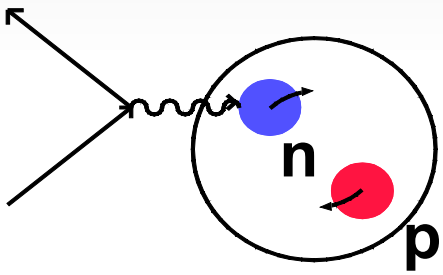
The JLab BoNuS Experiment:

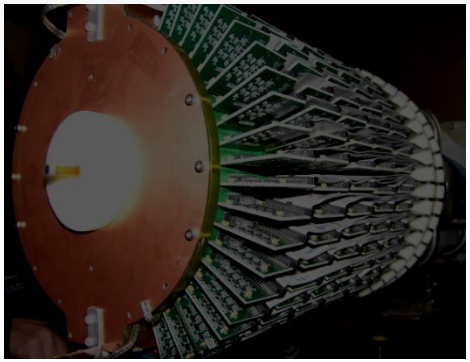
measurement of the free neutron structure function at large *x* and nuclear effects in deuterium via spectator tagging.



M. Eric Christy

Hampton University

For the CLAS Collaboration



NuInt12 Workshop - Rio de Janeiro, Brazil
October 23, 2012

More than 40 years after discovery of the partonic substructure of nucleons, the neutron structure at large-x is still not well determined.

In addition, we would like to understand how the simplest nucleus, the deuteron, is *built* from a proton and neutron.

Why study large-x structure functions?

- Study $pQCD$ DGLAP evolution
- Separation of parton distributions, *e.g.*,
  - *d/u for* x → 1,
  - singlet / non-singlet (valence/non-valence) separation.
- Precise PDFs needed to constrain limits on new physics at LHC and Tevatron
- Separation and study of perturbative / non-perturbative physics
  - *Higher-twist operators (parton-parton correlations)*
  - *Study quark-hadron duality*

Much can be learned about pQCD from DIS on a neutron target

✓ **Need proton *and* neutron targets to pin down u/d PDFs from DIS**

At Leading order

$$F_2^p = x[4/9u(x) + 1/9d(x)]$$

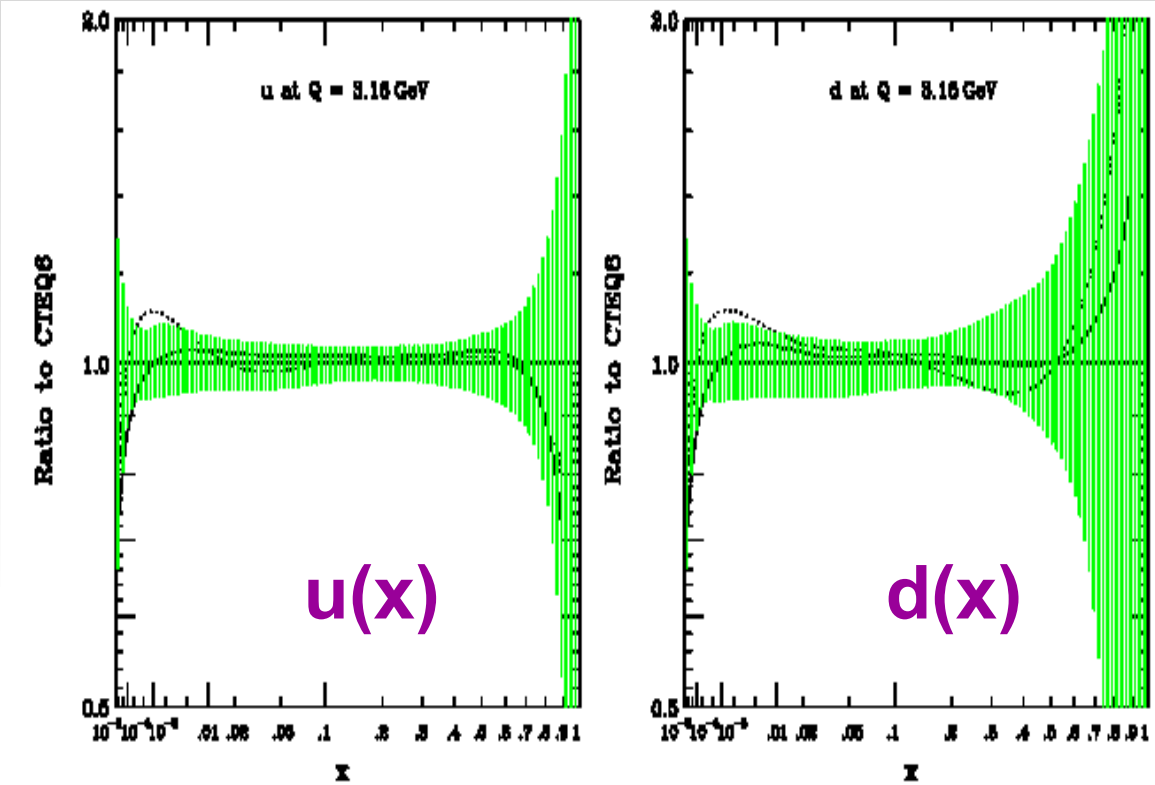
$$F_2^n = x[4/9d(x) + 1/9u(x)]$$

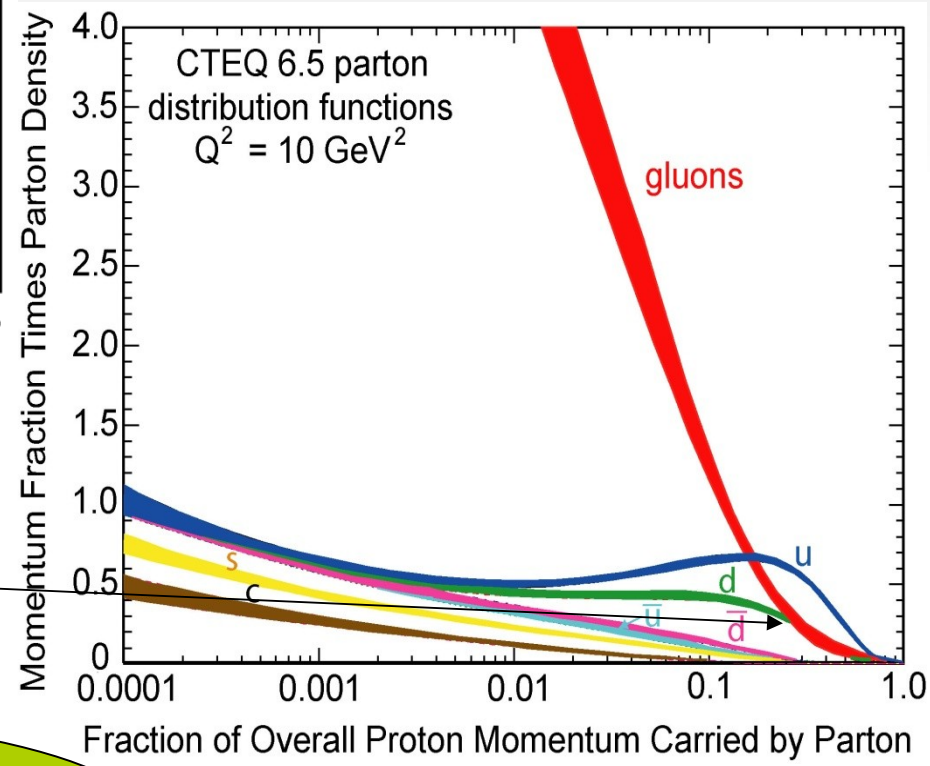
At large x proton dominated by $u(x)$
neutron by $d(x)$
due to charge weighting.

→ u quark is well determined from proton data
→ Free neutron target would provide comparable information on d quark

Problem: no high density neutron target exists!

PDFs Uncertainties





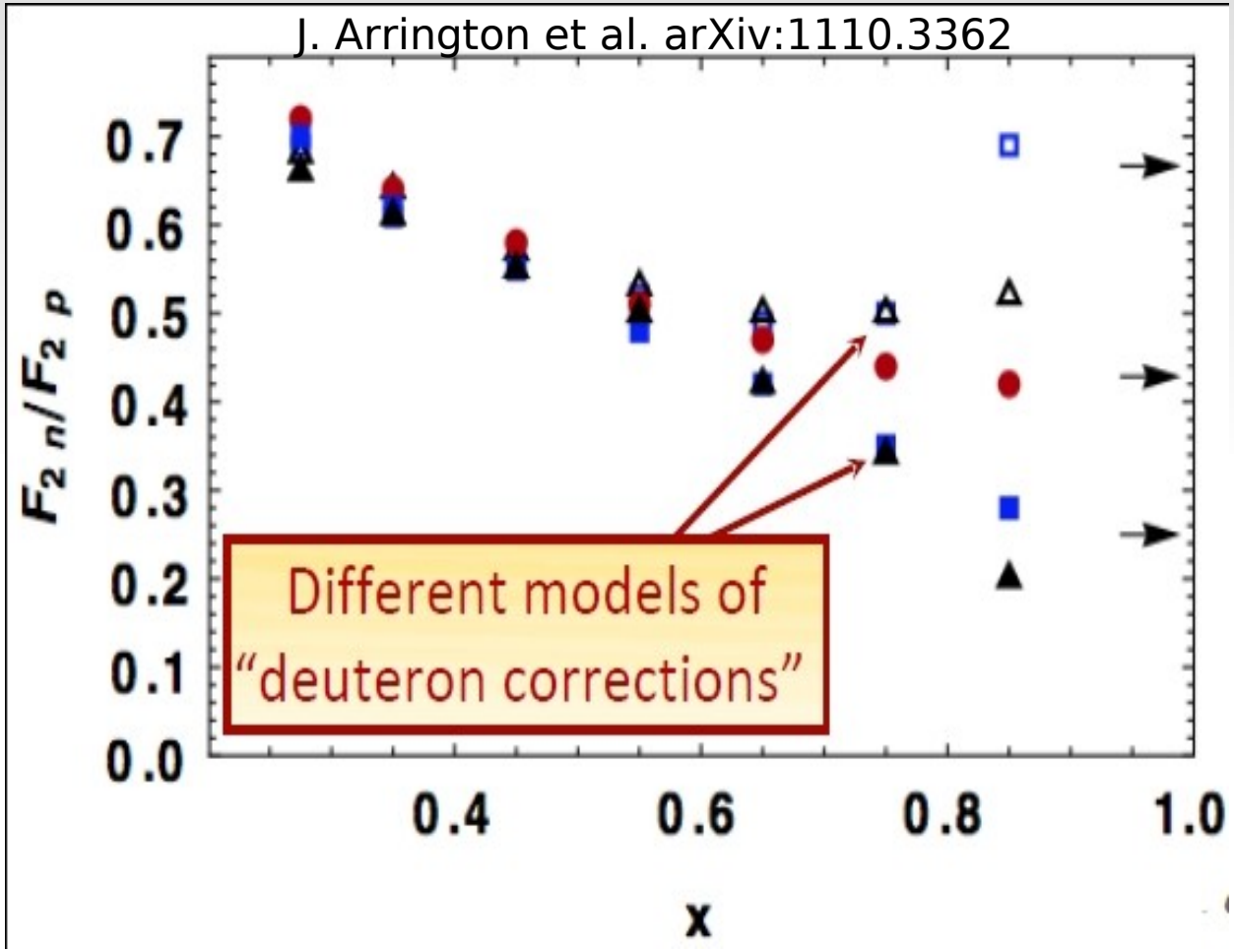
PDF's *least* well known at large *x*

Gluon comparable in size to d_v at x~0.3

not well known here.

***Proton + neutron data provides way to separate valence cleanly.**

Even F_2^n *not* well known for x > 0.6



Non-pertabative models

SU(6) spin-flavor

Hard gluon exchange

S=0 diquark dominance

What about current state-of-the-art PDF fits including deuterium nuclear corrections?

New CJ PDF fits include Large-x + deuterium

- **Collaborators:**
  - A.Accardi, E.Christy, C.Keppel, W.Melnitchouk, P.Monaghan, J.Owens (J.Morfín, L.Zhu)
- **Goals:**
  - Global QCD fits of unpolarized PDFs focused on large *x*
  - Improve the PDF experimental precision ("PDF errors") by enlarging the fitted data set
  - Include all relevant large-*x* / small-Q^2 theory corrections
  - ***Quantitatively evaluate theoretical systematic errors***
  - ***Use PDFs as tools for nuclear and particle physics***
- **Papers:**
  - A.Accardi et al., Phys.Rev.D81 (2010) 034016 **"CJ10"**
  - A.Accardi et al., Phys.Rev.D84 (2011) 014008 **"CJ11"**
  - New fit in preparation with latest data

including nuclear corrections on D_2 !

Available on request

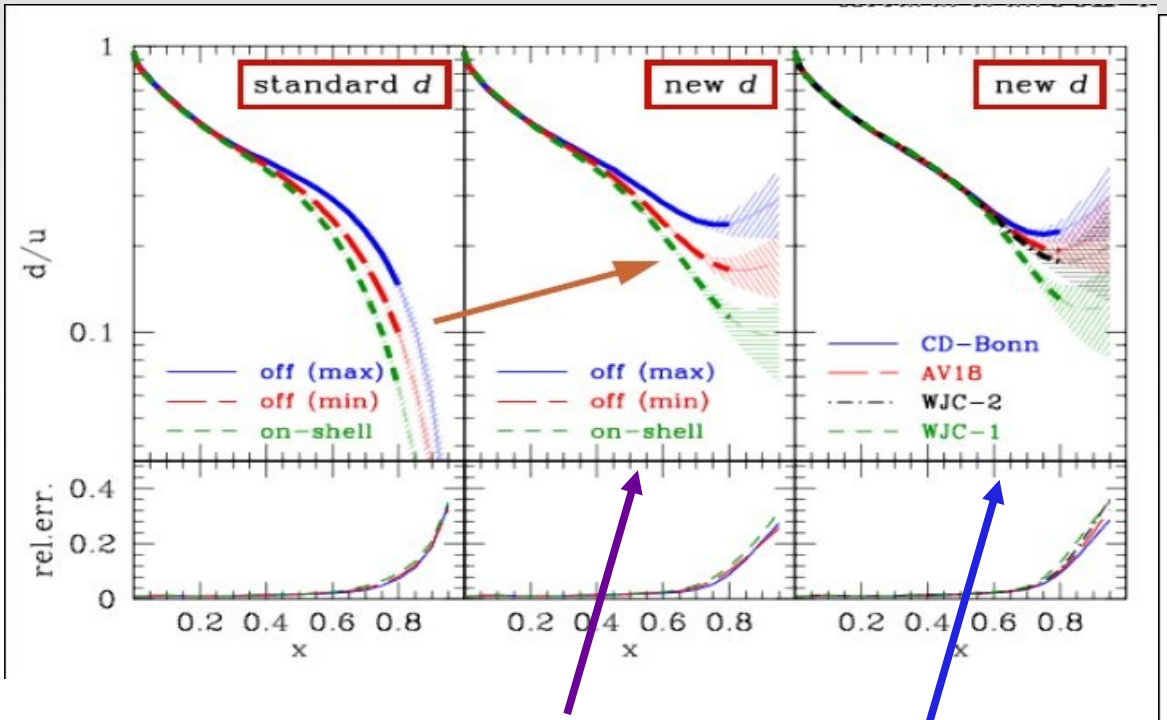
Public release planned

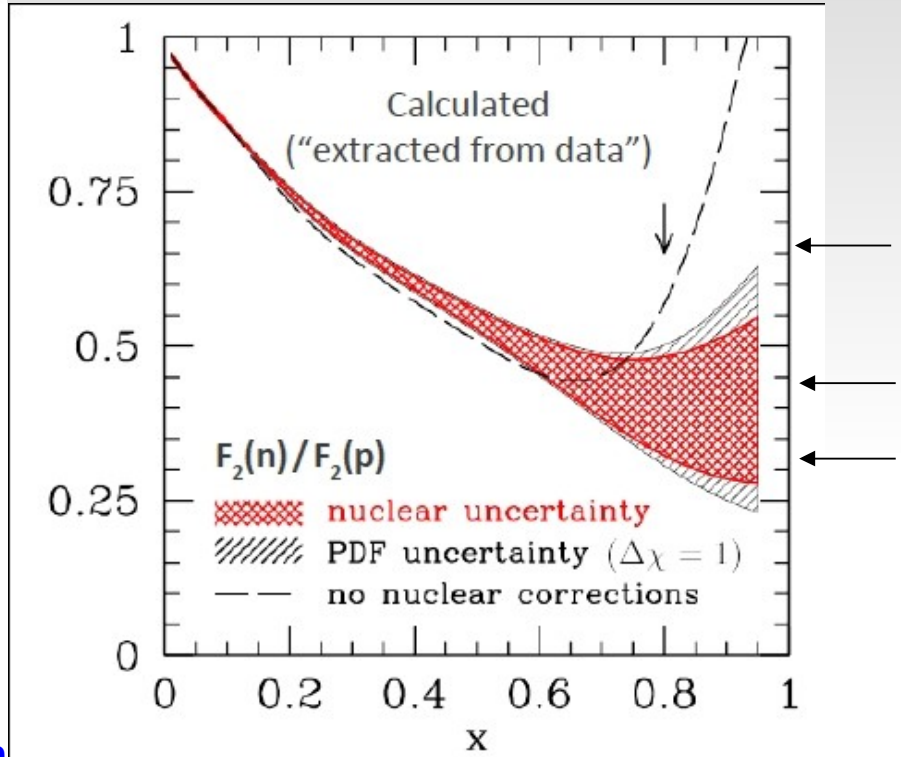
accardi@jlab.org QCD@LHC, 22 Aug 2012

Slide from Alberto Accardi

Nuclear uncertainties results from CJ11

Accardi et al. PRD 84, 014008 (2011)





Off-shell model spread

Nuclear Wave-Fn spread

Still significant uncertainties from nuclear models at large-x

Free neutron targets would provide solution

→ No high density neutron targets exist

→ Use deuterium and assure that scattering took
Place from a 'nearly' on-shell effectively free neutron

