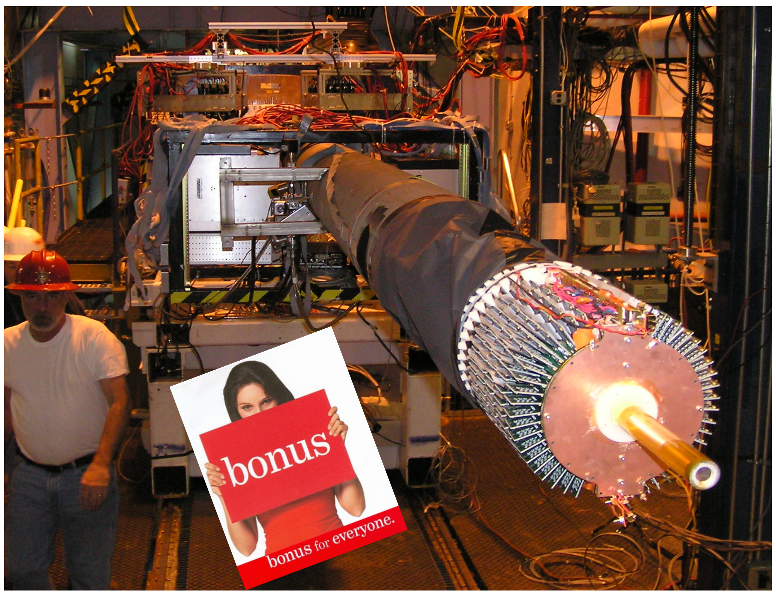
# Spectator Tagging with **BONuS/BONuS12**




Supported under grant DE-FG02-96ER40960 by

U.S. DEPARTMENT OF ENERGY | Office of Science

Sebastian Kuhn

*Old Dominion University*

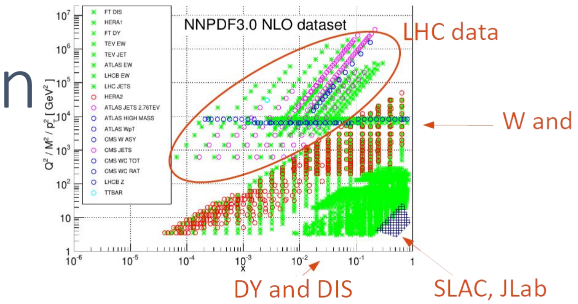
ODU

Jefferson Lab

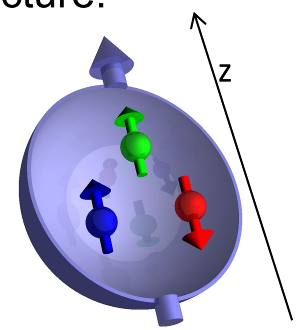
# Overview

- Motivation
- (**B**arely) **O**ffshell **Nu**cleon **S**tructure -> Spectator Tagging
- Minimizing Theoretical Uncertainties
- Low-Momentum Spectators in the Lab
- From 6 -> 12 (-> 22?) GeV
- EIC
- Conclusion

# Collinear Parton Distributions of the Nucleon




- The 1D world of nucleon collinear structure:
  - Take a nucleon
  - Move it real fast along z
    ⇒ light cone momentum
    $P_+ = P_0 + P_z$ (>>M)
  - Select a “parton” (quark, gluon) inside
  - Measure **its** l.c. momentum
    $p_+ = p_0 + p_z$ (m≈0)
  - ⇒ Momentum Fraction $x = p_+/P_+$ *)
  - In DIS **): $p_+/P_+ \approx \xi = (q_z - \nu)/M \approx x_{Bj} = Q^2/2M\nu$
  - measure Probability: $f_1^i(x), i = u, d, s, \ldots, G$ ($f_1^u \equiv u(x)$ etc.)

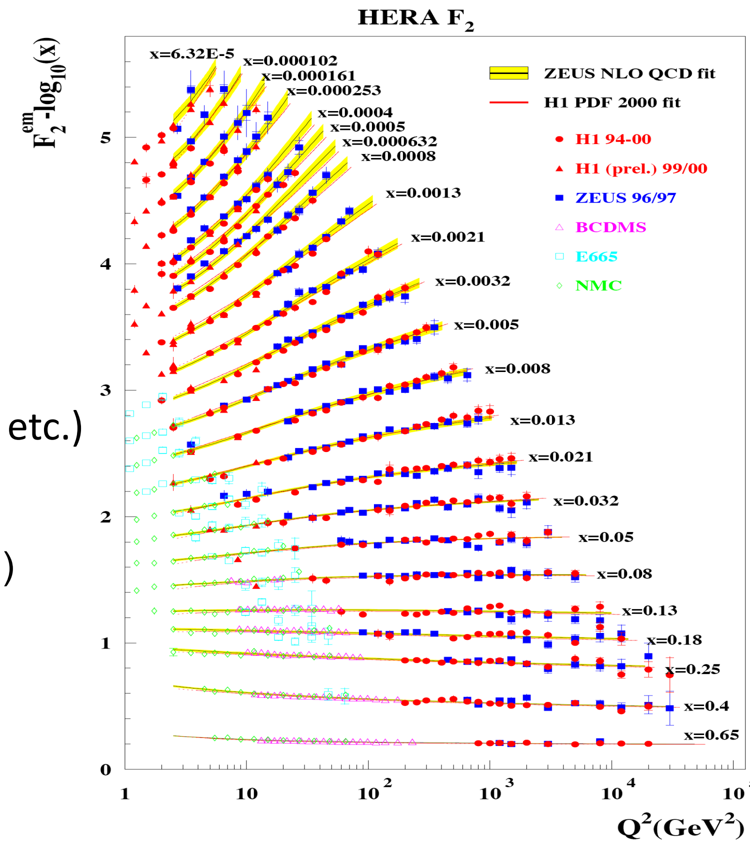



Humongous data set on the proton; no DIS data on the neutron

Neutron very desirable since $d_p \approx u_n \rightarrow$ flavor separation (isospin)

Workaround: neutrons bound in nuclei

Drawback: obscured by binding effects (e.g., EMC effect)




*) Advantage: Boost-independent along *z*

**) DIS = “Deep Inelastic (Lepton) Scattering; here assuming target rest frame

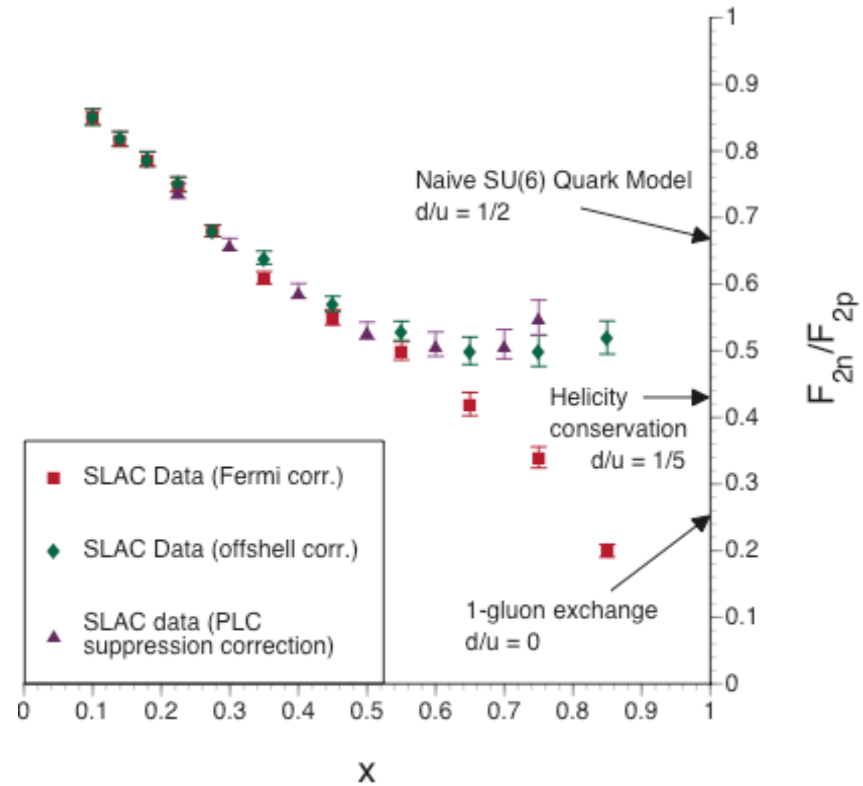
# Why neutron data (esp. at high x)?

