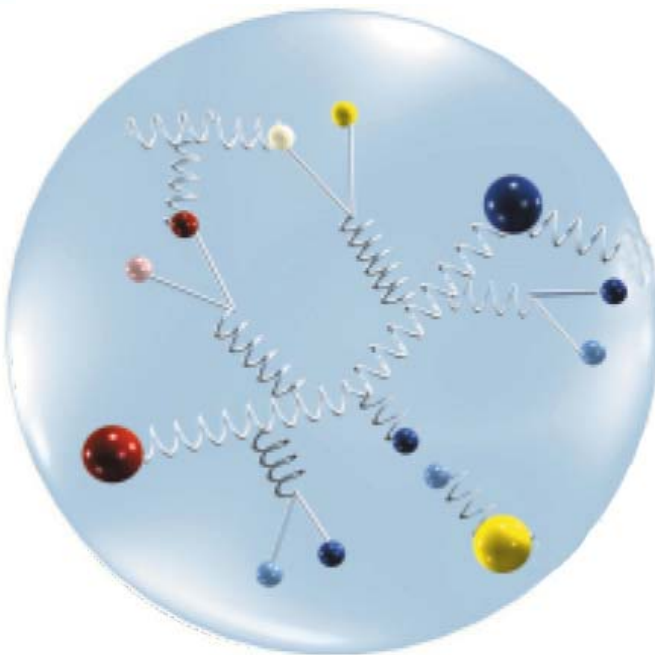


The Structure of the Neutron and the BoNuS experiment

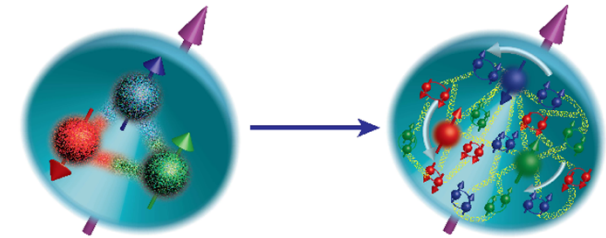
Gabriel Niculescu

James Madison University

Baryons 2016



Motivation



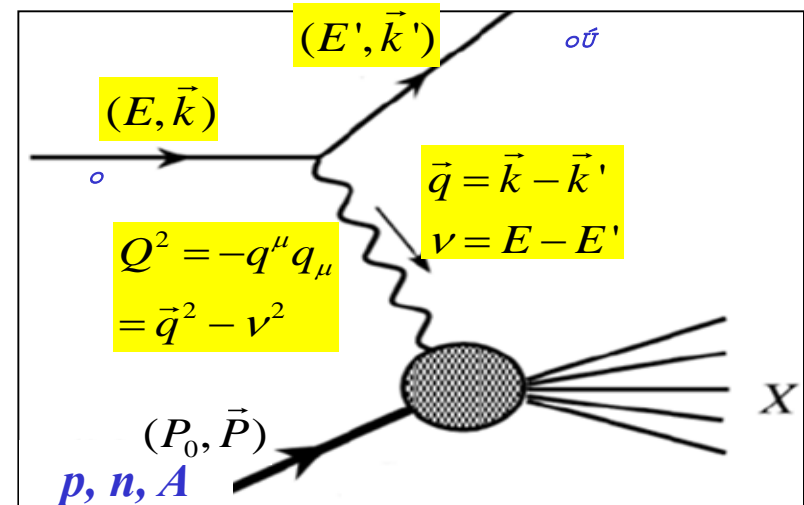
Probing the longitudinal structure of the nucleon (in 7 easy steps!):

- + Take a nucleon. Move it real fast along z . Def. l.c. mom.: $P_+ = P_0 + P_z (>>M)$
- + Hit a “parton” (q, g, \dots) inside with a lepton of your choice...
- + Measure **its** l.c. momentum: $p_+ = p_0 + p_z (m \approx 0)$
- + 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





Motivation

BoNuS

Results

Outlook



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

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

So sf give access to PDFs!

$q_f(x \rightarrow 1)$ 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.

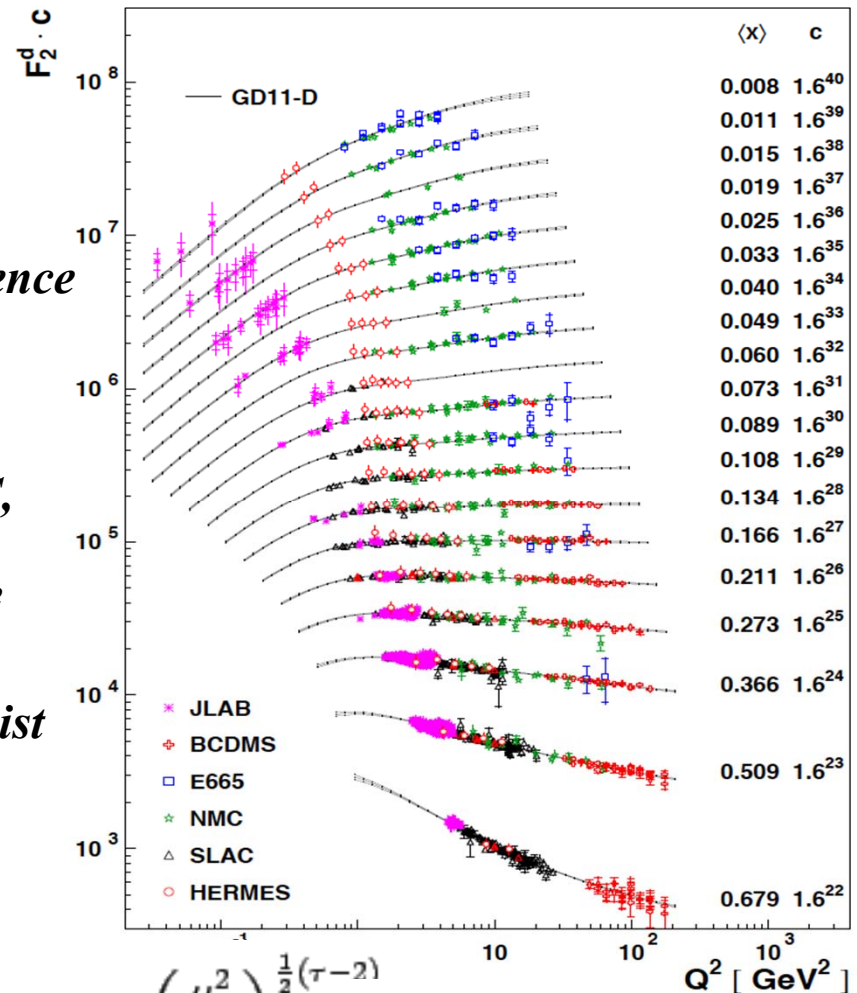
Large x , medium Q^2 evolves to medium x , large Q^2

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



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

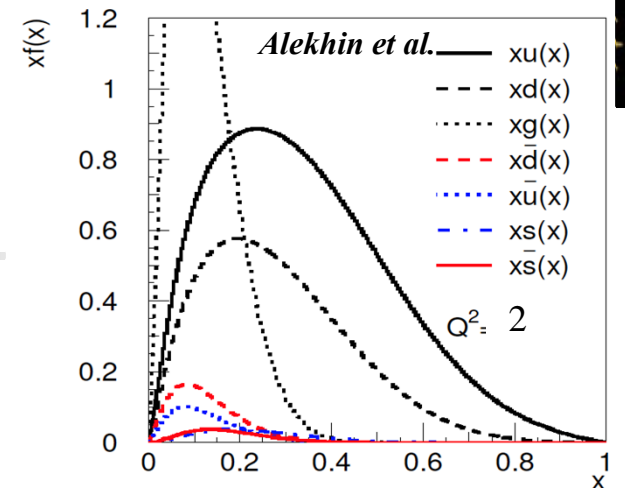


Motivation

BoNuS

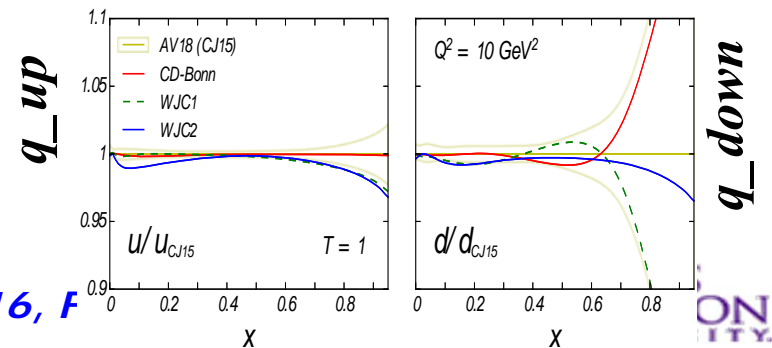
Results

Motivation (III)



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 \rightarrow mostly constraints on u and Δu
- Knowledge on d limited by lack of free neutron target (nuclear binding effects in d , ^3He)
- Large x requires very high luminosity and resolution; binding effects become dominant uncertainty for the neutron



