High-energy neutrino D.I.S. cross sections from 100 GeV to 1000 EeV †

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†based on CT18 Parton Distribution Functions

High-energy neutrino deeply inelastic scattering cross sections from 100 GeV to 1000 EeV

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(CTEQ-TEA Collaboration)

arXiv:2303.13607 [hep-ph]

1. Introduction

Particle Data Group Figure 52.1

$\frac{\sigma}{E\nu}$

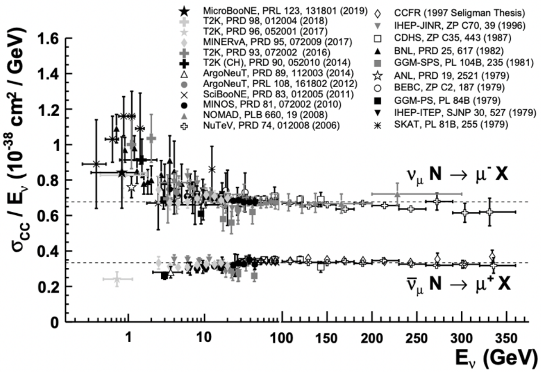


Figure 52.1: Measurements of per nucleon ν_μ and $\overline{\nu}_\mu$ CC inclusive scattering cross sections divided by neutrino energy as a function of neutrino energy. Note the transition between logarithmic and linear scales occurring at 100 GeV. Neutrino cross sections are typically twice as large as their corresponding antineutrino counterparts, although this difference can be larger at lower energies. NC cross sections (not shown) are generally smaller compared to their CC counterpart.

E_ν = neutrino energy in the target rest frame

σ / E from 1 ~ 350 GeV ∎ accelerator expts

σ (E) ~ linear ∎ 4 – fermion contact interaction

$\sqrt{s} = \sqrt{2\,m\,E} \in (1.4,\ 26\ \text{GeV})$

→ FASERν ~ 1 TeV → IceCube ~ 10 PeV

Ice Cube data

[IceCube Collaboration, Phys. Rev. D 104, 022001 (2021); arXiv:2011.03560v1]

Measurements of $\sigma^{\dagger}$ for 4 ranges of E_ν † CC, ν&$\bar{\nu}$, isoscalar

The dashed curve = Theory = the CSMS Model

A. Cooper-Sarkar, P. Mertsch, S. Sarkar, JHEP 08, 042 (2011); arXiv:1106.3723[hep-ph].

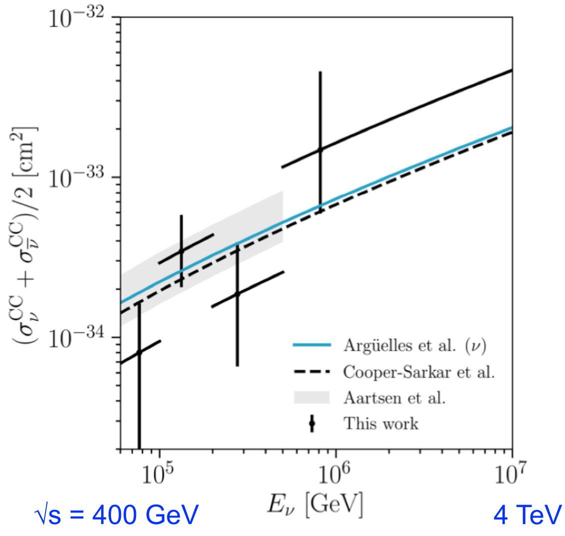
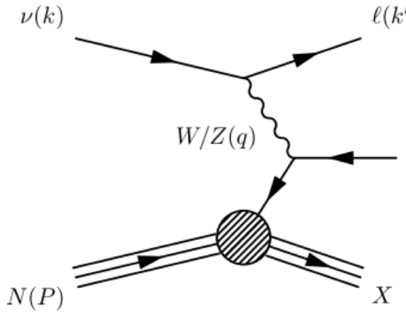


FIG. 5. The charged-current, high-energy neutrino cross section as a function of energy, averaged over ν and $\bar{\nu}$. The Wilks' 1-sigma CI is shown along with two cross section calculations [14, 16]. The confidence intervals from [21] are also shown for comparison

Parameter	Energy range	68.3% HPD	68.3% CI
x_0	60 TeV to 100 TeV	$0.21^{+0.52}_{-0.21}$	$0.48^{+0.49}_{-0.37}$
x_1	100 TeV to 200 TeV	$1.65^{+1.49}_{-0.84}$	$1.50^{+1.03}_{-0.60}$
x_2	200 TeV to 500 TeV	$0.68^{+1.11}_{-0.43}$	$0.54^{+0.60}_{-0.35}$
x_3	500 TeV to 10 PeV	$4.31^{+13.26}_{-3.32}$	$2.44^{+5.10}_{-1.47}$

TABLE II. Measured 68.3% HPD (Bayesian) and CI (frequentist) for the four cross section parameters.

