# JLab Hall B BONuS Experiment neutron structure


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On behalf of the CLAS Collaboration


*HiX2019, Kolympari, Crete, Greece*

*August 19, 2019*

# Important open questions in nucleon structure at high-x

## Already discussed by multiple speakers:

→ What is $F_2^n / F_2^p$ and *d/u* for $x \to 1$?

→ How well does quark-hadron duality hold in the neutron (Talk by I. Niculescu)

=> confront dynamical models of duality

→ How is the deuteron “constructed” from proton and neutrons?

I. What is the EMC effect in the deuteron?

II. Are there isospin dependent off-shell effects in light nuclei?

Answering these questions requires precision structure function data on: …

proton, deuteron, neutron, and A=3 mirror nuclei

- BONuS12

- MARATHON (see talk by Makis) and

- Hall C inclusive p,d cross sections
  (see talk by Simona Malace)

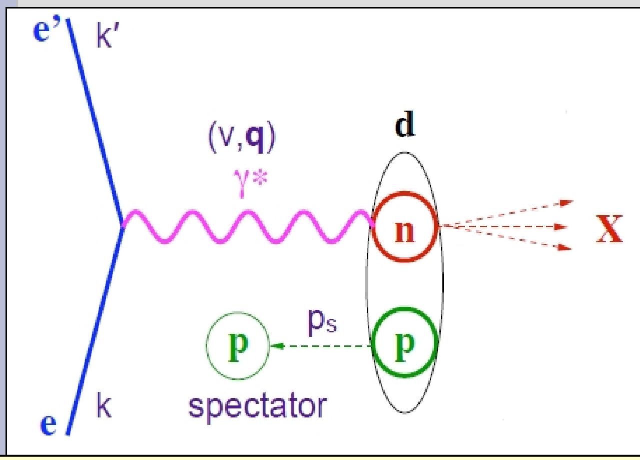
Will provide a basis for a robust program to answer the questions posed on the previous slide.

# Neutron Structure from Spectator Tagging in the "Barely Off-Shell Neutron Structure" (BONuS) Experiment

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

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

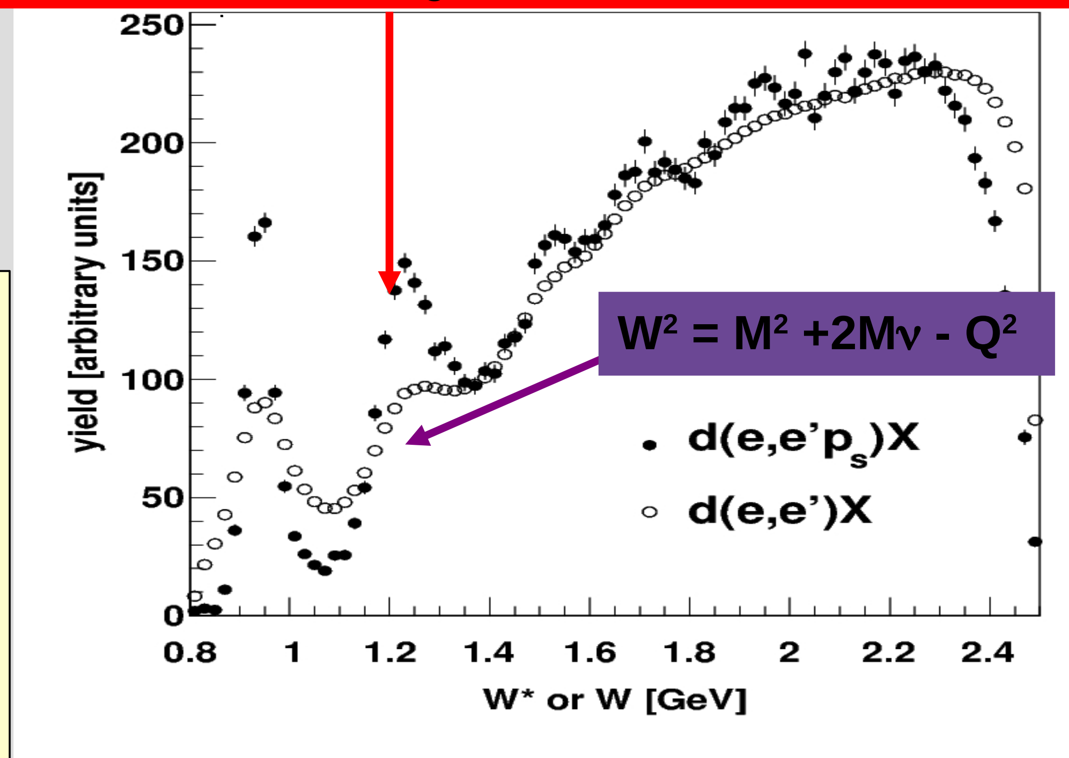
$$\approx M^{*2} + 2M\nu(2 - \alpha_S) - Q^2$$




PWIA Spectator Model:

→ Slow Backward proton is spectator
→ Neutron is offshell
→ measured proton momentum from recoil in weakly bound d

**=> correct for initial state neutron momentum**




$$W^2 = M^2 + 2M\nu - Q^2$$

# Select slow, backward protons to minimize:

1. **Off-shell effects**

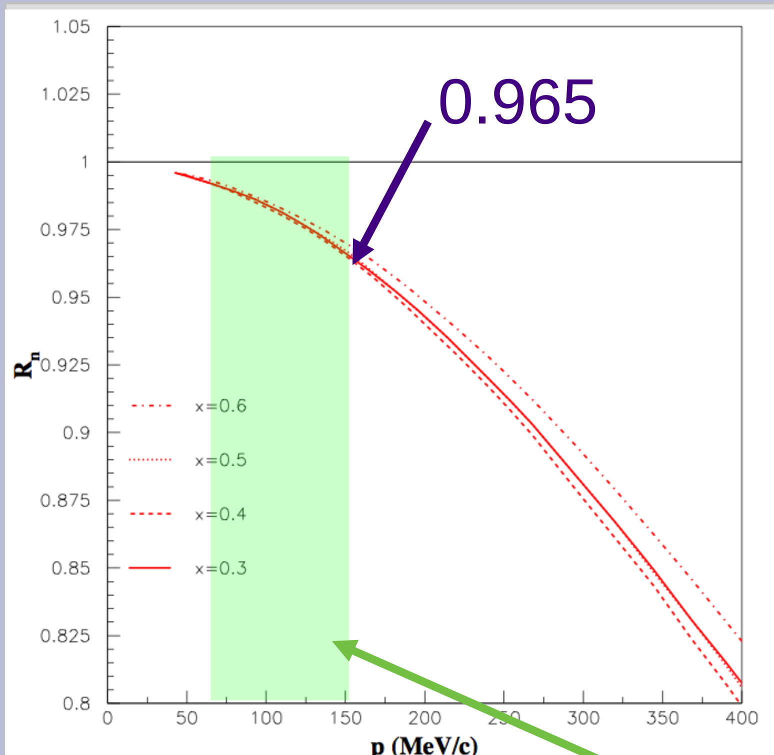
2. **Final state interactions**

3. **Enhancement to proton yield from target fragmentation**

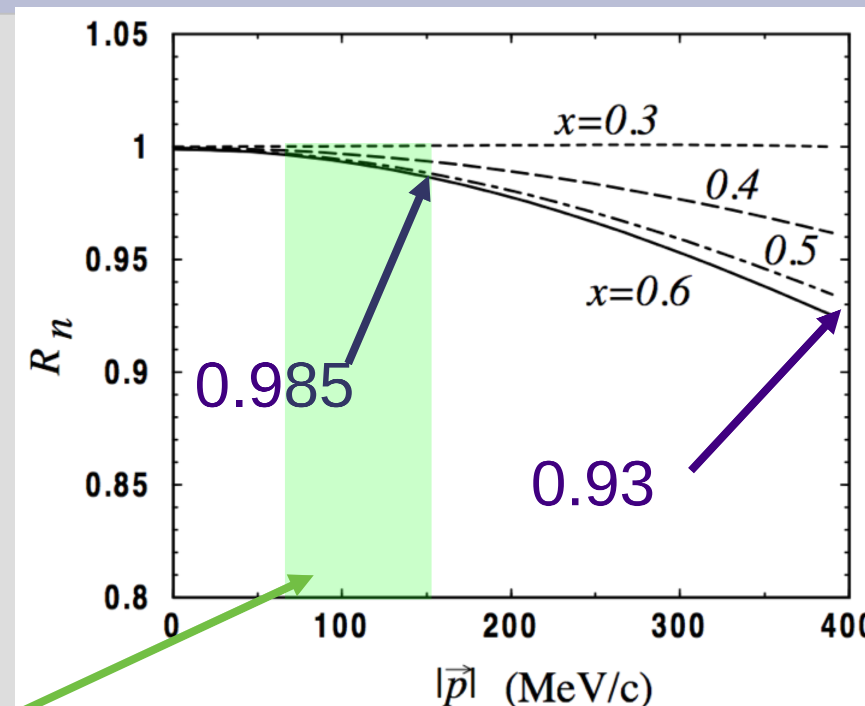
# Minimizing Off-Shell effects

$$R_n \equiv (F_2^n)^{\text{eff}} / (F_2^n)^{\text{free}}$$

Liuti & Gross PLB**356**(95)157



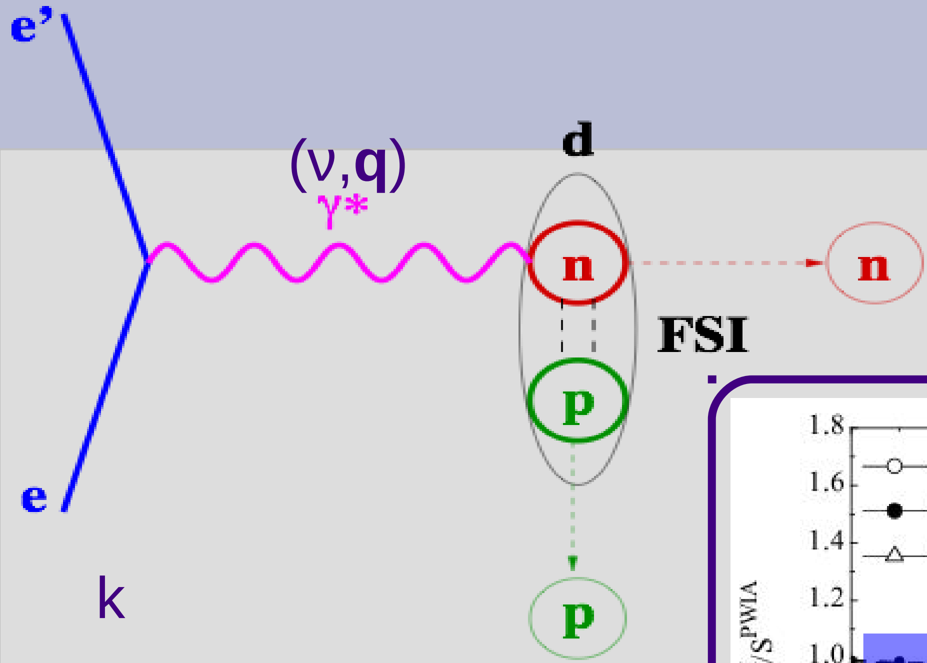

Melnitchouk et al, PLB**335**(94)11



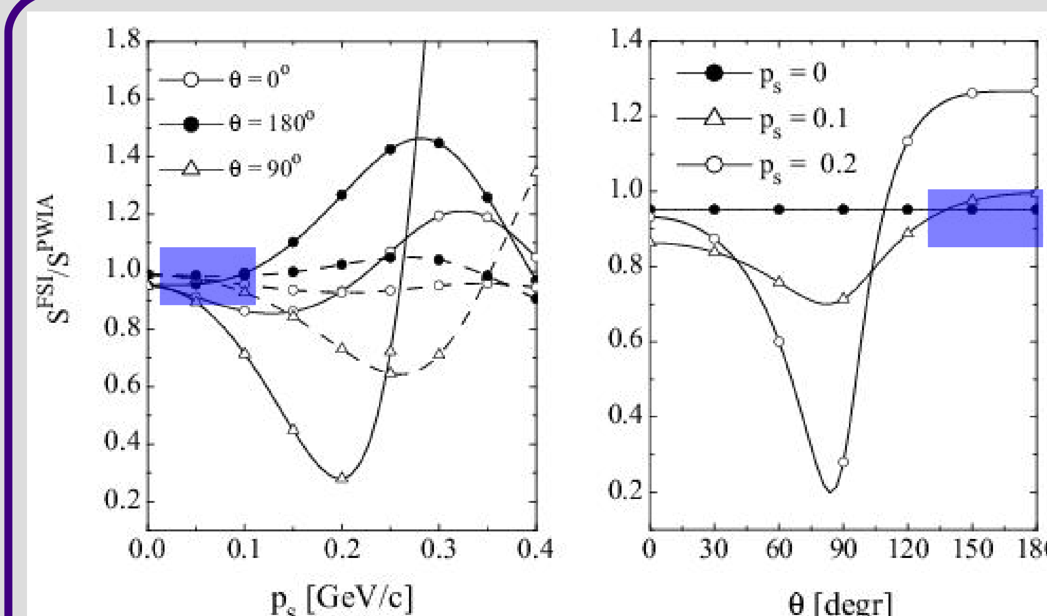

BoNuS "Very Important Protons" (VIPs) for free neutron

*tagged protons outside of VIP region used to study onset of FSIs, etc.

# Final State Interactions



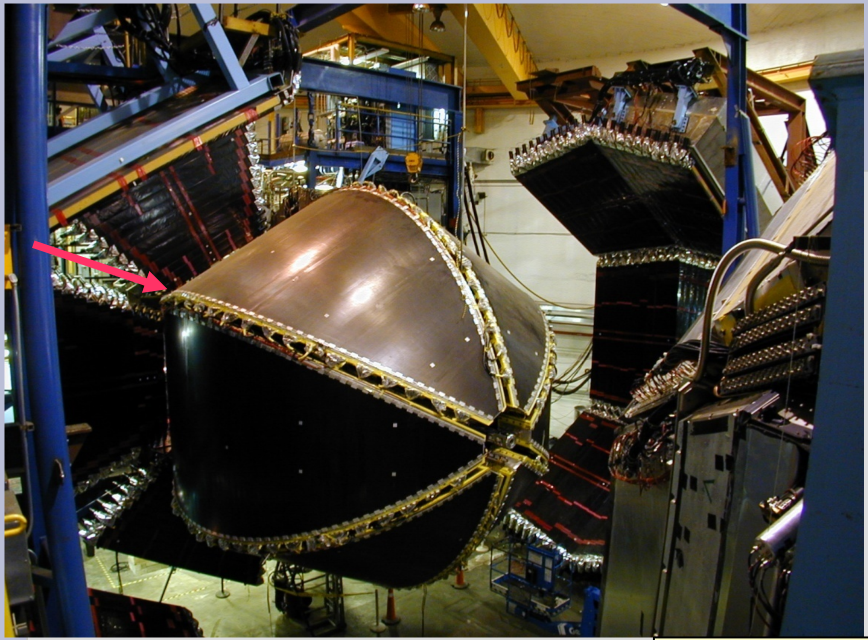

- Struck neutron can interact with the spectator proton
- Proton momentum is enhanced
- FSIs are small at low $p_s$ and large $\theta_{pq}$