Gabriel Niculescu – Baryons 2016, F

$d/u (x \rightarrow 1) \dots$

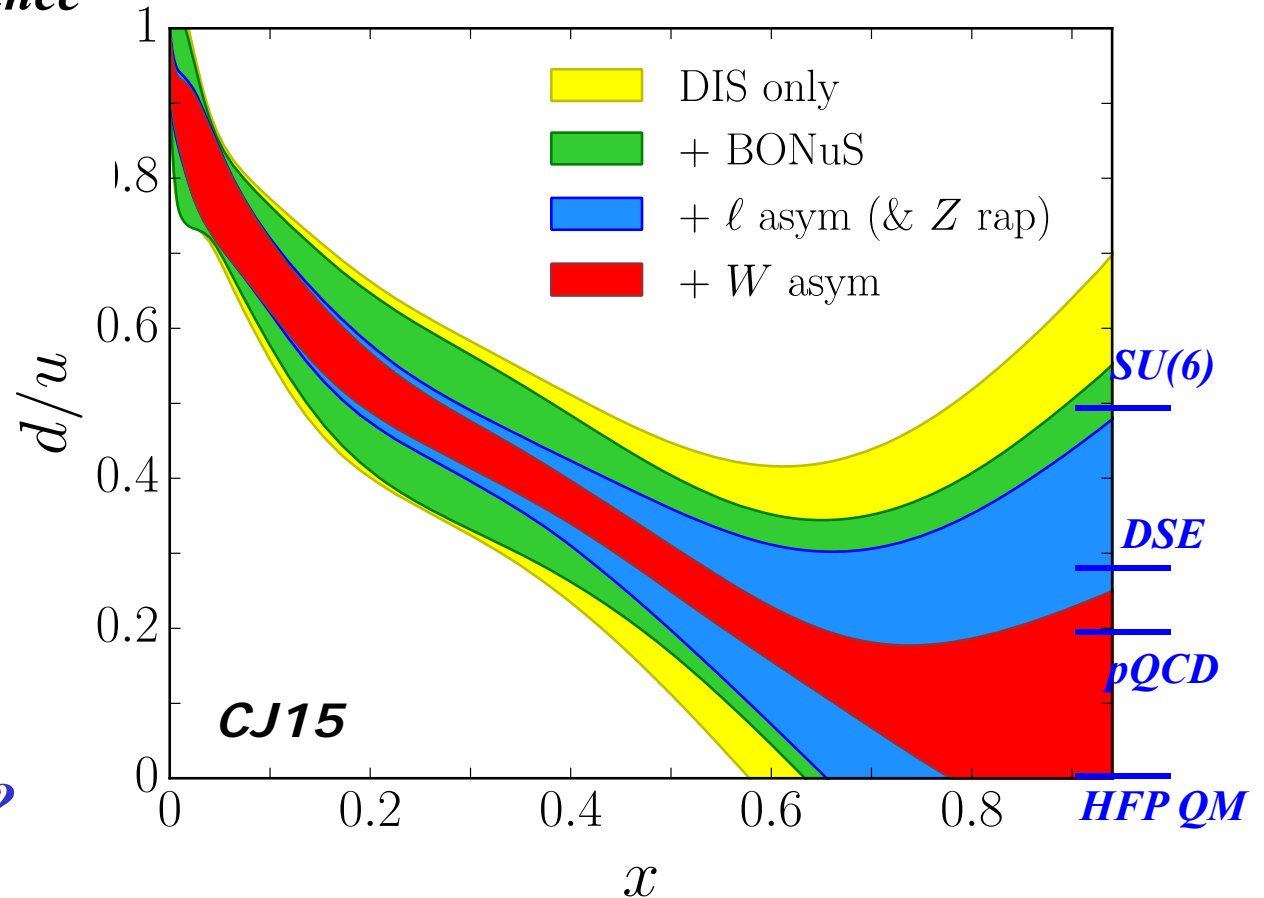
Assuming charge independence

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

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

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

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



Neutron data limited by “Nuclear Binding Uncertainties”

Gabriel Niculescu – Baryons 2016, FSU

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.



Magnetic bottle: $10^3 - 10^4$ n/cm² [TU München]

Typical proton target: $4 \cdot 10^{23}$ p/cm² [10 cm LH]

10^{14} p/cm² [HERMES]

- ✚ Impossible to make a dense target.



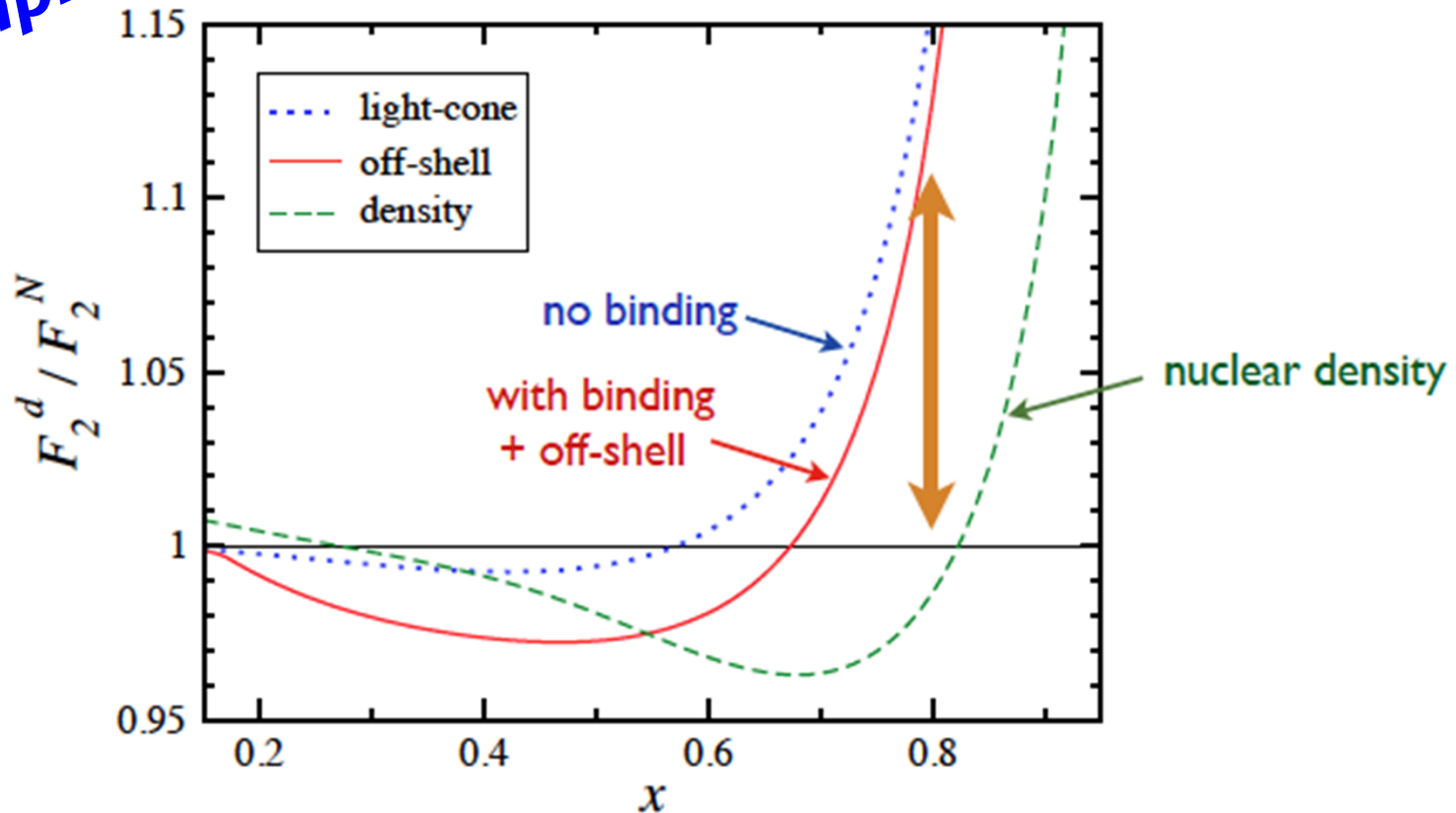
- ✚ Alternatives: use weakly bound nuclei (d) and/or

- ✚ 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...)

EMC effect in deuteron

For example...

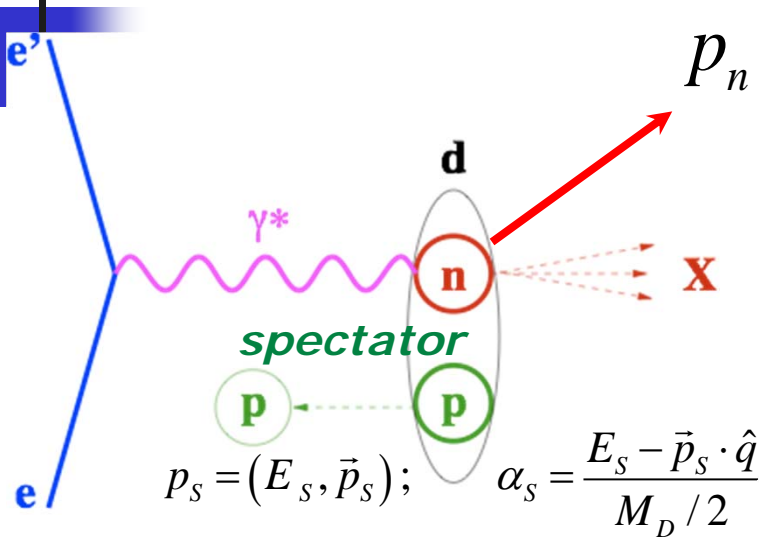


- using off-shell model, will get *larger* neutron *cf. light-cone* model
- but will get *smaller* neutron *cf. no nuclear effects* or *density* model

Even Fermi motion corrections become large at large x .

Alternative: Spectator Tagging

$$d(e, e' p_s) X$$



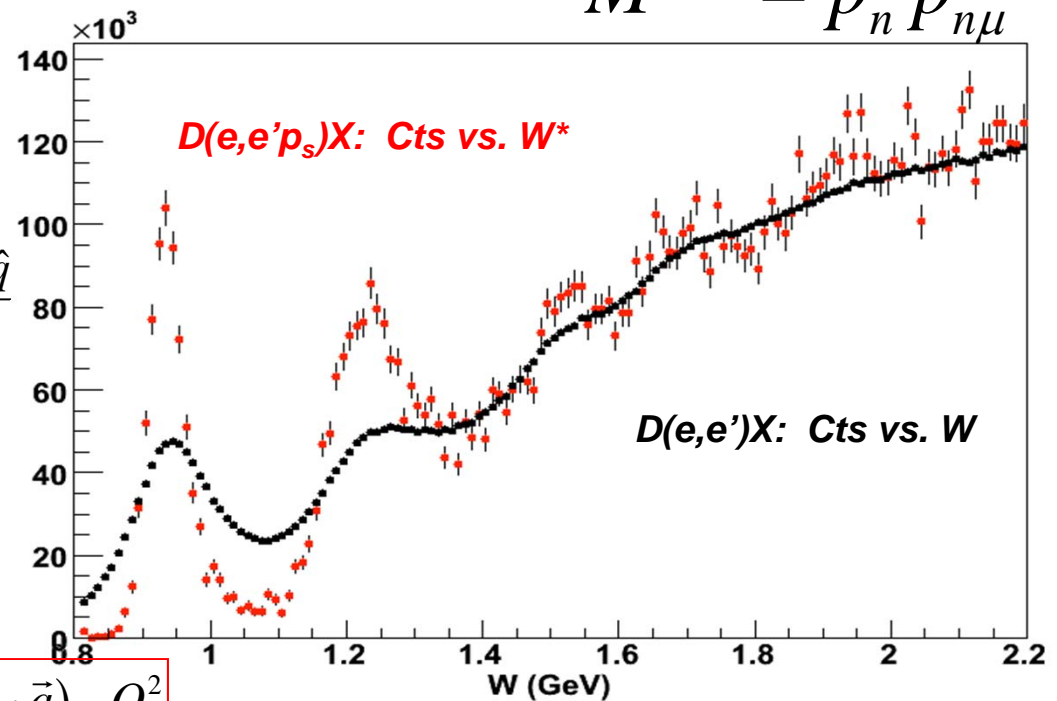
$$p_n = (M_D - E_s, -\vec{p}_s); \quad \alpha_n = 2 - \alpha_s$$

