Hall A TDIS Run Group Proposal C12-15-006B

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

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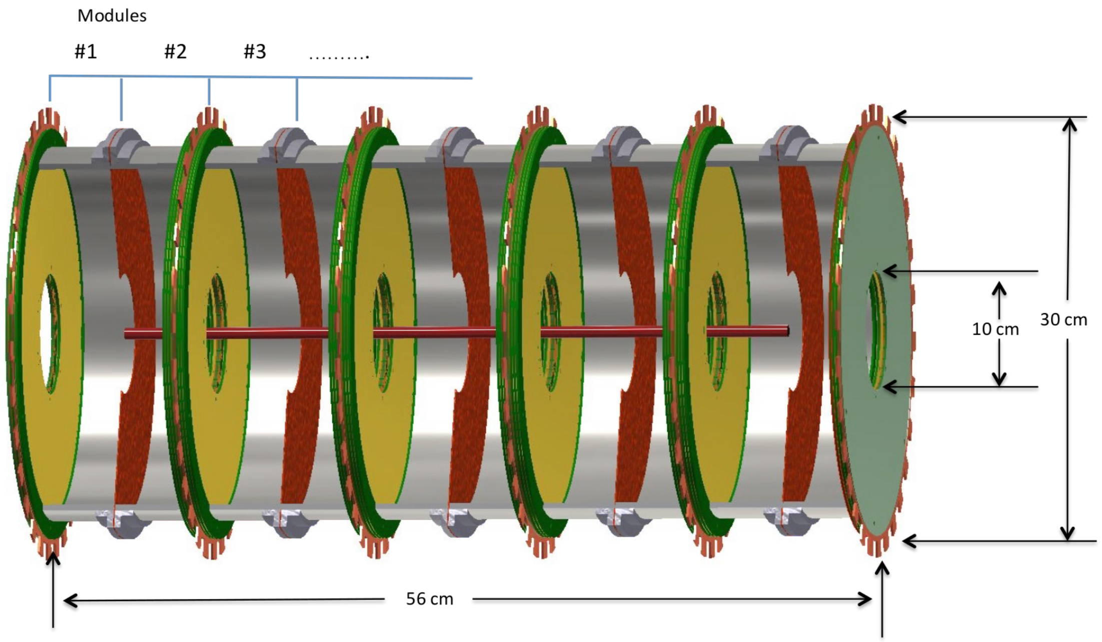
C.E. Keppel, S. Li, R. Montgomery, A.S. Tadepalli

PAC49, 21 July 2021

Paul M. King

for the TDIS Experiments



mTPC current design. Courtesy N.Liyanage

Review Process

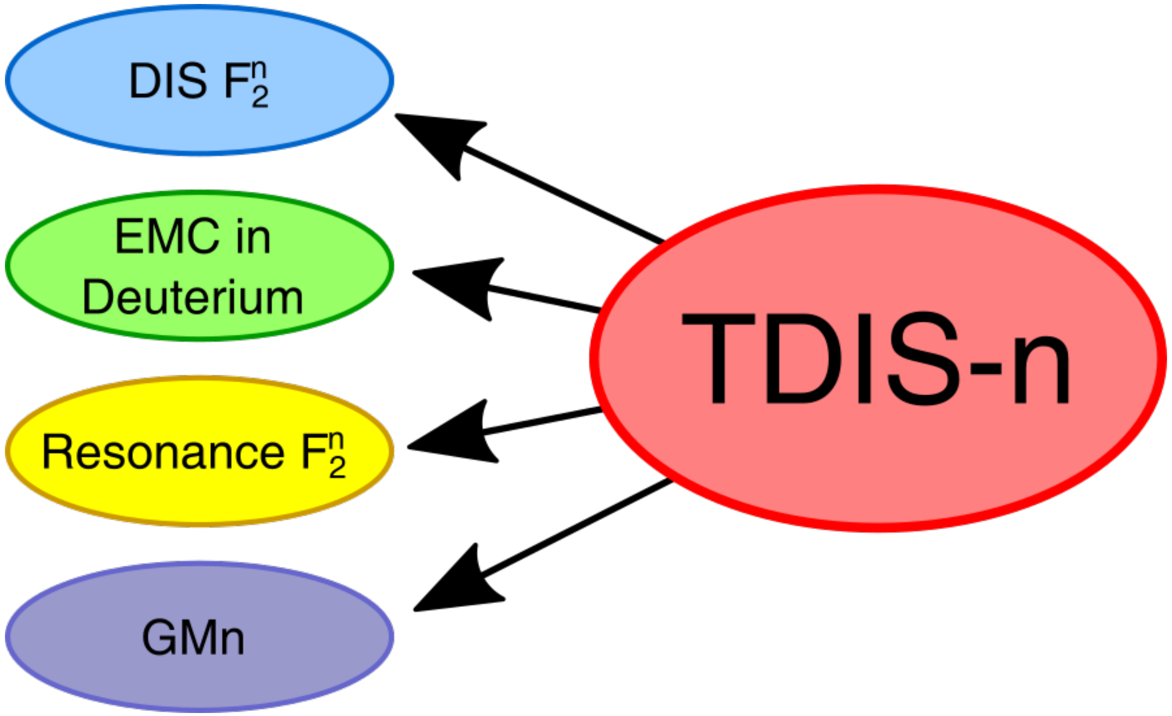
- Committee drawn from the TDIS experiments (C12-15-006 and C12-15-006A*), the Super Bigbite Spectrometer collaboration†, and the Hall A collaboration‡
  - Dipangkar Dutta; Florian Hauenstein‡; Tanja Horn*; Paul King (chair); Andrew Puckett†
- The review was held on 6 May 2021, with comments provided to the spokespeople on 10 May 2021.

- The review committee endorsed the run group proposal
  - TDIS-n would have a negligible impact on the existing TDIS experiments
    - No additional beam time is required
    - No changes in the experimental configuration are required
    - Would extract the neutron and proton SF from the data taken during the experiment and the tagged elastic n(e, e'n) from the calibration run.
  - Several physics goals are possible with different systematics as compared to other experiments

TDIS-n at Hall A

The Tagged Deep Inelastic Scattering experiment at JLab Hall A **allows access** to all these physics with an **increase of statistics and independent test of systematics.**

- ✓ An increase of **5-10 more statistics** than BoNuS12 in the kinematics covered by TDIS (thus TDIS-n).
- ✓ **An independent normalization** check of the procedure used in BoNuS, BoNuS12 and MARATHON.



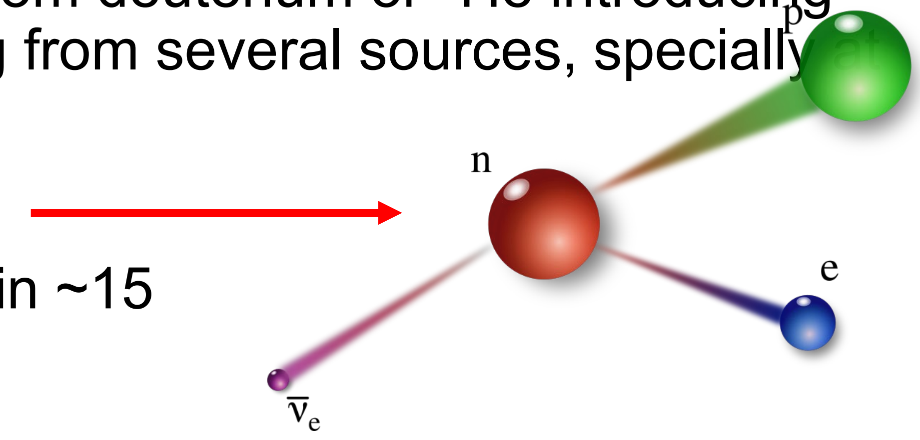
Motivation I: neutron DIS structure function

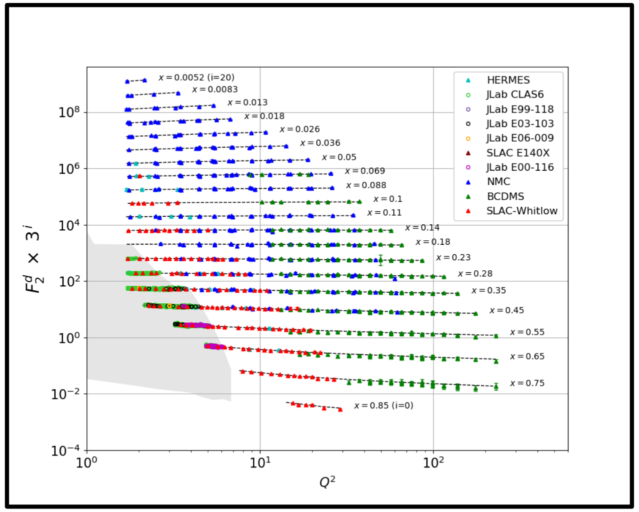
Proton and deuterium SF data is rich and very precise (**targets easily to produce**).