- Neutron and proton related via isospin rotation: replace $u_p \rightarrow d_n$ and $u_n \rightarrow d_p$ => using experiments with protons and neutrons one can extract information on u and d in the valence quark region:

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

- **EMC effect:** We can only gain high-precision understanding if we can compare the NUCLEAR structure functions to a prediction from PROTON and NEUTRON structure functions and a microscopic model of the nucleus. (We need to get away from defining "EMC ratio = F2A*2/A*F2D")

- To correct nuclear data for EMC effect, must consider that it affects p and n (and/or *u* and *d*) differently in different (non-isoscalar) nuclei

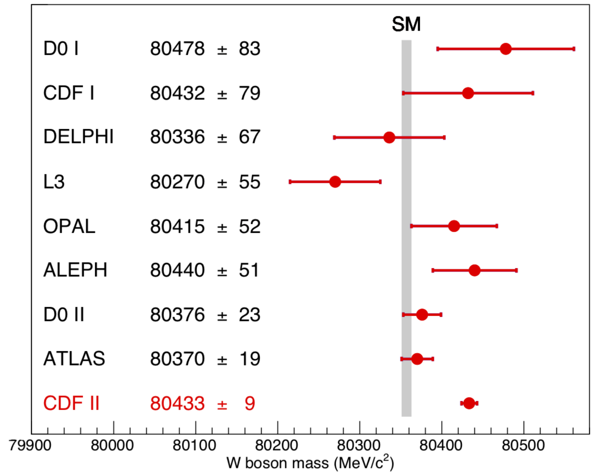


# High-x PDFs: Input for Collider experiments

## 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




CDF Collaboration *et al.*, *Science* **376**, 170–176 (2022)    8 April 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
- 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

**High-precision measurement of the *W* boson mass with the CDF II detector**

CDF Collaboration

Corresponding author: A. V. Kotwal, ashutosh.kotwal@duke.edu

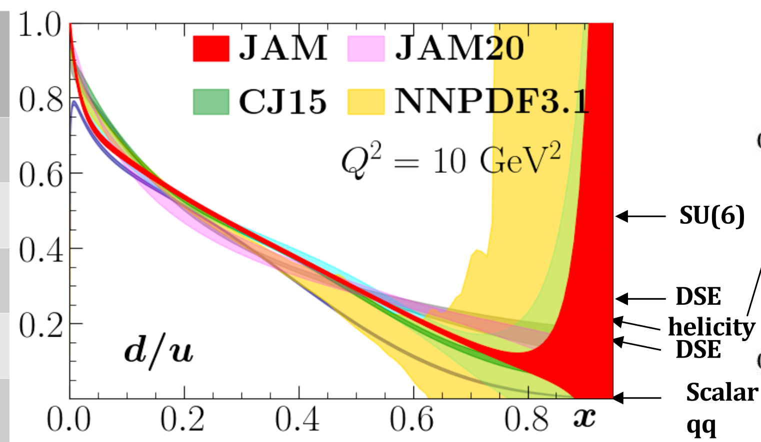
*Science* **376**, 170 (2022)
DOI: 10.1126/science.abk1781

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 $F_2$ structure function via spectator tagging with CLAS. *Phys. Rev. Lett.* **108**, 142001 (2012). doi:10.1103/PhysRevLett.108.142001 Medline

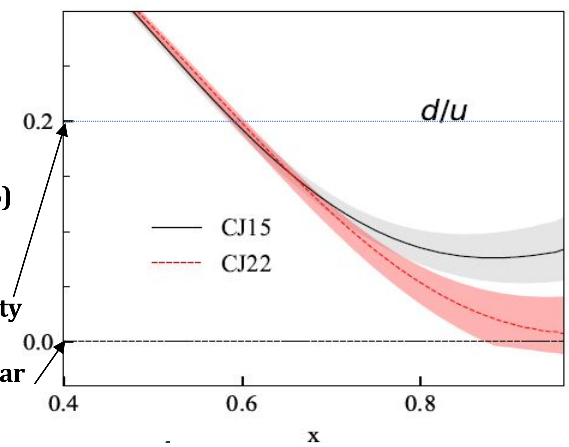
96. S. Tkachenko, N. Baillie, S. E. Kuhn, … D. Watts, X. Wei, L. B. Weinstein, M. H. Wood, L. Zana, I. Zonta, Measurement of the structure function of the nearly free neutron using spectator tagging in inelastic $^2H(e,e'p_s)X$ scattering with CLAS. *Phys. Rev. C* **89**, 045206 (2014).

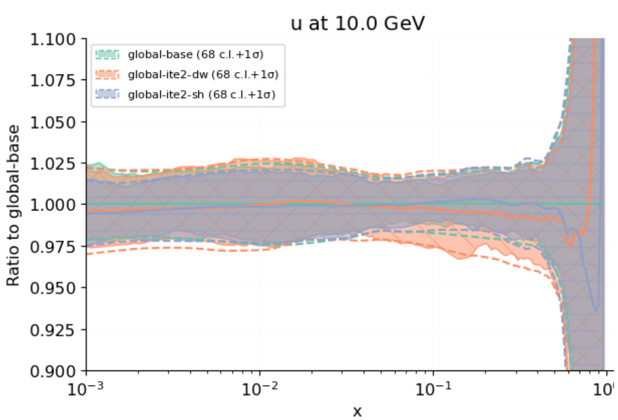
# Present Knowledge of *d/u* ($x \to 1$)

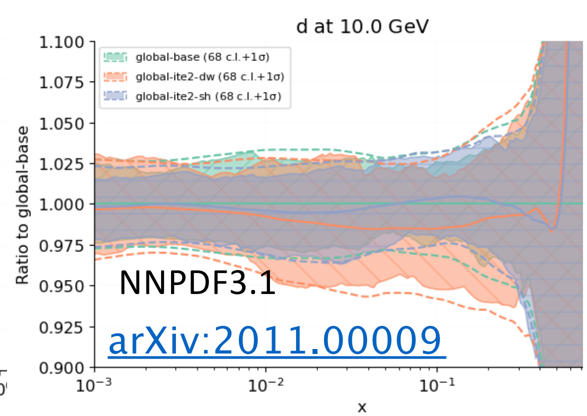
| Nucleon Model | $F_2^n/F_2^p$ $x \to 1$ | d/u $x \to 1$ |
|---|---|---|
| SU(6) Symmetry | 2/3 | 0.5 |
| Scalar diquark dominance | 1/4 | 0 |
| DSE contact interaction | 0.41 | 0.18 |
| DSE realistic interaction | 0.49 | 0.28 |
| PQCD (helicity conservation) | 3/7 | 0.2 |

