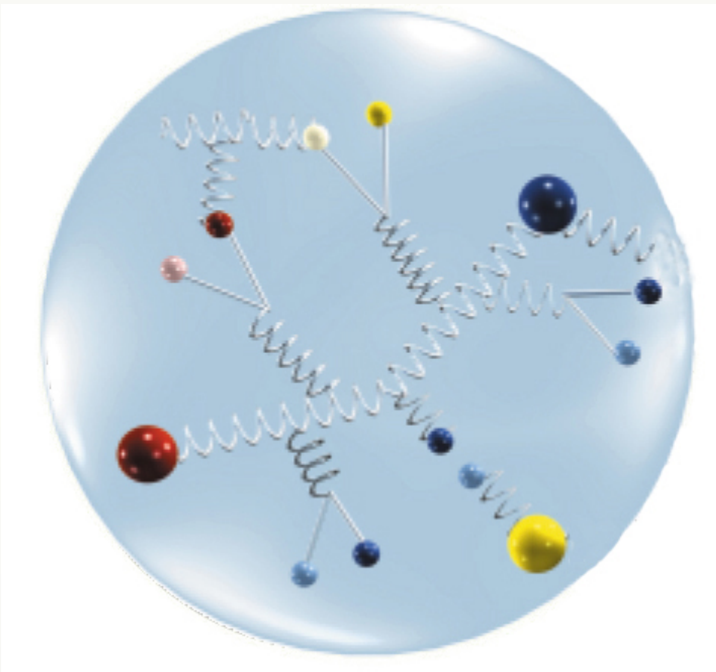
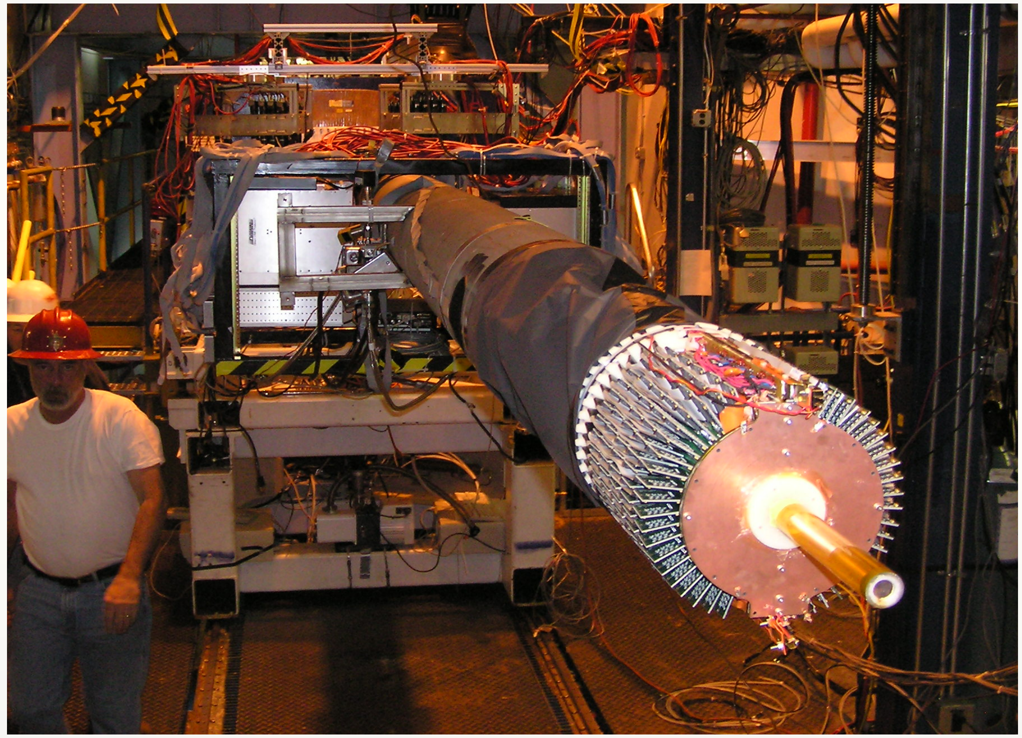
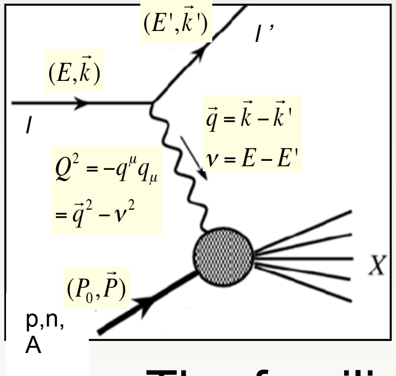
The Structure of (Free) Neutrons Through Spectator Tagging



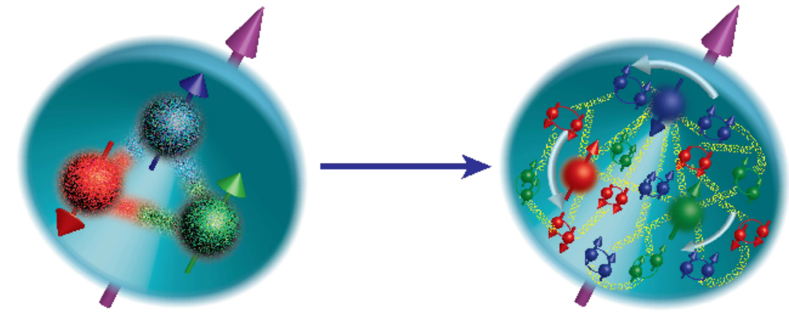


Sebastian Kuhn

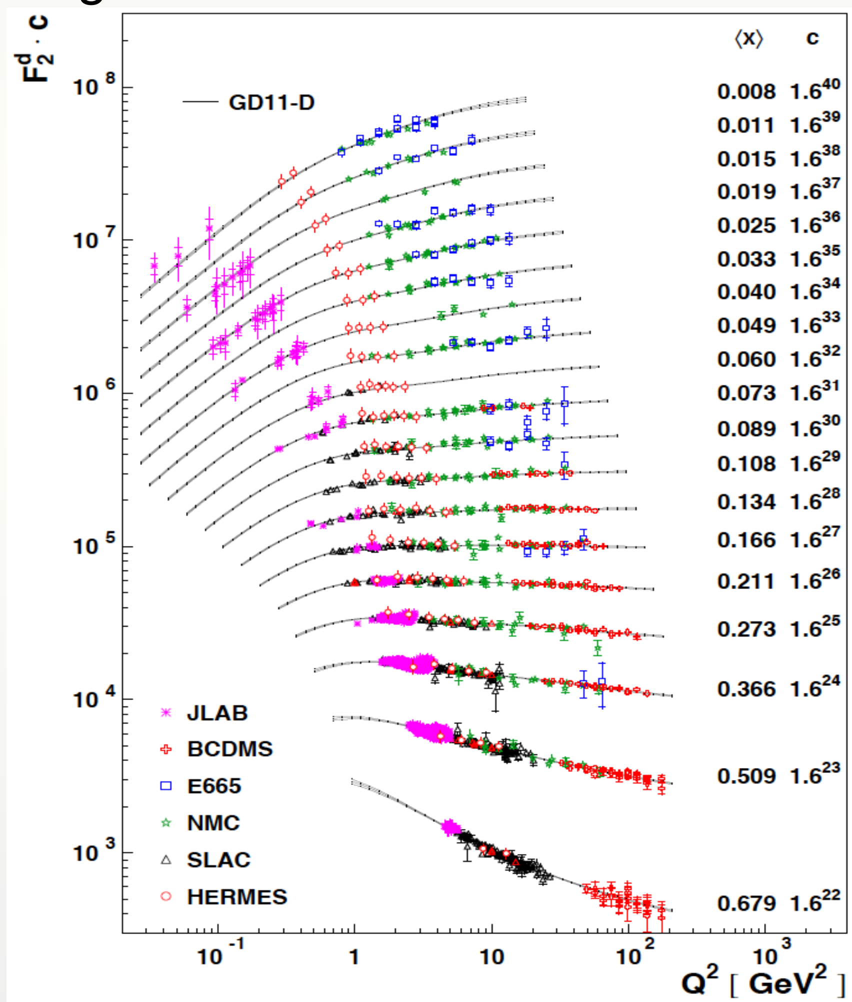
Old Dominion University



Introduction



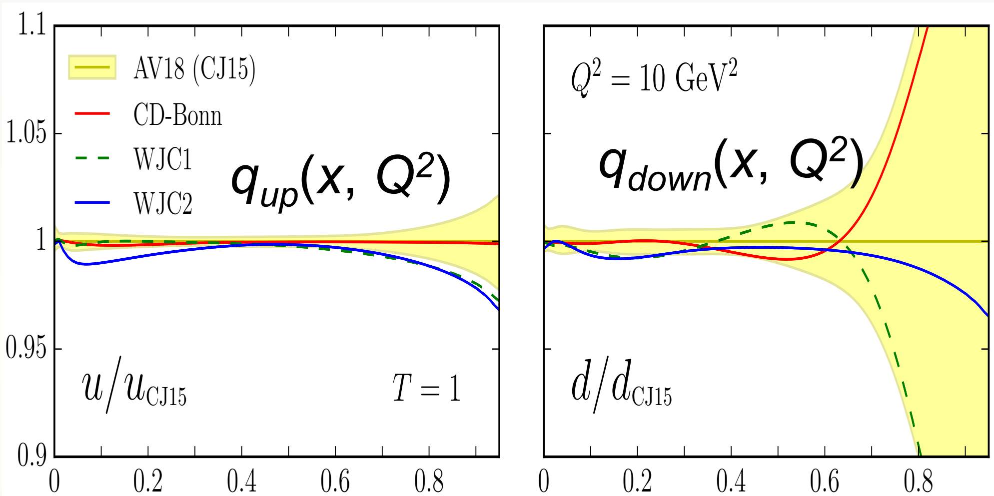
- The familiar (?) 1D world of Nucleon longitudinal structure:
  - Take a nucleon
  - Move it real fast along z
    $\Rightarrow$ light cone momentum
    $P_+ = P_0 + P_z$ (>>M)
  - Hit a "parton" (q, g,…) inside
  - Measure **its** l.c. momentum
    $p_+ = p_0 + p_z$ (m≈0)
  - $\Rightarrow$ Momentum Fraction $\xi = p_+ / P_+$ *)
  - In DIS: $\xi \approx (q_z - \nu)/M \approx x_{Bj} = Q^2/2M\nu$
    (in the target rest frame)
  - Probability: $F_1(x) = \frac{1}{2}\sum_i e_i^2 q_i(x)$
  - Because of spin-1/2: 2nd SF F_2(x)



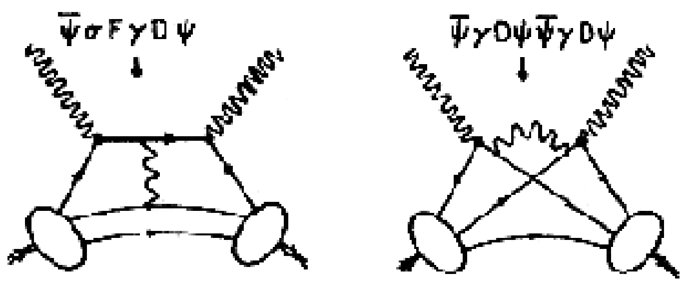
*) Advantage: Boost-independent

Structure Functions and Moments: Why large x? Why neutron?

$$\frac{d\sigma}{d\Omega dE'} = \sigma_{Mott}\left(\frac{F_2(x)}{\nu} + 2\tan^2\frac{\theta_e}{2}\frac{F_1(x)}{M}\right); \quad F_2(x,Q^2) = x \sum_{f=up,down,\ldots} z_f^2\left(q_f(x,Q^2) + \bar{q}_f(x,Q^2)\right)$$



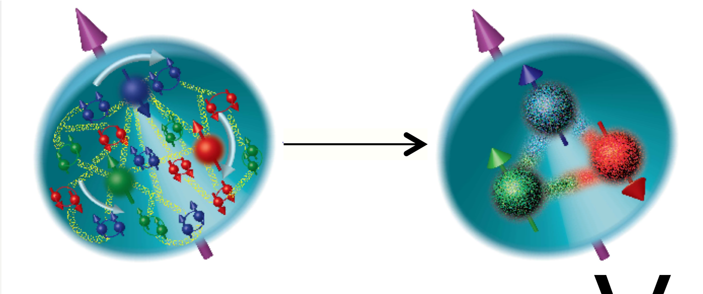
$\tau = 4$



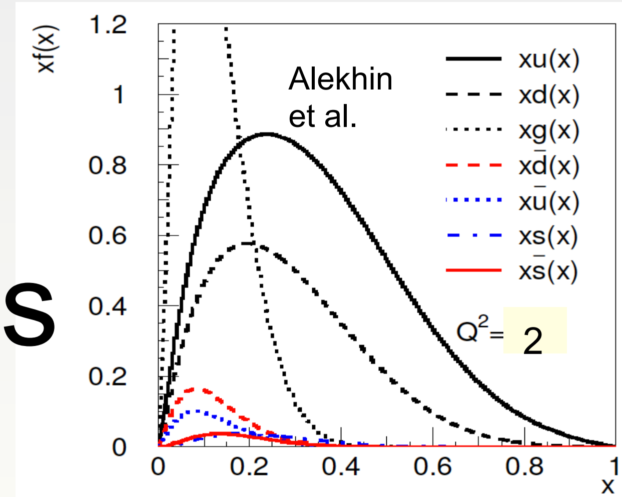
- $q_f(x \to 1)$ for both nucleons is a crucial test of valence quark models
  - Isospin, SU(6) breaking, pQCD,…
- Precise PDFs at large *x* needed as input for LHC, ν experiments etc.
  - Large *x*, medium Q^2 evolves to medium *x*, large Q^2
  - Also: NUCLEAR structure functions
- Moments can be directly compared with OPE (twist expansion), Lattice QCD and Sum Rules
  - All higher moments are weighted towards large *x*
- Quark-Hadron Duality

$$M_n^{CN}(Q^2) = \int_0^\infty dx\, \underline{x^{(n-2)}} F_2(x,Q^2) = \sum_{\tau=2k}^{\infty} E_{n\tau}(\mu,Q^2) O_{n\tau}(\mu)\left(\frac{\mu^2}{Q^2}\right)^{\frac{1}{2}(\tau-2)}$$

+ TM corr.



