14th International Conference on Nucleus-Nucleus Collisions

Whistler, British Columbia, Canada
August 18 – 23, 2024

Nucleon Structure Functions at Large-x

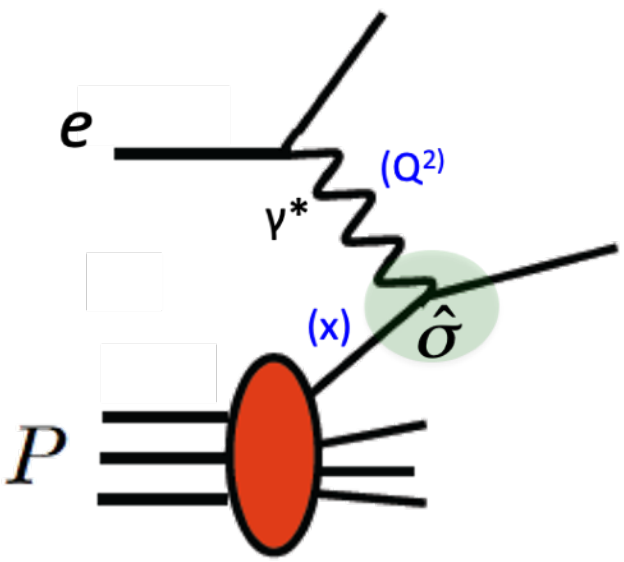
Sanghwa Park
Jefferson Lab

Nucleon Structure

- Partonic structure of hadrons
- Nucleon structure is encoded in parton distribution functions
- Various experimental tools: **lepton-nucleus scattering**, hadron collisions, e-e interactions
- This talk will focus on the recent results on structure functions from e-N DIS using unpolarized targets and collinear parton distributions
- Spin structure of nucleon (not covered in this talk), see the talk by O. Eyser on Tuesday

Deep Inelastic e-N Scattering

- DIS experiments have been successful mapping out the momentum distributions of quarks and gluons



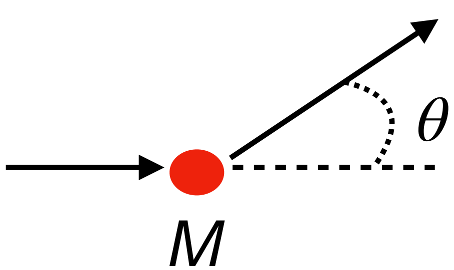
Q^2: squared momentum transfer to the lepton. Measure of resolution

x: Momentum fraction of the struck parton in a proton

$$\sigma_{DIS} \propto \sum f(x, Q^2) \otimes \hat{\sigma}$$

Determined from measurements

Can be calculated from perturbative QCD (pQCD)



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

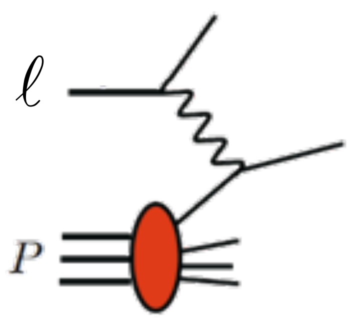
Information of internal structure of target nucleon

Directly link to parton distribution functions (PDFs)

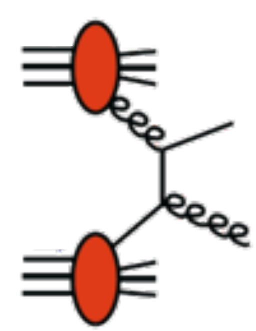
Parton Distribution Functions (PDFs)

$f(x, Q^2)$: Number density to find a parton carrying a momentum fraction of x

- **In the Parton model, PDFs contain information about the structure of the nucleon**
- Extracted from a global analysis of various experimental data
- **Universality of the PDFs:** Predictive power of QCD



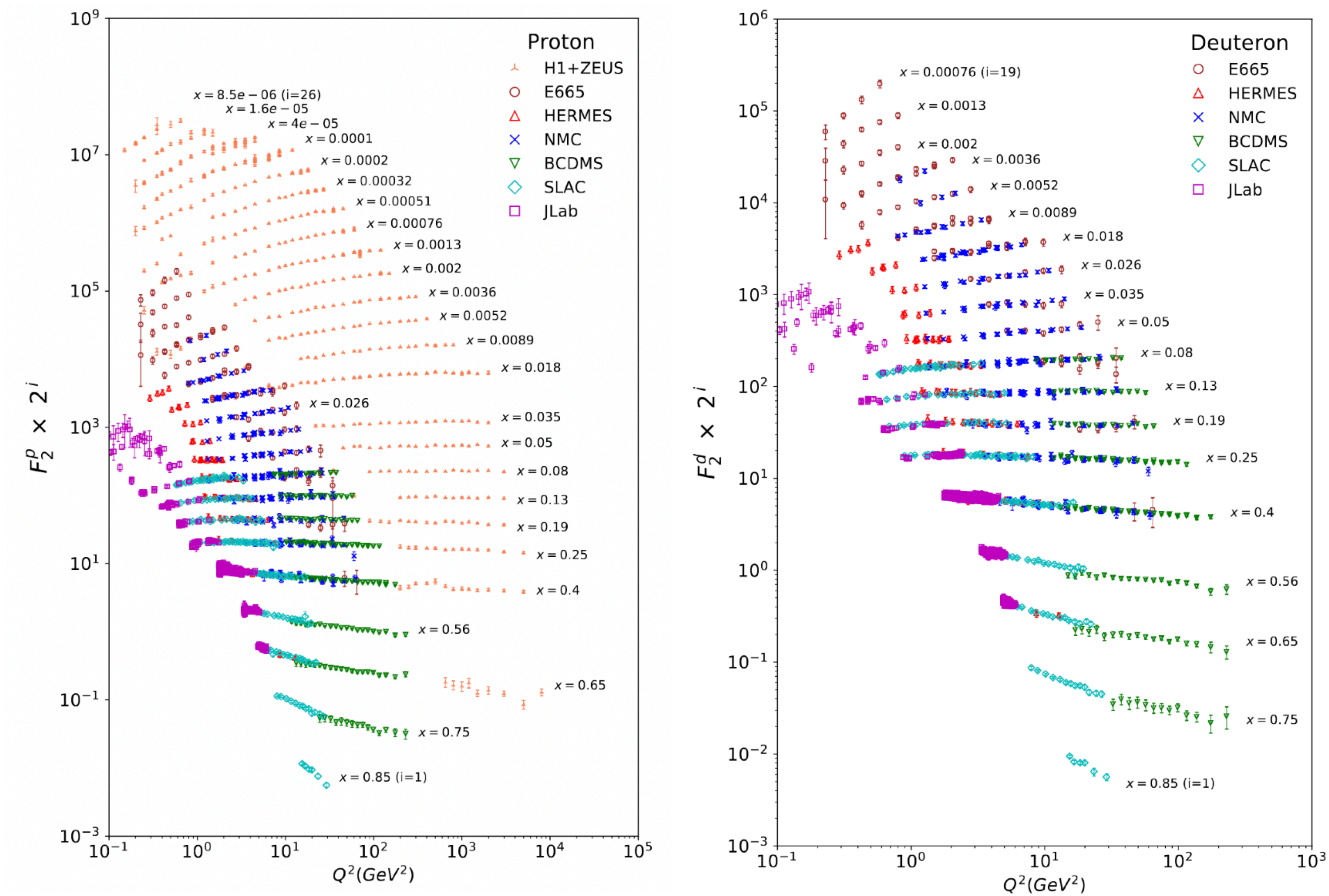
Use PDFs from DIS to predict the cross section in hardon collisions



$\sim \sum f(x,Q^2)\otimes\hat{\sigma}$

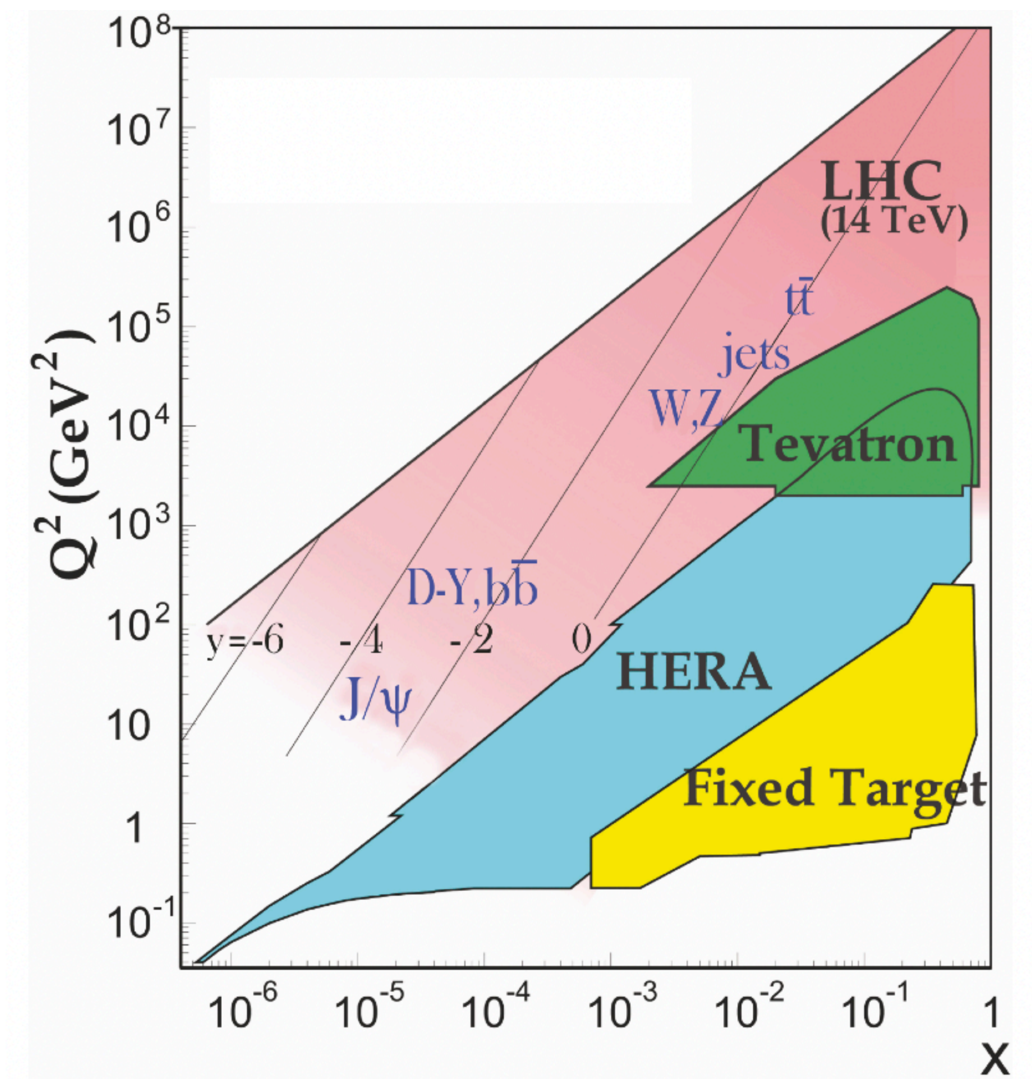
$\sim \sum f_a(x,Q^2)\otimes f_b(x,Q^2)\otimes\hat{\sigma}\otimes\ldots$

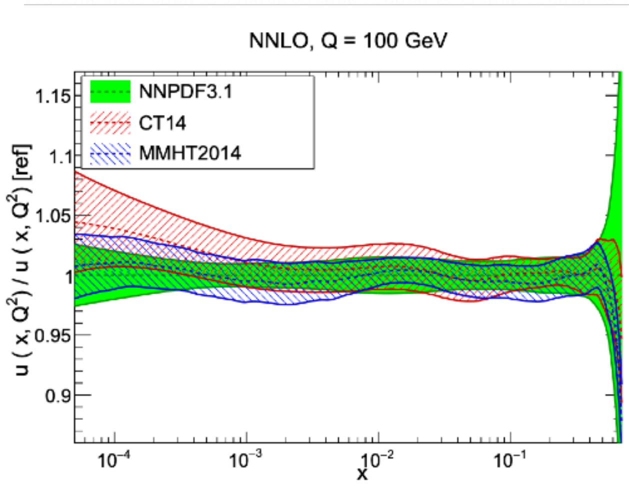
F_2 Structure Functions

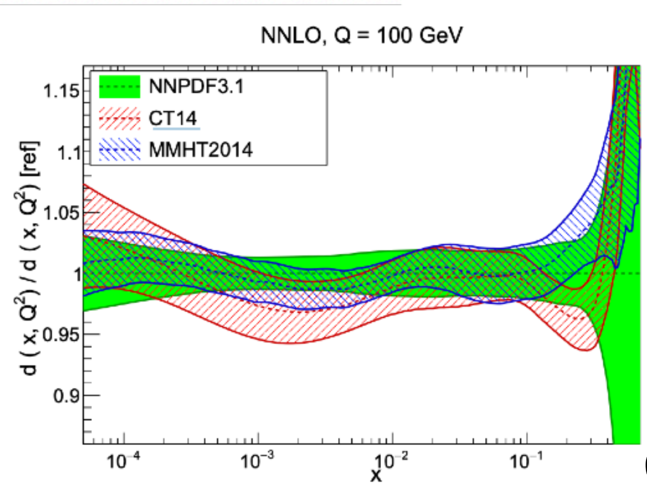


[R.L. Workman *et al.* (PDG), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)]

