The Structure of the Neutron and the BoNuS experiment

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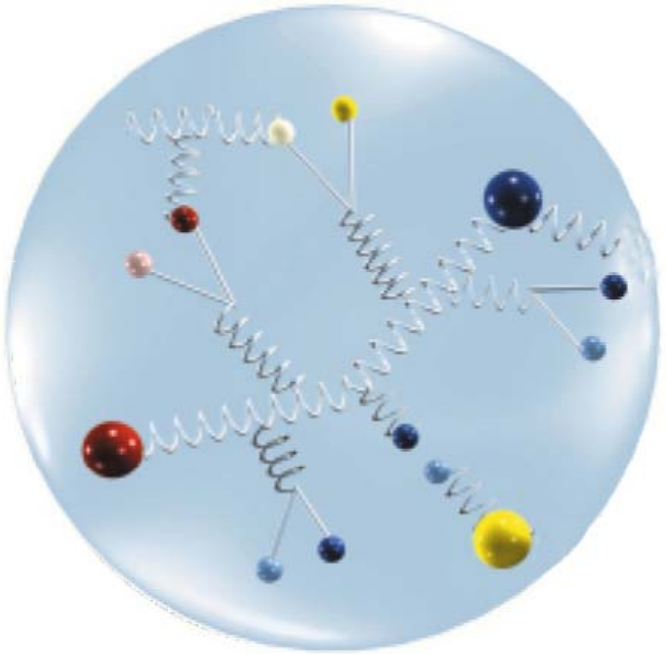
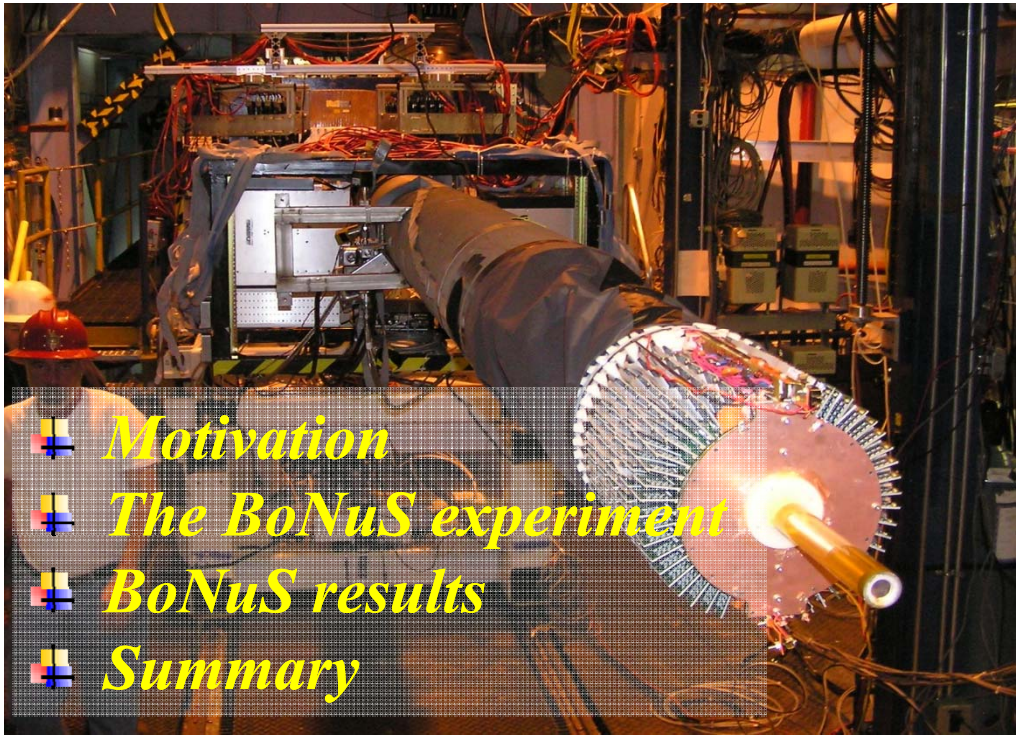
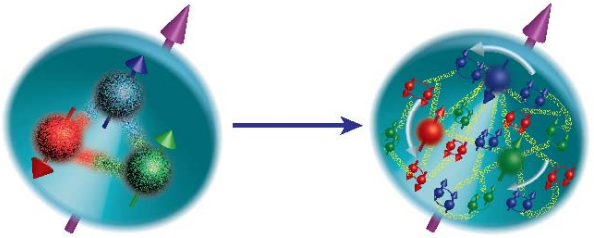
Baryons 2016





Motivation



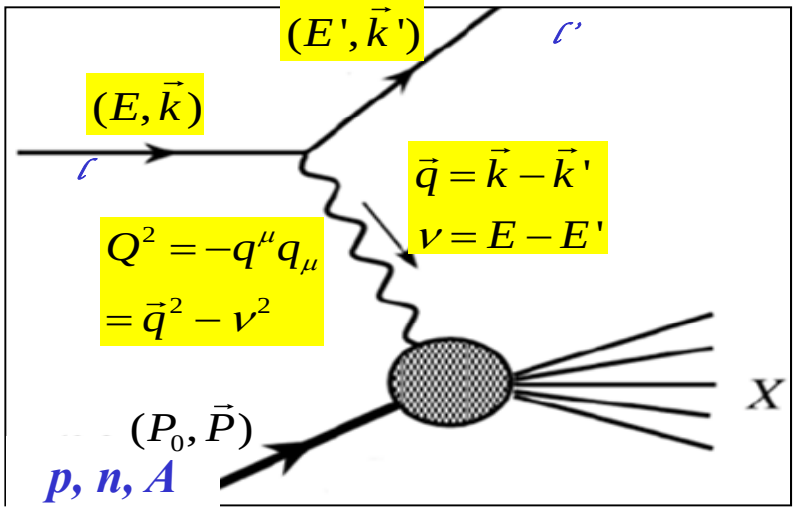
Probing the longitudinal structure of the nucleon (in 7 easy steps!):

- *Take a nucleon. Move it real fast along z. Def. l.c. mom.:* $P_+ = P_0 + P_z$ *(>>M)*
- *Hit a "parton" (q, g,…) inside with a lepton of your choice…*
- *Measure its l.c. momentum:* $p_+ = p_0 + p_z$ *(m≈0)*
- *Def. the Momentum Fraction:* $\xi = p_+ / P_+$ **)*
- *In DIS:* $x \approx (q_z - n)/M \approx x_{Bj} = Q^2/2Mn$

(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* $F_2(x)$

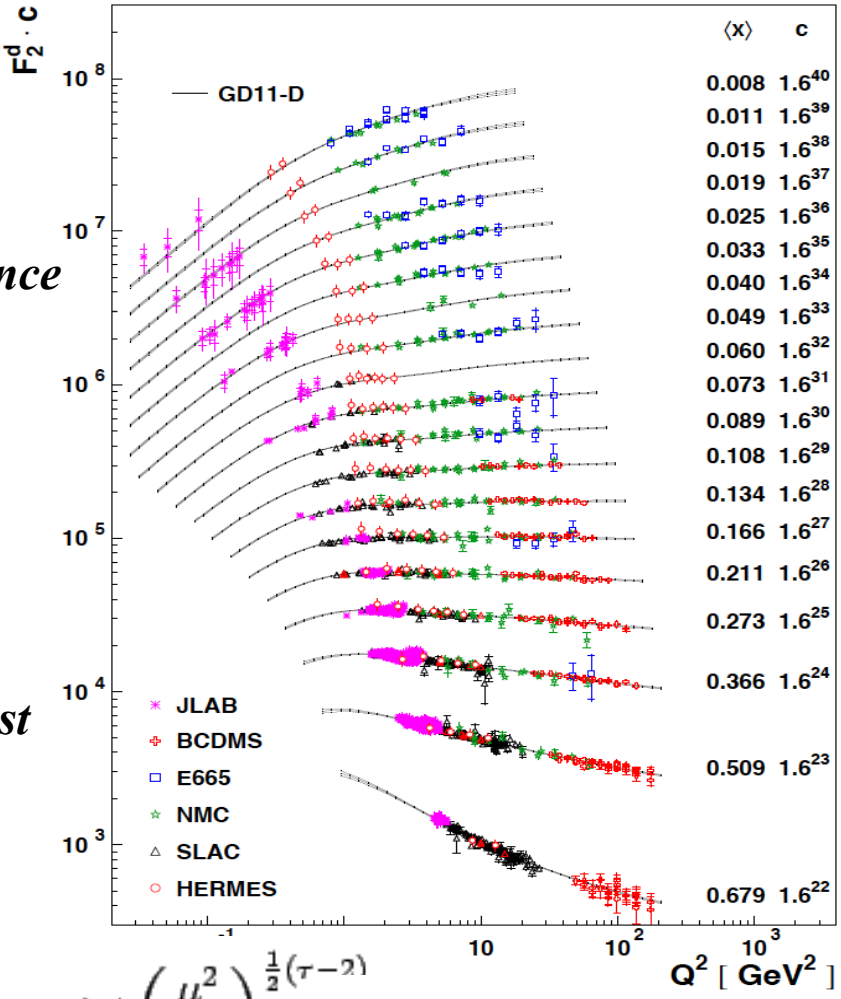
**) Advantage: Boost-independent*



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

$$F_1(x) = \tfrac{1}{2}\sum_i e_i^2 q_i(x)$$

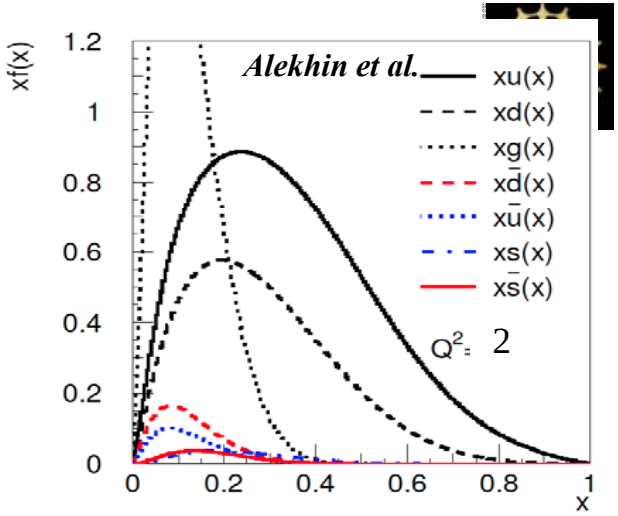
- ***So sf give access to PDFs!***
- ***$q_f(x\to 1)$ for both nucleons is a crucial test of valence quark models***
  - ***Isospin, SU(6) breaking, pQCD,…***
- ***Precise PDFs at large x needed as input for LHC, neutrino experiments, etc.***
  - ***Large x, medium Q^2 evolves to medium x, large Q^2***
  - ***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***



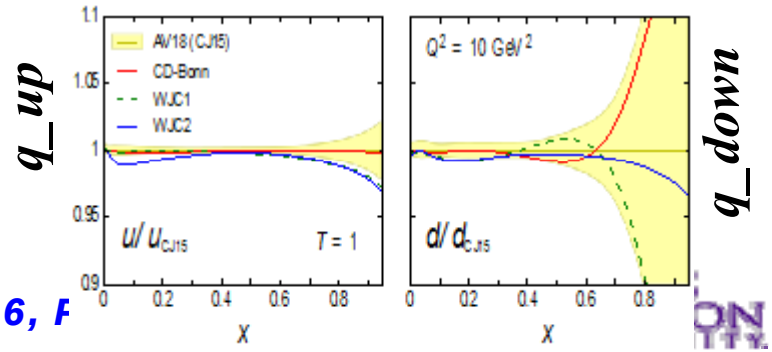
$$M_n^{CN}(Q^2) = \int_0^\infty dx x^{(n-2)} F_2(x,Q^2) = \sum_{\tau=2k}^{\infty} E_{n\tau}(\mu,Q^2) O_{n\tau}(\mu)\left(\frac{\mu^2}{Q^2}\right)^{\frac{1}{2}(\tau-2)}$$

+ TM corr.

