First Results from BONuS12

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Overview

- Collinear valence structure of the nucleon
 - Test of our understanding of bound-state QCD
- Unpolarized structure functions of the neutron
 - Present landscape
 - BONuS12 experiment at Jefferson Lab
- Future Facilities what more can we do?
 - JLab at 20+ GeV?
- Conclusions

Structure functions

- Important benchmarks for understand origin of mass and spin of hadrons
- Important as limiting cases and constraints for TMDs, GPDs etc.
- Large x: Stringent tests of pQCD, Lattice QCD, DS approach, and phenomenological models
 - NN…LO + DGLAP
 - Input for novel and mature PDF extractions
 - Test of higher twist and target mass effects, resummation
 - Quark-hadron duality
- Important input for collider physics
- Input for investigations of modifications of quark distributions in nuclei
- Naïve Parton Model: $F_1(x) = \frac{1}{2} \sum_i e_i^2 q_i(x) \text{ (and } F_2(x) \approx 2xF_1(x) \text{)}$

At finite Q²: pQCD evolution - $q(x,Q^2) \Rightarrow$ Also, non-zero $R = \frac{F_2}{2xF_1} \left(\frac{4M^2x^2}{Q^2} + 1\right) - 1$, DGLAP equations), and gluon radiation Fixed target kinematics: $Q^2 \approx M^2 \Rightarrow$ target mass effects, higher twist contributions and resonance excitation





 $q(x;Q^2), \langle h \cdot H \rangle q(x;Q^2)$

"1-D" Parton Distributions (PDFs) (integrated over all transverse variables)



Valence Region: Structure Functions for $x \rightarrow 1$

- Dominated by up and down valence quarks => quantum numbers of the nucleon
- Important for higher power xⁿ moments => Mellin Moments, LQCD
- Related to high-Q², moderate *x* through DGLAP => relevant for LHC Physics
- MANY predictions based on models, pQCD, DS equation and Lattice QCD *):

SU(6)-symmetric proton wave function in the "naïve" 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

Hyperfine structure effect in QM: S=1 suppressed => d/u = 0, $\Delta u/u = 1$, $\Delta d/d = -1/3$ for $x \rightarrow 1$

pQCD: helicity conservation (q[↑]↑p) => d/u -> 2/(9+1) = 1/5, $\Delta u/u$ -> 1, $\Delta d/d$ -> 1 for $x \rightarrow 1$

Other approaches: Dyson-Schwinger Equation, statistical models, pQCD + orbital angular momentum, AdS (Light-front holographic QCD)

QUESTION: How to access d und u quark PDFs? One approach: d in proton = u in neutron => $F_{2n}/F_{2p} = (4 d/u + 1) / (4 + d/u)$

^{*)} Moments, quasi-PDFs, pseudo-PDFs

High-x PDFs: Input for Collider experiments Ex.: High-Precision Measurement of the W Boson Mass with the CDF II Detector Ashutosh Kotwal, Duke University Jefferson Lab Users Meeting June 14, 2022

Parton Distribution Functions

- Affect W boson kinematic line-shapes through acceptance cuts
- We use NNPDF3.1 as the default NNLO PDFs
- Use ensemble of 25 'uncertainty' PDFs => 3.9 MeV A. V. Kotwal, JLab Users Meeting, 6/14/22
- Central values from NNLO PDF sets CT18, MMHT2014 and NNPDF3.1 agree within 2.1 MeV of their midpoint
- As an additional check, central values from NLO PDF sets ABMP16, CJ15, MMHT2014 and NNPDF3.1 agree within 3 MeV of their midpoint

"For example, the cj15 set includes all Tevatron data on the W -charge asymmetry, as well as the lepton- charge asymmetry from W boson decays and quasi-free neutron scattering data from the Jefferson Lab BONuS experiment [95, 96] "

Science

Supplementary Materials for A. V. Kotwal, JLab Users Meeting, 6/14/22 High-precision measurement of the *W* boson mass with the CDF II detector

CDF Collaboration

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Science 376, 170 (2022) DOI: 10.1126/science.abk1781 A. v. Kotwati, jlad Users inteeting, 0/14/22



CDF Collaboration *et al.*, *Science* **376**, 170–176 (2022)

95. N. Baillie, S. Tkachenko, J. Zhang, P. Bosted, S. Bültmann, M. E. Christy, H. Fenker, K. A. Griffioen, C. E. Keppel, S. E. Kuhn, W. Melnitchouk, V. Tvaskis, K. P. Adhikari, D. ... Measurement of the neutron F₂ structure function via spectator tagging with CLAS. *Phys. Rev. Lett.* 108, 142001 (2012). doi:10.1103/PhysRevLett.108.142001 Medline

96. S. Tkachenko, N. Baillie, S. E. Kuhn, ...

D. Watts, X. Wei, L. B. Weinstein, M. H. Wood, L. Zana, I. Zonta, Measurement of the structure function of the nearly free neutron using spectator tagging in inelastic ${}^{2}\text{H}(e,e'p_{s})X$ scattering with CLAS. *Phys. Rev. C* **89**, 045206 (2014).

JLab@12 GeV d/u- the full program



Neutron Data Are Important... ...but hard to get



Fermi motion, off-shell effects (binding), structure modifications (EMC effect), extra pions/Deltas, coherent effects, 6-quark bags, FSI...



BONuS12 with CLAS12 (Run Group F in 2020)





BONuS12 Radial Time Projection Chamber



BONuS12 Kinematics



Data vs. MC : D(e,e')X and D(e,e'p_s)X

- Full GEMC simulation of both tagged and inclusive spectra with detailed implementation of RTPC
- Generator: PWIA spectator model with 2014 Bosted/Christy fit to world data for F_{2n} and F_{2d} , AV14 D wave function, relativistic motion of struck nucleon, and equivalent radiator method for internal rad. effects



Data vs. MC: D(e,e'p_s)X



BONuS12 Present Results



D. Biswas et al., arXive hep-ex 2409.15236

BONuS12 Near-Final Results



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Future: JLab at 20+ GeV?

Alex Bogacz J-FUTURE Workshop Jefferson Lab / Messina University

22-24 GeV CEBAF FFA Energy Upgrade

- Halve distance to x = 1, higher Q²: Definite determination of asymptotic limit... *)
- ...AND to x = 0 => Study "valence" sea quarks (pion cloud)
- Increase Q² range for all x -> DGLAP => Study "valence" gluon helicity
- Even for same x, Q²: higher energy -> higher rates -> better statistics
- (Super)Rosenbluth expand range in ε for fixed x, $Q^2 => R$, g_2 , A_2
- Extend flavor tagging with SIDIS to higher x, Q^2 :
- Issues: Still need to deal with nuclear uncertainties.

^{*)} Higher Q²: Suppress higher twist, study logarithmic resummation

Conclusions

- Structure functions in the valence region remain of high theoretical interest and provide crucial input to precision collider experiments
- Jefferson Lab at 12 GeV is starting to have significant impact on our understanding of this region
- Jefferson Lab at 22 GeV can expand the coverage in x from 0.8 to 0.9 and more than double the range in Q², thereby minimizing the extrapolation to x -> 1.
- Essential ingredient: Extract neutron (polarized) structure functions from measurements on nuclei (d, ³He) => we must understand the EMC effect in detail.
- Vice versa, only precise data on the neutron can help us pin down nuclear binding effects across the periodic table