Measurements of the neutrino-nucleon cross section with IceCube

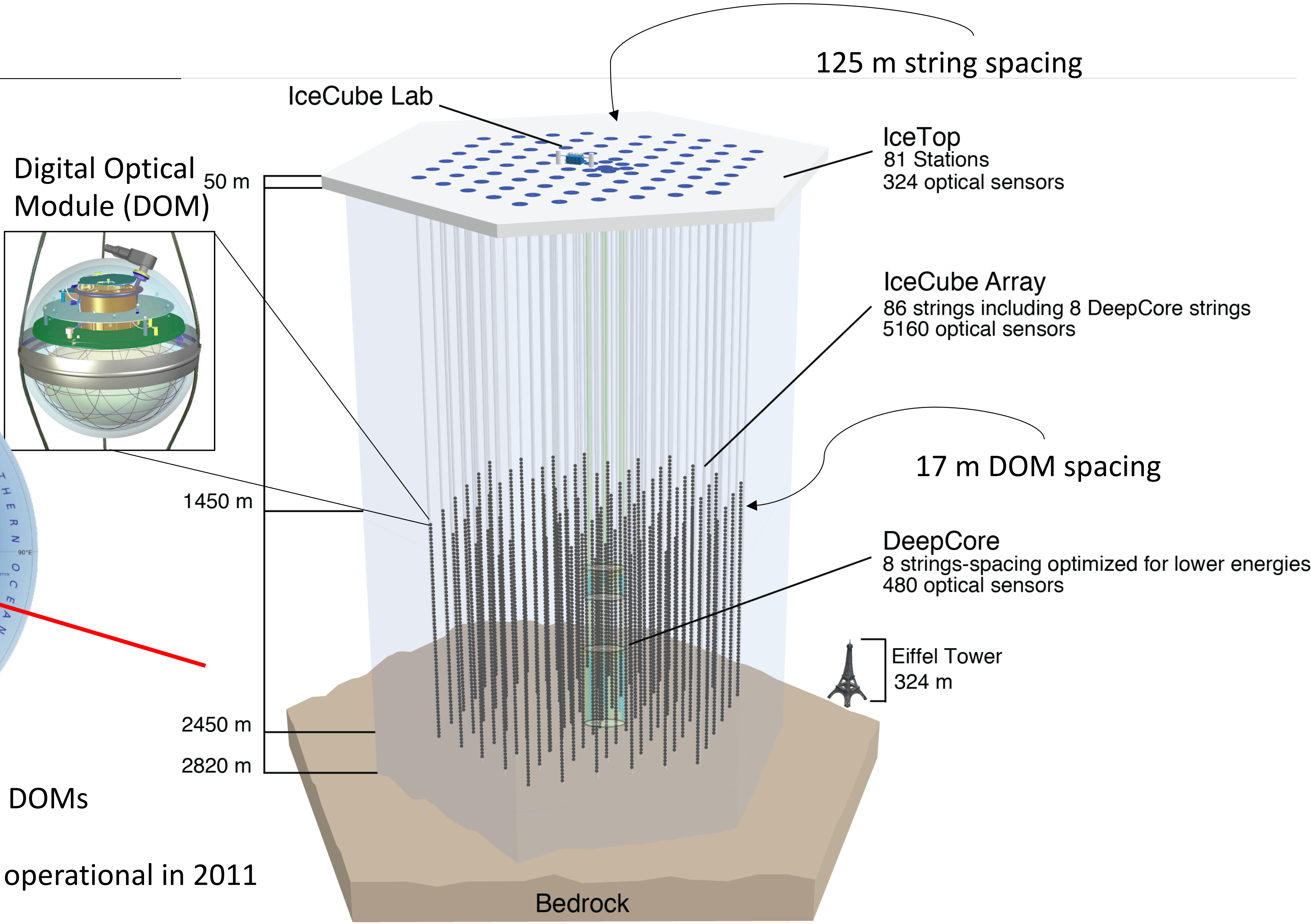
Tianlu Yuan for the IceCube collaboration

PPNT 2019

Uppsala, Sweden, 8 October 19

Credit: M. Wolf, IceCube/NSF

IceCube

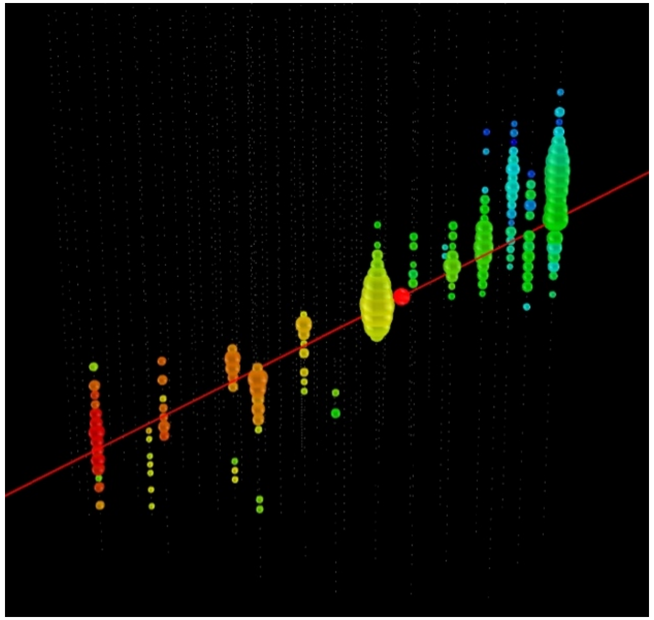


5160 DOMs

Fully operational in 2011

Event topologies

CC muon neutrino

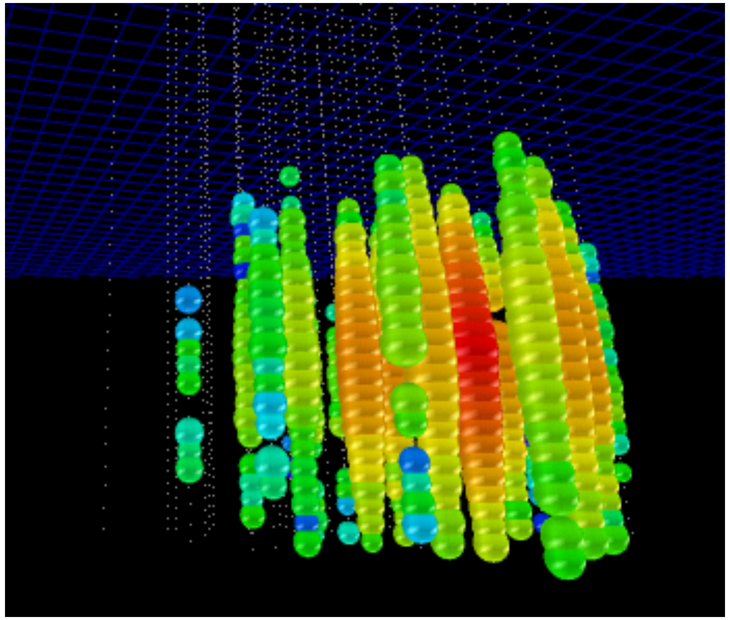


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

angular resolution ~ 0.5°
energy resolution ~ x2

NC or CC electron neutrino

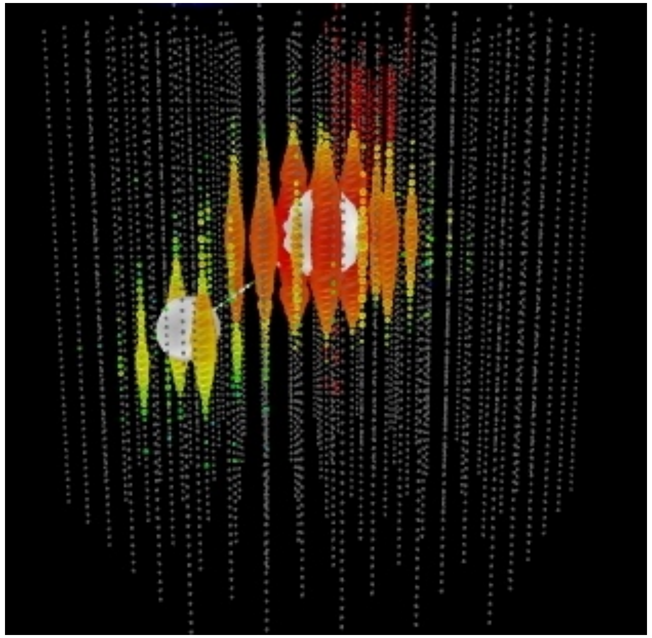


$$\nu_e + N \rightarrow e + X$$
$$\nu_x + N \rightarrow \nu_x + X$$

cascade (data)

angular resolution ~ 10°
energy resolution ~ 15%

CC tau neutrino



$$\nu_\tau + N \rightarrow \tau + X$$

"double-cascade"
(simulation)

~2 expected in 6 years

Why cross sections

We work with counting experiments

$$N_{\mathrm{MC}} = \Phi_{\mathrm{det}}(\sigma, \boldsymbol{\theta})\sigma N_{\mathrm{targets}}$$

Φ_{det} is the flux at detector and $\boldsymbol{\theta}$ is a set of model parameters

