Probing large-x PDFs at JLab in the 12GeV Era

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Teleworkshop on Strong QCD from Hadron Structure Experiments
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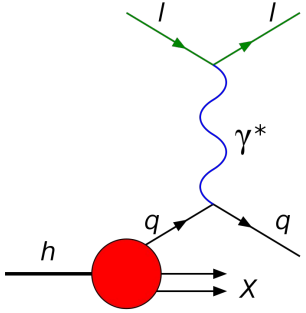
Deep Inelastic Scattering and Quark Parton Model

The unpolarized DIS cross section can be parameterized with structure functions F1 and F2:

$$\frac{d\sigma}{d\Omega dE'} = \sigma_{Mott}\left(\frac{F_2(x)}{\nu} + 2\tan^2\frac{\theta_e}{2}\frac{F_1(x)}{M}\right); \qquad \nu = E - E'$$

$$Q^2 = 4EE'\sin^2(\theta/2)$$



where $x = Q^2/(2M\nu)$ is the fraction momentum of the nucleon carried by the struck quark, and q_f is the longitudinal quark momentum distribution function. At large Q2 and nv:

$$F_2(x,Q^2) = x \sum_{f=up,down,\ldots} z_f^2\left(q_f(x,Q^2) + \bar{q}_f(x,Q^2)\right)$$

d/u at large x

At leading order (charge symmetry):

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

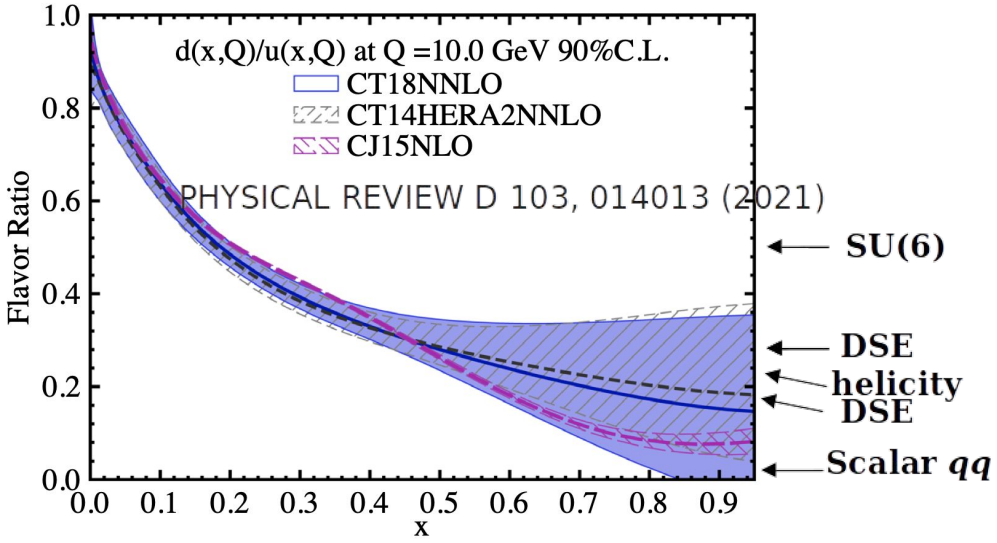
$$F_2^n = x\left[\frac{4}{9}(d+\bar{d}) + \frac{1}{9}(u+\bar{u}) + \frac{1}{9}(s+\bar{s})\right]$$

Small anti-quarks and strange quark contributions at x>0.3

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

- Precise PDFs at large x are needed as inputs for collision and neutrino experiments

- d/u at (x→1) is a crucial test of valence quark models and pQCD.



Nucleon Model	F_2^n/F_2^p $x\to 1$	d/u $x\to 1$
SU(6) Symmetry	2/3	0.5
Scalar diquark dominance	1/4	0
DSE contact interaction	0.41	0.18
DSE realistic interaction	0.49	0.28
PQCD (helicity conservation)	3/7	0.2

Courtesy of S. Kuhn

F2n Extraction from Deuteron Data

S. Li et. al. in preparation (2021)

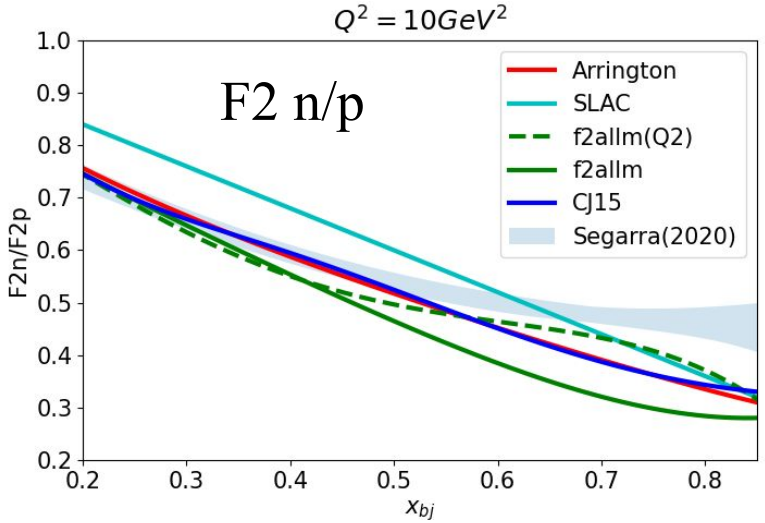
No "free neutron" target. Remove nuclear effect in deuteron **$R(D) = d_{calc}/(p+n)_{calc}$**:

Free nucleon

$$(p+n)_{data} = d_{data} / R(D)$$

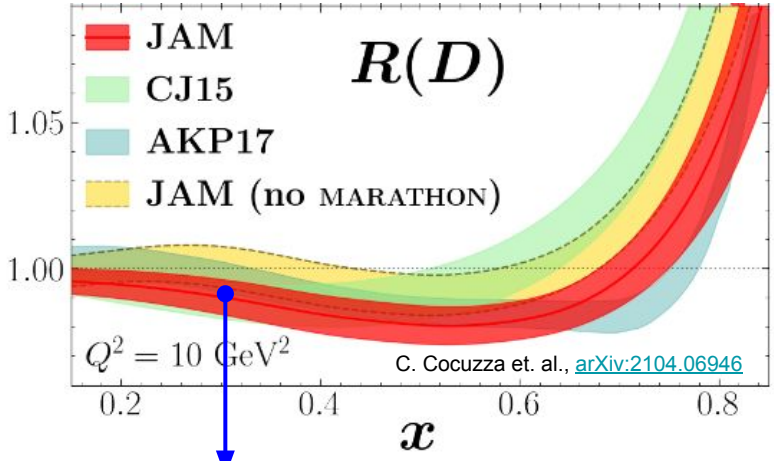
Free neutron

$$n_{data} = (p+n)^*_{data} - p^*_{data} = d^*_{data}/R(D) - p^*_{data}$$



Sources of Uncertainties:

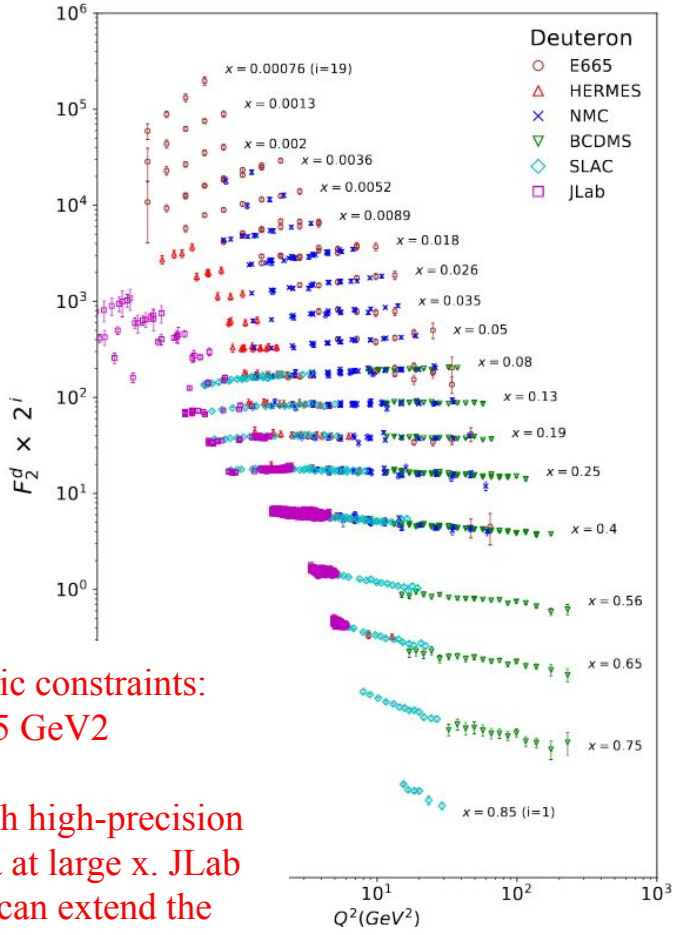
- Model dependence:
  - Deuteron wave function
  - Deuteron offshell effect
  - Finite Q2 corrections (higher twist, target mass corrections)
- Uncertainty propagated from proton data

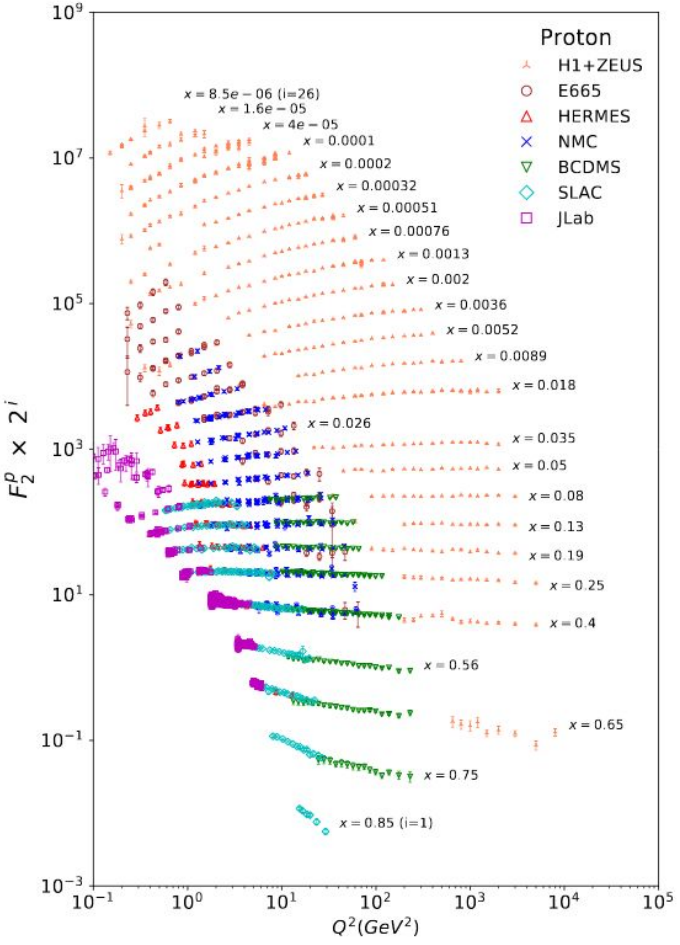


Small nuclear effect at x=0.3 : R(D)=1

* Careful study on the DIS/resonance separation to take use of low-W2 (mainly JLab) data

Unpolarized DIS World Data

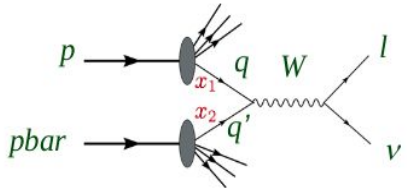




Kinematic constraints:
W2 > 3.5 GeV2

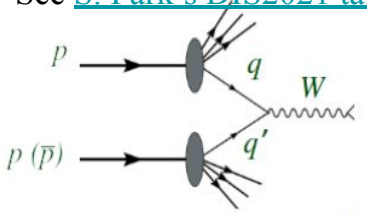
Not much high-precision DIS data at large x. JLab 12 GeV can extend the coverage upto x=0.85

d/u in Global QCD Analysis



D0, CDF asymmetries

See S. Park's DIS2021 talk



$$A_W(y) \xrightarrow{y \to y_{max}} \frac{1 - d/u(x_1)}{1 + d/u(x_1)}$$

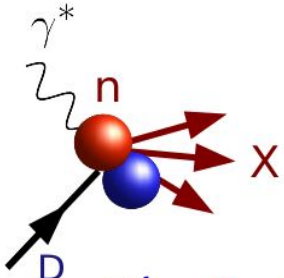
d/u

&

nucl. + offsh. dynamics

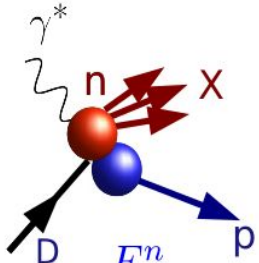
Deep inelastic deuterium

"BONuS" tagged neutron target



$$F_2^d \propto \mathcal{S}_D \otimes \left[x u_{\text{off}}(x) + x d_{\text{off}}(x) \right]$$

