Small-x Physics
and the detection of
Ultra-High Energy Neutrinos

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Outline

• The search for UHE cosmic neutrinos: $\nu_\tau$

• $\tau$ energy loss at UHE

• $\nu N$ DIS CC x-section
Detection of UHE neutrinos

- Neutrino-induced muons or showers in ice/water
  
  *IceCube, Antares, Nestor, Baikal*

- Neutrino-induced showers in air shower arrays
  
  *Pierre Auger*
  
  - Down-going neutrinos (inclined showers)
  
  - Up-going tau-neutrinos (Earth-skimming)
Earth-skimming neutrinos

- $\nu_\tau$ conversion into $\tau$ through D.I.S.
- $\tau$ energy loss (mostly photonuclear)
- $\tau$ emerges from the ground and decays in fly producing an extensive air shower
Event rate

- tau neutrino flux
- $\nu N$ x-section (CC DIS)
- $\tau N$ x-section (photonuclear)
- $\tau$ decay probability
- Detector acceptance
τ energy loss

\[-\left\langle \frac{dE}{dX} \right\rangle = a(E) + b(E)E\]

From Aramo et al Astrop. Phys. 23 (2005) 65

(Standard Rock: A=22, Z=11, density=2.65 g/cm3)
\[ b(E) = \frac{N_A}{A} \int dy \ y \int dQ^2 \frac{d\sigma^{lA}}{dQ^2 dy} \]

\[ Q_{\min}^2 = \frac{y^2 m_l^2}{1-y}, \quad Q_{\max}^2 = 2m_p E y - 2m_\pi m_p - m_\pi^2, \]

\[ y_{\min} = \frac{2m_\pi m_p + m_\pi^2}{2m_p E}, \quad y_{\max} = 1 - \frac{m_l}{E}, \]

\[ \frac{d\sigma^{lA}}{dQ^2 dy} = \frac{4\pi \alpha^2}{Q^4} \frac{F_2^A}{y} \left[ 1 - y - \frac{Q^2}{4E^2} + \left( 1 - 2\frac{m_l^2}{Q^2} \right) \frac{y^2 + Q^2/E^2}{2(1 + R^A)} \right] \]
Calculations of $b(E)$

- Generalized Vector Dominance (soft) + Color Dipole (hard)  
  Bezrukov, Bugaev 1981
  Bugaev, Shlepin 2003

- Regge theory (pomeron + reggeon) + pQCD (hard)  
  Dutta et al. 2001 (ALLM)
  Butkevich, Mikheyev 2002 (CKMT)
  Kuzmin et al 2004 (CKMT)
  Petrukhin, Timashkov 2005

- Geometric scaling property found in $\gamma^*p$ and $\gamma^*N$ x-section data (saturation)  
  Armesto, Merino, Parente, Zas 2008
  (ASW: Armesto, Salgado, Wiedemann 2005)
The $\tau$ energy loss from different $x$ and $Q^2$ regions

$$b(E) [x < x_{\text{cut}}]$$

$x$ range at $10^9$ GeV
$F_2$ proton at low and moderate $Q^2$

![Graph showing $F_2$ vs $x$ for different $Q^2$ values at HERA.]
\( \tau \) energy loss

\[ b(E) = -\frac{1}{E} \langle \frac{dE}{dX} \rangle = \frac{N_A}{A} \int dy y \int dQ^2 \frac{d\sigma^{IA}}{dQ^2 dy}, \]

\( \tau \)-lepton, \( A=22 \)

- ALIM
- CKMT
- ASW
- KLS
- BB/BS
- PT

Factors:
- Factor 2
- Factor 4
Nuclear correction factor

\[ F_2^A = f^A A F_2^p \]
The effect of nuclear corrections

factor 2
Neutrino-nucleon CC DIS x-section

\[
\frac{d\sigma_{CC}^{\nu N}}{dQ^2 dy} = \frac{G_F^2}{4\pi} \left( \frac{M_W^2}{M_W^2 + Q^2} \right)^2 \frac{F_2^{\nu N}}{y} \left[ 1 + (1 - y)^2 \right]
\]
\[ \log(Q^2) \]

- \( E_v = 10^{11} \text{ GeV} \)
- \( Q^2 = M_W^2 \)
$F_2$ at high $Q^2$
The graph shows the cross-section $\sigma_{\nu N}^{cc}$ as a function of the energy $E$ in GeV. The cross-section is given in units of pb (picobarns). The graph includes data from various sources, such as Anchordoqui et al., HERA, KOPA, and ASW. A notable feature is the indication of a factor 2 difference, which is marked on the graph.
Summary

• The establishment of a tau neutrino bound from air shower data is affected by important systematic effects due to the uncertainty in $F_2$ at low x.

• Several $F_2$ models have been explored in the low x range. For the neutrino-nucleon interaction at high $Q^2$ and for the tau interaction at low and moderate $Q^2$.

• For the tau energy loss at $10^9$ GeV the difference between the two extreme predictions reaches a factor 4. For the neutrino cross section it is a factor 2.

• GVD and Regge based (+ hard pQCD component) calculations of the tau energy loss agree within a 30% and go parallel to all energies.

• A much stronger nuclear shadowing at small x lower b(E) by a factor up to 2 but is not expected to affect the neutrino cross section.