

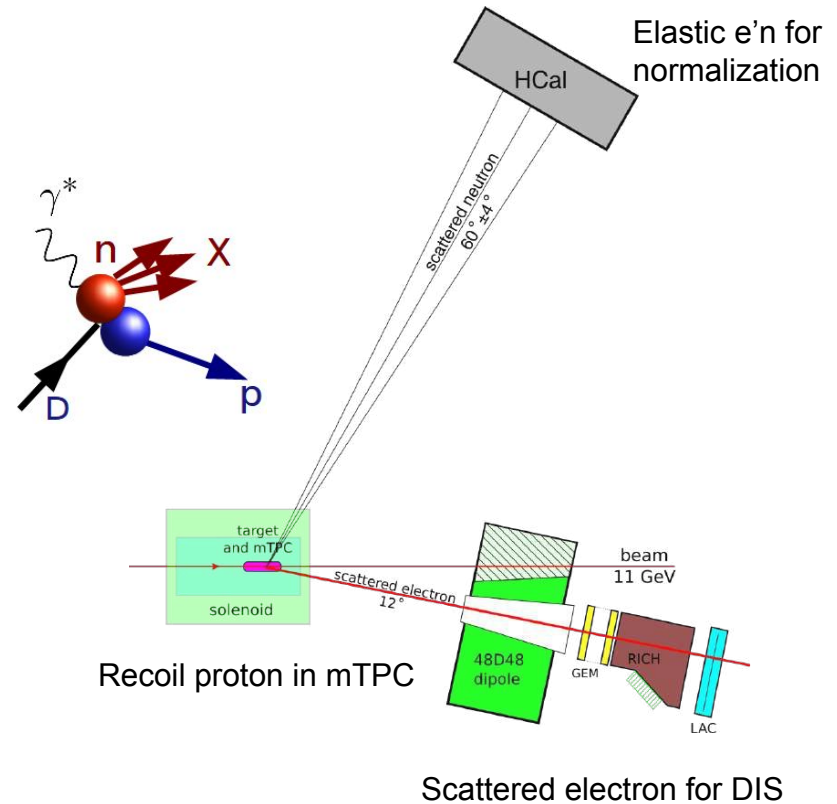
TDIS-n: Tagged DIS Measurement of the Neutron Structure Function

Shujie Li
for the TDIS-n (C12-15-006B) Collaboration

JLab Hall A/C Summer Meeting
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Experiment Overview

- **Status:** Proposal submitted to PAC 49 (C12-15-006B) and endorsed by the collaboration
- **Spokespersons:** John Arrington, Eric Christy, Carlos Ayerbe Gayoso, Eric Fuchey, Cynthia Keppel, Shujie Li, Rachel Montgomery, Arun Tadepalli
- **Beamtime:** **Parasitic** data-taking with already approved beam time on proton and deuteron target
- **Measurements:**
 - Proton DIS structure function
 - **Deuteron DIS with recoil proton in mTPC** to:
 - Identify **neutron** DIS event
 - Select “barely on-shell” neutrons
 - e'n with HCal for normalization



Neutron Structure Function

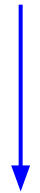
Constrain d/u at large x

At leading order (charge symmetry):

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

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

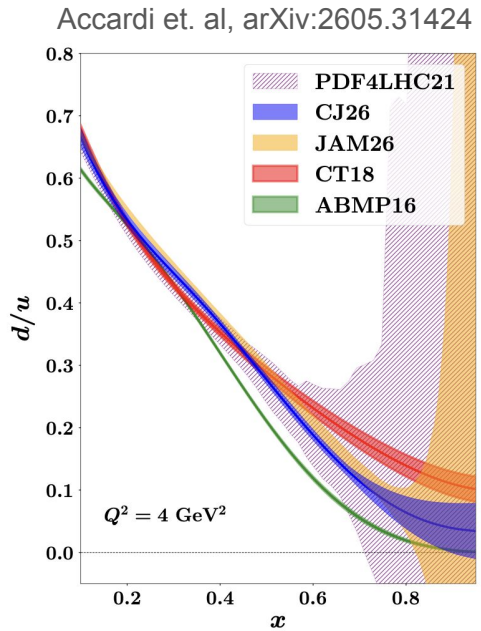
Small anti-quarks and strange quark contributions at x>0.3



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

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.



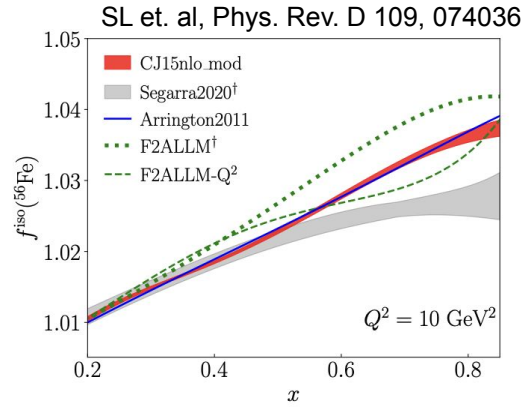
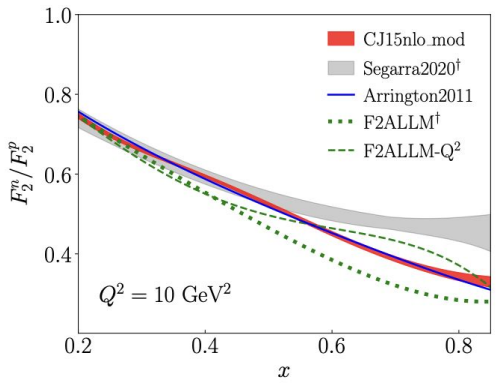
Nucleon Model	F_{2n}^n/F_{2p}^p $X \rightarrow 1$	d/u $X \rightarrow 1$
SU(6) Symmetry	2/3	0.5
Scalar diquark dominance	1/4	0
DSE contact interaction	0.41	0.18
DSE realistic interaction	0.49	0.28
PQCD (helicity conservation)	3/7	0.2