Motivation (III)



- *Behavior of PDFs still unknown for $x \to 1$*
  - *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, $d/u \to 0$, $\Delta u/u \to 1$, $\Delta d/d \to -1/3$*
  - *Helicity conservation (pQCD): Spectator spin $S_z \neq 0$ suppressed, $d/u \to 1/5$, $\Delta u/u \to 1$, $\Delta d/d \to 1$*
  - *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*



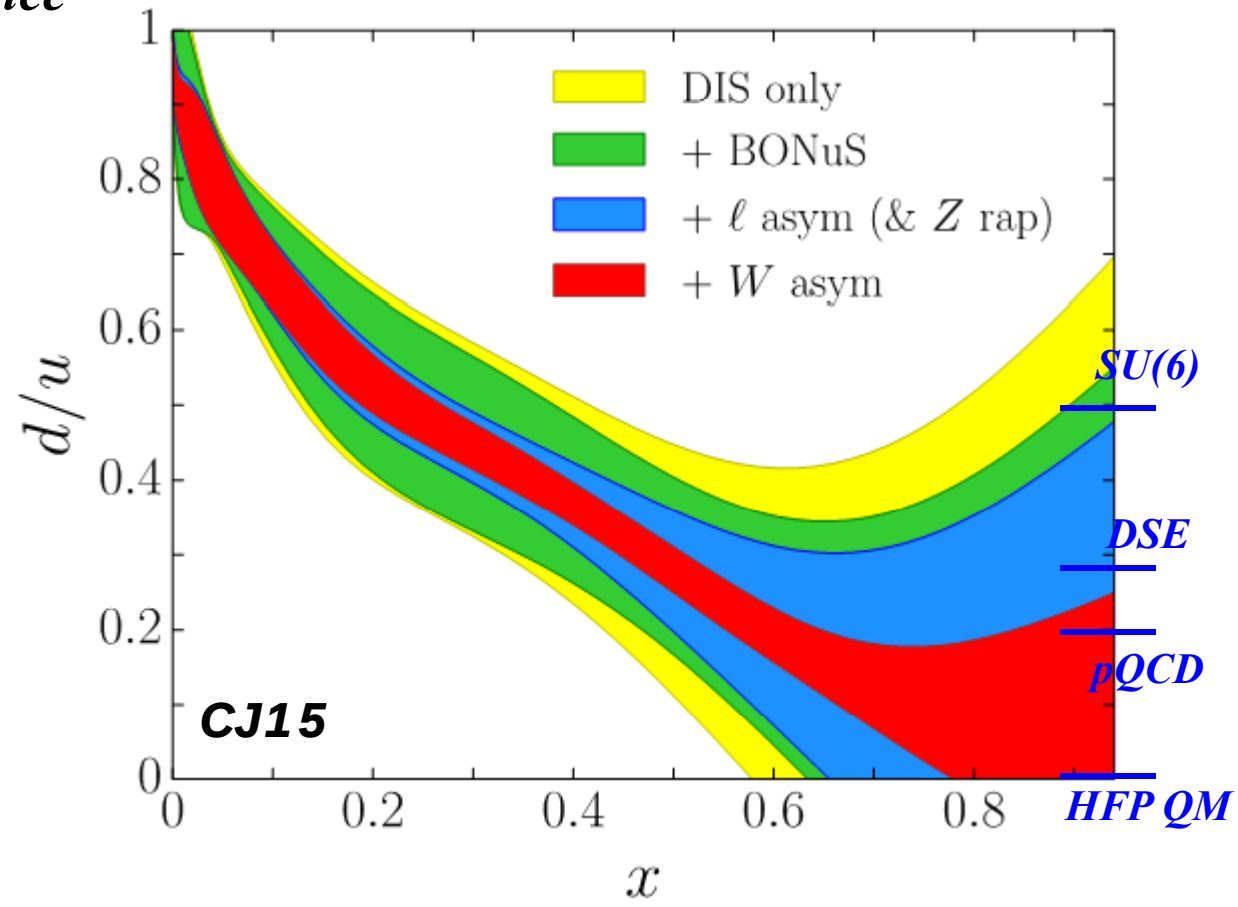
$d/u\ (x \to 1)$ ...

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

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

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

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

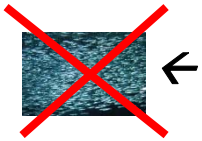


Neutron data limited by "Nuclear Binding Uncertainties"

To access d/u…

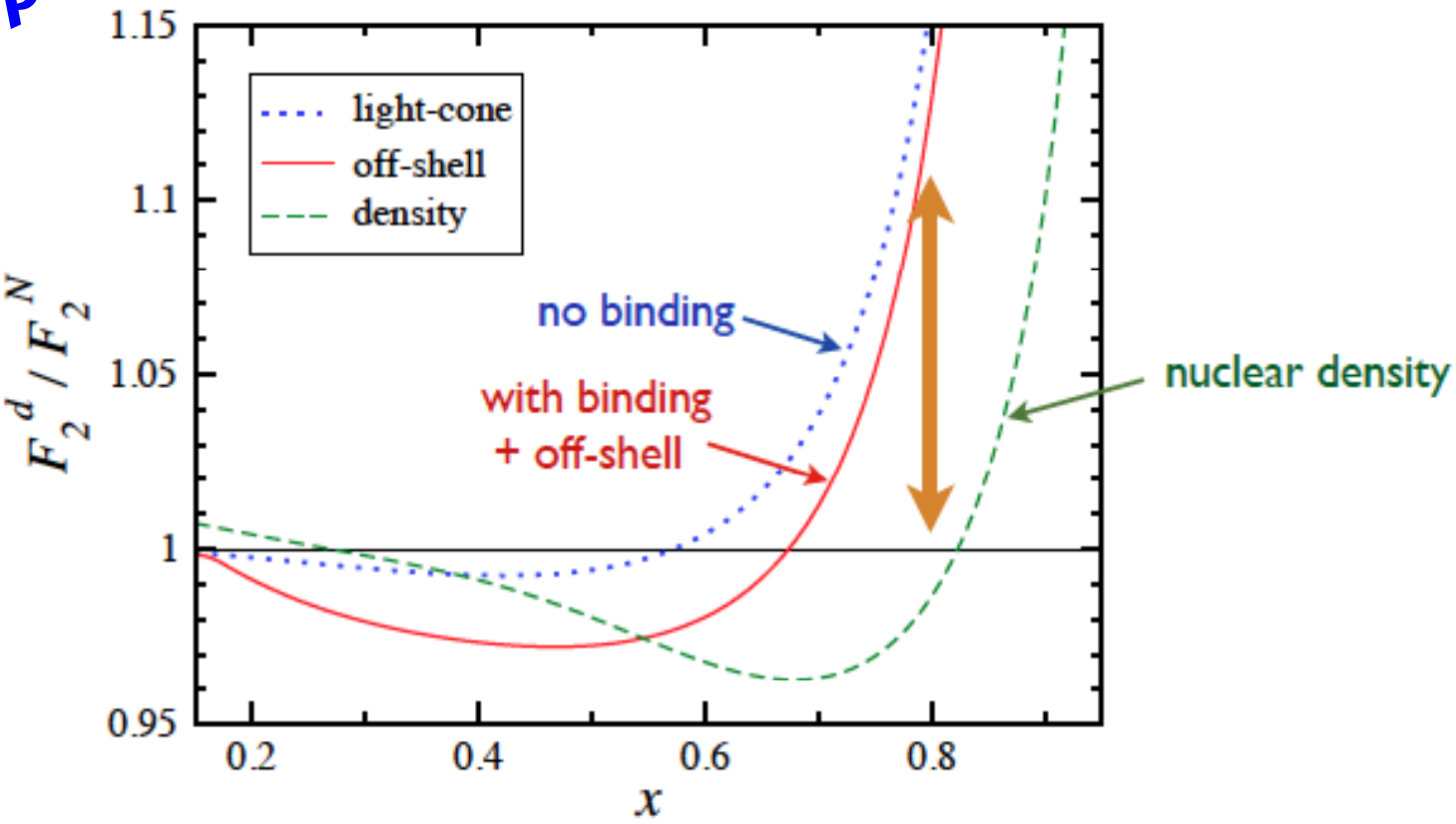
- *Use both charged and neutral lepton probes. Possible processes: W/Z production, PV DIS, charge exchange…*
  - *The cleanest, most direct approach.*
  - *No charge symm. assumptions*
  - *Limitation in stat. precision*
- *Use different targets, i.e. p & n*
  - *Free neutrons decay.*
  - *Impossible to make a dense target.*
  - *Alternatives: use weakly bound nuclei (d) and/or*
  - *Mirror nuclei (3He, 3H)*
  - *Nuclear Model uncertainties: (Fermi motion, off-shell effects (binding), structure modifications (EMC effect), extra pions/Deltas, coherent effects, 6-quark bags…)*

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]



For example...

EMC effect in deuteron



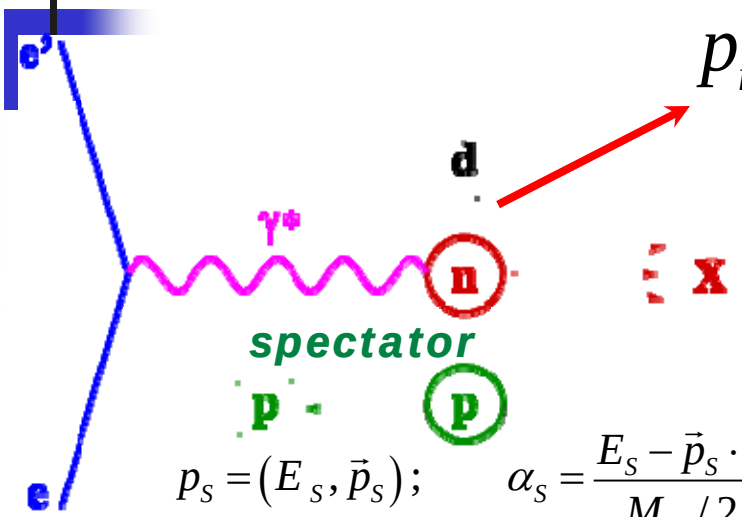
→ using off-shell model, will get *larger* neutron *cf. light-cone* model

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

Even Fermi motion corrections become large at large x.

