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"QCD Corrections" to the NuTeV Measurement

Outline of Talk

I) Implications of the NuTeV Experiment

1) Relationship to Other Measurements of $\sin^2\theta_W$

2) NuTeV and the Paschos-Wolfenstein Ratio

II) "QCD Corrections" to NuTeV Measurement

1) "Isoscalar" Correction [neutron excess in iron]

2) "CSV" Correction [isospin violation in valence PDFs]

3) "Strange" Correction [Momentum asymmetry for $s, \bar{s}$ quarks]

4) Shadowing Corrections

III) Conclusions

19th Int'l Workshop on Weak Interactions and Neutrinos

Lake Geneva, WI, Oct 8, 2003

Research supported by NSF PHY-0244822

in collaboration with A.W. Thomas [Adelaide]

Neutrino Total Cross Sections on Isoscalar Targets

$$
\begin{aligned}
R_\nu &\equiv \frac{\sigma\langle \nu\, N_0 \longrightarrow \nu\, X\rangle}{\sigma\langle \nu\, N_0 \longrightarrow \mu\, X\rangle} = g_L^2 + r\, g_R^2 \\
R_{\overline{\nu}} &\equiv \frac{\sigma\langle \overline{\nu}\, N_0 \longrightarrow \overline{\nu}\, X\rangle}{\sigma\langle \overline{\nu}\, N_0 \longrightarrow \overline{\mu}\, X\rangle} = g_L^2 + \frac{1}{r}\, g_R^2 \\
r &\equiv \frac{\sigma\langle \overline{\nu}\, N_0 \longrightarrow \overline{\mu}\, X\rangle}{\sigma\langle \nu\, N_0 \longrightarrow \mu\, X\rangle}
\end{aligned}
$$

- R_ν is more sensitive to $\sin^2\theta_W$
- NuTeV measure $R_\nu, R_{\overline{\nu}}$ simultaneously

Paschos-Wolfenstein Ratio

- Paschos & Wolfenstein [PR **D7**, 91 (73)]:
- Sensitivity to parton dist'ns, higher-order corrections minimized with *Paschos-Wolfenstein ratio*,

$$
R^{PW} \equiv \frac{R_\nu - r\, R_{\overline{\nu}}}{1-r} = \frac{\sigma\langle \nu\, N_0 \longrightarrow \nu\, X\rangle - \sigma\langle \overline{\nu}\, N_0 \longrightarrow \overline{\nu}\, X\rangle}{\sigma\langle \nu\, N_0 \longrightarrow \mu\, X\rangle - \sigma\langle \overline{\nu}\, N_0 \longrightarrow \overline{\mu}\, X\rangle} = \frac{1}{2} - \sin^2\theta_W
$$

- PW Ratio: independent determination of Weinberg angle in ν DIS
- PW Ratio requires the following assumptions:
  - isoscalar target [N=Z]
  - include only u, d quarks; neglect quark masses
  - assume isospin symmetry for PDFs
  - no parton shadowing

NuTev Determination of Weinberg Angle

- NuTeV group: Construct ratios R^ν and $R^{\overline{\nu}}$:
  - Separate ratios of neutrino and antineutrino cross sections less dependent on overall normalizations.

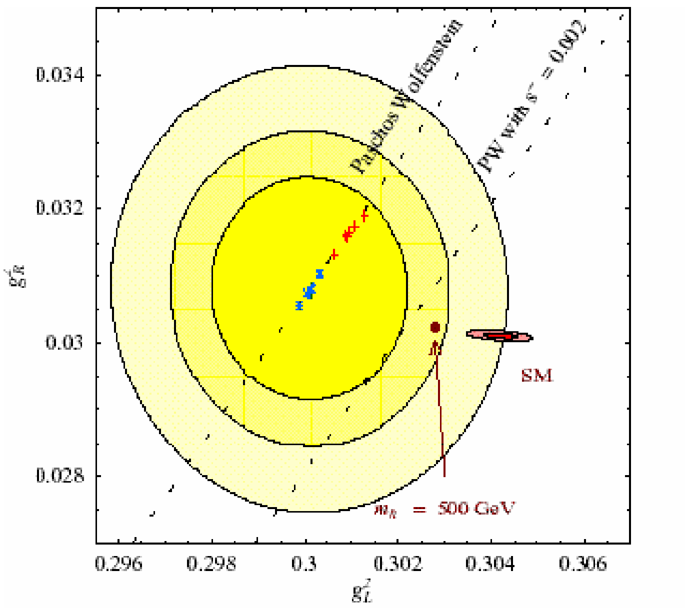
- Very precise charged/neutral current ratios:

$$\boxed{R^\nu = 0.3916 \pm 0.0007\,, \qquad R^{\overline{\nu}} = 0.4050 \pm 0.0016}$$

$$\boxed{\begin{array}{c} s_W^2 = 0.2276 \pm 0.0013_{stat} \pm 0.0006_{syst} \pm 0.0006_{th} \\ -.00003[M_t - 175] + .00032\ln[M_H/100] \end{array}}$$

- NuTeV value: $\sim 3\sigma$ *above measured fit to other electroweak processes,*

$$\boxed{s_W^2 = 0.2229 \pm 0.0004}$$



QCD Corrections to Paschos-Wolfenstein Ratio

- Uncertainties in PDF's: cancel in P-W ratio
- NLO Corrections: small *[see following talk by H. Reno]*
- EM Corrections: would be surprising
  - Work on new codes to update Bardin radiative corrections.
- Excess neutrons in iron *("isoscalar correction")*
- Isospin violation for valence PDFs *("CSV correction")*
- Difference in momentum carried by strange, antistrange quarks *("s quark correction")*
- Parton shadowing? Likely small; probably goes in wrong direction to remove NuTeV anomaly.

Note: above comments apply **only** to P-W ratio R^{PW}!

Does this hold for NuTeV measurement? Requires full NLO phenomenology, consistent treatment of quark masses, to answer!

In this talk, discuss isoscalar, CSV, strange corrections

Isoscalar Correction to NuTeV Measurement

- Isoscalar Correction to P-W ratio [$N \neq Z$ in iron]:

$$\delta R_I^{PW} = \delta\left(\sin^2\theta_W\right) \approx -\frac{(N-Z)}{A}\frac{U_V - D_V}{U_V + D_V}\left[1 - \frac{7}{3}\sin^2\theta_W + \frac{4\alpha_s}{9\pi}\left(\frac{1}{2} - \sin^2\theta_W\right)\right]$$

  - Depends only on second moments of valence PDFs
    [momentum carried by valence quarks]

- Isoscalar correction to Paschos-Wolfenstein ratio: $\boxed{\delta R_I^{PW} = -.0125}$;

- NuTeV: $\boxed{\delta R_I^{NT} = -.0080}$.

  1) NuTeV exp't doesn't evaluate Paschos-Wolfenstein ratio.
  2) Isoscalar correction determined from detailed Monte Carlo simulation of experiment.
  3) Kulagin: PR **D67**, 091301 (03): *error in isoscalar correction greater than estimated by NuTeV*
  4) PW → NuTeV: significant change *[33% decrease]*; should be under control. *[Davidson et al]*

Isospin Violating Corrections to P-W Ratio

- Changes in P-W ratio from isospin violating PDFs:

$$\begin{aligned}\delta R^{PW}_{CSV} &= \delta\left(\sin^2\theta_W\right) = \frac{\delta U_V - \delta D_V}{2(U_V + D_V)}\left[1 - \frac{7}{3}\sin^2\theta_W + \frac{4\alpha_s}{9\pi}\left(\frac{1}{2} - \sin^2\theta_W\right)\right] \\ \delta U_V &\equiv \int_0^1 x\left[u^p_V - d^n_V\right]\,dx \\ \delta D_V &\equiv \int_0^1 x\left[d^p_V - u^n_V\right]\,dx\end{aligned}$$

- This involves parton valence **Charge Symmetry Violation** (CSV)
  valence charge symmetry: takes $u_V \leftrightarrow d_V$, and $p \leftrightarrow n$.
  [rotation of π about 2 axis in isospin space]
- We know the **origins of CSV:**
  - quark mass difference $\delta m \equiv m_d - m_u$
  - electromagnetic contributions [most important EM contribution:
    $\delta M \equiv M_p - M_n$]
- **Models for CSV contributions** to valence PDFs:
  - Reproduce most important features of valence PDFs
  - Study the behavior of these models as $m_u \leftrightarrow m_d, M_p \leftrightarrow M_n$

