Using Neutrinos as a Probe of the Strong Interaction

Neutrino / Anti-neutrino Deep-Inelastic Scattering off of Massive Nuclear Targets

e-Nucleus XI
Elba – June, 2010

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With thanks to the many publications and presentations of Martin Tzanov, U. Colorado
Motivation for Studying $\nu$ DIS

- Interacting with the weak current means a much smaller interaction rate than $e/\mu$ scattering
  - Need huge, higher-A detectors and intense neutrino beams
  - The neutrino flux is difficult to predict and measure.
- However can select which set of quarks involved in the interaction via $\nu$ or $\bar{\nu}$
- While $F_2$ is measured precisely by the charge lepton scattering, $xF_3$ is accessible by neutrino DIS.
  - $\Delta xF_3$ yields increased sensitivity to the valence quark distributions.
  - However, through $\Delta xF_3 = 4x(s-c)$, $\Delta xF_3$ is also sensitive to heavy quarks.
- Speaking of heavy quarks, examining charm production with neutrinos also gives us insight into the strange quark distribution.
- Electroweak physics has been a rich neutrino subject for decades.
- Finally, recent phenomenological / experimental work is indicating some interesting differences concerning nuclear effects with neutrinos compared to charged lepton scattering.
The Parameters of $\nu$ DIS

Differential cross section in terms of structure functions:

$$\frac{1}{E_\nu} \frac{d^2 \sigma^{\nu(\bar{\nu})}}{dx dy} = \frac{G_F^2 M}{\pi \left( 1 + Q^2 / M_W^2 \right)} \left[ \left( 1 - y - \frac{M x y}{2 E_\nu} + \frac{y^2}{2} \frac{1 + 4 M^2 x^2 / Q^2}{1 + R(x, Q^2)} \right) F_2^{\nu(\bar{\nu})} \pm \left( y - \frac{y^2}{2} \right) x F_3^{\nu(\bar{\nu})} \right]$$

Structure Functions in terms of parton distributions (for $\nu$-scattering)

$$F_2^{\nu(\bar{\nu})} = \sum x q^{\nu(\bar{\nu})}(x) + \bar{x} q^{\nu(\bar{\nu})}(x) + 2 x k^{\nu(\bar{\nu})}(x)$$
$$xF_3^{\nu(\bar{\nu})} = \sum \left[ x q^{\nu(\bar{\nu})}(x) - \bar{x} q^{\nu(\bar{\nu})}(x) \right] = x (d_\nu(x) + u_\nu(x)) \pm 2 x (s(x) - c(x))$$

\[ R = \frac{\sigma_L}{\sigma_T} \]
Neutrino Experiments have been studying QCD for about 40 years.

- For example, Gargamelle made one of the first measurements of $\Lambda_{ST}$ in the early 1970’s using sum rules and the $x$-$Q^2$ behavior of the structure functions $F_2$ and $xF_3$ measured off heavy liquids.
- BEBC followed with QCD studies using $\nu + p$ and $\nu + D$ scattering.
Most “Recent” DIS Experiments

- There followed a long string of $\nu$ scattering experiments with increasing statistics and decreasing systematic errors ….

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$E_\nu$ range ($&lt;E_\nu&gt;$) (GeV)</th>
<th>Run</th>
<th>Target A</th>
<th>$E_\mu$ scale</th>
<th>$E_{\text{HAD}}$ scale</th>
<th>Detector</th>
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<tbody>
<tr>
<td>NuTeV (CCFR)</td>
<td>30-360(120)</td>
<td>96-97</td>
<td>Fe</td>
<td>0.7%</td>
<td>0.43%</td>
<td>Coarse</td>
</tr>
<tr>
<td>NOMAD</td>
<td>10-200(27)</td>
<td>95-98</td>
<td>Various (mainly C)</td>
<td>--</td>
<td>---</td>
<td>Fine-grained</td>
</tr>
<tr>
<td>CHORUS</td>
<td>10-200(27)</td>
<td>95-98</td>
<td>Pb</td>
<td>2%</td>
<td>5%</td>
<td>Fine-grained</td>
</tr>
<tr>
<td>MINOS</td>
<td>3-15</td>
<td>05-10</td>
<td>Fe</td>
<td>2.5%</td>
<td>5.6%</td>
<td>Coarse</td>
</tr>
</tbody>
</table>
Neutrino Beamlines