Alternative: Spectator Tagging

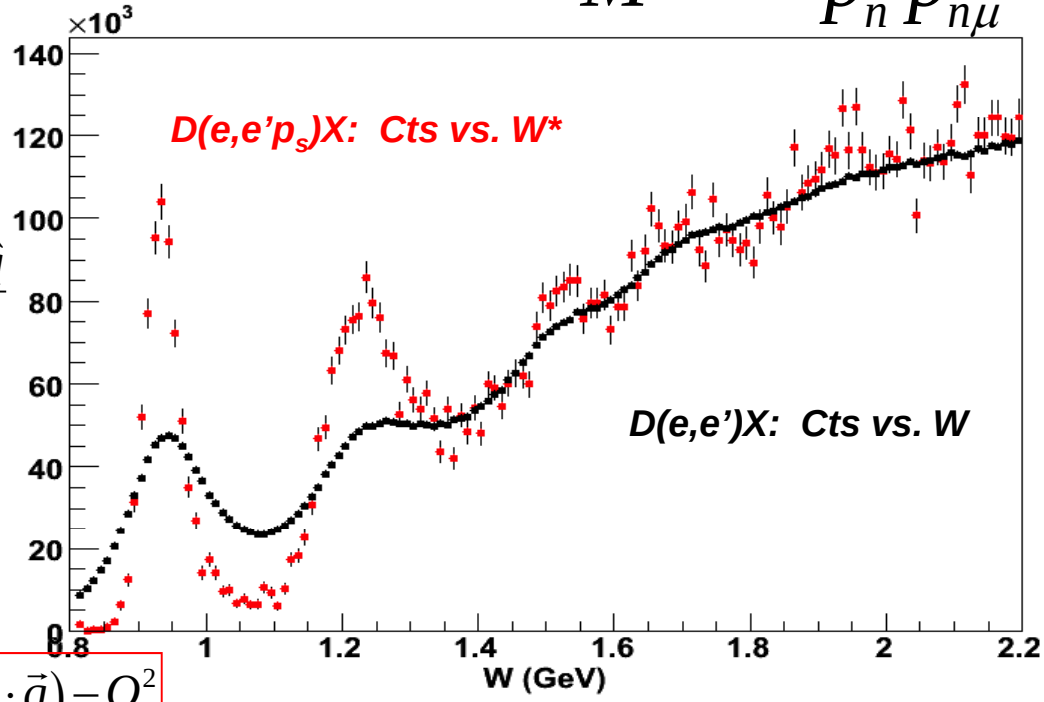
d(e,e'p$_s$)X



$$p_n = \left(M_D - E_S, -\vec{p}_S\right); \alpha_n = 2 - \alpha_S$$

$$M^{*2} = p_n^{\mu} p_{n\mu}$$

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

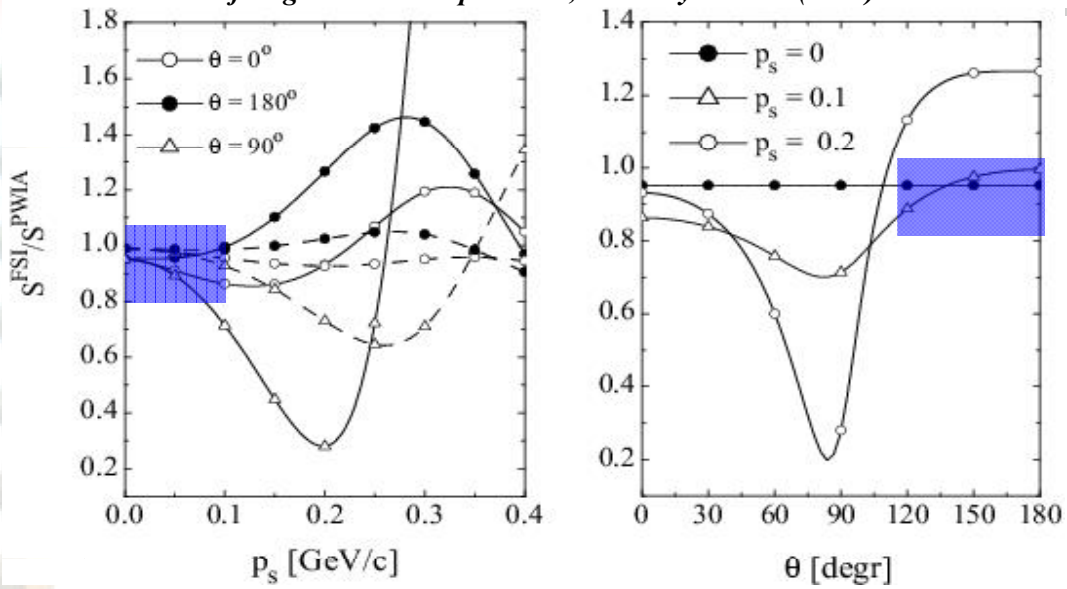


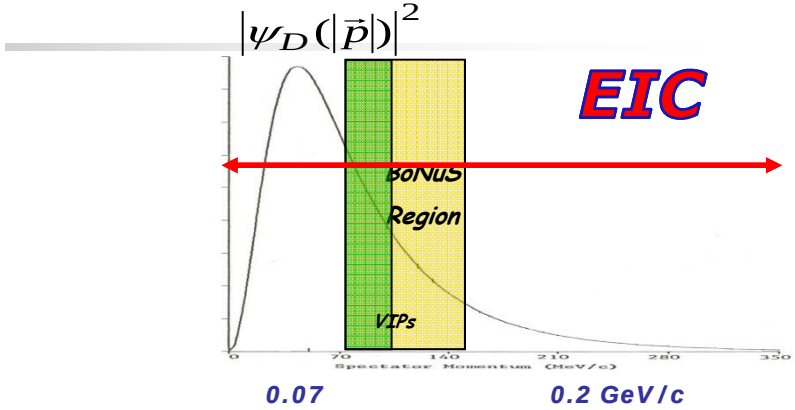
$$x = \frac{Q^2}{2 p_n{}^{\mu} q_{\mu}} \approx \frac{Q^2}{2M\nu(2-\alpha_S)}$$

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

Spectator Tagging Limitations

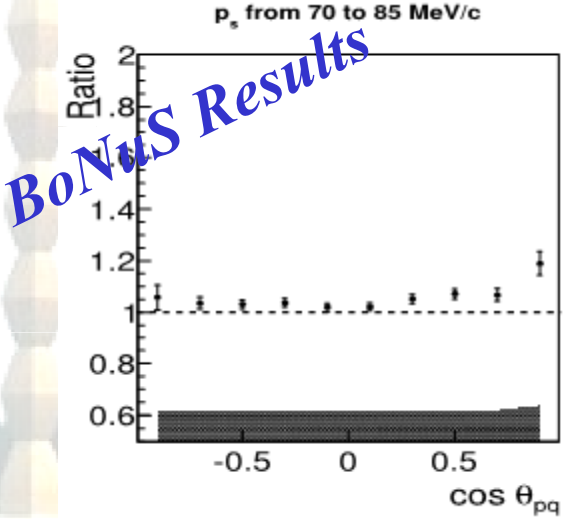
Ciofi degli Atti and Kopeliovich, Eur. Phys. J. A17(2003)133

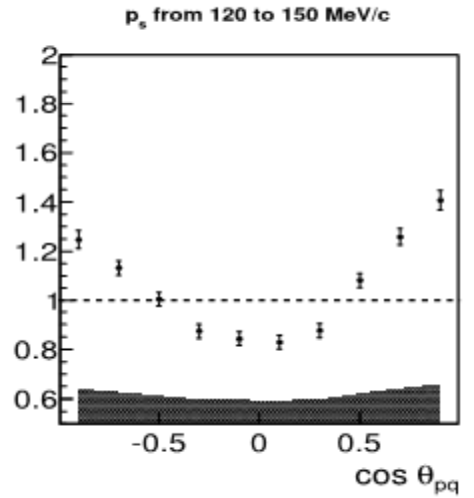




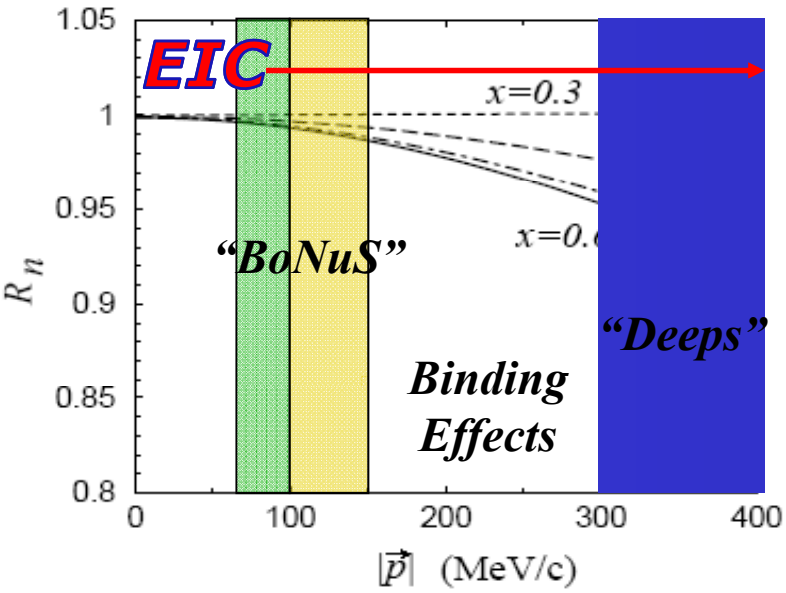
Finite coverage of WF

Final State Interactions

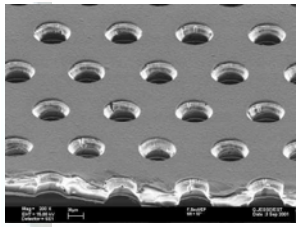




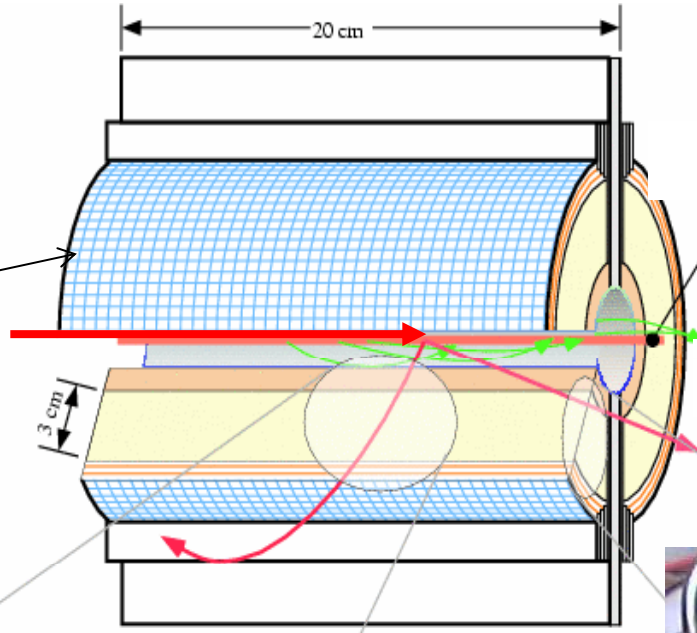
$$R_n \equiv F_2^{n(eff)}(W^2, Q^2, p^2)/F_2^n(W^2, Q^2)$$



