Inelasticity studies using TeV-scale starting track neutrino events in IceCube

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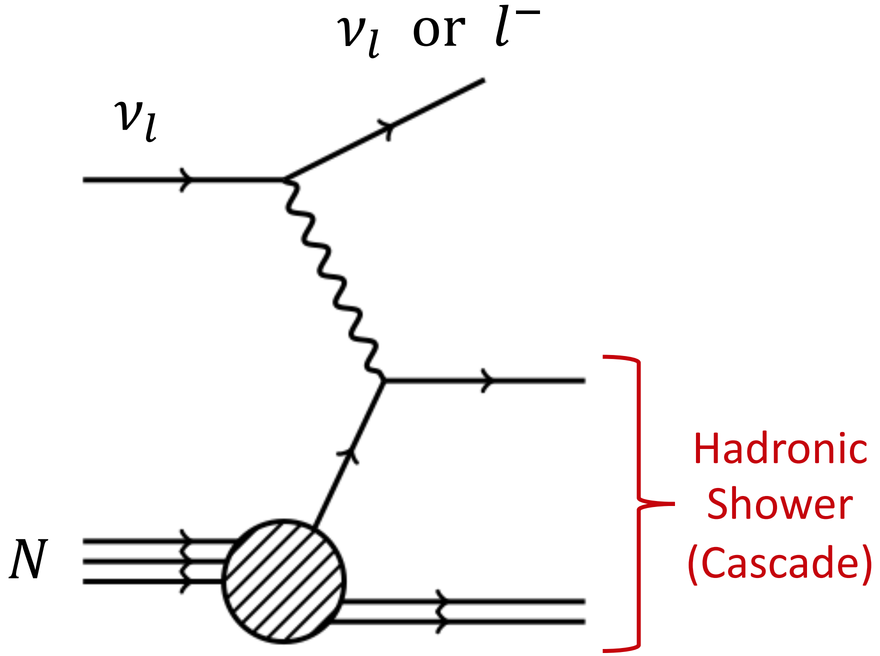
Photo credit:
Yuya Makino, IceCube/NSF

Deep Inelastic Scattering (DIS) and inelasticity

- Above 100 GeV neutrinos primarily interact via DIS
- Inelasticity (y) is an important kinematic variable:

$$y = \frac{E_{\text{Had.}}}{E_\nu} = 1 - \frac{E_\mu}{E_\nu}$$

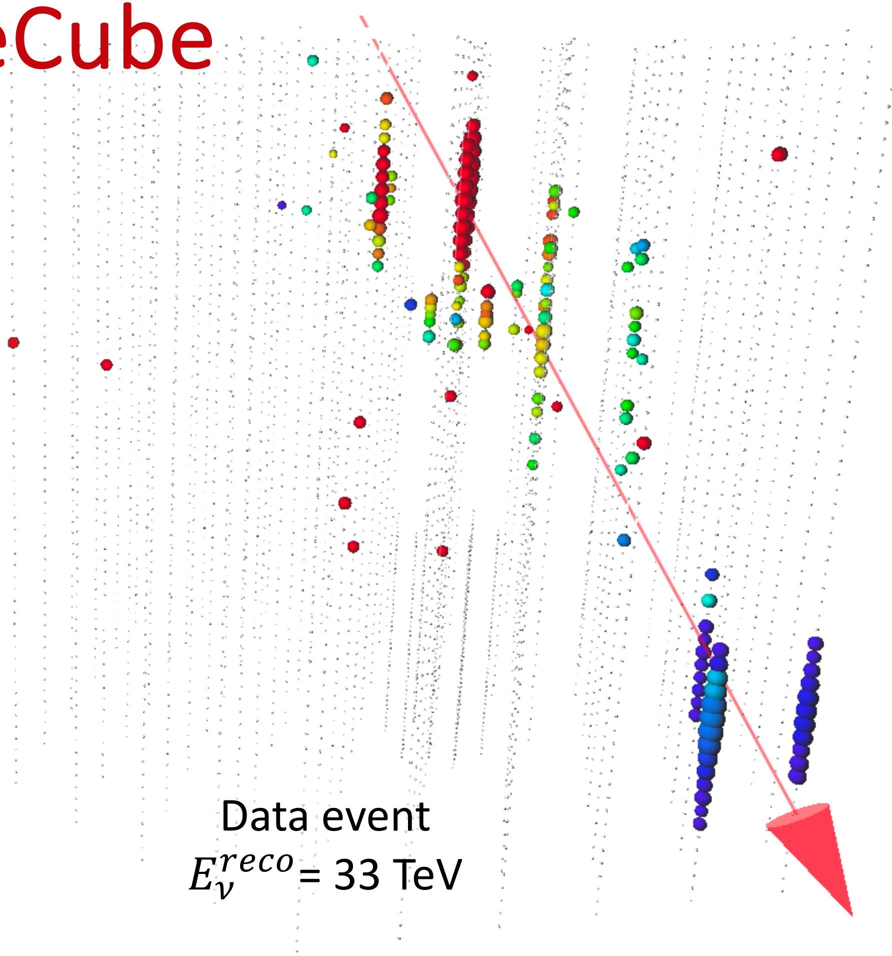
- Inelasticity enables a suite of possible studies:
    - Measure inelasticity itself
    - Measure $\nu/\bar{\nu}$ ratio
    - Search for neutrino-induced charm production
    - Measure astrophysical flavor composition
    - Search for BSM particles



ν_μ^{CC} Starting Event in IceCube

Starting events allow reconstruction of hadronic and leptonic energies, separately

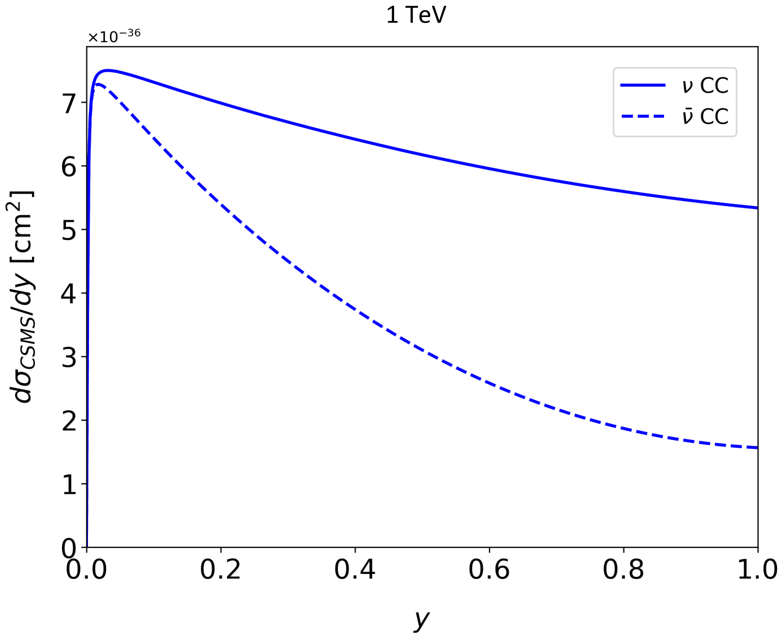
- Reconstruct neutrino energy
- Reconstruct inelasticity

