Probing Charge SymmetryViolation (CSV) in Quark Distributions Using Semi-Inclusive Deep Inelastic Scattering (SIDIS)

Hem Bhatt
Hall C Collaboration Meeting
Jan 28-29, 2021
Introduction

Charge Symmetry (CS) in Partons:
\[ u^p(x, Q^2) = d^n(x, Q^2) \]
\[ d^p(x, Q^2) = u^n(x, Q^2) \]

CS In Nuclei:
\[ nn = pp = np \] (identical interactions)
\[ M_p \approx M_n \] (1%)

After electromagnetic corrections, charge symmetry is expected to be valid to within 1%.

Charge Symmetry Violation (CSV):

1. \( \delta m = m_d - m_u \)
2. Electromagnetic interaction between the quarks

Of these two causes, the significant contribution to CSV is due the mass difference between the quarks.

For partonic systems, CSV = \( \delta m/ <M> \) where, \( <M> \) = average expectation value of strong Hamiltonian, with a value roughly 0.5-1.0 GeV => CSV effect of about 1%.
PDFs extracted from fits and Phenomenological Limits on CSV

\[ \delta u_v(x) = u_p(x) - d^n(x) \]
\[ \delta d_v(x) = d_p(x) - u^n(x) \]
\[ C(x) = \delta d_v - \delta u_v (CSV) \]

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

\[ \frac{\delta d_v}{d_v} \approx 2.5\% \]
\[ \frac{\delta u_v}{u_v} \approx 1.0\% \]

PDFs extracted from fits to DIS data

The best fit is obtained for \( \kappa = -0.2 \) (Eur. Phys. J.35(2004)325)

However, considering the uncertainty in the existing PDF data, at the 2-sigma level, allows upto 9% of CSV.
**Semi-Inclusive Deep Inelastic Scattering (SIDIS)**

**Few kinematic quantities:**

- $x = Q^2 / 2M_p \nu$: Fraction of proton’s momentum carried by the quark (Bjorken $x$)
- $M_p = \text{mass of proton}$
- $\nu = \text{energy Transfer in lab frame (E - E')}$
- $Q^2 = 4 \text{ momentum transfer squared} = 4E_E'\sin^2(\Theta/2)$
- $z = \text{fraction of energy transfer carried by outgoing hadron (pion)} = \frac{E_h}{\nu} = \sqrt{(m^2_{\pi} + p^2_{\pi})} / \nu$

**Assumptions:**

- $\Rightarrow \text{Factorization}$
- $\Rightarrow \text{Hadronization}$

We use SIDIS and the formalism of Londergan et. al. to extract the CSV in valence quark distributions

*Londergan, Pang and Thomas PRD54, 3154 (1996)*
Motivations for Direct Measurement of CSV

- Charge symmetry has been universally assumed in extracting PDFs but never been tested experimentally.
- CSV measurements are important on their own as a further step in studying the inner structure of the nucleon.
- CSV could be an explanation for the anomalous value of the Weinberg angle extracted by NuTeV experiment.
- CSV measurements are important for a complete understanding of the strong force.


<table>
<thead>
<tr>
<th>$Q^2$</th>
<th>x</th>
<th>z</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.9 – 4.0</td>
<td>0.35 – 0.5</td>
<td>0.4 – 0.7</td>
</tr>
<tr>
<td>4.75 – 5.0</td>
<td>0.45 – 0.6</td>
<td>0.4 – 0.7</td>
</tr>
<tr>
<td>5.50</td>
<td>0.5 – 0.65</td>
<td>0.4 – 0.7</td>
</tr>
</tbody>
</table>

Data Taking completed: March 2019.