Courtesy of S. Kuhn

Neutron Structure Function

Decouple nuclear effects

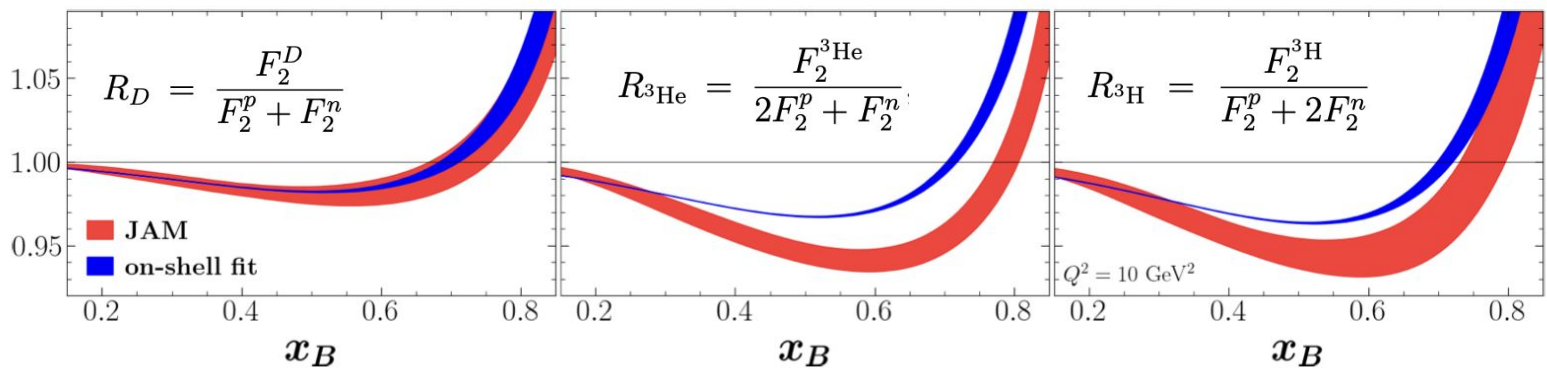
- f2n/p → isoscalar correction:



SL et. al, Phys. Rev. D 109, 074036

- Interpretation of nuclear DIS → free p and n

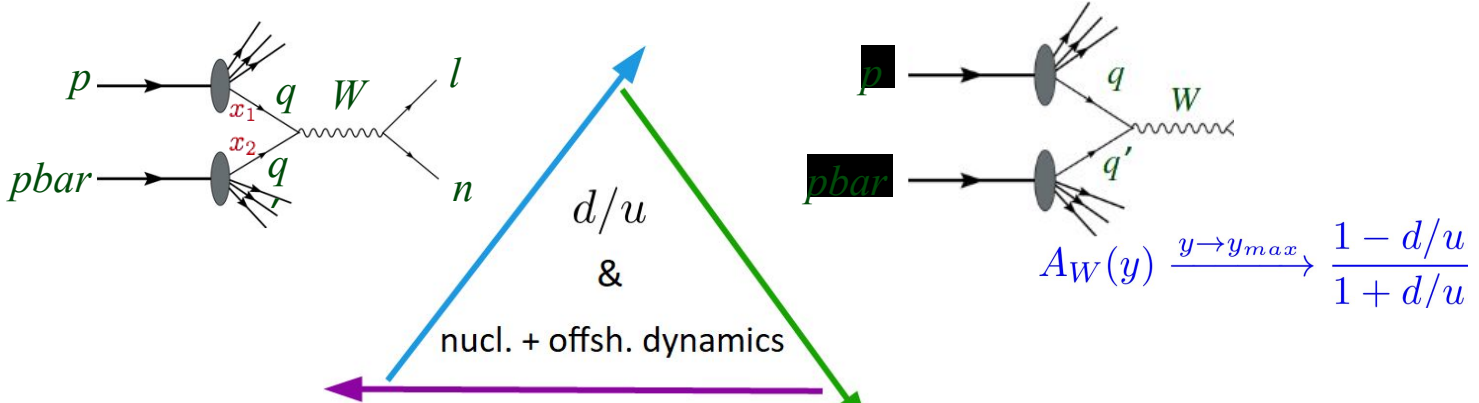
Cocuzza et. al, arxiv 2602.16589



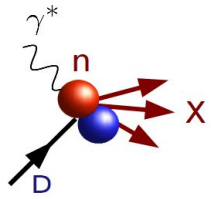
Neutron Structure Function without free neutron

Role of tagging

D0, CDF asymmetries

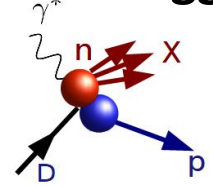


DIS on Deuterium



$$F_2^d \propto \mathcal{S}_D \otimes [xu_{\text{off}}(x) + xd_{\text{off}}(x)]$$