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

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

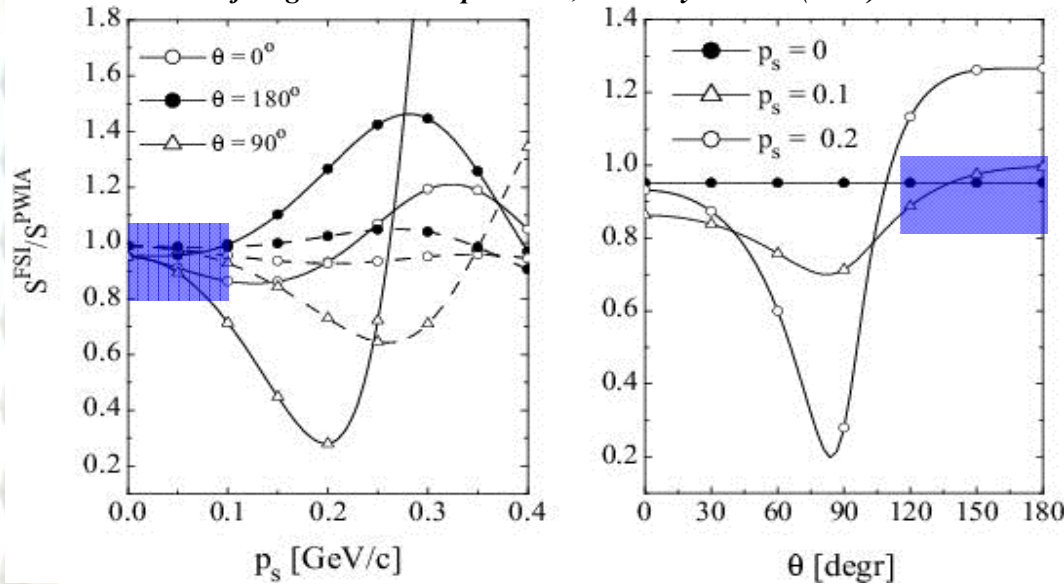
$$W^{*2} = (p_n + q)^2 = M^{*2} + 2((M_D - E_s)\nu - \vec{p}_n \cdot \vec{q}) - Q^2$$

$$\approx M^{*2} + 2 M \nu (2 - \alpha_s) - Q^2$$

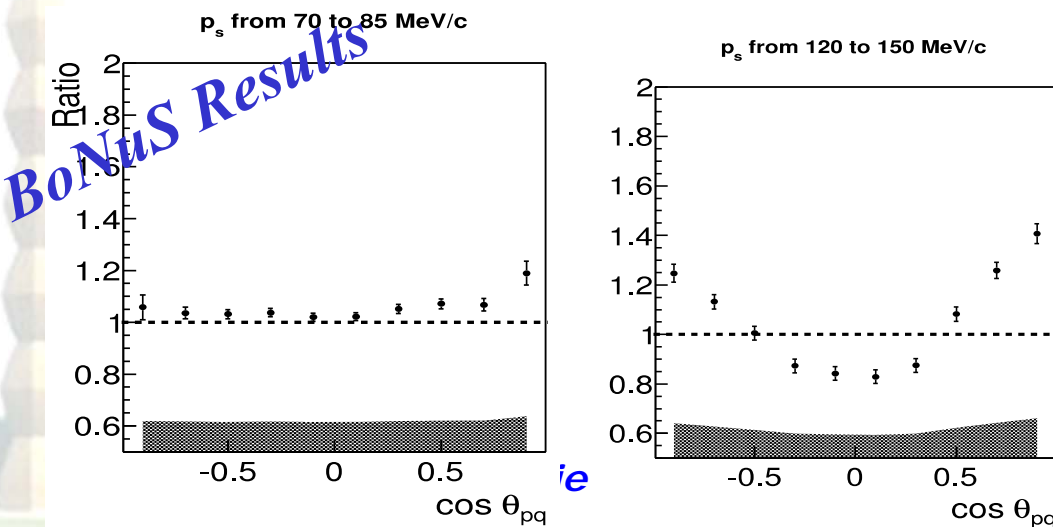


Spectator Tagging Limitations

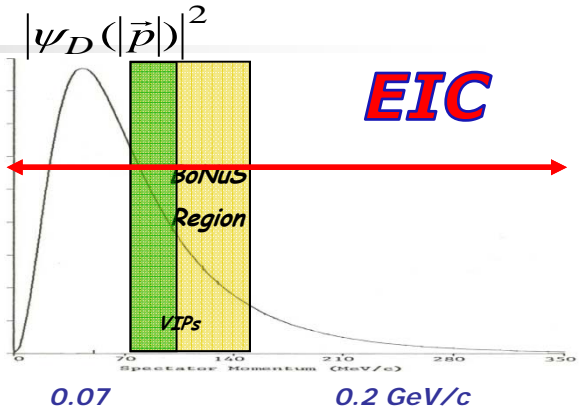
Ciofi degli Atti and Kopeliovich, Eur. Phys. J. A17(2003)133



Final State Interactions

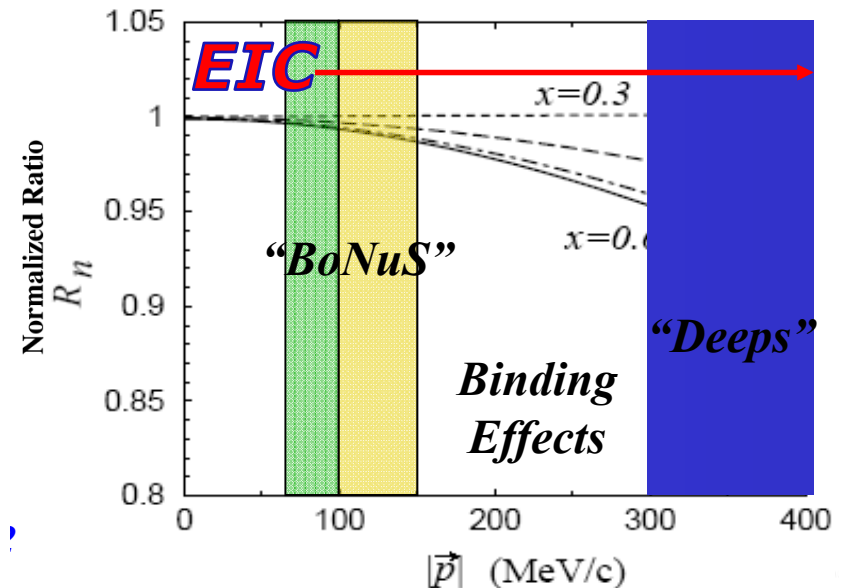


BoNuS Results

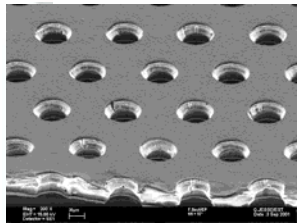


Finite coverage of WF

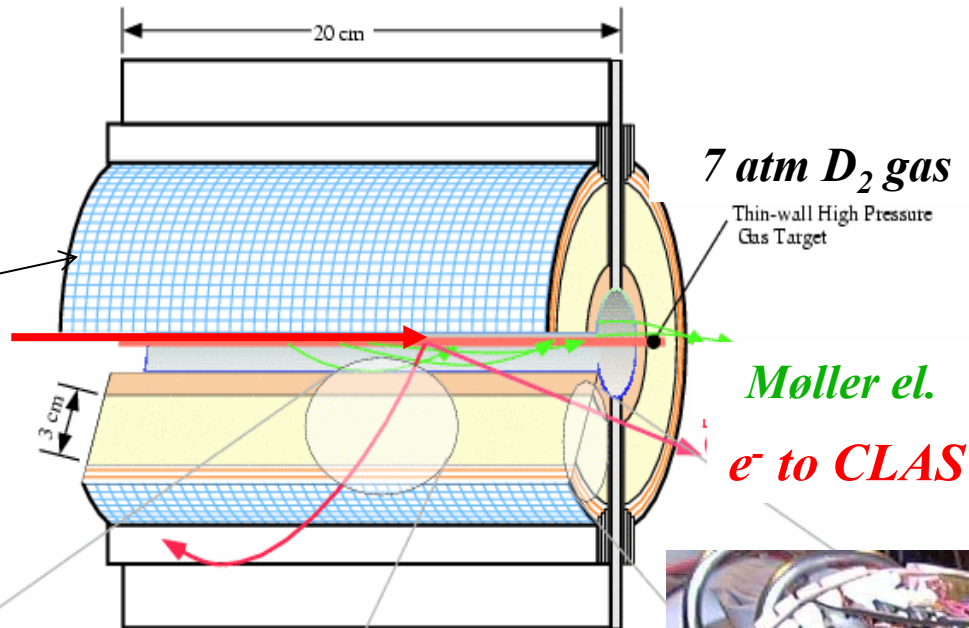
$$R_n \equiv F_2^{n(eff)}(W^2, Q^2, p^2) / F_2^n(W^2, Q^2)$$



Spectator Tagging. Enter: BoNuS



**Gas
Electron
Multiplier**



Thin Al-Mylar Window

Thin Al-Mylar Cathode

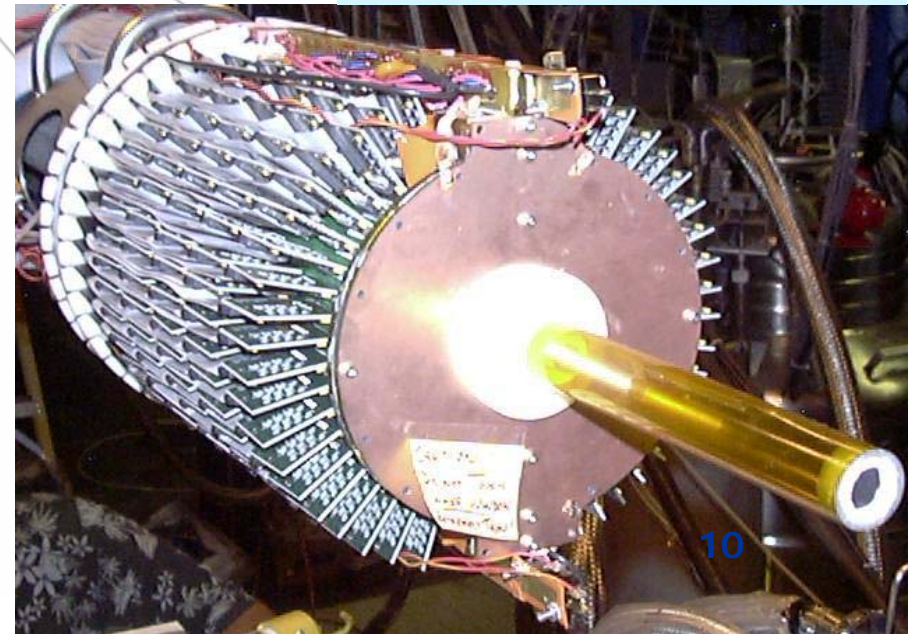
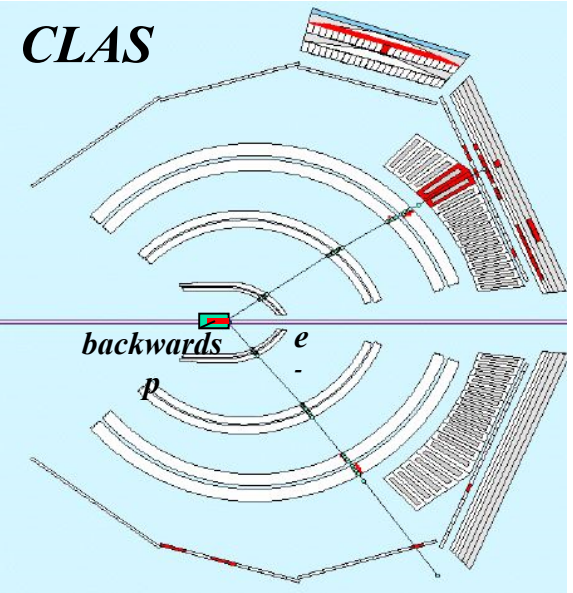
Helium/DME
at 80/20
ratio

