Charge Symmetry of Parton Distributions

Charge Symmetry for Parton Distributions
Theoretical Estimates of parton CSV
Models for valence quark CSV
Experimental Evidence for parton charge symmetry
Including CSV in phenomenological PDFs
Possible tests of parton charge symmetry
Conclusions

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Charge Symmetry of Parton Distributions:

Charge symmetry = 180° rotation about “2” axis in isospin space

At the partonic level, **charge symmetry operation (CS)** corresponds to: \(u(x) \leftrightarrow d(x), \text{ and } p \leftrightarrow n\).

(a similar relation holds for antiquarks)

- At low energies, **CS generally valid to fraction of %**

- Until 2003, all phenomenological PDFs assumed charge symmetry (reduced # of PDFs by a factor of 2)

We know the origins of parton CSV:
- **quark mass difference**: \(\delta m \equiv m_d - m_u \sim 4 \text{ MeV}\)
- **Electromagnetic contributions**: most important EM effect:
  - **n-p mass difference**: \(\delta M \equiv M_n - M_p = 1.3 \text{ MeV}\)
Models for CSV in Parton Distributions

Violation of approximate symmetries: “window” $\rightarrow$ non-perturbative physics

Construct quark models that reproduce qualitative features of PDFs

Examine their behavior under charge symmetry operations

$$\delta m \equiv m_d - m_u; \quad \delta M \equiv M_n - M_p$$

$\rightarrow$ Predict sign, magnitude of parton charge symmetry violation

Important to disentangle CSV effects from isospin violation, flavor symmetry effects $\rightarrow$ dedicated experiments
Quantitative Estimates, Valence Parton CSV

Quark-model formula for valence parton PDFs:

\[ q_\nu(x) = \sum_X |\langle X|\psi_+(0)|N\rangle|^2 M \delta(M(1-x) - p_X - E_X) \]

\[ x = qq; 3q+q\bar{b}; 4q+2 q\bar{b}. \ldots \]

\[ \delta d_\nu(x) = d_\nu^p(x) - u_\nu^n(x) \approx \frac{\partial d_\nu}{\partial M} \delta M + \frac{\partial d_\nu}{\partial m} \delta m \]

Large \( x \): dominated by \( X=\)diquark states
Sather: study variation with nucleon, quark mass: analytic approximation
(appears as derivatives of valence parton distribution)

\[ \delta d_\nu(x) = -\frac{\delta M}{M} \frac{d}{dx}[x d_\nu(x)] - \frac{\delta m}{M} \frac{d}{dx} d_\nu(x) \]

\[ \delta u_\nu(x) = u_\nu^p(x) - d_\nu^n(x) = \frac{\delta M}{M} \left( -\frac{d}{dx}[x u_\nu(x)] + \frac{d}{dx} u_\nu(x) \right) \]

require \( \int \delta q_\nu(x) \, dx = 0 \) (normalization of total valence quarks)
Phenomenological Valence Parton CSV PDFs

MRST Phenomenological PDFs include CSV for 1st time:
Martin, Roberts, Stirling, Thorne (03):
Choose restricted form for parton CSV:

\[ \delta d^\nu(x) = -\kappa f(x) = -\delta u^\nu(x) \]
\[ f(x) = x^{-0.5}(1 - x)^4(x - 0.0909) \]

[f(x): 0 integral; matches to valence at small, large x]

Best fit: \( \kappa = -0.2 \), large uncertainty!
Best fit remarkably similar to model CSV predictions

\[-0.8 < \kappa < +0.65 \text{ within 90\% confidence}\]
Phenomenological Sea Parton CSV PDFs

MRST also included sea quark CSV term:
Again chose restricted form:

$$\bar{u}^n(x) = (1 + \delta)\bar{d}^p(x)$$
$$\bar{d}^n(x) = (1 - \delta)\bar{u}^p(x)$$

[approximately maintains momentum carried by sea]

Best fit: $\delta = +0.08$, surprisingly large!
(corresponds to 8% CS violation in sea)

- Minimum in $\chi^2$ substantially deeper than for valence
- Increase in $u^n$ sea $\rightarrow$ better fit to NMC $\mu$-D data
- Much better fit to E605 Drell-Yan data
Flavor Asymmetry in Quark Sea

