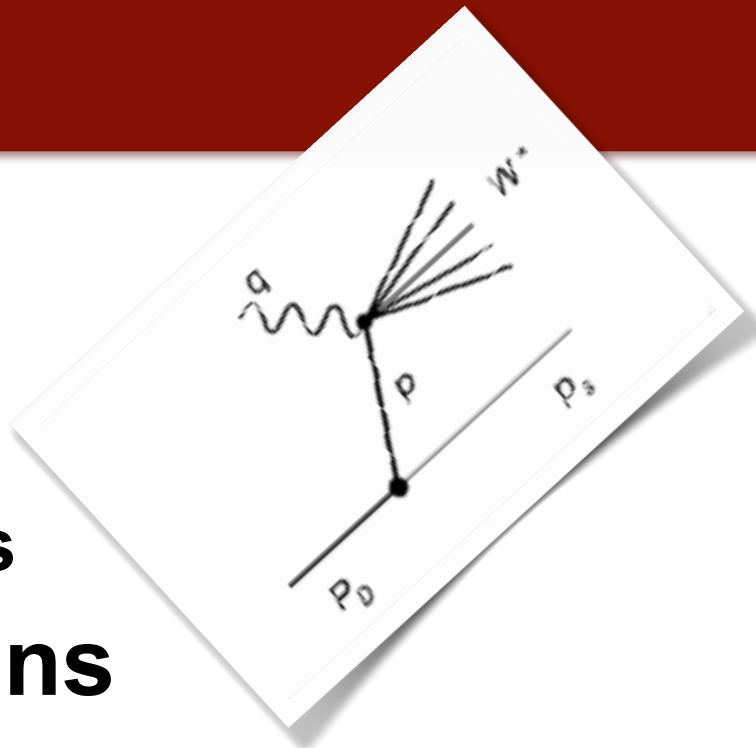
Tagged Deep Inelastic Scattering:
Exploring meson structure function and beyond at JLab

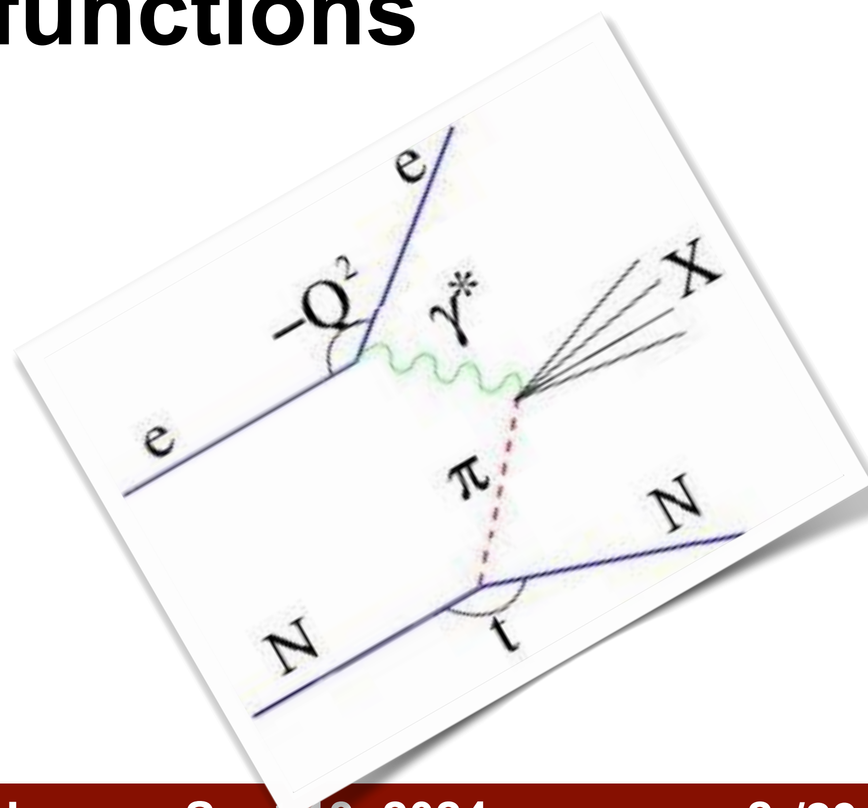
Dipangkar Dutta
Mississippi State University
for the TDIS collaboration

Diffraction & Low-x, Palermo, Sicily
Sept 8-14, 2024

Outline



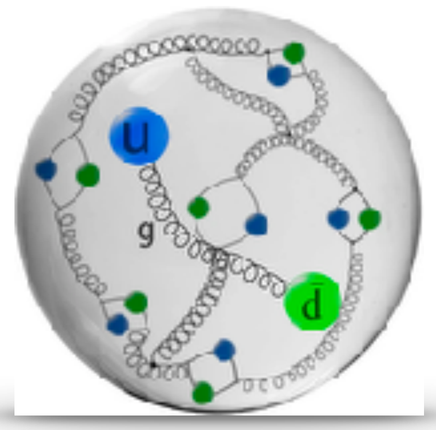
1. **Introduction**
   - Mesonic content and structure of nucleons
2. **Tagged& Meson structure functions**
   - Sullivan process and access to meson cloud of nucleon
   - The TDIS experiment at 11 GeV & 22 GeV
3. **Moving beyond meson structure functions**
4. **Summary**

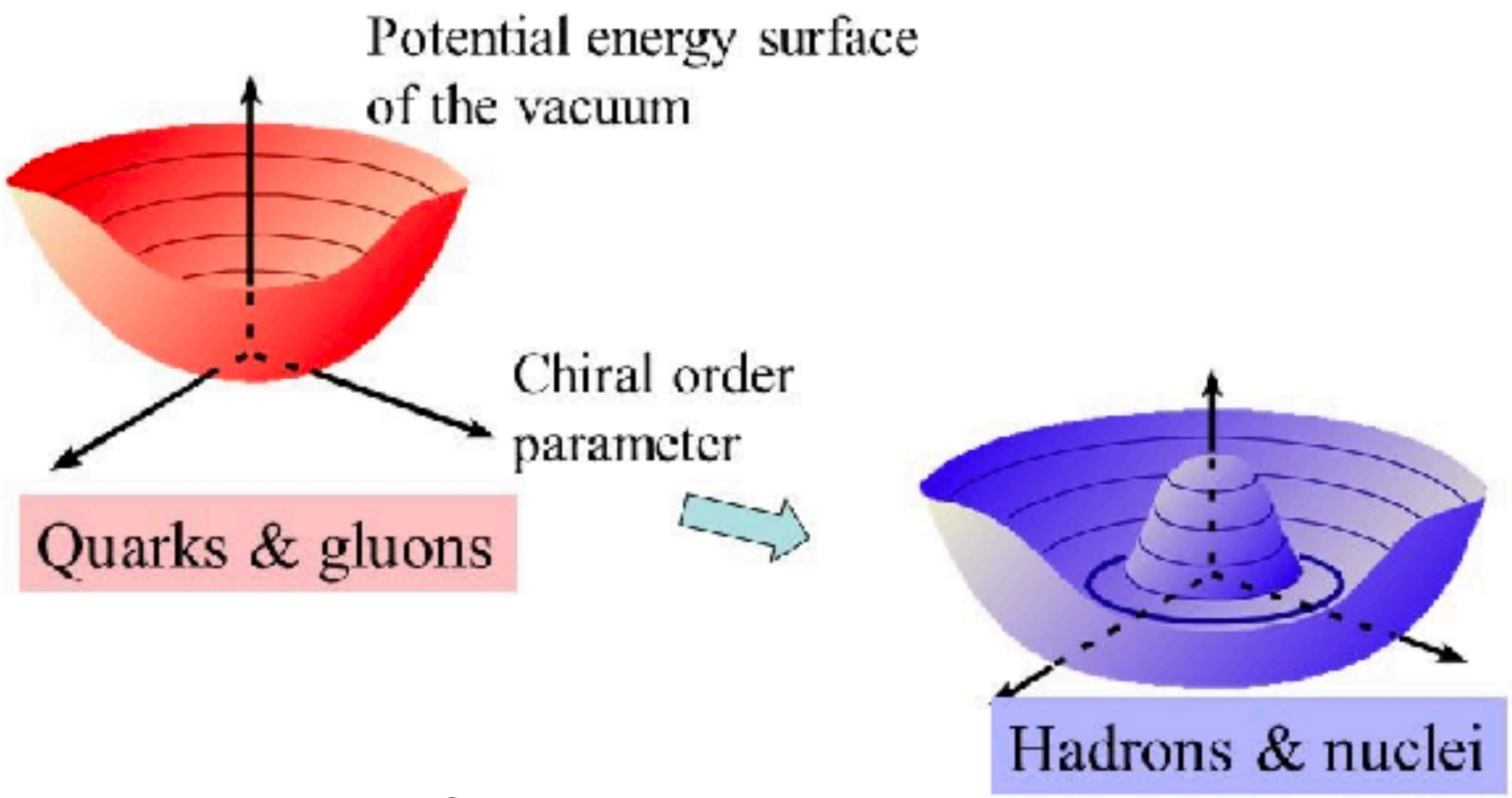


Pions and kaons are the simplest bound states of QCD and its mass-less Nambu-Goldstone bosons

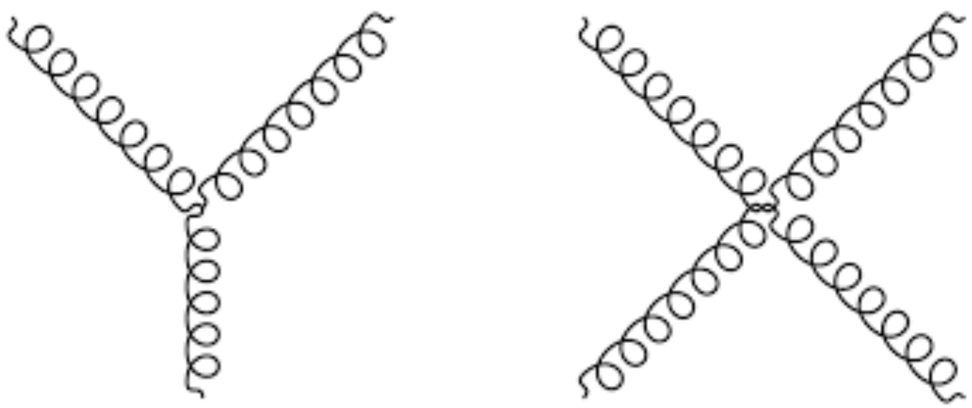
emergence of mass via dynamical chiral symmetry breaking

π+



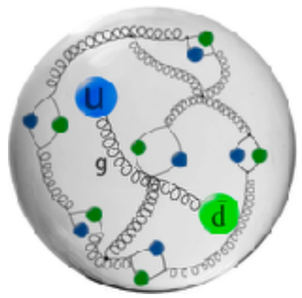


a consequence of
gluon self interaction

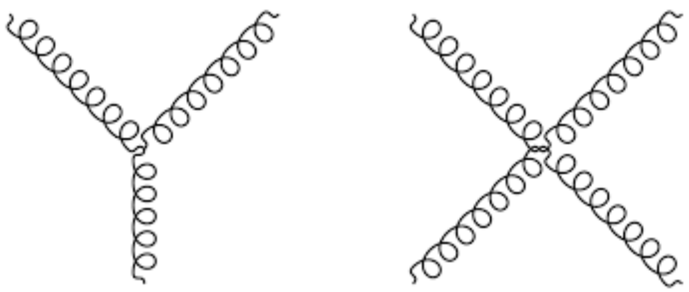


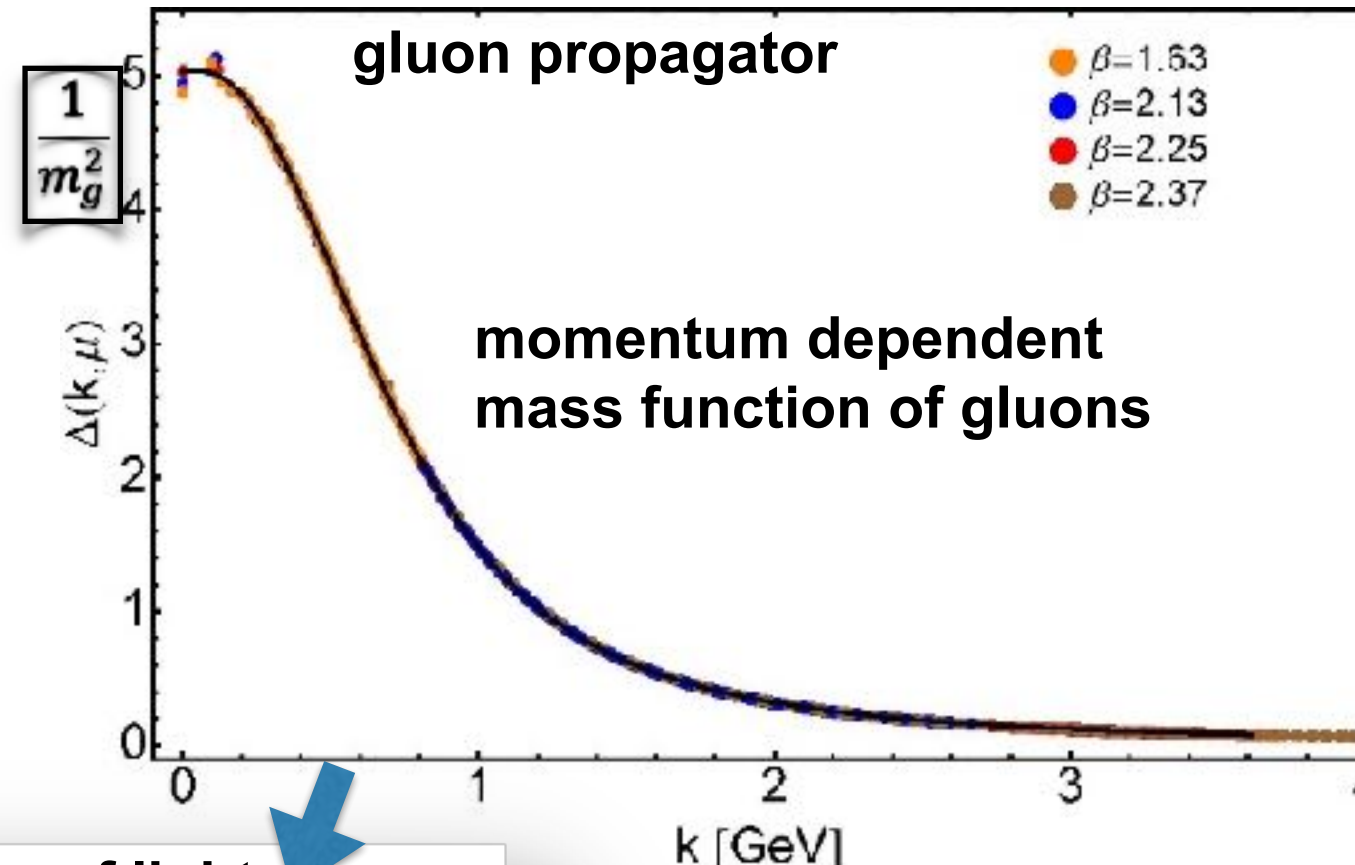
Pion and kaon mass emerge due to dynamical chiral symmetry breaking