CSV Corrections to P-W Ratio

- Changes in P-W ratio from valence quark CSV:

$$\delta R^{PW}_{CSV} = \delta\left(\sin^2\theta_W\right) = \frac{\delta U_V - \delta D_V}{2(U_V + D_V)}\left[1 - \frac{7}{3}\sin^2\theta_W + \frac{4\alpha_s}{9\pi}\left(\frac{1}{2} - \sin^2\theta_W\right)\right]$$

- Effect of parton valence CSV:
- P-W ratio involves 2^{nd} moment of valence distributions
  - Both numerator and denominator evolve identically with Q^2: under LO evolution,

$$Q_V(Q^2) = Q_V(Q_0^2)\left[\frac{\alpha(Q^2)}{\alpha(Q_0^2)}\right]^{32/81}$$

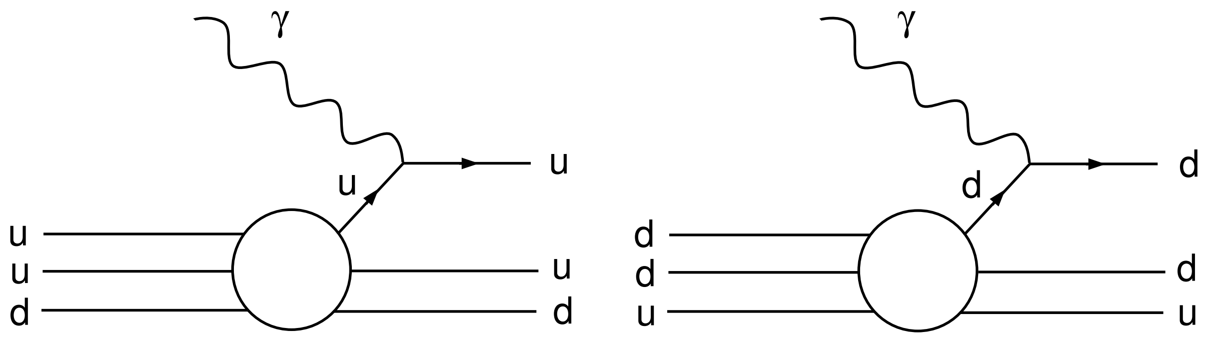
  - can evaluate at **any** Q^2 value.
- At low Q^2, nucleon valence distributions dominated by states with 3 valence quarks.

  $\Rightarrow$ derive simple relations for valence quark CSV.

Models for Valence Parton CSV Distributions

At low Q^2, construct valence parton distributions from constituent quark model

$$q_V(x) = M \sum_X |\langle X|\psi_+(0)|N\rangle|^2 \, \delta(M(1-x) - p_X^+)$$



- ψ_+ operator; removes q or creates $\overline{q}$.
- quark model wf's almost invariant under symmetry transformations
- CSV arises from **mass differences** of quarks, and $n-p$ mass difference, in energy-conserving delta function.
- At low Q^2, CSV effects related to **derivatives** of valence quark dist'ns

  multiplied by quark, nucleon mass differences

- Sather: approximate relation, valence PDFs $\Longleftrightarrow$ CSV dist'n

  [PL **B274**, 433 (92)]

$$\begin{aligned}
\delta d_V(x) &= d_V^p(x) - u_V^n(x) = -\frac{\delta M}{M}\frac{d}{dx}[x d_v(x)] - \frac{\delta m}{M}\frac{d}{dx} d_v(x) \\
\delta u_V(x) &= u_V^p(x) - d_V^n(x) = \frac{\delta M}{M}\left(-\frac{d}{dx}[x u_v(x)] + \frac{d}{dx} u_v(x)\right)
\end{aligned}$$

$$\begin{aligned}
\delta M &= M_n - M_p = 1.3 \text{ MeV} \\
\delta m &= m_d - m_u \sim 4 \text{ MeV}
\end{aligned}$$

Theory: CSV Corrections to P-W Ratio

- Charge-symmetry violation corrections to P-W ratio:

$$\delta R^{PW}_{CSV} = \frac{\delta U_V - \delta D_V}{2(U_V + D_V)}\left[1 - \frac{7}{3}\sin^2\theta_W + \mathcal{O}(\alpha)\right]$$