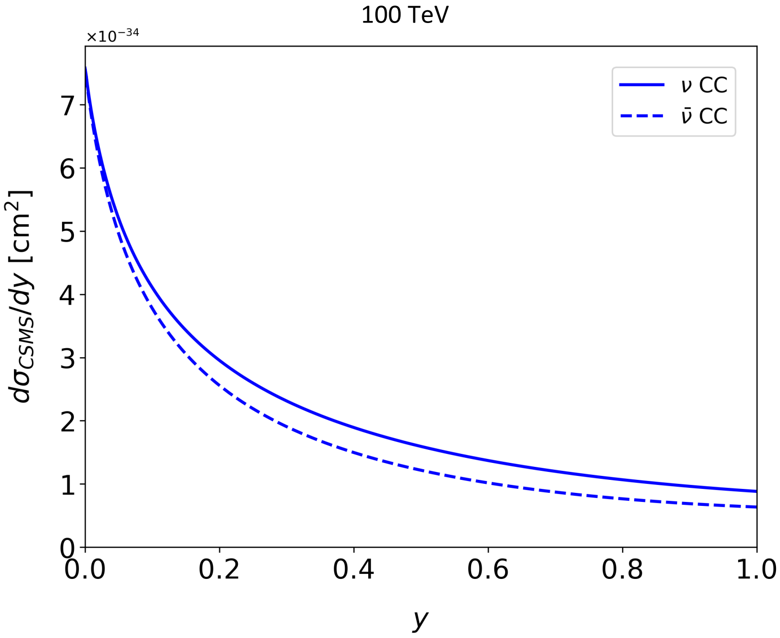


Data event
E_ν^{reco} = 33 TeV

Inelasticity predictions for neutrinos and antineutrinos

- Inelasticity predictions shown assuming Cooper-Sarkar Mertsch Sarkare (CSMS) calculation [1]
    - CSMS is a standard DIS calculation
- IceCube cannot distinguish between neutrinos and antineutrinos on an event-by-event basis
- Must perform a flux-averaged measurement → informs about neutrino-antineutrino ratio

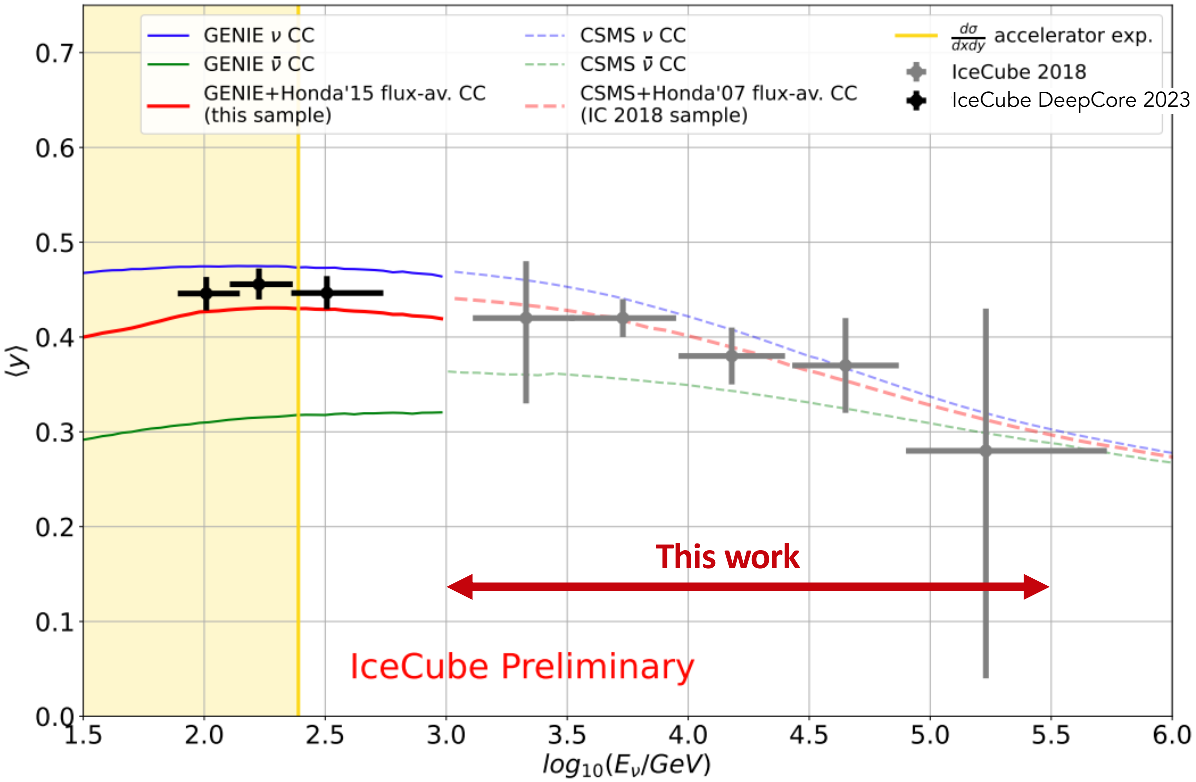




[1] JHEP 08 (2011) 042

Previous Work in IceCube

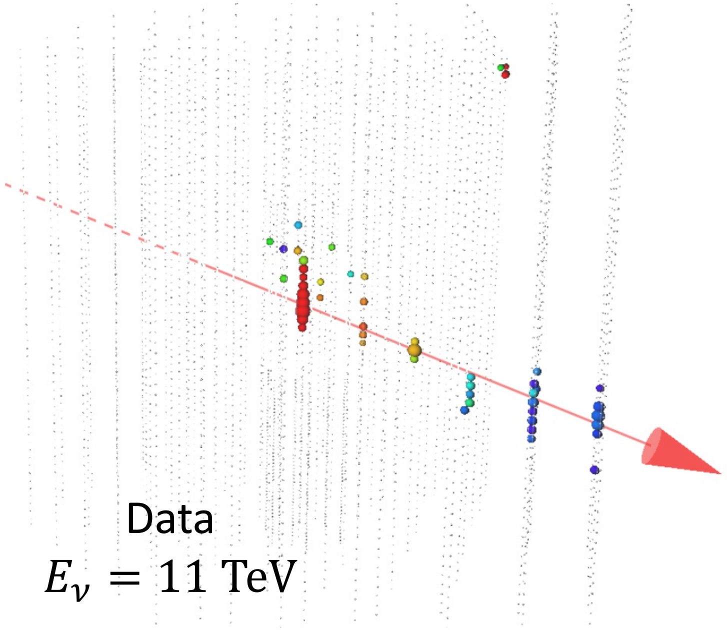
New sample has 4x statistics of previous high-energy sample



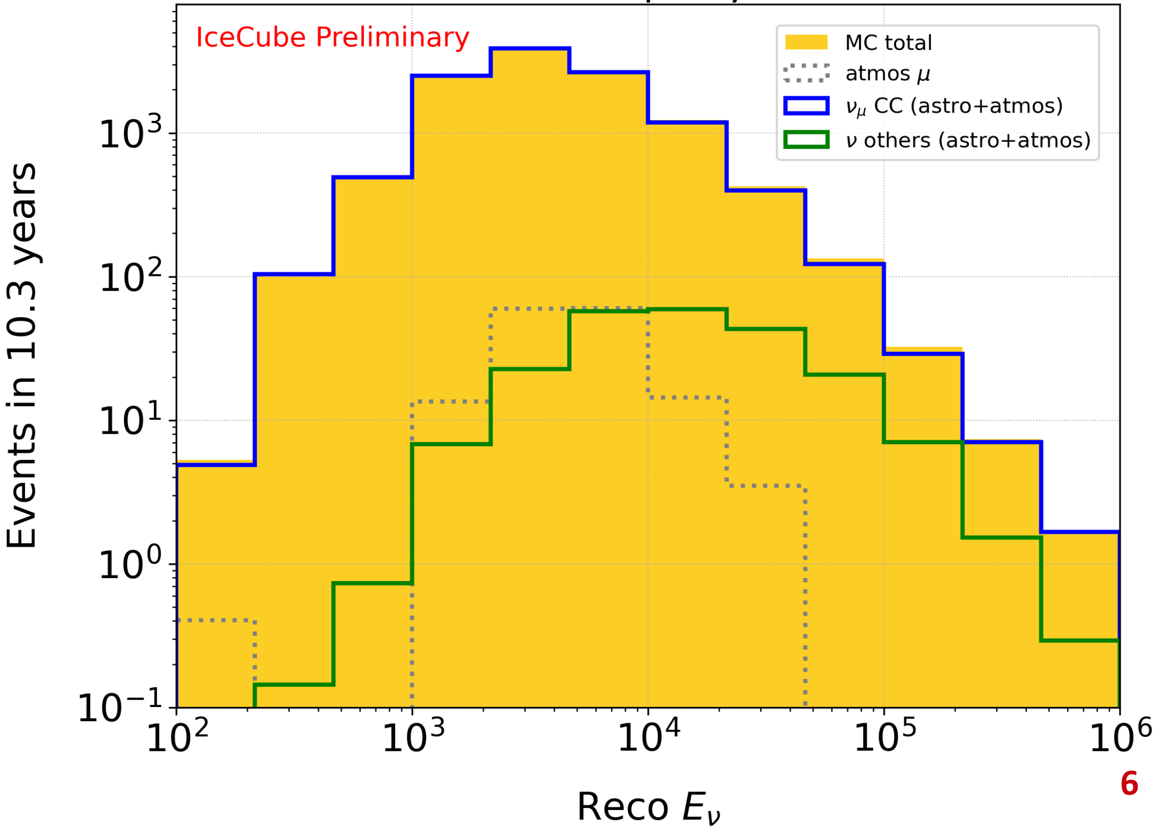
Phys. Rev. D 99, 032004 (2019)

