THE OHIO STATE UNIVERSITY

Neutrino-Nucleon Cross Sections at High Energies

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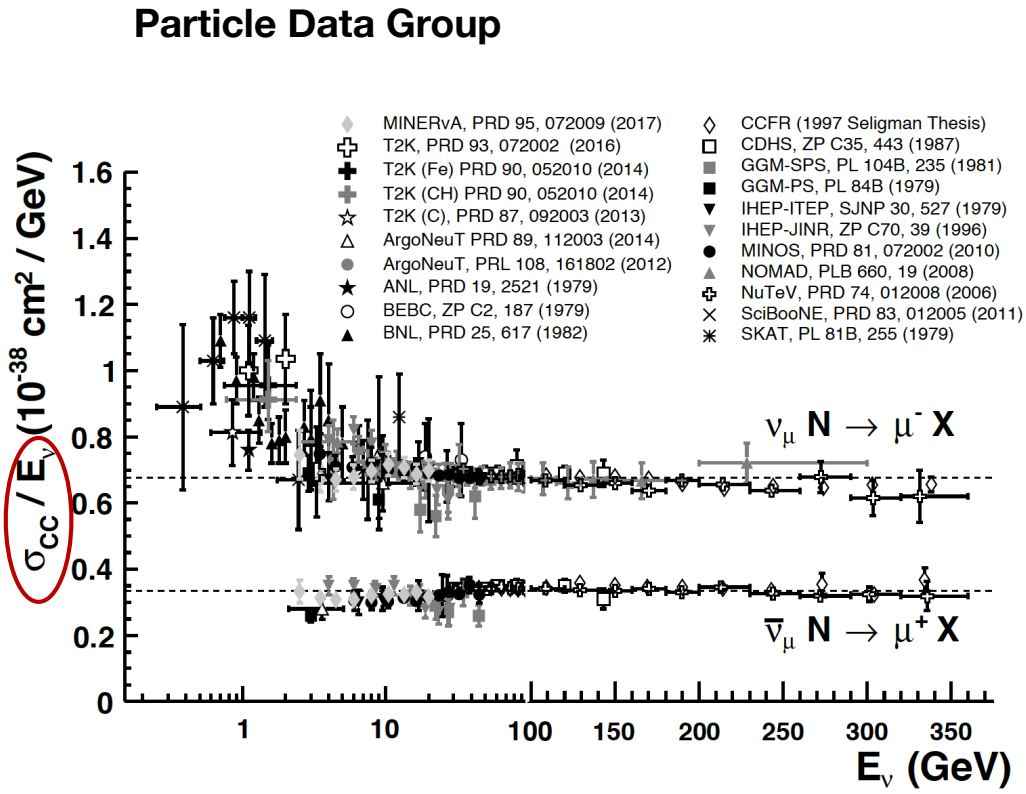
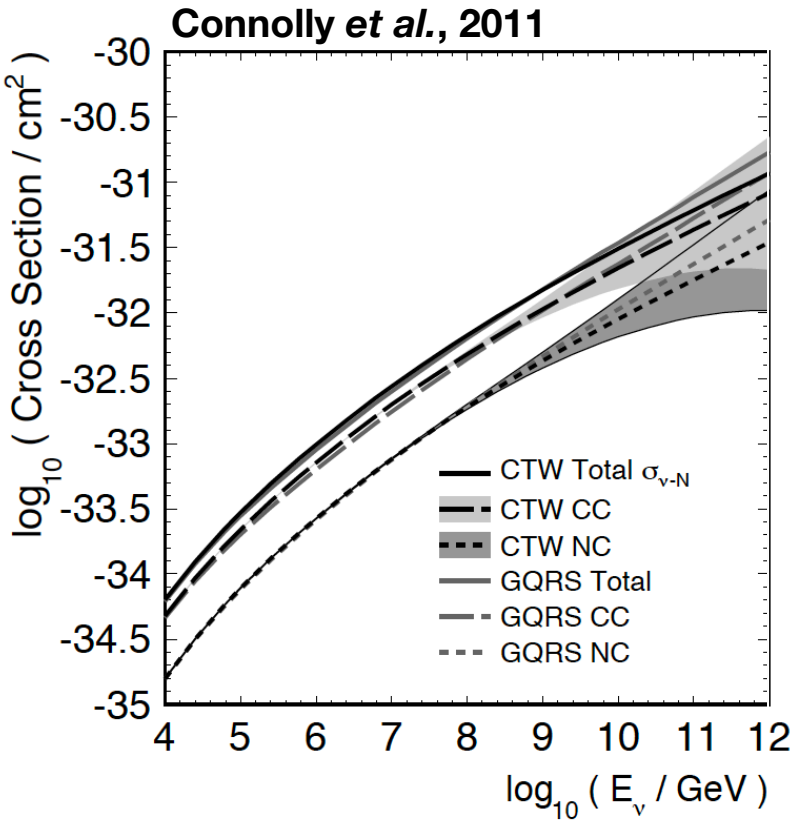
What is a cross section σ

- A quantity related to probability of an interaction between particles
- Units of area (e.g., cm^2)
- 1 barn=10^{-24} cm^2
- Weak interactions at LHC: ~nb, strong: ~10s of mb
- Interaction length $\ell = \frac{m_N}{\sigma \cdot \rho}$