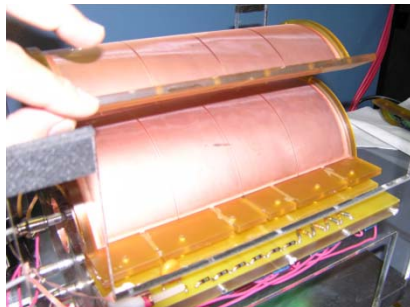
**Drift
Region**

3 GEMs

**Readout pad
and electronic**

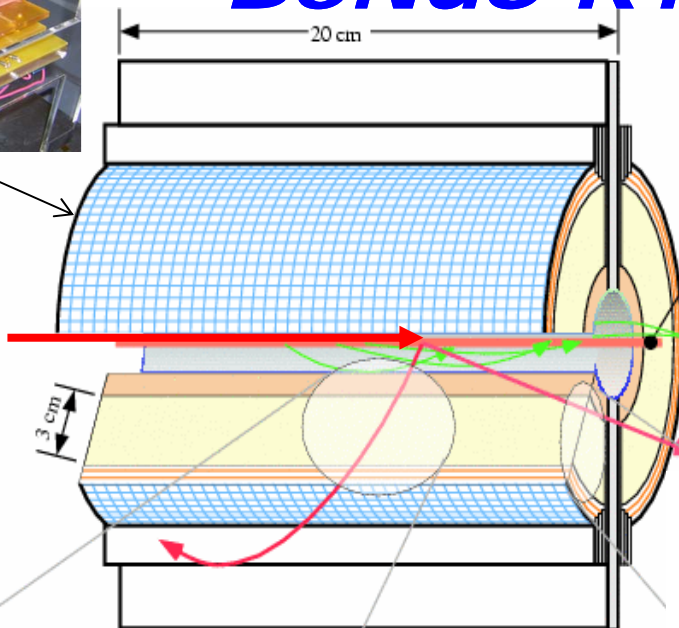
CLAS





activation BoNuS Results BoNuS RTPC

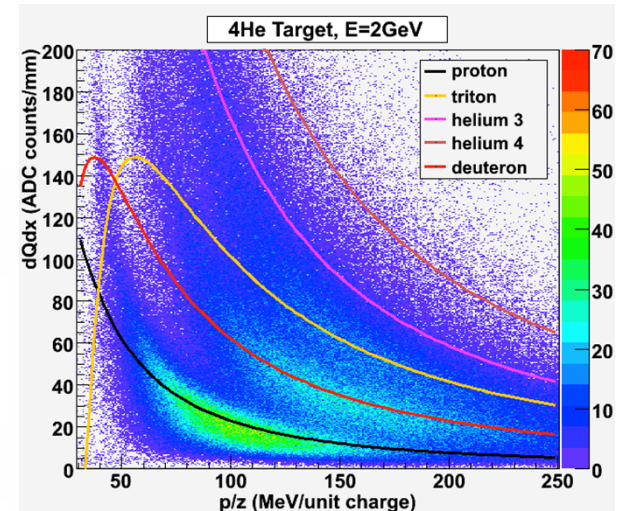
Gas
Electron
Multiplier



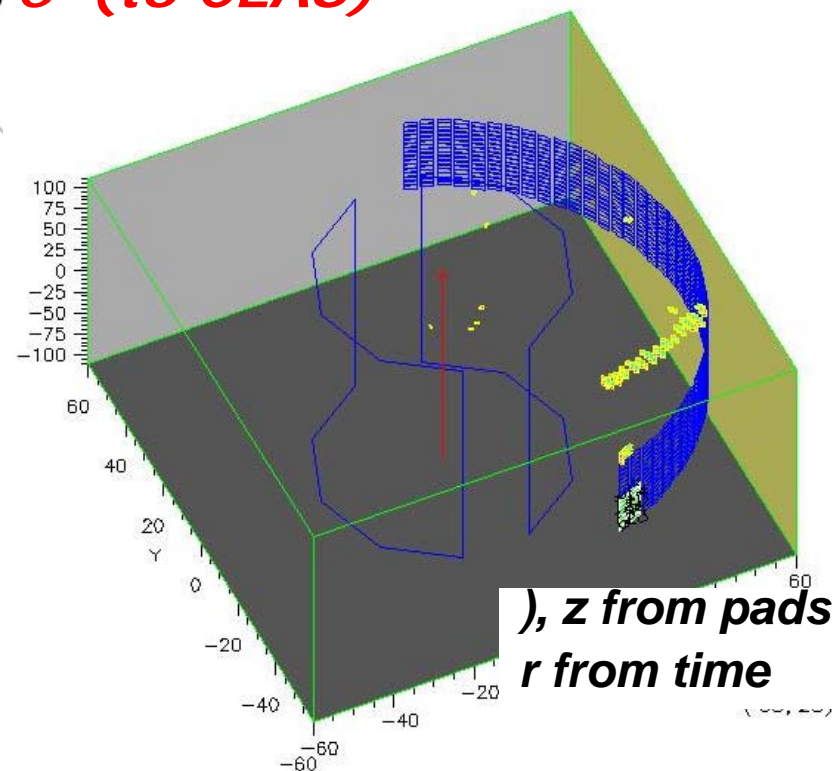
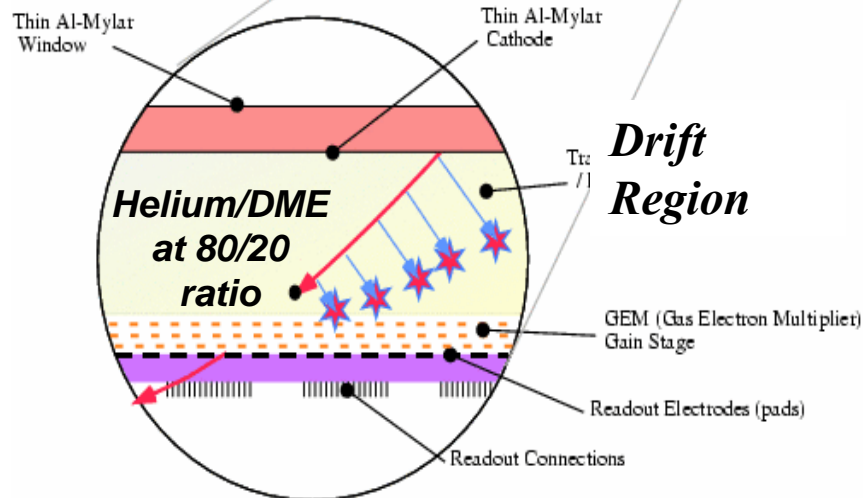
7 atm D_2
gas

Møller el.

e^- (to CLAS)



dE/dx from charge
along track (particle ID)