10.3-year Enhanced Starting Track Event Selection (ESTES)

10,000 neutrinos
above 1 TeV



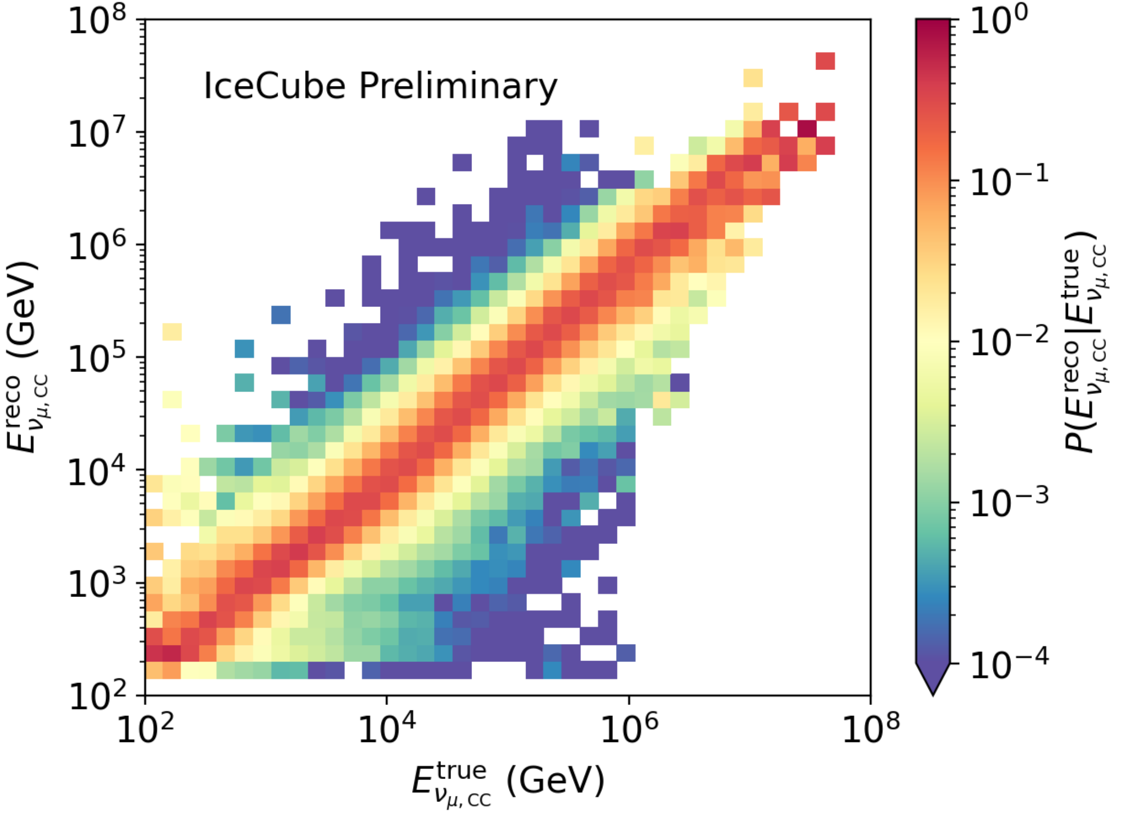
~97% purity



See earlier talk by Sarah Mancina

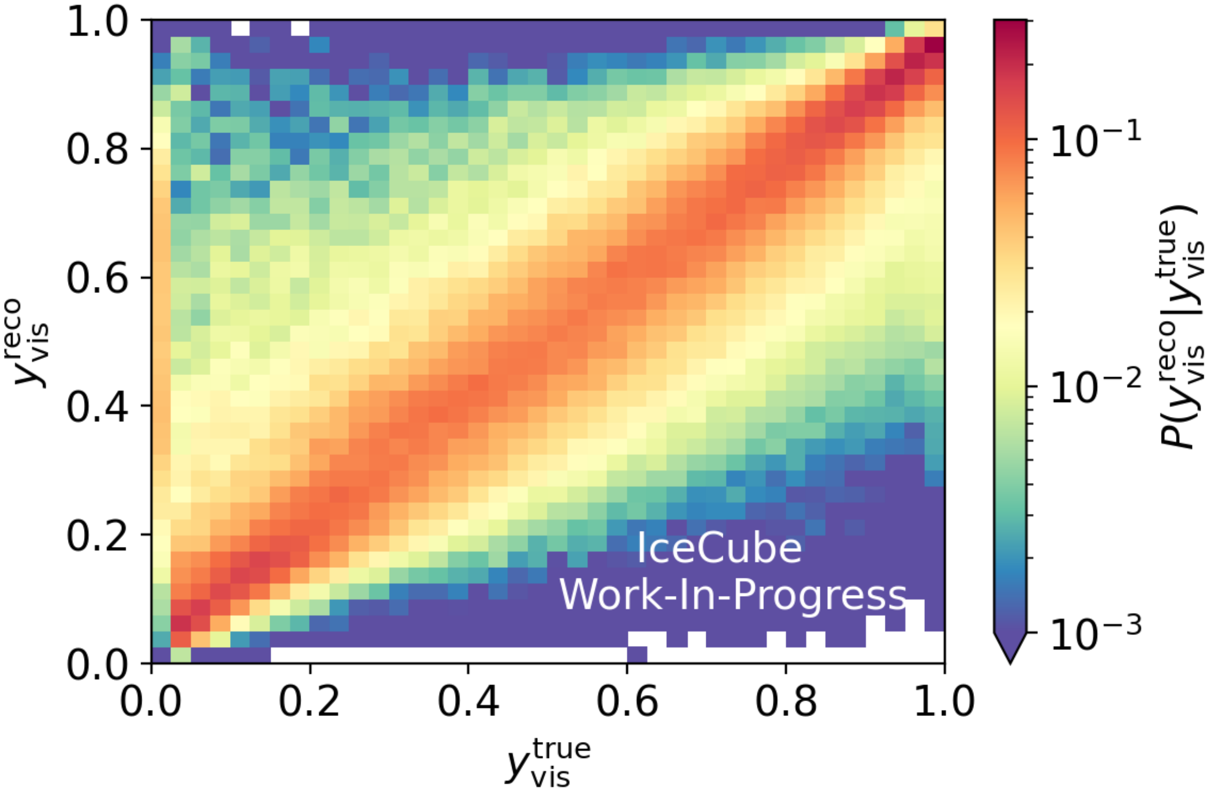
Energy reconstruction performance

- Reconstruct hadronic cascade and muon track energies with Random Forest
- $E_\nu \equiv E_\mu + E_{cascade}$
- $\log_{10}(E_\nu/\mathrm{GeV})$ RMS error: 0.24