1b. Neutrino-nucleon deep inelastic scattering



- Eight nucleon cross sections

  2 projectiles ; 2 targets ; 2 interactions

  ν and ν ; p and n ; CC and NC

- Four "isoscalar nucleon cross sections" $\sigma_i = \frac{1}{2}(\sigma_p + \sigma_n)$
- Nuclear cross sections, e.g., σ_O (Z=8,A=16) or σ_{Fe} (Z=26,A=56)

Differential cross sections, global analysis of QCD, PDFs

$$\frac{d^2\sigma}{\mathrm{dx\,dQ^2}} = \frac{G_F^2}{4\pi \mathrm{x}\left(1+Q^2/M_W^2\right)^2}\,[Y_+F_2 - y^2F_L \pm Y_-\,\mathrm{x}\,F_3\,]$$

$$F_2^{\nu W} = 2\mathrm{x}(\sum_i d_i + \sum_i \overline{u}_i) \;+ \mathrm{NLO} + \mathrm{NNLO} + \ldots$$

$$\mathrm{x}F_3^{\nu W} = 2\mathrm{x}(\sum_i d_i - \sum_i \overline{u}_i) \;+ \mathrm{NLO} + \mathrm{NNLO} + \ldots \text{ etc, etc, etc}$$

Data (CCFR, NuTeV) $\Longrightarrow$ determination of PDF's and their uncertainties.

- The CSMS model † (on which the IceCube Collaboration relies)

† HERAPDF1.5 + NLO PDFs + pre-LHC data

- This CTEQ-TEA model ‡ (based on CT18 global analysis)

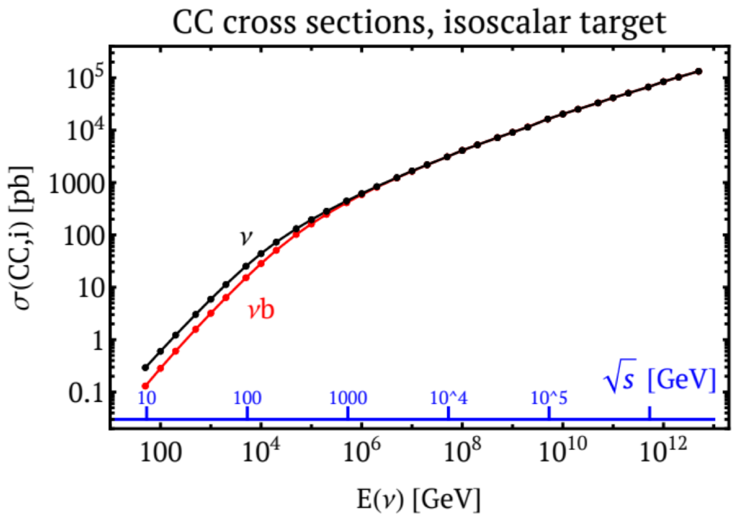
‡ NNLO PDFs + LHC data + CTEQ uncertainties + nuclear effects.

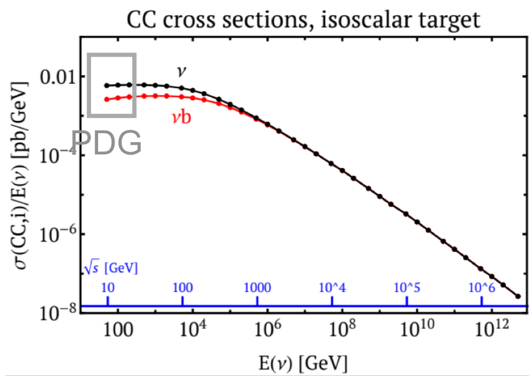
2. The CT18 calculations of high-energy neutrino-nucleon cross sections

First I'll show our results; then comment how.

