Partonic Charge Symmetry: Spin-dependent and Independent Parton Distribution Functions

Tim Londergan
Physics Dept and CEEM, Indiana Univ
Pacific Spin Conf Cairns
June 20-25, 2011

Supported by NSF PHY- 0854895
With Tony Thomas (JLab), Dave Murdock (Tenn Tech)

Partonic Charge Symmetry: Spin-dependent and Independent Parton Distribution Functions

Charge Symmetry for Parton Distributions
Theoretical Estimates of parton charge symmetry violation
Searching for CSV at high Q^2
Spin-dependent parton CSV
Testing Quark Model predictions with lattice QCD
Conclusions

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Charge Symmetry of Parton Distributions:

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

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

(a similar relation holds for antiquarks)

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

(a similar relation holds for antiquarks)

- **Nuclear physics** → CS generally valid to fraction of %
  (in general, isospin effects ~ 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:

o quark mass difference: $\delta m \equiv m_d - m_u \sim 4 \text{ MeV}$

o Electromagnetic contributions: one important EM effect:

n-p mass difference $\delta M \equiv M_n - M_p = 1.3 \text{ MeV}$

Experimental Limits on parton CSV

- **No direct evidence** for charge symmetry violation in PDFs
- Strongest expt'l upper limit → the **"charge ratio"**
- Compare **F_2 structure functions** from ν, EM DIS

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$$R_c(x) \equiv \frac{F_2^{\gamma N_0}(x) + x(s(x) + \bar{s}(x) - c(x) - \bar{c}(x))/6}{5\,\overline{F_2}^{W N_0}(x)/18}$$

$$\approx 1 + \frac{3x\left(\delta u(x) + \delta\bar{u}(x) - \delta d(x) - \delta\bar{d}(x)\right)}{10Q(x)}$$

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

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

$\overline{F}_2^{W\, N_0}$ = average F_2 neutrino+ antineutrino CC DIS (isoscalar target)

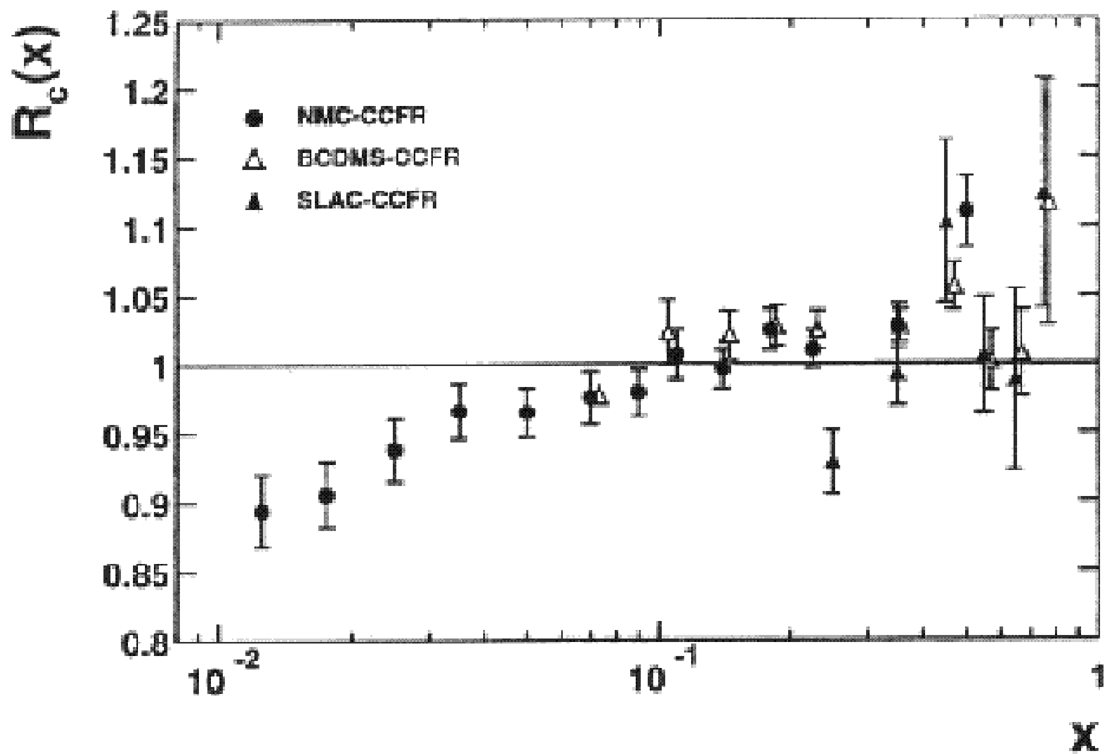
(sometimes called the **"5/18 rule"**)

Deviation of R_c from 1 → **evidence for CSV in PDFs**

Experimental Measurements of Charge Ratio

Latest experiments provide unprecedented precision

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



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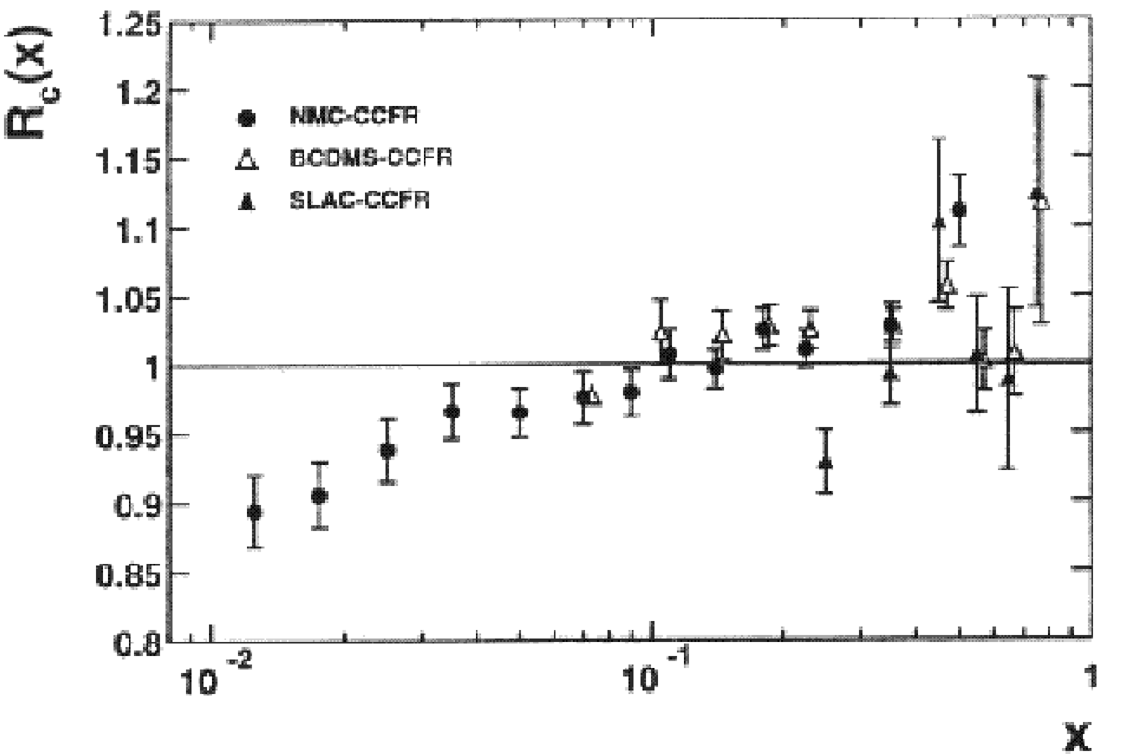
CCFR/NMC (LO) analysis:
Agreement for **0.1 < x < 0.4**
large errors for x > 0.4
(nuclear Fermi motion)

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

1) ratio R_c ~1 to ~ 2-3 %

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

→ parton CSV upper limit
at ~ 6-10 % level
(includes valence, sea CSV)



Models for CSV in Valence PDFs

In absence of direct experimental evidence,
we must rely on **models** for estimates of partonic CSV

Construct quark models that reproduce
qualitative features of PDFs

Examine their behavior under charge symmetry operations

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Examine their behavior under charge symmetry operations

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

$$\delta q_{\mathrm{V}} \approx \frac{\partial q_{\mathrm{V}}}{\partial m}\,\delta m + \frac{\partial q_{\mathrm{V}}}{\partial M}\,\delta M$$

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:

$$\delta q_{\mathrm{V}}(x) \approx \frac{\partial q_{\mathrm{V}}}{\partial m}\delta m + \frac{\partial q_{\mathrm{V}}}{\partial M}\delta M$$

$$q_{\mathrm{V}}(x) = \sum_X |\langle X|\psi_+(0)|N\rangle|^2 \, M \, \delta(M(1-x)-p_X-E_X)$$

Sather [PL B**274**, 433 (92)]: study variation with nucleon, quark mass:

assume wavefunction invariant under CS;

analytic approximation in static quark model

(appears as derivatives of valence parton distribution)

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$$\begin{aligned}
\delta d_{\mathsf{V}}(x) &= d^p_{\mathsf{V}}(x) - u^n_{\mathsf{V}}(x) = -\frac{\delta M}{M}\frac{d}{dx}[x d_{\mathsf{V}}(x)] - \frac{\delta m}{M}\frac{d}{dx}d_{\mathsf{V}}(x) \\
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require $\langle \delta q_{\rm V}\rangle = 0$ (valence quark normalization)

Rodionov, Thomas, JTL [Int J Mod Phys Lett **A9**, 1799 (94)]:

→ quark model CSV calculation;

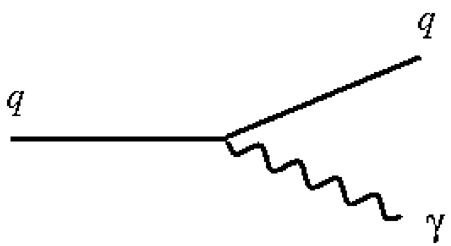
accounted for quark p_T (neglected by Sather); yet,

CSV PDFs agree to within 20%

“QED Splitting“: another Source of I-spin 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



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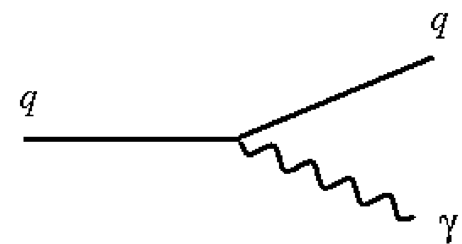

$$\frac{d}{d\,lnQ^2}\,\delta q_V(x,Q^2) \sim \pm\frac{\alpha}{2\pi}P\otimes q_V$$