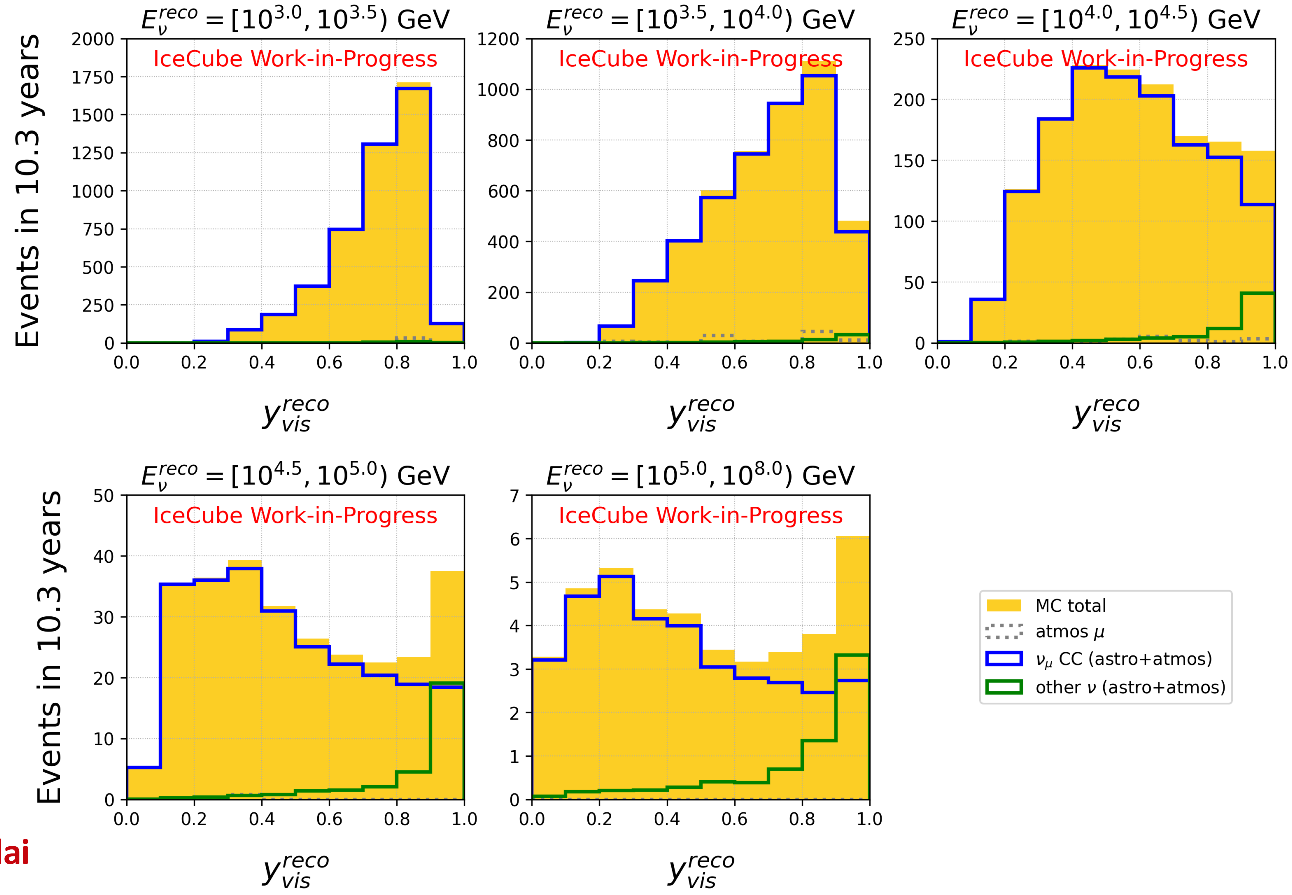
Visible inelasticity reconstruction performance

- Reconstruct hadronic cascade and muon track energies *deposited within detector* (E_{dep}) with Random Forest
- Visible inelasticity:
  $$y_{vis} \equiv E_{dep}^{cascade} / E_{dep}^{total}$$
- y_{vis} RMS error: 0.19



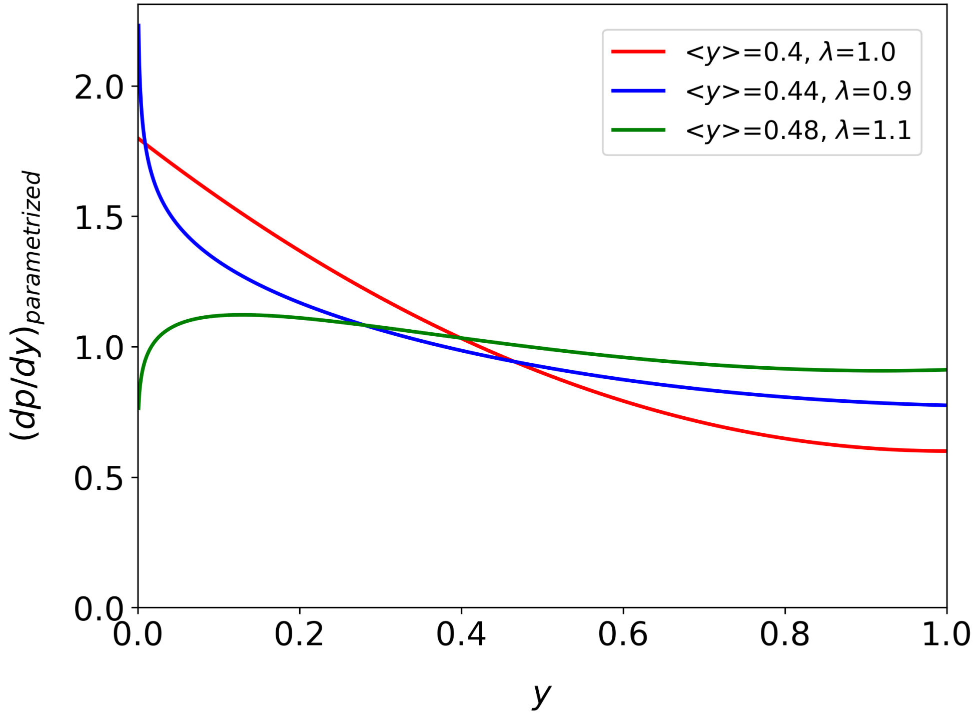
Event distributions

$$y_{vis} \equiv E_{dep}^{cascade} / E_{dep}^{total}$$



A useful parametrization of inelasticity

- Inelasticity distribution can be parametrized [1]:
  - $\frac{dp}{dy} = N(1 + \epsilon(1-y)^2)y^{\lambda-1}$
  - $N = \frac{\lambda(\lambda+1)(\lambda+2)}{2\epsilon+(\lambda+1)(\lambda+2)}$
  - $\epsilon = -\frac{(\lambda+2)(\lambda+3)}{2}\frac{\langle y\rangle(\lambda+1)-\lambda}{\langle y\rangle(\lambda+3)-\lambda}$
- Fit for $\langle y\rangle$, with λ as a nuisance parameter, and compare to prediction
- Fit for parameters in each energy bin

