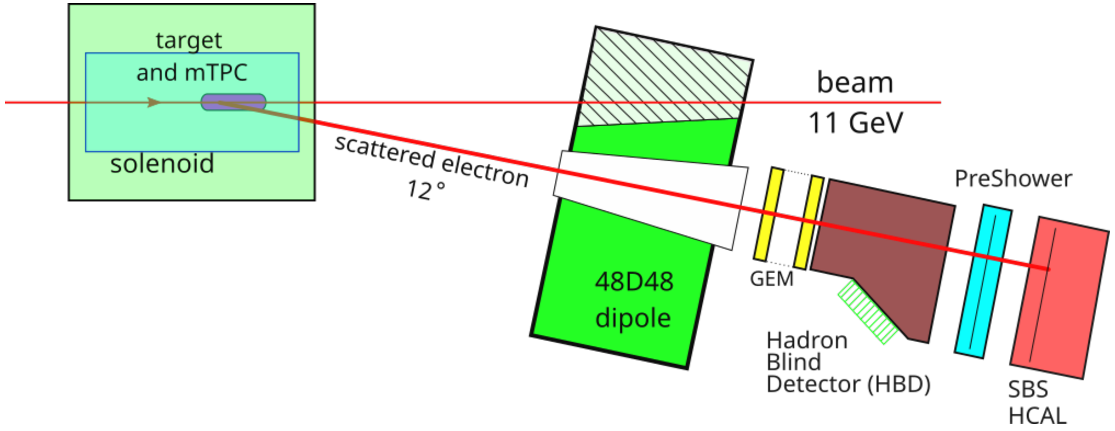
# J12-26-002 (previously C12-15-006)
## The Tagged Deep Inelastic Scattering (TDIS) Experiments

Run group of C12-15-006, C12-15-006A, and C12-15-006B

Spokespersons
J. Arrington, C. Ayerbe Gayoso, E. Christy, D. Dutta, E. Fuchey, T. Horn, C. Keppel, P. King, N. Liyanage, S. Li, R. Montgomery, A. Tadepalli, B. Wojtsekhowski




P. M. King (Ohio University)
for the TDIS Experiments

# Run group overview

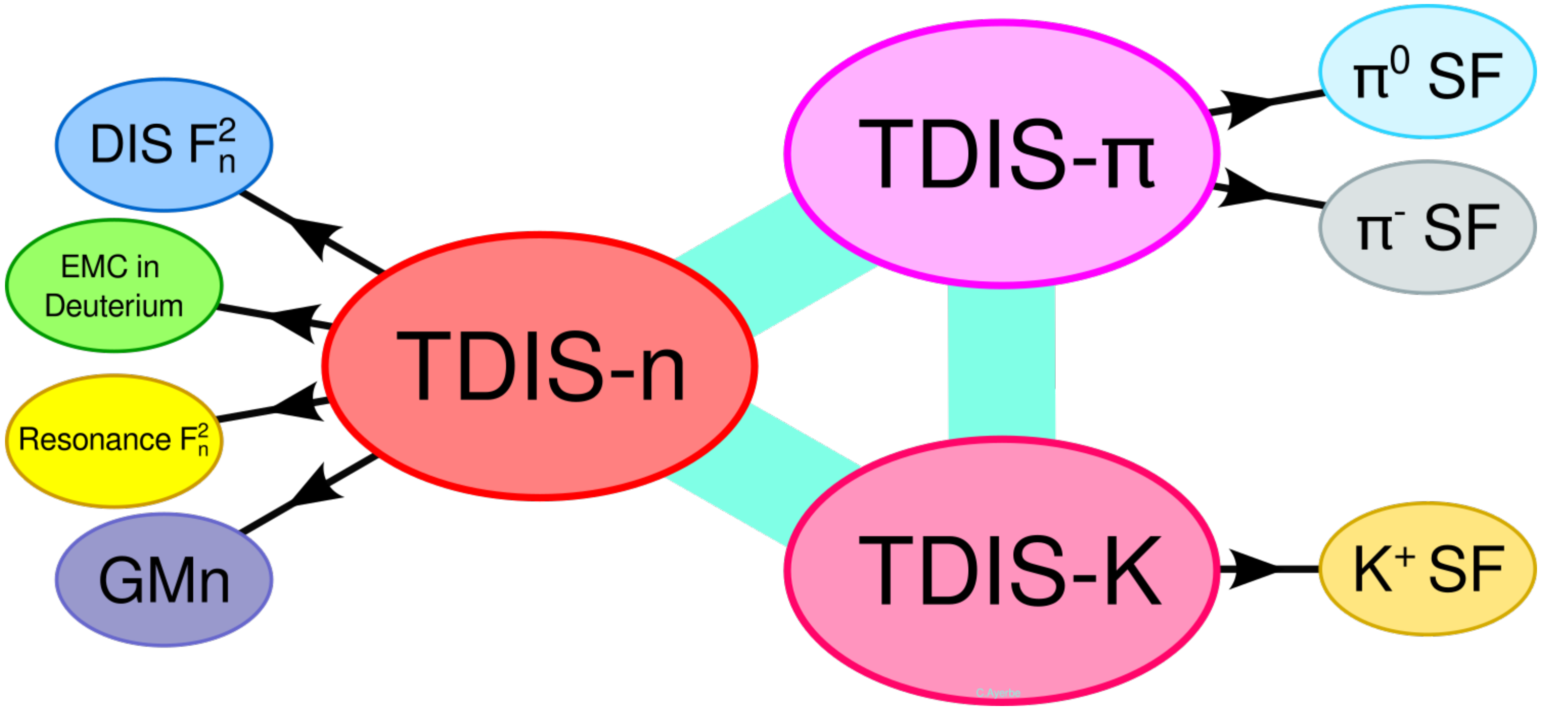
A pioneering experimental program at JLab employing spectator tagging to access the Sullivan process in a high luminosity ($3 \times 10^{36} cm^{-2} s^{-1}$), fixed target experiment on $H_2$ and $D_2$ targets.

An essential proof-of-principle for future experiments at the EIC & 22 GeV JLab.

- C12-15-006 (TDIS-$\pi$) and C12-15-006A (TDIS-K)
  - Direct measurement of the mesonic content of the nucleon and a unique extraction of the pion and kaon F2 structure functions, by scattering from a virtual meson target
  - There is ample evidence that nucleons have pionic content in them, but no direct measurements.
  - Pions and kaons are the simplest bound states of QCD and its Nambu-Goldstone bosons-knowledge of meson structure is critical to a complete understanding of the emergence of hadron mass.
- C12-15-006B (TDIS-n)
  - Extract the free neutron structure function from electron-deuterium scattering using a time projection chamber to detect low-momentum spectator protons, identifying nearly on-shell nucleons

# Physics goals for TDIS-π, TDIS-K, and TDIS-n

TDIS-π and TDIS-K would provide **access to the mesonic structure functions** and an important step toward similar measurements at the EIC

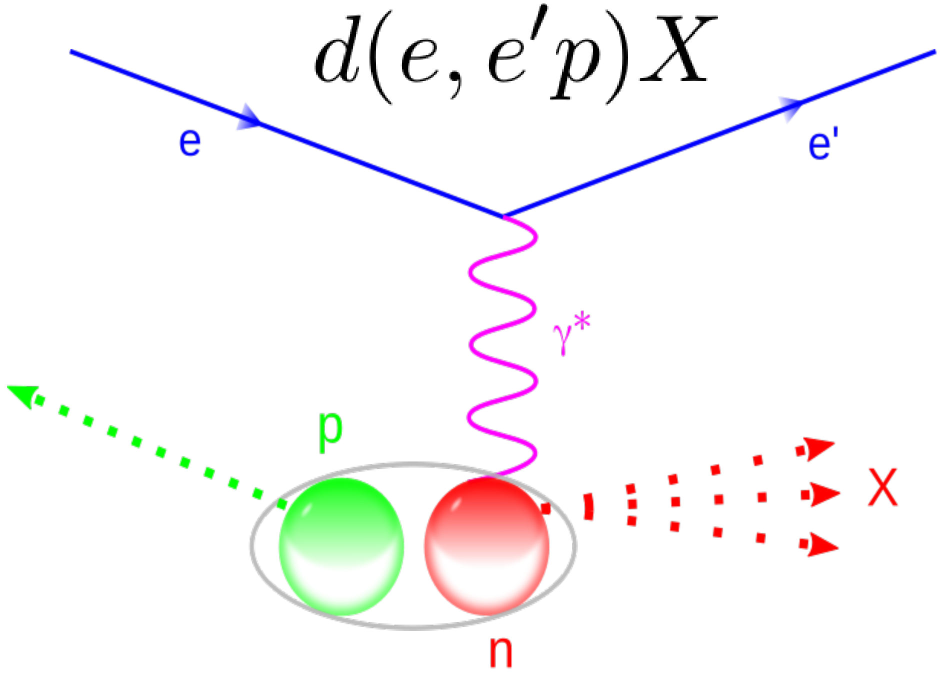



TDIS-n **allows access** to all these physics with an **increase of statistics and independent test of systematics**

✓ An increase of **5-10 more statistics** than BoNuS12 in the kinematics covered by TDIS

✓ **An independent normalization** check of the procedure used in BoNuS, BoNuS12 and MARATHON.

# Spectator tagging formalism: deuterium




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.

