Exploring Quark Helicity Distributions with a 22 GeV Beam at Jefferson Lab

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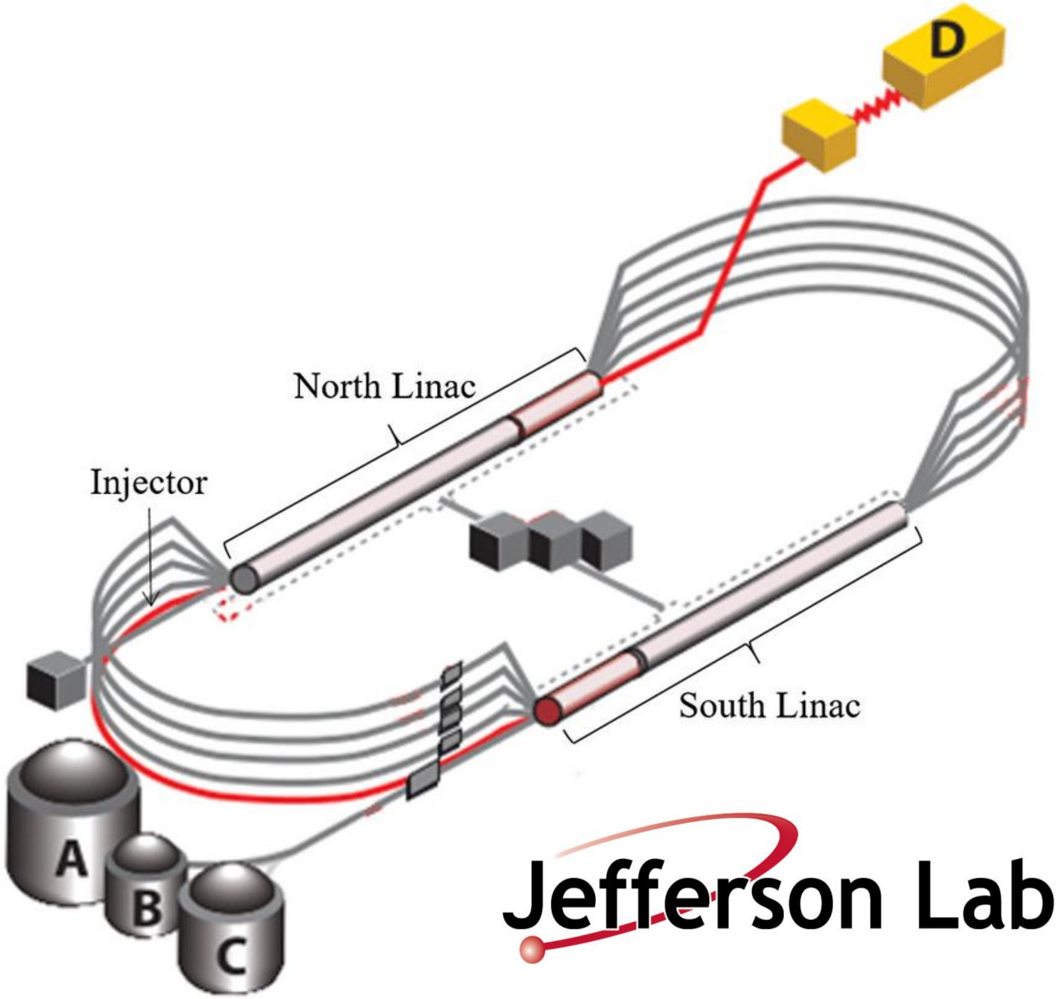
SPIN 2023

9.25.23

Jefferson Lab

Jefferson Lab is home to the Continuous Electron Beam Accelerator Facility (CEBAF) which produces a **high luminosity**, **medium energy** electron beam.

- An electron beam typically of 100's of uA enters the accelerator track from the Injector.
- The beam can then circle the track, passing through North and South Linacs up to six times to reach energies of nearly 12 GeV.

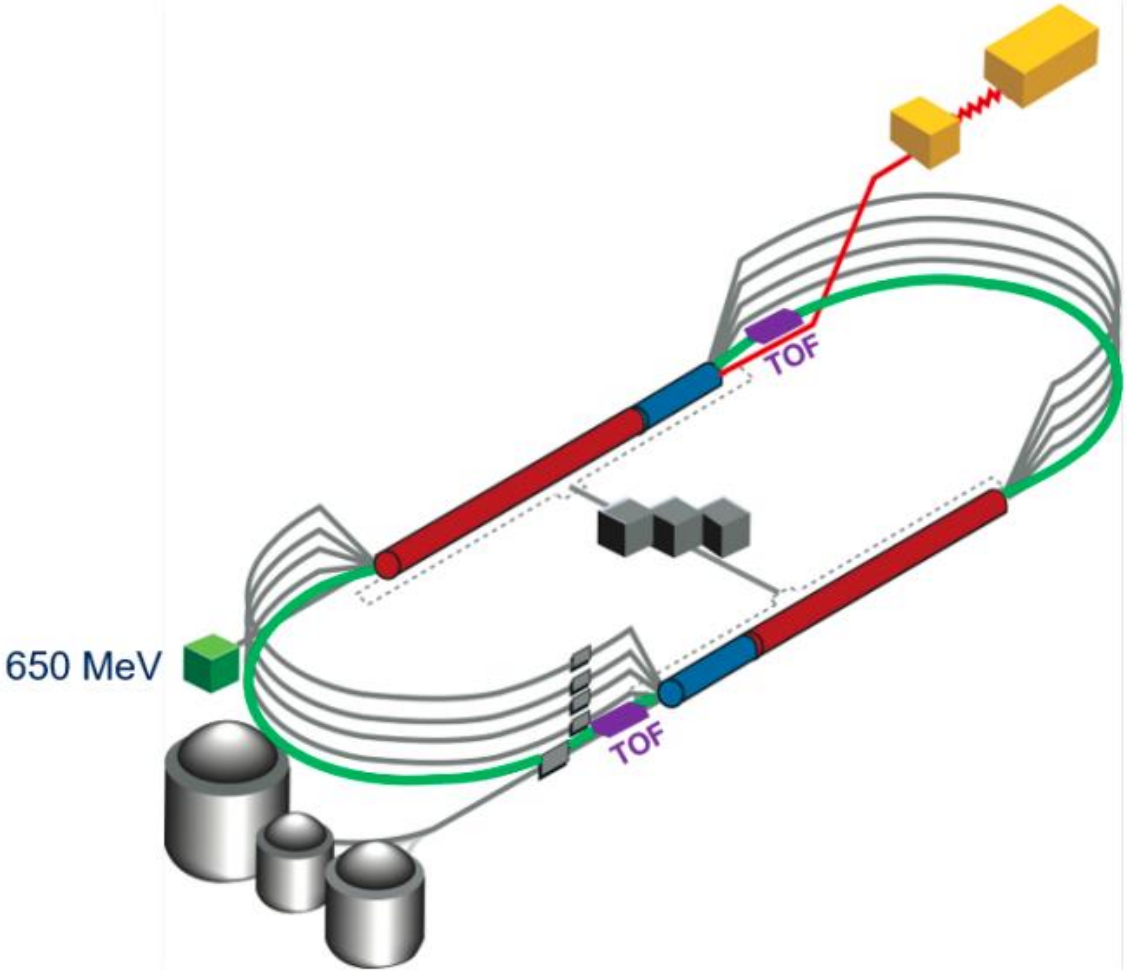


Motivation: 22 GeV

- Why 22 GeV?
  - CEBAF is currently running at ~12 GeV, however the tunnel is designed to handle a beam of up to ~22 GeV
  - This can be accomplished by replacing the highest energy arcs with Fixed Field Alternating Gradient (FFA) arcs.
  - Higher beam energies = larger kinematic coverage.

