Charge Symmetry Violation in the Valence Parton Distributions and Fragmentation Functions

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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.

$$[H, P_{CS}] = 0 \qquad P_{CS}\,|d\rangle = |u\rangle$$
$$P_{CS} = \exp(i\pi T2) \qquad P_{CS}\,|u\rangle = -\,|d\rangle$$

Low Energy: CS in nuclei

CS operator interchanges neutrons and protons

- 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

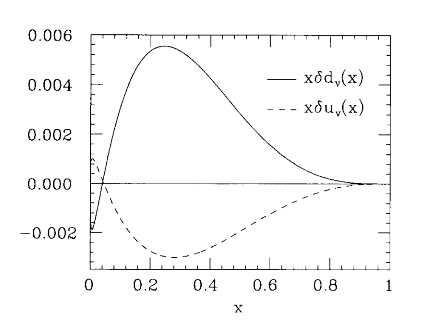
$$\delta u(x) = u^p(x) - d^n(x)$$
$$\delta d(x) = d^p(x) - u^n(x)$$

Model by Sather:

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

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

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

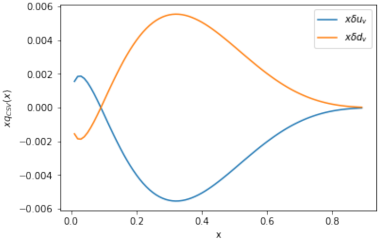


Model by Rodionov, Thomas and Londergan $\delta d(x)$ could reach up to 10% at high x

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

Upper Limits on CSV

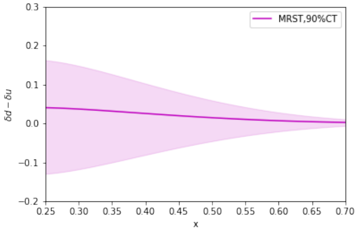
Phenomenological limits



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

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

The MRST group has included CSV in a phenomenological evaluation of PDFs. They used a wide range of high-energy data to get a global fit of PDFs
Eur. Phys. J.35(2004)325



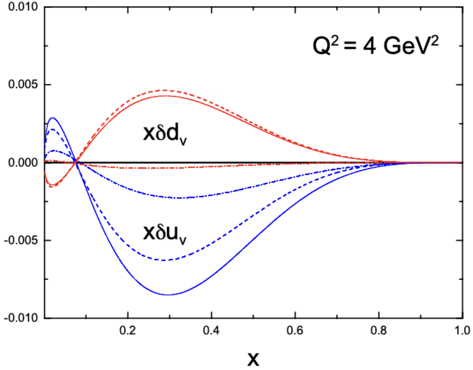
Upper Limits on CSV
Lattice QCD

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 comparable to the MRST prediction.

Physics Letters B, 753:595-599



Upper Limits on CSV

Experimental Limits

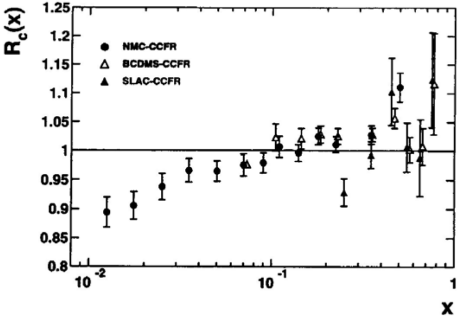
- Upper limit obtained by combining neutral and charged current data on isoscaler targets
- $F_{2\nu}$ by CCFR collaboration at FNAL (Fe data)
- $F_{2\gamma}$ by NMC collaboration using muons (D target)
- $0.1 \leq x \leq 0.4 \rightarrow$ **9% upper limit for CSV effect!**

"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, Progress in Nuclear and Particle Physics 41 (1998) 49-12

SIDIS Formalism

Charge Symmetry Violation

In the PDFs:
$\delta d(x) = d^p(x) - u^n(x), \delta u(x) = u^p(x) - d^n(x).$
$$CSV(x) = \delta d - \delta u$$

In Fragmentation Functions
$$\delta D(z) = \frac{D_u^{\pi^+} - D_d^{\pi^-}}{D_u^{\pi^+}}$$

Leading order methodology for iso-scaler targets (Londergan, Pang, and Thomas PRD54(1996)3154)

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

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

Factorization

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

Impulse Approximation

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

CSV in the Valence Region

Leading order experimental analysis $\rightarrow$ will need higher order global analysis