Spectator Tagging. Enter: BoNuS



Gas Electron Multiplier

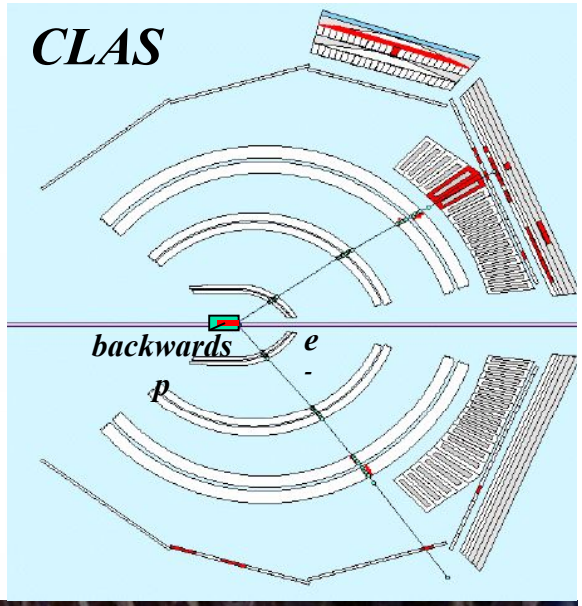


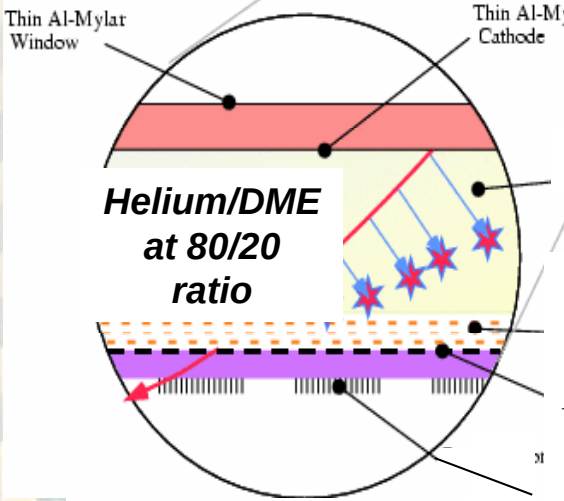
7 atm D_2 gas

Thin-wall High Pressure Gas Target

Møller el.

e^- to CLAS

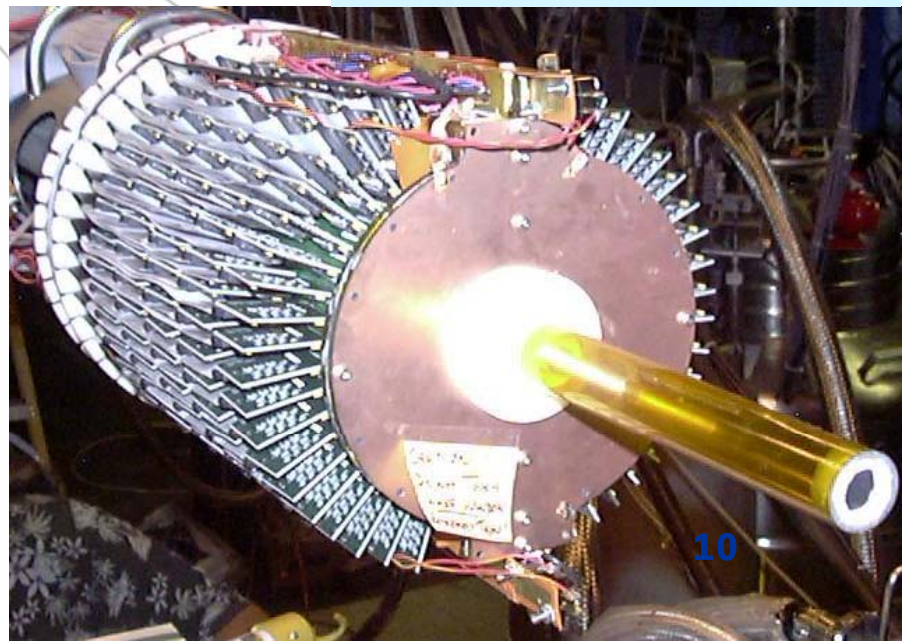




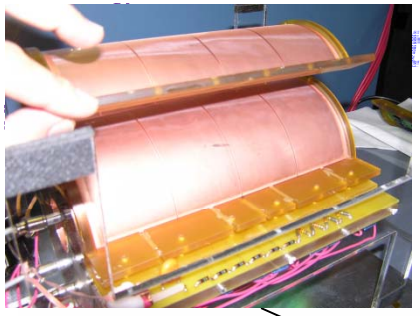
Drift Region

3 GEMs

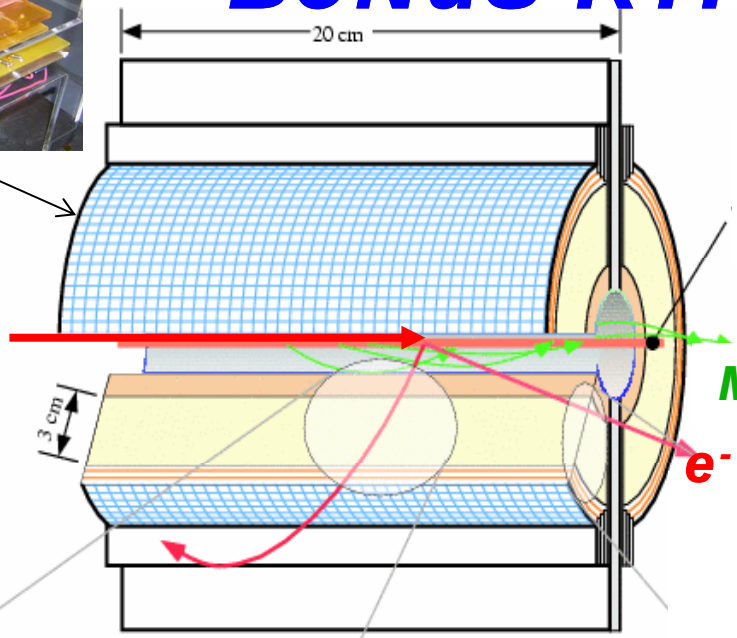
Readout pad and electronic



BoNuS RTPC



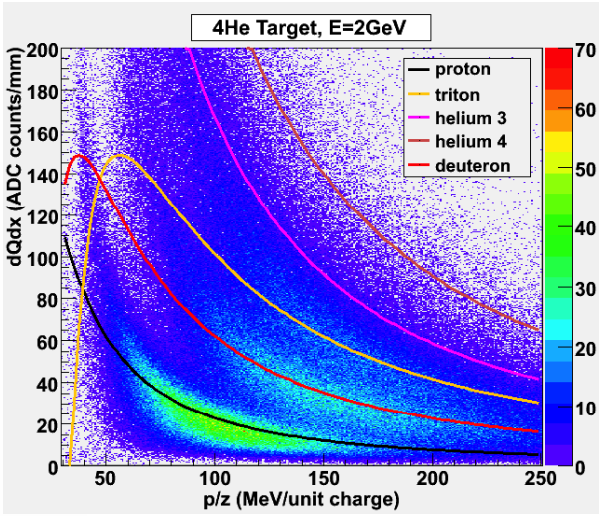
Gas Electron Multiplier



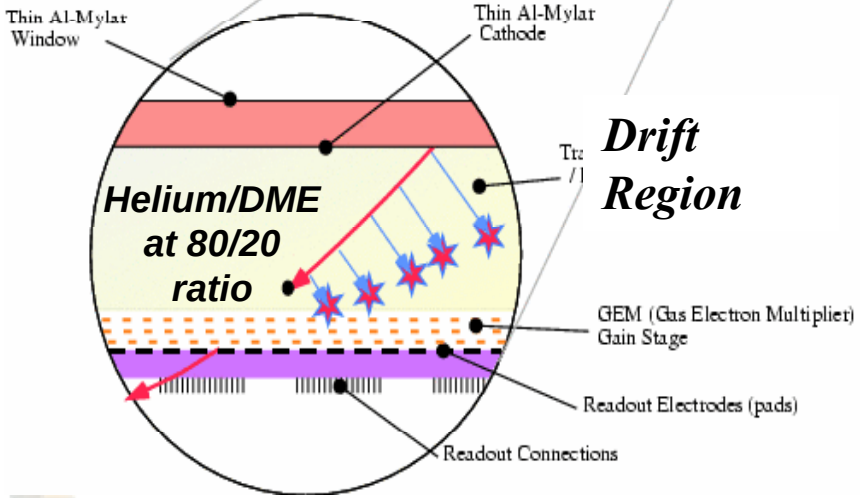
7 atm D_2 gas

Møller el.

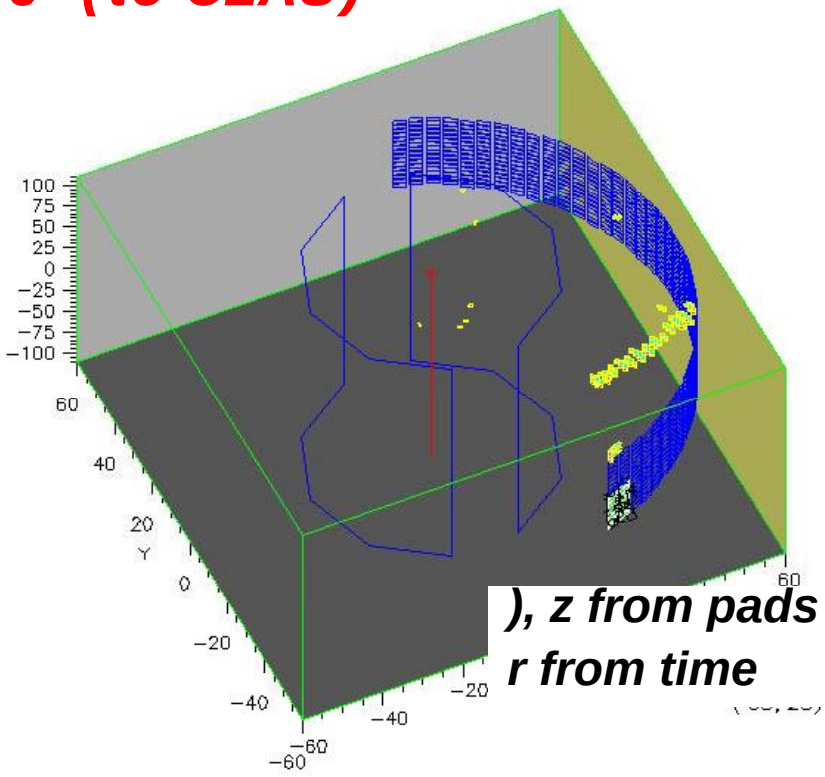
e^- (to CLAS)



dE/dx from charge along track (particle ID)



