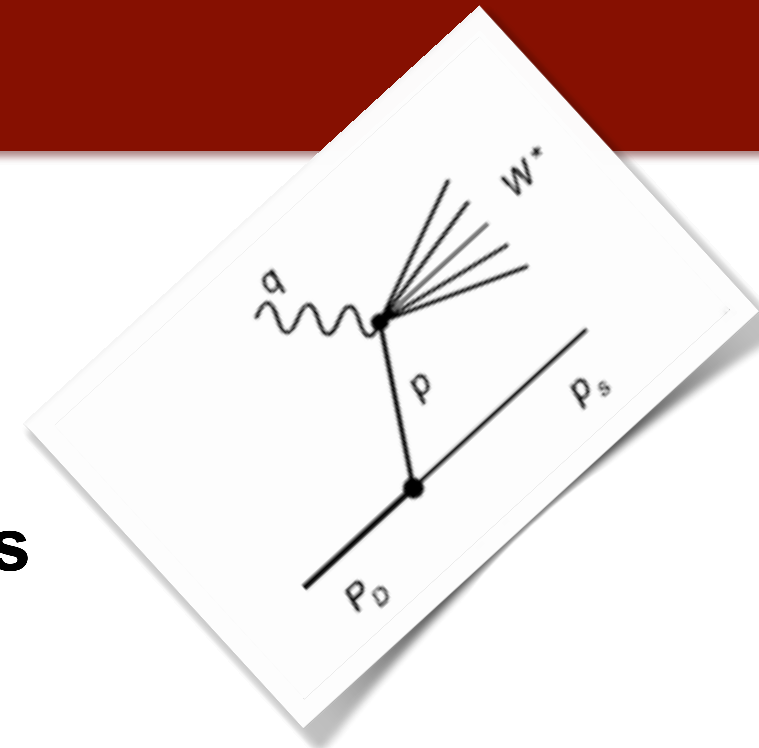
Tagged Deep Inelastic Scattering:
Exploring the mesonic content and structure of the nucleon

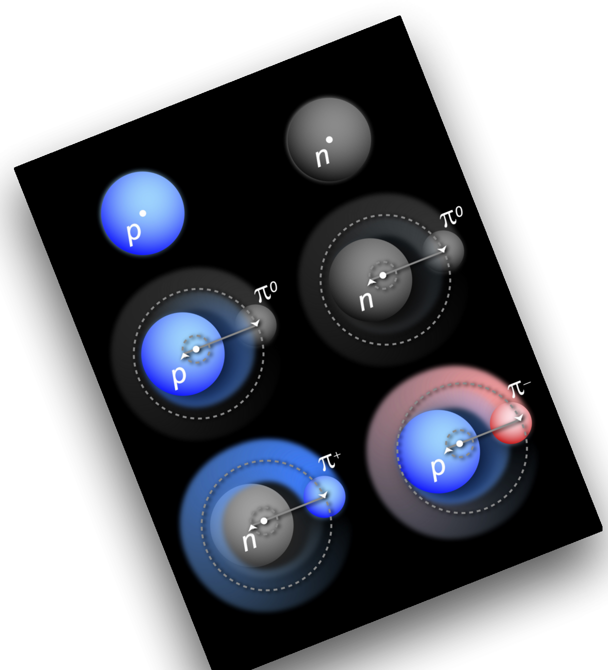
Dipangkar Dutta
Mississippi State University
for the TDIS collaboration

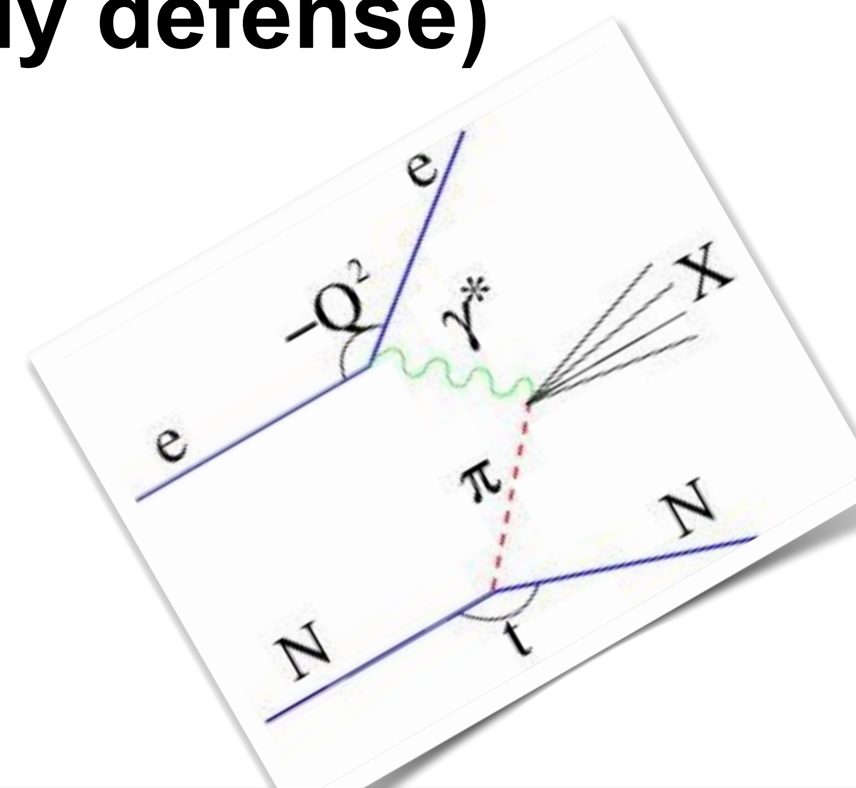
SBS Collaboration Meeting
July 18, 2023

Outline



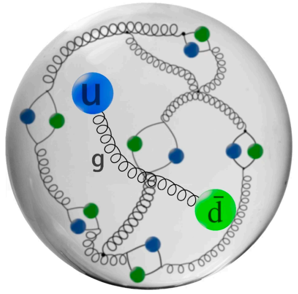
1. **Introduction**
   - Mesonic content and structure of nucleons
2. **Tagged structure functions**
   - Sullivan process and access to meson cloud of nucleon
   - The TDIS experiment at JLab
3. **Status of the experiment (jeopardy defense)**
4. **Summary**

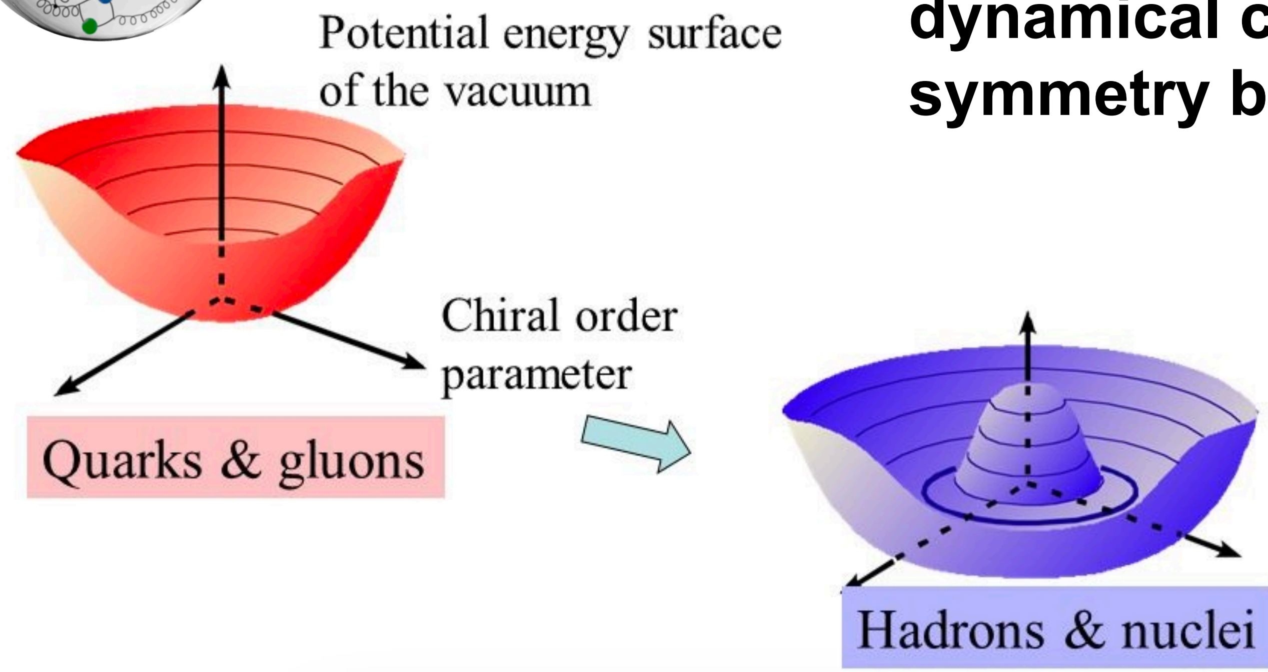




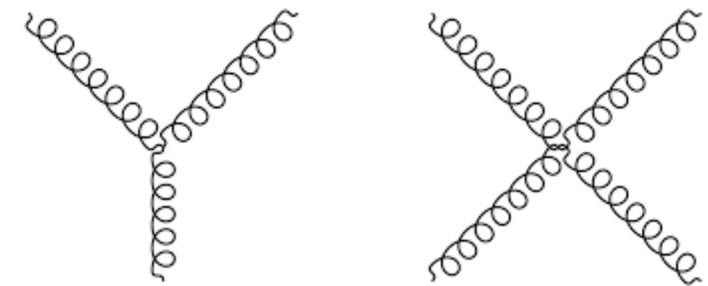
Pions and kaons are the simplest bound states of QCD and its mass-less Nambu-Goldstone bosons

π^+

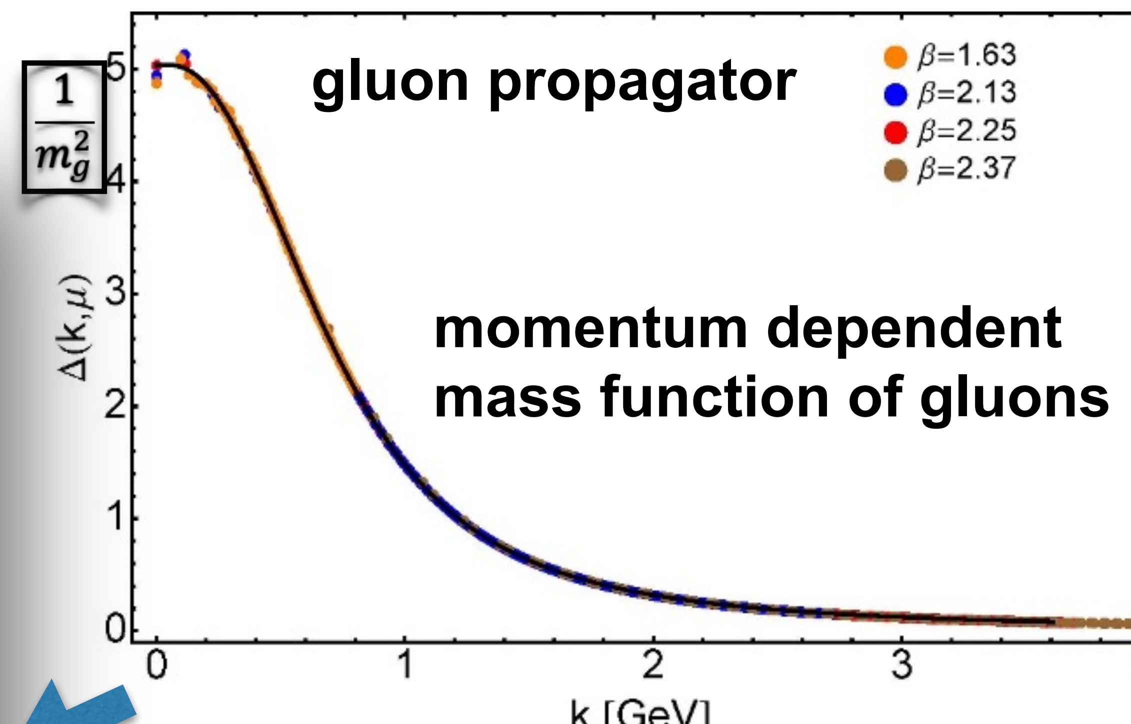




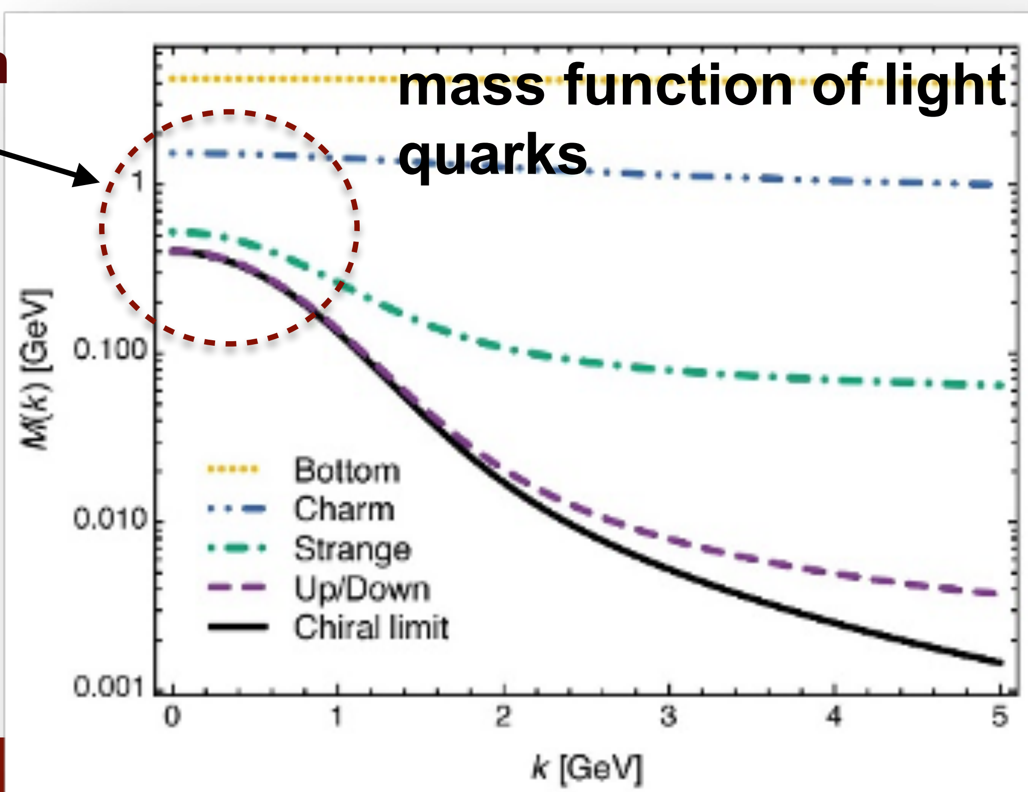
emergence of mass via dynamical chiral symmetry breaking



a consequence of gluon self interaction



Rapid increase in mass due to gluon cloud

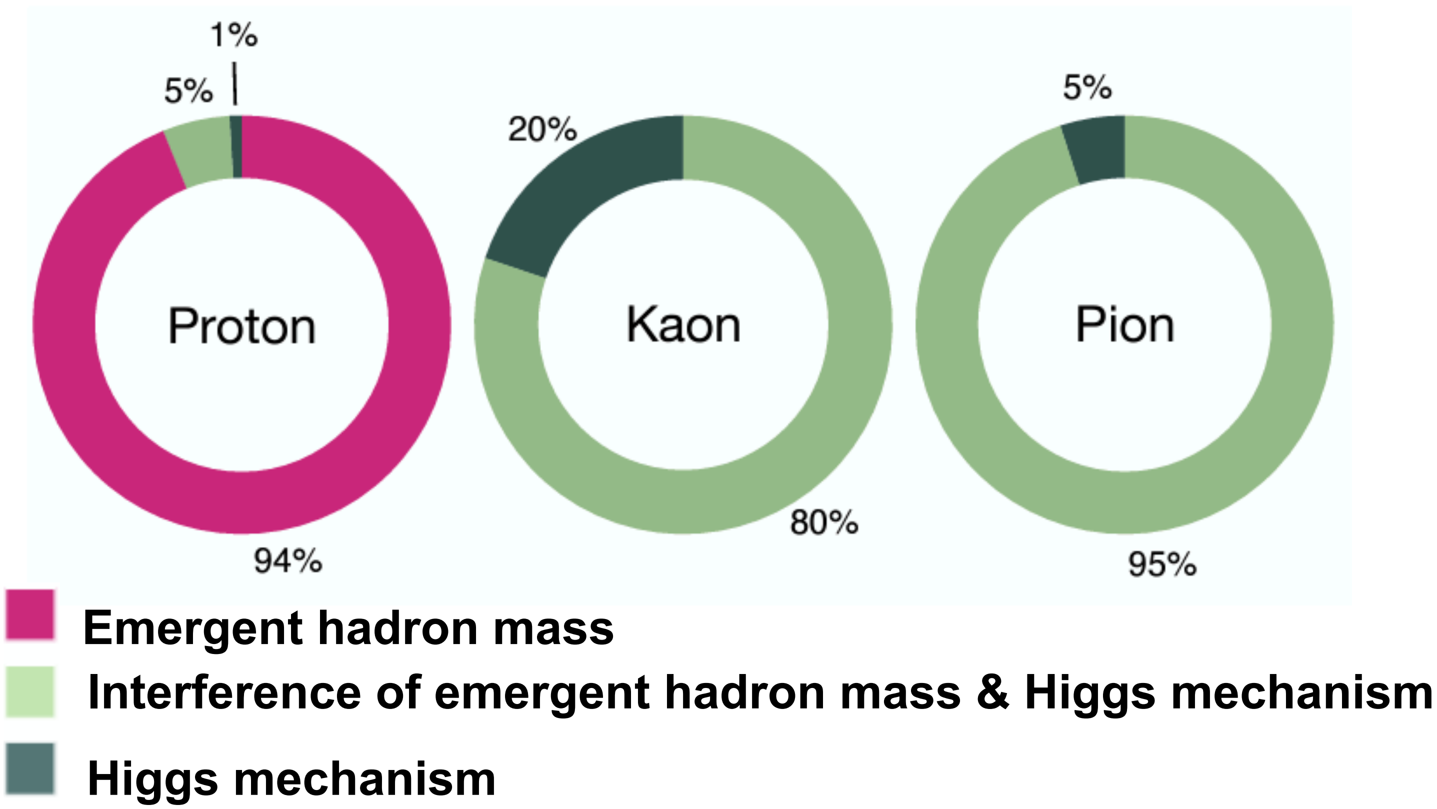


C. D. Roberts, Symmetry 12, 1468 (2020)

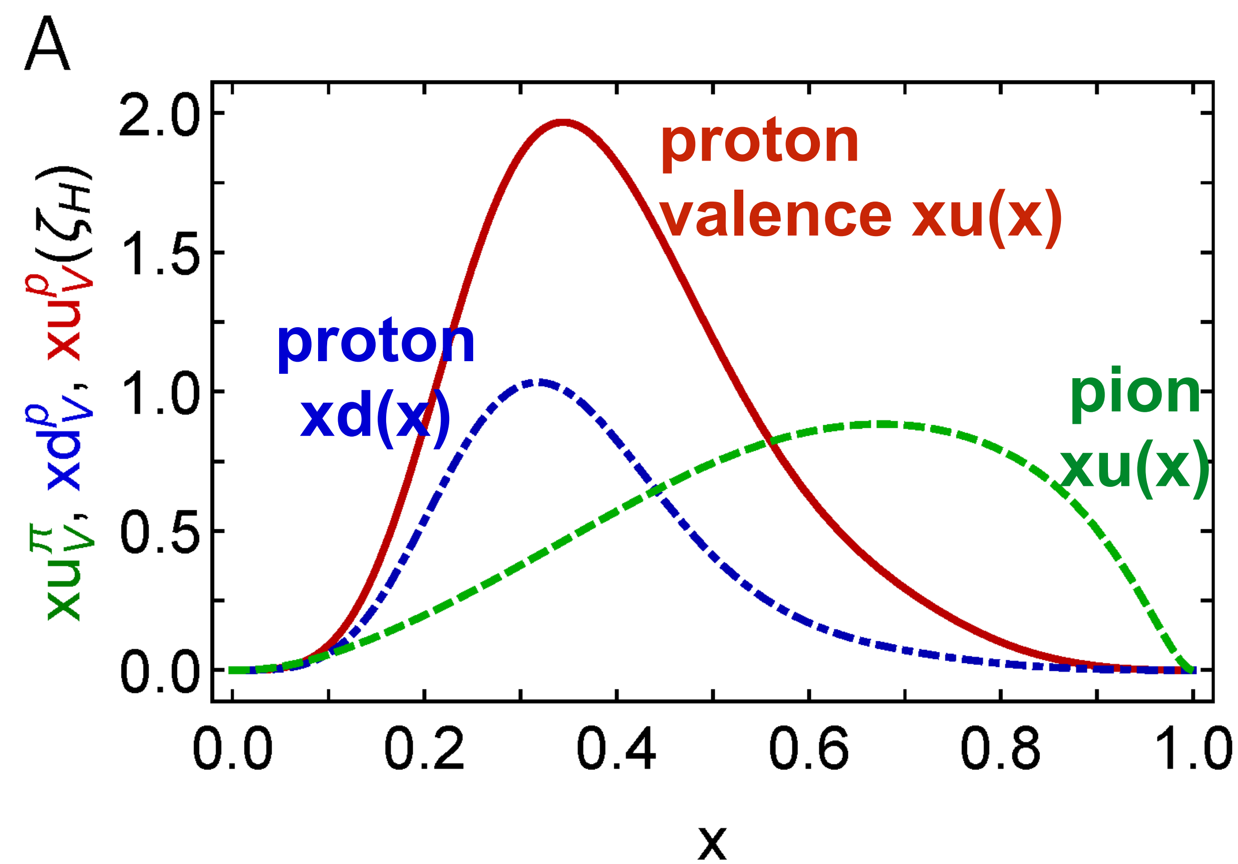
images courtesy of C. D. Roberts

knowledge of meson structure is critical to a complete understanding of the emergence of hadron mass

Mass budget for mesons and nucleons are vastly different



D. Binosi, Few-Body Systems, 63, 42 (2022)



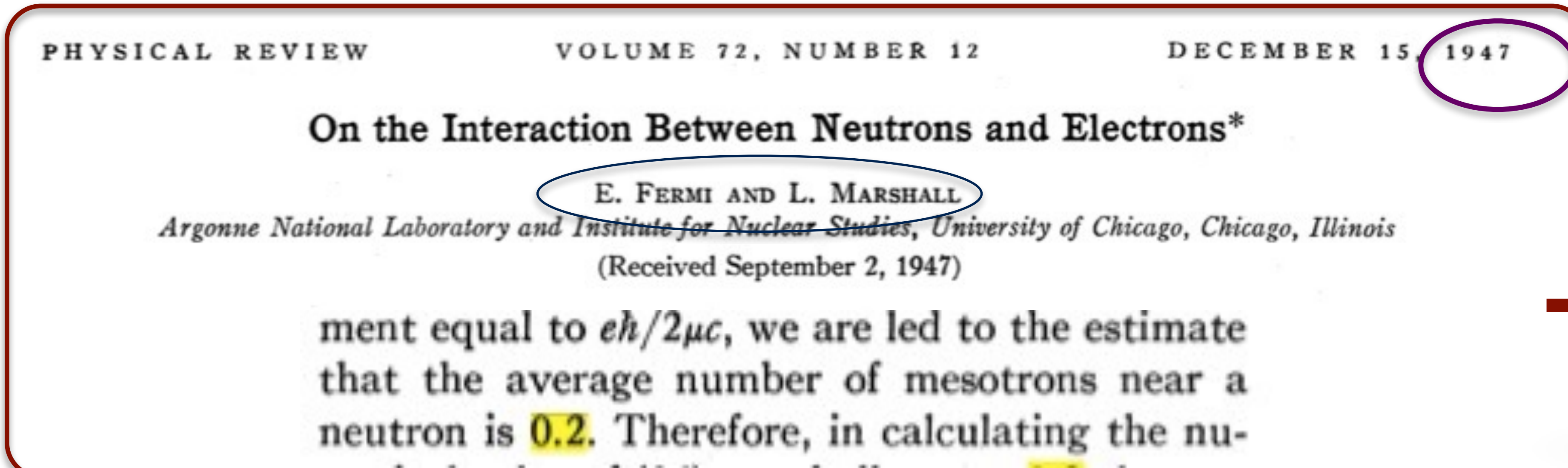
pion/proton valence quark distributions are also very different

difference between meson PDFs: direct information on emergent hadron mass

Lack of stable meson targets ⇒ scant experimental data

How about mesons in nucleons?

