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The BONuS measurements of the free neutron structure function

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During the 6 GeV era of Jefferson Lab's Continuous Electron Beam Accelerator (CEBAF), the BONuS experiment took the first set of data on the "Barely Off-shell NeUtron Structure" using the spectator tagging method. After the upgrade to 12 GeV, this experiment will be repeated ("BONuS12") with higher precision and much improved kinematic reach, to study the valence quark structure of the neutron and the ratio of down over up quark distributions in the limit of Bjorken-x close to 1. In this paper, we present the results from the original BONuS experiment and plans for BONuS12.

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I. INTRODUCTION

Understanding how the fundamental force between constituent quarks and gluons, described by Quantum Chromodynamics, leads to the structure of the protons and neutrons comprising the atomic nuclei of ordinary matter is one of the overarching questions in modern nuclear physics. Of particular interest is the spin, momentum and spatial distribution of the valence quarks that give these nucleons their quantum numbers. For a complete understanding of the valence quark structure of the nucleon and its excitations, we need data on inclusive and exclusive cross sections for both protons and neutrons. These data are necessary, for instance, to access the asymptotic behavior (as Bjorken $x \to 1$) of the valence quark distributions (PDFs) and in particular the ratio of d over u quark PDFs. This ratio depends sensitively on the mechanism by which spin-flavor symmetry is broken and has therefore been a longstanding problem of high theoretical interest [2, 3]. At the same time, quark distributions at large Bjorken-x are also needed as input for cross section calculations at colliders such as the LHC, to extract spin structure functions of the neutron from measured asymmetries [4, 5], for tests of quark-hadron duality in the neutron [6, 7] and as ingredients for precision measurements of the EMC effect [8].

Unfortunately, free neutrons are unavailable in sufficient target densities for scattering experiments, and hence, information on the PDFs of the neutron has been obtained from measurements on nuclei, such as the deuteron. This leads to significant nuclear model uncertainties in the extracted PDFs, especially the d quark distribution [9]. To address this, a new approach was developed by the “BONuS” collaboration at the Thomas Jefferson National Accelerator Facility (Jefferson Lab), utilizing the novel technique of “spectator tagging” to access nearly free neutrons in deuterium. In BONuS, the slow, backward-going proton is detected in coincidence with the scattered electron in $\mathrm{D}(e, e'p_s)X$ to ascertain that the scattering took place on a relatively low-momentum neutron inside the deuteron, which is not far off-shell and doesn't have significant final state interactions with the spectator proton. In addition, the measured proton momentum can be used to kinematically correct the scattering kinematic variables for the initial motion of the neutron. BONuS has published first results from the data taken with 6 GeV at Jefferson Lab's CLAS spectrometer. In the near future, these data will be augmented by measurements at higher beam energies, with the 11 GeV beam of the energy-upgraded Continuous Electron Beam Accelerator (CEBAF) at Jefferson Lab and the upgraded CLAS12. In the following, we describe the original BONuS experiment and its results, as well as the plans for the new BONuS12 experiment.

II. THEORETICAL BASICS

The goal of the BONuS experiments is to measure the inclusive neutron structure function $F_2(x, Q^2)$ over a wide range in kinematics, but especially at the highest values of x accessible. Here, $Q^2 = -q^\mu q_\mu$ is the invariant square of the virtual photon four-momentum and determines the resolution of the probe, while $x = Q^2/(2P^\mu q_\mu)$ measures the fraction of the nucleon's four-momentum, P^μ, carried by the struck quark.

At very large x, this structure function is dominated by the contributions from valence quarks. Assuming isospin symmetry, the ratio of neutron over proton structure functions can be used to extract the ratio $d(x)/u(x)$ of down over up quarks in the limit where nearly all of the momentum of the nucleon is carried by a single quark:

$$\frac{d}{u} \approx \frac{4F_2^n/F_2^p - 1}{4 - F_2^n/F_2^p}. \tag{1}$$

There is a wide range of predictions of this ratio, ranging from d-quark suppression ($d/u = 0$) to SU(6) symmetry ($d/u = 2/3$) as $x \to 1$. Determining this ratio experimentally has therefore great interest. Unfortunately, neutron targets only exist in the form of neutrons bound in nuclei, making the simplest nucleus, the deuteron, a target of choice.

