# The Tagged Deep Inelastic Scattering (TDIS) experiment at JLab


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**On behalf of TDIS collaboration**



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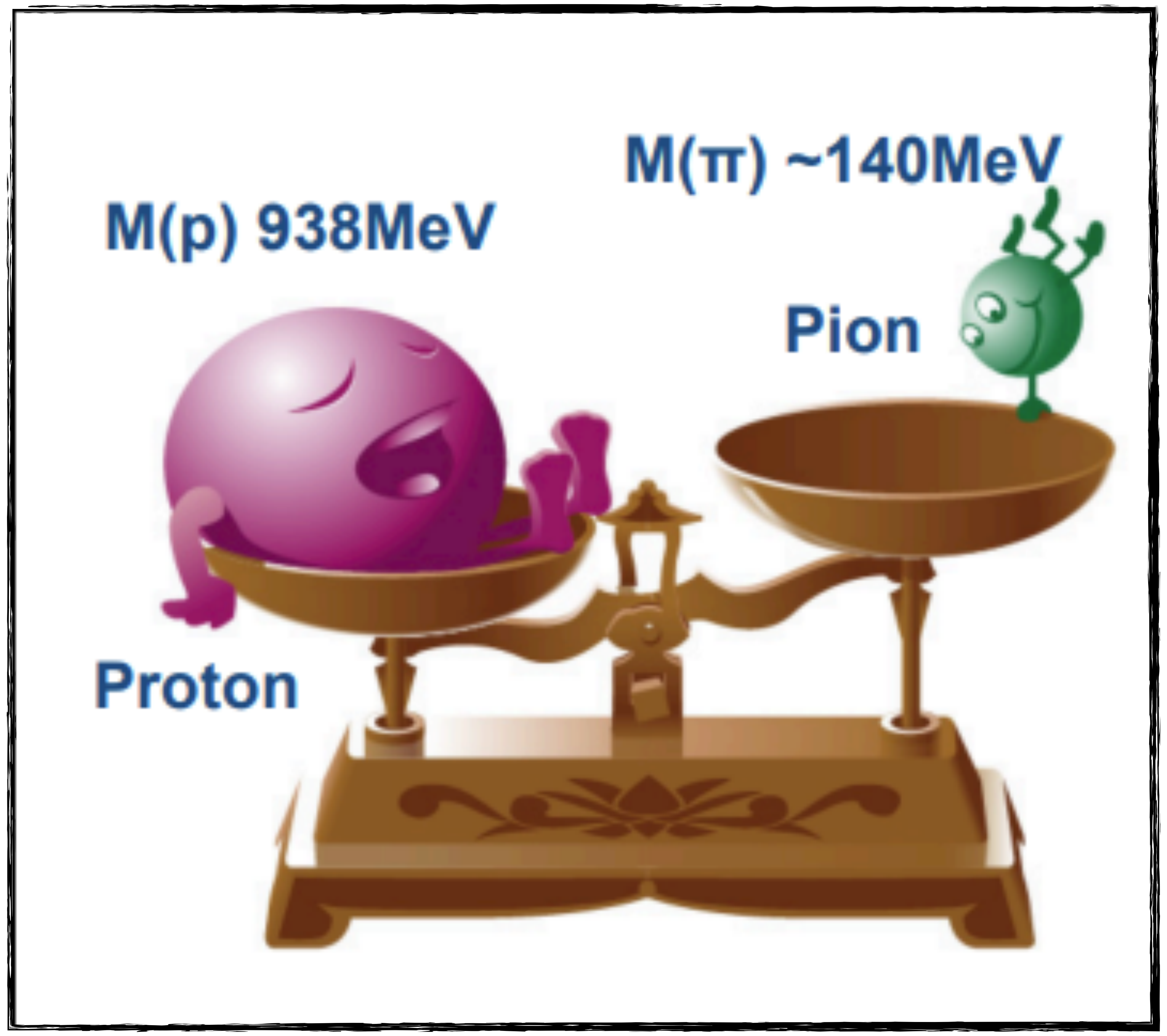
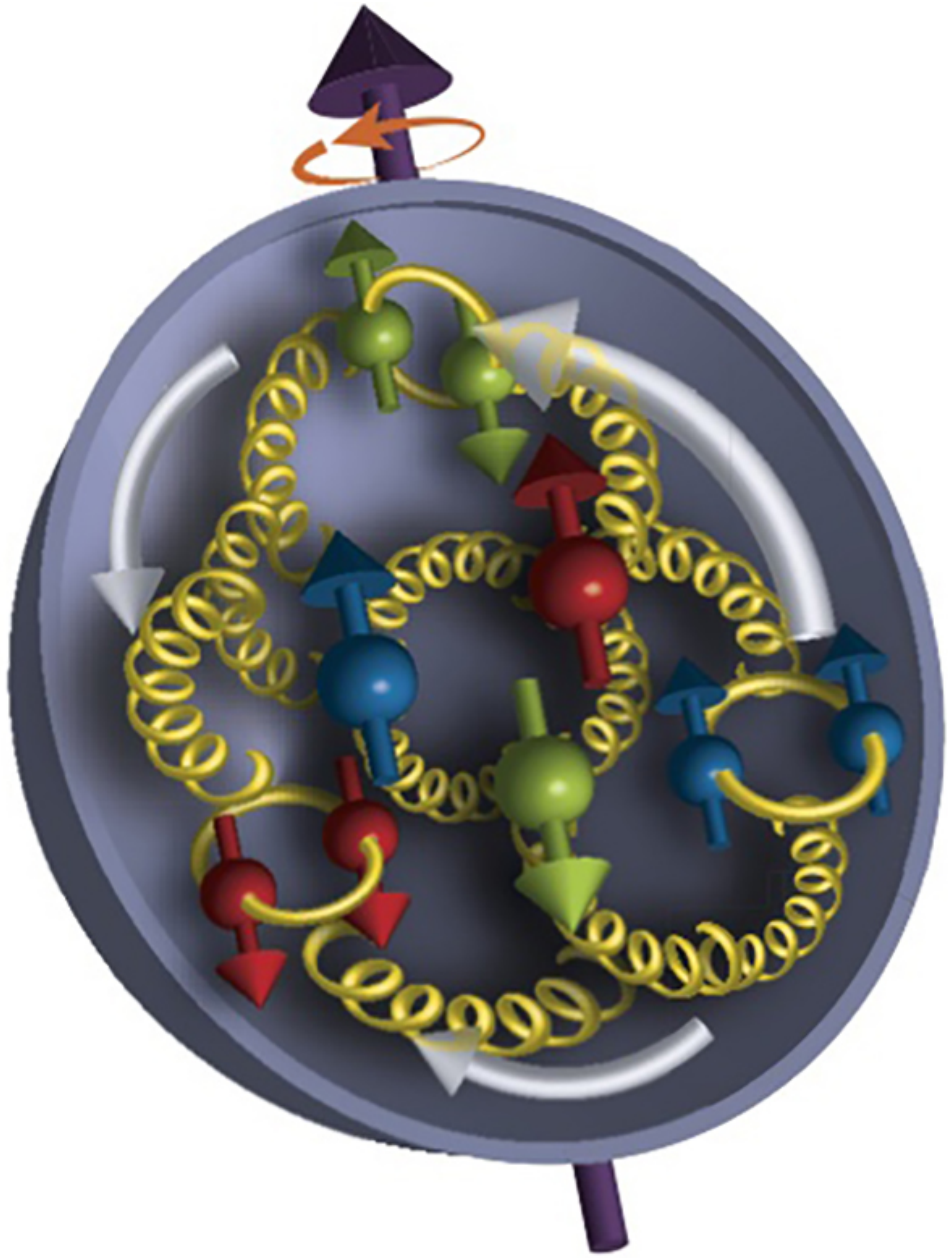
# Outline

- Introduction
  - Mesonic content and structure of Nucleons
  - Sullivan process and physics motivation
- TDIS experiment at 11 GeV
  - Experimental setup
  - Ongoing developments
- mTPC detector and Tracking algorithm
- Summary



# Introduction

## Structure of the pion



- As the lightest QCD bound state, the pion has historically played a central role in the study of the strong nuclear interactions.
- On one hand, it has been the critical ingredient for understanding the consequences of dynamical chiral symmetry breaking in QCD and how this dictates the nature of hadronic interactions at low energies.
- As the simplest $q\bar{q}$ state, the structure of the pion is relatively more straightforward to compute theoretically than baryons

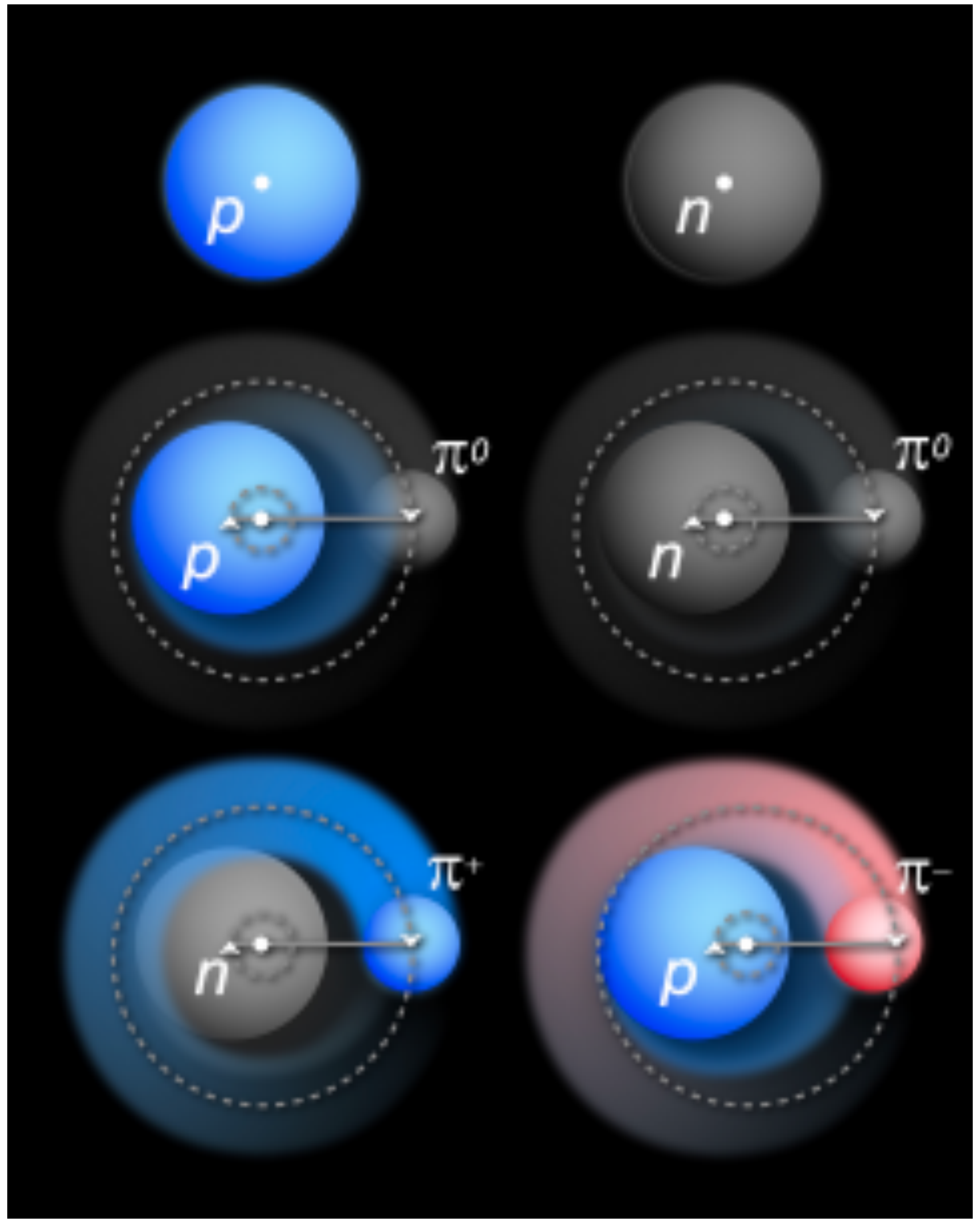
# Introduction

## Mesonic content and nucleon structure

- The experimental knowledge of the partonic structure of the pion is very limited due to lack of stable pion targets.
- There are ample evidence that nucleons have pionic content in them.
- Experimental evidence pointed to the nucleon existing ~20% of the time in a virtual meson nucleon state.
- The idea of considering meson cloud as a virtual pion target was used in HERA e-p collider.
- Most of the current results were obtained with Drell-Yan scattering.
- The theoretical calculations tend to disagree with each other.

These discrepancies tell us that it is essential to measure the pion structure function over a wide range of x using new technique

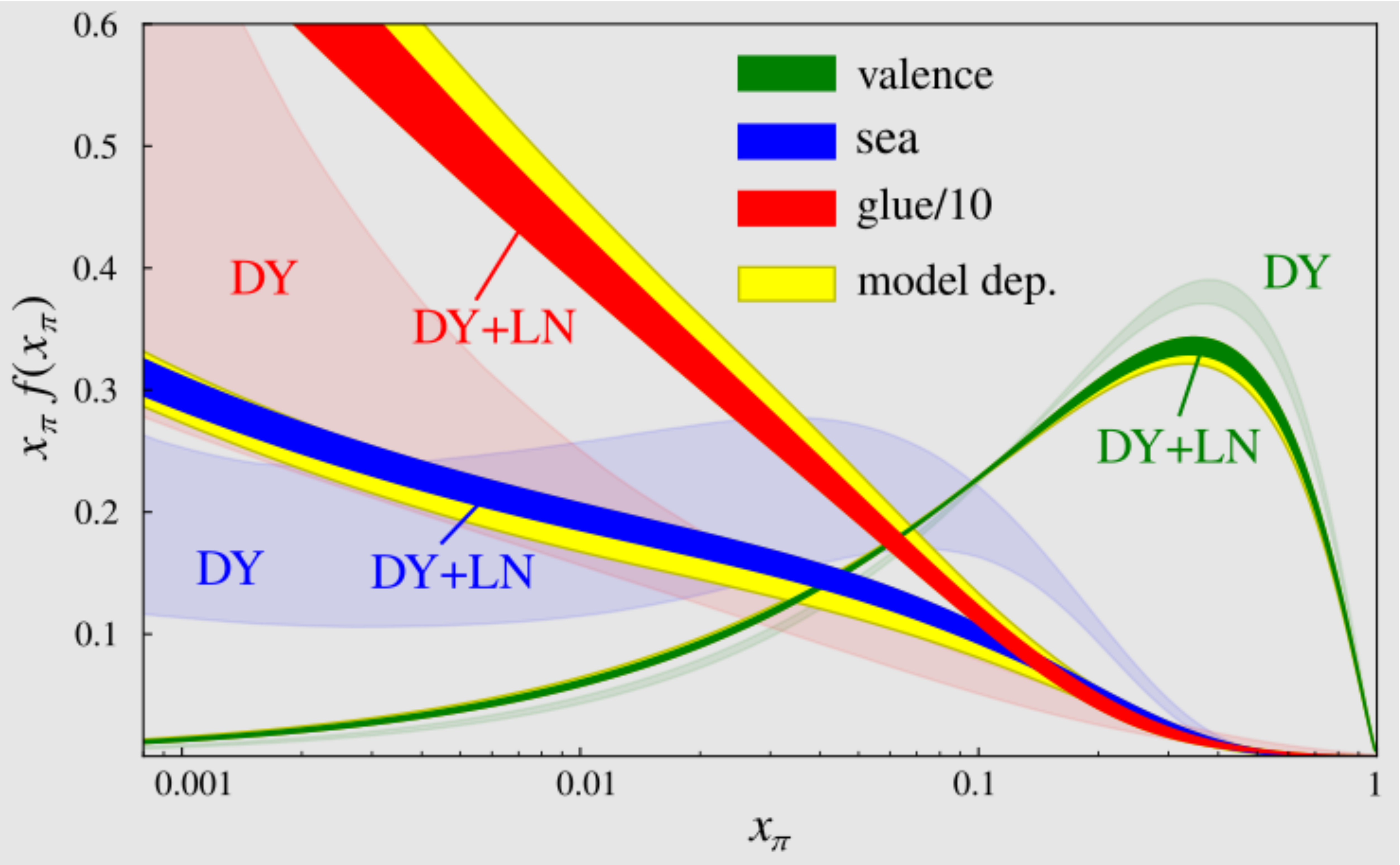
Illustration of the impact of the "pion cloud" of the charge distribution of the proton and neutron charge radii https://arxiv.org/abs/1208.4047



# Global QCD analysis of PDFs in the pion

P.C. Barry, N. Sato, W. Melnitchouk, C-R Ji, Phys. Rev. Lett. 121 (2018) no.15, 152001

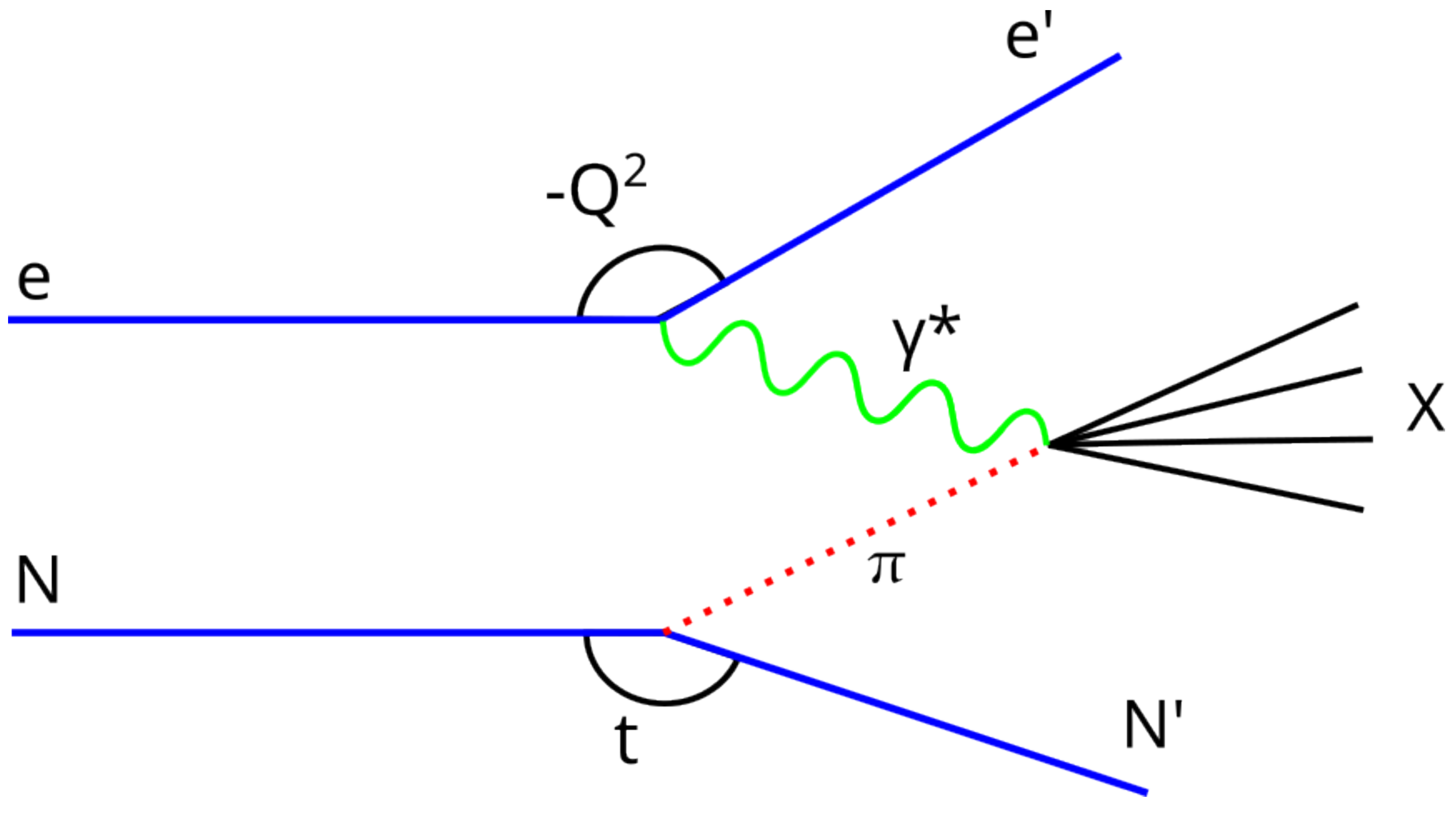
- The Jefferson Lab Angular Momentum (JAM) collaboration performed the first global QCD analysis of parton distribution functions (PDFs) in the pion .
- This study completed by combining π-A Drell-Yan data with leading neutron electro-production from HERA within a Monte Carlo approach.
- The combined analysis reveals that gluons carry a significantly higher pion momentum fraction, than that inferred from Drell-Yan data alone, with sea quarks carrying a somewhat smaller fraction.
- Drell-Yan cross sections are included at the next-to-leading log accuracy, results indicate the large-x behavior of the valence quark distribution can differ significantly.
- Based on these new developments the rate of TDIS signal events is expected to be less sensitive to the pion flux factor and also ~ 30% larger than what was assumed for the proposal approved in 2015.
- These studies have also shown that TDIS data could be used to probe resonances of the virtual pion and the associated duality.
- There is a high demand from the theorists for more meson structure data to constrain better PDFs.



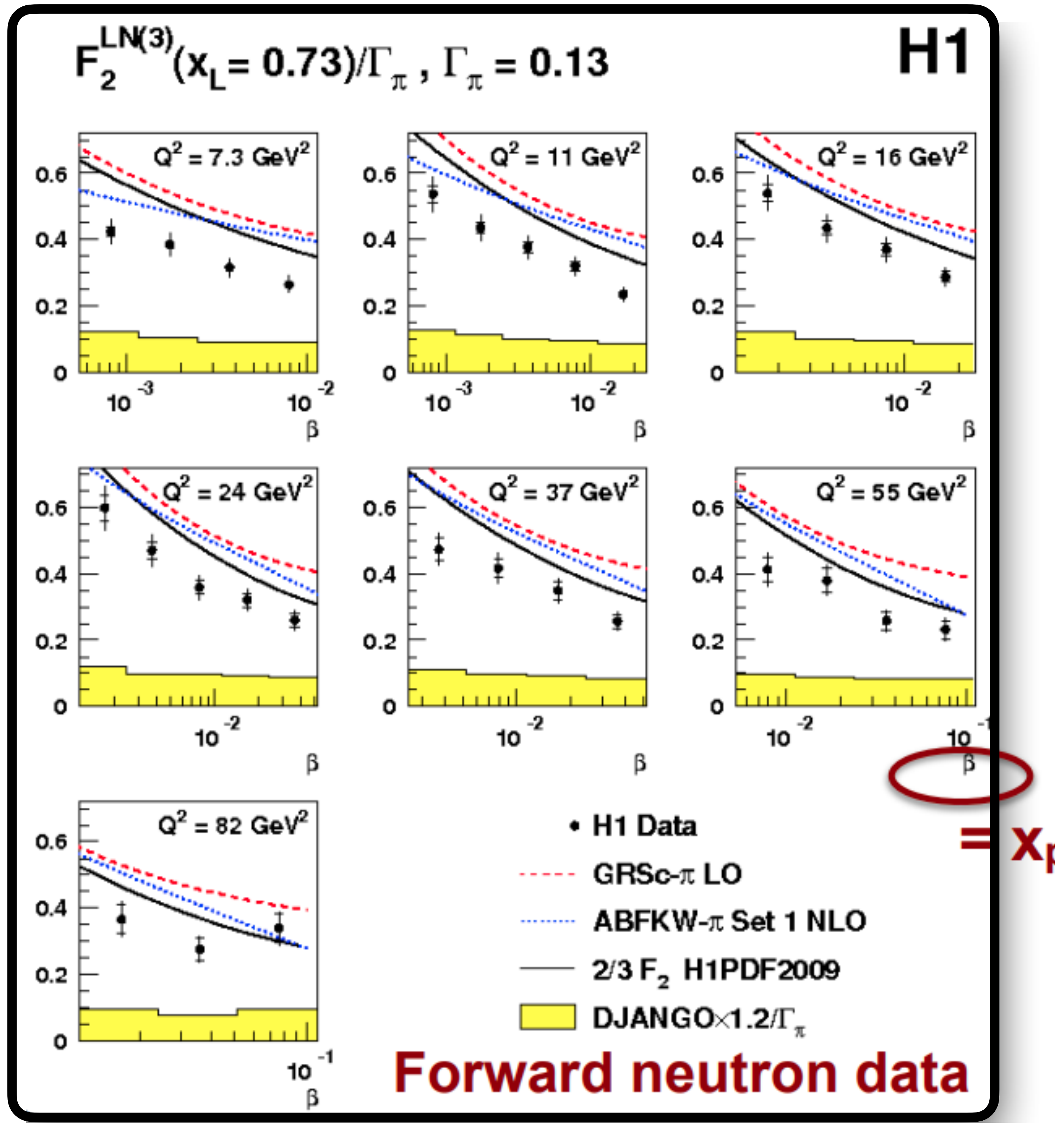

In the future, pion PDFs will be further constrained by new $\pi A$ DY data from COMPASS, as well as from the Tagged DIS (TDIS) experiment at Jefferson Lab.

