Scattering of HE and UHE neutrinos off hadronic targets in the QCD dipole picture

Inclusive and diffractive productions

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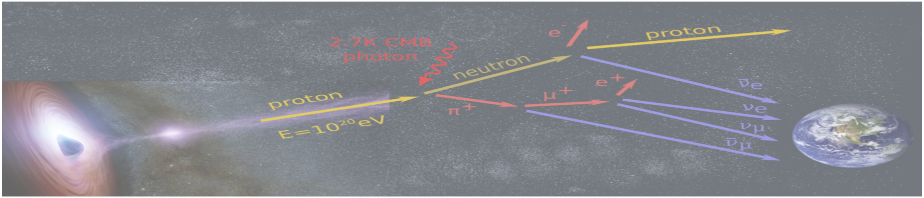
HE and UHE neutrinos



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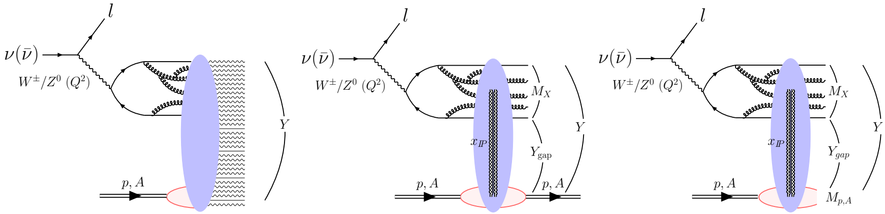
- HE (TeV–PeV) and UHE (≥ 100 PeV) cosmic neutrinos can probe physics at energy scales inaccessible in the lab (M. Ackermann et al., Snowmass white paper).
  - $E_\nu = 1\ \mathrm{EeV} \Rightarrow \sqrt{\mathrm{s}} \approx 44\ \mathrm{TeV}$!
  - Different facilities are designed for such neutrino's energy regimes (IceCube, IceCube-Gen2, ANTARES, Trinity ...)
- For high-energy QCD: sensitive to the regime of (very) small Bjorken-x
  - $E_\nu \sim 10^{12}\ \mathrm{GeV} \Rightarrow \mathrm{x}_{\mathrm{typical}} \sim 10^{-8}$ (not accessible at HERA)
- Fundamental observables: neutrino-nucleon (nucleus) cross-sections
  - Inclusive: determination of neutrino fluxes from experimental data,
  - Diffractive: smoking gun for gluon saturation.

QCD dipole model for neutrino scattering

- Two relevant large-logs give rise to two orthogonal approaches:
  - ln Q^2: collinear factorization with DGLAP,
  - ln$(1/x)$: dipole factorization with BFKL (or BK-JIMWLK).



(a) Inclusive production (b) Coherent production (c) Incoherent production

- Neutrino scatters off the target via $W^{\pm}$ (charged-current) or Z^0 (neutral-current) exchange.
- Vector boson interacts via its quark-antiquark dipole state (at LO).
- Some studies using the dipole picture for nucleon case: Gluck et al. 2010, Goncalves and Hepp, 2011, Albacete et al., 2015.

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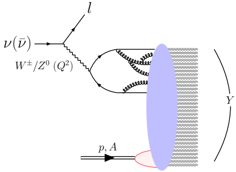
Inclusive production (1): cross-sections

Differential cross-sections in the limit of massless quarks

$$\frac{\mathrm{d}^2\sigma^{CC/NC}_{\nu A;\mathrm{tot}}}{\mathrm{d}x\mathrm{d}Q^2} = \frac{G_F^2}{4\pi x}\left(\frac{M^2_{W/Z}}{M^2_{W/Z}+Q^2}\right)^2 \left[\mathcal{Y}_+ F_2^{CC/NC} - y^2 F_L^{CC/NC}\right]$$

$(\mathcal{Y}_+ = 1 + (1-y)^2, y = Q^2/(xs), s = 2M_N E\nu)$

$(Y = \ln(1/x)$: *rapidity*)