Valence PDFs



CJ15

- Behavior of PDFs still unknown for $x \rightarrow 1$
  - SU(6): d/u = 1/2, $\Delta u/u$ = 2/3, $\Delta d/d$ = -1/3 for all x
  - Relativistic Quark model: Δu, Δd reduced
  - Hyperfine effect (1-gluon-exchange): Spectator spin 1 suppressed, $d/u \rightarrow 0$, $\Delta u/u \rightarrow 1$, $\Delta d/d \rightarrow -1/3$
  - Helicity conservation (pQCD): Spectator spin $S_z \neq 0$ suppressed, $d/u \rightarrow 1/5$, $\Delta u/u \rightarrow 1$, $\Delta d/d \rightarrow 1$
  - Orbital angular momentum: can explain slower convergence to $\Delta d/d = 1$
- Plenty of data on proton → mostly constraints on u and Δu
- Knowledge on d limited by lack of free neutron target (nuclear binding effects in d, ^{3}He)
- Large x requires very high luminosity and resolution; binding effects become dominant uncertainty for the neutron

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

Assuming charge independence

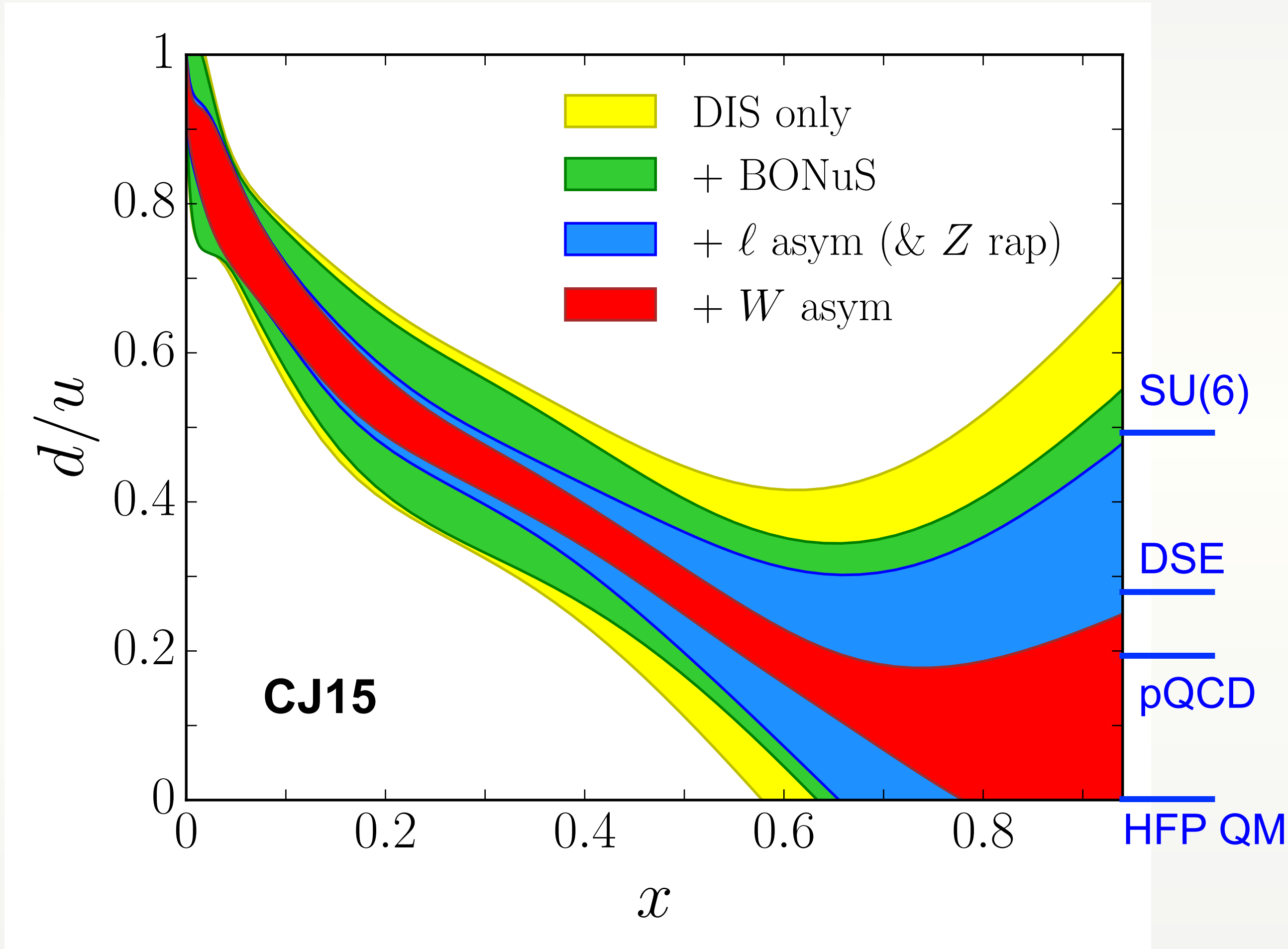
(= invariance under 180° rotations in isospin space):

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

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

$F_{2n}/F_{2p} = F_{2d}/F_{2p} - 1$

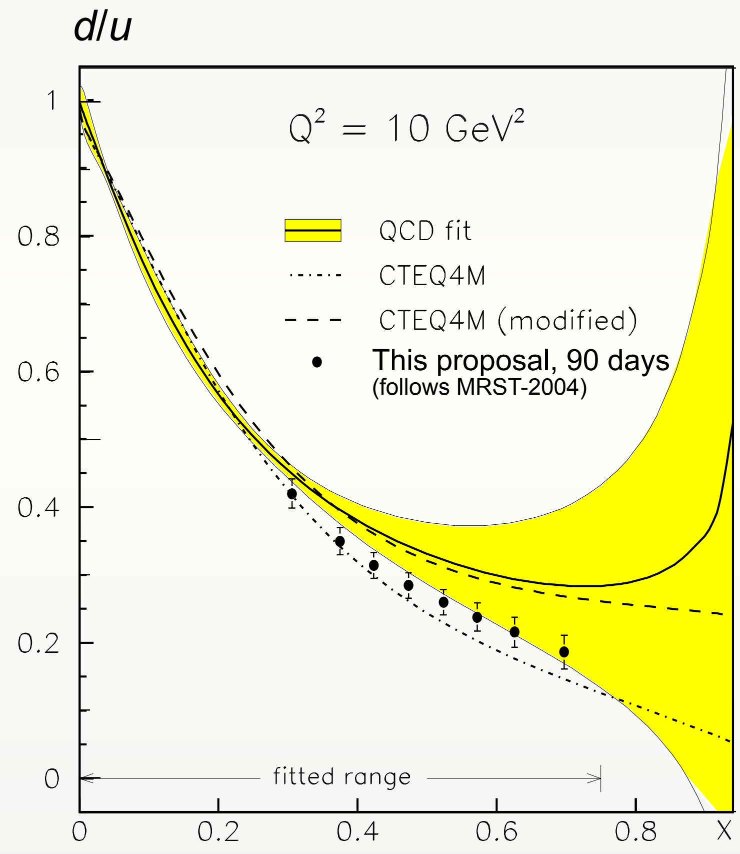
???



- Neutron data limited by “Nuclear Binding Uncertainties”

Cleanest way to access *d/u*

- Exploit different “charge” ratios for weak and electromagnetic interaction.
- Possible processes: W/Z production, neutrino → muon scattering, parity-violating lepton scattering (PV DIS).
- Advantage: Direct measurement on the proton; does not require assumptions about charge symmetry.
- Limitations in statistical precision.

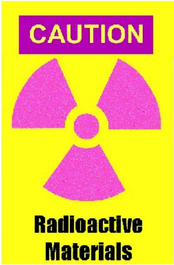


PV DIS on p target, 90 days with SoLID. E12-10-007 in Jefferson Lab’s Hall A, approved with A rating.

Neutron Data Are Important…
…but hard to get

• Free neutrons decay in 15 minutes.

• Radioactivity!



• Zero charge makes it difficult to create a dense target

Magnetic bottle: 10^3 - 10^4 n/cm^2 [TU München]

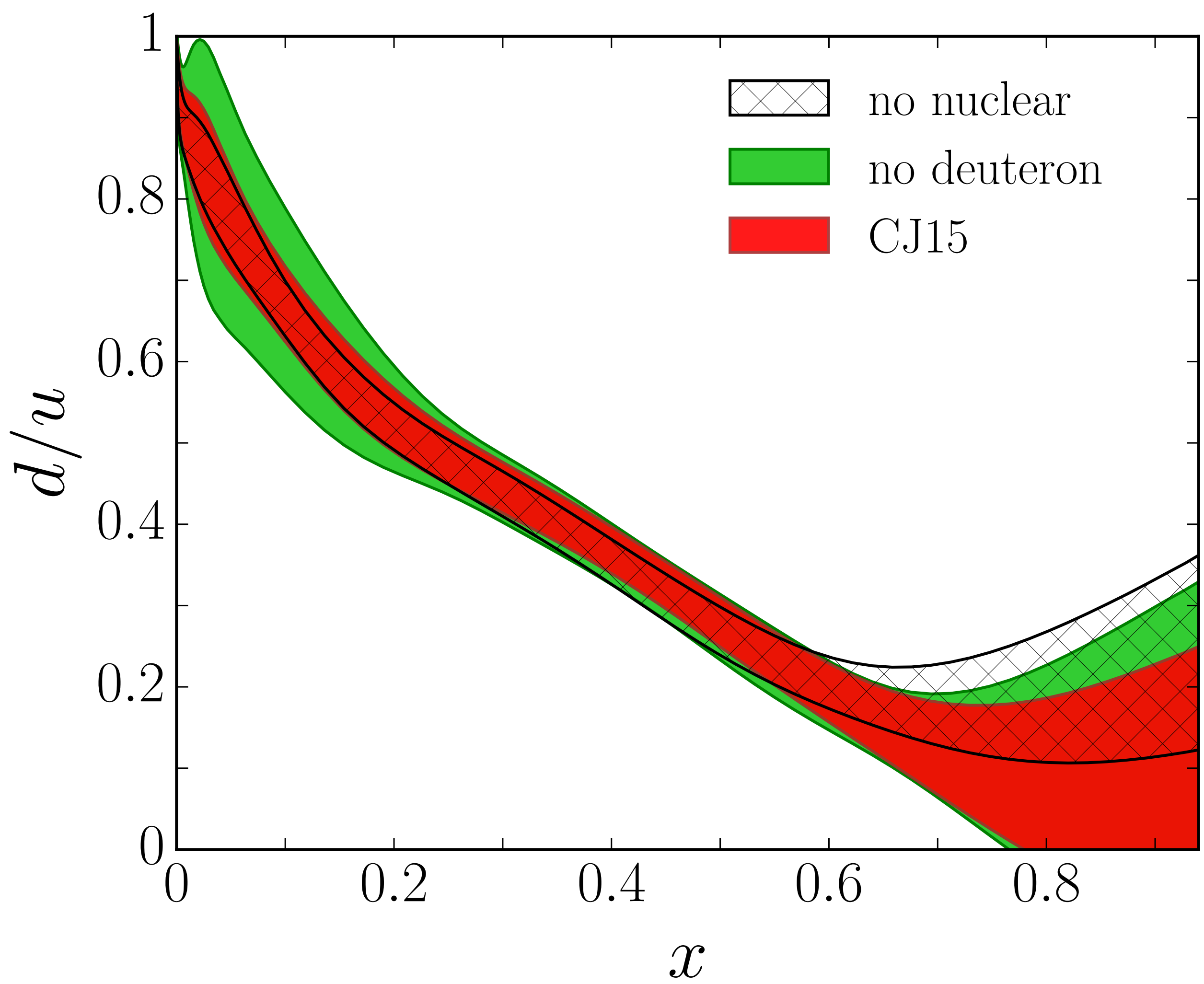
Typical proton target: $4{\cdot}10^{23}$ p/cm^2 [10 cm LH] – 10^{14} p/cm^2 [HERMES]

=> Alternative Solution: Deuterons, Tritons and Helium-3…

BUT: Nuclear Model Uncertainties:

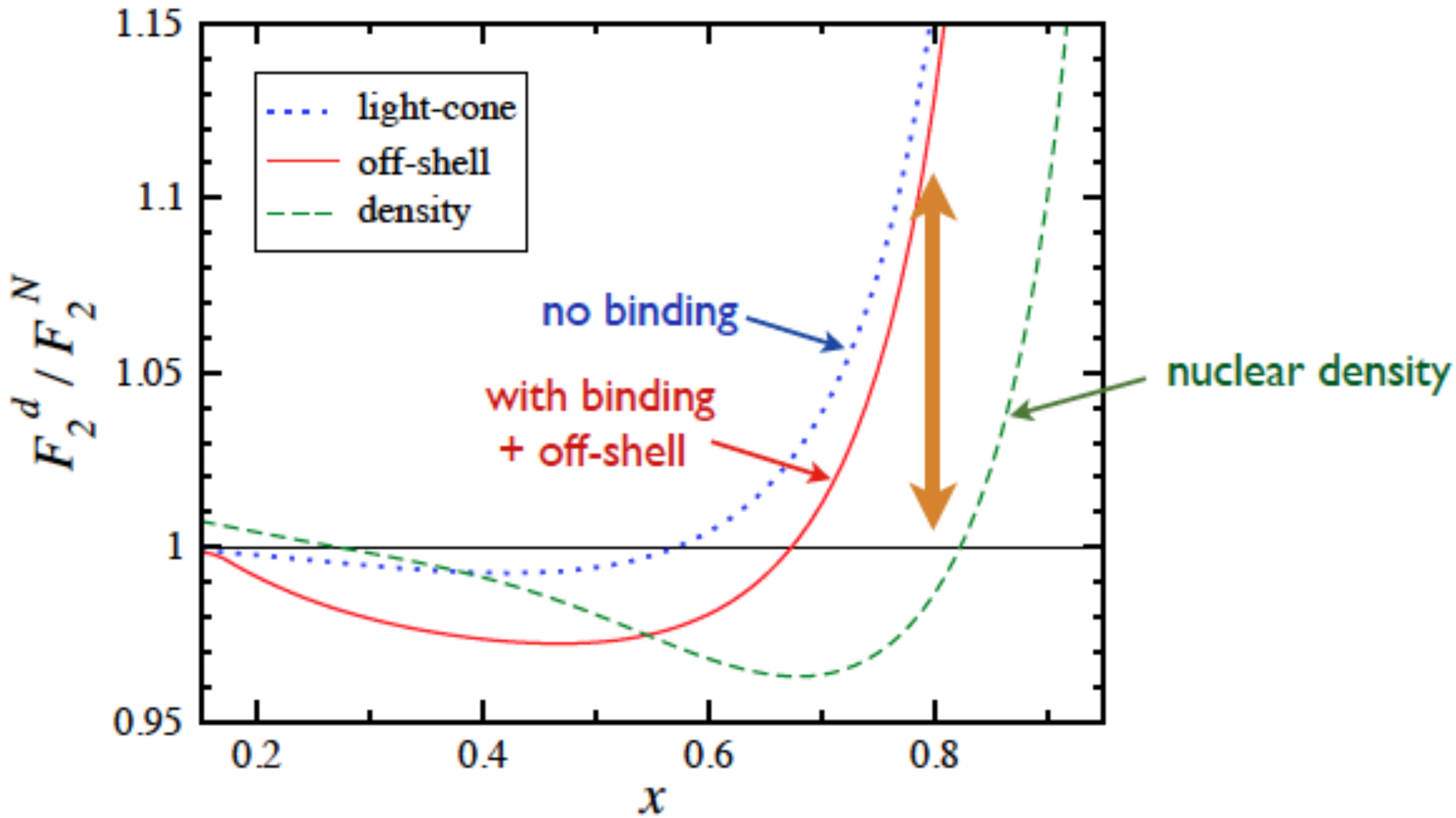
Fermi motion, off-shell effects (binding), structure modifications (EMC effect), extra pions/Deltas, coherent effects, 6-quark bags…

Large *x* - Large Nuclear Effects



- Even simple “Fermi Smearing” leads to significant dependence on D wave function
- Different models for off-shell and “EMC” effects lead to large additional variations
- Contributions from MEC, Δ(1232) and “exotic” degrees of freedom unknown
- FSI?