- P-W ratio independent of Q^2, evaluate at low Q^2 (quark models).
- Sather approximation: valence CSV dist'n from parton dist'n
- Integrate over x;

$$\begin{aligned}
\delta D_V &= \int_0^1 x\left[-\frac{\delta M}{M}\frac{d}{dx}(x d_V(x)) - \frac{\delta m}{M}\frac{d}{dx}d_V(x)\right] dx \\
&= \frac{\delta M}{M}D_V + \frac{\delta m}{M} \quad > 0 \\
\delta U_V &= \frac{\delta M}{M}\left[\int_0^1 x\left(-\frac{d}{dx}\left[x u_V(x)\right] + \frac{d}{dx}u_V(x)\right) dx\right] \\
&= \frac{\delta M}{M}(U_V - 2) \quad < 0
\end{aligned}$$

- $\delta D_V > 0$, $\delta U_V < 0$. These effects *add*, and *decrease* extracted $\sin^2\theta_W$.
- At low Q^2, CSV correction related to momentum carried by valence quarks.
- Obtain: $\boxed{\delta R^{PW}_{CSV} \sim -0.0020}$.

(*PW correction removes 40% of NuTeV discrepancy*)

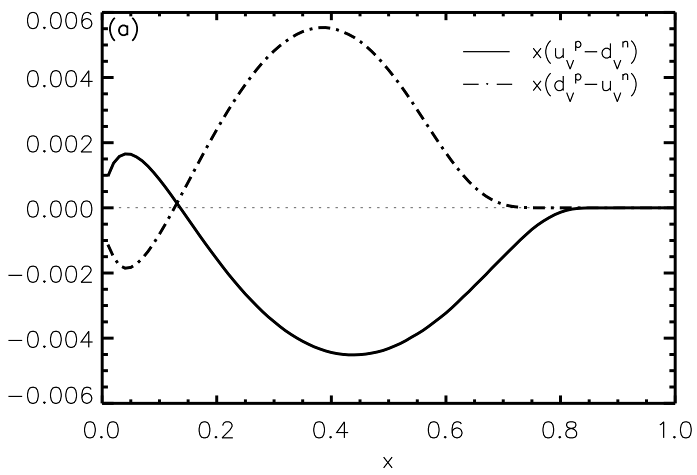
(excellent agreement between theory, CTEQ4LQ phenomenology)

CSV Corrections to NuTeV Result

- Since NuTeV don't evaluate Paschos-Wolfenstein ratio, must evaluate corrections to their experiment

$$\left(\delta \sin^2 \theta_W\right)_{CSV} = \int_0^1 F_q[CSV; x]\, x\delta q_V(x)\, dx$$

- Functional (provided by NuTeV) evaluates effect of CSV on Weinberg angle
- Phenomenological PDFs [CTEQ4LQ] in Sather relation, low Q^2
  - Construct CSV parton dist'ns; evolve to high Q^2
  - Fold with NuTeV functionals → CSV contribution to NuTeV



- Sather/CTEQ4LQ/NuTeV: $\boxed{\delta \sin^2 \theta_W \sim -0.0014}$
  (*CSV effects remove 30% of NuTeV discrepancy*)
- Conclusion: **CSV provides significant reduction of NuTeV anomaly** [$3\sigma \to 2\sigma$ effect]

[JTL/AWT PL **B558**, 132 (03); PR **D67**, 111901 (03)]

NuTeV Estimate/ CSV Corrections

- NuTeV construct CSV PDFs by

$$\delta d_V(x) = \left[\frac{\delta d_V(x)}{d_V(x)}\right] d_V(x)$$

  - $\delta d_V(x)/d_V(x)$ taken from quark model calc'n [Rodionov]

    [include "smearing" over diquark mass]
  - $d_V(x)$ taken from NuTeV PDFs

- Obtain very small CSV contribution, $\boxed{\delta \sin^2\theta_W \sim -0.0001}$

- This calculation "mixes" PDFs from quark model, NuTeV analysis

- "Mixed" prescription violates valence quark normalization

$$\langle \delta q_V \rangle \neq 0$$

- NuTeV don't include contrib'n from δU_V (1/3 of theor CSV effect)

- Theoretical arguments should constrain sign, relative magnitude of CSV effect [to within $\sim 25\%$]

