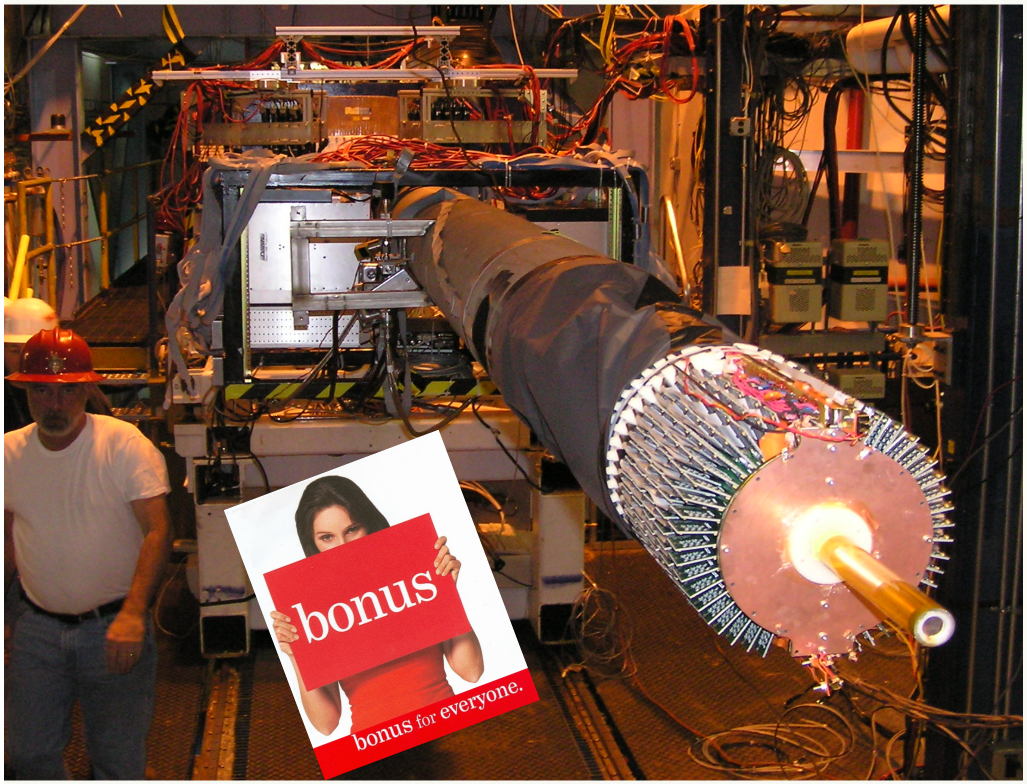
A Brief History of Spectator Tagging at Jefferson Lab



Supported under grant
DE-FG02-96ER40960 by

U.S. DEPARTMENT OF ENERGY | Office of Science

Sebastian Kuhn

Old Dominion University

ODU

Jefferson Lab

Overview

- Spectator Tagging – How and Why?
- The Neutron at Large *x*
- The DEEPS experiment
- The “BONuS” Experiment
- BONuS12
- Other tagging experiments
- Conclusion and Outlook

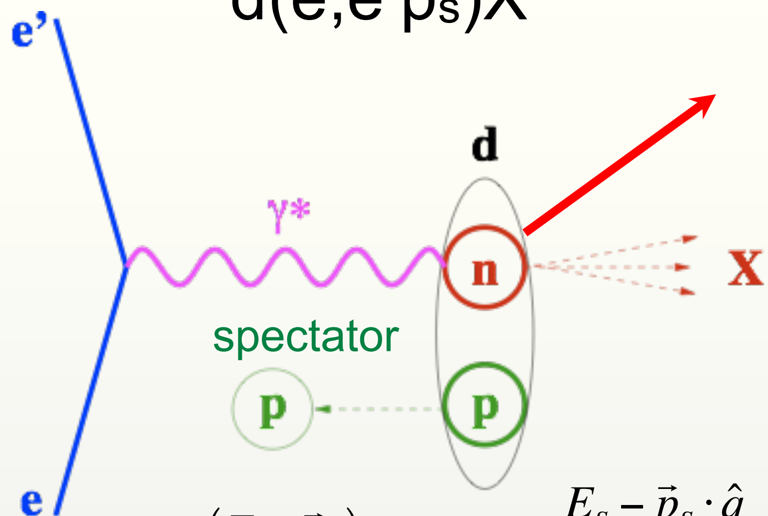
What is Spectator Tagging?

- Study a reaction on a PART of a nuclear/nucleon target by observing, in coincidence, a ”spectator” correlated with that part (e.g., another nuclear fragment) to infer the initial state of the struck part.
- Examples: observe a protron in p(e,e’p)X to tag scattering on the virtual pion cloud; observe a nuclear fragment in A(e,e’A-1) to study bound nucleons; observe a proton in D(e,e’p)X to study the neutron.
- Advantages: Selectivity (“I didn’t scatter on the spectator”) and kinematic corrections (account for Fermi motion).

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

d(e,e’p_s)X



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

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

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

$$\boxed{\begin{aligned} W^{*2} &= \left(p_n + q\right)^2 = M^{*2} + 2\left((M_D - E_s)\nu - \vec{p}_n \cdot \vec{q}\right) - Q^2 \\ &\approx M^{*2} + 2M\nu(2-\alpha_s) - Q^2 \end{aligned}}$$

…however, FSI ***must*** change this picture **by necessity** since “struck nucleon” is off-shell

Correlations and Spectators

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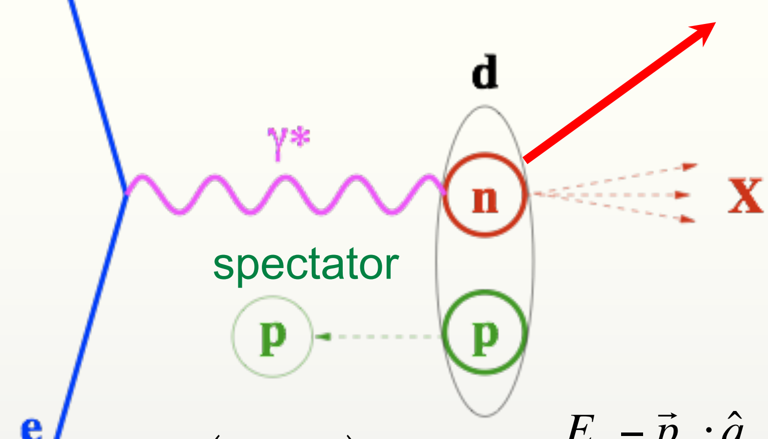
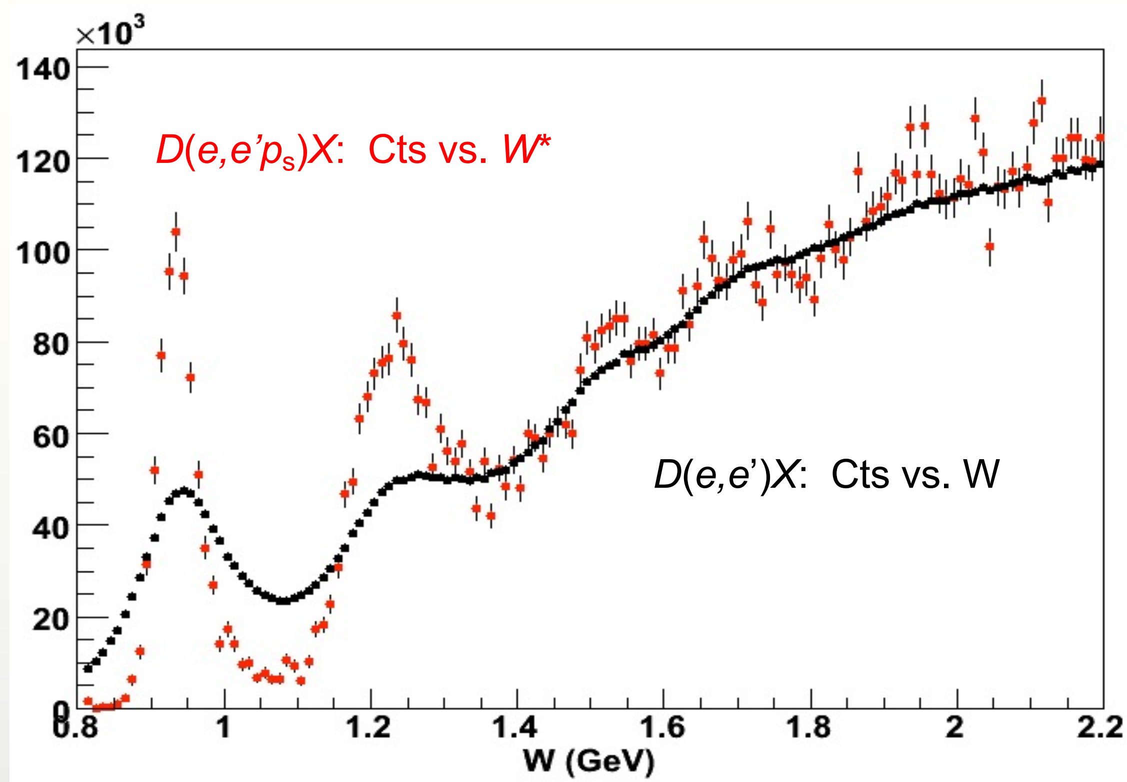
$d(e,e'p_s)X$



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



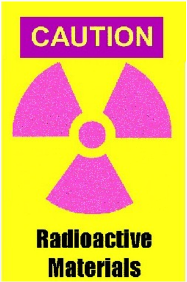
Application: Study neutron structure!

- *d*/*u* at large *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, d, Δu and Δd in the valence quark region:

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

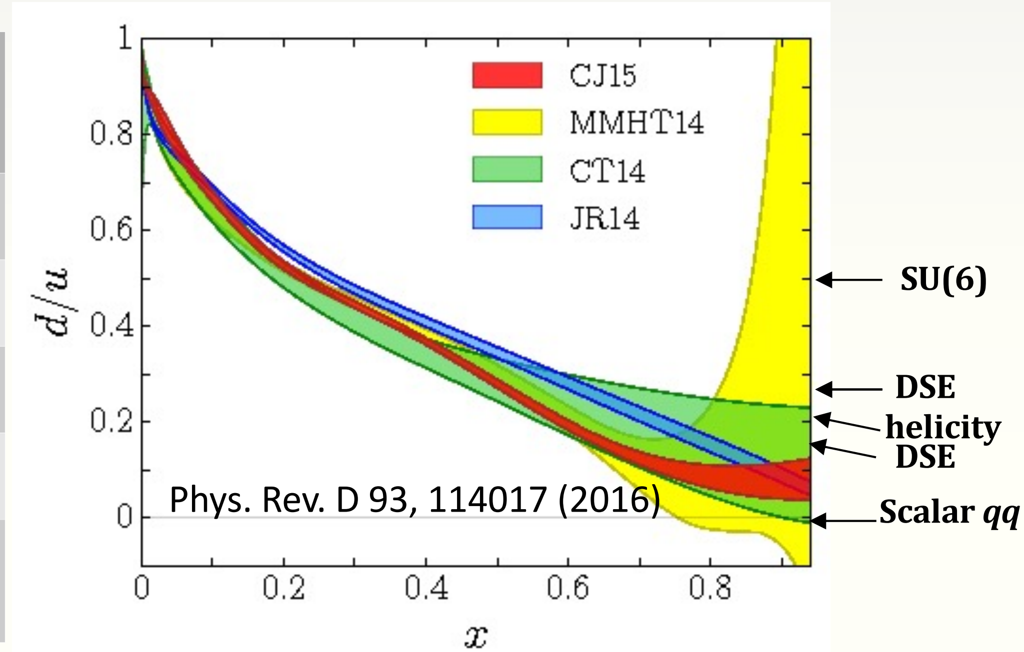
- Study Duality in both nucleons to understand its underlying cause.

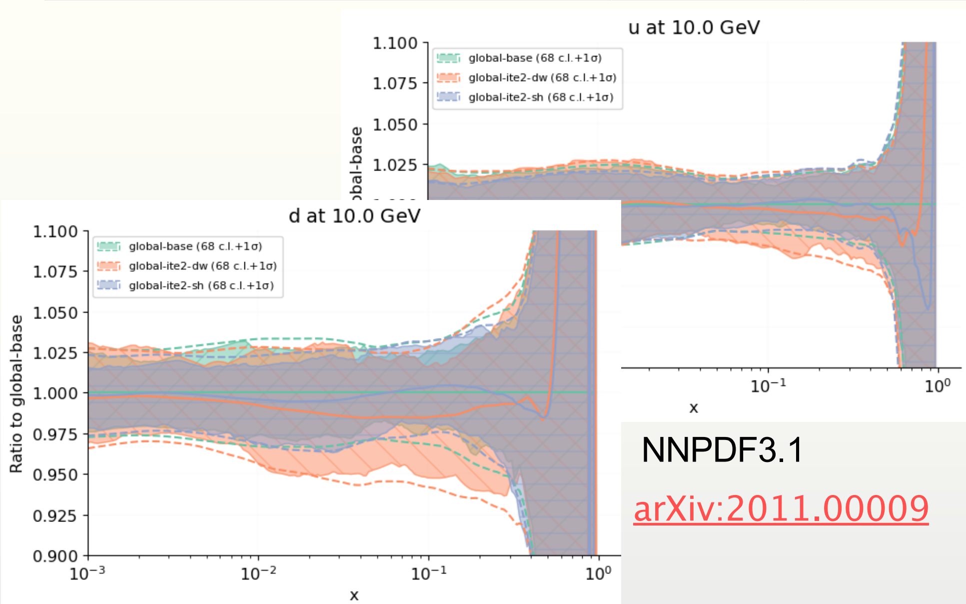
- **EMC effect:** We can only gain high-precision understanding if we can compare the NUCLEAR structure functions to a prediction from PROTON and NEUTRON structure functions and a microscopic model of the nucleus. (We need to get away from defining “EMC ratio = $F_{2A}/A/(F_{2D}/2)$”)
- => All of these require knowledge of $F_{2n}(x)$ at high *x*, but:
  - Free neutrons decay and can’t be made into a target
  - Neutrons bound in nuclei are moving, off-shell and have potentially a modified structure (EMC effect), plus may be swamped by more copious reactions on the proton