Neutron SF data from fixed targets relies on extraction from deuterium or ^{3}He introducing large uncertainties from the extraction procedure coming from several sources, specially medium-high x:

- *Fermi motion*
- *Off-shell effects*
- *EMC effect*
- *Final State interactions*

Free neutron decays in ~15 min





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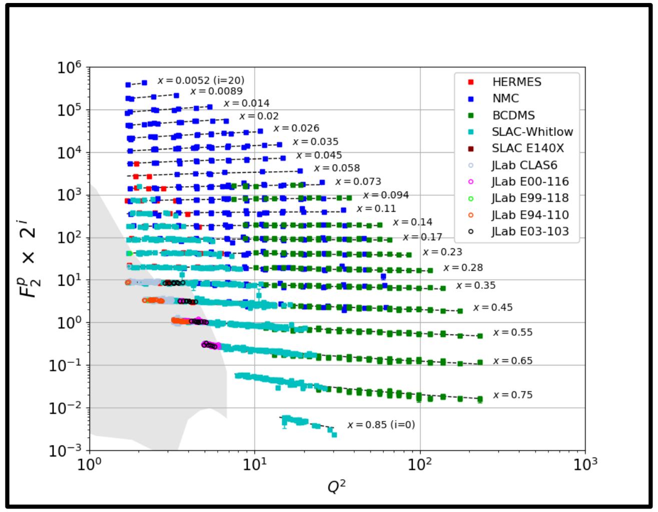

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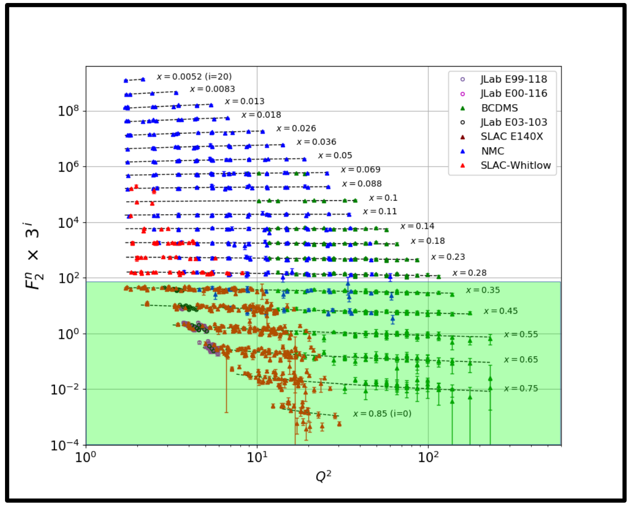
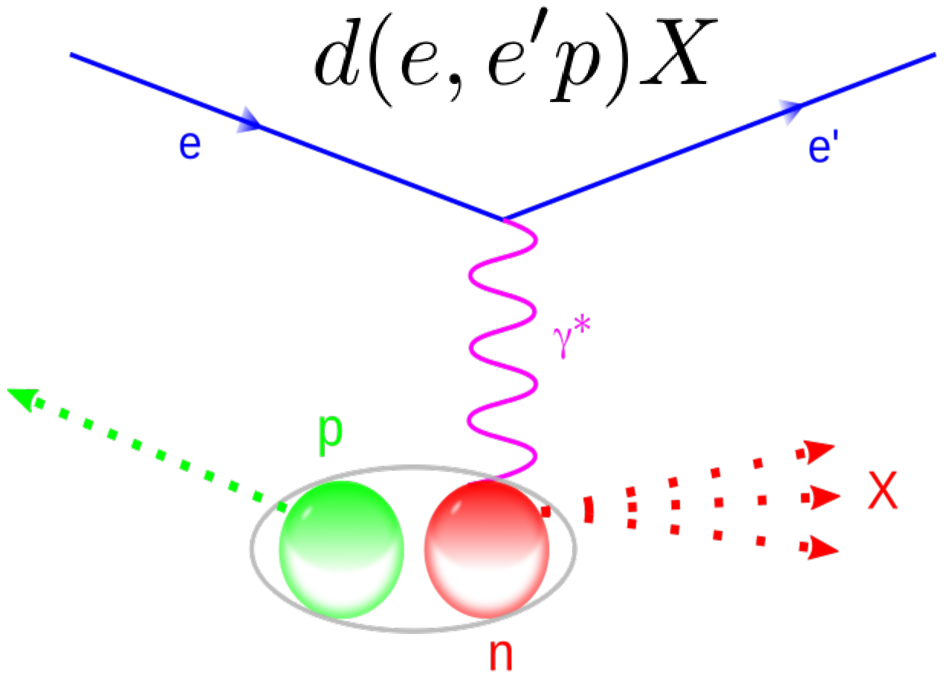


TDIS-n coverage

Spectator tagging formalism



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.

The 4-momentum of the nucleons are:

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

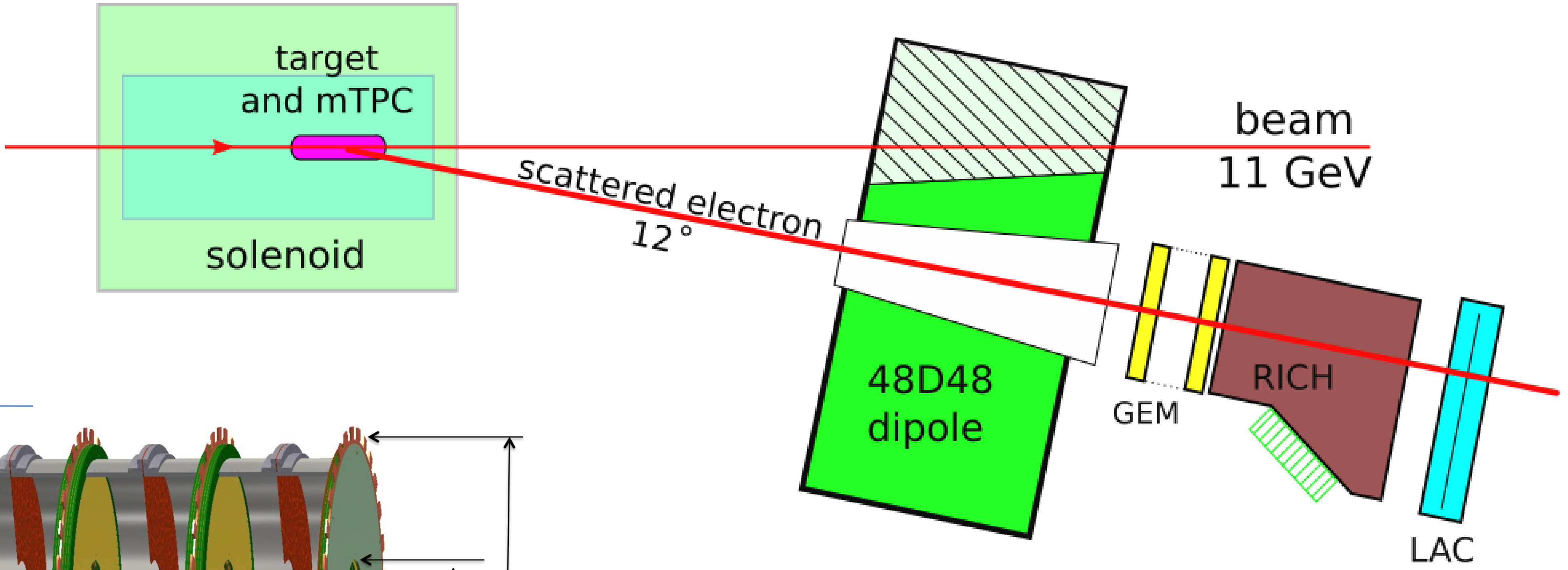
$$p_n = (M_d - E_p, -\vec{p_p})$$

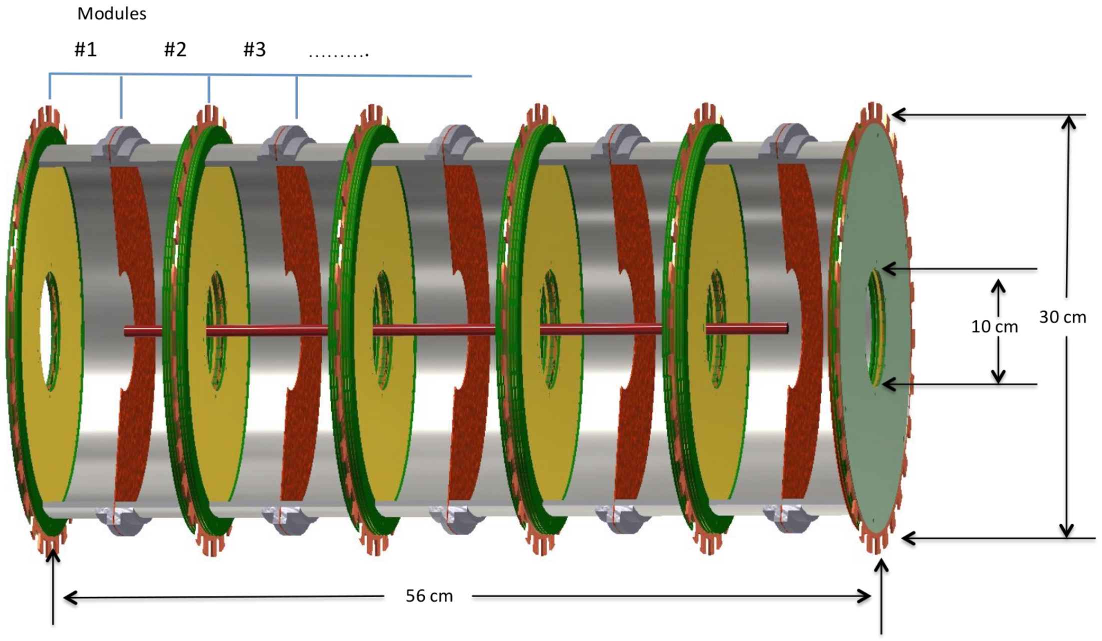
Spectator final state can be described by the light-cone fraction

$$\alpha_p = \frac{E_p - \vec{p}_p \hat{q}}{M_p}$$

← Direction of the moment transfer

TDIS experimental layout (TDIS-π, TDIS-κ, TDIS-n)





