A first measurement of high-energy neutrino cross sections with astrophysical neutrinos

Mauricio Bustamante

In collaboration with Amy Connolly

CCAPP Summer Seminar Series

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The Ohio State University
Center for Cosmology and Astroparticle Physics

Two seemingly unrelated questions —

1. Where are the most energetic particles coming from?

2. What is the structure of matter at the smallest scales?

Symmetry Magazine

Neutrino interactions are weak . . .

. . . but we are persistent

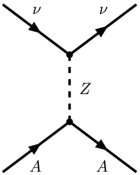
At center-of-mass energy of 1 GeV:

$$\begin{aligned}\sigma_{pp} &\sim 10^{-28}\ \text{cm}^2\\ \sigma_{\gamma p} &\sim 10^{-29}\ \text{cm}^2\\ \sigma_{\nu p} &\sim 10^{-38}\ \text{cm}^2\end{aligned}$$

Neutrino interactions at different energy scales

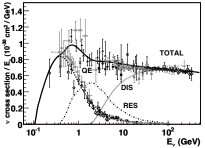
< 1 MeV

Not observed — Coherent neutrino-nucleus scattering, capture on radioactive nuclei



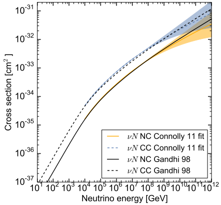
1 MeV – 350 GeV

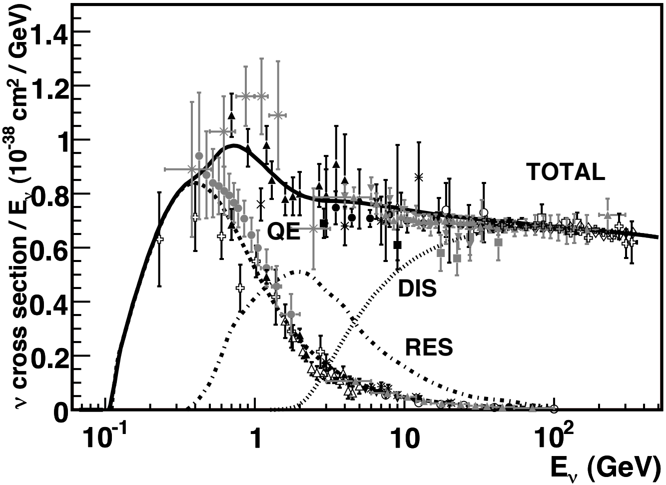
Lots of data — Quasi-elastic scattering, resonance production, deep inelastic scattering



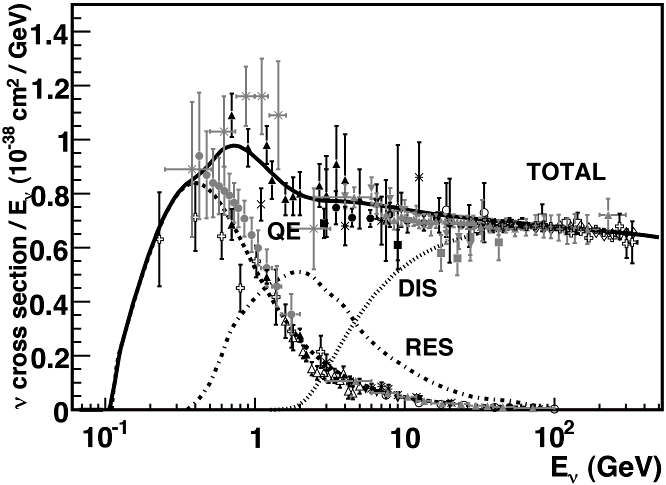
> 350 GeV

Not observed — No high-energy neutrino beam available... til now




ν cross section / E_ν (10^{-38} cm^2 / GeV)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
TOTAL
QE
DIS
RES
10^{-1}
1
10
10^2
E_ν (GeV)

