

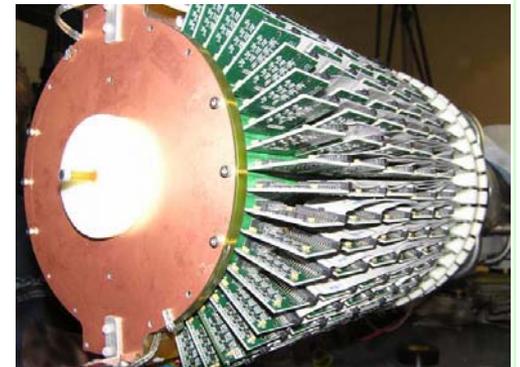
# Large x Neutron Results from **BONUS, Duality, and Sum Rules**

**Ioana Niculescu**

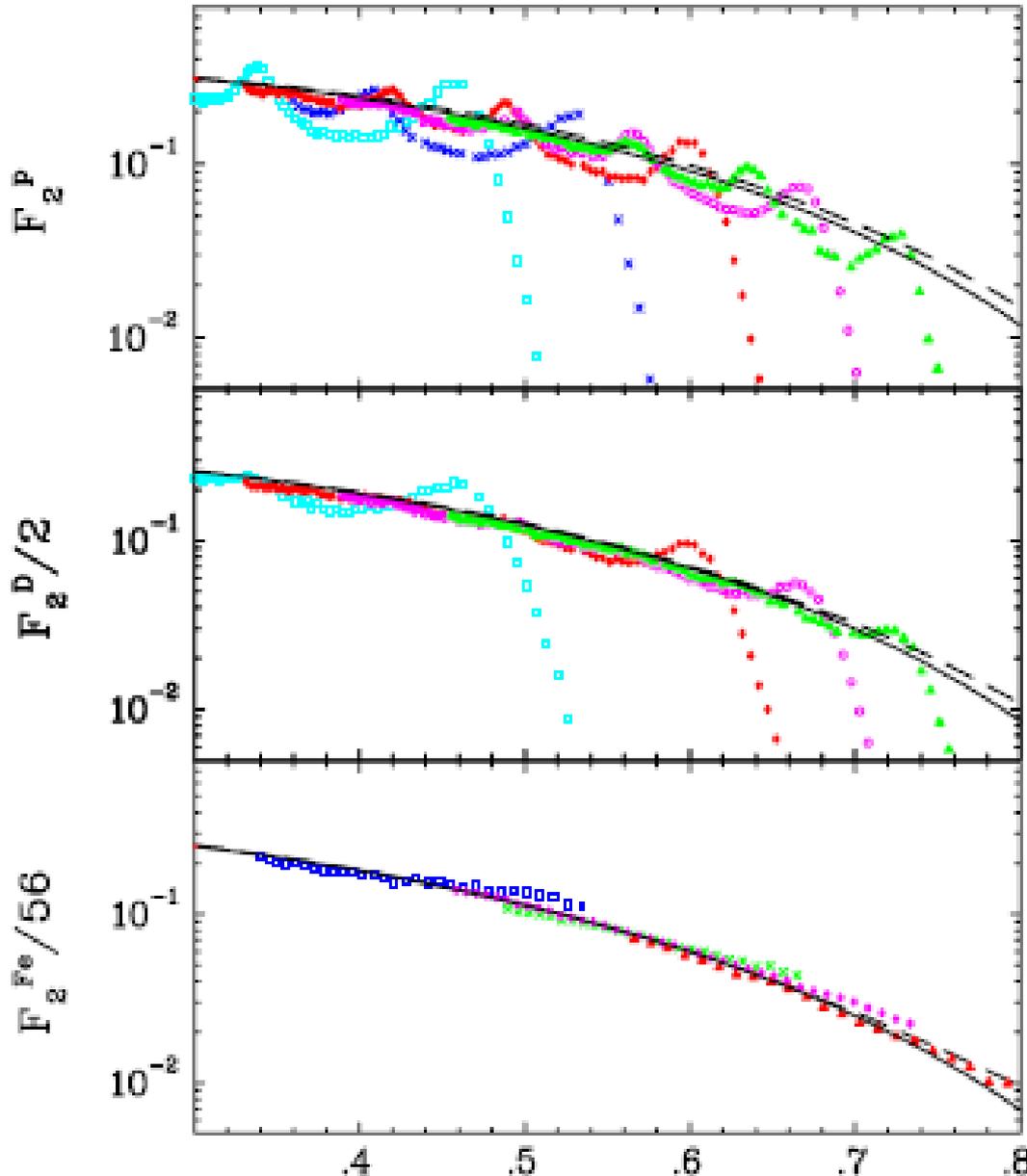
**James Madison University**

**November 18, 2014**

- ❖ **Why study duality on the neutron?**
- ❖ **The BONuS experiment**
- ❖ **Local duality on the neutron**
- ❖ **Gottfried Sum Rule**
- ❖ **Summary**



# The Proton and the Deuteron



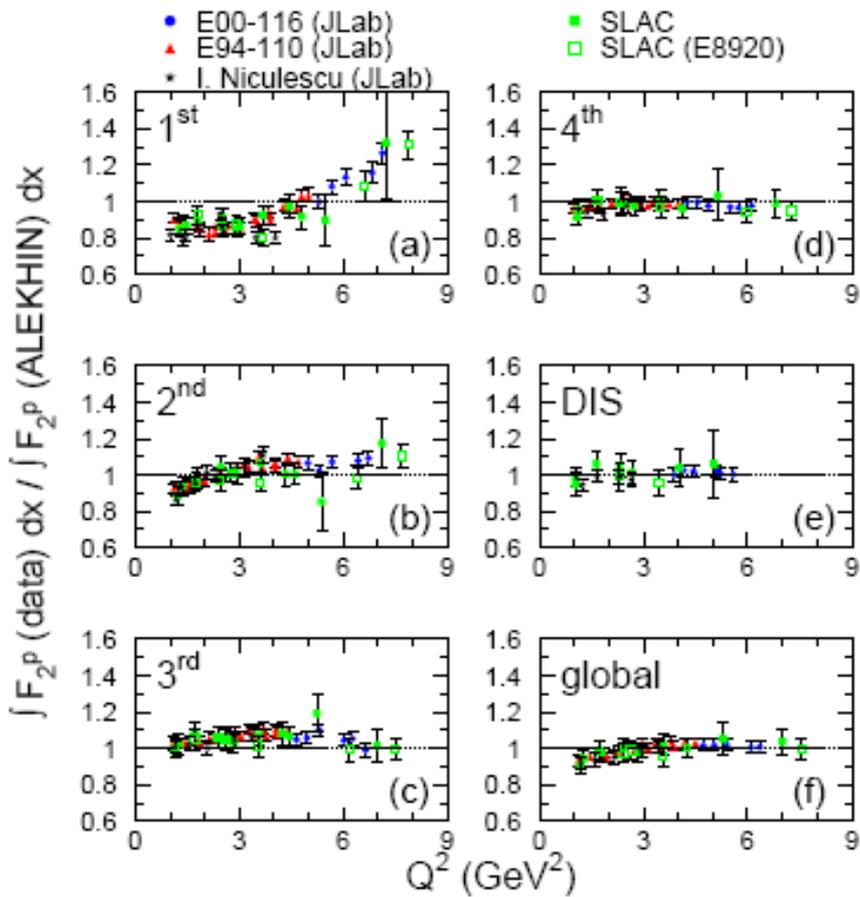
**Scaling (duality) is observed in nuclei**