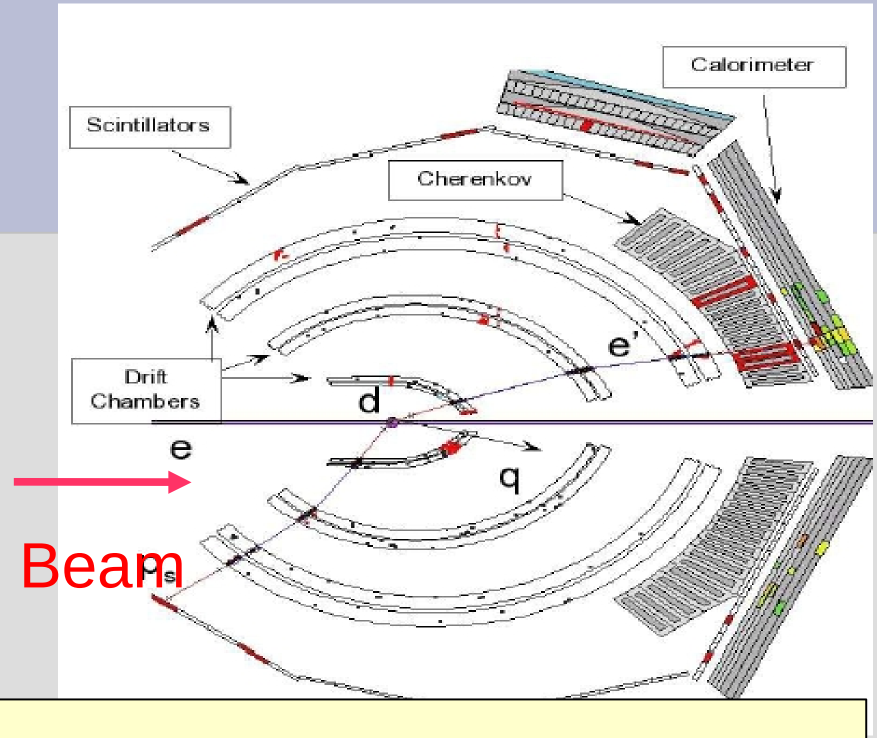


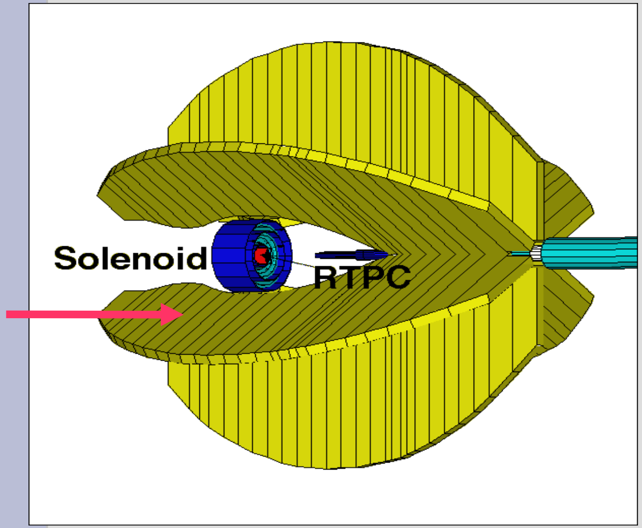

Ciofi degli Atti and Kopeliovich, Eur. Phys. J. A17(2003)133

- Several groups have calculated FSIs
- $\theta_{pq} > 110^o$ and $p_s$<100 MeV/c greatly reduces FSIs

# Tag inclusive e' in CLAS Spectrometer



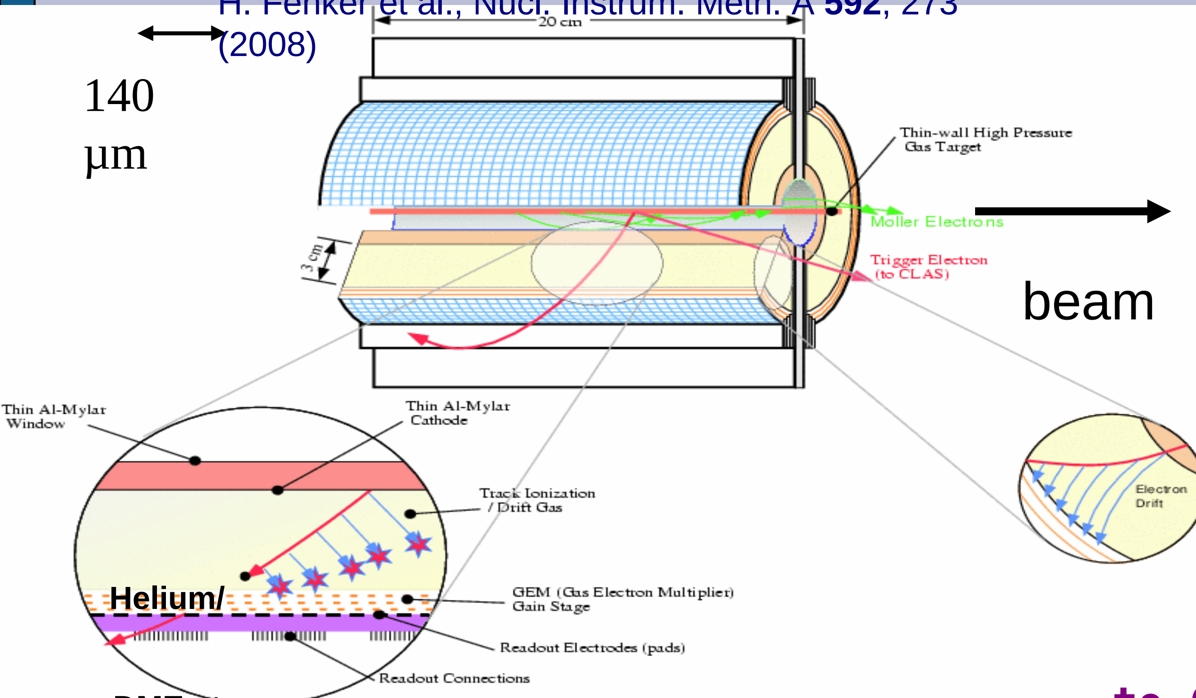



- Detect electrons in CLAS spectrometer
- Detect slow protons in radial time projection chamber (RTPC)
- Moller electrons bottled up by Solenoid field around target
- Solenoid field allows momentum determination

# Tag spectator proton in RTPC

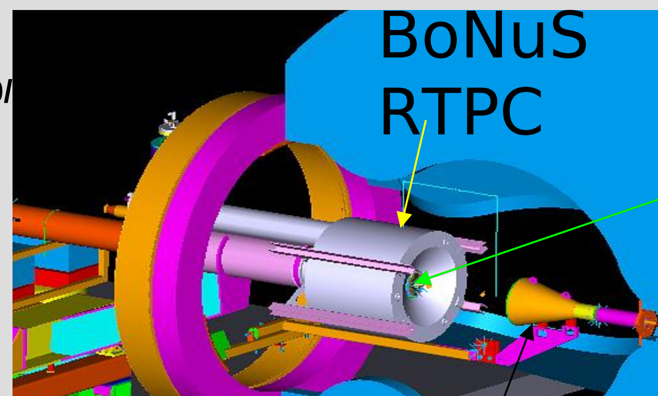
H. Fenker et al., Nucl. Instrum. Meth. A **592**, 273 (2008)

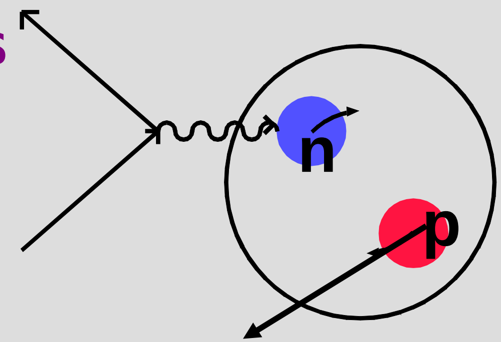



Fit RTPC points to determine helix of proton trajectory.

Momentum determined from track curvature in solenoid field.

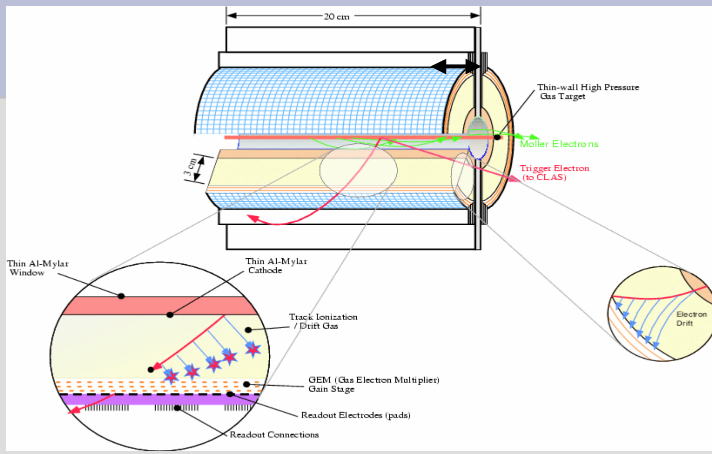
dE/dx along track in RTPC also provides momentum information and PID.

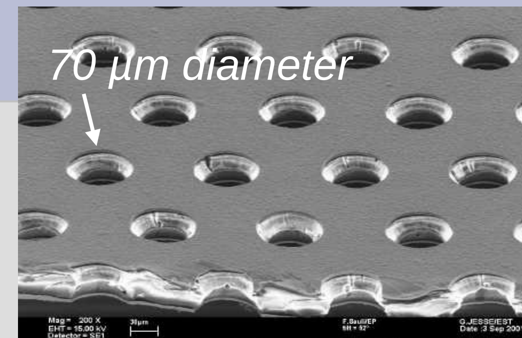


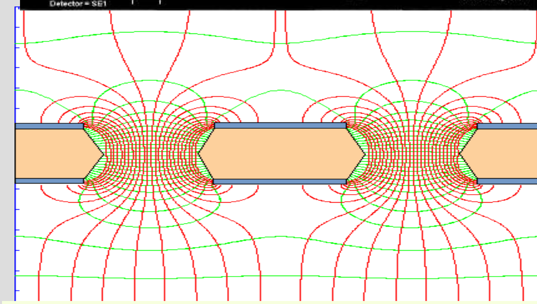



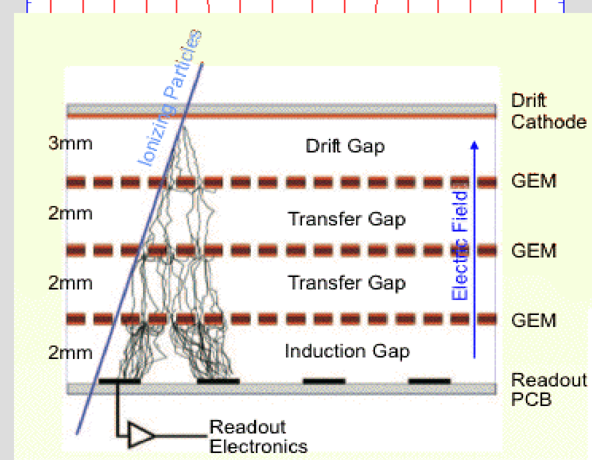
# Charge Amplification using Gas Electron Multipliers (GEMs)

F. Sauli et al., NIMA 386 (1997) 531



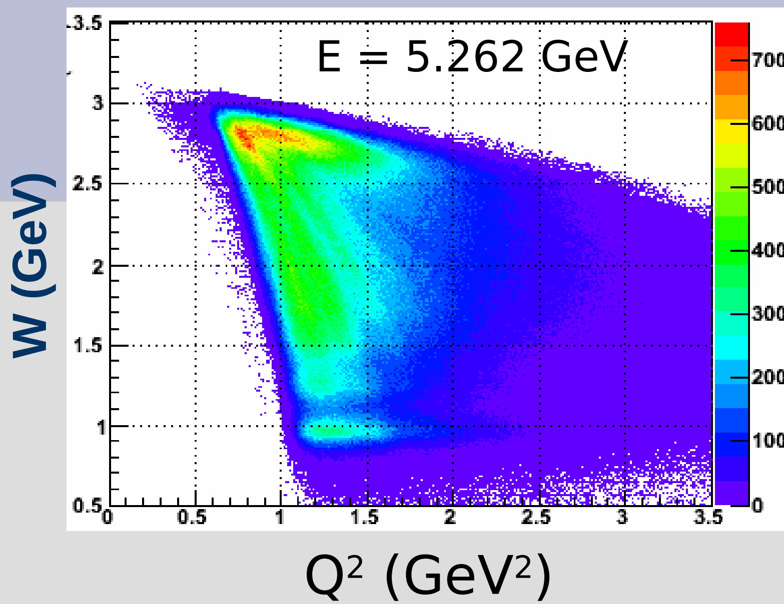



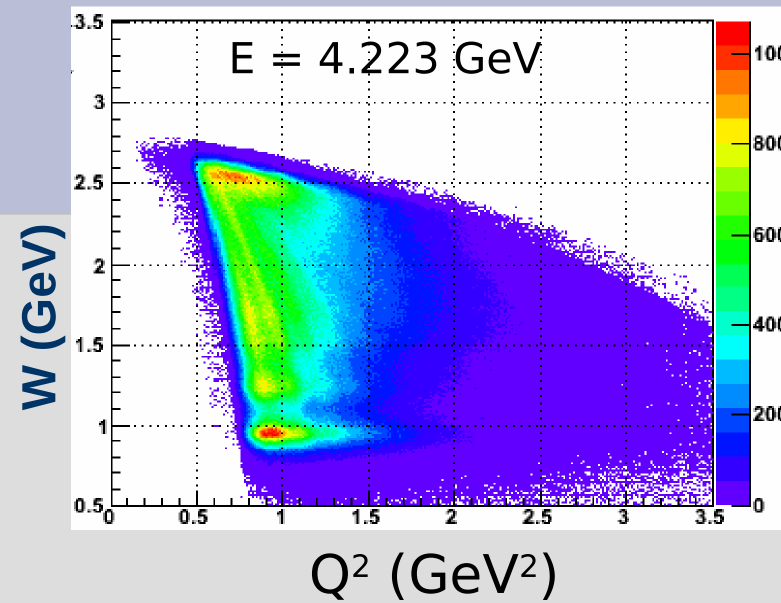



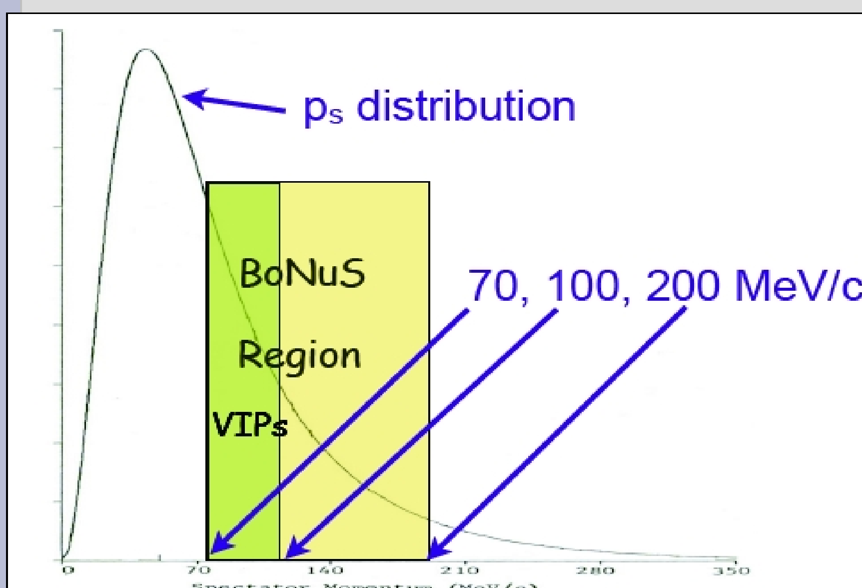


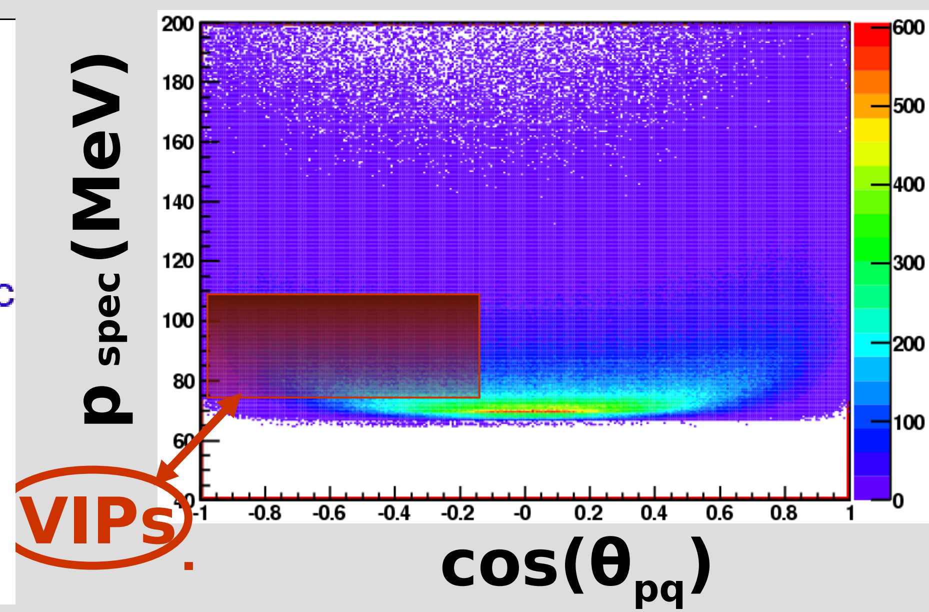

- → Holes chemically etched in kapton layered front and back with copper.
- → Gas amplification due to large local field in holes.
- → More amplification from more GEM layers.
- → Can operate at very high rates.
- → Can conform to curved geometries