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

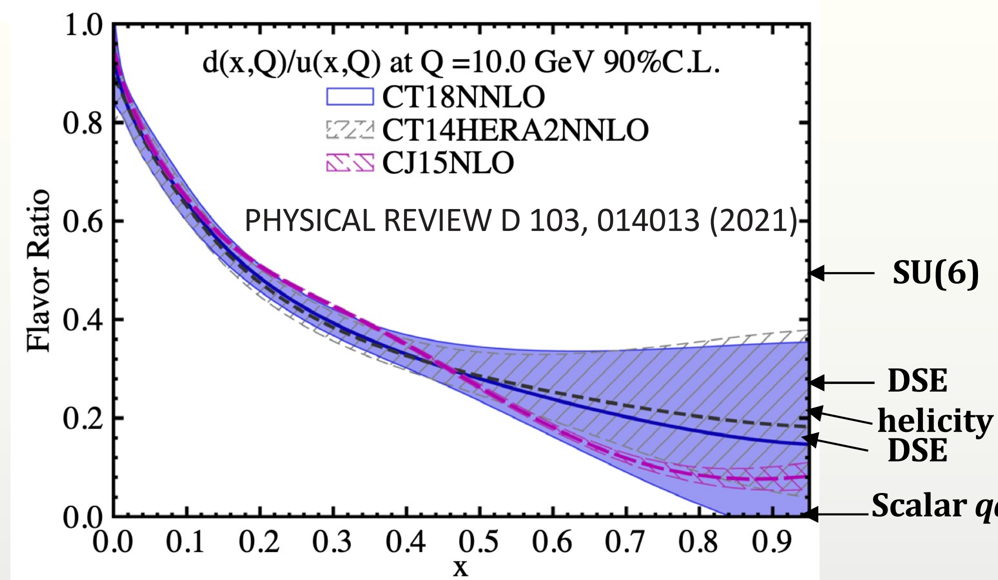
Nucleon Model	F_2^n/F_2^p $x \to 1$	d/u $x \to 1$
SU(6) Symmetry	2/3	0.5
Scalar diquark dominance	1/4	0
DSE contact interaction	0.41	0.18
DSE realistic interaction	0.49	0.28
PQCD (helicity conservation)	3/7	0.2



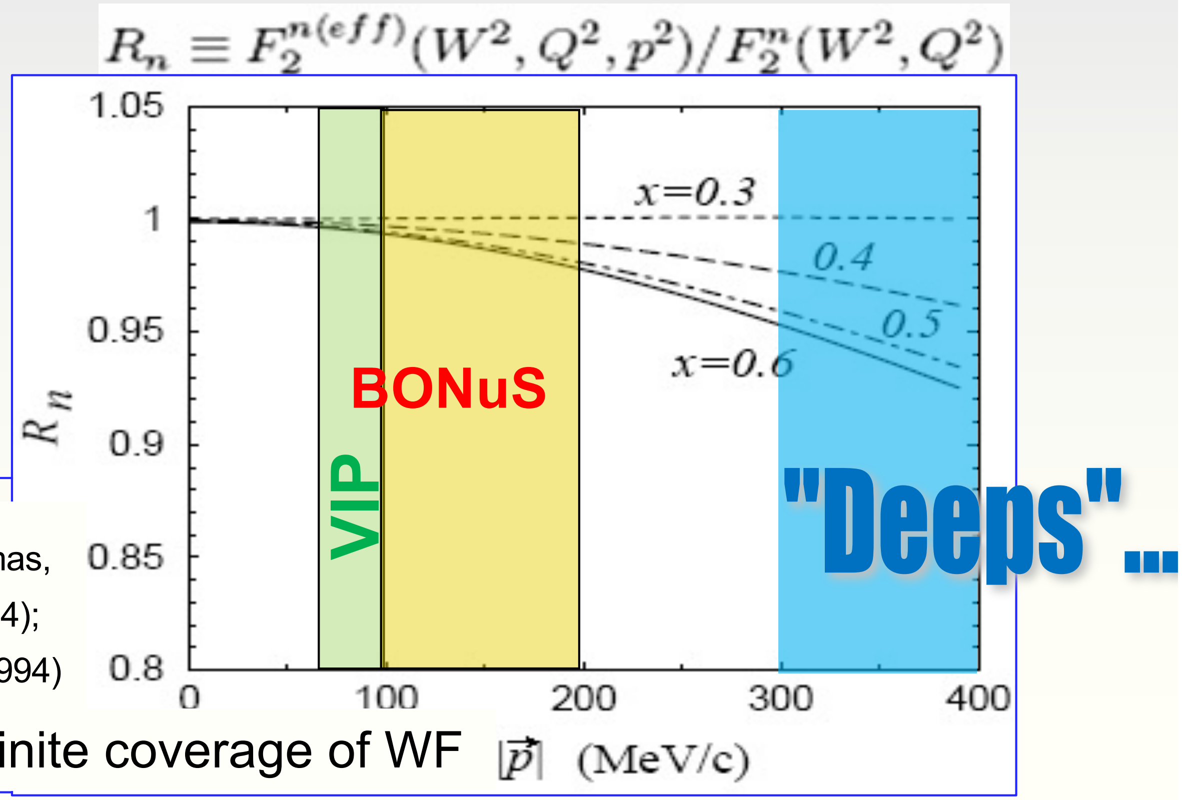


NNPDF3.1

arXiv:2011.00009



Modifications to Simple Spectator Picture

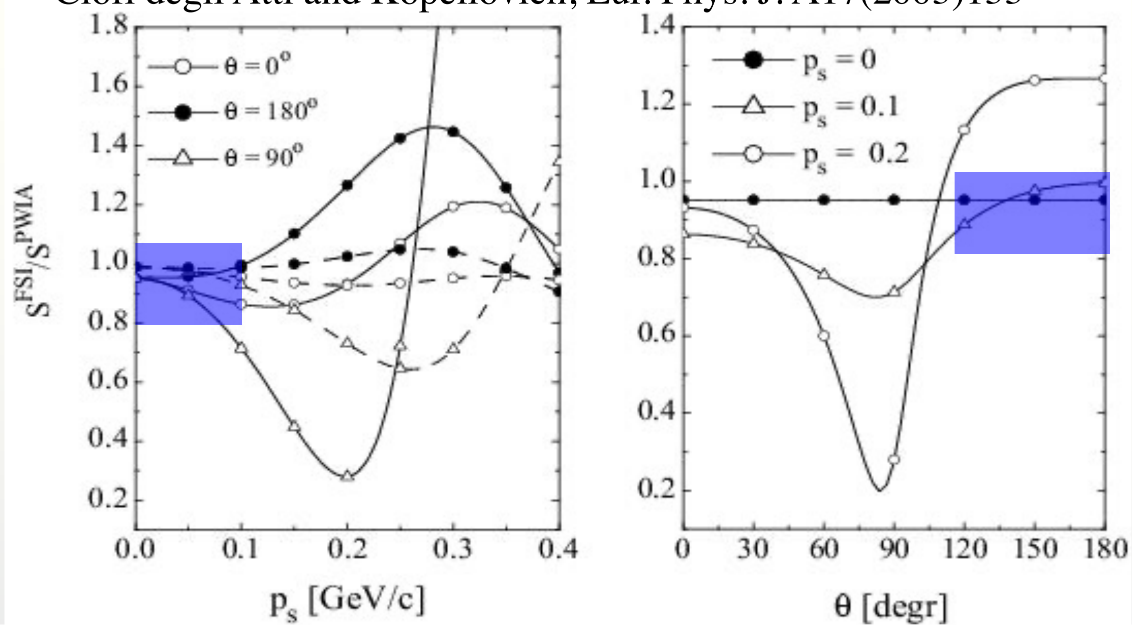


W. Melnitchouk, A.W. Schreiber and A.W. Thomas, Phys. Lett. B335, 11 (1994); Phys. Rev. D 49, 1183 (1994)

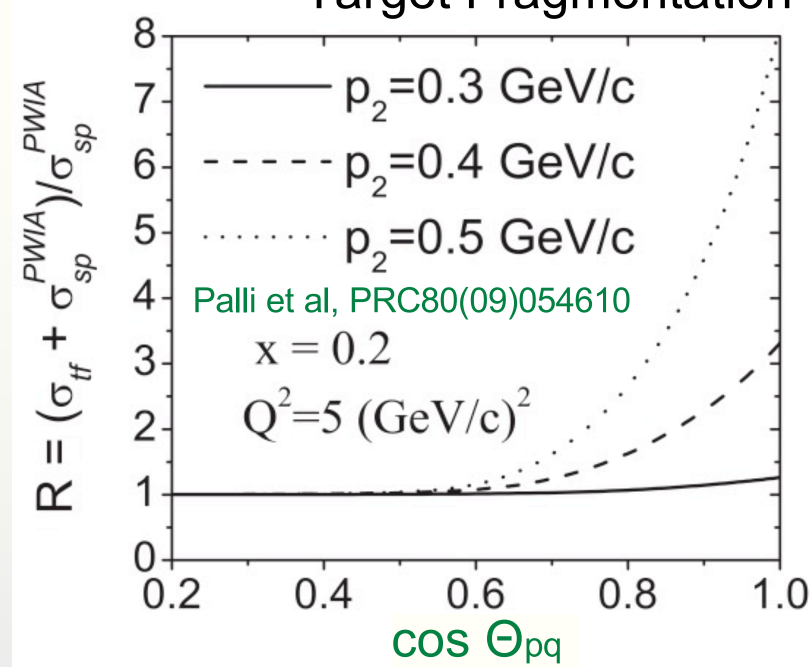
Off-shell effects, Finite coverage of WF

Final State Interactions

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



Target Fragmentation



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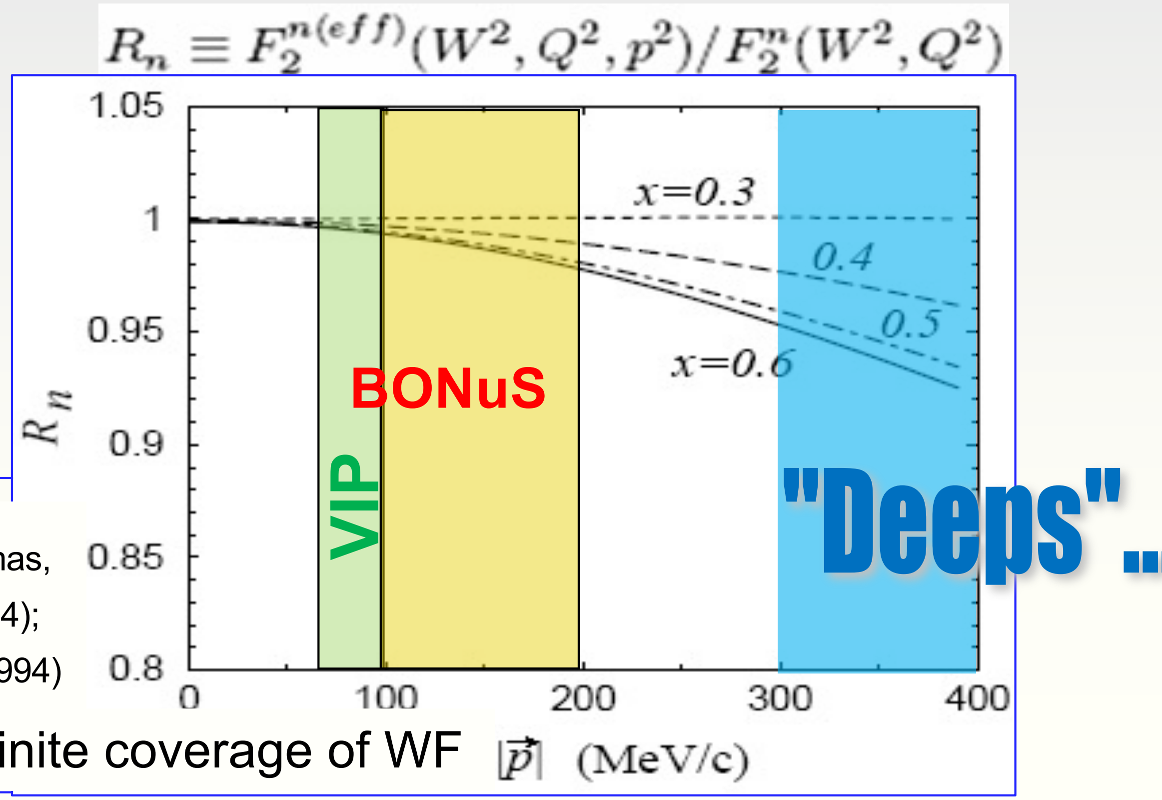

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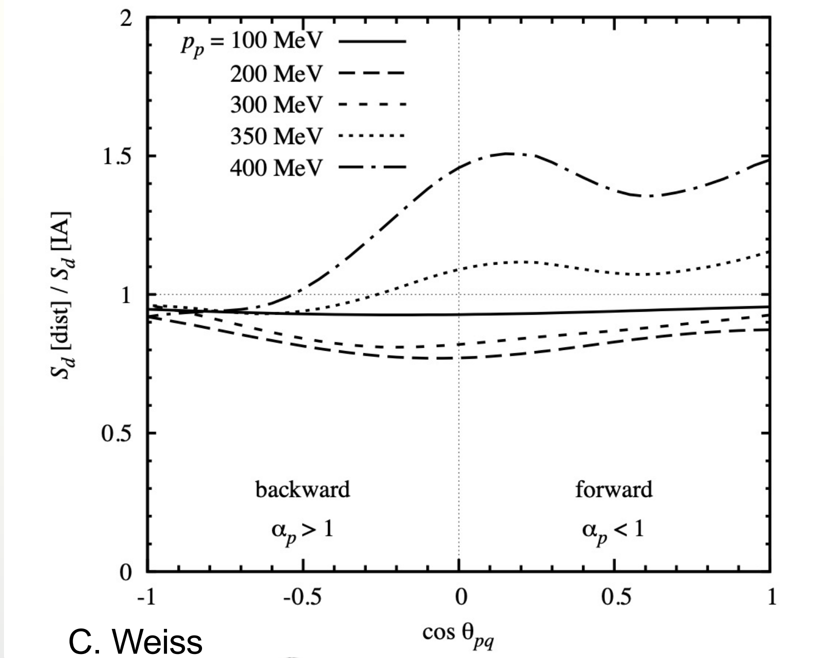
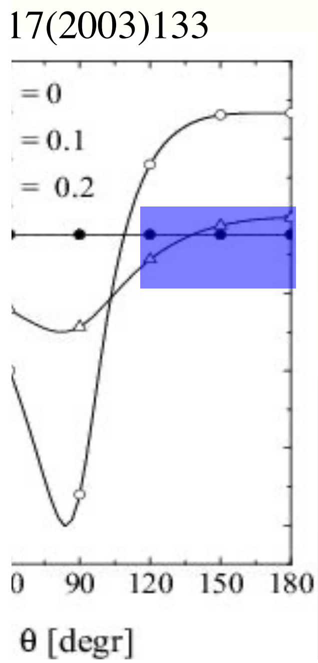
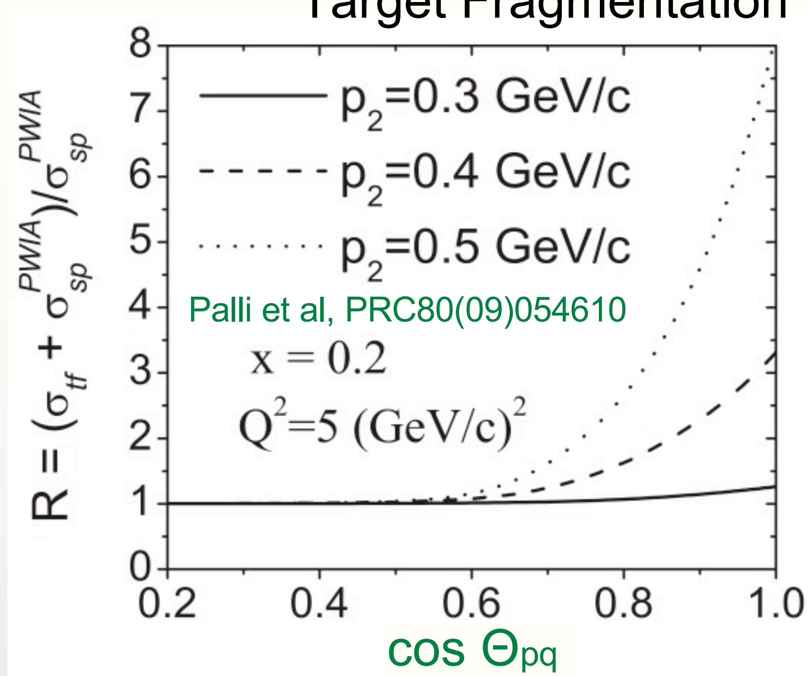


