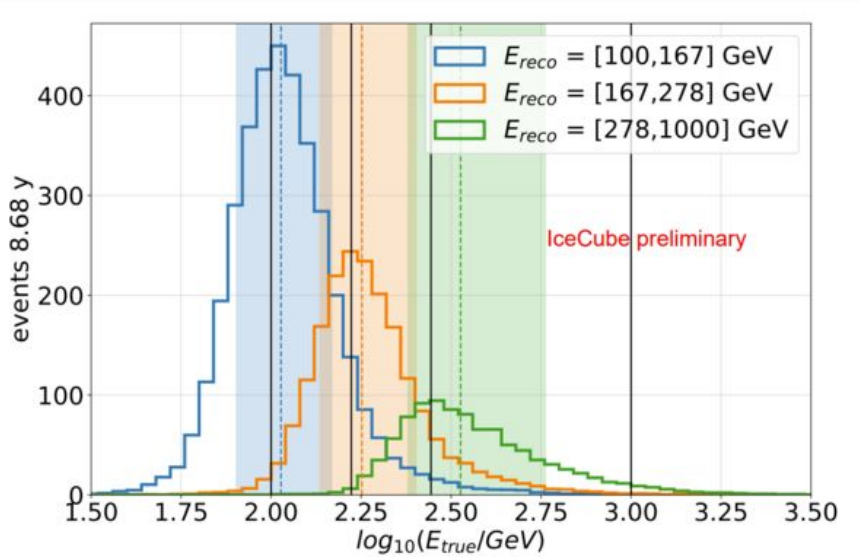
- ★ 7268 events from 9.28 years of IceCube data
- ★ Expectation from nominal MC (GENIE 2.12.8)
  - ✧ Total non-DIS - 2.2% (exp. 160 events/9.28y)
  - ✧ RES - 1.3% (exp. 97 events/9.28y)
  - ✧ QE - 0.7 (exp. 48 events/9.28y)
  - ✧ Other non-DIS - 0.2% (exp. 15 events/9.28y)

Energy and y resolutions





True energy distribution by bin



Physically allowed parameters space

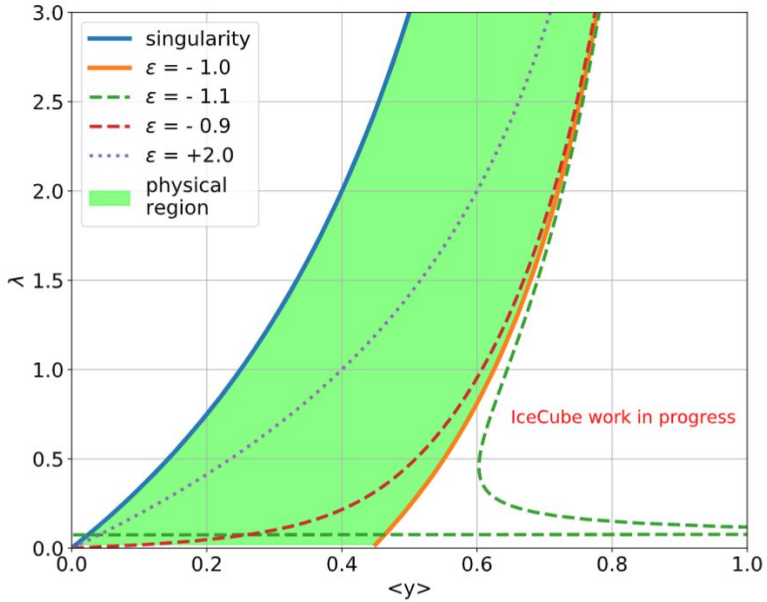


Figure 4.6: Physically allowed region in $(\langle y \rangle, \lambda)$ space (shaded in green) with physics boundaries (solid lines).

Inelasticity in IceCube

★ In IceCube, inelasticity can be reliably reconstructed for ν_μ CC events