There is ample evidence that nucleons have pionic content in them.



PHYSICAL REVIEW VOLUME 72, NUMBER 12 DECEMBER 15, 1947

On the Interaction Between Neutrons and Electrons*

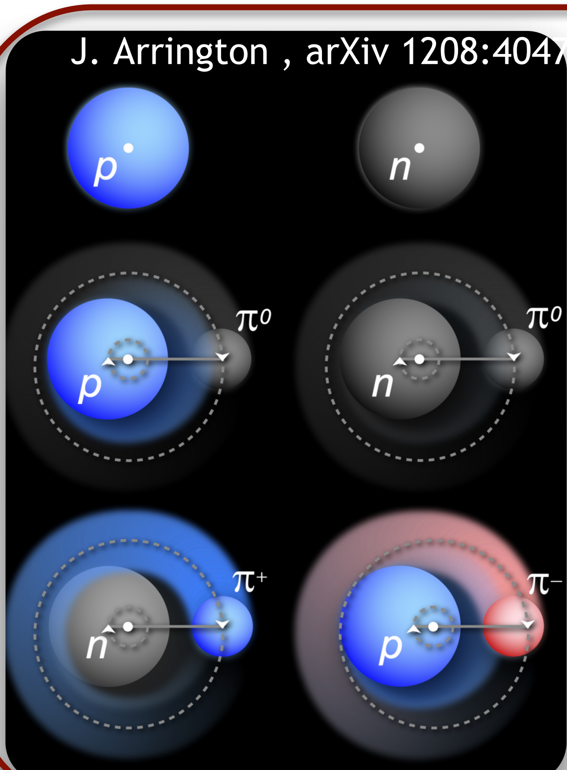
E. Fermi and L. Marshall

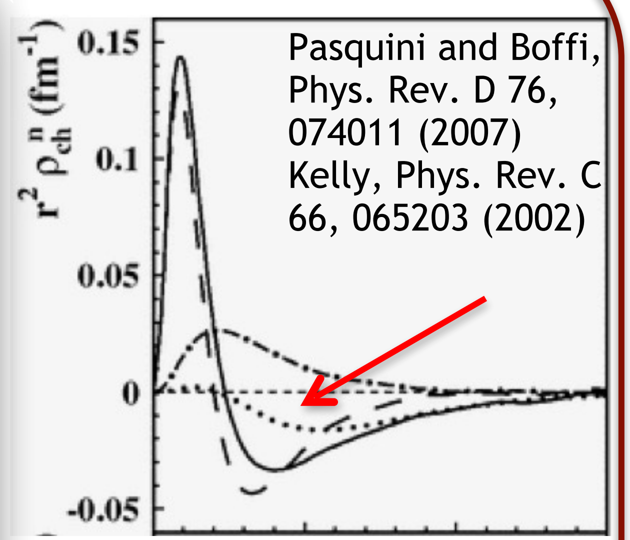
Argonne National Laboratory and Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

(Received September 2, 1947)

ment equal to $eh/2\mu c$, we are led to the estimate that the average number of mesotrons near a neutron is 0.2. Therefore, in calculating the nu-

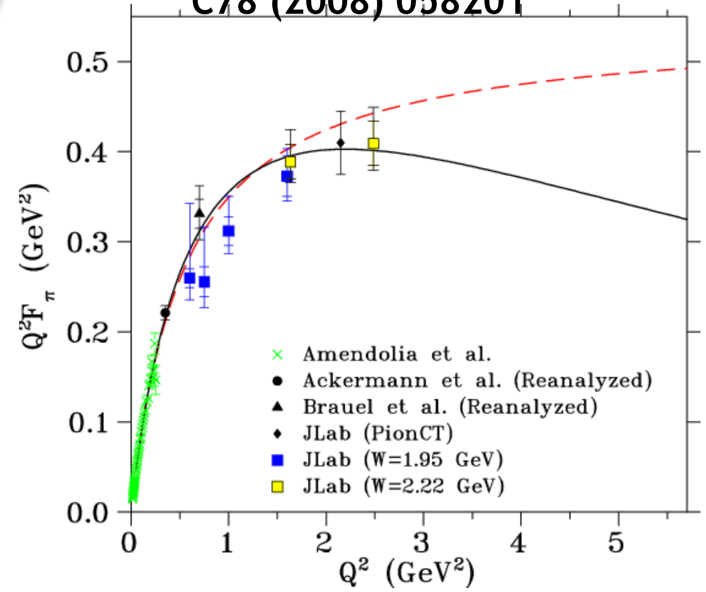
Experimental evidence pointed to the nucleon existing ~20% of the time in a virtual meson-nucleon state.





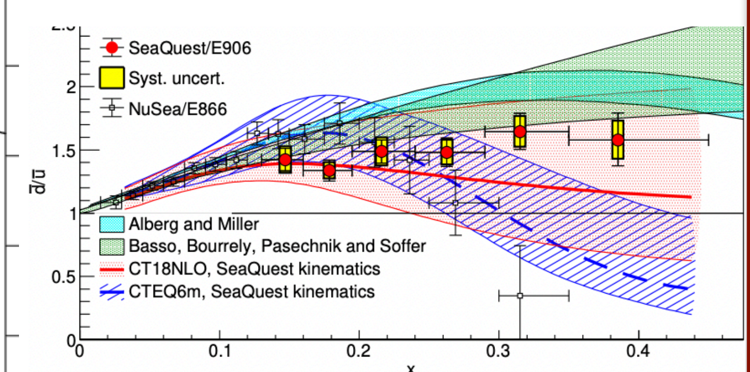
Proton & Neutron Charge Distribution

Horn et al., Phys.Rev. C78 (2008) 058201



Pion Form Factor

J. Dove et al., Nature 590, 561 (2021).

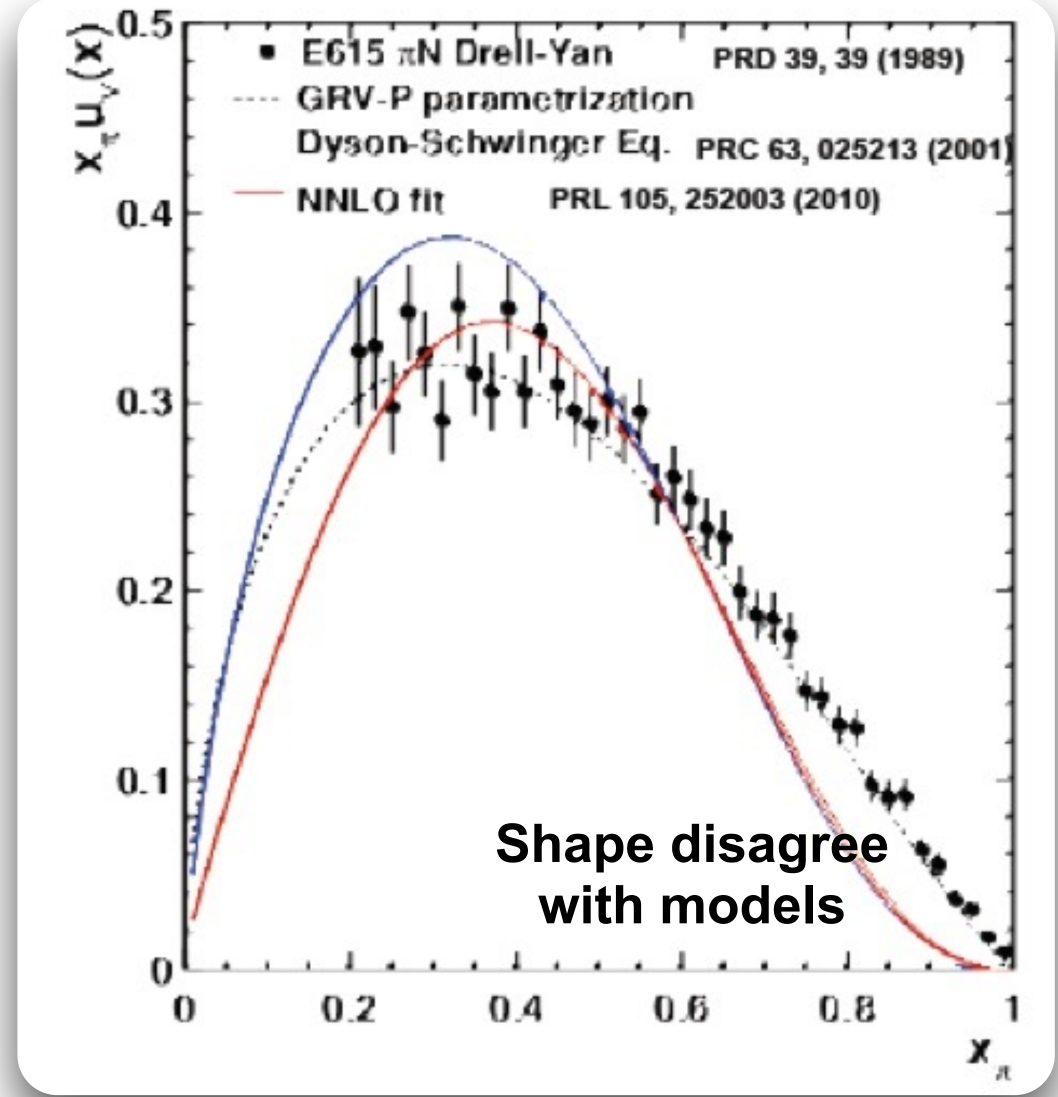


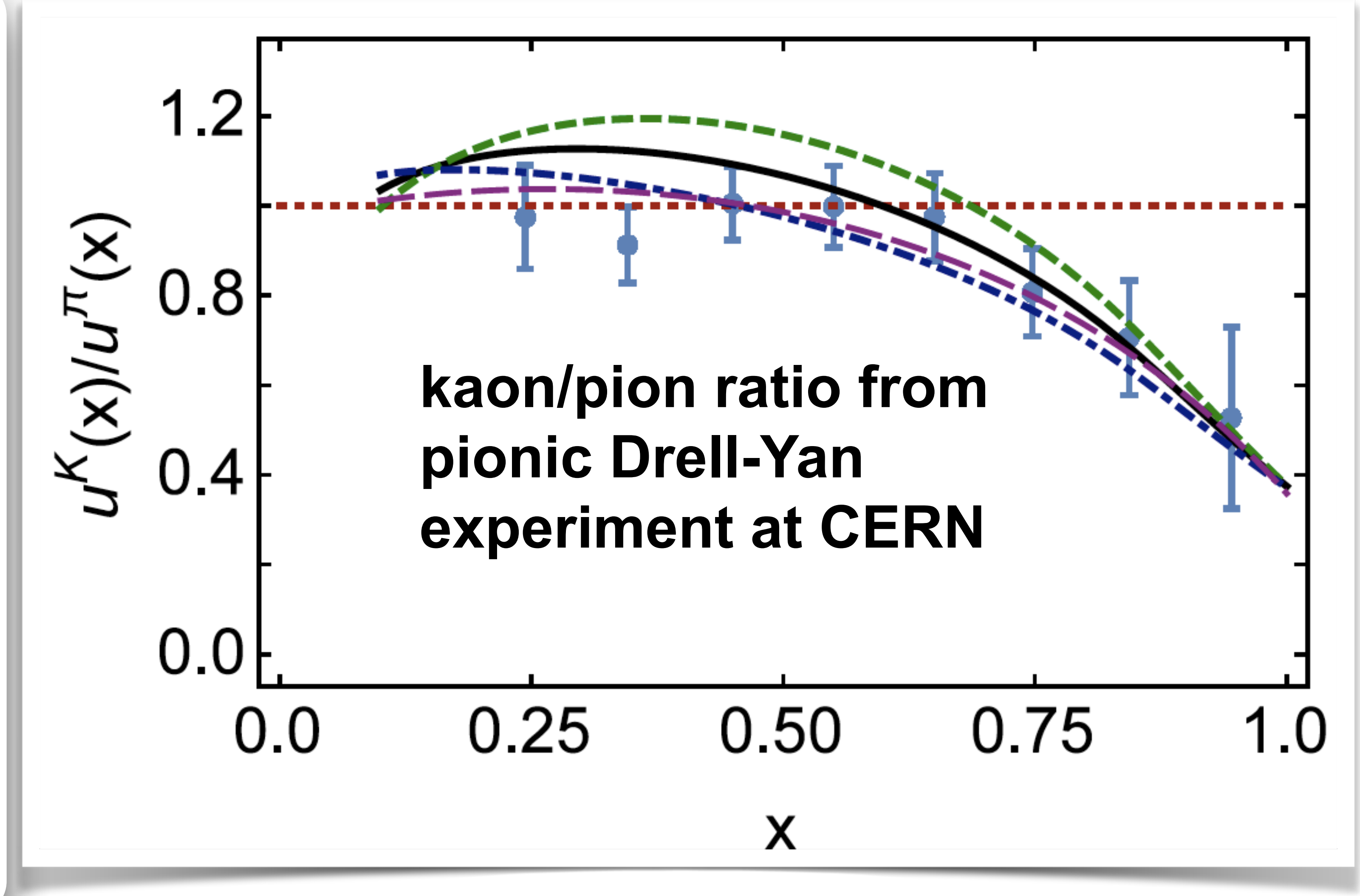
up/down sea-antiquark flavor asymmetry

No direct measurements

There is no direct measurement of magnitude of mesonic content of nucleons.

In the valence region some data from Drell-Yan experiments





Calculations with the gluonic contributions can explain data

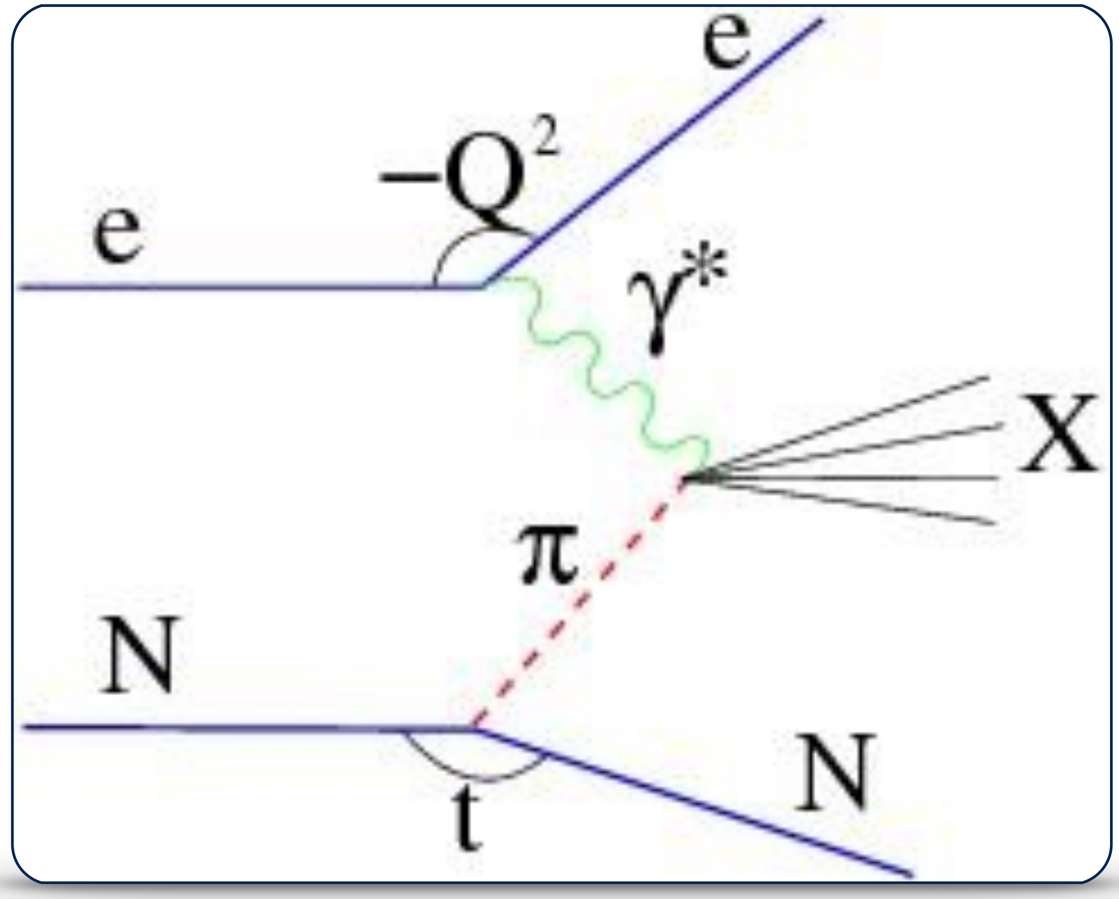
Need more and precise data

L. Chang, C. Mezrag, H. Moutarde, C. D. Roberts, J. Rodriguez-Quintero, P. C. Tandy, Phys. Lett. B420, 267 (2014)

C. Chen, L. Chang, C. D. Roberts, S. Wan and H.-S. Zong, Phys. Rev. D 93, 074021 (2016)

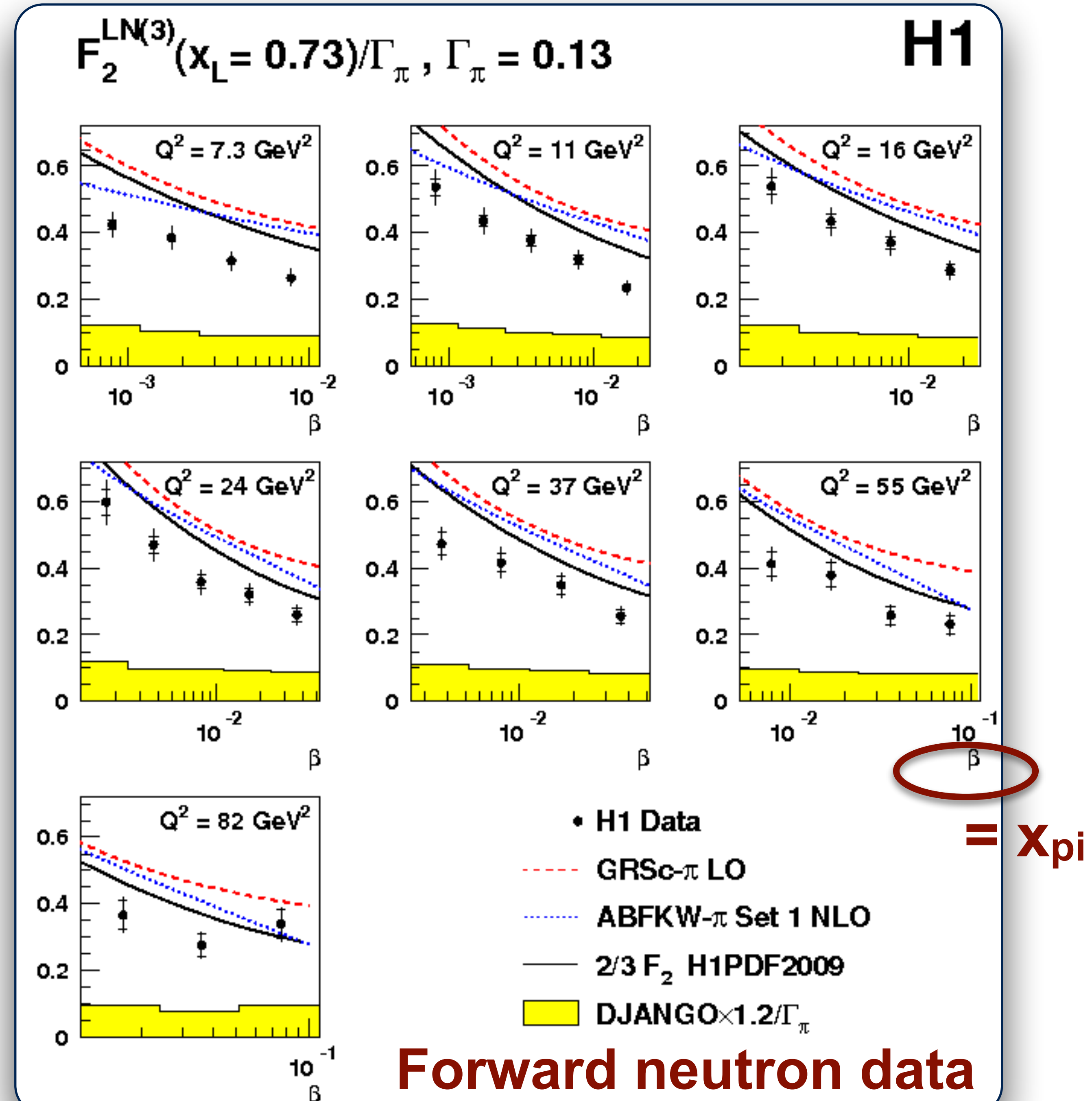
Deep-inelastic Scattering off a virtual-meson cloud is a possible experimental technique.