Tagged DIS



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

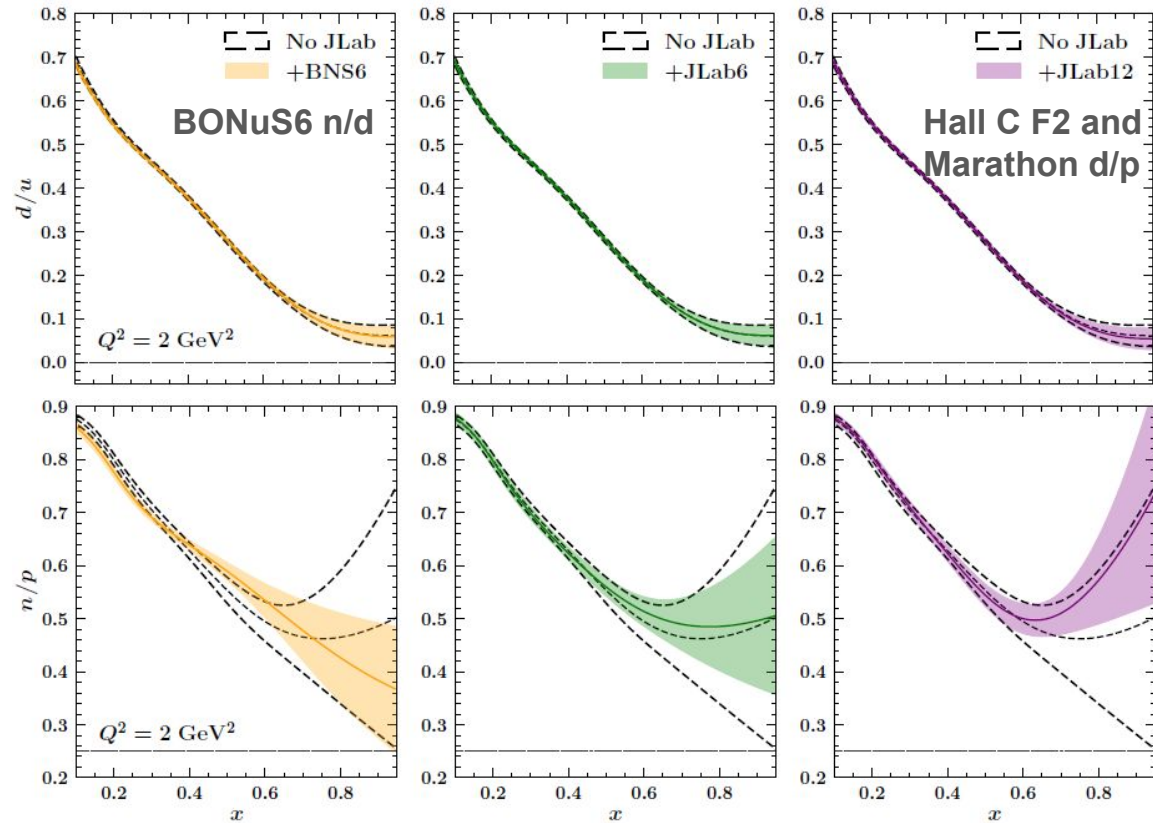
Neutron Structure Function

Role of tagging

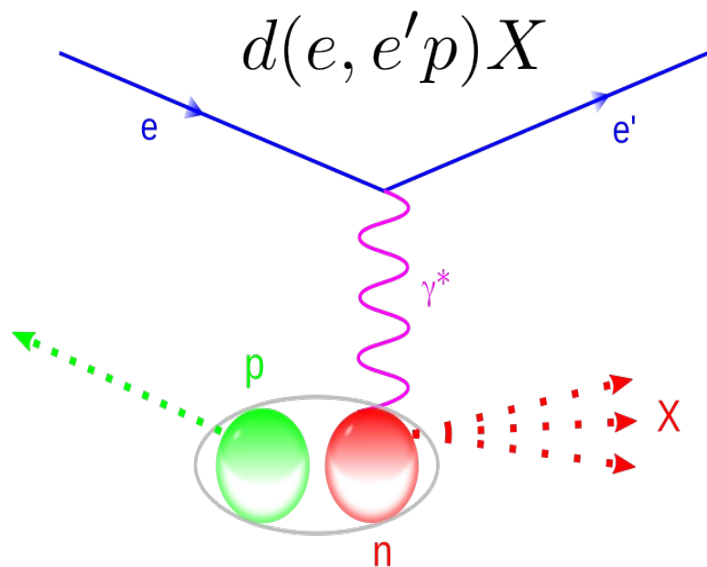
Current:

- Large power corrections, offshell effects and uncertainties at large x
- Tension between tagging and DIS data

⇒ need more tagging measurements to resolve ambiguities.



Spectator tagging formalism



The 4-momentum of the nucleons are:

$$p_p = (E_p, \vec{p}_p)$$

$$p_n = (M_d - E_p, -\vec{p}_p)$$

Deuterium mass:

$$E_p + E_n = M_d$$

but:

$$m_p + m_n > M_d$$

→neutron and proton cannot be on-shell at the same time.

We can consider one nucleon on-shell (spectator) while the other is off-shell.

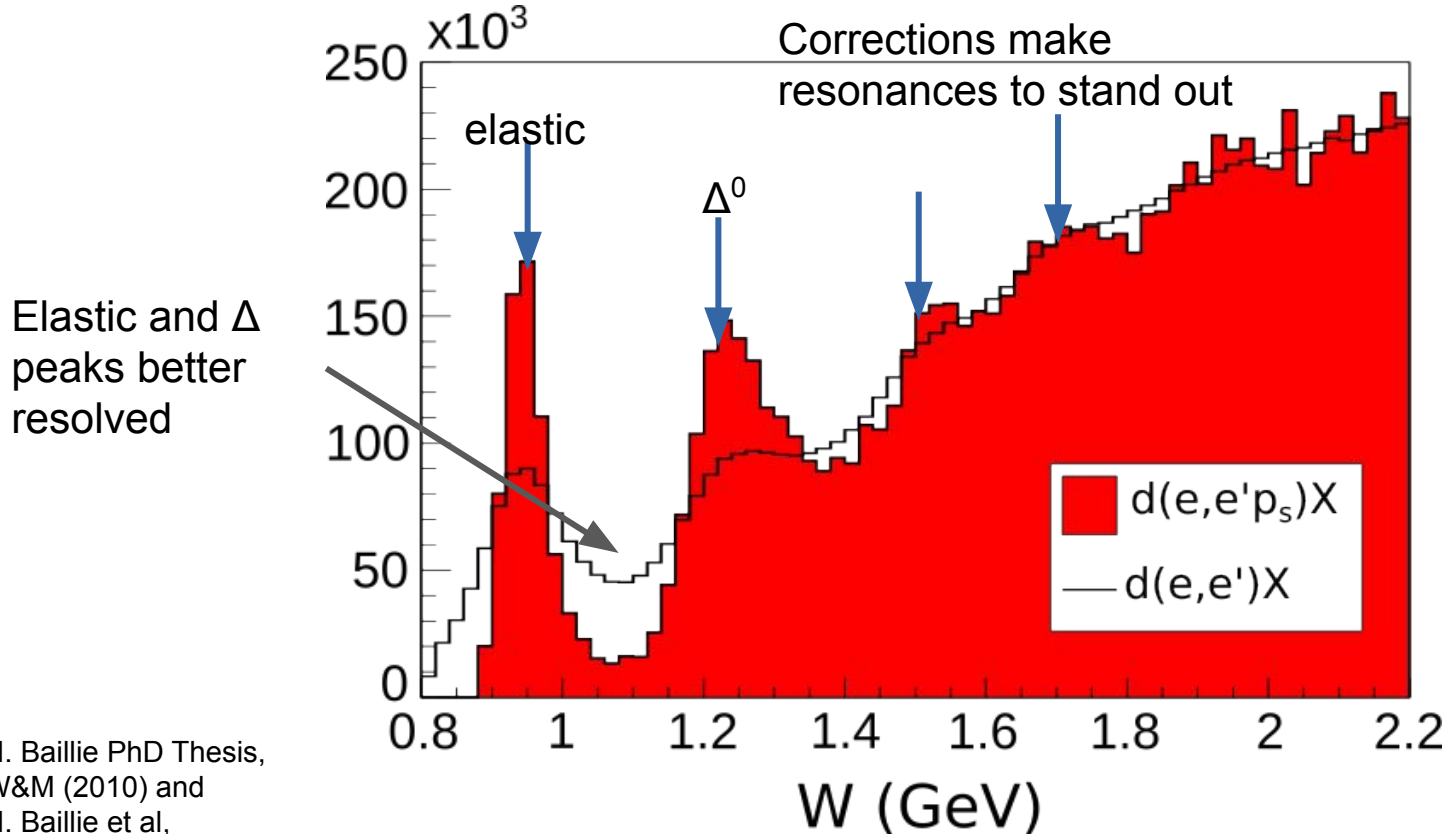
In the PWIA approximation **the proton is the spectator** and receives no energy or momentum transfer.