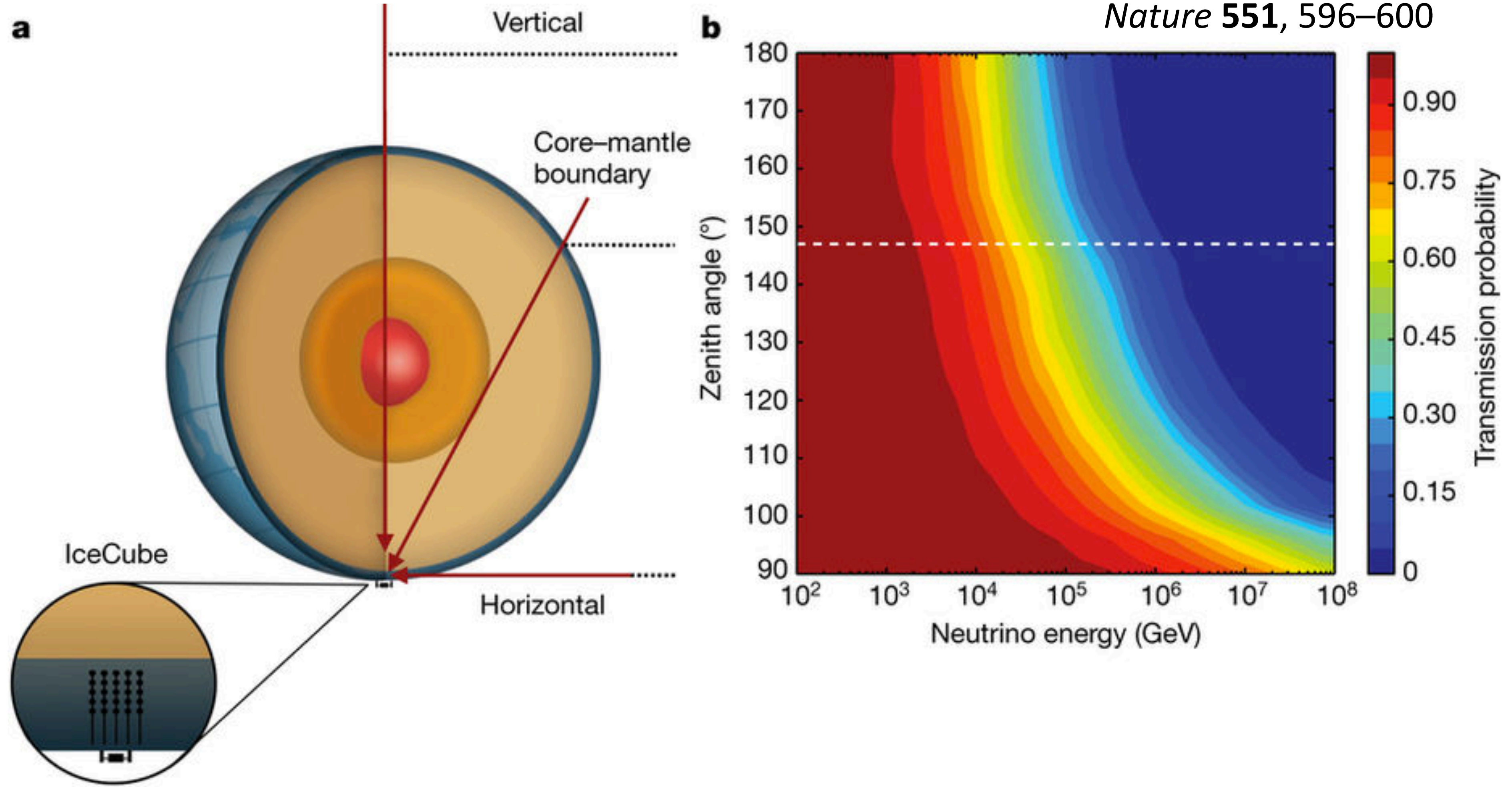
Need to know σ in order to predict N_{MC} and perform fits to data

In-Earth neutrino flux attenuation

High-energy neutrinos interact in the Earth → flux attenuation

Depends on energy E_ν and direction θ_ν

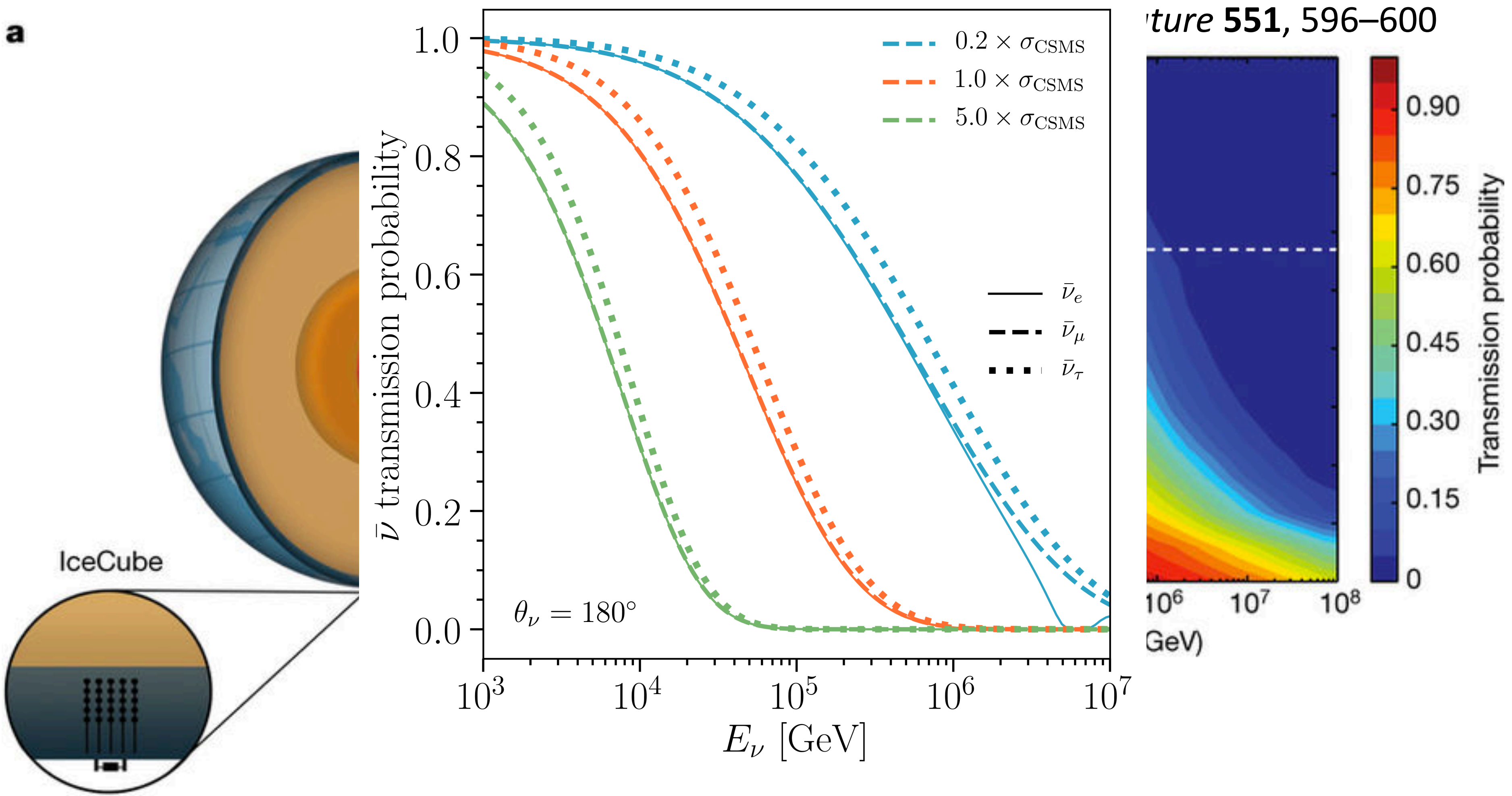
Nature **551**, 596–600



In-Earth neutrino flux attenuation

High-energy neutrinos interact in the Earth → flux attenuation

Depends on energy E_ν and direction θ_ν **and cross section**

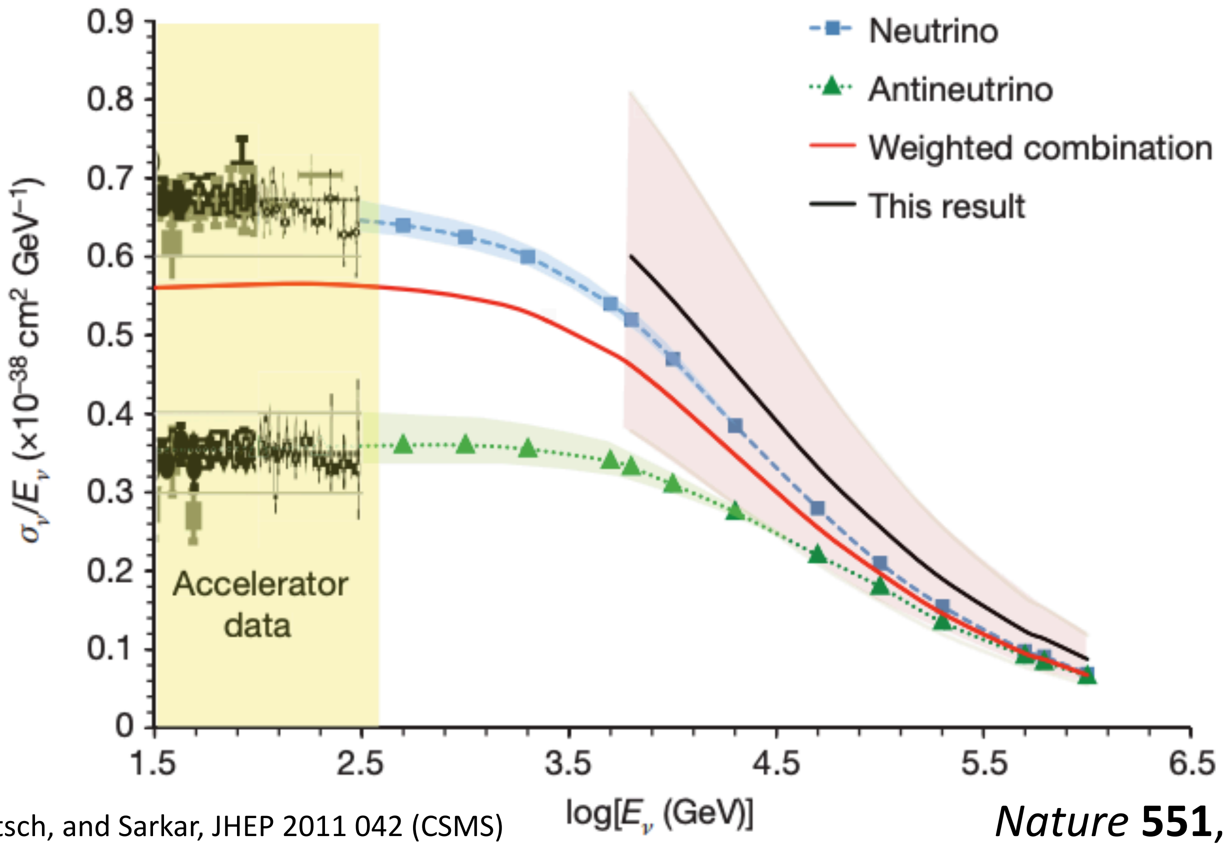


Neutrino-nucleon cross section with upgoing events

Data from 2009-2010 (79 string configuration)

10,784 upward-going events

Fit single parameter $R = \sigma_{\text{meas}}/\sigma_{\text{SM}}$ in zenith and energy