- Intense proton beam on a target. Collect $\pi$ and $K$ and steer into a decay area. Absorb hadrons and muons from beam leaving only neutrinos.
The NuTeV Experiment: 800 GeV Protons
> 3 million neutrino/antineutrino events with $20 \leq E_\nu \leq 400 \text{ GeV}$

Target Calorimeter:
- Steel-Scintillator Sandwich (10 cm)
  - Resolution: $\frac{\delta E}{E} \approx 0.86\%$ for $\sqrt{E}$
- Tracking chambers for muon track and vertex

Muon Spectrometer:
- Three toroidal iron magnets with five sets of drift chambers
  - Average value: $\langle B_\varphi \rangle \approx 1.7T$, $p_t \approx 2.4\text{GeV/c}$
  - Resolution: $\frac{\delta(1/p)}{1/p} \sim 11\%$ for MCS dominated
- Always focusing for leading muon

To confront leading systematic errors, there was a continuous calibration beam that yielded

$$\frac{\Delta E_{\text{HAD}}}{E_{\text{HAD}}} = 0.43\%$$

$$\frac{\Delta E_\mu}{E_\mu} = 0.7\%$$
CHORUS Experiment – nuclear emulsions

- 450 GeV protons $\rightarrow$ 10 – 200 GeV $\nu$, 6% wrong-sign background
- Nuclear Emulsion Target (Pb, Fe, Ca and C)
- Scintillating Fiber tracker

Muon energy scale – 2.5%
Hadron Energy Scale - 5%
(test beam exposure)
NuTeV CC Differential Cross Section $d\sigma/dy$ for different $E_{\nu}$

- NuTeV has increased statistics compared to other $\nu$-Fe experiments.
- Significant reduction in the largest systematic uncertainties: $E_\mu$ and $E_{HAD}$ scales
Estimated systematic error: $E_{\mu}$ scale
NuTev achieved 0.7%
Estimated systematic error: $E_{\text{had scale}}$

NuTev achieved 0.43%
**F_2 and xF_3 Measurement**

\[ F_2 \]

\[
\left[ \frac{d^2 \sigma}{dx \, dy} + \frac{d^2 \sigma}{dx \, dy} \right] \frac{\pi}{G_F^2 \, ME} = \\
2 \cdot F_2 \left[ 1 - y \left( 1 - \frac{M_{xy}}{2E} + \frac{y^2}{2} \frac{1+4M^2x^2/Q^2}{1+R} \right) \right] + y \left( 1 - \frac{y}{2} \right) \Delta xF_3
\]

- Perform 1-parameter fit for F_2
- ΔxF_3 model
- R_L model

\[ xF_3 \]

\[
\left[ \frac{d^2 \sigma}{dx \, dy} - \frac{d^2 \sigma}{dx \, dy} \right] \frac{\pi}{G_F^2 \, ME} = \\
\Delta F_2 \left[ 1 - y \left( 1 - \frac{M_{xy}}{2E} + \frac{y^2}{2} \frac{1+4M^2x^2/Q^2}{1+R} \right) \right] + 2y \left( 1 - \frac{y}{2} \right) xF_3
\]

- Perform 1-parameter fit for xF_3
- ΔF_2 is very small and is neglected

- Radiative corrections applied
- Isoscalar correction applied
NuTeV $F_2$ Measurement

- Comparison of NuTeV $F_2$ with global fits

- At $x > 0.4$ NuTeV is systematically above CCFR
At $x>0.5$ NuTeV is systematically above CCFR

NuTeV $F_2$ agrees with theory for medium $x$.

At low $x$ different $Q^2$ dependence.

