ν Interactions from the Heavens:

Measuring Neutrino Cross Sections Above 10 TeV

Mauricio Bustamante

Niels Bohr Institute, University of Copenhagen

GRAPPA@5

Amsterdam, October 18, 2017

Two seemingly unrelated questions —

1. Where are the most energetic particles coming from?

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


ν

ν Interactions from the Heavens:

Measuring Neutrino Cross Sections Above 10 TeV

WITH ASTROPHYSICAL NEUTRINOS

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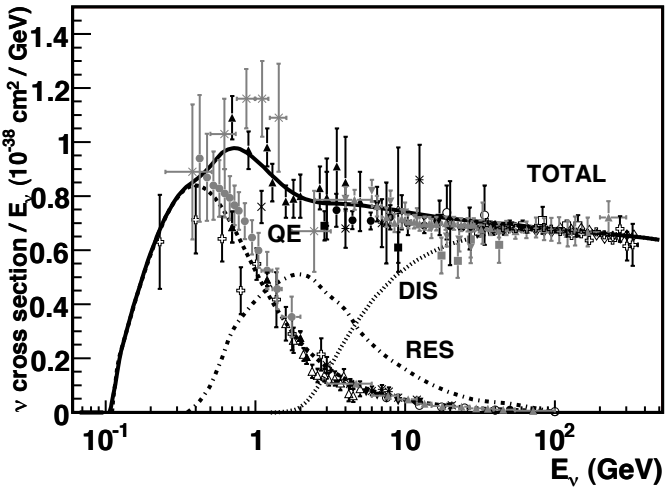
Neutrino interactions are weak . . .

. . . but we are persistent

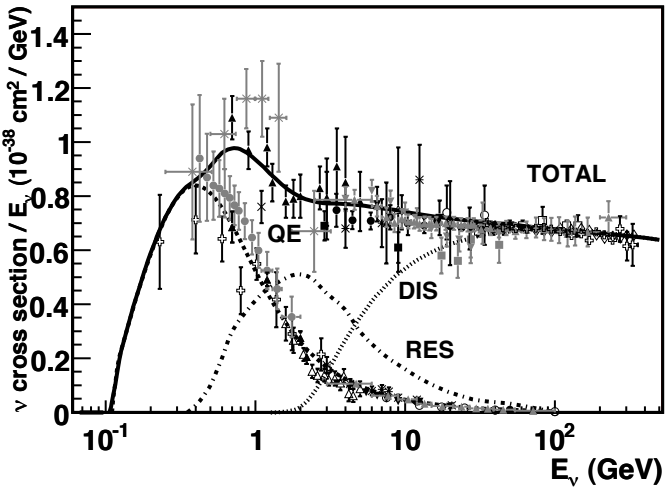
At center-of-mass energy of 1 GeV:

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



Particle Data Group

Accelerator experiments

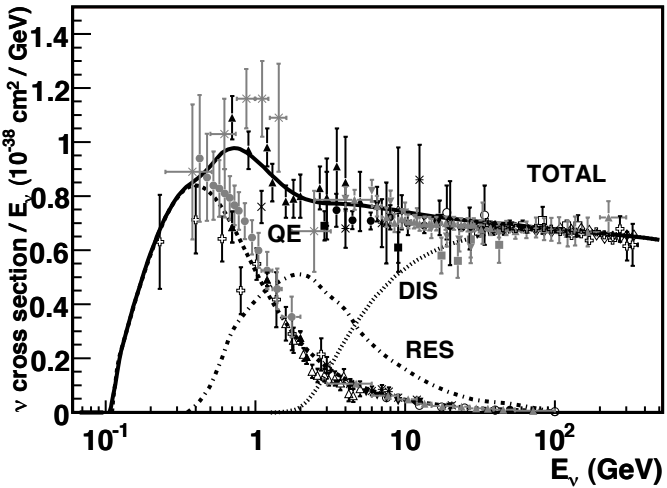


Particle Data Group

Accelerator experiments

←

One recent measurement (COHERENT)



Particle Data Group

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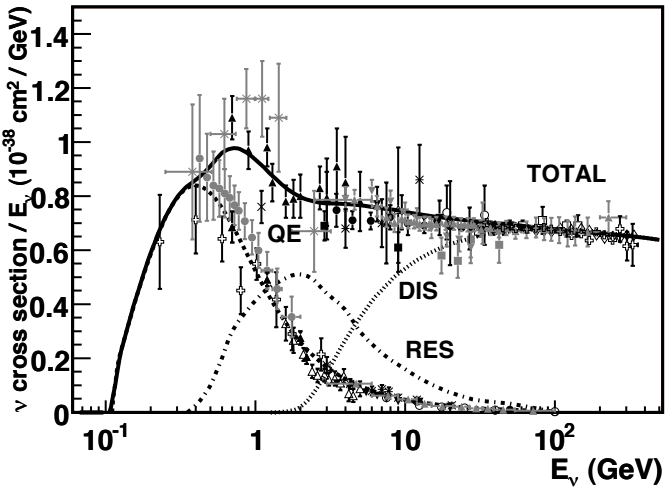
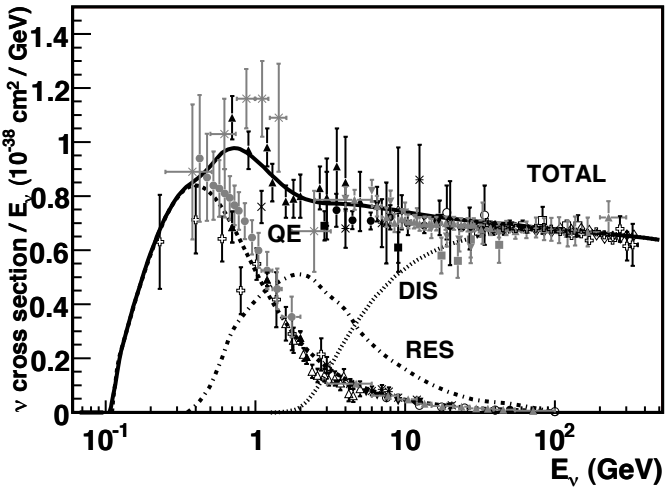


→ No measurements

Particle Data Group

Accelerator experiments

← One recent measurement (COHERENT)

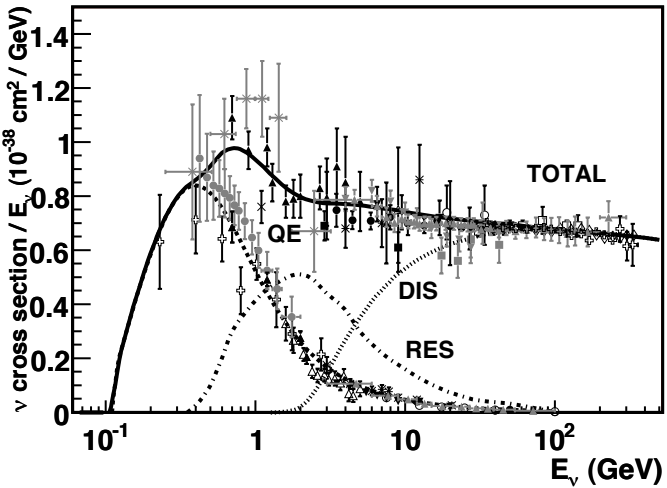


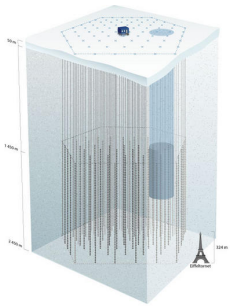
→ No measurements ... until now!

Particle Data Group

Accelerator experiments

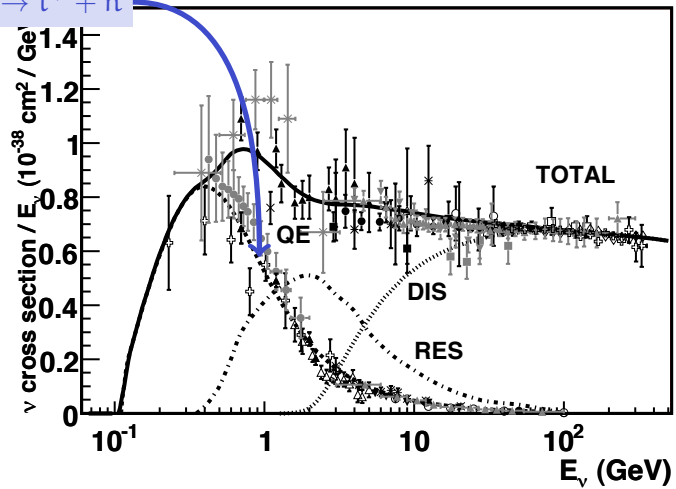
← One recent measurement (COHERENT)