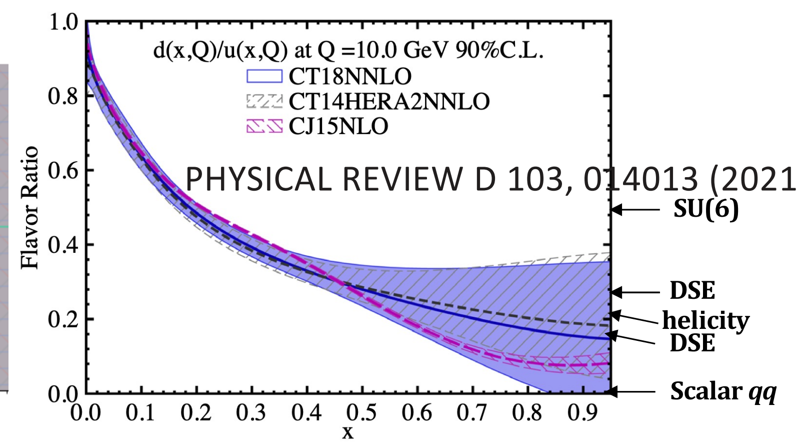



*Accardi et al., PLB* 801 (2020) 135143

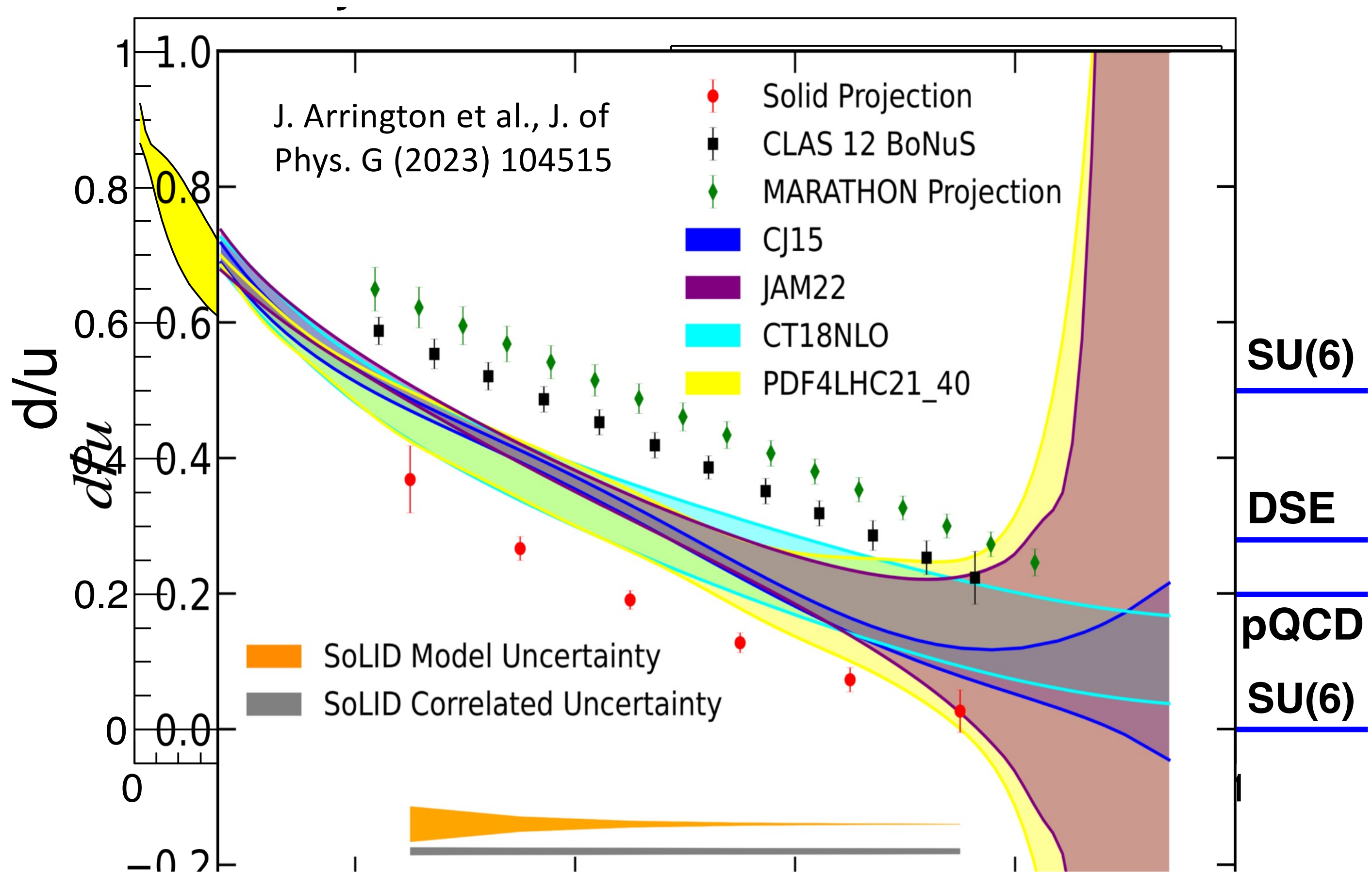


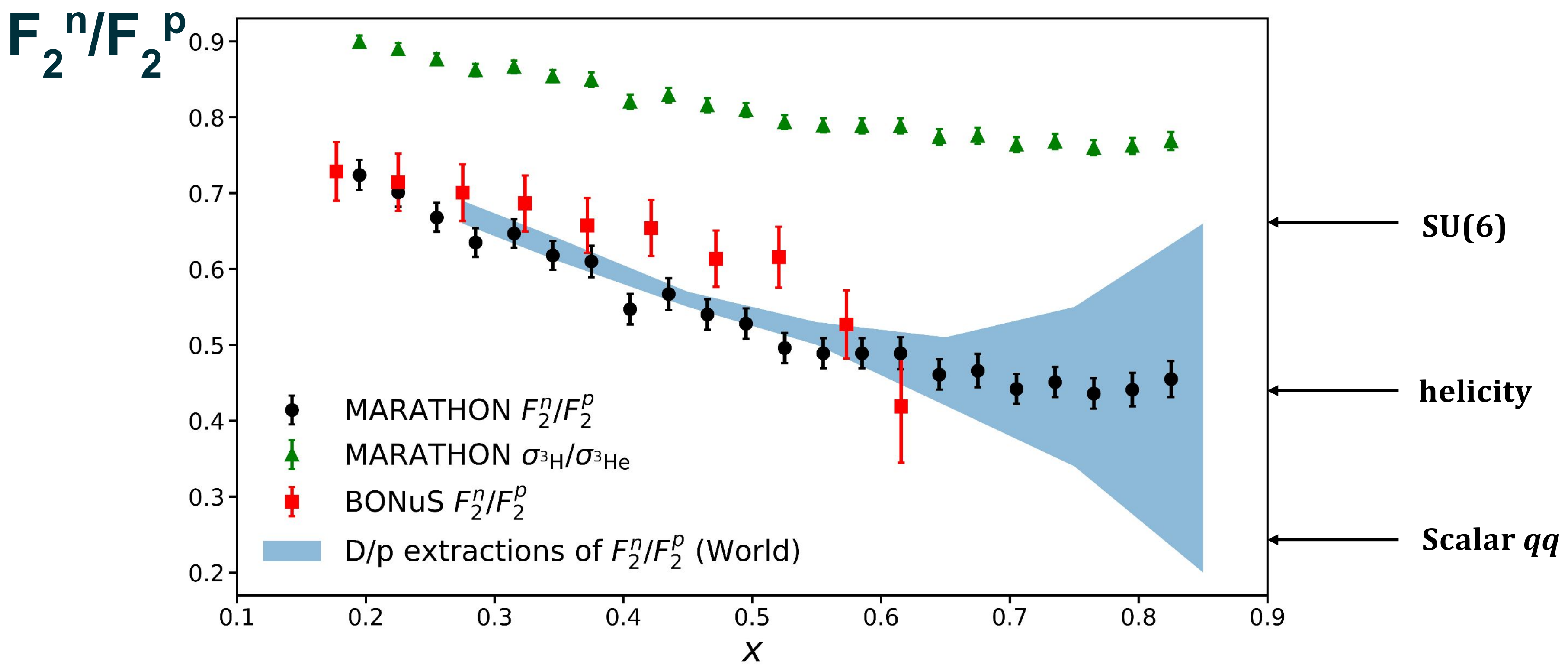



# LRP 2015: Projected results from JLab@12 GeV



# Marathon Results

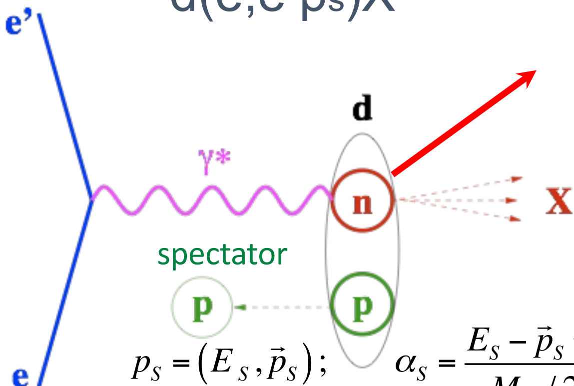





Jefferson Lab Hall A Tritium Collaboration, *et al* PRL 128 (2022)

# Spectator Tagging – BONuS

d(e,e'ps)X




$$p_S = (E_S, \vec{p}_S); \quad \alpha_S = \frac{E_S - \vec{p}_S \cdot \hat{q}}{M_D/2}$$

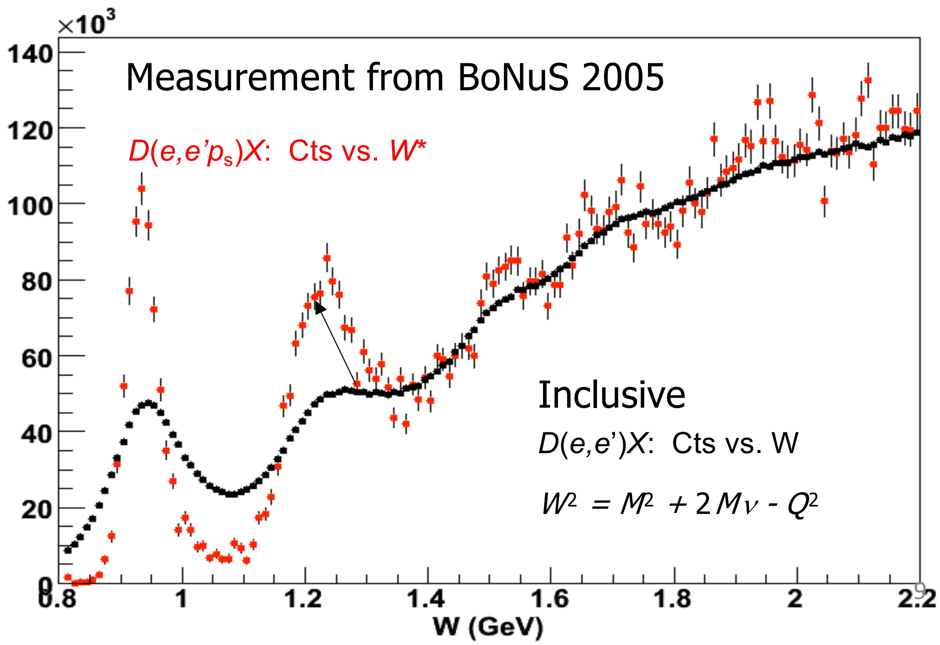
$$p_n = (M_D - E_S, -\vec{p}_S); \alpha_n = 2 - \alpha_S \qquad M^{*2} = p_n^{\mu} p_{n\mu}$$