Nucleon structure at large-x, low Q^2



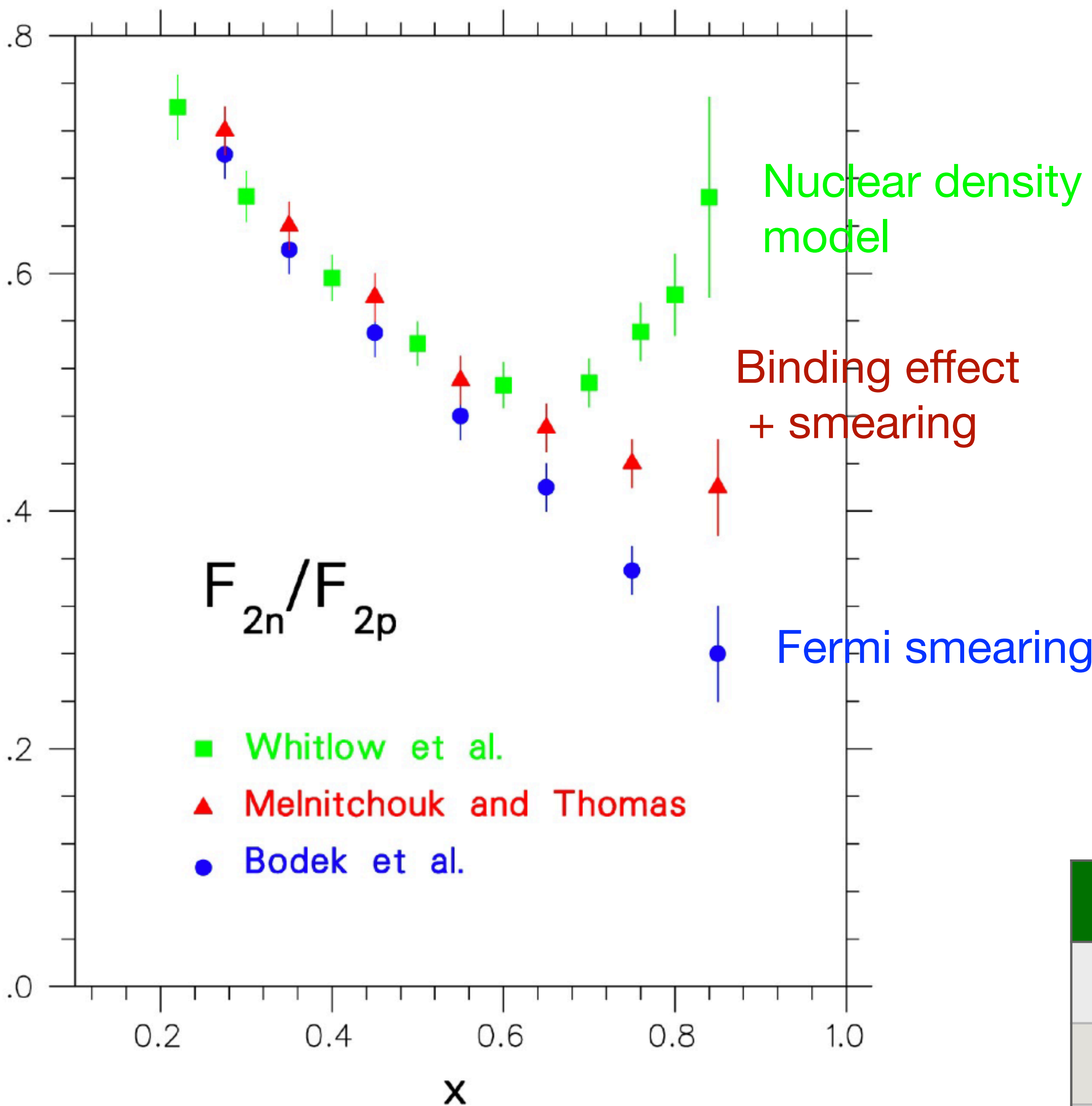




- Fixed-target experiments
- Valence structure of hadron
  - Partonic structure in the valence region defines a hadron
- F2n/F2p ratio (d/u ratio) at x-> 1 limit unknown
  - Predictions from different theory models
- Provide important input for PDF analysis at large-x,
  Improve constraints on PDFs at large x, low Q2

-> (evolution) low x, high Q2

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 theory models

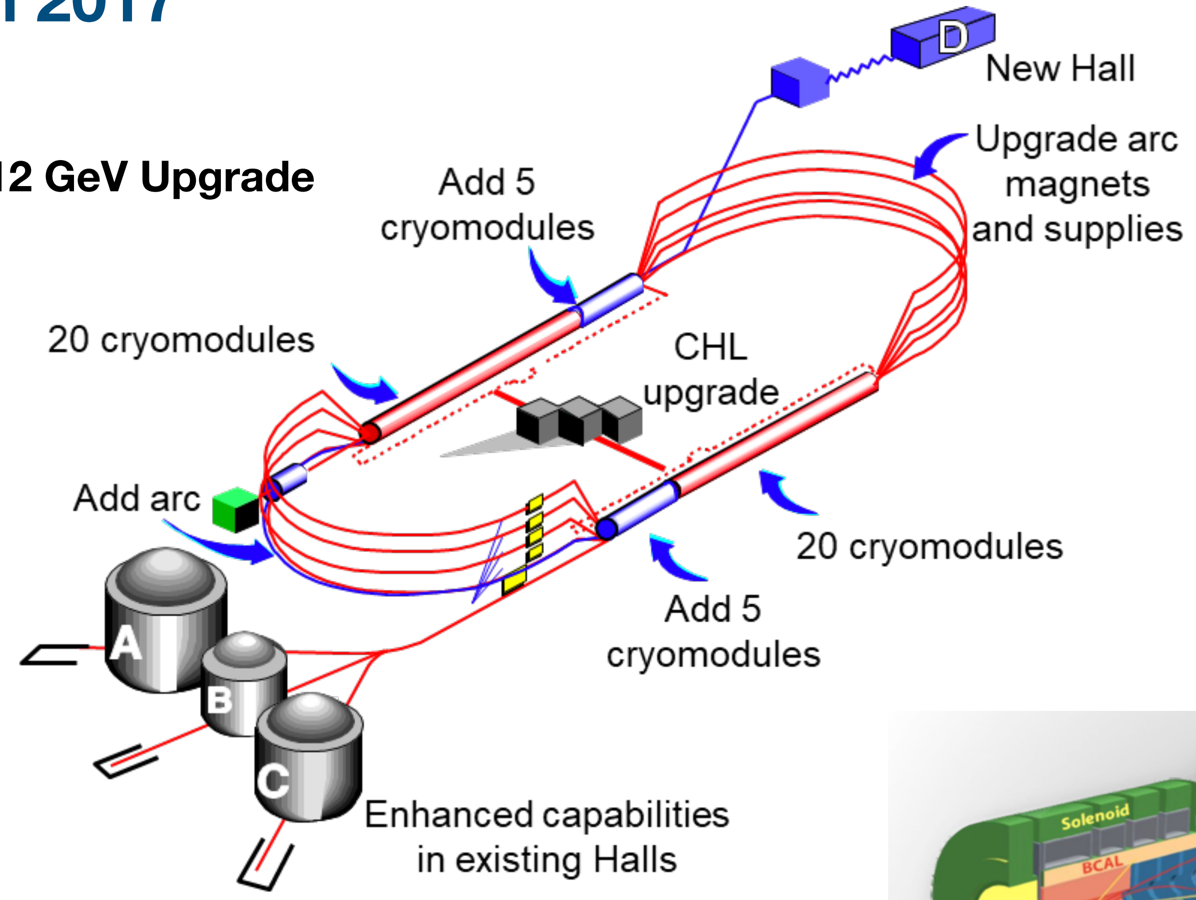
	$F_2(n/p)$	d/u
SU(6)	2/3	1/2
Diquark model/Feynman	1/4	0
Quark model/Isgur	1/4	0
pQCD	3/7	1/5
QCD counting rules	3/7	1/5

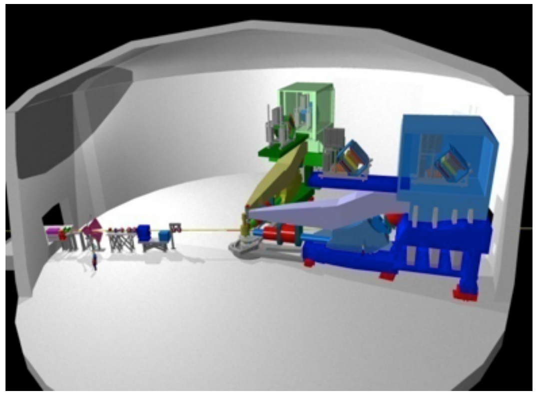
The case of Neutron

- No free neutron target exists
- Deuteron is a weakly bound system - chosen as effective neutron target
- $F_2(d) \neq F_2(n) + F_2(p)$
  - Large theory uncertainty from nuclear effects
  - Significant model dependence on deuteron wave function, off-shell corrections, ..
- Different approaches to extract the F_2 ratio:
  - Model-dependent extraction from deuteron with precision data
  - Less model-dependence measurements:
    - 3H/3He DIS
    - Spectator tagging
  - Model-independent approach using parity-violating DIS (PVDIS)

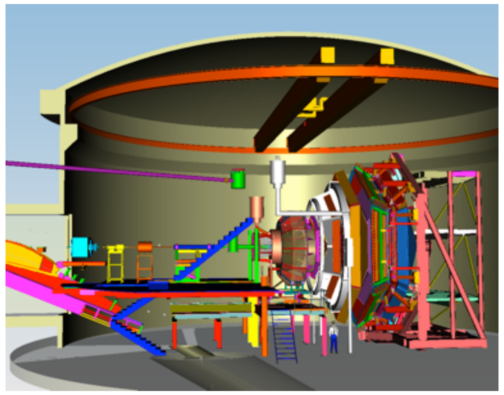
CEBAF at Jefferson Lab

Successfully completed 12 GeV upgrade in 2017

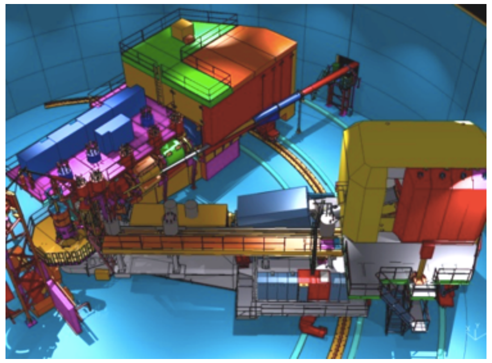




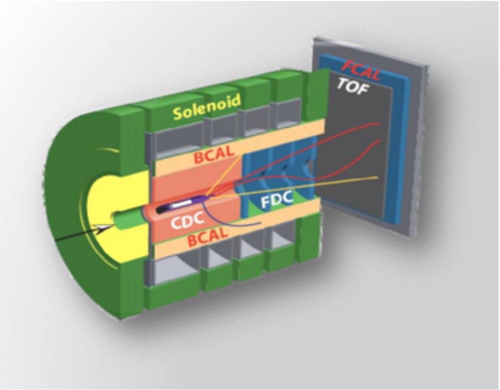
Hall A: SRC, form factors, future new experiments (MOLLER, SoLID)



Hall B: understanding nucleon structure (GPDs and TMDs) CLAS12



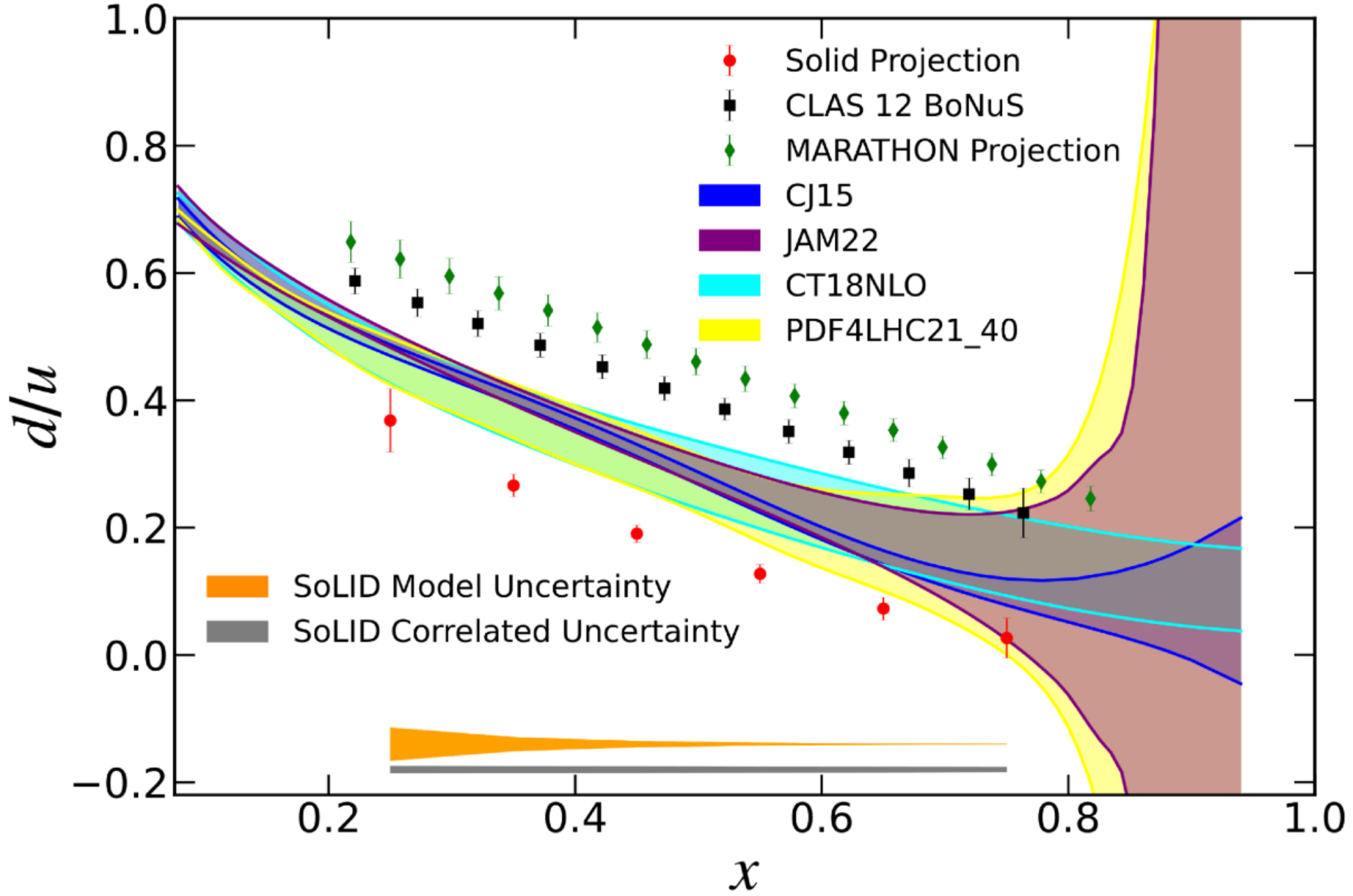
Hall C: precision determination of valence quark properties of nucleons and nuclei