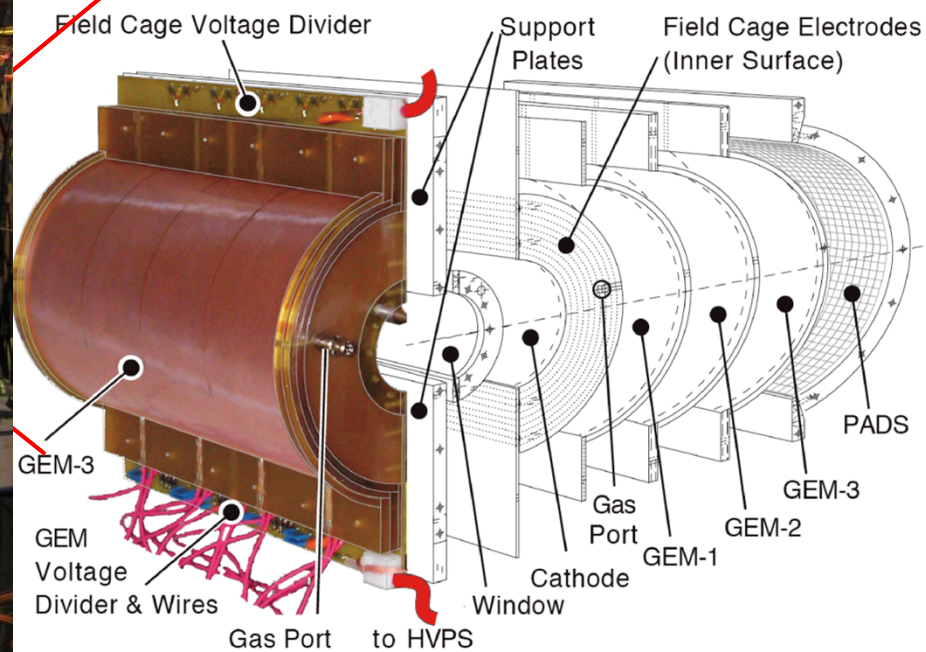
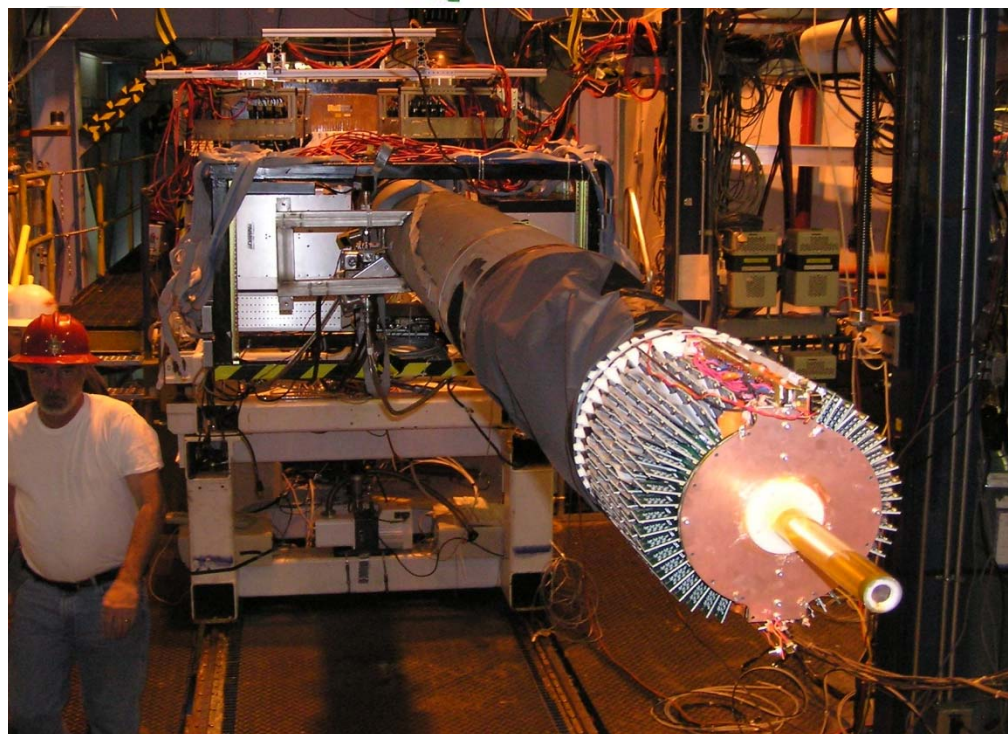
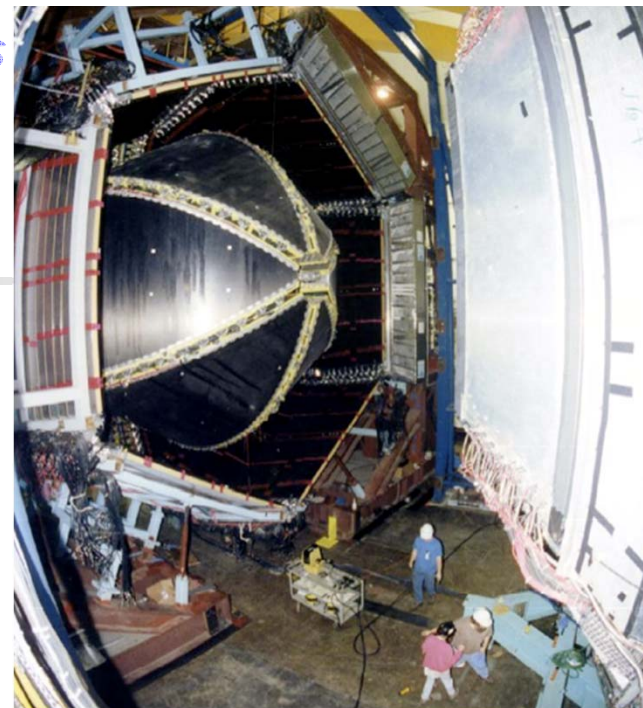
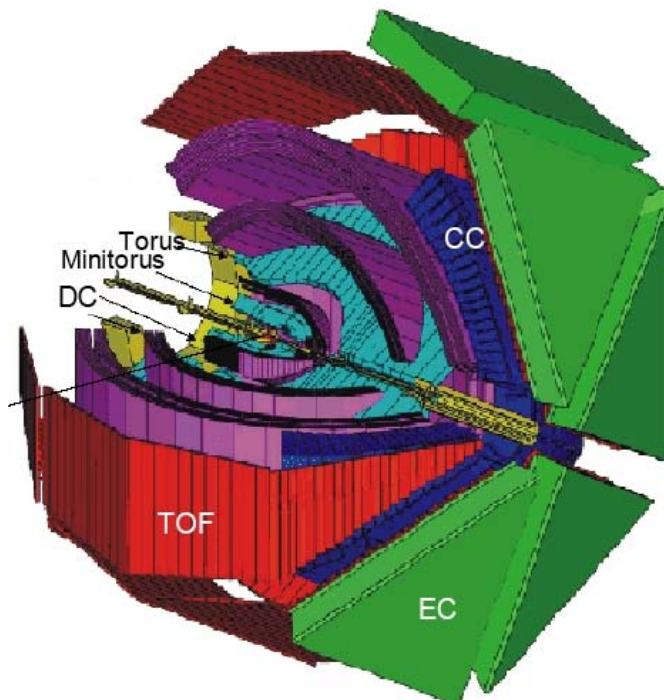


), z from pads
r from time

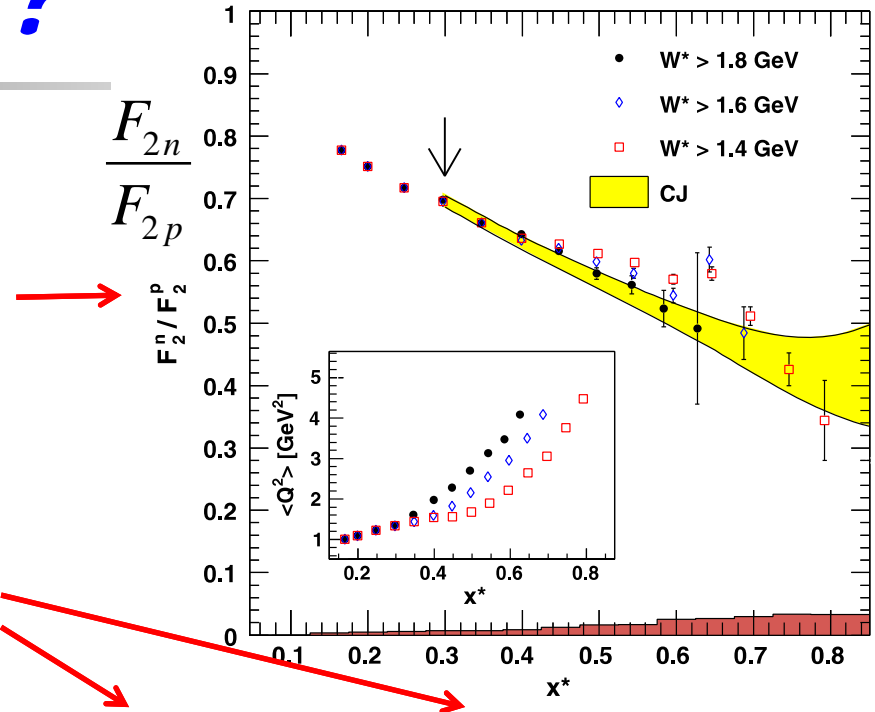
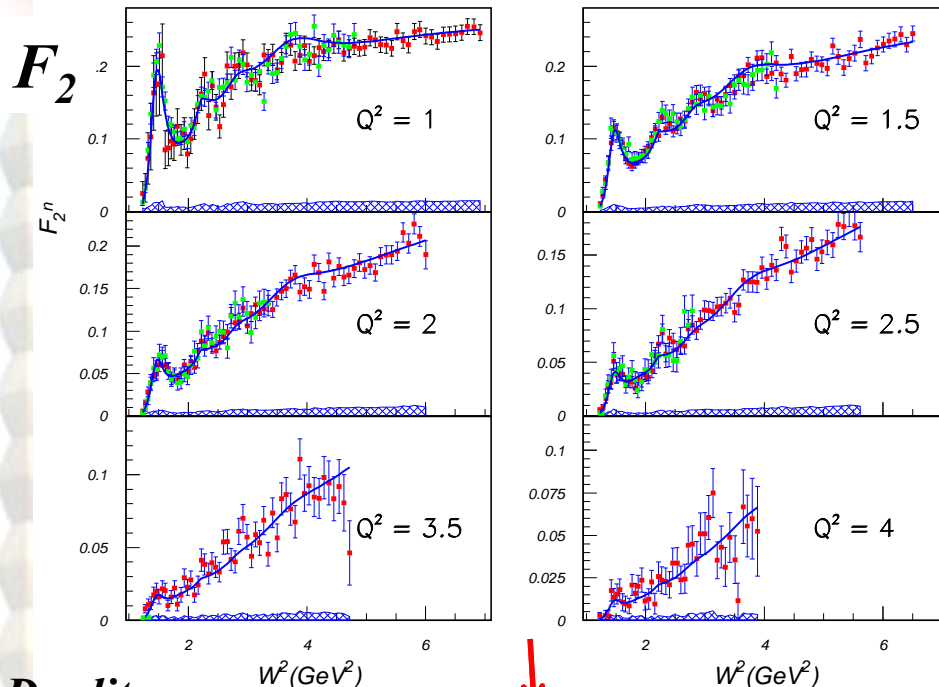
Nucl. Instr. Meth. A592, 273 (2008)

BoNuS Results

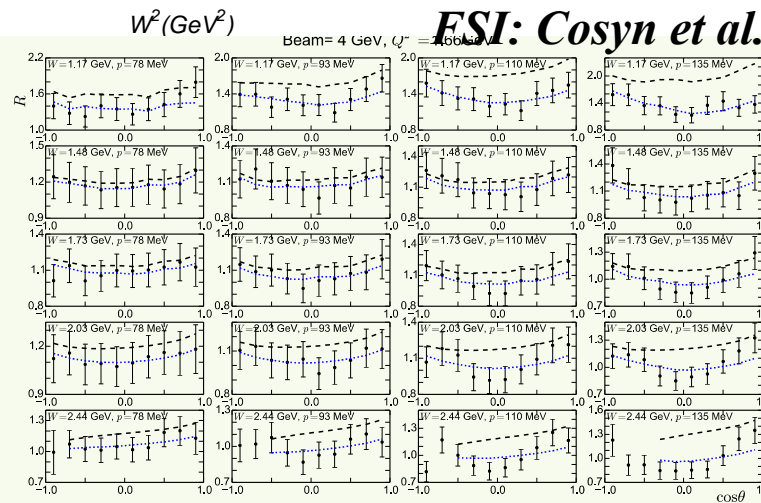
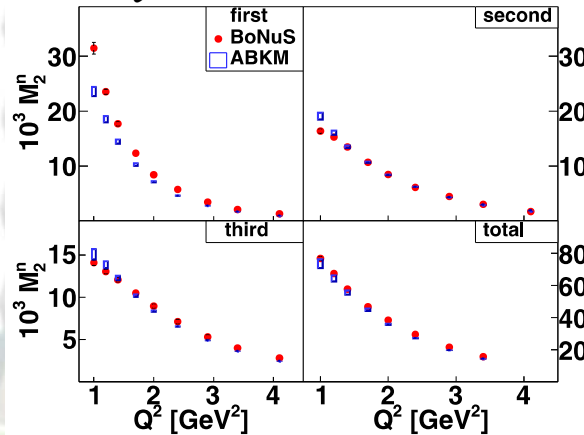
BoNuS in CLAS



Did it work?