NMC Expt (Amaudruz et al, PRL66, 2712 (91)): measured $F_2$ in $\mu$-p, $\mu$-D reactions

Constructed Gottfried Sum Rule $S_G$

$$S_G = \frac{<\frac{F_{2}^{\mu p} - F_{2}^{\mu n}}{x}>}{3} = \frac{2}{3} <\bar{d} - \bar{u}>$$

$$= 0.235 \pm 0.026 \Rightarrow <\bar{d} - \bar{u}> \approx 0.147 \pm 0.039$$

Strong evidence for flavor asymmetry in proton sea!

Drell-Yan Measurement of Flavor Asymmetry

• DY measurements for protons on p, D

$$\frac{\sigma_{DY}^{pD}}{2\sigma_{DY}^{pp}} \rightarrow \frac{1}{2} \left[ 1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)} \right]$$

• E866 Exp’t at FNAL: 450 GeV p on p, D targets

extract $\bar{d}/\bar{u}$ vs $x$ at $Q^2 \sim 54$ GeV$^2$

Incorporate E866 flavor asymmetry into global PDF’s

$$<\bar{d} - \bar{u}> \sim 0.101 \Rightarrow$$

too small for NMC $S_G$
Isospin Violation in Quark Sea

Previous Relations assumed isospin symmetry for PDF’s
Allowing parton charge symmetry violation

\[ S_G \rightarrow \frac{1}{3} - \frac{2}{3} < \bar{d} - \bar{u} > + \frac{8}{9} < \delta \bar{d} > + \frac{2}{9} < \delta \bar{u} > \]

Additional terms allow one to simultaneously fit NMC, E866 results

MRST Parameterization for CSV in parton sea

\[ \delta \bar{d}(x) \equiv -\bar{d}(x) \quad \delta \bar{u}(x) \equiv +\bar{u}(x) \]

\[ S_G \Rightarrow \frac{1}{3} - \frac{2}{3} \left(1 + \frac{\tilde{\delta}}{3}\right) < \bar{d} - \bar{u} > - \frac{2\tilde{\delta}}{3} < \bar{d} > \]

MRST: \( \tilde{\delta} = +0.08 \), improve agreement w/NMC in measured \( x \) region

[Unfortunately gives \( \infty \) value for \( S_G \) – change form for sea CSV]
Experimental Limits on parton CSV

- No Direct evidence for charge symmetry violation
- Strongest limits \( \rightarrow \) the “charge ratio”
- Compare \( F_2 \) structure functions from \( \nu, \) EM DIS

\[
R_c(x) \equiv \frac{F_2^{\gamma N_0}(x) + x(s(x) + \bar{s}(x) - c(x) - \bar{c}(x))}{5} \frac{F_2^{W N_0}(x)}{18} \\
\approx 1 + \frac{3x(\delta u(x) + \delta \bar{u}(x) - \delta d(x) - \delta \bar{d}(x))}{10Q(x)}
\]

\[
Q(x) \equiv \sum_{j=u,d,s} x \left[ q_j(x) + \bar{q}_j(x) \right]
\]

- \( F_2^{\gamma N_0} \) = \( F_2 \) structure function for charged lepton DIS on isoscalar target
- \( F_2^{W N_0} \) = average \( F_2 \) neutrino+ antineutrino CC DIS, isoscalar target

(sometimes called the “5/18 rule”)

Deviation of \( R_c \) from 1 \( \rightarrow \) evidence for CSV in parton PDFs
Experimental Measurements of Charge Ratio

Necessary to account for many experimental quantities

- Normalization between charged-lepton, $\nu$ DIS
- Isoscalar corrections $\rightarrow \nu$ DIS on iron targets
- Charm quark mass effects in $\nu$ reactions
- Nuclear effects in $\nu$ reactions
- Strange quark effects

CCFR/NMC (LO) analysis:
Agreement for $0.1 < x < 0.4$
Large errors for $x > 0.4$
(nuclear Fermi motion)
Apparent disagreement at small $x < 0.1$
Charge ratio: removal of low-x Discrepancy

Re-analysis of CCFR ν data

→ Agreement at low x;