Spectator final state can be described by the light-cone fraction

$$\alpha_p = \frac{E_p - \vec{p}_p \hat{q}}{M_p} \leftarrow \text{Direction of the moment transfer}$$

Kinematics Correction with Tagging

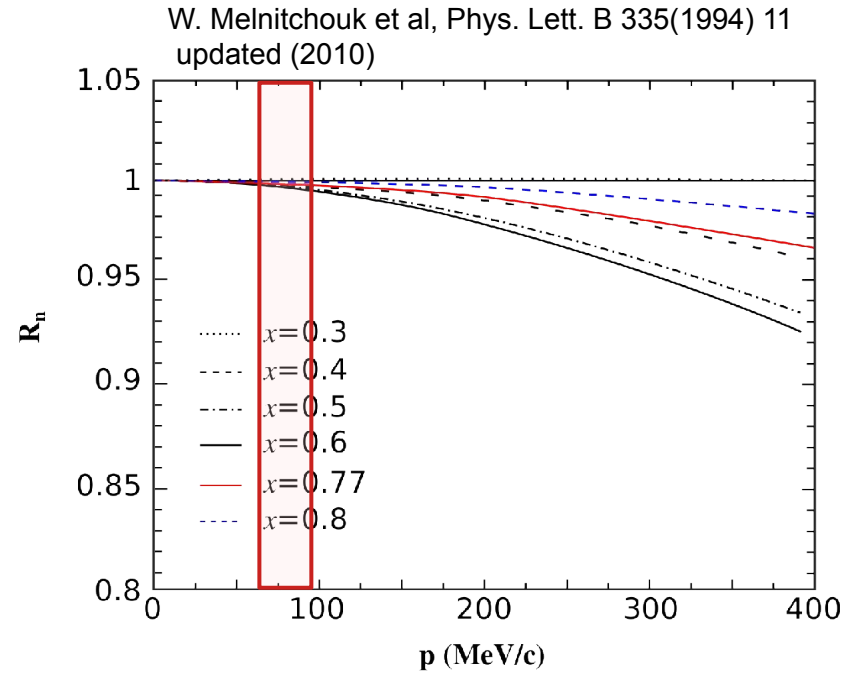
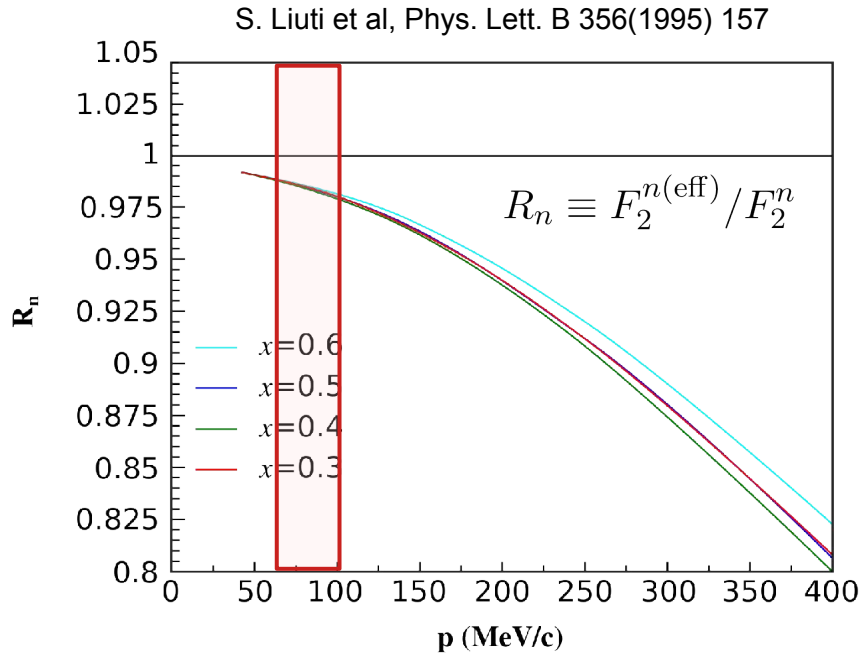
$$W^{*2} = M^{*2} - Q^{*2} + 2M\nu(2 - \alpha_s)$$