νN σ's important for experiments

- Needed at all energies to model experiments





Logarithmic

Linear

~$E^{0.36}$

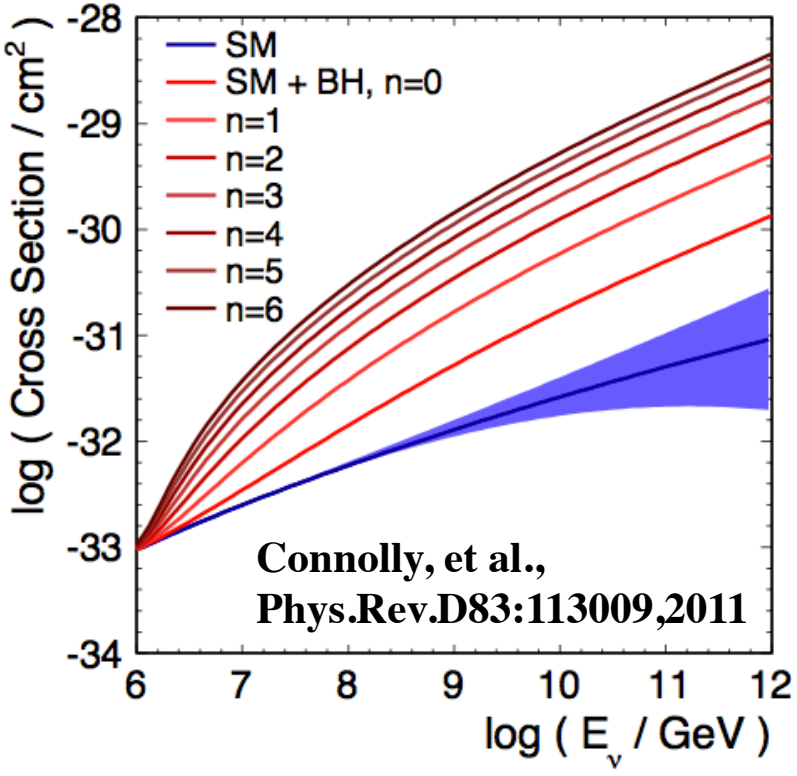
ν-quark point-to-point

$W^{\pm}$, Z^0 propagators

νN σ's important for probing new physics

- Center of mass $\sqrt{s}$ of νN interactions » LHC energies

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



$$\sqrt{s} = \sqrt{2 m_N E_\nu}$$

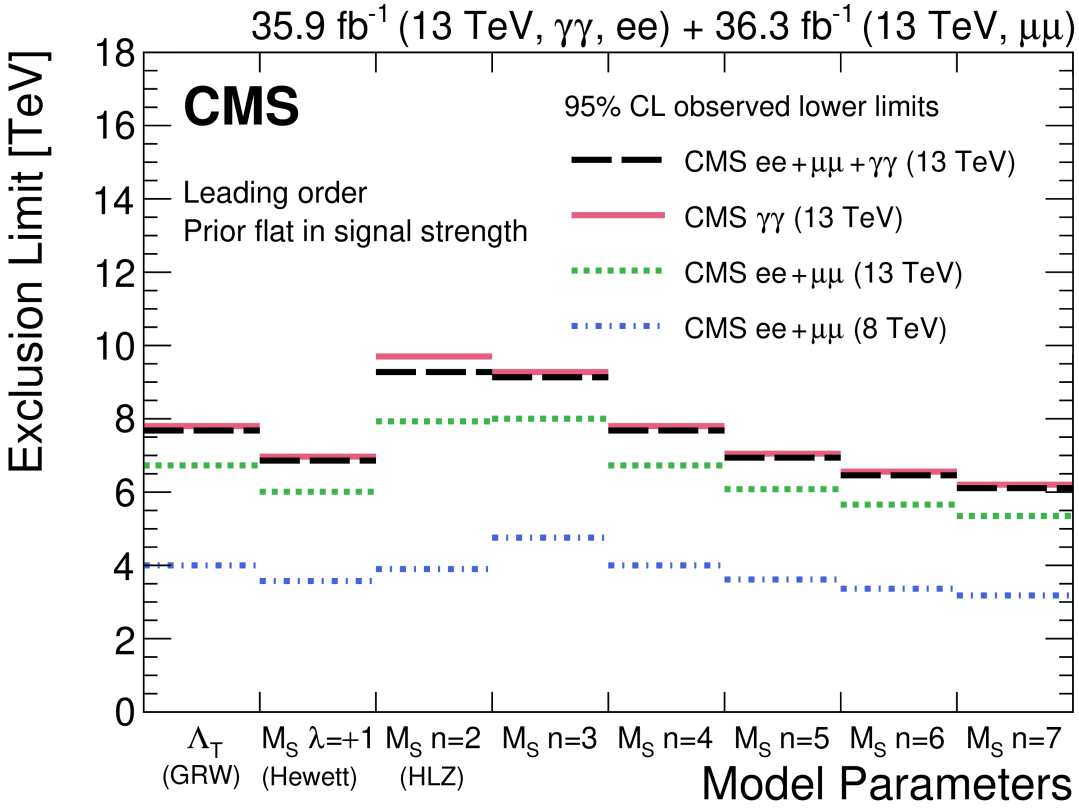
- Center of mass $\sqrt{s}$ of νN interactions » LHC energies

$$E_\nu = 10^{18}\,\mathrm{eV} \rightarrow \sqrt{s} = 45\,\mathrm{TeV}!$$

$$E_\nu = 10^{20}\,\mathrm{eV} \rightarrow \sqrt{s} = 450\,\mathrm{TeV}$$

- Example: could probe models of n extra dimensions

Complementing LHC



- LHC excludes extra-dimensions parameter space we'd probe in the near future
- But what if something shows up uniquely in νN interactions?