Method of Spectator Tagging

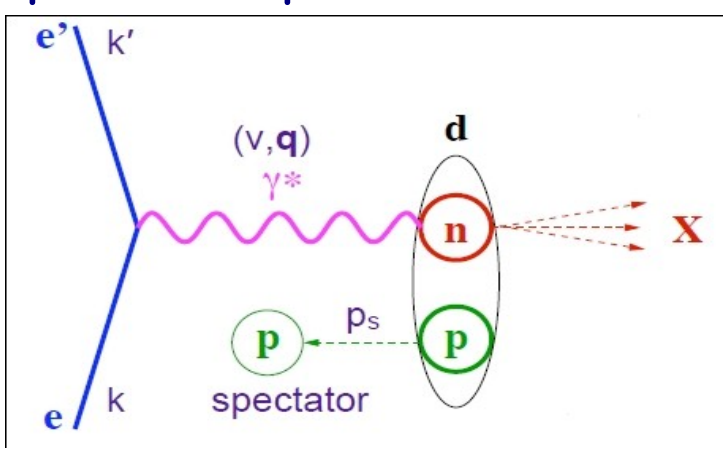
$$\frac{d\sigma}{dx^* dQ^2} = \frac{4\pi\alpha_{\rm EM}^2}{x^* Q^4}\left[\frac{y^2}{2(1+R)} + (1-y) + \frac{M^{*2}x^{*2}y^2}{Q^2}\frac{1-R}{1+R}\right] F_2(x^*, \alpha_s, p_T, Q^2) \times S(\alpha_s, p_T)\frac{d\alpha_s}{\alpha_s} d^2 p_T,$$

With $S(\alpha_s, P_T)$ the nucleon spectral function in the deuteron

and F_2 the effective *off*-shell neutron structure function

$R=\sigma_L/\sigma_T$

Tag spectator proton in scattering



$$\nu = E - E'$$

$$\alpha = (E_s - p_{s^z})/M$$

$$Q^2 = 4EE'\sin^2\frac{\theta}{2}$$

The spectator proton's four momentum:

$$p^\mu = -(E_s - M_D, p_s)$$

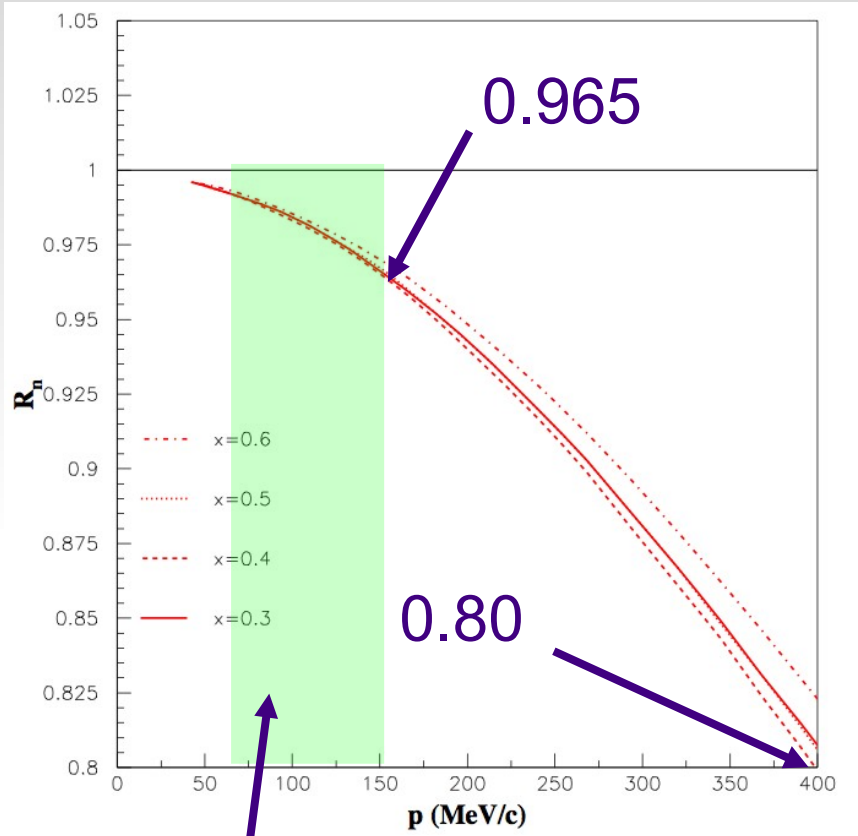
Hadronic W (x) of debris:

For free neutron structure must kinematically select to minimize:

1. Off-shell effects
2. Final state interactions
3. Target fragmentation enhancement to proton yield

Off-Shell Structure Functions

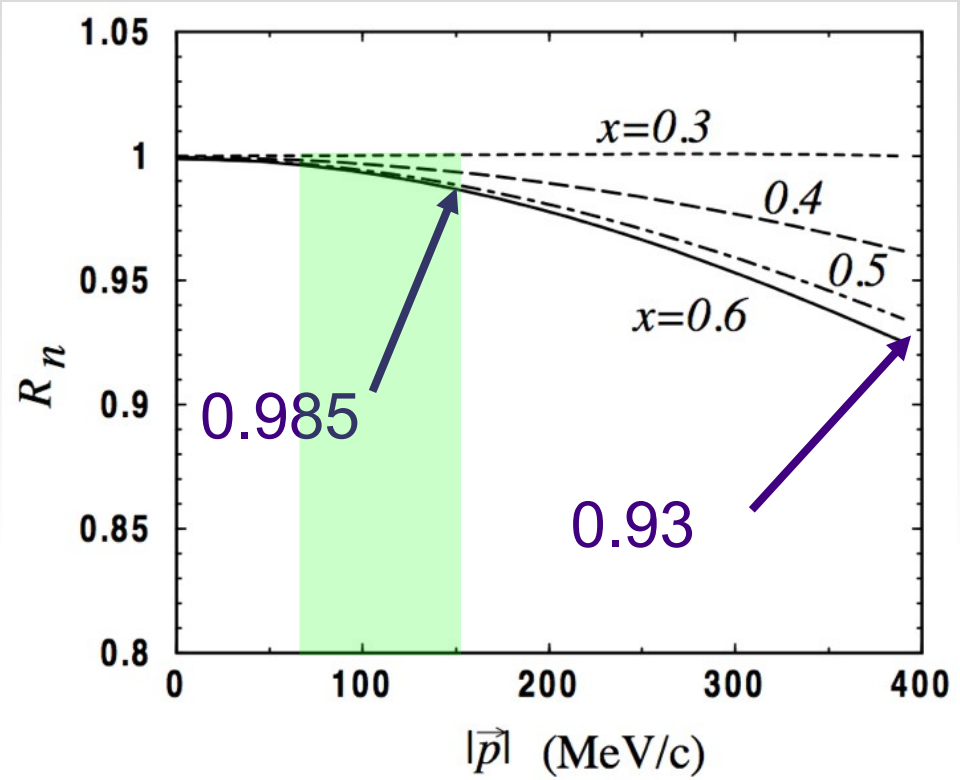
Liuti & Gross PLB**356**(95)157



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

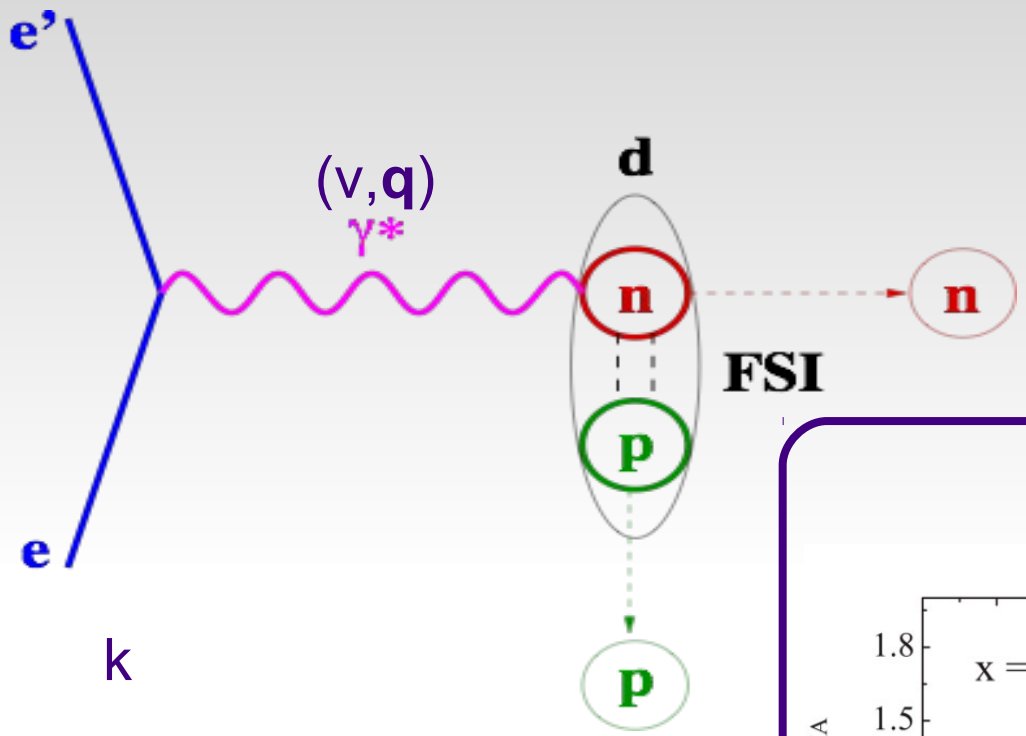
BoNuS p_s detection range

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



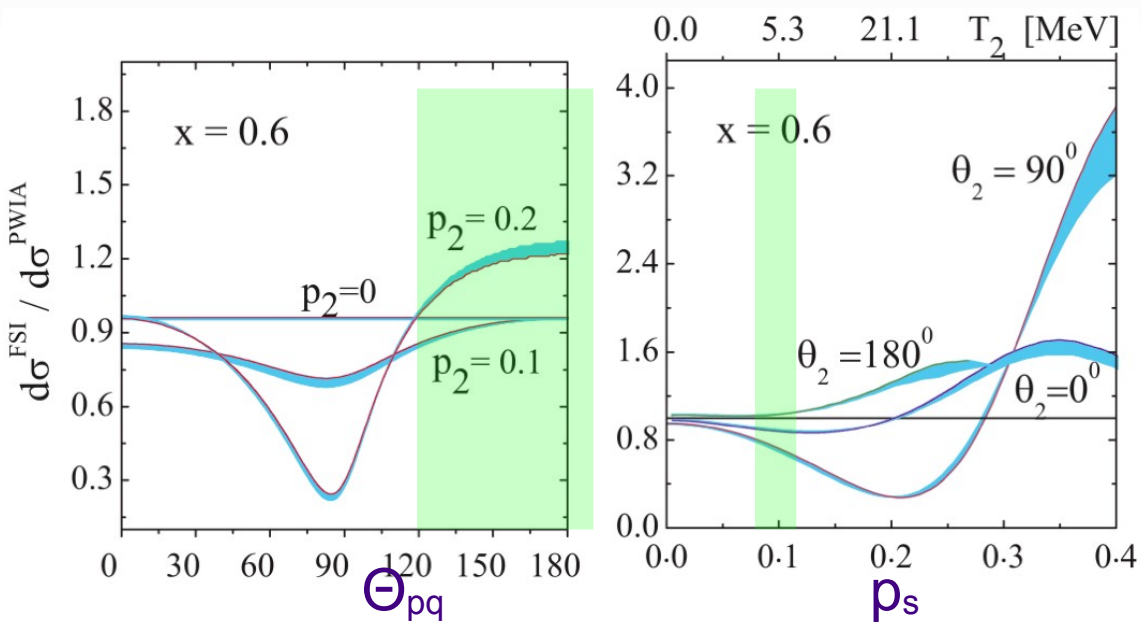
- R_n decreases with p_s or α_s
- At x*=0.5 and p_s=400 MeV/c, R_n deviates from unity by 7-20% in these models

Final State Interactions



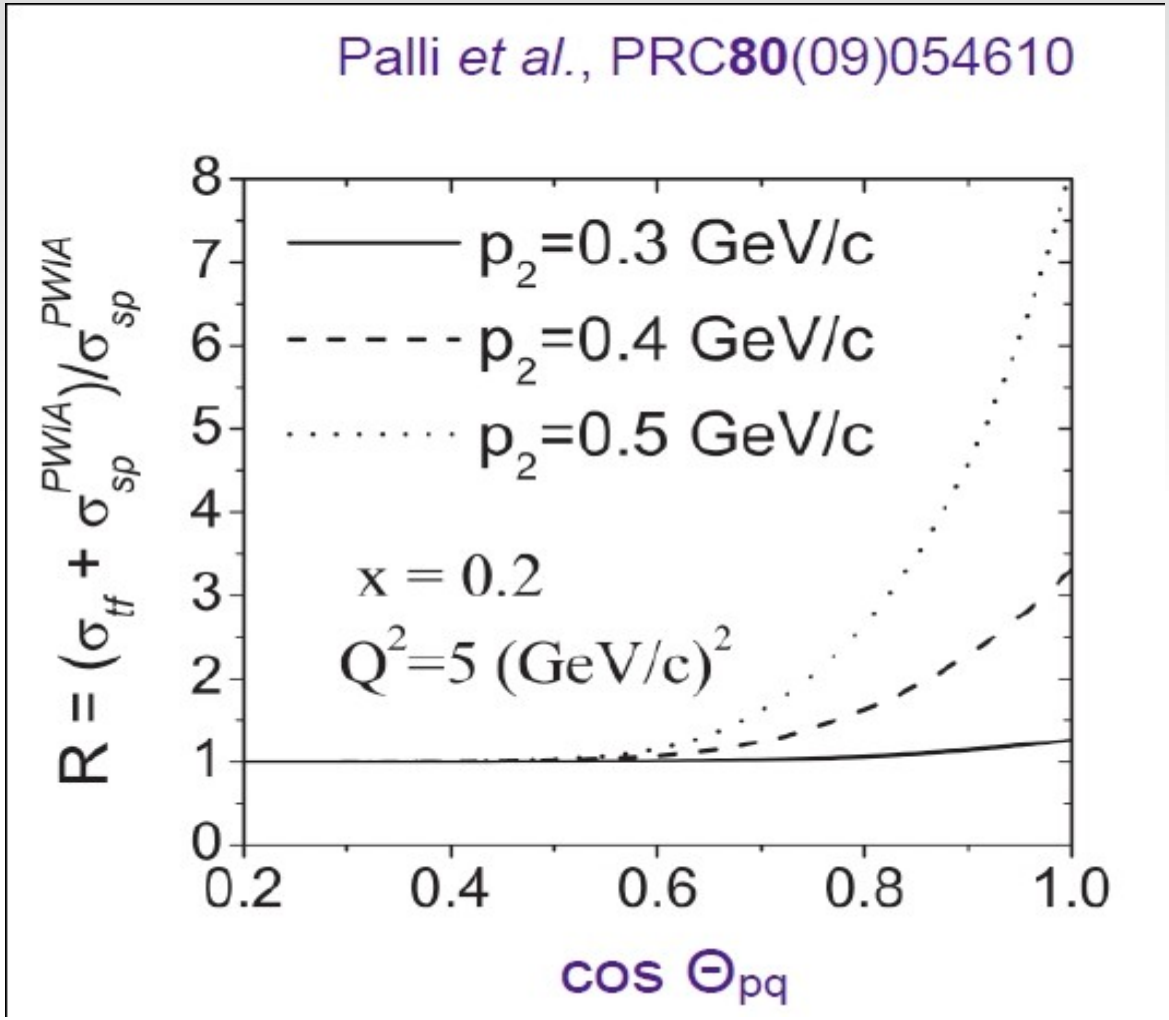
- Struck neutron can interact with the spectator proton
- Proton momentum is enhanced
- FSIs are small at low p_s and large Θ_{pq}

Palli et al, PRC**80**(09)054610



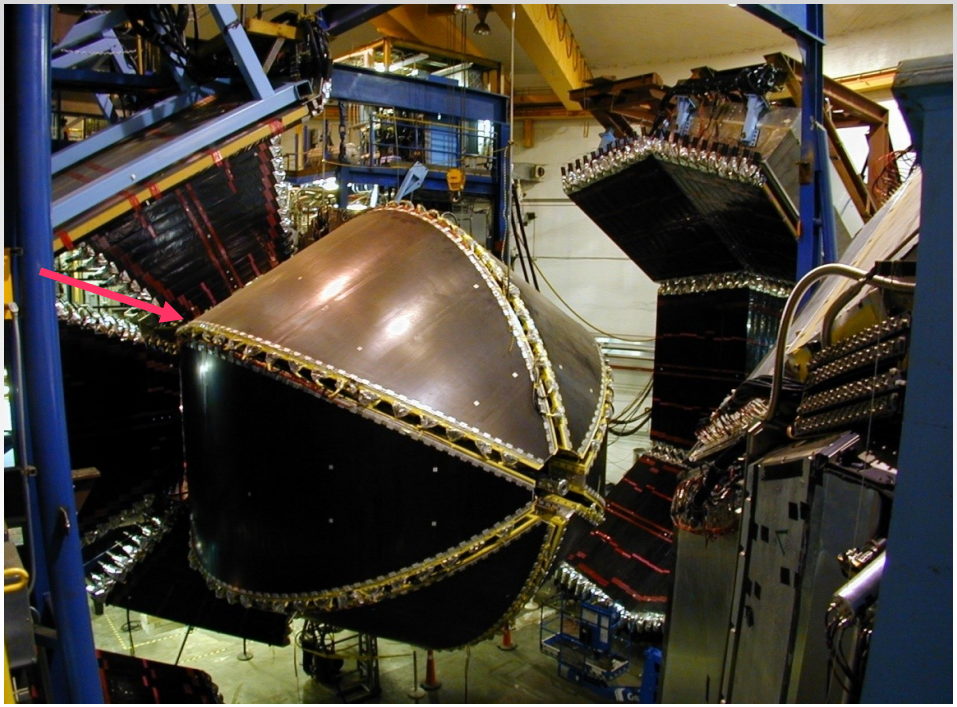
- Several groups have calculated FSIs
- $\Theta_{pq} > 110^o$ and p_s<100 MeV/c greatly reduces FSIs

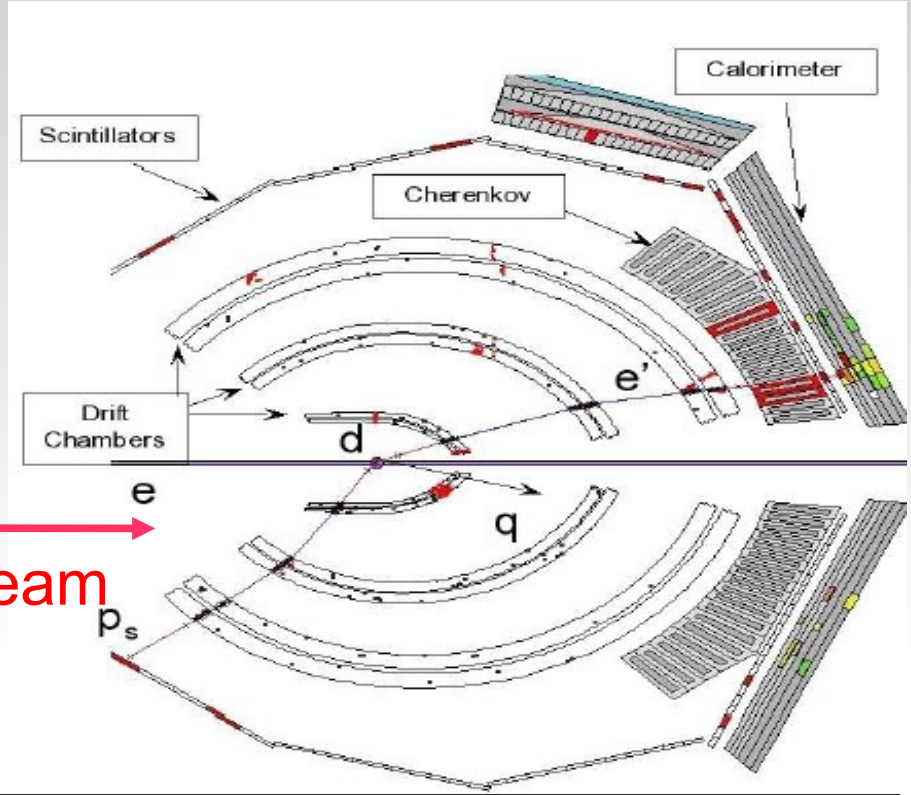
Target Fragmentation

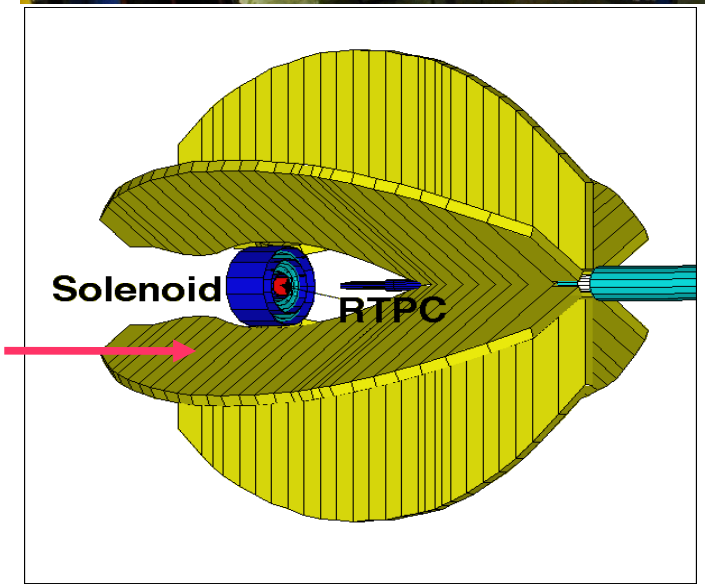


Enhancement in proton Yield Over PWIA *negible* for *backward* protons!