$\alpha_S$ = light cone momentum fraction of spectator nucleon

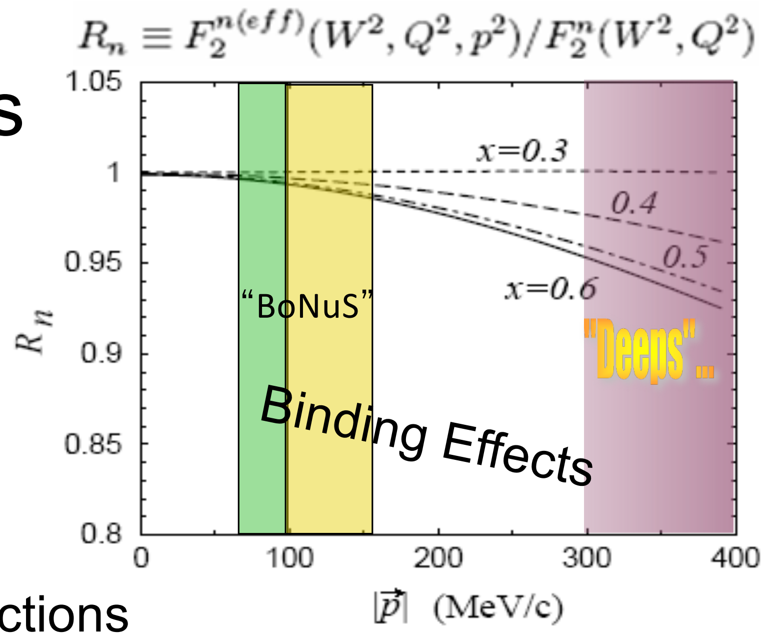
$$x^* = \frac{Q^2}{2 p_n{}^{\mu} q_{\mu}} \approx \frac{Q^2}{2M\nu(2-\alpha_S)}$$

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

Spectator proton detected in the BONuS 12 Radial Time Projection Chamber (RTPC)



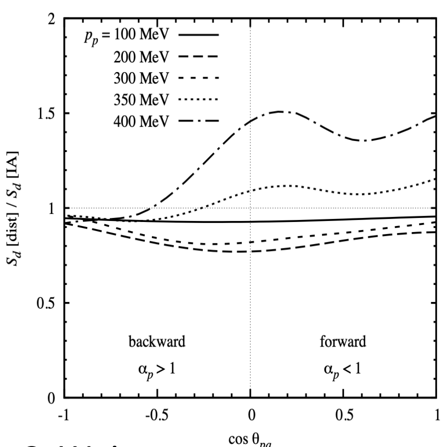
# Modifications to Simple Spectator Picture




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

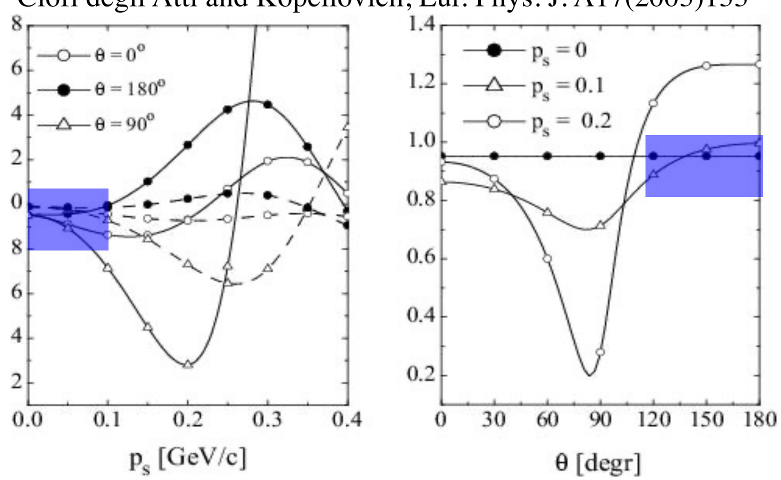
Phys. Lett. B335, 11 (1994); Phys. Rev. D 49, 1183 (1994).