← ?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E_ν (GeV)
TOTAL
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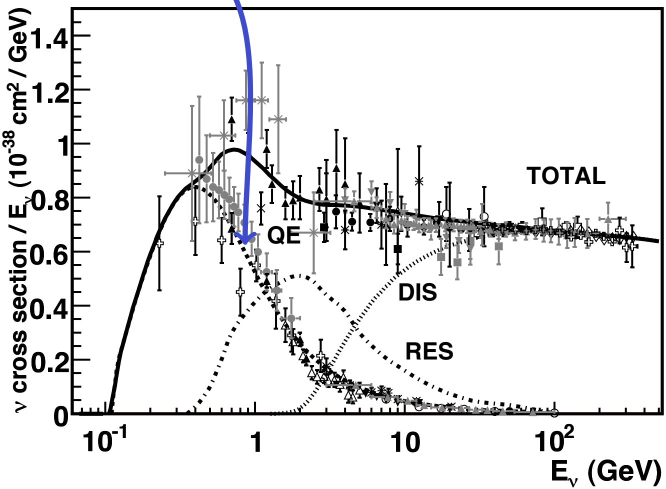
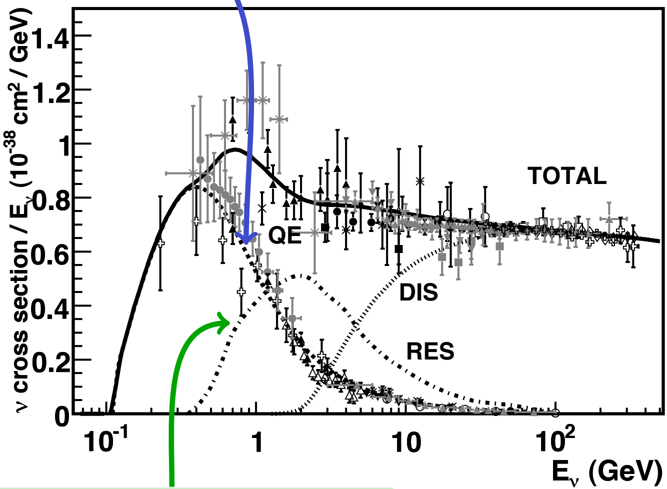
? →

$$\nu_l + n \rightarrow l^- + p$$
$$\bar{\nu}_l + p \rightarrow l^+ + n$$



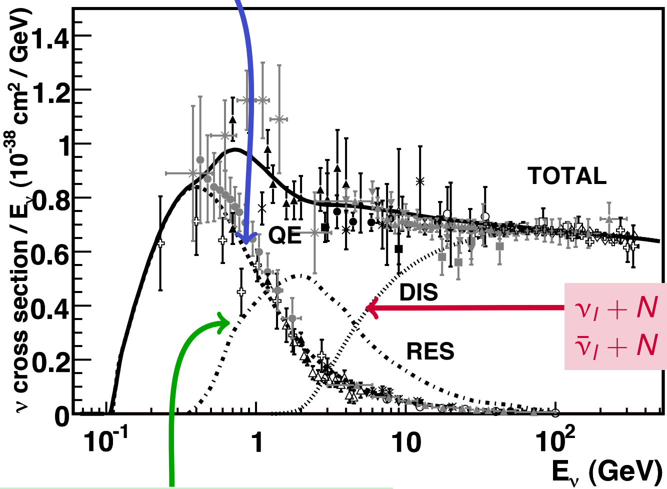
$$\nu_l + n \to l^- + p$$
$$\bar{\nu}_l + p \to l^+ + n$$



$$\nu_l + N \to l^- + N^* \to l^- + \pi + N'$$

PARTICLE DATA GROUP

$$\nu_l + n \to l^- + p$$
$$\bar{\nu}_l + p \to l^+ + n$$

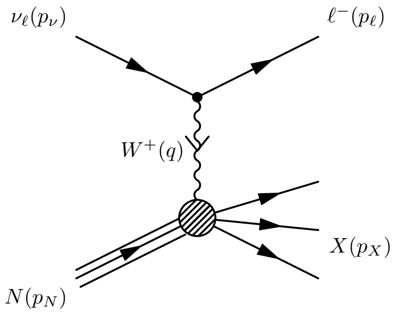


$$\nu_l + N \to l^- + X$$
$$\bar{\nu}_l + N \to l^+ + X$$

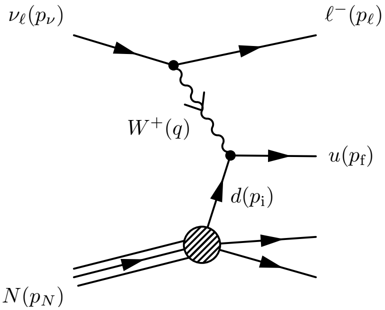
$$\nu_l + N \to l^- + N^* \to l^- + \pi + N'$$

How does DIS probe nucleon structure?

