Neutrino-Nucleon Cross Sections at High Energies

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Motivation

- Center of mass (COM) of UHE neutrino interactions with nuclei well exceed LHC energies
  - $\sqrt{s}=\sqrt{2M_N E_\nu}$, $E_\nu=10^{18}$ eV → **$\sqrt{s}$=45 TeV!**
- Predictions of SM νN cross section (σ) at high energies rely on measurements of quark, anti-quark number densities at low x (parton momentum fraction)
  - $E_\nu > 10^{17}$ eV → $x \lesssim 10^{-5}$
  - HERA measures $x \gtrsim 10^{-4} - 10^{-5}$
- UHE νN σ's sensitive to region of low x and high COM energies inaccessible with accelerators
- νN σ's at all energies needed to model experiments

Outline

- Latest high energy vN cross section predictions and uncertainties
  - Different assumptions made by different models
- Measuring cross sections with an *in situ* array
- Summary

High energy νN cross section calculations (First 2 of 4)

- R. Gandhi, C. Quigg, M.H. Reno, I. Sarcevic (1998)
  - CTEQ4-DIS PDFs (early ZEUS data)
  - $xq_s^{[CTEQ4]}(x) \propto x^{-0.227}$
- A. Connolly, R. Thorne and D. Waters (2011)
  - Using MSTW 2008 PDFs (Thorne is the 'T') based on global fits
  - quarks $\propto a + b \ln(1/x)$
  - $x\, g(x) \propto A_1\, x^{\delta 1} + A_2\, x^{\delta 2}$

High energy νN cross section calculations (next 2 of 4)

- Cooper-Sarkar, Mertsch and Sarkar (2011)
  - PDFs that use HERA data that is more recent than MSTW 2008
  - $g(x) \propto x^{\delta}$
- M. Block, L. Durand, P. Ha, D. McKay (2013)
  - $F_2^{\gamma p}(x,Q^2) \sim \ln^2(1/x)$ at low x which saturates the Froissart bound
  - Froissart bound: total cross section does not increase faster than $\ln E^2$

νN Cross Section Calculation

$$\sigma_{CC}(E_\nu) = \frac{2G_F^2 M_N E_\nu}{\pi} \int_0^1 \int_0^1 \left[q + (1-y)^2 \bar{q}\right] \left(\frac{M_W^2}{Q^2 + M_W^2}\right)^2 dy\, dx$$

$$\sigma_{NC}(E_\nu) = \frac{2G_F^2 M_N E_\nu}{\pi} \int_0^1 \int_0^1 \left[q^0 + (1-y)^2 \bar{q^0}\right] \left(\frac{M_Z^2}{Q^2 + M_Z^2}\right)^2 dy\, dx$$