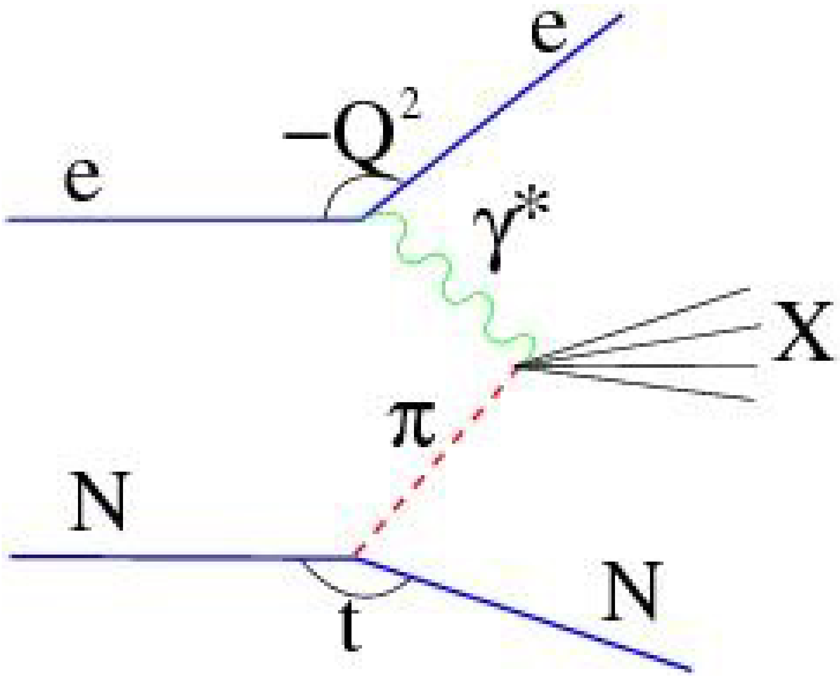
Spectator final state can be described by the light-cone fraction

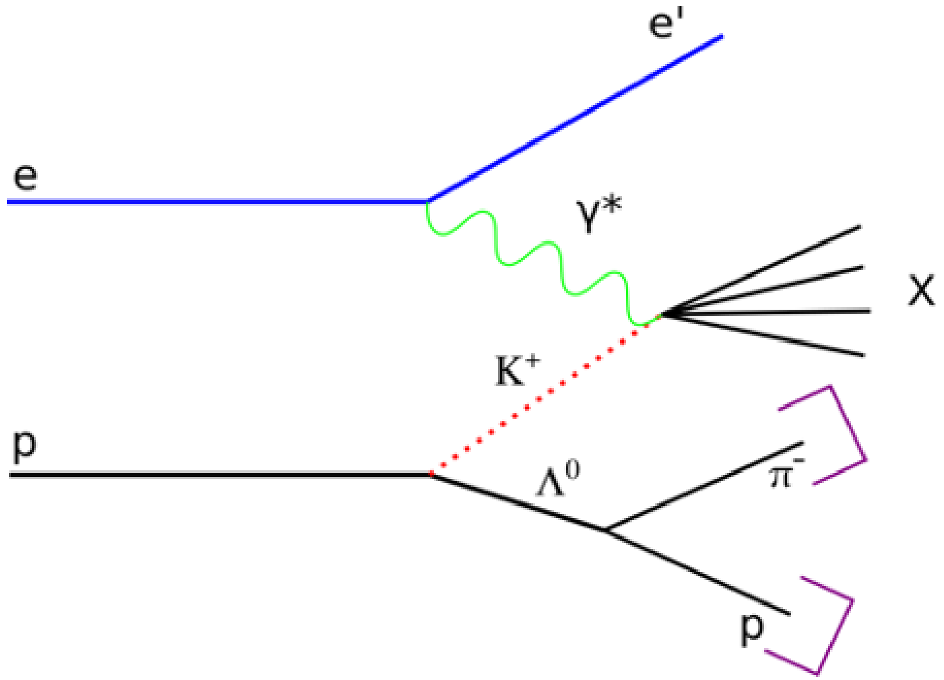
$$\alpha_p = \frac{E_p - \vec{p}_p \hat{q}}{M_p}$$

Direction of the moment transfer

Technique successfully used in BONuS (PRL 108, 142001; PRC 89, 045206) and BONuS12 (NIM A1062, 169190)

# Spectator tagging for mesons: Sullivan process




$p(e,e'p')X$ allows access to the $\pi^0$

$d(e,e'p_sp')X$ allows access to the $\pi^-$

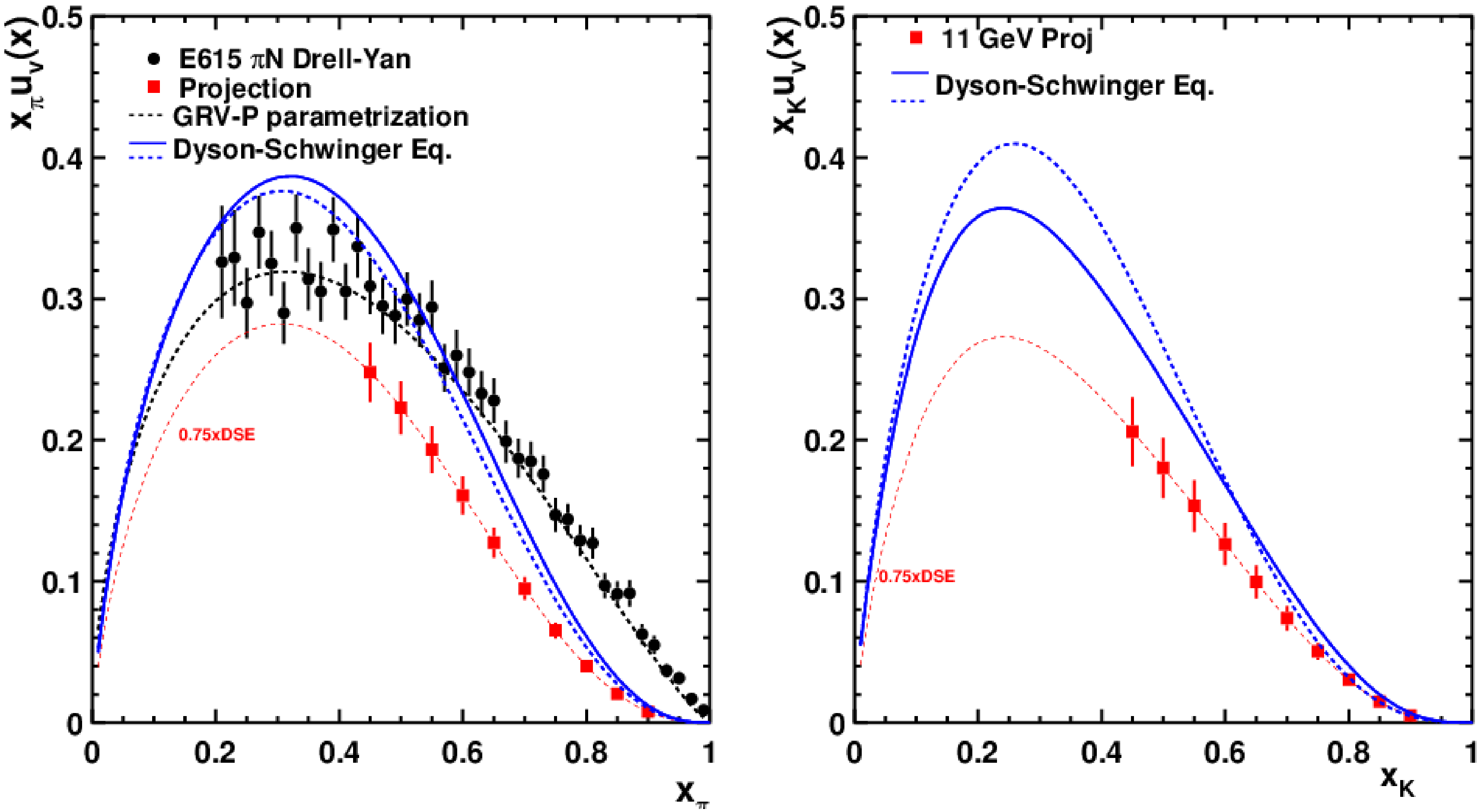
$p(e,e\Lambda)X$ allows access to the K+

# Projections for TDIS-π and TDIS-K

All Pion SF data comes from Drell-Yan on nuclei or from HERA TDIS at low-x and high $Q^2$

- High $x_\pi$ behavior differs from Dyson-Schwinger model
- TDIS-π high-x data would allow verification & study

Essentially no data exists for the kaon

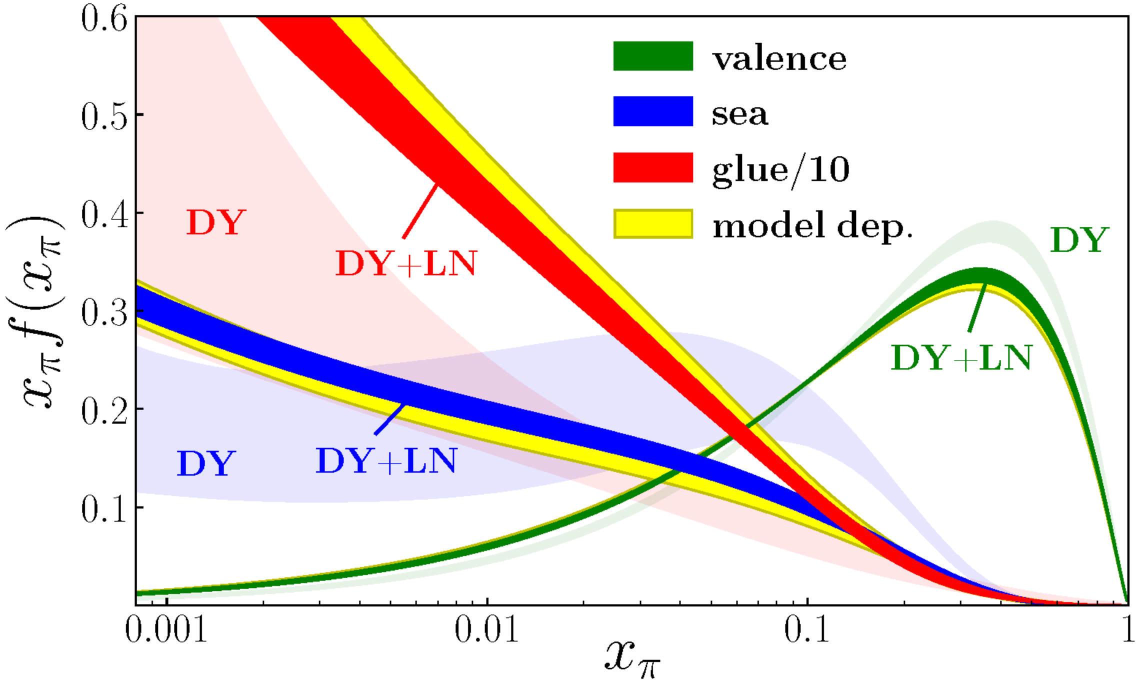



Studies to understand emergent hadron mass have stressed that measuring the similarity or difference between pion, kaon, and proton SFs would be a crucial input