What you see

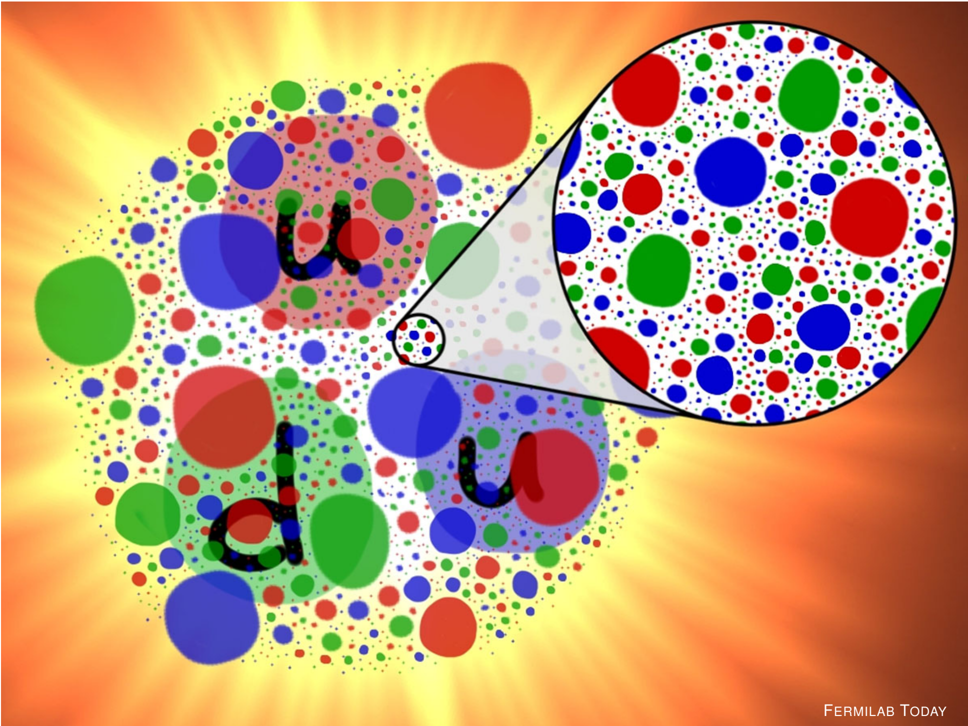


Beneath the hood



Plus the equivalent neutral-current process (Z-exchange)

GIUNTI & KIM, *Fundamentals of Neutrino Physics & Astrophysics*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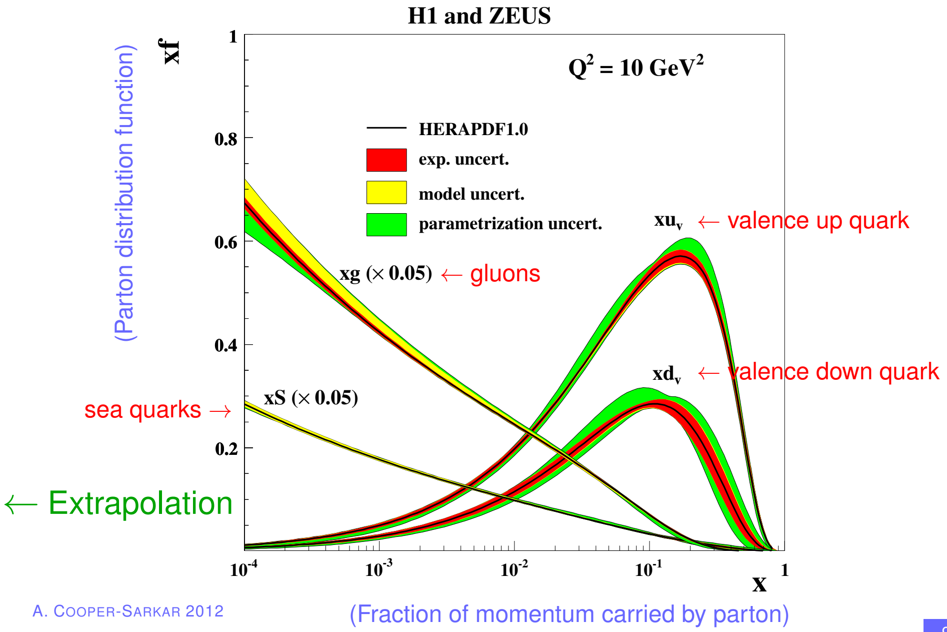
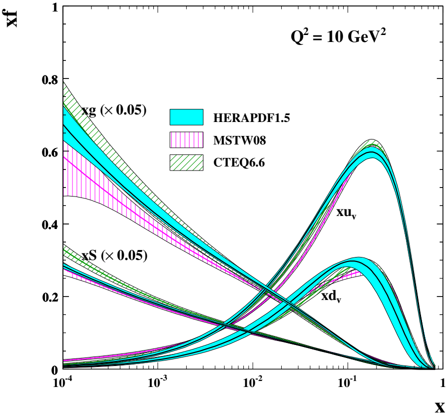
Peeking inside a proton