**For more on 22 GeV, see Dr. Alex Bogacz's talk Tuesday at 5pm in the Futures session.*

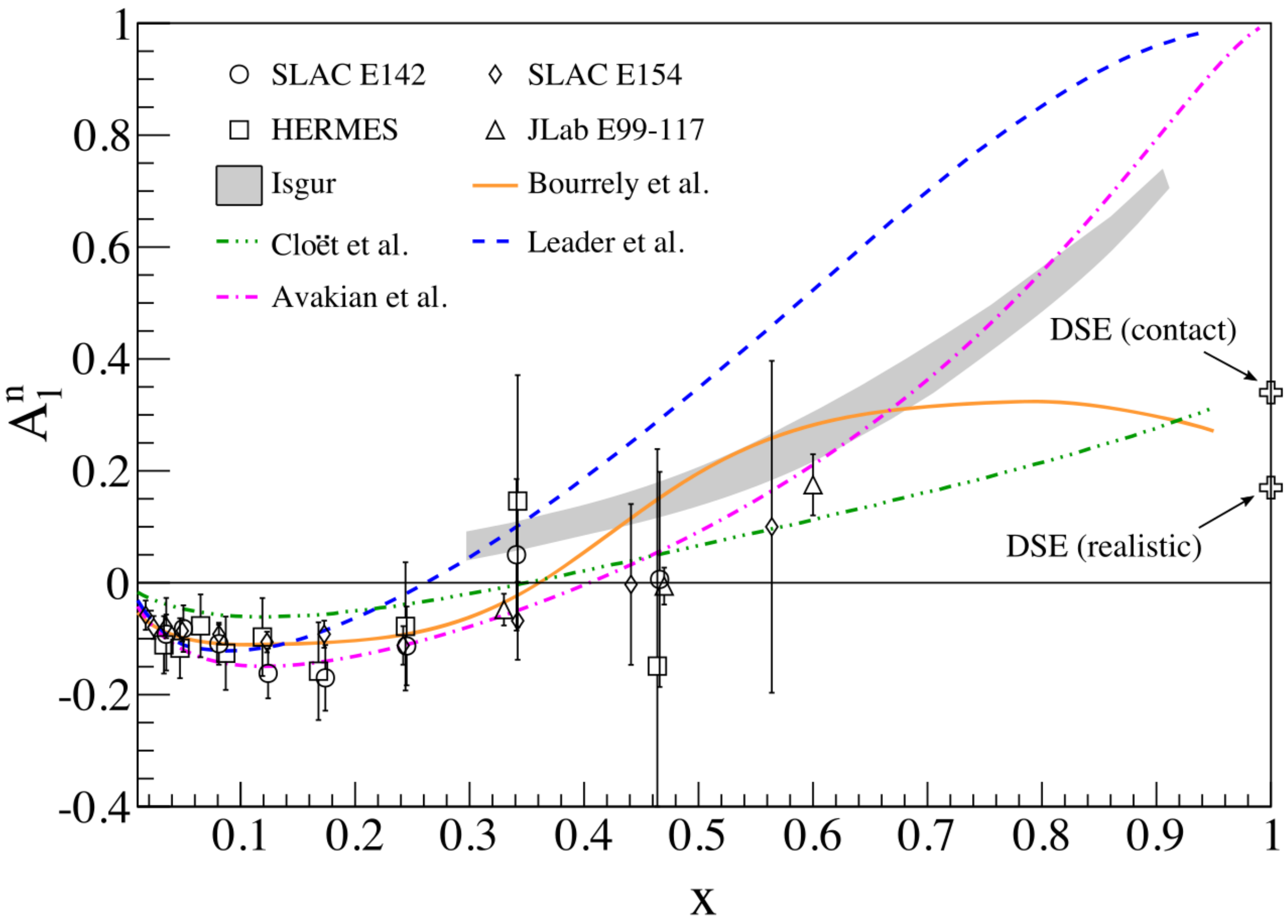
arXiv:2306:09360 **[nucl-ex]**



CEBAF accelerator with the two highest energy arcs, Arc 9 and Arc A, replaced with a pair of FFA arcs (green).

Motivation: High-x Quark Spin

- Why Quark Helicity at 22 GeV?
  - Theoretical models make vastly different predictions for spin asymmetries as Bjorken x->1. Precise measurements of these quantities at large x offer a compelling avenue by which to test these models.
  - Big Question: How do the constituents of protons and neutrons contribute to its overall spin?



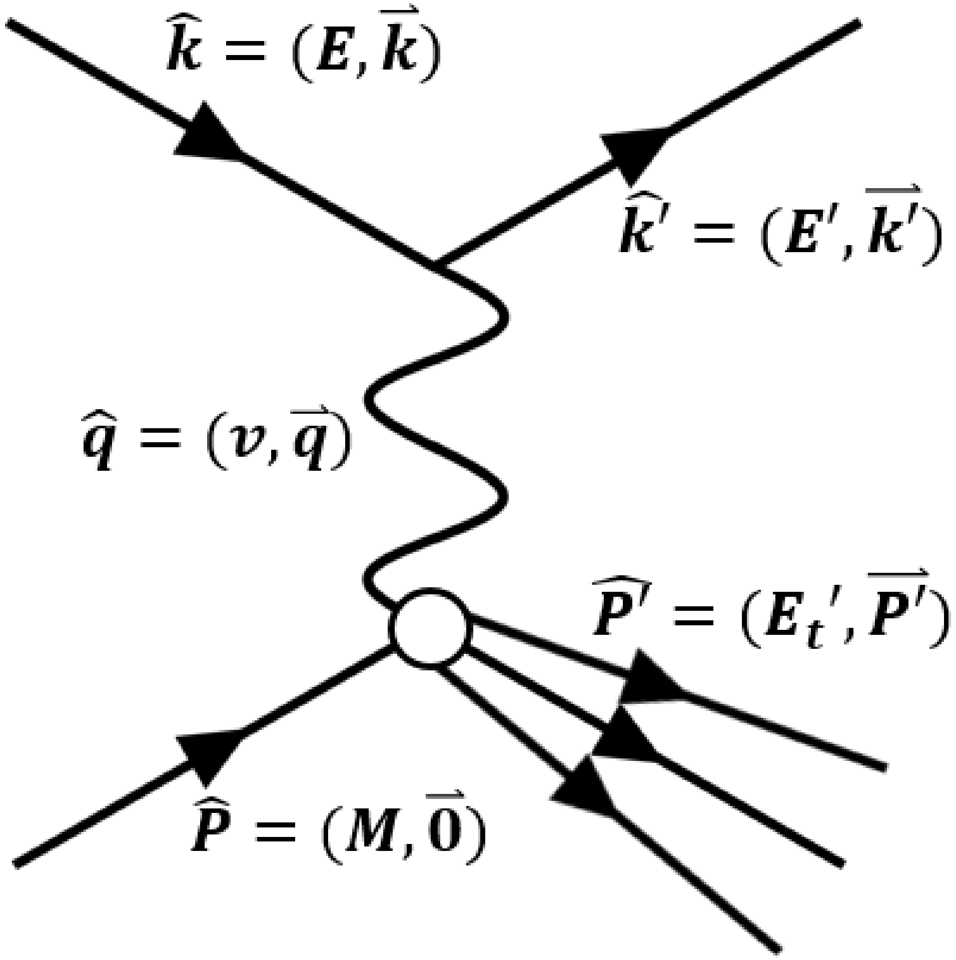
Models and Existing World Data for the Neutron A1 Asymmetry (A_1^n)

D.Flay et al., Phys. Rev D 94, 052003 (2016).