# Deep-inelasic Scattering off a virtual-meson cloud is a possible experimental technique.

## The Sullivan process



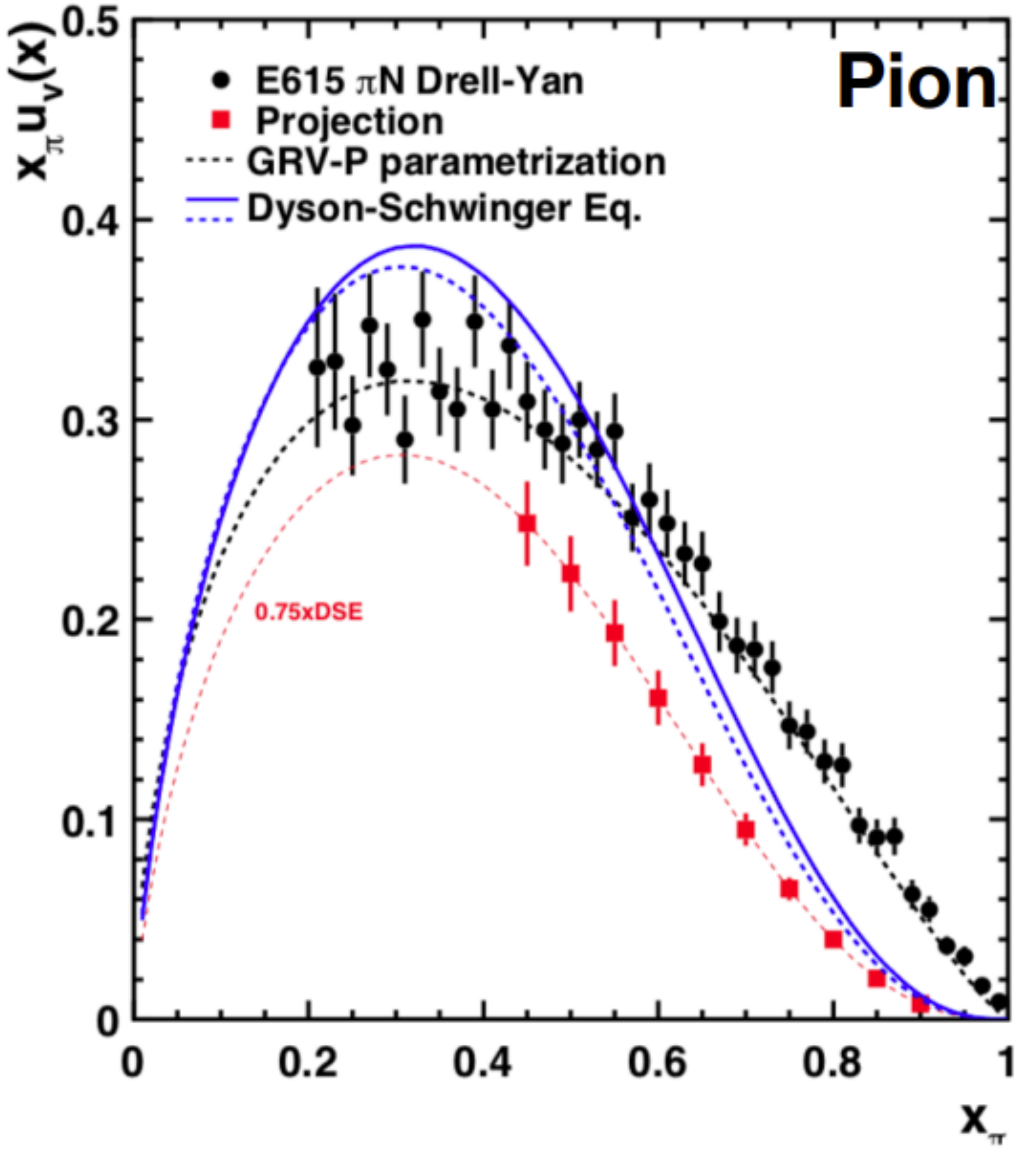

Tagged DIS at HERA
Lower x. (1.5e-4 < x < 3.0e-2)
Higher $Q^2$ ($6 < Q^2 < 100 GeV^2$)




DIS events with forward going neutrons in coincidence

Successfully demonstrated at HERA for very low-x used to measure the pion structure function

Projected range of coverage for relevance to valence quark distribution




Tagged DIS at JLAB
Higher x
Lower $Q^2$

Direct measurement of the mesonic content of the nucleon

# The Tagged Deep Inelastic Program

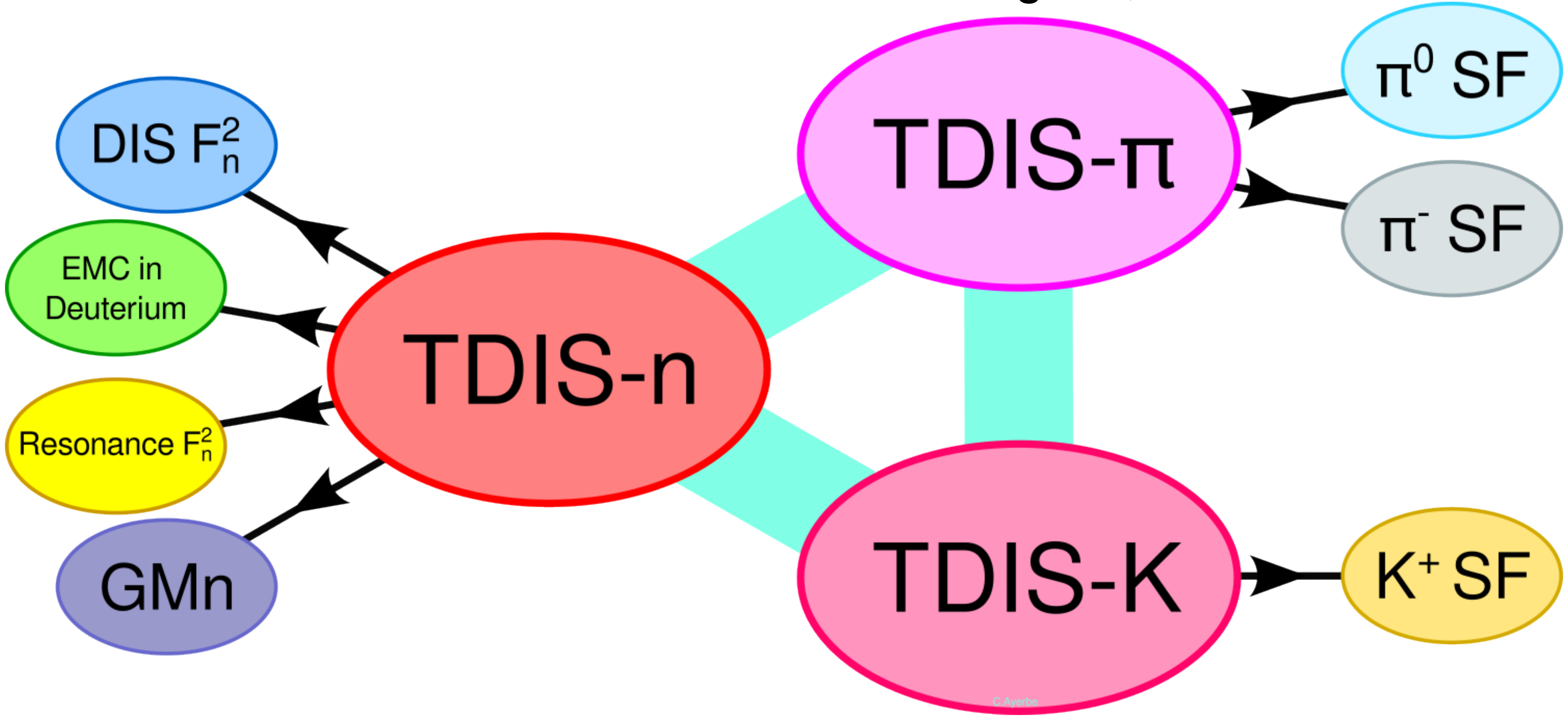
The TDIS experiment was approved in JLab PAC 43 (2015) to measure high $W^2$ and $Q^2$ electrons scattering from hydrogen and deuterium in coincidence with low momentum recoiling protons. PR12-15-006

Run groups additions:

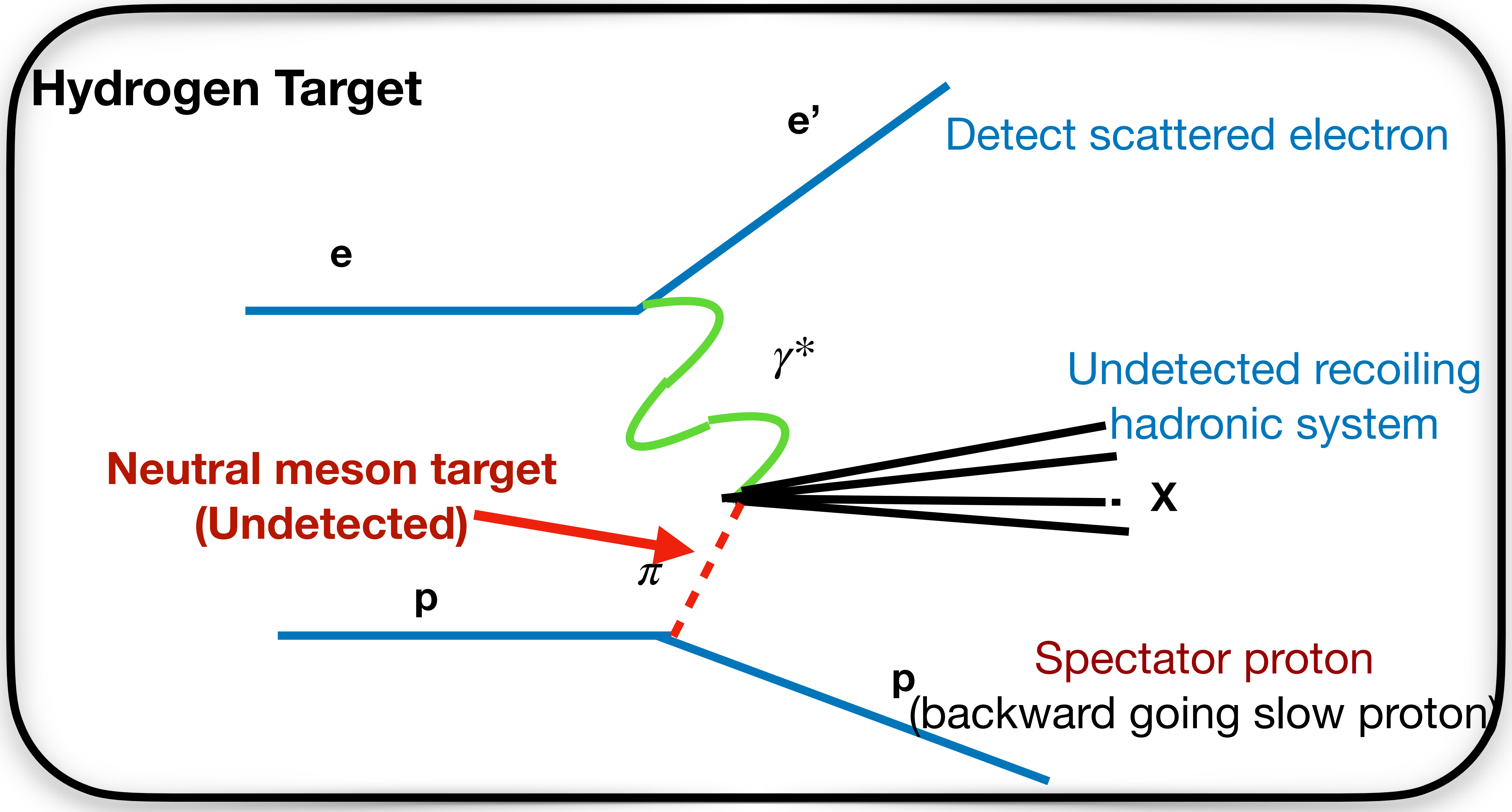
- C12-15-006 Measurement of kaon SF through TDIS. JLab PAC 45 (2017)
  World-first direct extraction of kaon SF

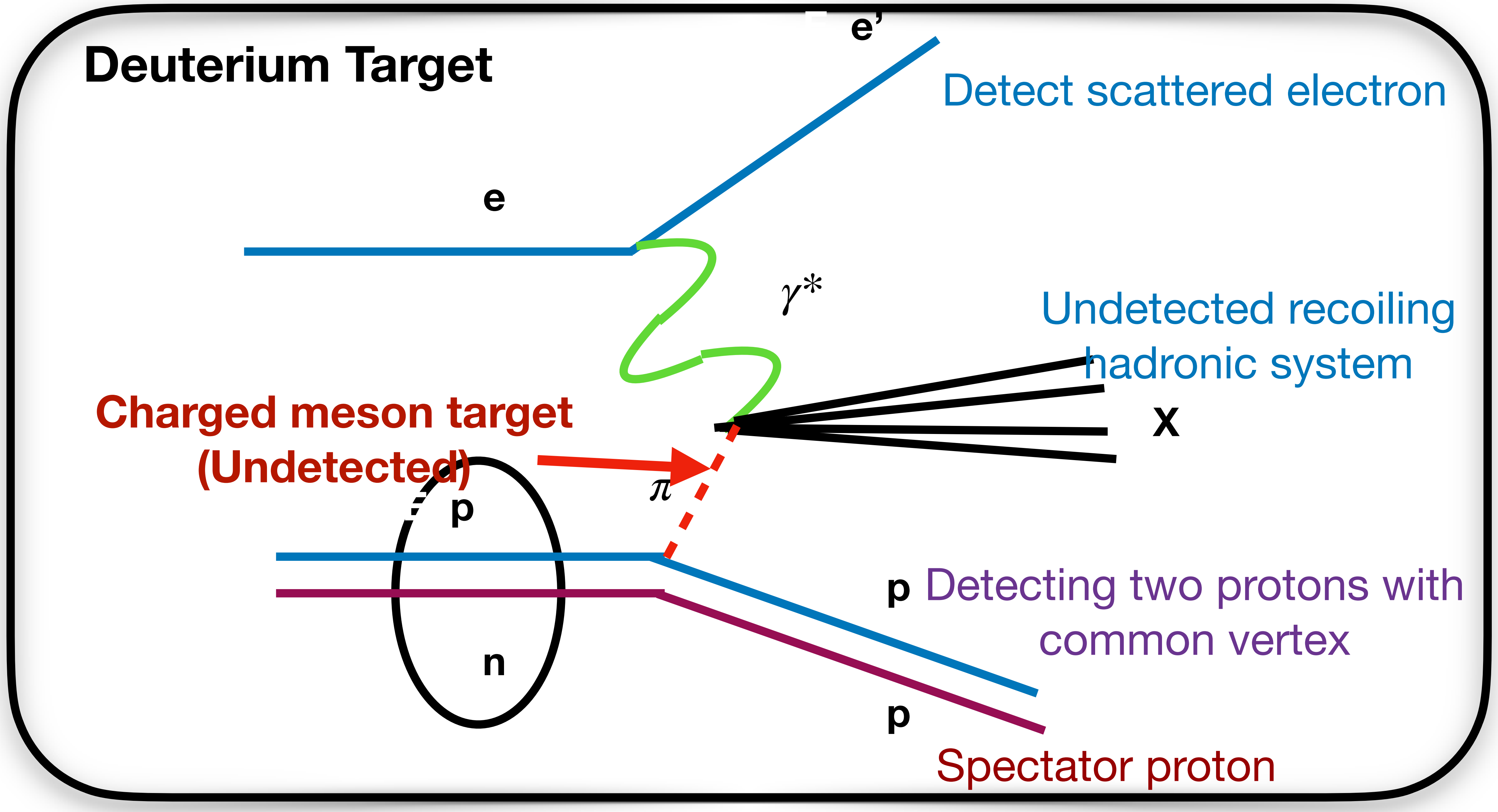
- C12-15-006B TDIS-n: Tagged DIS Measurement of the Neutron Structure Function. JLab PAC 49 (2021)
  A broad study of the neutron structure at DIS and resonance regime, with EMC effect in the deuteron studies and GMn.

ShuJie Lee's talk
n-TDIS



# Spectator tagging can be used to tag the “meson cloud” target




DIS event -reconstruct $x, Q^2, W^2$, also $M_X$ of recoiling hadronic system

$$R^T = \frac{d^4\sigma(ep \rightarrow e'Xp')}{dxdQ2dzdt} / \frac{d^4\sigma(ep \rightarrow e'X)}{dxdQ2} \Delta z \Delta t \approx \frac{F_2{}^T(x, Q^2, z, t}{F_2{}^p(x, Q^2)} \Delta z \Delta t \,.$$

Where $R^T$ is ratio of tagged to total inclusive cross sections

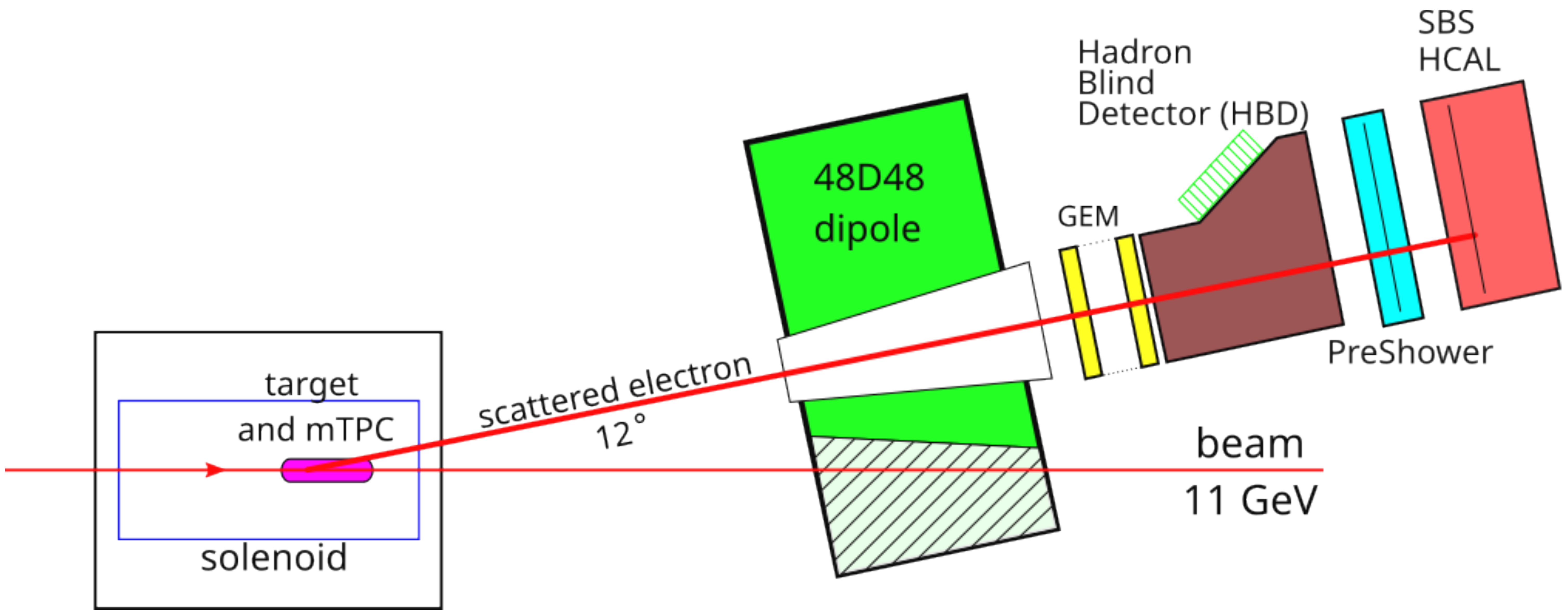
Tagged structure function a direct measure of the mesonic content of nucleons

$$F_2^T(x, Q^2, z, t) = \frac{R^T}{\Delta z \Delta t} F_2^P(x, Q^2)$$

Very low momentum recoiling protons 100 - 400 MeV/c ⟶ Need novel detector

# Experimental setup for TDIS experiment

- 50 $\mu$A 11 GeV electron beam on high density fixed target (H/D gas; 40 cm length, 1 cm diameter; 25 $\mu$m walls; 3-4 atm)
- 8 < $W^2$ < 18 GeV
- 1 < $Q^2$ < 3 $(GeV/c)^2$
- 0.05 < x < 0.2
- High luminosity is required : Tagged signal is orders of magnitude smaller than DIS signal ~3 *$10^{36}$Hz/$cm^2$




e' detection in reconfigured SBS
- GEMs (from SBS);
- Cherenkov;
- Calorimeter (HCAL)
- Electron PID and (L2) trigger tracking

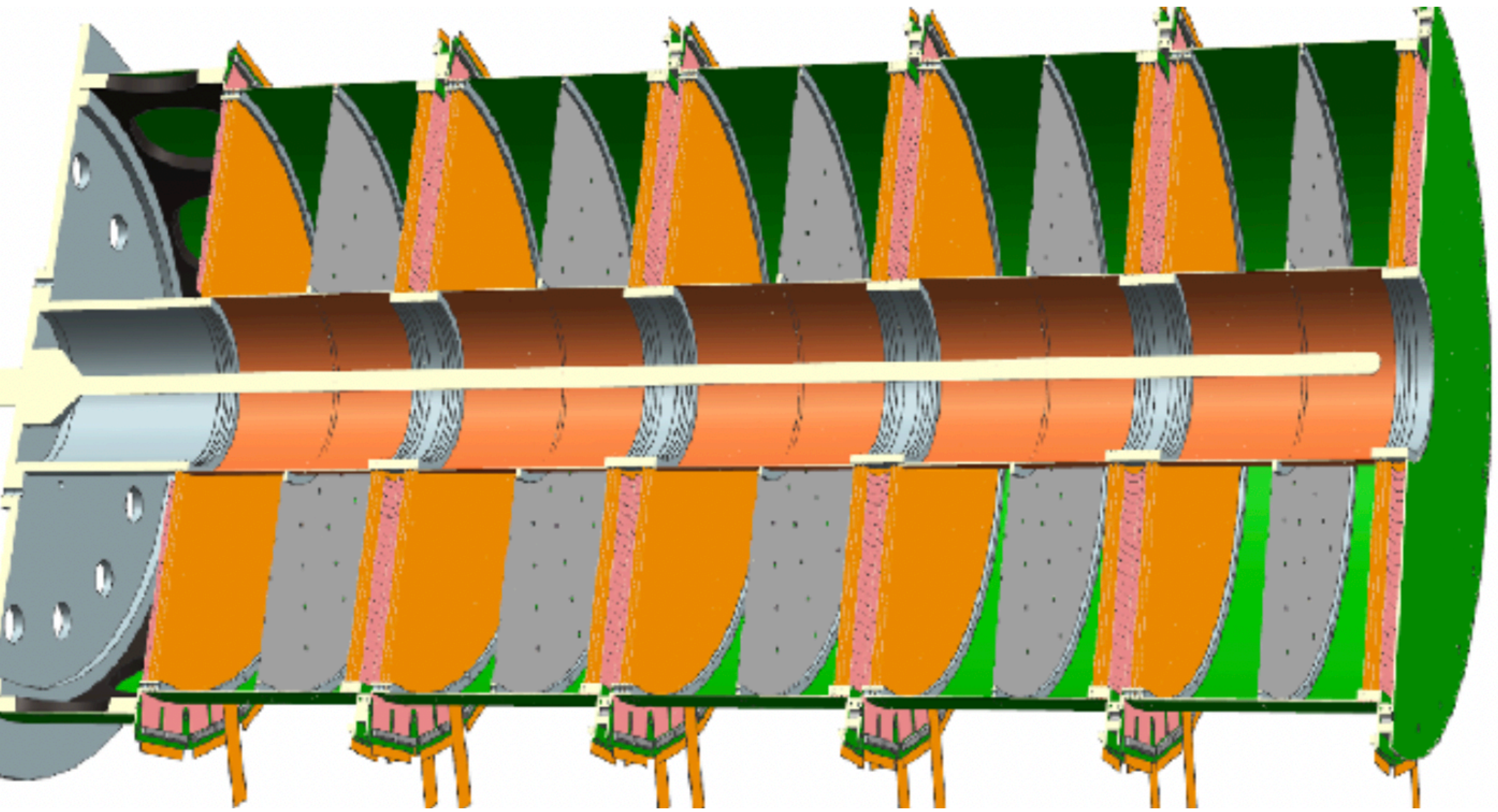
High rate multiple time projection chamber (mTPC) for tagging

# The multiple- Time Projection Chamber (mTPC)

The drift field is parallel to the magnetic field, leading to reduced drift times and significantly simplified track reconstruction

CAD design by Ibrahim Albayrak, Concept : UVA group

Module coupling locations



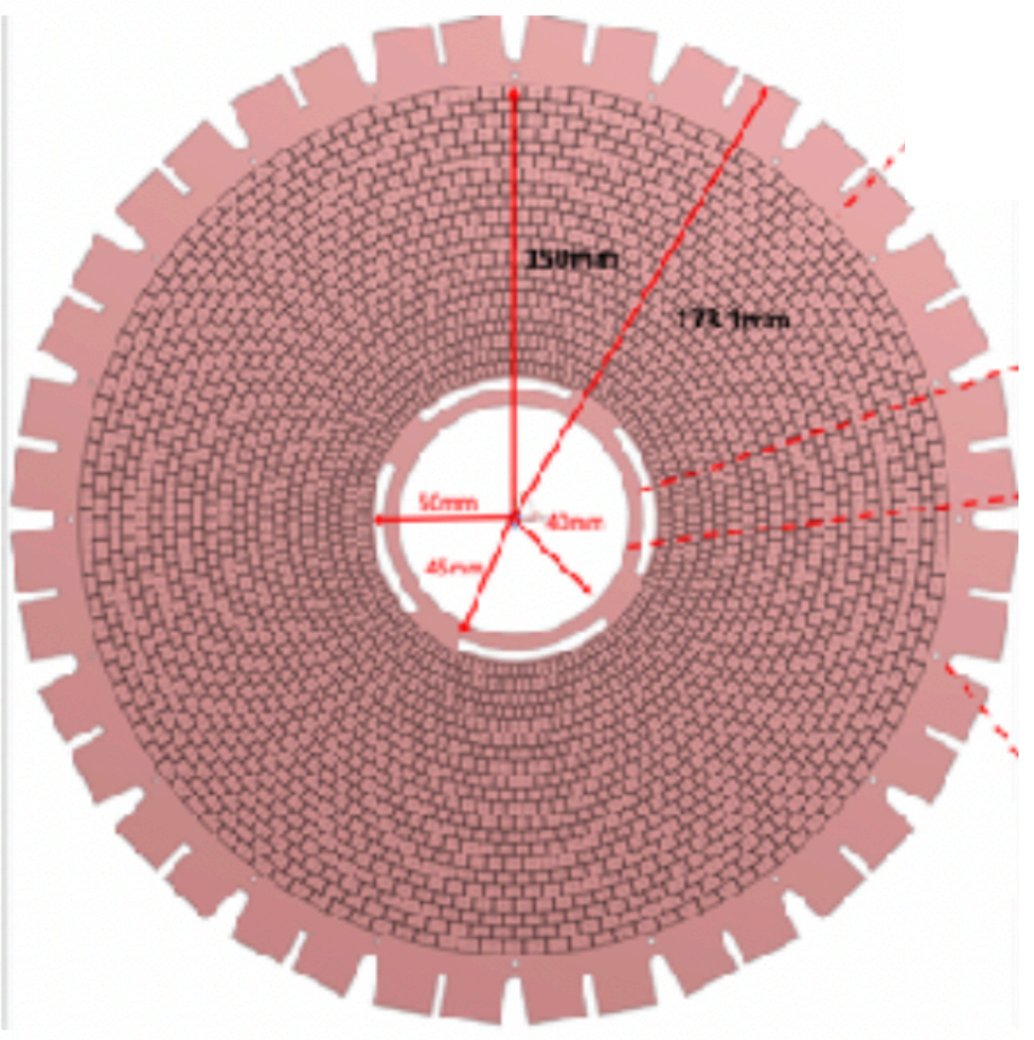
Dimension :55 cm long, Inner radii =5 cm , Outter radii =15 cm

- The idea of RTPC is good for BONuS12 . But for TDIS we need to optimize the RTPC idea....

- High luminosity (50 µA, $L = 3 \times 10^{36}$ Hz/cm$_{2}$)
→ higher background

- long electron drift path→ wider time window

Multiple Time Projection Chamber



- Will be placed in the bore of the superconducting solenoid magnet (L=152.7 cm, $\vec{B} = 4.7$ T) to fit the requirement of strong magnetic field parallel to $\boldsymbol{E}$

- Consist of 10 TPC modules to form one composite mTPC à takes care of high rates compared to single radial TPC

# TDIS setup : on going developments

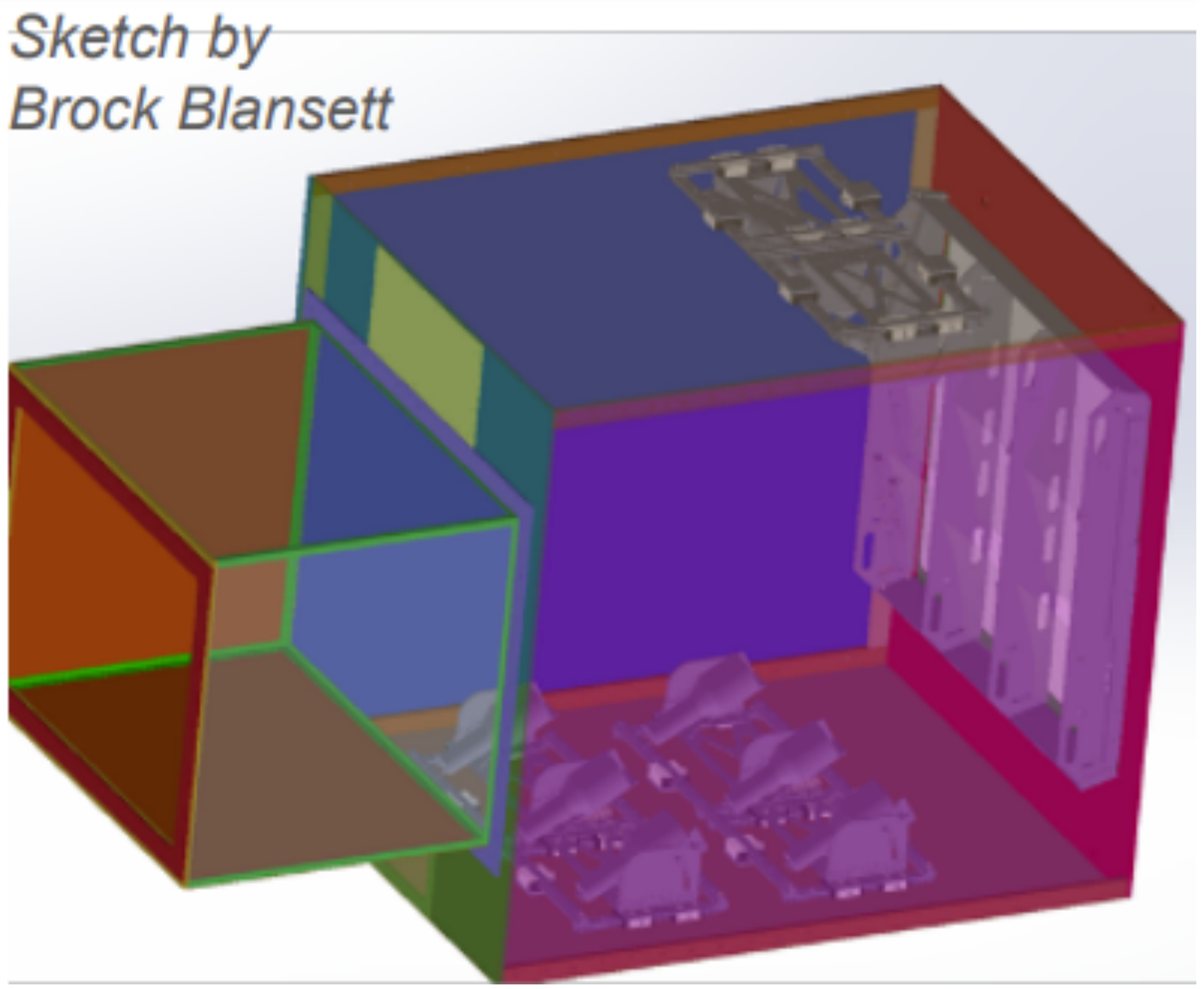
- Straw target prototyping (MSU) : 25 $\mu m$ kapton walls; Spiral wound;3 atm;room temperature

- New hadron blind gas Cherenkov under design (UT): 4m Neon or Ne/Ar, 1 atm, Distinguish e/$\pi$ over 2-11 GeV.

- Simulations with proposed HCAL is ongoing.

- Front end electronics development and prototyping at JLab (Jlab, University of Sao Paolo)

- Potential to run at lower beam current: Recent theory suggests TDIS signal ~30% larger and less sensitive to pion flux factor than expected.

