The Strange-Antistrange Asymmetry
The NuTeV Measurement & a Peek at Future Prospects...

David A. Mason
Fermilab
Talking about a slightly different energy regime...
NuTeV

• $\nu$-N DIS ($\langle E_\nu \rangle \sim 120 GeV$)
• FNAL ’96-’97 fixed target run
• $3.15 \times 10^{18}$ protons on target
  – 886,004 $\nu$, 255,045 $\bar{\nu}$ CC events
  – 5163 $\nu$ and 1380 $\bar{\nu}$ Dimuons
• Detector calibration beam throughout run
  – hadron, e, and muon beams
• High purity, selectable $\nu$ and $\bar{\nu}$ beams
The NuTeV Collaboration:

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NuInt '07: June 3, 2007
$\sin^2 \theta_W$ and the Strange Asymmetry

- NuTeV measured $R^- = \frac{\sigma^{\nu}_{NC} - \sigma^{\mu}_{NC}}{\sigma^{\nu}_{CC} - \sigma^{\mu}_{CC}}$
- From that $\sin^2 \theta_W$ was extracted
  - Insensitive to sea quark uncertainties
  - But assumed $s(x) = \bar{s}(x)$
- $0.22773 \pm 0.00135$ (stat) $\pm 0.00093$ (syst)
- 3 $\sigma$ above world average
- $R^-$ correction from asymmetric strange sea is proportional to $S^- \equiv \int x[s(x) - \bar{s}(x)]dx$
- Led to much theoretical speculation $\Rightarrow$
- $S^- \sim 0.0068$ required to bring to world ave.
The Strange Uncertainty

- Not well constrained in global fits (through structure function differences)
- Parameterizations (e.g. CTEQ, MRST...) typically assume $s = \bar{s} = 0.2(\bar{u} + \bar{d})$
- Uncert. in pdf sets represent $\bar{u} + \bar{d}$ error, not error on strange
- Freeing strange in CTEQ6 fit $\Rightarrow$
- Constraint from data is needed!
- (But must be in useful form for fits)

(F. Olness talk DIS 2005)
A Pantheon of Asymmetry Predictions

Cao & Signal \((x_s - \bar{x}_s)\)

Alwai et al \((x_s - \bar{x}_s)\)

Wakamatsu \((x_s - \bar{x}_s)\)

Catani et al \((s - \bar{s})\)

Brodsky & Ma \((s - \bar{s})\)

NuTeV can directly measure this!

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Charm Production $\Rightarrow$ Dimuons

- CC $\nu N$ makes charm
- $\rightarrow$ fragmentation
- $\rightarrow$ semileptonic decay to $\mu$
- Very clear signature
- Direct look at strange sea
- With sign selected beam NuTeV can look at $s(x)$, $\bar{s}(x)$ independently
- Can also measure charm mass
The Onion Representation of Dimuons

Physics convolved with experimental effects is what’s measured

Detector Smearing
Acceptance

\( E_{\mu 2} > 5 \text{ GeV} \)

Measured

\( \mu_2 \)
The Dimuon Cross Section

Dimuon Cross Section

Detector Smearing
Acceptance
$E_{\mu_2} > 5$ GeV

Data

Measured Independently
(CCFR Testbeam)

Measured Independently
(NuTeV Calibration Beam)
The Forward Dimuon Cross Section

- Measure Dimuon rather than charm cross section
- Eliminates model dependence from:
  - Semileptonic Decay
  - Fragmentation
  - Order in $\alpha_s$ of Cross Section
- Model dependence only from effects which cross “⊗” boundary
- Minimized in high acceptance events ($E_{\mu-\text{charm}} > 5$ GeV)
- With model dependence removed, can use simple (LO) model for extraction!

**Forward Dimuon Cross Section:** Cross section of dimuon events in iron such that the charm decay muon has energy $> 5$ GeV.