- Structure functions (λ: polarization of W/Z)

$$F_L^{CC/NC} = \frac{Q^2}{4\pi^2\alpha_{W/Z}}\sigma^{CC/NC}_{\lambda=0},$$

$$F_T^{CC/NC} = \frac{Q^2}{4\pi^2\alpha_{W/Z}}\frac{1}{2}\left(\sigma^{CC/NC}_{\lambda=+1} + \sigma^{CC/NC}_{\lambda=-1}\right),$$

- *Dipole factorization:*

$$\sigma_\lambda^{CC/NC}(x,Q^2) = \int \mathrm{d}^2\mathbf{r}\int_0^1 \frac{\mathrm{d}z}{4\pi z(1-z)} \overbrace{\left|\Psi_\lambda^{W/Z}(\mathbf{r},z,Q^2)\right|^2}^{wave\ \ function} \times \overbrace{2\int \mathrm{d}^2\mathbf{b} N(x,\mathbf{r};\mathbf{b})}^{dipole\ \ cross-section}.$$

$N(x,\mathbf{r};\mathbf{b})$: forward amplitude for the scattering of a dipole of transverse size $\mathbf{r}$ off target at Bjorken-x and impact parameter $\mathbf{b}$.

Inclusive production (2): small-x evolution

Balitsky-Kovchegov evolution for dipole amplitude

$$\partial_{\ln 1/x} N(x, \mathbf{r}; \mathbf{b}) = \int \mathrm{d}^2\mathbf{r}_1 \mathcal{K}_{\mathbf{r},\mathbf{r}_1,\mathbf{r}_2} \left[N(x, \mathbf{r}_1; \mathbf{b}_1) + N(x, \mathbf{r}_2; \mathbf{b}_2) - N(x, \mathbf{r}; \mathbf{b}) - N(x, \mathbf{r}_1; \mathbf{b}_1) N(x, \mathbf{r}_2; \mathbf{b}_2)\right]$$

$(\mathbf{r}_2 = \mathbf{r} - \mathbf{r}_1,\ \mathbf{b}_1 = \mathbf{b} - \mathbf{r}_2/2,\ \mathbf{b}_2 = \mathbf{b} + \mathbf{r}_1/2)$

- $\alpha_s \ln(1/x)$ resummation
- Running-coupling kernel:

$$\mathcal{K}_{\mathbf{r},\mathbf{r}_1,\mathbf{r}_2} = \frac{\alpha_s(\mathbf{r}^2)}{2\pi}\left[\frac{\mathbf{r}^2}{\mathbf{r}_1^2 \mathbf{r}_2^2} + \frac{1}{\mathbf{r}_1^2}\left(\frac{\alpha_s(\mathbf{r}_1^2)}{\alpha_s(\mathbf{r}_2^2)} - 1\right) + \frac{1}{\mathbf{r}_2^2}\left(\frac{\alpha_s(\mathbf{r}_2^2)}{\alpha_s(\mathbf{r}_1^2)} - 1\right)\right]$$

- QCD running coupling: $\alpha_s(\mathbf{r}^2) = \frac{12\pi}{(11N_c - 2N_f)\ln \frac{4C^2}{\mathbf{r}^2 \Lambda^2_{\mathrm{QCD}}}}$, $(N_c = N_f = 3)$
- Require an input at some x_0 small (here $x_0 = 0.01$)

Inclusive production (3): nucleon (proton) vs. nucleus

Nucleon

- $\mathbf{b}$ dependence factorized:

$$N(x, \mathbf{r}; \mathbf{b}) = T_p(\mathbf{b})\mathcal{N}(x, \mathbf{r}),\ \int \mathrm{d}^2\mathbf{b}\, T_p(\mathbf{b}) = \sigma_0/2,\ \mathcal{N}(x, \mathbf{r}) \text{ obeys BK.}$$

- Initial condition:

$$\mathcal{N}(x_0, \mathbf{r}) = 1 - e^{-\frac{\mathbf{r}^2 Q_0^2}{4} \ln\left(e \cdot e_c + \frac{1}{|\mathbf{r}|\Lambda_{QCD}}\right)}$$

  - MV : $e_c = 1$ fixed, Q_0 free parameter,
  - MV^e : e_c, Q_0 free parameters.