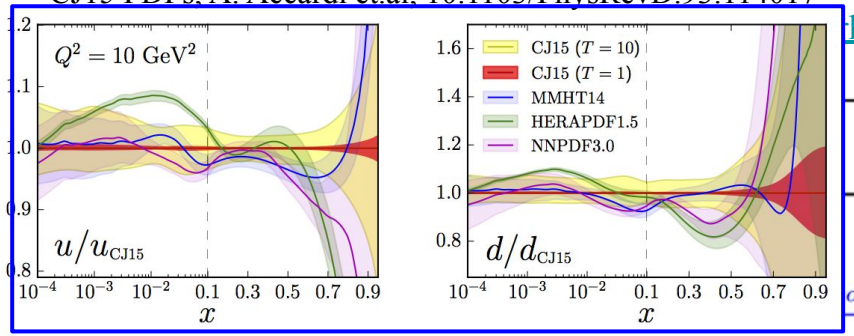
JLab experiments

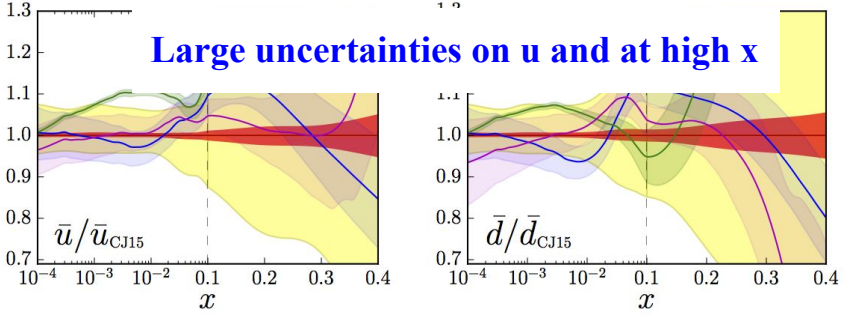


$$\frac{F_2^n}{F_2^d} \propto x u(x) + 4 x d(x)$$

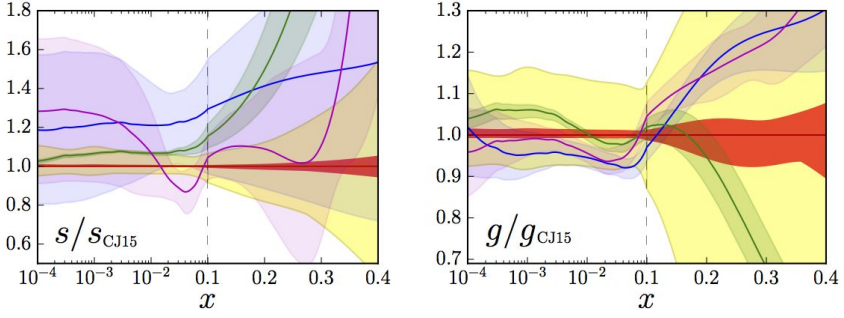
d/u in Global QCD Analysis

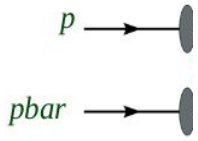
CJ15 PDFs, A. Accardi et.al, 10.1103/PhysRevD.93.114017

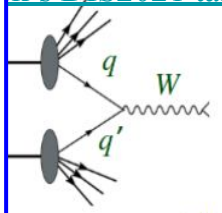




Large uncertainties on u and at high x



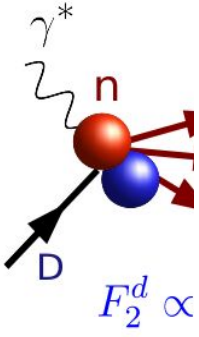




[k's DIS2021 talk]

$$\xrightarrow{a\,x} \frac{1 - d/u(x_1)}{1 + d/u(x_1)}$$

Deep ine
deuteriu



$F_2^d \propto$

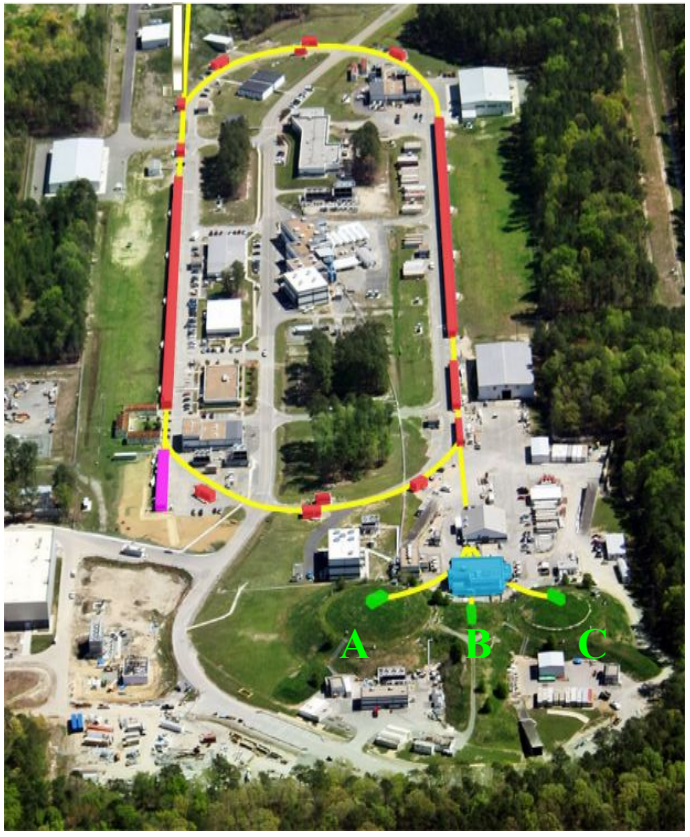
d neutron target

p

$xu(x) + 4xd(x)$

JLab experimer

Recent Large-x Measurements from JLab 12 GeV Program



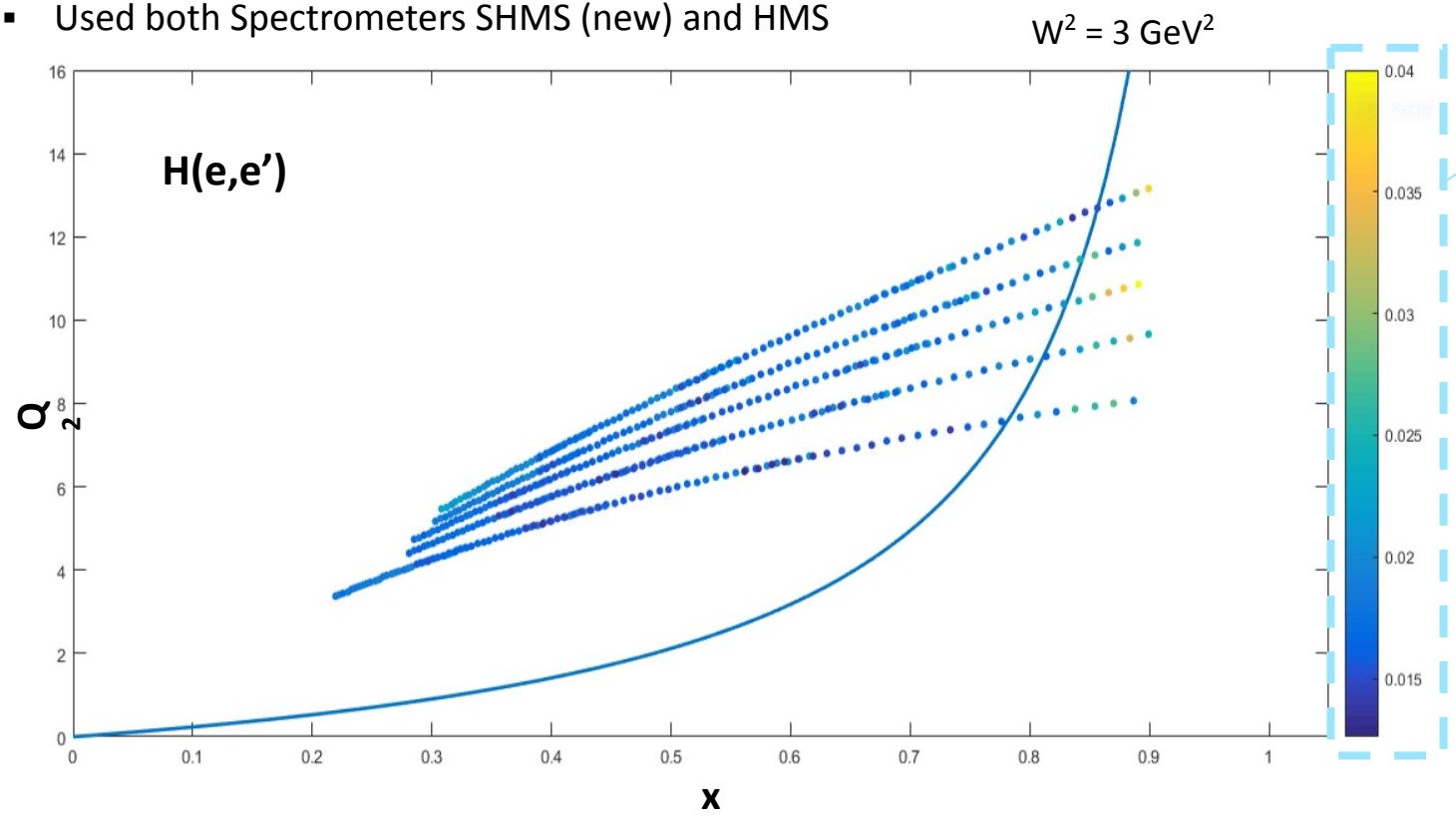
- HALL C E12-10-002:
  - Expand kinematic coverage up to x=0.82 with W2>3 GeV2 with traditional F2 p and d measurements
- HALL B BONuS:
  - Control nuclear effect in d with spectator tagging
- HALL A MARATHON:
  - Minimize the ratio of nuclear effects with mirror nuclei 3H and 3He, and study the isospin-dependence of offshell effect