Experimental Setup I: CLAS Spectrometer



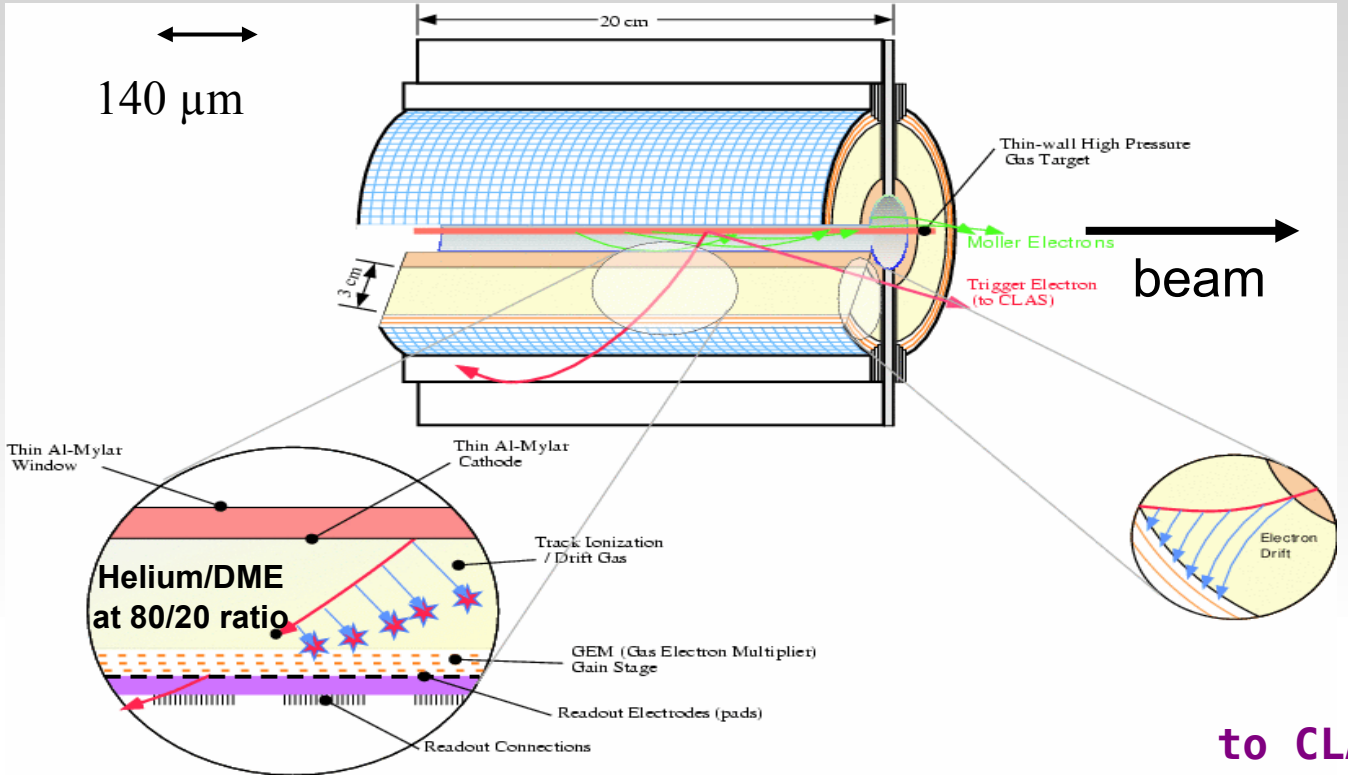




- Detect electrons in CLAS spectrometer
- Detect slow protons in radial time projection chamber (RTPC)
- Moller electrons bottled up by Solenoid field around target
- Solenoid field allows momentum determination

Experimental Setup II: BoNuS RTPC

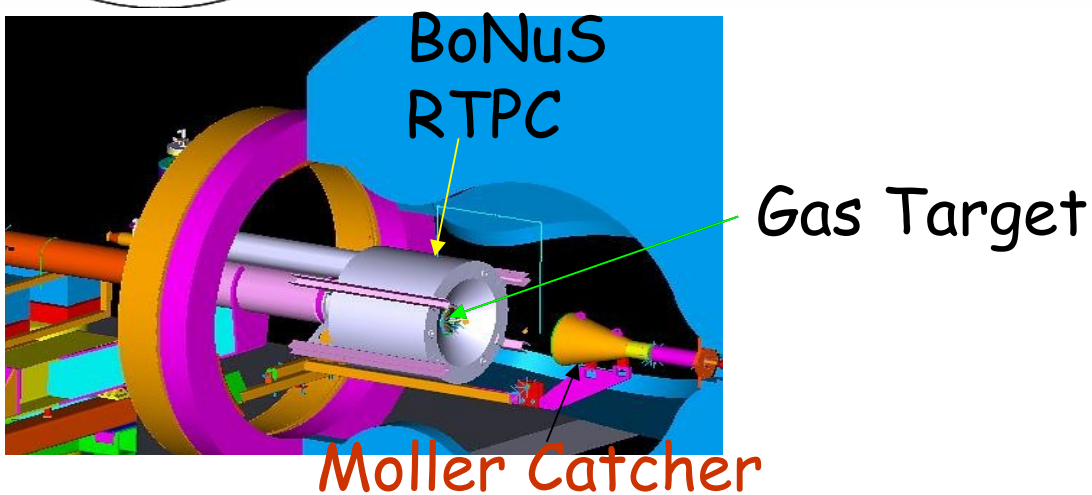
H. Fenker et al., Nucl. Instrum. Meth. A **592**, 273 (2008)

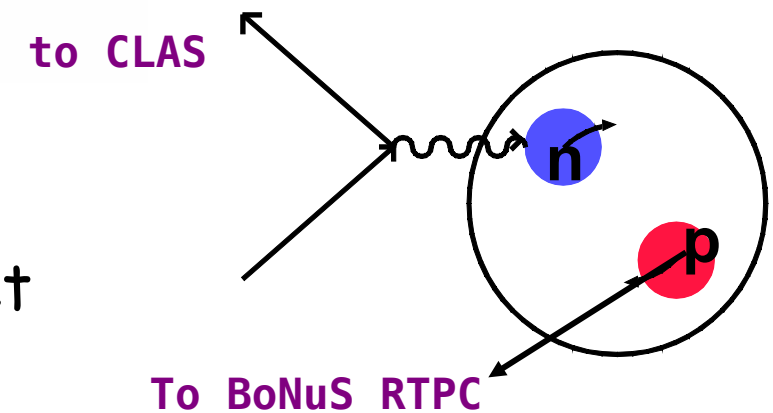


Fit RTPC points to determine helix of proton trajectory.

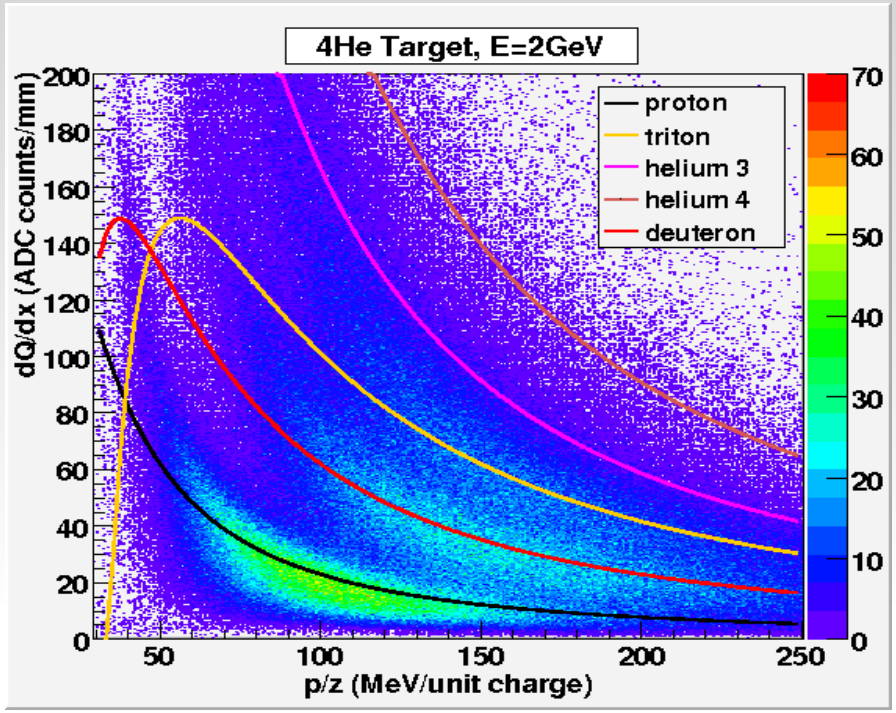
Momentum determined from track curvature in solenoid field.

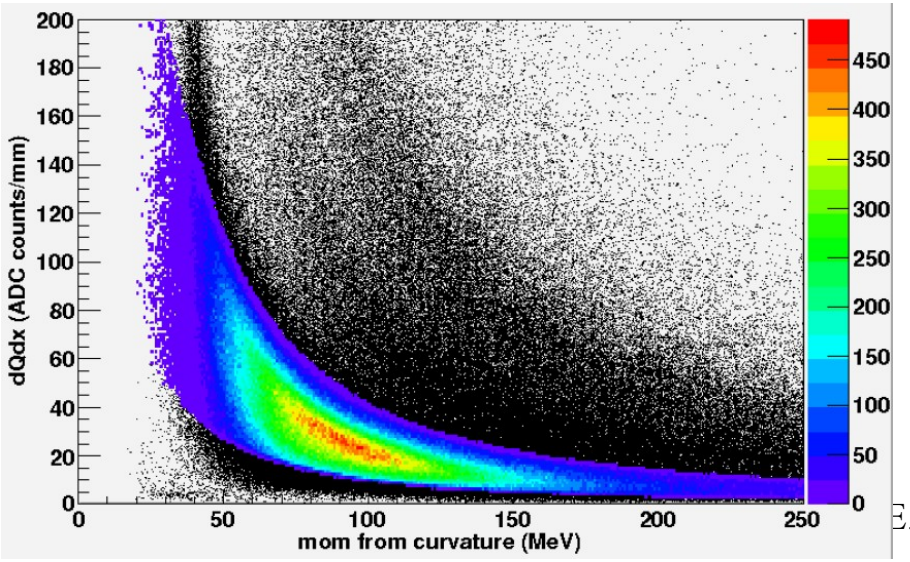
dE/dx along track in RTPC also provides momentum information.



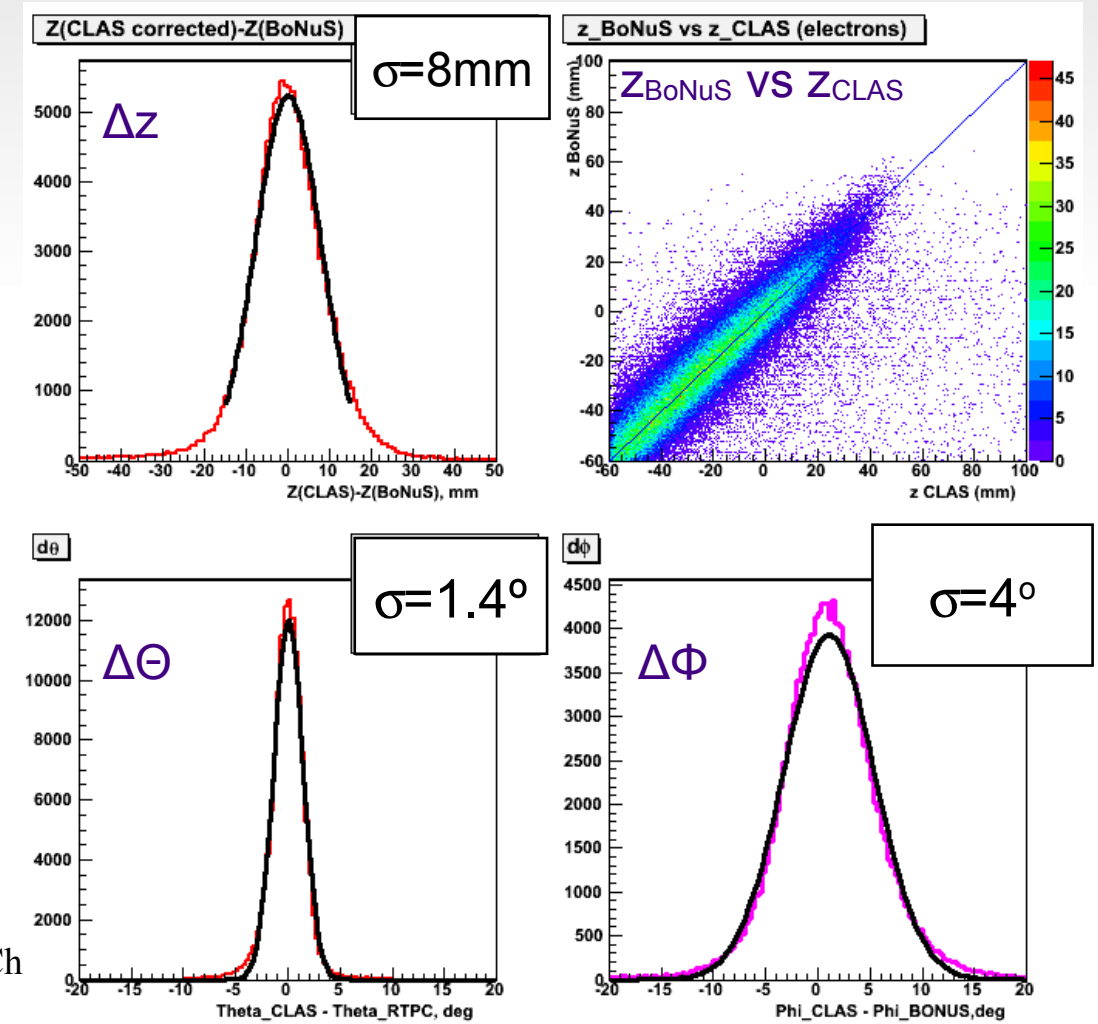


RTPC Performance



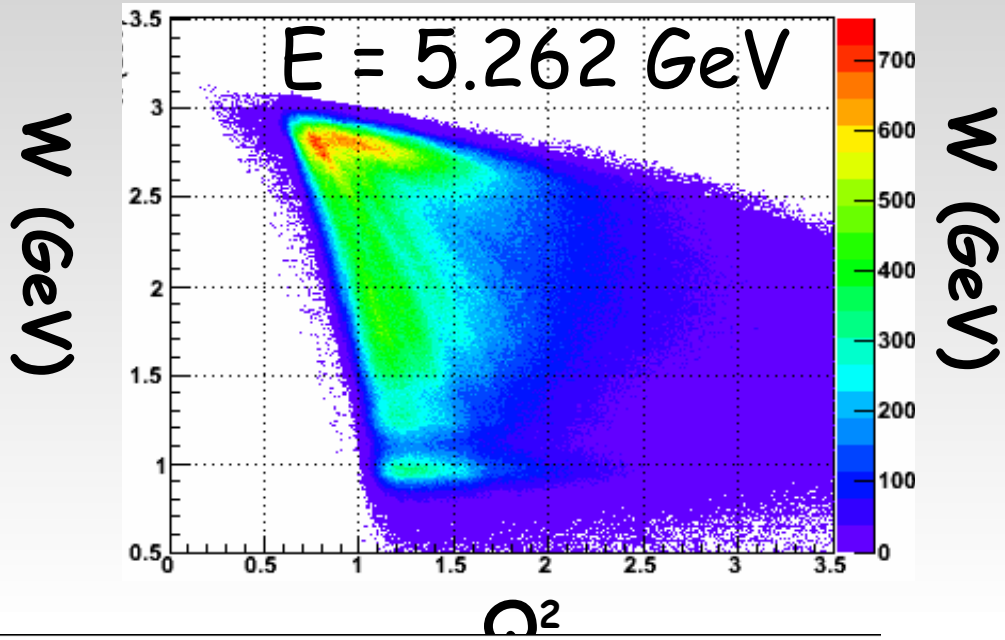


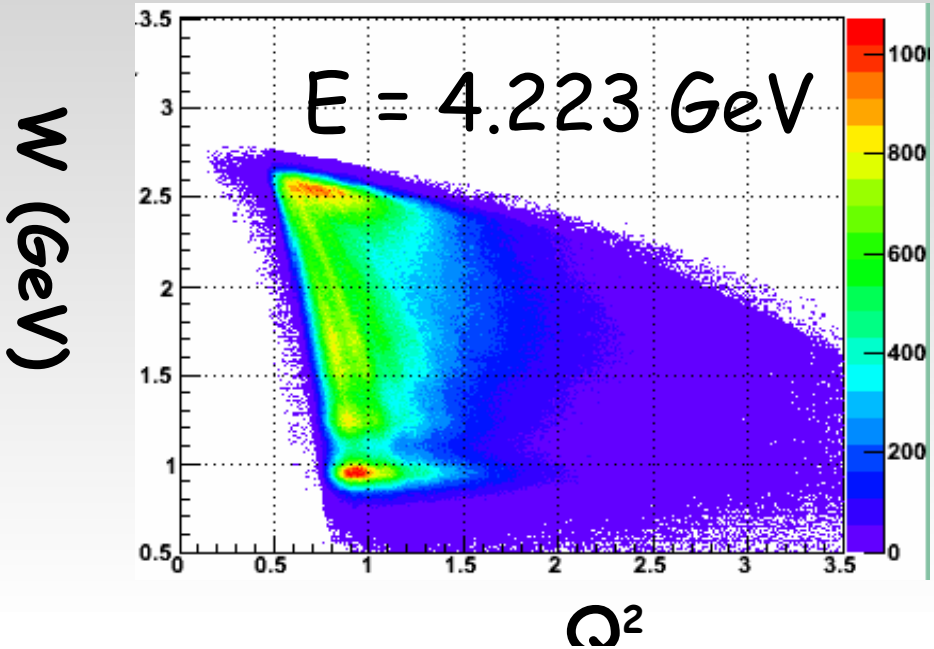
- Upper left: dE/dx vs. p/Z for He target
- Lower left: dE/dx vs. p for deuterium target
- Below RTPC+CLAS resolution for common e^- events