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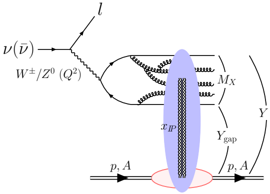
Nucleus (optical Glauber)

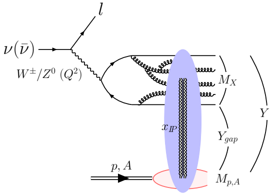
- *After evol.* scenario: $N_A(x,\mathbf{r};\mathbf{b}) = 1 - \left[1 - \frac{\sigma_0}{2} T_A(\mathbf{b})\mathcal{N}(x,\mathbf{r})\right]^A$,
  ($T_A(\mathbf{b})$: Woods-Saxon profile).
- *Before evol.* scenario: amplitude at each $\mathbf{b}$ evolves independently starting from the initial condition at x_0

$$N_A(x_0,\mathbf{r};\mathbf{b}) = 1 - \left[1 - \frac{\sigma_0}{2} T_A(\mathbf{b})\mathcal{N}(x_0,\mathbf{r})\right]^A.$$

Free params (C^2, $\sigma_0/2$, Q_0, e_c) from fits to HERA inclusive data → T. Lappi & H. Mäntysaari, arXiv:1309.6963 [hep-ph]

Diffractive production(1)





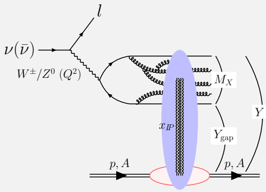
Differential diffractive cross-section (massless quarks)

$$\frac{\mathrm{d}^3\sigma^{CC/NC}_{\nu A;D}}{\mathrm{d}x_{I\!P}\mathrm{d}x\mathrm{d}Q^2} = \frac{G_F^2}{4\pi x}\left(\frac{M_V^2}{M_V^2+Q^2}\right)^2\left(\mathcal{Y}_+ F_2^{D(3);CC/NC} - y^2 F_L^{D(3);CC/NC}\right),$$

- Rapidity gap $Y_{gap} = \ln 1/x_{I\!P}$ due to color-singlet exchange.
- M_X due to dissociation of vector boson's Fock state
  - Consider only LO ($q\bar{q}$) and tree-level NLO (transverse $q\bar{q}g$) contributions at large Q^2.
- Target can break up (incoherent) or not (coherent).

Diffractive production(2): Coherent vs. incoherent

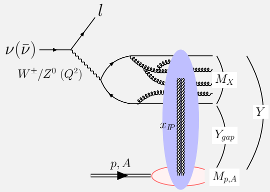
Coherent



- Target remains in its ground state
- Average over target's config. at the amplitude level

$$\sigma_{coh} \propto |\langle \mathcal{A} \rangle|^2$$

Incoherent



- Target breaks up
- Average over target's config. at the squared amplitude level

$$\sigma_{incoh} \propto \langle |\mathcal{A}|^2 \rangle - |\langle \mathcal{A} \rangle|^2$$

Notes:

- $\sigma_{\nu N;D} \propto \int \mathrm{d}^2\mathbf{b}\, T_p^2(\mathbf{b}) \Rightarrow$ Detailed shape of T_p is important at given $\sigma_0/2 \to$ Use the incomplete Gamma profile with optimal shape parameter from T. Lappi, ADL & H. Mäntysaari, arXiv:2307.16486 [hep-ph] .
- Incoherent diffraction: only for nucleus, only fluctuation in nucleons' position (sampling according to Woods-Saxon density), and only *after evol.* setup.

Integrated cross-sections

$$\sigma^{CC/NC}_{\nu A;\mathrm{tot}} = \int_{Q^2_{min}}^{x_{max}s} \mathrm{d}Q^2 \int_{Q^2/s}^{x_{max}} \mathrm{d}x \frac{\mathrm{d}^2\sigma^{CC/NC}_{\nu A;\mathrm{tot}}}{\mathrm{d}x\mathrm{d}Q^2}$$

$$\sigma^{CC/NC}_{\nu A;\mathrm{D}} = \int_{Q^2_{min}}^{x_{max}s} \mathrm{d}Q^2 \int_{Q^2/s}^{x_{max}} \mathrm{d}x \int_{x}^{x_{max}} \mathrm{d}x_{I\!P} \frac{\mathrm{d}^3\sigma^{CC/NC}_{\nu A;\mathrm{tot}}}{\mathrm{d}x\mathrm{d}Q^2\mathrm{d}x_{I\!P}}$$