(Goncharov et al:PRD64 (2001) 112006)

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Good LO Data/MC Agreement: Neutrinos

- Red points are data, black is MC, energies in GeV
Good LO Data/MC Agreement: Antineutrinos

- **Red** points are data, black is MC, energies in GeV

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Forward Dimu Cross Section Table

- Plotting xsec vs x, normalized so $\frac{G_F^2 M_\pi}{\pi} = 1$
- Table is available in electronic form for global fits!
With the LO model having served its purpose
We now move to NLO:
NLO charm production

- 1st order in QCD
- NLO of global interest
- Substantial gluon pdf
- But fragmentation requires convolution integral
- Dimuon acceptance depends on $z$, charm $p_{\perp}$
Elements in Dimuon Cross Section Table Fit

\[ \frac{d\sigma_{\text{charm}}(E_\nu, x, y; m_c, s, \bar{s})}{dxdy} \otimes \mathcal{N}(A, x, Q^2) \cdot B_c \cdot A_{\mu 2}(E_\nu, x, y; \epsilon, m_c) = \text{fit} \Rightarrow \frac{d\sigma_{\mu}(E_\nu, x, y)}{dxdy} \]

- Measured NuTeV dimuon cross section
- Calculated inclusive charm cross section. depends on \( m_c \), strange and antistrange seas.
- Nuclear corrections (iron target, proton pdfs) dependent on nucleus \( A \), \( x \), and \( Q^2 \), is convolved with pdf
- Semileptonic branching ratio.
- Acceptance function due to the 5 GeV cut on the muon from semileptonic charm decay \( \frac{\mathcal{N}(E_{\mu 2q} > 5\text{GeV})}{\mathcal{N}(\text{all})} \).

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Nuclear Corrections: $N(A, x, Q^2)$

- Proton based global fit pdf’s require nuclear corrections (iron target)
- $N$ depends on nucleus type, $x$, and $Q^2$
  - And whether valence, sea quarks or gluons involved
- Past analyses have used simple $Q^2$ independent parameterization
- First time $N$ from global fits have been used
- de Florian et al, NLO corrections $\Rightarrow$
Semi-muonic Branching Ratio: $B_c$

- $B_c$ is an average semi-$\mu$ branching ratio over all charm states
- Fitting to cross section table requires taking from external measurements
- 2004 PDG value of $0.099 \pm 0.012$ used
- $B_c$ uncertainty $\Rightarrow$ half of uncertainty in this strange asymmetry measurement
\( E_{\mu - \text{charm}} > 5 \text{ GeV} \) Acceptance \( \mathcal{A}_{\mu 2} \) –DISCO!

- Fitting table requires \( E_{\mu 2} > 5 \text{ GeV} \) acceptance correction
- \( 2\mu \) acceptance depends on fragmentation
- Also depends on charm \( p_\perp \) at NLO
- \( \Rightarrow \) need cross section differential in both
- i.e. need:

\[
\frac{d\sigma_{\text{charm}}}{d\xi \, dy \, dz \, d\eta_c}
\]

where \( \eta_c = \frac{1}{2} \log \frac{E_c + p_{c\parallel}}{E_c - p_{c\parallel}} \)

(i.e. a true rapidity, not pseudorapidity)

Acceptance Tables

- Ratio of dimuons which pass $E_{\mu-\text{charm}} > 5$ GeV cut
- Acceptances calculated for each of 90 table points (1 shown) →
- In grid of 12 $\epsilon$, 6 $m_c$ points
  - $m_c$ dependence is NLO effect from rapidity
- In each table bin, 20 $z \times 40 \eta_c$ bins
- Decay 20,000 dimuons in each
NLO fits table well!

- Plotting xsec vs x, normalized so $\frac{G_F^2 M_E}{\pi} = 1$
A Progression of Fits...

- Performed several fits, taking charm mass, nonstrange pdfs, branching ratio from external measurements:
  1. Treating strange/antistrange seas as modification of pre-evolved pdfs
  2. Defining $s, \bar{s}$ pdfs at $Q_0$, evolving properly
  3. Using CTEQ parameterization, evolving properly, satisfying sum rules

- Also studied dependence of strange asymmetry on shape
Traditional fit first...

\[
s(x, Q^2) = \kappa (1-x)^\alpha \left[ \frac{u(x, Q^2) + d(x, Q^2)}{2} \right]
\]

\[
\bar{s}(x, Q^2) = \bar{\kappa} (1-x)^{\bar{\alpha}} \left[ \frac{\bar{u}(x, Q^2) + \bar{d}(x, Q^2)}{2} \right]
\]

- Factors applied to already evolved pdfs
- \( S^- = 0.0023 \pm 0.0006 \) (stat)
  \[
  S^- \equiv \int x \left[ s(x) - \bar{s}(x) \right] dx
  \]
- But do we get this answer because of the approximate QCD evolution?

