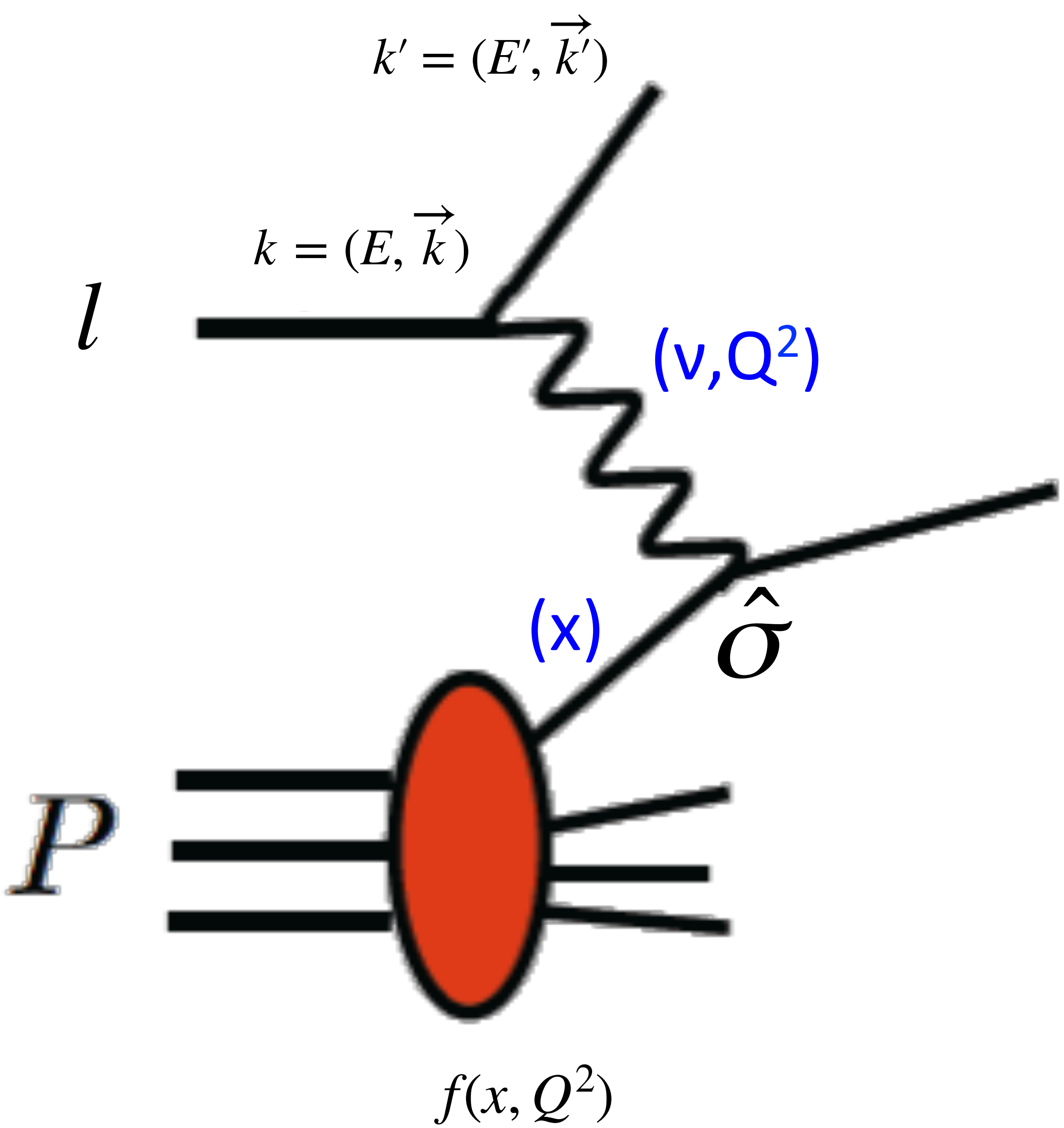
Nucleon structure functions at large-x

Sanghwa Park
(Stony Brook University)

Deep Inelastic Scattering

microscope to see inside the hadron



Brief recap of DIS kinematics

$$Q^2 = -q^2 = -(k - k')^2$$

Measure of resolution

$$y = \frac{p \cdot q}{p \cdot k}$$

Inelasticity

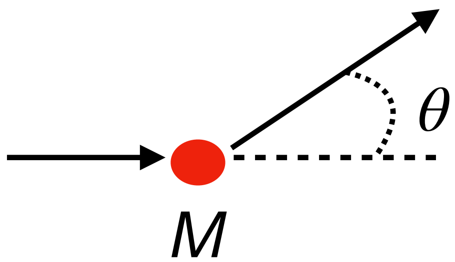
$$x = \frac{Q^2}{2p \cdot q}$$

Momentum fraction carried by struck quark

$$W^2 = (q + p)^2$$

Inv. mass square of produced hadron

Deep Inelastic Scattering



$$\frac{d^2\sigma}{d\Omega dE'} = \frac{8\alpha^2 cos^2(\theta/2)}{Q^4}\left[\frac{F_2(x,Q^2)}{\nu} + \frac{2F_1(x,Q^2)}{M}tan^2(\theta/2)\right]$$

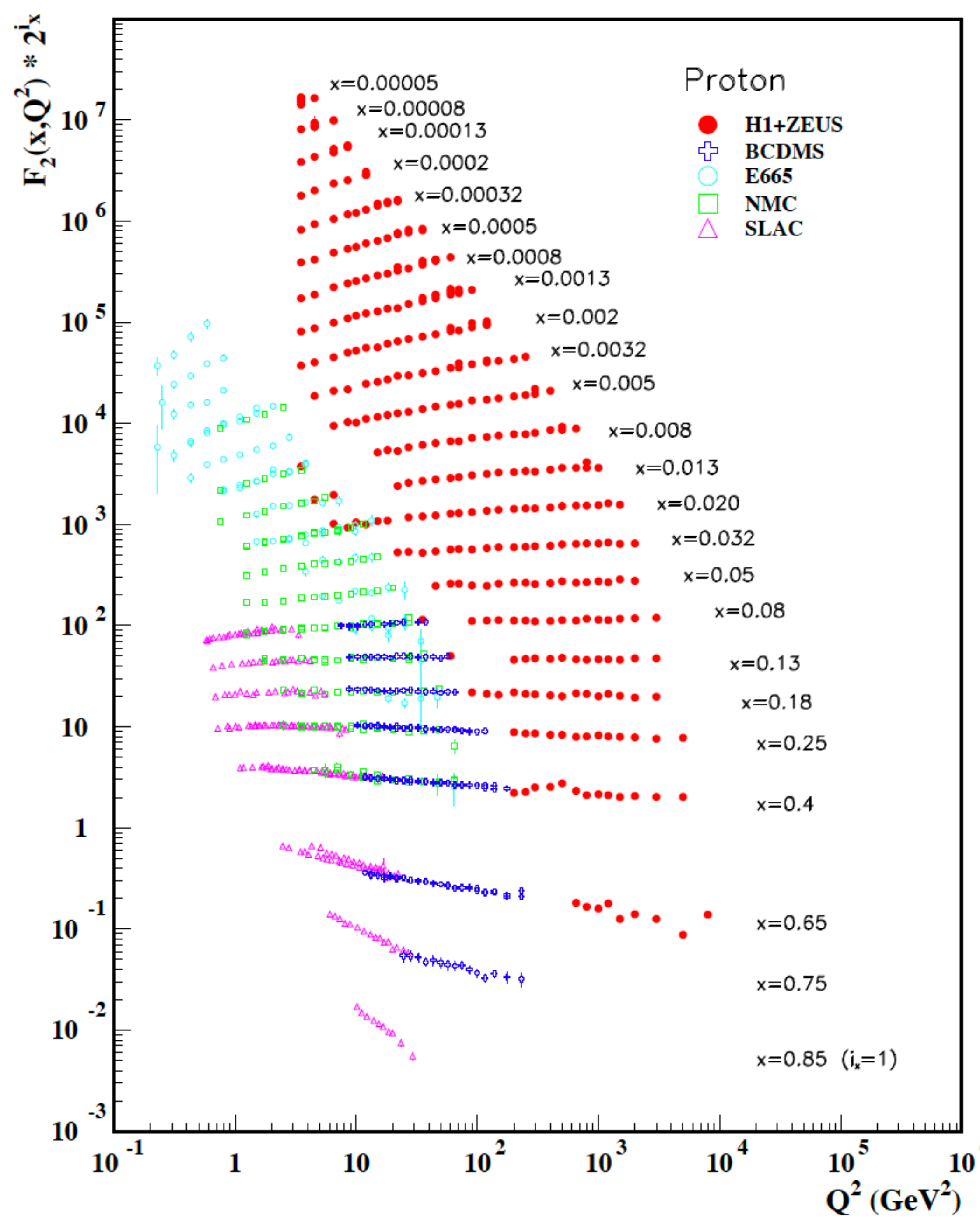
$$R = \frac{\sigma_L}{\sigma_T} = \frac{F_2 M}{F_1 \nu}\left(1 + \frac{\nu^2}{Q^2}\right) - 1$$

Information of internal structure of target nucleon

Directly related to parton distribution functions (PDFs)

In Quark parton model, $F_1(x) = \frac{1}{2}\sum_i e_i^2 q_i(x,Q^2)$ $\quad F_2(x,Q^2) = x\sum_i e_i^2 q_i(x,Q^2)$