π+

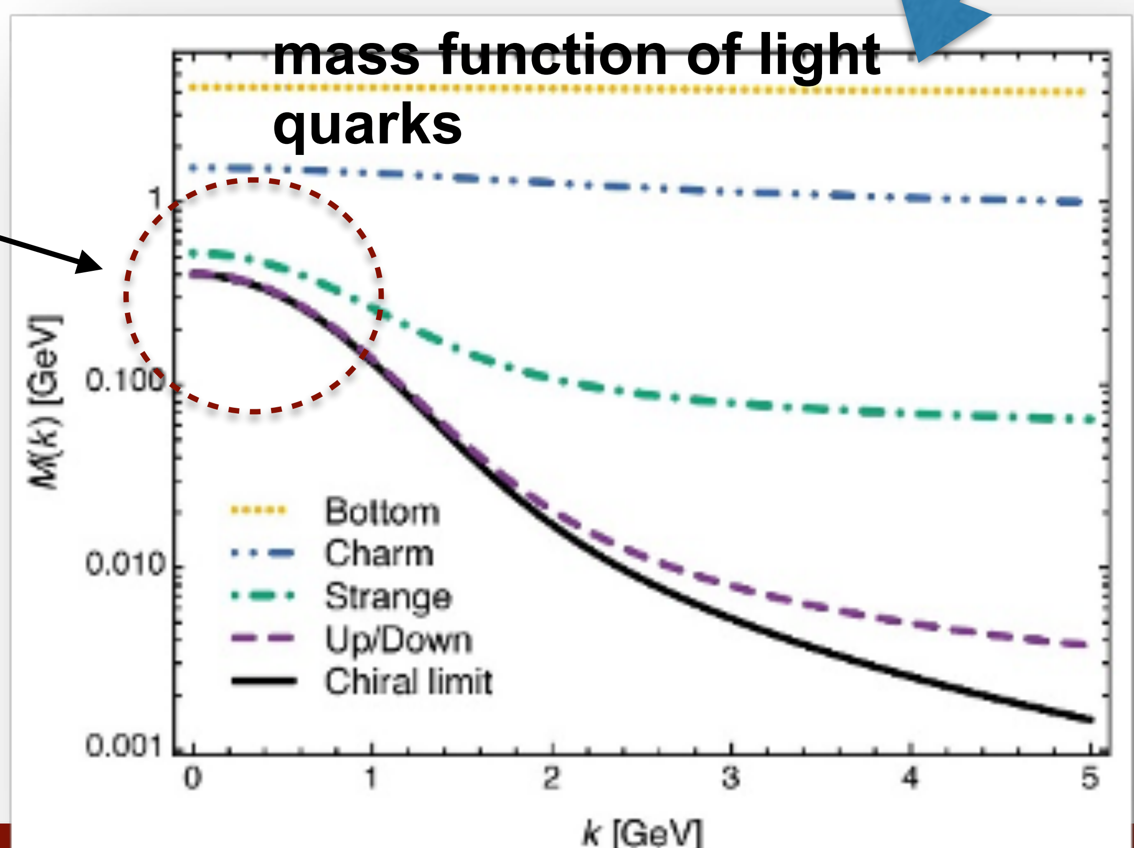


a consequence of gluon self interaction





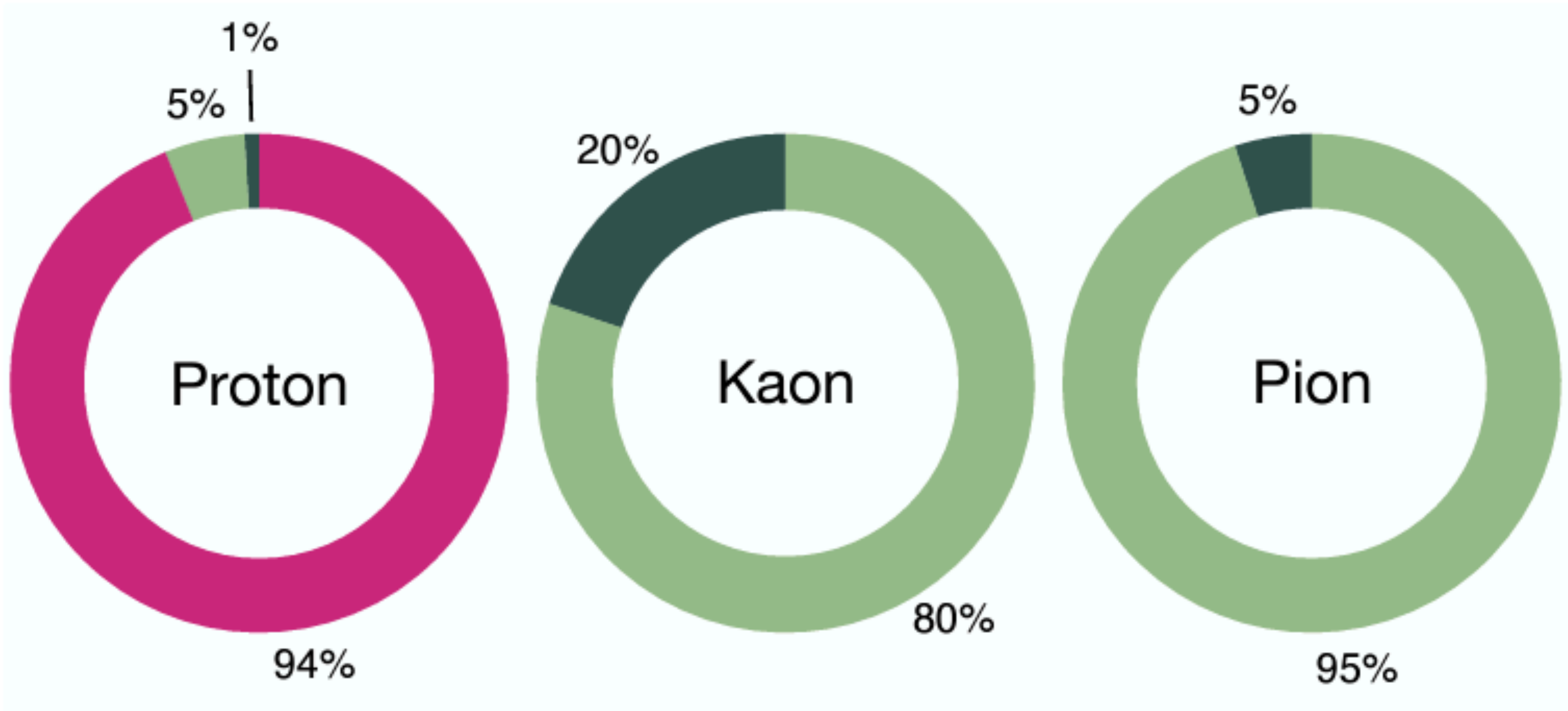
Rapid increase in mass due to gluon cloud



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

images courtesy of C. D. Roberts

Mass budget for mesons and nucleons are vastly different



Emergent hadron mass

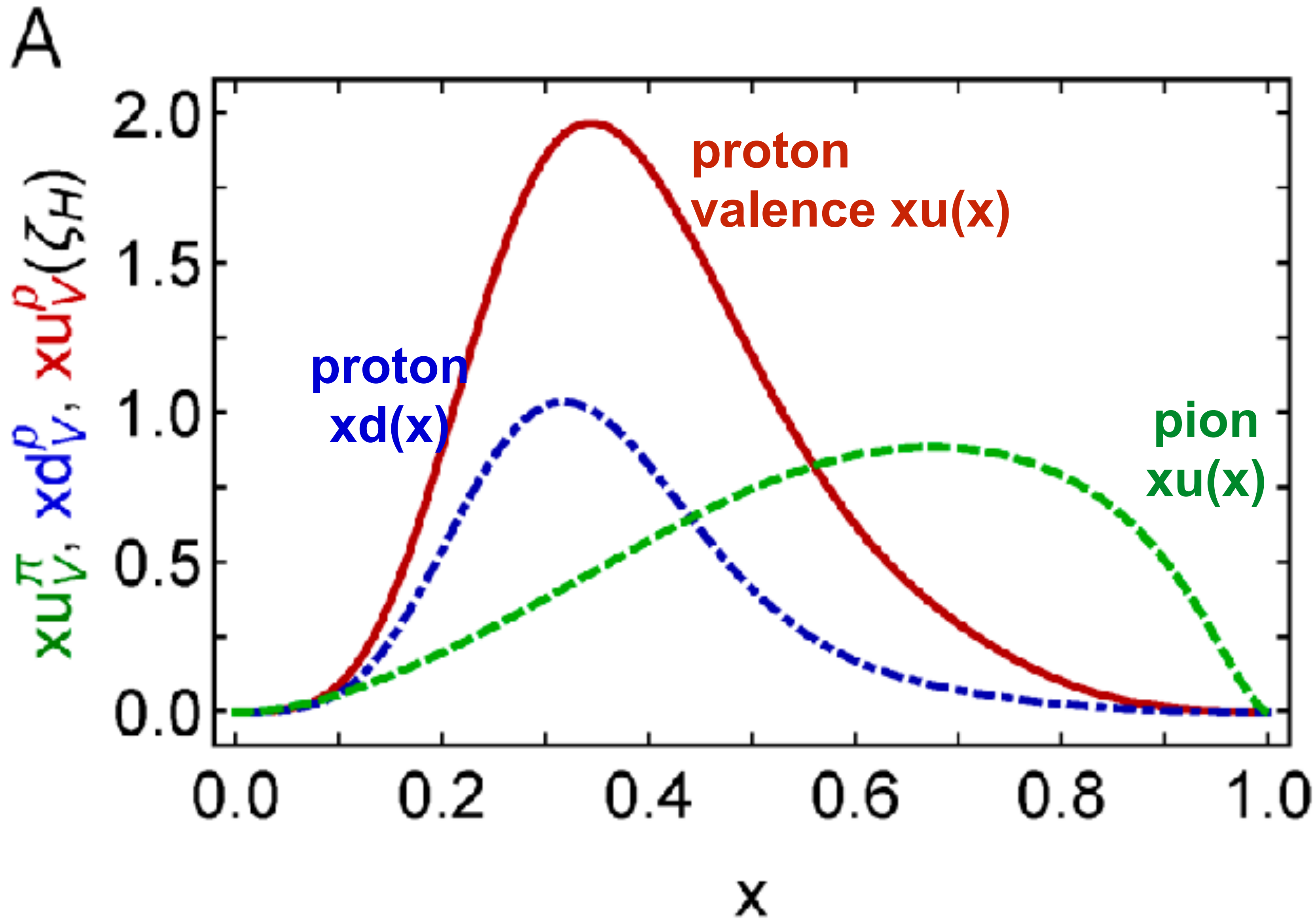
Interference of emergent hadron mass & Higgs mechanism

Higgs mechanism

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

Knowledge of meson structure is critical for a complete understanding of the emergence of hadron mass

pion/proton valence quark distributions are also very different



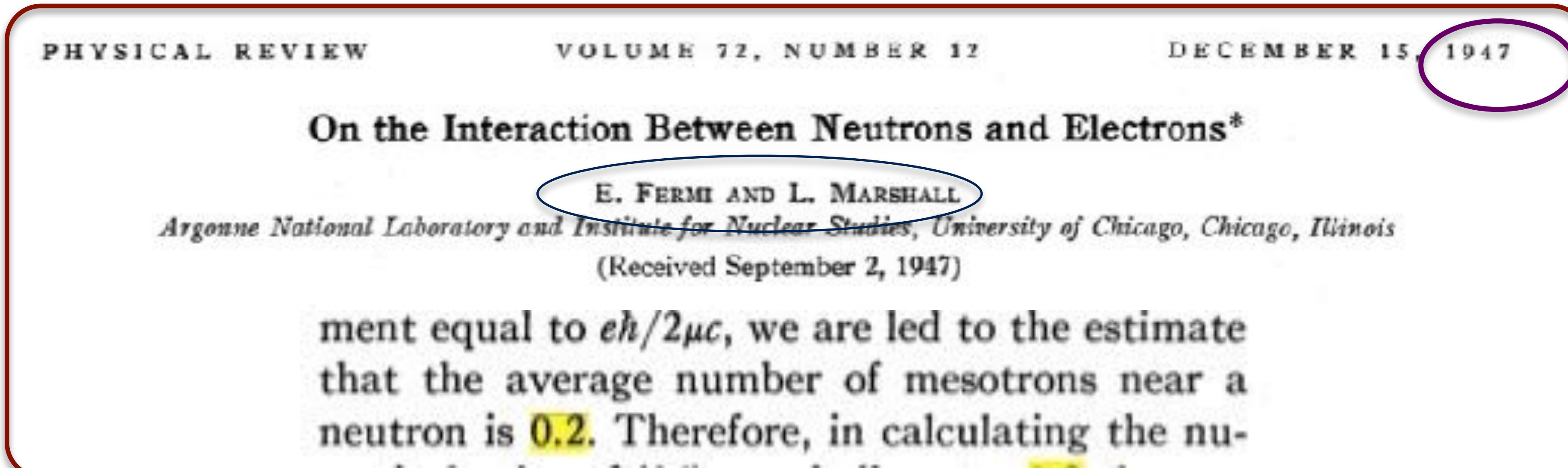
difference between meson PDFs: direct information on emergent hadron mass

Lack of stable meson targets ⇒ scant experimental data

How about mesons in nucleons?

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

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


PHYSICAL REVIEW VOLUME 72, NUMBER 12 DECEMBER 15, 1947

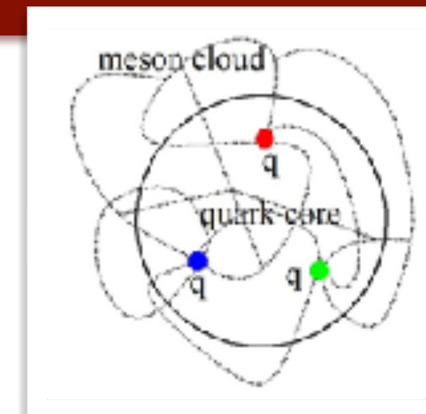
On the Interaction Between Neutrons and Electrons*

E. FERMI AND L. MARSHALL

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

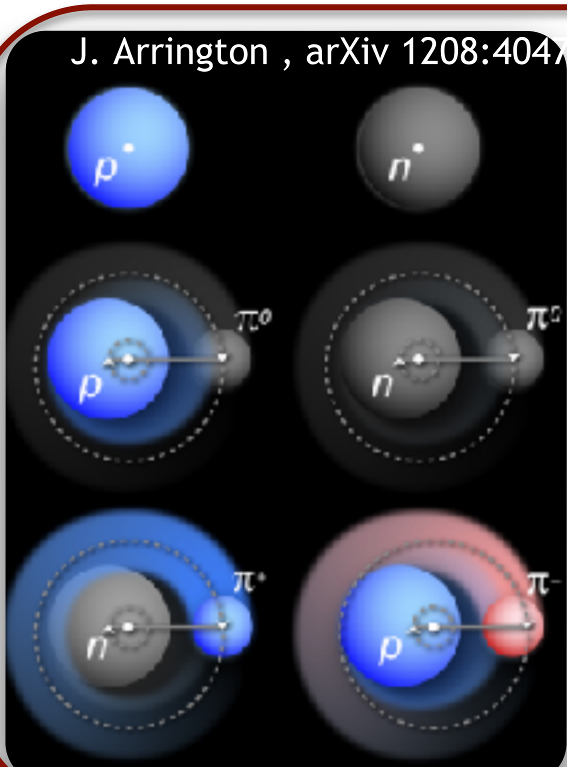
(Received September 2, 1947)

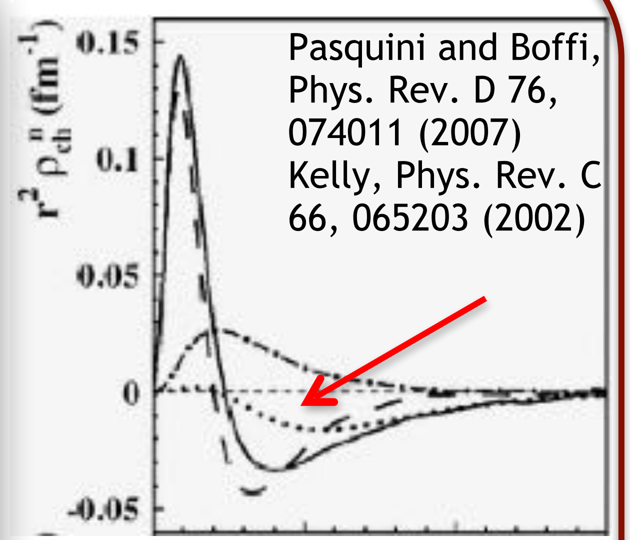
ment equal to $e\hbar/2\mu c$, we are led to the estimate that the average number of mesotrons near a neutron is 0.2. Therefore, in calculating the nu-