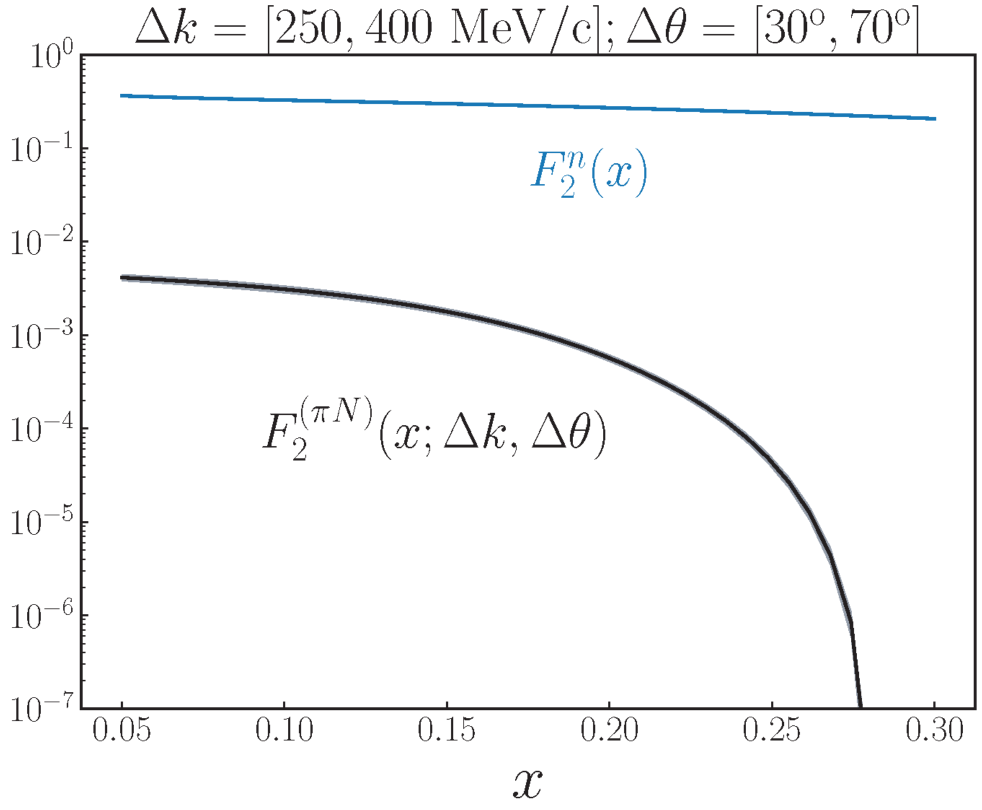
# Developments in TDIS theory

Global QCD analysis by the JAM collaboration of PDFs in the pion, combining π-A Drell-Yan data with leading neutron electroproduction from HERA within a Monte Carlo approach

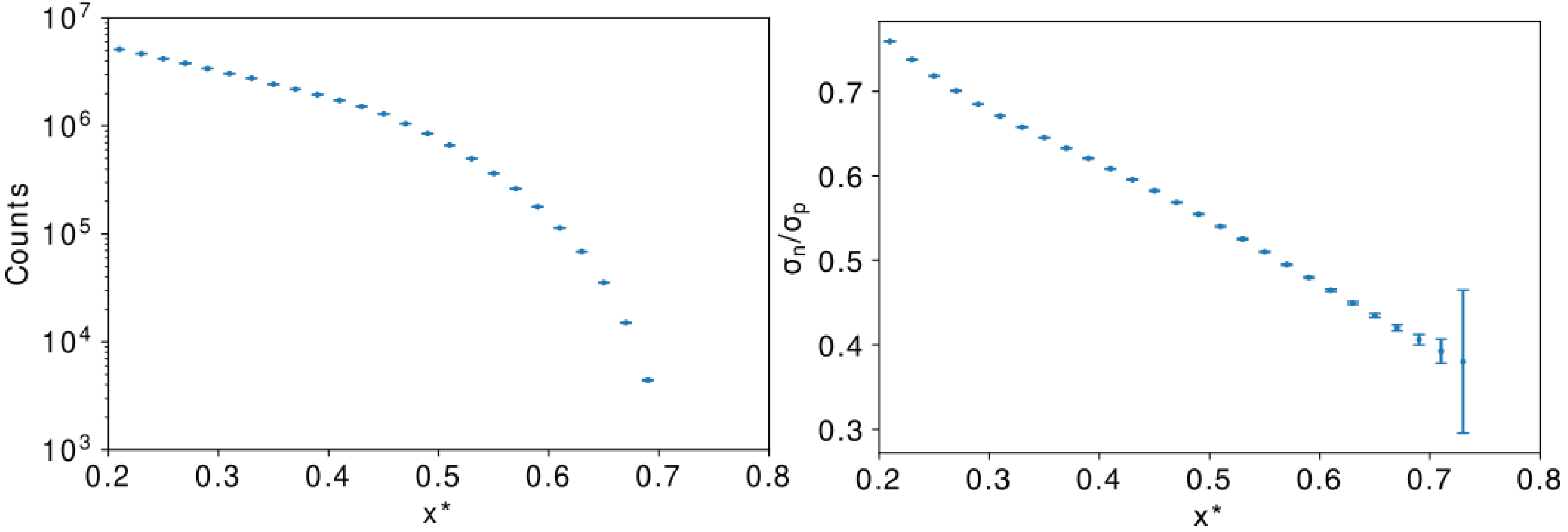
Based on this, the TDIS signal rate is expected to be less sensitive to the pion flux factor and also ~ 30% larger than what was assumed for the original TDIS-π proposal




P. C. Barry, N. Sato, W. Melnitchouk, and C-R. Ji (Jefferson Lab Angular Momentum (JAM) Collaboration), Phys. Rev. Lett. 121, 152001 (2018).



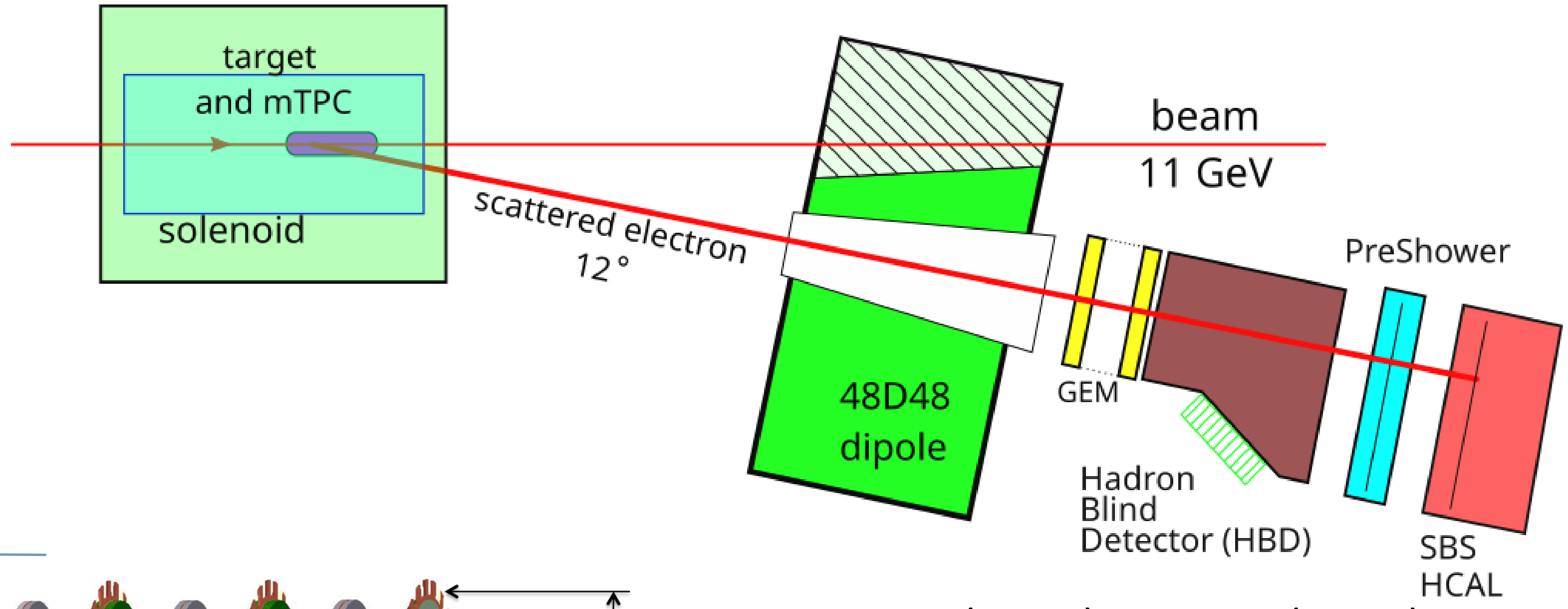
# TDIS-n projected results: DIS and EMC

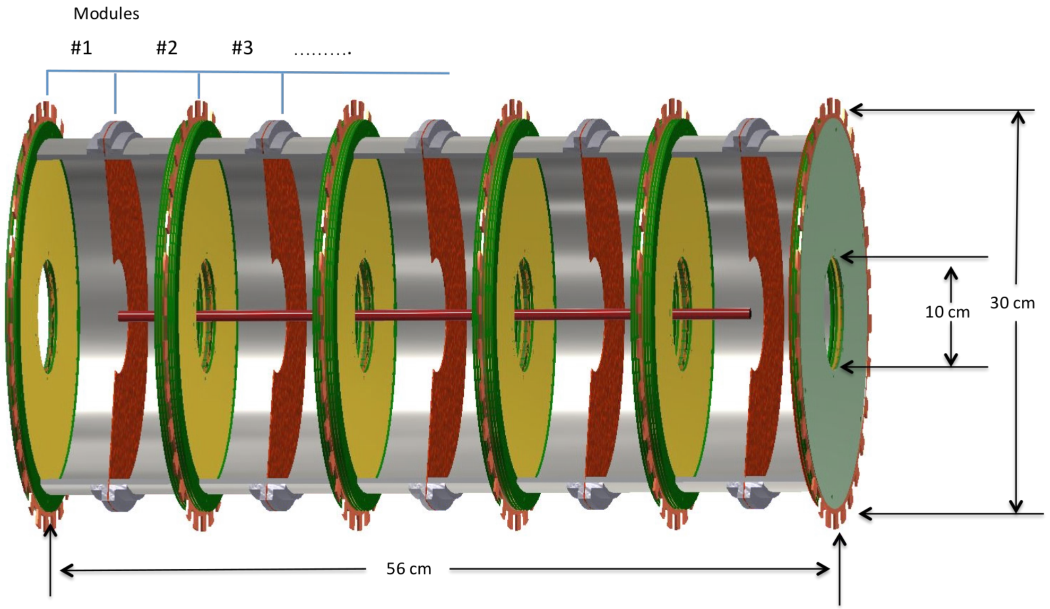



Projected statistics of tagged neutrons for $F_2^n$ (left) and $F_2^n/F_2^p$ (right) in the DIS region ($Q^2 > 1$ $(GeV/c)^2$, $W^2 > 3.5$ $GeV^2$) and 5 days of beam

- 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.