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

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

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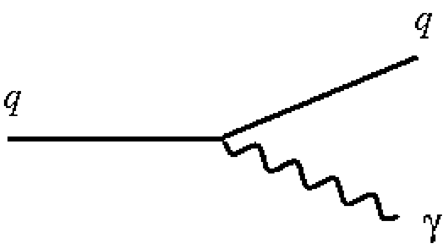

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- correct to lowest order in α_{QED}
- qualitatively similar to quark model CSV
- QED varied while quarks "frozen"
- contributes even if $m_u = m_d$ and $M_n = M_p$
- evolve from m_q to Q
- for $m_q^2 < q^2 < Q_0^2$, Glueck "freeze" quark PDFs
- (Q_0^2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

CSV Effects arising from "QED Splitting":

MRST, Eur.Phys.J. **39**, 155 (05);
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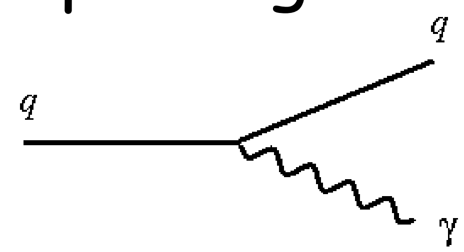

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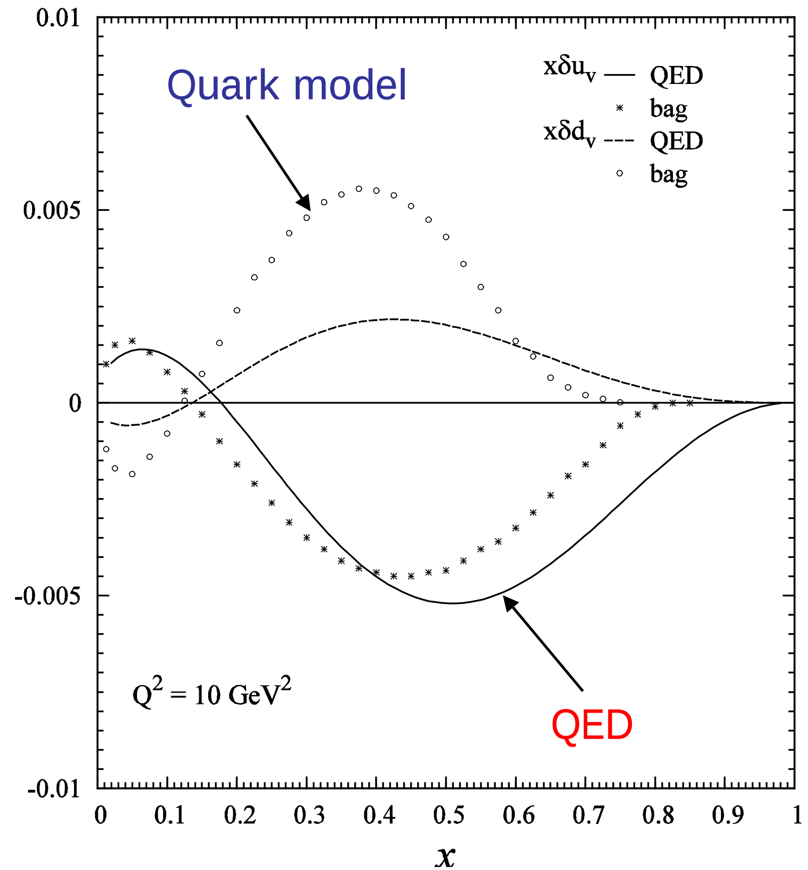
Glueck results:



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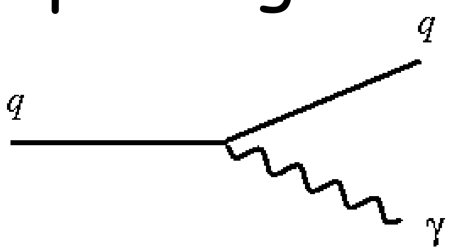

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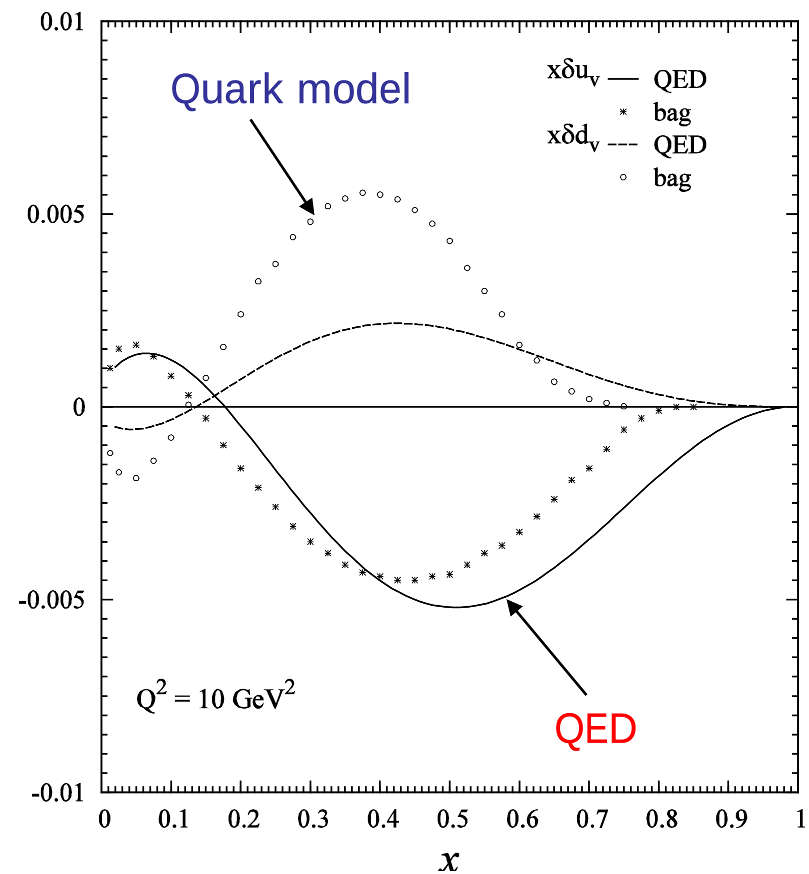
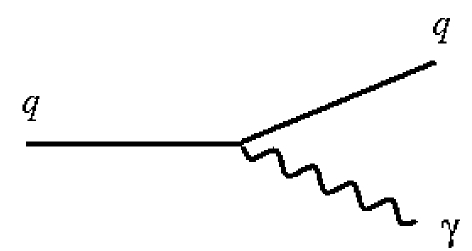


- **add to** quark model CSV term →
- **increase CSV ~ factor 2**
- MRST incorporate QED splitting with PDFs in global fit to high energy data
- Glueck: CSV effects relatively large at high x

CSV effects grow as Q^2 increases

(relative to non-CSV parton dist'ns)



With increasing Q^2, parton distributions radiate gluons, lose momentum:
DGLAP QCD evolution equations

$$\frac{\partial u^-(x,\mu^2)}{\partial \ln \mu^2} = \frac{\alpha_S}{2\pi} P_{qq} \otimes u^-$$

$$\frac{\partial d^-(x,\mu^2)}{\partial \ln \mu^2} = \frac{\alpha_S}{2\pi} P_{qq} \otimes d^-$$

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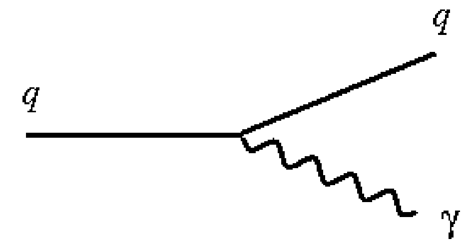

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$$q^{\pm}(x) = x\left[q(x) \pm \bar{q}(x)\right],$$

$$\delta u(x) = u^p(x) - d^n(x),$$

$$\delta d(x) = d^p(x) - u^n(x).$$

- CSV distributions $\delta u^-(x) = u^-(p) - d^-(n)$
- to lowest order gluon radiation **cancels for CSV evolution**
- valence PDFs shift to lower x with increasing Q^2
- valence CSV PDFs: **significantly slower shift to low x**
- CSV/(non-CSV) ratio: **slow (logarithmic) increase with Q^2**

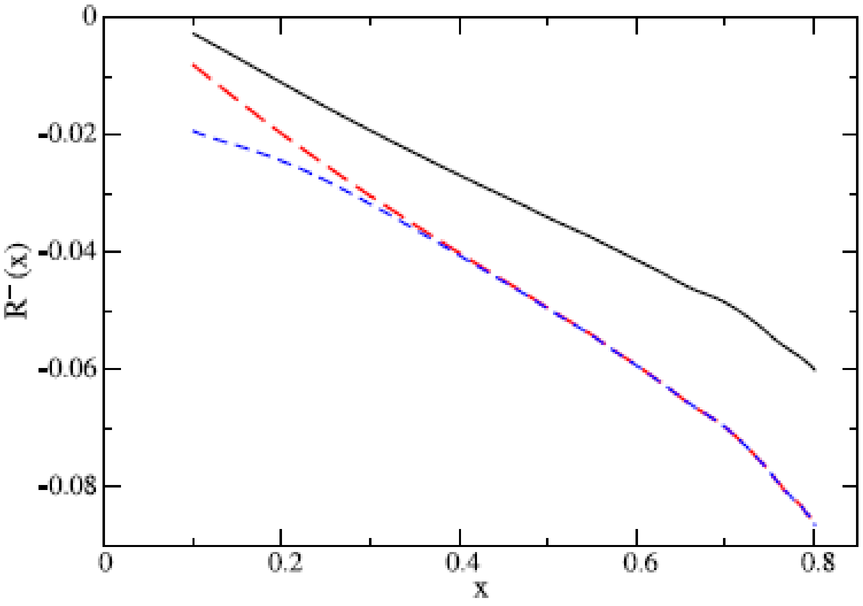
CSV effects grow with increasing Q^2

e^+, e^- collisions with p, D

(Hobbs, JTL, Murdock, AWT, PLB698, 123 (11)

$$R^-(x) \equiv \frac{2(F_2^{W^-D}(x) - F_2^{W^+D}(x))}{F_2^{W^-p}(x) + F_2^{W^+p}(x)}.$$

$$R^-(x) = \frac{x[-2s^-(x) + \delta u^-(x) - \delta d^-(x)]}{x[u^+(x) + d^+(x) + s^+(x) + 2c(x)]}$$