EMC effect in deuteron

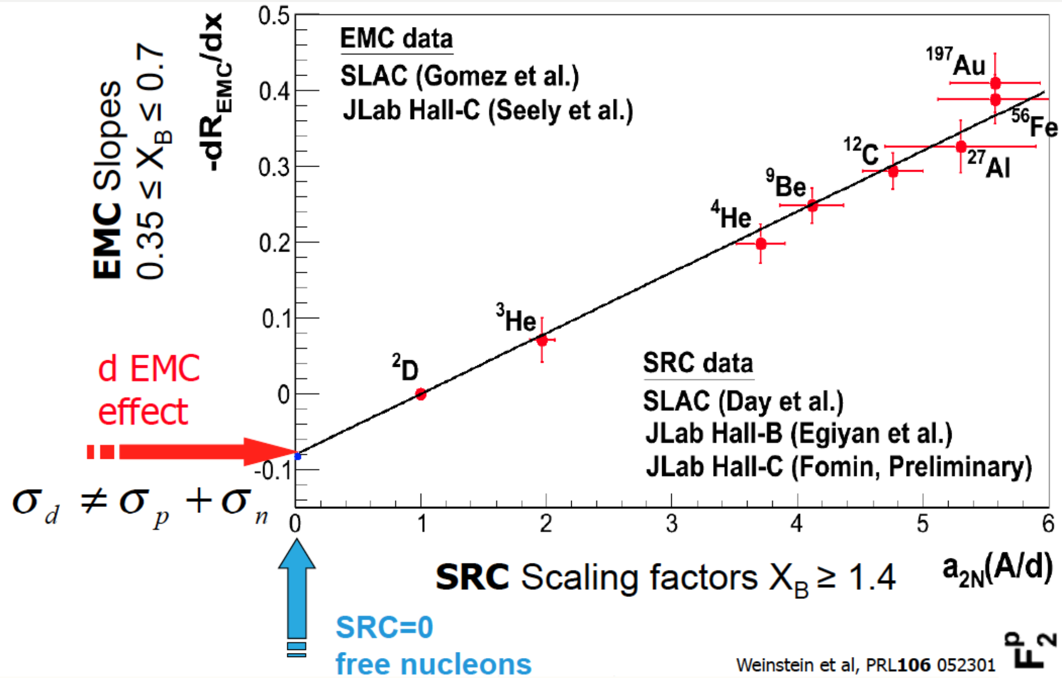


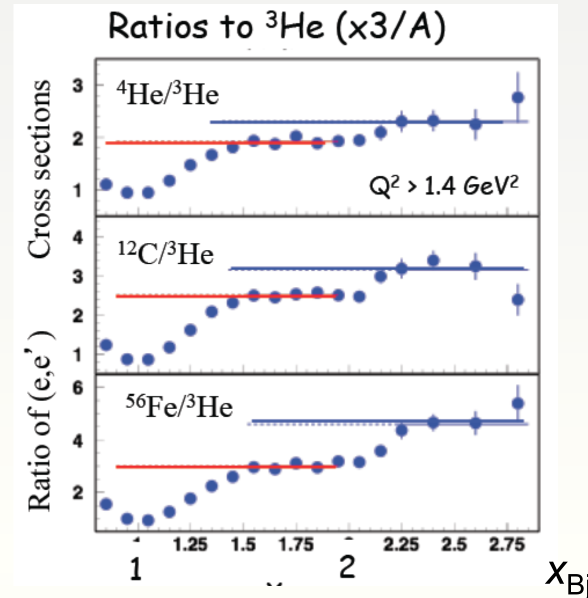
→ using off-shell model, will get *larger* neutron *cf. light-cone* model

→ but will get *smaller* neutron *cf. no nuclear effects* or *density* model

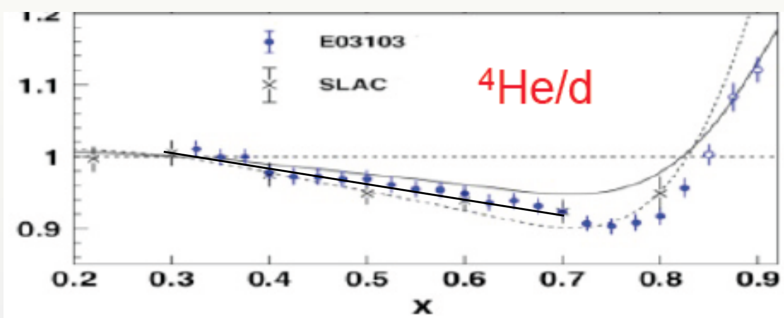
Estimating the EMC effect in Deuterium

L. Weinstein, E.I. Piasetzky, D. Higinbotham, J. Gomez, O. Hen and R. Shneor, PRL106 052301 (2011)

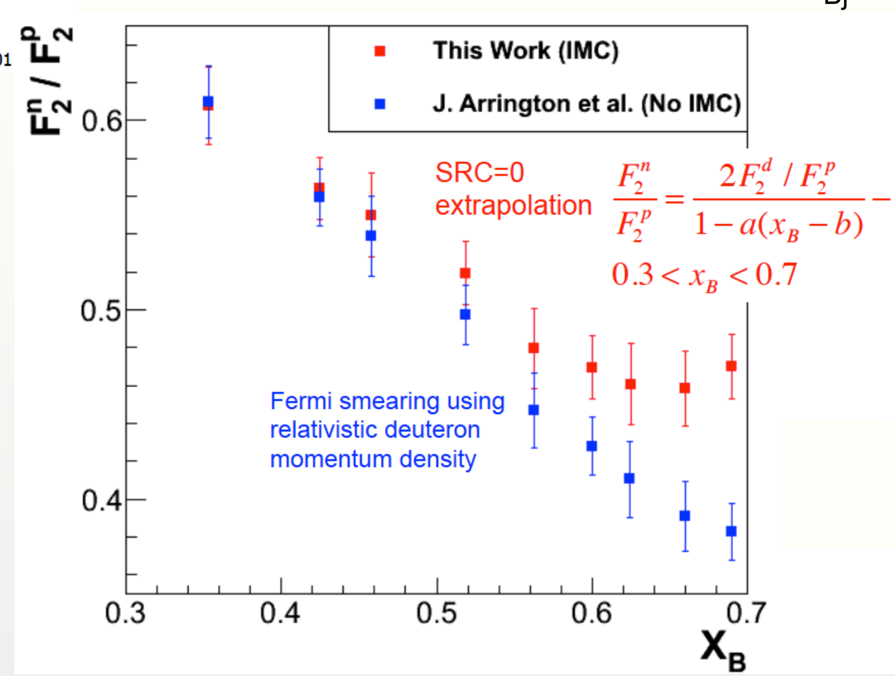




Probability of a nucleon inside the nucleus to be in a “short-range” (tensor) correlation (dominated by pn correlations 10:1)

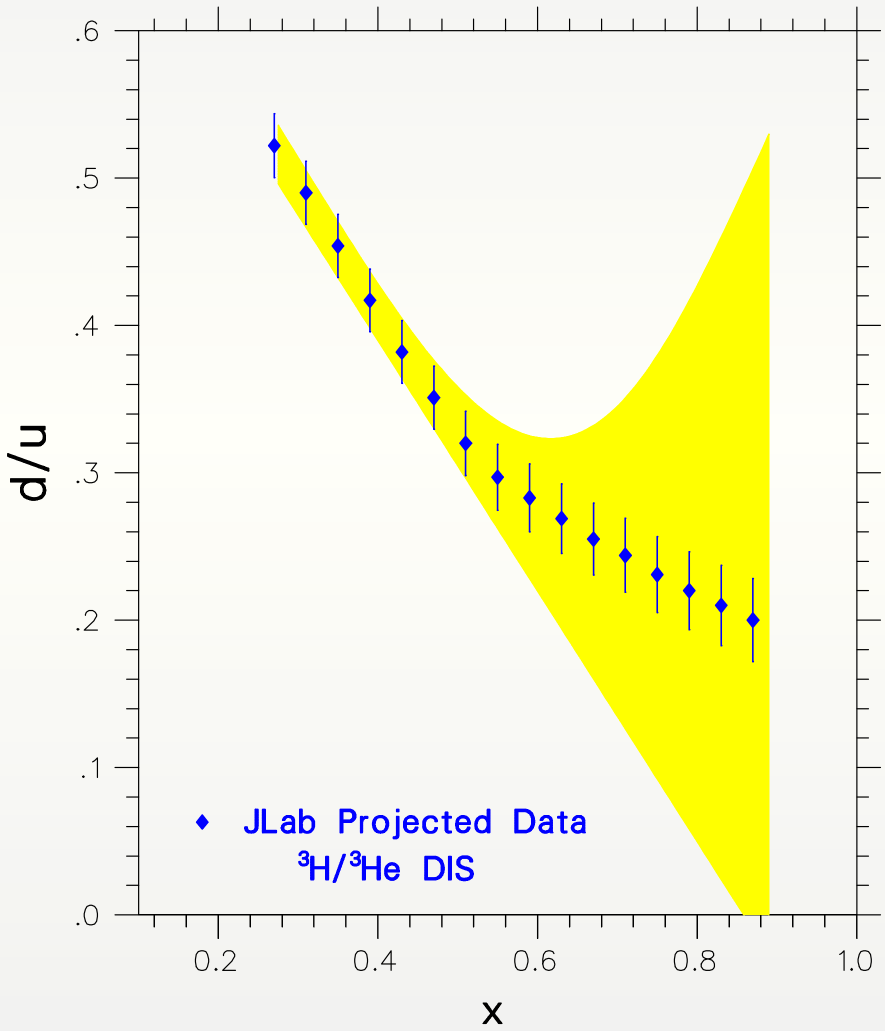


J. Seely, PRL 103, 202301 (2009)



One Solution: take ratio of nearly identical nuclei (EMC effect largely cancels)

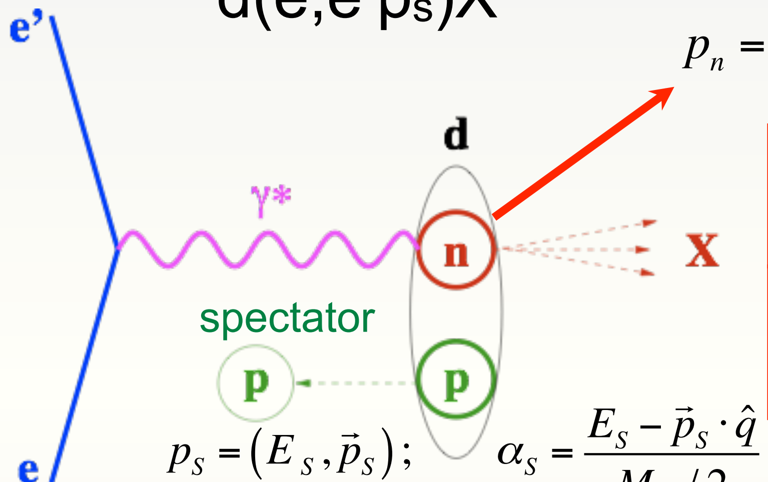
- Best case: Isospin doublet $^3He/^3H$.
- $$\frac{F_2^{^3H}(x)}{F_2^{^3He}(x)} = \frac{\left(\frac{4}{9}+2\frac{1}{9}\right)u(x)+\left(\frac{1}{9}+2\frac{4}{9}\right)d(x)}{\left(2\frac{4}{9}+\frac{1}{9}\right)u(x)+\left(2\frac{1}{9}+\frac{4}{9}\right)d(x)} = \frac{\frac{2}{3}+d(x)/u(x)}{1+\frac{2}{3}d(x)/u(x)}$$
- Several experiments with tritium target planned for 2017 in Jefferson Lab's Hall A



"Marathon" Experiment in Hall A. W > 1.8 GeV.
Experiment E12-10-103 42d, A rating, * from PAC41.