Spectator Proton Selections

60 < p < 100 MeV/c :

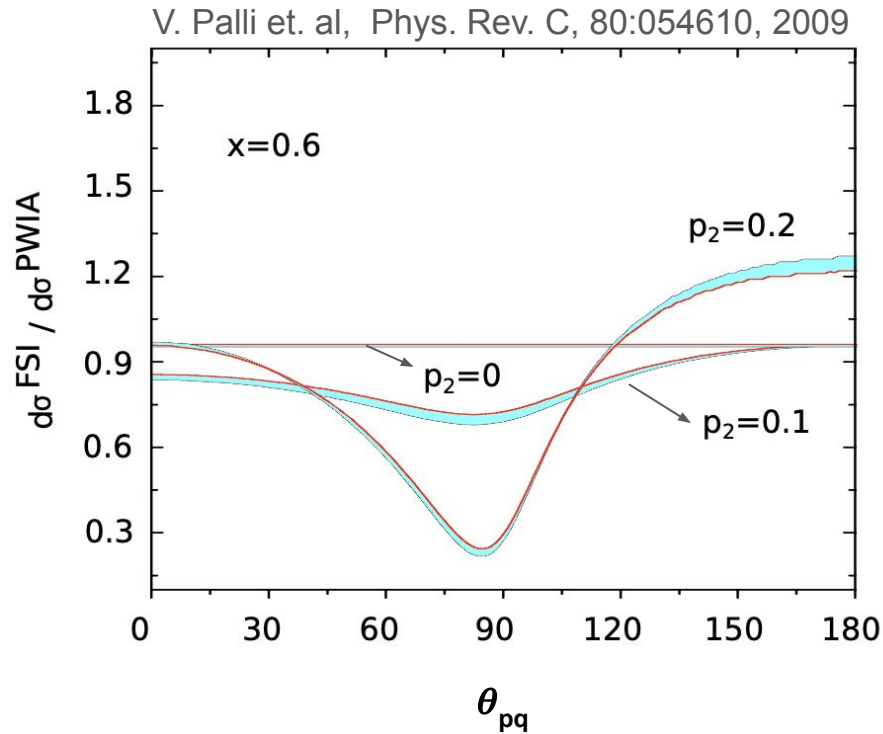
- The **offshell** impact on F_2^n is less than 2%
- Up to 3 momentum bins to study α -dependence



Spectator Proton Selections

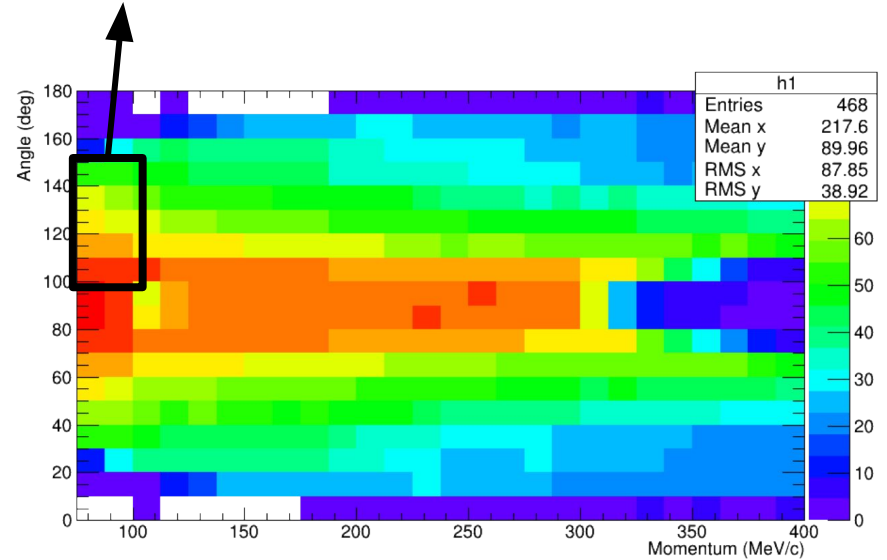
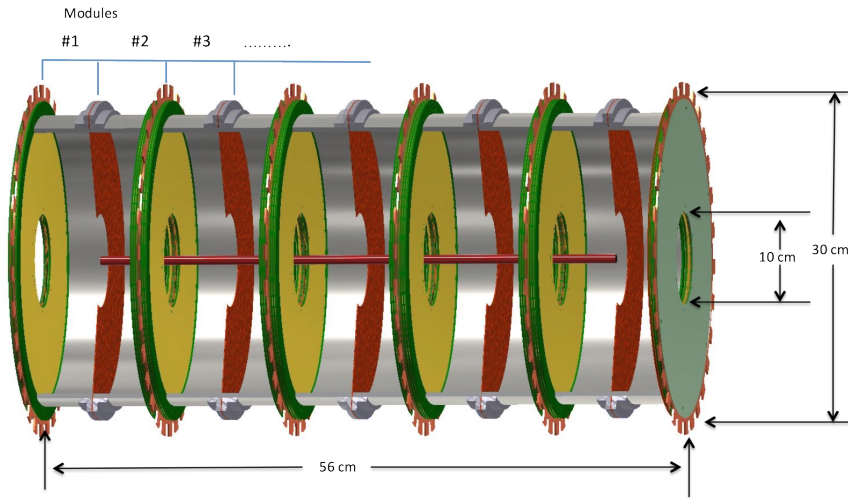
$\theta_{pq} > 100$ degrees:

- At $p < 0.1$ GeV, the FSI impact is $< 20\%$ at backward angle.