Theoretical Background: Scattering

There are several key kinematic variables used when studying quarks using Deep Inelastic Scattering (DIS). In an Inclusive DIS experiment, only the electron is detected in the final state. Quantities measured in the lab frame are:

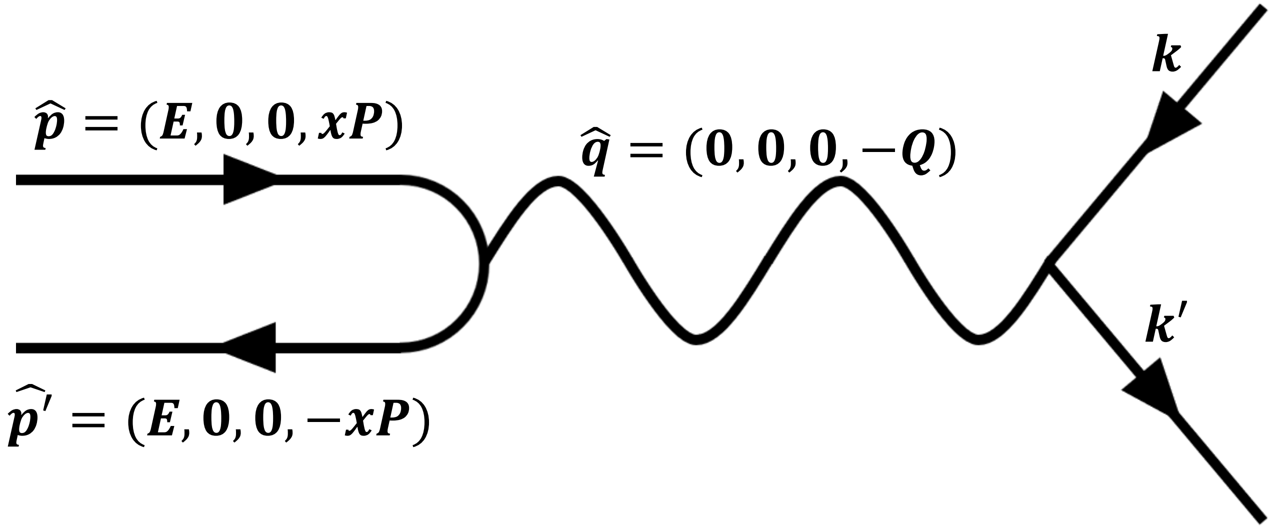
- $\boldsymbol{E/E'}$
  - Electron initial/final state energy
- $\boldsymbol{\nu = E - E'}$
  - Energy transfer
- $\boldsymbol{M}$
  - Target (nucleon) rest mass
- $\boldsymbol{\theta}$
  - Scattering angle of electron



Theoretical Background: Scattering

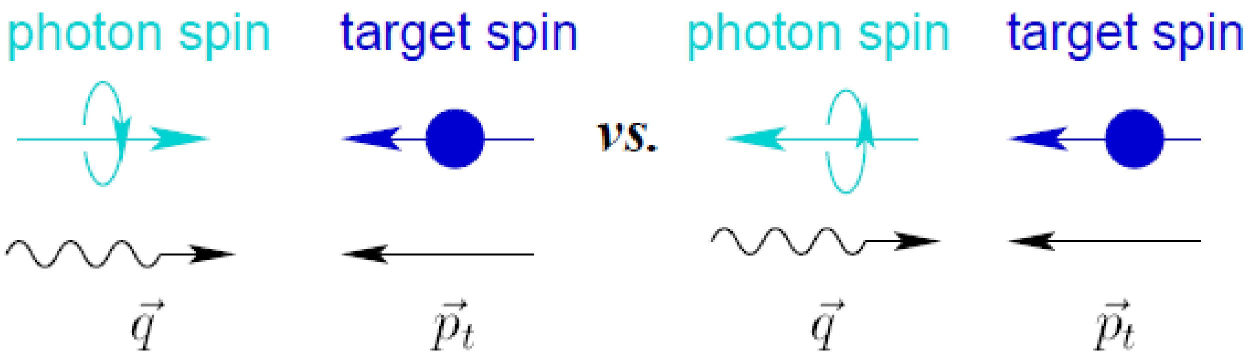
There are also important Lorentz invariant quantities determined from the measured values:

- $\boldsymbol{Q^2} = -\widehat{\boldsymbol{q}}^2 = 2EE'(1 - \cos\theta)$
  - Mass or virtuality of the exchanged virtual photon
- $\boldsymbol{W^2} = (\widehat{\boldsymbol{P}} + \widehat{\boldsymbol{q}})^2 = M^2 + 2M\nu - Q^2$
  - Invariant mass
- $\boldsymbol{x} = x_{Bj} = \frac{Q^2}{2P\cdot q} = \frac{Q^2}{2M\nu}$
  - Bjorken x - fraction of nucleon momentum carried by struck quark in the Breit frame.



Theoretical Background: A_1

- A_1 is the longitudinal virtual photon-nucleon asymmetry. A_1 is defined in the equation below, where:
  - $\sigma_{1/2(3/2)}$ is the cross section of the spin 1/2 (3/2) configuration
  - $g_{1(2)}$ are the polarized structure functions
  - $F_{1(2)}$ are the unpolarized structure functions
  - Kinematic quantities x, v, Q^2 defined as before



Definition of Virtual Photon-Nucleon Asymmetry A1

$$A_1(x, Q^2) = \frac{g_1(x, Q^2) - \frac{Q^2}{v^2} g_2(x, Q^2)}{F_1(x, Q^2)} = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$

Theoretical Background: $A_\parallel$ and $A_\perp$

- While we can't directly polarize the virtual photon, we can polarize the electron beam and determine A_1 from a linear combination of asymmetries defined in terms of the electron polarization, $A_\parallel$ and $A_\perp$.

$$A_\parallel = \frac{\sigma_{\downarrow\uparrow} - \sigma_{\uparrow\uparrow}}{\sigma_{\downarrow\uparrow} + \sigma_{\uparrow\uparrow}}$$

$$A_\perp = \frac{\sigma_{\downarrow\rightarrow} - \sigma_{\uparrow\rightarrow}}{\sigma_{\downarrow\rightarrow} + \sigma_{\uparrow\rightarrow}}$$