Target: LH2, LD2 and Al Dummy
- HMS Angle = 13 - 21 Degrees
- SHMS Angle = 11 - 21 Degrees
- HMS $P = 4.4 - 6.4$ GeV/c (electrons)
- SHMS $P = 1.7 - 4.5$ GeV/c ($\pi^+$ and $\pi^-$)

LD2: Production
LH2: Factorization Test, Cross-section Measurement
Al dummy: Background subtraction
Jefferson Lab Hall C

Super High Momentum Spectrometer (SHMS):
Magnets: HB, Q1, Q2, Q3, Dipole
Characteristics:
Momentum Range: 2-11 GeV/c
Momentum Acceptance: -10% to +22%
Momentum resolution: dP/P < 0.2
Scattering angle: 5.5 to 40 degrees
Solid Angle Acceptance: > 4 mSr
Beam Capacity: upto 90 μA

High Momentum Spectrometer (HMS):
Magnets: Q1, Q2, Q3, Dipole
Characteristics:
Momentum Range 0.5-7.5 GeV/c
Momentum Acceptance -10% to +10%
Momentum Resolution: dP/P < 0.1%
Scattering angle = 12.5 to 90 degrees
Solid Angle Acceptance > 6 mSr
Beam Capacity upto 90 μA

Detector Hut: HMS and SHMS:
- Drift Chambers
- Hodoscopes
- Cerenkovs
- Calorimeter
Analysis Workflow

Reference time and timing window
Detector Calibration
  Calorimeter
  Drift Chamber
  Cherenkov
  Hodoscope
  BCM

Efficiency Studies
  Tracking Efficiency
  Computer Dead Time
  Luminosity Scan
  Calorimeter and Aerogel Efficiency
  RF Time
  Heavy Gas Cherenkov Efficiency
  Trigger Efficiency

Comparison of extracted Yield with simulation
  Correction/Uncertainty from Diffractive $\rho^0$ production
  Uncertainty from radiative correction
  Yield Ratio of Pi+/Pi-
  Acceptance Correction
  Optics Study

Precise Cross-Section Ratio of Pi+/Pi-
  Extraction of $C(x)$ and $D(z)$ using the yield ratio from the full grid of $x, z$ for various $Q^2(x,z)$

Factorization Test [H2 data]
  Cross-section extraction
We detect charged pions in SHMS in coincidence with electrons in HMS

**RF Time** = time of flight between the target and hodoscope (~ 20 m apart) for beam buckets arriving at the target every 4.008 ns. An offset is added to align the pions at 1.0

**RF Timing Signal**: To separate pions from kaons or protons

- **Calorimeter**: To separate pions from electrons or positrons
- **Aerogel Cherenkov**: To separate pions from kaons and protons
- **Heavy Gas Cherenkov**: To separate pions from kaons

**Counts**

<table>
<thead>
<tr>
<th>Counts</th>
<th>pions</th>
<th>protons</th>
<th>kaons</th>
</tr>
</thead>
</table>

**SHMS Calorimeter E/P vs RF Time (ns)**

**Coincidence Time (ns)**

- **coincidence events**
- **accidentals**
We use RF Timing Peak to separate Kaons from Pions: Cut Used: 0.5 to 1.5. (AeroNpeSum > 4)

Kaon contamination = kaon fit integral (0.5-1.5) / all fit integral (0.5-1.5)

Pion Purity = 1 – kaon contamination

Higher the particle momentum, more will be kaon contamination. Also, more kaons are at positive Polarity (Production of K+ > K-)

Pi+, 3.46 GeV

Pi+, 3.19 GeV

Pi+, 2.66 GeV

Pi-, 3.46 GeV

Pi-, 3.19 GeV

Pi-, 2.66 GeV

Pion Selection Cut
Pi- Kinematics

Pi+ Kinematics

Kaon contamination = kaon fit integral (0.5-1.5) / all fit integral (0.5-1.5)
Pion Purity = 1 − kaon contamination
Aerogel Efficiency (overlap between 4-z settings) (AeroNpeSum > 4)

\[ Z = 0.4 \ (1.8 \text{ GeV}) \]
\[ z = 0.5 \ (2.3 \text{ GeV}) \]
\[ z = 0.6 \ (2.7 \text{ GeV}) \]
\[ Z = 0.7 \ (3.2 \text{ GeV}) \]
SHMS Calorimeter Efficiency vs $z$ (showing the kinematic overlap between 3-$z$ regions)