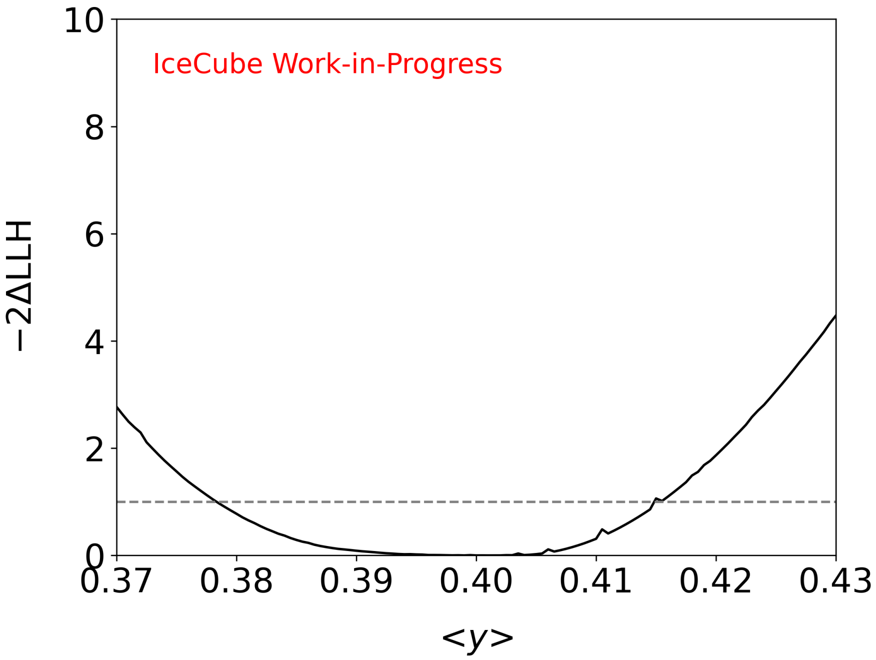


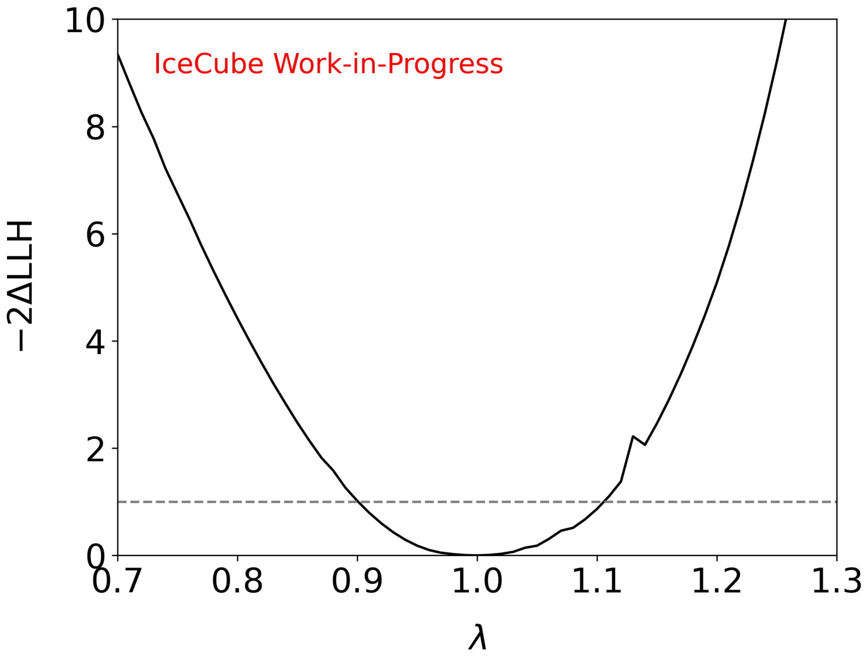
[1] https://arxiv.org/pdf/1808.07629.pdf

Inelasticity measurement analysis

- Likelihood-based fit for $\langle y \rangle$ and λ from inelasticity parametrization in bins of E_ν^{reco}
- Systematic uncertainties:
  - Astrophysical flux (normalization & spectral index)
  - Conventional atmospheric flux normalization
  - Prompt atmospheric flux normalization
  - Atmospheric muon normalization
  - Cosmic ray model
  - Hadronic interaction model
  - Neutrino self-veto effect
  - Neutrino-antineutrino ratio
  - DOM efficiency
  - Light scattering and absorption in bulk ice
  - Hole ice

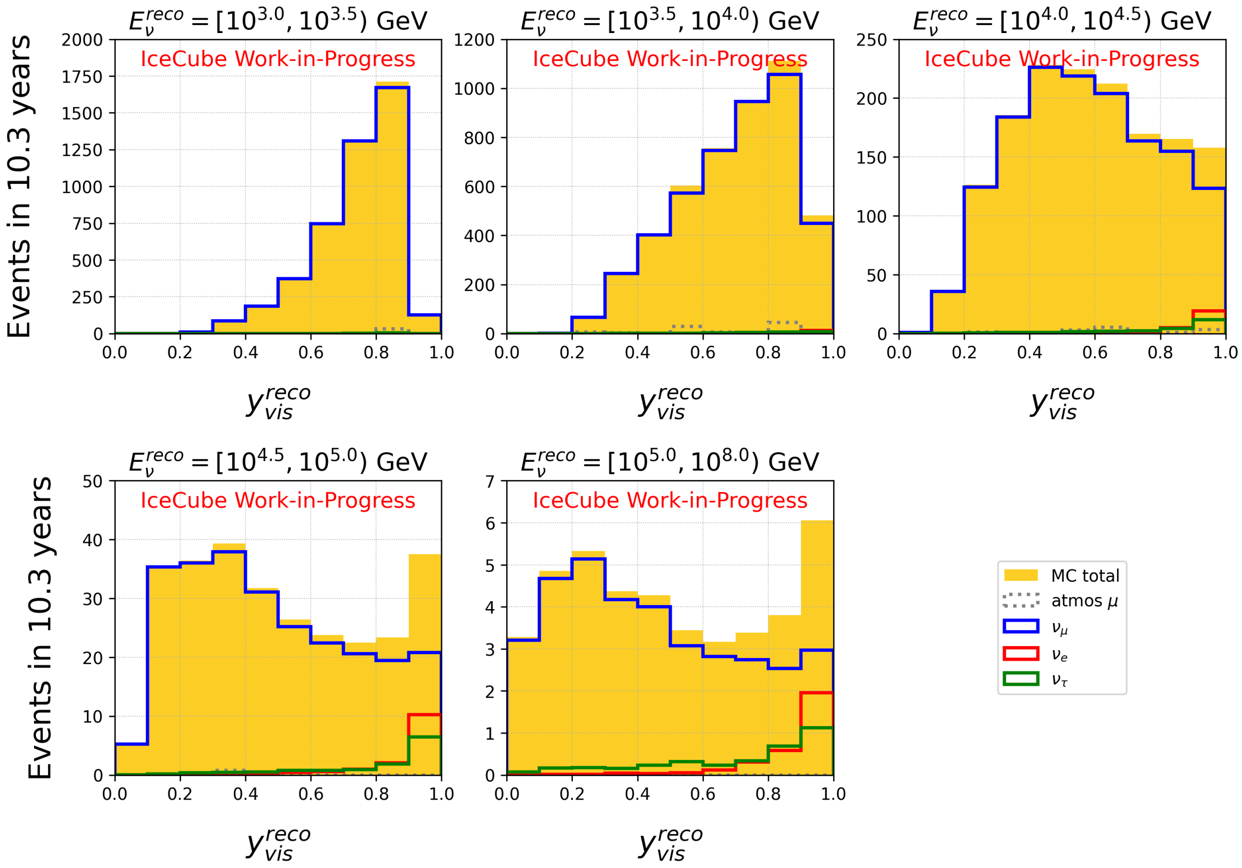
Preliminary Asimov sensitivity: $\log_{10}(E_\nu/\mathrm{GeV})$ =[4.0,4.5)