$$A_1 = \frac{1}{D(1+\eta\xi)} A_\parallel - \frac{\eta}{d(1+\eta\xi)} A_\perp$$

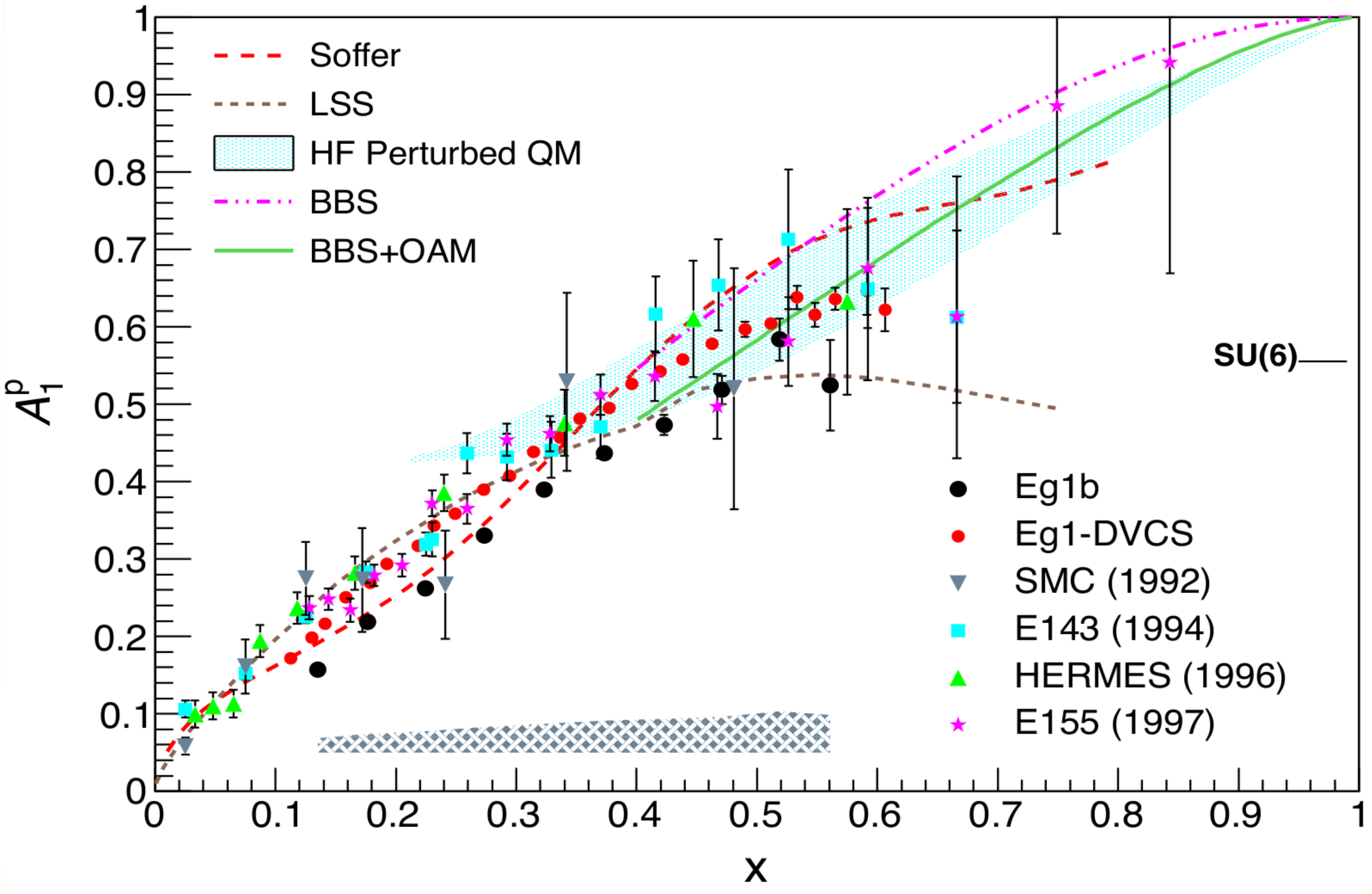
Theoretical Background: A_1^n

- There is no free neutron target so instead we measure the A_1 asymmetry of Helium 3 as its neutron is effectively polarized along the same direction as the nucleus. We can then convert from Helium 3 asymmetry to the neutron asymmetry using the equation below, where $P_{n(p)}$ are the neutron (proton) polarizations in Helium 3.

$$A_1^n = \frac{F_2^{3He}}{P_n F_2^n \left(1 + \frac{0.056}{P_n}\right)} \left(A_1^{3He} - 2 \frac{F_2^p}{F_2^{3He}} P_p \left(1 - \frac{0.014}{2P_p}\right) A_1^p \right)$$

Theoretical Background: A_1^p

- While a free proton target does exist, getting reasonable target polarizations and densities are challenging, so an NH3 target is used instead.
- To get a rough estimate of the uncertainty of A_1 for the proton from A_1 for NH3, the statistics are simply scaled by 3/17 (dilution factor) and multiplied by an additional x-dependent factor (F2 ratio) to account for the difference in cross sections between the proton and neutron.



Theoretical Background: ${}^{\Delta q}/_{q}$

- Finally, since this study provided projections for both A1n and A1p, we are able to perform a flavor decomposition of the polarized quark distribution functions and obtain ${}^{\Delta u}/_{u}$ and ${}^{\Delta d}/_{d}$ using the following equations:

$$\frac{\Delta u + \Delta \bar{u}}{u + \bar{u}} = \frac{4}{15}\frac{g_1^p}{F_1^p}(4 + \frac{d + \bar{d}}{u + \bar{u}}) - \frac{1}{15}\frac{g_1^n}{F_1^n}(1 + 4\frac{d + \bar{d}}{u + \bar{u}})$$

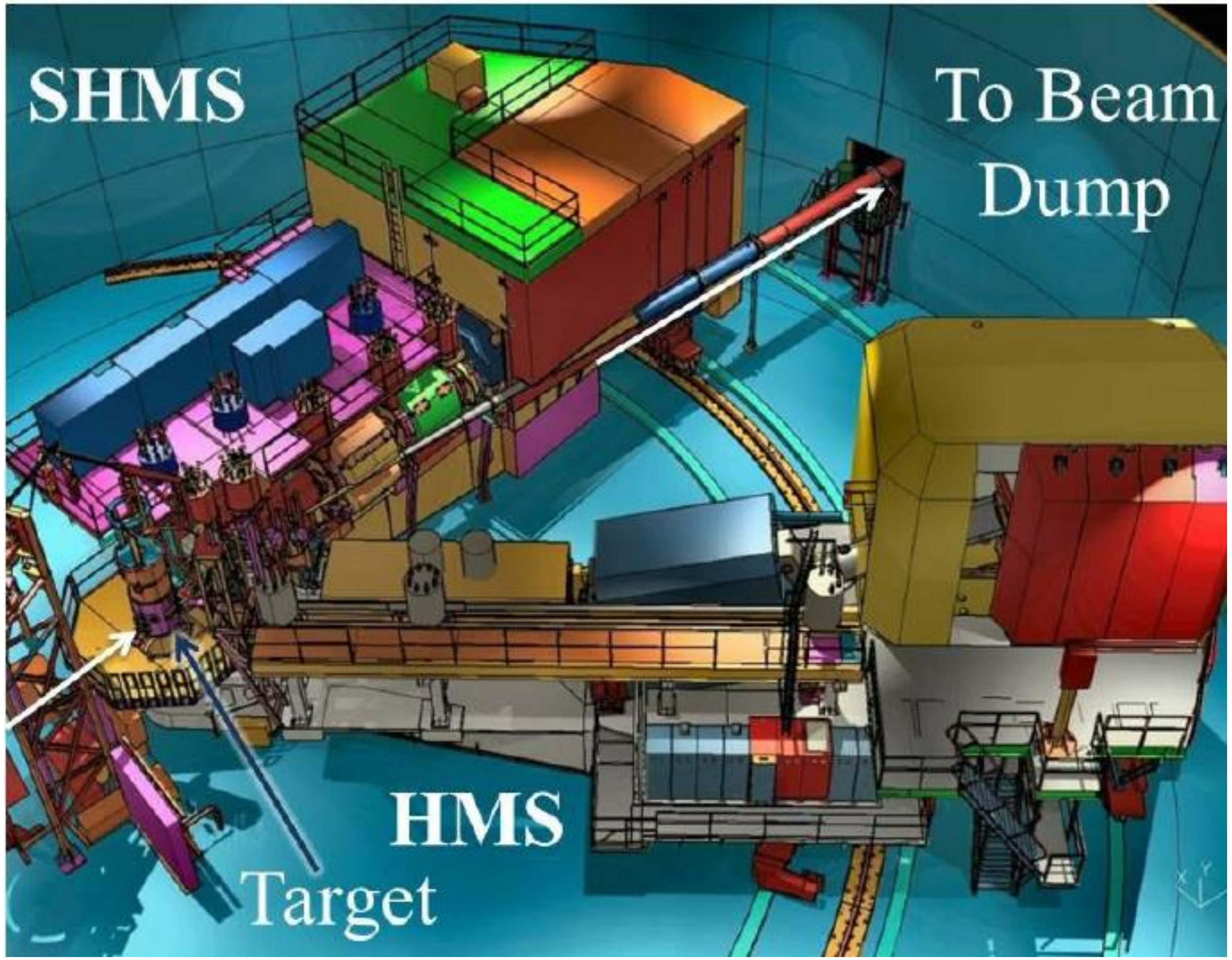
$$\frac{\Delta d + \Delta \bar{d}}{d + \bar{d}} = \frac{4}{15}\frac{g_1^n}{F_1^n}(4 + 1/\frac{d + \bar{d}}{u + \bar{u}}) - \frac{1}{15}\frac{g_1^p}{F_1^p}(1 + 4/\frac{d + \bar{d}}{u + \bar{u}})$$

Simulation & Analysis: Overview

- The goal of this work was to perform a Figure of Merit (FOM) study of potential 22 GeV inclusive DIS experiments in Halls B and C that could be used to extract A_1^p and A_1^n, which could then be used to extract polarized quark distribution functions.