C. Weiss



Target Fragmentation



Alternative: Pole extrapolation

$$t' = M^{*2} - M_n^2 = (P_D - p_s)^2 - M_n^2 = \left(M_D - \sqrt{M_p^2 + \vec{p}_s^{\,2}}\right)^2 - \vec{p}_s^{\,2} - M_n^2 \approx -2\left(M_n\varepsilon + \vec{p}_s^{\,2}\right);\ \varepsilon = 2.2\ \mathrm{MeV}$$

- Measure F_{2n} at fixed spectator angle, but varying momentum
- Extrapolate to on-shell neutron

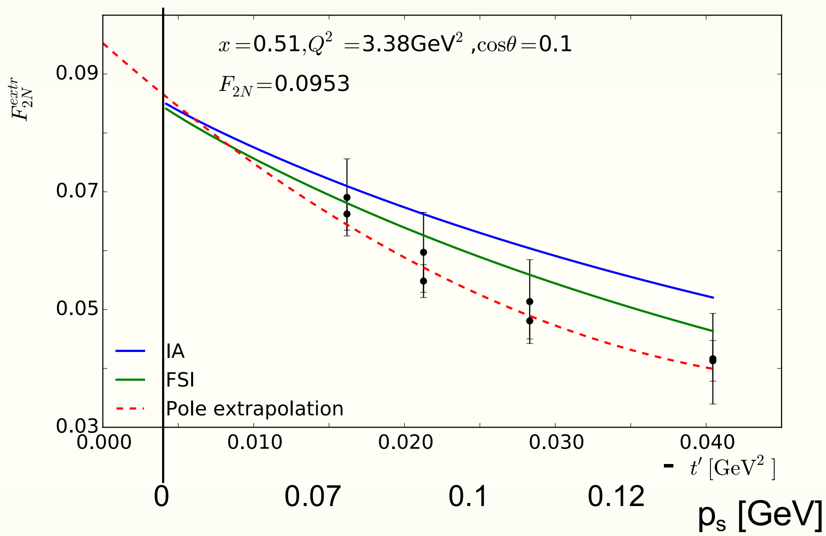


Figure 3. Example of the pole extrapolation method using the renormalized BONuS data (black circles) with the quadratic pole extrapolation curve (red dashed curve) as a function of $t'^2 = p_i^2 - m_n^2$. The IA (full blue curve) and FSI (full green curve) calculations are shown for comparison.

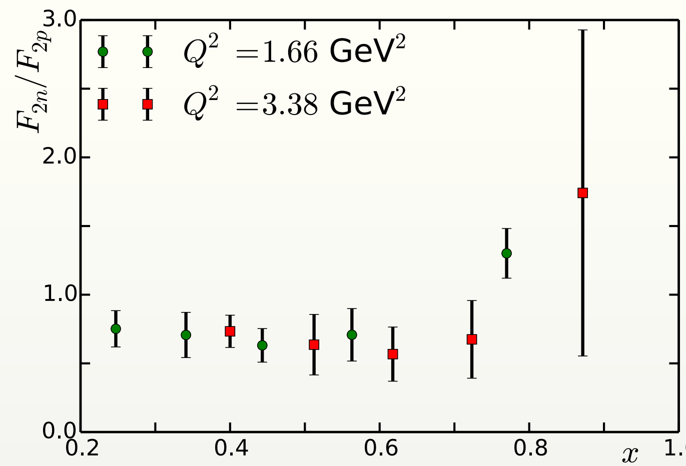


FIG. 4: (Color online) F_{2n} to F_{2p} ratio obtained using the pole extrapolation method on the renormalized BONUS data for $Q^2 = 1.66$ (green circles), 3.38 Gev^2 (red squares). The F_{2p} values are estimated using fit of Ref. [21].

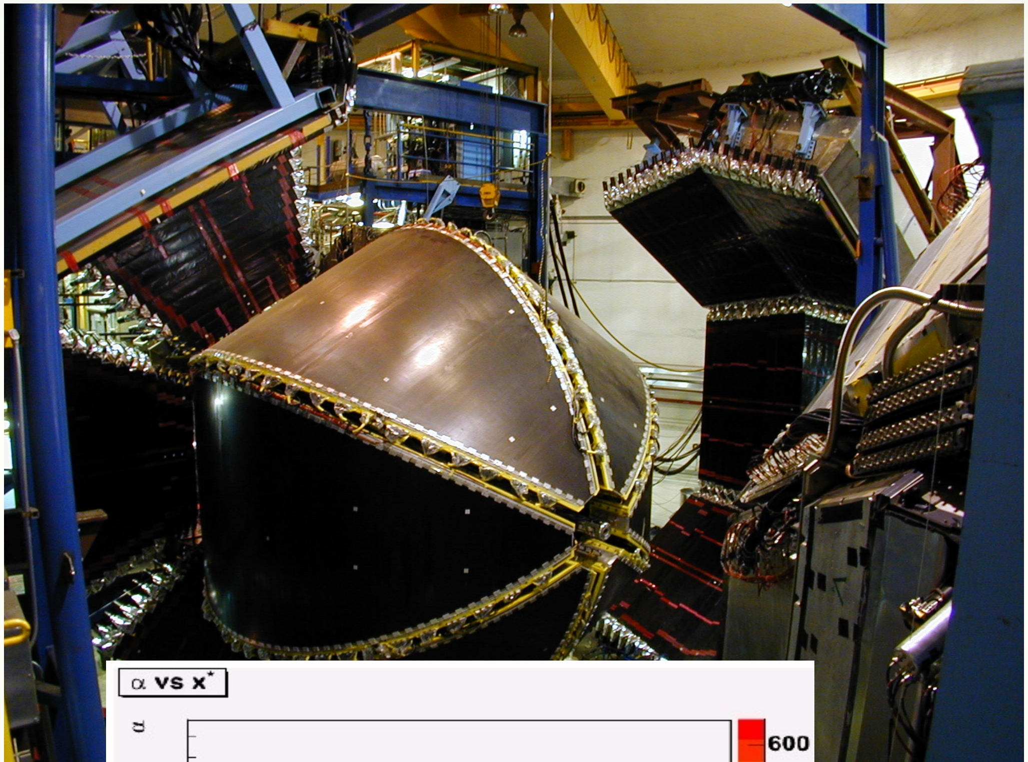
Wim Cosyn (Gent U.) , Misak Sargsian (Florida Intl. U.)

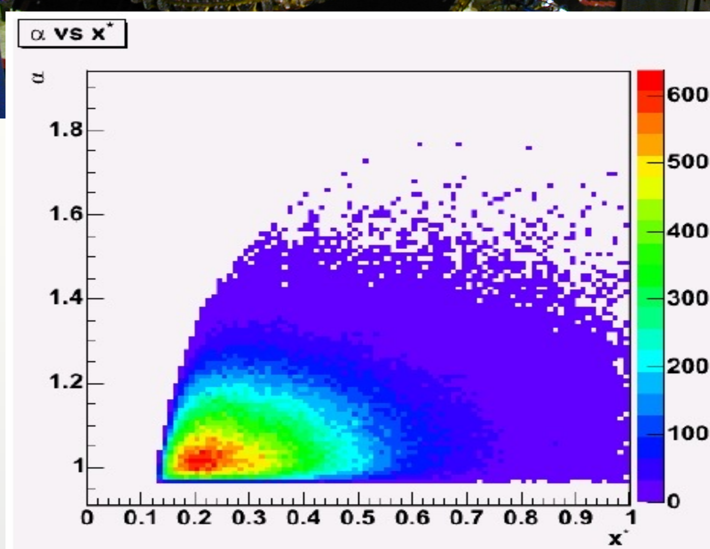
Mar 2, 2016 - 6 pages

EPJ Web Conf. 112 (2016) 03001
(2016-03-21)
DOI: 10.1051/epjconf/201611203001
Conference: C15-09-07.1
Proceedings
e-Print: arXiv:1603.00685 [nucl-th] | PDF

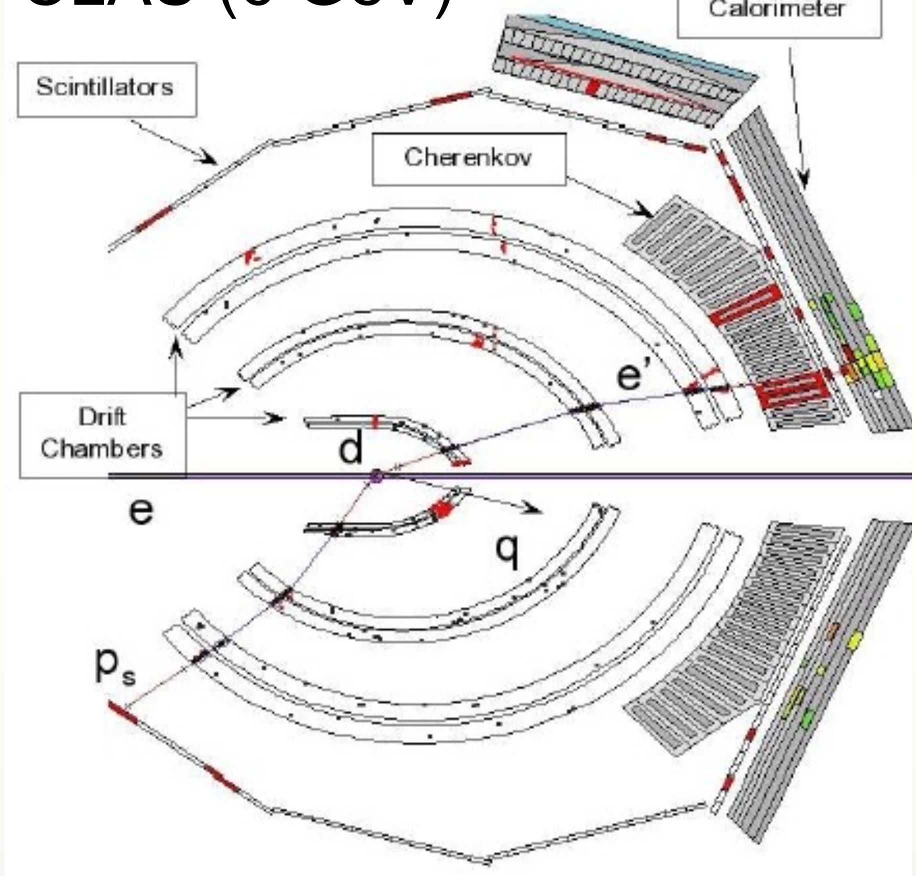
First Tagging Experiment at Jefferson Lab: “Deeps”

(High spectator momenta 0.25 - 0.7 GeV/c)





CLAS (6 GeV)