Since the deuteron is a weakly bound system with binding energy $\epsilon_d = -2.2$ MeV (only about 0.1% of the deuteron mass), on average the deuteron structure function may be reasonably well approximated by a sum of free proton and neutron structure functions. At large values of x, however, the deuteron structure functions receive increasingly greater contributions from nucleons carrying a larger fraction of the deuteron's momentum. These contributions are sensitive to the details of the high-momentum tails of the deuteron wave function, which are not as well constrained by nucleon–nucleon scattering data as the low-momentum components. Consequently, in the high-x region there is a more significant dependence on the model for the smearing of the nucleon structure due to binding and Fermi motion effects, as well as to possible modifications of nucleon structure when the nucleon is off its mass shell (the EMC effect).

The nuclear model uncertainties in the extraction of the neutron structure function from inclusive electron–deuteron scattering data can be significantly reduced by detecting low-momentum protons produced at backward kinematics, relative to the momentum transfer, in coincidence with the scattered electron,

$$e + D \rightarrow e + p_s + X. \tag{2}$$

By measuring the momentum of the spectator proton, P_s^μ , one can infer the initial motion of the struck neutron, $P^\mu = P_D^\mu - P_s^\mu$ and hence correct for kinematic shifts that would otherwise "smear" out the free neutron structure, see Fig. 1. Furthermore, by selecting events with low spectator momenta, $P_s^\mu < 0.1$ GeV/c, one is mostly sensitive to the part of the deuteron wave function where the two nucleons are well-separated and close to being on-shell (meaning $P^\mu P_\mu \approx M^2$, with M the free nucleon mass).

There could still be final state interactions between the struck nucleon and the spectator; however, various models [10–12] show that these are minimized in the case where the spectator proton has low momentum and moves backwards relative to the momentum transfer vector $\vec{q}$. Hence the BONuS experiment focuses on the detection of slow, backward moving spectators (so-called "VIPs" - Very Important Protons).

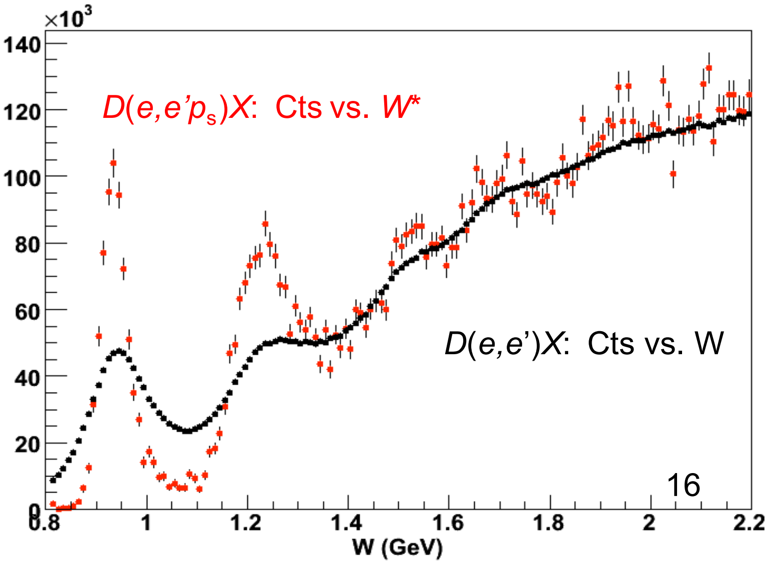

FIG. 1. Effect of correcting the kinematics for electron scattering on a moving nucleon bound in deuterium. The black data points come from inclusive scattering, where the final state mass W is calculated assuming an initially free nucleon at rest and is smeared out by the initial state motion of the struck nucleon. By using the kinematics of the observed spectator proton to correct for that initial state motion, replacing W with $W^* = \sqrt{(P^\mu + q^\mu)(P_\mu + q_\mu)}$, the washed-out resonance peaks are sharpened (red data points).

