Charge Symmetry Violation in SIDIS

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Overview

- What is Charge Symmetry?
- Sources of Charge Symmetry Violation
- Charge Symmetry in SIDIS
- CSV Experiment in Hall C
- Summary

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
- $M_n \simeq M_p$
- $B(n, {}^3\mathrm{He}) \simeq B(p, {}^3\mathrm{H})$ and energy levels in other mirror nuclei are equal (to 1%)
- $m({}^3\mathrm{He}) \simeq m({}^3\mathrm{H})$

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

Charge Symmetry in the Parton Distribution Functions

CS

$$u^p(x) \overset{\text{CS}}{=} d^n(x)$$
$$d^p(x) \overset{\text{CS}}{=} u^n(x)$$
$$\Delta u^p(x) \overset{\text{CS}}{=} \Delta d^n(x), etc.$$

CSV PDFs

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

$$\delta d - \delta u \neq 0$$
$$\Delta\delta d - \Delta\delta u \neq 0$$

Gottfried Sum Rule:

$$S_G = \int_0^1 dx\left[\frac{F_2^p - F_2^n}{x}\right] = \int dx\left(\frac{u^+ - d^+}{3} + \frac{4\delta d^+ + \delta u^+}{9}\right)$$
$$= \frac{1}{3} + \frac{2}{9}\int_0^1 dx\left[4\bar{u}^p + \bar{d}^p - 4\bar{u}^n - \bar{d}^n\right]$$
$$\overset{\text{CS}}{=} \frac{1}{3} + \frac{2}{3}\int_0^1 dx\left[\bar{u} - \bar{d}\right]$$

where $q^+ = q + \bar{q}$

Bjorken Sum Rule:

$$\int dx\left(g_1^p - g_1^n\right) = \frac{G_A}{6G_V} = \int dx\left(\frac{\Delta u - \Delta d}{6} + \frac{4\delta\Delta d + \delta\Delta u}{18}\right)$$

Upper Limits on CSV

Theoretical Limits

Charge Symmetry Violation

$$CSV(x) = \delta d - \delta u \neq 0 \quad \text{where} \quad \begin{aligned} \delta u(x) &= u^p(x) - d^n(x) \\ \delta d(x) &= d^p(x) - u^n(x) \end{aligned}$$

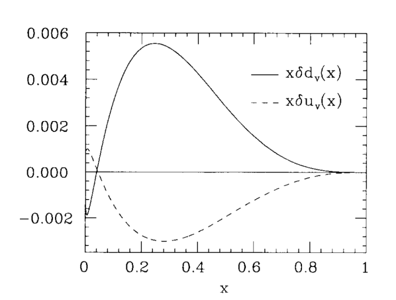
Model by Sather: $\delta d(x) \sim 2-3\%, \delta u(x) \sim 1\%$

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

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

$\delta M = 1.3 MeV$ is the n-p mass difference,
$\delta m = m_{dd} - m_{uu} \sim 4 MeV$ is the down-down up-up diquark mass difference (remaining diquark for "minority" quark scattering)

E. Sather, Phys. Lett. B274, 433 (1992)



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

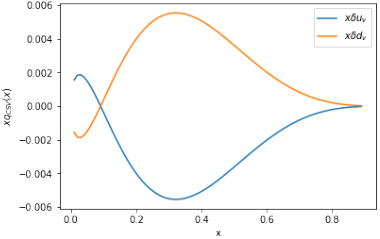
E. N. Rodionov, A. W. Thomas and J. T. Londergan, Mod. Phys. Lett. A 9, 1799 (1994)

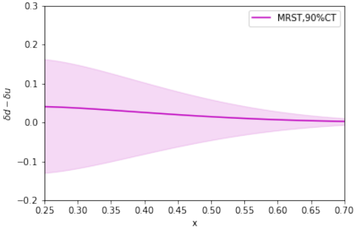
Upper Limits on CSV

Phenomenological limits

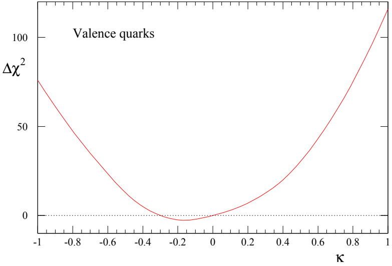
MRST included CSV in a phenomenological evaluation of PDFs