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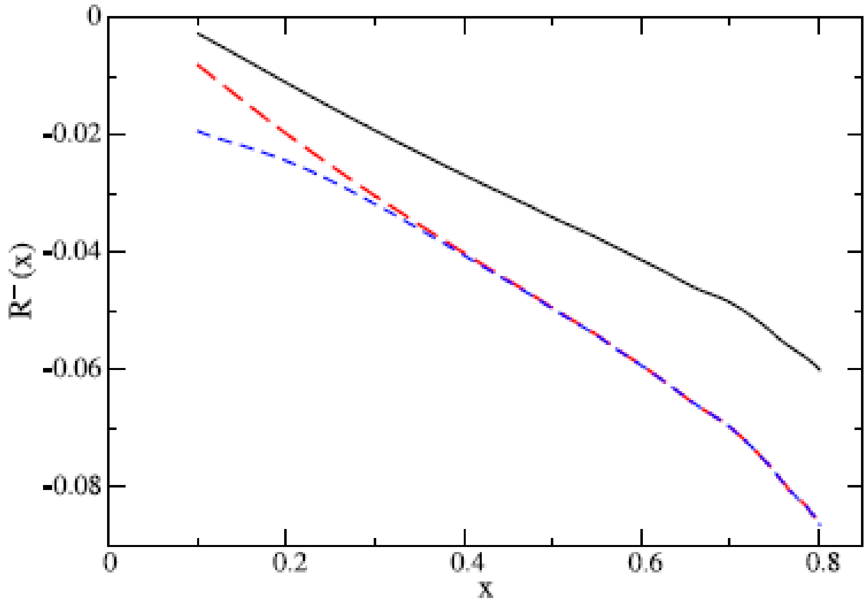

- $Q^2 = 10^5$ GeV^2 (could be accessed w e-collider at LHC)
- red dashed curve: CSV due to **quark mass + QED splitting**
- blue dashed curve: includes also strange quarks
- CSV contribution: **several % for x > 0.4**
- typical CSV effects at lower $Q^2 \leq 1\%$ effects

Spin-dependent parton distributions

- Leader/Sidorov/Stamenov [PR **D75**, 074027 (07)]:
- construct spin-dependent PDFs in terms of unpolarized

$$x\Delta f(x,\mu^2) = N_f A_f x^{a_f}\, x f(x,\mu^2)$$

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We took MRST2001 for the unpolarized distributions;
Leader/Sidorov/Stamenov normalize so that 1st moments of spin distributions obey

$\Delta U^- = +0.926, \ \Delta D^- = -0.341$

(from expt'l data + new measurements from CLAS and COMPASS)

We use same distributions as Leader etal for polarized PDFs

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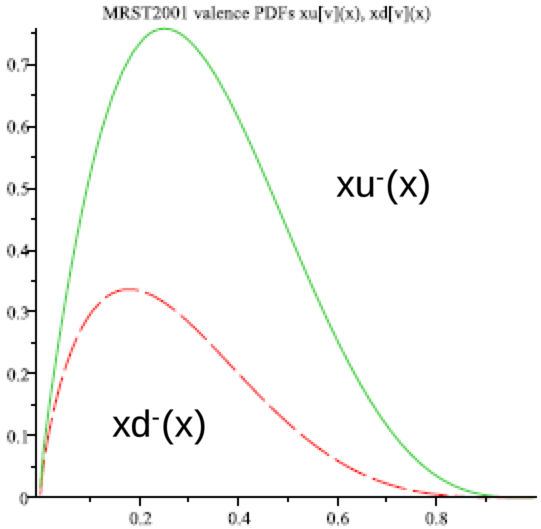

unpolarized (MRST2001)

Parton distributions at starting scale (Q_0^2 = 1 GeV^2)

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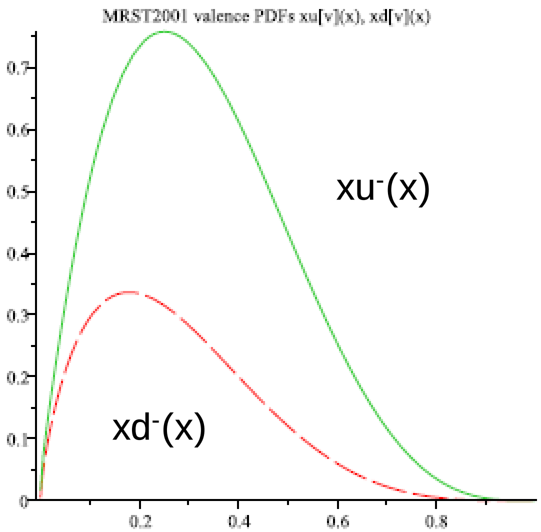

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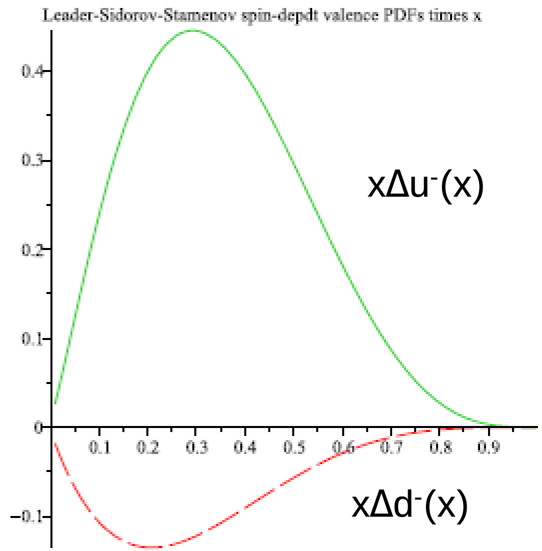

polarized (Leader)

Parton distributions at starting scale (Q_0^2 = 1 GeV^2)

Spin-dependent parton CSV distributions

- To obtain spin CSV distributions, we use the static quark model result of Sather, applied now to spin distributions:

obtain CSV spin distributions in terms of spin PDFs:

$$\Delta d^-_{CSV}(x) = -\frac{\delta M}{M}\frac{d}{dx}\left[x\Delta d^-(x)\right] - \frac{\delta\widetilde{m}}{M}\frac{d}{dx}\Delta d^-(x)$$

$$\Delta u^-_{CSV}(x) = \frac{\delta M}{M}\left(-\frac{d}{dx}\left[x\Delta u^-(x)\right] + \frac{d}{dx}\Delta u^-(x)\right)$$

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Using the spin-dependent parton distributions of Leader/Sidorov/Stamenov, we can obtain spin CSV PDFs using the static quark approx’n of Sather: here δM = n-p mass difference and δm = uu-dd diquark mass difference

Since Leader polarized PDFs (from MRST2001 unpolarized) are analytic, can differentiate analytically at starting Q^2 value

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From this equation the 2nd moment of spin CSV PDFs can be obtained analytically, as a function of moments of the polarized distributions:

$$\left(\Delta U^-_{(2)}\right)_{CSV} = \frac{\delta M}{M}\left(\Delta U^-_{(2)} - \Delta U^-_{(1)}\right) ,$$
$$\left(\Delta D^-_{(2)}\right)_{CSV} = \frac{\delta M}{M}\Delta D^-_{(2)} + \frac{\delta\widetilde{m}}{M}\Delta D^-_{(1)}$$

RHS = 1st + 2nd moments of spin distributions;

LHS = 2nd moment of CSV spin distribution

(valid at quark model starting scale)

2^{nd} moment of spin-dep't parton CSV distributions

- Integrating the static quark approximation of Sather,

$$\left(\Delta U^-_{(2)}\right)_{CSV} = \frac{\delta M}{M}\left(\Delta U^-_{(2)} - \Delta U^-_{(1)}\right) \; ,$$
$$\left(\Delta D^-_{(2)}\right)_{CSV} = \frac{\delta M}{M}\,\Delta D^-_{(2)} + \frac{\delta\widetilde{m}}{M}\Delta D^-_{(1)}$$

From the Leader etal spin PDFs we obtain moments

$\Delta U^-_{(1)} = 0.926$, $\Delta U^-_{(2)} = 0.210$;
$\Delta D^-_{(1)} = -0.341$, $\Delta D^-_{(2)} = -0.057$.

This leads to the CSV results
$(\Delta U^-_{(2)})_{CSV} = -9.93 \times 10^{-4}$; $(\Delta D^-_{(2)})_{CSV} = -1.53 \times 10^{-3}$.

2^{nd} moment of spin-dep't parton CSV distributions

We obtain

$$(\Delta U^{-}_{(2)})_{CSV} = -9.93 \times 10^{-4}; \quad (\Delta D^{-}_{(2)})_{CSV} = -1.53 \times 10^{-3}\ .$$

- These are very small numbers!
- spin CSV 2^{nd} moments are the same sign
  (for spin PDFs, 2^{nd} moments have opposite sign)
- Although Δd is smaller than Δu, 2^{nd} moment of spin CSV $(\Delta d)_{csv}$ is larger than $(\Delta u)_{csv}$.

Calculating polarized CSV distributions

- Using the Sather static quark approximation, we can in principle calculate polarized CSV spin distributions:

$$\Delta d^-_{CSV}(x) = -\frac{\delta M}{M}\frac{d}{dx}\left[x\Delta d^-(x)\right] - \frac{\delta\widetilde{m}}{M}\frac{d}{dx}\Delta d^-(x)$$

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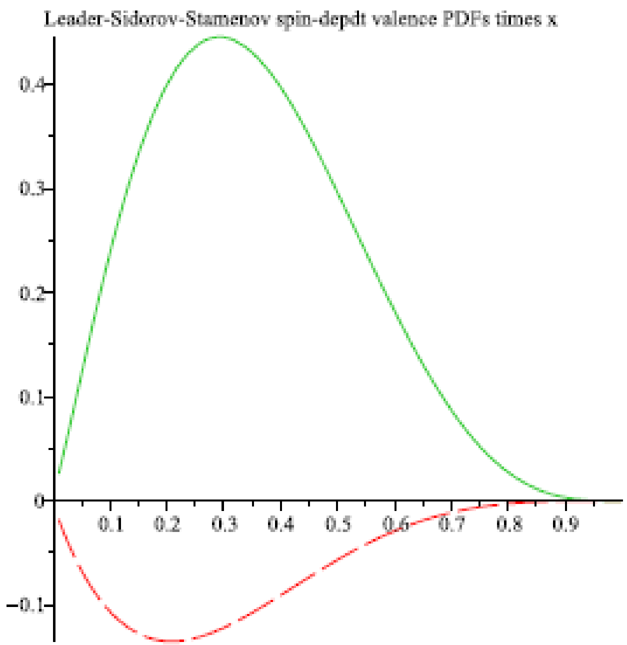
But we encounter a problem: phenomenological parton PDFs blow up at small x [q(x) ~ $x^{-0.25}$, x → 0].
This is due to Regge behavior at very small x; this is also the case for Leader spin PDFs.