At high $x$ ($x>0.5$) NuTeV is systematically higher.
CHORUS Structure Functions: $\nu$ Pb

- First $\nu$-Pb differential cross section and structure functions
- CHORUS measurement favors CCFR over NuTeV
- Much larger systematic errors than the NuTeV experiment
Parton Distribution Functions:
What Can We Learn With All Six Structure Functions?

Recall Neutrinos have the ability to directly resolve flavor of the nucleon’s constituents:
\( \nu \) interacts with d, s, \( \bar{u} \), and \( \bar{c} \) while \( \bar{\nu} \) interacts with u, c, d and s.

Using Leading order expressions:
\[
F_{2}^{\nu_{N}}(x, Q^{2}) = x[u + \bar{u} + d + \bar{d} + 2s + 2c]
\]
\[
F_{2}^{\bar{\nu}_{N}}(x, Q^{2}) = x[u + \bar{u} + d + \bar{d} + 2s + 2c]
\]
\[
xF_{3}^{\nu_{N}}(x, Q^{2}) = x[u + d - \bar{u} - \bar{d} - 2s + 2c]
\]
\[
xF_{3}^{\bar{\nu}_{N}}(x, Q^{2}) = x[u + d - \bar{u} - \bar{d} + 2s - 2c]
\]

Taking combinations of the Structure functions
\[
F_{2}^{\nu} - xF_{3}^{\nu} = 2(\bar{u} + \bar{d} + 2\bar{c})
\]
\[
F_{2}^{\bar{\nu}} - xF_{3}^{\bar{\nu}} = 2(\bar{u} + \bar{d} + 2\bar{s})
\]
\[
xF_{3}^{\nu} - xF_{3}^{\bar{\nu}} = 2[(s + \bar{s}) - (c + \bar{c})]
\]
Charm Production by Neutrinos
a direct look at strange sea.

- Charm quark is produced from CC neutrino interaction with s(d) quark in the nucleon. d-quark interaction is CKM suppressed.
- Detect charm via the semi-leptonic decay which yields a very clear signature – two opposite sign muons.
- It is sensitive to $m_c$ through $E_\nu$ dependence.
- With high-purity $\nu$ and $\bar{\nu}$ beams, NuTeV made high statistics separate s and $\bar{s}$ measurements: 5163 $\nu$ and 1380 $\bar{\nu}$.
- Could then make a measurement of $s - \bar{s}$. 
Strange Sea Asymmetry

\[ s^- = (s - \bar{s}) \]

\[ S^- = \int_0^1 x s^-(x) dx = 0.00196 \pm 0.00046 \pm 0.00045 \pm 0.00128 \]

- CTEQ inspired NLO model,
- in the fit net strangeness of the nucleon is forced to 0.

\[ m_c = 1.41 \pm 0.10 \text{(stat)} \pm 0.008 \text{(syst)} \pm 0.12 \text{(ext)} \text{ GeV/c}^2 \]

This is an analysis of strange quarks in an Fe nucleus!
Are \( \nu \) nuclear effects known? Are they the same for \( \nu \) and \( \bar{\nu} \)?
Summary $\nu$ Scattering Results – NuTeV

NuTeV accumulated over 3 million neutrino / antineutrino events with $20 \leq E_\nu \leq 400$ GeV.

NuTeV considered 23 systematic uncertainties.

NuTeV $\sigma$ agrees with other $\nu$ experiments and theory for medium $x$.
   At low $x$ different $Q^2$ dependence.
   At high $x$ ($x > 0.6$) NuTeV is systematically higher.

NuTeV extracts the strange quark distribution via charm production using both $\nu$ and $\bar{\nu}$ and gets a value of $S^-(x)$.

All of the NuTeV Results are for $\nu$ – Fe interactions and where necessary have assumed the nuclear corrections for neutrino interactions are the same as $l^\pm$.  Is this really the case?
Nuclear Structure Function Corrections \( \ell^\pm (\text{Fe/D}_2) \)

See yesterday’s talk by Solvignon!

- \( F_2 \) / nucleon changes as a function of \( A \). Measured in \( \mu/e - A \), not in \( \nu - A \).