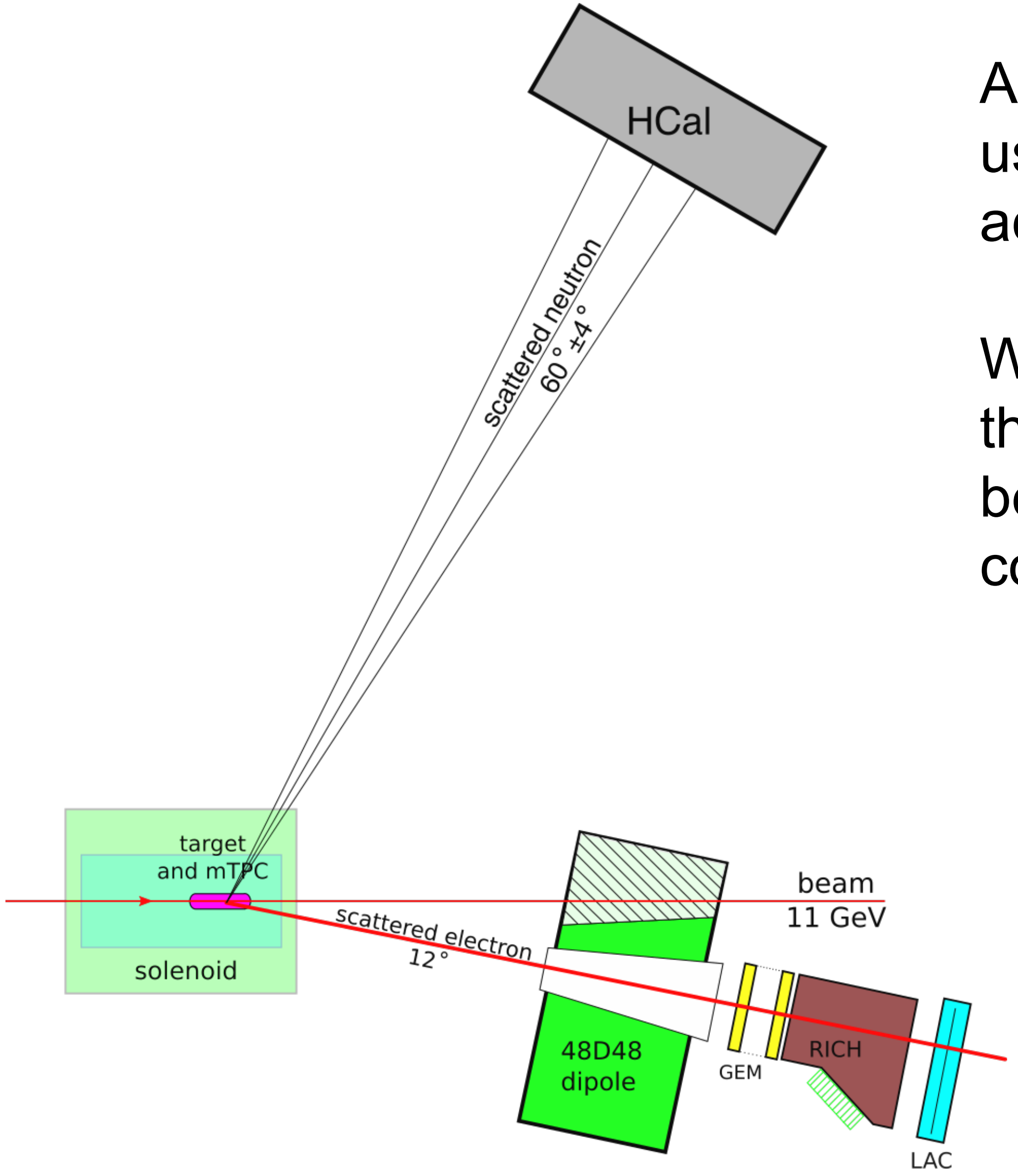
mTPC current design. Courtesy N.Liyanage

Target: 40-cm long 1-cm straw gas target (D_2 or H_2) at 4atm
Beam: 50μA
Luminosity: $2.9x10^{36}$ cm^{-2} s^{-1}

Trigger is electron identified in modified SBS

One (TDIS-n) or two (TDIS-π, TDIS-κ) spectator protons measured in mTPC

Calibration of the mTPC



A particular feature of the TDIS experiment will be the use of the Hadron Calorimeter 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 in HCal.

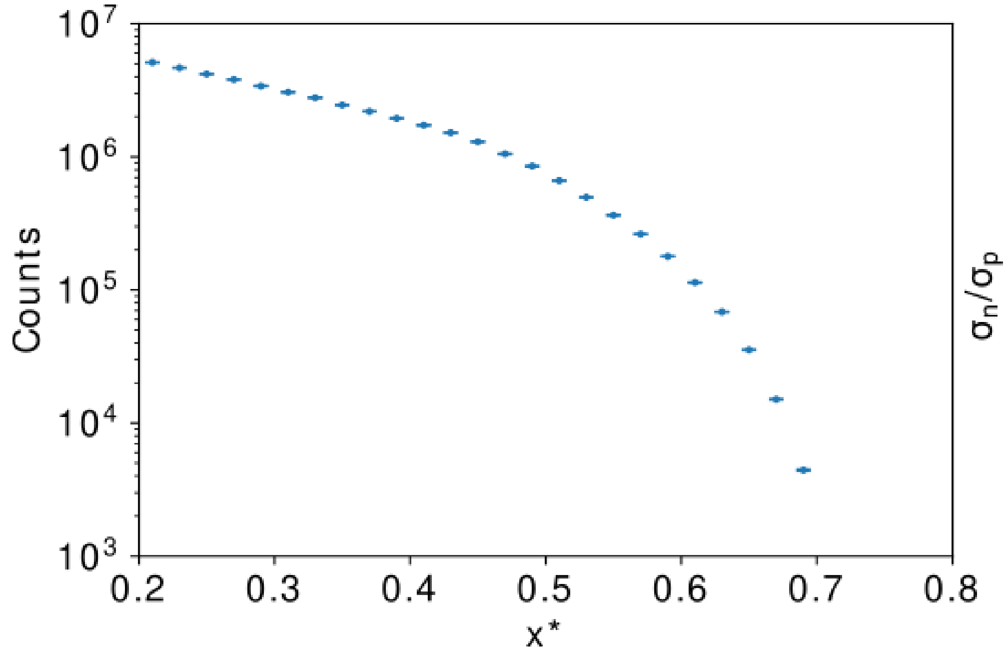
The calibration will be performed as:

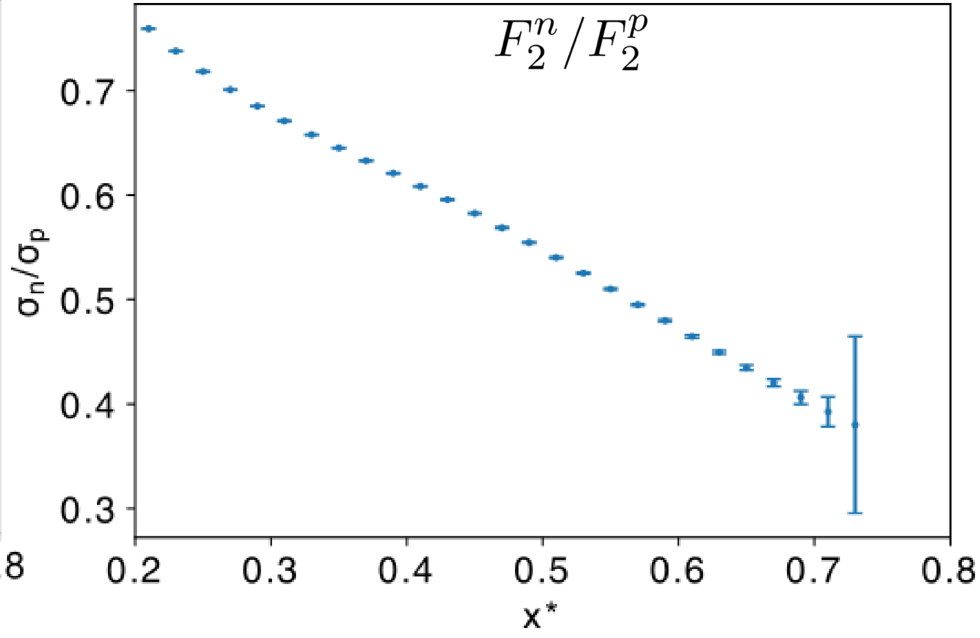
- Beam energy: 4.4 GeV
- e-N luminosity of 0.3×10^{36} Hz/cm^2
- HCal placed 15 m from target at 60 deg

Such calibration will allow an model independent normalization of the measurements

TDIS-n projected results: DIS and EMC

Projected statistics of tagged neutrons in the DIS region ($Q^2 > 1\ (\mathrm{GeV/c})^2$, $W^2 > 3.5\ \mathrm{GeV}^2$) for 5 days of beam





Modified tagged variables

$$x^* = \frac{x}{2 - \alpha_p}$$

$$\alpha_p = \frac{E_p - \vec{p}_p \hat{q}}{M_p}$$

- Would provide a comparison with the recent MARATHON data with **different systematics.**
- It will provide tests of the tagging efficiency **not achievable** by BoNuS12
- 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 SF (EMC effect)
- We project **a factor 7 higher statistics** than the BoNuS12 measurement.