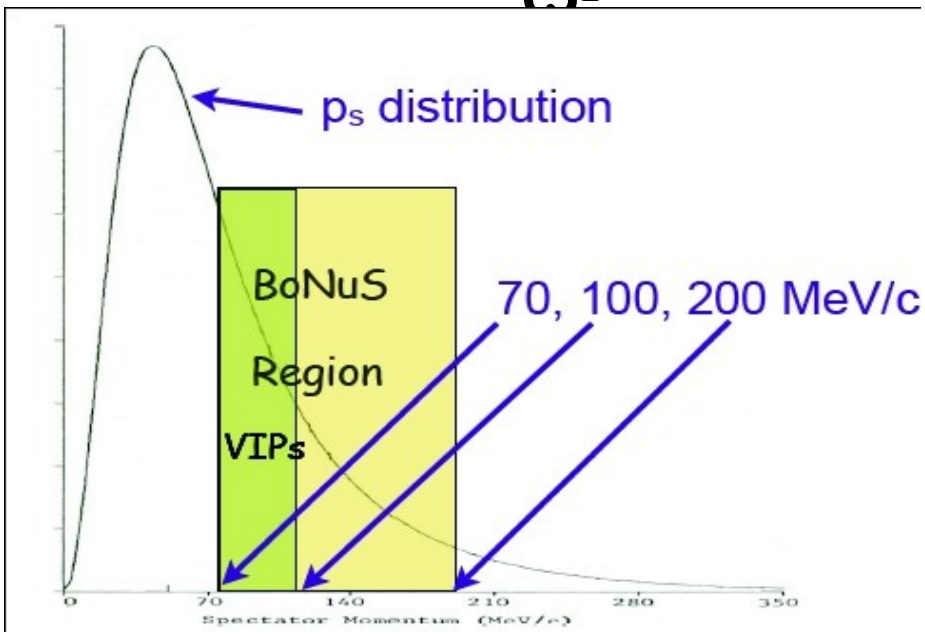


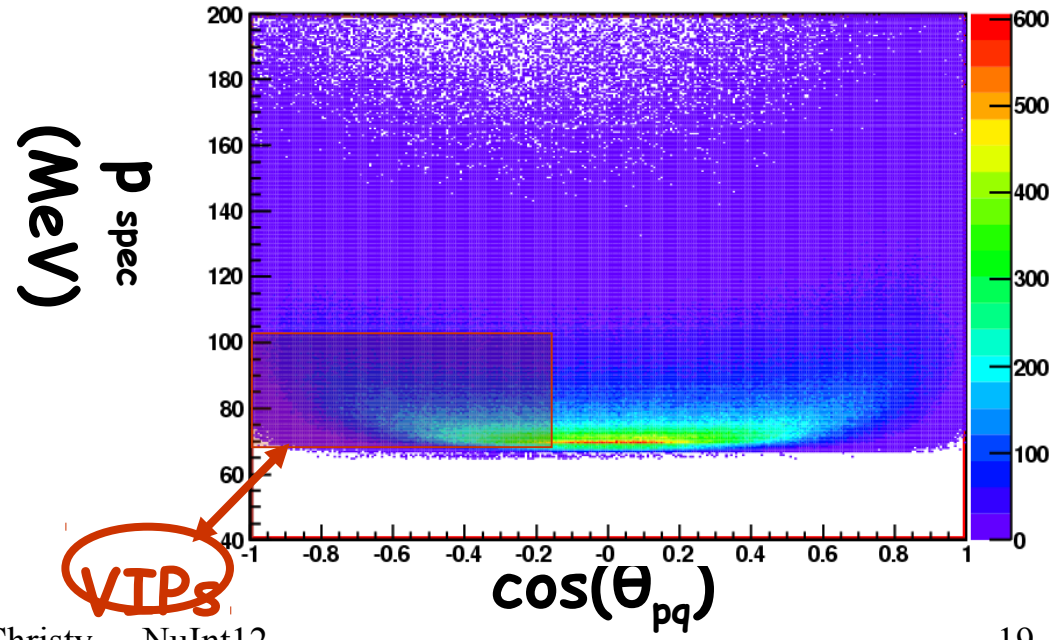
E. Ch

Kinematic Coverage

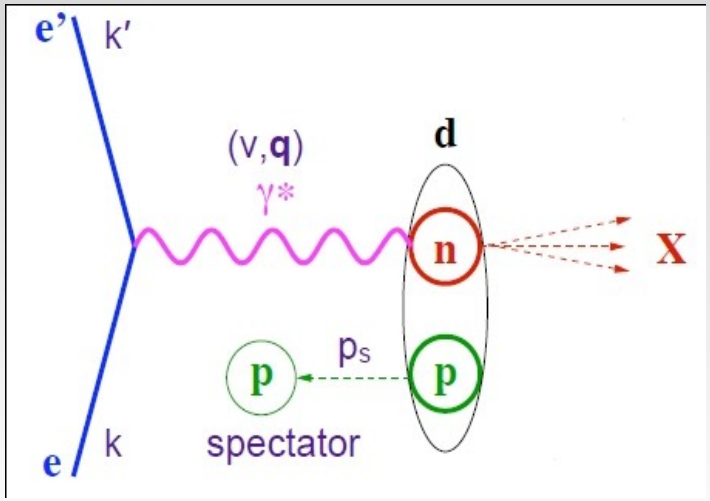




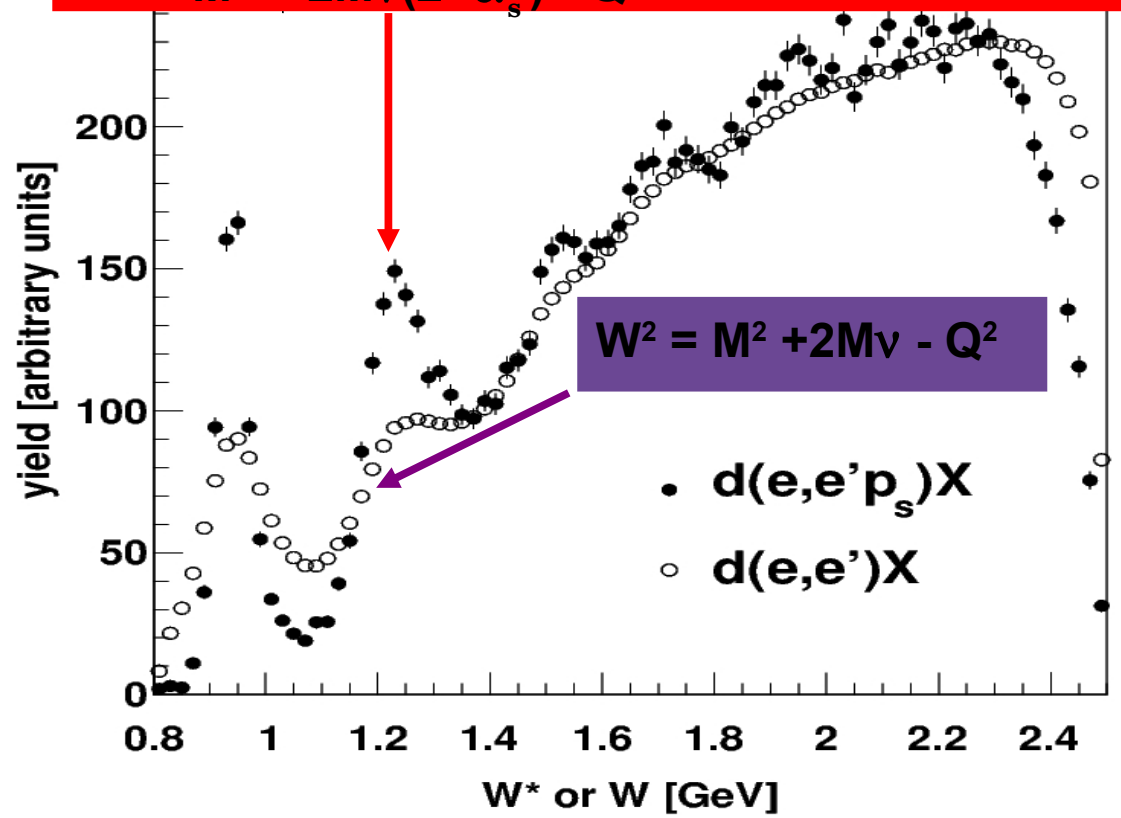




Kinematic reconstruction with tagged protons



$$W^2 = (p_n + q)^2 = p_n^{\mu}\, p_{n\mu} + 2([M_D - E_s]\nu - p_n \cdot q) - Q^2$$
$$\approx M^{*2} + 2M\nu(2 - \alpha_s) - Q^2$$



PWIA: → Backward P is spectator
→ Neutron is offshell
→ $\mathbf{p}_n = -\mathbf{p}_p$
=> correct for neutron momentum

Ratio Method

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

First make experimental ratio:

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

In terms of structure function ratio:

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

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

P_s < 100 MeV/c, θ_p > 110

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

A_p : tagged proton Efficiency * Acceptance

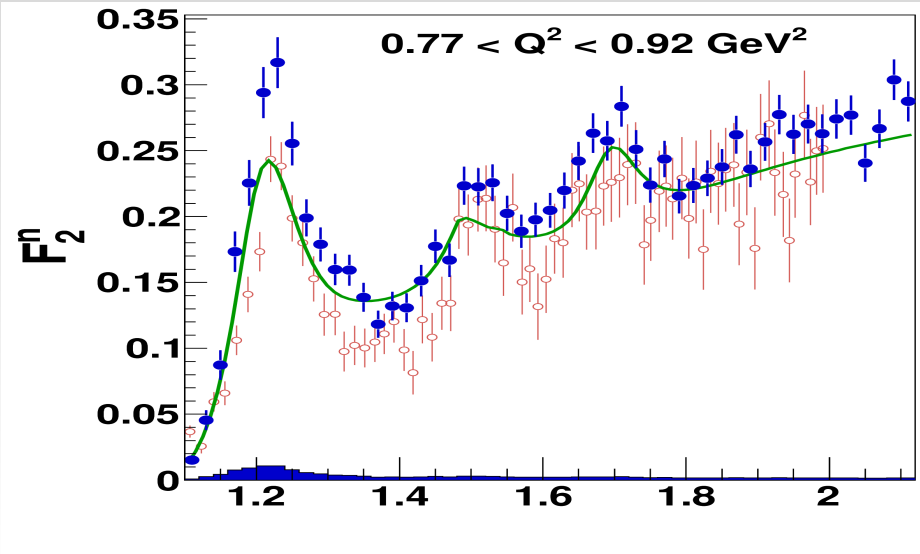
→ Integral I_{vip} is largely independent of W* (x*) and Q^2

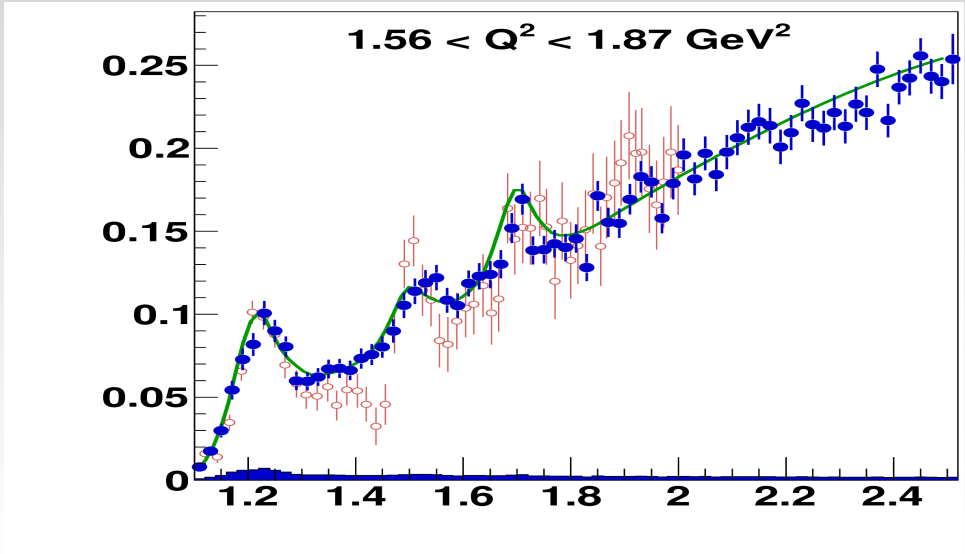
→ Determined from R_{exp} at x=0.3, where nuclear effects are small using F_2^n / F_2^d from CJ PDF fit.

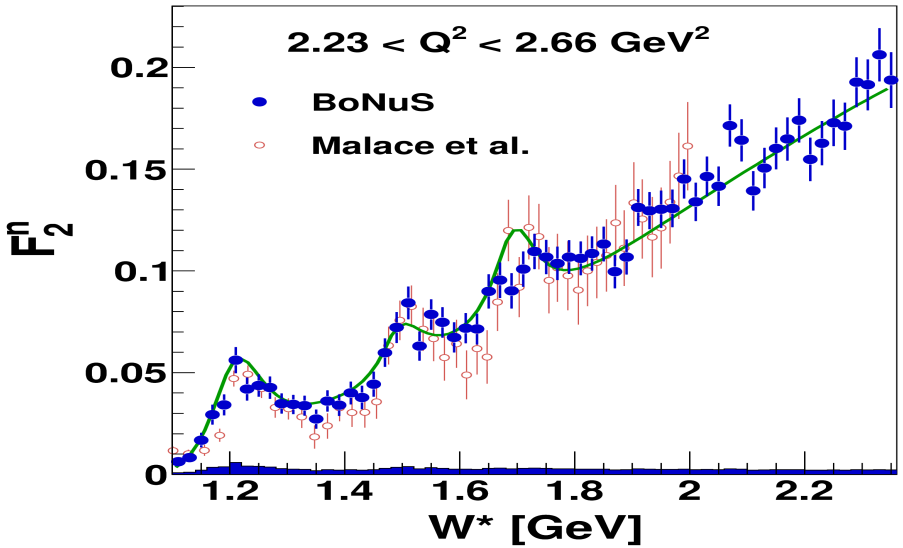
Then $F_2^n = F_2^d * R_{exp} * I_{vip}$

Resonance F_2^n results

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







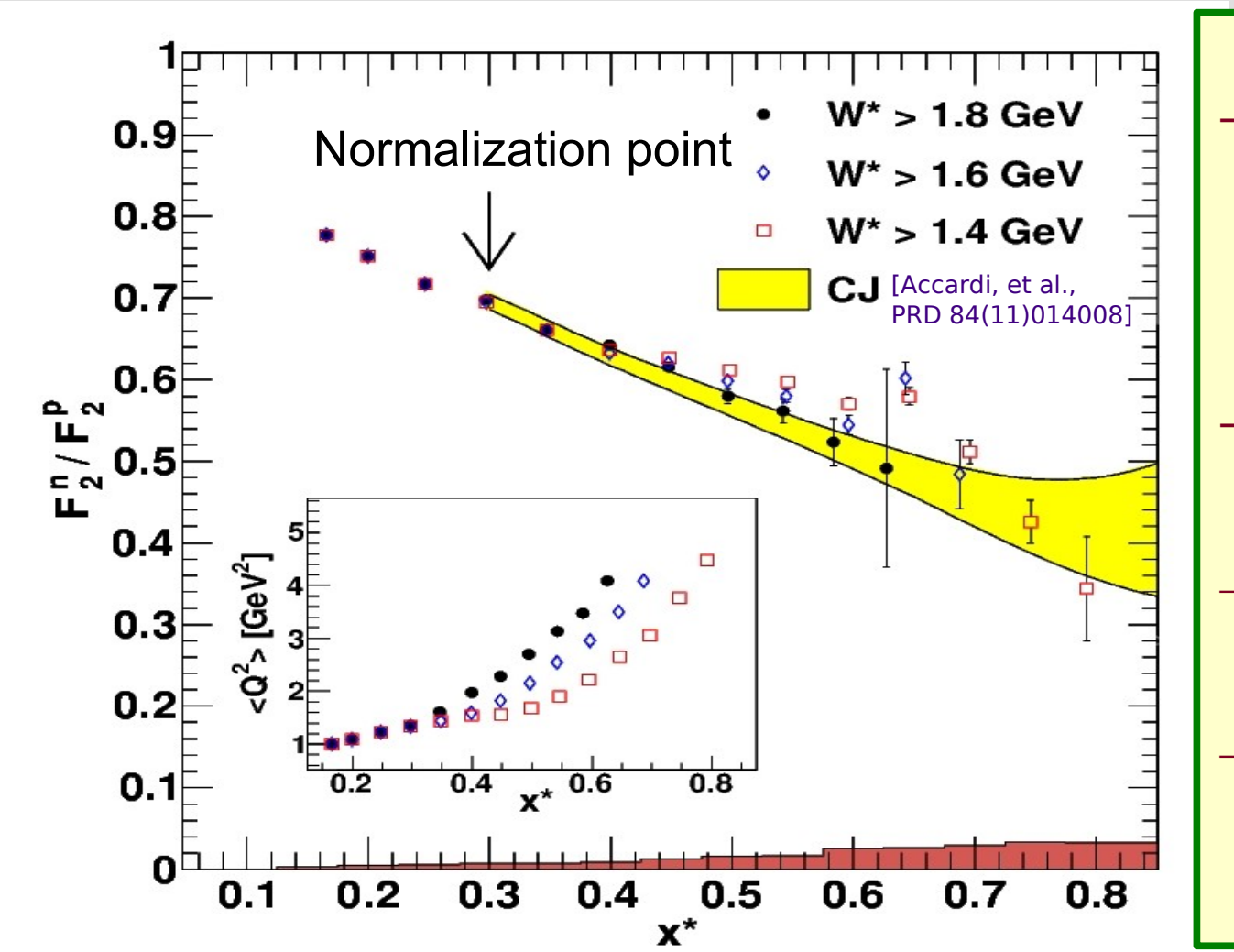
→ Clear neutron resonant structure

→ Compares reasonably well to Bosted-Christy fits to p, d,
(extracts neutron using PWIA + Paris potential)

→ Studies of duality in F_2^n being finalized now.