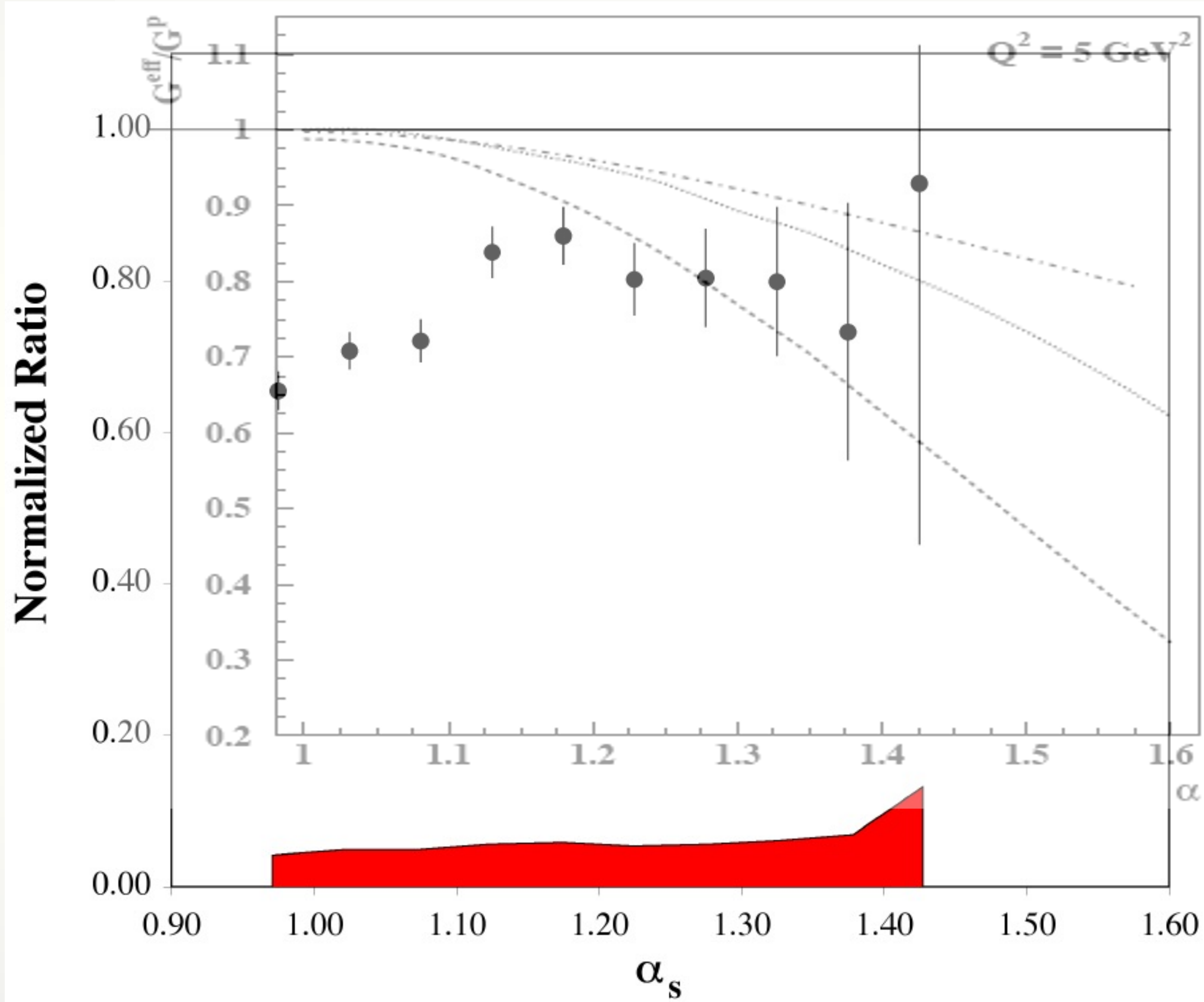


Results from “Deeps”: Ratio Method

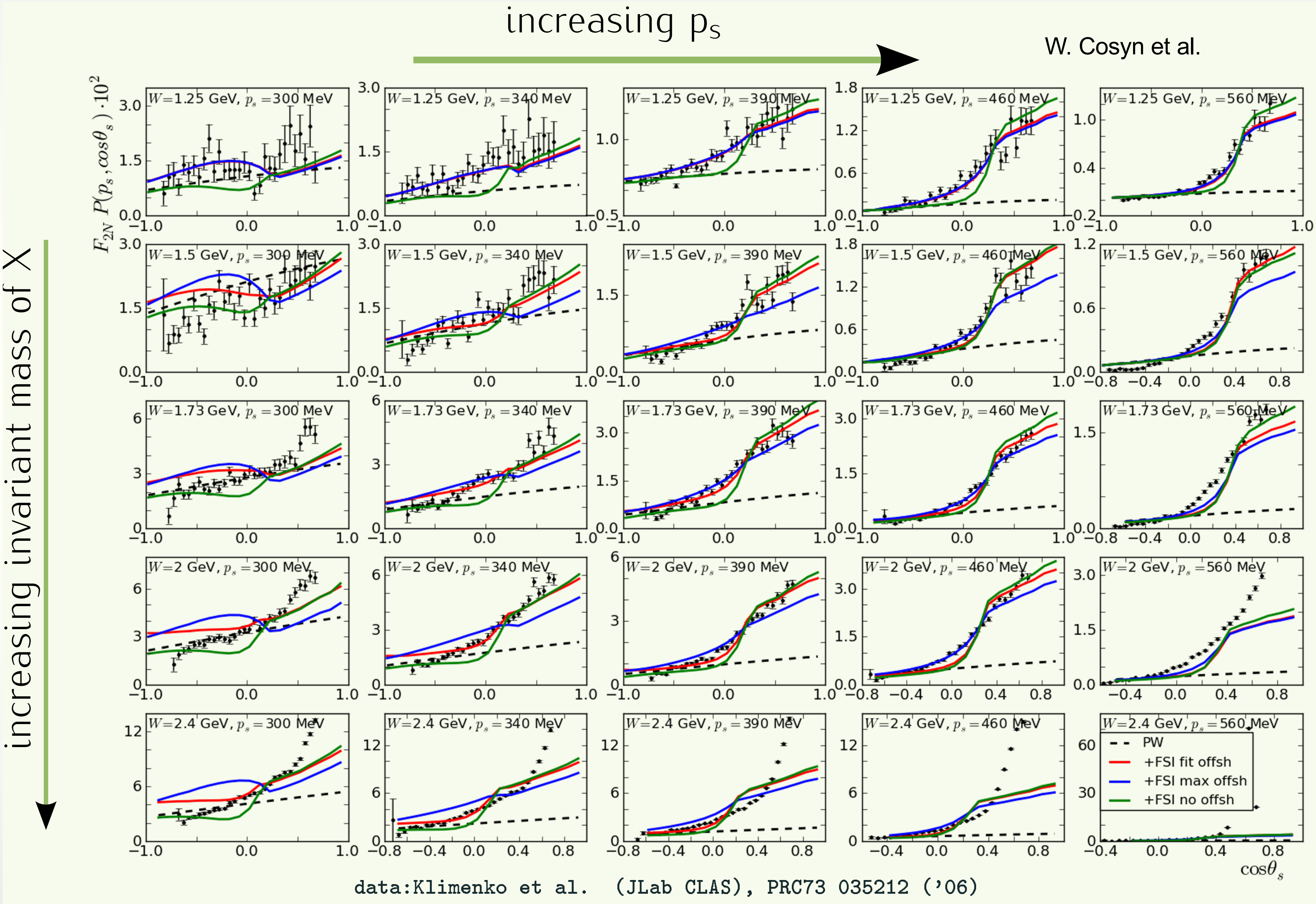
Ratio =

$$\frac{\dfrac{\sigma(x^*=0.55,\alpha_s)}{\sigma(x^*=0.25,\alpha_s)}(\text{bound n})}{\dfrac{\sigma(x=0.55)}{\sigma(x=0.25)}(\text{free n})}$$

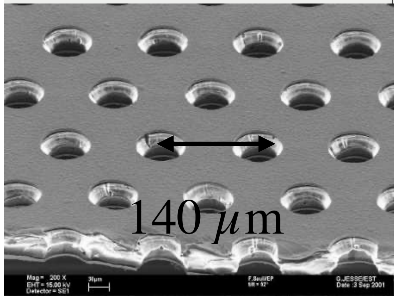
- Independent of deuteron WF, acceptance, kinematic factors
- Should be sensitive to off-shell effects at large x, but also influenced by FSI and target fragmentation
- Fixed p_T = 0.3 GeV/c - TOO LARGE!



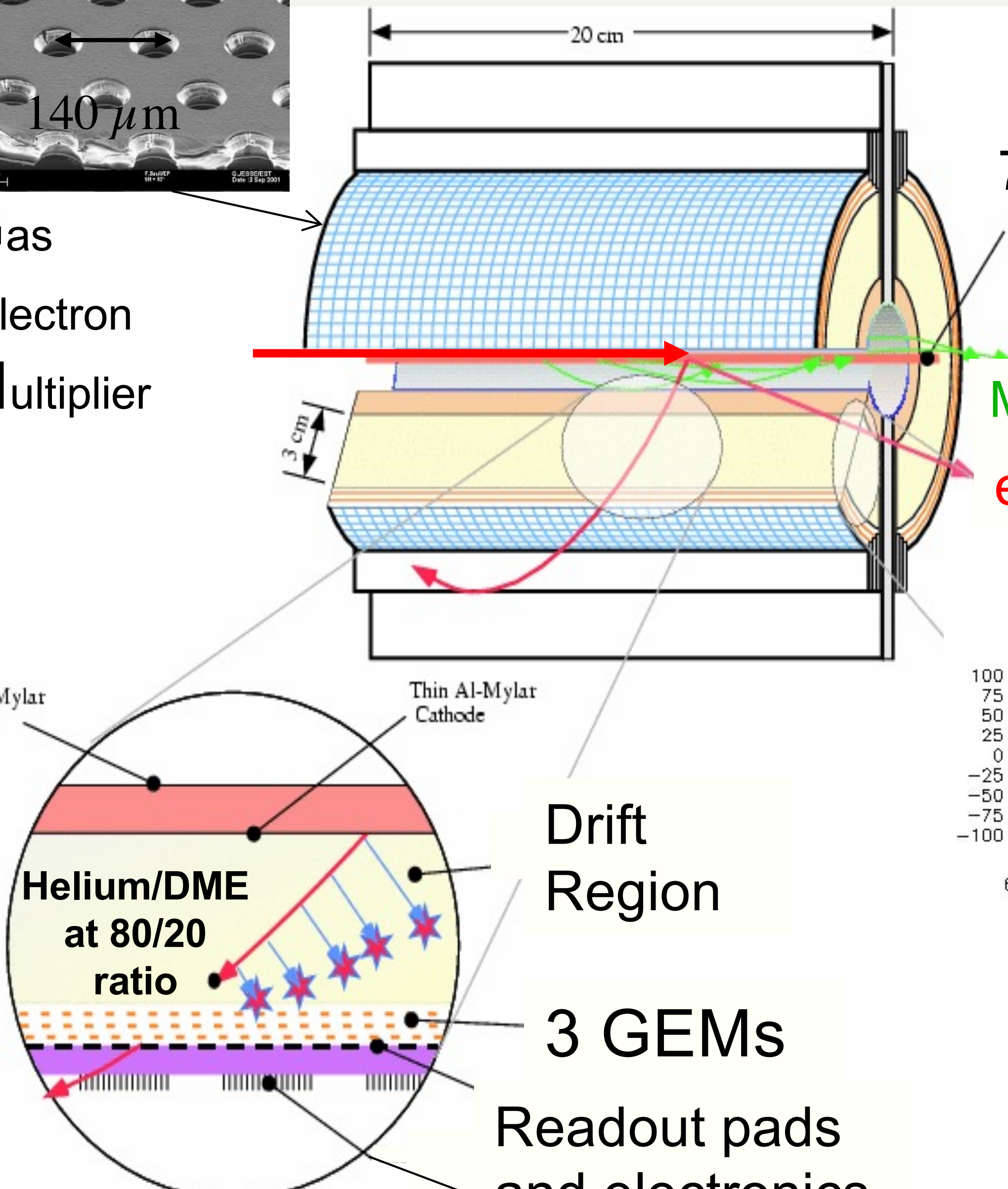
Results from “Deeps”: FSI



Spectator tagging -BoNuS6 RTPC



Gas
Electron
Multiplier



7 atm D_2 gas

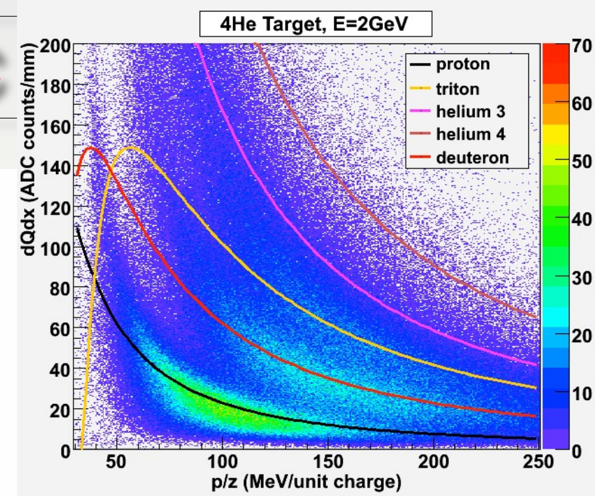
Møller el.

e^- (to CLAS)

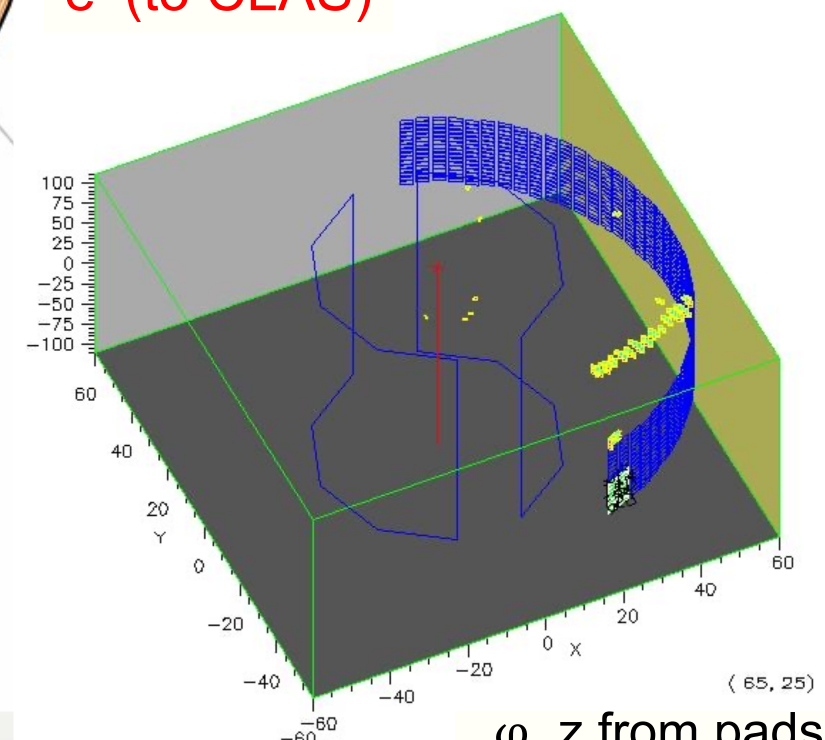
Drift Region

3 GEMs

Readout pads and electronics



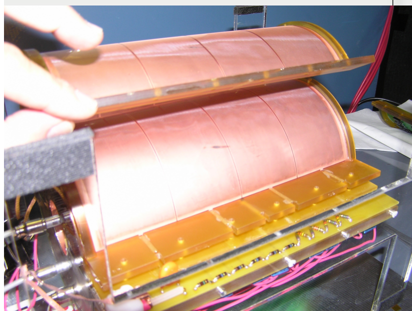
dE/dx from charge along track (particle ID)



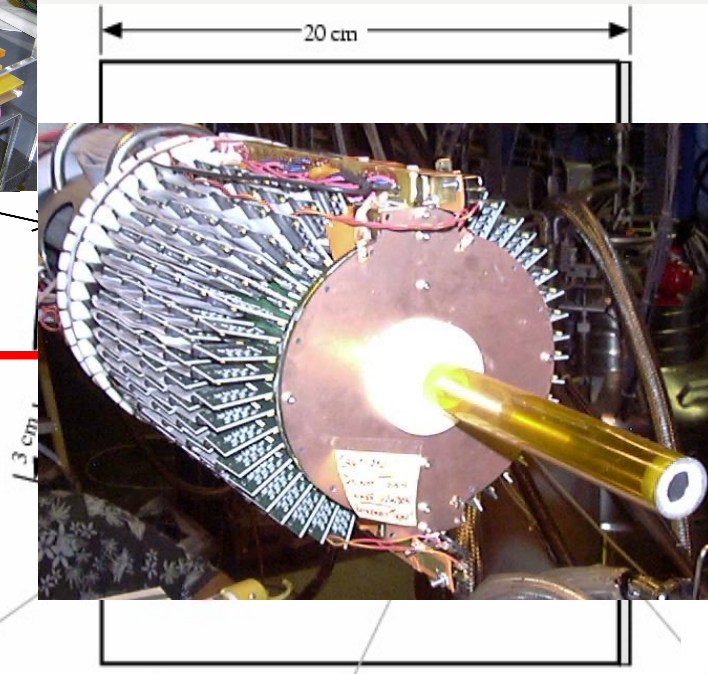
φ, z from pads
r from time

Nucl. Instr. Meth. **A592**, 273 (2008)

Spectator tagging -BoNuS6 RTPC



Gas
Electron
Multiplier



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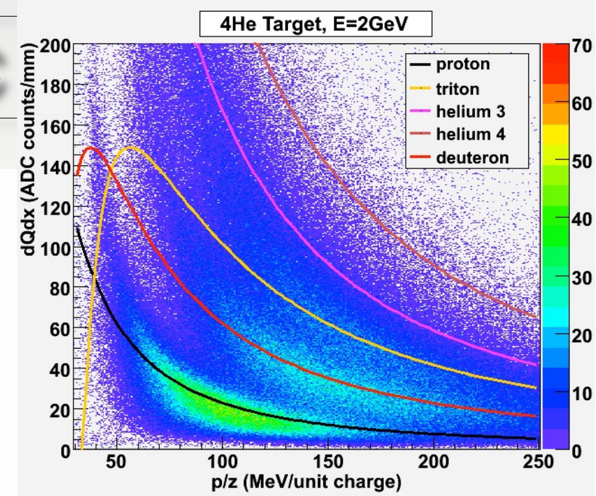
e^- (to CLAS)