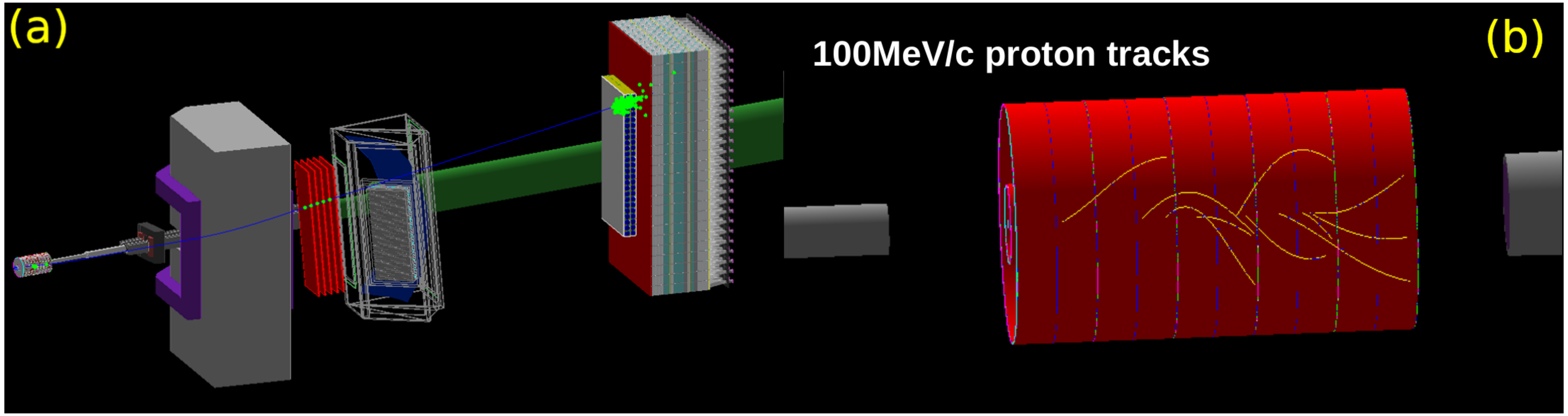


# TDIS setup : on going developments

- The simulations were carried out using the Hall A Super Bigbite Spectrometer (SBS) GEANT4-based simulation framework, G4SBS.

Implemented the detailed MTPC geometry and using necessary particle generators to simulate the experiment signals and backgrounds.

- Developed digitization routines (not currently integrated with G4SBS) using the files produced by G4SBS.




a): Full TDIS experiment in G4SBS, including the target and mTPC, the SBS dipole, the RICH detector, the GEM trackers, and the SBS HCal with preshower; (b): mTPC geometry with 100 MeV/c proton tracks.

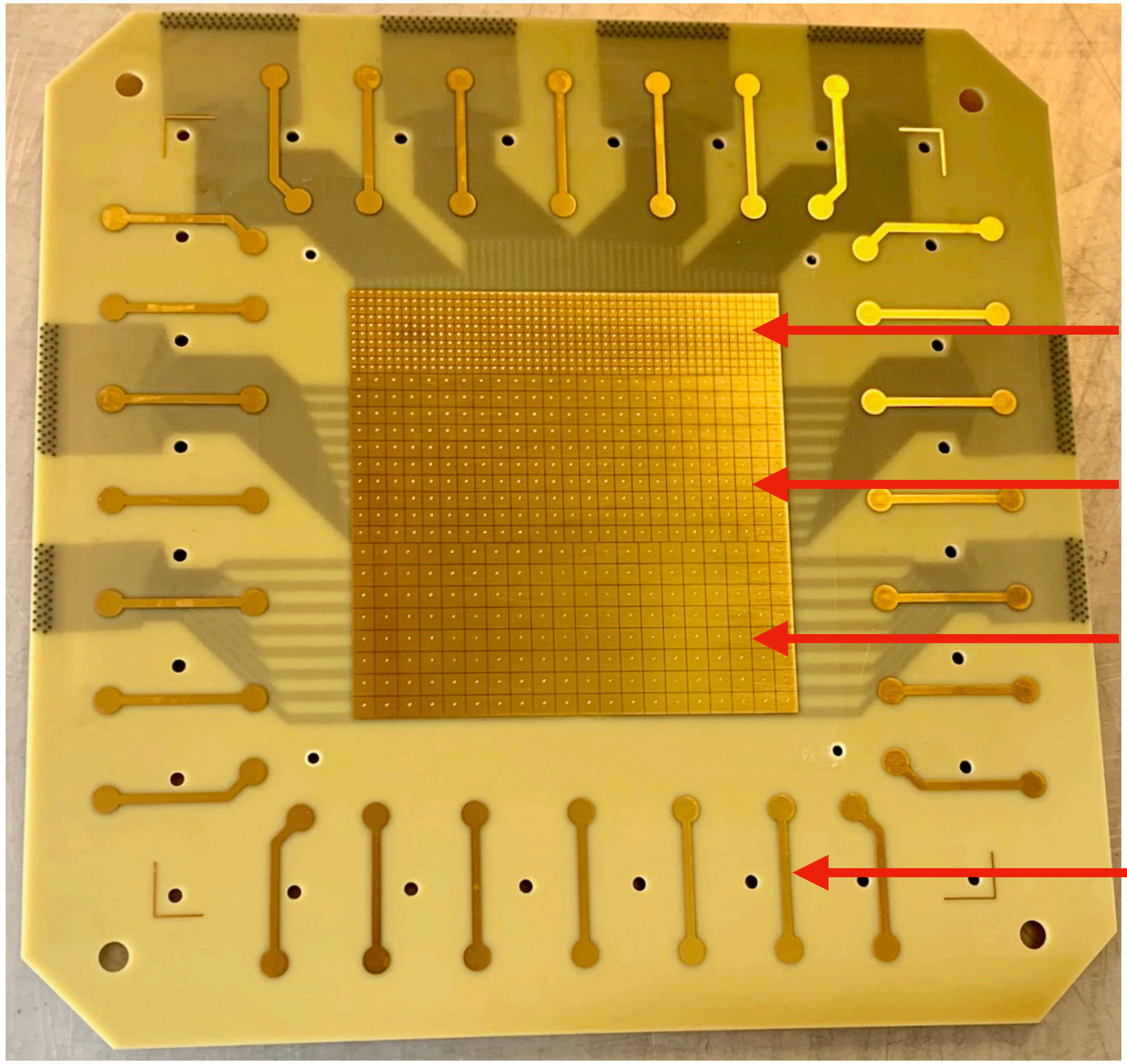
Contributors:Carlos Ayerbe Gayoso, Eric Fuchey and Rachel Montgomery

# TDIS setup : on going developments

## mTPC prototyping and development

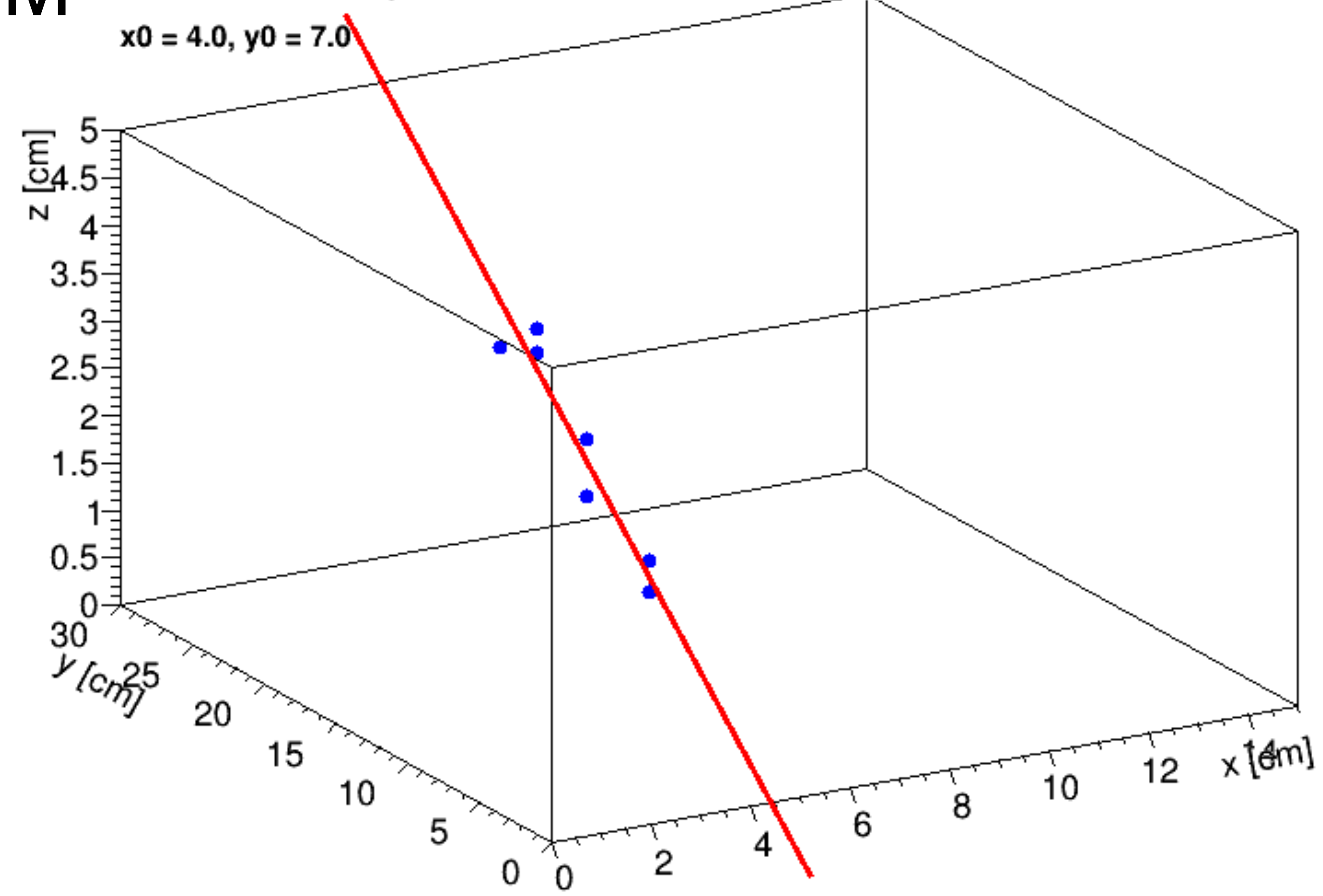
Square shaped prototype TPC to validate and test concepts of the larger cylindrical shaped mTPC. The concepts that will be evaluated using this prototype include

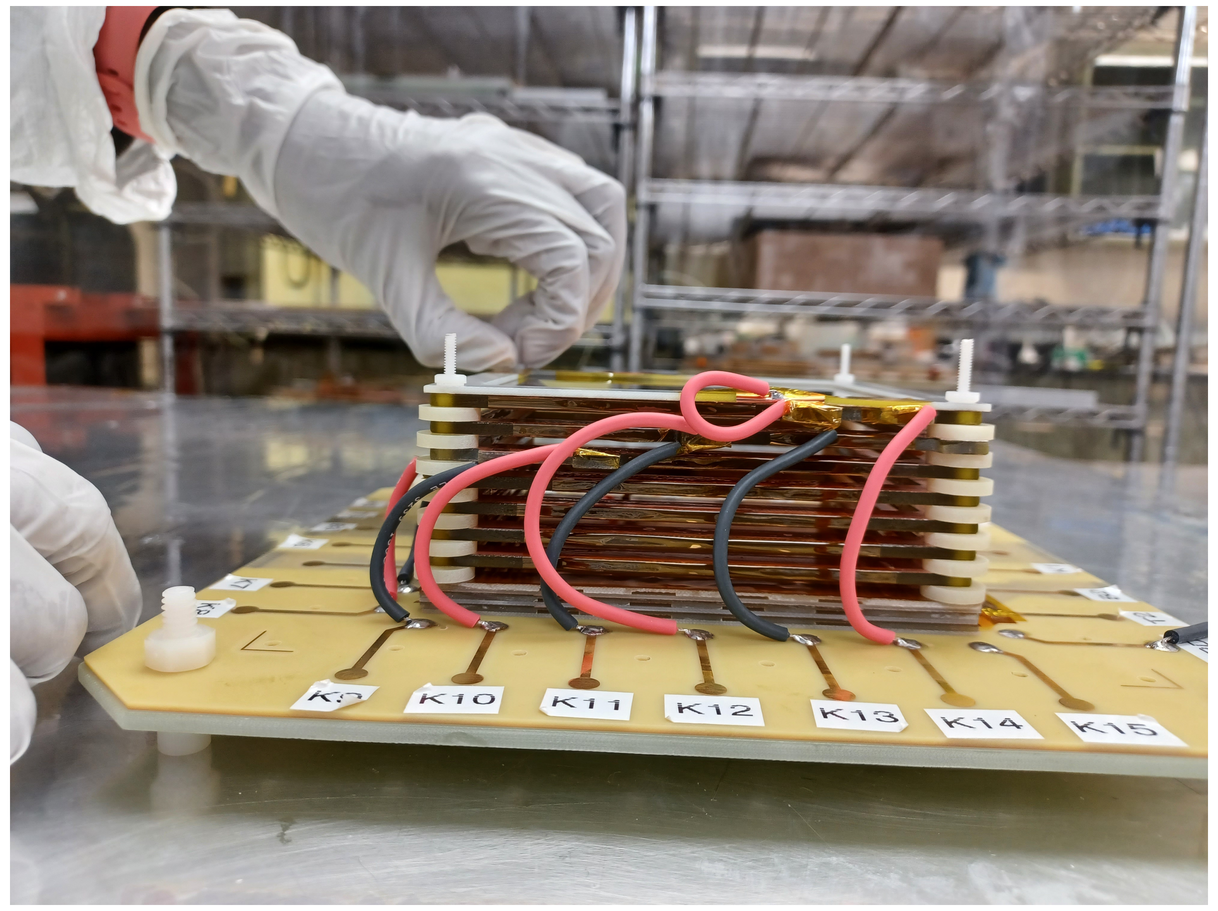
1. Validate field cage, readout
2. Test tracking algorithm
3. Study track resolution vs pad sizes
4. Study drift gas



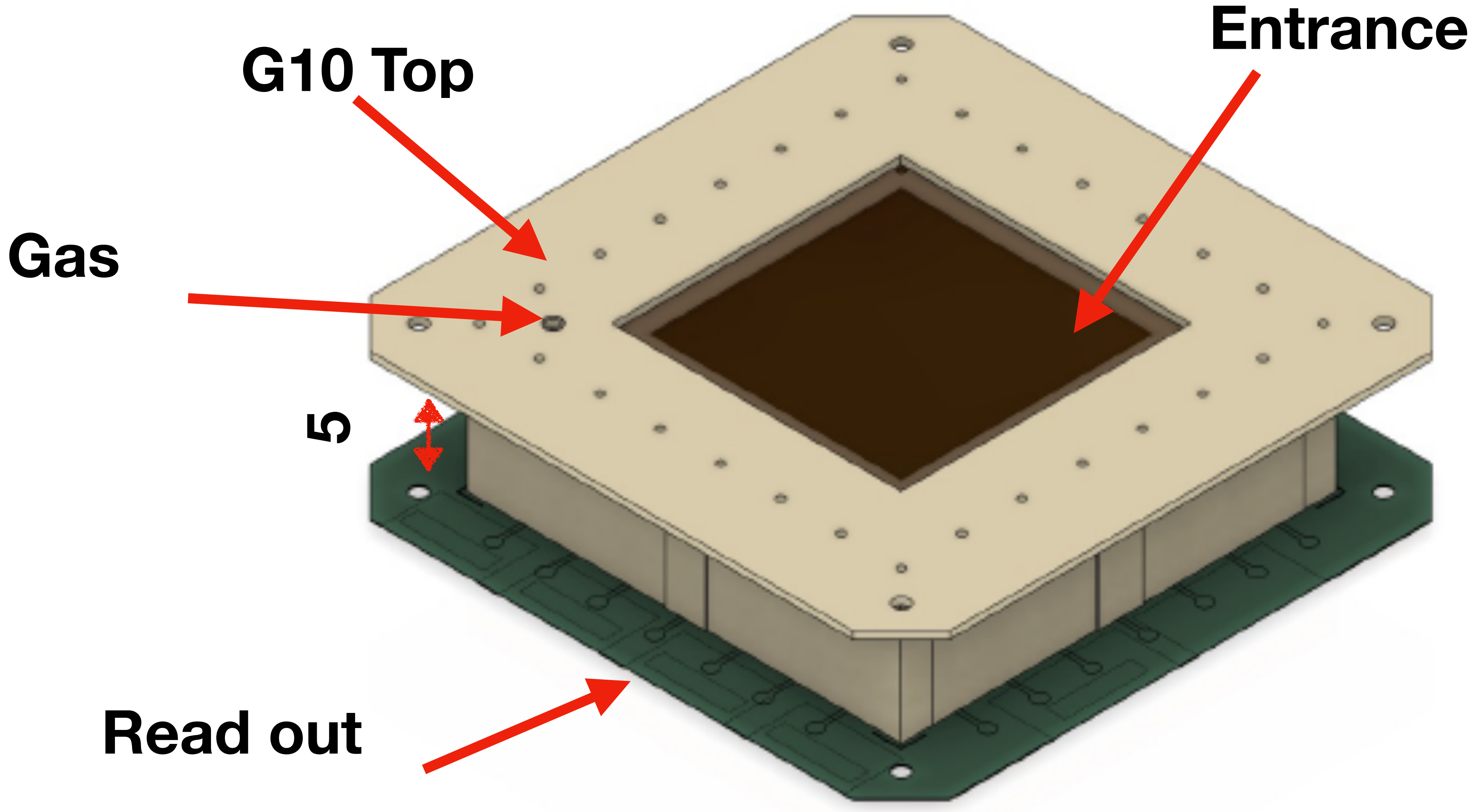
# TDIS set up : on going developments

- Design small prototype with 10 x 10 $cm^2$ GEM active area
- Anode (Read Out plane),
- Three GEMs stacked with 2 mm spacing (provided by spacers)
- Aluminized Kapton to act as cathode
- 5 cm space between anode and cathode endplates



The prototype was successfully tested with a real beam and data were collected. Analysis is currently ongoing.




Contributors: Jack Cleveland, Eric Christy and Aruni Nadeeshani, Nilanga Liyanage, Huong Nguyen

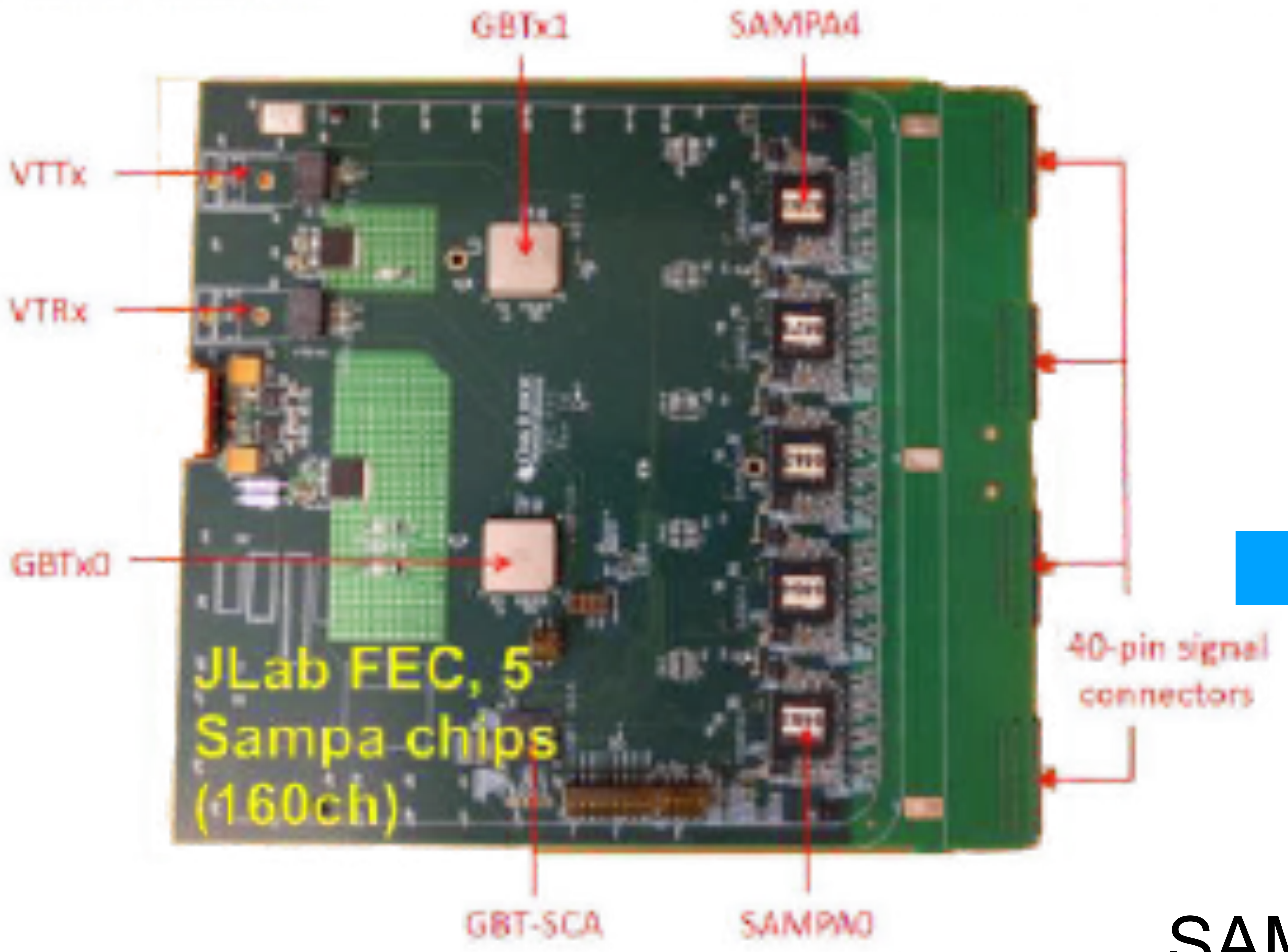
# Streaming Data Acquisition

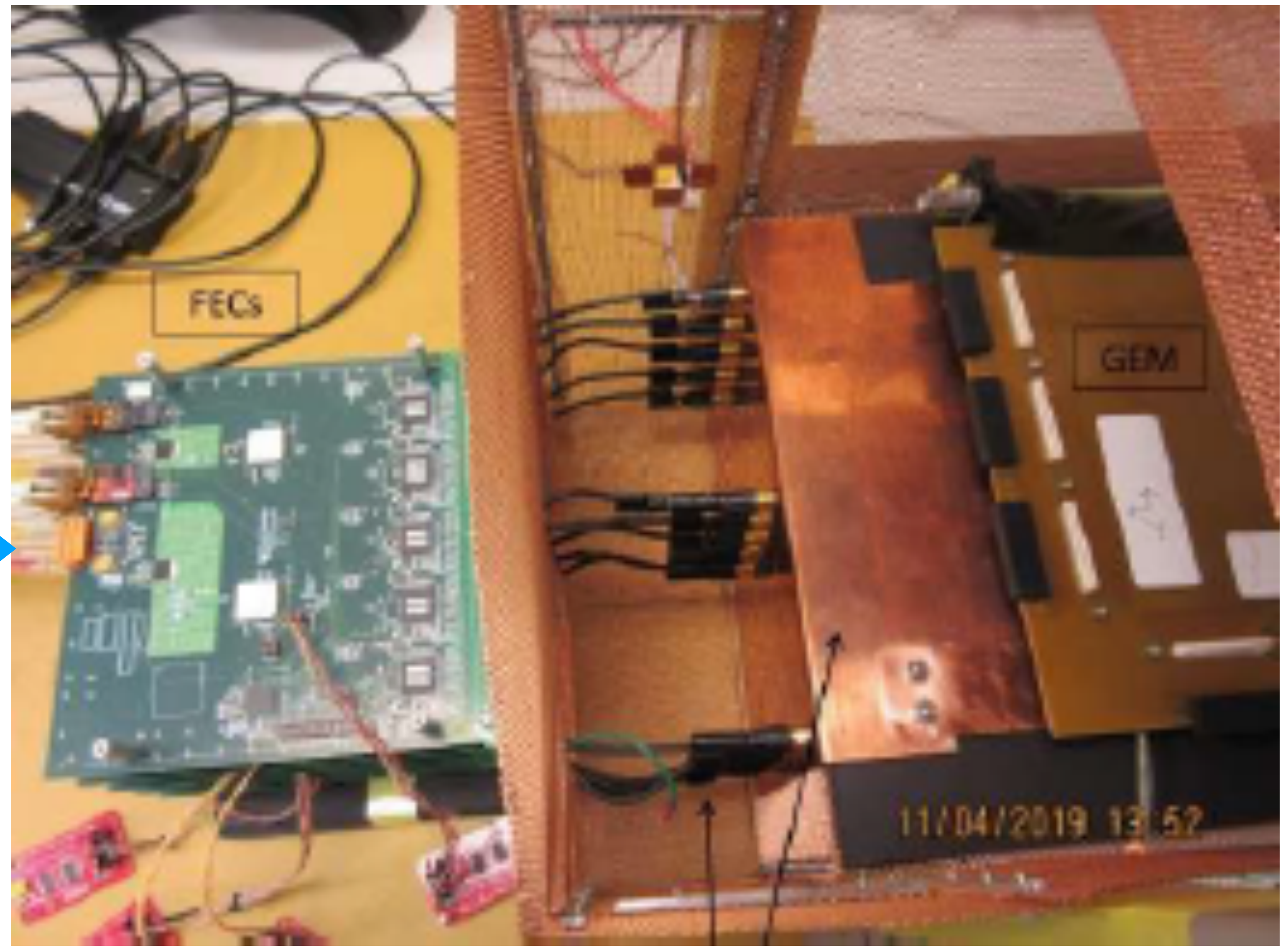
Readout electronic updates

- Obtain radiation hard components from CERN

-2nd generation data transmission and power conversion components

Design/prototyping/testing
E. Jastrzembski, E. Pooser,
G. Heyes (JLab)
SAMPA chip
M. Bregant (U. Sao Paulo) and streaming readout developed for ALICE TPC upgrade