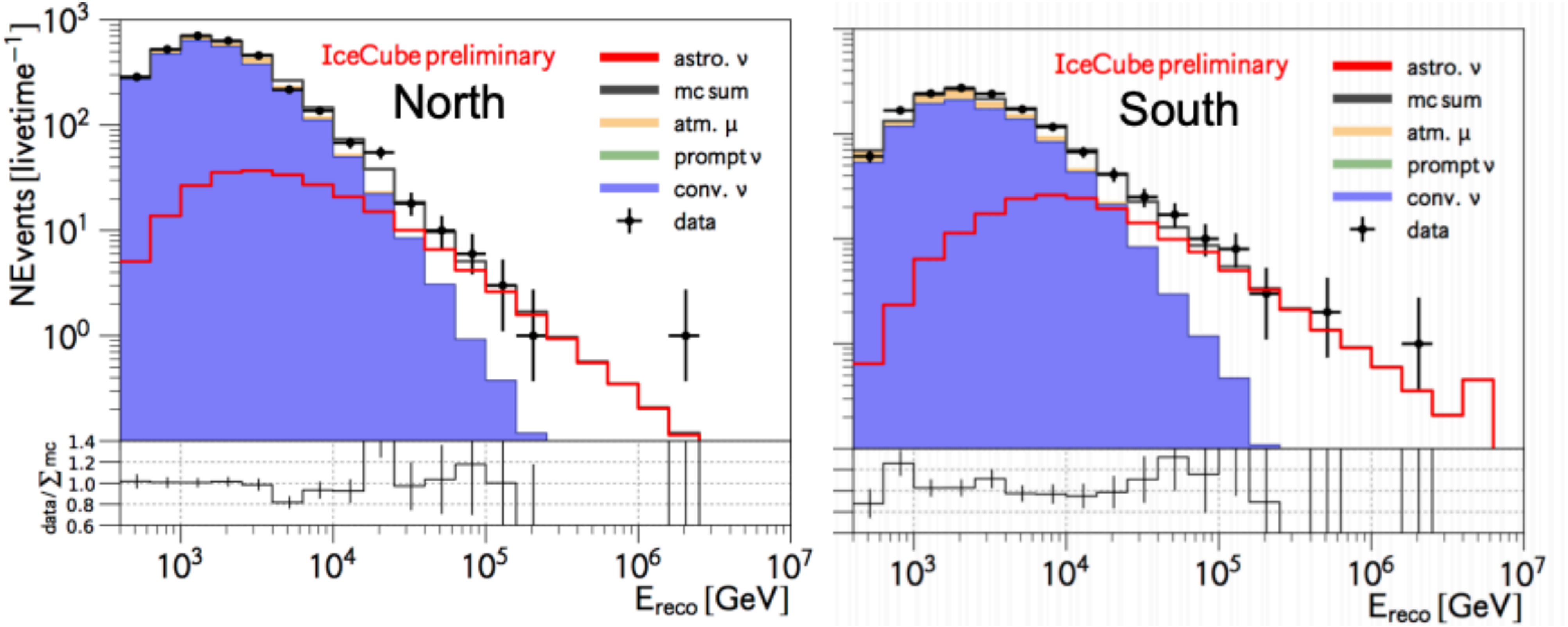
Predictions by Cooper-Sarkar, Mertsch, and Sarkar, JHEP 2011 042 (CSMS)

Nature **551**, 596–600

Using contained cascades

BDT-based selection sensitive down to ~10 TeV

2012-2015 data (4 years)



H. Niederhausen
EDS Blois 2019

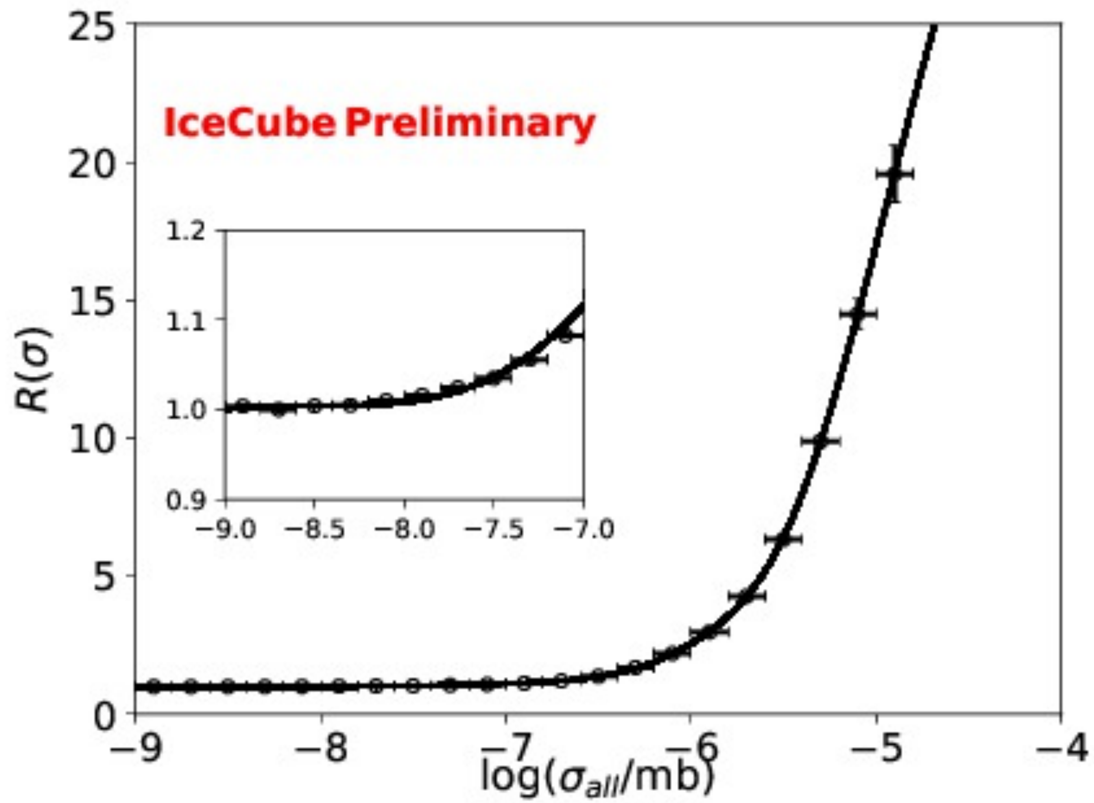
PoS(ICRC2017)968
PoS(ICRC2015)1109
IC40 PRD89 102001 (2014)
IC22 PRD84 072001 (2011)

Idea for measurement

Split sample into Northern (upgoing) and Southern (downgoing) regions

Ratio of down- vs up-going events depends on cross section

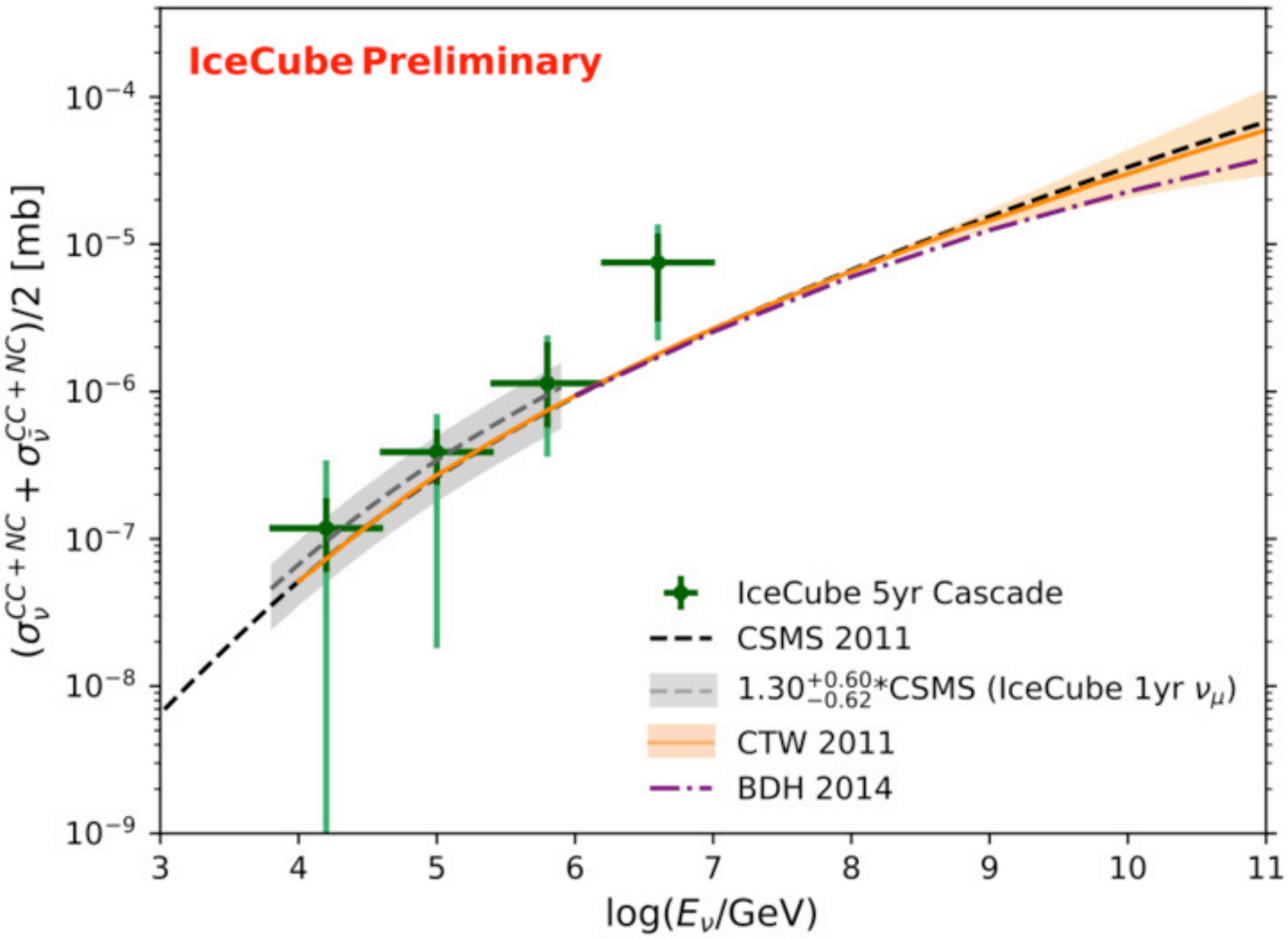
Iterative unfolding from reco → true



Cross section with contained cascades

Result presented at DIS 2018

Paper in prep.