# TDIS experimental layout (TDIS-π, TDIS-K, TDIS-n)




mTPC current design. Courtesy N.Liyanage

Beam: 50 μA (on $H_2$) or 25 μA (on $D_2$)
Target: 40-cm long 1-cm dia. straw gas target ($D_2$ or $H_2$) at 3-4 atm
Luminosity: $3.0\times10^{36}$ cm$^{-2}$ s$^{-1}$

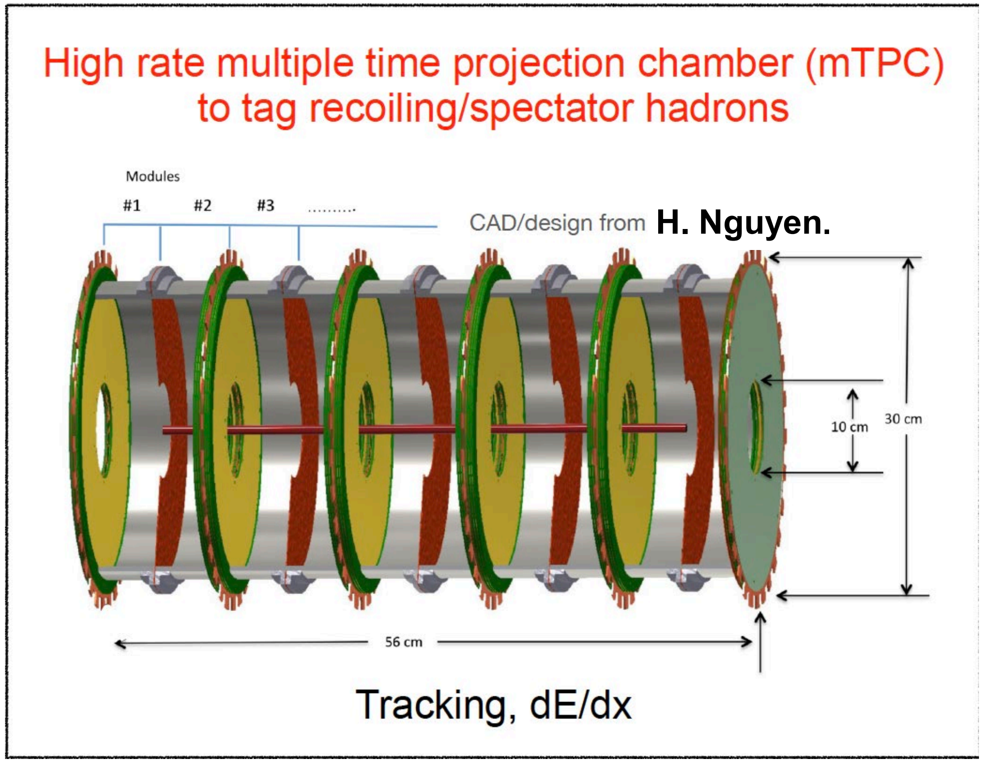
mTPC: Stack of 10 TPC volumes

- Drift field is parallel to solenoidal magnetic field
- Gas volume is room temp. and atmospheric pressure
- Total rate in mTPC: ~500 MHz

Trigger is electron identified in modified SBS

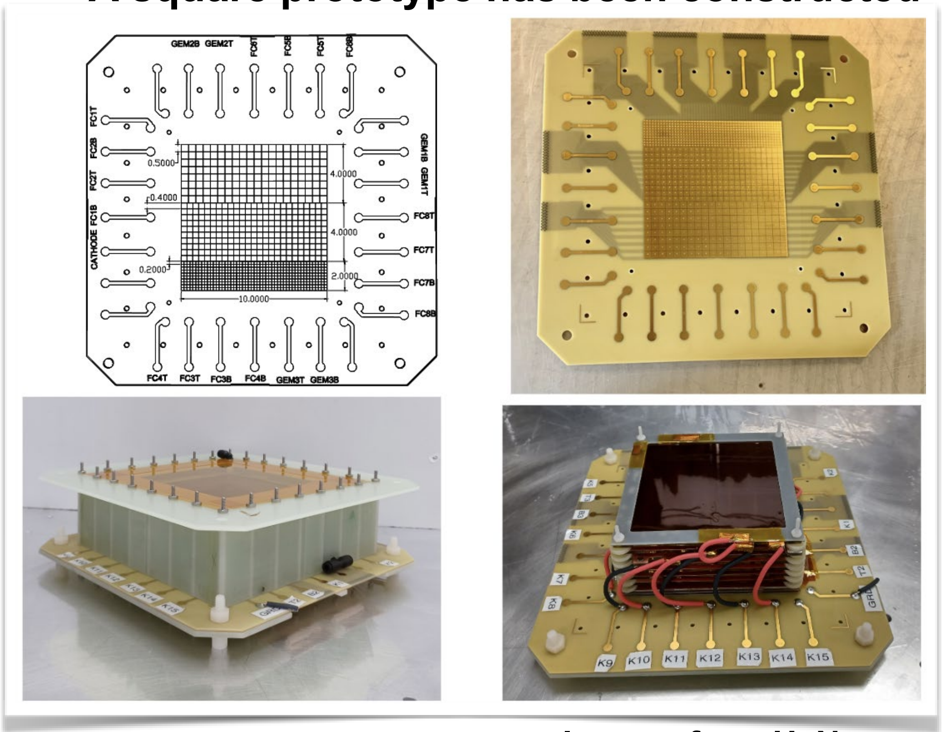
One (TDIS-n) or two (TDIS-π, TDIS-K) spectator protons measured in mTPC

# MTPC developments




- Each TPC has 5-cm drift region along *z*, with active volume 5 cm < *r* < 15 cm
- Drift field is parallel to the magnetic field, leading to reduced drift times and significantly simplified track reconstruction.
- Each TPC unit of the composite mTPC will be exposed to a fraction of the background rate.

**A square prototype has been constructed**

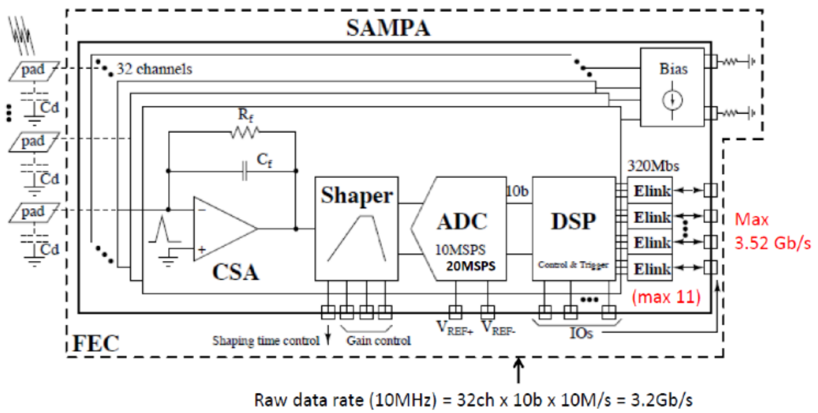


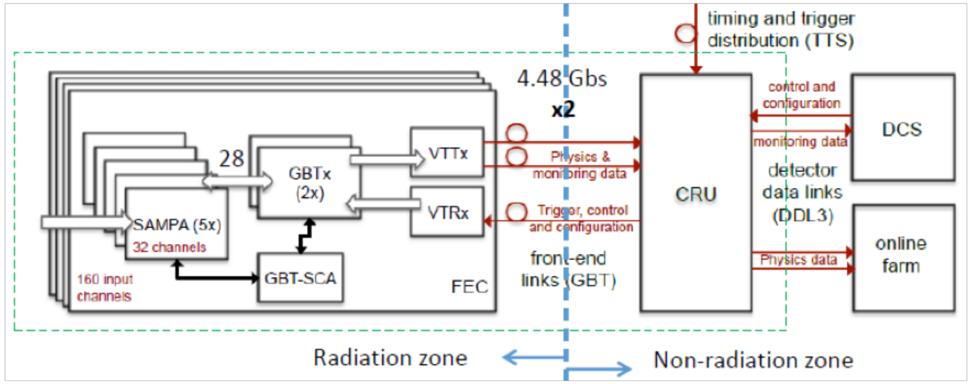
**Images from H. Nguyen**

Validation of the time projection field cage and pad readout configuration is being performed with a square prototype with the same 5-cm drift region

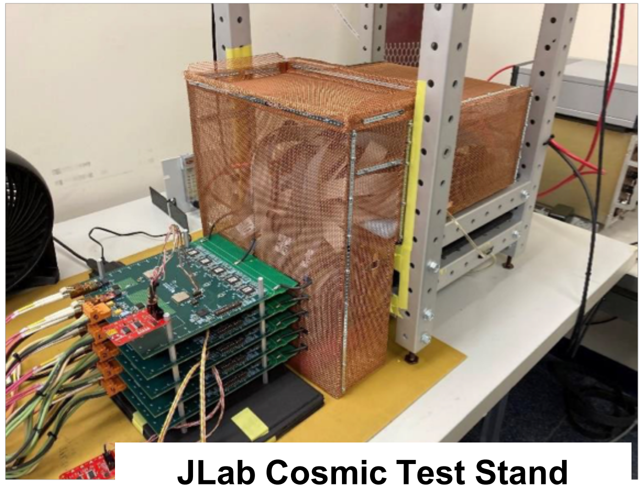
A cylindrical prototype of two TPC units is under construction

# SAMPA readout




FEC – Front End Card (160 ch / FEC)
CRU – Common Readout Unit (~12 FECs / CRU = ~1920 ch / CRU)
GBTx – Giga Bit Transceivers
GBT-SCA – GBT Slow Controls Adapter
VTTX, VTRx – Fiber optic tranceivers

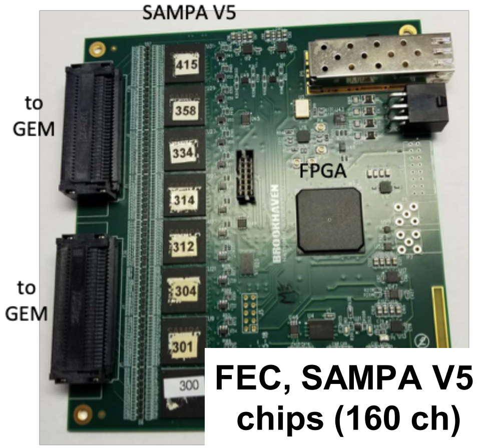


**JLab Cosmic Test Stand FEC, coupled to GEM detector**

SAMPA V5 - 80 ns shaping time

SAMPA can be used in streaming mode or triggered mode

SAMPA readout system of five Front-end cards tested (with PCIe readout unit) using a small GEM detector and performance is appropriate