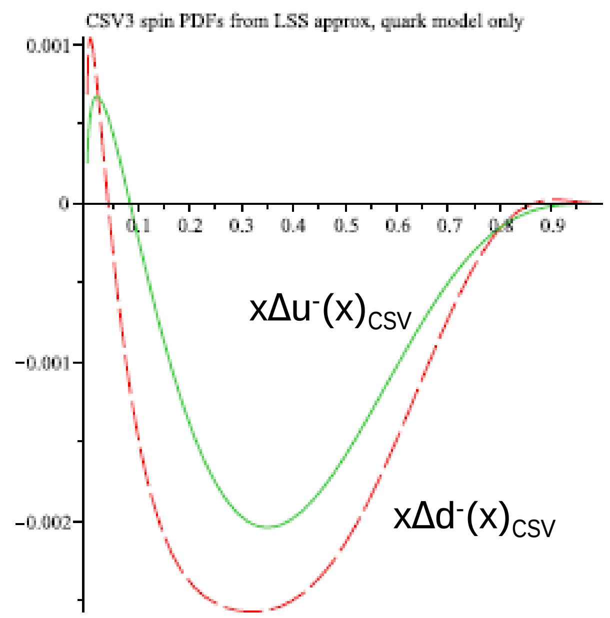
Thus, Sather equations using phenomenological spin distributions will produce unacceptable low-x CSV PDFs.
[Quark model wavefunctions do not possess Regge low-x behavior]

Calculating polarized CSV distributions

- If we use Sather equations to obtain spin CSV distributions from polarized spin PDFs, we need to "regularize" the low-x behavior of the spin PDFs.
- The resulting CSV spin PDFs will retain some dependence on the low-x regularization procedure



valence spin PDFs

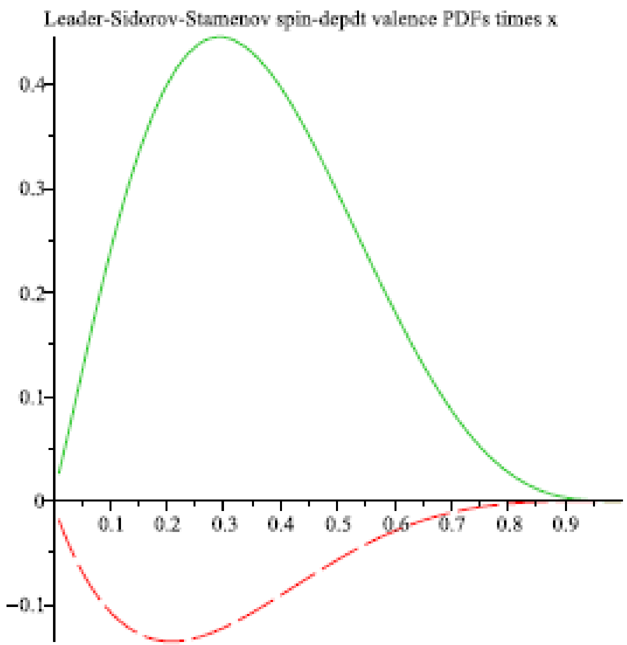


CSV spin PDFs using one "regularization" procedure for low-x behavior of polarized PDFs.

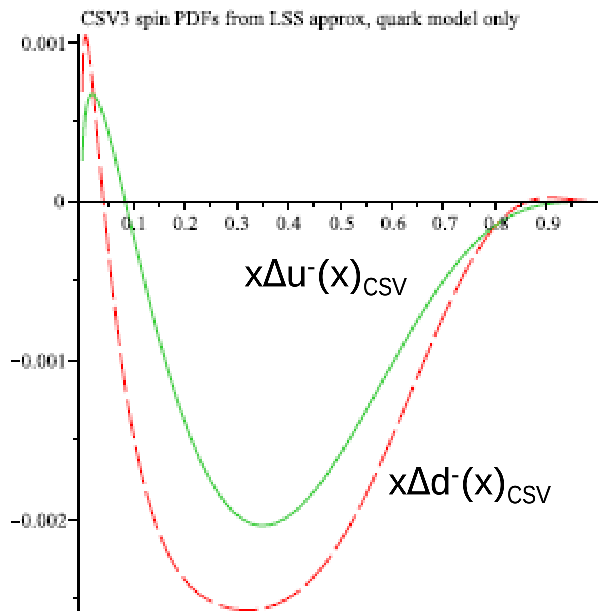
Features of polarized CSV distributions

- spin CSV distributions Δu^-_{CSV} and Δd^-_{CSV} have same sign
  (unpolarized CSV dist'ns have opposite sign)

- Although $\Delta d^-(x)$ is substantially smaller than $\Delta u^-(x)$,
  Δd^-_{CSV} is actually larger than Δu^-_{CSV}



valence spin PDFs



CSV spin PDFs using one "regularization" procedure for low-x behavior of polarized PDFs.

Lattice Calculation of Parton CSV Effects

(with J. Zanotti & A.W. Thomas)

Calculating polarized CSV distributions (in progress);
Review how this works for unpolarized PDFs.

(Horsley etal, PR **D83**, 051501 (2011))
Want to measure:

$$\delta u^- = \langle x \rangle^p_{u^-} - \langle x \rangle^n_{d^-}$$

$$\delta d^- = \langle x \rangle^p_{d^-} - \langle x \rangle^n_{u^-}$$

Lattice Calculation of Parton CSV Effects

(Horsley etal, PR **D83**, 051501 (2011))
Want to measure:

$$\delta u^- = \langle x \rangle^p_{u^-} - \langle x \rangle^n_{d^-}$$

$$\delta d^- = \langle x \rangle^p_{d^-} - \langle x \rangle^n_{u^-}$$

Make calculations about the SU(3) flavor symmetric limit $m_s = m_l$

consider small fluctuations about the charge-symmetric point

compare "doubly-represented" quarks (u in p and Σ^+, s in Ξ^0)

and "singly-represented" quarks (d in p, s in Σ^+, u in Ξ^0)

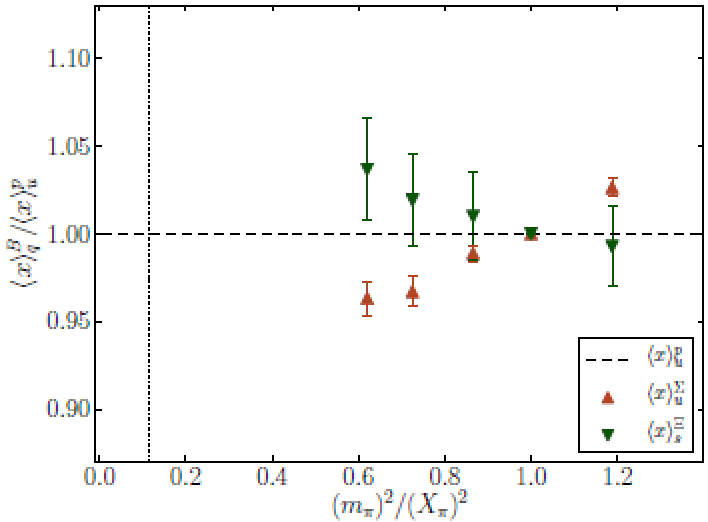


FIG. 1. Ratio of doubly represented quark momentum fractions, $\langle x \rangle^\Sigma_u / \langle x \rangle^p_u$ and $\langle x \rangle^\Xi_s / \langle x \rangle^p_u$ as a function of m_π^2/X_π^2, where we have determined X_π from the masses in Tab. I.

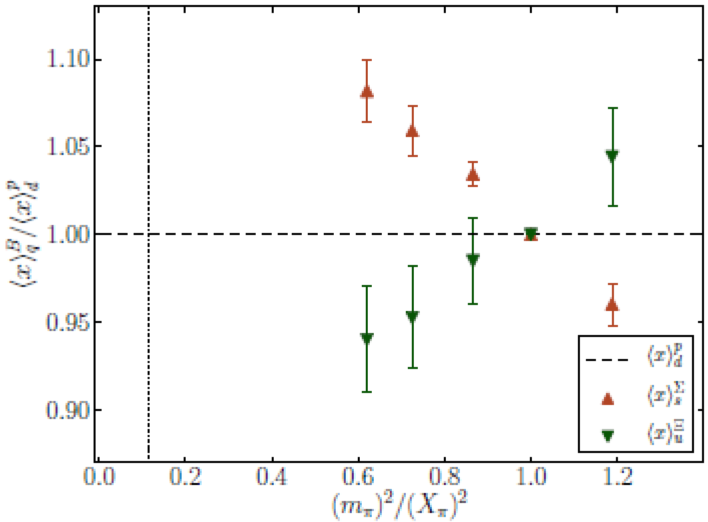


FIG. 2. Ratio of singly represented quark momentum fractions, $\langle x \rangle^\Sigma_s / \langle x \rangle^p_d$ and $\langle x \rangle^\Xi_u / \langle x \rangle^p_d$ as a function of m_π^2/X_π^2, where we have determined X_π from the masses in Tab. I.

Lattice Calculation of Partonic CSV

(Horsley etal, PR **D83**, 051501 (2011))

Partonic CSV for light quarks given by:

where $m_\delta = m_d - m_u$

$$\delta u = m_\delta \frac{\langle x \rangle_u^{\Sigma^+} - \langle x \rangle_s^{\Xi^0}}{m_s - m_l}\,, \quad \delta d = m_\delta \frac{\langle x \rangle_s^{\Sigma^+} - \langle x \rangle_u^{\Xi^0}}{m_s - m_l}\,.$$

Lattice: **$\delta u^+ = -0.0023\ (6)$, $\delta d^+ = +0.0020\ (3)$**

Lattice Calculation of Partonic CSV

(Horsley etal, PR **D83**, 051501 (2011))

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Lattice: **$\delta u^+ = -0.0023$ (6), $\delta d^+ = +0.0020$ (3)**

Compare with quark model calculations (Rodionov etal, Mod Phys Lett **A9**, 1799 (94))

$\delta u^- = -0.0014$, $\delta d^- = +0.0015$

Sign, magnitude of lattice in good agreement with quark model theory:
Lattice results 30-50% larger than quark model values.

(**caution:** lattice measures "+" components, rather than "-")

Conclusions:

- ✓ **Theoretical models** suggest magnitude, sign of valence parton CSV
- ✓ CSV arises from quark mass diff's, **"QED splitting"**
- ✓ **Ratio of CSV/(non-CSV) PDFs** should increase with Q^2
  (could measure at e-collider at LHC, several % effect)
- ✓ "I-spin Corrections" to NuTeV measurement of
  (most likely single explanation of NuTeV anomaly)
- ✓ **Calculations of spin CSV PDFs:**
  Use same approximations as for spin-independent case
  First calculations of sign, magnitude of spin CSV PDFs
- ✓ **Lattice calculations of CSV:**
  Results published for spin-independent case
  Lattice calculations underway for spin CSV PDFs

Additional Slides

The NuTeV Anomaly

Weak mixing angle claimed 3σ above standard model result
How to interpret this? Corrections?