Detect the Recoil Protons in mTPC

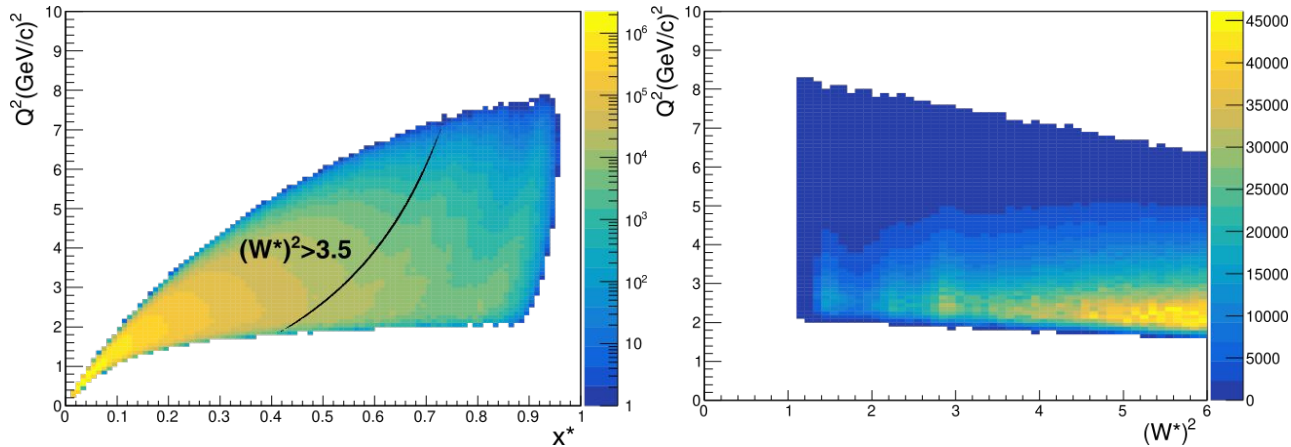
Region of interest: efficiency > 50%



GEM-based mTPC for low-momentum tracking at high rate.

See [Aruni's talk](#) for TDIS configuration and specs

TDIS-n projected results: phase space

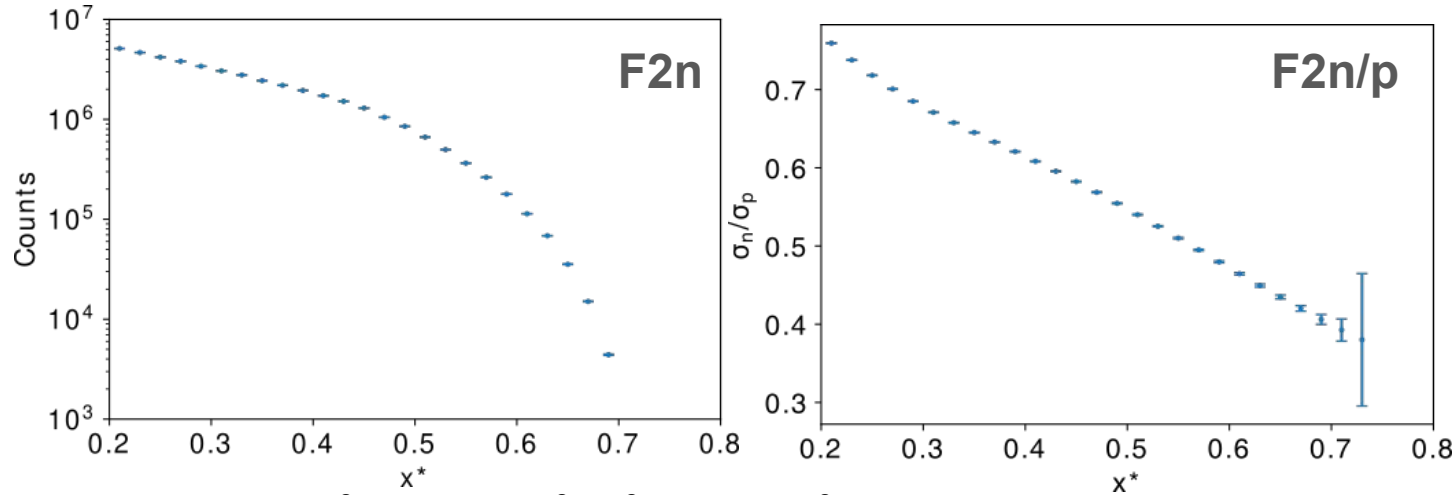


kinematic coverage for SBS at 12°, making use of F1F209 model.
* indicates the correction by tagging.

Because G4SBS simulation does not include resonant region contributions, fast simulation is used to estimate the estimated data for TDIS-n

- F1F209 to handle DIS + resonance cross section
- Counts from luminosity of **1.5×10^{36} deuterons Hz/cm⁻²** and **5 days beam**
- Fraction of spectator protons with $60 < p < 100$ MeV/c and $\theta_{pq} > 100$ is 9.9% (Av18)
- 50% spectator efficiency + 80% SBS efficiency and livetime

TDIS-n projected results: DIS and EMC



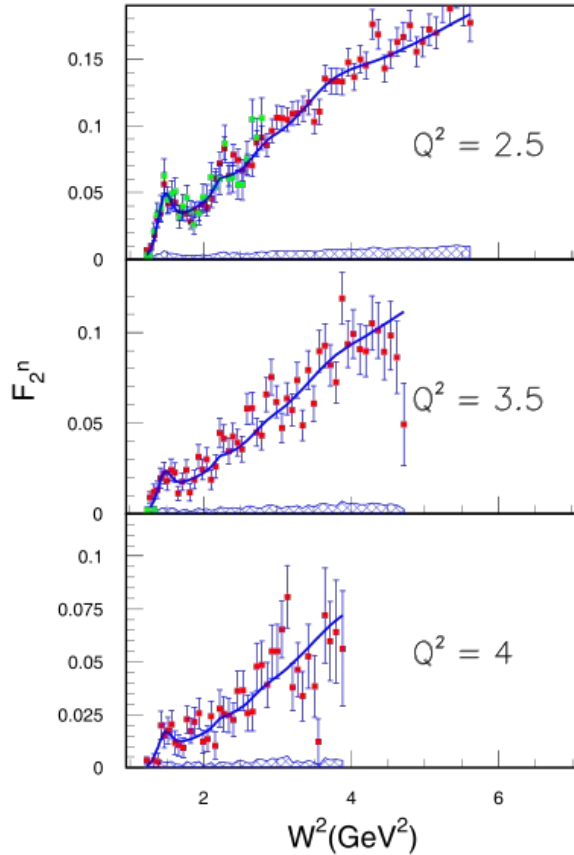
DIS Cuts: $Q^2 > 1$ (GeV/c) 2 , $W^2 > 3.5$ GeV 2