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





Eur. Phys. J.35(2004)325



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

Upper Limits on CSV

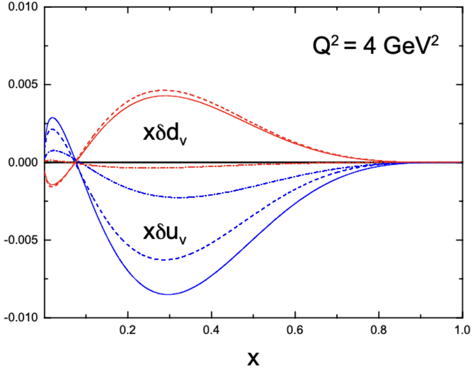
Lattice QCD

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

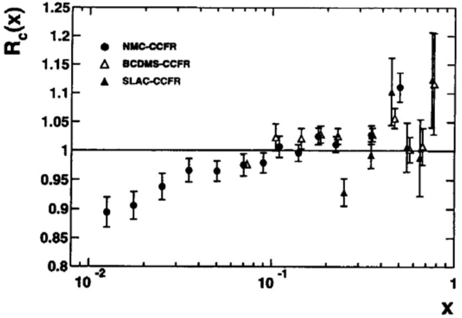
- Upper limit obtained by combining neutral and charged current data on isoscaler targets
- $F_{2\nu}$ by CCFR collaboration at FNAL (Fe data)
- $F_{2\gamma}$ by NMC collaboration using muons (D target)
- $0.1 \leq x \leq 0.4 \rightarrow$ **9% upper limit for CSV effect!**

"Charge Ratio"

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

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

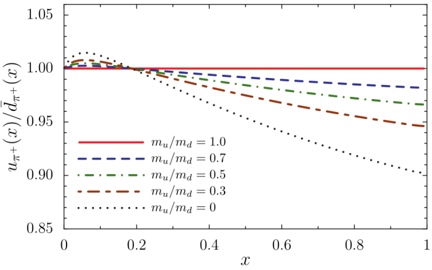
$$\bar{Q}(x) = \sum_{u,d,s}\left(q(x) + \bar{q}(x)\right)$$



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

Charge Symmetry in the Pion

- CS *breaking* in partonic structure of light mesons has been studied
- For example, the quark mass difference leads to different u and $\bar{d}$ PDFs in the charge pion
- However, CS is exact between π^+ and π^-
- For charged pion SIDIS, the question becomes: what is the role CS in the fragmenting quark?
- If present, will CSV effects be strongest in the favored or unfavored fragmentation?



Hutauruk,et al. Phys.Rev.C 97 (2018)

Symmetries in Fragmentation Functions

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

$$A_{\text{quark}}^{\text{Fav}} = \frac{D_u^{\pi^+} - D_d^{\pi^-}}{D_u^{\pi^+} + D_d^{\pi^-}} \qquad A_{\text{quark}}^{\text{Un-fav}} = \frac{D_u^{\pi^-} - D_d^{\pi^+}}{D_u^{\pi^-} + D_d^{\pi^+}}$$

$$A_{\text{anti-quark}}^{\text{Fav}} = \frac{D_{\bar{u}}^{\pi^-} - D_{\bar{d}}^{\pi^+}}{D_{\bar{u}}^{\pi^-} + D_{\bar{d}}^{\pi^+}} \qquad A_{\text{anti-quark}}^{\text{Un-fav}} = \frac{D_{\bar{u}}^{\pi^+} - D_{\bar{d}}^{\pi^-}}{D_{\bar{u}}^{\pi^+} + D_{\bar{d}}^{\pi^-}}$$

Charge Conj. Symmetry

$$A_{\text{quark}}^{\text{Fav}} = A_{\text{anti-quark}}^{\text{Fav}}$$

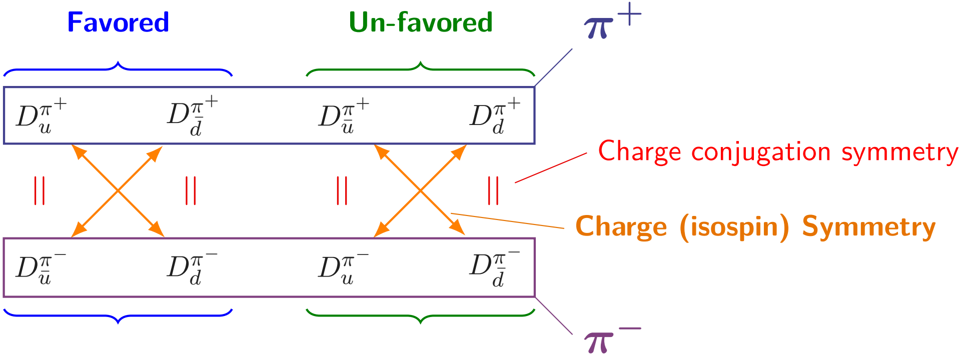
$$A_{\text{quark}}^{\text{Un-fav}} = A_{\text{anti-quark}}^{\text{Un-fav}}$$