Particle Data Group

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



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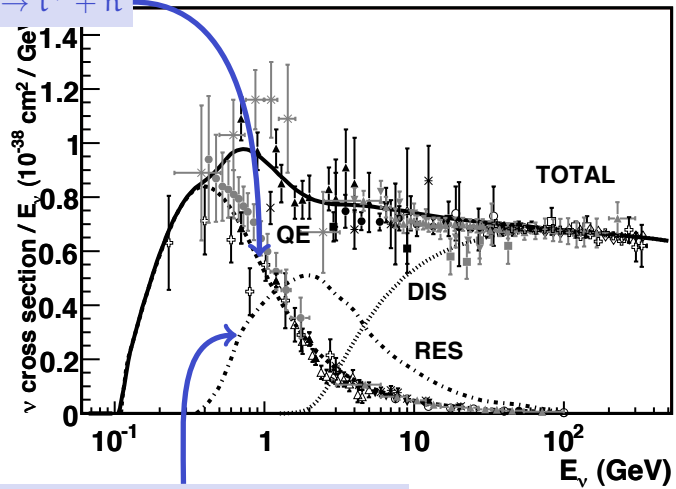

$\nu_l + N \to l^- + N^* \to l^- + \pi + N'$

Particle Data Group

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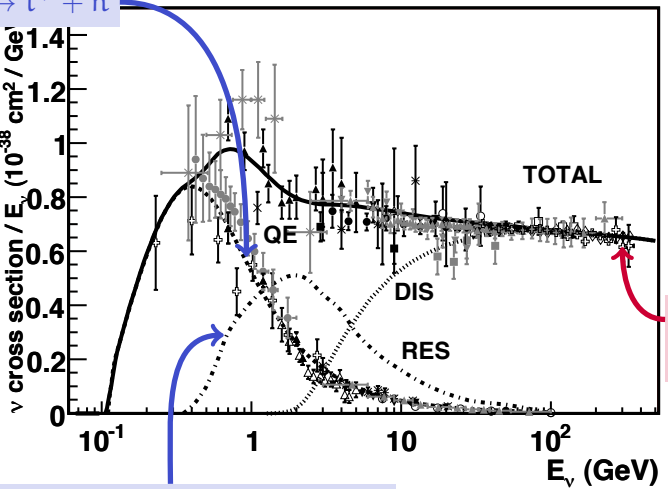

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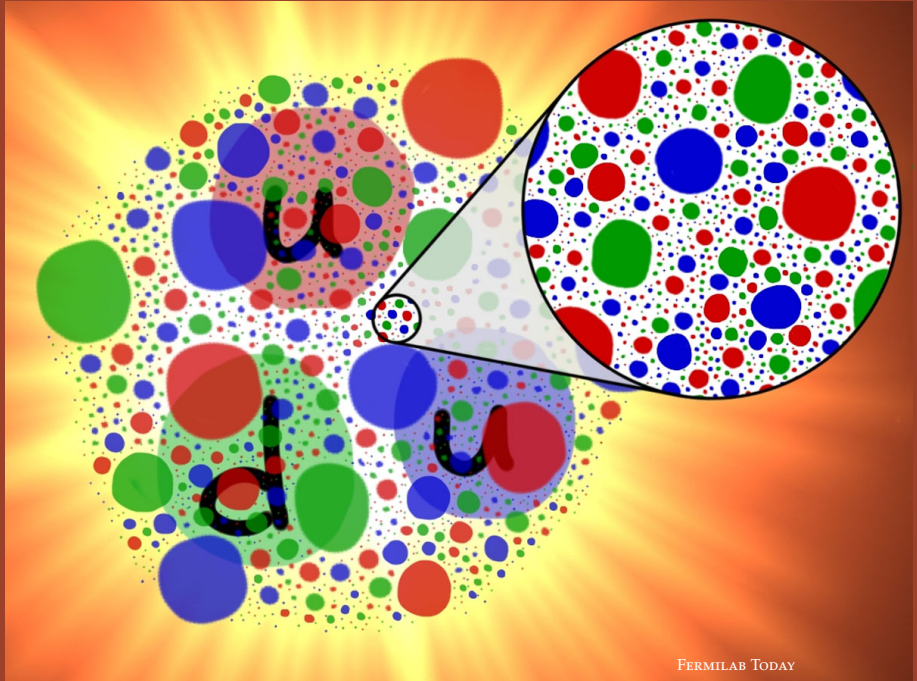
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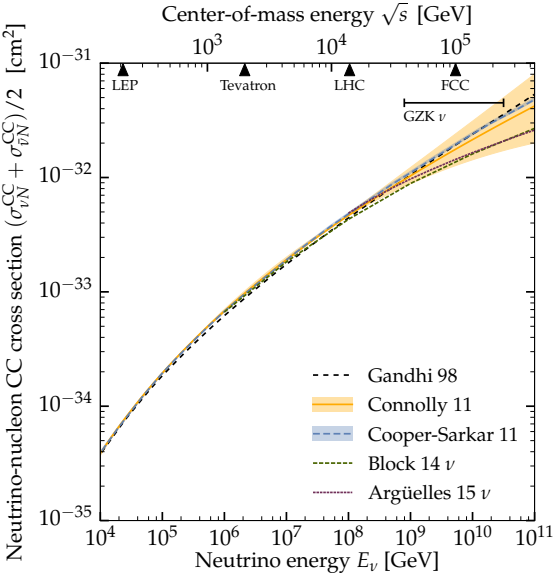
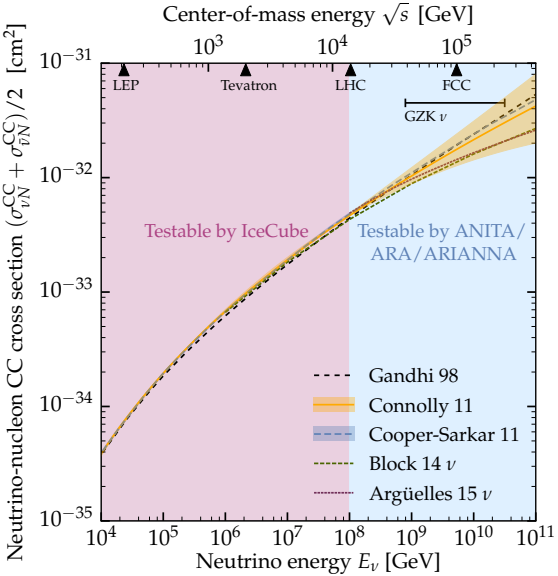
Extrapolating the neutrino-nucleon cross section



MB & A. Connolly, *In prep.*

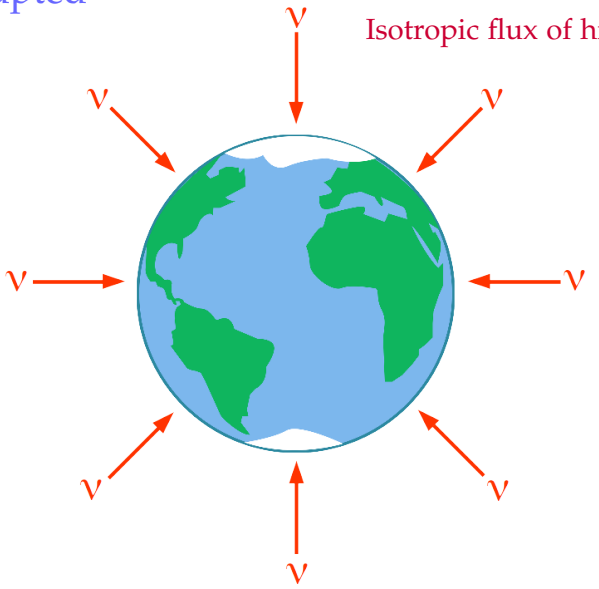
What can we measure *now* and later?