# Kinematic Coverage



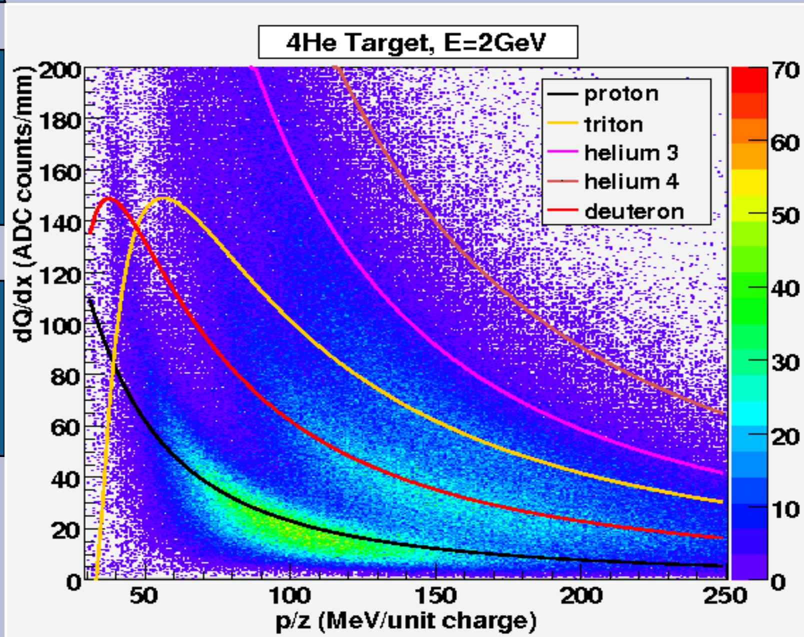



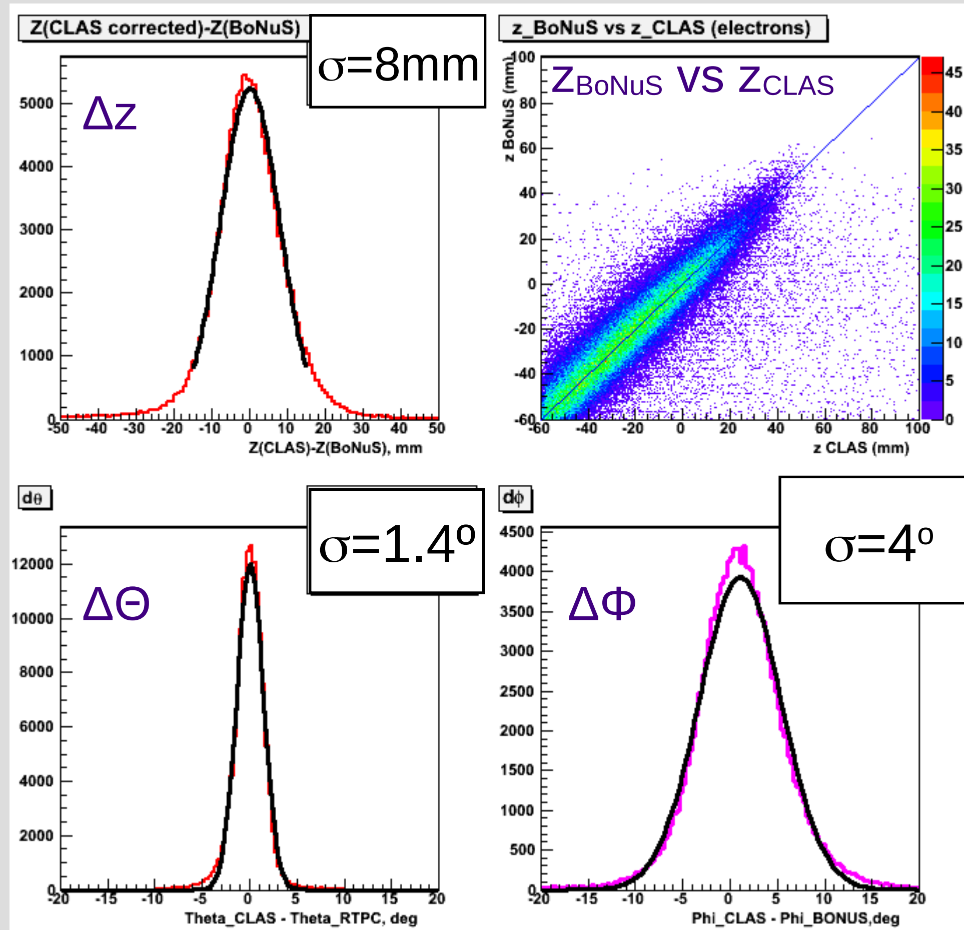
BONuS detector able to cover large enough range in spectator momentum / angle

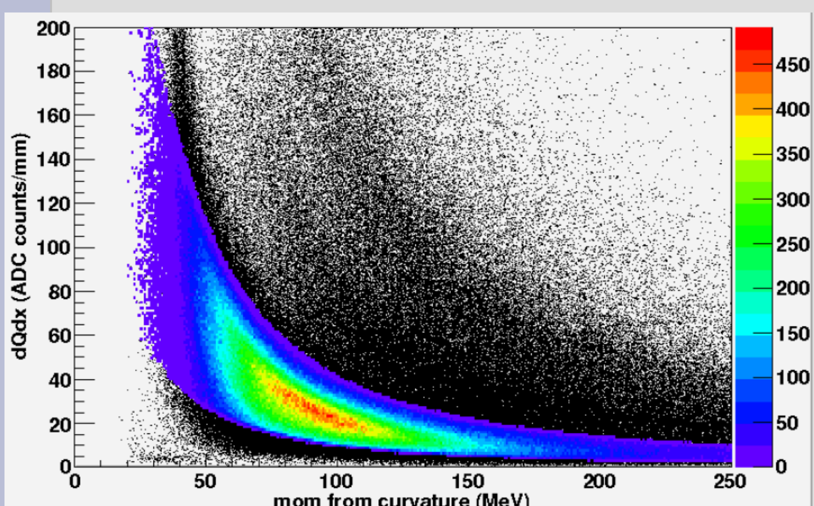
To probe onset of FSIs and validate the spectator tagging procedure

# RTPC Performance




- Upper left: dE/dx vs. p/Z for He target
- Lower left: dE/dx vs. p for deuterium target
- Below RTPC+CLAS resolution for common $e^-$ events



# Ratio Method

First make experimental ratio:

$$R_{\exp} = \frac{N_{\text{tagged}}(\Delta Q^2, \Delta W^*, \Delta^{(\text{VIP})}\vec{p}_s)/A_e(Q^2, W^*)}{N_{\text{incl}}(\Delta Q^2, \Delta W)/A_e(Q^2, W)}$$

$N_{tagged}$ is yield with VIP after accidental subtraction passing:

$P_s$ < 100 MeV/c, $\theta_p$ > 110

$A_e$ : electron acceptance in CLAS (*mostly cancels!*)

In terms of structure function ratio:

$$R_{\exp} = \frac{F_2^n(W^*, Q^2)}{F_2^d(W, Q^2)} \underbrace{\int_{\text{VIP}} d\alpha_s dp_s^{\perp} A_p S(\alpha_s, p_s^{\perp})}_{\mathbf{I_{VIP}}}$$

$A_p$ : tagged proton

Efficiency * Acceptance

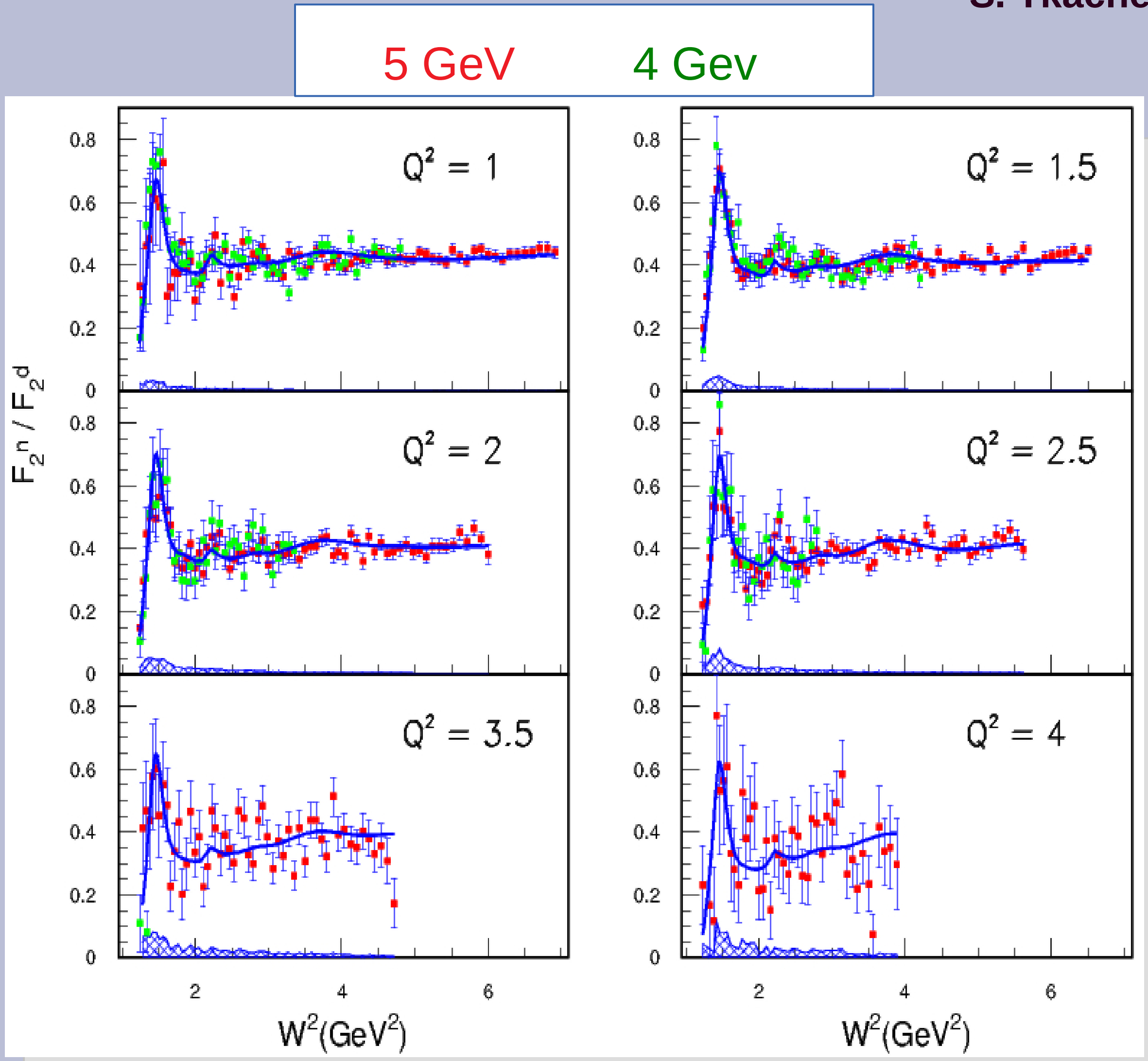
→ Integral $I_{vip}$ is largely independent of W* (x*) and $Q^2$

→ Determined from $R_{exp}$ at x=0.3, where nuclear effects are small using $F_2^n$ / $F_2^d$ from CJ PDF fit.

$$\boxed{\text{Then } \mathbf{F_2^n / F_2^d = R_{exp} * I_{vip}}}$$

# BONuS Results - $F_2^n / F_2^d$

S. Tkachenko et.al PRC 89 (2014) 045206




Curve is fit to inclusive deuteron Cross section using same Weak-binding Convolution formalism as CJ pdf fits.

(see talk by A. Accardi)

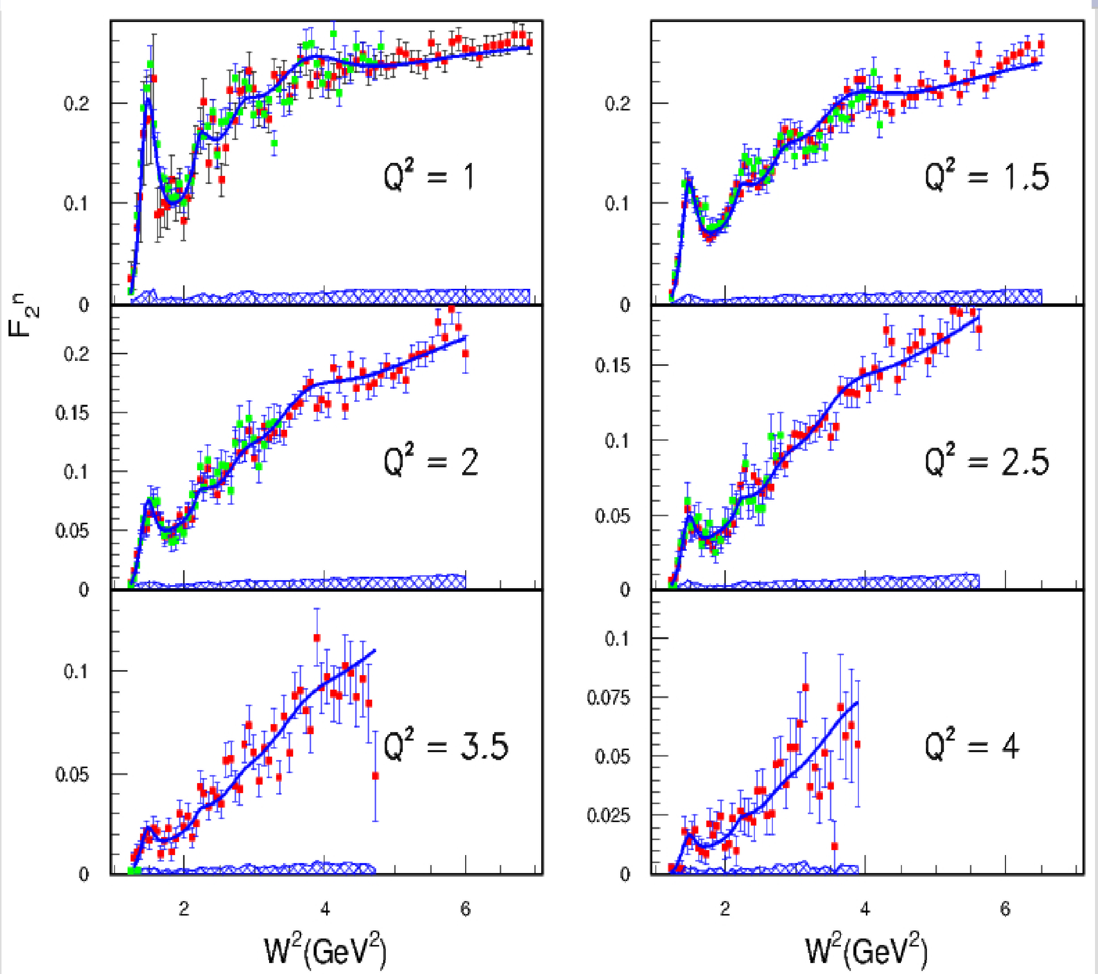
M.E. Christy, N. Kalantarians, J. Ethier, W. Melnitchouk

Proton input is provide by Christy-Bosted fit.

→ BONuS data *not* included in This version of fit.