50 years later…



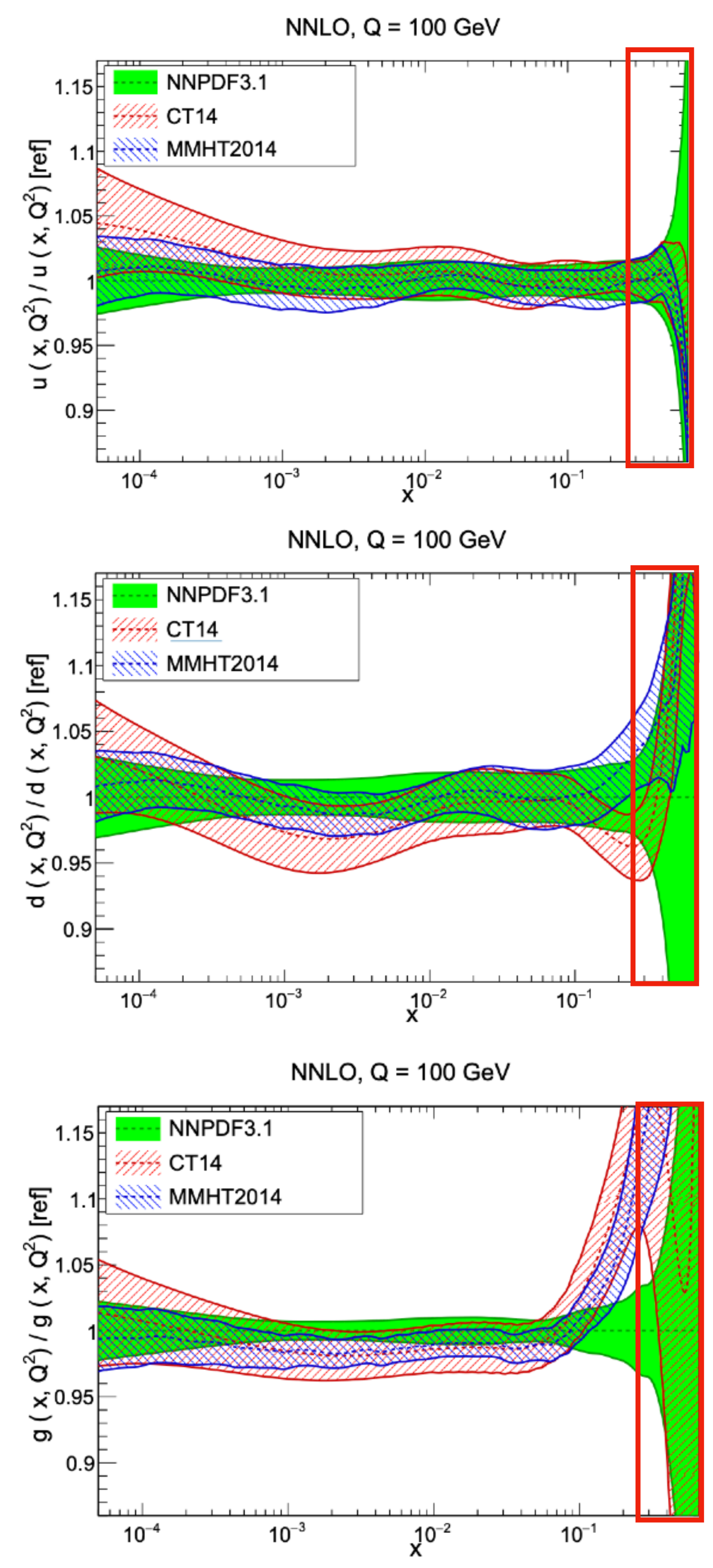
Large x PDFs

- Valence structure of hadron
- Improve constraints on PDFs at large-x

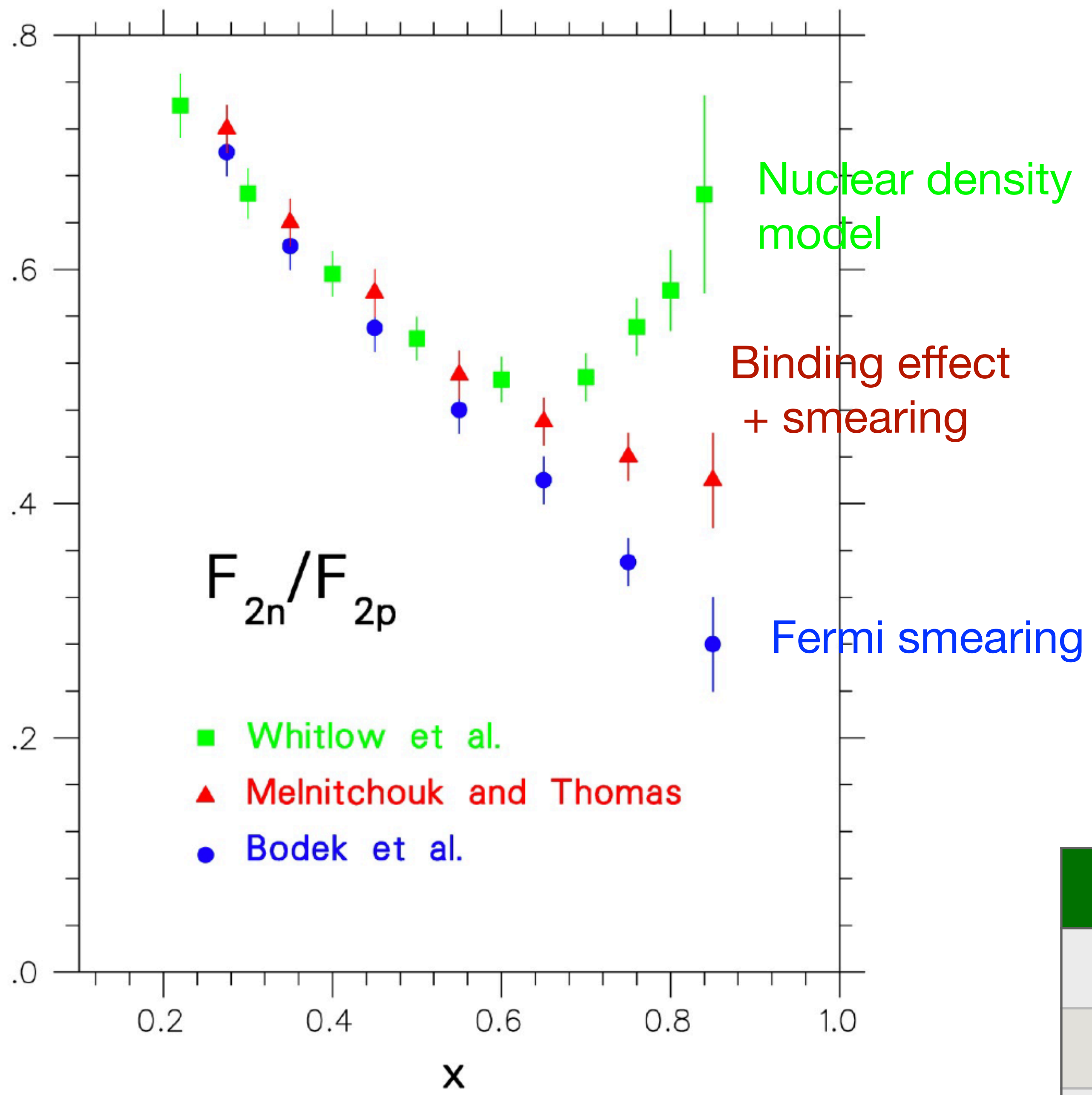
  large x, low Q2
  -> (evolution) low x, high Q2

  Dominant systematic uncertainty source for precision cross sections and BSM search at LHC

- F2n/F2p ratio: d/u ratio at x-> 1 limit
- Resonance structure of the hadron
- Quark-hadron duality



Predictions for $F_2(n/p)$, d/u at x→1



$$F_2^p = x\left[\frac{4}{9}(u+\bar{u}) + \frac{1}{9}(d+\bar{d}) + \frac{1}{9}(s+\bar{s})\right]$$

$$F_2^n = x\left[\frac{4}{9}(d+\bar{d}) + \frac{1}{9}(u+\bar{u}) + \frac{1}{9}(s+\bar{s})\right]$$

At large x,

$$\frac{F_2^n}{F_2^p} \approx \frac{1+4(d/u)}{4+(d/u)}$$

Testing ground for hadron structure

	$F_2(n/p)$	d/u	$A_1(n)$	$A_1(p)$
SU(6)	2/3	1/2	0	5/9
Diquark model/Feynman	1/4	0	1	1
Quark model/Isgur	1/4	0	1	1
pQCD	3/7	1/5	1	1
QCD counting rules	3/7	1/5	1	1

$F2(d) \neq F2(n) + F2(p)$

No free neutron target exists

Deuteron is a weakly bound system

- chosen as effective neutron target

But, $F2(d) \neq F2(n) + F2(p)$

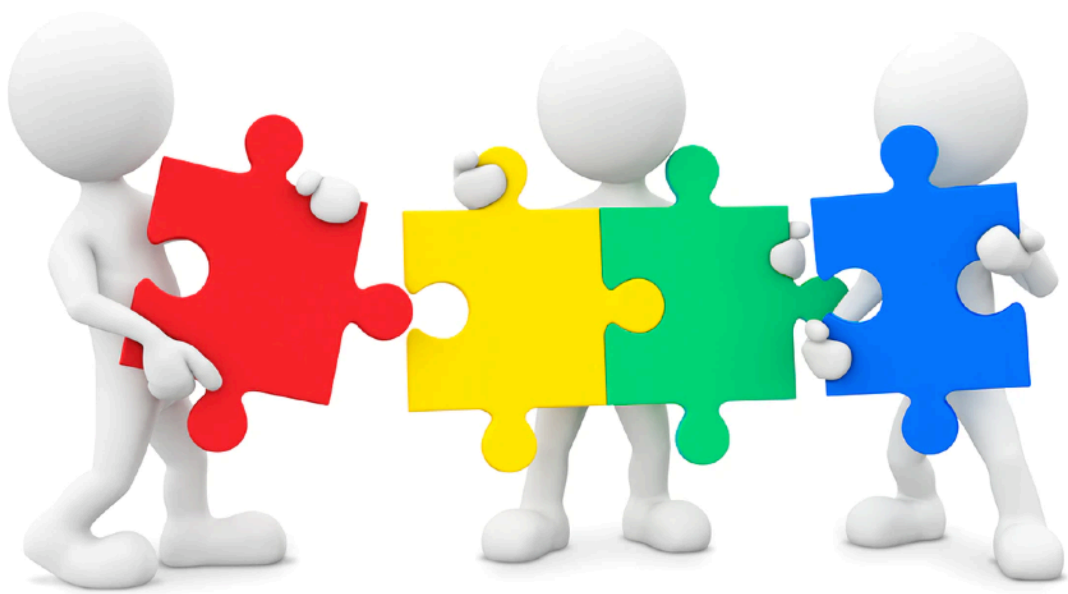
Large theory uncertainty from nuclear corrections

Binding and Fermi motion -> significant model dependence on Deuteron wave function

Off-shell corrections

Need more precise, preferably model-independent neutron target data!

Recent progress



A. Accardi (HiX2019)

	JLab & BONUS	HER MES	HERA I+II	Tevatron W,Z	LHC	ν+A di-μ	Large-x treatment: Nucl. & offsh	HT TMC	Flex d	low-W DIS
CJ15 *	✓✓	✓	✓	✓	*in prog.*	✗	✓✓	✓	✓	✓
CT18			✓	✓ ¤¤	✓	✓			✓	
MMHT14			¤¤¤	✓ ¤¤	✓	✓	✓			
NNPDF3.1			✓		✓	✓		TMC only		
JR14	✓				✓	✓	✓	✓		
ABMP16/AKP				✓ ¤¤	✓	✓	✓/✓	✓	(✓)	✓
HERAPDF2.0			✓	¤						

* NLO only ** No jet data ¤ see 1503.05221 ¤¤¤ see 1508.06621 ¤¤ no reconstructed W

CTEQ-JLab (CJ)

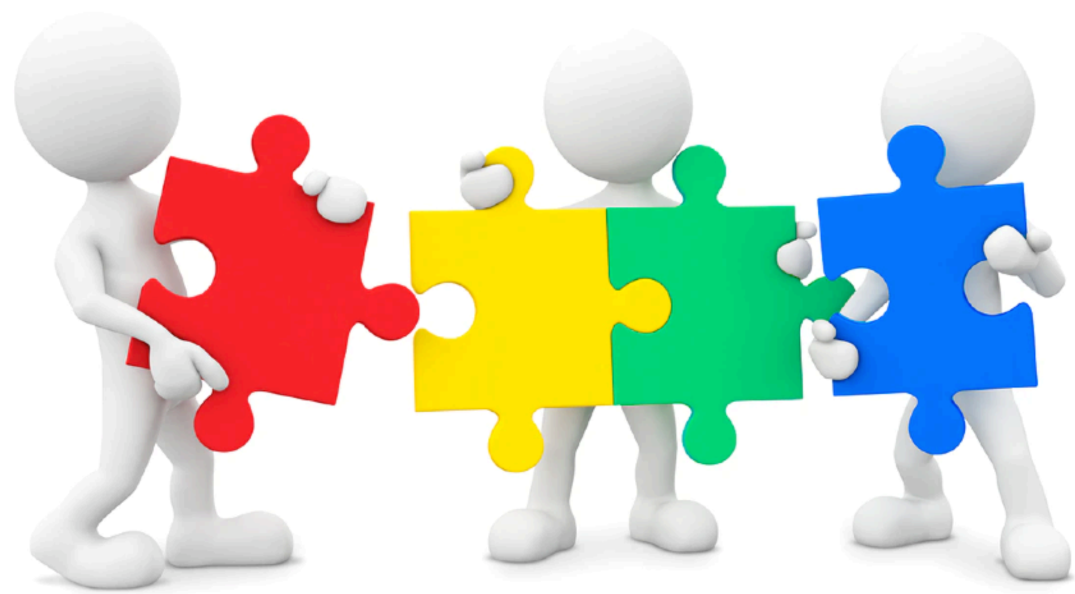
With focus on large x, low Q2

Relaxing kinematic cuts to access larger x

→ need to take into account subleading effects (target mass, higher twist, ..)

