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, H. Nguyen, B. Wojtsekhowski

C1 conditionally approved with A- rating for 27 PAC days

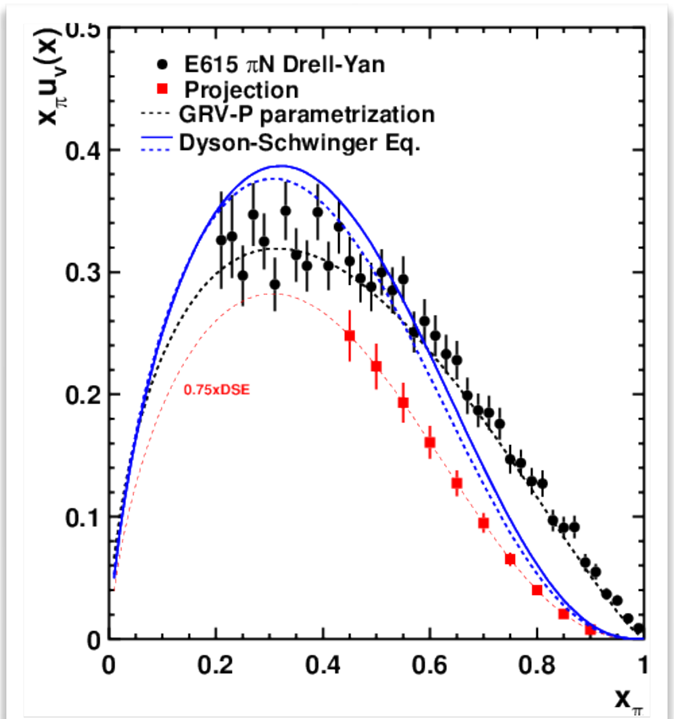
Motivations:

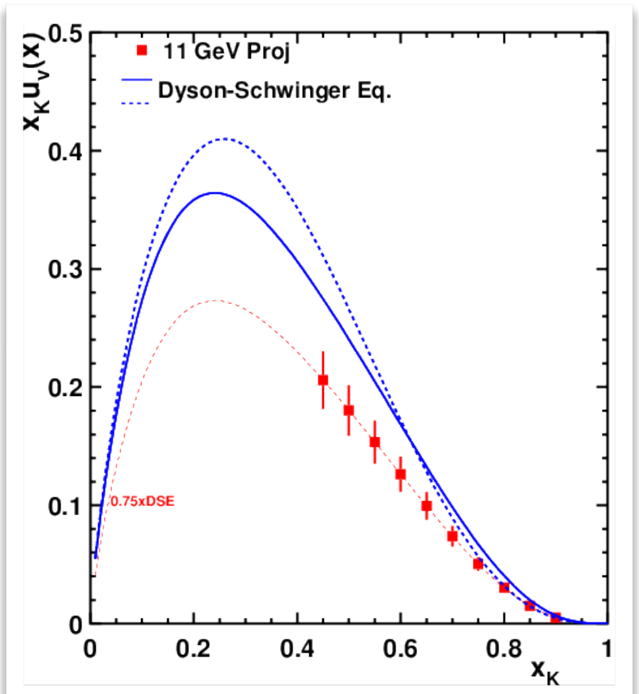
There is ample evidence that nucleons have pionic content in them, but no direct measurements.

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

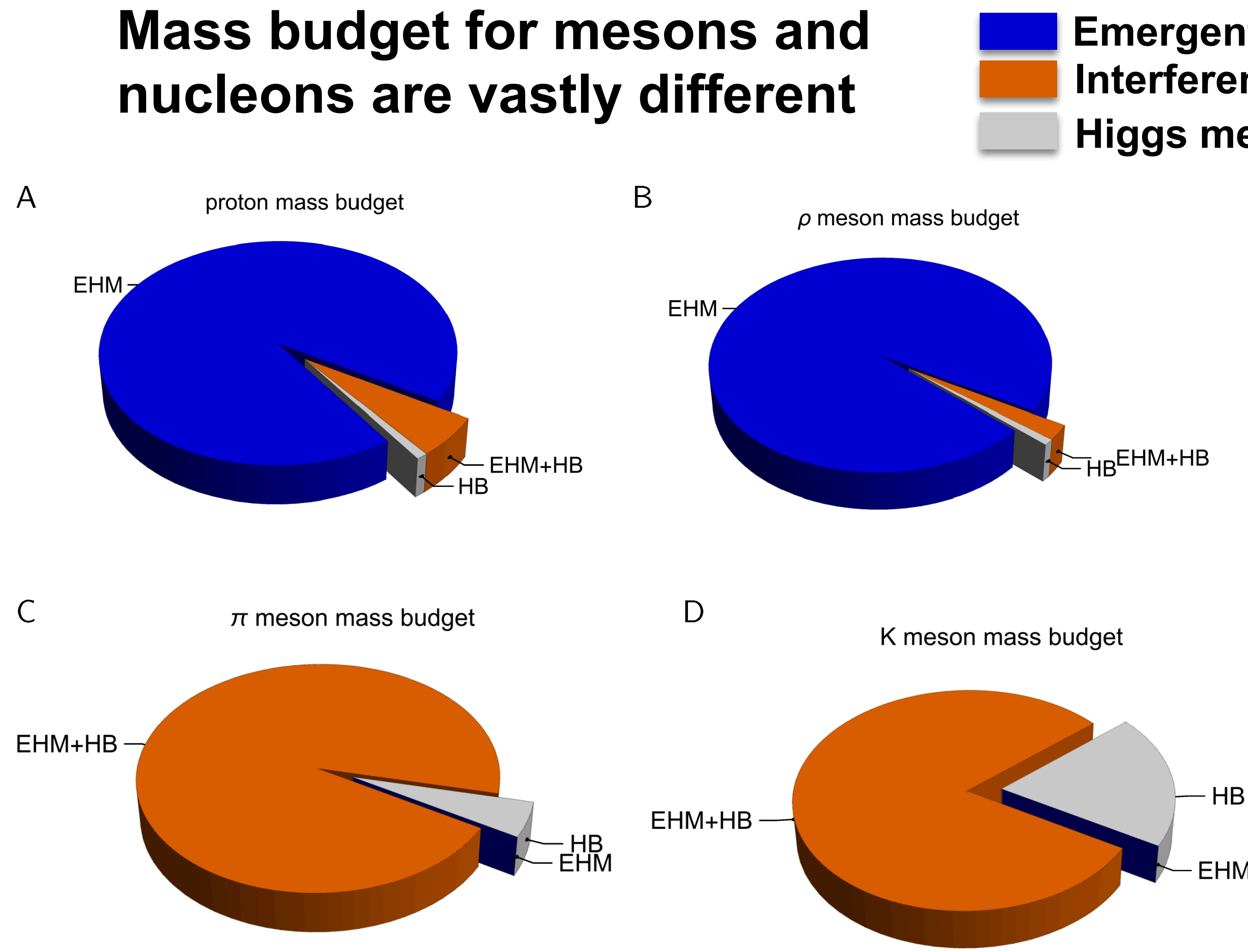




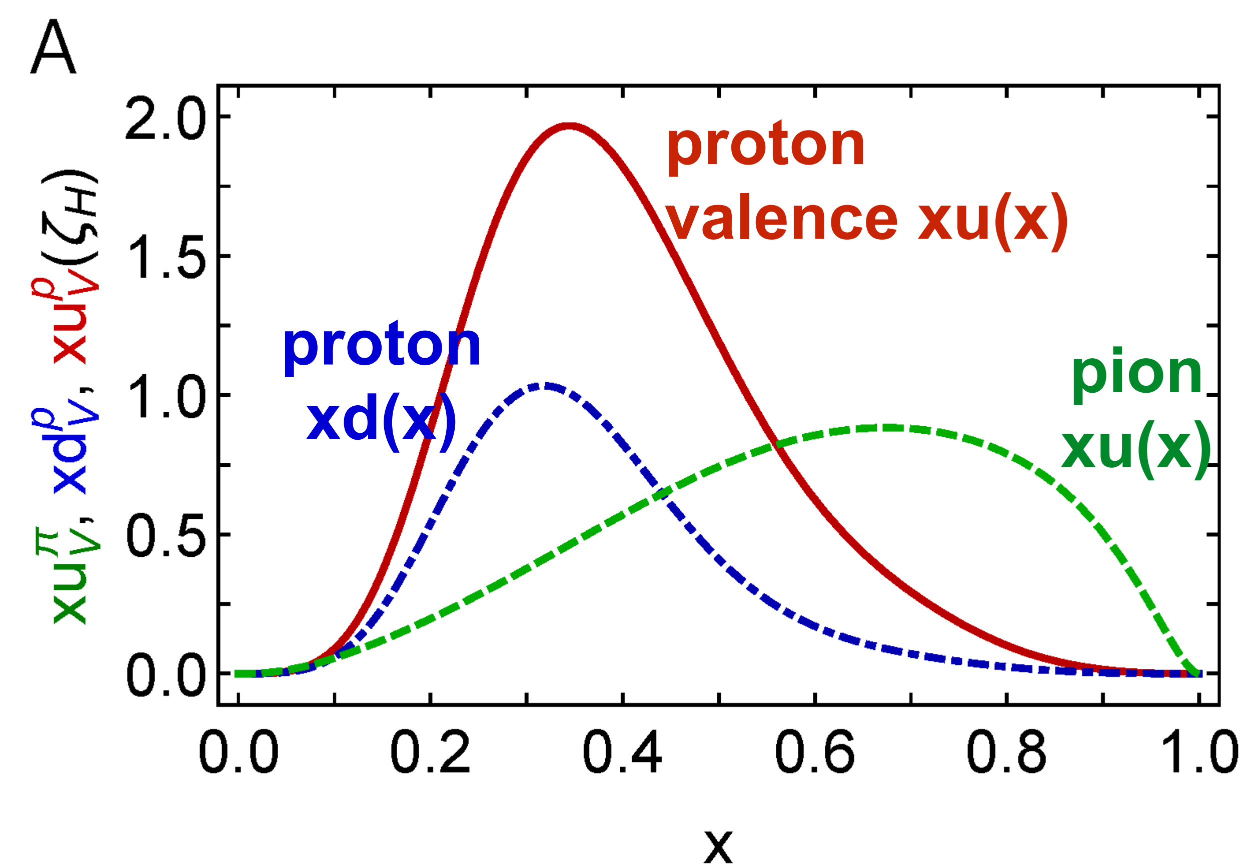
Since approval, there has been a surge of interest in both the technique and the science goal

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)



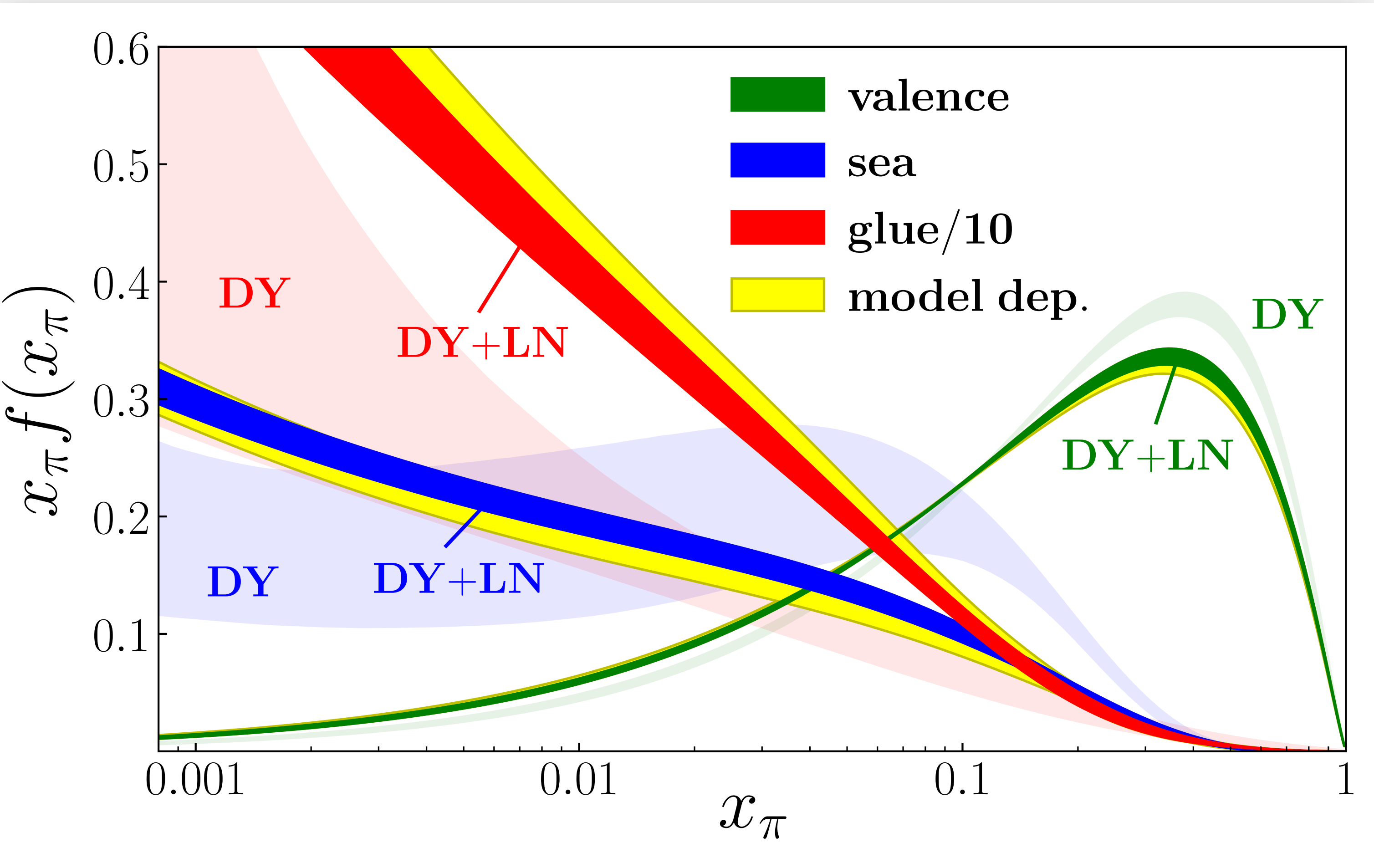
pion/proton valence quark distributions are very different

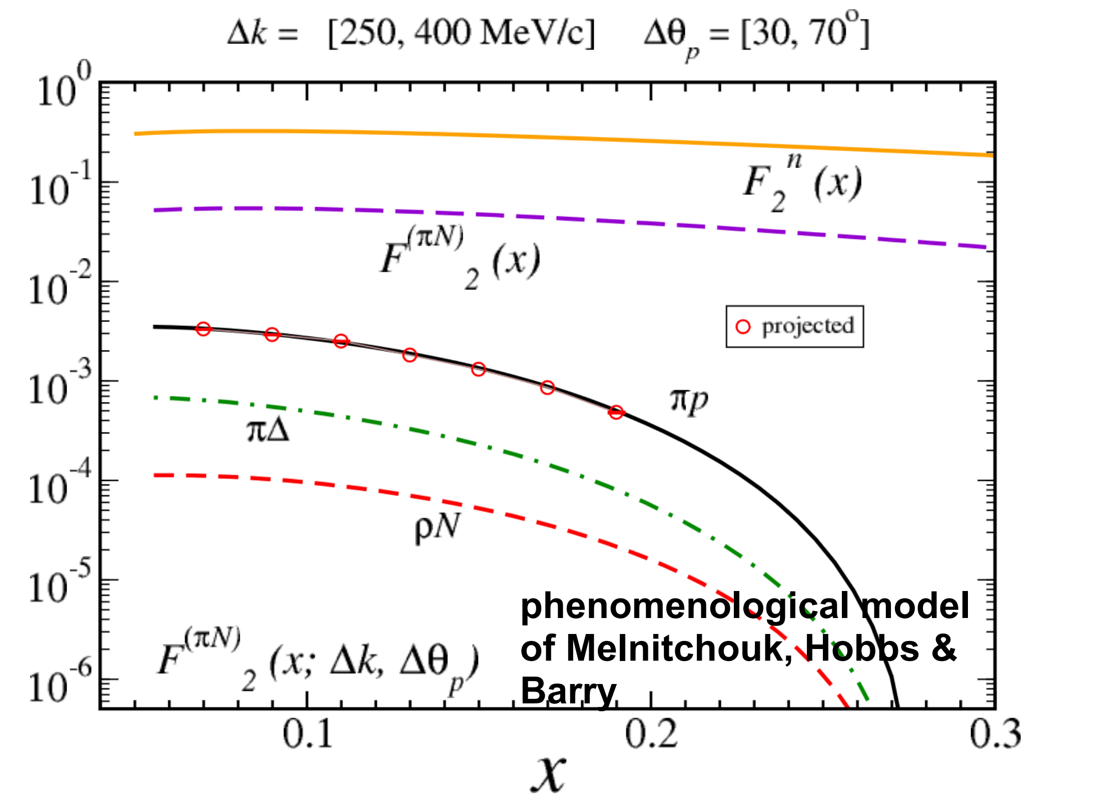
difference between meson PDFs: direct information on emergent hadron mass

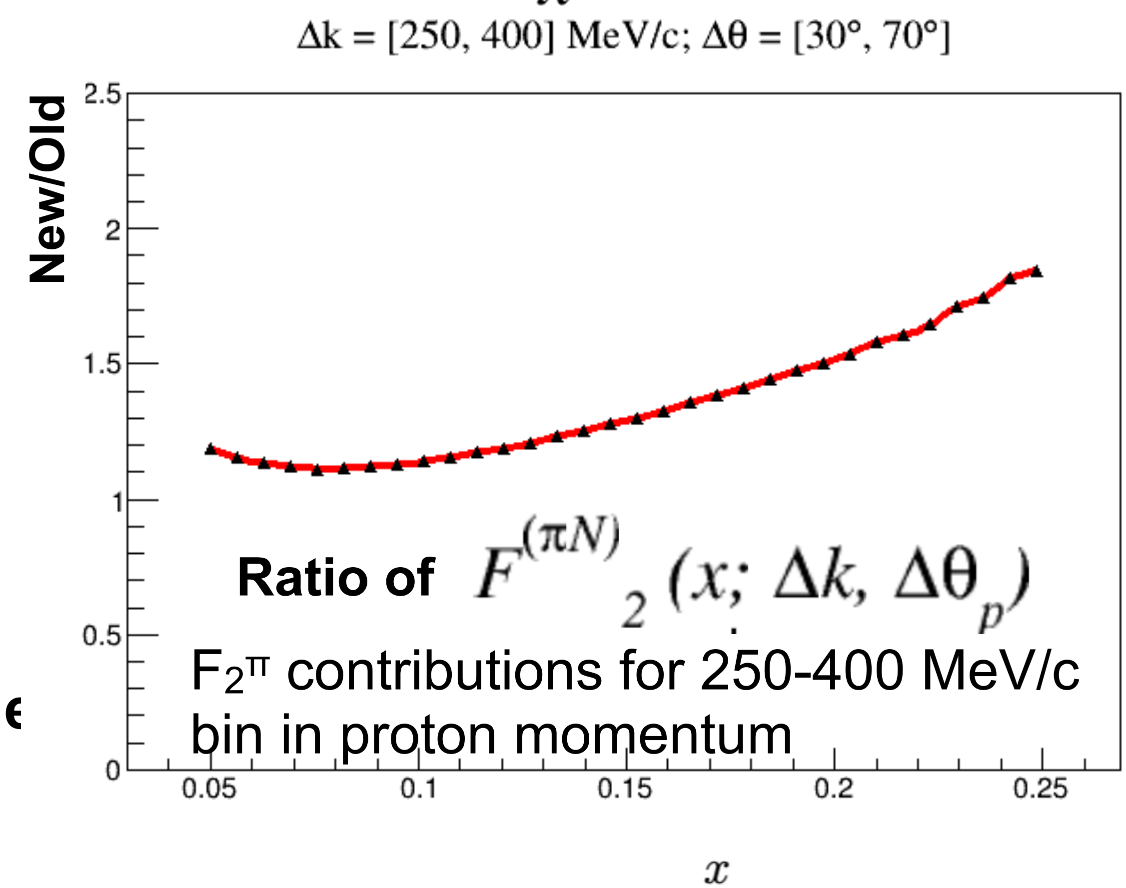
A global QCD analysis including the leading neutron HERA data has been completed

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)





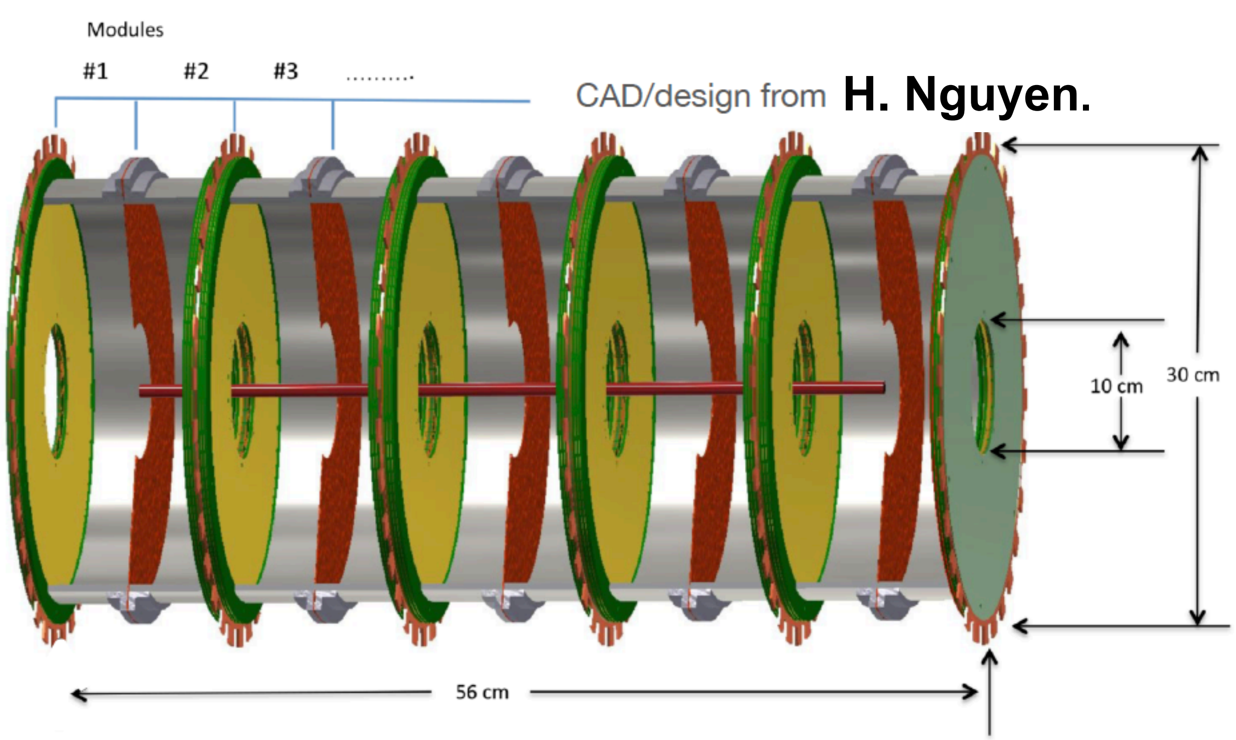


Rate of TDIS signal events is expected to be larger and less sensitive to the pion flux factor; will help reduce the beam current to improve background and tracking.

