TDIS-n: Tagged DIS measurement of the Neutron Structure Function C12-15-006B

A run group proposal to Jefferson Lab PAC49

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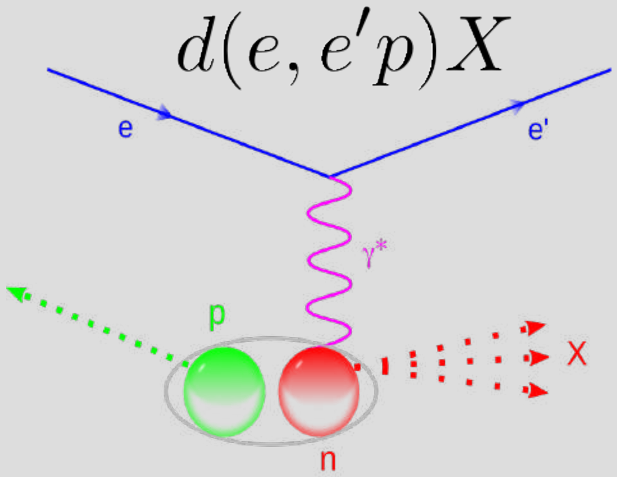
The TDIS experiment

- The TDIS experiment (E12-14-010) with the multi Time Projection Chamber (mTPC) in conjunction with SBS, offers an unique setup which fulfills the requirements for **low recoil proton momentum detection.**
- The primary goal of TDIS is to study pion structure function from tagged DIS measurements. With no modification to the original physics program and experimental settings, we can explore different physics topics.
  - In particular, access to neutron information ‘a la BONuS’

How the neutron could be considered free



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.

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

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

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:

Measuring the proton → $p_p = (E_p, \vec{p_p})$

We can infer this → $p_n = (M_d - E_p, -\vec{p_p})$

We assume that the off-shell SF is equal to the free SF *

$$F_2(x^*, \alpha_p, p_T, Q^2) = F_2^{\text{free}}(x^*, Q^2)$$

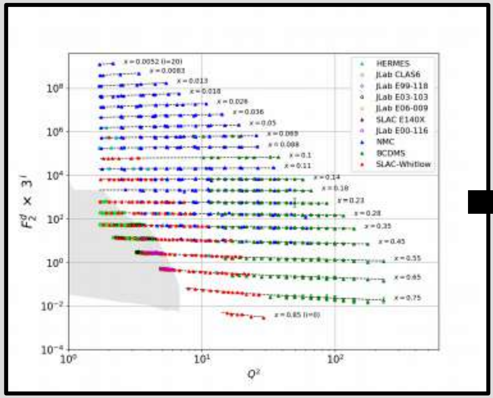
* true under certain conditions...

$p^2 \to M^2 \quad \alpha_p \to 1$

Motivation I: neutron DIS structure function

- Proton and deuterium SF data is rich and very precise **(stable targets)**.
- Neutron SF data from fixed targets relies on extraction from deuterium, introducing large uncertainties, from the extraction procedure, coming from several sources, especially at medium-high *x:*

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



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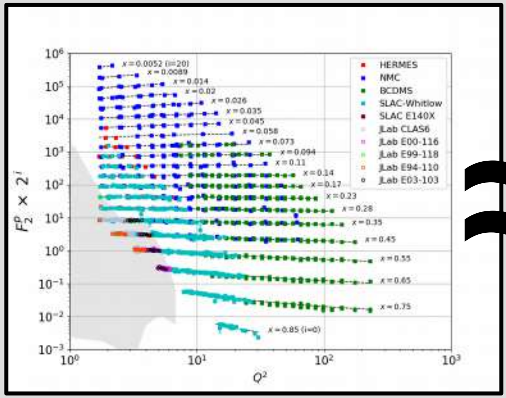

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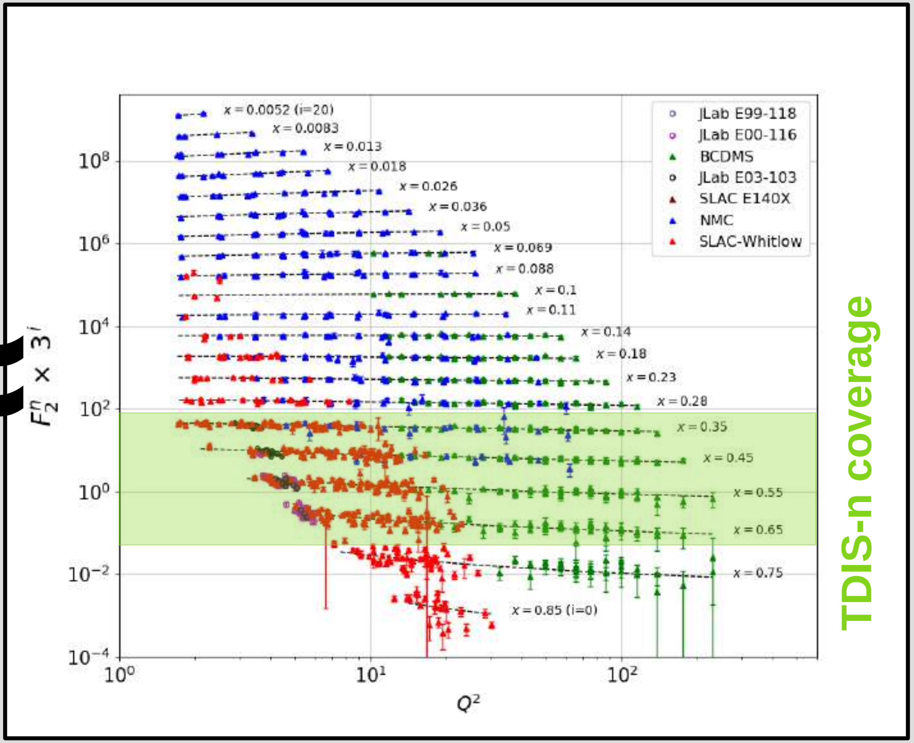
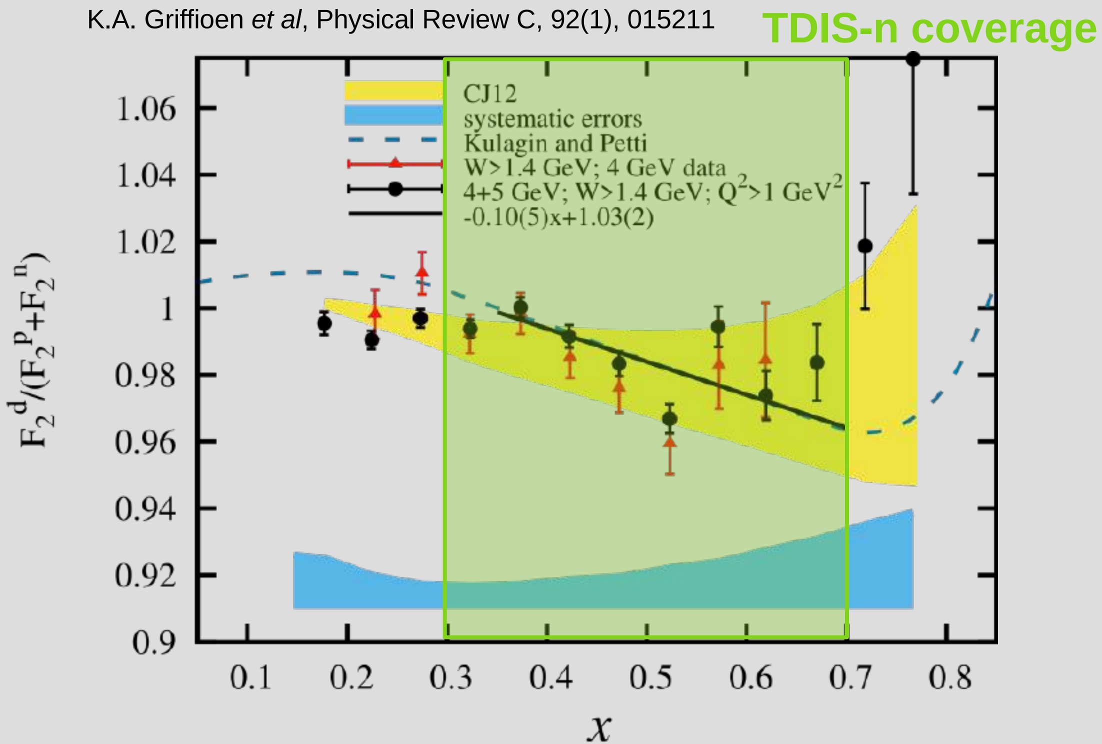


TDIS-n coverage

Motivation II: EMC effect in the deuteron

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

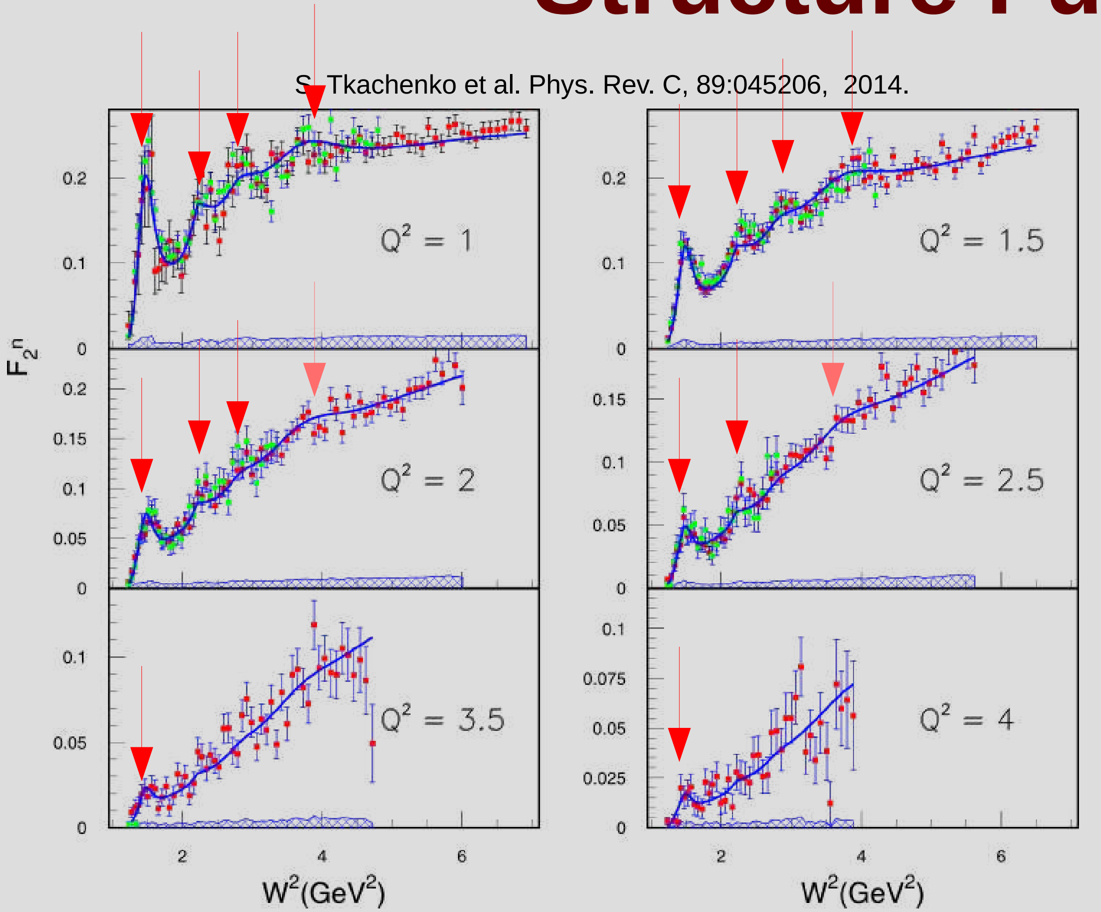


$$\frac{F_2^d}{F_2^p + F_2^n}$$

	SLOPE (0.3 < x < 0.7)
BoNuS	0.1 ± 0.05
J.Arrington and N.Fomin, PRL 123 (2019) 042501	
High Virtuality model	0.075
Local Density model	0.05