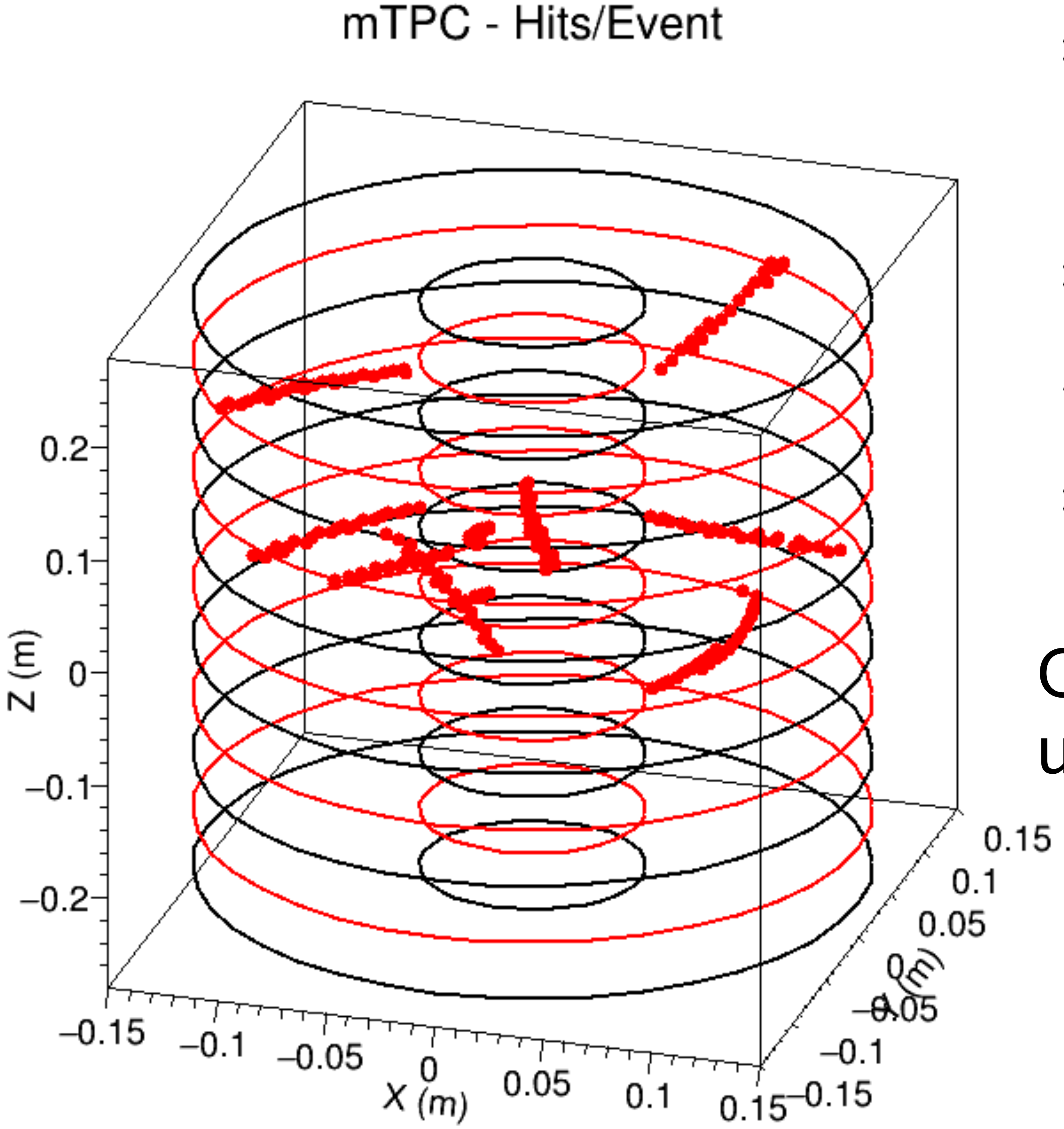



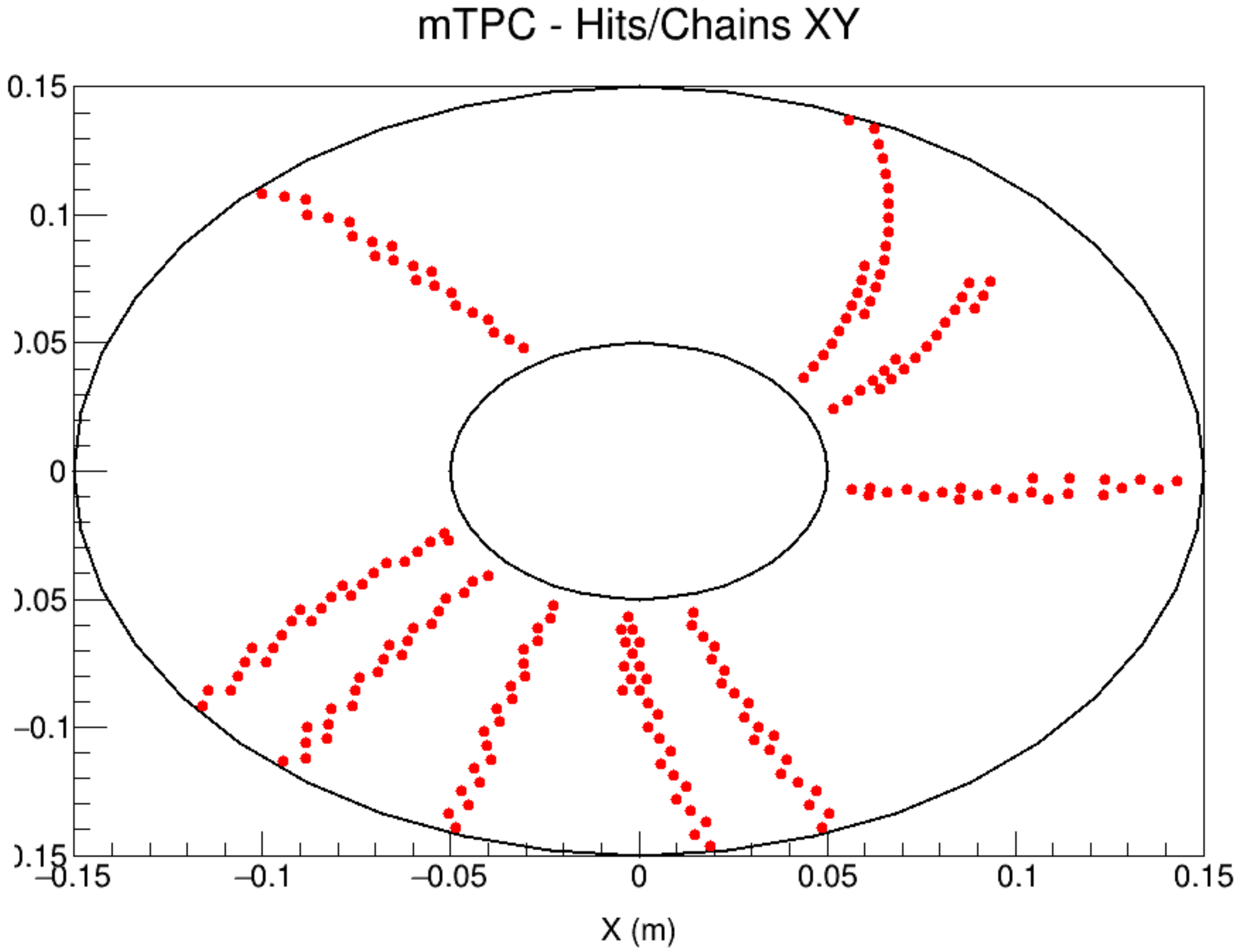

SAMPA - charge-sensitive pre-amp, ADC, DSP
(zero-suppresion e.g.)

# TDIS experiment mTPC tracking algorithm

- High number of tracks makes mandatory a good identification of tracks and fit
- There are three approaches to complete the tracking algorithm for mTPC detector. They are

1. Python script using toy model.
2. Using graph neutral network.
3. Using ACTS.

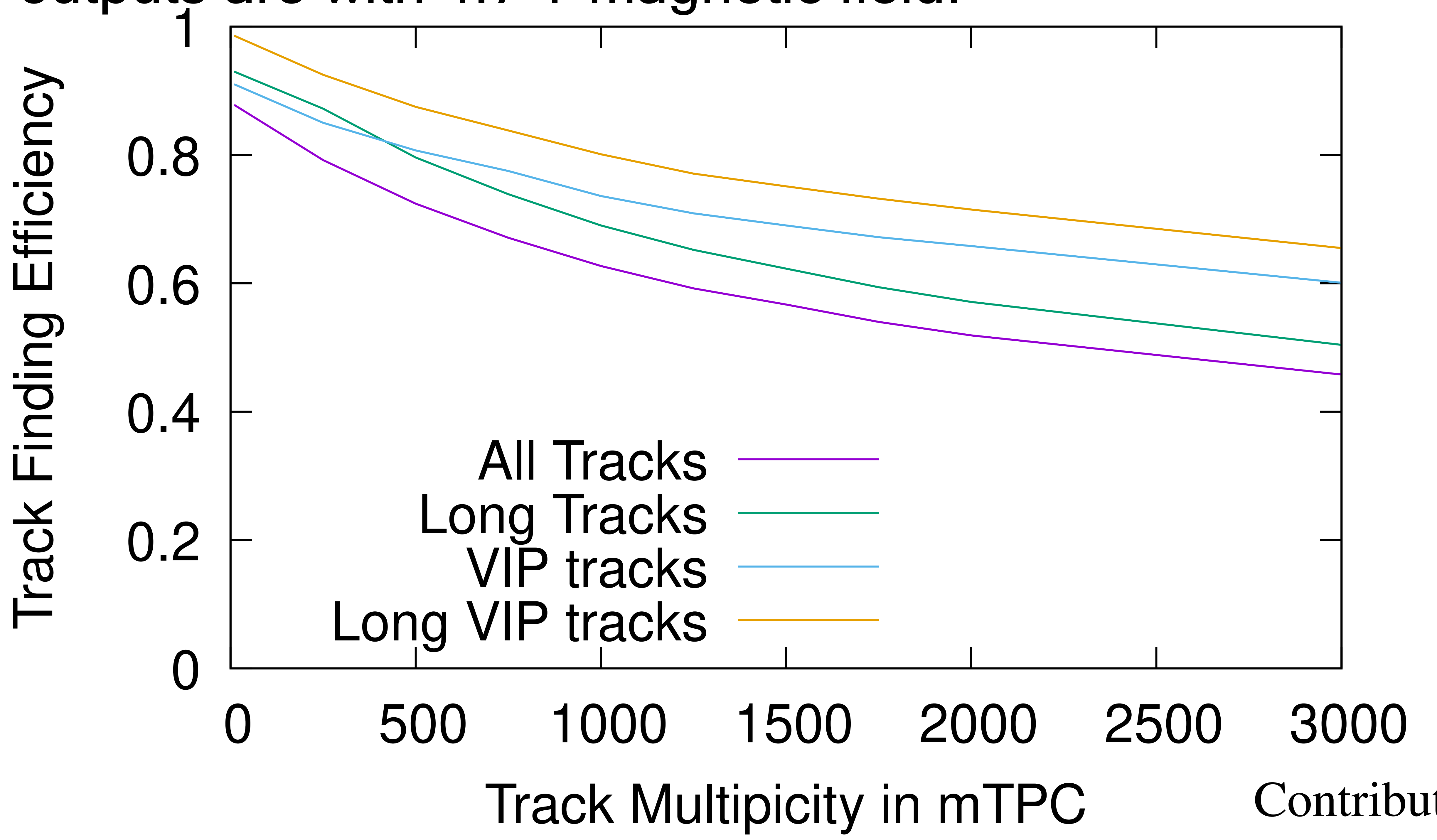



Outputs from Python based toy model using Event Display

# Using Python based toy model

- Steve developed a chain finder method using a Python-based toy model simulation of the mTPC (multiple Time Projection Chamber).
- Subsequently, this method was applied to digitized hits derived from proton events in the G4SBS based TDIS Geant4 simulation.
- The toy model serves as a valuable tool for swiftly grasping the mTPC's angle and momentum acceptance, which is determined by its geometry.
- Additionally, it aids in testing tracking algorithms.
- The chain finder method demonstrates track finding efficiencies exceeding 50% for multiplicities of up to 3000.
- All these outputs are with 4.7 T magnetic field.



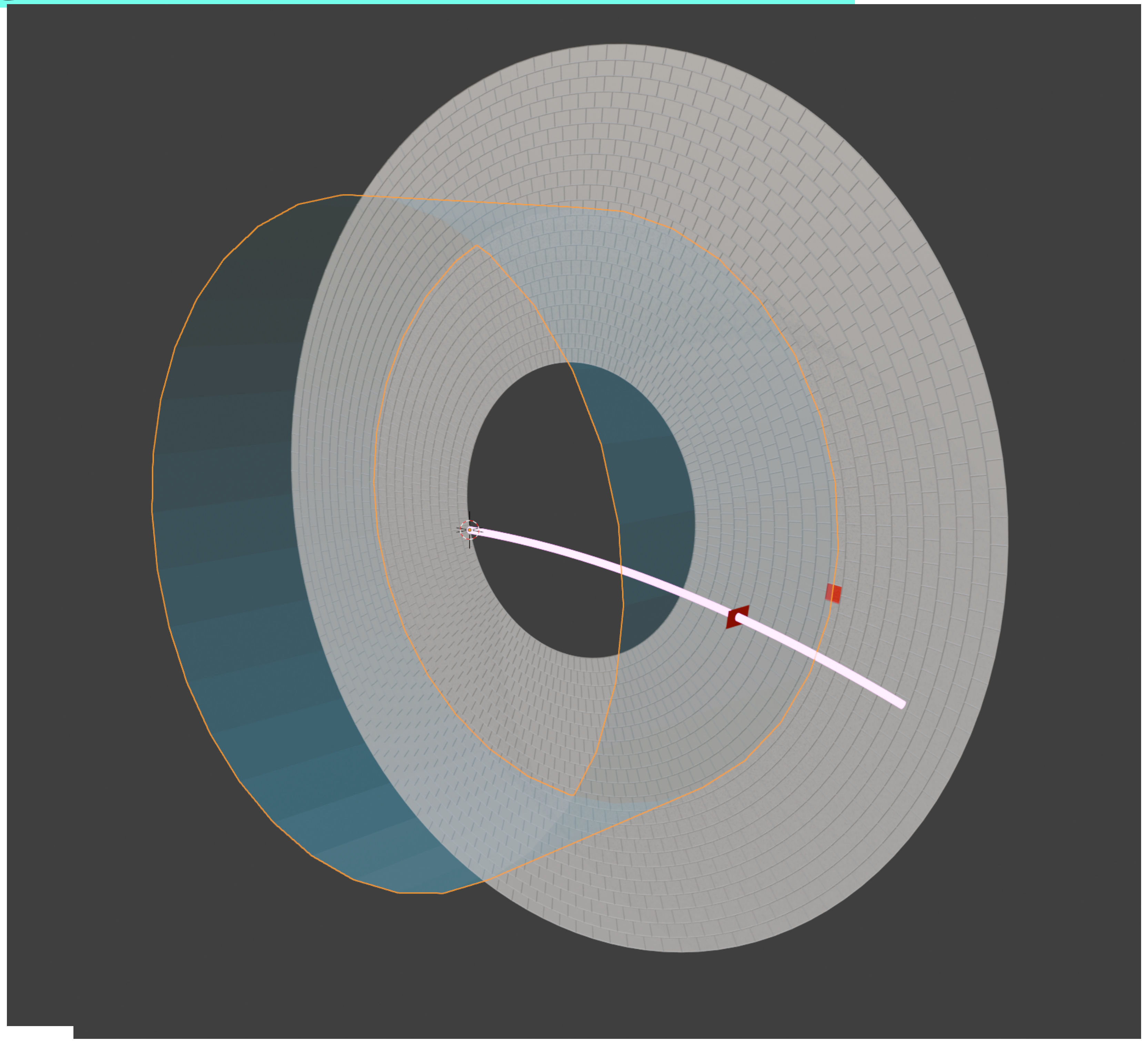

Toy model is useful for quickly understanding the angle and momentum acceptance of the mTPC

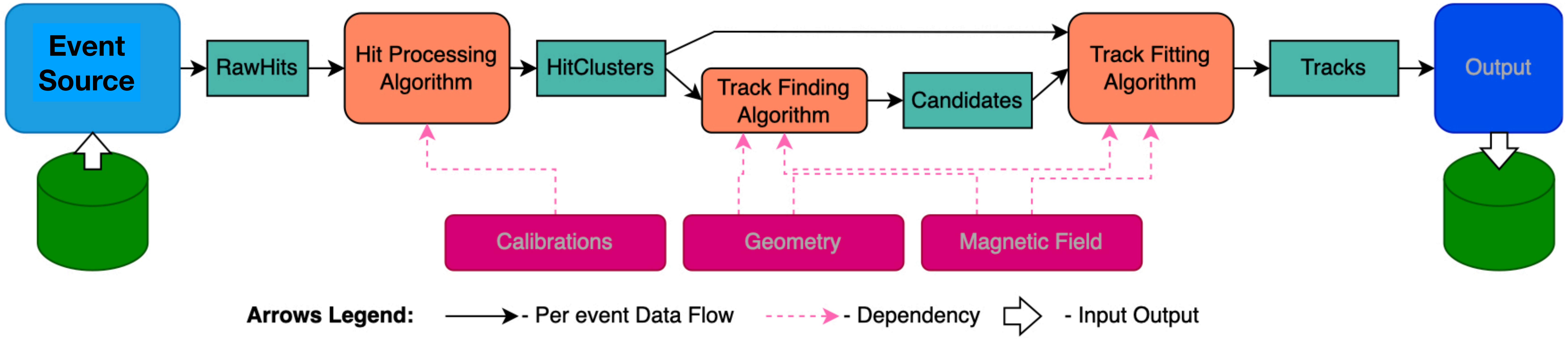
Contributors: Steve wood, Carlos Ayerbe Gayoso and Aruni Nadeeshani

# Track reconstruction Using A Common Tracking Software

- The mTPC tracking detector geometry translate in to analogous ACTS geometry :ACTS takes many formats of geometry input eg: GEANT4, Fun4All, DD4hep. For TDIS experiment we used the existing geometry in the GEANT4 and make gdml files.
- ACTS has available ROOT Geometry plugin that can take relevant active TGeo objects and covert them into Acts: Surfaces. TGeo plugging developments were completed.

The track finding efficiency within this framework is Currently being studied using simulated events

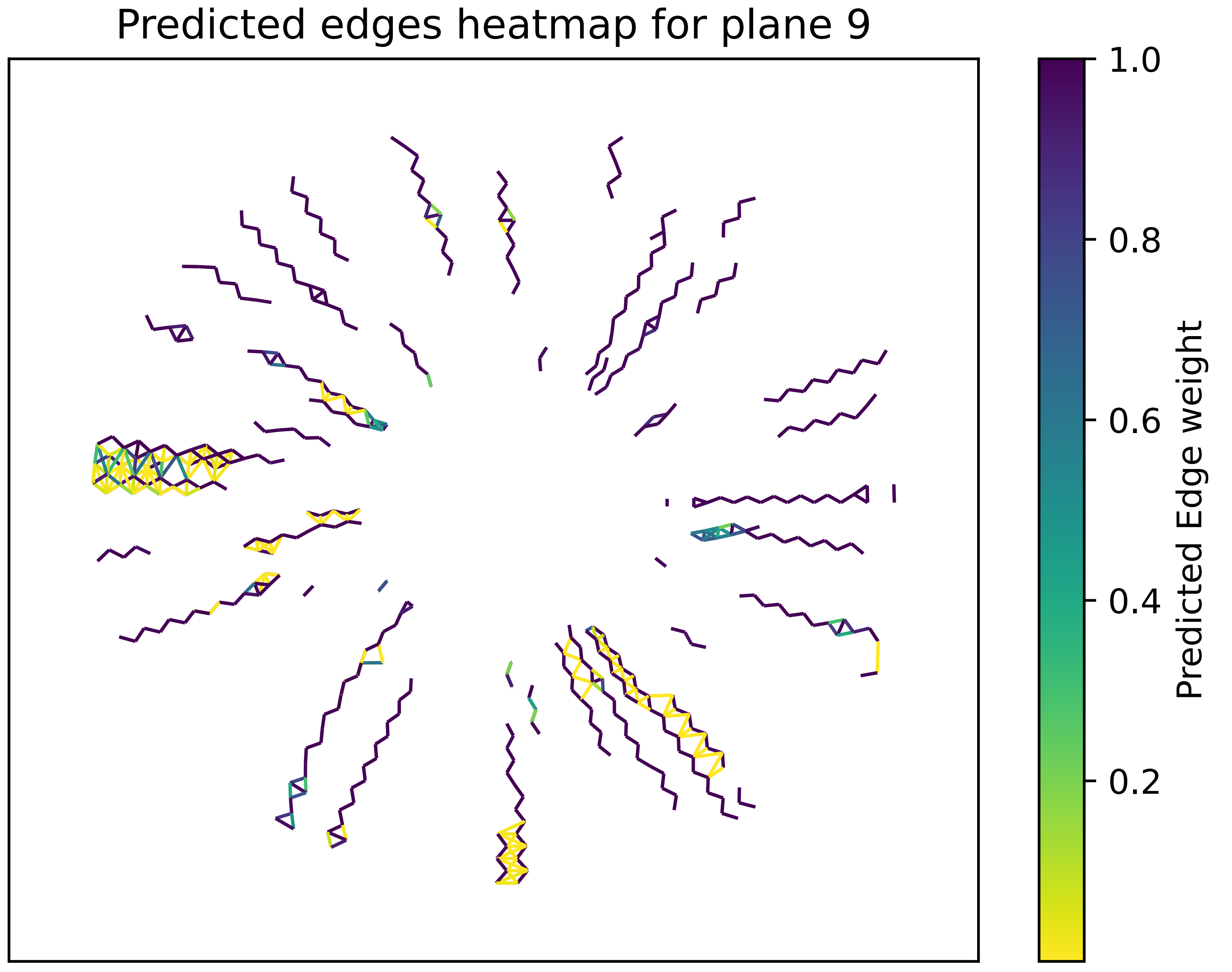


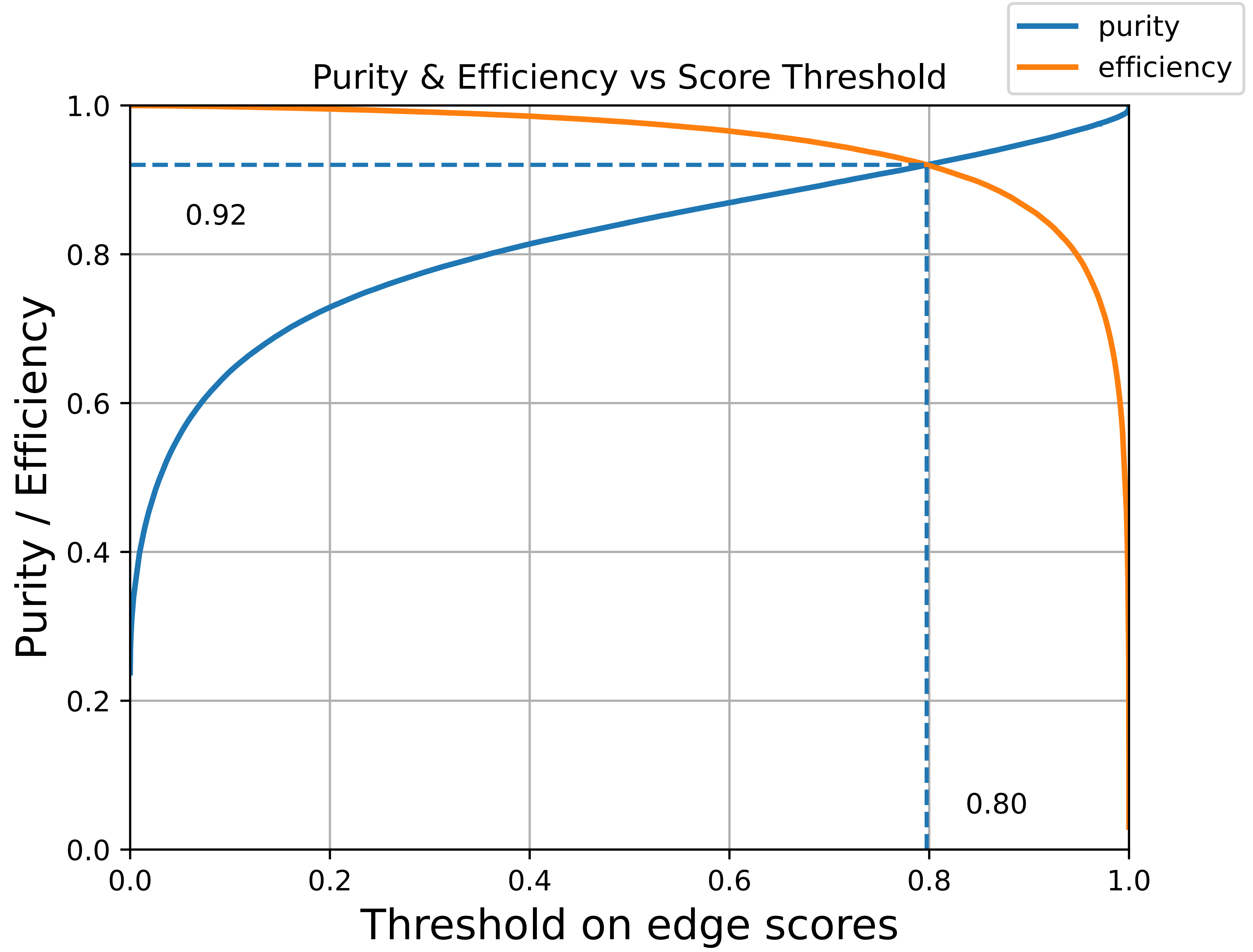



The ACTS virtual cylinder planes definition and a hit-on-a-plane corresponding to a pad for ACTS kalman filter algorithm with covariants out of spacial x,y,z information.

Contributors: Dmitry Ramonov, Aruni Nadeeshani and Eric Fuchey

# Using Graphic Neutral Network (GNN)




- Developing a Graph Neural Network (GNN)based track finding workflow.
- A subset of the simulated data is used to train the model, which is then tested on the rest of the simulated data.
- Preliminary studies with edge+node classifiers show > 90% edge-level efficiency and purity.
- The track-level classifier/clustering algorithm is under development, with the goal to achieve high tracking efficiency.

Contributors: Steve wood, Shujie Li and Amir

# Summary

- There is a high demand for new meson structure data to pin down meson pdfs and understood better the nucleon content.

- Tagged DIS: Spectator tagging, provides new tools to access to the mesonic content of the nucleon structure and meson structure function directly, with DIS being a very clean probe.

- Additional two run group proposals to measure kaon SF and neutron SF have been approved.

- In the future, pion PDFs will be further constrained by new DY data from COMPASS, as well as from the Tagged DIS (TDIS) experiment at Jefferson Lab, which will study pion structure through the charge exchange mechanism in leading proton production from a quasi-free neutron in the deuteron

- TDIS at JLab status:

- jeopardy proposal for 2026 PAC

- Numerous active developments on-going (prototyping, tracking, front-end …) with lots more to come.

THANK YOU!!!

# Backups

# Why are we interested in the pion ?

- The pion is fundamental. Viewed one way ,the pion is the simplest hadron with only two valence quarks.

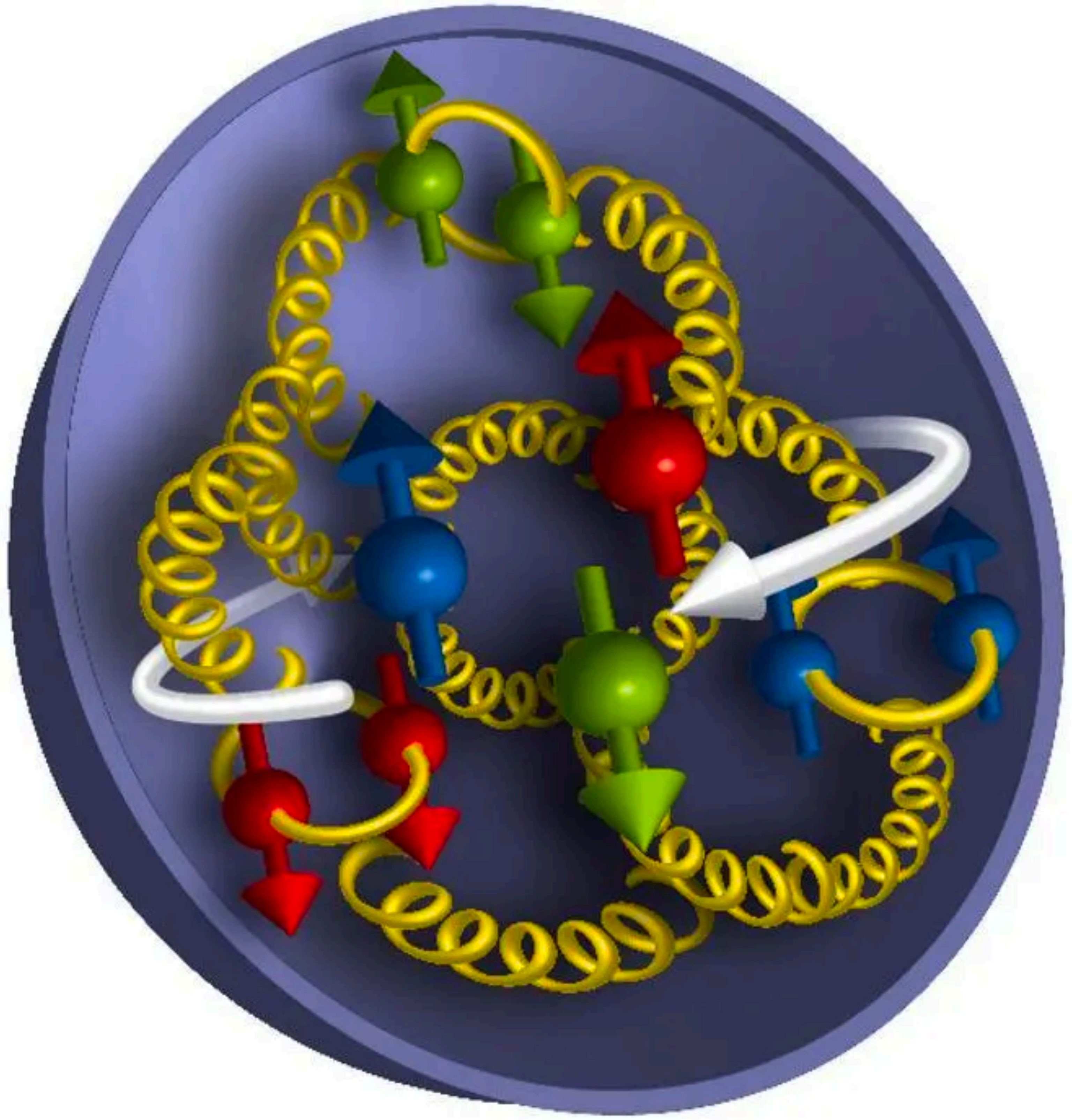
  Should be (relatively )easy to model, a test bed for predictions.
  It plays important role in nucleon and nuclear structure.

- Critical role in long range nucleon-nucleon interaction.