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

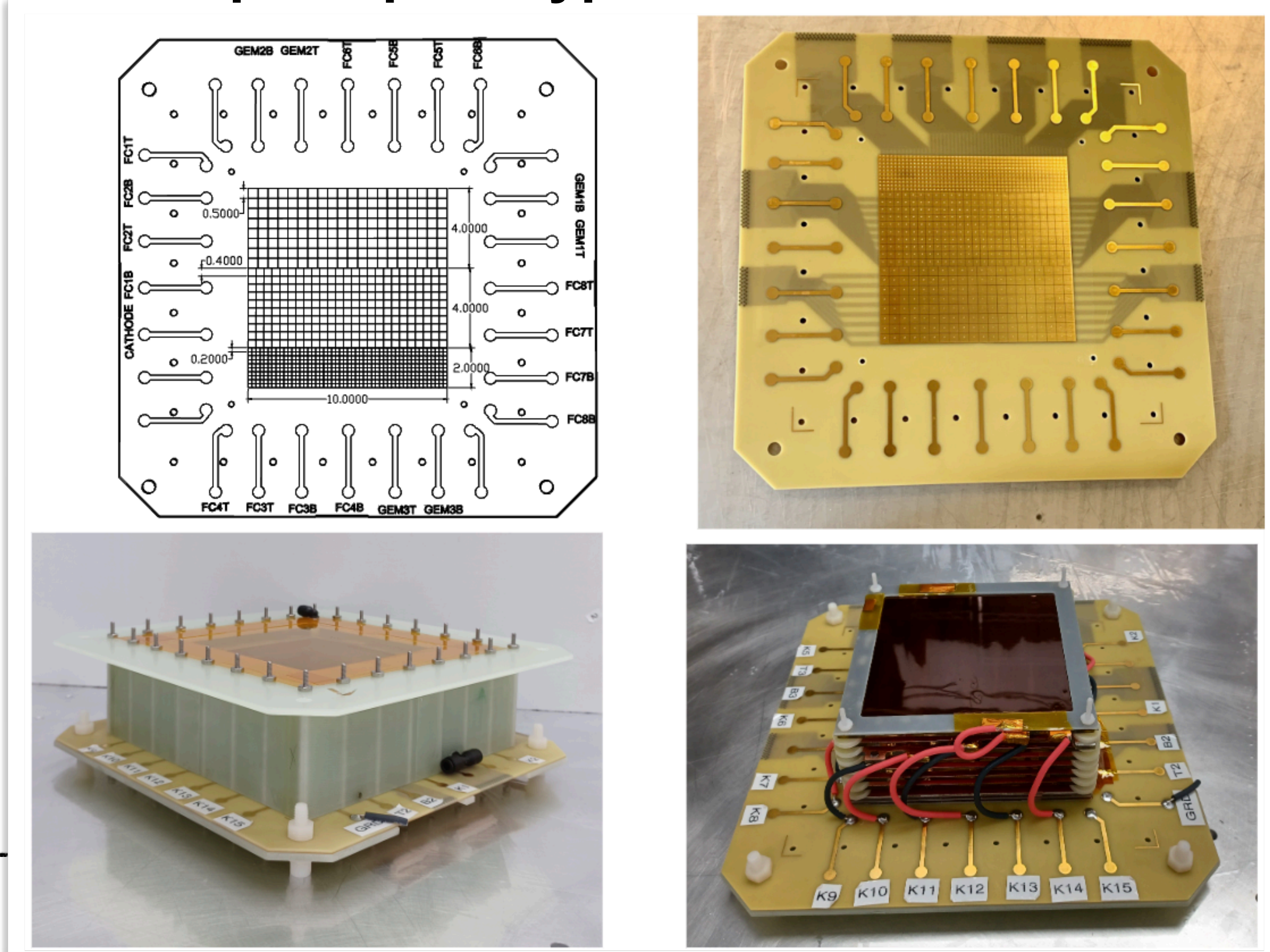


Tracking, dE/dx

- 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

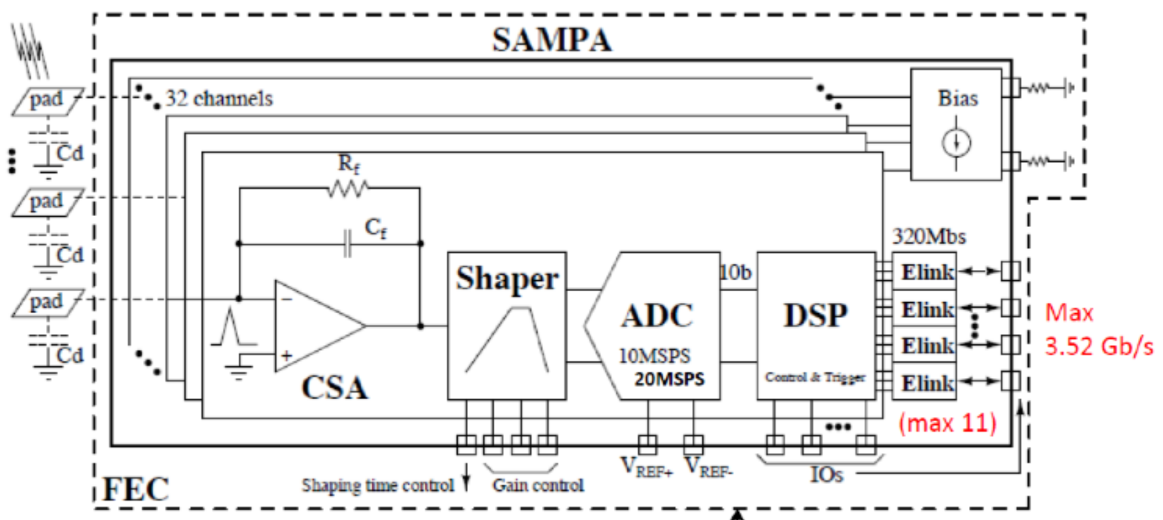


Images from H. Nguyen

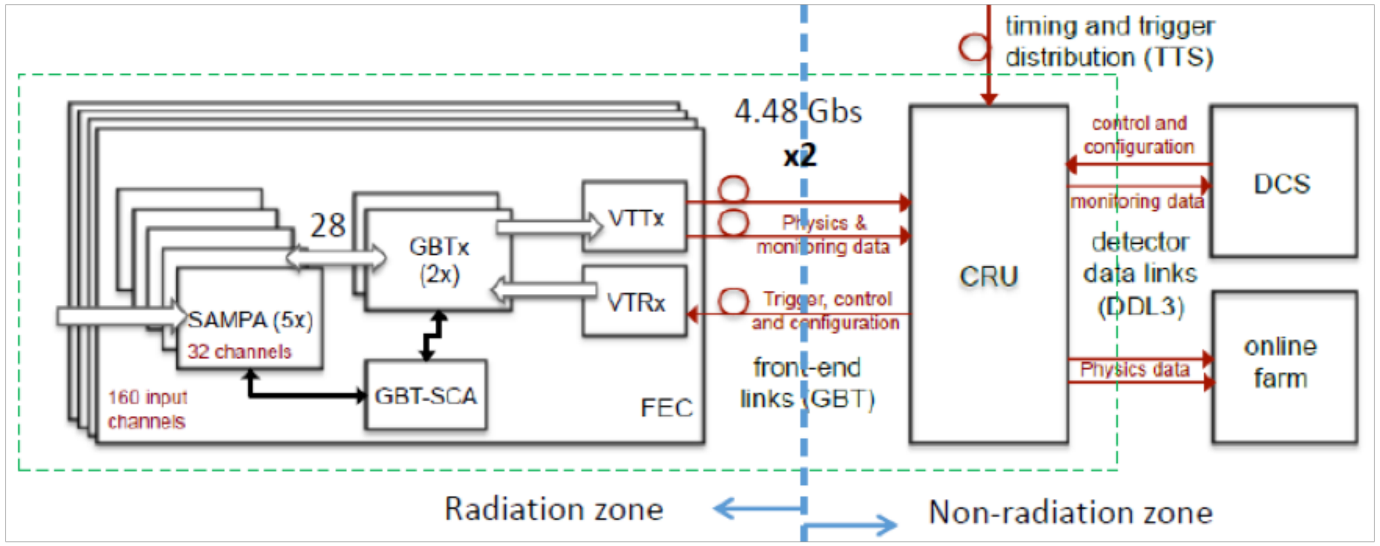
Testing is currently underway at UVa and JLab to validate the time projection field cage and the readout configuration.

A cylindrical prototype will be built after validation.

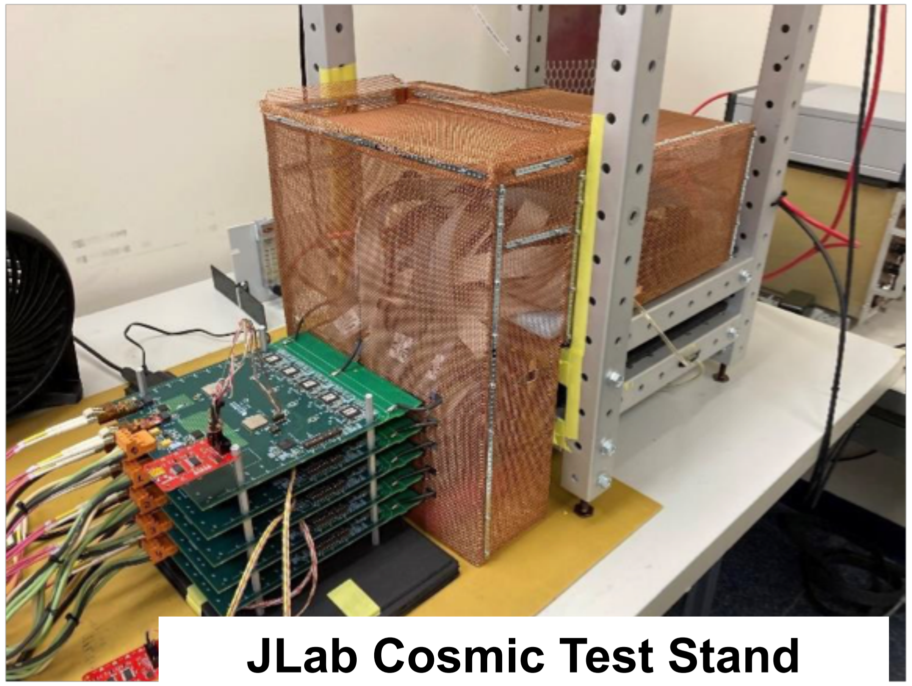
Readout for mTPC has been developed using the SAMPA chip



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 Cosmic Test Stand
FEC, coupled to GEM detector

SAMPA V5 - 80 ns shaping time

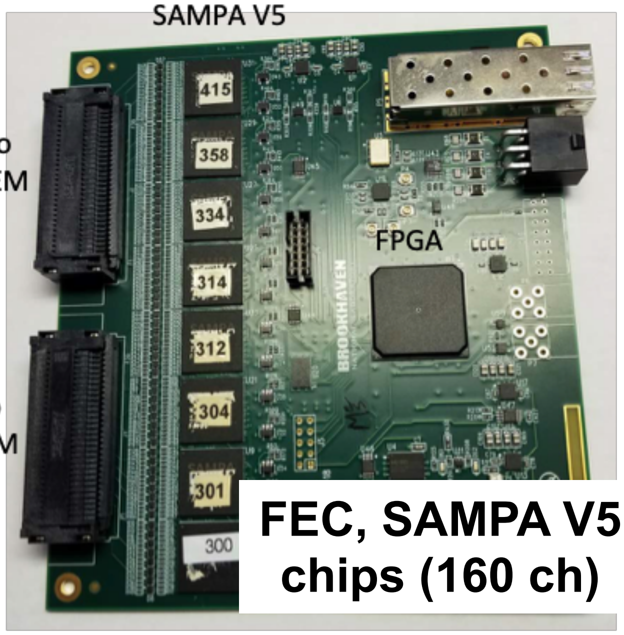
SAMPA can be used in streaming mode or triggered mode

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

SAMPA V5

to GEM

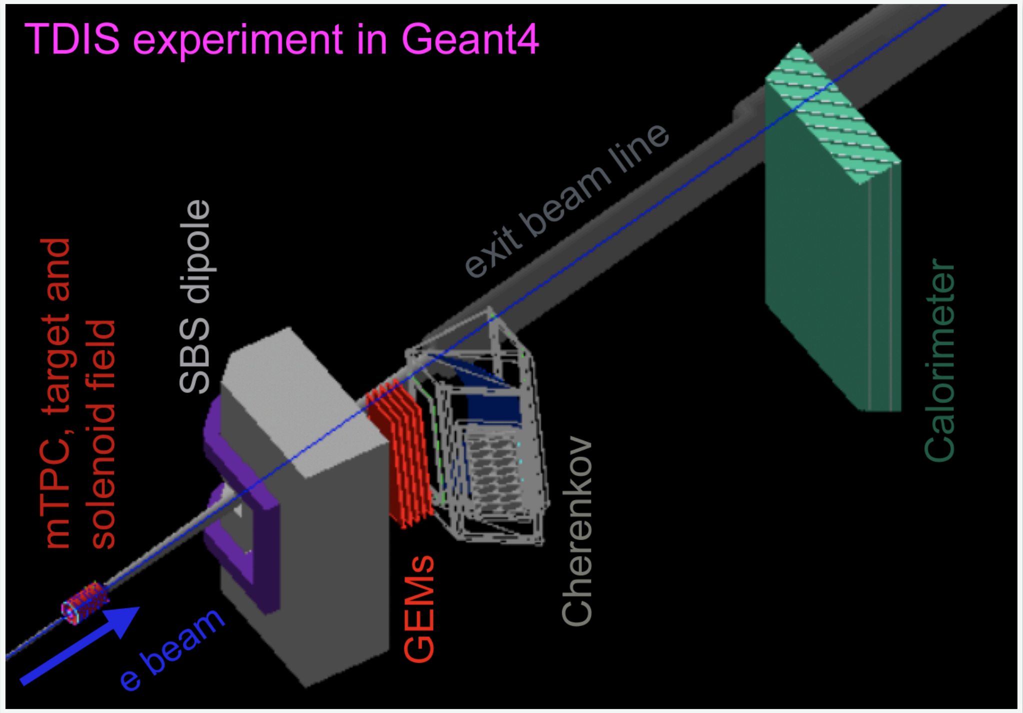
to GEM



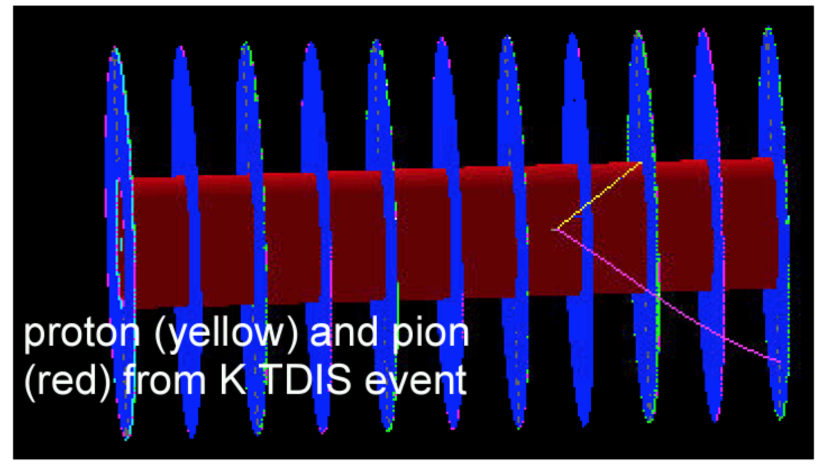
FEC, SAMPA V5 chips (160 ch)