Phenomenological Parton CSV Distributions

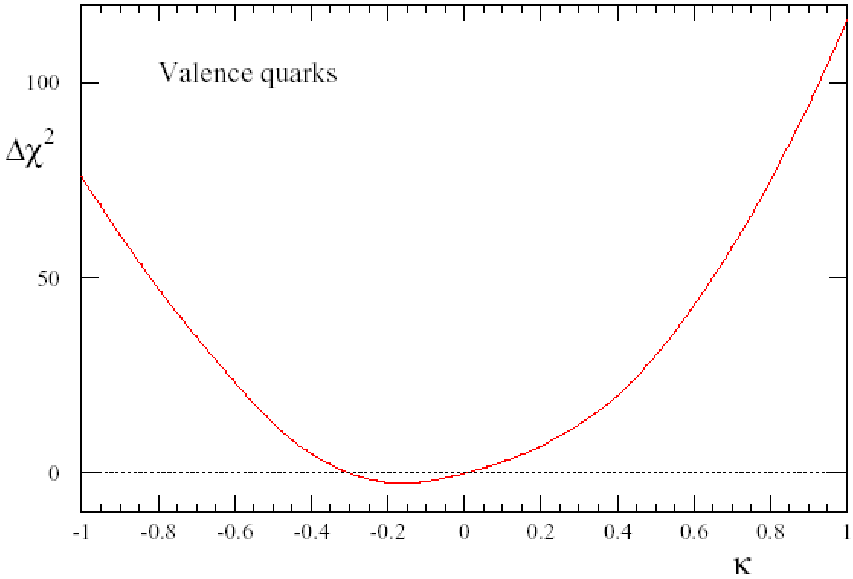
MRST [hep-ph/0308087] include parton charge symmetry violation.

- Parameterize valence quark CSV effects through

$$\begin{aligned} \delta d_V(x) &= -\kappa f(x) = -\delta u_V(x) \\ f(x) &= x^{-0.5}(1-x)^4(x-.0909) \end{aligned}$$

- As $x \to 0$ and $x \to 1$, $f(x)$ has same behavior as MRST parton distributions.
- First moment of $f(x)$ is zero [preserves valence quark normalization]
- Best fit $\kappa = -0.2$ [weak dependence of data on κ]

  90% confidence level $\kappa = -0.8 \to +0.65$



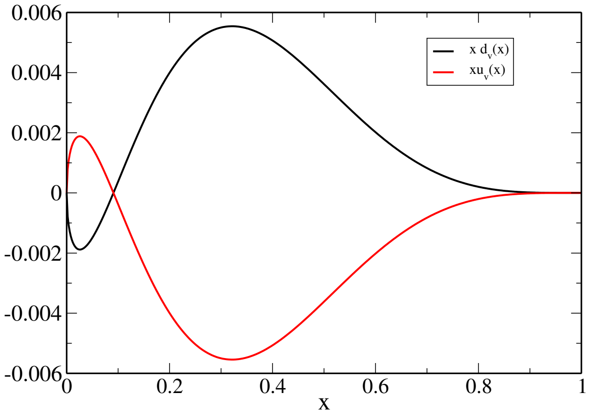
MRST CSV PDFs, and NuTeV Anomaly

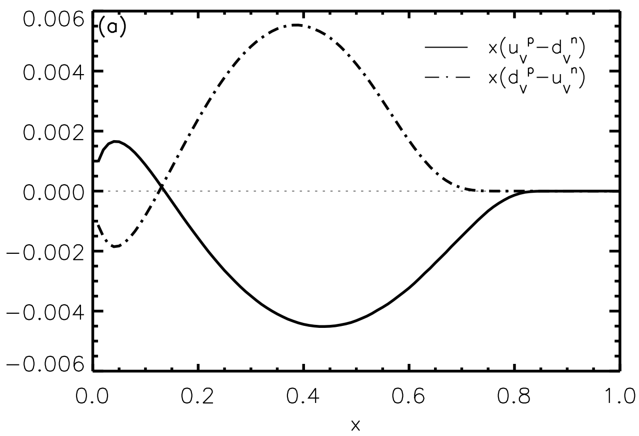
- MRST valence CSV PDFs of the form

$$\begin{aligned} \delta d_V(x) &= -\kappa f(x) = -\delta u_V(x) \\ f(x) &= x^{-0.5}(1-x)^4(x-.0909) \end{aligned}$$

- Best fit $\kappa = -0.2$

  90% confidence level $\kappa = -0.8 \rightarrow +0.65$





- *good agreement between MRST best fit, theor. model*

  1) MRST: $\delta d_V = -\delta u_V$ not bad approx'n

  2) "crossing point" $x = .0909$, reasonable agreement with theor models.