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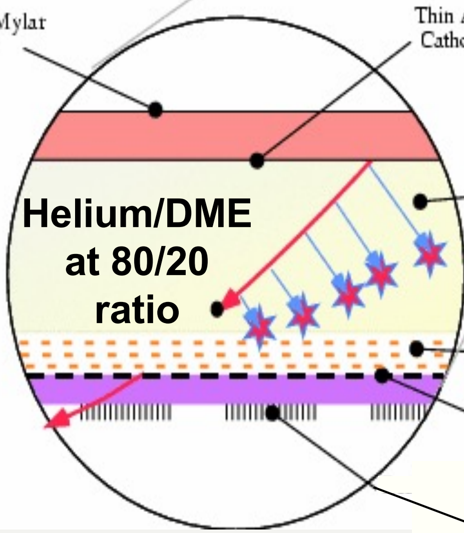

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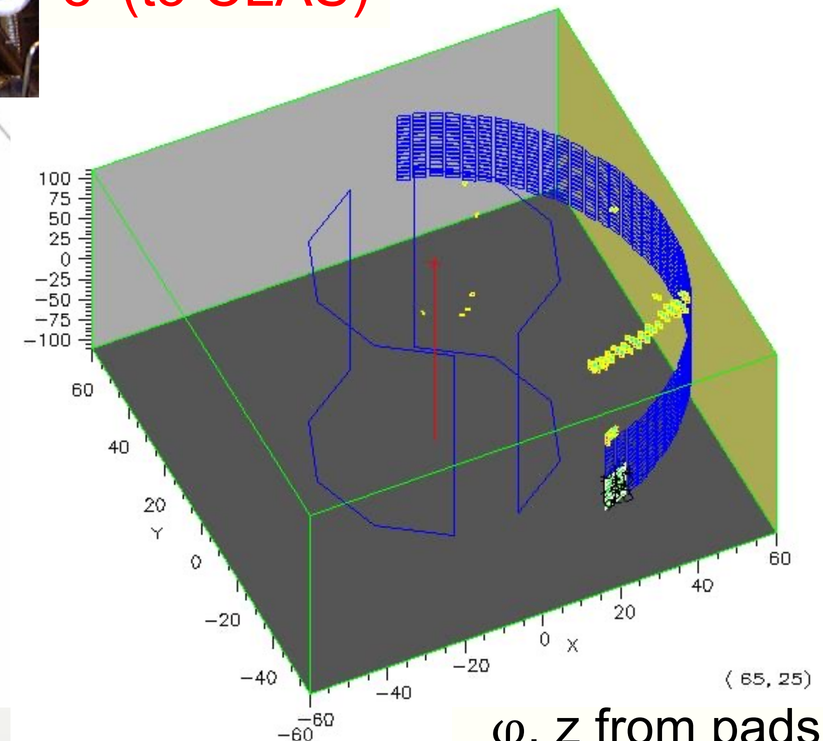
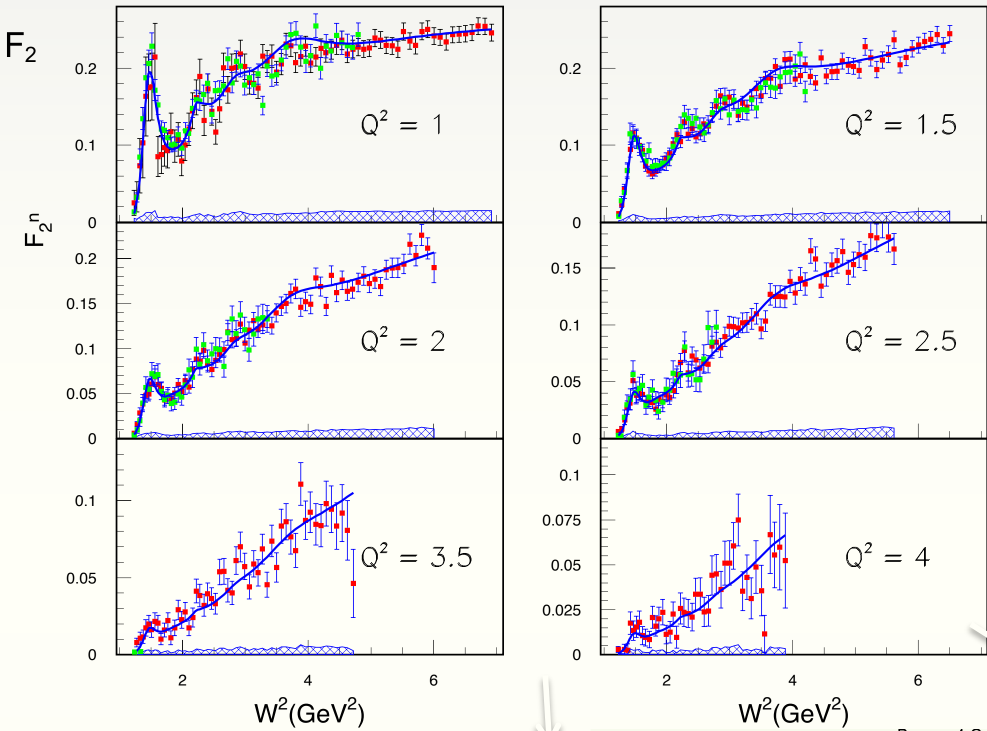
Readout pads and electronics

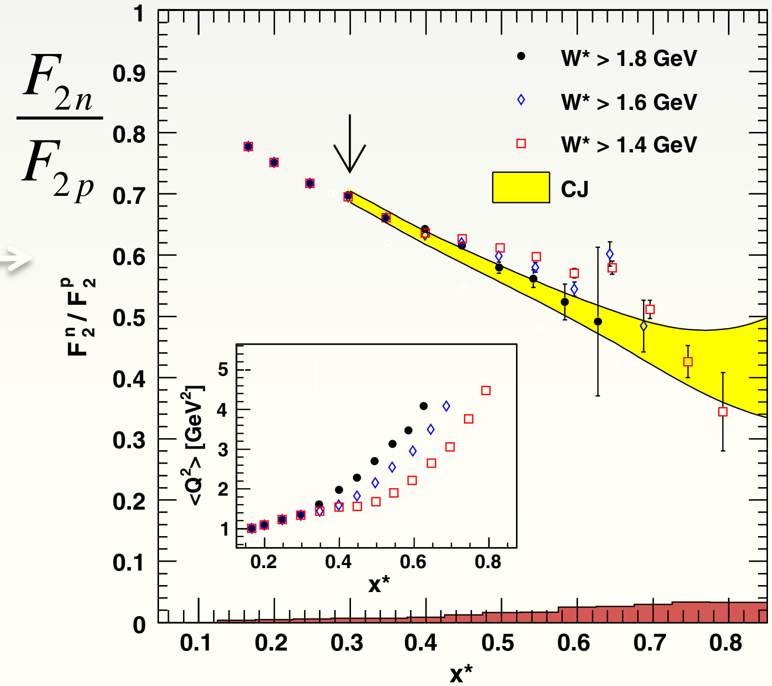


φ, z from pads
r from time

Nucl. Instr. Meth. **A592**, 273 (2008)

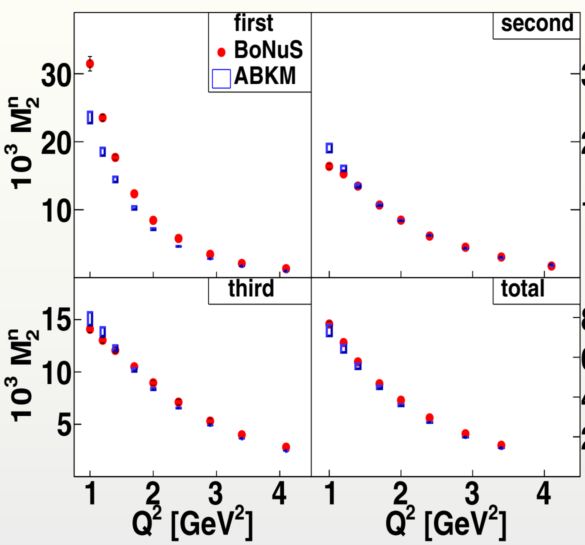
BONuS6 Results

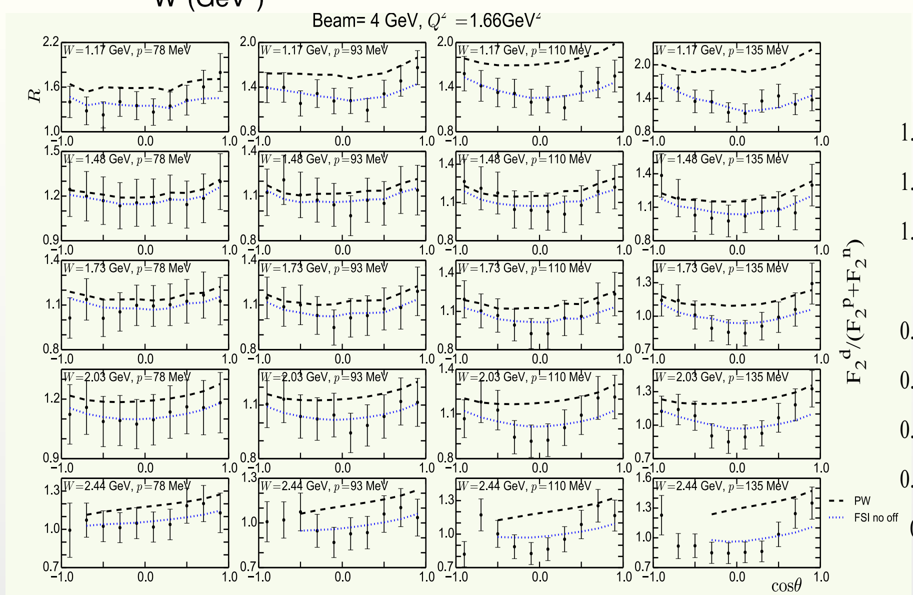




FSI: Cosyn et al.

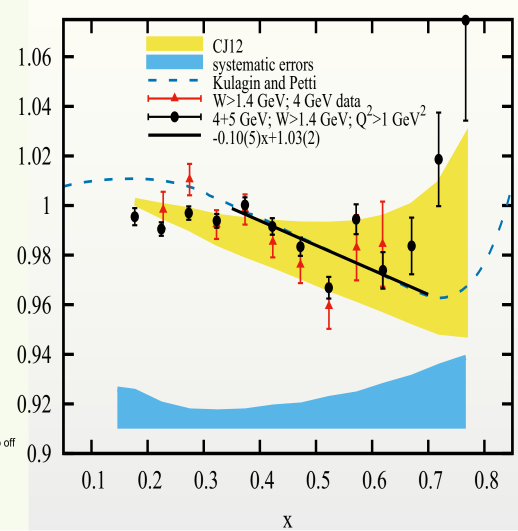
Duality





EMC Ratio

PHYSICAL REVIEW C **92**, 015211 (2015)



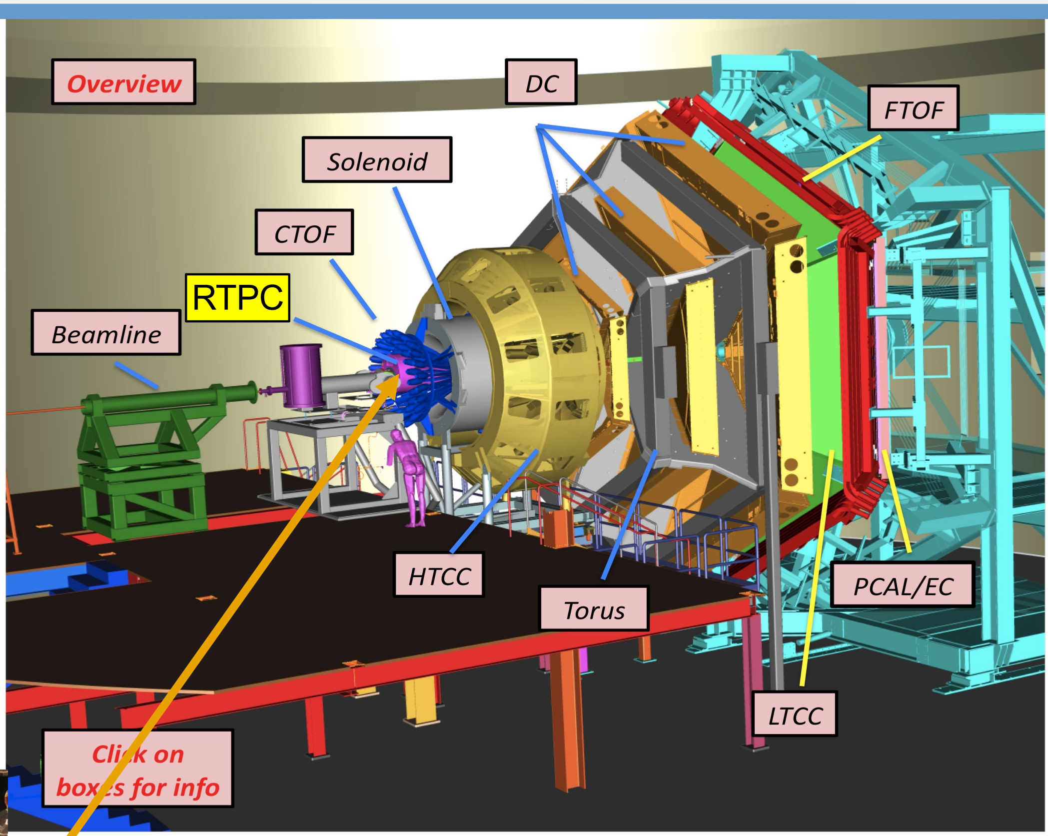
BONuS12 withCLAS12

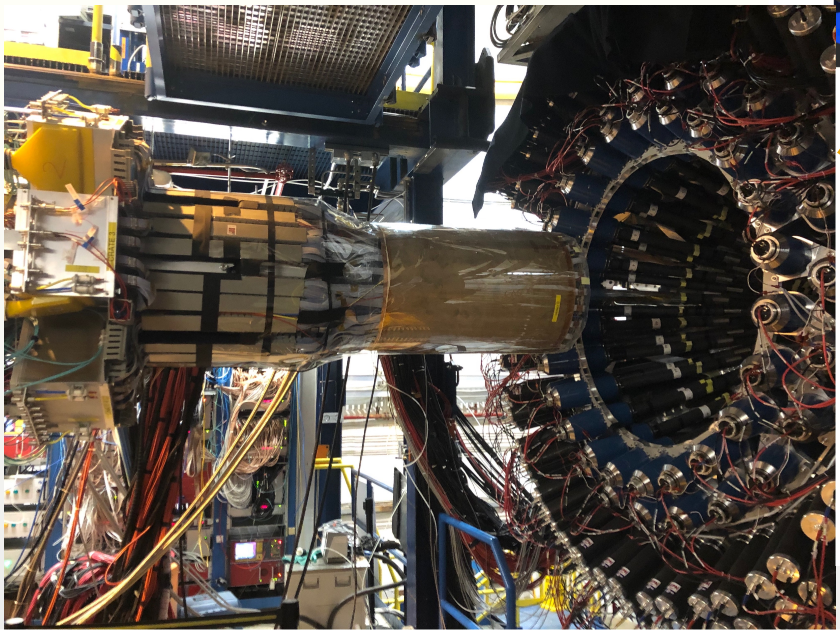
$e^- d \rightarrow e^- p X$

- 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)
→ Target: D gas @ 6 atm, 293 K
→ BONuS12 RTPC
→ FMT
→ CTOF, and CND