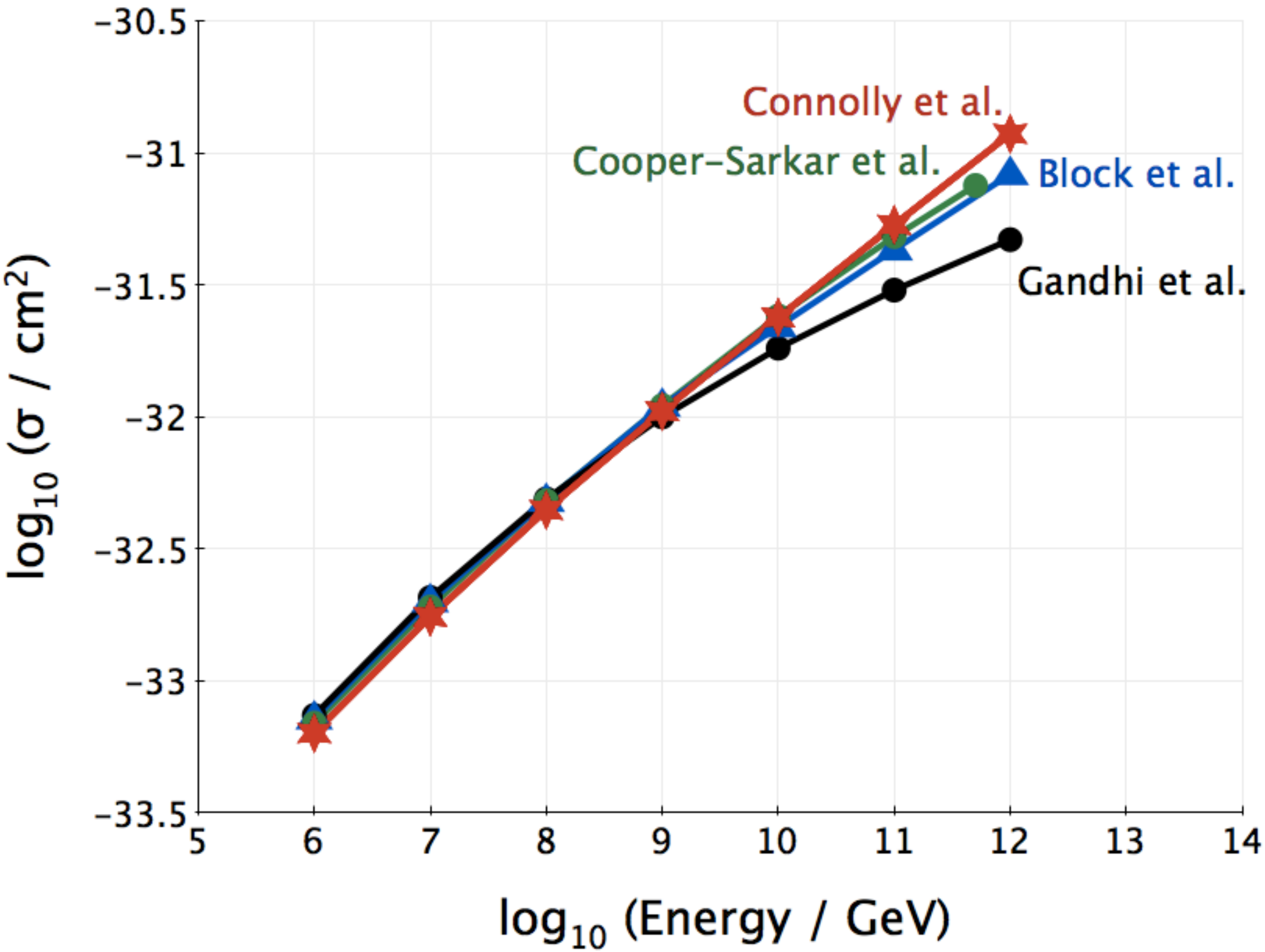
$$q = \frac{d+u}{2} + s + b \qquad \bar{q} = \frac{\bar{d}+\bar{u}}{2} + c + t$$

$$q^0 = \frac{u+d}{2}\left(L_u^2 + L_d^2\right) + \frac{\bar{u}+\bar{d}}{2}\left(R_u^2 + R_d^2\right) + (s+b)\left(L_d^2 + R_d^2\right) + (c+t)\left(L_u^2 + R_u^2\right)$$

$$\bar{q^0} = \frac{u+d}{2}\left(R_u^2 + R_d^2\right) + \frac{\bar{u}+\bar{d}}{2}\left(L_u^2 + L_d^2\right) + (s+b)\left(L_d^2 + R_d^2\right) + (c+t)\left(L_u^2 + R_u^2\right)$$

$$L_u = 1 - \frac{4}{3}x_W \qquad L_d = -1 + \frac{2}{3}x_W \qquad R_u = -\frac{4}{3}x_W \qquad R_d = \frac{2}{3}x_W$$