- Good reason to consider nuclear effects are DIFFERENT in \( \nu - A \).
  - Presence of axial-vector current.
  - Different nuclear effects for valance and sea --> different shadowing for \( xF_3 \) compared to \( F_2 \).
Had to use $l^\pm$-Fe correction factors to combine NuTeV $\nu$-Fe results with E866 p-H and p-D Drell-Yan results. Tension between NuTeV and E866 started us on a rather convoluted path to extracting **nuclear effects from neutrino interactions**.
NuTeV ($\nu$-Fe) Compared to CCFR (in PDF fits). At High-x NuTeV Indicates Effect Opposite to E866 D-Y. (CHORUS ($\nu$-Pb) in between CCFR and NuTeV at high x)

Is the tension between NuTeV and E866 coming from applying $1^{\pm}$-Fe nuclear corrections to the NuTeV $\nu$-Fe measurements?
CTEQ High-x Study: nuclear effects
No high-statistics D2 data – “make it” from PDFs

Form reference fit mainly nucleon (as opposed to nuclear) scattering results:

- BCDMS results for $F_2^p$ and $F_2^d$
- NMC results for $F_2^p$ and $F_2d/F_2^p$
- H1 and ZEUS results for $F_2^p$
- CDF and DØ result for inclusive jet production
- CDF results for the W lepton asymmetry
- E-866 results for the ratio of lepton pair cross sections for pd and pp interactions
- E-605 results for dimuon production in pN interactions.

Correct for deuteron nuclear effects
NuTeV(Fe) and CHORUS (Pb) $\nu$ scattering (unshifted) $\sigma$ results compared to reference fit

no nuclear corrections

$$\frac{\sigma(\nu_{\text{Fe or Pb}})}{\sigma(\nu''D_2'')}$$
NuTeV $\sigma$(Fe) & CHORUS $\sigma$(Pb) $\nu$ scattering (un-shifted) results compared to reference fit

Kulagin-Petti nuclear corrections

$\frac{\sigma(\text{Fe or Pb})}{\sigma(D_2)}$
NuTeV $\sigma$(Fe) & CHORUS $\sigma$(Pb) $\nu$ scattering (shifted) results compared to reference fit

Kulagin-Petti nuclear corrections

$\frac{\sigma(\text{Fe or Pb})}{\sigma(D_2)}$
Nuclear PDFs from neutrino deep inelastic scattering

I. Schienbein (SMU & LPSC-Grenoble, J-Y. Yu (SMU)
C. Keppel (Hampton & JeffersonLab) J.G.M. (Fermilab),
F. Olness (SMU), J.F. Olness (Florida State U)

Same Reference Fit as Earlier Analysis

- Form reference fit mainly nucleon (as opposed to nuclear) scattering results:
  - BCDMS results for $F_2^p$ and $F_2^d$
  - NMC results for $F_2^p$ and $F_2d/F_2^p$
  - H1 and ZEUS results for $F_2^p$
  - CDF and DØ result for inclusive jet production
  - CDF results for the W lepton asymmetry
  - E-866 results for the ratio of lepton pair cross sections for pd and pp interactions
  - E-605 results for dimuon production in pN interactions.

- Correct for deuteron nuclear effects
F₂ Structure Function Ratios: ν-Iron
F₂ Structure Function Ratios: ν-Iron
F₂ Structure Function Ratios: \( \bar{\nu} \)-Iron
$F_2$ Structure Function Ratios: $\bar{\nu}$-Iron
First Conclusions

- All high-statistics neutrino data is off nuclear targets. Need nuclear correction factors to include data off nuclei in fits with nucleon data.

- Nuclear correction factors (R) different for neutrino-Fe scattering compared to charged lepton-Fe.

- Results from one experiment on one nuclear target… careful.