Alternative: Spectator Tagging

d(e,e'p$_s$)X

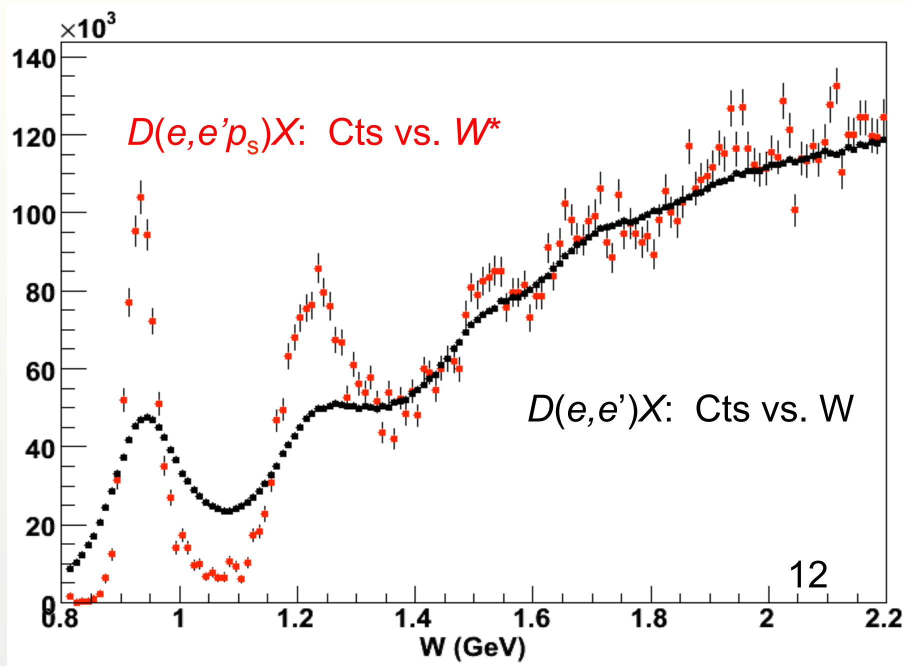


$$p_n = \left(M_D - E_S, -\vec{p}_S\right);\ \alpha_n = 2 - \alpha_S \qquad M^{*2} = p_n^{\mu} p_{n\mu}$$

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

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

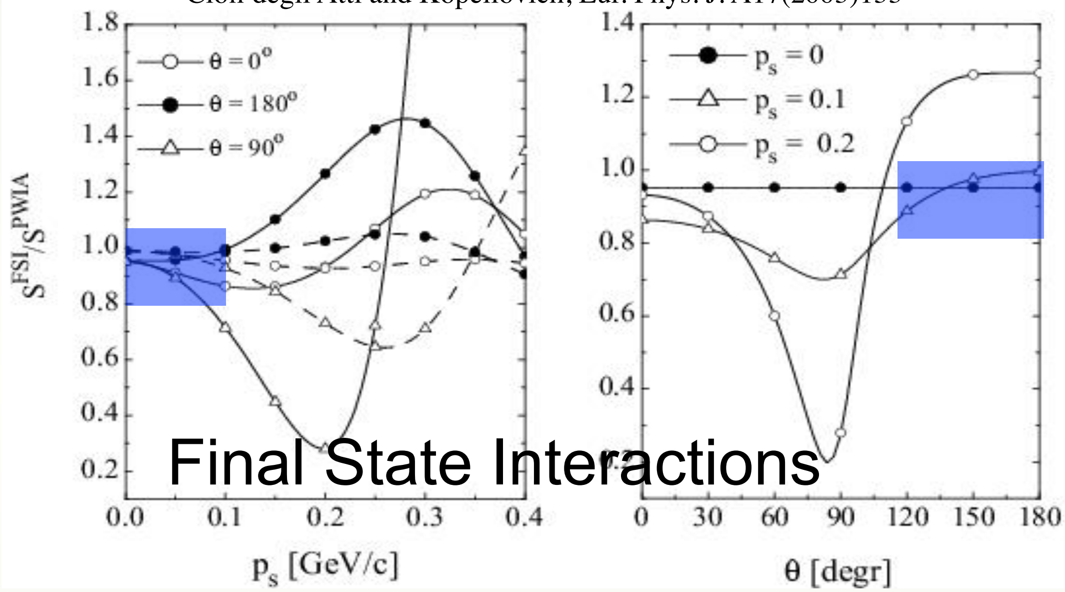
$$p_S = \left(E_S, \vec{p}_S\right); \qquad \alpha_S = \frac{E_S - \vec{p}_S \cdot \hat{q}}{M_D/2}$$

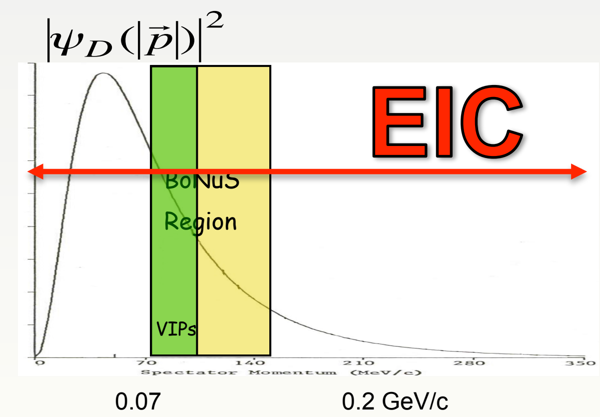


Spectator Tagging

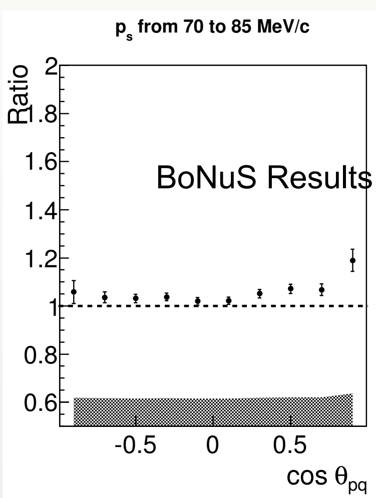
Limitations

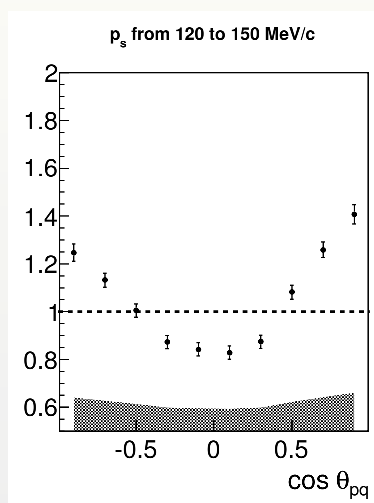
Ciofi degli Atti and Kopeliovich, Eur. Phys. J. A17(2003)133