  Yukawa particles of the nuclear force-
  but no evidence for excess of nuclear pions or anti quakes

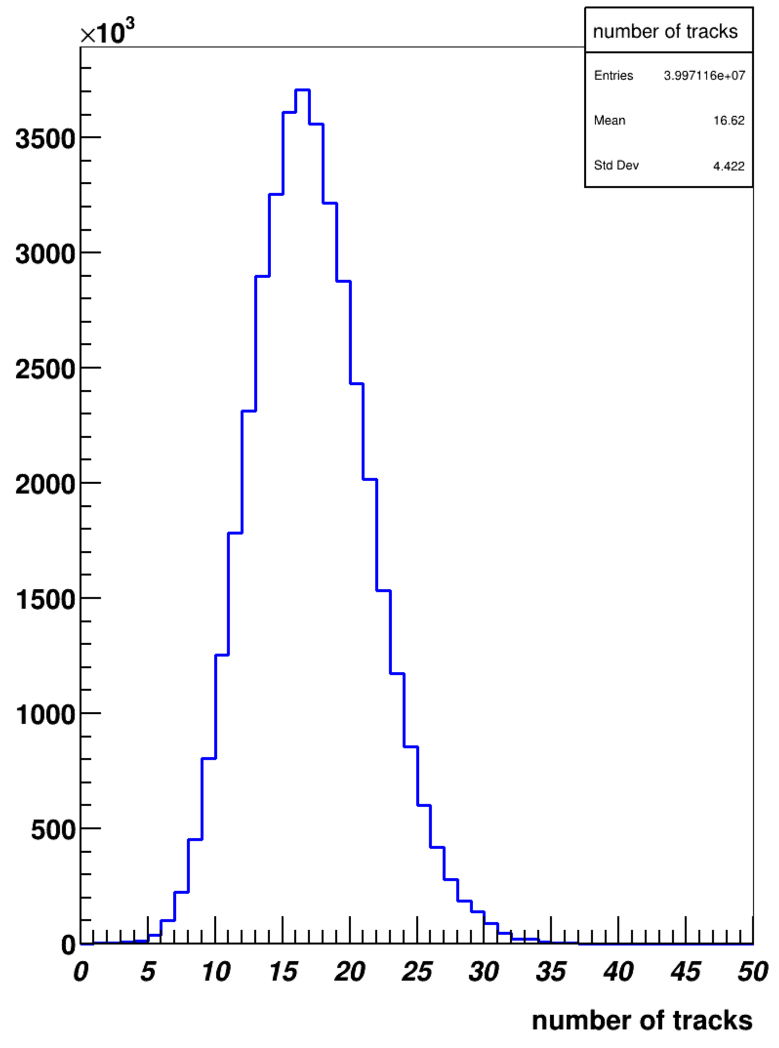
- Pion parton distributions play a role in nucleon and nuclear Parton distributions

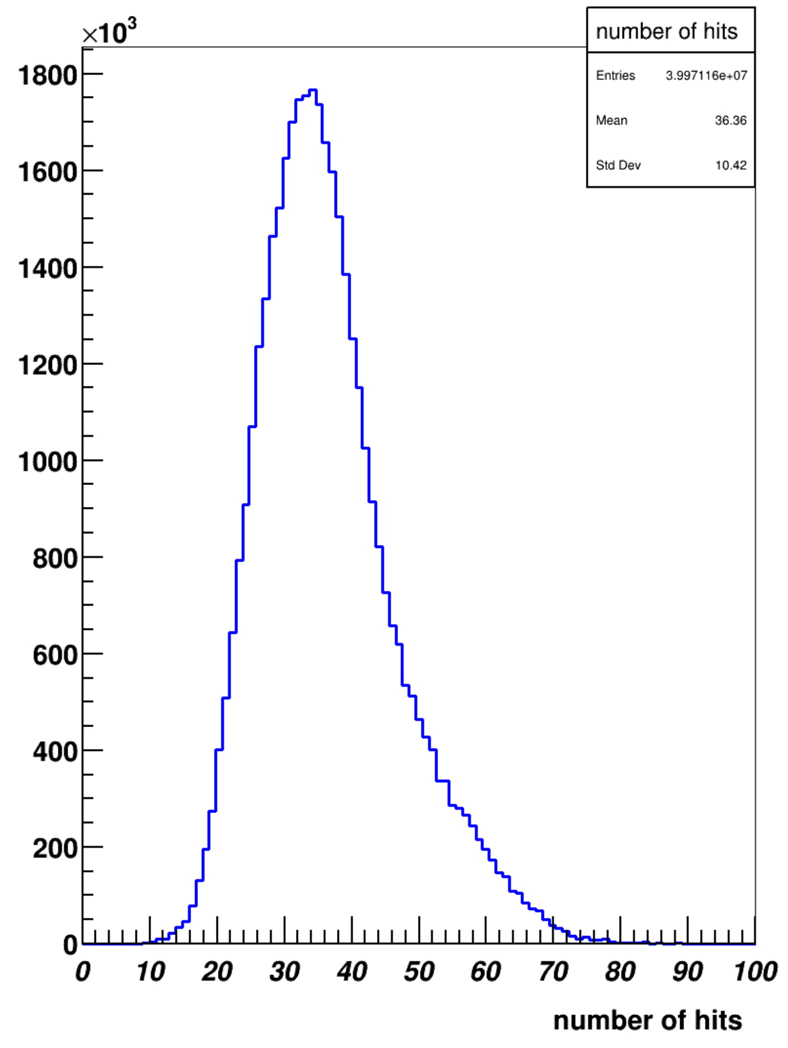
  QCD tells us how Parton distributions evolve,
  but need measurements to obtain PDFs.



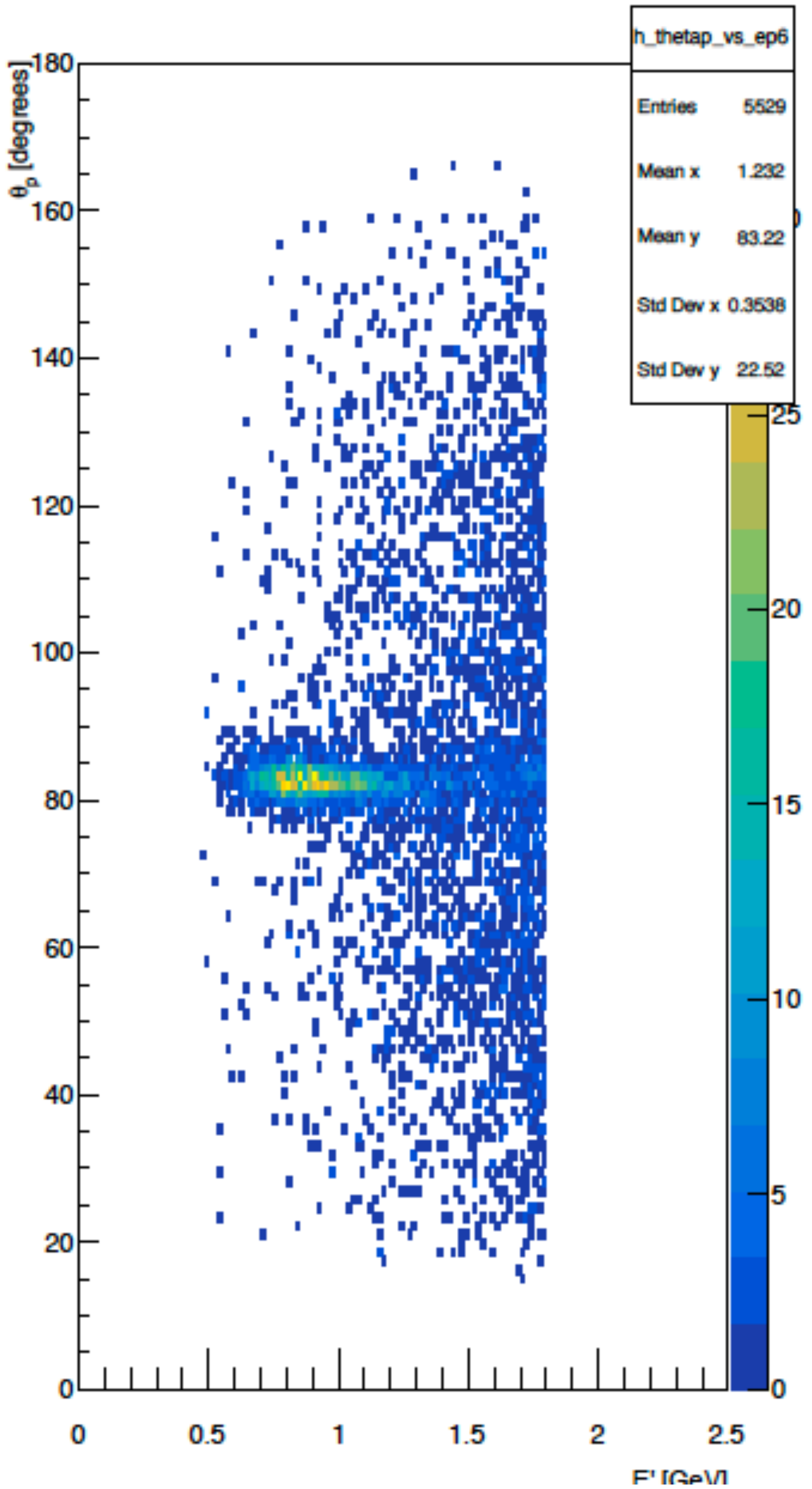
# Background studies using BONuS12

- **BONuS12 targets are Deuterium and Hydrogen.**
- **How many protons in the large angle range in BONuS12 with deuterium target -> background for TDIS (Obtain rate of DIS protons BONuS12 RTPC getting)**




Simulation benchmarked with BONuS12 data.
TDIS simulated rates match observed BONuS12 rates.
E.g. expected ~500 tracks per event.

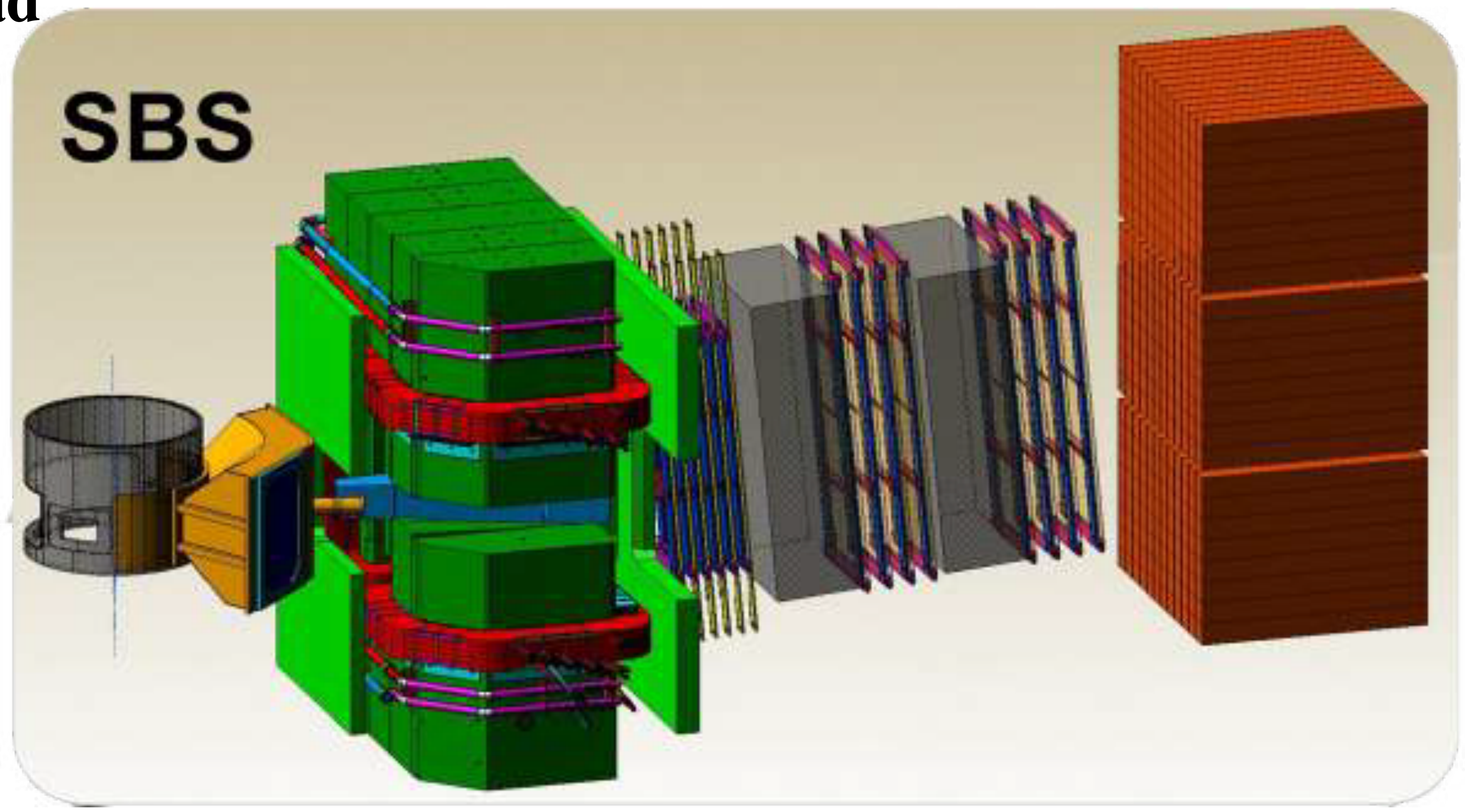



*2-D histogram of scattered electron momentum in GeV versus polar angle of recoil proton for the target filled with hydrogen gas and a beam energy of 2.2 GeV.*

# $e'$ detection:Super BigBite Spectrometer

- $\Delta\Omega$ 76 msr @$15^0$,5 msr @$3.5^0$ (forward/small angle hadrons detected)
- $\Delta p$ 2-10 GeV/c
- $\sigma_p/p$ -$1 \times 10^{-4}$
- Angular resolution 0.5 mrad

Hadron detection configuration




LAC at ESB

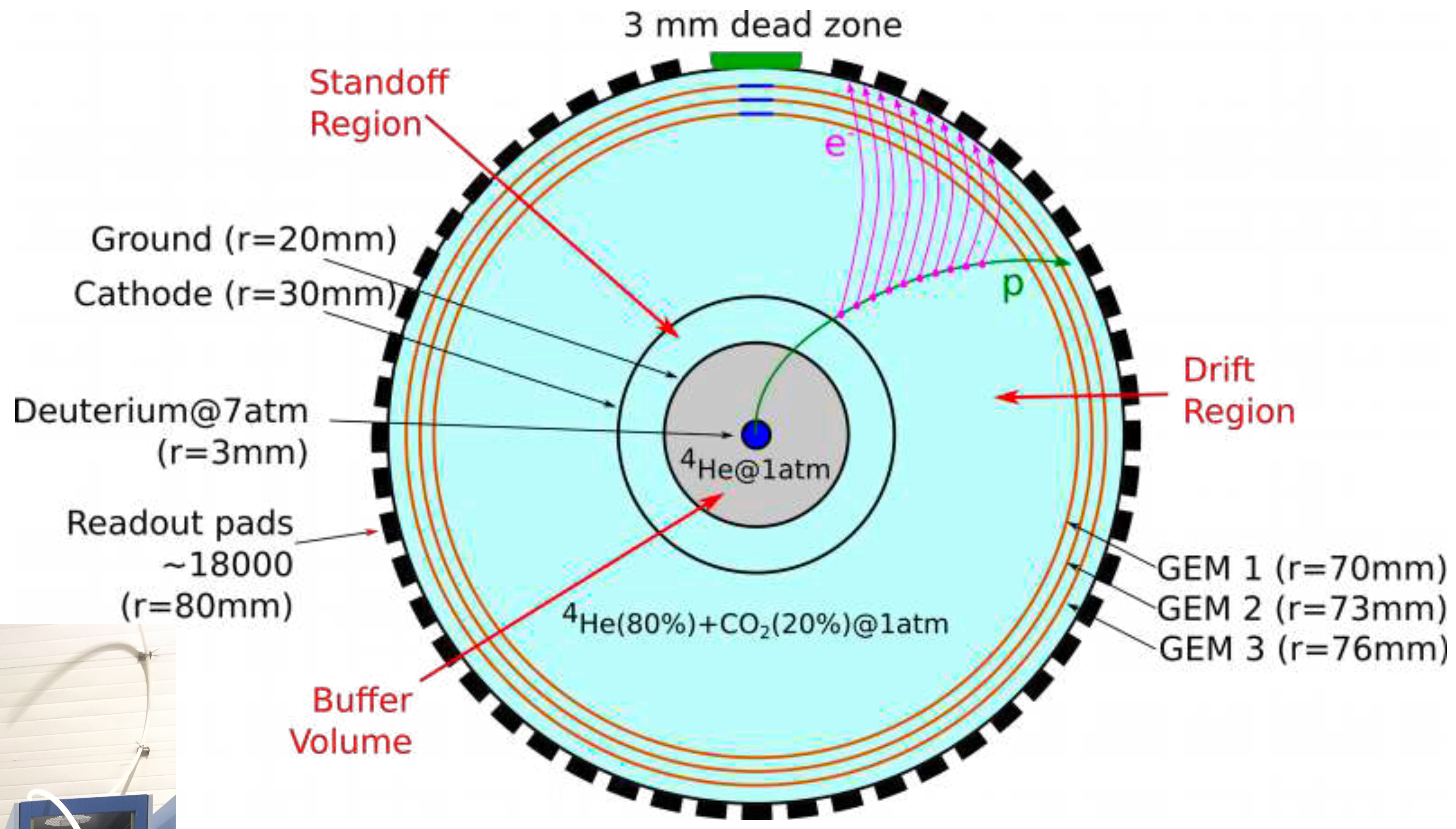
RICH at ESB

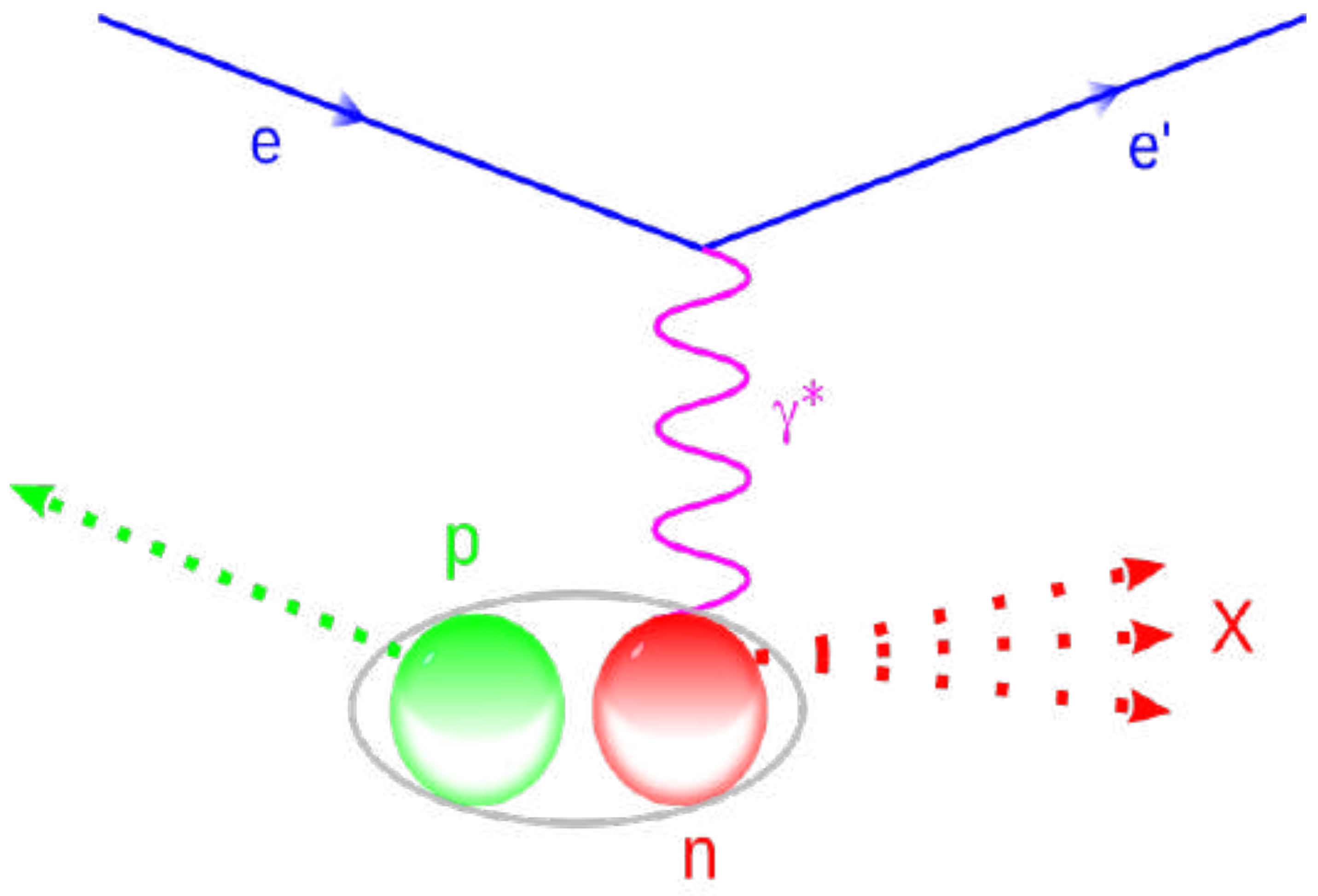
SBS configured for $e'$ detection

- $12^0$ scattering angle (large acceptance, -50 msr)
- 5 GEM tracker planes (70 $\mu m$ resolution)
- Threshold $CO_2$ Cherenkov detector (modified HERMES RICH)
- Large angle calorimeter (From Hal B CLAS)
- $e^-$ PID and $e^-$ trigger (L2) = Cherenkov + calorimeter (combined $\pi$ rejection factor)

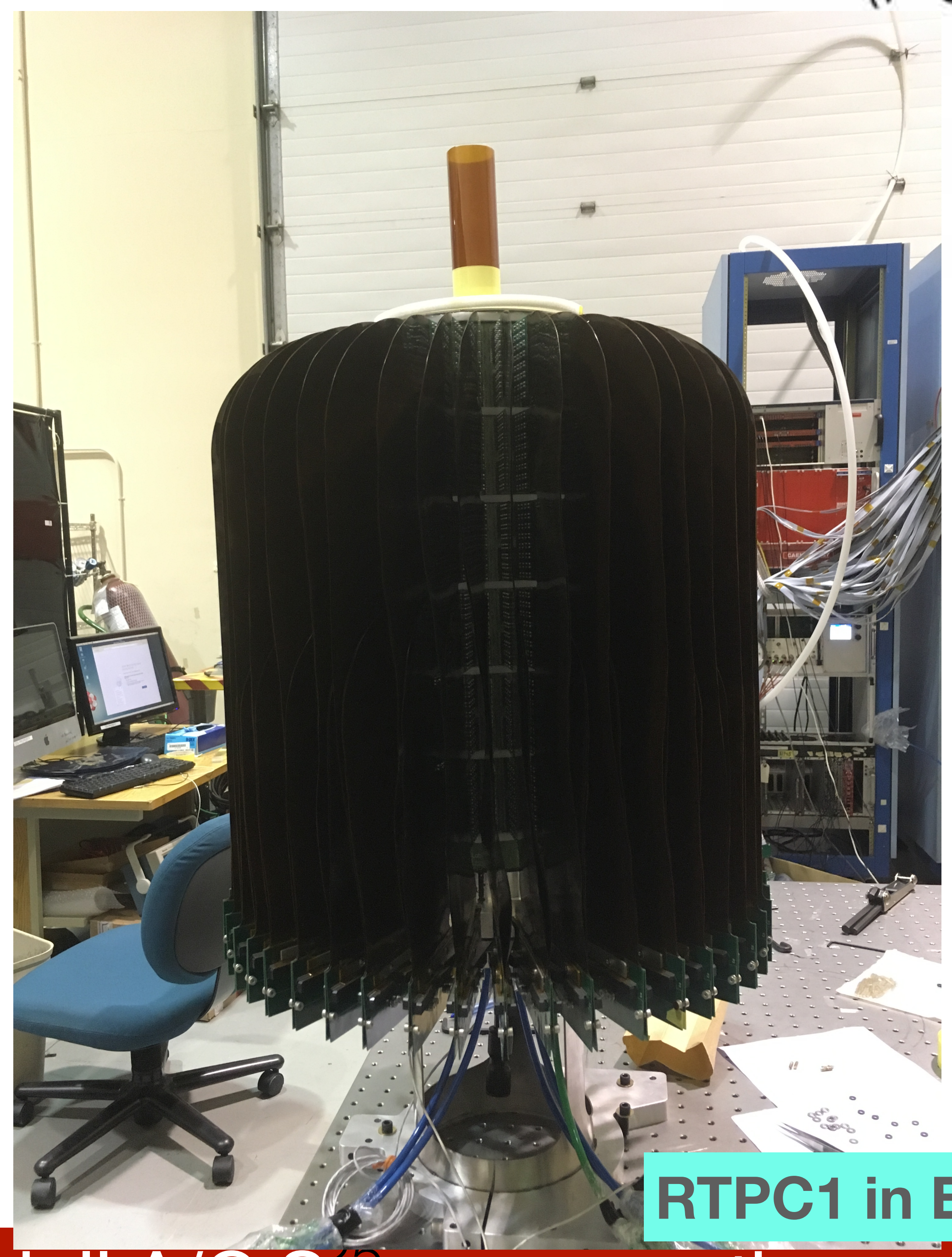
# BONuS12 RTPC

- BONuS and TDIS both use TPCs to detect tagged protons in the low momentum 70 <Ps<400 MeV/c
- BONuS12 done with the Radial Time Projection Chamber (RTPC)




BONuS12 reaction



RTPC1 in EEL building before move to HallB

# Why mTPC?

- The idea of RTPC is good for BONuS12 . But for TDIS we need to optimize the RTPC idea….

  - High luminosity (50 μA, L = 3 x 10 $^{36}$ Hz/cm$^2$) → higher background

  - long electron drift path→ wider time window

Increase of occupancy

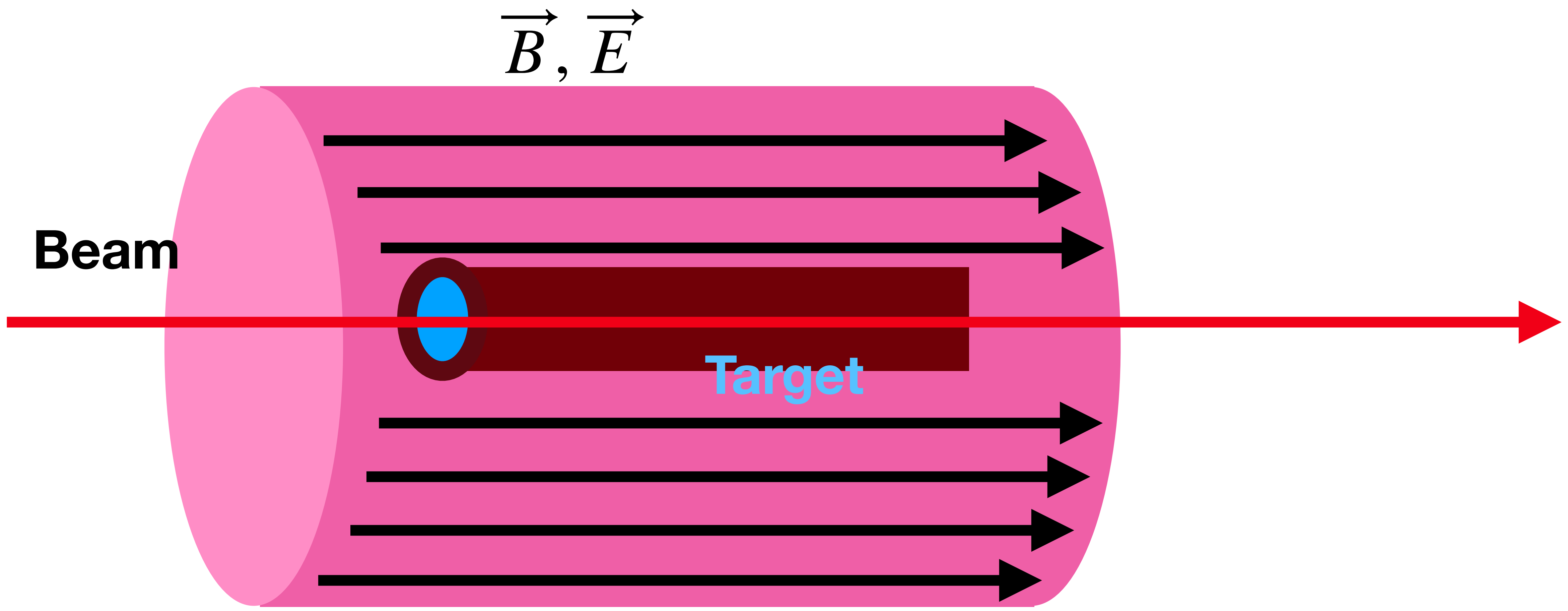
Multiple Time Projection Chamber

# Features proposed to meet this high rate

- The use of a composite TPC device consisting of multiple TPC modules instead of a single TPC detector. Each TPC unit of the composite mTPC will be exposed to a fraction of the background rate, unlike a single TPC exposed to the full rate.

- The drift electric field will be parallel to the solenoidal magnetic field, as opposed to the perpendicular field configuration used in a radial TPC. The longitudinal electron drift parallel to the magnetic field minimizes the Lorentz force on the drift electrons leading to significantly simplified track reconstruction and reduced drift times.