Factors in re-analysis of data:
• Extraction of $\Delta x F_3$
• Charm threshold effects

Charm quark mass: “old” analysis
“slow rescaling” (Georgi/Politzer '76)
new NLO analysis → significant effects
at low x (no longer $Q^2$ independent)

\[
\frac{d^2\sigma^\nu}{dxdy} + \frac{d^2\bar{\sigma}^\nu}{dxdy} \sim 2(1 - y - y^2/2)\bar{F}_2(x) + (y - y^2/2)\Delta x F_3(x)
\]

\[
\Delta x F_3(x) \approx 2x(s + \bar{s} - c - \bar{c})
\]

Initial analysis: bin in x only; $\Delta x F_3$ calculated from phenom PDFs
Re-analysis: bin in x, y; separate both $F_2$, $\Delta x F_3 \neq$ phenom
Constraints on Parton Charge Symmetry Violation

1) charge ratio $R_c$ determined to $\sim 2-3\%$

$$\frac{\Delta q(x)}{Q(x)} = \frac{10}{3} (R_c(x) - 1)$$

$\rightarrow$ parton CSV determined to $\sim 6-9\%$ level (includes valence, sea CSV)

2) momentum carried by quarks determined to within $\sim 2\%$

(limits on valence CSV)

Momentum of valence partons:

$$\kappa = -0.2 \quad \text{(best value)}$$

$$|\frac{\Delta q}{Q}| = 0.5\%$$

All MRST valence, sea CSV in agreement with expt'l constraints:

$$-0.8 \leq \kappa \leq +0.65$$
CSV and The Paschos-Wolfenstein Ratio:

Neutrino Total Cross Sections on Isoscalar Target:

\[
R^\nu \equiv \frac{\sigma\langle \nu N_0 \rightarrow \nu X \rangle}{\sigma\langle \nu N_0 \rightarrow \mu X \rangle} = g_L^2 + r g_R^2
\]

\[
R^{\bar{\nu}} \equiv \frac{\sigma\langle \bar{\nu} N_0 \rightarrow \bar{\nu} X \rangle}{\sigma\langle \bar{\nu} N_0 \rightarrow \bar{\mu} X \rangle} = g_L^2 + \frac{1}{r} g_R^2
\]

\[
R^{PW} \equiv \frac{R^\nu - r R^{\bar{\nu}}}{1 - r} = \frac{\sigma\langle \nu N_0 \rightarrow \nu X \rangle - \sigma\langle \bar{\nu} N_0 \rightarrow \bar{\nu} X \rangle}{\sigma\langle \nu N_0 \rightarrow \mu X \rangle - \sigma\langle \bar{\nu} N_0 \rightarrow \bar{\mu} X \rangle} = \frac{1}{2} - \sin^2 \theta_W
\]

**Paschos/Wolfenstein**: Independent measurement of Weinberg angle

PW ratio → minimizes sensitivity to PDFs, higher-order corrections

**NuTeV**: different cuts, acceptances for \( R^\nu, R^{\bar{\nu}} \)

→ can’t simply construct PW ratio:

Monte Carlo procedure (errors differ from PW estimates!)
NuTeV Determination of Weinberg Angle:

- Construct ratios $R^\nu$, $R^{\bar{\nu}}$
- Individual ratios less dependent on overall normalization
  Very precise charged/neutral current ratios:
  - $R^\nu$: depends strongly on Weinberg angle
  - $R^{\bar{\nu}}$: weak dependence on Weinberg angle

\[
R^\nu = 0.3916 \pm 0.0013 \ [\text{SM: 0.3950}] \quad \text{3}\sigma \text{ from SM}
\]
\[
R^{\bar{\nu}} = 0.4050 \pm 0.0027 \ [\text{SM: 0.4066}] \quad \text{agree with SM}
\]

These ratios lead to a NuTeV value for the Weinberg angle:

\[
s^2_W = 0.2276 \pm 0.0013_{stat} \pm 0.0006_{syst} \pm 0.0006_{th} \\
\quad - 0.00003[M_t - 175] + 0.0032 \ln[M_H/100]
\]