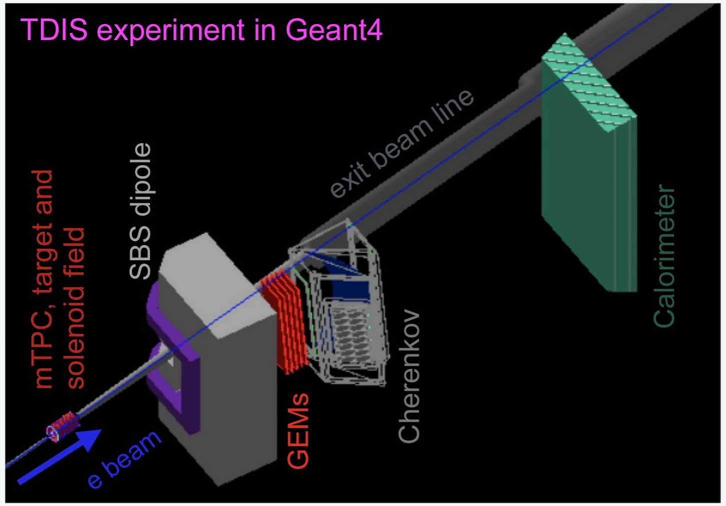



**FEC, SAMPA V5 chips (160 ch)**

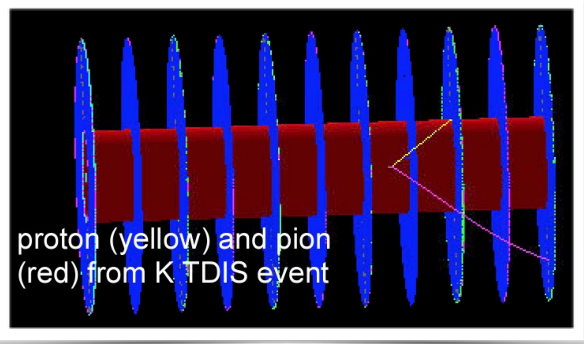
**Image credit**
**E. Jastrzembski JLab**

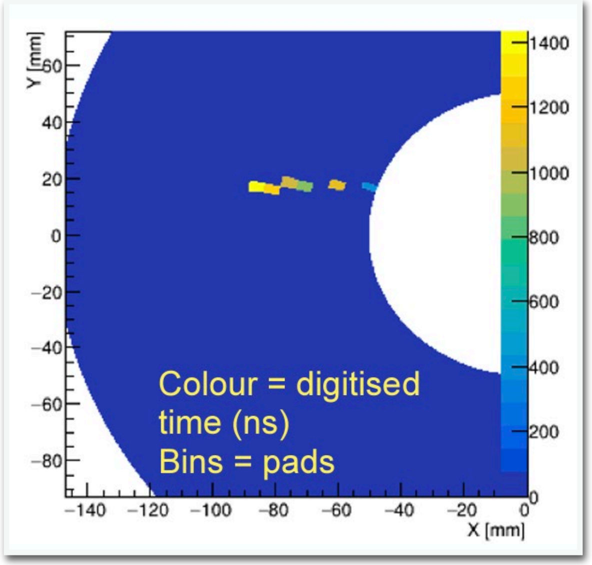
# Simulation

A comprehensive Geant4 based simulation with digitization has been developed and validated with BoNUS12 data.




**mTPC simulated with Magboltz/Garfield**

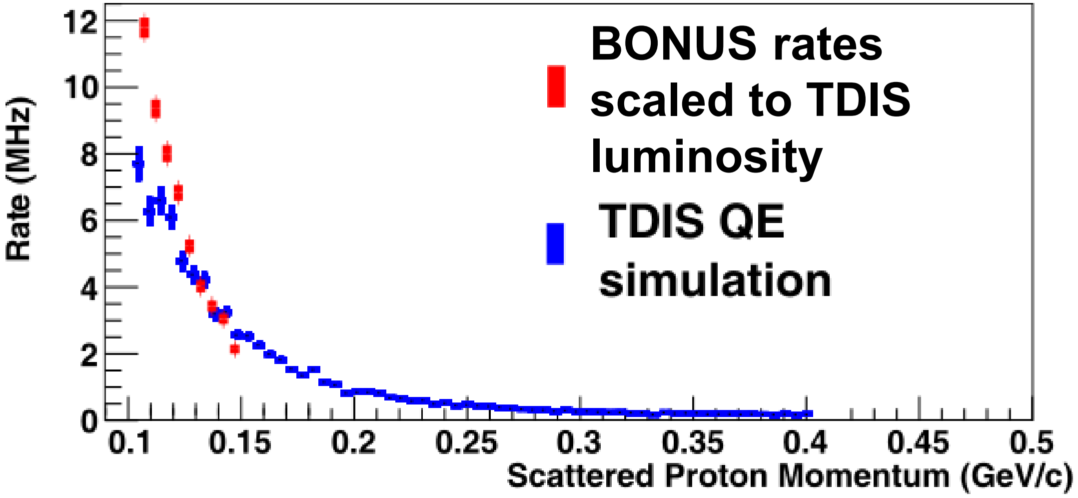


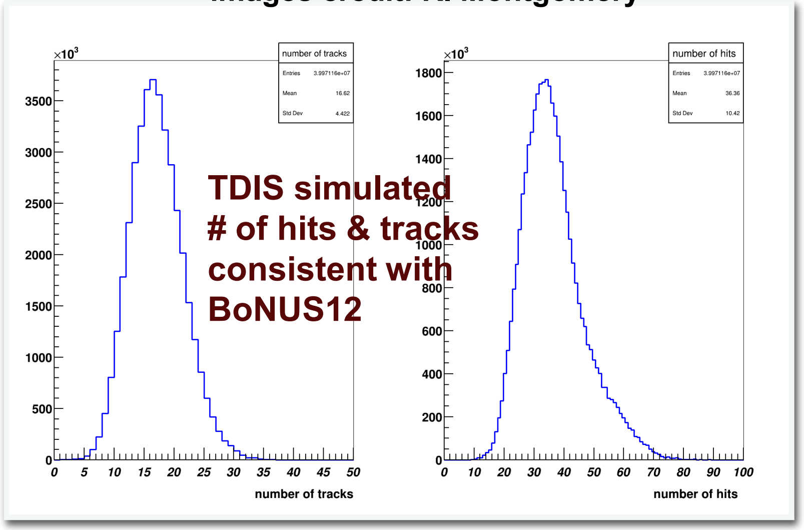




**images credit: R. Montgomery**

**TDIS simulated rates match observed BoNUS12 proton rates**

**plot credit: C. Ayerbe-Gayoso/ A. Nadeeshani**



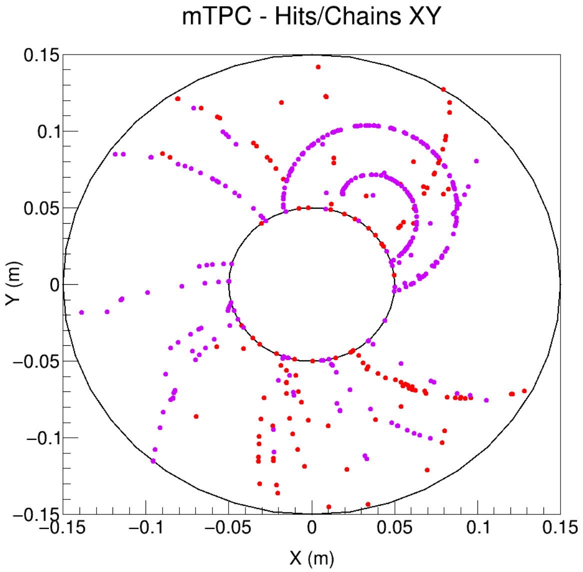



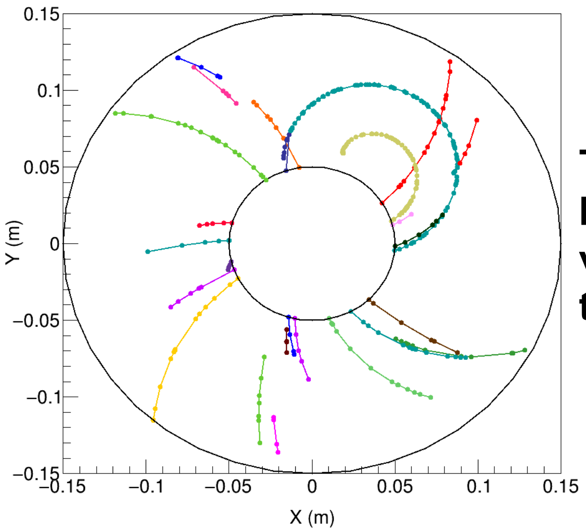

**TDIS simulated # of hits & tracks consistent with BoNUS12**

# Tracking:  Chain Finder Algorithm

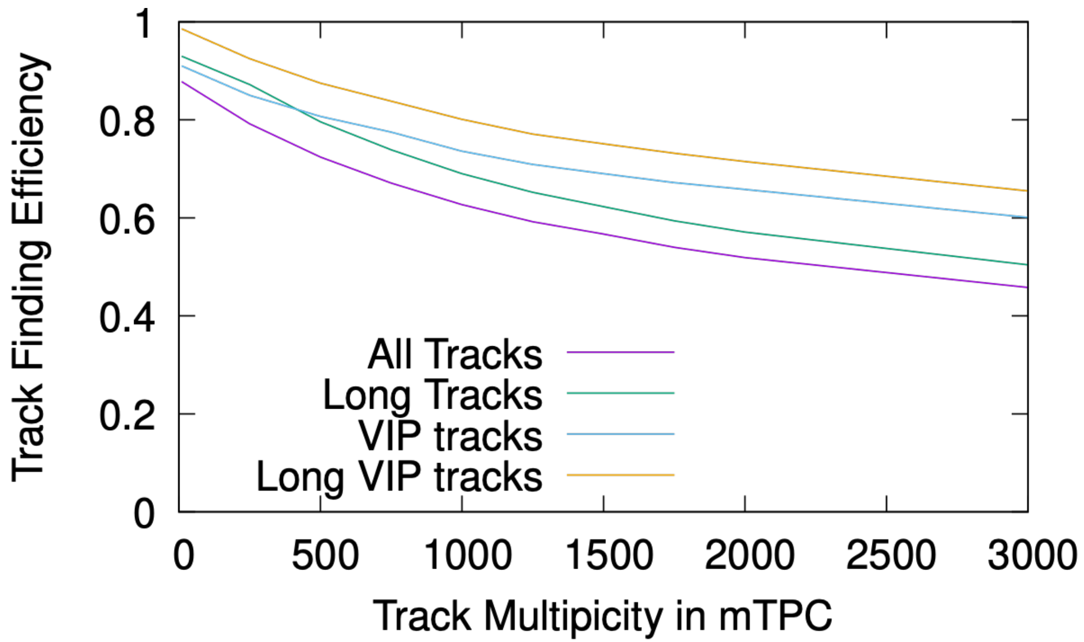
High rate and high occupancy tracking algorithms have been developed and are being optimized

- Key initiative for lifting the C1 condition and full approval.