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 ϕ)
- → Pad readout: **2.8 mm x 4 mm**

=> **17,280 channels**

FEU electronics → Signal height vs. Time bin

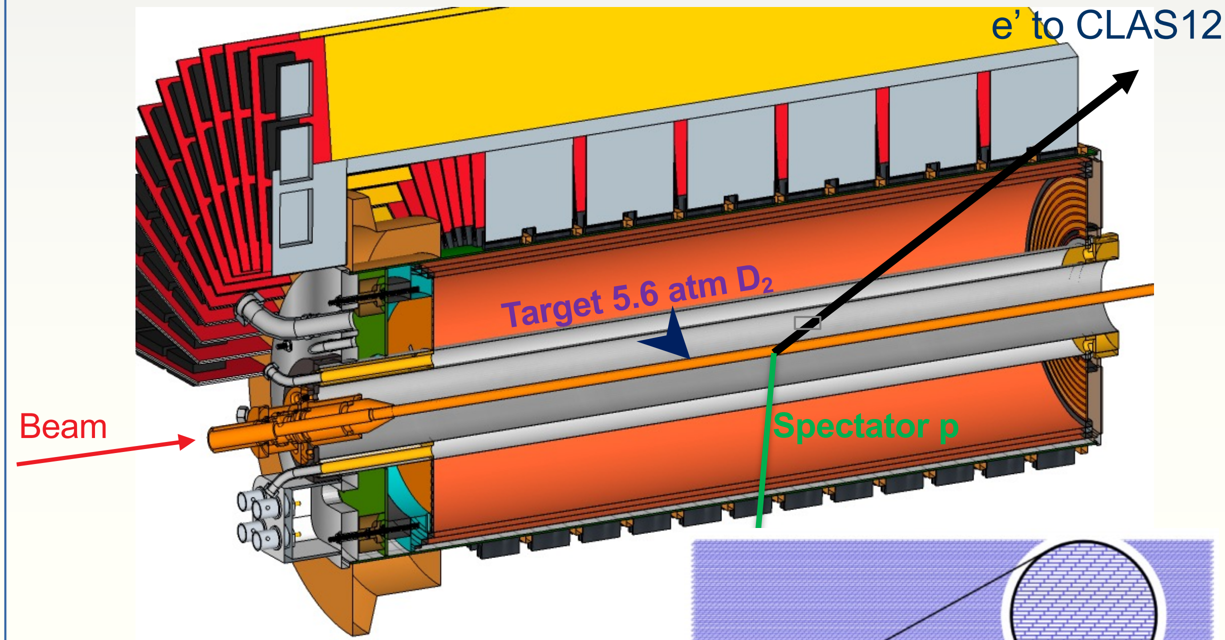
- Pad position + Time + drift path → hit position

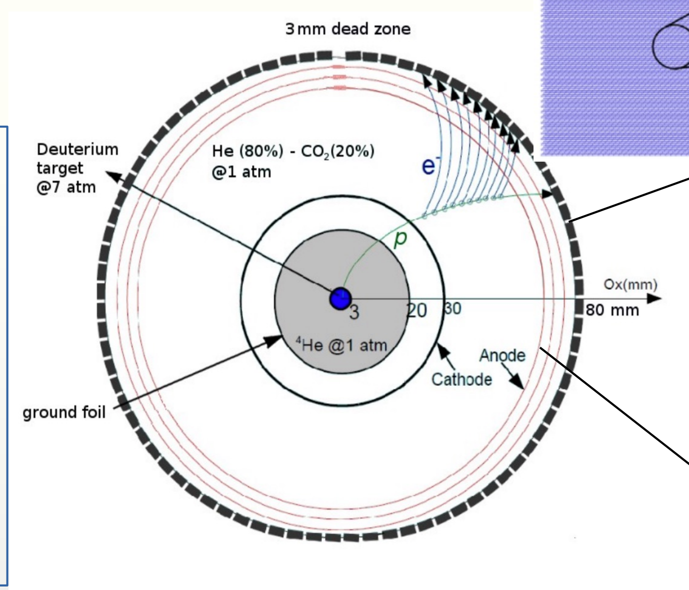
  => track reconstruction

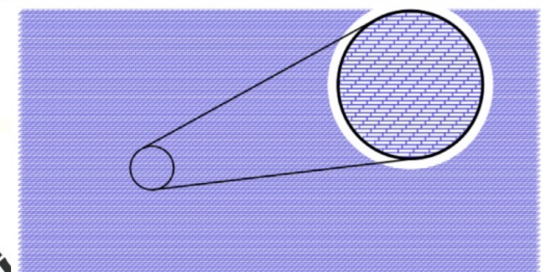
  vertex + momentum vector

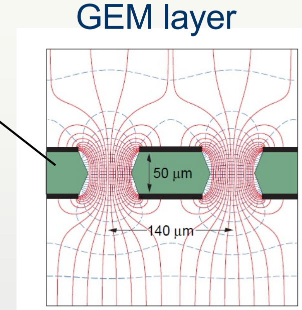
- integrated signal + pad gains (G_i) →

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

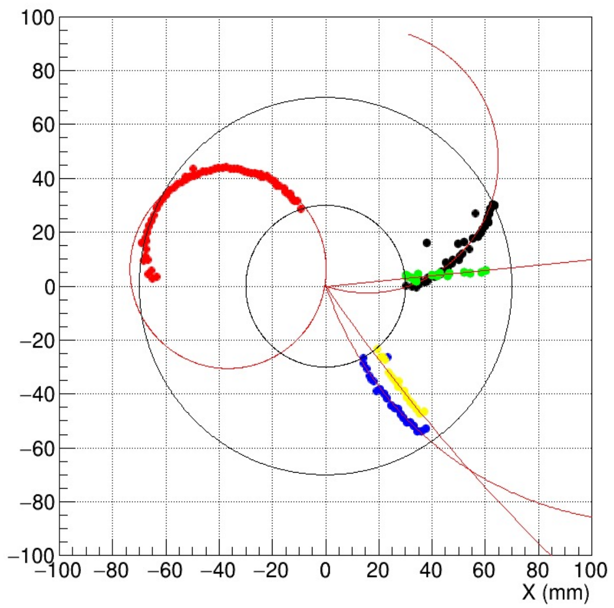


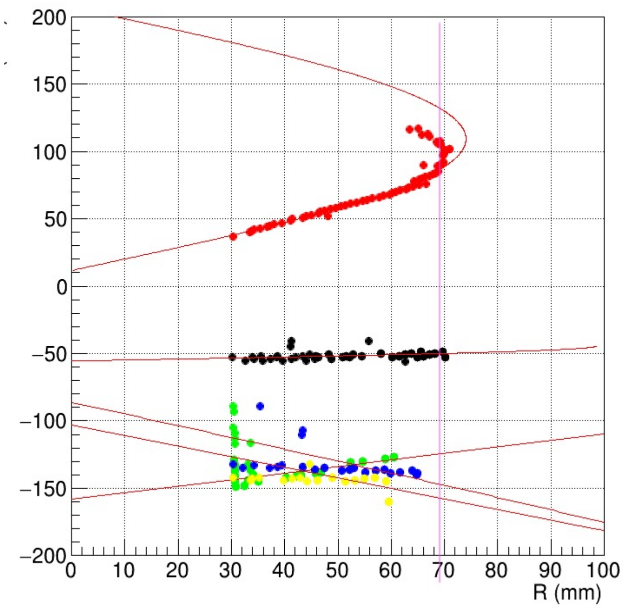


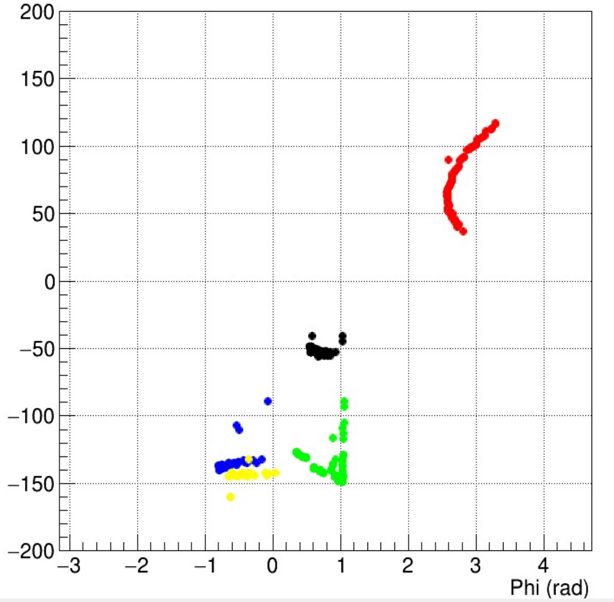




BONuS12 RTPC







chi2: 25.9 7.3 9.0 37.4 10.6

p: 0.055 0.054 6.592 0.190 0.954

r: -49.23 -36.85 -5311.06 -128.61 -672.28

a: 15.62 -36.65 -475.64 122.00 552.60

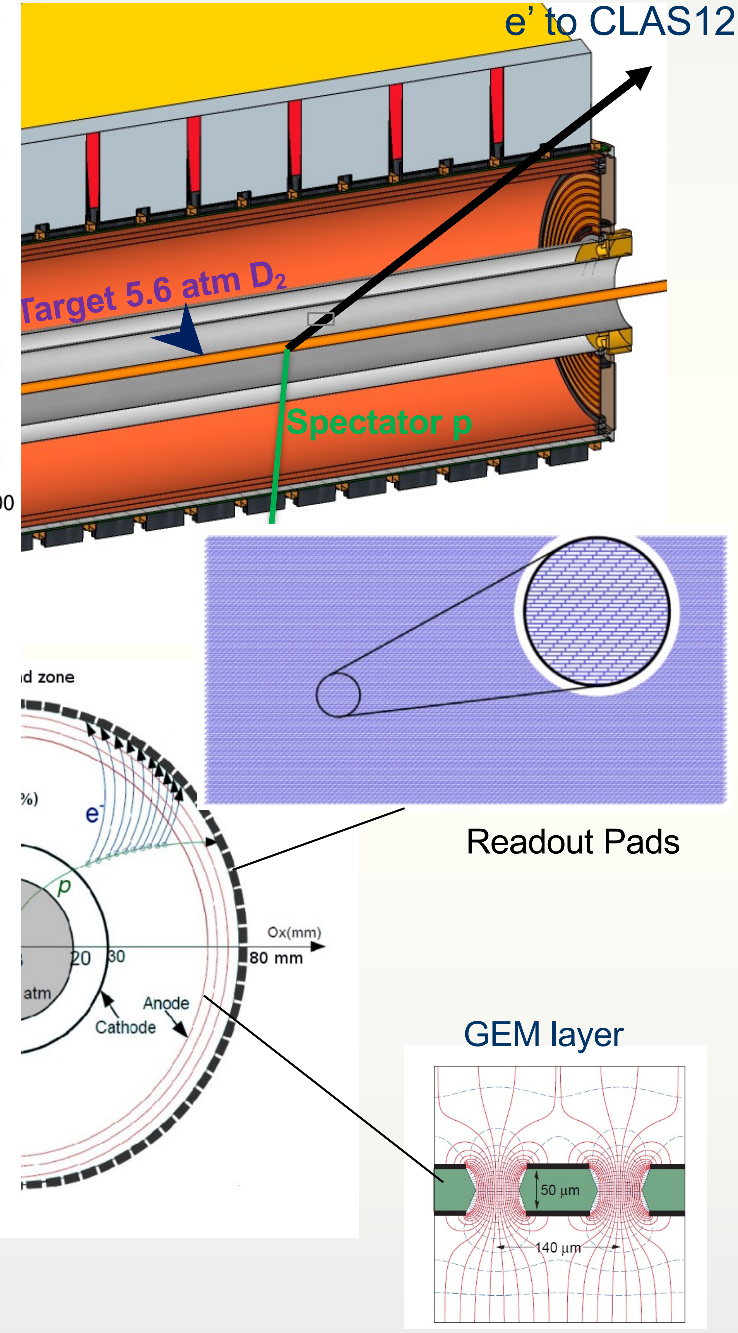
b: 46.71 6.30 5289.68 41.11 382.89

z: -55.55 11.68 -158.04 -86.15 -103.13

theta: 85.88 49.87 64.20 130.99 128.05

phi: -18.49 80.25 5.14 -71.38 -55.28

tdiff [mus]: -0.792 -2.035 -2.075 1.941 0.626

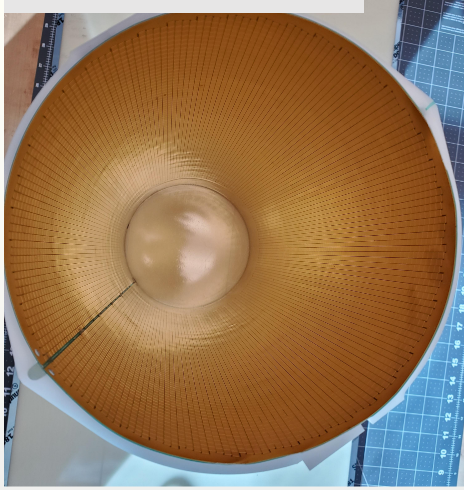


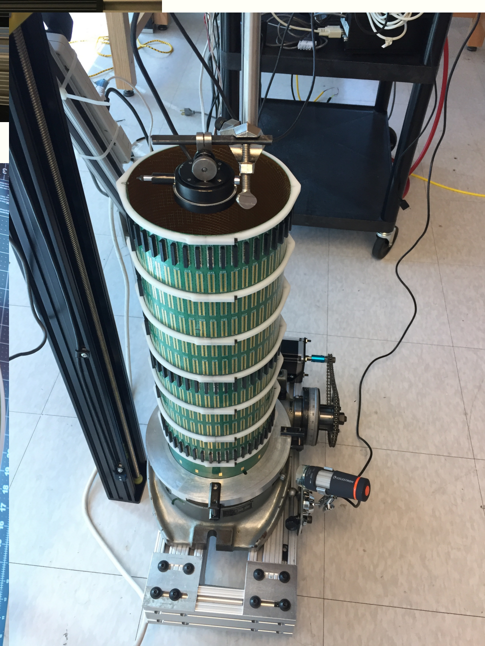
RTPC Assembly @ Hampton U. In Collaboration with ODU & JLab