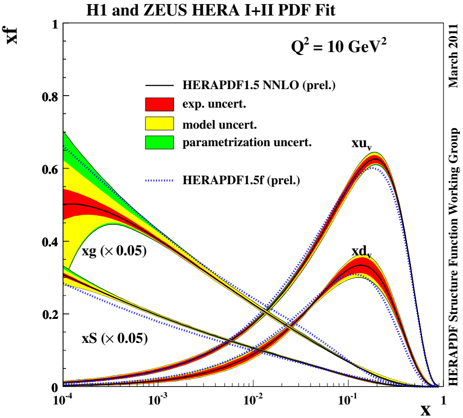


The world of PDFs is messy

Different fitting groups

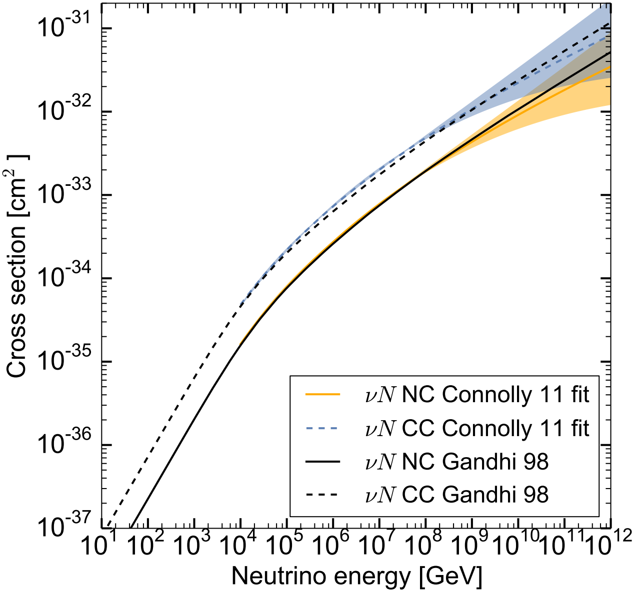


Different QCD prescriptions

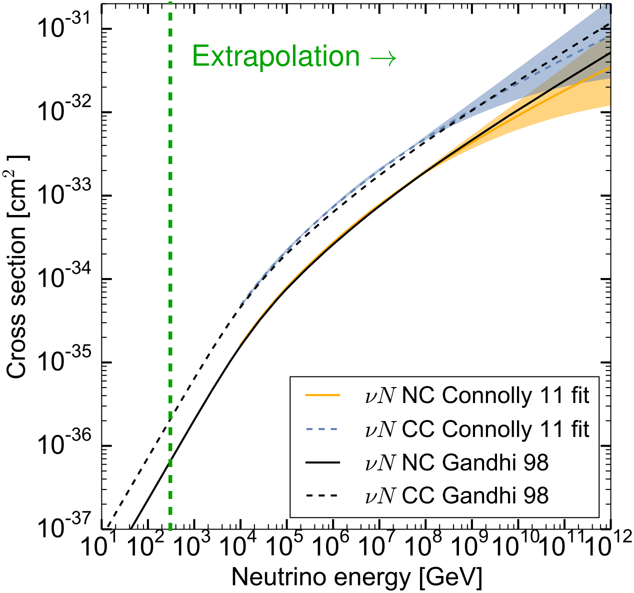


A. Cooper-Sarkar 2012

Extrapolating the neutrino cross section

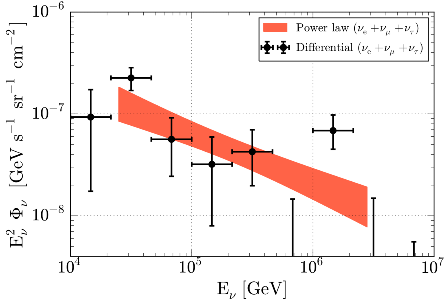


Extrapolating the neutrino cross section



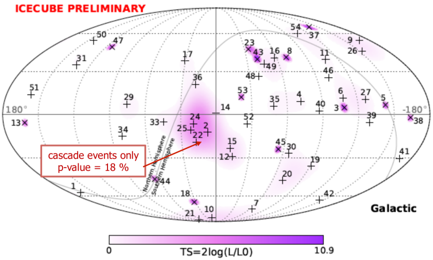
High-energy neutrinos in IceCube

54 (contained) events with 30 TeV – 2 PeV in 4 years



◄ Astrophysical neutrinos dominate above ~ 100 TeV

Arrival directions compatible with isotropy ►



How does IceCube see neutrinos?

