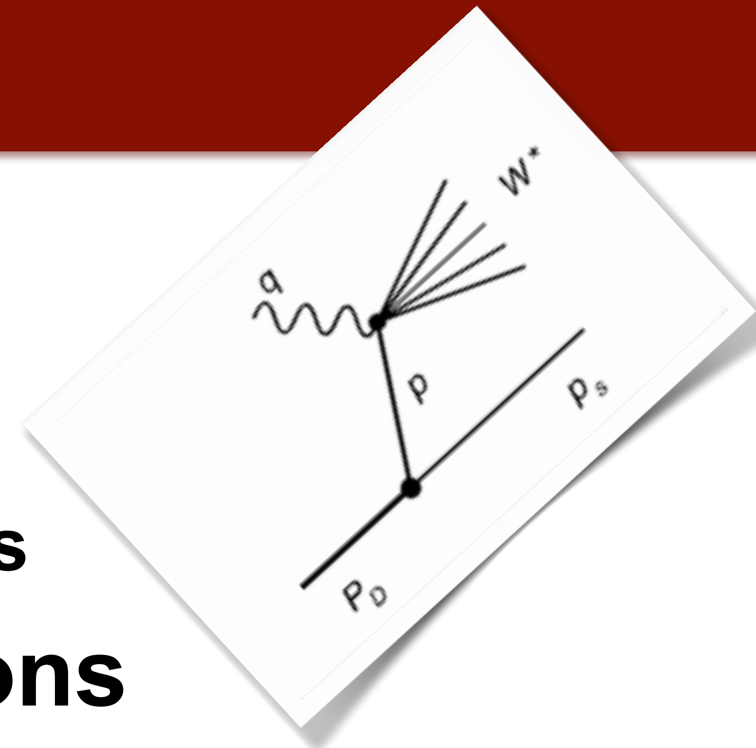
The Sullivan Process and TDIS:
Exploring beyond the meson structure functions

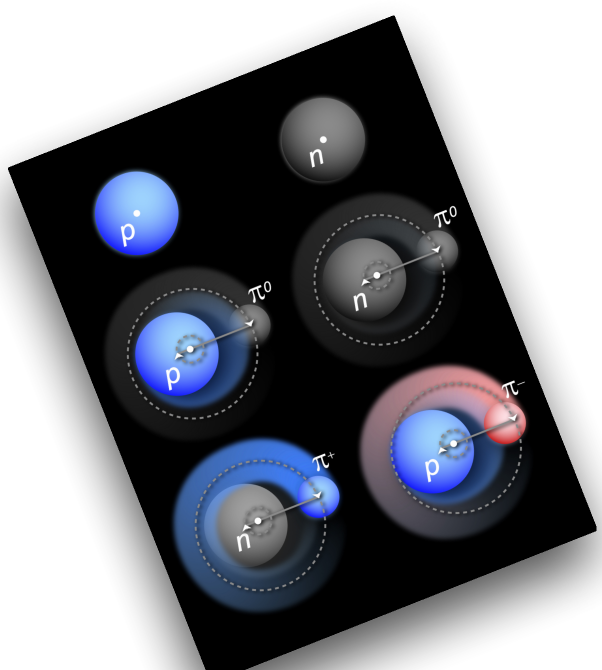
Dipangkar Dutta
Mississippi State University
for the TDIS collaboration

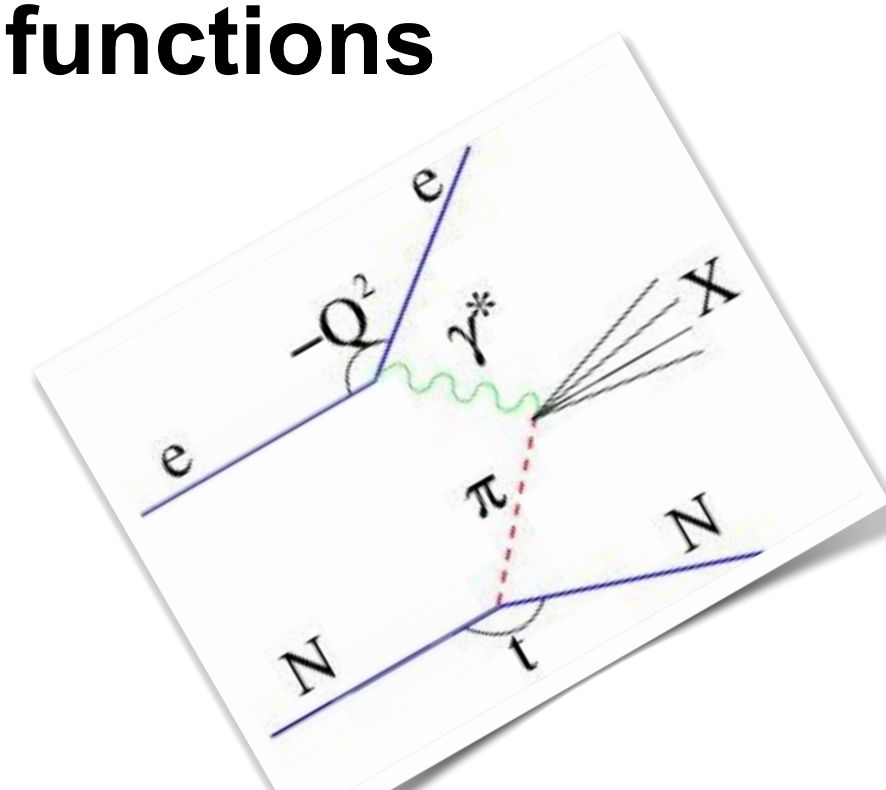
Towards Improved Hadron Femtography with Hard Exclusive Reactions
Aug 7-11, 2023

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**
   - pion TMDs
   - nuclear pions
   - pionic EMC
4. **Summary**

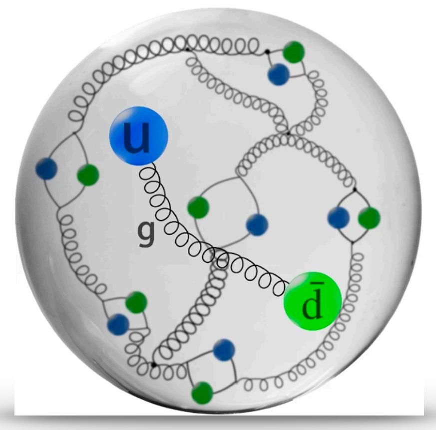


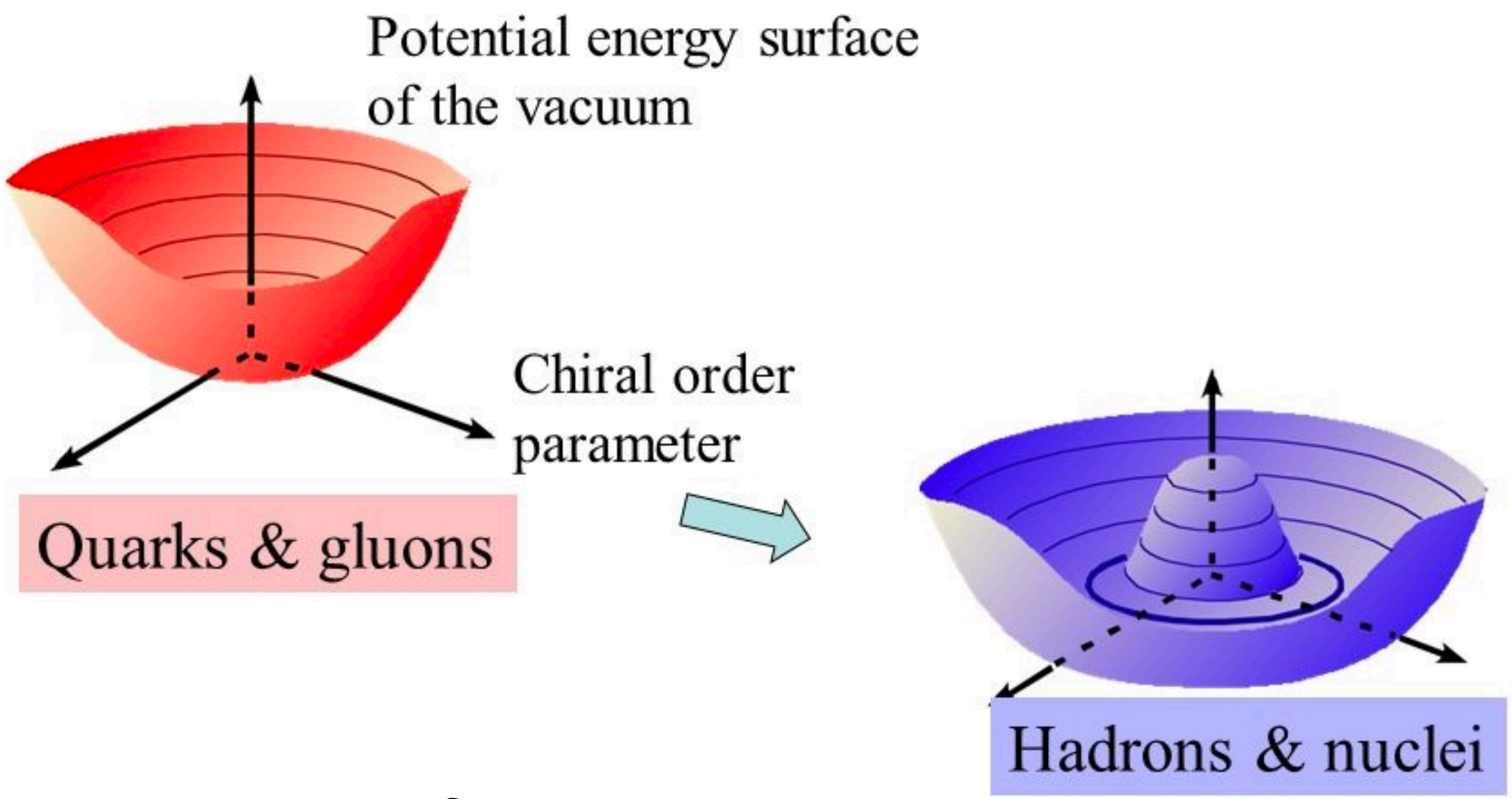


Pions and kaons are the simplest bound states of QCD and its mass-less Nambu-Goldstone bosons

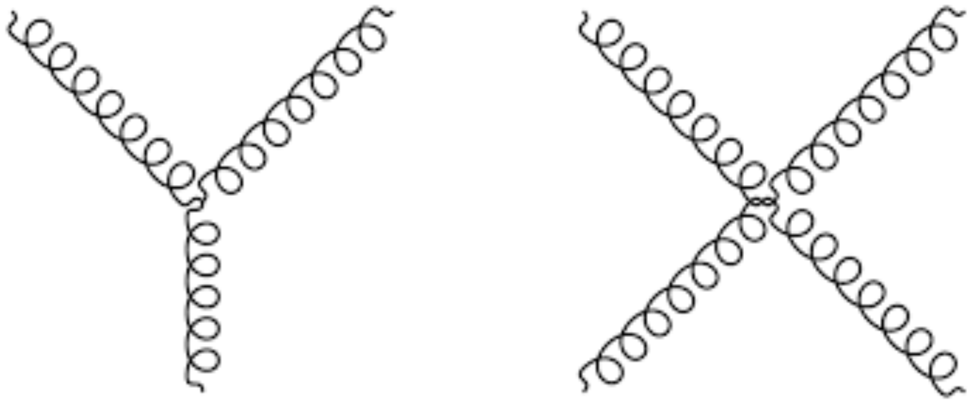
emergence of mass via dynamical chiral symmetry breaking

π+



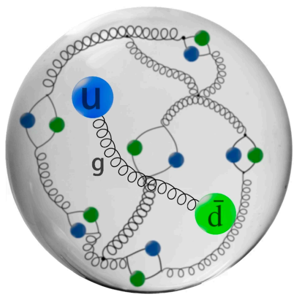


a consequence of gluon self interaction

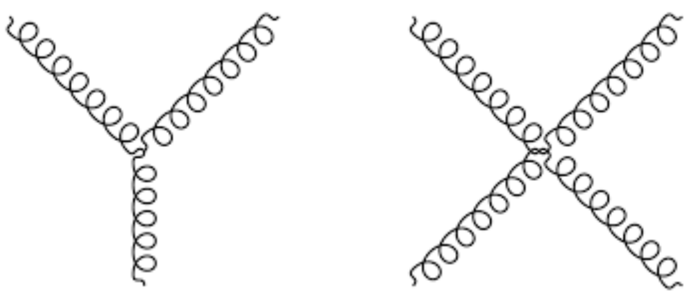


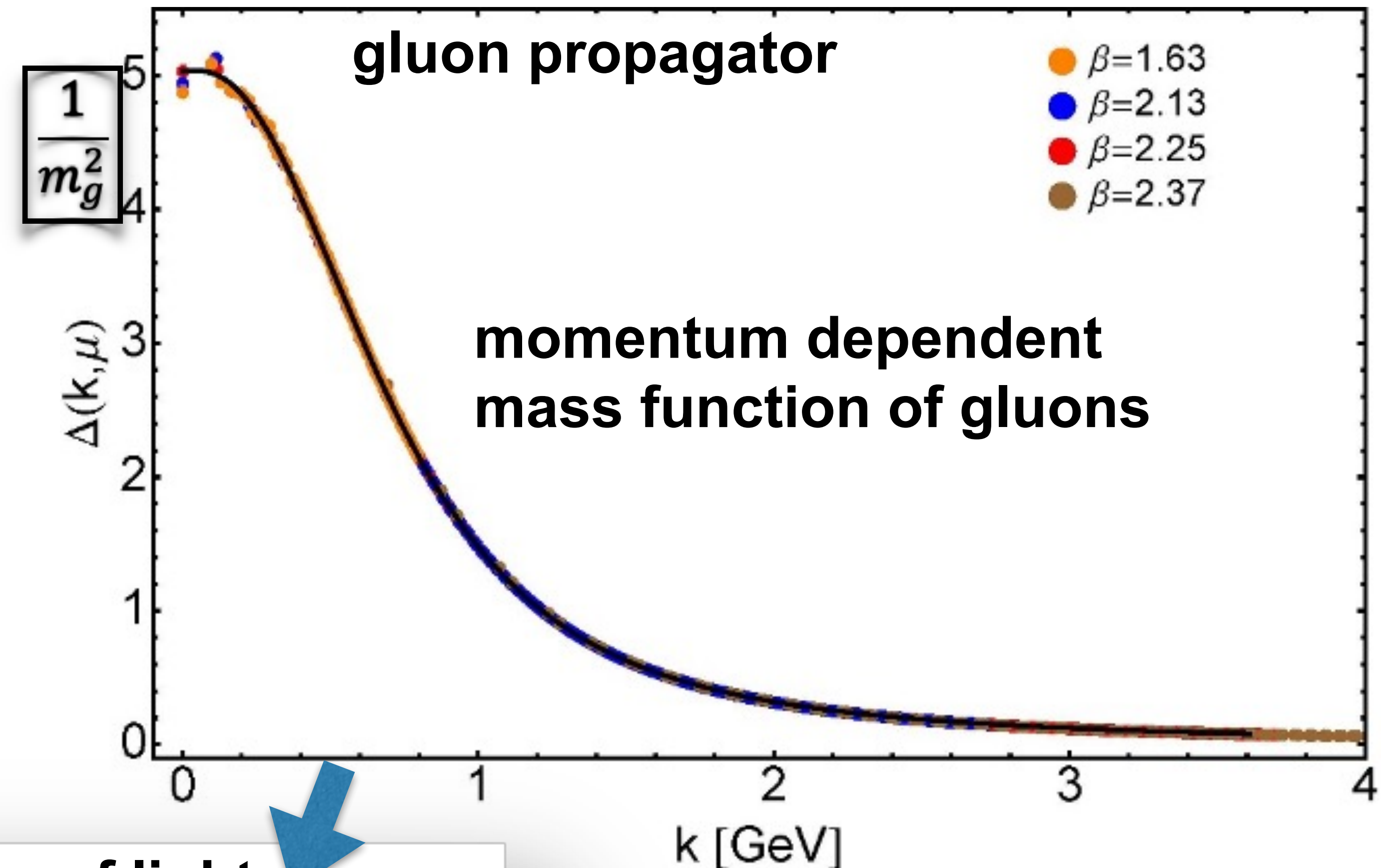
Pion and kaon mass emerge due to dynamical chiral symmetry breaking

π+

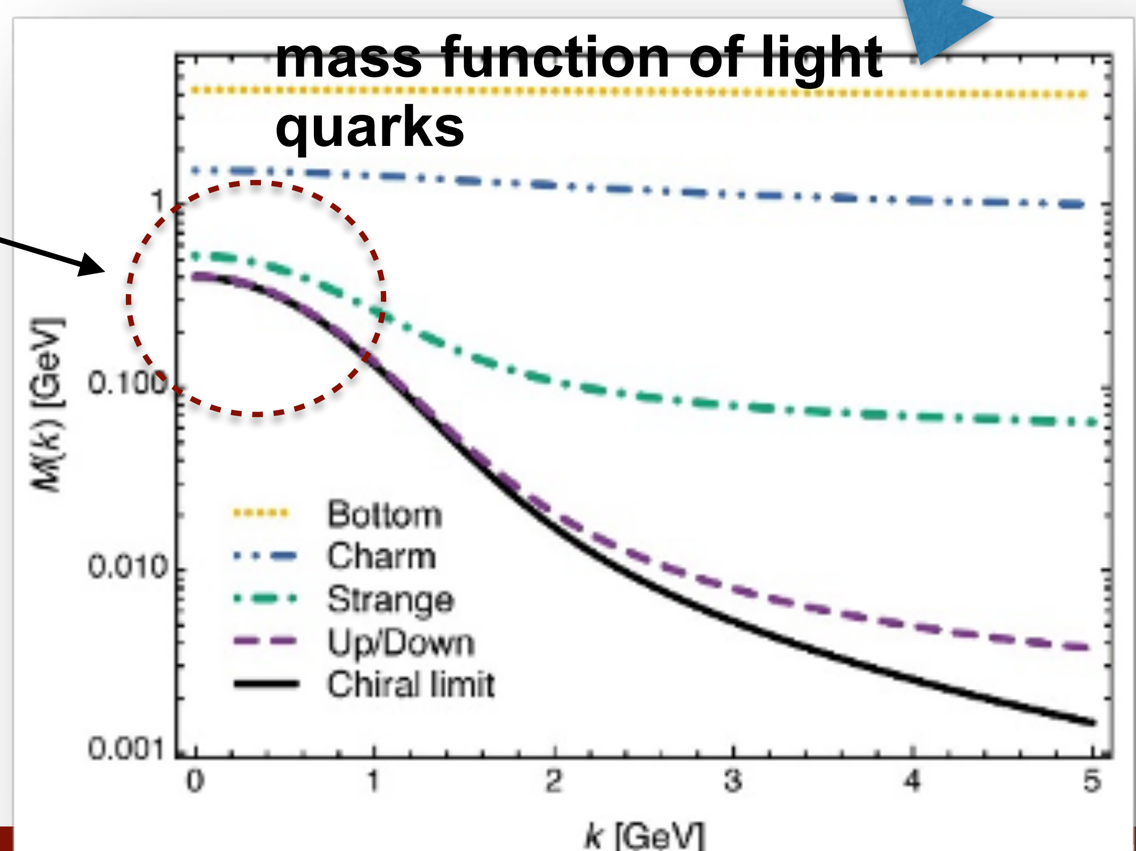


a consequence of
gluon self interaction





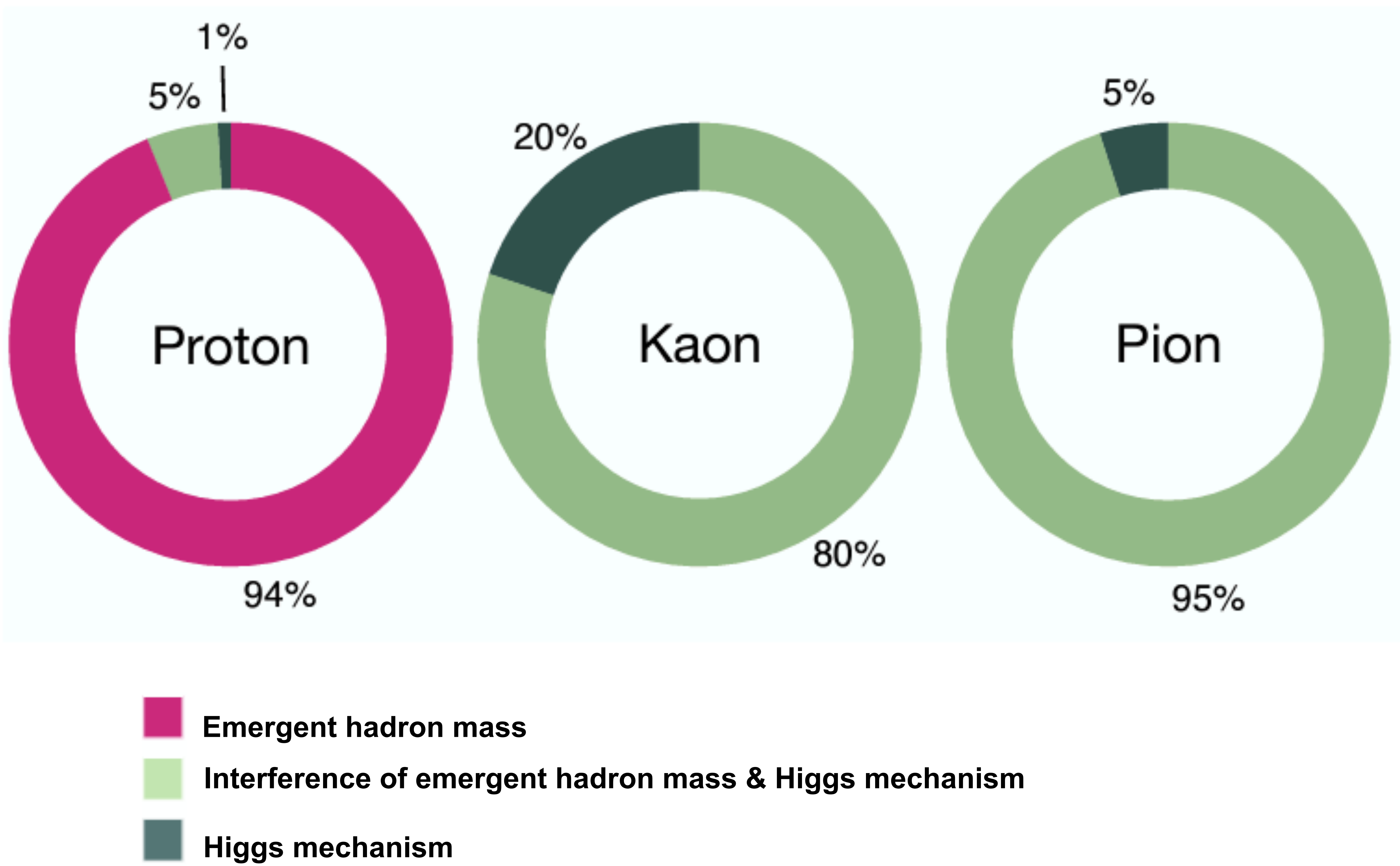
Rapid increase in
mass due to
gluon cloud



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

images courtesy of
C. D. Roberts

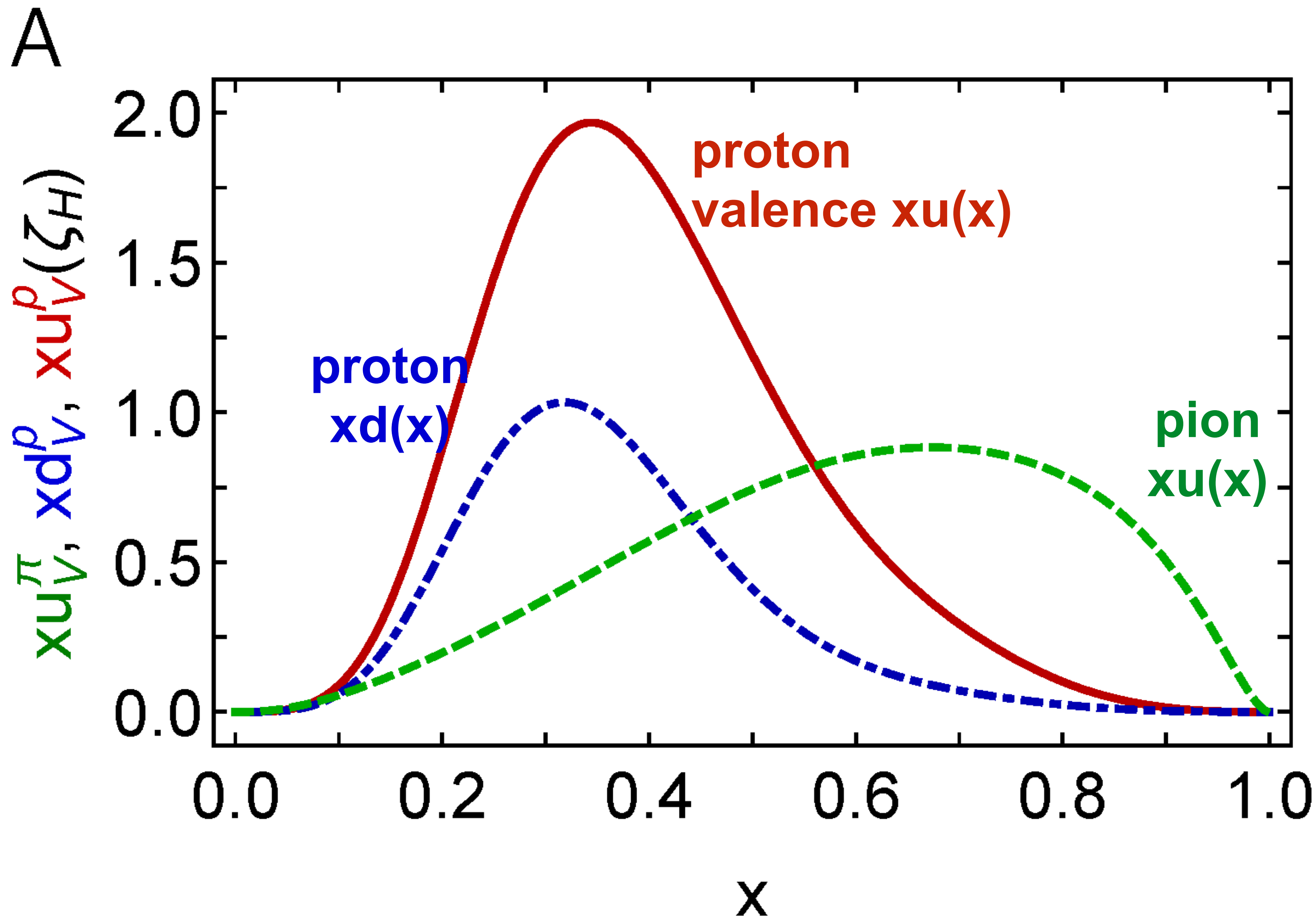
Mass budget for mesons and nucleons are vastly different



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



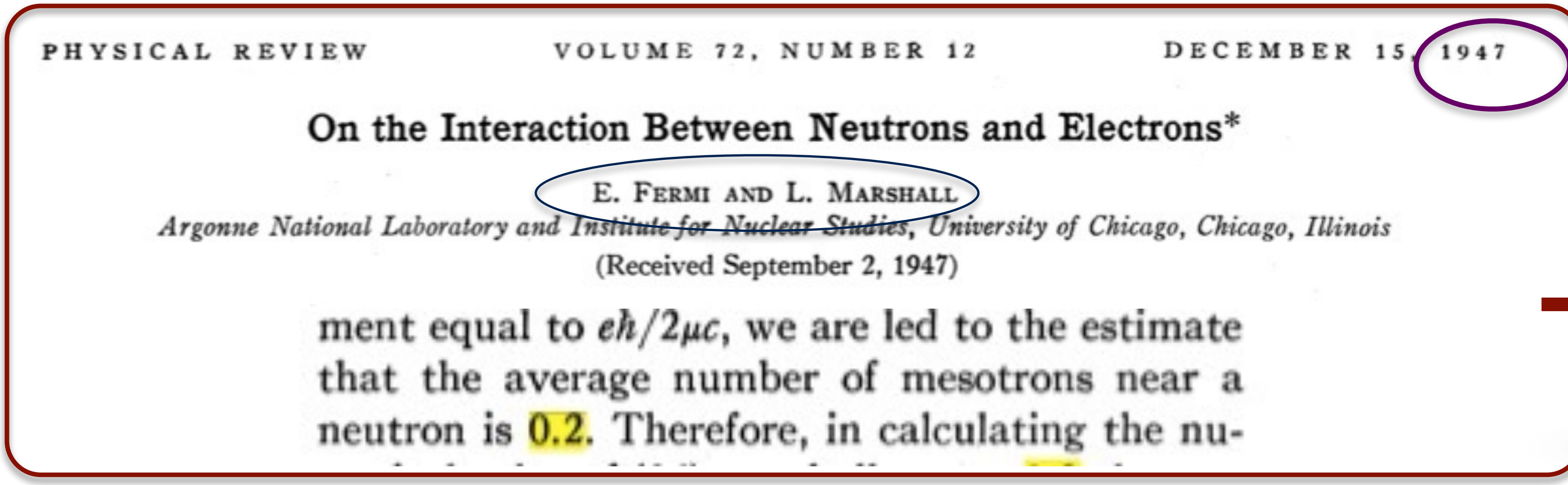
difference between meson PDFs: direct information on emergent hadron mass

Lack of stable meson targets ⇒ scant experimental data

How about mesons in nucleons?