Simulation & Analysis: A_1^n

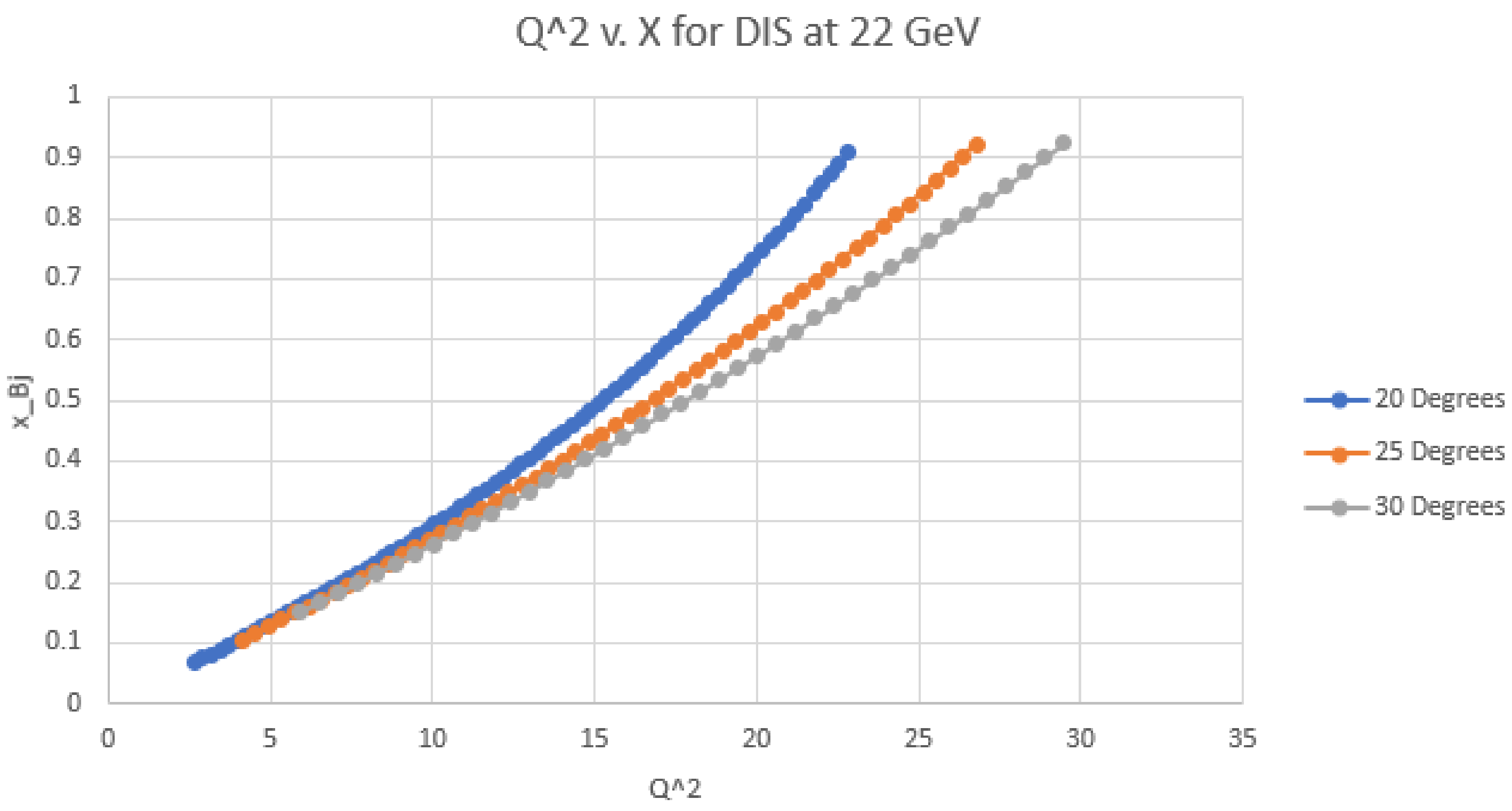
- To get projections for A_1^n at 22 GeV, I simulated the experiment under the following conditions:
  - Both spectrometers in Hall C, the HMS and SHMS, are used for simultaneous inclusive measurements and rotated to 30° and 20°, respectively.
    - These are small acceptance detectors good at probing a small region of phase space with high precision.
  - 40cm Helium 3 target with polarization of 50% and density of $10\ amg$
  - Electron beam with polarization of 85%
  - 30 days of beam at 30uA



Simulation & Analysis: A_1^n

As we increase the spectrometer angle from 20 to 30 degrees, we get very minimal increase in maximum reachable Bjorken x, however we see a large increase in Q2 (which will result in significantly reduced statistics).

So we decided to run the SHMS at 20 degrees. The HMS was forced to run at 30 degrees due to limits with the maximum reachable E' with the detector. If this is upgraded in the future, statistical uncertainties will improve proportionally.



