Pion structure from leading neutron electroproduction

Wally Melnitchouk

with Chueng Ji (NCSU), Josh McKinney (UNC), Nobuo Sato (JLab), Tony Thomas (Adelaide)
SU(2) flavor asymmetry

One of the seminal discoveries of last 25 years has been the SU(2) flavor asymmetry in the proton sea, $\bar{d} \neq \bar{u}$

\[
\int_0^1 \frac{dx}{x} (F_2^p - F_2^n) = \frac{1}{3} - \frac{2}{3} \int_0^1 dx (\bar{d} - \bar{u}) = 0.235(26)
\]

violation of Gottfried sum rule

\[
\frac{\sigma^{pd}}{2\sigma^{pp}} \approx \frac{1}{2} \left( 1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)} \right)
\]

$\ x_b \gg x_t$

\[
\int_0^1 dx (\bar{d} - \bar{u}) = 0.118 \pm 0.012
\]
SU(2) flavor asymmetry

One of the seminal discoveries of last 25 years has been the SU(2) flavor asymmetry in the proton sea, $\bar{d} \neq \bar{u}$

→ paradigm shift – nucleon not simply 3 valence quarks + homogenous $\bar{q}q$ sea!

→ vital role played by nonperturbative dynamics, e.g. chiral symmetry breaking & nucleon’s pion cloud

→ asymmetry actually predicted a decade earlier from “Sullivan” process

\[ (\bar{d} - \bar{u})(x) = \int_x^1 \frac{dy}{y} f_{\pi^+n}(y) \bar{q}_v^\pi(x/y) \]

pion momentum distribution in nucleon, or $p \to \pi^+n$ “splitting function”

A.W. Thomas, PLB 126, 97 (1983)
Chiral effective theory

Splitting function can be computed in chiral effective theory of QCD (e.g. chiral perturbation theory)

At lowest order, effective (low-energy) $\pi N$ Lagrangian

\[
\mathcal{L}_{\pi N} = \frac{g_A}{2f_\pi} \bar{\psi}_N \gamma^\mu \gamma_5 \vec{\pi} \cdot \partial_\mu \vec{\pi} \psi_N - \frac{1}{(2f_\pi)^2} \bar{\psi}_N \gamma^\mu \vec{\pi} \cdot (\vec{\pi} \times \partial_\mu \vec{\pi}) \psi_N
\]

\[
= -g_{\pi NN} \bar{\psi}_N i\gamma_5 \vec{\pi} \cdot \vec{\pi} \psi_N + \sigma NN \text{ term} + \text{ higher order}
\]

\[g_A = 1.267 \quad f_\pi = 93 \text{ MeV}\]

Weinberg, PRL 18, 88 (1967)

→ pseudoscalar interaction often used for simplicity – results generally different from pseudovector theory
Chiral effective theory

Coupling of e.m. current to nucleon dressed by pions

- Bare (a)
- Wfn renormalization (b)
- $N$ rainbow (c)
- $\pi$ rainbow (d)
- Kroll-Ruderman (for gauge invariance) (e)
- $\pi$ bubble (f)
- Tadpole (g)

Ji, WM, Thomas, PRD 88, 076005 (2013)
Chiral effective theory

Coupling of e.m. current to nucleon dressed by pions

- Bare
- N rainbow
- $\pi$ rainbow
- $\pi$ bubble
- Tadpole

Contribute to $\bar{d} - \bar{u}$

Ji, WM, Thomas, PRD 88, 076005 (2013)
Pion splitting functions

Splitting function for pion rainbow diagram has on-shell and $\delta$-function contributions

$$f_\pi(y) = f^{(on)}(y) + f^{(\delta)}(y)$$

- $f^{(on)}(y) = \frac{g_A^2 M^2}{(4\pi f_\pi)^2} \int dk_\perp^2 \frac{y(k_\perp^2 + y^2 M^2)}{[k_\perp^2 + y^2 M^2 + (1 - y)m_\pi^2]^2} \mathcal{F}^2$

- $f^{(\delta)}(y) = \frac{g_A^2}{4(4\pi f_\pi)^2} \int dk_\perp^2 \log \left( \frac{k_\perp^2 + m_\pi^2}{\mu^2} \right) \delta(y) \mathcal{F}^2$