P.M. King

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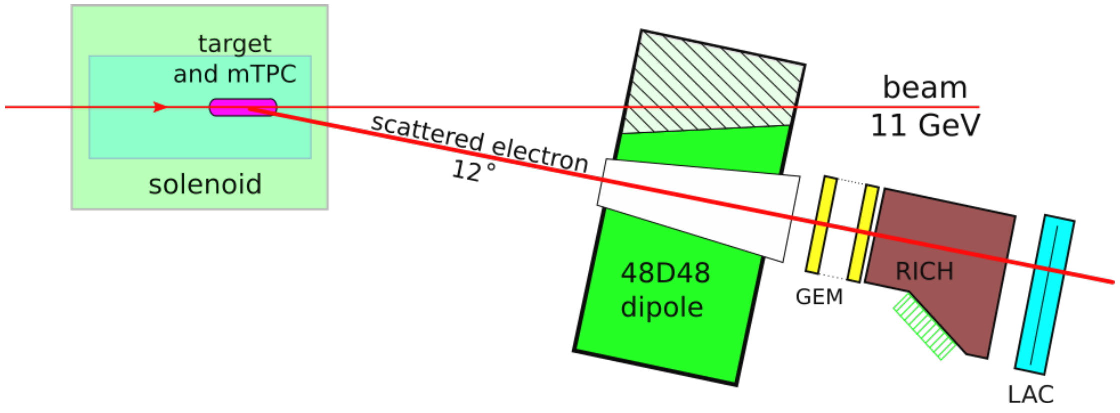
- TDIS-n would use the same data as the other Hall A TDIS experiments
- Physics topics accessible
  - Neutron structure function, F2n
  - EMC effect in deuterium
  - F2n in resonance region
  - GMn
- Complementary to other experiments with these goals, with different systematics



Response to questions

- **Question about PR12-14-010 being deferred**: We should not refer to PR12-14-010 which is deferred, but to C12-15-006 which is a conditionally approved proposal. C12-15-006 received C1 approval for 27 days with an A- rating from PAC43, and does not need to return to the PAC. The conditional issue is technical, specifically to show that track reconstruction in this mTPC is feasible in a high rate environment, and is being worked on by the TDIS collaboration. The TDIS-κ run group proposal, C12-15-006A, was approved by PAC45.
- **Question about change or open the trigger**: All data for all run group measurements (including kaon TDIS) and all kinematics of all measurements will be taken simultaneously with the same trigger conditions (electron-only trigger). This proposal would focus on the D_2 target data, corresponding to 12 of the 27 days in the approved proposal.
- **In the section where you discuss the trigger, there is a statement claiming that your singles proton rate would be 125 MHz. This sounds like a high rate for the TPC. How do I have to understand this number?** The singles rate of 125 MHz should be interpreted as the rate that is estimated for the whole mTPC (which has 10 GEM chambers), the rate per chamber is approx 12.5 MHz. The individual chambers in the mTPC design are shown in Figure 13 of the submitted proposal. According to the current design of the mTPC by the TDIS collaboration, each of the individual chambers has a high segmentation of GEM pad readout with smaller pads at inner radii and larger pads at the outer radii that will account for the expected rates in that specific region. TDIS collaboration is currently prototyping readout electronics which are expected to handle the rates as well as moving on to prototyping a mini mTPC chamber to study a complete system. This is indeed a high rate environment, which is not specific to TDIS-n but it is common to all TDIS measurements and active efforts are underway to remove the conditional status which, as mentioned before, is dependent on demonstrating that track reconstruction is possible in this high rate environment.

Backup slides

Spectator tagging formalism

The mass of the off-shell neutron is:

$$M^{*2} = (M_d - E_p)^2 - \vec{p_p}^{\,2}$$

Assuming:

$$M_d \approx 2M$$

$$\vec{p}_p \vec{q} = p_{p||} |\vec{q}|$$

$$|\vec{q}|/\nu \to 1$$

Bjorken variable changes as:

$$x^* = \frac{Q^2}{2p_n^\mu q_\mu} = \frac{Q^2}{2\left((M_d - E_p)\nu + \vec{p}_p \vec{q}\right)}$$

$$x^* = \frac{Q^2}{2M\nu\left(2 - \frac{E_p - p_{p||}(|\vec{q}|/\nu)}{M}\right)} \approx \frac{Q^2}{2M\nu(2-\alpha_p)} = \frac{x}{2-\alpha_p}$$

$$\alpha_p = \frac{E_p - \vec{p}_p \hat{q}}{M_p}$$

Slide courtesy of C. Ayerbe

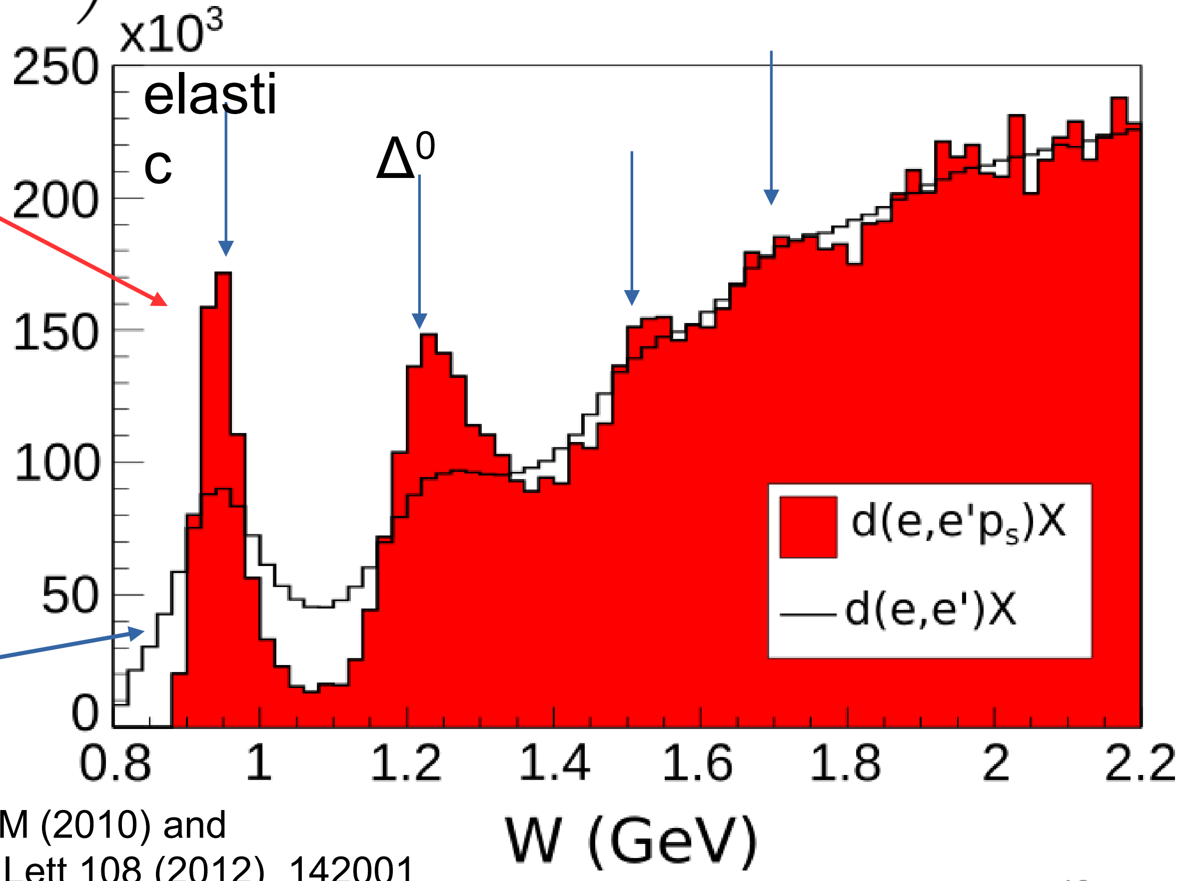
A successful method

$$W^{*2} = (p_n^\mu + q^\mu)^2 = M^{*2} - Q^2 + 2(M_d - E_s)\nu + 2\vec{p}_s\vec{q}$$
$$= M^{*2} - Q^2 + 2M\nu\left(2 - \frac{E_s - p_{s\|}(|\vec{q}|/\nu)}{M}\right)$$
$$\approx M^{*2} - Q^2 + 2M\nu(2 - \alpha_s)$$

Corrections make resonances stand out

Elastic and Δ peaks better resolved

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



N. Baillie PhD Thesis, W&M (2010) and
N. Baillie et al, Phys. Rev. Lett 108 (2012) 142001

Slide courtesy of C. Ayerbe

Tagging efficiency studies

- TDIS-n have several ways to calibrate the tagging efficiency not available for BoNuS6/12.
  - BoNuS rely the overall tagging efficiency in the normalization of the F_2^n/F_2^p at x≈3 from extractions of the deuteron. It implies a model dependence of the n-SF at x=3, thus BoNuS extraction at x≈3 is not truly an independent measurement.
  - Although not using the tagging method, MARATHON makes a similar normalization of the $^3H/^3He$ cross section ratio.
- TDIS-n can perform the same normalization, but the TDIS setup **opens the opportunity** of **two additional ways** to estimate the tagging efficiency:

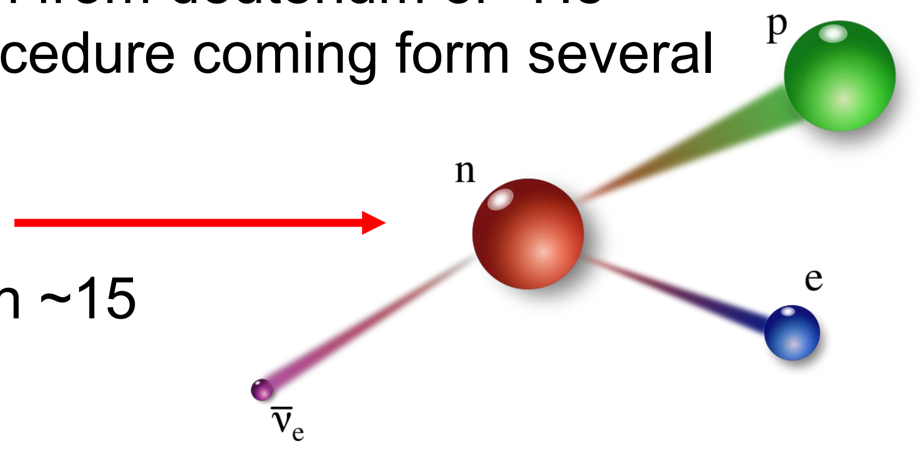
1. Through the use of SBS HCal to calibrate the mTPC Based on the elastic e-n cross section at moderate values of Q^2. It will provide a normalization factor and tagging efficiency determined **from a physics measurement.**
2. Making use of the high statistics of the measurement, the n-SF can be extracted from three different bins of the spectator and compare the highest momentum spectator in our analysis (90-100 MeV/c) with the *W. Meltnichouk et al. (1994)* prediction. Comparing the SF for the highest momentum to the lower spectator momentum, will **set upper limits to the off-shell corrections.**

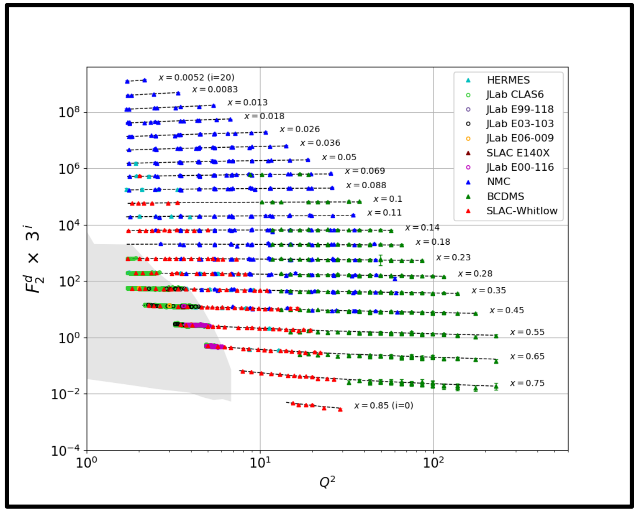
Slide courtesy of C. Ayerbe

Motivation I: neutron DIS structure function

- Proton and deuterium SF data is rich and very precise (**targets easily to produce**).
- Neutron SF data from fixed targets relies on extraction from deuterium or ^{3}He introducing large uncertainties from the extraction procedure coming form several sources, specially at medium-high *x:*
  - *Fermi motion*
  - *Off-shell effects*
  - *EMC effect*
  - *Final State interactions*

Free neutron decays in ~15 min





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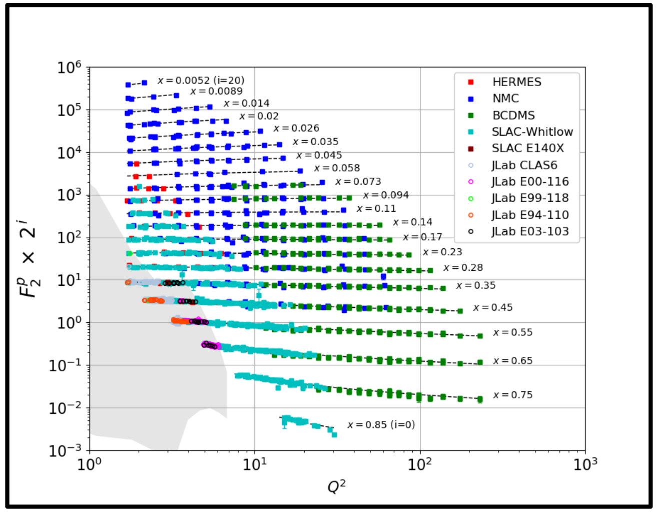

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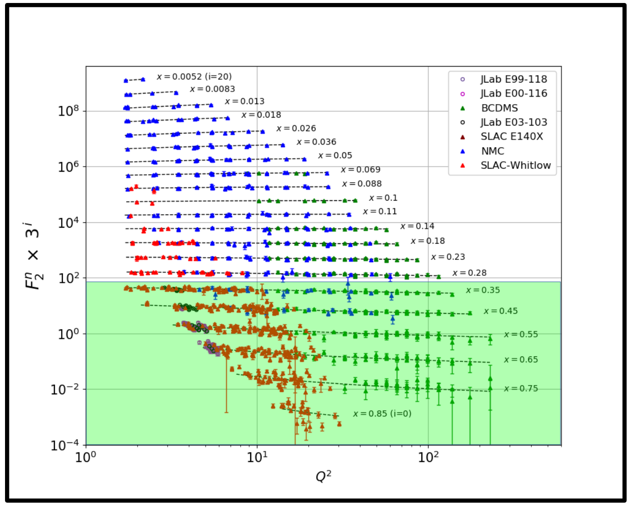
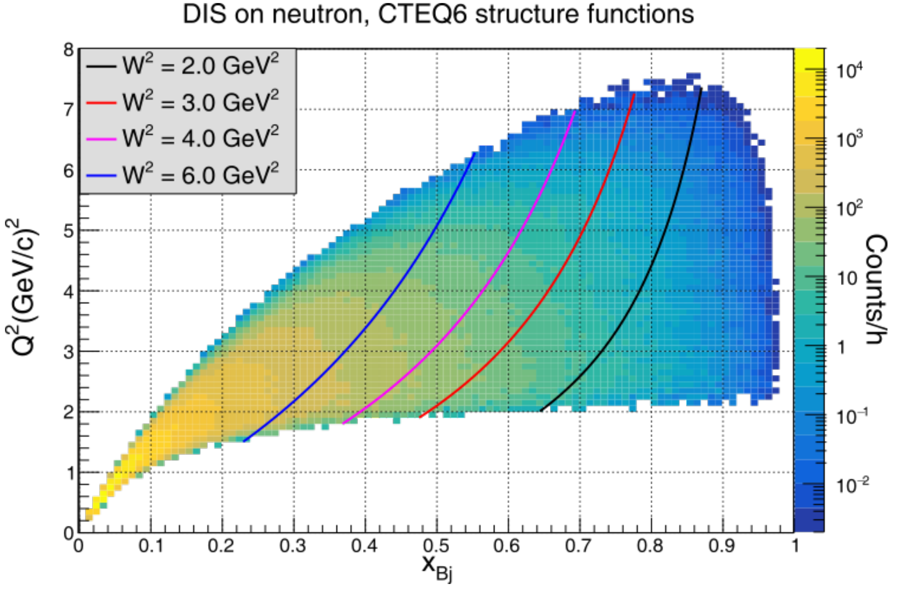


TDIS-n coverage

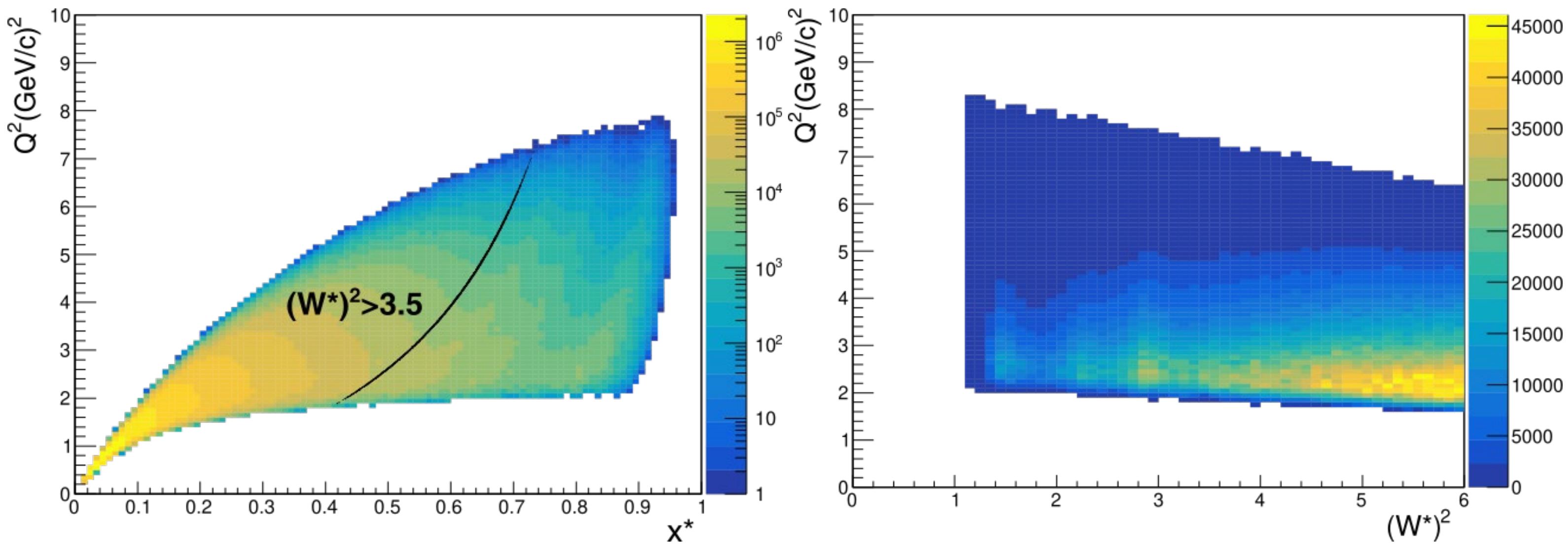
Slide courtesy of C. Ayerbe

P.M.King; TDIS-n run group proposal; JLab PAC49

TDIS-n projected results



SBS kinematic coverage of the TDIS configuration with G4SBS, making use of CTQ6 parametrization