The Sullivan process



direct measurement of the mesonic content of the nucleon

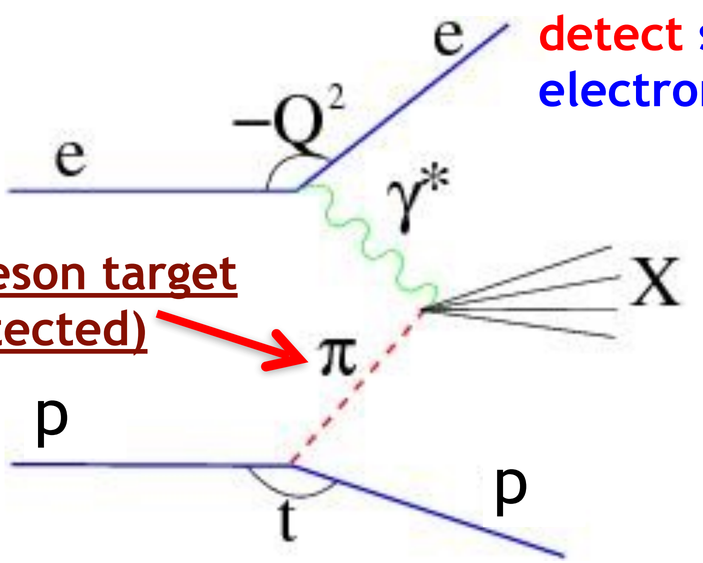
DIS events with forward going neutrons in coincidence



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

Spectator Tagging can be used to tag the "meson cloud" target.

Hydrogen Target



detect scattered electron

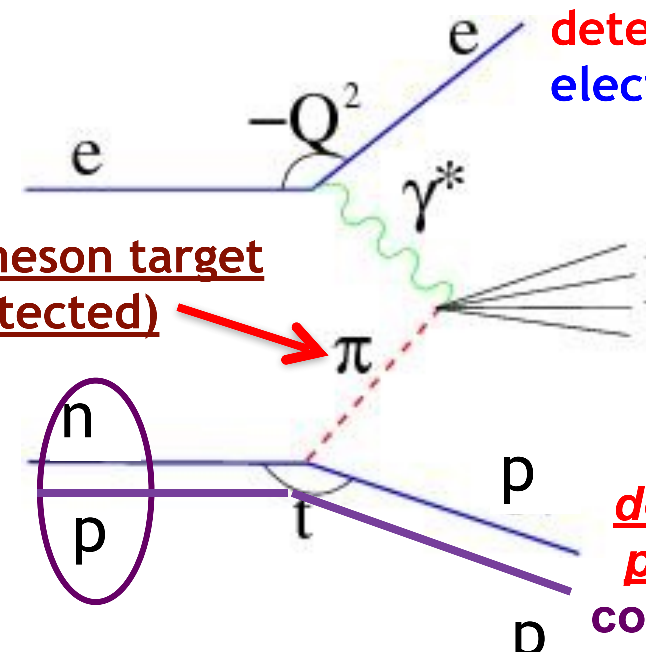
undetected recoiling hadronic system

neutral meson target (undetected)

Spectator proton

(backward going slow proton)

Deuterium Target



detect scattered electron

undetected recoiling hadronic system

charged meson target (undetected)

detecting two protons **with common vertex**

Spectator proton

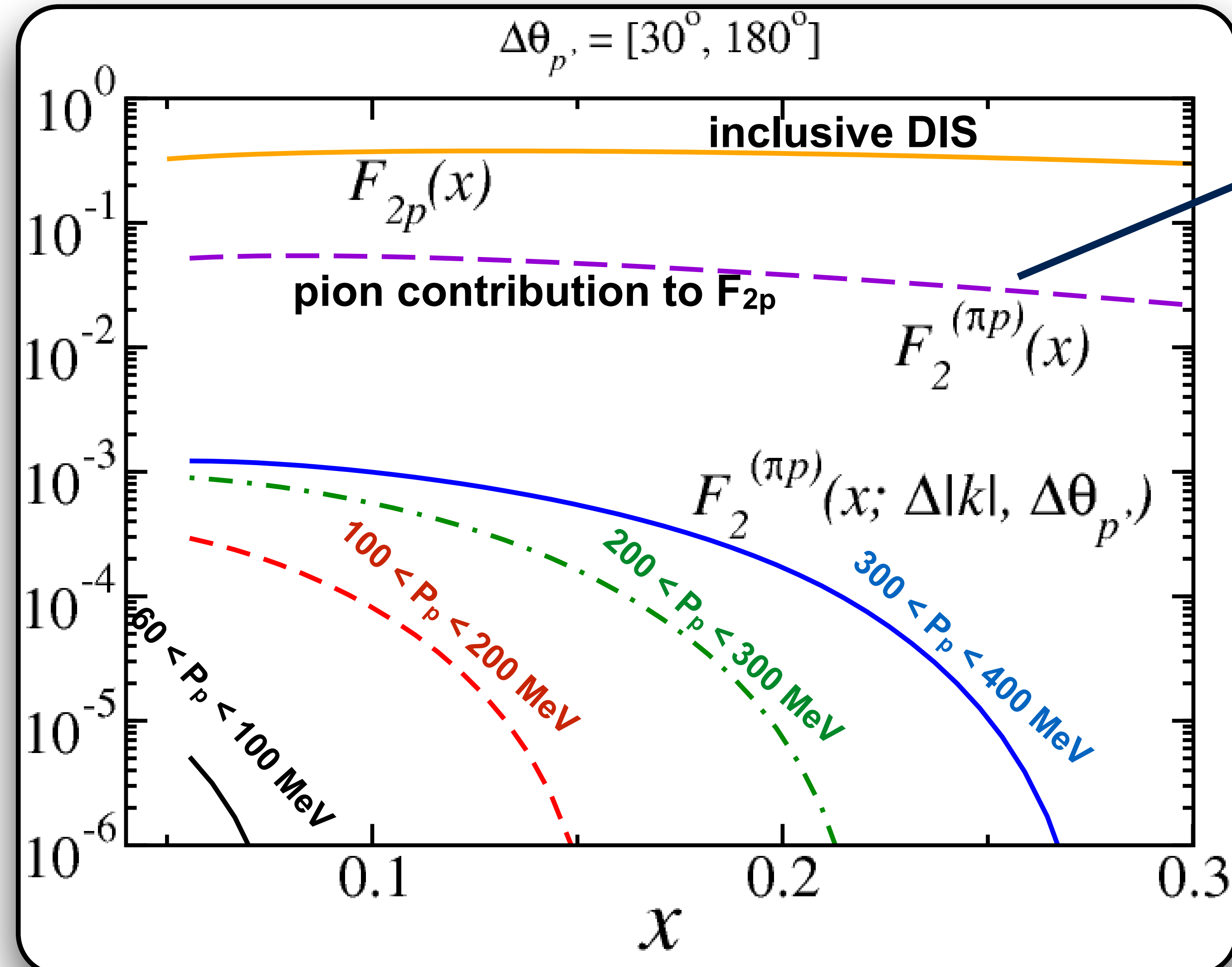
DIS event – reconstruct x, Q^2, W^2, also M_X of recoiling hadronic system

$$R^T = \frac{d^4\sigma(ep \to e'Xp')}{dxdQ^2dzdt} \Big/ \frac{d^2\sigma(ep \to e'X)}{dxdQ^2} \Delta z \Delta t \sim \frac{F_2^T(x,Q^2,z,t)}{F_2^p(x,Q^2)} \Delta z \Delta t.$$

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

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

Phenomenological models can be used to interpret the measured tagged structure function.



$$F_2^{(\pi N)}(x) = \int_x^1 dz\, f_{\pi N}(z)\, F_{2\pi}\left(\frac{x}{z}\right),$$

light-cone momentum distribution of pions in the nucleon

z = k⁺/p⁺ - light cone momentum fraction of the initial nucleon carried by the virtual pion,

where k is π 3-momentum = -p'

When tagging pion by detecting recoil proton

$$F_2^{(\pi N)}(x, z, k_\perp) = f_{\pi N}(z, k_\perp)\, F_{2\pi}\left(\frac{x}{z}\right)$$

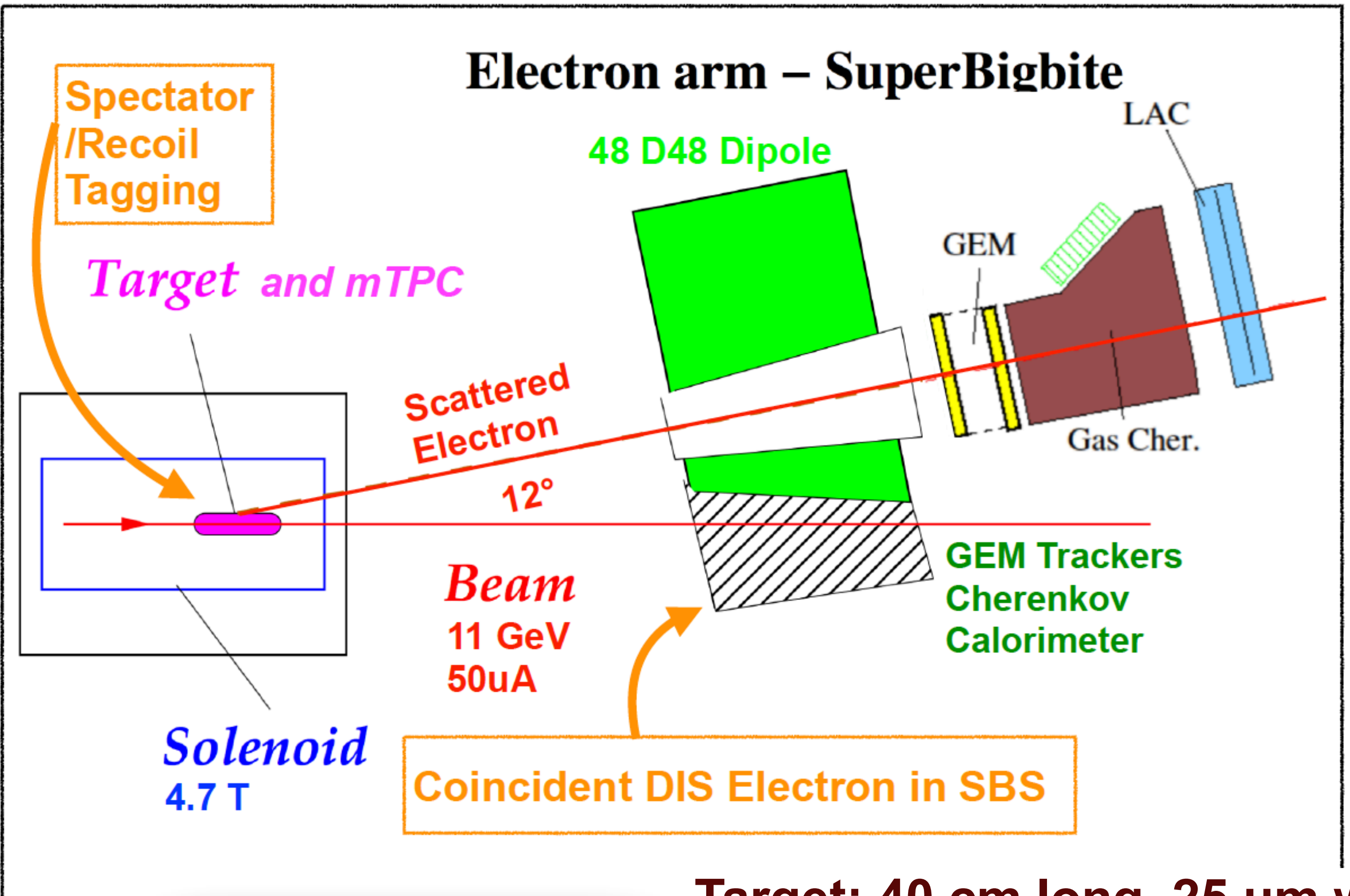
Tagged SF **pion "flux"** **Pion SF**

Pion contribution dominates at JLab kinematic (with ~ 1% for P_p < 400 MeV/c)

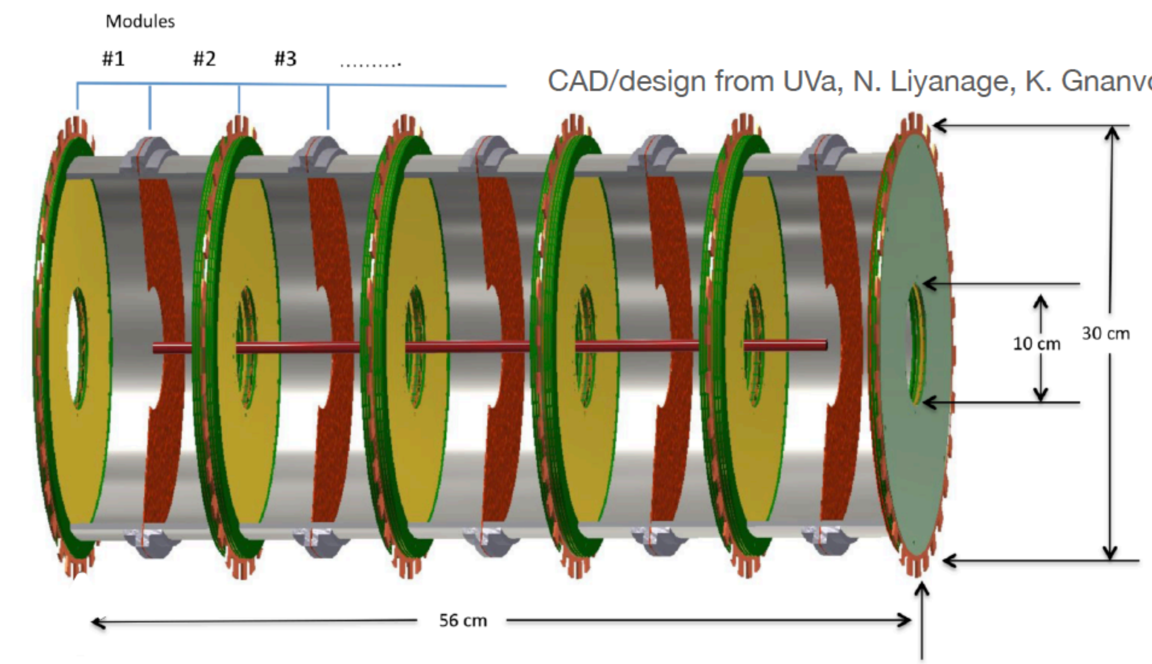
T. J. Hobbs, Few-Body Cyst. 56, 363–368 (2015);
H. Holtmann, A. Szczurek and J. Speth, Nucl. Phys. A 596, 631 (1996);
W. Melnitchouk and A. W. Thomas, Z. Phys. A 353, 311 (1995)

Spectator Tagging - a well established technique at JLab - can be used to tag the "meson cloud" target.

The TDIS experiment will use spectator tagging in a cylindrical recoil detector

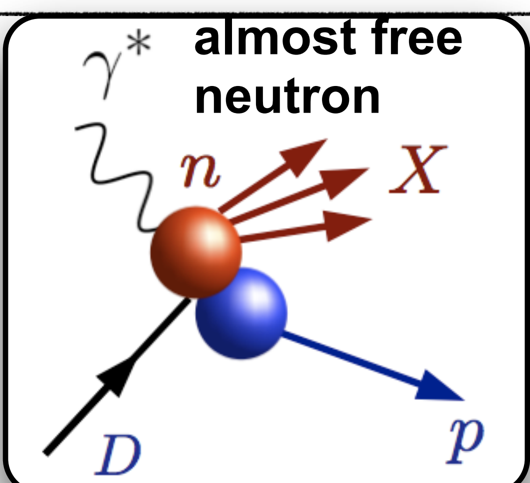


High rate multiple time projection chamber (mTPC) to tag recoiling/spectator hadrons



Tracking, dE/dx

Target: 40 cm long, 25 um wall thickness Kapton straw at room temperature and 3 atm. pressure.

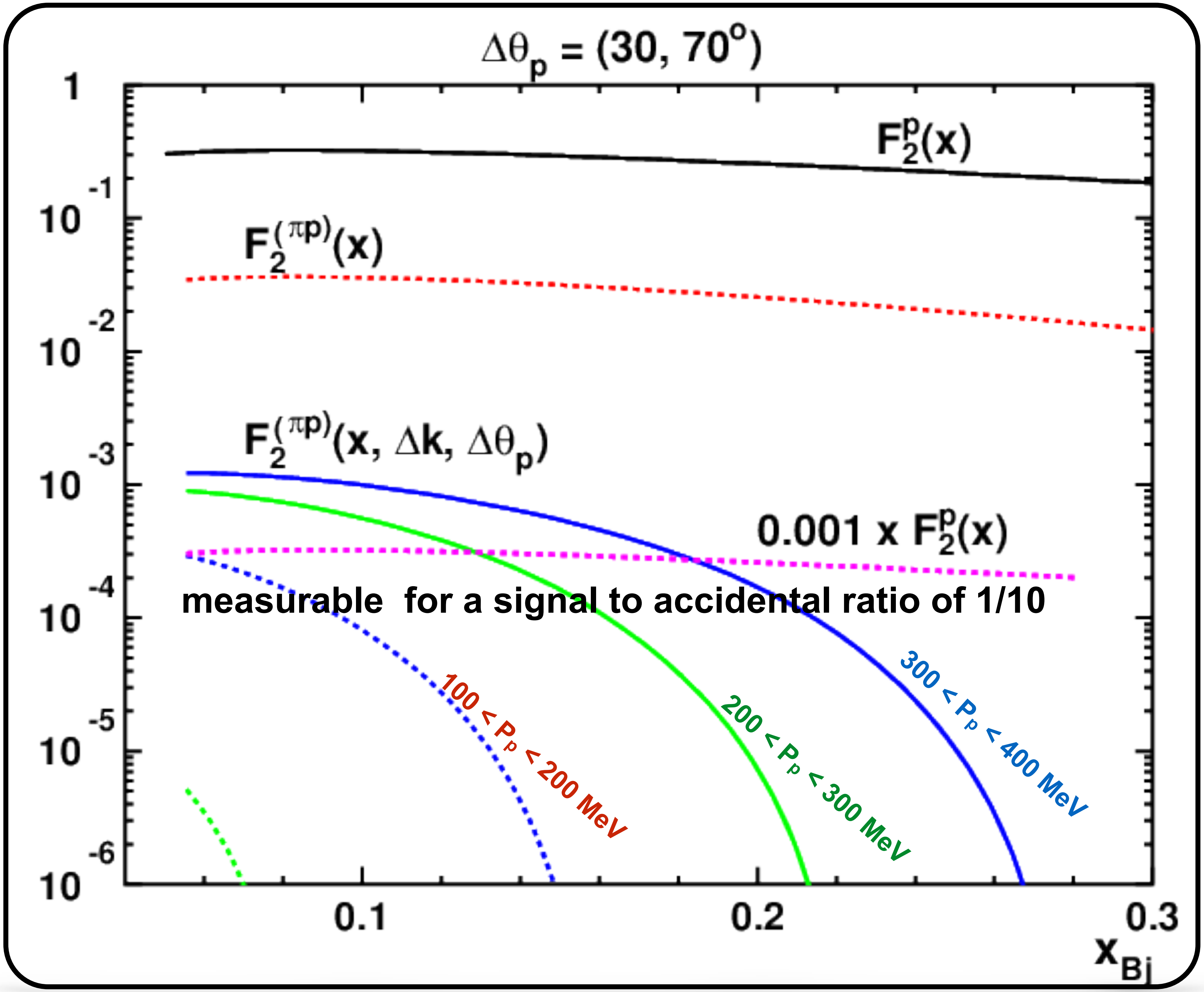


Deuteron **Spectator proton (backward going slow proton)**

TDIS will be a pioneering experiment that will be the first direct measure of the mesonic content of nucleons.