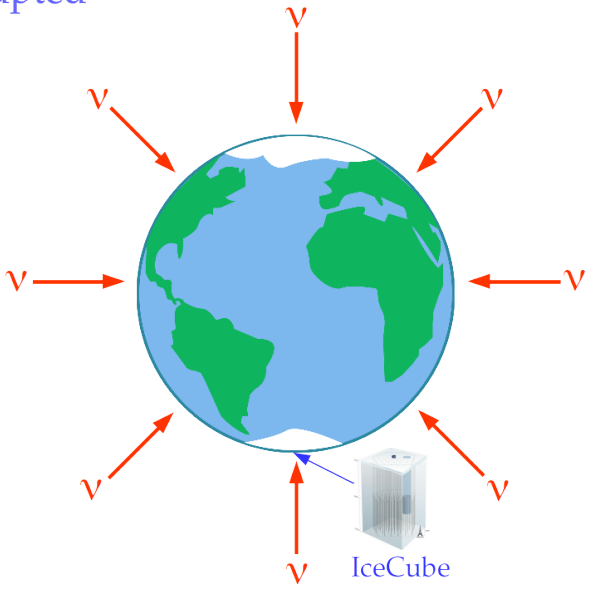
MB & A. Connolly, *In prep.*

Neutrino, interrupted

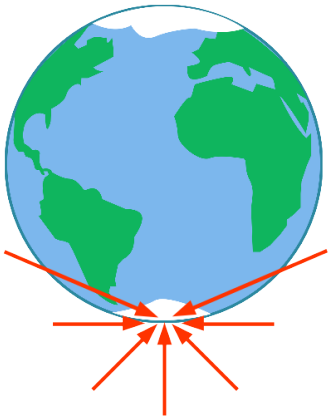
Isotropic flux of high-energy neutrinos



Neutrino, interrupted



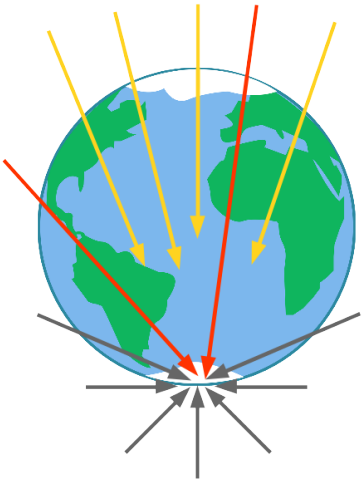
Neutrino, interrupted



Most of these neutrinos reach IceCube

Neutrino, interrupted

Many of these neutrinos are stopped by the Earth

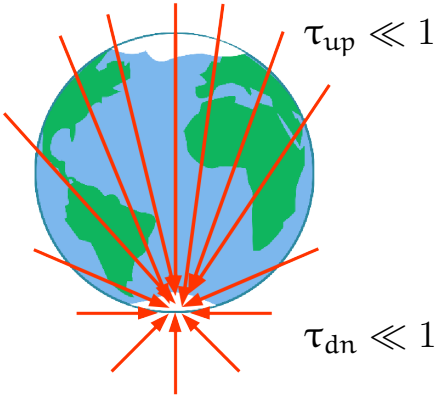


Most of these neutrinos reach IceCube

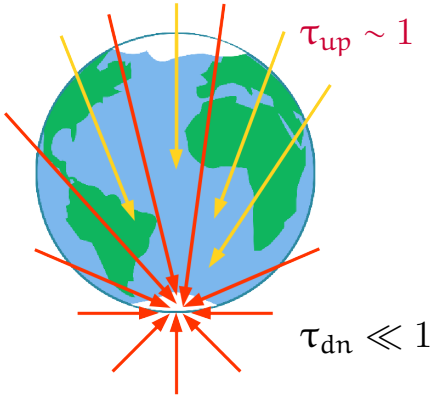
How do we measure the high-energy cross section?

$$\text{Optical depth to } \nu\text{N int's} = \frac{\text{Distance from Earth's surface to IceCube}}{\text{Mean free path inside Earth}} \equiv \tau(E_\nu, \theta_z) \propto \sigma_{\nu N}$$

Below ~ 10 TeV: Earth is transparent



Above ~ 10 TeV: Earth is opaque



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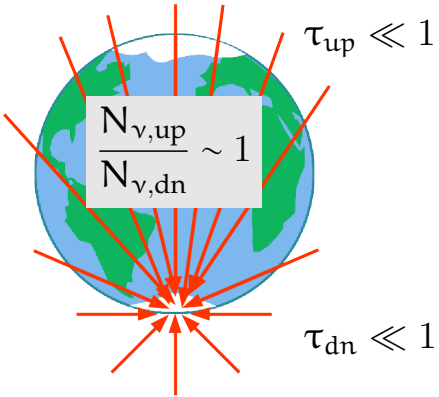

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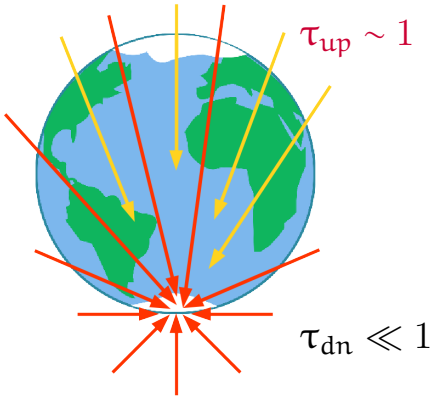

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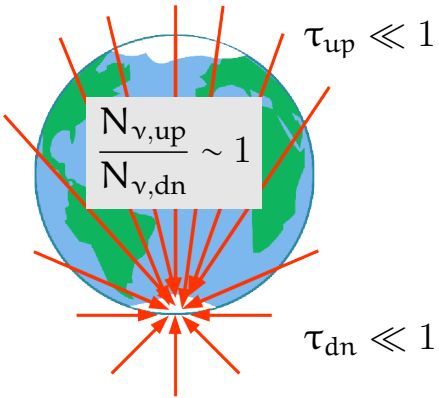

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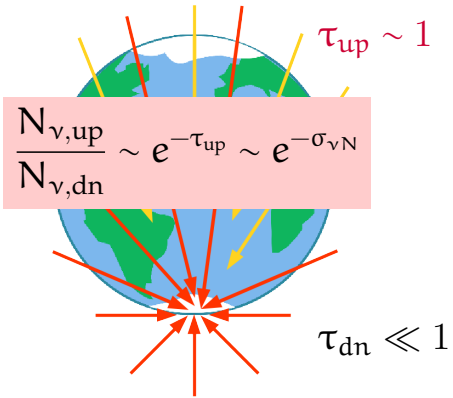
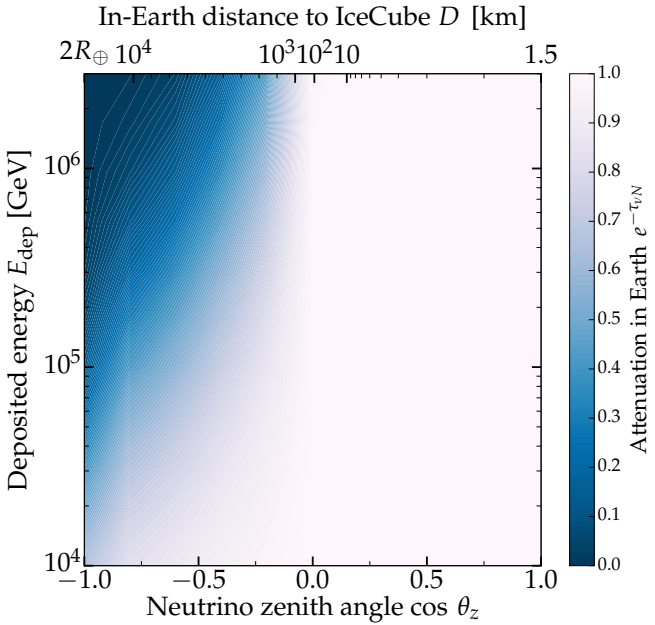
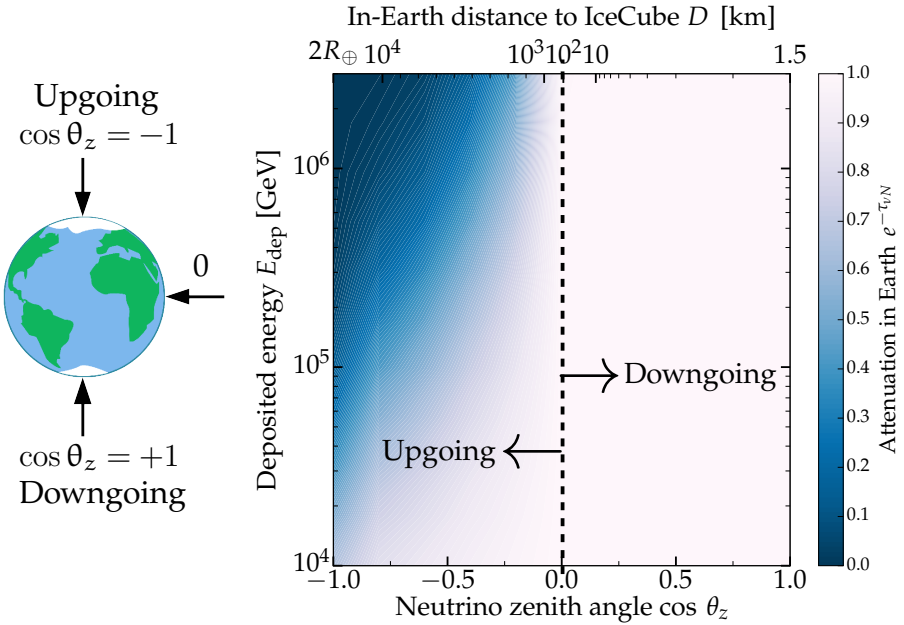



In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4
10^3 10^2 10
1.5
Deposited energy $E_{\rm dep}$ [GeV]
10^6
10^5
10^4
−1.0
−0.5
0.0
0.5
1.0
Neutrino zenith angle cos θ_z
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0