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

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

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

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

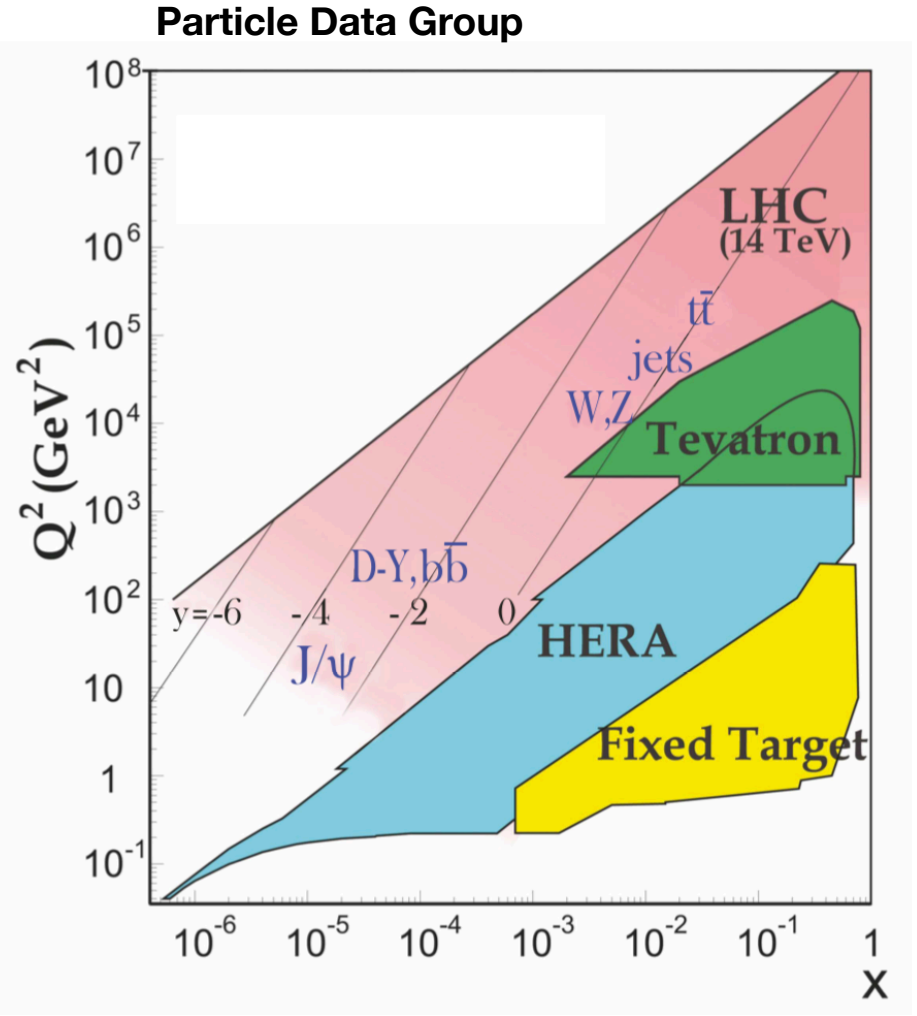
$$q^0 = \frac{u+d}{2}\left(L_u^2 + L_d^2\right) + \frac{\bar{u}+\bar{d}}{2}\left(R_u^2 + R_d^2\right) + (s+b)\left(L_d^2 + R_d^2\right) + (c+t)\left(L_u^2 + R_u^2\right)$$

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

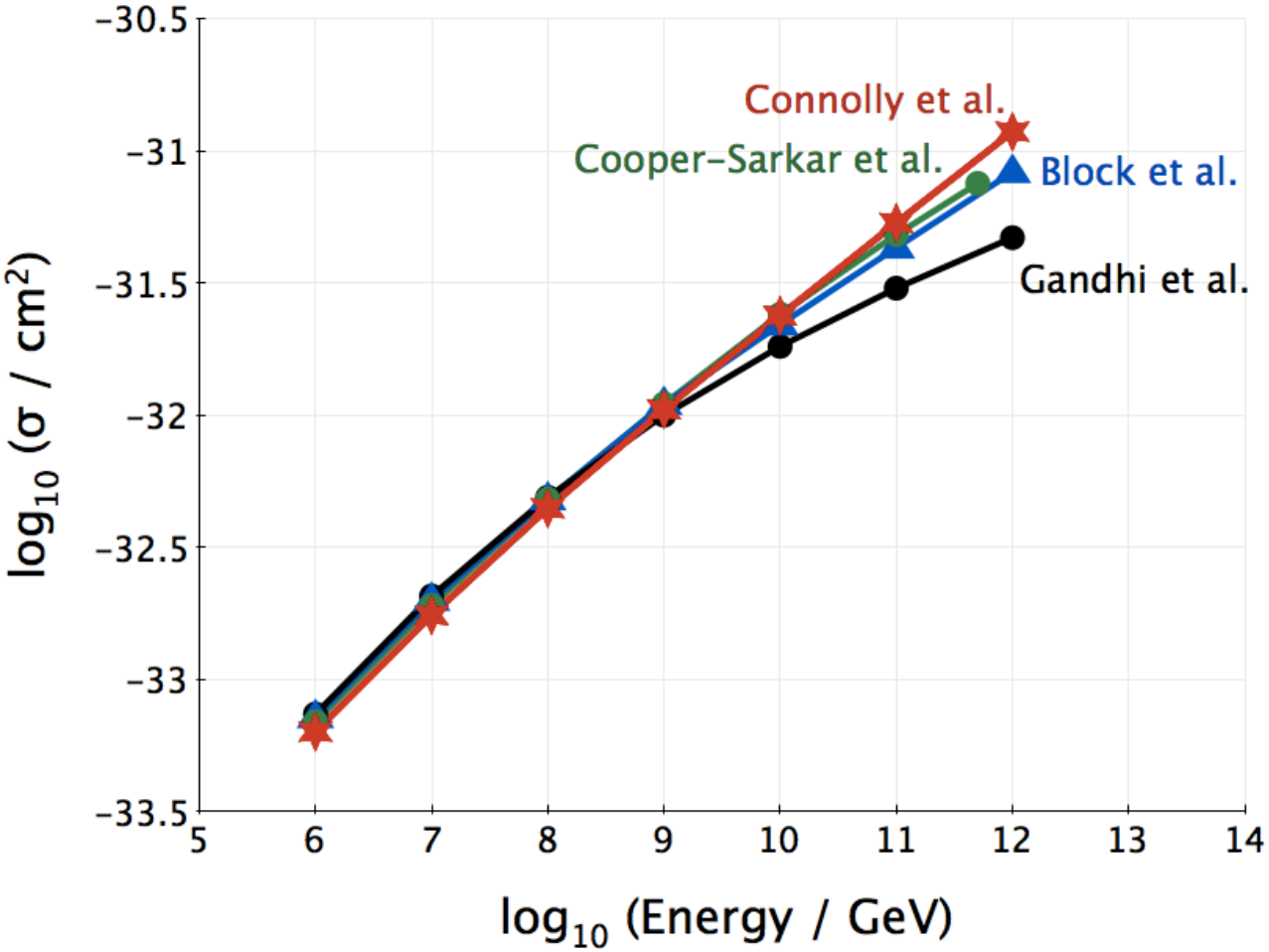
$$L_u = 1 - \frac{4}{3}x_W \qquad L_d = -1 + \frac{2}{3}x_W \qquad R_u = -\frac{4}{3}x_W \qquad R_d = \frac{2}{3}x_W$$