Motivation III: Resonance region Structure Functions

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

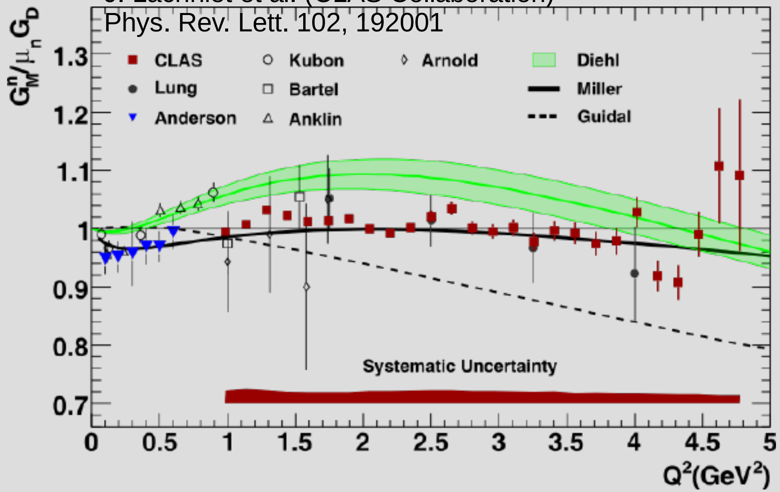


Extraction of the neutron SF in the resonance region suffers the same issues as in the DIS.

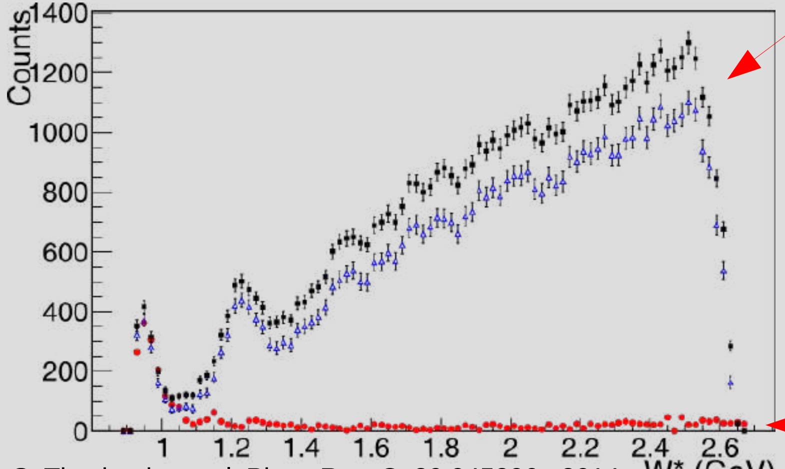
The BoNuS experiment has shown that resonance structure function extraction is possible but is limited by statistical precision in the **high Q^2 and W^2 region.**

Motivation IV: Elastic e-*n* scattering

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



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

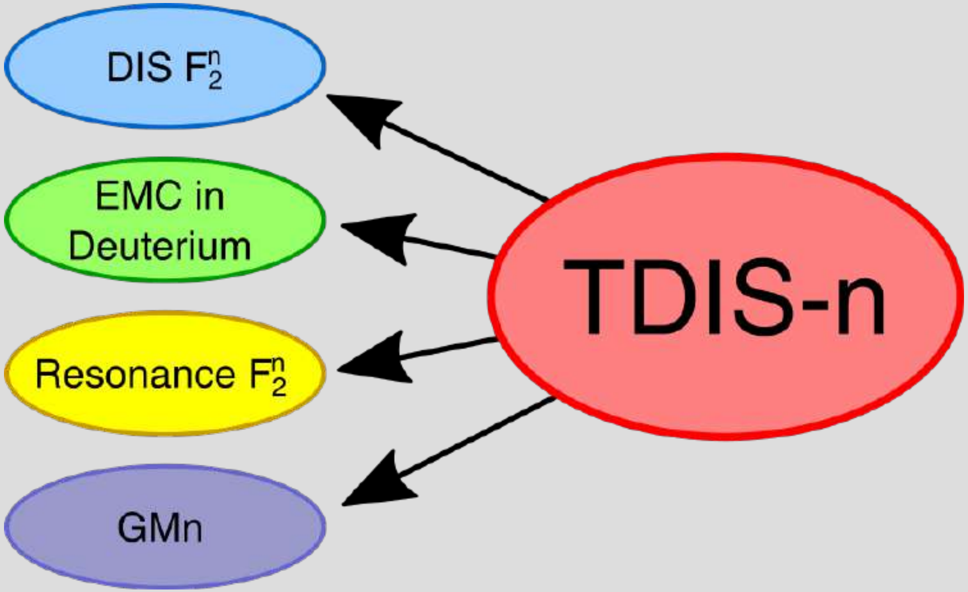
BoNuS demonstrated the capability to the isolate and model elastics events, but **the limited statistics did not allow for** a meaningful extraction of G_{Mn}

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

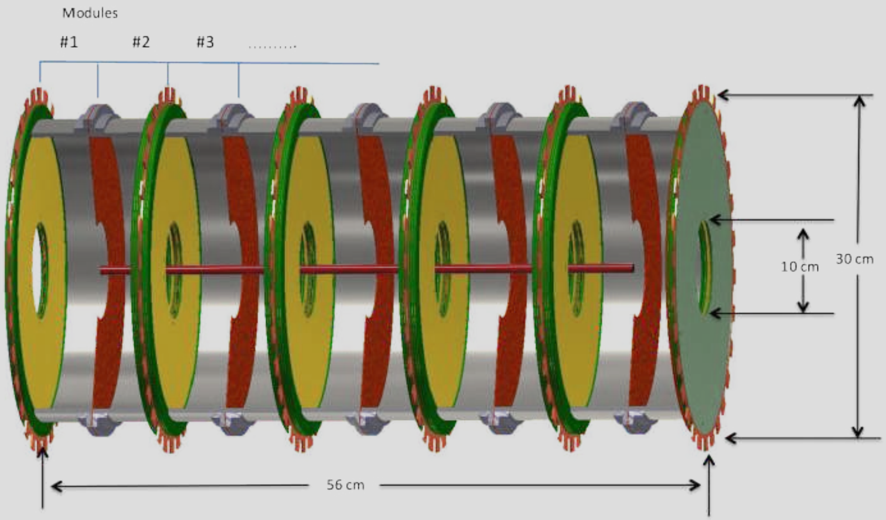
TDIS-n at Hall A

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.**

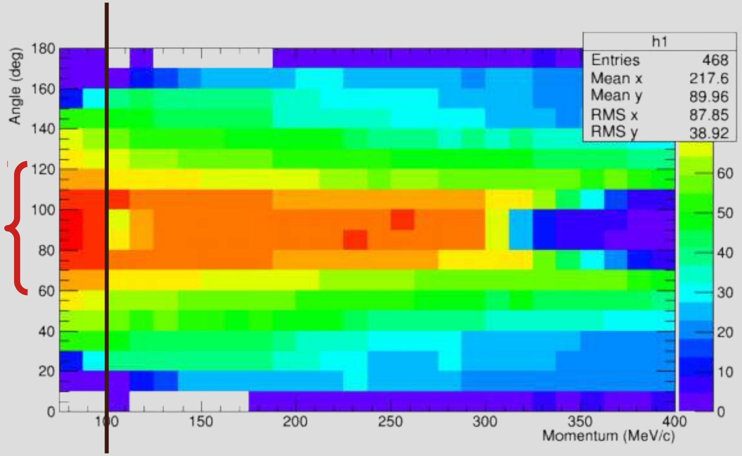
- ✔ An increase of 5-10 more statistics than BoNuS12 in the region of overlap (thus TDIS-n).
- ✔ **An independent normalization** check of the procedure used in BoNuS6/12.



The TDIS experiment



mTPC current design. Courtesy N.Liyanage



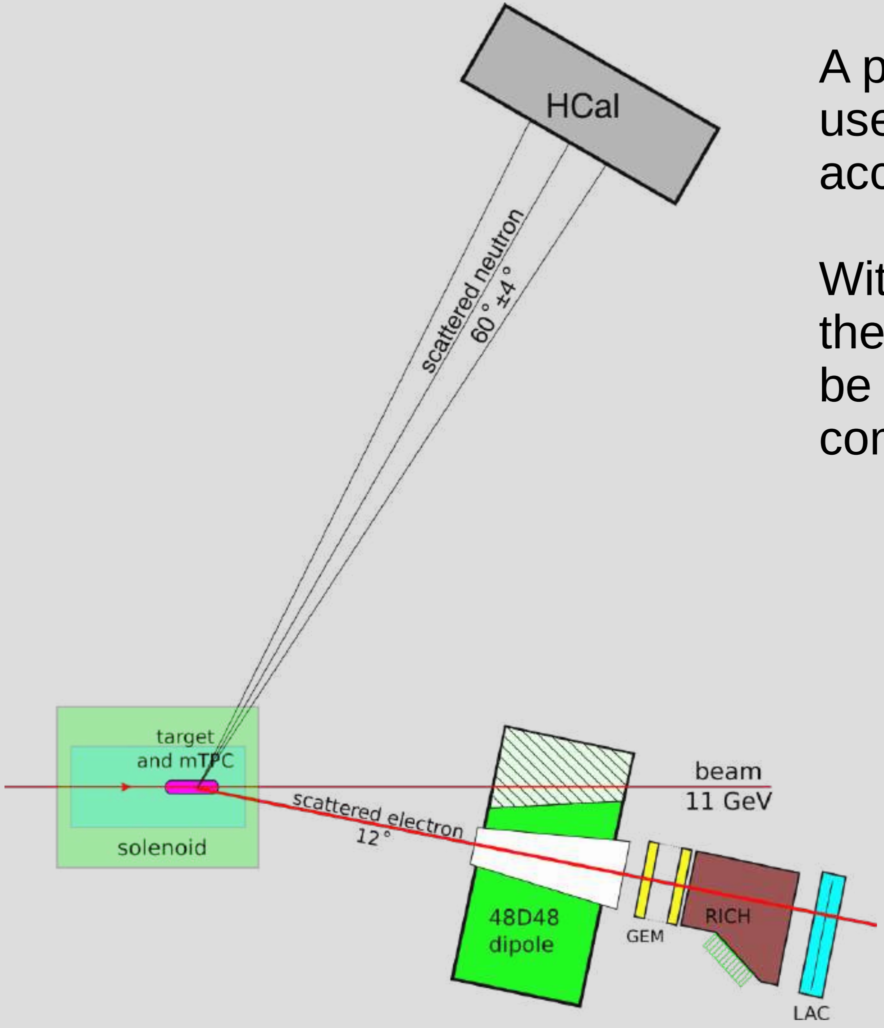
Efficiency > 50% for transverse recoil protons with p < 300 MeV/c