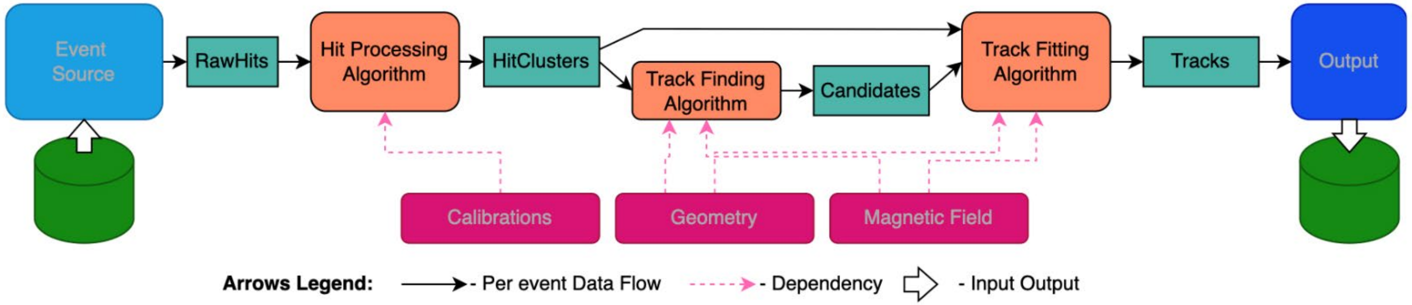

**Two tracking algorithms have been developed, a new hybrid version is being developed using the best features of each.**



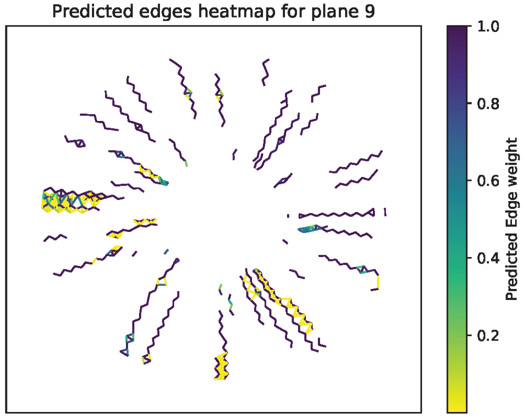

**At multiplicity of 2000 tracks per event (i.e. rate of 1 GHz in the mTPC) shows an efficiency of 68% for clean tracks**

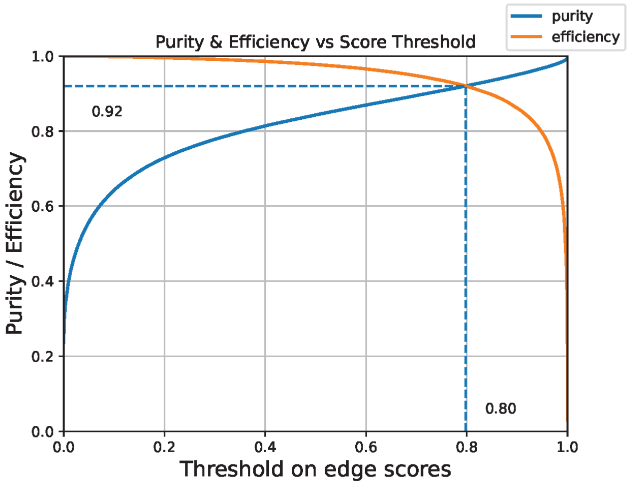
**plots credit: C. Ayerbe Gayoso, S. Wood**

# Tracking: ACTS Framework and GNN Enhancements




- The TDIS detector geometry has been successfully ported into A Common Tracking Software (ACTS) framework.
- The track finding efficiency within this framework is currently being studied using simulated events.
- Developing a Graph Neural Network (GNN) based track finding workflow to be used within ACTS

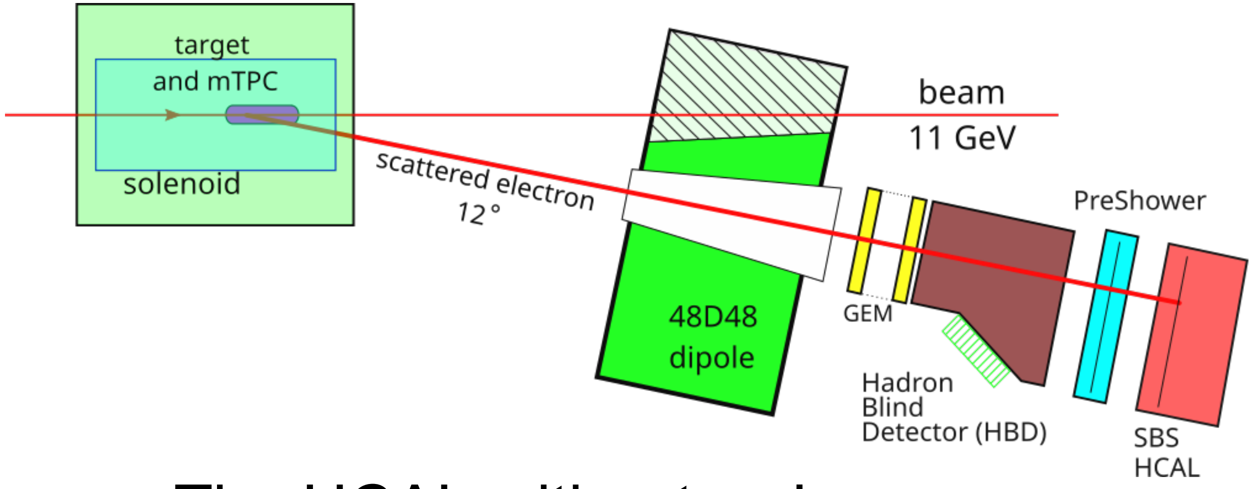


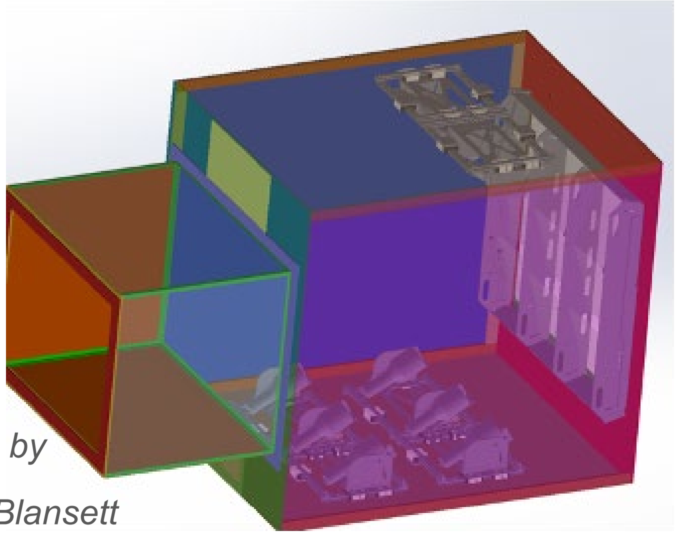



# Electron arm updates

A hadron-blind gas Cherenkov detector is being designed by U. of Tennessee to discriminate between electrons and pions in the 2 GeV – 11 GeV range

- Similar to the SHMS NGC
  - 4 meters long
  - Neon or Argon/Neon at 1atm
  - 9 PE at 11 GeV/c

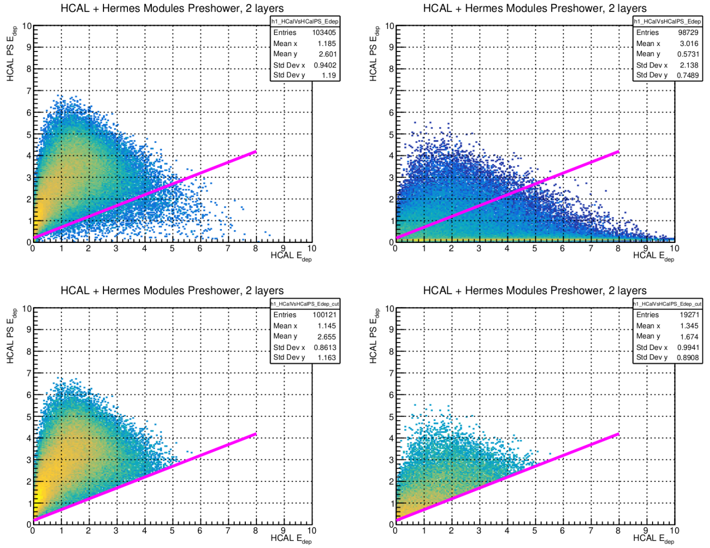


*Sketch by*

*Brock Blansett*

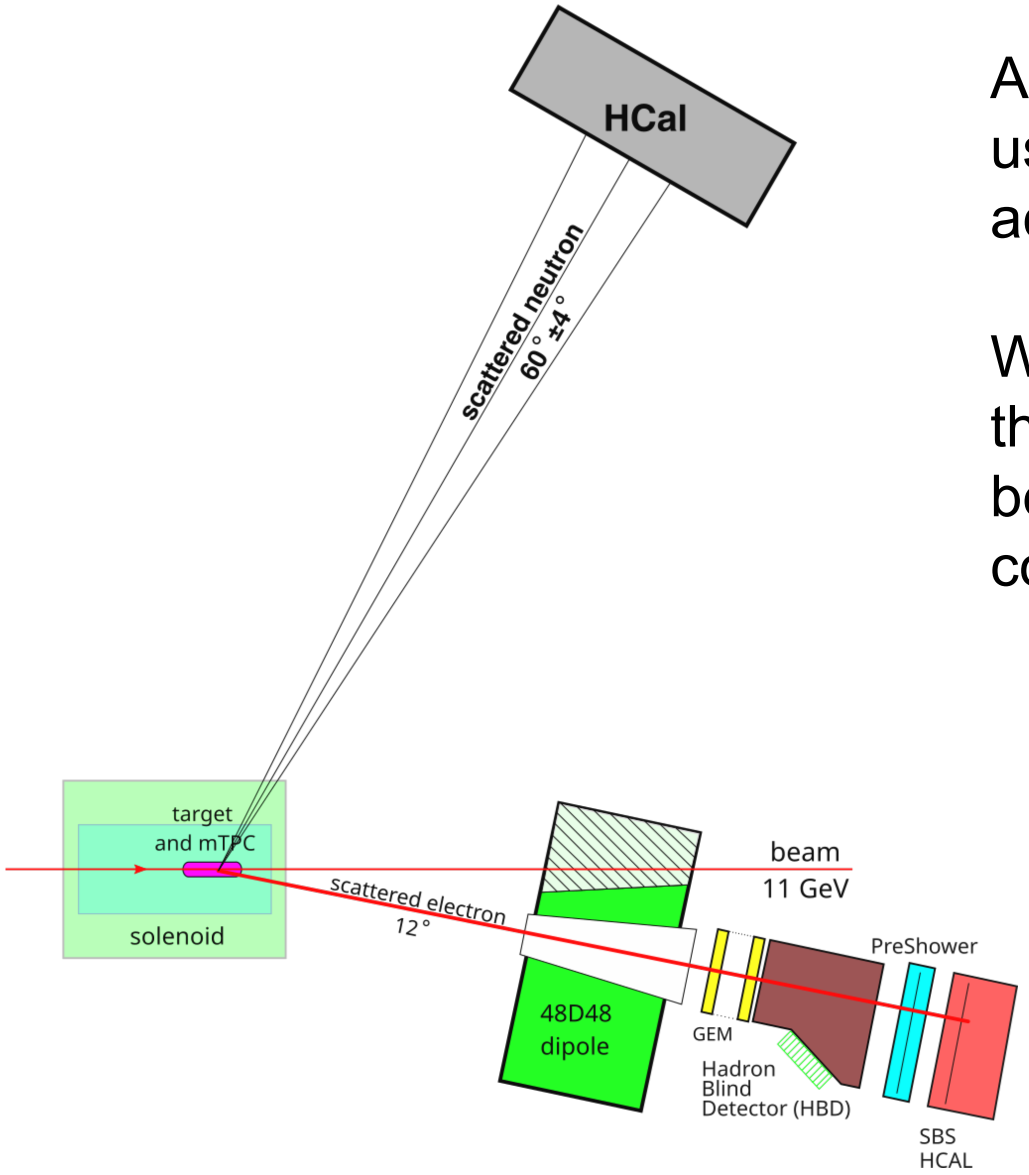
The HCAL with a two layer preradiator will give pion rejection of ~80% and electron efficiency of ~97%