Possible "New Physics" beyond the Standard Model?

look at most likely possible new particles
can any remove the NuTeV anomaly?

Normal ("QCD") Explanations of NuTeV Anomaly?

nuclear corrections (N ≠ Z effects)
parton charge symmetry violation
strange quark momentum asymmetry

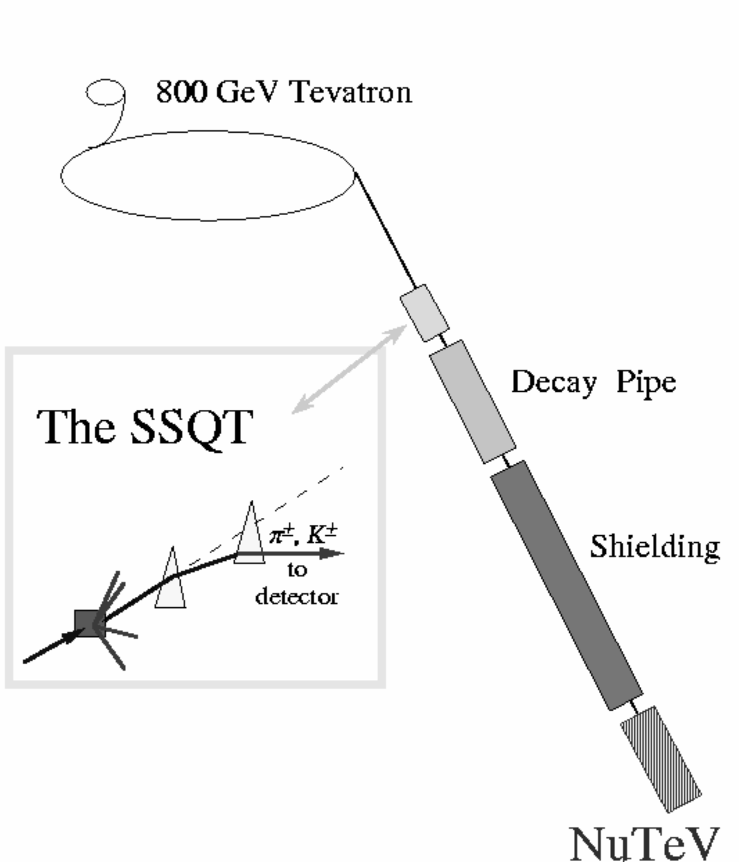
Which explanations seem most plausible?

quantitative evaluation of QCD corrections

Conclusion –

QCD corrections remove the NuTeV anomaly
(still some uncertainties)

Neutrino DIS: the NuTeV Experiment:
charged, neutral currents from neutrino DIS



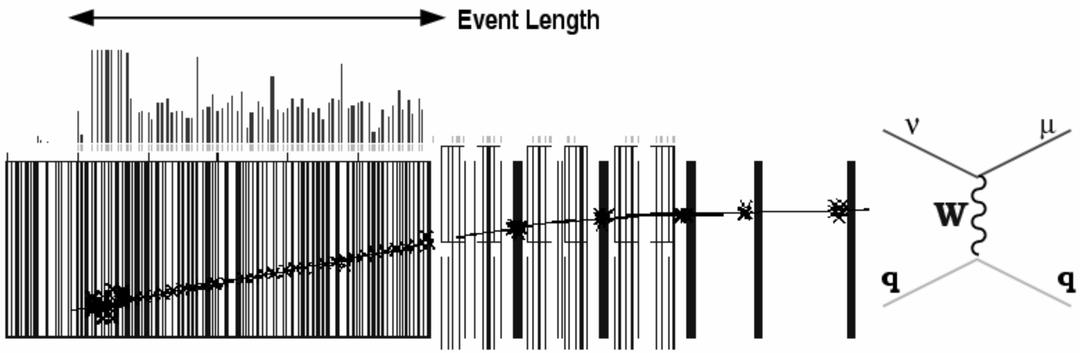
800 GeV p at FNAL produce pi, K from interactions in BeO target;
Decay of charged pi, K produces neutrinos, antineutrinos;
Almost pure muon neutrinos;
(small ν_ε contamination from K_{e3} decay)
Only neutrinos penetrate shielding

Dipoles select sign of charged meson:
- Determine nu/nubar type
- remove ν_e from K_L

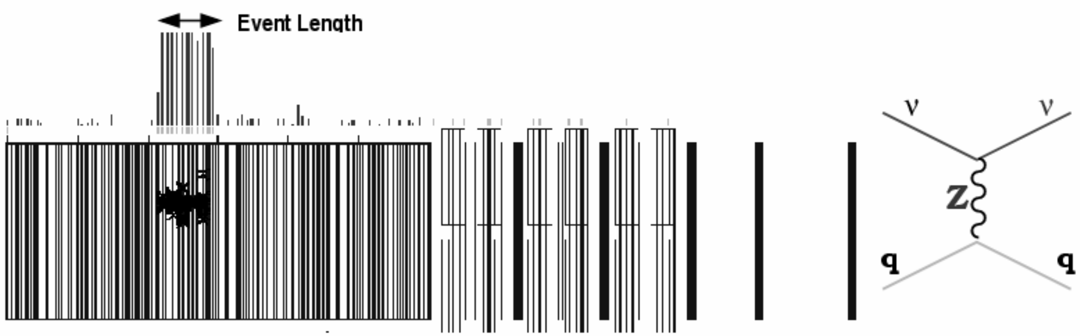
NuTeV: Rochester/Columbia/FNAL/Cincinnati/Kansas State/Northwestern/Oregon/Pittsburgh neutrino collaboration

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 Events:
- 1.62 million ν
- 351,000 $\overline{\nu}$

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

CSV in Neutrino Reactions:

the Paschos-Wolfenstein Ratio:

Neutrino Total Cross Sections on Isoscalar Target:

$$R^{\nu} \equiv \frac{\sigma\langle \nu\, N_0 \longrightarrow \nu\, X\rangle}{\sigma\langle \nu\, N_0 \longrightarrow \mu\, X\rangle} = g_L^2 + r\, g_R^2$$

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

$$r \equiv \frac{\sigma\langle \overline{\nu}\, N_0 \longrightarrow \overline{\mu}\, X\rangle}{\sigma\langle \nu\, N_0 \longrightarrow \mu\, X\rangle}$$

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

Paschos/Wolfenstein: Independent measurement of Weinberg angle
PW ratio → 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 $R^{\nu}, R^{\overline{\nu}}$
→ can't simply construct PW ratio:
Monte Carlo procedure (errors differ from PW estimates)

NuTeV Determination of Weinberg Angle:

- Construct ratios $R^{\nu}, R^{\overline{\nu}}$
- Individual ratios less dependent on overall normalization

Very precise charged/neutral current ratios:

- R^{ν} : depends strongly on Weinberg angle
- $R^{\overline{\nu}}$: weak dependence on Weinberg angle

$$R^{\nu} = 0.3916 \pm 0.0013\,[\mathrm{SM} : 0.3950]$$ ← **3σ from SM**

$$R^{\overline{\nu}} = 0.4050 \pm 0.0027\,[\mathrm{SM} : 0.4066]$$ ← **agree with SM**

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

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

The NuTeV result is **~ 3 σ above very precise value** (from EW processes at LEP)

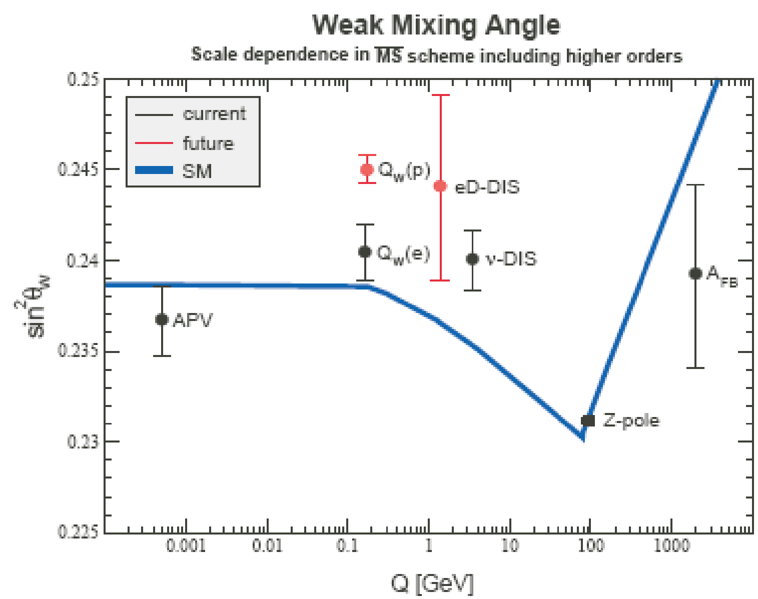
$$s_W^2 = 0.2229 \pm 0.0004$$

$$\delta\, s_W^2 = +0.0046$$

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:

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

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

PW Correction → valence parton **charge symmetry violation (CSV)**

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

→ 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:

$$\delta d_V(x) = d_V^p(x) - u_V^n(x) = -\frac{\delta M}{M}\frac{d}{dx}[x d_V(x)] - \frac{\delta m}{M}\frac{d}{dx} d_V(x)$$

$$\delta u_V(x) = u_V^p(x) - d_V^n(x) = \frac{\delta M}{M}\left(-\frac{d}{dx}[x u_V(x)] + \frac{d}{dx} u_V(x)\right)$$

CSV contrib'n to PW relation ~ 2nd moment of CSV PDFs

Sather → analytic result for 2nd moment! [JTL/AWT PRD**67**, 111901 (03)]