Not a complete list, apology for missing any…

Hall C Completed Large-x **Experimental** Program: **E12-10-002**

Courtesy of S. Malace

- Measured yields from H(e,e') and D(e,e') to extract cross sections and F_2^p and F_2^d structure functions in a large x and Q^2 range
  - Beam: 10.6 GeV, unpolarized
  - Targets: cryogenic H and D, Al
  - Used both Spectrometers SHMS (new) and HMS



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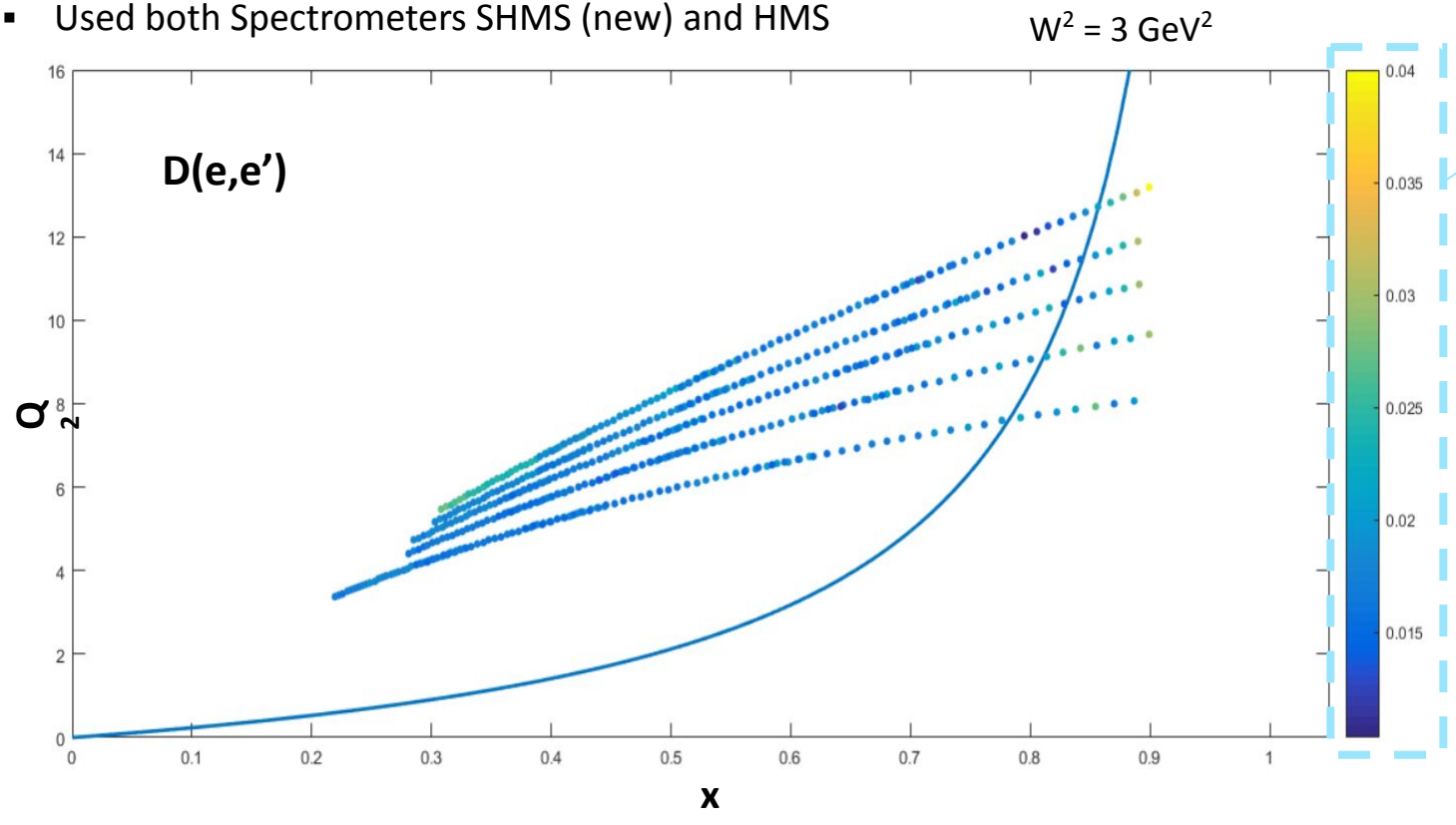