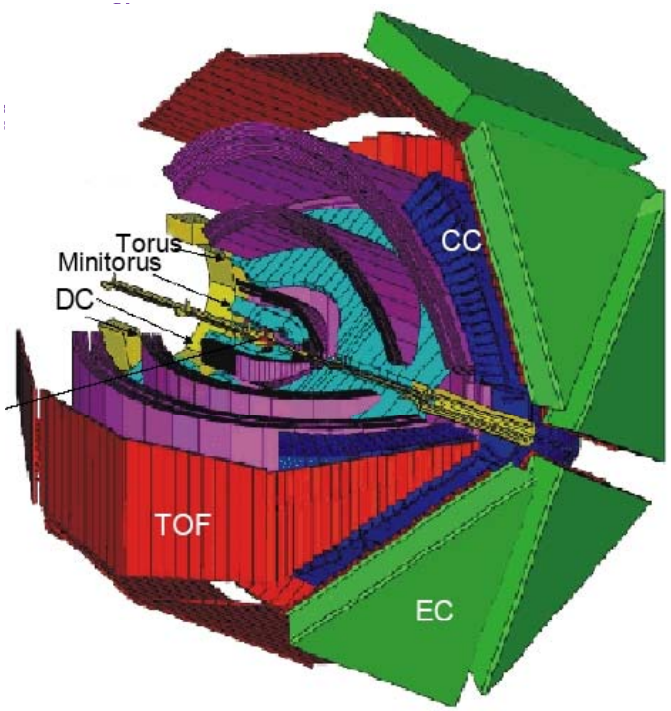
Drift Region

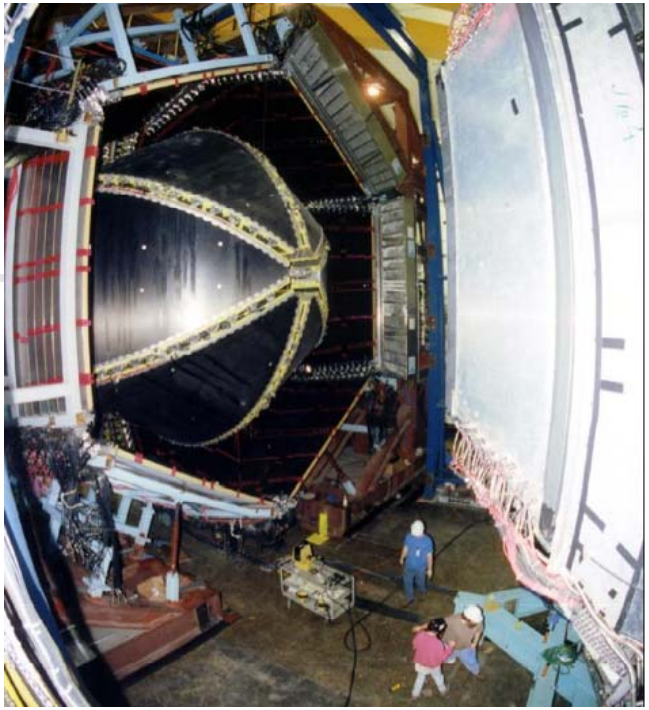


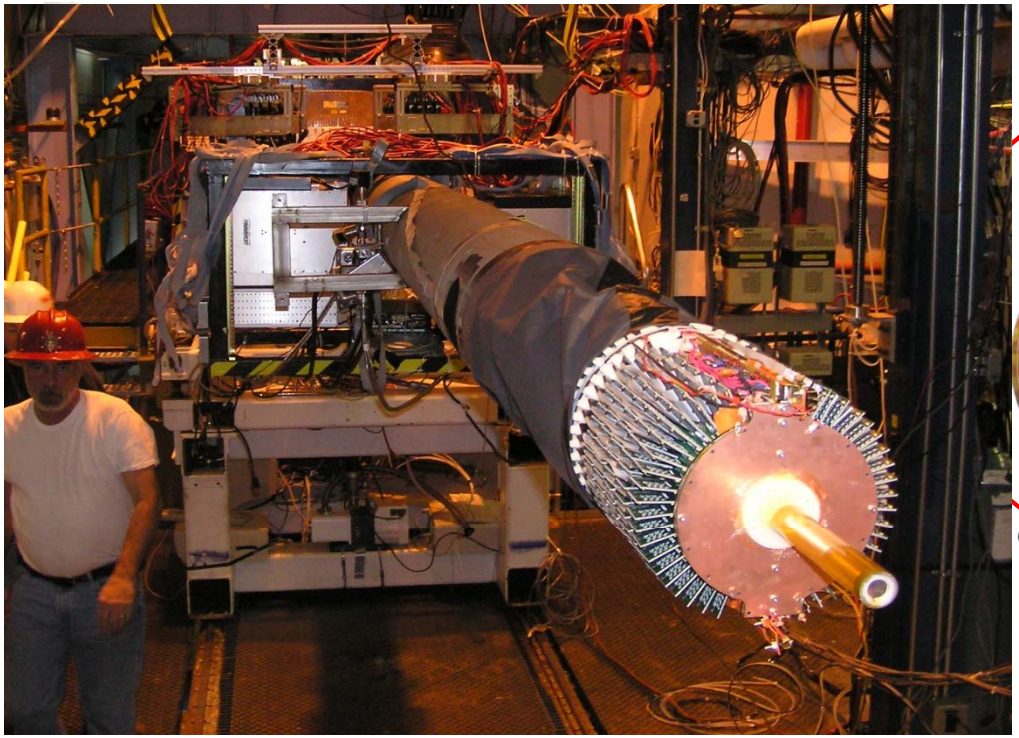
), z from pads r from time

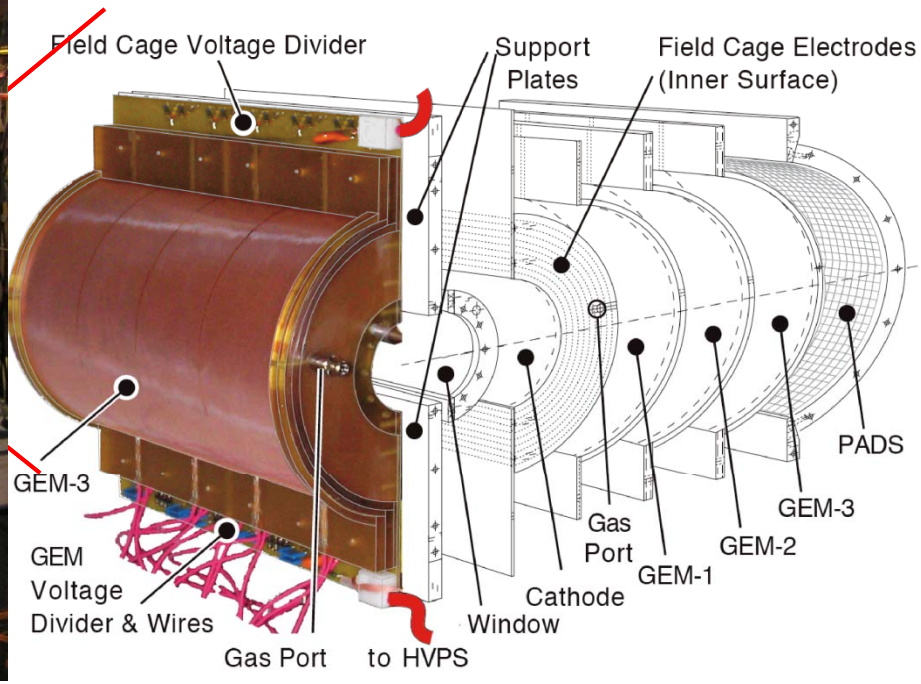
Nucl. Instr. Meth. A592, 273 (2008)

BoNuS in CLAS



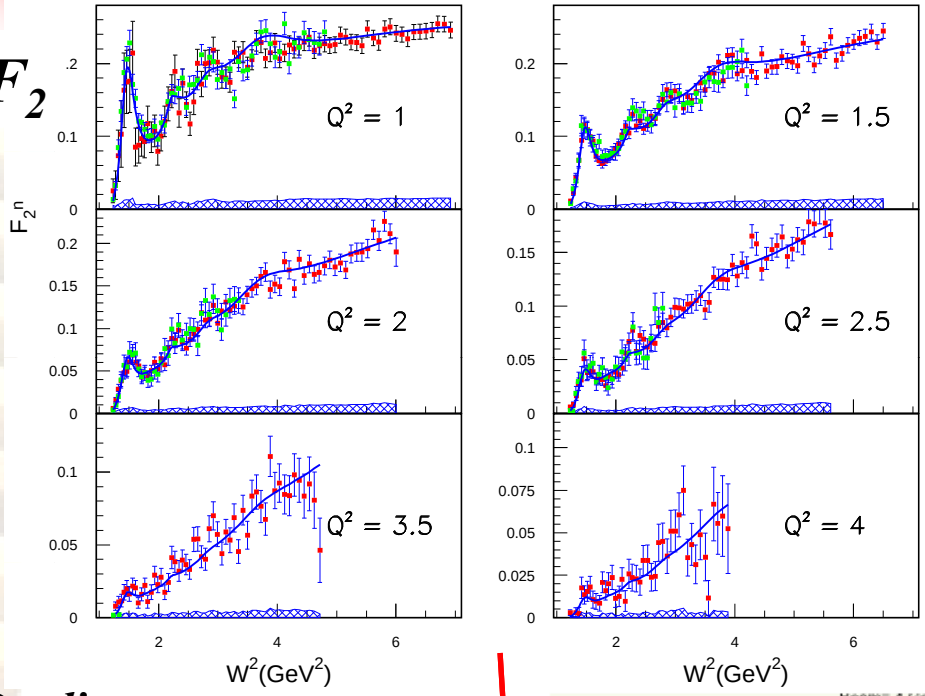




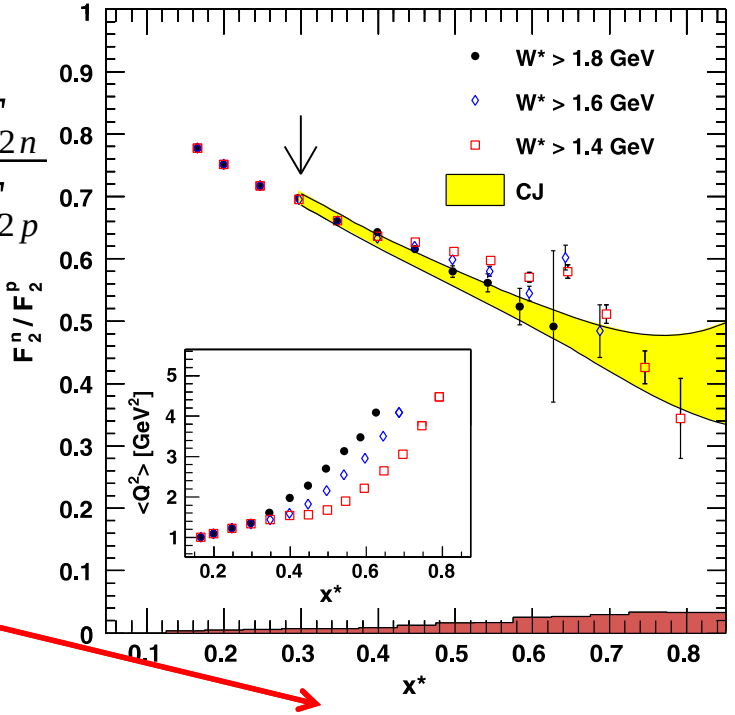


Did it work?