The NuTeV result is $\sim 3\sigma$ above very precise value
(from EW processes at LEP)

\[
s^2_W = 0.2229 \pm 0.0004
\]

$\delta s^2_W = +0.0046$
Isospin Violating Corrections to PW Ratio:

Changes in PW ratio from isospin violating PDFs:

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

\[
\delta U_V \equiv \int_0^1 x \left[ u_V^p(x) - d_V^n(x) \right] \, dx; \quad \delta D_V \equiv \int_0^1 x \left[ d_V^p(x) - u_V^n(x) \right] \, dx
\]

PW Correction \(\rightarrow\) valence parton charge symmetry violation (CSV)

- CSV correction to PW ratio independent of \(Q^2\)

\[
\delta R_{CSV}^{PW} \sim \frac{\delta U_V - \delta D_V}{U_V + D_V}
\]

- Both numerator, denominator involve 2\textsuperscript{nd} moment of valence dist'ns
- numerator, denominator evolve identically with \(Q^2\)
- evaluate with quark models, low \(Q^2\) OK
CSV and Weinberg angle (MRST)

MRST determines valence CSV
\[-0.8 \leq \kappa \leq +0.65\]
- $\kappa = -0.6 \rightarrow$ completely removes Weinberg anomaly!
- $\kappa = +0.6 \rightarrow$ Weinberg anomaly twice as large!
- parton CSV can remove anomaly, without disagreeing with any high-E data
- CSV a viable candidate to explain NuTeV anomaly
  \rightarrow would produce **observable effects** ($\sim$ few %) in certain reactions
New Expt’s to Search for Charge Symmetry Violation??
Charge Symmetry Test: Pion Drell-Yan

Compare X-sections in pi-D DY processes (e.g., FNAL)

\[ \pi^\pm + D \rightarrow \mu^+ + \mu^- \]

Valence region, large \( x_\pi, x_N \)

\[ \pi^+ \sim u \bar{d} \quad \pi^- \sim d \bar{u} \]

\[ R \equiv \frac{4\sigma^{\pi^+D}_{DY} - \sigma^{\pi^-D}_{DY}}{\sigma^{\pi^-D}_{DY} - \sigma^{\pi^+D}_{DY}} \]

At large \( x_\pi \), significant cancellation, CSV terms dominate

- differences, limits of MRST CSV \( \sim 30\% \)
- (note: LO calculation)
- DY CS X-sections cancel to within few percent
- (normalize to \( J/\psi \) production)
- Old pi PDFs, measure these in same pi DY experiment

[Sutton et al, PR D45, 2349 (92)]
Charge Asymmetry in Semi-Inclusive Leptoprod’n

\[ e^+ D \rightarrow n^\pm + X \]
\[ \Delta(z) = \text{favored/unfavored fragmentation} \]
(favored \( u \rightarrow p^+ \); unfavored \( u \rightarrow p^- \))
\[ Y_{Dh} = \text{yield of hadron } h \text{ per scattering from } D \]

\[ R(x, z) = \left( \frac{1 - \Delta(z)}{1 + \Delta(z)} \right) \frac{4Y_{D\pi^-} - Y_{D\pi^+}}{Y_{D\pi^+} - Y_{D\pi^-}} \]
\[ \approx \frac{5(1 - z)}{2} + R_{CSV}(x) + R_{sea}(x, z) \]

Ratio of yields:
- large term depends only on \( z \); constant in \( x \)
- CSV term depends only on \( x \); relatively large for large \( x \)
- remaining (sea) term few % of other terms
- essential to map ratio of yields in both \( x, z \)
- could measure at future e-Collider (BNL, JLab) \( \rightarrow R \text{ Ent talk} \)
Charge Symmetry Test: W Charge Asymmetry

W Asymmetry in p-D collisions (e.g, RHIC)
\[ p + D \rightarrow W^{\pm} + X \]

If CS valid, then the favored W prod’n equal for W^{±}

\[ \overline{\sigma} \equiv \frac{d\sigma_{W^+}}{dx_F} + \frac{d\sigma_{W^-}}{dx_F} \]

\[ A(x_F) \equiv \frac{\overline{\sigma}(x_F) - \overline{\sigma}(-x_F)}{\overline{\sigma}(x_F) + \overline{\sigma}(-x_F)} \]