Londergan, Pang and Thomas PRD54(1996)3154

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

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

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

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

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

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

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

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

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

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

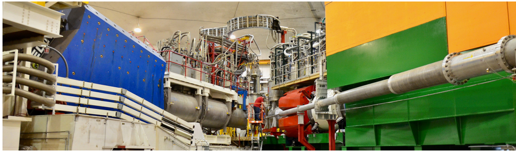
$A(x)$ and $B(x,z)$ are computed from PDF and FF fits

CSV

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

Experiment in Hall C – E12-09-002

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



Setup

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

Each x setting has 4 z measurements

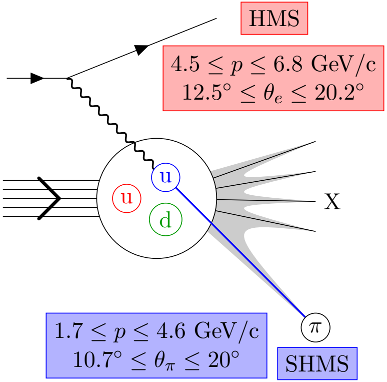
$$z_j = 0.4,\ 0.5,\ 0.6,\ 0.7$$

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

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

$$Q^2 = 3.5\ \text{GeV}^2 \rightarrow x = 0.30,\ 0.35,\ 0.40,\ 0.45$$

$$Q^2 = 5.1\ \text{GeV}^2 \rightarrow x = 0.45,\ 0.50,\ 0.55,\ 0.60$$



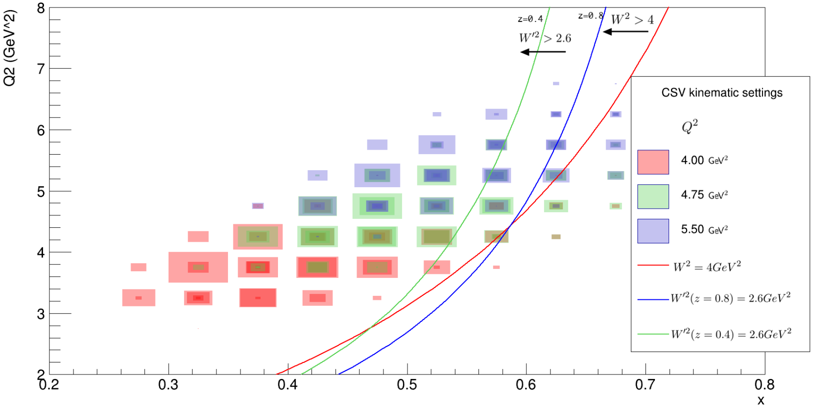
Assuming $\delta D(z) = 0$, for each Q^2 we have 16 equations and 8 unknowns: $D(z_j)$ and $CSV(x_i)$

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

Experiment E12-09-002

Kinematic Coverage

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



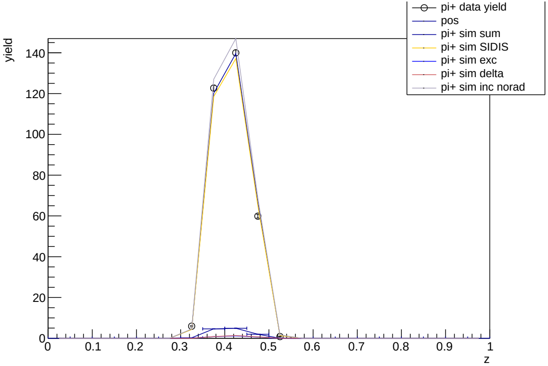
$$W'^2 = M^2 + Q^2(1 - z)(1/x - 1)$$

Measured Yields

Radiative Corrections and Background Subtractions

Looking at a single setting:

$\langle x\rangle = 0.35$, $\langle Q^2\rangle = 4$ GeV^2, $\langle z\rangle = 0.4$



Backgrounds

- Y_{Dummy}: Target window subtraction from dummy target
- Y_{exc}: Exclusive radiative tail
- Y_{Δ}: Δ production background
- Y_{ρ}: Symmetric ρ production background
  $\rho \to \pi^+\pi^-$
  The dominant systematic the uncertainty