**Resonances less pronounced – washed out by Fermi motion**

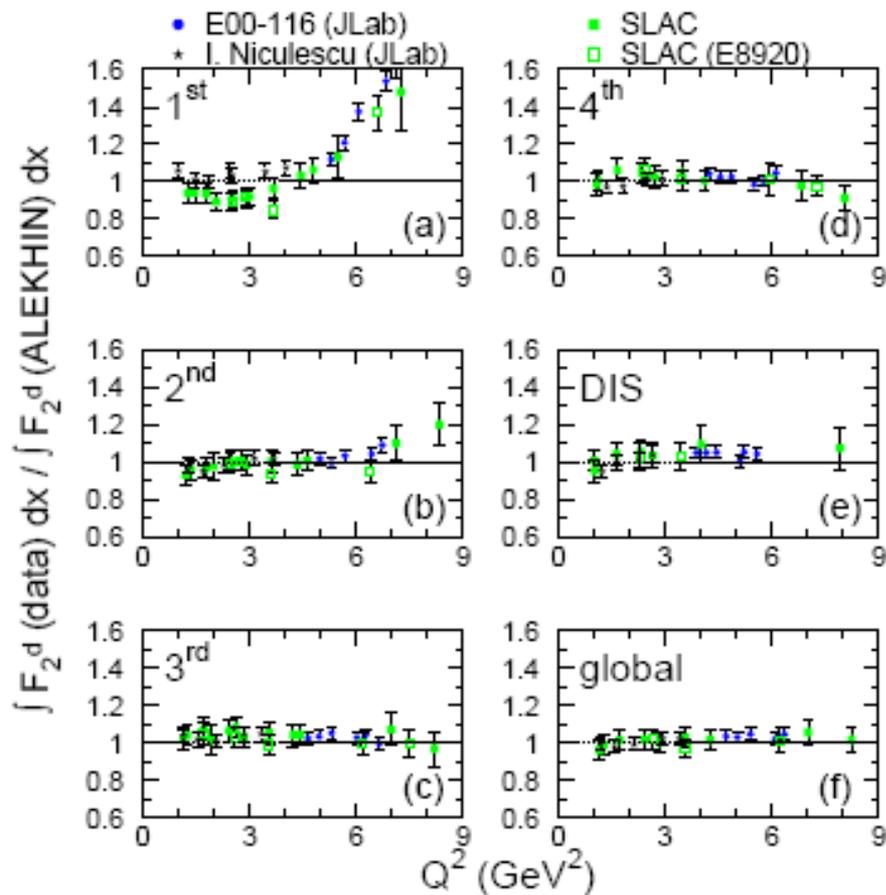
# Local duality



## The proton



## The deuteron



# Does it work for the Neutron?

Frank E. Close, Nathan Isgur PLB 509 (2001) 81

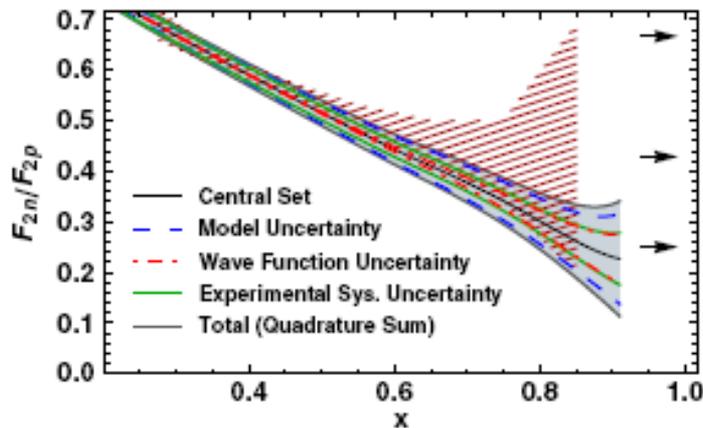
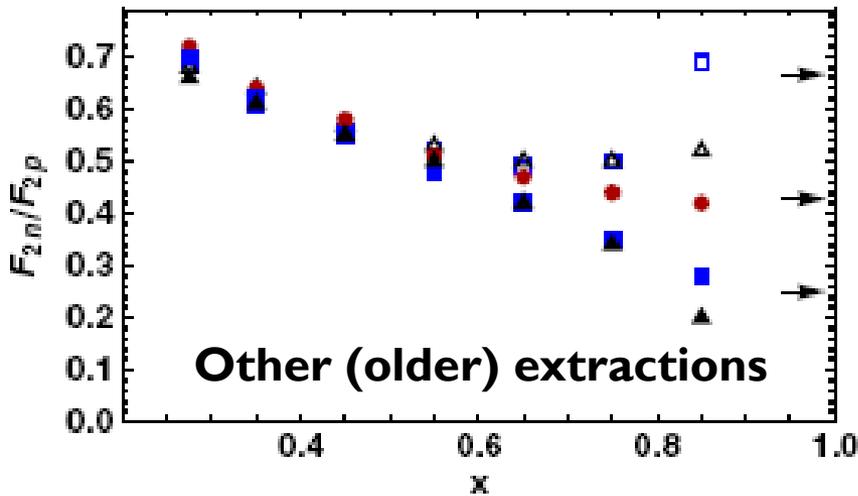
- “for the proton duality may be satisfied by  $W < 1.6 \text{ GeV}$ ”
- “For neutron targets [...] we anticipate systematic deviations from local duality”
- “the  $S11(1530)$  [...] and the  $F15(1680)$  are enhanced relative to the deep inelastic scaling curve for proton targets”
- for neutron targets, the  $S11(1530)$  region will fall below the scaling curve

# Extract neutron from deuteron data

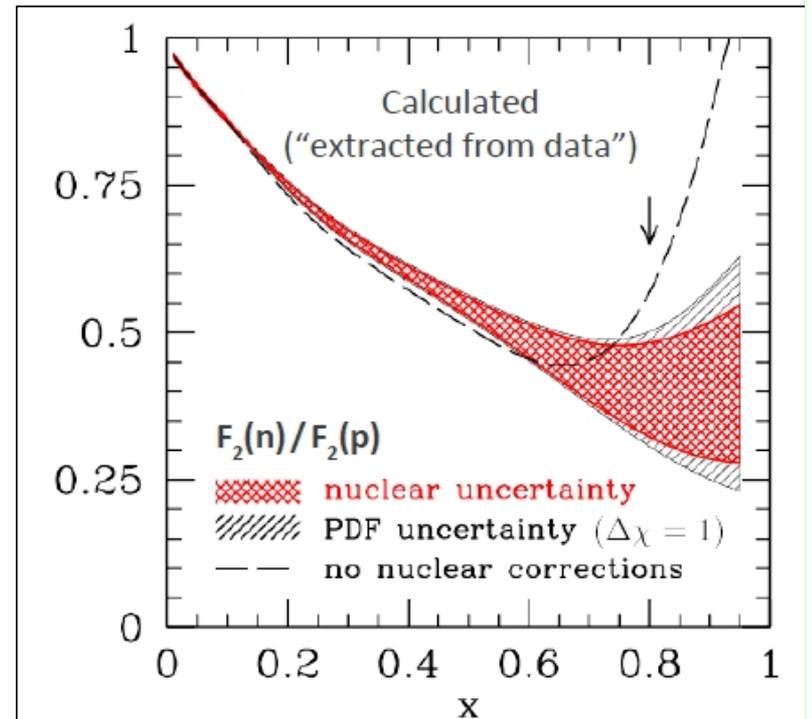


Large uncertainties due to nuclear effects

J. Arrington, J. G. Rubin, W. Melnitchouk PRL 108, 252001 (2012)

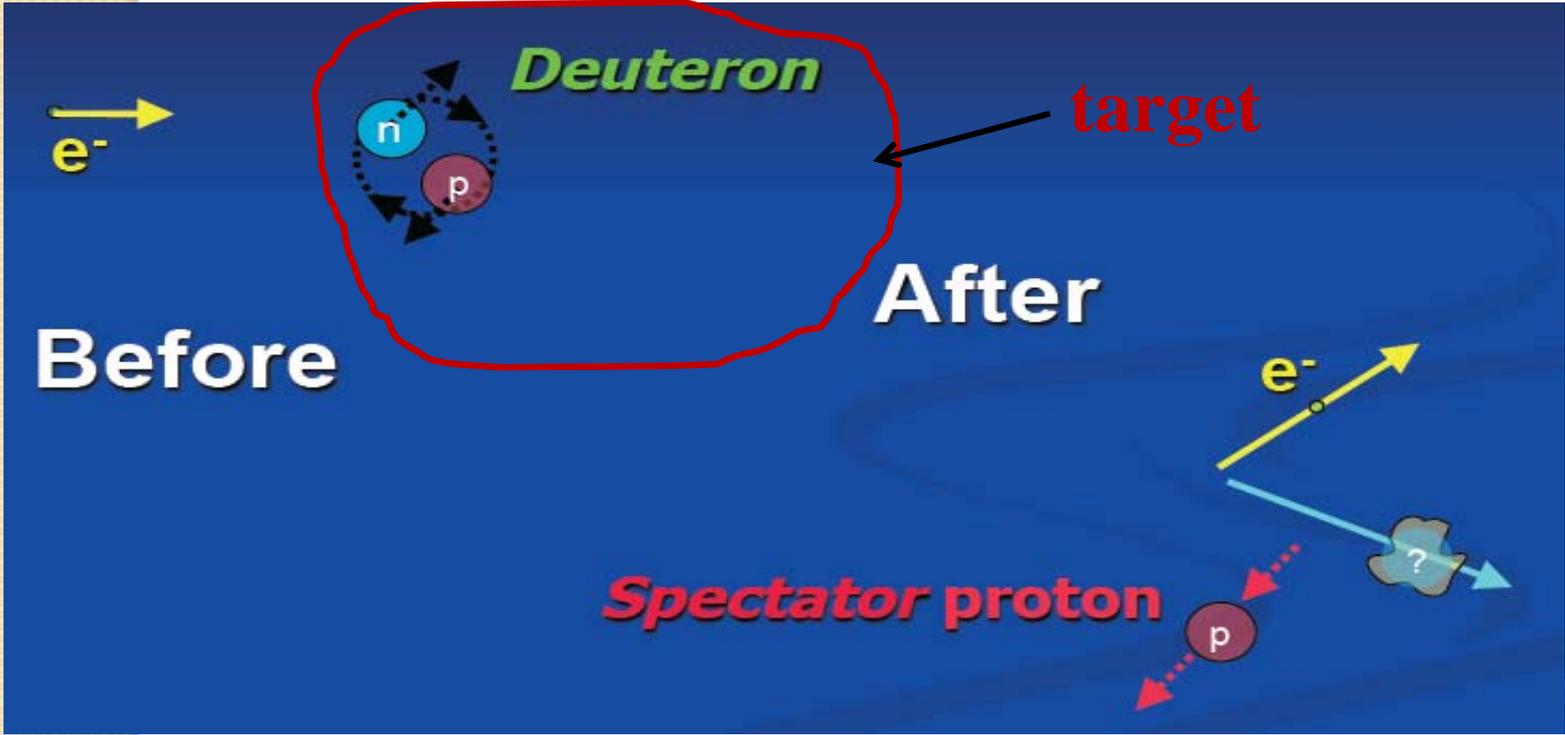


A. Accardi et al., PRD 84 014008 (2011)

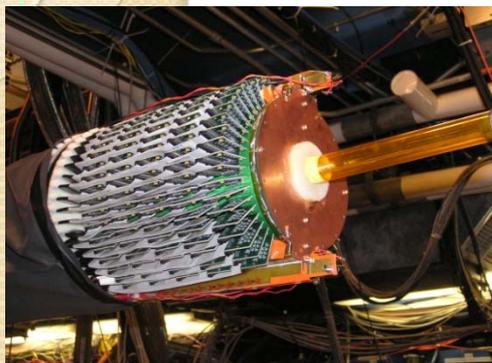




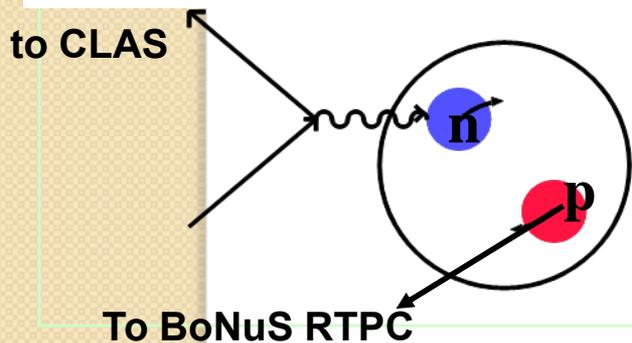
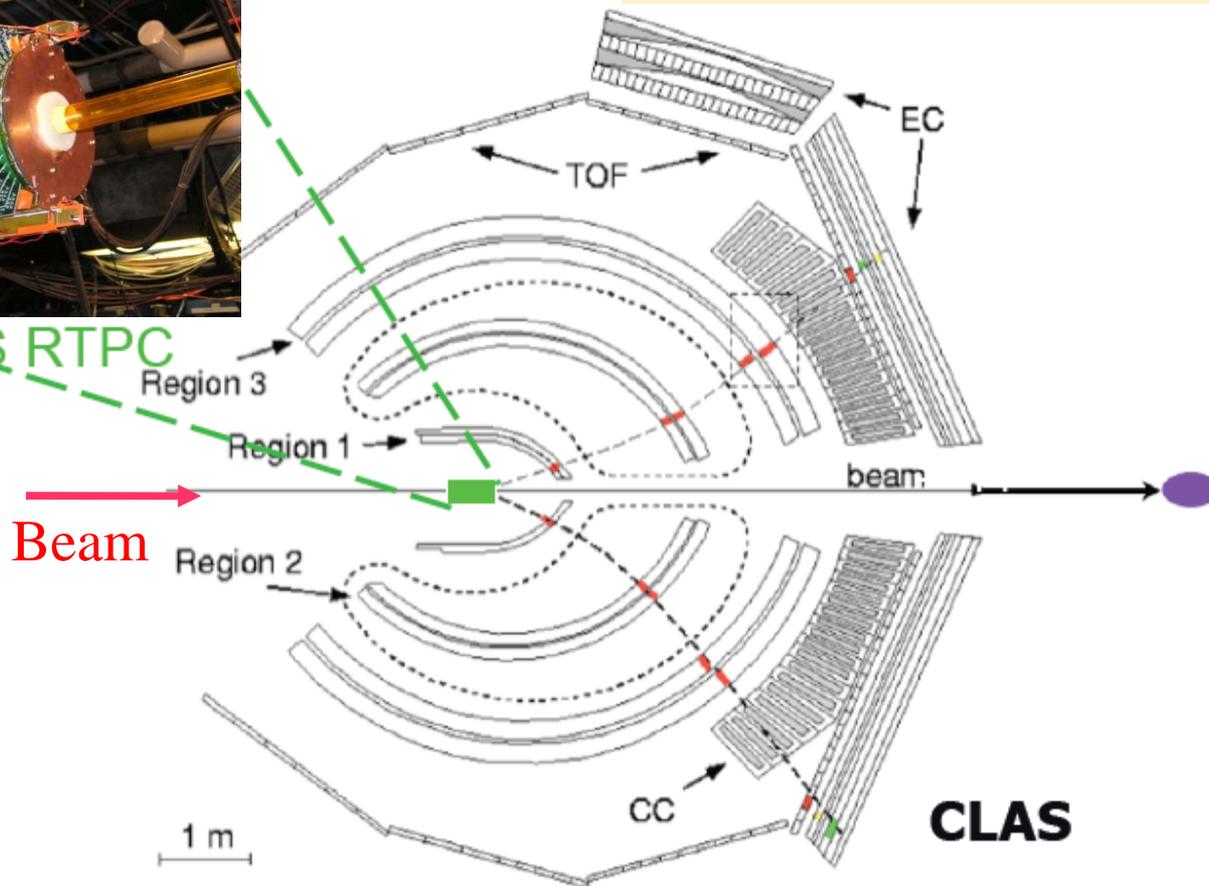
# The **BONUS** Experiment