σ(ν or $\bar{\nu}$, CC, i) results :

σ(E) σ(E)/E

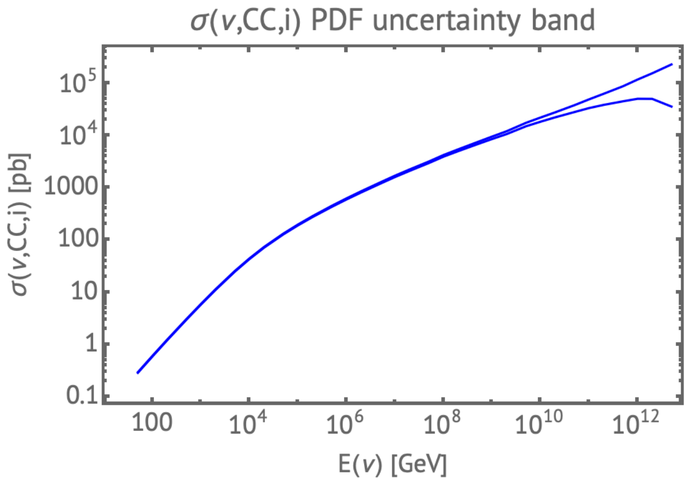


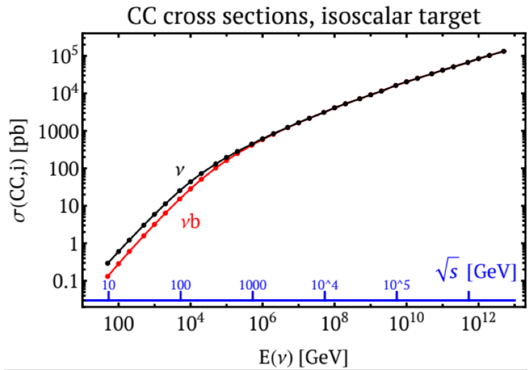


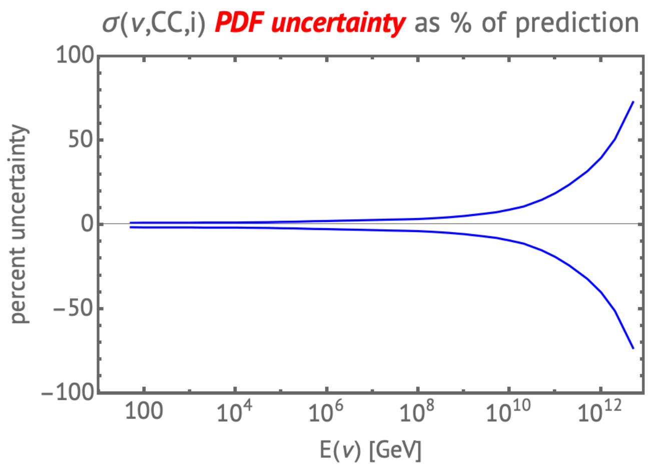
$\sqrt{s} = \sqrt{2\, m\, E_\nu}$

Similarly, the NC cross sections ⟶ important but small differences.

PDF uncertainties for CC cross sections







Comparing cross sections

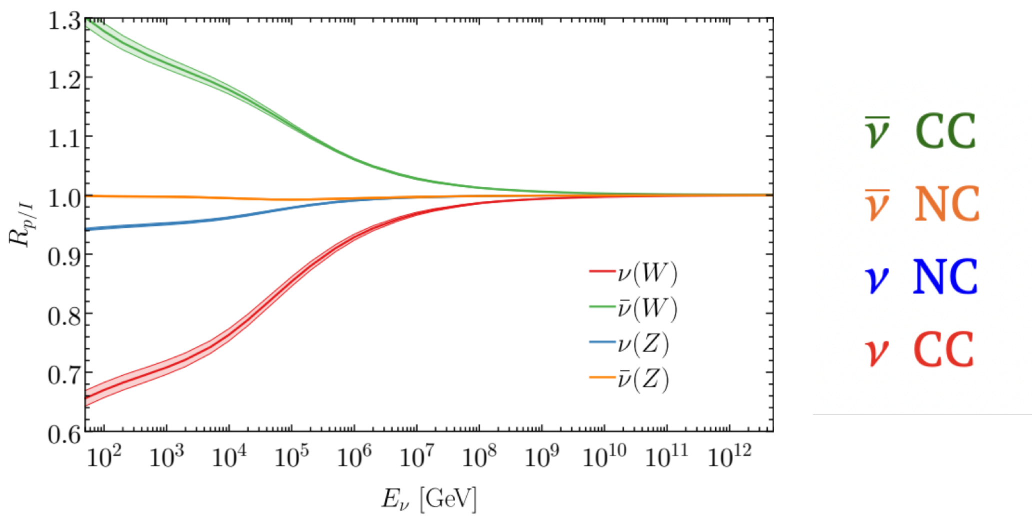
There are too many comparisons to show them all.