Charge Symmetry

$$A_{\text{quark}}^{\text{Fav}} = 0$$

$$A_{\text{quark}}^{\text{Un-fav}} = 0$$

Symmetries in Fragmentation Functions



$$A^{\text{Fav}}_{\text{quark}} = \frac{D_u^{\pi^+} - D_d^{\pi^-}}{D_u^{\pi^+} + D_d^{\pi^-}}$$

$$A^{\text{Fav}}_{\text{anti-quark}} = \frac{D_{\bar{u}}^{\pi^-} - D_{\bar{d}}^{\pi^+}}{D_{\bar{u}}^{\pi^-} + D_{\bar{d}}^{\pi^+}}$$

$$A^{\text{Un-fav}}_{\text{quark}} = \frac{D_u^{\pi^-} - D_d^{\pi^+}}{D_u^{\pi^-} + D_d^{\pi^+}}$$

$$A^{\text{Un-fav}}_{\text{anti-quark}} = \frac{D_{\bar{u}}^{\pi^+} - D_{\bar{d}}^{\pi^-}}{D_{\bar{u}}^{\pi^+} + D_{\bar{d}}^{\pi^-}}$$

Charge Conj. Symmetry

$$A^{\text{Fav}}_{\text{quark}} = A^{\text{Fav}}_{\text{anti-quark}}$$

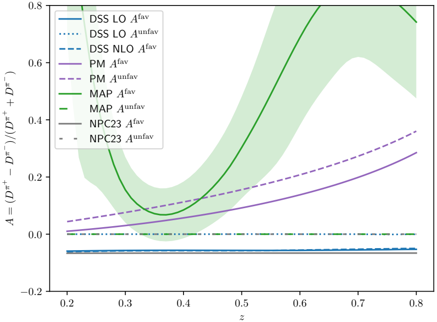
$$A^{\text{Un-fav}}_{\text{quark}} = A^{\text{Un-fav}}_{\text{anti-quark}}$$

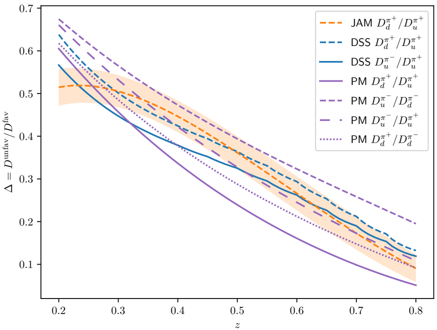
Charge Symmetry

$$A^{\text{Fav}}_{\text{quark}} = 0$$

$$A^{\text{Un-fav}}_{\text{quark}} = 0$$

CSV in Fragmentation Functions





- Ma and Peng allow for CSV in favored and un-favored
- MAP1.0 global analysis relaxed their CS constraint leading to large CSV in the favored
- JAM FF does not include any CSV

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 $\rightarrow$ will need higher order global analysis

Londergan, Pang and Thomas PRD54(1996)3154

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

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

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

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

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

$$\delta D(z) = \frac{D_u^+ - D_d^-}{D_u^+} \simeq 0$$

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

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

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

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

$$F(z) = \frac{4+\Delta}{3(1-\Delta^2)}$$

$A(x)$ 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 in Hall C – E12-09-002

Measurements: D$(e, e'\pi^+)$ and D$(e, e'\pi^-)$

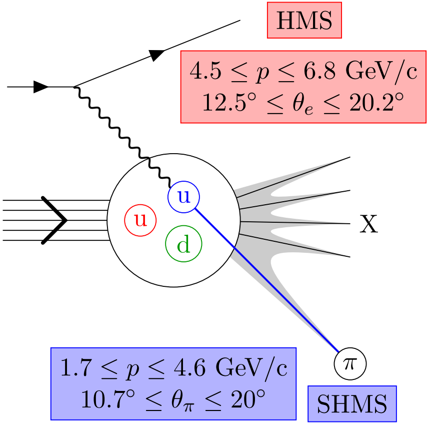
Setup

- 10.6 GeV e^- beam
- 10 cm LD_2 target
- SHMS $\rightarrow \pi^\pm$, HMS $\rightarrow e'$