Including new fixed target data and LHC, Tevatron

Recent progress

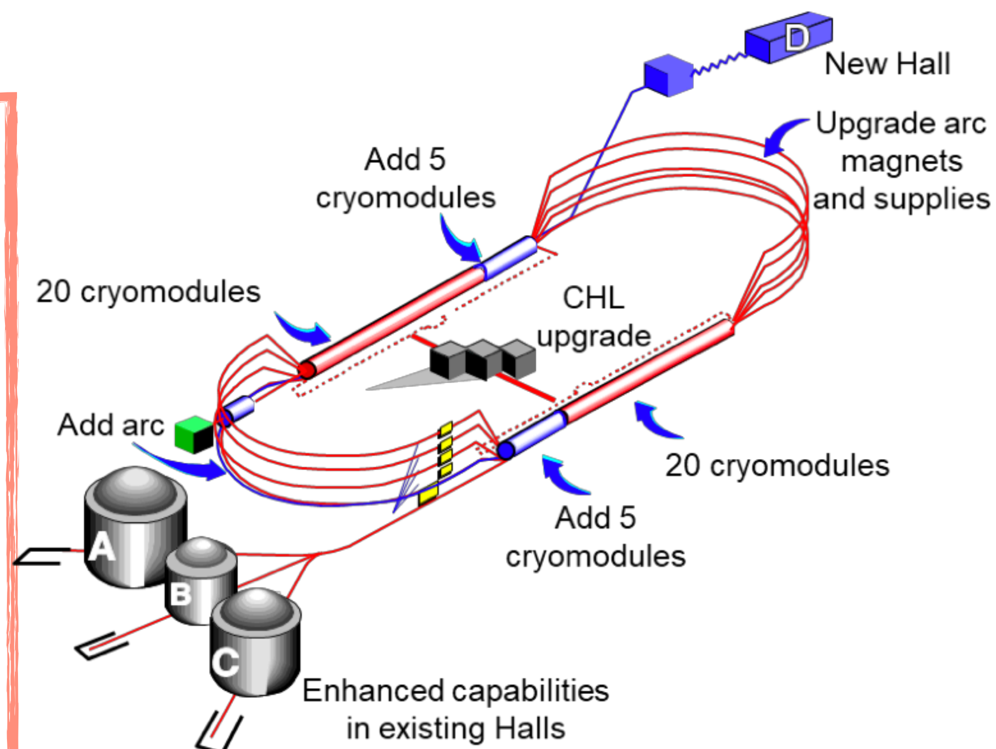


News from JLab

Precision F2 data at large x, low Q^2

Less model dependent F2n/F2p
- A=3 mirror nuclei
- Spectator tagging

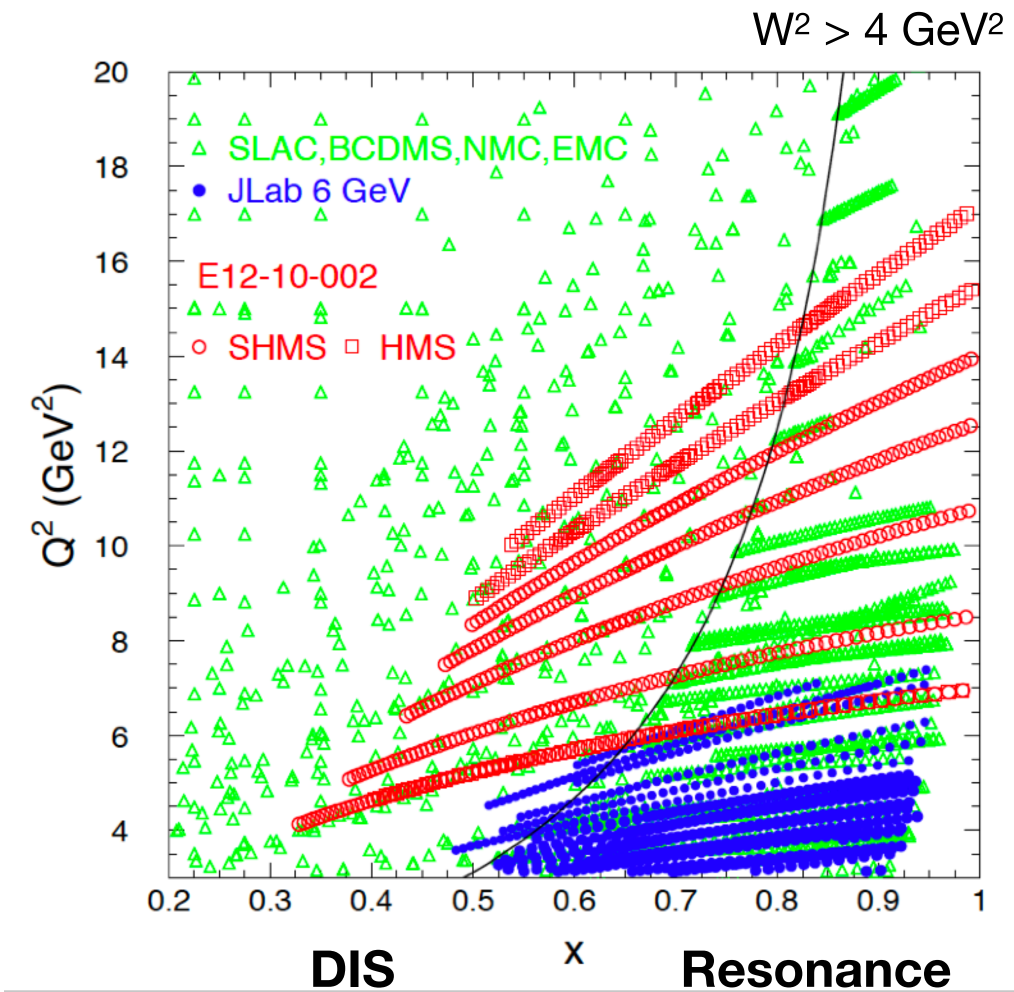
Model independent approach - SoLID PVDIS

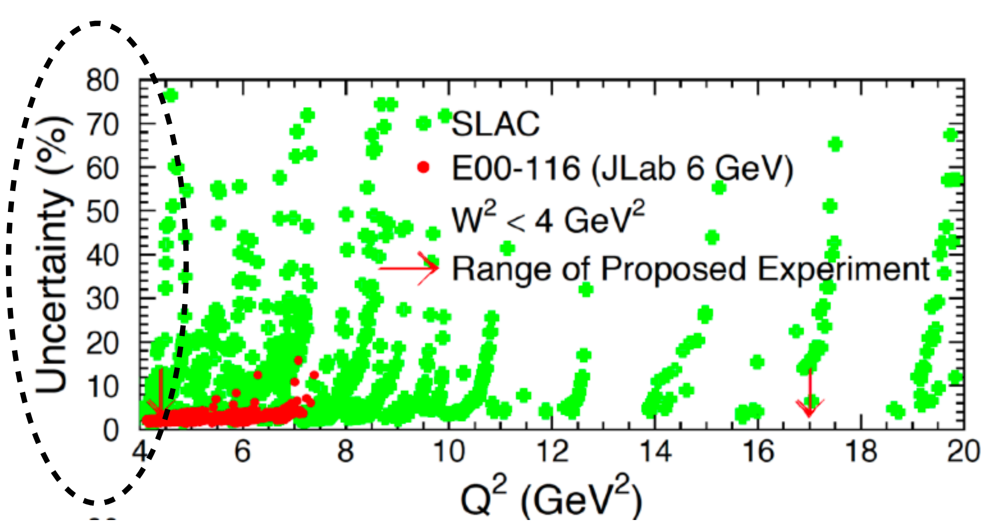


Successfully completed 12 GeV upgrade in 2017

And, W asymmetry (FNAL, LHC, RHIC) puts strong constraints on d quark

Precision F_2 measurement at large x



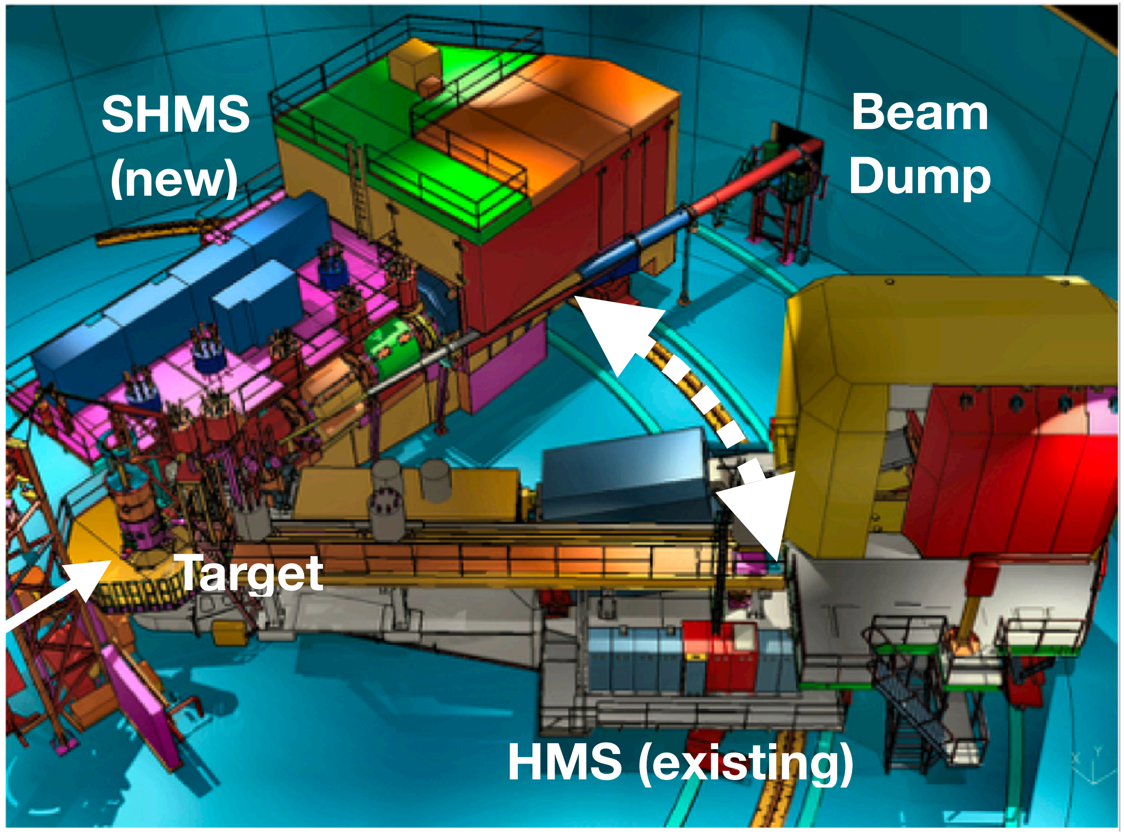


- SLAC data - limited statistics, mostly low Q^2
  -> JLab 12 GeV can extend Q^2 coverage with high precision
- Inclusive H(e,e') and D(e,e') measurements at Hall C
- New data taken in 2018 - extended x and Q2 coverage
- Extend quark-hadron duality studies from 6 GeV experiment (E00-116)

S.P. Malace *et al*., Phys. Rev. C 80 035207 (2009)

S.P. Malace et al., Phys.Rev.Lett. 104 (2010) 102001

Hall C High Momentum Spectrometers

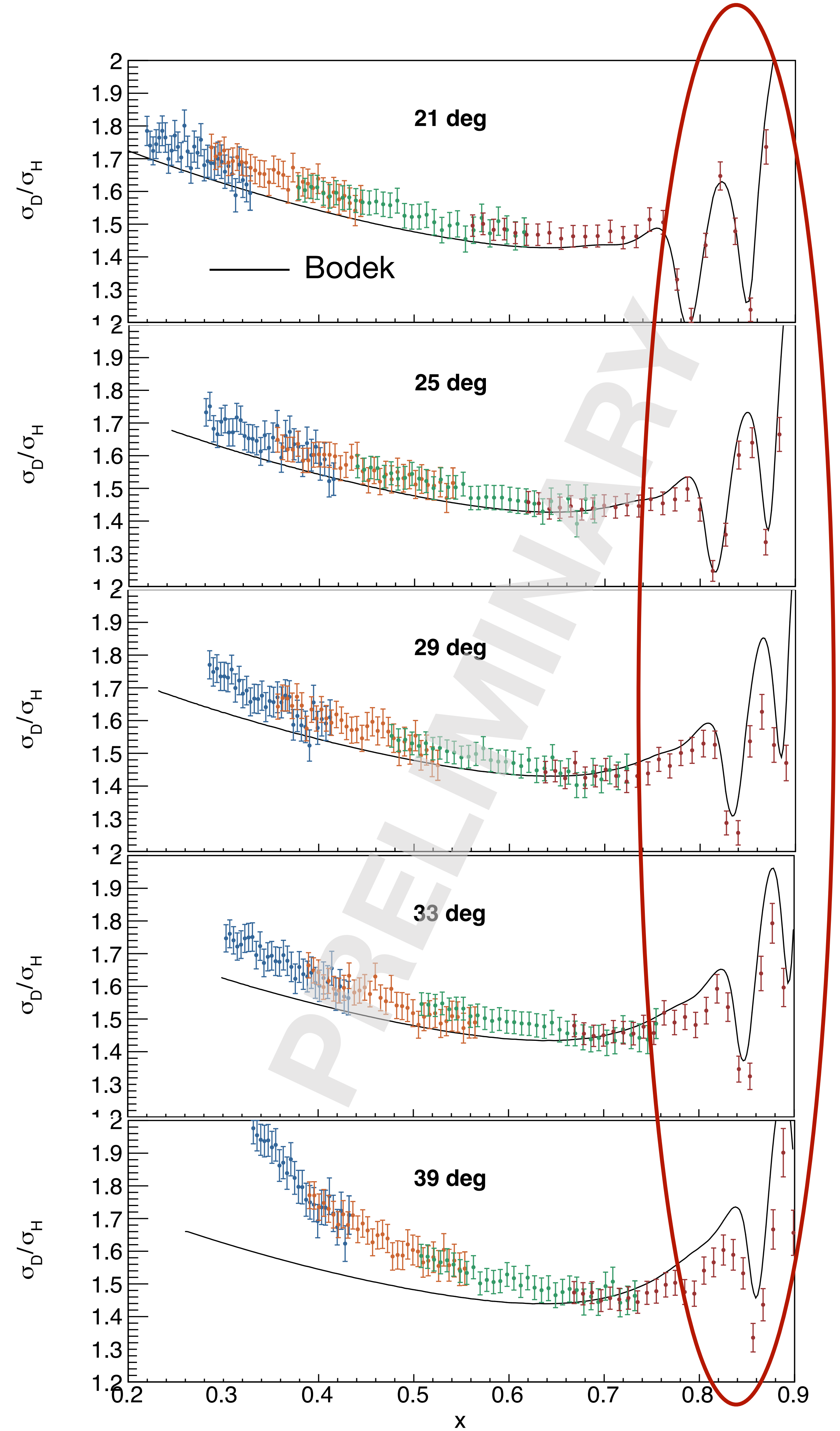


Inclusive D/H cross section ratio from new Hall C data (LH2 and LD2 targets)