Substantial W charge asymmetry predicted
- relatively large sea quark CSV necessary \textit{(agree w/MRST)}
- don’t include s ≠ sbar contributions
- few % asymmetry for \( x_F \sim 0.5 \)
Conclusions:

- **Theoretical models** suggest magnitude, sign of valence parton CSV
- "Charge ratio" provides few % limits on magnitude of CSV
- **First phenomenological CSV PDFs** (MRST 03):
  - valence CSV – weak evidence, remarkable agreement w/models
  - sea CSV – roughly 8% effect; improved fit, NMC, E605 data
- "I-spin Corrections" to NuTeV measurement of $\sin^2 \theta_W$
  - at present, most likely single explanation of NuTeV anomaly
    - suggested experiments to measure CS violation
    - require excellent precision, must remove s quark effects
- New experiments → **new precision for partonic quantities**
  - (charge symmetry, strange quarks, sea)
The NuTeV Experiment: charged, neutral currents from neutrino DIS

800 GeV p at FNAL produce pi, K from interactions in BeO target; Decay of charged pi, K produces neutrinos, antineutrinos; Almost pure muon neutrinos; (small $\nu_e$ contamination from $K_{e3}$ decay) Only neutrinos penetrate shielding

Dipoles select sign of charged meson:
- Determine $\nu/\bar{\nu}$ type
- remove $\nu_e$ from $K_L$

NuTeV: Rochester/Columbia/FNAL/Cincinnati/Kansas State/Northwestern/Oregon/Pittsburgh neutrino collaboration
Separate Neutral, Charged-Current Events

NuTeV Detector: 18 m long, 690-ton steel scintillator; Steel plates interspersed with liq scintillator, drift chambers

NuTeV Events:
- 1.62 million $\nu$
- 351,000 $\bar{\nu}$

Charged current:
- Track through several plates
- Large visible energy deposit

Neutral current:
- Short visible track
- Large missing energy

NuTeV event selection:
- Large $E$ in calorimeter $20 < E_{\text{vis}} < 180$ GeV
- event vertex in fiducial volume

Charged current:
- Track through several plates
- Large visible energy deposit

Neutral current:
- Short visible track
- Large missing energy

NuTeV Events:
- 1.62 million $\nu$
- 351,000 $\bar{\nu}$
“New Physics” explanation for NuTeV?

The problem: extremely precise data confirms SM!
- Mass, width of Z, W
- X-sections, branching ratios at Z peak [LEP, SLD]
- LR and FB asymmetries in e⁺e⁻ scattering
- new particles must satisfy all these constraints
- EW constraints ~ 0.1% level [NuTeV ~ 1.2%]

Very little room for new physics!

NuTeV
“Designer Particles” I: delicately adjust to fit all existing data

- oblique corrections [high mass scale, couples only to vector bosons]: parameters constrained by EW data – can’t fit NuTeV

- extra $Z'$ (unmixed) – possible; may run into trouble with muon g-2
“Designer Particles” II: More Attempts to fit NuTeV

- minimal SUSY loops – No – *most have wrong sign*; others violate existing constraints

- Leptoquarks (bosons that couple to leptons & quarks): models with very carefully tuned mass splittings still possible – *could be tested at Tevatron, LHC* [Davidson, Gambino et al]

![MSSM, light sleptinos, gauginos](image1.png)

![Leptoquark (solid); extra gauge bosons (red)](image2.png)
“QCD Corrections” to the NuTeV Result:

( “Something Old”)

Isoscalar Effect (N ≠ Z for Fe)

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

\[ Q_v = \int_0^1 x q_v^p(x) \, dx \]

Depends only on 2\textsuperscript{nd} moment of light quark valence PDFs (momentum carried by up, down valence quarks)

Isoscalar correction to PW ratio:

\[ \delta R_I^{PW} = -0.0125 \]

NuTeV Isoscalar correction:

\[ \delta R_I^{NT} = -0.0080 \]

• NuTeV exp’t doesn’t evaluate PW ratio
• Isoscalar correction from Monte Carlo simulation of exp’t
• Although NuTeV significant difference from PW corr’n, under control
CSV Contribution to NuTeV Result:

Sather Expression for Valence Parton CSV. 