# BONuS Results - $F_2^n$

5 GeV 4 Gev




→ $F_2^n = F_2^n/F_2^d * F_2^d$

with $F_2^d$
from inclusive deuteron Fit

→ Resonant structure clearly visible

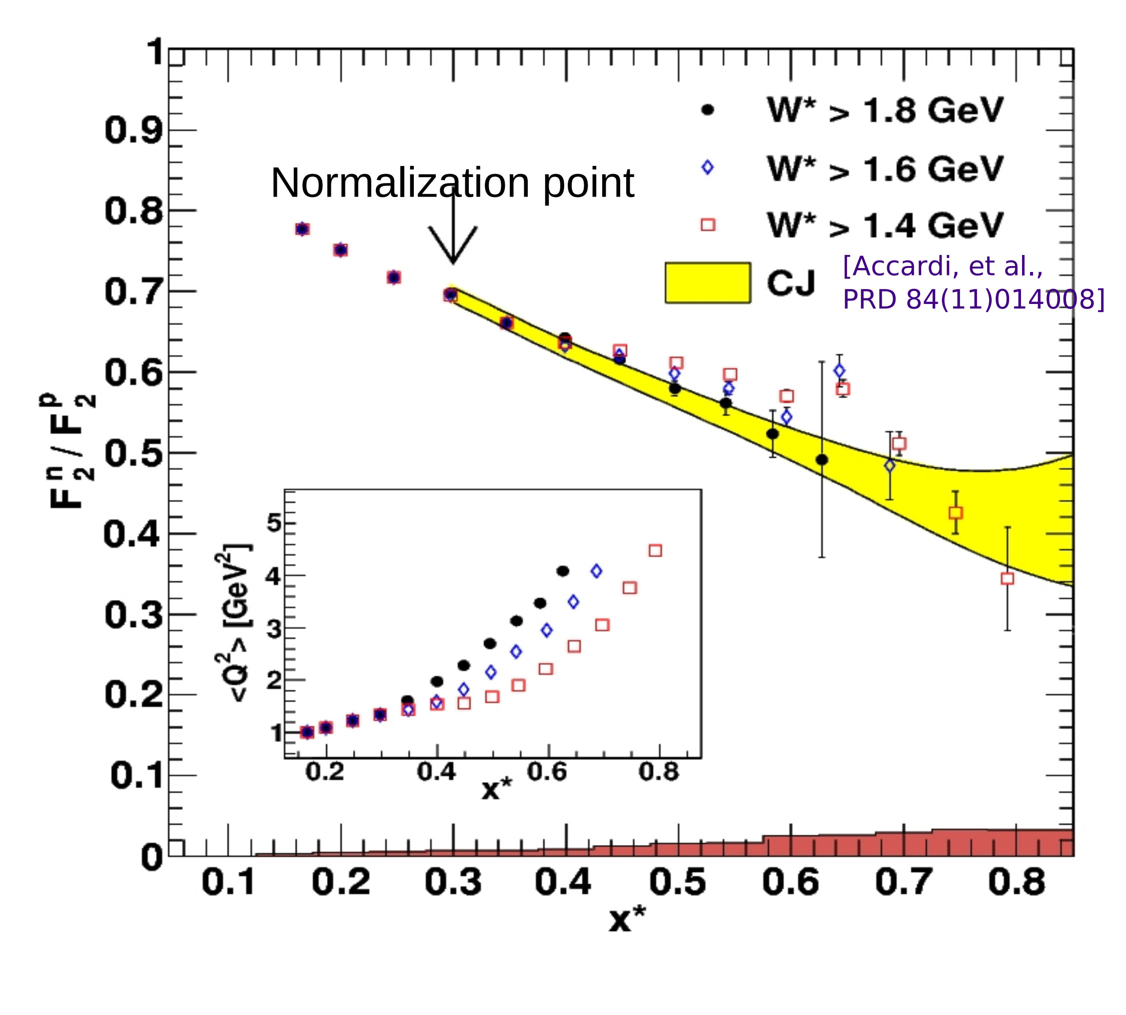
=> study local Q-H duality

→ Weak binding convolution fit describes data reasonably well.

=> No tension between BONuS ratio and inclusive deuteron cross sections

# Results on $F_2^n / F_2^p$

N.Baillie et al., PRL 108 (2012) 199902




→ $F_2^n/F_2^p = F_2^n/F_2^d * F_2^d/F_2^p$ with $F_2^d/F_2^p$ from Bosted/Christy fits PRC77(08)065206, PRC81(10)055213

→ Trend in x consistent with CJ11.

→ Below normalization point $Q^2$ less than CJ scale point.

→ Lower W* cuts reduce stat. uncertainty, but increase resonant contribution at x >0.6

# Additional (Bonus) Physics results

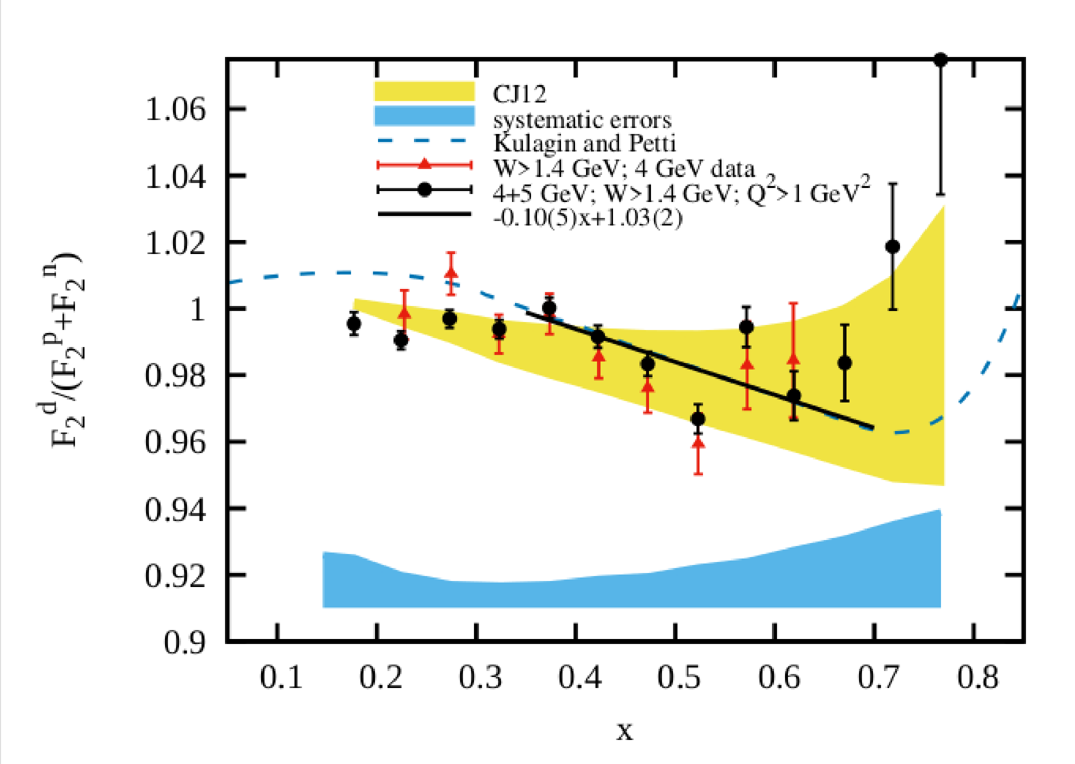
## EMC effect in the deuteron

$F_2^N/F_2^D = \underbrace{F_2^n/F_2^D}_{\text{BONuS}} + \underbrace{F_2^p/F_2^D}_{\text{Global fit including precision Hall C data*}}$

BONuS

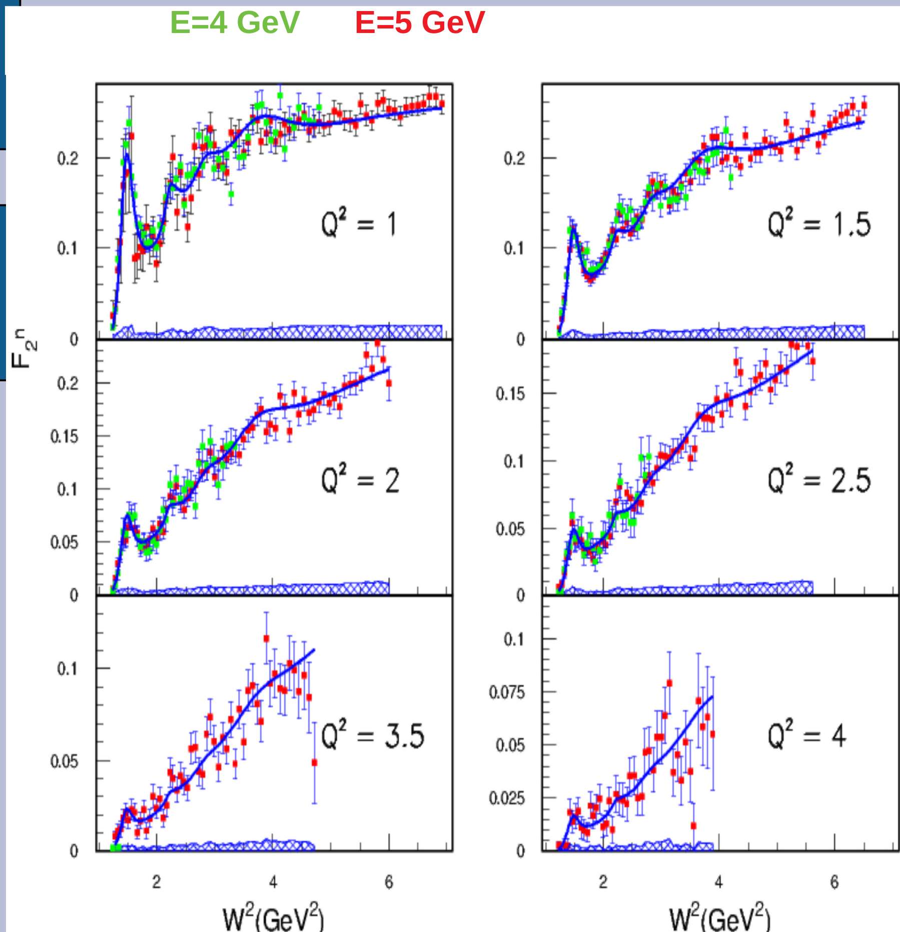
Global fit including
precision Hall C data*

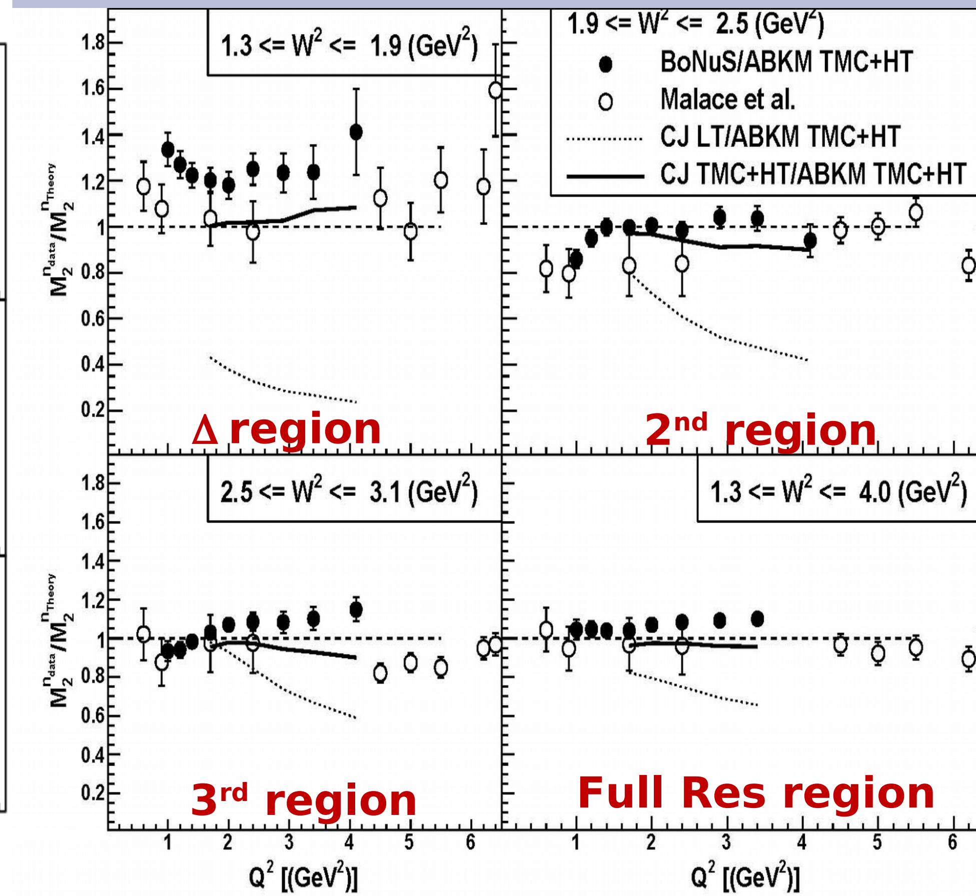
* can also be measured in CLAS



# Neutron Resonance region and Quark-Hadron duality

**Local duality integrals compared to pQCD vs $Q^2$**

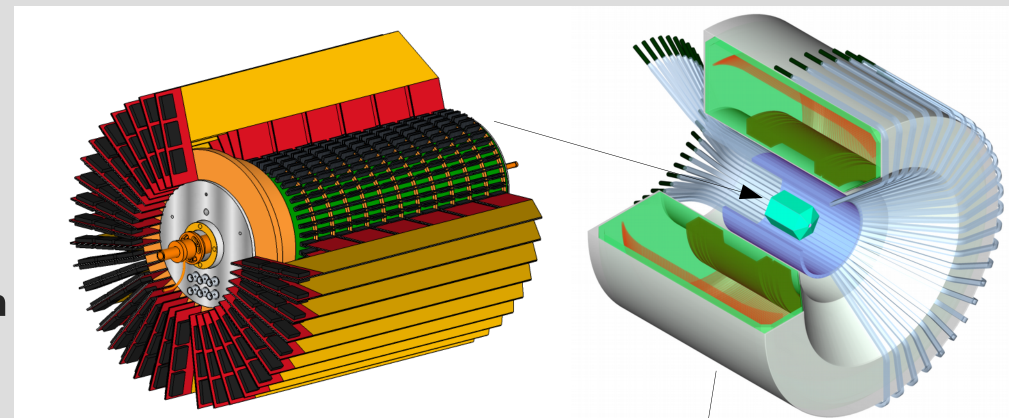



- Duality observed for neutron locally within: ~30% for $\Delta$ and ~10% for higher W
- As for the proton, TM and H-T must be part of the scaling curve

# The future of BONuS

The BONuS experiment with 12 GeV JLab (BONuS12) was approved as a "high impact" experiment utilizing the upgraded CLAS12 spectrometer