Two types of fundamental interactions:

Charged-current

$\nu_l + N \rightarrow \boxed{l} + \boxed{\text{hadrons}}$

Neutral-current

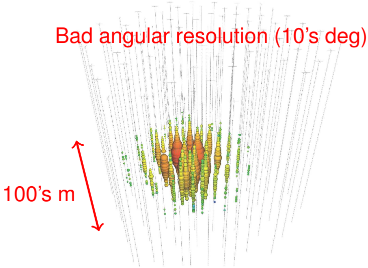
$\nu_l + N \rightarrow \nu_l + \boxed{\text{hadrons}}$

these shower and make light

Two event topologies (below $E_\nu \sim 5$ PeV):

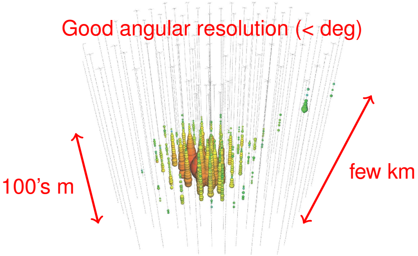
Showers

Made by CC ν_e or ν_τ; or by NC ν_x



Tracks

Made mainly by CC ν_μ



How do we measure the cross section?

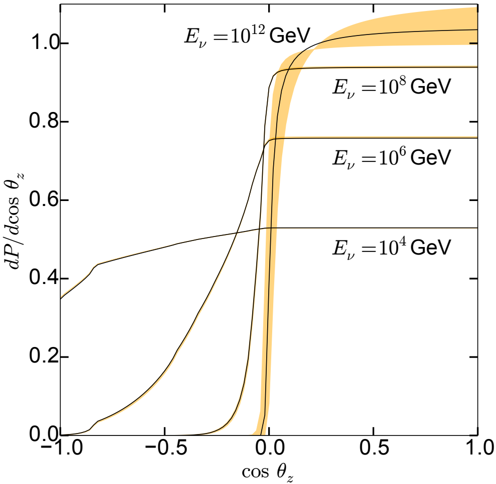
By looking at the angular distribution of events —

- Earth absorbs neutrinos
- Absorption factor:

$$e^{-D(\theta_z)/L_{\rm int}(E_\nu,\theta_z)}$$

- Interaction length:

$$L_{\rm int} = \frac{m_N}{\sigma_{\nu N}^{\rm CC+NC}(E_\nu)\cdot\langle\rho_\oplus(\theta_z)\rangle}$$



(Cosine of zenith angle)

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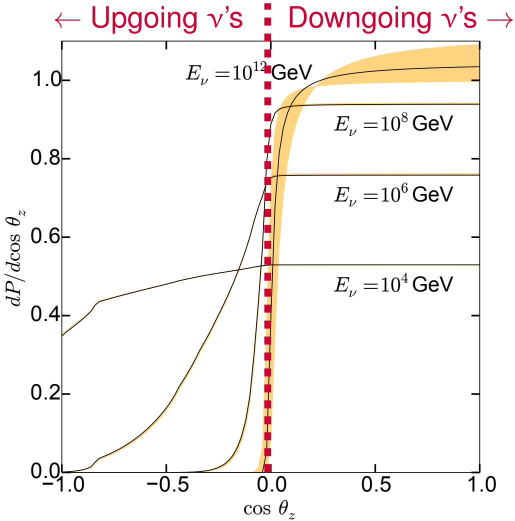
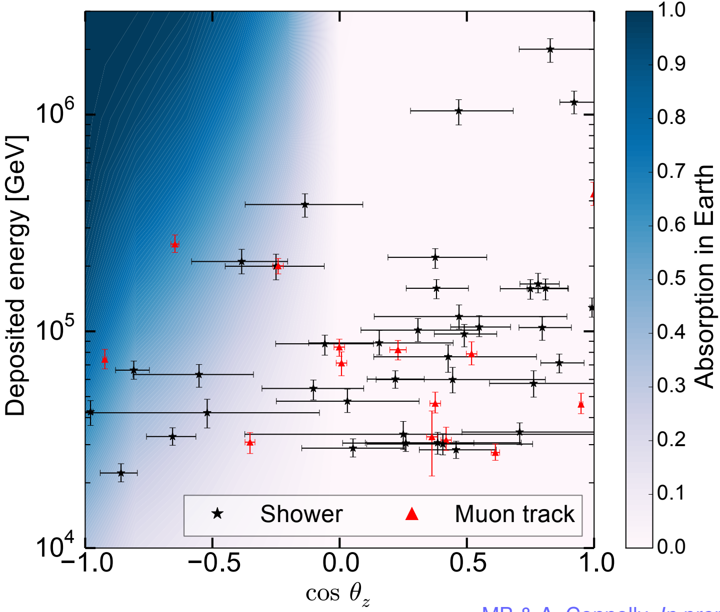