## Final State Interactions

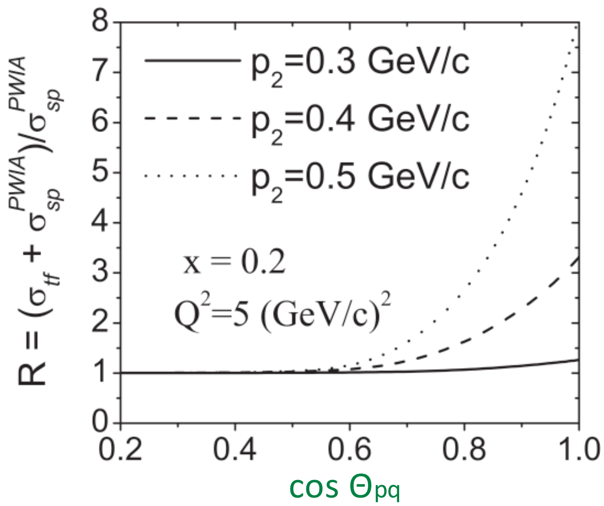



C. Weiss

Ciofi degli Atti and Kopeliovich, Eur. Phys. J. A17(2003)133




## Target Fragmentation




Palli et al, PRC80(09)054610

# BONuS12 withCLAS12

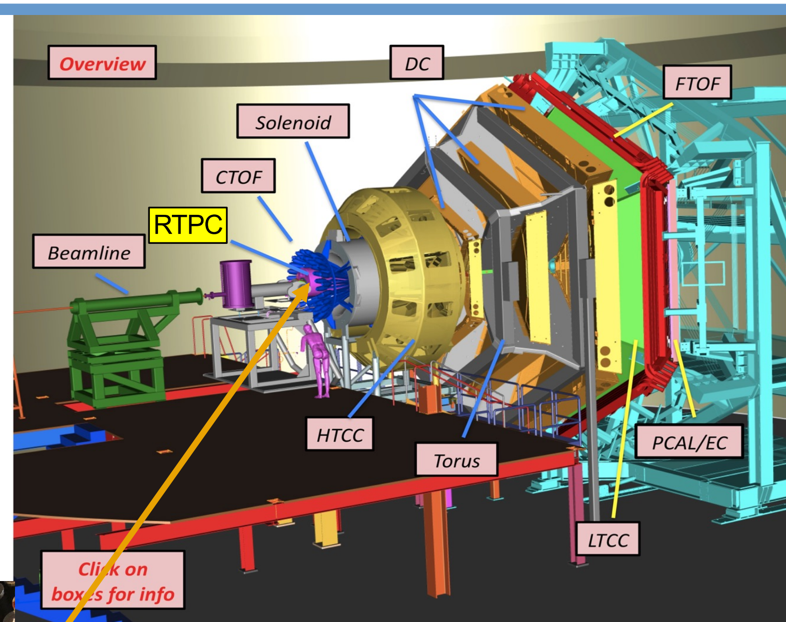
## $e^- \, d \rightarrow e^- \, p \, X$

**- CLAS12 Forward Detector:**

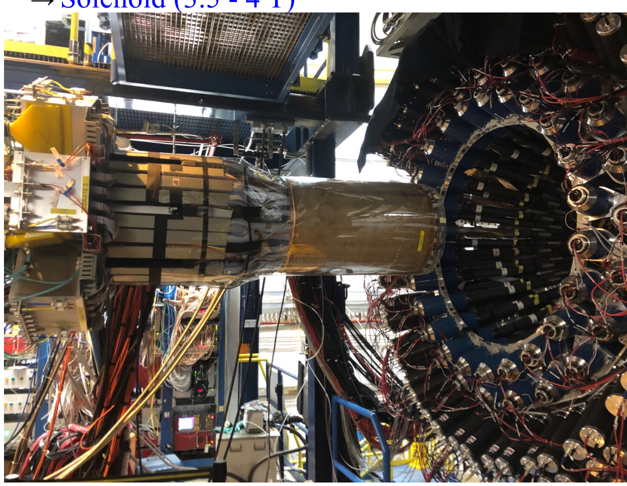
→ Superconducting Torus magnet.
→ 6 independent sectors:
  → HTCC
  → 3 regions of DCs
  → LTCC /RICH
  → FTOF Counters
  → PCAL and ECs

**- Central Detector:**

→ Solenoid (3.5 - 4 T)




BONuS12
RTPC



| Beam Energy | Target | Spring 2020 | Summer 2020 |
|---|---|---|---|
| 1 Pass Data | H2 | 81M | 185M |
| | D2 | 37M | 45M |
| | 4He | 19M | 44M |
| | Empty | 1M | 22M |
| | Total | 138M | 296M |
| 5 Pass Data | H2 | 151M | 266M |
| | D2 | 2275M | 2355M |
| | 4He | 77M | 51M |
| | Empty | 21M | 45M |
| | Total | 2524M | 2717M |

February – March 2020 | MEDCON6 | August-September 2020

# BONuS12 RTPC

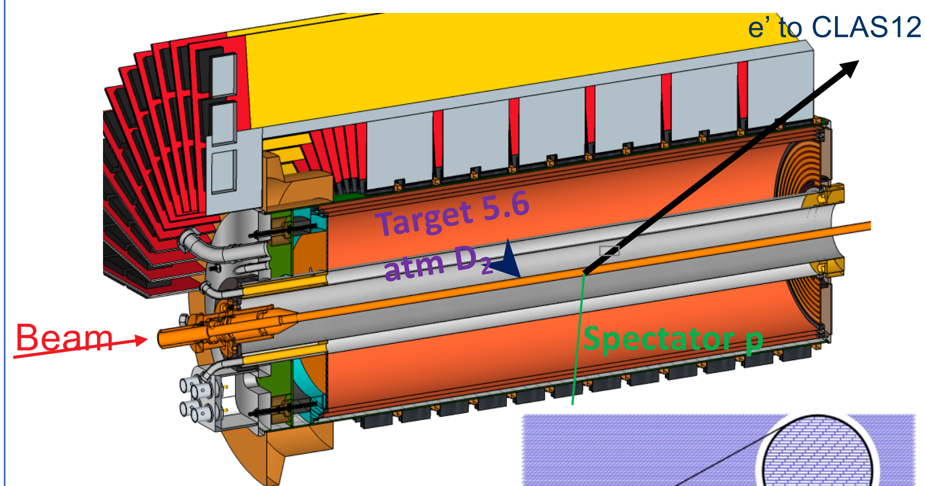
- → Active length: **40 cm**
- → Radial drift distance: **4 cm**
- → Drift gas **He/$CO_2$ (80/20)**
- → **3** GEM amplification layers
- → **16** HV sectors per GEM
  (Segmented in $\phi$)
- → Pad readout: **2.8 mm x 4 mm**

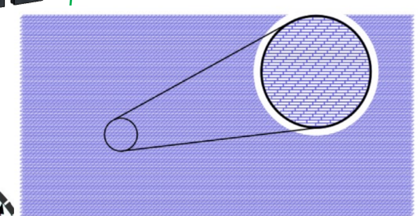
=> **17,280 channels**

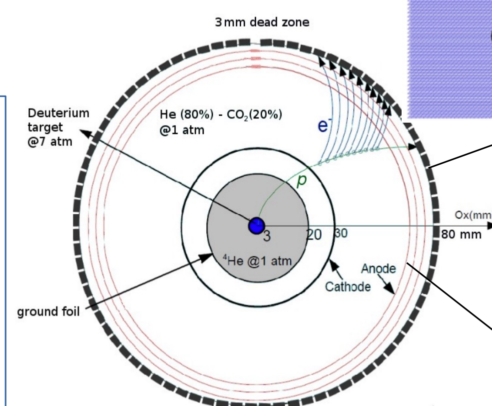
**FEU electronics → Signal height vs. Time bin**