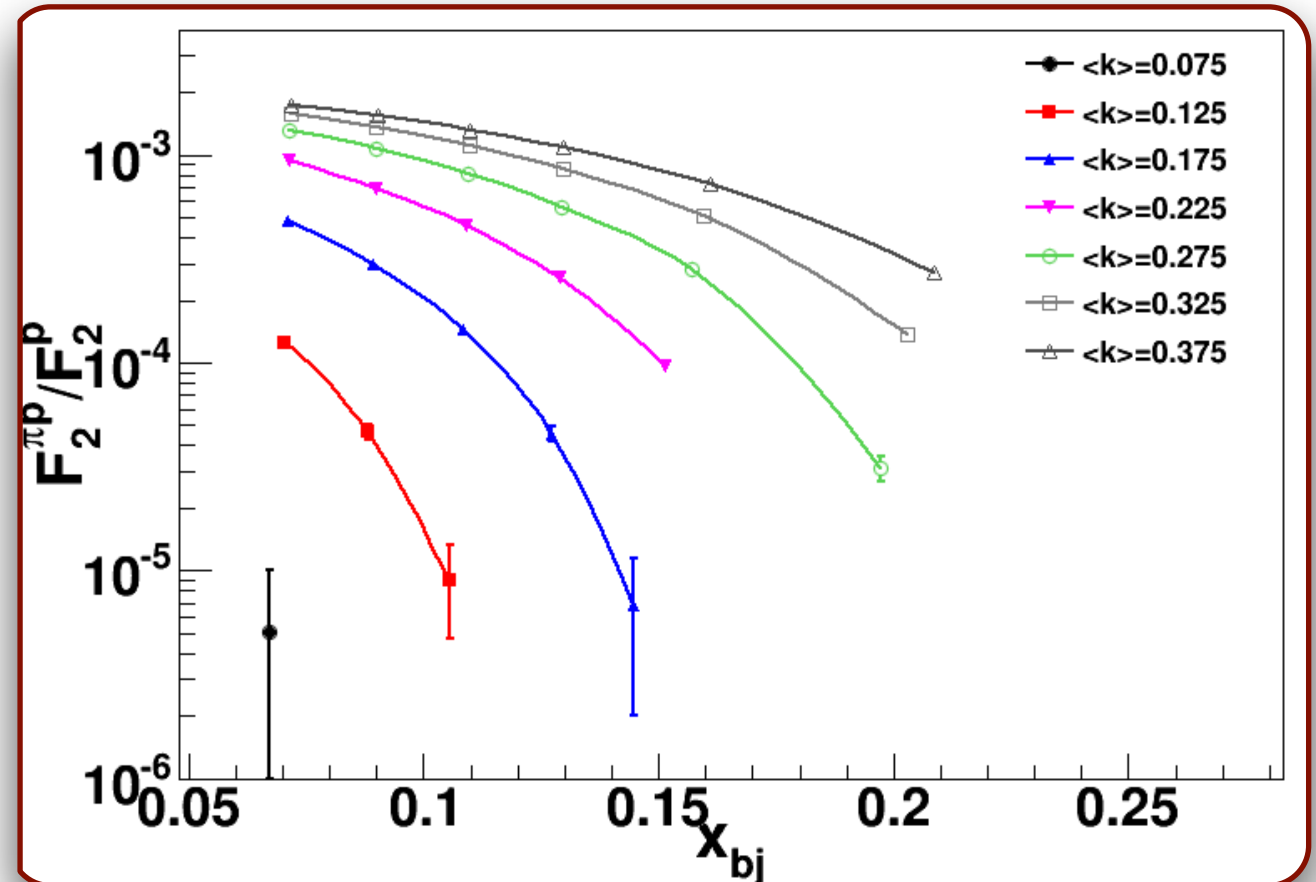
The techniques used to extract meson structure function will be a necessary first step for future experiments

A signal to accidental ratio > 0.1 will allow measurement of proton rates > 0.1% of DIS rate

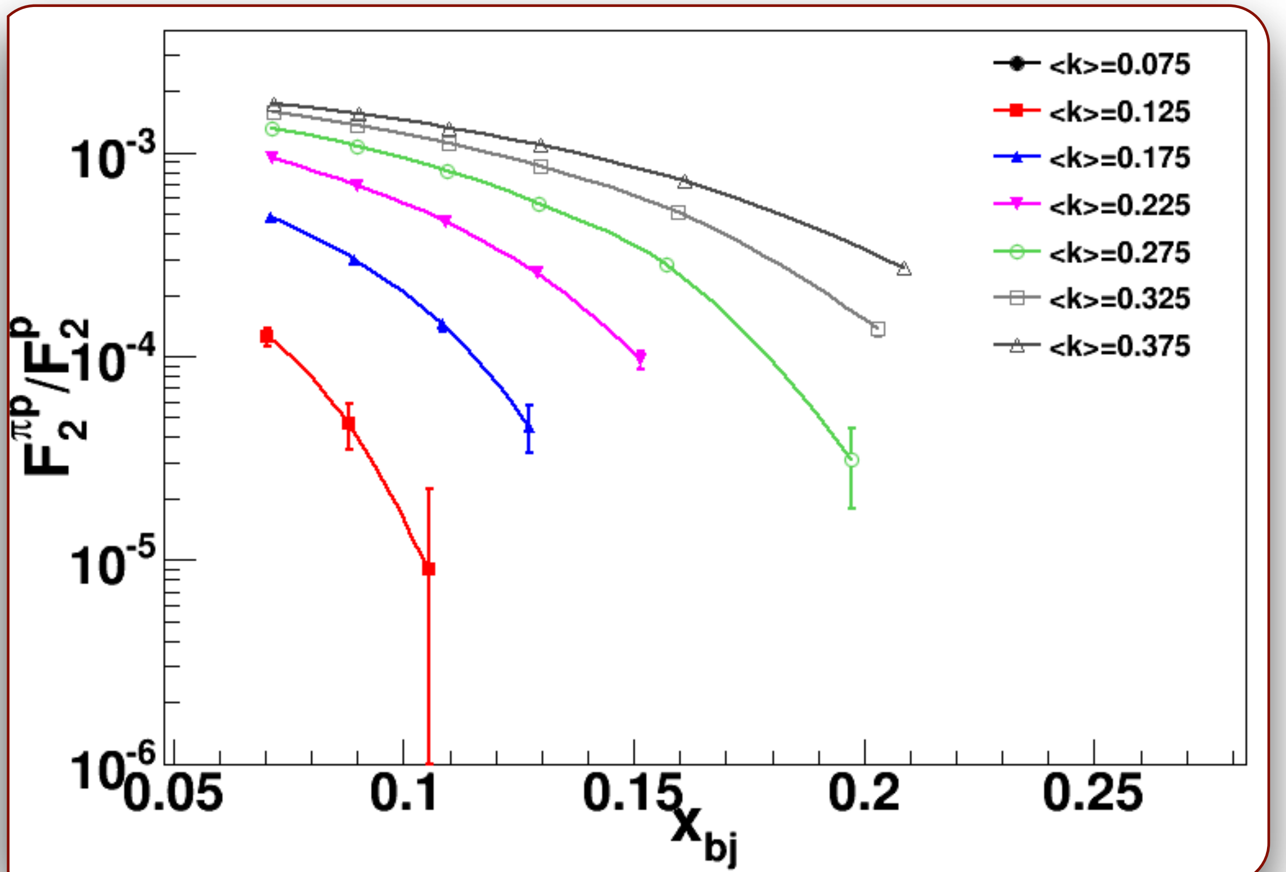


The TDIS experiment will measure tagged structure functions for protons and neutrons

proton target



neutron target



Full momentum range (collected simultaneously) - all momentum bins in MeV/c
Error bars largest at highest x points - at fixed x, these are the lowest t values

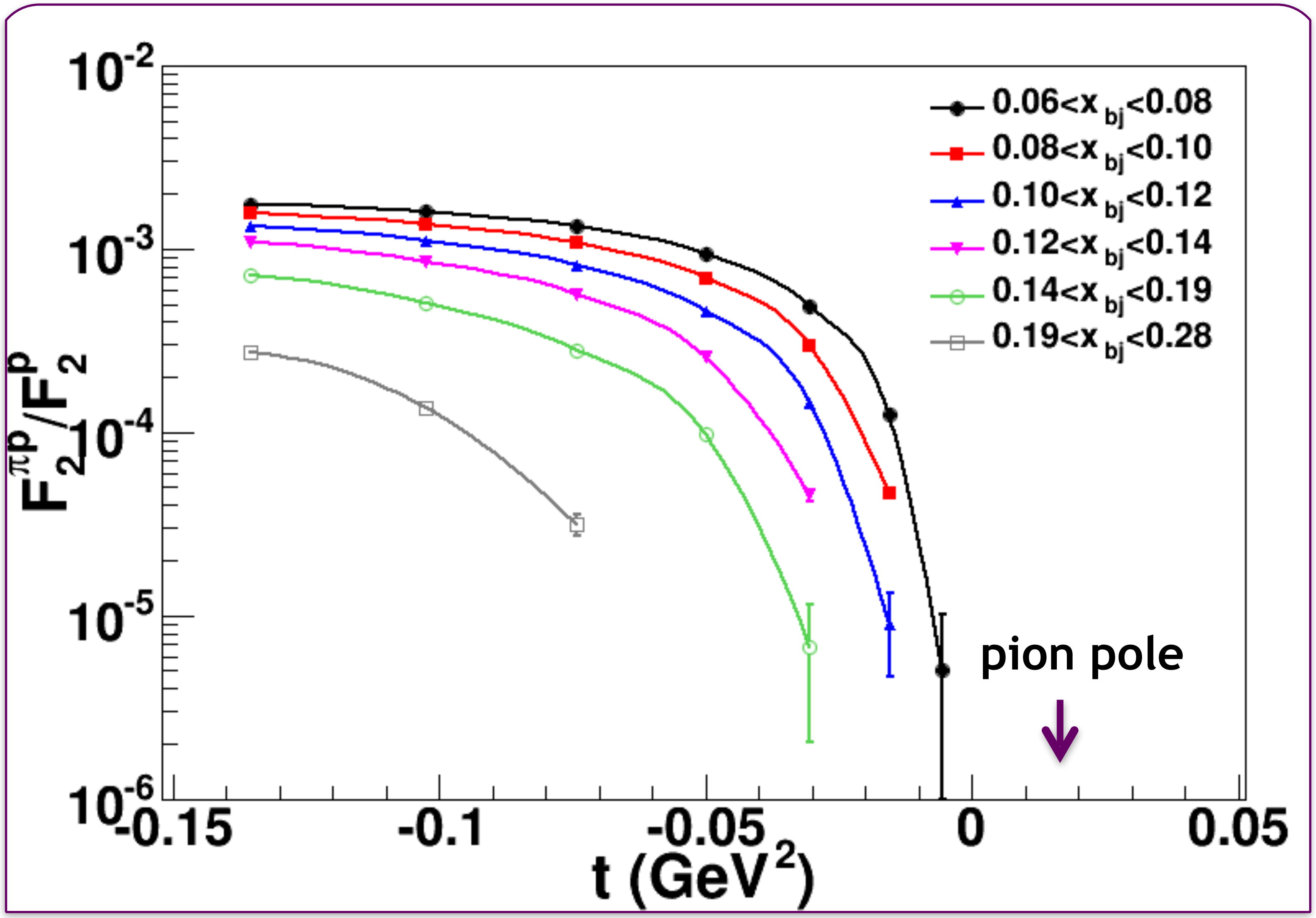
some kinematic limits:
- 150 < k < 400 MeV/c corresponds to z < ~0.2
- Also, x < z
- Low x, high W at 11 GeV means Q^2 ~2 GeV^2

The TDIS experiment will also extract the pion structure function.

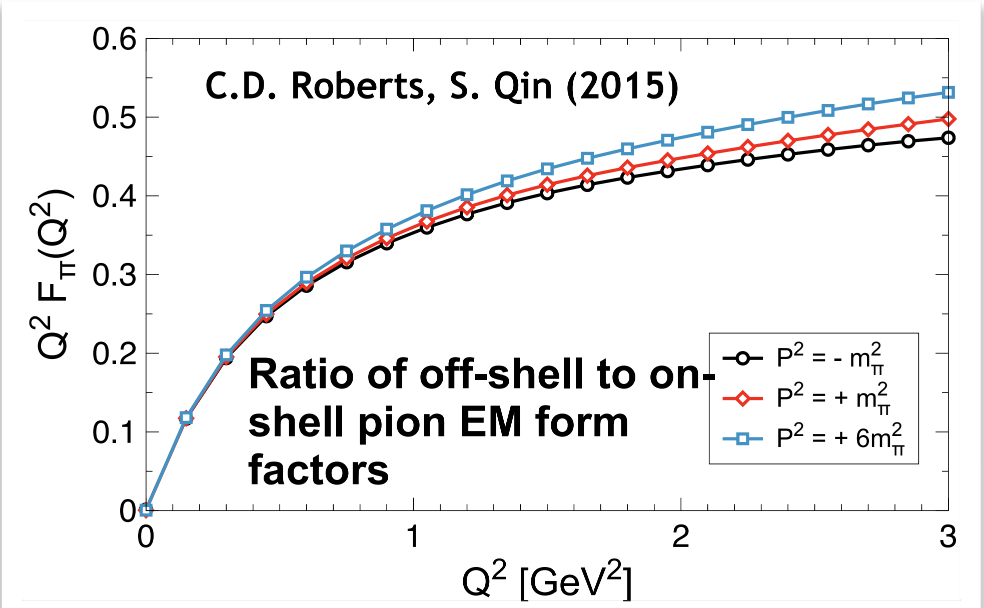
It requires extrapolation to the pion pole

low momentum protons helps cover a range of low |t|

- Low t extrapolation to the pion pole



virtuality-independent form factor implies virtuality-independent pion structure function



The uncertainty in extrapolation to the pion pole within ~5% at JLab kinematics

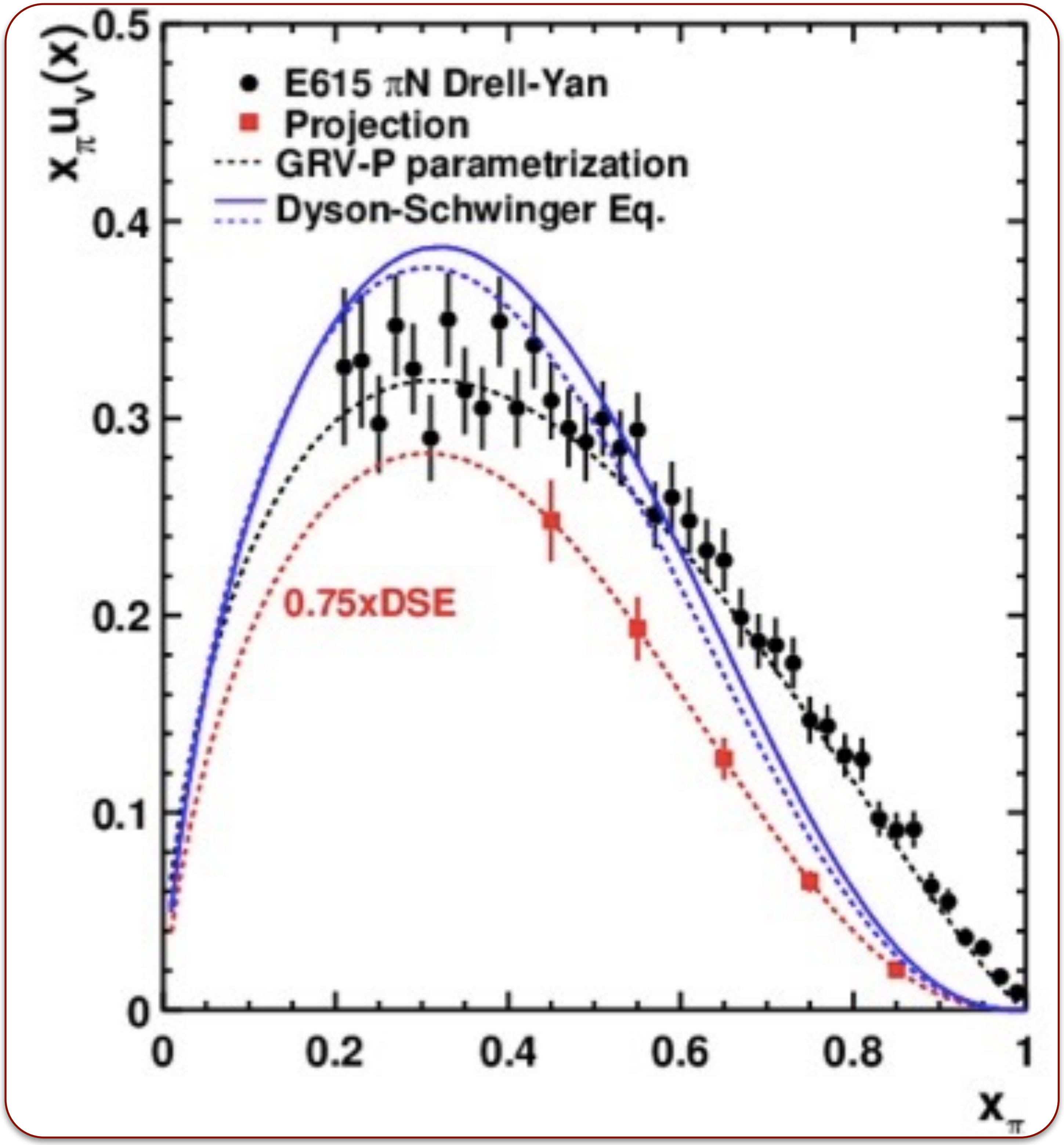
The TDIS experiment will provide a unique extraction of the pion structure function at large x.

Large x behavior will help verify resummed Drell-Yan results;

Large x, low Q complementary to HERA low x, high Q

Will also measure (π^-, π^0) difference - look for isospin dependence

C1 conditionally approved for 27 PAC days with A- rating



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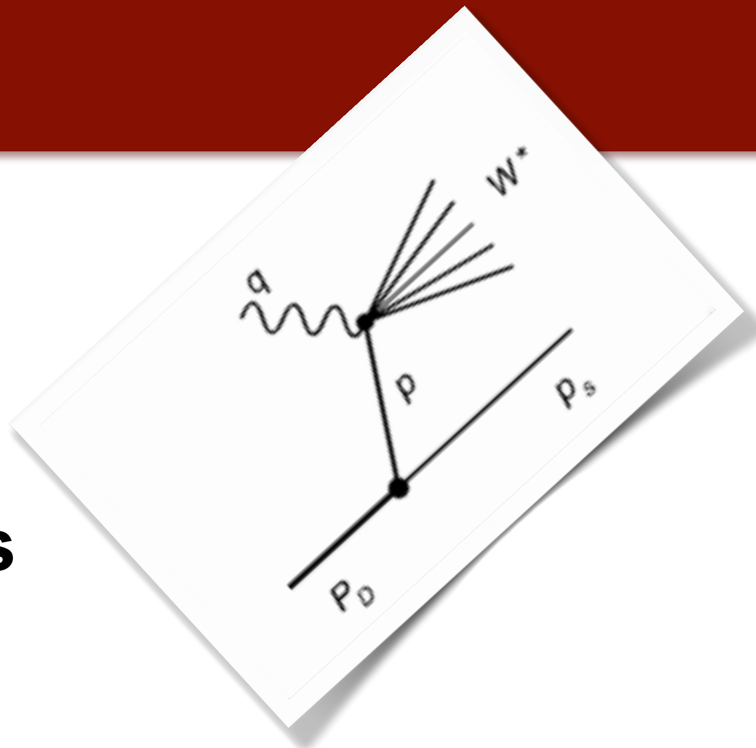
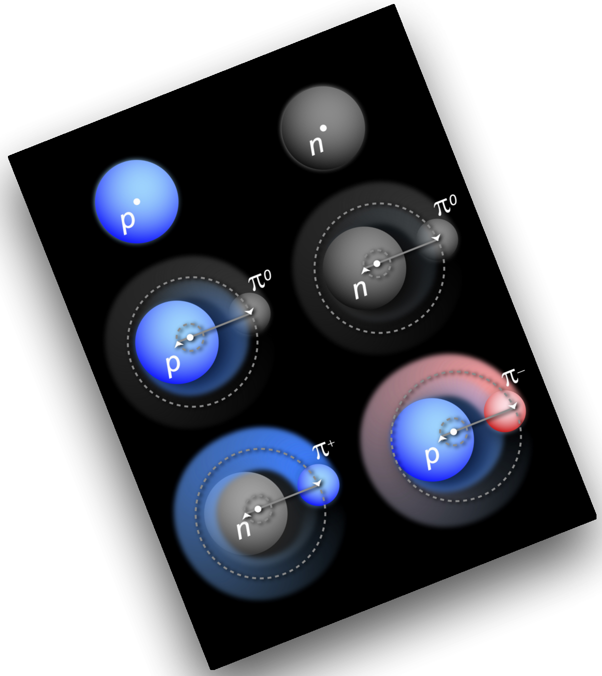
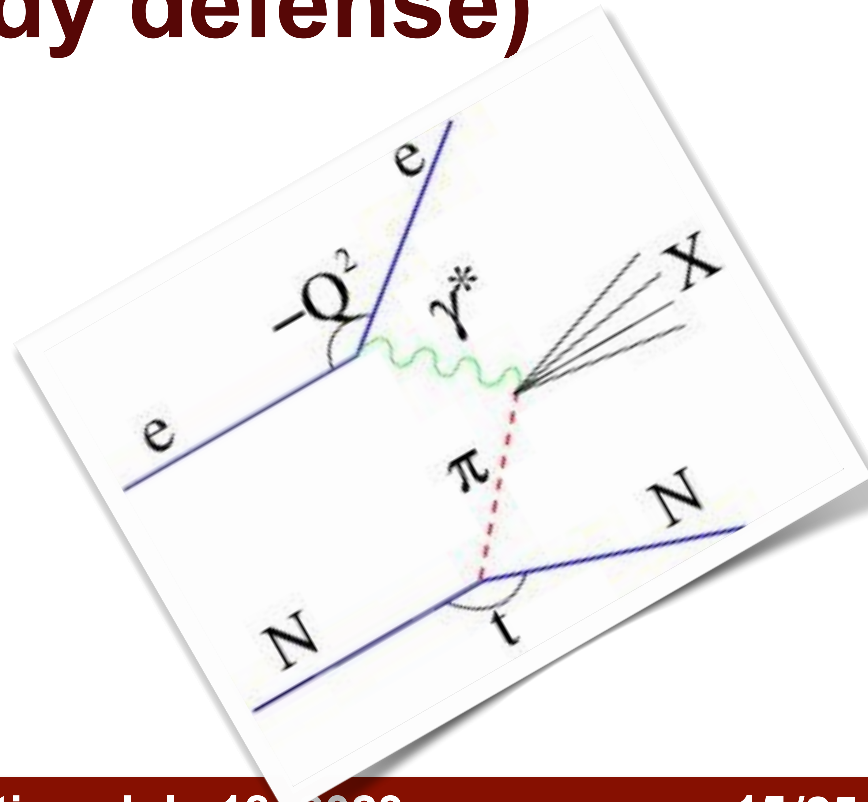






C12-15-005
The Tagged Deep Inelastic Scattering (TDIS) Experiment

Goal:

A direct measurement of the mesonic content of the nucleon and a unique extraction of the **pion's F_2 structure functions**, by scattering from a **virtual pion target**, accessed via **spectator tagging**.