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_c )</td>
<td>1.20 GeV (fixed)</td>
</tr>
<tr>
<td>( \epsilon )</td>
<td>0.60 (fixed)</td>
</tr>
<tr>
<td>( \kappa )</td>
<td>0.596 \pm 0.028</td>
</tr>
<tr>
<td>( \bar{\kappa} )</td>
<td>0.521 \pm 0.026</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>1.34 \pm 0.49</td>
</tr>
<tr>
<td>( \bar{\alpha} )</td>
<td>1.54 \pm 0.46</td>
</tr>
<tr>
<td>( B_c )</td>
<td>0.099 (fixed)</td>
</tr>
</tbody>
</table>

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To evolve properly...

\[
\mu^2 \frac{d}{d\mu^2} \phi_{i,h}(x, \mu^2) = \sum_{j=q,\bar{q},G} \int_x^1 \frac{d\xi}{\xi} \ P_{ij} \left( \frac{x}{\xi}, \alpha_s(\mu^2) \right) \phi_{j,h}(\xi, \mu^2)
\]

- pdf must be solution of DGLAP equation (above)
- Define at an initial scale (\(\mu_0 = Q_0\)) then numerically solve to find pdf \(\phi_{j,h}(\xi, \mu^2)\), at arbitrary scale, \(\mu\).
- Some freedom in pdf definitions is required (\(s \neq \bar{s}\))
- Use modified version of EVLCTEQ evolution code which allows \(s \neq \bar{s}\) (thanks to Wu-Ki Tung)
- Use LHApdf v1.2 package as a wrapper
- CTEQ6M pdfs, defining \(s, \bar{s}\) at \(Q_0 = 1.3\) GeV
Redo $\kappa - \alpha$ fit, evolving properly:

<table>
<thead>
<tr>
<th>Description</th>
<th>$\kappa$</th>
<th>$\kappa'$</th>
<th>$\alpha$</th>
<th>$\alpha'$</th>
<th>$\delta^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central value</td>
<td>0.415</td>
<td>0.332</td>
<td>0.87</td>
<td>1.09</td>
<td>0.00195</td>
</tr>
<tr>
<td>Statistical error</td>
<td>0.031</td>
<td>0.030</td>
<td>0.68</td>
<td>0.71</td>
<td>0.00055</td>
</tr>
<tr>
<td>$\nu \pi$-K (15%)</td>
<td>0.012</td>
<td>0.009</td>
<td>0.38</td>
<td>0.08</td>
<td>0.00041</td>
</tr>
<tr>
<td>$\bar{\nu}$ $\pi$-K (21%)</td>
<td>0.006</td>
<td>0.018</td>
<td>0.05</td>
<td>0.14</td>
<td>0.00031</td>
</tr>
<tr>
<td>Emuff scale (1%)</td>
<td>0.007</td>
<td>0.016</td>
<td>0.19</td>
<td>0.01</td>
<td>0.00002</td>
</tr>
<tr>
<td>Had energy scale (0.5%)</td>
<td>0.008</td>
<td>0.009</td>
<td>0.15</td>
<td>0.04</td>
<td>0.00010</td>
</tr>
<tr>
<td>$R_L$ (20%)</td>
<td>0.011</td>
<td>0.018</td>
<td>0.06</td>
<td>0.02</td>
<td>0.00005</td>
</tr>
<tr>
<td>MC statistics</td>
<td>0.014</td>
<td>0.021</td>
<td>0.16</td>
<td>0.06</td>
<td>0.00000</td>
</tr>
<tr>
<td>Emu2 rangeout</td>
<td>0.013</td>
<td>0.021</td>
<td>0.31</td>
<td>0.06</td>
<td>0.00012</td>
</tr>
<tr>
<td>Flux norm</td>
<td>0.002</td>
<td>0.006</td>
<td>0.07</td>
<td>0.00</td>
<td>0.00000</td>
</tr>
<tr>
<td>Total Table Systematics</td>
<td>0.028</td>
<td>0.044</td>
<td>0.58</td>
<td>0.18</td>
<td>0.00054</td>
</tr>
<tr>
<td>Charm mass</td>
<td>0.015</td>
<td>0.011</td>
<td>0.07</td>
<td>0.14</td>
<td>0.00006</td>
</tr>
<tr>
<td>Fragmentation $\epsilon$</td>
<td>0.009</td>
<td>0.009</td>
<td>0.25</td>
<td>0.06</td>
<td>0.00023</td>
</tr>
<tr>
<td>$B_C$</td>
<td>0.053</td>
<td>0.055</td>
<td>1.32</td>
<td>0.19</td>
<td>0.00125</td>
</tr>
<tr>
<td>Total External Measurement</td>
<td>0.056</td>
<td>0.057</td>
<td>1.35</td>
<td>0.24</td>
<td>0.00127</td>
</tr>
<tr>
<td>Total Systematics</td>
<td>0.063</td>
<td>0.072</td>
<td>1.47</td>
<td>0.30</td>
<td>0.00138</td>
</tr>
</tbody>
</table>
\[ \kappa - \alpha \times s^{-}(x) \text{ vs } x \]