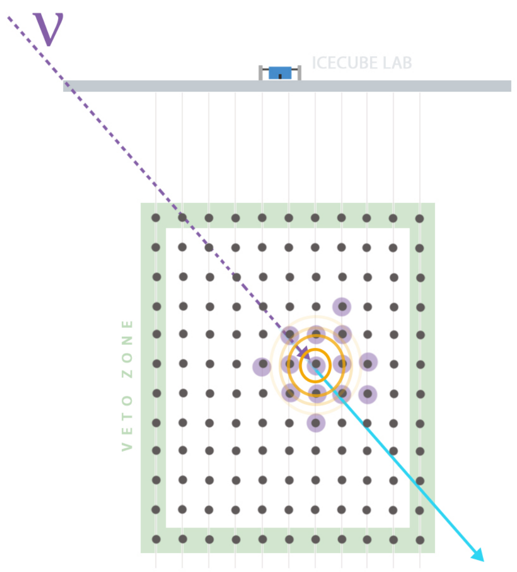


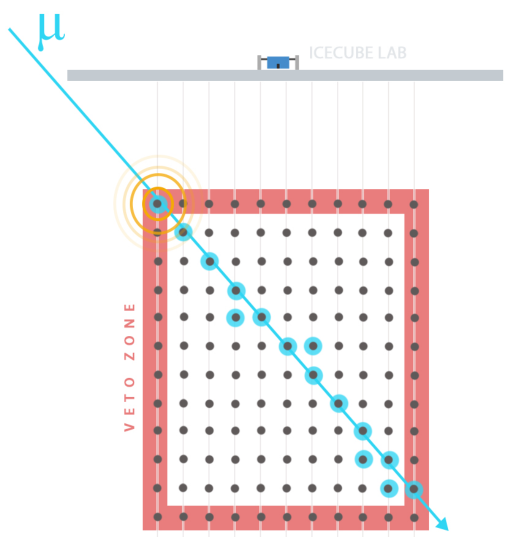
High energy starting event (HESE) selection

Contained search at high energies

Sensitive above **60 TeV**

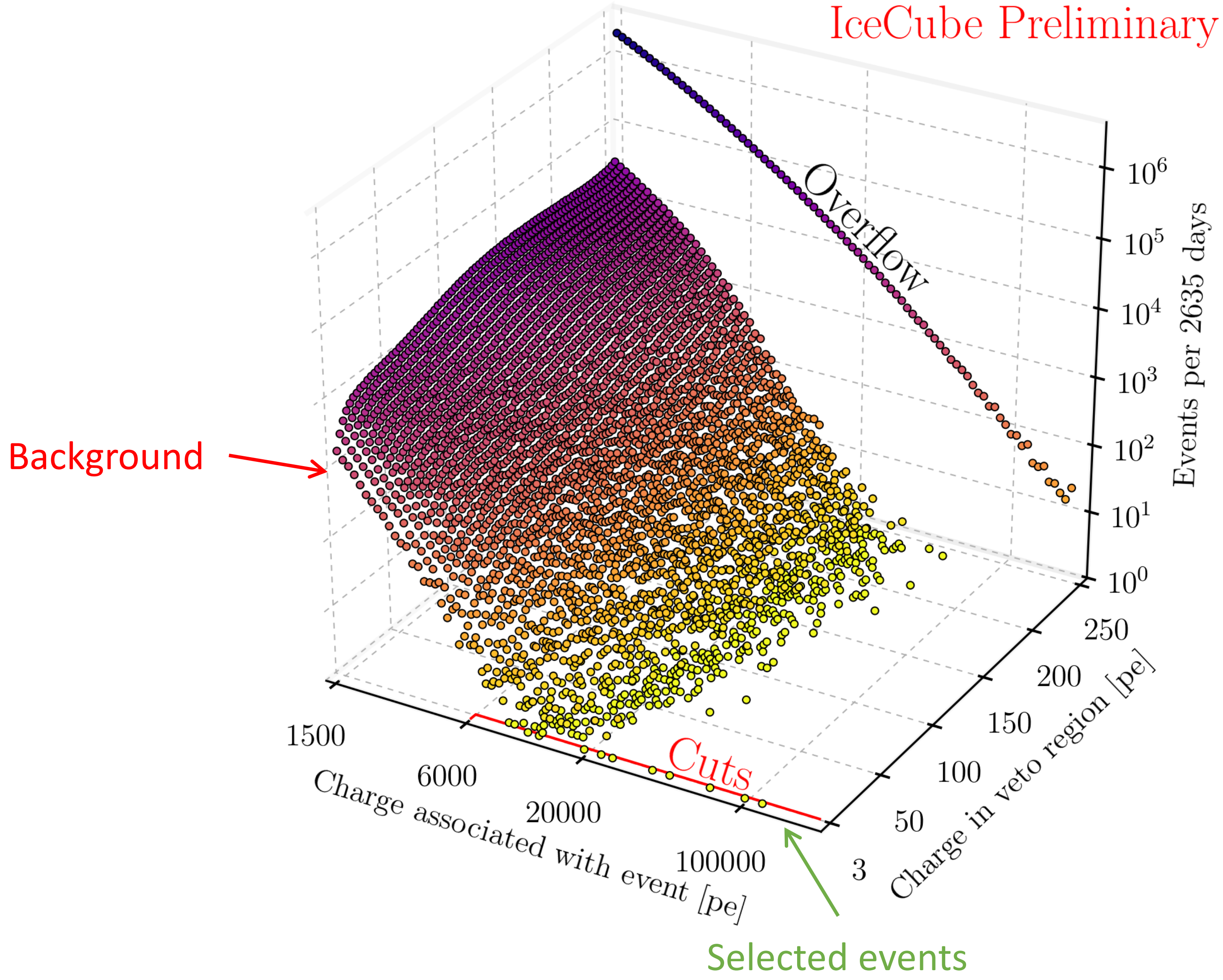
Outer layer acts as **active veto** of atmospheric muon *and* **indirect veto** of atmospheric neutrinos accompanied by sibling muons





Neutrinos in a haystack

Large muon background **rejected** by veto



Event distribution in HESE-7.5

102 events, with **60 events >60 TeV**

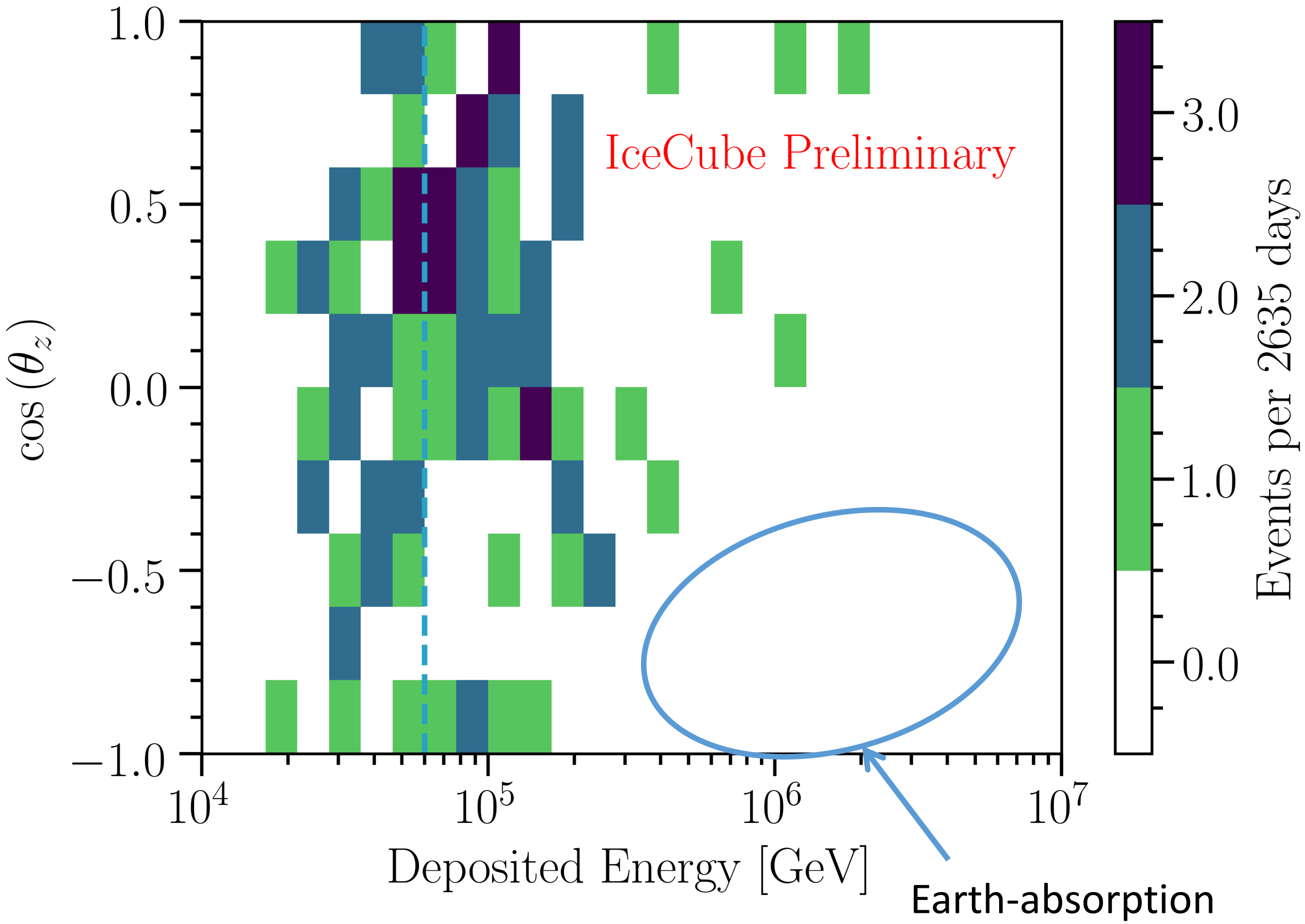
Fit performed for events above 60 TeV

Updates:

- MC-likelihood **JHEP06(2019) 030**
- Newer ice model and reconstruction
- Updated atmospheric-ν estimate **JCAP 1807 (2018) no.07, 047**
- Additional systematics treatment

Above 60 TeV:

16 new events in last 1.5 years



Analysis method

Four bins as a function of E_ν, with edges at 60 TeV, 100 TeV, 200 TeV, 500 TeV, and 10 PeV