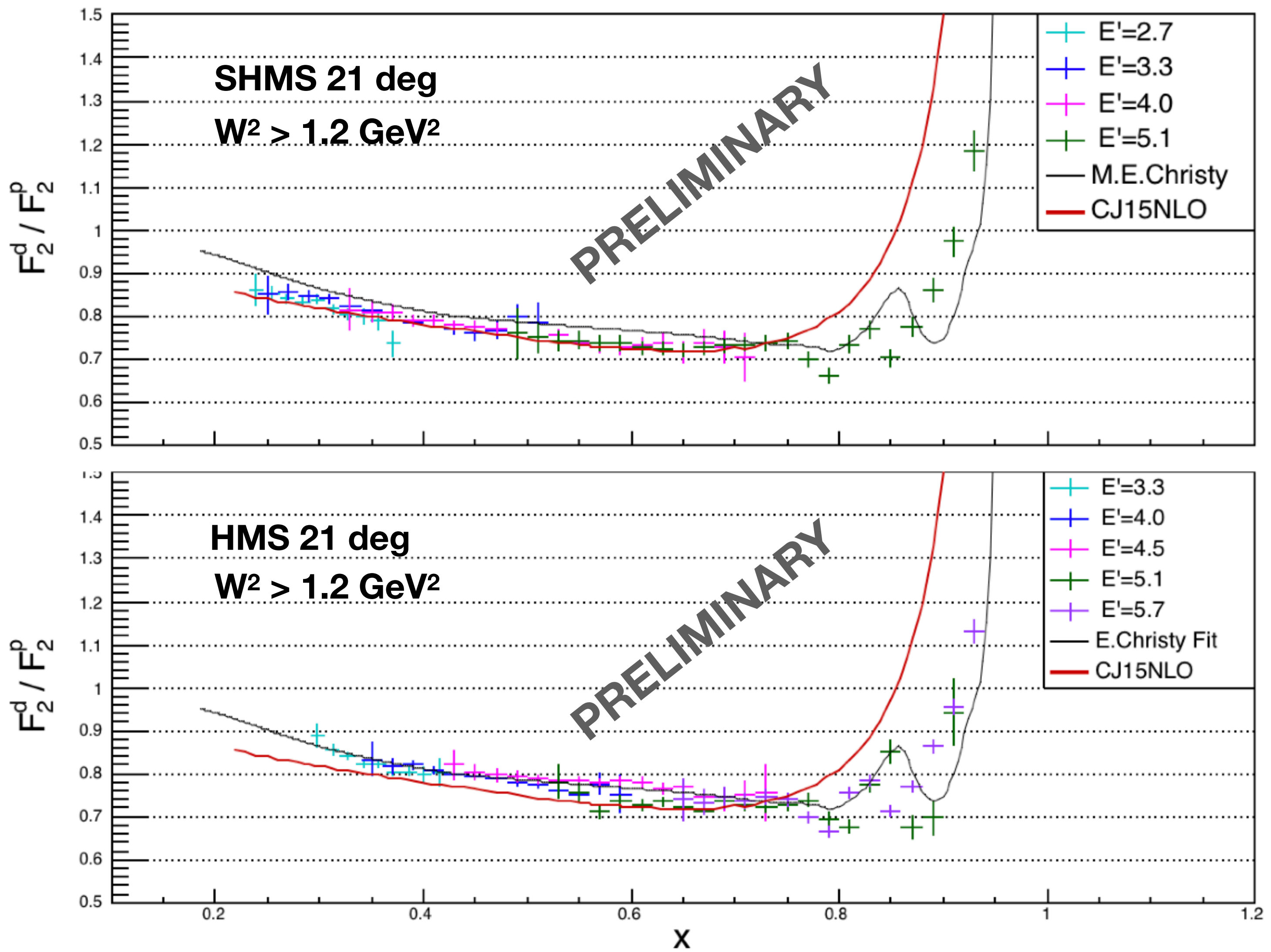
Preliminary results shown charge symmetry background, residual pion contamination not taken into account

Resonance structure shown at large-x region

Higher Q2 reach



F_2^d/F_2^p Ratio



(* Statistical uncertainty only)

Very first look of structure function ratio

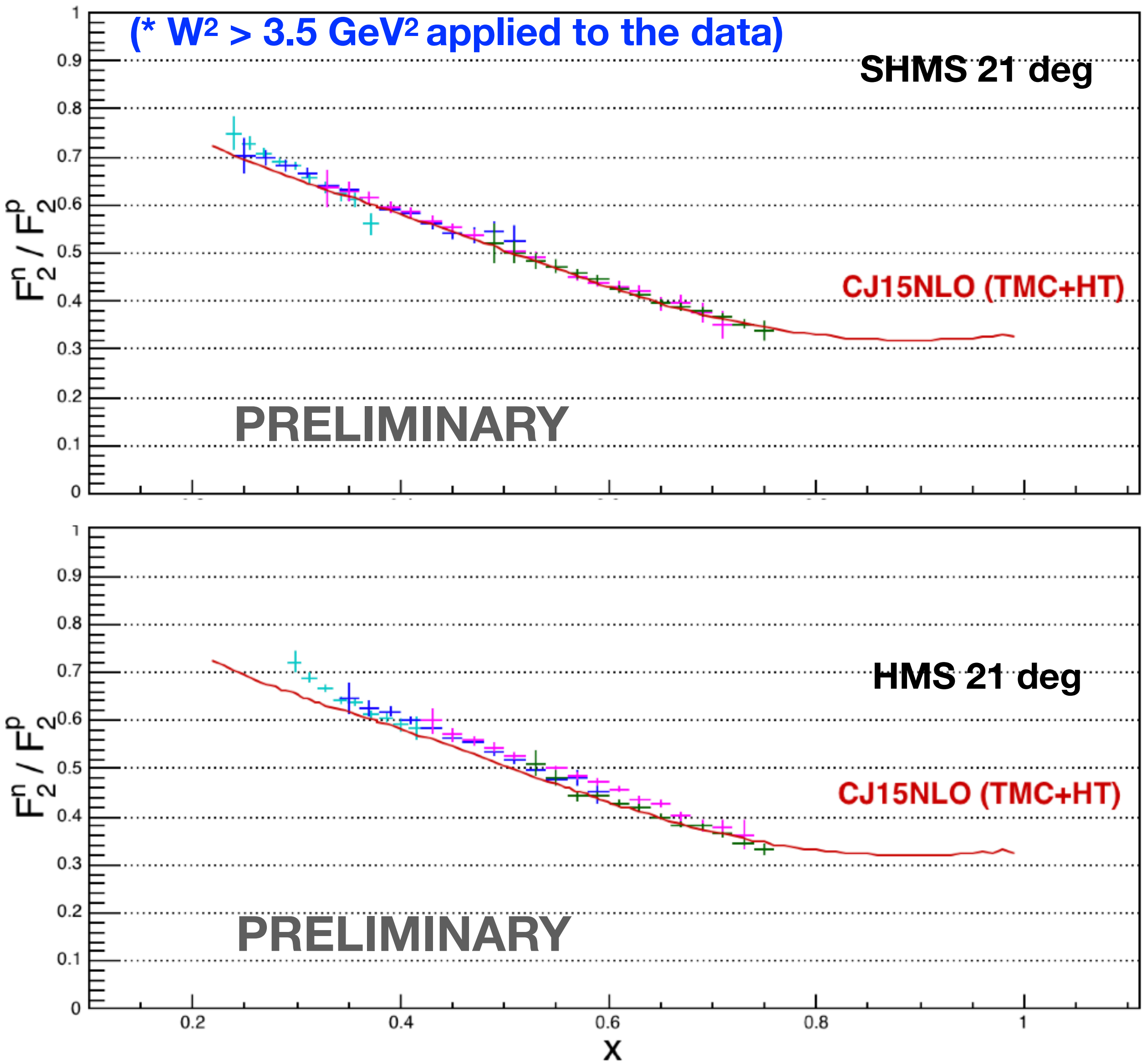
Assume Rd = Rp $\frac{\sigma^d}{\sigma^p} \approx \frac{F_2^d}{F_2^p}$

Only small subset of data shown here

M.E. Christy and P.E. Bosted fit: Phys. Rev. C 81, 055213 (2010) includes resonance data

CJ15NLO: https://www.jlab.org/theory/cj/ DIS only

F_2^n/F_2^p Ratio



$F2^n/F2^p$ using CJ15NLO F_2 ratio

$$\left(\frac{F_2^d}{F_2^p}\right)_{Data} \times \left(\frac{F_2^n}{F_2^p}\right)_{CJ} / \left(\frac{F_2^d}{F_2^p}\right)_{CJ}$$

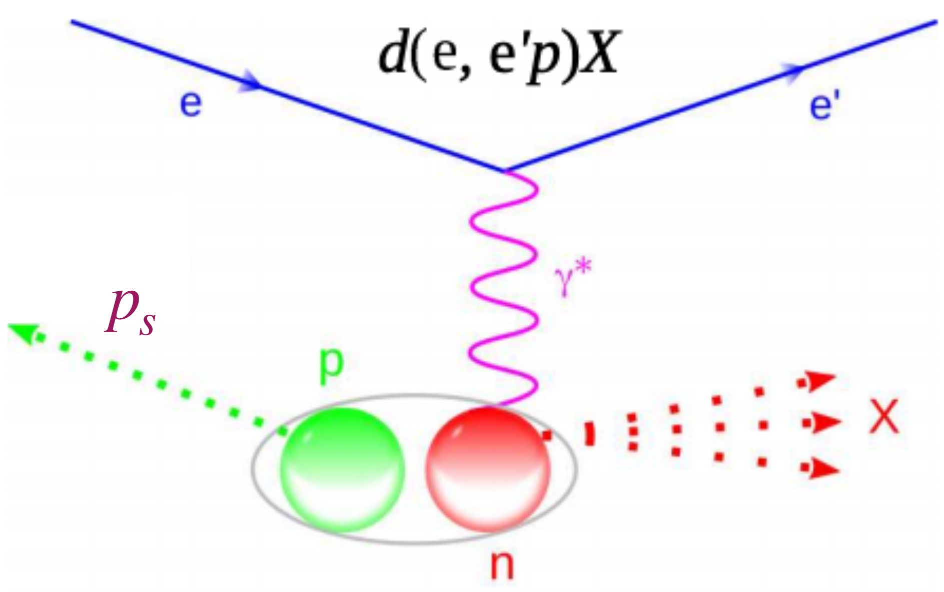
- CJ PDF extraction includes state-of-the-art deuteron nuclear corrections (smearing, off-shell, ..)
- Multiply $F2^d/F2^p$ from data by $F2^n/F2^d$ from CJ to extract $F2^n/F2^p$ ratio

- Can be compared with MARATHON $F2^n/F2^p$ from 3H/3He ratio data

***Statistical uncertainty only. Theory uncertainties not included**

BoNus: Spectator tagging

Barely Off-shell Nucleon Structure experiment (@ Hall B)



Tagging spectator protons in coincidence with the scattered electrons

$$e + d \rightarrow e' + p_s + X$$

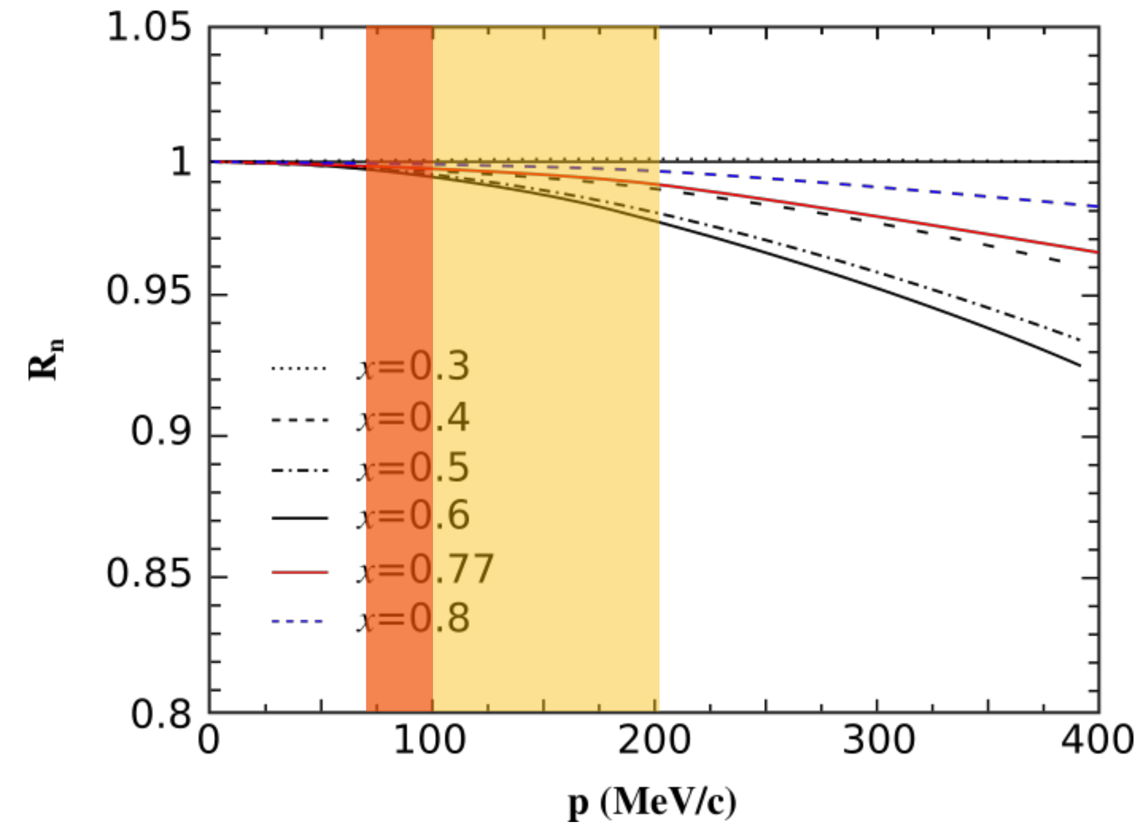
Proton with small momentum in the backward hemisphere

$$p_s \leq 100MeV$$

$$\theta_{pq} \geq 100$$

→minimize probability of rescattering of spectator proton with hadronic debris

$R_n \equiv F_2^{n(\mathrm{eff})}/F_2^n$ W. Melnitchouk et al



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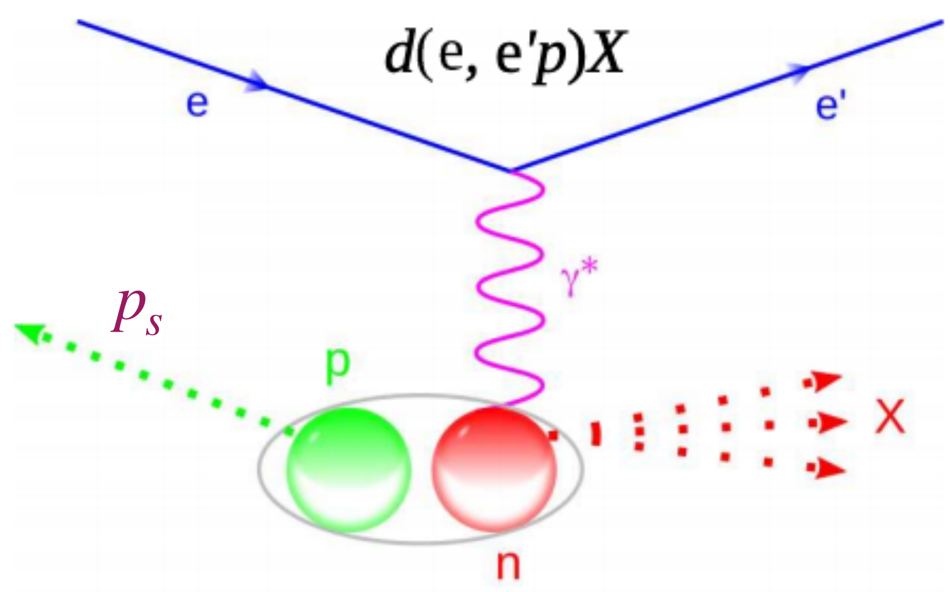