Simulation & Analysis: A_1^n

- Once we determined the run conditions, we then used Hall C's *mc-single-arm* event generator and a cross section model (F1F2IN21) to determine the statistical uncertainty of A_1^n we expect to achieve with the experiment.

```
!---------------------------------------------------------------------------
! Input file for mc-single-arm                                   05/20/2021
! 22GeV A1n FOM Study at 20deg, He3 target, SHMS
!---------------------------------------------------------------------------
  100000      Monte-Carlo trials
       2      Spectrometer (1=HMS, 2=SHMS, 3=..)
  7800.0      Spectrometer momentum (in MeV/c)
    20.0      Spectrometer angle (in degrees)
   -15.0      M.C. DP/P  down limit
    30.0      M.C. DP/P  up   limit
   -50.0      M.C. Phi   down limit (mr)
    50.0      M.C. Phi   up   limit (mr)
   -55.0      M.C. Theta down limit (mr)
    55.0      M.C. Theta up   limit (mr)
    0.01      Horiz beam spot size in cm (Full width of +/- 1 sigma)
    0.01      Vert  beam spot size in cm (Full width of +/- 1 sigma)
   40.00      Thickness of target (Full width, cm)
     0.1      Raster half-width x (cm)
     0.1      Raster half-width y (cm)
    50.0      DP/P  reconstruction cut (half width in % )
   100.0      Theta reconstruction cut (half width in mr)
   100.0      Phi   reconstruction cut (half width in mr)