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

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


PHYSICAL REVIEW VOLUME 72, NUMBER 12 DECEMBER 15, 1947

On the Interaction Between Neutrons and Electrons*

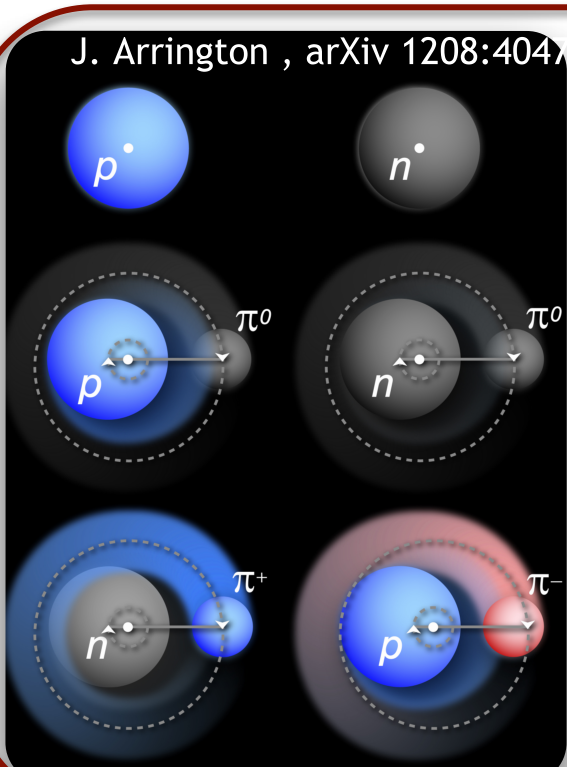
E. FERMI AND L. MARSHALL

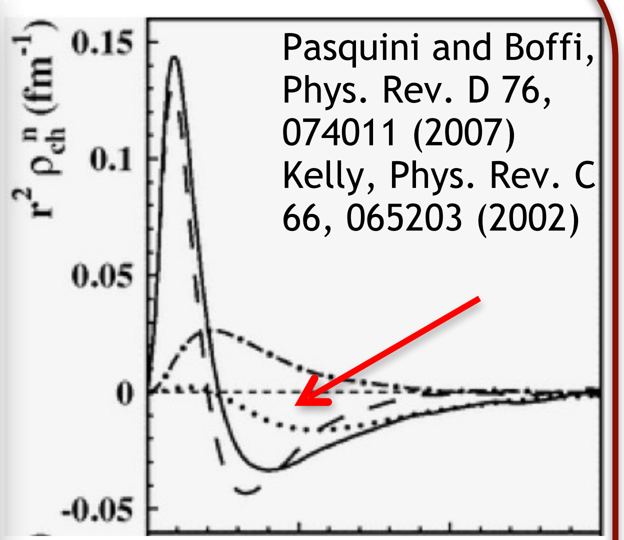
Argonne National Laboratory and Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

(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-

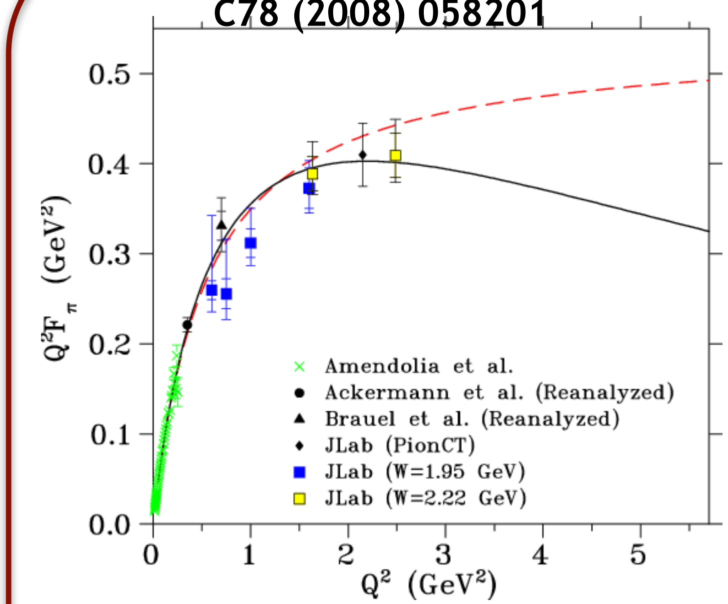
Experimental evidence pointed to the nucleon existing ~20% of the time in a virtual meson-nucleon state.





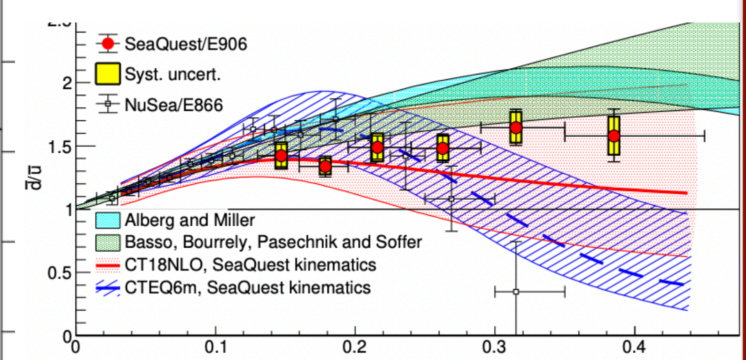
Proton & Neutron Charge Distribution

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



Pion Form Factor

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

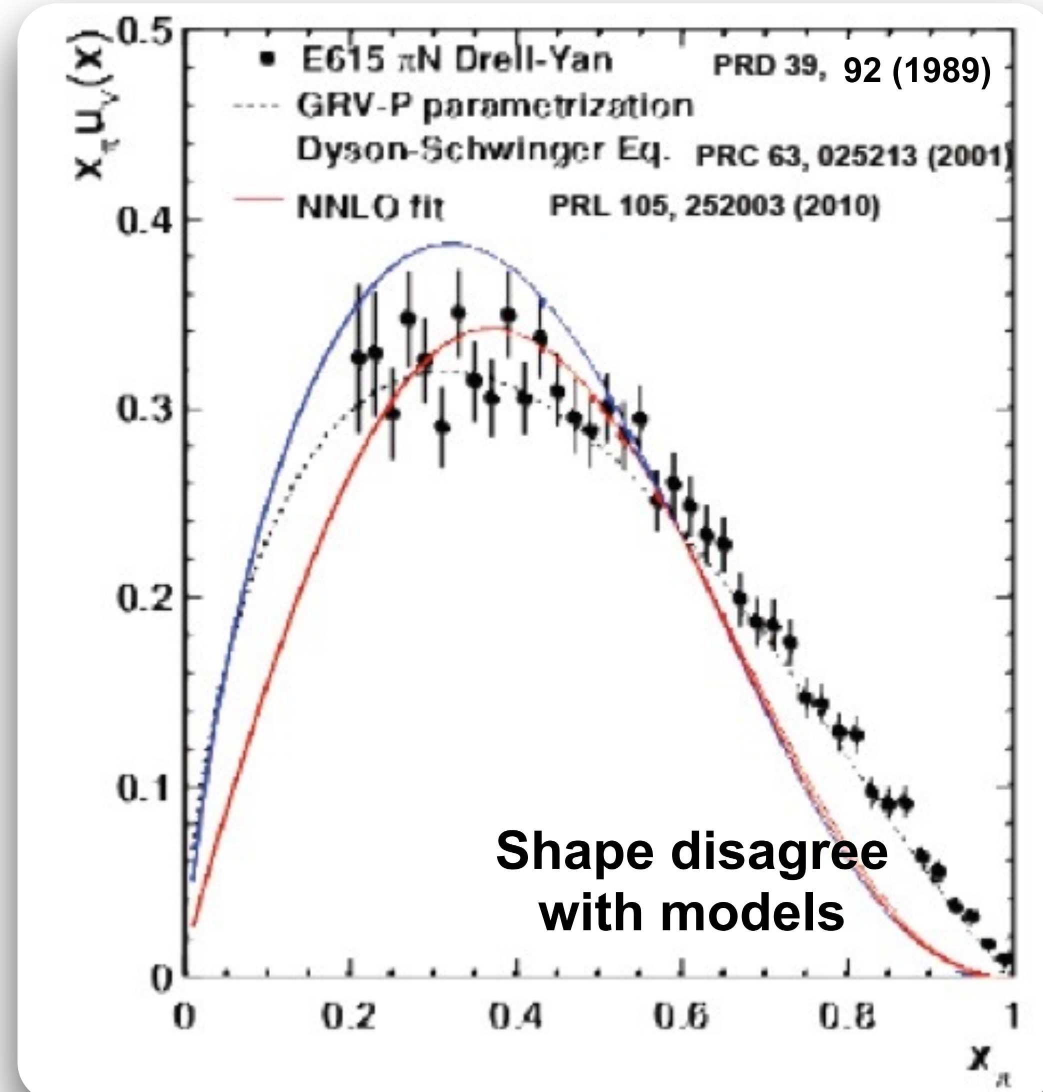


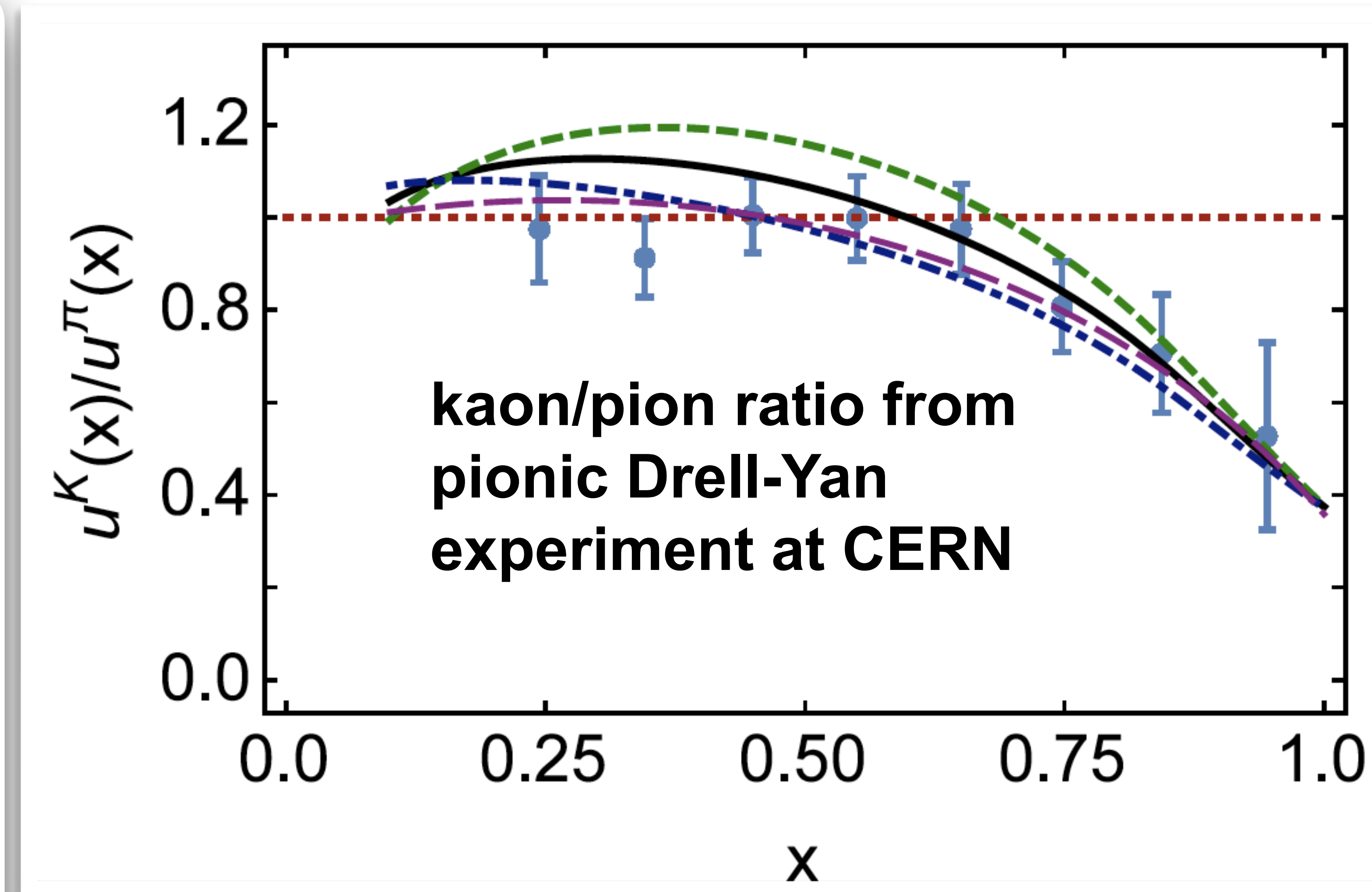
up/down sea-antiquark flavor asymmetry

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

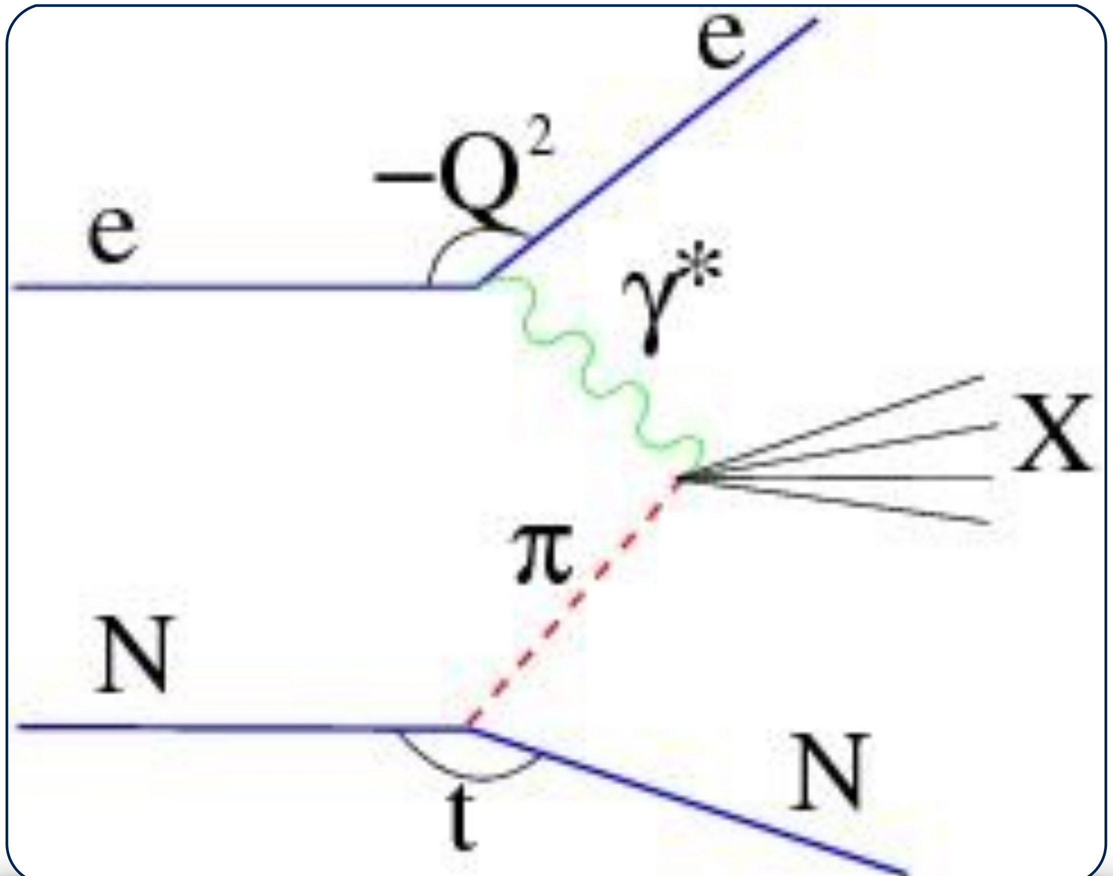
Need more and precise data

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)

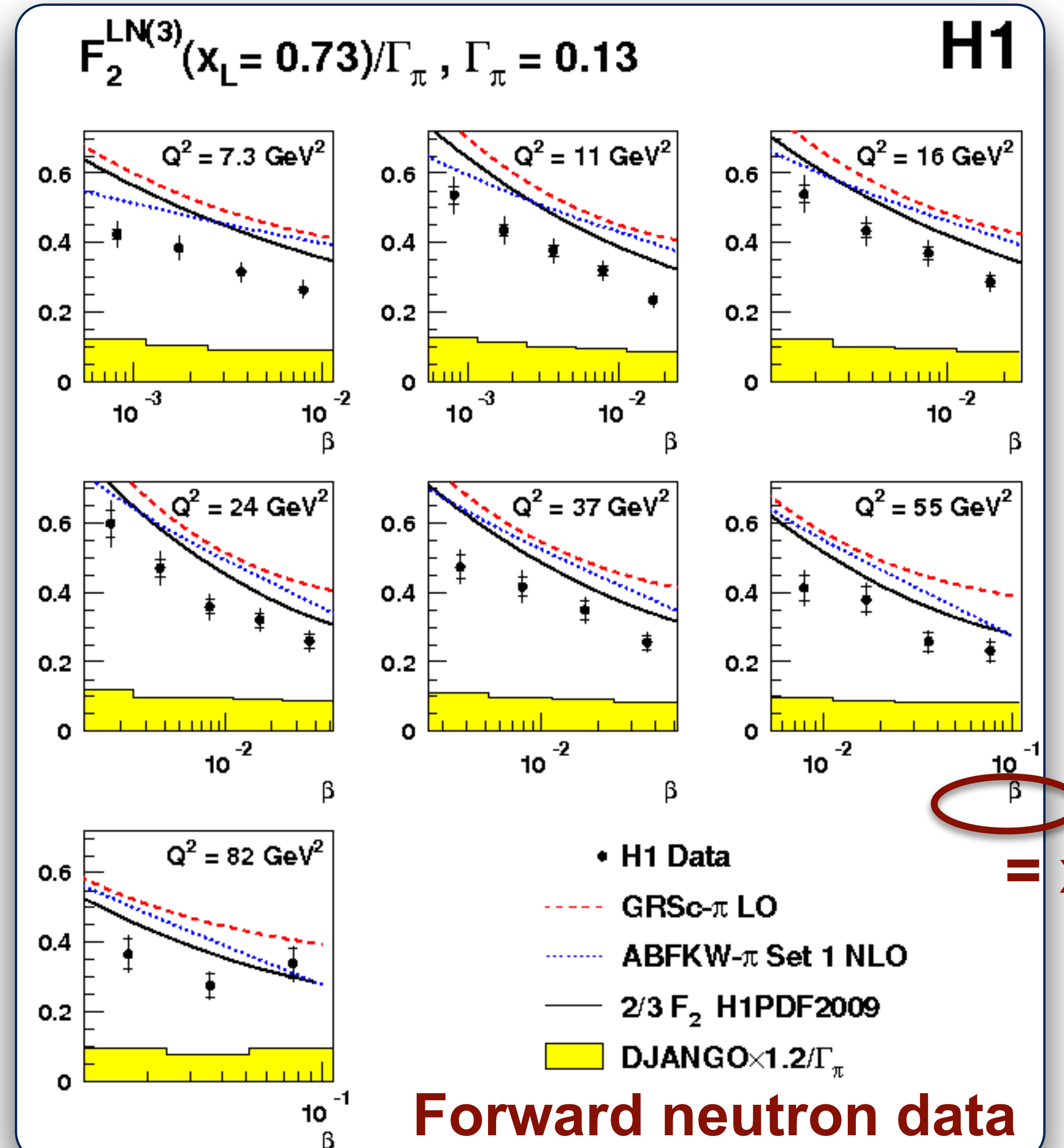
Deep-inelastic Scattering off a virtual-meson cloud is a possible experimental technique.

The Sullivan process



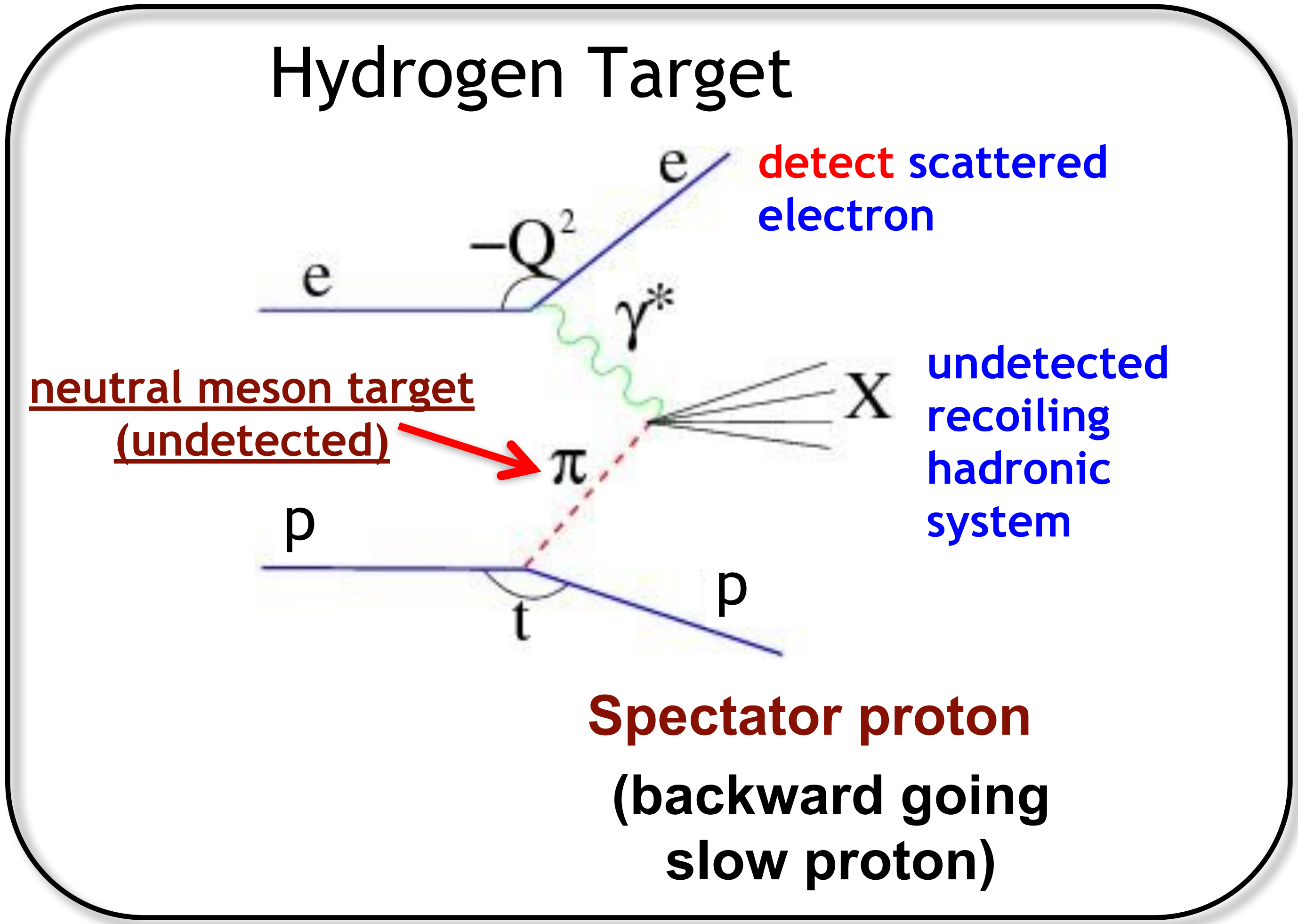
direct measurement of the mesonic content of the nucleon

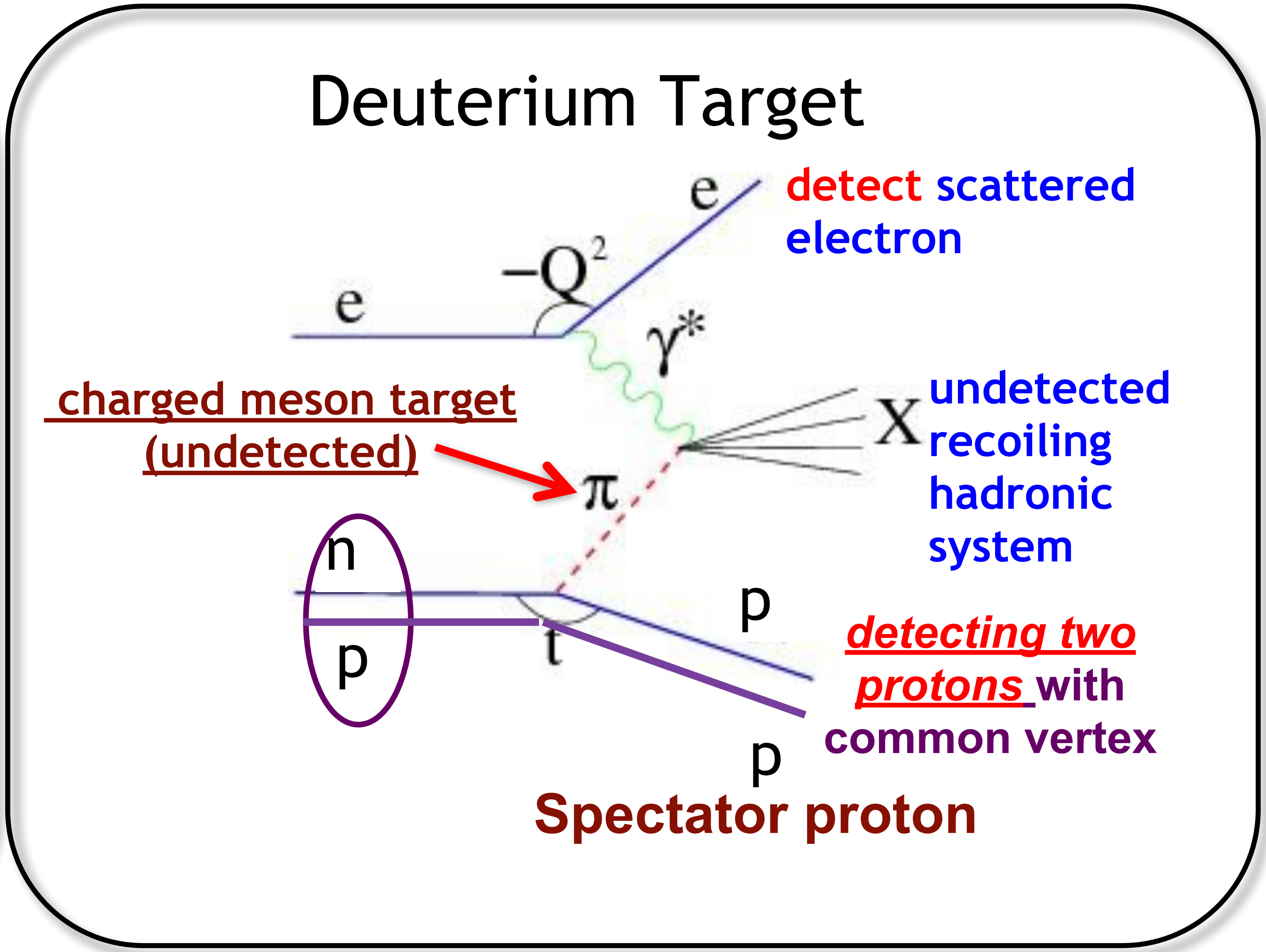
DIS events with forward going neutrons in coincidence



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.