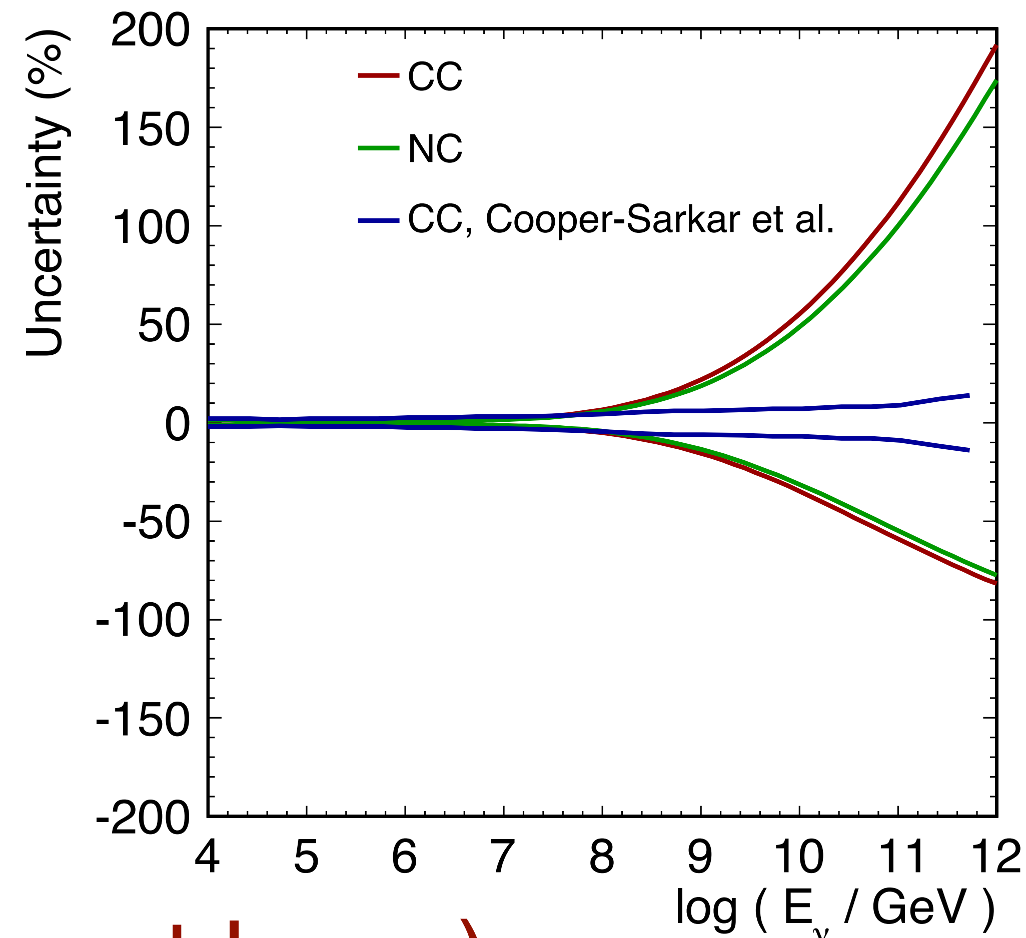
νN Cross Sections



Weaker low-x dependence gives lower cross sections at high energies

Uncertainties

- Gandhi *et al*: factor of 2±1 uncertainties
- Connolly *et al*:
  - < few % below $10^{7.5}$ GeV
  - ~factor of 2 at 10^{11} GeV
- Cooper-Sarkar *et al*:
  - < few % below $10^{7.5}$ GeV
  - <10% at 10^{11} GeV (due to weaker g(x) dependence at low x)