- Pad position + Time + drift path → hit position
  => track reconstruction
  vertex + momentum vector
- integrated signal + pad gains ($G_i$) →

$$\left\langle \frac{dE}{dX} \right\rangle = \frac{\sum_i \frac{ADC_i}{Gi}}{vtl}$$

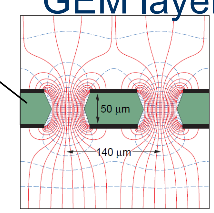





Readout Pads

GEM layer

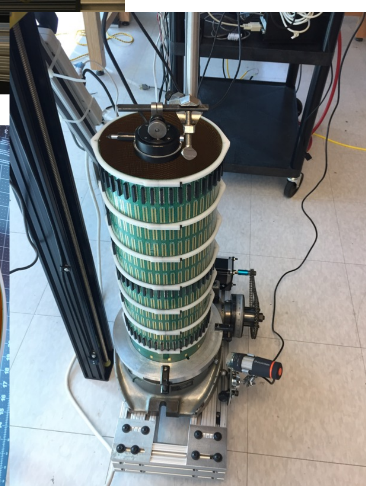


# RTPC Assembly @ Hampton U. In Collaboration with ODU & JLab

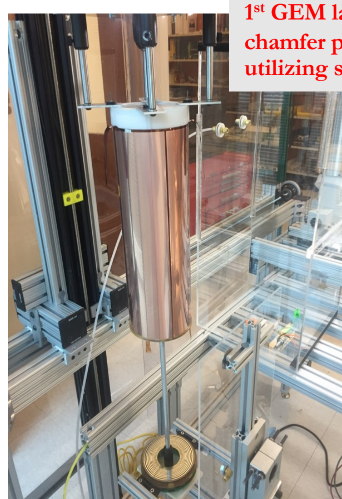
GEM foil wrapping and gluing

Automated epoxy application

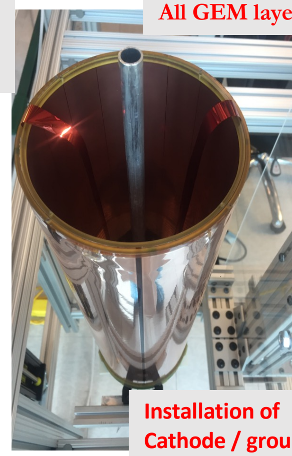
Wrapped Padboard inner surface



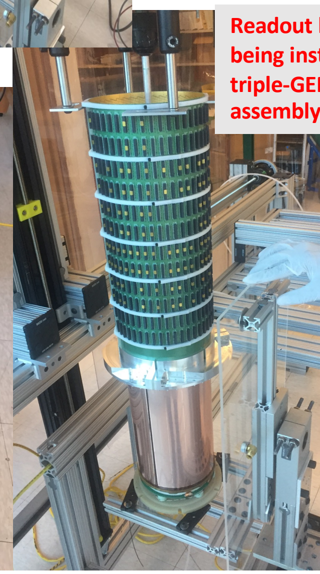
1st GEM layer lowered onto chamfer plate assembly utilizing self-alignment jig



All GEM layers installed



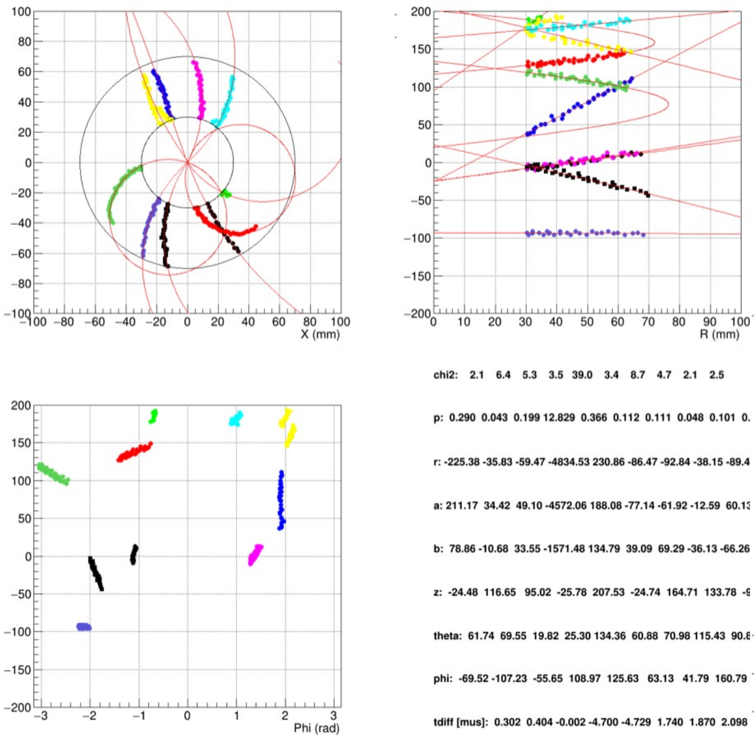
Readout board being installed on triple-GEM assembly



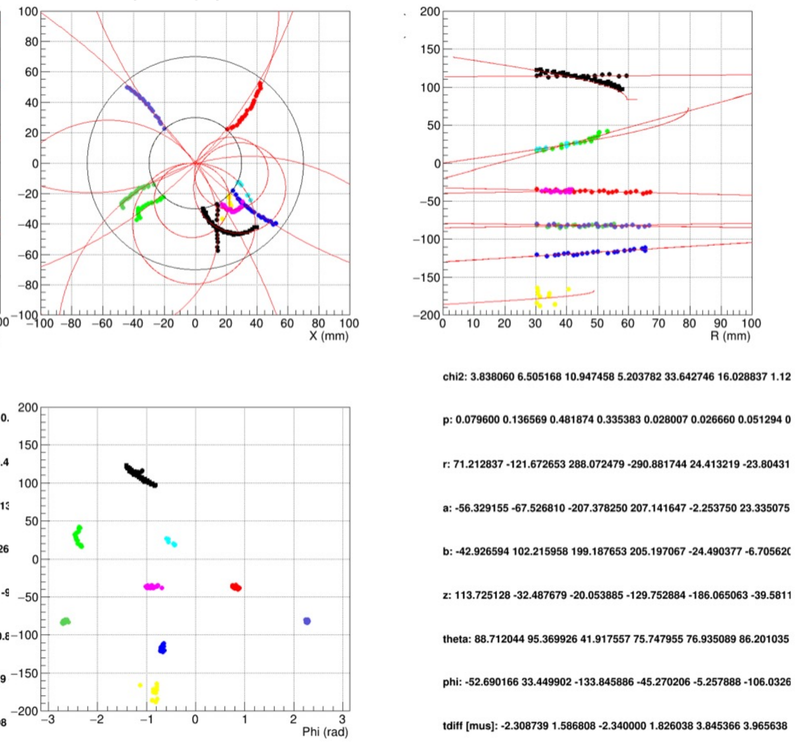
Installation of Cathode / ground assembly

