Independent Fragmentation and Role of Charge Symmetry

Science at the Luminosity Frontier: Jefferson Lab at 22 GeV Workshop

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Introduction

What is Charge symmetry?

Charge symmetry (CS) is a specific rotation in isospin space. It is the invariance with respect to rotation of π about the T2 axis.

$$P_{CS} = \exp(i\pi T2)$$

$$P_{CS} |d\rangle = |u\rangle$$
$$P_{CS} |u\rangle = -|d\rangle$$

Low Energy: CS in nuclei

CS operator interchanges neutrons and protons

- CS goes back to the charge independence of N force.
- pp and nn scattering lengths are nearly the same
- $M_n \simeq M_p$
- $B(n, {}^3He) \simeq B(p, {}^3H)$ and energy levels in other mirror nuclei are equal (to 1%)
- $m({}^3He) \simeq m({}^3H)$

After electromagnetic corrections CS respected down to $\sim$ 1%

QCD: Quark level

- $u^p(x, Q^2) = d^n(x, Q^2)$
  $d^p(x, Q^2) = u^n(x, Q^2)$
- Origin of CS violations:
  $\rightarrow$ Electromagnetic interaction
  $\rightarrow \delta m = m_d - m_u$

Naively, one would expect CSV would be on the order of $(m_d - m_u)/\langle M\rangle$, where $\langle M\rangle$ is roughly $0.5 - 1.0$ GeV
$\rightarrow$ CSV effect about 1%

Motivation

- **Charge symmetry violation** is an important ingredient for pushing the **precision frontier in the partonic structure of the nucleon**
- Charge symmetry is often assumed in extracting PDFs from data – where the data is limited in sensitivity to CS violation
- The validity of charge symmetry is a necessary condition for many relations between structure functions and sum rules
- Flavor symmetry violation extraction $\bar{u}(x) \neq \bar{d}(x)$ relies on the implicit assumption of charge symmetry (in the sea quarks)
- Charge symmetry violation viable part of explanation for the anomalous value of the Weinberg angle extracted by NuTeV experiment
- CSV is related to our understanding of the flavor dependence of the quark masses (one of the key unsolved problems in Physics –
  why is $m_d \sim m_u \neq m_s \neq m_c \neq m_b \neq m_t$)

Upper Limits on CSV

Theoretical Limits

Charge Symmetry Violation

$$CSV(x) = \delta d - \delta u \neq 0$$

where

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

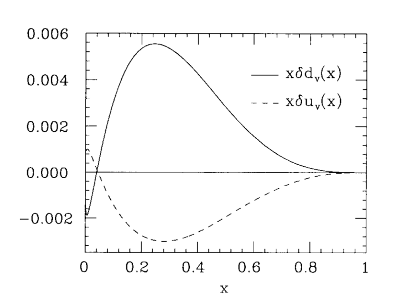
Model by Sather:

$$\delta d(x) \sim 2 - 3\%, \delta u(x) \sim 1\%$$

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

$$\delta u_v(x) = \frac{\delta M}{M}(-\frac{d}{dx}[x u_v(x)] + \frac{d}{dx} u_v(x))$$

where $\delta M = 1.3 MeV$ is the n-p mass difference, and $\delta m = m_d - m_u \sim 4 MeV$ is the down-up quark mass difference. E. Sather, Phys. Lett. B274, 433 (1992)



Model by Rodionov, Thomas and Londergan $\delta d(x)$ could reach up to 10% at high x

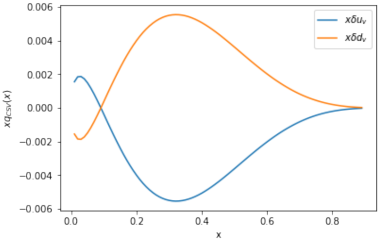
E. N. Rodionov, A. W. Thomas and J. T. Londergan, Mod. Phys. Lett. A 9, 1799 (1994)