Theory

- 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 $\rightarrow x \lesssim 10^{-5}$
- Extrapolation to low-x necessary



νN Cross Section calculations



R. Gandhi, C. Quigg, M.H. Reno, I. Sarcevic (1998)

A. Connolly, R. Thorne and D. Waters (2011)

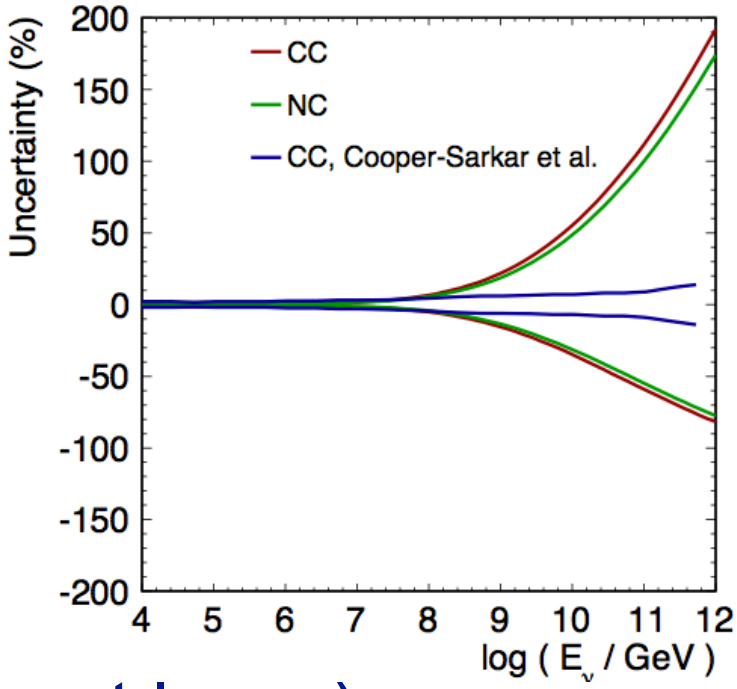
Cooper-Sarkar, Mertsch and Sarkar (2011)

M. Block, L. Durand, P. Ha, D. McKay (2013)

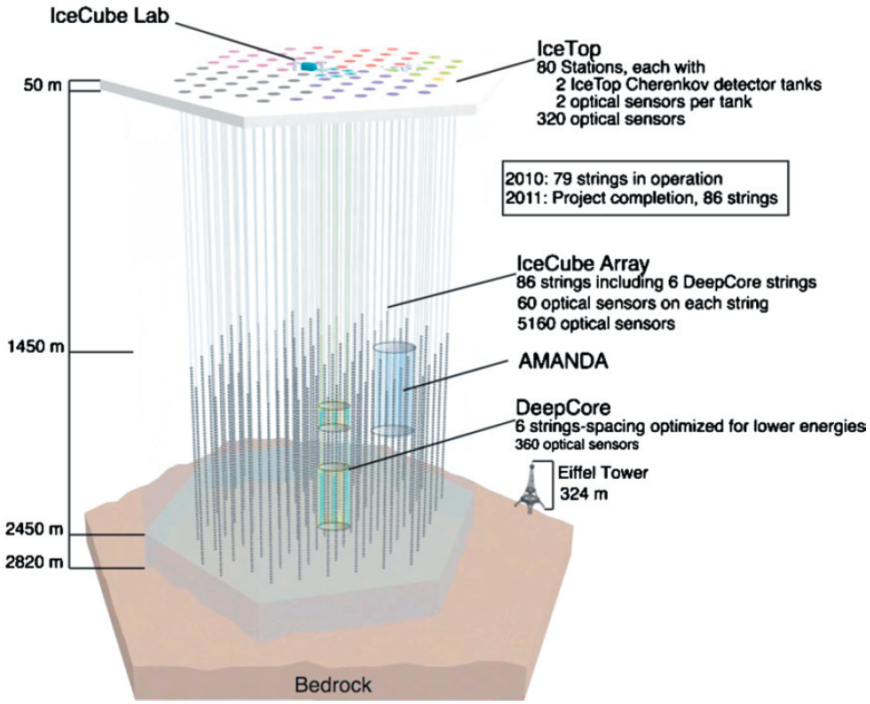
Weaker low-x dependence gives lower cross sections at high energies