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

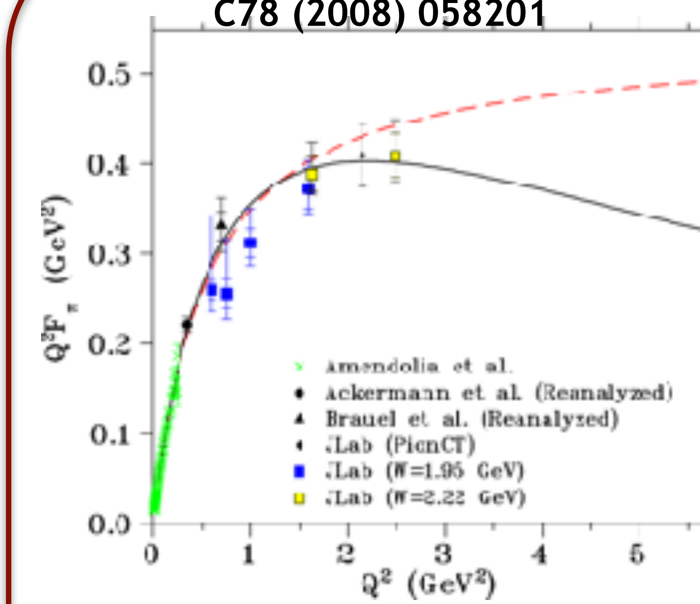
J. Arrington , arXiv 1208:4047





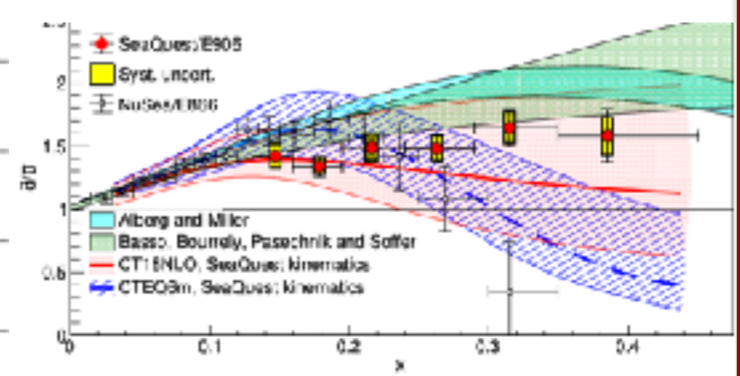
Proton & Neutron Charge Distribution

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



Pion Form Factor

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

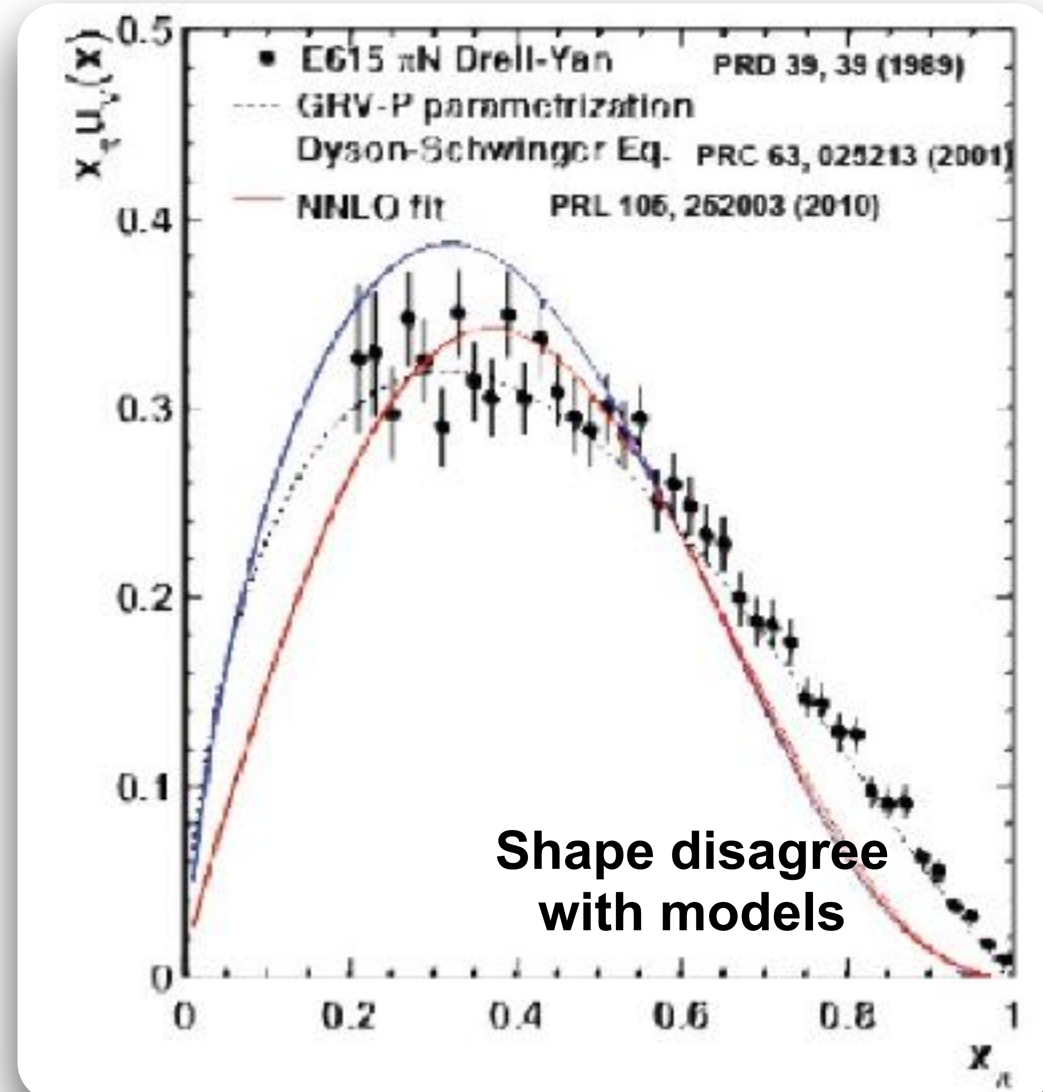


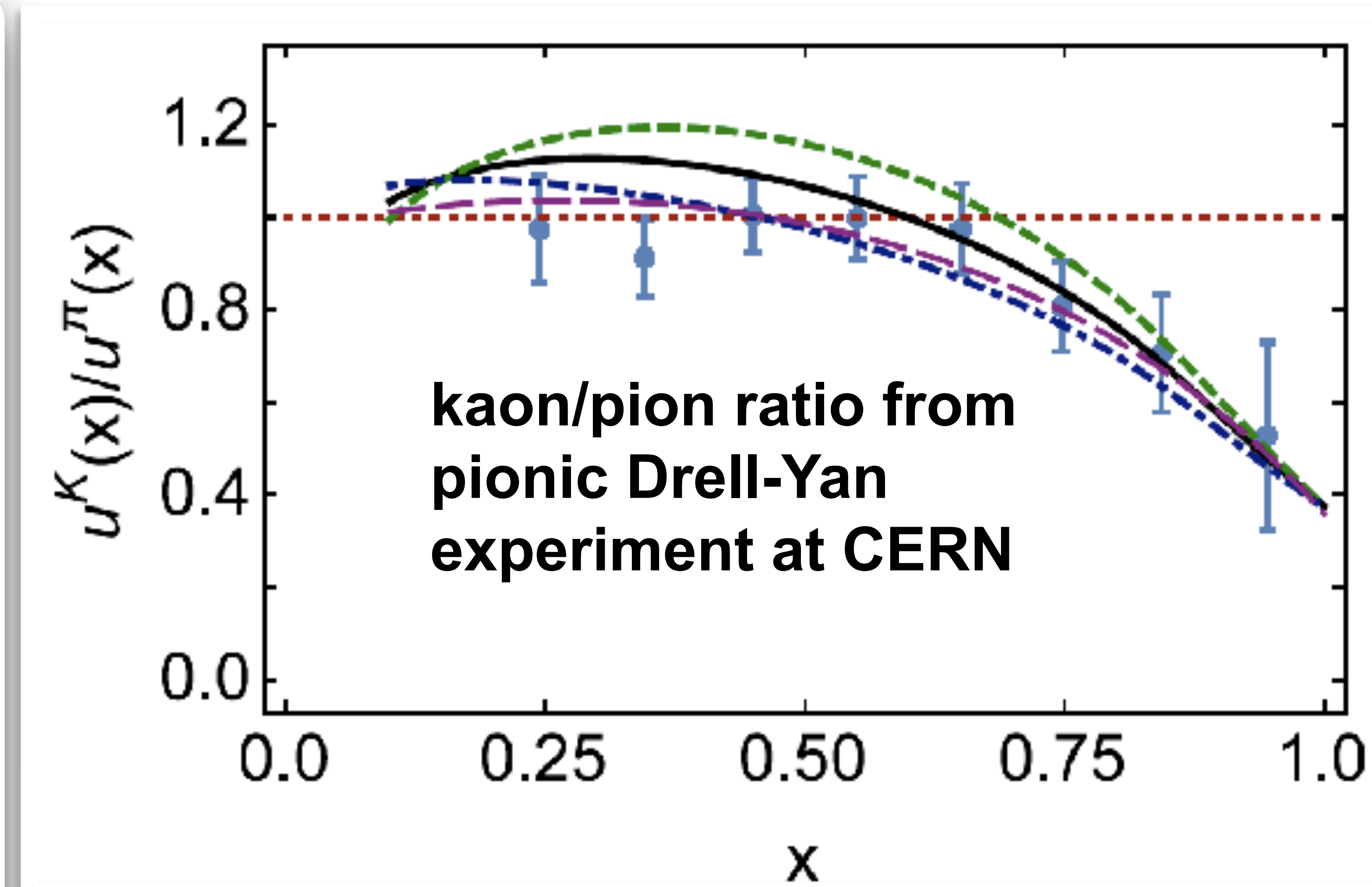
up/down sea-antiquark flavor asymmetry

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

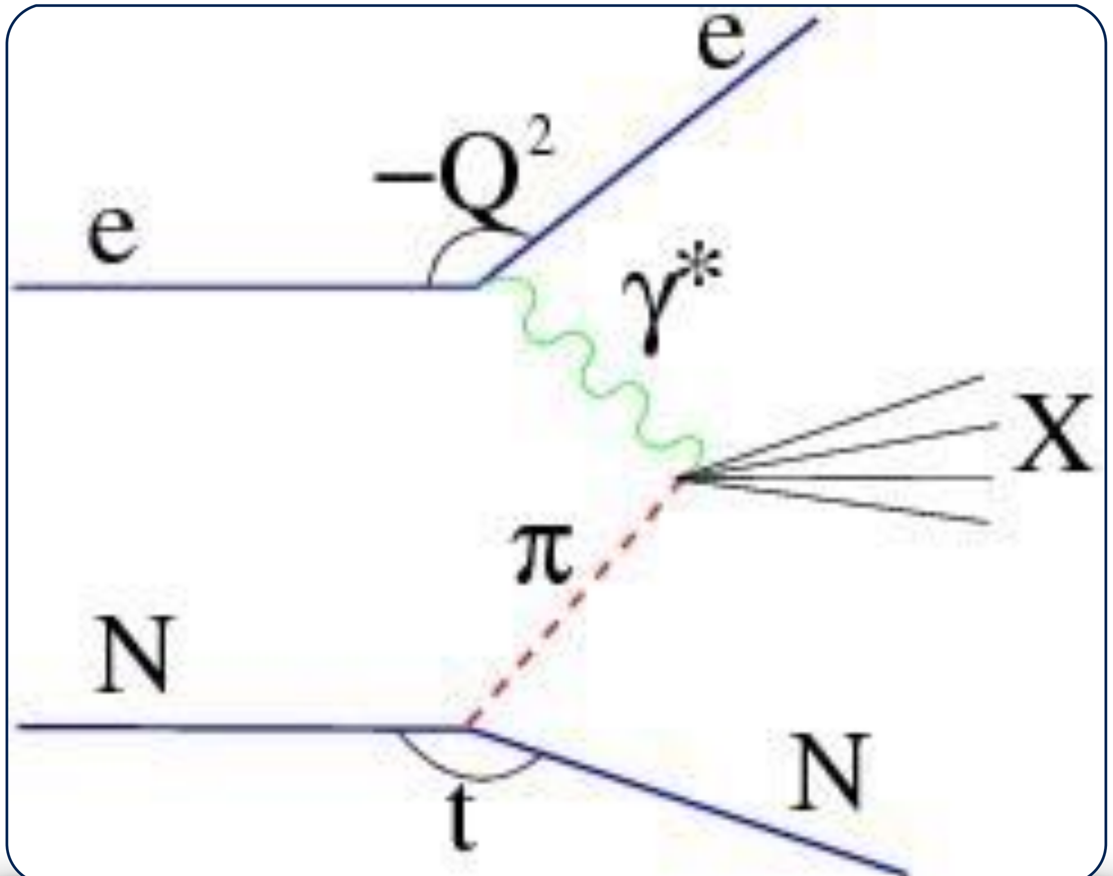
Need more and precise data

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)

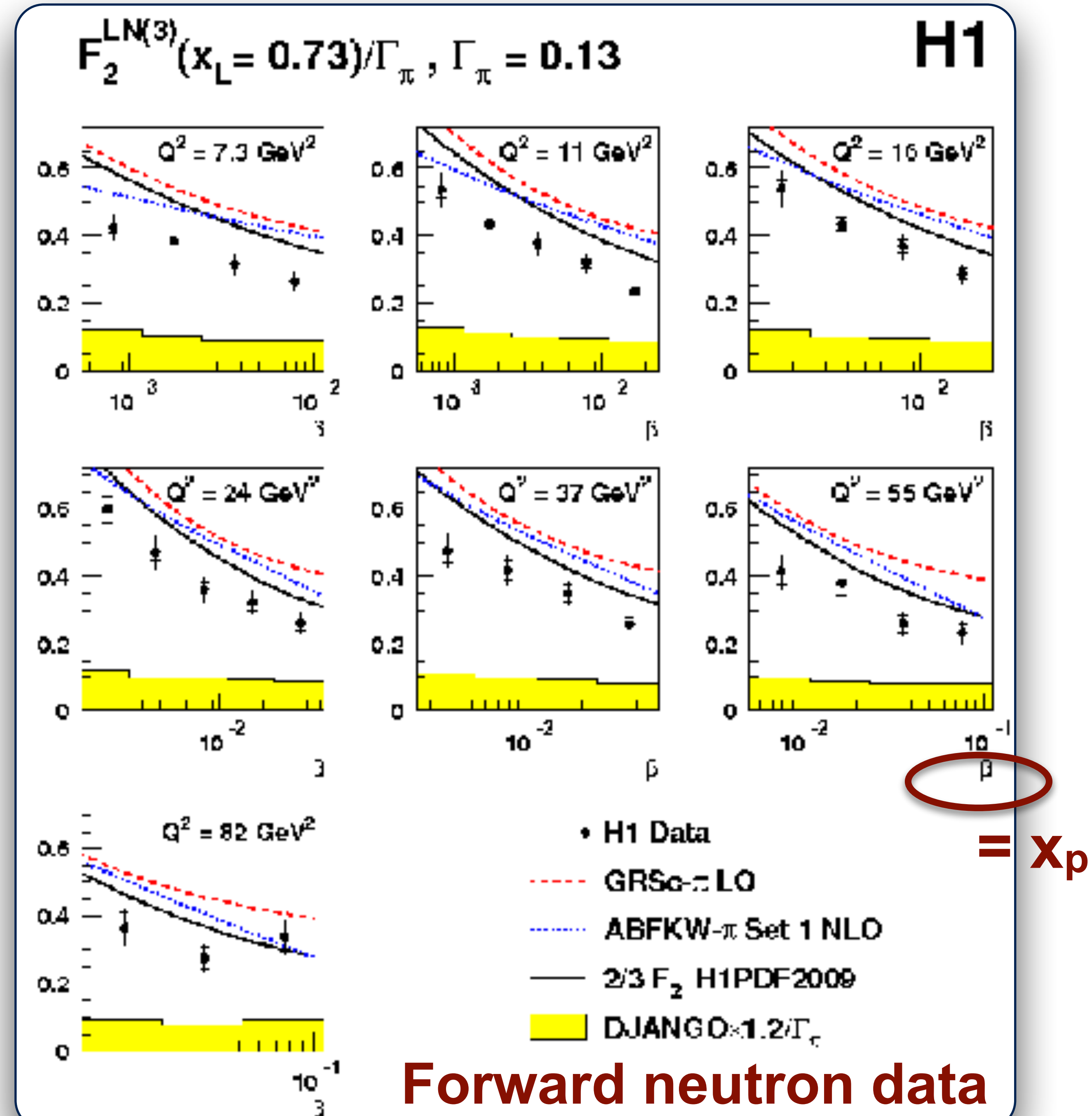
Deep-inelastic Scattering off a virtual-meson cloud is a possible experimental technique.

The Sullivan process



direct measurement of the mesonic content of the nucleon

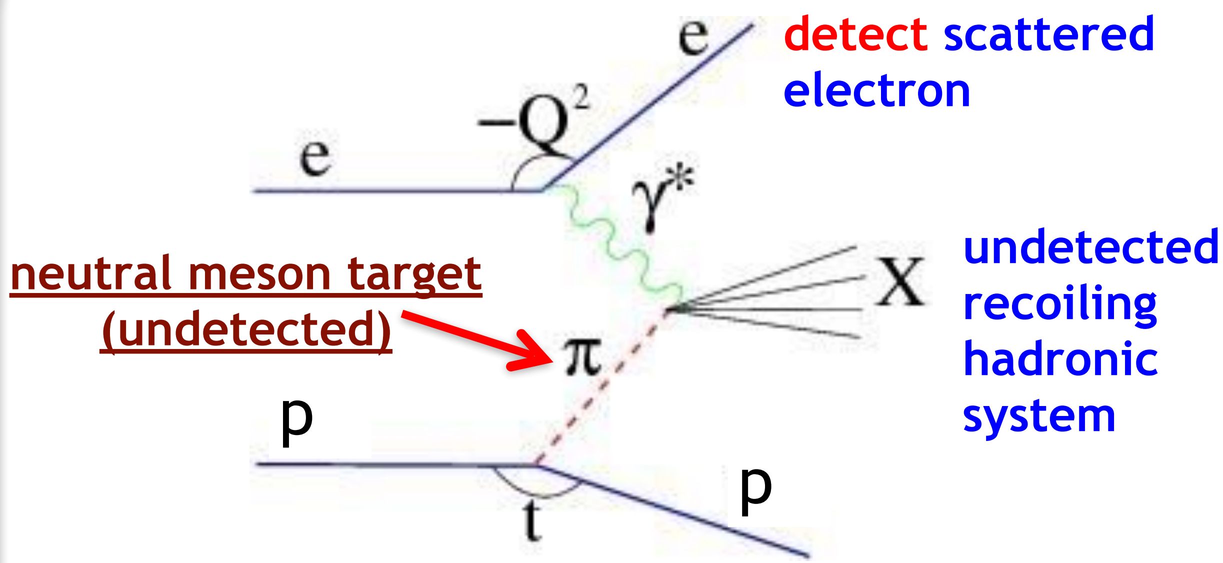
DIS events with forward going neutrons in coincidence



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.

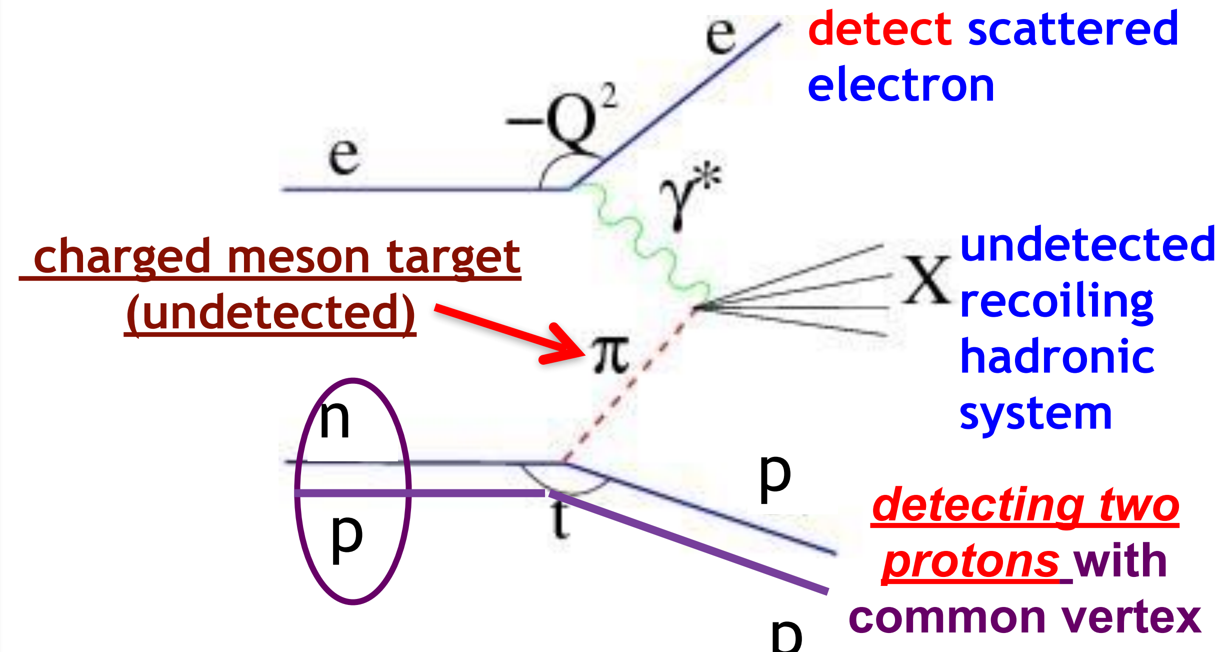
Hydrogen Target



Spectator proton

(backward going slow proton)