→ analytic result for 2nd moment!

\[
\delta D_V = \int x \left[ d^p_V(x) - u^m_V(x) \right] dx = \frac{\delta M}{M} D_V + \frac{\delta m}{M} > 0
\]

\[
\delta U_V = \int x \left[ u^p_V(x) - d^m_V(x) \right] dx = \frac{\delta M}{M} (U_V - 2) < 0
\]

PW Ratio CSV Corr’n using Sather:

Rodionov:  \( \delta R^{PW} = -0.0021 \)

Sather:  \( \delta R^{PW} = -0.0020 \)

CTEQ4LQ:  \( \delta R^{PW} = -0.0020 \)

NuTeV: **Don’t evaluate** PW Ratio!

CSV Contrib’n to NuTeV result:

- Calculate parton CSV at low (quark model) momentum scale
- Evolve up to \( Q^2 \) of NuTeV exp’t (20 GeV^2)
- Evaluate with NuTeV functional

\[
\delta R_{CSV}^{NT} \sim -0.0014
\]

40\% decrease in anomaly!

30\% decrease in anomaly
Limits on parton CSV
- charge ratio $R_c$
- momentum carried by valence CSV partons

Momentum of valence partons:
$$\kappa = -0.2 \quad \text{(best value)}$$
$$\left| \frac{\delta q}{Q} \right| = 0.5\%$$

All MRST valence CSV are in reasonable agreement with all expt’l constraints:

$\kappa = -0.8$ removes 100% of NuTeV anomaly:
**NuTeV seriously underestimates CSV error bars**
Strange Quark Contributions to PW Ratio:

Contribution from strange quarks:

\[
\delta R^\text{PW}_S = \delta \left( \sin^2 \theta_W \right) \approx \frac{-S_\nu}{U_\nu + D_\nu} \left[ 2\Delta_d^2 + 3(\Delta_d^2 + \Delta_u^2)\epsilon_c \right]
\]

\[
S_\nu = \int_0^1 x(s(x) - \bar{s}(x)) \, dx
\]

Strange quark normalization: constrained \( \int (s - \bar{s}) \, dx = 0 \)
(no net strangeness in nucleon)

If \( s \) quarks carry more momentum than \( \bar{s} \) bar \( \Rightarrow \) decrease anomaly

Determination of strange quark PDFs: **Opposite sign dimuons from neutrinos**

\( \nu \)
\( \bar{\nu} \)
\( \mu^- \)
\( \mu^+ \)
\( W^+ \)
\( s \)
\( c \)
\( s \)
\( \bar{s} \)
\( \bar{c} \)

- (charge of faster muon determines neutrino or antineutrino);
- most precise way to determine \( s, \bar{s} \) PDFs \( \rightarrow \) CCFR, NuTeV
CCFR-NuTeV: Analysis of s quark dist’n:

- Analyzed $s$, $\bar{s}$ for small $x$: $0 < x \leq 0.3$
- Best fit: $s - \bar{s} < 0$
- **Did not** enforce normalization condition $\langle s - \bar{s} \rangle = 0$

- But, from normalization:
  - If $s < \bar{s}$ for small $x$, requires $s > \bar{s}$ for large $x$

CTEQ: [Kretzer, Olness, Tung, Reno, ....]

- Global analysis of parton PDFs $\rightarrow$ CTEQ6
- Includes CCFR, NuTeV dimuon data
- (includes expt’l cuts on dimuons)
- Extract “best fit” for $s$, $\bar{s}$ dist’ns
  [enforce $s$ normalization cond’n]
Results: CTEQ Global fit vs. Bjorken x

positive [S⁻]

- CTEQ: S⁻ > 0, strange asymmetry decreases NuTeV anomaly;
- dimuon data: most sensitive for s PDFs
- CTEQ: s contrib’n removes \( \sim 30-50\% \) of anomaly

\( \chi^2 \)

1σ: \([S^-]\cdot100 \sim 0.17\)
NuTeV on Strange Quark Dist’n:

Re-analyzed dimuon data:
- preliminary analysis $[S^{-}] \sim 0$
- $s - \bar{s}$ crosses 0 twice
- strangeness not conserved
- “NuTeV” PDFs: not global fit

CTEQ global fit:
- global fit of PDFs
- fit to $\mu^{\pm}$ NuTeV data not as good?