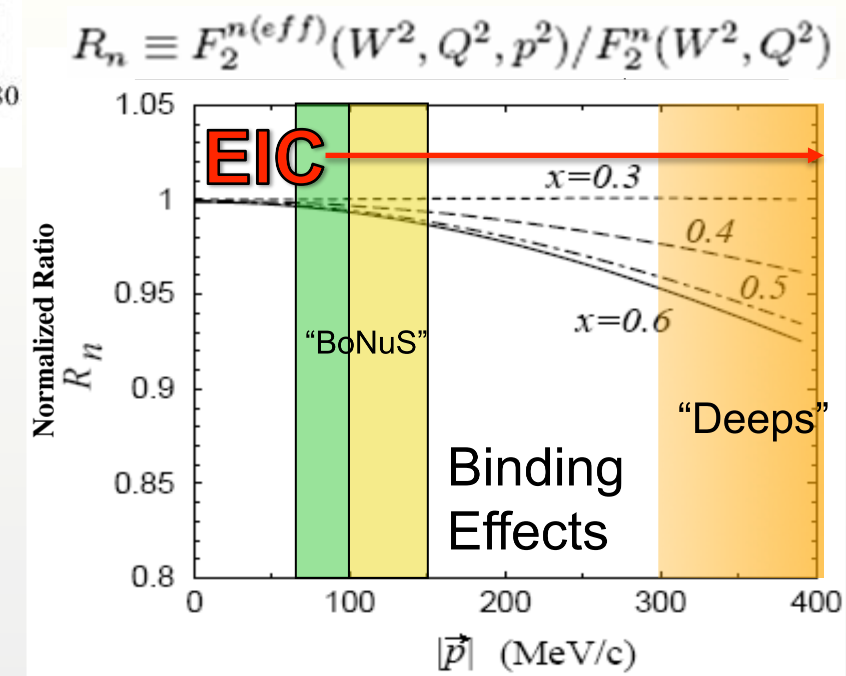




Finite coverage of WF





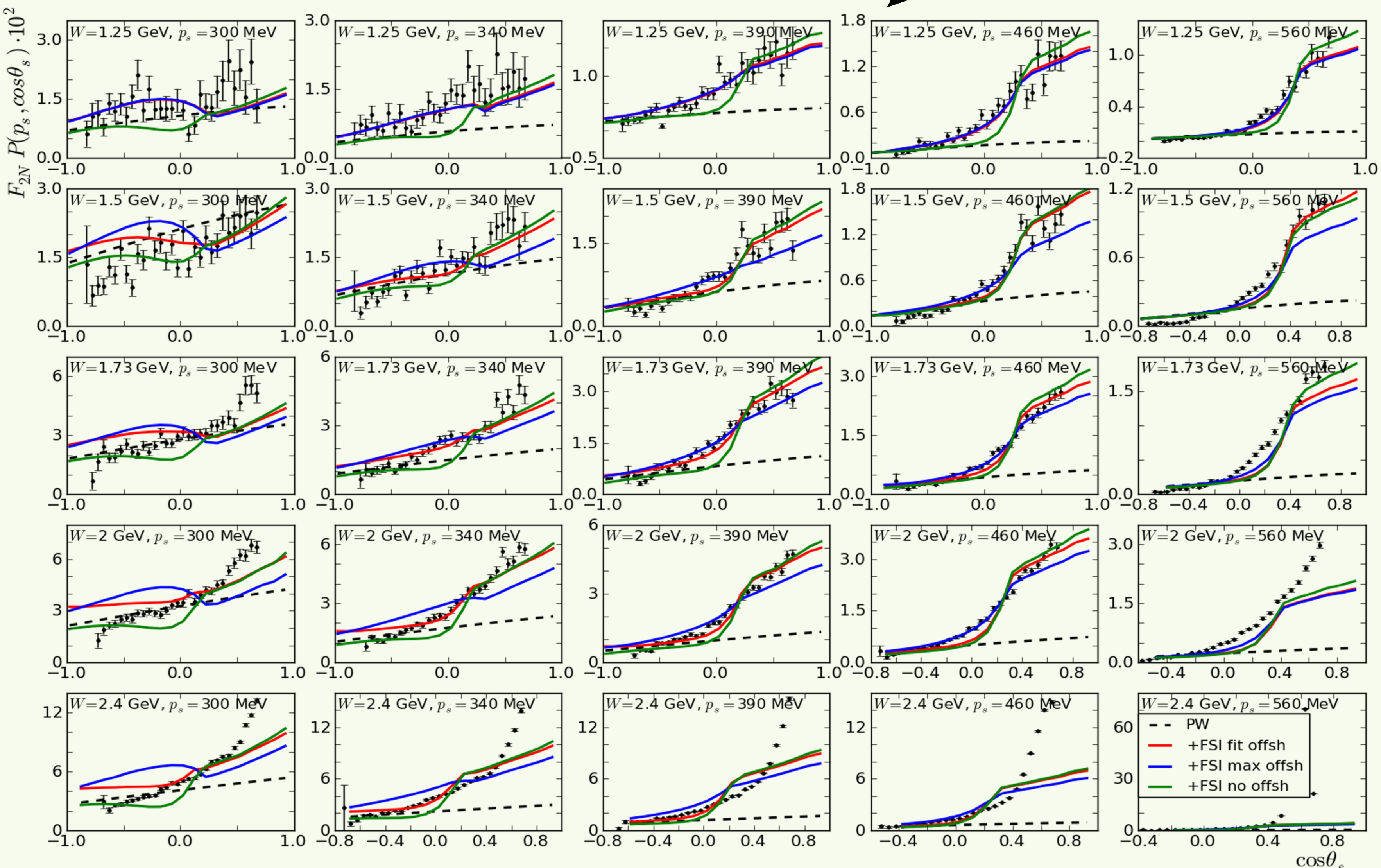


Spectator Tagging

increasing p_s

W. Cosyn et al.

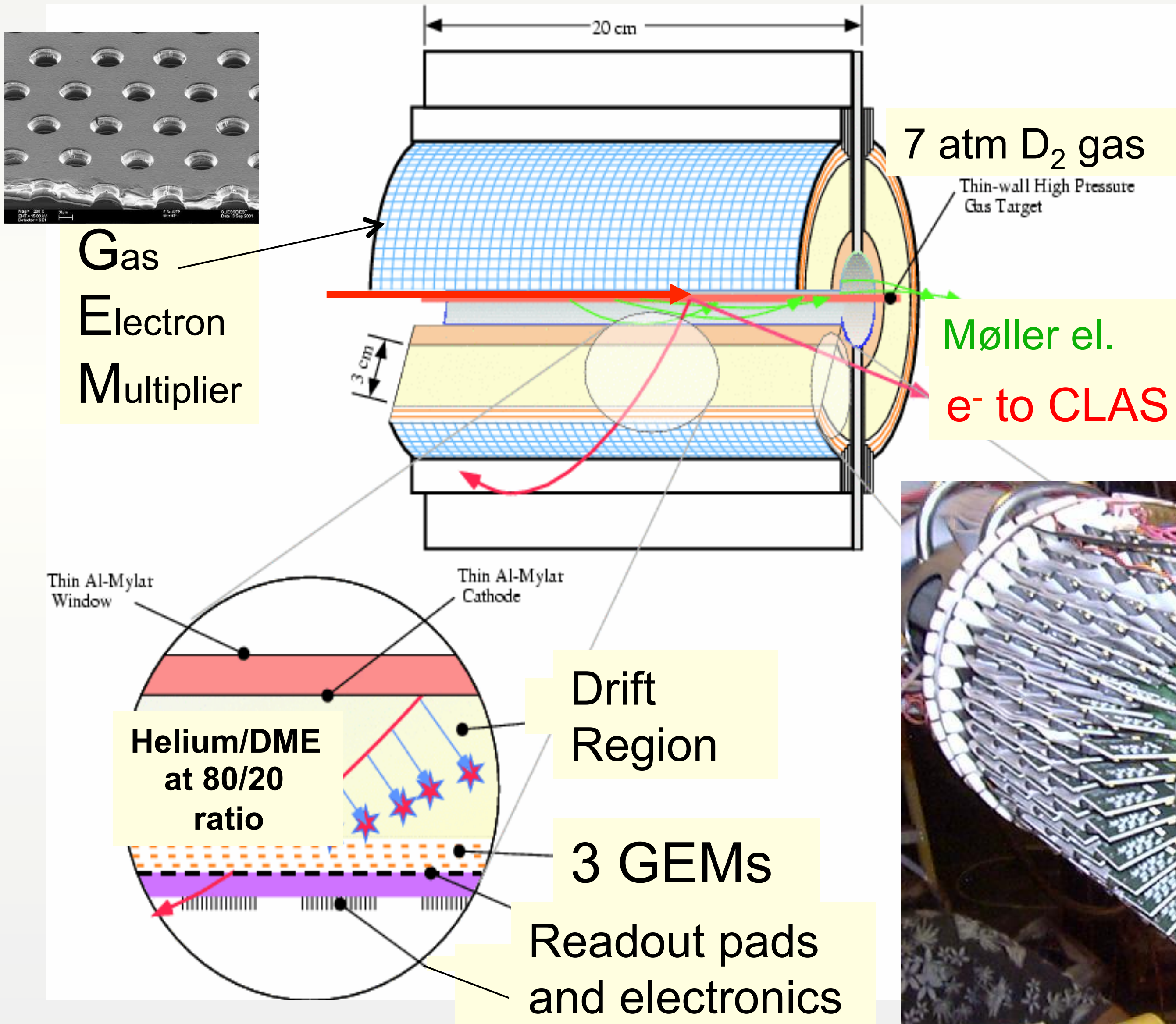
increasing invariant mass of X

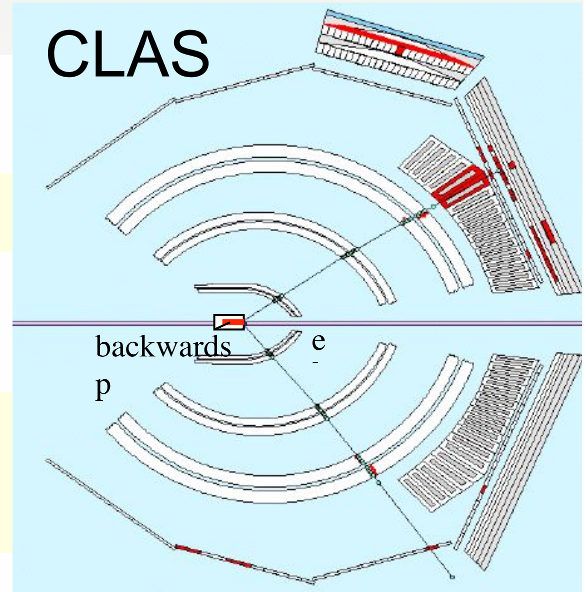


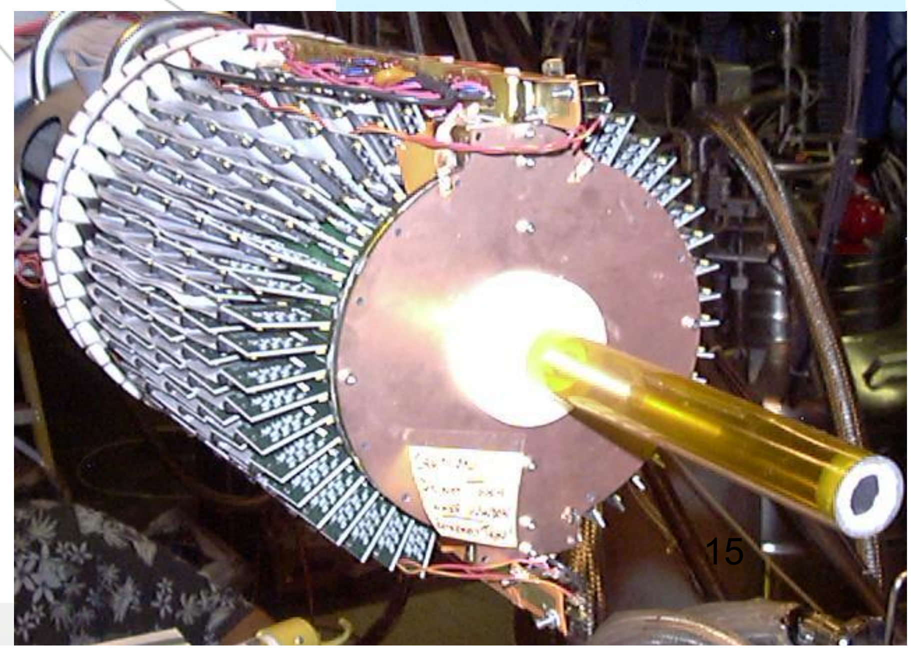
data:Klimenko et al. (JLab CLAS), PRC73 035212 ('06)

Spectator Tagging

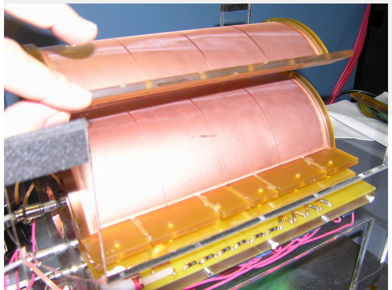
Example: BoNuS



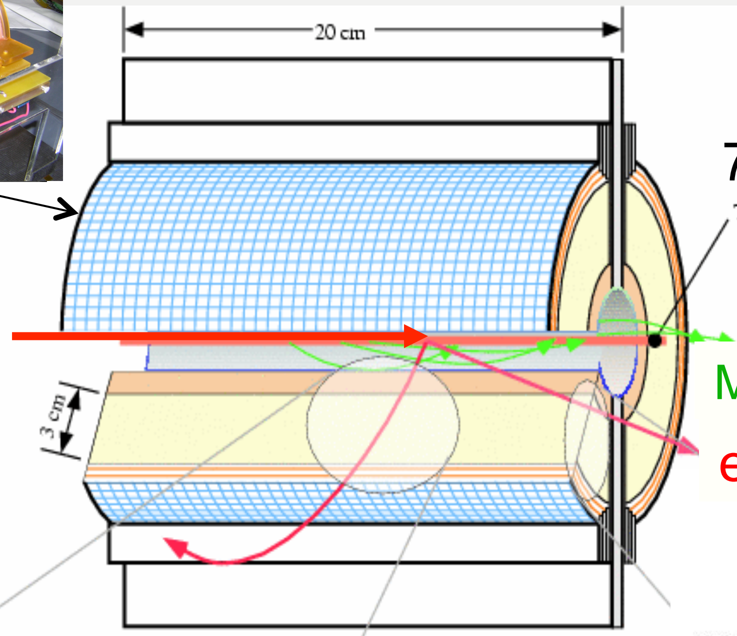




BoNuS RTPC



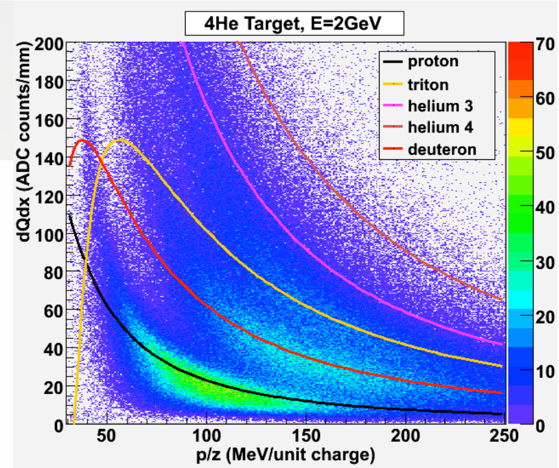
Gas
Electron
Multiplier



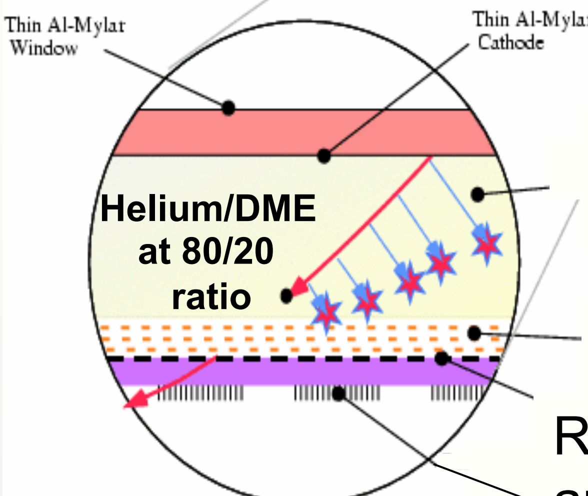
7 atm D_2 gas

Møller el.

e⁻ (to CLAS)



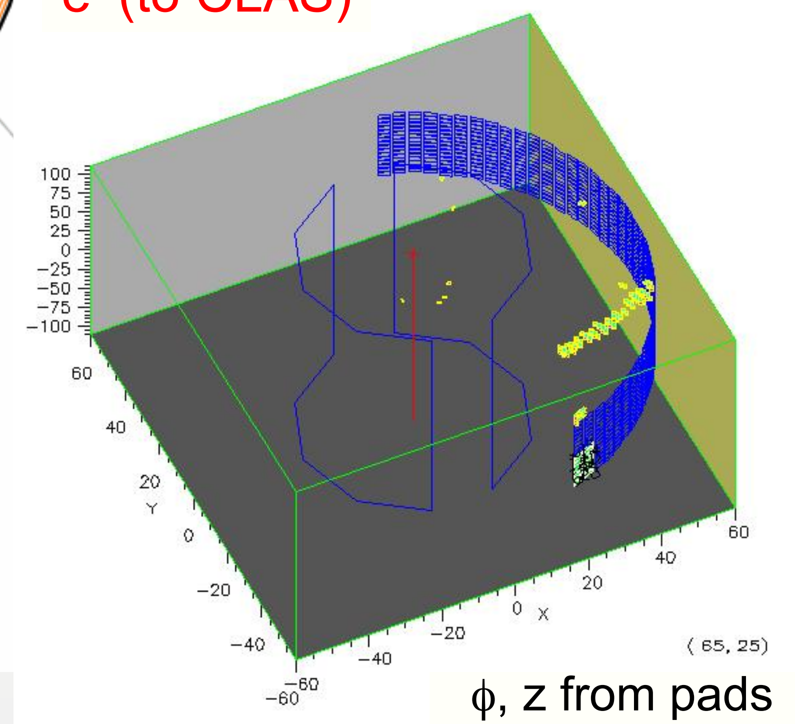
dE/dx from charge along track (particle ID)



Drift Region

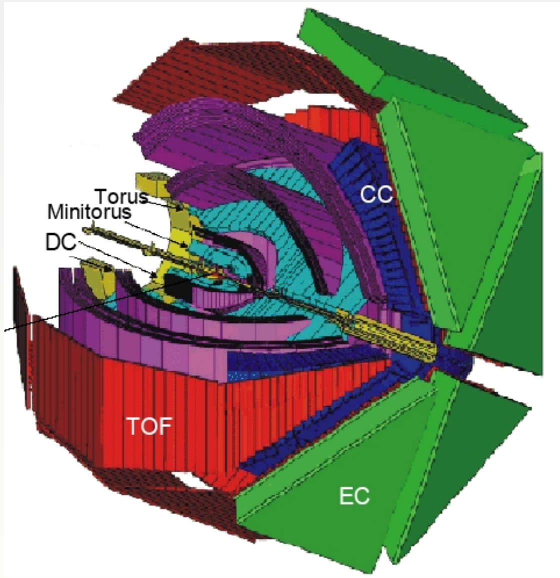
3 GEMs

Readout pads and electronics

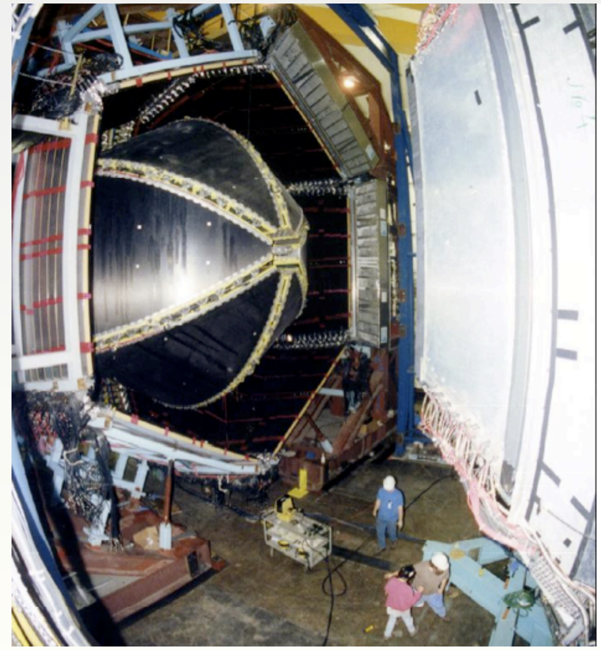


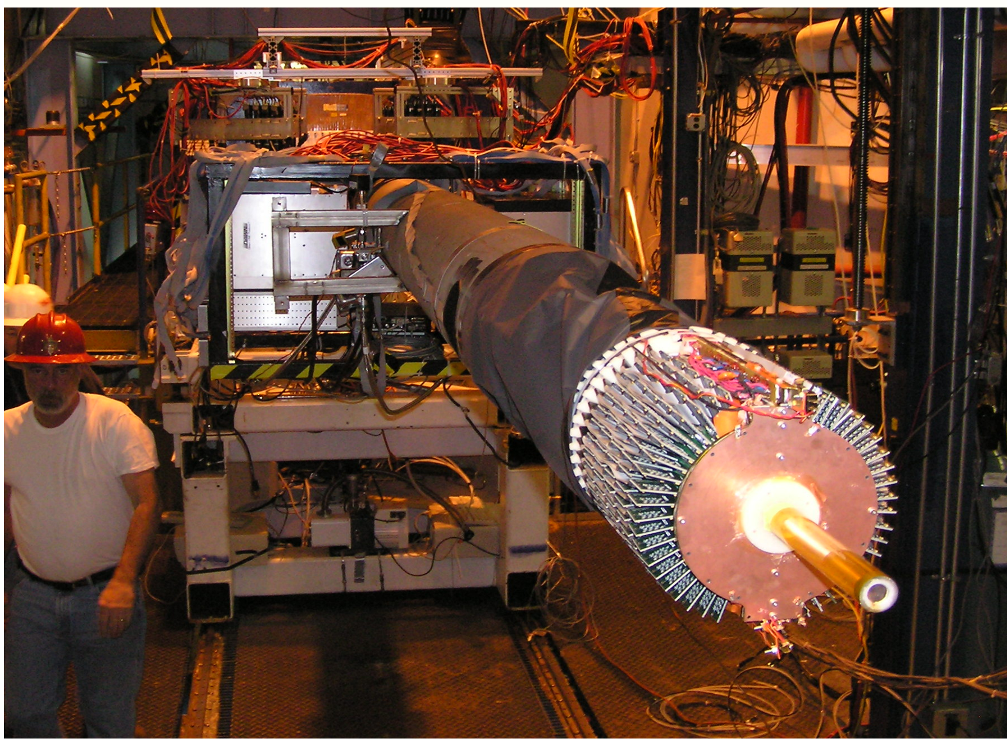
ϕ, z from pads
r from time

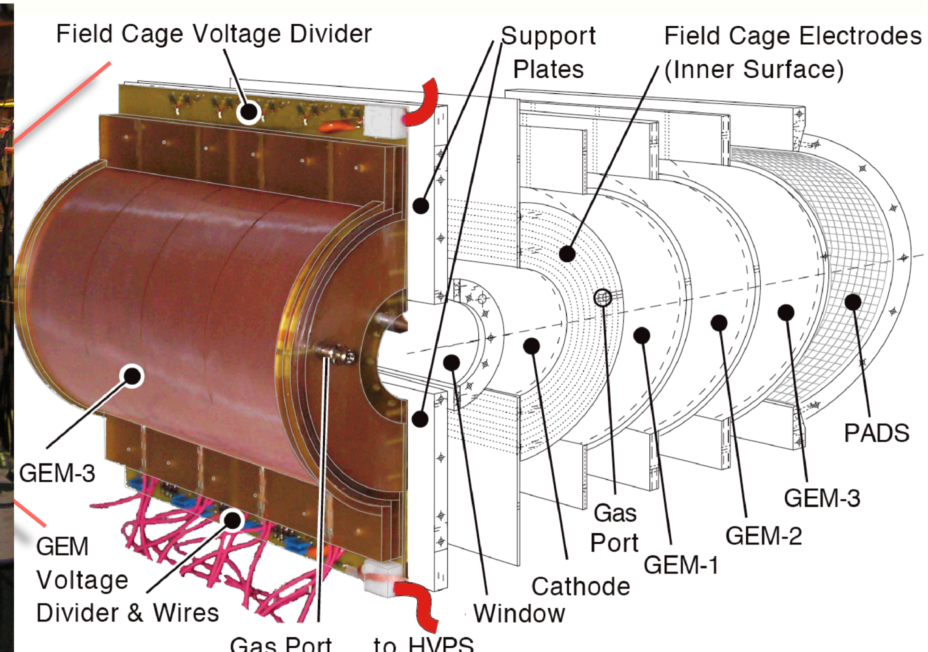
Nucl. Instr. Meth. **A592**, 273 (2008)