Latest TDIS configuration from conditional release document used for our studies and satisfactory as is

Running over Hydrogen or Deuterium at 4 atm with a beam intensity of 50 μA will be capable of providing instantaneous luminosity of:

2.9×10^{36} cm^{-2} s^{-1}

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 by HCal.

The calibration will be performed at:

- Energy beam: 4.4 GeV
- e-N luminosity of 0.3×10^{36} Hz/cm^2
- HCal placed 15 m from target at 60 deg
- ~95 % neutron detection efficiency

Such a calibration will allow for a cross-check of the physics-based efficiency determinations

Systematic studies of tagging

- BoNuS6 calibrates the overall tagging efficiency by matching F_2^n/F_2^p at x ≈ 0.3 to extractions from the deuteron.

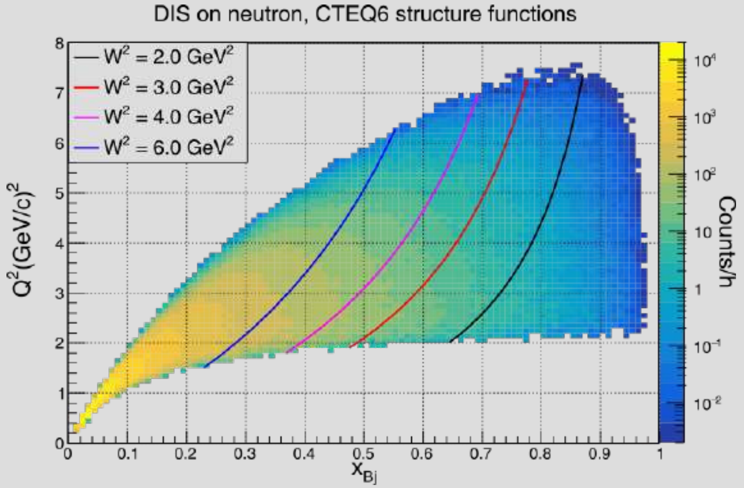
- TDIS-n provides additional cross checks of the normalization procedure:

  1. Can perform same physics normalization against F_2^n/F_2^p at x=0.3, but also an **independent physics normalization** using high statistics **e-n elastic scattering** at lower Q^2 (without using HCAL).
  2. Can use SBS (electron) + HCAL (neutron) elastics to identify sample of events with expected spectator proton for direct comparison to mTPC

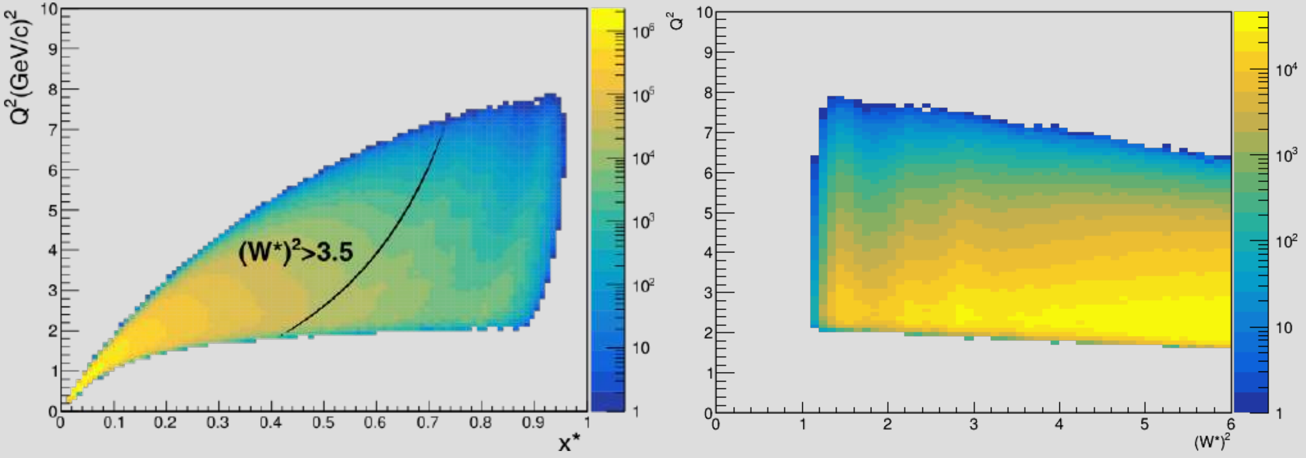
- TDIS-n can also set limits on FSI and off-shell corrections by looking at the neutron structure function (or elastic scattering) as a function of spectator momentum

  ✔ Divide the 60-100 MeV/c region into 3 momentum bins, and compare largest spectator momentum (largest off-shell effects) to the lower momentum data

TDIS-n projected results



SBS kinematic coverage of the TDIS configuration with G4SBS, making use of CTEQ6 parametrization

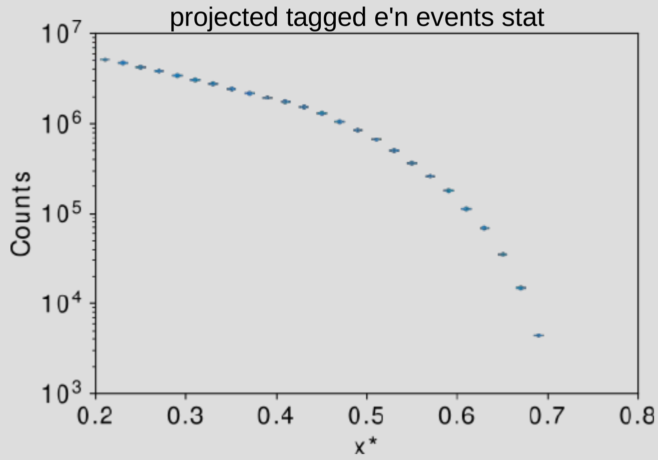


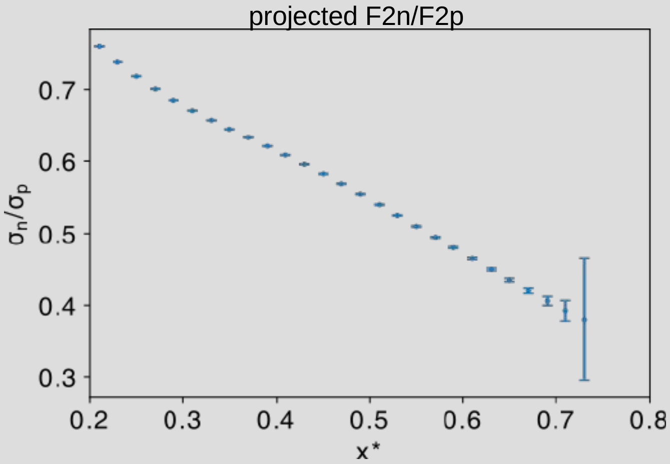
FS kinematic coverage for SBS at 12º, making use of F1F209 model.
* indicates the correction by tagging.

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

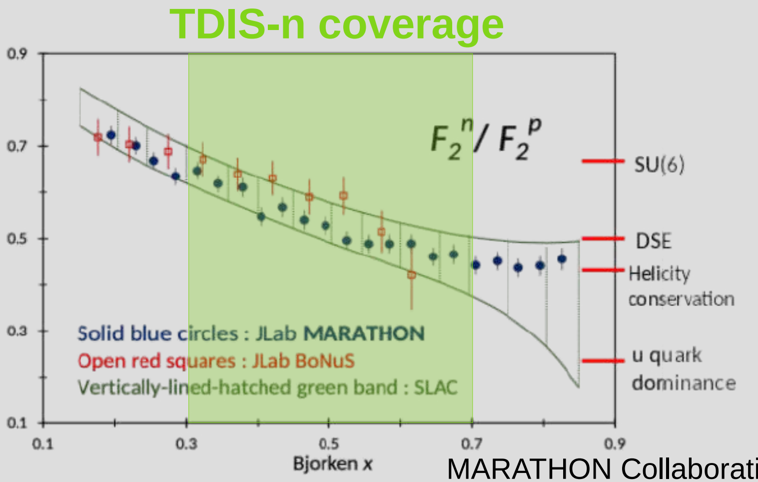
- Neutron cross section from F1F209
- Counts from luminosity of 1.5×10^{36} deuterons Hz/cm^2 and 5 days beam
- Fraction of spectator protons with 60<p<100 MeV/c and θ_{pq} > 100 is 9.9% (Av18)
- 50% spectator efficiency + 80% SBS efficiency and livetime

TDIS-n projected results: DIS and EMC





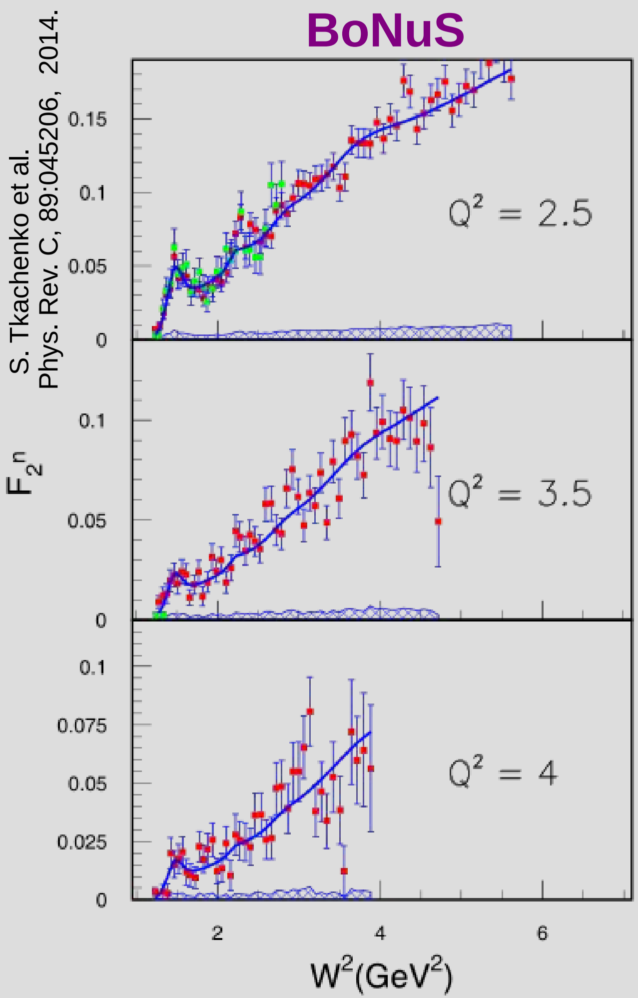
- It will provide tests of the tagging efficiency **not achievable** by BoNuS12
- Making use of the inclusive TDIS data, in the region 0.3<x<0.7 provides an excellent opportunity to compare the deuteron to proton+neutron SF (EMC effect)
- We project a **factor 7 higher statistics** than the BONUS12 measurement in the region of overlap.