Deuterium Target



Spectator proton

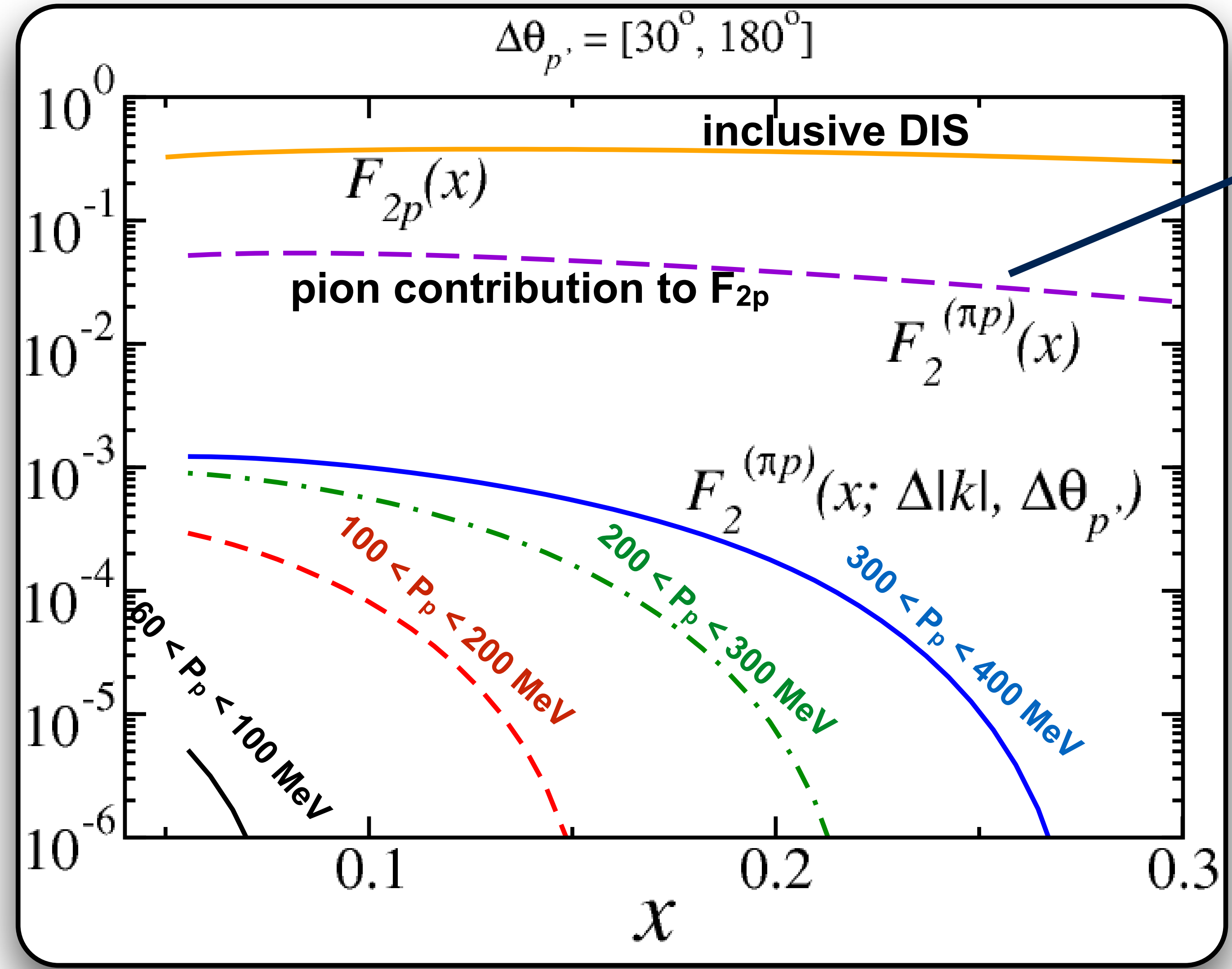
DIS event – reconstruct x, Q^2, W^2, also M_X of recoiling hadronic system

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

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

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

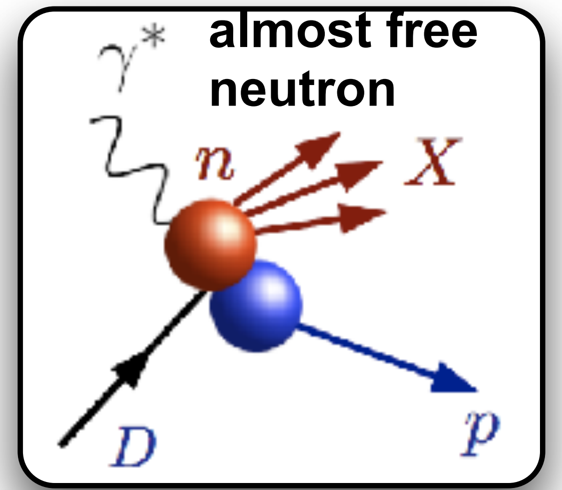
Tagged SF **pion "flux"** **Pion SF**

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)

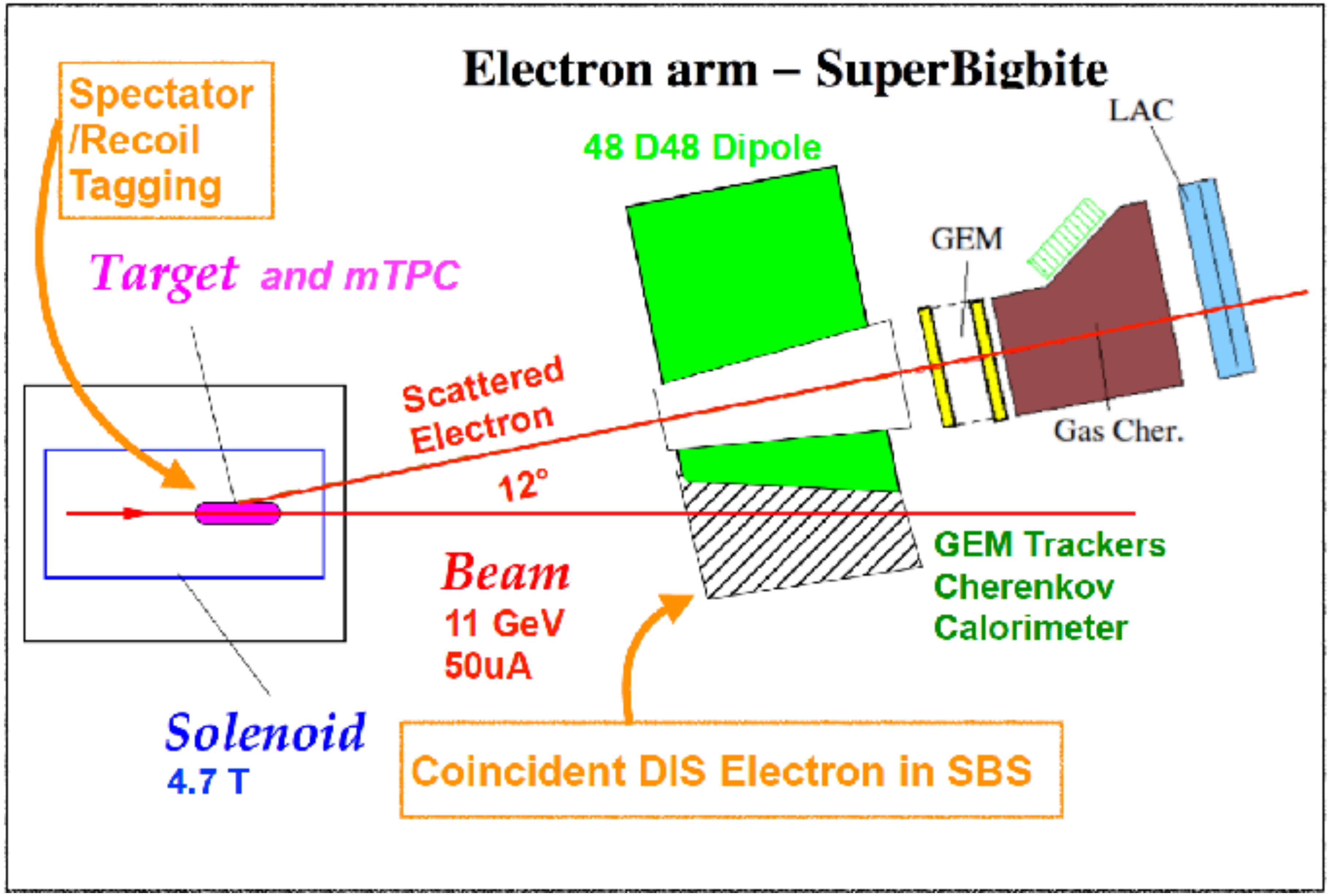
Spectator Tagging - a well established technique at JLab - can be used to tag the "meson cloud" target.

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



Deuteron **Spectator proton**

(backward going slow proton)

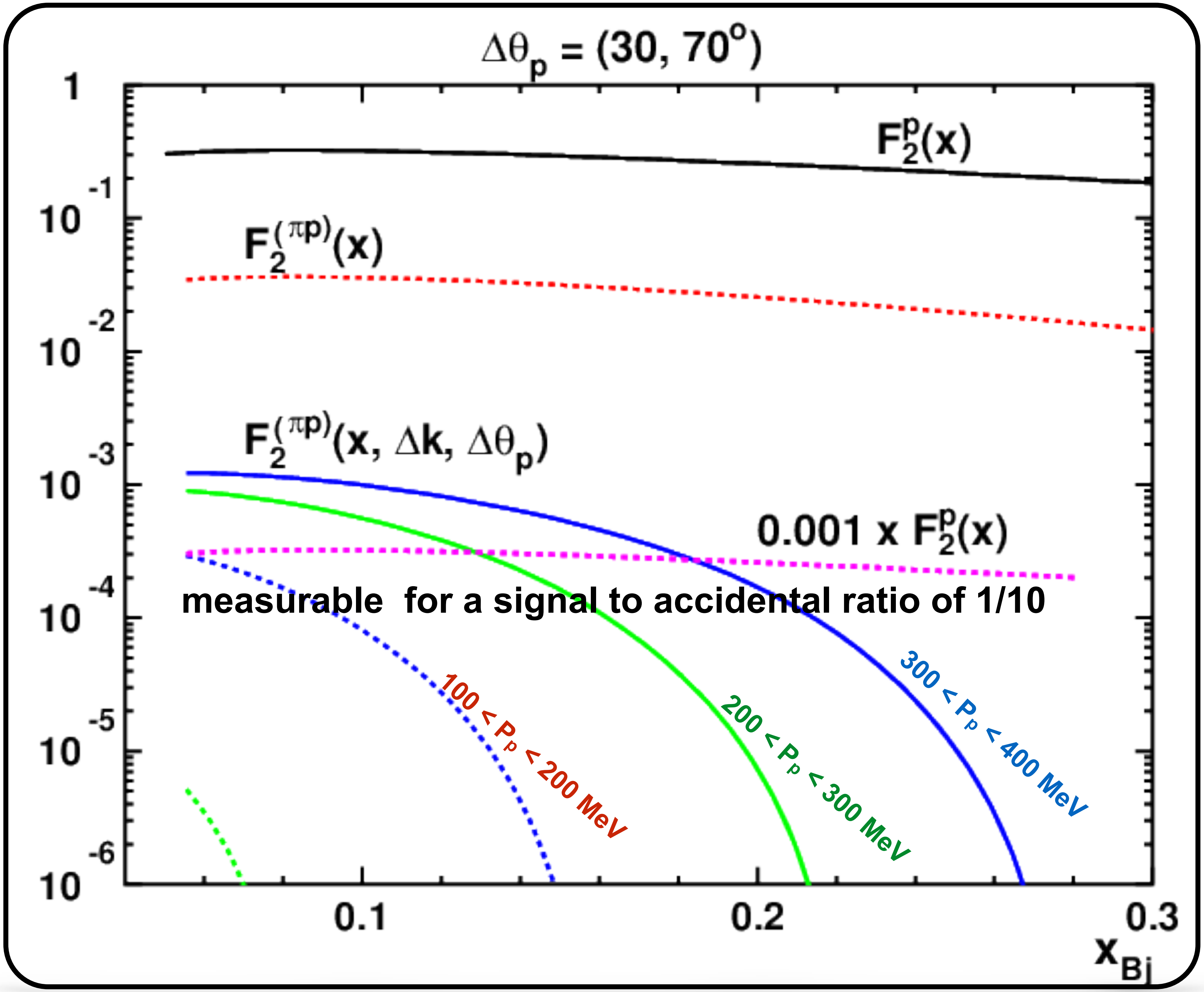


Target: 40 cm long, 25 um wall thickness Kapton straw at room temperature and 3 atm. pressure.

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

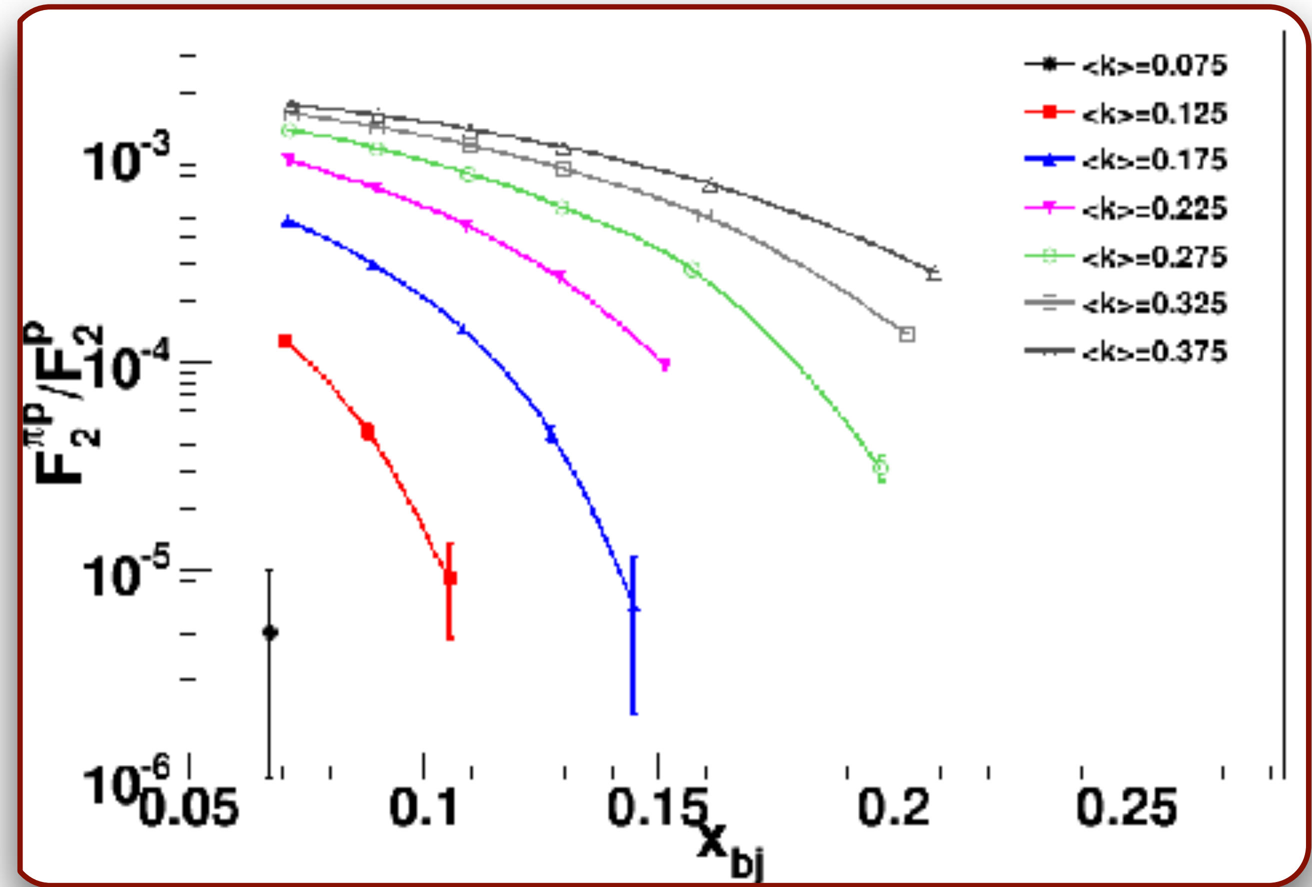
The techniques used to extract meson structure function will be a necessary first step for future experiments

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

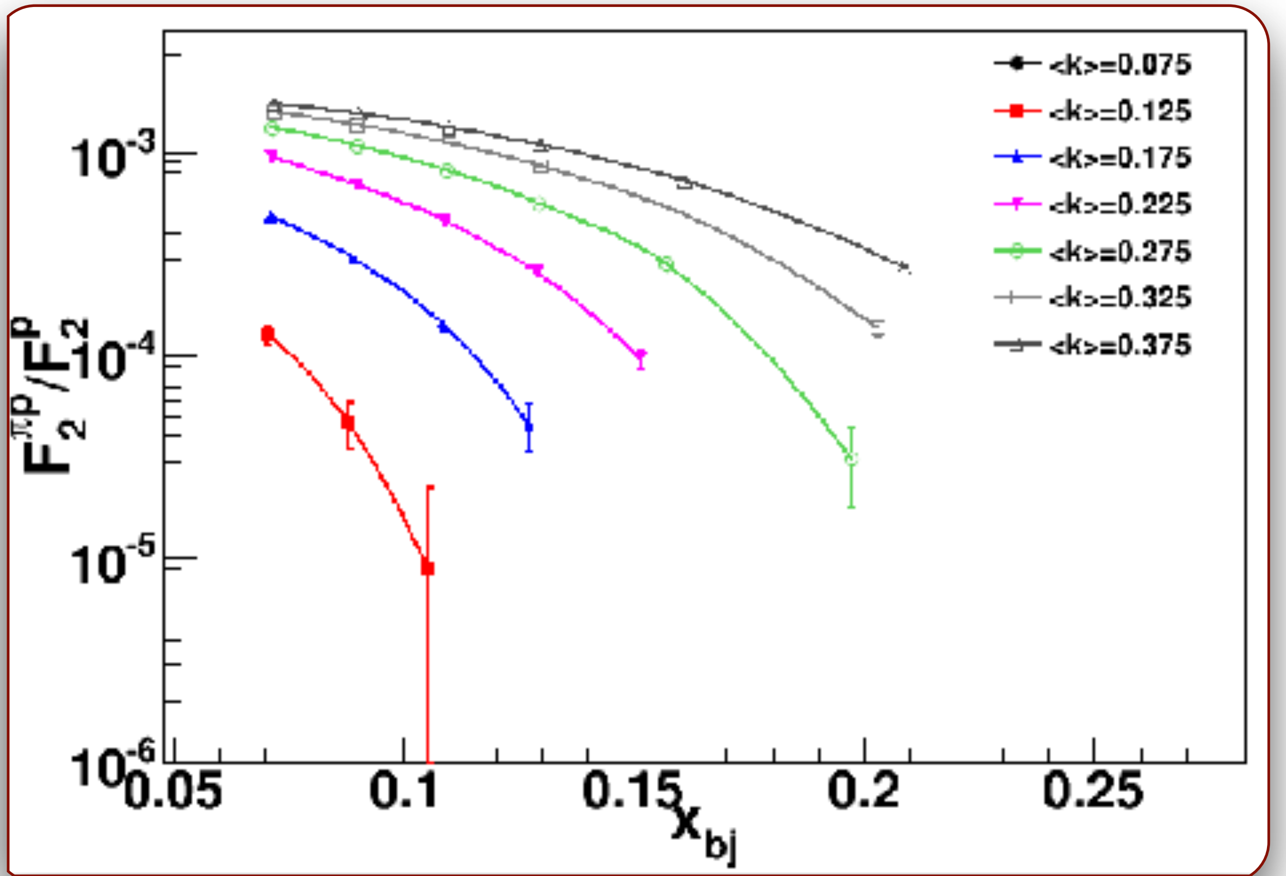


The TDIS experiment will measure tagged structure functions for protons and neutrons