GEM foil wrapping and gluing

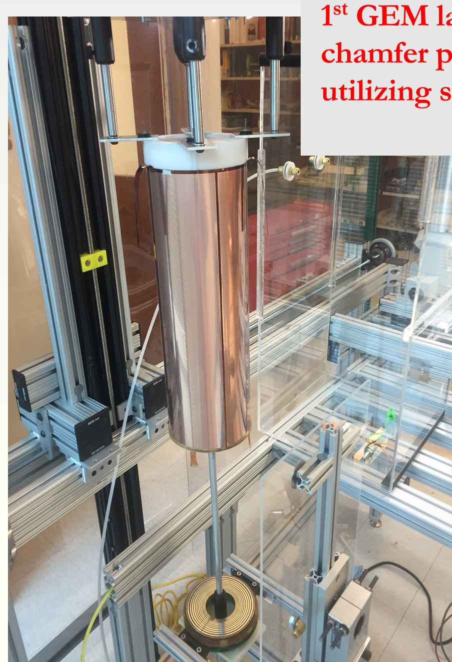
Automated epoxy application

Wrapped Padboard inner surface

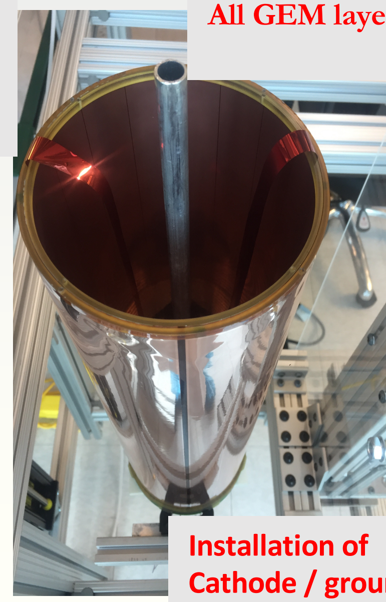




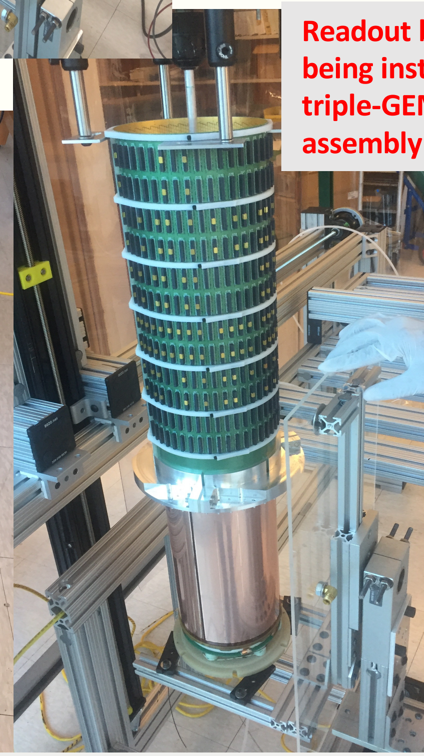
1st GEM layer lowered onto chamfer plate assembly utilizing self-alignment jig



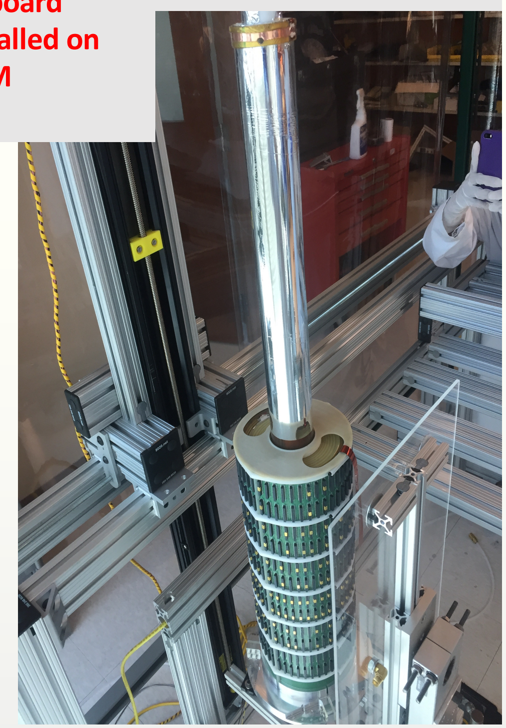
All GEM layers installed



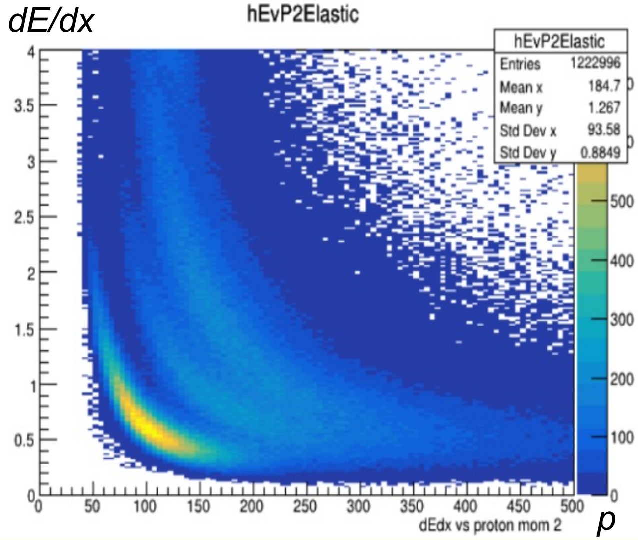
Readout board being installed on triple-GEM assembly

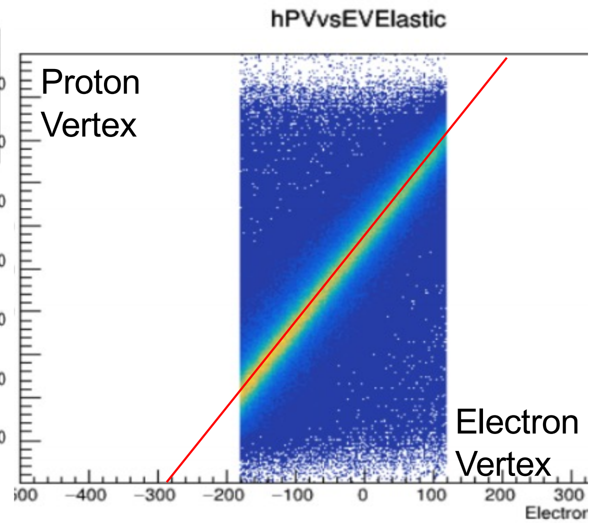


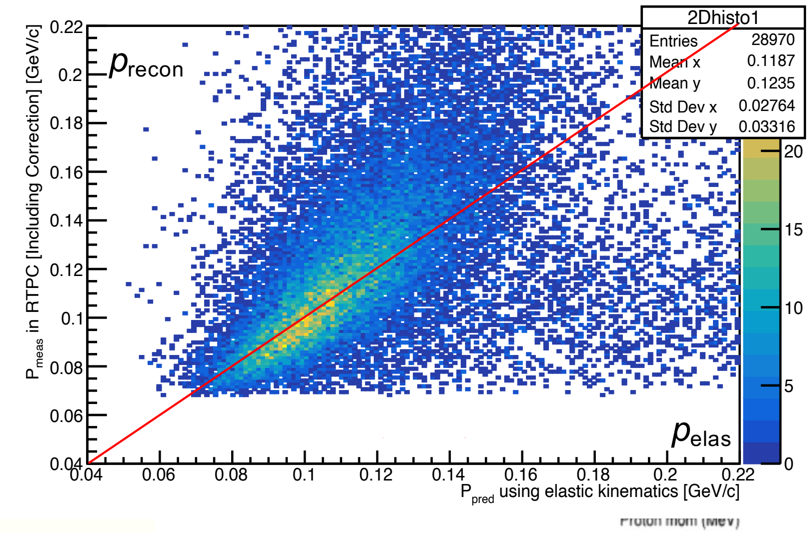
Installation of Cathode / ground assembly