- \( \chi^2 = 36.9 \) out of 39.8 DoF
- \( xs^{-}(x) \text{ vs } x \), inner band stat. error, outer band total \( \implies \)
- Asymmetry agrees well with approximate evolution fit
- But \( \int_{0}^{1} [s(x) - \bar{s}(x)]dx \) isn’t zero.
- Technically should also satisfy sum rules.
Further Satisfying QCD requirements

- Stepped up collaboration with phenomenologists
  (Amundson, Kretzer, Olness, Soper, Tung)

- Using a “CTEQ inspired” parameterization (hep-ph/0312323)

\[
s^+(x, Q_0) = \kappa^+(1 - x)^{\alpha^+} x^{\gamma^+} \left[ u(x, Q_0) + d(x, Q_0) \right]
\]

\[
s^-(x, Q_0) = s^+(x) \tanh \left[ \kappa^- (1 - x)^{\alpha^-} x^{\gamma^-} \left( 1 - \frac{x}{x_0} \right) \right]
\]

\[
s = \frac{s^+ + s^-}{2} \quad \bar{s} = \frac{s^+ - s^-}{2}
\]

- Flavor sum rule satisfied by \( x_0 \) such that \( \int s^-(x, Q_0) dx = 0 \)

- Total momentum sum rule satisfied by rescaling gluon to balance any change in \( \int x s^+ \) (thanks to Dave Soper)
  - Gluon sea is large, uncertainty is also large
  - Strange sea is small
  - \( \Rightarrow \) gluon uncertainty can handle small perturbation (< 1%)
**s^+, s^- fit results:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_c$</td>
<td>1.20 GeV (fixed)</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>0.60 (fixed)</td>
</tr>
<tr>
<td>$\kappa^+$</td>
<td>0.551 ± 0.126</td>
</tr>
<tr>
<td>$\kappa^-$</td>
<td>$(-0.881 \pm 0.567) \times 10^{-2}$</td>
</tr>
<tr>
<td>$\alpha^+$</td>
<td>1.11 ± 0.69</td>
</tr>
<tr>
<td>$\alpha^-$</td>
<td>6.31 ± 4.06</td>
</tr>
<tr>
<td>$\gamma^+$</td>
<td>0.072 ± 0.064</td>
</tr>
<tr>
<td>$\gamma^-$</td>
<td>$-0.102 \pm 0.080$</td>
</tr>
<tr>
<td>$B_c$</td>
<td>0.099 (fixed)</td>
</tr>
</tbody>
</table>