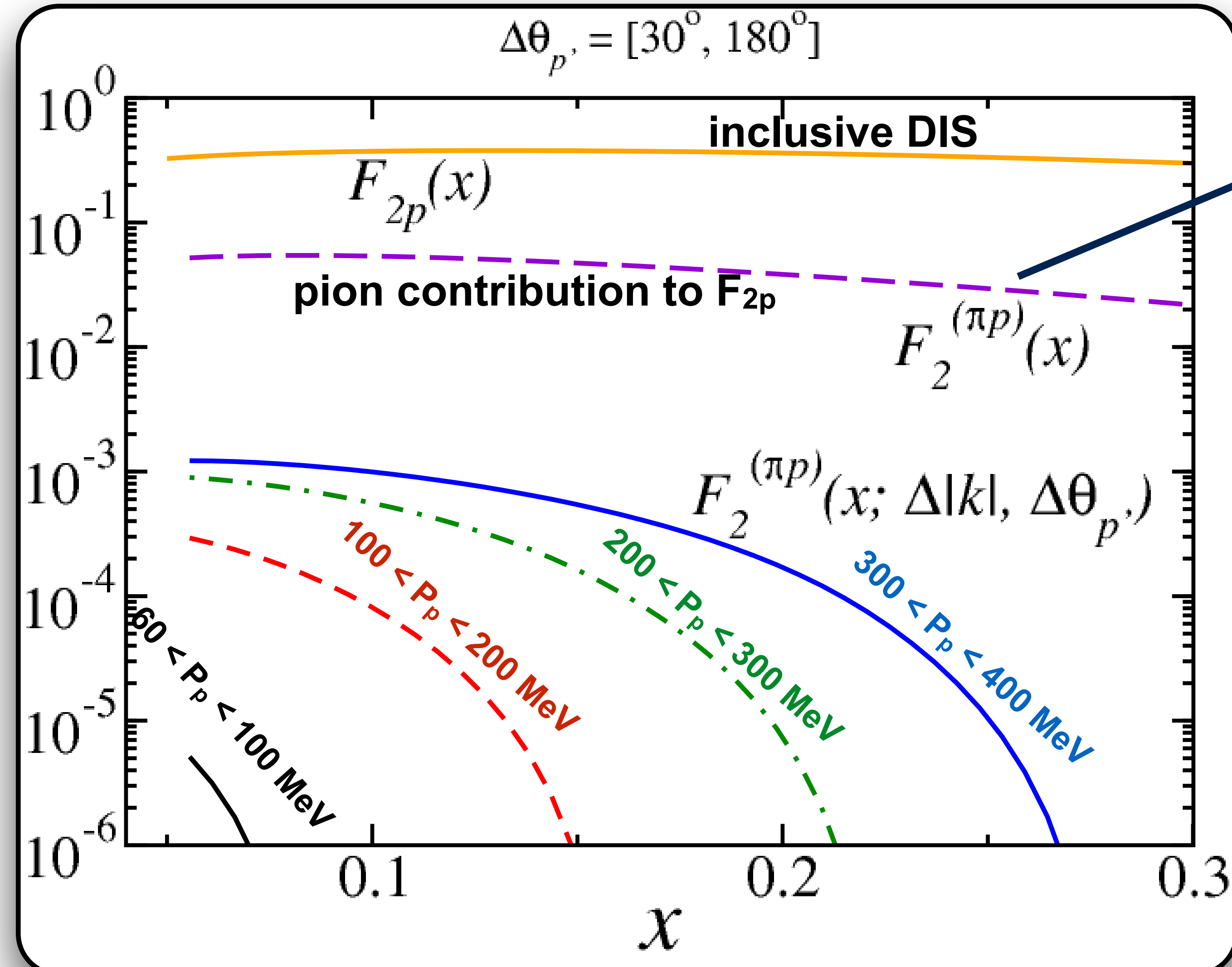
DIS event – reconstruct x, Q^2, W^2, also M_X of recoiling hadronic system

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

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

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

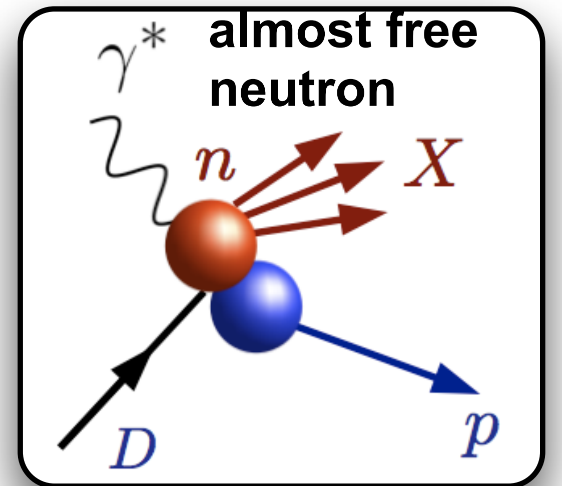
Tagged SF **pion "flux"** **Pion SF**

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)

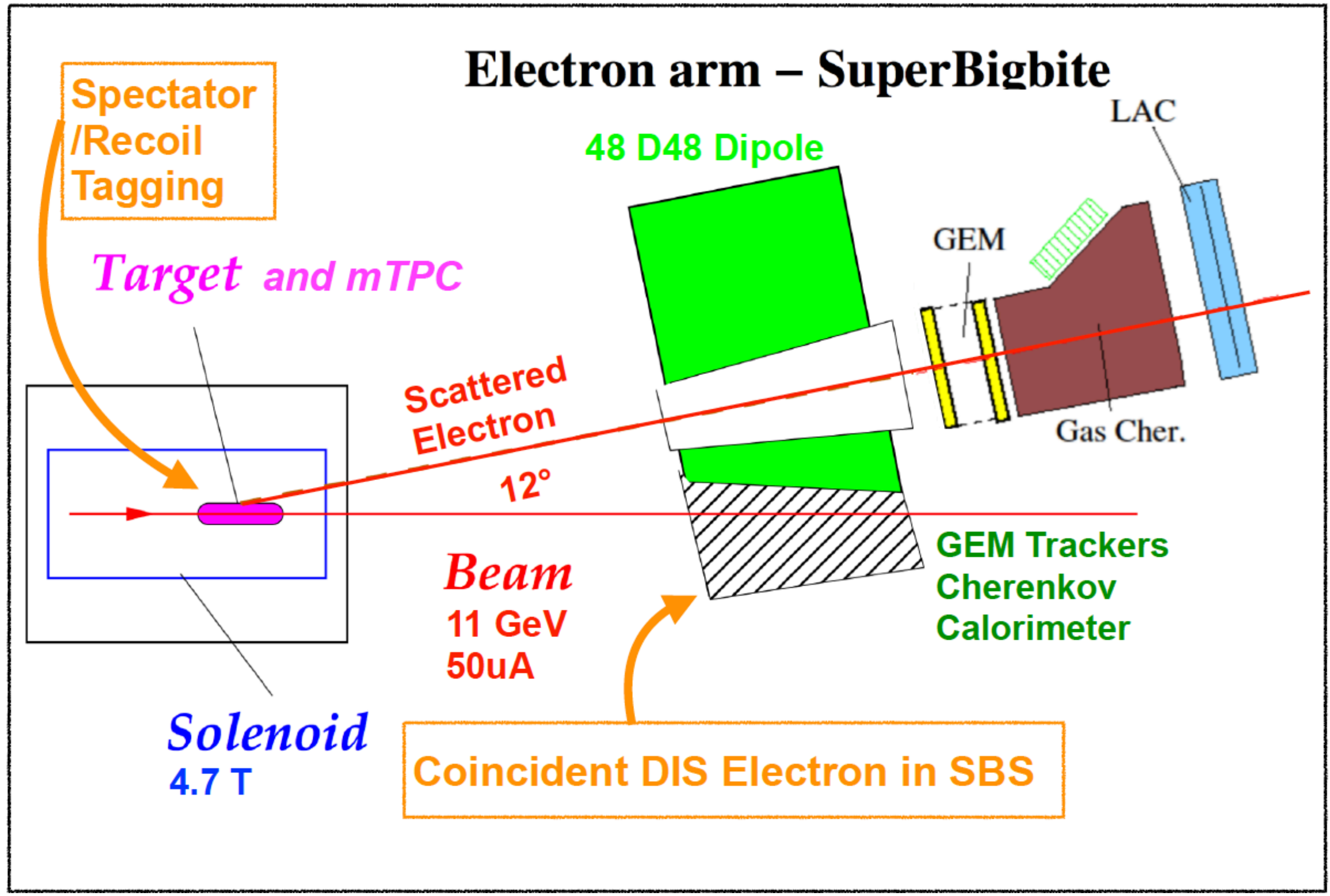
Spectator Tagging - a well established technique at JLab - can be used to tag the "meson cloud" target.

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



Deuteron Spectator proton

(backward going slow proton)

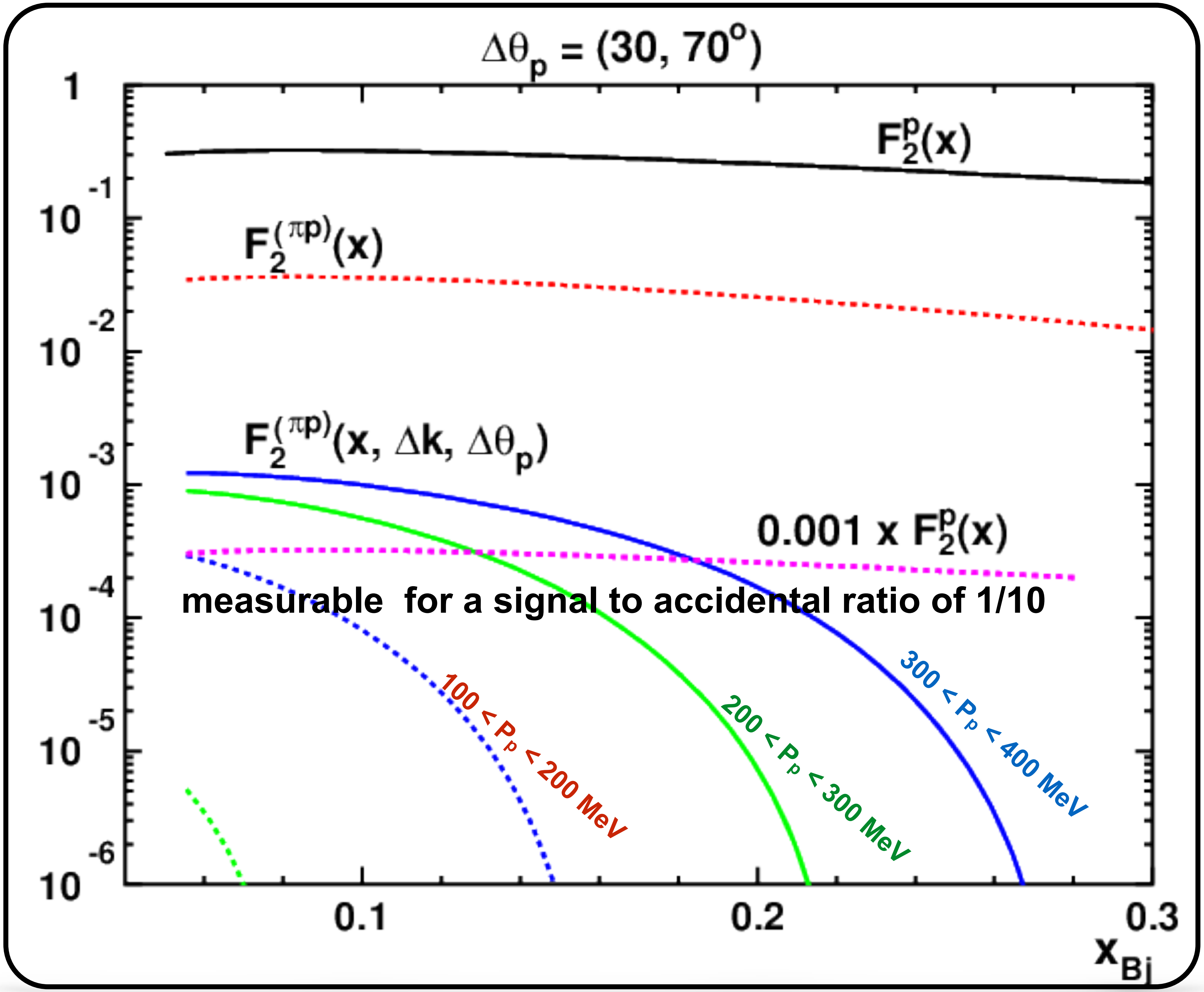


Target: 40 cm long, 25 um wall thickness Kapton straw at room temperature and 3 atm. pressure.

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

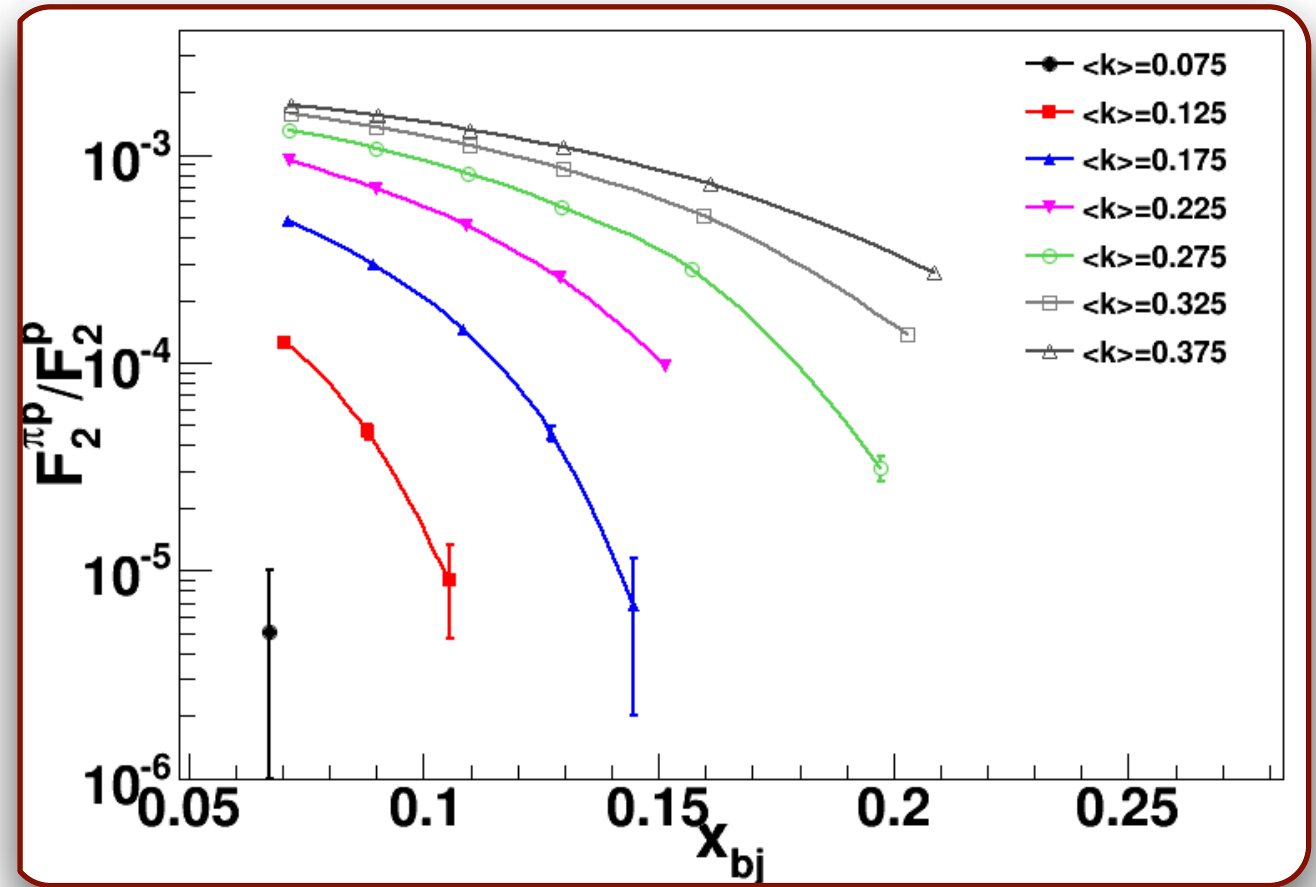
The techniques used to extract meson structure function will be a necessary first step for future experiments

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

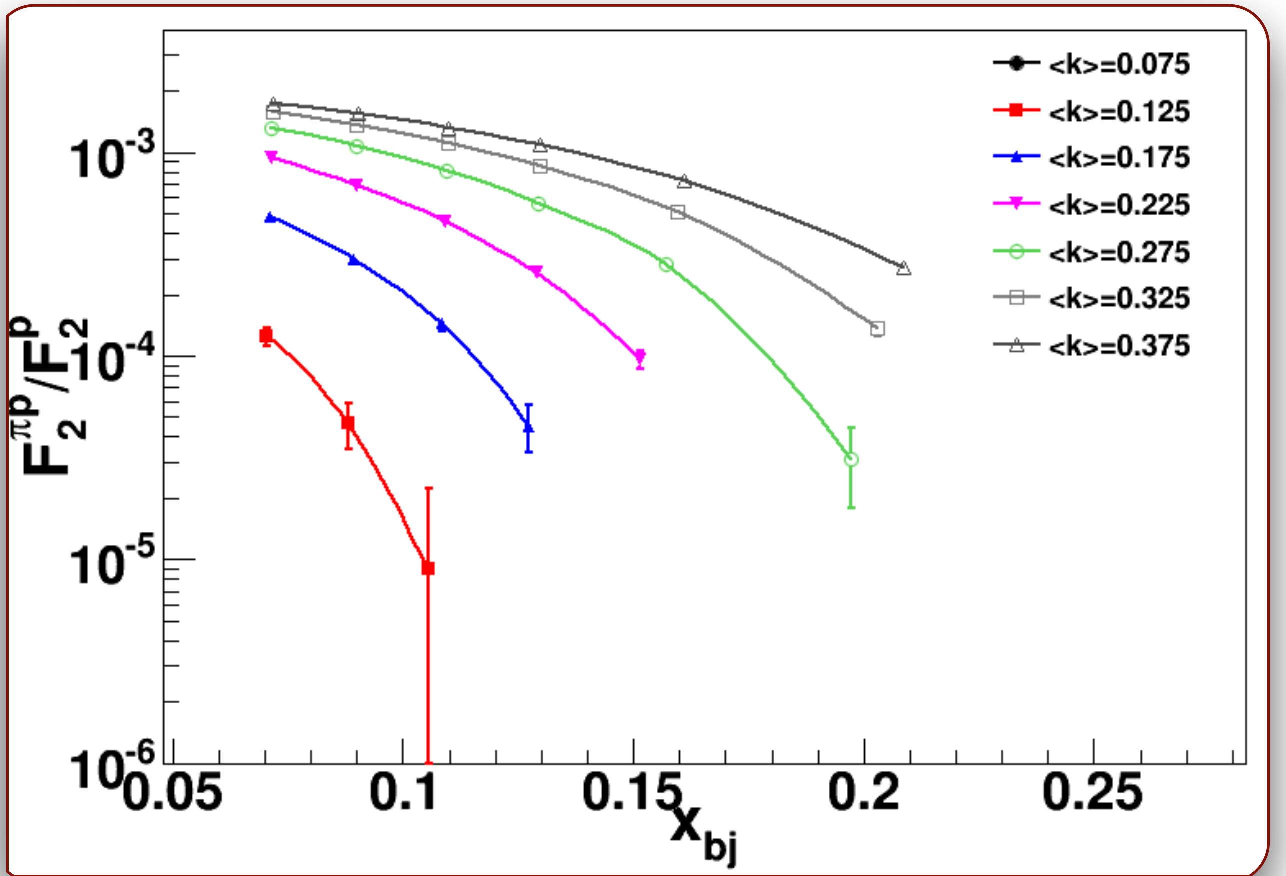


The TDIS experiment will measure tagged structure functions for protons and neutrons

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:

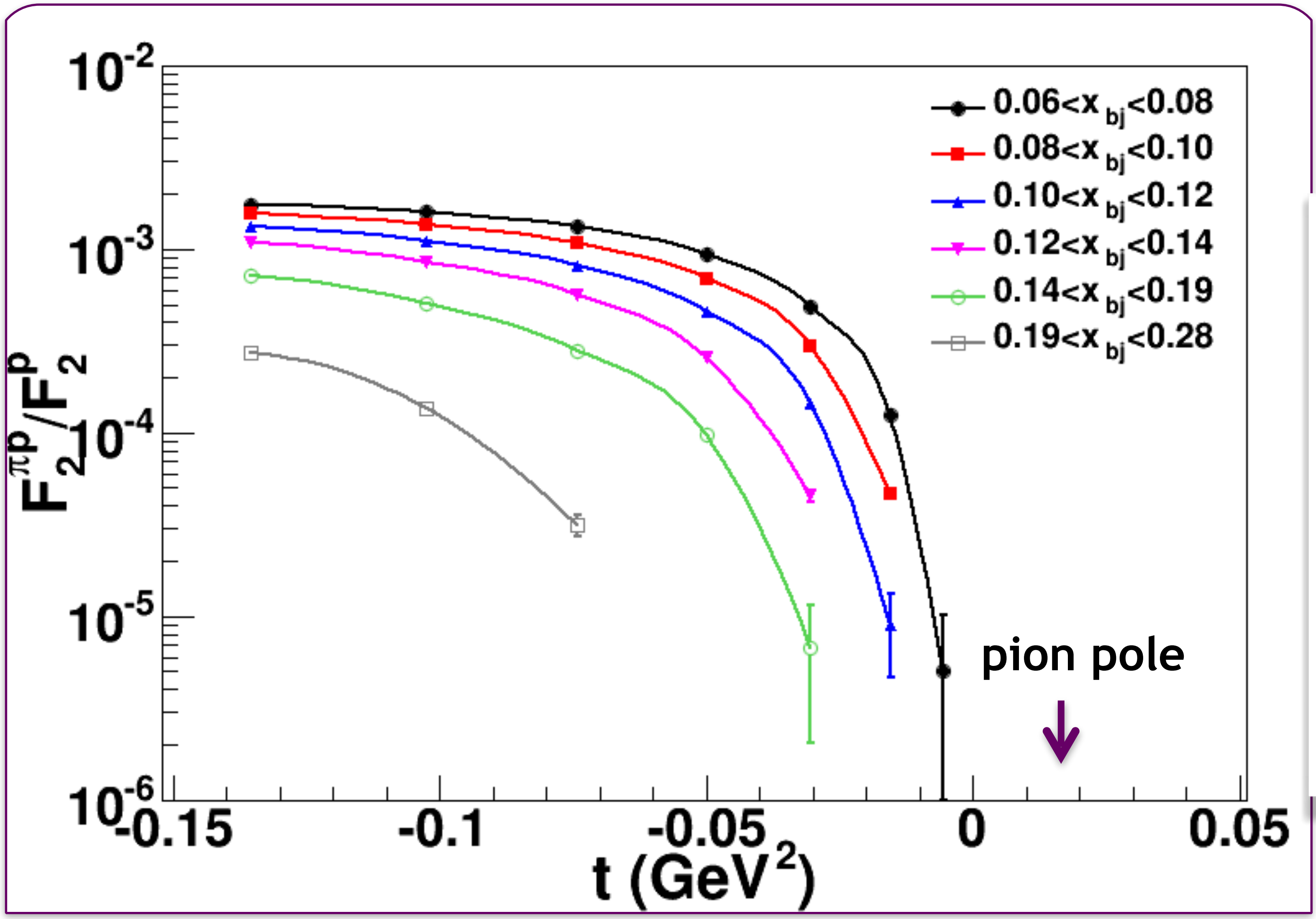
- 150 < k < 400 MeV/c corresponds to z < ~0.2
- Also, x < z
- Low x, high W at 11 GeV means Q^2 ~2 GeV^2

The TDIS experiment will also extract the pion structure function.