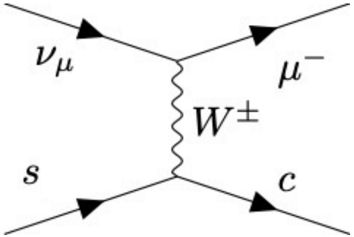
Neutrino flavor composition

$$y_{vis} \equiv E_{dep}^{cascade} / E_{dep}^{total}$$



Neutrino-induced charm production

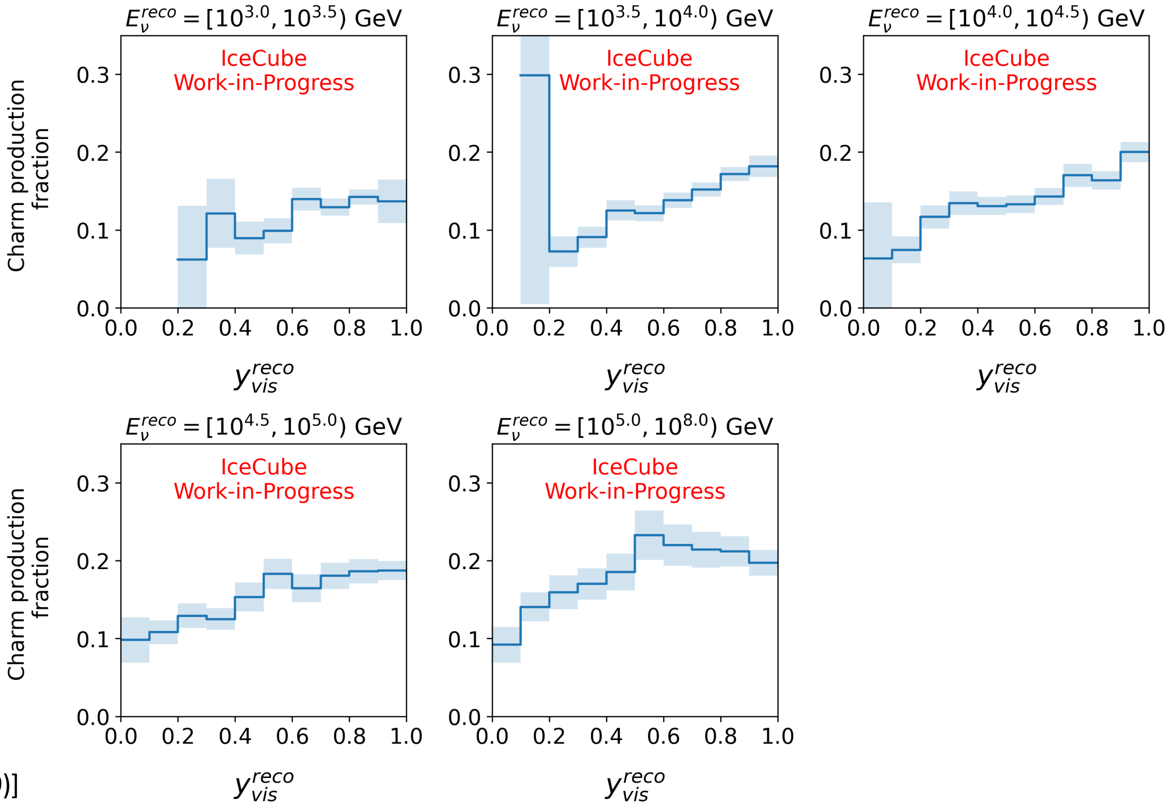
$$y_{vis} \equiv E_{dep}^{cascade} / E_{dep}^{total}$$



- CC DIS interactions with strange quarks will produce charm quarks
  - $D^\pm,\ D^0,\ \overline{D}^0,\ D_s^\pm,\ \Lambda_c^+$
- Charm production has not been definitively observed at IceCube energies → Test SM
- Inform about strange sea of nucleon
- Strange quarks have a smaller mean Bjorken-*x* than other light quarks
- These events tend to have higher inelasticity

$$xy = Q^2/(2M_N E_\nu)$$

- Previous IceCube result: Zero charm production excluded at 91% CL [Phys. Rev. D 99, 032004 (2019)]



Takeaway

- Starting ν_μ charged current events allow for a suite of astro/particle physics measurements involving inelasticity
    - Inelasticity
    - Flavor composition
    - Neutrino-induced charm production
    - Neutrino-to-antineutrino ratio
- Complete sensitivities are forthcoming

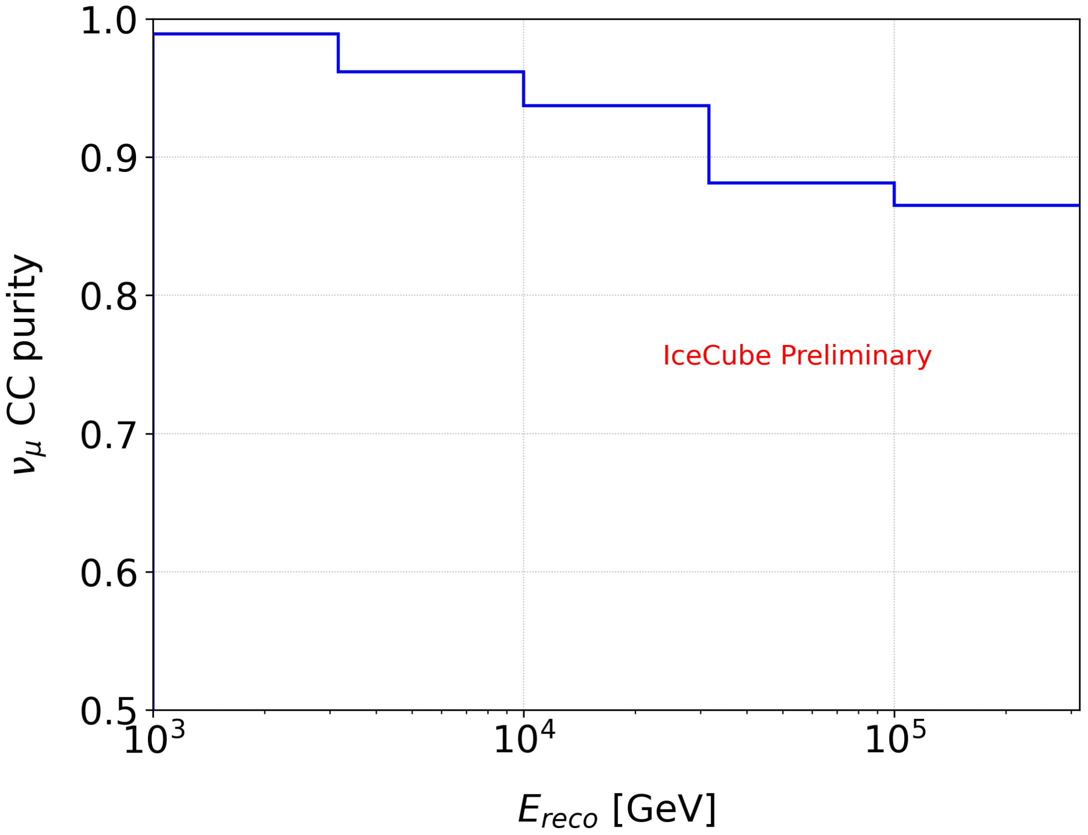
Thank you!
Questions?