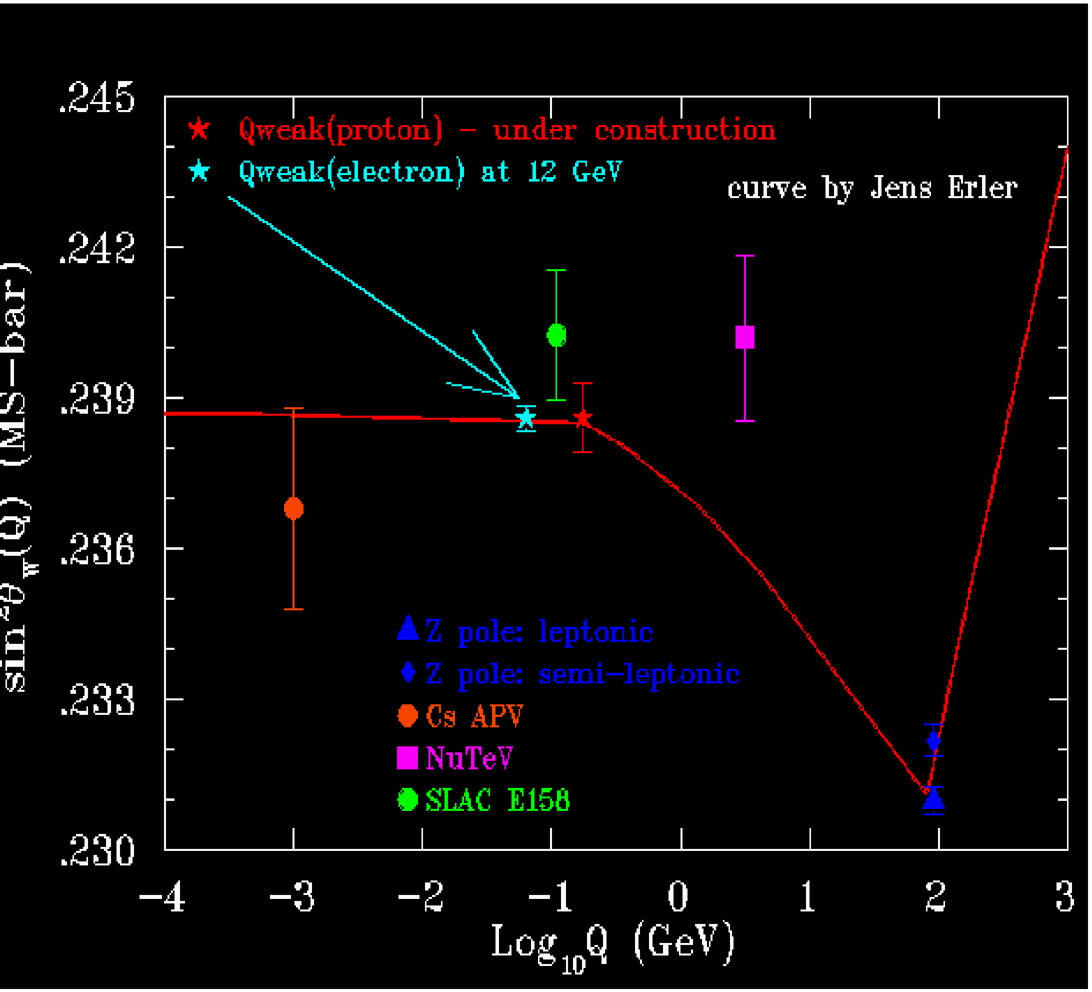
$$\delta D_V = \int x \left[d_V^p(x) - u_V^n(x)\right] dx = \frac{\delta M}{M} D_V + \frac{\delta m}{M} \quad > 0$$

$$\delta U_V = \int x \left[u_V^p(x) - d_V^n(x)\right] dx = \frac{\delta M}{M}(U_V - 2) \quad < 0$$

- analytic expressions for CSV contributions: **'model-indep'** ??
- easily see that $\delta D_V > 0, \ \delta U_V < 0$
- CSV removes ~ 30% of NuTeV anomaly
- QED CSV contribution removes another 30% of anomaly
- Best theoretical estimate CSV accounts for 60% of NuTeV

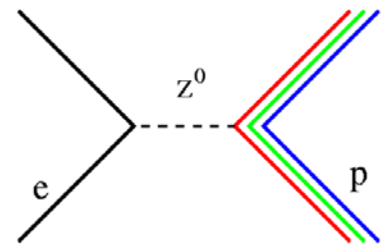
Running of the Weak Mixing Angle

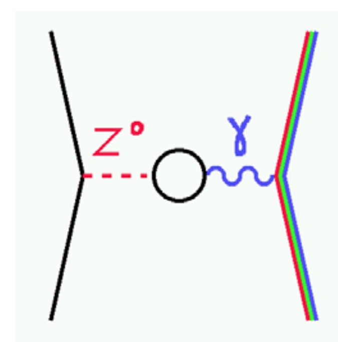
(Before Re-assessment)



CS APV, PRL**82** 2484 (‘99)
E158 Møller, PRL**95** 081601 (‘05)
NuTeV, PRL**88** 091802 (‘02)
LEP, e^+e^- at Z pole

Erler, Kurylov, Ramsey-Musolf
PR **D68** 016006 (‘03)



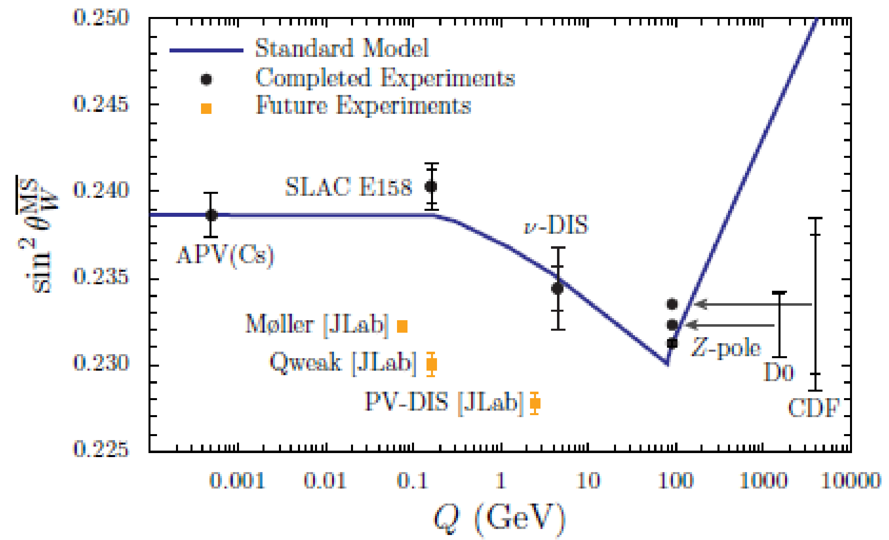


All prior expt’s clearly demonstrate the running.
The NuTeV result is an “outlier” (3σ).

Reassessment: NuTeV weak mixing angle

NuTeV corrections include:

- Isovector-vector field correction for Fe (40%)
- CSV effects (60%)
- strange quark asymmetry
- Note: **all** effects of same sign!



- inner error bars = statistical uncertainty
- outer errors = total uncertainty
- weak mixing angle now **in excellent agreement** with best running curve
- can be easily re-calculated if s quark asymmetry changes
- Note: APV point has changed upon theoretical re-analysis

Bentz, Cloet, JTL, AWT, Phys Lett **B693**, 462 (2010)

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 PRD**77**, 114023 (08)]

$$
\begin{aligned}
A_{PV}^{e-D} &\sim -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[a_1^d + f(y) a_3^d\right] \ ; \\
f(y) &= \frac{1-(1-y)^2}{1+(1-y)^2} \ ; \\
a_1^d &= \frac{6 g_A^e}{5}(2g_V^u - g_V^d) \ ; \\
a_3^d &= \frac{6 g_V^e}{5}(2g_A^u - g_A^d) \ .
\end{aligned}
$$

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

$$
\begin{aligned}
a_1^d &\rightarrow a_1^{d(0)} + \delta^{(CSV)} a_1^d \ , \\
a_3^d &\rightarrow a_3^{d(0)} + \delta^{(CSV)} a_3^d \ ; \\
\frac{\delta^{(CSV)} a_1^d}{a_1^{d(0)}} &= \left[-\frac{3}{10} + \frac{2g_V^u + g_V^d}{2(2g_V^u - g_V^d)} \right] \frac{\delta u(x) - \delta d(x)}{u(x) + d(x)} \ ; \\
\frac{\delta^{(CSV)} a_3^d}{a_3^{d(0)}} &= \left[-\frac{3}{10} + \frac{2g_A^u + g_A^d}{2(2g_A^u - g_A^d)} \right] \frac{\delta u(x) - \delta d(x)}{u(x) + d(x)} \ .
\end{aligned}
$$

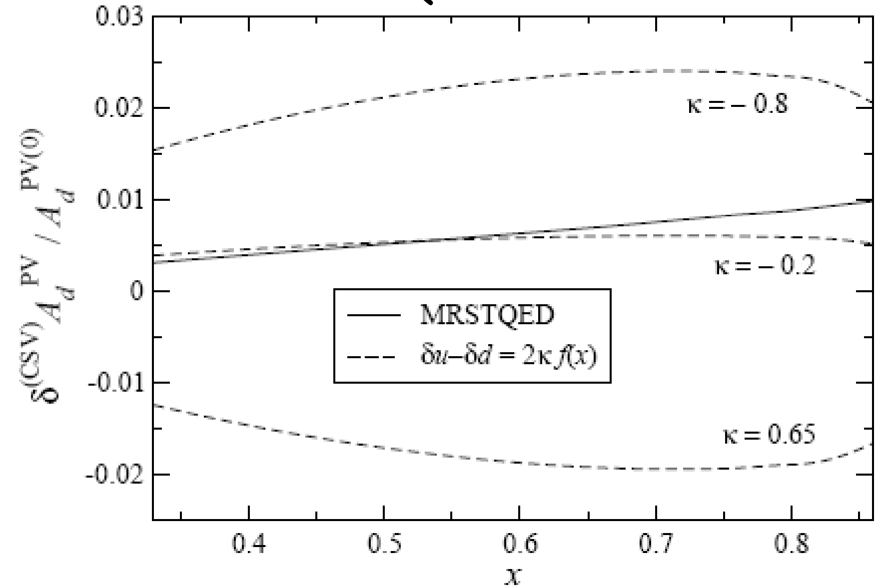
In these expressions,

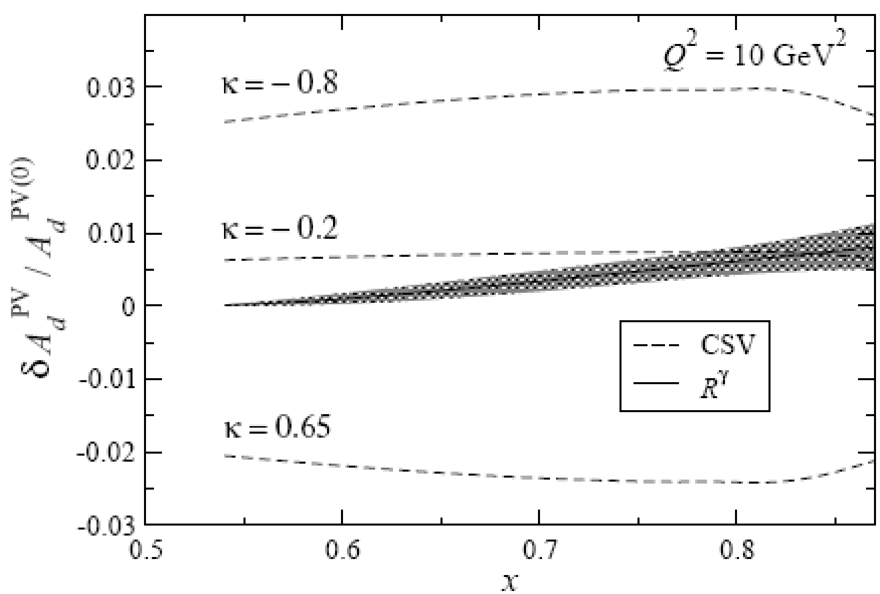
- largest term is 3/10 → comes from denominator
- **CSV terms can be estimated from MRST global fits**
- appear as combination $\delta u(x) - \delta d(x)$
- since these are opposite sign, should add