Upgoing
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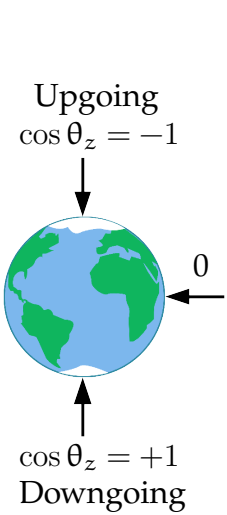
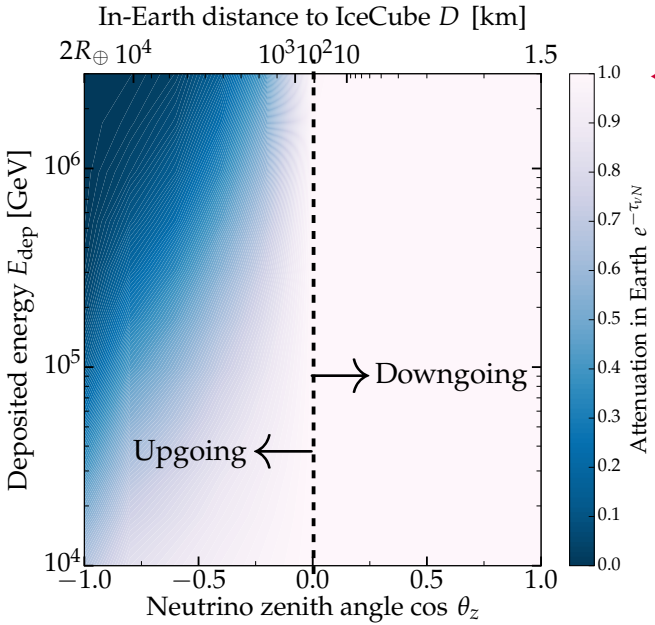
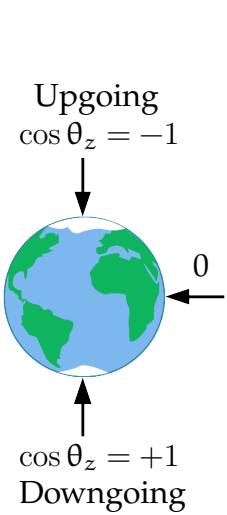
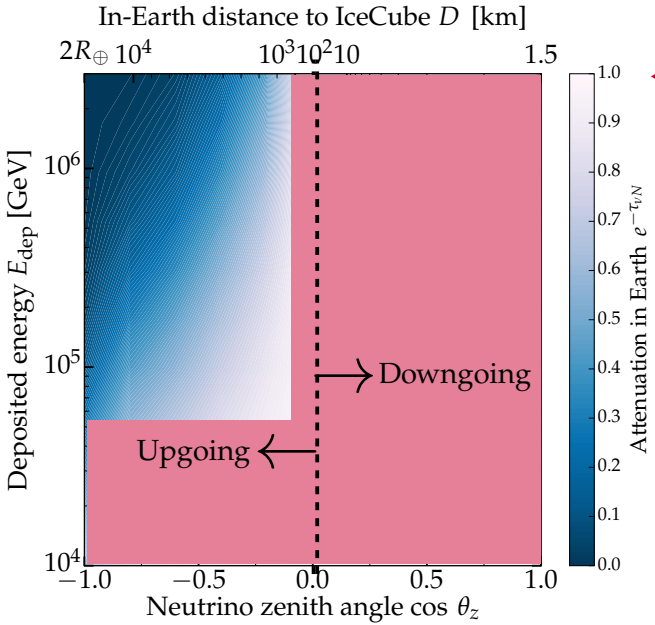




← Transparent Earth
$e^{-\tau} \sim 1$





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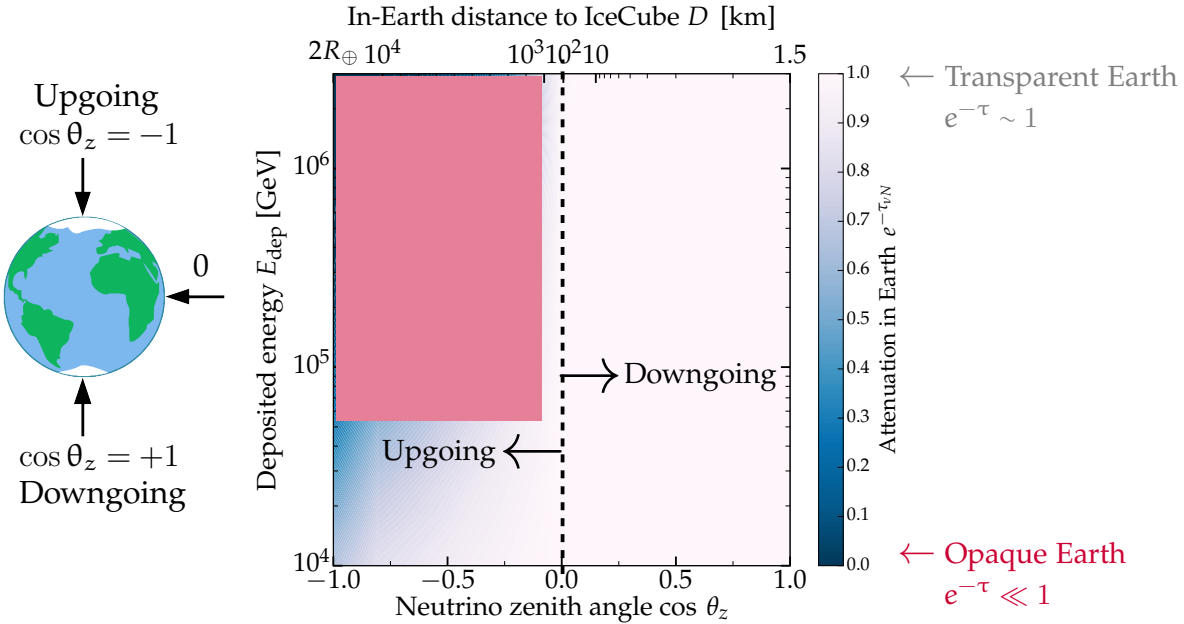
Upgoing
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0.3
0.2
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0.0
← Transparent Earth
$e^{-\tau} \sim 1$
← Opaque Earth
$e^{-\tau} \ll 1$

How does IceCube see neutrinos?

Two types of fundamental interactions . . .

Charged-current (CC)

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

Neutral-current (NC)

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

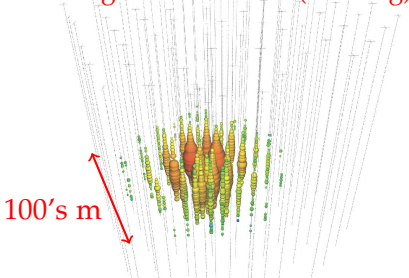
These shower and make light

. . . create two event topologies . . .

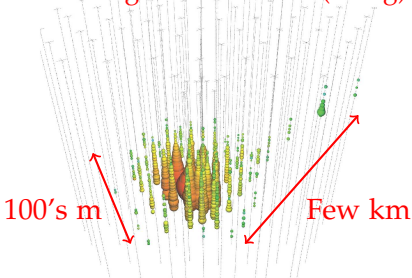
Showers — From CC ν_e or ν_τ, or NC ν_x

Tracks — From CC ν_μ mainly

Bad angular resolution (10's deg)

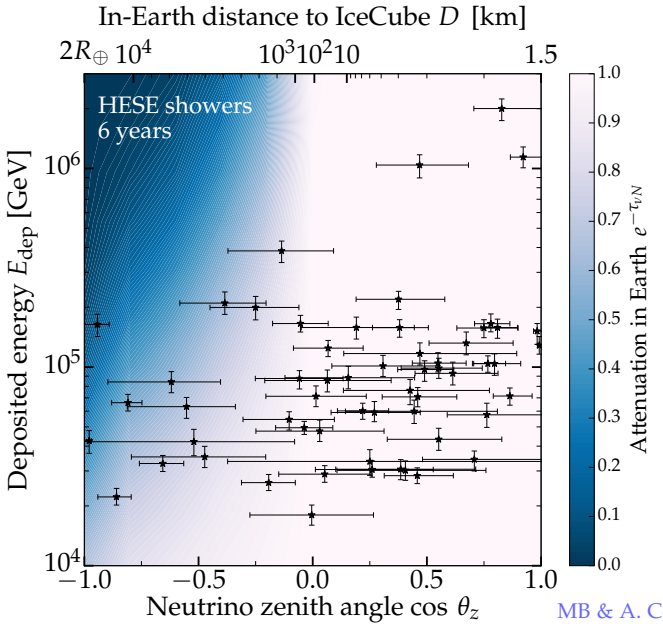


Good angular resolution (< deg)



What events do we use?

- $\sigma_{\nu N}$ varies with neutrino energy $\Rightarrow$ use events where E_ν is well-reconstructed
- These are IceCube High-Energy Starting Events (HESE):
  - νN interaction occurs inside the detector
  - ☑ **Showers:** completely contained in the detector ($E_{dep} \approx E_\nu$)
  - ☒ **Tracks:** partially contained ($E_{dep} < E_\nu$)
- We use only the 58 publicly available HESE showers (6-year sample)
- HESE tracks *could* be used
  — but we would need non-public data to reconstruct E_ν without bias



MB & A. Connolly, *In prep.*

Where does the sensitivity to σ come from?