BoNuS in CLAS

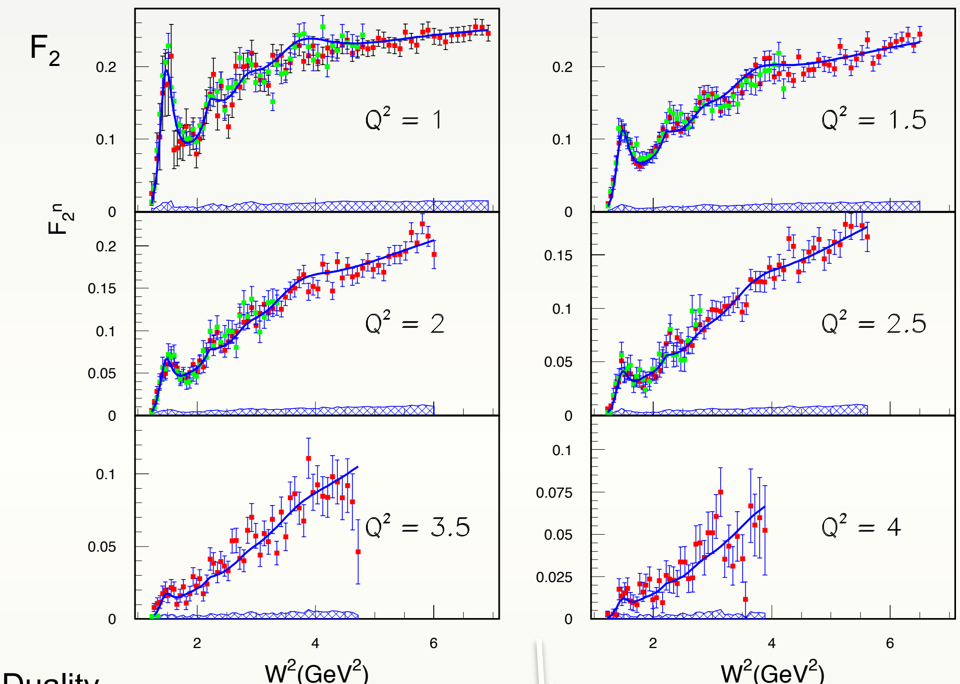


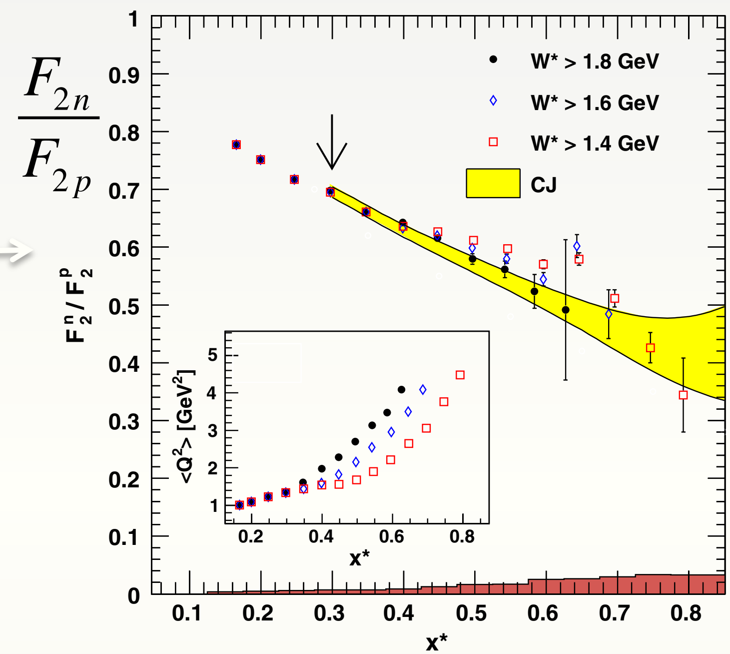




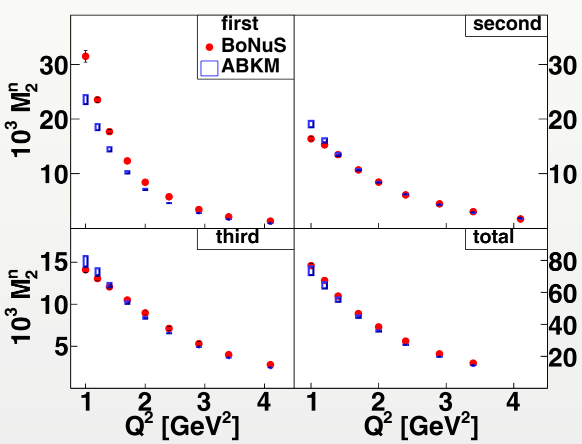
Spectator Tagging

Example: BoNuS - Results

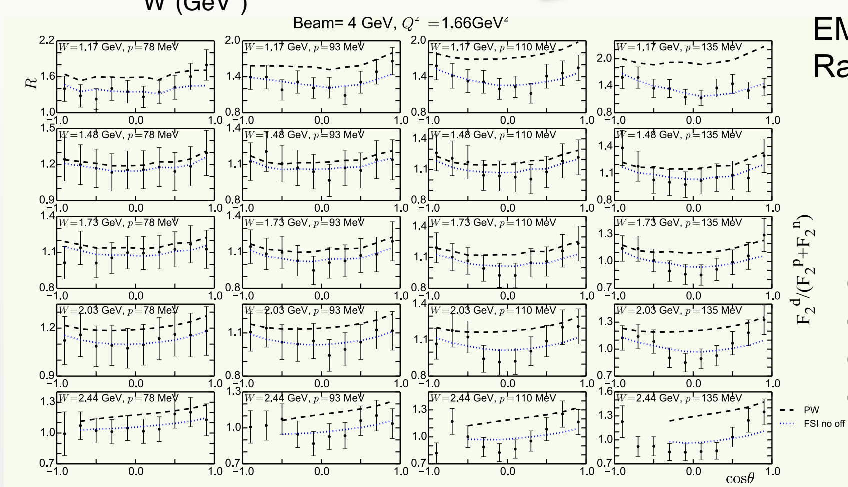




Duality

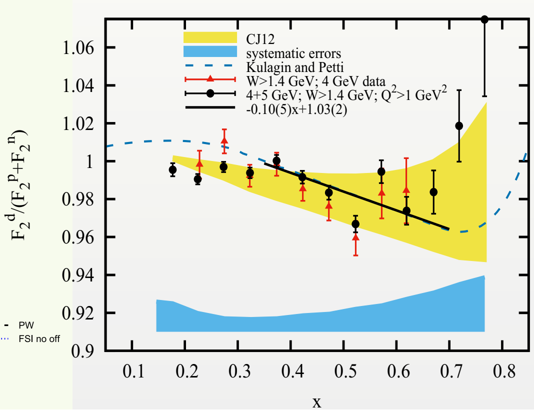


FSI: Cosyn et al.



EMC Ratio

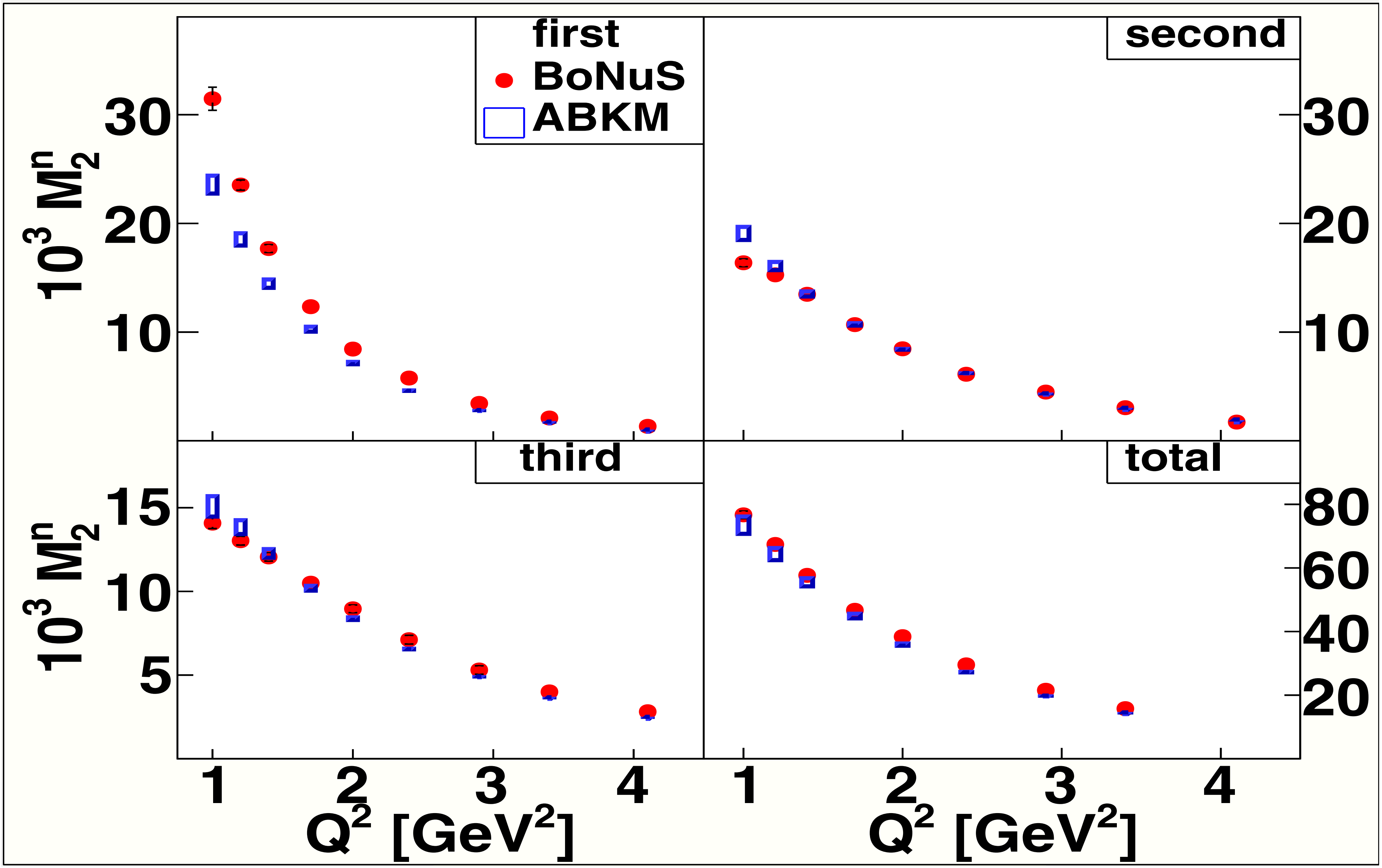
PHYSICAL REVIEW C **92**, 015211 (2015)



Spectator Tagging

Example: BoNuS - Results

Duality: Comparing F_{2n} moments in x integrated over various resonance regions (red) to pQCD PDF fits (blue squares) integrated over the same x-range

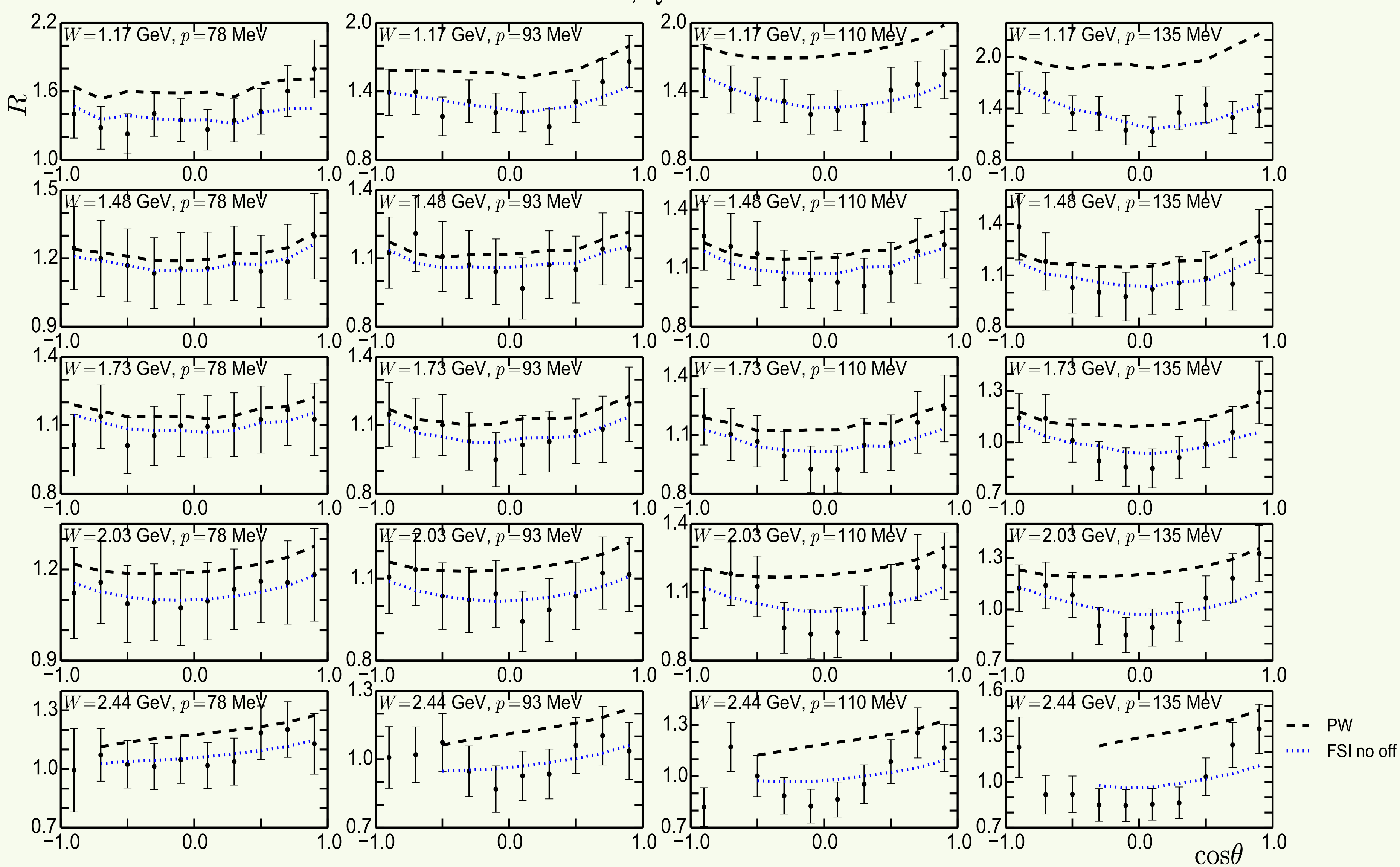


BoNuS - Results

FSI: Cosyn et al.