It requires extrapolation to the pion pole

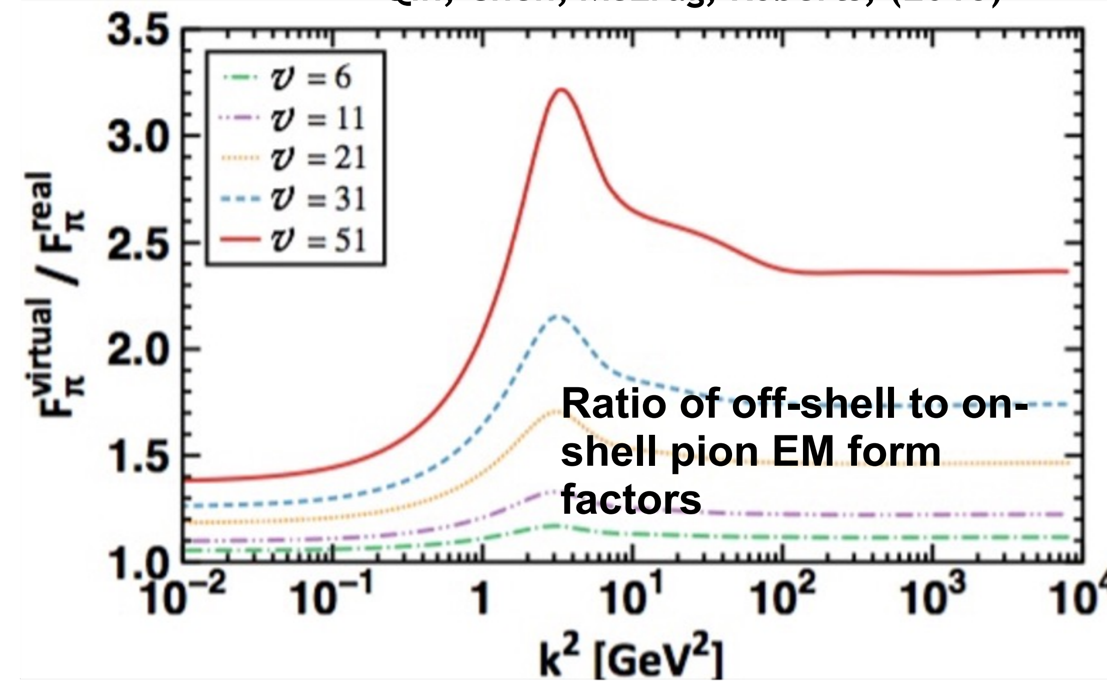
low momentum protons helps cover a range of low |t|

- Low t extrapolation to the pion pole



virtuality-independent form factor implies virtuality-independent pion structure function
virtuality $\nu = 30 \Rightarrow t = -0.6$ GeV²
TDIS covers $|t| = 0.01 - 0.16$ GeV²

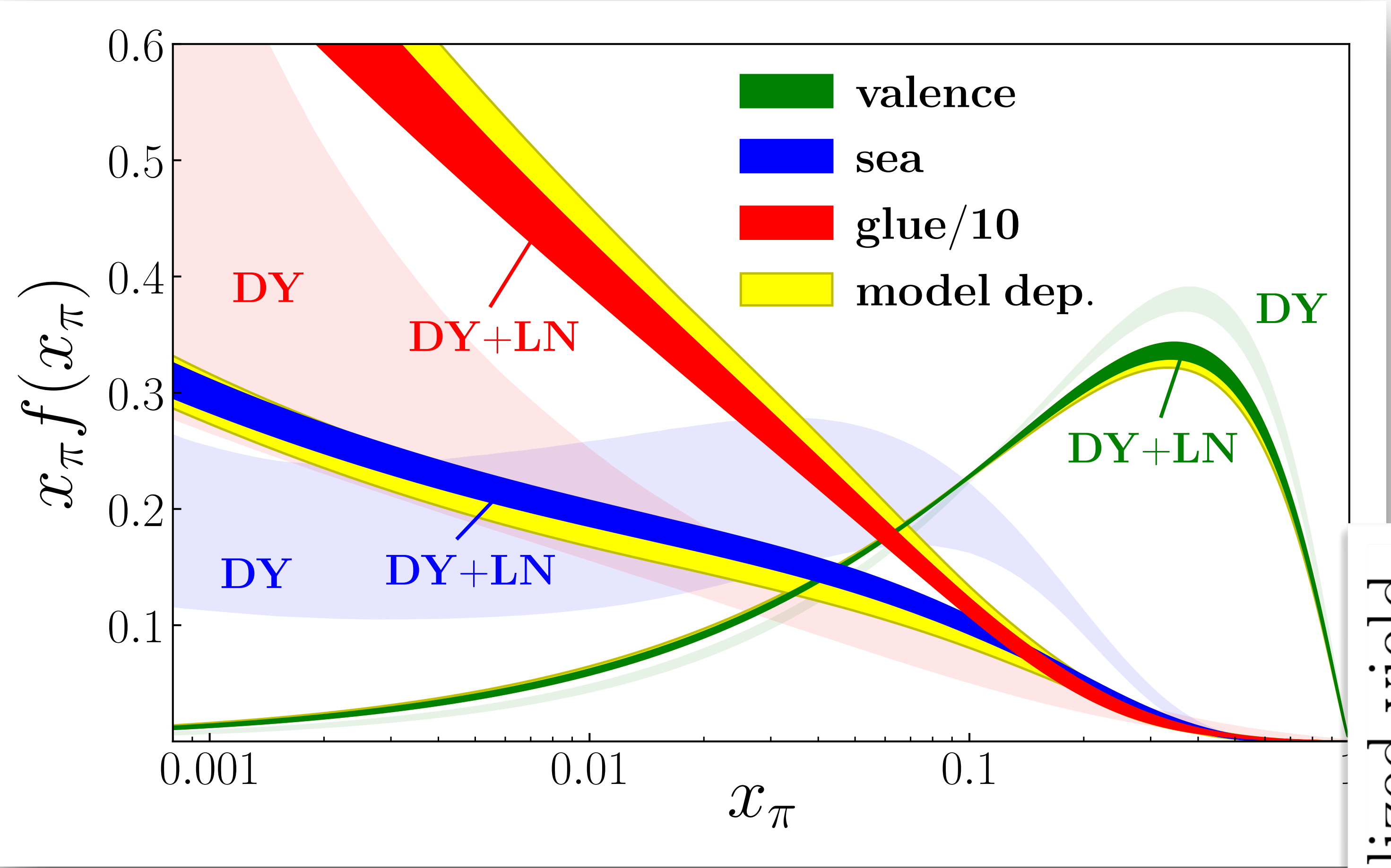
Qin, Chen, Mezrag, Roberts, (2018)

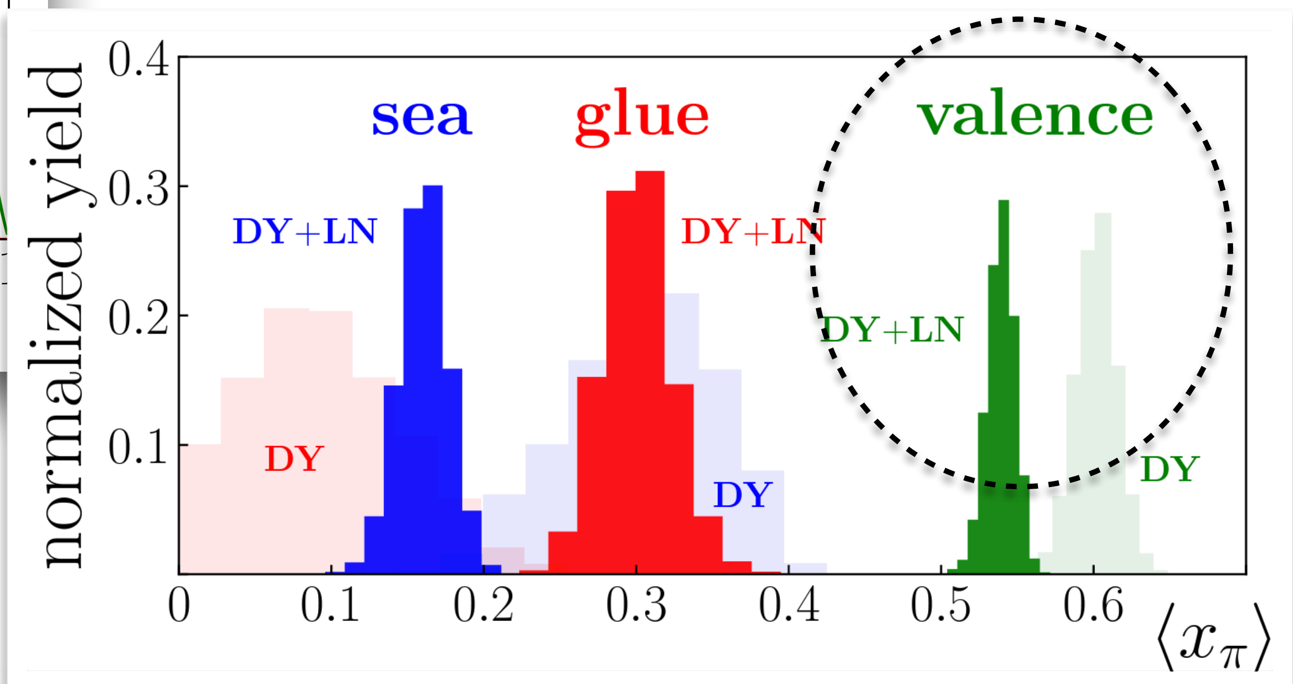


The uncertainty in extrapolation to the pion pole within ~5% at JLab kinematics

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

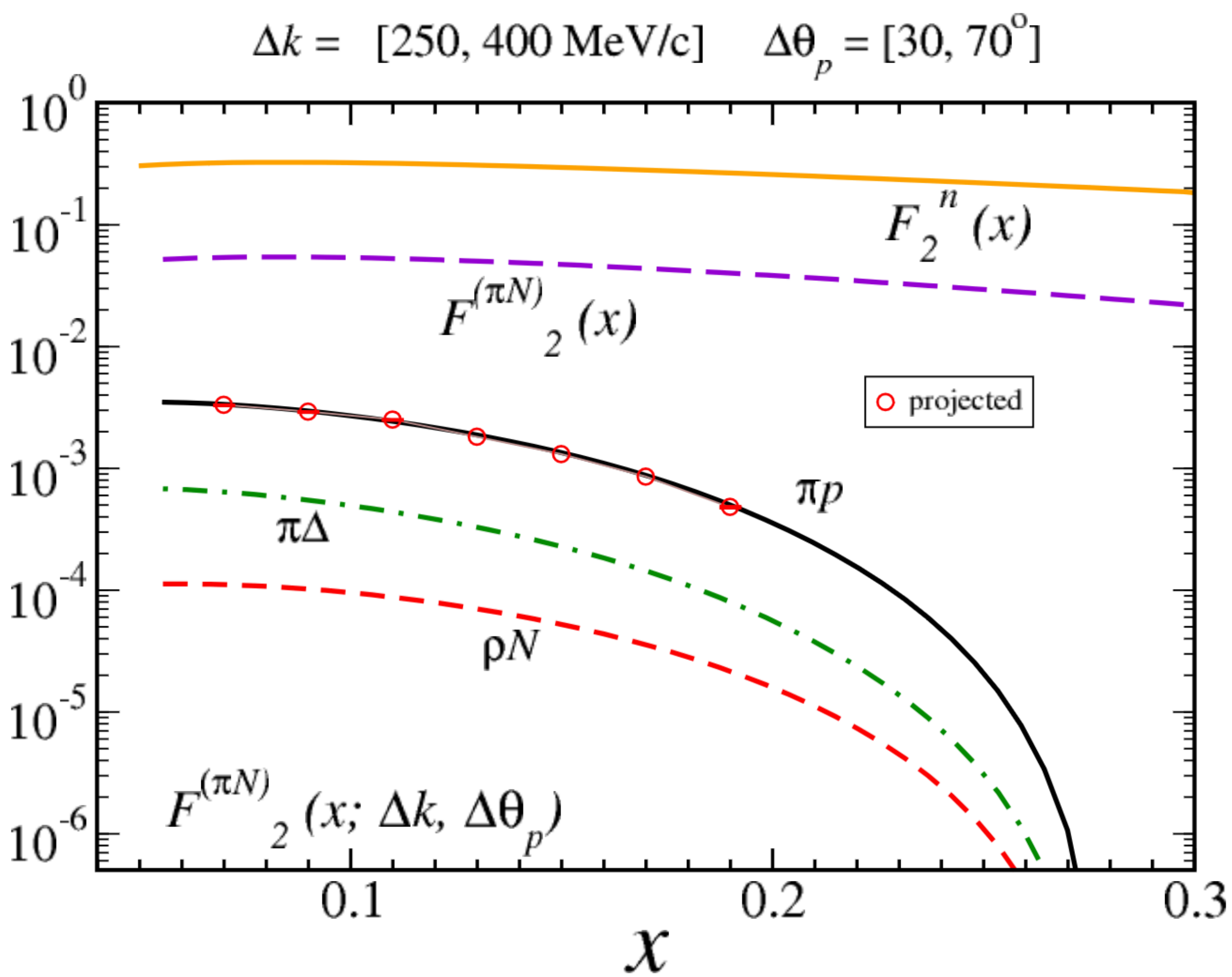
Peak of valence quarks momentum fraction shifted to smaller x, than that inferred from Drell-Yan data alone



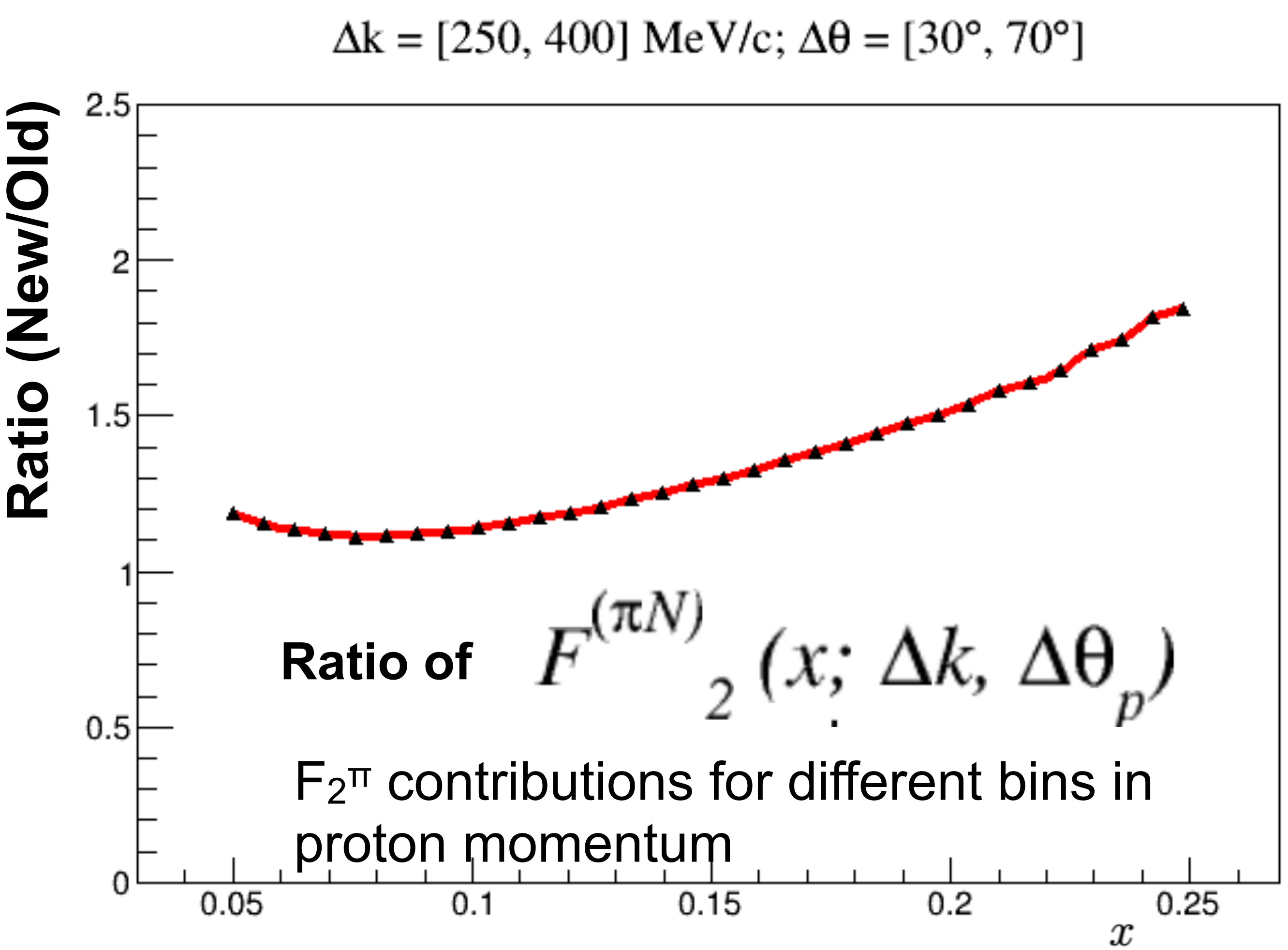


P. C. Barry, N. Sato, W. Melnitchouk, and C-R. Ji,
Phys. Rev. Lett. 121, 152001 (2018)

The rate of TDIS signal events is expected to be larger and less sensitive to the pion flux factor



phenomenological model of Melnitchouk, Hobbs & Barry

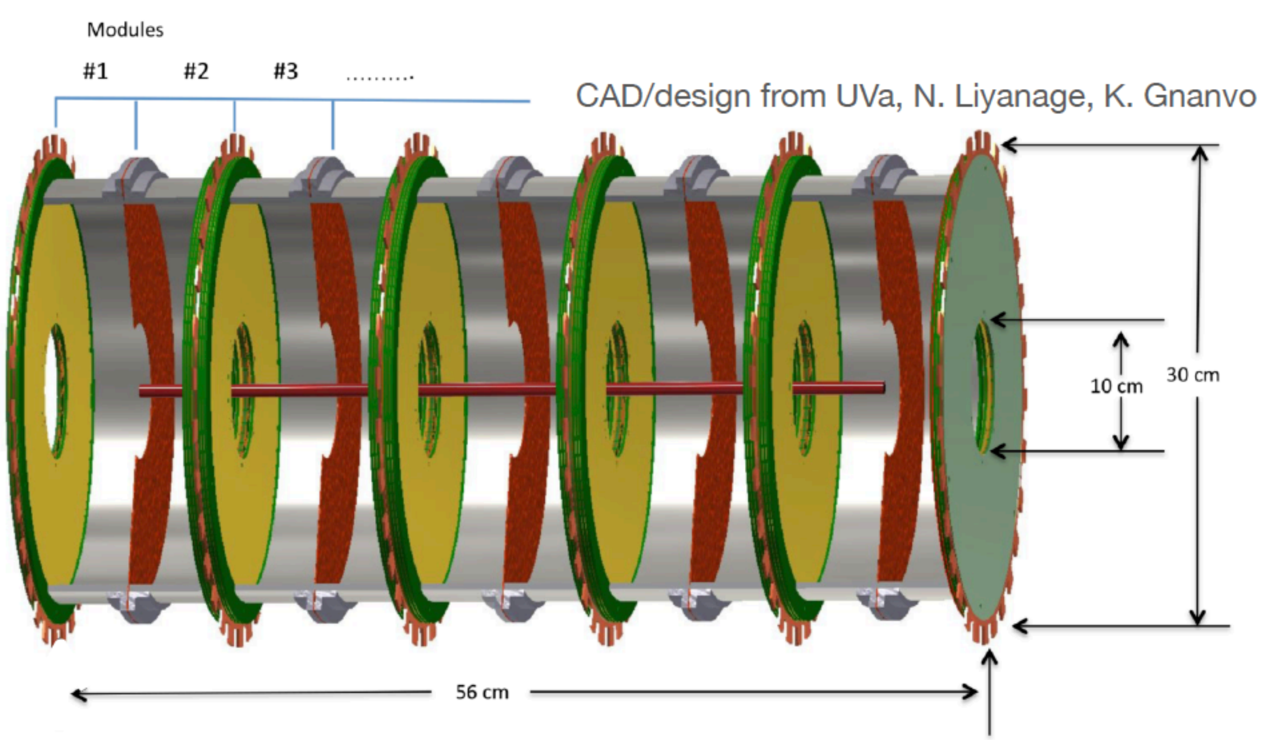


will help reduce the beam current to improve background and tracking.

plots credit: P. Barry & C. Ayerbe Gayoso

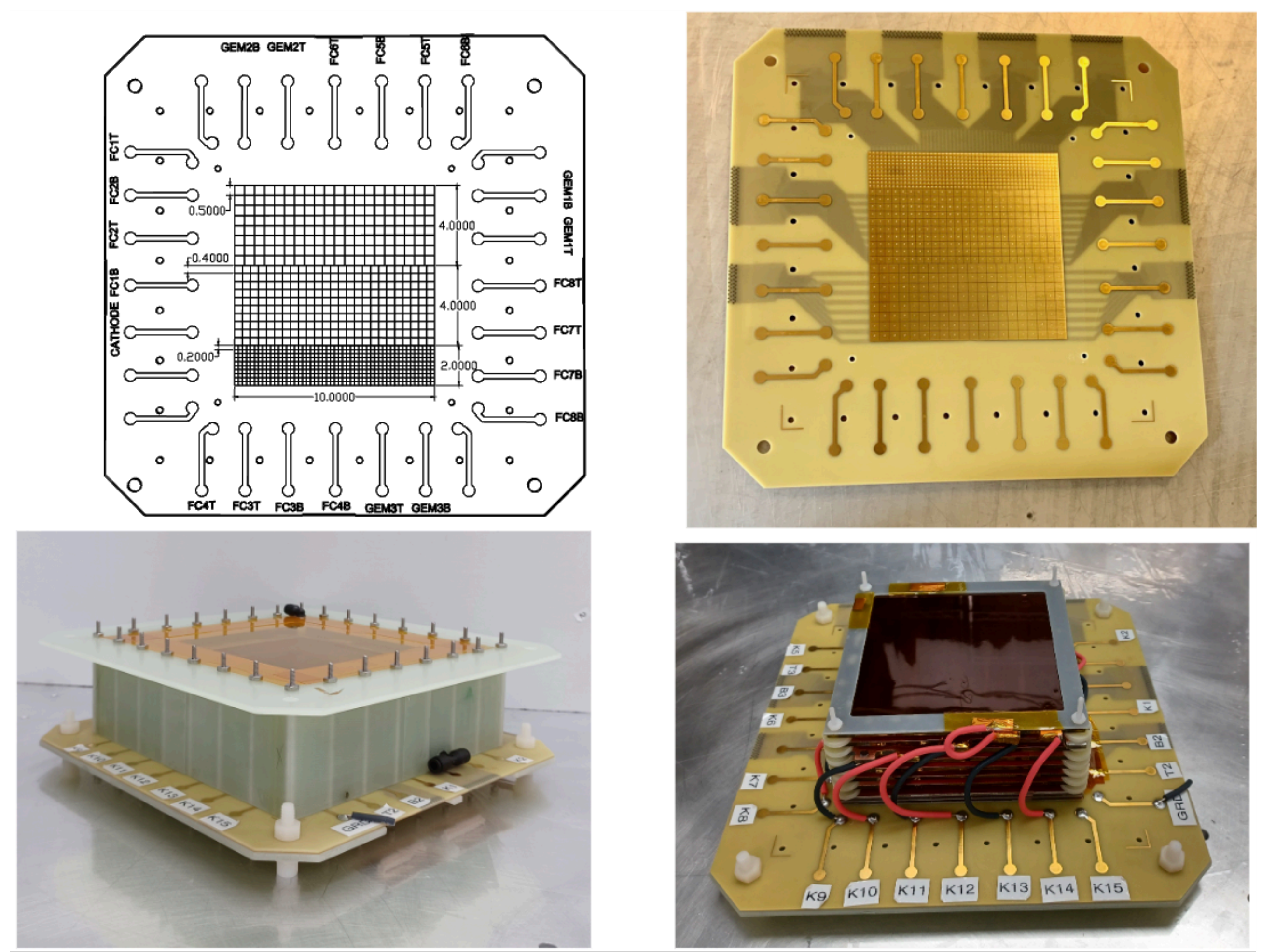
We have converged on a design for the recoil detector- a multi-Time Projection Chamber (mTPC)

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.

Prototype mTPC is currently being tested at JLab and the first cosmic tracks have been observed

Examples of reconstructed 3-D track hits

(Sudipta Saha, JLab)

- Tracks not fitted - lines just to guide the eye

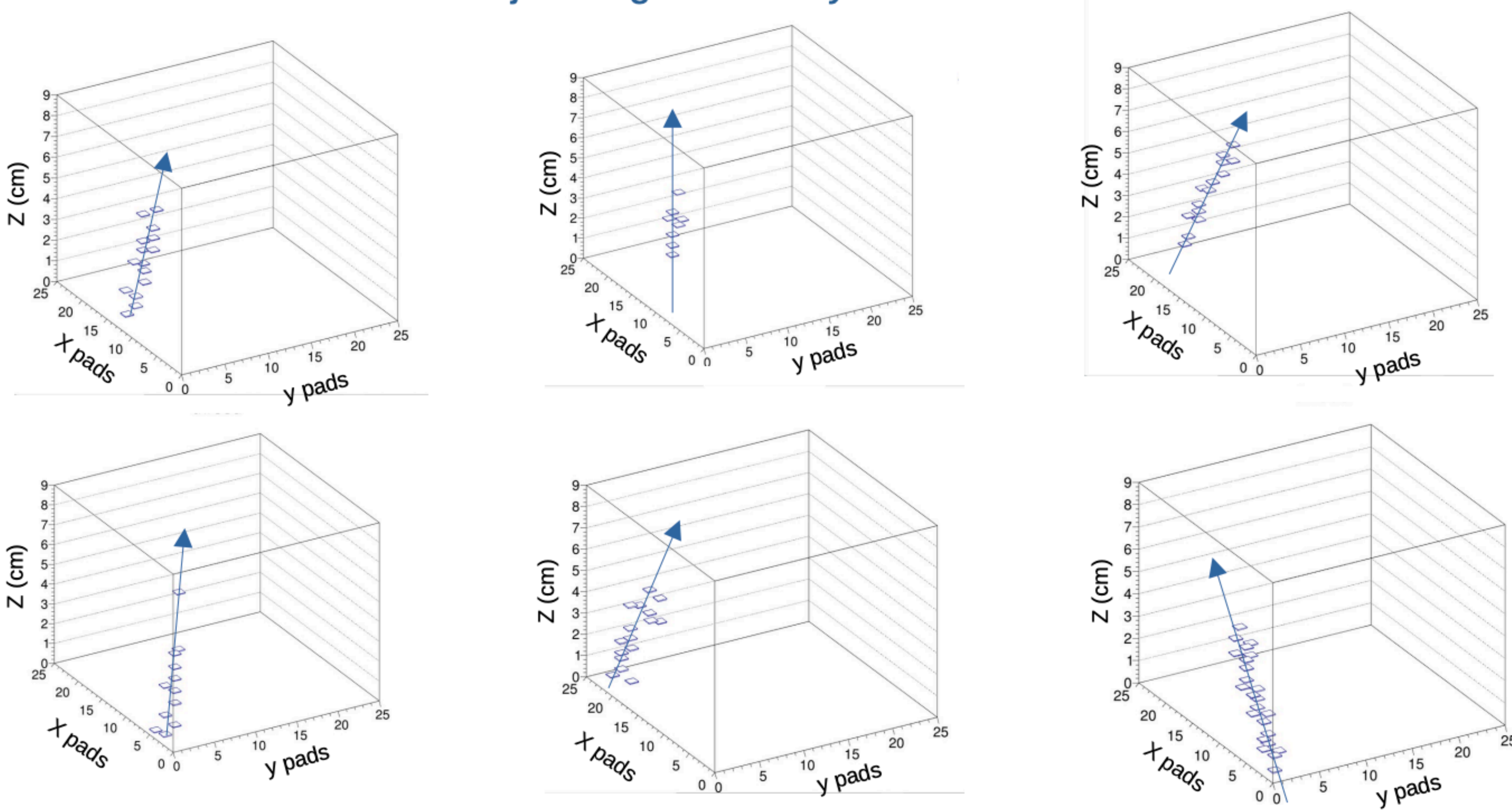
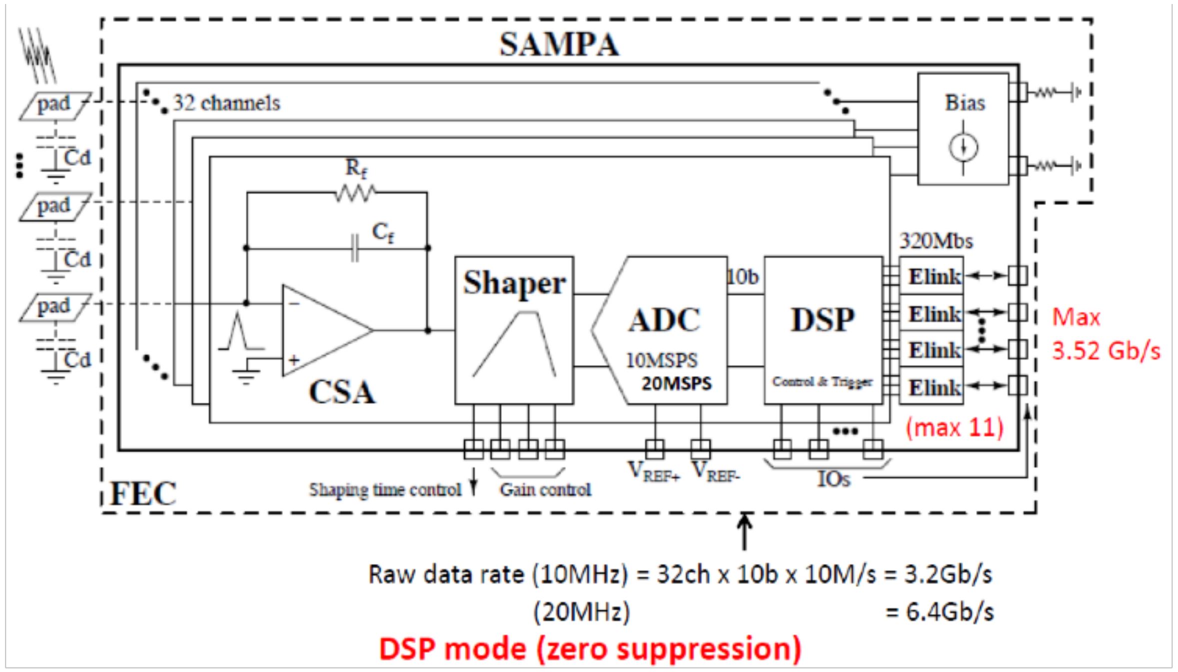
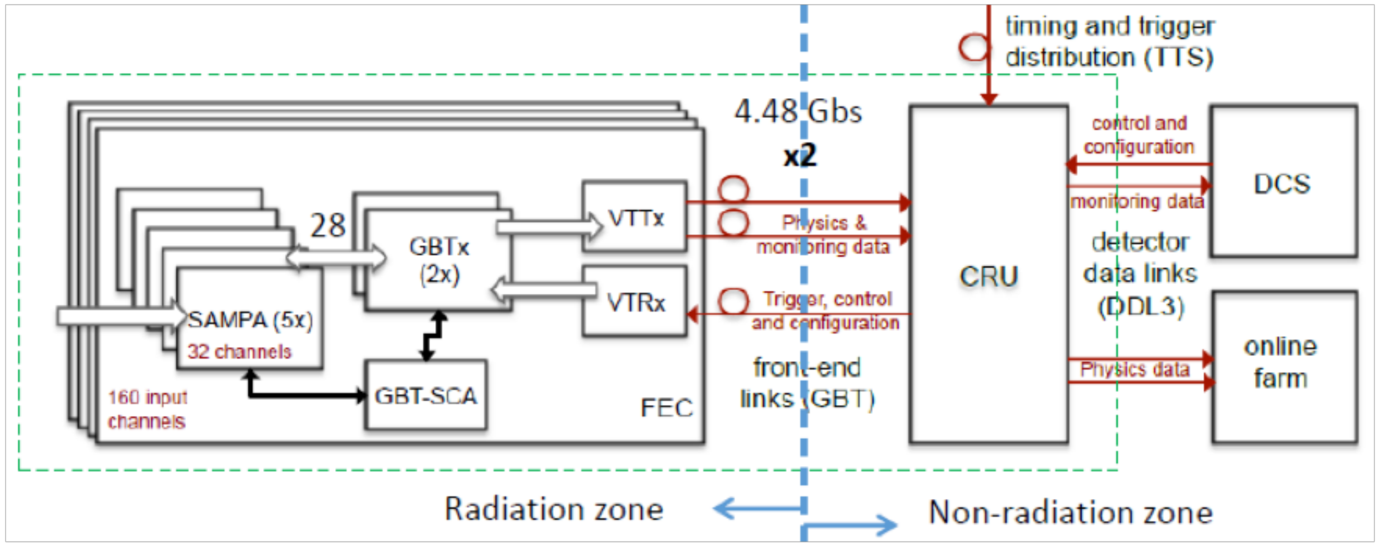