Number of contained events in an energy bin:

$$N_\nu \sim \Phi_\nu \cdot \sigma_{\nu N} \cdot e^{-\tau} = \Phi_\nu \cdot \sigma_{\nu N} \cdot e^{-L \sigma_{\nu N} n_N}$$

Downgoing (no matter)

$$N_{\nu,\mathrm{dn}} \sim \Phi_\nu \cdot \sigma_{\nu N}$$

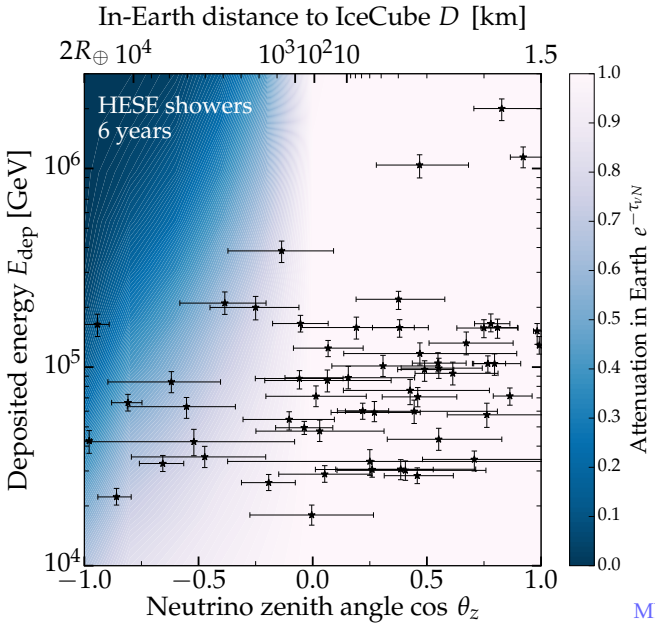
Downgoing events fix the product $\Phi_\nu \cdot \sigma_{\nu N}$

Upgoing (lots of matter)

$$N_{\nu,\mathrm{up}} \sim N_{\nu,\mathrm{dn}} \cdot e^{-\tau}$$

Upgoing events measure $\sigma_{\nu N}$ via τ

Reality check:
Few events (per energy bin), so we are statistics-limited



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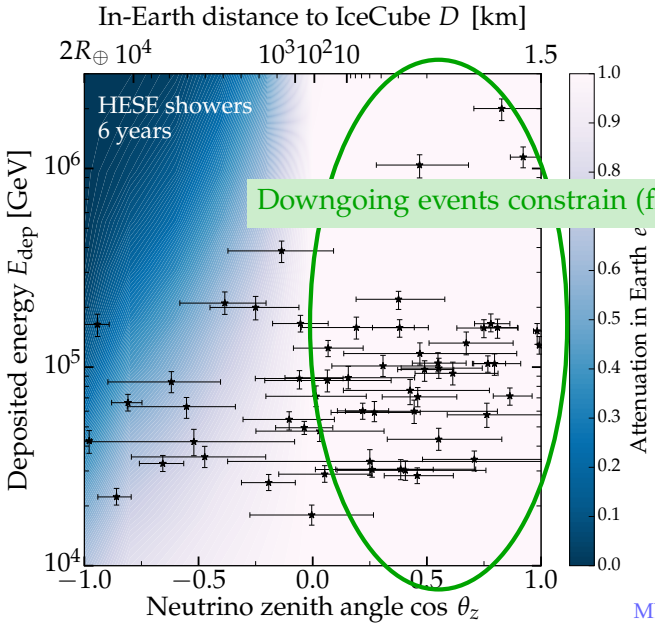
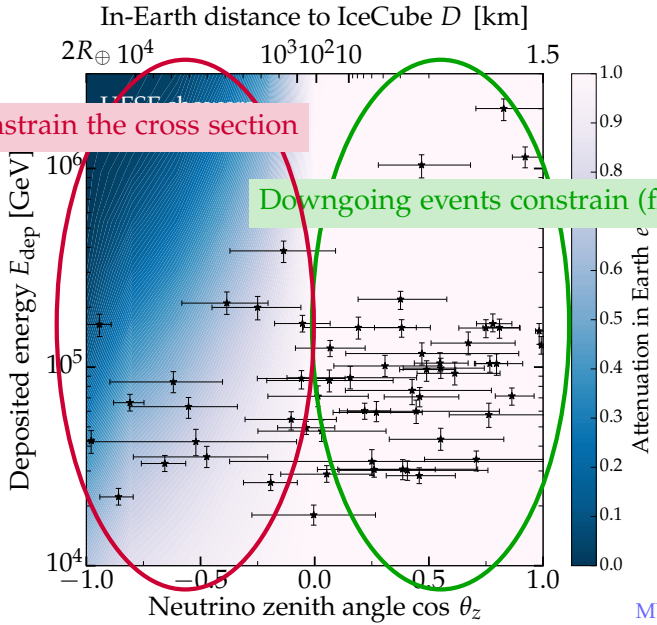


Downgoing events constrain (flux × cross section)

MB & A. Connolly, *In prep.*

Upgoing events constrain the cross section

Downgoing events constrain (flux × cross section)



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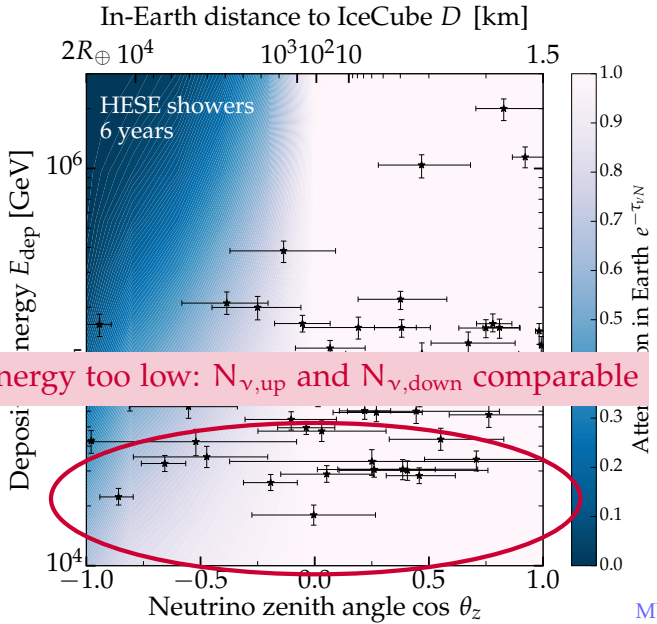
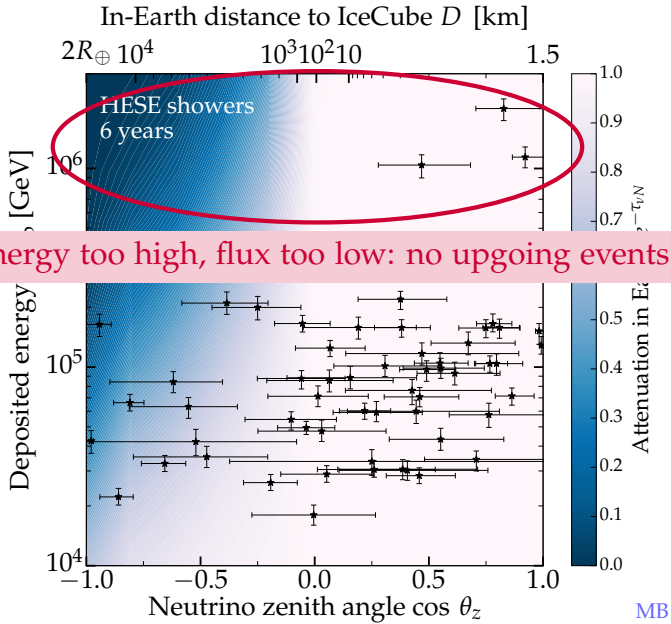


Energy too low: $N_{\nu,up}$ and $N_{\nu,down}$ comparable

MB & A. Connolly, *In prep.*



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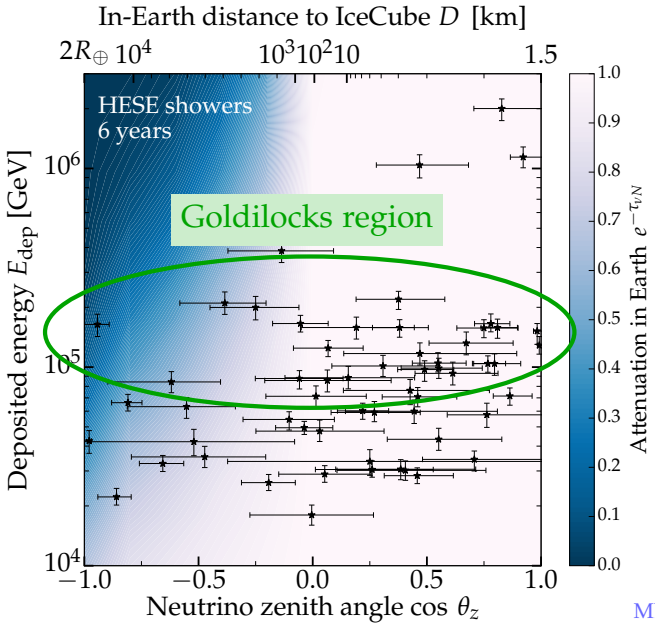