R = ratio of tagged SF in d(e,e'p_s) to "free" n SF, vs. momentum and angle (relative to **q** vector) of spectator p_s

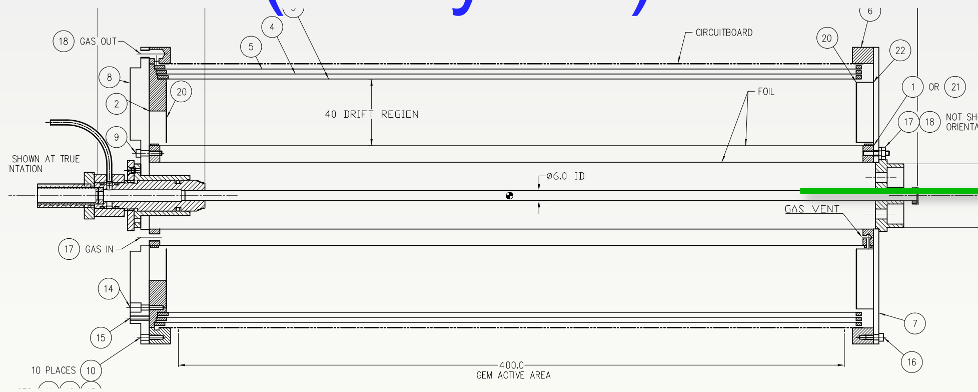
Beam= 4 GeV, Q^2 =1.66GeV^2

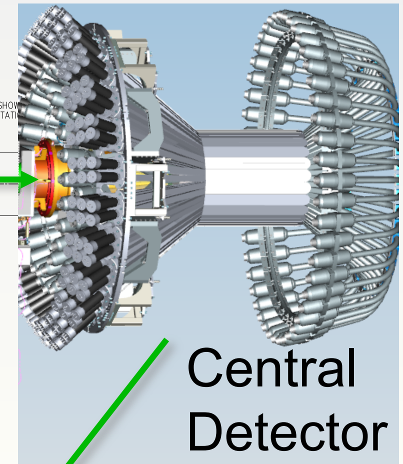


Plans for 12 (really: 11) GeV

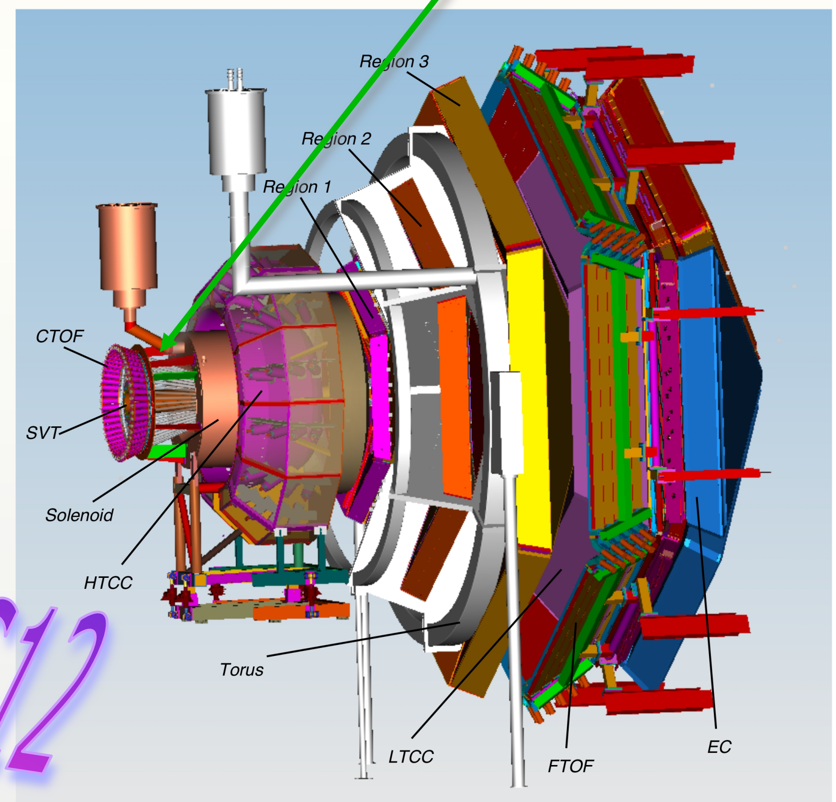
BoNuS12

E12-06-113





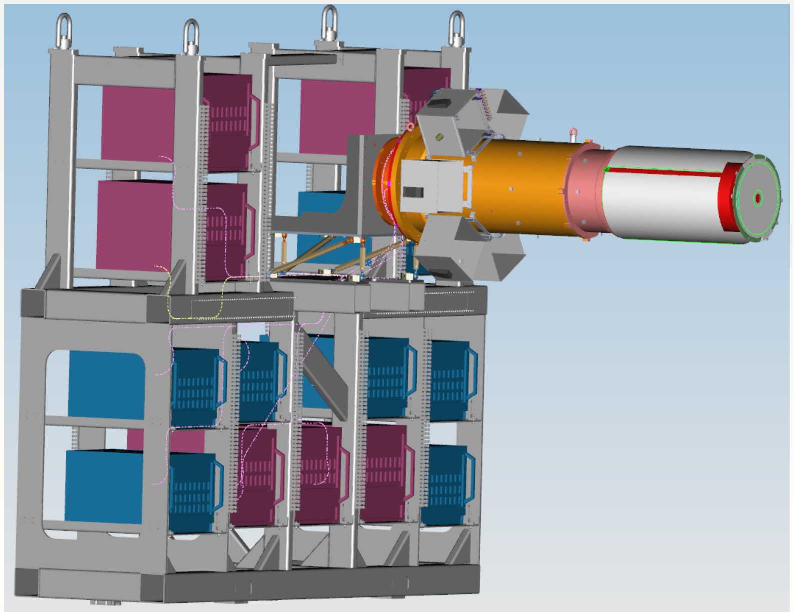
- Data taking of 35 days on D_2 and 5 days on H_2 with $\mathcal{L} = 2 \cdot 10^{34}$ cm^{-2} sec^{-1}
- **Planned** BoNuS detector DAQ and trigger **upgrade**
- DIS region with
  - $Q^2 > 1$ GeV$^2/c^2$
  - $W^* > 2$ GeV
  - $p_s > 70$ MeV/c
  - $10° < \theta_{pq} < 170°$
- Extend to higher momenta using central detector alone



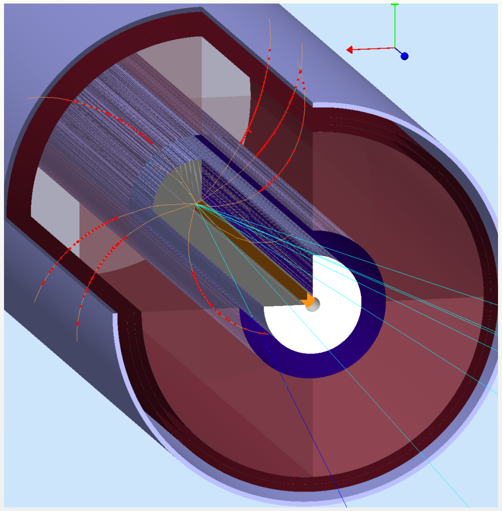
CLAS12

Plans for 12 (really: 11) GeV

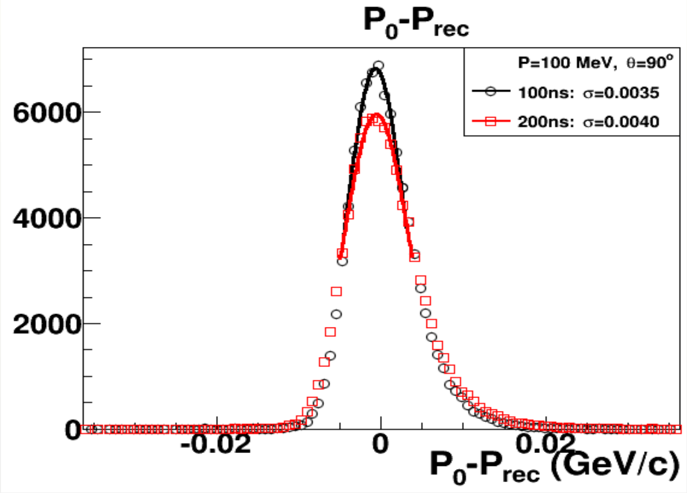
BoNuS12 **E12-06-113**



- Replaces SiVtx and micro-megas barrel trackers
- Trigger rate about 2 KHz
- 18,000 "pads" read out at 5MHz over 10 μs
  1-2 mm radial spacing, 4 cm in z, 2 degrees in phi
  => Fully reconstructed track in 3D, suppression of
  < 5 MHz background through timing and vertex
  cuts
- Readout electronics: "DREAM" chip (Saclay)

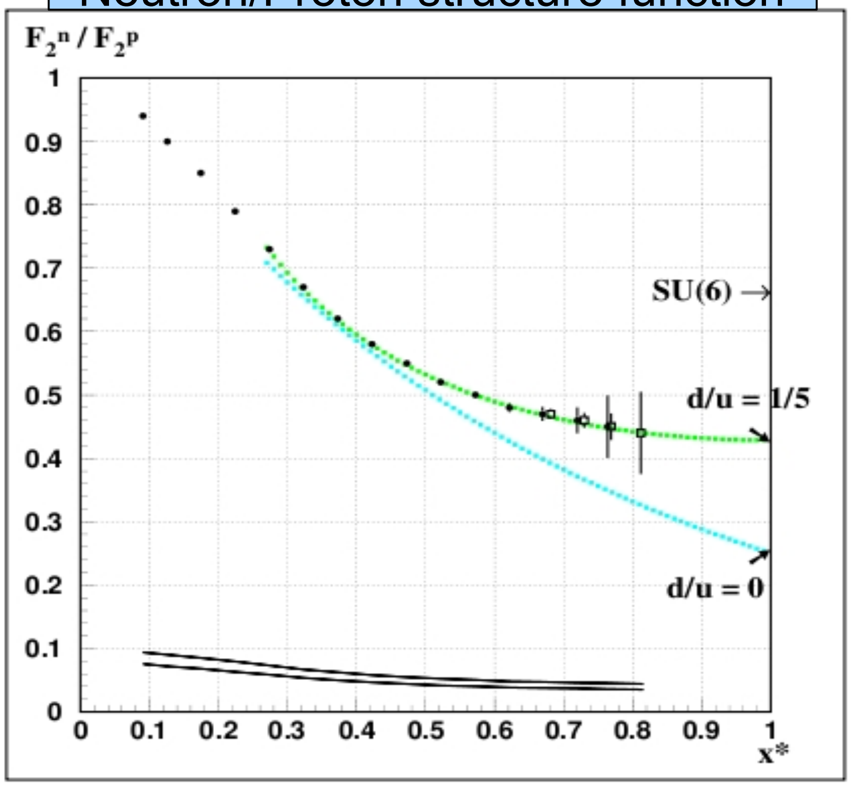


- Full simulation with GEANT-4 based CLAS12 GEMC
- < 4% momentum resolution
- < 2mm vertex resolution