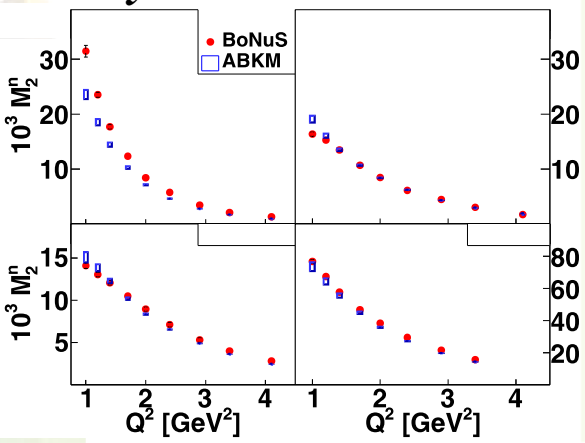
F_2



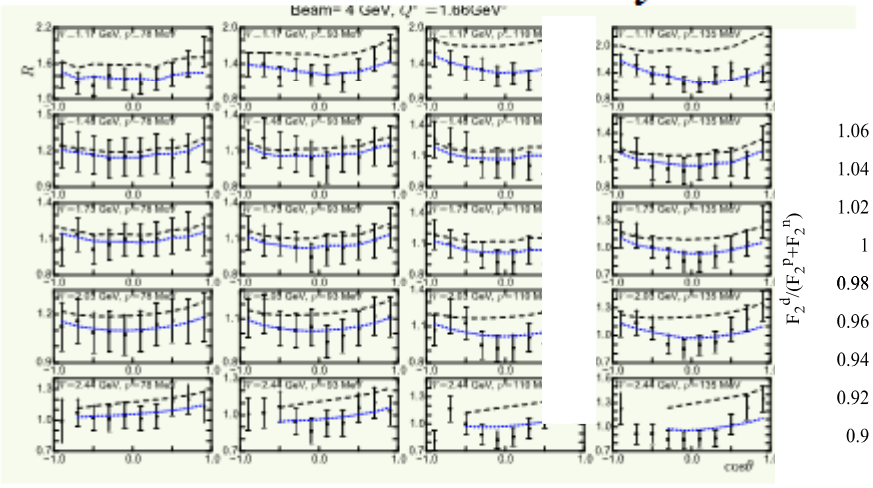
$\frac{F_{2n}}{F_{2p}}$



Duality

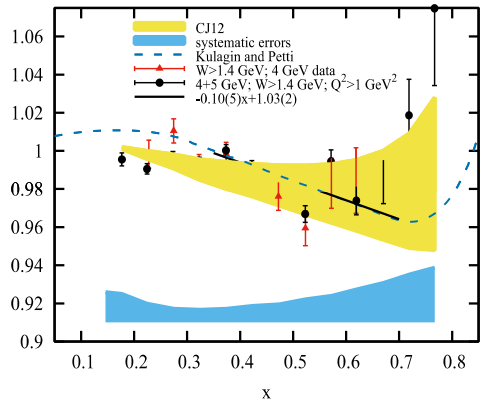


FSI: Cosyn et al.