III. THE BONUS EXPERIMENT

The first BONuS experiment scattered electrons up to 5.3 GeV from a 7 atm, 20 cm long deuterium gas target. The scattered electrons were detected in CLAS [13] (the CEBAF Large Acceptance Spectrometer in Jefferson Lab's Hall B), while the low-momentum spectator protons were detected in a custom-built radial time projection chamber (RTPC, see Fig. 2). The target is enclosed in a thin (6 mm diameter) straw with 50 μm Kapton walls to minimize energy loss of the low-energy protons. The protons then traverse a buffer volume filled with helium gas, cross a ground foil and finally reach the drift volume of the RTPC (between a radius of 3 cm and 6 cm). Electrons liberated in this drift region propagate to the amplification section consisting of three GEM (gaseous electron multiplier) foils in series. The produced secondary electrons arrive at a readout board segmented in pads of about 4x5 mm size.

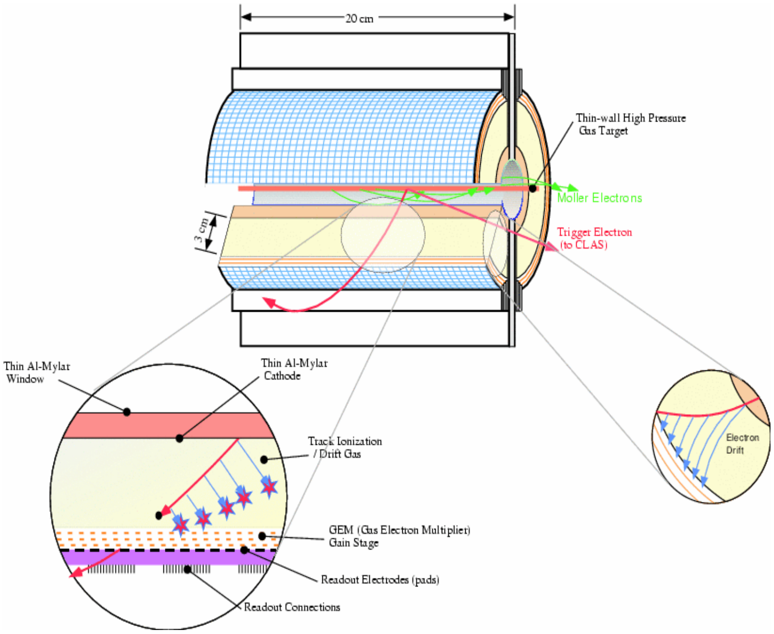

FIG. 2. Layout of the Radial Time Projection Chamber – RTPC – for BONuS at 6 GeV. See explanation in text.

By identifying the pad coordinates and measuring the drift time, the ionization point can be located in all three dimensions, and hence the proton track fully reconstructed. More details, including about the readout electronics based on the CERN ALTRO chip, can be found in the paper by Fenker et al. [14].

The whole apparatus is immersed in a longitudinal magnetic field of about 5 Tesla. This field has the dual purpose to curl up electromagnetic background (Møller electrons) and to bend the tracks of the protons, providing a method to measure their momenta. Finally, the energy deposited over a full track can be used to identify protons of interest and separate them from other background particles.

The first BONuS experiment ran in 2004. Due to data rate limitations, the luminosity was limited to about $L = 10^{33}$ nucleons/cm$^2\times$ e$^-$/s. In the following section we present some selected results from this run.

IV. RESULTS AT 6 GEV

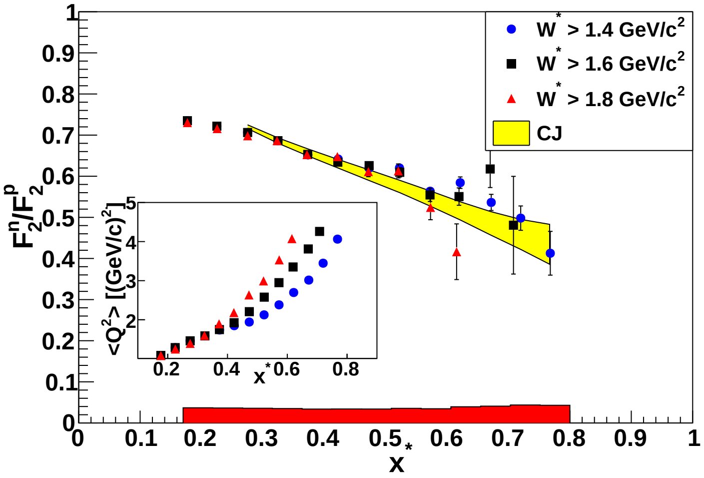

FIG. 3. Results for the ratio of neutron to proton structure function $F_2(x)$ from BONuS. The different data points correspond to different cuts in the unobserved final state mass W^*. Error bars are statistical only, while the systematic uncertainty is indicated by the red band near the x-axis. The inset shows the average Q^2 for each data point.