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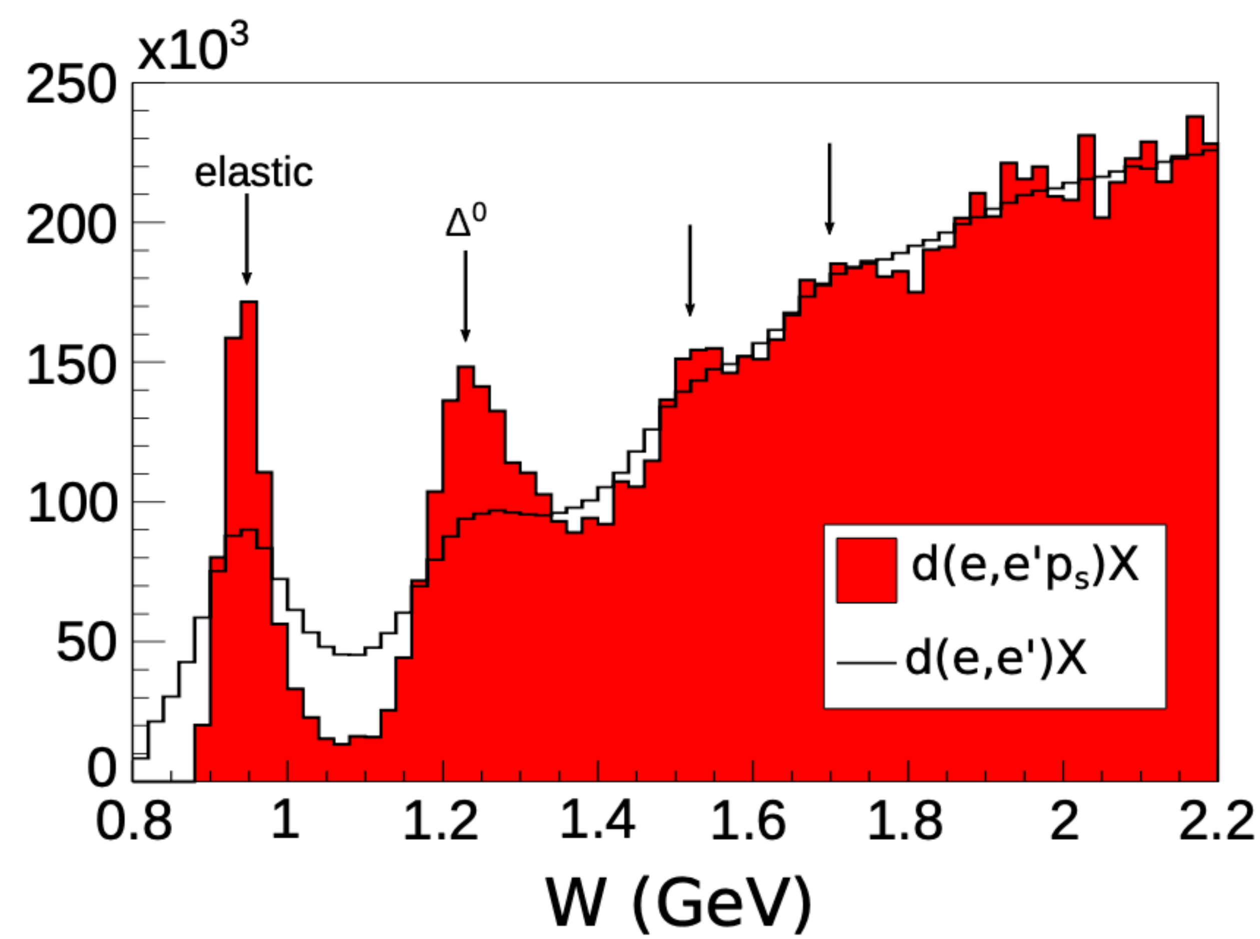
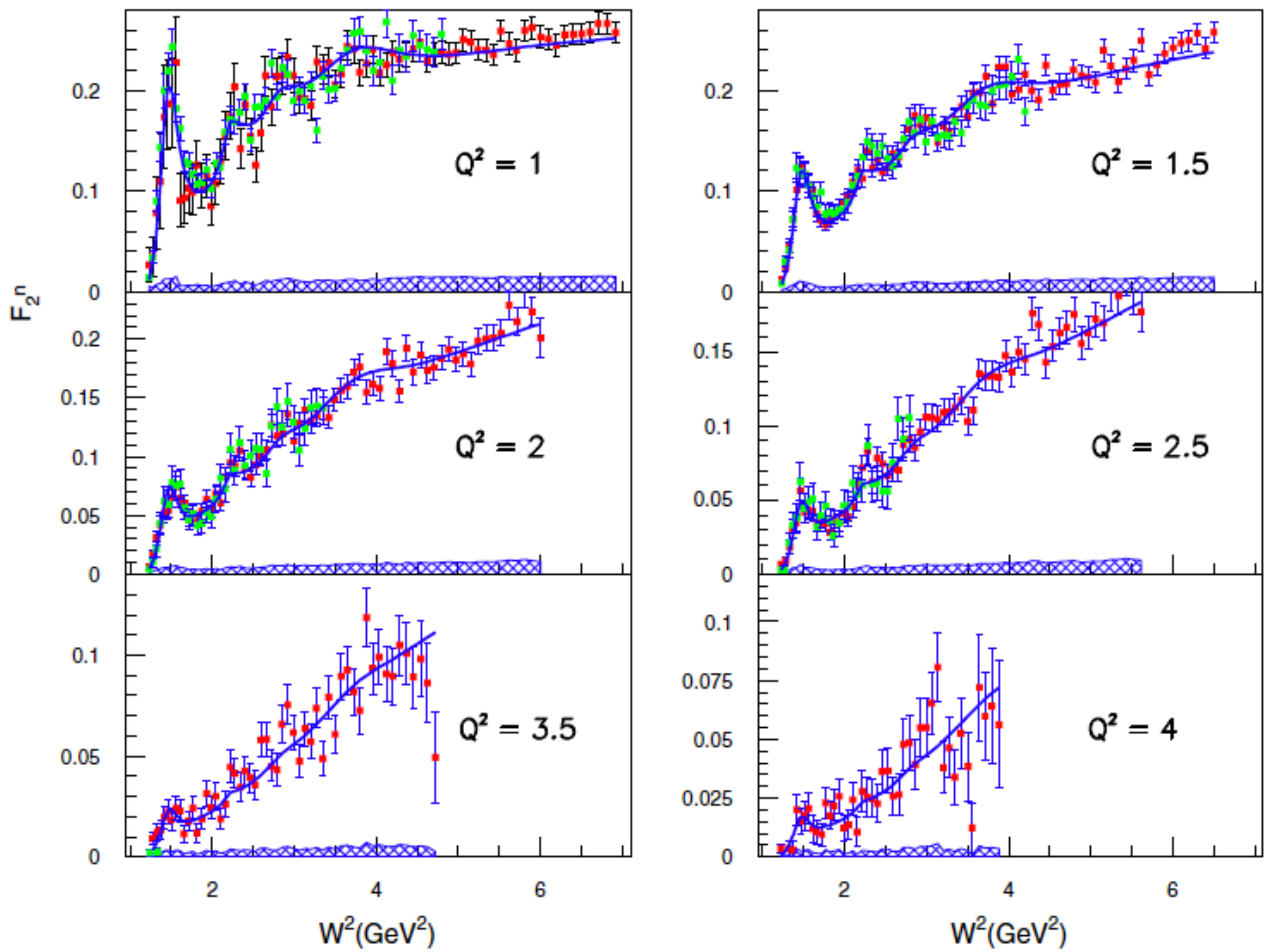


BoNus results

S. Tkachenko et al., Phys. Rev. C 89, 045206 (2014)

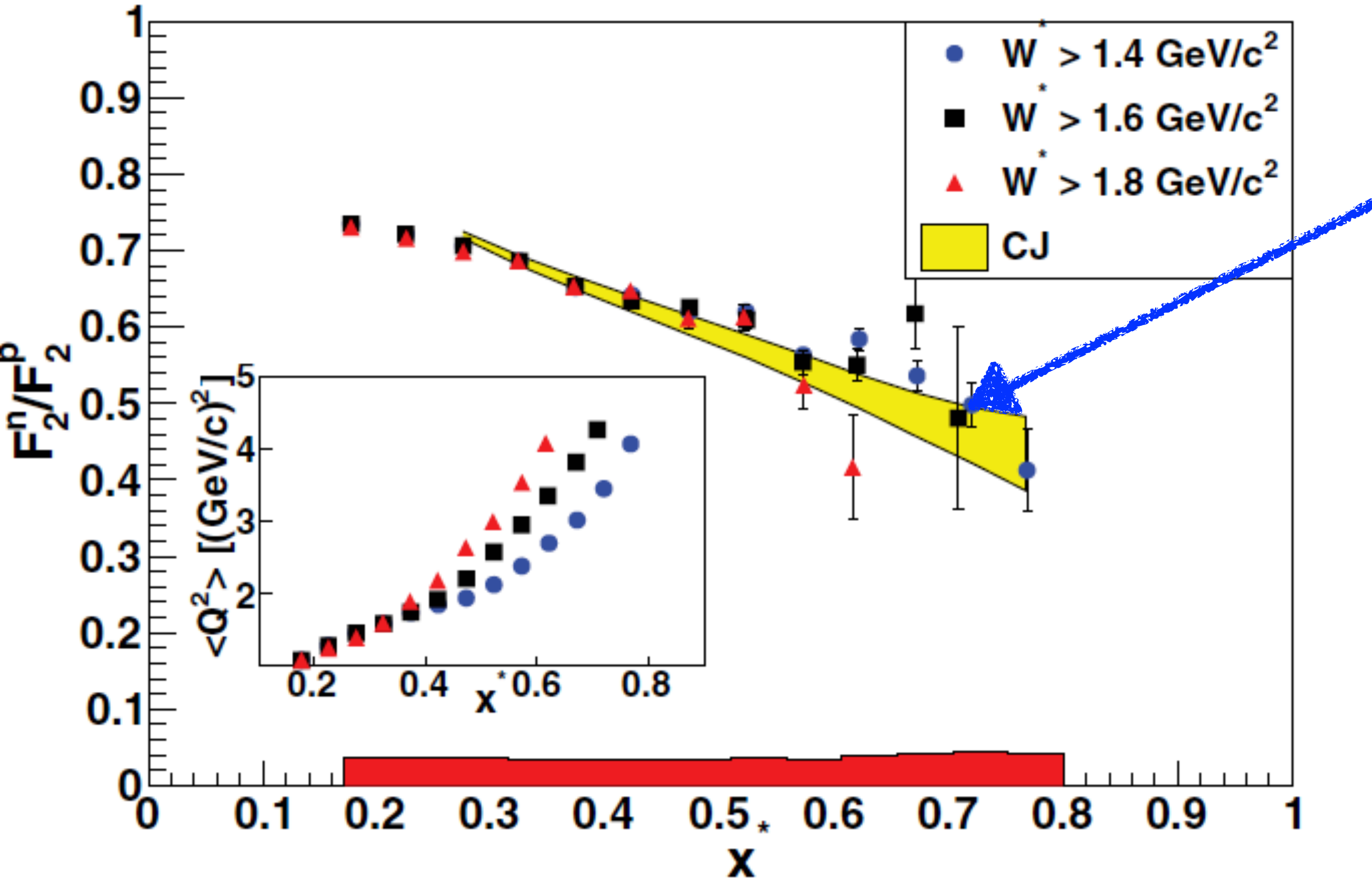


Extracted (nearly) free neutron structure function using F_2^d from inclusive deuteron and proton data fit (M. Christy and P. Bosted)

