Tagged Structure Functions

Sebastian Kuhn
Old Dominion University
Overview

• Spectator Tagging – the why and how
• BONuS

• BONuS12
  – New RTPC
  – RG F: Other options
Why neutron?

\( d(x) \) and \( u(x) \) as \( x \to 1 \)

- Valence structure of the nucleon - sea quarks and gluons don’t contribute
- SU(6)-symmetric wave function of the proton in the quark model:

\[
|p \uparrow\rangle = \frac{1}{\sqrt{18}} \left( 3u \uparrow [ud]_{S=0} + u \uparrow [ud]_{S=1} - \sqrt{2}u \downarrow [ud]_{S=1} - \sqrt{2}d \uparrow [uu]_{S=1} - 2d \downarrow [uu]_{S=1} \right)
\]

- In this model: \( d/u = 1/2, \Delta u/u^* = 2/3, \Delta d/d = -1/3 \) for all \( x \)
- Relativistic quark model: quark helicities reduced, orbital angular momentum introduced
- Hyperfine structure effect (1-gluon exchange): \( S=1 \) suppressed for small spectator pair mass \( \Rightarrow d/u = 0, \Delta u/u = 1, \Delta d/d = -1/3 \) for \( x \to 1 \)
- pQCD: helicity conservation \( (q^{\uparrow\uparrow}p) \Rightarrow \)
  \( d/u = 2/(9+1) = 1/5, \Delta u/u = 1, \Delta d/d = 1 \) for \( x \to 1 \)
- Wave function of the neutron via isospin rotation:
  replace \( u \to d \) and \( d \to u \) \( \Rightarrow \) using experiments with protons and neutrons one can extract information on \( u, d, \Delta u \) and \( \Delta d \) in the valence quark region.

*) spin dependent quark density \( \Delta q = (q^{\uparrow} - q^{\downarrow}) \) for Nucleon \( \uparrow \)
Structure Functions and Resonances

- Precise structure functions in Resonance Region constrain nucleon models
  [Separate resonant from non-resonant background; isospin decomposition]
- Needed as input for spin structure function data, radiative corrections,…
- Compare with DIS structure functions to test duality
Present Knowledge of $d/u \ (x \rightarrow 1)$

Assuming charge independence (= invariance under $180^\circ$ rotations in isospin space):

$$\frac{F_{2n}}{F_{2p}} \approx \frac{1 + 4d/u}{4 + d/u} \Rightarrow$$

$$d \approx \frac{4 F_{2n}/F_{2p} - 1}{4 - F_{2n}/F_{2p}}$$

$$F_{2n}/F_{2p} = F_{2d}/F_{2p} - 1 \quad \text{???}$$

- Neutron data limited by “Nuclear Binding Uncertainties”
Neutron Data Are Important…
…but hard to get

- Free neutrons decay in 15 min.
- Radioactivity!
- Zero charge makes it difficult to create a dense target
  - Magnetic bottle: $10^3 - 10^4$ n/cm$^2$ [TU München]
  - Typical proton target: $4 \cdot 10^{23}$ p/cm$^2$ [10 cm LH – 10$^{14}$ p/cm$^2$ [HERMES]]

For the present neutron lifetime experiment, two options for the absorber height are used: $Hd = 55$ cm and $Hd = 75$ cm. The number of UCNs in the trap is equal respectively to $\approx 7.0 \cdot 10^4$ and $\approx 13.7 \cdot 10^4$.

• Alternative Solution: Deuterons, Tritons and Helium-3…

BUT: Nuclear Model Uncertainties:
Fermi motion, off-shell effects (binding), structure modifications (EMC effect), extra pions/Deltas, coherent effects, 6-quark bags…

“Although an underground nuclear explosion is not the most conventional neutron source, it offers definite advantages...”

Polarization Phenomena in Nuclear Reactions
Proceedings (1970)
Correlations and Spectators

- “Short-Range” Correlations in Nuclei: high-momentum nucleon balanced by opposite momentum nucleon “nearby” (< 2 fm ≪ nuclear radius).
- Correlations in deuterium: 100% all the time (high or low momentum). Except for FSI, 2 nucleons are perfectly entangled → can infer initial state of one from measured final state of the other.