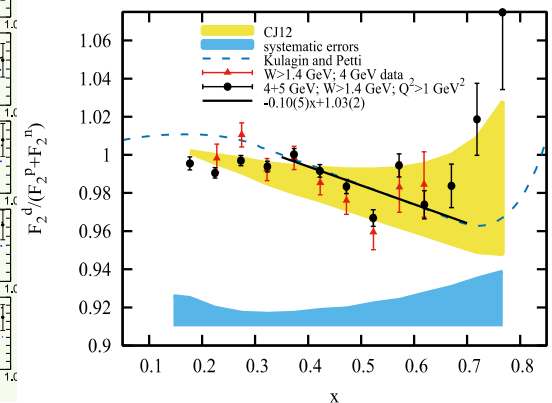


Duality

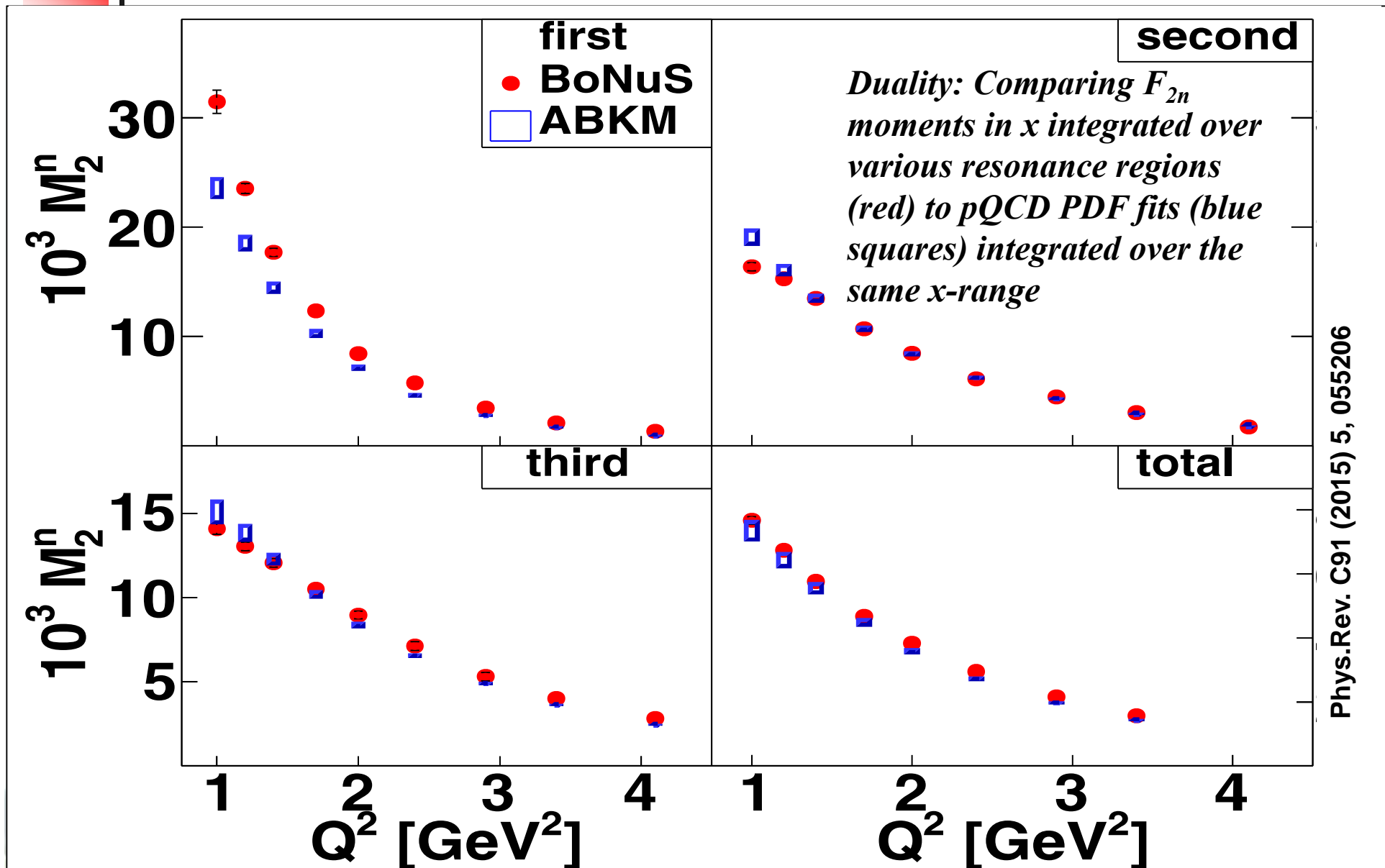


EMC Ratio

PHYSICAL REVIEW C 92, 015211 (2015)



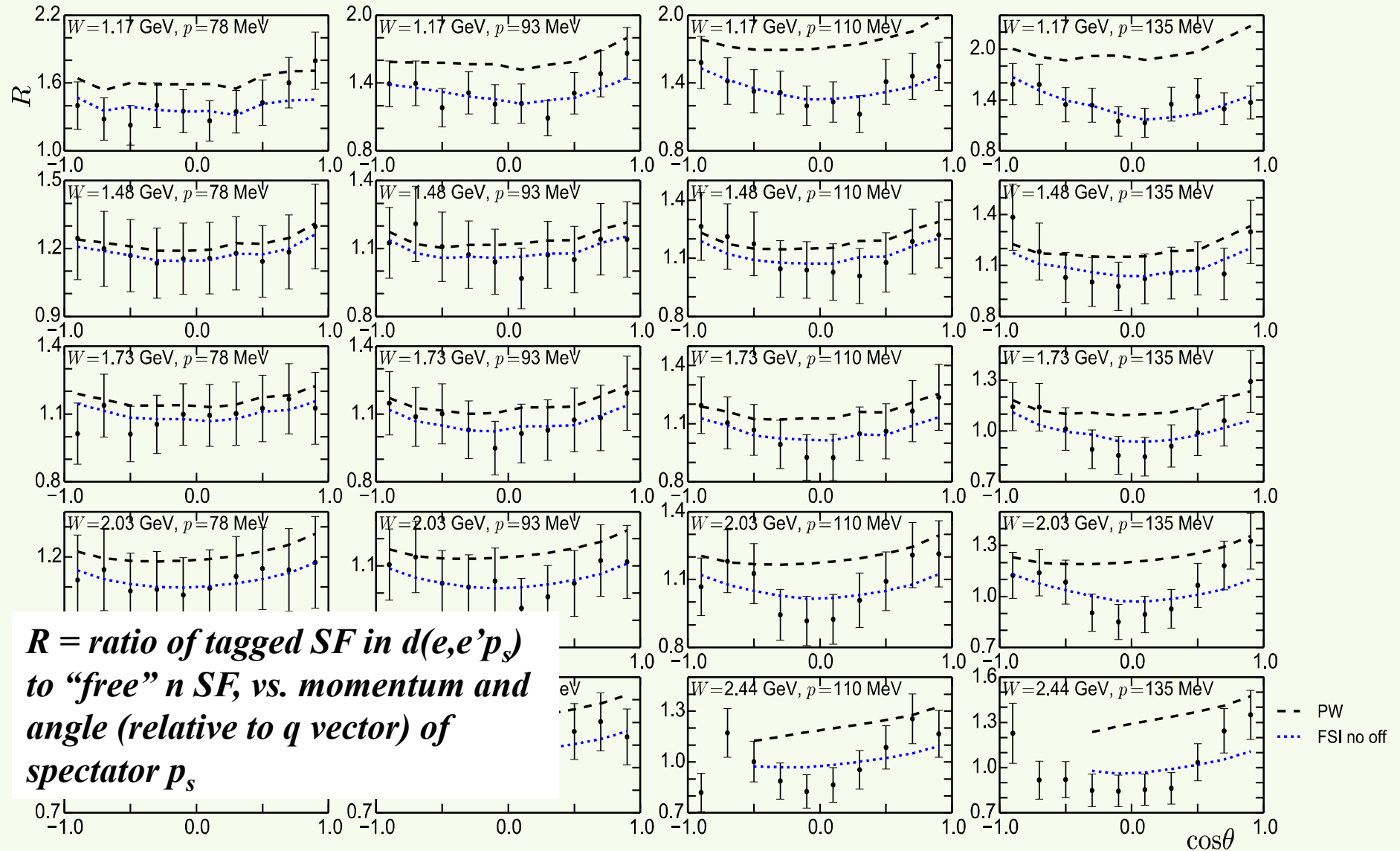
BoNuS: Truncated Moments

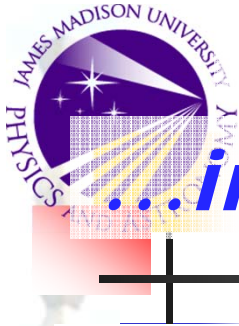


BoNuS: FSI

FSI: Cosyn et al.

Beam= 4 GeV, $Q^2 = 1.66 \text{ GeV}^2$

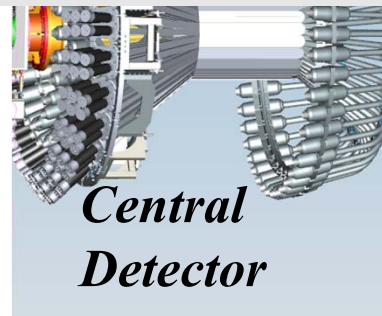
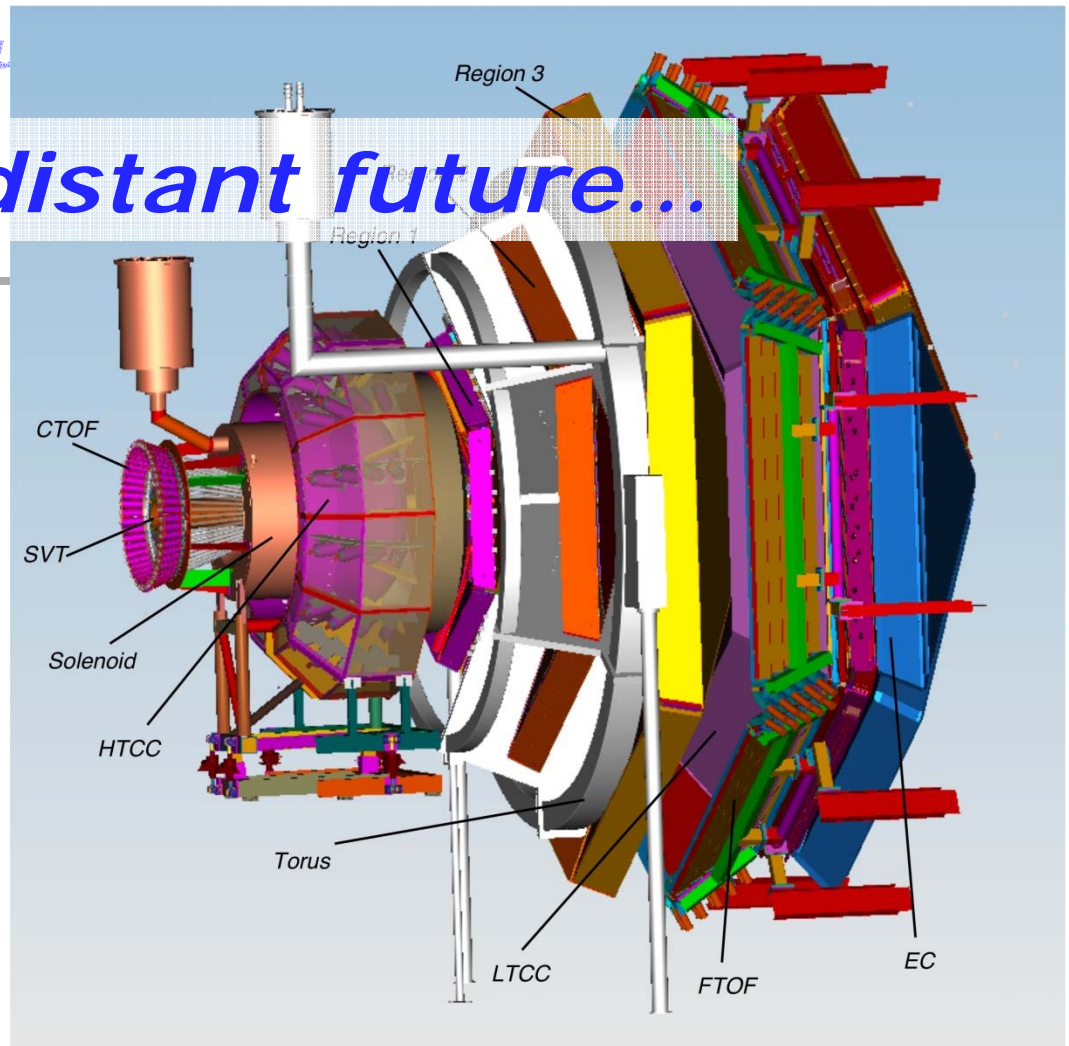




...in the not so distant future...