Hall D: exploring origin of confinement by studying exotic mesons

Constraints on d/u from JLab 12GeV

J. Phys. G: Nucl. Part. Phys., 50:110501, 2023

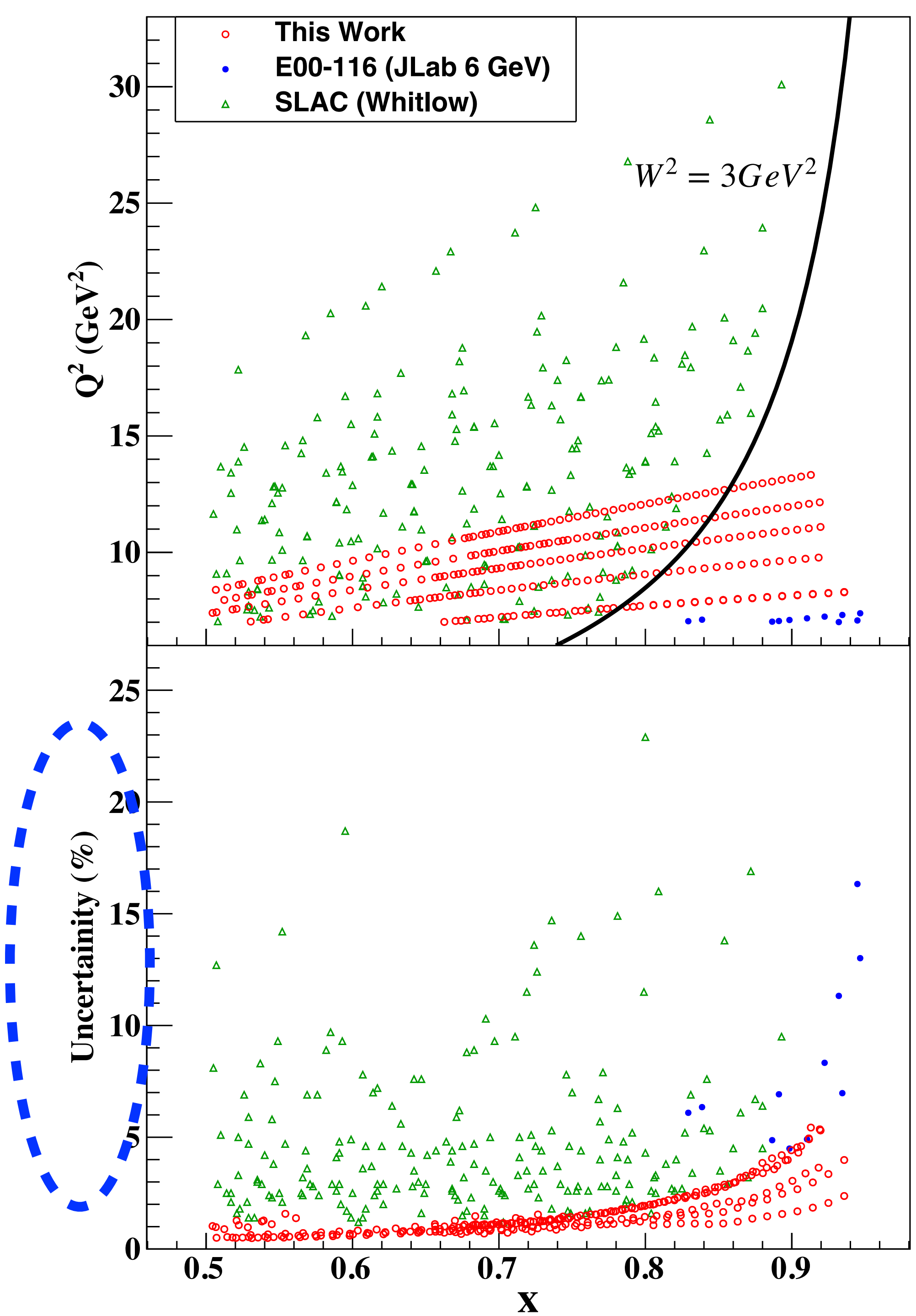


- Model dependent approach: Traditional Inclusive Measurements with deuterium

- Less model dependent approaches:
  3H/3He ratio (MARATHON) - results published (Phys.Rev.Lett. 128 (2022) 13, 132003)
  Spectator tagging (BoNus) - new data taken in 2020

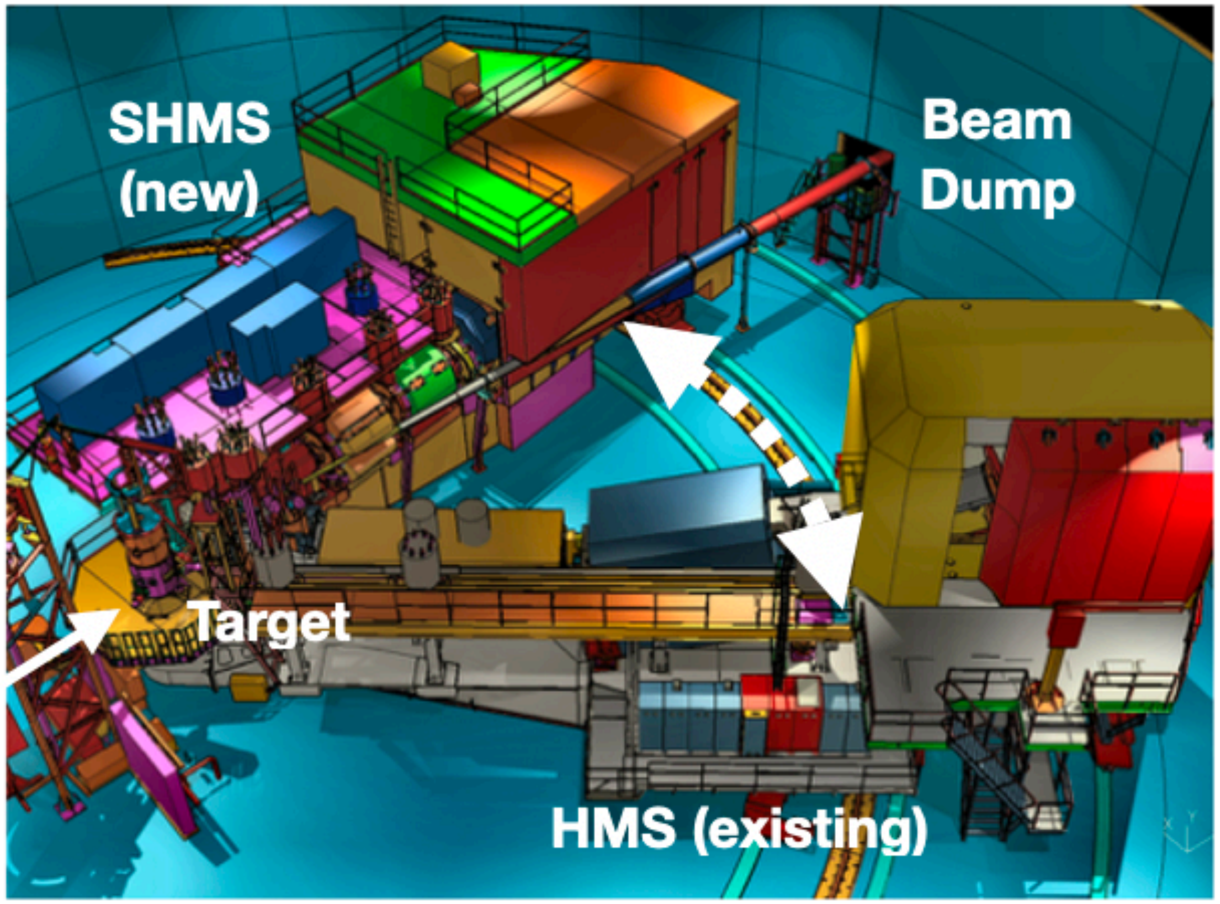
- Model independent approach: **Future PVDIS on proton (SoLID)**

Precision data with deuteron target



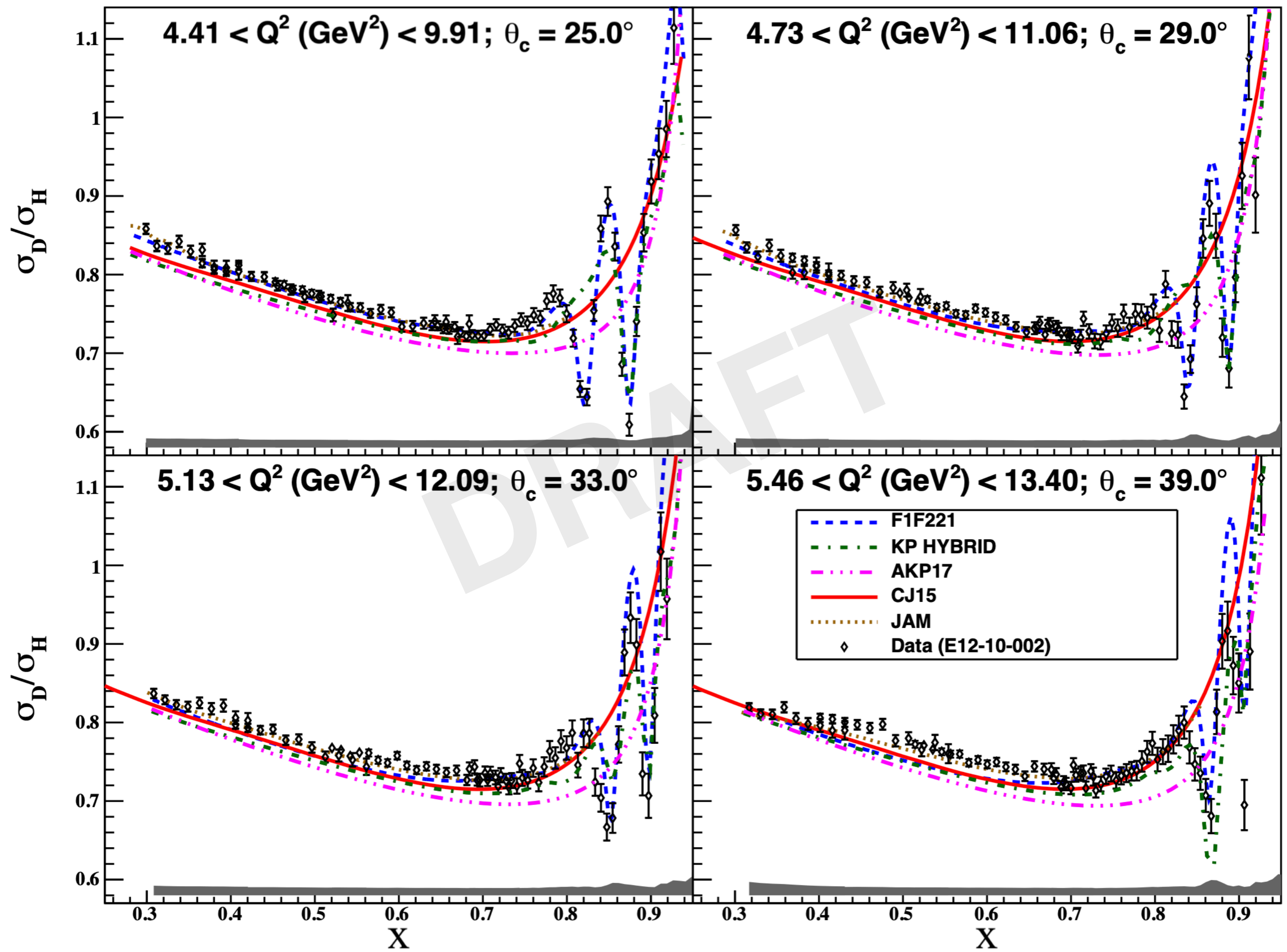
- JLab 12GeV extends Q^2 coverage with high precision
- Precise inclusive H(e,e') and D(e,e') measurements using LH2 and LD2 targets
- Took data 2018 at Hall C
- Publication of the final results in preparation

Hall C High Momentum Spectrometers

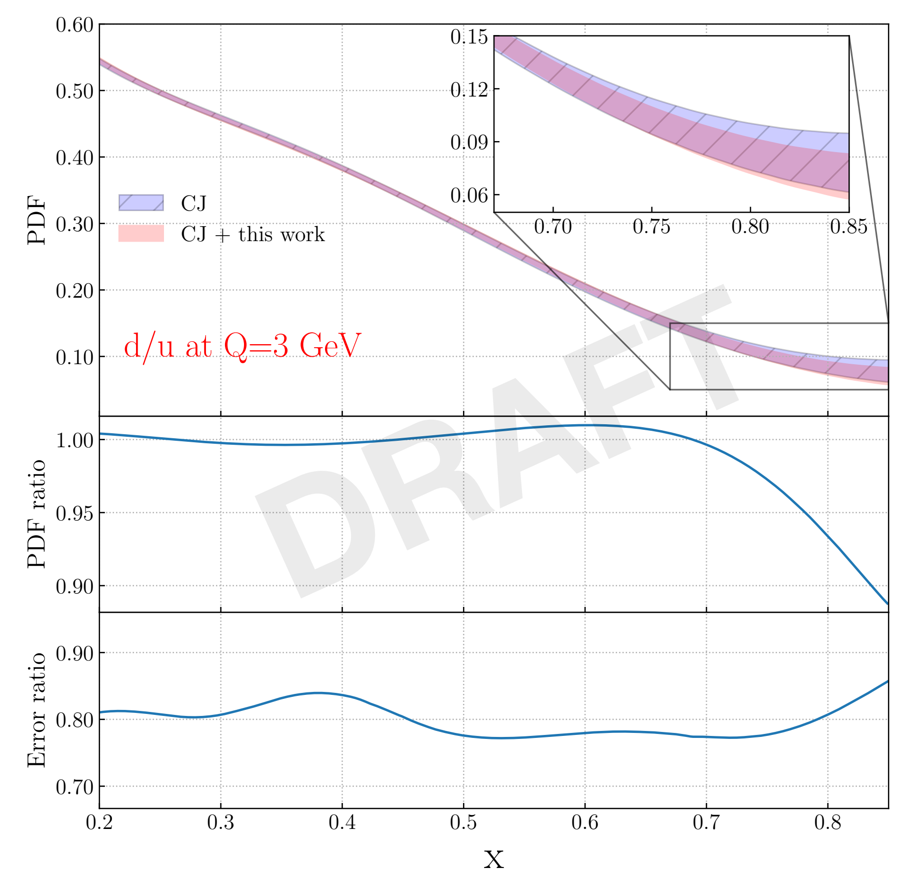


Precision data with deuteron target

- New precision data for $3.4 < Q^2 < 13.4$ GeV^2, $0.3 < x < 0.93$
- **Will provide significant constraints on large-x PDFs combined with the other 12 GeV JLab data (MARATHON, BoNUS)**