Hall C Completed Large-x **Experimental** Program: **E12-10-002**

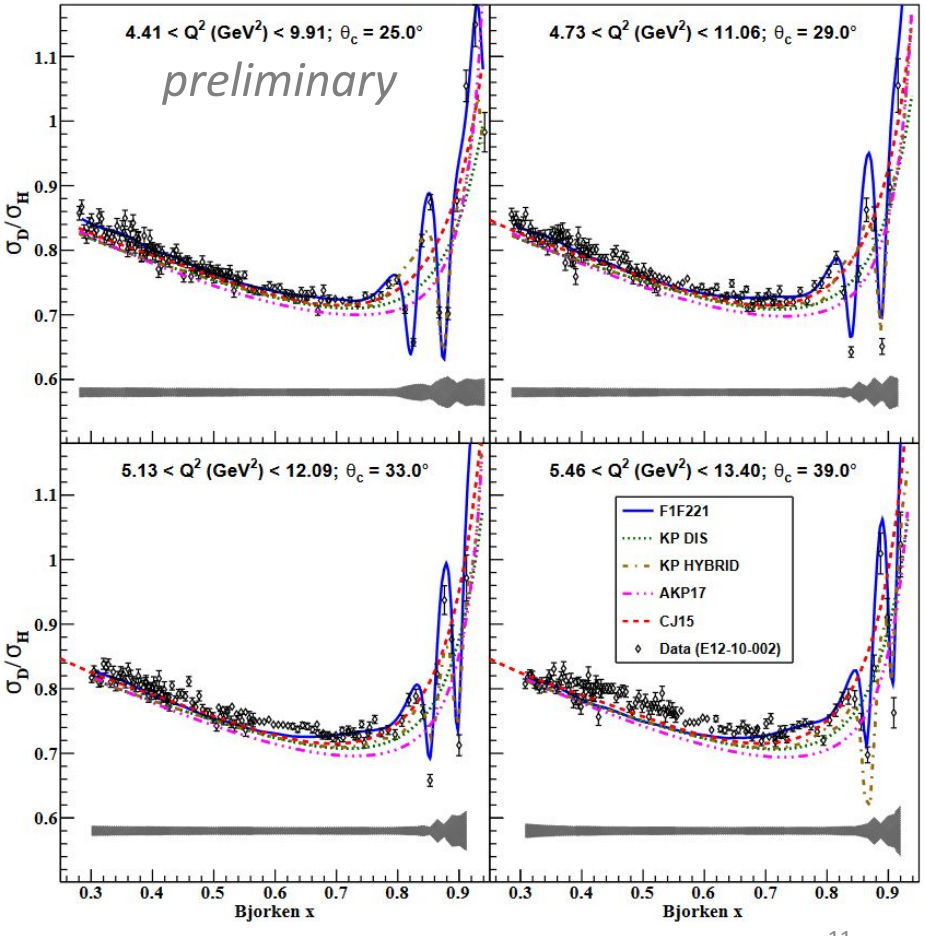
Courtesy of S. Malace

- Large volume of high-precision data spanning a wide range in x and Q^2

  - Additional constraints for global PDF fits like CJ and AKP (d-quark vs nuclear corrections in deuterium)
  - Tests for hybrid models like Kulagin's
  - Extends precision quark-hadron duality studies to higher Q^2 than before
  - Will test lattice calculations by extracting non-singlet moments

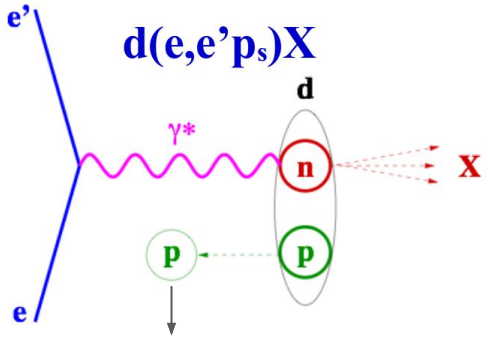
Status:
The preliminary results are now available, and final results will be submitted for publication within one month.

not all kinematics shown



BONuS (Barely Offshell Nucleon Structure) - 6 GeV

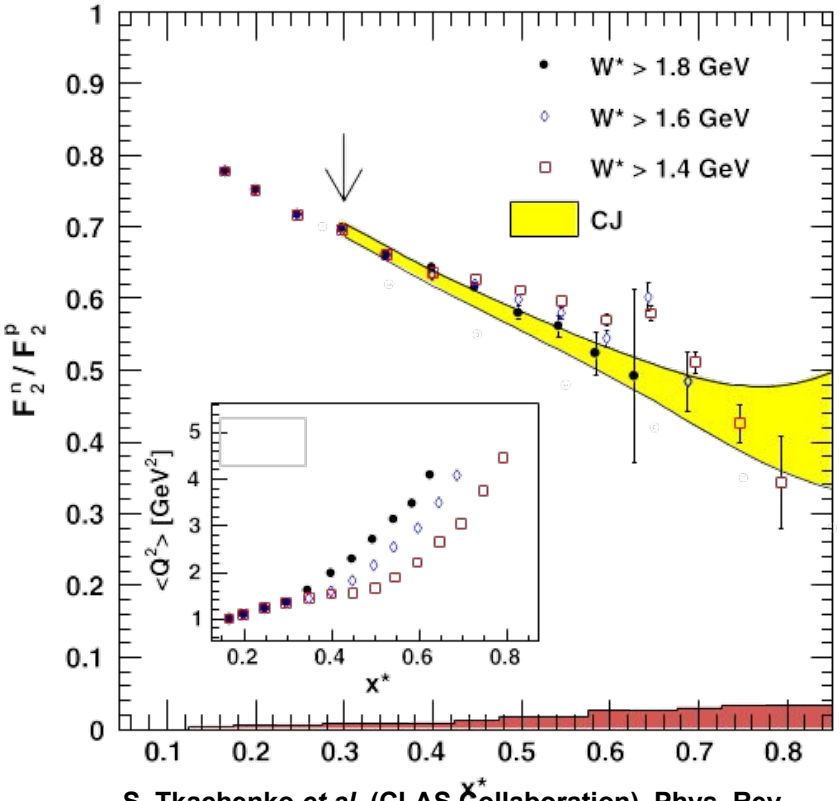
Measures F2n and n/D to extract n/p



Select DIS events tagged with low-momentum spectator protons (70 - 100 MeV) which have negligible offshell effect.

- No offshell correction needed. Systematic uncertainty evaluated with models.
- Tagging efficiency normalized against n/p ratio at x=0.3
- x range limited by beam energy

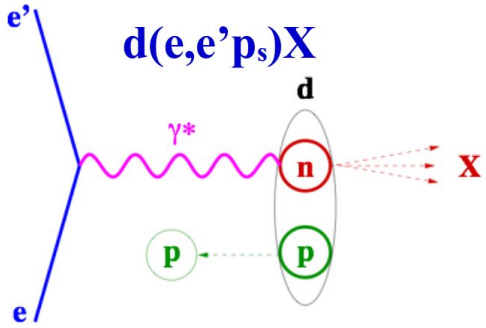
BONuS6 extracted n/p



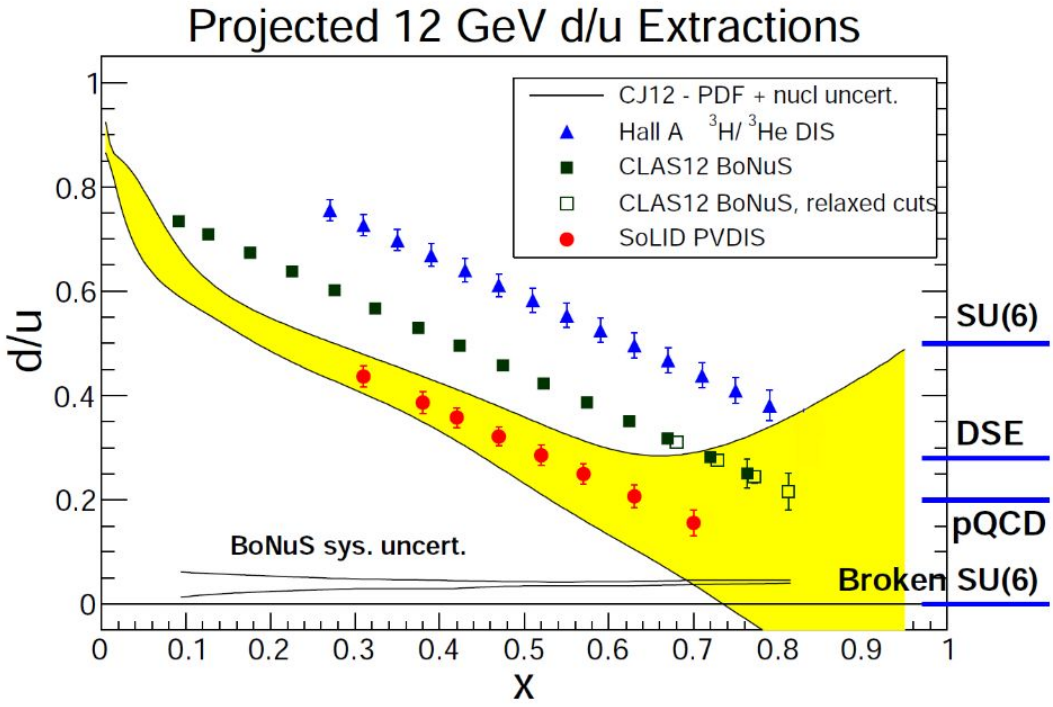
S. Tkachenko *et al.* (CLAS Collaboration), Phys. Rev. C 89, 045206. More data available now