The first BONuS experiment took data on the tagged deuteron (neutron) structure function at beam energies of 2.1, 4.2 and 5.3 GeV. The first results on the ratio F_{2n}/F_{2p} where published in 2012 [15], see Fig. 3. While the data showed good agreement with recent fits (yellow band labeled "CJ" [16]), the kinematic reach and the precision at high x are not yet sufficient to constrain the behavior of d/u as $x \rightarrow 1$.

The complete data set taken with BONuS is summarized in an archival paper [17] – for an example, see Fig. 4. These data were then used to extract higher twist matrix elements and to study the validity of quark-hadron duality for the neutron [18], and, for the first time, the presence of the EMC effect in deuterium [19] (see Fig. 5). Within the (rather large) experimental uncertainties, strongly suggestive evidence of an EMC slope of order -0.1 was found, which is consistent with an extrapolation from heavier nuclei down to the deuteron.

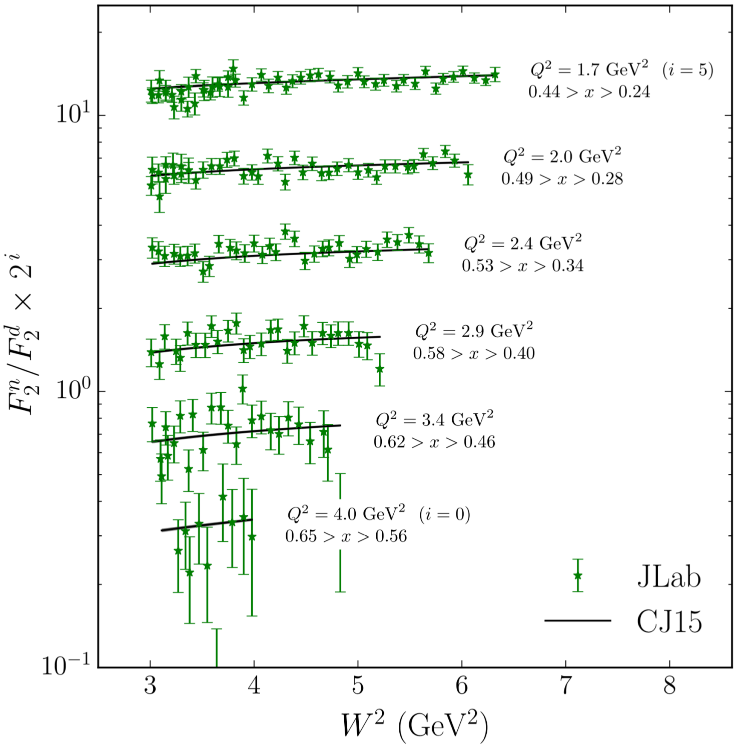

FIG. 4. Measured ratio of the neutron over the deuteron structure function $F_2(x)$ in the DIS region for several bins in Q^2 from the first BONuS experiment. The figure is from the paper [16] by the CJ collaboration, which included our data in their fit (indicated by the black line) of world data to extract unpolarized PDFs for all quark flavors.

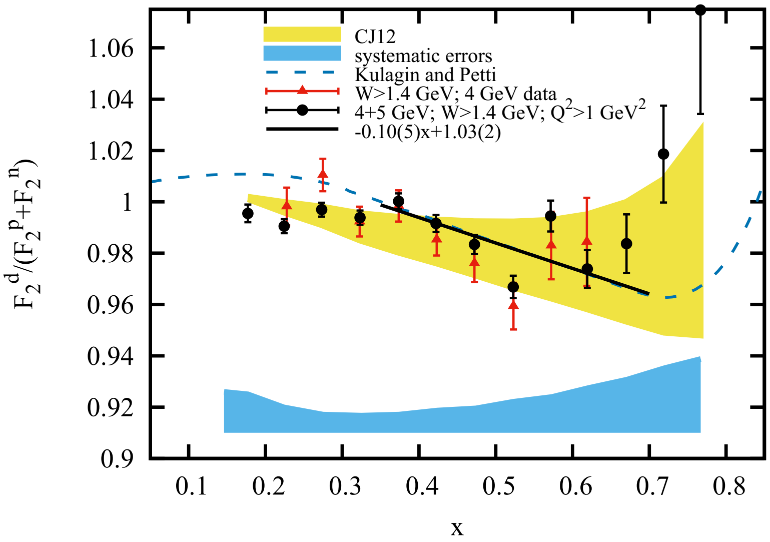

FIG. 5. EMC effect in Deuterium [19]. See text for explanation.