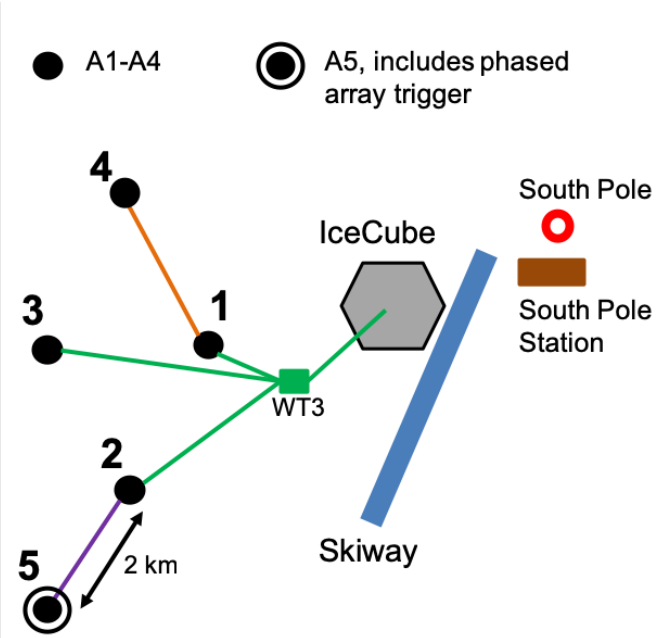
Uncertainties

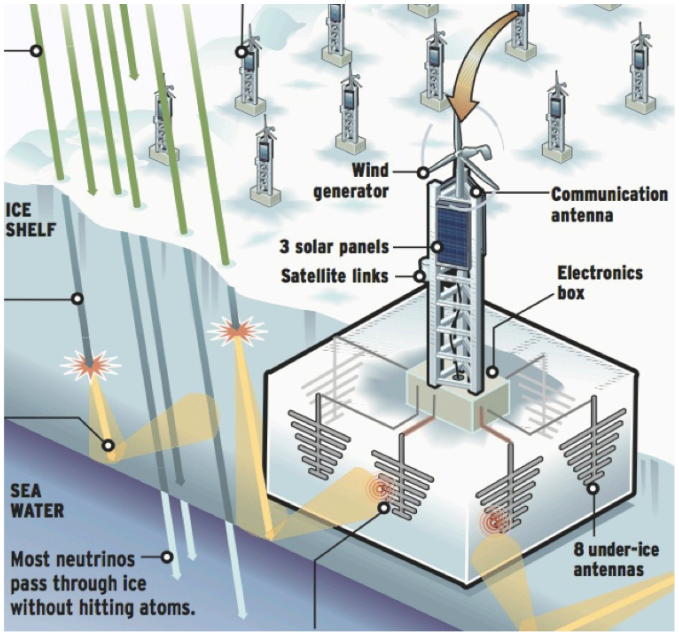
- Gandhi *et al*: factor of 2±1 uncertainties
- Connolly *et al*:
  - < few % below $10^{7.5}$ GeV
  - ~factor of 2 at 10^{11} GeV
- Cooper-Sarkar *et al*:
  - < few % below $10^{7.5}$ GeV
  - <10% at 10^{11} GeV
    (due to weaker g(x) dependence at low x)
- M. Block *et al*:
  - 2% all the way up to 10^{17} GeV! (re
    (relying on Foissart bound)



σ measurements in-ice

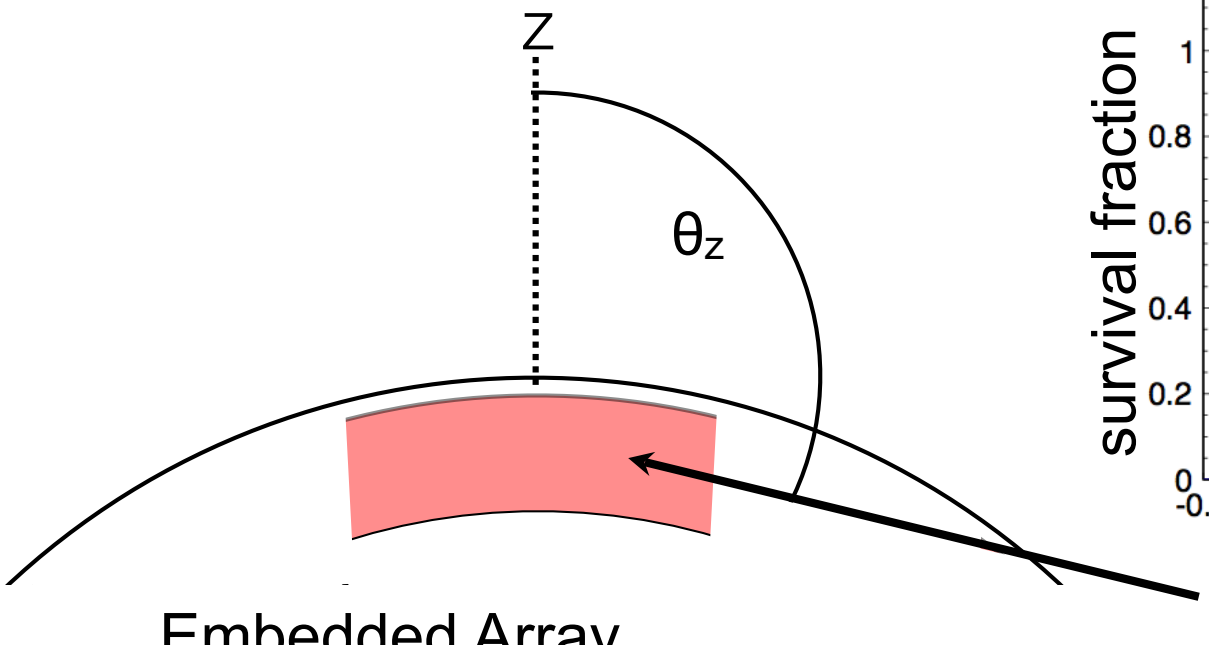




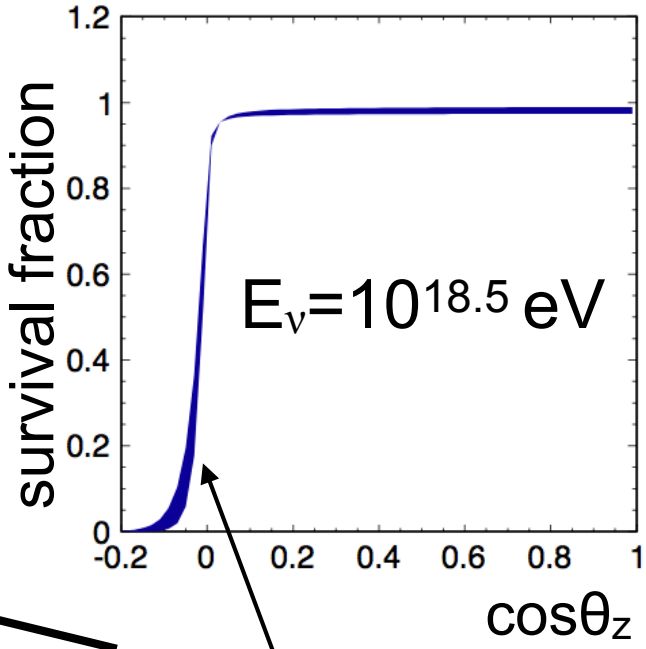


σ measurements in-ice

- Incident neutrinos subject to earth absorption
- Zenith angle dependence sensitive to cross section