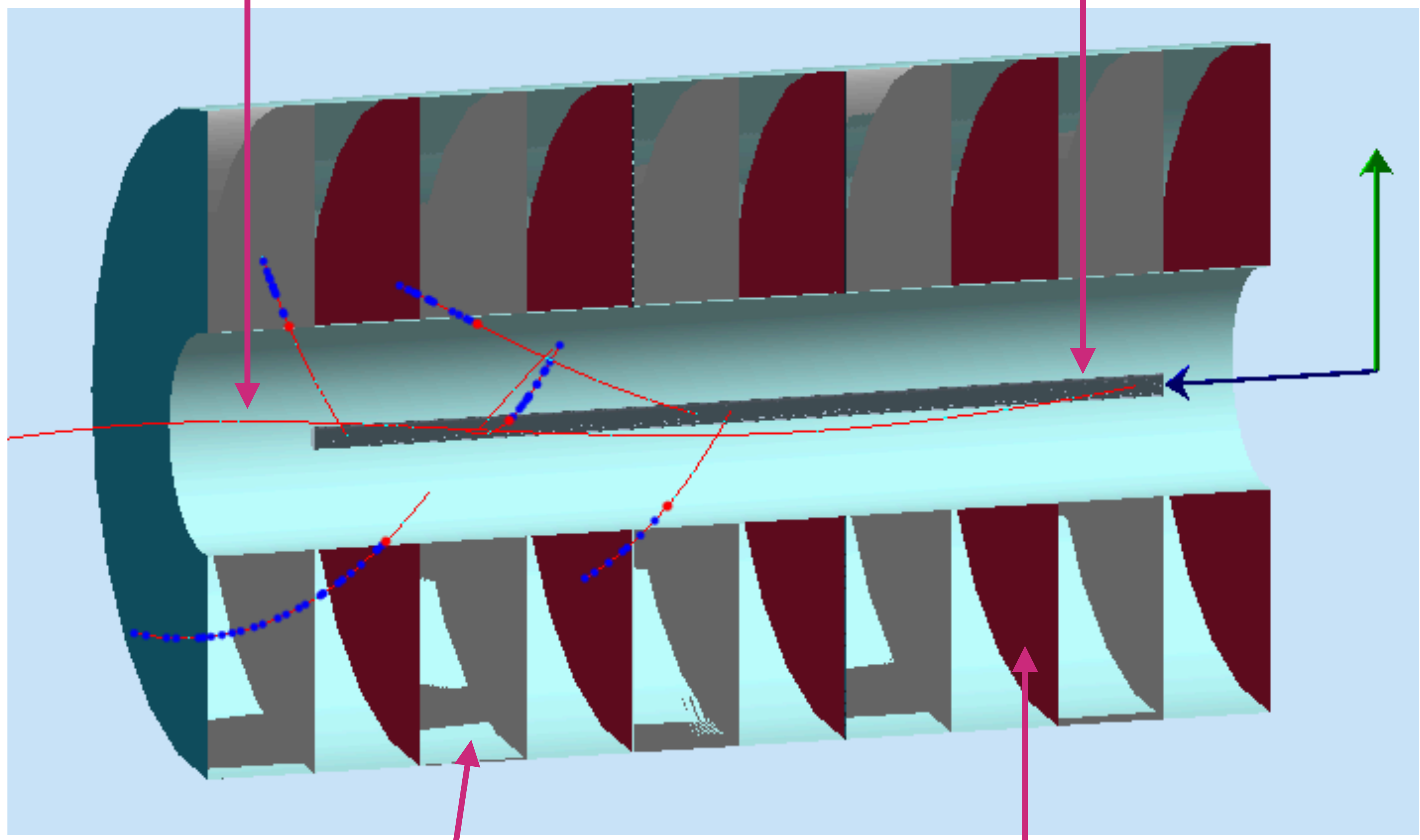
- A strong solenoidal magnetic field to confine most of the background -electrons created in the target outside the TPC ionization region.



# Design of mTPC in TDIS

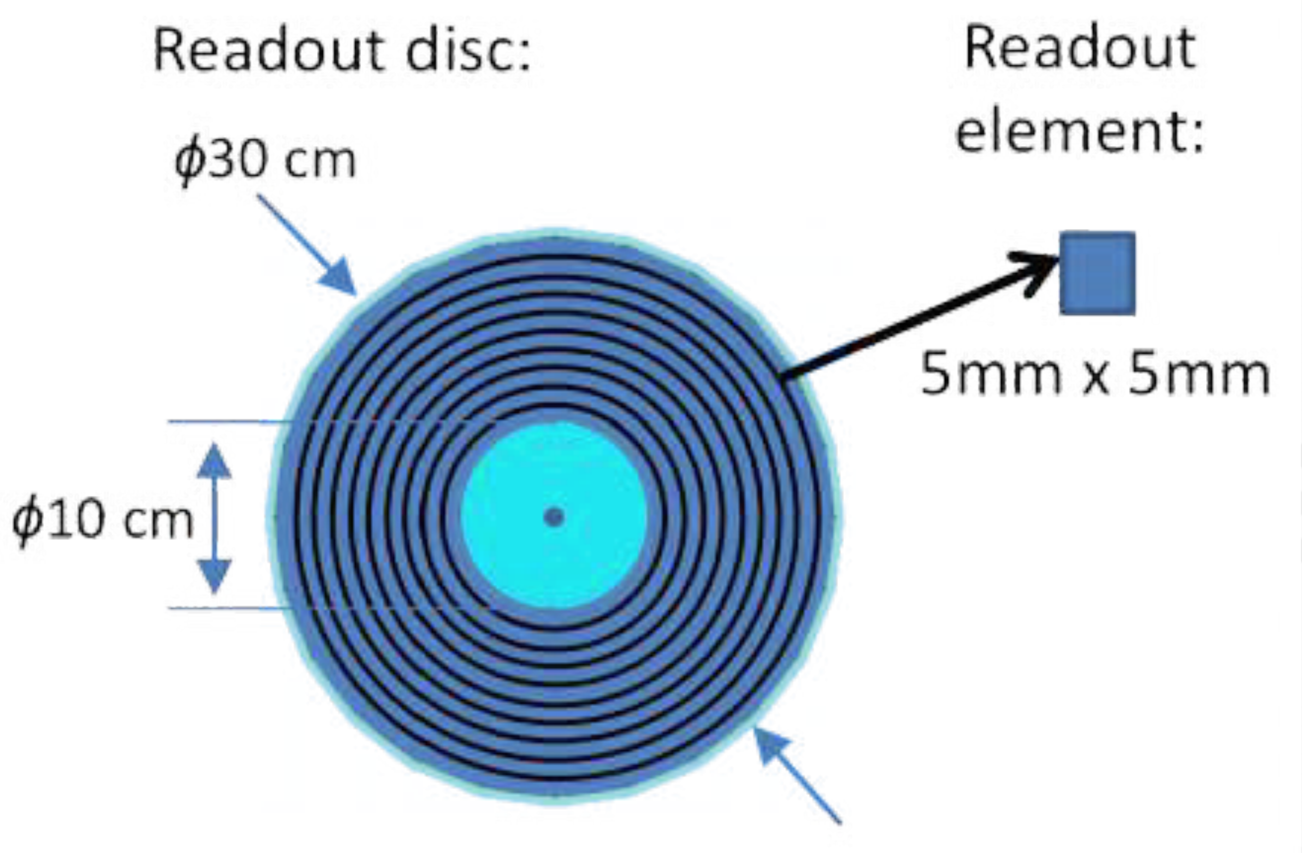
Low energy electron track

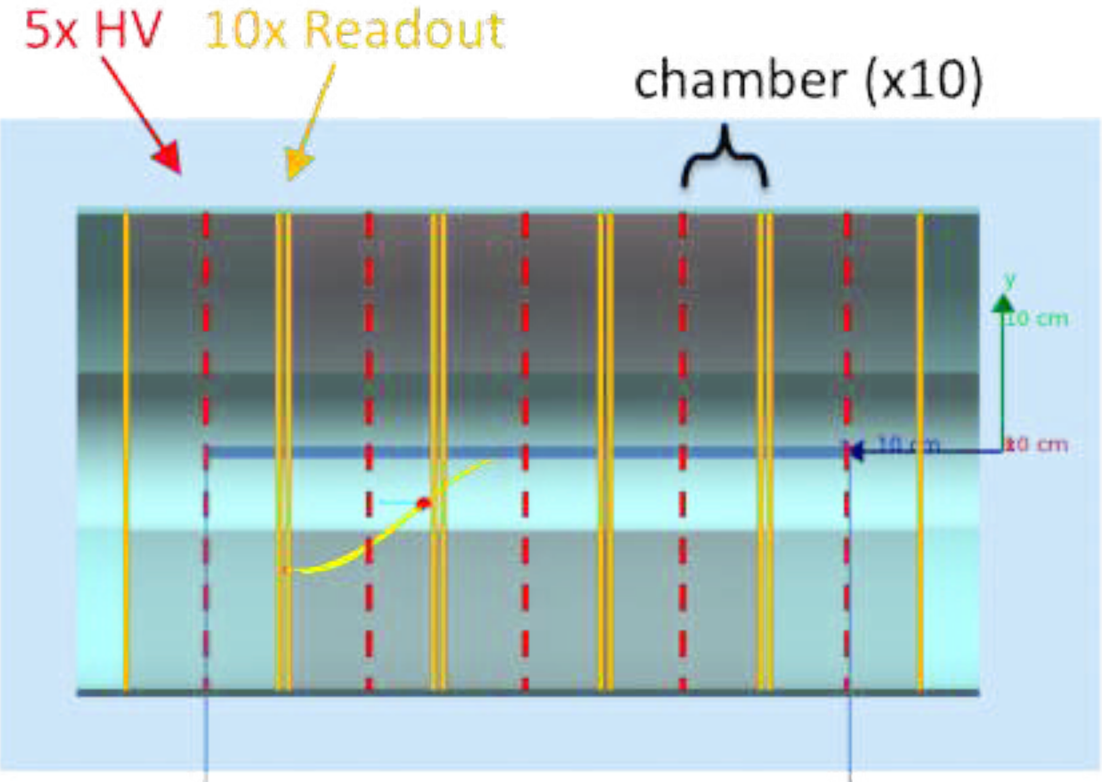
Target

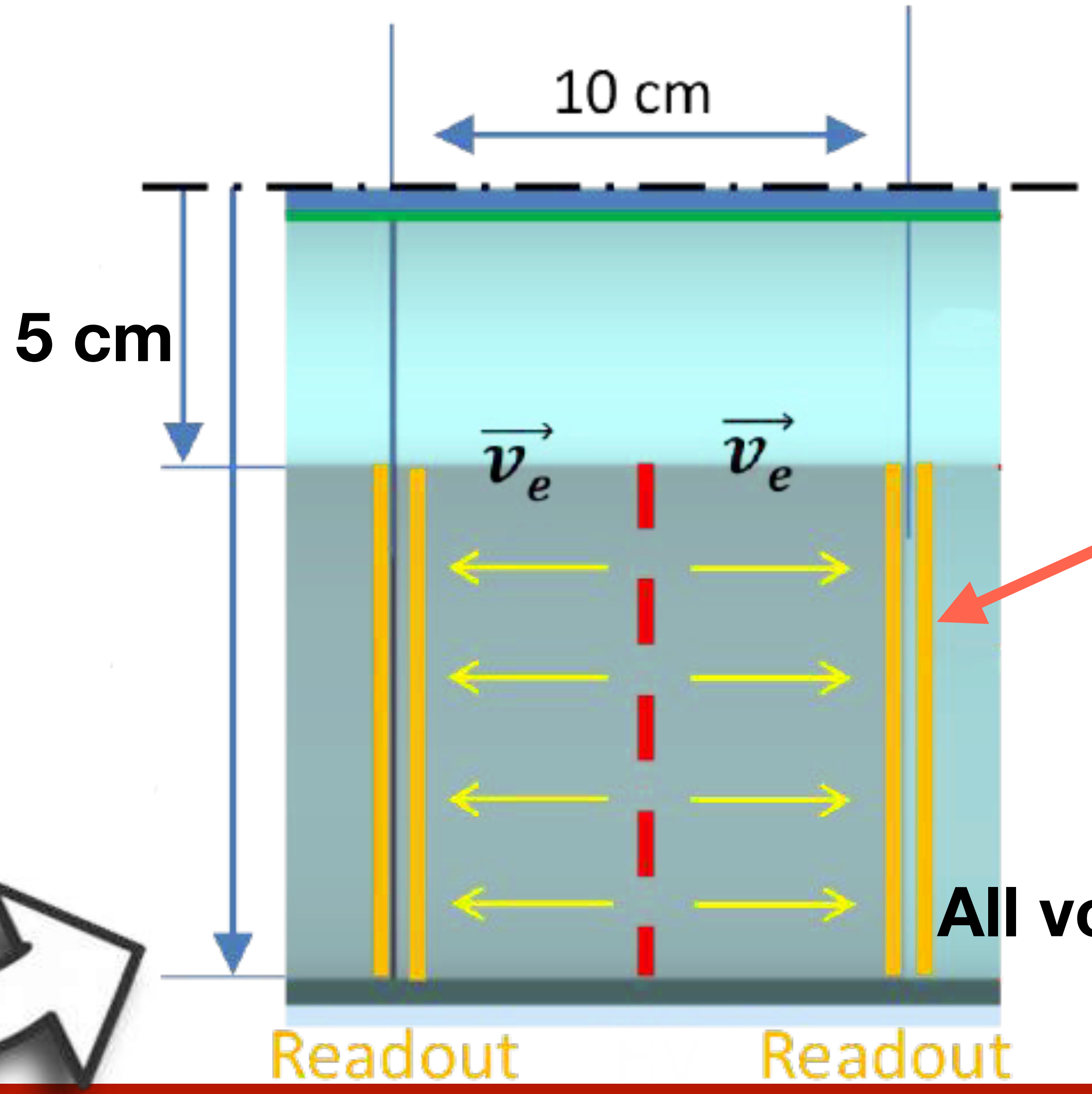


GEM based readout units

Double sided cathode planes




Each readout disc
1.readout
2.GEM

All volumes filled with He
(under study)

# Streaming Data Acquisition

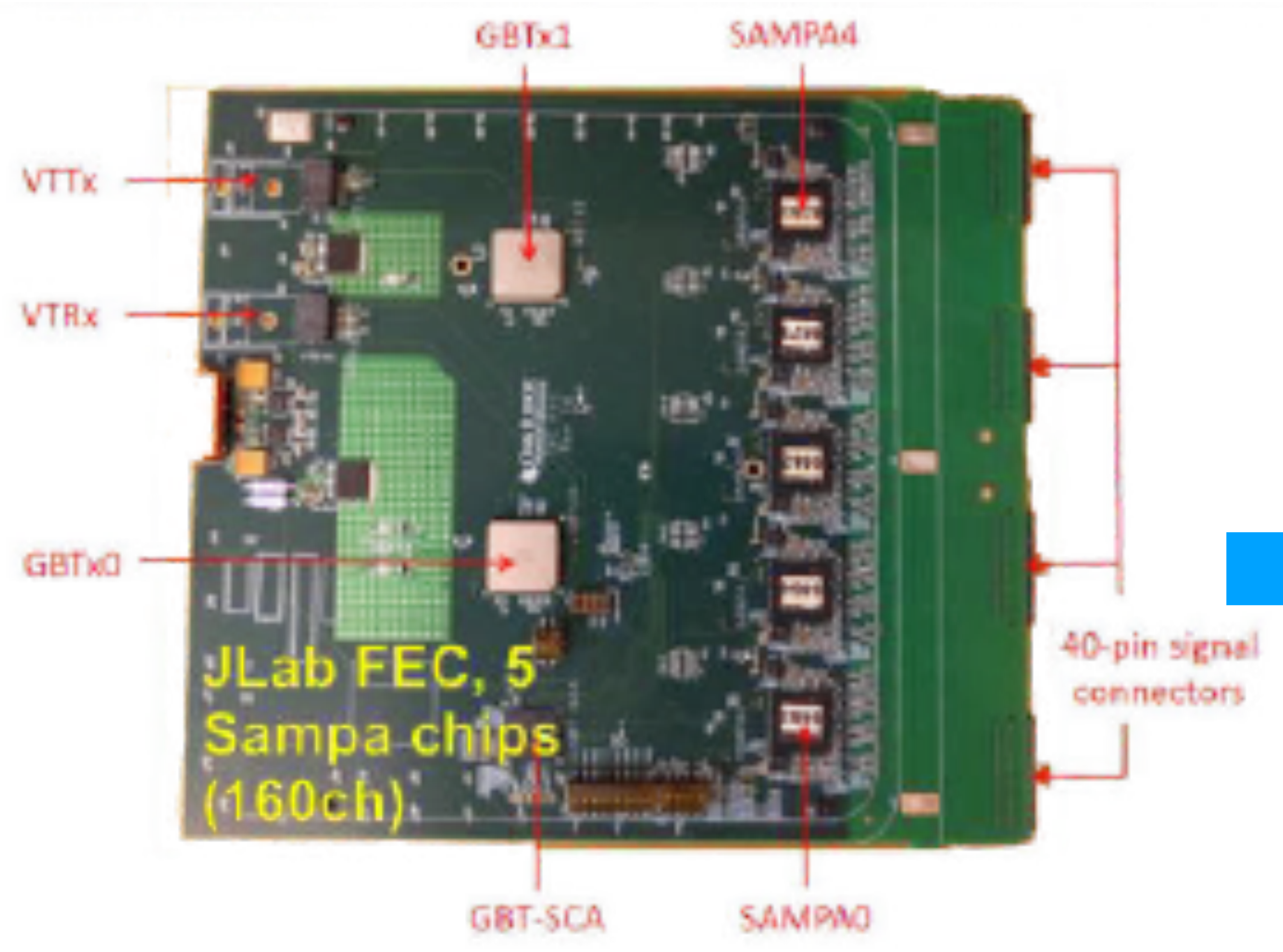
- Readout electronic updates

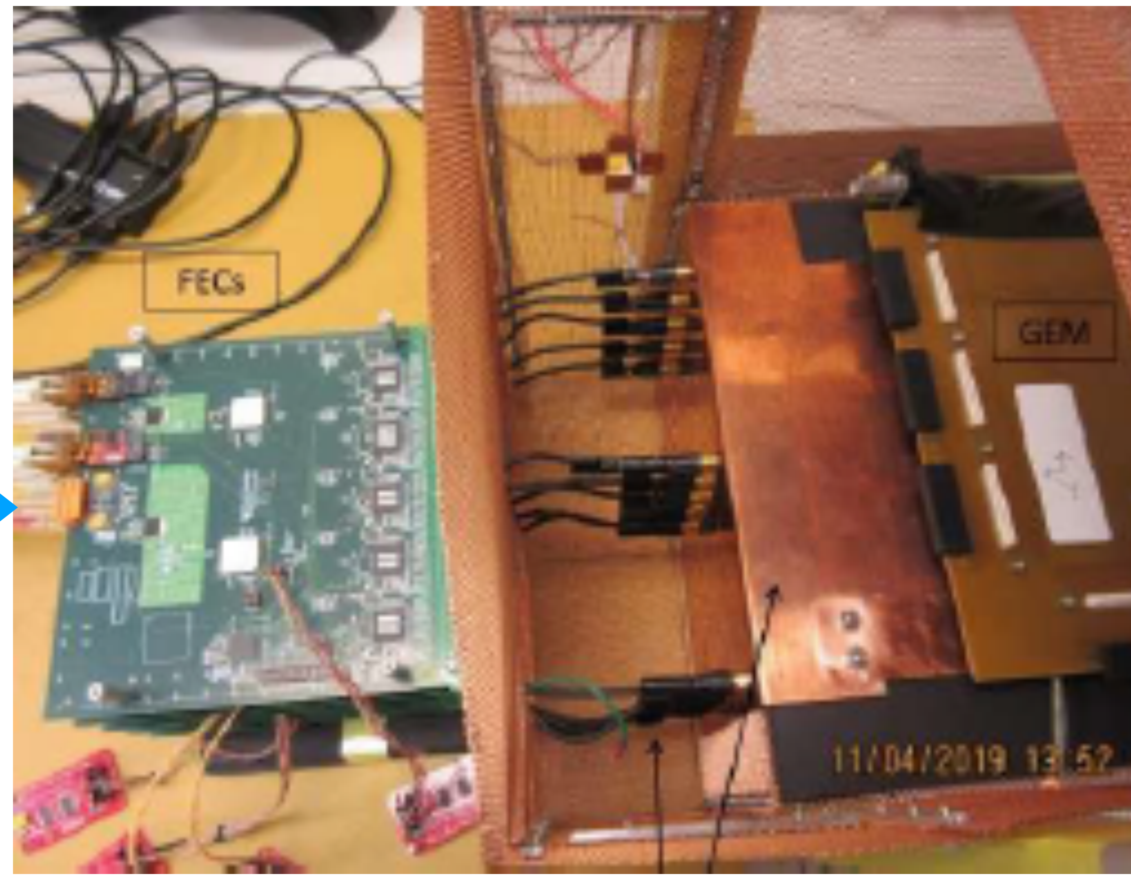
- Obtain radiation hard components from CERN

- 2nd generation data transmission and power conversion components

•lpGBT, VTRX+ (for High Luminosity LHC)

•bPOL12V, bPOL2V5, linPOL12V (for HL LHC)



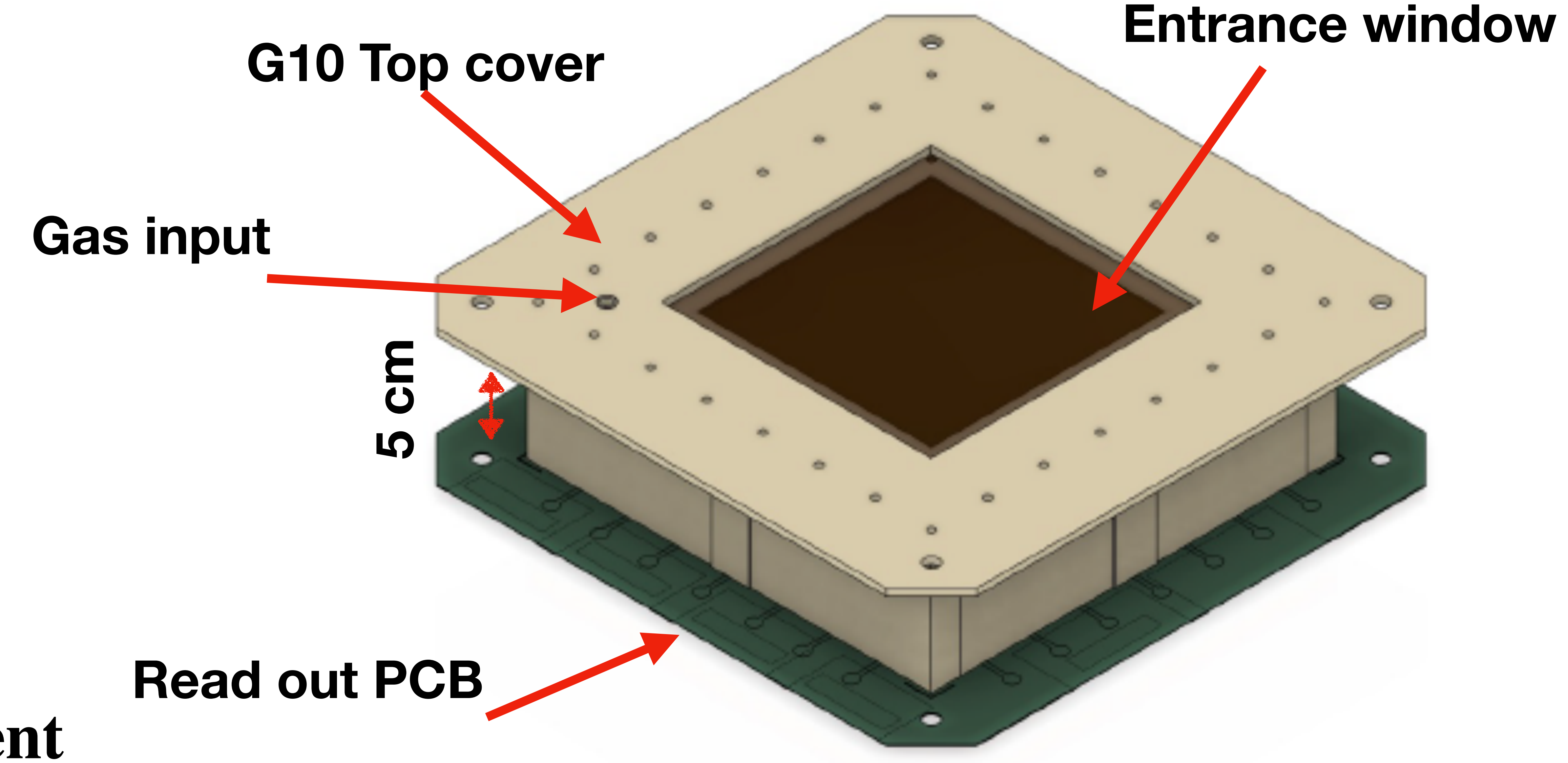

**SAMPA - charge-sensitive pre-amp, ADC, DSP (zero-suppresion e.g.)**

**Design/prototyping/testing**
E. Jastrzembski, E. Pooser,
G. Heyes (JLab)
**SAMPA chip**
M. Bregant (U. Sao Paulo) and streaming readout developed for ALICE TPC upgrade

# mTPC prototyping and development

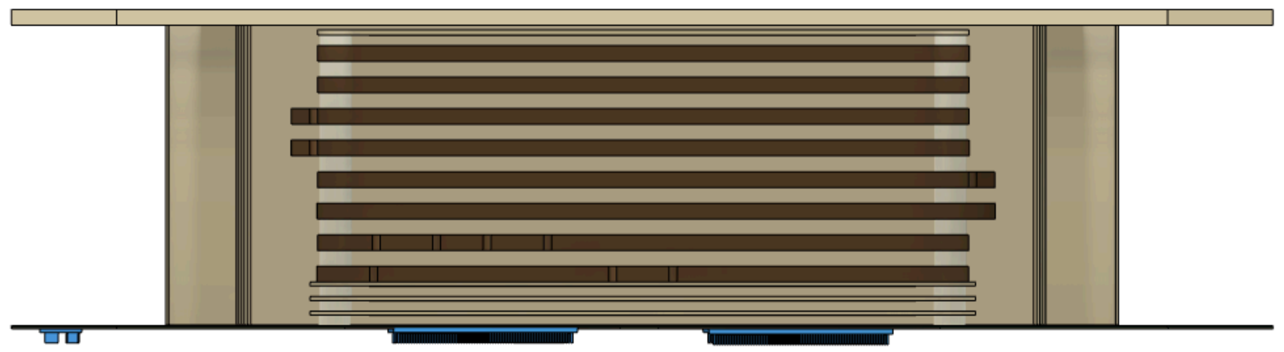
Square shaped prototype TPC to validate and test concepts of the larger cylindrical shaped mTPC. The concepts that will be evaluated using this prototype include

1. The pad readout configuration
2. Drift region
3. Time projection field cage,
4. Track reconstruction with the 5 cm drift arrangement under high rates
5. Cable lengths for the electronics.