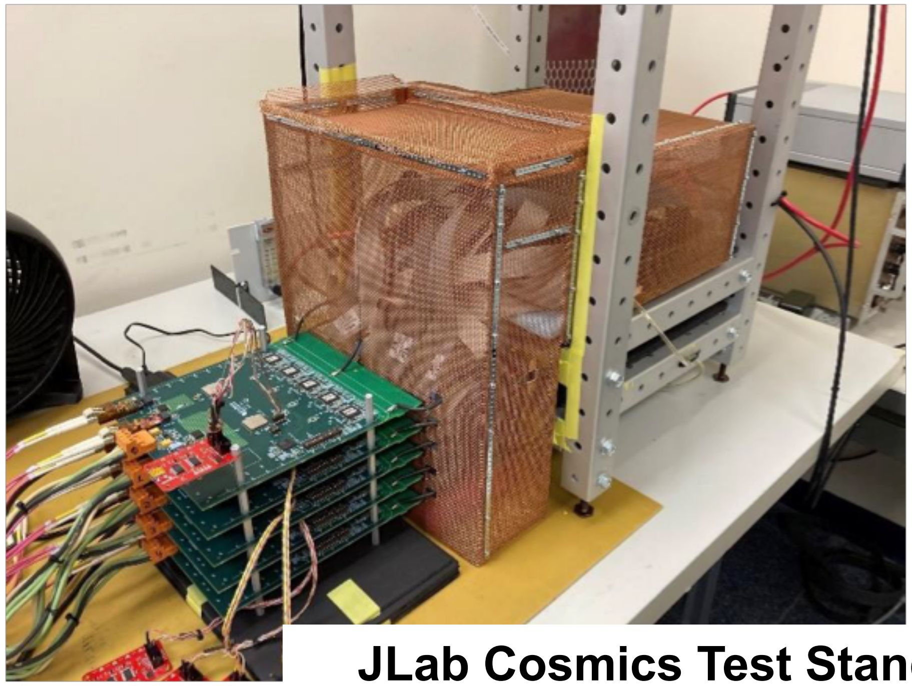
Image credit
E. Christy JLab

Readout for mTPC has been developed using the SAMPA chip





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

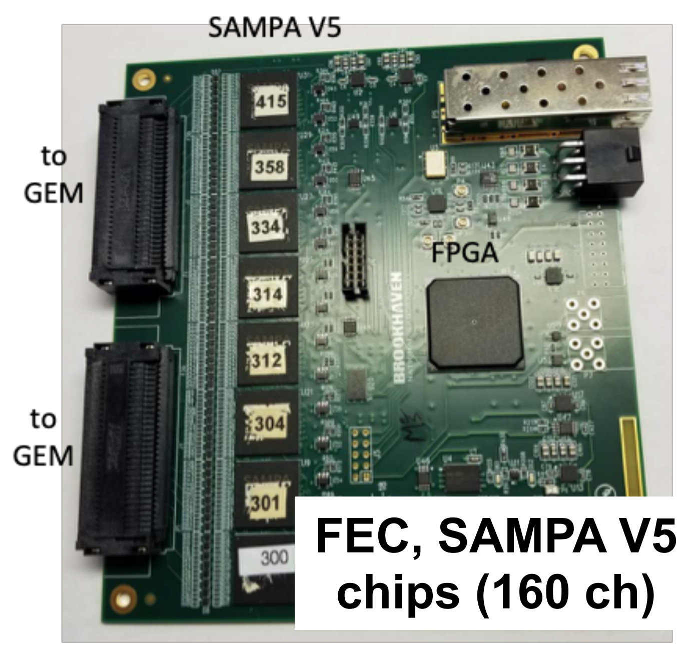


JLab Cosmics Test Stand
FEC, coupled to GEM detector

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)



FEC, SAMPA V5 chips (160 ch)

Image credit
E. Jastrzembski JLab

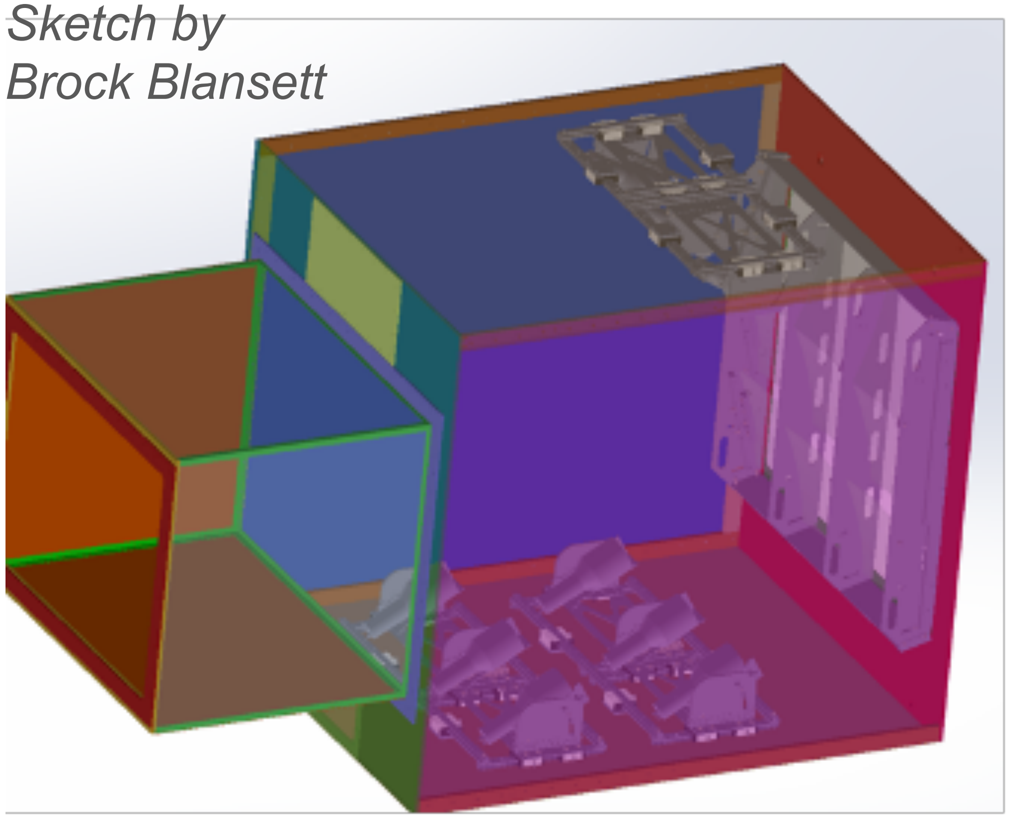
The SBS get a new hadron blind gas Cherenkov detector & a the repurposed CLAS6 large angle calorimeter

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

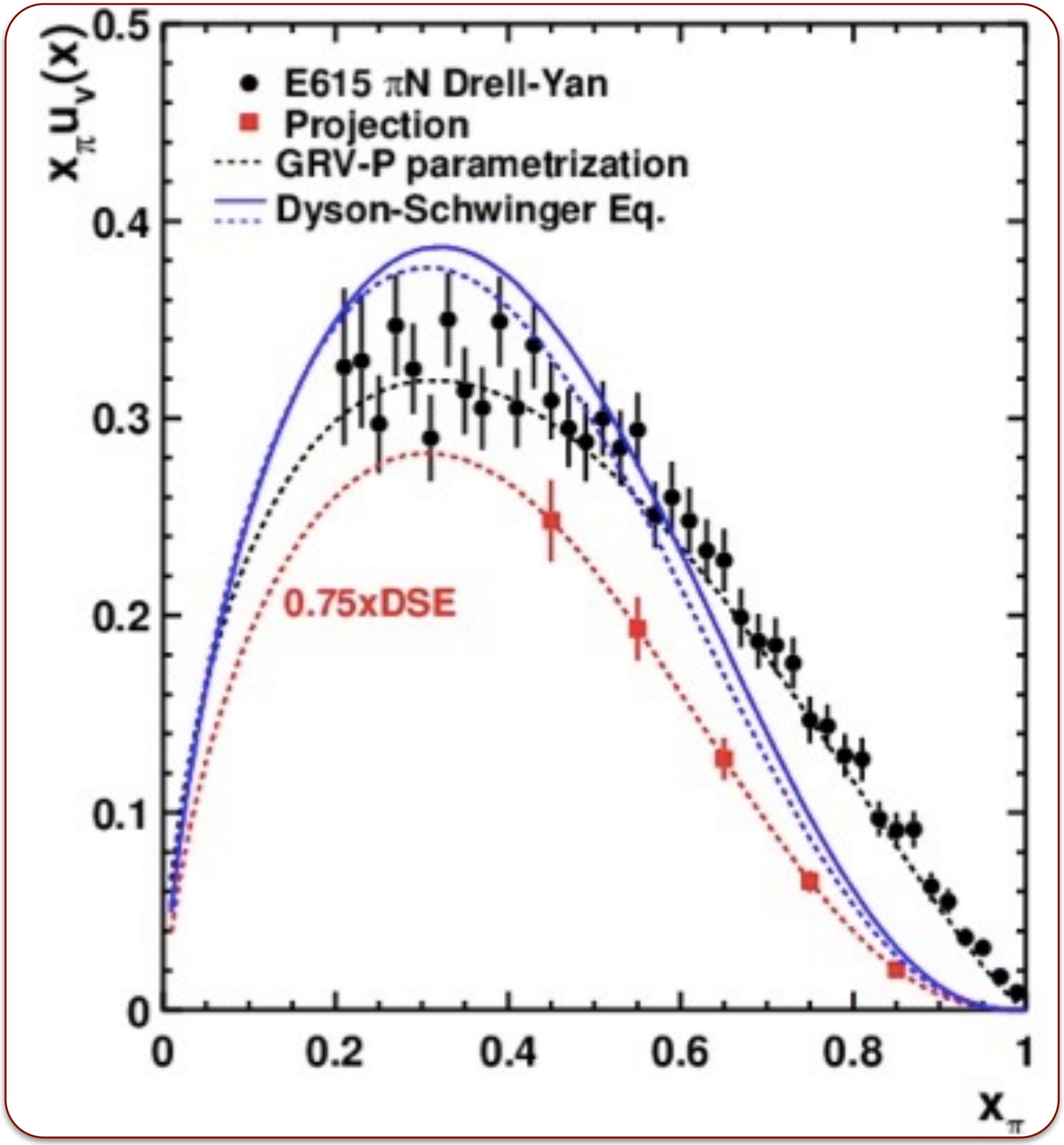
The TDIS experiment will provide a unique extraction of the pion structure function at large x.

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

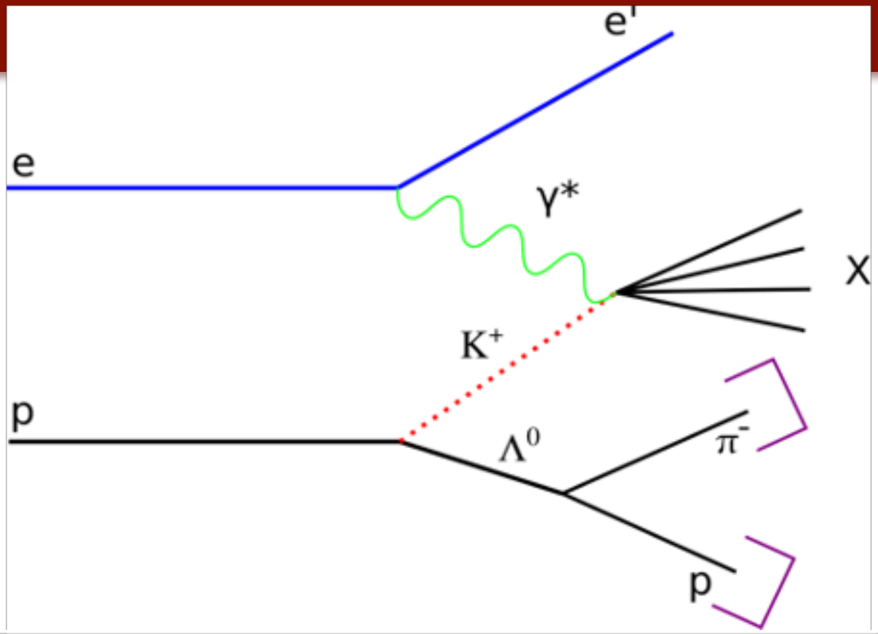
Large x, low Q complementary to HERA low x, high Q

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

C1 conditionally approved for 27 PAC days with A- rating



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

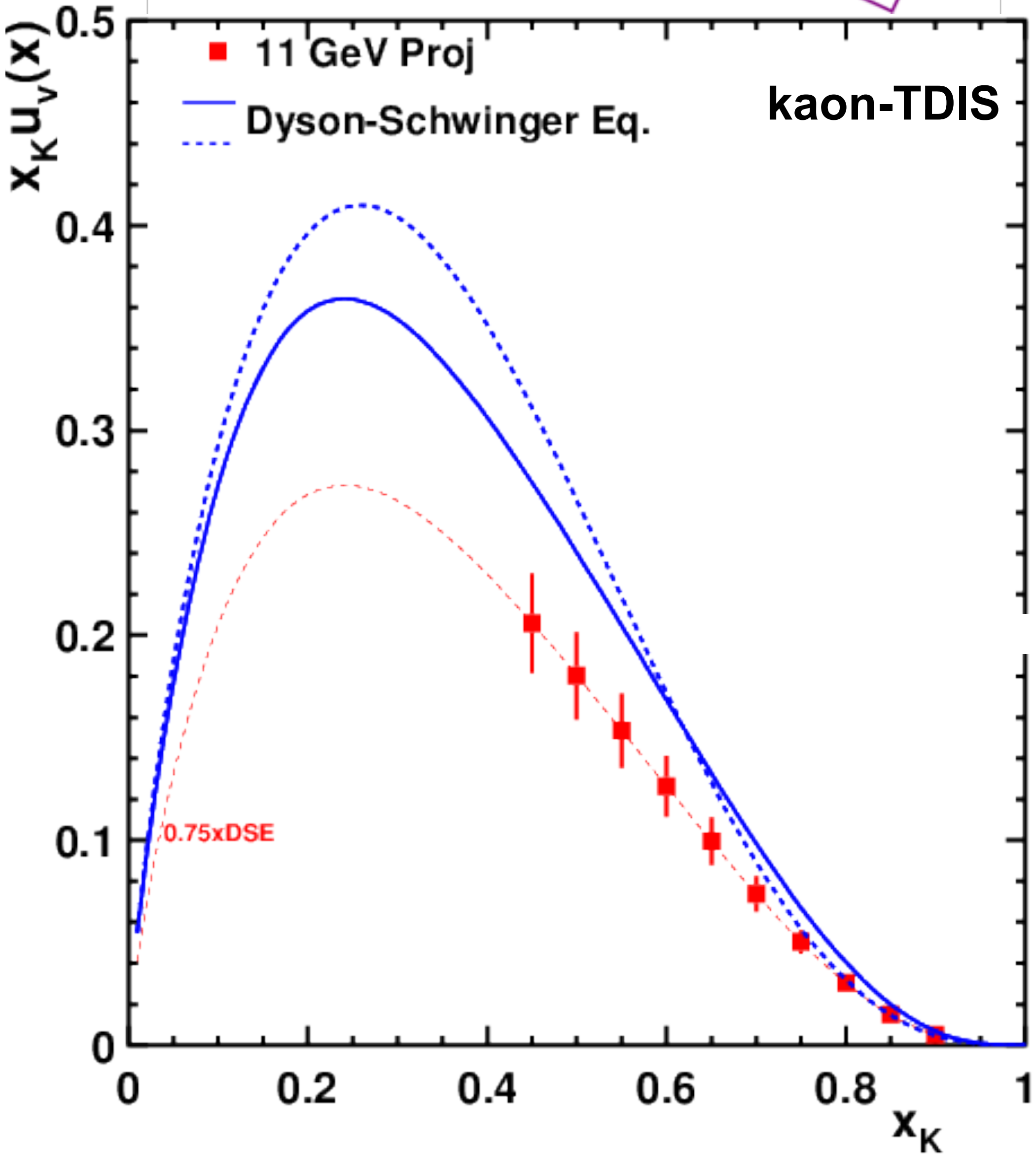


C12-15-006A
Measurement of Kaon Structure Function through Tagged Deep Inelastic Scattering(TDIS)

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

Kaon TDIS events are "background" for pion TDIS

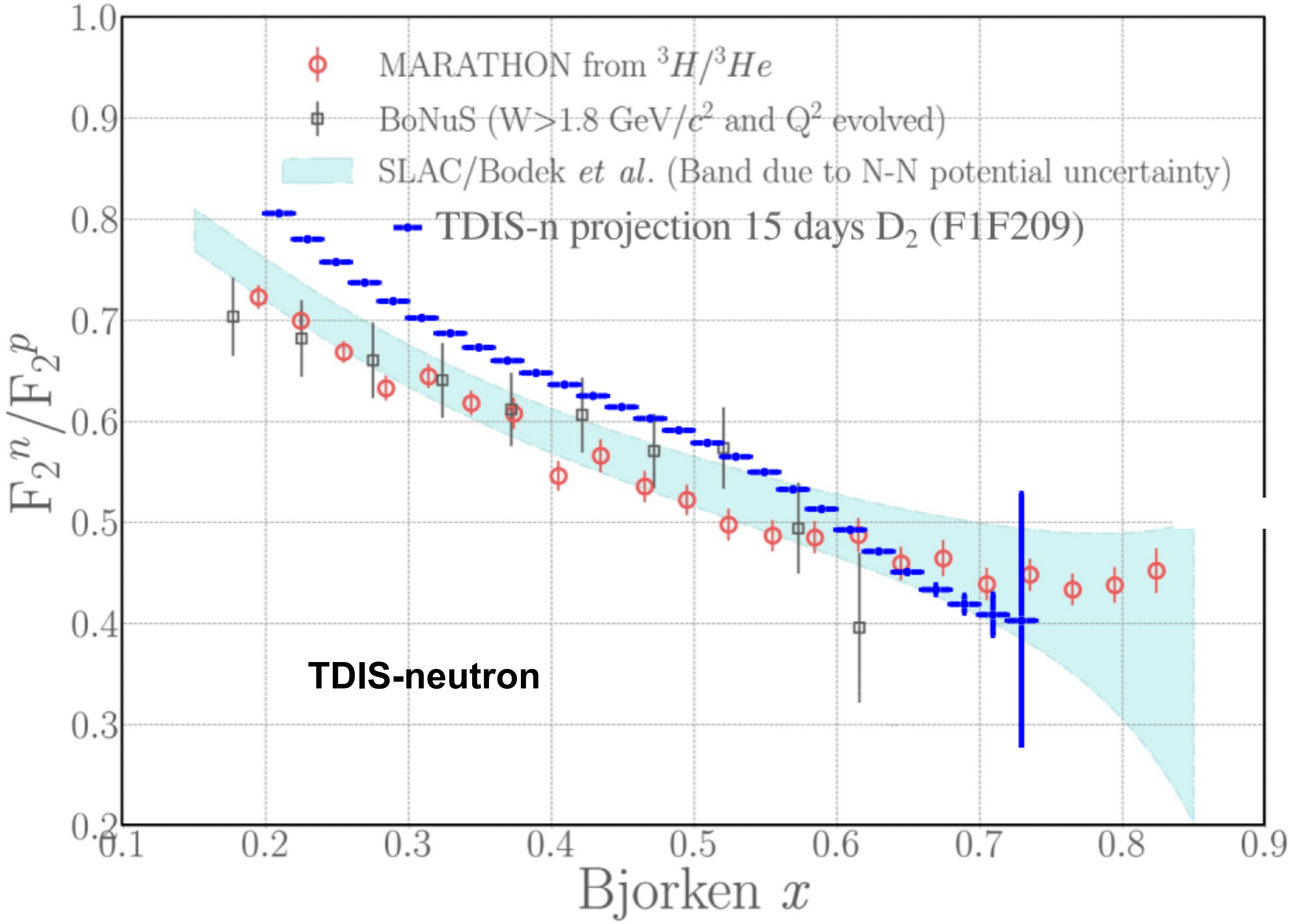
First direct measurement of the kaon structure function



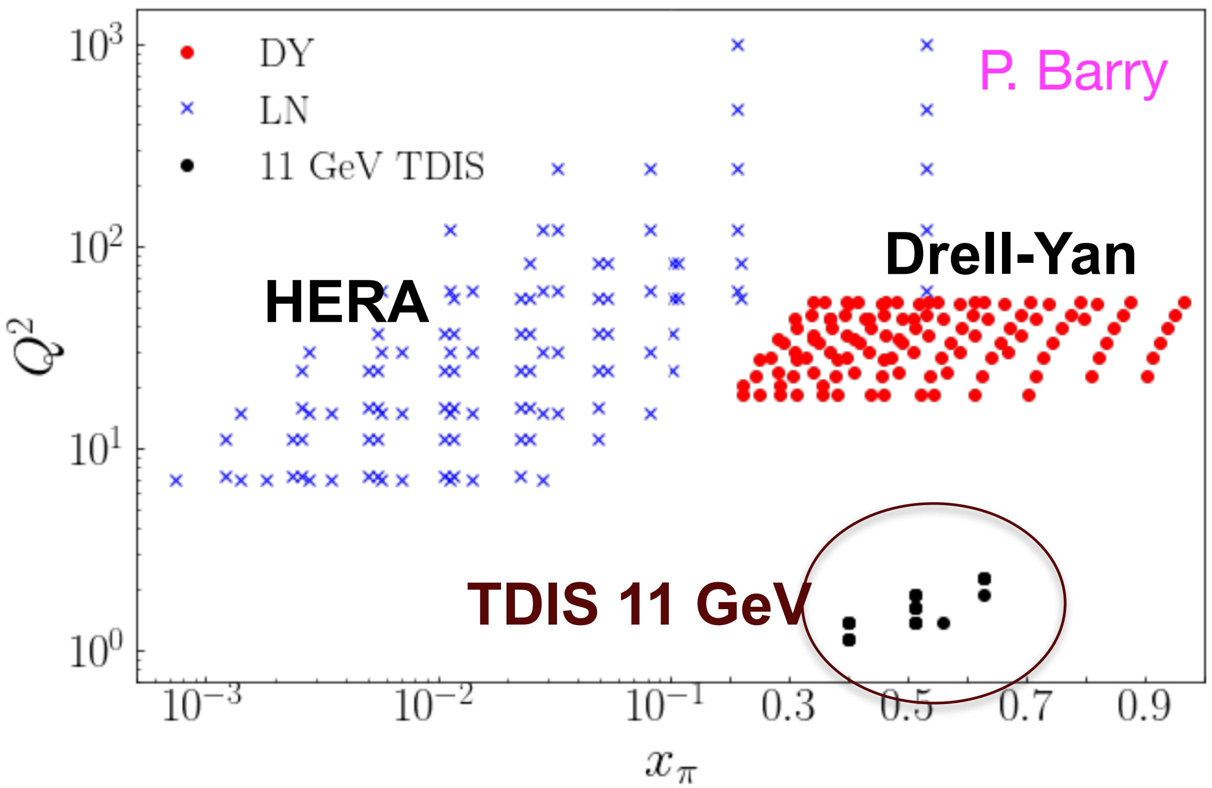
Two run group experiments (kaon TDIS & nTDIS) have been endorsed