- Denoted as: x_0, x_1, x_2, x_3

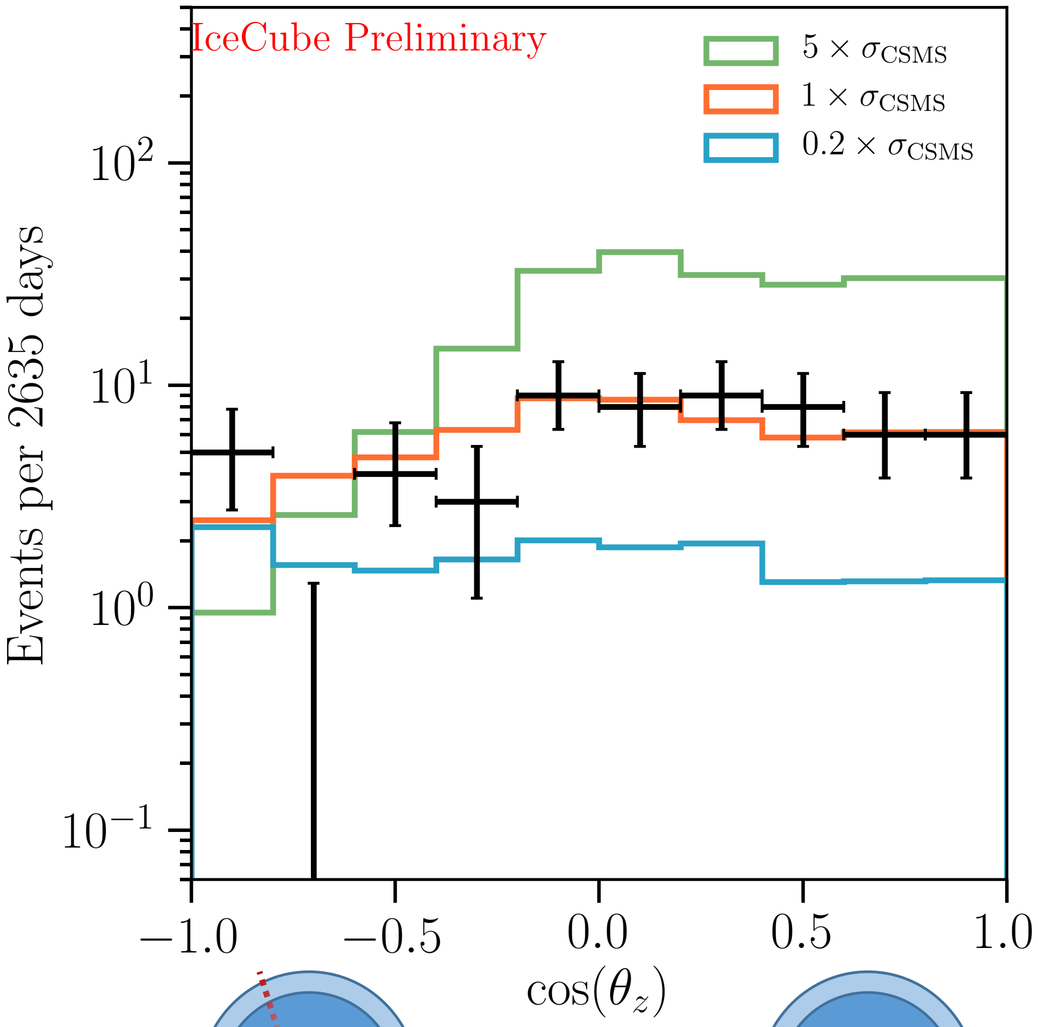
Scale nominal neutrino-nucleon cross section in each bin separately

- Assume: fixed σ_{CC}/σ_{NC} ratio, fixed $\sigma_\nu/\sigma_{\bar{\nu}}$ ratio, single-power-law flux
- CSMS calculation

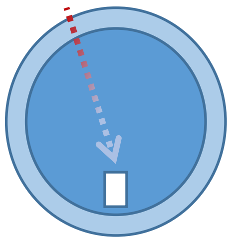
Varied cross section leads to different **MC expectations** using nuSQUIDS

Ternary PIDs for three neutrino flavors, **full-sky** information, **improved** detector modeling and background calculations

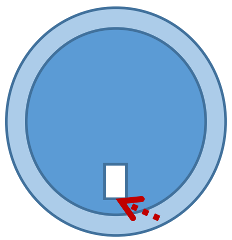
Expected distributions and data



Assuming SPL flux with floating normalization can **measure** cross section



N. sky: Flux attenuation depends on cross section, energy, zenith



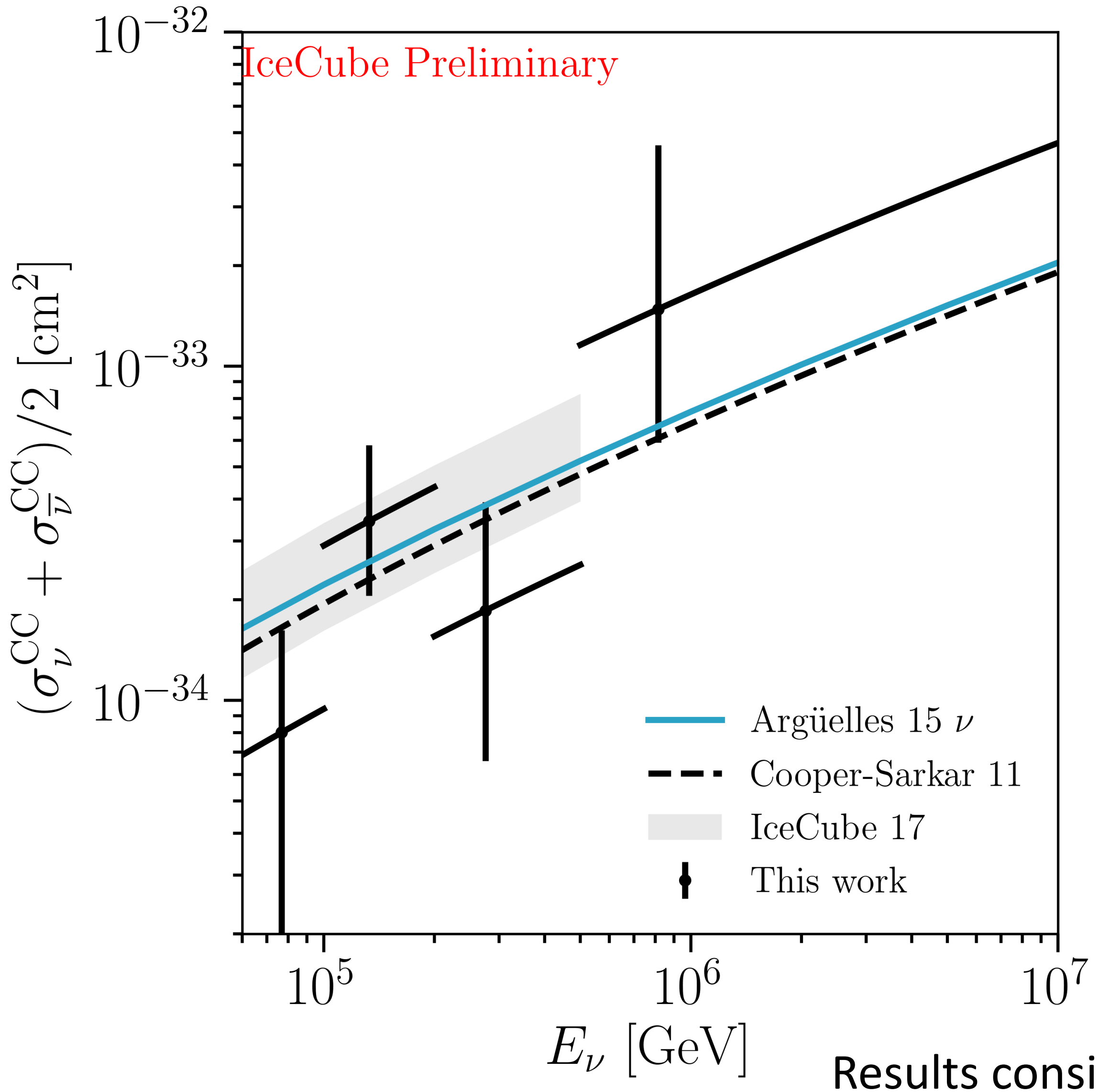
S. sky: Event rate **linearly** scales with cross section

Systematics and priors/constraints

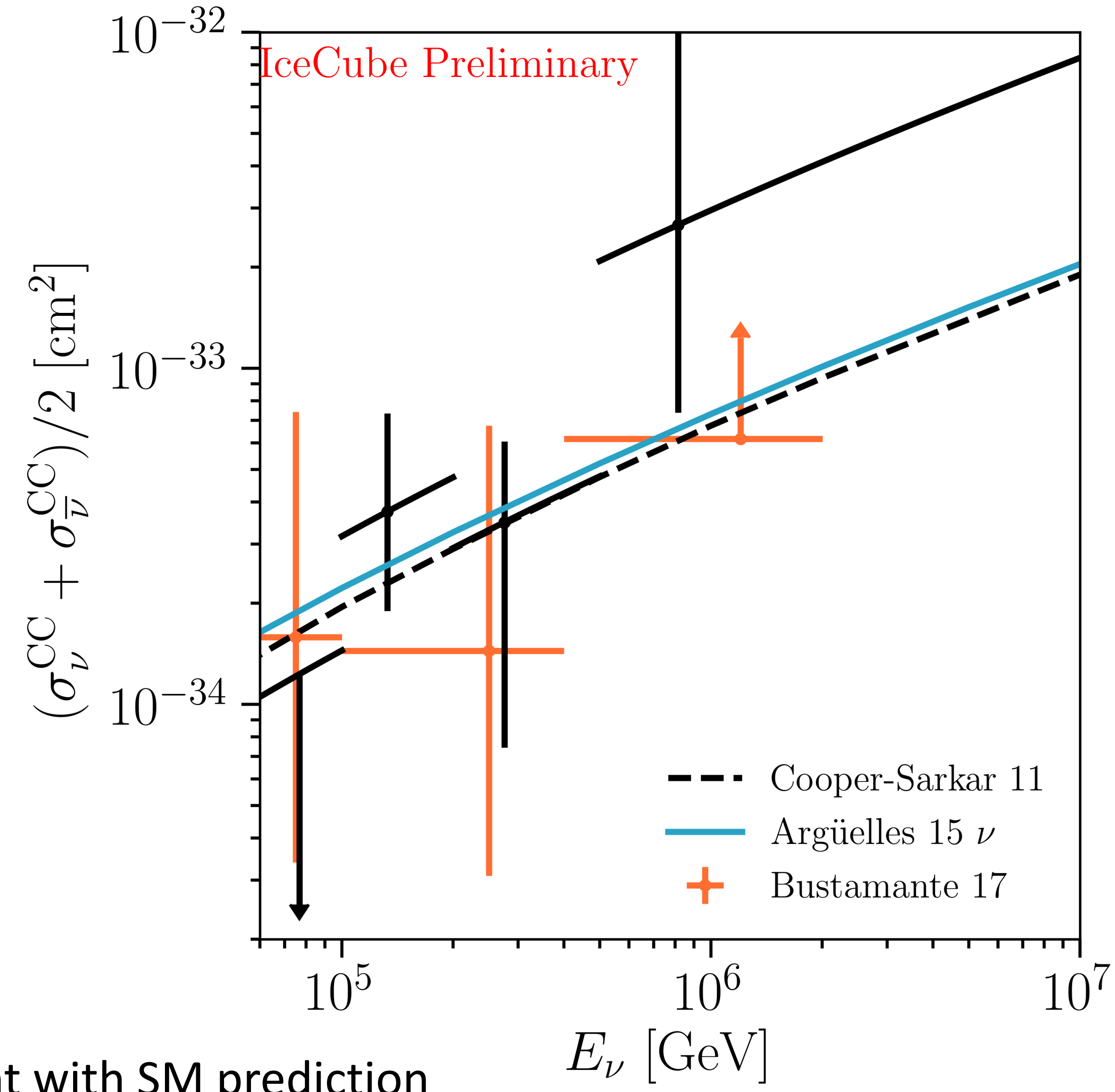
Parameter	Constraint/Prior	Range
Astrophysical neutrino flux:		
$\Phi_{\texttt{astro}}$	-	$[0, \infty)$
$\gamma_{\texttt{astro}}$	2.0 ± 1.0	$(-\infty, \infty)$
Atmospheric neutrino flux:		
$\Phi_{\texttt{conv}}$	1.0 ± 0.4	$[0, \infty)$
$\Phi_{\texttt{prompt}}$	1.0 ± 3.0	$[0, \infty)$
π/K	1.0 ± 0.1	$(-\infty, \infty)$
$2\nu/\left(\nu + \bar{\nu}\right)_{\texttt{atmo}}$	1.0 ± 0.1	$[0, 2]$
Cosmic ray flux:		
$\Delta\gamma_{\texttt{CR}}$	-0.05 ± 0.05	$(-\infty, \infty)$
Φ_{μ}	1.0 ± 0.5	$[0, \infty)$