# Experimental Setup:



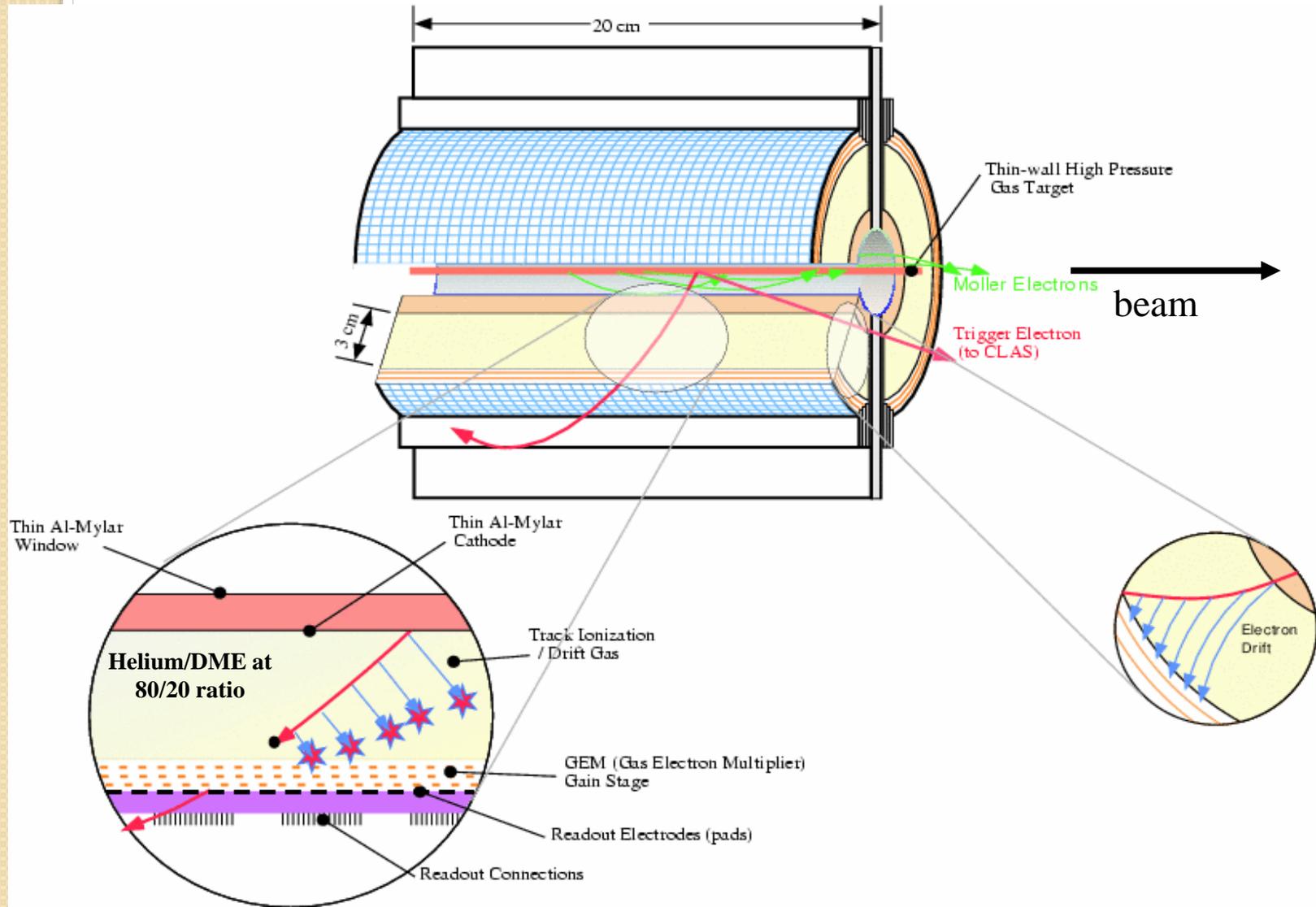
BoNuS RTPC



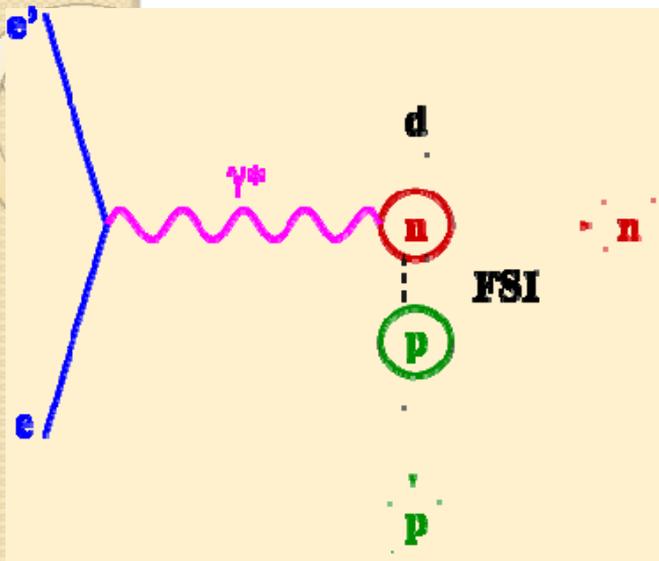
To BoNuS RTPC

# Experimental Setup: BoNuS RTPC

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

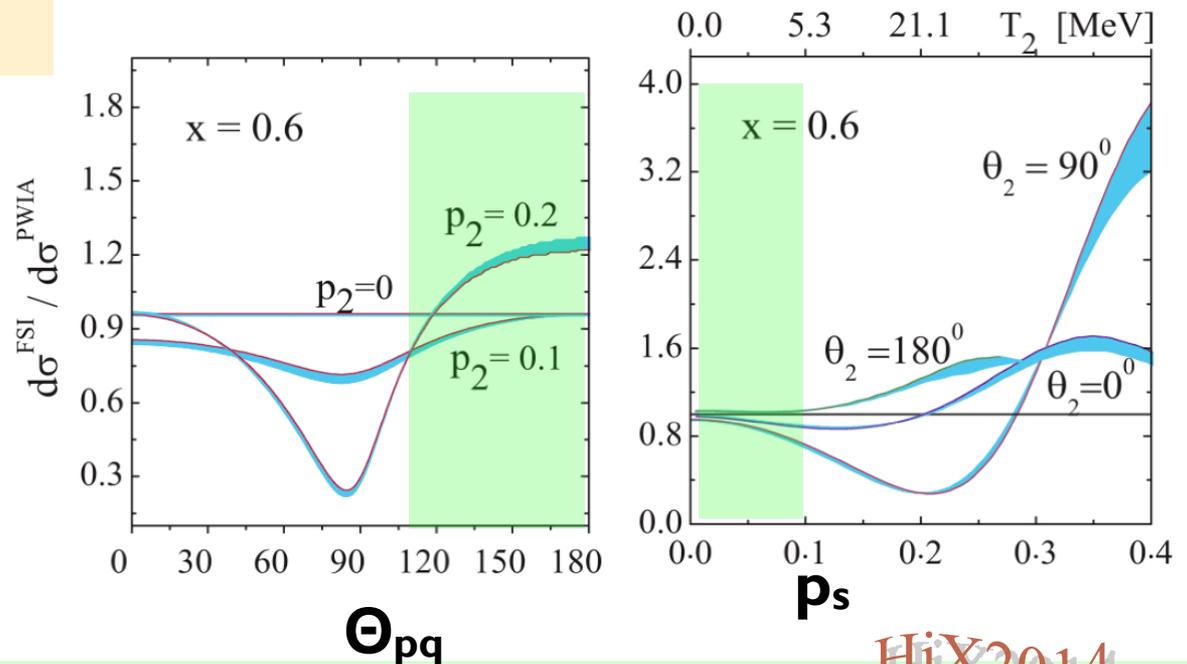


# Final State Interaction



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

Palli et al, PRC80(09)054610



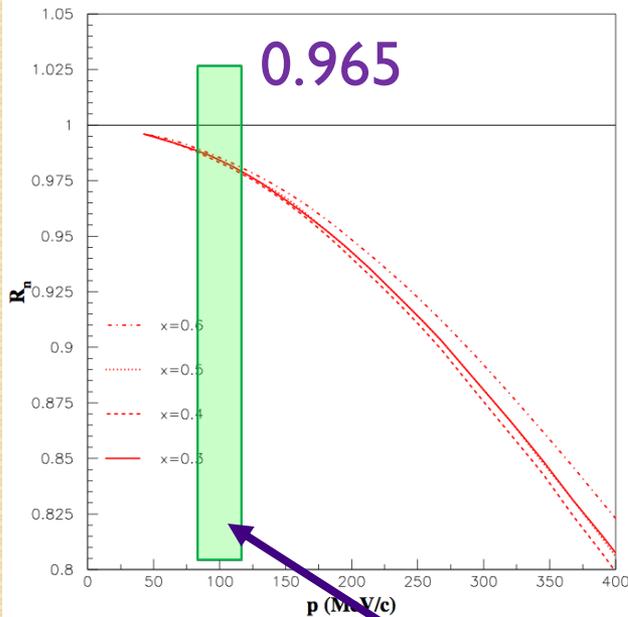
- Several groups have calculated FSIs
- Few percent for low momentum