# Reconstructed Tracks

GEMC simulation

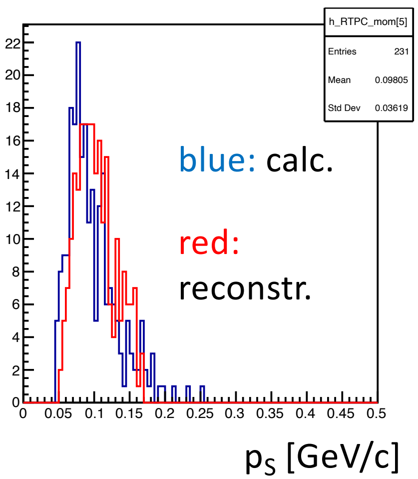



Run 12736 Summer – $D_2$ target, 10.4 GeV

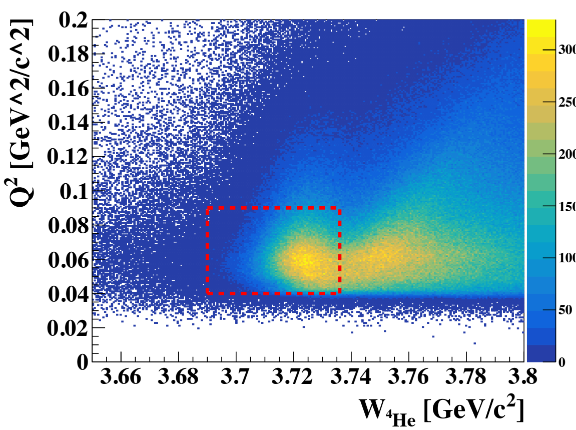


# BONuS12 – Quality Checks

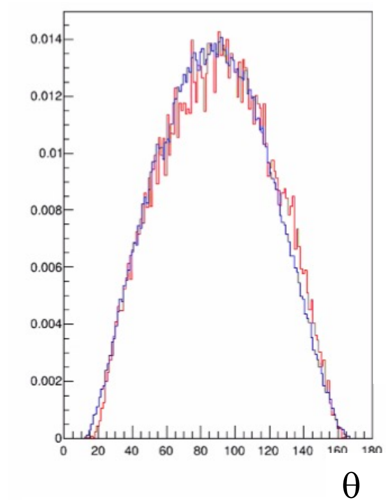
D(e,e'pπ)$p_S$ 2.1 GeV



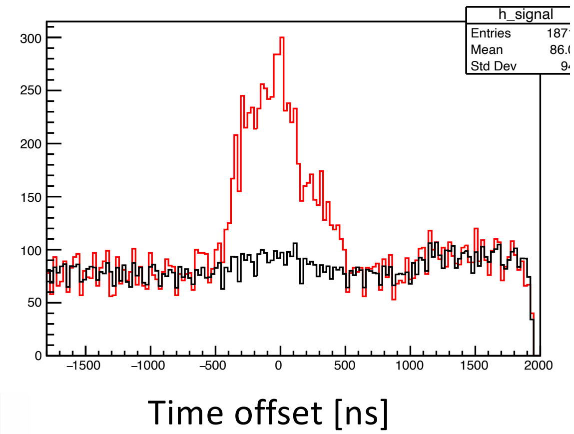

$^4$He(e,e')$^4$He 2.1 GeV

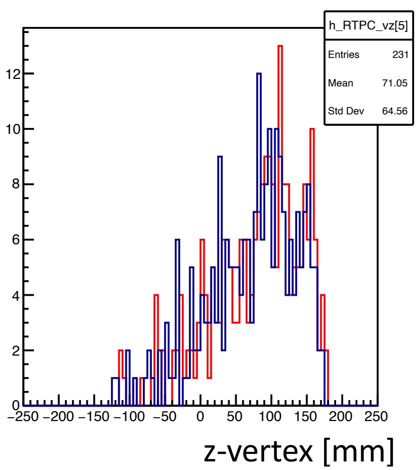


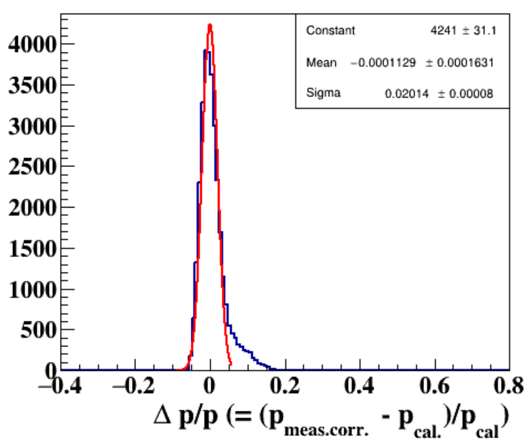

MC vs. Data

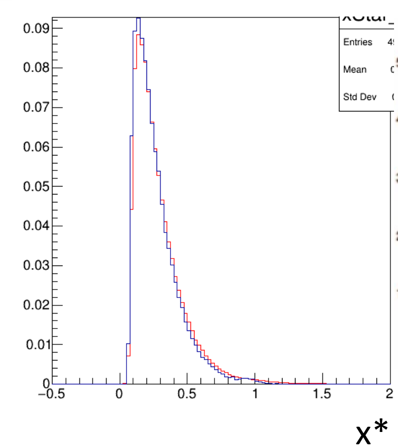


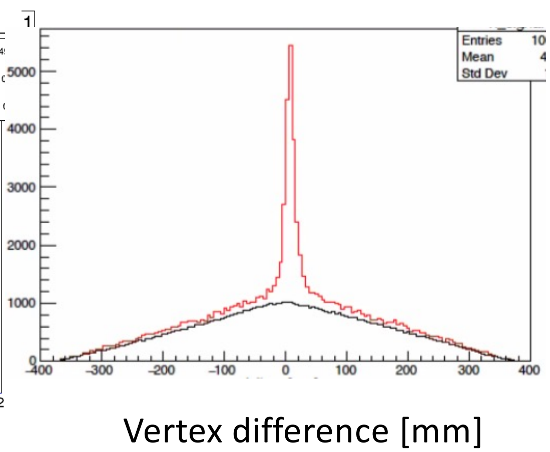

Acc. Background Subtraction



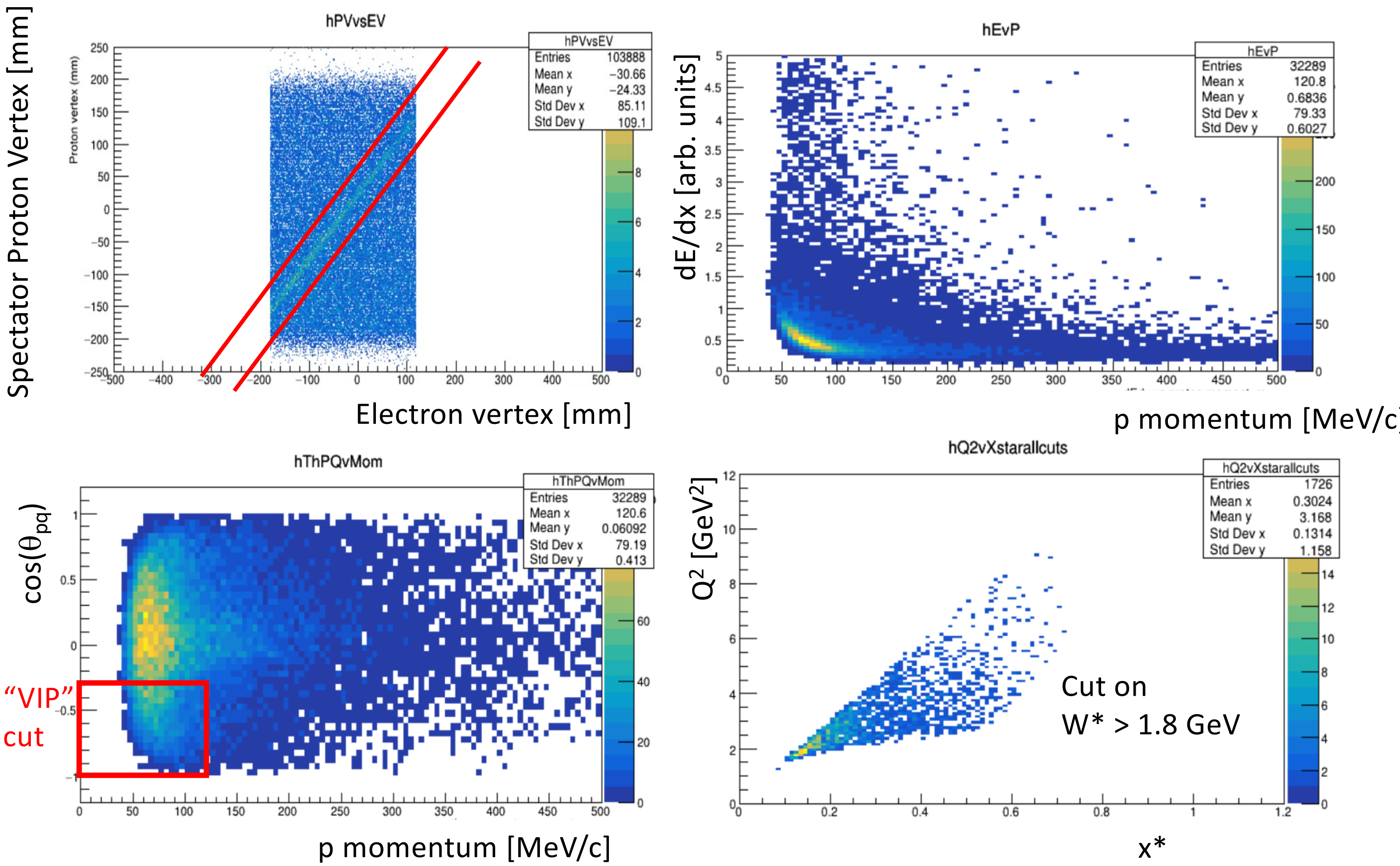



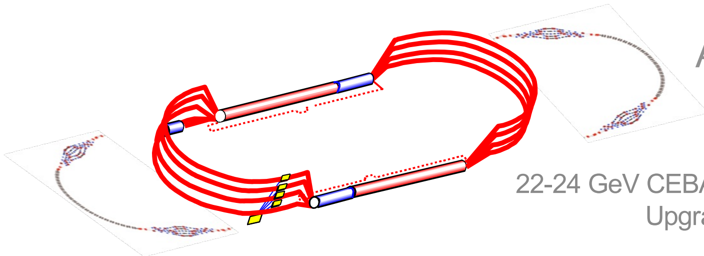



# BONuS12 – 10.4 GeV Data sample



# 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 $Q^2$: Definite determination of asymptotic limit... *)
- ...AND to $x = 0$ => Study "valence" sea quarks (pion cloud)
- Increase $Q^2$ range for all $x$ -> DGLAP => Study "valence" gluon helicity
- Even for same $x$, $Q^2$: higher energy -> higher rates -> better statistics
- *(Super)Rosenbluth* – expand range in $\varepsilon$ 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 $Q^2$: Suppress higher twist, study logarithmic resummation

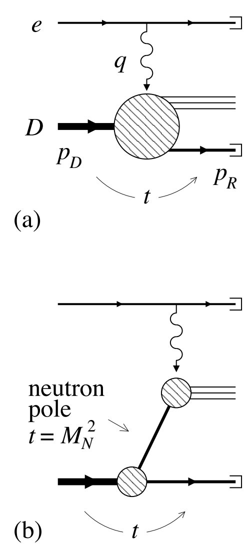
# Future: EIC

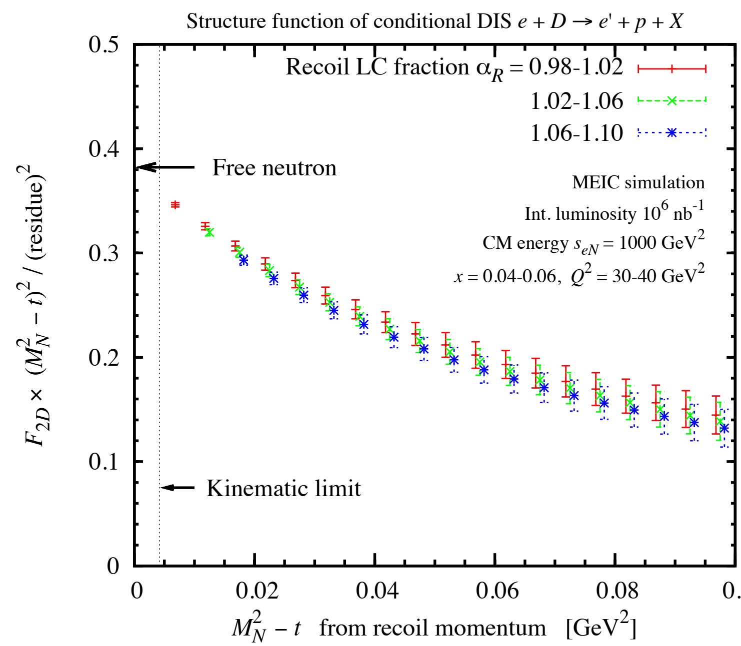
See talks tomorrow by
C. Weiss and S. Kumano

**Tagging is easier:**

- Acceptance down to zero spectator momentum