Results with HESE-7.5

Frequentist result

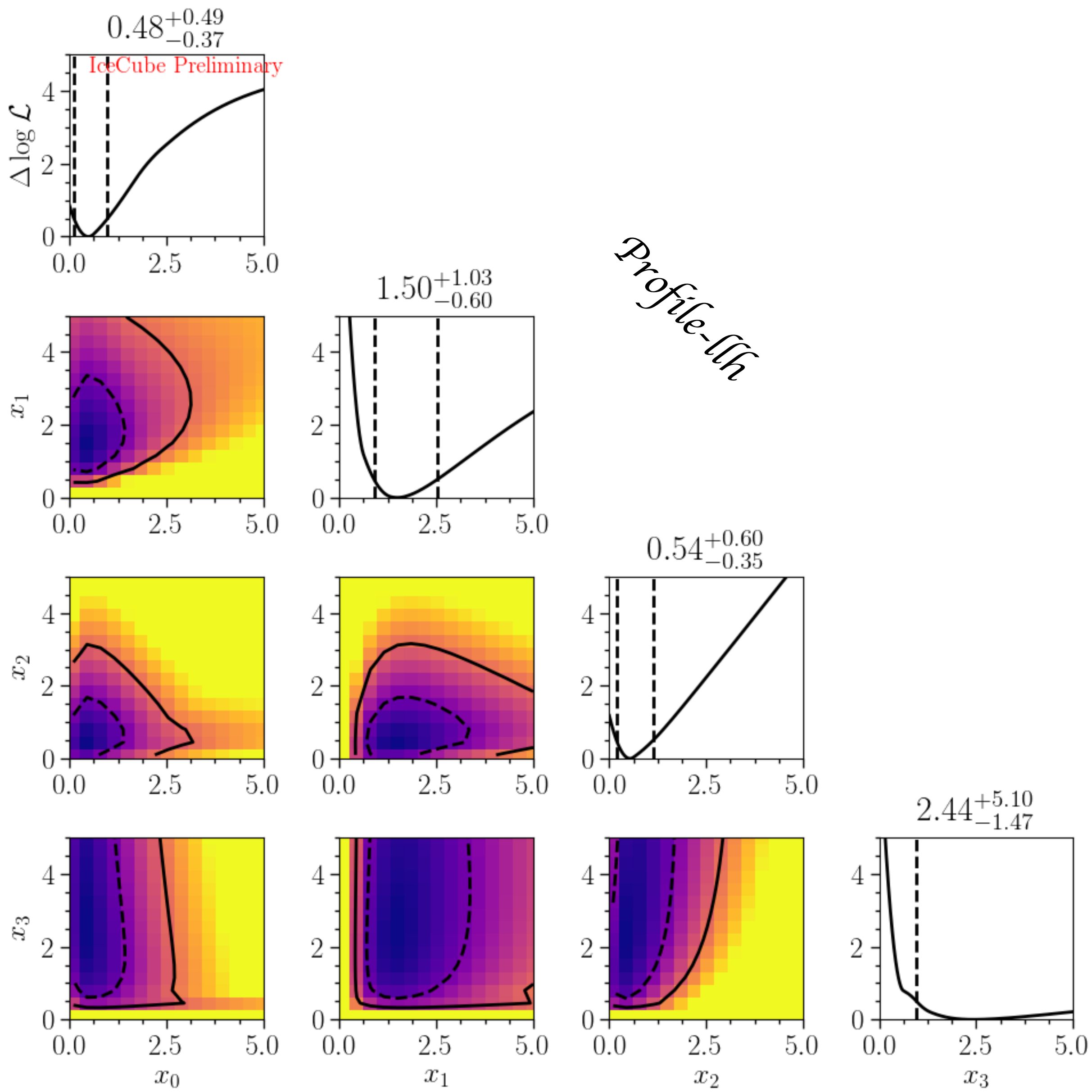


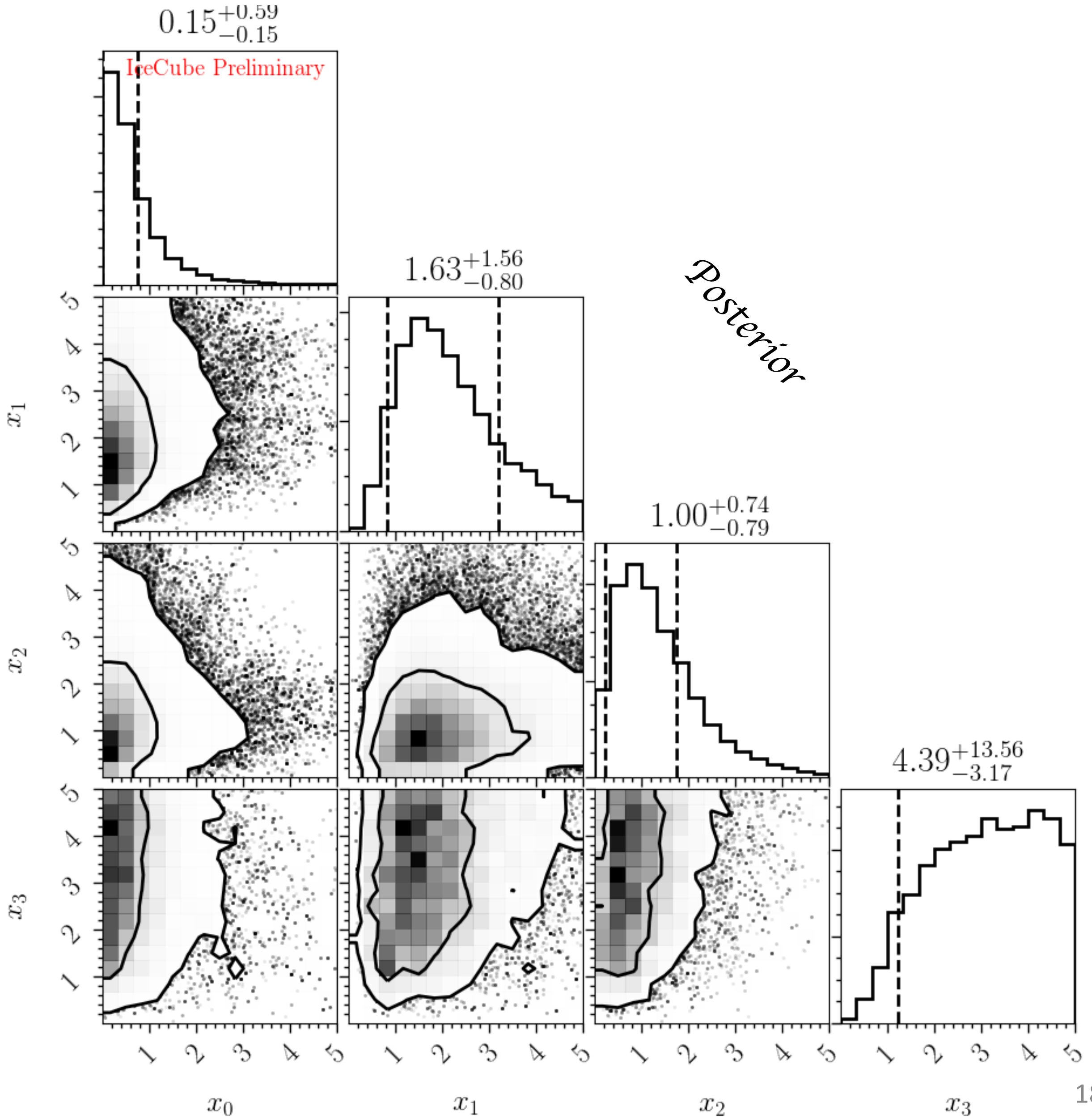
Bayesian result



Results consistent with SM prediction

Likelihood and posterior





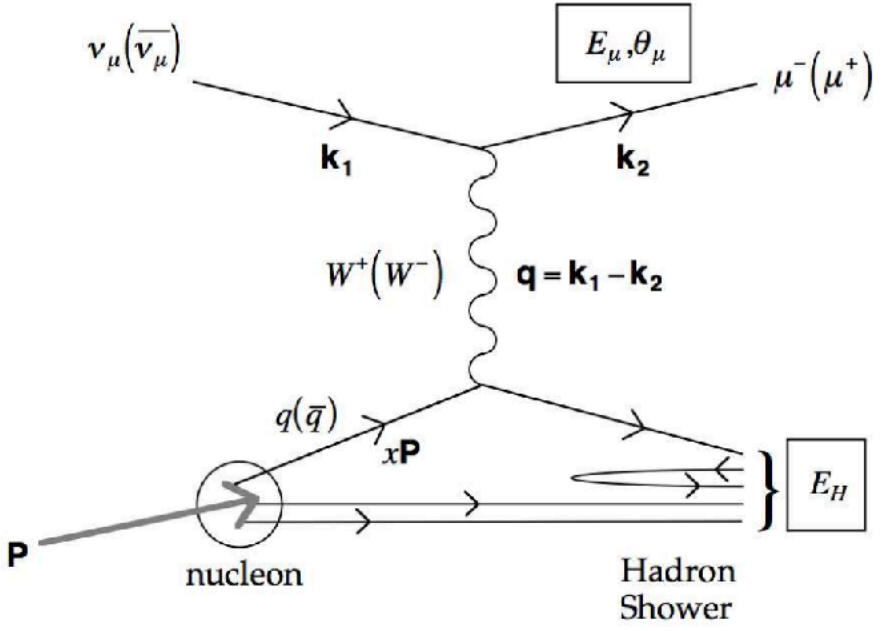
Inelasticity y

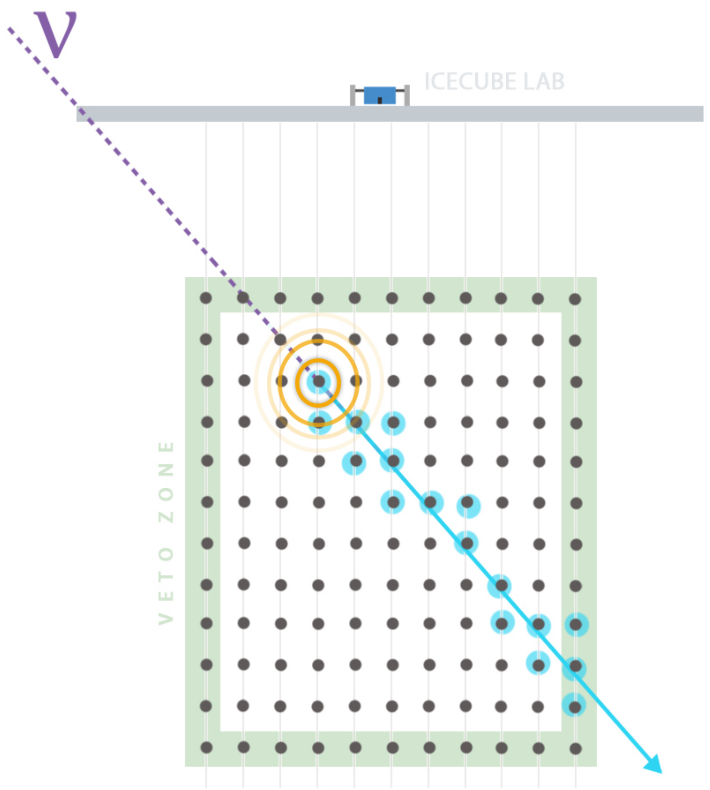
Ratio of hadronic cascade energy to total neutrino energy