Predicted CSV with MRST PDFs

- uncertainty in MRST CSV PDFs → limits on CSV in PV e-D asymmetry
- asymmetry grows slowly with increasing x
- at x= 0.6, CSV asymm ~ 2% for Q^2 = 5 GeV^2, and 3% for Q^2 = 10 GeV^2
- need to be able to measure asymmetry to within 2%
- Note – for x > 0.8, Fermi motion effects become significant (Melnitchouk)

Q^2 = 5 GeV^2





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
- ✓ "I-spin Corrections" to NuTeV measurement of $\sin^2\theta_W$
  (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?)

Phenomenological Parton CSV PDFs

MRST PDFs from global fits include CSV for 1st time:

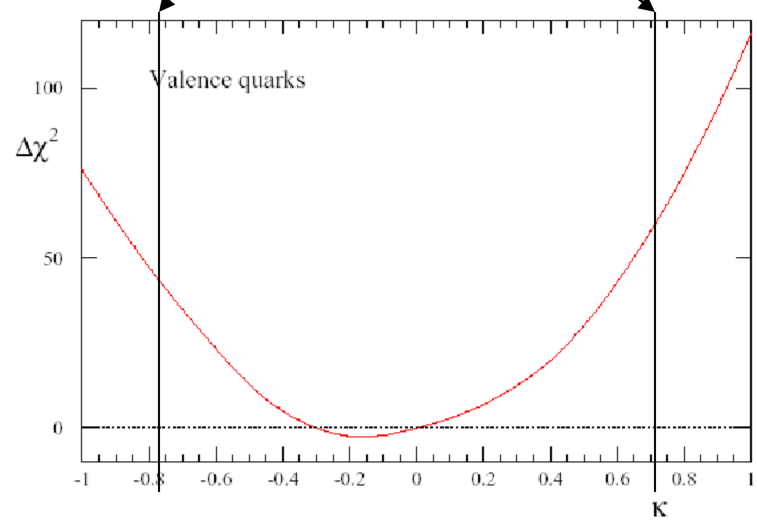
Martin, Roberts, Stirling, Thorne [Eur Phys J C**35**, 325 (04)]:

Choose specific form for parton CSV:

$$\delta d_{\mathrm{V}}(x) = -\kappa f(x) = -\delta u_{\mathrm{V}}(x)$$
$$f(x) = x^{-0.5}(1-x)^4(x-.0909)$$

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

90% conf limit (κ)



$$u_{\mathrm{V}}^p(x) + d_{\mathrm{V}}^p(x) = u_{\mathrm{V}}^n(x) + d_{\mathrm{V}}^n(x)$$

Very shallow minimum found in global fit to HE data

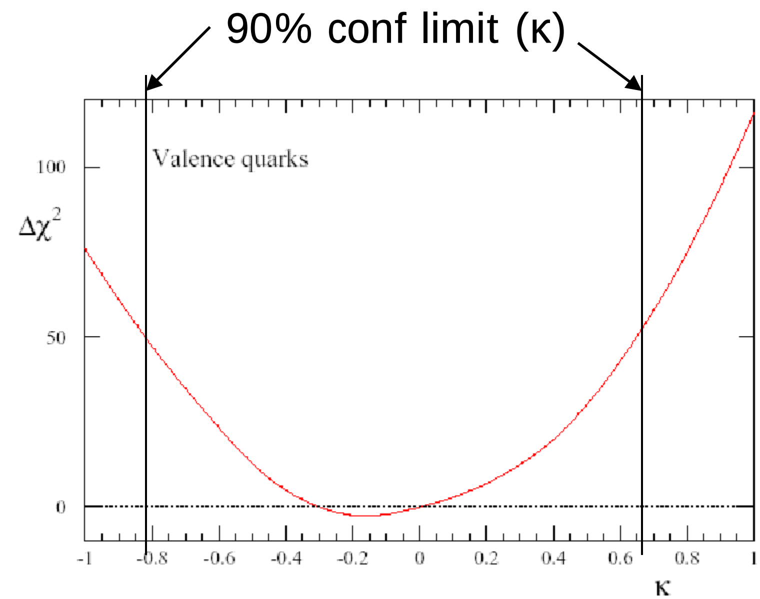
Best fit: **κ = -0.2**, large uncertainty !

90% confidence limit: $-0.8 \leq \kappa \leq +0.65$

Note: MRST neglected Q^2 dep in global fit → important in **estimates of CSV effects** !!

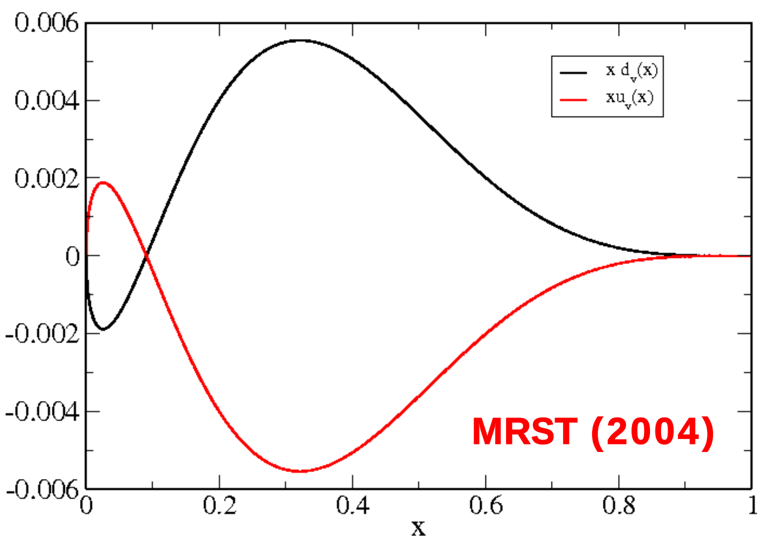
CSV PDFs: Phenomenology & Theory

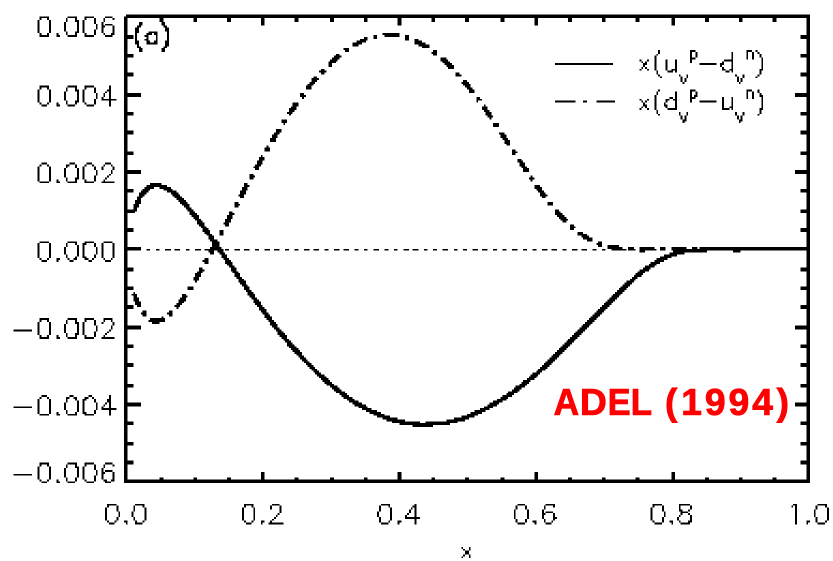
MRST PDFs → global fits including CSV:
Martin, Roberts, Stirling, Thorne [Eur Phys J C**35**, 325 (04)]:



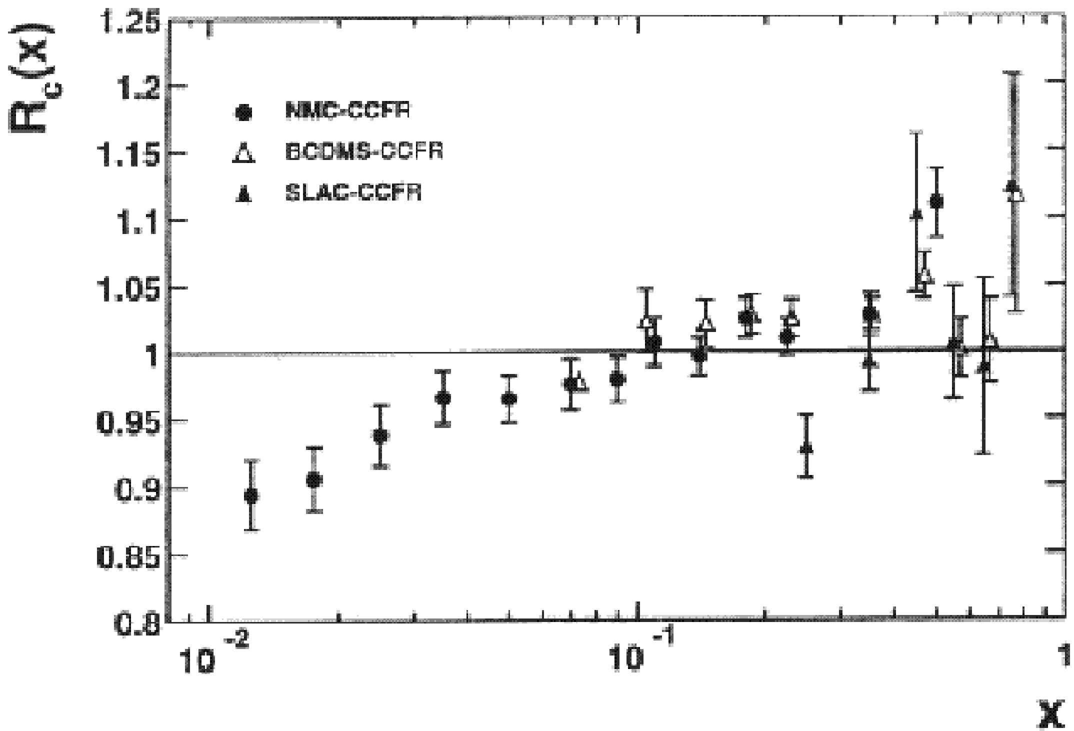
$$\delta d_{\mathrm{V}}(x) = -\kappa f(x) = -\delta u_{\mathrm{V}}(x)$$
$$f(x) = x^{-0.5}(1-x)^4(x-.0909)$$