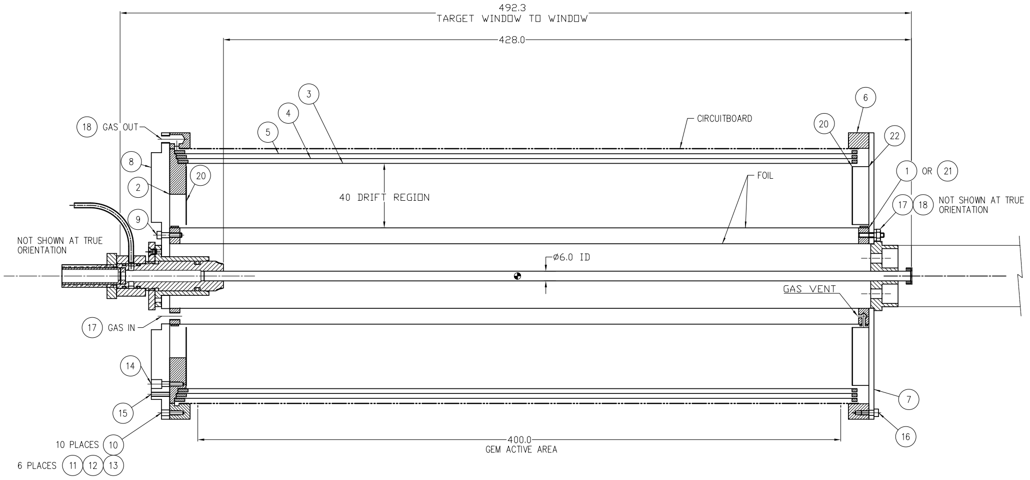

FIG. 6. Preliminary engineering drawing of the new RTPC detector. Beam direction is from left to right through a 40 cm long, 6 mm diameter target with 7 atm deuterium gas. From the center outwards, spectator protons traverse the target cylinder (50 μm Kapton), an inert volume filled with ^{4}He, and, after a grounded 5 μm aluminized Mylar foil at 2 cm radius, the detector volume filled with a mixture of 70% He and 30% ^{4}He gas. The drift region extends from 3 cm to 7 cm radius with a drift voltage of about 3000 V supplied by a thin cathode. Drift electrons are amplified by a set of three concentric GEM foils (3-5) at 7 cm, 7.3 cm and 7.6 cm radius. The signal is read out by approximately 18000 pads 4 mm long and 2.75 mm wide on a readout board at 7.9 cm radius. All pads are read out every 120 ns (yielding about 50 individual space points per track) by the DAQ system based on the DREAM chip developed by Saclay. Each proton track is curved in the 5 T magnetic field of the central detector solenoid of CLAS12 and can be reconstructed in 3 dimensions, using the pad ID and timing information.

V. THE PLANNED BONUS12 EXPERIMENT AT 11 GEV

The BONuS program will continue with the newly upgraded 12 GeV beam of CEBAF, utilizing the upgraded CLAS12 spectrometer and a new recoil detector (Fig. 6). Due to various improvements in design and data acquisition electronics, both the resolution and the data rate will be vastly improved, allowing us to run at approximately 20 times the previous luminosity. The resulting high statistics, together with the higher beam energy, will allow us to extend our knowledge of neutron structure and the ratio of d to u quark PDFs to the highest x possible, $x \approx 0.8$ (see Fig. 7). This expanded kinematic range and the much higher luminosity will allow us, for the first time, to answer definitively the question whether the asymptotic ratio of down to up quarks at the limit $x \to 1$ follows the expectations of pQCD (in particular parton helicity conservation [3]), or one of the alternative models indicated on the right vertical axis of Fig. 7. Experiment E12-06-113 (also dubbed “BONuS12” [20]) has been fully approved by the Jefferson Lab PAC with the highest rating (“A”). Furthermore, PAC41 selected the BONuS12 experiment as one of the high impact experiments that should be run early in the 12 GeV program at Jefferson Lab. Expected results have been featured in the 2015 NSAC Long Range Plan (see Fig. 7 which is reproduced as Fig. 2.3 in the LRP). BONuS12 is presently foreseen to run (within“run group F” at CLAS12) in 2019.