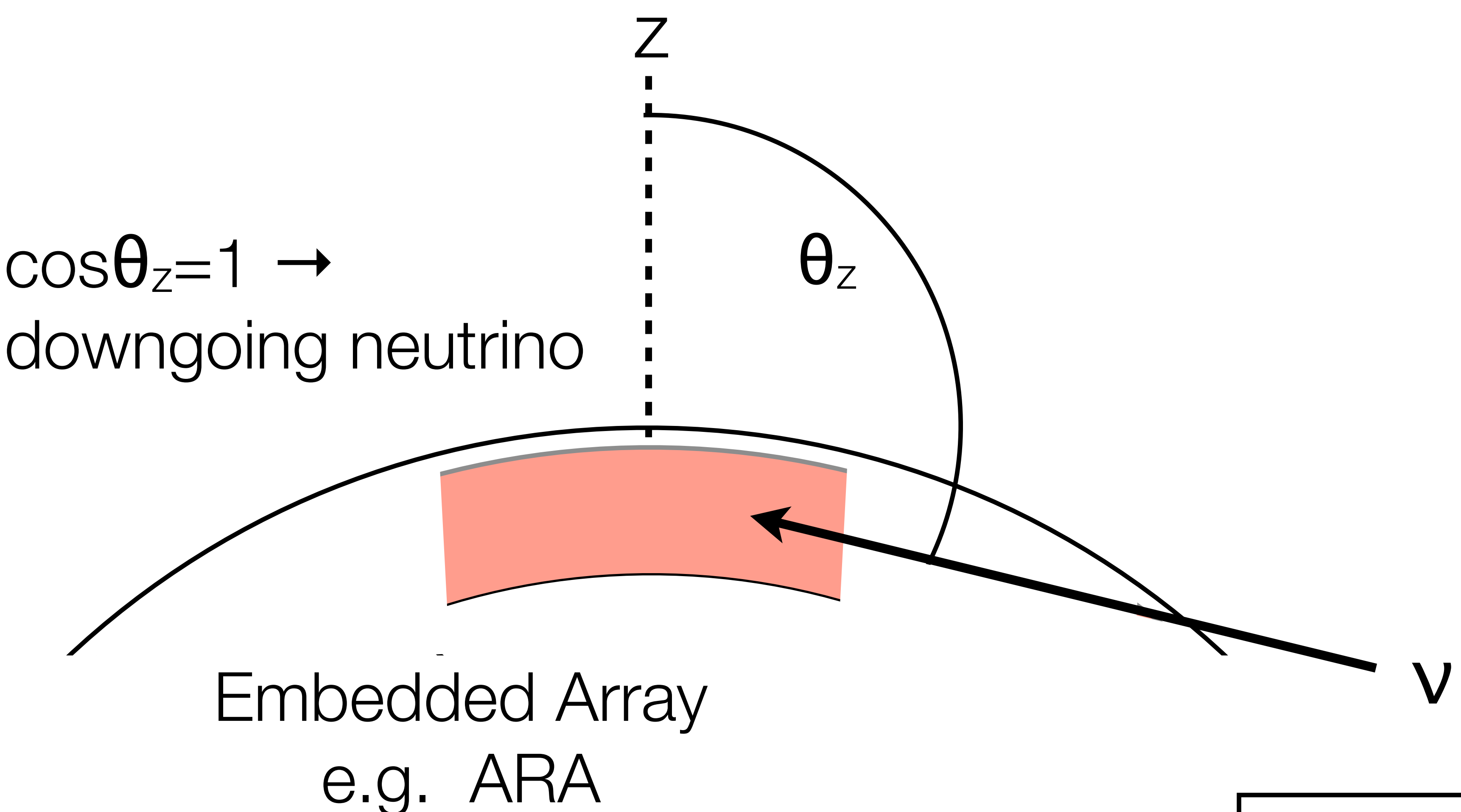
- M. Block *et al*:
  - 2% all the way up to 10^{17} GeV! (due to faith in parametrization at Foissart bound)

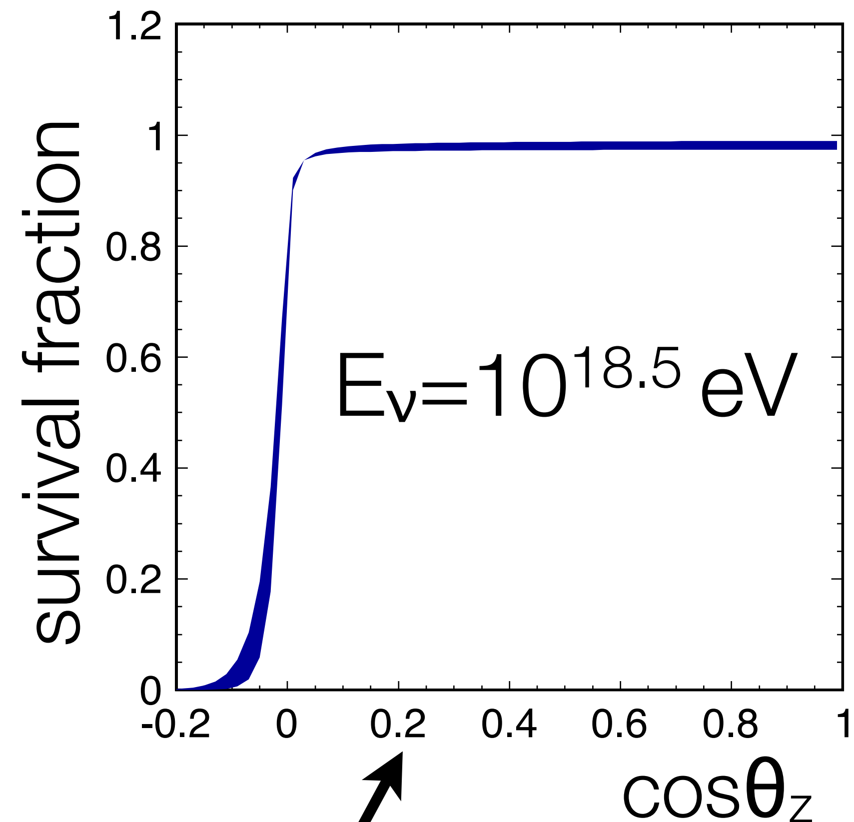
Advertisement: Cross section parametrizations for your convenience