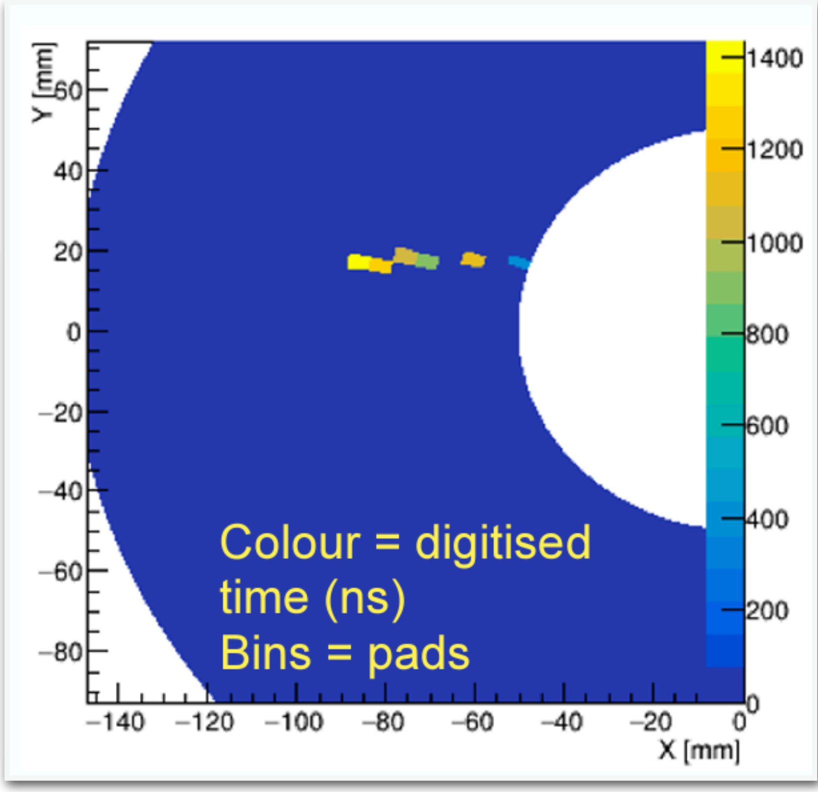
Image credit
E. Jastrzembski JLab

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



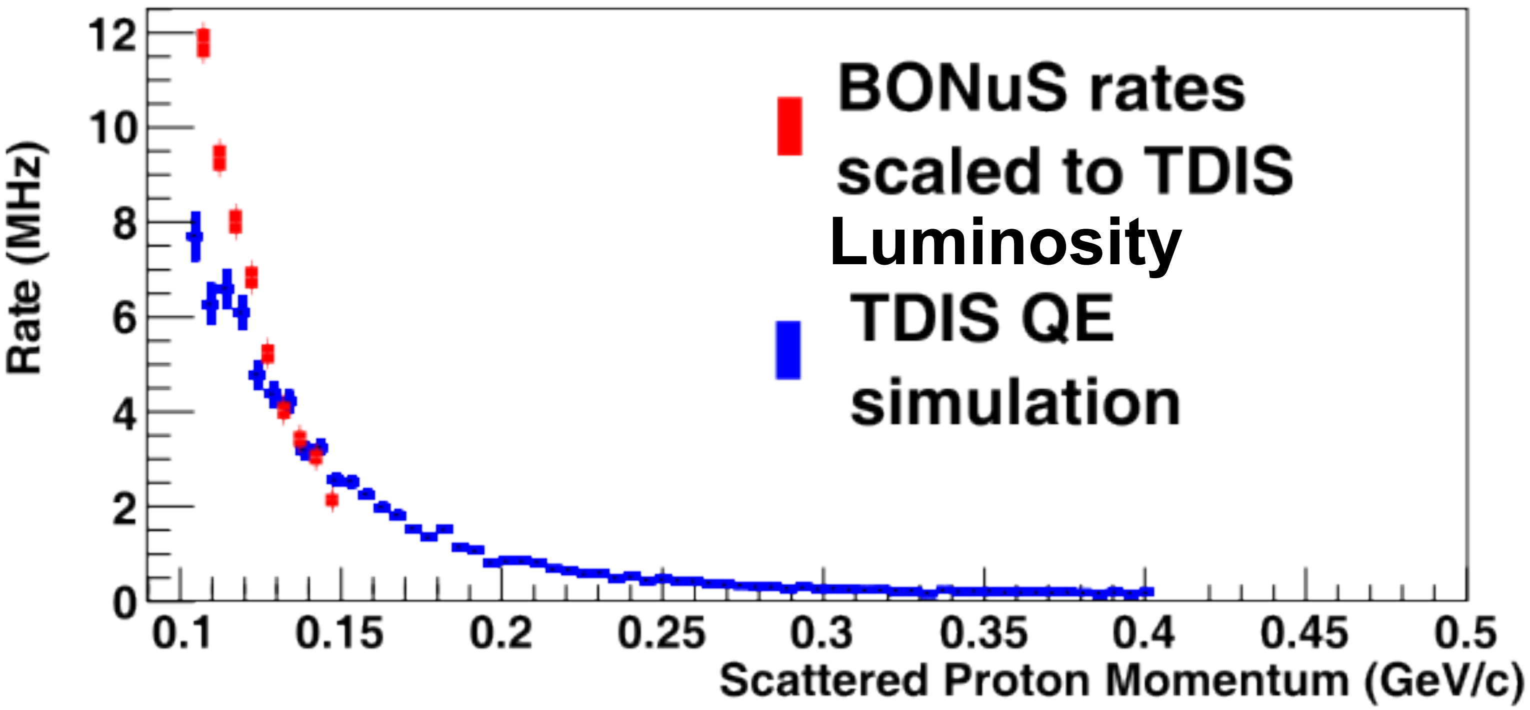
mTPC simulated with Magboltz/Garfield

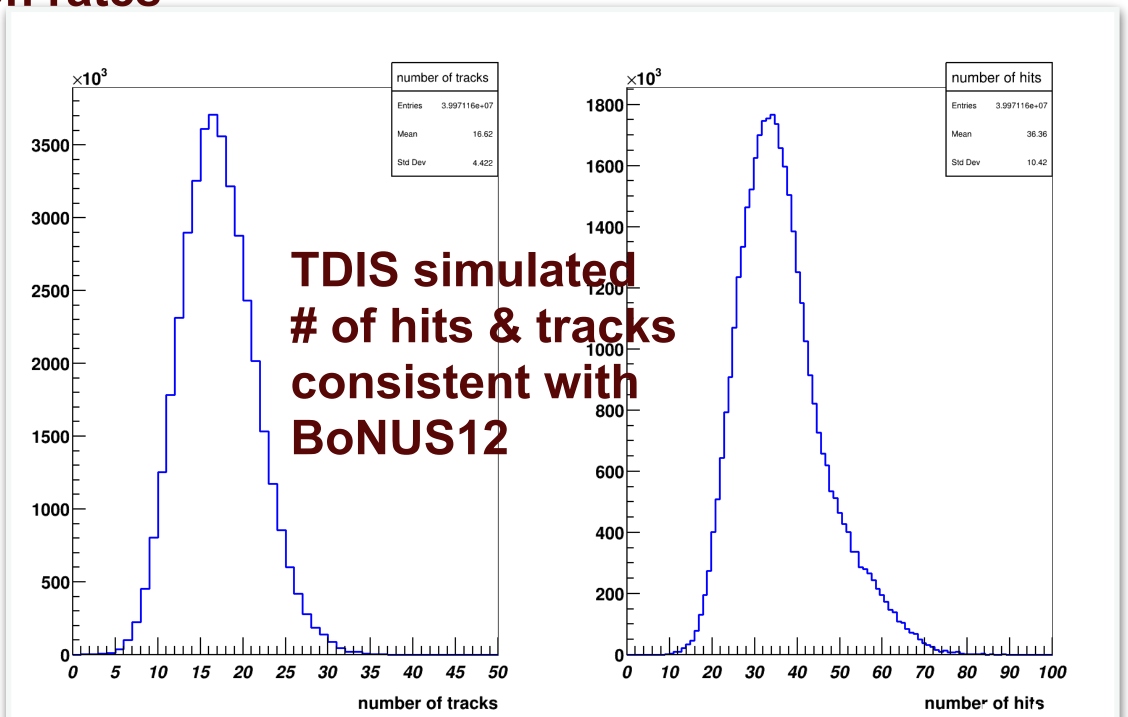




images credit: R. Montgomery

TDIS simulated rates match observed BoNUS12 proton rates



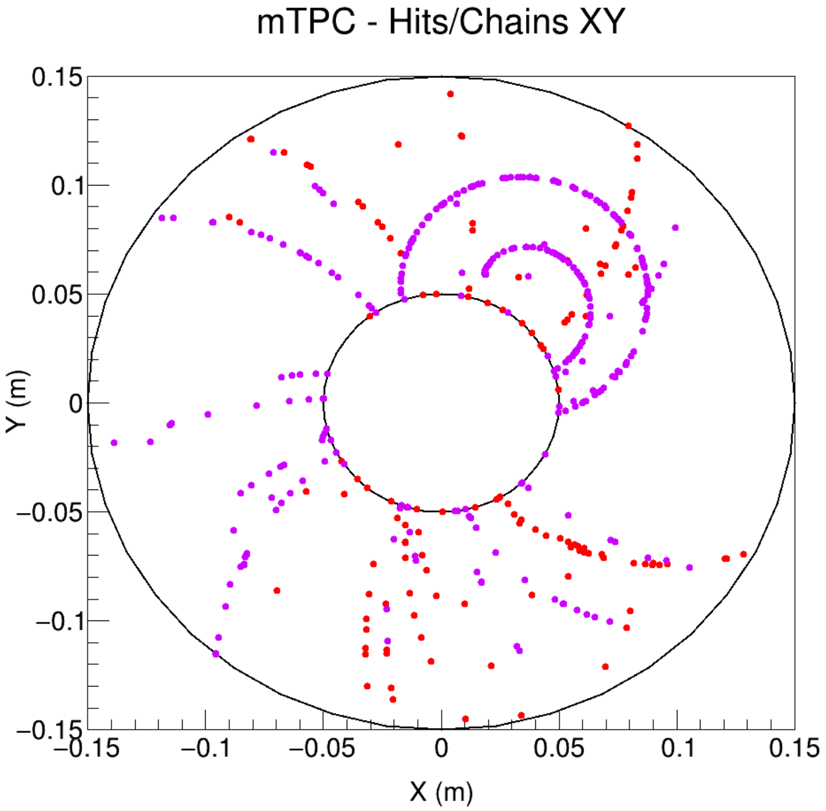


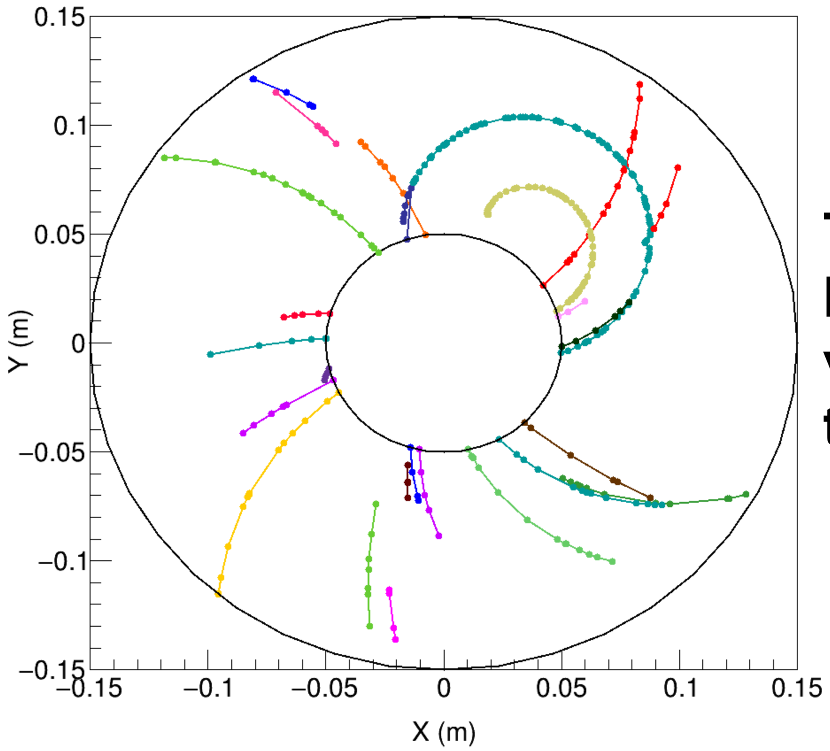
plot credit: C. Ayerbe-Gayoso/ A. Nadeeshani

plots credit: A. Nadeeshani

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

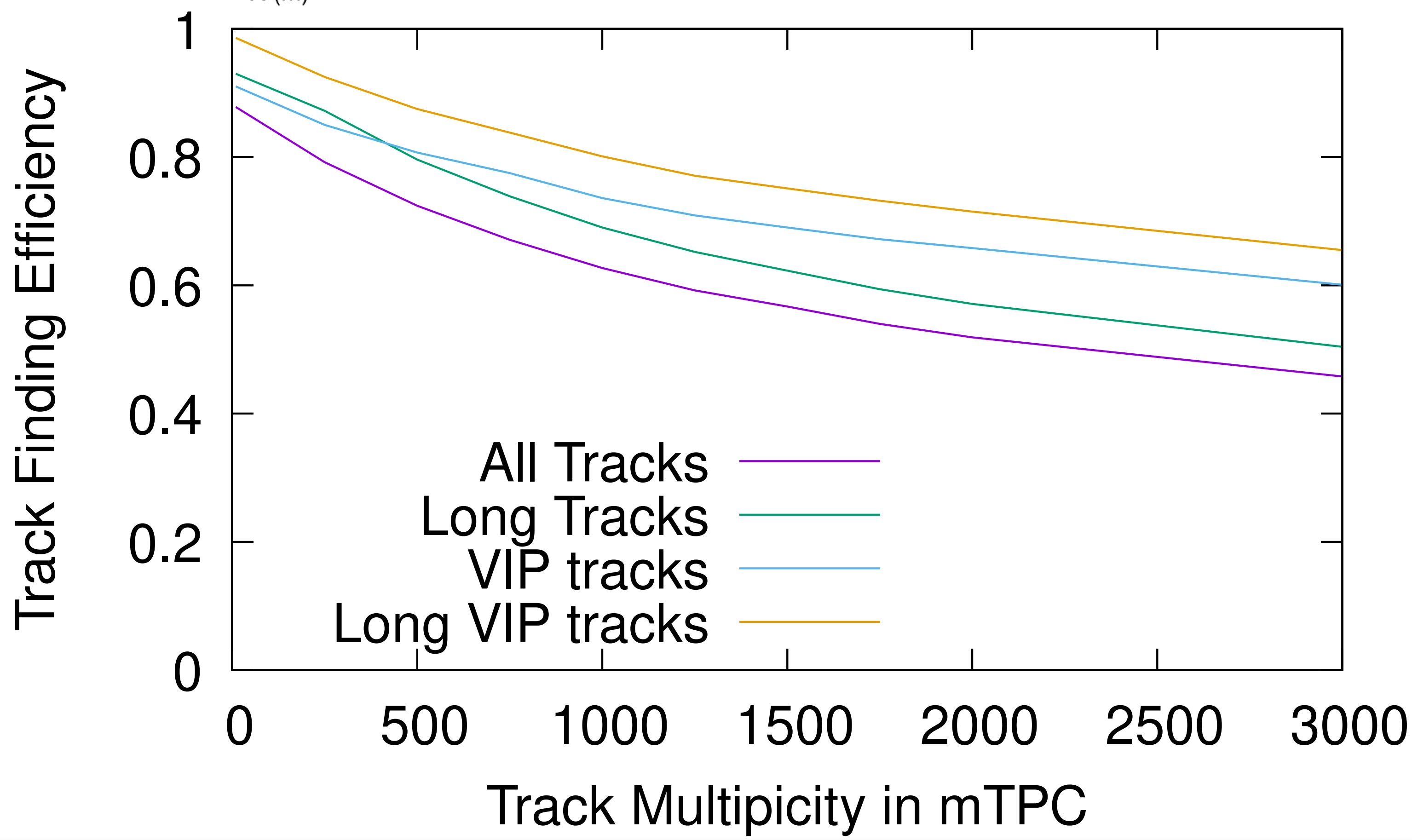
Key initiative for lifting the C1 condition and full approval.





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

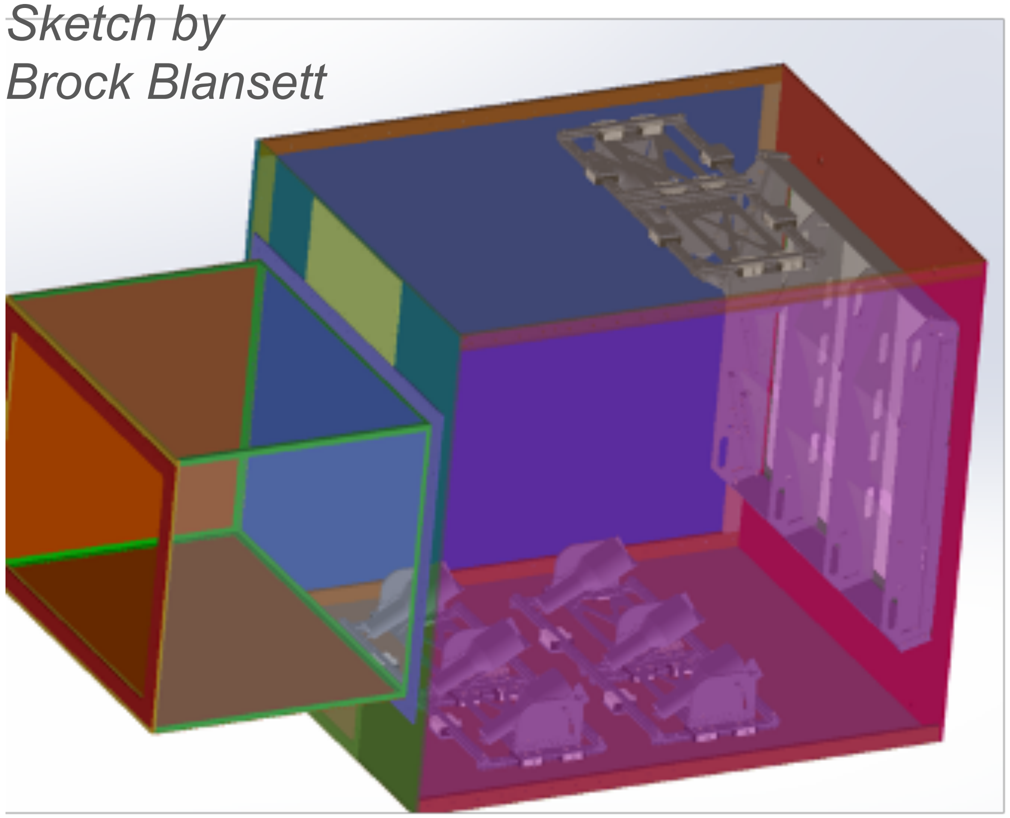
A new hadron blind gas Cherenkov detector is being designed by new collaborators from U. of Tennessee

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

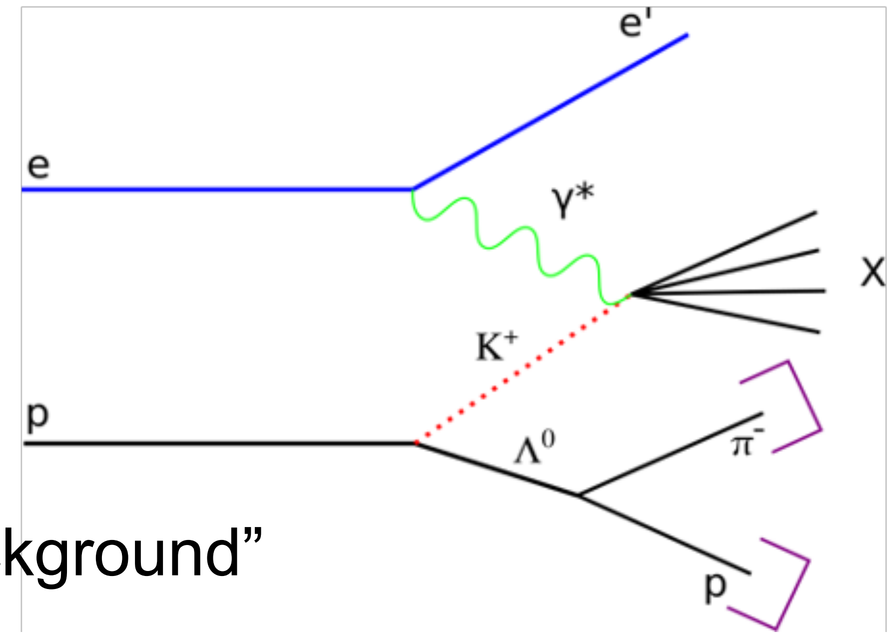


The LAC has been refurbished and is being tested and a FPGA based electron trigger is being developed

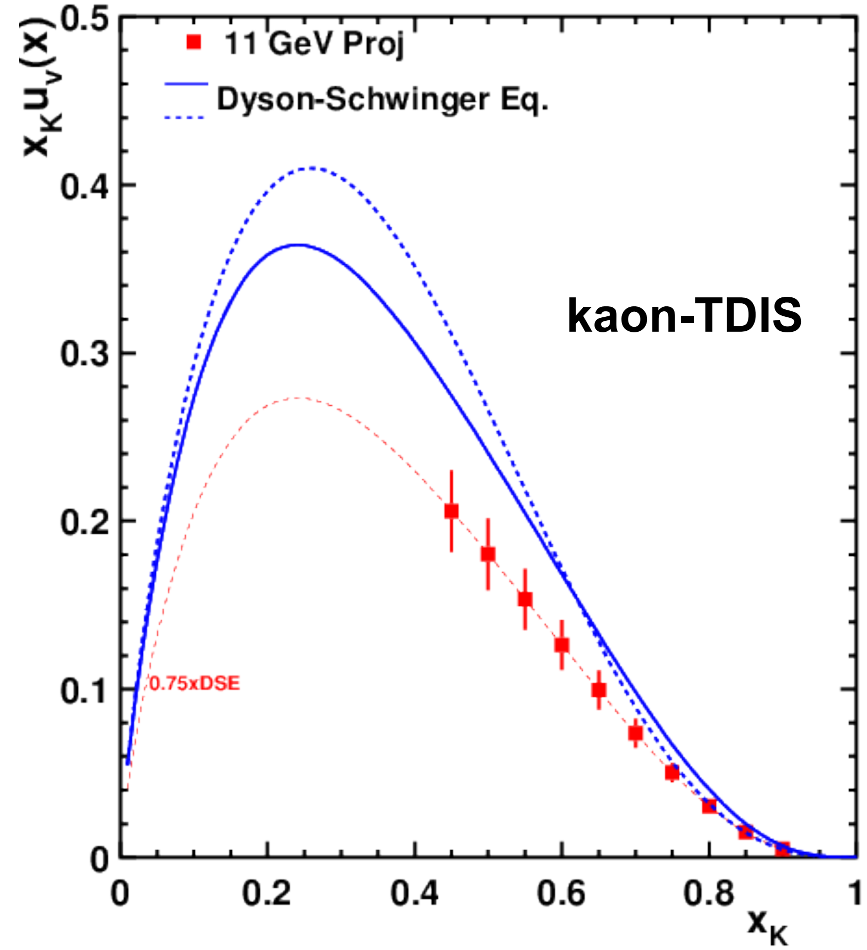
Two run group experiments (kaon TDIS & nTDIS) have been endorsed

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

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

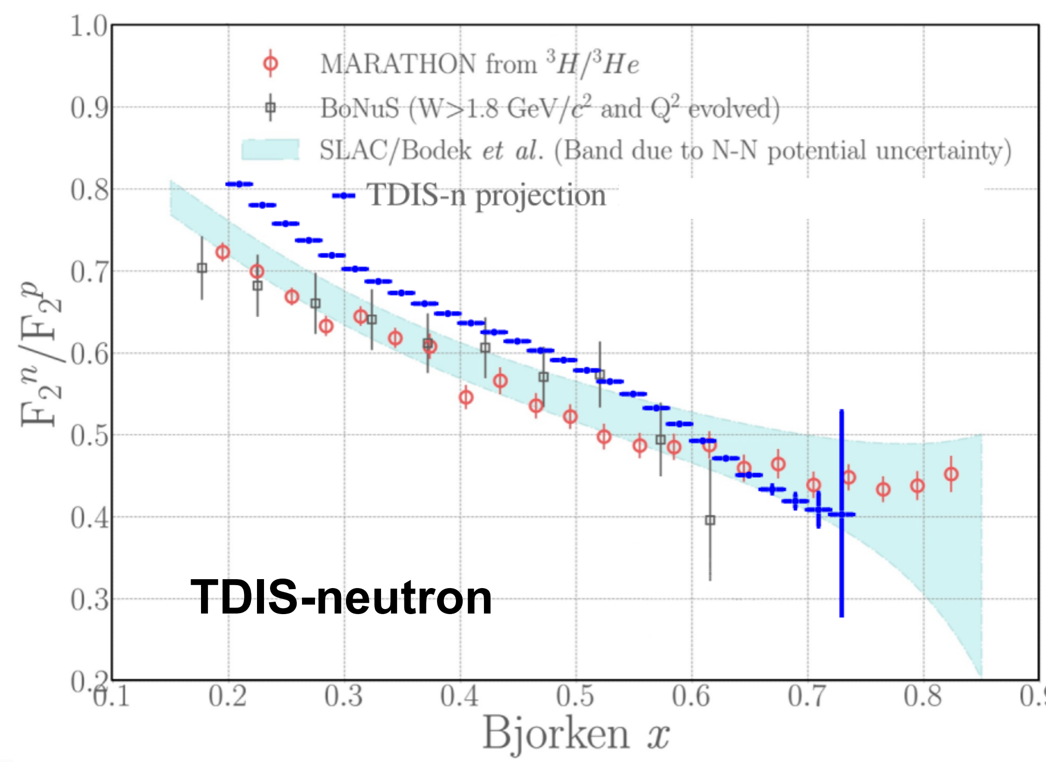


Kaon TDIS events are "background" for pion TDIS



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

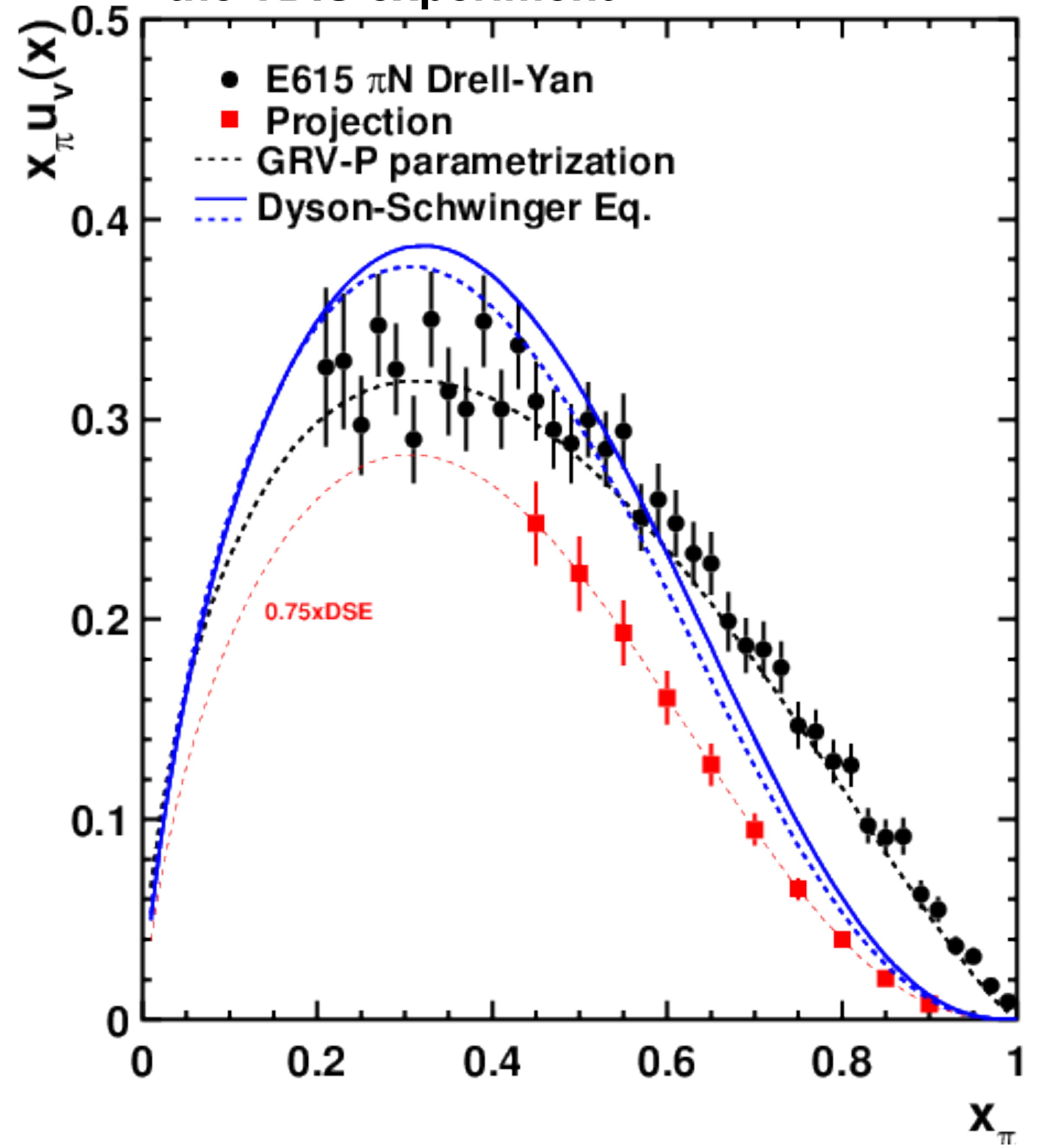


Active and strong collaboration preparing to remove the C1 condition and be fully approval.