→ **Improved gain uniformity**

**Better momentum resolution**

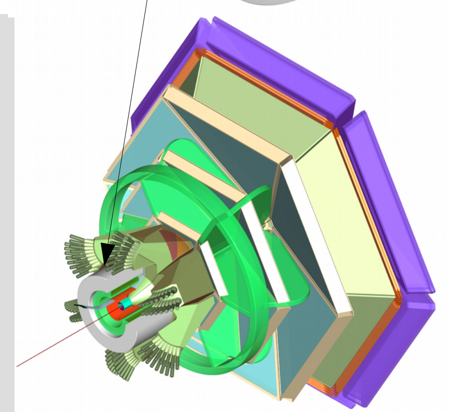
→ **Increased drift region 3cm → 4cm**

**Better track sampling**

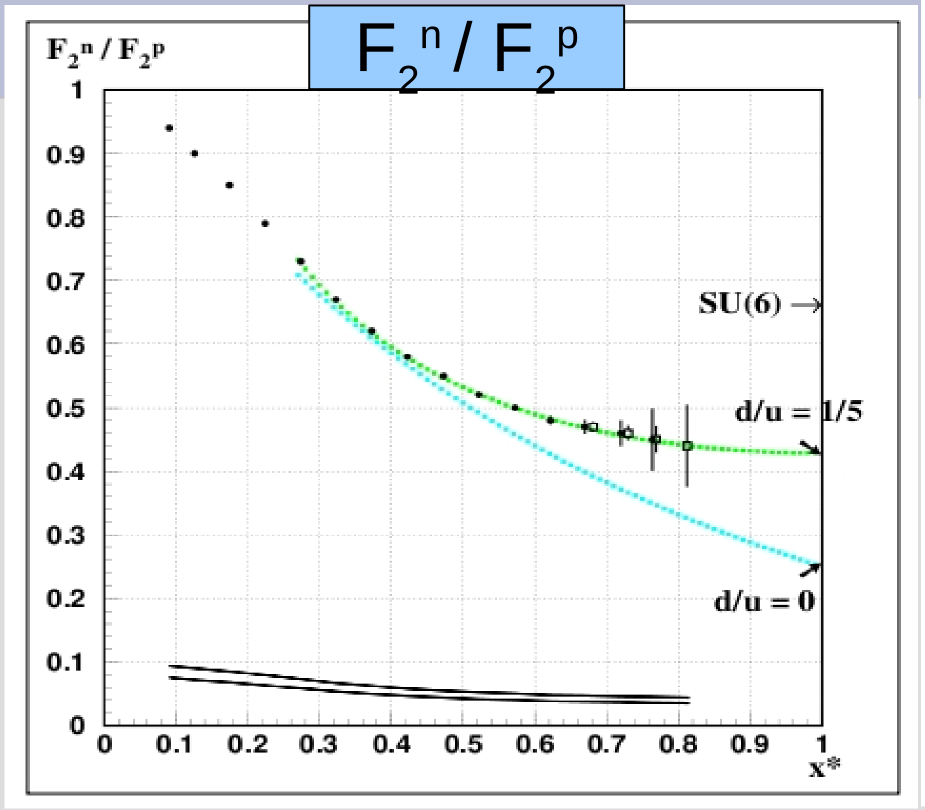
→ **Improve $\phi$ acceptance**

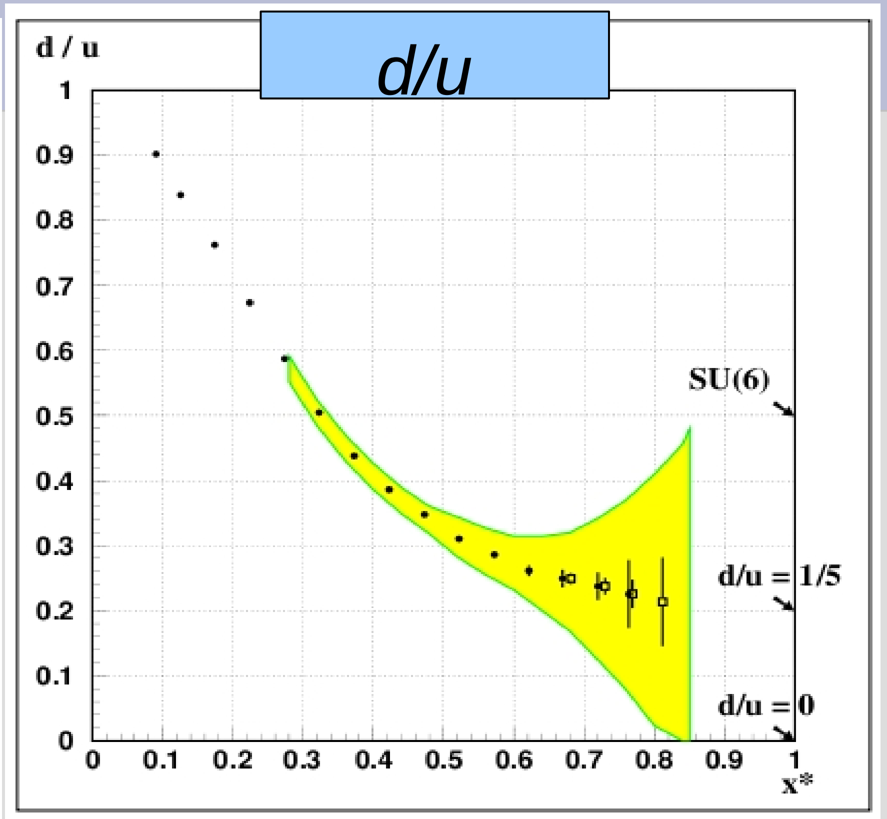
→ **Doubled detector length and improve front end**

**Electronics => increase luminosity to** $2\times10^{34} cm^{-2} s^{-1}$



# Expected BONuS12 precision

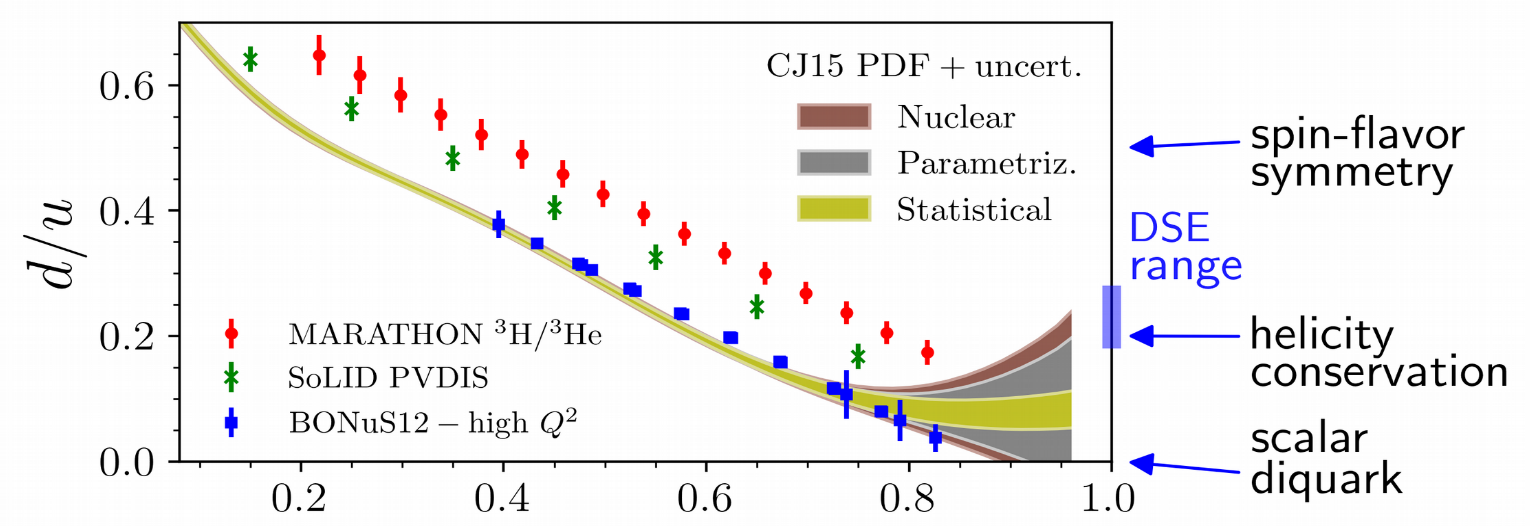


# Multiple experiments in JLab 12 GeV era to determine *d/u* at high-*x*

# With *different* systematics

- MARATHON - 3H / 3He mirror nuclei (see next talk by Makis)
- SoLID PVDIS (see talk by Krishna Kumar)
- BONuS12 – proton recoil tagging




A. Accardi

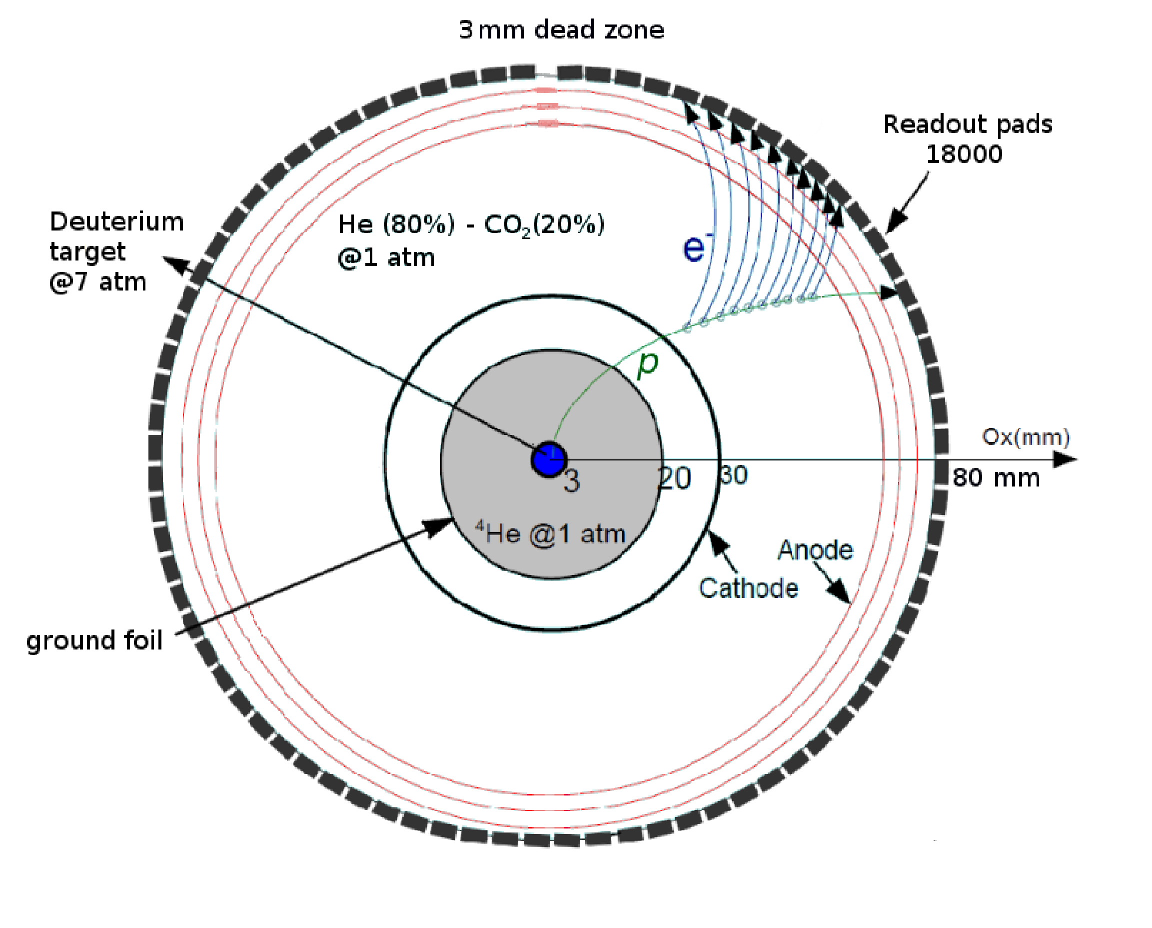
# BONuS12 RTPC Overview

→ Utilize CLAS solenoid And radius of curvature to determine momentum.

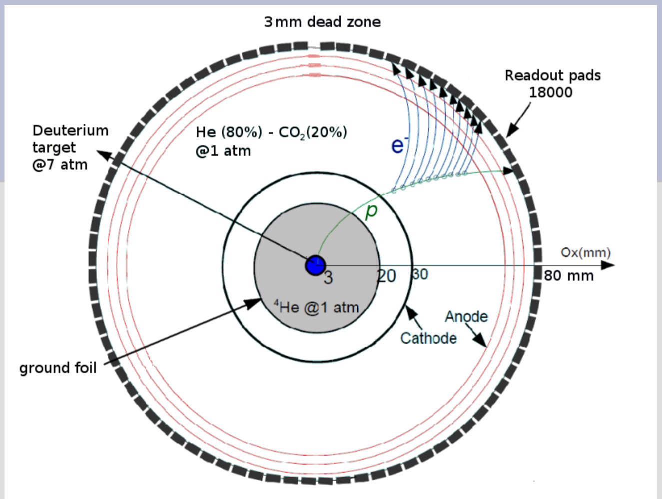
→ Proton momentum reconstruction down to 70 MeV/c.

→ Utilize drift time to project to 'hit' position.

→ Amplification of ionization signal utilizes 3 Gas Electron Muliplier (GEM) Layers



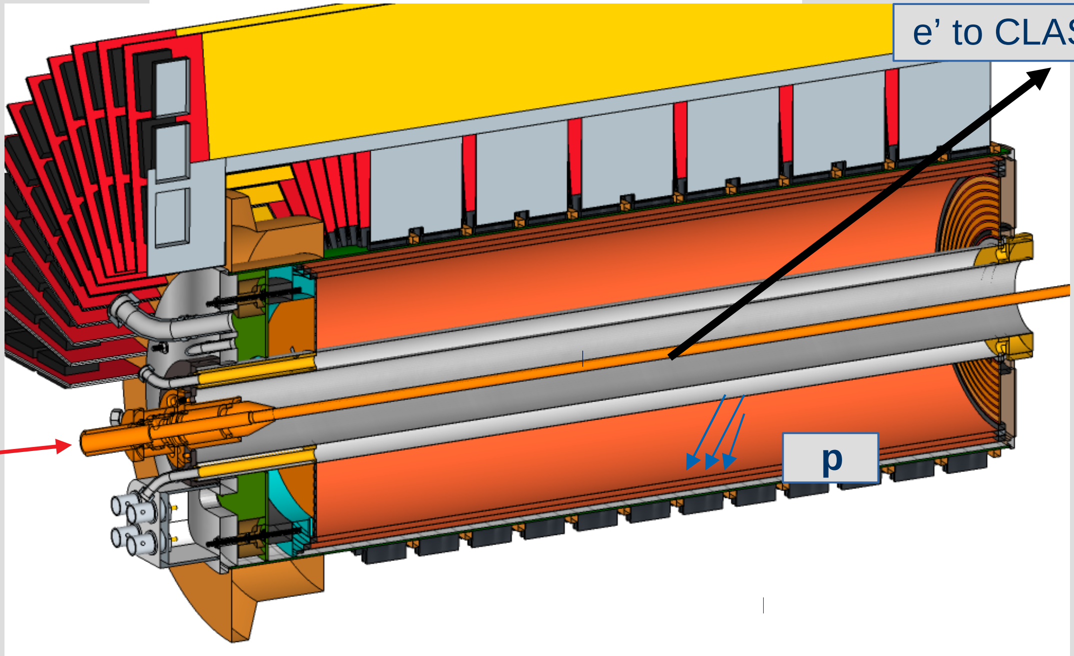
# BONuS RTPC General Specifications




- → 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

=> ~18k channels

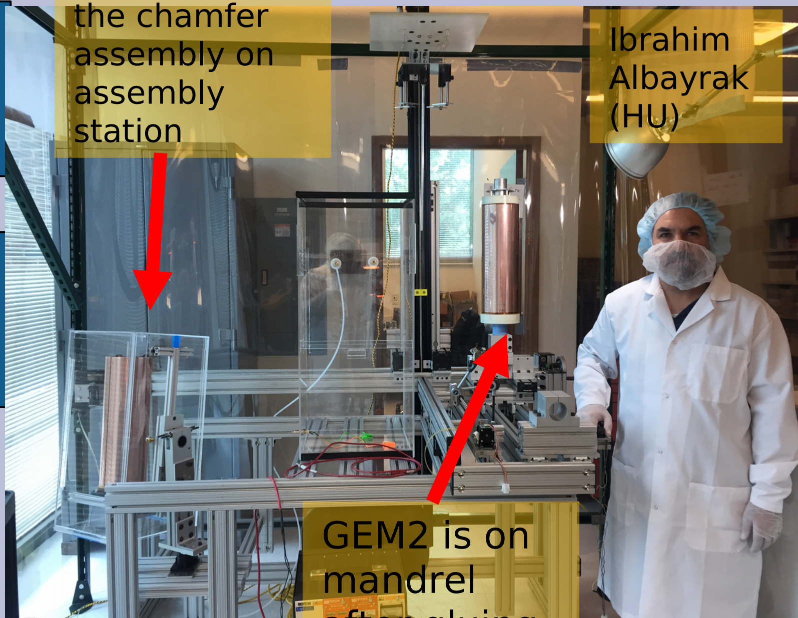
Beam



# RTPC Construction at Hampton U.

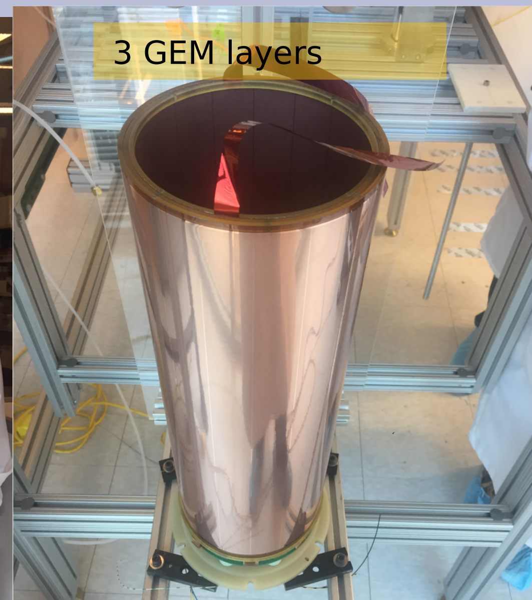
GEM1 is on the chamfer assembly on assembly station