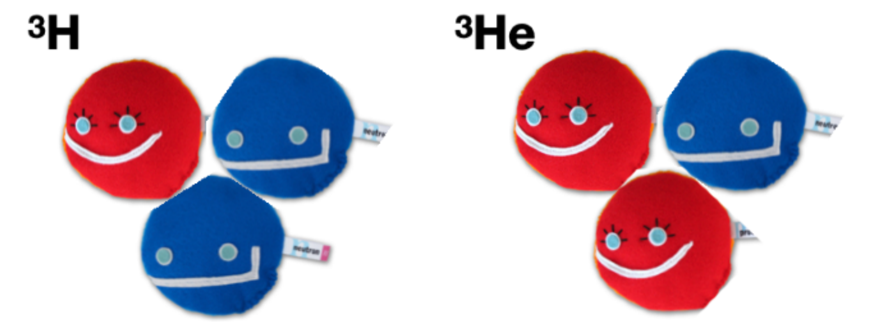


- CJ impact studies
  - $W^2 > 3.5$
  - ~20% uncertainty reduction in d/u



3H/3He DIS

- A=3 mirror nuclei: nuclear corrections expected be similar
- Form EMC type ratios:



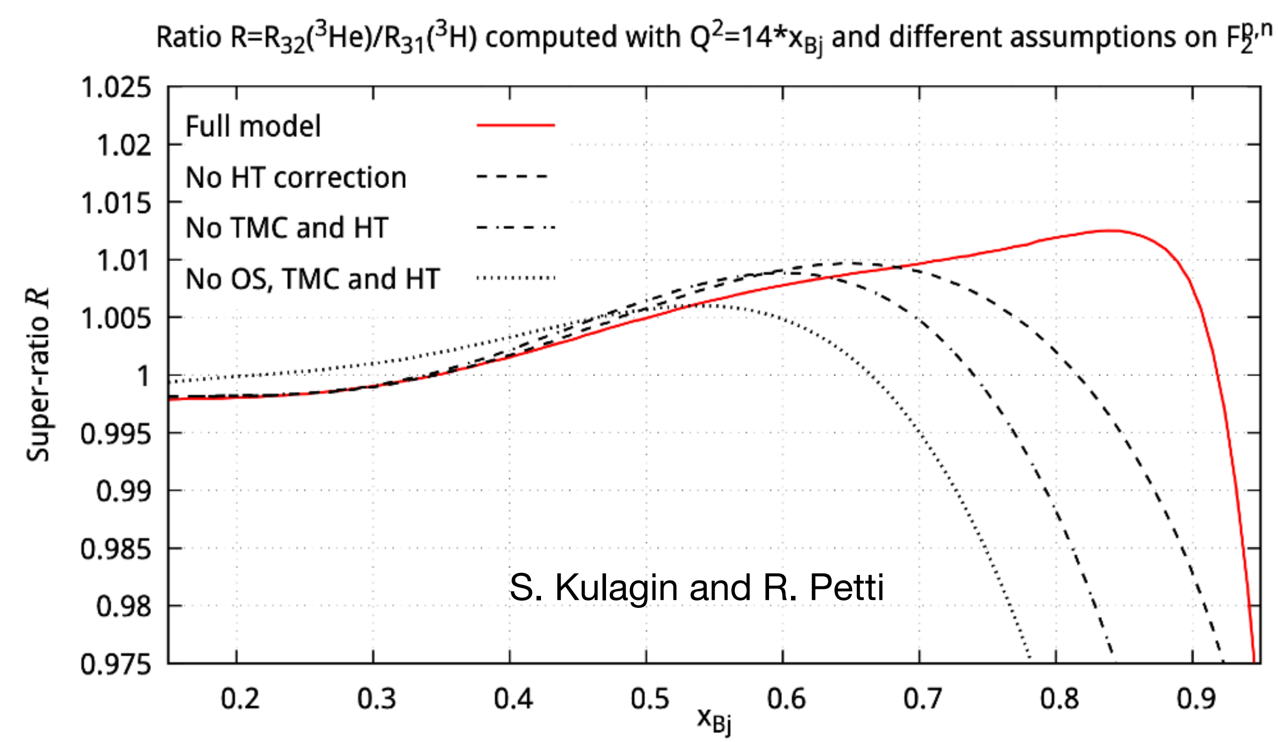
$$R(^3He) = \frac{F_2^{^3He}}{2F_2^p + F_2^n} \qquad R(^3H) = \frac{F_2^{^3H}}{F_2^p + 2F_2^n}$$

Form a super ratio $$R^* = \frac{R(^3He)}{R(^3H)}$$

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

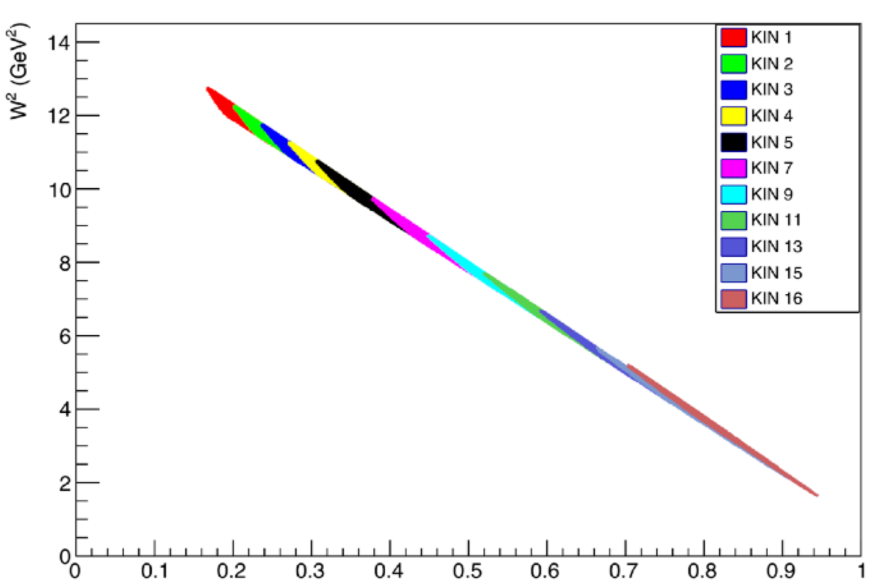
Now relies on the relative difference in nuclear effects in 3He, 3H

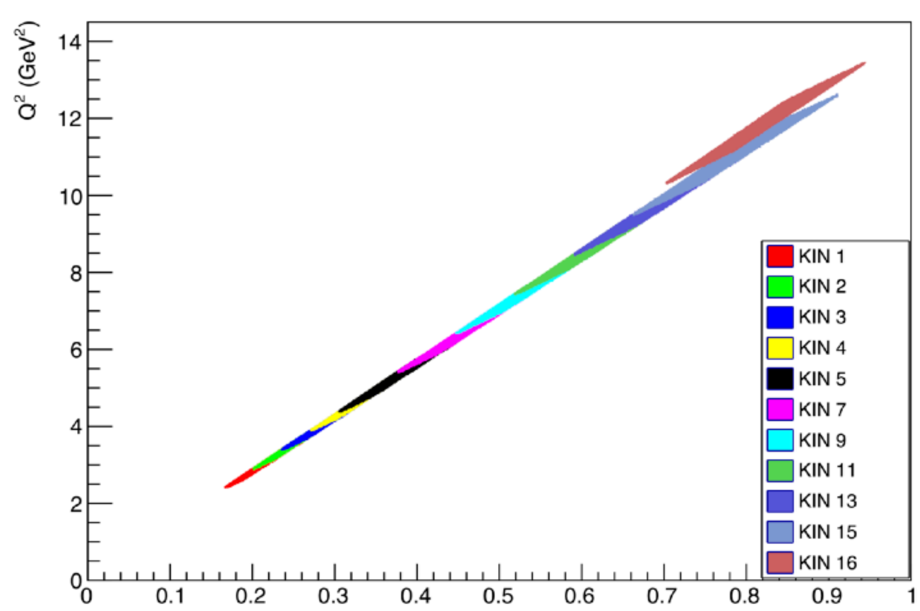
Differences small R*≈1, calculated to within 1%



MARATHON experiment @ Hall A

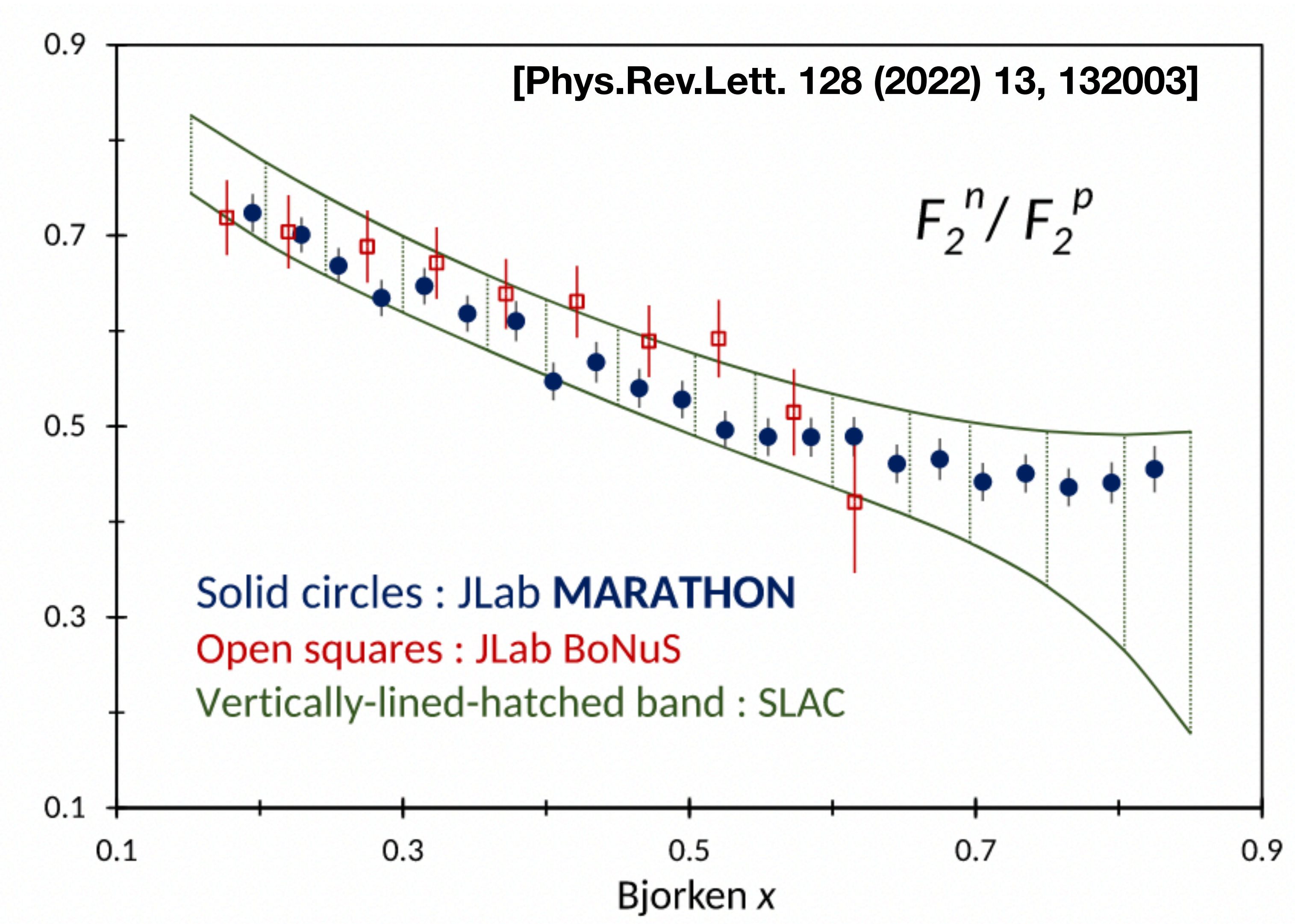
- 10.6 GeV beam, fixed scattered electron momentum (3.1 and 2.9 GeV), scattering angle 17-36 deg
- 3H, 3He, 2H, 1H targets
- Also measured EMC effects in 3He and 3H (first experimental data) and others





3H/3He DIS

- Final results published [Phys.Rev.Lett. 128 (2022) 13, 132003]
- KP model is used to extract the $F_2(n)/F_2(p)$ ratio