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

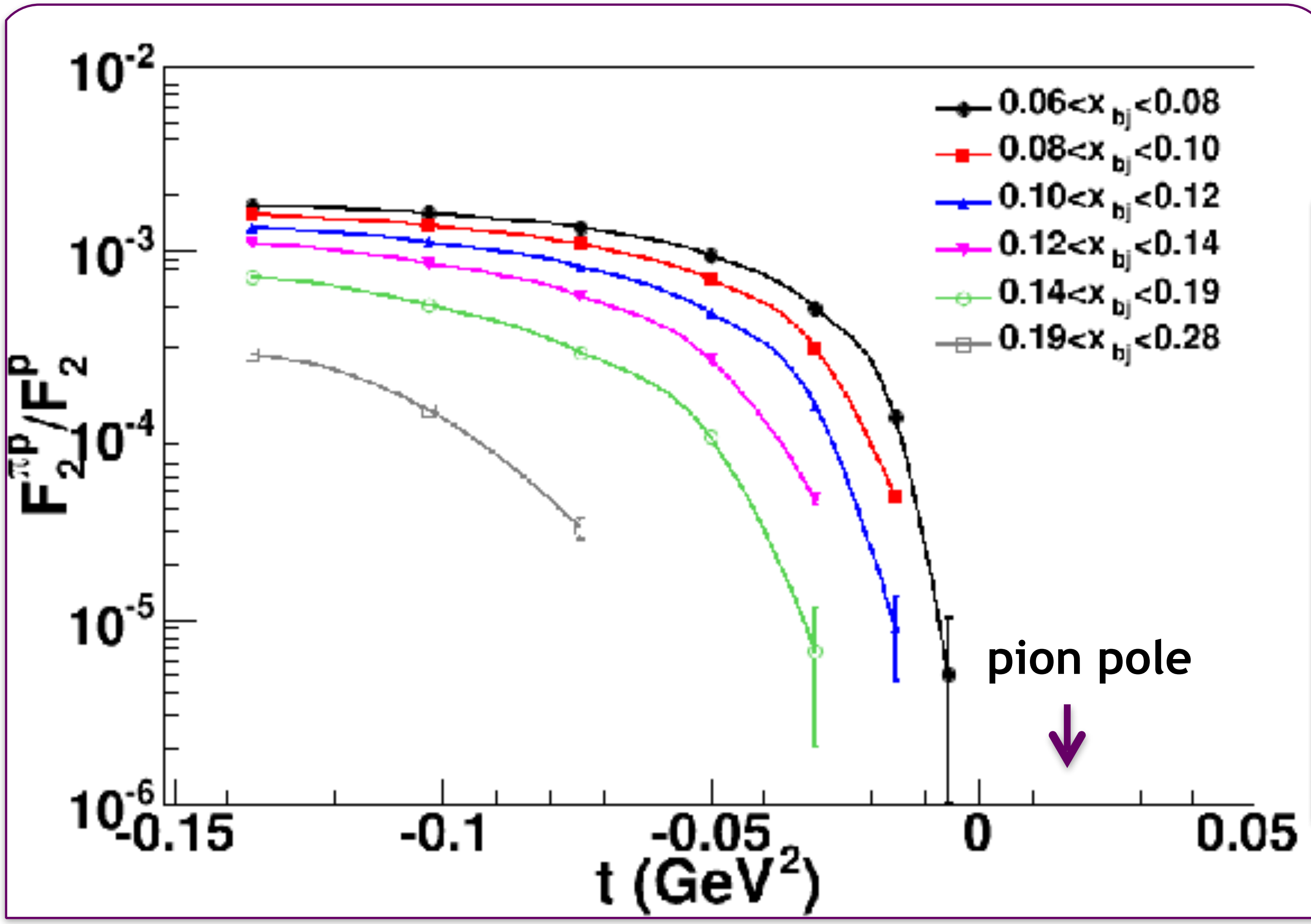
some kinematic limits:
- 150 < k < 400 MeV/c corresponds to z < ~0.2
- Also, x < z
- Low x, high W at 11 GeV means Q^2 ~2 GeV^2

The TDIS experiment will also extract the pion structure function.

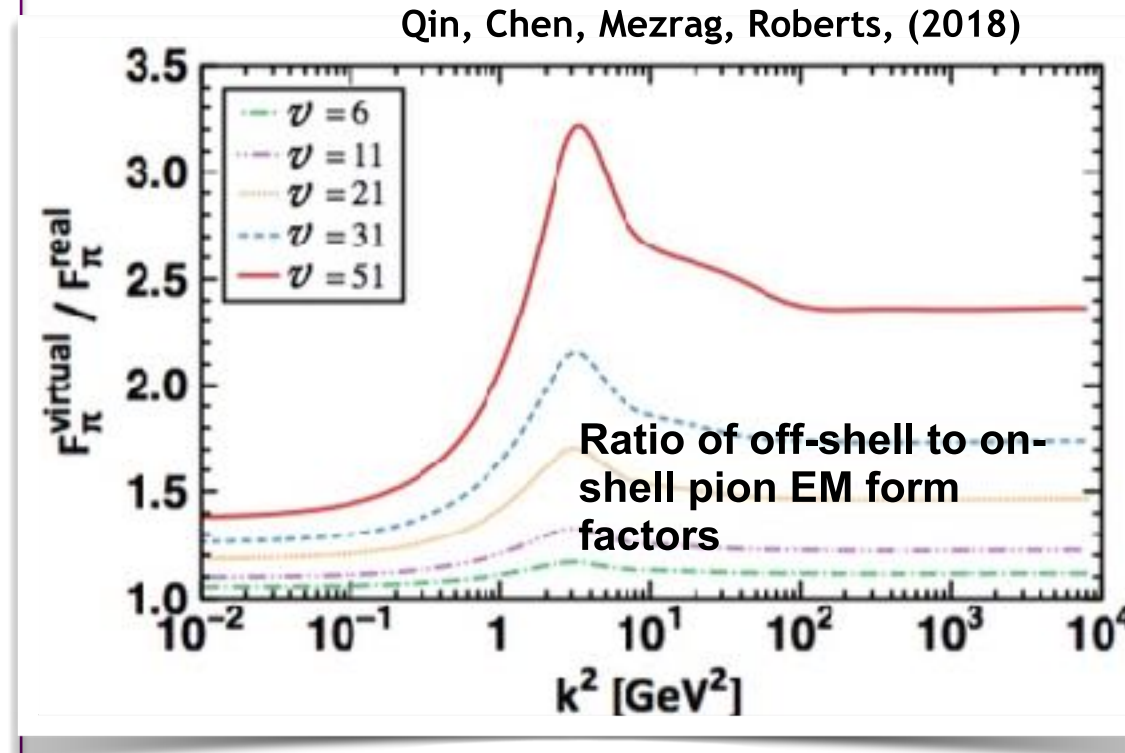
It requires extrapolation to the pion pole

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

- Low t extrapolation to the pion pole



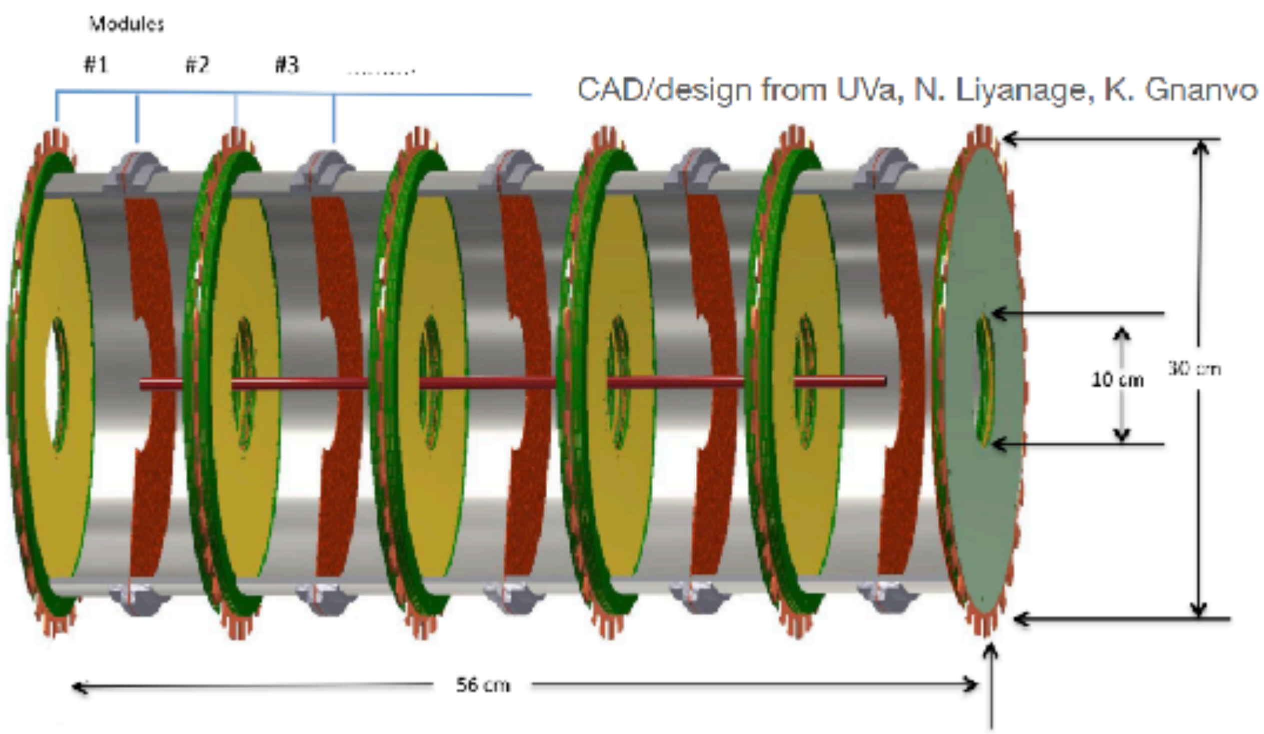
virtuality-independent form factor implies virtuality-independent pion structure function
virtuality ν = 30 ⇒ t = -0.6 GeV²
TDIS covers |t| = 0.01 - 0.16 GeV²



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

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

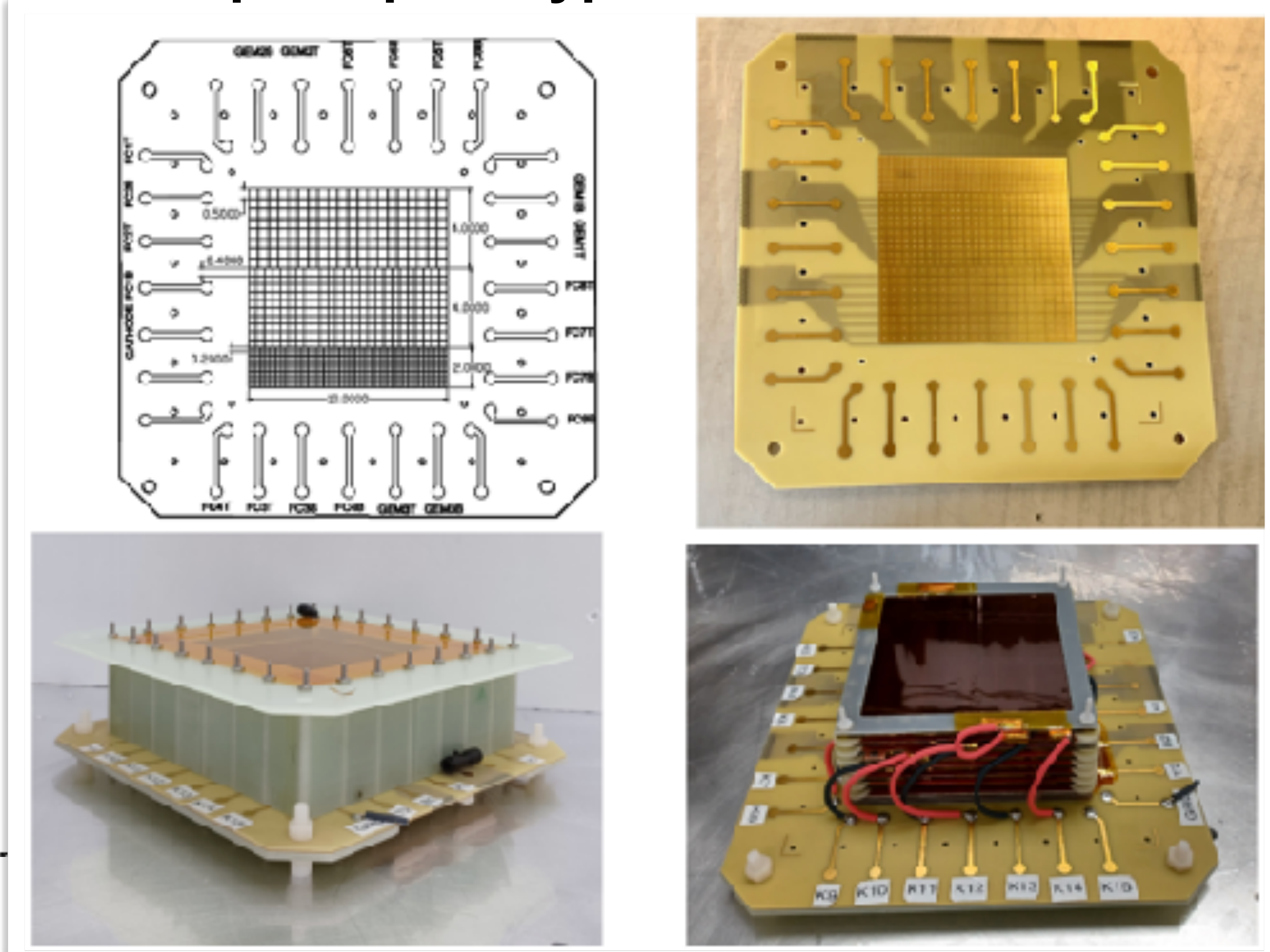


Tracking, dE/dx

- 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.

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

A square prototype has been constructed



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

A cylindrical prototype will be built after validation.

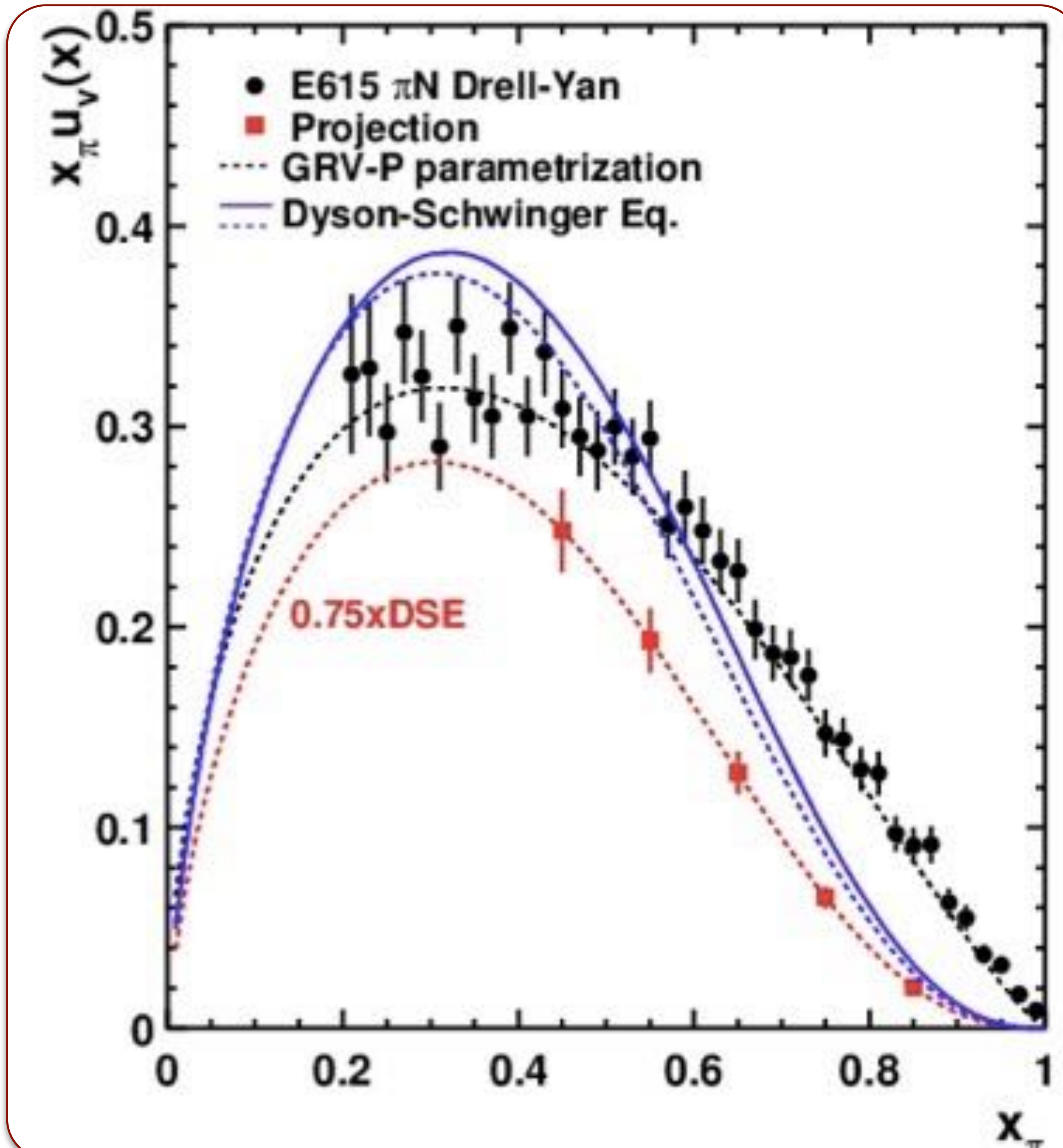
The TDIS experiment will provide a unique extraction of the pion structure function at large x.