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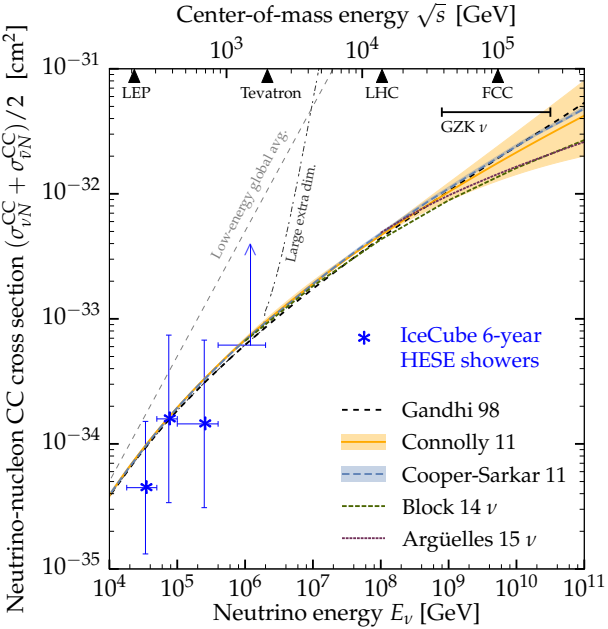
The fine print

- High-energy ν's: astrophysical (isotropic) + atmospheric (non-isotropic)
  $\longmapsto$ We account for the angular spectrum of atmospheric neutrinos
- The shape of ν energy spectrum is still uncertain
  $\longmapsto$ We take a $\sim E_\nu^{-\gamma}$ spectrum in a narrow energy bin
- NC showers are sub-dominant to CC showers, but they are indistinguishable
  $\longmapsto$ Following standard predictions, we take $\sigma_{\nu N}^{NC} = \sigma_{\nu N}^{CC}/3$
- IceCube does not distinguish ν from $\bar{\nu}$
  $\longmapsto$ We assume equal fluxes, expected from production via pp collisions
- The flavor composition of astrophysical neutrinos is still uncertain
  $\longmapsto$ We assume equal flux of each flavor, compatible with theory and observations

What goes into the (likelihood) mix?

- Inside each energy bin, we freely vary
  - N_{sh}^{atm} (showers from atmospheric neutrinos)
  - N_{sh}^{st} (showers from astrophysical neutrinos)
  - γ (astrophysical spectral index)
  - $\sigma_{\nu N}^{CC}$ (neutrino-nucleon charged-current cross section)
- For each combination, we generate the angular and energy neutrino spectrum ...
- ...and compare it to the measured spectrum via a likelihood
- Maximizing the likelihood yields the best-fit, marginalized value of $\sigma_{\nu N}^{CC}$
- Bins are independent of each other — no cross-bin correlations

The result



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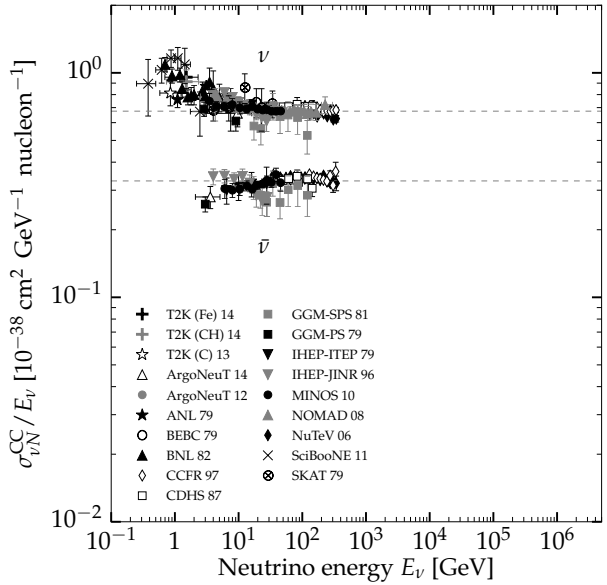
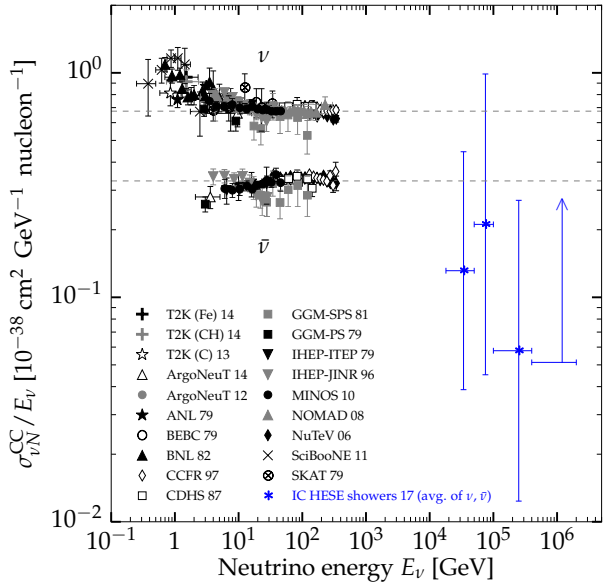
Extending the cross section measurements



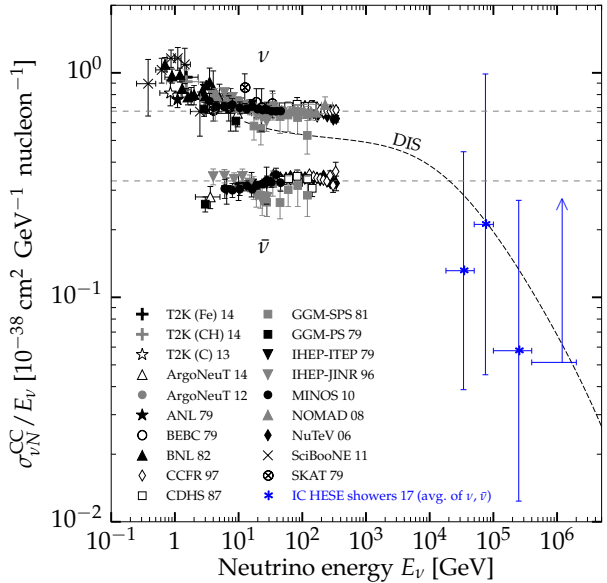
MB & A. Connolly, *In prep.*

Extending the cross section measurements



MB & A. Connolly, *In prep.*

Extending the cross section measurements

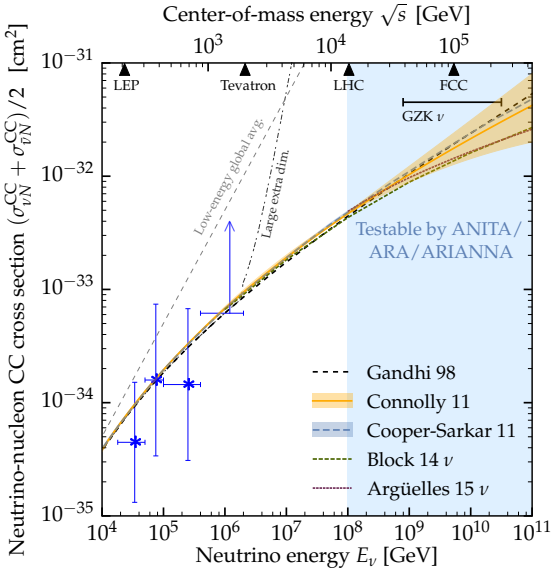


MB & A. Connolly, *In prep.*

How to do better, more?

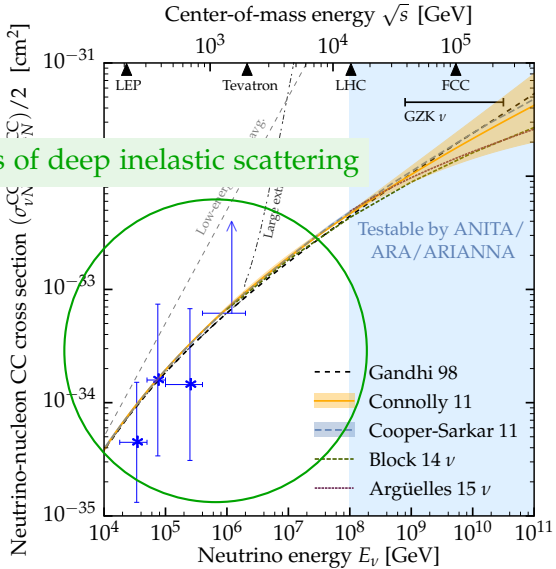
- Limited statistics (for now)
  $\longmapsto$ Solvable with more IceCube + IceCube-Gen2 + KM3NeT
- Large errors in arrival directions give errors in attenuation
  $\longmapsto$ Solvable with ongoing IceCube improvements + KM3NeT
- Only constrains charged-current + neutral-current cross section
  $\longmapsto$ Solvable (?) with muon and neutron echoes (Li, MB, Beacom 16)
- Cannot separate ν from $\bar{\nu}$
  $\longmapsto$ Wait for Glashow resonance, sensitive only to $\bar{\nu}_e$
- Use starting track events / through-going muons
  $\longmapsto$ Doable / done by the IceCube Collaboration