Efficiency for $E/P < 0.75$

- $Z = 0.5$ (2.6 GeV)
- $Z = 0.6$ (3.1 GeV)
- $Z = 0.7$ (3.7 GeV)
The Standard Hall C Monte Carlo (SIMC)

Features:

=> Optics (COSY), spectrometer apertures and all material

=> Radiative Corrections, multiple scattering, ionization energy loss, particle decay

=> Coulomb corrections, off-shell corrections

=> Parameterization of SIDIS cross-sections from HERMES experiment and Preliminary Jlab Hall C measurements at 12 GeV.

Reactions:

=> H(e,e' π⁺) n, A(e,e' π⁺/-) (exclusive: quasifree or coherent)

=> H(e,e' π⁺/-) X, D(e,e' π⁺/-) X (semi-inclusive)

=> H(e,e' Δ), D(e,e' Δ) (Delta production)

Δ++ → π⁺ + p
Δ⁺ → π⁺ + n
Δ⁰ → π⁻ + p
Δ⁻ → π⁻ + n

=> H(e,e' ρ), D(e,e' ρ) (Rho production)

ρ⁰ → π⁺ + π⁻

Peter Bosted and Dave Gaskell are working on improving SIDIS model, Delta Production, and Exclusive model.
Data and Simulation (SIMC) Yields \((x = 0.4, z = 0.7, Q^2 = 4.0 \text{ GeV}^2)\)

\[ W^2 > 4 \text{ GeV}^2, M_x^2 > 1.6 \text{ GeV}^2 \]

\[
\text{SIMC}_{\text{sum}} = (\text{Inclusive} + \text{Exclusive} + \text{Delta}) \text{ Pion-Production using SIMC}
\]
Data and Simulation (SIMC) Yields: $x = 0.4$, $z = 0.6$ (top), and $z = 0.5$ (bottom), $Q^2 = 4.0\text{ GeV}^2$

SIMC\_sum = (Inclusive + Exclusive + Delta) Pion-Production using SIMC
Data and SIMC Yield Ratios: $x = 0.4, Q^2 = 4.0 \text{ GeV}^2, z = 0.7, 0.6, \text{ and } 0.5$

Red Points are $\text{Pi}^+/\text{Pi}^-$ Yield Ratio From SIMC

Blue Points are $\text{Pi}^+/\text{Pi}^-$ Yield Ratio From Data

Black Points are $\text{Pi}^+/\text{Pi}^-$ SuperYield Ratio
i.e $\text{Data Yield Ratio} / \text{SIMC Yield Ratio}$
Projected Uncertainties from the Proposal

Predicted uncertainties for the charge symmetry violating quark distributions
This Experiment will:

- Extract the precise ratio of charged pion electro production using semi-Inclusive deep inelastic scattering from deuterium.

- Constrain the strength of charge symmetry violation in valence PDFs for the first time.

- Constrain the x-dependence of charge symmetry violating valence PDF

**Completed:** Detector calibrations, live time study, tracking efficiency, target boiling study.

**In Progress:** PID study, Detector efficiency study, optics study, comparison of extracted yield with simulation, radiative correction, uncertainty from diffractive $\rho^0$ production.

**Plan:** Obtain the precise cross-section ratio: $\pi^+/\pi^-$ and extraction of CSV.
I would like to acknowledge my advisors Dr. James Dunne, Dr. Dipangkar Dutta and Dr. Dave Gaskell for their continuous support. Many thanks to Dr. Peter Bosted, Dr. Whitney Armstrong, Dr. Arun Tadapalli, Shuo Jia and the Hall C Collaboration.