# Off – shell Effects

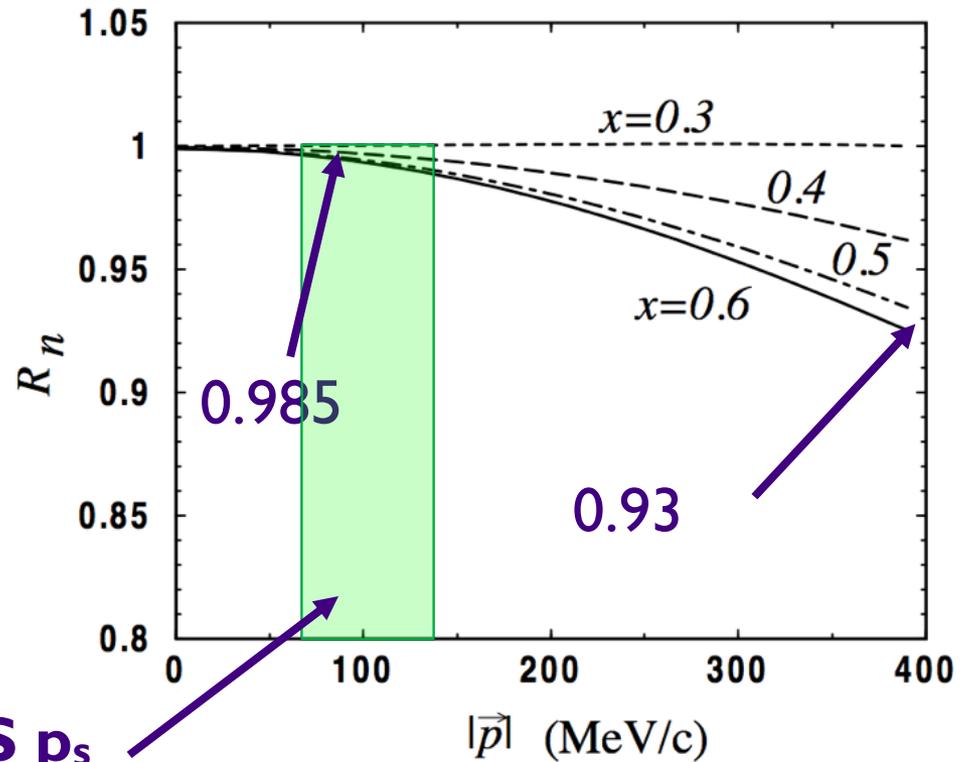


$$R_n \equiv (F_2^n)^{\text{eff}} / (F_2^n)^{\text{free}}$$

Liuti & Gross PLB356(95)157



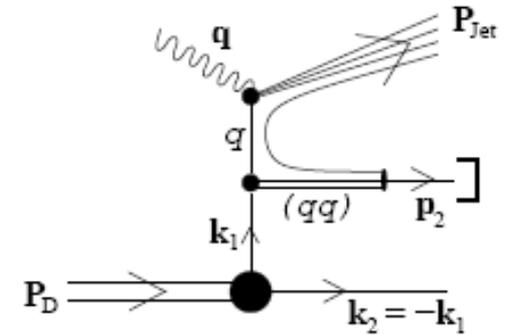
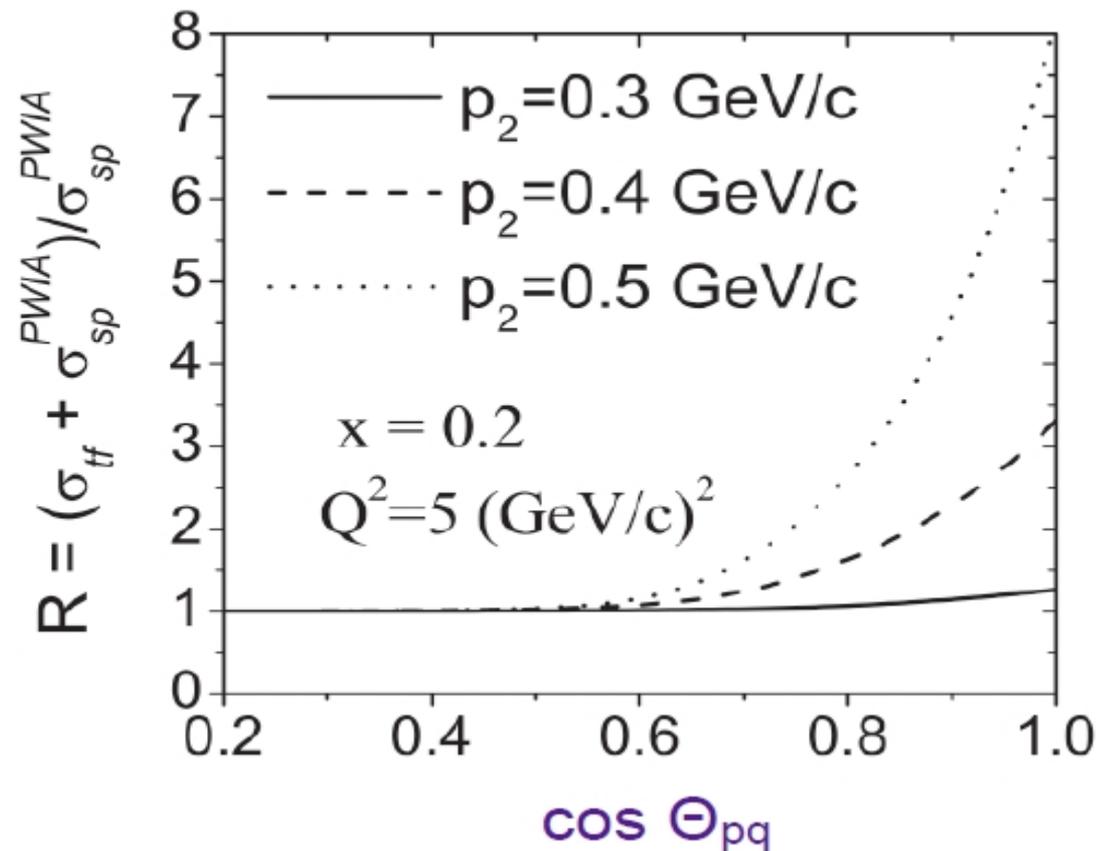
Melnitchouk et al, PLB335(94)11