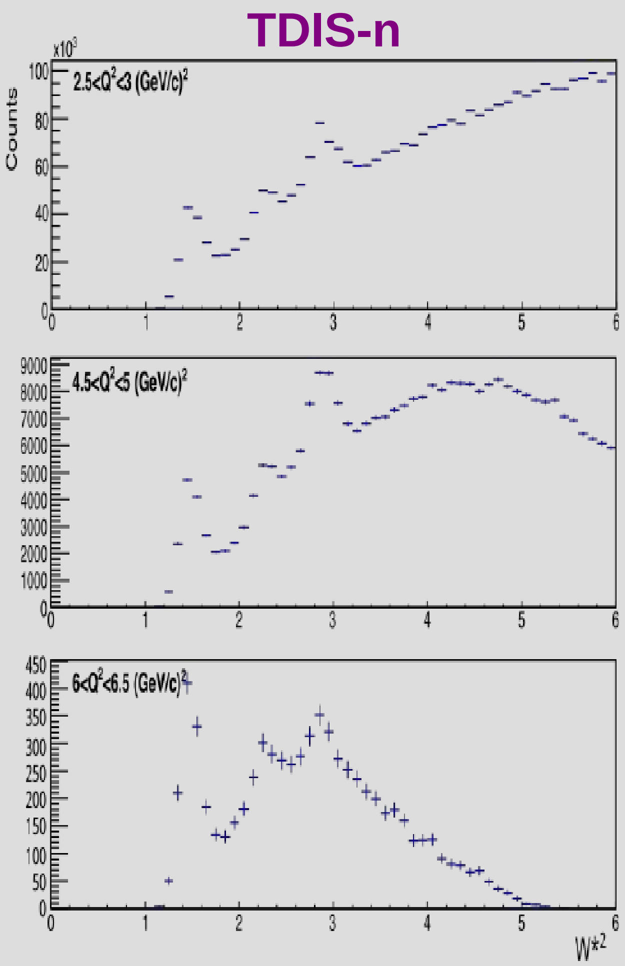


These results provide a comparison with the recent MARATHON data with **different systematics.**

MARATHON Collaboration arXiv hep-ex:2104.05850 2021

TDIS-n projected results: Resonance SF I





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

TDIS-n projected results: Resonance SF II

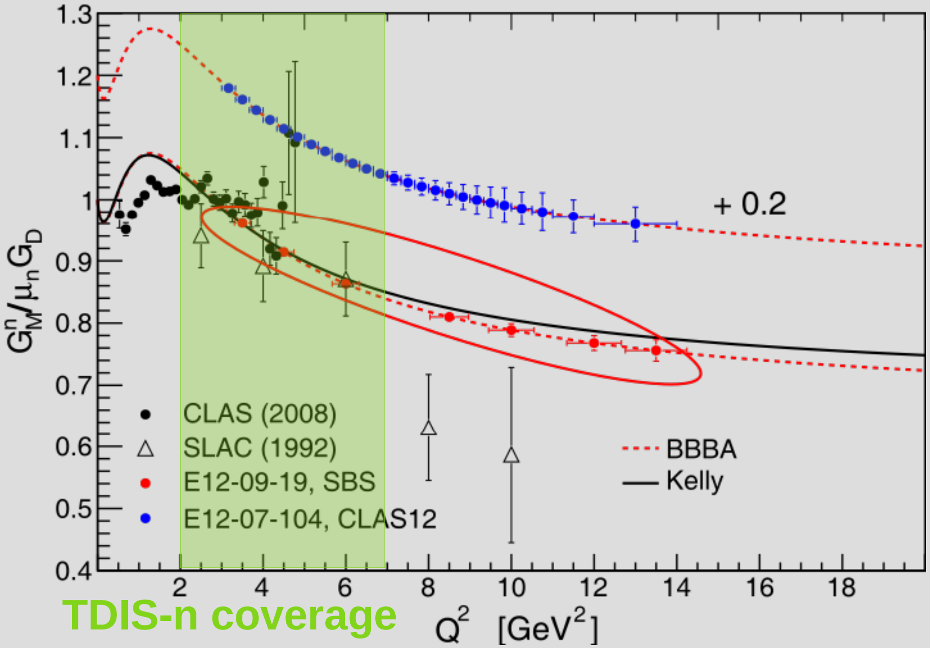
In addition to the n-SF, we plan to analyze p- and d-SF in the resonance region which allows **better comparison of the three SF with common systematics**

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.

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

B. Wojtsekhowski, January 22, 2021, Hall A/C meeting



Taking the elastic data and splitting into bins of ΔQ^2=0.5 (GeV/c)^2 we estimate sub-percent statistical precision

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

Summary

TDIS-n will extract the neutron and proton SF **from the data taken during the TDIS experiment** and the tagged elastic *n(e, e'n)* from the calibration run.

With higher statistics and a different normalization method, TDIS-n will cross check previous results at intermediate values of x.

BACKUP SLIDES

Executive summary

We propose to extract the neutron structure function from the electron-deuterium scattering, making use of the spectator tagging method.

This method, which consists of detecting low momentum spectator protons in order to identify on-shell nucleons, has been shown to be feasible; we will also provide new tests of the tagging technique.

TDIS-n will reach $Q^2 \sim 6\text{-}7$ $(\mathrm{GeV}/c)^2$ with a statistical accuracy of better that 3% at large x.

Our projected results will be compared with those from BoNuS6 experiment, the only published JLab data making use of the tagging technique.

This experiment will use the SBS experimental setup and the multiple Time Projection Chamber (mTPC) of the Conditionally Approved Hall A TDIS experiment (E12-14-010).

Relationship with other experiments

E12-10-002: inclusive measurements of p- and d-SF at large x and Q^2. Will extract n-SF focusing at large Q^2

- TDIS-n lightly overlaps their kinematic region

MARATHON: extraction of the n- to p-SF ratio (one of their goals)

- TDIS-n won't reach x>0.7 as MARATHON goal, but will be complementary at the overlap region, providing an independent cross-check of the normalization. Also, they have a model-dependence in the n/p extraction in order to remove smearing in ^{3}He and ^{3}H. TDIS-n control the off-shell effect by directly selecting events with low initial momentum.

BoNuS12: extraction of the free n-SF over a wide x and Q^2 region with the same technique as TDIS-n

- Although TDIS-n won't reach high x values, we can provide independent checke of the tagging efficiency and x7 increase of statistics.

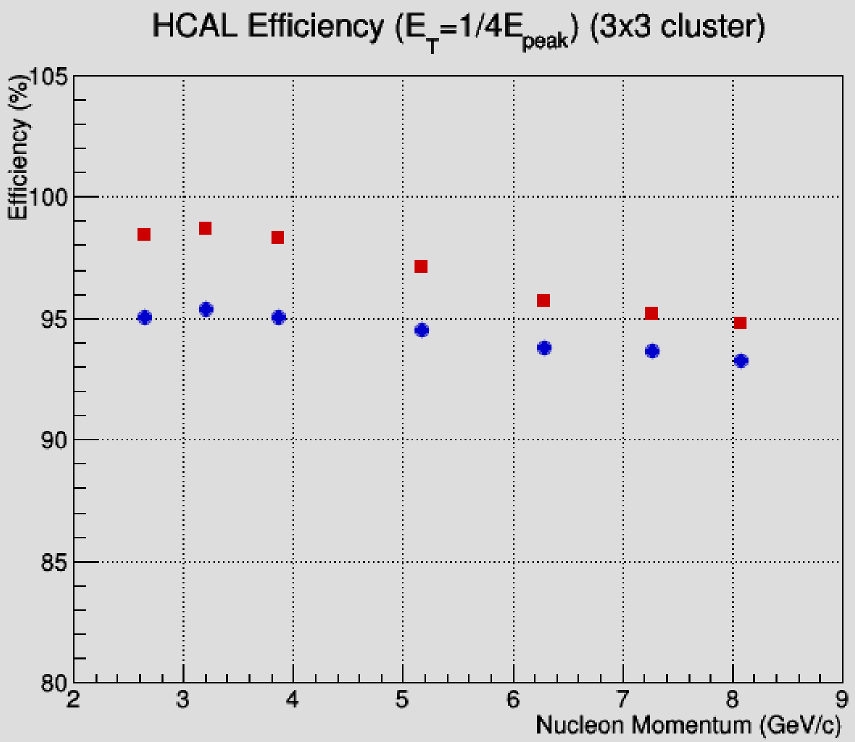
ALERT: focusing to large spectator momentum, it will have have acceptance to low-momentum tagging, could make similar measurements to BoNuS12 and TDIS-n.