- NuTeV measured up to 250 GeV

Starting tracks and cascades → Veto based

Rev. Mod. Phys. 84, 1307



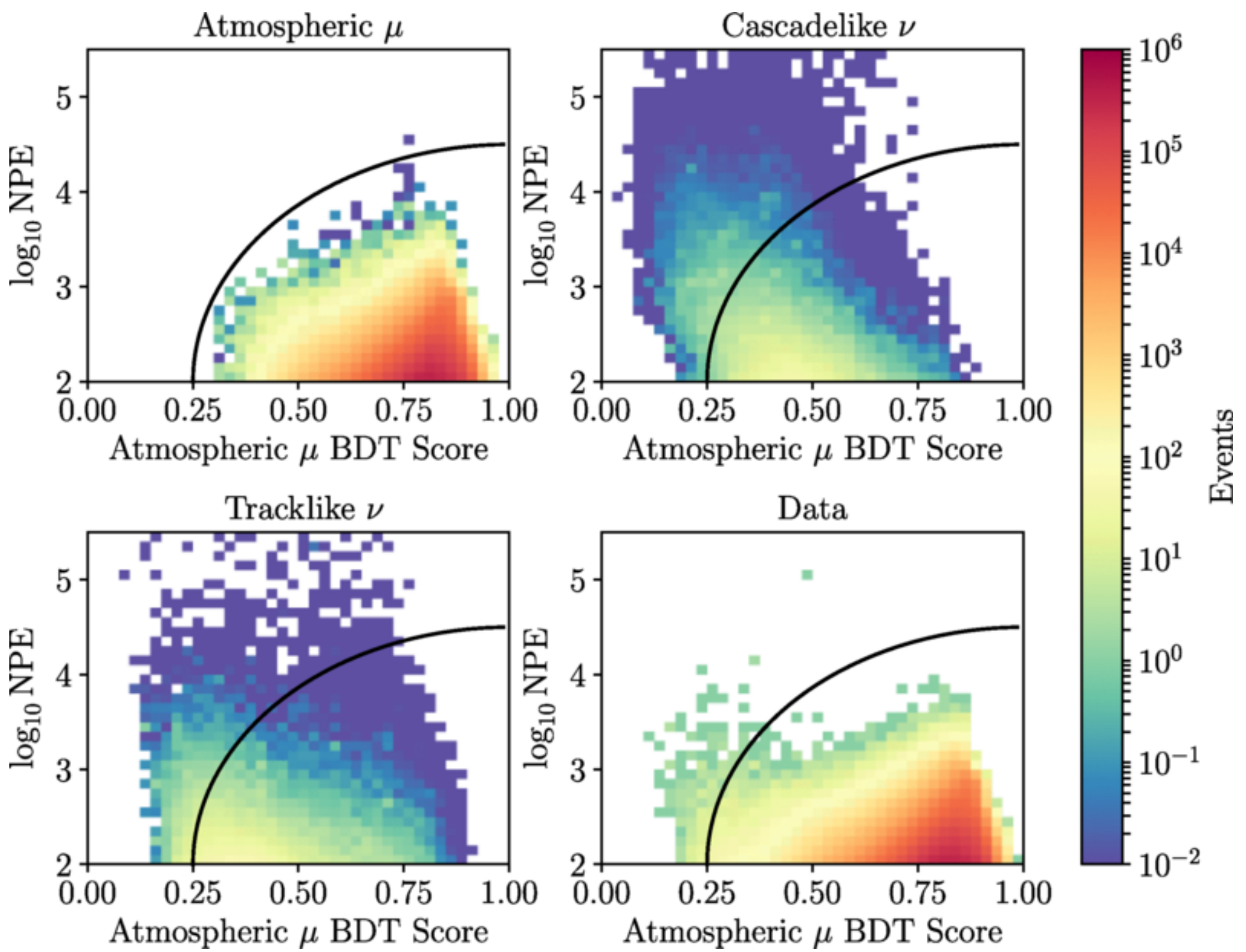


BDT event classification

PRD **99**, 032004

15 input variables

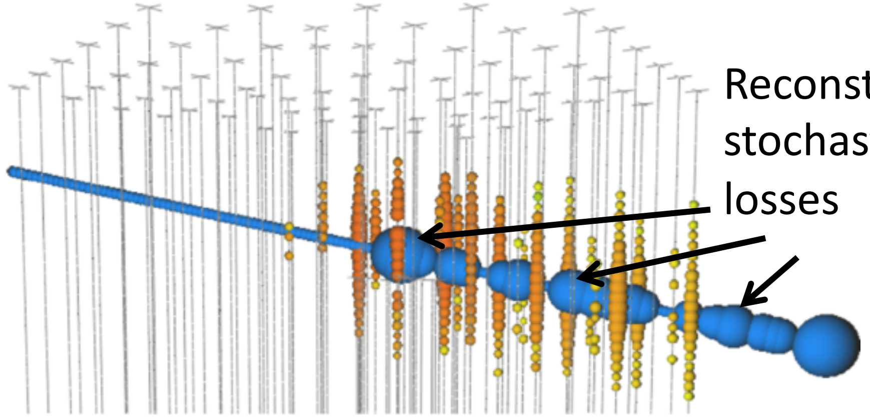
Further reject atmospheric μ bkg and classify signal into tracks/cascades