Ibrahim Albayrak (HU)

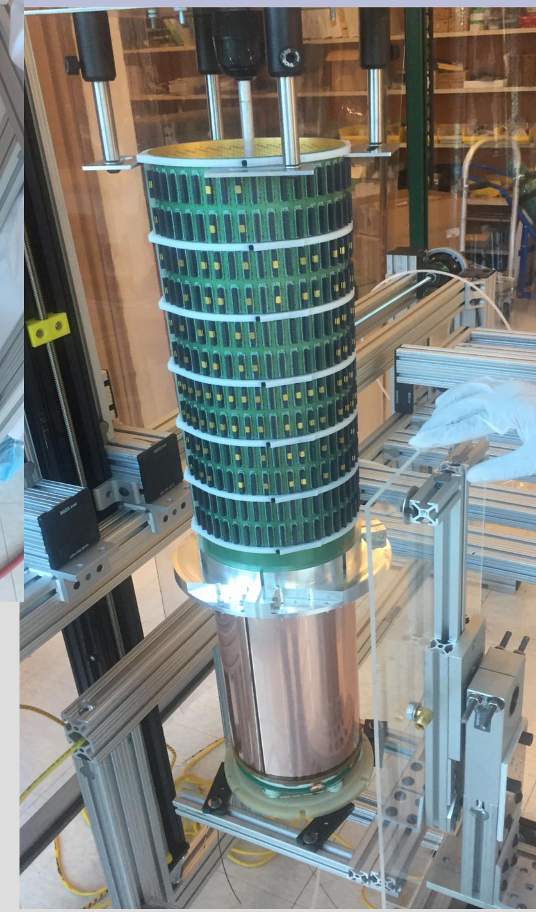


GEM2 is on mandrel after gluing

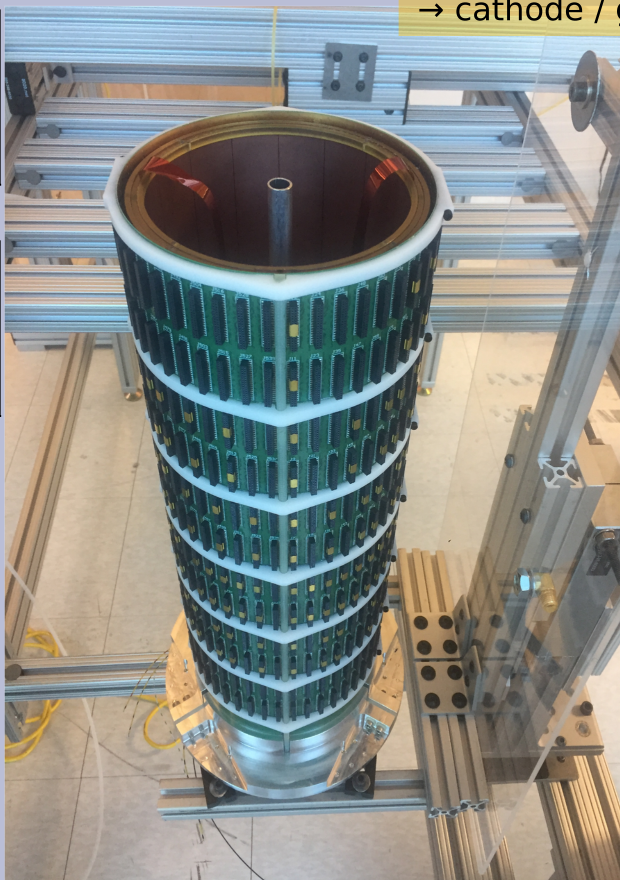
3 GEM layers

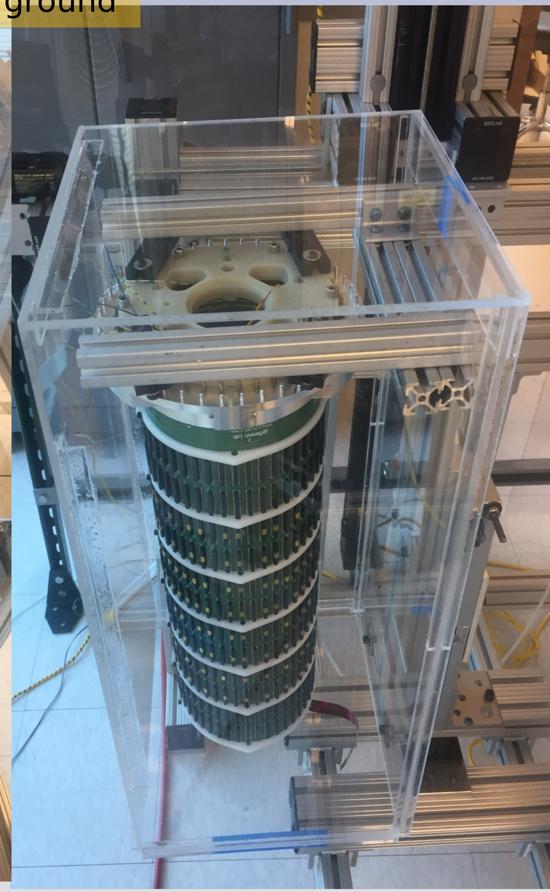


Charge Readout Layer “Padboard” Installation

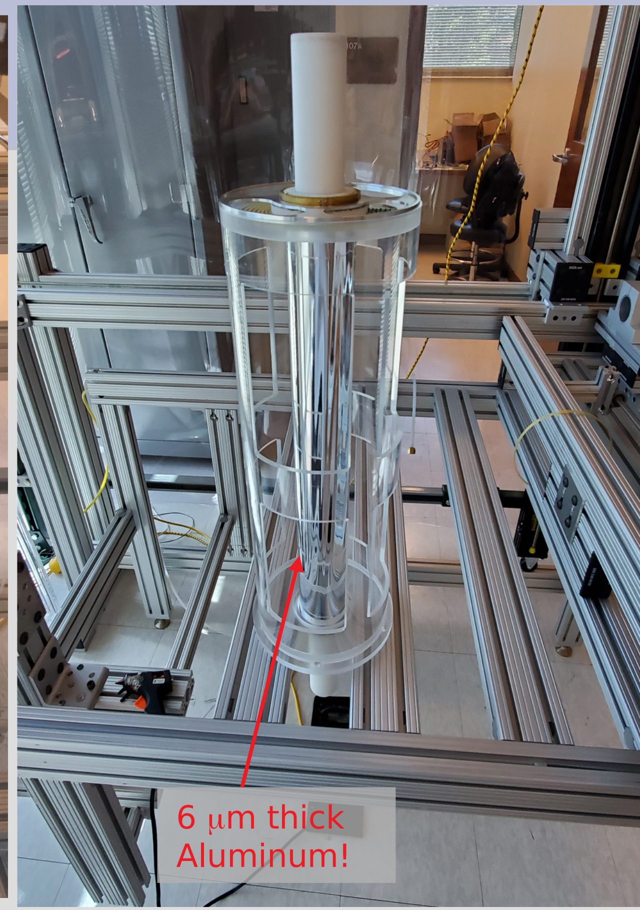


Detector sans:
→ downstream fieldcage / plate
→ cathode / ground





Cathode / ground assembly tension transfer test




→ Completion of detector imminent

→ Testing at JLab to begin in next few weeks.

# BONuS12 Status and Timeline

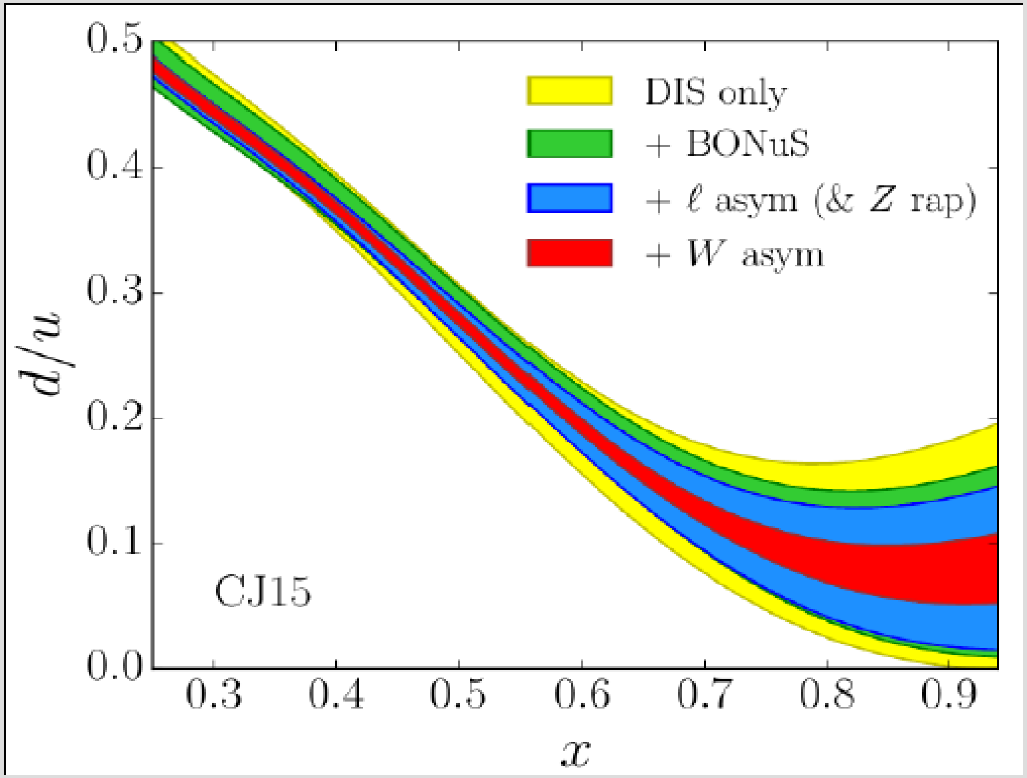
Aug 30, 2019:  Detector ready for testing at JLab

January 2019:  Detector installed in CLAS

February 2019:  BONuS12 run begins

# Thanks

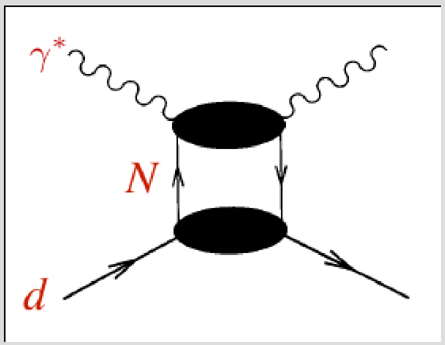
# Recent CJ15 PDFs



# Deuteron corrections

- No free neutron! Best proxy: Deuteron
  - Parton distributions (to be fitted)
  - nuclear wave function (AV18, CD-Bonn, WJC1, ...)
  - Off-shell nucleon modification (model dependent)

Theoretical uncertainty




y: lightcone momentum fraction of d carried by N

γ: kinematic factor

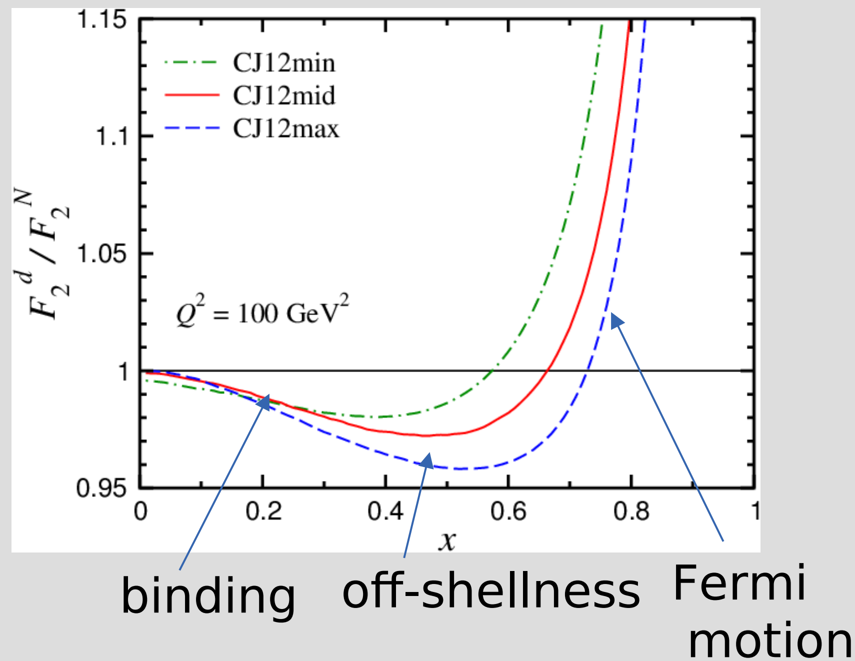
$$F_2^d(x,Q^2) = \int_x dy\; f(y,\gamma)\; F_2^N(x/y,Q^2) + \delta^{(\text{off})} F_2^d$$

$N=p+n$

nucleon momentum distribution in $d$ ("smearing function")