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

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

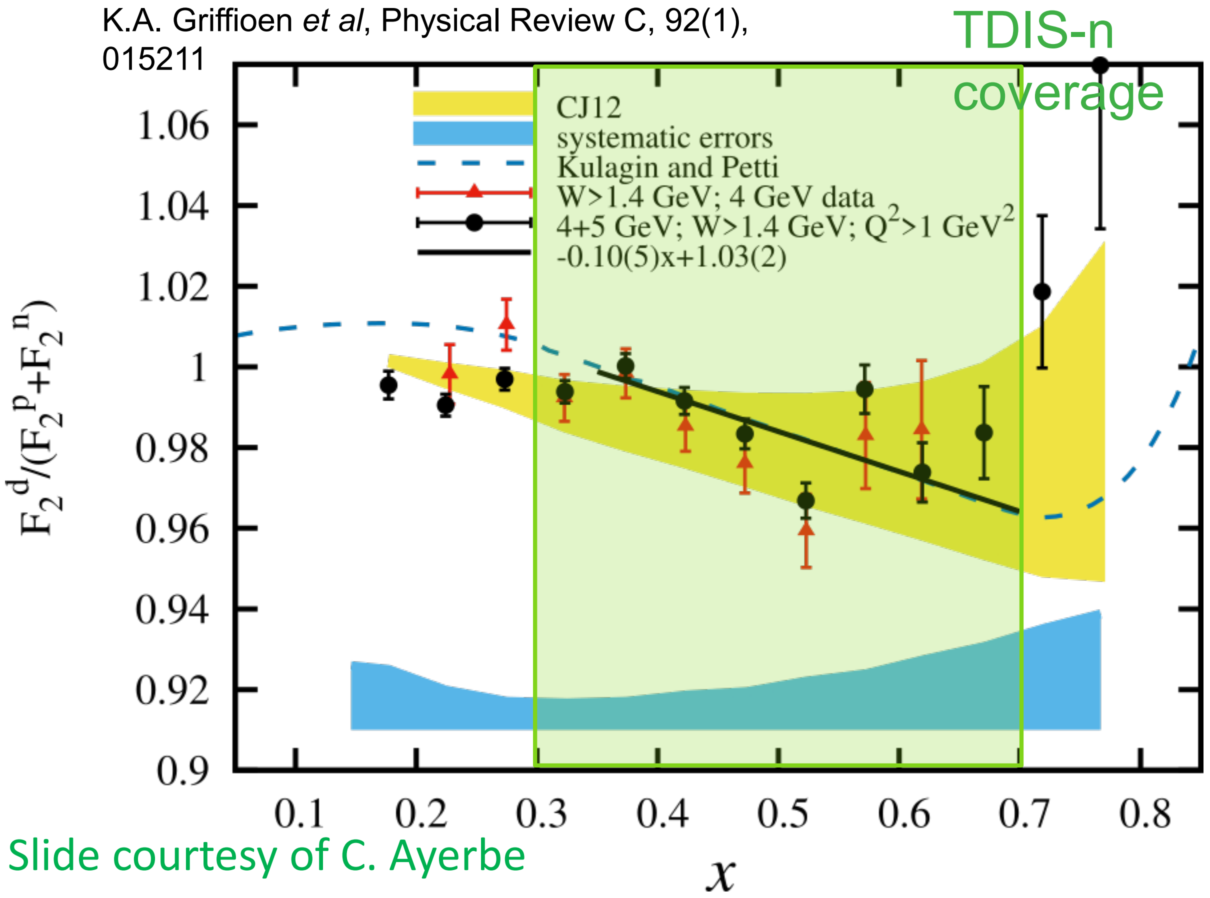
- Neutron cross section from F1F209
- Counts from luminosity of 1.5×10^{36} deuterons Hz/cm^{-2} and 5 days beam
- Fraction of spectator protons with 60<p<100 MeV/c and θ_{pq} > 100 is 9.9% (Av18)
- 50% spectator efficiency + 80% SBS efficiency and livetime

Slide courtesy of C. Ayerbe

Motivation II: EMC effect in the deuteron

Similarly as BoNuS experiments, we plan to measure the proton and deuteron structure function from inclusive data. This, with the quasi-free neutron structure function, allows **a direct extraction** of the EMC effect in the deuteron.

K.A. Griffioen *et al*, Physical Review C, 92(1), 015211



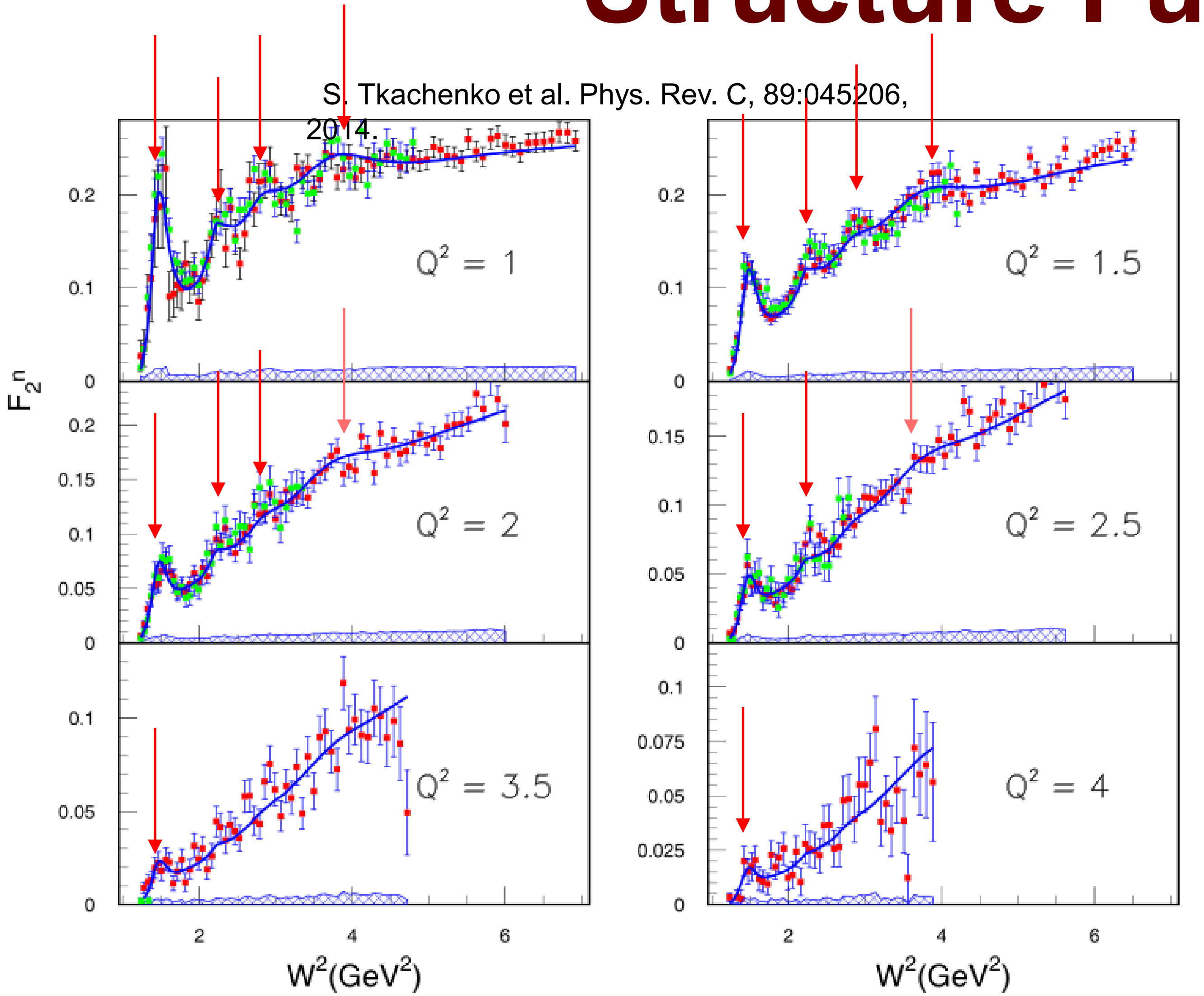
	SLOPE (0.3 < x < 0.7)
BoNuS	0.1 ± 0.05
High Virtuality model	0.05 ±0.03