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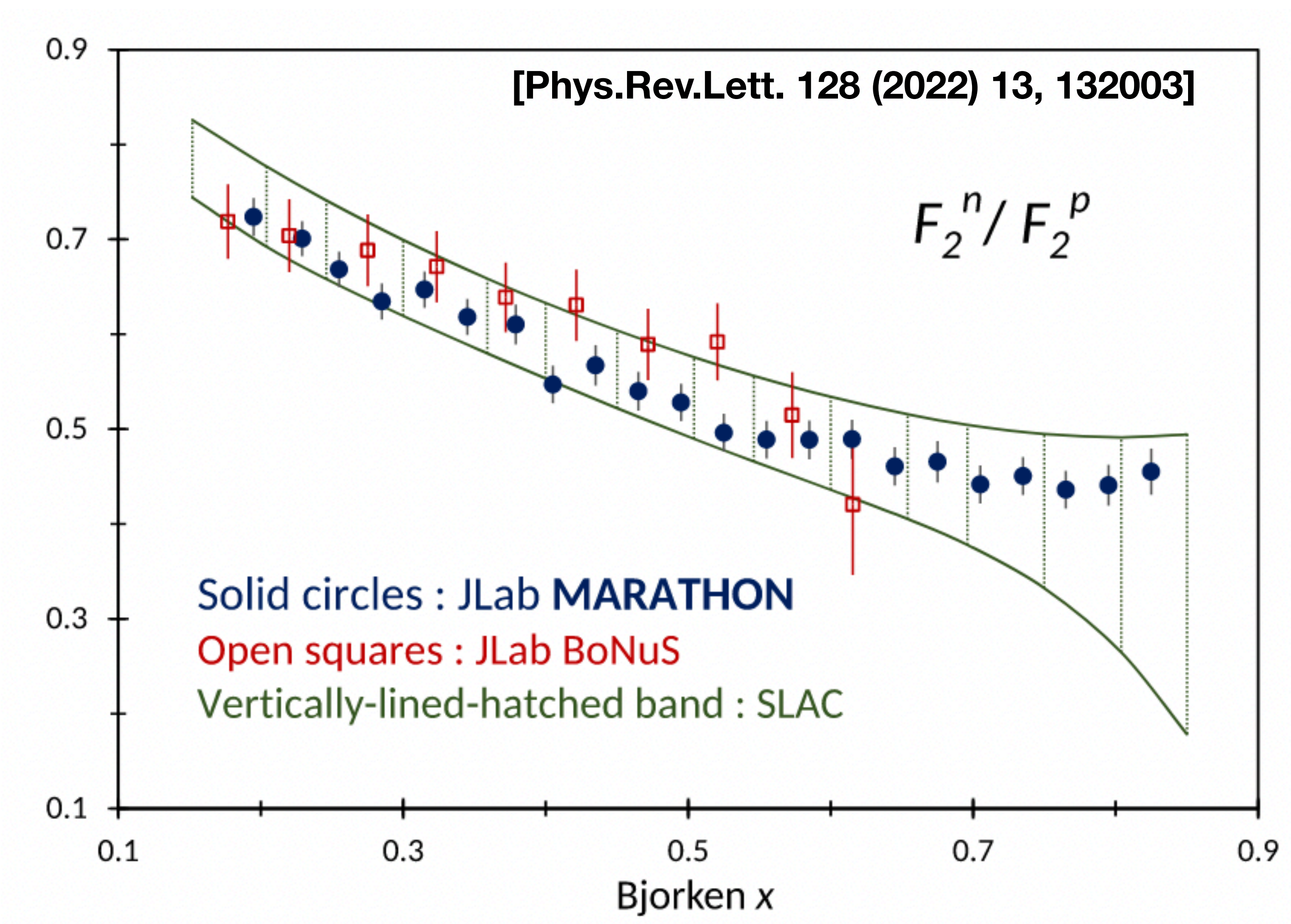
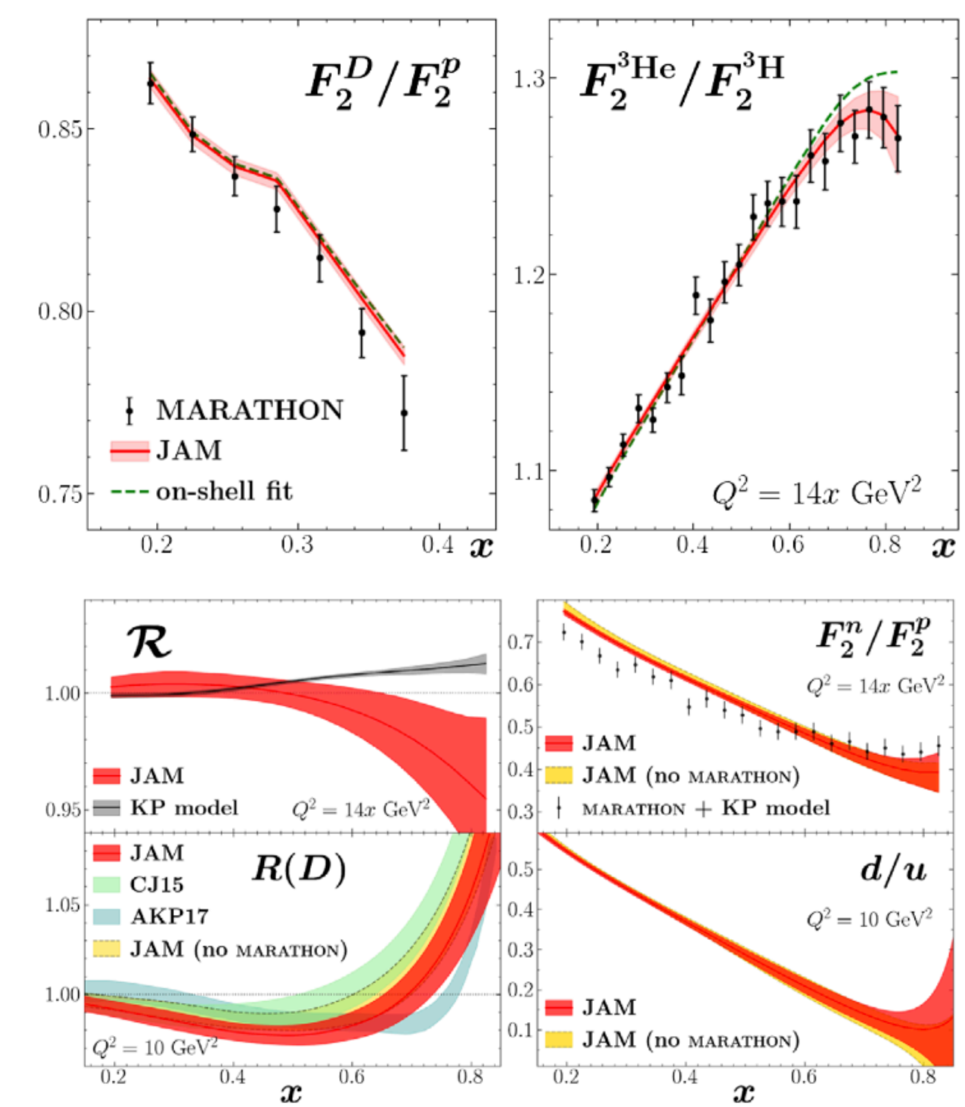
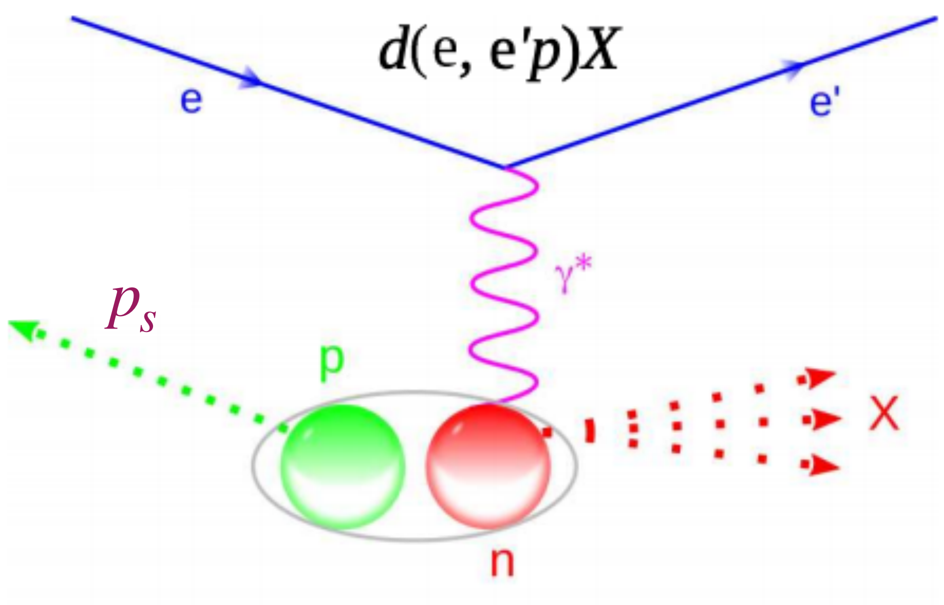




- Included in the global QCD analysis:
  - JAM analysis [Phys. Rev. Lett. 127, 242001]

Spectator tagging



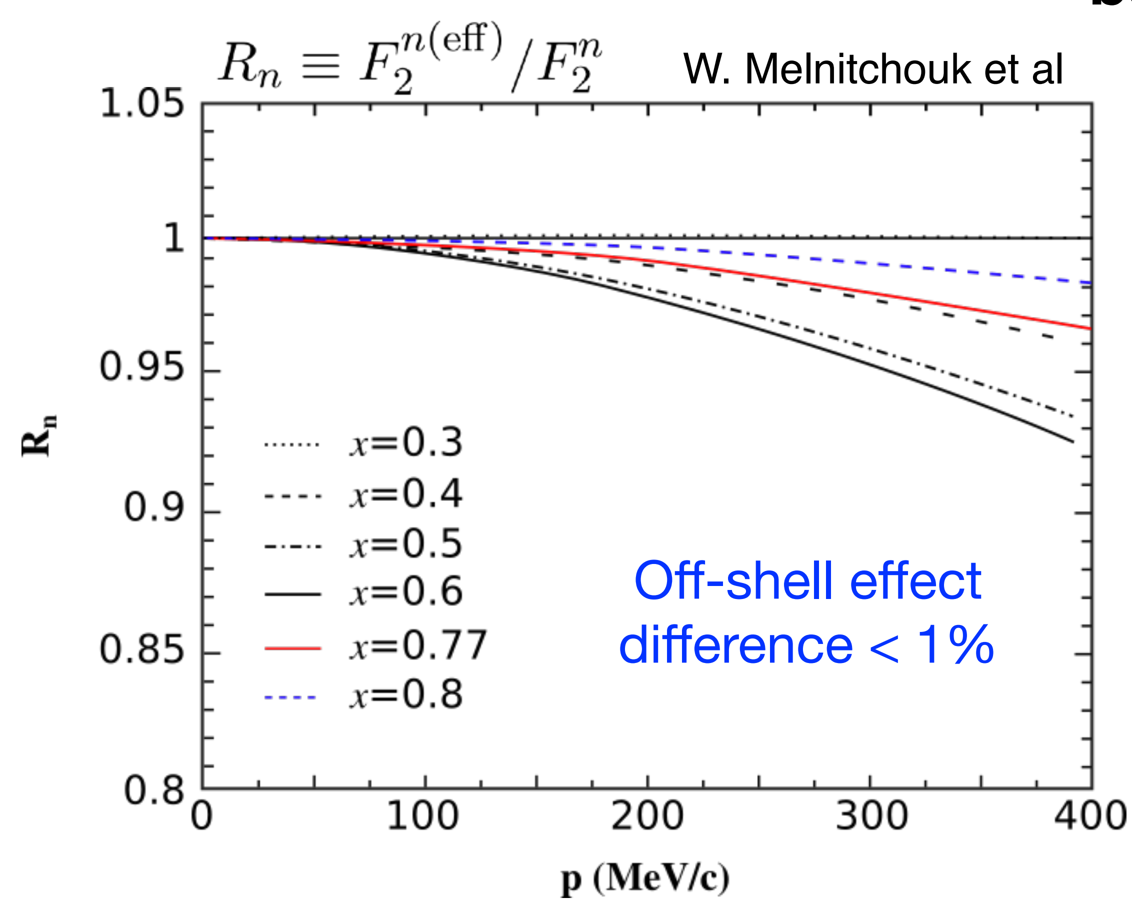
Tagging spectator protons in coincidence with the scattered electrons

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

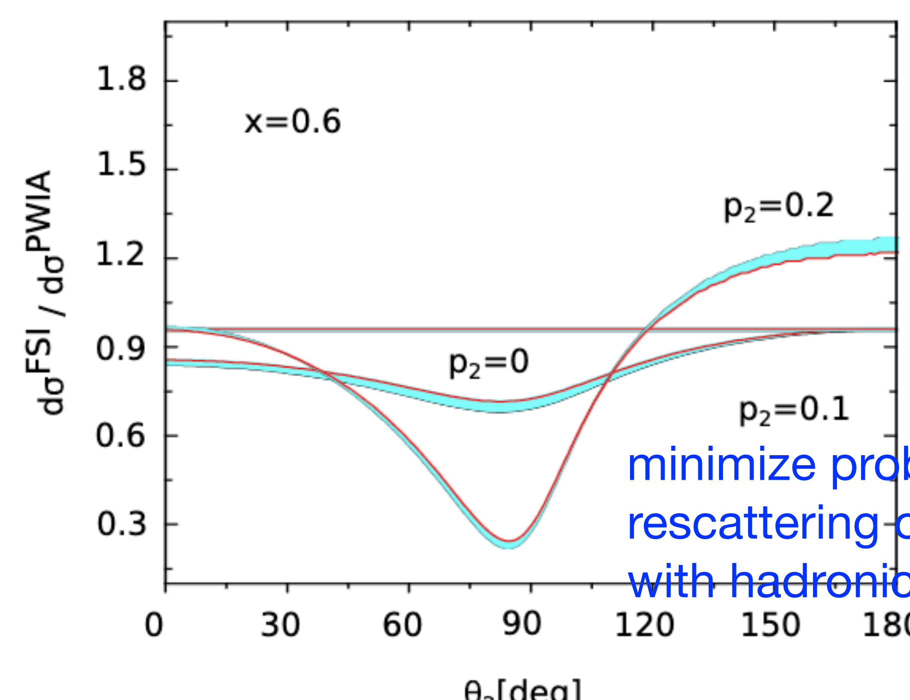
Proton with very low momentum in the backward hemisphere