TDIS run group: 14 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: E. Christy, 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)
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

SBS & BoNUS12 start-up difficulties with high rate tracking- include running at lower currents ⇒ **^{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

Backup Slides

Theory Comments

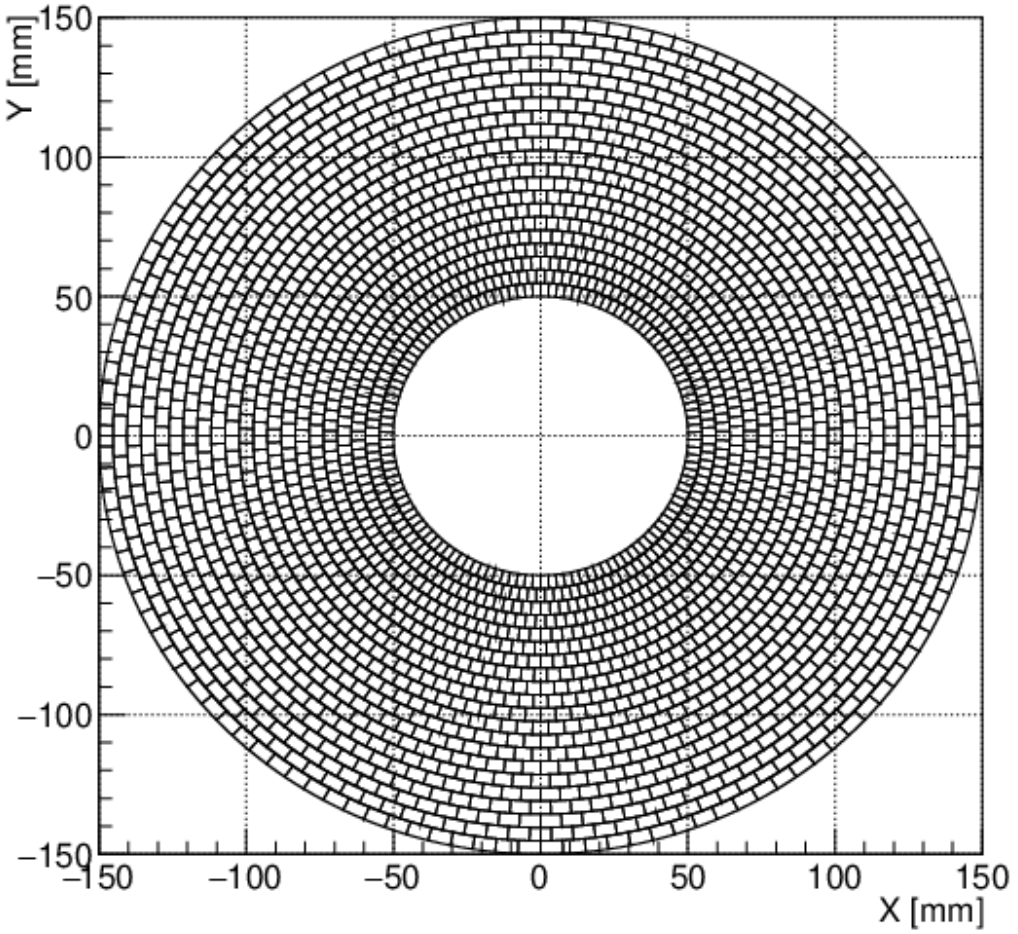
In summary, the interest for the physics of this jeopardy proposal is significantly increased, and is now more timely to carry out the proposed measurements. The data from the proposed TDIS experiments at JLab can provide better test of the validity of Sullivan process for extracting partonic structure of mesons. The projected accuracy of the data at the large-x region can be critically important for determining the behavior of valence PDF in a pion as the momentum fraction x approaches to 1. The knowledge to be learned from this and the two other approved TDIS experiments could impact the TDIS effort for the future EIC.

Mock engineering run plan

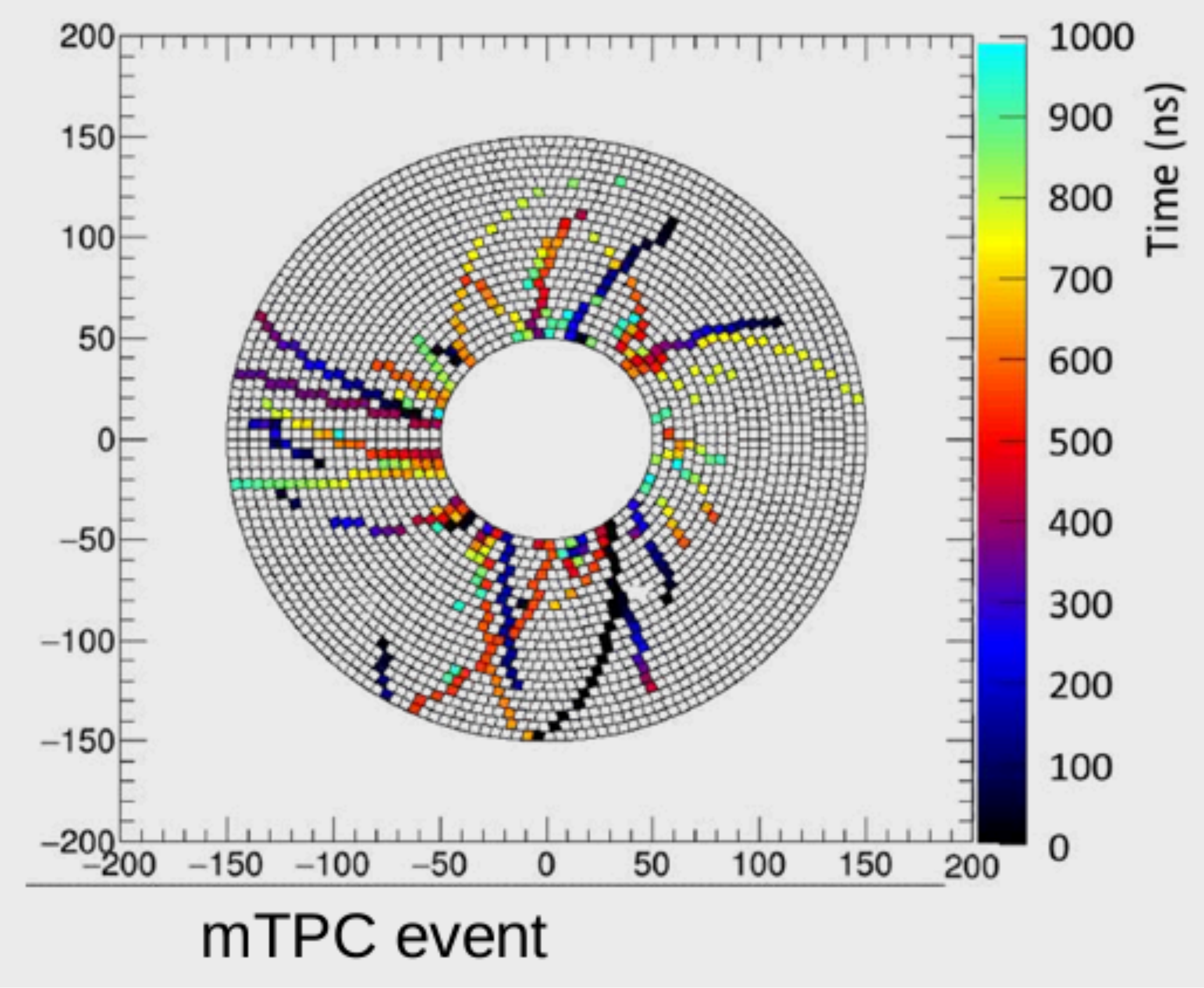
1. Establishing beam through 1 cm diameter 40 cm long straw target with and without solenoid field ON.
2. Establishing optimal solenoid field. (0.5 days for tasks 1 & 2)
3. Commissioning new Cherenkov and refubished LAC as an electron detector. (1 day)
4. Establish and program electron roads for FPGA to get high-efficiency electron trigger with the SBS. (0.5 days)
5. Establishing high rate mTPC DAQ and deadtimes as a function of luminosity. ((1 day, in parallel with task 3).
6. Calibration map of HV and gas flow settings for optimal operation of mTPC at different luminosity and target gas pressure. (0.5 day, in parallel with task 4).
7. Establishing coincidence between electron DAQ and mTPC DAQ. (0.5 days).
8. 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) (4 days)
9. Establishing and calibrating two proton tracking in mTPC as a function of luminosity while monitoring rates and occupancy (with empty and D2 gas) (4 days)
10. Establishing and calibrating proton and pion tracking in mTPC as a function of luminosity while monitoring rates and occupancy for kaon-TDIS (with empty and D2 gas). (4 days, in parallel with task 9.)
11. Establishing background rates of two proton tracks in mTPC as a function of luminosity while monitoring rates and occupancy (with empty and 4He gas) (4 days)
12. 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) (4 days in parallel with task 11).

Total: 15 days- an increase of 13 days from the original proposal.

Readout pixel configuration and simulated hits

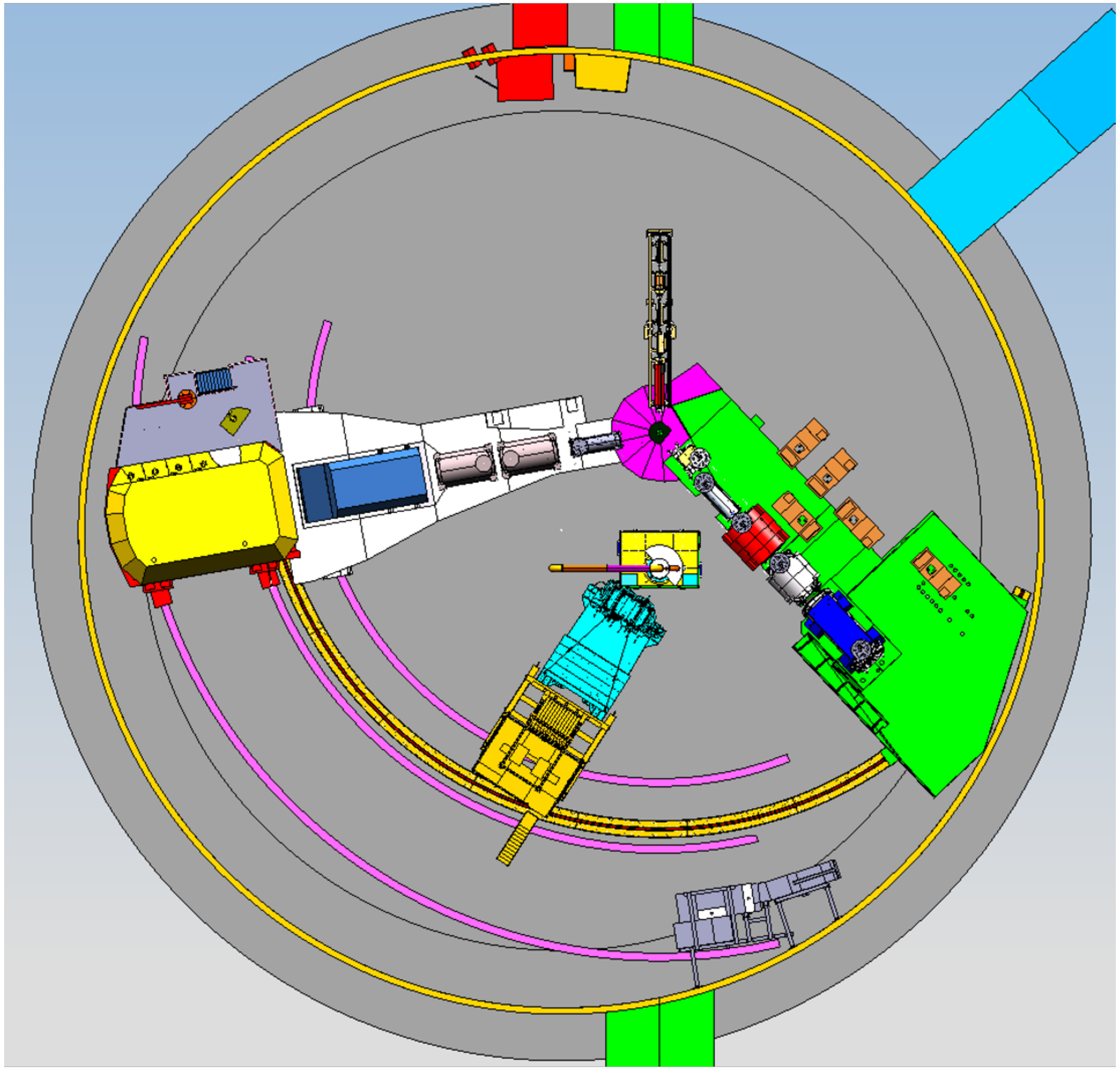


CAD design: K. Gnanvo



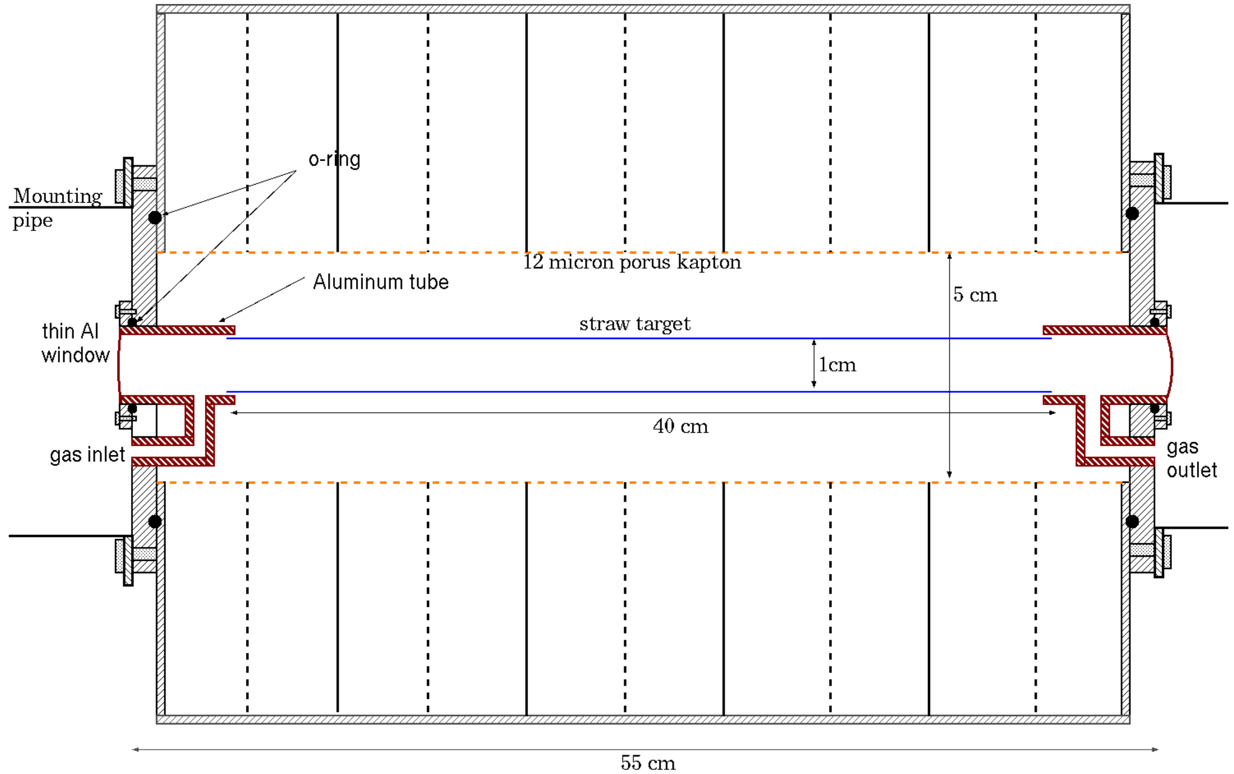
Plot credit: M. Carmignotto

SBS in Hall C



Solenoid & Target

spiral wound 25 um kapton straw Target (not to scale)



UVa 4T Solenoid

Pressure tested to 60 psi

SAMPA

- 80, 160 ns shaping time (V5)
- 10-bit ADC
- 20 MHz maximum sampling rate
- Zero suppression (DSP) is required when sampling at 20 MHz due to max data bandwidth off chip

ALICE SYSTEM

- SAMPA V4 (160 ns shaping time)
- Radiation tolerant data transport components (CERN GBT, VTRx); we will use 2nd generation of these (lpGBT, VTRx+)
- PCI based **C**ommon **R**eadout **U**nit (modern unit is FELIX from ATLAS)

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

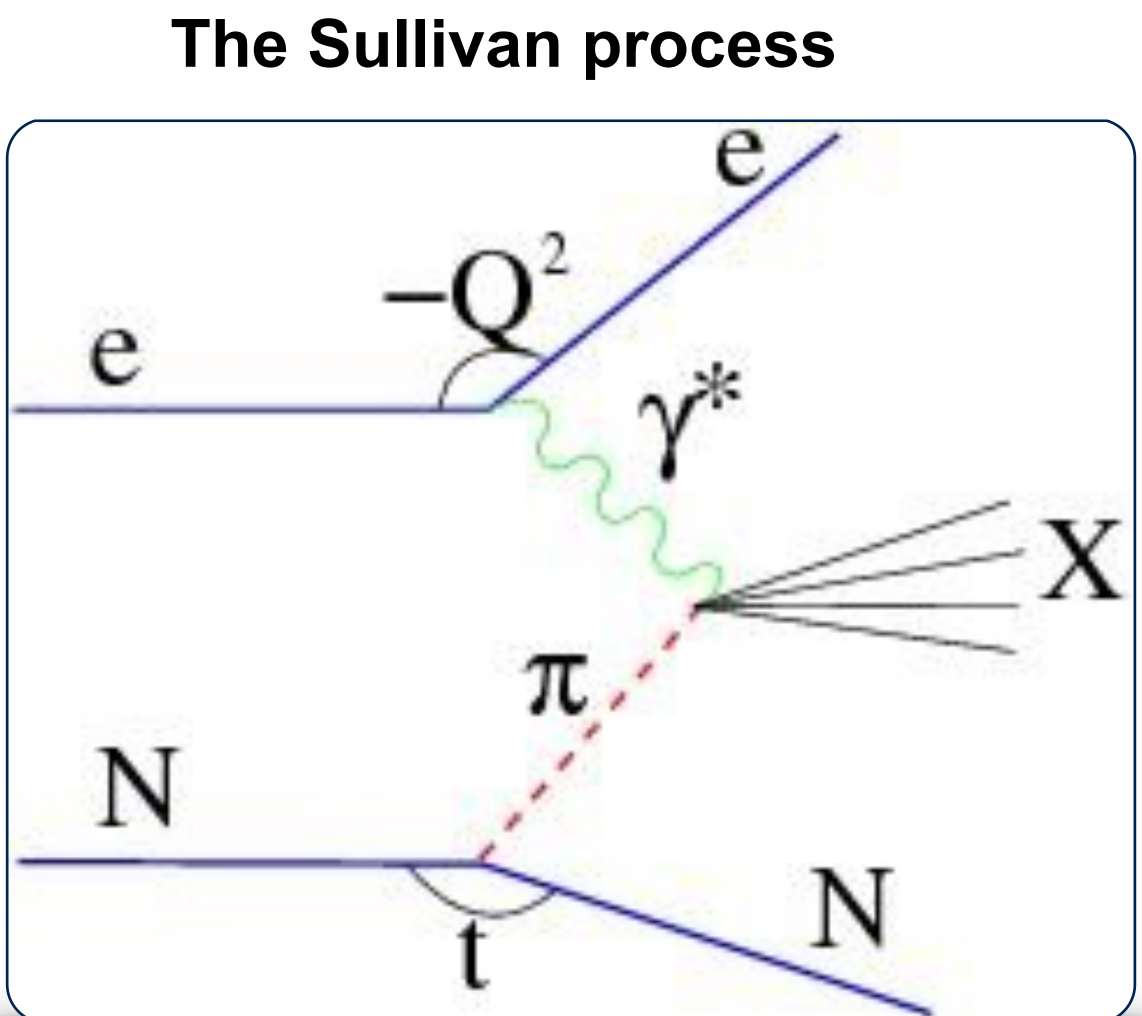
Prototype system

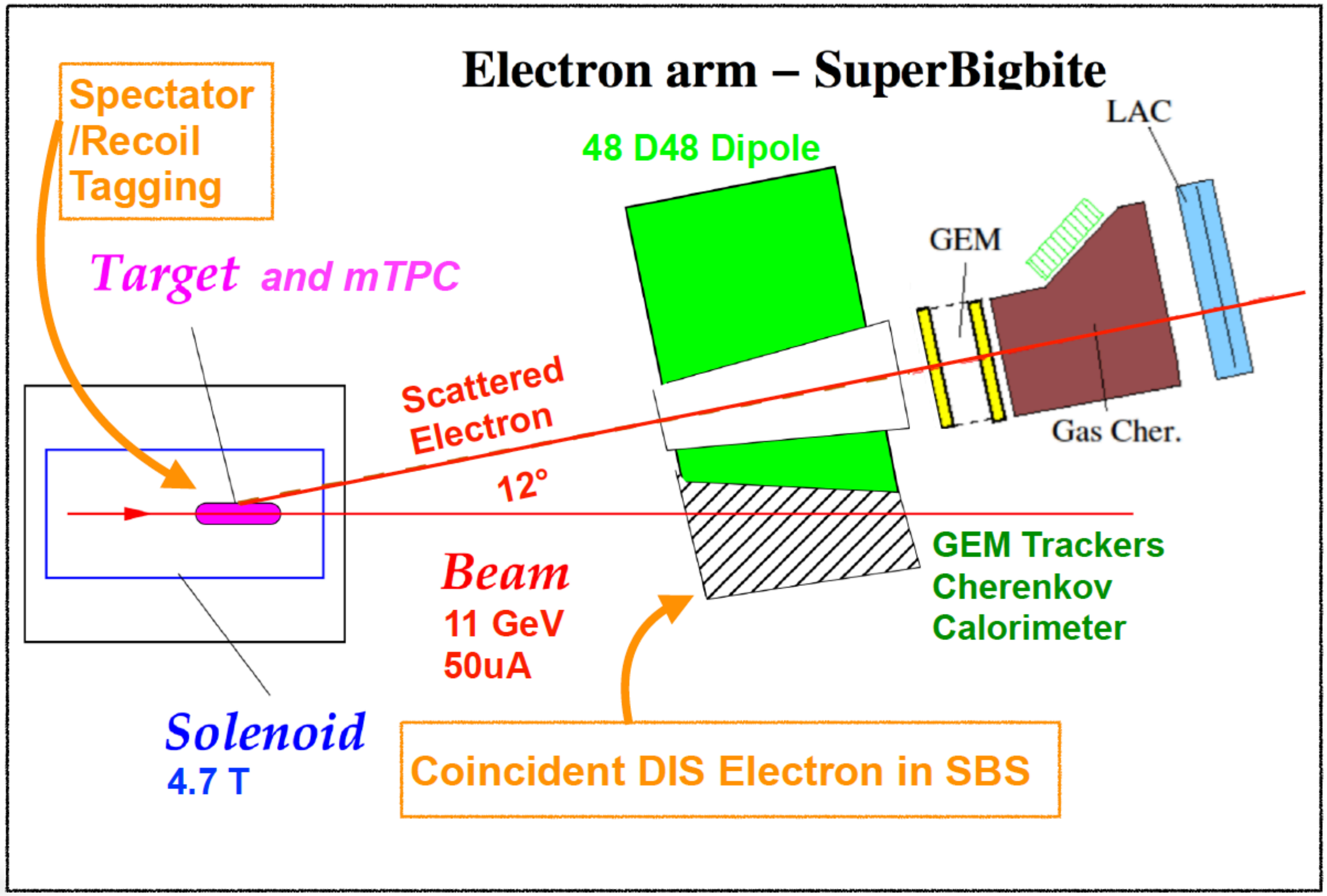
- SAMPA V4 (160 ns shaping time)
- 5 FEC (800 channels)