off-shell correction

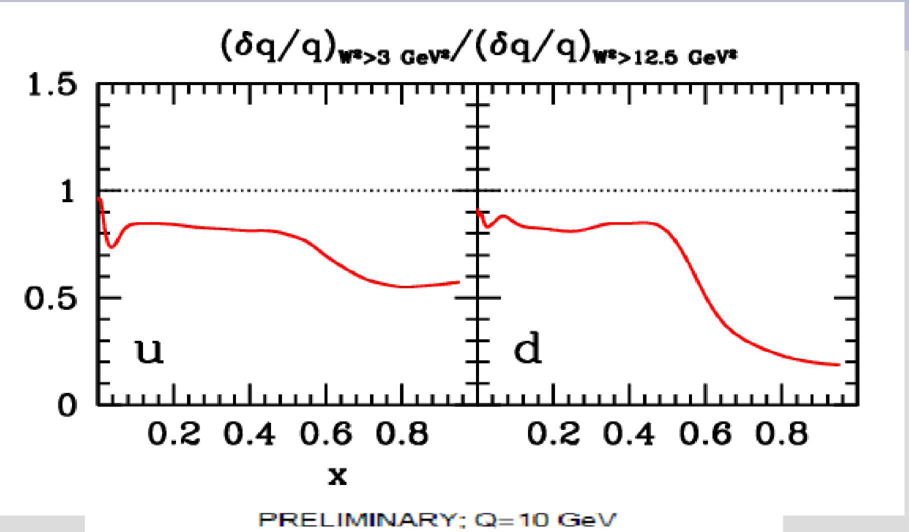
Bound vs. free proton+neutron



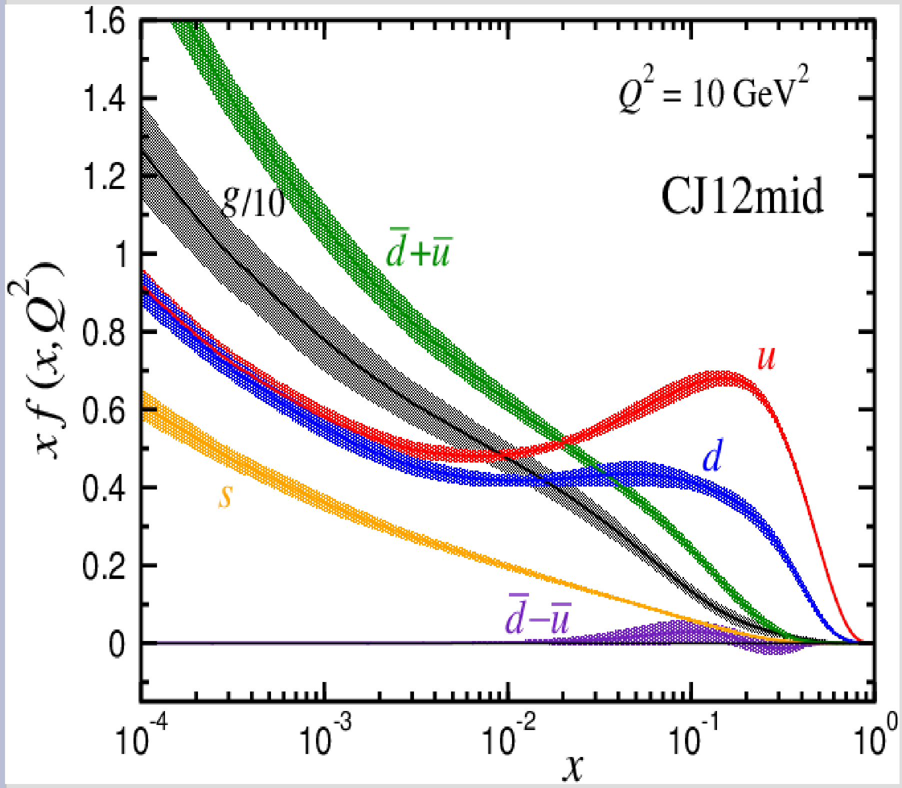
# CJ12 parton distributions

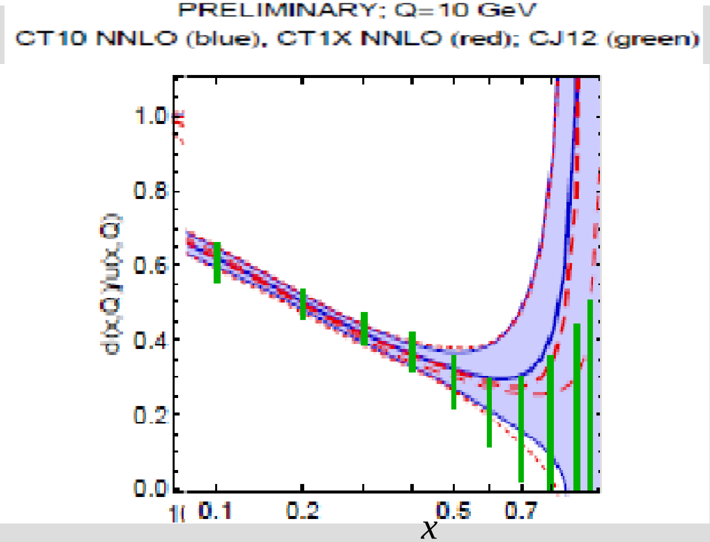
*Owens, Accardi, Melnitchouk, PRD87 (2013) 094012*

**Large reduction in *d*-quark error:**

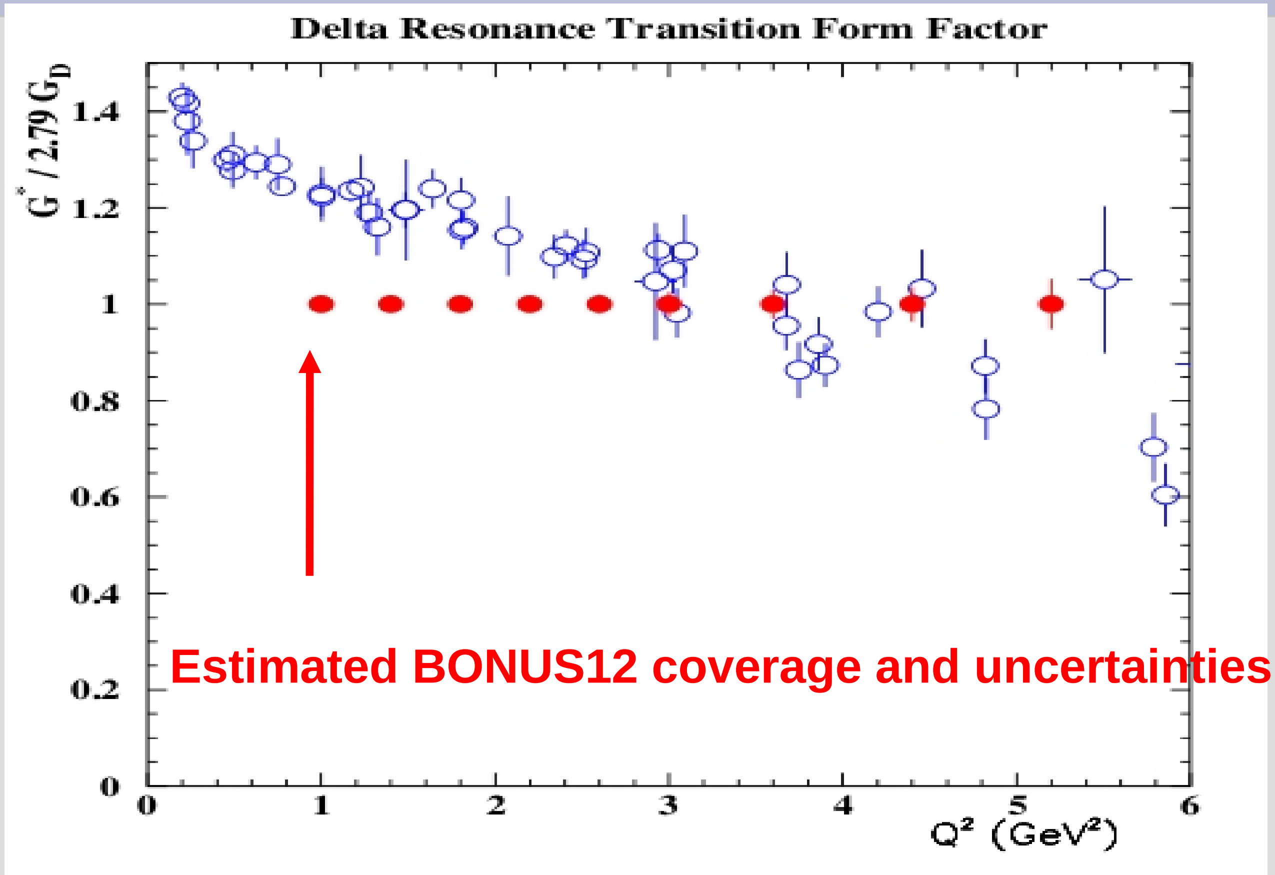



**All-x parton distributions:**

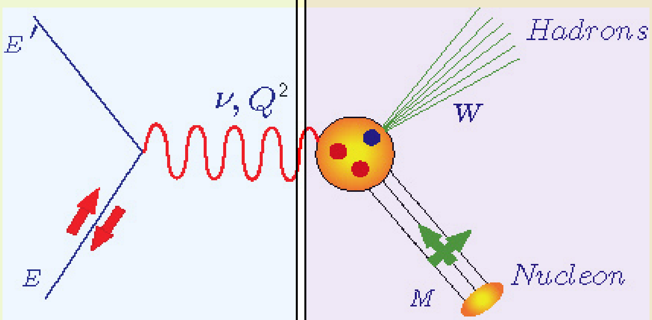


# Δ transition form factor from neutron with Bonus1



# cattering of virtual photons from nucleon




Calculable in Quantum Electrodynamics (QED)

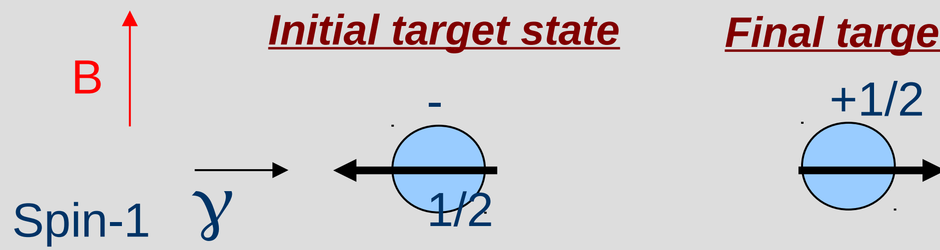
Physics of interest (proton/neutron structure)

→ Virtual photon scatters from nucleon or from constituents.

→ Exchanged photon can have helicity (0,+/-1) corresponding to **B**-field (longitudinal, transverse)

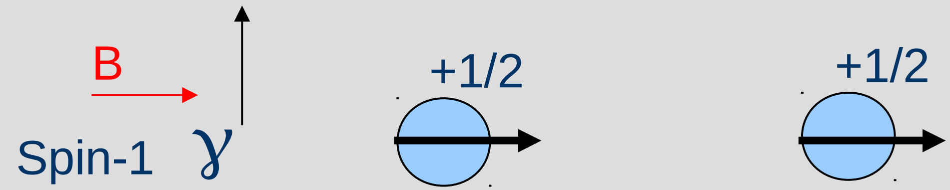
***Initial target state*** ***Final target state***

**Transverse Photon exchange (helicity -1 or +1)**




**Helicity flip**

**Longitudinal Photon exchange (helicity 0)**




**Helicity non-flip**

# Inclusive Charged-Lepton Scattering

$$\frac{d\sigma}{d\Omega\, dE'} \propto \Gamma\ [2xF_1(x,Q^2) + \varepsilon\ F_L(x,Q^2)]$$

$Q^2$ : photon 4-momentum

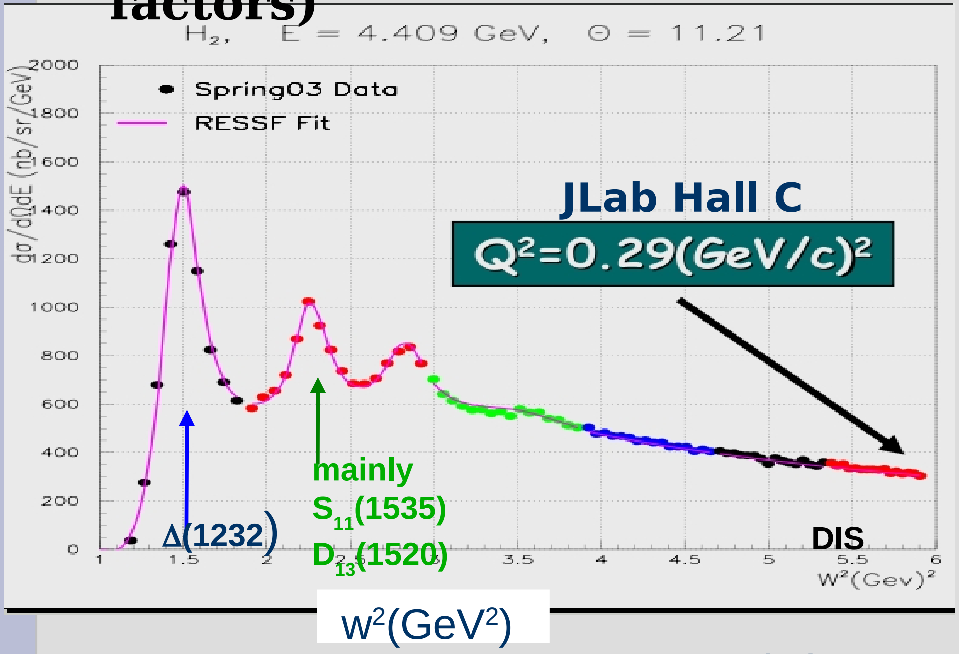
$\nu$: photon energy

W: Final state hadron mass

$x$: Bjorken variable

**Corresponding to absorption of transverse (longitudinal) photon**

**with polarization $\varepsilon$ and flux $\Gamma$ (given by kinematic factors)**

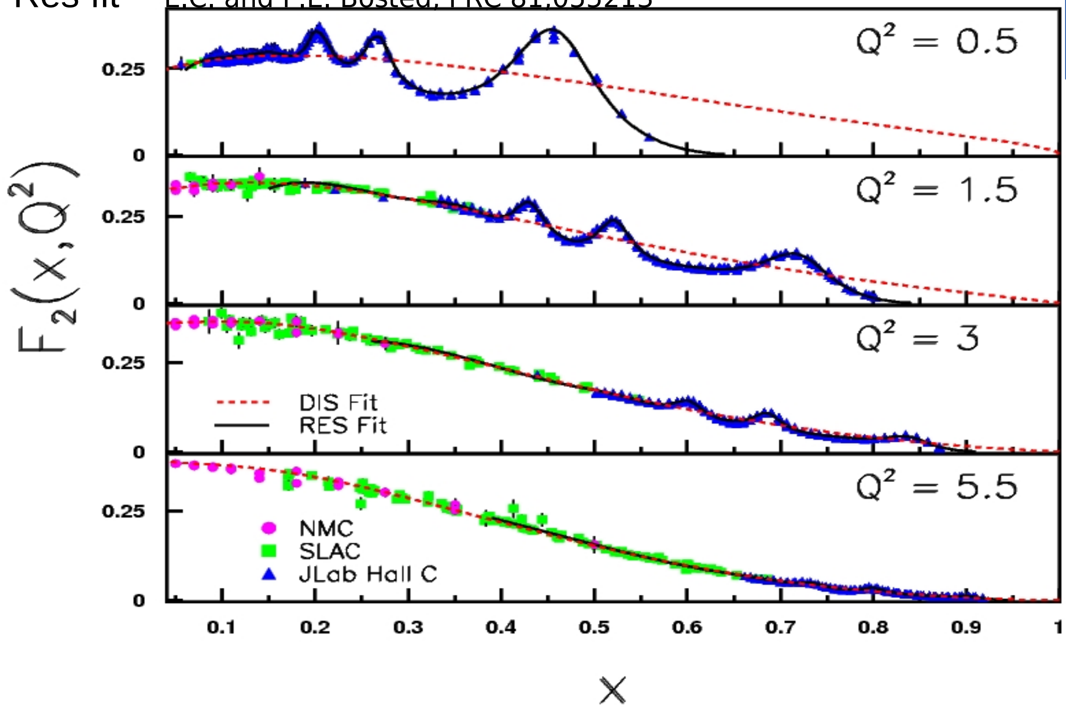



**Study the W (or x), $Q^2$ dependence of the structure functions from**

**Elastic → resonance → Continuum**

# Proton $F_2$ extremely well measured

DIS fit – 'F2ALLM' H.Abramowicz and A.Levy, hep-ph/9712415
Res fit - E.C. and P.E. Bosted, PRC 81,055213