BoNuS  $p_s$   
detection range

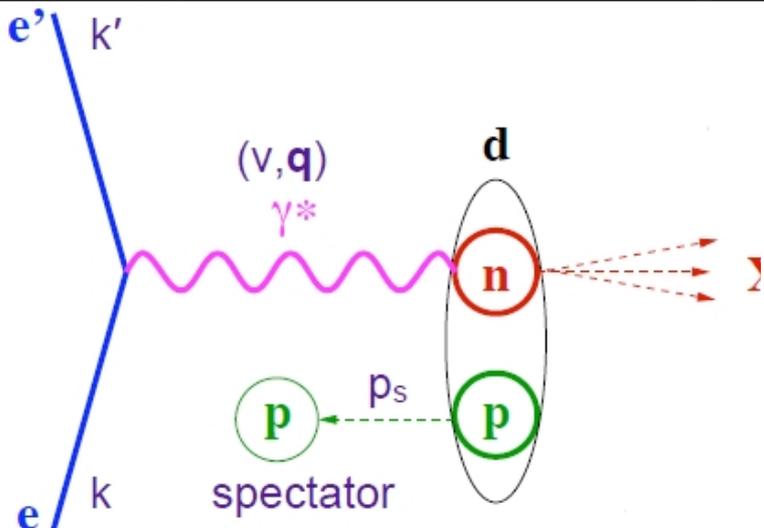
# Target Fragmentation

Palli *et al.*, PRC80(09)054610

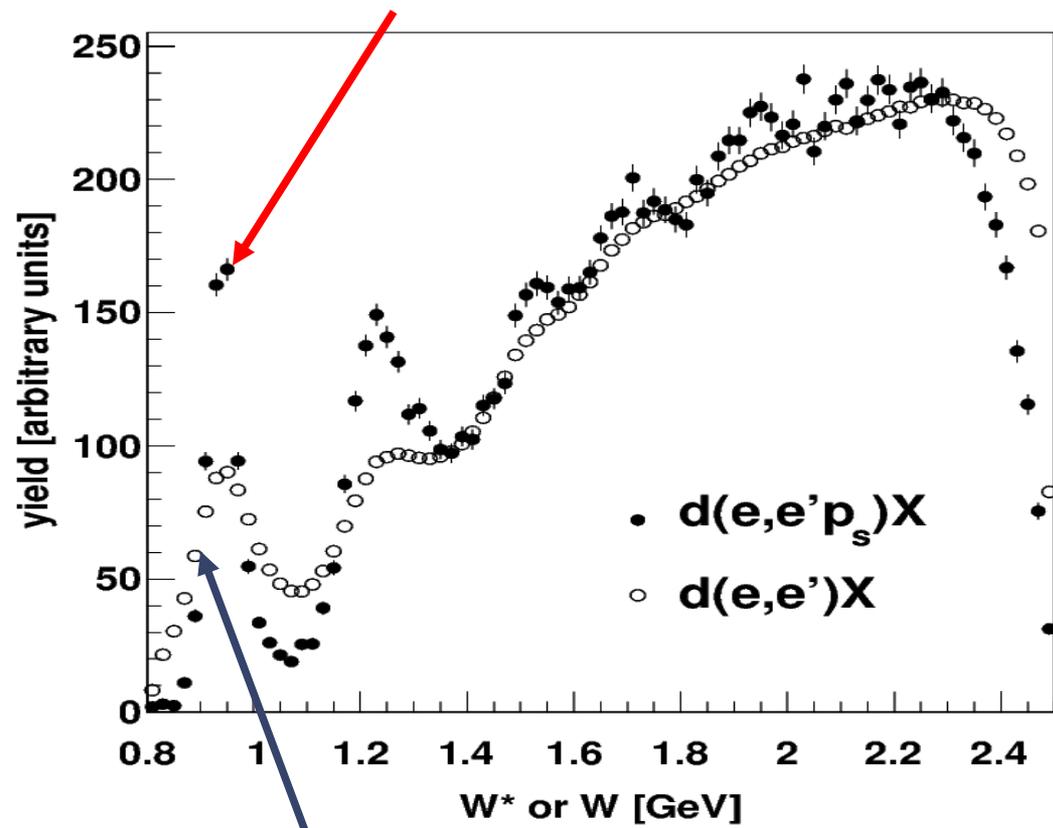


Enhancement in proton yield over PWIA negligible for backward protons

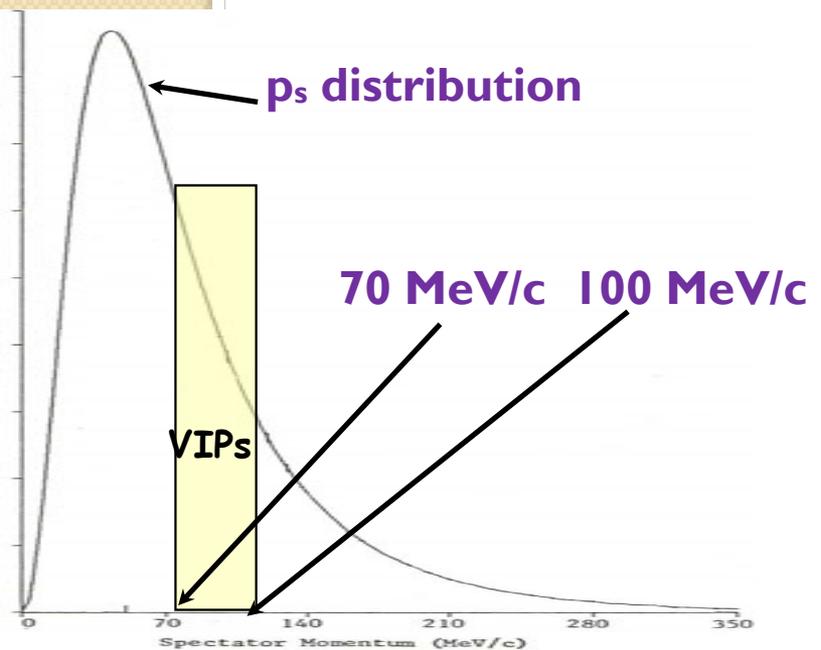
# Kinematic reconstruction with tagged protons



$$W^{*2} = (p_n + q)^2 \approx M^{*2} + 2Mv(2 - \alpha_s) - Q^2$$



$$W^2 = M^2 + 2Mv - Q^2$$



# Ratio Method

N. Baillie et al., PRL108, 199902 (2012)

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

**VIP (Very Important Protons)**

$P_s < 100 \text{ MeV}/c$ ,  $\square_{pq} \geq 100 \text{ deg}$

**Experimental ratio**

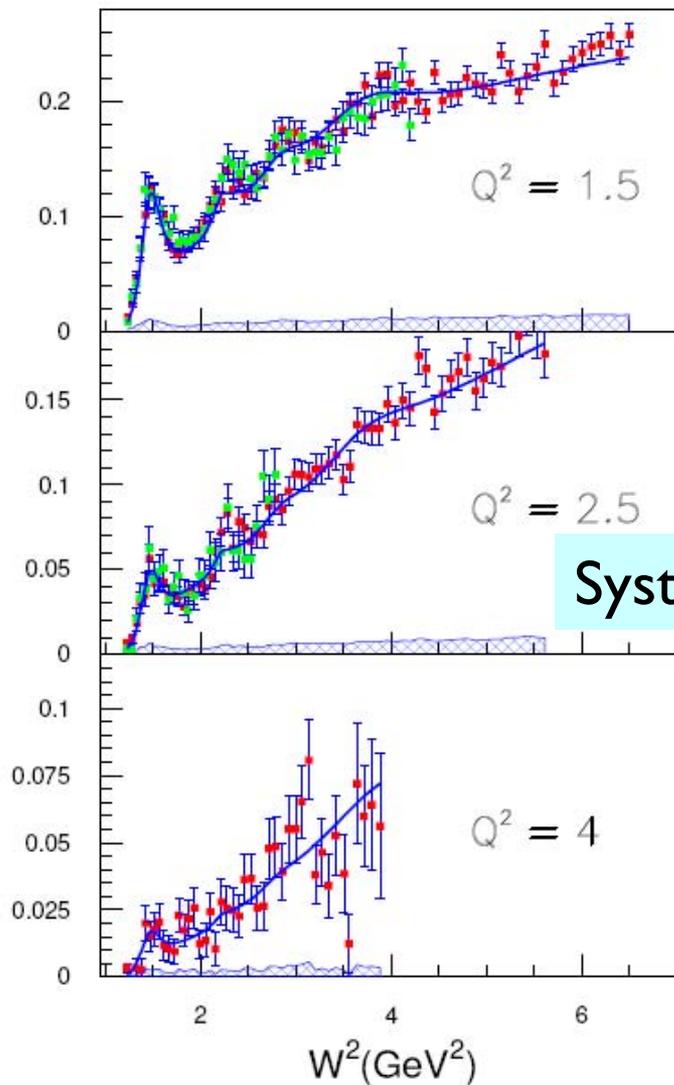
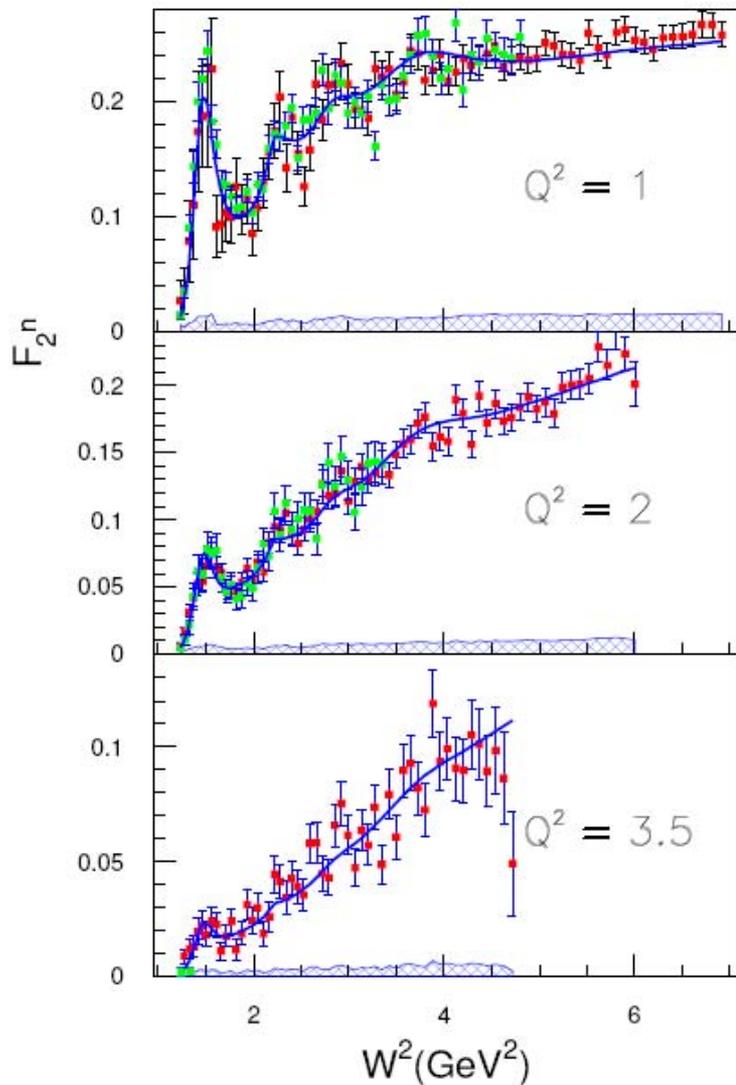
$$R_{exp} = \frac{N_{d(e,e'p_s)}(W^*, Q^2)}{N_{d(e,e')}(W, Q^2)} C(E_b, W^*, W, Q^2) =$$

$$\frac{F_2^n(W^*, Q^2)}{F_2^d(W, Q^2)} \int_{VIP} d\alpha_s dp_s^\perp A_p(\alpha_s, p_s^\perp) S(\alpha_s, p_s^\perp).$$

$$F_2^n = F_2^d \times R_{exp}$$

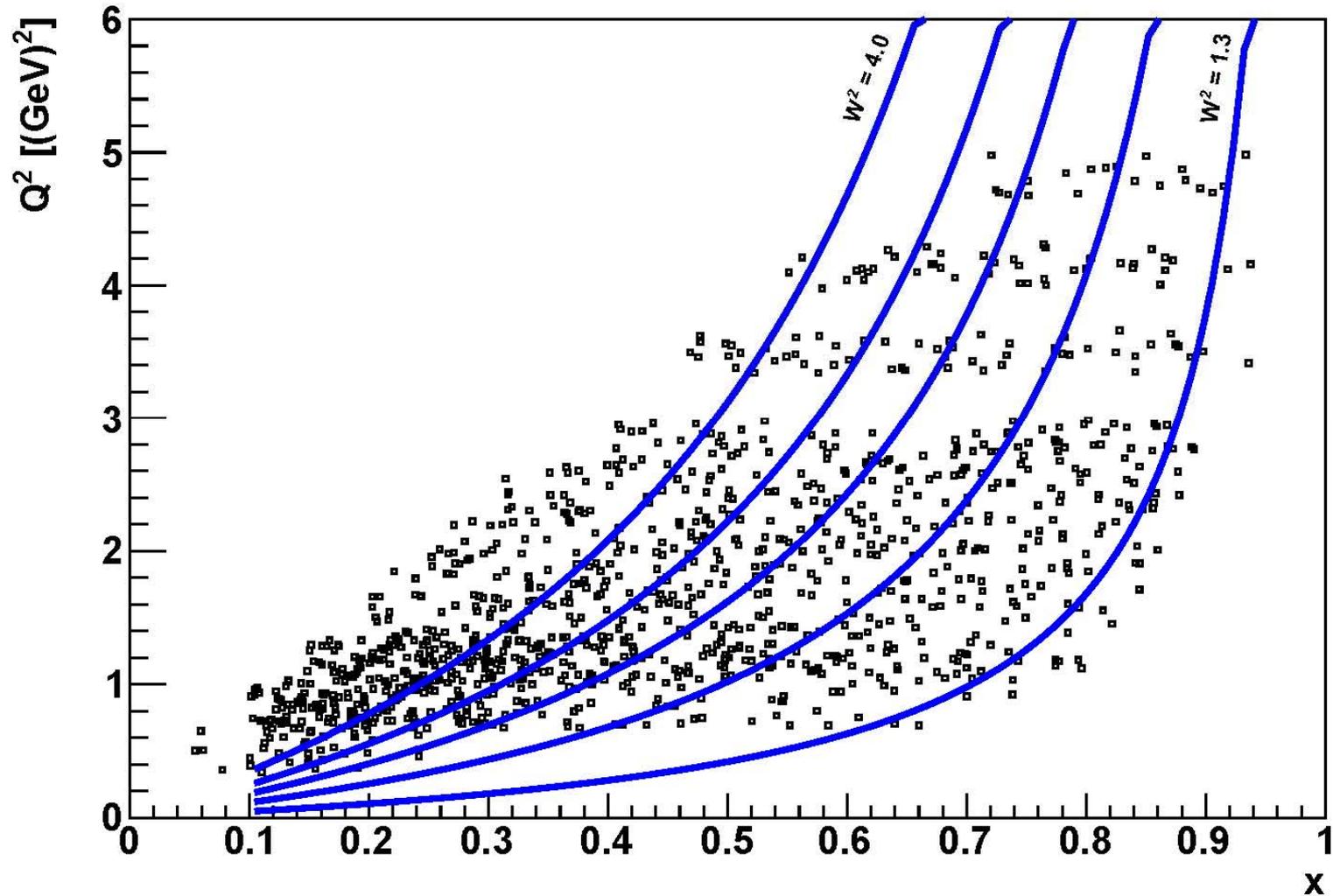
# Results

E=4.2 and 5.3 GeV



Systematic unc.