- Connolly *et al.* provide energy-dependent parametrizations for $4 < \log_{10}(E/GeV) < 12$
  - CC, NC cross sections
  - Cross section uncertainty bands
  - Inelasticity distributions
- Code for inelasticities provided at:
  - http://www.physics.ohio-state.edu/~connolly/crosssections/y.html.

Cross section measurement in an *in situ* array

- For any detector in the earth, incident neutrinos subject to earth absorption
- Zenith angle dependence sensitive to cross section



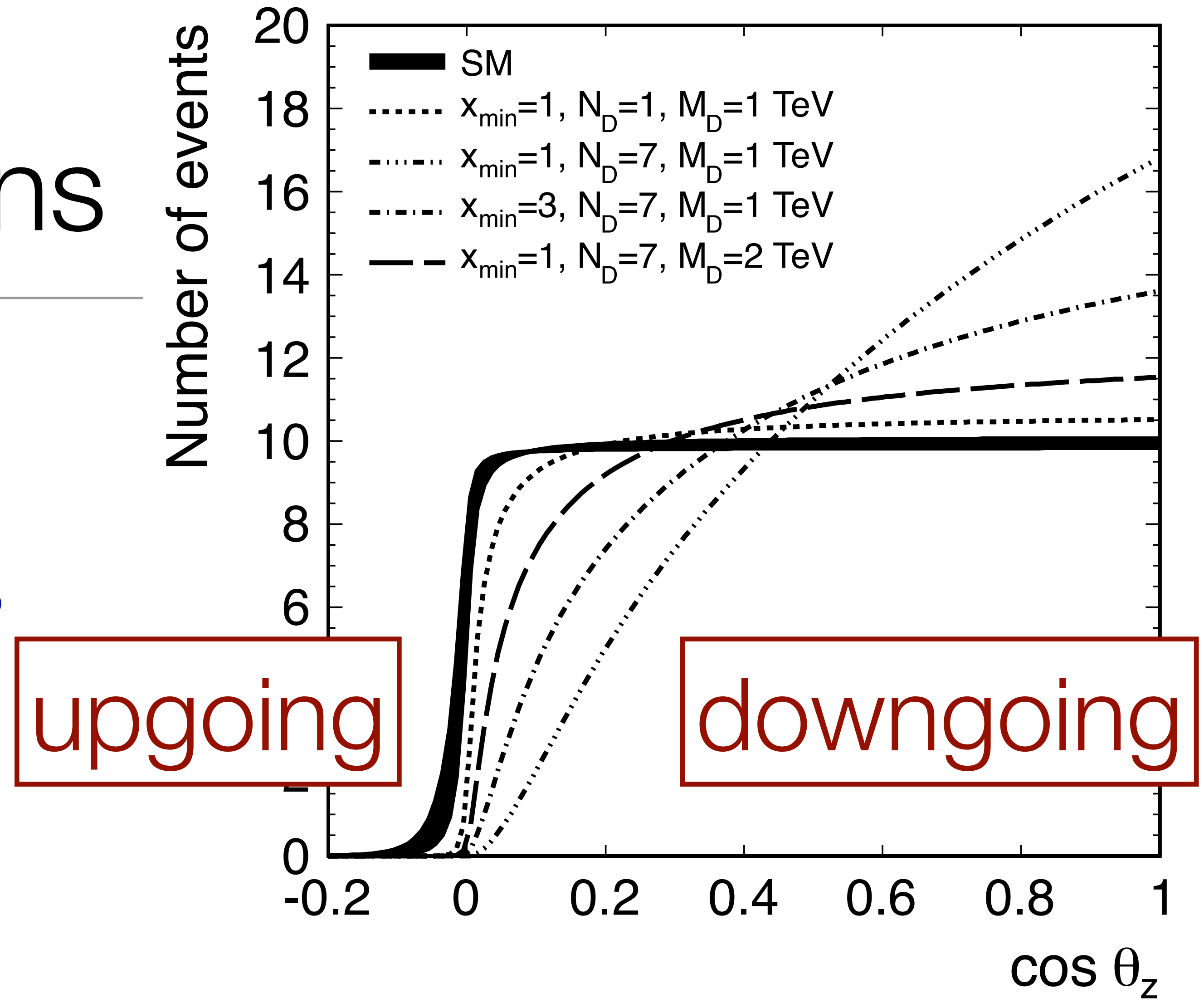


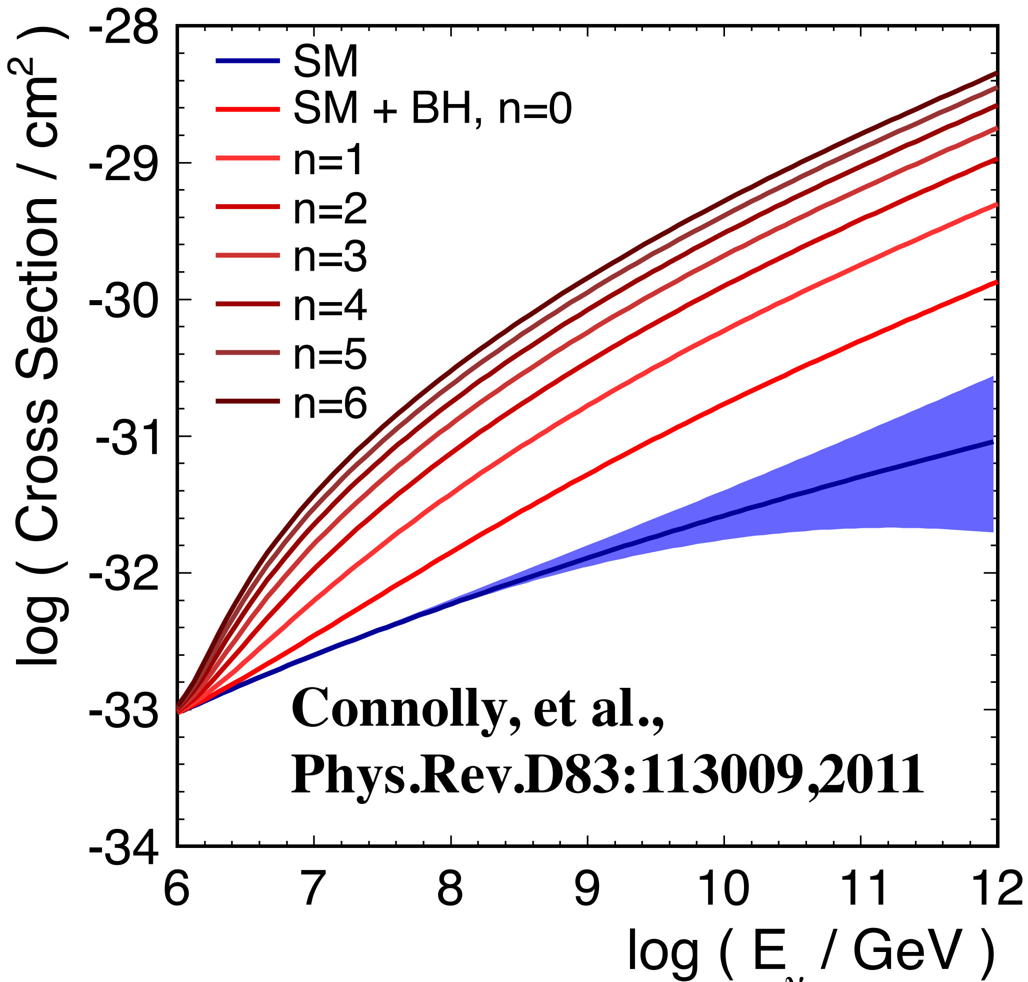
SM prediction: band due to uncertainties on cross section

Enhanced Cross Sections

- Models with extra space-time dimensions lead to enhanced νN cross sections due to micro-black hole production