Embedded Array
e.g. IceCube, ARA

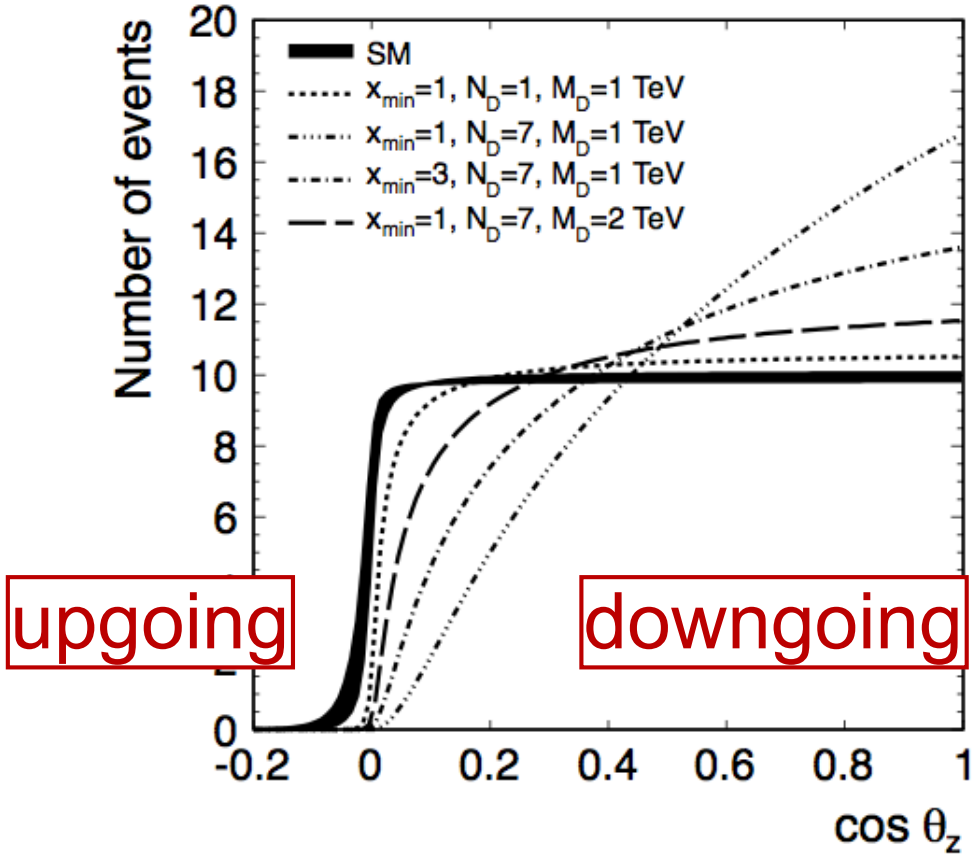


cosθz=1 → down-going neutrino

Band due to σ uncertainties

Enhanced Cross Sections

- Models with extra space-time dimensions lead to enhanced νN cross sections
- Leptoquarks can too

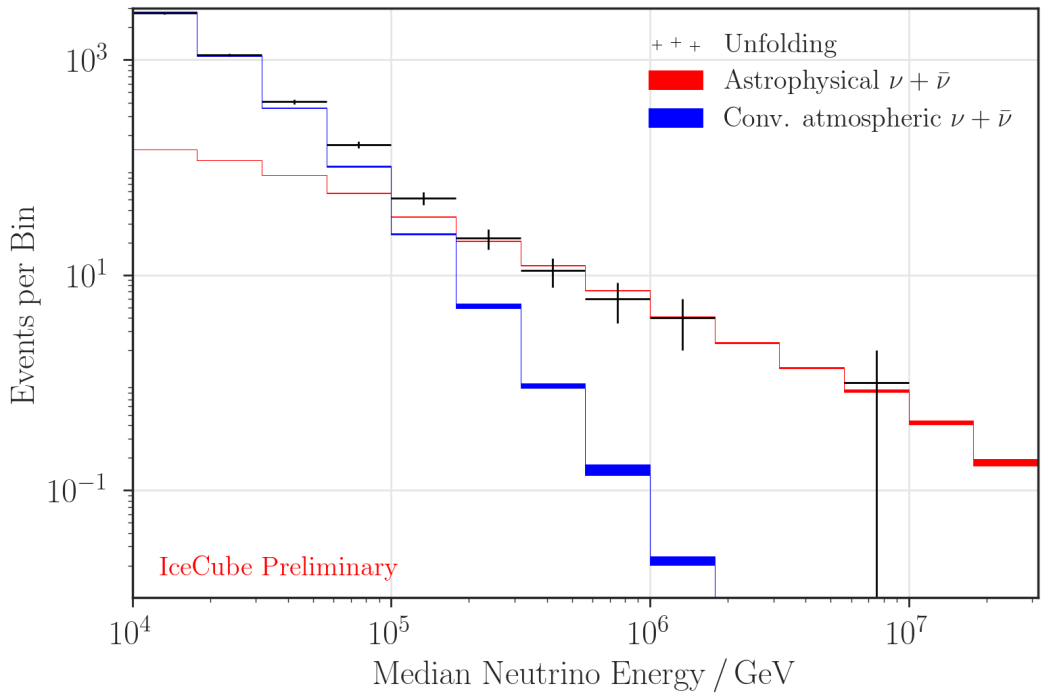


IceCube neutrino spectrum

- Observed E_ν > 1 PeV

$$E_\nu = 1\,\mathrm{PeV} \rightarrow \sqrt{s} = 1.4\,\mathrm{TeV}$$

- Atmospheric and astrophysical can be used for cross section measurements → assume incident fluxes isotropic