- MRST best value for CSV, remove 30-50% of NuTeV discrepancy

Strange Quark Corrections to P-W Ratio

- Changes in P-W ratio from **strange quarks**:

$$\begin{aligned} \delta R_S^{PW} &= \delta\left(\sin^2\theta_W\right) \approx \frac{-S_V}{U_V + D_V}\left[2\Delta_d^2 + 3(\Delta_d^2 + \Delta_u^2)\epsilon_c\right] \\ S_V &= \int_0^1 x[s(x) - \bar{s}(x)]\,dx \end{aligned}$$

  ϵ_c: Kinematic suppression of charm quark production ($m_c \neq 0$).

- Effect of strange quarks:

  If $S_V > 0$ (s quarks carry more momentum than $\overline{s}$), *decrease* $\sin^2\theta_W$ (decrease expt'l discrepancy).

  If $S_V < 0$, *increase* $\sin^2\theta_W$ (increase expt'l discrepancy).

- Most sensitive estimates of $s, \overline{s}$: dimuons in $\nu, \overline{\nu}$ processes: [charm production]

Original NuTeV Estimate: s Quark Corrections

- Estimates of strange quark asymmetry:
- Changes in P-W ratio for **strange quarks**:

$$\begin{aligned} \delta R_S^{PW} &\approx \frac{-S_V}{U_V + D_V} \\ S_V &= \langle\, x(s - \bar{s})\,\rangle \end{aligned}$$

- CCFR/NuTeV: measure dimuon production in $\nu, \overline{\nu}$ processes.

  best expt'l fit: $s < \overline{s}$ at small x.

  Leads to: $\boxed{S_V = -0.0027 \pm 0.0013}$

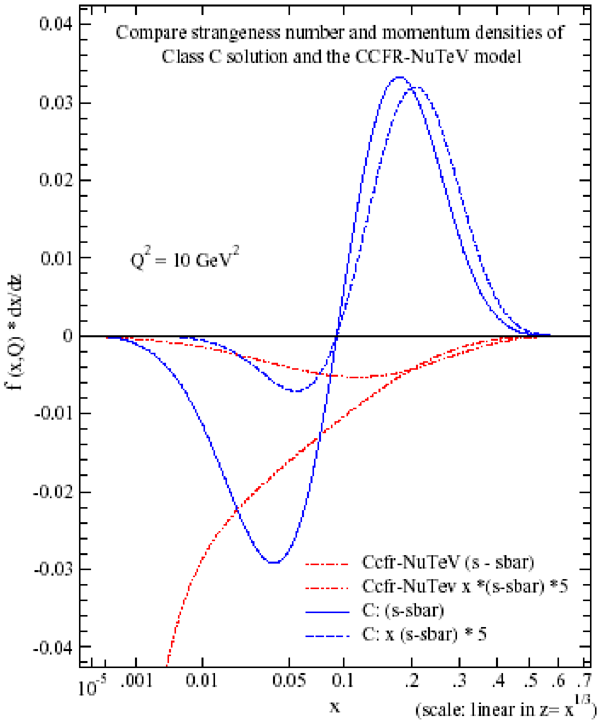
  Increases discrepancy in $\sin^2\theta_W \sim 3.7\sigma$.

- However, NuTeV fit:
  - Does not enforce $\langle\, s - \overline{s}\,\rangle = 0$ [normalization wrong]
  - Not a global fit of S_V [parton PDFs are **universal**]

- s-quark contrib'n can be resolved through expt'list $\leftrightarrow$ phenomenologist collaboration
  - Phenomenologists: experience in QCD analysis; extracting PDFs
  - dimuon X-sections would provide strongest constraints on global fits of $(s - \bar{s})$

CTEQ Analysis, Strange Quark Corrections

- Kretzer *etal*, [Lepton-Photon 03]:
  - Analyze CCFR, NuTeV dimuon data; NLO fit together with all PDFs.
  - : $s < \overline{s}$ for small x; qualitatively similar to NuTeV.
  - Strange parton normalization requires $s > \overline{s}$ for large x
  - This gives $S_V > 0$, reduces NuTeV anomaly



- Most reasonable range: $\boxed{0.001 < S_V < 0.003}$
  - CTEQ: **Strange quarks reduce NuTeV anomaly**
  - NuTeV: Re-analysis of dimuon data shows $S_V \approx 0$?