Spokespersons: D. Dutta, N. Liyanage, C. Keppel, P. King, R, Montgomery, B. Wojtsekhowski

C1 conditionally approved with A- rating for **27 PAC days**

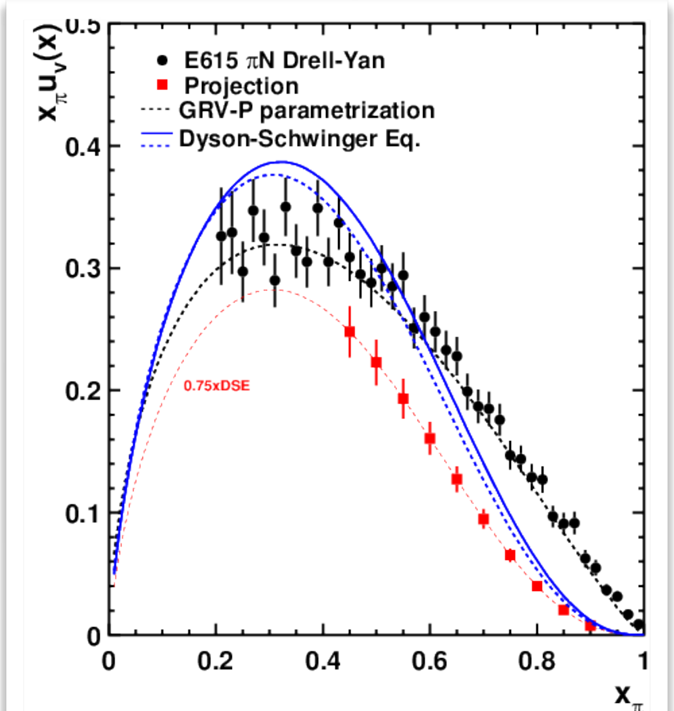
Motivations:

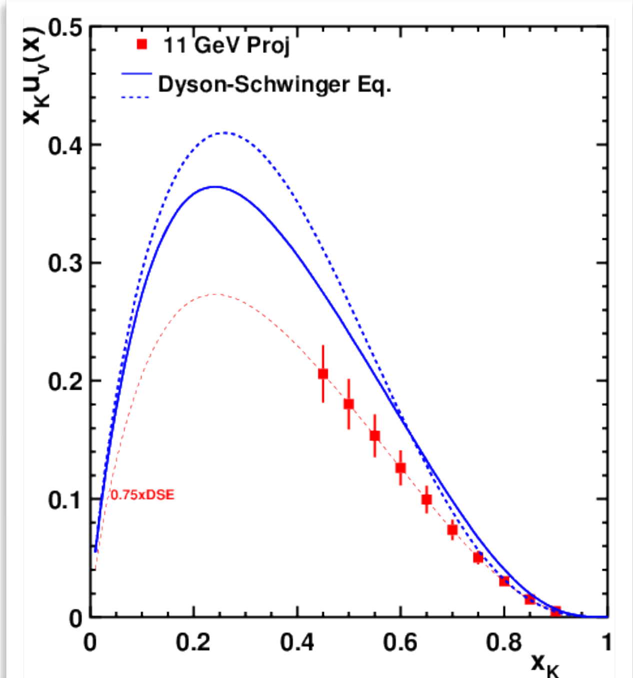
There is ample evidence that nucleons have pionic content in them, but no direct measurements.

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.
But, very little data due to the lack of "meson targets".

TDIS will use spectator tagging - a well established technique- to tag the "meson cloud" of the nucleon.

TDIS is a pioneering experiment but the proposed technique to extract meson structure function is an essential first step for future experiments at the EIC & 22 GeV JLab.

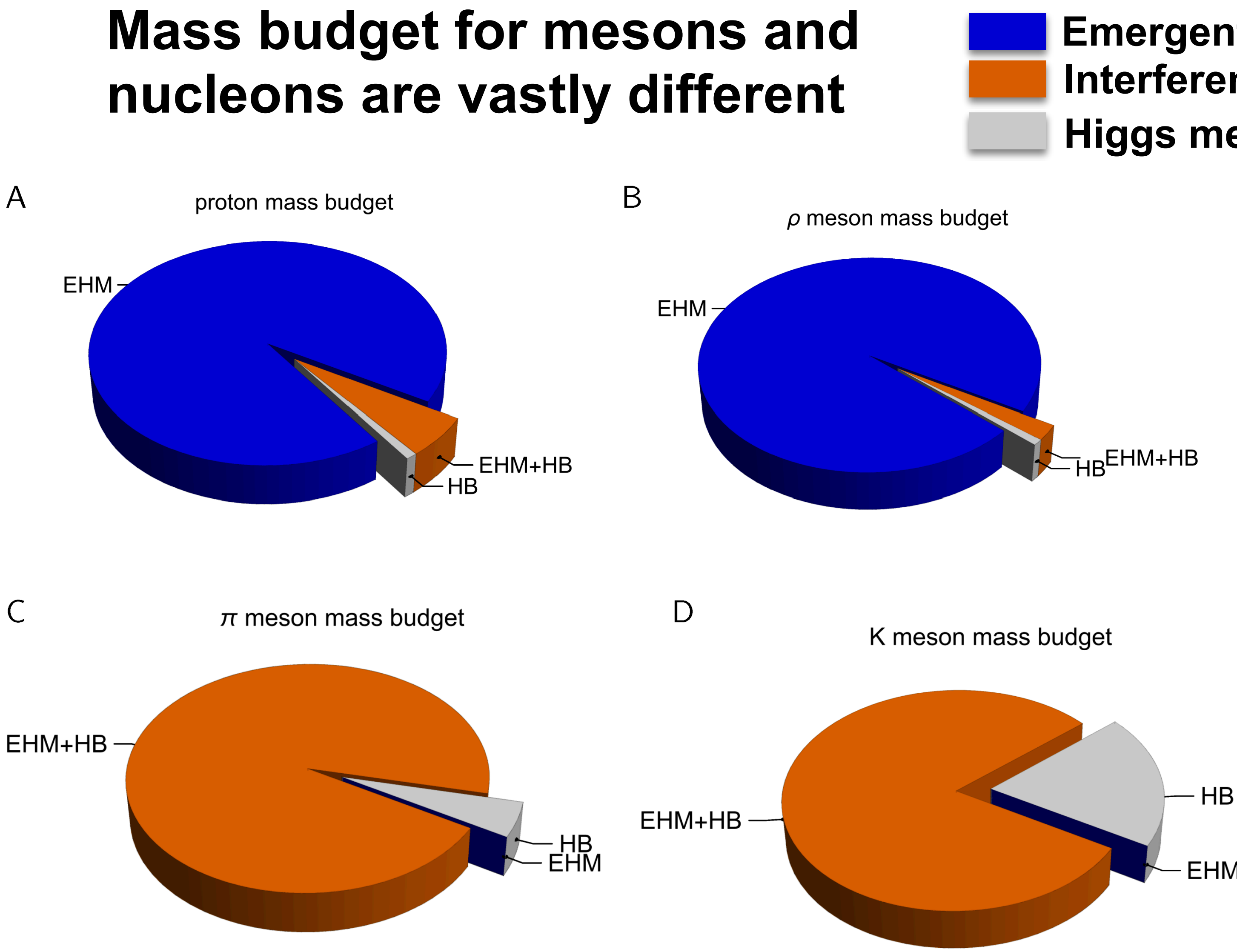




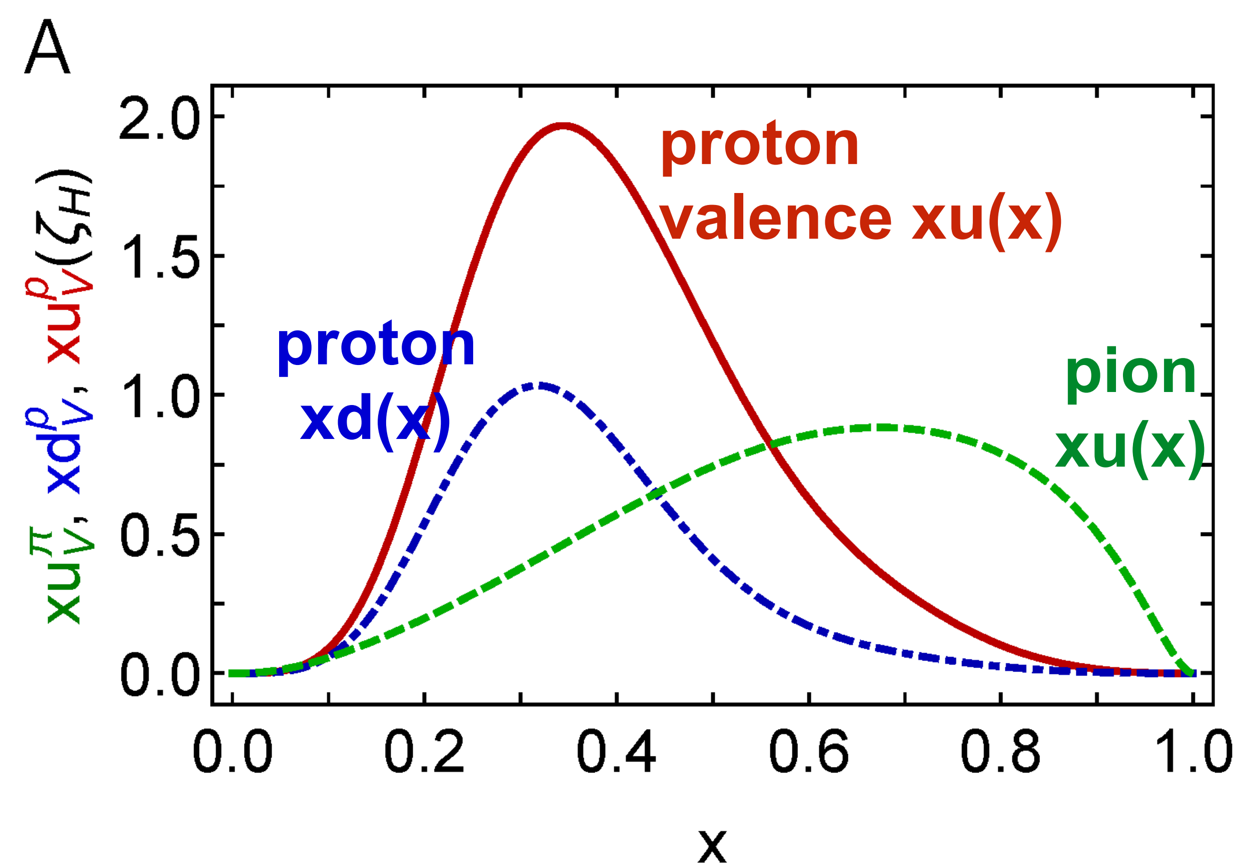
Since approval, there has been a surge of interest in both the technique and the science goal

Significant progress in understanding meson structure through emergent hadron mass - over 50 publications with more than 1200 citations (including LRP white paper & EIC yellow report).

Mass budget for mesons and nucleons are vastly different



M. Ding, C.D. Roberts & S.M. Schmidt, *Particles* 6, 57 (2023)



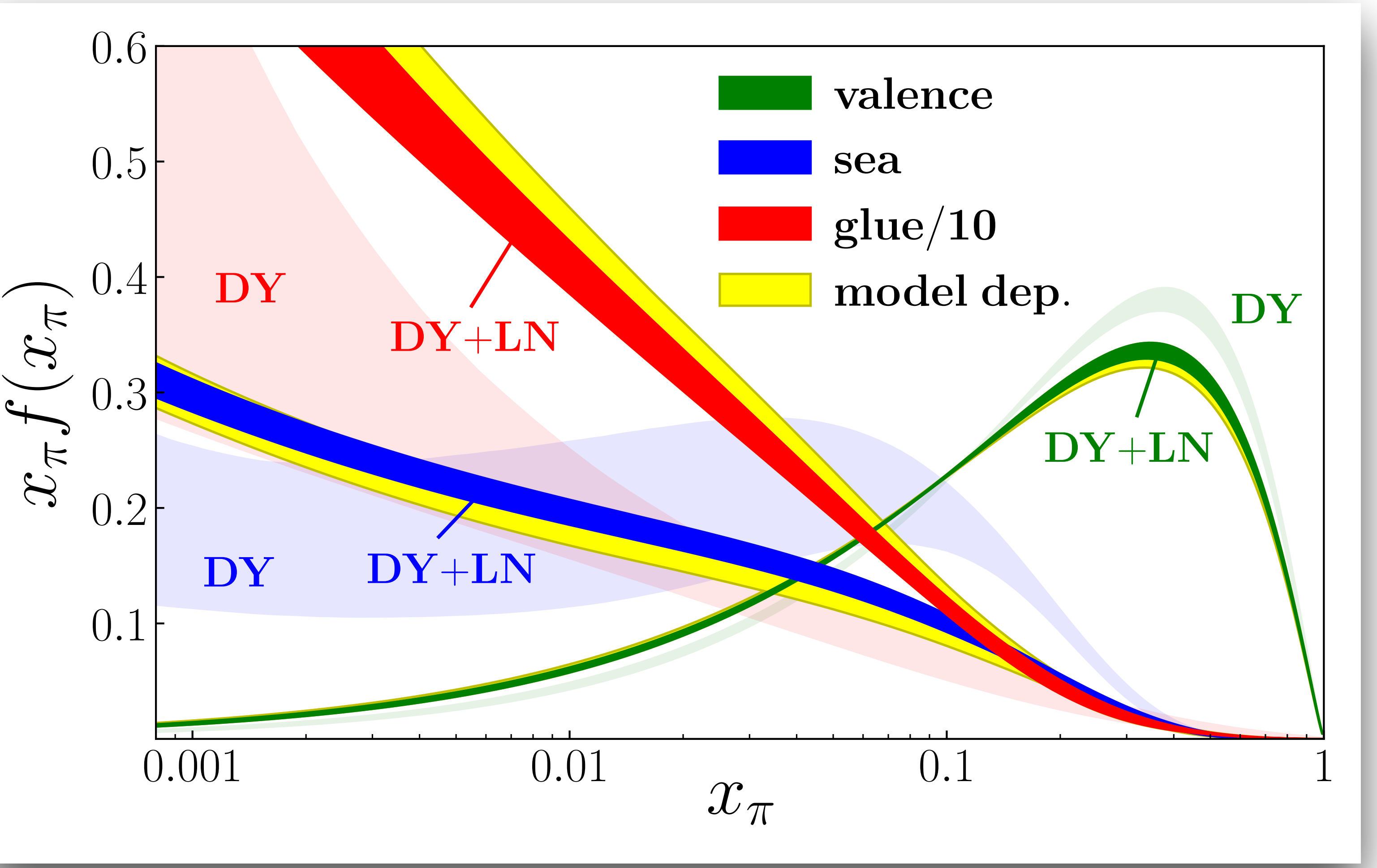
pion/proton valence quark distributions are very different

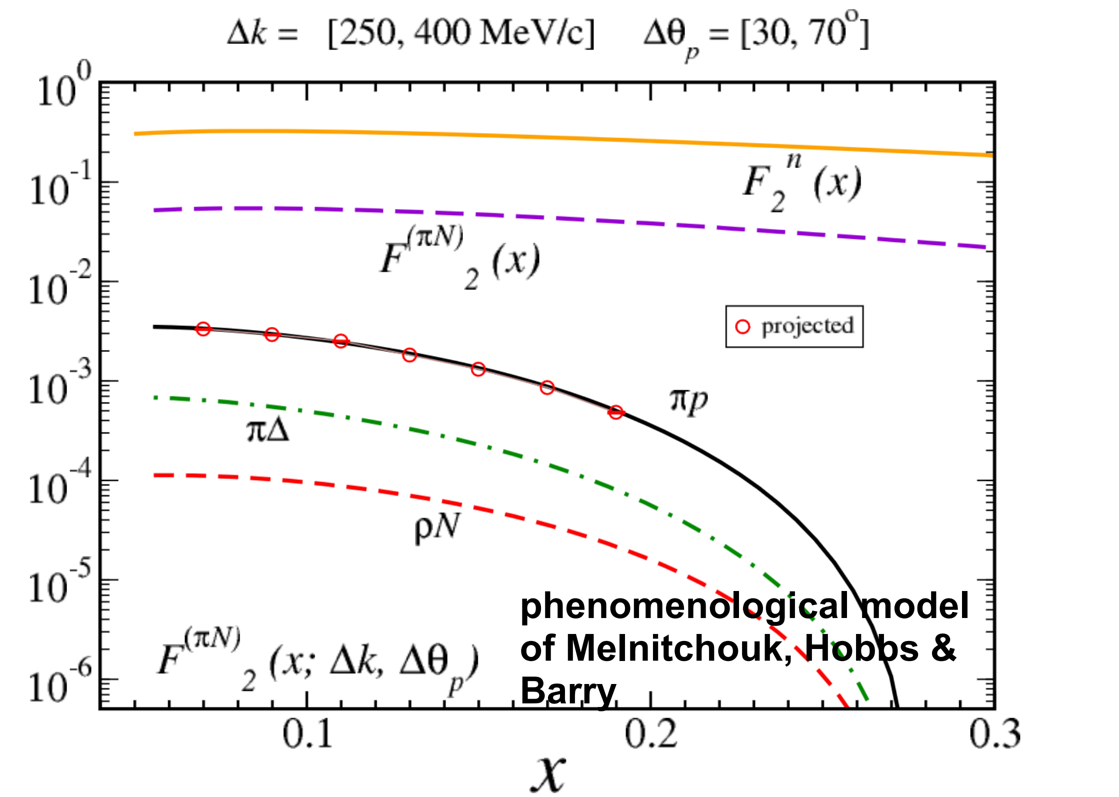
difference between meson PDFs: direct information on emergent hadron mass

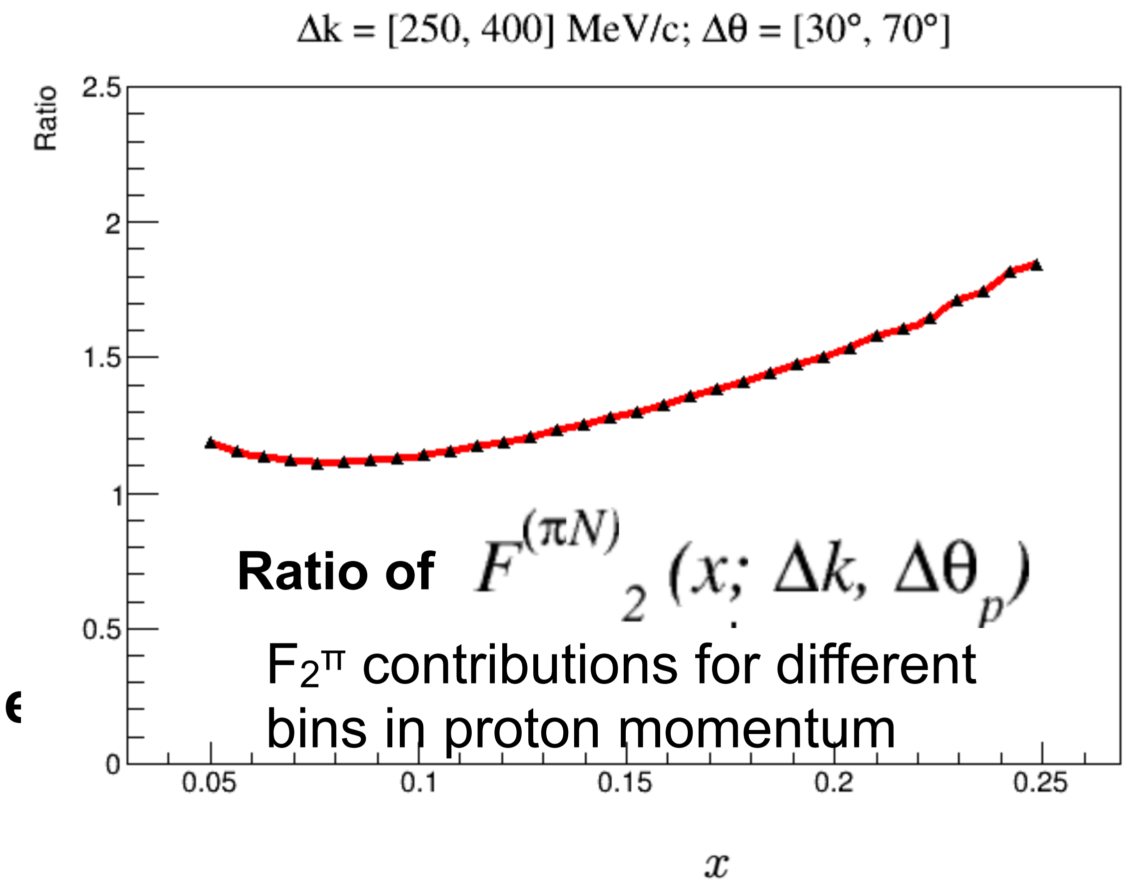
A global QCD analysis including the leading neutron HERA data has been completed

Peak of valence quarks momentum fraction shifted to smaller x, than that inferred from Drell-Yan data alone