Bubble diagram contributes only at $y = 0$ (hence $x = 0$)

$$f^{(bub)}(y) = \frac{8}{g_A^2} f^{(\delta)}(y)$$

Salamu, Ji, WM, Wang
PRL 114, 122001 (2015)
Pion splitting functions

- **Infrared behavior is model independent**

- **leading nonanalytic (LNA) structure of moments**

\[
\int_0^1 dx \ (\bar{d} - \bar{u}) = \frac{(3g_A^2 - 1)}{(4\pi f_\pi)^2} \ m_\pi^2 \log(m_\pi^2/\mu^2) + \text{analytic in } m_\pi^2
\]

*Thomas, WM, Steffens, PRL 85, 2892 (2000)*

- **can only be generated by pion loops – nonzero \( \pi \) cloud contribution predicted by QCD!**

- **vital e.g. for chiral extrapolation of lattice data**

*Detmold et al. PRL 87, 172001 (2001)*
Ultraviolet-divergent integrals for point-like particles

Finite size of nucleon provides natural scale to regularize integrals, but does not prescribe form of regularization

→ freedom in choosing regularization prescription

\[ \mathcal{F} = \Theta(\Lambda^2 - k_{\perp}^2) \]

\[ \mathcal{F} = \left( \frac{\Lambda^2 - m_{\pi}^2}{\Lambda^2 - t} \right) \]

\[ \mathcal{F} = \exp \left[ \frac{(t - m_{\pi}^2)}{\Lambda^2} \right] \]

\[ \mathcal{F} = \exp \left[ \frac{(M^2 - s)}{\Lambda^2} \right] \]

\[ \mathcal{F} = \left[ 1 - \frac{(t - m_{\pi}^2)^2}{(t - \Lambda^2)^2} \right]^{1/2} \]

\[ \mathcal{F} = y^{-\alpha_{\pi}(t)} \exp \left[ \frac{(t - m_{\pi}^2)}{\Lambda^2} \right] \]

\[ \mathcal{F} = y^{-\alpha_{\pi}(t)} \]

\( k_{\perp} \) cutoff

monopole in \( t \equiv k_{\perp}^2 = -\frac{k_{\perp}^2 + y^2 M^2}{1 - y} \)

exponential in \( t \)

exponential in \( s = \frac{k_{\perp}^2 + m_{\pi}^2}{y} + \frac{k_{\perp}^2 + M^2}{1 - y} \)

Pauli-Villars

Regge

Bishari
Detailed shape of splitting function depends on regularization, but common general features

e.g. on-shell function

At \( x > 0 \), only on-shell part contributes

\[
(\bar{d} - \bar{u})(x) = [2f^{(on)} \otimes q^\pi_v](x)
\]
Flavor asymmetry

- E866 $d - \bar{u}$ data can be fitted with range of regulators

with exception of $k_\perp$ cutoff and Bishari models, all others give reasonable fits, $\chi^2 \lesssim 1.5$

- large-$x$ asymmetry to be probed by FNAL SeaQuest expt.

average pion "multiplicity"

$$\langle n \rangle_{\pi N} = 3 \int_0^1 dy f_{N}^{(on)}(y)$$

$$\sim 0.25 - 0.3$$
Flavor asymmetry

- E866 $\bar{d} - \bar{u}$ data can be fitted with range of regulators

- Is pion cloud the only explanation for the asymmetry?

  - are there other data that can discriminate between different mechanisms?

  - semi-inclusive production of “leading neutrons” (LN) at HERA!
**Leading neutron production at HERA**

- **ZEUS & H1 collaborations** measured spectra of neutrons produced at very forward angles, $\theta_n < 0.8$ mrad

- Can data be described within the same framework as E866 flavor asymmetry?