But for example... Compare a proton target to an "isoscalar target";

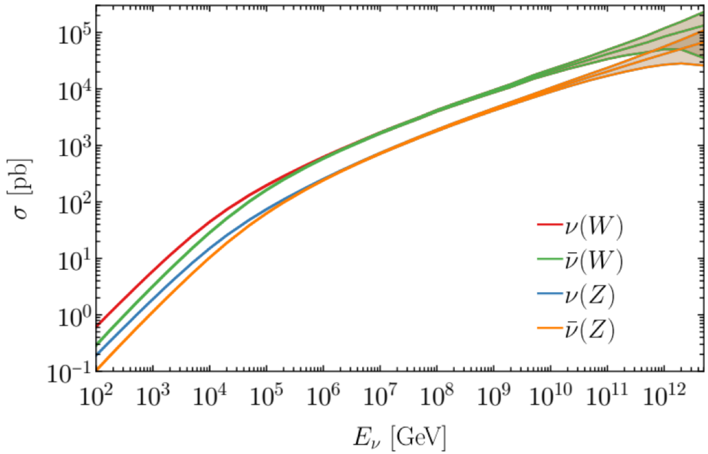
For example, neutrino projectiles, p and n targets:

$\sigma_p = \sigma(\nu + p \longrightarrow l^- + X)$ ■ $\sigma_n = \sigma(\nu + n \longrightarrow l^- + Y)$ ■ $\sigma_I = \frac{1}{2}(\sigma_p + \sigma_n)$

Consider this ratio $R_{p/I} = \dfrac{\sigma_p}{\sigma_I}$ vs E_ν

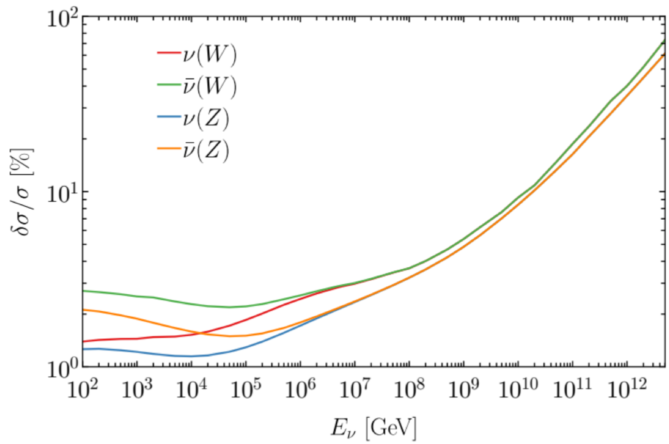


These figures show our final results; Tables are provided.



central predictions

the CT18 uncertainties



3. Comments on the Calculations

1/ Small-x Partons

$$\sigma_{\text{DIS,total}}(E_\nu) = \int_0^{2mE_\nu} dQ^2 \int_0^1 dx \; \frac{d^2\sigma}{dx\,dQ^2}(x, Q\hat{}2)\,,$$

but PDF's are only published for Q > $Q_{\min}$ and x > $x_{\min}$.

And for UHE ν the important range of x extends to very small x; $\sim 10^{-9}$.

∃ a practical problem, and physics questions.

cf. talk by Keping Xie
earlier in WG2

2/ NNLO QCD perturbation theory

The CT18 Global Analysis of QCD provides NNLO PDFs,
and a complete set of uncertainties (eigenvectors of the Hessian matrix).

- But ∃ different treatments for parton masses (ZM-VFN, GM-VFN, S-ACOT-χ)
- Also ***some*** N^3LO corrections are known (APFEL, HELL)

Extensive studies are described in the paper.