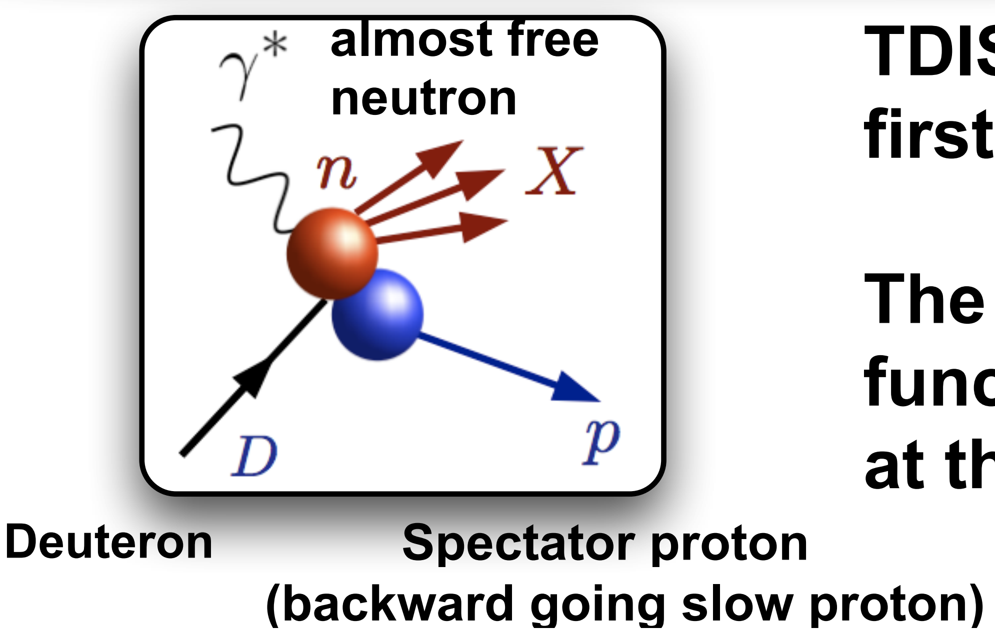
TDIS

- SAMPA V5 allows for higher rates (80 ns shaping)
- Use triggered mode of SAMPA
- < 2 us drift time of mTPC means small collection window
- Less components than streaming mode
- Test mTPC prototypes with existing SAMPA V5 FEC (sPHENIX)

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



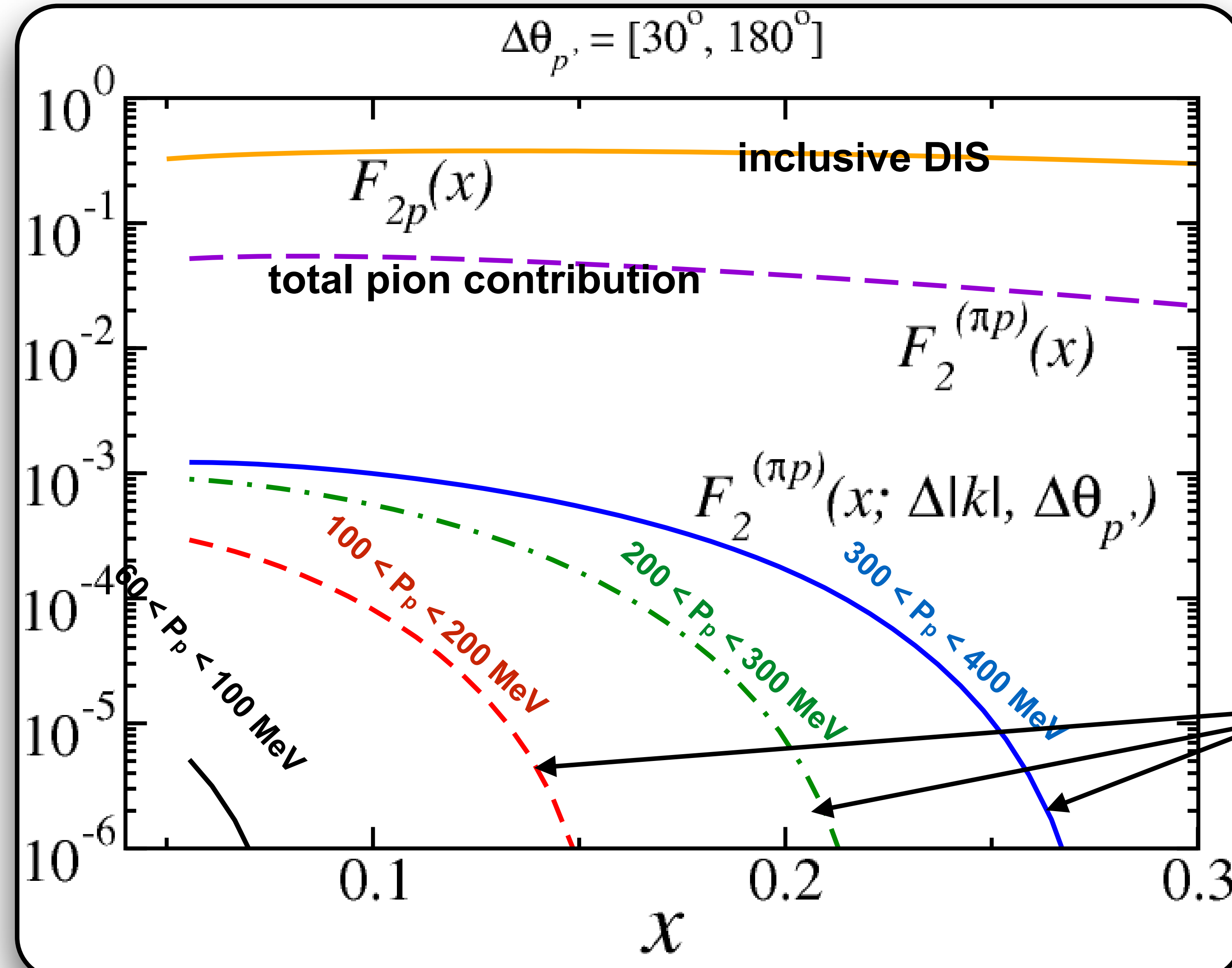




TDIS is a pioneering experiment that will provide the first direct measure of the mesonic content of nucleons.

The techniques used to extract meson structure function is a necessary first step for future experiments at the EIC & 22 GeV JLab.

Tagged structure functions to pion structure function.



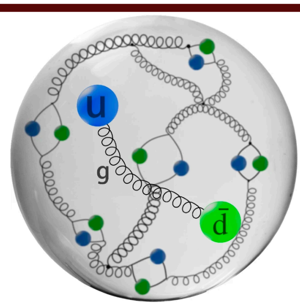
contributions for different bins in proton momentum

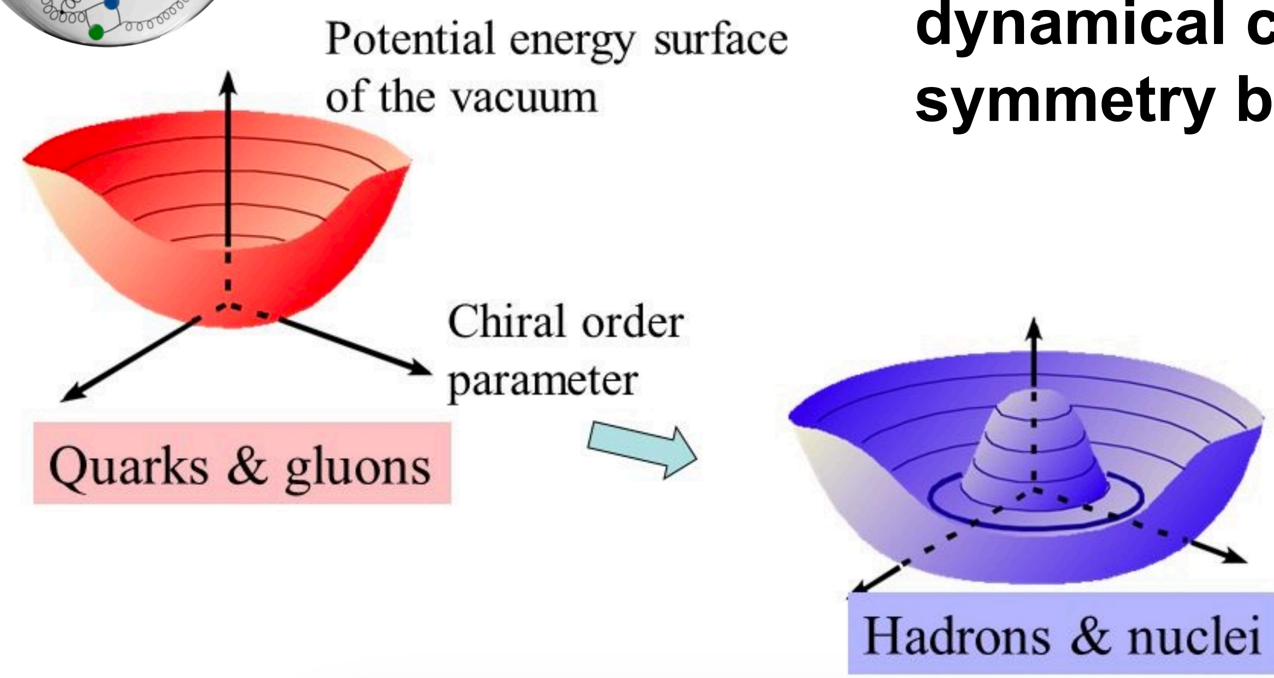
$$F_2^{(\pi N)}(x, z, k_\perp) = f_{\pi N}(z, k_\perp)\, F_{2\pi}\left(\frac{x}{z}\right)$$

Tagged SF (from spectator tagging) **pion "flux"** **Pion SF**

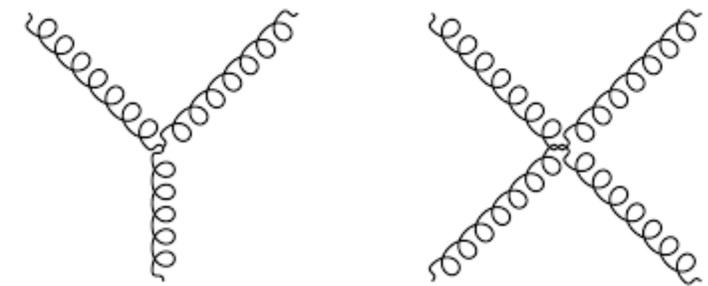
Pions and kaons are the simplest bound states of QCD and its mass-less Nambu-Goldstone bosons

π+



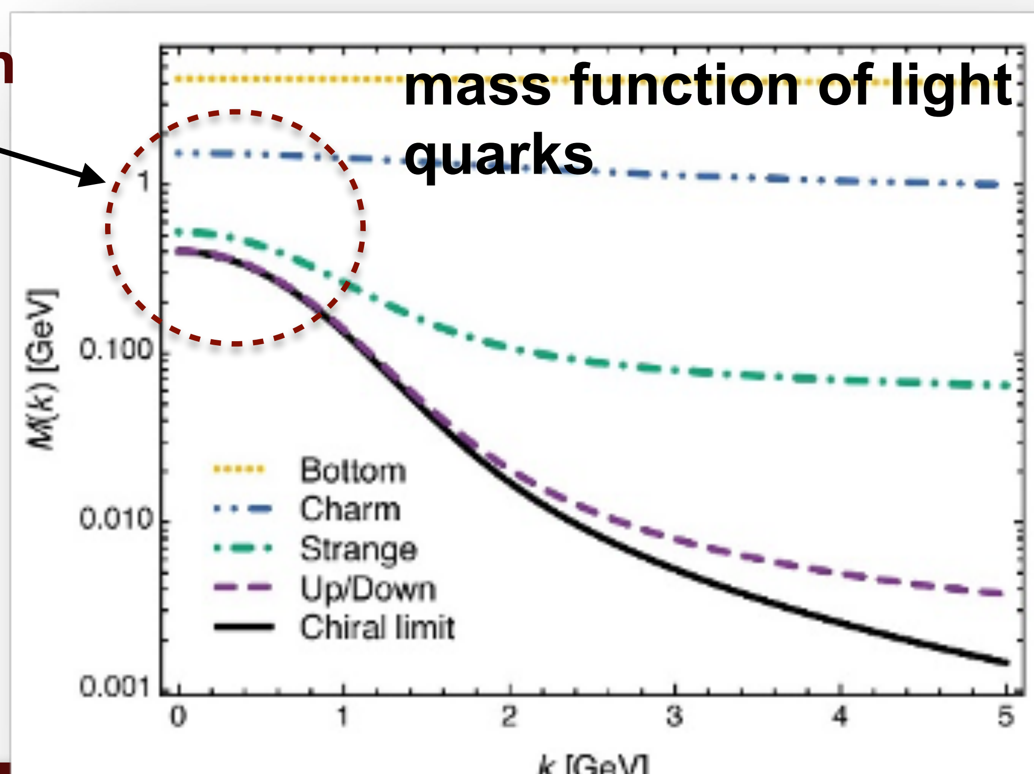


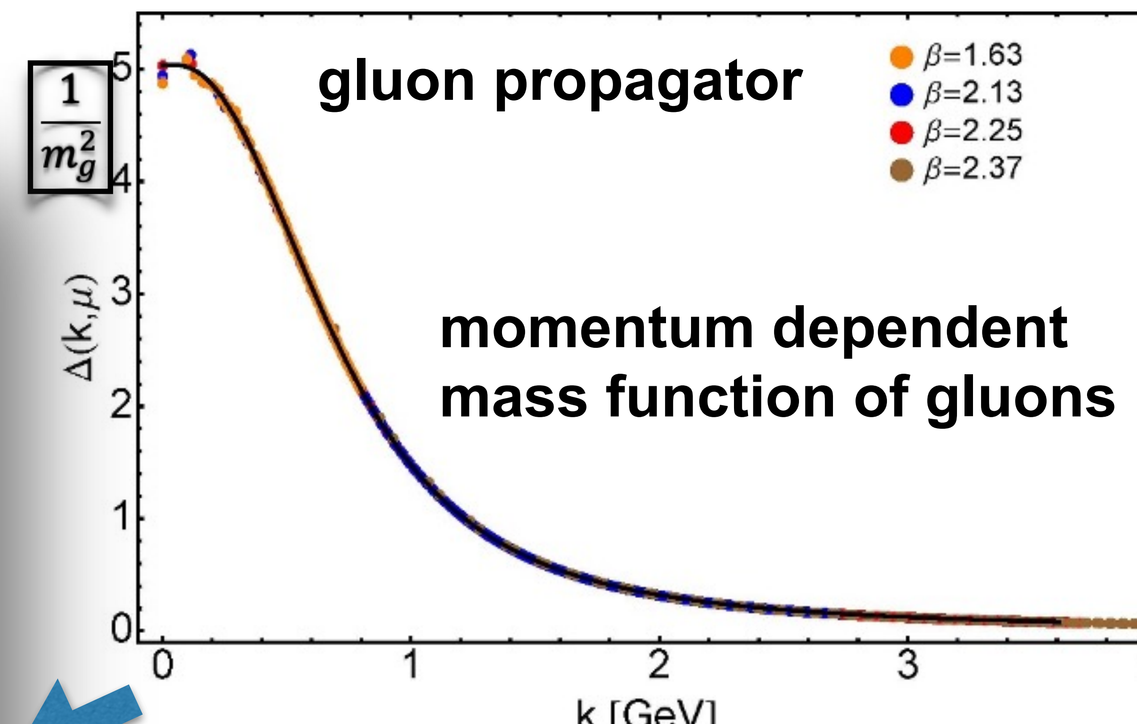
emergence of mass via dynamical chiral symmetry breaking



a consequence of gluon self interaction

Rapid increase in mass due to gluon cloud

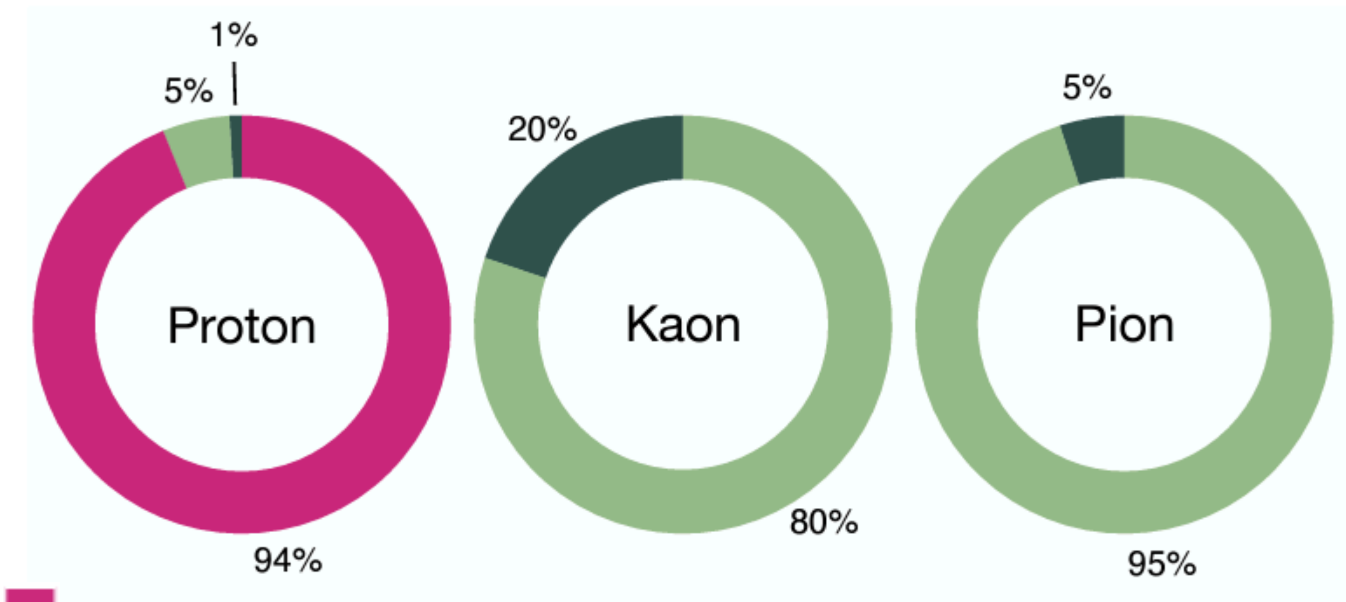




images courtesy of C. D. Roberts

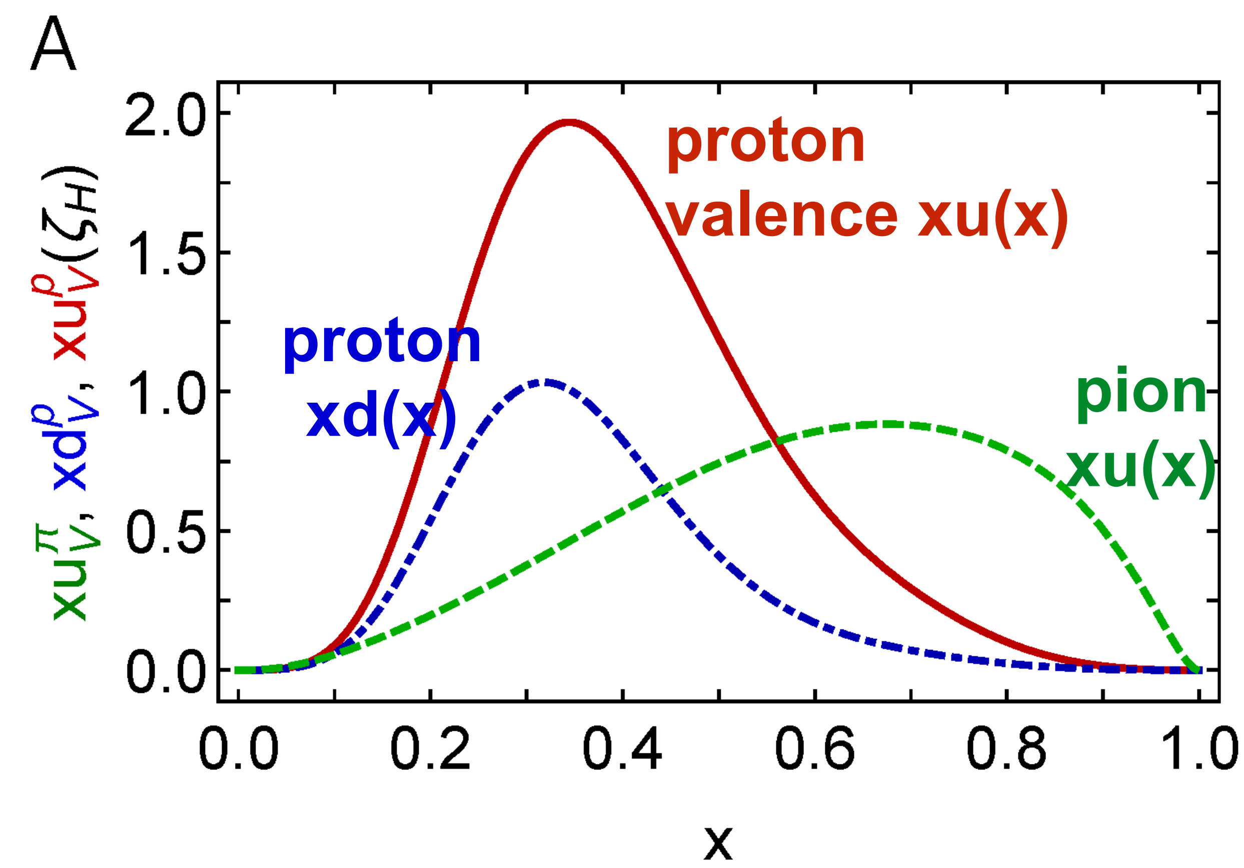
knowledge of meson structure is critical to a complete understanding of the emergence of hadron mass