For each x setting we conducted z scans:
4 z settings of SHMS measured with both polarities

$$R_Y(x,z) = Y^{D\pi^-}(x,z)/Y^{D\pi}(x,z)$$

$$R^D_{\text{Meas}}(x,z) = \frac{4R_Y(x,z) - 1}{1 - R_Y(x,y)}$$

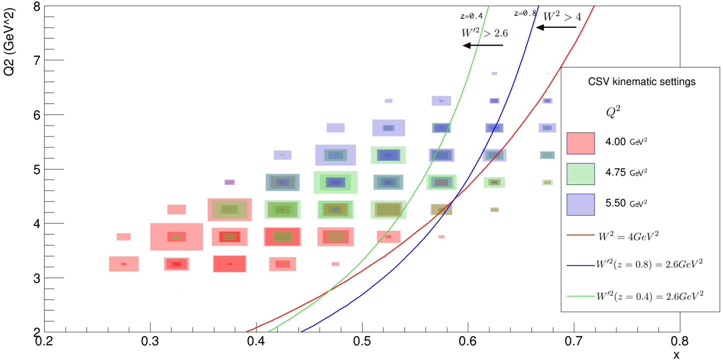


$$D(z)\,(5/2 + R^D_{meas}(x,z)) + A(x)C(x) = B(x,z)$$

Experiment E12-09-002

Kinematic Coverage

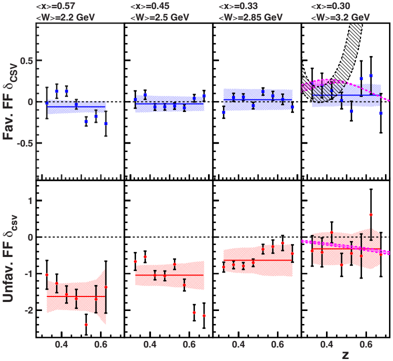
Charge Symmetry Violating Quark Distributions via Precise Measurement of π^+/π^- *Ratios in Semi-inclusive Deep Inelastic Scattering.*



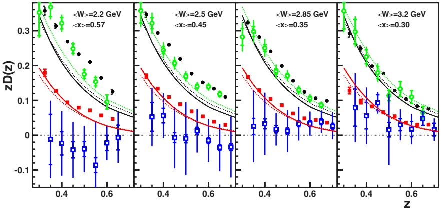
$$W'^2 = M^2 + Q^2(1 - z)(1/x - 1)$$

Beam Energy: 10.6 GeV, LD_2(10 cm), LH_2(10 cm), Al-dummy, Fall 2018 and Spring 2019;
HMS: electron, 13-21°, 4.4-6.4 GeV/c   SHMS: hadron, 11°-21°, 1.7-4.5 GeV/c

CSV in Fragmentation Functions



$$\delta^{f}_{\mathrm{CSV}}(z) = \frac{D_{d\pi^-} - D_{u\pi^+}}{D_{u\pi^+}}$$
$$\delta^{uf}_{\mathrm{CSV}}(z) = \frac{D_{d\pi^+} - D_{u\pi^-}}{D_{u\pi^-}}$$



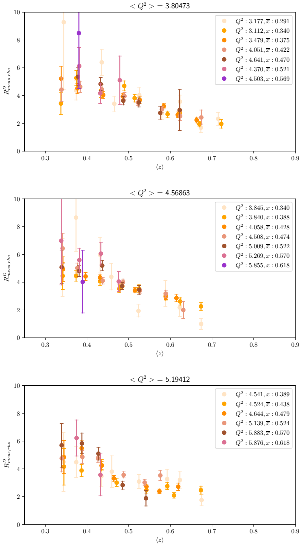
Favored: Black $D_u^{\pi^+}$, green $D_d^{\pi^-}$,
Unfavored: red $D_u^{\pi^-}$, and Blue $D_d^{\pi^+}$
Fits by P.Bosted

- H and D multiplicities fit to extract LO fragmentation functions
- At high W, Favored FFs consistent with zero
- Unfavored consistent with zero due to large uncertainty
  $\rightarrow$ unfavored fragmentation from down quark highly suppressed
- See talks from Hem and Ed for more details.