$$p_s \leq 100MeV$$

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



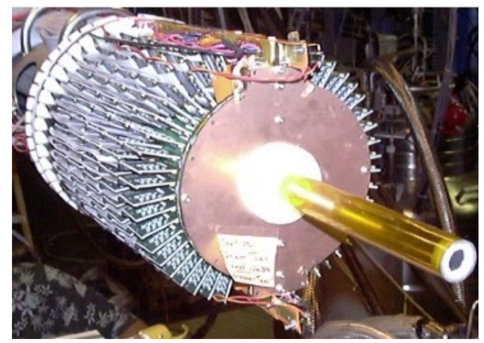
Off-shell effect difference < 1%



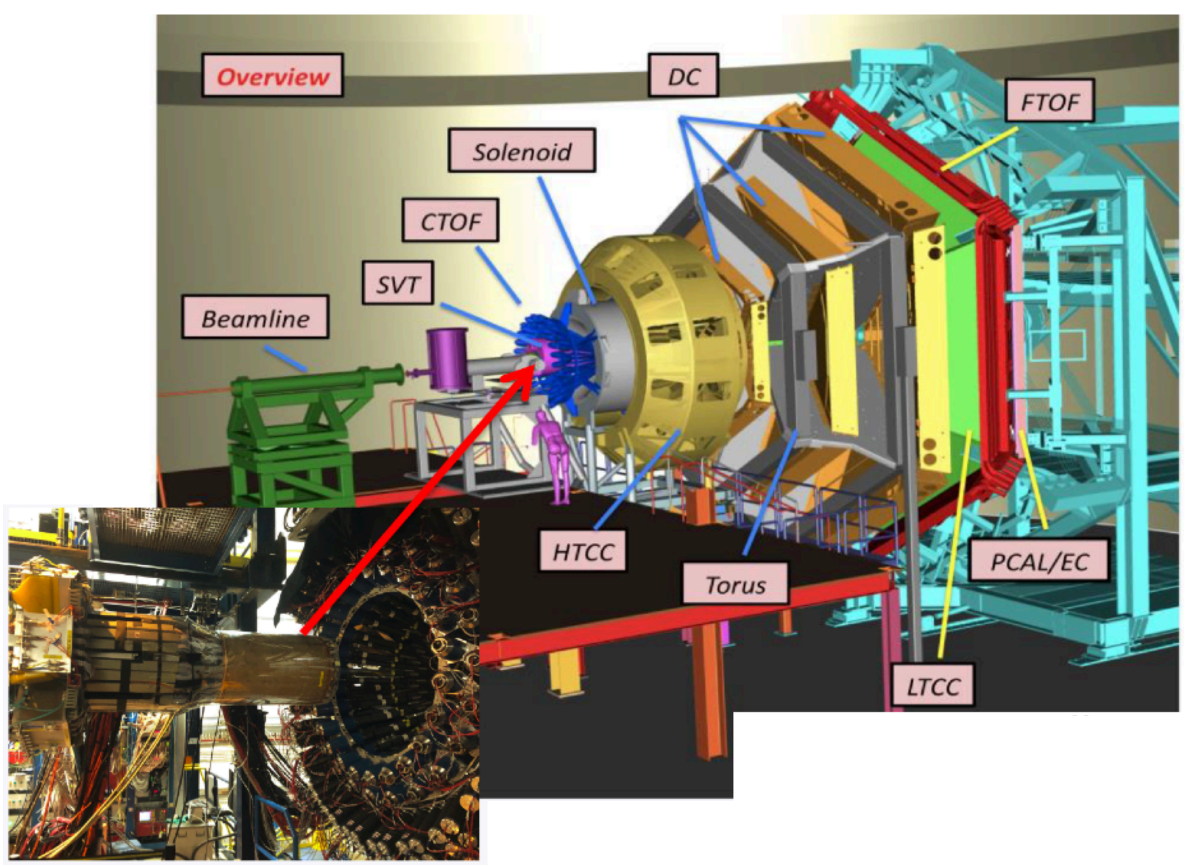
minimize probability of rescattering of spectator proton with hadronic debris

BoNuS experiment at Hall B

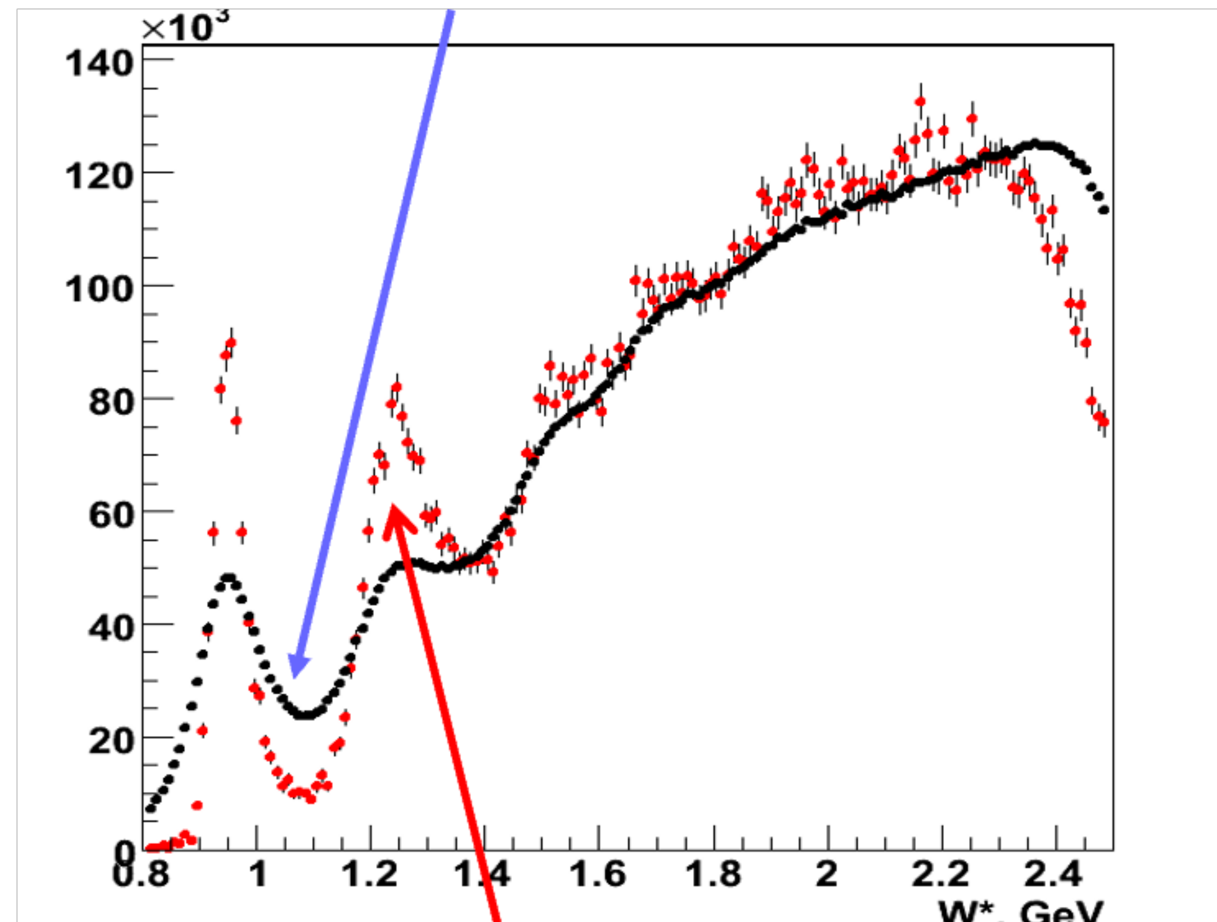
- Radial TPC detector to tag spectator proton



- New data taken with CLAS12



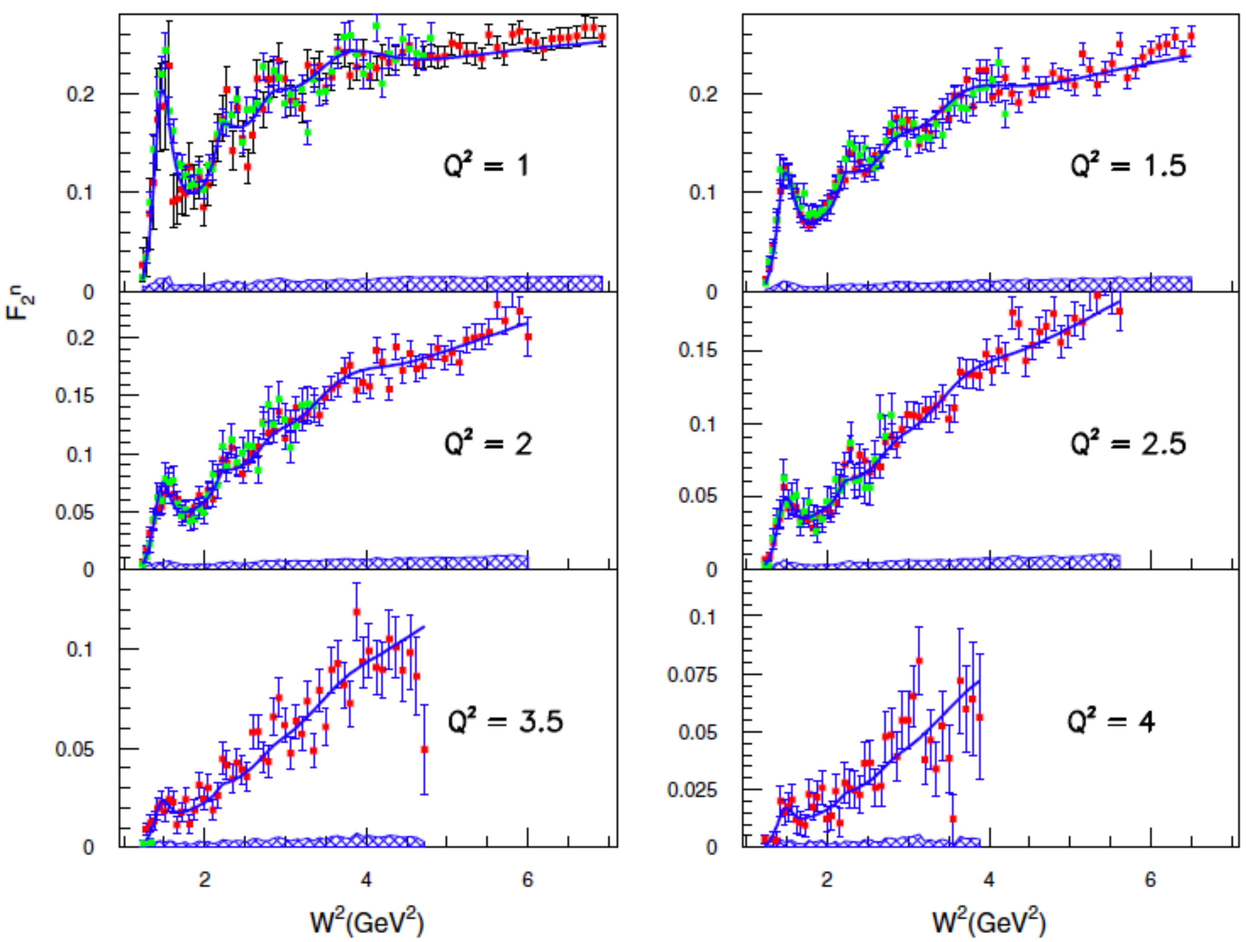
$$W^2 = M^2 + 2M\nu - Q^2$$

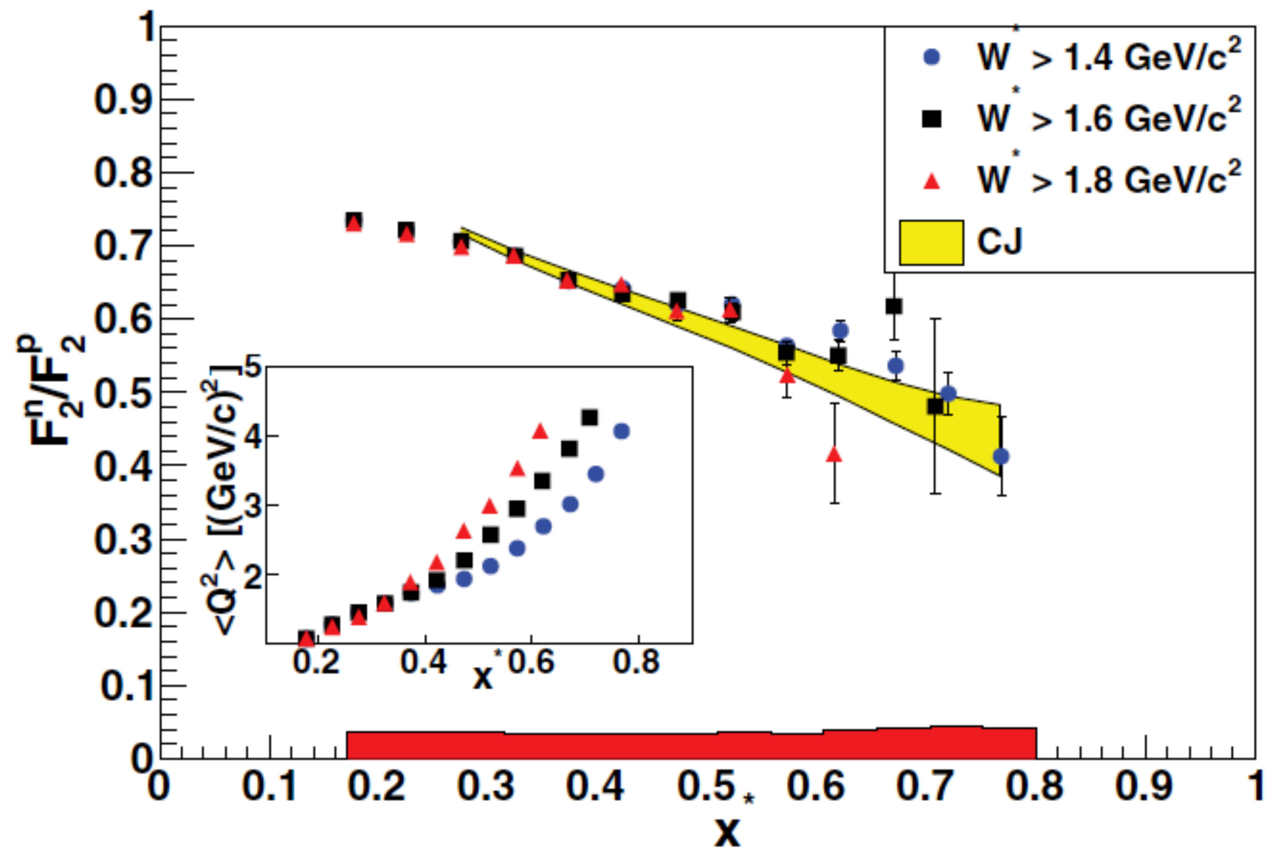


$$W^{*2} = (p_n + q)^2 = p_n^{\mu} p_{n\mu} + 2\left((M_D - E_s)\nu - \vec{p}_n \cdot \vec{q}\right) - Q^2$$
$$\approx M^{*2} + 2M\nu(2 - \alpha_S) - Q^2$$