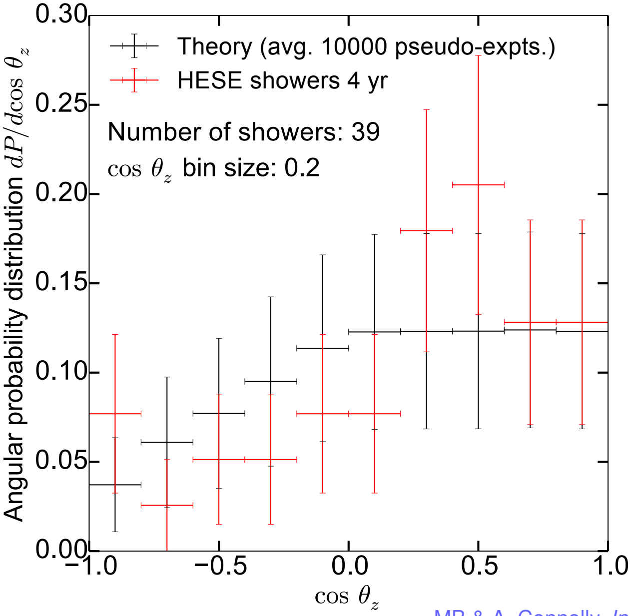
(Cosine of zenith angle)

The IceCube neutrino sample



MB & A. Connolly, *In prep.*

Comparing theory to observations (preliminary)



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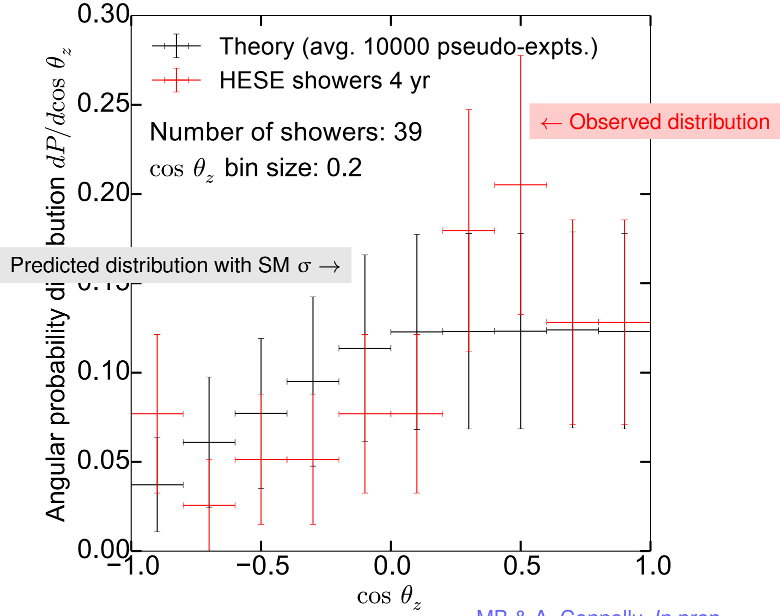

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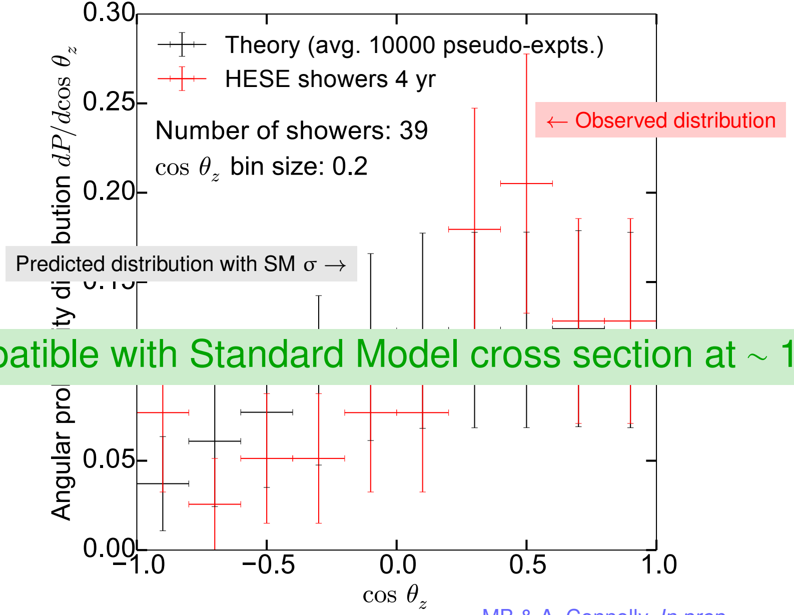