BoNuS12: *E12-06-113*

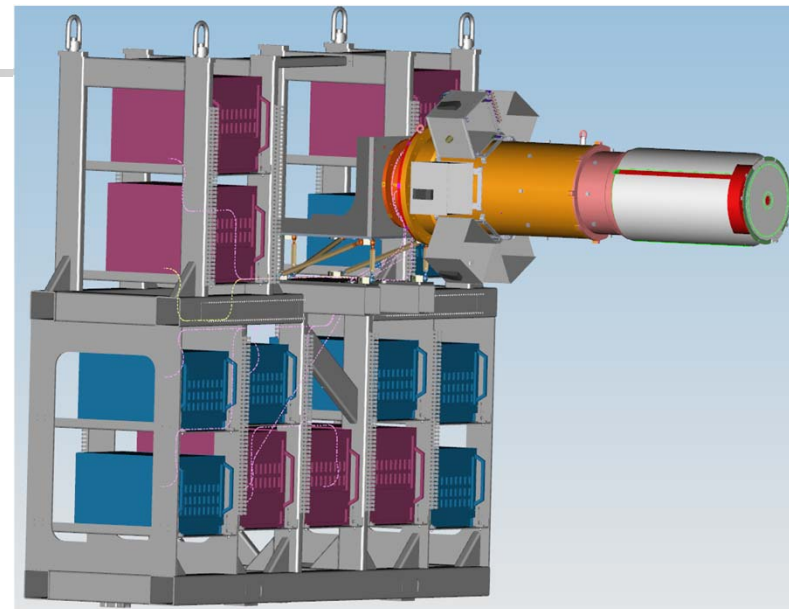
- ✦ One of the “Flagship” 12 GeV – era experiments!
- ✦ Data taking of 35 days on D_2 and 5 days on H_2 with $L = 2 \cdot 10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$
- ✦ Planned BoNuS detector DAQ and trigger upgrade
- ✦ DIS region with
 - ✦ $Q^2 > 1 \text{ GeV}^2/c^2$
 - ✦ $W^* > 2 \text{ GeV}$
 - ✦ $p_s > 70 \text{ MeV}/c$
 - ✦ $10^\circ < \theta_{pq} < 170^\circ$
- ✦ Extend to higher momenta using central detector alone



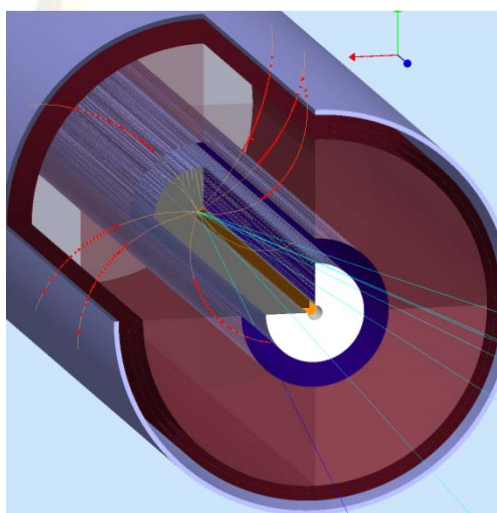
Gabriel Niculescu – Baryons 2016, FSU

Plans for "12" GeV

BoNuS12 *E12-06-113*

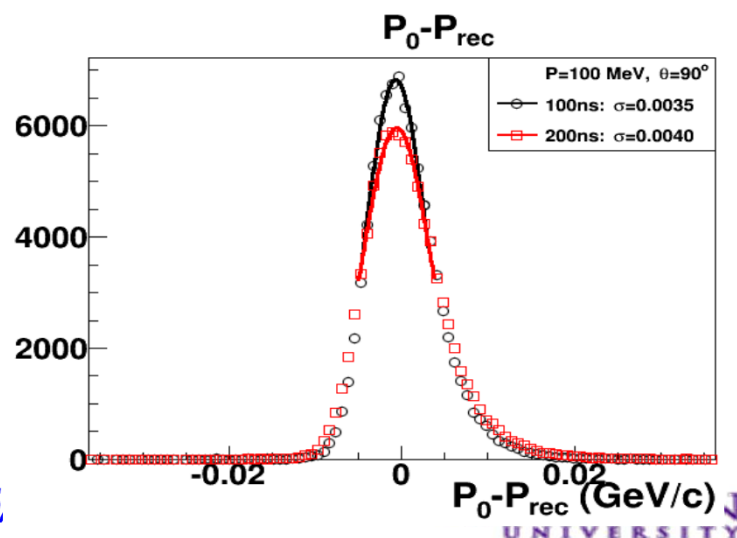


- Replaces SiVtx and micro-megas barrel trackers
- Trigger rate about 2 KHz
- 18,000 "pads" read out at 5MHz over 10 μ s
1-2 mm radial spacing, 4 cm in z, 2 degrees in $\phi \Rightarrow$ Fully reconstructed track in 3D,
suppression of < 5 MHz background through
timing and vertex cuts
- Readout electronics: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



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

Gabriel Niculescu – Baryons 2016,





Motivation

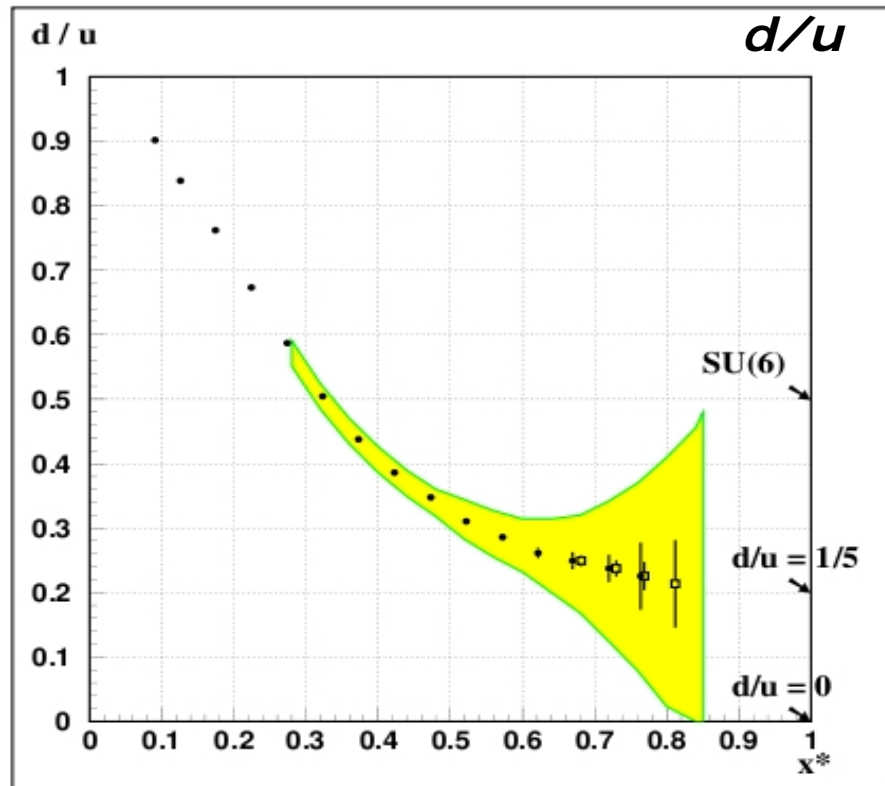
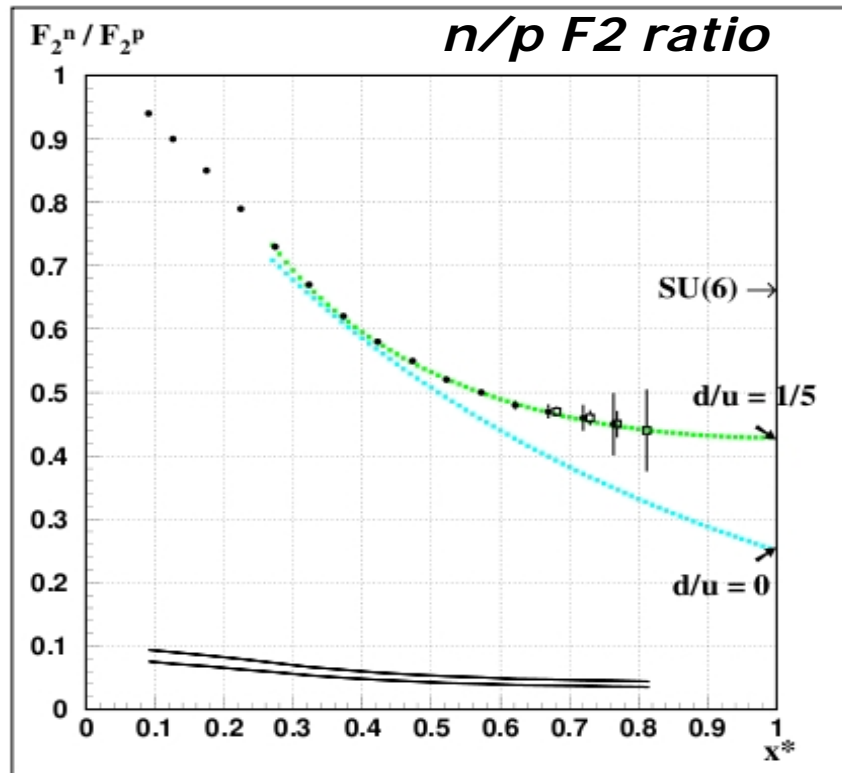
BoNuS