Upper Limits on CSV

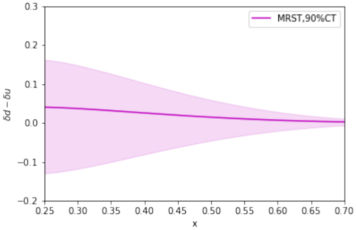
Phenomenological limits

MRST included CSV in a phenomenological evaluation of PDFs

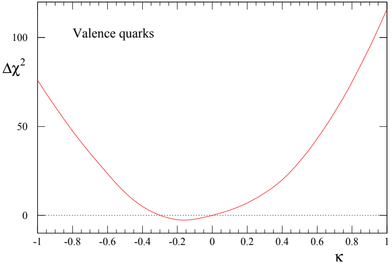
$$\delta u_v(x) = -\delta d_v(x) = \kappa f(x)$$
$$f(x) = (1-x)^4 x^{-0.5}(x - 0.0909)$$



Using the uncertainties in PDFs studied by MRST Group, CSV is constrained to less than 9%



Eur. Phys. J.35(2004)325



Upper Limits on CSV

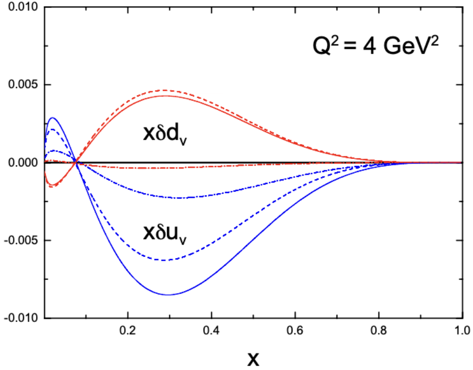
Lattice QCD

The charge symmetry violation via lattice simulation:

$$\delta U = \int_0^1 dx x \delta u(x) = 0.0023(7)$$

$$\delta D = \int_0^1 dx x \delta d(x) = 0.0017(4)$$

The dash-dotted, dashed and solid curves represent pure QED, pure QCD and the total contributions. The results is compatible with the MRST analysis. Physics Letters B, 753:595–599



Upper Limits on CSV

Experimental Limits

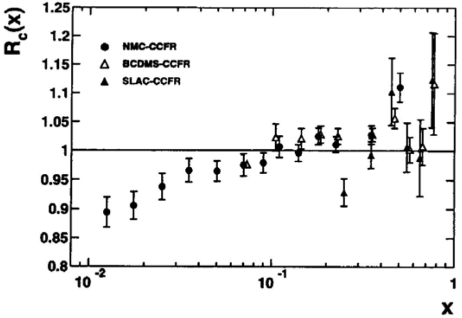
- Upper limit obtained by combining neutral and charged current data on isoscaler targets
- $F_{2\nu}$ by CCFR collaboration at FNAL (Fe data)
- $F_{2\gamma}$ by NMC collaboration using muons (D target)
- $0.1 \leq x \leq 0.4 \rightarrow$ **9% upper limit for CSV effect!**

"Charge Ratio"

$$R_c(x) = \frac{F_2^{\gamma}(x) + x\left[s(x) + \bar{s}(x) - c(x) - \bar{c}(x)\right]/6}{5\bar{F}_2^{W(x)}/18}$$

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

$$\bar{Q}(x) = \sum_{u,d,s}\left(q(x) + \bar{q}(x)\right)$$



Londergan and Thomas. Prog. Part. Nucl. Phys. 41 (1998) 49-124

Formalism

Charge Symmetry Violation

$CSV(x) = \delta d - \delta u \neq 0$ where $\delta u(x) = u^p(x) - d^n(x)$, $\delta d(x) = d^p(x) - u^n(x)$