# BONUS Kinematic Coverage

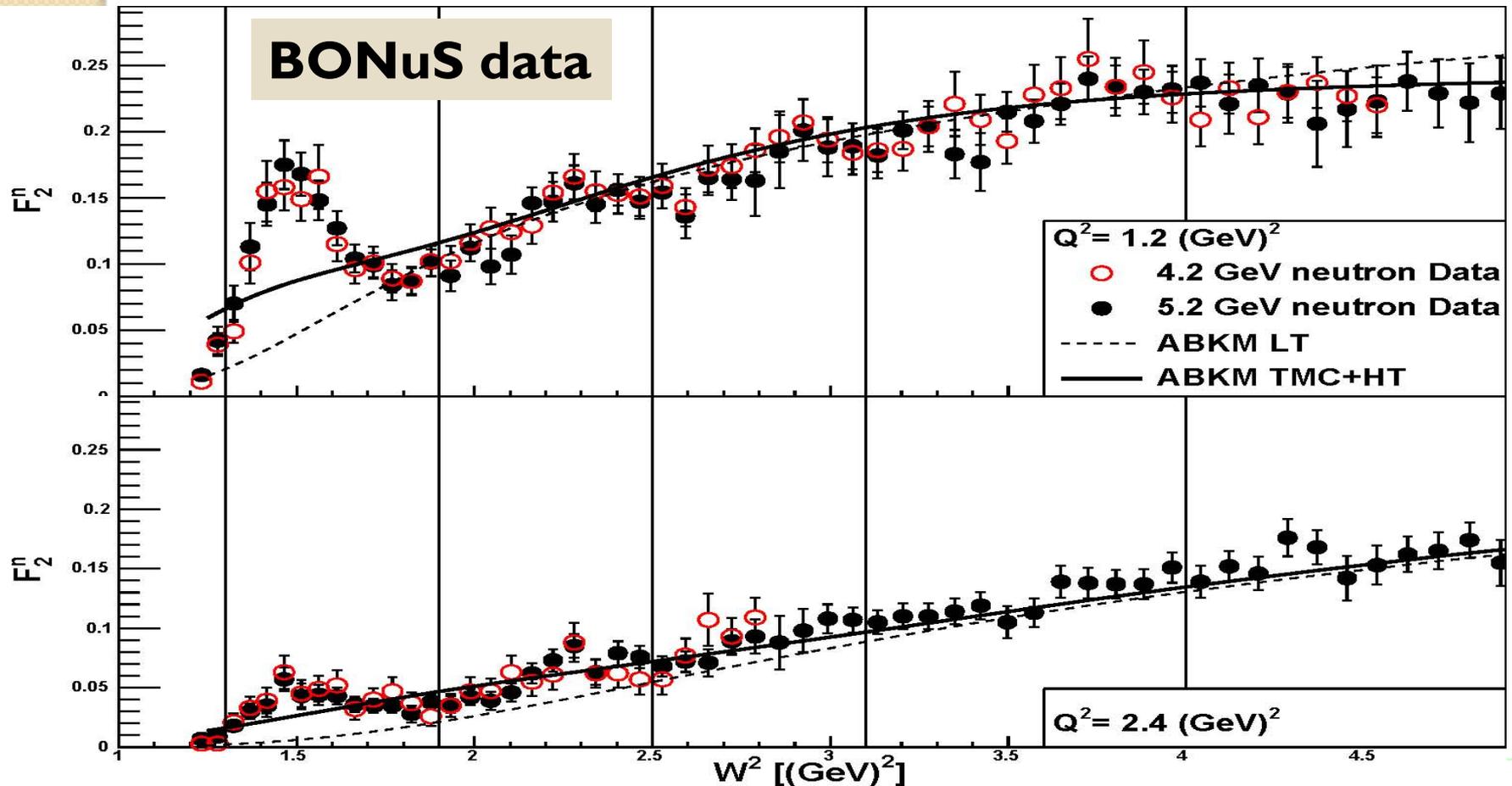


# Truncated Moments and Local Duality

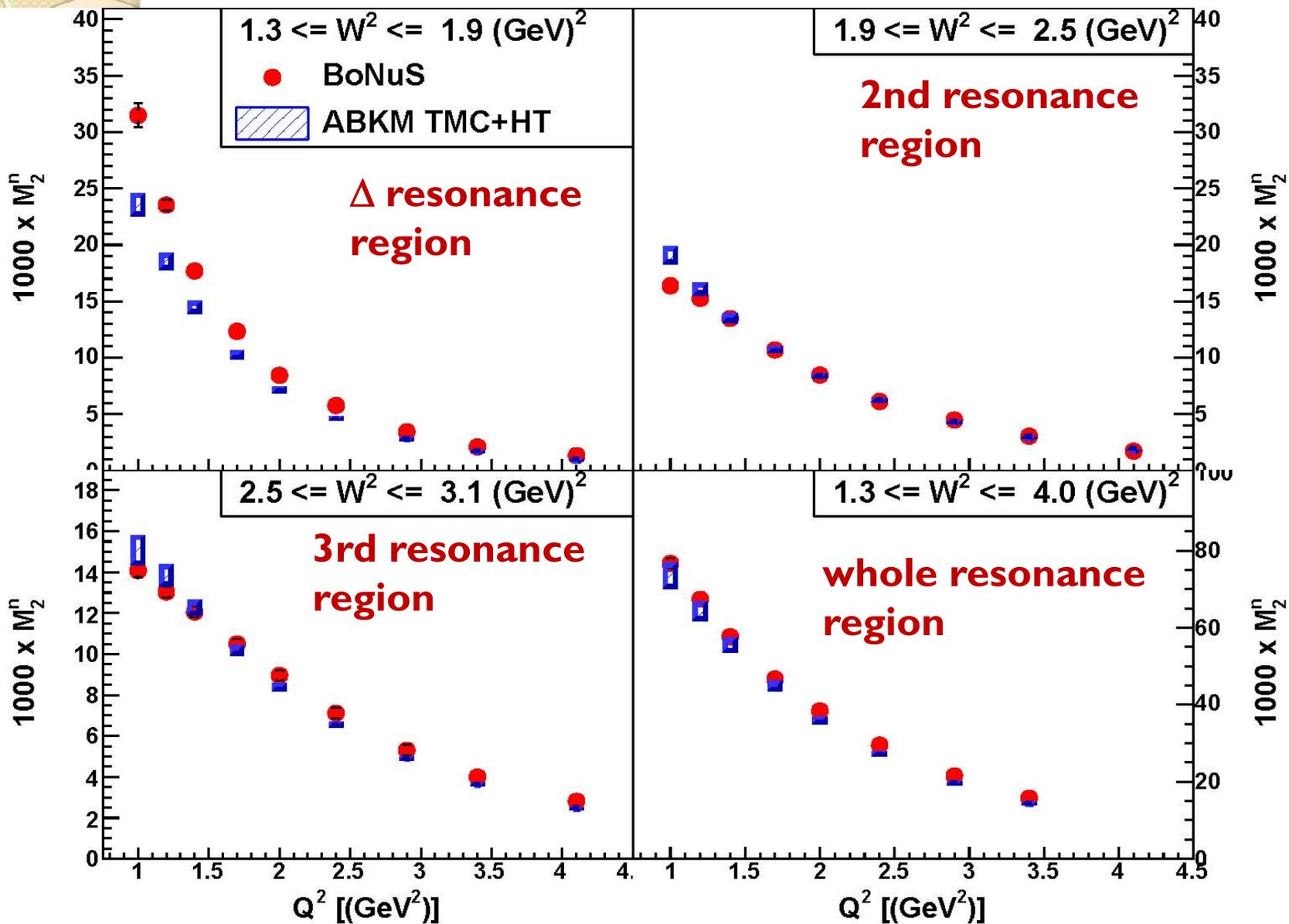


$$M_n(x \min, x \max, Q^2) = \int_{x \min}^{x \max} x^{n-2} F(x, Q^2) dx$$

As defined in A. Psaker, W. Melnitchouk, E. Christy, C. Keppel, PRC 78 025206 (2008).