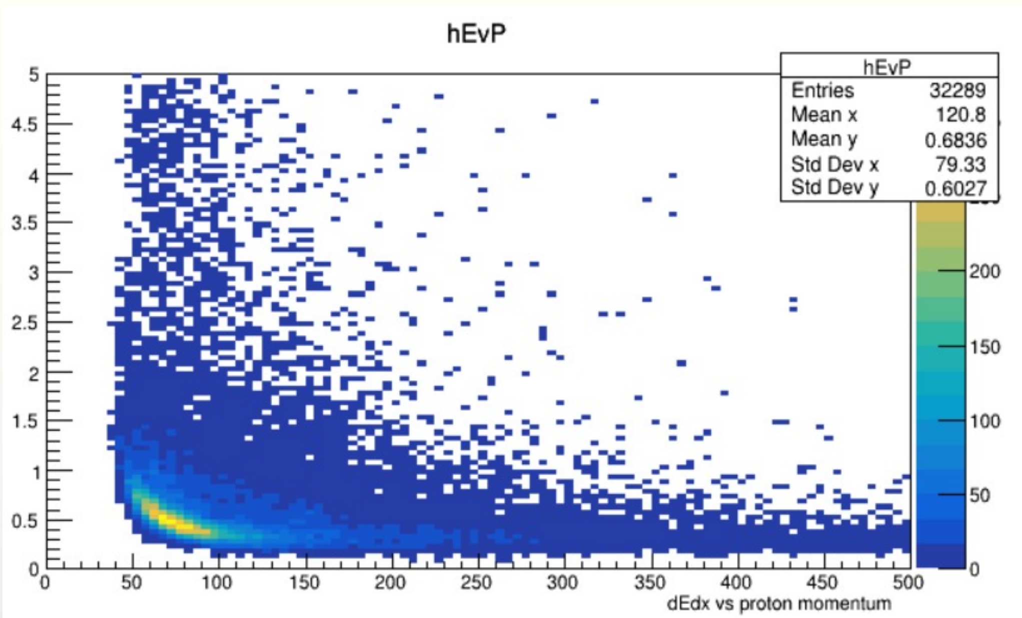
BONuS12 - 2.1 GeV Data

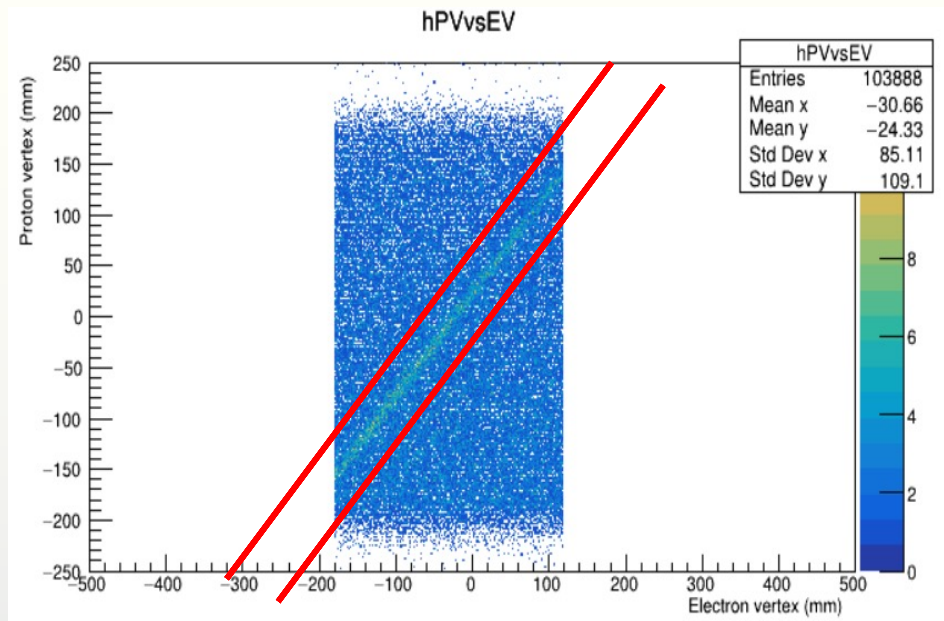




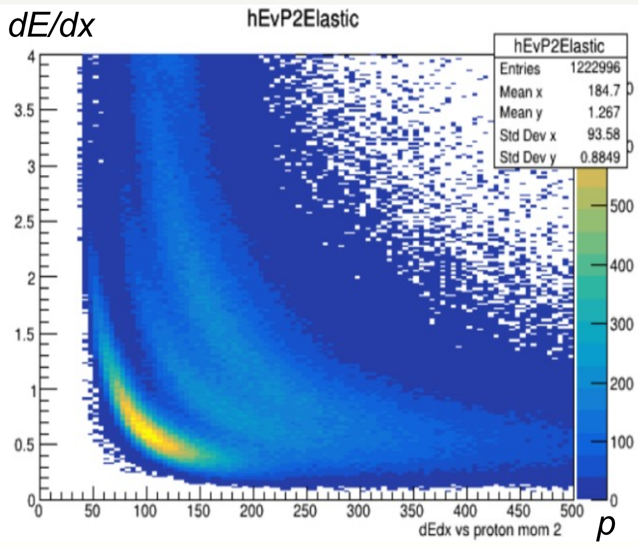


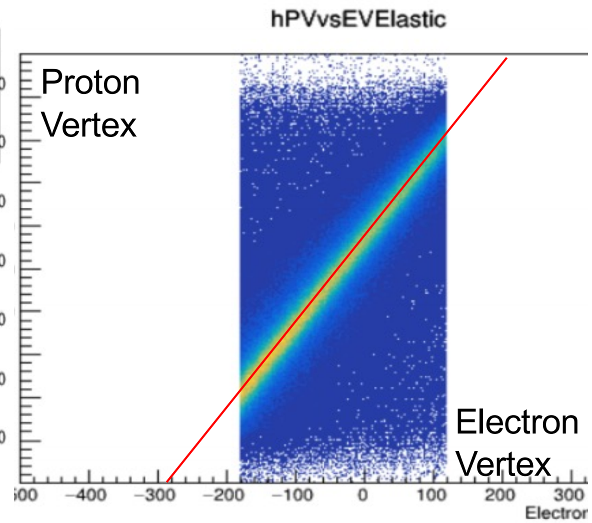
BONuS12 – 10.4 GeV Data

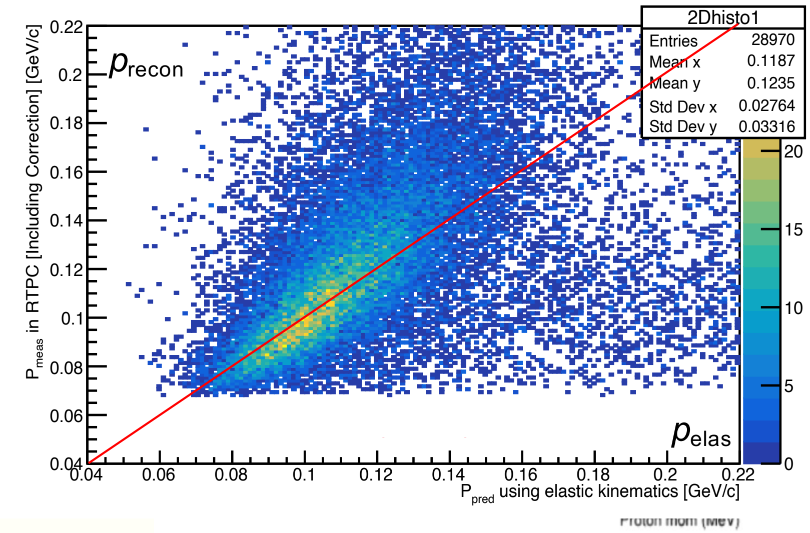




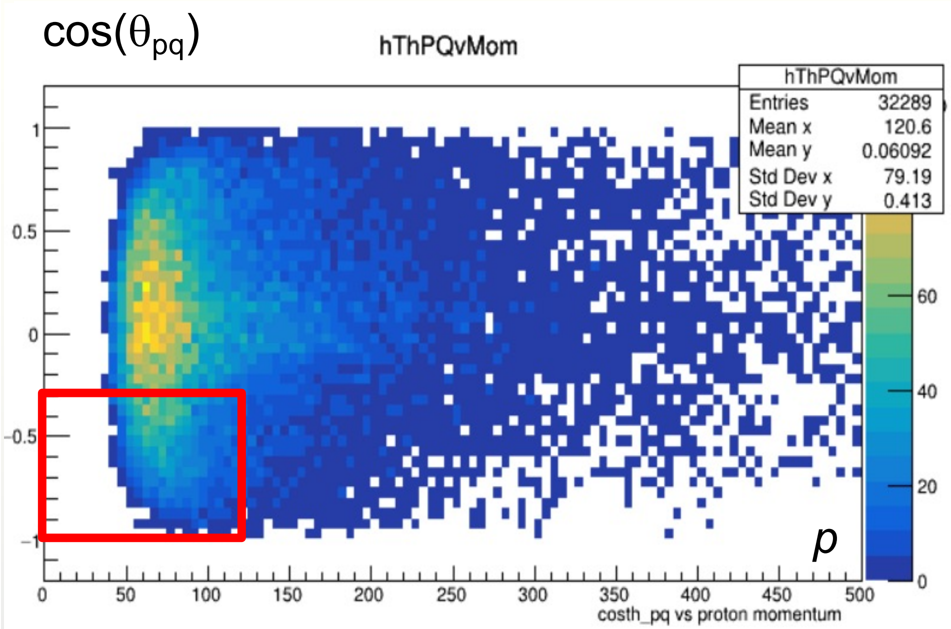
BONuS12 - 2.1 GeV Data

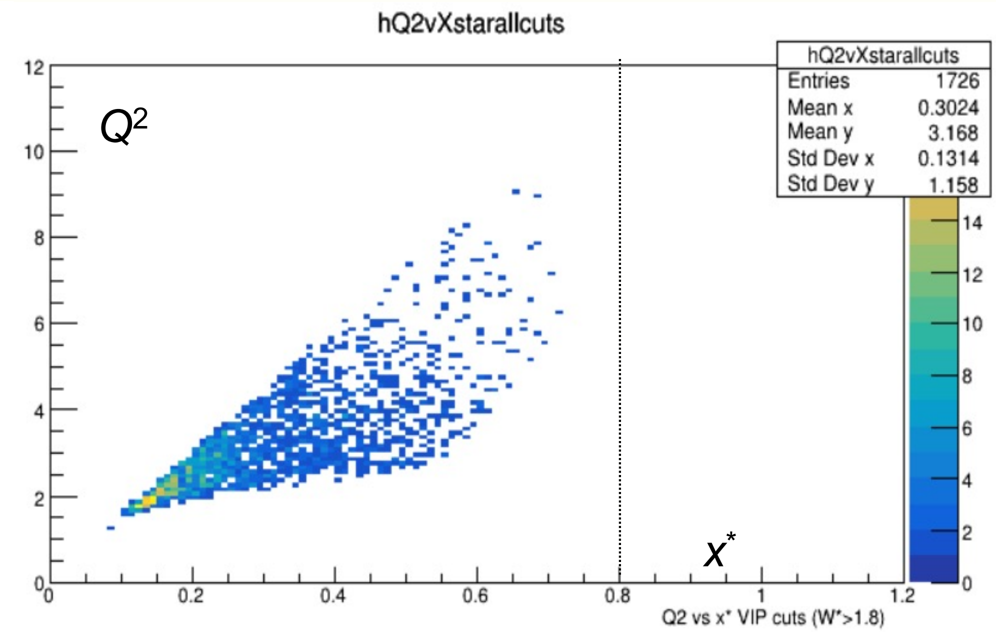




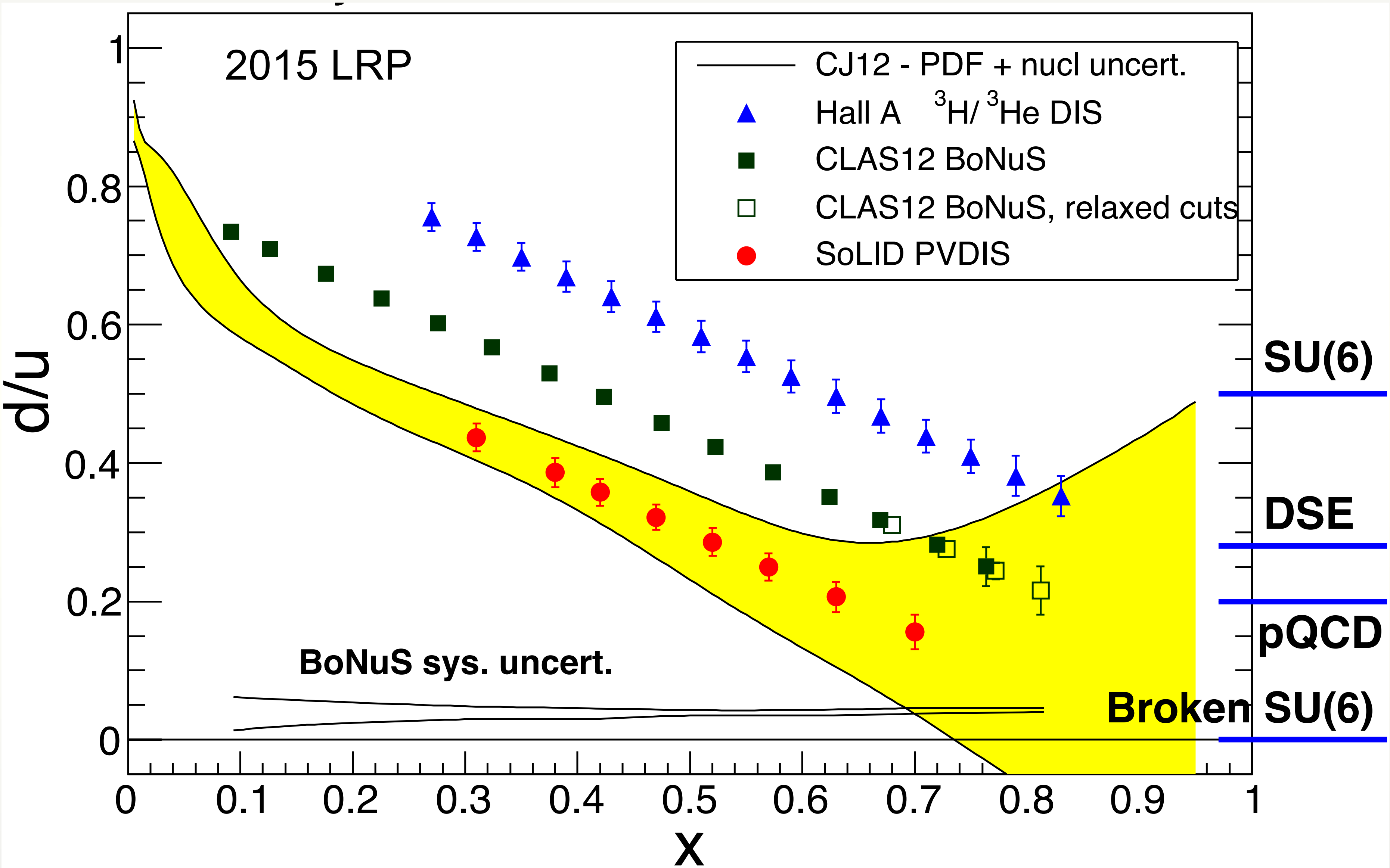


BONuS12 – 10.4 GeV Data





Projected JLab@12 GeV d/u Extractions

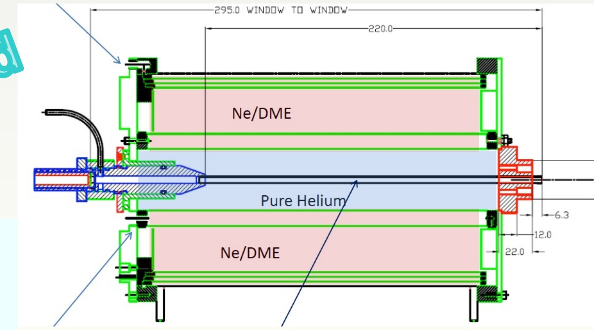


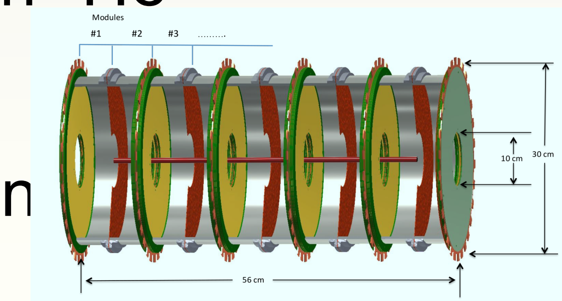
Other Tagging Experiments

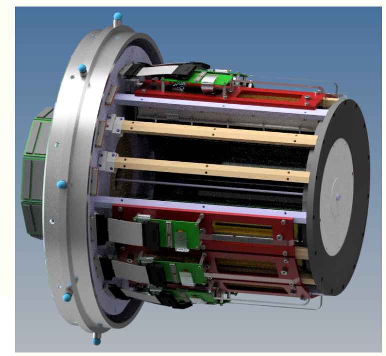
Completed

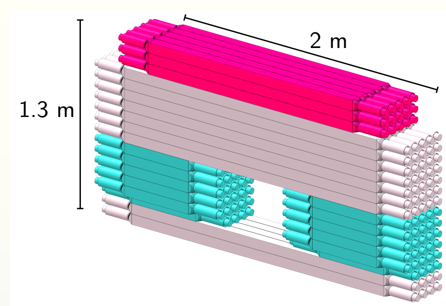
- EG6:
  DVCS on ^{4}He and p in ^{4}He
- TDIS:
  Pion structure function
- ALERT
  EMC-effect in DVCS, DIS
- BAND
  Structure of bound proton in D
- LAD
  Structure of bound n in D
- EIC

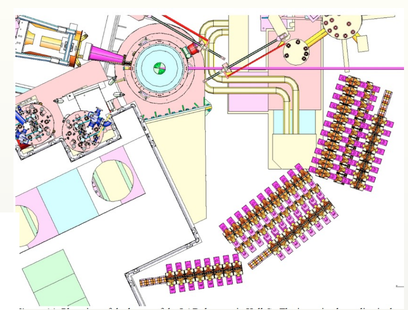
First Results

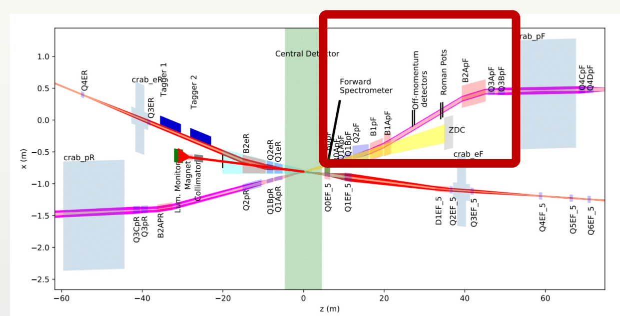




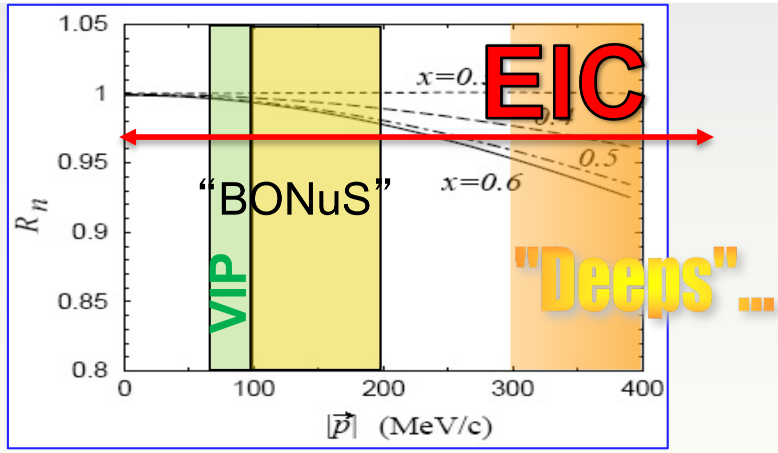








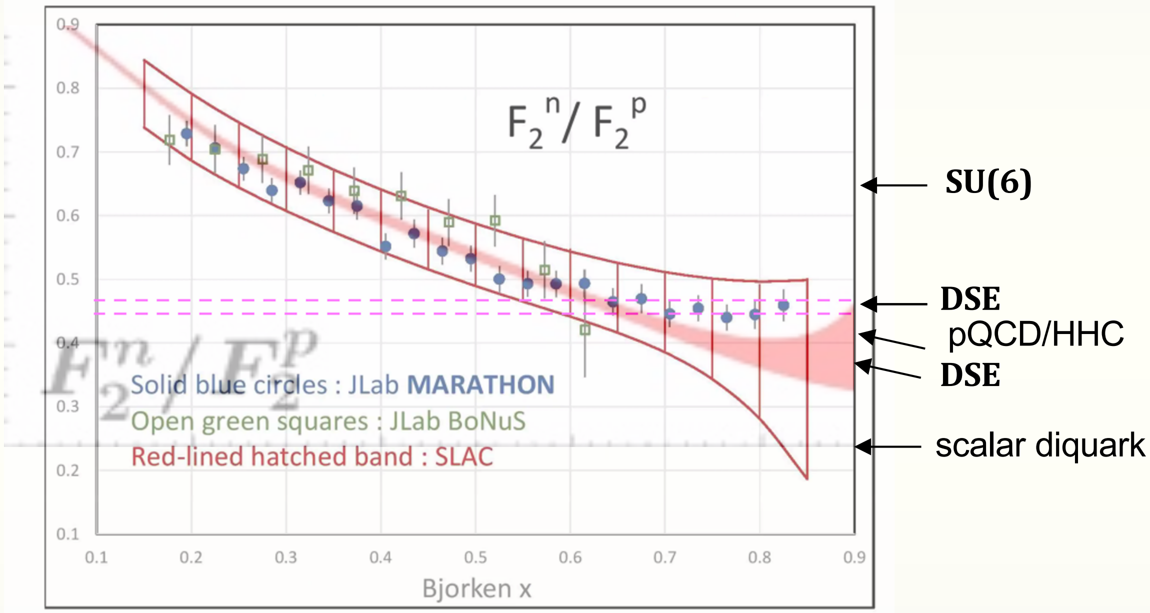
Conclusion



- Few-body nuclei continue to be "neutron targets of choice" – needed to study valence structure of nucleons
- Nucleons can serve as "virtual pion targets"
- Interpretation of results complicated by off-shell effects, possible structure modifications and final state interaction…
- …but we can also learn a lot about interactions and structure modifications due to binding by studying these effects (large kinematic coverage)
- Spectator tagging allows us to minimize binding effects or study them in detail, and select intended target INSIDE a bound system
- BONuS6 was the 1st experiment to tag low-momentum spectator p's
- BONuS12 had successful Physics run -> stay tuned for F_{2n}, d/u,…
- Lots more experiments at 12 GeV – ALERT, TDIS, BAND, LAD
- Future of spectator tagging: EIC

Backup Slides

MARATHON Preliminary F2n/F2p Results



Error Bars and Band include ALL uncertainties added in quadrature