Results on F_2^n / F_2^p

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



→ F2n/F2p = F2n/F2d * F2d/F2p with F2d/F2p 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

Nuclear effects Studies with BoNuS

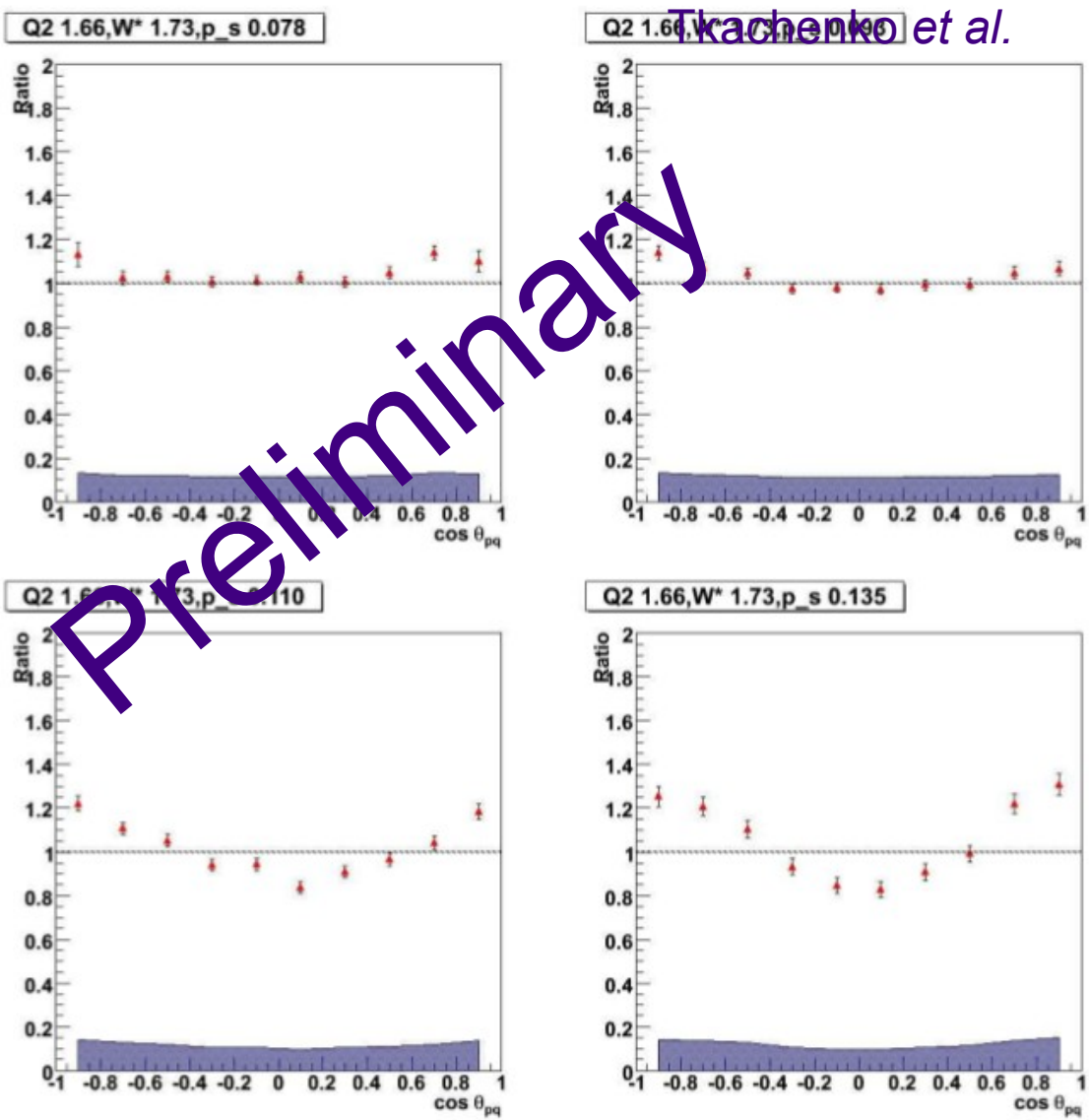
Can test

- spectator model assumptions and
- nuclear effect models

Using full kinematics coverage for tagged protons.

Analysis of S. Tkachenko.

Spectator model test:
Data/MC cosθ distributions



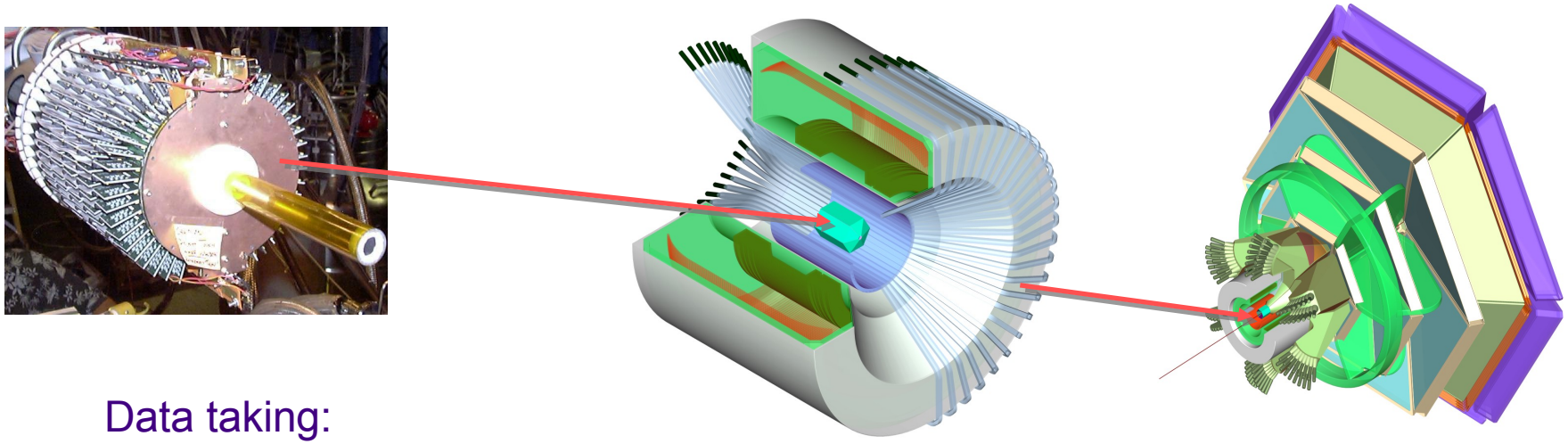
- Analysis of S. Tkachenko utilizes larger kinematic coverage to test spectator model.
- At low p_s the data agree with the spectator model quite well.
- At higher p_s the distributions deviate significantly from unity, indicating that VIP particles should have p_s<100 MeV/c.

With n+p and deuterium Structure functions in hand...

Study of EMC effect in the deuteron is currently in progress

BoNuS Plans for 12 GeV

E12-06-113



Data taking:

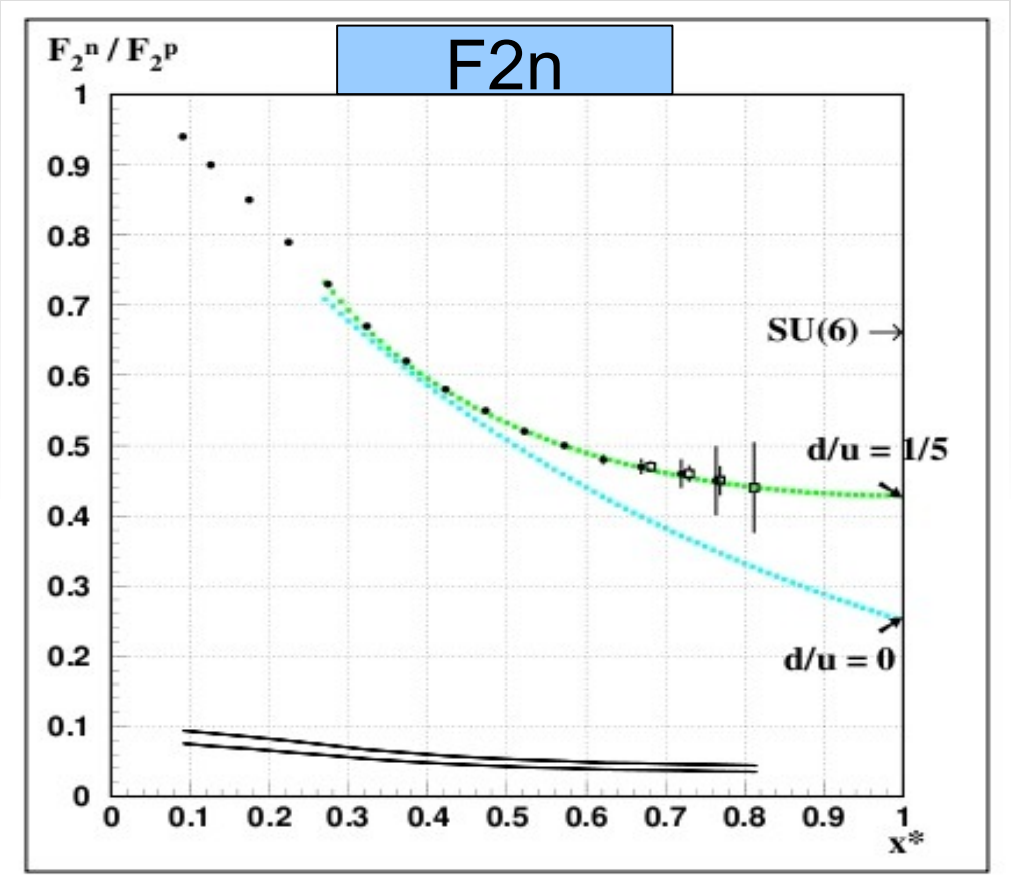
- 35 days on D_2
- 5 days on H_2
- $L = 2 \times 10^{34}\ cm^{-2}\ sec^{-1}$

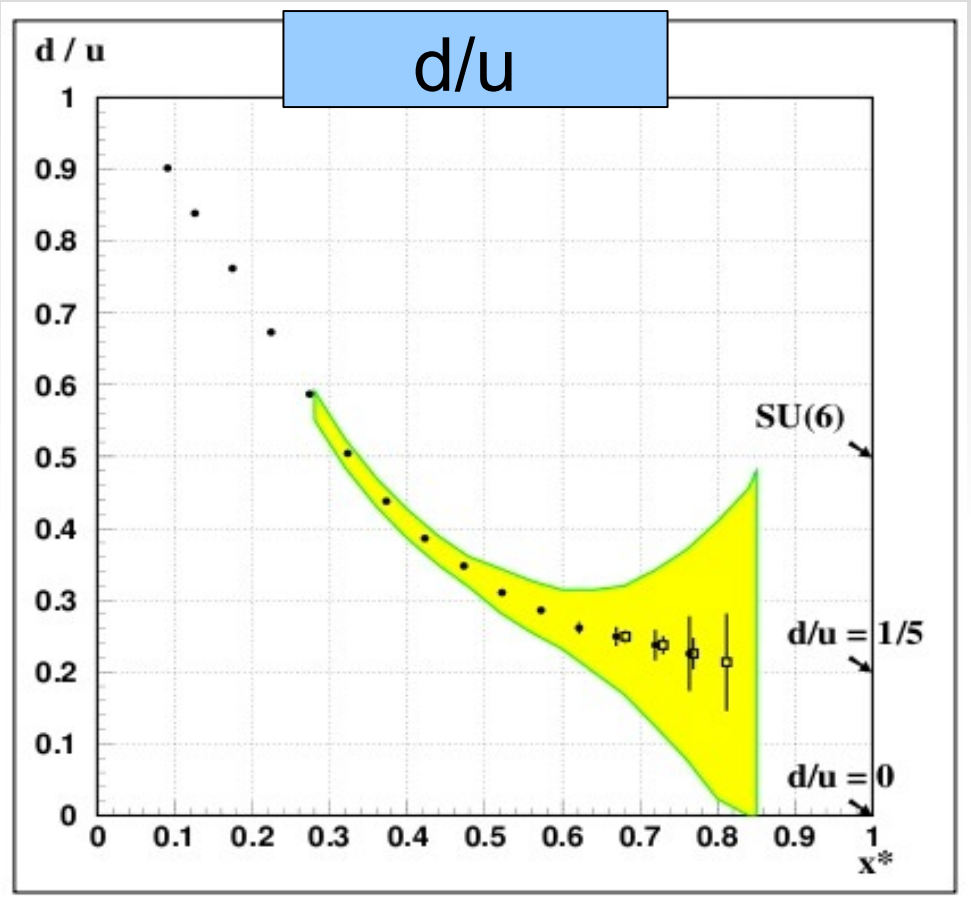
DIS region:

- $Q^2 > 1\ GeV^2$
- $W^* > 2$ GeV
- $p_s < 100$ MeV/c
- $\theta_{pq} > 110°$
- $x^*_{max} = 0.80$

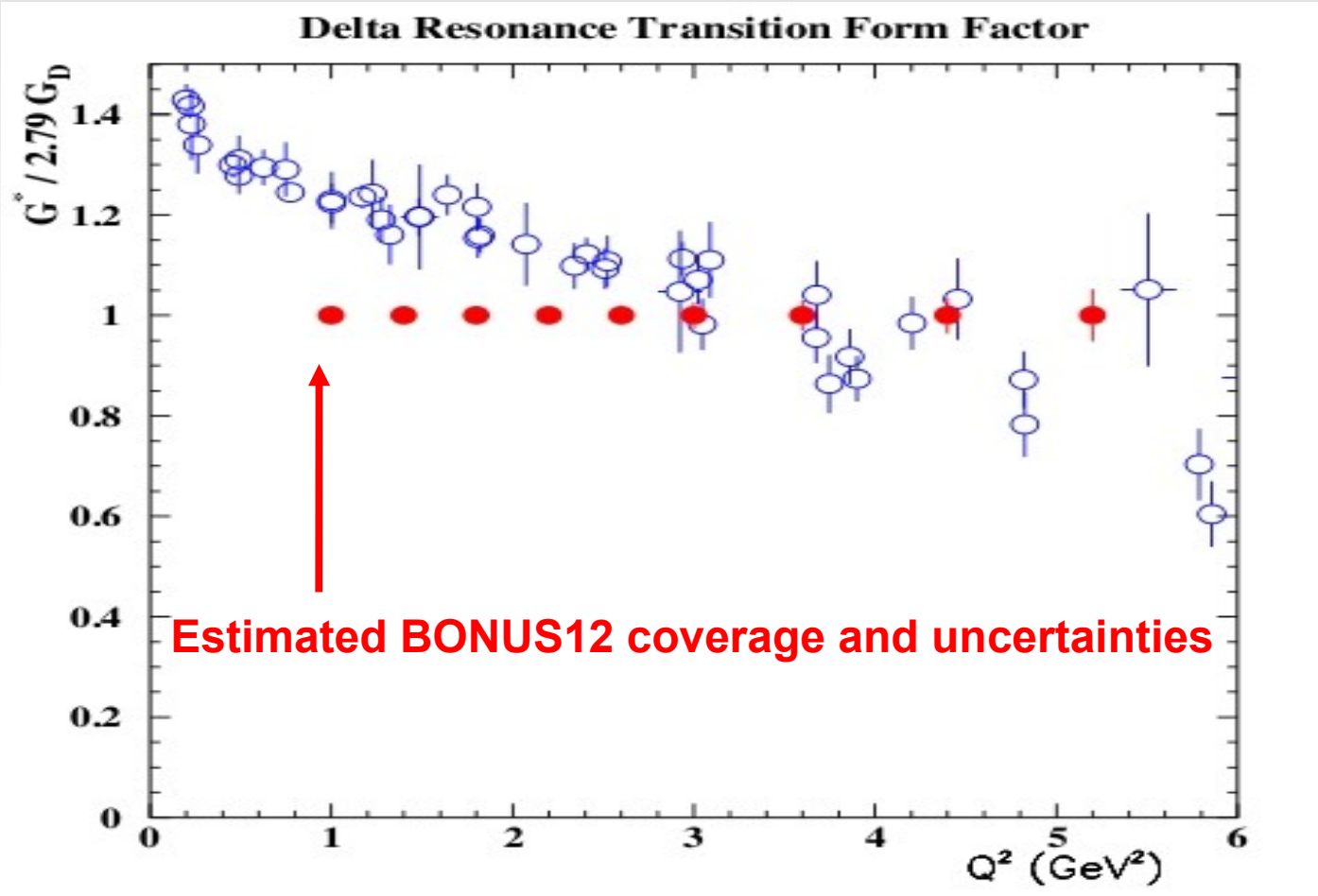
$W^* > 1.8$ GeV: $x^*_{max} = 0.83$

BONUS @ 12 GeV Jlab (BONUS12)





Δ transition form factor from neutron with Bonus12



Summary

→ Spectator tagging method demonstrated to allow Extraction of free neutron structure.

→ Allows significant reduction in nuclear model uncertainties On d-quark distribution at $x > 0.6$.

→ First look at EMC effect extracted for deuterium.

→ BONUS data allow study of nuclear effects.