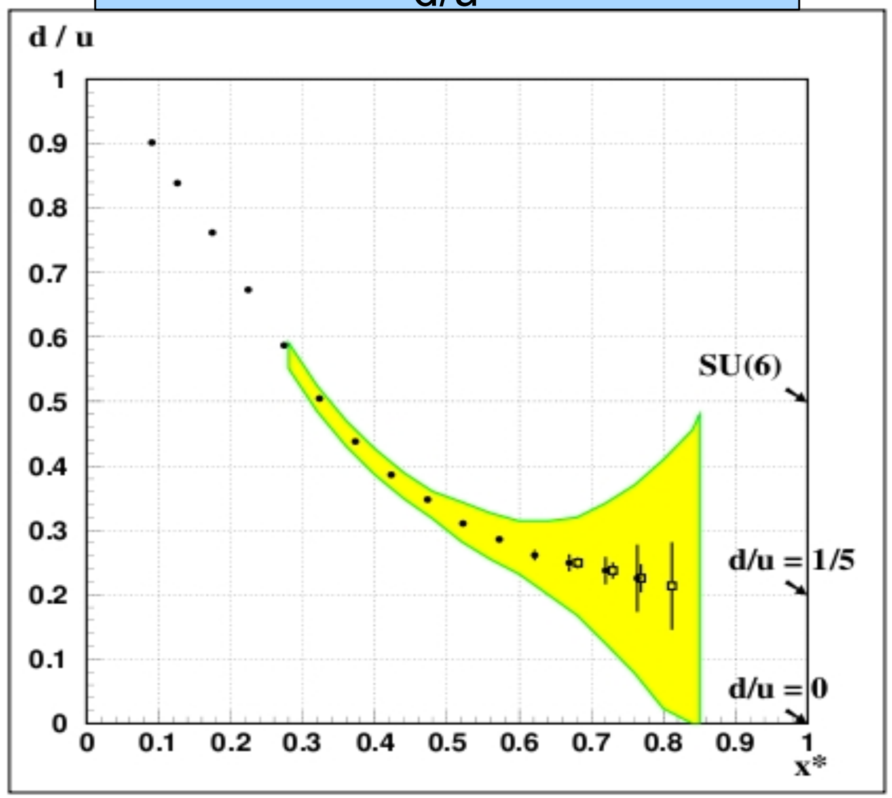


Expected Results

Neutron/Proton structure function



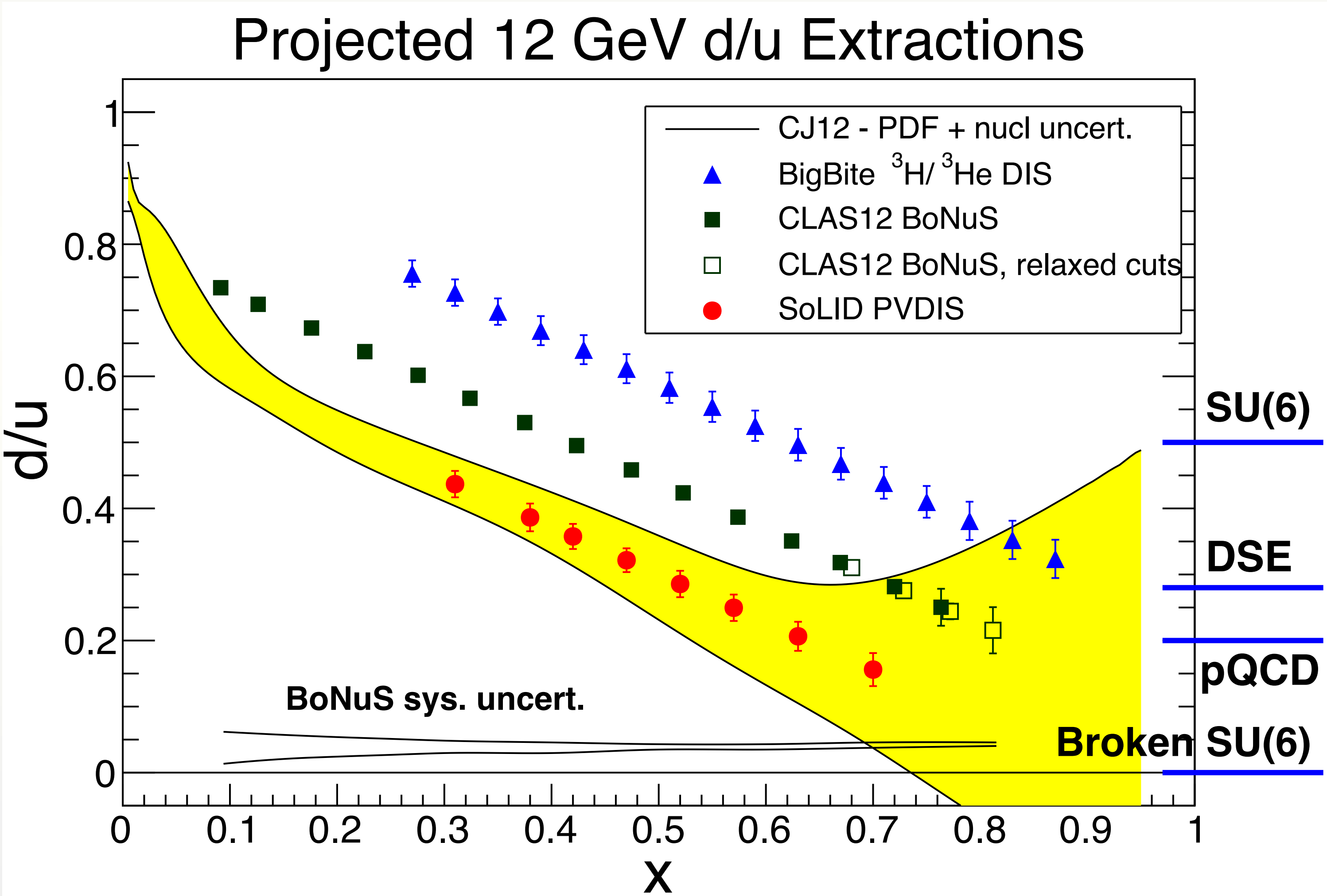
d/u



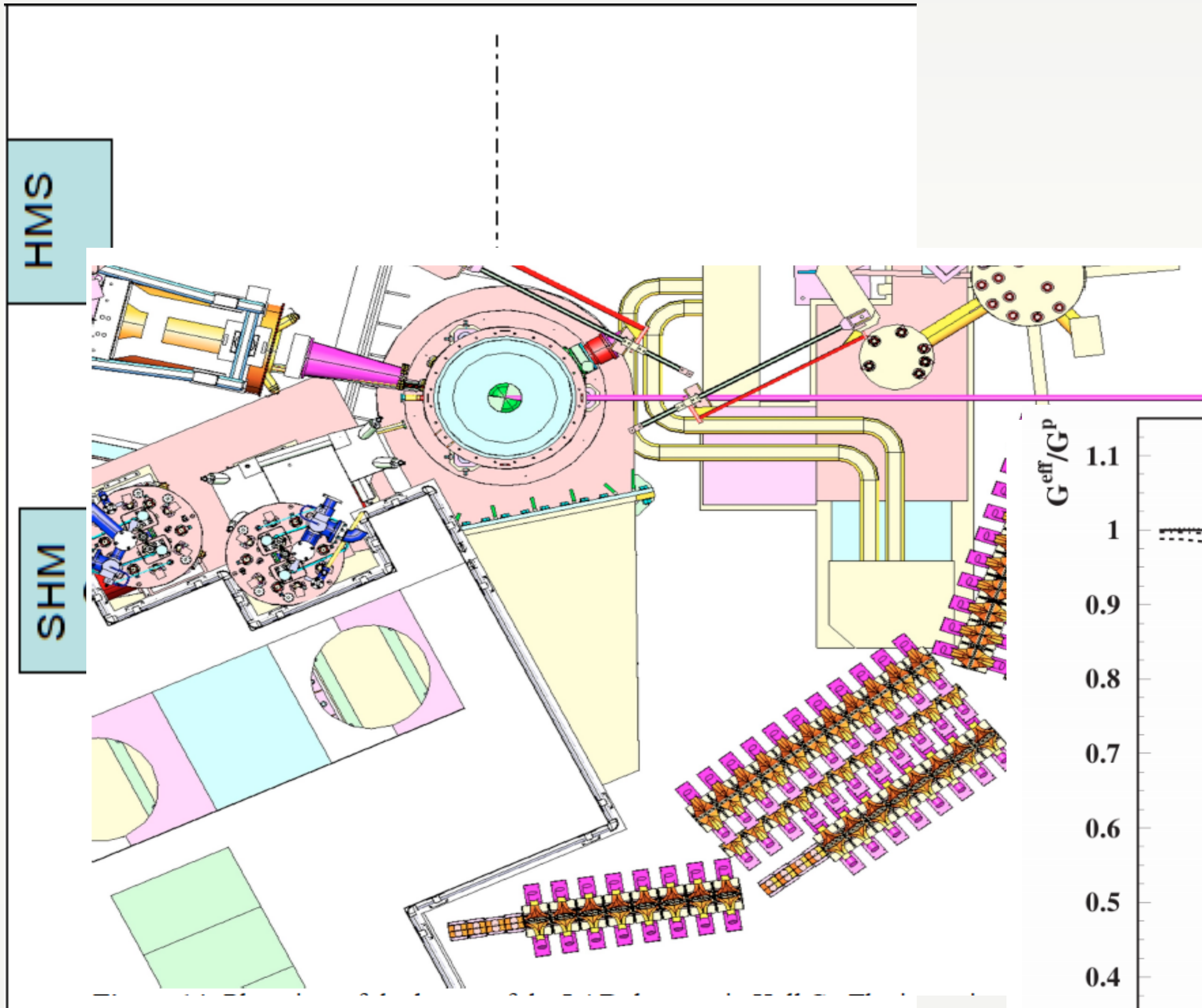
Dark Symbols: W* > 2 GeV (x* up to 0.8, bin centered x* = 0.76)

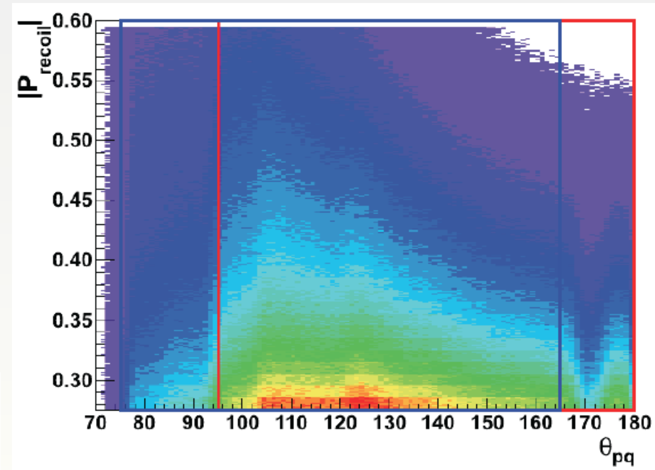
Open Symbols: “Relaxed cut” W* > 1.8 GeV (x* up to 0.83)

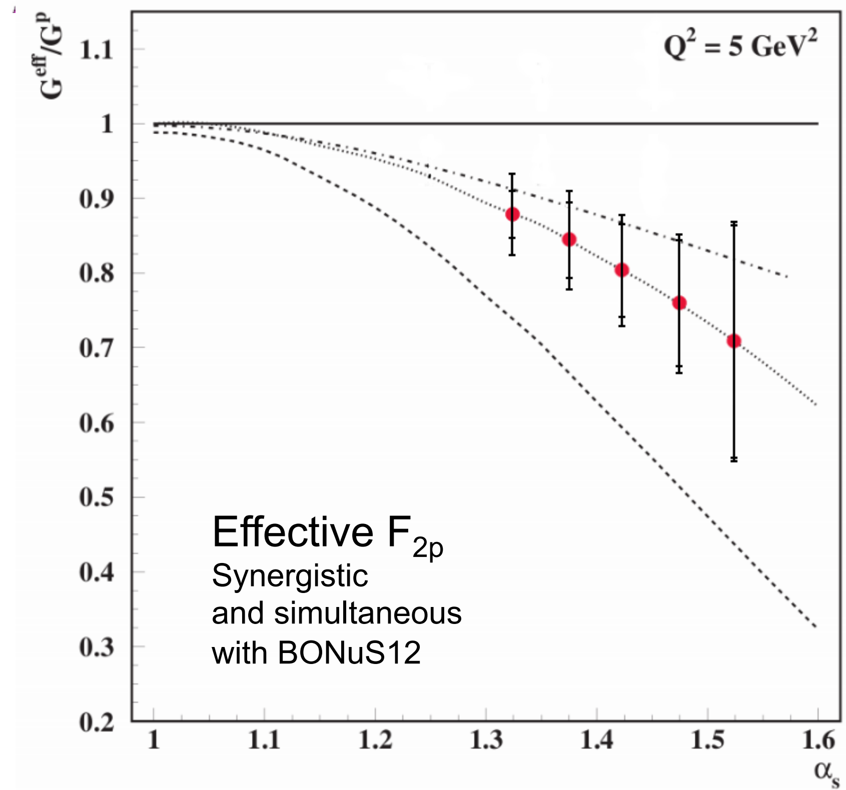
The future: JLab at 11 GeV



The future: JLab at 11 GeV



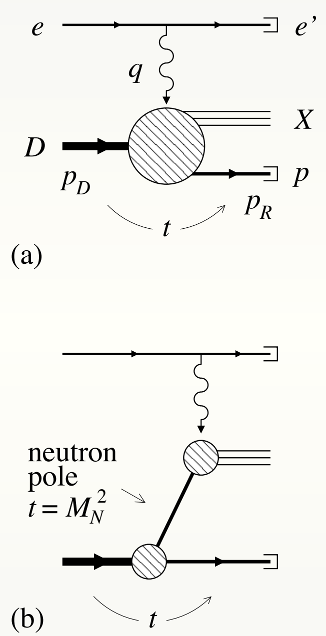


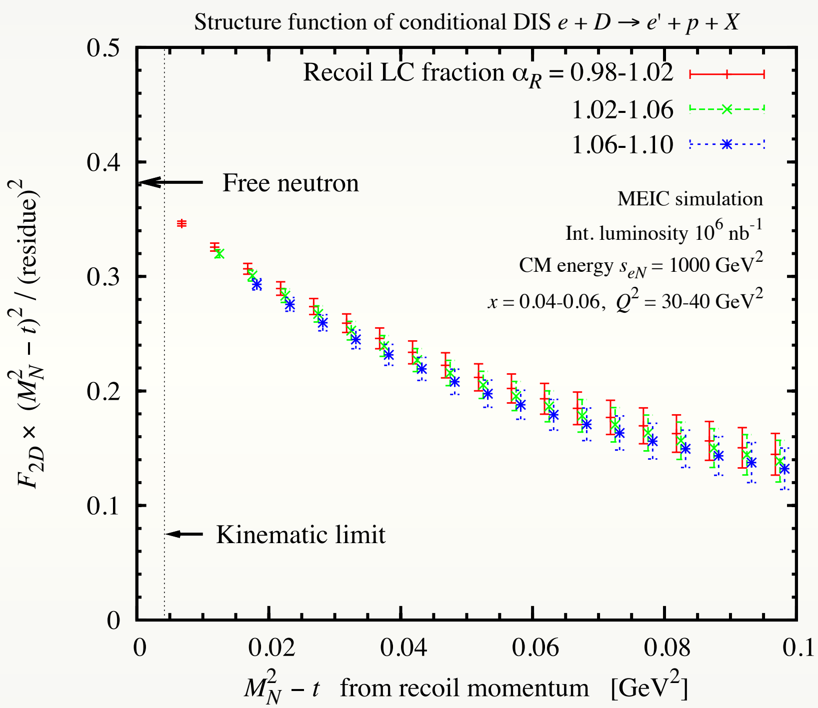


"Tagged EMC Effect"

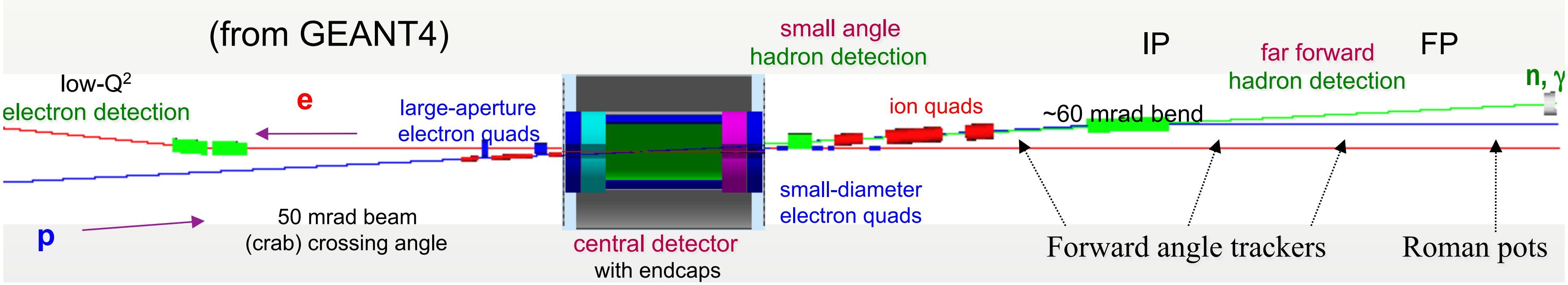
PR12-11-107

The more distant future: EIC





(from GEANT4)



Conclusion - Status of Spectator Experiments

- Growing body of data with coincident spectator detection already exist
  - FSI seems important in perpendicular and forward kinematics
  - simple spectator picture with LC wave functions seems to work at low spectator momenta, backward angles
  - Possible modifications of internal nucleon structure (dependent on spectator momentum) still an open question
  - First results on "free" neutron SF; moments, duality, binding effects in D
- Data mining on existing 6 GeV data sets still underway
- Lots more exciting experiments beginning with energy upgraded JLab!
  - F_{2n} out to x = 0.8
  - Detailed test of momentum-dependence of EMC effect
- We will need to develop sophisticated theoretical models to minimize and correct for in-medium effects and FSI
- ULTIMATE GOAL: EIC - smoothly map out $p_{spect.}$ from 0 to 1 GeV/c