Investigating neutrino-hadron interactions at high energies within the color dipole formalism

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Physical Motivation

- Neutrino interactions at high energies are important for astroparticle physics (cosmic rays).
- Air showers directly depend on ν-cross sections. Horizontal showers $\propto \sigma_{\nu,\bar{\nu}}^{tot}$, whereas upgoing air showers $\propto 1/\sigma_{\nu,\bar{\nu}}^{tot}$.
- Ultrahigh energy neutrinos at $E_\nu \gtrsim 10^6$ GeV probe very low-x region, sensitive to nonlinear (saturation) QCD dynamics.
- Correct theoretical description of energy dependence and nuclear effects are required to perform precise estimations of those cross sections.
- Color dipole formalism rises as a robust theoretical approach to describe small-x structure functions.

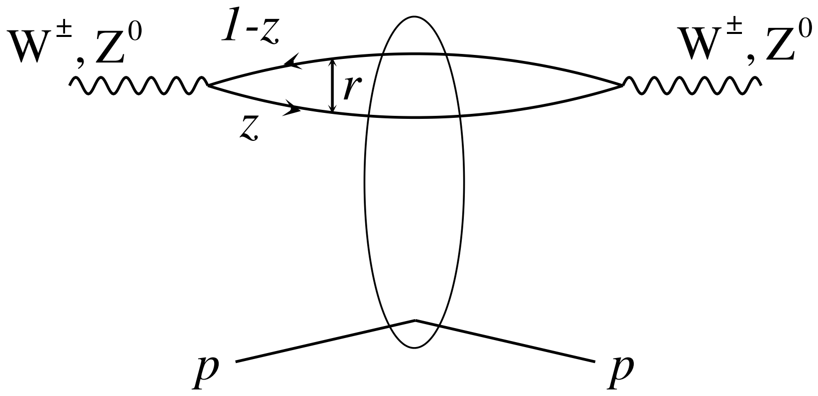
Deep inelastic neutrino-hadron

- Neutrino cross section for charged current process:

$$\frac{d\sigma^{\nu,\bar\nu}}{dx\,dy} = \frac{G_F^2\, m_N\, E_\nu}{\pi}\left[\left(1 - y - \frac{m_N x y}{2E_\nu}\right) F_2(x,Q^2) + \frac{y^2}{2}\, 2xF_1(x,Q^2) \pm y\left(1-\frac{y}{2}\right) xF_3(x,Q^2)\right]$$

- Notation: Neutrino energy E_ν, where $s = 2m_N E_\nu$, with nucleon mass m_N. Boson virtuality Q^2 and G_F Fermi constant. Inelasticity variable $y = Q^2/xs$.
- Structure functions $F_2^{\nu N}$, $2xF_1^{\nu N}$ and $xF_3^{\nu N}$.
- In quark-parton model (LO), $F_2^{\nu N} \propto xq^S = x\sum(q+\bar q)$ and $xF_3^{\nu N} \propto xq^{NS} = xu_V + xd_V$.
- Main theoretical uncertainties: role of nuclear shadowing and better understanding of low-Q^2 limit.

Dipole formalism for νN scattering



$$\sigma^{CC}_{T,L}(x,Q^2) = \int d^2\boldsymbol{r} \int_0^1 dz\, |\psi^{W^\pm}_{T,L}(x,r,Q^2)|^2\, \sigma_{dip}(x,\boldsymbol{r})$$

- Dipole transverse size, $\boldsymbol{r}$, and z is the longitudinal momentum fraction carried by quarks.
- $\psi^{W}_{T,L}$ are the W-boson light-cone wavefunctions.
- Dipole-hadron interaction cross section, σ_{dip}.
- Cabibbo favored transitions are $u\bar{d}\,(d\bar{u})$, $c\bar{s}\,(s\bar{c})$ for charged current (CC) interactions.

Modeling the dipole cross section

- The Iancu-Itakura-Munier (IIM) model [PLB590(2004)199]:

$$\sigma_{dip}(x, \boldsymbol{r}) = \sigma_0 \begin{cases} \mathcal{N}_0 \left(\frac{\bar{\tau}^2}{4}\right)^{\gamma_{\rm eff}(x,r)}, & \text{for } \bar{\tau} \leq 2\,, \\ 1 - \exp\left[-a \ln^2(b\,\bar{\tau})\right], & \text{for } \bar{\tau} > 2\,, \end{cases}$$

  where $\bar{\tau} = \boldsymbol{r} Q_{\rm sat}(x)$ and $\gamma_{\rm eff}(x,\, r) = \gamma_{\rm sat} + \frac{\ln(2/\tilde{\tau})}{\kappa\,\lambda\,y}$, where $\gamma_{\rm sat} = 0.63$ is the LO BFKL anomalous dimension at saturation limit.