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

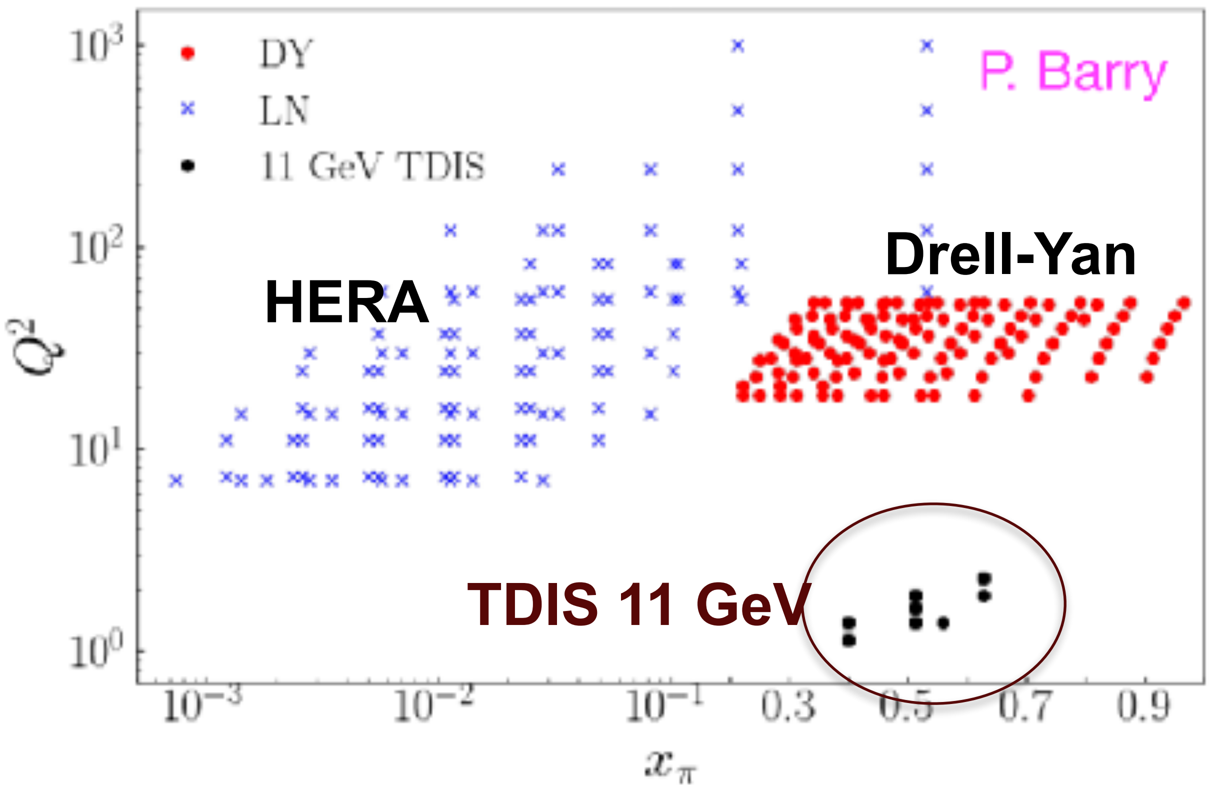
Large x, low Q complementary to HERA low x, high Q

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

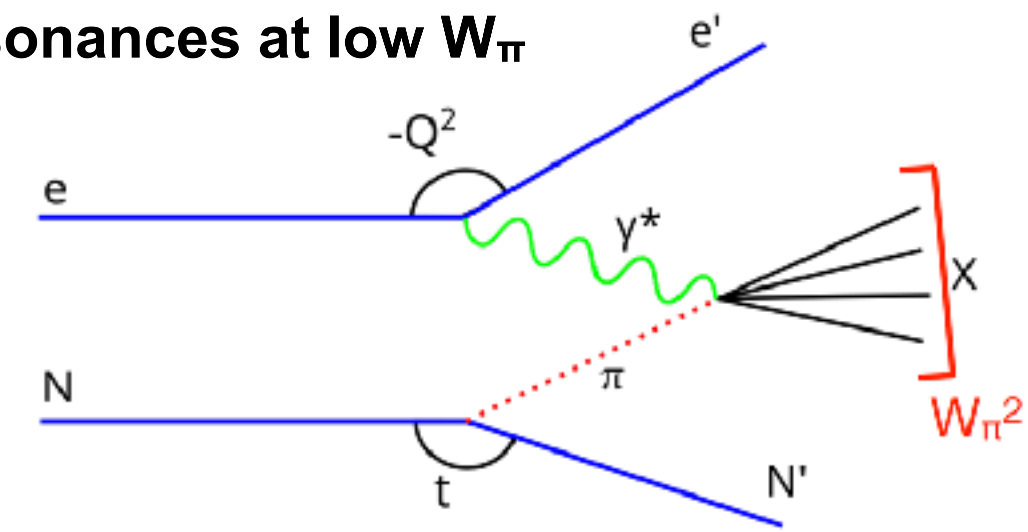
C1 conditionally approved for 27 PAC days with A- rating



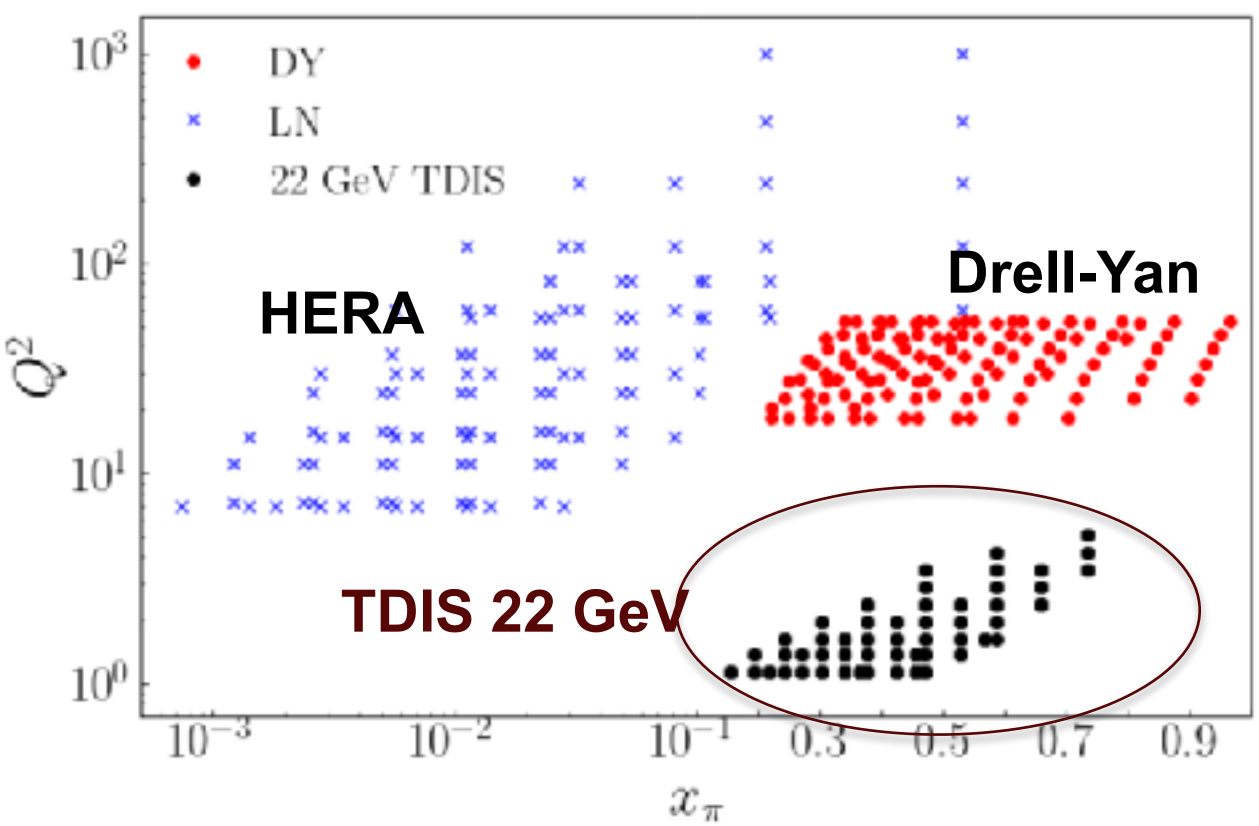
Simulations of a TDIS experiment using a 22 GeV beam indicate very significant advantages

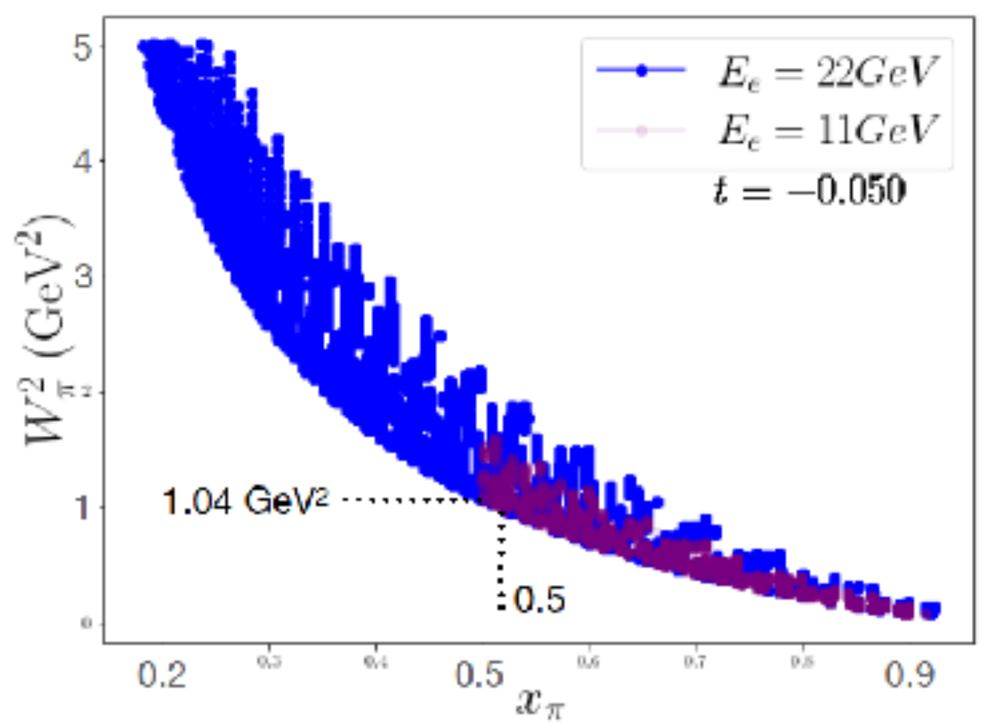


The 11 GeV TDIS data could be impacted by resonances at low W_π



Using $W_\pi^2 > 1.04$ GeV² to remove ρ meson contribution would significantly reduce kinematic coverage at 11 GeV but not at 22 GeV

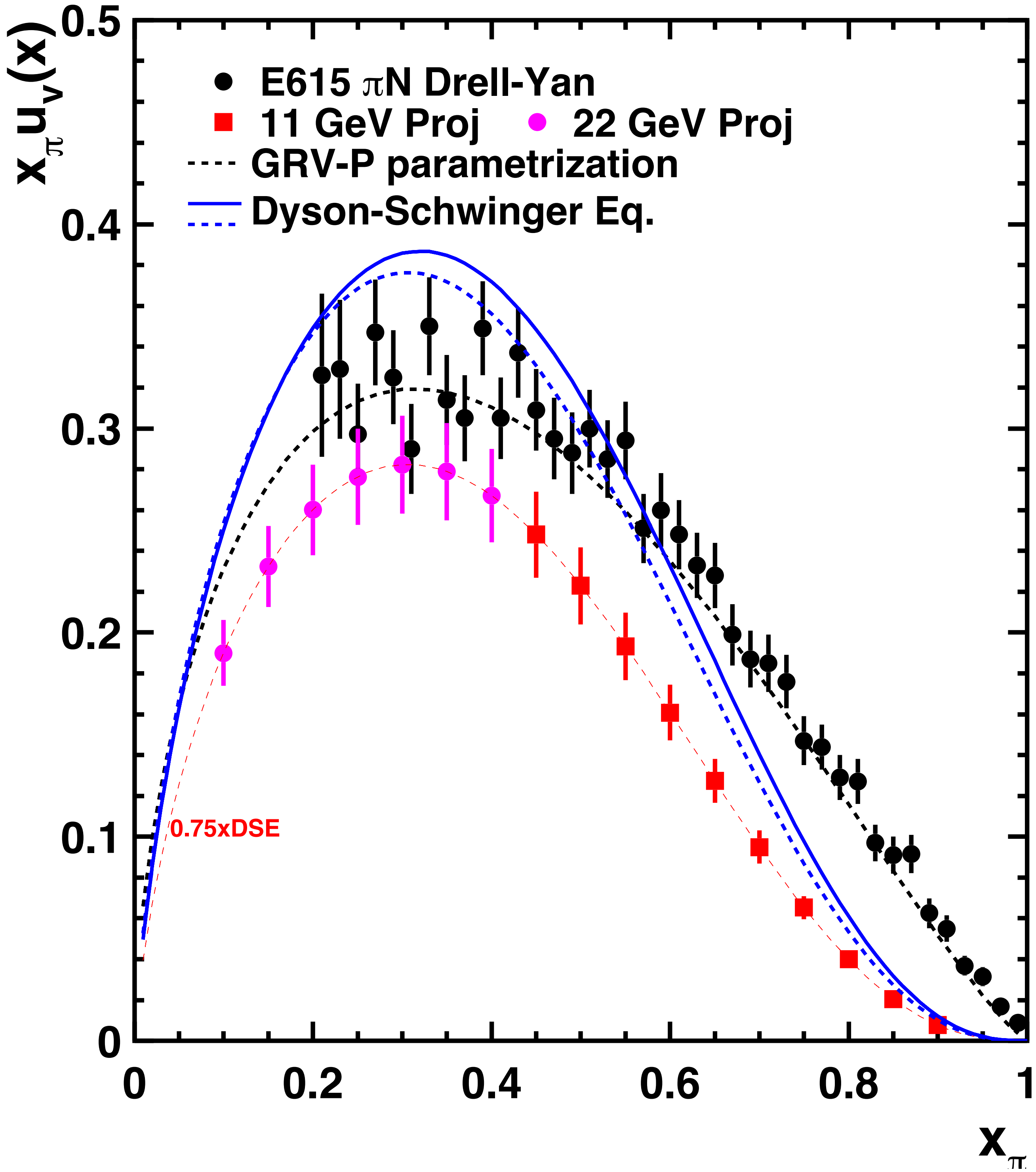




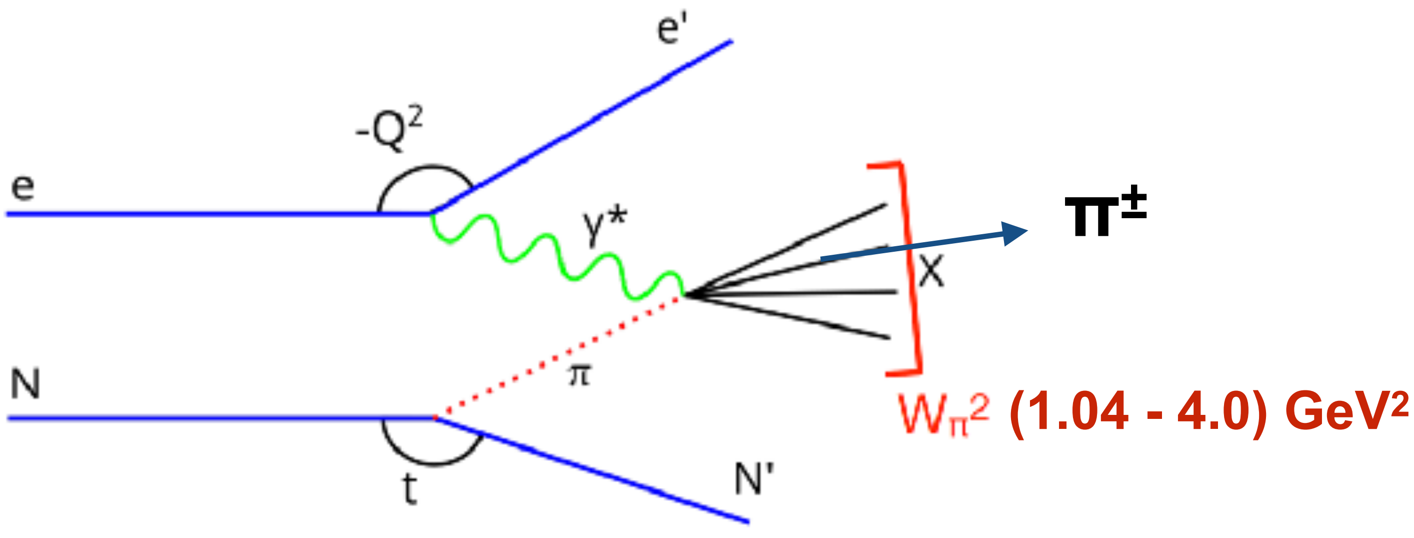
Based on simulations by P. Barry (JLab)