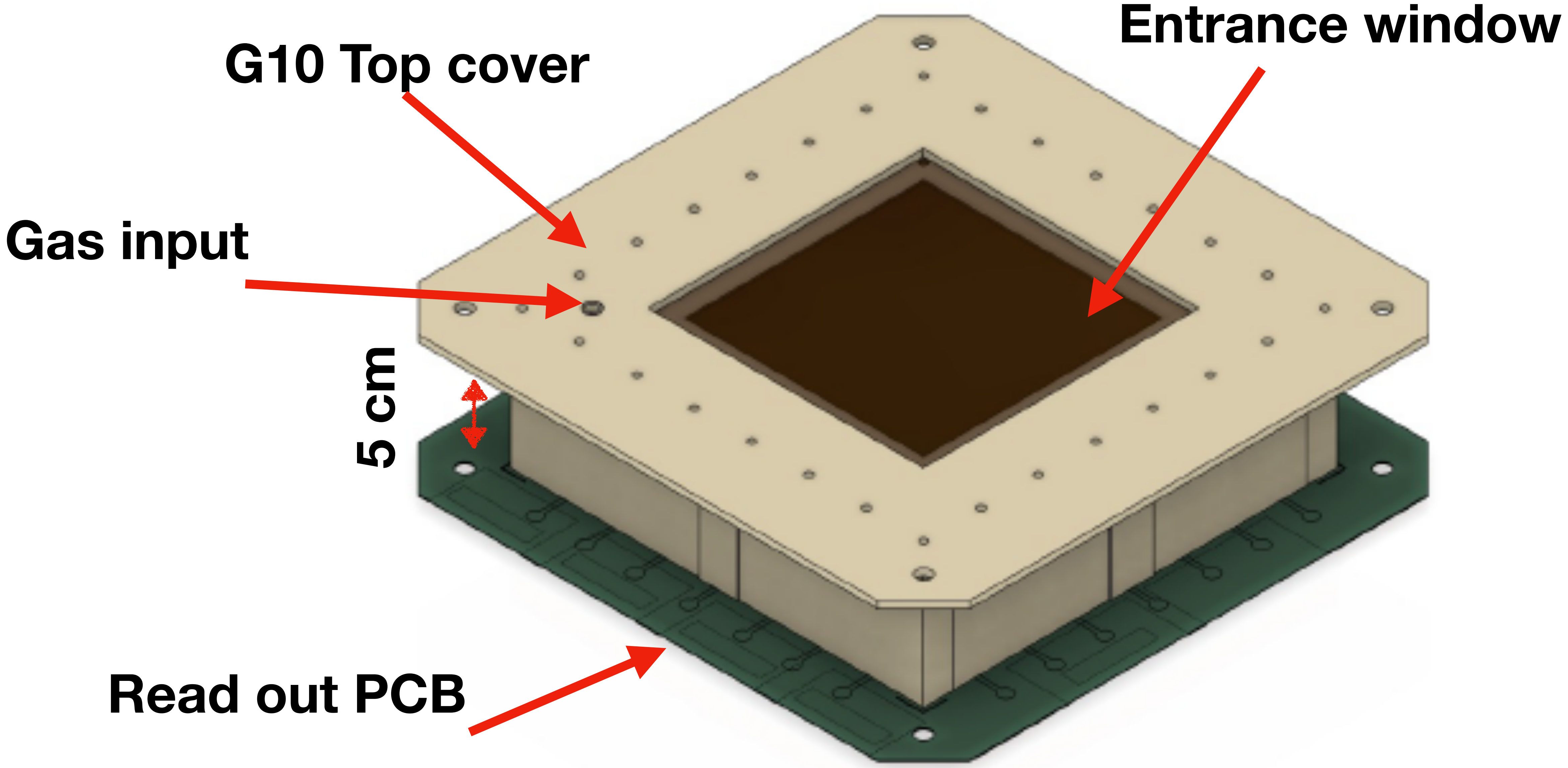


# mTPC prototyping and development

- **Design small prototype with 10 x 10 cm$^2$ GEM active area**
- **Anode (Read Out plane),**
- **Three GEMs stacked with 2 mm spacing (provided by spacers)**
- **Aluminized Kapton to act as cathode**
- **5 cm space between anode and cathode endplates**



*a side view perspective of the readout, 3 GEM layers, 8 layer field cage, cathode layer and the spacers between the layers.*

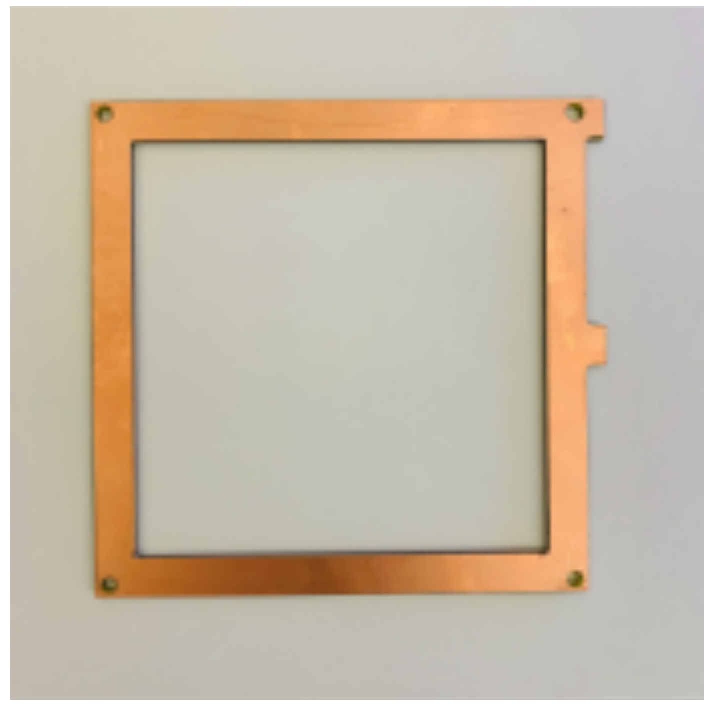


# mTPC prototyping and development

- The height of the prototype is approximately 6 cm, with a 5 cm drift region to realize the time projection concept and uniform electric field.

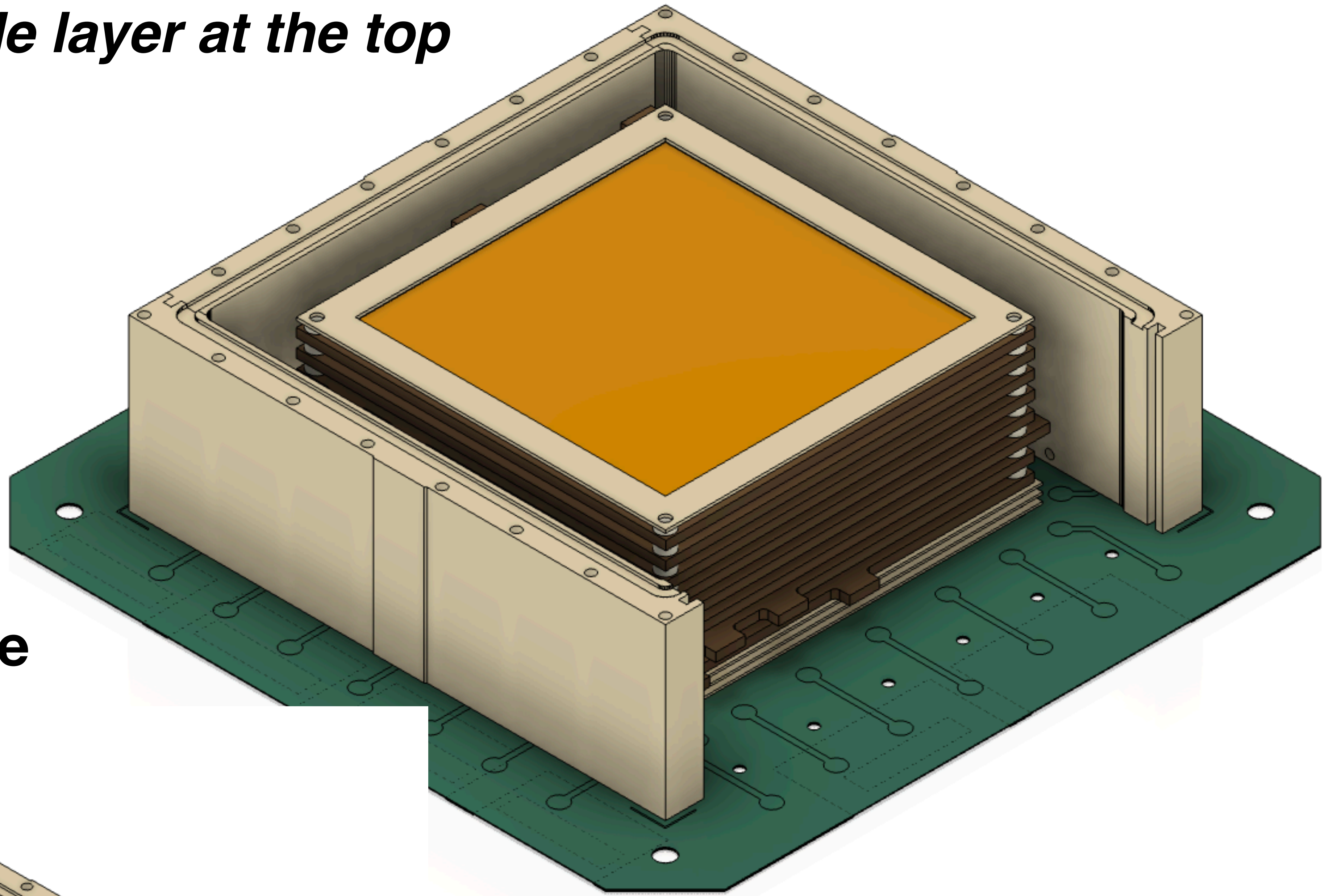
- The cathode layer of the prototype consists of 50 micron thick Aluminized Kapton glued to a 0.5 mm thick G-10 frame, and is placed 2 mm above the top field cage frame

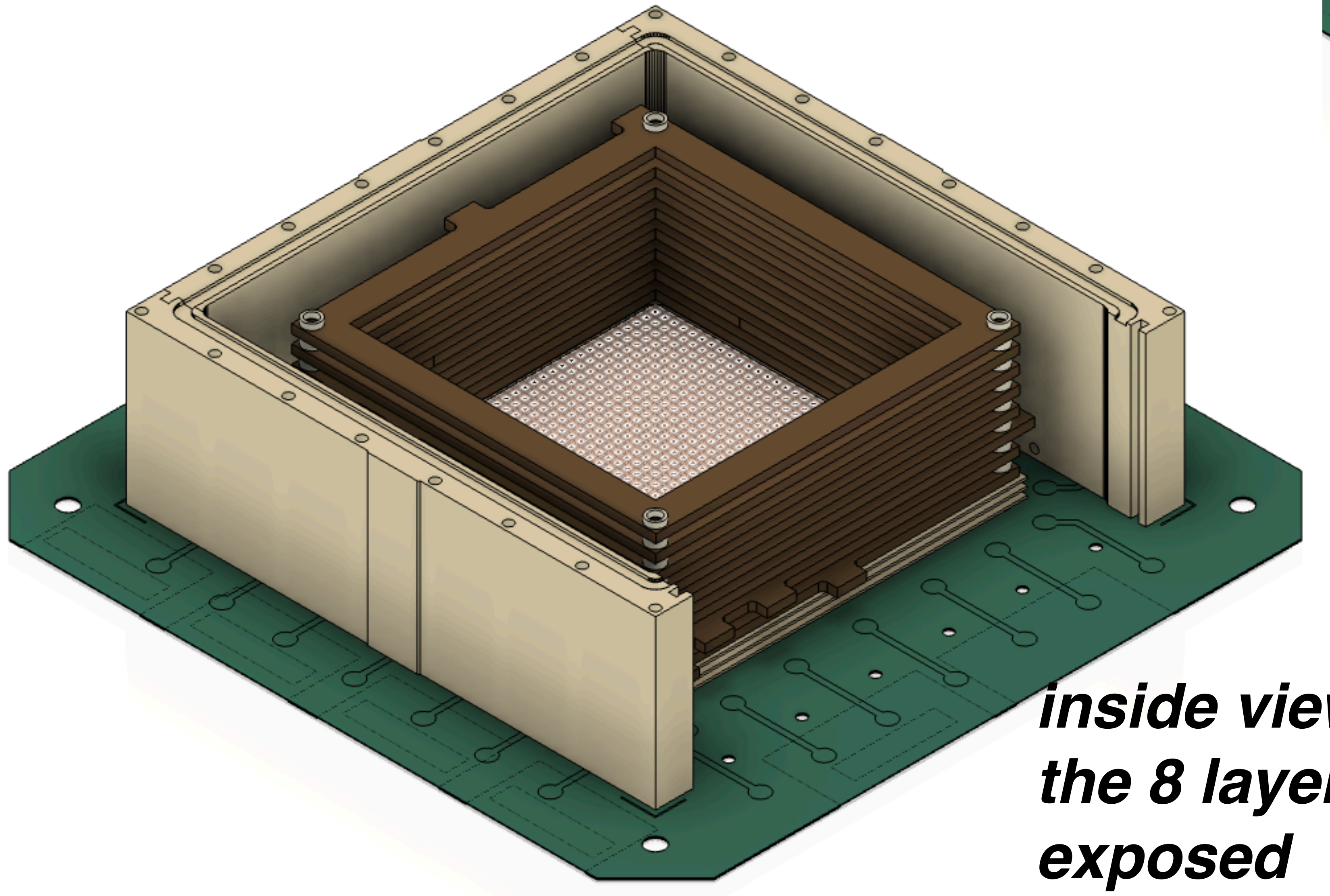
- The entire prototype structure is enclosed in a gas box with the gas input located on the top cover, and the gas output is toward the bottom on one side of the gas box to accommodate a uniform distribution of gas. This arrangement allows testing the prototype with different drift gasses to optimize the gas mixture for the final mTPC.



Top view of field cage frame

*side view showing 3 GEM layers, 8 layer field cage, and cathode layer at the top*

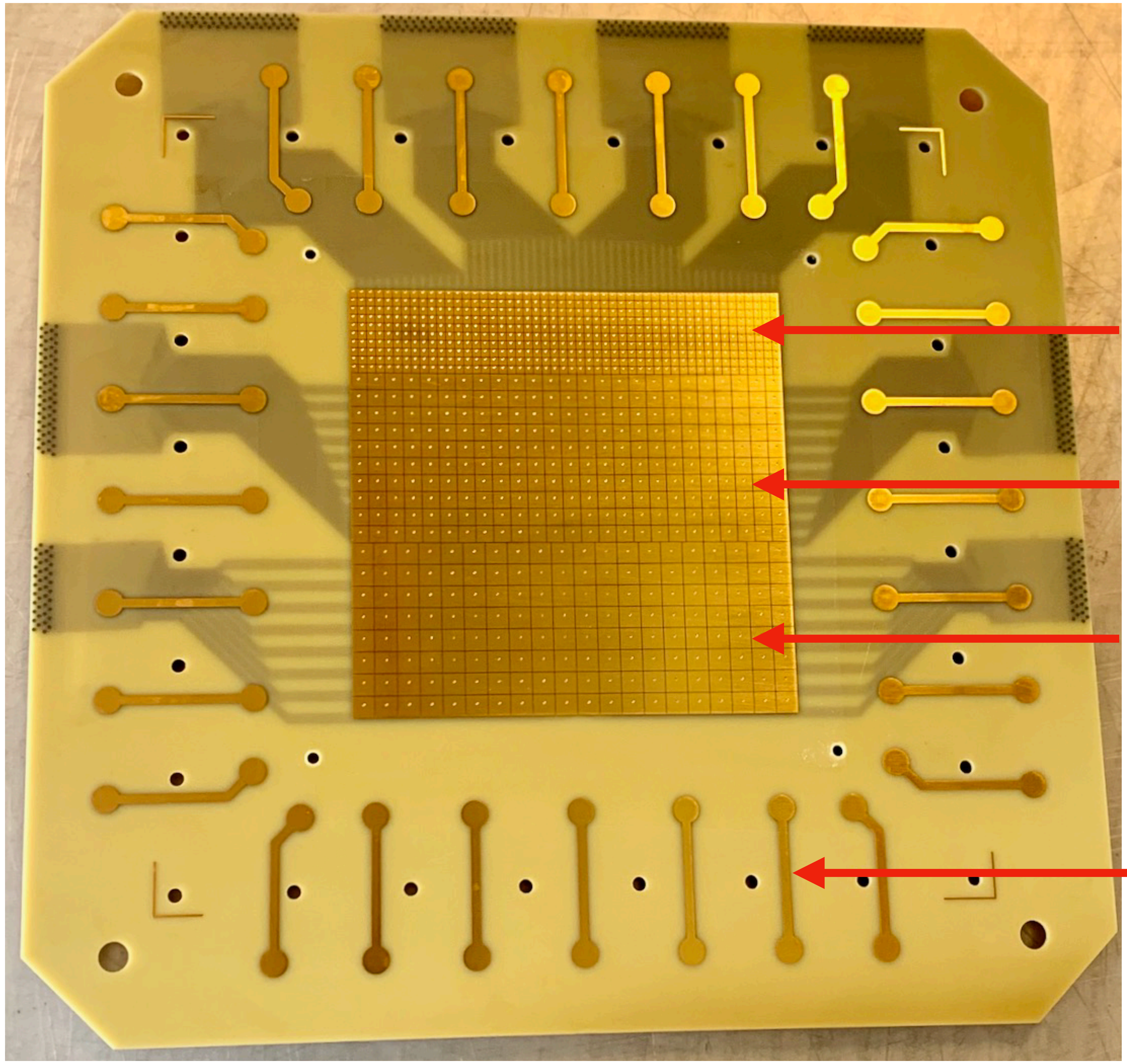




*inside view without the cathode layer showing the 8 layer field cage with the top GEM layer exposed*

# Readout board design

- To validate the readout pad configuration of the cylindrical mTPC, pads of different sizes were implemented in the readout of the square prototype within the limits of the 10× 10 cm² GEM active area.
- 910 total readout pads of three different sizes



$2 \times 2mm^2$

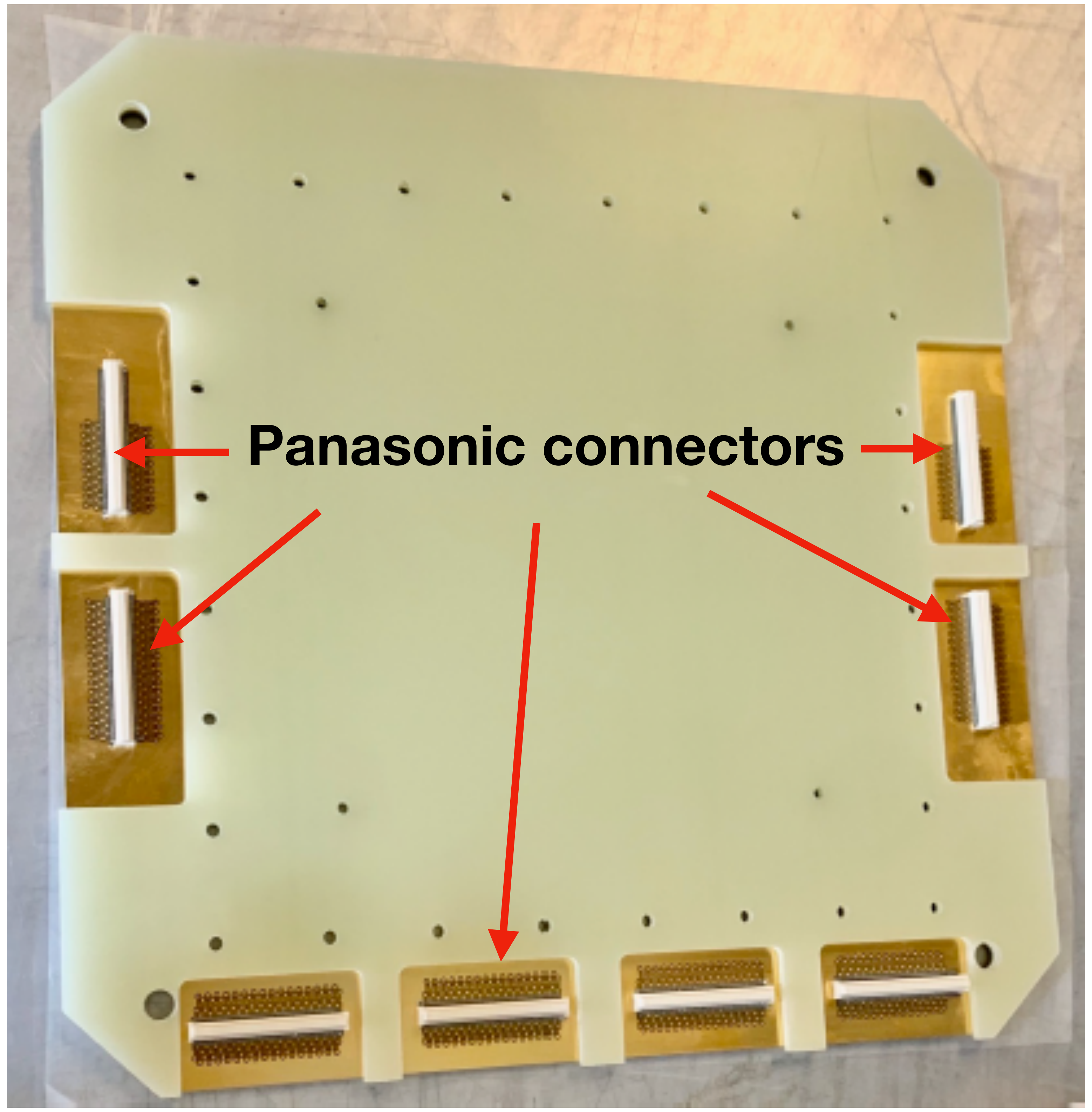
$4 \times 4mm^2$

$5 \times 5mm^2$

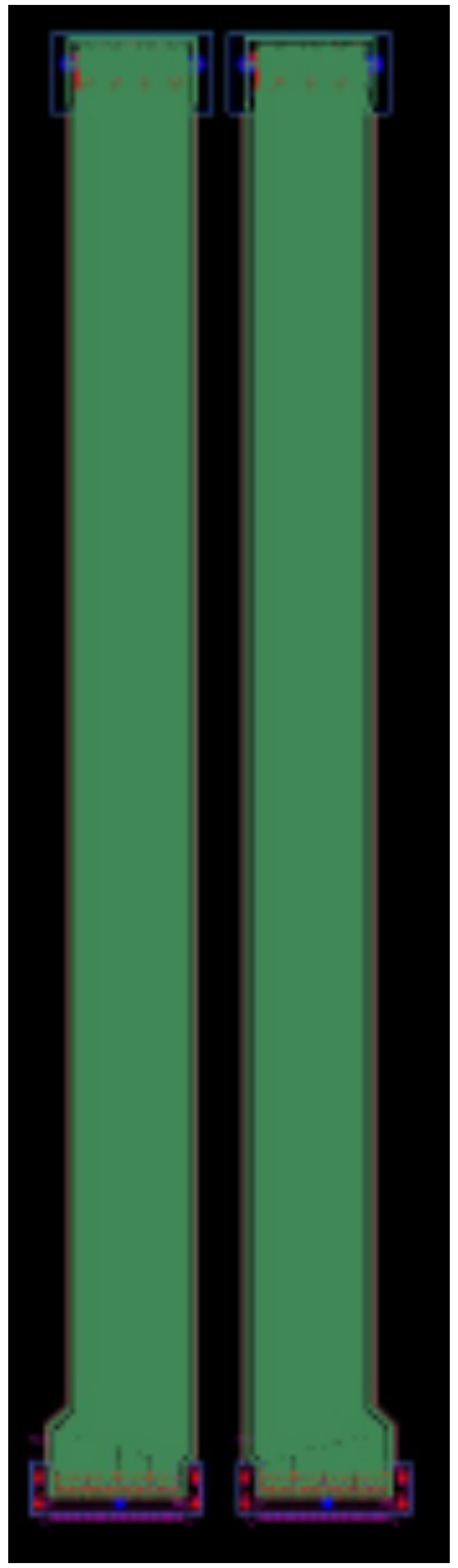
**HV strips**

# Readout board design

- Panasonic connectors (130 pins each) connected to signals from readout pads (910 channels).
- APV25 chip will be used to readout signals in initial testing
- APV25 to SAMPA flex circuit: Signals will be mapped via 40 cm long flex circuit adapter



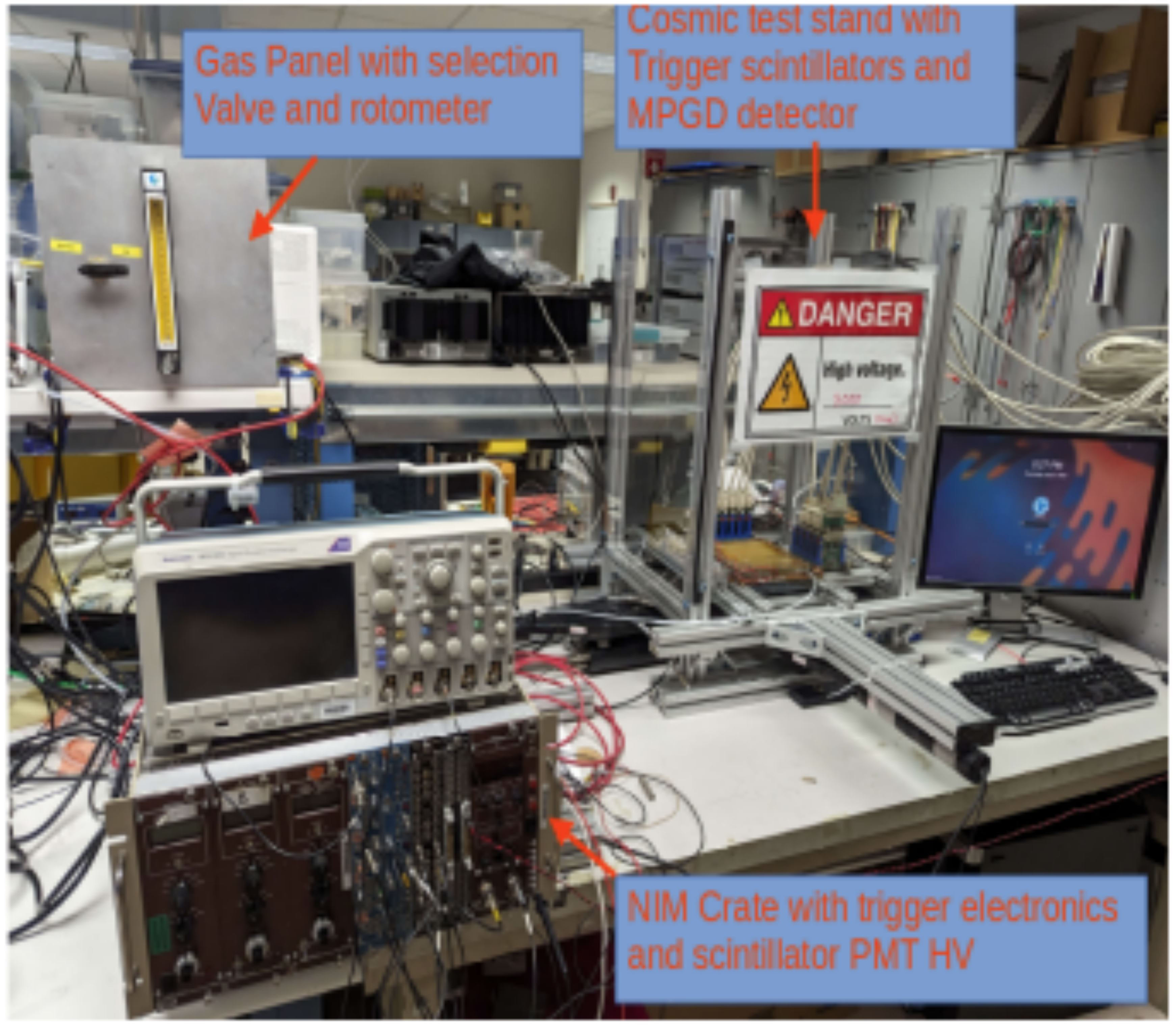

Back of the readout board



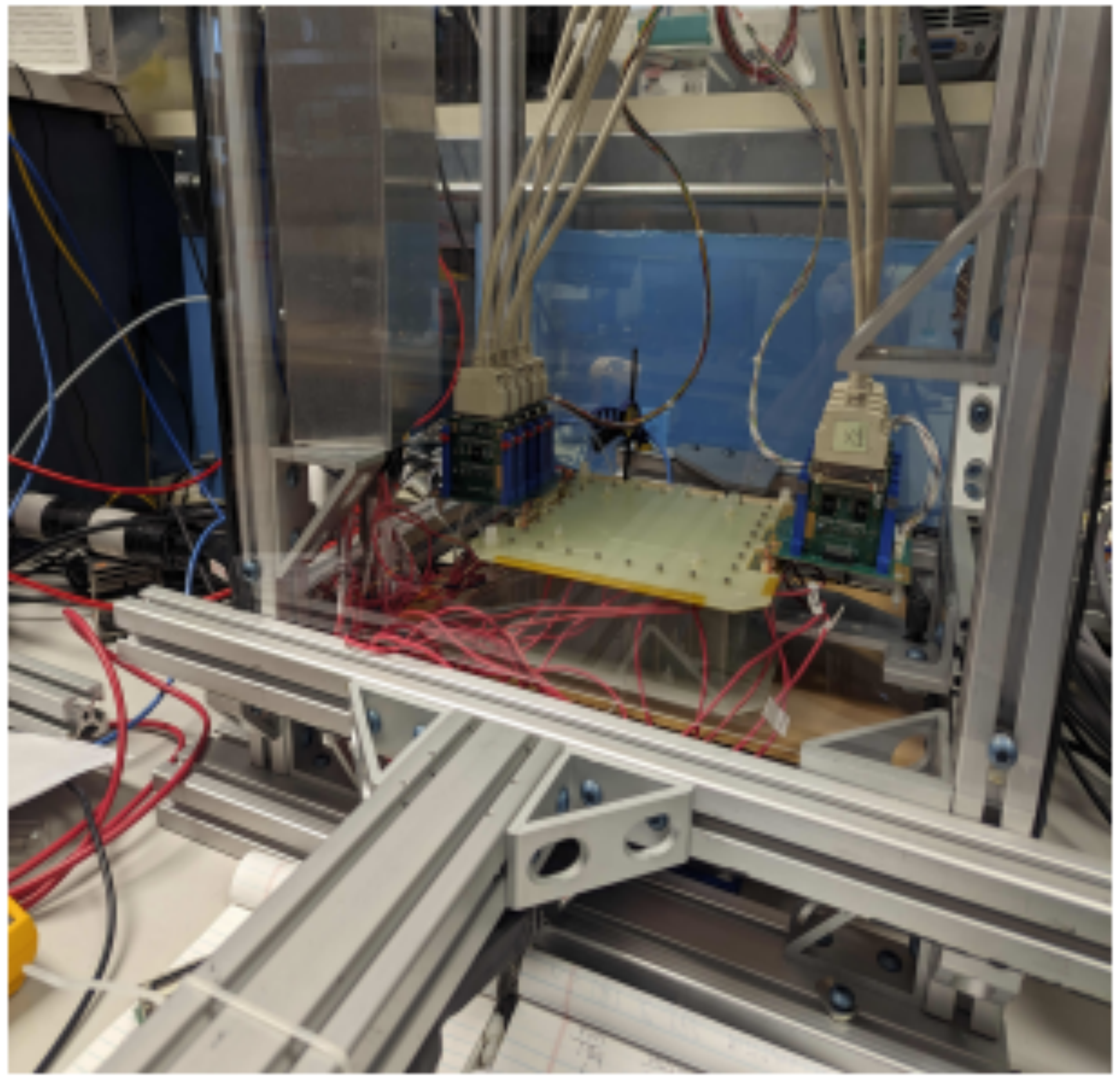
40 cm long flex adapter (GBR)