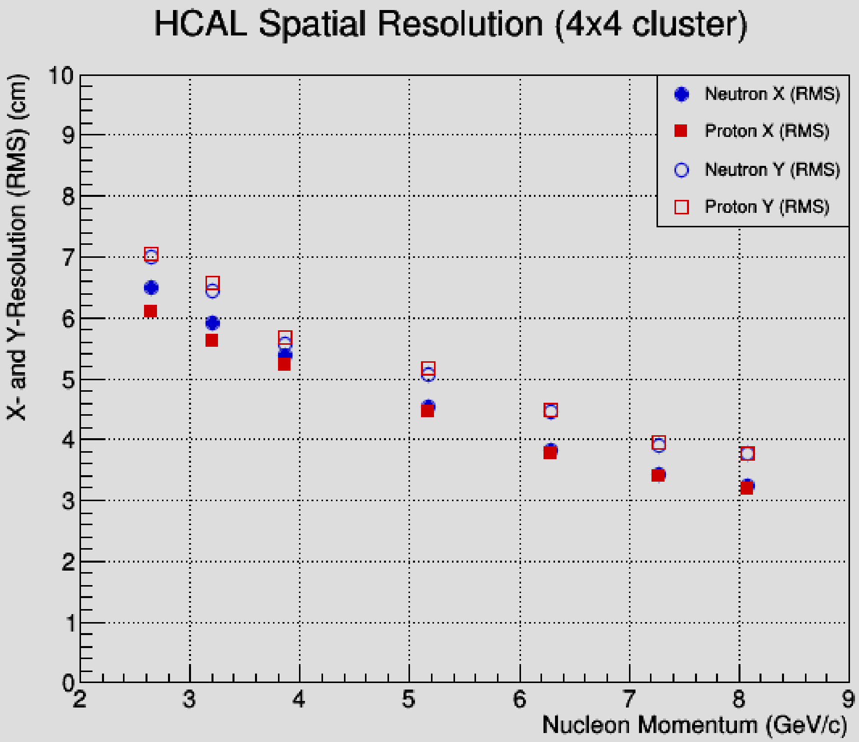
- As BoNuS12, ALERT will have larger kinematic coverage than TDIS-n, but with a factor ~15 lower statistics in our overlapping kinematics.

E12-07-104 (CLAS) and E12-09-109 (SBS): will extract GMn at high Q^2.

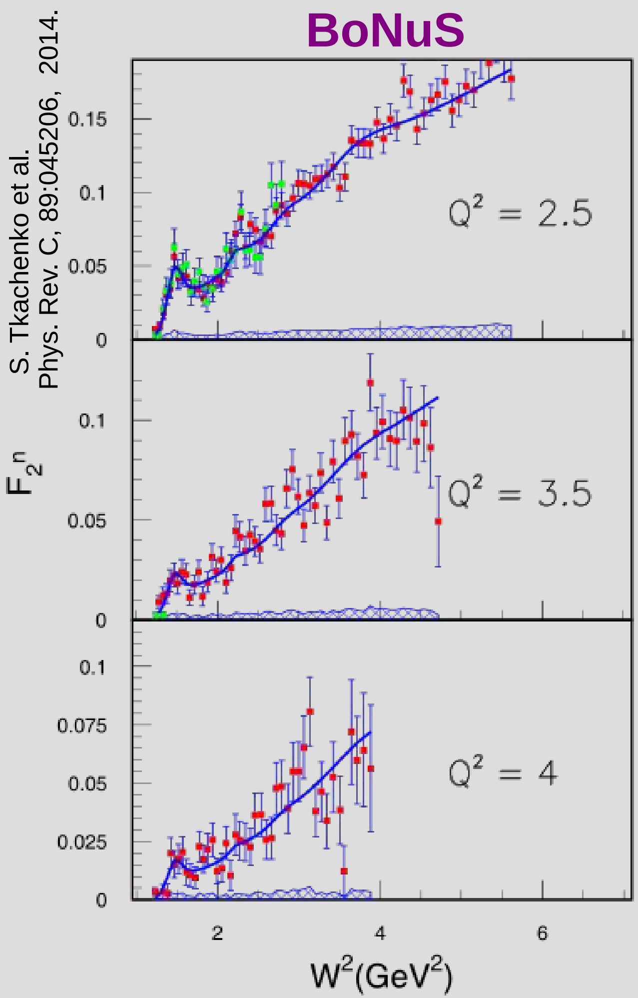
- Both experiments will extend higher Q2 than TDIS-n, both in the overlap region, TDIS-n could extract GMn with a completely different set of systematics.

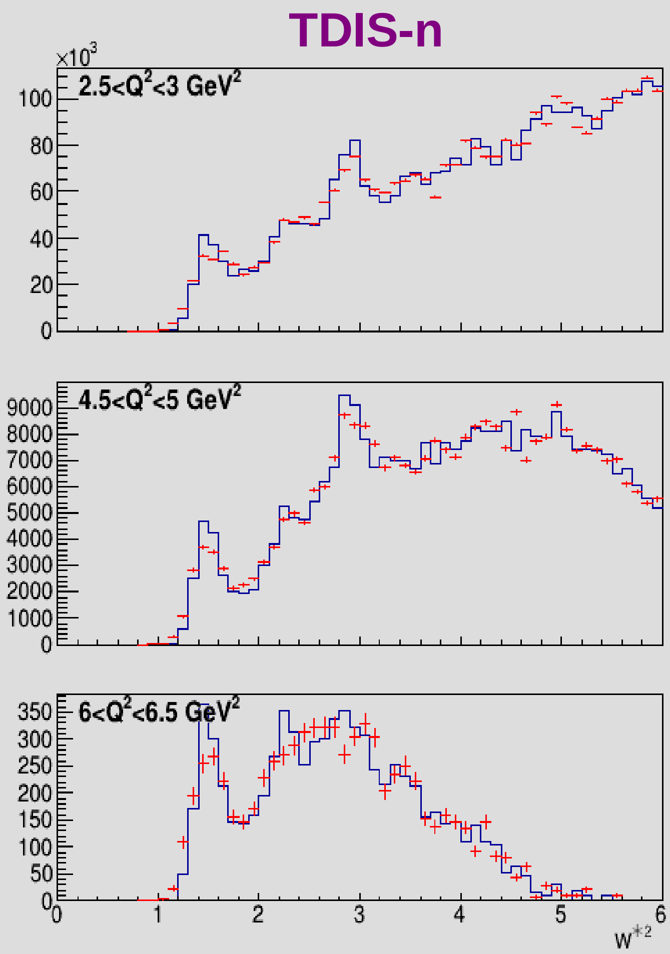
HCal efficiency and position resolution





TDIS-n projected results: Resonance SF I





Projected results of the n-SF as a function of W^{*2} with(red) / without 0.5% of momentum smearing for three Q^2 selected bins

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

Simulations are without resolution (SBS or tagging). First estimate of **the impact yields a 25% reduction** in the height of the prominent peaks. Final resolution **should be about the same as BONUS 12**

Spectator tagging formalism

A.V. Klimenko et al,
Phys. Rev. C73 035212 (2006)

$$\frac{d\sigma}{dx^* dQ^2} = \frac{4\pi\alpha_{EM}^2}{x^* Q^4}\left[\frac{y^2}{2(1+R)} + (1-y) + \frac{M^{*2}x^{*2}y^2}{Q^2}\frac{1-R}{1+R}\right]$$

$$\times F_2(x^*, \alpha_p, p_T, Q^2)\,\underbrace{S(\alpha_p, p_T)\frac{d\alpha_p}{\alpha_p}d^2p_T}$$

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

Modified tagged variables

$$\boxed{M^{*2} = (M_d - E_p)^2 - \vec{p}_p^{\;2}}$$

Off-shell structure function of the struck neutron

Probability of finding the spectator at p_T and α_p with the given kinematics

$$R = \frac{\sigma_L}{\sigma_T}$$

$$y = \nu / E$$

We assume here that the off-shell SF is equal to the free SF *

$$F_2(x^*, \alpha_p, p_T, Q^2) = F_2^{\text{free}}(x^*, Q^2)$$

* true under certain conditions...

$p^2 \to M^2 \quad \alpha_p \to 1$

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:

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

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

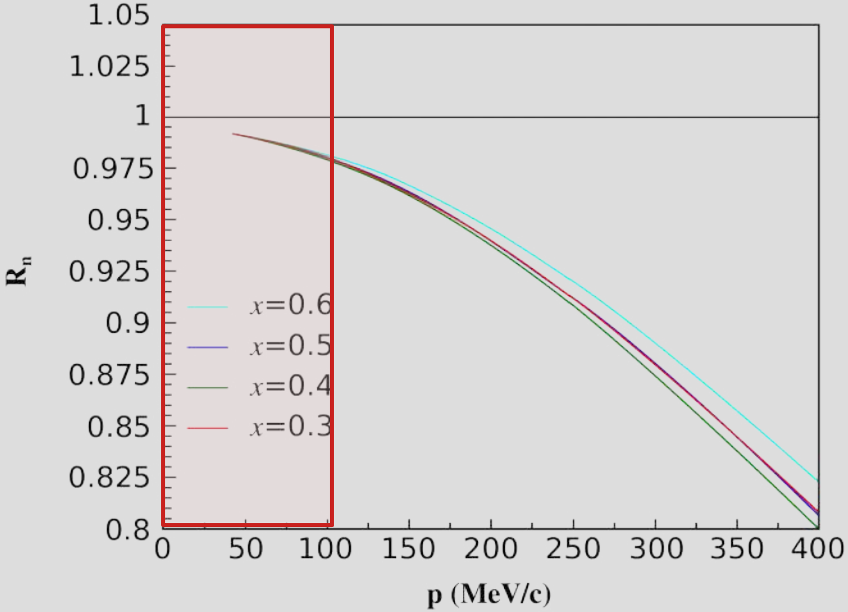
$$\alpha_p = \frac{E_p - \vec{p}_p \hat{q}}{M_p}$$