This work is supported by U.S. DOE Grant Number: DE-FG02-07ER41528

Thank You
Back Up Slides
CUTS

Pdelta = (-10 to 20)
Hdelta = (-8 to 8)
Hcal E/P > 0.75
Event type > 3 (all coincidence events)
Dipole Exit ==1 (Inside of the dipole)
GoodHosdostart =1
RF time = peak +/- 0.5 (total 1 ns width)
Coin Time = +/- 2 ns (for fall or even +/- 2.2 ns, depends) and +/- 1.5 ns (Spring)
Aero > 4
HGCE not used so far.
Pcal E/P < 0.75
HCER not used so far.
HMS Xptar (H.gtr.th) = (-0.060 to + 0.060)
HMS Yptar (H.gtr.ph) = (-0.025 to + 0.025)
SHMS Xptar (P.gtr.th) = (-0.045 to + 0.045)
SHMS Yptar (P.gtr.th) = (- 0.028 to + 0.028)
W2 > 4 GeV2, Mx2 > 1.6 GeV2 (for data, simc Yield)
Current cut > 3 (or 5) uA
Data and SIMC Yield Ratios: $x = 0.4$, $Q^2 = 4.0 \text{ GeV}^2$, $z = 0.7, 0.6, \text{ and } 0.5$

Red Points are $\pi^+/\pi^-$ Yield Ratio From SIMC
Blue Points are $\pi^+/\pi^-$ Yield Ratio From Data
Black Points are $\pi^+/\pi^-$ SuperYield Ratio
i.e Data Yield Ratio/ SIMC Yield Ratio

Ratio Plots from Page 14-15, with same number of bins as in the $z$ distribution
HMS CAL Plots: hcer > 10, Aero > 8, xptar, yptar Cuts
Blue: All, Red = Acc. , Green = Acc Subtracted

Hcal Eff = 0.999
Pcal Eff = 0.927
Get this ratio:

\[ D(z) \frac{R(x,z)}{R_{\text{Meas}}(x,z)} + A(x) C(x) = B(x,z) \]

\[ R_Y(x,z) = \text{Yield ratio} = \frac{Y_{\pi^+}(x,z)}{Y_{\pi^-}(x,z)}: \text{from the data} \]

\[ R_{\text{Meas}}^D(x,z) = \frac{(4 - R_Y(x,z))}{(R_Y(x,z)-1)} \]

\[ R(x,z) = \frac{5}{2} + R_{\text{Meas}}^D(x,z) \]

Goal: By using the measured yield ratio of \( \pi^+ \) over \( \pi^- \) for different \( Q^2 \) at various \( x \) and \( z \), we will extract \( C(x) \) and \( D(z) \).
\[ \Delta(z) = \frac{D_{u}^{-}}{D_{u}^{+}} \]

where \( \Delta(z) \) is the ratio of the unfavored to the favored quark fragmentation functions;

\[ D(z) = \frac{1 - \Delta(z)}{1 + \Delta(z)} \]

\[ A(x) = \left[ \frac{-4}{3(u_{v}(x) + d_{v}(x))} \right] \]

\[ B(x,z) = \frac{5}{2} \left( \frac{\bar{u}(x) + \bar{d}(x)}{u_{v}(x) + d_{v}(x)} \right) + \frac{\Delta_{s}(z) [s(x) + \bar{s}(x)]}{u_{v}(x) + d_{v}(x)} \]

\[ R(x,z) = \frac{5}{2} + R_{Meas}^{D}(x, z) \]

\[ C(x) = CSV \, parameter = \delta d_{v} - \delta u_{v} \]

\[ D(z) \, R(x,z) + A(x) \, C(x) = B(x,z) \]
In 2001 NuTeV collaboration, using ν DIS, measured:

\[ \sin^2 \theta_W = 0.2277 \pm 0.0013 \text{(stat)} \pm 0.0009 \text{(syst)} \]

World average (not including NuTeV):

\[ \sin^2 \theta_W = 0.2227 \pm 0.0037 \]

3 \( \sigma \) discrepancy!!! \( \Rightarrow \) “NuTeV anomaly”

CSV corrections reduces the anomaly by about \( \sim 30\% \) (1\( \sigma \))


J.T. Londergan, Possible Explanations for The NuTeV Weinberg Angle Measurement

Huge amount of theoretical and experimental interests:
One of the Highly Cited Topic