    50.0      ZTGT  reconstruction cut (Half width in cm)
   53960      one radiation length of target material (in cm)
     0.0      Beam x offset (cm)  +x = beam left
     0.0      Beam y offset (cm)  +y = up
     0.0      Target z offset (cm)+z = downstream (0.25)
     0.0      Spectrometer x offset (cm) +x = down
     0.0      Spectrometer y offset (cm)
     0.0      Spectrometer z offset (cm)
     0.0      Spectrometer xp offset (mr)
     0.0      Spectrometer yp offset (mr)
       0      particle identification :e=0, p=1, d=2, pi=3, ka=4
       1      flag for multiple scattering
       1      flag for wire chamber smearing
       1      flag for storing all events (including failed events with stop_id > 0)
       0      flag for sieve slit
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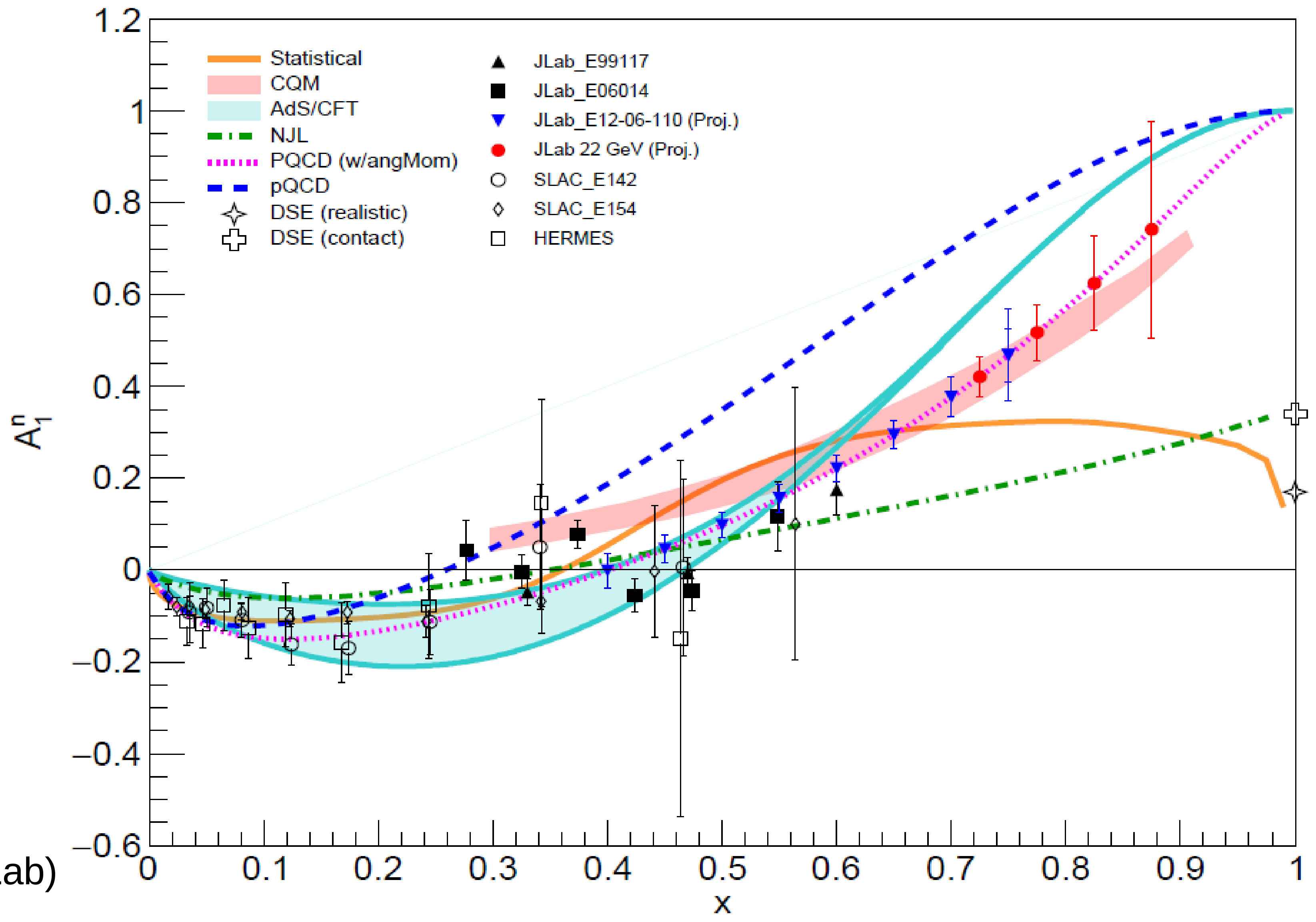
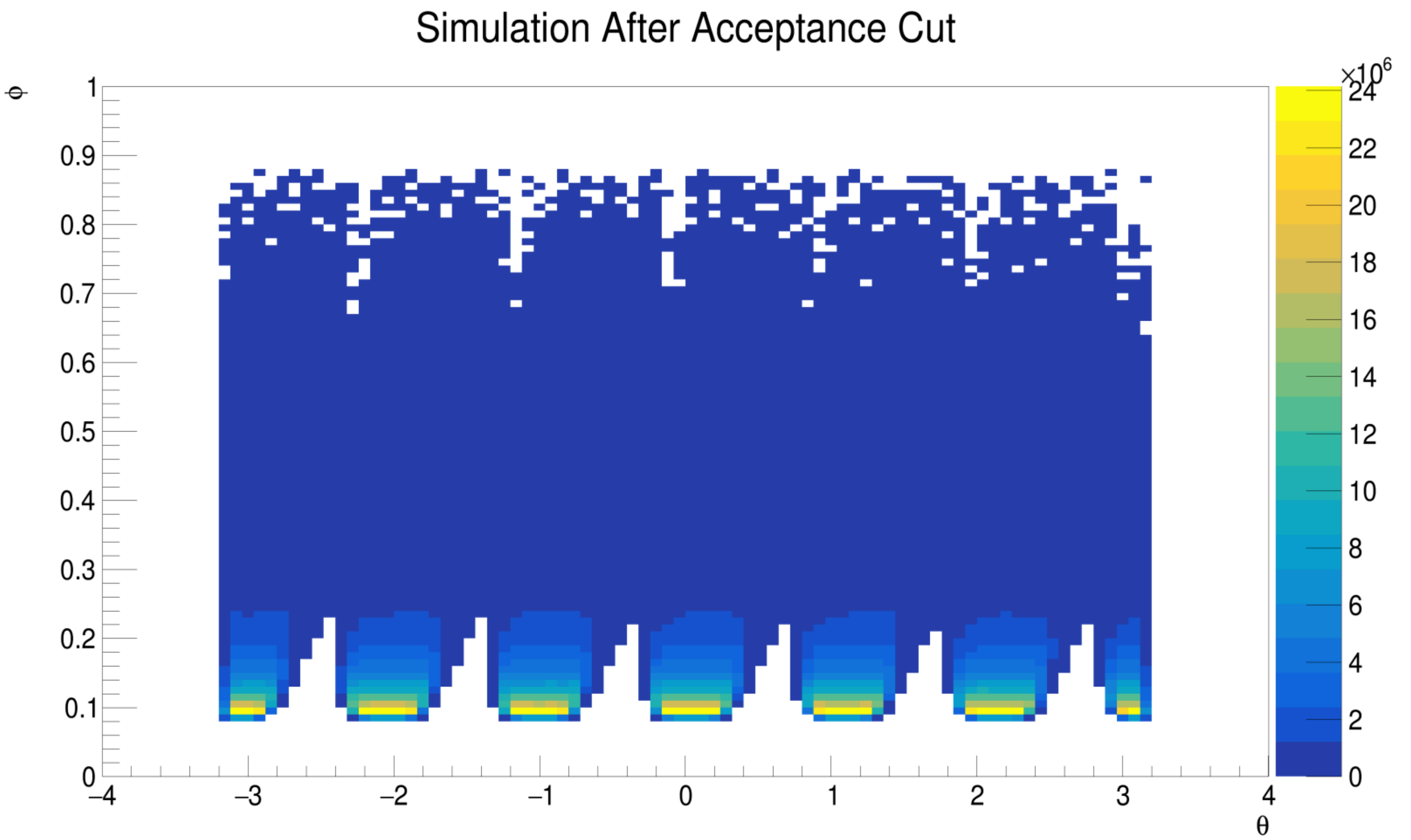
Projections: A_1^n



FC: Dave Flay (JLab)

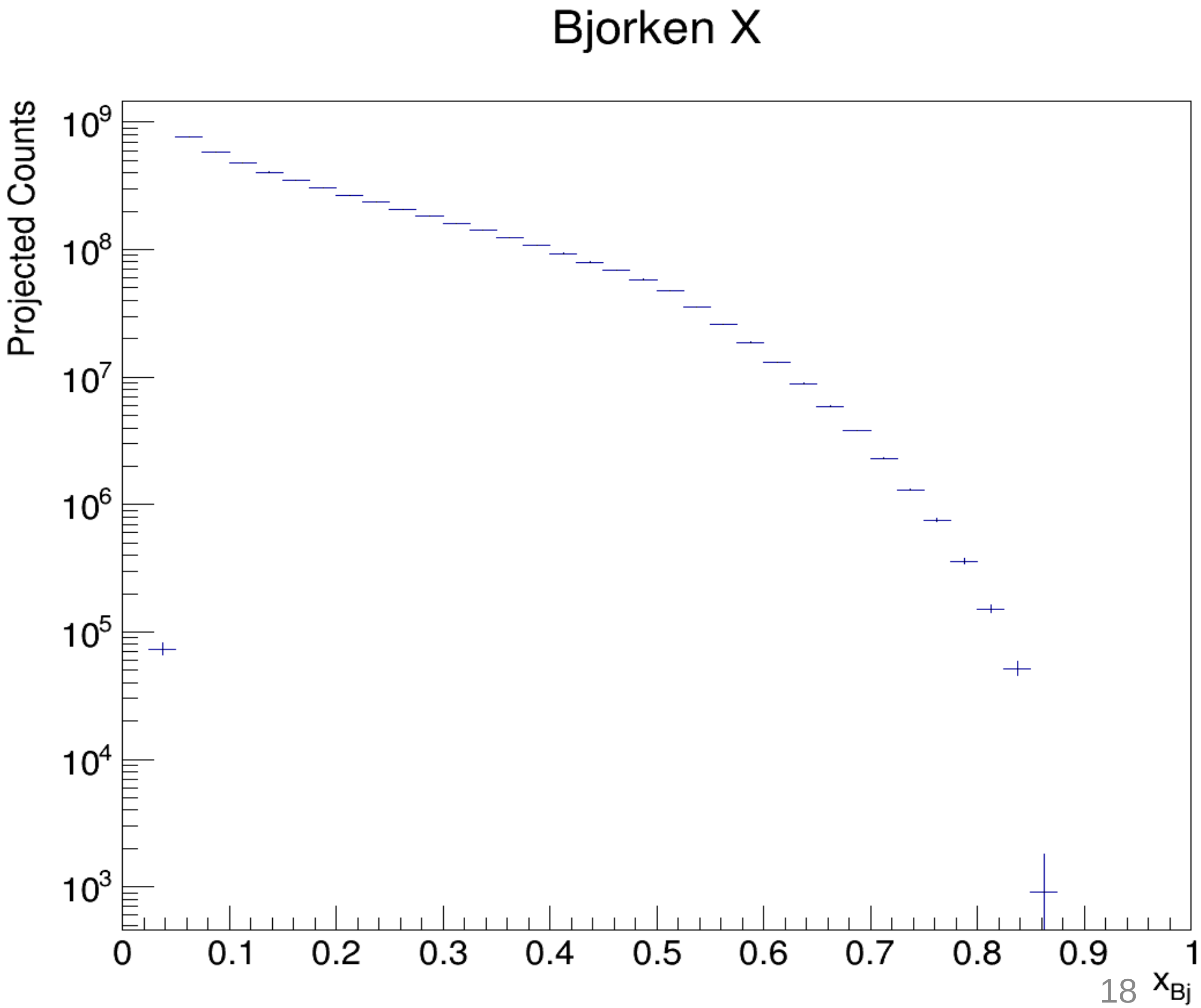
Simulation & Analysis: A_1^p

- To get projections for A_1^p at 22 GeV, I simulated the experiment under the following conditions:
  - CLAS12 in Hall B, used for inclusive DIS measurements.
  - NH3 – Luminosity of $10^{35} cm^{-1} s^{-1}$ (upgrade planned, but used present value to be conservative as it is not critical for this measurement)
  - Beam*Target Polarization at 50%