  [Following talk by Kretzer]

<u>Nuclear Shadowing Effects: Charged Leptons</u>

- μ/e beams: well established experimentally
- Small x, low Q^2: dominated by "VMD" Shadowing:
  $\gamma \to \rho$ fluctuations, ρ strongly absorbed
  (vector meson dominance [VMD]).
- Small x, high Q^2 (scaling region): Pomeron dominates shadowing.

<u>Nuclear Shadowing Effects: Neutrinos</u>

- ν_{CC} reactions: replace $\gamma^* \to W^*$ from EM shadowing
  low $Q^2, VMD_\gamma \to PCAC_W$
  [add'l contribution from axial mesons]
- ν_{NC} reactions: **very small** shadowing in NC processes
  [$Z^0 \to \rho^0$ coupling extremely small]

Nuclear Shadowing Effects: Miller/Thomas Estimate

- ν CC Reactions: propagating virtual W shadowed

  (extension of VMD: Boros/JTL/AWT PR **D58**, 114030 (98); **D59**, 074021 (99)).

- ν NC Reactions: essentially no shadowing

- $\overline{\nu}$ X-sections significantly smaller than ν X-sections

  (weaker coupling to valence quarks)

  $\Rightarrow$ Shadowing for $\overline{\nu} + Fe$ **larger** (relatively) than for $\nu + Fe$

- Assume: shadowing suppression of ν CC reactions $1/(1+\epsilon)$

  shadowing for $\overline{\nu}$ CC reactions $1/(1+\overline{\epsilon})$.

$$\delta R_{sh}^{PW} = \left(\frac{1}{2} - \sin^2\theta_W\right)\left[1 + \epsilon - \frac{r}{1-r}(\overline{\epsilon} - \epsilon)\right]$$

- NuTeV discrepancy in $\sin^2\theta_W$ could be accounted for by:

$$\boxed{0.005 \leq \ \epsilon \ \leq 0.01, \ 0.02 \leq \ \overline{\epsilon} \ \leq 0.04}$$

Nuclear Shadowing Effects: NuTeV Estimate

- VMD shadowing effects only very low Q^2 processes:

  very small fraction of NuTeV events.

- Shadowing will *increase* NC/CC ratio (by decreasing CC X-section).

  However, **both** R_ν and $R_{\overline{\nu}}$ ratios measured by NuTeV are smaller than anticipated.

- Nuclear shadowing tends to affect sea quark cross sections that contribute equally to ν and $\overline{\nu}$ X-sections.

- Shadowing is likely to *increase* the discrepancy between NuTeV and EM values for $\sin^2\theta_W$.

- Conclusion:

  shadowing effects unlikely to be significant

  in any event, shadowing unlikely to resolve anomaly.

Conclusions

⋆ **The NuTeV Anomaly**

- $\sin^2\theta_W$ value 3σ from best LEP value
- Significant difference from Weinberg angle obtained in atomic expt's, Moller scatt (?), EW measurements at Z pole

⋆ **$N \neq Z$ Corrections to NuTeV Measurement**

- "Isoscalar" correction: significant, but should be under control

⋆ **CSV Contributions to NuTeV Measurement**

- model calc'n: reduce NuTeV anomaly from $3\sigma \Rightarrow 2\sigma$.
- Theoretical arguments for sign, magnitude of CSV contribution.
- First phenomenological fits of parton CSV PDFs

⋆ **s Quark Contributions to NuTeV**:

- Proportional to $\boxed{S_V \equiv \langle x(s - \overline{s})\rangle}$ [$s, \overline{s}$ momentum asymmetry].
- Original NuTeV analysis: $S_V < 0$; increase NuTeV anomaly.
  - CTEQ: $S_V > 0$; decrease NuTeV anomaly.
  - NuTeV re-analysis: now obtain $S_V \sim 0$.

⋆ **Parton Shadowing Contributions to NuTeV**:

- Miller/Thomas: Decrease CC contrib'ns, fractionally larger effect for $\overline{\nu}$. Shadowing could be significant.
- NuTeV: Shadowing would increase R_ν, $R_{\overline{\nu}}$, but both smaller than expected

  Shadowing largest for sea quarks, but this cancels in PW ratio

  Possibility that shadowing would increase anomaly

⋆ **If $S_V > 0$, CSV + s quarks can remove much of NuTeV anomaly**.