- If we combine $\nu$-nucleus with charged $l^{\pm}$-nucleus results and D-Y in a single global fit can we find a common description acceptable to both?
Combined Analysis of $\nu$ A, $\not\nu$A and DY data

Work in progress: Kovarik, Yu, Keppel, Morfin, Olness, Owens, Schienbein, Stavreva

- Take an earlier analysis of $\not\nu$±A data sets (built in A-dependence)
  - Schienbein, Yu, Kovarik, Keppel, Morfin, Olness, Owens,
  - PRD80 (2009) 094004
- For $\not\nu$±A take $F_2(A)/F_2(D)$ and $F_2(A)/F_2(A')$ and DY $\sigma(pA)/\sigma(pA')$
  - 708 Data points with $Q > 2$ and $W > 3.5$
- Use 8 Neutrino data sets
  - NuTeV cross section data: $\nu Fe, \bar{\nu} Fe$
  - NuTeV dimuon off Fe data
  - CHORUS cross section data: $\nu Pb, \bar{\nu} Pb$
  - CCFR dimuon off Fe data
- Initial problem, with standard CTEQ cuts of $Q > 2$ and $W > 3.5$ neutrino data points (3134) far outnumber $\not\nu$±A (708).
Use the usual procedure of observing the behavior of the fits as you adjust the “weight” of the dominant data sample

\[ W = 0 \]

\[ R[F_2(\ell^{\pm} \text{ Fe})] \quad R[F_2(\nu \text{ Fe})] \]
$W = 1/2$

$R[F_2(\ell^\pm \text{Fe})]$  

$R[F_2(\nu \text{Fe})]$
$W = 1$

$R[F_2(\ell^\pm \text{Fe})]$  

$R[F_2(\nu \text{Fe})]$
\[ W = \infty \]

\[ R[F_2(\ell^\pm \text{Fe})] \quad R[F_2(\nu \text{Fe})] \]
Fit results

<table>
<thead>
<tr>
<th>Weight</th>
<th>Fit name</th>
<th>$\ell$ data</th>
<th>$\chi^2$ (pt)</th>
<th>$\nu$ data</th>
<th>$\chi^2$ (pt)</th>
<th>total $\chi^2$ (pt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$w = 0$</td>
<td>decut3</td>
<td>708</td>
<td>639 (0.90)</td>
<td>-</td>
<td>-</td>
<td>639 (0.90)</td>
</tr>
<tr>
<td>$w = 1/7$</td>
<td>glofac1a</td>
<td>708</td>
<td>645 (0.91)</td>
<td>3134</td>
<td>4710 (1.50)</td>
<td>5355 (1.39)</td>
</tr>
<tr>
<td>$w = 1/4$</td>
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<td>4501 (1.43)</td>
<td>5155 (1.34)</td>
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<tr>
<td>$w = 1/2$</td>
<td>glofac1b</td>
<td>708</td>
<td>680 (0.96)</td>
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<tr>
<td>$w = 1$</td>
<td>global2b</td>
<td>708</td>
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<td>4277 (1.36)</td>
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<td>-</td>
<td>-</td>
<td>3134</td>
<td>4192 (1.33)</td>
<td>4192 (1.33)</td>
</tr>
</tbody>
</table>

- $w = 0$: **No.** Problem: $R[F_2(\nu \ Fe)]$.
- $w = 1/7$: **No.** Problem: $R[F_2(\nu \ Fe)]$.
- $w = 1/4; 1/2$: **No.**
  - $Q2 = 5$: Undershoots $R[F_2(\ell^{\pm} \ Fe)]$ for $x < 0.2$. Overshoots $R[F_2(\nu \ Fe)]$ for $x \in [0.1; 0.3]$.
  - $Q2 = 20$: $R[F_2(\ell^{\pm} \ Fe)]$ still ok. Overshoots $R[F_2(\nu \ Fe)]$.
- $w = 1$: **No.** Possibly there is a compromise if more strict $Q2$ cut?
  - $Q2 = 5$: Undershoots $R[F_2(\ell^{\pm} \ Fe)]$ for $x < 0.2$. $R[F_2(\nu \ Fe)]$ ok.
  - $Q2 = 20$: $R[F_2(\ell^{\pm} \ Fe)]$ still ok. $R[F_2(\nu \ Fe)]$ ok.
- $w = \infty$: **No.** Problem: $R[F_2(\ell^{\pm} \ Fe)]$. 