Compatible with Standard Model cross section at $\sim 1\sigma$

MB & A. Connolly, *In prep.*

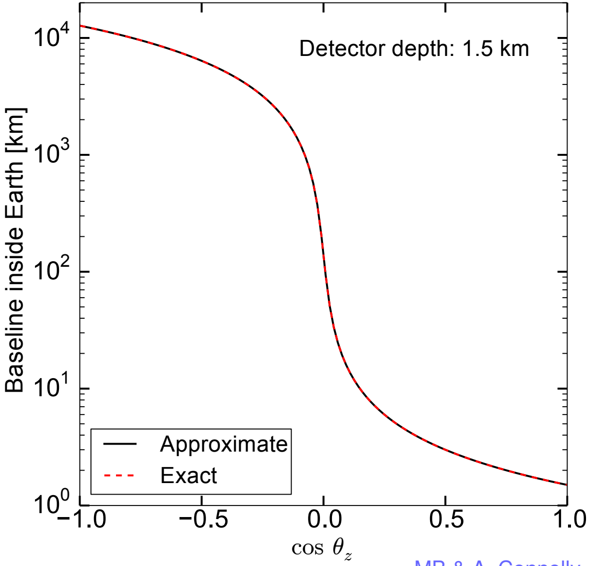
Caveats

- Limited statistics (for now)
- Large errors in arrival directions $\rightarrow$ errors in attenuation factor
- Only constrains charged-current + neutral-current cross section
- Cannot separate ν from $\bar{\nu}$
- Astrophysical flux has large uncertainties