Quo vadis: IceCube vs. ANITA/ARA/ARIANNA

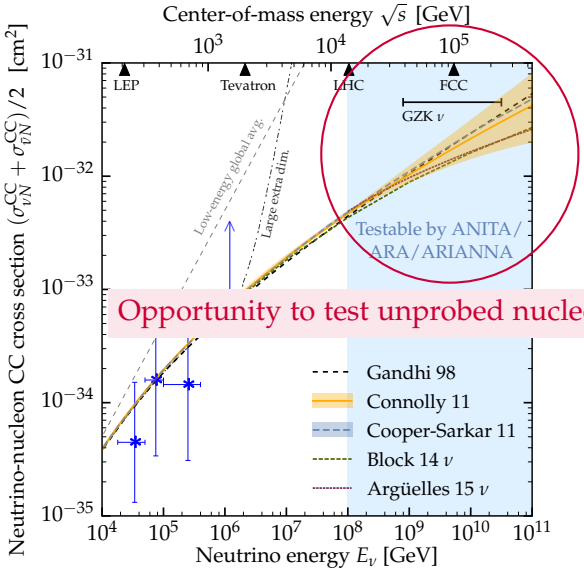


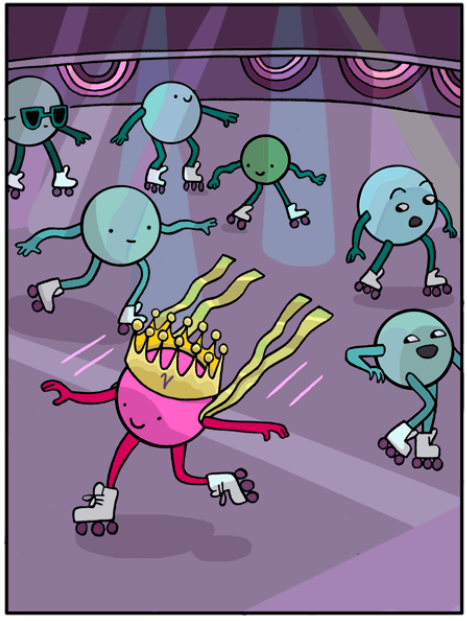
Quo vadis: IceCube vs. ANITA/ARA/ARIANNA

Test predictions of deep inelastic scattering



Quo vadis: IceCube vs. ANITA/ARA/ARIANNA





GRAPPA

GRavitation AstroParticle Physics Amsterdam

YOU'RE BASICALLY UNSTOPPABLE

Happy Birthday!

symmetrymagazine.org

Backup slides

Neutrino interactions: what we (do not) know

< 1 MeV

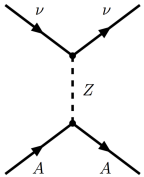
☑ (Somewhat) observed — Coherent neutrino-nucleus scattering (just measured!), capture on radionuclei

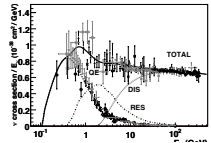
1 MeV – 350 GeV

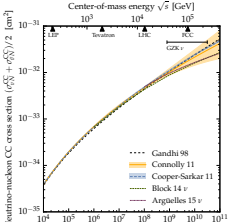
☑ Lots of data — Quasi-elastic scattering, resonance production, deep inelastic scattering

> 350 GeV

☒ Not observed — No neutrino beam available... *til now*

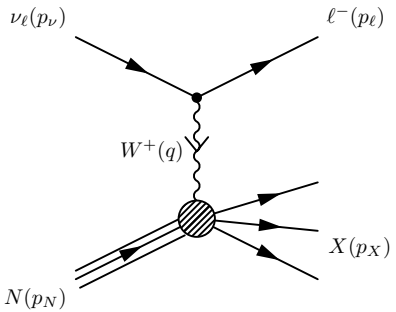




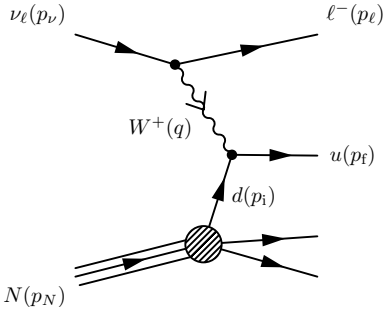


How does DIS probe nucleon structure?

What you see



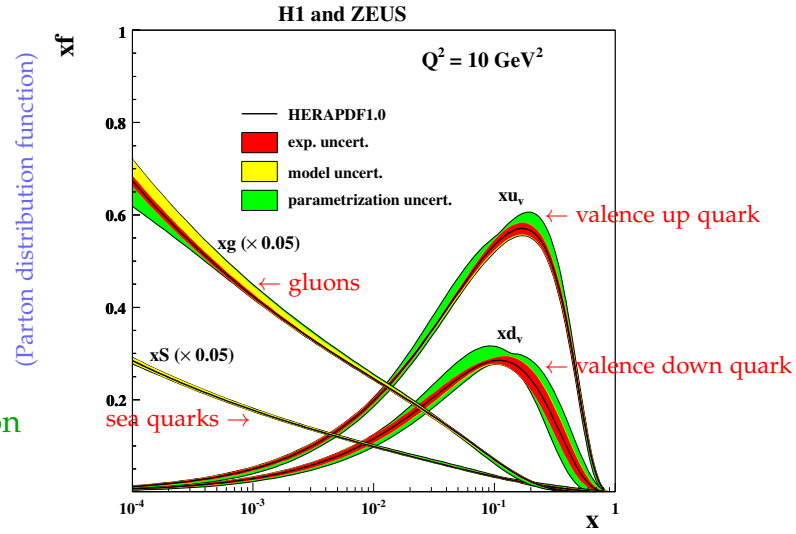
Beneath the hood



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

Giunti & Kim, *Fundamentals of Neutrino Physics & Astrophysics*

Peeking inside a proton



(Parton distribution function)

← valence up quark

← gluons

← valence down quark

← Extrapolation

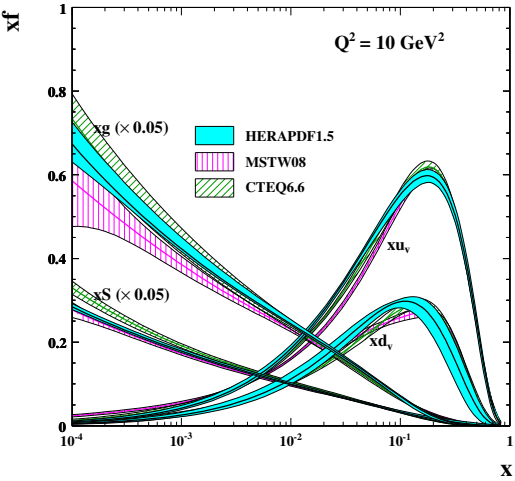
sea quarks →

A. Cooper-Sarkar 2012

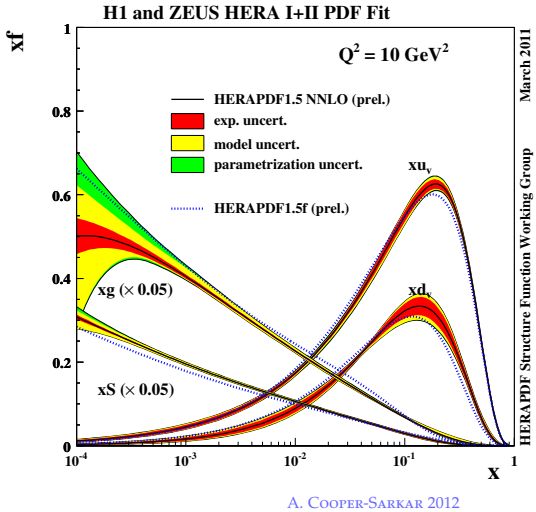
(Fraction of momentum carried by parton)