BONuS (Barely Offshell Nucleon Structure) - 12 GeV

Measures F2n and n/D to extract n/p



- DIS data with x up to 0.82 with 11 GeV beam
- Higher momentum resolution
- Additional independent check of tagging efficiency



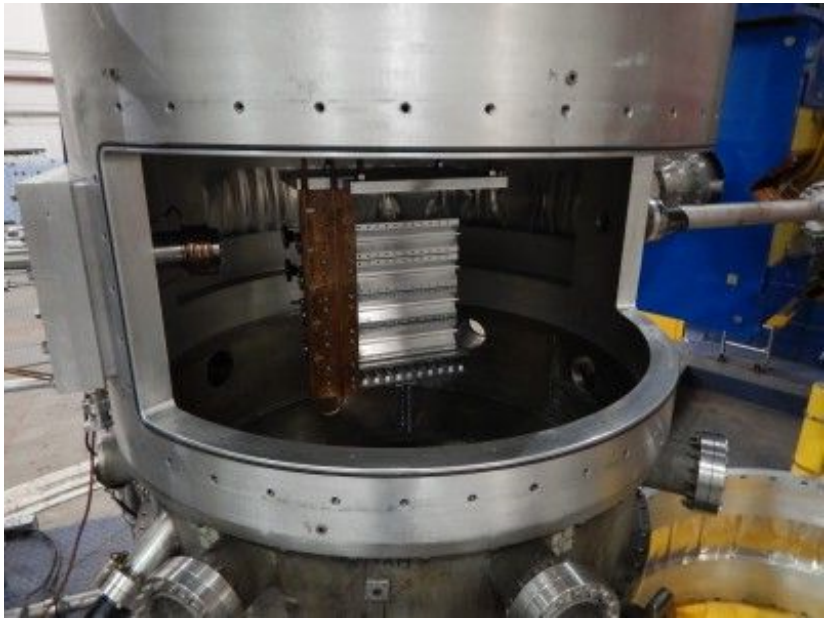
Status:

Data taken in 2020. First round of calibrations completed.

Expect to have first results in Winter 2021/2022

MeAsurement of F2n /F2p , d/u RAtios and A=3 EMC Effect in Deep Inelastic Electron Scattering Off the Tritium and Helium MirrOr Nuclei (MARATHON)

- 3 months of data-taking in 2018
- Classic (e,e') scattering with the unique low-density gas target system
- x → 0.83 with high statistics
- $\sigma_h/\sigma_t \rightarrow F_2^h/F_2^t$
  - Systematical uncertainties canceled in ratio
  - L/T cross section ratio assumed to be the same for both nuclei



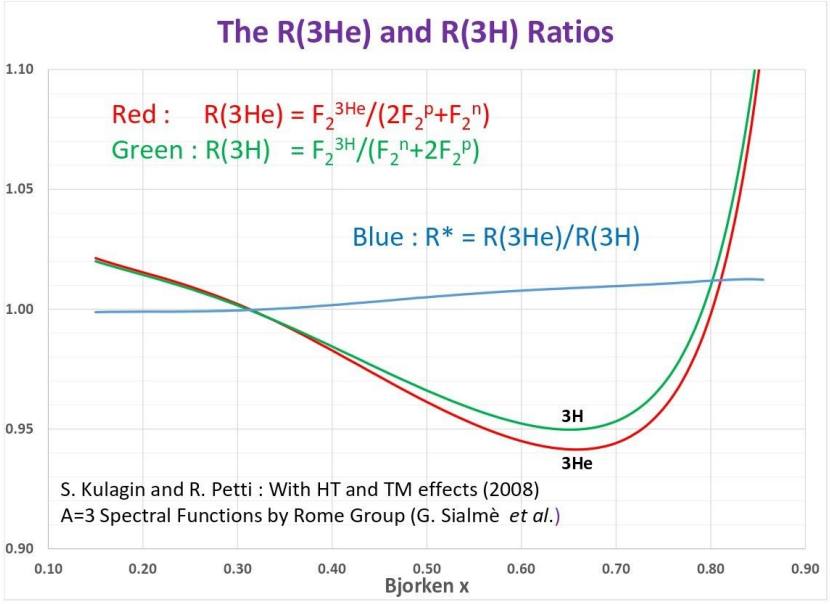
See also: *the MARATHON marathon seminar*

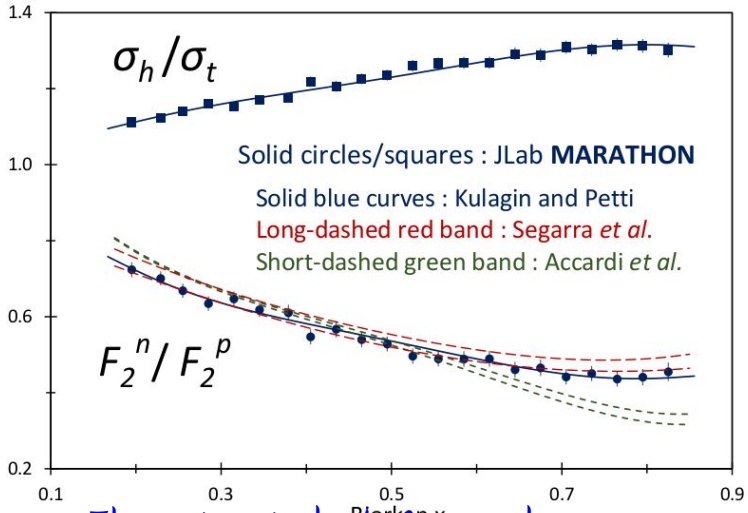
F2n/p from MARATHON

arXiv:2104.05850, submitted to PRL

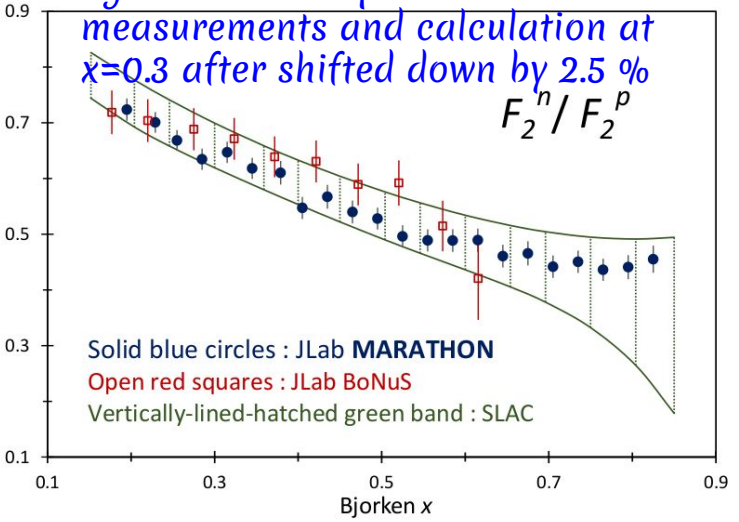
Remove nuclear effects in mirror nuclei with calculation from Kulagin and Petti (nuclear effect fitted with heavier nuclei):

$$R_h = F_2^h/(2F_2^p + F_2^n)$$
$$R_t = F_2^t/(F_2^p + 2F_2^n)$$
$$\Rightarrow \quad \frac{F_2^n}{F_2^p} = \frac{2\mathcal{R}_{ht} - F_2^h/F_2^t}{2F_2^h/F_2^t - \mathcal{R}_{ht}}.$$