Corrections in extracting the free neutron

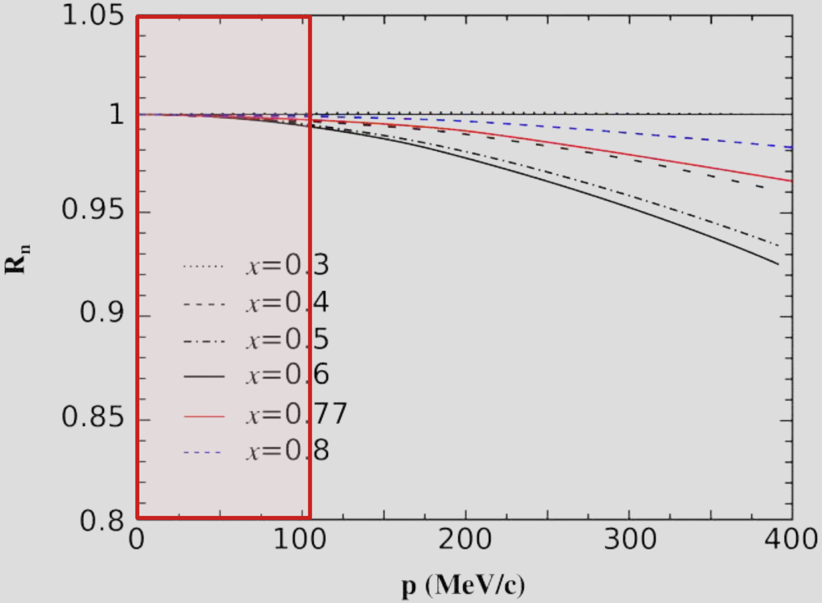
Off-shell effect dependence

$$R_n \equiv F_2^{n(\mathrm{eff})} / F_2^n$$

S. Liuti et al, Phys. Lett. B 356(1995) 157



W. Melnitchouk et al, Phys. Lett. B 335(1994) 11
updated (2010)



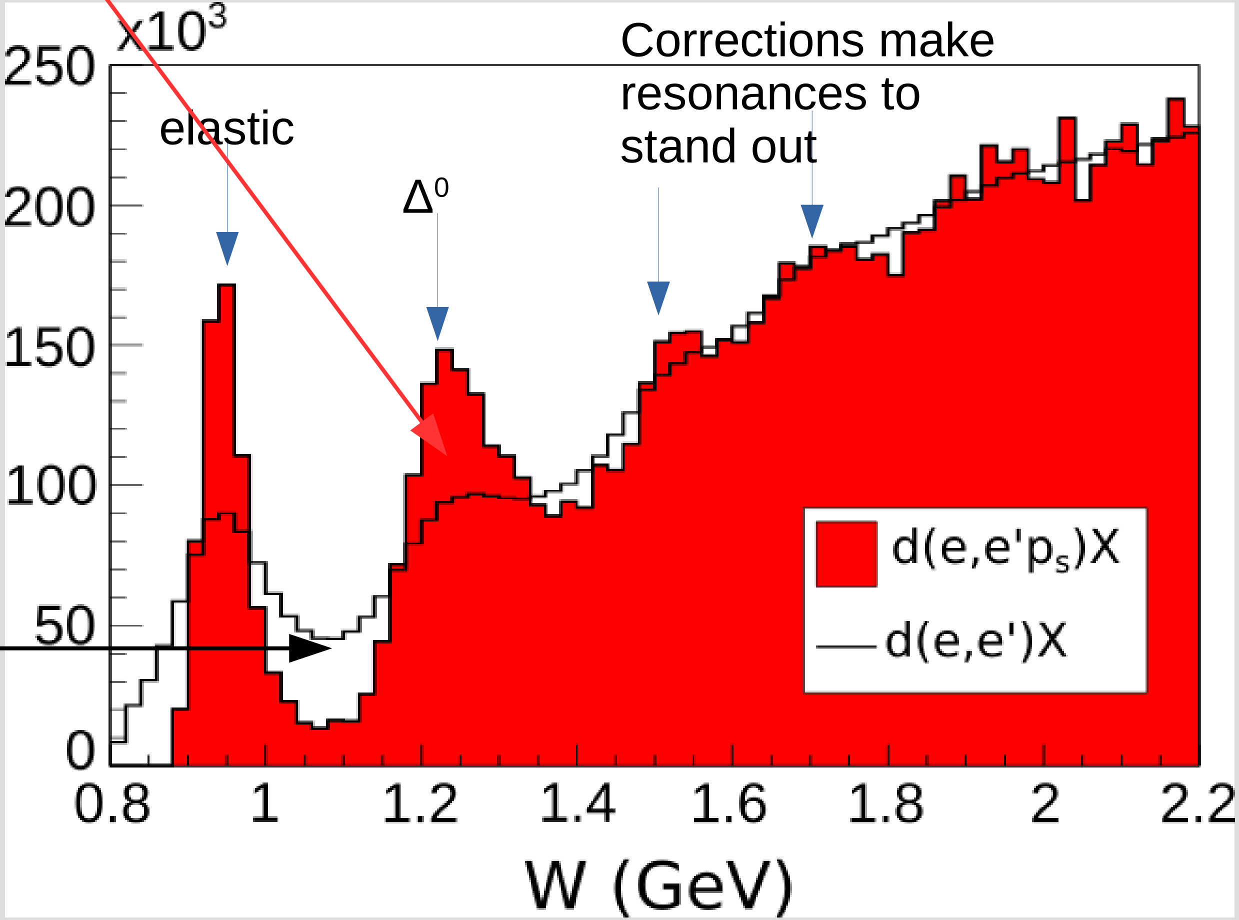
At very low recoil momentum, the deviation from unity < 1-2%

A successful method

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

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

A successful method

$$W^{*2} = (p_n^\mu + q^\mu)^2 = M^{*2} - Q^2 + 2(M_d - E_s)\nu + 2\vec{p}_s\vec{q}$$

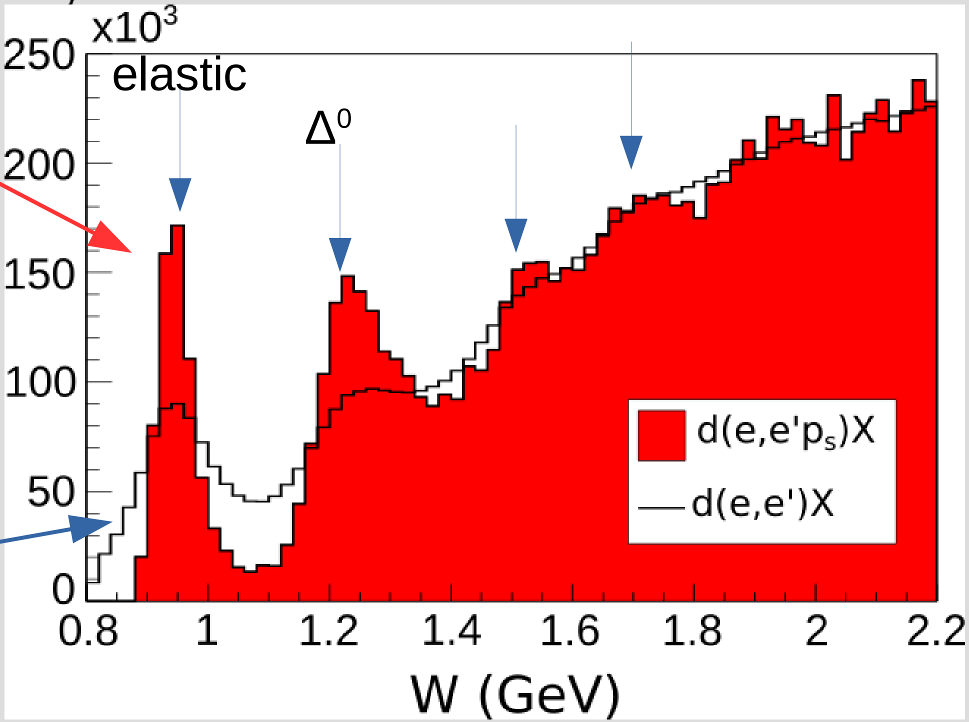
$$= M^{*2} - Q^2 + 2M\nu\left(2 - \frac{E_s - p_{s\|}(|\vec{q}|/\nu)}{M}\right)$$

$$\approx \boxed{M^{*2} - Q^2 + 2M\nu(2 - \alpha_s)}$$

Corrections make resonances to stand out

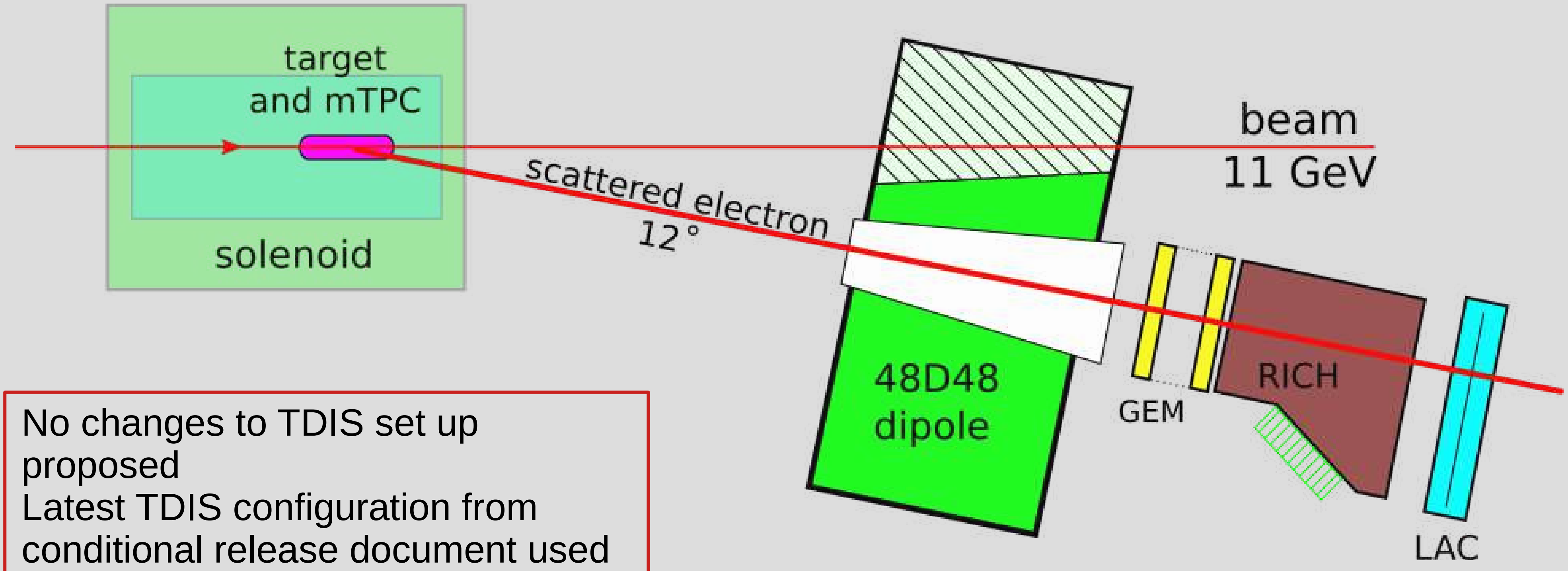
Elastic and Δ peaks better resolved

$$\boxed{W^2 = M^2 + 2M\nu - Q^2}$$



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

Experimental layout

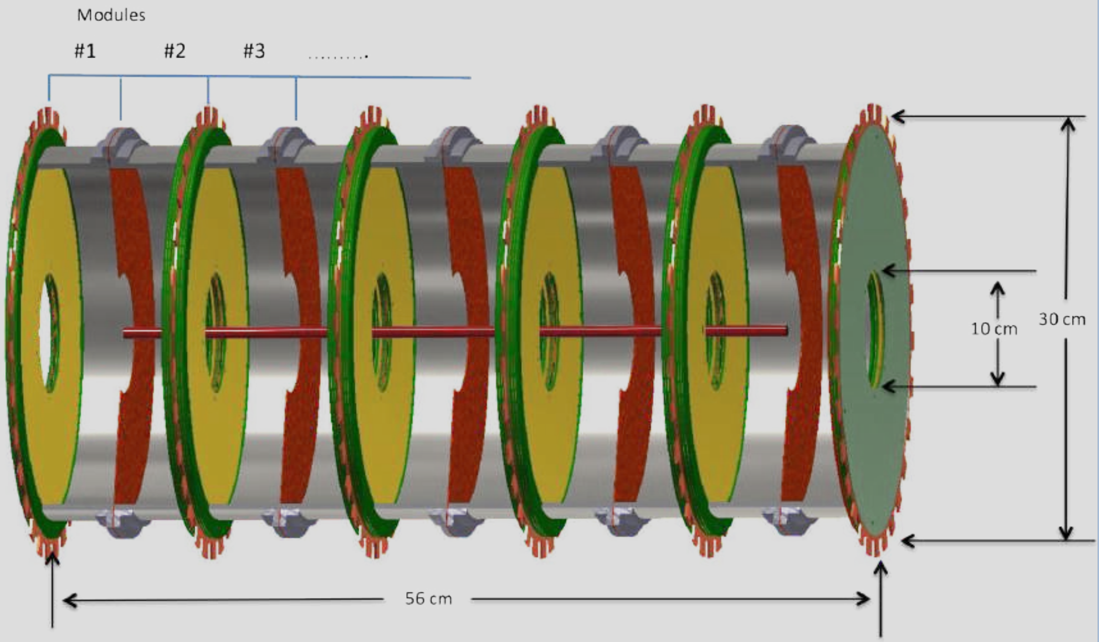


No changes to TDIS set up proposed
Latest TDIS configuration from conditional release document used for our studies and satisfactory as is