Reconstructing y_{vis}

PRD **99**, 032004

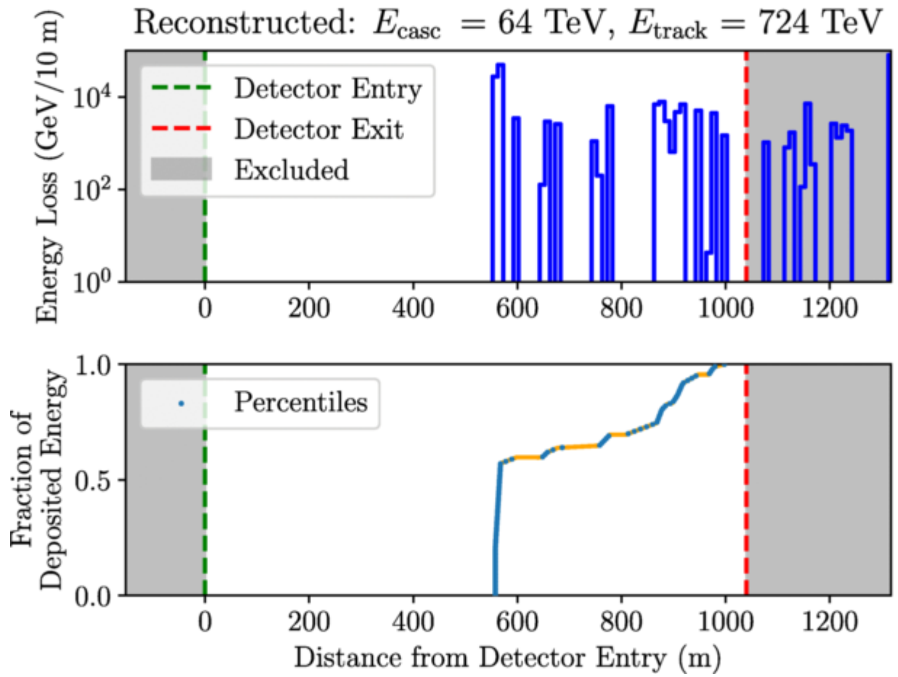
Most energetic data event

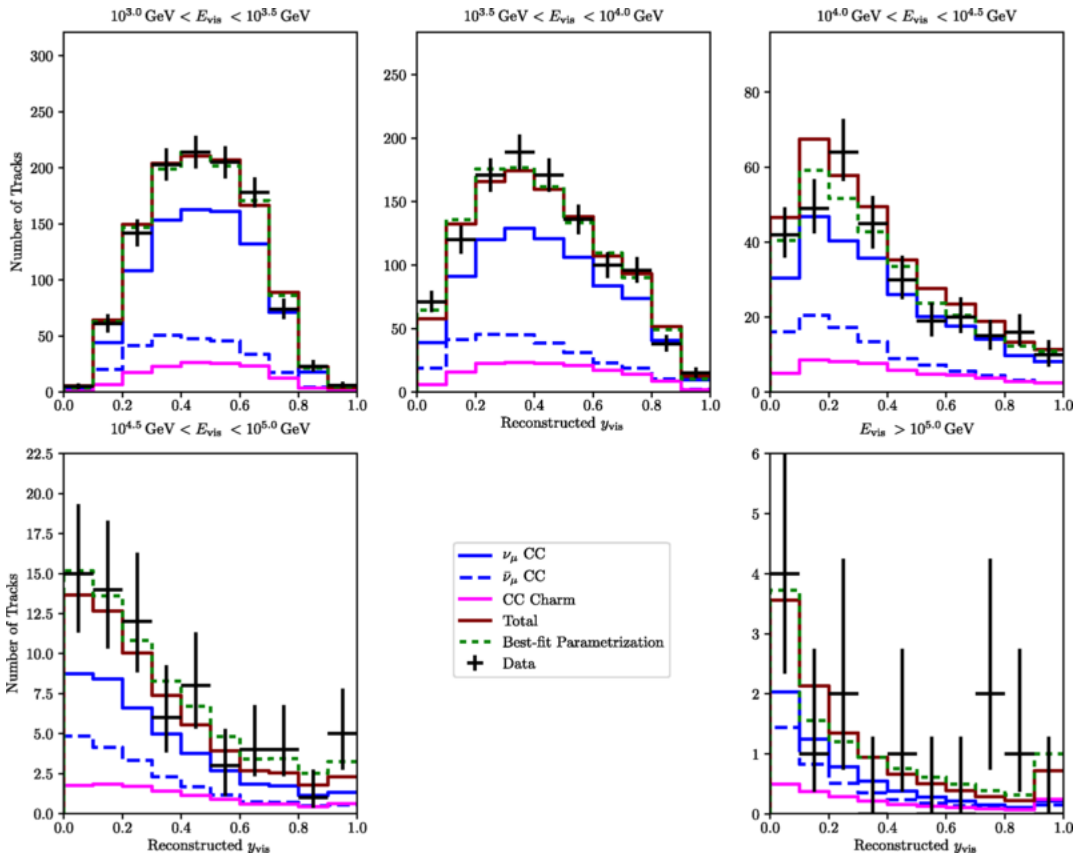


Reconstructed stochastic energy losses

$$E_{\mathrm{vis}} = E_{\mathrm{casc}} + E_{\mathrm{track}}$$
$$y_{\mathrm{vis}} = E_{\mathrm{casc}}/E_{\mathrm{vis}}$$

Random forest for E_{casc} and E_{track}



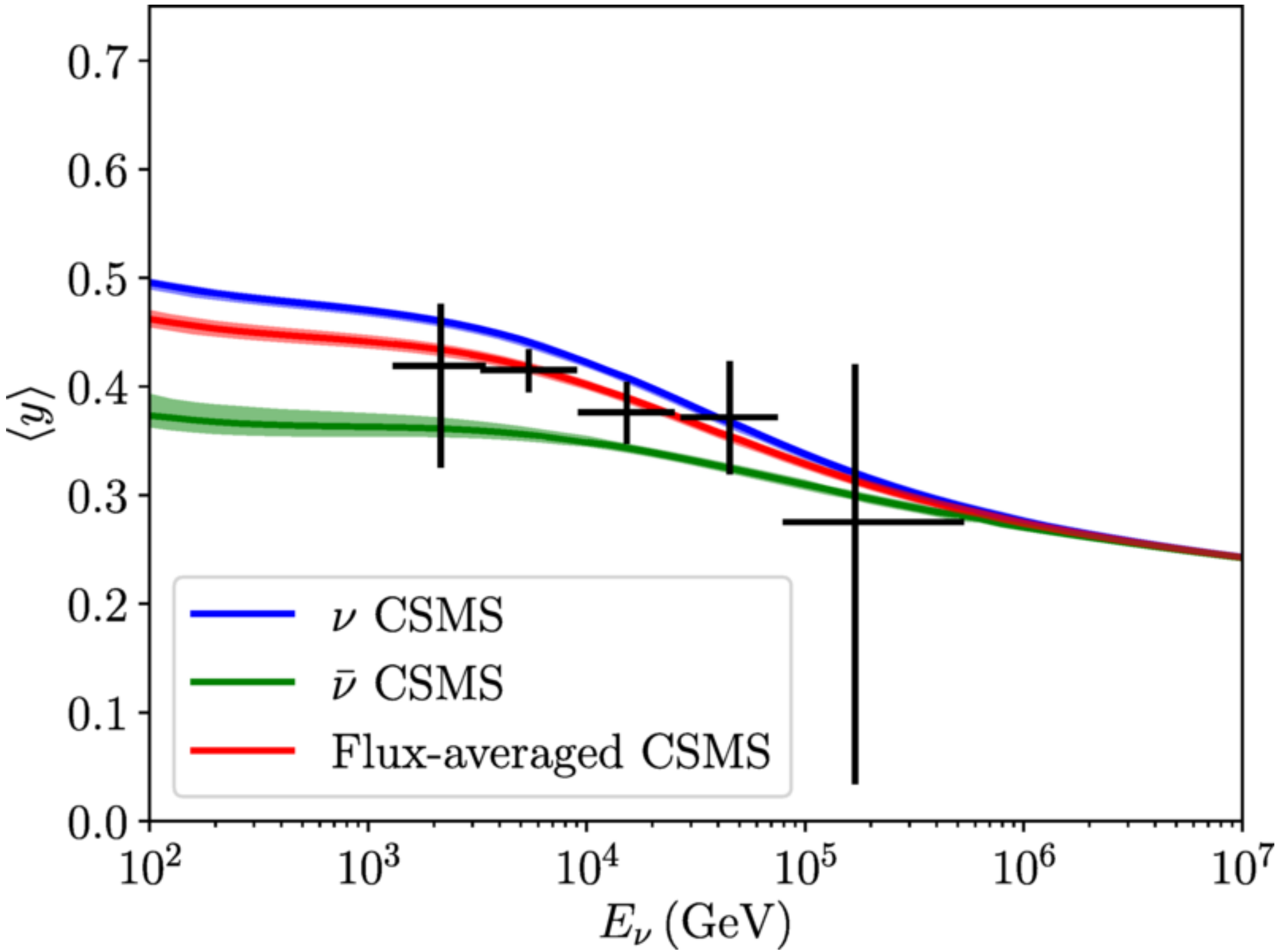


Fit for mean inelasticity

PRD **99**, 032004

Parameterize and reweight MC in terms of mean $\langle y \rangle$

Fit to y_{vis} distributions in each energy range



Summary

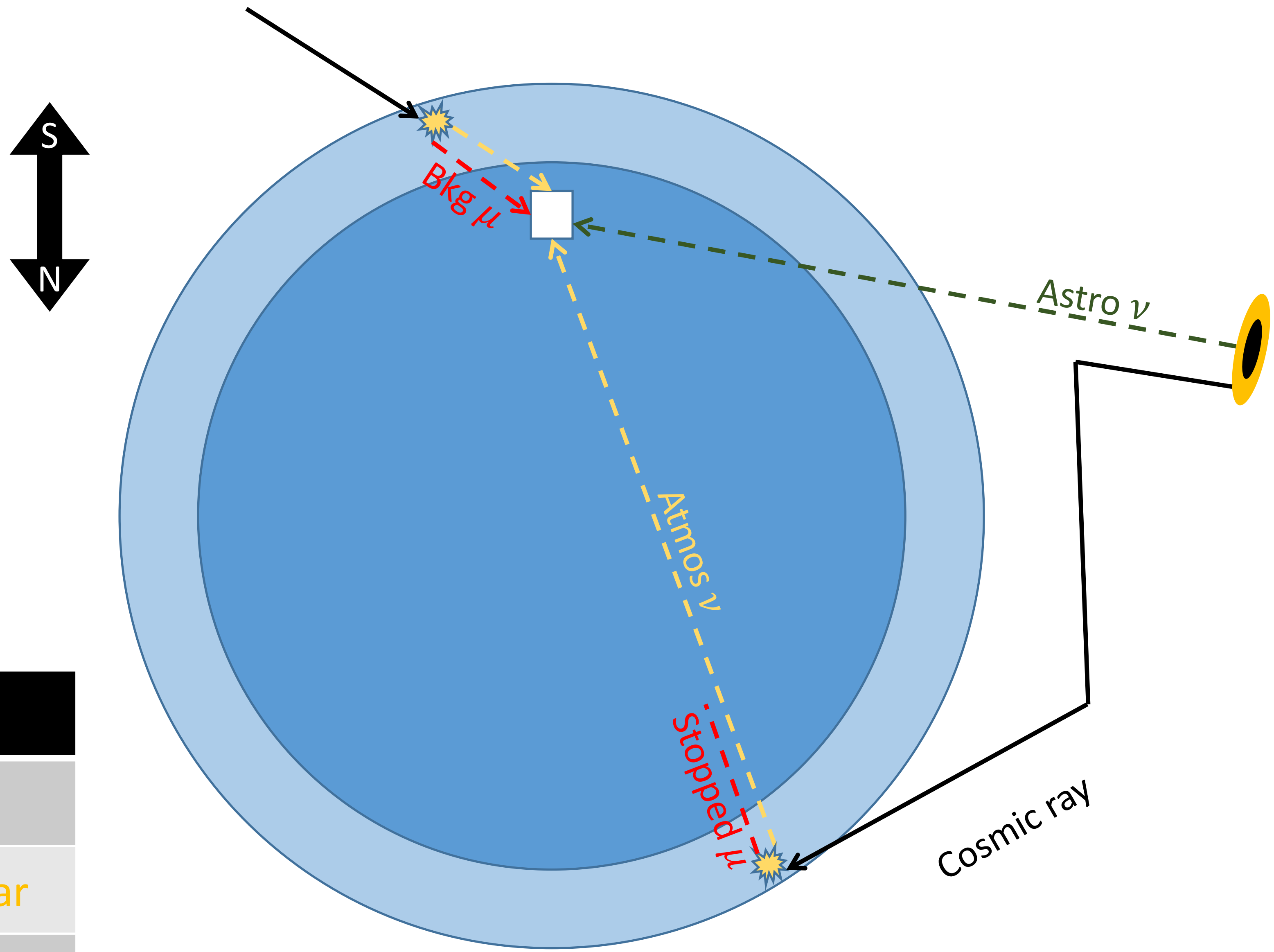
Several measurements of neutrino-nucleon interactions above TeV energies

- Neutrino-nucleon cross sections with various samples
- Inelasticity

Updates in the pipeline will incorporate additional years of data

Backups

Muons and neutrinos



Event type	Rate
Atmospheric μ	~3 kHz
Atmospheric ν	~100k per year
Astrophysical ν	~100 per year