P. C. Barry, N. Sato, W. Melnitchouk, and C-R. Ji, Phys. Rev. Lett. 121, 152001 (2018)





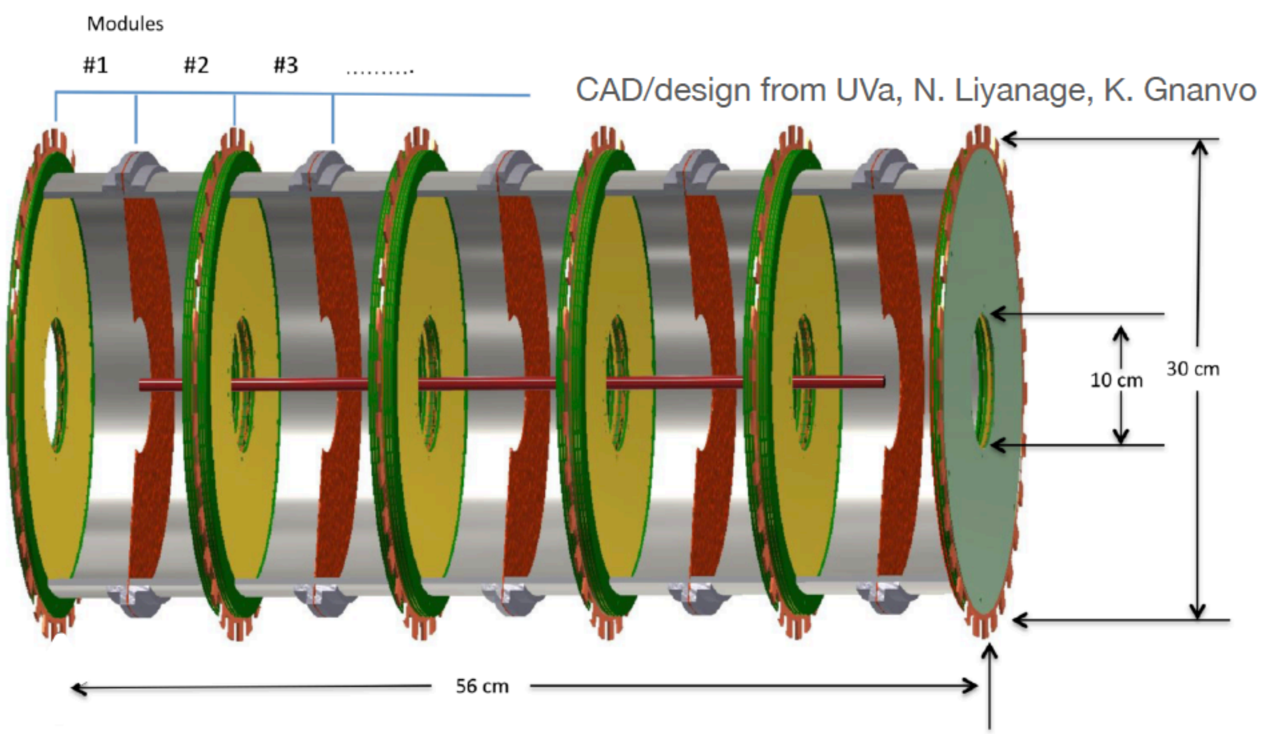


Rate of TDIS signal events is expected to be larger and less sensitive to the pion flux factor; will help reduce the beam current to improve background and tracking.

plots credit: P. Barry & C. Ayerbe Gayoso

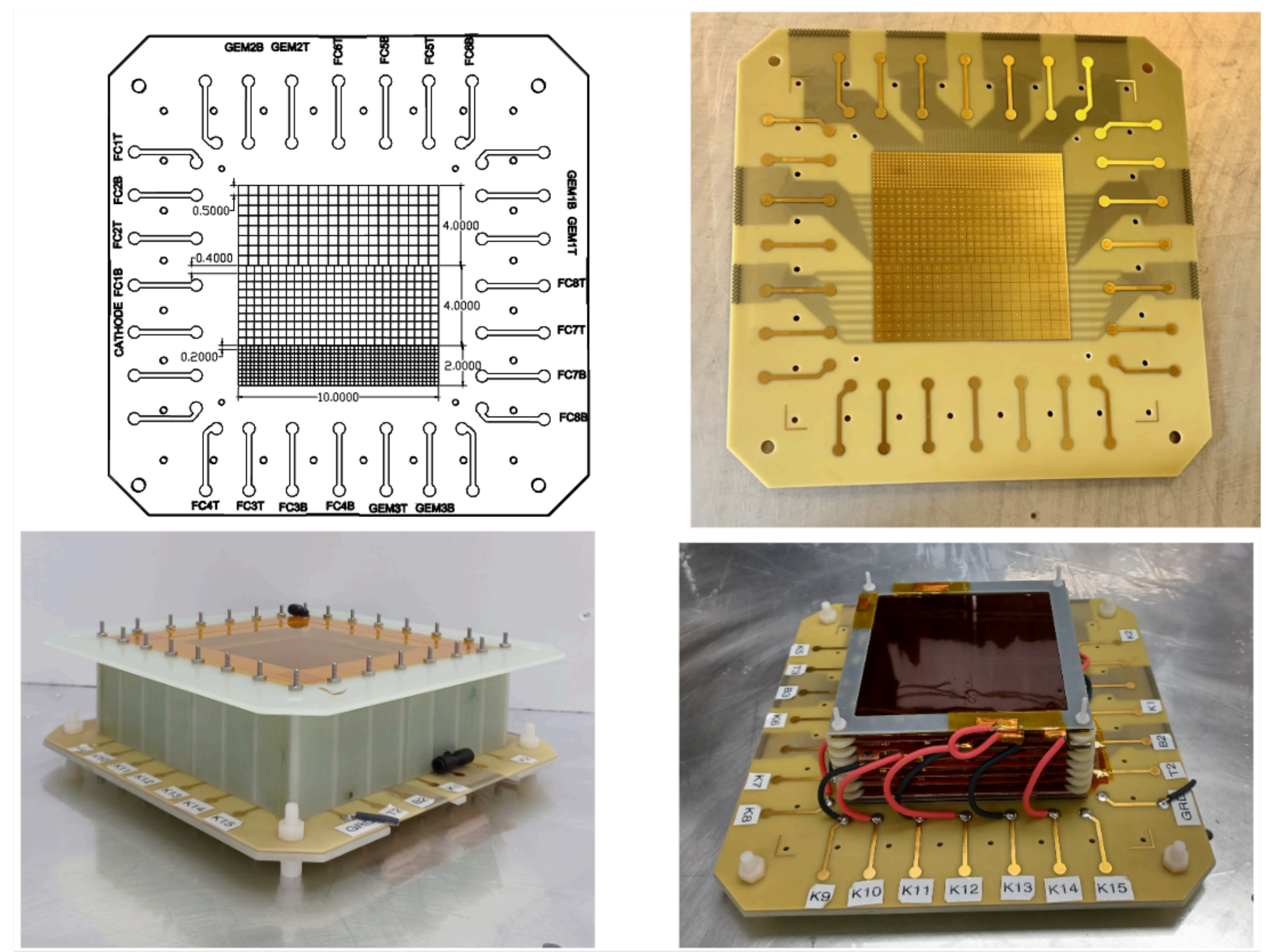
We have converged on a design for the recoil detector- a multi-Time Projection Chamber (mTPC)

High rate multiple time projection chamber (mTPC) to tag recoiling/spectator hadrons



Tracking, dE/dx

A square prototype has been constructed



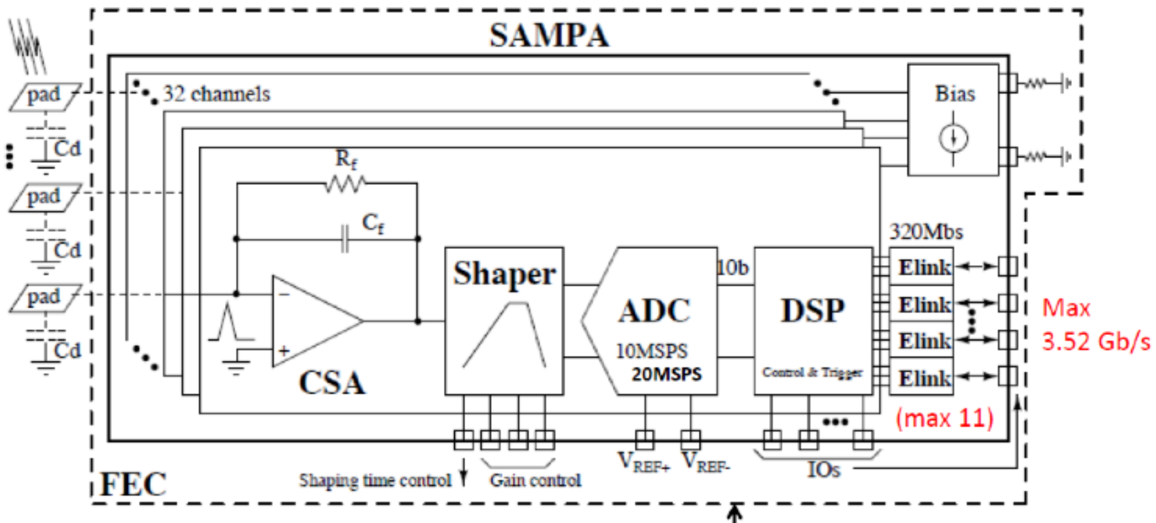
- **Each TPC unit of the composite mTPC will be exposed to a fraction of the background rate.**
- **The drift field is parallel to the magnetic field, leading to reduced drift times and significantly simplified track reconstruction.**

Testing is currently underway at UVa and JLab to validate the time projection field cage and the readout configuration.

Target: 40 cm long, 25 um wall thickness Kapton straw at room temperature and 3 atm. pressure.

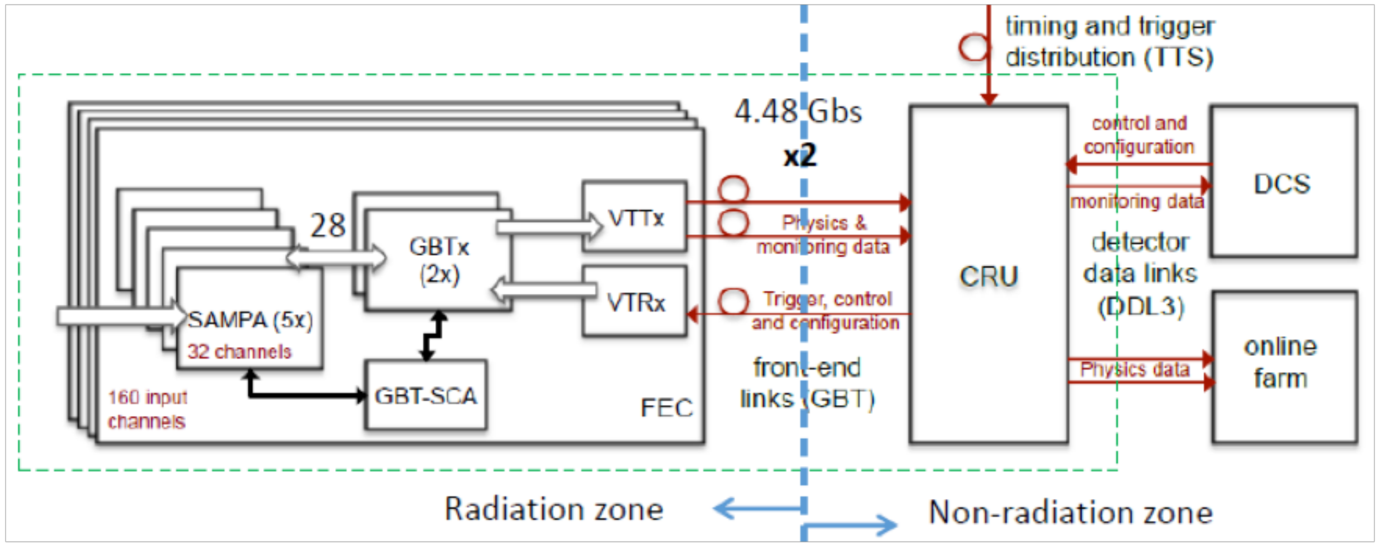
A cylindrical prototype will be built after validation.

Readout for mTPC has been developed using the SAMPA chip

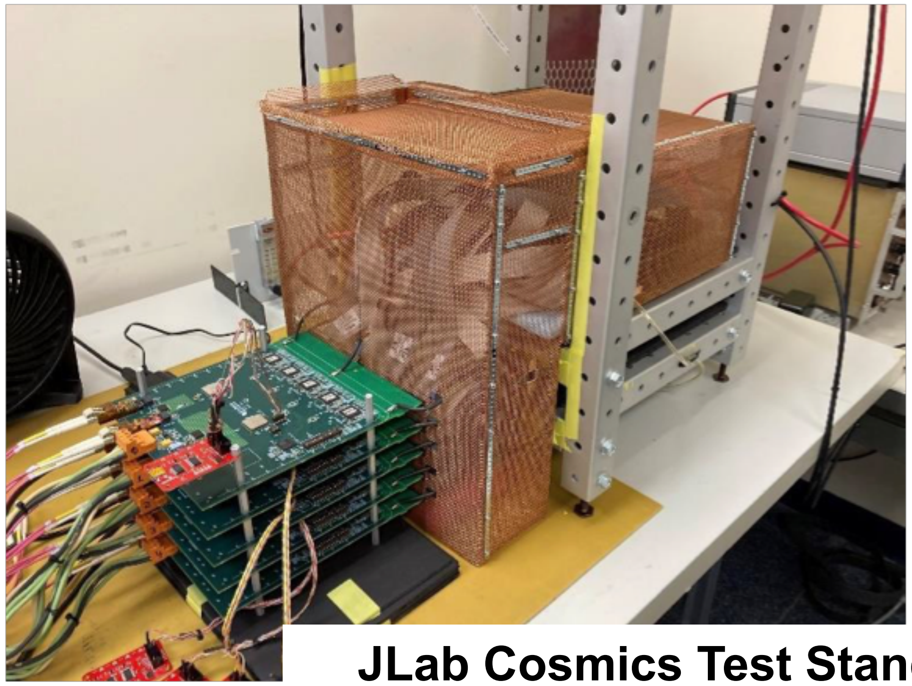


Raw data rate (10MHz) = 32ch x 10b x 10M/s = 3.2Gb/s
(20MHz) = 6.4Gb/s

DSP mode (zero suppression)



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 Cosmics Test Stand
FEC, coupled to GEM detector

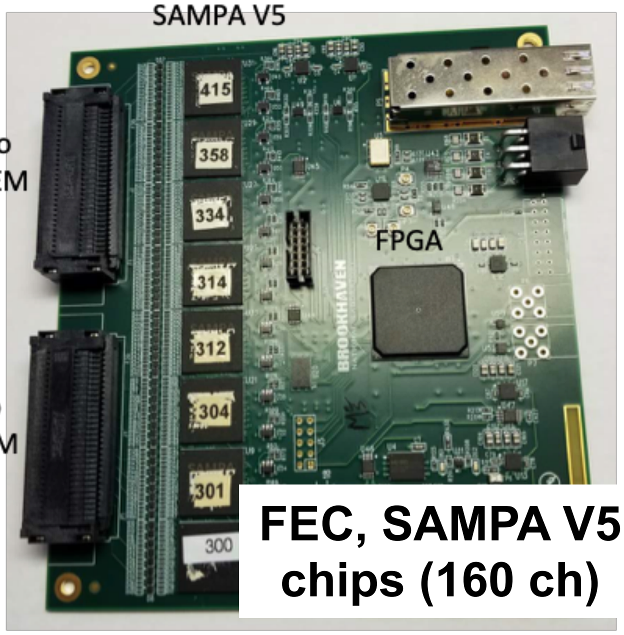
SAMPA V5 - 80 ns shaping time

SAMPA can be used in streaming mode or triggered mode

mTPC prototype will be testing using the sPHENIX TPC Front-end card (FEC)

SAMPA V5

to GEM

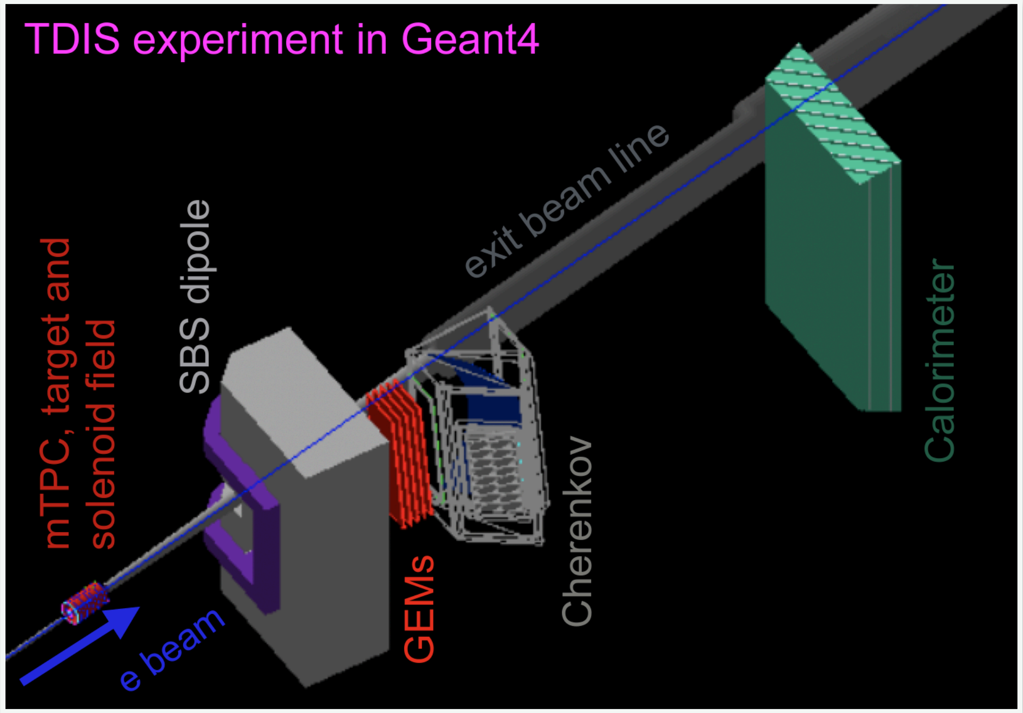


to GEM

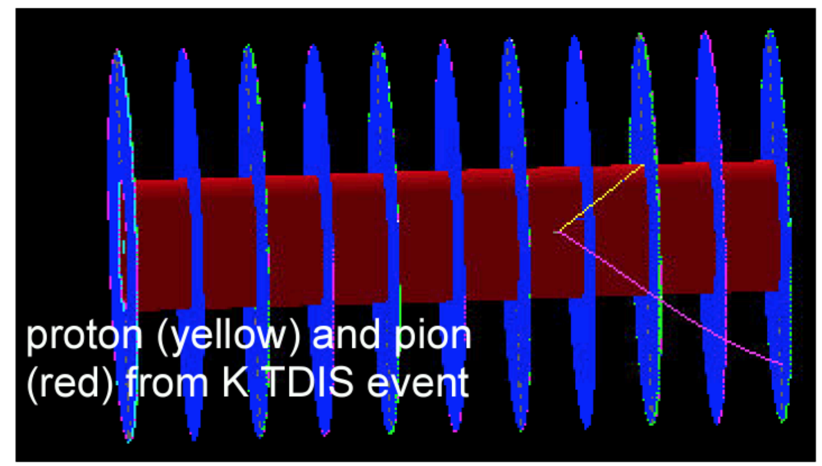
FEC, SAMPA V5 chips (160 ch)