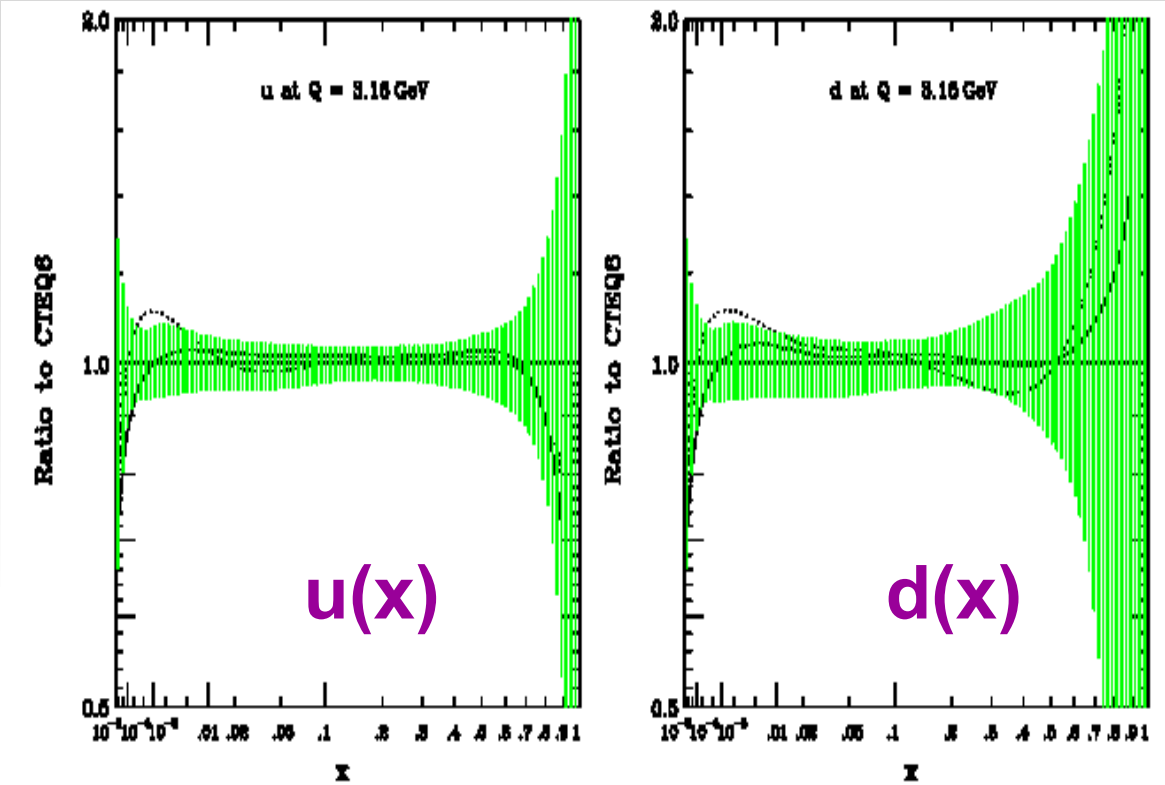
→ Upcoming 12 GeV BONUS will provide F_2^n precision Comparable to proton data up to $x \sim 0.8$.

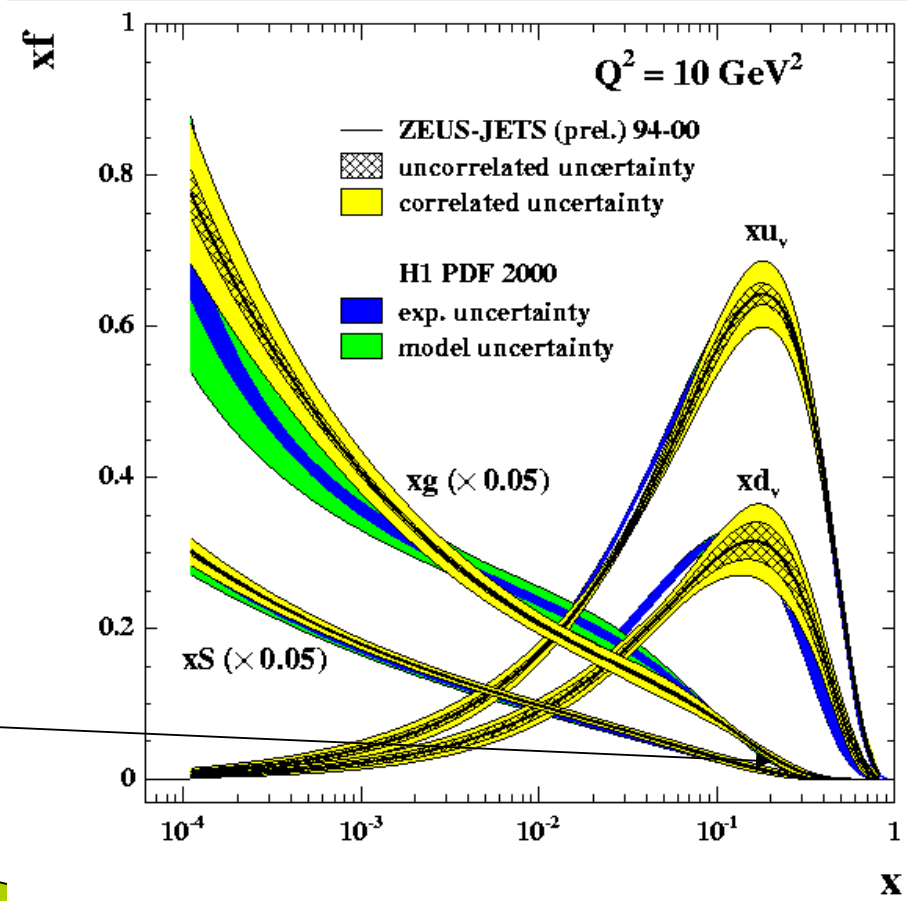
Much More to come

Thank You!

Backup Slides

PDFs Uncertainties





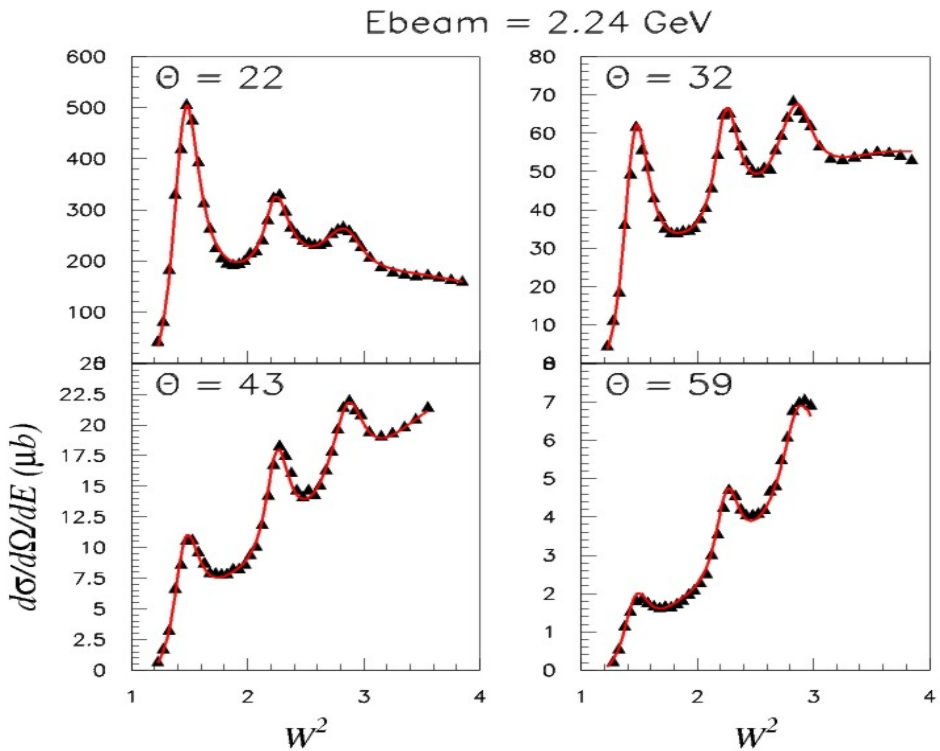
PDF's *least* well known at large *x*

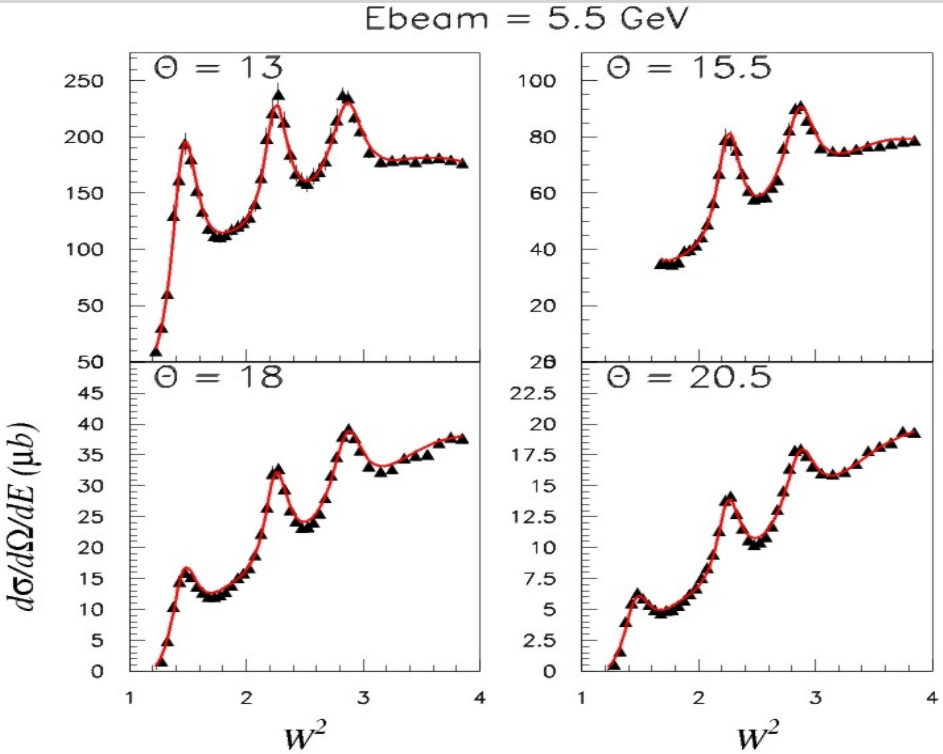
Gluon comparable in size to d_v at x~0.3

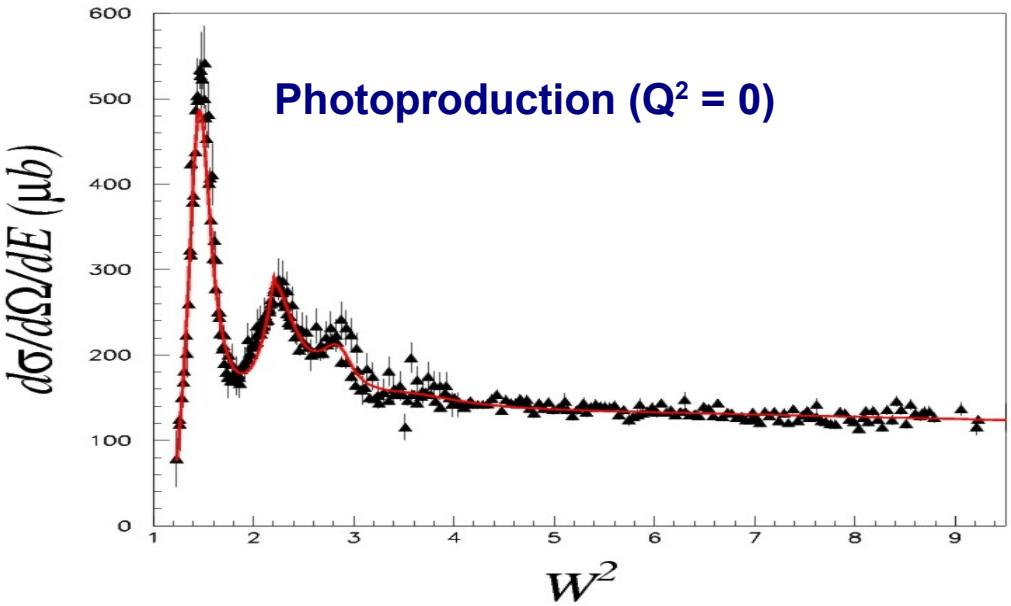
not well known here.

***Proton + neutron data provides way to separate valence cleanly.**

Resonance Proton fit (M.E. Christy)







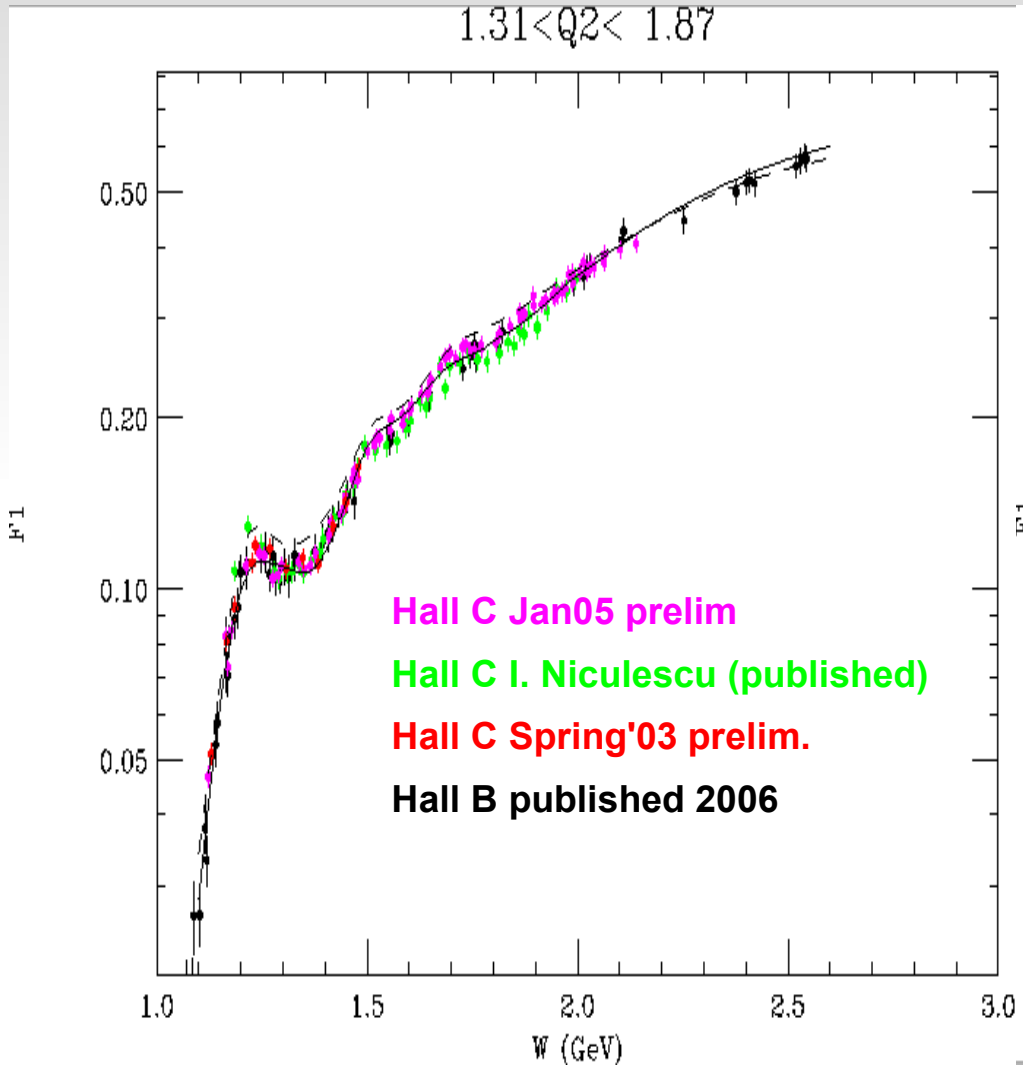
Kinematic range of fit:

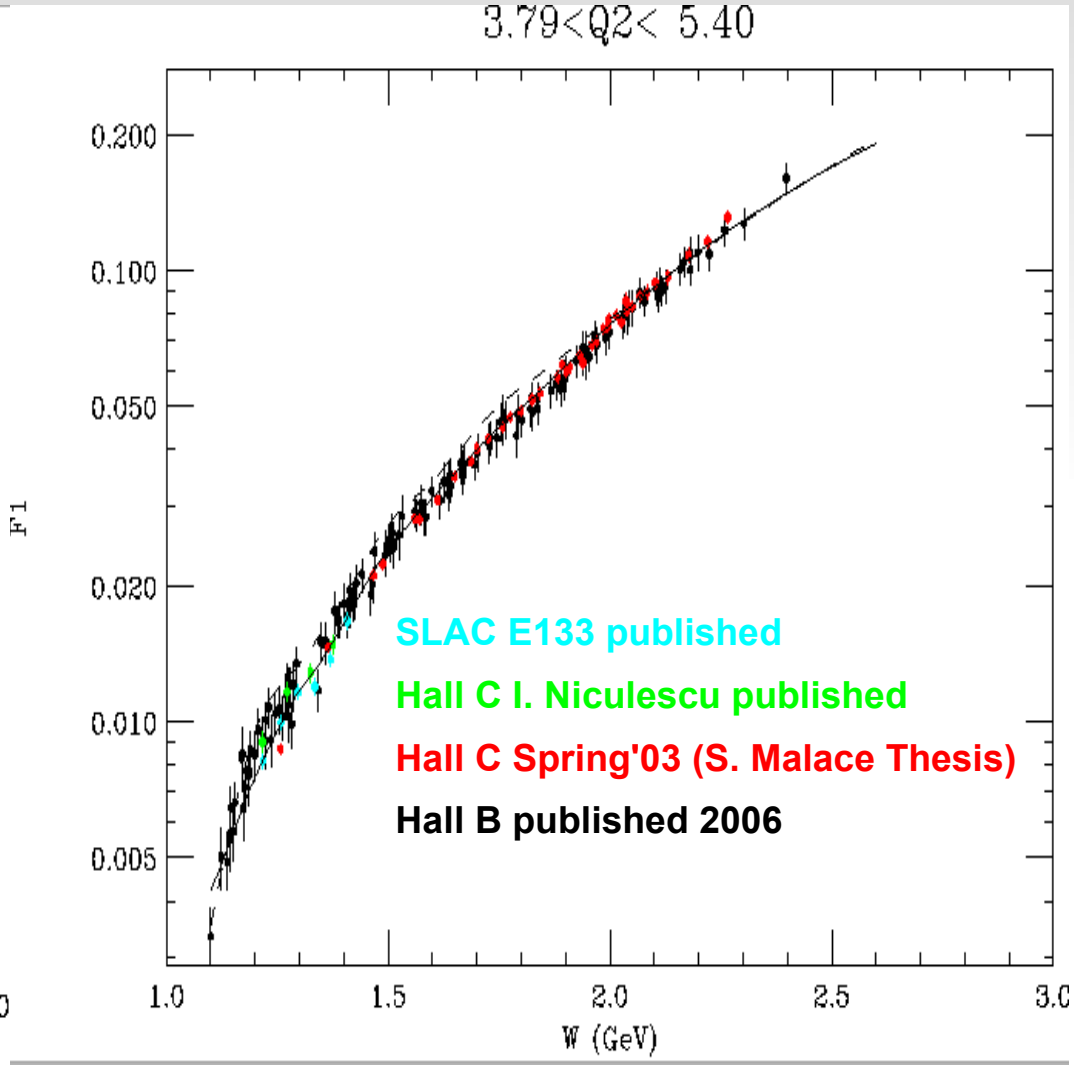
$$0 < Q^2 < 8$$

and $W_{\pi\ \mathrm{thresh}} < W < 3$

- **reproduces cross section data to ~3%**

Fit compared to deuteron data



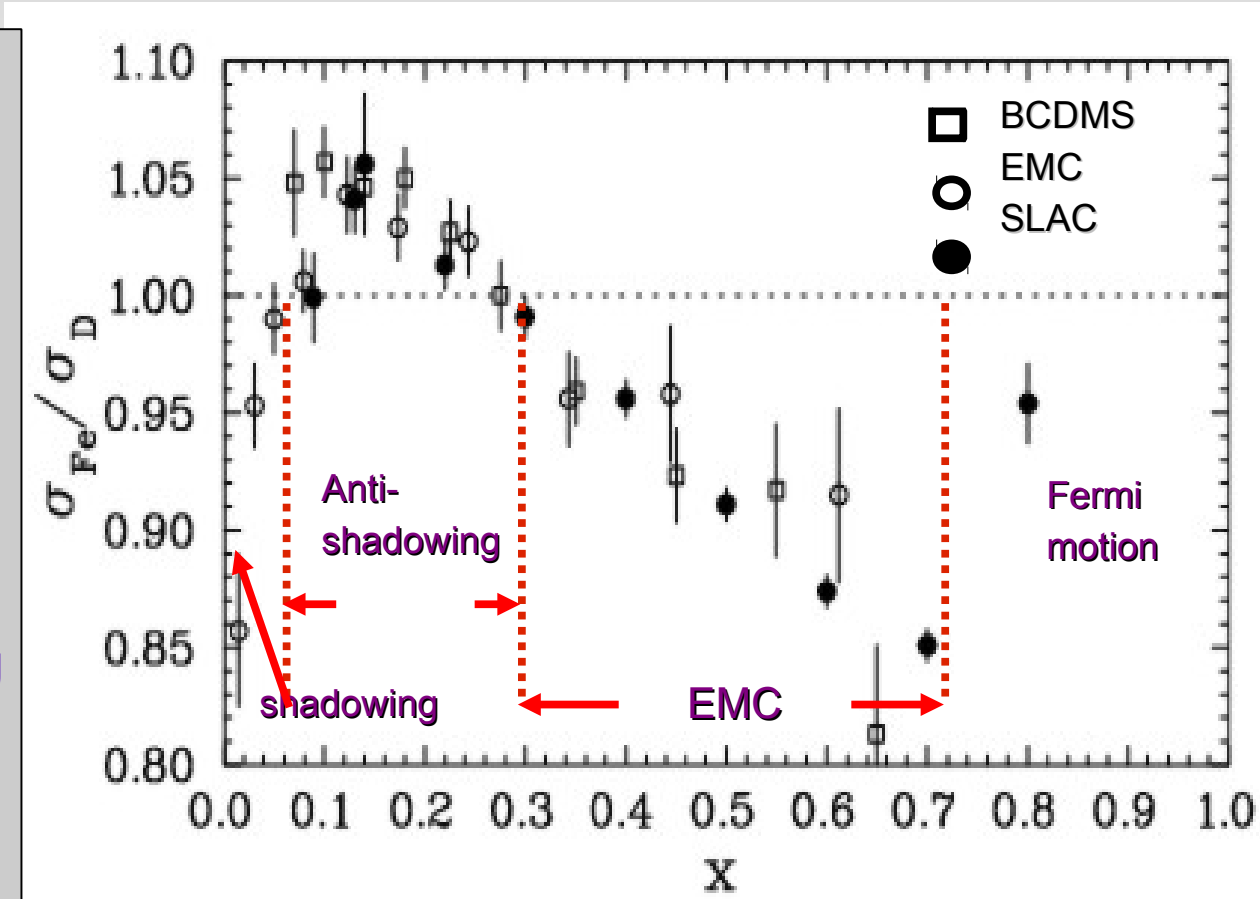


The EMC Effect

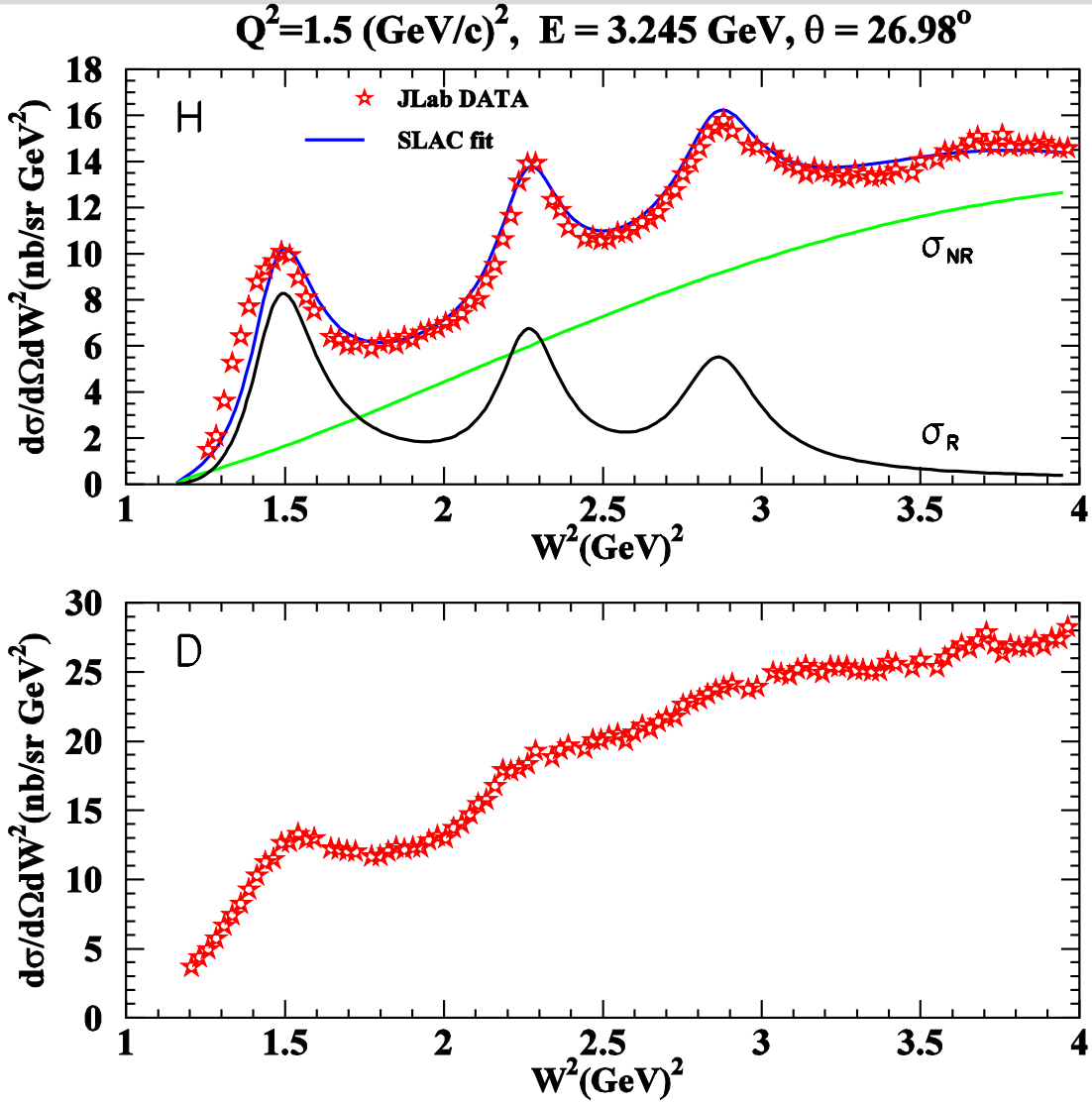
- Effects such as binding, off-shell, and final state interactions have largest impact on classic EMC region

- Need to get a handle on these to study more exotic effects.

Hard to imagine understanding the EMC effect *without* a firm grasp of nuclear effects in the deuteron



Inclusive Neutron Resonance Electroproduction



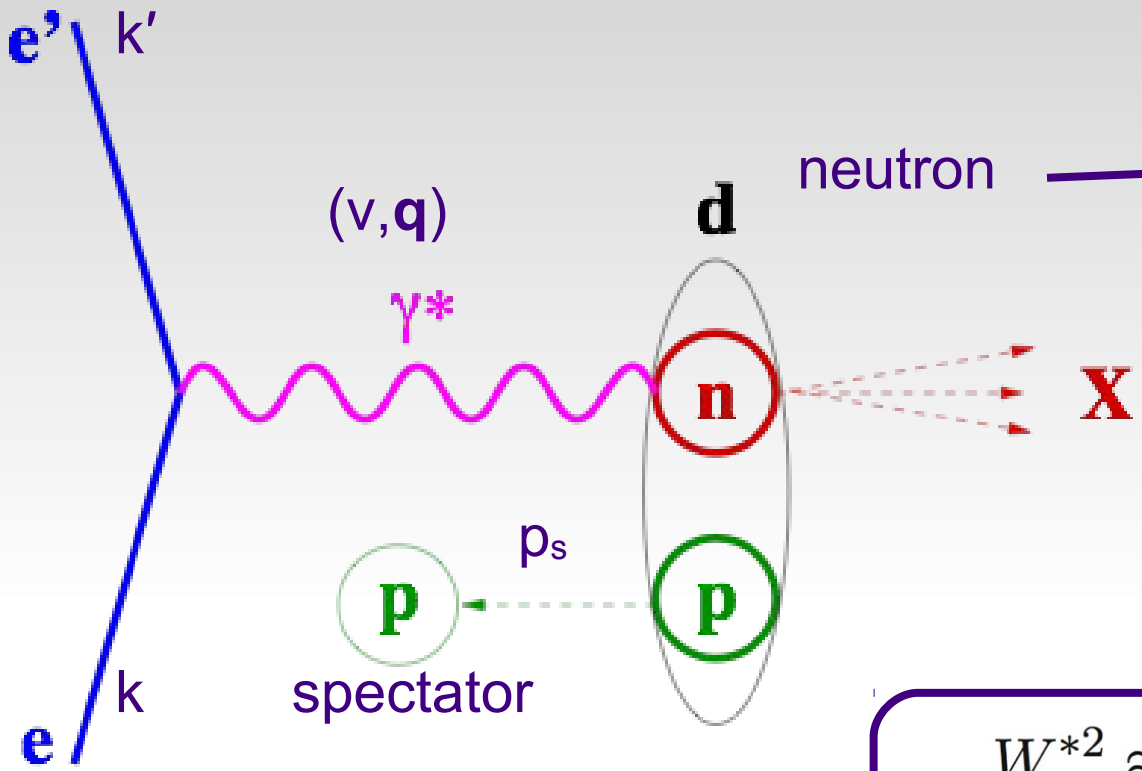
- Neutron structure functions in the deuteron have contributions from binding, fermi motion, nucleon off-shell effects, final state interactions (FSI), etc.

- We would like to know the *free* neutron structure to learn about:

-

moments of the neutron structure function (and non-singlet)
-neutron (transition) form factors
- quark-hadron duality for the neutron

d(e,e'p_s)X



before

$$p_n = (M_d - E_s, -\vec{p}_s)$$
$$M_d = E_n + E_s$$
$$E_n = M_d - \sqrt{M_s^2 + p_s^2}$$
$$M^{*2} = (M_d - E_s)^2 - \vec{p}_s^{\,2}$$

after

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

$$\alpha_s = \frac{E_s - p_{s\|}}{M_s}$$

$$x^* = \frac{Q^2}{2p_n \cdot q} \approx \frac{Q^2}{2M_s\nu(2-\alpha_s)} = \frac{x}{2-\alpha_s}$$

- Plane-wave impulse approximation
- Backward-emitted p is a spectator
- Struck neutron is off-shell
- **p_s** and **p_n** are equal and opposite
- Lorentz invariants are corrected for initial neutron 4-momentum

PWIA Spectator Formalism

$$\frac{d\sigma}{dx^* dQ^2} = \frac{4\pi\alpha_{\rm EM}^2}{x^* Q^4}\left[\frac{y^{*2}}{2(1+R)} + (1-y^*) + \frac{M^{*2}x^{*2}y^{*2}}{Q^2}\frac{1-R}{1+R}\right] F_2(x^*, \alpha_s, p_T, Q^2) \times S(\alpha_s, p_T)\frac{d\alpha_s}{\alpha_s}d^2p_T,$$

Cross Section

Off-Shell F_2

$R=\sigma_L/\sigma_T$

Light Cone

Spectral Function

Nonrelativistic w.f.

$$P(\vec{p}_s) = J|\psi_{\rm NR}(p_s)|^2$$

$$J = 1 + \frac{p_{s_{||}}}{E_n} = \frac{(2-\alpha_s)M_d}{2(M_d - E_s)}$$

$$S(\alpha_s, p_T)\frac{d\alpha_s}{\alpha_s}d^2p_T = P(\vec{p}_s)d^3p_s$$

$$S^{\rm LC}(\alpha_s, p_T)\frac{d\alpha_s}{\alpha_s}d^2p_T = |\psi_{\rm NR}(|\vec{k}|^2)|^2 d^3k$$

$$|\vec{k}| = \sqrt{\frac{M^2 + p_T^2}{\alpha_s(2-\alpha_s)} - M^2} \qquad \alpha_s = 1 - \frac{k_{||}}{\sqrt{M^2 + \vec{k}^2}}$$

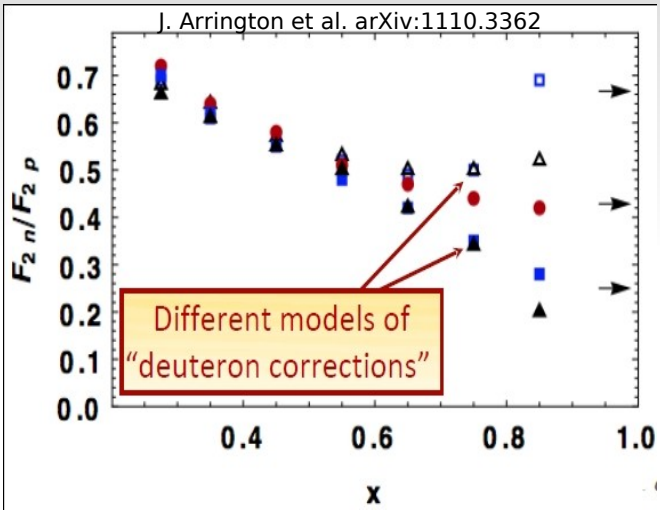
$$k_0 = \sqrt{M^2 + \vec{k}^2} \qquad \vec{p}_T = \vec{k}_T$$

$$\int\int\int S^{\rm LC}(\alpha_s, p_T)\frac{d\alpha_s}{\alpha_s}d^2p_T = 1$$

More than 40 years after discovery of the partonic substructure of nucleons, the neutron structure at large-x is still not well determined.

In addition, we would like to understand how the simplest nucleus, the deuteron, is *built* from a proton and neutron.

Even F_2^n *not* well known for x > 0.6



Non-pertabative models

SU(6) spin-flavor

Hard gluon exchange

S=0 diquark dominance

What about current state-of-the-art PDF fits including deuterium nuclear corrections?

New CJ PDF fits include Large-x + deuterium

- **Collaborators:**
  - A.Accardi, E.Christy, C.Keppel, W.Melnitchouk, P.Monaghan, J.Owens (J.Morfín, L.Zhu)
- **Goals:**
  - Global QCD fits of unpolarized PDFs focused on large *x*
  - Improve the PDF experimental precision ("PDF errors") by enlarging the fitted data set
  - Include all relevant large-*x* / small-Q^2 theory corrections
  - ***Quantitatively evaluate theoretical systematic errors***
  - ***Use PDFs as tools for nuclear and particle physics***

including nuclear corrections on D_2 !