Study local quark-hadron duality of neutron (I.N et al PRC91 (2015) 055206)

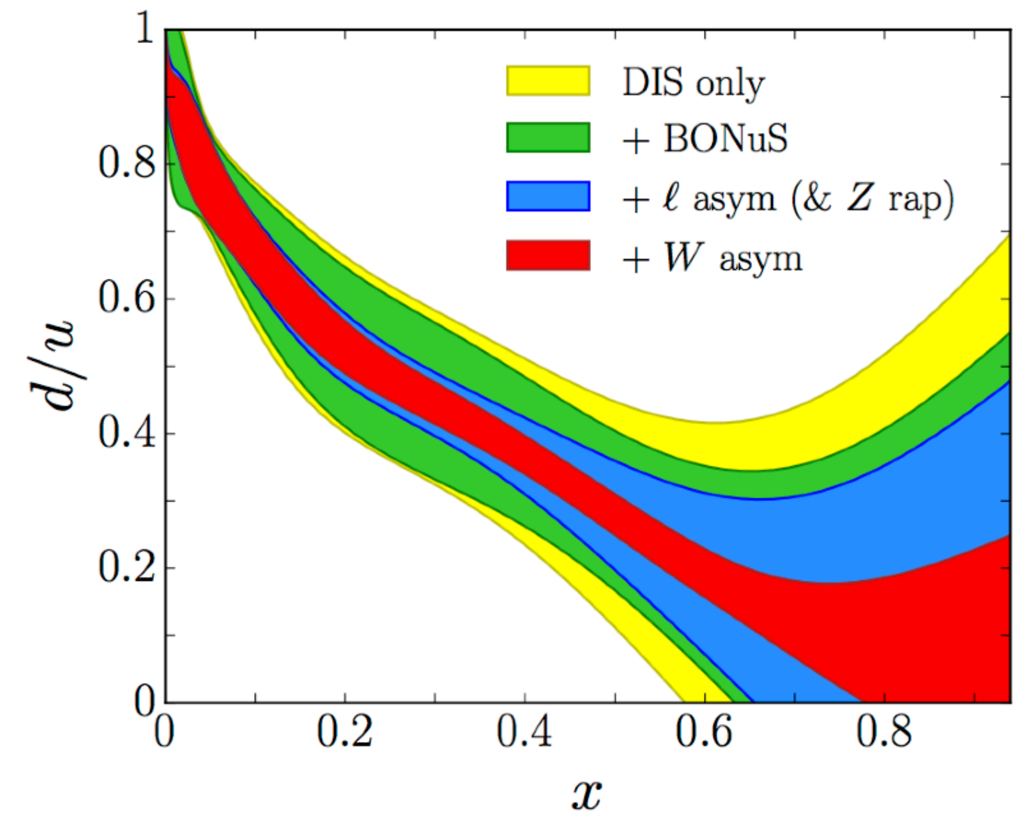
BoNus results

S. Tkachenko et al., Phys. Rev. C 89, 045206 (2014)



Relaxing W cut add statistical power, but also start showing resonance structure

Impact of BoNus data
-> Included to CJ15



Successor experiment BoNus12 schedule to run 2020

Extends kinematic coverage:

$0.1 < x < 0.8$, Q^2 of 1-14 GeV², W up to 4GeV

Also, at EIC! (EPJ Web Conf. 112 (2016) 01022)

3H/3He DIS - MARATHON @Hall A

A=3 mirror nuclei

^{3}H ^{3}He

Form EMC-type ratios

$$R(^3He) = \frac{F_2^{^3He}}{2F_2^p + F_2^n} \qquad R(^3H) = \frac{F_2^{^3H}}{F_2^p + 2F_2^n}$$

Super ratio $R^* = \dfrac{R(^3He)}{R(^3H)}$

Now depends on relative difference in nuclear effects

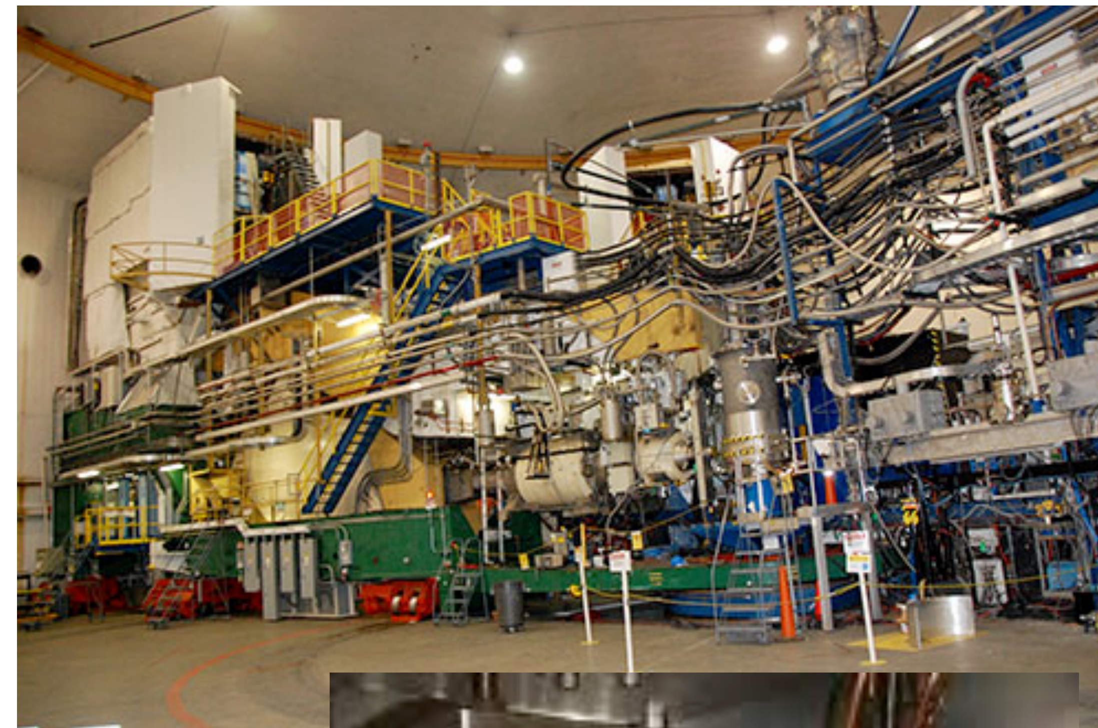
$$\frac{\sigma^{^3He}}{\sigma^{^3H}} = \frac{F_2^{^3He}}{F_2^{^3H}} = R* \frac{2F_2^p + F_2^n}{F_2^p + 2F_2^n}$$

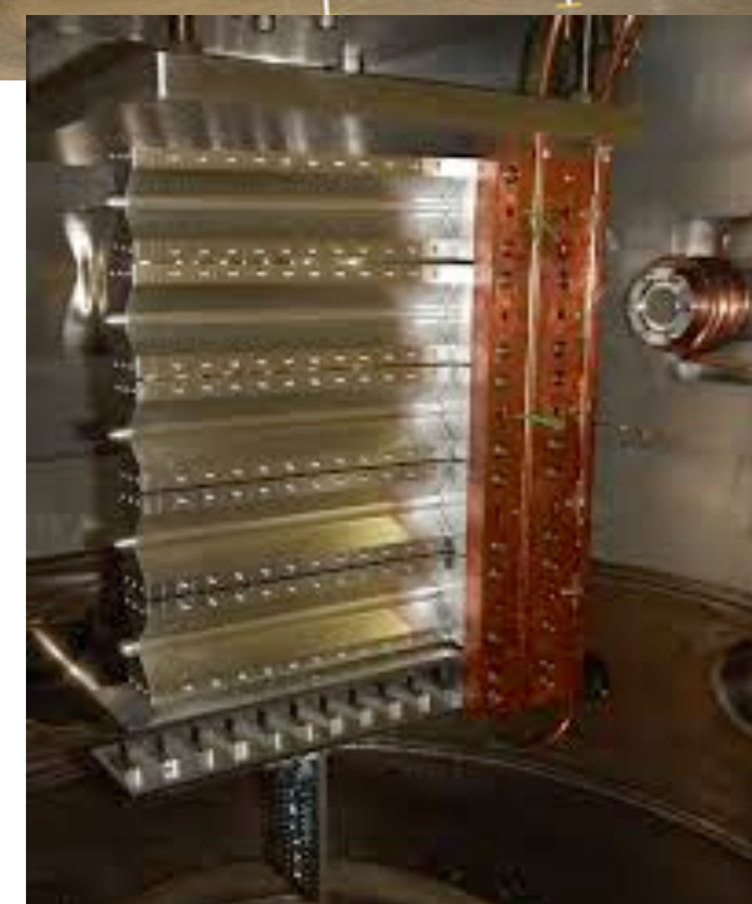
Differences in the nuclear effects small, R*≈1 (theory calculations)

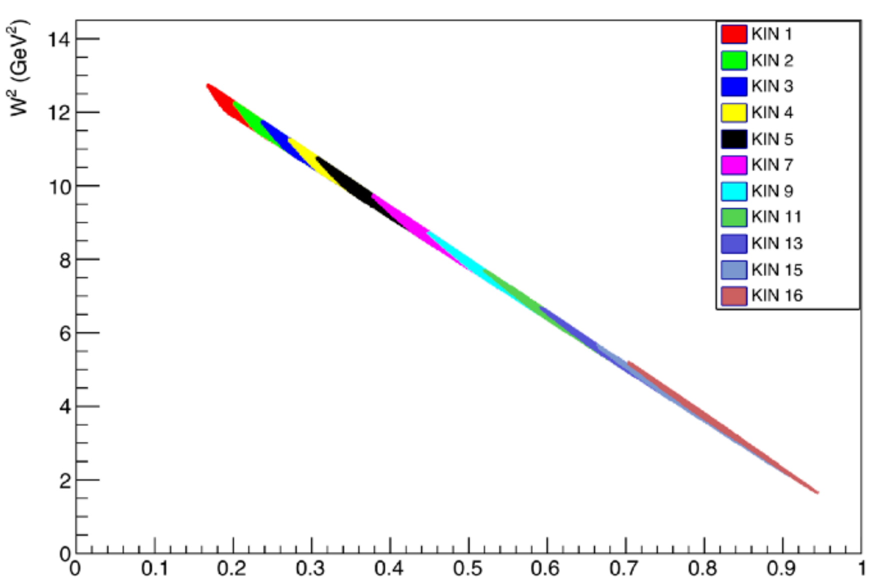
$$\frac{F_2^n}{F_2^p} = \frac{2R^* - \sigma^{^3He}/\sigma^{^3H}}{2\sigma^{^3He}/\sigma^{^3H} - R^*}$$

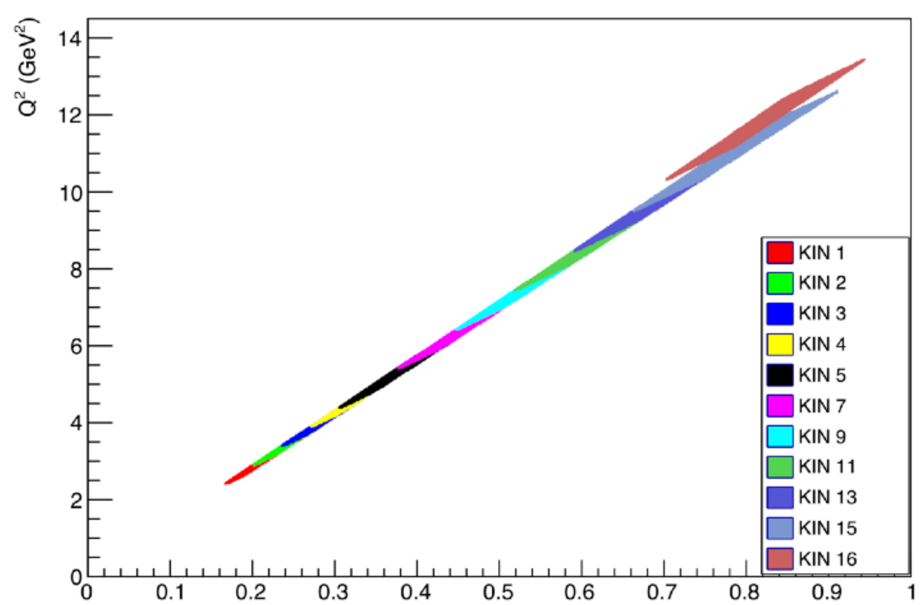
MARATHON experiment

- 10.6 GeV beam, fixed scattered electron momentum (3.1 and 2.9 GeV), scattering angle 17-36 deg
- 3H, 3He, 2H, 1H targets
- Also measure EMC effects in 3He and 3H (first experimental data) and others