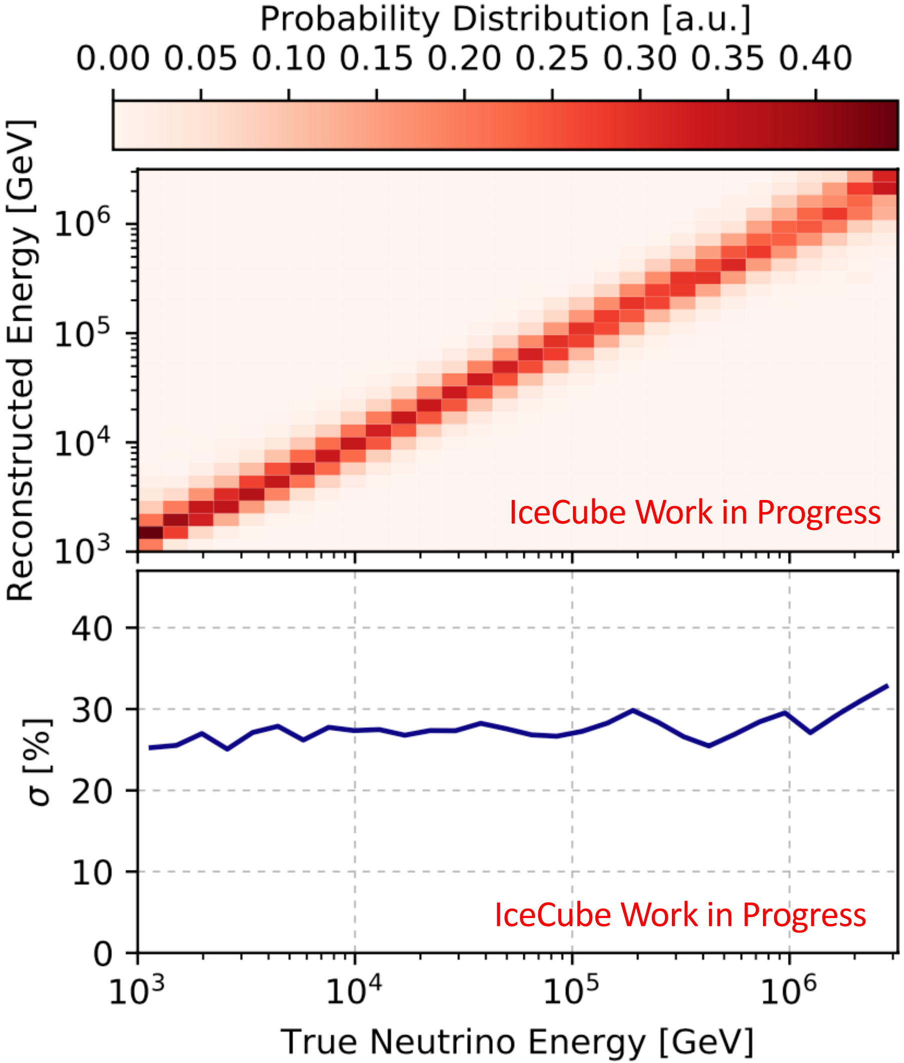
Photo credit:
John Hardin, IceCube/NSF

Back-up

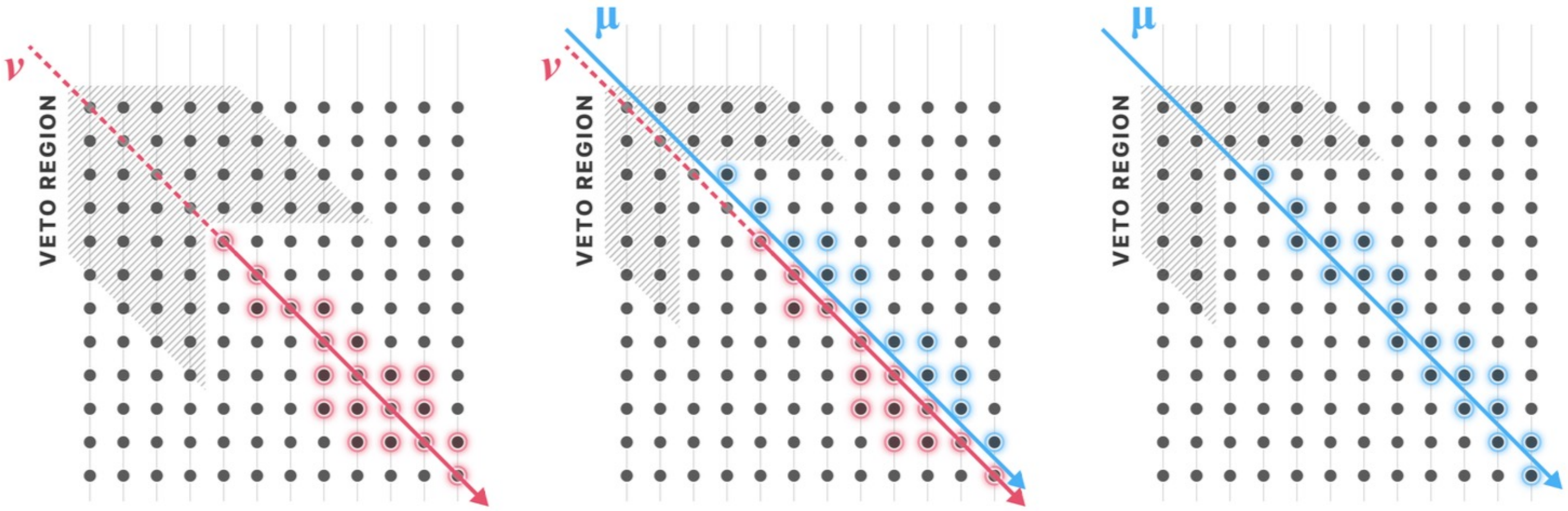
Photo credit:
John Hardin, IceCube/NSF

Starting track sample purity




Probability Distribution [a.u.]
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40
Reconstructed Energy [GeV]
10^6
10^5
10^4
10^3
IceCube Work in Progress
40
30
20
10
0
σ [%]
IceCube Work in Progress
10^3 10^4 10^5 10^6
True Neutrino Energy [GeV]

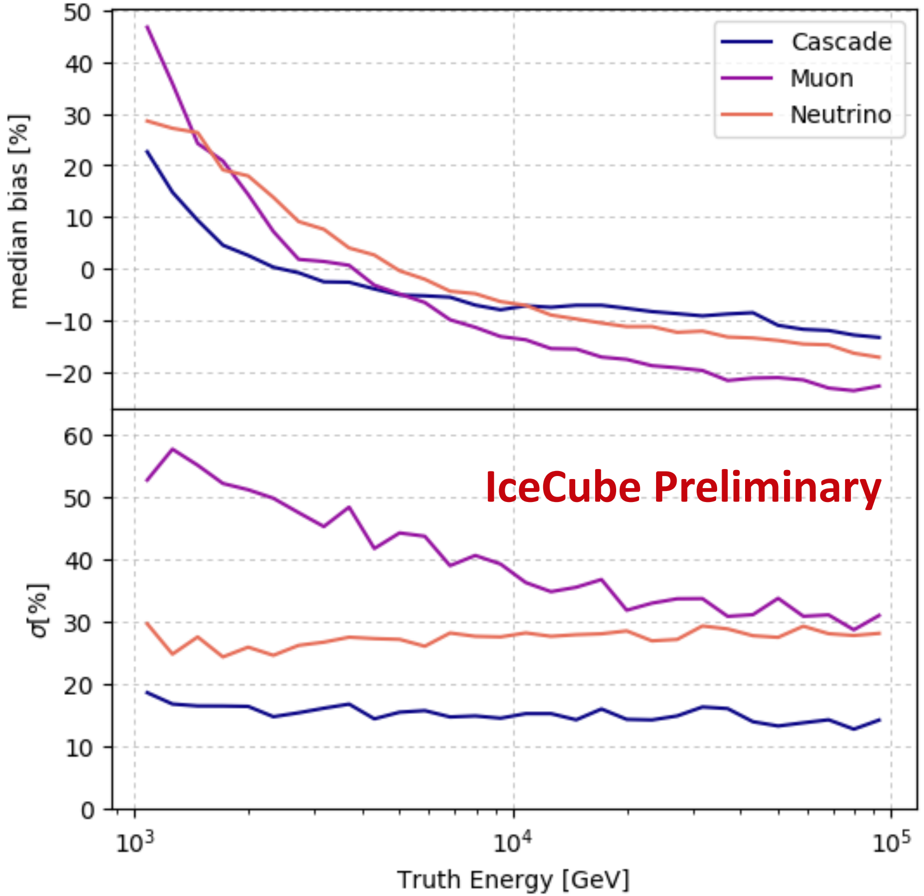
Enhanced Starting Track Event Selection



1. Cut events based on probability of light in veto region
2. Cut events based on BDT with 13 variables

Random Forest Energy Estimation

- Inputs:
  - 1% quartiles of total energy
  - Distance along track at 1% quantiles of total energy
  - Reconstructed azimuth and zenith
- Reconstruct cascade and muon energies individually