In the end, we made some choices…

(CT18NNLO, n_f = 6, N3LO', NL_Lx)

and provide Tables of …

$\sigma_{\nu \mathrm{I}}^{\mathrm{CC}}(E_\nu)$, $\sigma_{\bar{\nu} I}^{\mathrm{CC}}(E_\nu)$, $R_{\nu \mathrm{O}:I}^{\mathrm{CC}}$, $R_{\bar{\nu}\, O:I}^{\mathrm{CC}}$ and $\delta\sigma$ and δR

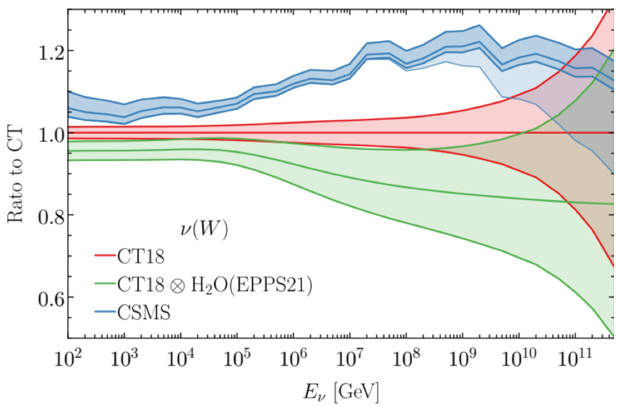
$\sigma_{\nu \mathrm{I}}^{\mathrm{NC}}(E_\nu)$, $\sigma_{\bar{\nu} I}^{\mathrm{NC}}(E_\nu)$, $R_{\nu \mathrm{O}:I}^{\mathrm{NC}}$, $R_{\bar{\nu}\, O:I}^{\mathrm{NC}}$ and $\delta\sigma$ and δR

The IceCube Collaboration has consistently used the CSMS model of neutrino-nucleon cross sections.

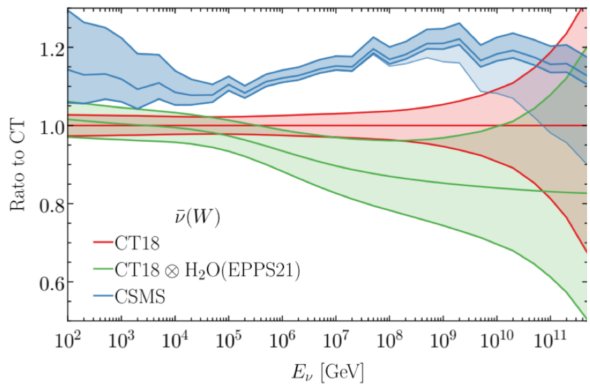
3/ Comparing the CT18 and CSMS models for 10^2 GeV < E_ν < 10^{12} GeV

■ **Plot ratios of other cross sections to the CT18 central prediction.**
Red = the CT18 uncertainty band; Blue = the CSMS Model w/ unc. band;
Green = a calculation with nuclear PDF's (EPPS21; O-16);

CC, ν



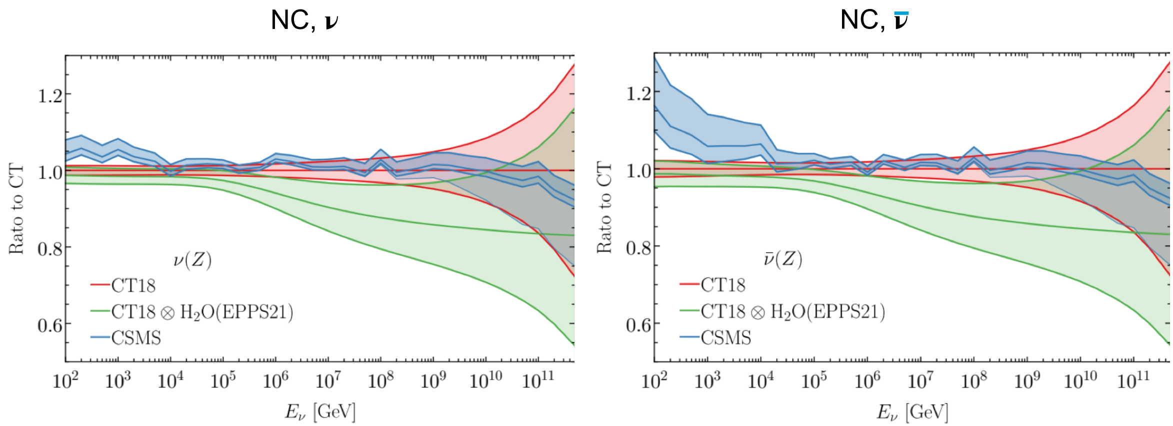
CC, $\bar{\nu}$



■ **nuclear shadowing at small x;** ■ **larger uncertainties than free nucleons at small x;**