**Deuteron data of same quality**

→ At low $Q^2$ resonances dominate high-*x* behavior

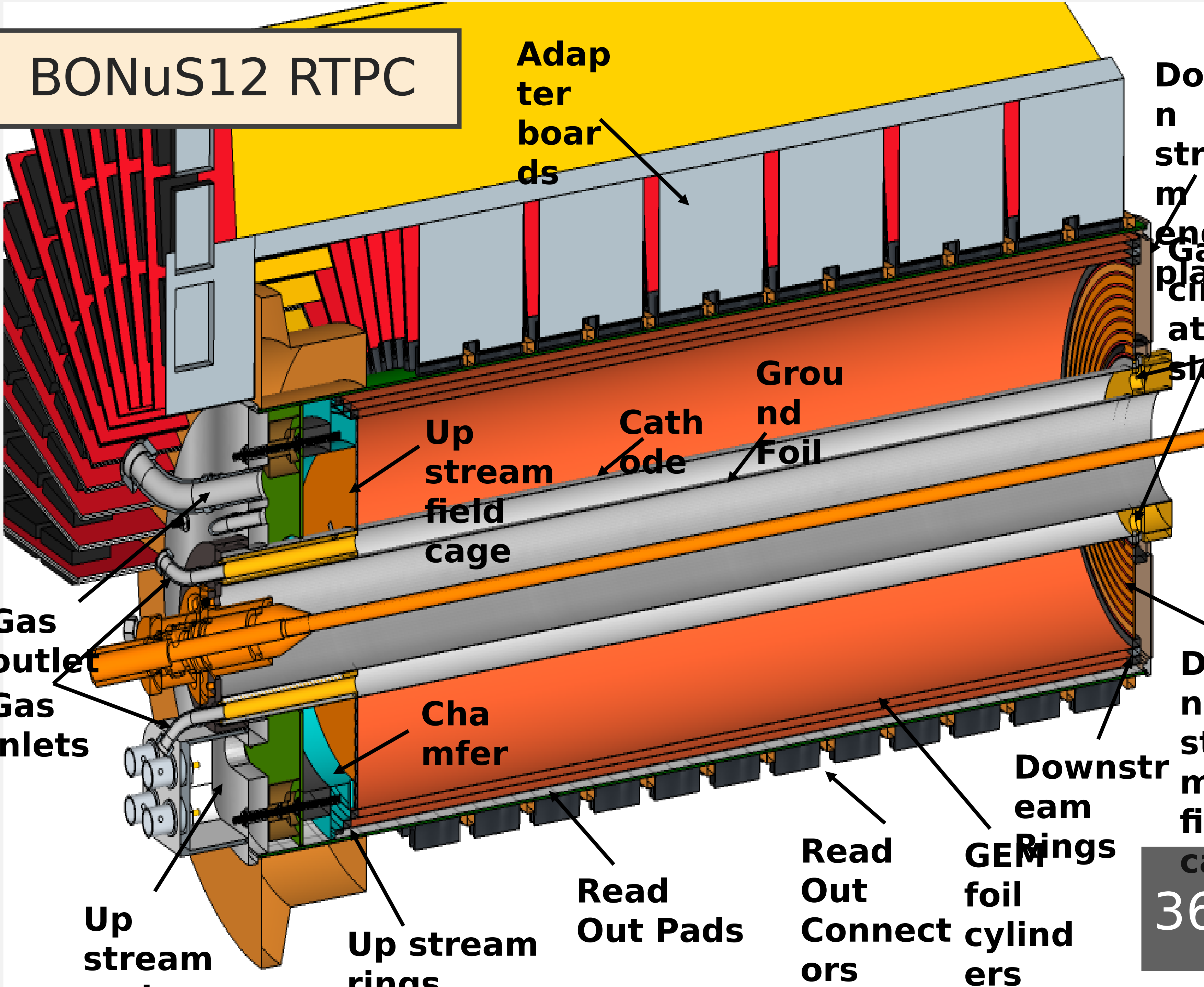
→ As $Q^2$ increases resonances at fixed W Appear to slide down the DIS scaling curve to higher *x*

→ *Resonant production sits a top a smooth non-resonant Background.*

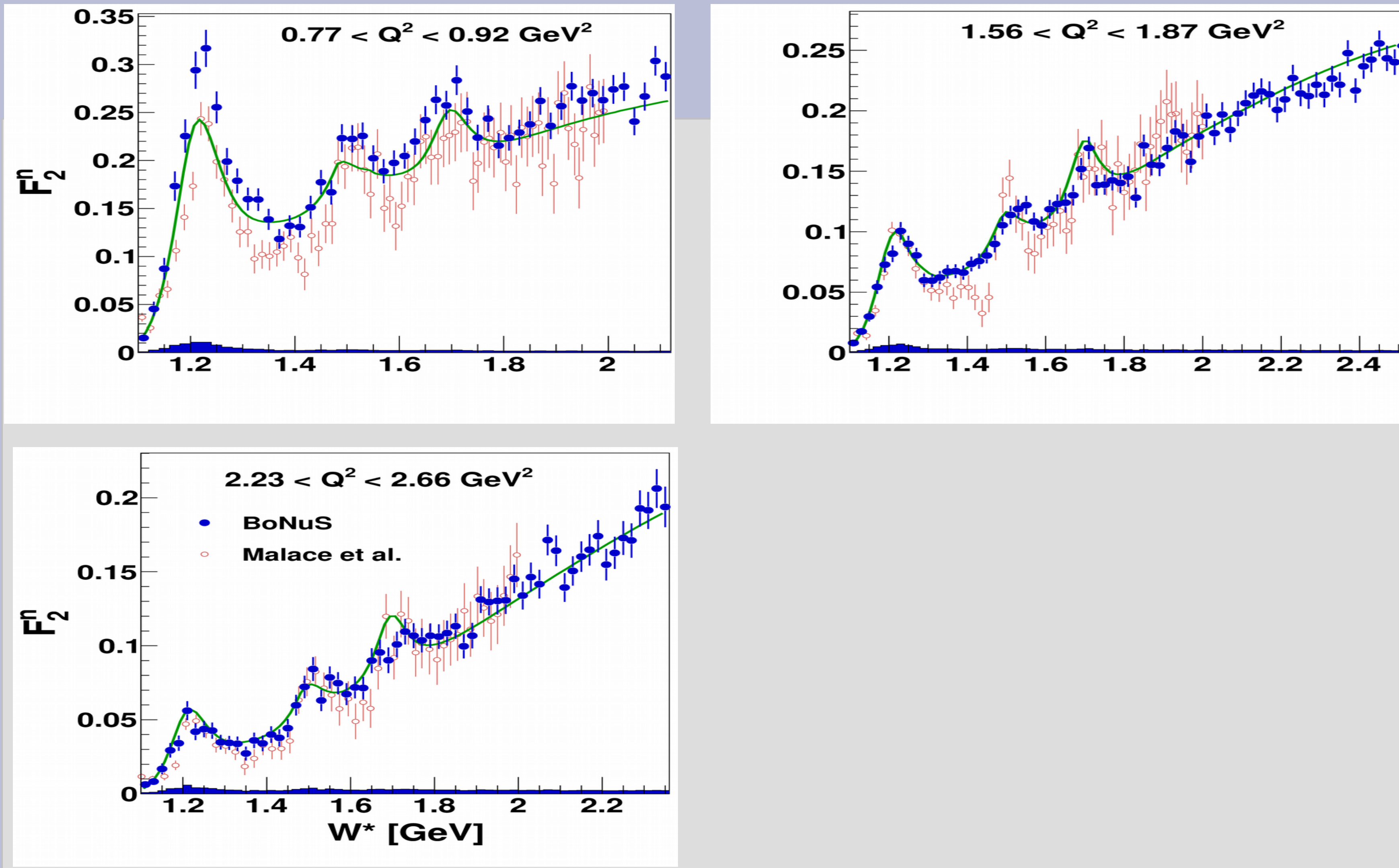
**To model neutrino scattering cross sections we need to know:**

1. DIS (reasonably well known except at large *x*)
2. Resonance (limited measurements of a few resonances, eg $P_{33}$ (1232).
3. Non-Res continuum (very little is known)

# BONuS12 RTPC



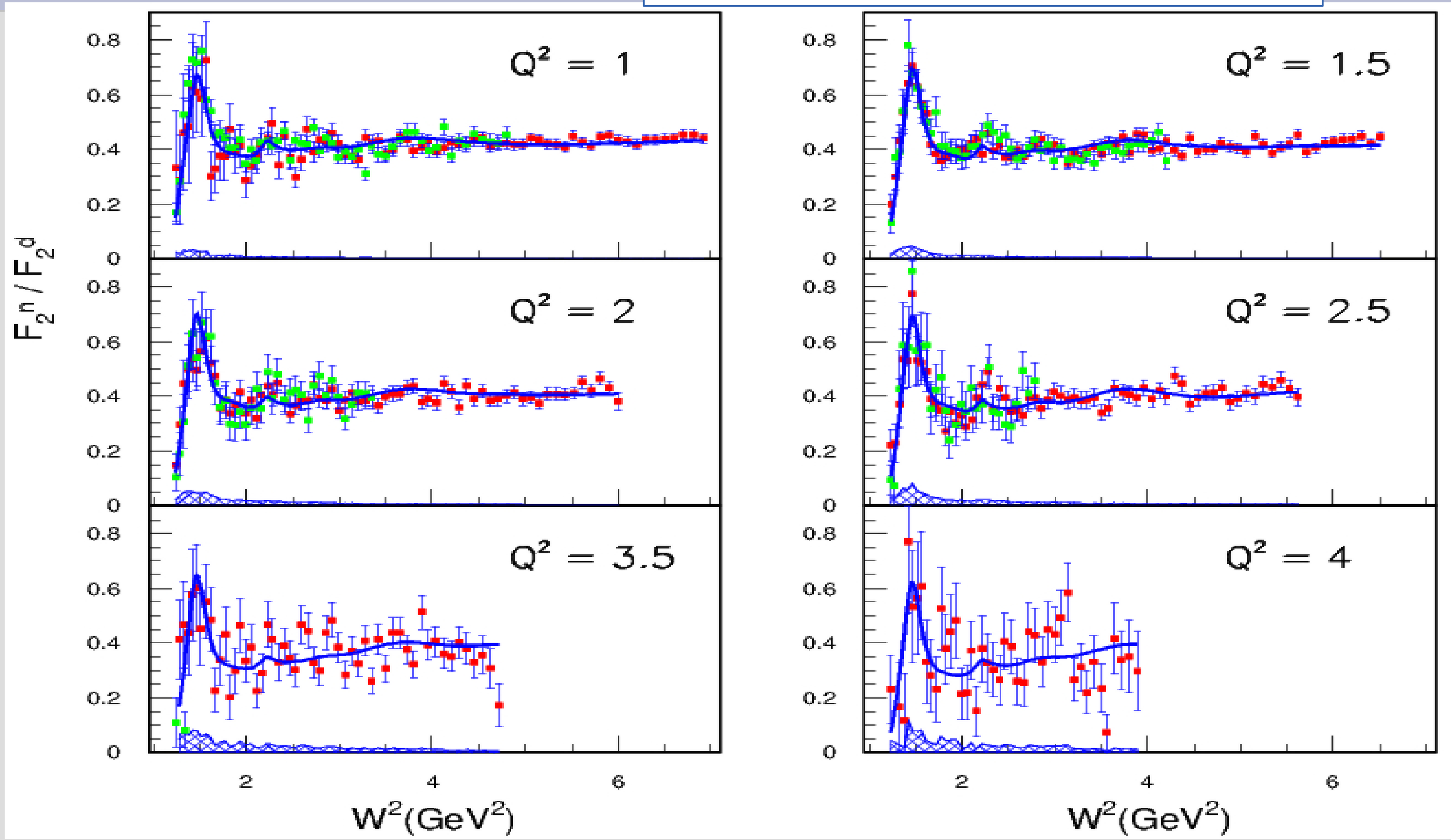
# Resonance $F_2^n$ results



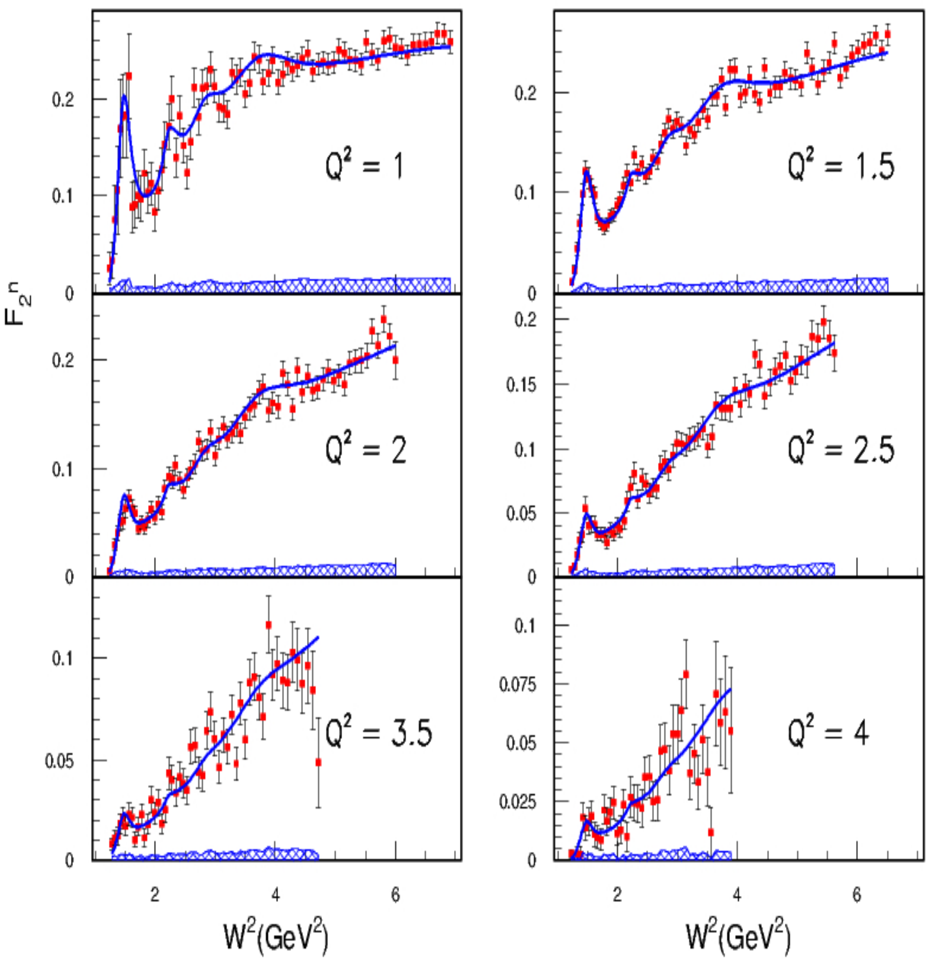
# Comparison to Bonus $F_{2n}/F_{2d}$

M.E. Christy, N. Kalantarians, J. Ethier, W. Melnitchouk

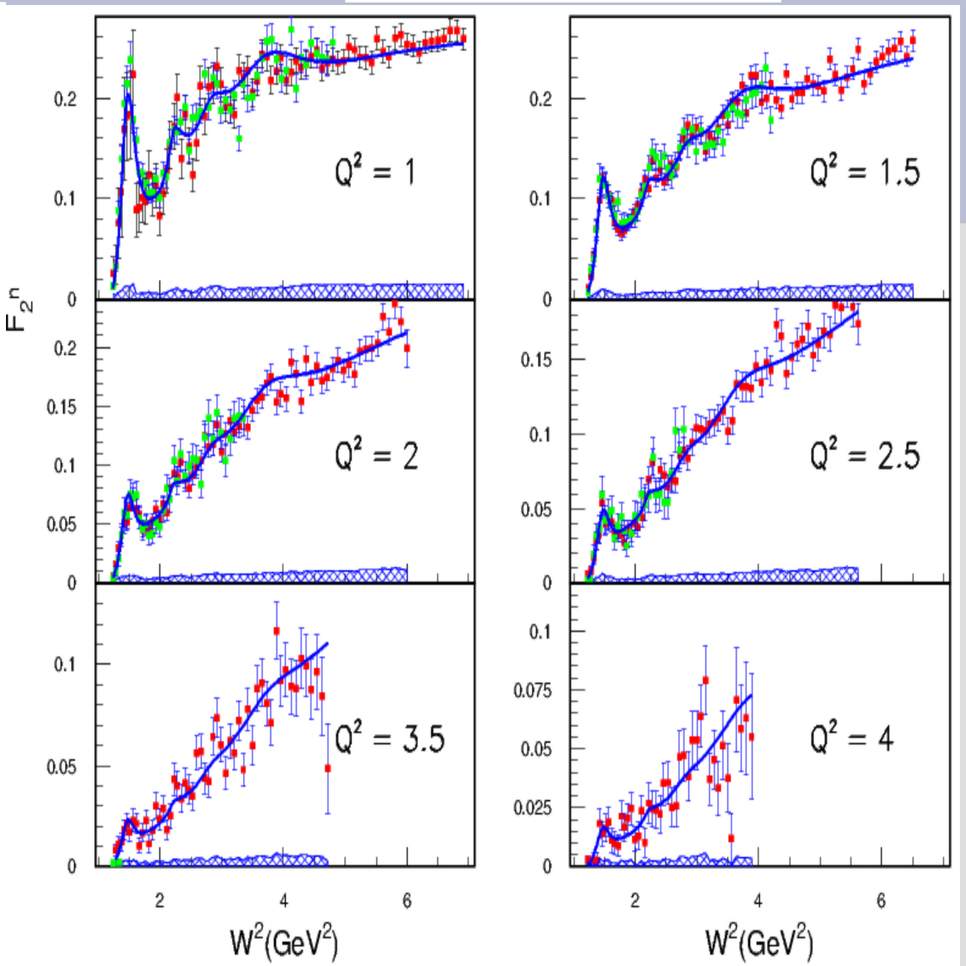
5 GeV 4 Gev



5 GeV




4 GeV




→ ***Not*** a fit to this data

=> Provides check on theoretical construction of deuteron and parametrization of neutron structure functions