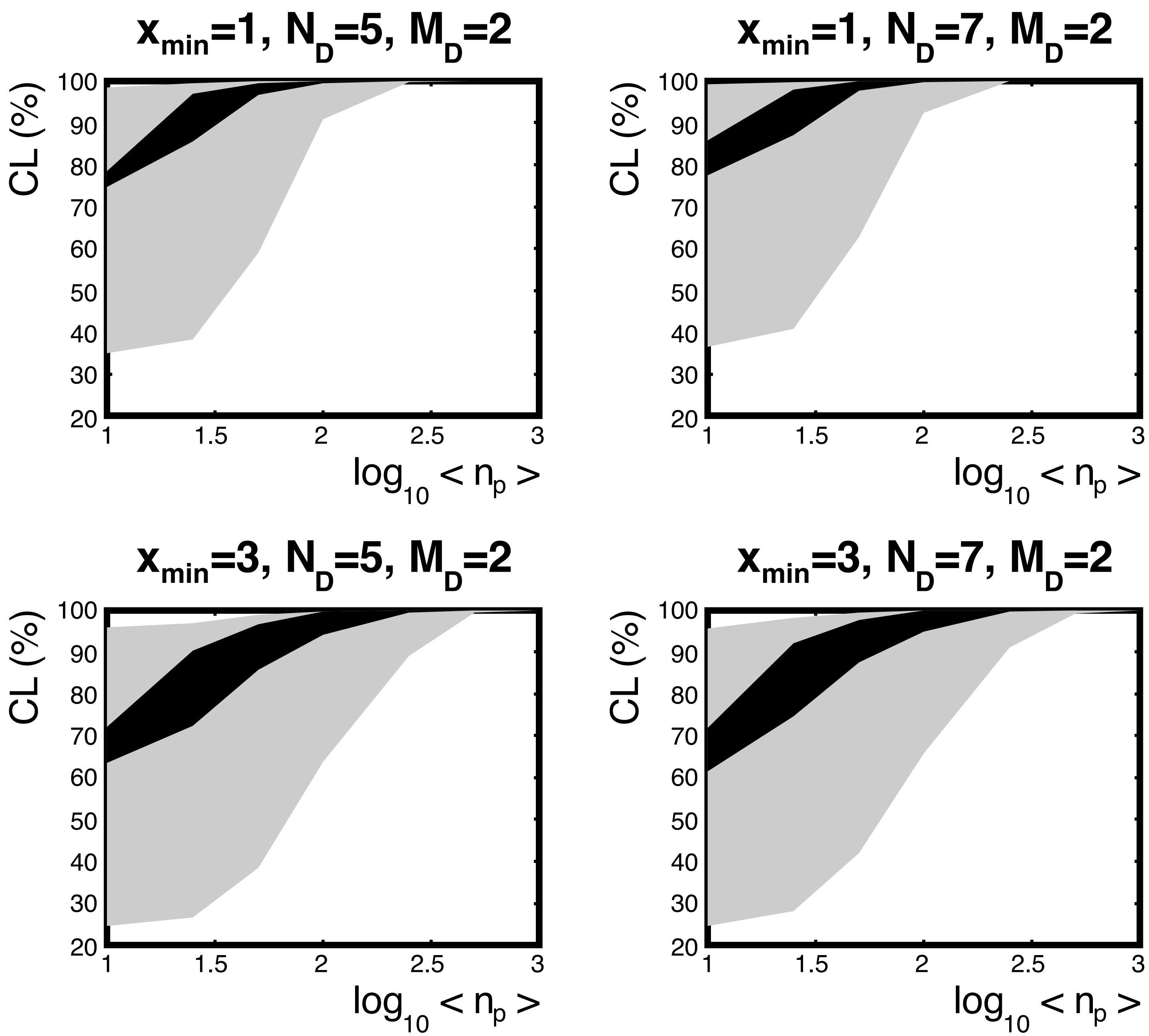
J. Alvarez-Muniz and E. Zas, Phys. Lett. B411, 218 (1997)





- These would modify the θ_z distributions from the Standard Model (SM) expectation
- N_D = # extra dimensions, M_D = reduced Planck scale, $x_{min} = M^{BH}_{min} / M_D$