- Simultaneous fit never previously been performed
Leading neutron production at HERA

**Measured LN differential cross section (integrated over $p_{\perp}$)**

\[
\frac{d^3\sigma^{\text{LN}}}{dx\,dQ^2\,dy} \sim F_2^{\text{LN}(3)}(x, Q^2, y)
\]

E.g.

\[
2f_N^{(\text{on})}(y) F_2^\pi(x/y, Q^2)
\]

for $\pi$ exchange

\[
r = \frac{d\sigma^{\text{LN}}}{d\sigma^{\text{inc}}}
\]

→ quality of fit depends on range of $y$ fitted
At large $y$, non-pionic mechanisms contribute (e.g. heavier mesons, absorption)

To reduce model dependence, fit the value of $y_{\text{cut}}$ up to which data can be described in terms of $\pi$ exchange
Fit requires higher momentum pions with increasing $y_{\text{cut}}$

- Larger values of $y_{\text{cut}}$ more in conflict with E866 data
Leading neutron production at HERA

Combined fit to HERA LN and E866 Drell-Yan data

$\chi^2_{\text{dof}}$ vs $y_{\text{cut}}$

**ZEUS + H1**

$t_{\text{mon}}$
$t_{\text{exp}}$
$s_{\text{exp}}$
$PV$
$\text{Regge}$
$\text{Bishari}$
$k_{\perp}\text{ cut}$

**ZEUS + H1 + E866**

McKenney, N. Sato, WM, C. Ji
*PRD 93, 700205 (2016)*
Leading neutron production at HERA

Combined fit to HERA LN and E866 Drell-Yan data

best fits for largest number of points afforded by $t$-dependent exponential (and $t$ monopole) regulators

McKenney, N. Sato, WM, C. Ji
PRD 93, 700205 (2016)
Leading neutron production at HERA

Fit to ZEUS LN spectra for $y_{\text{cut}} = 0.3$ ($t$-dependent exponential)
Leading neutron production at HERA

**Fit to H1 LN spectra for** \( y_{\text{cut}} = 0.3 \) \((t\text{-dependent exponential})\)

\[ F_{2}^{\text{LN}(3)} \times (2^i) \]

\[ Q^2 = 7.3 \text{ GeV}^2 \]

\[ Q^2 = 11 \text{ GeV}^2 \]

\[ Q^2 = 16 \text{ GeV}^2 \]

\[ Q^2 = 24 \text{ GeV}^2 \]

\[ Q^2 = 37 \text{ GeV}^2 \]

\[ Q^2 = 55 \text{ GeV}^2 \]

\[ Q^2 = 82 \text{ GeV}^2 \]

\[ y = 0.095 \]

\[ y = 0.185 \]

\[ y = 0.275 \]

HERA+E866 fit

\[ \chi_{\text{dof}}^2 = 1.27 \]

for 202 (187+15) points

\textit{H1, EPJC 68, 381 (2010)}
Extracted pion structure function

\[ F_2^\pi = N x_\pi^a (1 - x_\pi)^b, \quad a = a_0 + a_1 \eta \]
\[ \eta \sim \log(\log Q^2) \]

\[ y_{\text{cut}} = 0.3 \]

- stable values of \( F_2^\pi \) at \( 4 \times 10^{-4} \lesssim x_\pi \lesssim 0.03 \) from combined fit
- shape similar to GRS fit to \( \pi N \) Drell-Yan data (for \( x_\pi \gtrsim 0.2 \)), but smaller magnitude

McKenney, N. Sato, WM, C. Ji
PRD 93, 700205 (2016)
Predictions at TDIS kinematics

\[ F_{2}^{LP (3)} = f_{\pi-p}(y) F_{2}^{\pi}(x_{\pi}, Q^2) \]

→ JLab TDIS (“tagged” DIS, \(e d \rightarrow e p p X\)) experiment can fill gap in \(x_{\pi}\) coverage between HERA and \(\pi N\) Drell-Yan kinematics
Outlook

- Combined analysis can be extended by including also $\pi N$ Drell-Yan data

  $\rightarrow$ constrain large-$x_\pi$ region ($x_\pi \gtrsim 0.2$)

- Generalize parametrization by fitting individual pion valence and sea quark PDFs, rather than $F^\pi_2$

- Ultimate goal will be to use all data sensitive to pion structure (including TDIS, EIC?) to constrain pion PDFs over full range $10^{-4} \lesssim x_\pi \lesssim 1$