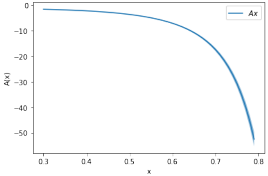
Results for R^D_{meas}

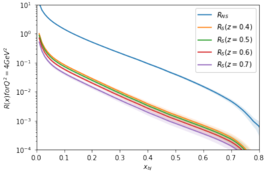
$$D(z)\left[\frac{5}{2}+R^D_{meas}(x,z)\right]+A(x)CSV(x)=B(x,z)$$

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



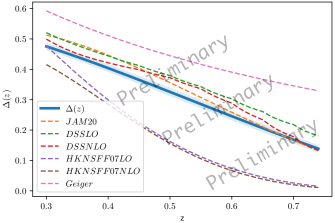
Model inputs:

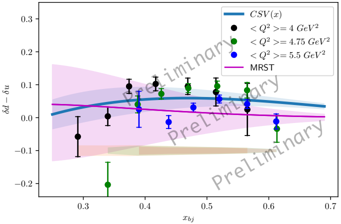




$$A(x)=\frac{-4}{3(u_v+d_v)}$$

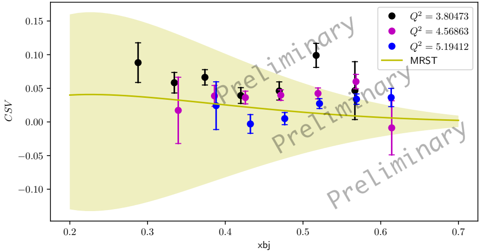
$$B(x,z)=\frac{5}{2}+R^D_{sea\_S}(x,z)+R^D_{sea\_NS}(x$$





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
- Results hint at non-zero CSV for $x > 0.5$
- Global analysis ultimately needed to extract best CSV in PDFs

Summary

- Conducted precision semi-inclusive measurements of the π^-/π^+ ratio on a deuterium target
- Extracted the CSV parton distribution and fragmentation function ratio
- Fragmentation functions appear to preserve CS
- Various FF models and fits suggest CSV in FFs because of tension in a global analysis
- Results for the CSV parton distribution are consistent with previous estimates

Future

- Global analysis with precision pion ratio to constrain CSV in valence PDFs
- 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?

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

Factorization

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

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

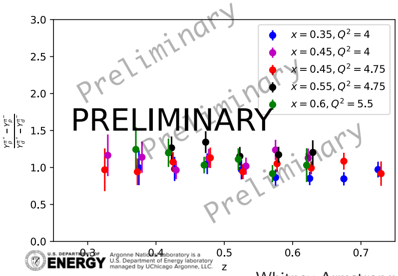
	JLab 6 GeV	11 GeV	22 GeV	HERMES
$z^{\pi}_{min} \rightarrow$	0.29	0.22	0.16	0.14
$z^{K}_{min} \rightarrow$	N/A	0.79	0.56	0.50

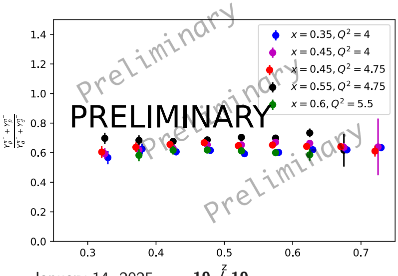
See Chapter 8 from S.J. Joosten, Ph.D. thesis, Illinois Univ., Urbana (2013).
Mulders AIP Conf.Proc. 588 (2001) 1, 75-88

Charge Ratio Sum and Differences

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

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





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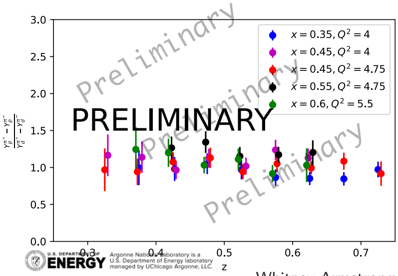
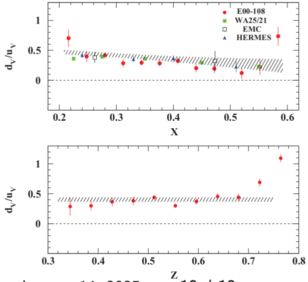
$$\frac{d_v}{u_v} = \frac{4 - 3R^-}{3R^- + 1}$$





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