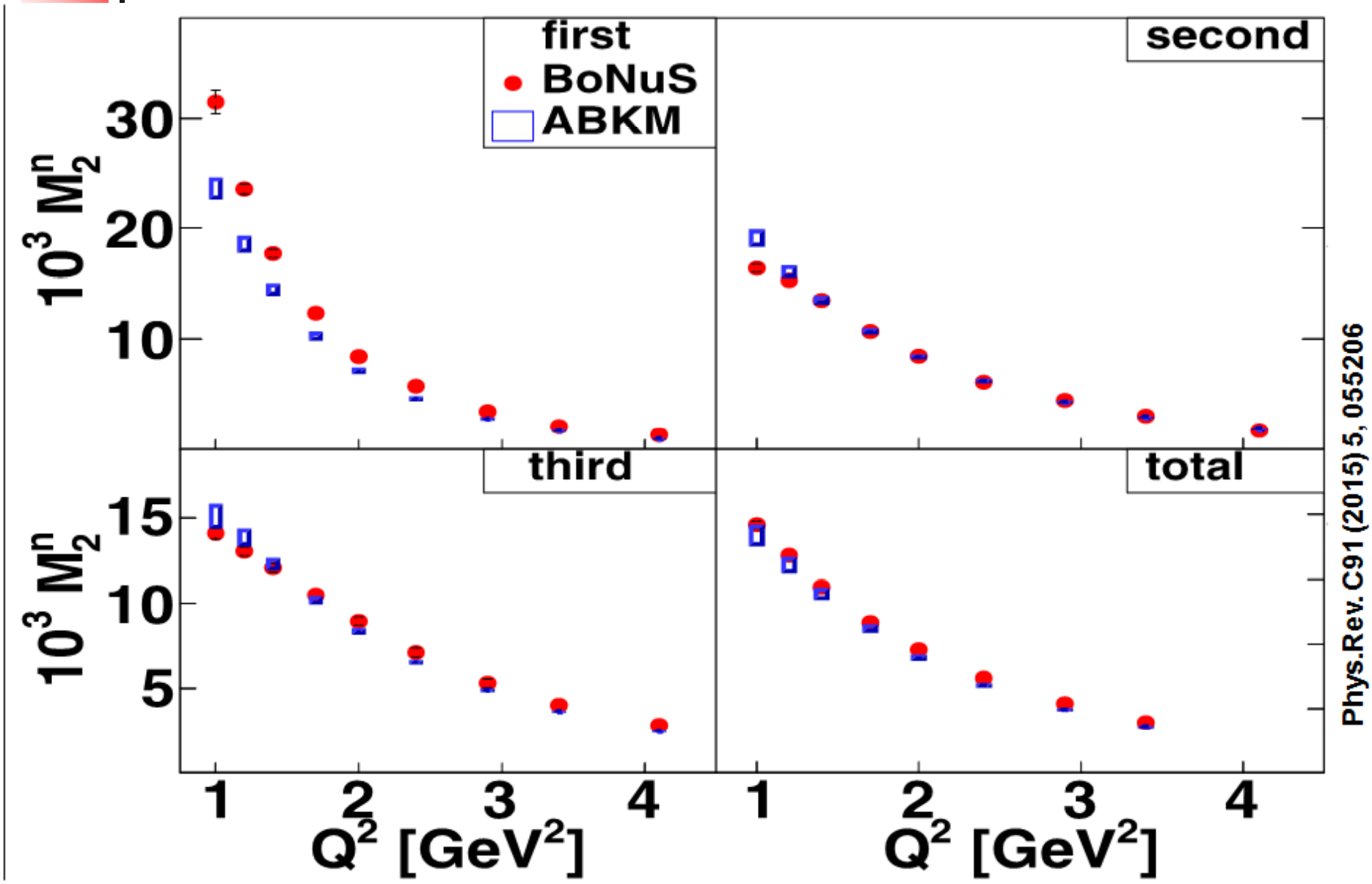


EMC Ratio

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

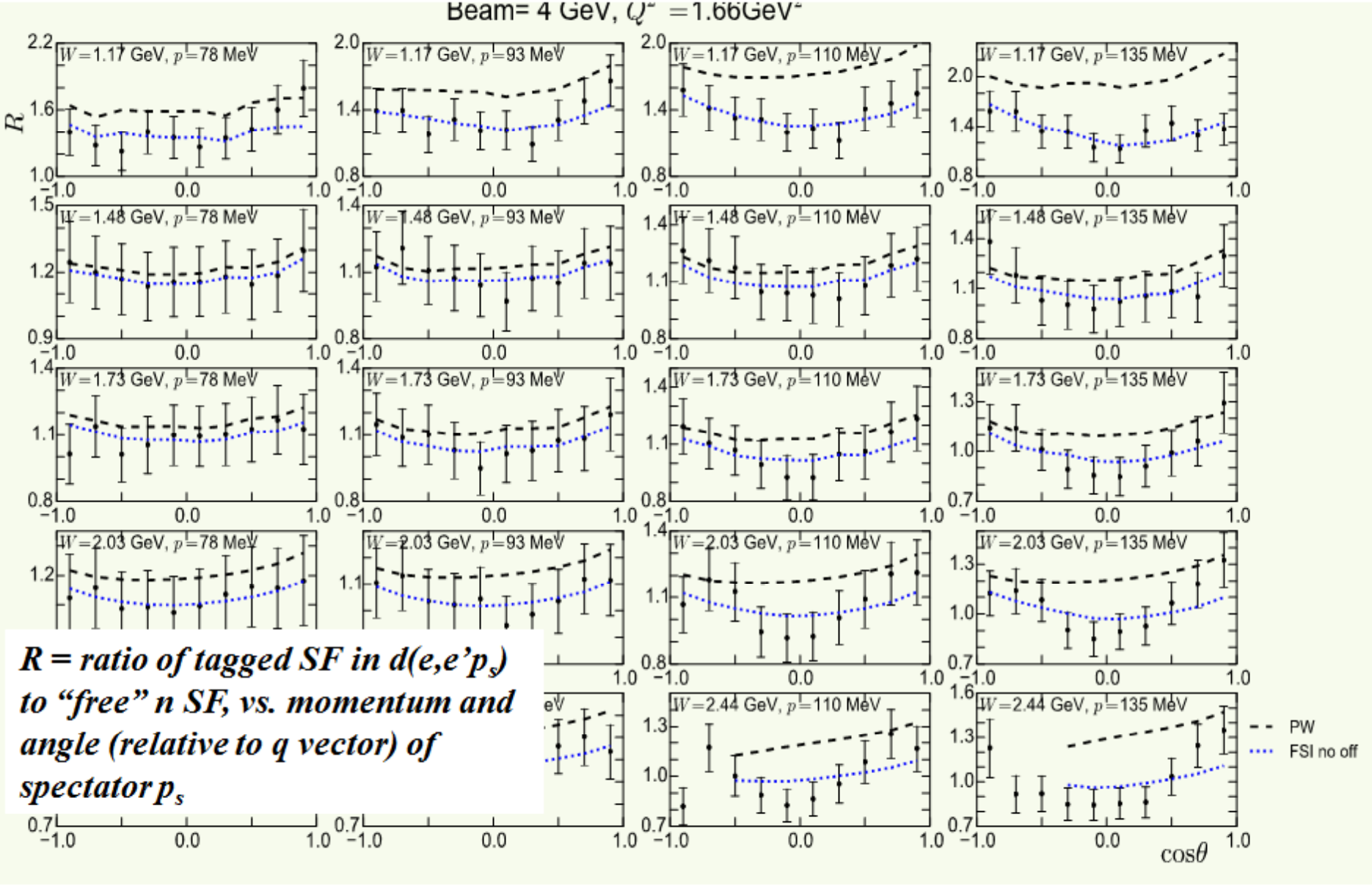


BoNuS: Truncated Moments



BoNuS: FSI

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$_s$

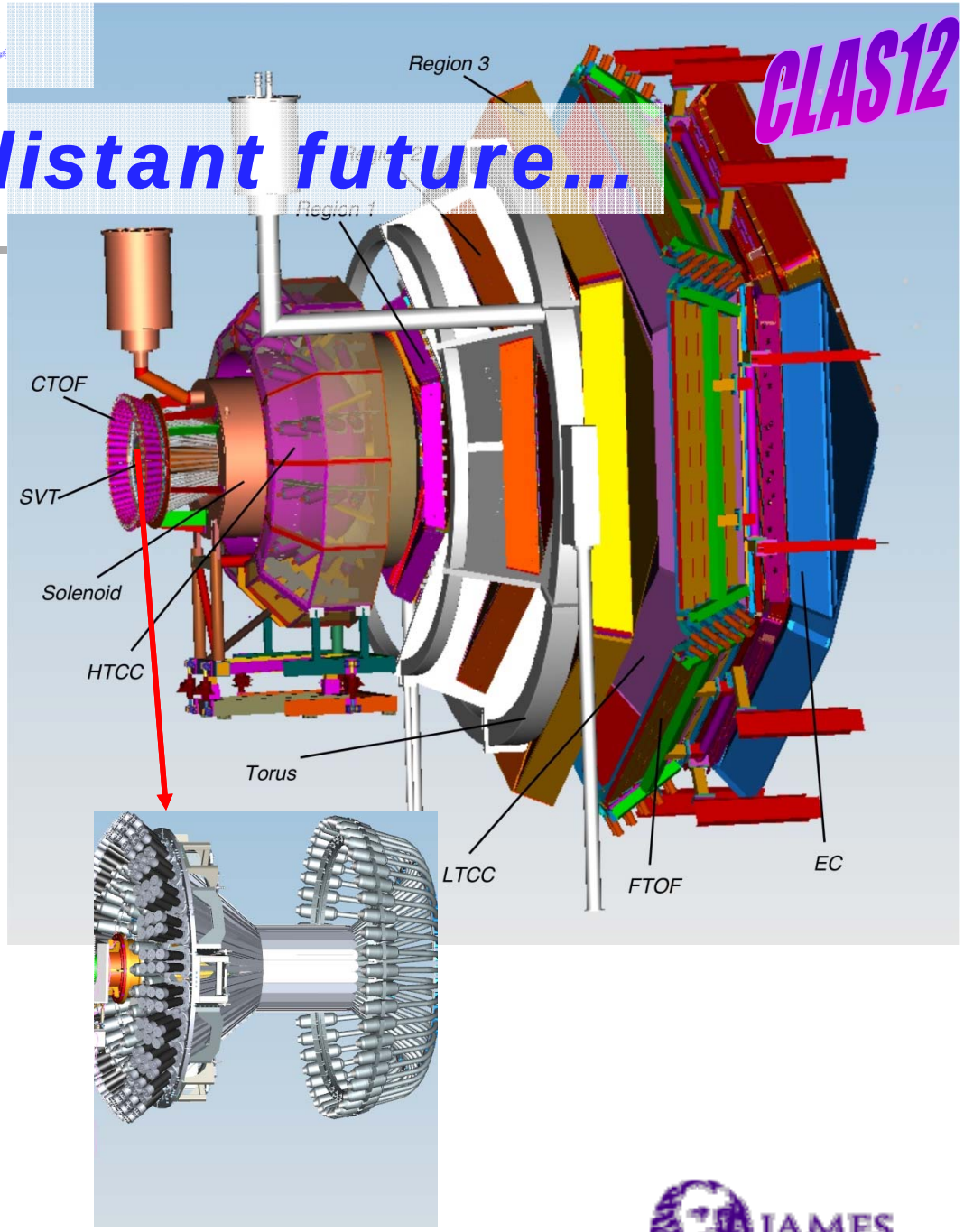
...in the not so distant future...

BoNuS12: E12-06-113

- *One of the "Flagship" 12 GeV – era experiments!*
- *Data taking of 35 days on D_2 and 5 days on H_2 with*

$L = 2 \cdot 10^{34}\ cm^{-2}\ sec^{-1}$

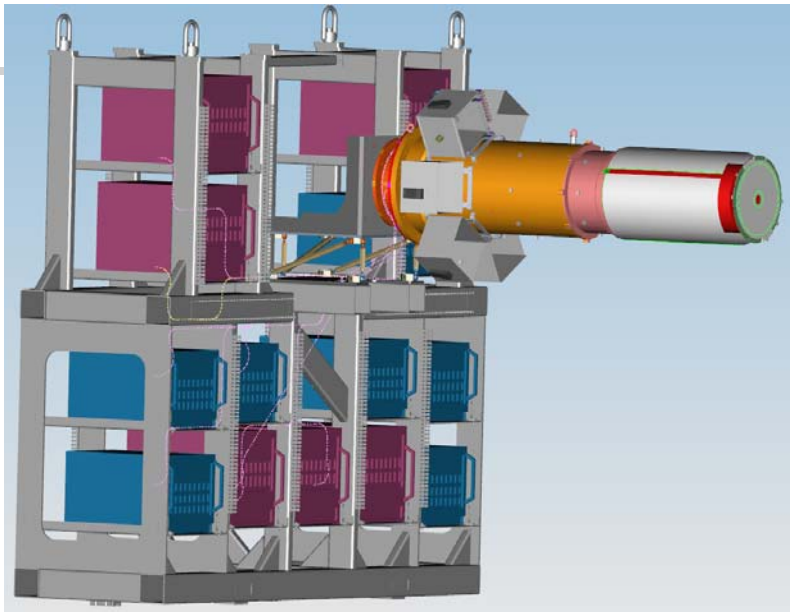
- *Planned BoNuS detector DAQ and trigger upgrade*
- *DIS region with*
  - $Q^2 > 1\ GeV^2/c^2$
  - $W^* > 2\ GeV$
  - $p_s > 70\ MeV/c$
  - $10^\circ < \theta_{pq} < 170^\circ$
- *Extend to higher momenta using central detector alone*

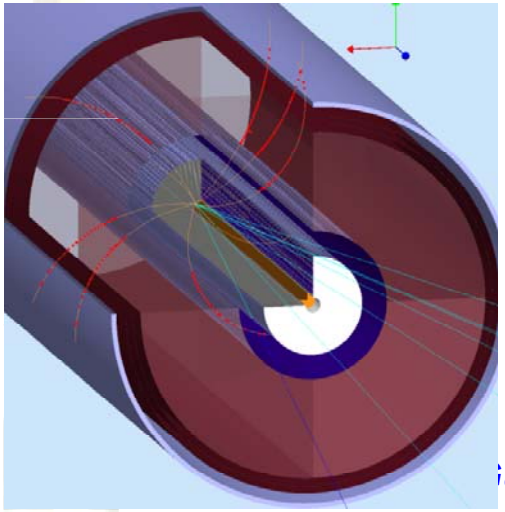


Plans for "12" GeV

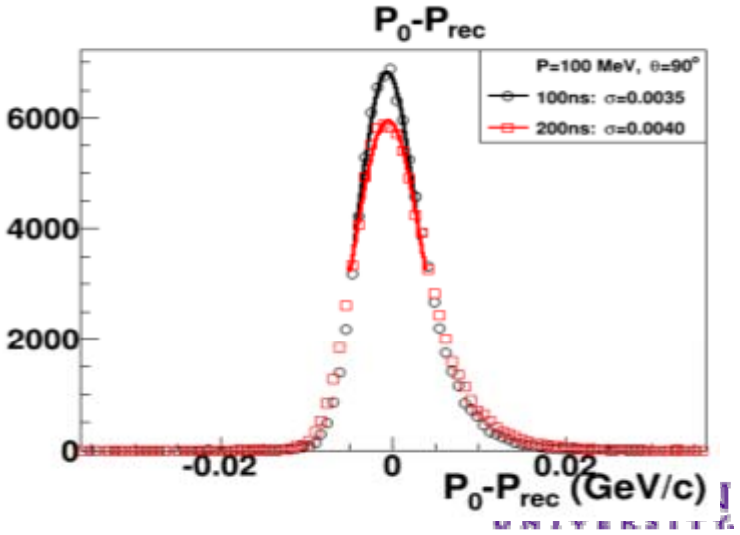
BoNuS12 E12-06-113

- *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)*

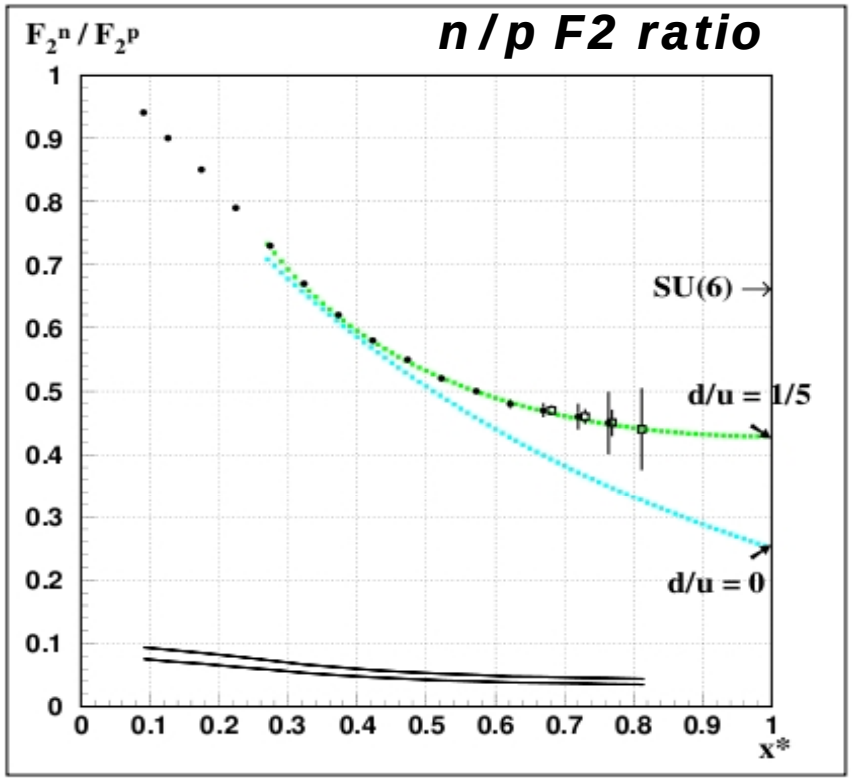


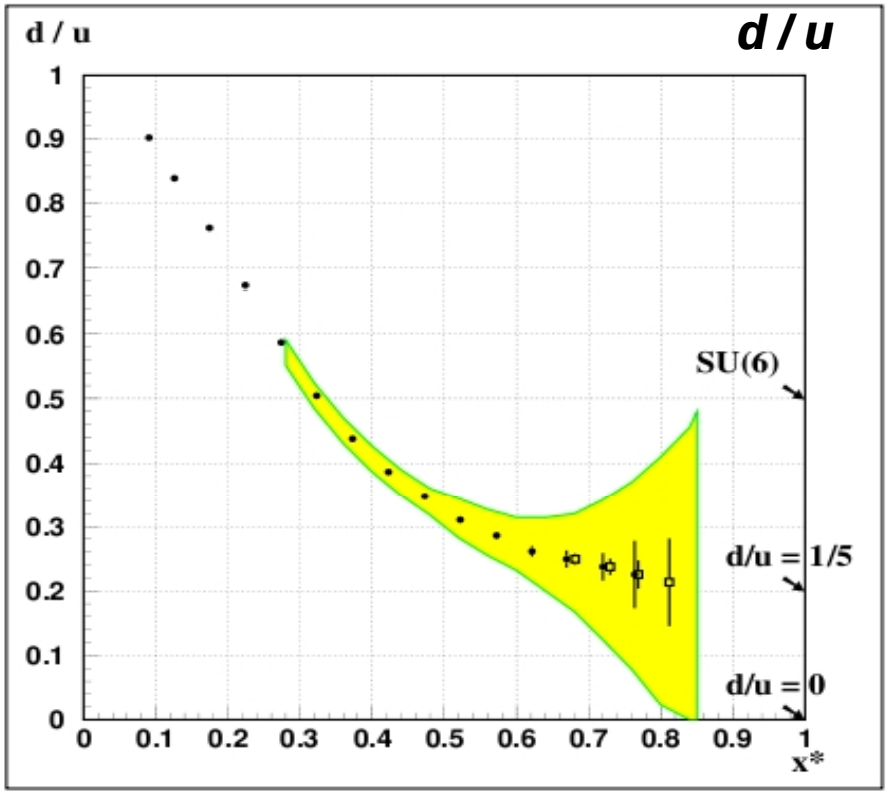


- *Full GEANT-4 MC based on CLAS12 GEMC*
- *< 4% p resolution*
- *< 2mm vertex resolution*