Results

Outlook



Expected Results



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

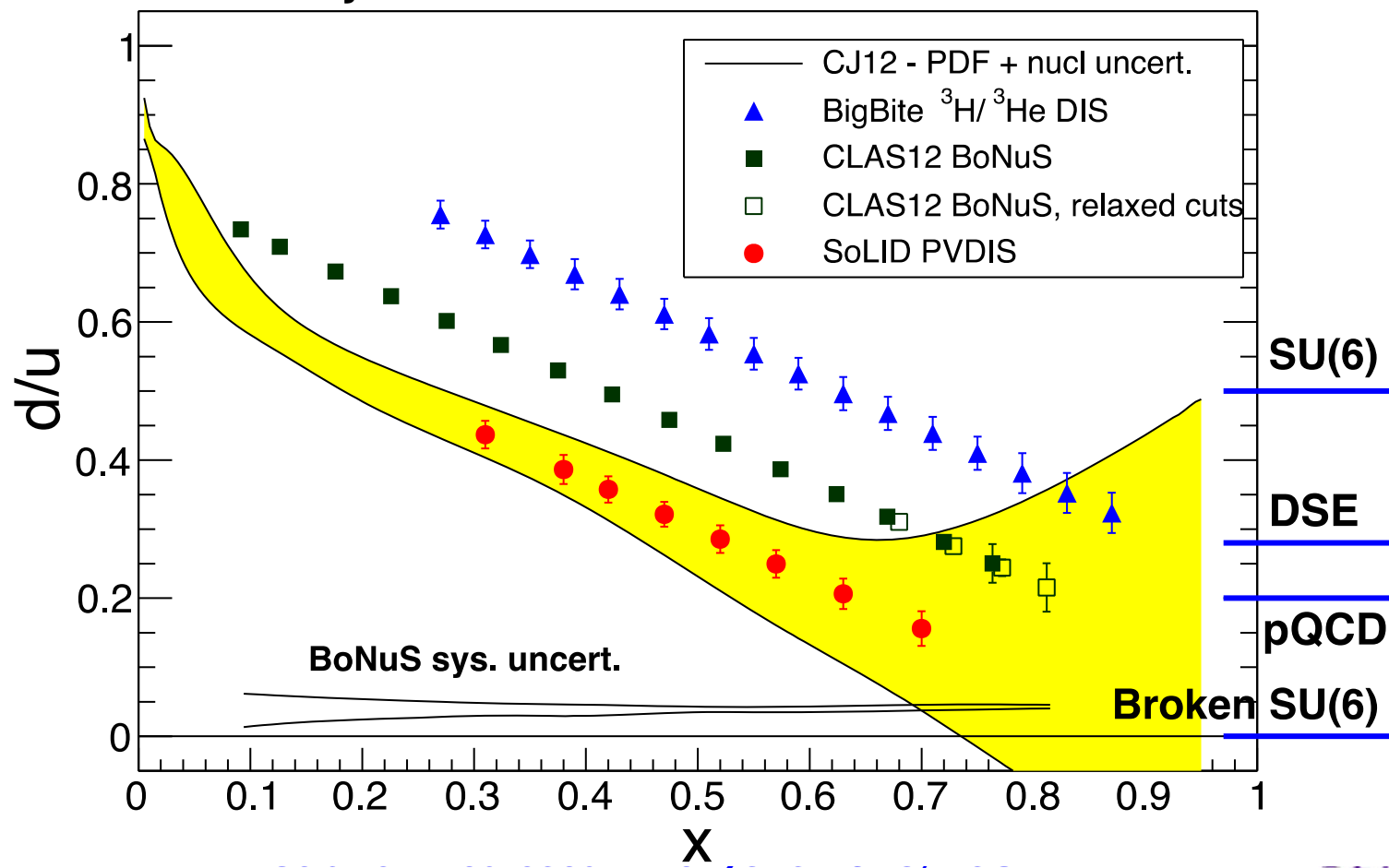
Open Symbols: "Relaxed cut" $W^* > 1.8$ GeV (x^* up to 0.83)

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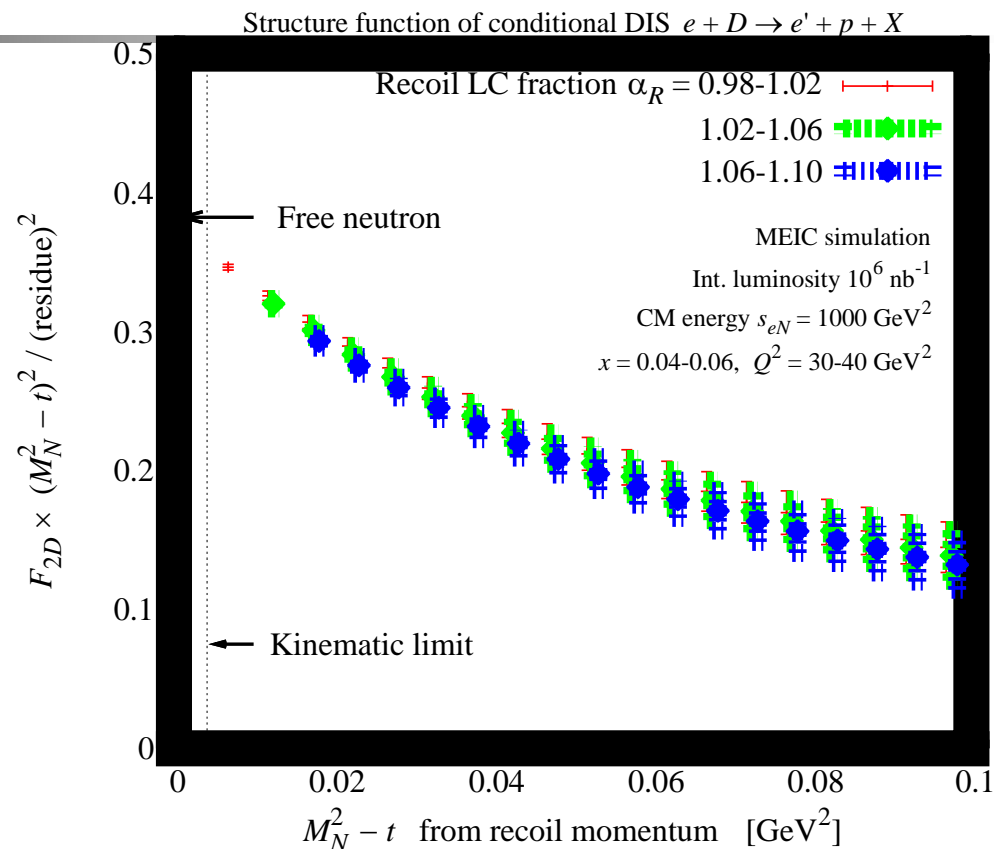
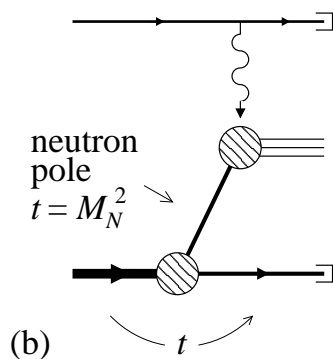
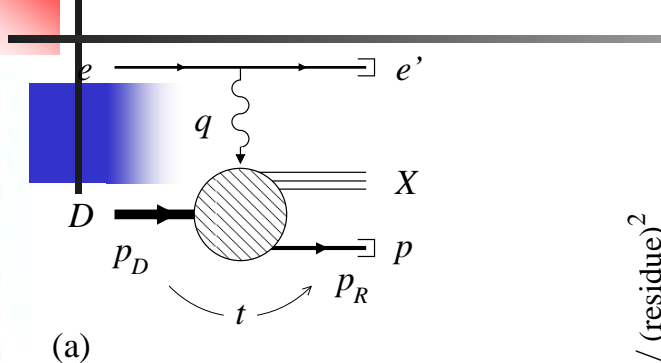


The future: JLab at 11 GeV

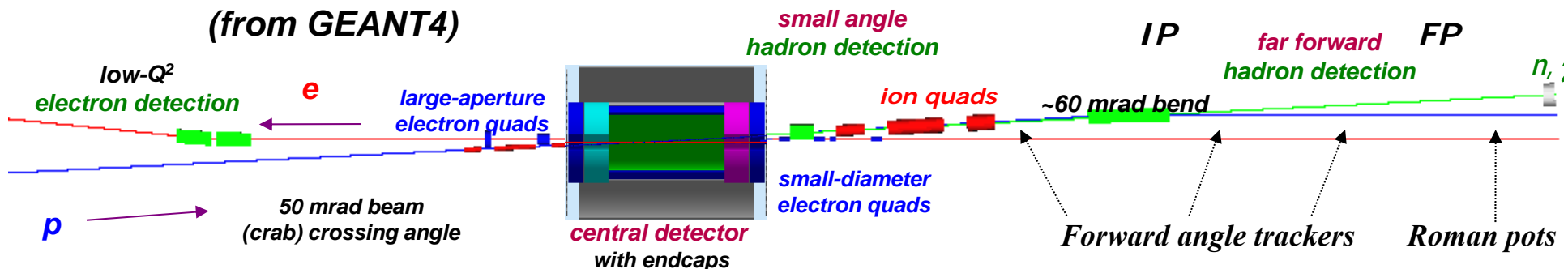
Projected 12 GeV d/u Extractions



The more distant future: EIC



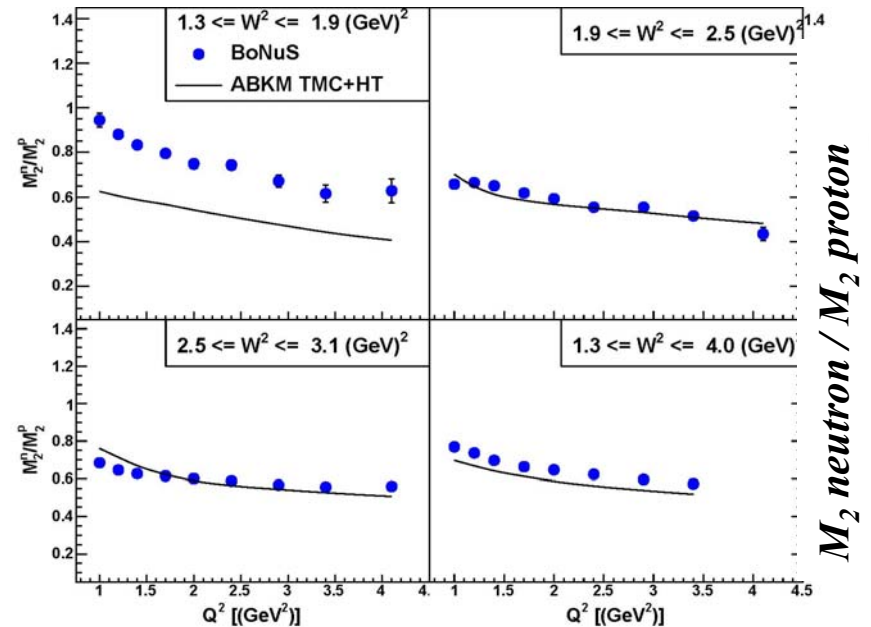
(from GEANT4)





Motivation BoNuS

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.