- Saturation scale $Q^2_{\rm sat}(x) = \left(\frac{x_0}{x}\right)^{\lambda} \simeq \left(\frac{10^{-4}}{x}\right)^{0.3}\ {\rm GeV}^2$
- Extension for nuclei using the Glauber-Gribov formalism.

$$\sigma^{A}_{dip}(\tilde{x},\, \boldsymbol{r}^2, A) = 2 \int d^2b \left\{1 - \exp\left[-\frac{1}{2}\, A\, T_A(b)\, \sigma^{\rm proton}_{dip}(\tilde{x},\, \boldsymbol{r}^2)\right]\right\}$$

- Nuclear profile function $T_A(b)$ (3-parameter Fermi distr.).

Structure Function $F_2^{\nu N}(x, Q^2)$

- Considering an isoscalar target, $N = (p+n)/2$.

$$F_2^{\nu N}(x, Q^2) = \frac{Q^2}{4\,\pi^2} \int d^2\boldsymbol{r} \int_0^1 dz\, \left[|\psi_{T,L}^{W^\pm}|^2 + |\psi_{T,L}^{W^\pm}|^2\right]\, \sigma_{dip}(x, \boldsymbol{r})$$

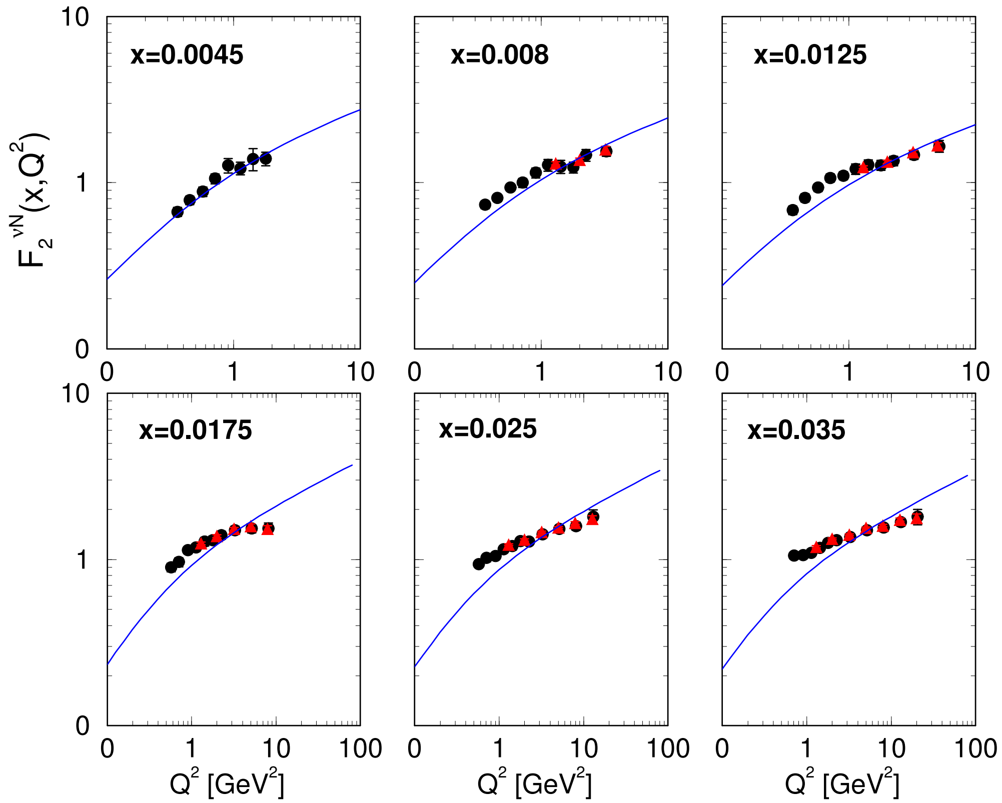
- Light-cone wavefunctions for T and L polarized W-boson:

$$|\psi_T^{W^\pm}|^2 = \frac{4N_c}{(2\pi)^2} \left\{\left[(1-z)^2\, m_q + z^2\, m_{\bar{q}}^2\right]\, K_0^2(\varepsilon r) + \left[z^2 + (1-z)^2\right]\, \varepsilon^2\, K_1^2(\varepsilon r)\right\}$$

$$|\psi_L^{W^\pm}|^2 = \frac{4N_c}{(2\pi)^2\, Q^2} \left\{\left[\left(z(1-z)Q^2 + \varepsilon^2\right)^2 + m_q^2 m_{\bar{q}}^2\right] K_0^2(\varepsilon \boldsymbol{r}) + \left[\frac{a_-^2 + a_+^2}{2}\right] \varepsilon^2 K_1^2(\varepsilon \boldsymbol{r})\right\}$$

- Notation: $\varepsilon^2 = z(1-z)\, Q^2 + (1-z)m_q^2 + z m_{\bar{q}}^2$.
- Notation: $a_+ = (m_q + m_{\bar{q}})$, $a_- = (m_q - m_{\bar{q}})$, with quark and anti-quark masses m_q and $m_{\bar{q}}$, respectively.