- High resolution in l.c.f.
- transverse momentum ⇔ angle

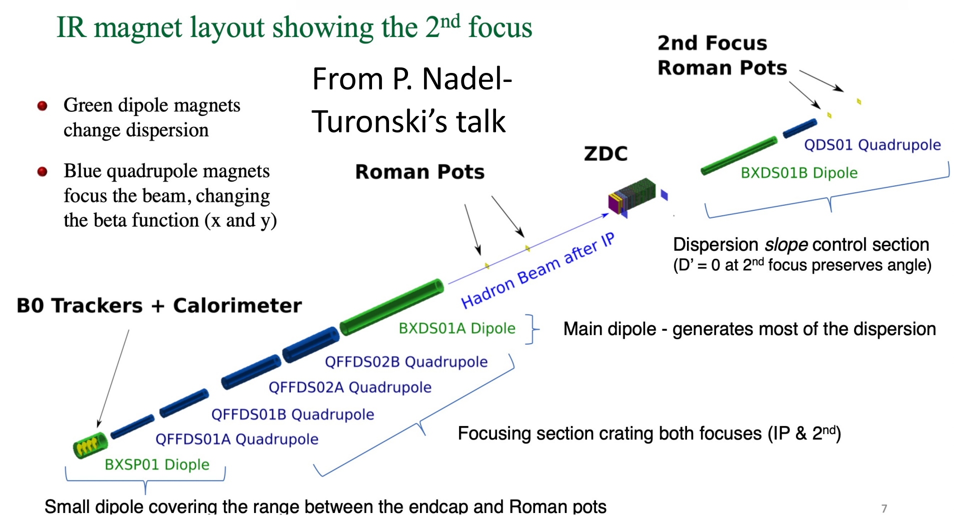
$$P_{\|p} \approx \frac{P_D}{2}\left(1+\frac{p_p^z}{m}\right)$$




## Far-forward detectors

From P. Nadel-Turonski's talk




Magnetic spectrometer for protons, integrated in beam line, several subsystems: good acceptance and resolution

Zero-Degree Calorimeter for neutron

Advantage over fixed target: No target material, can detect spectators with rest frame momenta down to ~zero

# Conclusion

- Few-body nuclei (D and $^3He/^3H$) continue to be "neutron targets of choice" – needed to study valence structure of nucleons
- Interpretation of results complicated by off-shell effects, possible structure modifications and final state interaction…
- …but we can also learn a lot about NN interaction and few-body nuclear structure by studying these effects (large kinematic coverage)
- New, more precise theoretical calculations are becoming available and can be tested experimentally
- Spectator tagging allows us to minimize binding effects or study them in detail
- Radial Time Projection Chambers have proven their value
- BONuS12 had successful Physics run -> stay tuned for $F_{2n}$, d/u, nDVCS…
- Lots more experiments at 12 GeV – ALERT, TDIS, BAND, LAD
- Can be extended to 22 GeV
- Future of spectator tagging: EIC