But this is the best one can do in the foreseeable future

Backup slides

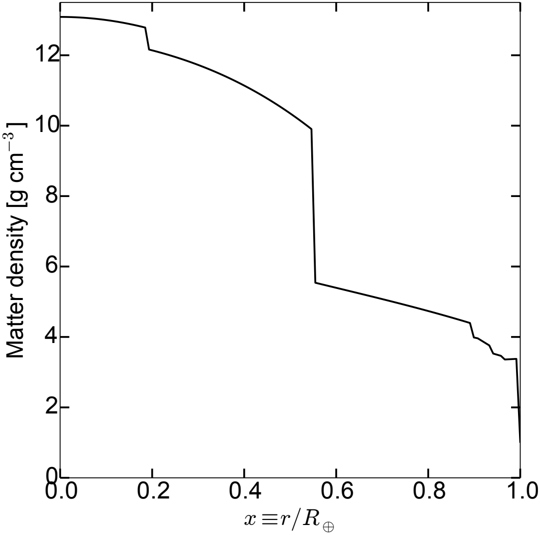
Neutrino baseline inside the Earth



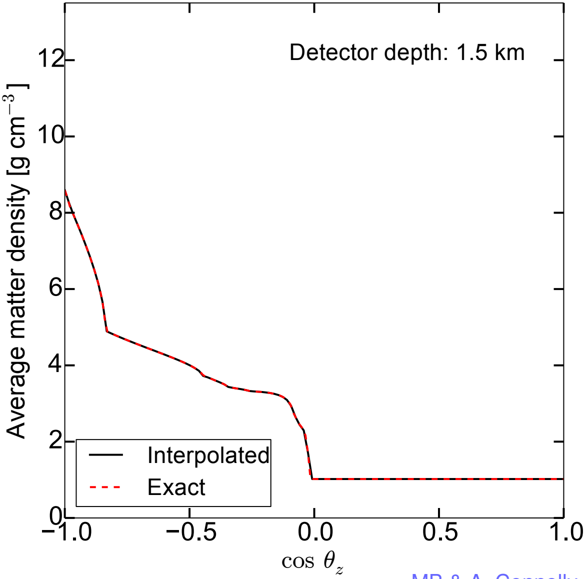
MB & A. Connolly, *In prep.*

Earth density profile

From the Preliminary Reference Earth Model —



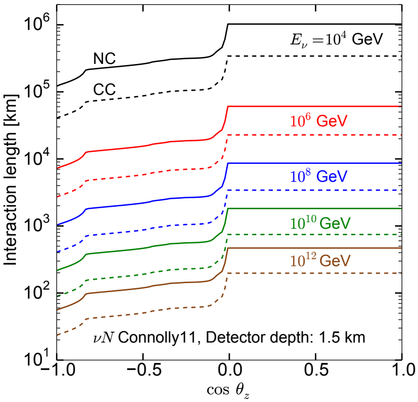
Average Earth density



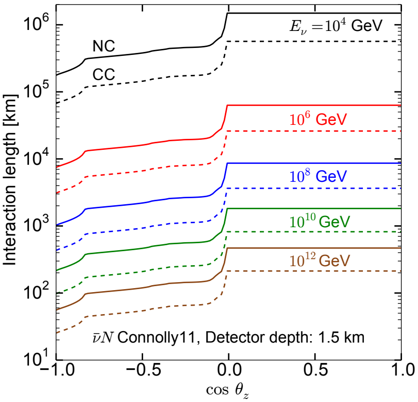
MB & A. Connolly, *In prep.*

Neutrino interaction length inside the Earth

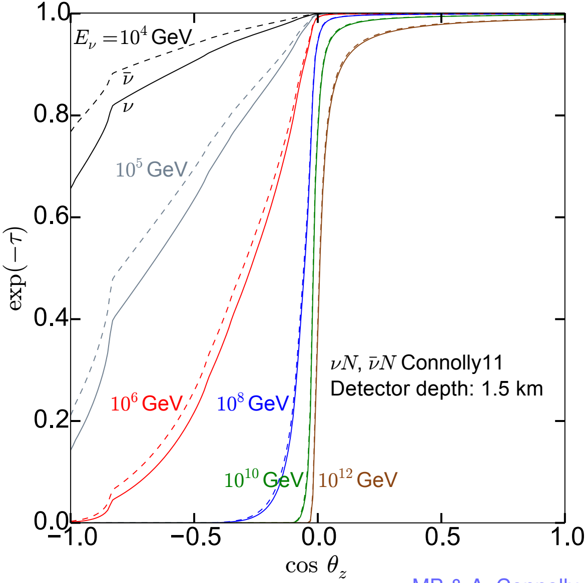
Neutrino



Anti-neutrino



Neutrino absorption in the Earth



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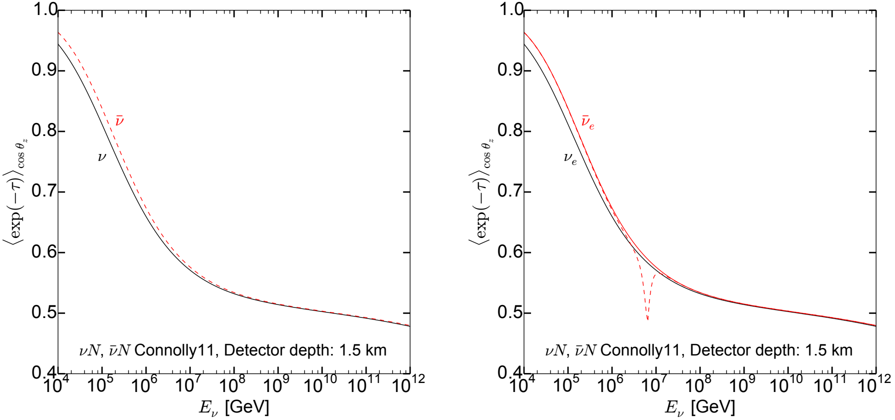
Angle-averaged neutrino absorption in the Earth



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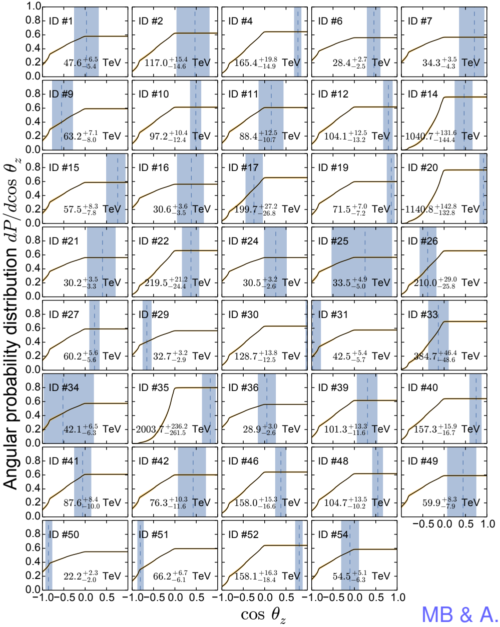
Angular probability distribution for 4-yr HESE events



MB & A. Connolly, *In prep.*