BoNus 6GeV results

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





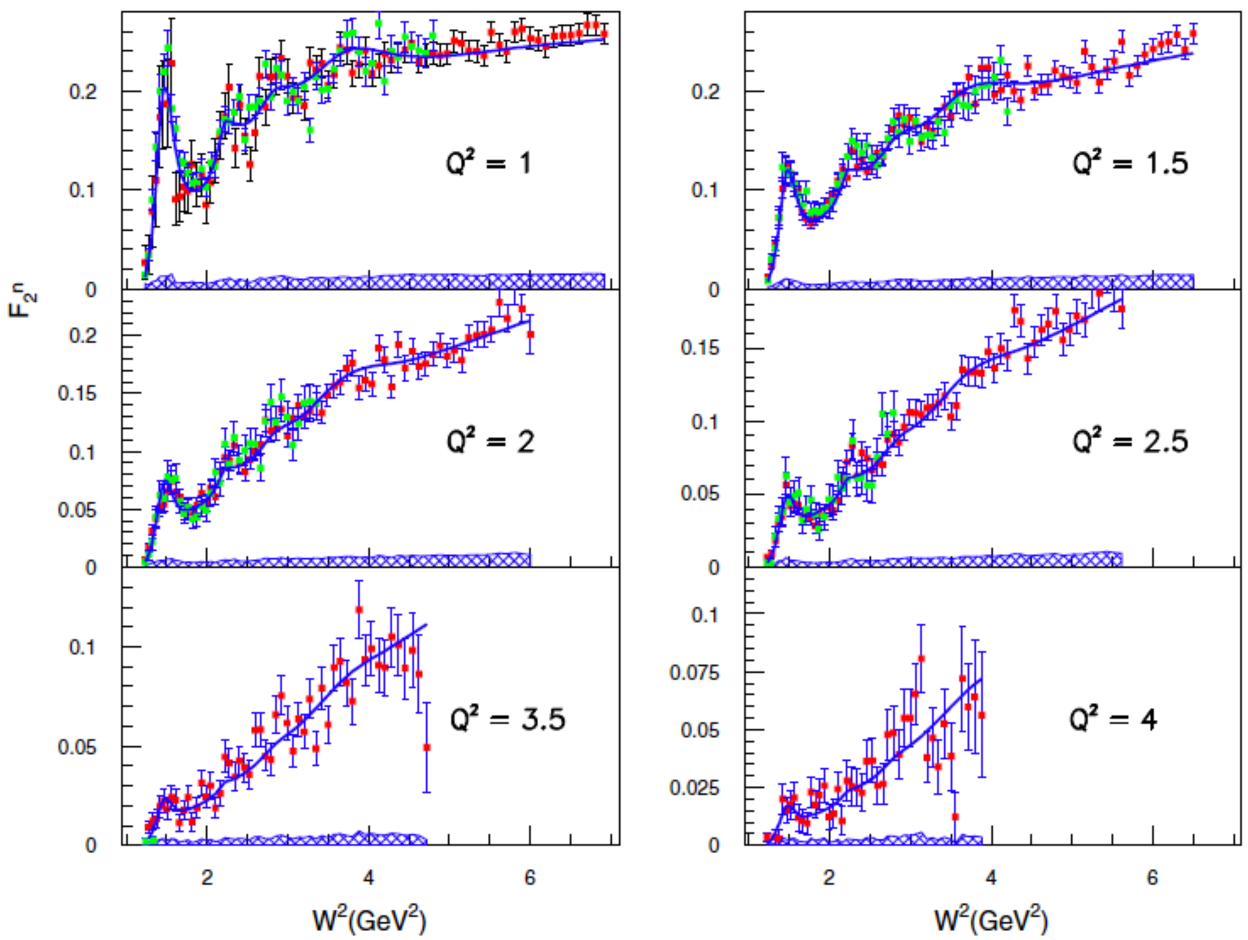
Successor experiment BoNus12 took data in 2020

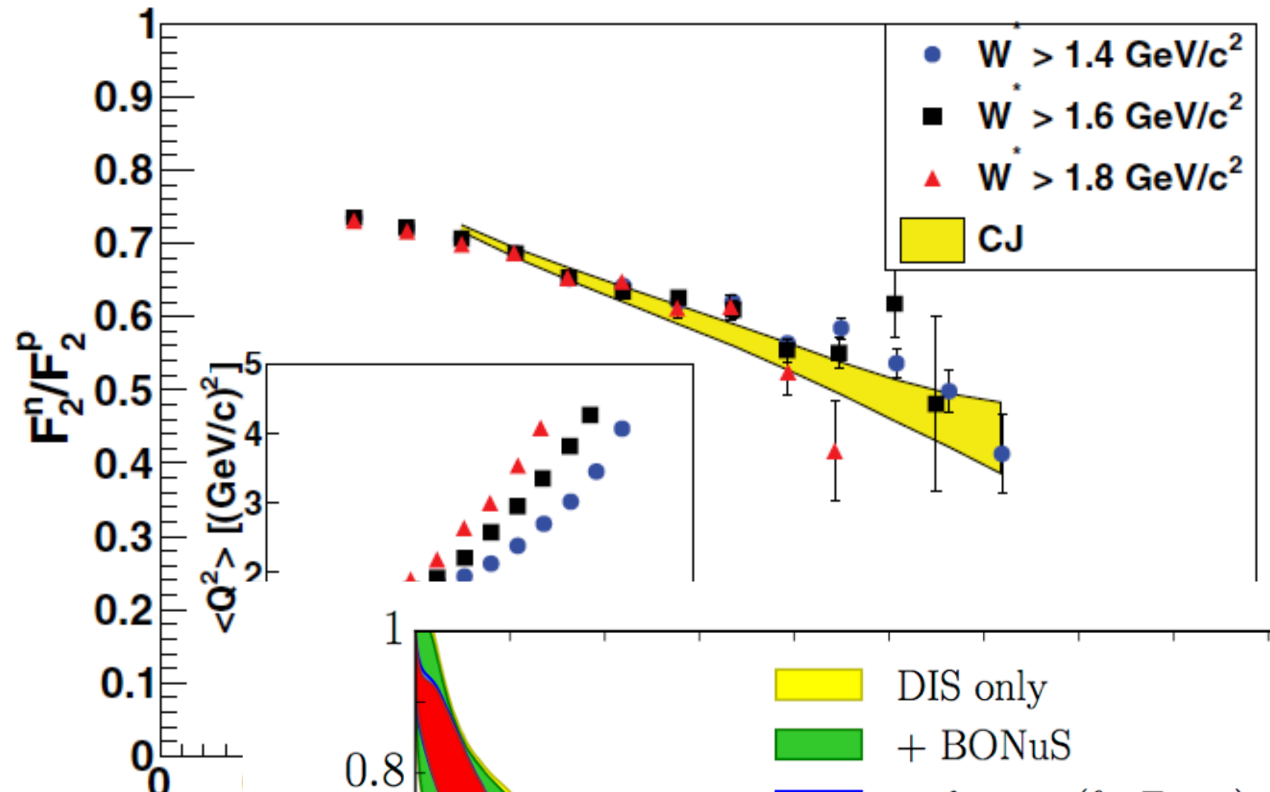
Extends kinematic coverage:

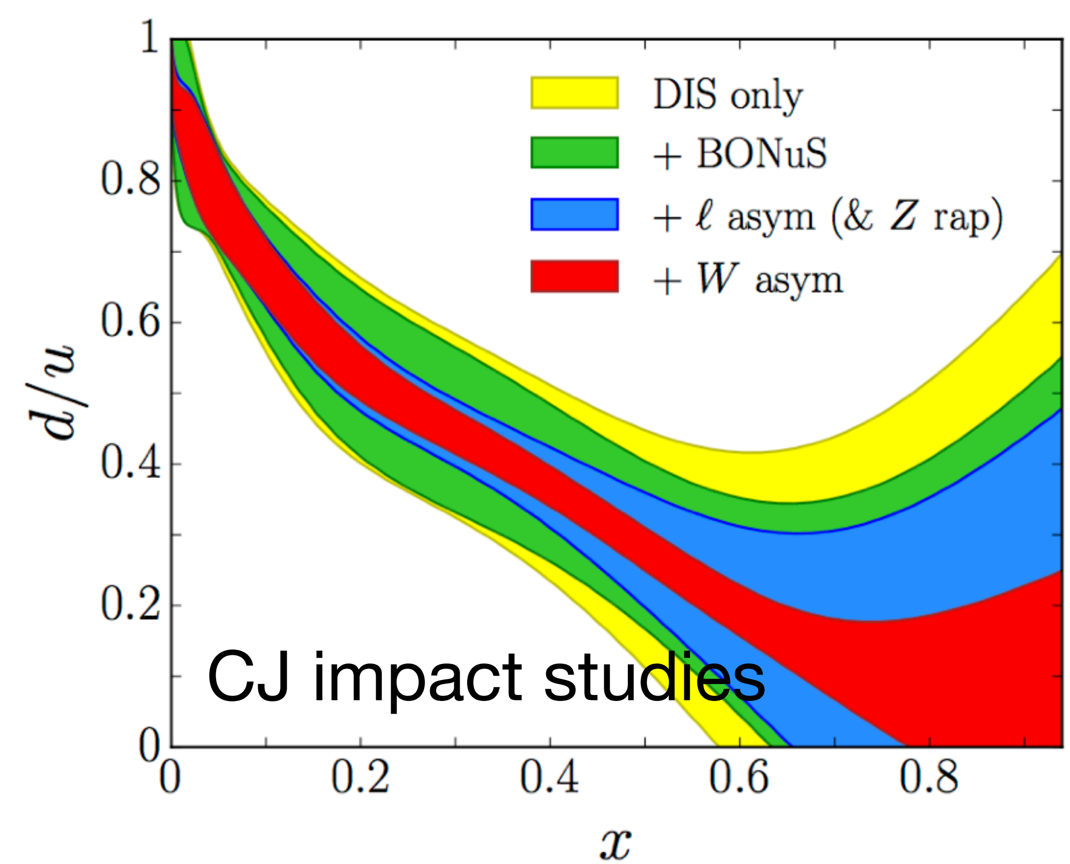
$0.1 < x < 0.8$, Q^2 of 1-14 GeV^2, W up to 4GeV

BoNus 6GeV results

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







Successor experiment BoNus12 took data in 202

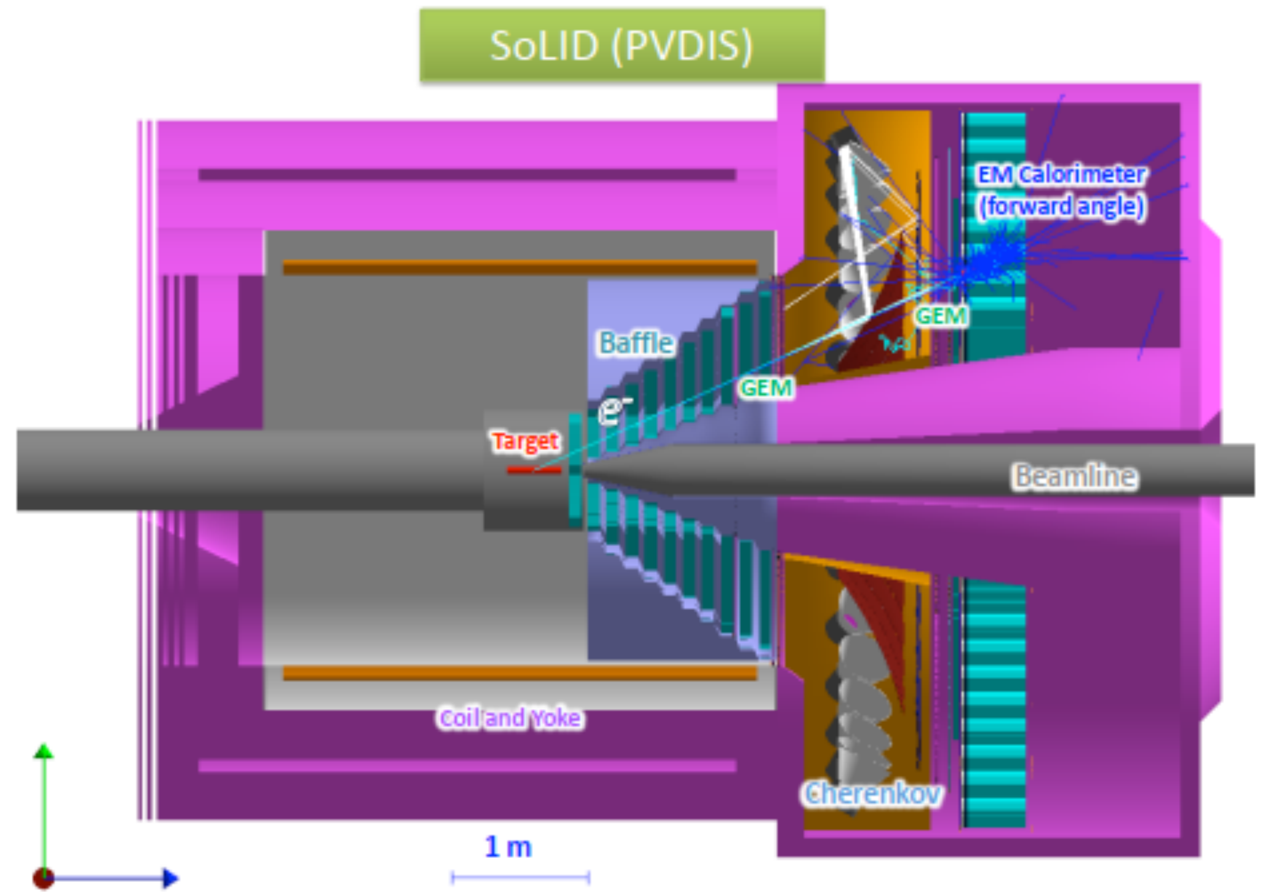
Extends kinematic coverage:

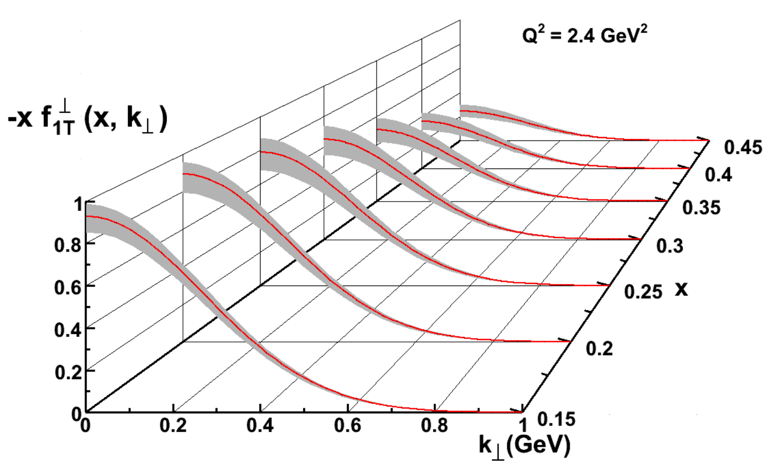
$0.1 < x < 0.8$, Q^2 of 1-14 GeV^2, W up to 4GeV