Radiative corrections

$\mathrm{R_c} = \frac{Y_{norad}}{Y_{rad}+Y_{exc}+Y_{\Delta}+Y_{\rho}}$

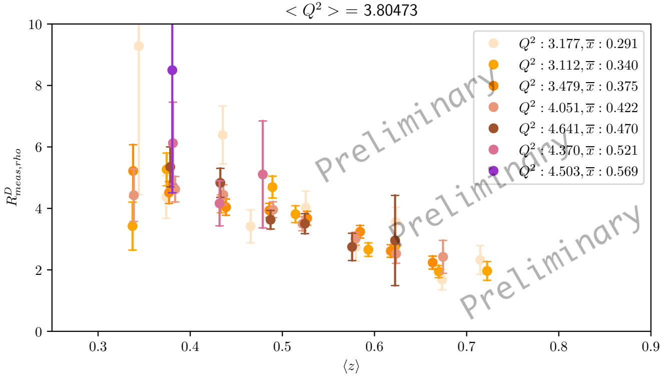
where $Y_{rad/norad}$ are simulated yields with radiative effects turned on/off.

$$Y_D(x,z) = R_c(Y^D_{\mathrm{corr}} - 0.245Y_{\mathrm{Dummy}})$$

R^D_{meas} Results

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

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



$R^D_{meas}(x,z)$ for $Q^2 = 4$ GeV^2 bin projected on z axis.

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

Simultaneous Extraction of $\Delta(z)$ and $CSV(x)$

Fragmentation ratio and valence CSV parton distribution

Four parameter fit

$$\Delta(z) \equiv \frac{D_u^{\pi^-}(z)}{D_u^{\pi^+}(z)} = z^{\alpha}(1-z)^{\beta}$$

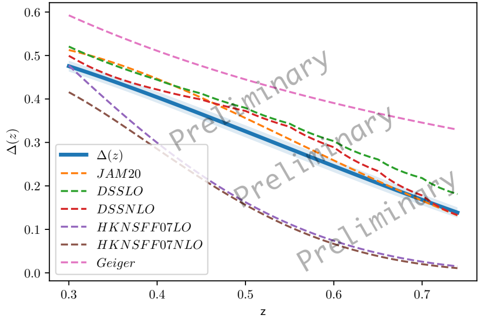
$$CSV x \equiv \delta d - \delta u = x^a(1-x)^b(x-c)$$

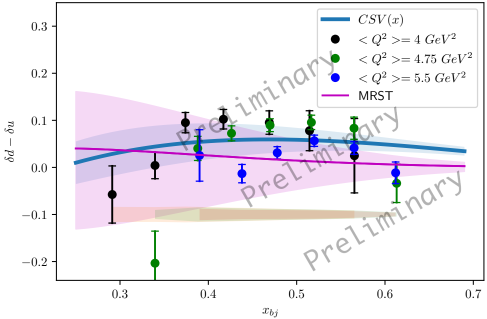
c is determined from the constraint: $\int_0^1 CSV(x)dx = 0$

$$c = \frac{\int_0^1 x^{(a+1)}(1-x)^b}{\int_0^1 x^a(1-x)^b} = \frac{B(a+2,b+1)}{B(a+1,b+1)}, B(x,y) = \frac{\Gamma(x)\Gamma(y)}{\Gamma(x+y)}$$

$$R^D_{fit}(x,z) = \frac{B(x,z) - A(x)CSV(x)}{D(z)} - \frac{5}{2}$$

Results after standard ρ background subtraction





$$\Delta(z) \equiv D_u^{\pi^-}(z)/D_u^{\pi^+}(z) = z^{\alpha}(1-z)^{\beta}$$

$$CSVx \equiv \delta d - \delta u = x^{a}(1-x)^{b}(x-c)$$

The data points on the right are plotted using the extracted Δ, $R^{D}_{meas}(x,z)$, and the equation below

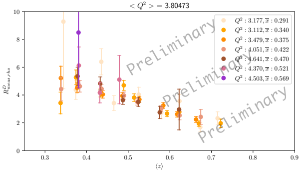
$$CSV(x) = \frac{B(x,z) - D(z)\ R(x,z)}{A(x)}$$

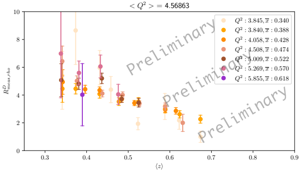
Preliminary R^D_{meas}

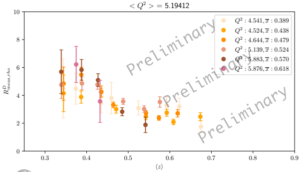
$$D(z)\ \left[\frac{5}{2} + R^D_{meas}(x,z)\right] + A(x)CSV(x) = B(x,z)$$