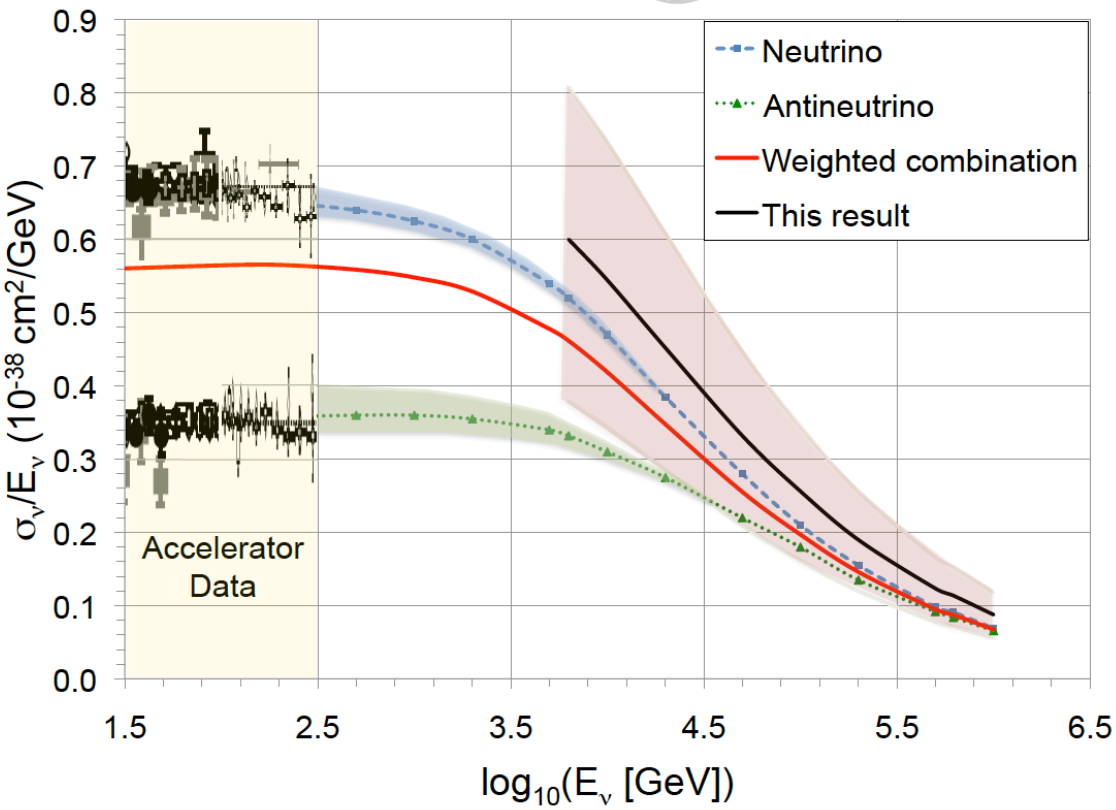


σ measurements happening now!

- Previously, νN cross section measurements up to E_ν~400 GeV
- First measurement of neutrino absorption in earth
- Using a sample of ~11,000 upward-going neutrino-induced muons from outside

IceCube Collaboration
Nature 551 (2017) 596-600

IceCube South Pole Neutrino Observatory



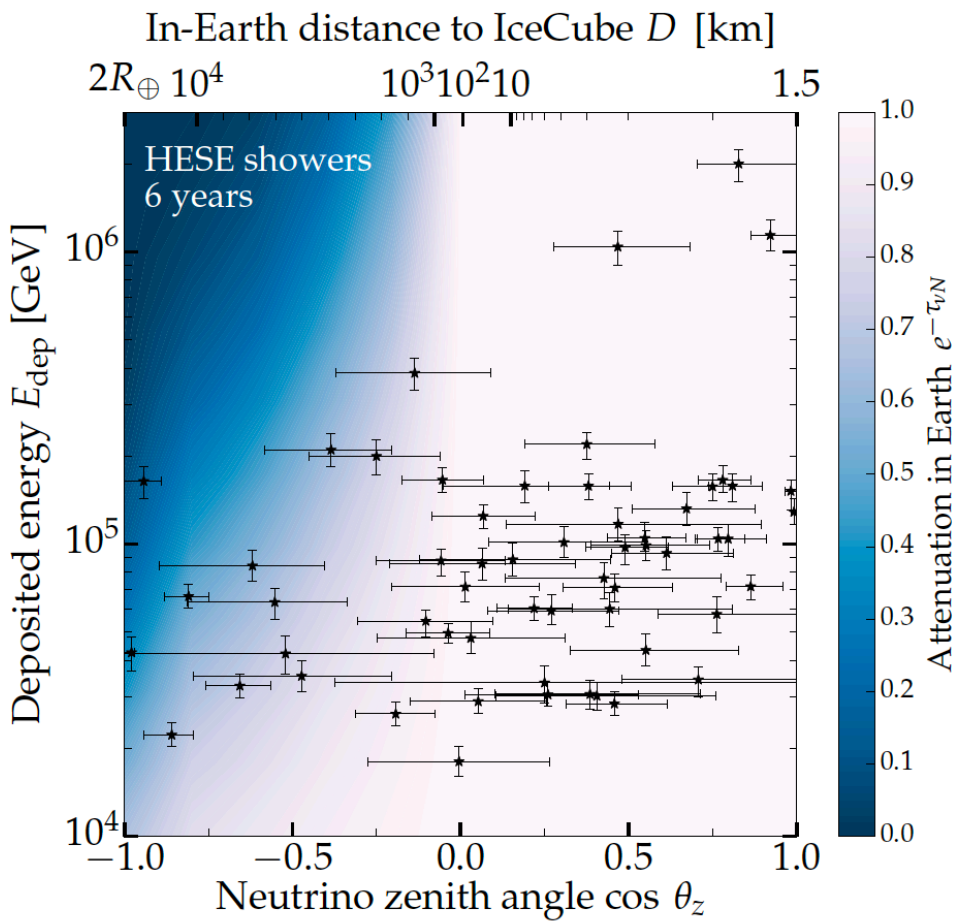
$$1.30^{+0.21}_{-0.19}\ (\text{stat.})^{+0.39}_{-0.43}\ (\text{syst.}) \times \text{SM}\ \sigma$$

(Note I am not currently a member of IceCube)

σ measurements happening now!