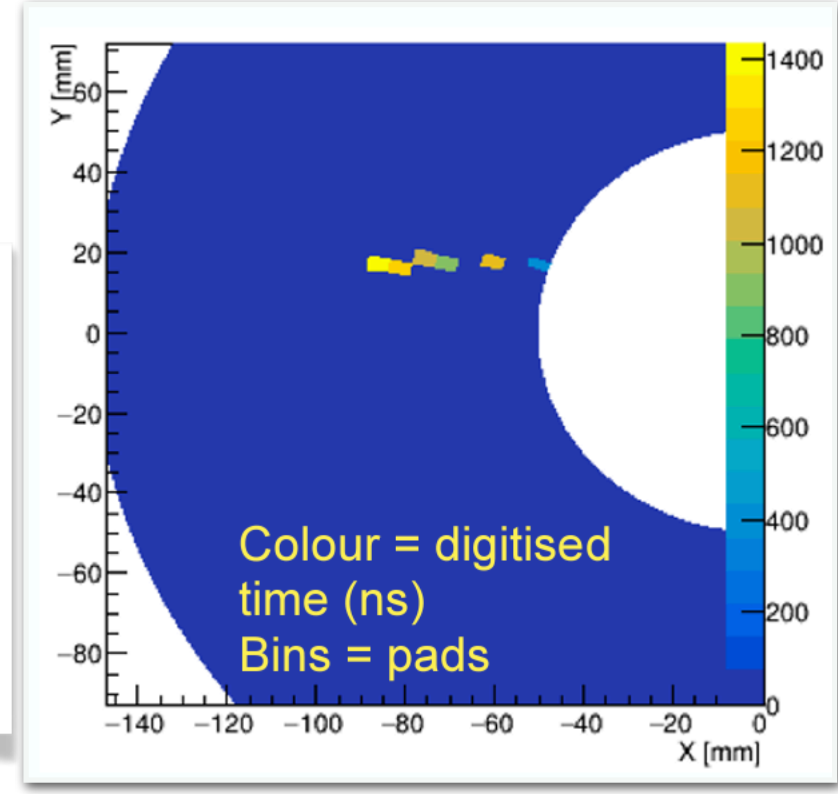
Image credit
E. Jastrzembski JLab

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

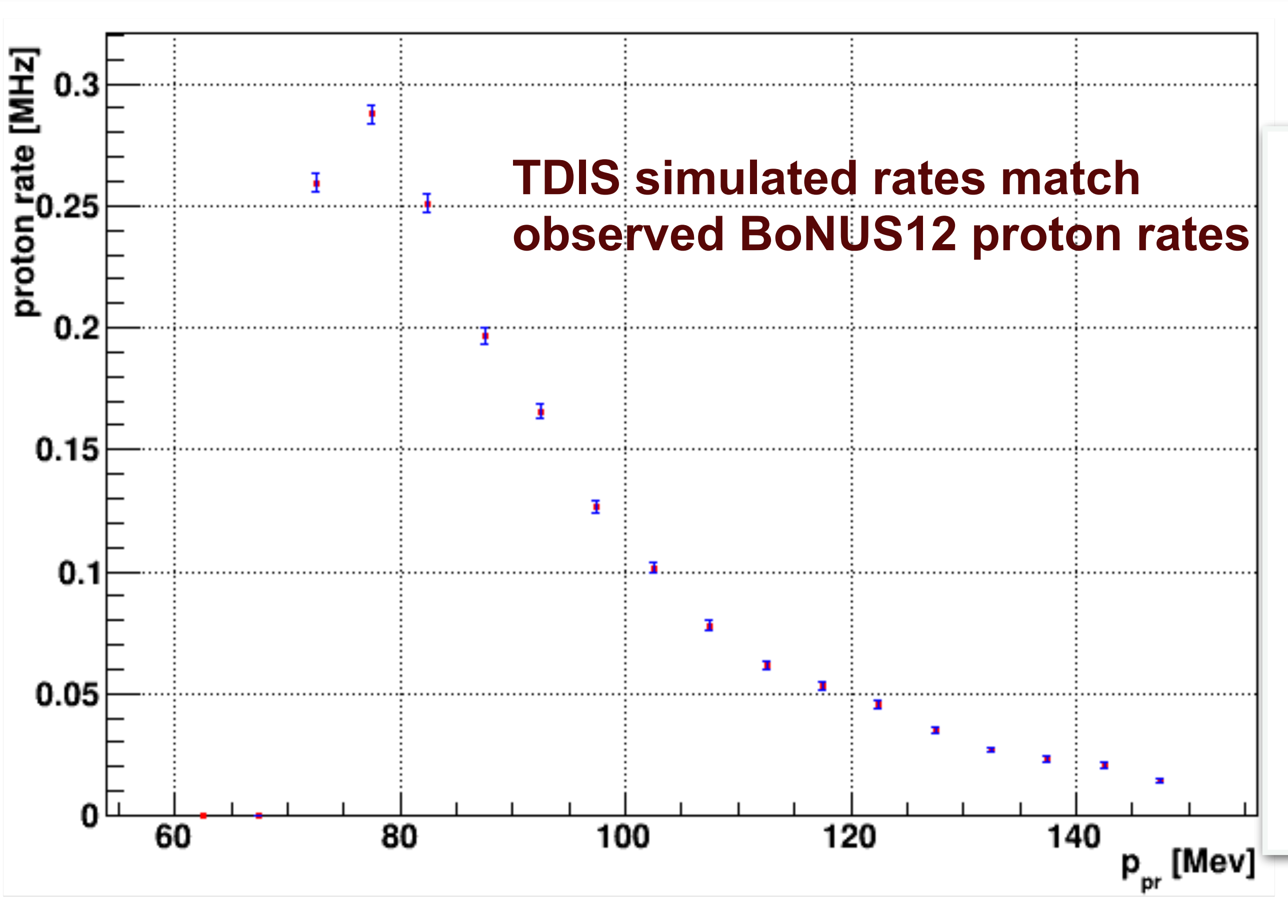


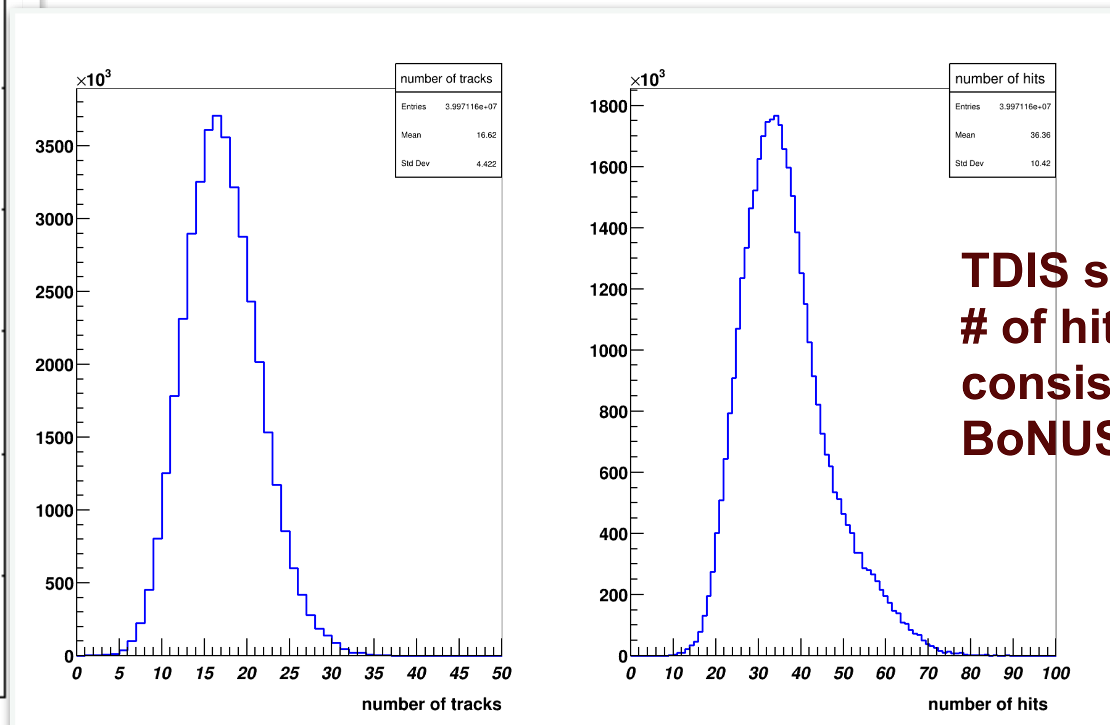
mTPC simulated with Magboltz/Garfield





images credit: R. Montgomery



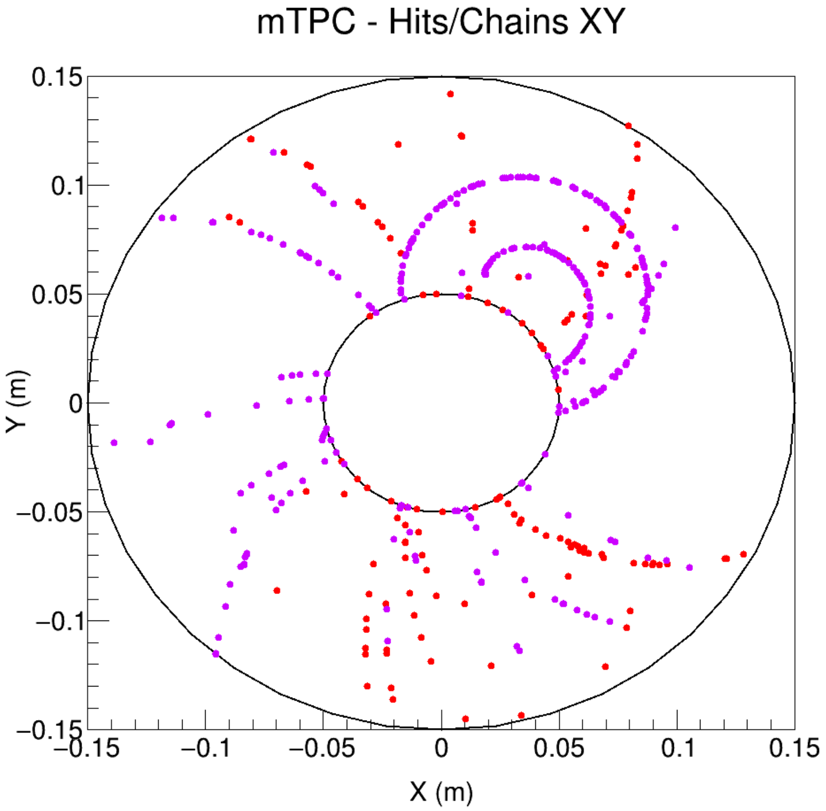


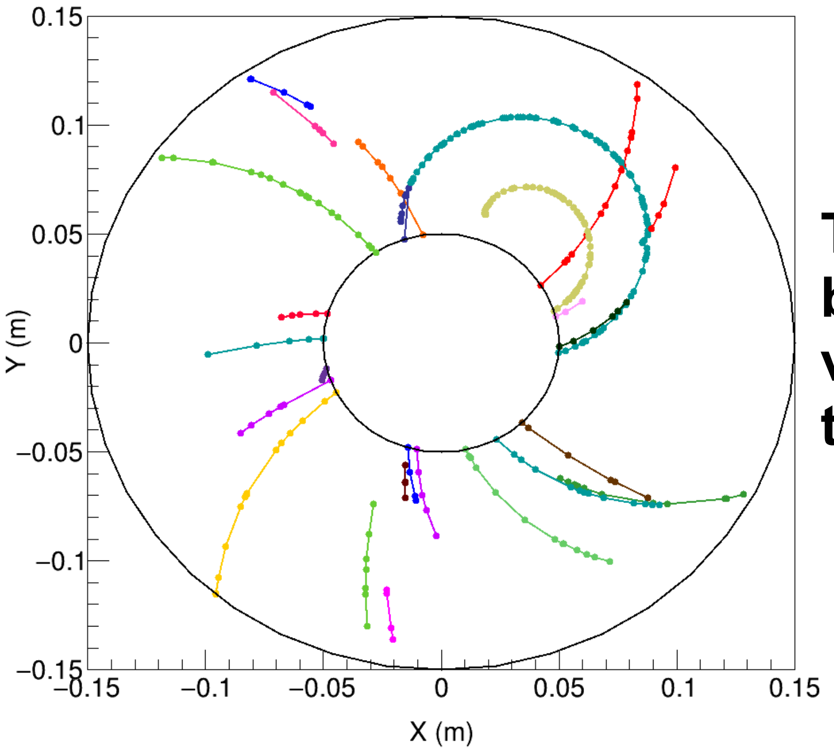
TDIS simulated # of hits & tracks consistent with BoNUS12

plots credit: A. Nadeeshani

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

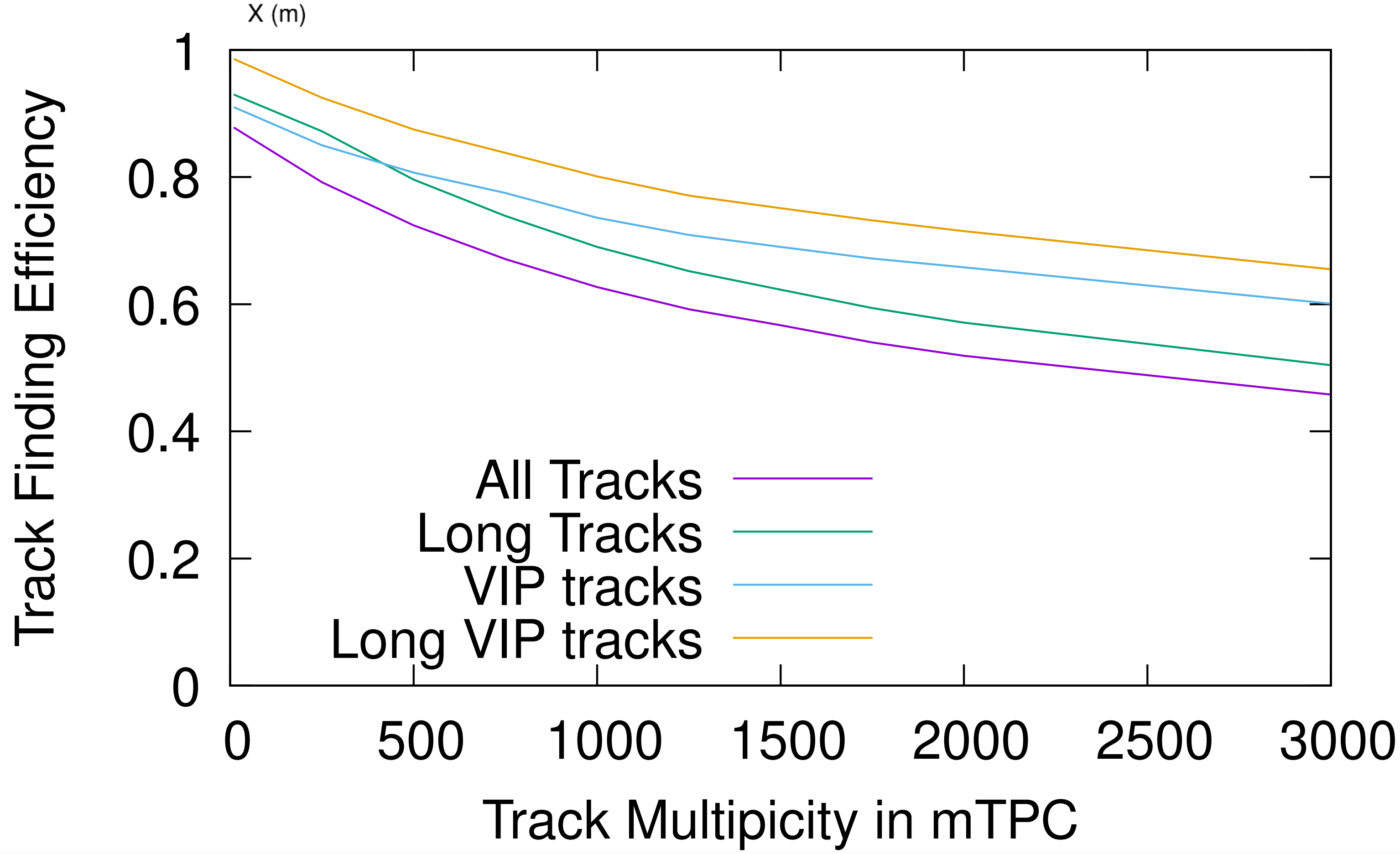
Key initiative for lifting the C1 condition and full approval.





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

A new hadron blind gas Cherenkov detector is being designed by new collaborators from U. of Tennessee

Penny Duran (UofA), Burcu Duran (UT), Nadia Fomin (UT)

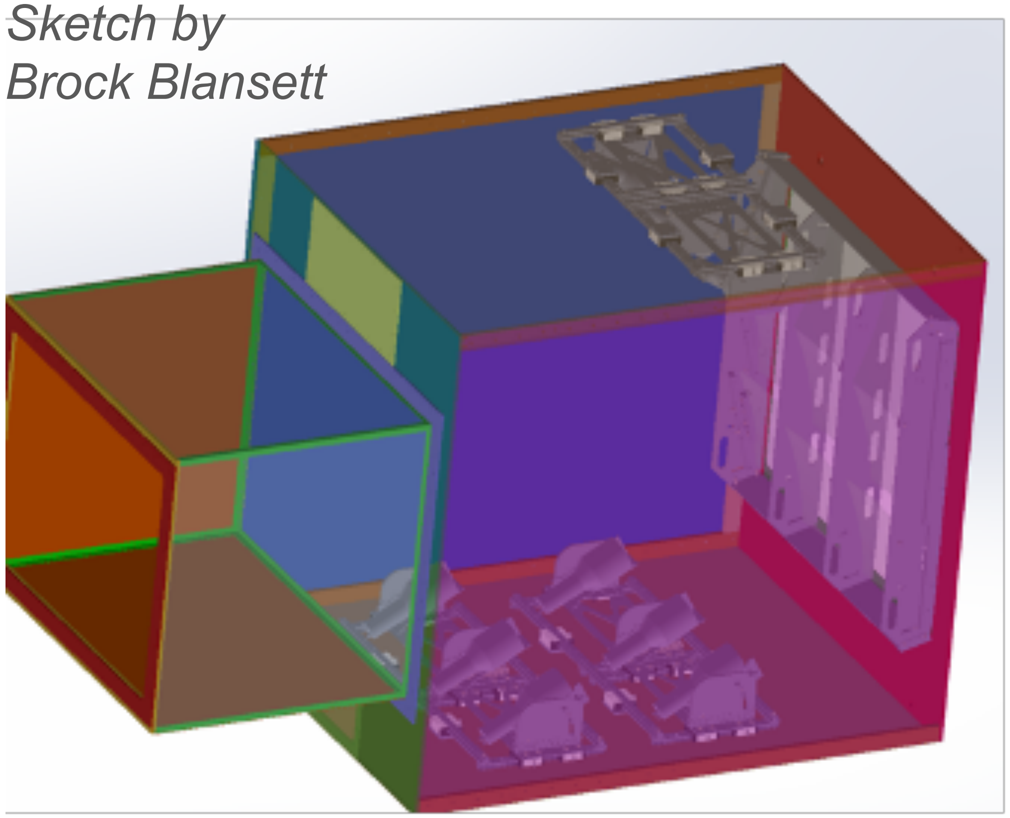
- Requirements: discrimination between electrons and pions in the 2 GeV – 11 GeV range
- UT proposes a threshold Cherenkov detector based on SHMS NGC

4 meters long

Neon or Argon/Neon at 1atm

9 PE at 11 GeV/c

Sketch by Brock Blansett

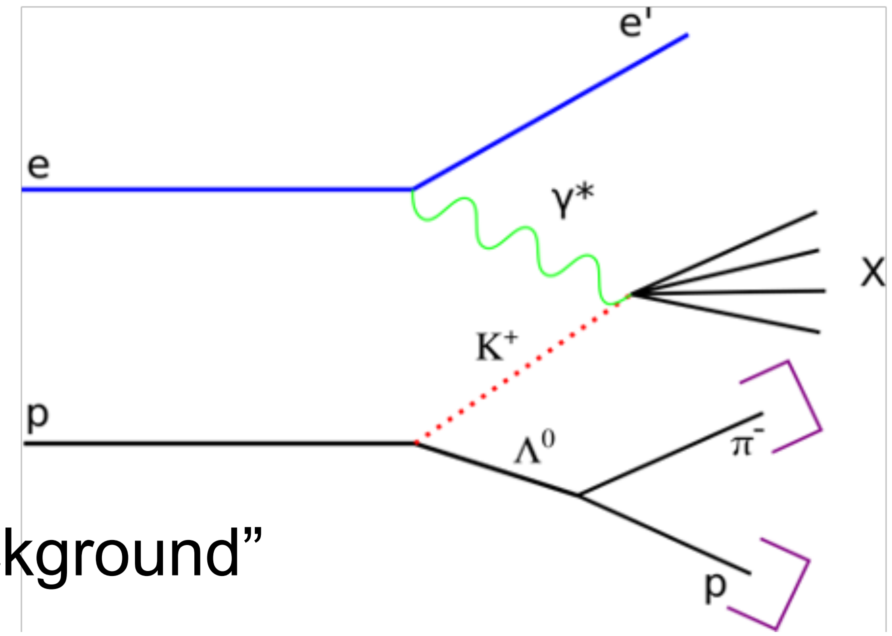


The LAC has been refurbished and is being tested and a FPGA based electron trigger will be developed

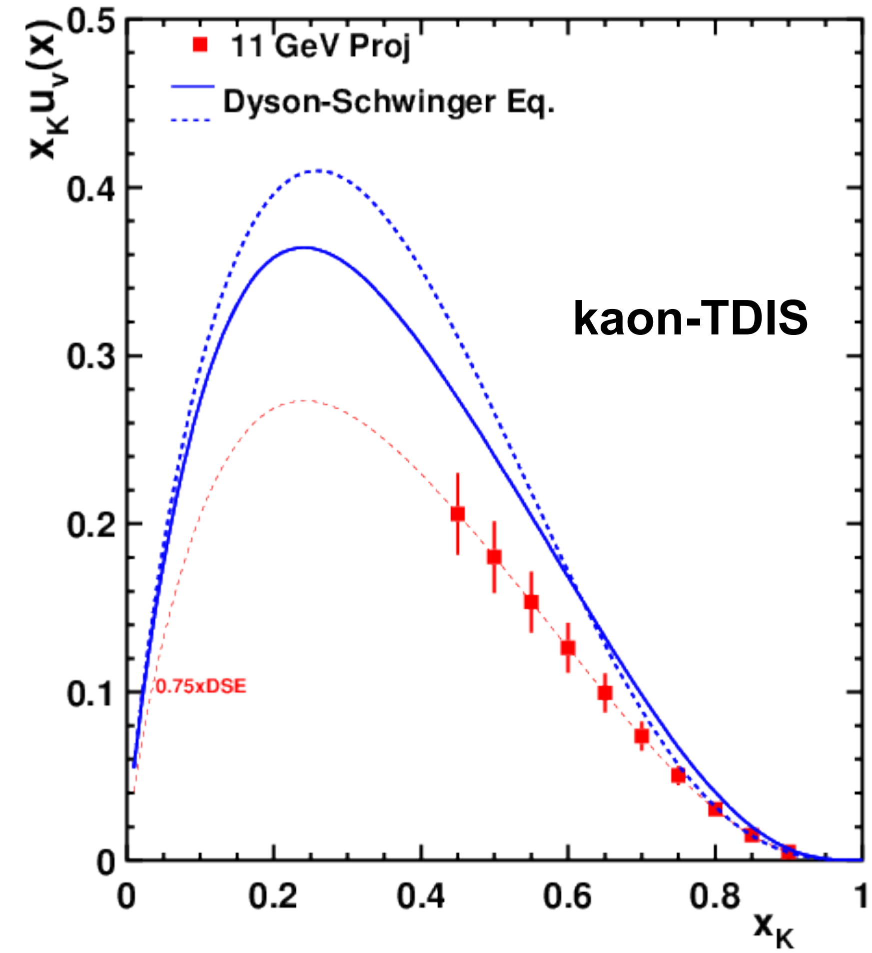
Two run group experiments (kaon TDIS & nTDIS) have been endorsed

C12-15-006A
Measurement of Kaon Structure Function through Tagged Deep Inelastic Scattering(TDIS)

Spokespersons:
T. Horn, R. Montgomery & K. Park

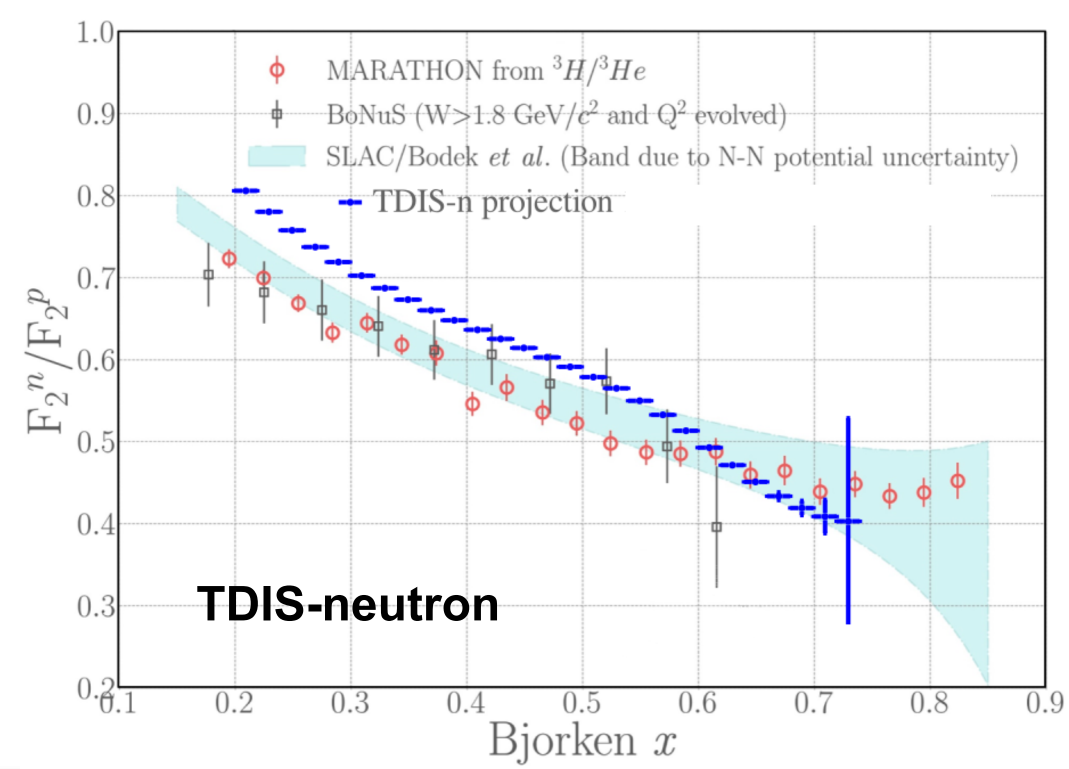


Kaon TDIS events are “background” for pion TDIS



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

Spokespersons:
J. Arrington, C. Ayerbe Gayoso, E. Fuchey, C. Keppel, S. Li, R. Montgomery, A. Tadepalli