# Relation to BONuS12

- BONuS12 experiment ran in Hall-B during 2020 utilizing a radial TPC (rTPC) to reconstruct the recoiling protons resulting from the DIS scattering of beam electrons from quasi-free neutrons in the deuteron
  - The target was a 40 cm long spirally wound kapton straw containing deuterium gas at a nominal pressure of 5.5 atm.
  - The experiment ran with beam currents up to 250 nA resulting in a luminosity of $1.7\times10^{34}$ $cm^{-2}$ $s^{-1}$
  - The typical track multiplicity for BONuS12 on deuterium is ~ 20 (max ~ 35) proton and deuteron tracks within a 7.2 μs acquisition window.
- The TDIS luminosity on deuterium is a factor of ~ 100 larger, but the data acquisition window is significantly narrower at 2 μs and hence the average number of tracks per event will be ~ 550 (max ~ 900 tracks) which is consistent with the TDIS simulations and the design goal for the mTPC and the tracking software.
- TDIS plans to operate with a factor of ~180 larger luminosity compared to the BONuS12 experiment, by using a pioneering mTPC instead of an rTPC.

# 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 $0.3 \times 10^{36}$ Hz/cm$^2$
- HCal placed 15 m from target at 60 deg

**Such calibration will allow a model independent normalization of the measurements**

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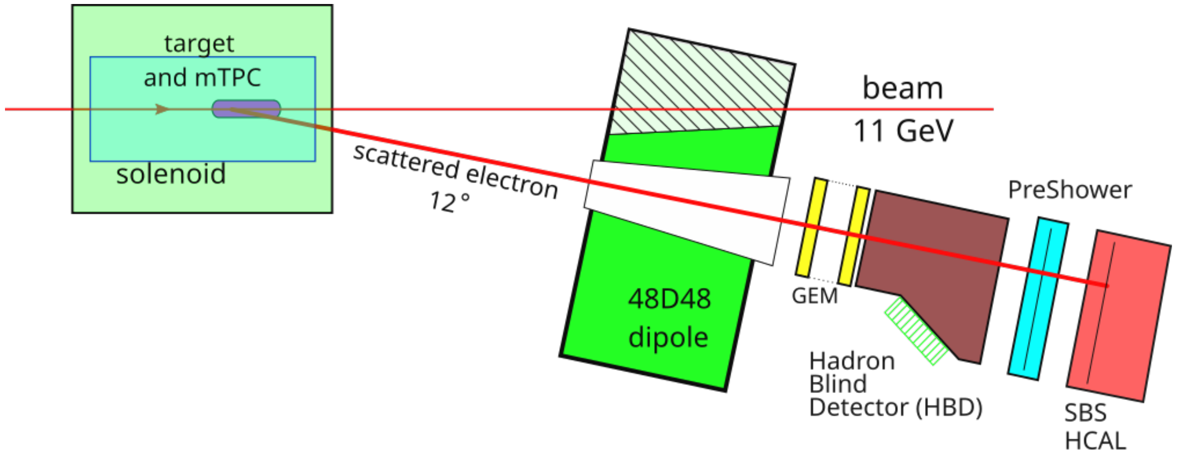
- Interest in the TDIS program has significantly increased, as evidenced by ~60 publications since the PAC approval of this experiment.
- Recent advances in theory have made the measurement of pion and kaon SF even more relevant for its role in understanding emergent hadron mass.
- TDIS-$\pi$, TDIS-K, and TDIS-n would use the same trigger and data (27 beam days) with difference in the analyzed event selection
- We have made significant progress addressing questions from the previous technical review and expect to request a full technical review by the end of 2026



# Backup slides

# Original beam request (Table 8 from C12-15-006)

| Target | Beam current (μA) | Beam Energy (GeV) | Beam Time (hrs) | Notes |
|---|---|---|---|---|
| Hydrogen | 50 | 11 | 240 | Includes 1 day for commissioning |
| Deuterium | 25 | 11 | 240 | Includes 1 day for commissioning |
| Hydrogen | 5 | 11 | 120 | |
| Deuterium | 5 | 4.4 | 48 | RTPC calibration with HCAL |
| | | | 8 | Beam energy changes |
| **Total** | | | **656** | **27 days** |

# Simulated rates per mTPC module

Table 1 from J12-26-002 proposal

Simulated rates (in MHz) of all particles capable of depositing energy in each mTPC module (there are 10 modules), for different processes and production mechanisms, assuming a 2 μs time window, with beam currents of 50 μA on H2 and 25 μA on D2.

| Reaction | π+ | π− | p |
|---|---|---|---|
| Elastic (H2) | | | 17 |
| Quasielastic (D2) | | | 12 |
| Inelastic (H2) | 7.1 | 3.0 | 3.1 |
| Inelastic (D2) | 1.8 | 1.5 | 1.2 |

# Tagging efficiency studies

TDIS-n has several ways to calibrate the tagging efficiency not available for BoNuS6/12.

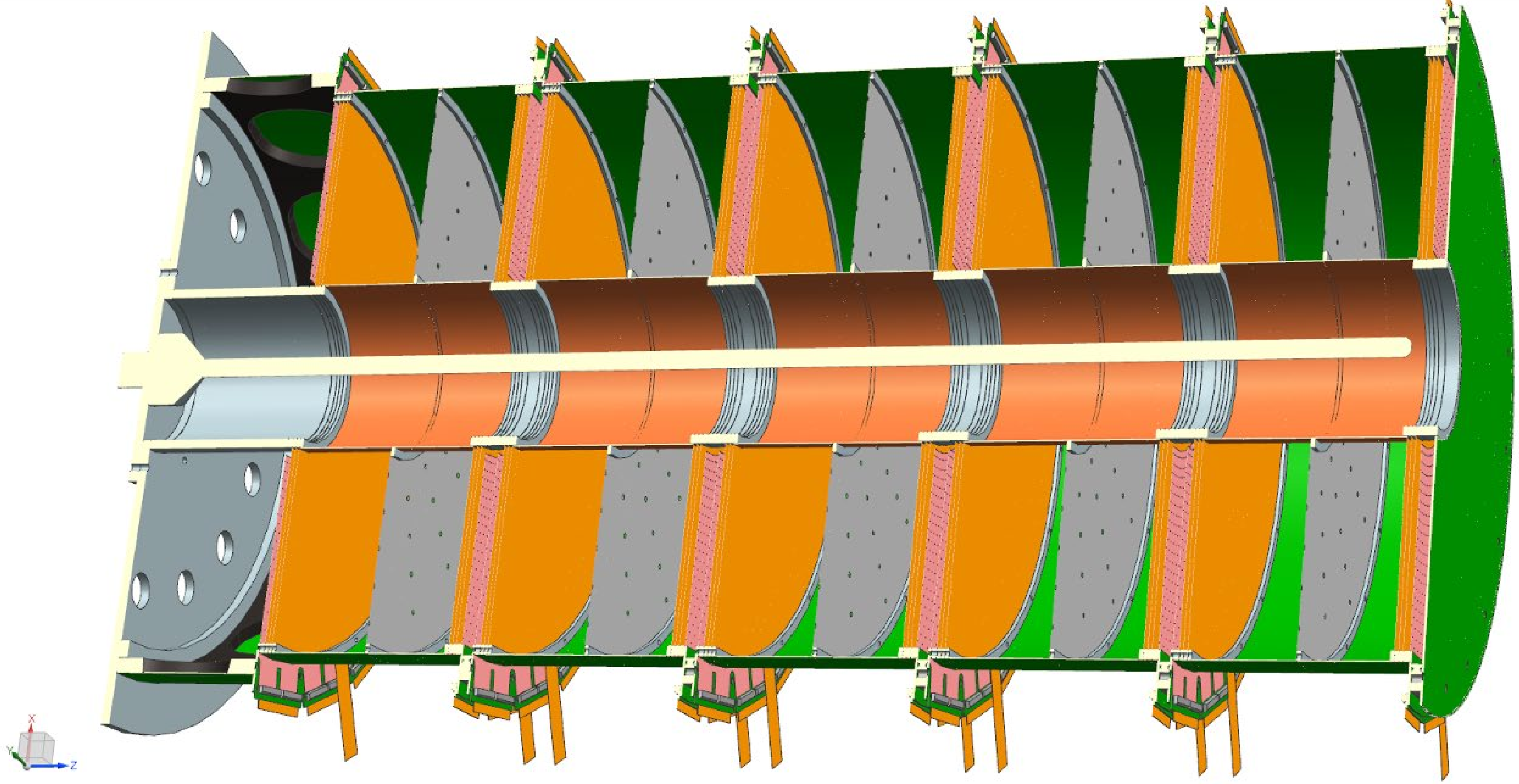
- BoNuS rely the overall tagging efficiency in the normalization of the $F_2^n/F_2^p$ at x≈3 from extractions of the deuteron. It implies a model dependence of the n-SF at x=3, thus BoNuS extraction at x≈3 is not truly an independent measurement.
- Although not using the tagging method, MARATHON makes 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.**