Mass budget for mesons and nucleons are vastly different



Emergent hadron mass
Interference of emergent hadron mass & Higgs mechanism
Higgs mechanism

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



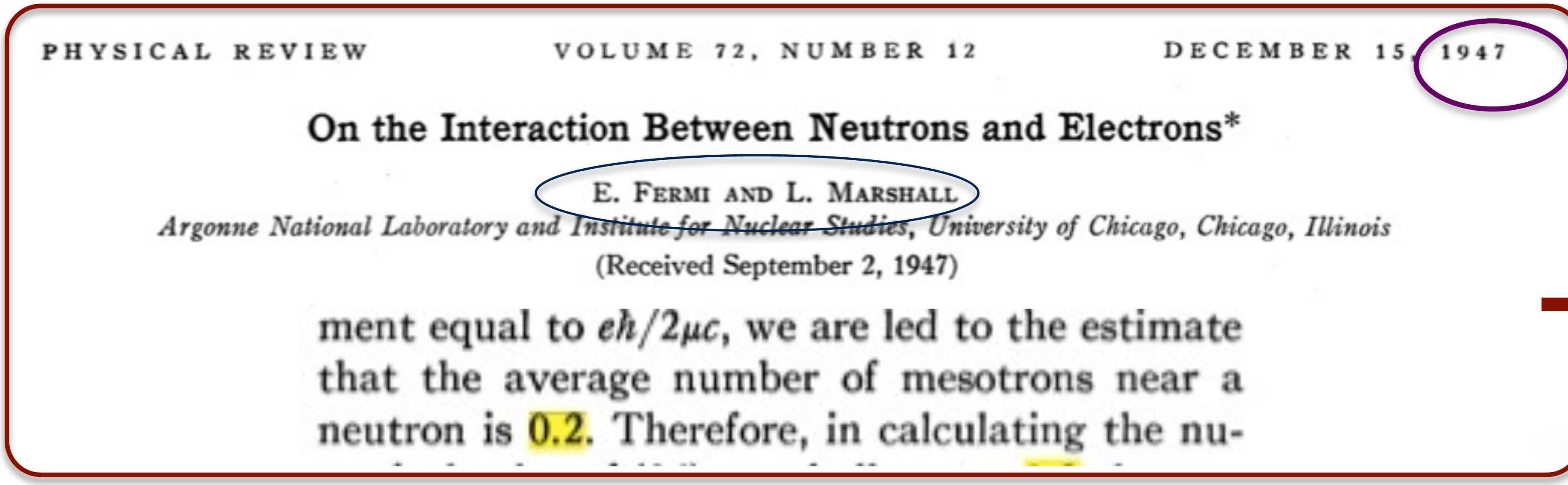
pion/proton valence quark distributions are also very different

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*

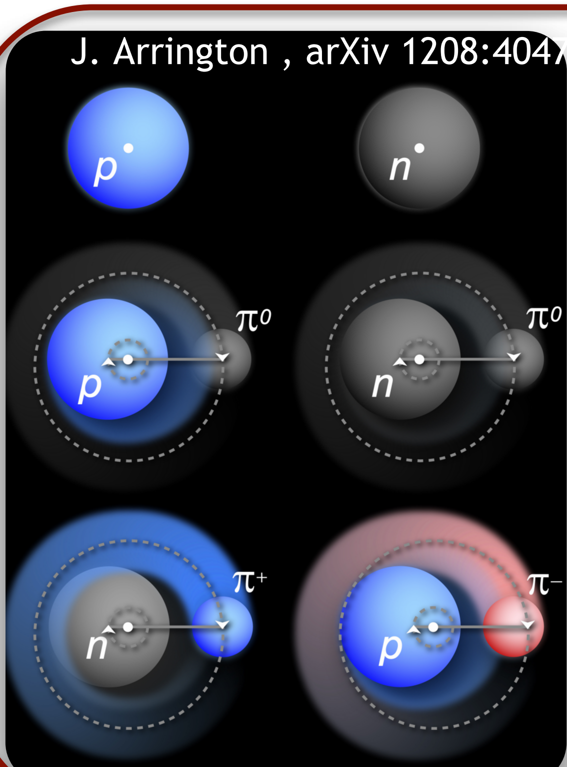
E. FERMI AND L. MARSHALL

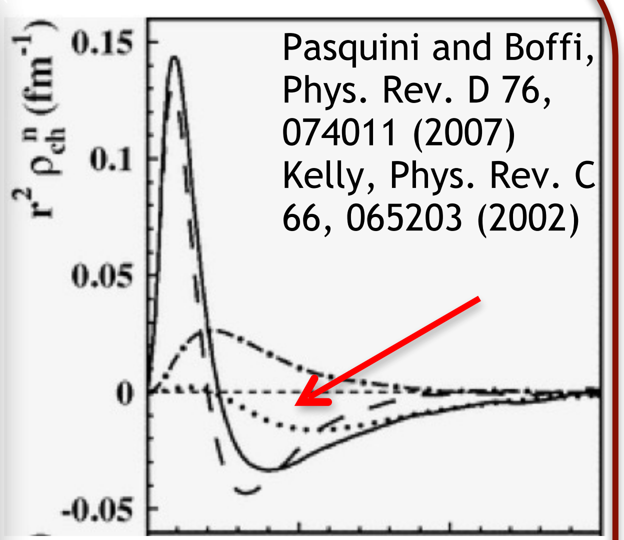
Argonne National Laboratory and Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

(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-

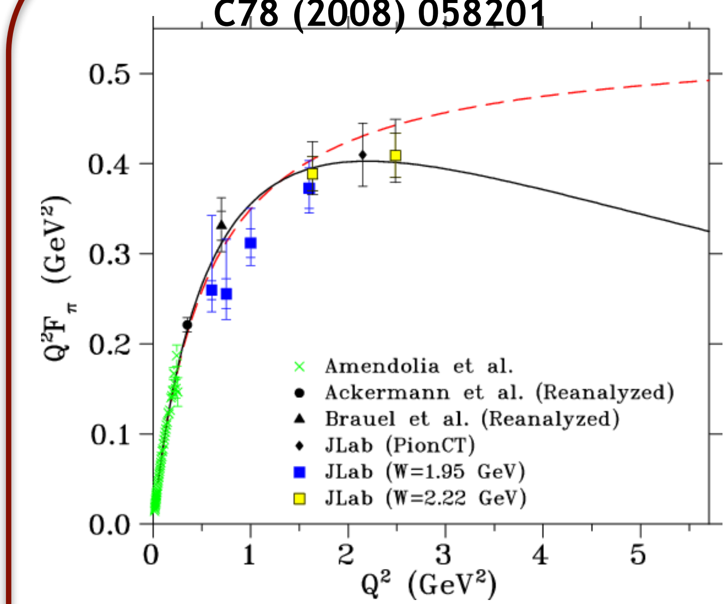
Experimental evidence pointed to the nucleon existing ~20% of the time in a virtual meson-nucleon state.





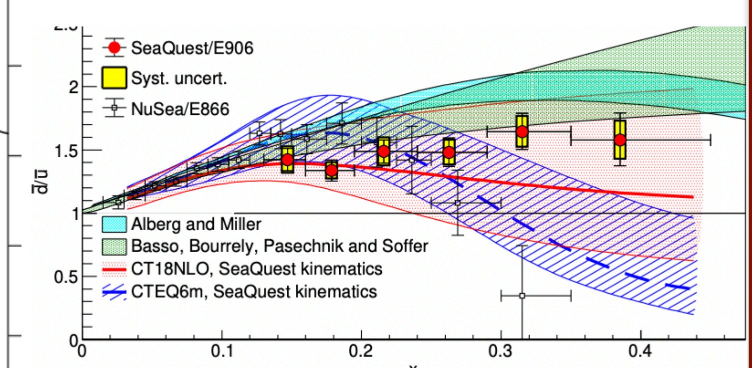
Proton & Neutron Charge Distribution

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



Pion Form Factor

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

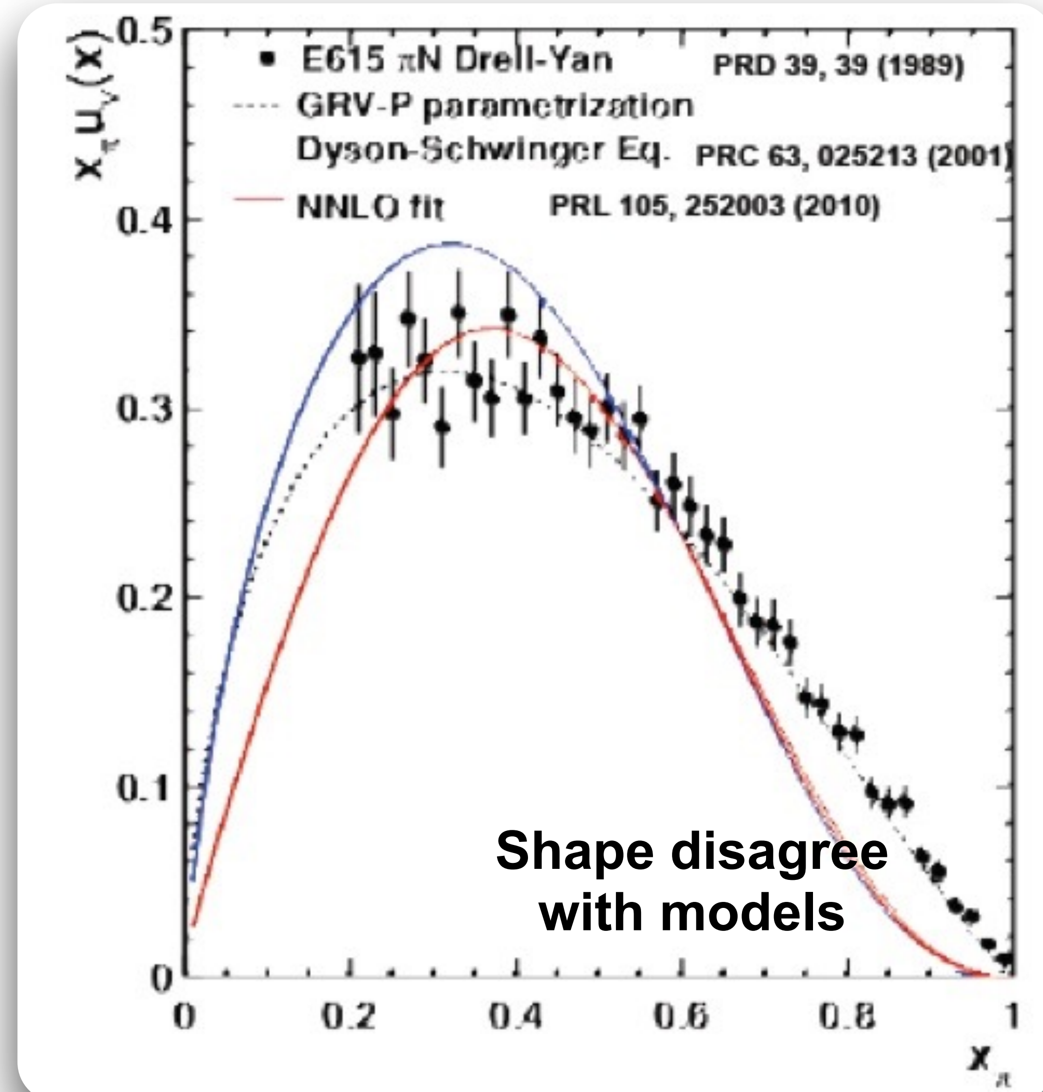


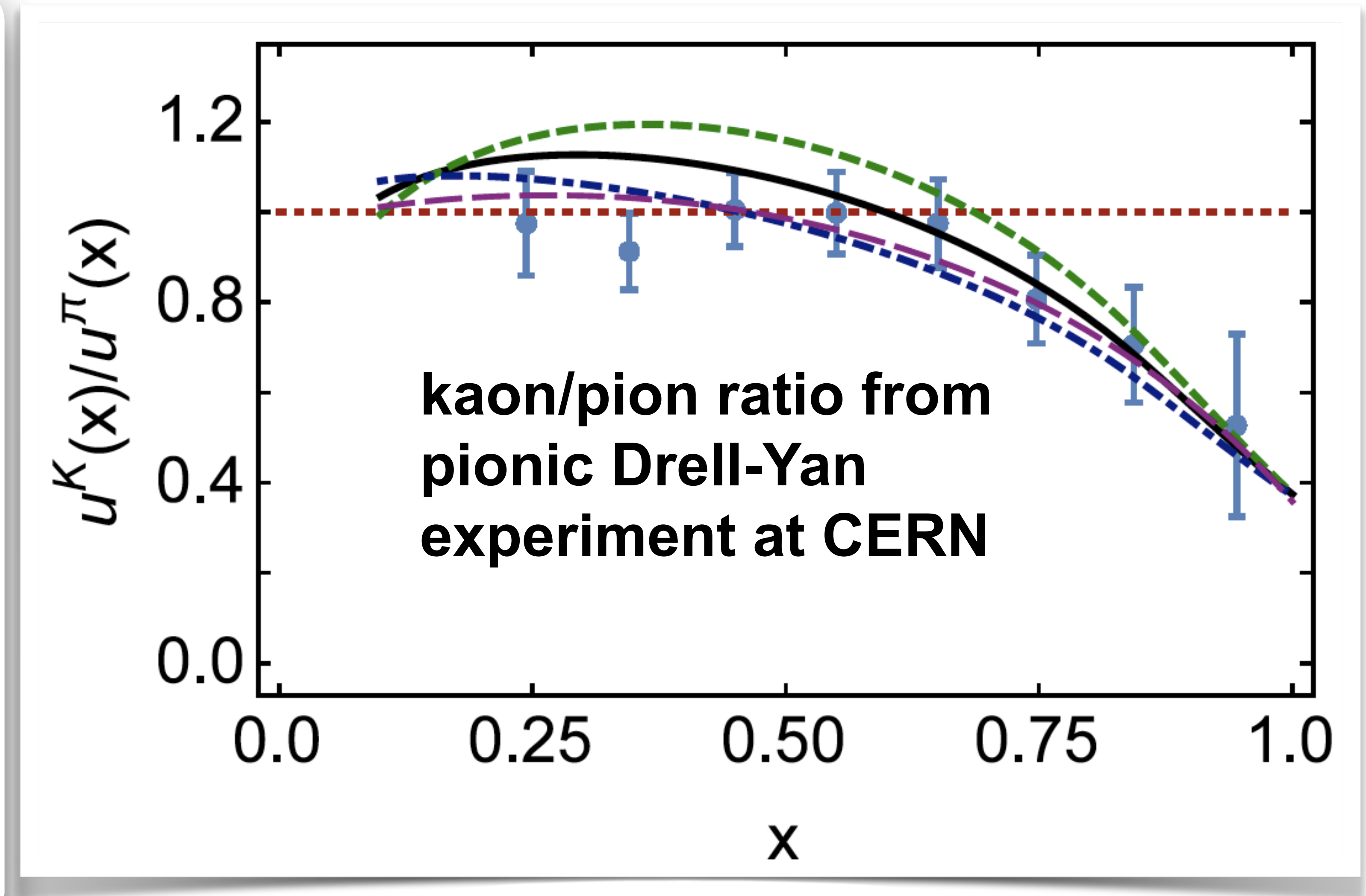
up/down sea-antiquark flavor asymmetry

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

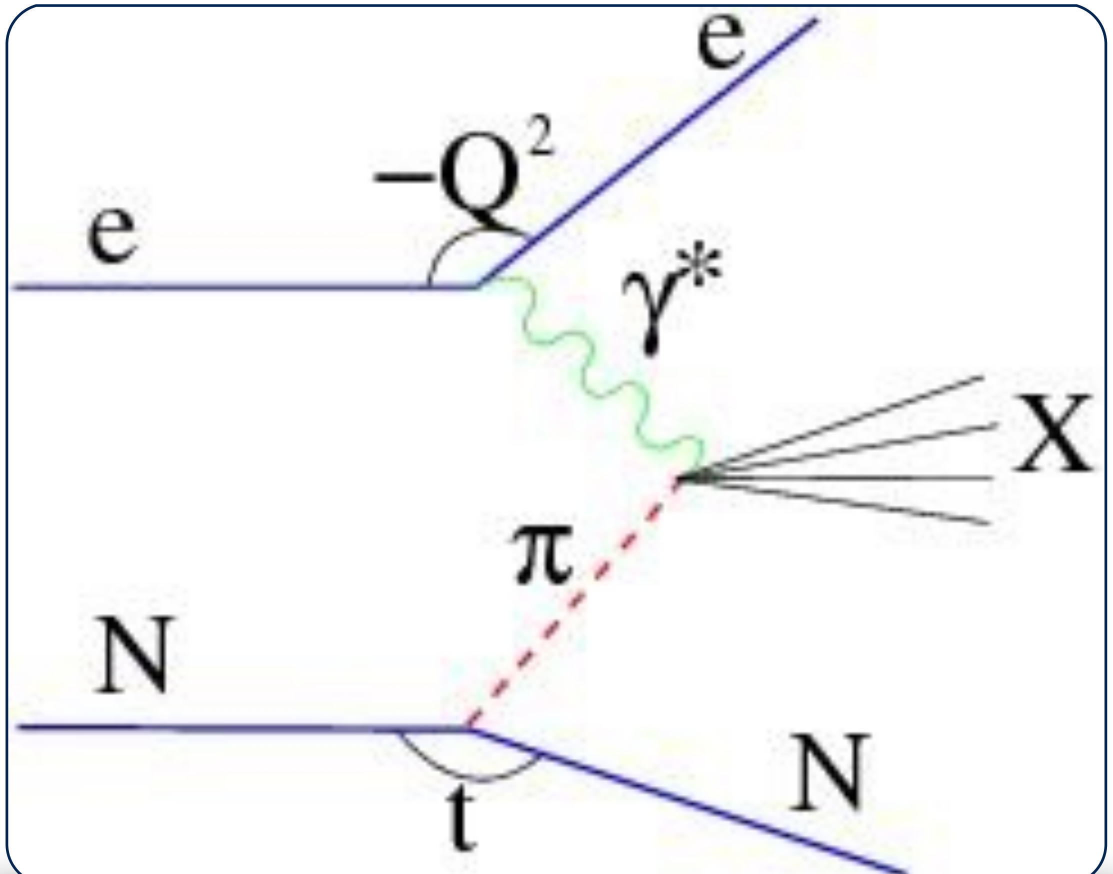
Need more and precise data

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)

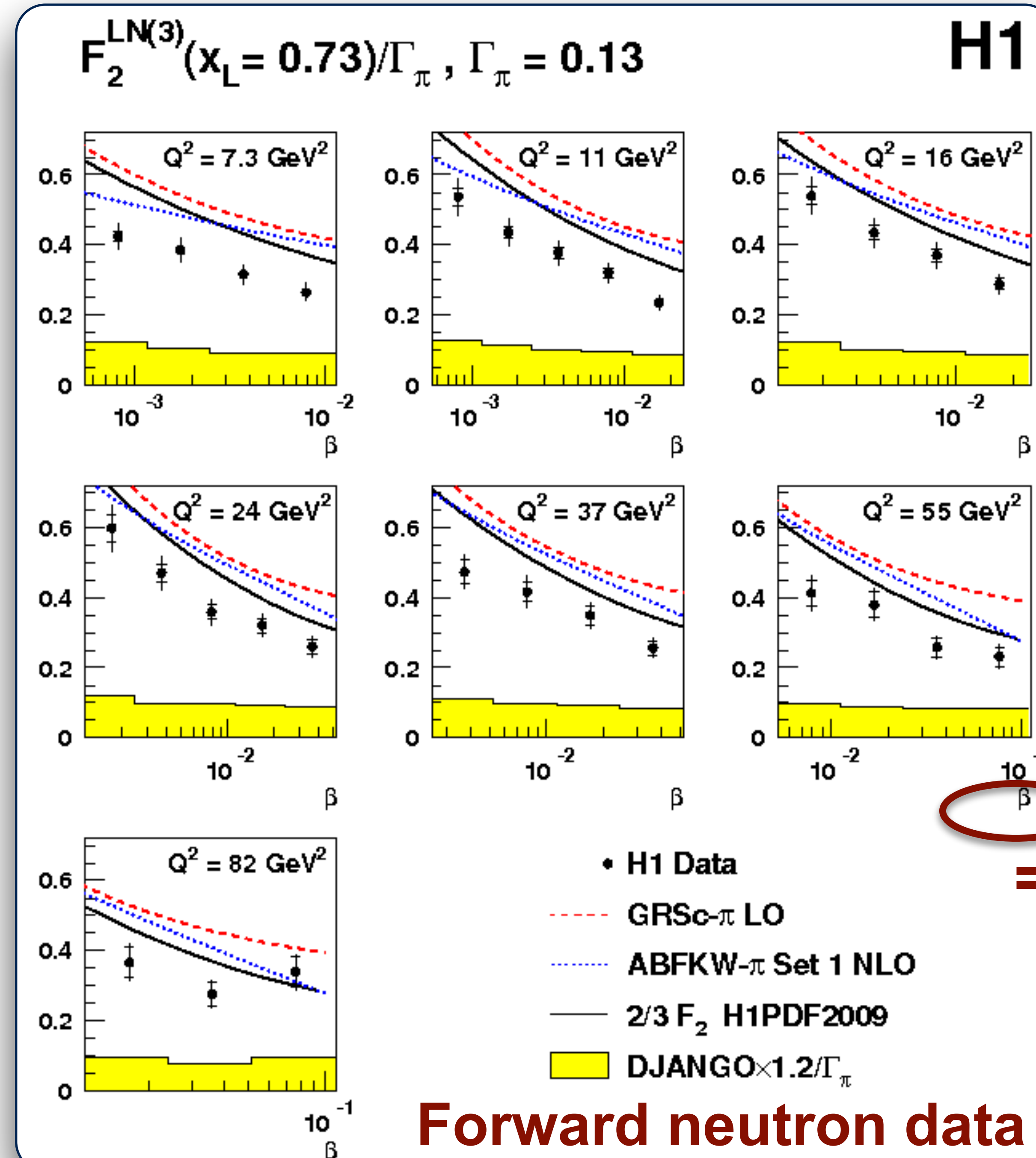
Deep-inelastic Scattering off a virtual-meson cloud is a possible experimental technique.