\[ \text{d(e,e'p_s)X} \]

\[ p_n = \left( M_D - E_S, -\vec{p}_S \right); \quad \alpha_n = 2 - \alpha_S; \quad M^*^2 = p_n^\mu p_{n\mu} \]

\[ x = \frac{Q^2}{2p_n^\mu q_\mu} \approx \frac{Q^2}{2M\nu(2-\alpha_S)} \]

\[ W^*^2 = (p_n + q)^2 = M^*^2 + 2((M_D - E_s)\nu - \vec{p}_n \cdot \vec{q}) - Q^2 \]

\[ \approx M^*^2 + 2M\nu(2-\alpha_S) - Q^2 \]

...however, FSI **must** change this picture by **necessity** since “struck nucleon” is off-shell.
The Solution: Spectator Tagging

\[ d(e,e'p_s)X \]

\[ p_n = (M_D - E_S, -\vec{p}_s); \alpha_n = 2 - \alpha_S \]

\[ \gamma^* \]

\[ p_s = (E_S, \vec{p}_s); \quad \alpha_S = \frac{E_s - \vec{p}_s \cdot \hat{q}}{M_D / 2} \]

Relativistic Invariants

\[ x = \frac{Q^2}{2 p_n^\mu q_\mu} \approx \frac{Q^2}{2 M \nu (2 - \alpha_S)} \]

\[ M^*^2 = p_n^\mu p_n^{\mu} \approx \left( M_n - \varepsilon - \frac{\vec{p}_s^2}{M_n} \right)^2 \approx M_n^2 - 2 M_n \varepsilon - 2 \vec{p}_s^2 \]

\[ W^*^2 = (p_n + q)^2 = M^*^2 + 2 ((M_D - E_s)\nu - \vec{p}_n \cdot \hat{q}) - Q^2 \]

\[ \approx M^*^2 + 2 M \nu (2 - \alpha_S) - Q^2 \]

\[ D(e,e'p_s)X: \text{ Cts vs. } W^* \]

\[ D(e,e')X: \text{ Cts vs. } W \]
Modifications to Simple Spectator Picture


Palli et al, PRC80(09)054610

W. Melnitchouk, A.W. Schreiber and A.W. Thomas,
BoNuS RTPC

Helium/DME at 80/20 ratio
dE/dx from charge along track (particle ID)

Gas Electron Multiplier

7 atm D$_2$ gas
Thin-wall High Pressure Gas Target

Drift Region

3 GEMs

Møller el. e$^-$ (to CLAS)

Thin Al-Mylar Window

3 GEMs

Readout pads and electronics

φ, z from pads r from time

Results from BONUS

FIG. 10. Ratio of experimental data (with subtracted background and elastic tail) to the simulation as a function of $Q^2$. The range of $Q^2$ is from 1.35 to 1.6 GeV/$c^2$. The inset shows the average value was obtained from a global analysis of the EMC effect

FIG. 2. (Color online) The deuteron EMC ratio for the different cases, the 1% scale uncertainty, expected rise above the statistical and systematic errors from the BONuS data, and the French Commissariat à l'Energie Atomique, the U.S. person Lab accelerator, Scottish Universities Physics Alliance (SUPA), and the Chilean Comisión Nacional de Energía Atómica (CNEA) as well as the U.S. Department of Energy.

Overall systematic uncertainties were estimated by varying the statistical and systematic errors from the BONuS data, and the BONuS systematic uncertainty. The ratio gives us the most direct information as expected rise above the statistical and systematic errors from the BONuS data, and the statistical and systematic errors from the BONuS data. The ratio is either binned finely in 90 bins of 0.03-GeV/$c^2$ or integrated over bins in momentum transfer is averaged over 10 evenly spaced bins.

The goal of this section is to assess in which kinematic region of its applicability, the within the kinematic region of its applicability, the Scottish Universities Physics Alliance (SUPA), and the U.S. person Lab accelerator. The hypothesis that variations in the various systems, more precise studies of the nuclear EMC effect are expected as a result of the BONuS experiment, which accessed for the first time the DIS limit for the different cases, the 1% scale uncertainty, expected rise above the statistical and systematic errors from the BONuS data, and the French Commissariat à l'Energie Atomique, the U.S. person Lab accelerator, Scottish Universities Physics Alliance (SUPA), and the Chilean Comisión Nacional de Energía Atómica (CNEA) as well as the U.S. Department of Energy.

Overall systematic uncertainties were estimated by varying the statistical and systematic errors from the BONuS data, and the BONuS systematic uncertainty. The ratio gives us the most direct information as expected rise above the statistical and systematic errors from the BONuS data, and the French Commissariat à l'Energie Atomique, the U.S. person Lab accelerator, Scottish Universities Physics Alliance (SUPA), and the Chilean Comisión Nacional de Energía Atómica (CNEA) as well as the U.S. Department of Energy.