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Quantitative $\chi^2$ Analysis

- Up to now we are giving a qualitative analysis. Consider next quantitative criterion based on $\chi^2$
- Introduce “tolerance” (T). Condition for compatibility of two fits: The 2nd fit $\chi^2$ should be within the 90% C.L. region of the first fit $\chi^2$
- Charged: $638.9 \pm 45.6$ (best fit to charged lepton and DY data)
- Neutrino: $4192 \pm 138$ (best fit to only neutrino data)

<table>
<thead>
<tr>
<th>Weight</th>
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<th>$\ell$ data</th>
<th>$\chi^2$</th>
<th>$\nu$ data</th>
<th>$\chi^2$</th>
<th>total $\chi^2$ (p/t)</th>
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<tr>
<td>$w = 0$</td>
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<td></td>
<td>nnnn NO</td>
<td>639 (0.90)</td>
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<td>$w = 1/7$</td>
<td>glofac1a</td>
<td>708</td>
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<td>3134</td>
<td>4710 NO</td>
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<td>$w = 1/4$</td>
<td>glofac1c</td>
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<td>4192</td>
<td>4192 (1.33)</td>
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</tbody>
</table>
Summary and Conclusions

- Neutrino scattering can provide an important look at the nucleon from a different (and complimentary) angle than electro-production.
  - The ability of neutrinos and anti-neutrinos to taste particular flavors of quarks can help isolate PDFs
- To understand the neutrino (oscillations, mixing, matter effects and $\delta^{\text{CP}}$) neutrino experiments use heavy nuclear targets to obtain statistics. **Need to understand $\nu$-induced nuclear effects!**
  - Use the difference between $\nu$ and $\bar{\nu}$ to measure $\delta^{\text{CP}}$. Are and nuclear effects the same?
- There are indications from one experiment using one nucleus that $\nu$-induced nuclear effects are different than $l^\pm$-nuclear effects.
  - Based on nuclear corrections factors R and the tolerance criterion, there is no good compromise fit to the $l^\pm A + DY + \nu A$ data.
- Need a systematic experimental study of $\nu$-induced nuclear effects (next talk).
- Need collaborative NP input to fully and correctly analyze crucial high-accuracy neutrino experiments!
Additional Details
Iron PDFs
Charged lepton data points

- DIS $F_2^A / F_2^D$ data sets: 862 points (before cuts)
- DIS $F_2^A / F_2^{A'}$ data sets: 297 points (before cuts)
- DY data sets $\sigma_{DY}^p / \sigma_{DY}^{p'}$: 92 points (before cuts)

Table from Hirai et al., arXiv:0909.2329
Physics Results: Six Structure Functions for Maximal Information on PDF’s

\[
\frac{d\sigma_{\nu A}}{dx dQ^2} = \frac{G_F^2}{2\pi x} \left[ \frac{1}{2} \left( F_{2A}^\nu(x, Q^2) + xF_{3A}^\nu(x, Q^2) \right) + \frac{(1-y)^2}{2} \left( F_{2A}^\nu(x, Q^2) - xF_{3A}^\nu(x, Q^2) \right) \right]
\]

\[
\frac{d\sigma_{\bar{\nu} A}}{dx dQ^2} = \frac{G_F^2}{2\pi x} \left[ \frac{1}{2} \left( F_{2A}^{\bar{\nu}}(x, Q^2) - xF_{3A}^{\bar{\nu}}(x, Q^2) \right) + \frac{(1-y)^2}{2} \left( F_{2A}^{\bar{\nu}}(x, Q^2) + xF_{3A}^{\bar{\nu}}(x, Q^2) \right) \right]
\]

\[
\frac{\sigma(x, Q^2, (1-y)^2)}{G^2/2\pi x}
\]

\[
X = 0.1 - 0.125
\]
\[
Q^2 = 2 - 4 \text{ GeV}^2
\]