The extracted n/p in good agreement with previous measurements and calculation at x=0.3 after shifted down by 2.5 %



Alternative Approach: PDF fitting with JAM

arXiv:2104.06946
See also C. Cocuzza's talk

- **Allow different offshell effects in n and p**
- Assume charge symmetry:

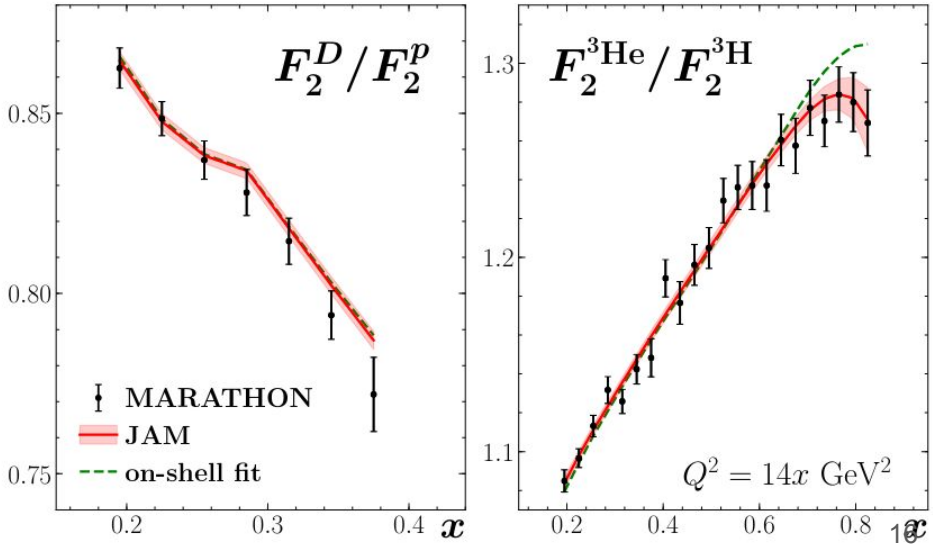
$$\delta u_{p/D} = \delta d_{n/D}, \quad \delta d_{p/D} = \delta u_{n/D},$$
$$\delta u_{p/^3\mathrm{He}} = \delta d_{n/^3\mathrm{H}}, \quad \delta d_{p/^3\mathrm{He}} = \delta u_{n/^3\mathrm{H}},$$
$$\delta u_{p/^3\mathrm{H}} = \delta d_{n/^3\mathrm{He}}, \quad \delta d_{p/^3\mathrm{H}} = \delta u_{n/^3\mathrm{He}},$$

TWO offshell parameters to fit

$$\delta u_{p/D} = \delta u_{p/^3\mathrm{H}} \equiv \delta u,$$
$$\delta d_{p/D} = \delta d_{p/^3\mathrm{H}} \equiv \delta d,$$

- Perform QCD analysis with world data including MARATHON. Fit n/p and offshell simultaneously.

process	N_{dat}	χ^2/N_{dat}	fitted norm.
DIS			
MARATHON ^{3}He/^{3}H	22	0.64	1.009(5)
MARATHON D/p	7	0.72	1.016(4)
JLab E03-103 ^{3}He/D	16	0.20	1.012(8)
NMC D/p	189	0.89	0.991(5)
other fixed target	2489	1.06	
HERA	1185	1.28	
Drell-Yan	250	1.08	
lepton rapidity	156	1.57	
W charge asym.	27	1.48	
Z rapidity	56	0.94	
jet	196	0.87	
total	**4593**	**1.11**	



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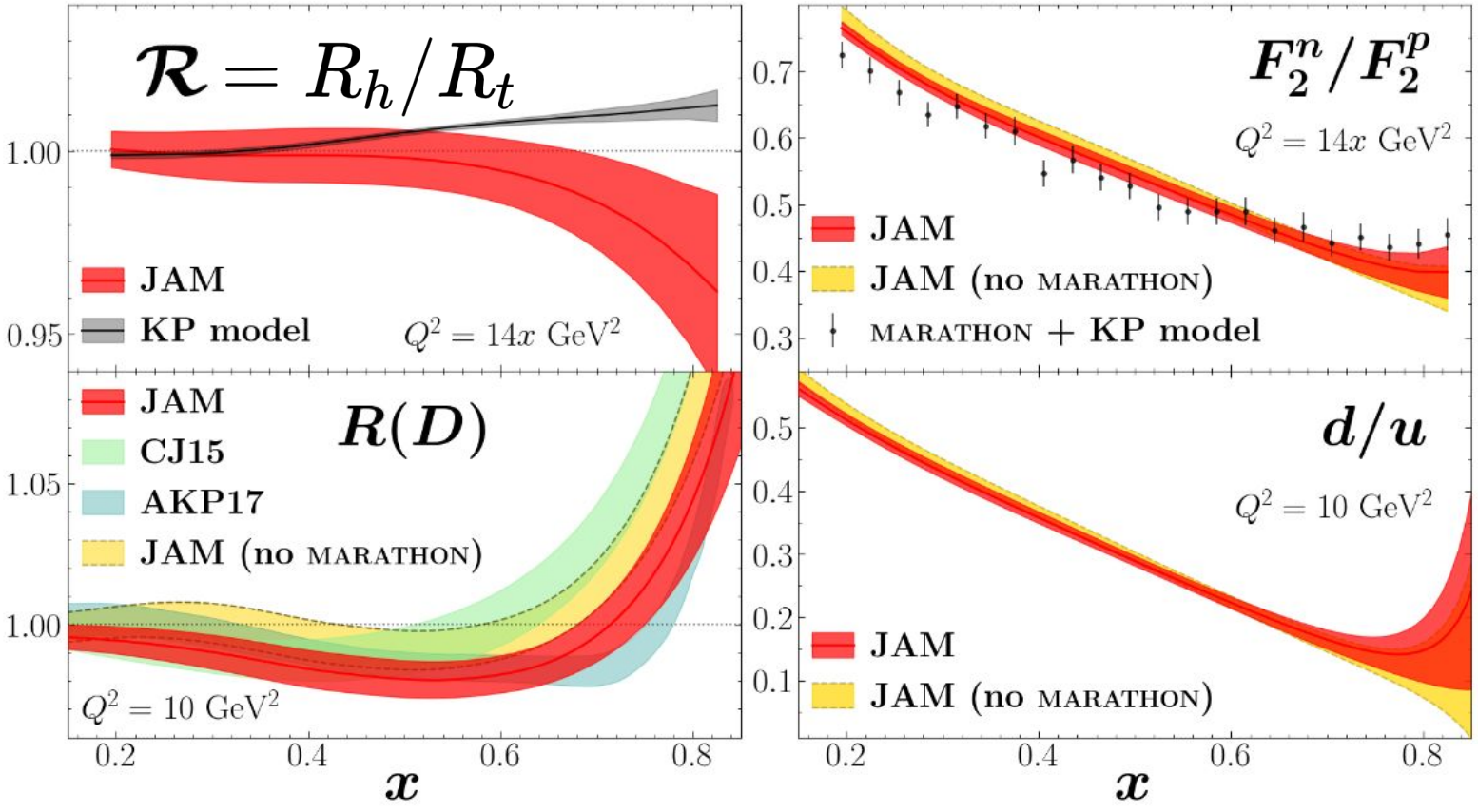
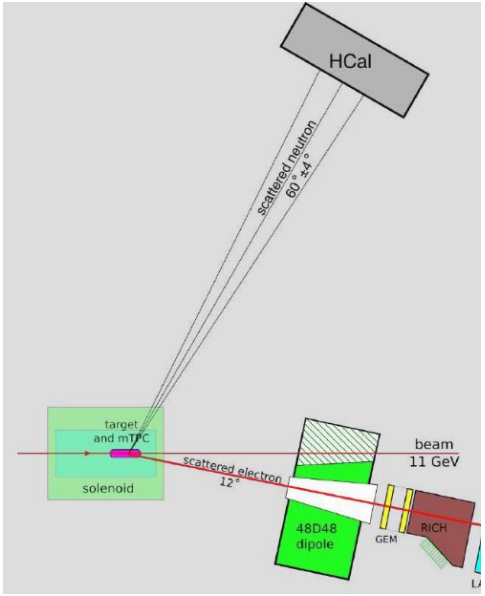