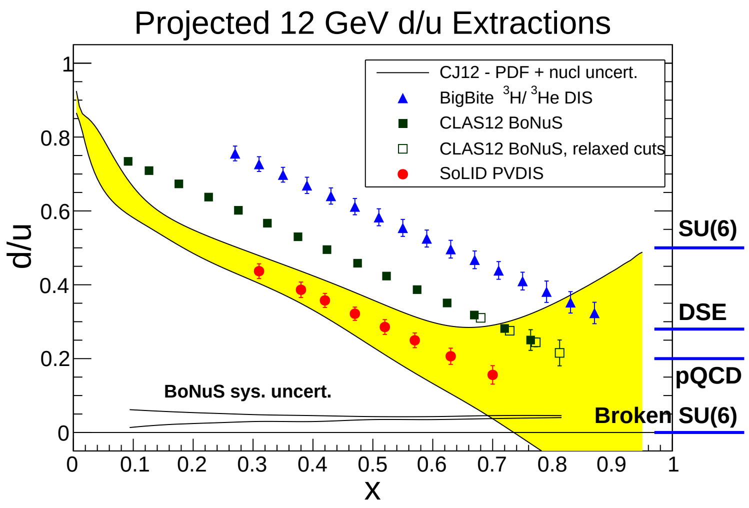

FIG. 7. Anticipated experimental uncertainties on the ratio of d over u quarks vs. Bjorken-x from various Jefferson Lab experiments. The expected BONuS12 data are shown as dark green squares, with statistical error bars (invisible except for the highest points in x), and systematic uncertainties indicated by the black lines near the axis (lower line: point to point systematic uncertainties; upper line: overall uncertainty including normalization). Several predictions for the asymptotic value of the ratio are indicated on the right axis.

The centerpiece of BONuS12 is the new low-momentum proton recoil detector that will tag DIS events on the neutron inside deuterium. This detector must support much higher luminosity (at least $L = 2 \cdot 10^{34}$ nucleons/cm$^2\times$ e$^-$/s), a correspondingly large data acquisition rate, and improved proton momentum reconstruction and acceptance over a range of at least 70 MeV/c to 100 MeV/c, with a resolution of $\Delta p/p$ <10%, to maximize the statistical and kinematic precision achievable with BONuS12. After detailed studies of various detector concepts, the BONuS collaboration has decided to once again use a radial time projection chamber (RTPC) with triple GEM amplification to fully measure the tracks of low-momentum protons, see Fig. 6. This RTPC will be double as long as the BONuS6 one, and will be equipped with a new data acquisition electronics based on the DREAM chip, which can handle the expected data rate.

VI. OUTLOOK AND CONCLUSIONS

Including BONuS12, several experiments in the 12 GeV era of Jefferson Lab will use the technique of “spectator tagging” to directly study DIS on bound nucleons inside the nucleus. BONuS and BONuS12 applies this method to select slow-moving protons from a deuterium target, to tag nearly on-shell neutrons and measure their free structure functions. On the other hand, by measuring high momentum spectators, one can ensure that the electron scattering took place on a nucleon that was part of a short-range correlation, thereby accessing any possible enhancement of binding (off-shell) effects in such nucleon pairs. This will be exploited by experiment E12-11-107 (with proton spectators) and a companion experiment looking for fast backward neutrons, both with deuterium targets. Beyond that, plans are underway to extend this technique to heavier nuclei (see the recently approved “ALERT” proposal at Jefferson Lab).

Ultimately, an electron-ion-collider as proposed by the US nuclear physics community will be required to complete our picture of parton distributions both in nucleons and in nuclei. In particular, such a machine will be uniquely suited to extend the range of tagged spectator momenta, from the highest kinematically allowed values down to zero.

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