Londergan, Pang and Thomas PRD54(1996)3154

$$R^D_{meas}(x,z) = \frac{4N^{D\pi^-}(x,z) - N^{D\pi^+}(x,z)}{N^{D\pi^+}(x,z) - N^{D\pi^-}(x,z)} = \frac{4R_Y(x,z) - 1}{1 - R_Y(x,z)} \quad (1)$$

where $N^{D\pi^\pm}(x,z)$ is the **measured yield** of $\pi^\pm$ electroproduction on a deuterium target, R_Y is the $N^{D\pi^-}/N^{D\pi^+}$ yield ratio and We rely on

Factorization

$$N^{Nh} = \sum_i e_i^2 q_i^N(x) D_i^h(z)$$

Impulse Approximation

$$N^{D\pi^\pm}(x,z) = N^{p\pi^\pm}(x,z) + N^{n\pi^\pm}(x,z)$$

Formalism

Leading order experimental analysis → will need higher order global analysis

Londergan, Pang and Thomas PRD54(1996)3154

$$D(z)\ R(x,z) + A(x) CSV(x) = B(x,z)$$

$$D(z) = \frac{1-\Delta(z)}{1+\Delta(z)}, \Delta(z) = \frac{D_u^{\pi^-}(z)}{D_u^{\pi^+}(z)}$$

$$R(x,z) = \frac{5}{2} + R^D_{meas}$$

$$CSV(x) = \delta d - \delta u$$

$$A(x) = \frac{-4}{3(u_v + d_v)}$$

$$B(x,z) = \tfrac{5}{2} + R^D_{sea\_S}(x,z) + R^D_{sea\_NS}(x)$$

$$R^D_{sea_{NS}}(x) = \frac{5(\overline{u}^p(x) + \overline{d}^p(x)}{[u_v^p(x) + d_v^p(x)]}$$

$$R^D_{sea_S}(x,z) = \frac{\Delta_s(z)[s(x) + \overline{s}(x)]/(1+\Delta(z))}{[u_v^p(x) + d_v^p(x)]}$$

$$\Delta_s(z) = \frac{D_s^-(z) + D_s^+(z)}{D_u^+(z)}$$

$A(x)$ and $B(x,z)$ are known and $R(x,z)$ is **measured**

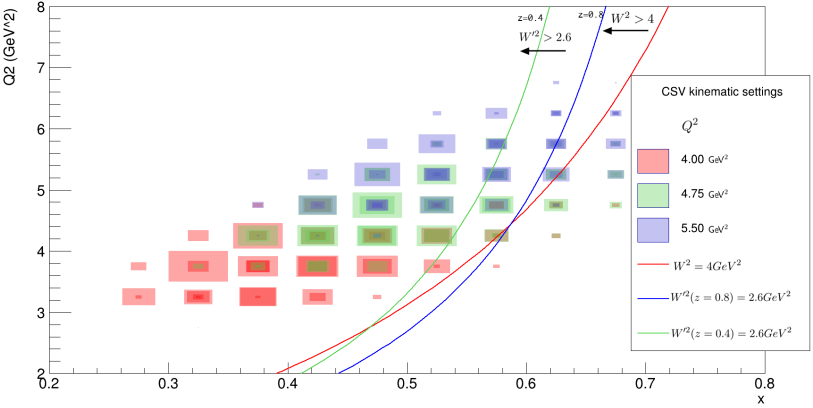
CSV

Extract simultaneously D(z) and CSV(x) from each $(Q^2$,x) setting

Experiment E12-09-002

Kinematic Coverage

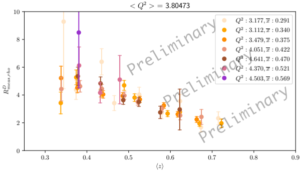
Charge Symmetry Violating Quark Distributions via Precise Measurement of π^+/π^- Ratios in Semi-inclusive Deep Inelastic Scattering.