$$
\eta_s = \frac{\int_0^1 x s^+(x) dx}{\int_0^1 [\bar{u}(x)+\bar{d}(x)] dx}
$$

<table>
<thead>
<tr>
<th>$\eta_s$</th>
<th>$s^-$</th>
<th>Systematic</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0612</td>
<td>0.00196</td>
<td>central value</td>
</tr>
<tr>
<td>0.0011</td>
<td>0.00046</td>
<td>statistics</td>
</tr>
<tr>
<td>0.0026</td>
<td>0.00034</td>
<td>$\nu \pi$-K model</td>
</tr>
<tr>
<td>0.0019</td>
<td>0.00025</td>
<td>$\pi$-K model</td>
</tr>
<tr>
<td>0.0020</td>
<td>0.00004</td>
<td>$\mu$ spectrometer $p$ scale (1%)</td>
</tr>
<tr>
<td>0.0014</td>
<td>0.00008</td>
<td>hadron energy scale (0.5%)</td>
</tr>
<tr>
<td>0.0018</td>
<td>0.00005</td>
<td>$R_L$ in table model (20%)</td>
</tr>
<tr>
<td>0.0026</td>
<td>0.00001</td>
<td>table extraction MC statistics</td>
</tr>
<tr>
<td>0.0030</td>
<td>0.00012</td>
<td>$\mu_2$ range out energy (2.5%)</td>
</tr>
<tr>
<td>0.0006</td>
<td>0.00005</td>
<td>$\nu$, $\bar{\nu}$ relative normalization</td>
</tr>
<tr>
<td>0.0060</td>
<td>0.00045</td>
<td>total systematics</td>
</tr>
<tr>
<td>0.0022</td>
<td>0.00002</td>
<td>$\Delta m c = 0.10$</td>
</tr>
<tr>
<td>0.0020</td>
<td>0.00021</td>
<td>$\Delta\epsilon_{C-S} = 0.3$</td>
</tr>
<tr>
<td>0.0101</td>
<td>0.00111</td>
<td>$\Delta B_c = 0.012$</td>
</tr>
<tr>
<td>0.0068</td>
<td>0.00046</td>
<td>CTEQ6 PDF uncertainties</td>
</tr>
<tr>
<td>0.0007</td>
<td>0.00038</td>
<td>Nuclear corrections</td>
</tr>
<tr>
<td>0.0126</td>
<td>0.00128</td>
<td>total external measurement</td>
</tr>
</tbody>
</table>
$s^+, s^- \text{ asymmetry}$

- $\chi^2 = 38.2$ out of 37.8 DoF
- $s^-$ prefers to satisfy sum rule by spiking negative at low $x$
- Crossing point at $x_0=0.004$
- Gluon sea only needs 0.07% change
- Asymmetry still consistent with previous two fits
A Reminder of the Pantheon of Asymmetries

Cao & Signal ($x s - x \bar{s}$)

Alwal et al ($x s - x \bar{s}$)

Wakamatsu ($x s - x \bar{s}$)

Catani et al ($s - \bar{s}$)

Brodsky & Ma ($s - \bar{s}$)

David A. Mason

NuInt '07: June 3, 2007
So we look at the asymmetry vs. crossing point...

\[ s^- (x, Q_0) = s^+ (x) \tanh \left[ \kappa^- (1 - x) \alpha^- x \gamma^- \left( 1 - \frac{x}{x_0} \right) \right] \]
• We have measured the strange asymmetry to be positive
  – First complete NLO analysis for this process
  – Sign selected beam ensures pure $\nu, \bar{\nu}$ samples
  – Multiple fits, including proper evolution, QCD sum rules satisfied
  – Modern nuclear corrections
• Found asymmetry difficult to accommodate with $x_0$ at high $x$
• What might we expect experimentally beyond this measurement?
Other $\nu_s - \bar{s}$ measurements?

From CERN?

- **CHORUS & NOMAD:**
  - Ran in CERN SPS horn focused beam, mostly $\nu$, some $\bar{\nu}$
  - $\nu_\mu \to \nu_\tau$ oscillation experiments $\Rightarrow$ fine grained detectors.
  - Many charm measurements, dimuon results expected soon

- **Future – CNGS?**

![Diagram showing the layout of the CERN SPS and the proposed CNGS project.](image)
NuMI beam? MINOS?

- MINOS near detector has unprecedented $\nu$ CC event sample on tape
- $\Rightarrow$ large dimuon sample
- Low energy would make hard to separate from backgrounds
- Would need pure $\bar{\nu}$ sample as well to measure $s - \bar{s}$
MINER$\nu$A?

- Fine grained detector with good particle ID
  - Strange particle tagging will be possible
  - Can NC strange particle production provide additional insight into $s(x)$?
  - MINER$\nu$A’s particle ID should allow charm production measurements beyond the “traditional” dimuon signature ($\nu$ energy permitting)
- To look at $s - \bar{s}$ would need $\nu$ and $\bar{\nu}$ data
Possibly further in the future: “CMF”

- An idea for the interim between Collider & ILC
- A $\nu$ DIS experiment to run in the “original” FNAL $\nu$ beamline
- 100x NuTeV statistics with a high energy sign selected beam
- Test beam calibrated CHARMII-like glass detector
- Primary goals include precision electroweak & SF measurements
- Statistics coupled with more precise $B_c$ could really nail strange sea
In the meantime, here is what we know:

\[ S_{NLO, CTEQ6}^- = +0.00196 \pm 0.00046 \pm 0.00045 \pm 0.00128 \]

\[ m_c = 1.41 \pm 0.10 \pm 0.08 \pm 0.12 \text{ GeV/c}^2 \]