$$\frac{F_2^d}{F_2^p + F_2^n}$$

Slide courtesy of C. Ayerbe

Motivation III: Resonance region Structure Functions

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

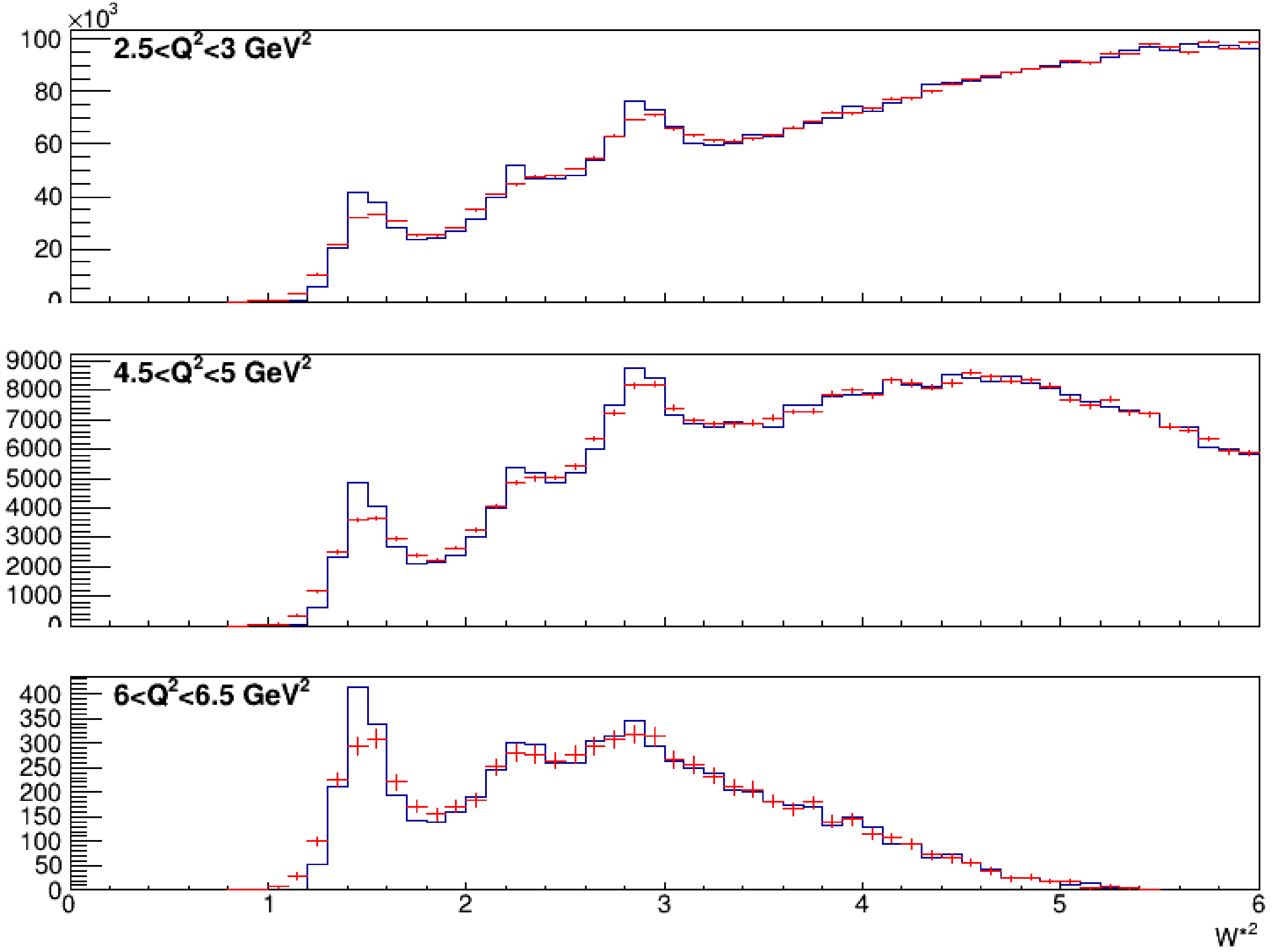


Extraction of the neutron SF in the resonance region suffers the same issues as in the DIS.

The BoNuS experiment has shown a great improvement in its extraction is possible, but it is evident that the resonant structure is visible only **at low Q^2 and W^2 mainly to the low statistics.**

Slide courtesy of C. Ayerbe

TDIS-n projected results: Resonance SF



Projected results of the n-SF as a function of W^{*2} for three Q^2 bins.

The estimated figure-of-merit i**s 7 times higher** than BoNuS12 in the overlap region and **improving the statistics** at our larger Q^2 values.

Slide courtesy of C. Ayerbe

TDIS-n projected results: Resonance SF

In addition to the n-SF, we plan to analyze p- and d-SF in the resonance region which allows **better comparison of the three SF with common systematics**

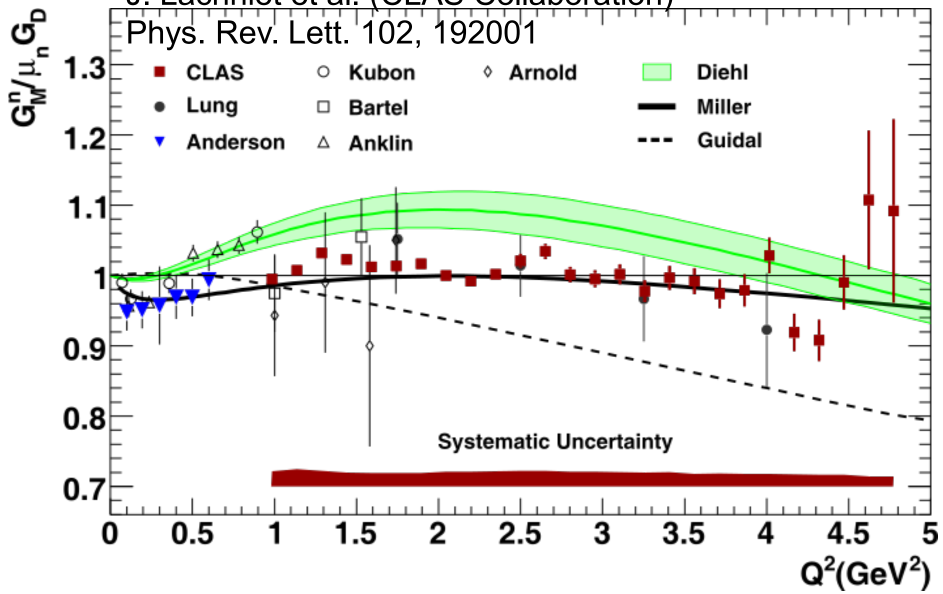
This allows to **compare the isospin structure** of resonance electroproduction, in particular for the Δ, if $\sigma_p \approx \sigma_n$ as expected for isovector transitions

High statistics of n-SF in the resonance region will allows additional **checks of duality** in neutron, **without relying on model dependent** extractions of neutron from deuteron.

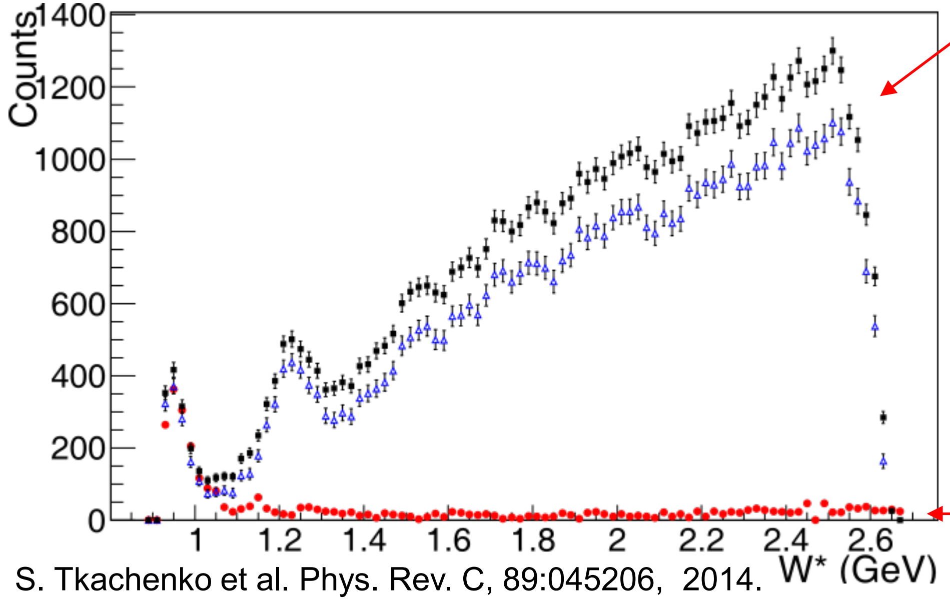
Slide courtesy of C. Ayerbe

Slide courtesy of C. Ayerbe

Motivation IV: Elastic *n* scattering



High precision measurements of G_{Mn} are limited to $Q^2 < 5\ (GeV/c)^2$ and they are mainly from one measurement.