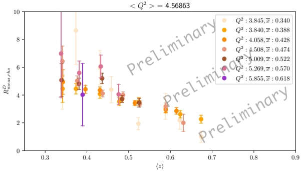


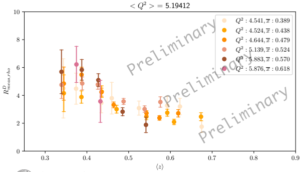
$$W'^2 = M^2 + Q^2(1 - z)(1/x - 1)$$

Preliminary R^D_{meas}

$$D(z)\ \left[\frac{5}{2} + R^D_{meas}(x,z)\right] + A(x)CSV(x) = B(x,z)$$

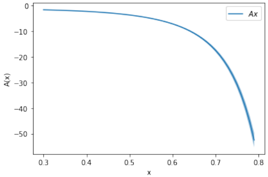


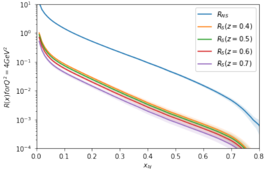




$\leftarrow$ $$R^D_{meas}(x,z) = \frac{4N^{D\pi^-}(x,z) - N^{D\pi^+}(x,z)}{N^{D\pi^+}(x,z) - N^{D\pi^-}(x,z)}$$

Model inputs:





$$A(x) = \frac{-4}{3(u_v + d_v)}$$

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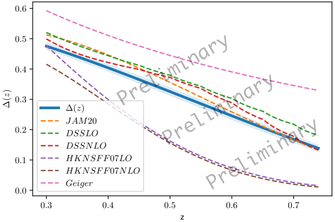
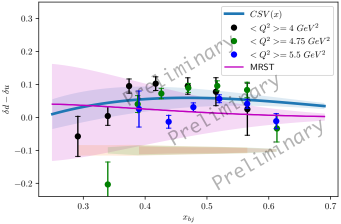
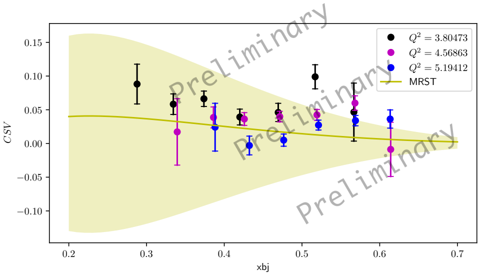
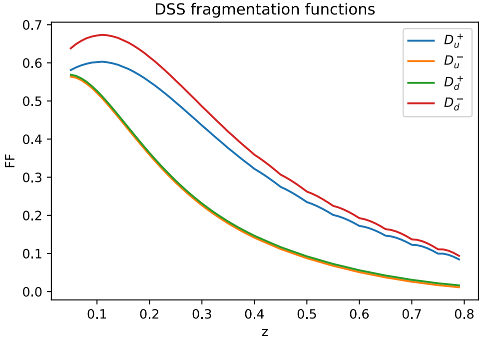




From Shuo Jia

CSV in Parton Distribution and Fragmentation Functions





- Early results show best agreement with data when CSV is included in FFs (i.e. when we use DSS)
- Leads to nominal ρ background subtraction
- Ratios should be come

Factorization

Berger's criterion: $\Delta\eta \gtrsim 2$

Sets z_{min} for a given W_{max} (for pions)

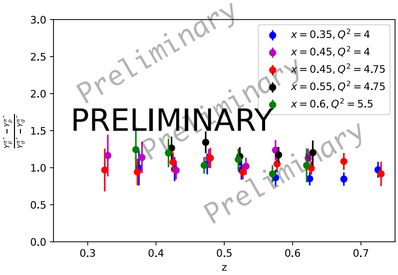
	JLab 6 GeV	11 GeV	22 GeV	HERMES
$z_{min} \rightarrow$	0.29	0.22	0.16	0.135