  - 30 days of beam

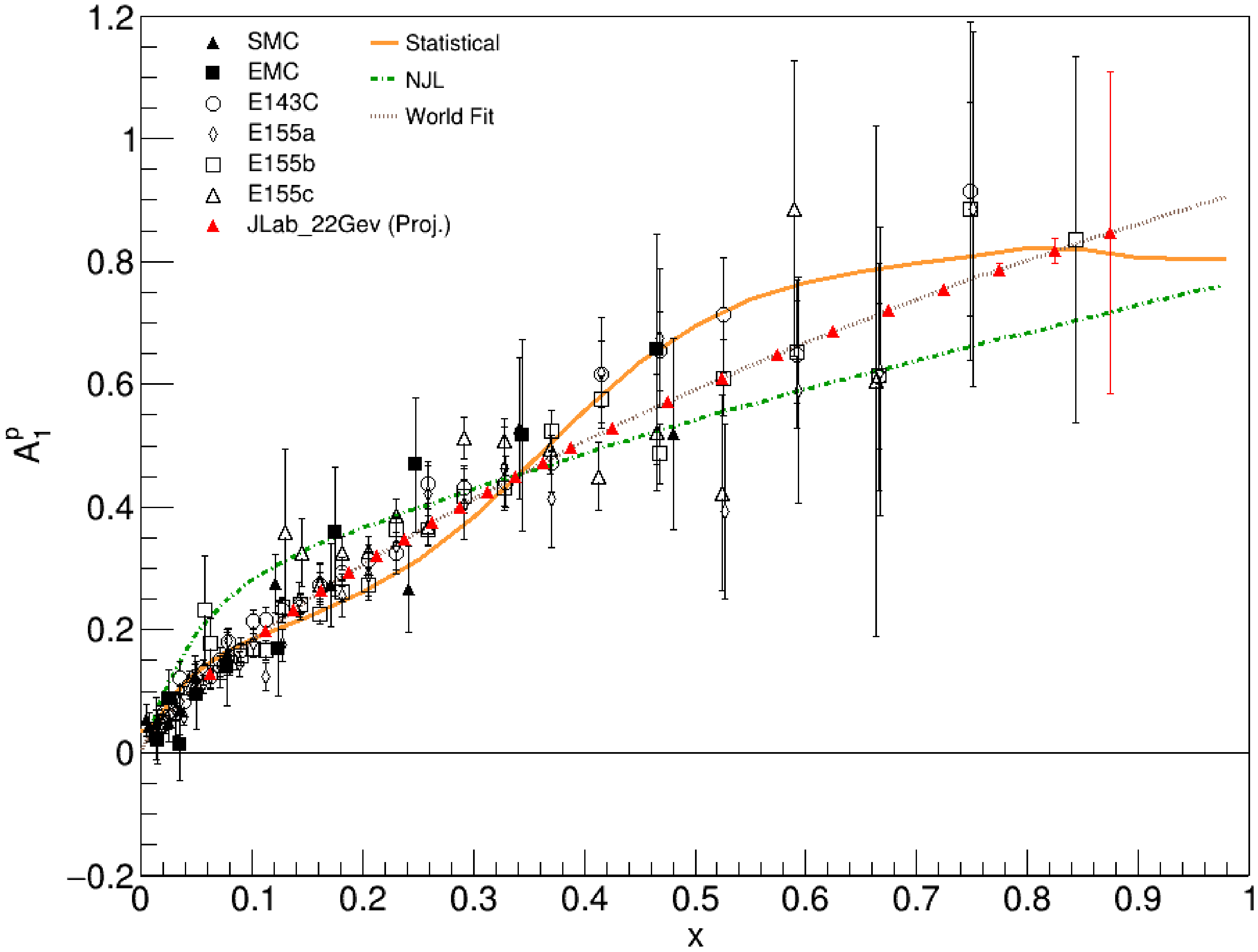


Simulation & Analysis: A_1^p

- We then used the CLASDIS event generator to generate a sample of 10M events to determine the statistical uncertainty of A_1^p we expect to achieve with the experiment.

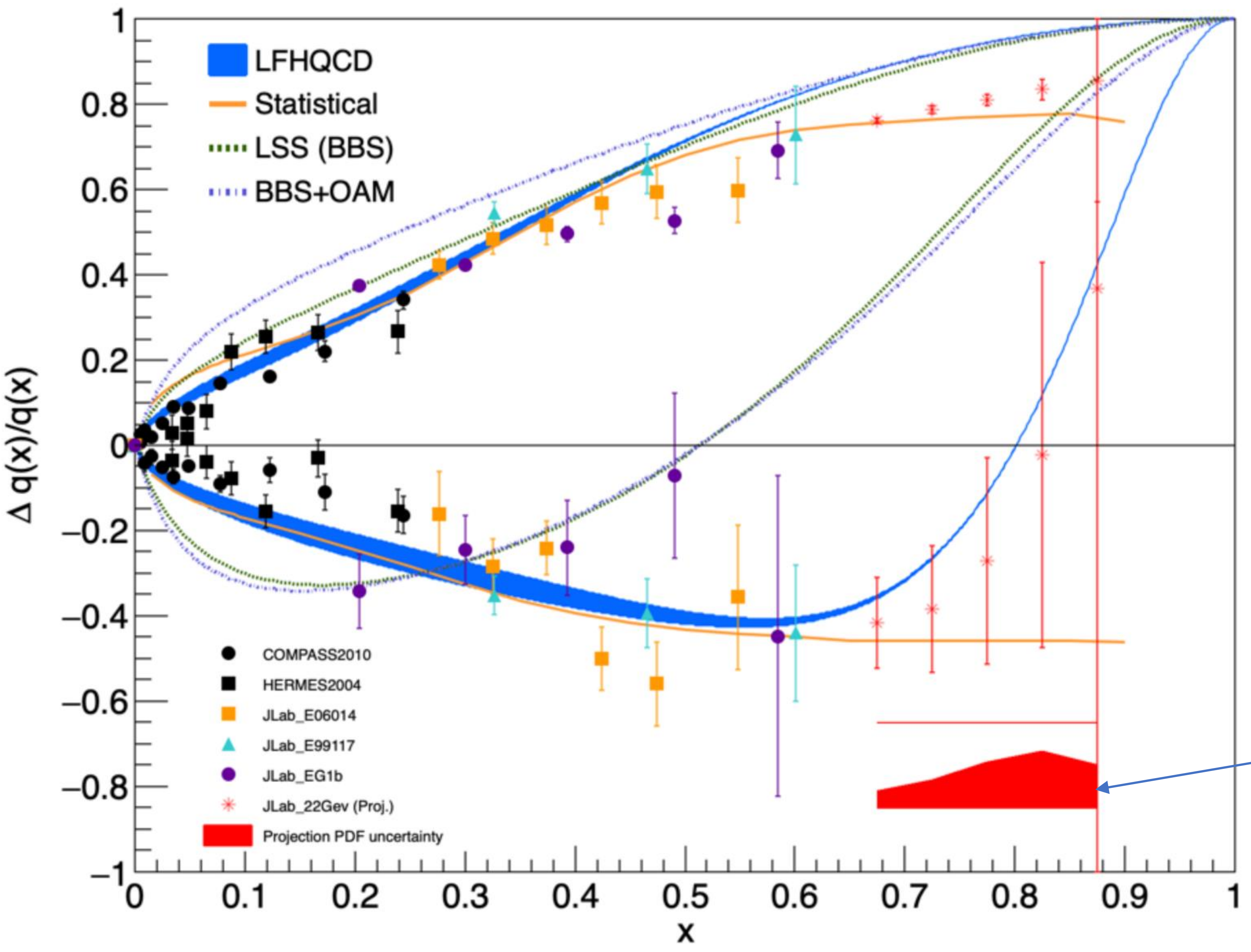


Projections: A_1^p



FC: Jesse Smith (UVA Summer 2023 Undergrad Project)

Projections: $\Delta q / q$



CJ15NLO used for PDF and uncertainty

FC: Jesse Smith (UVA Summer 2023 Undergrad Project)

Summary

- From this preliminary study, we have found that with a 22 GeV electron beam at Jefferson Lab we can push measurements of A_1^n and A_1^p all the way up from x ~ 0.75 to x ~ 0.9 with reasonable statistics, allowing us to probe further into the valence quark region than ever before.
- By making projections of A_1 for both the proton and the neutron, we were able to perform a flavor decomposition and make projections for the polarized quark distribution functions as well.

Acknowledgments

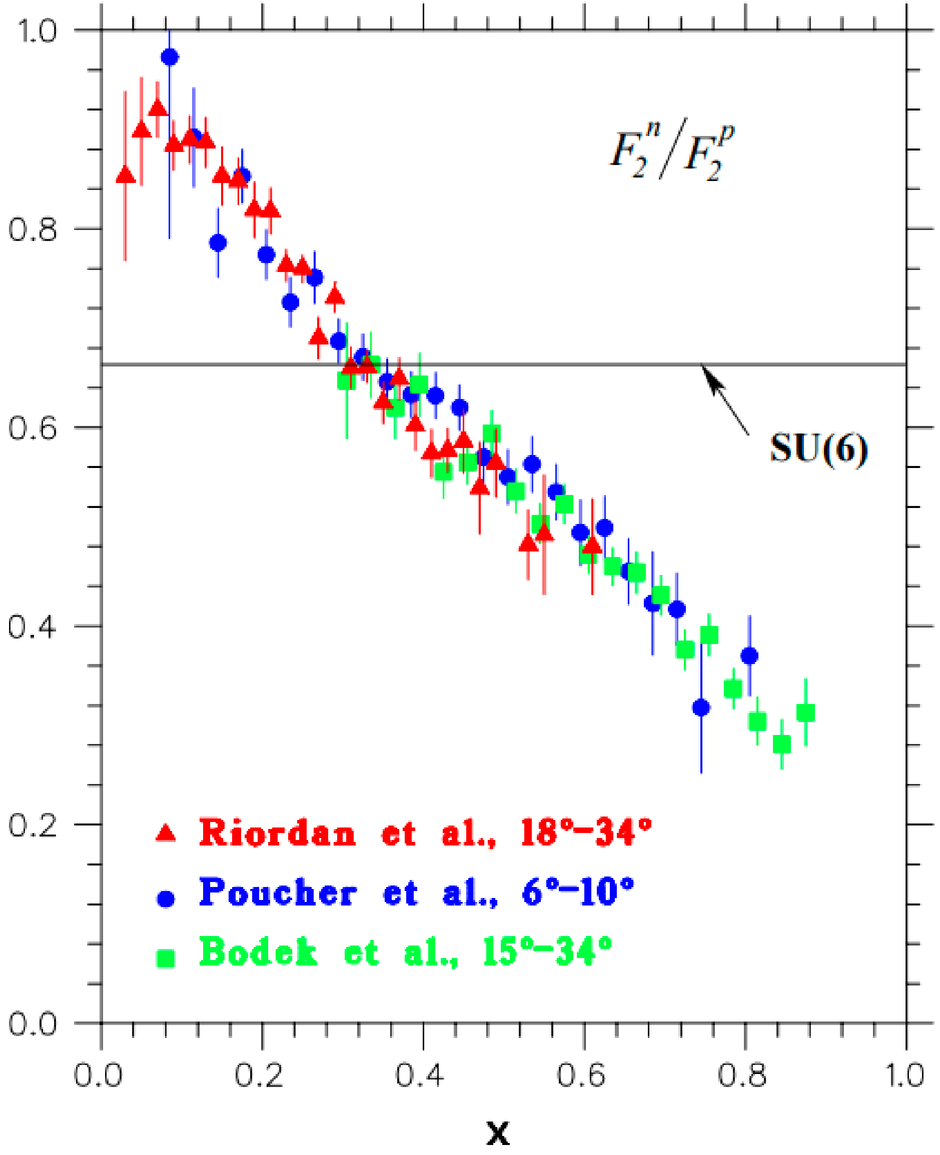
- Harut Avakian, David Flay (Jefferson Lab)
- Dien Nguyen (UTK)
- Mike Nycz, Jesse Smith, Jixie Zhang, Xiaochao Zheng (UVA)

Questions?

Backup Slides

F2 Ratio

NH3 dilution scaled by F2 ratio to account for difference between proton and neutron cross sections



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