EPPS21 nuclear PDFs: K.J.Eskola, P.Paakkinen, H.Paukunen, C.A.Salgado, Eur. Phys. J. C82, 413 (2022) ; arXiv:2112:12462[hep-ph]

Similarly,



■ ■ ■

∃ observable differences between the CT18 and CSMS predictions of σ(E), ranging from 5 ~ 20 percent for CC;

■ σ(CT18) < σ(CSMS); ■ the CT18 uncertainties are larger;

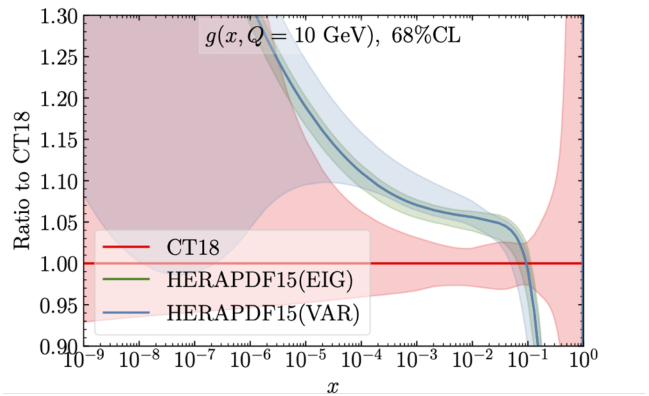
■ nuclear effects are interesting and uncertain.

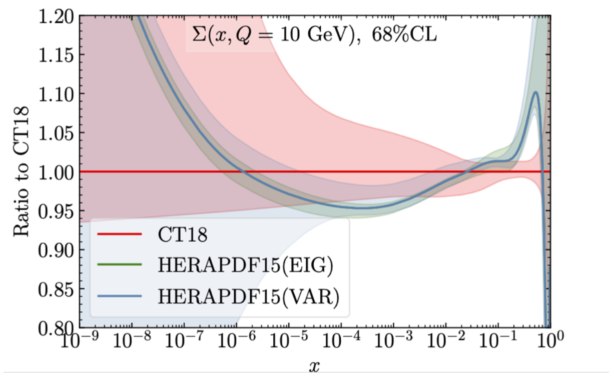
Similarly,

4/ Comparing PDFs : CT18(NNLO) and HERAPDF(NLO)

Ratio to CT18 central; $10^{-9} < x < 1$

gluon quarks





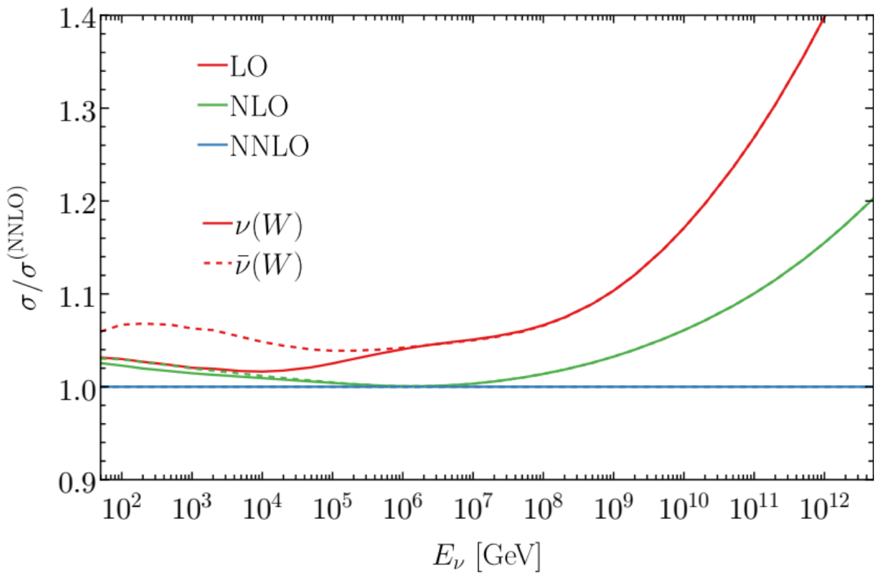
- HERAPDF gluon > CT18 gluon; presumably because the 2 groups used different data sets in their global analyses.