The Sullivan process



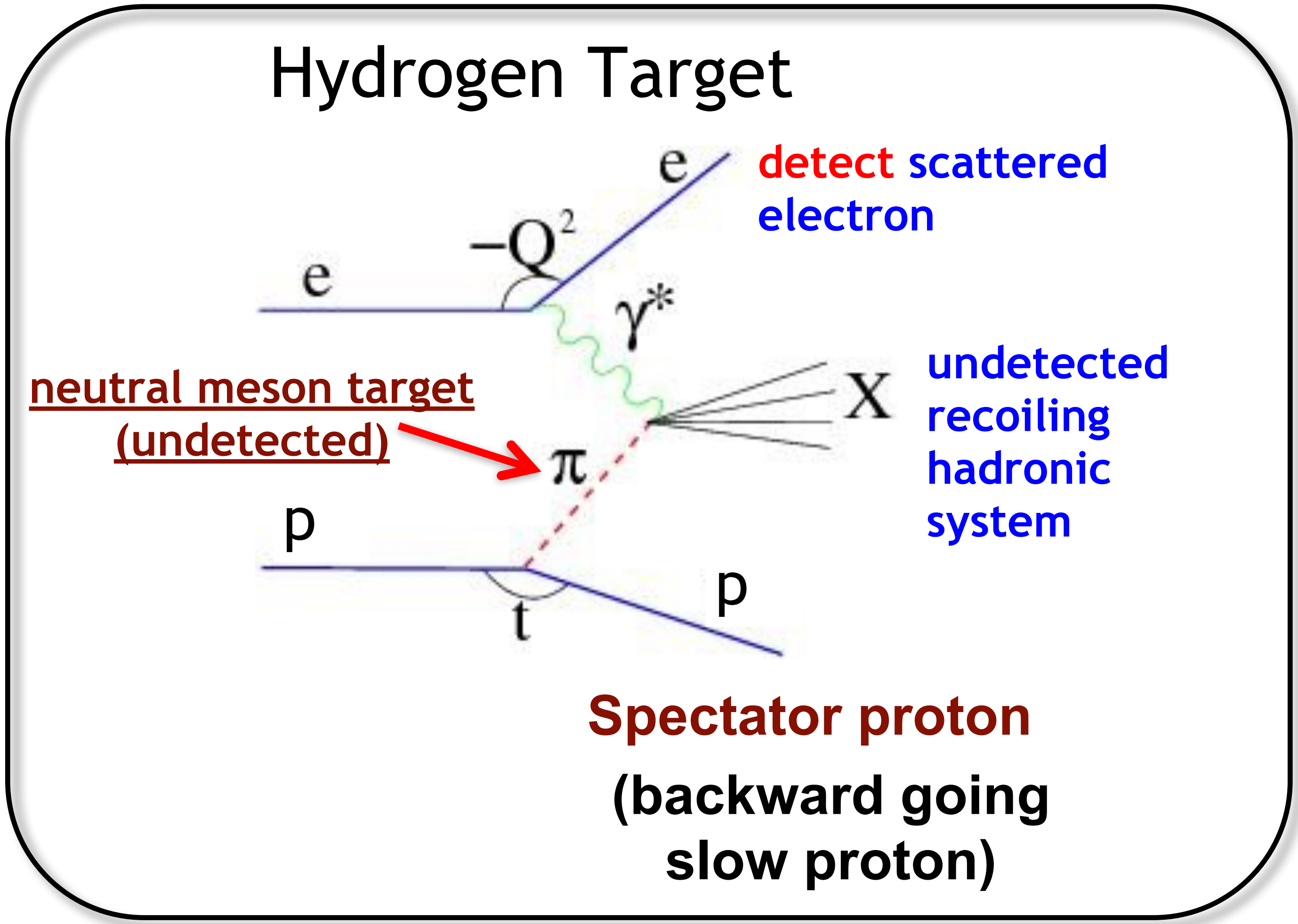
direct measurement of the mesonic content of the nucleon

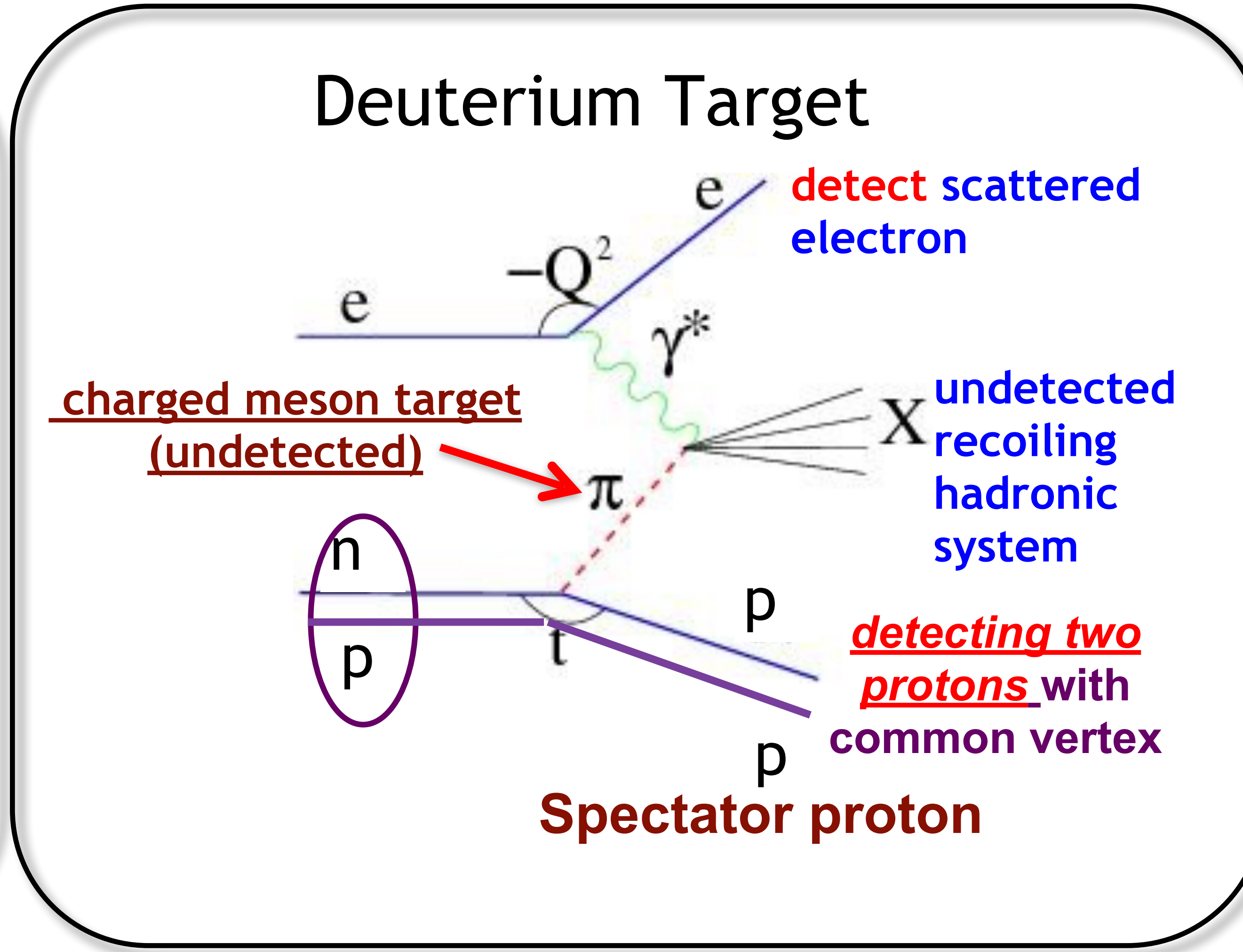
DIS events with forward going neutrons in coincidence



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.





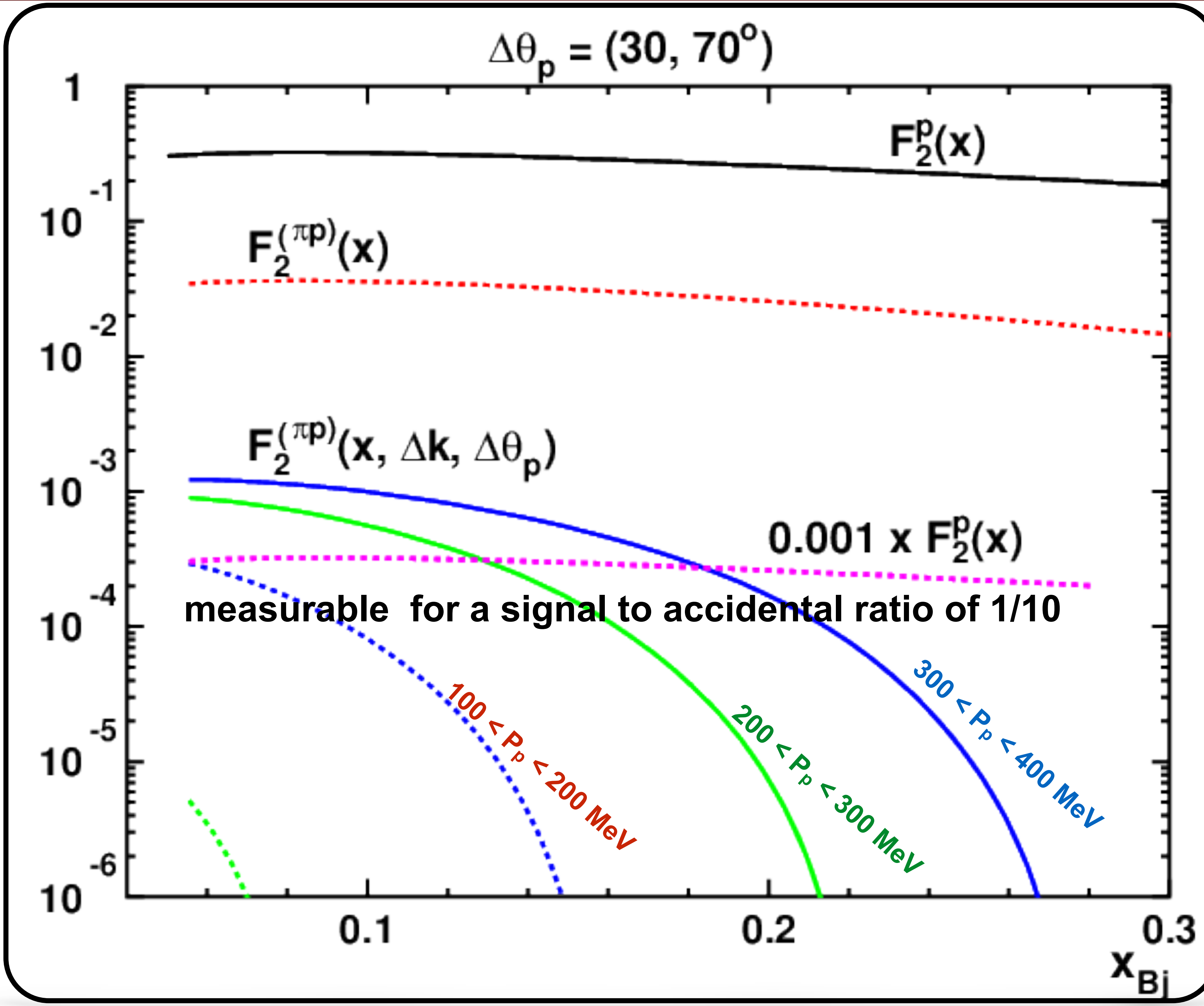
DIS event – reconstruct x, Q^2, W^2, also M_X of recoiling hadronic system

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

Tagged structure function

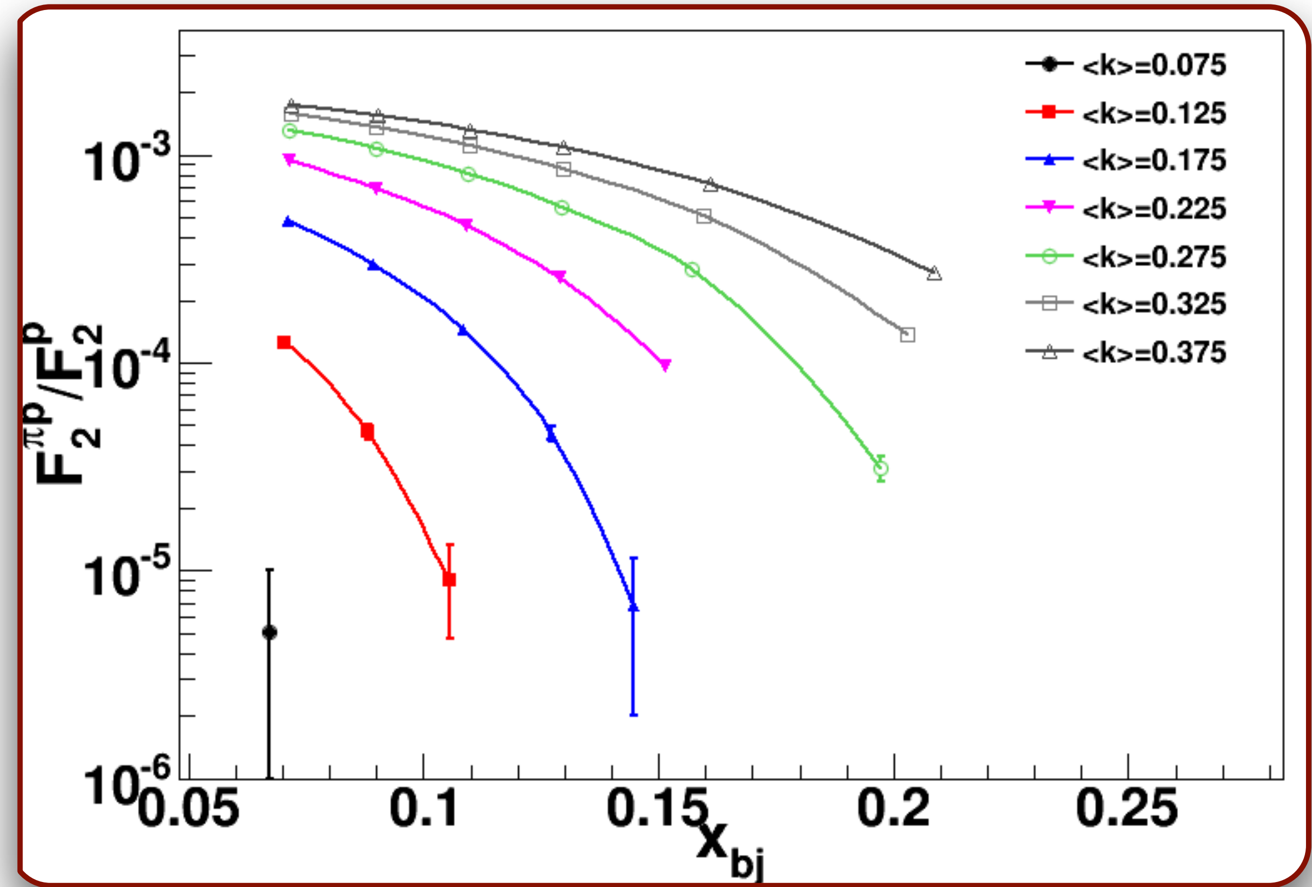
$$F_2^T(x,Q^2,z,t) = \frac{R^T}{\Delta z \Delta t} F_2^p(x,Q^2).$$

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

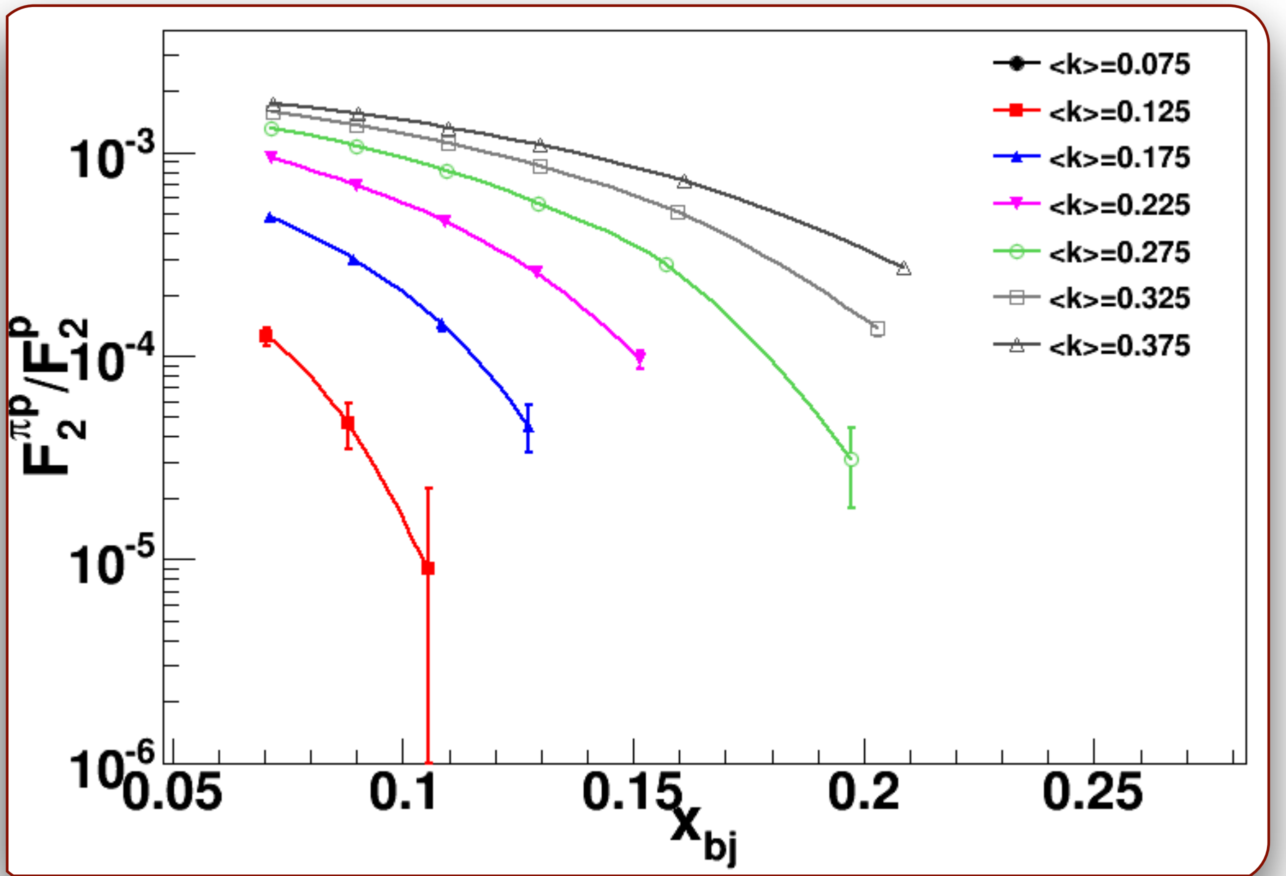


The TDIS experiment will measure tagged structure functions for protons and neutrons

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:

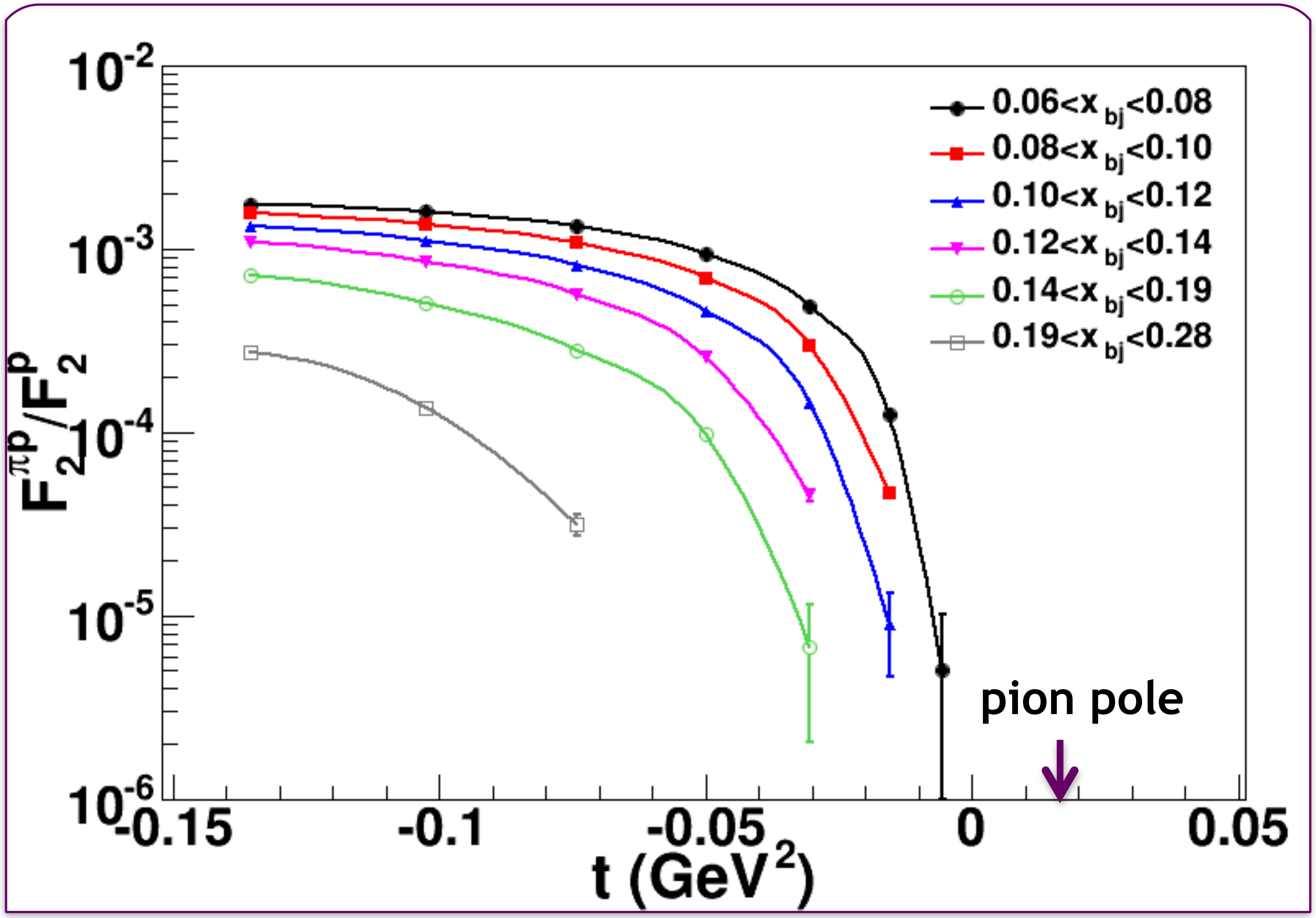
- 150 < k < 400 MeV/c corresponds to z < ~0.2
- Also, x < z
- Low x, high W at 11 GeV means Q^2 ~2 GeV^2

The TDIS experiment will also extract the pion structure function.