The world of PDFs is messy

Different fitting groups

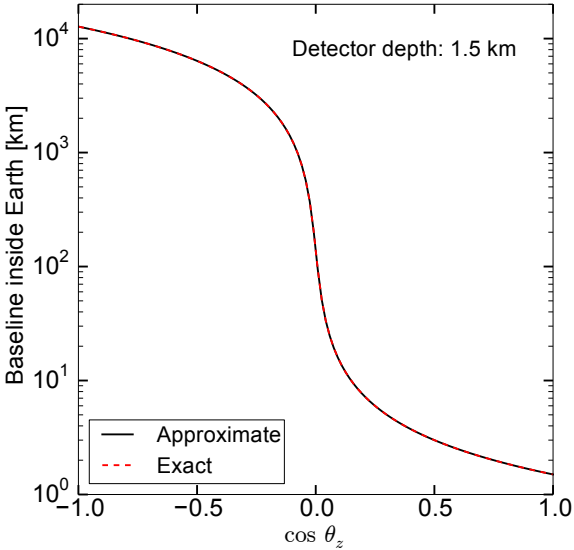


Different QCD prescriptions

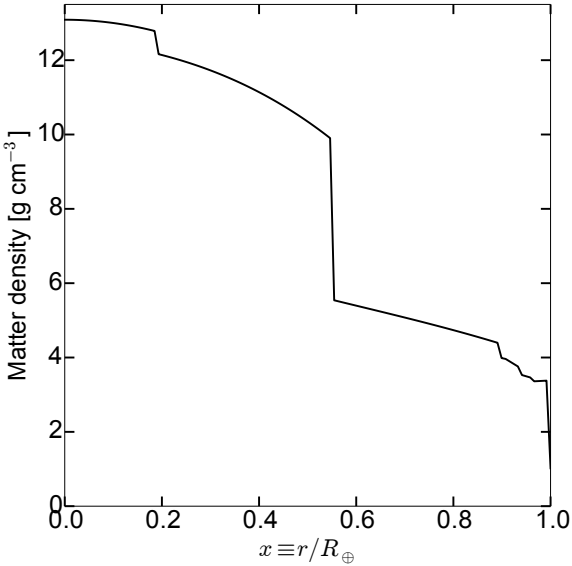


A. Cooper-Sarkar 2012

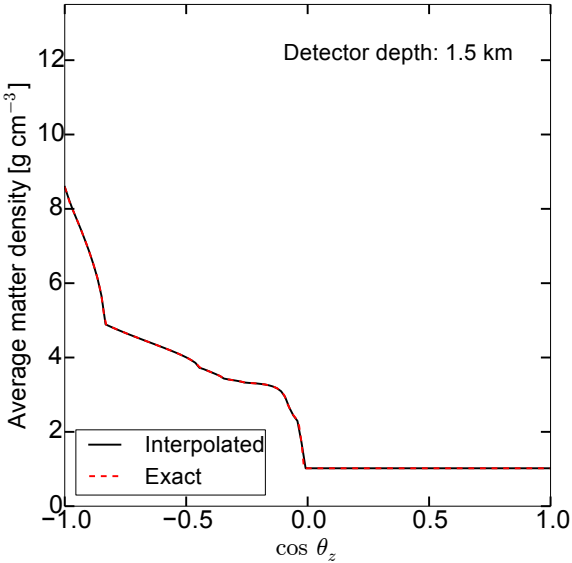
Neutrino baseline inside the Earth



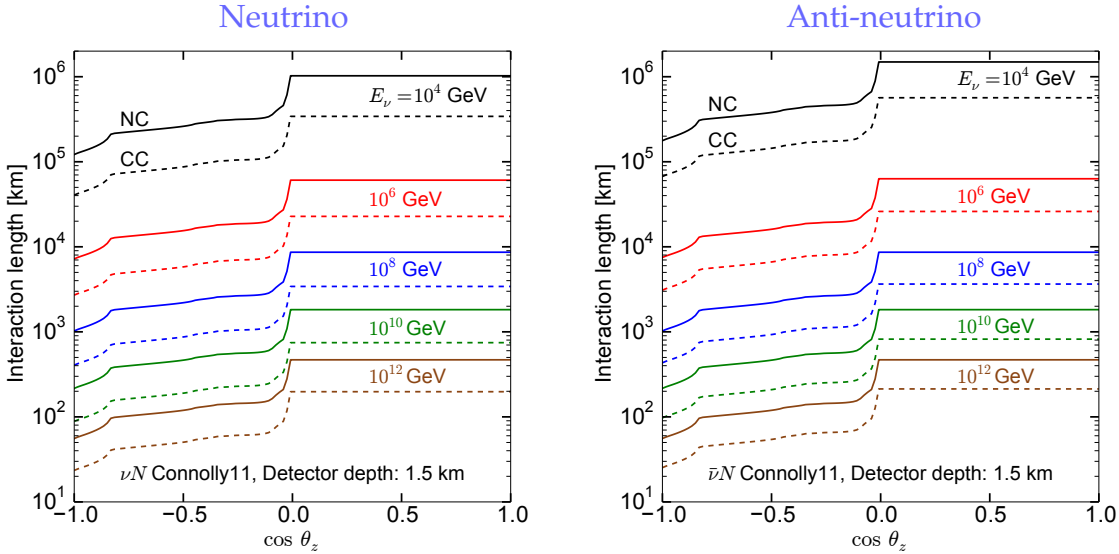
Earth density profile — Preliminary Reference Earth Model



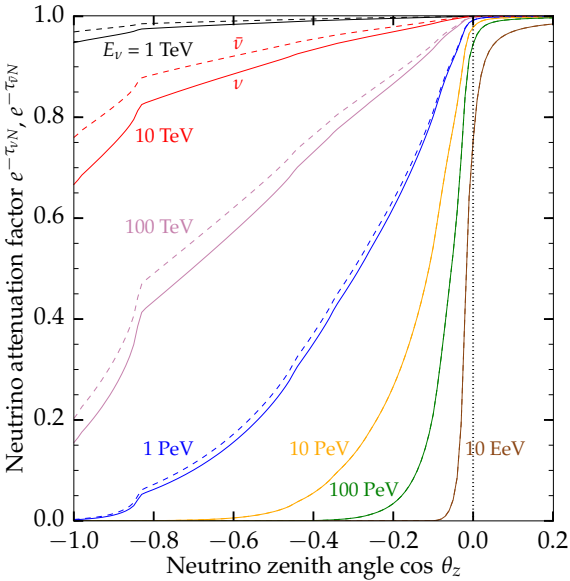
Average Earth density



Neutrino interaction length inside the Earth

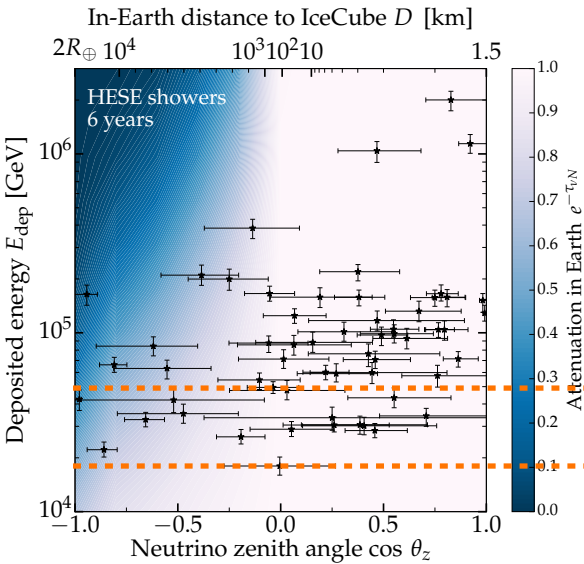


Neutrino attenuation in the Earth



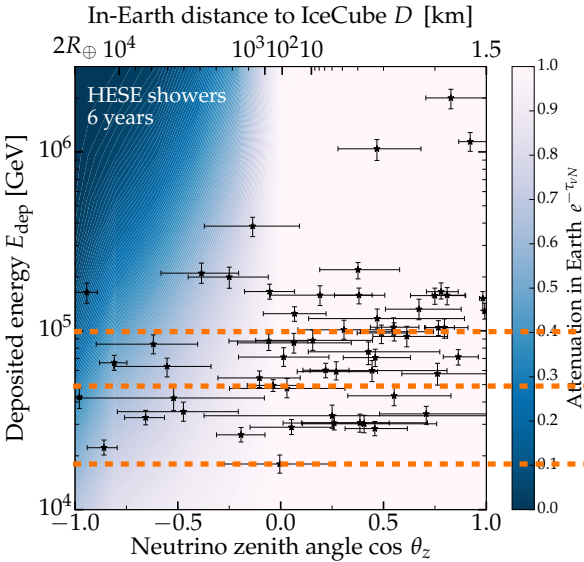
MB & A. Connolly, *In prep.*

Bin-by-bin analysis



18 TeV – 50 TeV (17 showers)

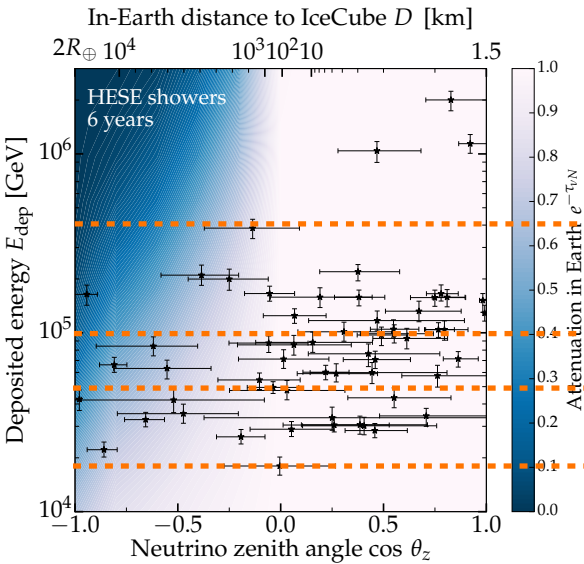
Bin-by-bin analysis



50 TeV – 100 TeV (18 showers)

18 TeV – 50 TeV (17 showers)

Bin-by-bin analysis



100 TeV – 400 TeV (20 showers)

50 TeV – 100 TeV (18 showers)

18 TeV – 50 TeV (17 showers)

Bin-by-bin analysis