CTEQ – NuTeV now working together:
new results at DIS04?
Nuclear Effects ??

NuTeV: All data neutrino DIS on iron

Nuclear modification of PDFs:

- **Shadowing**  
- **EMC Effect**  
- **Fermi motion ....**

Miller/Thomas: Shadowing effect for NuTeV??

charged leptons: $\gamma \rightarrow \rho$  
Vector meson dominance

$\nu$ CC events: $W \rightarrow \rho, \pi, a_2, ...$

$\nu$ NC events: $Z^0 \rightarrow \rho$

Miller/Thomas: $\nu$ shadowing very different from $\mu$

$Z^0$: very small coupling to $\rho \rightarrow$ NC shadowing $\sim 0$

Different shadowing for $R^\nu$, $R^{\bar{\nu}}$ → account for anomaly??

NuTeV: **NO!**  
- Shadowing low $Q^2$, data much higher $Q^2$
  
  - $R^{\bar{\nu}}$ value very close to SM value  
    (should be quite different in MT scenario)

Analysis of nuclear effects in $\nu$ reactions: Morfin et al

Shadowsing: increase NuTeV anomaly??

NuTeV use “own” PDFs
The Paschos-Wolfenstein Ratio:

\[ R^{PW} \equiv \frac{R^\nu - r R^\bar{\nu}}{1 - r} = \frac{\sigma(\nu N_0 \rightarrow \nu X) - \sigma(\bar{\nu} N_0 \rightarrow \bar{\nu} X)}{\sigma(\nu N_0 \rightarrow \mu X) - \sigma(\bar{\nu} N_0 \rightarrow \bar{\mu} X)} = \frac{1}{2} \sin^2 \theta_W \]

PW Ratio depends on the following assumptions:

- Isoscalar target (N=Z)
- include only u, d quarks
- neglect heavy quark masses
- assume isospin symmetry for PDFs
- no nuclear effects (parton shadowing, EMC, ....)
Qualitative Features, Valence Parton Distributions

Valence dist’n: at low $Q^2$, generate from quark models:

Remove quark from $N \rightarrow$ final state $X$; sum over all final states

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

$|X\rangle = 2q; 3q+q\overline{q}: 4q+ 2q\overline{q}$ ....

“Minority” valence quark

contribution from state $X$ produces a peak in $q_V(x)$ at $x \sim M_X / M$

large $x$ dominated by diquark contrib’n

$d_{N}^{p}$ residual (uu) diquark

100% spin 1 (Pauli principle)
“Majority” valence quark:

Spin dependence of diquark interaction:

\[ M_{S=0} \sim 600 \text{ MeV}; \quad M_{S=1} \sim 800 \text{ MeV} \]

(to reproduce N-\(\Xi\) splitting)

Thus, for “majority” valence quark,
\[ M_D \sim 700 \text{ MeV}; \quad \text{peak at} \]
\[ x = 1 - \frac{M_D}{M} \sim 0.27 \]

For “minority” valence quark,
\[ M_D \sim 800 \text{ MeV}; \quad \text{peak at} \]
\[ x = 1 - \frac{M_D}{M} \sim 0.12 \]

Quark model of proton structure: predicts up valence quark peak at substantially larger \(x\) than for down valence quark

Good quantitative agreement with exp’t (DGLAP evolution up to desired \(Q^2\))
Conclusions:

- **Theoretical models** suggest magnitude, sign of valence parton CSV

- **“Charge ratio”** provides few % limits on magnitude of CSV

- **First phenomenological CSV PDFs** (MRST 03):
  - valence CSV – weak evidence, remarkable agreement w/models
  - sea CSV – roughly 8% effect; significant improvement w/some data

- **“I-spin Corrections”** to NuTeV measurement of $\sin^2 \theta_W$ ??

  - suggested experiments to measure CS violation
  - require excellent precision, must remove s quark effects

- New experiments → **new precision for partonic quantities**
  (charge symmetry, strange quarks, sea)