Expected Results

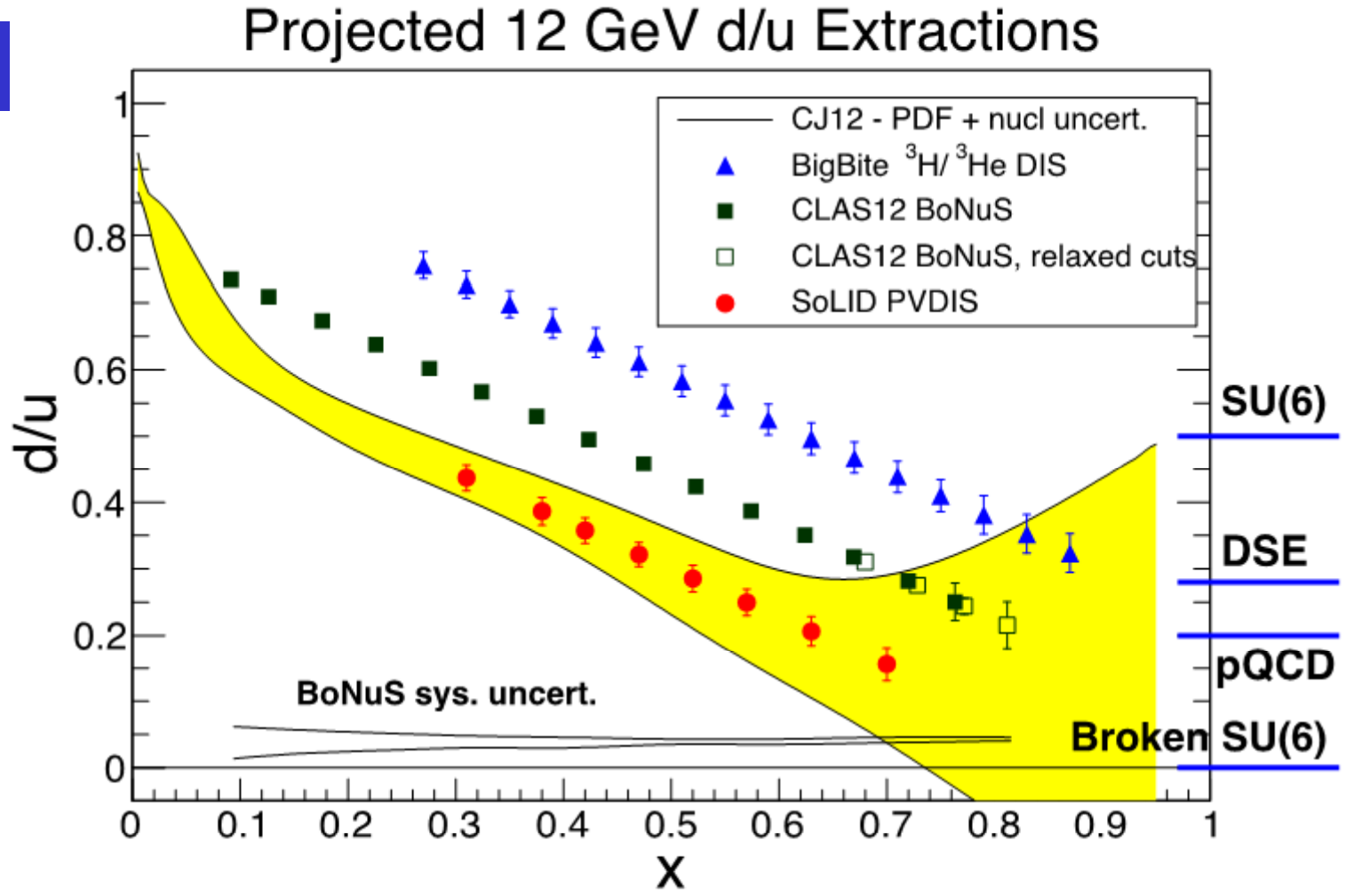




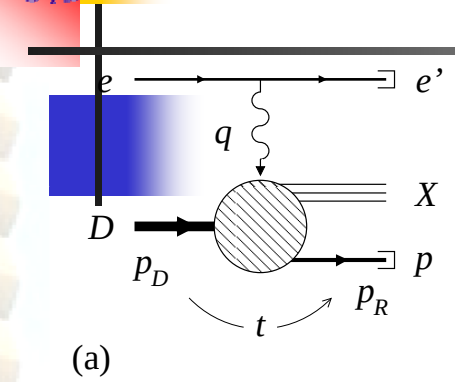
Dark Symbols: W* > 2 GeV (x* up to 0.8, bin centered x* = 0.76)

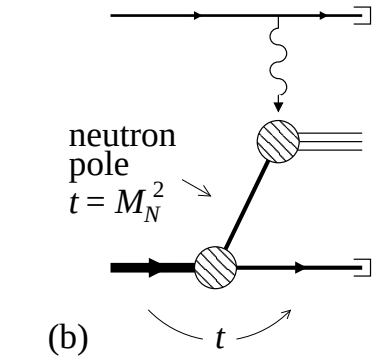
Open Symbols: "Relaxed cut" W* > 1.8 GeV (x* up to 0.83)

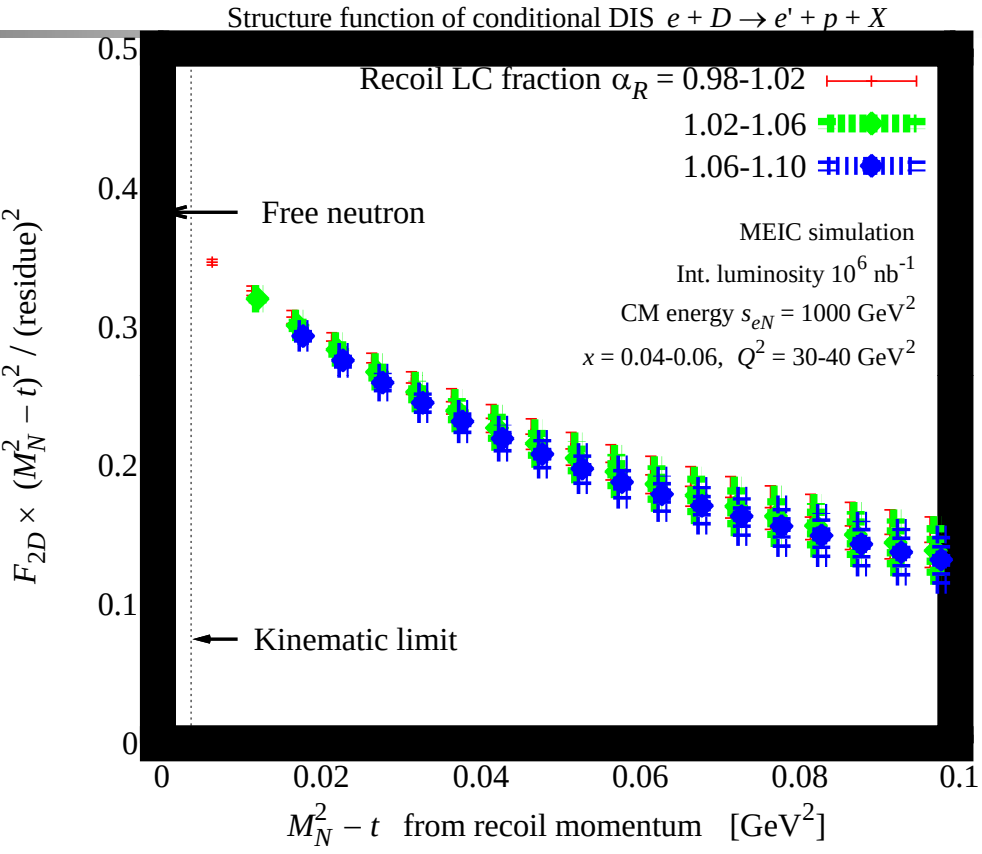
The future: JLab at 11 GeV

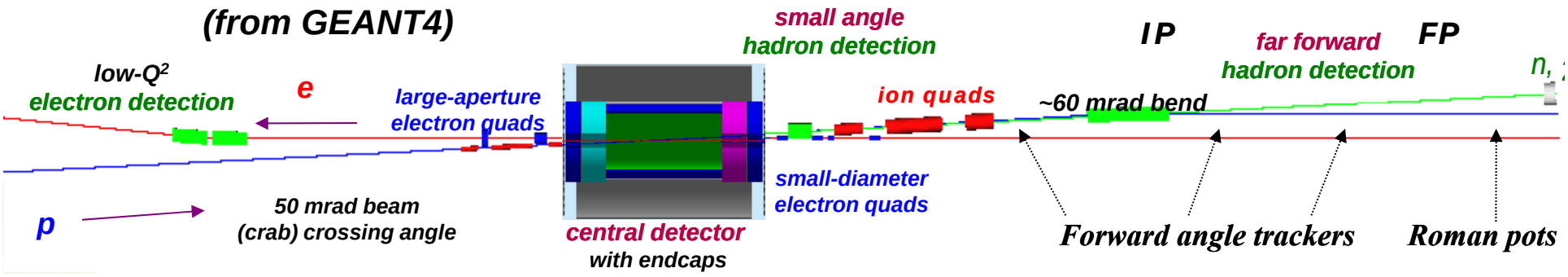


The more distant future: EIC

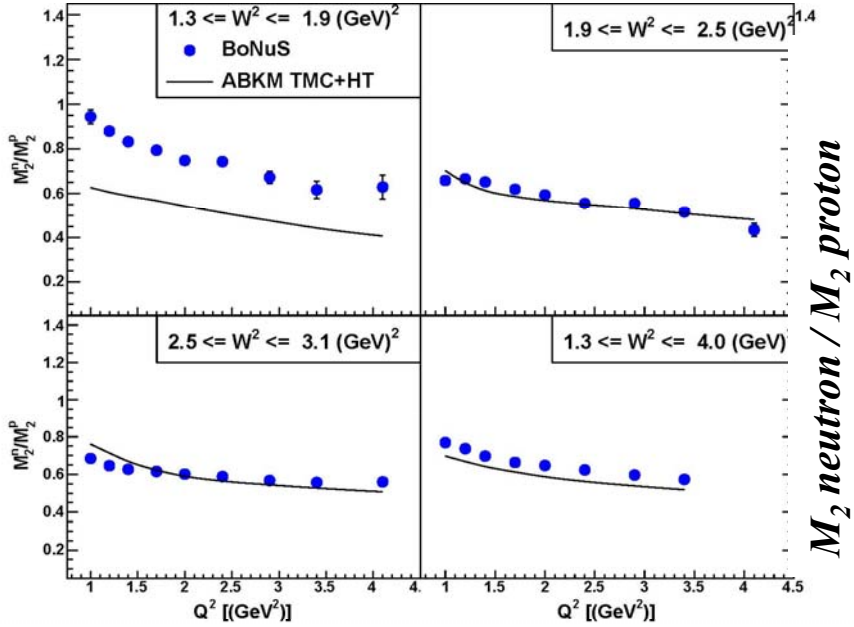








Quo Vadis?



- *Coincident spectator proton data is here!*
  - *FSI important in fwd, perp. kinematics.*
  - *"simple spectator" picture works well at low mom, bwd angles.*
  - *Modifications of internal n structure (mom. dependent) still an open question.*
  - *First results on "free" neutron: SF, moments, duality, binding effects in d.*
  - *Data mining on existing 6 GeV data sets ongoing.*
- *Lots more exciting experiments beginning with energy upgraded JLab!*
  - *F_{2n} out to x = 0.8*
  - *Detailed test of momentum-dependence of EMC effect*
- *Need to develop advanced models to minimize & correct for: in-medium effects and FSI.*
- *ULTIMATE GOAL: EIC - smoothly map out $p_{spect.}$ from 0 to 1 GeV/c.*