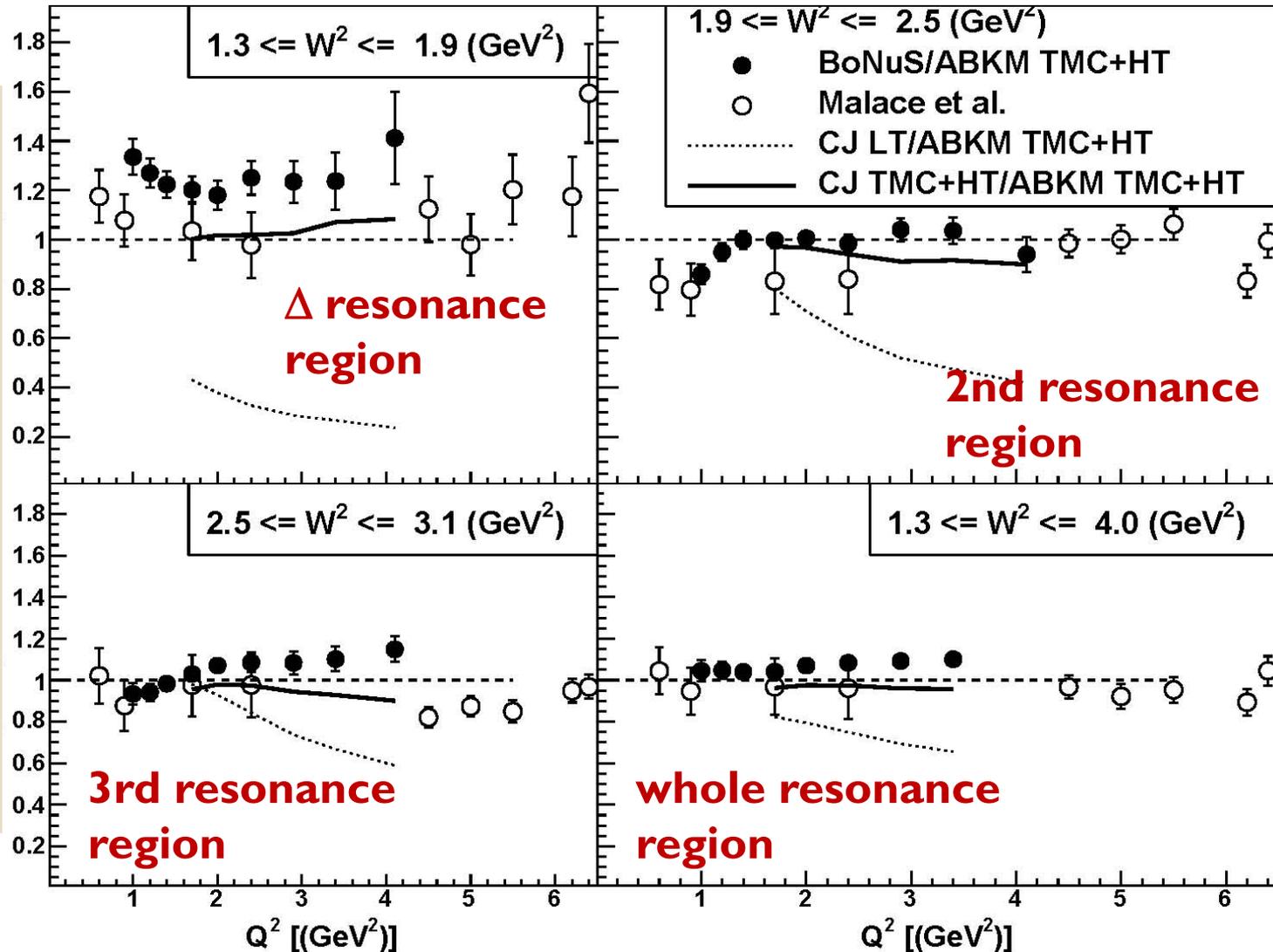
# BONUS Truncated Moments



# Local Quark Hadron Duality – Neutron



$M_2^n$  data /  $M_2^n$  theory

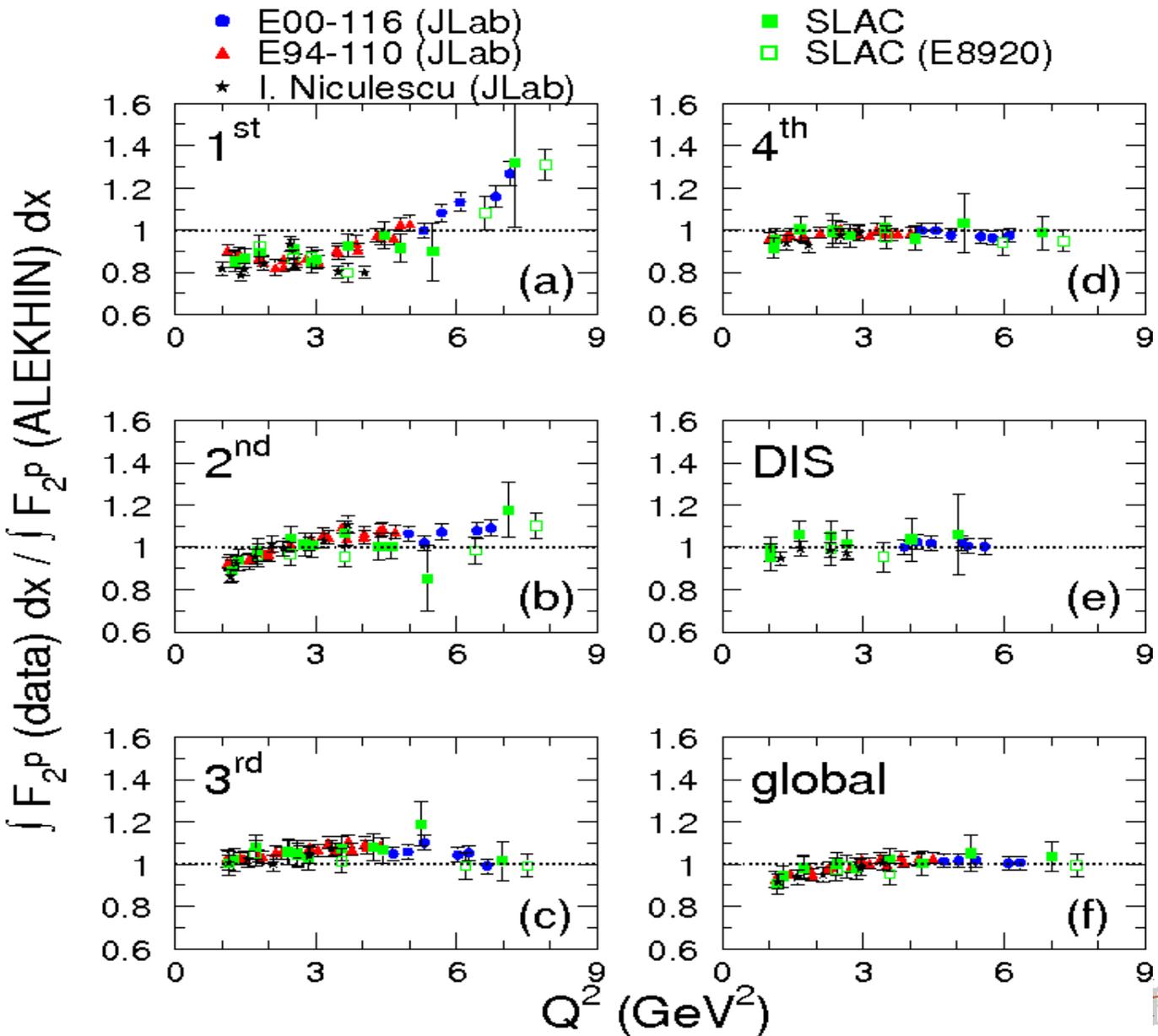


S. Malace et al., PRL 104, 102001 (2010)

# Local Quark Hadron Duality – Proton

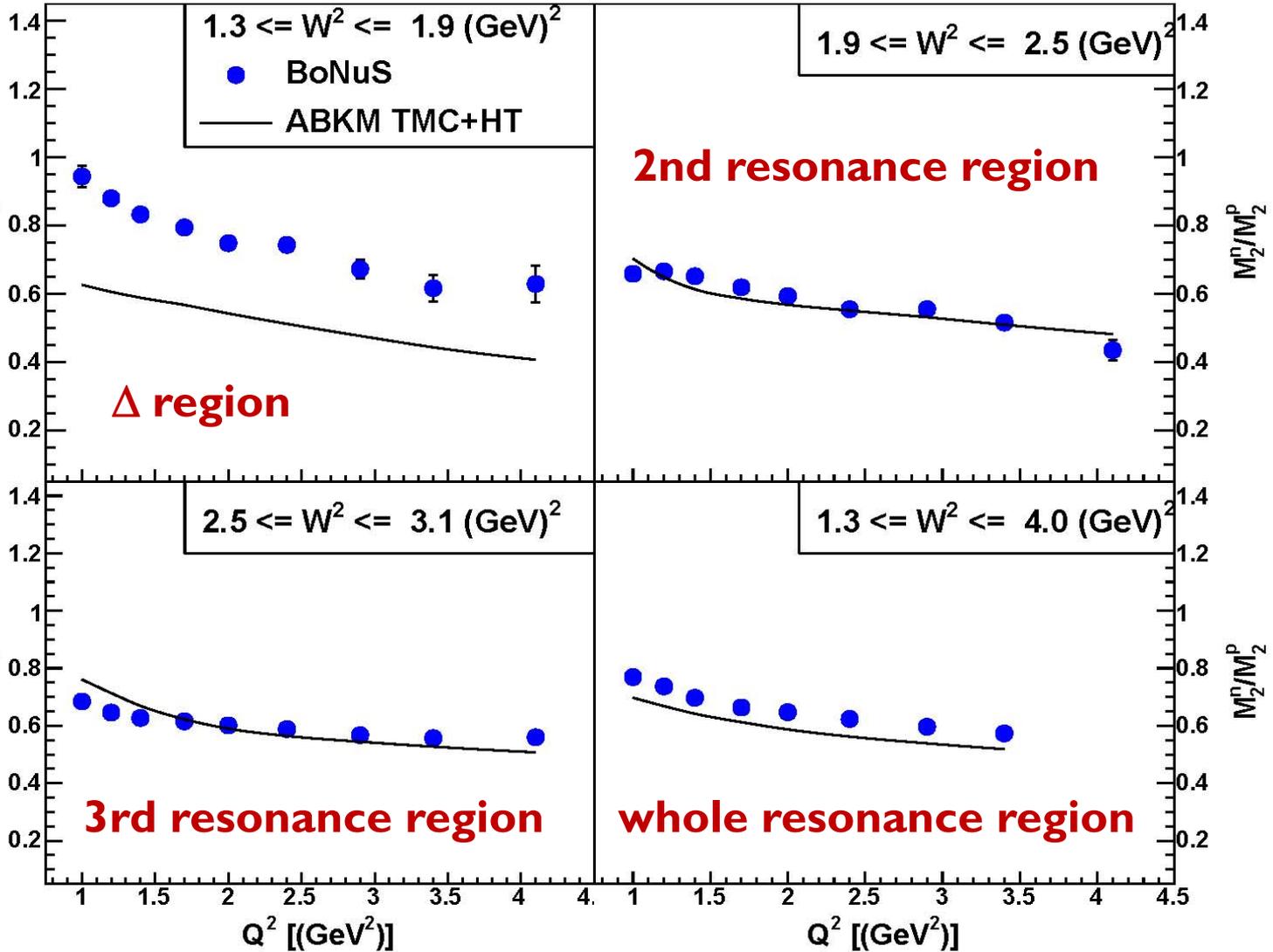


S. Malace et al., PRC 80, 035207 (2009)



# Proton/Neutron Comparison

$M_2$  neutron /  $M_2$  proton



# Conclusion

- Investigated local quark - hadron duality in the neutron structure function.
- Smaller systematic uncertainties than earlier studies. (S.P. Malace, Y. Kahn, W. Melnitchouk, C.E. Keppel, PRL 104, 102001 (2010).)
- Truncated  $F_2$  moments compared to DIS PDFs.
- Truncated  $F_2$  moments compared to similar proton moments.
- Quark - hadron duality holds locally for second and third resonance region.
- Deviations in the Delta region (15% or more).