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)

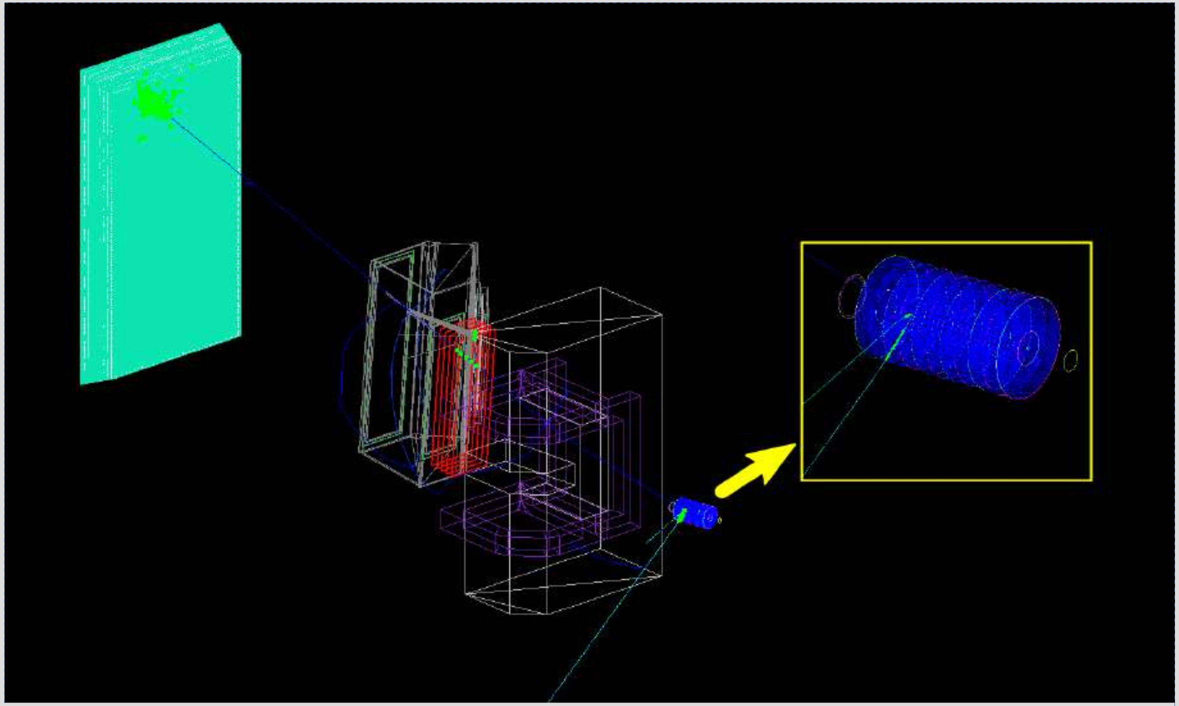


mTPC current design. Courtesy N.Liyanage

TDIS-n projected results

In order to estimate the counting rates, TDIS-n used two simulations, the **G4SBS** package with full detailed simulation of the SBS detector and a fast simulation (**FS**) with geometric acceptance and effective free neutron target

G4SBS simulation includes the mTPC geometry already incorporated into the SBS simulation with the GEMs, RICH and LAC geometries



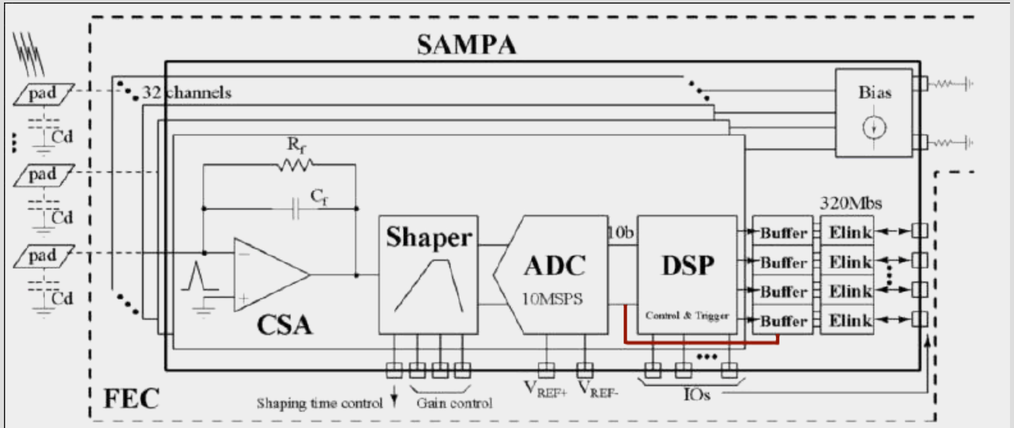
For TDIS-n:

- G4SBS made use of a DIS generator making use of CTEQ6 SF parametrization
  - **Does not include** resonant contributions
- FS made use of the F1F209 model from Bosted and Christy

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

Background rates

Expected background rates for TDIS-n are the same as TDIS

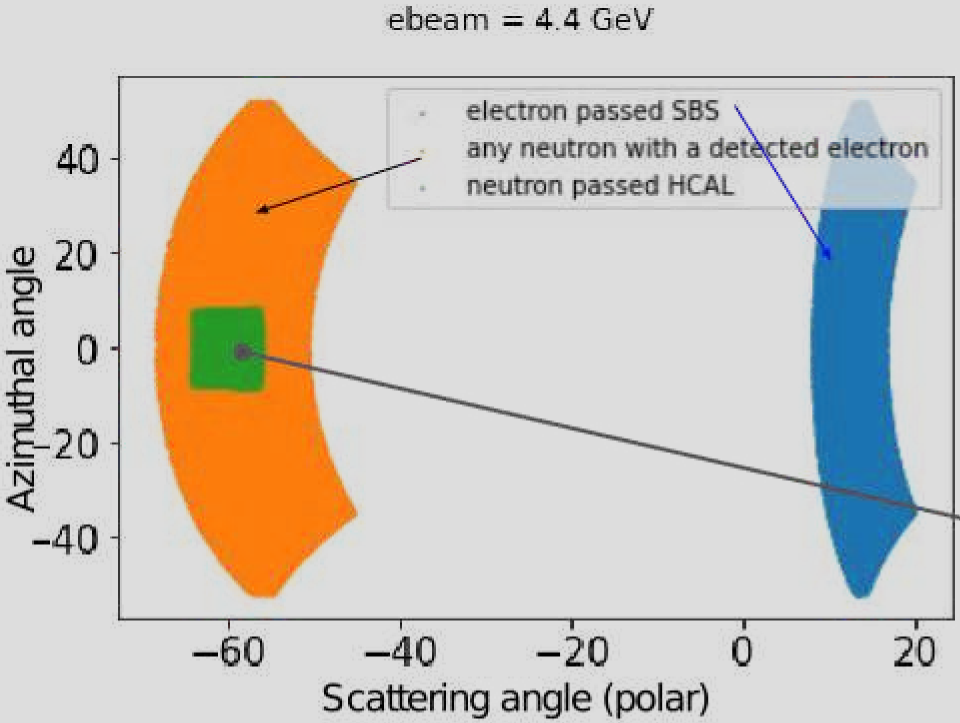
Source of background:	Estimated rates
Elastic protons (H_2)	10 MHz in 30º < θ_p < 70º range
Quasi-elastic scattering (D_2)	~128 MHz (protons < 1.2 GeV/c)
DIS products (pions and protons)	(PYTHIA) ~9.3 MHz (H_2) ~14.1 MHz (D_2)

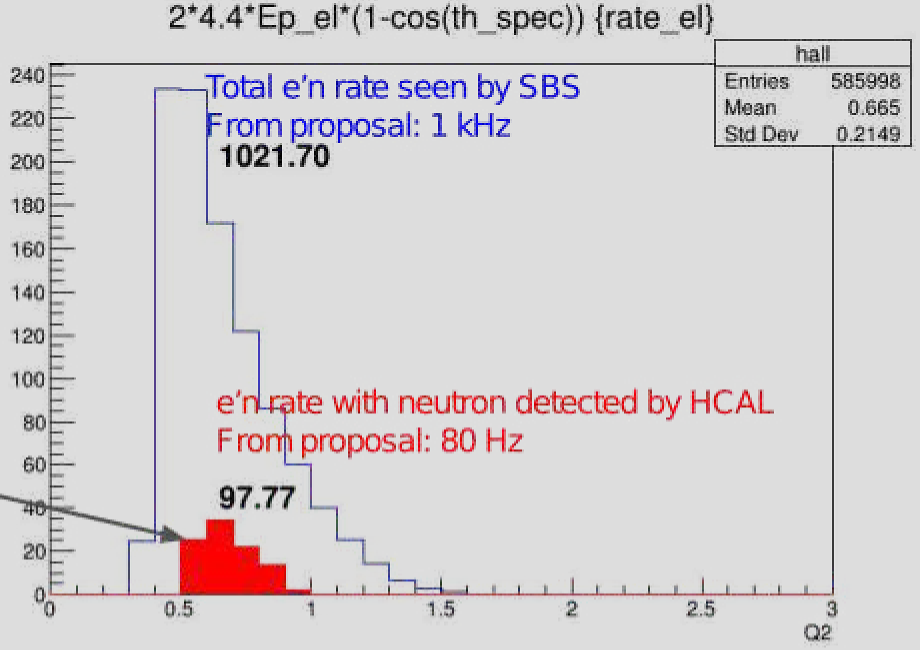
The rate per mTPC chamber is 1/10 these values