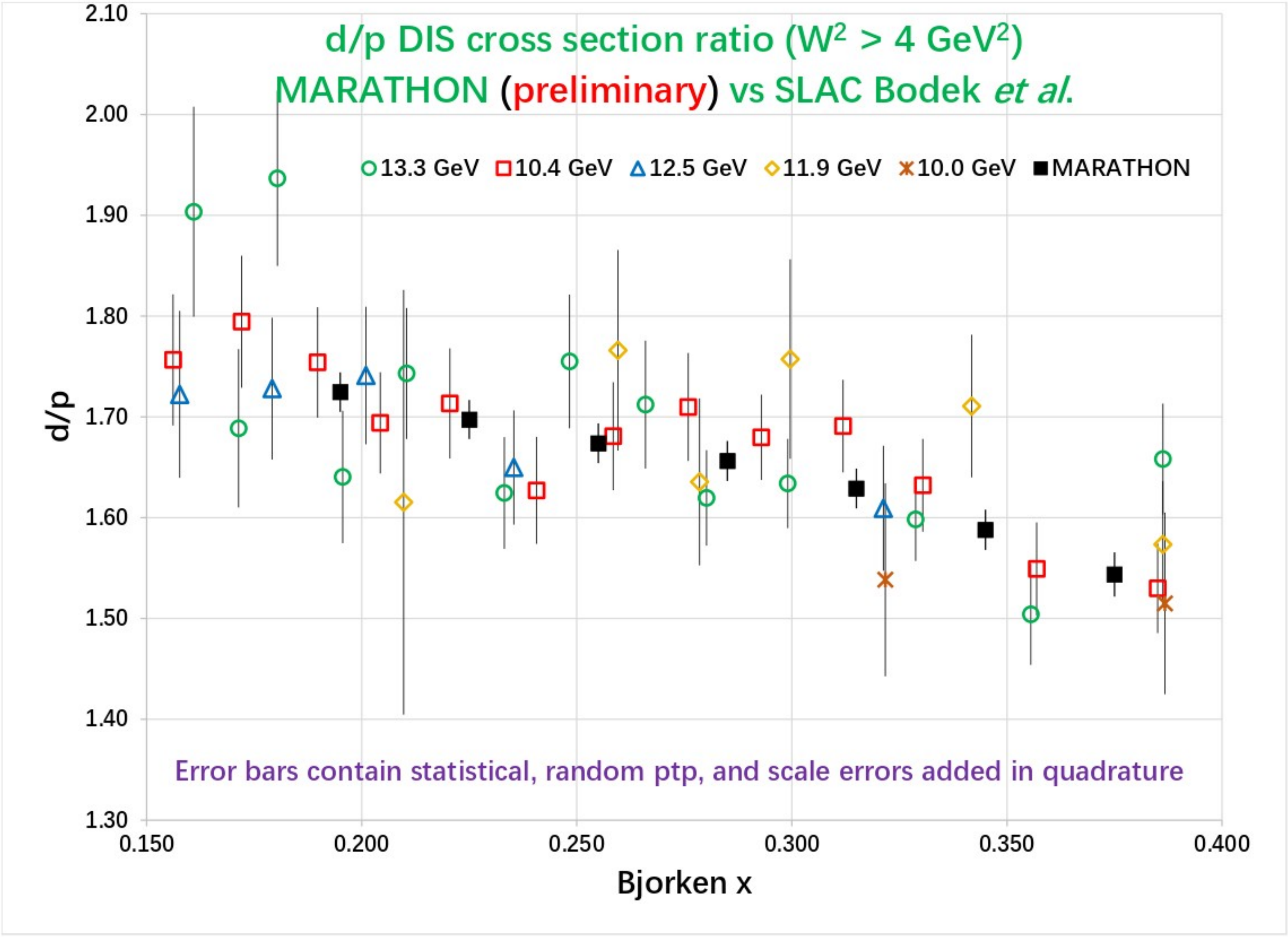








d/p DIS cross section ratio

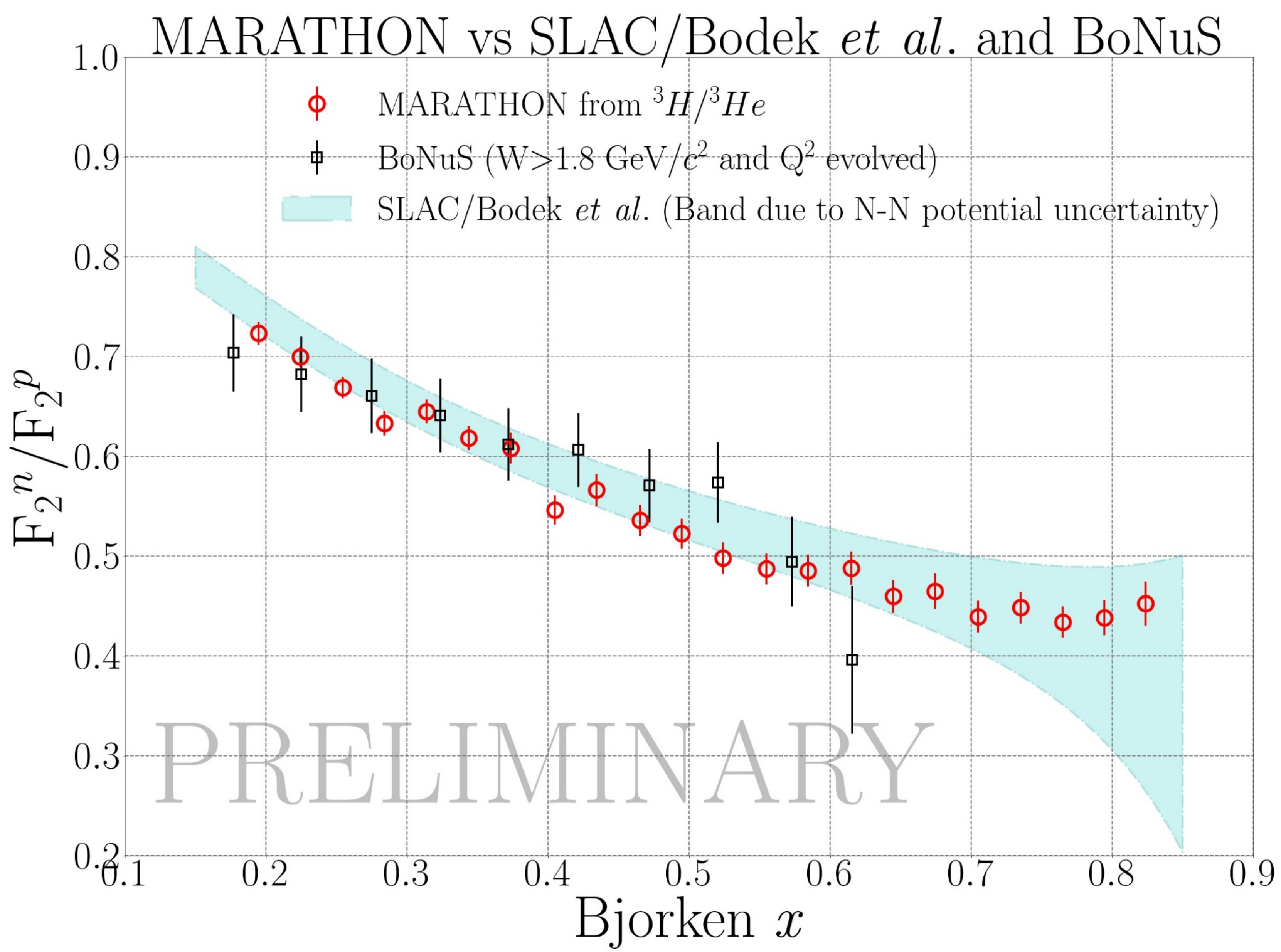


d/p cross section ratio measured at relatively low x with high precision

In excellent agreement with SLAC data

Used to normalize F2(n/p) ratio from 3H/3He data

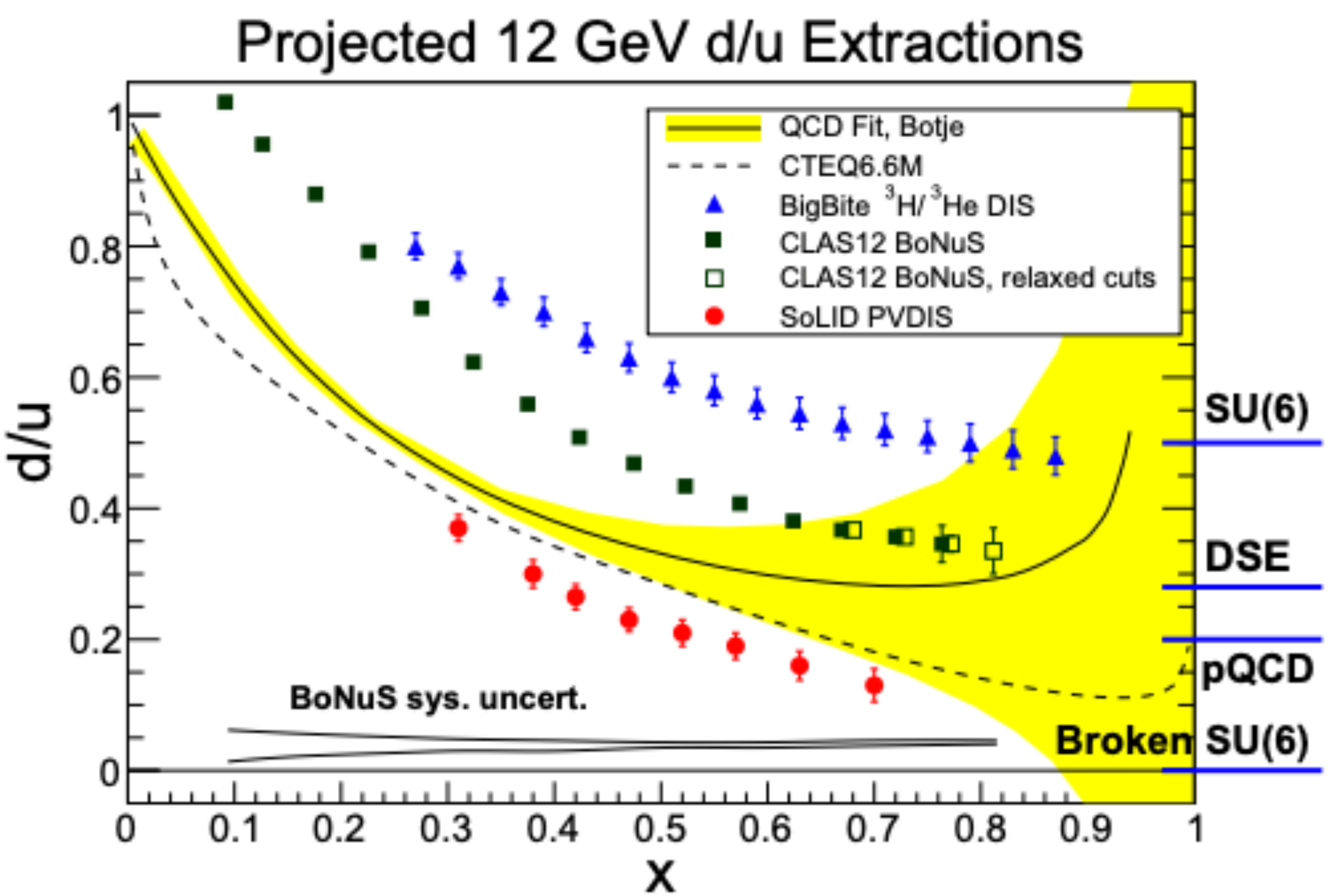
F2 ratio from 3H/3He



F2 neutron to proton ratio from 3H and 3He cross section ratio + R* from Kulagin and Petti model

x_{max} reaches to ~0.83, analysis in progress towards publication

Constraints on d/u from JLab 12GeV



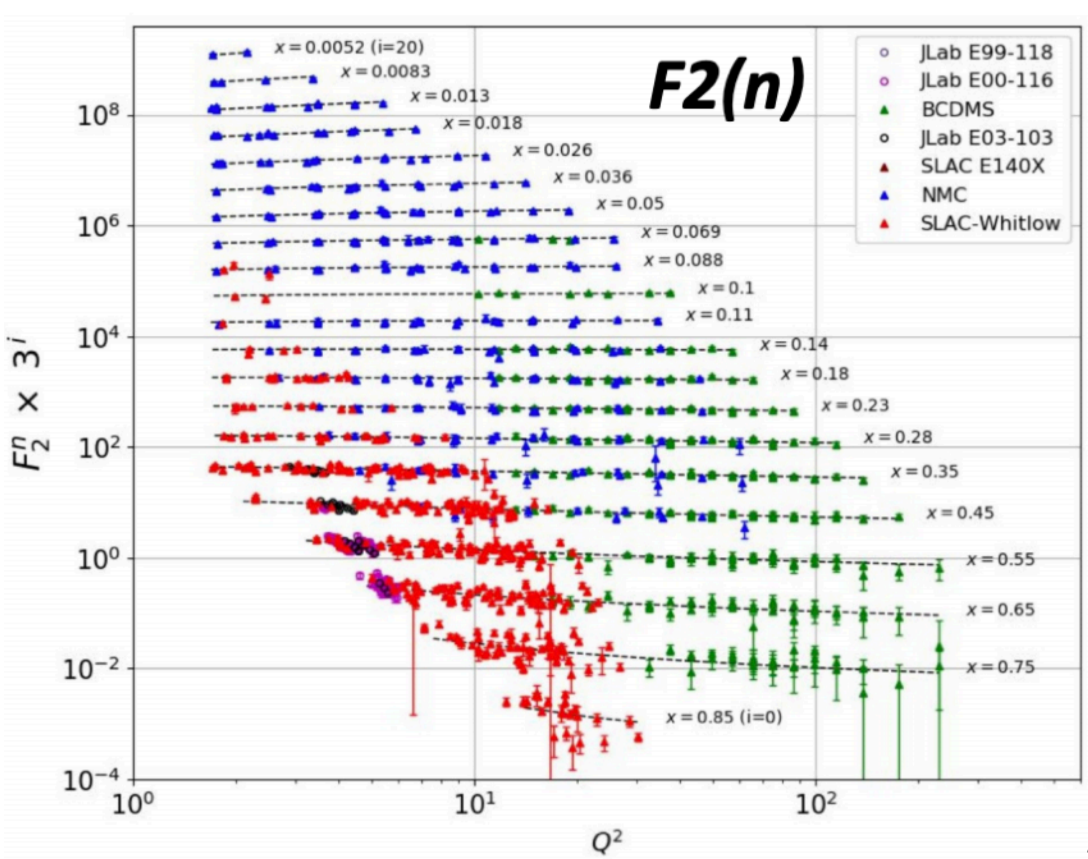
- Model dependent approach: Traditional Inclusive Measurements with deuterium
- Less model dependent approaches:
  3H/3He ratio (MARATHON) - took data in 2018!
  Spectator tagging (BoNus12) - will run in 2020
- Model independent approach:
  PVDIS on proton (SoLID)