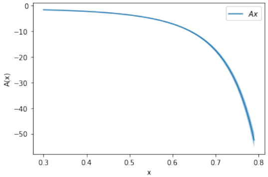
$$\leftarrow \quad R^D_{meas}(x,z) = \frac{4N^{D\pi^-}(x,z) - N^{D\pi^+}(x,z)}{N^{D\pi^+}(x,z) - N^{D\pi^-}(x,z)}$$

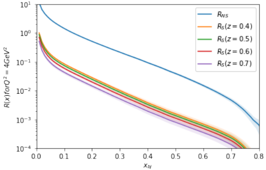
Model inputs:





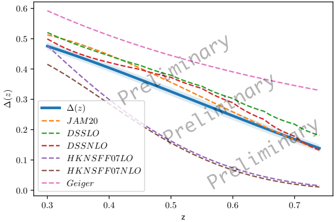


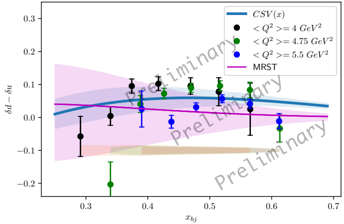




$$A(x) = \frac{-4}{3(u_v + d_v)}$$

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





From Shuo Jia

Using Fragmentation Functions from Global Fits

Directly compute $CSV(x)$ from data

$$CSV(x) = \frac{B(x,z) - D(z)\ R(x,z)}{A(x)}$$

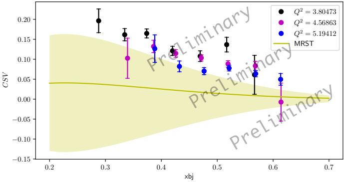
$$D(z) = \frac{1-\Delta(z)}{1+\Delta(z)}$$

$$\Delta(z) = D_u^{\pi^-}(z)/D_u^{\pi^+}(z)$$

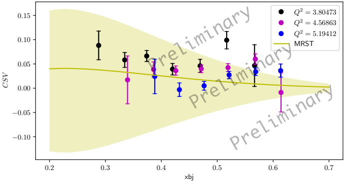
Where is the CS violation?

- Using FFs without CSV there is a tension with previous analyses/limits
  - Insufficient ρ background subtraction
  - High order corrections
- FFs **with CSV** lead to much better agreement with
  $\rightarrow$ CSV in FFs

JAM PDFs and FFs



JAM PDFs and DSS FFs

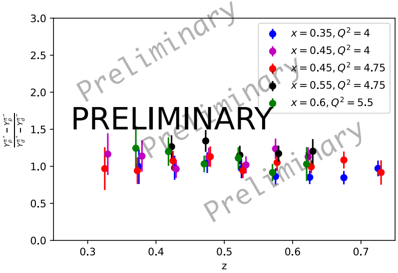


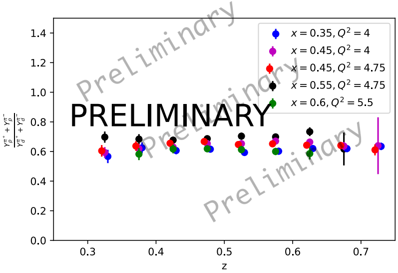
Factorization

Charge Ratio Sum and Differences

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

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





Ratios should not depend on z.

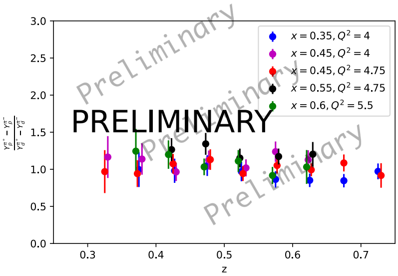
$$\frac{\sigma_p^{\pi^+} + \sigma_p^{\pi^-}}{\sigma_d^{\pi^+} + \sigma_d^{\pi^-}} = \frac{4u + 4\overline{u} + d + \overline{d}}{5(u + \overline{u} + d + \overline{d})}$$

Factorization

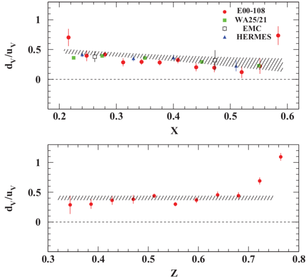
Charge Ratio Sum and Differences

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

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



Ratios should not depend on z.



