Charge Symmetry for Parton Distributions
Phenomenological PDFs including CSV
Theoretical Estimates of parton charge symmetry
Experimental Constraints on parton CSV
CSV and neutrino reactions → the NuTeV anomaly
CSV and electron scattering → PV electron asymmetry
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 (CS) operation** corresponds to: \( u(x) \leftrightarrow d(x), \text{ and } p \leftrightarrow n \).

(a similar relation holds for antiquarks)

- **Nuclear physics** \( \rightarrow \) CS generally valid to fraction of %
  (in general, isospin effects \( \sim 3\% \))

- Until 2003, all phenomenological parton distribution functions (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**: one important EM effect:
  n-p mass difference \( \delta M \equiv M_n - M_p = 1.3 \text{ MeV} \)
Models for CSV in Valence PDFs

Violation of approximate symmetries: “window” → non-perturbative physics

Construct quark models that reproduce qualitative features of PDFs

Examine their behavior under charge symmetry operations

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

\[ \delta q_V \approx \frac{\partial q_V}{\partial m} \delta m + \frac{\partial q_V}{\partial M} \delta M \]

Quark models → predict sign, magnitude of valence parton charge symmetry violation

Important to disentangle CSV effects from other I-spin violation, flavor symmetry, “new physics” → dedicated experiments
Quantitative Estimates, Valence Parton CSV

Use quark-model wavefunctions for valence parton PDFs:

$$\delta q_V(x) \approx \frac{\partial q_V}{\partial m}\delta m + \frac{\partial q_V}{\partial M}\delta M$$

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

Sather [PL B274, 433 (92)]: study variation with nucleon, quark mass:
assume wavefunction invariant under CS;

**obtain analytic approximation**
(appears as derivatives of valence parton distribution)

$$\delta d_V(x) = d_P^V(x) - u^n_V(x) = -\frac{\delta M}{M} \frac{d}{dx} [x d_V(x)] - \frac{\delta m}{M} \frac{d}{dx} d_V(x)$$

$$\delta u_V(x) = u_P^V(x) - d^n_V(x) = \frac{\delta M}{M} \left( -\frac{d}{dx} [x u_V(x)] + \frac{d}{dx} u_V(x) \right)$$

require $$\langle \delta q_V \rangle = 0$$ (valence quark normalization)

Rodionov, Thomas, JTL [Int JModPhysLett A9, 1799 (94)]:
\rightarrow quark model CSV calculation;
accounted for quark p_T (neglected by Sather); yet,

CSV PDFs agree to within 20%
Phenomenological Parton CSV PDFs

MRST PDFs from global fits include CSV for 1st time:
Martin, Roberts, Stirling, Thorne [Eur Phys J C35, 325 (04)]:
Choose specific form for parton CSV:

\[
\delta d_V(x) = -\kappa f(x) = -\delta u_V(x) \\
\]
\[
f(x) = x^{-0.5} (1 - x)^4 (x - 0.0909)
\]

- \( f(x) \) has zero first moment (preserves valence quark norm)
- \( f(x) \) similar to valence PDFs at large, small \( x \)
- requires \( \delta d_v, \delta u_v \) equal & opposite (equal valence momentum for p, n)
- model dependent !!

Very shallow minimum found in global fit to HE data
Best fit: \( \kappa = -0.2 \), large uncertainty !
90% confidence limit: \(-0.8 \leq \kappa \leq +0.65\)
Note: MRST neglected \( Q^2 \) dep in global fit \( \rightarrow \)
important in estimates of CSV effects !!
CSV PDFs: Phenomenology & Theory

MRST PDFs → global fits including CSV:
Martin, Roberts, Stirling, Thorne [Eur Phys J C35, 325 (04)]:

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

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

90% conf limit (\( \kappa \))

Valence quarks

MRST (2004)

ADEL (1994)
"QED Splitting": a New Source of Isospin Violation

MRST, Eur.Phys.J. **39**, 155 (05); Glueck, Jimenez-Delgado, Reya, PRL**95**, 022002 (05)

"QED evolution", quark radiates photon
Evolve in $Q^2$

$$\frac{d}{d \ln Q^2} \delta q_V(x, Q^2) \sim \pm \frac{\alpha}{2\pi} P \otimes q_V$$

$$P(z) = (e_u^2 - e_d^2) \left( \frac{1 + z^2}{1 - z} \right) +$$

$$\delta u_V(x, Q^2) = \frac{\alpha}{2\pi} \int_{m_q^2}^{Q^2} d \ln q^2 \int_x^1 \frac{dy}{y} P \left( \frac{x}{y} \right) u_V(y, q^2)$$

- correct to lowest order in $\alpha_{\text{QED}}$
- qualitatively similar to quark model CSV
- QED varied while quarks “frozen”
- contributes even if $m_u = m_d$ and $M_n = M_p$
- evolve from $m_q$ to $Q$
- for $m_q^2 < q^2 < Q_0^2$, Glueck “freeze” quark PDFs
- ($Q_0^2 = \text{GRV starting scale for QCD evolution}$)
CSV Effects arising from “QED Splitting”:

MRST, Eur.Phys.J. 39, 155 (05); Glueck et al., PRL 95, 022002 (05)

\[
\frac{d}{d\ln Q^2} \delta q_V(x, Q^2) = \pm \frac{\alpha}{2\pi} P \otimes q_V
\]

\[
P(z) = (e_u^2 - e_d^2) \left( \frac{1 + z^2}{1 - z} \right)
\]

- **add to** quark model CSV term
- **increase CSV ~ factor 2**
- MRST incorporate QED splitting with PDFs in global fit to high energy data
- Glueck: CSV effects relatively large at high x

![Graph showing CSV effects](image)
Experimental Limits on parton CSV

- **No direct evidence** for charge symmetry violation in PDFs
- Strongest limits \(\rightarrow\) the "charge ratio"
- Compare \(F_2\) structure functions from \(\nu\), EM DIS

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

\[
Q(x) \equiv \sum_j x \left[ q_j(x) + \bar{q}_j(x) \right]
\]

\(F_2^{\gamma N_0}\) = \(F_2\) structure function for charged lepton DIS on isoscalar target

\(F_2^{\gamma W N_0}\) = 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 PDFs
Experimental Measurements of Charge Ratio

Recent experiments provide unprecedented precision

- Best comparison: NMC mu-D DIS; CCFR nu-Fe CC DIS
- Many corrections must be made in comparison

CCFR/NMC (LO) analysis:
Agreement for $0.1 < x < 0.4$
Large errors for $x > 0.4$
(nuclear Fermi motion)

(apparent disagreement $x < 0.1$ → removed on re-analysis)

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

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

→ parton CSV upper limit
at $\sim 6-9 \%$ level
(includes valence, sea CSV)
Direct Tests of Parton CSV

- Note: no serious limits established for $x \geq 0.4$
- **Any** direct measurement for $x \geq 0.4$ would be new
- For $x > 0.4$, current results $\geq 6\%$ on $R_c$
- This translates to $20\%$ (or larger) limit on CSV
Neutrino DIS: 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

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

NuTeV Events:
• 1.62 million $\nu$
• 351,000 $\bar{\nu}$
CSV in Neutrino Reactions:

the Paschos-Wolfenstein Ratio:

Neutrino Total Cross Sections on Isoscalar Target:

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

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

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

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

PW ratio \( \Rightarrow \) minimizes sensitivity to PDFs, higher-order corrections

**NuTeV expt**: nu, nubar total X-sections (CC, NC) on Fe target

(weak decays of pi, K from 800 GeV protons at FermiLab)

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

\( \rightarrow \) 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

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

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

\[
\begin{align*}
\sin^2 W & = 0.2276 \pm 0.0013_{\text{stat}} \pm 0.0006_{\text{syst}} \pm 0.0006_{\text{th}} \\
& \quad - 0.00003[M_t - 175] + 0.00032 \ln[M_H/100]
\end{align*}
\]

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

\[
\begin{align*}
\sin^2 W & = 0.2229 \pm 0.0004 \\
\delta \sin^2 W & = +0.0046
\end{align*}
\]
Explanations for NuTeV Anomaly ??

✓ “New Physics” – many expt’s at Z mass extremely precise
  “new particles” difficult to simultaneously fix NuTeV, leave LEP results unchanged

✓ Radiative Corrections” to NuTeV result?? unlikely but new calculation → need to include in re-analysis

✓ strangeness (diff in momentum carried by s, sbar) possible, NuTeV, CTEQ now agree

✓ parton CSV? at present, most plausible single explanation for NuTeV anomaly

✓ nuclear effects (shadowing, EMC effect)? unlikely – calculations show effect < 20%
Charge Symm Violating Corrections to NuTeV:

Changes in PW ratio from isospin violating PDFs:

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

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

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

- quark models: remove 1\(\sigma\) of NuTeV effect
- "QED splitting": also remove 1\(\sigma\) of NuTeV effect
- Phenomenology (MRST): can remove 100% of NuTeV effect  
  (or make the effect twice as big)

\(\rightarrow\) CSV sufficiently large to remove NuTeV anomaly would produce observable effects in certain reactions
CSV Contribution to NuTeV Result:

Sather: derived analytic approx’n for CSV PDFs:

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

CSV contrib’n to PW relation \(\sim 2^{nd}\) moment of CSV PDFs
Sather \(\rightarrow\) analytic result for \(2^{nd}\) moment! [JTL/AWT PRD67, 111901 (03)]

\[
\delta D_\nu = \int x \left[ d_\nu^p(x) - u_\nu^n(x) \right] dx = \frac{\delta M}{M} D_\nu + \frac{\delta m}{M} > 0
\]
\[
\delta U_\nu = \int x \left[ u_\nu^p(x) - d_\nu^n(x) \right] dx = \frac{\delta M}{M} (U_\nu - 2) < 0
\]

- analytic expressions for CSV contributions: 'model-indep' ??
- easily see that \(\delta D_\nu > 0\), \(\delta U_\nu < 0\)
- CSV removes \(\sim 1/3\) of NuTeV anomaly
- QED CSV contribution removes another 1/3 of anomaly
- Best theoretical estimate CSV accounts for \(\sim 2/3\) of NuTeV
Strange Quark Contributions to PW Ratio:

Contribution from strange quarks:

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

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

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

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

Determination of strange quark PDFs: \textbf{Opposite sign dimuons from neutrinos}

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

• Analyze s, sbar production:
  • NuTeV $\rightarrow$ separate nu, nubar beams
  • Important to enforce normalization condition $\langle s - \bar{s} \rangle = 0$

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, sbar 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 ~ up to 30% of anomaly [at $1\sigma$, consistent with 0]

$1\sigma: [S^-] \cdot 100 \sim 0.17$
NuTeV on Strange Quark Dist’n:

Re-analyzed dimuon data:
- sensitive to point where $\bar{s} - \bar{s}$ crosses 0
- now consistent with CTEQ

CTEQ – NuTeV new results:
Mason etal, PRL 99, 192001 (07)
Now agrees with CTEQ!
New Expt’s to Search for Charge Symmetry Violation ??

- PV electron scattering *
- pi-D Drell-Yan Reactions
- SIDIS e-production of pions
- Charge asymmetry in W production

Note: every experiment has significant challenges (searching for small effect)
CSV Contribution to PV Asymmetry

PV asymmetry in e-D scattering [Hobbs/Melnitchouk PRD77, 114023 (08)]

\[ A_{PV}^{e-D} \sim -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha} \left[ a_1^d + f(y) a_3^d \right] ; \]

\[ f(y) = \frac{1 - (1 - y)^2}{1 + (1 - y)^2} ; \]

\[ a_1^d = \frac{6g_A^e}{5} (2g_V^u - g_V^d) ; \]

\[ a_3^d = \frac{6g_V^e}{5} (2g_A^u - g_A^d) . \]

We have assumed the following (Melnitchouk talk):

- neglected small corrections to \( f(y) \)
- large \( x > 0.3 \), dominated by valence quark PDFs
- use tree-level couplings for a coefficients
CSV Contribution to PV Asymmetry

Lowest-order CSV corrections

\[ a_1^d \rightarrow a_1^{d(0)} + \delta(CSV) a_1^d \]
\[ a_3^d \rightarrow a_3^{d(0)} + \delta(CSV) a_3^d \]

\[ \frac{\delta(CSV) a_1^d}{a_1^{d(0)}} = \left[ -\frac{3}{10} + \frac{2g_u^u + g_v^d}{2(2g_u^u - g_v^d)} \right] \frac{\delta u(x) - \delta d(x)}{u(x) + d(x)} \]
\[ \frac{\delta(CSV) a_3^d}{a_3^{d(0)}} = \left[ -\frac{3}{10} + \frac{2g_A^u + g_A^d}{2(2g_A^u - g_A^d)} \right] \frac{\delta u(x) - \delta d(x)}{u(x) + d(x)} . \]

In these expressions,
• largest term is 3/10 \( \rightarrow \) comes from denominator
• **CSV terms can be estimated from MRST global fits**
• appear as combination \( \delta u(x) - \delta d(x) \)
• since these are opposite sign, should add
Predicted CSV with MRST PDFs

- uncertainty in MRST CSV PDFs \( \rightarrow \) limits on CSV in PV e-D asymmetry
- asymmetry grows slowly with increasing \( x \)
- at \( x = 0.6 \), CSV asymm \( \sim 2\% \) for \( Q^2 = 5 \, \text{GeV}^2 \), and 3% for \( Q^2 = 10 \, \text{GeV}^2 \)
- need to be able to measure asymmetry to within 2%
- Note - for \( x > 0.8 \), Fermi motion effects become significant (Melnitchouk)
Prospects for Measuring PDF CSV Effects:

- Can parton CSV be measured in PV DIS asymm at 11 GeV JLab?

- **QED + QCD models**: valence parton CSV asymm a few % at large $x$

- Asymm measurements at the 1% level could see effect (assuming validity of MRST + QCD calculations!)

- Can this be interpreted as CSV? Probably not by itself (uncertainty in $d/u$ - need to combine D, H measurements; higher-twist effects, “new physics” could also contribute)

- Fermi motion effects set in at very large $x$

- Likely to set stronger upper limits on partonic CSV

- Any “direct” measurement, even upper limits, for large $x$ would be unique (current limits highly indirect)
Conclusions:

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

✓ “Charge ratio” → few % limits on magnitude of CSV, $x \leq 0.4$

✓ “QED splitting” → new I-spin violating ($Q^2$ dependent) effect

✓ **First phenomenological CSV PDFs** (MRST 04):
  - valence CSV – weak evidence, remarkable agreement w/models
  - sea CSV – roughly 8% effect; improved fit, NMC, E605 data
  - $\sin^2 \theta_W$

✓ “I-spin Corrections” to NuTeV measurement of
  - (most likely single explanation of NuTeV anomaly)

  - dedicated experiments to measure CS violation
  - need excellent precision, dedicated experiments; difficult!

✓ **PVDIS exp’t** → possibly test CSV at large $x$
  - (limits of MRST CSV PDFs → large enough to test?)