$(s = 2M_N E_\nu)$

- $Q^2_{min} = 1\ \mathrm{GeV}^2$
- BK evolution is a small-x resummation ($x \leq 0.01$)
  - $x_{max} = x_0 = 0.01$: only small-x sector included
  - $x_{max} = 1$: large-x extrapolation required

$$\mathcal{N}(x > x_0, r) = \mathcal{N}(x_0, r)\left(\frac{1-x}{1-x_0}\right)^6$$

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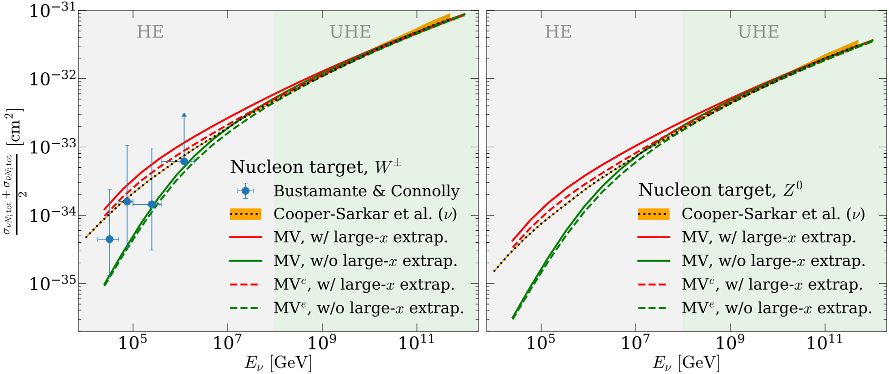
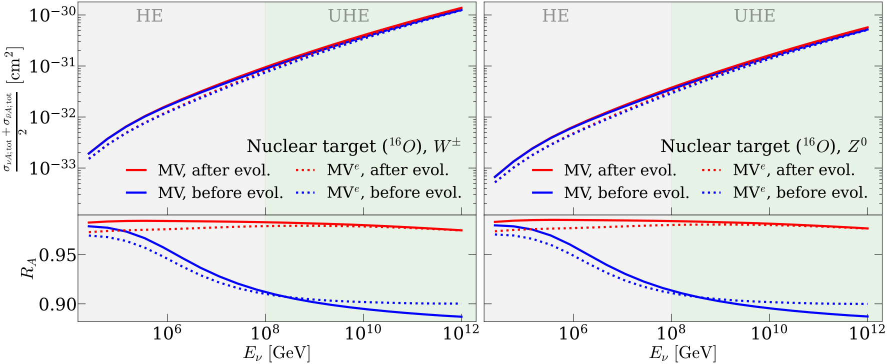
Inclusive scattering off nucleon (proton)



- Scattering in the UHE regime only sensitive to small-x
- Steeper initial condition (MV^e) closer to the collinear result
- The rise in UHE ($E_\nu > 10^{11}$ GeV) from the current calculation seems to slower than that from collinear approach (but very small effect) $\rightarrow$ nonlinear (saturation) effects might be relevant at such ultra-high energies

Inclusive scattering off nucleus



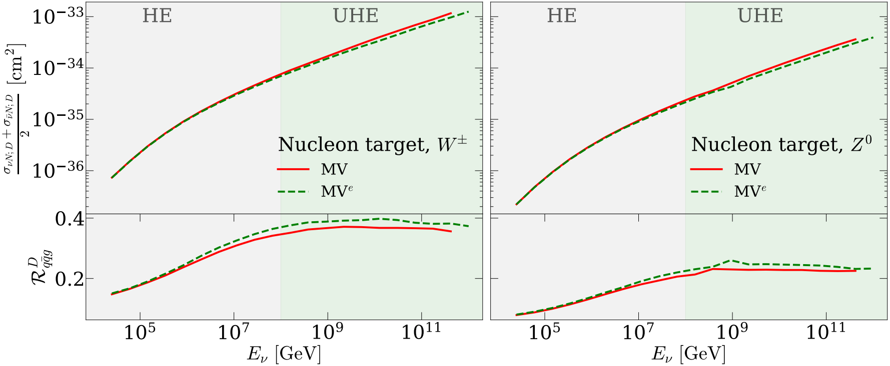
- Different nuclear suppression behaviors for *before evol.* and *after evol.*.