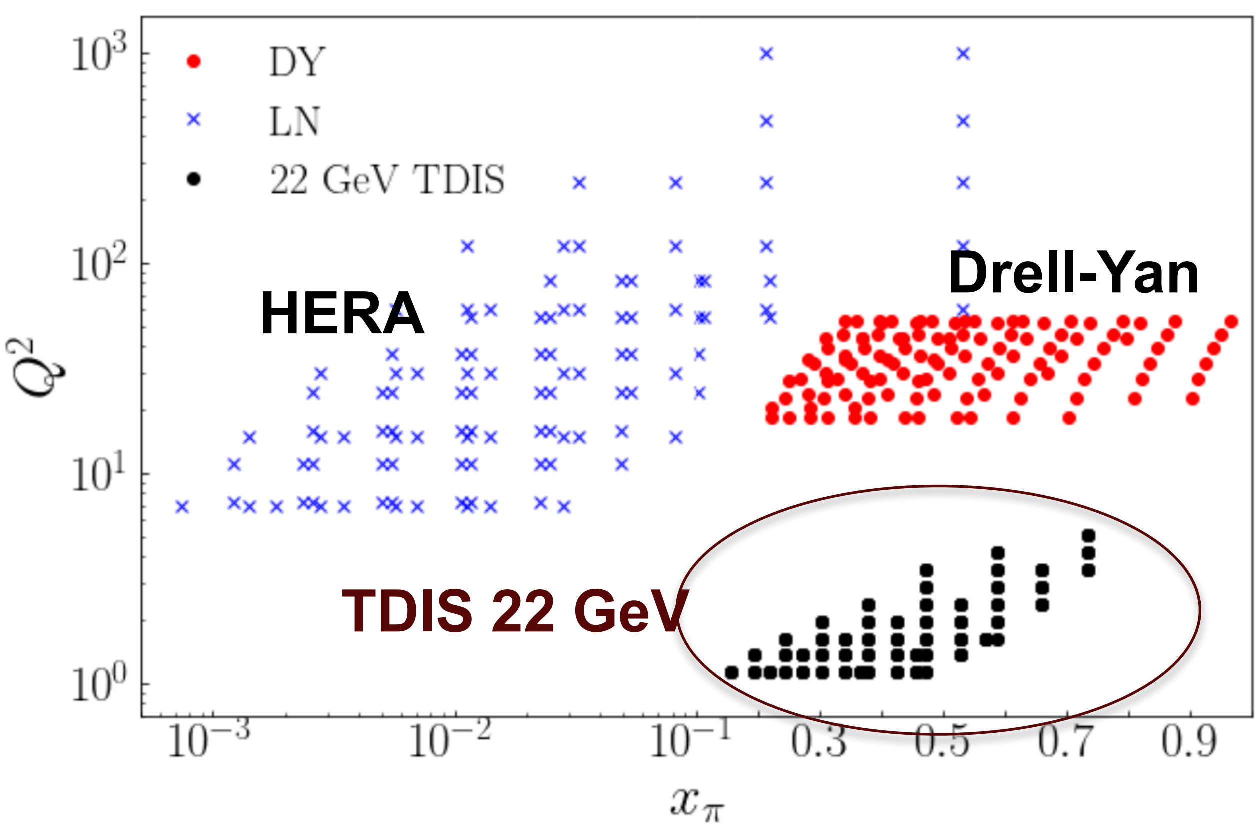
C12-15-006B
TDIS-n:Tagged DIS measurement of the Neutron Structure Function

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

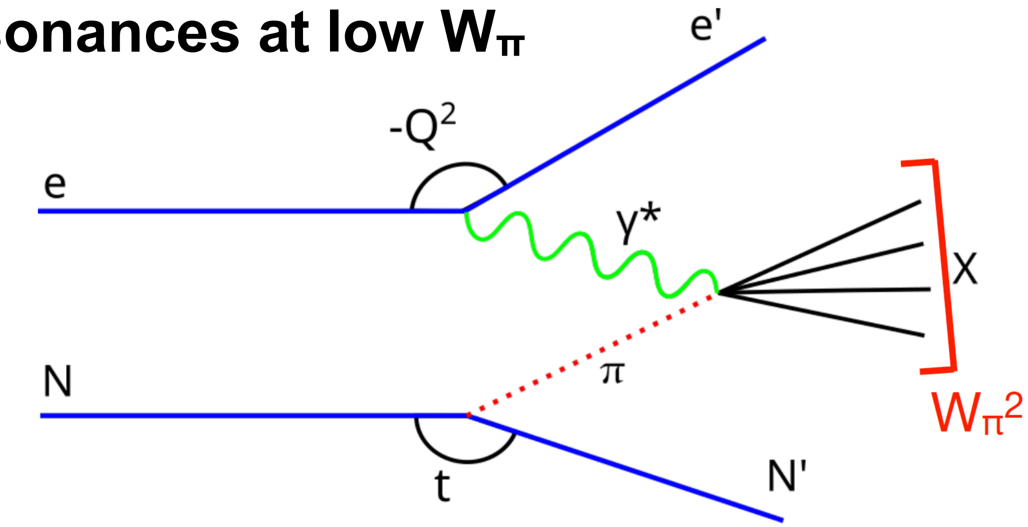


Simulations of a TDIS experiment using a 22 GeV beam indicate very significant advantages

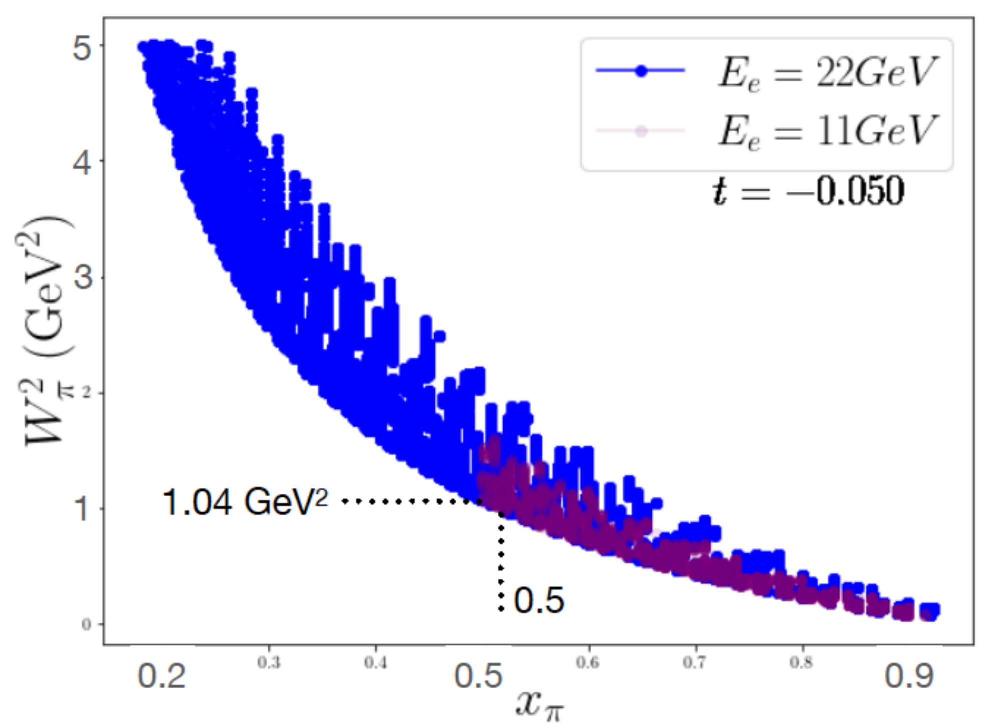




The 11 GeV TDIS data could be impacted by resonances at low W_π



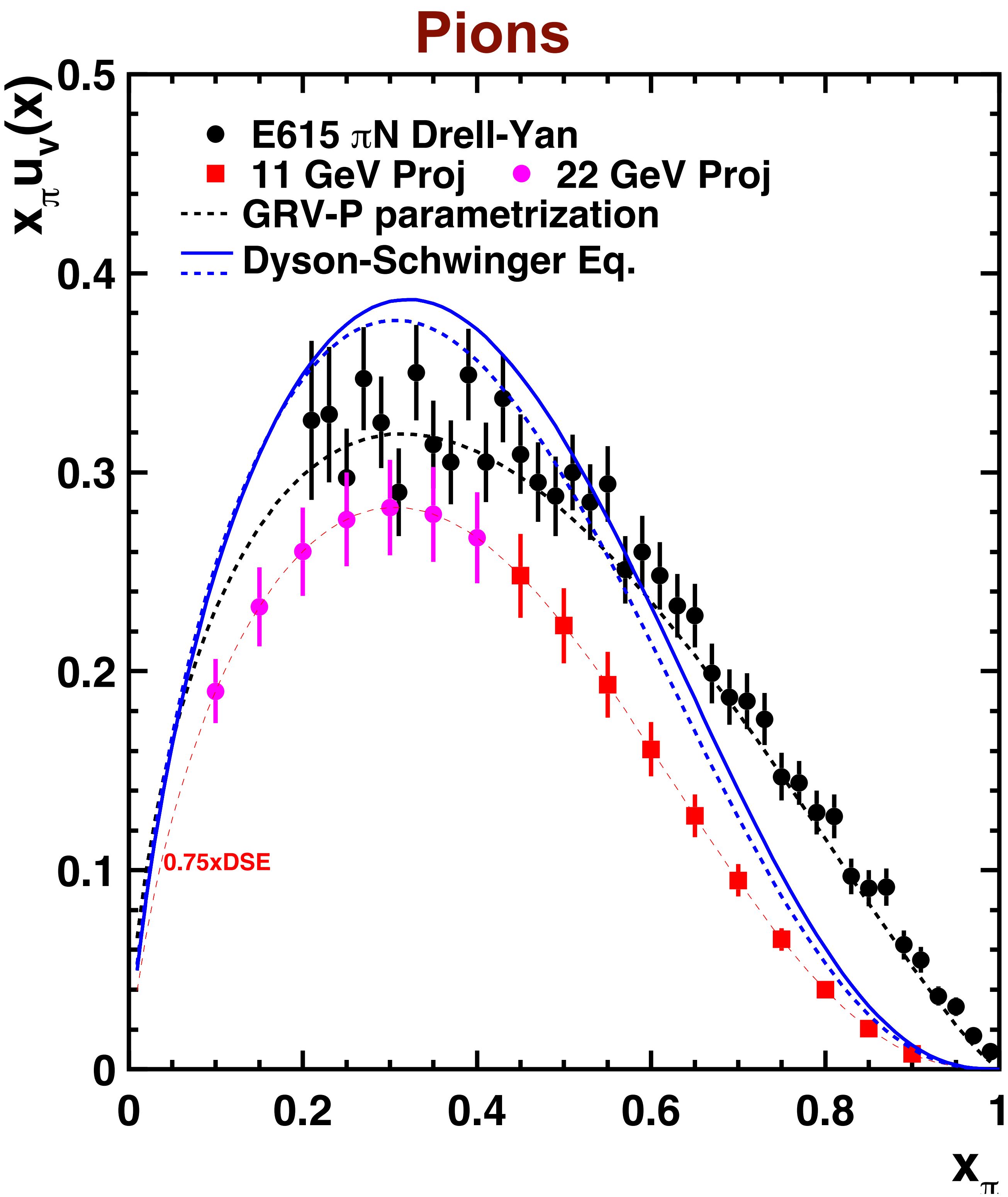
Using $W_\pi^2 > 1.04$ GeV² to remove ρ meson contribution would significantly reduce kinematic coverage at 11 GeV but not at 22 GeV

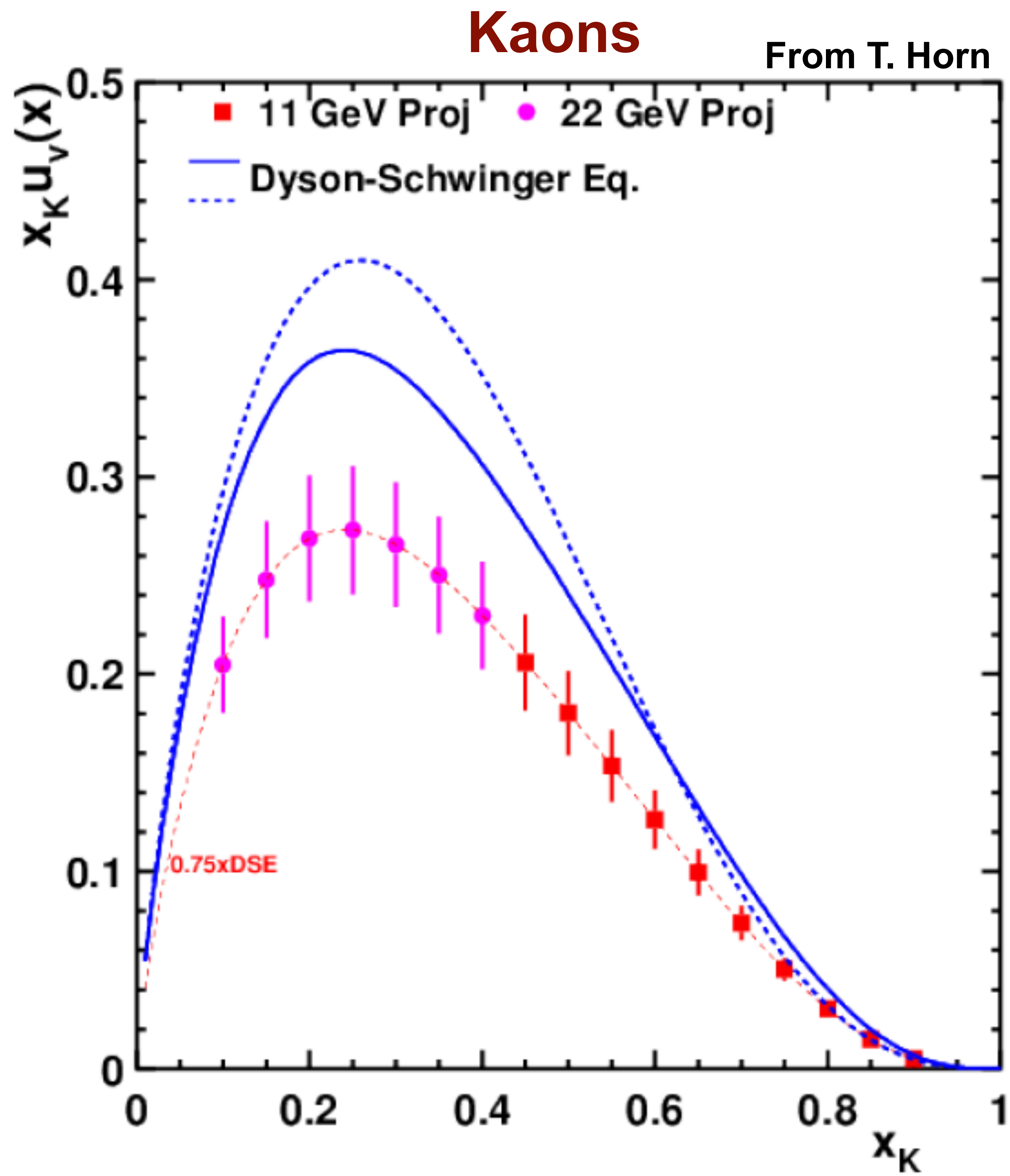


Based on simulations by P. Barry (JLab)

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

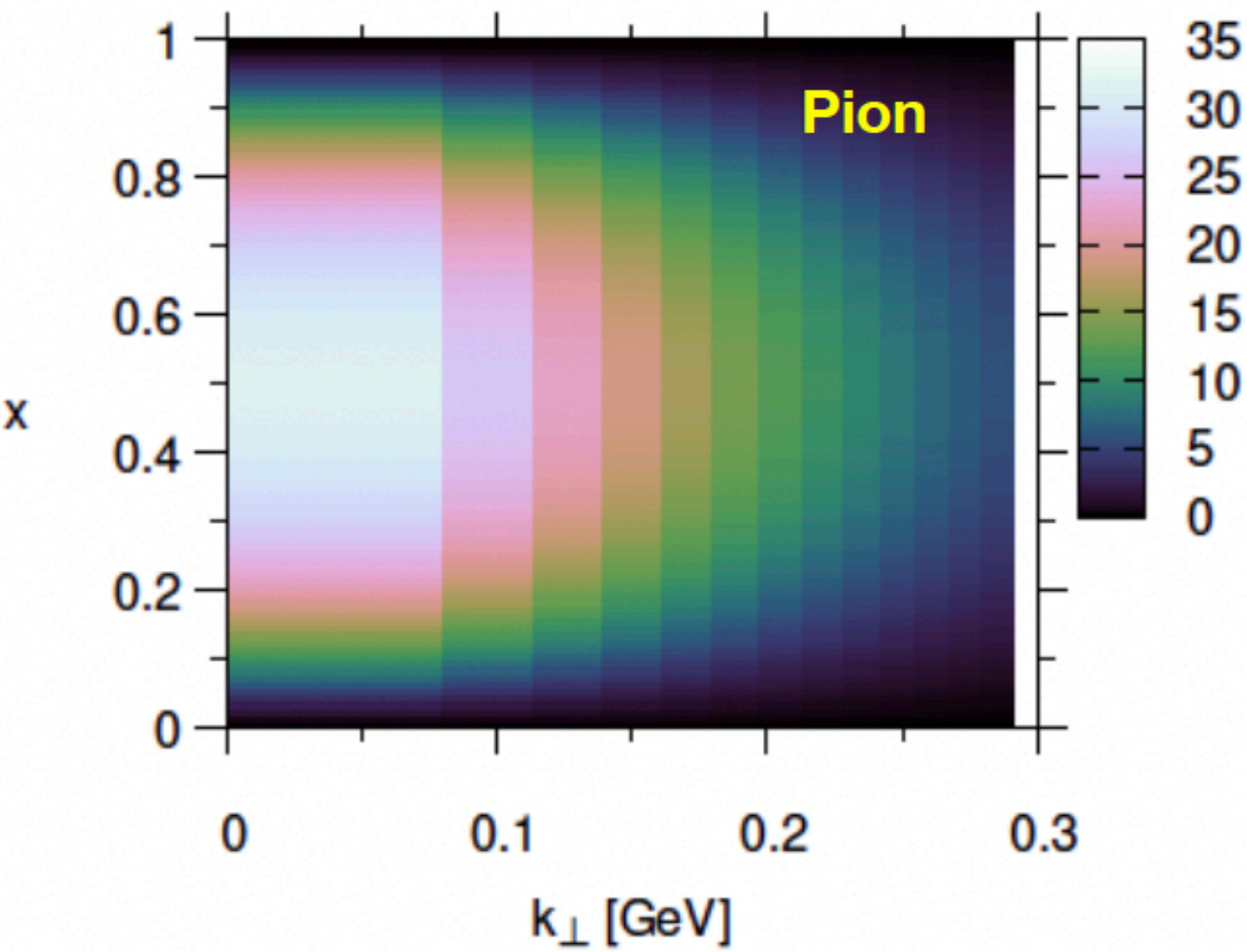
Projected results



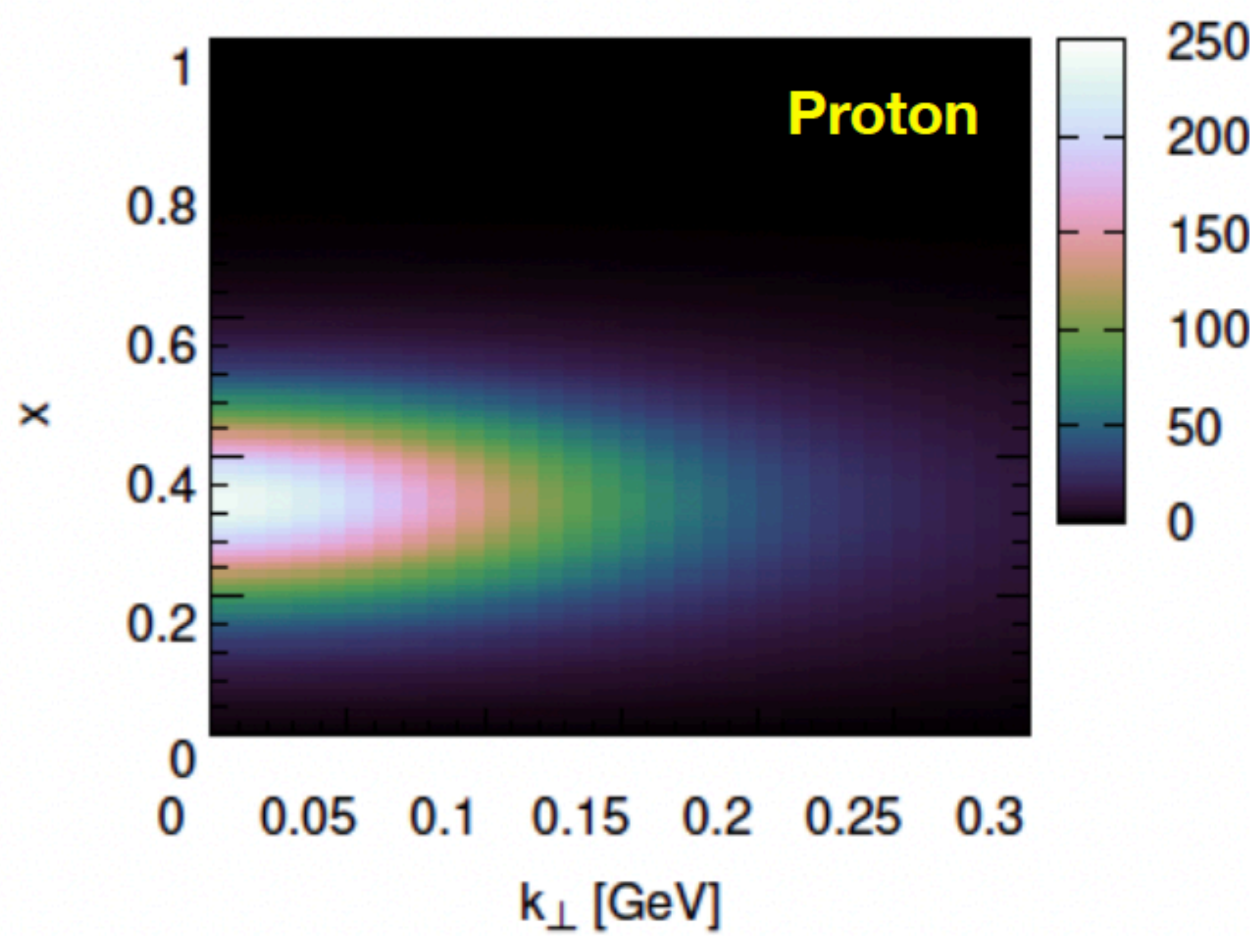


Pion and proton leading twist TMDs expected to be different

PRD 105, L071505 (2022); PRD 104, 114012 (2021)
E. Ydrefore & T. Frederico



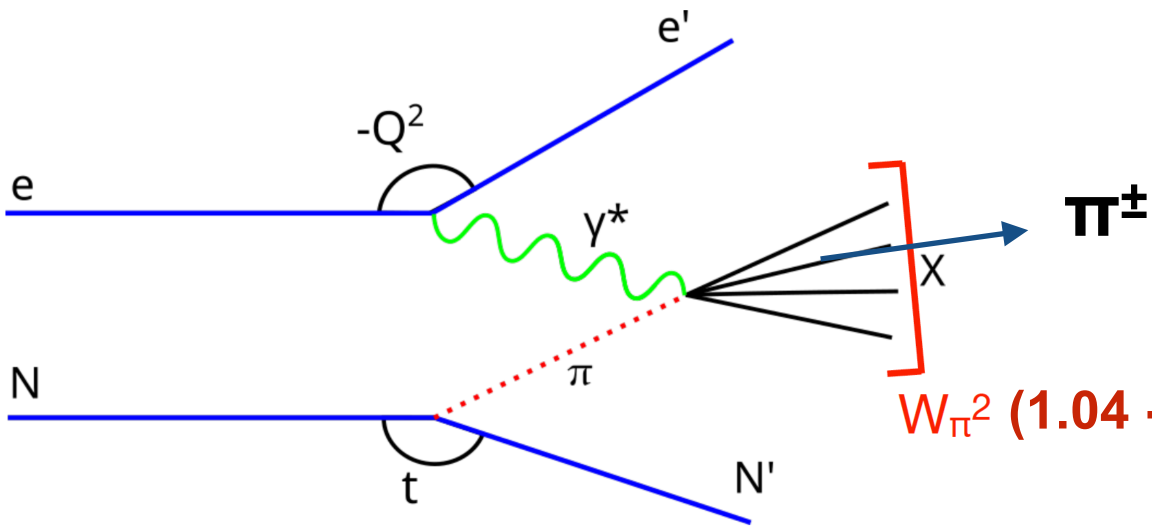
Pion TMDs from
Bethe-Saltpeter equation



Proton TMDs from
Light-Front Model

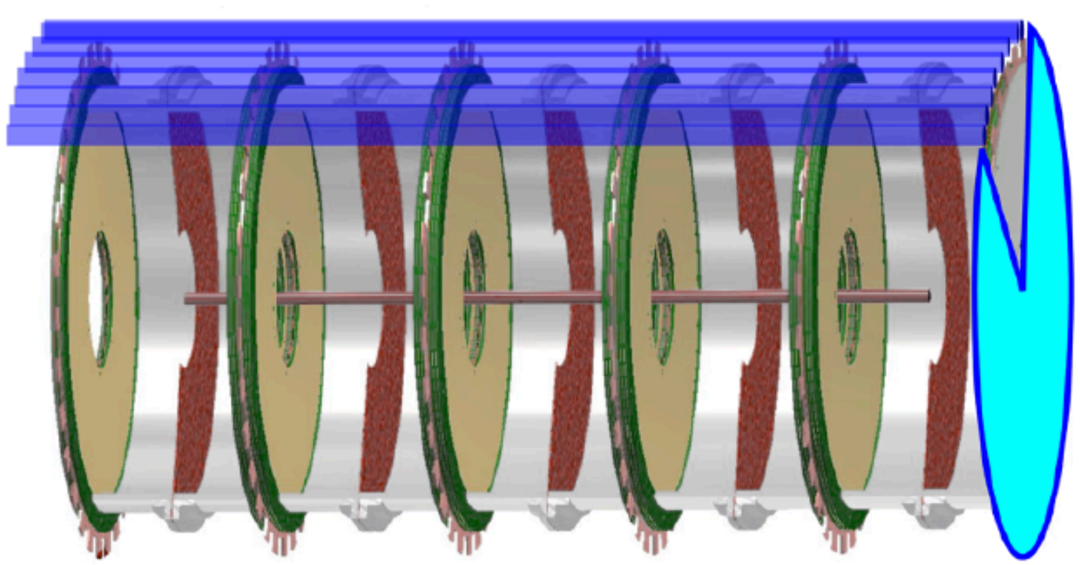
Significant x-broadening of Pion TMDs compared to proton TMDs