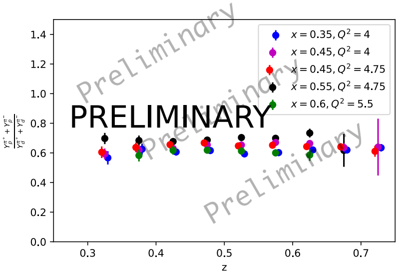
See Chapter 8 from S.J. Joosten, Ph.D. thesis, Illinois Univ., Urbana (2013).
Mulders AIP Conf.Proc. 588 (2001) 1, 75-88

Charge Ratio Sum and Differences

$$\frac{\sigma_p^{\pi^+} - \sigma_p^{\pi^-}}{\sigma_d^{\pi^+} - \sigma_d^{\pi^-}} = \frac{4u_v(x) - d_v(x)}{3\,(u_v() + d_v(x))} = R^-$$

$$\frac{d_v}{u_v} = \frac{4 - 3R^-}{3R^- + 1}$$





Ratios should not depend on z.

$$\frac{\sigma_p^{\pi^+} + \sigma_p^{\pi^-}}{\sigma_d^{\pi^+} + \sigma_d^{\pi^-}} = \frac{4u + 4\overline{u} + d + \overline{d}}{5(u + \overline{u} + d + \overline{d})}$$

Factorization

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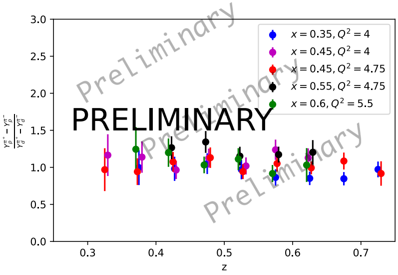

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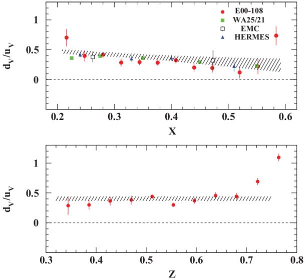

JLab E00-108: PRC 85, 015202 (2012)

Summary

- Conducted precision semi-inclusive measurements of the π^-/π^+ ratio on a deuterium target
- Extracted the CSV parton distribution and fragmentation function ratio for a range of x... Q2 and z...
- Different FF models suggests a CSV fragmentation function should be considered in a global analysis
- Results for the CSV parton distribution are consistent with previous estimates

JLab at 22 GeV Ideas

- Extend the kinematics of a precision ratio measurement to higher $Q^2 \rightarrow$ should have some phase space overlap with standard global analyses
- Use other isoscalar targets: compare D to ^{4}He – Either fragmentation is independent and just EMC effect, or something else?
- Need to investigate momentum upper limits of spectrometers?

Thank you!

Backups

Charge Symmetry in QPM

Charge-conjugation symmetry

$$D_{\bar{u}}^{\pi^{\pm}} = D_{\bar{u}}^{\pi^{\mp}}$$

Charge Symmetry

$$D_{u}^{\pi^{+}} = D_{d}^{\pi^{-}} \qquad D_{\bar{u}}^{\pi^{+}} = D_{\bar{d}}^{\pi^{-}}$$
$$D_{d}^{\pi^{+}} = D_{u}^{\pi^{-}} \qquad D_{\bar{d}}^{\pi^{+}} = D_{\bar{u}}^{\pi^{-}}$$

Gottfried Sum Rule

$$\begin{aligned} S_G &= \int_0^1 dx \left[\frac{F_2^p - F_2^n}{x}\right] \\ &= \frac{1}{3} + \frac{2}{9}\int_0^1 dx \left[4\bar{u}^p + \bar{d}^p - 4\bar{u}^n - \bar{d}^n\right] \\ &\overset{\text{CS}}{=} \frac{1}{3} + \frac{2}{3}\int_0^1 dx \left[\bar{u}^p - \bar{d}^p\right] \end{aligned}$$

Londergan and Thomas. Prog. Part. Nucl. Phys. 41 (1998) 49-124