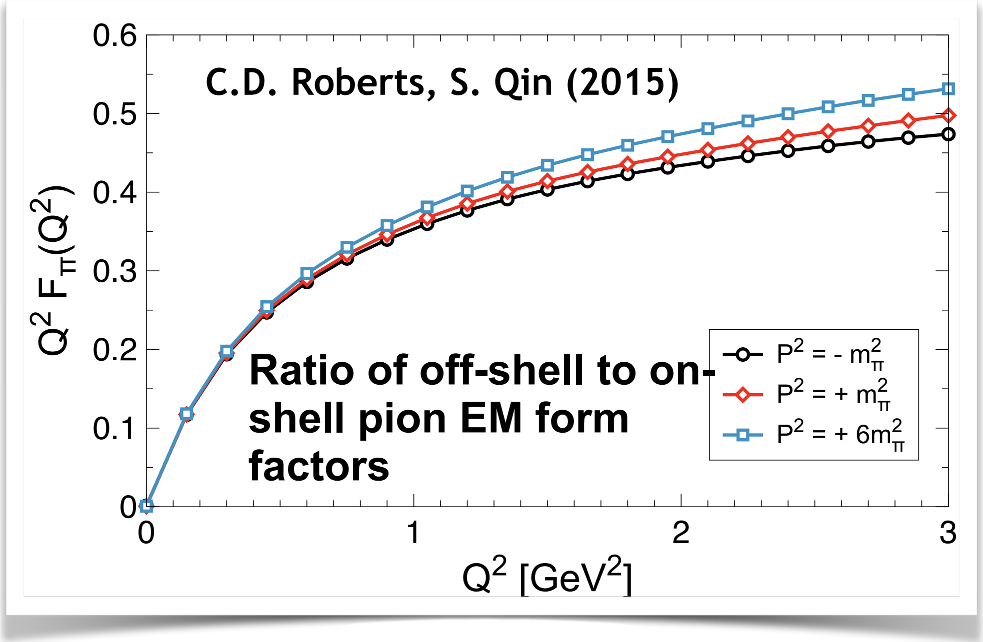
It requires extrapolation to the pion pole

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

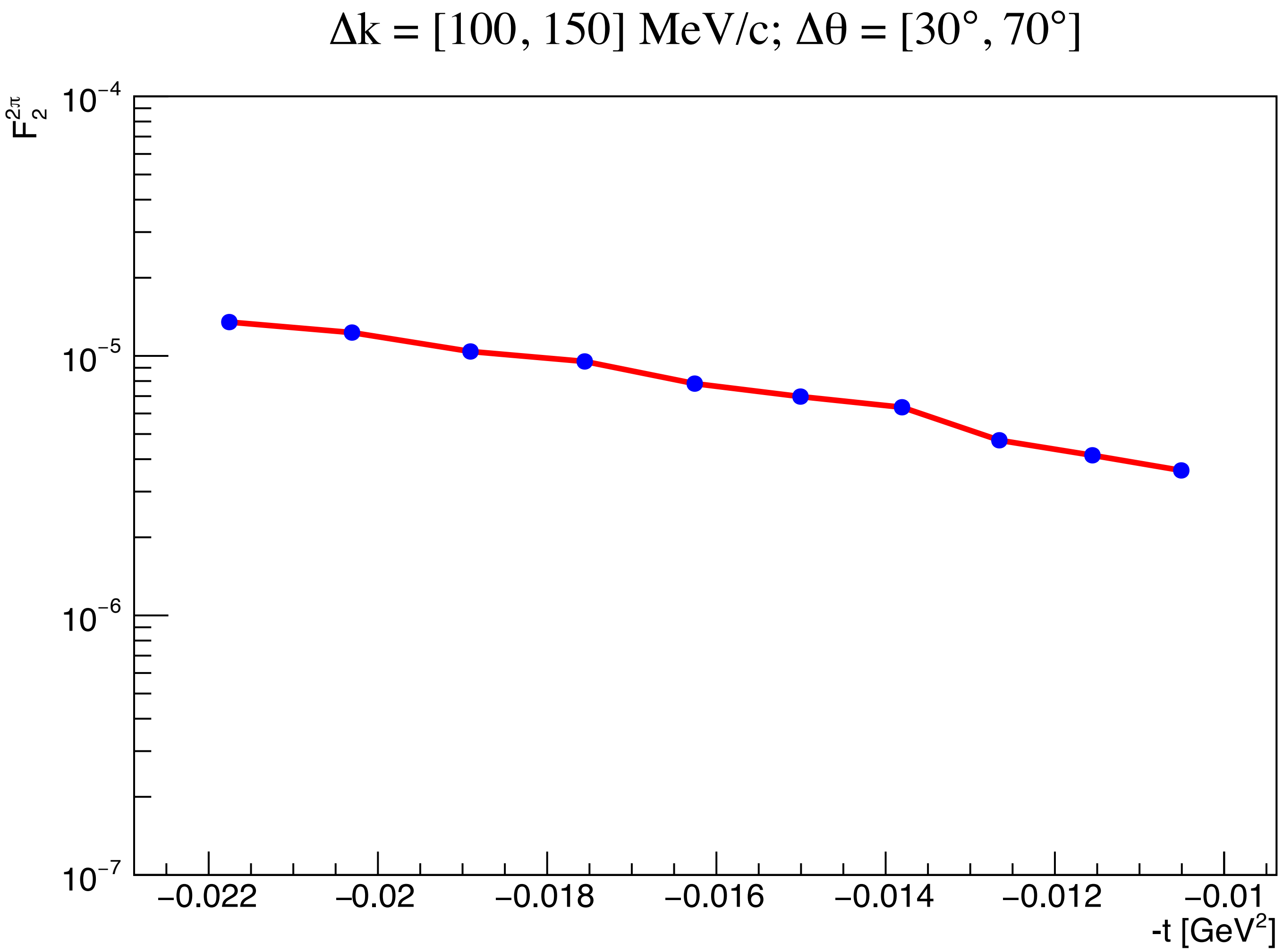
- Low t extrapolation to the pion pole

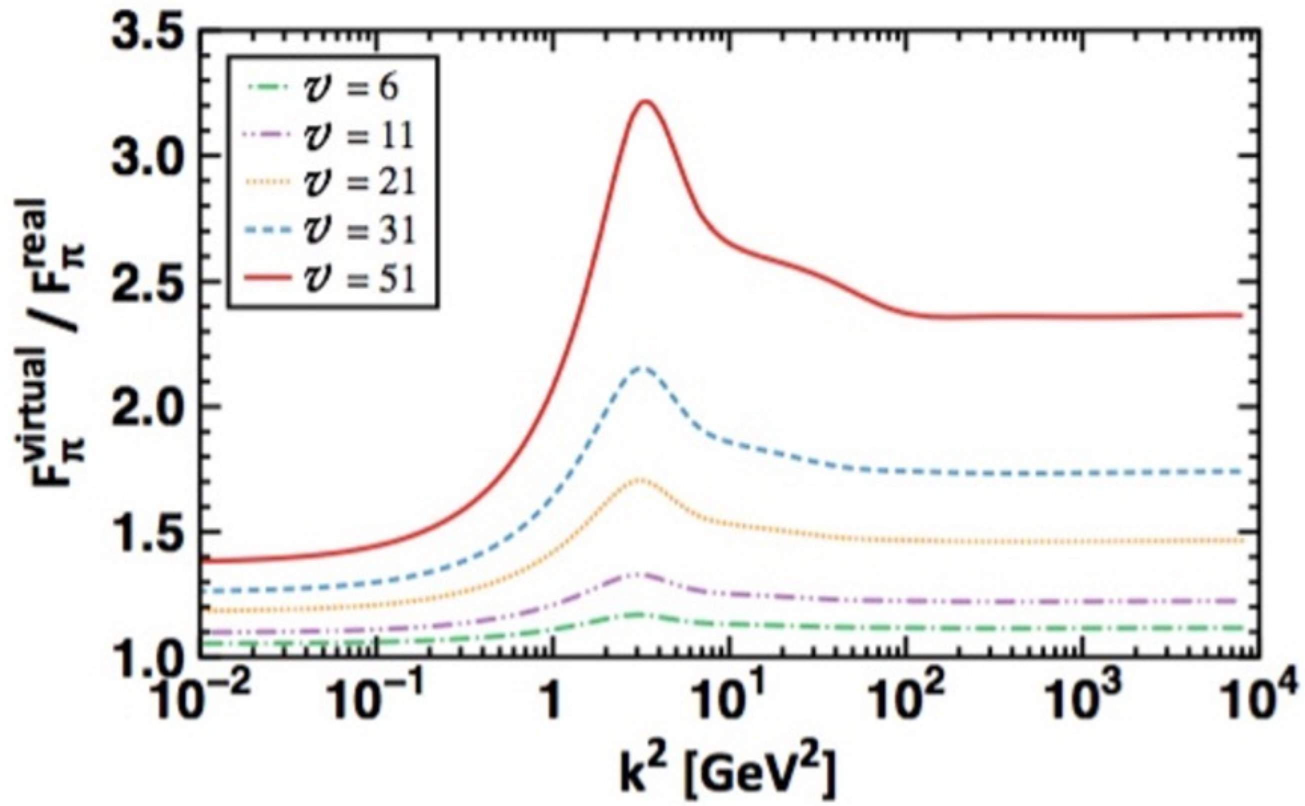


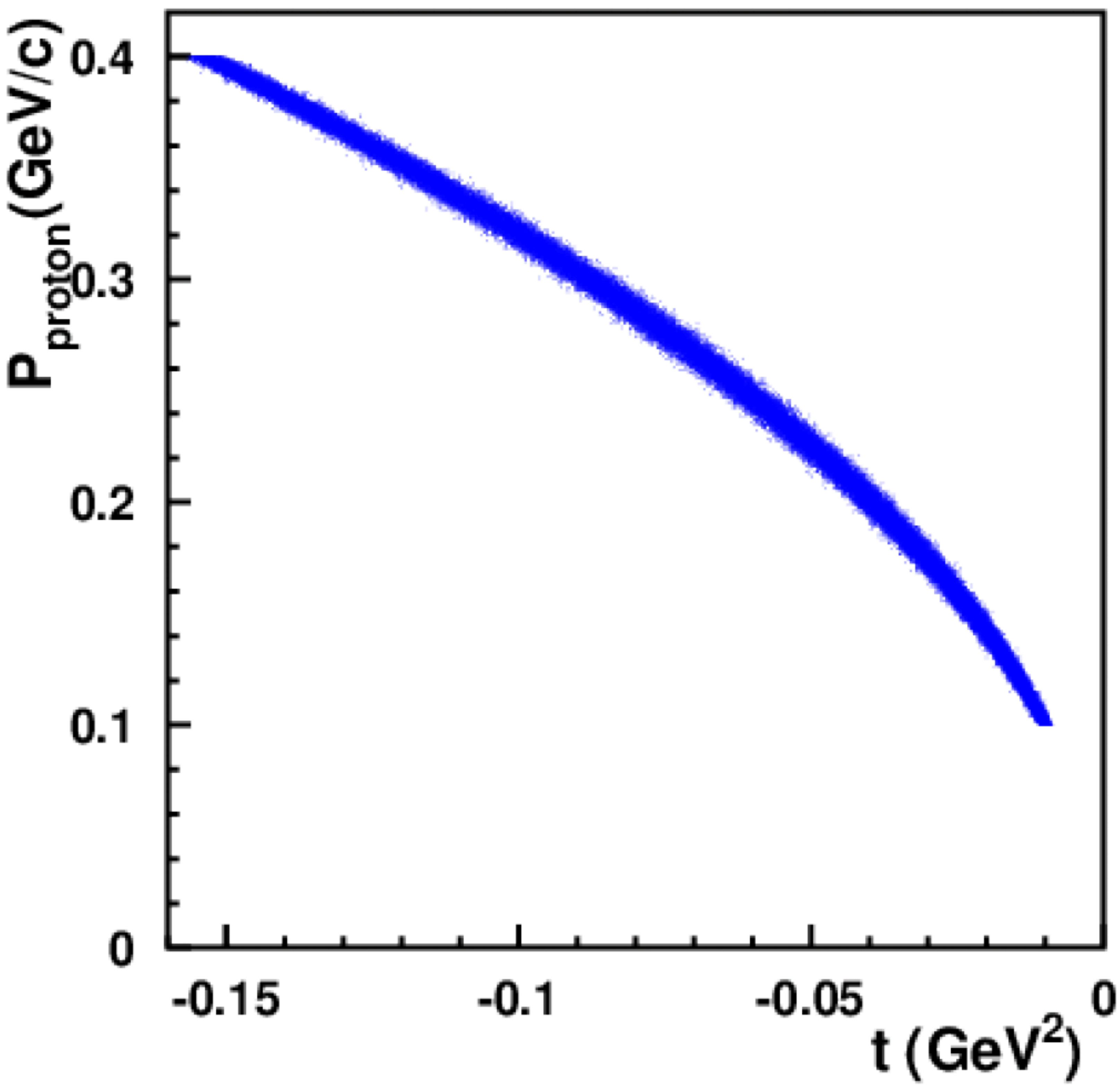
virtuality-independent form factor implies virtuality-independent pion structure function



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


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]

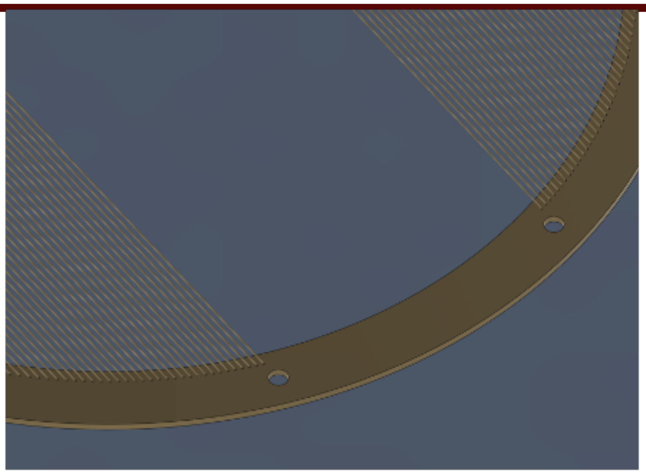

v = 6
v = 11
v = 21
v = 31
v = 51
$F_\pi^{virtual} / F_\pi^{real}$
3.5
3.0
2.5
2.0
1.5
1.0
10^{-2}
10^{-1}
1
10^1
10^2
10^3
10^4
k^2 [GeV^2]



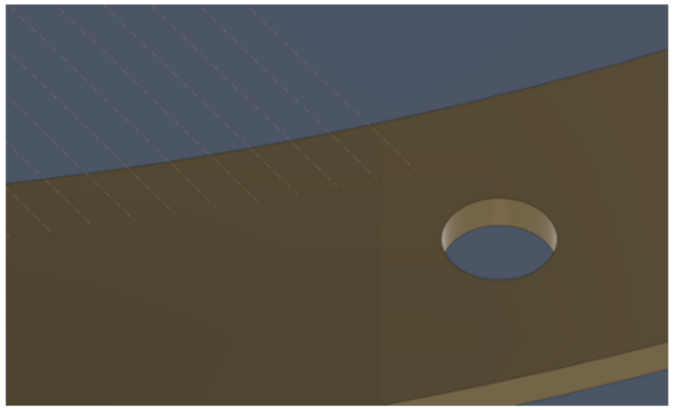
P_{proton} (GeV/c)
0.4
0.3
0.2
0.1
0
-0.15
-0.1
-0.05
0
t (GeV^2)

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

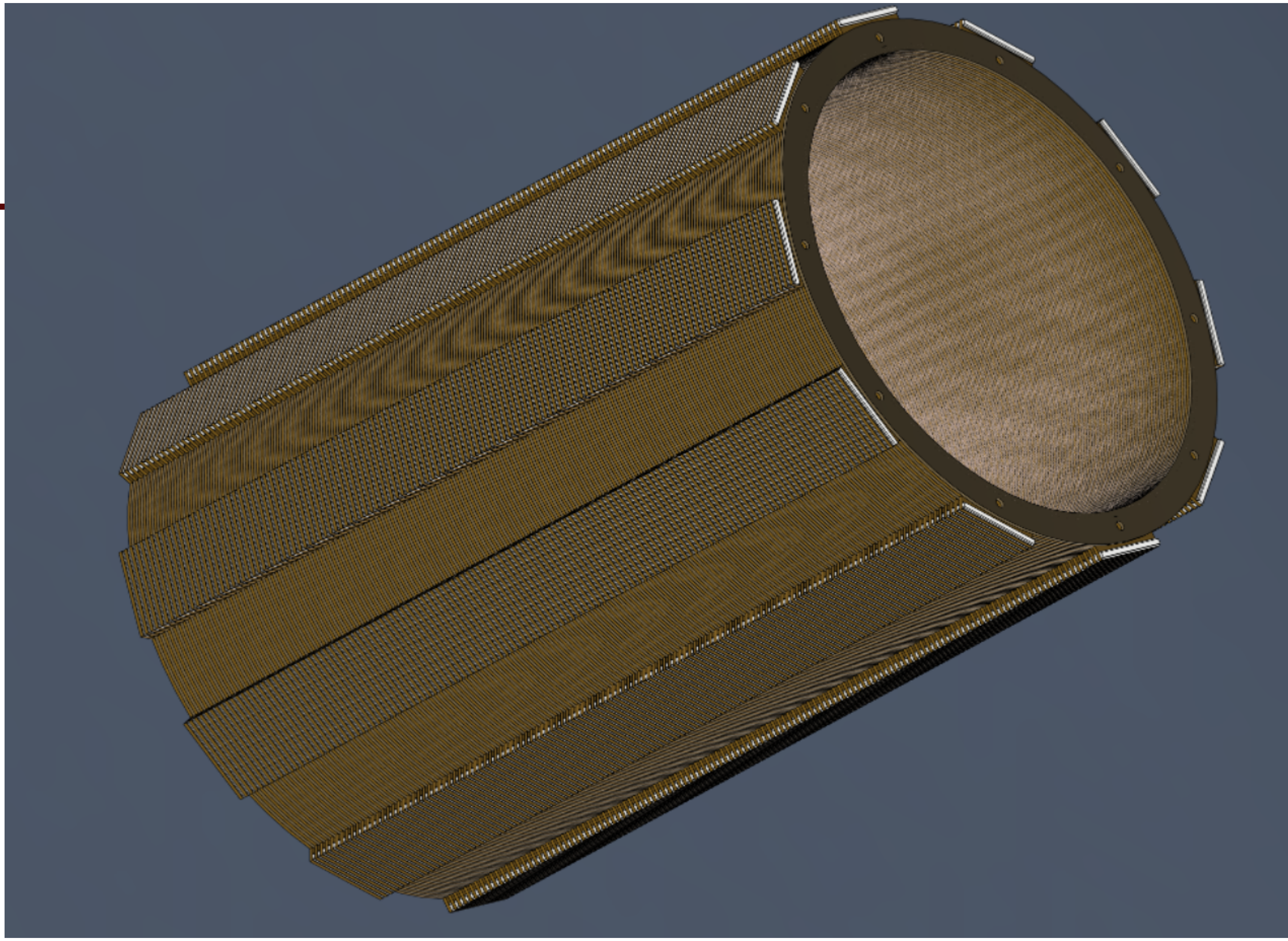
- Idea from Bogdan: build the recoil detector with wire planes; 2 mm wire pitch, 1 mm plane separation: compared to mTPC
  - Drift length feeding into signals down from 50 to 2 mm: factor of 25 reduction in plane occupancy.
  - mTPC has an integration time for 50 mm to form a track; but we need only 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.



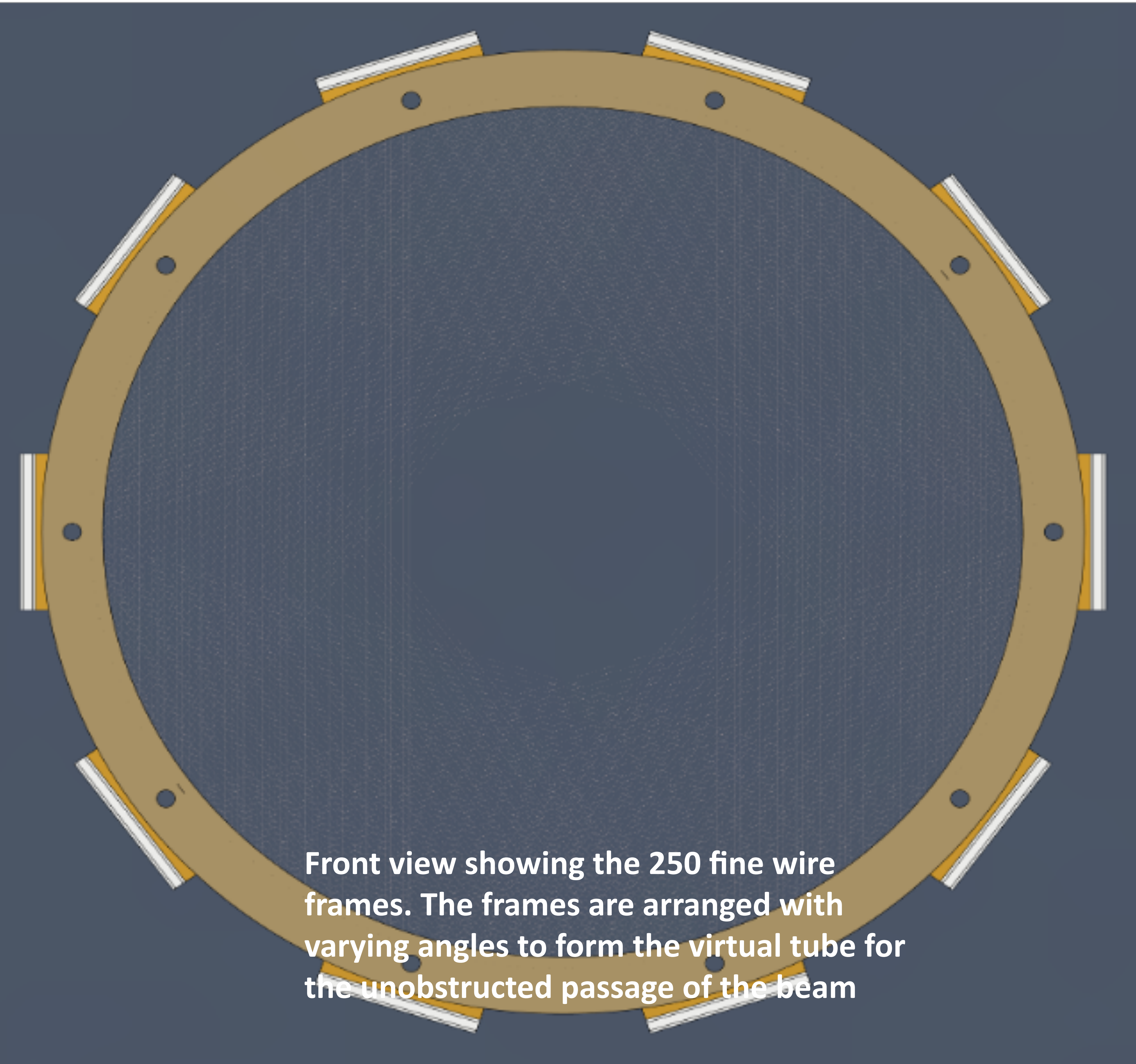
One frame, showing the gap which forms the beam "pipe". The wires are enlarged to 0.5mm for view (all other images are for actual 0.025mm wires.



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