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

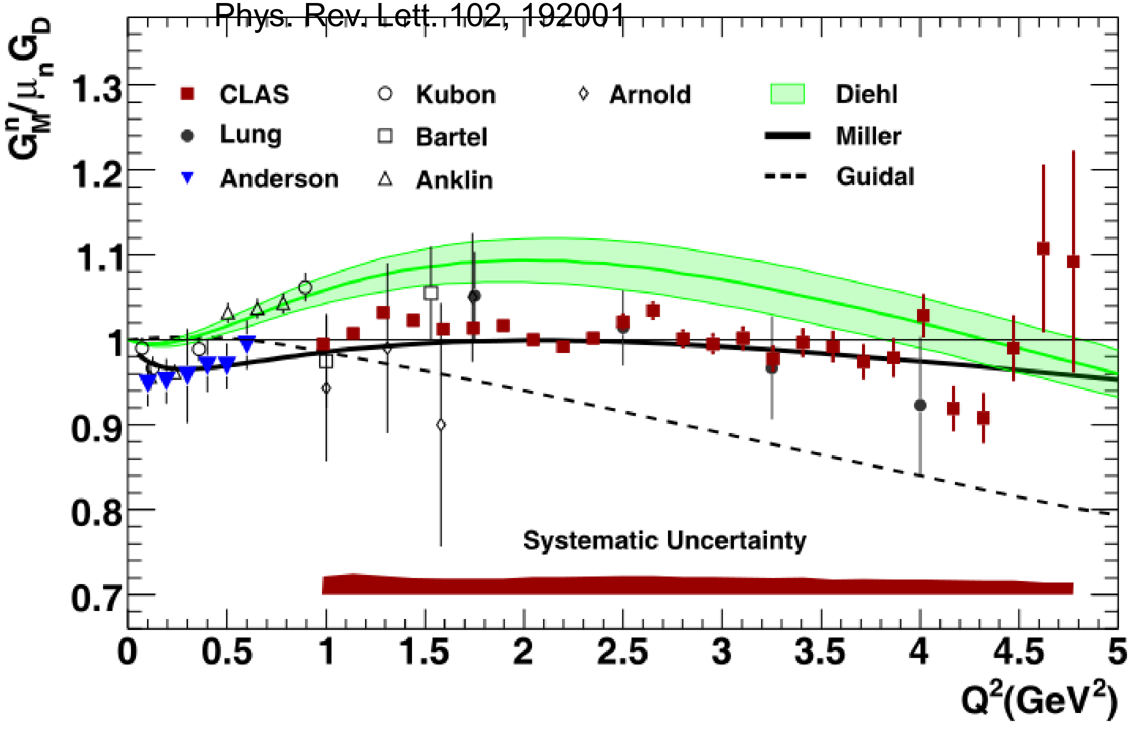
Before (black) and after (blue) accidentals correction data points

BoNuS has demonstrated the capability to extract the elastics events, but **the limited statistics was not enough** for a meaningful extraction of G_{Mn}

Simulated yield (red) for the elastic peak including radiative tail

TDIS-n projected results: elastic e-n scattering data

J. Lachniet et al. (CLAS Collaboration)
Phys. Rev. Lett. 102, 192001



Taking the elastic data and splitting into bins of ΔQ^2=0.5 (GeV/c)^2 we estimate:

- ~10k events for Q^2=7 (GeV/c)^2
- >100k events for Q^2 up to 6 (GeV/c)^2

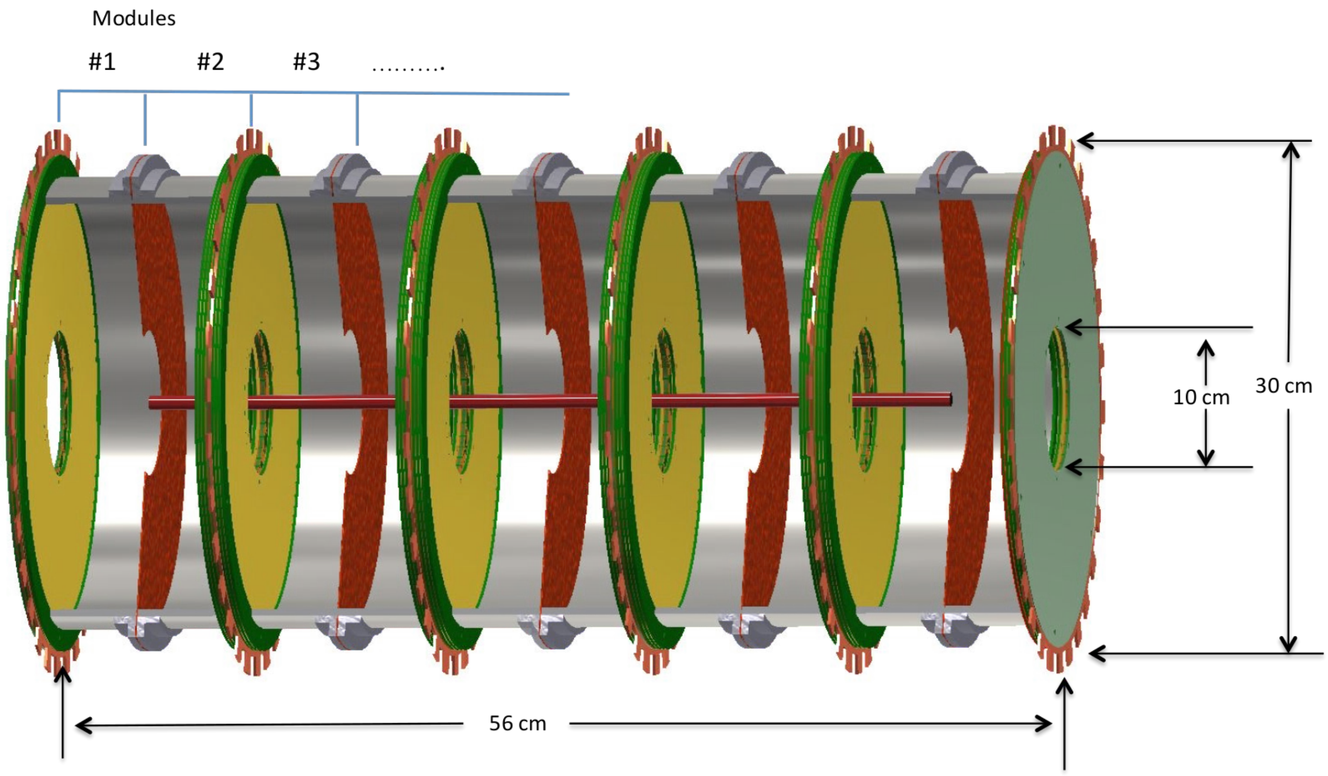
This will provide high precision overlap with the CLAS data and future 12 GeV proposed experiments that go from Q^2=3 to ~16 (GeV/c)^2 but with the particularity of being the **only measurement** using spectator tagging providing independent cross-checks with different systematics

Slide courtesy of C. Ayerbe

The multiple Time Projection Chamber: mTPC

The core of the TDIS project, is the mTPC. This detector has been designed to be high-rate capable and to operate at room temperature.

- 10 chambers joined in series
- Each chamber:
  - 5 cm long
  - Active volume inner radius 5 cm, outer 15 cm
- 40 cm long, 1 cm dia. straw target at ~4 atm
- 2 GEM layers per chamber
- Readout pad, concentrically segmented in 5x5 mm^2 (TBD) pad
  - 2500 pads/readout
- Drift gas $^4He/CH_4$ (70:30)



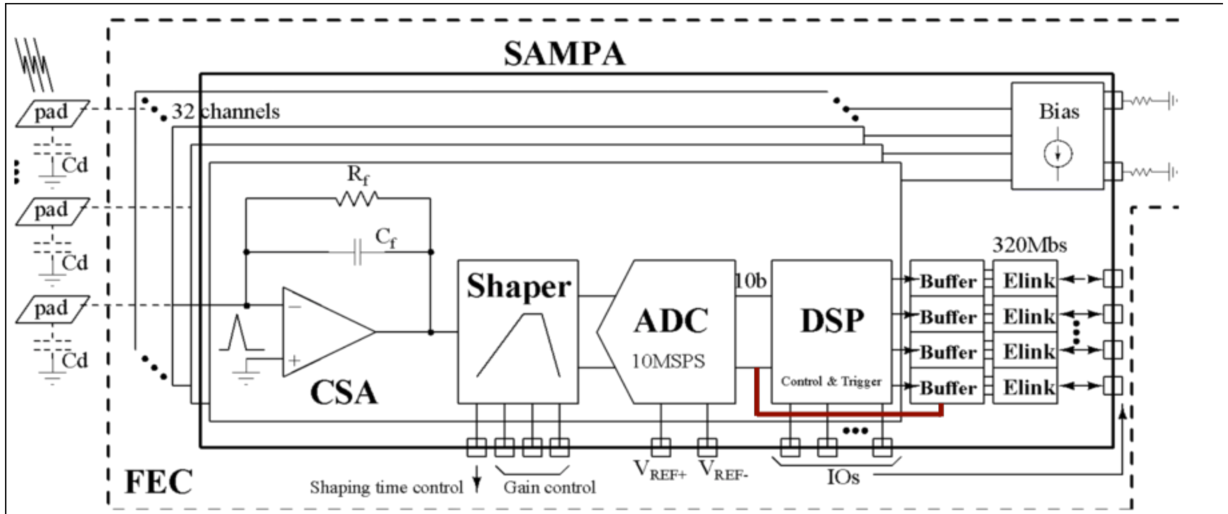
mTPC current design. Courtesy N.Liyanage

Slide courtesy of C. Ayerbe

MTPC readout and DAQ

SAMPA ASIC

- Developed by University of Sao Paulo (Brazil) for TPC in ALICE (LHC) upgrade
- Continuous sampling with high data readout speed up (ideal for high rate applications, can be operated triggered or trigger-less)
- SAMPA ASIC has 32chans/chip, 160ns shaping time, 10MSamples/s 10 Bit ADC,baseline correction, zero suppression



Courtesy of E. Jastrzembski
07/09/2019

Slide courtesy of C. Ayerbe