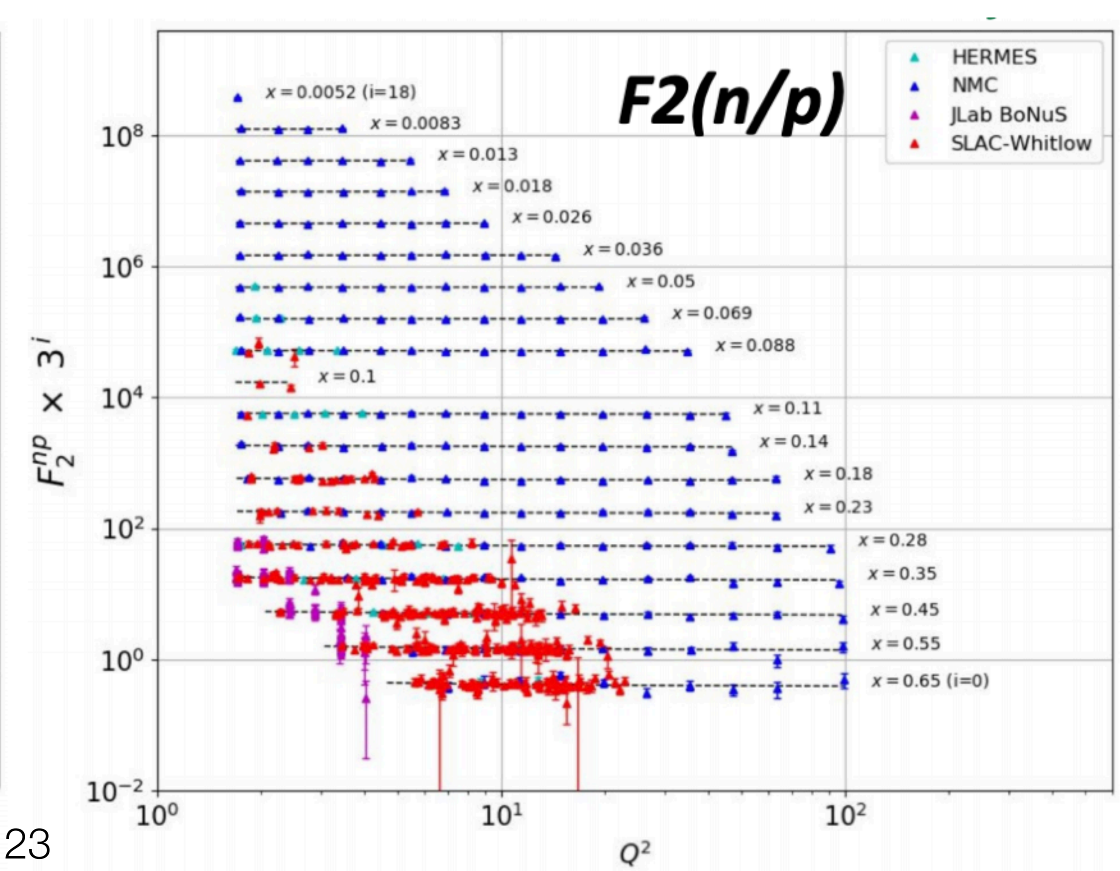
Talk by K. Kumar (Parity violation program at Jefferson Lab)

Database of neutron F_2

S. Li (Univ. New Hampshire) + CJ

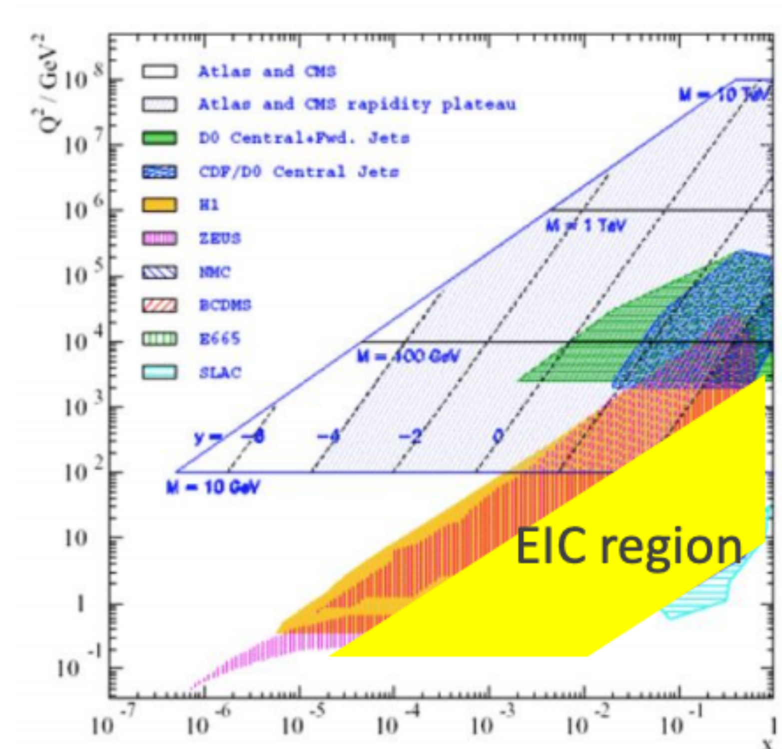
- F_2^n extraction from world DIS data
- Unpolarized proton and deuterium DIS data (F_2 and ratios) + nuclear corrections from global QCD analysis → F_2 neutron
- Extract $F_2^n, F_2^p, F_2(n/p)$, nonsinglet moment

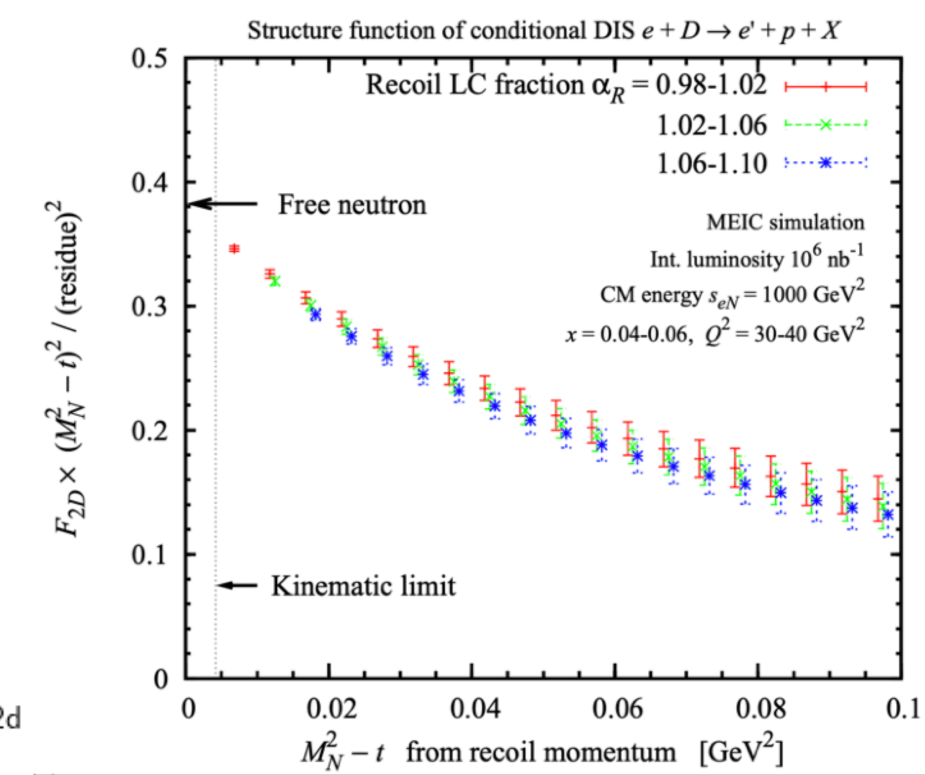




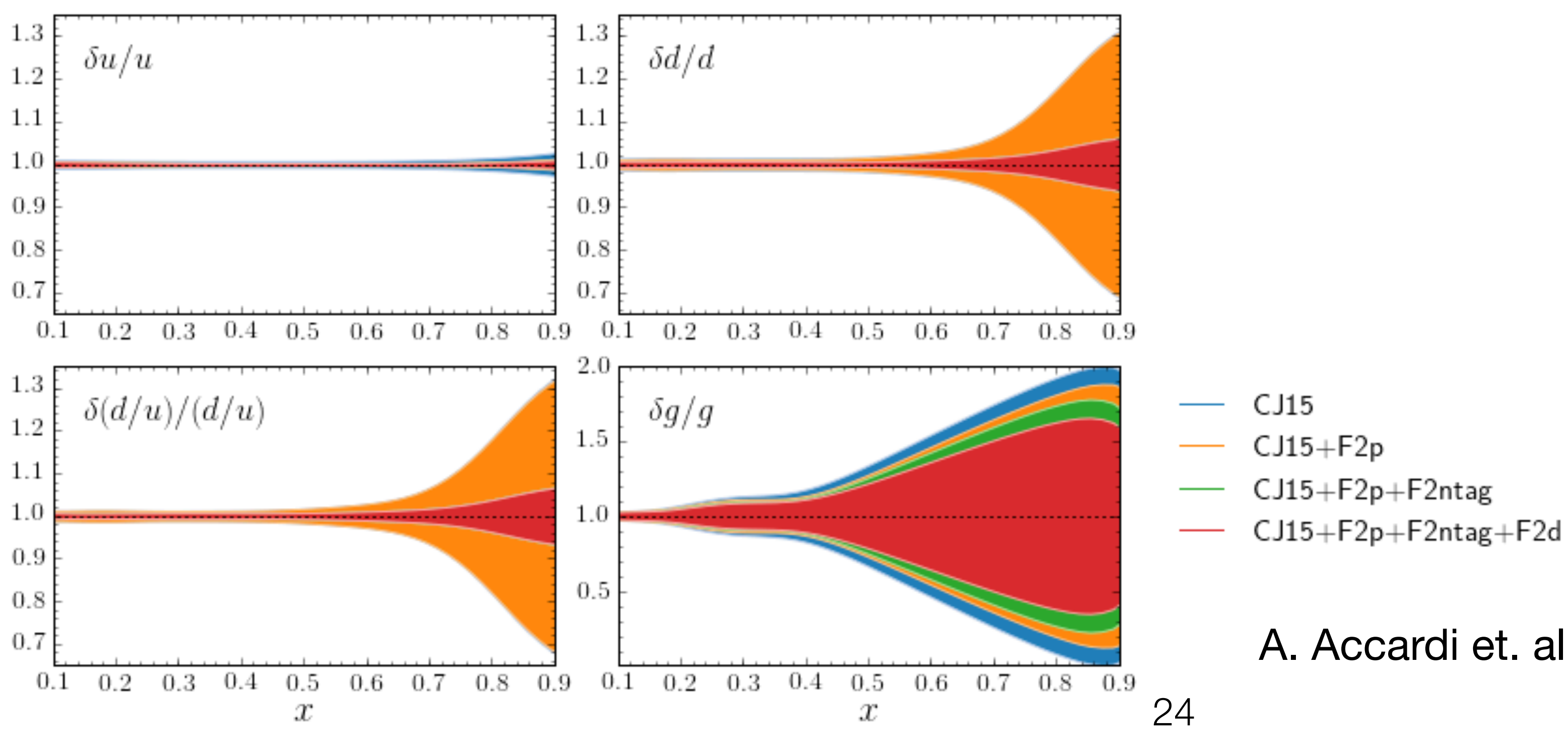
Opportunities with EIC

- F_1, F_2, F_L proton and deuteron
- High luminosity -> improve high x precision
- F2 neutron with spectator tagging
- Impact studies with pseudo data show d quark precision significantly improved (comparable to current u precision)
- Also explore details of nuclear effects





W. Cosyn et al
EPJ Web Conf. 112 (2016) 01022



A. Accardi et. al

Summary

- Structure functions contain information of internal structure of nucleons

- Large x region - large PDF uncertainties become a dominant systematic source for LHC physics

- Precise measurements of proton structure function

- Limited knowledge of neutron - lack of data, large uncertainty from nuclear effects

- Recent fixed target data and future program at JLab and EIC will provide significant constraints on neutron F_2

Thank you for your attention!