Systematics: 5% overall including 3% from SBS and 3% from tagging, 1-2% from luminosity

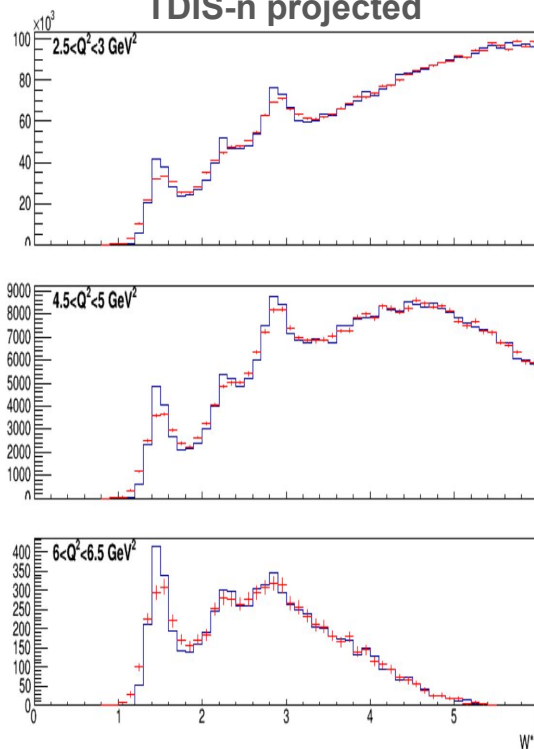
- These results provides a comparison with MARATHON and BONuS12 data with **different systematics**.
- Making use of the inclusive TDIS data, in the region $0.3 < x < 0.7$ provides an excellent opportunity to compare the deuteron to proton+neutron F2 (EMC effect in deuteron)
- We project **a factor 7 higher statistics** than the BONuS12 measurement.

TDIS-n projected results: resonance structure

BONuS 6



TDIS-n projected

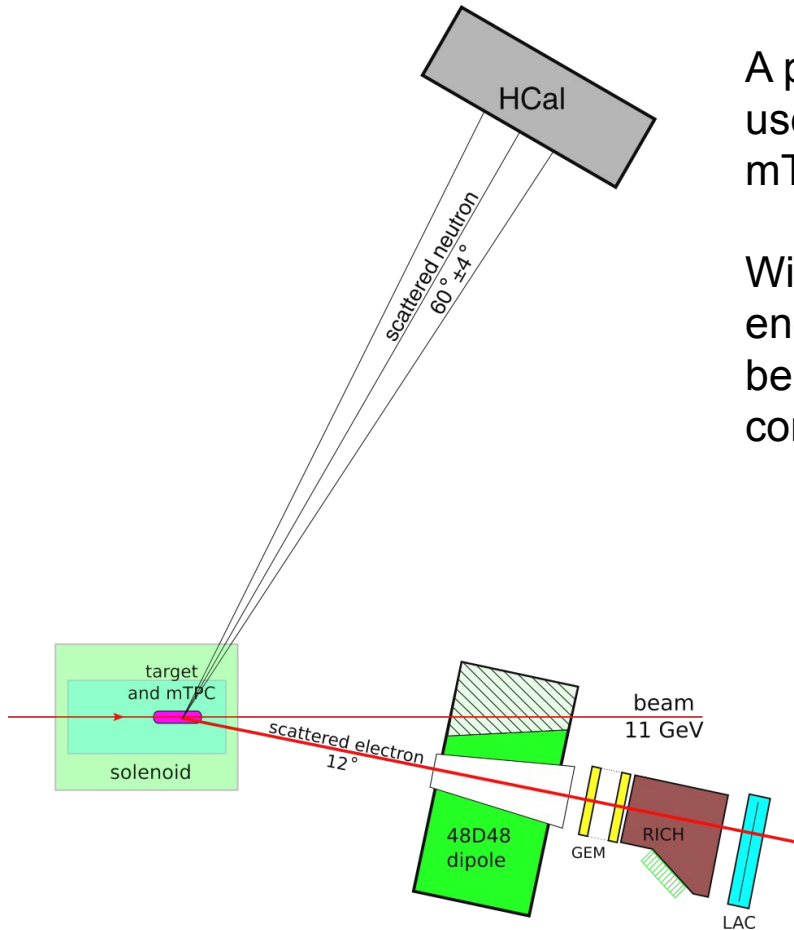


Projected results of the F_2^n as a function of W^2 for three Q^2 bins (right plots). For comparison, three Q^2 bins from BONuS6 are shown.

Our projected results:

- **7x higher FOM** in the region of overlap compared to BONuS12
- **Improved statistics** in the larger Q^2 region compared to BONuS12

Control Normalization



A particular feature of the TDIS experiment will be the use of the Hadron Calorimeter (HCal) to calibrate the mTPC acceptances and efficiencies.

With the use of quasi-elastic scattering in deuterium, the energy and direction of the spectator proton may be determined with a scattered electron in the SBS in combination with a neutron measured HCal.