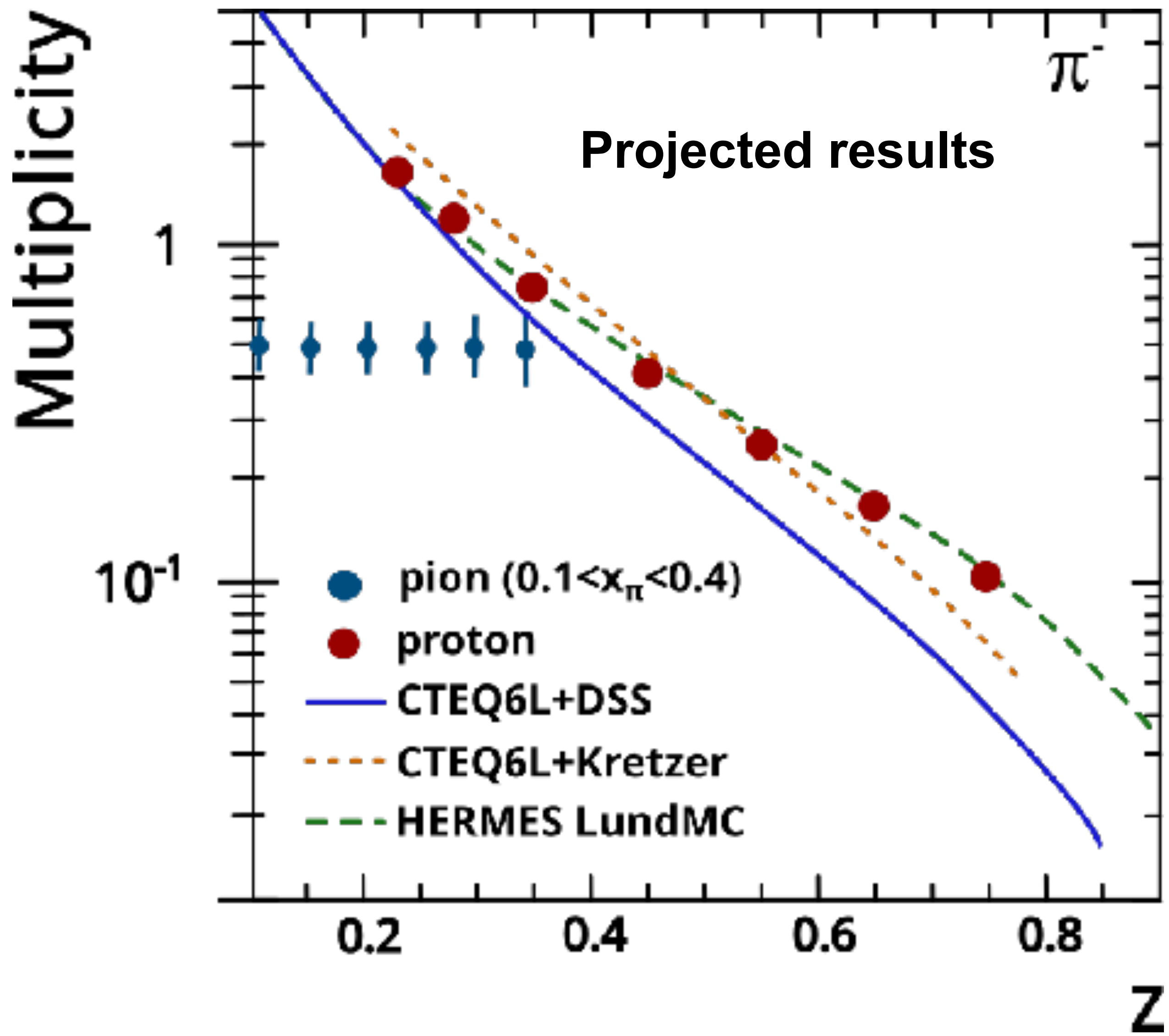
TDIS experiment with a 22 GeV beam would allow a more complete extraction of the pion structure functions

Projected results

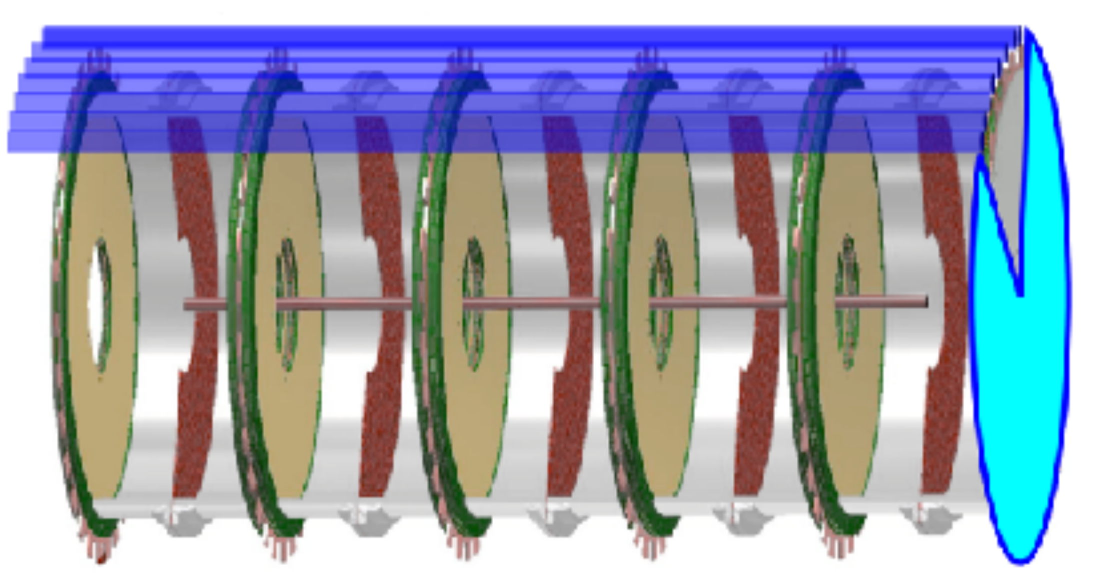


TDIS experiment with a 22 GeV beam will also provide access to pion TMDs





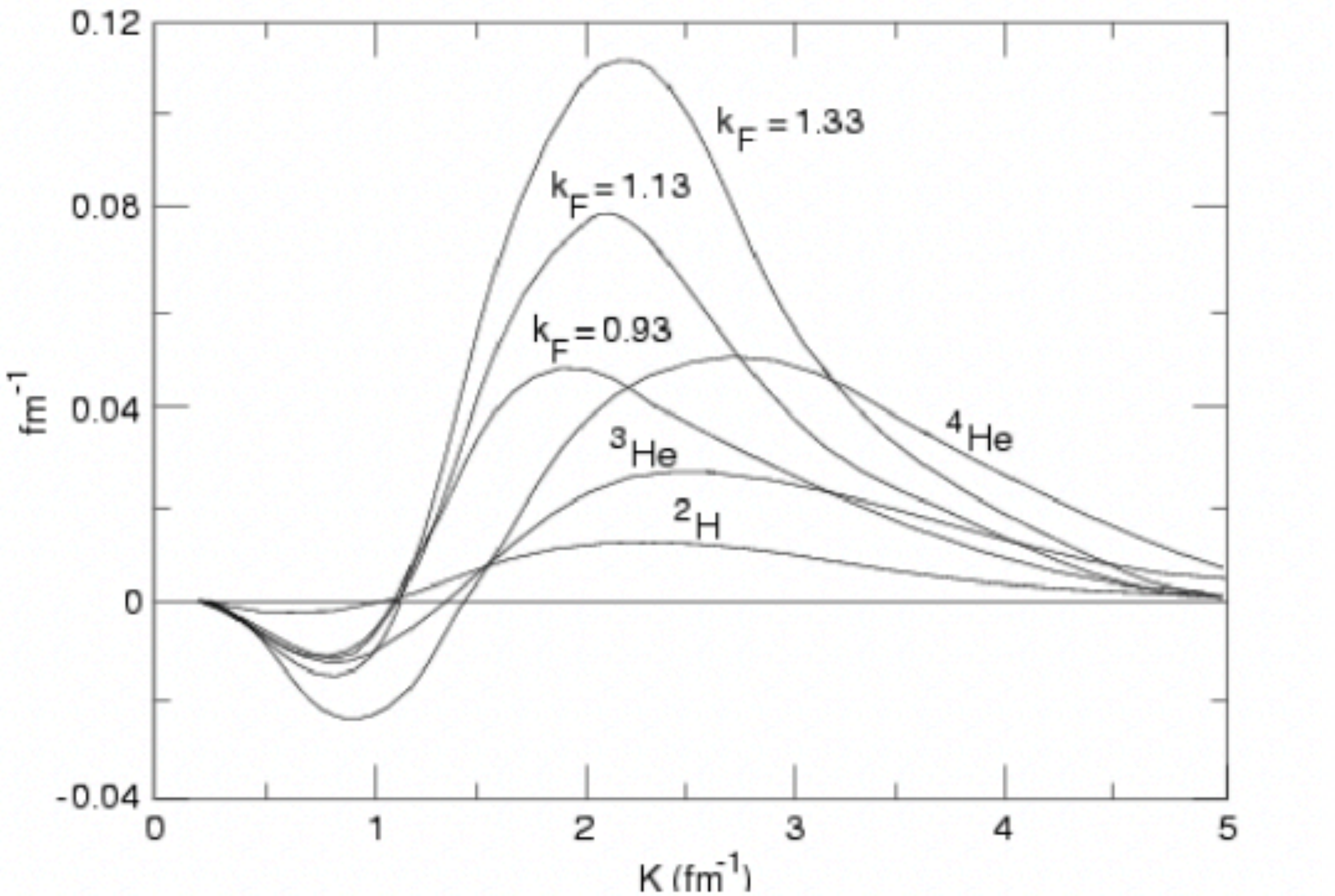
mTPC + scintillator



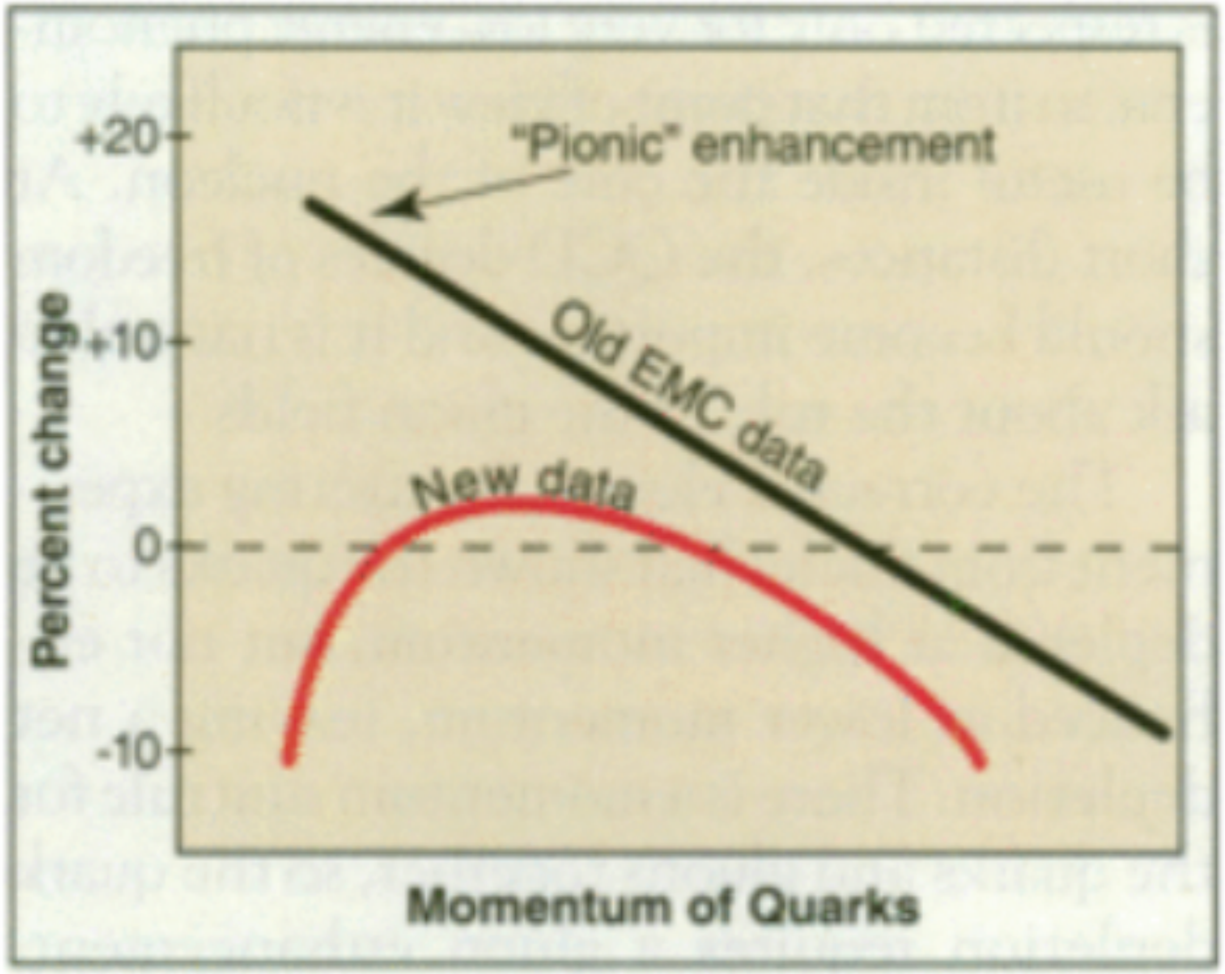
smaller diameter mTPC to fit within solenoid bore

"Nuclear pions" is a long-standing prediction in nuclear physics

Friman, Pandharipande, and Wiringa, PRL **51** 763 (1983)

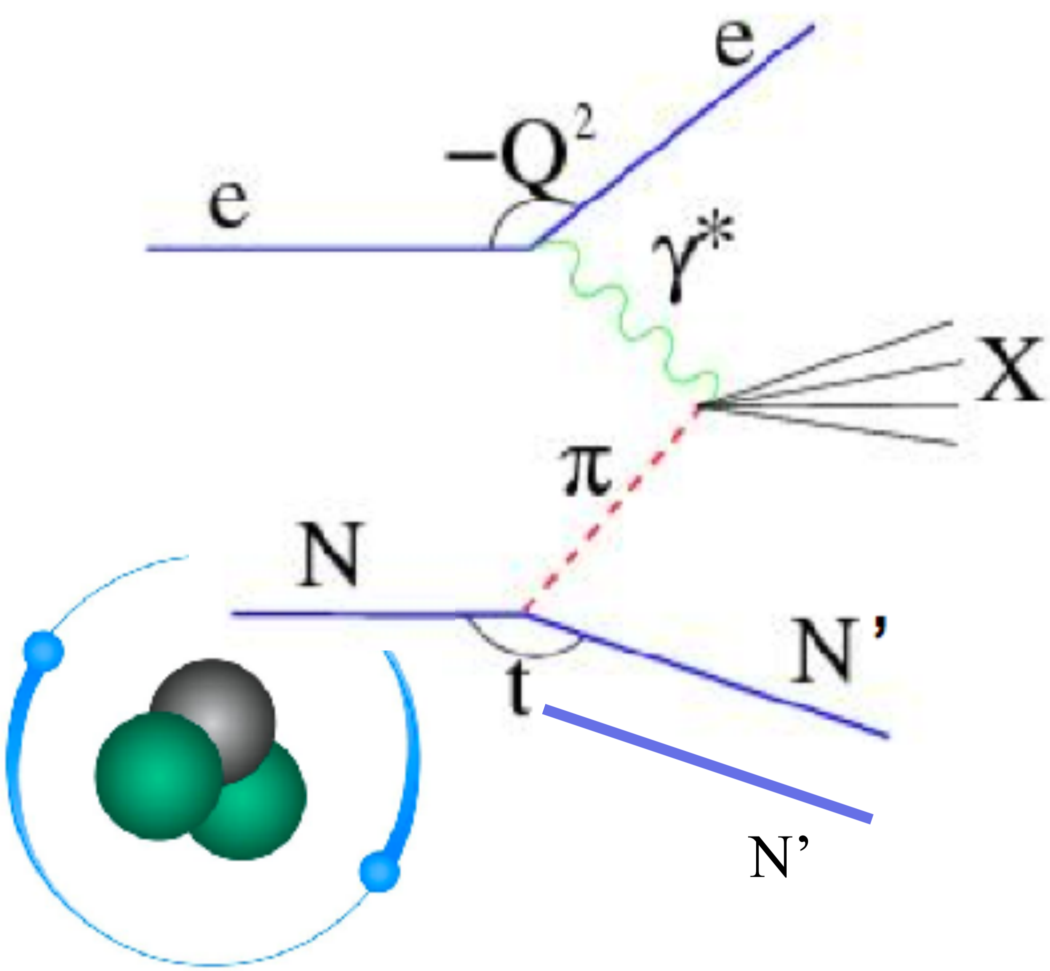


Pion excess $k^2\langle\delta n_\pi(k)\rangle/2\pi A$
as a function of virtual pion momentum