Comparison with CCFR/NuTeV data



- Consistent description for $x \leq 0.0175$ without adjusting model parameters, including nuclear shadowing (using Glauber-Gribov formalism).
- Includes only sea quark contribution (color dipole approach).

Structure Function $xF_3^{\nu N}(x, Q^2)$

- Contribution of open charm/strangeness to the hadron absorption cross section for left-handed (L) and right-handed (R) W-boson.

$$\sigma_{L,\,R}\,(x,Q^2) \;=\; \int d^2\boldsymbol{r} \int_0^1 dz \sum_{\lambda_1,\lambda_2} |\Psi_{L,\,R}^{\lambda_1,\lambda_2}(z,\boldsymbol{r},Q^2)|^2\,\sigma_{dip}$$

$$\sum_{\lambda_1,\lambda_2} \Psi_L^{\lambda_1,\lambda_2}\left(\Psi_L^{\lambda_1,\lambda_2}\right)^* \;=\; \frac{4\,N_c}{(2\pi)^2}\,z^2\,\left[m_{\bar{q}}^2\,K_0^2(\varepsilon r) + \varepsilon^2\,K_1^2(\varepsilon r)\right]$$

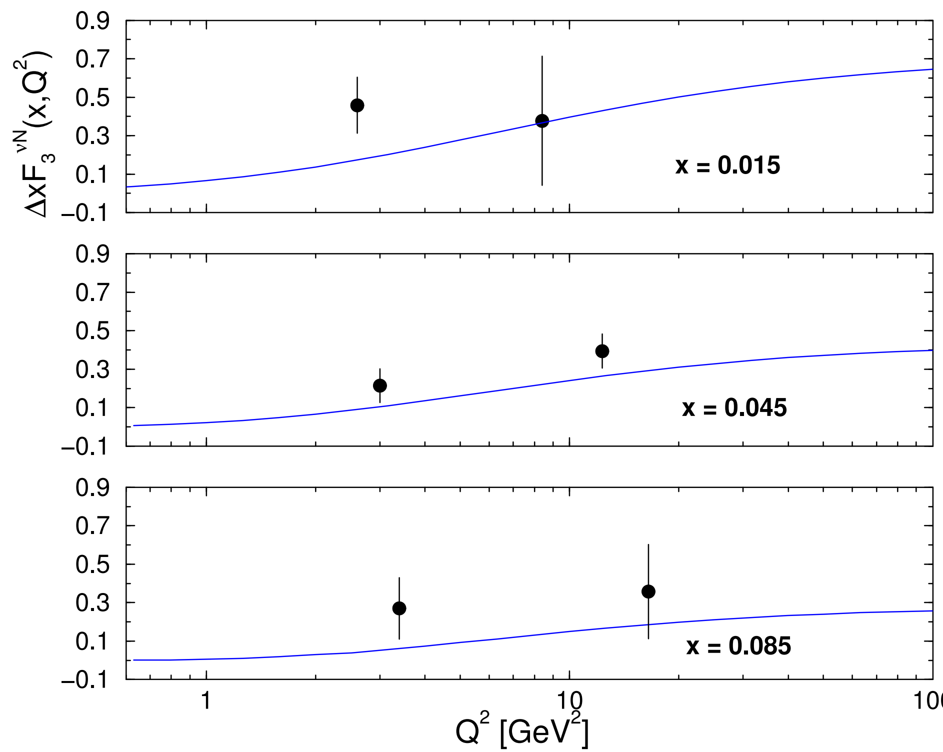
$$\sum_{\lambda_1,\lambda_2} \Psi_R^{\lambda_1,\lambda_2}\left(\Psi_R^{\lambda_1,\lambda_2}\right)^* \;=\; \frac{4\,N_c}{(2\pi)^2}\,(1-z)^2\,\left[m_q^2\,K_0^2(\varepsilon r) + \varepsilon^2\,K_1^2(\varepsilon r)\right]$$

- Sea-quark contribution to structure function xF_3:

$$xF_3^{\nu N}\,(x,Q^2) = \frac{Q^2}{4\pi^2}\,\left[\sigma_L(x,Q^2) - \sigma_R(x,Q^2)\right]$$

The quantity $\Delta x F_3^{\nu N}(x, Q^2)$

- Difference $\Delta x F_3 = x F_3^{\nu} - x F_3^{\bar{\nu}}$ gives a determination of the sea (strange) density.