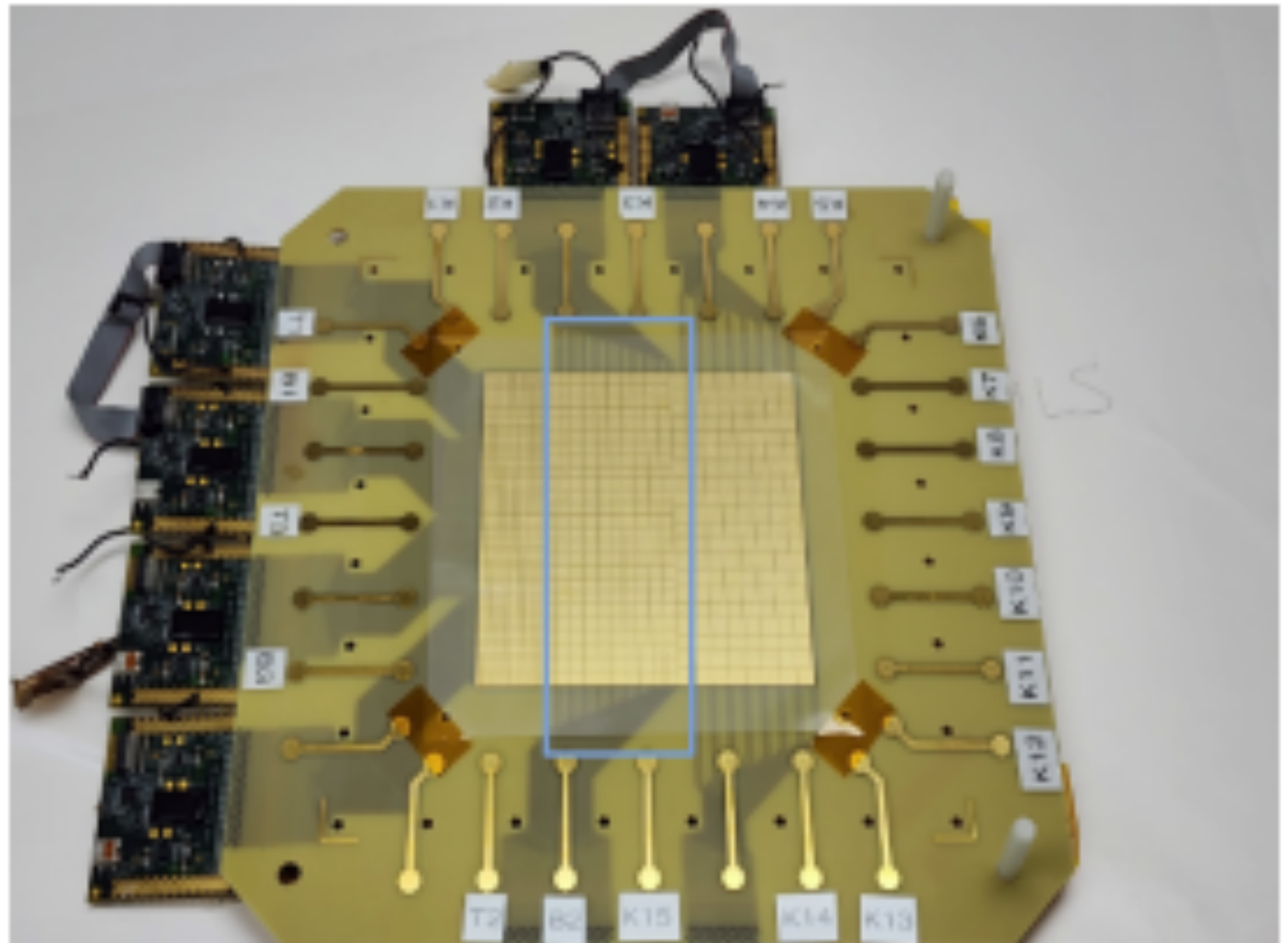
m

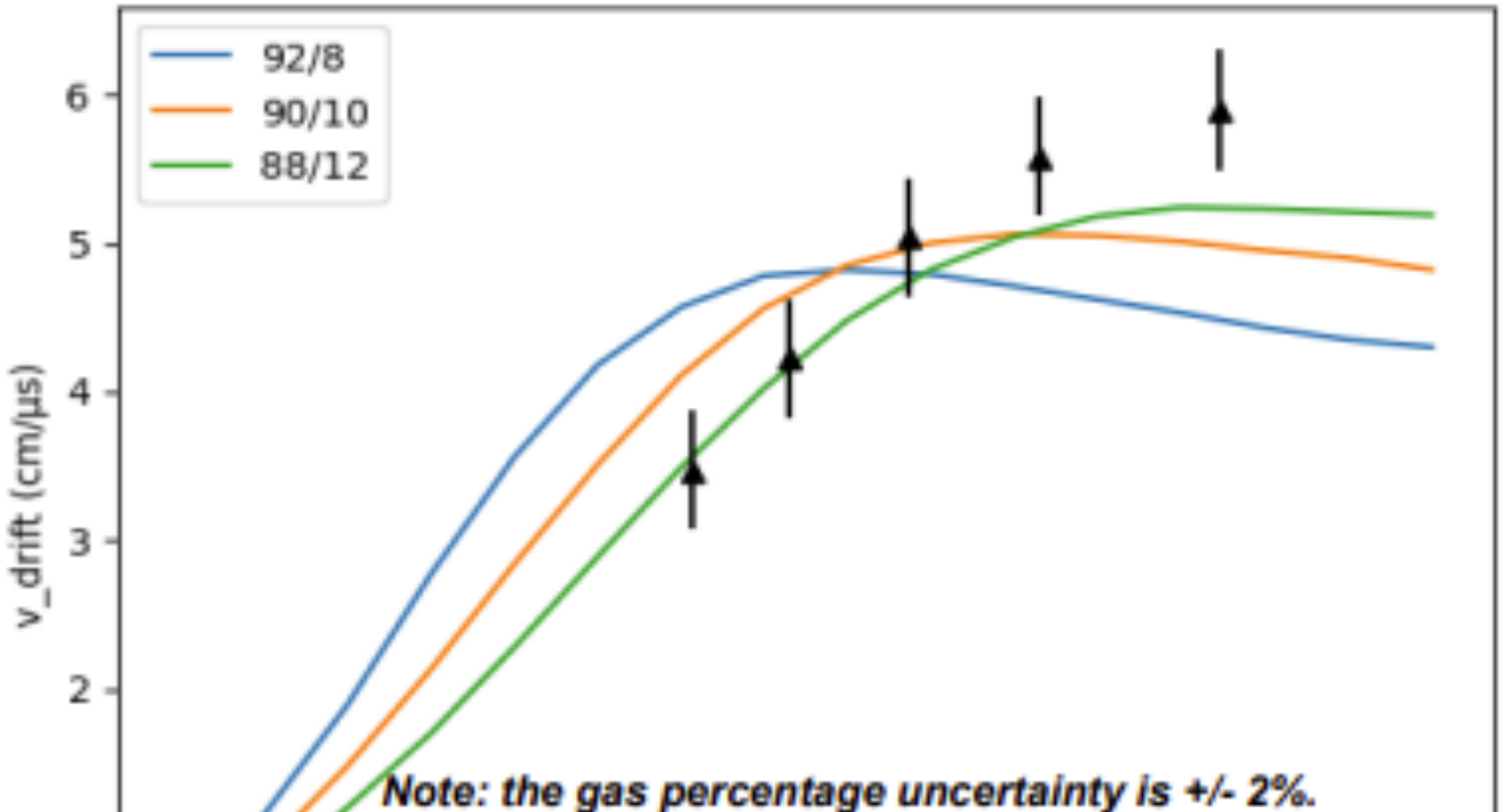
From E. Christy (JLab)



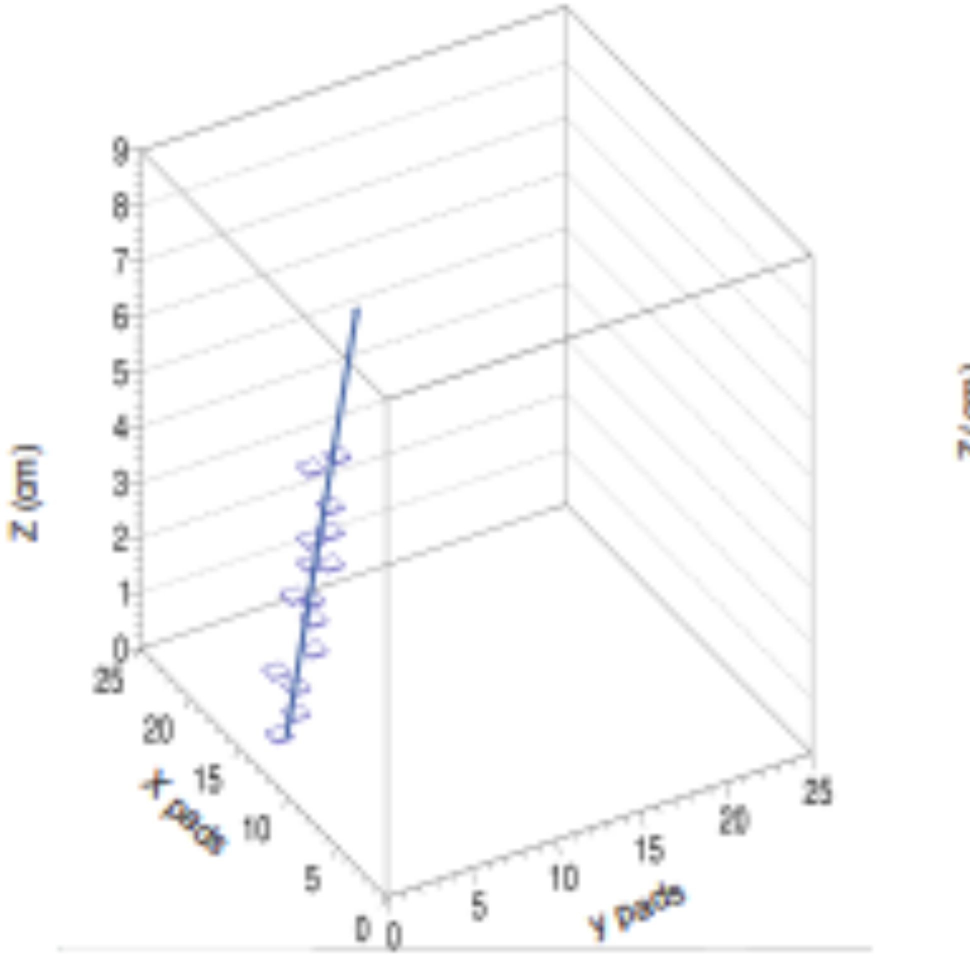

Preamp cards with shaper
24 channels per card / 5 cards per baseboard

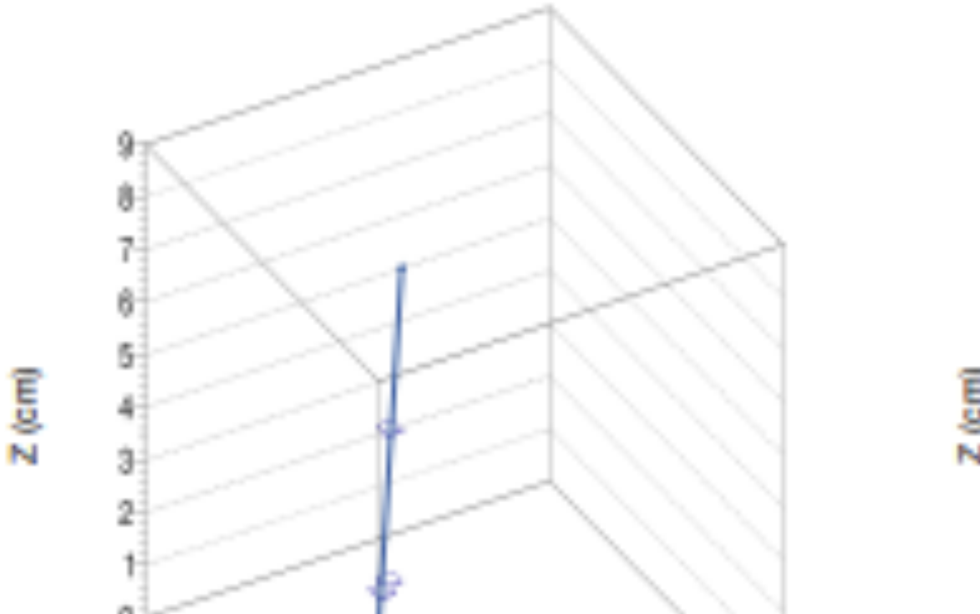







- Tests on-going with JL
- Will move to TDIS ele
- Cosmics triggers of o
  - Testing drift times 
  - Recording tracks
  - (Horizontal orienta
- Reported some HV di

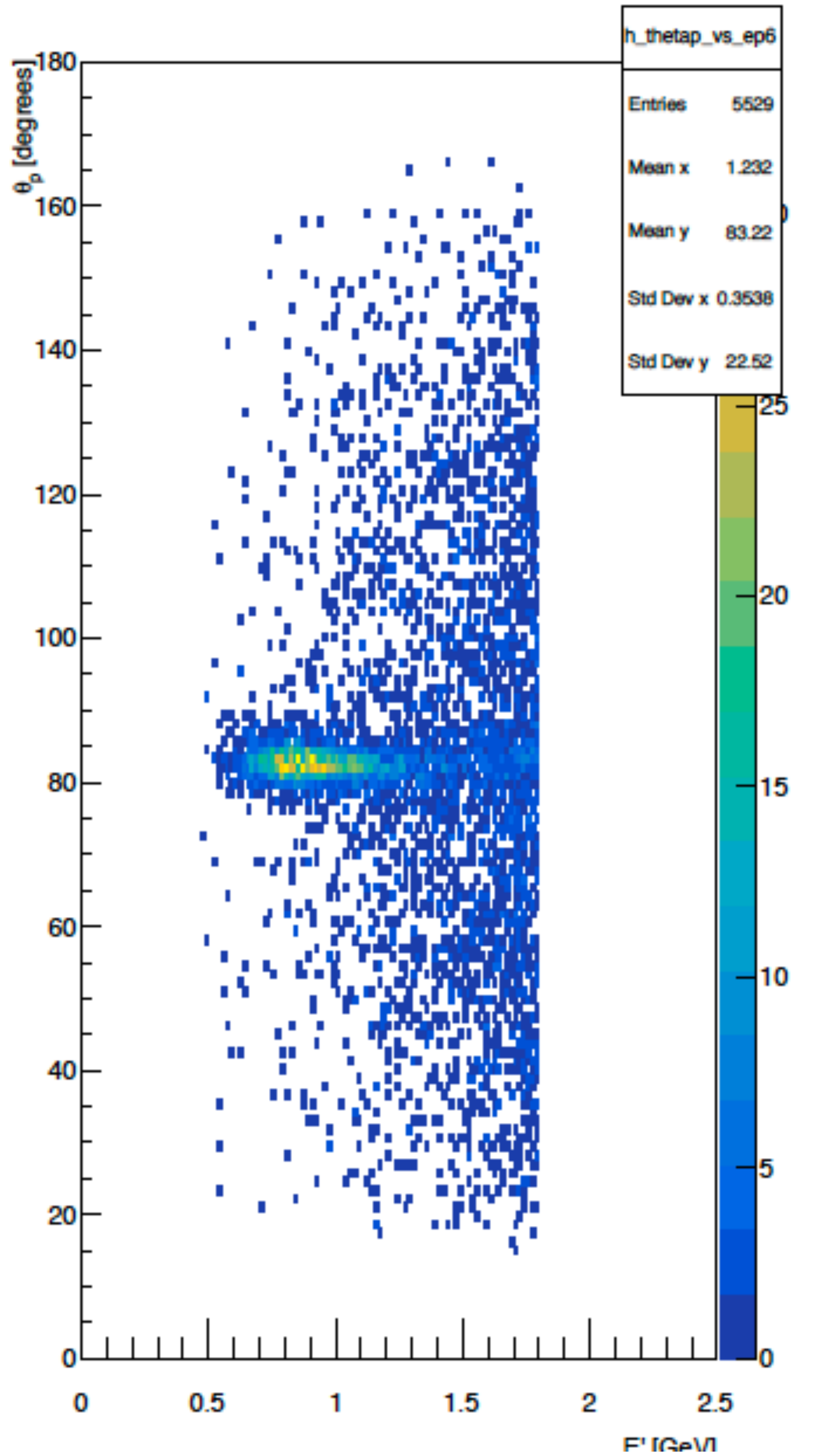


# Background studies using BONuS12

- **BONuS12 targets are Deuterium and Hydrogen.**

- **How many protons in the large angle range in BONuS12 with deuterium target -> background for TDIS (Obtain rate of DIS protons BONuS12 RTPC getting)**

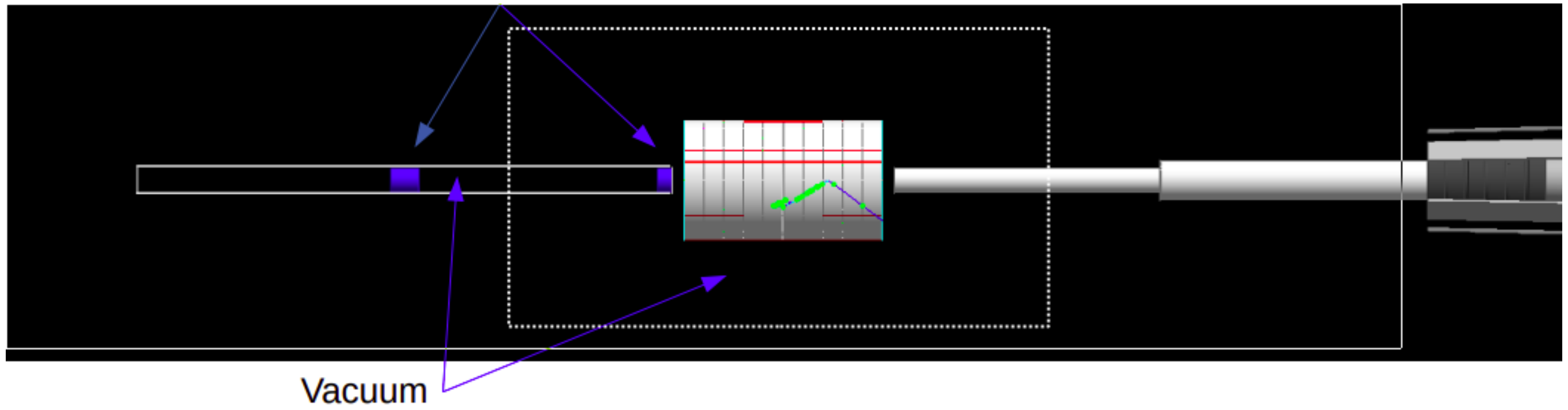


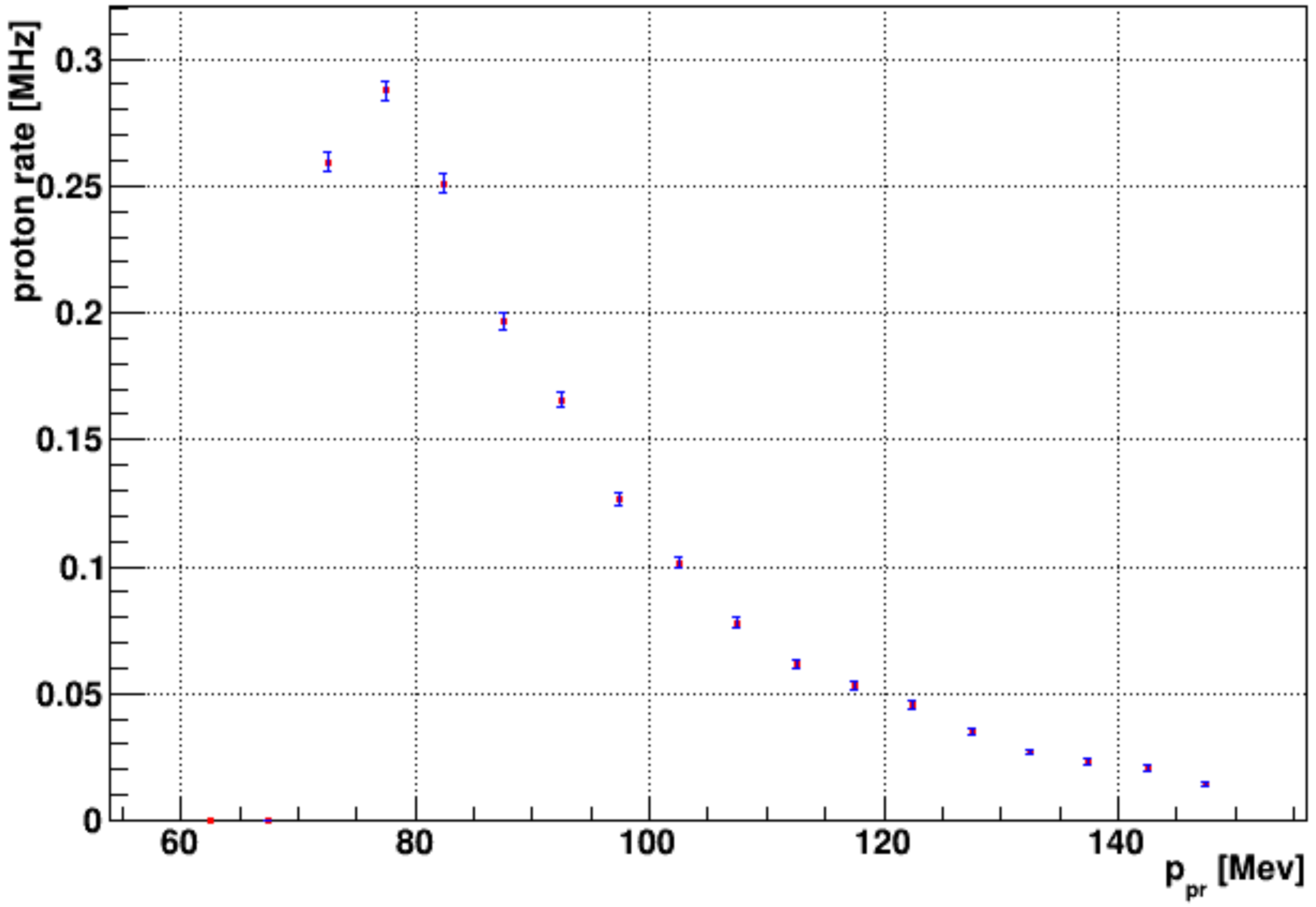

*2-D histogram of scattered electron momentum in GeV versus polar angle of recoil proton for the target filled with hydrogen gas and a beam energy of 2.2 GeV.*

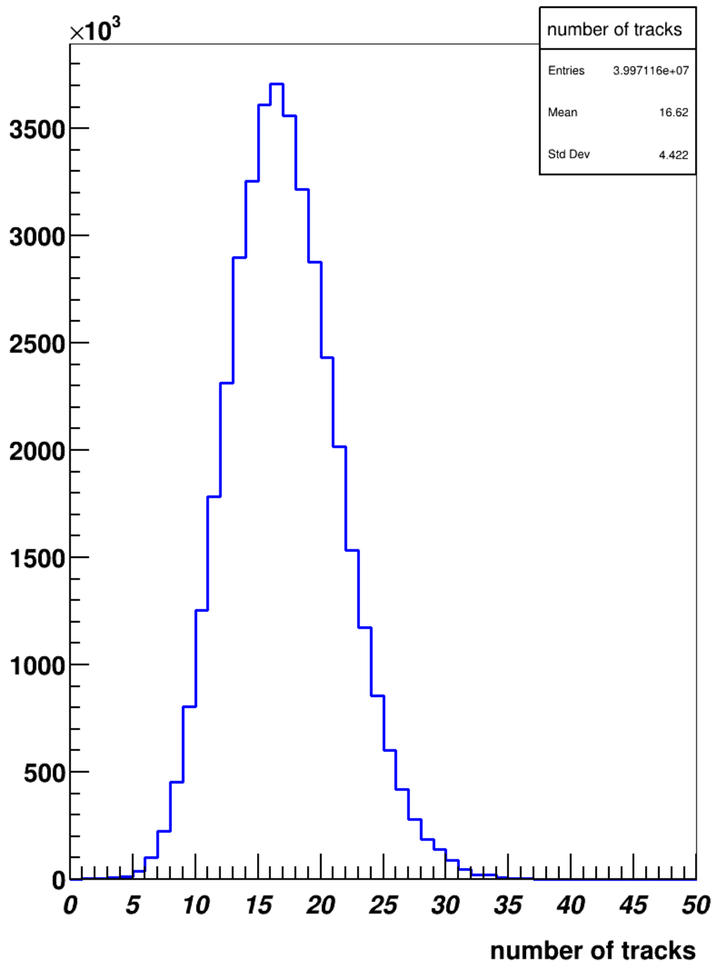
# Simulated fully in g4sbs

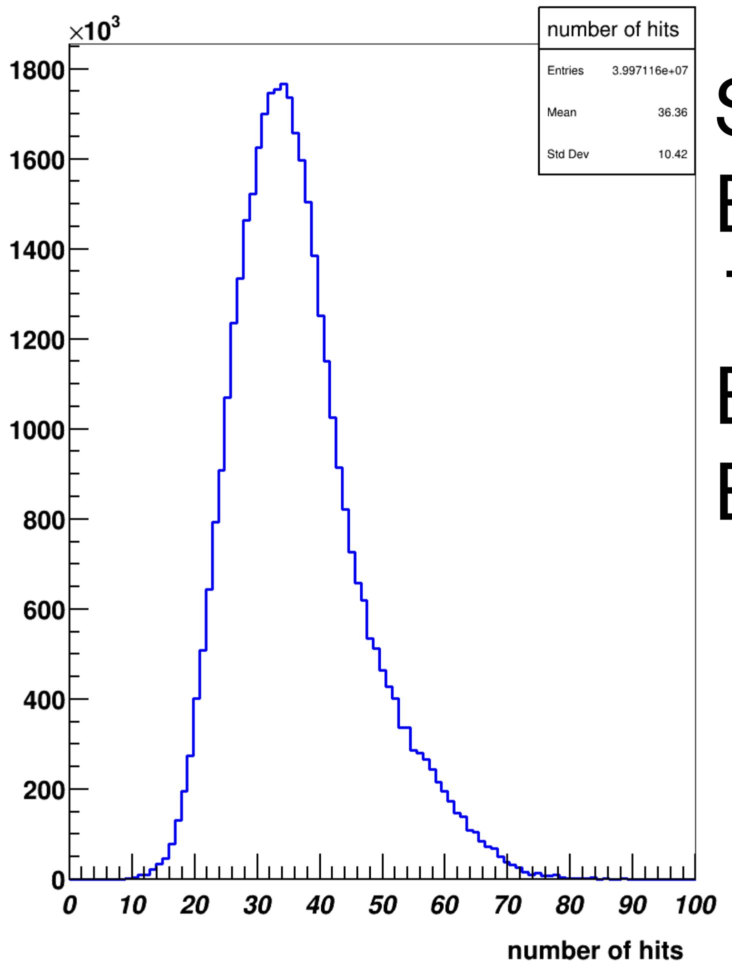
Team of contributors (E. Fuchey, C. Ayerbe, R. Montgomery, A. Nadeeshani , A. Puckett, M. Carmignotto,….

mTPC also simulated using CERN’s magboltz/garfield




Simulation benchmarked with BONuS12 data.
TDIS simulated rates match observed BONuS12 rates.
E.g. expected ~500 tracks per event.

# ACTS

ACTS provides a whole chain of tracking tasks, such as:

- digitization,
- clustering,
- seeding,
- track fitting,
- vertexing,
- calibration and alignment
- various tools, tunings, data model etc. etc. etc.

- The first step we need to do to implement correctly working track fitting.
- And after this, move to the track finding.
- After this, having track finding and track fitting correctly working in the modes close to what we expect from the experiment, move to the vertexing and other options.

To implement this, we initially will use truth seeding. Here it is explained. Since seeding is not going to be implemented in the first order, but track fitting algorithms need some seeding; initially we will use smeared initial truth track parameters as a seeding input for the fitting.