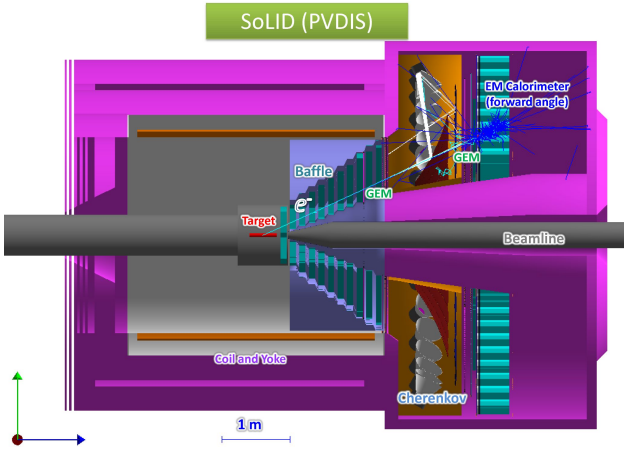
More discussions on model-dependence and isospin-dependence of nuclear effect, see E.P. Segarra et. al. arxiv: 2104.07130.

Future experiments

- Tagged DIS in Hall A with SBS (PAC 49 proposal):
  - BONuS-like tagging with additional neutron detector to check normalization
  - Higher luminosity, DIS with x up to 0.7,
  - Test offshell effects by varying spectator momentum



- PVDIS with SoLID in Hall A:
  - Clean measurement with no nuclear effects
  - Limited x range <0.7
  - Not scheduled



Summary

- d/u at large x is of great interest to the nuclear physics and particle physics community. Global QCD analysis didn't provide strong constraint at large x.
- Neutron structure functions can be extracted from deuteron data with a nuclear effect model. The offshell effect was assumed to be the same in n and p.
- JLab 12 GeV measurements are probing the large-x PDFs with various methods:
  - Hall C F2 experiments will provide more precise DIS and resonance region data at large x.
  - MARATHON is first high-x, high-statistics extraction that avoids nuclear effects in the deuteron
    - Much better precision in F2n/F2p, using KP model for nuclear effects
    - Lots of interest in using MARATHON data to test nuclear effects
  - BONuS12 data will give 2nd, independent extraction of F2n/F2p, allowing much cleaner comparisons
  - The TDIS-n measurements will provide another independent check of n/p with tagging. And eventually SoLID PVDIS measurement will (hopefully) give us a clean extraction of d/u

Thanks to

Simona Malace, Hanjie Liu, John Arrington, Alberto Accardi, Peter Monaghan, Wally Melnitchouk, Thia Keppel, Sebastian Kuhn

Parton Distribution Functions from Global Analysis

No "free" neutron target

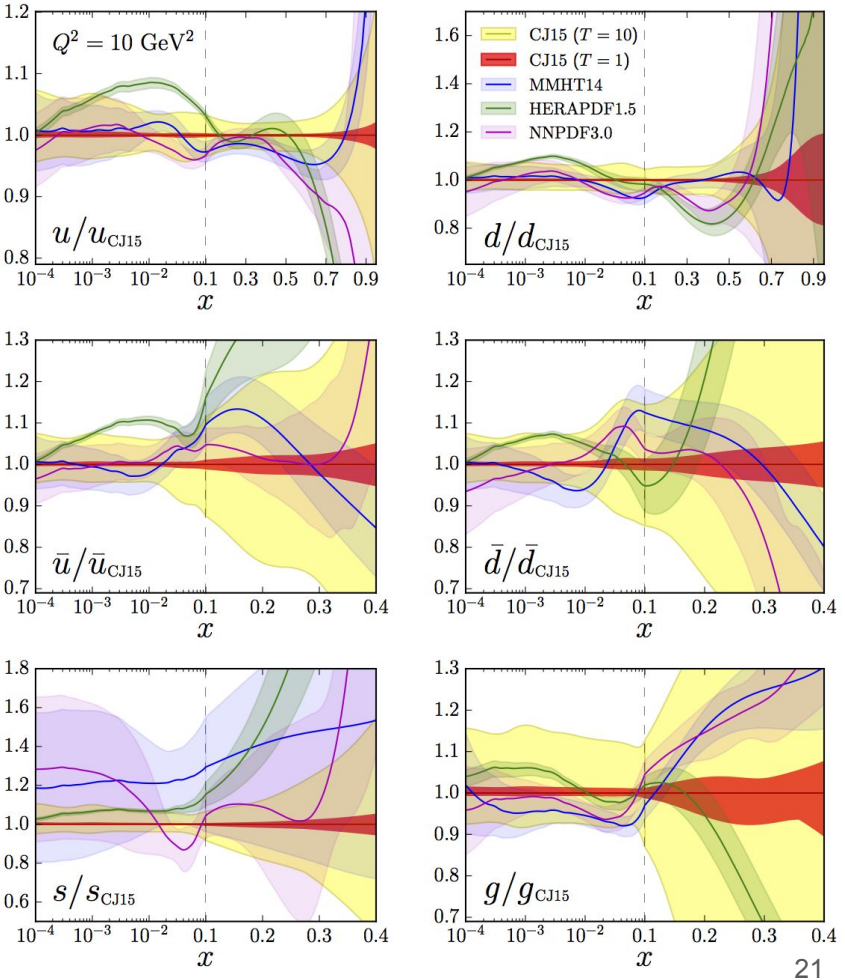
- Remove nuclear effect in deuteron, then subtract large proton contribution to get "free" neutron
- Deuteron wave function models

Finite Q2 (especially for JLab data)

- higher twist, target mass corrections important for low Q2, and large x data)

	JLab	HERMES	HERA	Tevatron W,Z	LHC, RHIC	nu+A, di-mu	nucl.&of fshell	HT, TMC	Flexible d	low-W DIS
CJ15	x	x	x	x	*		x	x	x	x
CT18			x	x	x				x	
MMHT14			*	x	x		x			
NNPDF3.1			x		x			TMC only		
ABMP16/AKP				x	x	x	x	x	x	x
HERAPDF 2.0			x							
JAM21	x		x	x	x		x	x	x	x

CJ15 PDFs



* see Shanghai CHP talk