$$R_A = \frac{\sigma_{\nu A;tot}}{A\sigma_{\nu N;tot}}$$

$\rightarrow$ Multiple scattering leads to stronger shadowing in *before evol.*

- Smaller suppression (from a realistic nuclear geometry (optical Glauber)) compared to K. Kutak and J. Kwiecinski, arXiv:hep-ph/0303209] (nuclear $A^{1/3}$ scaling)

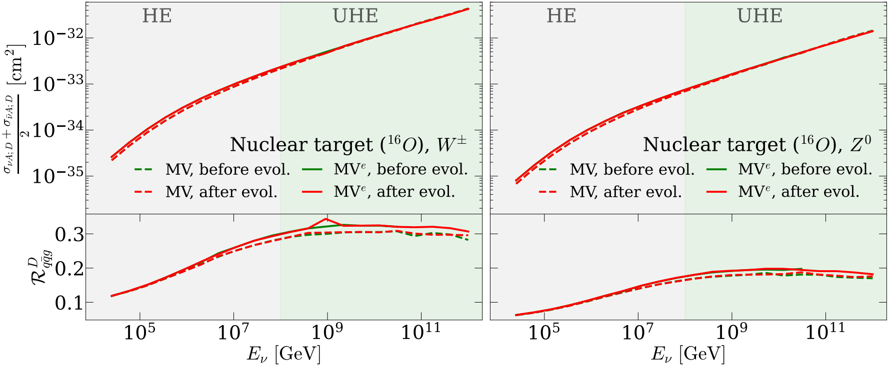
Diffractive scattering off proton



$$\mathcal{R}^D_{q\bar{q}g} = \frac{\sigma_{D;qqg}}{\sigma_{D;qqg} + \sigma_{D;qq}}$$

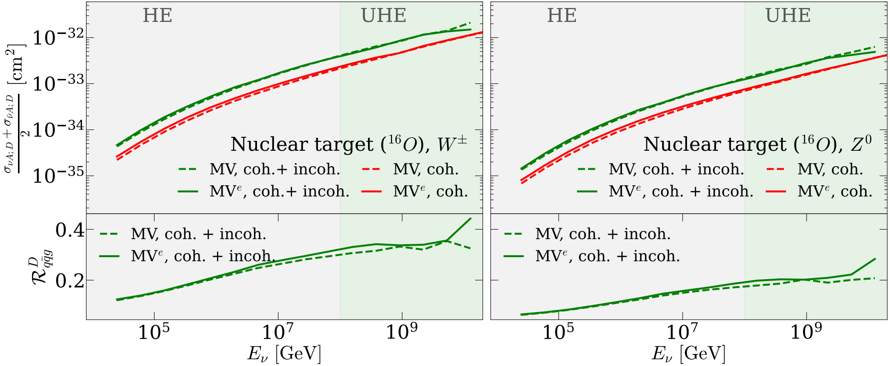
- Gluon contribution becomes more important at higher neutrino energies (seems to reach plateau in UHE).
- NC $\approx 1/3$ CC, like inclusive case

Diffractive scattering off nucleus: coherent



- *before evol.* and *after evol.* provide almost the same predictions.
- Smaller $q\bar{q}g$ contribution than the nucleon case.

(After evol. setup)



- Coherent and incoherent contributions are comparable

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Conclusions

QCD dipole model + BK evolution are employed for neutrino-nucleon and neutrino-nucleus scatterings at HE and UHE

- Different initial conditions provide slightly different predictions.
  - Steeper initial condition (MV^e) expected to provide better predictions.
- Realistic impact parameter dependence (optical Glauber) to predict nuclear scattering, without free parameters
  - Nuclear setup affects the nuclear suppression: grouping nucleons before evolution leads to stronger suppression.
- First estimation for diffraction in the QCD dipole model ($q\bar{q}$ + $q\bar{q}g_T$, coherent + incoherent)
  - Nuclear breakup and non-breakup give similar contributions for diffractive scattering.
  - Gluon contribution is more important at higher E_ν and in the nucleon case.

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THANK YOU !