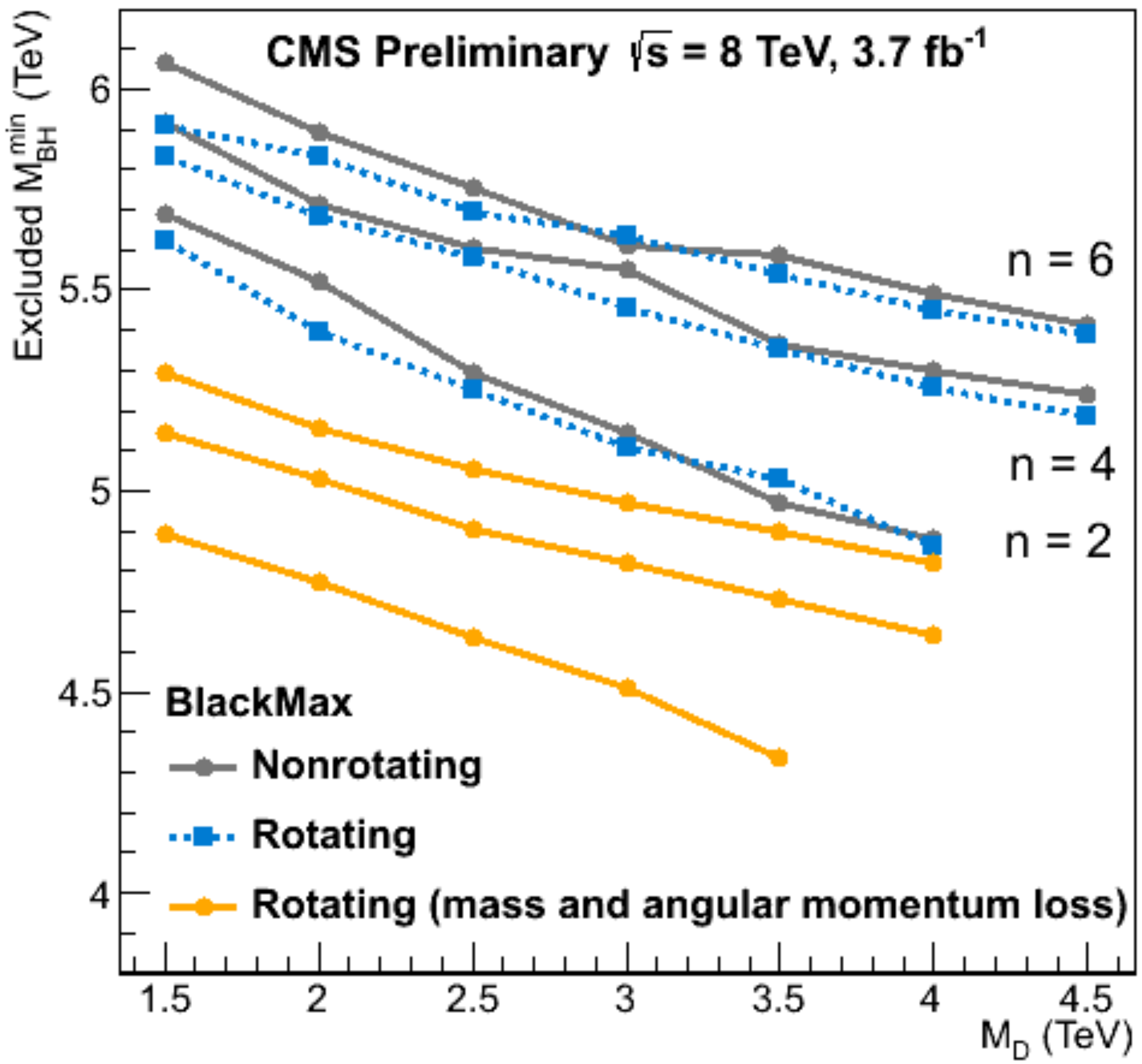
Expected Constraints



- Black bands: systematic uncertainty on SM cross sections
- Gray bands: statistical uncertainties
- On average, with 100 events, expect to exclude:
- $x_{min} = 1, M_D = 1, N_D \geq 2$
  $x_{min} = 3, M_D = 1, N_D \geq 3$
  $x_{min} = 1, M_D = 2, N_D \geq 3$
- $x_{min} = 3, M_D = 2, N_D = 7$ excluded with 110 events

Some of these are already excluded by the LHC. BUT unique opportunity to probe the theory w/ UHE neutrinos

CMS constraints for reference



Conclusions

- UHE vN cross sections sensitive to enormous COM energies and miniscule parton momentum fractions inaccessible by colliders
- Current predictions for high energy vN cross sections agree at and below 10^8 GeV where they depend on measured region of x
- Differences in calculations at high energies originate from low-x parametrizations of PDFs
- UHE cross sections can be measured, new physics probed in a unique way, with a detector on earth that measures a sample O(100) events