Previous 6-GeV era JLab experiment in Hall-C observed nearly z-independent ratio. JLab E00-108: PRC 85, 015202 (2012)

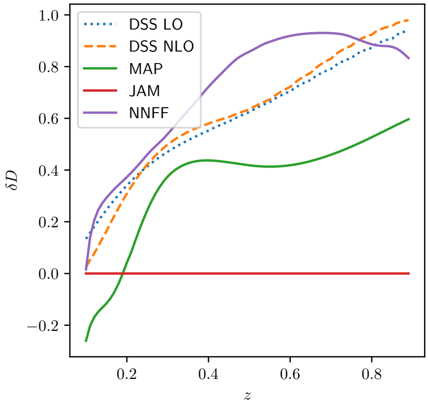
Summary

- Conducted precision semi-inclusive measurements of the π^-/π^+ ratio on a deuterium target
- Extracted the LO valence CSV parton distribution and fragmentation function ratio
- Using different FF models input suggests a CSV contribution from the fragmentation functions should be considered in a global analysis
- Results for the CSV parton distribution are consistent with MRST limits.
- Some CSV in the fragmentation functions improves shapes of fits and leads to good agreement with nominal ρ BG subtraction

Thank you!

Backups

CSV in Fragmentation Function



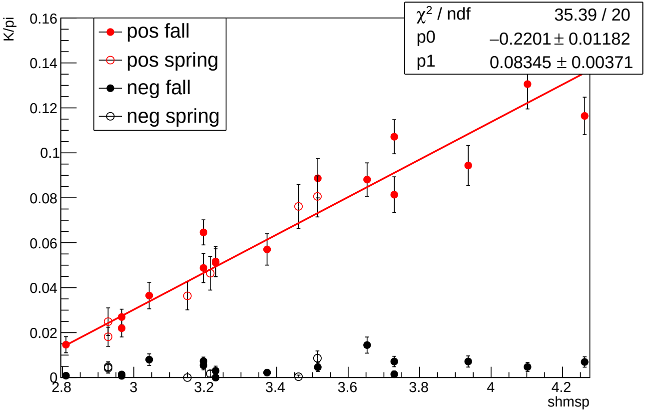
2007 HKNS - no CSV
2007 DSS - CSV
2014 DEHSS - no CSV
2017 NNFF - CSV
2020 JAM - no CSV
2021 MAPFF - CSV

Update to DSS, DEHSS finds $\delta D = 0$.

Kaon/Pion Ratio

$$R_{K/pi} = \frac{N^{K}_{antiHGC}}{N^{\pi}_{withHGC} + N^{\pi}_{antiHGC}}$$

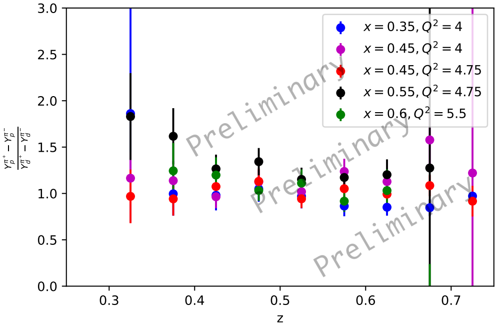
One point for each Run-group, plotted as a function of momentum. The kaon to pion ratio increases with high momentum, which is higher z. There are more K^+ than K^-

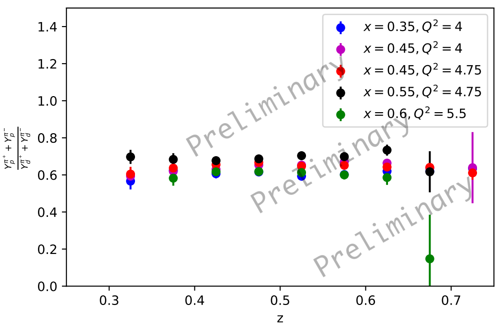


H_2 runs results

H_2 runs are taken for some kinematic to test the assumption of factorization.

$$\frac{\sigma_p^{\pi^+} - \sigma_p^{\pi^-}}{\sigma_d^{\pi^+} - \sigma_d^{\pi^-}} = \frac{4u_v - d_v}{3(u_v + d_v)} \qquad \frac{\sigma_p^{\pi^+} + \sigma_p^{\pi^-}}{\sigma_d^{\pi^+} + \sigma_d^{\pi^-}} = \frac{4u + 4\overline{u} + d + \overline{d}}{5(u + \overline{u} + d + \overline{d})}$$





Charge Symmetry in QPM

Charge-conjugation symmetry

Relates quarks and anti-quarks

$$D_{\bar{u}}^{\pi^{\pm}} = D_{\bar{u}}^{\pi^{\mp}} \quad (2)$$

$$D_{\bar{d}}^{\pi^{\pm}} = D_{\bar{d}}^{\pi^{\mp}} \quad (3)$$

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