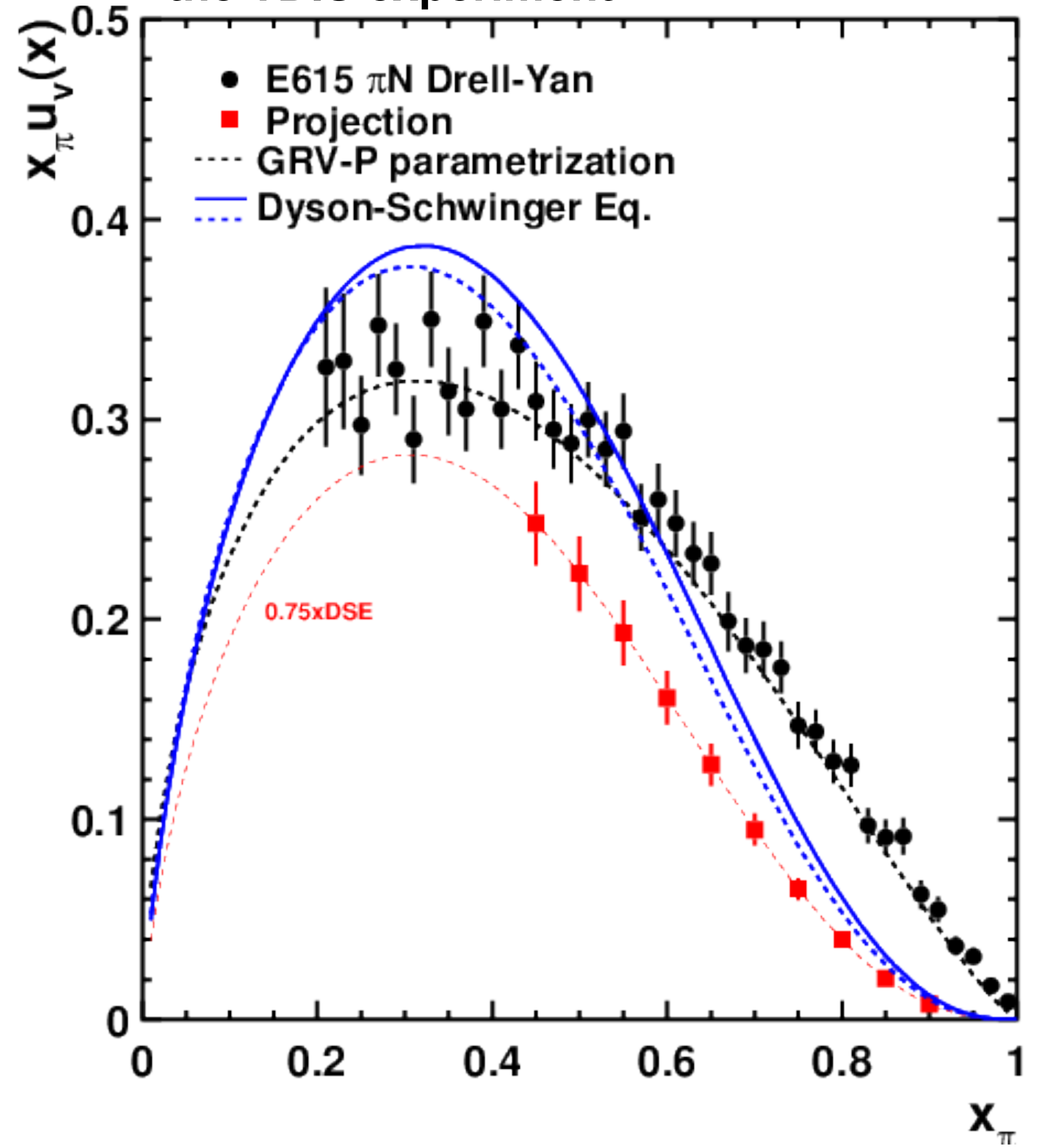


Active and strong collaboration preparing to remove the C1 condition and be fully approval.

TDIS run group: 12 Spokespersons
20 institutions (new collaborators from U. Tenn.)
Hall A collaboration & SBS collaboration
Postdocs: A. Nadeeshani (MSU), B. Duran (UTenn)
Prospective Grad Students: MSU, OU, UG, U. Tenn & UVa

mTPC: N. Liyanage H. Nguyen (UVa)
mTPC prototype: A. Nadeeshani (MSU), H. Nguyen (UVa), E. Christy (JLab)
Tracking: C. Ayerbe Gayoso (W&M), A. Nadeeshani (MSU), A. Tadepalli, S. Wood (JLab)
Streaming DAQ: E. Jastrzembski (JLab), M. Bregant (Sao Paolo)
Simulations: C. Ayerbe Gayoso, E. Fuchey (W&M), R. Montgomery (U. Glasgow), A. Tadepalli (JLab)
LAC + electron trigger: S. Malace (JLab)
Cherenkov: N. Fomin, B. Duran (UTenn)
Target: D. Dutta, J. Jimenez-Rojas (MSU)

Projected pion structure function for the TDIS experiment



Beam time request increased from 27 to 60 days

BoNUS12 experience suggests possible lower recoil detector efficiency ⇒ **^{2}H runtime increased from 10 to 20 days**
^{1}H runtime increased from 10 to 20 days

3 new complex detectors ⇒ **Engineering runtime increased from 2 to 15 days**
5 days for mTPC calibration

A dramatic surge of interest in the physics goals prompts us to seek an A rating

Summary

1. Tagged DIS: Spectator tagging, provide new tools to access to the mesonic content of the nucleon structure and the meson structure function.

2. The TDIS experiments at JLab take advantage of these new avenue using the 11 GeV beam, it will be a pioneering experiment. It will help demonstrate the feasibility of the technique.

3. There has been a significant increase in the physics of the TDIS experiment and technical progress toward putting the experiment together.

4. Based on this we request a A rating and look forward to meeting the requirements of the technical review for lifting the C1 condition.

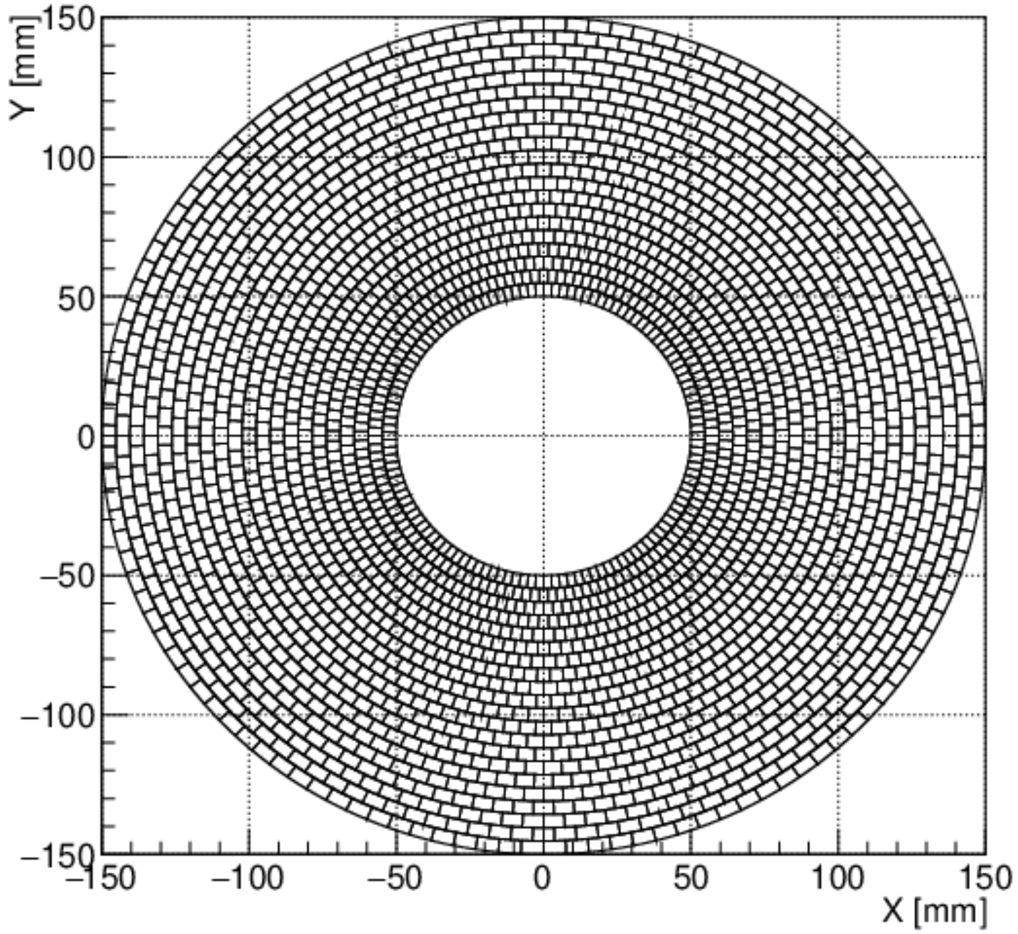
This work is supported by US Dept. Of Energy under contract # DE-FG02-07ER41528

Backup Slides

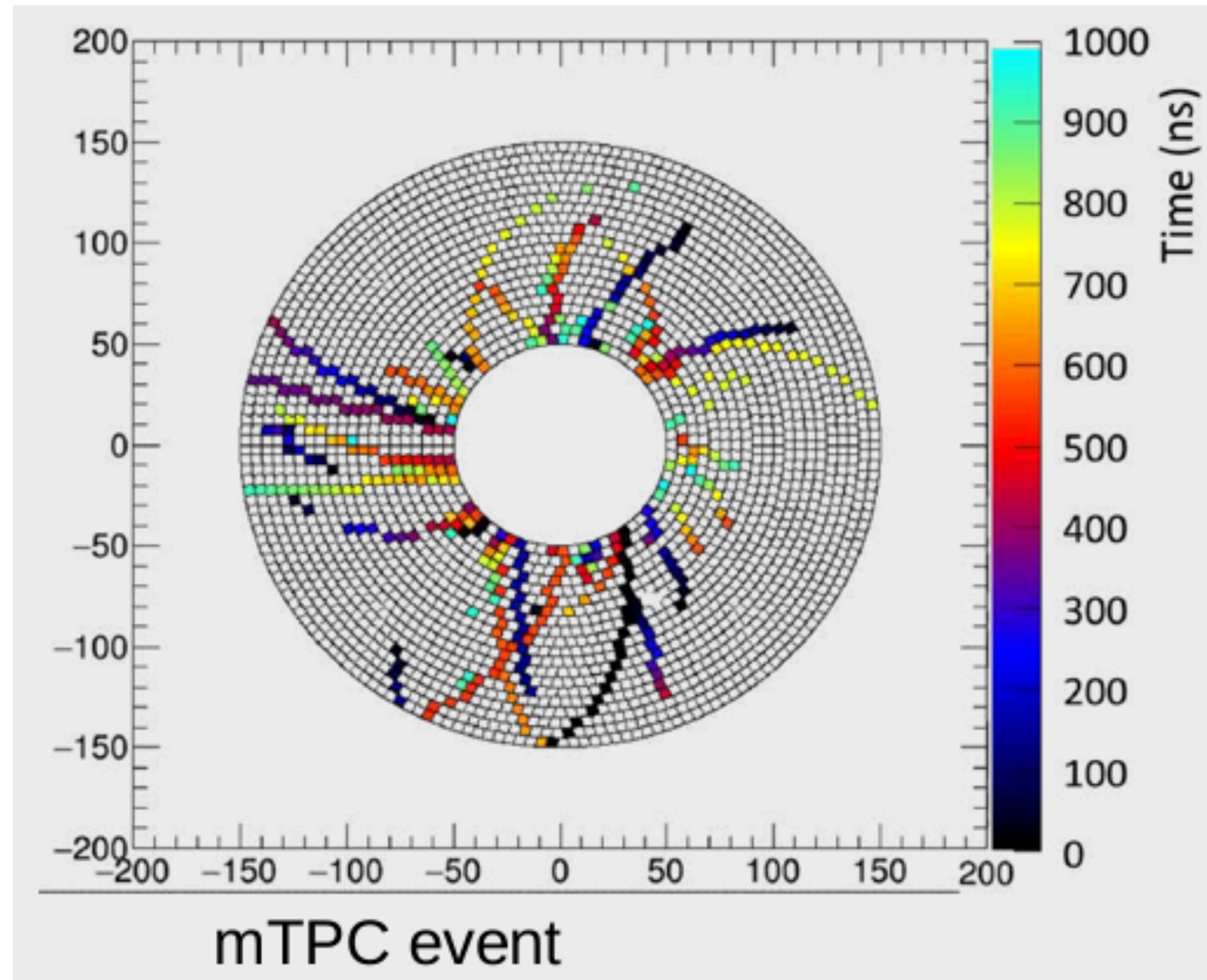
Mock engineering run plan

- Establishing beam through 1 cm diameter 40 cm long straw target with and without solenoid field ON.
- Establishing optimal solenoid field.
- Commissioning new Cherenkov and refubished LAC as an electron detector
- Establish and program electron roads for FPGA to get high-efficiency electron trigger with the SBS.
- Establishing high rate mTPC DAQ and deadtimes as a function of luminosity.
- Calibration map of HV and gas flow settings for optimal operation of mTPC at different luminosity and target gas pressure.
- Establishing and calibrating large angle single proton tracking in mTPC as a function of luminosity while monitoring rates and occupancy (with empty and H2 gas)
- Establishing and calibrating two proton tracking in mTPC as a function of luminosity while monitoring rates and occupancy (with empty and D2 gas)
- Establishing background rates of two proton tracks in mTPC as a function of luminosity while monitoring rates and occupancy (with empty and 4He gas)
- Establishing background two hadron (proton/pion) tracks in mTPC as a function of luminosity while monitoring rates and occupancy (with empty, D2 and 4He gas).

Readout pixel configuration and simulated hits

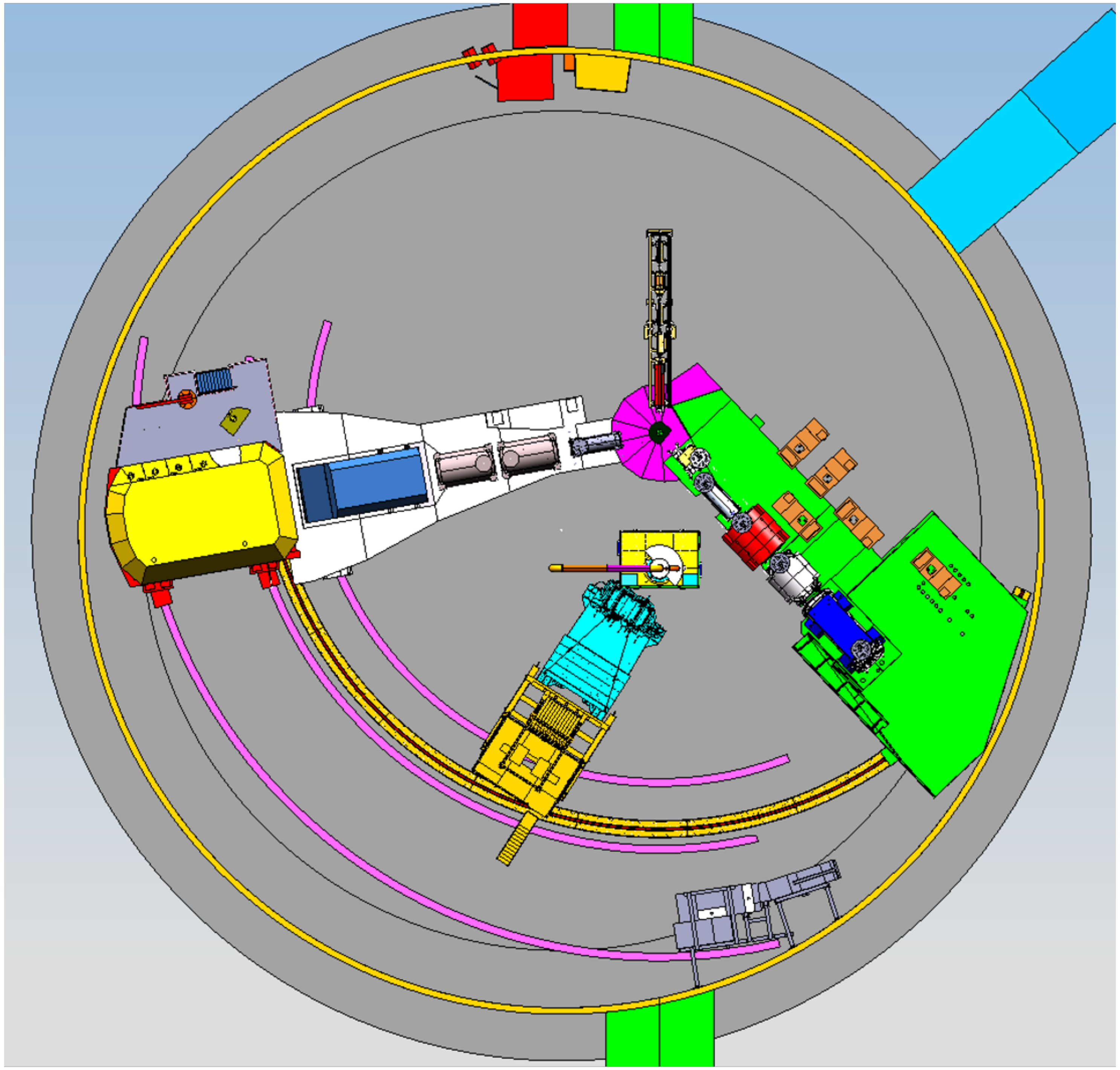


CAD design: K. Gnanvo



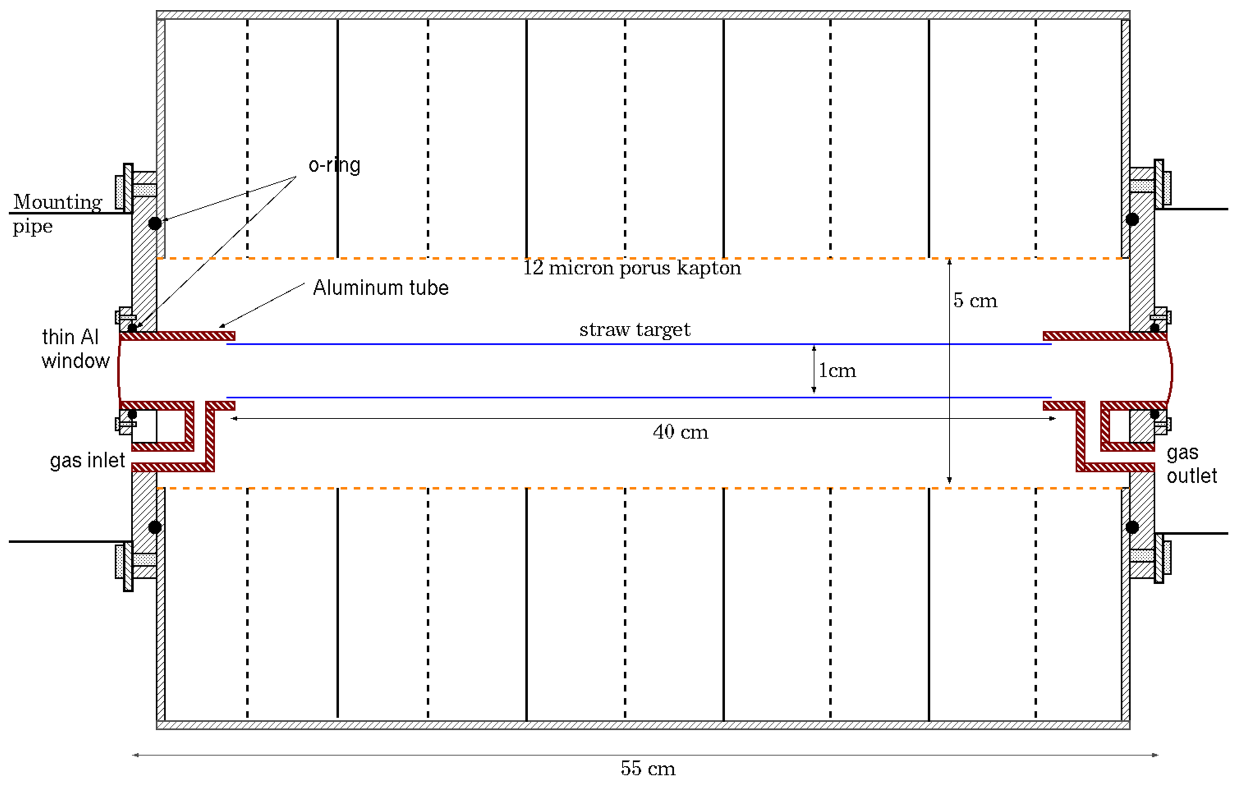
Plot credit: M. Carmignotto

SBS in Hall C



Solenoid & Target

spiral wound 25 um kapton straw Target



UVa 4T Solenoid

Pressure tested to 60 psi