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

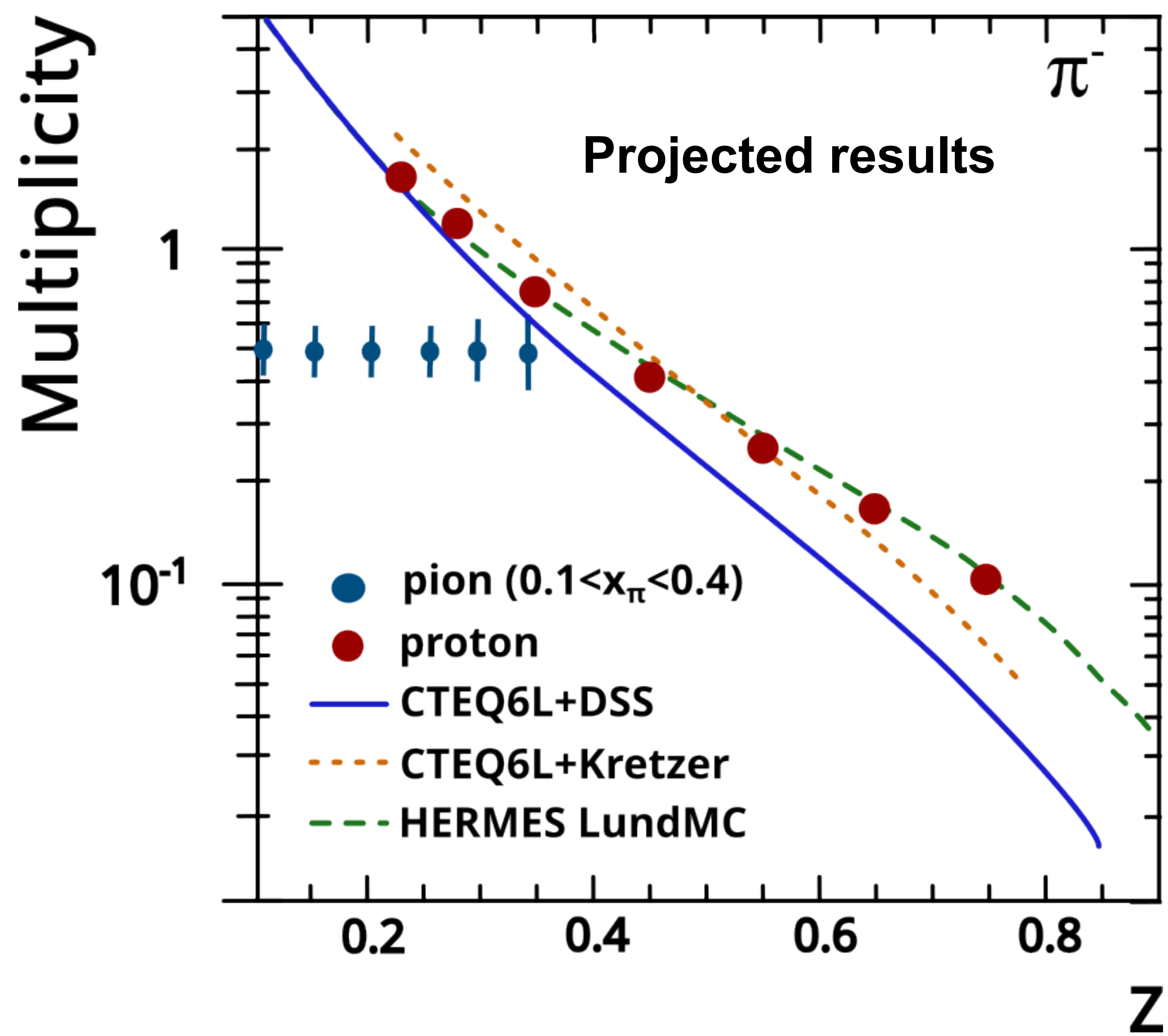


W_π^2 (1.04 - 4.0) GeV²

mTPC + scintillator

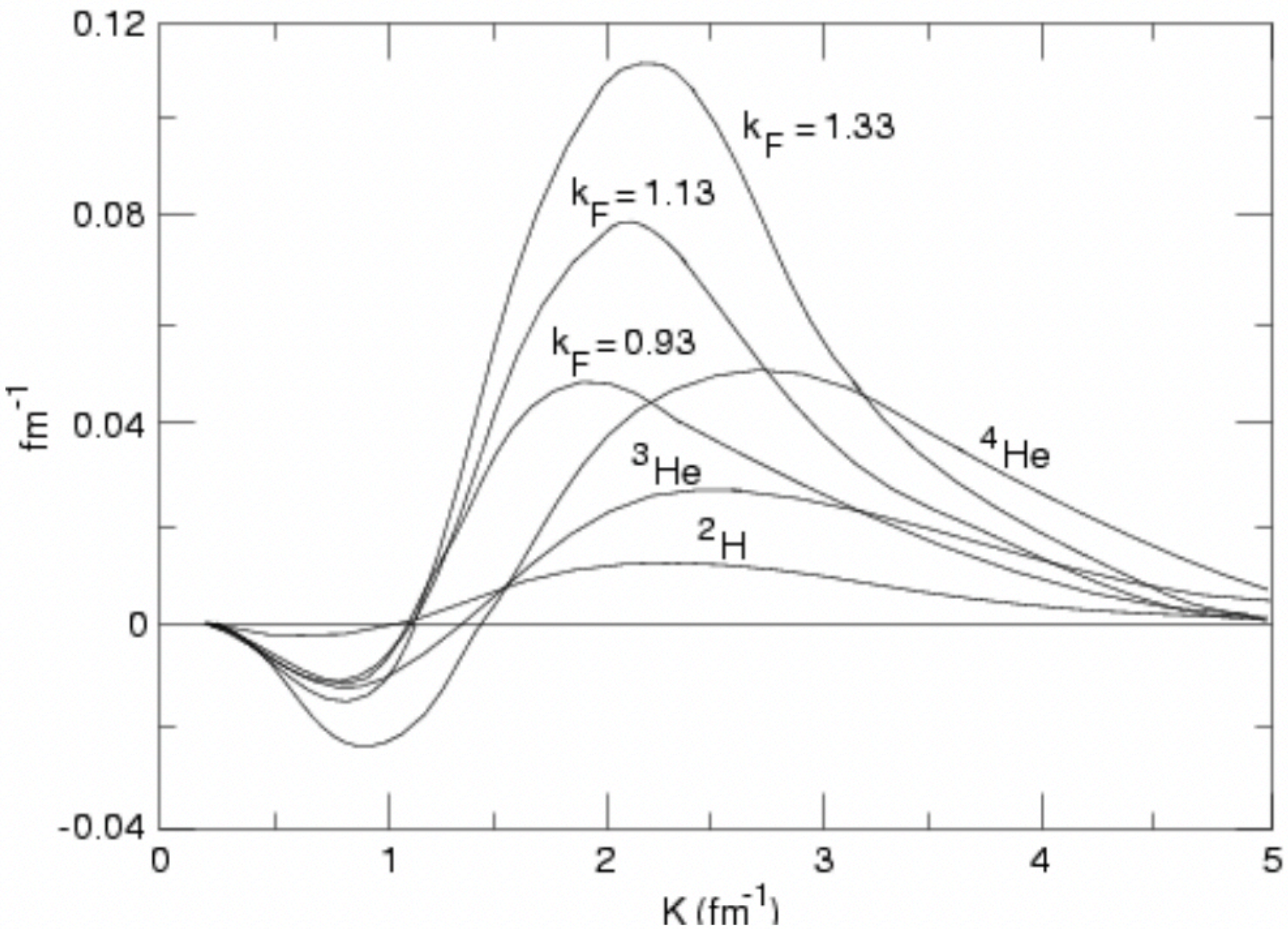


smaller diameter mTPC to fit within solenoid bore

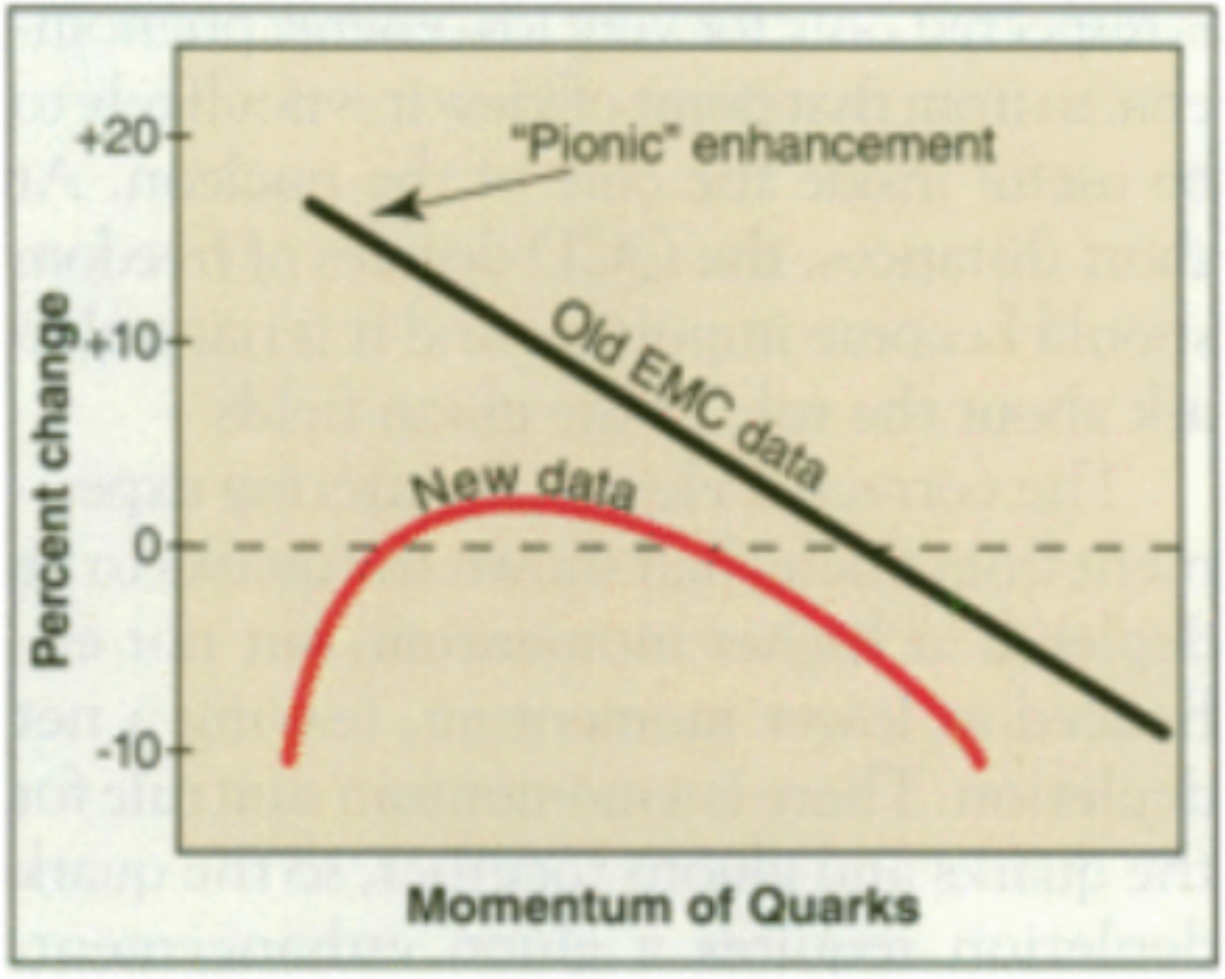


“Nuclear pions” is a long-standing prediction in nuclear physics

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

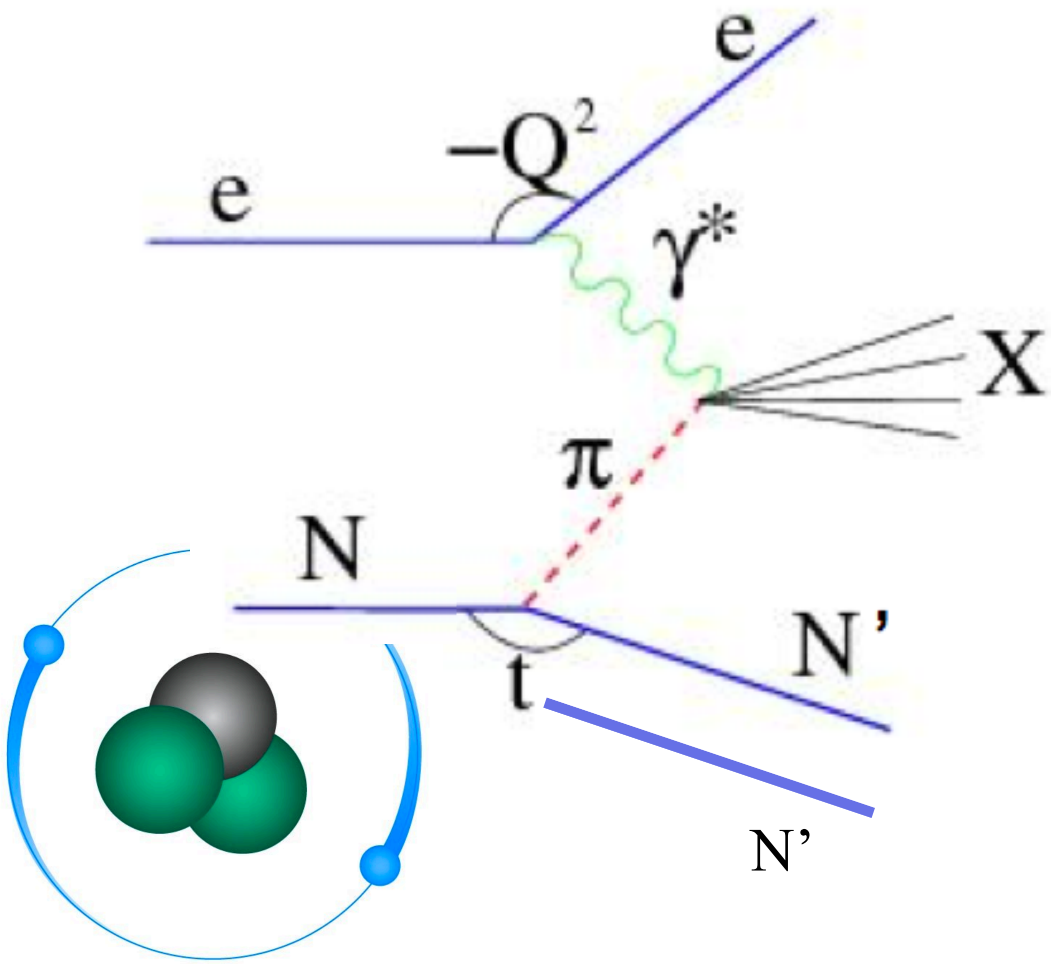


Pion excess $k^2\langle\delta n_\pi(k)\rangle/2\pi A$
as a function of virtual pion momentum

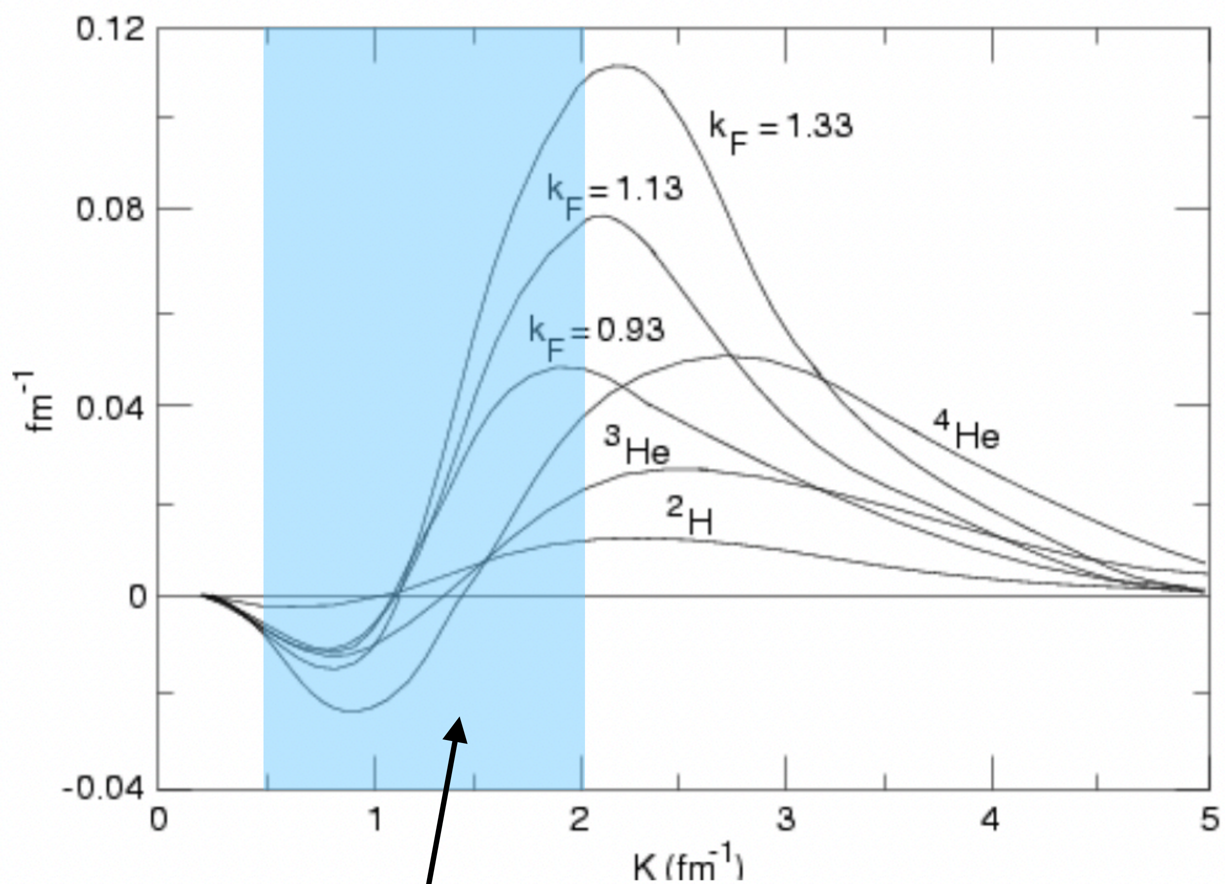


Bertsch, Frankfurt & Strikman,
Science 259, 773 (1993)

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.

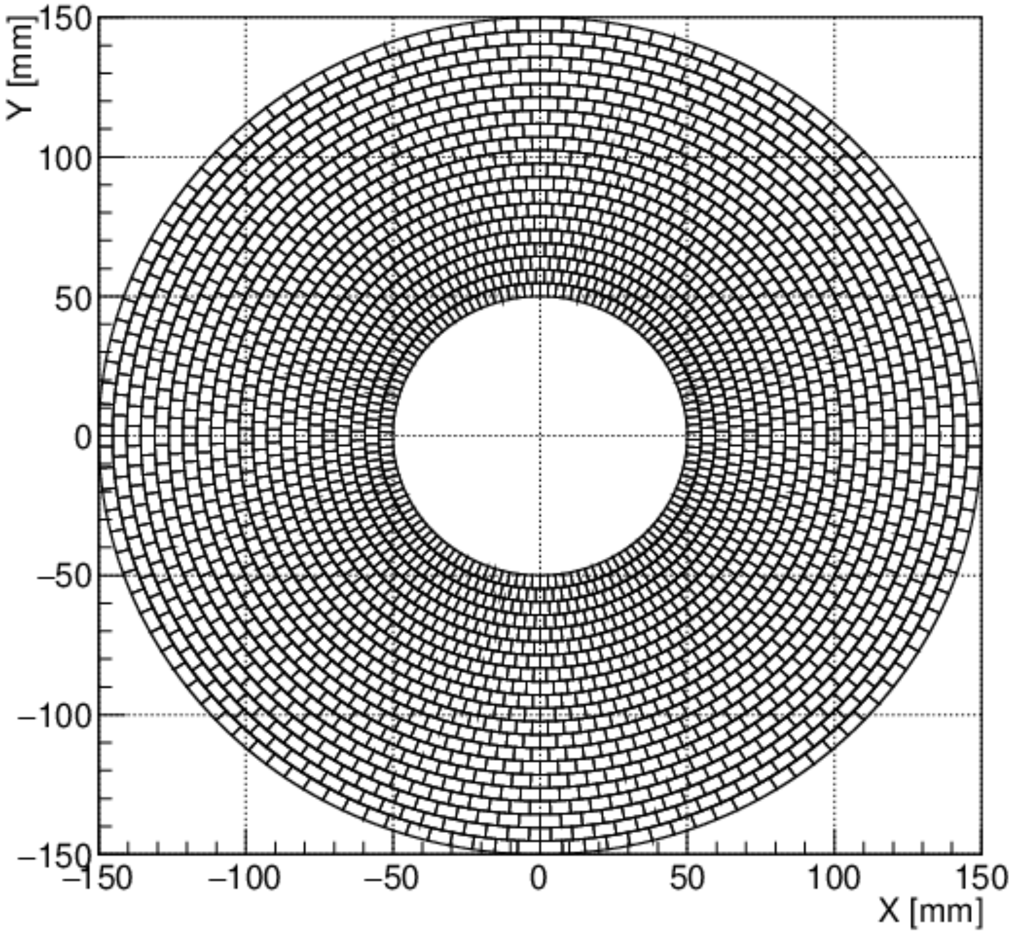
3. The upgrade of the beam to 22 GeV would vastly improve the kinematic coverage and the possible impact of these type of experiments.

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

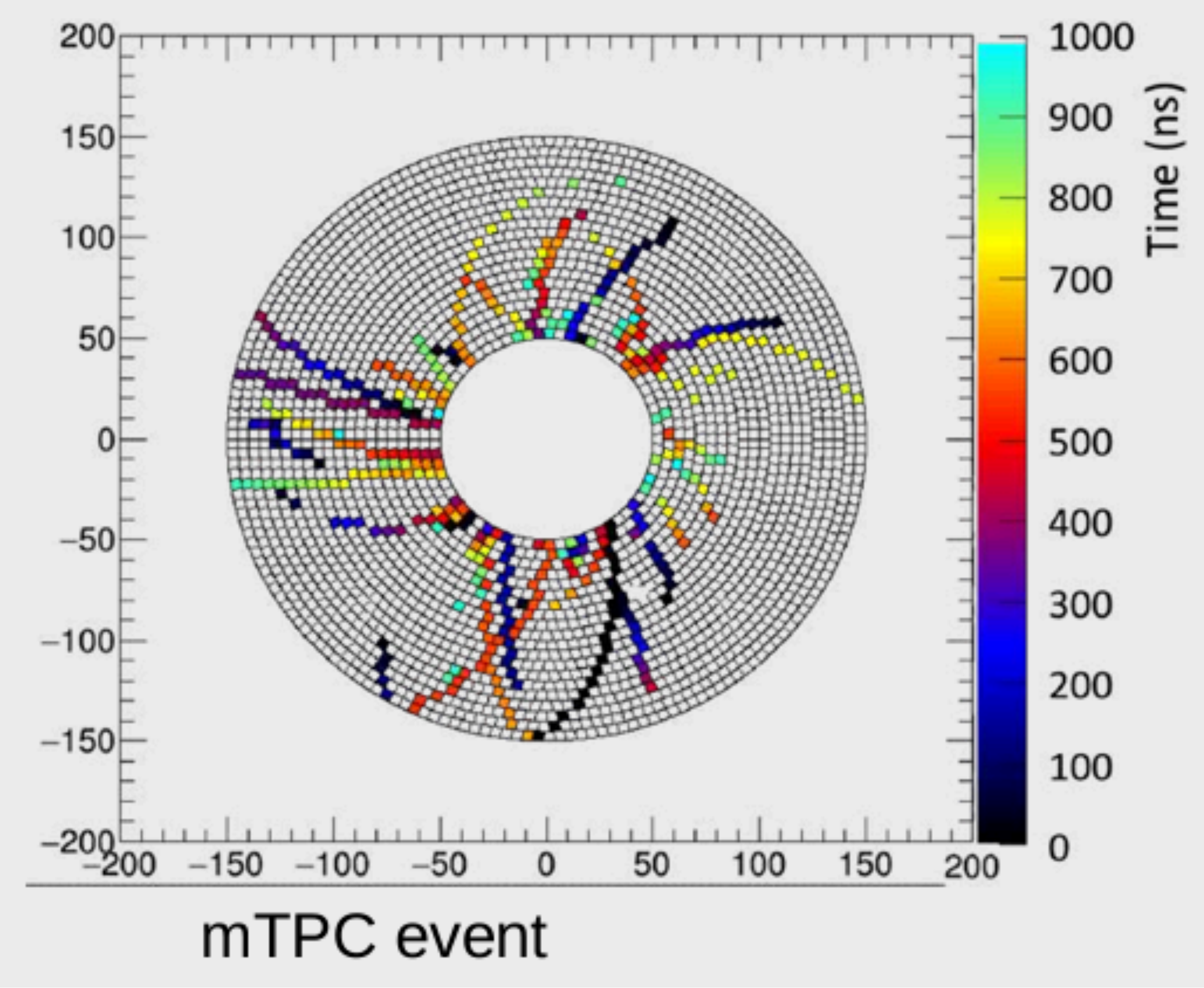
This work is supported in part by US Dept. Of Energy under contract # DE-FG02-07ER41528