- **Papers:**
  - A.Accardi et al., Phys.Rev.D81 (2010) 034016 **"CJ10"**
  - A.Accardi et al., Phys.Rev.D84 (2011) 014008 **"CJ11"**
  - New fit in preparation with latest data

Available on request

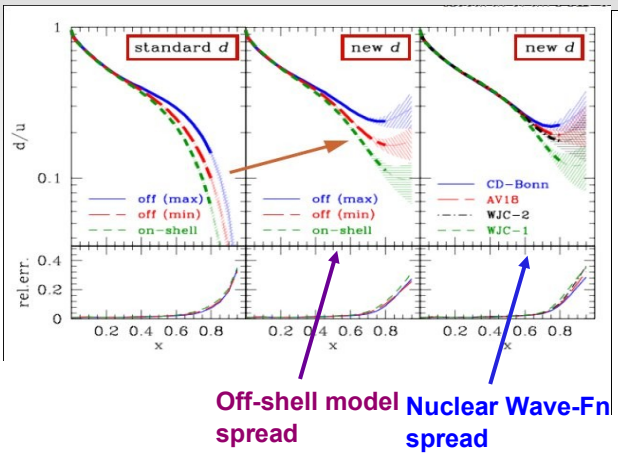
Public release planned

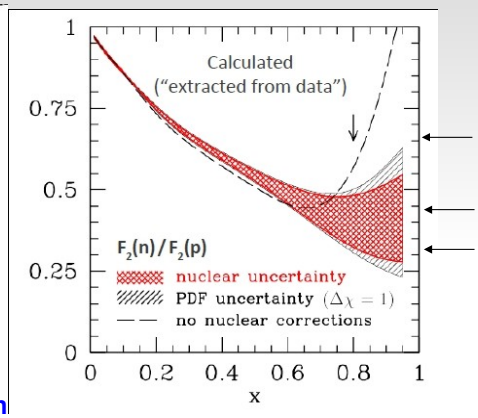
accardi@jlab.org QCD@LHC, 22 Aug 2012

Slide from Alberto Accardi

Nuclear uncertainties results from CJ11

Accardi et al. PRD 84, 014008 (2011)





Off-shell model spread

Nuclear Wave-Fn spread

Still significant uncertainties from nuclear models at large-x

Free neutron targets would provide solution

→ No high density neutron targets exist

→ Use deuterium and assure that scattering took
Place from a 'nearly' on-shell effectively free neutron

alpha – analogous to x for the nucleus

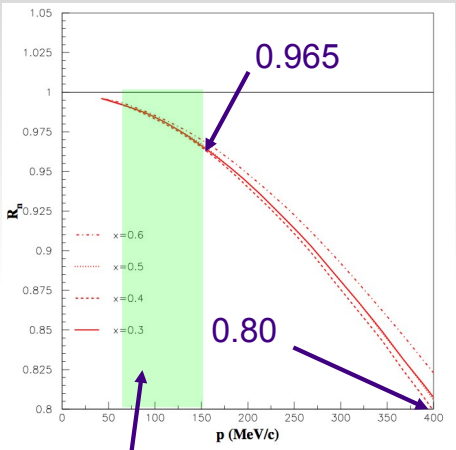
s – deuteron spectral function – proportional to the deuteron wave function

For free neutron structure must kinematically select to minimize:

1. Off-shell effects
2. Final state interactions
3. Target fragmentation enhancement to proton yield

Off-Shell Structure Functions

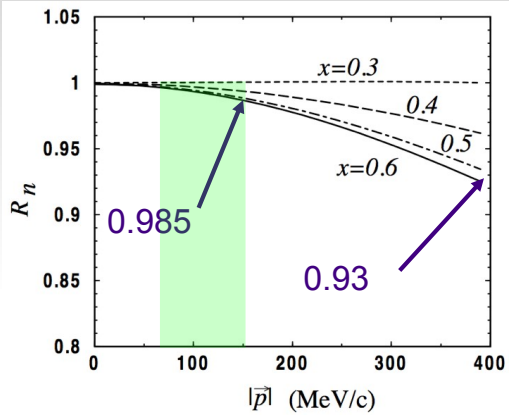
Liuti & Gross PLB**356**(95)157



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

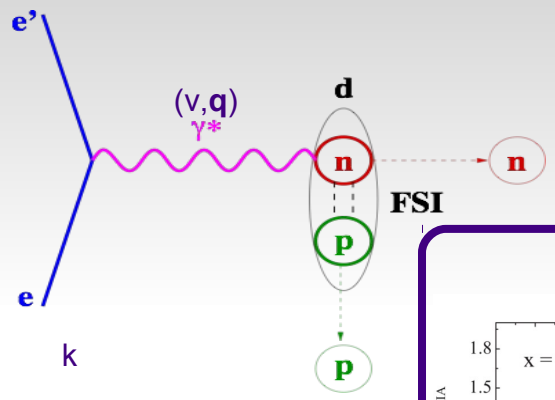
BoNuS p_s detection range

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



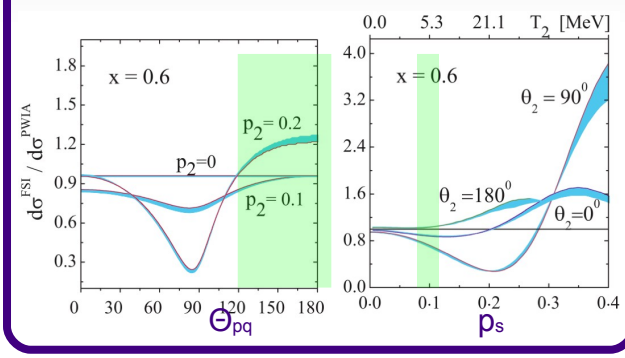
- R_n decreases with p_s or α_s
- At x*=0.5 and p_s=400 MeV/c, R_n deviates from unity by 7-20% in these models

Final State Interactions



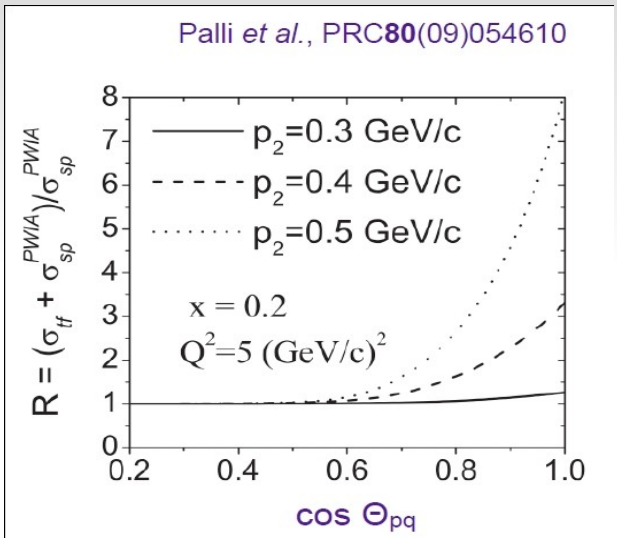
- Struck neutron can interact with the spectator proton
- Proton momentum is enhanced
- FSIs are small at low p_s and large Θ_{pq}

Palli et al, PRC**80**(09)054610



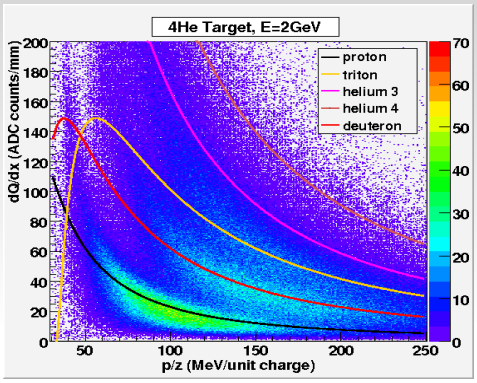
- Several groups have calculated FSIs
- Θ_{pq} > 110° and p_s<100 MeV/c greatly reduces FSIs

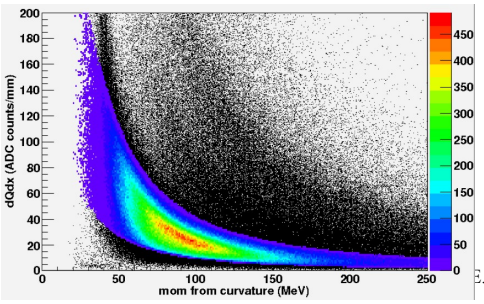
Target Fragmentation



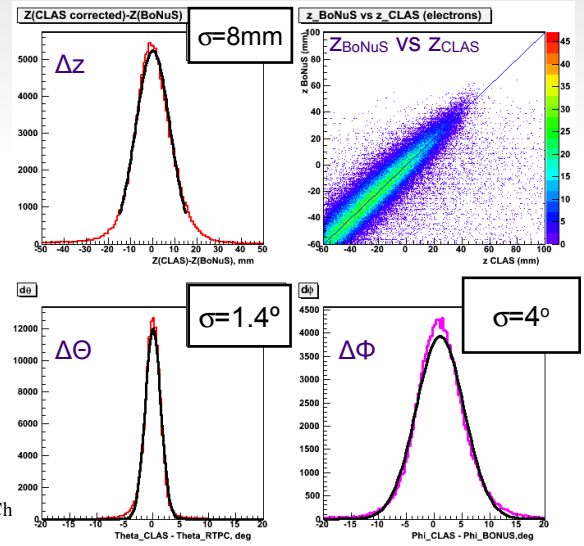
Enhancement in proton Yield Over PWIA *negible* for *backward* protons!

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



E. Ch

Ratio Method

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

First make experimental ratio:

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

In terms of structure function ratio:

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

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

P_s < 100 MeV/c, θ_p > 110

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

A_p : tagged proton Efficiency * Acceptance

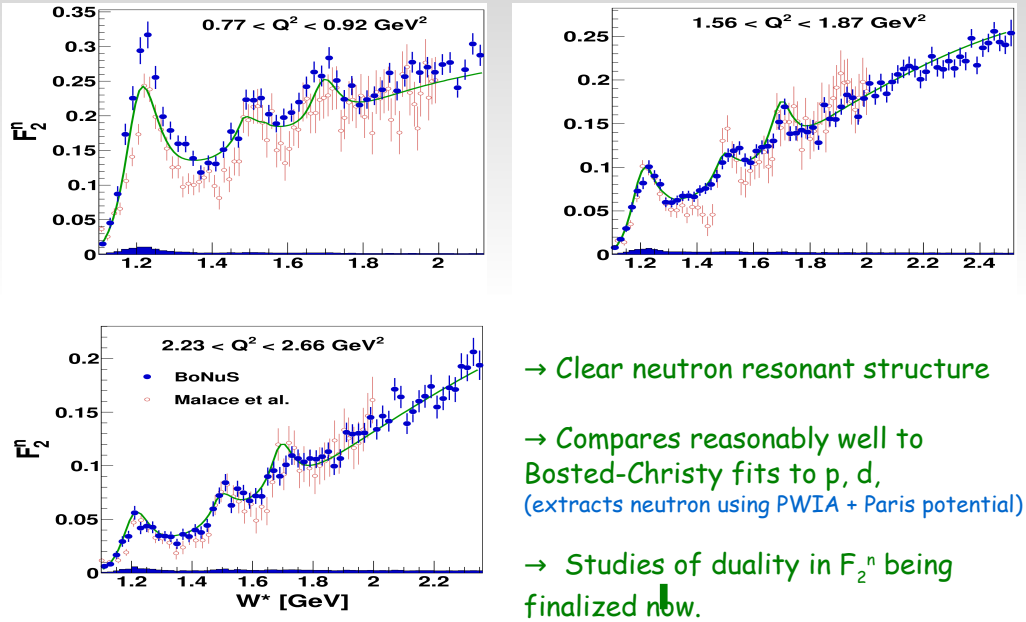
→ Integral I_{vip} is largely independent of W* (x*) and Q^2

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

Then $F_2^n = F_2^d * R_{exp} * I_{vip}$

Resonance F_2^n results

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



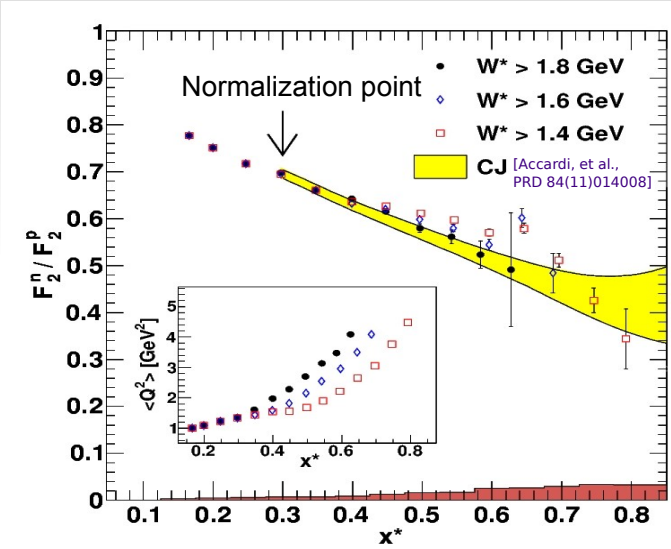
→ Clear neutron resonant structure

→ Compares reasonably well to Bosted-Christy fits to p, d,
(extracts neutron using PWIA + Paris potential)

→ Studies of duality in F_2^n being finalized now.

Results on F_2^n / F_2^p

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



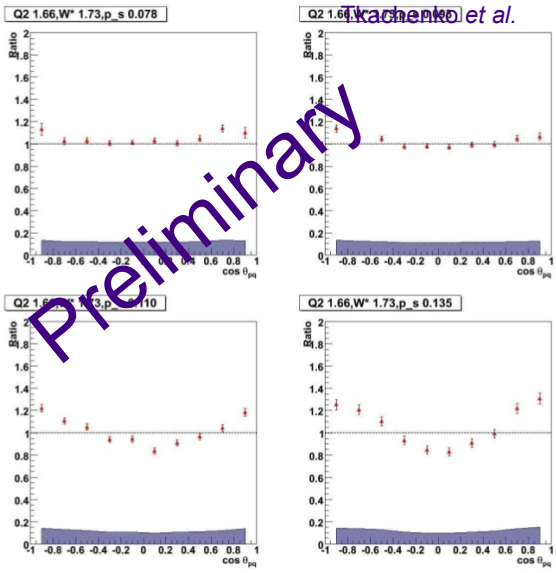
→ F2n/F2p = F2n/F2d * F2d/F2p with F2d/F2p from Bosted/Christy fits PRC77(08)065206, PRC81(10)055213

→ 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

Spectator model test:
Data/MC cosθ distributions



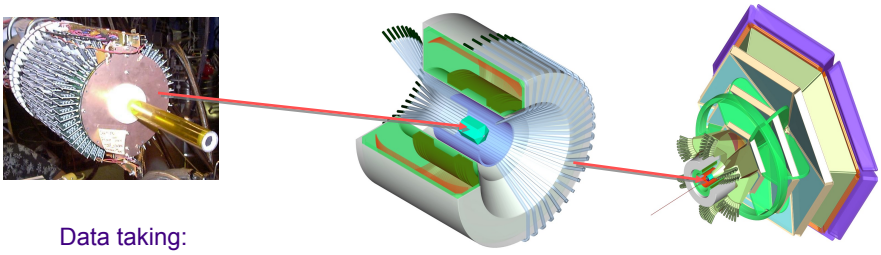
- Analysis of S. Tkachenko utilizes larger kinematic coverage to test spectator model.
- At low p_s the data agree with the spectator model quite well.
- At higher p_s the distributions deviate significantly from unity, indicating that VIP particles should have p_s<100 MeV/c.

With n+p and deuterium Structure functions in hand...

Study of EMC effect in the deuteron is currently in progress

BoNuS Plans for 12 GeV

E12-06-113

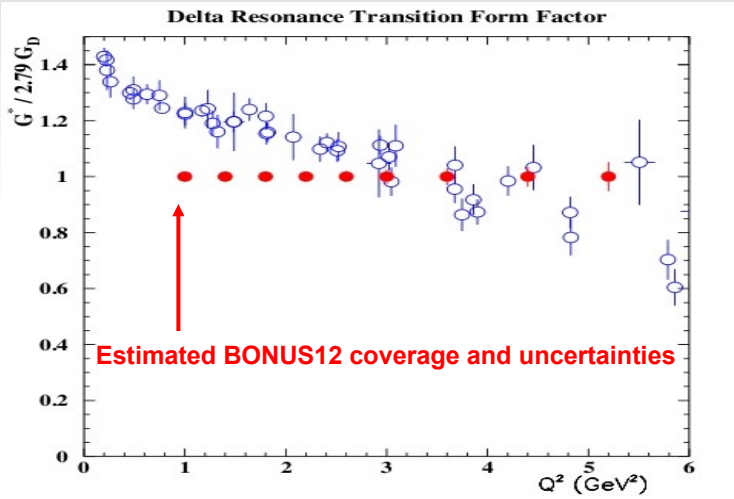


Data taking:
- 35 days on D_2
- 5 days on H_2
- $L = 2 \times 10^{34}\ cm^{-2}\ sec^{-1}$

DIS region:
- $Q^2 > 1\ GeV^2$
- $W^* > 2$ GeV
- $p_s < 100$ MeV/c
- $\theta_{pq} > 110°$
- $x^*_{max} = 0.80$

$W^* > 1.8$ GeV: $x^*_{max} = 0.83$

Δ transition form factor from neutron with Bonus12



Summary

→ Spectator tagging method demonstrated to allow Extraction of free neutron structure.

→ Allows significant reduction in nuclear model uncertainties On d-quark distribution at $x > 0.6$.

→ First look at EMC effect extracted for deuterium.

→ BONUS data allow study of nuclear effects.

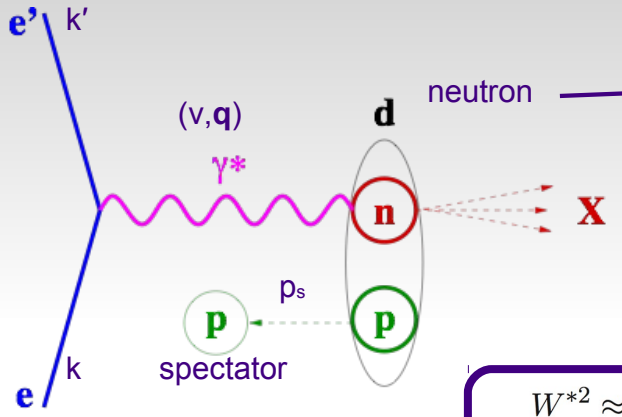
→ Upcoming 12 GeV BONUS will provide F_2^n precision Comparable to proton data up to $x \sim 0.8$.

Much More to come

Thank You!

point out that resonance structure of proton is obvious, neutron resonance must be extracted from deuterium data – fermi motion of the nucleus washes out the peaks. we need a free neutron target

d(e,e'p_s)X



before

$$p_n = (M_d - E_s, -\vec{p}_s)$$
$$M_d = E_n + E_s$$
$$E_n = M_d - \sqrt{M_s^2 + p_s^2}$$
$$M^{*2} = (M_d - E_s)^2 - \vec{p}_s^{\,2}$$

after

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

$$\alpha_s = \frac{E_s - p_{s\|}}{M_s}$$

$$x^* = \frac{Q^2}{2p_n \cdot q} \approx \frac{Q^2}{2M_s\nu(2-\alpha_s)} = \frac{x}{2-\alpha_s}$$

- Plane-wave impulse approximation
- Backward-emitted p is a spectator
- Struck neutron is off-shell
- **p_s** and **p_n** are equal and opposite
- Lorentz invariants are corrected for initial neutron 4-momentum

PWIA Spectator Formalism

$$\frac{d\sigma}{dx^* dQ^2} = \frac{4\pi\alpha_{\rm EM}^2}{x^* Q^4}\left[\frac{y^2}{2(1+R)} + (1-y) + \frac{M^{*2}x^{*2}y^2}{Q^2}\frac{1-R}{1+R}\right] F_2(x^*, \alpha_s, p_T, Q^2) \times S(\alpha_s, p_T)\frac{d\alpha_s}{\alpha_s}d^2p_T,$$

Cross Section

Off-Shell F_2

$R=\sigma_L/\sigma_T$

Light Cone

Spectral Function

Nonrelativistic w.f.

$$P(\vec{p}_s) = J|\psi_{\rm NR}(p_s)|^2$$

$$J = 1 + \frac{p_{s_{||}}}{E_n} = \frac{(2-\alpha_s)M_d}{2(M_d - E_s)}$$

$$S(\alpha_s, p_T)\frac{d\alpha_s}{\alpha_s}d^2p_T = P(\vec{p}_s)d^3p_s$$

$$S^{\rm LC}(\alpha_s, p_T)\frac{d\alpha_s}{\alpha_s}d^2p_T = |\psi_{\rm NR}(|\vec{k}|^2)|^2 d^3k$$

$$|\vec{k}| = \sqrt{\frac{M^2 + p_T^2}{\alpha_s(2-\alpha_s)} - M^2} \qquad \alpha_s = 1 - \frac{k_{||}}{\sqrt{M^2 + \vec{k}^2}}$$

$$k_0 = \sqrt{M^2 + \vec{k}^2} \qquad \vec{p}_T = \vec{k}_T$$

$$\int\int\int S^{\rm LC}(\alpha_s, p_T)\frac{d\alpha_s}{\alpha_s}d^2p_T = 1$$