# Gottfried Sum Rule

- Flavor symmetry of the proton sea



$$\bar{u} = \bar{d}$$

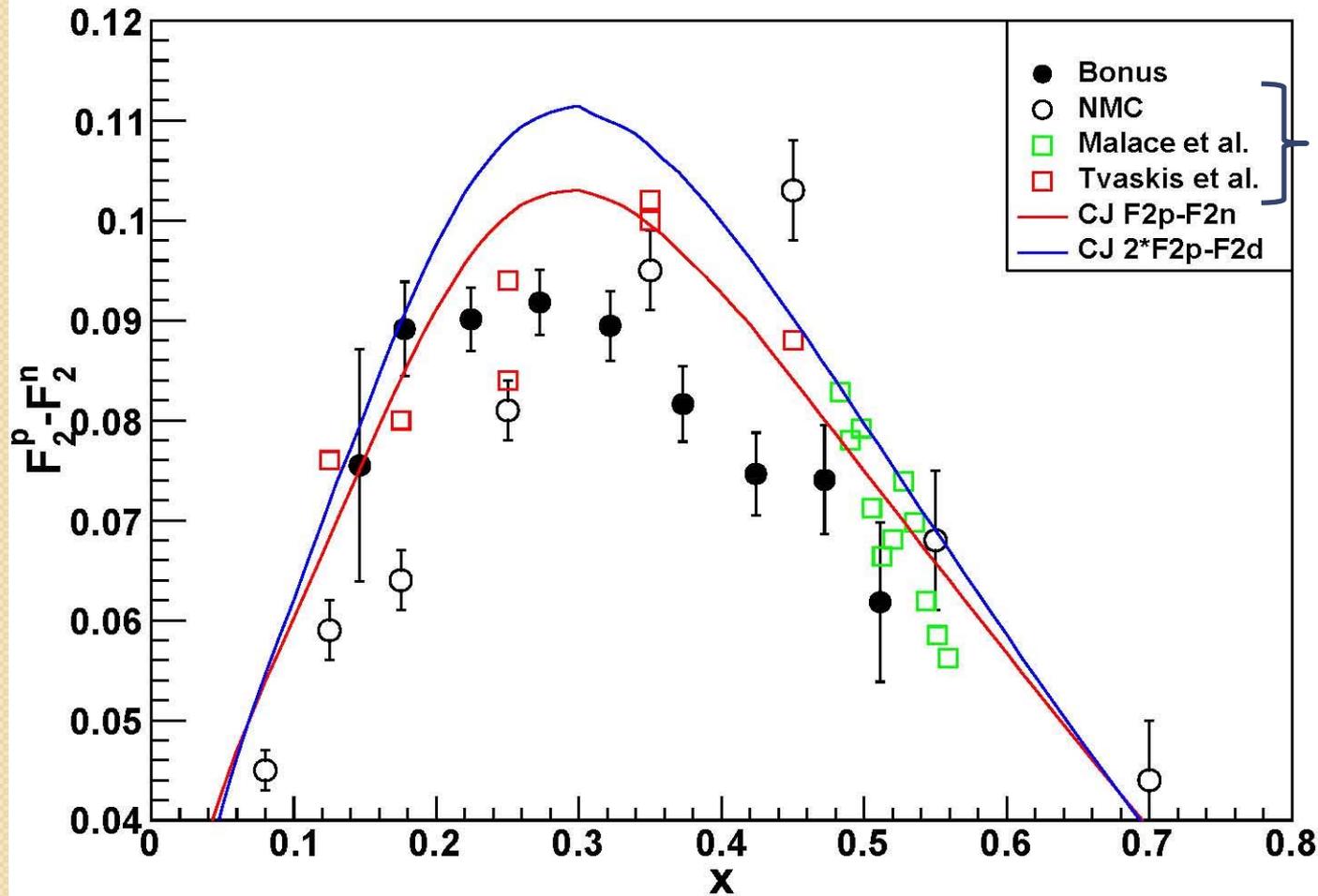
- Test by using Gottfried sum rule (GSR):

$$S_G = \int_0^1 \frac{F_2^p(x) - F_2^n(x)}{x} dx = \frac{1}{3} + \frac{2}{3} \int_0^1 \underbrace{(\bar{u}_p(x) - \bar{d}_p(x))}_{=0 \text{ for symmetric sea}} dx = \boxed{\frac{1}{3}}$$

- NMC result (1994):

$$S_G(0,1) = 0.235 \pm 0.026$$

# The Integrand



$$F_2^p - F_2^n = 2F_2^p - F_2^d$$

# Results



R. Abbate, S. Forte **PRD 72 (2005) 11750**

TABLE I: The contribution to the Gottfried sum at  $Q^2 = 4 \text{ GeV}^2$  from the region  $x_{\min} \leq x \leq 0.8$  as obtained by NMC [2] and with neural networks. The error is only statistical for NMC, while it is the total combined statistical and systematic uncertainty for NNPDF. The total NMC systematics on  $S_G(0.004 \leq x \leq 0.8)$  is equal to 0.019.

$x_{\min}$	$S_G(x_{\min} < x < 0.8)$	
	NMC	NNPDF
0.004	$0.221 \pm 0.008$	$0.2281 \pm 0.0437$
0.010	$0.213 \pm 0.005$	$0.2378 \pm 0.0273$
0.020	$0.203 \pm 0.004$	$0.2334 \pm 0.0232$
0.040	$0.183 \pm 0.004$	$0.2157 \pm 0.0217$
0.060	$0.171 \pm 0.003$	$0.1985 \pm 0.0202$
0.100	$0.149 \pm 0.003$	$0.1693 \pm 0.0169$
0.150	$0.125 \pm 0.003$	$0.1398 \pm 0.0133$
0.200	$0.107 \pm 0.003$	$0.1154 \pm 0.0107$
0.300	$0.074 \pm 0.003$	$0.0761 \pm 0.0074$
0.400	$0.047 \pm 0.002$	$0.0460 \pm 0.0052$
0.500	$0.025 \pm 0.002$	$0.0241 \pm 0.0035$
0.600	$0.012 \pm 0.002$	$0.0102 \pm 0.0019$

$$S_G(0.14, 0.52) \approx 0.14$$

$$S_G(0.004, 0.8) = 0.228 \pm 0.044$$

## Original NMC (1994)

$$S_G(0.14, 0.5) \approx 0.110$$

$$S_G(0.004, 0.8) = 0.221 \pm 0.008$$

**BONuS**  $x$  coverage: (0.143-0.52)

$Q^2$  coverage: (1 – 4 GeV)

$$S_G(0.14, 0.52) = 0.113$$

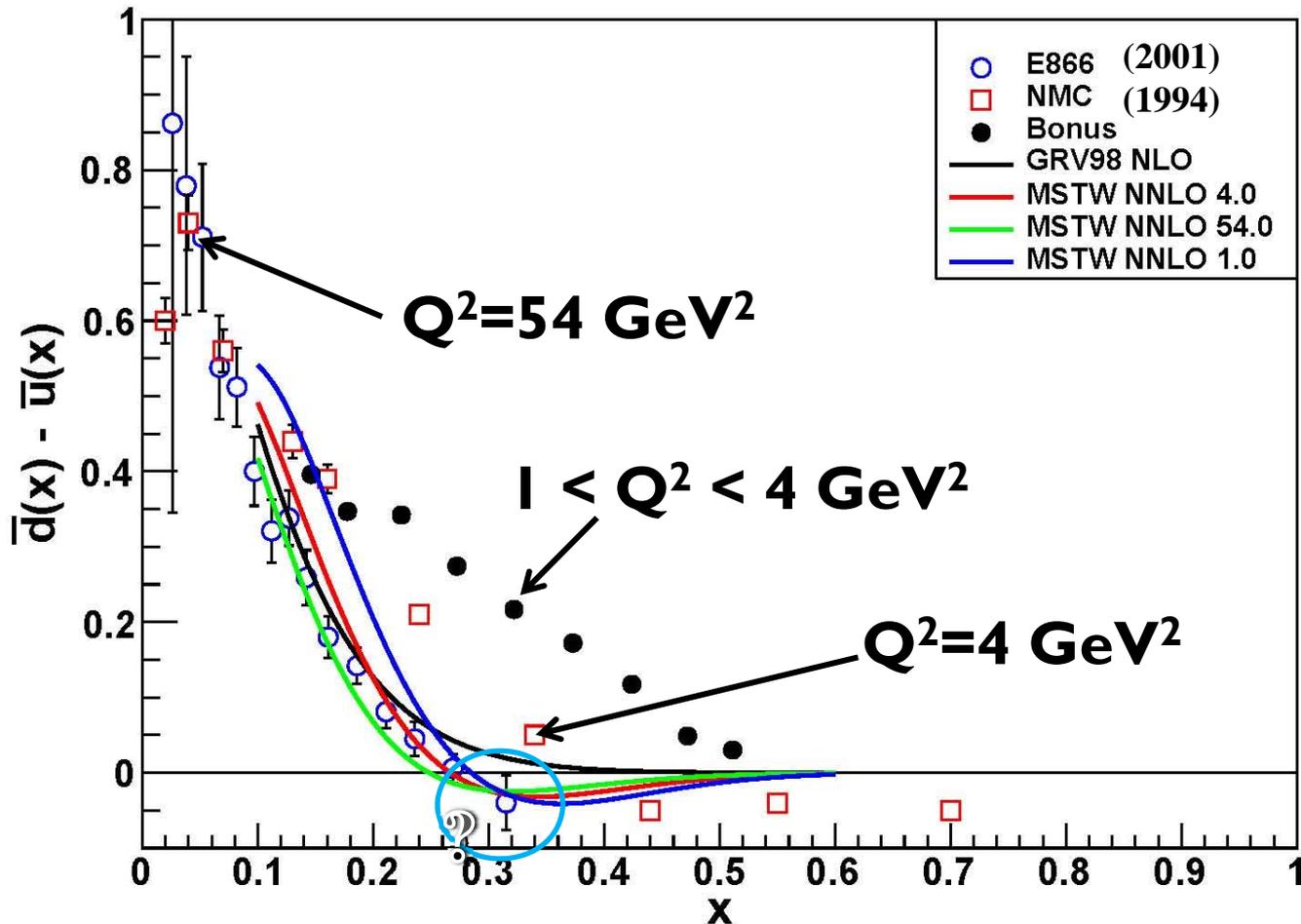
Extrapolate to  $x=0.004$  and 0.8 using A&F method (Regge-like behavior)

$$S_G(0.004, 0.8) = 0.220$$

# Flavor Structure of Nucleon Sea

J.C. Peng et al., PLB 736 (2014) 411

$$\bar{d}(x) - \bar{u}(x) = \frac{1}{2}[u_v(x) - d_v(x)] - \frac{3}{2x}[F_2^p(x) - F_2^n(x)]$$



# Summary

- Investigated local quark - hadron duality in the neutron structure function.
- Influence of BONuS data on Gottfried Sum Rule
- Momentum dependence of nucleon sea flavor asymmetry