Backup Slides

Readout pixel configuration and simulated hits

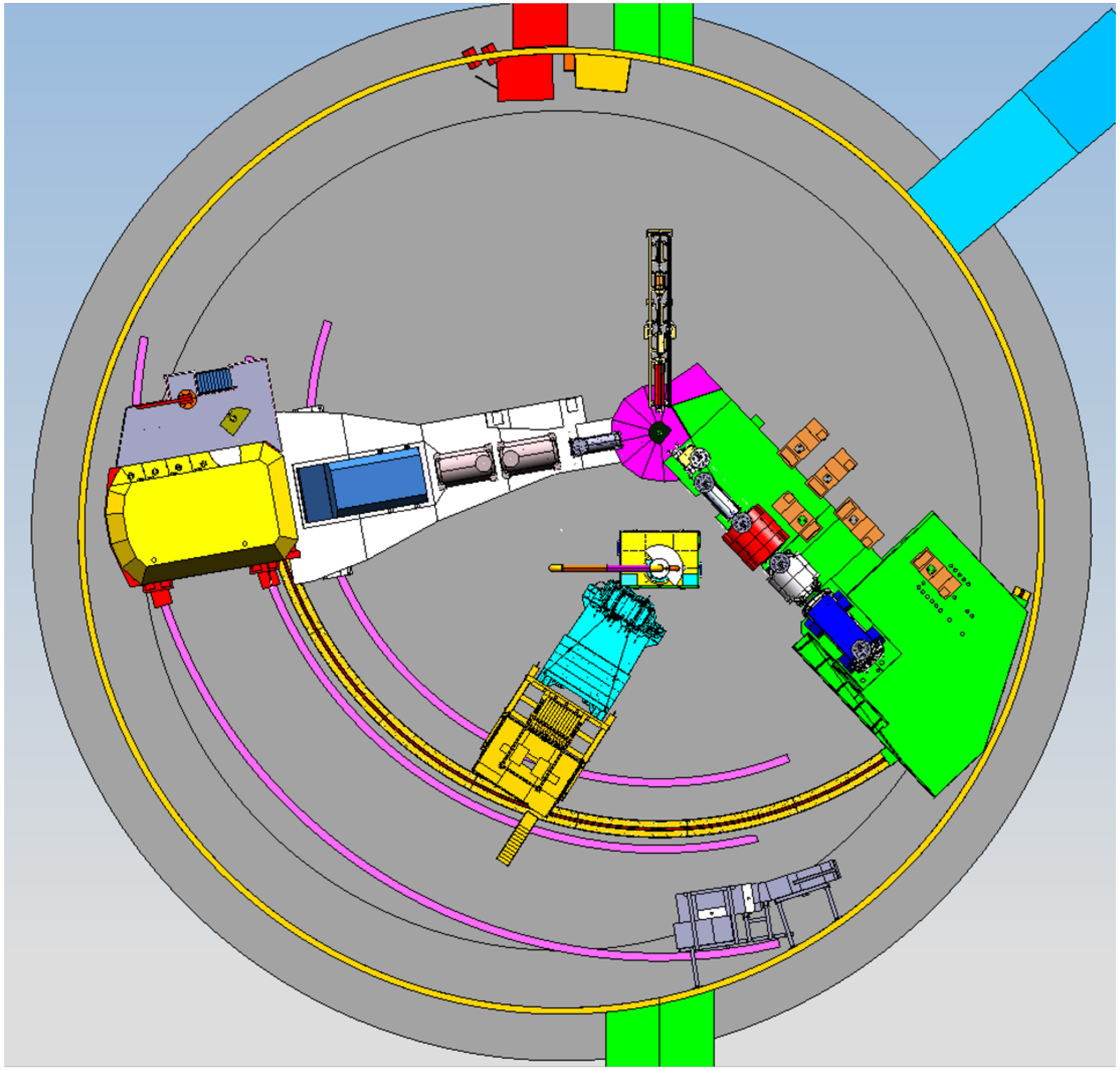


CAD design: K. Gnanvo



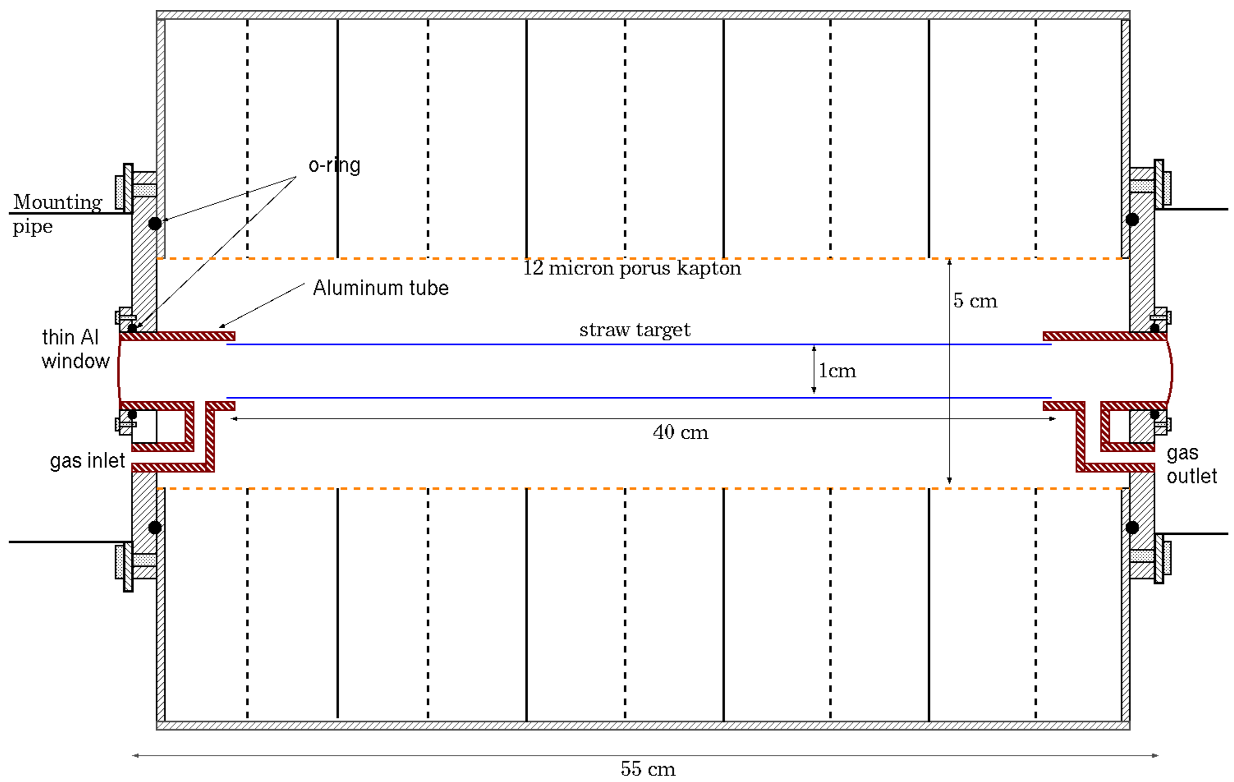
Plot credit: M. Carmignotto

SBS in Hall C



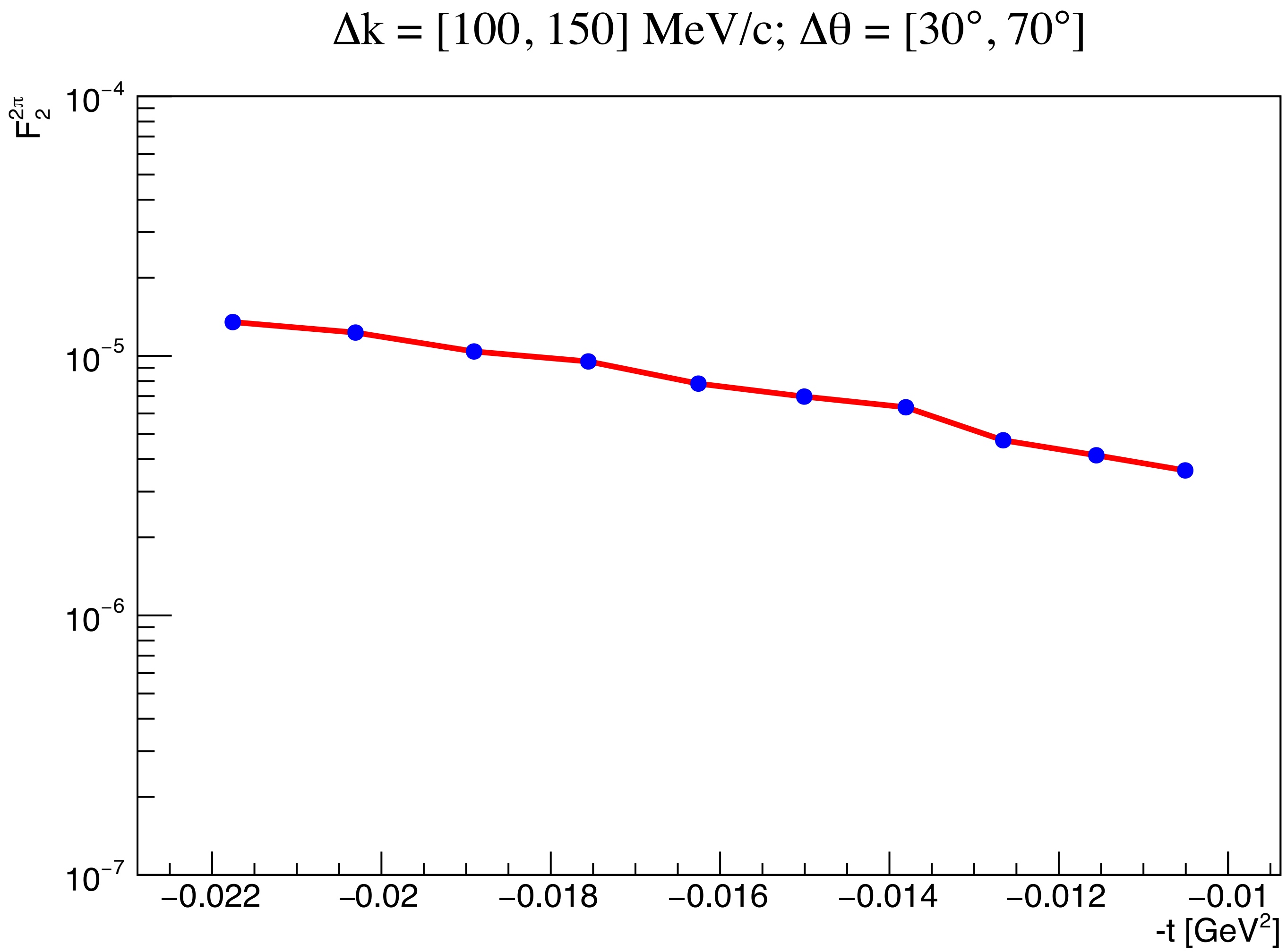
Solenoid & Target

spiral wound 25 um kapton straw Target

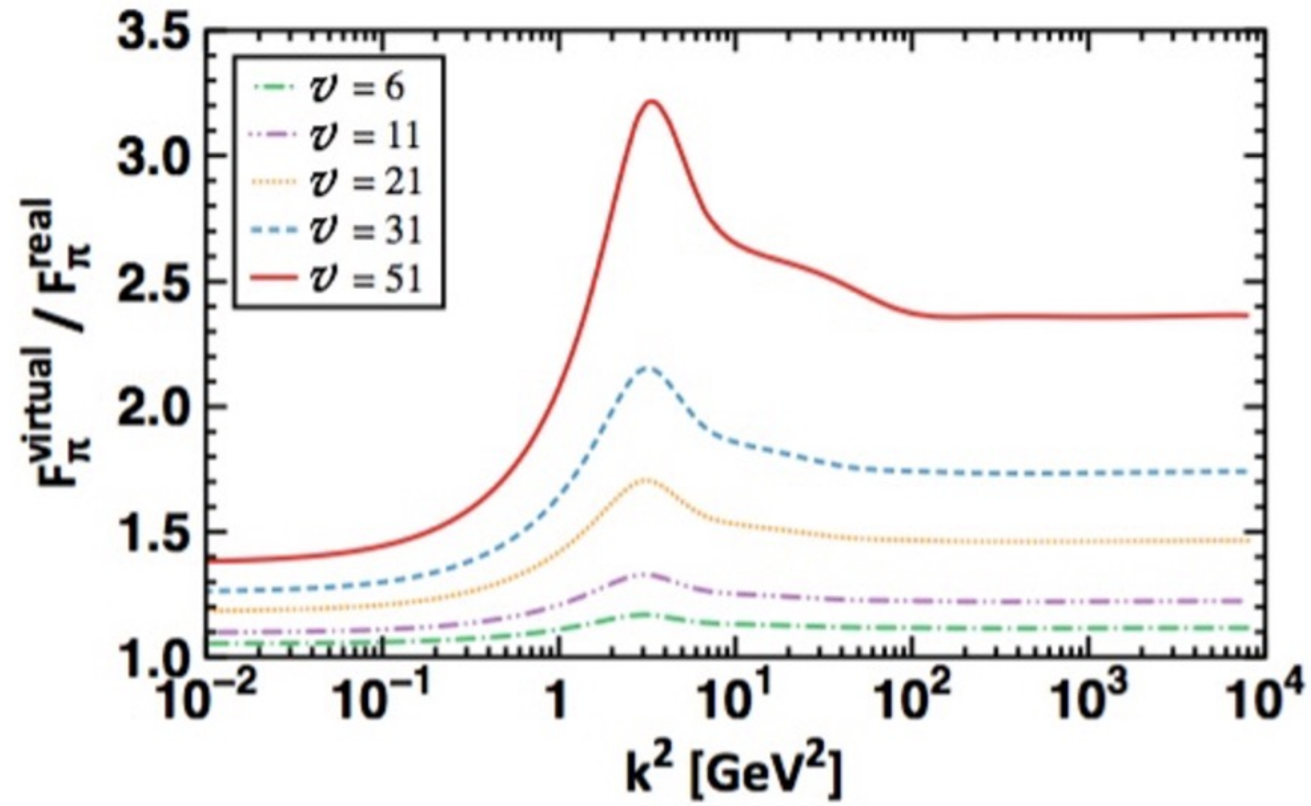


UVa 4T Solenoid

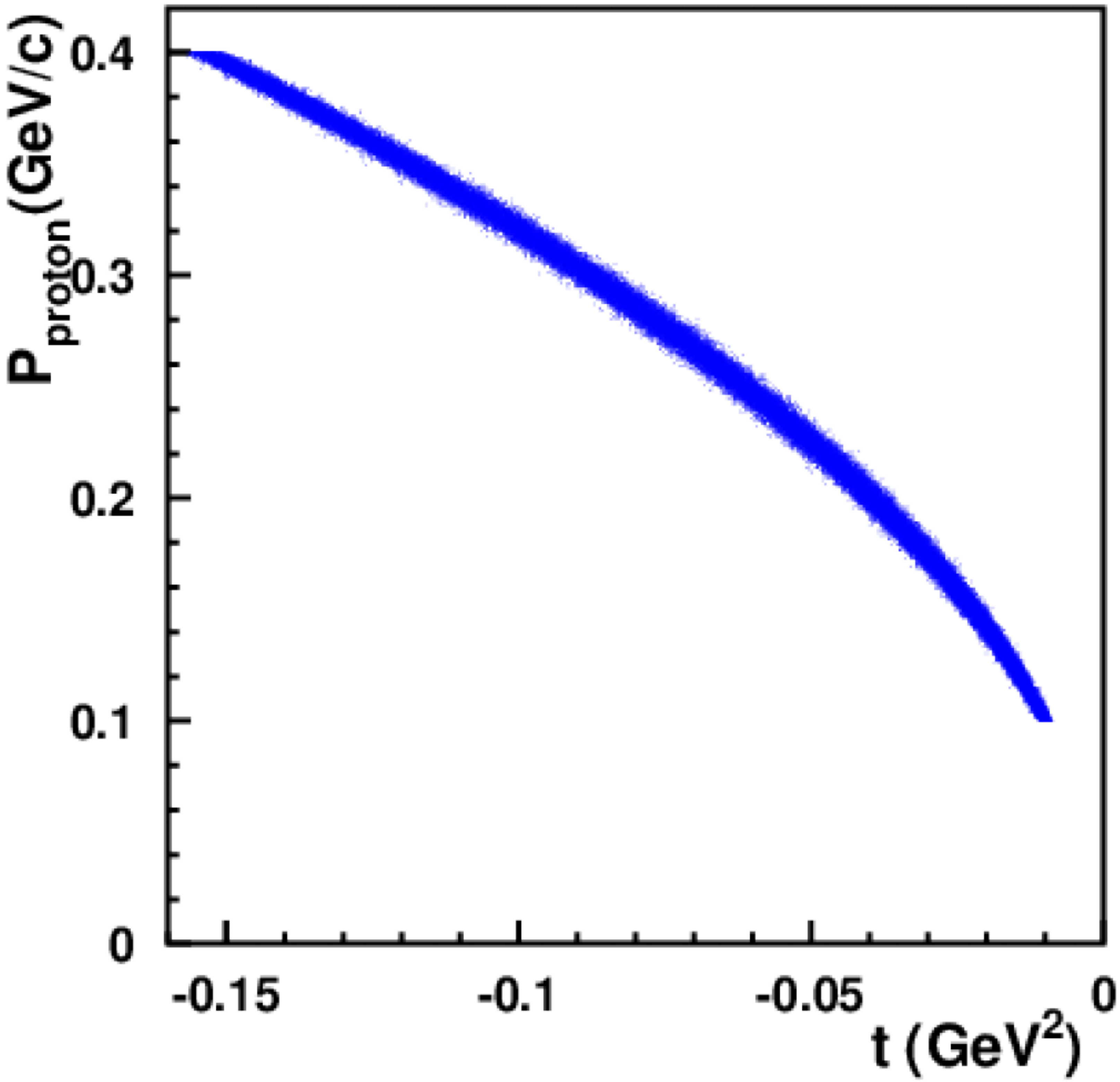
Pressure tested to 60 psi



Δk = [100, 150] MeV/c; Δθ = [30°, 70°]
$F_2^{2\pi}$
10^{-4}
10^{-5}
10^{-6}
10^{-7}
−0.022
−0.02
−0.018
−0.016
−0.014
−0.012
−0.01
-t [GeV^2]

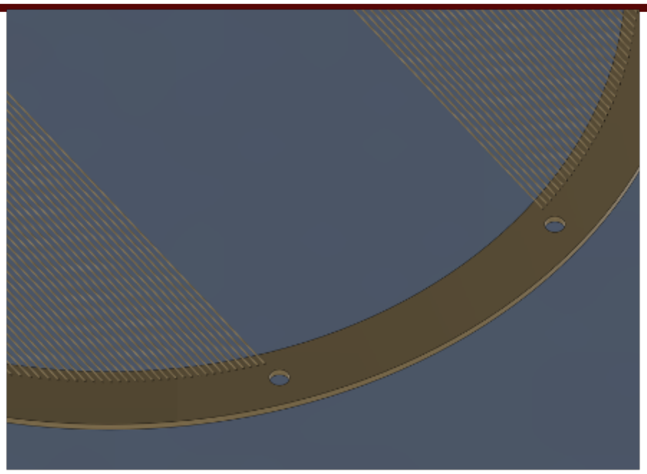


v = 6
v = 11
v = 21
v = 31
v = 51
$F_\pi^{virtual} / F_\pi^{real}$
3.5
3.0
2.5
2.0
1.5
1.0
10^{-2}
10^{-1}
1
10^1
10^2
10^3
10^4
k^2 [GeV^2]

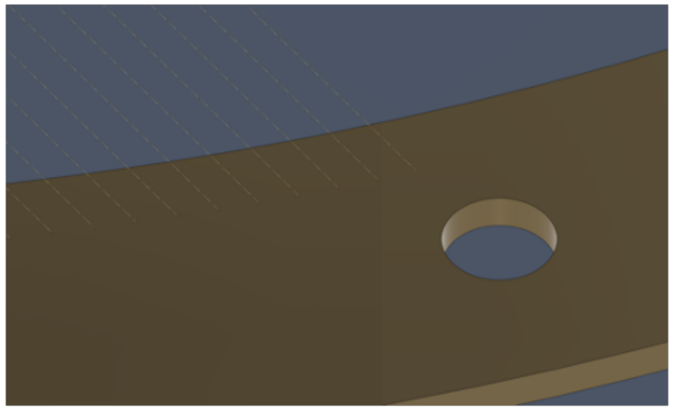

P_{proton} (GeV/c)
0.4
0.3
0.2
0.1
0
-0.15
-0.1
-0.05
0
t (GeV^2)

Fine wire based ultra high rate "Pixel Projection Chamber" R&D for TDIS

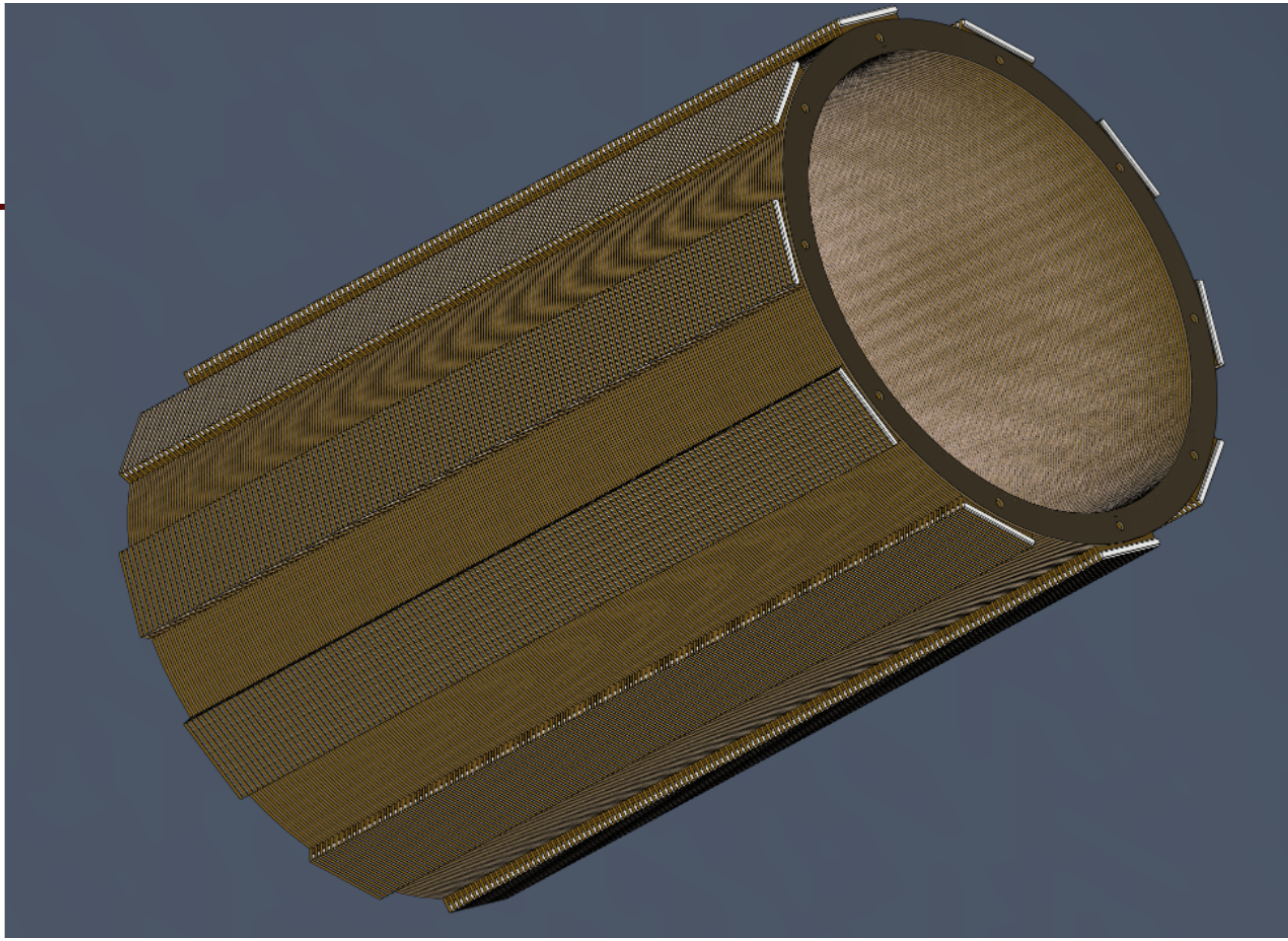
- Idea from Bogdan: build the recoil detector with wire planes; 2 mm wire pitch, 1 mm plane separation: compared to mTPC
  - Drift length feeding into signals down from 50 to 2 mm: factor of 25 reduction in plane occupancy.
  - mTPC has an integration time for 50 mm to form a track; but we need only about 5 pixels to form the curved track: so with the wire detector integration time goes down to ~ 5 mm - factor of 10 reduction in track occupancy.
  - Wire frames are 99% transparent to protons tracks: no track loss at planes - higher efficiency than mTPC
- Still keeps the strong features of the mTPC:
  - Highly segmented TPC to reach unprecedented high rates
  - E and B fields parallel to each other, so no Lorentz force on the drift electrons, easy to do x to t conversion.
  - 10 cm diameter hole through the detector for beam; but in this case the hole is "virtual" with no foil to block the protons.
- The Plan:
  - The UVa team is already working on a 10x10 cm^2 prototype with 5 planes each of anode and cathode.
  - Expect to have this ready and tested in less than 3 months: since no GEM foils are needed; quick turn around time.
  - Then will build and test a cylindrical prototype within a ~ 9 month time frame following that: this would be in parallel to mTPC prototyping.
  - Test the prototypes with cosmics, high flux x-rays and strong alpha source placed inside the detector to mimic low energy protons.
  - Tue UVa team has secured $ 20 k for this prototyping work; this is in addition to the $ 20 k from Glasgow for the mTPC prototype.



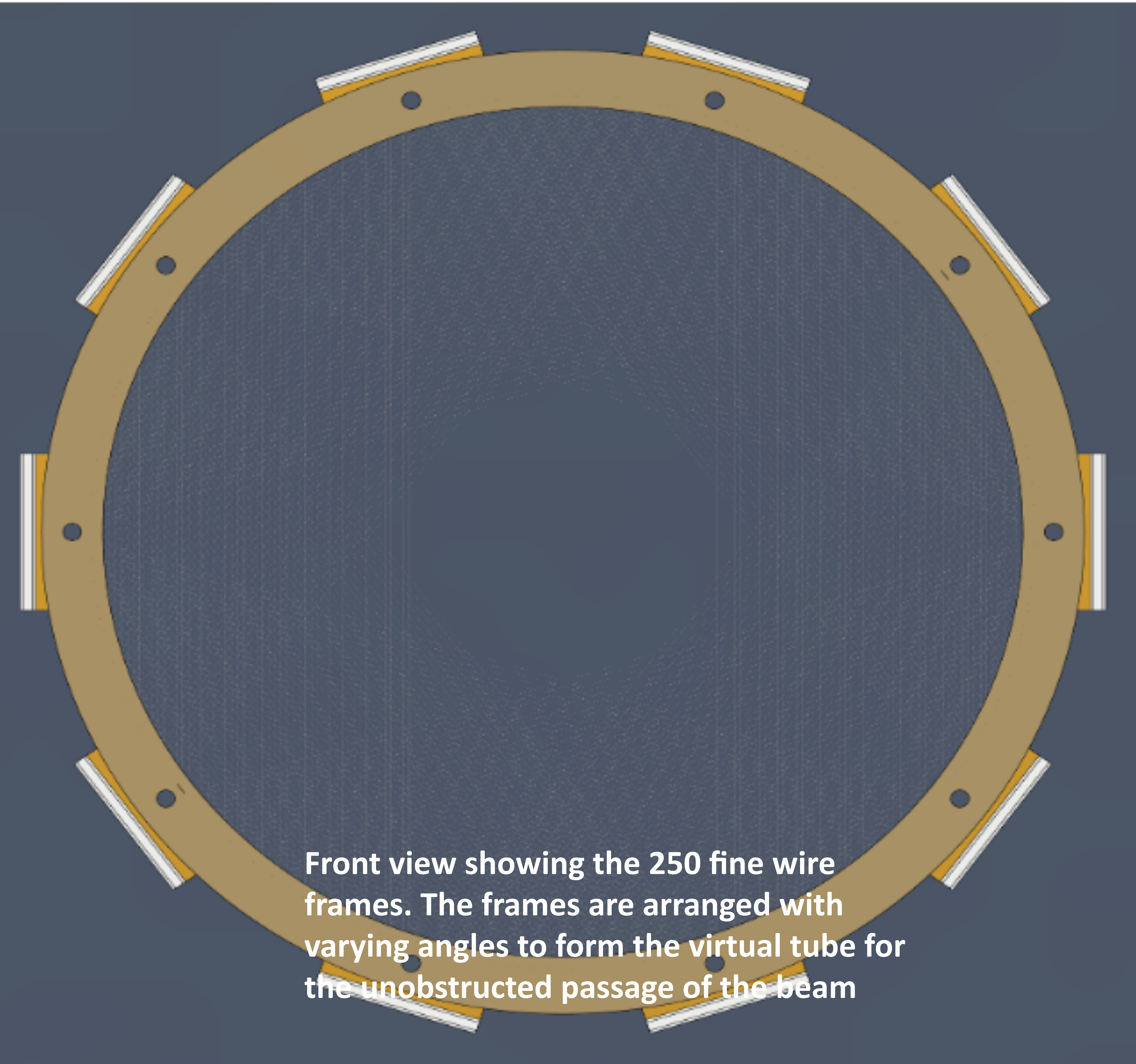
One frame, showing the gap which forms the beam "pipe". The wires are enlarged to 0.5mm for view (all other images are for actual 0.025mm wires.



About 99% of the area in a plane is open for the protons to pass through



30 cm diameter, 50 cm long cylindrical detector formed by 500 alternating anode and cathode wire frames, each with a thickness of 1 mm. The 25 micron wires at a pitch of 2 mm occupy ~ 1% of the area of each plane, thus allowing most of the protons tracks to pass through.



Front view showing the 250 fine wire frames. The frames are arranged with varying angles to form the virtual tube for the unobstructed passage of the beam