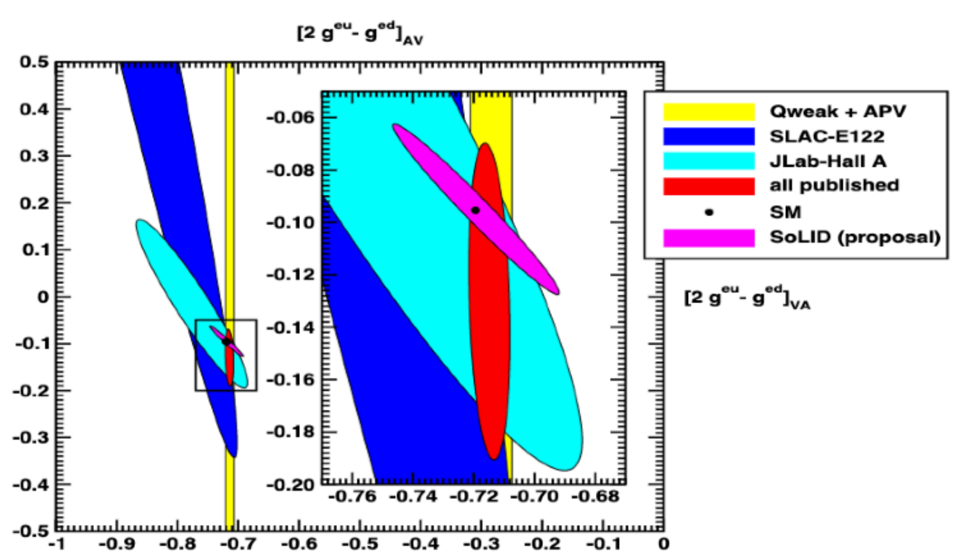
Parity-Violating DIS with SoLID

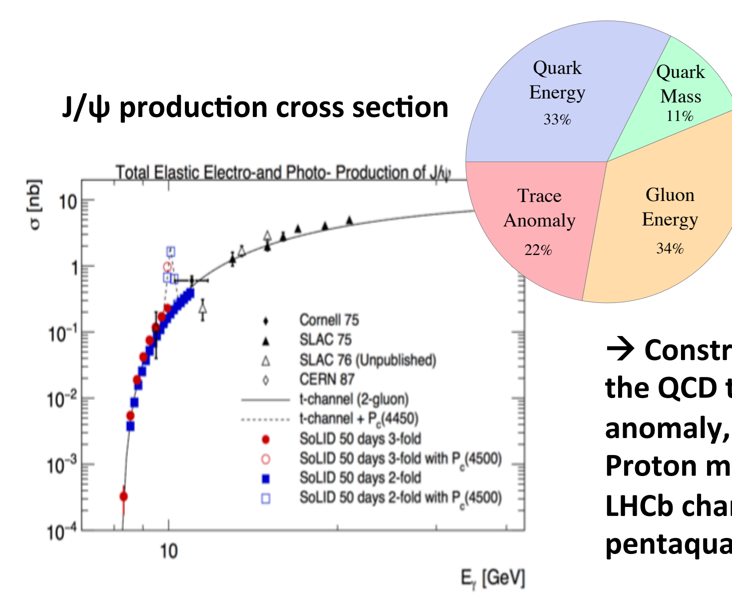
J. Phys. G: Nucl. Part. Phys. **50** 110501

- **Take full advantage of JLab 12 GeV upgrade**
  - High luminosity (10^{37} - 10^{39})
  - Large acceptance with full azimuthal coverage
- **Rich physics program**
  - Precision in 3D imaging of the nucleon
  - Near threshold J/psi production
  - Parity-Violating DIS









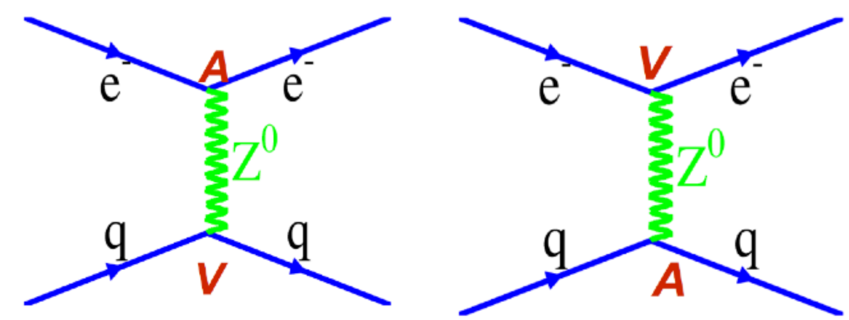
→ Constrain the QCD trace anomaly, Proton mass , LHCb charmed pentaquark

Parity-Violating DIS with SoLID

- PVDIS on deuteron: precision determination of electroweak parameters, BSM search
- PVDIS on proton: d/u in the valence region (free of nuclear model dependence)
- PVDIS on nuclear targets (PVEMC): isospin dependence of EMC effect using neutron-rich isotopes

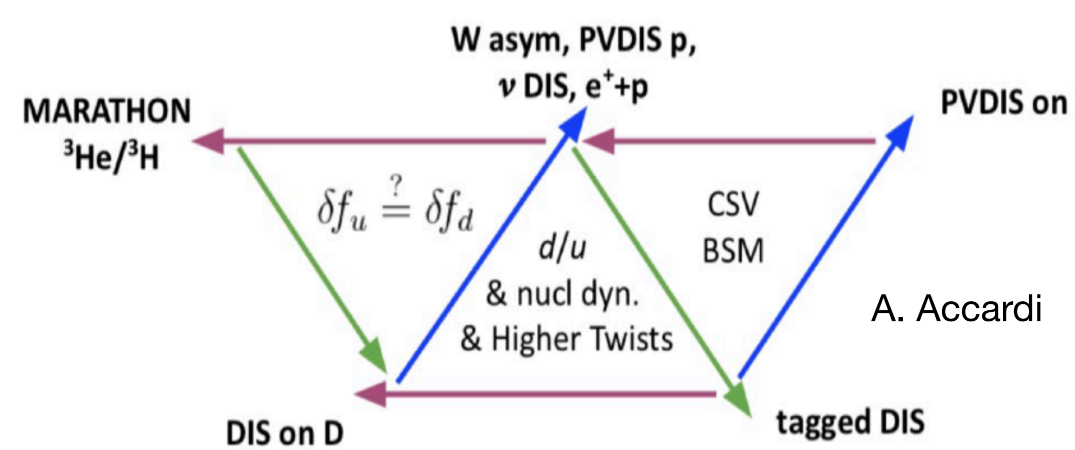
$$A_{RL}^{p} = \frac{3G_F Q^2}{2\sqrt{2}\pi\alpha} \frac{(2C_{1u} - d/u\, C_{1d}) + Y(2C_{2u} - d/u\, C_{2d})}{4 + d/u}$$

$$Y = \frac{1-(1-y)^2}{1+(1-y)^2}$$



$C_{1q} = 2g_A^e g_V^q$ $\quad C_{2q} = 2g_V^e g_A^q$

- **Extraction of d/u directly from PVDIS on proton: without complications of nuclear corrections**
- **Complementary to the other JLab d/u measurements**



A. Accardi

Database of neutron F_2

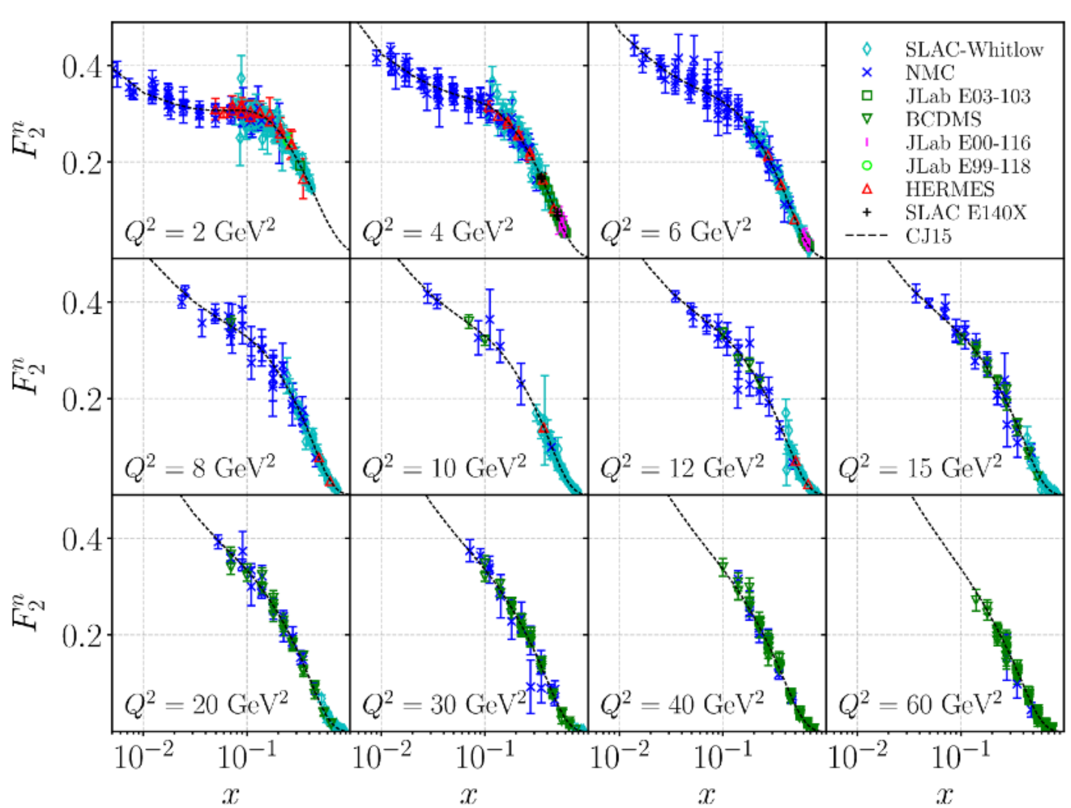
- F_2^n extraction from world DIS data
- Unpolarized proton and deuteron DIS data (F_2 and ratios) + full treatment of nuclear corrections → F_2 neutron
- p, d data matching and data cross normalization
- Extract $F_2^n, F_2^p, F_2(n/p)$, nonsinglet moment

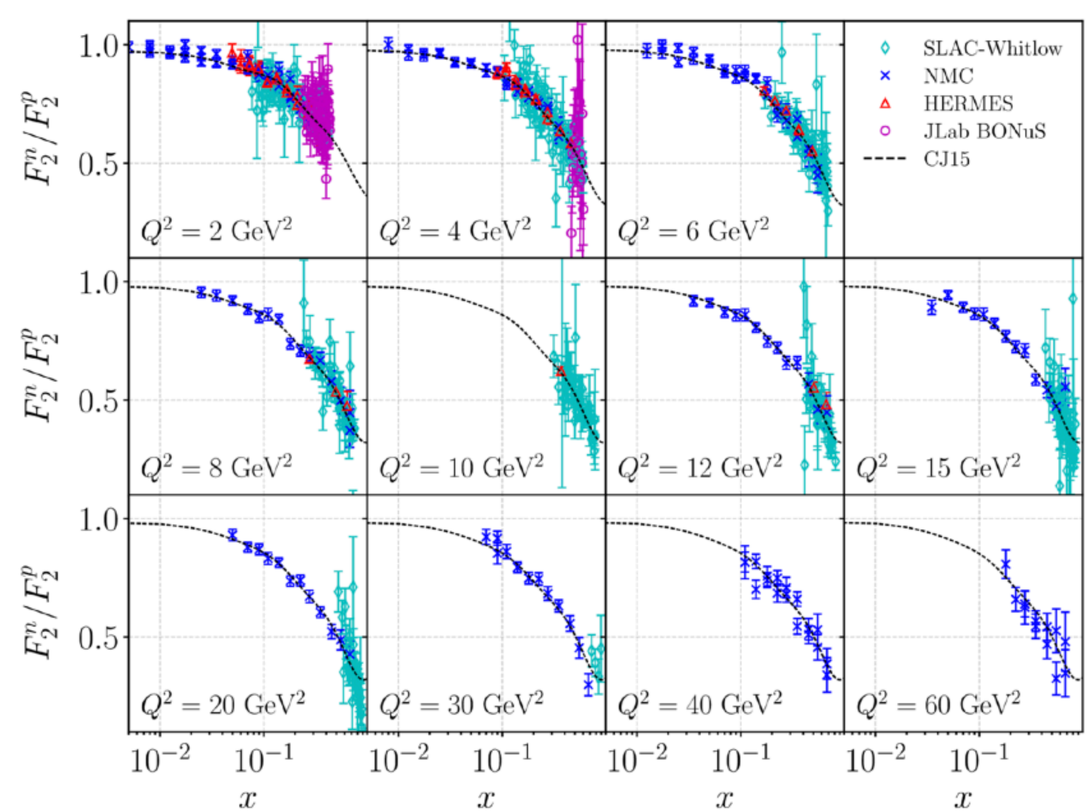
CTEQ-Jefferson Lab Collaboration

$$\hat{F}_2^{n(0)}(x,Q^2) = \frac{2\hat{F}_2^{d(0)}(x,Q^2)_{\rm expt}}{R^{\rm CJ}_{d/N}(x,Q^2)} - \hat{F}_2^{p(0)}(x,Q^2)_{\rm expt}.$$

S.Li et al, Phys. Rev. D 109, 074036 (2024)

https://github.com/JeffersonLab/CJ-database/





Summary

- Structure functions contain information on internal structure of nucleons
- New experiments at JLab 12 GeV provide access to the region where valence quarks are dominant
  - Large x region - large PDF uncertainties become dominant source for precision high energy physics
  - Limited knowledge of neutron due to lack of data, theoretical uncertainty from nuclear effects
  - New datasets and future program will significantly improve constraints on the neutron F2 extraction and d quark PDF at large-x, low Q^2 region