- Public IceCube High-Energy Starting Events
  - 58 contained showers
  - Energy better measured

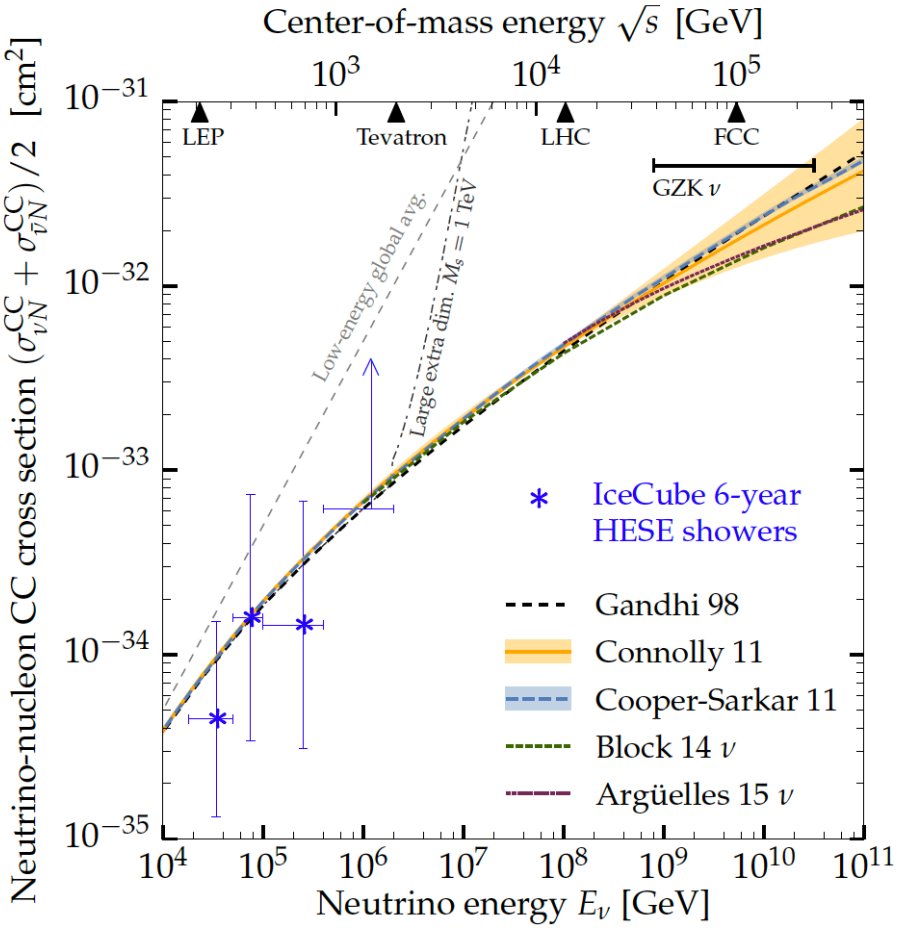
M. Bustamante & A. Connolly
Phys.Rev.Lett. 122 (2019) no.4, 041101



σ measurements happening now!

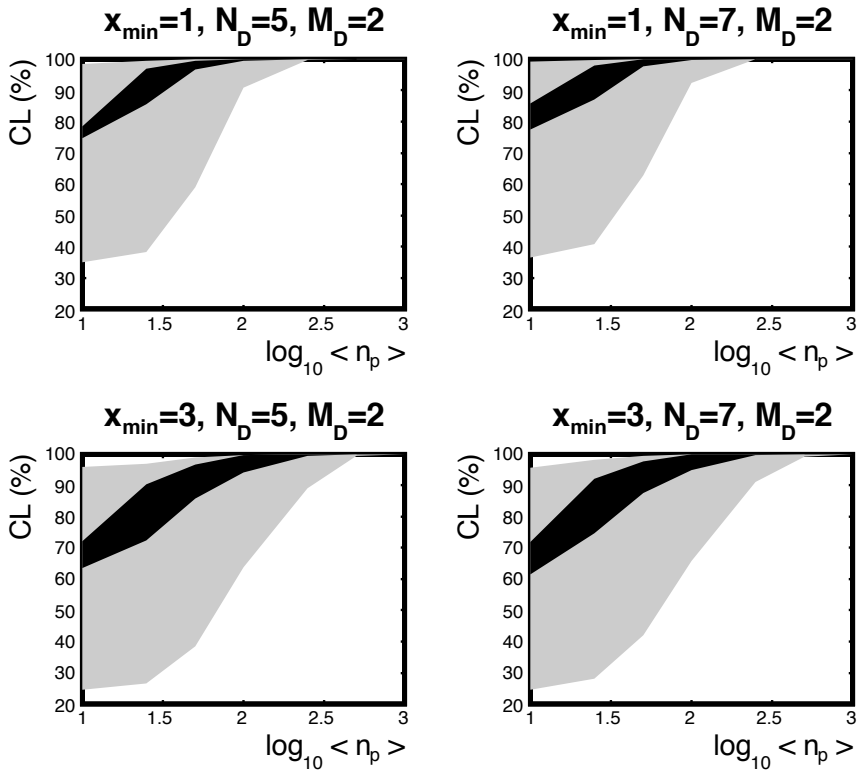
- First energy-dependent measurement in this regime where $\sigma \propto E^{0.36}$
- First to show that the energy dependence agrees with the predicted softer-than-linear dependence
- No new physics

M. Bustamante & A. Connolly
Phys.Rev.Lett. 122 (2019) no.4, 041101



Future

- IceCube-Gen2 (optical) will improve energy resolution, improve statistics
- Future analyses will need to take anisotropies into account
- Radio arrays will extend to ultra-high energy regime opening up windows to new physics



Conclusions

- The dream is here!
- Can't wait for precision measurements with new experiments and new data
- Let's find new physics before colliders!

High energy vN σ calculations

- 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 vN σ calculations

- 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 $\ln E^2$

Advertisement: σ parametrizations for your convenience

- Connolly *et al.* provide energy-dependent parametrizations for $4 < \log_{10}(E/\mathrm{GeV}) < 12$
  - 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.