# mTPC CAD Design

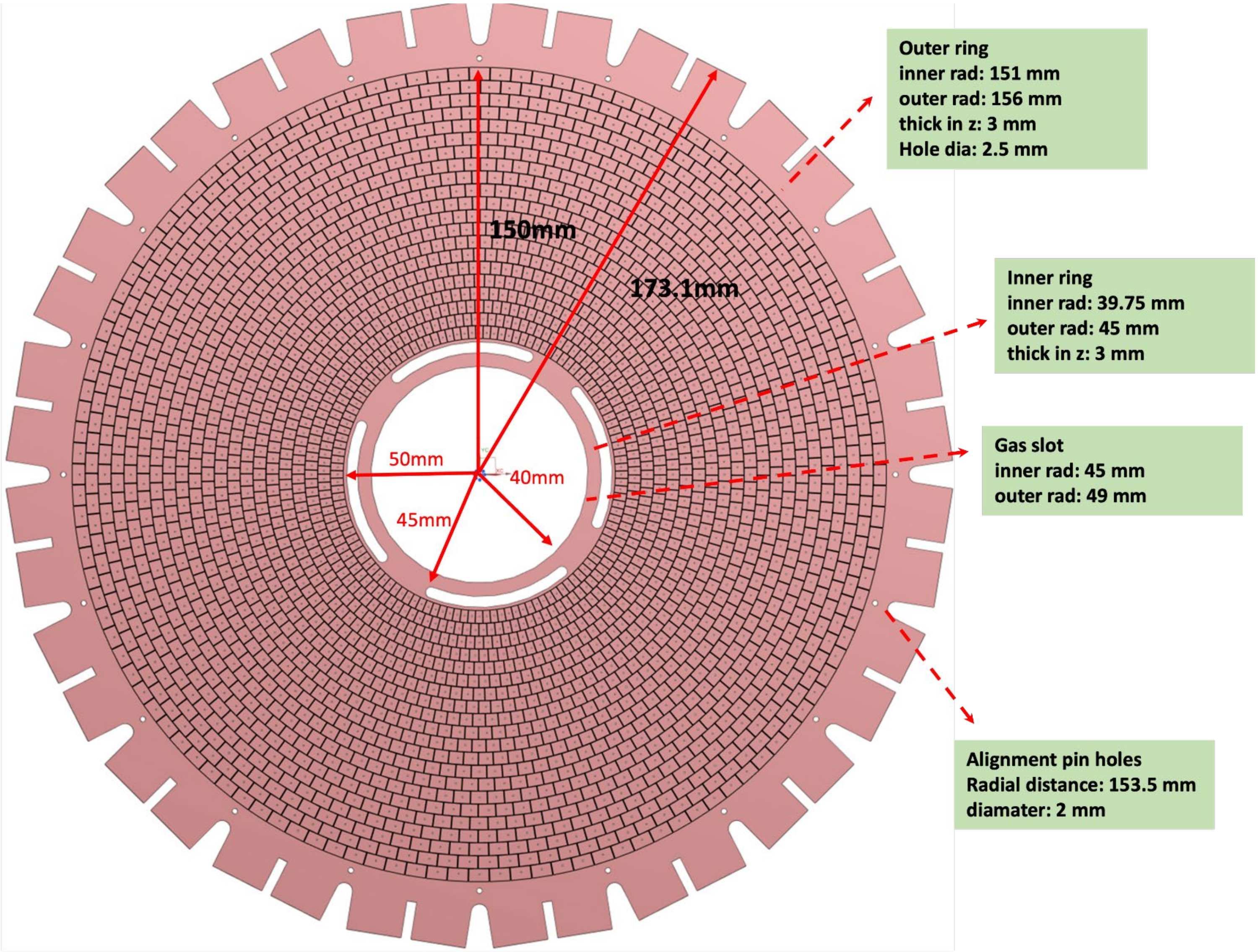
The mTPC design team has made good progress over the last year in developing a detailed design of the full detector and working through the construction procedures. A mechanical prototype will be completed in summer 2026, to be followed by a prototype double module.



# Readout plane layout

There are 21 rings, each with 122 pads
Uniform ring widths of 10 cm/21

Pads per readout plane:  2562

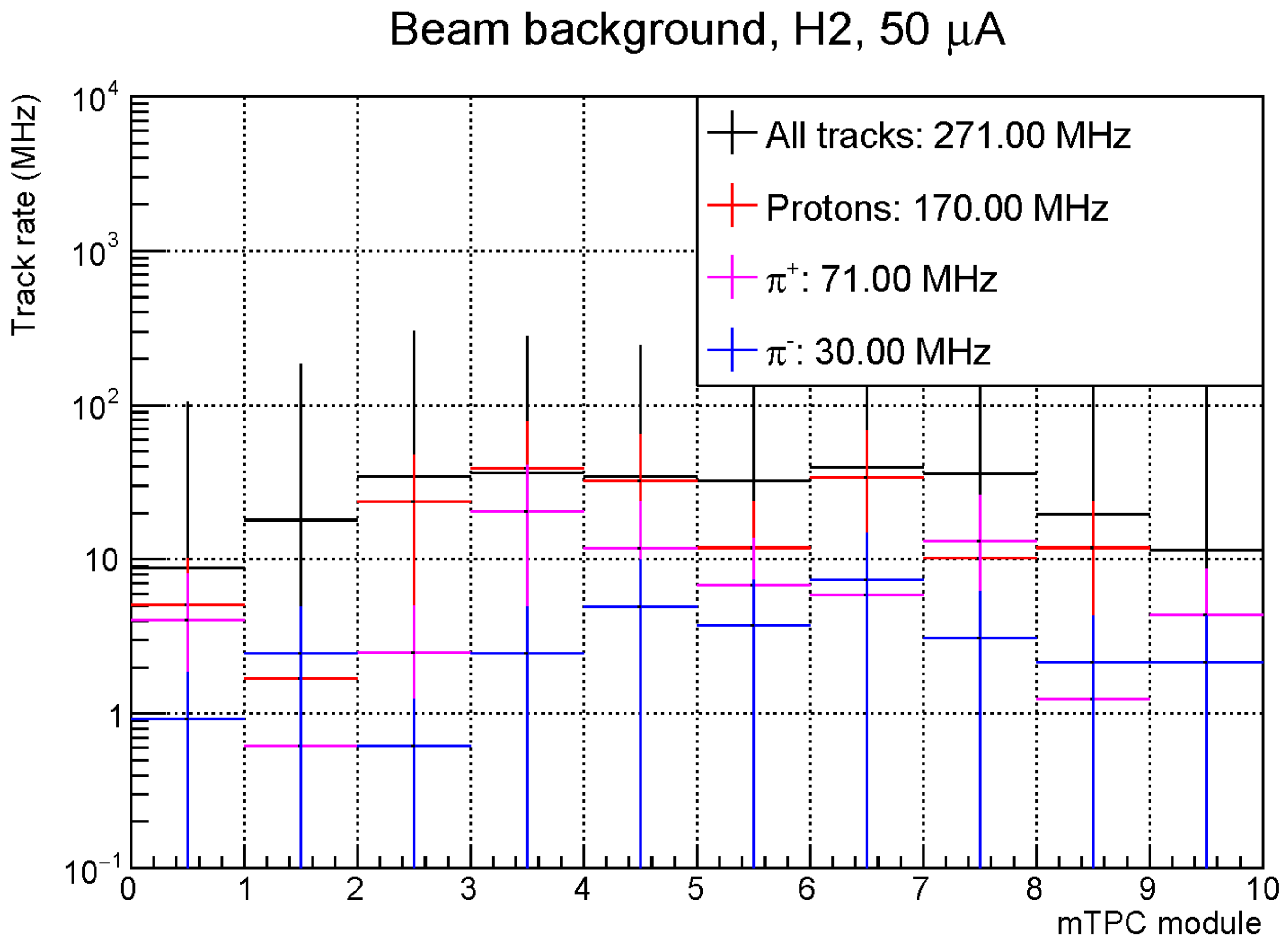


# Response to PAC 54 Reader Questions

1. page 2: did you estimate the background rate for each of the TPC unit? I could not find this information in the document but only the total rate of about 410 MHz from simulation and BONuS12 data extrapolation. So should I simply assume that this background rate is divided by 10 for a TPC unit?

- Response: Yes that is correct, we have generated pions and protons in the detector geometry modeled in Geant4 using various generators such as EPC for protons and the Geant4 hadronic physics process for pions (evaluated by recording the secondaries of beam electrons generated through the target geometry). These simulations are in acceptable agreement with the track multiplicities observed during BoNuS12. We have verified that the rates were about evenly distributed between all modules (see Fig. 1). Hence, the background rate in each TPC module is the total rate divided by the number of modules (10). This is one of the significant advantages of the mTPC design over the radial TPC.

# Response to PAC 54 Reader Questions (figure for response #1)



# Response to PAC 54 Reader Questions

2. Was the max. rate expected for a TPC unit tested in the Hall D test beam facility during the test beam that took place last Fall?

- Response: We have not performed a high rates test of the prototype. The Hall D beam test was to validate the longer than typical drift distance (5 cm) and also to test the different readout pad sizes

3. What is the estimated timeline to complete the technical development (final mTPC design, digitization, prototype beam test analysis, ....)?

- Response: Over the last few years we have made significant progress towards addressing the questions raised at the previous technical review. We believe that we have credible answers for all of the questions, and we expect to go before the technical review panel by the end of calendar year 2026. We hope to demonstrate to the committee the maturity of the design and feasibility of tracking. These were the two main concerns of the committee.

# Response to PAC 54 Reader Questions

4. Could you also let me know the status of the collaboration, i.e. how many institutes are participating, how many committed staff and prospective students that would contribute?

## The TDIS Collaboration

**TDIS run group: 13 Spokespersons (MSU, JLab, UVa, Ohio U, LBL, Glasgow, CUA, ODU, W&M)**
**22 institutions (new collaborators in 2023 - U. of Tenn and VUU, and new since 2023 - Tel Aviv U)**
**Hall A collaboration & SBS collaboration**

**Postdocs: C Ayerbe Gayoso (ODU), E. Fuchey (W&M), A. Nadeeshani (MSU)**
**Prospective Grad Students: MSU, Ohio U, U Glasgow, U. Tenn, UVa & Tel Aviv U**

**mTPC:** N. Liyanage H. Nguyen (UVa), E. Christy (JLab), I. Albayrak (JLab)
**mTPC prototype:** A. Nadeeshani (MSU), H. Nguyen (UVa), E. Christy (JLab), B. Wojtsekhowski (JLab), C. Ayerbe Gayoso (ODU), I. Albayrak (JLab)
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