Neutrino-induced charm production

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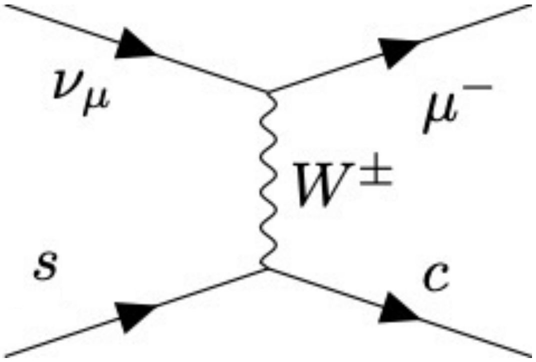
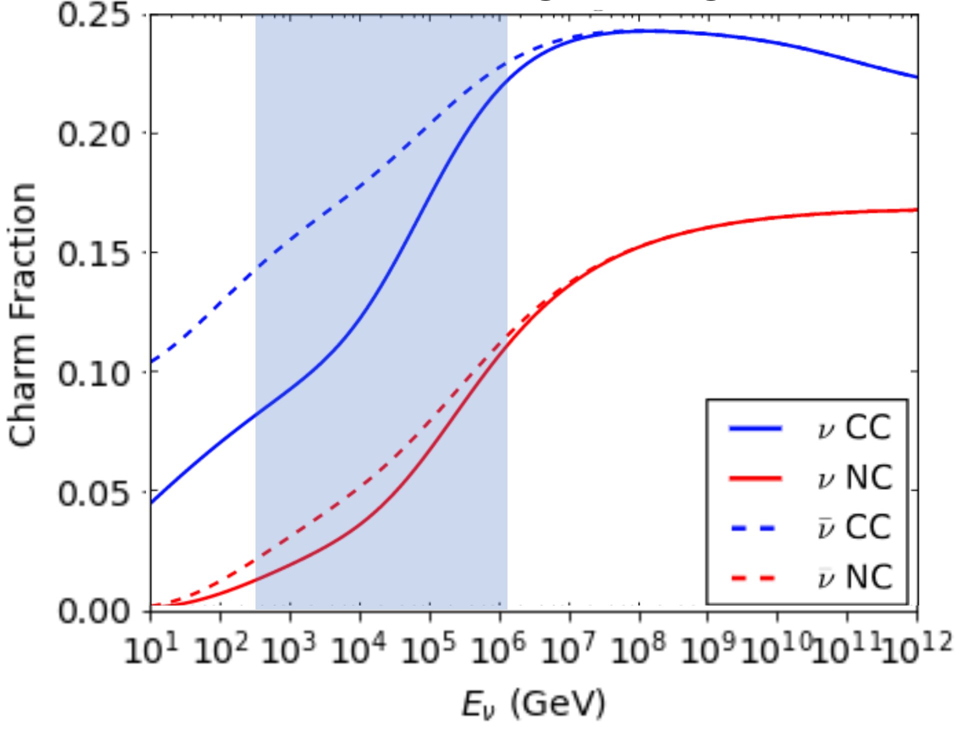


ν on isoscalar target, using CSMS



Adapted from G. Binder, "Neutrino-Induced Charm Production in IceCube" Technical Note

Neutrino-induced charm production

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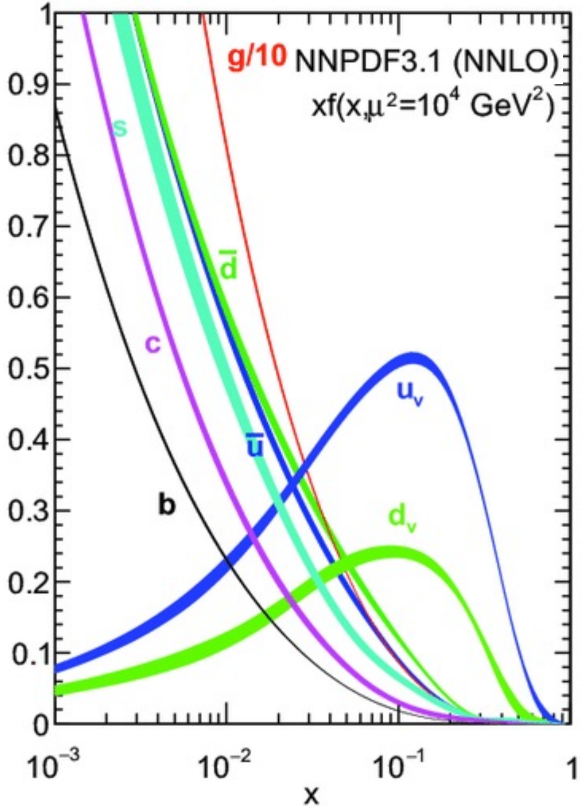
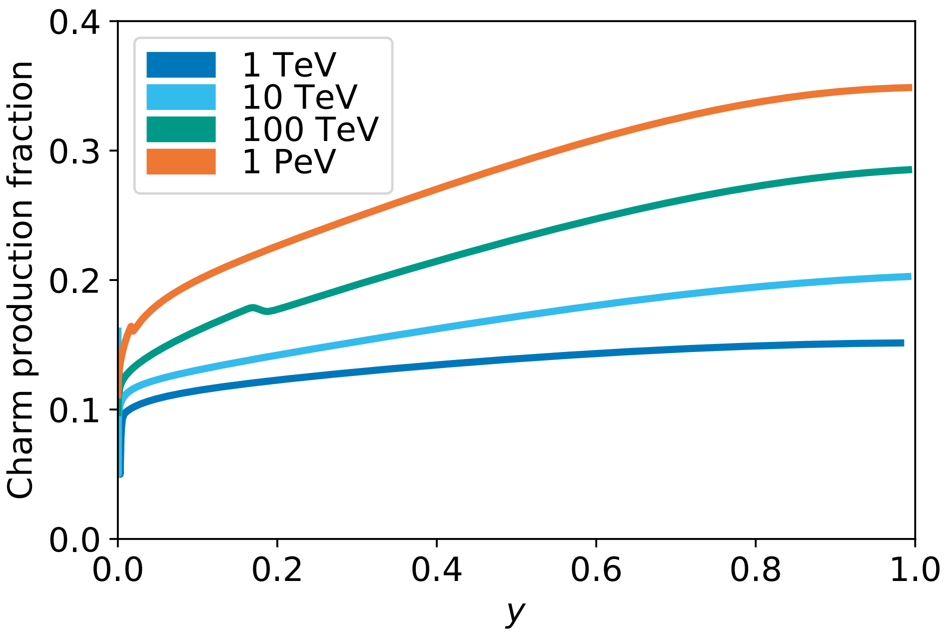
- These events tend to have higher inelasticity $xy = Q^2/(2M_N E_\nu)$



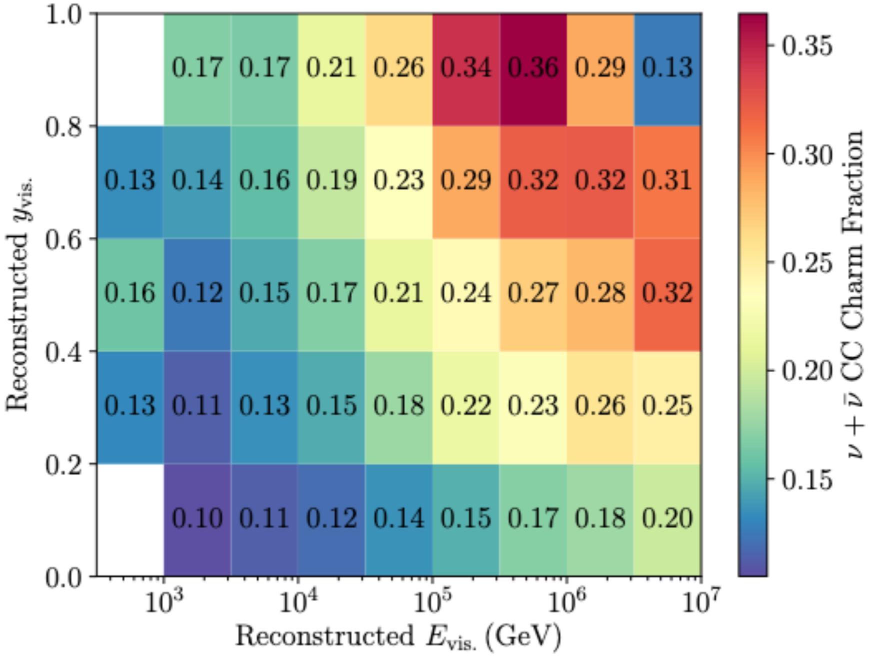
arXiv: 1706.00428



For ν CC interactions on isoscalar target
Calculated with GENIE-HEDIS CSMS

Previous Work in IceCube

- 5-year inelasticity analysis
  - $R_{CC,\mathrm{charm}} = 0.93^{+0.73}_{-0.59}$
  - Zero charm production excluded at 91% CL



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