Meant to give an impression only!
Kinematic cuts in (1-y) not shown.
High-x PDFs
\(\nu - p\) Scattering

\[
\begin{align*}
F_2^{\nu p} &= 2x (d + \bar{u} + s) \\
F_2^{\bar{\nu} p} &= 2x (\bar{d} + u + \bar{s})
\end{align*}
\]

\text{At high } x

\[
\frac{F_2^{\nu p}}{F_2^{\bar{\nu} p}} = \frac{d}{u}
\]

Add in…

\[
\begin{align*}
xF_3^{\nu p} &= 2x (d - \bar{u} + s) \\
xF_3^{\bar{\nu} p} &= 2x (-\bar{d} + u - \bar{s})
\end{align*}
\]

\[
\begin{align*}
F_2^{\nu p} - xF_3^{\nu p} &= 4x\bar{u} \\
F_2^{\bar{\nu} p} + xF_3^{\bar{\nu} p} &= 4xu
\end{align*}
\]
Further indications that the valence quarks not quite right at high-x??
E866 -Drell-Yan Preliminary Results (R. Towell - Hix2004)

- $x_{beam}$ distribution measures $4u + d$ as $x \rightarrow 1$.
- Both MRST and CTEQ overestimate valence distributions as $x \rightarrow 1$ by 15-20%.
- Possibly related to $d/u$ ratio as $x \rightarrow 1$, but requires full PDF-style fit.
- Radiative corrections have recently been calculated. (Not yet fully applied)
Present Status: $\nu$-scattering
High $x_{Bj}$ parton distributions

- Ratio of CTEQ5M (solid) and MRST2001 (dotted) to CTEQ6 for the u and d quarks at $Q^2 = 10 \text{ GeV}^2$. The shaded green envelopes demonstrate the range of possible distributions from the CTEQ6 error analysis.

- CTEQ / MINERvA working group to investigate high-$x_{Bj}$ region.
Knowledge of Nuclear Effects with Neutrinos: essentially NON-EXISTENT

- $F_2$ / nucleon changes as a function of A. Measured in $\mu/e - A$ not in $\nu - A$.
- Good reason to consider nuclear effects are DIFFERENT in $\nu - A$.
  - Presence of axial-vector current.
  - SPECULATION: Much stronger shadowing for $\nu - A$ but somewhat weaker “EMC” effect.
  - Different nuclear effects for valance and sea --> different shadowing for $xF_3$ compared to $F_2$.
  - Different nuclear effects for d and u quarks.
Formalism

- PDF Parameterized at $Q_0 = 1.3$ GeV as

$$xf_i(x, Q_0) = \begin{cases} 
A_0x^{A_1}(1 - x)^{A_2}\ e^{A_3x}(1 + e^{A_4x})^{A_5} & : i = u_v, d_v, g, \bar{u} + \bar{d}, s, \bar{s}, \\
A_0x^{A_1}(1 - x)^{A_2} + (1 + A_3x)(1 - x)^{A_4} & : i = \bar{d}/\bar{u},
\end{cases}$$

- PDFs for a nucleus are constructed as:

$$f_i^A(x, Q) = \frac{Z}{A} f_i^{p/A}(x, Q) + \frac{(A - Z)}{A} f_i^{n/A}(x, Q)$$

- Resulting in nuclear structure functions:

$$F_i^A(x, Q) = \frac{Z}{A} F_i^{p/A}(x, Q) + \frac{(A - Z)}{A} F_i^{n/A}(x, Q)$$

- The differential cross sections for CC scattering off a nucleus:

$$\frac{d^2\sigma}{dx\ dy}^{(\bar{\nu})^A} = \frac{G^2 ME}{\pi} \left[ (1 - y - \frac{Mxy}{2E})F_2^{(\bar{\nu})^A} + \frac{y^2}{2} 2xF_1^{(\bar{\nu})^A} \pm y(1 - \frac{y}{2})xF_3^{(\bar{\nu})^A} \right]$$

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