Best fit: **κ = -0.2**, large uncertainty !
Best fit remarkably similar to quark model CSV calculations





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

Strange Quark Contributions to PW Ratio:

Contribution from strange quarks:

$$\delta R_S^{PW} = \delta\left(\sin^2\theta_W\right) \approx \frac{-S_{\rm V}}{U_{\rm V}+D_{\rm V}}\left[2\Delta_d^2 + 3(\Delta_d^2+\Delta_u^2)\epsilon_c\right]$$

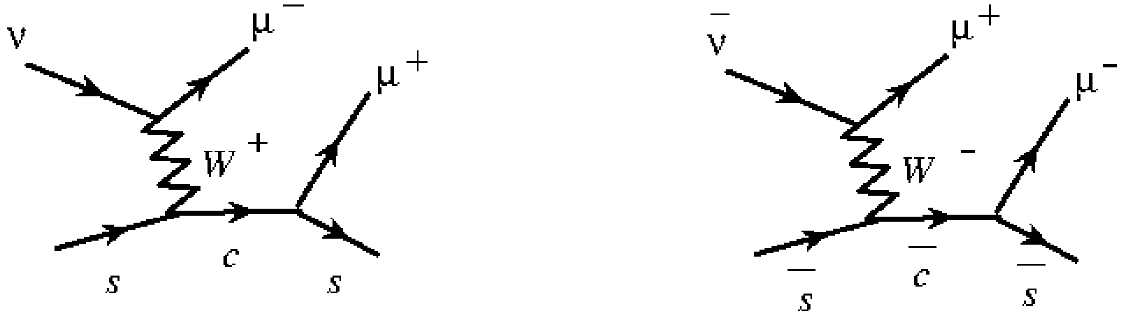
$$S_{\rm V} = \int_0^1 x(s(x)-\bar{s}(x))\,dx$$

Strange quark normalization: constrained $\int(s-\bar{s})\,dx = 0$

(no net strangeness in nucleon)

If s quarks carry more momentum than sbar $\Longrightarrow$ decrease anomaly

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



- (charge of faster muon determines neutrino or antineutrino);
- most precise way to determine s, sbar PDFs→ **CCFR, NuTeV**

CCFR-NuTeV: Analysis of s quark dist'n:

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

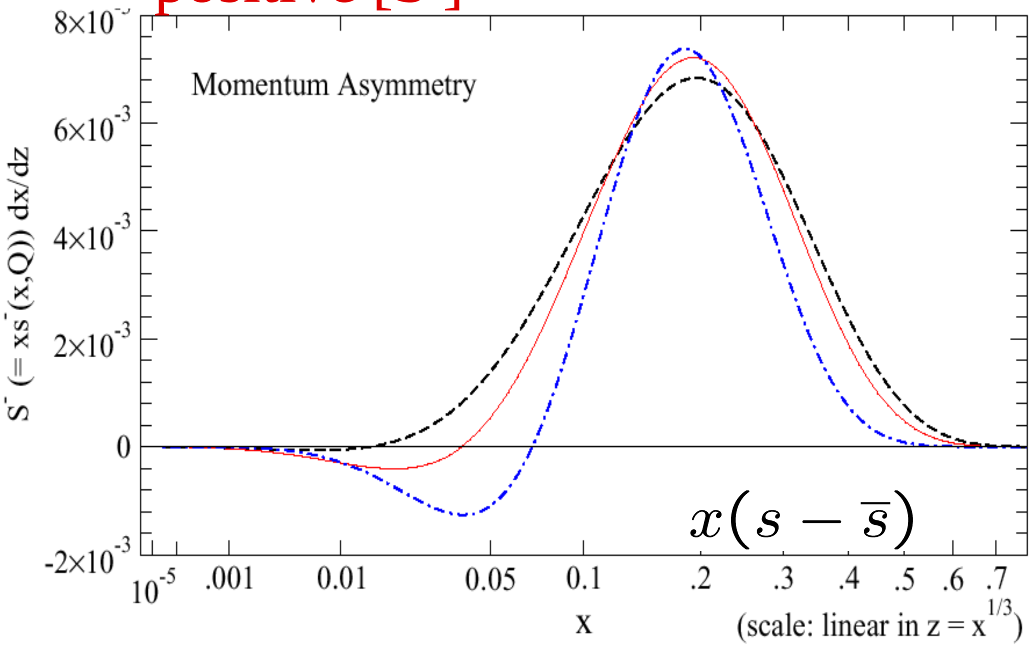
CTEQ: [Kretzer, Olness, Tung, Reno, ...]

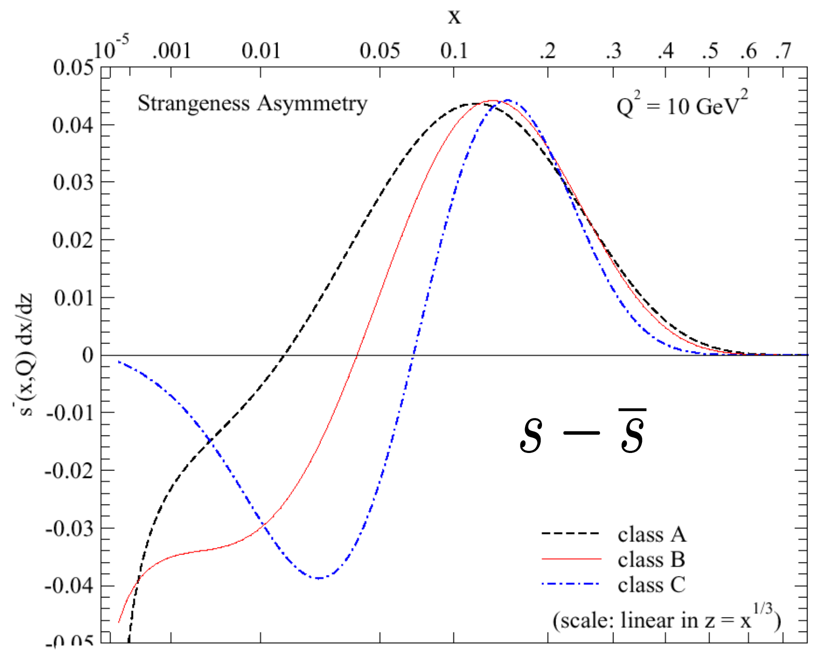
- Global analysis of parton PDFs → CTEQ6
- Includes CCFR, NuTeV dimuon data
- (includes expt'l cuts on dimuons)
- Extract "best fit" for s, sbar dist'ns
  [enforce s normalization cond'n]

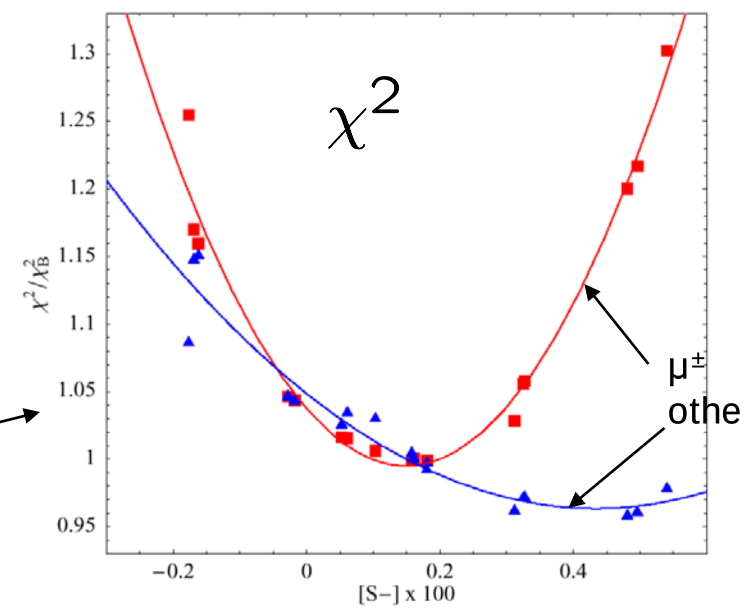
Results: CTEQ Global fit

vs. Bjorken x

positive [S^-]







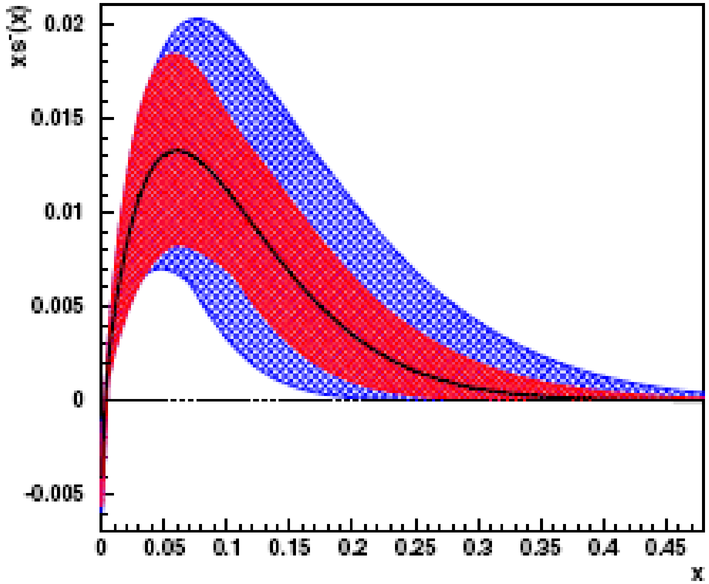
- CTEQ: $S^- > 0$, strange asymmetry **decreases NuTeV anomaly**;
- dimuon data: most sensitive for s PDFs
- CTEQ: s contrib'n removes ~ up to **30% of anomaly** **[at 1σ, consistent with 0]**

1σ: [S^-]·100 ~ 0.17

NuTeV on Strange Quark Dist'n:

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

$x(s - \overline{s})$



x

CTEQ – NuTeV new results:
Mason etal, PRL 99, 192001 (07)
Now agrees with CTEQ !