Projected elastic e-n rates

Calibration setting as in TDIS proposal:

Ebeam = 4.4 GeV, HCAL at 60 degree, lumi = 0.3e36

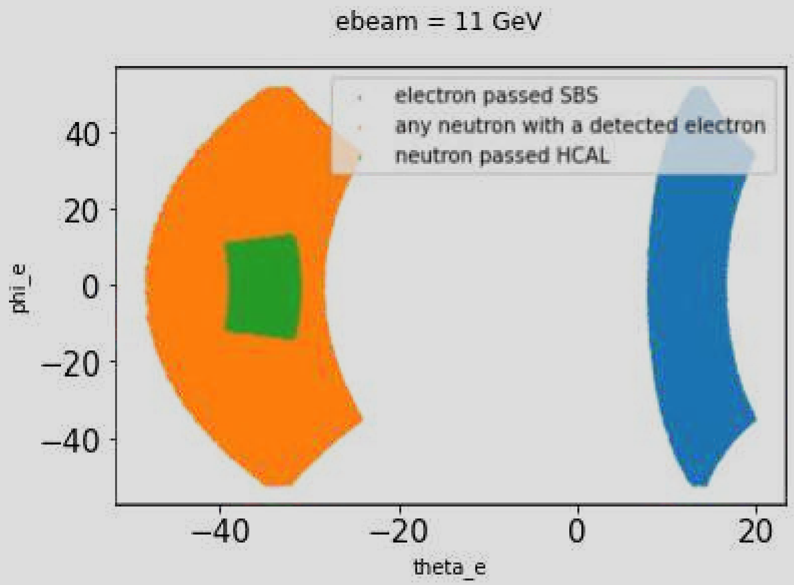


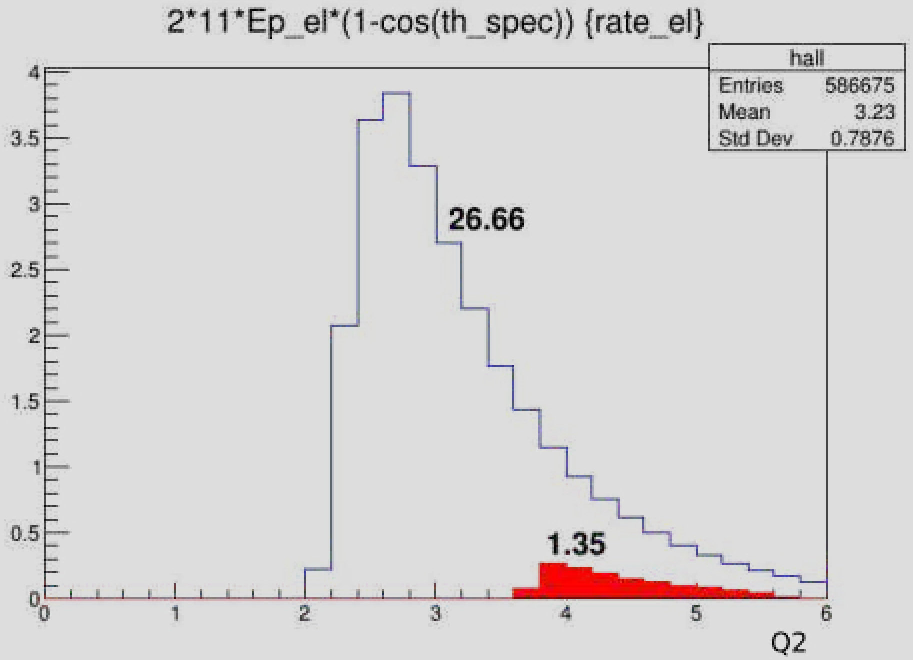


Projected elastic e-n rates

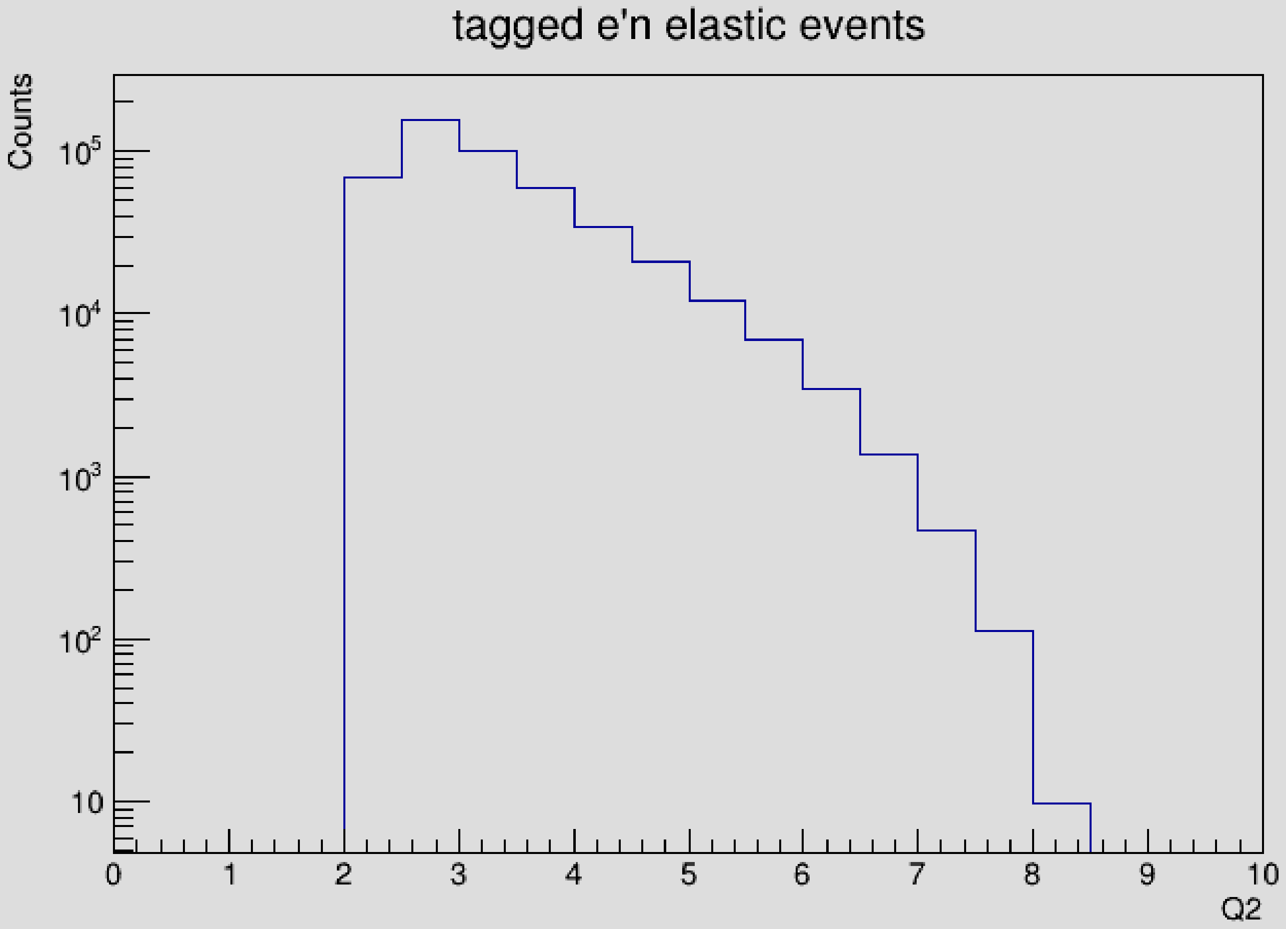
Calibration setting as in TDIS proposal:

Ebeam = 11 GeV, HCAL at 35 degree , lumi = 1.5e36



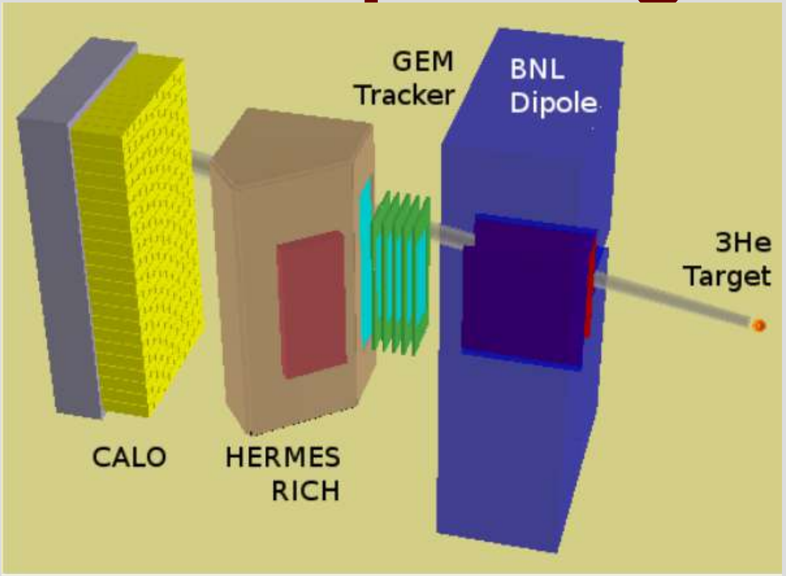


Projected elastic e-n rates



Super BigBite Spectrometer

SBS configuration for SIDIS experiment



SBS configured for e$^-$ detection:

- 12° scattering angle (large acceptance, ~50msr)
- 5 GEM tracker planes (70μm resolution)
- Threshold CO_2 Cherenkov detector (modified HERMES RICH)
- Large angle calorimeter (from Hall B CLAS)
- e$^-$ PID and e$^-$ trigger (L2) = Cherenkov + calorimeter (combined π rejection factor ~10^4)

courtesy D. Dutta

courtesy A. Puckett

Target, Luminosity and trigger

TDIS is planning to run at room temperature conditions ⇨ novel design in order to have high pressure and keep thin target walls.

- 40 cm long, 1 cm diameter
- Deuterium or hydrogen gas at 6.4×10^{-4} g/cm^3 at 4 atm
- Wall thickness ~20 μm

Target straw prototype. courtesy D. Dutta

This target design combined with a beam intensity of 50 μA will be capable of providing instantaneous luminosity of:

$$\boxed{2.9 \times 10^{36}\ \text{cm}^{-2}\ \text{s}^{-1}}$$

- Trigger is based in electron detection from the LAC and RICH.
- A minimum electron energy deposition of 1 GeV in the LAC is required to trigger.
- e^- PID and e^- trigger (L2) = RICH + LAC (combined π rejection factor ~10^4)

Run Group Request

- This run group **does not** request with respect to the E12-14-110 setup:
  - Any additional beamtime
  - Any changes in the experimental configuration

TDIS-n will 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.