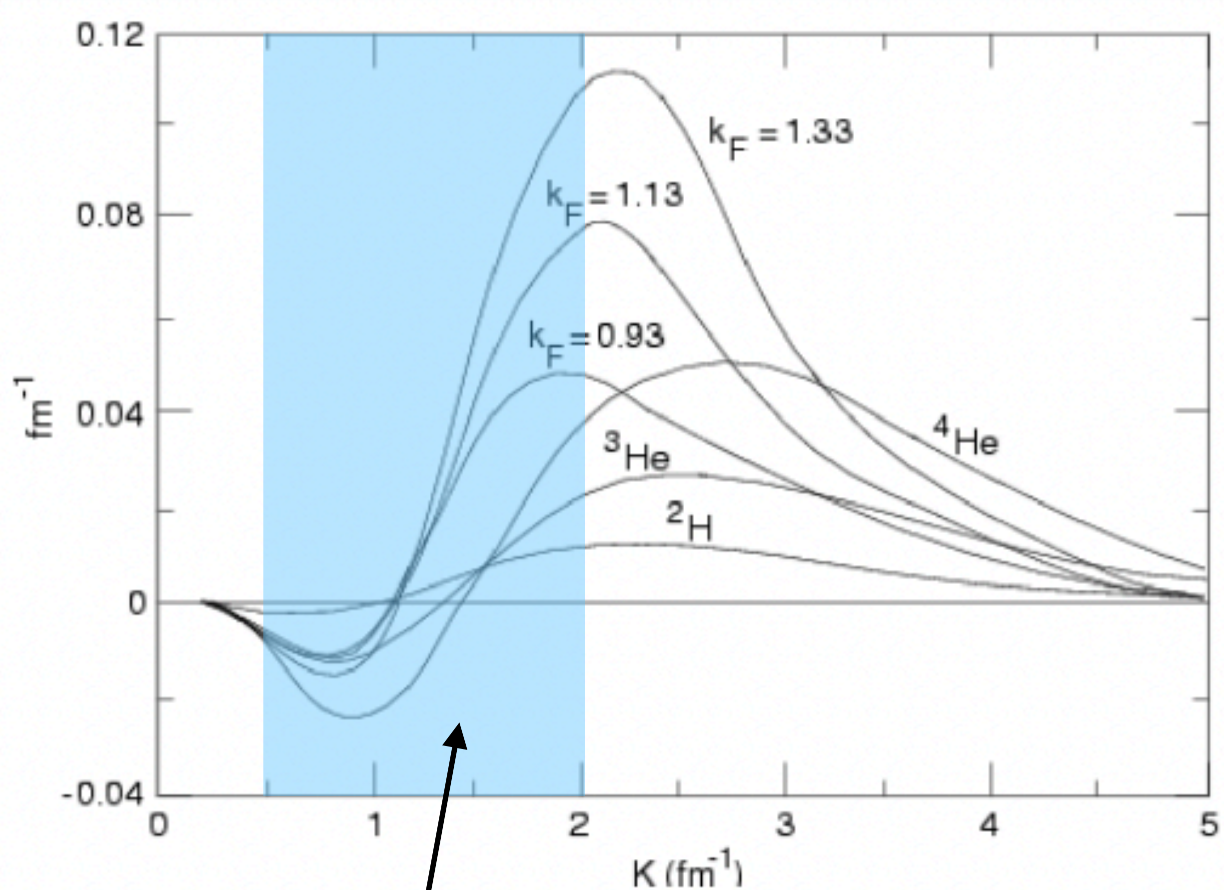


Bertsch, Frankfurt & Strikman,
Science 259, 773 (1993)

TDIS experiment with light nuclear targets will allow exploring “nuclear pions”



Friman, Pandharipande, and Wiringa, PRL **51** 763 (1983)



Pion excess $k^2\langle\delta n_\pi(k)\rangle/2\pi A$
as a function of virtual pion momentum

TDIS Recoil proton momentum: P_p = 0.1 - 0.4 GeV/c & $P_p = -P_\pi$

Use TDIS setup to measure the pionic content of ^{3}He and ^{4}He

look for excess pions relative to ^{2}H

Pion structure function from ^{2}H, ^{3}He and ^{4}He will allow a pionic EMC effect measurement @ 22 GeV high W^2 coverage of 0.05 < x < 0.3

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.

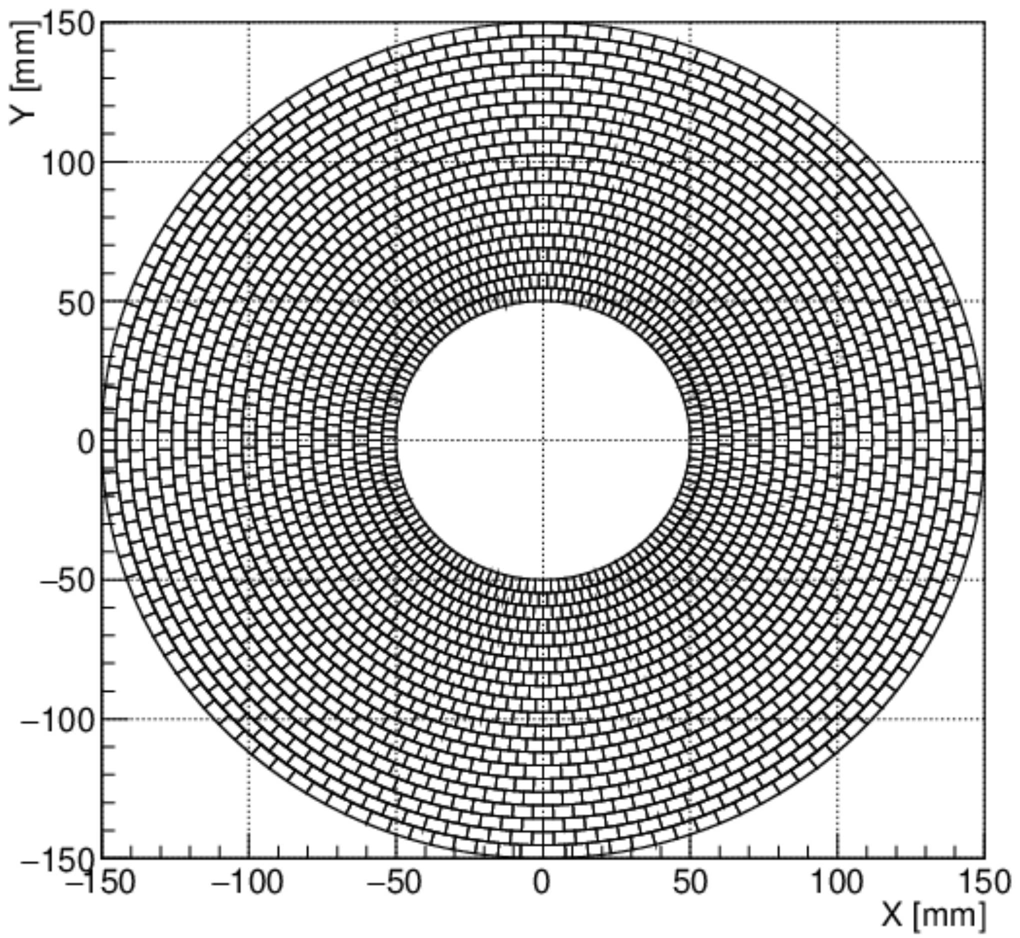
3. The upgrade of the beam to 22 GeV would vastly improve the kinematic coverage and the possible impact of these type of experiments.

4. It may also provide access to pion TMDs and the “nuclear pions”

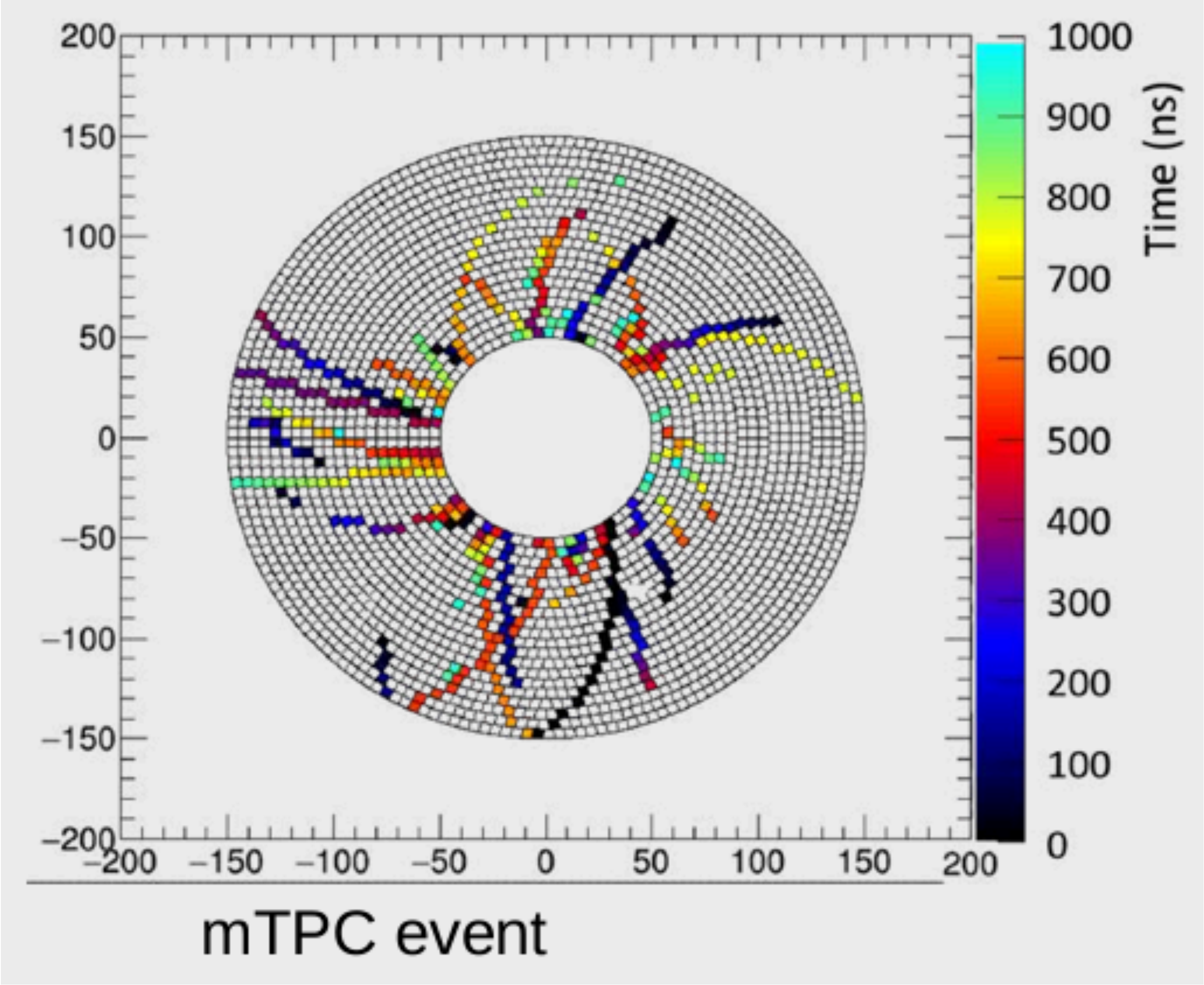
This work is supported by US Dept. Of Energy under contract # DE-FG02-07ER41528

Backup Slides

Readout pixel configuration and simulated hits

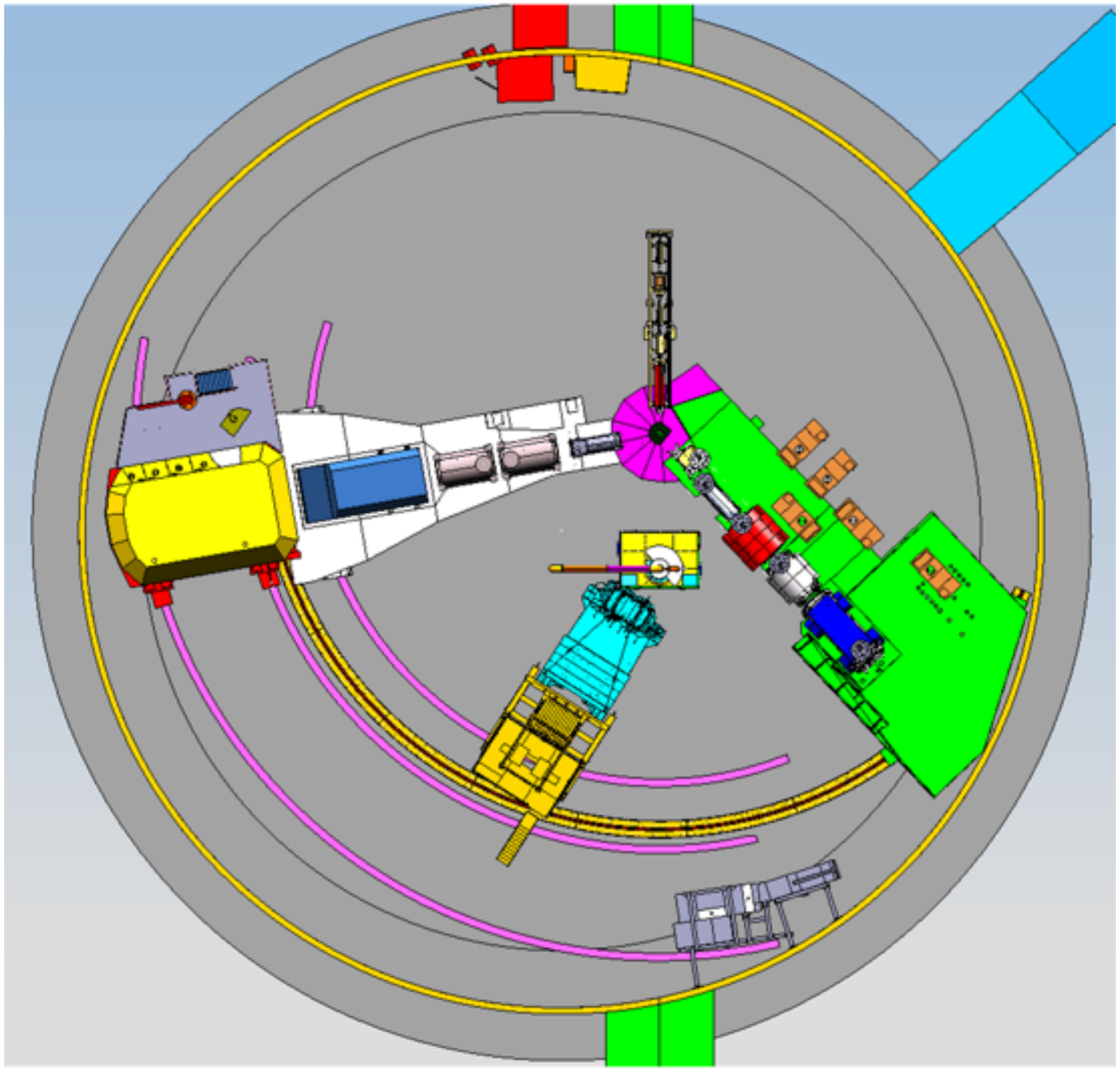


CAD design: K. Gnanvo



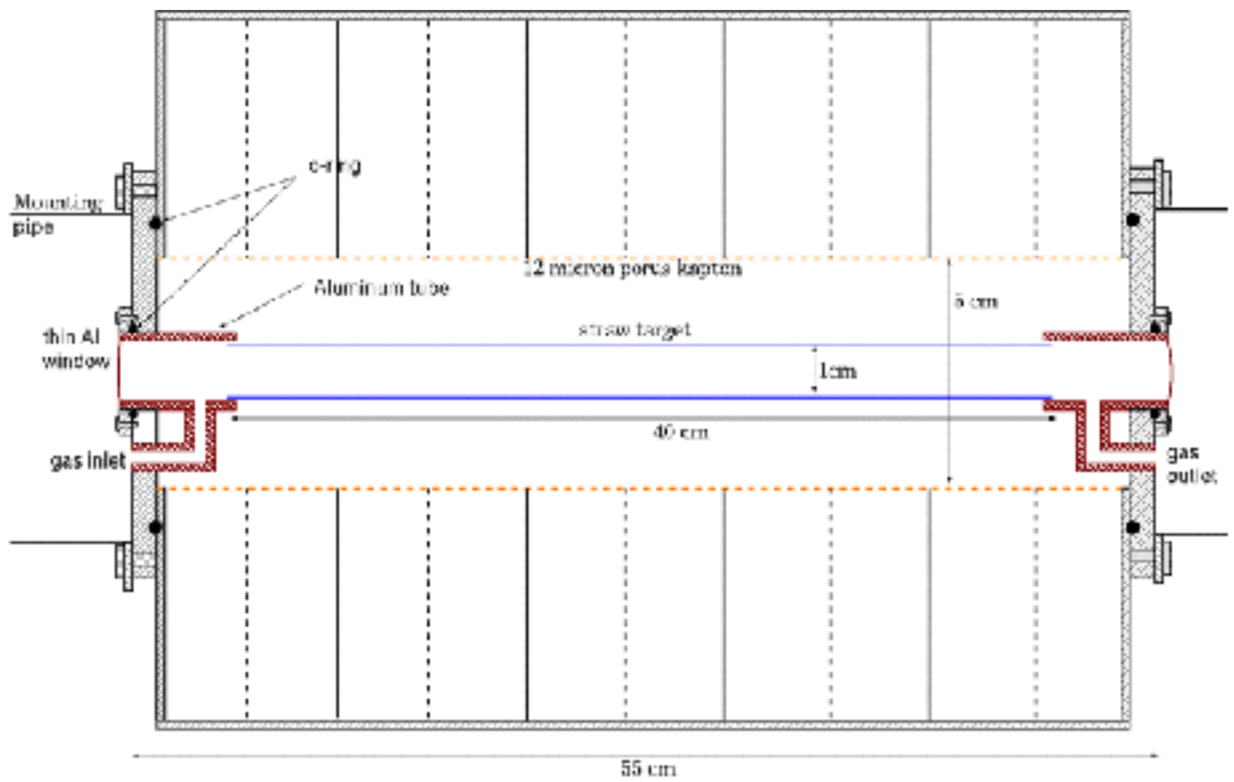
Plot credit: M. Carmignotto

SBS in Hall C



Solenoid & Target

spiral wound 25 um kapton straw Target



UVa 4T Solenoid

Pressure tested to 60 psi