- In parton model:

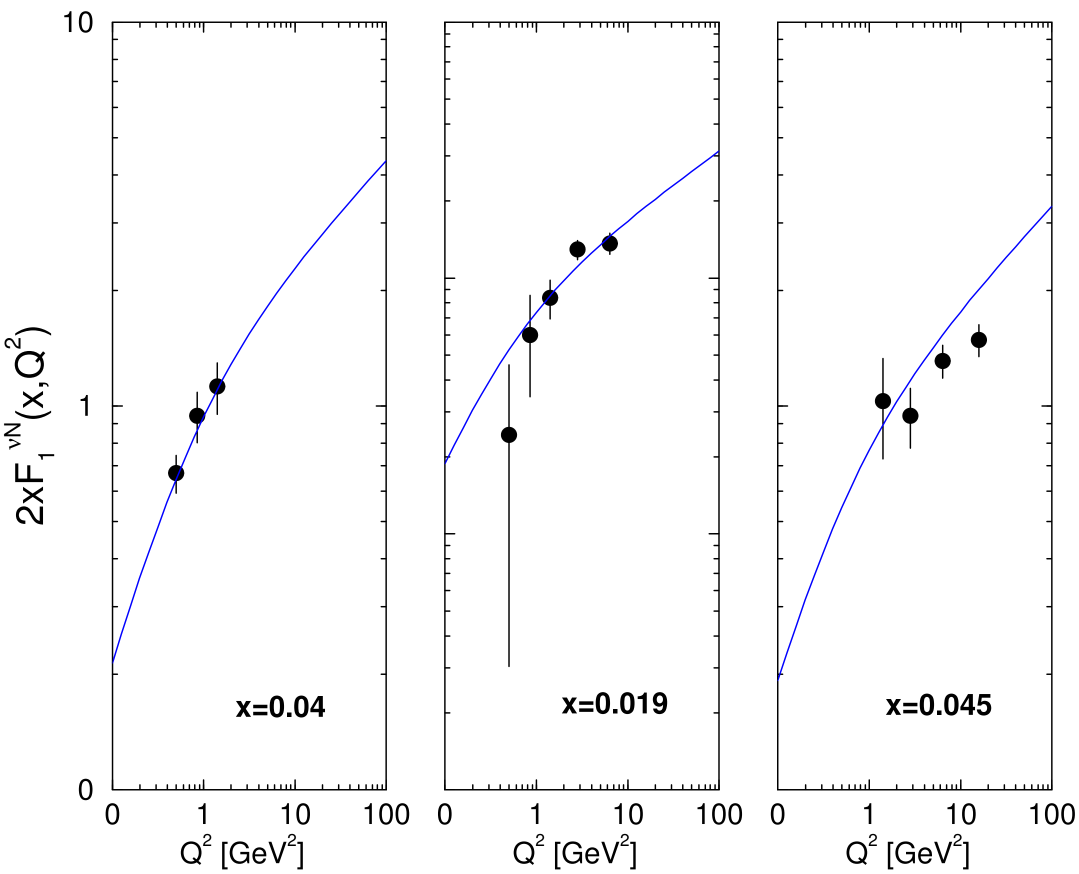
$$x F_3^{\nu N} = x q_{val} - 2x\bar{c}(x) + 2xs(x)$$
$$x F_3^{\bar{\nu} N} = x q_{val} + 2xc(x) - 2x\bar{s}(x)$$

- Therefore, $\Delta x F_3 = 4x[s(x) - c(x)]$.

Structure Function $2xF_1^{\nu N}(x, Q^2)$

- Structure function $2xF_1$ proportional to transverse piece for boson-hadron cross section.

$$2xF_1(x,Q^2) = \frac{Q^2}{4\pi^2}\left[\sigma_L\left(x,Q^2\right) + \sigma_R\left(x,Q^2\right)\right]$$



Summary

- Consistent description of small-x structure functions in neutrino-hadron interaction without any additional free parameter using color dipole formalism.
- Parameterizations for the dipole cross section allow all twist resummation for the structure functions, important at low Q^2.
- Nuclear shadowing included via Glauber-Gribov formalism for multiple dipole scattering.
- Testing the color dipole approach in the limit of its validity, namely $x \leq 0.01$ and intermediate Q^2.
- Important framework to perform reasonable estimations for future νA experiments (Minerνa and Neutrino Factory).