Within the kinematic region of its applicability, the within the kinematic region of its applicability, the Scottish Universities Physics Alliance (SUPA), and the French Commissariat à l'Energie Atomique, the U.S. person Lab accelerator, Scottish Universities Physics Alliance (SUPA), and the Chilean Comisión Nacional de Energía Atómica (CNEA) as well as the U.S. Department of Energy.

Overall systematic uncertainties were estimated by varying the statistical and systematic errors from the BONuS data, and the BONuS systematic uncertainty. The ratio gives us the most direct information as expected rise above the statistical and systematic errors from the BONuS data, and the French Commissariat à l'Energie Atomique, the U.S. person Lab accelerator, Scottish Universities Physics Alliance (SUPA), and the Chilean Comisión Nacional de Energía Atómica (CNEA) as well as the U.S. Department of Energy.

Within the kinematic region of its applicability, the within the kinematic region of its applicability, the Scottish Universities Physics Alliance (SUPA), and the French Commissariat à l'Energie Atomique, the U.S. person Lab accelerator, Scottish Universities Physics Alliance (SUPA), and the Chilean Comisión Nacional de Energía Atómica (CNEA) as well as the U.S. Department of Energy.

Overall systematic uncertainties were estimated by varying the statistical and systematic errors from the BONuS data, and the BONuS systematic uncertainty. The ratio gives us the most direct information as expected rise above the statistical and systematic errors from the BONuS data, and the French Commissariat à l'Energie Atomique, the U.S. person Lab accelerator, Scottish Universities Physics Alliance (SUPA), and the Chilean Comisión Nacional de Energía Atómica (CNEA) as well as the U.S. Department of Energy.
Data from “BONuS” experiment with CLAS and 6 GeV beam. Spectator proton momenta from 70 – 150 MeV/c
BONuS12 at 11 GeV

BoNuS12 E12-06-113

• Data taking for 35 days on $D_2$, 4 days on $H_2 + 1$ day aux.
  with $\mathcal{L} = 2 \cdot 10^{34}$ nuclei/cm$^2$ s$^{-1}$
  plus 2 days commissioning at 2.2 GeV

• **NEW** RTPC detector, DAQ

• DIS region with
  - $Q^2 > 1$ GeV$^2/c^2$
  - $W^* > 2$ GeV
  - $p_s > 70$ MeV/$c$
  - $10^\circ < \theta_{pq} < 170^\circ$
BONuS12 RTPC replaces SiVtxT + Barrel μmegas (but forward Vtx tracking may be needed!)
BONuS12 RTPC w/ target

Complete Assembly

- Readout Board
- GEM layers (3)
- Field Cage disks
- Ground foil
- Cathode foil
- Outlet gas port
- Inlet gas ports (4)
- Chamfer

Beam
BONuS12 Detector Construction

- GEM foil wrapping and gluing
- Prototype read-out board on surface uniformity test station
- Detector assembly station
- Puller assembly
- Automated epoxy application
- GEM foil wrapping and gluing
- Removal of glued GEM foil using puller mechanism

Readout adapter board with overvoltage protection

• Replace SVT+MVT by the RTPC detector
• Use MVT DAQ crate for BONuS12
• Coordination with SVT and MVT group for the deinstallation and installation of the detectors

CEBAF Large Acceptance Spectrometer (CLAS) at Hall B
Figure 2.3: Projected uncertainties (offset for display) for JLab 12-GeV measurements of the ratios of the PDFs for the d and u quarks at large momentum fraction x. The yellow band represents the uncertainty in the existing measurements under several theoretical assumptions. Various predictions for this ratio in the limit of x = 1 are given by the blue lines.
What else can we do with RG F?

- EMC effect in D
  - tag on slow/fast p; bench mark for heavier nuclei? FSI, d WF,…
- “LAND” experiment E12-11-003A
  - tag p structure in d with backward n (Approved Run Group proposal, PAC43; Or Hen, L. Weinstein, E. Piasetzky, H. Hakobyan)
- nDVCS?
  - At least calibrate CND and get first sample without nuclear distortions; fully exclusive!
- n Form Factors? Alternative method to cross check
- n resonances? (Use forward tagger)
- n SIDIS? (Flavor tagging, TMDs)
- phi-N bound state: Au(γ*,pK+K−)