- HERAPDF uncertainty < CT18 uncertainty;

PDF ***uncertainty analyses*** can differ.

Comparing different orders of perturbative QCD

LO, NLO, NNLO ÷ NNLO



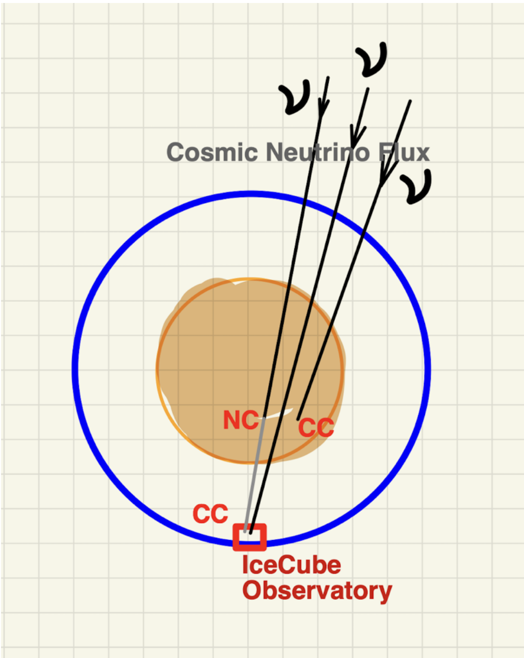
LO

NLO

NNLO

4. Relevance to the IceCube Observatory

The IceCube Observatory ■ measure the HE cosmic neutrino flux ■ discover cosmic neutrino sources ■ test the Standard Model ■ which depend on νN cross sections.



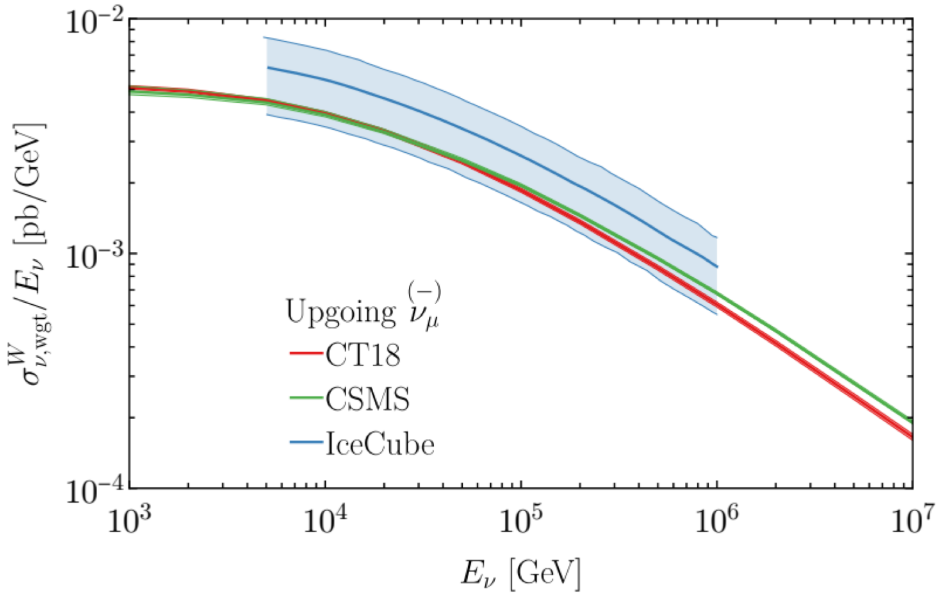
Both CC and NC cross sections are used.

Cherenkov detector

Both CC and NC cross sections are used.