The calibration will be performed as:

- Energy beam: 4.4 GeV
- e-N luminosity of 0.3×10^{36} Hz/cm²
- HCal placed 15 m from target at 60 deg

Such calibration will allow an independent model normalization of the measurements

Summary

TDIS-n will reach Q^2 values of 6-7 GeV² with a statistical accuracy of better than 3% at the large x . This allows us to make several interesting physics measurements:

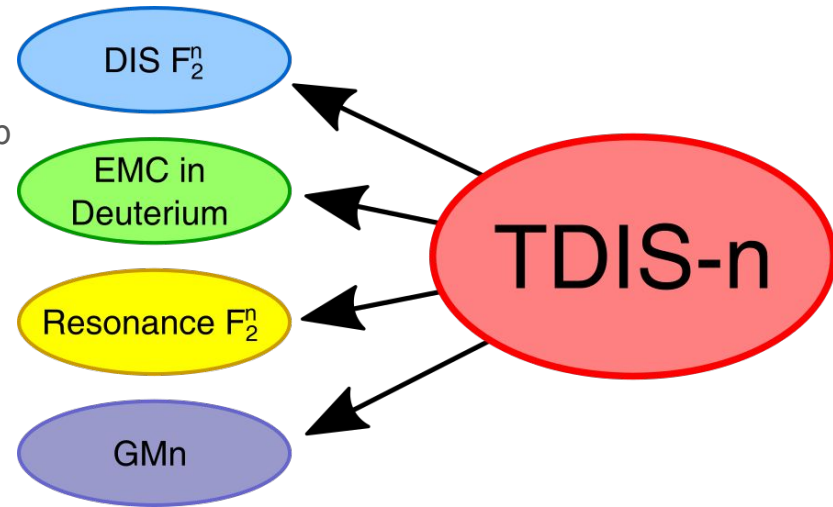
- A high-statistics extraction of $F_2^n(x)/F_2^p(x)$ for $0.3 < x < 0.7$ with completely different systematic uncertainties than the recent result from MARATHON [1] and different systematics plus new tagging efficiency studies compared to BoNuS12 [2].
- High-statistics measurements of F_2^n (and F_2^p) in the resonance region Q^2 from 2-7 GeV². This provides a comparison of resonance production off the neutron and the proton, and will allow us to determine if the falloff of the Δ resonance in e-p scattering is also observed in scattering from the neutron.
- The tagged neutron measurements will allow us to measure the elastic electron-neutron cross section and extract the magnetic form factor without the need for subtracting proton contributions (as for e-d quasielastic measurements) and without having to correct for a neutron detection efficiency.
- Combining the tagged neutron structure function measurement with inclusive data from the proton and deuteron, TDIS-n will extract the “EMC effect” for the deuteron, i.e. $F_2^d/(F_2^p + F_2^n)$, in a way that allows for cancellation of several systematics in the measurements.

This neutron tagging measurement is a valuable addition to the TDIS program, and address the key questions in the neutron PDFs and nuclear effect studies. It is also another step forward for developing the tagging techniques from BONuS 12, towards future EIC era

Summary

This neutron tagging measurement (TDis-n) is a valuable addition to the TDis program, and address the key questions in the neutron PDFs and nuclear effect studies. Within 3% stat. uncertainties, it will enable

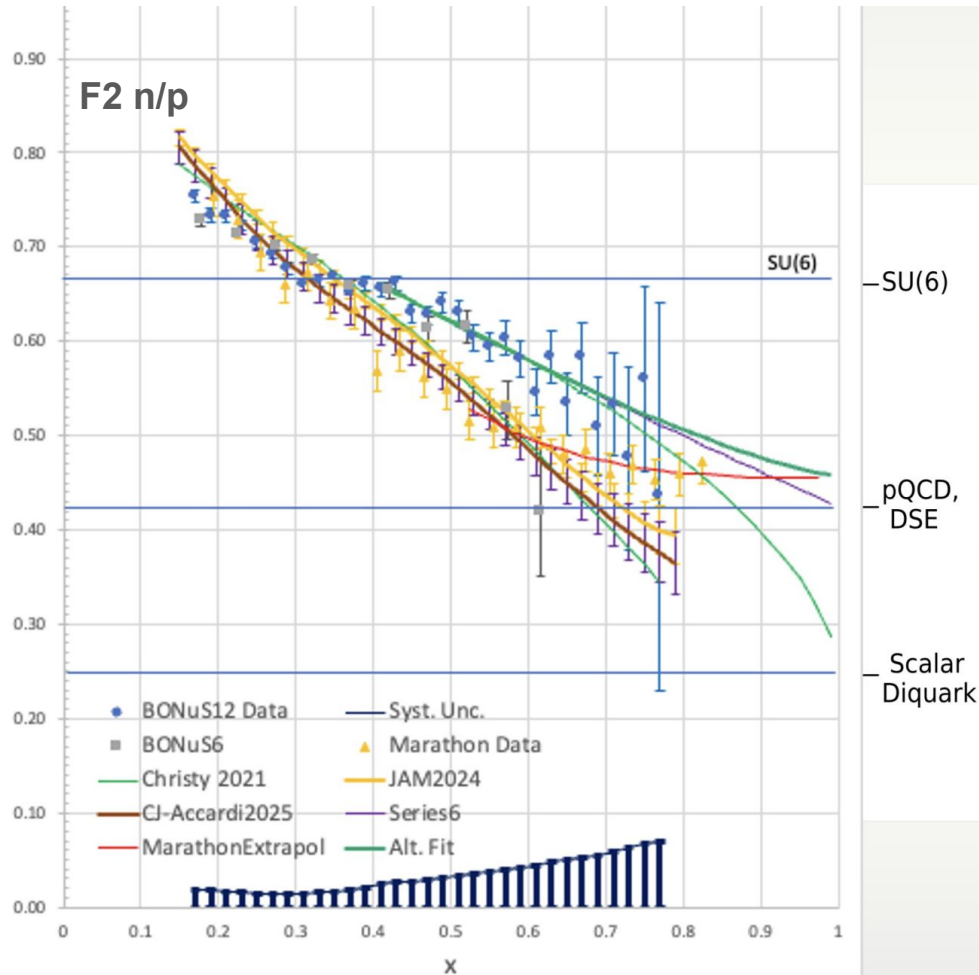
- Extraction of F_2^n/p at $0.3 < x < 0.7$
- Combine tagged F_2^n , and inclusive F_2^p and d to construct the EMC ratio on deuteron: $d/(n+p)$
- F_2^p and n at resonance region with Q^2 from 3 to 7 GeV^2
- Elastic e-N cross section for magnetic form factor



This is also another step forward to develop and validate the tagging techniques from BONuS12, and towards future EIC era

Thanks!

BONuS 12 near final result [link](#)



Neutron Structure Function

Resonance Structure

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