Data from Ice Cube ($\longrightarrow$ 2017)

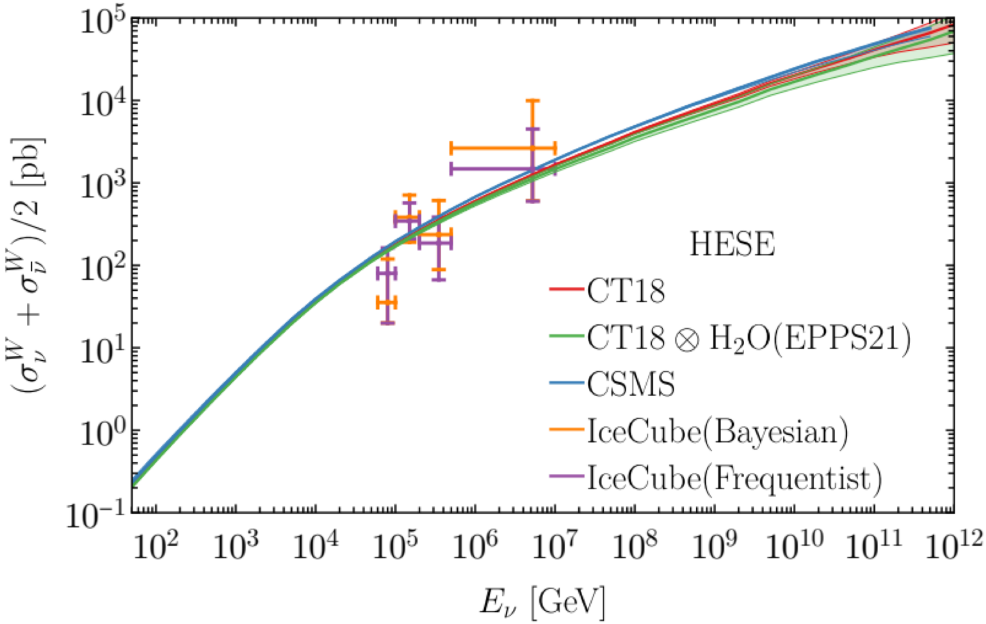
IceCube Collaboration, Nature 551, 596 (2017)   [arXiv:1711.08119v1]



Does this data suggest an excess neutrino cross section?
searching for BSM

Data from IceCube (⟶ 2021)

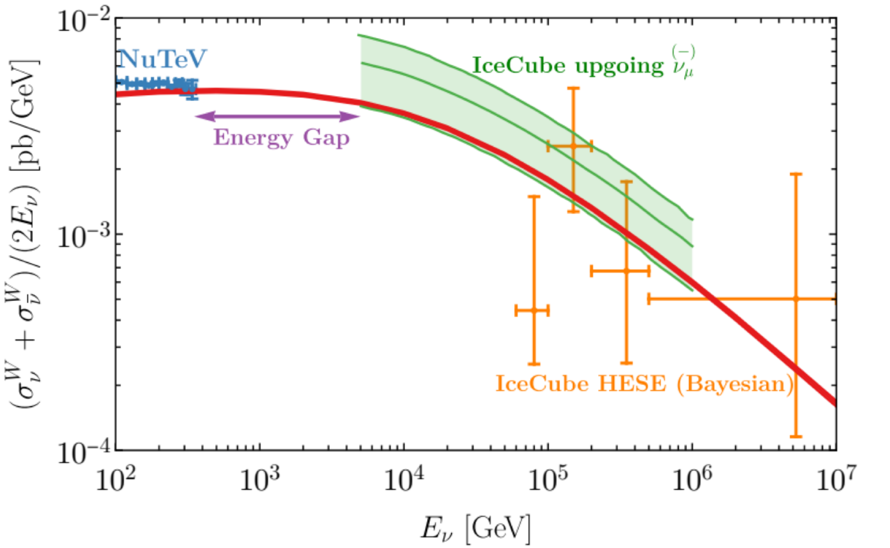
IceCube Collaboration, Phys. Rev. D 104, 022002 (2021) [arXiv:2011.03545v1]



No evidence here for BSM physics up to E_ν = 10 PeV; √s = 4 TeV;
Wanting higher statistics and IceCube Gen2;

Instead of a Conclusion Slide...

The Energy Gap and FASERν



New LHC experiments enter uncharted territory

The first observation of collider neutrinos by FASER and SND at the LHC paves the way for exploring new physics scenarios

22 MARCH, 2023 | By Kristiane Bernhard-Novotny (/authors/kristiane-bernhard-novotny) & Chetna Krishna (/authors/chetna-krishna)